NBER WORKING PAPER SERIES

FOREIGN SAFE ASSET DEMAND AND THE DOLLAR EXCHANGE RATE

Zhengyang Jiang
Arvind Krishnamurthy
Hanno Lustig

Working Paper 24439
http://www.nber.org/papers/w24439

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
March 2018

We thank Chloe Peng and Ziqing Wang for excellent research assistance. We also thank Mark Aguiar, Mike Chernov, Magnus Dahlquist, Wenxin Du (discussant), Greg Duee, Charles Engel, Emmanuel Farhi, Maury Obstfeld (discussant), Pierre-Olivier Gourinchas (discussant), Ben Hébert, Zhiguo He (discussant), Oleg Itskhoki, Matteo Maggiori, Brent Neiman, Alexi Savov, Jesse Schreger (discussant), Lukas Schmid (discussant), Dongho Song (discussant), Jeremy Stein, Adrien Verdelhan and Stanley Zin for helpful discussions, and seminar participants at the BIS, Carnegie Mellon, Chicago Booth, Columbia, Harvard Business School, Northwestern Kellogg, New York Fed, NYU, Ohio State, San Francisco Fed, Stanford, UT-Austin and UC-Boulder as well as the participants at CESifo Area Conference, the NBER SI IFM 2018, Vienna Symposium on Foreign Exchange Markets, the NBER Fall AP 2018, the 2019 inaugural David Backus conference on macro-nance, the 2019 Toulouse/CBL conference, and the 2019 AEA for their comments. We have read the Journal of Finance disclosure policy and have no conicts of interest to disclose. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

Foreign Safe Asset Demand and the Dollar Exchange Rate
Zhengyang Jiang, Arvind Krishnamurthy, and Hanno Lustig
NBER Working Paper No. 24439
March 2018, Revised in September 2020
JEL No. G15

ABSTRACT

We develop a theory that links the U.S. dollar's valuation in FX markets to the convenience yield that foreign investors derive from holding U.S. safe assets. We show that this convenience yield can be inferred from the Treasury basis: the yield gap between U.S. government and currency-hedged foreign government bonds. Consistent with the theory, a widening of the basis coincides with an immediate appreciation and a subsequent depreciation of the dollar. Our results lend empirical support to models which impute a special role to the U.S. as the world's provider of safe assets and the dollar, the world's reserve currency.

Zhengyang Jiang
Kellogg School of Management
Northwestern University
2211 Campus Drive
Evanston, IL 60610
zhengyang.jiang@kellogg.northwestern.edu

Arvind Krishnamurthy
Stanford Graduate School of Business
Stanford University
655 Knight Way
Stanford, CA 94305
and NBER
akris@stanford.edu

Hanno Lustig
Stanford Graduate School of Business
655 Knight Way
Stanford, CA 94305
and NBER
hlustig@stanford.edu

In the post-war era, the U.S. has been the world's most favored supplier of safe assets. Investors forgo a sizeable return, the convenience yield, to own these assets (see Krishnamurthy and Vissing-Jorgensen, 2012, for example). Moreover, during episodes of global financial instability, there is a flight to the safety of U.S. Treasury bonds as the convenience yield on Treasurys rises. At the same time, the dollar appreciates in foreign currency markets. Our paper develops a theory that explains these stylized facts. In our new convenience yield theory of exchange rates, the dollar's valuation reflects the current and future convenience yields that foreign investors derive from the ownership of U.S. safe assets. We find that the convenience yields earned by foreign investors on U.S. Treasurys are large and account for a sizeable share of the variation in the dollar exchange rate. On average, foreign investors earn an extra convenience yield of 2% on Treasury holdings; 90% of this yield is directly attributable to their dollar denomination. Thus, our study sheds light on how the U.S.' role as the world's safe asset supplier, analyzed by Gourinchas and Rey (2007b); Caballero et al. (2008); Caballero and Krishnamurthy (2009); Maggiori (2017); He et al. (2019); Gopinath and Stein (2018), has shaped the dynamics of the dollar exchange rate.

Our paper explores the response of the dollar exchange rate when foreign investors impute a higher convenience yield to U.S. safe assets, such as U.S. Treasurys, than U.S. investors. In equilibrium, foreign investors should receive a lower return in their own currencies on holding U.S. safe assets than U.S. investors. To produce lower expected returns on U.S. safe assets in foreign currency, the dollar has to appreciate today and, going forward, depreciate in expectation to deliver a lower expected return to foreign investors. We derive a novel expression for the dollar exchange rate as the expected value of all future interest rate differences and convenience yields less the value of all future currency risk premia, extending the work by Campbell and Clarida (1987); Clarida and Gali (1994); Froot and Ramadorai (2005). Our theory predicts that a country's exchange rate will appreciate whenever foreign investors increase their valuation of the current and future convenience properties of that country's safe assets.

To develop a measure of the unobserved convenience yield on U.S. safe assets derived by foreign investors, we focus on U.S. Treasury bonds as the safest among the set of U.S. safe assets. U.S. Treasury bonds are known to offer liquidity and safety services to investors which results in lower equilibrium returns to investors from holding such bonds (see Krishnamurthy and Vissing-Jorgensen, 2012; Greenwood et al., 2015). In our model, the foreign convenience yield is proportional to the Treasury basis, the difference in yields between the dollar yield on short-term U.S. Treasury bonds and short-term foreign government bonds, currency-hedged, into U.S. dollars. Even in the absence of frictions, covered interest rate parity (henceforth CIP) cannot hold for Treasurys when investors derive convenience yields from cash positions in these securities.

We measure this wedge using data on spot exchange rates, forward exchange rates, and pairs of government bond yields in a panel of G10 countries that starts in 1988. We supplement our analysis with a dataset for the U.S/U.K. cross that begins in 1970.[1] The U.S. Treasury basis is generally negative and widens during global financial crises. These negative bases are pervasive even before the 2007—2009 global financial crisis.

On average, foreigners earn at least an additional 2% convenience yield on U.S. Treasurys according to our estimates. Around 90% of the extra convenience yield is attributable to the dollar exposure rather than the safety/liquidity of Treasurys. If safe and liquid U.S Treasurys were not issued in dollars, they would carry a convenience yield of about 0.2% more than the average non-US G10 government bond. Thus, investors particularly value safe and liquid payoffs that are denominated in dollars. Our findings imply that dollar-Libor deposits as well as other safe dollar-denominated assets are good substitutes for U.S. Treasurys and also carry a convenience yield.

[1] Results for this dataset are reported in Section H of the Appendix and are broadly consistent with the results reported in the main text.

Exchange rates seem only weakly correlated with the macro-economic and financial variables that ought to drive exchange rate variation (see, e.g., Froot and Rogoff, 1995; Frankel and Rose, 1995, on the exchange rate disconnect puzzle). Our work helps to resolve the exchange rate disconnect puzzle. Using simple univariate regressions, we show that innovations in the U.S. Treasury basis account for 17% of the variation in the spot dollar exchange rate, with the right sign: a decrease in the basis coincides with an appreciation of the dollar. Moreover, a decrease in the basis today predicts a future depreciation of the dollar at longer horizons. We find a much weaker relation between foreign Treasury bases and the exchange rates of the corresponding currencies. For example, a widening of the U.K. Treasury basis does not lead to a significant appreciation of the pound against other currencies. Our result lends support to the proposition that the U.S. and the U.S. dollar occupy a unique position in the international monetary system.

Complete market models of exchange rates fall short when confronted with the data. Real exchange rates do not co-vary with macroeconomic quantities in the right way (see Backus and Smith, 1993; Kollmann, 1995). Real exchange rates do not vary counter-cyclically, and real exchange rates are not volatile enough when confronted with the evidence from asset prices (Brandt et al., 2006). Convenience yields introduce a wedge into the foreign investors' Euler equation. Adopting a preference-free approach, Lustig and Verdelhan (2019) demonstrate that incomplete markets models without these wedges cannot simultaneously address the U.I.P. violations, the exchange rate disconnect, i.e. the countercyclical variation, and the exchange rate volatility puzzles, while Itskhoki and Mukhin (2017) show that models with such a wedge can address the exchange rate disconnect puzzle. Our work identifies convenience yields as a key wedge between the real exchange rates and the difference in the log pricing kernels that can quantitatively help to resolve this disconnect.

In our VAR analysis, we find that a one standard deviation positive shock to the convenience yield widens the annualized Treasury basis by 20 bps, and results in a 3% appreciation in the dollar over the next 2 quarters. Subsequently, there is a gradual reversal over the next two to three years as the high convenience yield leads to a negative excess return on owning the U.S. dollar. Using our new convenience-yield valuation equation for the exchange rate, we implement a Campbell-Shiller-style decomposition of exchange rate innovations into a cash flow component which tracks interest rate differences, a discount rate component which tracks currency risk premia, and, finally, a convenience yield component. The convenience yield channel is quantitatively important: under our benchmark calibration in which around 90% of the Treasury's convenience yield is attributable to the dollar exposure, the convenience yield accounts for between 16% and 28% of the variation in the quarterly exchange rate. In Froot and Ramadorai (2005)'s decomposition, the convenience yield component would have been absorbed by the discount rate component.

The paper proceeds as follows. Section II sets out the stylized facts regarding the U.S. Treasury basis. Section III lays out the convenience yield theory of exchange rates. Section IV takes the theory to data. Section V decomposes the dollar exchange rate variation into a convenience yield, an interest rate and a risk premium component. Section VI concludes. The figures and tables are printed at the end of the paper. The proofs and the state space representation are in the appendix. The separate online appendix provides further derivations of the theory, additional empirical evidence, and details our data sources.

I. Related Literature

Our results lend empirical support to theories of the U.S. as the provider of world safe assets. There is ample empirical evidence that non-U.S. borrowers tilt the denomination of their borrowings (loans, deposits, bonds) especially towards the U.S. dollar (see Shin, 2012; Brauning and Ivashina, 2017; Bruno and Shin, 2017, on bank borrowing, and corporate bond borrowing respectively). Moreover, foreign investors tilt their portfolio towards owning U.S.

dollar-denominated corporate bonds when they invest in bonds denominated outside their home currencies (see Maggiori et al., 2020a). This quantity evidence does not identify whether demand or supply factors are the main drivers of the dollar bias in credit markets . Our evidence from sovereign bond markets supports a demand-based explanation. The Treasury dollar basis is typically negative and reductions in the basis appreciate the dollar, suggesting that foreign investors' special demand for dollar-denominated assets lowers their expected returns.

There is a separate literature on the special role of the U.S. dollar and U.S. asset markets in the world economy. Gourinchas and Rey (2007a); Pierre-Olivier et al. (2011); Maggiori (2017) focus on the "exorbitant privilege" of the U.S. that drives low rates of return on U.S. dollar assets. In their analysis, the U.S. provides insurance to the rest of the world, while Gopinath (2015) highlights the dominant role of the dollar as an invoicing currency. Lustig et al. (2014) present evidence that a global dollar factor drives currency returns around the world. Our results underscore that there is something special about the dollar but does not directly speak to the evidence of this literature.

Our empirical approach is directly related to four other recent papers. First, Du et al. (2018a) also study the Treasury basis, but for a different purpose. They note that the U.S. Treasury basis is negative for short-maturity bonds, suggesting that short-maturity bonds carry a convenience yield. They delve into the term-structure of the basis, noting that the basis for long-maturity bonds has been positive recently. We use the basis to infer a convenience yield, but our main interest is in showing that the basis has explanatory power for the dollar exchange rate.[2]

Second, Valchev (2020) shows that the quantity of outstanding U.S. Treasury bonds helps to explain the return on the dollar. Valchev (2020) builds an open-economy model to relate the quantity of U.S. Treasury bonds to the convenience

[2] An abridged version of the theory in this paper as well as results similar to that presented in Table 3 are published in Jiang et al. (2018).

yield on Treasury bonds and the failure of uncovered interest parity. We show that the existence of a foreign convenience yield for U.S. Treasury bonds causes both uncovered interest parity and covered interest parity to fail. Moreover, we show that variation in the convenience yields as measured by the dollar basis explains a sizeable portion of the variation in the dollar exchange rate. In closely related work, Koijen and Yogo (2020) estimate a global demand system for assets (short-term bonds, long term bonds and equities) in which exchange rates help to clear assets markets. Downward sloping demand for sovereign bonds is consistent with convenience yields. They find that latent demand shocks play an important role in accounting for exchange rate variation.

Third, there is a recent literature that explores the failure of LIBOR covered interest rate parity (see Ivashina et al., 2015; Du et al., 2018b). A common conclusion from this literature is the LIBOR-based CIP fails in part because of financial constraints faced by banks. Our results reinforce this conclusion, and we add to it by showing that LIBOR CIP fails when there is *both* foreign demand for dollar-LIBOR assets and financial constraints faced by banks in supplying dollar-denominated LIBOR deposits. When these constraints bind, the LIBOR basis reflects the foreign demand for dollar-denominated safe assets and will help to explain movements in the dollar exchange rate. Our empirical evidence is consistent with this LIBOR mechanism.

Finally, in work subsequent to ours, Engel and Wu (2018) analyze non-dollar currency pairs, and report evidence that CIP violations in sovereign bond markets for non-dollar pairs have significant explanatory power for bilateral exchange rates. In our sample, we find this relation to be much weaker for other currencies when we exclude the dollar from all bilateral pairs.

II. The U.S. Treasury Basis: Stylized Facts

Our paper relates movements in the value of the dollar exchange rate to the demand for dollar safe assets. The key metric for this demand for dollar safe assets is the U.S. Treasury basis. This section defines the Treasury basis and presents some stylized facts on the movement of the basis. The next sections present theory to tie the basis to the demand for dollar safe assets.

We define the U.S. Treasury basis as the difference between the yield on a cash position in U.S. Treasurys $y_t^{\$}$ and the synthetic dollar yield constructed from a cash position in a foreign government bond, which earns a yield y_t^* in foreign currency, that is hedged back into dollars:

$$x_t^{Treas} \equiv y_t^{\$} + (f_t^1 - s_t) - y_t^*. \tag{1}$$

Here s_t denotes the log of the nominal exchange rate in units of foreign currency per dollar and f_t^1 denotes the log of the forward exchange rate. x_t^{Treas} measures the violation of CIP constructed from U.S. Treasury and foreign government bond yields. A negative U.S. Treasury basis means that the U.S. Treasurys are expensive relative to their foreign counterpart. We also construct the LIBOR basis (x_t^{LIBOR}) using LIBOR rates. There is a recent literature examining the failure of the LIBOR CIP condition (see Ivashina et al. (2015); Du et al. (2018b)). Our Treasury basis measure is closely related to the LIBOR CIP deviation. That deviation is constructed using LIBOR rates for home and foreign countries while our basis measure is the same deviation but constructed using government bond yields for home and foreign countries. We discuss the relation between the Treasury basis and the LIBOR basis fully in Section B in the Appendix.

We develop and use two datasets, a panel of countries that spans 1988-2017 and a longer single time series from 1970 to 2016 for the United States/United Kingdom pair. The shorter panel is based on quarterly data from 10 developed economies. The countries are Australia, Canada, Germany, Japan, New Zealand, Norway, Sweden, Switzerland, United States, and United Kingdom. The sample starts in 1988Q1 and ends in 2017Q2. However, the panel is unbalanced, with data for only a few countries at the start of the sample. In order to ensure results from Treasury basis and results from Libor basis are comparable, we only include the country/quarter observations if both Treasury basis and Libor basis are available. Because New Zealand's 12-month Treasury yield is available from 1987 whereas its 12-month Libor rate is available from 1996, and Sweden's 12-month Treasury yield is available from 1984 whereas its 12-month Libor rate is available from 1991, we leave out some observations in which Treasury basis is available but Libor basis is not. We have confirmed our main empirical results are robust in the sample that contains these additional observations of Treasury basis. We also present results using the Treasury basis measurement for bonds with maturities greater than 1 year from Du et al. (2018a). Their sample is shorter but includes longer maturity bonds.

Our data comprises the bilateral exchange rates with respect to the U.S. dollar, 12-month bilateral forward foreign exchange contract prices, and 12-month government bond yields and LIBOR rates in all 10 countries. We use actual rather than fitted yields for government bonds whenever possible. The Bloomberg yield data used by Du et al. (2018a) is from a fitted yield curve, which can induce measurement errors. The main exception is the 2001:9—2008:5 period when the U.S. stopped issuing 12-month bills. We convert the daily data to quarterly frequencies using end-of-quarter observations on the same day for bond yields, interest rates, forward rates and exchange rates. There are some quarters for which all of the data are not available on the last day of the quarter, in which case we find a date earlier in the quarter, but as close to the end-of-quarter as possible, when all data are available. The Data Appendix in the separate online appendix contains information about data sources.

We construct the Treasury and LIBOR basis using the 12-month yields and forwards for each currency following (1). In each quarter, we construct the mean basis across all the countries in the panel for that quarter. Because the panel is unbalanced, we construct country-level changes in the basis first, and then take the cross-country average to arrive at the change in the basis. We denote the cross-sectional mean basis in the panel as $\overline{x}_t^{Treas}$. Similarly, we use $\overline{y}_t^* - y_t^\$$ to denote the cross-sectional average of yield differences, and $\bar{s}_t$ denotes the equally weighted cross-sectional average of the log of bilateral exchange rates against the dollar. For each of these cross-sectional averages, we employ the same set of countries that are in the sample at time t.

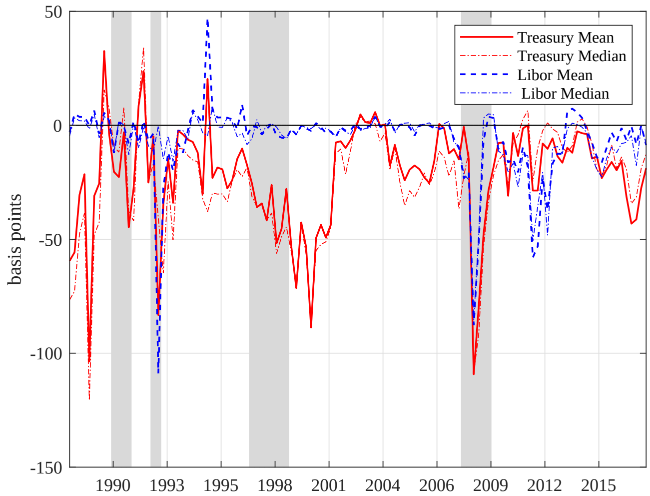

Figure 1. U.S. LIBOR and Treasury Bases

U.S. LIBOR and Treasury basis in basis points from 1988Q1 to 2017Q2. The maturity is one year. We plot the cross-sectional mean and median for each of the bases.

Figure 1 plots these series. The dotted line is the mean LIBOR basis of the U.S. dollar against the basket of currencies. The pre-crisis spikes in the average LIBOR basis are driven by idiosyncrasies of LIBOR rates in Sweden (currency crisis) in 1992 and Japan in 1995 (note the difference between the mean and median LIBOR basis in 1992 and 1995). The LIBOR basis is close to zero for most of the sample and turns negative and volatile beginning in 2007. These stylized facts about the LIBOR basis are known from the work of Du et al. (2018b).

The solid line is the mean Treasury basis. Unlike the LIBOR basis, the Treasury basis has always been negative and volatile. Table I reports the time-series moments of the Treasury basis, the Libor basis, the 12M (12-month) Treasury yield difference and the 12M forward discount. The average mean Treasury basis is -22 bps per annum, which means that foreign investors are willing to give up 22 bps per annum more for holding currency-hedged U.S. Treasurys than their own bonds. The standard deviation of the mean Treasury basis is 23 bps per quarter. In contrast, the average LIBOR basis is -6 bps. Section A of the Appendix consider the U.S./U.K. Treasury basis over a longer sample and finds similar dynamics.

Table I. Summary Statistics of Cross-sectional Mean Basis and Interest Rate Difference

Table reports summary statistics in percentage points for the 12M Treasury dollar basis $\overline{x}^{Treas}$, the Libor dollar basis $\overline{x}^{Libor}$, the 12M yield spread $y^{\$} - \overline{y}^{*}$, and the 12M forward discount $\overline{f-s}$ in logs. Table reports time-series averages, time-series standard deviations and correlations. Numbers reported are time-series moments of the cross-sectional means of the unbalanced Panel. The countries are Australia, Canada, Germany, Japan, New Zealand, Norway, Sweden, Switzerland, United States, and United Kingdom. The sample starts in 1988Q1 and ends in 2017Q2. For each of these cross-sectional averages, we employ the same set of countries that are in the sample at time t.

	$\overline{x}^{Treas}$	$\overline{x}^{Libor}$	$y^{\$} - \overline{y}^{*}$	$\overline{f-s}$
Panel A: 1988Q1—2017Q2				
mean	−0.22	−0.06	−0.74	−0.52
stdev	0.23	0.17	1.68	1.75
skew	−1.22	−3.04	−1.14	−0.89
$\overline{x}^{Treas}$	1.00	0.40	−0.24	−0.36
$\overline{x}^{Libor}$	0.40	1.00	0.37	0.30
$y^{U.S.} - \overline{y}^{*}$	−0.24	0.37	1.00	0.99
Panel B: 1988Q1—2007Q4				
mean	−0.22	−0.03	−0.76	−0.53
stdev	0.24	0.14	1.98	2.06
skew	−0.82	−4.51	−1.01	−0.79
$\overline{x}^{Treas}$	1.00	0.33	−0.29	−0.40
$\overline{x}^{Libor}$	0.33	1.00	0.46	0.40
$y^{U.S.} - \overline{y}^{*}$	−0.29	0.46	1.00	0.99
Panel C: 2008Q1—2017Q2				
mean	−0.21	−0.14	−0.70	−0.49
stdev	0.22	0.20	0.69	0.72
skew	−2.31	−1.84	0.54	0.59
$\overline{x}^{Treas}$	1.00	0.62	0.00	−0.30
$\overline{x}^{Libor}$	0.62	1.00	0.42	0.22
$y^{U.S.} - \overline{y}^{*}$	0.00	0.42	1.00	0.95

When LIBOR CIP holds, the Treasury basis is simply the difference between the U.S. Treasury-LIBOR spread and its foreign counterpart:

$$x_t^{Treas} = \left(y_t^{\$} - y_t^{\$,Libor}\right) - \left(y_t^{*} - y_t^{*,Libor}\right). \tag{2}$$

Before the financial crisis, when the LIBOR basis was close to zero (-3 bps), the Treasury basis (−22 bps) is mostly due to this differential in the Treasury-LIBOR spreads. The U.S. LIBOR-Treasury spread is 23 bps larger than its foreign counterpart. During and after the crisis, this U.S. LIBOR-Treasury spread is only 7 bps per annum higher than the foreign one, while the average LIBOR basis widens to −14 bps per annum. Over the entire sample, the Treasury and LIBOR basis have a correlation of 0.40. This correlation is largely driven by the post-crisis relation where the correlation 0.62. Finally, the Treasury basis is negatively correlated with the U.S.-foreign Treasury yield difference and the forward discount.

Table II. The Treasury Basis and Interest Rate Spreads

We regress the quarterly average Treasury basis, $\overline{x}^{Treas}$, on a number of U.S. money market spreads and the U.S. to foreign government bond interest rate differential. The spreads and interest rate differential are constructed as the quarterly average of the indicated series. Data is from 1988Q1 to 2017Q2 for the regressions with 118 observations and 2001Q4 to 2017Q2 for the regressions with 63 observations. OLS standard errors in parentheses. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	(1)	(2)	(3)	(4)	(5)	(6)
U.S. 6-month OIS−T-bill	0.03					
	(0.17)					
U.S. 6-month LIBOR−OIS		-0.38^{***}			-0.44^{***}	
		(0.04)			(0.03)	
U.S. 6-month LIBOR−T-bill			-0.43^{***}			-0.42^{***}
			(0.05)			(0.05)
$y^{\$} - \overline{y}^{*}$				-0.03^{***}	-0.08^{***}	-0.02^{**}
				(0.01)	(0.01)	(0.01)
Observations	63	63	118	118	63	118
R^2	0.0004	0.62	0.39	0.06	0.77	0.41

Table II provides some statistics on the covariates of the Treasury basis. In the first column, we regress the basis on the OIS-T-bill spread which is a measure of the liquidity premium on Treasury bonds. Note that the basis is negative on average (see Figure 1). There is little relation between the basis and OIS-Tbill. The second column instead uses the spread between LIBOR and OIS. This spread is strongly negatively related to the basis and the R^2 of the regression is 62%. When the LIBOR-OIS spread rises, as in a flight-to-quality, the basis goes more negative. Note that OIS data is only available since 2001. Column (3) reports the correlation with the LIBOR-Tbill spread which we can construct to the start of our sample in 1988. There is a strong negative relation between the spread and the basis, and we learn from columns (1) and (2) that the relation is likely due to the LIBOR-OIS component of this spread (note also that the coefficient on LIBOR-OIS is quite similar to the coefficient on LIBOR-T-bill). Column (4) includes the spread between U.S. interest rates and the mean foreign interest rate. When U.S. rates are high relative to foreign rates, the basis is more negative. We have run specifications where we include both U.S. and foreign interest rates, and subject to the caveat that these rates do move together, the correlation seems to be driven by the U.S. interest rate and not the foreign rate. Column (5) and (6) include both the LIBOR spread and the U.S. to world interest rate differential. The explanatory power for the basis is largely driven by the LIBOR spread. To see this, compare the R^2 in columns (5) and (6) to those in columns (3) and (4).

During episodes of global financial instability, there is a flight to the safety of U.S. Treasury bonds which increases their convenience yield (see Krishnamurthy and Vissing-Jorgensen, 2012, for example). During these episodes, the wedge between U.S. and foreign currency hedged Treasury yields rises. Figure 1 illustrates this pattern for the 2008 financial crisis. The dollar appreciates by about 30% over this period. The hypothesis of this paper is that the increase in the convenience yield on U.S. Treasury bonds assigned by foreign investors will also be reflected in an appreciation of the U.S. dollar. The spot exchange rate of a safe asset currency will reflect the cumulative value of all future convenience yields.

III. A Theory of Spot Exchange Rates, Forward Exchange Rates and Convenience Yields on Bonds

This section develops a theory of spot and forward exchange rates and convenience yields. There are two countries, foreign ($*$) and the U.S. (\$), each with its own currency. We use S_t to denote the nominal exchange rate in units of foreign currency per dollar, so that an increase in S_t corresponds to an appreciation of the U.S. dollar. There are domestic (foreign) nominal default-free government bonds denominated in dollars (in foreign currency). We derive bond and exchange rate pricing conditions that are implied by no-arbitrage.

