Global Natural Rates in the Long Run: Postwar Macro Trends and the Market-Implied r^* in 10 Advanced Economies

Josh Davis[1] Cristian Fuenzalida[2] Leon Huetsch[3]
Benjamin Mills[1] Alan M. Taylor[4]

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[1] PIMCO

[2] Graham Capital Management

[3] University of Pennsylvania

[4] Columbia University; PIMCO; NBER; CEPR

What we do

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New estimates of r^*

a puzzle, a new method, expanded data, decompose drivers

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  - yields explained by yields, "ketchup" ($\bar{y}$, PCs,...)

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  - r^* matters for practitioner/policy worlds

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  - r^* matters for practitioner/policy worlds
- “finance” and “macro” get different results (unsurprising)
  - document this *natural rate puzzle*, US & global

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- bridge ATSM and Wicksellian models
- current: either exogenous or free-estimated r^*
- new: **macro-finance** model with *joint* estimation
- what we mean: simultaneously link yield curve $y_t^{(n)}$ to cyclical HF yield factors $\bar{y}$ and slow-moving LF trends r^*, π^*

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- expanded coverage
- N=10 countries, post-WWII era

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Results

- model-consistent, market-implied estimates of r^*, BRP
- plausible, resolve puzzle, different bond-market narrative
- covary with key determinants: growth and demography

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    - post GFC....
    - stable π^*
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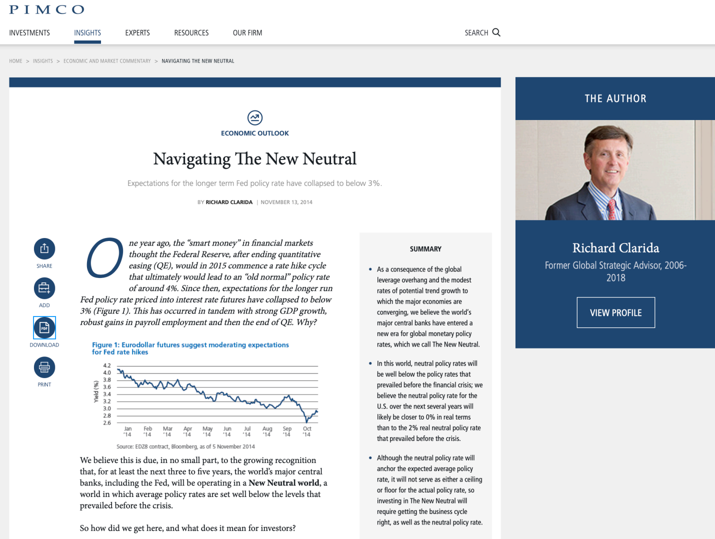

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ECONOMIC OUTLOOK

Navigating The New Neutral

Expectations for the longer term Fed policy rate have collapsed to below 3%.

BY RICHARD CLARIDA | NOVEMBER 13, 2014

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One year ago, the "smart money" in financial markets thought the Federal Reserve, after ending quantitative easing (QE), would in 2015 commence a rate hike cycle that ultimately would lead to an "old normal" policy rate of around 4%. Since then, expectations for the longer run Fed policy rate priced into interest rate futures have collapsed to below 3% (Figure 1). This has occurred in tandem with strong GDP growth, robust gains in payroll employment and then the end of QE. Why?

Figure 1: Eurodollar futures suggest moderating expectations for Fed rate hikes

Source: EDZ8 contract, Bloomberg, as of 5 November 2014

We believe this is due, in no small part, to the growing recognition that, for at least the next three to five years, the world's major central banks, including the Fed, will be operating in a **New Neutral world**, a world in which average policy rates are set well below the levels that prevailed before the crisis.

So how did we get here, and what does it mean for investors?

SUMMARY

- As a consequence of the global leverage overhang and the modest rates of potential trend growth to which the major economies are converging, we believe the world's major central banks have entered a new era for global monetary policy rates, which we call The New Neutral.
- In this world, neutral policy rates will be well below the policy rates that prevailed before the financial crisis; we believe the neutral policy rate for the U.S. over the next several years will likely be closer to 0% in real terms than to the 2% real neutral policy rate that prevailed before the crisis.
- Although the neutral policy rate will anchor the expected average policy rate, it will not serve as either a ceiling or floor for the actual policy rate, so investing in The New Neutral will require getting the business cycle right, as well as the neutral policy rate.

THE AUTHOR

Richard Clarida

Former Global Strategic Advisor, 2006-2018

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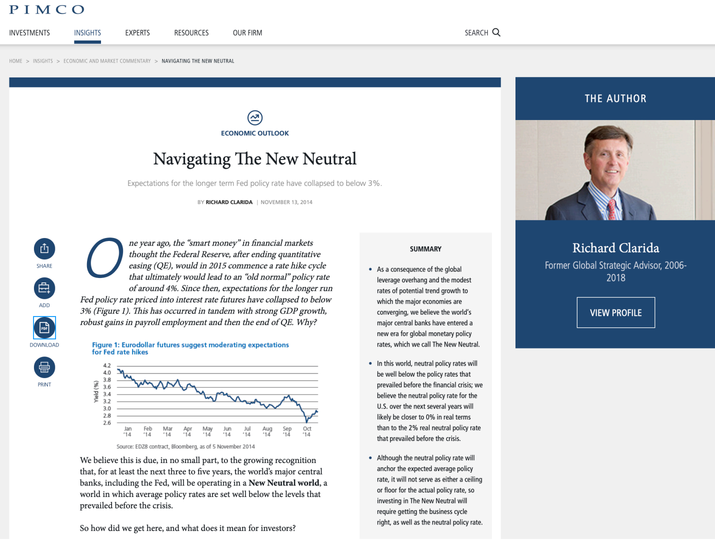
  - post GFC....
  - stable π^*
  - lower r^*