We focus on the pricing of government bonds as the assets that produce convenience yields. As we will make clear, our theory is about the pricing of all U.S. dollar-denominated safe assets, not just U.S. Treasury bonds, but our empirical work is largely about the measured convenience yields on U.S. Treasury bonds. As a result, the expressions we derive for U.S. Treasury bonds will guide our empirical work.

A. Convenience yields and exchange rates

We use y_t^* to denote the nominal yield on a one-period risk-free zero-coupon bond in foreign currency. Likewise, $y_t^\$$ denotes the nominal yield on a one-period risk-free zero-coupon Treasury bond in dollars. The stochastic discount factor (SDF) of the foreign investor is denoted M_t^*, while that of the U.S. investor is denoted $M_t^\$$. We use $\lambda_t^{i,j}$ to denote the convenience yield of investors in country j for bonds issued by the government in country i. Foreign investors price foreign bonds denominated in foreign currency, and the foreign investor's Euler equation is given by:

$$\mathbb{E}_t \left(M_{t+1}^* e^{y_t^*} \right) = e^{-\lambda_t^{*,*}}, \qquad \lambda_t^{*,*} \geq 0. \tag{3}$$

The expression on the left side of the equation is standard. On the right side, we allow foreign investors to derive a convenience yield, $\lambda_t^{*,*}$, on their domestic bond holdings. $\lambda_t^{*,*}$ is asset-specific and hence cannot be folded into the stochastic discount factor. Our model abstracts away from the fact that the value of Treasury bonds is ultimately derived from the government's budget constraint. Chernov et al. (2020); Jiang (2019a,b); Jiang et al. (2019); Liu et al. (2019) study how the government budget affects currency returns and bond valuation.

Foreign investors can also invest in U.S. Treasurys. To do so, they convert local currency to U.S. dollars to receive $\frac{1}{S_t}$ dollars, invest in U.S. Treasurys, and then convert the proceeds back to local currency at date $t+1$ at S_{t+1}. Foreign investors in U.S. Treasurys derive a convenience yield, $\lambda_t^{\$,*}$, on their Treasury bond holdings:

$$\mathbb{E}_t\left(M_{t+1}^* \frac{S_{t+1}}{S_t} e^{y_t^{\$}}\right) = e^{-\lambda_t^{\$,*}}, \qquad \lambda_t^{\$,*} \geq 0. \tag{4}$$

Suppose the convenience yield $\lambda_t^{\$,*}$ rises, lowering the right side of equation (4). Then, the required return on the investment in U.S. Treasury bonds (the left side of the equation) falls; either the expected rate of dollar appreciation declines or the yield $y_t^{\$}$ declines, or both.

Next, we use these pricing conditions to derive an expression linking the exchange rate and the convenience yield. We assume that $m_t^* = \log\ M_t^*$ and $\Delta s_{t+1} = \log \frac{S_{t+1}}{S_t}$ are conditionally normal. Then, the Euler equation for the foreign bond in (3) can be rewritten as,

$$\mathbb{E}_t\left[m_{t+1}^*\right] + \frac{1}{2} var_t\left[m_{t+1}^*\right] + y_t^* + \lambda_t^{*,*} = 0, \tag{5}$$

and the Euler equation for the U.S. bond in (4) as,

$$\mathbb{E}_t\left[m_{t+1}^*\right] + \frac{1}{2} var_t\left[m_{t+1}^*\right] + \mathbb{E}_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] + y_t^{\$} + \lambda_t^{\$,*} - RP_t^* = 0. \tag{6}$$

$RP_t^* = -cov_t\left(m_{t+1}^*, \Delta s_{t+1}\right)$ is the risk premium the foreign investor requires for the exchange rate risk when investing in U.S. bonds. We combine these two expressions to find:

LEMMA 1: *The expected return in levels on a long position in dollars earned by a foreign investor is decreasing in the convenience yield gap:*

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) + \frac{1}{2} var_t[\Delta s_{t+1}] = RP_t^* - (\lambda_t^{\$,*} - \lambda_t^{*,*}). \tag{7}$$

The left hand side is the excess return earned by a foreign investor from investing in the U.S. bond relative to the foreign bond. This is the return on the reverse carry trade, given that U.S. yields are typically lower than foreign yields. On the right hand side, the first term is the familiar currency risk premium demanded by a foreign investor going long U.S. Treasurys in dollars. The second term is the convenience yield attached by foreign investors to U.S. Treasurys minus the convenience yield foreign investors derive from their holdings of their own bonds ("convenience yield gap"). A positive convenience yield gap, $\lambda_t^{\$,*} - \lambda_t^{*,*} > 0$, lowers the required return on the reverse carry trade, i.e., the return to investing in U.S. Treasury bonds. Even in the absence of priced currency risk, $RP_t^* = 0$, uncovered interest parity fails when the convenience yield gap is greater than zero.

B. U.S. demand for foreign bonds

Since U.S. investors have access to foreign bond markets, there is another pair of Euler equations to consider. An increase in the foreign convenience yield imputed to U.S. Treasurys implies an expected deprecation of the dollar. For a U.S. investor, buying foreign bonds when the dollar is expected to depreciate produces a high carry return. The U.S. investor's Euler equation when investing in the foreign bond is:

$$\mathbb{E}_t\left(M_{t+1}^{\$}\frac{S_t}{S_{t+1}}e^{y_t^*}\right) = e^{-\lambda_t^{*,\$}}, \qquad \lambda_t^{*,\$} \geq 0. \tag{8}$$

We also assume that U.S. investors derive a convenience yield when investing in U.S. Treasurys:

$$\mathbb{E}_t\left(M_{t+1}^{\$}e^{y_t^{\$}}\right) = e^{-\lambda_t^{\$,\$}}, \qquad \lambda_t^{\$,\$} \geq 0. \tag{9}$$

An increase in the U.S. investor's convenience yield lowers U.S. Treasury bond yields, holding the SDF fixed: $y_t^{\$} = \rho_t^{\$} - \lambda_t^{\$,\$}$, where $\rho_t^{\$} = -\log \mathbb{E}_t\left(M_{t+1}^{\$}\right)$. We assume log-normality and rewrite these equations to derive an expression for the carry trade return,

$$\left(y_t^* - y_t^\$\right) - \mathbb{E}_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] = RP_t^\$ + (\lambda_t^{\$,\$} - \lambda_t^{*,\$}). \tag{10}$$

where, $RP_t^\$ = -cov_t\left(m_{t+1}^\$, -\Delta s_{t+1}\right)$ is the risk premium the U.S. investor requires for the exchange rate risk when investing in foreign bonds (i.e. the risk premium attached to the dollar appreciating).

Finally, we combine (7) and (10) to derive a cross-country restriction on the convenience yields imputed to Treasurys and the currency risk premia,

$$(\lambda_t^{\$,*} - \lambda_t^{*,*}) - (\lambda_t^{\$,\$} - \lambda_t^{*,\$}) = rp_t^\$ + rp_t^*, \tag{11}$$

where we use $rp_t^\$ = RP_t^\$ - \frac{1}{2} var_t[\Delta s_{t+1}]$ and $rp_t^* = RP_t^* - \frac{1}{2} var_t[\Delta s_{t+1}]$ to denote the log currency risk premia.

LEMMA 2: *Under the assumption that the log currency risk premia are symmetric, $rp_t^\$ = -rp_t^*$, foreign and domestic investors agree on the relative convenience of Treasurys vs. foreign bonds:*

$$(\lambda_t^{\$,*} - \lambda_t^{*,*}) = (\lambda_t^{\$,\$} - \lambda_t^{*,\$}). \tag{12}$$

We will develop our model for this symmetric case because it easiest to exposit. Under the symmetry assumption, the convenience yield gaps between foreign and domestic bonds are the same for either foreign or U.S. investors, and it is this gap that enters exchange rate determination. We can deviate from symmetry in log currency risk premia and relax equation (12); however, this comes at the cost of additional complexity that we do not think adds to the analysis. We pursue this approach more systematically in related work (see, e.g. Jiang et al., 2020a,b).

C. Exchange rates, Interest Rates and Convenience yields

Next, we explore the implications of our theory for the level of the exchange rate. By forward iteration on (7), the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia and the future convenience yields (see Froot and Ramadorai, 2005, for a version without convenience yields). Campbell and Clarida (1987); Clarida and Gali (1994) developed an early version of this decomposition that imposed U.I.P.

LEMMA 3: *The level of the nominal exchange can be written as:*

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} (\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}) + \mathbb{E}_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^{*}) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^{*} + \mathbb{E}_t[\lim_{T\to\infty} \ s_{t+T}]. \tag{13}$$

The term $\mathbb{E}_t[\lim_{\tau\to\infty} \ s_{t+\tau}]$ is constant only if the nominal exchange rate is stationary.

The exchange rate level is determined by yield differences, the convenience yields, and the currency risk premia. This is an extension of Froot and Ramadorai (2005)'s expression for the level of exchange rates. The first term involves the sum of expected convenience yields $\lambda_{t+\tau}^{\$,*}$ earned by *foreign investors* on their holdings of U.S. Treasurys in excess of the convenience yields $\lambda_{t+\tau}^{*,*}$ earned on their own bonds. The second term involves the sum of bond yield differences. Note that the convenience yield earned by *U.S. investors* on their holdings of U.S. Treasurys lowers the U.S. Treasury yield $y_{t+\tau}^{\$}$ and hence lowers the second term. This expression implies that an increase in the expected future convenience yields earned by foreigners relative to those earned by U.S. investors should cause the dollar to appreciate today.

To clarify this latter point regarding convenience yields of foreign investors relative to U.S. investors, we rewrite (13) as the sum of the convenience yield differentials, the fundamental yield differences, stripped of the convenience yields, and the risk premia:

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} (\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{\$,\$}) + \mathbb{E}_t \sum_{\tau=0}^{\infty} (\rho_{t+\tau}^{\$} - \rho_{t+\tau}^{*}) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^{*} + \mathbb{E}_t [\lim_{\tau \to \infty} s_{t+\tau}]. \tag{14}$$

where $\rho_t^{\$} = -\log \mathbb{E}_t \left(M_{t+1}^{\$} \right) = y_t^{\$} + \lambda_t^{\$,\$}$ is the fundamental (no convenience effect) bond yield in dollars, and likewise for foreign. Expression (14) clarifies that the exchange rate responds only to the difference in convenience yields on U.S. Treasurys earned by foreigners and by domestic investors. When the foreign investors' convenience yields on Treasurys increases relative to the U.S. convenience yields, then the dollar appreciates.

Thus far we have not derived a process for the exchange rate. We begin by noting that when markets are complete, the unique exchange rate process that is consistent with absence of arbitrage opportunities is,

$$\Delta s_{t+1} = m_{t+1}^{\$} - m_{t+1}^{*}. \tag{15}$$

See for example Backus et al. (2001). When markets are incomplete, an exchange rate process that satisfies all of four of the Euler equations (two investors in two bonds) is:

$$\Delta s_{t+1} = m_{t+1}^{\$} - m_{t+1}^{*} + \eta_{t+1} + \lambda_t^{\$,\$} - \lambda_t^{\$,*} \tag{16}$$

where η_{t+1} is an incomplete markets wedge that satisfies restrictions to enforce the Euler equations for bond investors (Lustig and Verdelhan, 2019). This expression also underscores that markets must be incomplete in our convenience yield theory. If markets were complete, $\eta_{t+1} = 0$ are zero in all states of the world and the convenience yield gap, $\lambda_t^{\$,\$} - \lambda_t^{\$,*}$, must be zero. We can derive an expression for s_t by forward substitution (16), and after taking expectations, we recover the expression in (13). Section B of the Appendix contains a detailed derivation behind these statements.

Next, we derive expressions for the real exchange rate, which is likely to be stationary regardless of the macroeconomic environment. We denote the log of the foreign and domestic price levels as p_t^* and $p_t^\$$, respectively. The real exchange rate is,

$$q_t = s_t + p_t^\$ - p_t^*. \tag{17}$$

We substitute the real exchange rate expression, (17), into the earlier expressions for nominal exchange rates and rewrite to find the following result.

LEMMA 4: *The level of the real exchange rate can be written as:*

$$q_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} (\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}) + \mathbb{E}_t \sum_{\tau=0}^{\infty} (r_{t+\tau}^\$ - r_{t+\tau}^*) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t[\lim_{T\to\infty} q_{t+T}] \tag{18}$$

where $r_t^\$$ and r_t^* are the real interest rates, i.e., $y_t^\$ - \mathbb{E}_t[\Delta p_{t+1}^\$]$ is the real dollar interest rate.

The last term, $\bar{q} = \mathbb{E}_t[\lim_{\tau\to\infty} q_{t+\tau}]$, is constant if the real exchange rate is stationary.

The first component measures the impact of variation in the convenience yield earned by foreign investors from holding U.S. Treasurys on the real exchange rate. The second component measures real yield differences, which the effects of convenience yields earned by U.S. investors. The last component measures risk premia. In Section V of this paper, we estimate each of these components.

D. *The Treasury basis, Convenience Yields, and Dollarness*

The key variable in our theory is $\lambda_t^{\$,*} - \lambda_t^{*,*}$, the extra convenience yield earned by foreign investors on their holdings of U.S. Treasurys in excess of the foreign government bond. This object can be inferred from the Treasury basis. To do so, we consider the foreign investor's Euler equation for an investment in a foreign government bond that is swapped into dollars via the forward market. The investors owns a bundle of a safe foreign government bond, providing a convenience yield $\lambda_t^{*,*}$, and a forward position. Together, these produce a synthetic

"Treasury" that is not as safe and liquid as the cash position in U.S. Treasurys, because the synthetic position involves some bank counter-party risk and the foreign bond is not as liquid as the U.S. Treasury bonds. Thus, we posit that the synthetic position provides a convenience yield between that of the foreign government bond and U.S. Treasurys:

$$\mathbb{E}_t \left[M^*_{t+1} \frac{S_{t+1}}{S_t} \frac{S_t}{F^1_t} e^{y^*_t} \right] = e^{-\lambda^{*,*}_t - \beta^* (\lambda^{\$,*}_t - \lambda^{*,*}_t)}. \tag{19}$$

Here F^1_t denotes the one-period forward exchange rate, in foreign currency per dollar, and β^*, with $0 < \beta^* < 1$, denotes the fraction of convenience yield on the cash position in the foreign bond hedged into dollars relative to the U.S. Treasury investment. We will estimate this fraction in our empirical work. If $\beta^* = 0$, then the "dollarness" created by adding the forward position to the foreign government bond provides no incremental convenience benefits to the foreign investor. In this case, both U.S. Treasury bonds and foreign government bonds are valued for their liquidity and safety properties in their respective currencies. If $\beta^* = 1$, then the "dollarness" provided by the hedge converts the foreign government bond to the equivalent of a U.S. Treasury. In this case, we learn that investors particularly value safe and liquid bonds whose payoffs are denominated in dollars.

We can use (19) along with the foreign investor's Euler equation for the U.S Treasury bond, (4), to find an expression for the unobserved U.S. Treasury convenience yield gap.

LEMMA 5: *The foreign convenience yield gap on U.S. Treasury bonds is proportional to the Treasury basis:*

$$x^{Treas}_t \equiv y^{\$}_t + (f^1_t - s_t) - y^*_t = -(1 - \beta^*)(\lambda^{\$,*}_t - \lambda^{*,*}_t). \tag{20}$$

This lemma is the key to our empirical work as it provides a measure of the convenience yields that drives our theory.

We can also consider the basis from from the standpoint of the U.S. investor. Suppose the U.S. investor invests in the foreign bond swapped into dollars, and receives a convenience yield equal to $\lambda_t^{*,\$} + \beta^{\$}(\lambda_t^{\$,\$} - \lambda_t^{*,\$})$. Here again $\beta^{\$}$ measures the fraction of convenience gained, relative to the U.S. Treasury bond, by converting the foreign government bond into a dollar payoff. The basis can be shown to be equal to,

$$x_t^{Treas} = -(1-\beta^{\$})(\lambda_t^{\$,\$} - \lambda_t^{*,\$}),$$

which is equal to (20) when $\beta^{\$} = \beta^*$, given the symmetry restriction in (12).[3]

E. Summary

We arrive at five key implications of our theory relating the Treasury basis to the dollar exchange rate. We will test each of these in the data.

PROPOSITION 1: **Treasury basis and the dollar**

1. *The level of the nominal exchange can be written as:*

$$s_t = -\mathbb{E}_t \sum_{\tau=0}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + \mathbb{E}_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^*) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t[\lim_{T\to\infty} s_{t+T}]. \tag{21}$$

2. *The level of the real exchange can be written as:*

$$q_t = -\mathbb{E}_t \sum_{\tau=0}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + \mathbb{E}_t \sum_{\tau=0}^{\infty} (r_{t+\tau}^{\$} - r_{t+\tau}^*) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t[\lim_{T\to\infty} q_{t+T}]. \tag{22}$$

   where $\mathbb{E}_t[\lim_{\tau\to\infty} q_{t+\tau}]$ is constant under the assumption that the real exchange rate is stationary. The terms $r_t^{\$}$ and r_t^* are the real interest rates, i.e., $y_t^{\$} - \mathbb{E}_t[\Delta p_{t+1}^{\$}]$ is the real dollar interest rate.

3. *The expected log excess return to a foreign investor of a long position in*

[3] The observation that Treasury-based CIP violations may be driven by convenience yields was pointed out by Adrien Verdelhan in a discussion at the Macro Finance Society (2017).

Treasury bonds is increasing in the risk premium and the Treasury basis:

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) = rp_t^* + \frac{1}{1-\beta^*} x_t^{Treas}. \tag{23}$$

4. *The expected log return to a foreign investor of going long the dollar via the forward contract is:*

$$\mathbb{E}_t[\Delta s_{t+1}] - (f_t^1 - s_t) = rp_t^* + \frac{\beta^*}{1-\beta^*} x_t^{Treas}. \tag{24}$$

5. *The change in the nominal exchange rate can be decomposed as* $\Delta s_{t+1} = (\mathbb{E}_{t+1} - \mathbb{E}_t)\, s_{t+1} + \mathbb{E}_t[\Delta s_{t+1}]$ *where the innovation is given by:*

$$\begin{aligned}(\mathbb{E}_{t+1} - \mathbb{E}_t)\, s_{t+1} \quad &= \quad -(\mathbb{E}_{t+1} - \mathbb{E}_t) \sum_{\tau=1}^{\infty} \frac{x_{t+\tau}^{Treas}}{1-\beta^*} + (\mathbb{E}_{t+1} - \mathbb{E}_t) \sum_{\tau=1}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^*) \\ &- \quad (\mathbb{E}_{t+1} - \mathbb{E}_t) \sum_{\tau=1}^{\infty} rp_{t+\tau}^* + (\mathbb{E}_{t+1} - \mathbb{E}_t) \lim_{T\to\infty} s_{t+T}. \end{aligned} \tag{25}$$

IV. Joint Dynamics of the Dollar Exchange Rate, the Treasury Basis, and the Convenience Yield

Next, we explore the empirical implications of our theory. We begin by showing that innovations to the Treasury basis covary with innovations in the nominal dollar exchange rate, consistent with Result 5 of Proposition 1. We also show that the basis predicts future returns to a foreign investor going long Treasury bonds relative to foreign bonds, consistent with Result 3 of Proposition 1. We then show that our results are more broadly about dollar safe assets, relate our results to the violation of LIBOR-based covered interest parity, and show that our results are strongest for the dollar and do not extend to other currencies to the same extent.

A. Variation in the Treasury Basis and the Dollar

We start from the expression for exchange rate innovations (5) in Proposition 1. We run a regression of exchange rate innovations on innovations to the basis, controlling for news about future interest rate differences and currency risk premia, to estimate the effect of convenience yield news on the value of the dollar. Innovations to the basis measure shocks to the demand for safe dollars.[4] This regression does not require exchange rate stationarity. After controlling for discount rate and interest rate news, we get consistent estimates of the slope coefficient β^* provided that the covariance between the news about convenience yields and the long-run exchange rate tends to zero: $\lim_{T\to\infty} Cov\left((\mathbb{E}_t - \mathbb{E}_{t-1})\sum_{\tau=0}^{T} x_{t+\tau}^{Treas}, (\mathbb{E}_t - \mathbb{E}_{t-1})\ s_{t+T}\right) = 0$. If exchange rates are stationary, this condition is trivially satisfied.

We construct quarterly AR(1) innovations in the Treasury basis by regressing $\overline{x}_t^{Treas} - \overline{x}_{t-1}^{Treas}$ on $\overline{x}_{t-1}^{Treas}$ and $y_{t-1}^{\$} - \overline{y}_{t-1}^{*}$ and computing the residual, $\Delta\overline{x}_t^{Treas}$. We then regress the contemporaneous quarterly change in the spot exchange rate, $\Delta\overline{s}_t \equiv \overline{s}_t - \overline{s}_{t-1}$, on this innovation. Note that we have verified the robustness of the results reported here to the case where the innovation $\Delta\overline{x}_t^{Treas}$ is the simple change in $\overline{x}_t^{Treas}$ rather than the AR(1) innovation. The results are reported in the Separate Online Appendix. We simply use the change in the log exchange rate as the innovation.

Table III reports the results. From columns (1), (3), (5), (6) and (8) in Panel A, we see that the innovation in the Treasury basis strongly correlates with changes in the exchange rate. In the context of the well-known exchange rate disconnect puzzle (Froot and Rogoff, 1995; Frankel and Rose, 1995), the R^2s are quite high. Our regressors account in panel A for 17% to 43% of the variation in the dollar's rate of appreciation. The sign is negative as predicted by Proposition 1. The point estimates increase in absolute value in the post-crisis, as does the explanatory power. From column (1), we see that a 10 bps

[4]We cannot rule out that these include shocks to the demand for dollars that are subsequently invested in safe assets.

decrease in the basis (or an increase in the foreign convenience yield) below its mean coincides with a 1.02% appreciation of the U.S. dollar.

The regression estimates provide a way to estimate β^* which is the incremental convenience yield attached to safe and liquid dollar payoffs relative to foreign-currency safe and liquid payoffs. We assume that the annual basis follows an AR(1) with coefficient ϕ_a. From (5) in Proposition 1, it follows that the innovation to the log exchange rate reflects the revision in the forecast of the basis at t:

$$(\mathbb{E}_t - \mathbb{E}_{t-1})s_t = -\frac{(\mathbb{E}_t - \mathbb{E}_{t-1})x_t}{(1-\phi_a)(1-\beta^*)} + \mathbb{E}_t \sum_{\tau=0}^{\infty} (y^{\$}_{t+\tau} - y^*_{t+\tau}) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp^*_{t+\tau} + \bar{s}. \quad (26)$$

The basis is mean-reverting with a quarterly AR(1) coefficient of $\phi = 0.47$. Then, from (26) the sum of expected future increases in the 12-month basis in response to a 10 bp rise in the 12-month basis today is $10 \times \frac{1}{1-0.47^4} = 10.5$. In order to rationalize the 1.02% appreciation in the exchange rate, we need a value of β^* of $1 - \frac{10.5}{102} = 0.90$, suggesting that much of the convenience yield attached to U.S. Treasury bonds derives from its attribute as a safe and liquid *dollar* payoff. Put differently, if U.S. Treasurys were issued in foreign currency, their convenience yields would be substantially lower.

Column (3) of Table III includes the contemporaneous and the lagged innovation to the basis. This specification increases the R^2 to 25%. The explanatory power of the lag is certainly not consistent with our rational expectations model, but it is the signature of delayed adjustment in the exchange rate to shocks to the basis. Time-series momentum has been shown to be a common phenomenon in many asset markets, including currency markets (see Moskowitz et al., 2012), although there is no commonly agreed upon explanation for such phenomena. The delayed adjustment lends support to the notion of expectational errors on the part of currency market investors. Section D of the Appendix develops a model of sticky expectations in currency markets that replicates the momentum evidence. Froot and Thaler (1990); Gourinchas and Tornell (2004); Bacchetta

Table III. Average Treasury Basis and the USD Spot Nominal Exchange Rate

The dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. In panel A, the independent variables are the innovation in the average Treasury basis, $\Delta\bar{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, the innovation in the LIBOR basis, and the innovation in the U.S.-to-foreign Treasury yield differential. Panel B includes the quarterly change in the VIX (in percentage unit). Data is quarterly. The constant term is omitted. OLS standard errors in parentheses. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

Panel A: Benchmark Results

	1988Q1−2017Q2					1988Q1−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	−10.20***		−10.23***		−9.81***	−8.48***		−14.93***	
	(2.09)		(1.98)		(1.73)	(2.62)		(3.20)	
$\Delta\bar{x}^{LIBOR}$		−2.85					4.63		−13.51***
		(3.09)					(4.22)		(4.05)
Lag $\Delta\bar{x}^{Treas}$			−6.92***		−6.47***				
			(1.97)		(1.73)				
$\Delta(y^{\$} - \bar{y}^{*})$				3.76***	3.57***				
				(0.71)	(0.60)				
Observations	117	117	116	117	116	80	80	37	37
R^2	0.17	0.01	0.25	0.20	0.43	0.12	0.02	0.38	0.24

Panel B: Control for VIX

	1988Q1−2017Q2					1988Q1−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	−9.62***		−9.22***		−9.66***	−7.10**		−10.44***	
	(2.40)		(2.31)		(1.94)	(3.14)		(3.35)	
$\Delta\bar{x}^{LIBOR}$		−1.89					5.19		−8.07**
		(3.09)					(4.10)		(3.94)
Lag $\Delta\bar{x}^{Treas}$			−7.06***		−4.33**				
			(2.28)		(1.95)				
$\Delta(y^{\$} - \bar{y}^{*})$				4.71***	4.48***				
				(0.73)	(0.66)				
Δvix	0.05	0.09	0.06	0.12**	0.08	−0.12	−0.13	0.21***	0.26***
	(0.07)	(0.07)	(0.06)	(0.06)	(0.05)	(0.10)	(0.10)	(0.08)	(0.08)
Observations	109	109	109	109	109	72	72	37	37
R^2	0.15	0.02	0.22	0.29	0.46	0.09	0.05	0.50	0.42

and Van Wincoop (2005) have argued that expectational errors are behind the failure of uncovered interest rate parity in currency markets.

Column (4) of the table includes the innovation in the interest rate differential, $y^{\$} - \overline{y}^{*}$, constructed by taking an equal-weighted average of the one-year Treasury yields. We see that increases in this interest rate spread has significant explanatory power in our sample. A rise in the U.S. rate relative to foreign appreciates the currency, which is what textbook models of exchange rate determination will predict (and is what equation (13) predicts). Note that a decrease in the convenience yields earned by U.S. investors will increase the U.S. Treasury yield $y^{\$}$, and cause the dollar to appreciate. We include this covariate in column (5) along with the basis innovation. The R^2 rises to 43% and the coefficient estimates and standard errors are nearly unchanged. This is because the basis innovation and interest rate innovation are nearly uncorrelated in this sample (note: the levels are negatively correlated).

These results are largely robust to controlling for changes in the VIX, a commonly used measure of the quantity of risk in global equity markets. These results are reported in Panel B. The baseline coefficient estimate decreases slightly to -9.62. Following the same logic, we need a value of β^* of $1 - \frac{10.5}{96.2} = 0.89$. In the post-crisis sample, controlling for VIX brings the coefficient estimates back in line with the pre-crisis estimates. The point estimate decreases from -14.93 to -10.44.

Krishnamurthy and Vissing-Jorgensen (2012) estimate that the convenience yield on U.S. Treasury bonds relative to AAA rated corporate bonds averages 0.75%. They interpret the 0.75% in terms of the liquidity services and extra safety of Treasury bonds relative to corporate bonds. We estimate that foreigners earn an extra convenience yield between 1.96% ($\frac{1}{0.112} \times 0.22$) and 2.09% ($\frac{1}{0.105} \times 0.22$) per annum on dollar Treasury bonds relative to foreign-currency government bonds. Since β^* is around 0.9, we additionally learn that much of this convenience benefit derives from the fact that the U.S. Treasury bond is a liquid and safe dollar payoff.

Another approach to estimating the average convenience yield is to evaluate the spread between the real long-run returns earned by foreign investors on U.S. Treasurys and domestic bonds:

$$\lambda^{\$,*} - \lambda^{*,*} = -(R^{\$,*} - R^{*,*}).$$

In the short run, the dollar exchange rate adjusts in response to changes in the convenience yields. If real exchange rates are stationary, then there is no long-run currency adjustment and the long-horizon currency risk premium disappears from (13) (see Backus et al., 2018; Lustig et al., 2019). Hence, this spread reveals the (average) extra convenience yields earned by foreign investors when buying Treasurys.

Our convenience yield estimates implies that real returns earned by foreign investors on Treasurys need to be about 2% lower than the returns earned on foreign bonds to maintain a stationary exchange rate.[5] The Treasury International Capital (TIC) system records the purchases of Treasurys by foreign investors. We use the TIC system data to compute the dollar-weighted returns realized by foreign investors: The dollar-weighted return is the internal rate of return realized on the cash flows invested by foreign investors. We assume that investors are fully invested in the Bloomberg Barclays Treasury Index. Between 1980 and 2019, private foreign investors earned a dollar-weighted real return on their Treasury purchases of 2.77%, expressed in real dollars. In comparison, foreign investors earned a dollar-weighted real return of 4.66% on their holdings of foreign bonds.

$$R^{*,*} - R^{\$,*} = 4.66\% - 2.77\% = 1.89\% = \lambda^{\$,*} - \lambda^{*,*}.$$

The 1.89% gap is a direct estimate of the long-run difference in convenience

[5] Our result is qualitatively in line with the savings glut hypothesis (see, e.g., Caballero et al., 2008; Caballero and Krishnamurthy, 2008) and the low r-star discussion (see Laubach and Williams, 2003, 2016; Holston et al., 2017).

yields ($\lambda^{\$,*} - \lambda^{\$,\$}$). Foreign investors buy U.S. Treasurys when Treasurys are expensive, consistent with our hypothesis that foreigners have a special demand for U.S. dollar safe assets. This estimate is quantitatively in line with the estimates we backed out of the Treasury basis and FX markets.

B. *LIBOR and Treasury Bases*

Columns (2), (7), and (9) of Table III shows that the LIBOR basis has explanatory power in the post-crisis sample. This result has been documented in prior work by Avdjiev et al. (2019). We note that the LIBOR basis has no explanatory power in the pre-crisis sample, and moreover has less explanatory power for the dollar than the Treasury basis. Furthermore, Du et al. (2018b) document that the LIBOR basis was near zero pre-crisis and has often been significantly different than zero post-crisis. They show that the movements in the LIBOR basis are closely connected to frictions in financial intermediation that hamper arbitrage activities. We next discuss these results and connect them to our safe asset theory. Section B of the Appendix develops a model of the supply of dollar-denominated LIBOR deposits. Suppose that foreign investors derive a convenience yield on both dollar Treasury bonds and other dollar safe assets, including bank deposits paying LIBOR, consistent with our estimate of β^* near 0.9. Krishnamurthy and Vissing-Jorgensen (2012) present evidence that there is a convenience yield on both U.S. Treasury bonds and other near-riskless private bonds such as U.S. bank deposits. Some investors view near-riskless private bonds as partial substitutes for Treasury bonds.

This being the case, we expect an increase in foreign demand for Treasurys to drive down the foreign return to holding Treasurys, that is to induce a widening of the Treasury basis, and drive down the foreign return to holding dollar LIBOR bank deposits. In particular, consider the LIBOR basis, which is the spread between dollar LIBOR deposits and a foreign LIBOR deposit swapped into dollars,

$$x_t^{LIBOR} \equiv y_t^{\$,LIBOR} + \left(f_t^1 - s_t - y_t^{*,LIBOR} \right). \tag{27}$$

All else equal, an increase in foreign demand for dollar safe assets will drive down $y_t^{\$,LIBOR}$ and widen the LIBOR basis. However, this widening of the LIBOR basis presents a riskless profit opportunity for a bank that funds itself in both dollars and foreign currency. In particular, faced with a widening LIBOR basis, a bank can increase its supply of dollar deposits by one dollar, swap the one dollar into foreign currency so that its currency risk remains unchanged and strictly increase its profits by x_t^{LIBOR}.

In the pre-crisis period, banks were active on this margin and hence the LIBOR basis is zero, consistent with the analysis of Du et al. (2018b). The LIBOR basis did not reflect foreign safe asset demand. Effectively, quantities rather than prices adjusted to accommodate any shifts in safe-asset demand. In the post-crisis period, regulatory constraints on banks limit the capacity of banks to conduct the arbitrage, as Du et al. (2018b) emphasize. In this case, the LIBOR basis opens up. Prices adjust because quantities cannot. The LIBOR basis now reflects both safe asset demand and banks' regulatory constraints. In our explanation, the LIBOR basis widens because of both "demand" – a willingness on the part of one set of agents to overpay for dollar deposits – and "supply" – a limited capacity of other agents to supply these dollar deposits. Other recent papers similarly cite both a demand factor and limited supply factor as driving the LIBOR basis (see Ivashina et al., 2015).

Our analysis explains why the LIBOR basis comoves with the Treasury basis in the post-crisis period, as is evident from Figure 1 and why the LIBOR basis explains movements in the dollar exchange rate post-crisis. In short, when bank regulatory constraints restrict their arbitrage activities, the LIBOR basis reflects movements in $\lambda_t^{\$,*}$. This raises the question of why the Treasury basis persists, given that the Treasury is unconstrained and could issue more Treasurys, similar to what banks do in LIBOR markets prior to the crisis. The answer must be that the Treasury, unlike unconstrained banks, chooses not to exploit this basis, because it has other objectives in managing the government debt portfolio. For example, as in the analysis of Farhi and Maggiori (2018), the U.S. Treasury may seek to earn monopoly rents on in its provision of convenience-yielding Treasury bonds.

C. *Term Structure of Treasury Bases*

Thus far we have focused exclusively on the 1Y Treasury basis, but there is additional information contained in the term structure of Treasury bases about convenience yields. We compute the average G10 Treasury basis for each tenor, 1Y, 2Y, 3Y, 5Y, 7Y, and 10Y, by averaging across countries in a similar manner as we have described. The 1Y basis is from our data, and the rest is from Du et al. (2018a). To reduce the dimension of the Treasury bases constructed by Du et al. (2018a), we carry out a principal component analysis (PCA) on these Treasury bases. Their data covers a shorter sample than we do and hence we limit our analysis to the period ranging from 1991Q2 to 2017Q2.

The results of the PCA are reported in Table IV. Similar to the term structure of bond yields, the first three PCs of the Treasury bases correspond to a level, a slope and a curvature basis factor. We can see this from the loadings on the PCs. These three factors explain 96% of the variation in the Treasury bases.

Table IV. PCA of Treasury Bases

Data is quarterly from 1991Q2 to 2017Q2. Treasury bases with tenors of 1Y, 2Y, 3Y, 5Y, 7Y, and 10Y. Panel A reports the standard deviation and the variance of the PCs. Panel B reports the loadings of each PC on the bases.

Panel A: Summary Statistics			
	PC_1	PC_2	PC_3
Std Dev	0.41	0.19	0.17
% of Variance	69.50	15.14	11.44
Cumulative %	69.50	84.64	96.08
First-Order Autocorrelation	0.86	0.48	0.79
Panel B: Loadings			
1Y Basis	0.30	−0.93	−0.15
2Y Basis	0.43	−0.05	0.41
3Y Basis	0.46	0.09	0.33
5Y Basis	0.51	0.24	0.13
7Y Basis	0.36	0.20	−0.21
10Y Basis	0.35	0.17	−0.80

Table V reports the results of a regression of the quarterly rate of appreciation of the dollar on the innovations in the level factor and the slope factor, controlling for changes in the interest rate differences. The quarterly innovations are obtained from an AR(1) model with lagged PC1, lagged PC2 and lagged Treasury yield differential. A one standard deviation decline in the level of the bases by 0.41% induces an appreciation of the dollar by 3.78% (9.29×0.41). There is also information in the innovations in the slope factor. If the slope rises, i.e., short-term bases fall relative to the long-term bases, the dollar appreciates. A rise in the slope may be coincident with a flight to quality which affects short-term bonds more than long-term bonds. That is, the basis on the 1 year bond may be a better measure of foreign investors' convenience valuations than the basis on the long-term bonds.

Table V. Principal Components in Treasury Basis and the USD Spot Nominal Exchange Rate

The dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. Data is quarterly. OLS standard errors in parentheses. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	1991Q2−2017Q2					1991Q2−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta PC1$	−9.29***		−8.19***		−5.13***	−7.92**	−4.39*	−7.18**	−3.47
	(2.06)		(2.13)		(1.75)	(3.10)	(2.44)	(3.51)	(3.19)
$\Delta PC2$		7.69***	4.76*		7.09***	3.27	5.91**	8.61	9.09*
		(2.70)	(2.65)		(2.14)	(3.25)	(2.52)	(5.82)	(5.01)
$\Delta(y^{\$} - \bar{y}^{*})$				4.86***	4.60***		4.34***		10.57***
				(0.66)	(0.60)		(0.64)		(2.94)
Observations	104	104	104	105	104	67	67	37	37
R^2	0.17	0.07	0.19	0.35	0.49	0.11	0.48	0.38	0.56

D. Monetary Policy Shocks and the Basis

To help us identify the causal effect of shocks to the basis on the dollar exchange rate, we rely on Federal Funds Rate (FFR) surprises. There is a growing literature on high-frequency identification, going back to Rudebusch (1998); Kuttner (2001); Cochrane and Piazzesi (2002); Faust et al. (2004). FOMC announcements are useful source of variation because the news in these announcements is primarily about short rates. We use Kuttner (2001)'s FFR surprises as our measure of monetary shocks. There are 96 observations in our sample.

We end the sample when the FFR hits the zero lower bound.[6]

How does a monetary policy surprise cause a change in the convenience yield? In Jiang et al. (2020a), we develop a theory that creates a role for monetary policy in the determination of convenience yields. In that model, tighter monetary policy induces banks to scale down their balance sheets. Since banks are important providers of dollar safe assets, the contraction reduces the supply of dollar safe assets. As a result, demanders of safe assets drive up the price of these assets leading to an increased convenience yield.

In the first stage, we regress the change in the first principal component of the basis on the MP shock. We argue that a contractionary monetary policy shrinks the supply of liquid and safe assets and widen the basis. The first stage regressions confirm this effect. These results are reported in the upper panel in Table VI. We use PC_1 as the average basis measure. A 10 bps surprise rate increase widens the average Treasury basis by more than 5.8 basis points. In the second stage, we regress the dollar appreciation on the exogenous variation in the basis induced by the FFR surprise. These results are reported in the lower panel in Table VI. The exclusion restriction is that shocks to MP do not covary with the exchange rates, once we control for changes in interest rates. In terms of the exchange rate decomposition in (21), we assume that only the future convenience yields and future interest rates respond to FFR surprises, but not the future currency risk premia. Given that most of the news on these days is about short rates, that seems like a plausible restriction. There is one caveat: we include unscheduled announcements, which are more likely to include the release of news about fundamentals. The second stage slope coefficients are comparable in magnitude to the OLS estimates in Table III: The slope coefficients vary between -11.98 and -13.93. A 10 bps widening of the Treasury bases induces an appreciation of the dollar between 1.20% and 1.39%. Controlling for changes in VIX decreases the size of these coefficients in absolute value, but only moderately so.

[6] These results are also discussed and reported in Krishnamurthy and Lustig (2019).

Table VI. Average Treasury Basis and the USD Spot Nominal Exchange Rate Around FOMC Announcements

Regression of change in dollar exchange rate on change in basis induced by the FOMC shock (2nd stage regression), controlling for the change in interest rate differences (top panel) and change in VIX (bottom panel). The change in the basis is the change in the 1st PC (ΔPC_1) of the average Treasury bases across maturities. The interest rate difference is the 1st PC of the average yield differences across maturities. The sample covers 96 FOMC Announcements (excluding unscheduled FOMC meetings) between 22 Jan 1997 and 30 Dec 2008. 1st stage Regression of change in basis on MP shock. We use a 1-day window around the FOMC announcements.

	1st-Stage	
	(1)	(2)
Monetary Policy Shock	-0.58	-0.58
	(0.25)	(0.25)
Observations	96	96
R^2	0.05	0.05
	2nd-Stage	
	(1)	(2)
$\Delta\overline{x}^{Treas}$	-13.93	-11.98
	(2.71)	(2.89)
$\Delta(y^{\$} - \bar{y}^{*})$	0.71	1.00
	(0.55)	(0.57)
ΔVIX		0.08
		(0.05)
Observations	96	96
R^2	0.25	0.27

Based on these results, a more precisely identified estimate of the fraction β^* is given by $1 - \frac{10.5}{119.8} = 0.91$. Hence, a better estimate of the average convenience yield earned by foreign investors is 2.51% per annum ($\frac{1}{1-0.91} \times 0.22$).

E. The Treasury Basis and Dollar Safe Asset Demand

Our theory posits that a specific form of capital flows consisting of flows into safe dollar assets drives the value of the U.S. dollar. This section discusses how our evidence supports this interpretation.

First, note that we construct the basis from the safest asset, the U.S. Treasury bond, and document a relation between this basis and the dollar. Second, we have shown that the LIBOR basis also helps explain movements in the dollar post-crisis, consistent with the broad dollar safe asset demand theory. Third, we have shown that β^* is around 0.90 indicating that safe foreign government bonds when swapped into dollars carry a convenience yield. Fourth, we compute a KfW bond basis in section A of the separate Online Appendix. KfW is a German issuer whose bonds are backed by the German government, so that they are near default free. KfW issues bonds in different currencies allowing us to compute the basis for the bonds of the same issuer, i.e., holding safety fixed, in different currencies. We compute the basis for KfW bonds using one-year yields on these bonds for Australia, Euro, UK, and Switzerland against the U.S.. The KfW and the Treasury bases have roughly the same magnitude and track each other closely. This evidence shows that foreign investors' demand is for all safe assets denominated in U.S. dollars.

Lastly, we perform a placebo test of dollar safe asset demand. We repeat the univariate regression of Table III, column (1), but using other non-U.S. countries as the base country. In Table VII, we use a different base country, and we calculate the equally weighted cross-sectional average of exchange rates and Treasury basis of other non-U.S. countries against this base country's currency. In the top panel, we report the coefficient of the regression of nominal exchange rate movement on the Treasury basis innovation. For other countries the regression coefficients are largely statistically insignificant and/or the R^2 are considerably lower than the U.S. regressions. That is, the negative association between the exchange rate movement and Treasury basis is a phenomenon that is particularly strong for the U.S. where we posit that these safe asset demand effects should be most pronounced. In Panel B of the table we include both the innovation in the basis and the change in interest rate differences. Now the regression R^2 rise uniformly. Additionally, more of the currencies exhibit the negative relation between bases and exchange rates. In the last panel, we report a univariate regression with only changes in interest rate differences. From comparing the regression R^2s in Panels B and C we can see that only in the case of the dollar does the basis add substantial explanatory power. The Euro shares some of the U.S. Dollar patterns, but to a much lesser extent.

F. Predictability of Exchange Rates and Excess Returns

We next turn to Result 3 of Proposition 1, which can be read as a forecasting regression. A more negative x_t (i.e. a higher convenience yield) today is associated with a higher dollar exchange rate today, which induces an expected depreciation in the future. For the forecast horizon k, we define the annualized log excess return as $rx_{t\to t+k} = \frac{4}{k}\left(\Delta s_{t\to t+k} + y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}\right)$. Note that the LHS of equation (23), reproduced below,

$$\mathbb{E}_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^{*}\right) = \frac{1}{1-\beta^{*}} x_t^{Treas} + rp_t^{*},$$

is akin to the return on the reverse currency carry trade. It involves going long the U.S. Treasury bond, funded by borrowing at the rate of the foreign government bond. The carry trade return has a risk premium term (RP), and following the literature, a proxy for this risk premium is the interest rate differential across the countries. Thus we include the mean Treasury yield differential $\left(y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}\right)$ as a control in our regression. As we have shown in Table III, there is a slow adjustment to basis shocks. So, we use the average Trea-

Table VII. Explain Exchange Rate Movement Using Treasury Basis Innovation in Different Countries.

We regress the exchange rate movement on concurrent Treasury basis innovation and change in the Treasury yield. A higher exchange rate means a stronger base currency. For each non-U.S. country, we exclude the U.S. when we calculate its average Treasury basis and average exchange rate movement against other non-U.S. countries. One, two and three stars denote statistical significance at the 10%, 5% and 1% level. We use DEM as stand-in for EUR prior to the creation of the Euro.

Panel A: Univariate Regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	USD	AUD	CAD	EUR	JPY	NZD	NOK	SEK	CHF	GBP
Innov $\overline{x}^{Treas}$	-10.20^{***}	0.19	2.06	-6.21	4.31	-3.97^{**}	0.24	-0.80	1.94	2.45
	(2.09)	(3.48)	(1.67)	(3.81)	(4.86)	(1.90)	(0.96)	(0.85)	(1.50)	(2.38)
Observations	117	70	94	79	88	52	109	105	109	79
R^2	0.17	0.000	0.02	0.03	0.01	0.08	0.001	0.01	0.02	0.01

Panel B: Bivariate Regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	USD	AUD	CAD	EUR	JPY	NZD	NOK	SEK	CHF	GBP
Innov $\overline{x}^{Treas}$	-9.79^{***}	-2.76	2.13	-8.71^{**}	3.70	-4.75^{**}	0.38	-1.85^{*}	3.21^{**}	-0.61
	(1.81)	(3.22)	(1.70)	(3.68)	(4.49)	(1.97)	(0.95)	(1.09)	(1.55)	(2.32)
Change in IR Diff	3.80^{***}	6.23^{***}	0.26	4.41^{***}	6.87^{***}	1.62	1.11^{*}	0.88	-1.65^{**}	4.62^{***}
	(0.61)	(1.51)	(0.82)	(1.38)	(1.72)	(1.16)	(0.62)	(0.58)	(0.66)	(1.19)
Observations	117	70	94	79	88	52	109	105	109	79
R^2	0.38	0.20	0.02	0.15	0.17	0.12	0.03	0.03	0.07	0.18

Panel C: IR Differential Only

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	USD	AUD	CAD	EUR	JPY	NZD	NOK	SEK	CHF	GBP
Change in IR Diff	3.92^{***}	5.94^{***}	0.12	3.72^{***}	6.92^{***}	1.17	1.09^{*}	0.25	-1.21^{*}	4.51^{***}
	(0.68)	(1.47)	(0.81)	(1.39)	(1.71)	(1.04)	(0.62)	(0.46)	(0.63)	(1.11)
Observations	117	70	94	79	88	70	109	105	109	79
R^2	0.22	0.19	0.000	0.09	0.16	0.02	0.03	0.003	0.03	0.18

sury basis $\overline{x}_{t-1}^{Treas}$ lagged by 1 quarter as the main explanatory variable. The regression equation is

$$rx_{t\to t+k} = \alpha^k + \beta_x^k \overline{x}_{t-1}^{Treas} + \beta_y^k (y_{t\to t+k}^{\$} - \overline{y}_{t\to t+k}^{*}) + \epsilon_{t+k}^k$$

Our theory suggests that the coefficient β_x should be positive. We run this regression using quarterly data, but compute the returns on the LHS as 3-months, 1-year, 2-year, and 3-year returns. Because there is overlap in the observations, we compute heteroskedasticity and autocorrelation adjusted standard errors.

Table VIII reports the results obtained when forecasting the annualized excess returns on a long position in the dollar. Overall the results are in line with our theory: a more negative basis (i.e. higher convenience yields) predicts lower returns on the carry trade. However, we should note that the statistical significance of the results is weak, and the results of this section should be seen as a consistency check of our theory. The sample for a forecasting regression is relatively short, and even the known forecaster of currency returns, the interest rate differential, has limited power in this sample.

Panel A reports the regression results for the entire sample. The slope coefficient on the average basis β_x^k varies from -1.46 at the 3-month horizon to 4.44 at the 3-year horizon. The long-horizon estimates are an accurate reflection of the basis effect after stripping away the short-run momentum effect we have documented whereby the exchange rate adjusts slowly to changes in the basis. The effects are economically significant. A one-standard-deviation basis shock of 23 bps raises the expected excess return by 1.02% per annum over the next three years. These regressors jointly explain about 14% of the variation in excess returns at the 3-year horizon. The basis is not a persistent predictor, and the Stambaugh (1999) bias is likely small. Further, there is no strong mechanical relation between the forecasting horizon and the R^2.

Panel B and C of Table VIII report the regression results for the pre- and post-crisis sample. The momentum effect is only present prior to the crisis.

Table VIII. Forecasting Currency Excess Returns in Panel Data

The dependent variable is the annualized nominal excess return (in logs) $rx^{fx}_{t\to t+k}$ on a long position in U.S. Treasuries and a short position (equal-weighted) in all foreign bonds with maturities of k quarters. The independent variables are the average Treasury basis $\overline{x}^{Treas}$ lagged by 1 quarter, and the nominal Treasury yield difference $(y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k})$ with maturities of k quarters. Data is quarterly from 1988Q1 to 2017Q2. We omit the constant, and report Newey-West standard errors with lags equal to the length of the forecast horizon k. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	Panel A: 1988Q1—2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	-1.46	4.15	4.41	4.44^{*}
	(5.89)	(6.42)	(3.19)	(2.30)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.47	0.83	1.72	1.59
	(0.92)	(1.04)	(1.13)	(1.02)
Observations	117	117	117	115
R^2	0.004	0.03	0.13	0.14
	Panel B: 1988Q1—2007Q4			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	-10.00	-2.38	-0.42	3.59
	(6.25)	(7.64)	(2.96)	(2.58)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.64	0.69	1.64	2.42^{**}
	(0.91)	(1.06)	(1.24)	(0.96)
Observations	80	80	80	80
R^2	0.04	0.03	0.15	0.30
	Panel C: 2008Q1—2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	16.47	19.81^{***}	16.00^{***}	10.04^{***}
	(10.27)	(6.32)	(3.33)	(1.83)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	-5.52^{*}	0.52	1.41	1.28
	(3.10)	(0.91)	(0.96)	(1.01)
Observations	37	37	37	35
R^2	0.13	0.29	0.40	0.34

In the post-crisis sample, the slope coefficients on the basis are all positive. At the 3-year horizon, the coefficient is 10.04: A one-standard-deviation basis shock raises the expected excess return by 2.31% per annum over the next three years. Consistent with the findings of Lilley et al. (2019), we note that there is much more predictability after the crisis. In the post-crisis sample, these regressors jointly explain about 34% of the joint variation in excess returns at the 3-year horizon.

The return predictability is mostly driven by the exchange rate component of returns. Table A.9 in Section C of the Appendix report predictability results for exchange rate changes rather than excess returns. There is solid statistical evidence that the average Treasury basis forecasts changes in exchange rates: the slope coefficient estimate is 5.17, implying that the dollar appreciates by 1.19% per annum over the next 3 years following one-standard-deviation widening of average Treasury basis.

In Section H of the Appendix, we construct a longer sample for the U.S.-U.K. Treasury basis (the sample starts 1970Q1 and ends in 2016Q2), and we run the same battery of statistical tests. The results are broadly in line with the results obtained on the shorter sample for the G-10 currencies.

G. *Term Structure and Excess Returns*

We next investigate whether other maturities of the basis have forecasting power for excess returns on the reverse carry trade. We summarize the other maturities using the principal component of the term structure and use these to forecast excess returns. As before, we lag these principal components by one period.

Panel A of Table IX reports the predictability results for the entire sample. When the bases widen across all tenors, this leads to lower excess returns at all horizons, with results that are statistically stronger at longer horizons. A one standard deviation widening of PC_1 by 41 bps leads to a 2.92% (2.01%) per annum reduction in the excess return at the two-year (three-year) horizon. The second principal component, the slope factor PC_2, has much less information for returns than the level factor. The coefficient on PC_2 is positive but only statistically different than zero at the 3-month horizon. From our theory, the coefficient on the slope should be negative. That is, we find in Table V that increases in slope lead to a contemporaneous appreciation of the dollar. We thus should expect that increases in slope predict a future depreciation of the dollar. The results do not accord with this prediction. The positive coefficient at the 3-month horizon may be another manifestation of the momentum phenomenon. Panels B and C of Table IX report the results for the pre- and post-crisis subsamples. The results are stronger in the post-crisis sample consistent with earlier results.