- Implications for bond pricing? Limit result:

$$f \equiv r^* + \pi^* + BRP$$

- A new PIMCO Model
  - research project starts in 2014–15



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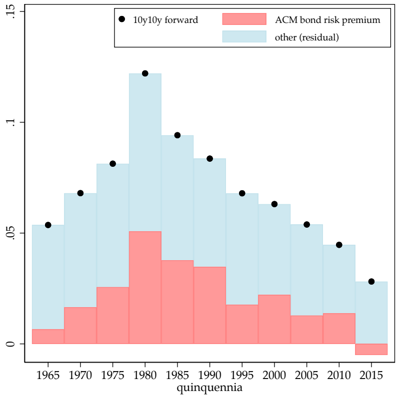
Puzzling history of the U.S. bond market



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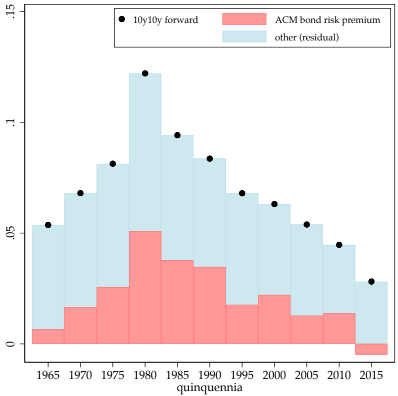

Period	f	r^*_{LW}	π^*_{CiP}	BRP_{ACM}
1981–2019	-1000			-600
2009–2019	-200			-200

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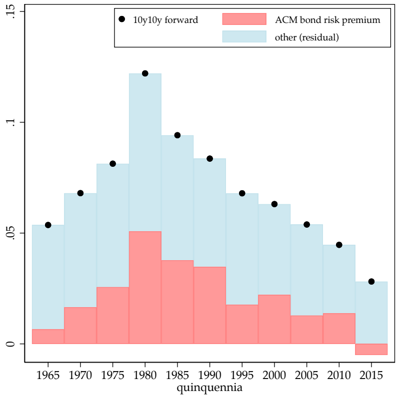

Period	f	r^*_{LW}	π^*_{CiP}	BRP_{ACM}	Discrepancy
1981–2019	-1000	-300	-600	-600	-500
2009–2019	-200	-200	-50	-200	-250

Roadmap

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- Data: global puzzle w. “macro” r^* + “finance” BRP [brief today]
- Theory: model of yield curve w. shifting endpoints [brief today]
- Positioning: evolution of the literature [brief today]
- New model: hybrid macro-finance state-space, $N = 10$ countries
- Results/evaluation: yields, returns, model fit (in and out of sample)
- Takeaways: new r^* estimates
  - how do they relate to influential determinants?
  - is this a revisionist history of the bond market?

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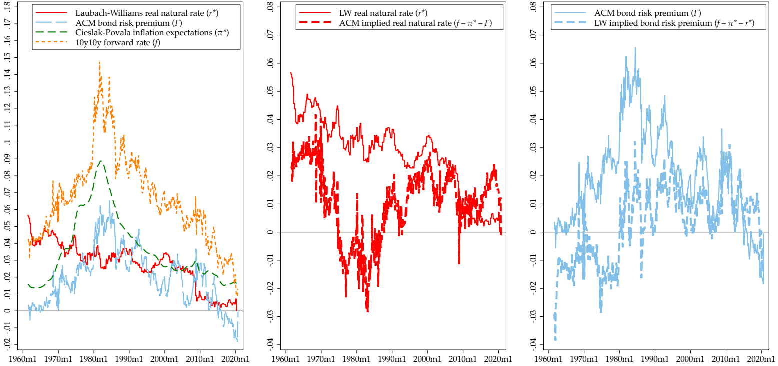

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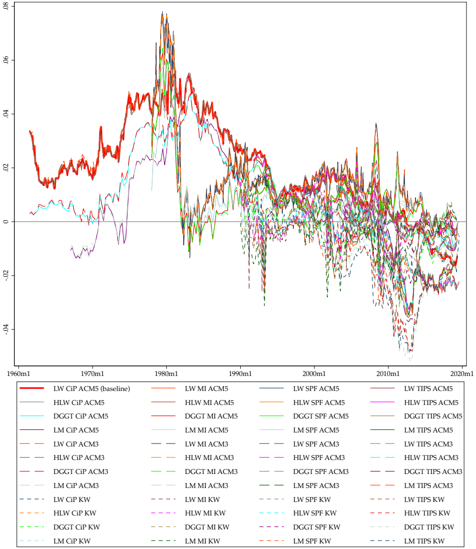

Data: how to replicate for other countries?

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Estimation of any ATSM requires yield-curve for ZCBs

Needed to infer f, replicate ACM, and for our own model
Svensson (1994) model to recover entire yield curve (1m to 180m)

$$y_t^{(n)} = \beta_0 + \beta_1 \frac{1 - e^{-n/\tau_1}}{n/\tau_1} + \beta_2 \left(\frac{1 - e^{-n/\tau_1}}{n/\tau_1} - e^{-n/\tau_1} \right) + \beta_3 \left(\frac{1 - e^{-n/\tau_2}}{n/\tau_2} - e^{-n/\tau_2} \right) .$$

- US: GSW, Federal Reserve Board, from 1961, updated
- UK: Bank of England data, from January 1980
- Japan, MoF yield curves (1 to 40y), from September 1974
- Germany, Bundesbank Svensson model, from 1972
- Canada, BoC yield curves (0.25 to 30y), from January 1986
- Australia, RBA yield curves (up to 10y), from August 1992
- **NEW:** Switzerland (SNB), Sweden (Riksbank), Spain (BIS), France (PSE)