A significant finding from this PC analysis is that there is considerable information in the entire term structure of the bases. We note the high R^2 in Table IX compared to that of Table VIII. The principal components explain significant variation in excess returns, rising to 30% at the 3-year horizon, compared to 14% at the 3-year horizon in Table VIII.

V. Reduced-Form VAR and Impulse Response Functions

We run a VAR with three variables: the basis, the real interest rate difference $i_{t-1} = d_{t-1} - \pi_t^{US} + \pi_t^*$, and the log of the real exchange rate q_t:

$$\boldsymbol{z}_t' = \begin{bmatrix} x_t & i_t & q_t \end{bmatrix}.$$

We estimate following the first-order VAR for $\boldsymbol{z}_t$:

$$\boldsymbol{z}_t = \boldsymbol{\Gamma}_0 + \boldsymbol{\Gamma}_1 \boldsymbol{z}_{t-1} + \boldsymbol{a}_t,$$

where $\boldsymbol{\Gamma}_0$ is a 3-dimensional vector, $\boldsymbol{\Gamma}_1$ is a 3×3 matrix and $\boldsymbol{a}_t$ is a sequence of white noise random vector with mean zero and variance covariance matrix Σ.

Table IX. Forecasting Currency Excess Returns using Principal Components

The dependent variable is the annualized nominal excess return (in logs) $rx^{fx}_{t\to t+k}$ on a long position in U.S. Treasuries and a short position (equal-weighted) in all foreign bonds with maturities of k quarters. The nominal Treasury yield difference ($y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$) also have maturities of k quarters, averaged across the same set of foreign countries. Data is quarterly from 1991Q2 to 2017Q2. We omit the constant. Heteroskedasticity and autocorrelation adjusted standard errors in parentheses; we use the Newey-West estimator with number of lags equal to the overlap in returns. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	(1)	(2)	(3)	(4)
Panel A: 1988Q1—2017Q2				
	3 months	1 year	2 years	3 years
Lag $PC1$	3.41	5.41	7.11^{**}	4.90^{*}
	(5.08)	(4.79)	(3.21)	(2.67)
Lag $PC2$	10.91^{*}	4.18	1.67	0.34
	(6.50)	(7.82)	(5.36)	(3.82)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.38	0.83	2.57^{**}	2.48^{***}
	(1.43)	(1.46)	(1.15)	(0.94)
Observations	104	104	104	102
R^2	0.02	0.05	0.29	0.30
Panel B: 1988Q1—2007Q4				
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $PC1$	−2.38	−0.13	5.40	4.78
	(4.35)	(6.81)	(4.50)	(3.90)
Lag $PC2$	20.80^{***}	11.91	4.18	−2.69
	(6.73)	(8.90)	(5.28)	(2.14)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	0.44	0.32	2.81^{**}	4.04^{***}
	(1.53)	(1.74)	(1.35)	(1.55)
Observations	67	67	67	67
R^2	0.09	0.06	0.29	0.50
Panel C: 2008Q1—2017Q2				
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $PC1$	16.16^{**}	11.28^{**}	11.60^{***}	9.90^{***}
	(7.87)	(4.81)	(1.75)	(1.94)
Lag $PC2$	17.56	−2.48	4.42^{**}	7.86^{*}
	(15.03)	(8.19)	(2.15)	(4.02)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	-8.34^{***}	−1.23	−0.68	−1.29
	(3.07)	(1.44)	(1.16)	(1.15)
Observations	37	37	37	35
R^2	0.17	0.34	0.57	0.63

A. Estimation

We estimate the VAR system using quarterly data. In order to convert the 1-year Treasury basis to an equivalent 3-month Treasury basis, we scale the 1-year Treasury basis and interest rate differentials. Section F of the Appendix contains the details.

We identified the VAR(1) as the optimal specification using the BIC. This specification assumes that the log of the real U.S. dollar index is stationary, which seems to be case in this sample period. We order the VAR so that shocks to the basis affect all variables contemporaneously, shocks to the interest rate affect the exchange rate and the interest rate differential but not the basis, and shocks to the exchange rate only affect itself. This ordering implies that nominal and real exchange rates can respond instantaneously to all of the structural shocks. As we discuss, the evidence from the VAR provides support for interpreting our regression evidence causally: shocks to convenience yields drive movements in the exchange rate.

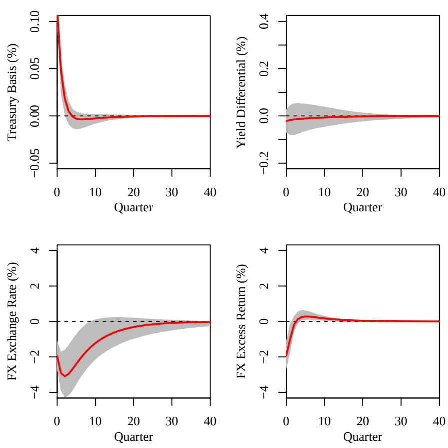

Figure 2. Dynamic Response to Treasury Basis Shocks: Panel.

The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the average Treasury basis on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. Standard errors were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^{*}, q_t\right]$.

Figure 2 plots the impulse response from orthogonalized shocks to the basis. The top left panel plots the dynamic behavior of the basis (in units of percentage points), the top right panel plots the dynamic behavior of the interest rate difference (in percentage points), and the bottom left panel plots the behavior of the exchange rate (in percentage points). The dynamics in the figure are consistent with the regression evidence from the Tables. An increase in the annualized Treasury basis of 0.2% (quarterly basis of 0.1% in figure) depreciates the real exchange rate contemporaneously by about 3% over two quarters. The finding that the depreciation persists over 2 quarters is consistent with the time-series momentum effect discussed earlier. Thus, the exchange rate exhibits classic Dornbusch (1976) overshooting behavior. Then there is a gradual reversal over the next 5 years; the effect on the level of the dollar gradually dissipates. There is no statistically discernible effect of the basis on the interest rate differential. Finally, the bottom right panel plots the quarterly log excess return on a long position in dollars, $rx_t = q_t - q_{t-1} + i_{t-1}$. Initially, the quarterly excess return drops, but after the first 2 quarters, it is higher than average for the next 15 to 18 quarters, consistent with higher expected returns on long positions in Treasurys.

Once we add the basis shock, U.I.P. roughly holds for the dollar against this panel of currencies. Figure 3 plots the response to the interest rate shocks. The dollar appreciates in real terms in the same quarter by more than 100 basis points in response to a 100 bps increase in the U.S. yields above the foreign yields. The bottom right panel of the figure plots the excess return on the currency, and we see that this return is zero after the first quarter indicating that U.I.P. holds once we account for shocks to the basis. As pointed out by Engel (2016), the deviations from U.I.P. in the univariate time series regressions are larger for the dollar. Our results indicate that these deviations may be largely due to variation in the convenience yield on dollar safe assets.

Figure 4 reports all of the impulse responses. The panel in the lower right corner plots the variance decomposition of the exchange rate against the horizon.

Basis shocks account for a large fraction of the exchange rate forecast error variance, especially at longer horizons. At the one-quarter horizon, basis shocks account for around 20% of the forecast error variance; this fraction increases to 35% at longer horizons. In contrast, the interest rate shocks account for less than 25% at all horizons. While the initial impact of a one-standard deviation interest rate shock on the dollar is similar to that of a one-standard deviation basis shock (roughly 2%), its effect builds up more gradually..

Importantly, the results are not sensitive to switching the order of the basis and interest rate differential, indicating that we can plausibly interpret the relation between the basis and exchange rate causally: A shock to convenience yields moves both the basis and the exchange rate. We say this because we have allowed for other known determinants of the exchange rate, relative price levels and relative interest rates, and yet recover the same relation between the basis and the exchange rate. These results are reported in Section F of the Appendix.

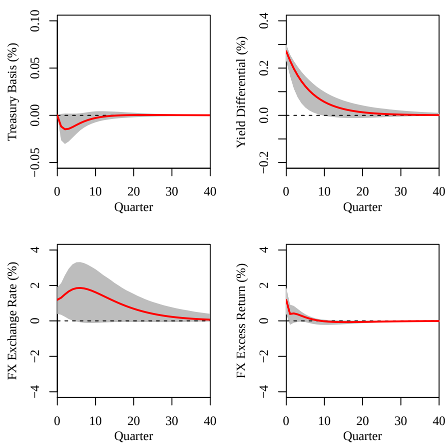

Figure 3. Dynamic Response to Interest Rate Shocks: Panel.

The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the yield difference on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. Standard errors were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^{*}, q_t\right]$.

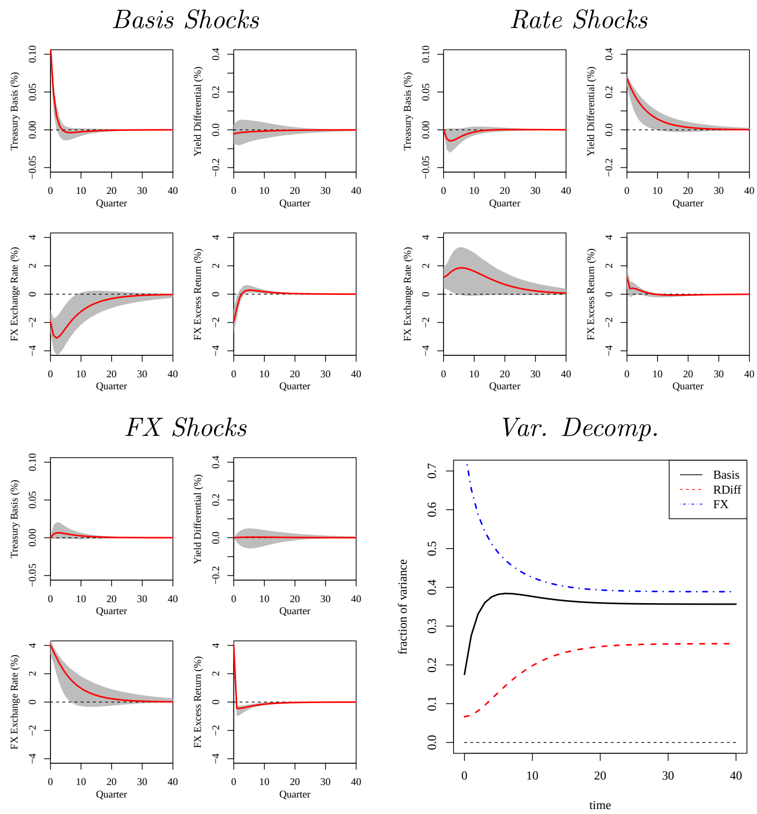

Figure 4. Panel Impulse Responses.

The red line plots the impulse response of an orthogonalized one-standard-deviation shock on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

B. Campbell-Shiller Decomposition

The log of the currency excess return is given by $rx_t = q_t - q_{t-1} + i_{t-1}$. By Proposition 1.3, the realized risk premium component of the log currency excess return is the realized log excess return minus the convenience yield: $rp_t = rx_t - \frac{1}{1-\beta^*} \times x_{t-1}$. As a result, we can add an equation for the risk premium component of the log excess return to the VAR, and we end up with the following first-order VAR:

$$\begin{bmatrix} rp_t \\ x_t \\ i_t \\ q_t \end{bmatrix} = \begin{bmatrix} \gamma_0 \\ \Gamma_{0,1} \\ \Gamma_{0,2} \\ \Gamma_{0,3} \end{bmatrix} + \begin{bmatrix} 0 & \Gamma_{3,1} - \frac{1}{1-\beta^*} & \Gamma_{3,2}+1 & \Gamma_{3,3}-1 \\ 0 & \Gamma_{1,1} & \Gamma_{1,2} & \Gamma_{1,3} \\ 0 & \Gamma_{2,1} & \Gamma_{2,2} & \Gamma_{2,3} \\ 0 & \Gamma_{3,1} & \Gamma_{3,2} & \Gamma_{3,3} \end{bmatrix} \begin{bmatrix} rp_{t-1} \\ x_{t-1} \\ i_{t-1} \\ q_{t-1} \end{bmatrix} + \begin{bmatrix} a_{3,t} \\ a_{1,t} \\ a_{2,t} \\ a_{3,t} \end{bmatrix} \tag{28}$$

Accordingly, we can define the state as the vector of demeaned variables: $\boldsymbol{y}_t' = \begin{bmatrix} \tilde{rp}_t & \tilde{x}_t & \tilde{i}_t & \tilde{q}_t \end{bmatrix}$. $\boldsymbol{y}_t$ is a VAR process of order 1:

$$\boldsymbol{y}_t = \boldsymbol{\Psi}_1 \boldsymbol{y}_{t-1} + \boldsymbol{u}_t,$$

where $\boldsymbol{\Psi}_1$ is the 4×4 matrix defined in (28) and $\boldsymbol{u}_t$ is the 4×1 vector of residuals defined above. Following Campbell and Shiller (1988), we can define the news about discount rates, news about cash flows and news about convenience yields:

$$\begin{aligned}
N_{DR,t} &= (\mathbb{E}_t - \mathbb{E}_{t-1}) \left[\sum_{j=1}^{\infty} rp_{t+j} \right] = \boldsymbol{e}_1' \boldsymbol{\Psi}_1 (I - \boldsymbol{\Psi}_1)^{-1} \boldsymbol{u}_t, \\
N_{CF,t} &= (\mathbb{E}_t - \mathbb{E}_{t-1}) \left[\sum_{j=0}^{\infty} i_{t+j} \right] = \boldsymbol{e}_3' (I - \boldsymbol{\Psi}_1)^{-1} \boldsymbol{u}_t, \\
N_{CY,t} &= -(\mathbb{E}_t - \mathbb{E}_{t-1}) \left[\sum_{j=0}^{\infty} \frac{1}{1-\beta^*} x_{t+j} \right] = -\frac{1}{1-\beta^*} \boldsymbol{e}_2' (I - \boldsymbol{\Psi}_1)^{-1} \boldsymbol{u}_t.
\end{aligned}$$

These components satisfy the following identity:

$$N_{CY,t} = -N_{CF,t} + N_{DR,t} + \boldsymbol{e}_1' \boldsymbol{u}_t.$$

We need an estimate of β^* to decompose the FX news. We use the estimate of $\beta^* = 0.90$ from the monetary policy shock analysis of Section D. We also estimate β^* under the VAR system following the procedure described in Section F of the Appendix, and obtain a similar estimate of $\beta^* = 0.91$.

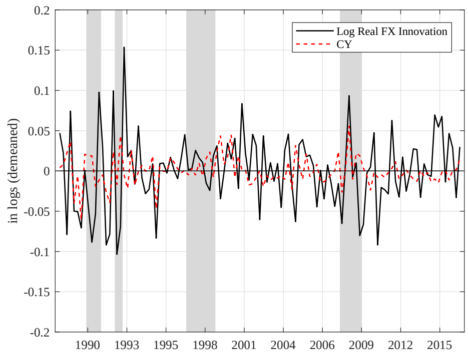

Figure 5. News about Convenience Yields

Plots quarterly news about convenience yields $N_{CY,t}$ against quarterly news about about exchange rates $\boldsymbol{e}_1' \boldsymbol{u}_t$ for the Panel. VAR is estimated using a sample from 1988Q1 to 2017Q2. The VAR(1) includes $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$. β^* is 0.9. Shaded areas include the ERM crisis, the Gulf war, the Russian default and LTCM crisis and the recent global financial crisis.

Figure 5 plots the dollar's news about convenience yields against the news about the dollar exchange rate. The light-shaded areas include the ERM crisis, the Gulf war, the Russian default and LTCM crisis and the recent global financial crisis. Most of the variation in CY news arises during periods of increased global uncertainty and during crises. During global crisis episodes, the CY news induces an appreciation of the USD during global financial crises, when global investors seek the safety of the USD safe assets. During the recent crisis, CY news induced an appreciation of 5% of the USD. However, these effects are largely transitory, given that the basis quickly reverts back to its mean.

While the convenience yield component is clearly tied to global crises, the cash flow and discount rate news seem more related to the U.S. business cycle. Figure 6 plots the cash flow news against the news about the dollar exchange rate. The dark-shaded areas indicate NBER recessions. The cash flow news component of the dollar is clearly counter-cyclical. At the start of NBER recessions, US yields decline relative to foreign yields, thus contributing to a

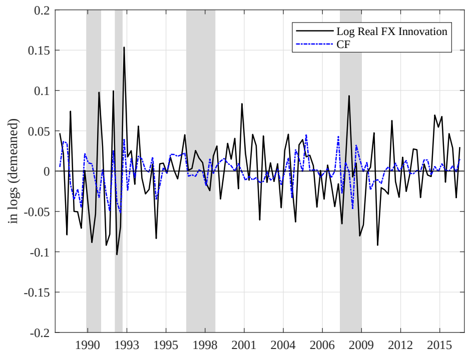

Figure 6. News about Cash Flows and Change in Real Exchange Rate

Plots quarterly news about convenience yields $N_{CY,t}$ against quarterly news about about exchange rates $\boldsymbol{e}_1'\boldsymbol{u}_t$ for the Panel. VAR is estimated using a sample from 1988Q1 to 2017Q2. The VAR(1) includes $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$. β^* is 0.9. The shaded areas include NBER recessions.

weakening of the dollar. Finally, Figure 7 plots the discount rate news, which is pro-cyclical. At the start of NBER recessions, the risk premium on the dollar declines, contributing to a strengthening of the dollar. The DR news is only weakly correlated with the dollar innovations.

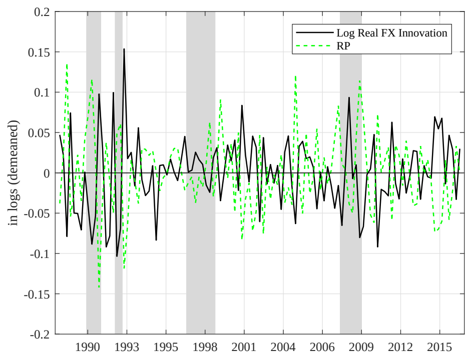

Figure 7. News about Risk Premia and Change in Real Exchange Rate

Plots quarterly news about convenience yields $N_{CY,t}$ against quarterly news about about exchange rates $\boldsymbol{e}_1'\boldsymbol{u}_t$ for the Panel. VAR is estimated using a sample from 1988Q1 to 2017Q2. The VAR(1) includes $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$. β^* is 0.9. The shaded areas include NBER recessions.

Table X presents the variance decomposition of quarterly dollar exchange rate innovations for the panel of countries. When $\beta^* = 0.90$, the convenience yield news (CY) accounts for 16% of the variance in quarterly exchange rates. Interest rate news (CF) accounts for a similar share of the variance, while risk premium news (DR) accounts for a sizable component of 110%. These results are sensitive to the exact value of β^*. When $\beta^* = 0.875$, the CY news accounts for only 10% of exchange rate innovations, while if $\beta^* = 0.95$, the CY news accounts for 63% of innovations. The ratio of the convenience yield to the observed basis, $\frac{1}{1-\beta^*}$, is highly sensitive to β^*.

Table X. News Decomposition of Real Exchange Rates Innovations

The table reports the decomposition of quarterly innovations in log of average USD real exchange rate in the Panel for different values of β^*. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The VAR(1) includes $\left[\overline{x}_t^{3m}, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

β^*	var(CY)	var(CF)	var(DR)	2cov(CY, CF)	$-$2cov(CY, DR)	$-$2cov(CF,DR)
0.95	0.63	0.17	1.62	0.36	-1.35	-0.43
0.925	0.28	0.17	1.24	0.24	-0.62	-0.31
0.9	0.16	0.17	1.10	0.18	-0.36	-0.25
0.875	0.10	0.17	1.04	0.14	-0.24	-0.22

VI. Conclusion

We present a theory of exchange rates which departs from existing theories by imputing a central role to international flows in Treasury debt and related dollar safe asset markets in exchange rate determination. In our theory, the spot exchange rate of a safe asset currency will reflect the cumulative value of all future convenience yields that are earned by foreign investors on safe assets denominated in that currency. The empirical evidence strongly supports the theory. Our results shed light on two important topics in international finance. First, we help to resolve the exchange rate disconnect puzzle by demonstrating that shocks to the demand for dollar-denominated safe assets drive a sizeable portion of the variation in the dollar exchange rate. Second, we provide strong empirical support for recent theories regarding safe assets and the central role of the U.S. in the international monetary system.

REFERENCES

Amador, Manuel, Javier Bianchi, Luigi Bocola, and Fabrizio Perri, 2020, Exchange rate policies at the zero lower bound, *The Review of Economic Studies* 87, 1605–1645.

Avdjiev, Stefan, Wenxin Du, Catherine Koch, and Hyun Song Shin, 2019, The dollar, bank leverage, and deviations from covered interest parity, *American Economic Review: Insights* 1, 193–208.

Bacchetta, Philippe, and Eric Van Wincoop, 2005, Rational inattention: A solution to the forward discount puzzle .

Bach, Christopher, 1972, Us balance-of-payments problems and policies in 1971, *Review* .

Backus, David, Nina Boyarchenko, and Mikhail Chernov, 2018, Term structures of asset prices and returns, *Journal of Financial Economics* 129, 1–23.

Backus, David, Silverio Foresi, and Chris Telmer, 2001, Affine models of currency pricing: Accounting for the forward premium anomaly, *Journal of Finance* 56, 279–304.

Backus, David K, and Gregor W Smith, 1993, Consumption and real exchange rates in dynamic economies with non-traded goods, *Journal of International Economics* 35, 297–316.

Brandt, Michael W, John H Cochrane, and Pedro Santa-Clara, 2006, International risk sharing is better than you think, or exchange rates are too smooth, *Journal of Monetary Economics* 53, 671–698.

Brauning, Falk, and Victoria Ivashina, 2017, Monetary policy and global banking .

Bruno, Valentina, and Hyun Song Shin, 2017, Global dollar credit and carry trades: a firm-level analysis, *The Review of Financial Studies* 30, 703–749.

Caballero, Ricardo J, Emmanuel Farhi, and Pierre-Olivier Gourinchas, 2008, An equilibrium model of "global imbalances" and low interest rates, *American Economic Review* 98, 358–93.

Caballero, Ricardo J, and Arvind Krishnamurthy, 2008, Collective risk management in a flight to quality episode, *The Journal of Finance* 63, 2195–2230.

Caballero, Ricardo J, and Arvind Krishnamurthy, 2009, Global imbalances and financial fragility, *American Economic Review* 99, 584–88.

Campbell, John Y, and Richard H Clarida, 1987, The dollar and real interest rates, in *Carnegie-Rochester Conference Series on Public Policy*, volume 27, 103–139, Elsevier.

Campbell, John Y, and Robert J Shiller, 1988, The dividend-price ratio and expectations of future dividends and discount factors, *The Review of Financial Studies* 1, 195–228.

Chernov, Mikhail, Lukas Schmid, and Andres Schneider, 2020, A macrofinance view of u.s. sovereign cds premiums, *The Journal of Finance* 75, 2809–2844.

Clarida, Richard, and Jordi Gali, 1994, Sources of real exchange-rate fluctuations: How important are nominal shocks?, in *Carnegie-Rochester Conference Series on Public Policy*, volume 41, 1–56, Elsevier.

Cochrane, John H, and Monika Piazzesi, 2002, The fed and interest rates-a high-frequency identification, *American Economic Review* 92, 90–95.

Dornbusch, Rudiger, 1976, Expectations and exchange rate dynamics, *Journal of Political Economy* 84, 1161–1176.

Du, Wenxin, Joanne Im, and Jesse Schreger, 2018a, The us treasury premium, *Journal of International Economics* 112, 167–181.

Du, Wenxin, Alexander Tepper, and Adrien Verdelhan, 2018b, Deviations from covered interest rate parity, *The Journal of Finance* 73, 915–957.

Engel, Charles, and Steve Pak Yeung Wu, 2018, Liquidity and exchange rates: An empirical investigation .

Evans, Martin DD, and Richard K Lyons, 2002, Order flow and exchange rate dynamics, *Journal of Political Economy* 110, 170–180.

Farhi, Emmanuel, and Matteo Maggiori, 2018, A model of the international monetary system, *The Quarterly Journal of Economics* 133, 295–355.

Faust, Jon, Eric T Swanson, and Jonathan H Wright, 2004, Identifying vars based on high frequency futures data, *Journal of Monetary Economics* 51, 1107–1131.

Frankel, Jeffrey A, and Andrew K Rose, 1995, Empirical research on nominal exchange rates, *Handbook of International Economics* 3, 1689–1729.

Froot, Kenneth A, and Tarun Ramadorai, 2005, Currency returns, intrinsic value, and institutional-investor flows, *The Journal of Finance* 60, 1535–1566.

Froot, Kenneth A, and Kenneth Rogoff, 1995, Perspectives on ppp and long-run real exchange rates, *Handbook of International Economics* 3, 1647–1688.

Froot, Kenneth A, and Richard H Thaler, 1990, Anomalies: foreign exchange, *Journal of Economic Perspectives* 4, 179–192.

Gabaix, Xavier, and Matteo Maggiori, 2015, International liquidity and exchange rate dynamics, *The Quarterly Journal of Economics* 130, 1369–1420.

Gopinath, Gita, 2015, The international price system .

Gopinath, Gita, and Jeremy C Stein, 2018, Banking, trade, and the making of a dominant currency .

Gourinchas, Pierre-Olivier, and Helene Rey, 2007a, From world banker to world venture capitalist: Us external adjustment and the exorbitant privilege, in *G7 Current Account Imbalances: Sustainability and Adjustment*, 11–66 (University of Chicago Press).

Gourinchas, Pierre-Olivier, and Helene Rey, 2007b, International financial adjustment, *Journal of Political Economy* 115, 665–703.

Gourinchas, Pierre-Olivier, and Aaron Tornell, 2004, Exchange rate puzzles and distorted beliefs, *Journal of International Economics* 64, 303–333.

Greenwood, Robin, Samuel G Hanson, and Jeremy C Stein, 2015, A comparative-advantage approach to government debt maturity, *The Journal of Finance* 70, 1683–1722.

He, Zhiguo, Arvind Krishnamurthy, and Konstantin Milbradt, 2019, A model of safe asset determination, *American Economic Review* 109, 1230–62.

Holston, Kathryn, Thomas Laubach, and John C Williams, 2017, Measuring the natural rate of interest: International trends and determinants, *Journal of International Economics* 108, S59–S75.

Itskhoki, Oleg, and Dmitry Mukhin, 2017, Exchange rate disconnect in general equilibrium .

Ivashina, Victoria, David S Scharfstein, and Jeremy C Stein, 2015, Dollar funding and the lending behavior of global banks, *The Quarterly Journal of Economics* 130, 1241–1281.

Jiang, Zhengyang, 2019a, Fiscal cyclicality and currency risk premia .

Jiang, Zhengyang, 2019b, Us fiscal cycle and the dollar .

Jiang, Zhengyang, Arvind Krishnamurthy, and Hanno Lustig, 2018, Foreign safe asset demand for us treasurys and the dollar, in *AEA Papers and Proceedings*, volume 108, 537–41.

Jiang, Zhengyang, Arvind Krishnamurthy, and Hanno Lustig, 2020a, Dollar safety and the global financial cycle .

Jiang, Zhengyang, Arvind Krishnamurthy, and Hanno N Lustig, 2020b, Beyond incomplete spanning: Convenience yields and exchange rate disconnect .

Jiang, Zhengyang, Hanno Lustig, Stijn Van Nieuwerburgh, and Mindy Z Xiaolan, 2019, The U.S. public debt valuation puzzle.

Koijen, Ralph SJ, and Motohiro Yogo, 2020, Exchange rates and asset prices in a global demand system .

Kollmann, Robert, 1995, Consumption, real exchange rates and the structure of international asset markets, *Journal of International Money and Finance* 14, 191–211.

Krishnamurthy, Arvind, and Hanno N Lustig, 2019, Mind the gap in sovereign debt markets: The us treasury basis and the dollar risk factor, in *2019 Jackson Hole Economic Symposium*.

Krishnamurthy, Arvind, and Annette Vissing-Jorgensen, 2012, The aggregate demand for treasury debt, *Journal of Political Economy* 120, 233–267.

Krishnamurthy, Arvind, and Annette Vissing-Jorgensen, 2015, The impact of treasury supply on financial sector lending and stability, *Journal of Financial Economics* 118, 571–600.

Kuttner, Kenneth N, 2001, Monetary policy surprises and interest rates: Evidence from the fed funds futures market, *Journal of Monetary Economics* 47, 523–544.

Laubach, Thomas, and John C Williams, 2003, Measuring the natural rate of interest, *Review of Economics and Statistics* 85, 1063–1070.

Laubach, Thomas, and John C Williams, 2016, Measuring the natural rate of interest redux, *Business Economics* 51, 57–67.

Lilley, Andrew, Matteo Maggiori, Brent Neiman, and Jesse Schreger, 2019, Exchange rate reconnect .

Liu, Yang, Lukas Schmid, and Amir Yaron, 2019, The risks of safe assets .

Lustig, Hanno, Nikolai Roussanov, and Adrien Verdelhan, 2014, Countercyclical currency risk premia, *Journal of Financial Economics* 111, 527–553.

Lustig, Hanno, Andreas Stathopoulos, and Adrien Verdelhan, 2019, The term structure of currency carry trade risk premia, *American Economic Review* 109, 4142–77.

Lustig, Hanno, and Adrien Verdelhan, 2019, Does incomplete spanning in international financial markets help to explain exchange rates?, *American Economic Review* 109, 2208–44.

Maggiori, Matteo, 2017, Financial intermediation, international risk sharing, and reserve currencies, *American Economic Review* 107, 3038–71.

Maggiori, Matteo, Brent Neiman, and Jesse Schreger, 2020a, International currencies and capital allocation, *Journal of Political Economy* 128, 2019–2066.

Maggiori, Matteo, Brent Neiman, and Jesse Schreger, 2020b, International currencies and capital allocation, *Journal of Political Economy* 128, 2019–2066.

Mankiw, N Gregory, and Ricardo Reis, 2002, Sticky information versus sticky prices: a proposal to replace the new keynesian phillips curve, *The Quarterly Journal of Economics* 117, 1295–1328.

Moskowitz, Tobias J, Yao Hua Ooi, and Lasse Heje Pedersen, 2012, Time series momentum, *Journal of Financial Economics* 104, 228–250.

Pierre-Olivier, Govillot-Nicolas Gourinchas, Helene Rey, and Nicolas Govillot, 2011, Exorbitant privilege and exorbitant duty .

Reis, Ricardo, 2006, Inattentive consumers, *Journal of Monetary Economics* 53, 1761–1800.

Rudebusch, Glenn D, 1998, Do measures of monetary policy in a var make sense?, *International Economic Review* 907–931.

Shin, Hyun Song, 2012, Global banking glut and loan risk premium, *IMF Economic Review* 60, 155–192.

Stambaugh, Robert F, 1999, Predictive regressions, *Journal of Financial Economics* 54, 375–421.

Valchev, Rosen, 2020, Bond convenience yields and exchange rate dynamics, *American Economic Journal: Macroeconomics* 12, 124–66.

Separate Online Appendix

1. Section A lists the data sources.
2. Section B develops the theory of convenience yields and exchange rates in complete and incomplete markets, and a model of the LIBOR basis and its relation to the Treasury basis.
3. Section C estimates long run returns on safe assets earned by foreign investors.
4. Section D develops the model with sticky expectations.
5. Section E develops alternative measures of the Treasury basis.
6. Section F discusses VAR identification.
7. Section G discusses robustness.
8. Section H discusses the UK/US evidence.

Appendix A. Data Sources

We start by discussing the Panel Dataset. For the FX data, before December 1996, we use the Barclays Bank source from Datastream. After December 1996, we use World Markets Reuters (WMR) from Datastream. The Datastream codes for the spot rates and 12M forward rates are: *BBGBPSP, BBGBPYF, BBAUDSP, BBAUDYF, BBCADSP, BBCADYF, BBDEMSP, BBDEMYF, BBJPYSP, BBJPYYF, BNZDSP, BBNZDYF, BBNOKSP, BBNOKYF, BBSEKSP, BBSEKYF, BBCHFSP, BBCHFYF, AUSTDOL, UKAUDYF, CNDOLLR, UKCADYF, DMARKER, UKDEMYF, JAPAYEN, UKJPYYF, NZDOLLR, UKNZDYF, NORKRON, UKNOKYF, SWEKRON, UKSEKYF, SWISSFR, UKCHFYF, UKDOLLR, UKUSDYF.*

For the Government Bond Yields (see Table A.2), most country-maturities pairs only use one source, except if there are gaps. If there are gaps, we use all the data from the first source wherever available, as indicated in the Table, and then fill in any gaps for some year

Table A.1. Country Composition of Unbalanced Panel

Country	Maturity	Source	Ranges			
'Australia'	12	All	199912 - 201707			
'Canada'	12	All	199312 - 201707			
'Germany'	12	All	199707 - 201707			
'Japan'	12	All	199504 - 201707			
'New Zealand'	12	All	199603 - 200905	201006 - 201212	201310 - 201412	201606 - 201707
'Norway'	12	All	199001 - 199611	199701 - 201707		
'Sweden'	12	All	199103 - 199611	199701 - 201304	201306 - 201707	
'Switzerland'	12	All	198801 - 201707			
'United Kingdom'	12	All	199707 - 201707			
'United States'	12	All	198801 - 201707			

Table A.2. Sources for Government Bond Yields

Country	Maturity	Months		Mnemonic
Australia	12	Bloomberg		GTAUD1Y Govt
Canada	12	Bank of Canada (Datastream)		CNTBB1Y
Germany	12	Bloomberg		GTDEM1Y Govt
Japan	12	Bloomberg		GTJPY1Y Govt
New Zealand	12	Bloomberg	1	GTNZD1Y Govt
New Zealand	12	Reserve Bank of New Zealand (Datastream)	2	NZGBY1Y
Norway	12	Oslo Bors		ST3X
Sweden	12	Sveriges Riksbank (from Researchers)	2	
Sweden	12	Sveriges Riksbank (website)	1	
Switzerland	12	Swiss National Bank		
United Kingdom	12	Bloomberg		GTGBP1Y Govt
United States	12	Bloomberg	1	GB12 Govt
United States	12	FRED	2	

The numbers indicate which source takes precedence.

month using the second data source (indicated by '2'). For LIBORs (see Table A.3), we use the BBA-ICE LIBOR when available. Coverage is good for Germany, Japan, Switzerland, UK, and U.S.. For other countries, we then use other interbank survey rates (BBSW, CDOR, NIBOR, STIBOR) to fill in any gaps. We then use deposit rates (Bank Bill, NKD, SKD) for any remaining gaps.

Table A.3. Sources for LIBOR

Country	Maturity	Source	Mnemonic
Australia	12	Bank Bill (Bloomberg)	ADBB12M Curncy
Australia	12	Bank Bill Swap (Bloomberg)	BBSW1Y Index/BBSW1MD Index
Canada	12	CDOR (Bloomberg)	CDOR12 Index
Australia	12	BBA-ICE LIBOR (Datastream)	BBAUD12
New Zealand	12	Bank Bill (Bloomberg)	NDBB12M Curncy
Canada	12	BBA-ICE LIBOR (Datastream)	BBCAD12
Germany	12	BBA-ICE LIBOR (Datastream)	BBDEM12
Japan	12	BBA-ICE LIBOR (Datastream)	BBJPY12
New Zealand	12	BBA-ICE LIBOR (Datastream)	BBNZD12
Norway	12	NIBOR (Bloomberg)	NIBOR12M Index
Norway	12	Norwegian Krone Deposit (Bloomberg)	NKDR1 Curncy
Sweden	12	BBA-ICE LIBOR (Datastream)	BBSEK12
Sweden	12	STIBOR (Bloomberg)	STIB1Y Index
Sweden	12	Swedish Krona Deposit (Bloomberg)	SKDR1 Curncy
Switzerland	12	BBA-ICE LIBOR (Datastream)	BBCHF12
United Kingdom	12	BBA-ICE LIBOR (Datastream)	BBGBP12
United States	12	BBA-ICE LIBOR (Datastream)	BBUSD12

Our second dataset covers the U.S./U.K. cross. This data begins much earlier, in 1970Q1 and ends in 2016Q2. The daily data quality is poor, with many missing values and implausible spikes in the constructed basis from one day to the next. To overcome these measurement issues, we take the average of the available data for a given quarter as the observation for that quarter. We construct the Treasury basis in the same manner as described earlier. We rely on Global Financial Data as the main data source.

Table A.4. Sources for U.S.-UK Time Series

	Source	Mnemonic	Range
Spot FX	GFD	*GBPUSD*	1960 – 2017
3M Forward	GFD	*GBPUSD3D*	1960 – 2017
12M Forward	GFD	*GBPUSD12D*	1960 – 2017
3M T-bill UK	GFD	*ITGBR3D*	1960 – 2017
1Y Note UK	GFD	*IGGBR1D*	1979 – 2017
1Y Note U.S.	FRED	*DTB1YR*	1960 – 2017
1Y Zero-Coupon	BoE		1970 – 1979

(GFD is Global Financial Data. FRED is the Federal Reserve Economic Database at the Federal Reserve Bank of St Louis. BoE is the Bank of England.)

Figure A.1 plots the resulting series. LIBOR rates do not exist back to 1971. The average U.S./U.K. Treasury basis is 0.84 bps per annum. On average, U.K. investors are close to indifferent between holding U.S. Treasurys on a currency-hedged basis and holding gilts. However, the standard deviation is 48 bps. per quarter. For comparison the figure also plots the mean basis from the cross-country panel. The two series track each other closely for the period where they overlap, but the U.S./U.K. basis is consistently higher than the panel basis. This result suggests that UK bonds also have a convenience yield, which is sometimes larger than that of U.S. bonds particularly in the 1970s, during which the basis is volatile and frequently positive. Suffering a balance-of-payments deficit in the early 1970s, the Nixon administration decided to suspend convertibility of the dollar into gold in 1973 and effectively ended the Bretton-Woods system. This action led to considerable uncertainty in the international monetary system, with some observers noting that foreigners became unwilling to continue to hold the dollar assets necessary to finance the balance-of-payments deficit (see Bach (1972) and Farhi and Maggiori (2018)). Additionally, the U.K. suffered a balance-of-payments crisis in 1976, turning to the IMF for a large loan. These reductions in asset demand, first for U.S. and then for U.K. bonds, are apparent in the figure: the basis turns positive in 1973 before subsequently turning negative in 1976.

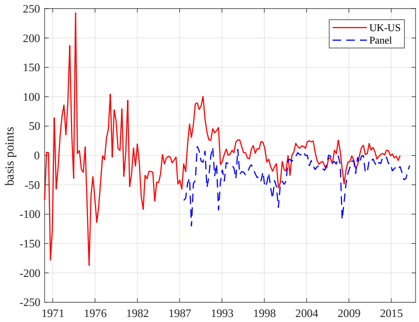

Figure A.1. U.S./U.K. Treasury Basis

U.S./U.K. Treasury basis from 1970Q1 to 2017Q2 and the mean Treasury basis across the panel of countries, in basis points. The maturity is one year.

Appendix B. Theory of Convenience Yields and Exchange Rates

This section explores two issues: (i) what happens in a complete markets environment to exchange rates when investors derive convenience yields, and (ii) an analysis of the role of the banking sector in LIBOR markets.

A. *Convenience Yields in Complete Markets*

We follow the approach of Backus et al. (2001). Consider the Euler equations (3) and (8) for the U.S. and foreign investor when investing in an asset with no convenience yield. To satisfy these Euler equations, we conjecture an exchange rate process that satisfies, $M_t^{\$} \frac{S_t}{S_{t+1}} = M_t^*$. This guess, as can easily be verified, satisfies the Euler equations for a no-convenience yield asset. If financial markets are complete, then this is the unique exchange rate process that is consistent with the absence of arbitrage opportunities. Using lower case letters to denote logs, and log-linearizing this expression, we find:

$$\Delta s_{t+1} \quad = \quad m_t^{\$} - m_t^*. \tag{B1}$$

Next consider the pair of Euler equations, (4) and (9), which apply to investments in the U.S. bond that gives a convenience yield. We conjecture an exchange rate process that satisfies,

$$M_t^* e^{\lambda_t^{\$,*}} \frac{S_{t+1}}{S_t} = M_t^{\$} e^{\lambda_t^{\$,\$}}.$$

After taking logs, we find:

$$\Delta s_{t+1} \quad = \quad \left(m_t^{\$} - m_t^*\right) + \left(\lambda_t^{\$,\$} - \lambda_t^{\$,*}\right) \tag{B2}$$

It is evident that (B1) and (B2) cannot both be satisfied in an equilibrium unless $\lambda_t^{\$,*} = \lambda_t^{\$,\$}$. But note that in this case, convenience yields have no impact on exchange rates.

B. *Convenience Yields in Incomplete Markets*

To develop a full-fledged exchange rate model, we conjecture that the exchange rate process satisfies:

$$\frac{S_{t+1}}{S_t} = \frac{M_{t+1}^{\$} \exp(\lambda_t^{\$,\$})}{M_{t+1}^* \exp(\lambda_t^{\$,*})} \exp(\eta_{t+1}),$$

where η_{t+1} represents an incomplete markets stochastic wedge. When markets are complete, $\eta_{t+1} = 0$ in all states of the world, and the U.S. and foreign bond investor's Euler equations for Treasurys are automatically satisfied. In addition, we assume that the wedges and the pricing kernels are jointly log-normal.

The change in the log exchange rate can be stated as follows: $\Delta s_{t+1} = \eta_{t+1} + m^{\$}_{t+1} - m^{*}_{t+1} - \lambda^{\$,*}_t + \lambda^{\$,\$}_t$. We impose the symmetry restriction on the convenience yields stated in (12).

PROPOSITION 2: *When the exchange rate change is* $\Delta s_{t+1} = \eta_{t+1} + m^{\$}_{t+1} - m^{*}_{t+1} - \lambda^{\$,*}_t + \lambda^{\$,\$}_t$, *and* $(\lambda^{\$,\$}_t - \lambda^{\$,*}_t) = (\lambda^{*,\$}_t - \lambda^{*,*}_t)$, *the wedges* η_{t+1} *have to satisfy:*

$$\begin{aligned} cov_t\left(m^{\$}_{t+1}, \eta_{t+1}\right) &= -E_t\left(\eta_{t+1}\right) - \frac{1}{2}var_t\left(\eta_{t+1}\right), \\ cov_t\left(m^{*}_{t+1}, \eta_{t+1}\right) &= -E_t\left(\eta_{t+1}\right) + \frac{1}{2}var_t\left(\eta_{t+1}\right). \end{aligned}$$

The variance of the exchange rate is given by: $var_t(\Delta s_{t+1}) = var_t(m_{t+1}) + var_t(m^{*}_{t+1}) - 2cov_t(m_{t+1}, m^{*}_{t+1}) - var_t(\eta_{t+1})$.

The incomplete market wedges have to satisfy restrictions to enforce the Euler equations for bond market investors (see Backus and Smith, 1993; Lustig and Verdelhan, 2019). That accounts for the covariance restrictions. Given the symmetry condition we impose on the convenience yields, the moment conditions for the incomplete markets wedges do not depend on the convenience yields.

COROLLARY 1: *The expected excess return in logs on a long position in dollars is given by:*

$$E_t[rx^{FX}_{t+1}] \equiv y^{\$}_t - y^{*}_t + E_t(\Delta s_{t+1}) = rp^{*}_t - \lambda^{\$,*}_t + \lambda^{*,*}_t,$$

where $rp^{*}_t = \frac{1}{2}\left[var_t\left(m^{*}_{t+1}\right) - var_t\left(m^{\$}_{t+1}\right)\right] + E_t\left(\eta_{t+1}\right)$.

If the foreign investor is risk-neutral, then the expected excess return in logs on a long position in dollars is given by: $E_t[rx^{FX}_{t+1}] \equiv y^{\$}_t - y^{*}_t + E_t(\Delta s_{t+1}) = -\frac{1}{2}var_t\left(m^{\$}_{t+1}\right) + E_t\left(\eta_{t+1}\right) - \lambda^{\$,*}_t + \lambda^{*,*}_t$.

COROLLARY 2: *The expected excess return in levels on a long position in dollars is given by:*

$$y^{\$}_t - y^{*}_t + E_t(\Delta s_{t+1}) + \frac{1}{2}var_t(\Delta s_{t+1}) = RP^{*}_t - \lambda^{\$,*}_t + \lambda^{*,*}_t,$$

where $RP^{*}_t = var_t(m^{*}_{t+1}) - cov_t\left(m^{*}_{t+1}, m^{\$}_{t+1}\right) + E_t\left(\eta_{t+1}\right) - \frac{1}{2}var_t\left(\eta_{t+1}\right)$.

If the foreign investor is risk-neutral, the expected excess return in levels on a long position in dollars is given by: $y^{\$}_t - y^{*}_t + E_t(\Delta s_{t+1}) + \frac{1}{2}var_t(\Delta s_{t+1}) = -\lambda^{\$,*}_t + \lambda^{*,*}_t$. Uncovered Interest Rate Parity (U.I.P.) fails even though the foreign investor is risk-neutral. The deviation from U.I.P. is governed by the convenience yields.

COROLLARY 3: *The expected excess return in levels on a long position in foreign currency* *is given by:*

$$y_t^* - y_t^\$ - E_t(\Delta s_{t+1}) + \frac{1}{2} var_t(\Delta s_{t+1}) = RP_t^\$ + \lambda_t^{\$,\$} - \lambda_t^{*,\$},$$

where $RP_t^\$ = var_t(m_{t+1}^\$) - cov_t\left(m_{t+1}^*, m_{t+1}^\$\right) - E_t\left(\eta_{t+1}\right) - \frac{1}{2} var_t\left(\eta_{t+1}\right)$.

Starting from this expression, we can compute the expected return of a US investor in logs by subtracting 1/2 of the variance:

$$y_t^* - y_t^\$ - E_t(\Delta s_{t+1}) = var_t(m_{t+1}) - cov_t\left(m_{t+1}^*, m_{t+1}^\$\right) + cov_t\left(m_{t+1}^\$, \eta_{t+1}\right) - \frac{1}{2} var_t(\Delta s_{t+1}) + \lambda_t^{\$,\$} - \lambda_t^{*,\$}.$$

Plug in the expression for the volatility of the changes in the spot rate to obtain: $y_t^* - y_t^\$ - E_t(\Delta s_{t+1}) = -rp_t^* + \lambda_t^{\$,\$} - \lambda_t^{*,\$}$. This is consistent with corollary 1, because $\lambda_t^{\$,\$} - \lambda_t^{*,\$} = -(\lambda_t^{*,*} - \lambda_t^{\$,*})$.

COROLLARY 4: *The incomplete markets exchange rate process given by*

$$\Delta s_{t+1} = m_{t+1}^\$ - m_{t+1}^* + \eta_{t+1} + \lambda_t^{\$,\$} - \lambda_t^{\$,*}, \tag{B3}$$

implies that:

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} (\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}) + \mathbb{E}_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^\$ - y_{t+\tau}^*) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp_{t+\tau}^* + \mathbb{E}_t[\lim_{T\to\infty} s_{t+T+1}]. \tag{B4}$$

C. *Convenience yields on LIBOR deposits, the LIBOR basis, and the Treasury basis*

In U.S. data, Krishnamurthy and Vissing-Jorgensen (2012) observe that there is a convenience yield on both Treasury bonds and other near-riskless private bonds such as bank deposits. They moreover show that some investors view near-riskless private bonds as partial substitutes for Treasury bonds. This section introduces LIBOR bank deposits which also offer convenience yields, but less so than U.S. Treasurys. That is, as noted earlier, our theory posits that investors receive convenience utility from U.S. safe assets, a set that includes both U.S. Treasurys and bank deposits. We first show how to understand the LIBOR basis and safe asset demand in this case, and then offer another way to understand the Treasury basis.

Foreign and domestic investors have access to U.S. LIBOR markets, and they satisfy the following Euler equations:

$$\mathbb{E}_t\left(M_{t+1}^\$ e^{y_t^{\$,LIBOR}}\right) = e^{-\beta^{\$,LIBOR}\lambda_t^{\$,\$}} \tag{B5}$$

$$\mathbb{E}_t\left(M_{t+1}^* \frac{S_{t+1}}{S_t} e^{y_t^{\$,LIBOR}}\right) = e^{-\beta^{*,LIBOR}\lambda_t^{\$,*}} \tag{B6}$$

where $\beta^{*,LIBOR} < 1$ ($\beta^{\$,LIBOR}$) denotes the fraction of convenience yield from the LIBOR bank deposit relative to the Treasury bond derived by foreign (U.S.) investors.

Next we construct the LIBOR basis in a similar manner as Section D. Suppose a foreign investor purchases a foreign LIBOR deposit and swaps the deposit into dollars. This investment satisfies the investor's Euler equation:

$$\mathbb{E}_t\left[M^*_{t+1}\frac{S_{t+1}}{S_t}\frac{S_t}{F^1_t}e^{y^{*,LIBOR}_t}\right] = e^{-\beta^{*,LIBOR-H}\lambda^{\$,*}_t}. \tag{B7}$$

Here F^1_t denotes the one-period forward exchange rate, in foreign currency per dollar, and $\beta^{*,LIBOR-H}\lambda^{\$,*}_t$ denotes the fraction of convenience yield on the cash position in the foreign bank deposit hedged into dollars relative to a U.S. Treasury investment. We use equation (B7) along with the foreign investor's Euler equation for the dollar LIBOR deposit, to find an expression for the LIBOR basis:

$$x^{LIBOR}_t \equiv y^{\$,LIBOR}_t + (f^1_t - s_t) - y^{*,LIBOR}_t = -(\beta^{*,LIBOR} - \beta^{*,LIBOR-H})\lambda^{\$,*}_t. \tag{B8}$$

If a synthetically created dollar deposit is as good as a cash dollar deposit for an investor, the right hand side is zero and the LIBOR basis is zero. From the investor demand-side, a negative LIBOR basis indicates a preference for the cash deposit compared to the synthetic deposit.

We next reconsider the Treasury basis in light of the LIBOR basis:

$$x^{Treas}_t \quad = \quad y^{\$}_t - y^*_t + f_t - s_t = (y^{\$}_t - y^{\$,LIBOR}_t) - (y^*_t - y^{*,LIBOR}_t) + x^{LIBOR}_t. \tag{B9}$$

The Treasury basis is the sum of the LIBOR basis and the difference between the two currency's Treasury-LIBOR spreads. From the Euler equations for the foreign investment in U.S. Treasurys and U.S. dollar LIBOR deposits we find that:

$$y^{\$,LIBOR}_t - y^{\$}_t = (1-\beta^{*,LIBOR})\lambda^{\$,*}_t$$

We make a parallel assumption that the foreign investor receives a fraction $\beta^{*,LIBOR}$ of the convenience when investing in the foreign deposit relative to the foreign bond. Thus the foreign Treasury-LIBOR spread is:

$$y^{*,LIBOR}_t - y^*_t = (1-\beta^{*,LIBOR})\lambda^{*,*}_t$$

Rewriting the Treasury basis we find that:

$$x^{Treas}_t = (1-\beta^{*,LIBOR})(\lambda^{\$,*}_t - \lambda^{*,*}_t) + x^{LIBOR}_t.$$

We conclude that the Treasury basis measures the foreign demand for U.S. safe assets through both the excess Treasury convenience yield, $\lambda^{\$,*}_t - \lambda^{\$,\$}_t$, as we showed in Section D, and through movements in the LIBOR basis. We can go one step further by substituting in from the LIBOR basis to find:

$$\begin{aligned} x_t^{Treas} &= (1-\beta^{*,LIBOR})(\lambda_t^{\$,*}-\lambda_t^{*,*}) - (\beta^{*,LIBOR}-\beta^{*,LIBOR-H})\lambda_t^{\$,*}. \\ &= (1-\beta^{*,LIBOR-H})\lambda_t^{\$,*} - (1-\beta^{*,LIBOR})\lambda_t^{*,*} \end{aligned}$$

When the cash position is more valiable to investors than the synthetic, $\beta^{*,LIBOR-H} < \beta^{*,LIBOR}$, the Treasury basis is effectively enlarged.

It is useful to compare this derivation of the basis to the one from Section D. We found that,

$$x_t^{Treas} = (1-\beta^*)(\lambda_t^{\$,*}-\lambda_t^{*,*})$$

Here β^* summarized the foreign investor's preference for the synthetic Treasury bond relative to the cash Treasury bond. Note that β^* does not have to be equal to $\beta^{*,LIBOR}$. However they are related in that both reflect dollarness, safety, and synthetic-vs-cash in convenience valuations.