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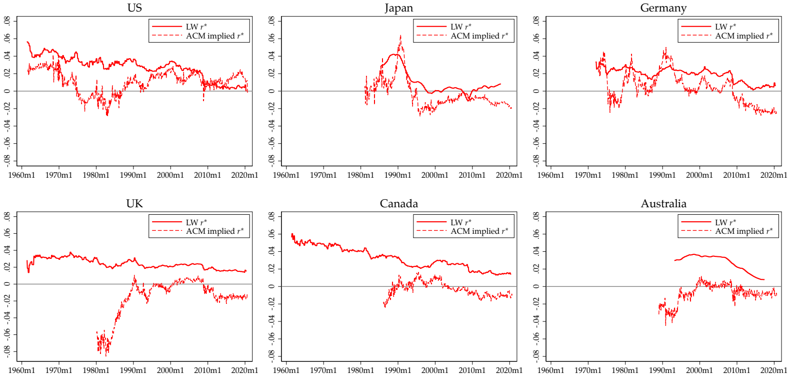

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Positioning: evolution of the literature

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Douglass (1738), Thornton (1811), Fisher (1896) nominal versus real

Campbell and Shiller (1987) stochastic trends

Kozicki and Tinsley (2001) shifting end-points

*Cieslak and Povala (2015) ATSM with inflation trend π^*

Bauer and Rudebusch (2017, 2020) nominal rate trend $i^* = r^* + \pi^*$

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- "Finance" view, regress yields on yield factors in ATSM:

$$(1) \qquad y_n = a_n + b_n^y \bar{y} + e^{cyc}$$

- "Macro" view, detrend: observable π^*, estimated latent r^*:

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- Q: assume (1) right, obtain BRP, inferred endpoint for r^*?
  assume (3) right, impose "external" endpoint for r^*?
- A: we prefer to assume neither is right... use both sets of information

Stationary ATSM with trends (Cieslak and Povala 2015)

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The short-rate process is assumed to depend on the factors, which follow independent AR(1) processes, with

$$y_t^{(1)} = \delta_0 + \delta_\pi \pi_t + \delta_r r_t \,, \tag{1}$$

$$r_t = \mu_r + \phi_r r_{t-1} + \sigma_r \epsilon_t^r \,, \tag{2}$$

$$\pi_t = \mu_\pi + \phi_\pi \pi_{t-1} + \sigma_\pi \epsilon_t^\pi \,, \tag{3}$$

where $\delta_\pi > 0, \delta_r > 0$, $\delta_x = 0$, and $\epsilon_t^\pi, \epsilon_t^r$ are standard normal, i.i.d.

Price-of-risk factor follow its own AR(1) process with i.i.d. normal shocks,

$$x_t = \mu_x + \phi_x x_{t-1} + \sigma_x \epsilon_t^x \,. \tag{4}$$

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Economy is described by process for factors $F_t = (\pi_t, r_t, x_t)'$, with

$$F_t = \mu + \Phi F_{t-1} + \Sigma \epsilon_t \,, \tag{5}$$

$$y_t^{(1)} = \delta_0 + \delta_1^\intercal F_t \,, \tag{6}$$

with Φ and Σ diagonal, $\delta_1 = (\delta_\pi, \delta_r, 0)^\intercal$, and $\epsilon_t = (\epsilon_t^\pi, \epsilon_t^r, \epsilon_t^x,)^\intercal$.

Assume log nominal SDF is exponentially affine in the risk factors,

$$m_{t+1} = -y_t^{(1)} - \frac{1}{2}\Lambda_t^\intercal \Lambda_t - \Lambda_t^\intercal \epsilon_{t+1} \,, \tag{7}$$

where Λ_t is compensation for risk of shock ϵ_{t+1}, $\Lambda_t = \Sigma^{-1}(\lambda_0 + \Lambda_1 F_t)$.

Stationary ATSM with trends (Cieslak and Povala 2015)

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Add structure; in Cieslak and Povala x_t is a single yield-based factor, assume

$$\lambda_0 = \begin{pmatrix} \lambda_{0r} \\ \lambda_{0\pi} \\ 0 \end{pmatrix}, \qquad \Lambda_1 = \begin{pmatrix} 0 & 0 & \lambda_{\pi x} \\ 0 & 0 & \lambda_{rx} \\ 0 & 0 & 0 \end{pmatrix}. \tag{8}$$

Motivated by Cochrane-Piazzesi etc. – single factor does well. (Can augment.)

Then model solution is a set of affine equations with unknown coefficients

$$y_t^{(n)} = A_n + B_n^\intercal F_t\,, \tag{9}$$

$$p_t^{(n)} = \mathcal{A}_n + \mathcal{B}_n^\intercal F_t\,, \tag{10}$$

$$f_t^{(n,m)} = (A_n - A_{n+m}) + (B_n - B_{n+m})^\intercal F_t\,, \tag{11}$$

$$rx_{t+1}^{(n)} = \mathfrak{B}_n^\intercal F_t + v_t^n\,, \tag{12}$$

where $A_n = -\frac{1}{n}\mathcal{A}_n$, $B_n = -\frac{1}{n}\mathcal{B}_n$, $v_t^n = \mathcal{B}_{n-1}^\intercal \Sigma \epsilon_{t+1}$.

Stationary ATSM with trends (Cieslak and Povala 2015)

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Coefficients come from Riccati equations, factor loadings of log bond prices are

$$\mathcal{B}_n^{\pi} = -\delta_{\pi} \frac{1 - \phi_{\pi}^{n}}{1 - \phi_{\pi}}\,, \tag{13}$$

$$\mathcal{B}_n^{r} = -\delta_{r} \frac{1 - \phi_{r}^{n}}{1 - \phi_{r}}\,, \tag{14}$$

$$\mathcal{B}_n^{x} = -\mathcal{B}_{n-1}^{\pi}\lambda_{\pi x} - \mathcal{B}_{n-1}^{r}\lambda_{rx} + \mathcal{B}_{n-1}^{x}\phi_{x}, \tag{15}$$

and loadings of excess returns are

$$\mathfrak{B}_n = \mathcal{B}_{n-1}^{\intercal}(\lambda_0 + \Lambda_1 \mathbf{1}_3)x_t - \frac{1}{2}\mathcal{B}_{n-1}^{\intercal}\Sigma\Sigma^{\intercal}\mathcal{B}_{n-1}\,. \tag{16}$$

Only the cyclical factor matters for excess returns.