We next consider the banks that make the supply-side of the deposit market. Suppose that $x_t^{LIBOR} < 0$, i.e. investors are willing to pay a premium for a cash dollar LIBOR deposit compared to the synthetically created deposit. Banks issue foreign and dollar deposits that pay LIBOR at rates $y_t^{*,LIBOR}$ and $y_t^{\$,LIBOR}$. The dollar deposits offer a convenience yield to investors but not to the banks, so that banks will wish to issue these deposits in equilibrium. Consider a given bank that has a mix of deposits in both currencies in (dollar-equivalent) amounts $(\bar{\theta}_t^{B,\$}, \bar{\theta}_t^{B,*})$. We suppose the mix is optimal for the bank given asset/liability management concerns and the currency mix of the rest of its balance sheet. If bank deposits offer convenience yields, than banks will create these deposits, and the limit on such deposit creation will be governed by bank costs in creating the deposits. See the model of Krishnamurthy and Vissing-Jorgensen (2015) for one specification of intermediaries doing asset/liability management and creating money where the cost is in terms of collateral backing. We have suppressed the specification of these costs to not stray from our primary analysis which is exchange rate determination. Think of the optimal mix $(\bar{\theta}_t^{B,\$}, \bar{\theta}_t^{B,*})$ as being driven by these costs.

Suppose that the bank also trades in the forward market. Clearly if the convenience yield on the cash dollar deposits rises relative to synthetic foreign deposits, the bank will want to supply more of these dollar deposits and hedge these using the forward market to maintain its optimal currency mix. Then the bank chooses θ_t^B, the quantity of this swap, to achieve deposit mix $(\bar{\theta}_t^{B,\$}+\theta_t^B, \bar{\theta}_t^{B,*}-\theta_t^B)$. If there is greater demand for dollar deposits the bank will on the margin increase θ_t^B. Suppose the bank solves:

$$\max_{\theta_t^B} \theta_t^B \left(y_t^{*,LIBOR} - (f_t - s_t) - y_t^{\$,LIBOR}\right) - \frac{\kappa}{2}\left(\theta_t^B\right)^2.$$

Here κ is a capital/leverage cost associated with doing the forward and hedging the dollar deposits. The term $y_t^{*,LIBOR} - (f_t - s_t) - y_t^{\$,LIBOR}$ is the funding cost reduction that the bank gets when taking advantage of the dollar convenience yield. The F.O.C. for the bank is,

$$\begin{aligned} -\kappa\theta_t^B &= y_t^{\$,LIBOR} - y_t^{*,LIBOR} + (f_t - s_t) \\ &= x_t^{LIBOR} \end{aligned}$$

where x_t^{LIBOR} denotes the LIBOR basis. If $y_t^{\$,LIBOR}$ is particularly low, e.g., driven by an increase in demand for dollar deposits, then x_t^{LIBOR} will rise and banks will increase the supply of dollar deposits, θ_t^B, while swapping these dollars deposits back into foreign currency to keep their exchange rate exposure unaffected. Suppose there are many banks and denote the aggregate quantity of dollar deposits supplied in equilibrium as Θ_t^B. Then, the equilibrium LIBOR basis is given by:

$$x_t^{LIBOR} = -\kappa\Theta_t^B. \tag{B10}$$

LEMMA 6: *The LIBOR basis depends on foreign demand for dollar deposits as follows: When banks face no capital/leverage costs in doing swaps and $\kappa = 0$, the LIBOR basis is zero and independent of Θ_t^B. When $\kappa > 0$, the LIBOR basis becomes more negative as the demand for dollar safe assets rises.*

In the frictionless case, as κ goes to zero, banks actively trade in the forward to earn the convenience yield on dollar deposits while not altering their exchange rate exposure. In equilibrium, the price of the forward will adjust to equalize these margins and the LIBOR CIP deviation goes to zero. Perhaps surprisingly. the forward price, f_t^1, can embed a convenience yield.

In an influential recent paper, Du et al. (2018b) document that the LIBOR basis was near zero pre-crisis and has often been significantly different than zero post-crisis. They show that the movements in the LIBOR basis are closely connected to frictions in financial intermediation that prevent arbitrage activities. Other papers have come to similar conclusions regarding the importance of financial frictions and capital controls (see Ivashina et al., 2015; Gabaix and Maggiori, 2015; Amador et al., 2020; Itskhoki and Mukhin, 2017). Our lemma shows, consistent with the findings of Du et al. (2018b), that when $\kappa > 0$, LIBOR CIP will fail. More novel, our theory implies that when $\kappa > 0$, x_t^{LIBOR} will, like $\lambda_t^{\$,*}$, reflect foreign investors's demand for safe dollar assets. We verify this prediction in the data post-crisis.

D. *Proofs*

- Proof of Proposition 2:

  Proof. We start from the domestic investor's Euler equation for the foreign risk-free asset, and the foreign investor's Euler equation for the domestic risk-free asset respectively:

$$
\begin{aligned}
E_t\left(M^{\$}_{t+1}\exp(\lambda^{\$,\$}_t)\right) &= E_t\left(M^{*}_{t+1}\frac{S_{t+1}}{S_t}\exp(\lambda^{\$,*}_t)\right) = E_t\left(M^{\$}_{t+1}\exp(\lambda^{\$,\$}_t)\exp(\eta_{t+1})\right) = \exp(-y^{\$}_t) \\
E_t\left(M^{*}_{t+1}\exp(\lambda^{*,*}_t)\right) &= E_t\left(M^{\$}_{t+1}\frac{S_t}{S_{t+1}}\exp(\lambda^{*,\$}_t)\right) = E_t\left(M^{*}_{t+1}\exp(\lambda^{*,*}_t)\exp(-\eta_{t+1})\right) = \exp(-y^{*}_t)
\end{aligned}
$$

where we have used:

$$
\frac{S_{t+1}}{S_t} = \frac{M^{\$}_{t+1}\exp(\lambda^{\$,\$}_t)}{M^{*}_{t+1}\exp(\lambda^{\$,*}_t)}\exp(\eta_{t+1}) = \frac{M^{\$}_{t+1}\exp(\lambda^{*,\$}_t)}{M^{*}_{t+1}\exp(\lambda^{*,*}_t)}\exp(\eta_{t+1}).
$$

By using conditional joint log normality of the foreign SDF and $exp(\eta)$, the first Euler equation implies that:

$$
\begin{aligned}
E_t\left(\log M^{\$}_{t+1}\right) + \frac{1}{2}var_t\left(\log M^{\$}_{t+1}\right) &= E_t\left(\log M^{\$}_{t+1}\right) + \mu_{t,\eta} + \frac{1}{2}var_t\left(\log M^{\$}_{t+1}\right) \\
&+ \frac{1}{2}var_t\left(\eta_{t+1}\right) + cov_t(\eta_{t+1}, \log M^{\$}_{t+1}),
\end{aligned}
$$

where $\mu_{t,\eta} = E_t\left(\eta_{t+1}\right)$. This implies that $cov_t\left(m^{\$}_{t+1}, \eta_{t+1}\right) = -\mu_{t,\eta} - 0.5var_t\left(\eta_{t+1}\right)$. We move on to the second equation. The second Euler equation for the domestic risk-free asset implies that:

$$
\begin{aligned}
E_t\left(\log M^{*}_{t+1}\right) + \frac{1}{2}var_t\left(\log M^{*}_{t+1}\right) &= E_t\left(\log M^{*}_{t+1}\right) - \mu_{t,\eta} + \frac{1}{2}var_t\left(\log M^{*}_{t+1}\right) \\
&+ (1/2)var_t\left(\eta_{t+1}\right) - cov_t(\eta_{t+1}, \log M^{*}_{t+1}).
\end{aligned}
$$

This implies that $cov_t\left(m^{*}_{t+1}, \eta_{t+1}\right) = -\mu_{t,\eta} + 0.5var_t\left(\eta_{t+1}\right)$.

To derive an expression for the variance of the exchange rate, we start from the definition of log changes in exchange rates: $var_t(\Delta s_{t+1}) = var_t(\eta_{t+1} + m^{\$}_{t+1} - m^{*}_{t+1})$. This can be simplified to:

$$
\begin{aligned}
var_t(\Delta s_{t+1}) &= var_t(m^{\$}_{t+1}) + var_t(m^{*}_{t+1}) + var_t(\eta_{t+1}) - 2cov_t(m^{\$}_{t+1}, m^{*}_{t+1}) \\
&+ 2cov_t(m^{\$}_{t+1}, \eta_{t+1}) - 2cov_t(m^{*}_{t+1}, \eta_{t+1}).
\end{aligned}
$$

Plug in the covariance expressions above, we obtain

$$
var_t(\Delta s_{t+1}) = var_t(m^{\$}_{t+1}) + var_t(m^{*}_{t+1}) - 2cov_t(m^{\$}_{t+1}, m^{*}_{t+1}) - var_t\left(\eta_{t+1}\right).
$$

□

- Proof of Corollary 1:

Proof. We use the following Euler equations for the foreign bond, and the domestic bond respectively:

$$\begin{aligned}\mathbb{E}_t\left[m^*_{t+1}\right]+\frac{1}{2}var_t\left[m^*_{t+1}\right]+y^*_t &= -\lambda^{*,*}_t,\\ \mathbb{E}_t\left[m^\$_{t+1}\right]+\frac{1}{2}var_t\left[m^\$_{t+1}\right]+y^\$_t &= -\lambda^{\$,\$}_t.\end{aligned}$$

By plugging these 2 equations into the log expected excess return given by $y^\$_t - y^*_t + E_t(\Delta s_{t+1})$, and by using the following expression for the expected rate of appreciation, $E_t\Delta s_{t+1} = E_t(\eta_{t+1} + m^\$_{t+1} - m^*_{t+1} - \lambda^{\$,*}_t + \lambda^{\$,\$}_t)$, we obtain an expression for the expected excess return in logs: $y^\$_t - y^*_t + E_t(\Delta s_{t+1}) = \frac{1}{2}\left[var_t\left(m^*_{t+1}\right) - var_t\left(m^\$_{t+1}\right)\right] - \lambda^{\$,*}_t + \lambda^{*,*}_t + E_t\left(\eta_{t+1}\right).$ □

- Proof of Corollary 2:

Proof. From the foreign investor's Euler equation, it follows that the expected excess return in levels is given by:

$$\begin{aligned}E_t[rx^{FX}_{t+1}]+(1/2)var_t(\Delta s_{t+1}) &\equiv y^\$_t - y^*_t + E_t(\Delta s_{t+1}) + (1/2)var_t(\Delta s_{t+1})\\ &= -cov_t(m^*_{t+1},\Delta s_{t+1}) - \lambda^{\$,*}_t + \lambda^{*,*}_t\end{aligned}$$

Next, note that: $-cov_t(m^*_{t+1},\Delta s_{t+1}) = -cov_t\left(m^*_{t+1}, \eta_{t+1} + m^\$_{t+1} - m^*_{t+1} - \lambda^{\$,*}_t + \lambda^{\$,\$}_t\right).$ This can be worked out to yield the following expression: $-cov_t(m^*_{t+1},\Delta s_{t+1}) = var_t(m^*_{t+1}) - cov_t\left(m^*_{t+1}, m^\$_{t+1}\right) - cov_t\left(m^*_{t+1},\eta_{t+1}\right)$, where $cov_t\left(m^*_{t+1},\eta_{t+1}\right) = -E_t\left(\eta_{t+1}\right) + \frac{1}{2}var_t\left(\eta_{t+1}\right)$ The latter follows from the restriction on the wedges in Proposition 2. This can then be worked out to yield the following expression: $-cov_t(m^*_{t+1},\Delta s_{t+1}) - \lambda^{\$,*}_t + \lambda^{*,*}_t = var_t(m^*_{t+1}) - cov_t\left(m^*_{t+1}, m^\$_{t+1}\right) + E_t\left(\eta_{t+1}\right) - \frac{1}{2}var_t\left(\eta_{t+1}\right) - \lambda^{\$,*}_t + \lambda^{*,*}_t.$ □

- Proof of Corollary 3:

Proof. Similarly, the excess return expected by the US investor on foreign bonds in levels is:

$$y^*_t - y^\$_t - E_t(\Delta s_{t+1}) + (1/2)var_t(\Delta s_{t+1}) = -cov_t(m^\$_{t+1}, -\Delta s_{t+1}) + \lambda^{\$,\$}_t - \lambda^{*,\$}_t$$

Next, note that $-cov_t(m^\$_{t+1},\Delta s_{t+1}) = -cov_t\left(m^\$_{t+1}, -\eta_{t+1} - m^\$_{t+1} + m^*_{t+1} + \lambda^{\$,*}_t - \lambda^{\$,\$}_t\right).$ This can be worked out to yield the following expression: $-cov_t(m^\$_{t+1},\Delta s_{t+1}) = var_t(m^\$_{t+1}) - cov_t\left(m^*_{t+1}, m^\$_{t+1}\right) + cov_t\left(m^\$_{t+1},\eta_{t+1}\right)$, where $cov_t\left(m^\$_{t+1},\eta_{t+1}\right) = -E_t\left(\eta_{t+1}\right) - \frac{1}{2}var_t\left(\eta_{t+1}\right).$ This follows from the restrictions on the wedges in Proposition 2. This can be worked out to yield the following expression: $-cov_t(m^\$_{t+1},\Delta s_{t+1}) = var_t(m^\$_{t+1}) - cov_t\left(m^*_{t+1}, m^\$_{t+1}\right) - E_t\left(\eta_{t+1}\right) - \frac{1}{2}var_t\left(\eta_{t+1}\right).$

□

- Proof of Corollary 4:

  Proof. We start from the expression for the change in the log exchange rate and we re-arrange this to produce: $s_t = -m^{\$}_{t+1} + m^{*}_{t+1} - \eta_{t+1} - \lambda^{\$,\$}_t + \lambda^{\$,*}_t + s_{t+1}$. Next, we take expectations to get the following expression for the log exchange rate:

$$s_t = -\mathbb{E}_t[m^{\$}_{t+1}] + \mathbb{E}_t[m^{*}_{t+1}] - \mathbb{E}_t[\eta_{t+1}] - \lambda^{\$,\$}_t + \lambda^{\$,*}_t + \mathbb{E}_t s_{t+1}.$$

  We use the expression for the yields:

$$\mathbb{E}_t\left[m^{*}_{t+1}\right] = -y^{*}_t - \frac{1}{2}var_t\left[m^{*}_{t+1}\right] - \lambda^{*,*}_t.$$

$$\mathbb{E}_t\left[m^{\$}_{t+1}\right] = -y^{\$}_t - \frac{1}{2}var_t\left[m^{\$}_{t+1}\right] - \lambda^{\$,\$}_t.$$

  Next, we plug these back into the exchange rate expression to get:

$$\begin{aligned} s_t &= y^{\$}_t + \frac{1}{2}var_t\left[m^{\$}_{t+1}\right] + \lambda^{\$,\$}_t - y^{*}_t - \frac{1}{2}var_t\left[m^{*}_{t+1}\right] - \lambda^{*,*}_t - \mathbb{E}_t[\eta_{t+1}] - \lambda^{\$,\$}_t + \lambda^{\$,*}_t + \mathbb{E}_t s_{t+1} \\ &= y^{\$}_t + \frac{1}{2}var_t\left[m^{\$}_{t+1}\right] - y^{*}_t - \frac{1}{2}var_t\left[m^{*}_{t+1}\right] + \lambda^{\$,*}_t - \lambda^{*,*}_t - \mathbb{E}_t[\eta_{t+1}] + \mathbb{E}_t s_{t+1}. \end{aligned}$$

  Next, we can use the following expression for the log currency risk premium: $rp^{*}_t = \frac{1}{2}\left[var_t\left(m^{*}_{t+1}\right) - var_t\left(m^{\$}_{t+1}\right)\right] + E_t\left(\eta_{t+1}\right)$, to obtain the following expression for the log of the exchange rate:

$$s_t = \left(y^{\$}_t - y^{*}_t\right) + \left(\lambda^{\$,*}_t - \lambda^{*,*}_t\right) - rp^{*}_t + \mathbb{E}_t s_{t+1}.$$

  After repeated substitution, we obtain:

$$s_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} (\lambda^{\$,*}_{t+\tau} - \lambda^{*,*}_{t+\tau}) + \mathbb{E}_t \sum_{\tau=0}^{\infty} (y^{\$}_{t+\tau} - y^{*}_{t+\tau}) - \mathbb{E}_t \sum_{\tau=0}^{\infty} rp^{*}_{t+\tau} + \mathbb{E}_t[\lim_{T\to\infty} s_{t+T+1}].$$

  □

Appendix C. Long-run Riskless Rate

In the short run, the dollar exchange rate adjusts in response to changes in the convenience yields. If real exchange rates are stationary, then there is no long-run currency adjustment. The currency risk premium disappears from the exchange rate determination equation (see Backus et al., 2018; Lustig et al., 2019). The spread between the real long-run returns earned by foreign investors on U.S. Treasurys and domestic bonds reveals the (average) extra convenience yields earned by foreign investors when buying Treasurys:

$$\lambda^{\$,*} - \lambda^{*,*} = -(R^{\$,*} - R^{*,*}) = 2\%.$$

Using our model, we inferred from the Treasury basis and the response of the dollar exchange rate that the extra convenience yield earned by foreign investors is around 2%. This implies that in the long run real returns earned by foreign investors on Treasurys need to be 2% lower than the returns on foreign bonds to maintain a stationary exchange rate. Our result is qualitatively in line with the savings glut hypothesis (see, e.g., Caballero et al., 2008; Caballero and Krishnamurthy, 2008) and the low r-star analysis (see Laubach and Williams, 2003, 2016; Holston et al., 2017).

Admittedly, these are large numbers. We take a different, more direct approach to estimating this gap $\lambda^{\$,*} - \lambda^{*,*}$. We compute this return gap, as explained below, finding estimates of $\lambda^{\$,*} - \lambda^{*,*}$ between 1.57% and 1.89%. To compute the realized returns, we take the timing of foreign purchases of Treasurys into account. Foreigners buy Treasurys when they are expensive.

The stylized model developed in the paper features a single maturity instrument. The maturity of the bonds and the holding period was fixed at one year, mainly to simplify the analysis, the equivalent of one period in the model. We want to compute the convenience yield that foreign investors derive on their entire portfolio of U.S. Treasurys and T-Bills. Foreign investors do not simply buy and hold Treasurys until maturity. To develop a precise measure of the average convenience yield earned by foreign investors on all of their Treasury holdings, we compute the effective return realized by foreign investors on all of their U.S. Treasury purchases ($R^{\$,*}$). This return is lower than what is suggested by average U.S. Treasury yields. To compute the dollar-weighted return $R^{\$,*}$, we solve the following standard IRR equation for $R^{\$,*}$:

$$-AUM_0^{\$,*} + \sum_{t=0}^{T} \frac{-Net\ Purchases_t^{\$,*}}{(1+R^{\$,*})^t} + \frac{AUM_T^{\$,*}}{(1+R^{\$,*})^T} = 0,$$

where T denotes the holding period. The terminal cash flow AUM_T is the market value of the U.S. (foreign) investor's Treasury holdings. We set $AUM_0^{\$,*}$ to zero.

We consider the returns earned by the stand-in foreign investor. This investor's net purchases of Treasurys in each quarter $Net\ Purchases_t^{\$,*}$ equals the net purchases of U.S. Treasurys by all foreign investors. We used the quarterly Flow of Funds data to measure net purchases of Treasurys by foreign investors. We assume that this foreign investor is fully invested in the Bloomberg Barclays Treasury Index. The Bloomberg Barclays US Treasury Index measures US dollar-denominated, fixed-rate, nominal debt issued by the US Treasury. Treasury bills are excluded by the maturity constraint, but are part of a separate Short Treasury Index. To develop a benchmark, we also consider the returns earned by the stand-in U.S. investor buying Treasurys. Each quarter, this investor buys all of the Treasurys issued by the U.S. Treasury less those Treasurys purchased by foreign investors. This index is constructed to measure the returns of a stand-in U.S. investor who buys all marketable

U.S. Treasurys. We assume that this U.S. investor is fully invested in the Bloomberg Barclays Treasury Index.

$$-AUM_0^{\$,\$} + \sum_{t=0}^{T} \frac{-Net\ Purchases_t^{\$,\$}}{(1+R^{\$,\$})^t} + \frac{AUM_T^{\$,\$}}{(1+R^{\$,\$})^T} = 0.$$

The results are reported in Panel A of Table A.5. Foreign investors earn low effective returns on their Treasury holdings. The USD effective return realized by foreign investors buying Treasurys over 39 years is only 5.27% p.a., well below the buy-and-hold return of 10.07 %.Hence, the yields, the buy-and-hold returns when the holding period is the maturity of the bond, do not produce good estimates of the foreign investor's returns. This number should be compared to the effective return of 7.45% realized by U.S. investors, 2.18% higher than the foreign investor's return. Foreign investors earn a real effective return ($R^{\$,*}_{real,PPP}$) of only 3.09% expressed in U.S. units of consumption. This is the relevant estimate of the foreign real return provided that PPP holds in the long run. Foreign investors buy (sell) Treasurys when U.S. Treasurys are expensive (cheap), i.e. when the convenience yields are high (low). This number can be compared to the effective return of 4.83% realized by U.S. investors, 1.74% higher than the foreign investor's return.

In Panel B of Table A.5, we assume that the stand-in foreign investor is fully invested in the WGBI World index ex-U.S to estimate the foreign investor's realized return on foreign local currency bonds ($R^{*,*}_{real,*}$). The FTSE World Government Bond Index (WGBI) measures the performance of fixed-rate, local currency, investment-grade sovereign bonds. The WGBI is a widely used benchmark that currently includes sovereign debt from over 20 countries, denominated in a variety of currencies, and has more than 30 years of history available. The WGBI provides a broad benchmark for the global sovereign fixed income market. WGBI is a market-cap-weighted index of local currency sovereign debt. The U.S. is excluded. The stand-in foreign investor simply holds the 'market for all foreign local currency debt'. Given the home currency bias in local currency sovereign and corporate debt holdings, this seems like a reasonable assumption (Maggiori et al., 2020b). The real buy-and-hold return realized by foreign investors on foreign, local currency bonds is 4.66%.

If P.P.P. holds in the long run, then the difference between the real returns earned by foreign investors on U.S. Treasurys and foreign bonds reveals the (average) extra convenience yields earned by foreign investors when buying Treasurys. As a result, we can get an estimate of the extra convenience yield on Treasurys by comparing dollar-weighted returns earned by foreign investors on Treasurys to those earned on foreign bonds:

$$R^{*,*}_{real,PPP} - R^{\$,*}_{real,PPP} = 4.66\% - 3.09\% = 1.57\% = \lambda^{\$,*} - \lambda^{*,*}.$$

Thus, from a different perspective, we estimate the convenience yield to be 1.57% per annum based on the Flow of Funds data.

Next, we consider the TICS data provided by the U.S. Treasury. Table A.6 uses the monthly TICS data instead of the quarterly Flow of Funds data. This allows us for more precise calculations of the returns earned by foreign investors. In addition, we can also look at private investor flows separately. In panel A, we consider total cross-border lows of U.S. Treasurys. Foreign investors earn a real effective return ($R^{\$,*}_{real,PPP}$) of only 3.24% (close to 3.09%). However, in Panel B, we exclude the foreign reserve purchases of central banks. The effective real return decreases to 2.77%. The 'private' estimate of the extra foreign convenience yield is 189 bps:

$$R^{*,*}_{real,PPP} - R^{\$,*}_{real,PPP} = 4.66\% - 2.77\% = 1.89\% = \lambda^{\$,*} - \lambda^{*,*}.$$

These different approaches to estimating the foreign convenience yield all give numbers in the same ballpark. This makes us more comfortable with our estimates.[7]

Table A.5. Foreign Dollar-weighted Returns on U.S. Treasurys and T-Bills

Investor Nationality	Dollar	Time	Δ(Time-Dollar)	Δ(US-Foreign)
		Panel A: Returns on U.S. Treasurys		
Foreign ($R^{\$,*}_{USD}$)	5.27%	10.07%	4.80%	2.18%
Foreign, Real ($R^{\$,*}_{real,PPP}$)	3.09%	6.77%	3.68%	1.74%
U.S. ($R^{\$,\$}_{USD}$)	7.45%	10.07%	2.62%	
U.S., Real ($R^{\$,\$}_{real,US}$)	4.83%	6.75%	1.92%	
		Panel B: Returns on Foreign Bonds		
Foreign ($R^{*,*}_{USD}$)		7.38%		
Foreign, Real ($R^{*,*}_{real,PPP}$)		4.66%		

Note: Sample 1980.Q1-2019.Q3. Quarterly data from the Federal Flow of Funds, Table F.210 'Treasury Securities'. The dollar-weighted return is the annualized IRR on the cash flows invested. The terminal cash flow is the market value of the foreign investor's Treasury holdings. The time-weighted return or buy-and-hold return is the annualized geometric mean return. In Panel A, we assume all cash flows are invested in the Barclays Bloomberg U.S. Treasury index. In Panel B, we assume that the foreign investor is fully invested in the FTSE World WGBI Ex-U.S. Bond Index; Sample starts only in 1985. The row labeled 'U.S.' takes all Treasury issuance as the cash flows invested, but excludes the Treasurys (T-Bills) purchased by the ROW from Treasury issuance. The row labeled 'Foreign' uses only Treasurys purchased by foreigners as the cash flows invested; returns expressed in dollars.

[7]Using the same logic, we could back out the extra convenience yield foreigners earn on Treasurys compared to U.S. investors: $R^{\$,\$}_{real,PPP} - R^{\$,*}_{real,PPP} = 4.83\% - 2.77\% = 2.06\% = \lambda^{\$,*} - \lambda^{\$,\$}$. By combining these 2 calculations, we get that: $\lambda^{\$,\$} - \lambda^{*,*} = 17$ bps. Krishnamurthy and Vissing-Jorgensen estimate an average $\lambda^{\$,\$}$ of 75 bps. This implies that $\lambda^{*,*}$ is 58 basis points.

Table A.6. Foreign Returns on U.S. Treasurys: Total vs. Private

	Dollar	Time	Δ(Time-Dollar)
		Panel A:Total	
Foreign ($R^{\$;*}_{USD}$)	5.46%	10.33%	4.87%
Foreign, Real ($R^{\$,*}_{real,PPP}$)	3.24%	7.00%	3.77%
		Panel B:Private	
Foreign ($R^{\$;*}_{USD}$)	4.90%	10.81%	5.91%
Foreign, Real ($R^{\$,*}_{real,PPP}$)	2.77%	7.05%	4.28%

Note: Sample 1980.M1-2019.M2. Monthly data from the TIC Treasury data on net purchases of U.S. Treasurys by foreigners. We assume these flows are fully invested in the Barclays Treasury Bond Index. The dollar-weighted return is the IRR realized on the cash flows invested by foreign investors. The terminal cash flow is the market value of the foreign investor's Treasury holdings. The time-weighted return is the annualized geometric mean.

Appendix D. Exchange Rate Model with Sticky Expectations

To accommodate the evidence of time-series momentum in the dollar exchange rate, we analyze a version of the model in which foreign exchange investors have sticky expectations: we posit that these investors do not update their expectations each period, but, when they do, they use the right model, as in Mankiw and Reis (2002). We assume that in any given period, a fraction $(1-\varpi)$ of investors update their information set each period. When they update, they use rational expectations. We use $\mathbb{F}_t$ to denote the cross-sectional average of the sticky information forecasts. Reis (2006) shows that the cross-sectional average forecast of a variable x_t h periods from now is simply given by: $\mathbb{F}_t x_{t+h} = (1-\varpi)\sum_{j=0}^{\infty}\varpi^j \mathbb{E}_{t-j} x_{t+h}$.

We posit the following autoregressive processes for the convenience yield earned by foreign investors, the real interest rate difference $i_t = r_t^{\$} - r_t^*$ and the (negative of the) risk premium $rp_t = -(RP_t^* - Var_t(\Delta q_{t+1}))$:

$$\lambda_{t+1}^* = \gamma_0 + \gamma_1 \lambda_t^* + \varepsilon_{t+1}^{\lambda}, \tag{D1}$$

$$i_{t+1} = \psi_0 + \psi_1 i_t + \varepsilon_{t+1}^{i}, \tag{D2}$$

$$rp_{t+1} = \delta_0 + \delta_1 rp_t + \varepsilon_{t+1}^{rp}. \tag{D3}$$

Next we assume that the equilibrium exchange rate reflects the cross-sectional average across all investors of their forecasts of the convenience yield earned by foreign investors, interest rate differences, and risk premium components of equation (22). We show in the appendix that:

PROPOSITION 3: *The log of the real exchange rate can be stated as a function of current and lagged fundamentals:*

$$q_t = \bar{q} + (1-\varpi)\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda_{t-j}^* - \theta_\lambda) + \frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t-j} - \theta_i) + \frac{\varpi^j\delta_1^j}{1-\delta_1}(rp_{t-j} - \theta_{rp})\right) \tag{D4}$$

The first term measures the impact of the convenience yields earned by foreign investors on the real exchange rate. The second term measures the interest rate differences. The U.S. Treasury yield includes the effect of the U.S. investors' convenience yields. The last term comprises the currency risk premia.

To understand this expression, it is helpful to consider the case of rational expectations. As $\varpi \to 0$, the expression simplifies to $q_t = \bar{q} + \frac{1}{1-\gamma_1}(\lambda_t^* - \theta_\lambda) + \frac{1}{1-\psi_1}(i_t - \theta_i) + \frac{1}{1-\delta_1}(rp_t - \theta_{rp})$, which is the equivalent of (12). The terms here correspond to the sum of future convenience yields earned by foreign investors, the interest rate differentials, and the risk premia, evaluated under the assumed AR(1) structure. When investors have sticky expectations ($\varpi > 0$), the log of the real exchange rate adjust slowly to new information about convenience yields, interest rates and risk premia, as captured by the lagged terms in the sum in (D4). The inertia in the response to basis shocks is essential to match the time-series dynamics of the real exchange rate.

We explicitly compute the impulse responses to innovations.

COROLLARY 5: *The impulse response function of the real exchange rate q_t to innovations $(\epsilon^{\lambda}, \epsilon^{i}, \epsilon_{rp})$ j periods after impact is given by:*

$$\begin{aligned}
\varphi_{\lambda,j} &= \frac{(1-\varpi)}{1-\gamma_1}\left[\frac{(1-\varpi^j)}{1-\varpi}\gamma_1^j + \left(\varpi^j\gamma_1^j - 1\right)\right] \text{ for } j = 0,1,2,\ldots. \\
\varphi_{i,j} &= \frac{(1-\varpi)}{1-\psi_1}\left[\frac{(1-\varpi^j)}{1-\varpi}\psi_1^j + \left(\varpi^j\psi_1^j - 1\right)\right] \text{ for } j = 0,1,2,\ldots. \\
\varphi_{rp,j} &= \frac{(1-\varpi)}{1-\delta_1}\left[\frac{(1-\varpi^j)}{1-\varpi}\delta_1^j + \left(\varpi^j\delta_1^j - 1\right)\right] \text{ for } j = 0,1,2,\ldots.
\end{aligned}$$

In the case of rational expectations $\varpi = 0$, the real exchange rate jumps upon impact and then gradually depreciates. In this case, there is no momentum in realized returns.

To help us understand the return predictability produced by this model, we derive an expression for the excess return expected by a rational investor who continuously updates her expectations:

PROPOSITION 4: *In the model with sticky expectations, the log excess return expected by a rational foreign investor on a long position in U.S. Treasury bonds relative to the foreign bond is:*

$$\begin{aligned}
\mathbb{E}_t rx_{t+1} = \mathbb{E}_t[\Delta q_{t+1}] + i_t &= i_t + (1-\varpi)\left(\frac{\gamma_1}{1-\gamma_1}(\lambda_t^* - \theta_\lambda) + \frac{\psi_1}{1-\psi_1}(i_t - \theta_i) + \frac{\delta_1}{1-\delta_1}(rp_t - \theta_{rp})\right) \\
&+ (1-\varpi)\left((\varpi\gamma_1 - 1)x_t^{\lambda} + (\varpi\psi_1 - 1)y_t^{i} + (\varpi\delta_1 - 1)z_t^{rp}\right).
\end{aligned}$$

When all agents have rational expectations $\varpi = 0$, this collapses to the standard expression:

$$\mathbb{E}_t[\Delta q_{t+1}] + i_t = RP_t^* - \lambda_t.$$

An increase in λ decreases the expected excess return one-for-one. However, in the sticky expectations case, returns will be predictable by all three state variables. Indeed, if ϖ is large enough, an increase in λ initially increases expected excess returns.

COROLLARY 6: *At longer horizons, the rate of appreciation expected by a rational investor is given by*

$$\begin{aligned}
\mathbb{E}_t(q_{t+k} - q_t) &= (1-\varpi^k)\left(\frac{\gamma_1^k}{1-\gamma_1}(\lambda_t^* - \theta_\lambda) + \frac{\psi_1^k}{1-\psi_1}(i_t - \theta_i) + \frac{\delta_1^k}{1-\delta_1}(rp_t - \theta_{rp})\right) \quad \text{(D5)} \\
&+ (1-\varpi)\left((\varpi^k\gamma_1^k - 1)x_t^{\lambda} + (\varpi^k\psi_1^k - 1)y_t^{i} + (\varpi^k\delta_1^k - 1)z_t^{rp}\right).
\end{aligned}$$

- Proof of Proposition 3:

Proof. We consider an environment with a continuum of currencies/investor pairs. For a foreign investor who had last updated k periods ago, his valuation of the real exchange rate can be written as:

$$q_t(k) = \mathbb{E}_{t-k}\sum_{\tau=0}^{\infty}\lambda^*_{t+\tau}+\mathbb{E}_{t-k}\sum_{\tau=0}^{\infty}(r^{\$}_{t+\tau}-r^*_{t+\tau})-\mathbb{E}_{t-k}\sum_{\tau=0}^{\infty}\left(RP^*_{t+\tau}-\frac{1}{2}Var[\Delta s_{t+\tau+1}]\right)+\bar{q}. \tag{D6}$$

where, $\bar{q} = \mathbb{E}_t[\lim_{\tau\to\infty}\ q_{t+\tau}]$ is constant under the assumption that the real exchange rate is stationary. The terms $r^{\$}_t$ and r^*_t are the real interest rates, i.e., $y^{\$}_t - \mathbb{E}_t[\Delta p^{\$}_{t+1}]$ is the real dollar interest rate.

We posit that the real dollar exchange rate is equal to the average valuation of the real dollar exchange rate across investors. In the case of information stickiness, the convenience yield component is given by:

$$\mathbb{F}_t\left[\sum_{k=0}^{\infty}(\lambda^*_{t+k}-\theta_\lambda)\right] = \sum_{k=0}^{\infty}(1-\varpi)\sum_{j=0}^{\infty}\varpi^j\gamma_1^{j+k}(\lambda^*_{t-j}-\theta_\lambda),$$

which can be simplified as

$$\mathbb{F}_t\left[\sum_{k=1}^{\infty}(\lambda^*_{t+k}-\theta_\lambda)\right] = \sum_{j=0}^{\infty}(\varpi)^j(1-\varpi)\frac{\gamma_1^j}{1-\gamma_1}(\lambda^*_{t-j}-\theta_\lambda).$$

By the same token, the aggregate cash flow and risk premium components are given by:

$$\begin{aligned}\mathbb{F}_t\left[\sum_{k=1}^{\infty}(i_{t+k}-\theta_i)\right] &= \sum_{j=0}^{\infty}(\varpi)^j(1-\varpi)\frac{\psi_1^j}{1-\psi_1}(i_{t-j}-\theta_i),\\ \mathbb{F}_t\left[\sum_{k=1}^{\infty}(rp_{t+k}-\theta_{rp})\right] &= \sum_{j=0}^{\infty}(\varpi)^j(1-\varpi)\frac{\delta_1^j}{1-\delta_1}(rp_{t-j}-\theta_{rp}).\end{aligned}$$

As a result, we end up with the following expression for the log of the real exchange rate:

$$q_t = \bar{q}+(1-\varpi)\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda^*_{t-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t-j}-\theta_i)+\frac{\varpi^j\delta_1^j}{1-\delta_1}(rp_{t-j}-\theta_{rp})\right).$$

□

- Proof of Proposition 4:

Proof. Armed with this expression, we can compute the (rationally) expected change in the real exchange given by:

$$\begin{aligned}
\mathbb{E}_t(q_{t+1}-q_t) &= \bar{q}+(1-\varpi)\mathbb{E}_t\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda^*_{t+1-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t+1-j}-\theta_i)\right)\\
&- \left[\bar{q}+(1-\varpi)\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda^*_{t-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t-j}-\theta_i)+\frac{\varpi^j\delta_1^j}{1-\delta_1}(rp_{t-j}-\theta_{rp})\right)\right].
\end{aligned}$$

This can be simplified as follows:

$$\begin{aligned}
\mathbb{E}_t(q_{t+1}-q_t) &= (1-\varpi)\left(\frac{\gamma_1}{1-\gamma_1}(\lambda^*_t-\theta_\lambda)+\frac{\psi_1}{1-\psi_1}(i_t-\theta_i)+\frac{\delta_1}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\sum_{j=1}^{\infty}\left(\frac{\varpi^j\gamma_1^j-\varpi^{j-1}\gamma_1^{j-1}}{1-\gamma_1}(\lambda^*_{t+1-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j-\varpi^{j-1}\psi_1^{j-1}}{1-\psi_1}(i_{t+1-j}-\theta_i)\right)\\
&+ (1-\varpi)\sum_{j=1}^{\infty}\left(\frac{\varpi^j\delta_1^j-\varpi^{j-1}\delta_1^{j-1}}{1-\delta_1}(rp_{t+1-j}-\theta_{rp})\right),
\end{aligned}$$

or, equivalently,

$$\begin{aligned}
\mathbb{E}_t(q_{t+1}-q_t) &= (1-\varpi)\left(\frac{\gamma_1}{1-\gamma_1}(\lambda^*_t-\theta_\lambda)+\frac{\psi_1}{1-\psi_1}(i_t-\theta_i)+\frac{\delta_1}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\sum_{j=0}^{\infty}\left((\varpi^j\gamma_1^j)\frac{\varpi\gamma_1-1}{1-\gamma_1}(\lambda^*_{t-j}-\theta_\lambda)+(\varpi^j\psi_1^j)\frac{\varpi\psi_1-1}{1-\psi_1}(i_{t-j}-\theta_i)\right)\\
&+ (1-\varpi)\sum_{j=0}^{\infty}\left((\varpi^j\delta_1^j)\frac{\varpi\delta_1-1}{1-\delta_1}(rp_{t-j}-\theta_{rp})\right).
\end{aligned}$$

Using the expression for the new state variables, $x_t^\lambda = \varpi\gamma_1 x_{t-1}^\lambda + \frac{1}{1-\gamma_1}(\lambda_t^*-\theta_\lambda)$, $y_t^i = \varpi\psi_1 y_{t-1}^i + \frac{1}{1-\psi_1}(i_t-\theta_i)$, $z_t^{rp} = \varpi\delta_1 z_{t-1}^{rp} + \frac{1}{1-\delta_1}(rp_t-\theta_{rp})$, we obtain the following expression for the (rational) expected rate of appreciation:

$$\begin{aligned}
\mathbb{E}_t(q_{t+1}-q_t) &= (1-\varpi)\left(\frac{\gamma_1}{1-\gamma_1}(\lambda^*_t-\theta_\lambda)+\frac{\psi_1}{1-\psi_1}(i_t-\theta_i)+\frac{\delta_1}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\left((\varpi\gamma_1-1)x_t^\lambda+(\varpi\psi_1-1)y_t^i+(\varpi\delta_1-1)z_t^{rp}\right)
\end{aligned}$$

□

- Proof of Corollary 6:

Proof. We can compute the (rationally) expected change in the real exchange given by:

$$\begin{aligned}
\mathbb{E}_t(q_{t+k}-q_t) &= \bar{q}+(1-\varpi)\mathbb{E}_t\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda^*_{t+k-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t+k-j}-\theta_i)+\frac{\varpi^j\delta_1^j}{1-\delta_1}(rp_{t+k-j}-\theta_{rp})\right)\\
&- \left[\bar{q}+(1-\varpi)\sum_{j=0}^{\infty}\left(\frac{\varpi^j\gamma_1^j}{1-\gamma_1}(\lambda^*_{t-j}-\theta_\lambda)+\frac{\varpi^j\psi_1^j}{1-\psi_1}(i_{t-j}-\theta_i)+\frac{\varpi^j\delta_1^j}{1-\delta_1}(rp_{t-j}-\theta_{rp})\right)\right].
\end{aligned}$$

This can be simplified as follows:

$$
\begin{aligned}
\mathbb{E}_t(q_{t+k}-q_t) &= (1-\varpi)\sum_{j=0}^{k-1}\left(\frac{\varpi^j\gamma_1^k}{1-\gamma_1}(\lambda_t^*-\theta_\lambda)+\frac{\varpi^j\psi_1^k}{1-\psi_1}(i_t-\theta_i)+\frac{\varpi^j\delta_1^k}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\sum_{j=k}^{\infty}\left(\frac{\varpi^j\gamma_1^j-\varpi^{j-k}\gamma_1^{j-k}}{1-\gamma_1}(\lambda_{t+k-j}^*-\theta_\lambda)+\frac{\varpi^j\psi_1^j-\varpi^{j-k}\psi_1^{j-k}}{1-\psi_1}(i_{t+k-j}-\theta_i)\right)\\
&+ (1-\varpi)\sum_{j=k}^{\infty}\left(\frac{\varpi^j\delta_1^j-\varpi^{j-k}\delta_1^{j-k}}{1-\delta_1}(rp_{t+k-j}-\theta_{rp})\right),
\end{aligned}
$$

or, equivalently,

$$
\begin{aligned}
\mathbb{E}_t(q_{t+k}-q_t) &= (1-\varpi)\sum_{j=0}^{k-1}\varpi^j\left(\frac{\gamma_1^k}{1-\gamma_1}(\lambda_t^*-\theta_\lambda)+\frac{\psi_1^k}{1-\psi_1}(i_t-\theta_i)+\frac{\delta_1^k}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\sum_{j=k}^{\infty}\left(\varpi^k\gamma_1^k\frac{\varpi^{j-k}\gamma_1^{j-k}-1}{1-\gamma_1}(\lambda_{t+k-j}^*-\theta_\lambda)+\varpi^k\psi_1^k\frac{\varpi^{j-k}\psi_1^{j-k}-1}{1-\psi_1}(i_{t+k-j}-\theta_i)\right)\\
&+ (1-\varpi)\sum_{j=k}^{\infty}\left(\varpi^k\delta_1^k\frac{\varpi^{j-k}\delta_1^{j-k}-1}{1-\delta_1}(rp_{t+k-j}-\theta_{rp})\right).
\end{aligned}
$$

Using the expression for the new state variables, $x_t^\lambda = \varpi\gamma_1 x_{t-1}^\lambda + \frac{1}{1-\gamma_1}(\lambda_t^*-\theta_\lambda)$, $y_t^i = \varpi\psi_1 y_{t-1}^i + \frac{1}{1-\psi_1}(i_t-\theta_i)$, $z_t^{rp} = \varpi\delta_1 z_{t-1}^{rp} + \frac{1}{1-\delta_1}(rp_t-\theta_{rp})$,

we obtain the following expression for the (rational) expected rate of appreciation:

$$
\begin{aligned}
\mathbb{E}_t(q_{t+k}-q_t) &= (1-\varpi^k)\left(\frac{\gamma_1^k}{1-\gamma_1}(\lambda_t^*-\theta_\lambda)+\frac{\psi_1^k}{1-\psi_1}(i_t-\theta_i)+\frac{\delta_1^k}{1-\delta_1}(rp_t-\theta_{rp})\right)\\
&+ (1-\varpi)\left((\varpi^k\gamma_1^k-1)x_t^\lambda+(\varpi^k\psi_1^k-1)y_t^i+(\varpi^k\delta_1^k-1)z_t^{rp}\right)
\end{aligned}
$$

□

Appendix E. Alternative Construction of Treasury Basis

A. KFW Bonds

Figure A.2 plots the basis for KfW bonds. KfW is a German issuer whose bonds are backed by the German government, so that they are near default free. KfW issues bonds in different currencies allowing us to compute the basis for the bonds of the same issuer, i.e., holding safety fixed, in different currencies. We compute the basis for KfW bonds using one-year yields on these bonds for Australia, Euro, UK, and Switzerland against the U.S.. The yield data is from Bloomberg and corresponds to a fitted yield at the one-year maturity (one-year maturity bonds do not always exist). Clearly this measure is not as reliable as our Treasury basis measure which only uses information from traded instruments. Figure A.2 plots the cross-country mean KfW basis and the Treasury basis (cross-country mean for the same countries) over a sample with daily data from 2011Q2 to 2017Q2.

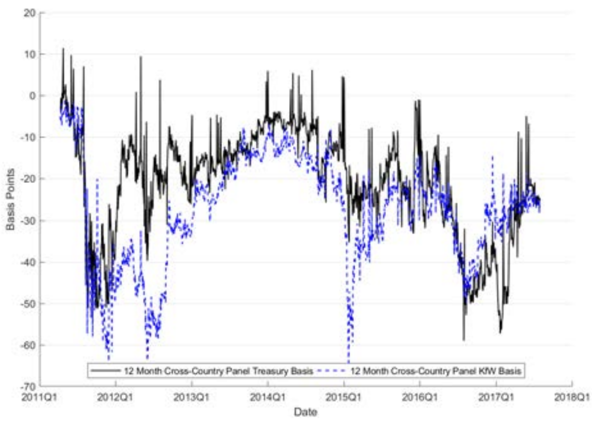

Figure A.2. KfW and Treasury Basis, 2011Q2 to 2017Q2

B. Credit Risk Adjustment

Figure A.3 plots the Treasury basis after we adjust for credit risk. Recall that the Treasury basis is defined as the different between Treasury yields plot the forward premium:

$$x_t^{Treas} \equiv y_t^{\$} + (f_t^1 - s_t) - y_t^*. \tag{E1}$$

Here, we define the credit-risk adjusted Treasury basis as

$$x_t^{Treas} \equiv (y_t^{\$} - cds_t^{\$}) + (f_t^1 - s_t) - (y_t^* - cds_t^*), \tag{E2}$$

where $cds_t^{\$}$ and cds_t^* are the U.S. and foreign sovereign default CDS spreads. We use the most liquid 5-year CDS contract from Markit, even though the Treasury yields are 1-year.

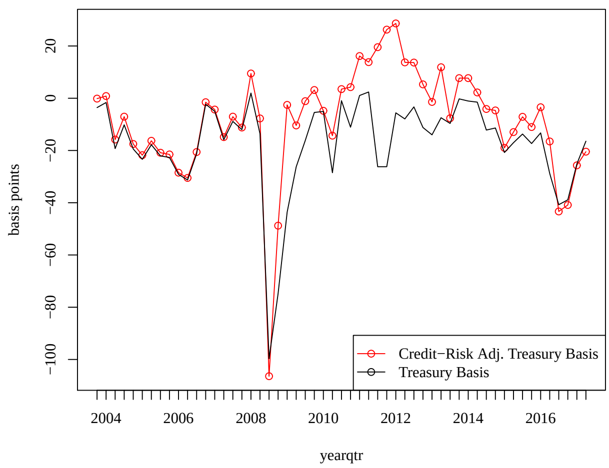

Figure A.3. Credit Risk Adjustment for Treasury Basis, 2003Q4 to 2017Q2

Appendix F. VAR Estimation Identification

Rescaling Bases and Interest Rate Differences in VAR We estimate the VAR system using quarterly data. In order to convert the 1-year Treasury basis to an equivalent 3-month Treasury basis, we scale the 1-year Treasury basis in the following way:

$$x_t^{3m} = \frac{1-\phi}{1-\phi^4} \cdot x_t^{12m},$$

where $\phi = 0.46$ is the quarterly AR(1) coefficient on the 1-year basis.This AR(1) coefficient is slightly different from the one calculated in Section A of the paper because in the VAR system we drop 4 quarterly observations for missing real interest rate data. With this scaling, a 1% increase in the 1-year basis at time t is spread into a $\frac{1-\phi}{1-\phi^4} \cdot 1\% = 0.56\%$ increase in the 1-quarter basis at time t (or equivalently a 2.25% increase in the annualized 1-quarter basis), an expected 0.26% increase in the 1-quarter basis at time $t+1$, an expected 0.12% increase in the 1-quarter basis at time $t+2$, an expected 0.06% increase in the 1-quarter basis at time $t+3$. In this way, the expected increases in the 1-quarter basis from time t to $t+3$ sum up to 1%. Moreover, note that in an annual model, a 1% increase in the 1-year basis raises the expected present-value of the convenience yield term in equation (22) by $\frac{1}{1-\phi^4} \cdot 1\%$. By our scaling, this shock raises the 1-quarter basis by $\frac{1-\phi}{1-\phi^4} \cdot 1\%$, which also leads to the same increase in the present value of the convenience yield by $\frac{1-\phi}{1-\phi^4}\frac{1}{1-\phi} \cdot 1\% = \frac{1}{1-\phi^4} \cdot 1\%$.

Similarly, we impose an AR(1) structure to the term structure of the interest rate differential. Under this structure, we scale the 1-year interest rate differential in the following way:

$$i_t^{3m} = \frac{1-\phi_i}{1-\phi_i^4} \cdot i_t^{12m},$$

where $\phi_i = 0.85$ is the quarterly AR(1) coefficient on the 1-year interest rate differential. With this scaling, a 1% increase in the 1-year interest rate differential at time t is spread into increases of 0.31%, 0.27%, 0.23% and 0.19% in the 1-quarter interest rate differential at time t to $t+3$.

A shock to the Treasury basis affects future Treasury basis, future interest rates, and future risk premia. In order to estimate the β^* coefficient under the VAR model, we assume that the response of the sum of expected risk premia to a Treasury basis shock is 0:

$$\Delta \mathbb{E}_t \sum_{\tau=0}^{\infty} RP_{t+\tau}^* = 0.$$

Under this identifying assumption, we can identify β^* from the response of the exchange rate to an orthogonal basis shock:

$$\frac{1}{1-\beta^*} = -\frac{\Delta q_t - \Delta\mathbb{E}_t \sum_{\tau=0}^{\infty}(r^{\$}_{t+\tau} - r^*_{t+\tau}) + \Delta\mathbb{E}_t \sum_{\tau=0}^{\infty} RP^*_{t+\tau}}{\Delta\mathbb{E}_t \sum_{\tau=0}^{\infty} x_{t+\tau}} \tag{F1}$$

$$= -\frac{\Delta q_t - \Delta\mathbb{E}_t \sum_{\tau=0}^{\infty}(r^{\$}_{t+\tau} - r^*_{t+\tau})}{\Delta\mathbb{E}_t \sum_{\tau=0}^{\infty} x_{t+\tau}}, \tag{F2}$$

where Δ traces out the impulse responses of different variables to the orthogonal basis shock in our VAR system.

More formally, notice the VAR system $\boldsymbol{z}_t' = [x_t, i_t, q_t]$ has the following dynamics

$$\boldsymbol{z}_t = \boldsymbol{\Gamma}_0 + \boldsymbol{\Gamma}_1 \boldsymbol{z}_{t-1} + \boldsymbol{a}_t.$$

We extract the orthogonalized basis shock from the Cholesky Decomposition:

$$var(\boldsymbol{a}_t) \equiv \Omega = AA'.$$

Define $\tilde{\boldsymbol{a}}_{\boldsymbol{t}} = A^{-1}\boldsymbol{a}_t$, then $var(\tilde{\boldsymbol{a}}_{\boldsymbol{t}}) = I$. The orthogonalized basis shock is defined as $A\boldsymbol{e}_1'\tilde{\boldsymbol{a}}_{\boldsymbol{t}}$. Then, we plug the impulse responses following the orthogonalized basis shock into Eq. (F1),

$$\frac{1}{1-\beta^*} = -\frac{\Delta q_t - \Delta\mathbb{E}_t \sum_{\tau=0}^{\infty}(r^{\$}_{t+\tau} - r^*_{t+\tau})}{\Delta\mathbb{E}_t \sum_{\tau=0}^{\infty} x_{t+\tau}} \tag{F3}$$

$$= -\frac{\boldsymbol{e}_3' A\boldsymbol{e}_1'\tilde{\boldsymbol{a}}_{\boldsymbol{t}} - \boldsymbol{e}_2'(\boldsymbol{I} + \boldsymbol{\Gamma}_1 + \boldsymbol{\Gamma}_1^2 + \ldots)A\boldsymbol{e}_1'\tilde{\boldsymbol{a}}_{\boldsymbol{t}}}{\boldsymbol{e}_1'(\boldsymbol{I} + \boldsymbol{\Gamma}_1 + \boldsymbol{\Gamma}_1^2 + \ldots)A\boldsymbol{e}_1'\tilde{\boldsymbol{a}}_{\boldsymbol{t}}}, \tag{F4}$$

and obtain an estimate of β^*.