Stationary ATSM with trends (Cieslak and Povala 2015)

Corollary 1: Long-dated forwards, macro trends, and the bond risk premium

For a 1-period forward at horizon n, $f_t^{(n,1)} = (\mathcal{A}_n - \mathcal{A}_{n+1}) + (\mathcal{B}_n - \mathcal{B}_{n+1})' F_t$.

Let the benchmark Fisher constraints hold, $\delta_0 = 0, \delta_\pi = \delta_r = 1$, then

$$\lim_{n\to\infty} f_t^{(n,1)} = \underbrace{r_\infty^{(t)}}_{\substack{\text{endpoint for}\\ \text{natural rate}}} + \underbrace{\pi_\infty^{(t)}}_{\substack{\text{endpoint for}\\ \text{inflation}}} + \underbrace{\mathcal{B}_\infty^\pi \lambda_{0\pi} + \mathcal{B}_\infty^r \lambda_{0r} - \frac{1}{2}\mathcal{B}_\infty' \Sigma\Sigma' \mathcal{B}_\infty}_{\text{bond risk premium as } n \to \infty} .$$

The limiting forward rate equals the sum of the natural rate and inflation endpoints and the bond risk premium.

Model: hybrid macro-finance state-space estimation

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Extract r^* from avg. bond yields, excess rtns, via 1 measurement equation

$$\bar{y}_t = a_y + b_\pi \pi_t^* + b_r r_t^* + \epsilon_t^{cyc}, \tag{17}$$

Where π_t^* is observable, Cieslak Povala measure $\pi_t^* = (1-\nu)\sum_{i=0}^{t-1} \nu^i \pi_{t-i}$.

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Macro state equation:

$$r_t^* = z_t + g_t \,. \tag{18}$$

Where g_t is trend GDP growth, observable (1-sided HP filter $\lambda = 25600$).

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Error terms ϵ_{t+1}^{cyc} and headwinds factor follow AR(1) processes

$$\epsilon_{t+1}^{cyc} = \rho_y \epsilon_t^{cyc} + e_{t+1}^y\,, \qquad e_{t+1}^{cyc} \sim N\left(0, \sigma_{cyc}^2\right)\,. \tag{19}$$

$$z_{t+1} = \rho_z z_t + e_{t+1}^z\,, \qquad e_{t+1}^z \sim N\left(0, \sigma_z^2\right)\,. \tag{20}$$

Model: hybrid macro-finance state-space estimation

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The Kalman system is a state equation

$$\begin{pmatrix} z_t \\ \epsilon_t^{cyc} \end{pmatrix} = \begin{pmatrix} \rho_z & 0 \\ 0 & \rho_{cyc} \end{pmatrix} \begin{pmatrix} z_{t-1} \\ \epsilon_{t-1}^{cyc} \end{pmatrix} + \begin{pmatrix} e_t^z \\ e_t^{ye} \end{pmatrix}, \tag{21}$$

and the associated measurement equation

$$\begin{pmatrix} \bar{y}_t \end{pmatrix} = \begin{pmatrix} a_y \end{pmatrix} + \begin{pmatrix} b_\pi & b_{r*} \end{pmatrix} \begin{pmatrix} \pi_t^* \\ g_t \end{pmatrix} + \begin{pmatrix} b_{r*} & 1 \end{pmatrix} \begin{pmatrix} z_t \\ \epsilon_t^{cyc} \end{pmatrix}. \tag{22}$$

Model: hybrid macro-finance state-space estimation

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- We run a random-walk Metropolis-Hastings (RWMH) algorithm on the model parameter vector for each country.
- Estimations are calculated with a number of simulations equal to 200,000
- Identification assumption is that r_t^* minus trend GDP growth g_t is stationary
- We assume the AR(1) for z_t has mean reversion compatible with a half-life within business cycle frequency, and not higher. (Tight prior)
  - This avoids the problem of r^* acting as a residual term that would capture high-frequency oscillations in bond markets.
  - Consistent with the LW view: r^* represents medium-run real rate anchor for monetary policy
- Prior tightness of shocks to z_t is country specific to account for differences in yield volatility, otherwise we use the same priors for all countries

Estimation and Priors

Results: yield regressions

$$y_t^{(n)} = \tilde{\mathcal{A}}_n + \tilde{\mathcal{B}}_n^r r_t^* + \tilde{\mathcal{B}}_n^\pi \pi_t^* + \tilde{\mathcal{B}}^x x_t$$

10-year maturity, close to (1,1) null, fit improved v. 1 or 0 trends.

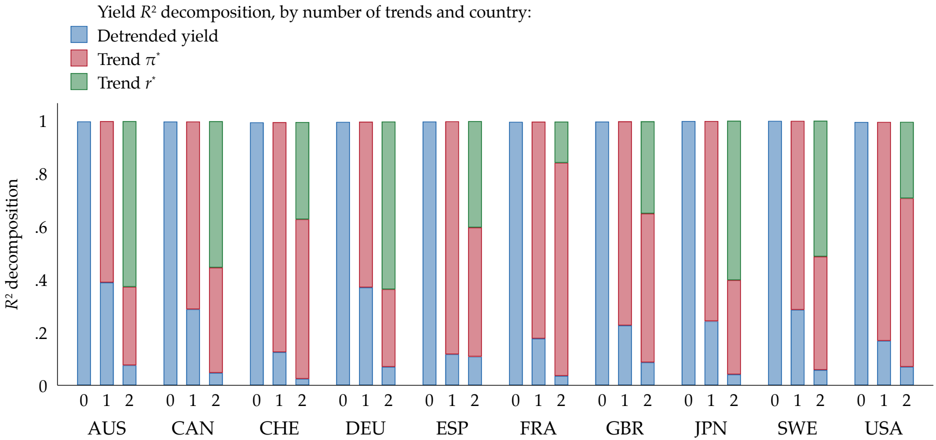
(c) Narrow window. Detrending: inflation and natural rate, $\bar{c}$ equal to projection of $\bar{y}$ on π^* and r^*.

	(1) AUS	(2) CAN	(3) CHE	(4) DEU	(5) ESP	(6) FRA	(7) GBR	(8) JPN	(9) SWE	(10) USA
π^*	1.058***	0.920***	1.104***	0.877***	0.886***	1.002***	0.689***	0.404***	0.990***	1.047***
	(0.012)	(0.008)	(0.010)	(0.009)	(0.027)	(0.004)	(0.004)	(0.003)	(0.007)	(0.006)
r^*	1.159***	1.197***	1.297***	1.590***	0.858***	1.109***	1.316***	0.778***	0.954***	1.082***
	(0.007)	(0.008)	(0.017)	(0.009)	(0.031)	(0.009)	(0.010)	(0.004)	(0.005)	(0.011)
$c^{(\pi^*,r^*)}$	0.948***	0.912***	0.812***	0.869***	1.020***	0.892***	0.983***	0.882***	0.969***	0.889***
	(0.012)	(0.014)	(0.022)	(0.010)	(0.011)	(0.015)	(0.009)	(0.010)	(0.011)	(0.011)
Constant	-0.001*	0.000	0.003***	0.003***	0.005***	0.000	-0.003***	-0.001***	0.003***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	354	432	408	591	342	561	624	553	349	634
R^2	0.996	0.996	0.993	0.995	0.996	0.994	0.995	0.997	0.997	0.994
RSS	0.0008	0.0017	0.0012	0.0028	0.0012	0.0046	0.0049	0.0013	0.0007	0.0036

Results: yield regressions

$$y_t^{(n)} = \tilde{\mathcal{A}}_n + \tilde{\mathcal{B}}_n^r r_t^* + \tilde{\mathcal{B}}_n^\pi \pi_t^* + \tilde{\mathcal{B}}^x x_t$$

Attribution exercise



Results: excess return regressions

$$\overline{rx}_{t+1} = \mathfrak{B}_n^{\intercal} F_t + v_t^n$$

Avg. inv.-maturity weighed, 0 trends.

(a) Narrow window. Detrending: none.										
	(1) AUS	(2) CAN	(3) CHE	(4) DEU	(5) ESP	(6) FRA	(7) GBR	(8) JPN	(9) SWE	(10) USA
$\bar{y}$	0.112***	0.031**	0.013	0.025*	0.082***	-0.012	0.019	0.035***	0.097***	0.021
	(0.019)	(0.012)	(0.016)	(0.011)	(0.019)	(0.011)	(0.010)	(0.009)	(0.017)	(0.013)
Constant	-0.002*	0.002**	0.002***	0.002***	0.001	0.003***	0.001	0.002***	0.001	0.002
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
Observations	348	426	403	586	330	538	618	547	345	629
R^2	0.090	0.016	0.002	0.008	0.053	0.002	0.006	0.027	0.089	0.004
RSS	0.0241	0.0221	0.0172	0.0402	0.0349	0.0492	0.0636	0.0223	0.0256	0.0624

Results: excess return regressions

$$\overline{rx}_{t+1} = \mathfrak{B}_n^\intercal F_t + v_t^n$$

Avg. inv.-maturity weighed, 1 trends.

(b) Narrow window. Detrending: inflation only, $\bar{c}$ equal to projection of $\bar{y}$ on π.

	(1) AUS	(2) CAN	(3) CHE	(4) DEU	(5) ESP	(6) FRA	(7) GBR	(8) JPN	(9) SWE	(10) USA
π^*	0.204***	-0.049*	-0.016	0.041	0.023	-0.050***	0.007	0.004	0.055	-0.045*
	(0.053)	(0.021)	(0.027)	(0.027)	(0.028)	(0.012)	(0.011)	(0.009)	(0.031)	(0.019)
$c^{(\pi^*)}$	0.132***	0.189***	0.152***	0.029	0.654***	0.148***	0.055**	0.132***	0.251***	0.263***
	(0.029)	(0.021)	(0.042)	(0.018)	(0.048)	(0.024)	(0.020)	(0.018)	(0.030)	(0.028)
Constant	-0.002	0.005***	0.002***	0.003**	0.005***	0.004***	0.002**	0.003***	0.003***	0.005***
	(0.002)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
Observations	348	426	403	586	330	538	618	547	345	629
R^2	0.092	0.174	0.033	0.008	0.360	0.096	0.012	0.089	0.180	0.128
RSS	0.0241	0.0186	0.0166	0.0402	0.0236	0.0445	0.0632	0.0209	0.0231	0.0546

Results: excess return regressions

$$\overline{rx}_{t+1} = \mathfrak{B}_n^\intercal F_t + v_t^n$$

Avg. inv.-maturity weighed, 2 trends.

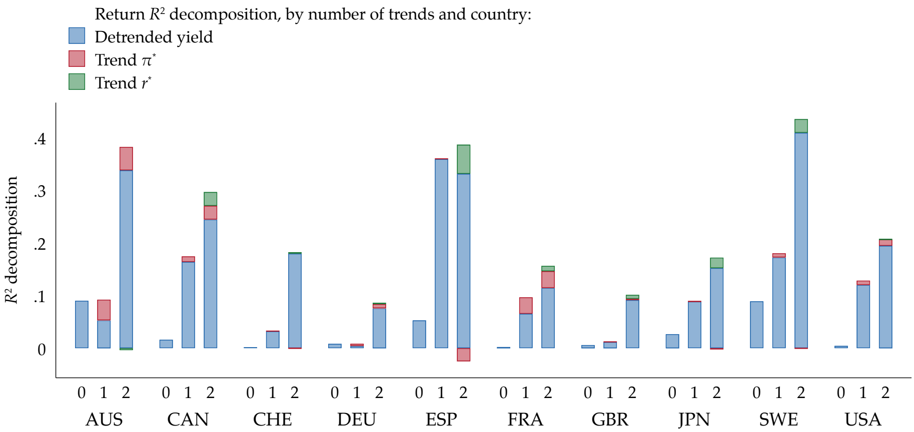
(c) **Narrow window. Detrending: inflation and natural rate, $\bar{c}$ equal to projection of $\bar{y}$ on π^* and r^*.**