Ordering Importantly, the results are not sensitive to switching the order of the basis and interest rate differential, indicating that we can plausibly interpret the relation between the basis and exchange rate causally: A shock to convenience yields moves both the basis and the exchange rate. We say this because we have allowed for other known determinants of the exchange rate, relative price levels and relative interest rates, and yet recover the same relation between the basis and the exchange rate. Figure A.4 switches the ordering of the interest rate difference and the basis in the VAR. The impulse responses to a basis shock are nearly identical to those of Figure 2. The exchange rate falls a little under 3% over two quarters and then gradually reverts over the subsequent 2 years. We find that the ordering does not matter because the reduced form VAR innovations to the basis and the interest rate difference are only weakly correlated. Finally, the ordering also does not affect the variance decomposition results.

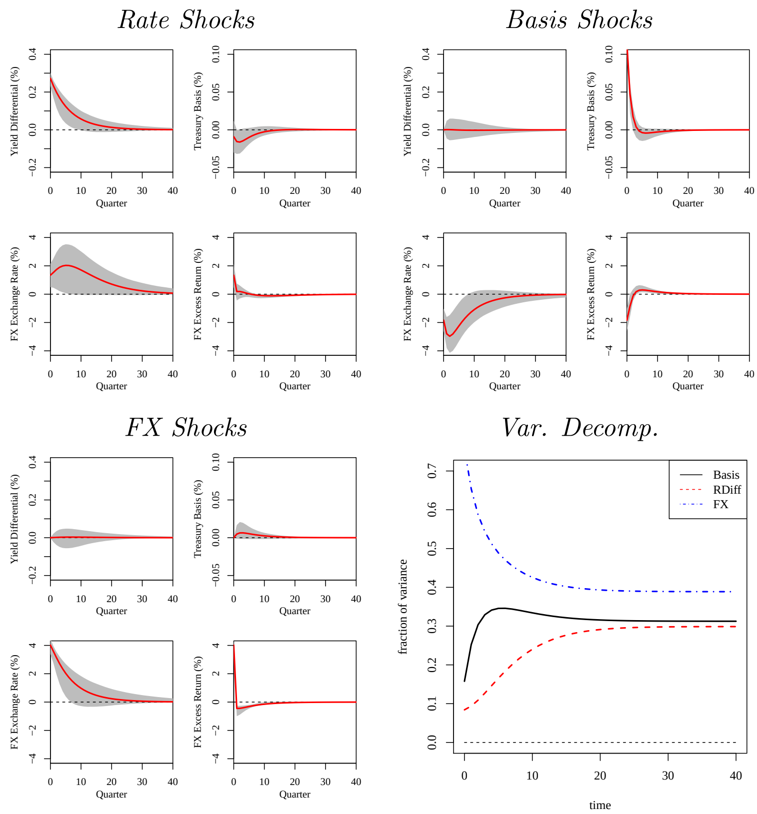

Figure A.4. Panel Impulse Responses, Alternative Ordering.

The red line plots the impulse response of an orthogonalized one-standard-deviation shock on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[r_t^{\$} - \overline{r}_t^*, \overline{x}_t, q_t\right]$.

Appendix G. Robustness

Our robustness tests include (1) replacing the innovation to Treasury basis by the change in Treasury basis, (2) re-running regressions in the subsample in which the Treasury basis is small in magnitude, (3) in the predictability regression, changing the dependent variable from the dollar's excess return to its exchange rate movement, (4) using the quarterly average basis instead of the end-of-quarter basis.

A. *Explaining Variation in the Dollar Using Change in Treasury Basis*

In Table III, we use the innovation in Treasury basis as the explanatory variable. Here we use the change $\Delta\bar{x}_t^{Treas} = \bar{x}_t^{Treas} - \bar{x}_{t-1}^{Treas}$ instead.

Table A.7. Average Treasury Basis and the USD Spot Nominal Exchange Rate

The dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. The independent variables are the change in the average Treasury basis, $\Delta\overline{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the change, the change in the LIBOR basis, and the change in the U.S.-to-foreign Treasury yield differential. Data is quarterly. OLS standard errors in parentheses. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	1988Q1−2017Q2					1988Q1−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\overline{x}^{Treas}$	-4.27^{**}		-9.50^{***}		-8.89^{***}	-2.08		-11.00^{***}	
	(1.90)		(1.96)		(1.73)	(2.32)		(3.11)	
$\Delta\overline{x}^{LIBOR}$		3.02					8.46^{***}		-7.61^{*}
		(2.57)					(3.18)		(3.84)
Lag $\Delta\overline{x}^{Treas}$			-12.15^{***}		-11.36^{***}				
			(2.31)		(2.04)				
$\Delta(y^{\$} - \bar{y}^{*})$				3.76^{***}	3.51^{***}				
				(0.71)	(0.61)				
Observations	117	117	116	117	116	80	80	37	37
R^2	0.04	0.01	0.23	0.20	0.41	0.01	0.08	0.26	0.10

B. *Explaining Variation in the Dollar when Treasury Basis is Small*

This section repeats the regressions in Table III in the sub-sample in which the U.S. Treasury basis is above or equal to the 25th percentile (-30 basis points), which represent the 75% of the data in which the Treasury basis is small in magnitude. We find that the U.S. dollar's exchange rate also comoves with the U.S. Treasury basis in these calm periods.

Table A.8. Average Treasury Basis and the USD Spot Nominal Exchange Rate, Calm Periods

The dependent variable is the quarterly change in the log of the spot USD exchange rate against a basket. The independent variables are the innovation in the average Treasury basis, $\Delta\bar{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, the innovation in the LIBOR basis, and the innovation in the U.S.-to-foreign Treasury yield differential. Data is quarterly. OLS standard errors in parentheses. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	1988Q1−2017Q2					1988Q1−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	-9.55^{***}		-13.30^{***}		-6.12^{*}	-6.75^{**}		-23.86^{***}	
	(2.47)		(2.96)		(3.08)	(2.78)		(5.11)	
$\Delta\bar{x}^{LIBOR}$		-7.28^{*}					-4.35		-11.44^{*}
		(3.90)					(5.20)		(5.81)
Lag $\Delta\bar{x}^{Treas}$			-7.76^{**}		-2.53				
			(3.54)		(3.38)				
$\Delta(y^{\$} - \bar{y}^{*})$				5.01^{***}	4.13^{***}				
				(0.78)	(0.89)				
Observations	88	88	88	88	88	58	58	30	30
R^2	0.15	0.04	0.19	0.32	0.36	0.10	0.01	0.44	0.12

C. *Forecasting Exchange Rate Movements using Treasury Basis*

This section checks the predictability of nominal exchange rate movements instead of the predictability of currency excess returns.

Table A.9. Forecasting Exchange Rate Movements in Panel Data

The dependent variable is the annualized change in the exchange rate (in logs) $(4/k)\Delta s_{t\to t+k}$ on a long position in the dollar over k quarters. The independent variables are the average Treasury basis $\overline{x}^{Treas}$ lagged by 1 quarter, and the nominal Treasury yield difference $(y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k})$ with maturities of k quarters. Data is quarterly from 1988Q1 to 2017Q2. We omit the constant, and report Newey-West standard errors with lags equal to the length of the forecast horizon k. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	Panel A: 1988Q1—2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	−0.59	1.34	4.65	5.17***
	(6.20)	(6.07)	(3.15)	(1.73)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	−0.21	0.15	0.77	0.63
	(0.87)	(0.72)	(1.11)	(0.79)
Observations	117	117	117	115
R^2	0.001	0.002	0.05	0.07
	Panel B: 1988Q1—2007Q4			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	−9.91	−6.39	−0.10	4.21
	(6.45)	(6.95)	(2.83)	(2.62)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	−0.03	−0.004	0.70	1.21
	(0.86)	(0.75)	(1.24)	(0.94)
Observations	80	80	80	80
R^2	0.02	0.03	0.03	0.10
	Panel C: 2008Q1—2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	18.84*	19.81***	16.00***	10.03***
	(10.54)	(6.32)	(3.33)	(1.89)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	−6.87**	−0.48	0.41	0.42
	(3.24)	(0.91)	(0.96)	(1.03)
Observations	37	37	37	35
R^2	0.17	0.30	0.40	0.31

D. Market Microstructure

The FX markets in both spot and forward are large and liquid. Nevertheless, one may want to know the extent to which the relation we uncover stems from micro-structure order flow effects as in Evans and Lyons (2002) or Froot and Ramadorai (2005). Our theory does not involve these types of effects, and to test our theory ideally our data would reflect the mid of the bid and ask. By computing a quarterly average, we average out bid-ask bounce and thus likely measure true mid-market prices. The relation we uncover is quite strong in this averaged data (in fact it is stronger than the end-of-quarter data of Table III).[8] The variation reflected in the exchange rate is an order of magnitude larger than typical bid-ask spreads. The standard-deviation of exchange rate changes in log points is 0.04, or 4%, which is well above typical bid-ask spreads. The standard-deviation of Treasury basis changes is 0.00134 (13.4 basis points). The slope coefficient on the fitted regression line of -14.5 implies that a one standard deviation change in the basis drives a 1.94% move in the exchange rate, which is also an order of magnitude larger than bid-ask spreads.

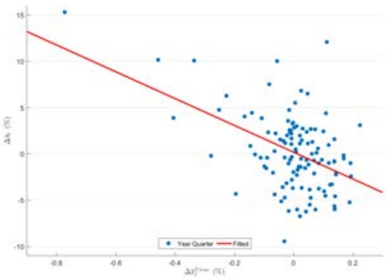

Figure A.5. Scatter plot of changes in the log exchange rate, averaged over a quarter, against shocks to the quarterly average basis. Data is from 1988Q1 to 2017Q2. In red we plot the fitted regression line. The R^2 is 22.8% and the slope coefficient is -14.6 with a t-statistic of 5.8.

[8] Figure A.5 presents a scatter plot of the change in the quarterly average log exchange rate against the change in the quarterly average basis.

Appendix H. The U.S. vs U.K. Treasury Basis and the USD/GBP Exchange Rate

A. Explaining Exchange Rate Movements

Figure A.6 plots the real exchange rate in units of GBP-per-USD (dashed line) against the U.S./U.K. Treasury basis (full line). Both series are based on quarterly averaged data. We use the real exchange rate because there are clear trends in the price levels of both countries in the 1970s and early 1980s that we would expect to enter exchange rate determination. It is evident that the two series are negatively correlated.

Table A.10 presents regressions analogous to that of Table III. We again see a strong relationship between shocks to the basis and real exchange rate changes. The relation becomes stronger later in the sample. We think this is in part because of measurement issues with the basis during the 1970s. Note the spikey behavior of the basis in the 1970s in Figure A.6. In column (5), where the sample starts in 1990, the coefficient of -11.67 is similar in magnitude to our earlier estimates in Table III. The regression R^2 is 28.4% which is a remarkably strong fit.

Column (2) considers the innovation in the interest rate differential as a regressor. In this sample in contrast to the cross-country sample, the interest rate differential has almost no explanatory power for the exchange rate. As noted in the introduction, the prior evidence linking interest rate changes and exchange rates is mixed and this is a clear example of this pattern. The source of the difference is the time period: If we focused on the sample from 1990 onwards, the interest rate differential has explanatory power similar to the result in Table III. Column (3) includes basis innovations and interest rate differential innovations. The coefficients on the basis in column (3) are almost identical to those of column (1).

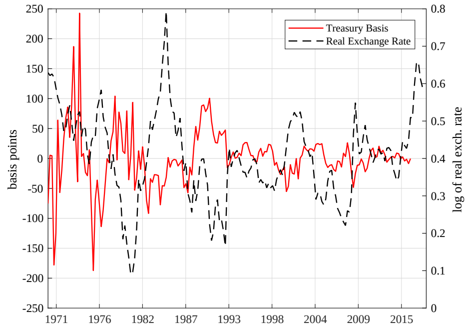

Figure A.6. U.S./U.K. Treasury Bases and Real Exchange Rate

One-year maturity Treasury basis from 1970Q1 to 2017Q2 for U.S./U.K., in basis points, and the log real U.S./U.K. exchange rate.

Table A.10. U.S./U.K. Treasury Basis and the Spot Real Exchange Rate

The dependent variable is the quarterly change in the quarterly-mean of the log of the spot USD/UK real exchange rate (quoted in GBP-per-USD). The independent variables are the innovation in the quarterly average Treasury basis, $\Delta\overline{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, and the innovation in the real U.S.-UK interest rate differential. Data is quarterly. OLS standard errors in parentheses.

	1970Q1 - 2016Q2			1980Q1 - 2016Q2	1990Q1 - 2016Q2
	(1)	(2)	(3)	(4)	(5)
$\Delta\overline{x}^{Treas}$	-1.77		-1.74	-3.40	-11.67
	(0.78)		(0.77)	(1.57)	(2.40)
Lag $\Delta\overline{x}^{Treas}$	-1.70		-1.69	-4.59	-3.89
	(0.78)		(0.77)	(1.52)	(2.36)
$\Delta(y^{\$} - \overline{y}^{UK})$		0.13	0.13		
		(0.08)	(0.08)		
R^2	5.0	1.6	6.5	10.3	28.4
N	183	185	183	144	104

In the following table, we include the change in the quarterly average Treasury basis and the change in the real U.S.-UK interest rate differential as independent variables.

	1970Q1 - 2016Q2			1980Q1 - 2016Q2	1990Q1 - 2016Q2
	(1)	(2)	(3)	(4)	(5)
$\Delta\overline{x}^{Treas}$	-1.23		-1.26	-3.05	-11.70
	(0.71)		(0.71)	(1.49)	(2.22)
Lag $\Delta\overline{x}^{Treas}$	-1.85		-1.67	-5.74	-11.69
	(0.71)		(0.71)	(1.45)	(2.22)
$\Delta(y^{\$} - \overline{y}^{UK})$		0.13	0.11		
		(0.06)	(0.06)		
R^2	4.0	2.4	5.8	10.3	33.2
N	183	190	183	144	104

In Table A.11, we repeat the exercise using 3-month U.S./U.K. Treasury basis. The 3-month U.S./U.K. Treasury basis also explains the current exchange rate movement, and this relationship is stronger later in the sample. In the post-1990 sample, the 12-month basis has an R^2 of 28.4%, whereas the 3-month basis has an R^2 of 17.3%.

Table A.11. U.S./U.K. 3M-Treasury Basis and the Spot Real Exchange Rate

The dependent variable is the quarterly change in the quarterly-mean of the log of the spot USD/UK real exchange rate (quoted in GBP-per-USD). The independent variables are the innovation in the quarterly average Treasury basis, $\Delta\overline{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, and the innovation in the real U.S.-UK interest rate differential. Data is quarterly. OLS standard errors in parentheses.

	1970Q1 - 2016Q2			1980Q1 - 2016Q2	1990Q1 - 2016Q2
	Average across 3 months				
$\Delta\overline{x}^{Treas}$	-0.92		-0.82	-0.08	-1.99
	(0.48)		(0.48)	(1.02)	(1.23)
Lag $\Delta\overline{x}^{Treas}$	-0.53		-0.52	-3.75	-5.61
	(0.48)		(0.48)	(0.99)	(1.23)
$\Delta(y^{\$} - \bar{y}^{UK})$		0.16	0.14		
		(0.08)	(0.08)		
R^2	2.8	2.1	4.4	9.7	17.3
N	183	185	183	144	104

B. Currency Return Predictability

The return predictability results for the U.S./U.K. Treasury basis are quite similar to those obtained on the shorter sample for the Panel. Table A.12 reports the results obtained when forecasting the annualized excess returns on a long position in the dollar and a short position in the pound. Panel A considers the results obtained on the entire sample. At the horizon of 3 years, the slope coefficient is positive and statistically significant: 4.55. This is a quantitatively significant response as well: a one-standard-deviation change in the U.S./U.K. Treasury basis increases the annual return by 2.19% in the next 3 years. These regressors jointly explain 20% of the variation in the 3-year excess returns. Panel B and C report results for the pre-and post-crisis sample. The slope coefficients at the 3-year horizon vary from 4.47 in the pre-crisis sample to 9.14 in the post-crisis sample.

Table A.13 repeats the exercise using the exchange rate movements as the dependent variables. The lag Treasury basis similarly predicts future exchange rate movements of the dollar against the pound.

Table A.12. Forecasting Currency Excess Returns: U.S./U.K.

The dependent variable is the annualized nominal excess return (in logs) $rx^{fx}_{t\to t+k}$ on a long position in U.S. Treasuries and a short position in U.K. bonds with maturities of k quarters. The independent variables are the average Treasury basis $\overline{x}^{Treas}$ lagged by 1 quarter, and the nominal Treasury yield difference $(y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k})$ with maturities of k quarters. Data is quarterly from 1970Q1 to 2017Q2. We omit the constant, and report Newey-West standard errors with lags equal to the length of the forecast horizon k. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

Panel A: 1970Q1-2017Q2

	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	0.62	0.64	2.52*	4.55***
	(3.53)	(2.28)	(1.36)	(1.24)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	2.65**	1.70	1.33	1.33**
	(1.27)	(1.08)	(0.89)	(0.64)
Observations	185	185	184	180
R^2	0.06	0.07	0.09	0.20

Panel B: 1970Q1-2007Q4

	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	−0.03	0.33	2.30*	4.47***
	(3.60)	(2.31)	(1.37)	(1.23)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	2.93**	1.70	1.32	1.31*
	(1.33)	(1.12)	(1.07)	(0.76)
Observations	152	152	152	152
R^2	0.08	0.07	0.09	0.20

Panel C: 2008Q1—2017Q2

	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	35.36*	18.12***	14.16	9.14
	(19.91)	(6.29)	(11.52)	(7.20)
$y^{\$}_{t\to t+k} - \overline{y}^{*}_{t\to t+k}$	−14.53**	−3.25	−2.65	−0.61
	(7.29)	(5.85)	(2.56)	(1.55)
Observations	33	33	32	28
R^2	0.31	0.19	0.29	0.18

Table A.13. Forecasting Exchange Rate Changes: U.S./U.K.

The dependent variable is the annualized change in the exchange rate (in logs) $(4/k)\Delta s_{t\rightarrow t+k}$ on a long position in the dollar over k quarters. The independent variables are the average Treasury basis $\overline{x}^{Treas}$ lagged by 1 quarter, and the nominal Treasury yield difference $(y^{\$}_{t\rightarrow t+k} - \overline{y}^{*}_{t\rightarrow t+k})$ with maturities of k quarters. Data is quarterly from 1970Q1 to 2017Q2. We omit the constant, and report Newey-West standard errors with lags equal to the length of the forecast horizon k. One, two and three stars denote statistical significance at the 10%, 5% and 1% level.

	Panel A: 1970Q1-2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	-0.03	0.52	2.59^{*}	4.70^{***}
	(3.60)	(2.49)	(1.37)	(1.09)
$y^{\$}_{t\rightarrow t+k} - \overline{y}^{*}_{t\rightarrow t+k}$	1.93	0.95	0.79	0.91
	(1.33)	(1.13)	(1.00)	(0.67)
Observations	152	152	152	152
R^2	0.04	0.02	0.05	0.19
	Panel B: 1970Q1-2007Q4			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	-0.03	0.33	2.30^{*}	4.47^{***}
	(3.60)	(2.31)	(1.37)	(1.23)
$y^{\$}_{t\rightarrow t+k} - \overline{y}^{*}_{t\rightarrow t+k}$	2.93^{**}	1.70	1.32	1.31^{*}
	(1.33)	(1.12)	(1.07)	(0.76)
Observations	152	152	152	152
R^2	0.08	0.07	0.09	0.20
	Panel C: 2008Q1—2017Q2			
	(1)	(2)	(3)	(4)
	3 months	1 year	2 years	3 years
Lag $\overline{x}^{Treas}$	35.36^{*}	18.09^{***}	13.97	8.84
	(19.91)	(6.37)	(11.80)	(6.21)
$y^{\$}_{t\rightarrow t+k} - \overline{y}^{*}_{t\rightarrow t+k}$	-15.53^{**}	-3.78	-2.98	-0.85
	(7.29)	(5.43)	(2.48)	(1.34)
Observations	33	33	32	28
R^2	0.34	0.21	0.32	0.19

C. Impulse Responses

We report the estimated impulse responses for the U.S./U.K., too. The variables included in the VAR are the Treasury basis, the interest rate differential and the log of the real exchange rate (GBP-per-USD). The impulse response patterns are similar to those documented in Figure 2. An increase in the quarterly basis of 23 basis points leads to a real depreciation in the dollar against the pound of about 1.3% over two quarters. Then, the effect gradually reverses out over 3 years. We also report the impulse responses that obtain when we switch the ordering of the interest rate differences and the basis. The responses to the basis shock again look identical.[9]

[9]Finally, we also adopted a local projection approach by projecting returns $rx_{t+k-1\to t+k}$ on $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$. These yield impulse responses that are quite similar to the ones produced by the Cholesky decomposition. The results are not reported.

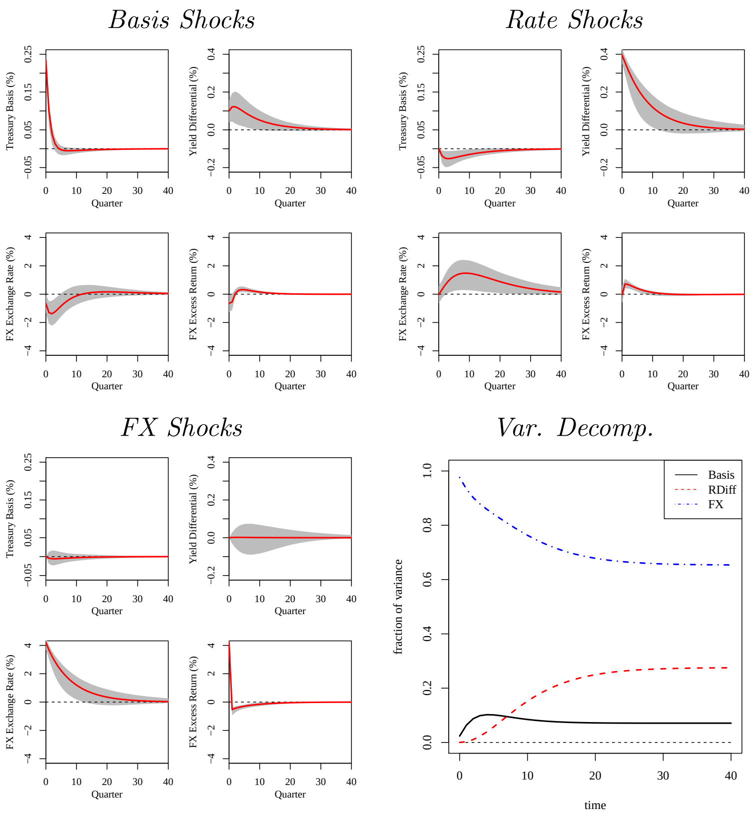

Figure A.7. UK/U.S. Impulse Responses.

The red line plots the impulse response of of a one-standard-deviation orthogonalized shock to the U.S./U.K. Treasury basis (top left panel), the real U.S./U.K. interest rate differential (top right panel), and the log real GBP-per-USD spot exchange rate (bottom left panel), as well as the quarterly excess return (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

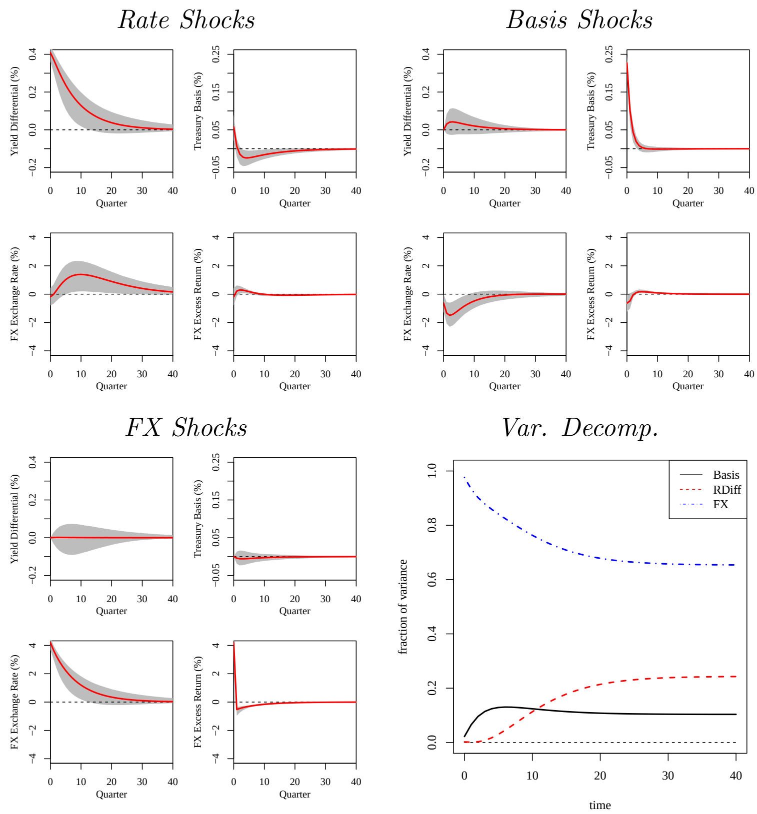

Figure A.8. UK/U.S. Impulse Responses: Alternate Ordering.

The red line plots the impulse response of of a one-standard-deviation orthogonalized shock to the real U.S./U.K. interest rate differential (top left panel), the U.S./U.K. Treasury basis (top right panel), and the log real GBP-per-USD spot exchange rate (bottom left panel), as well as the quarterly excess return (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The ordering is $\left[r_t^{\$} - \overline{r}_t^*, \overline{x}_t, q_t\right]$.