	(1) AUS	(2) CAN	(3) CHE	(4) DEU	(5) ESP	(6) FRA	(7) GBR	(8) JPN	(9) SWE	(10) USA
π^*	0.232***	-0.122***	0.004	0.080*	-0.439***	-0.051***	0.023	-0.025*	-0.004	-0.066**
	(0.053)	(0.024)	(0.034)	(0.032)	(0.123)	(0.011)	(0.012)	(0.012)	(0.031)	(0.021)
r^*	-0.030	0.124***	-0.054	-0.064*	0.562***	0.077**	-0.085*	0.050***	0.087**	0.074
	(0.033)	(0.025)	(0.060)	(0.032)	(0.146)	(0.030)	(0.034)	(0.015)	(0.027)	(0.041)
$c^{(\pi^*,r^*)}$	0.731***	0.511***	0.710***	0.248***	0.645***	0.399***	0.252***	0.372***	0.831***	0.492***
	(0.053)	(0.042)	(0.076)	(0.036)	(0.050)	(0.047)	(0.032)	(0.037)	(0.053)	(0.040)
Constant	-0.002	0.004***	0.002***	0.003***	0.009***	0.003***	0.004***	0.002***	0.003***	0.004***
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
Observations	348	426	403	586	330	538	618	547	345	629
R^2	0.378	0.296	0.182	0.086	0.361	0.156	0.101	0.170	0.434	0.207
RSS	0.0165	0.0158	0.0141	0.0370	0.0235	0.0416	0.0575	0.0190	0.0159	0.0497

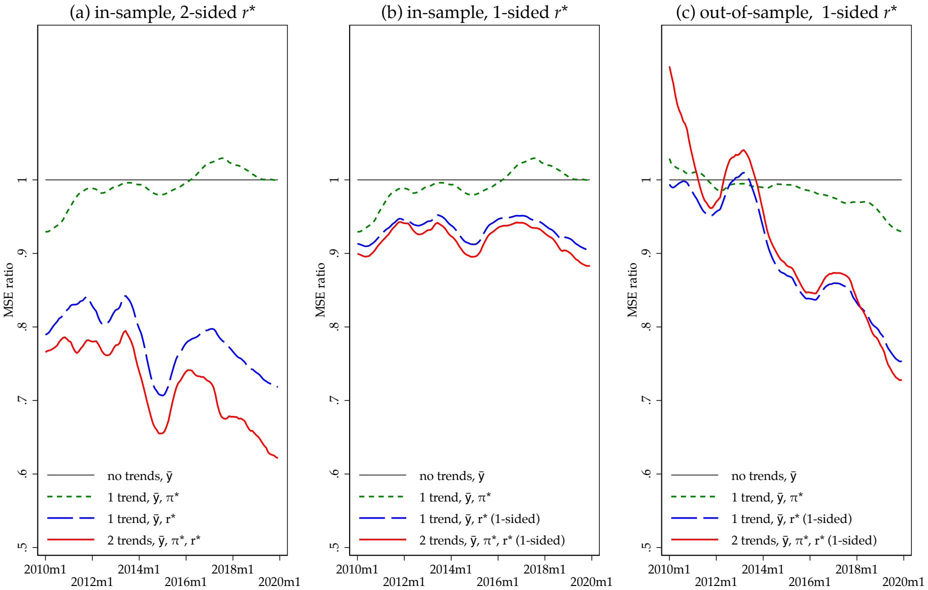
Results: excess return regressions

$$\overline{rx}_{t+1} = \mathfrak{B}_n^\intercal F_t + v_t^n$$

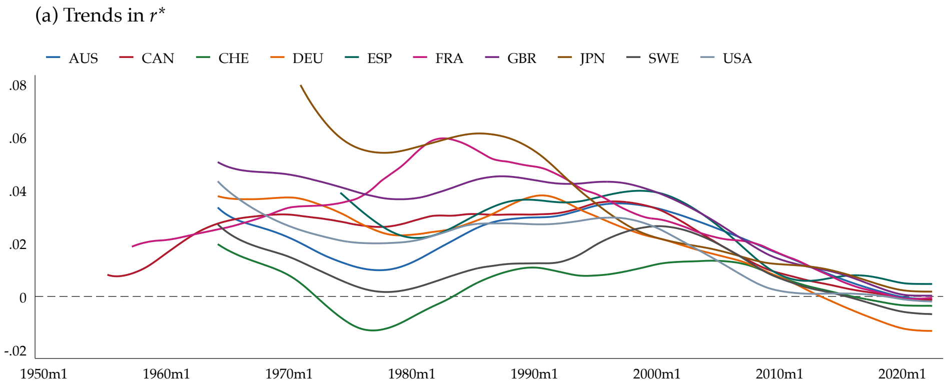
Avg. inv.-maturity weighed, 2 trends.



Results: excess return regressions, OOS MSE ratios v 0-trend

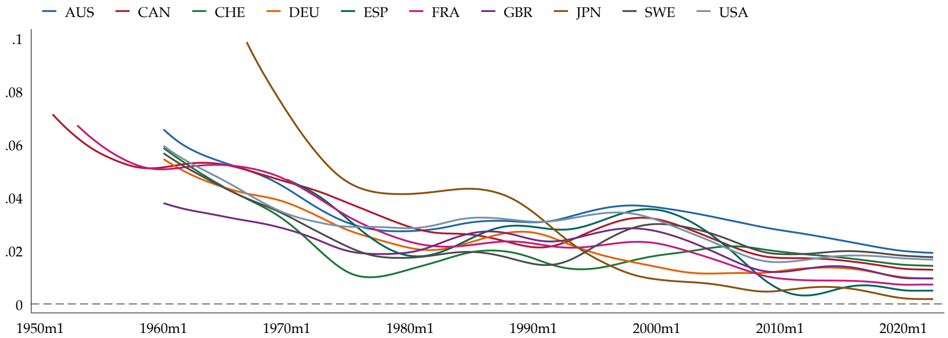


Main results: trends, r^*



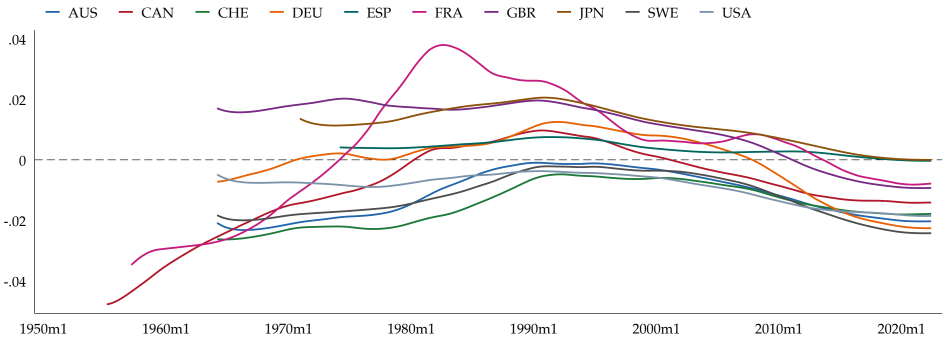
Main results: trends, g

(b) Trends in g



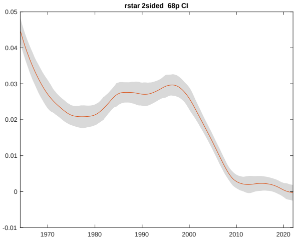
Main results: trends, z

(c) Trends in z

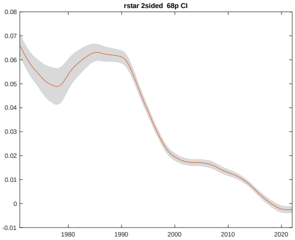


Main results: posterior coverage intervals (68%) [NEW]

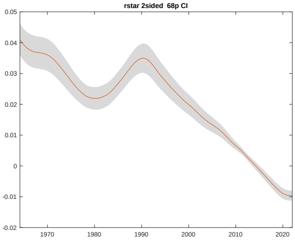
USA



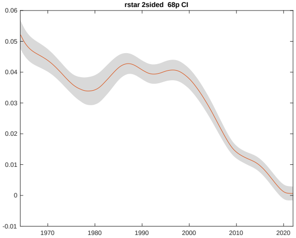
JPN



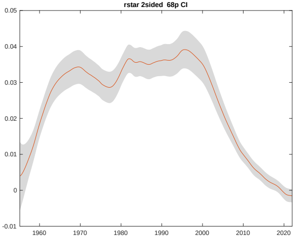
DEU



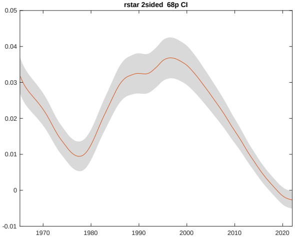
GBR



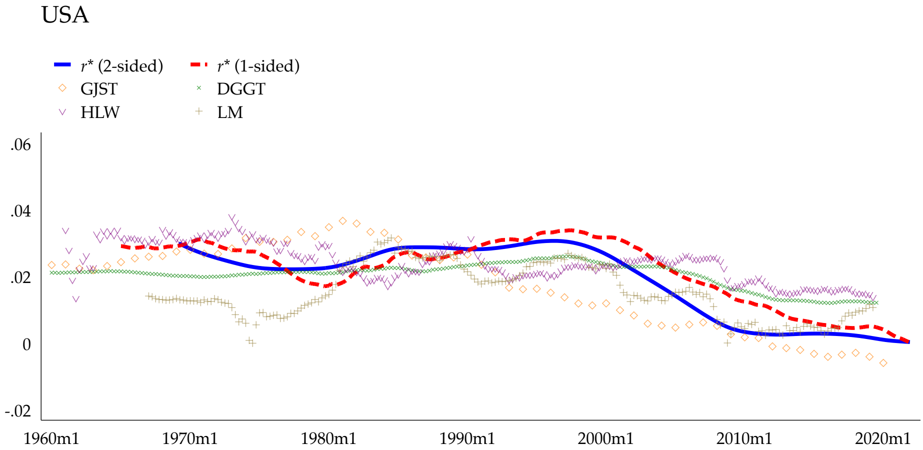
CAN



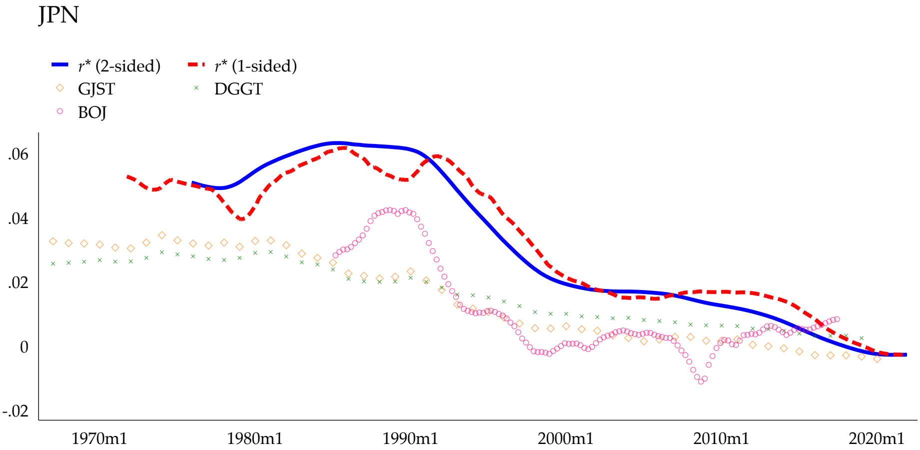
AUS



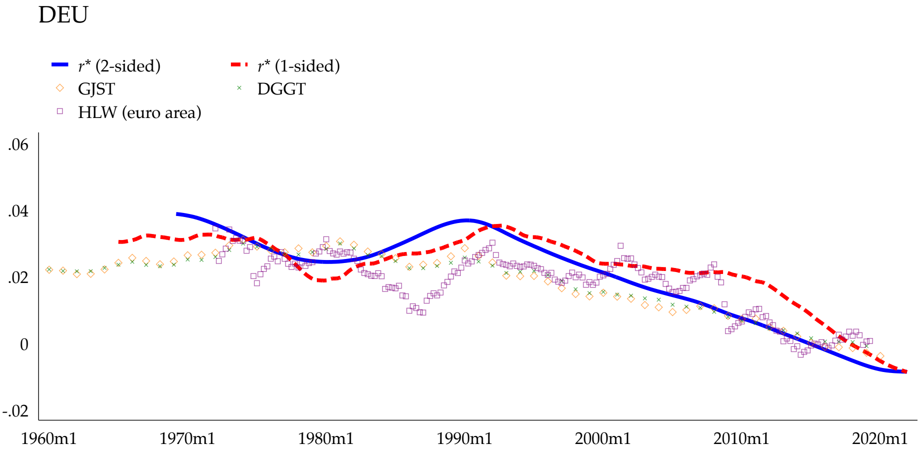
Main results: compared to others



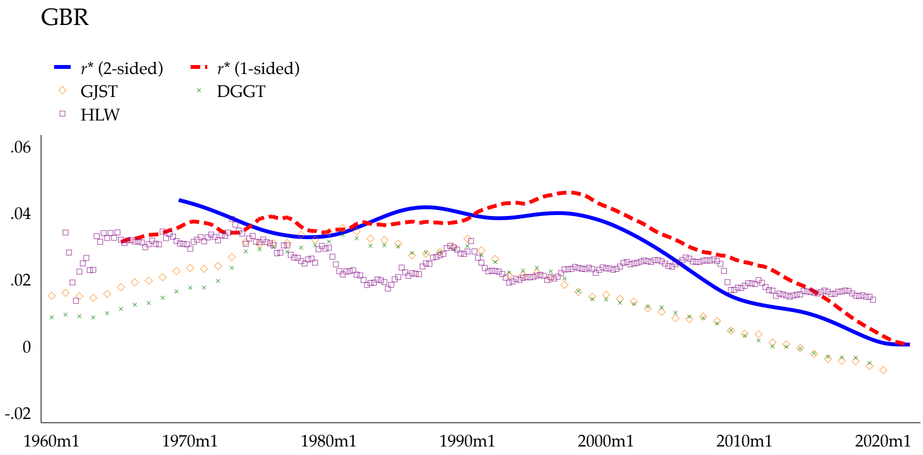
Main results: compared to others



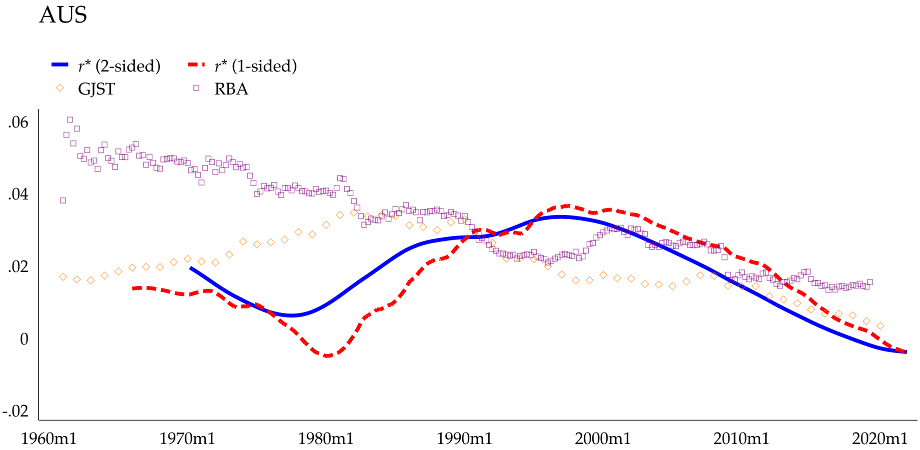
Main results: compared to others



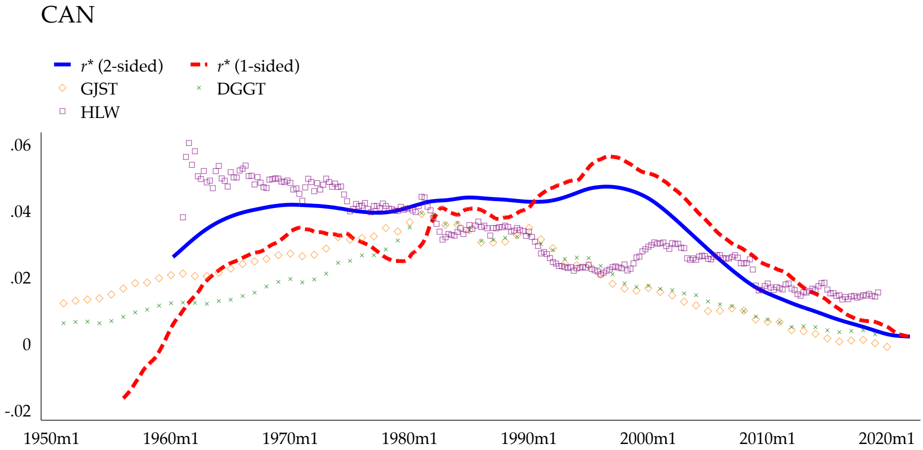
Main results: compared to others



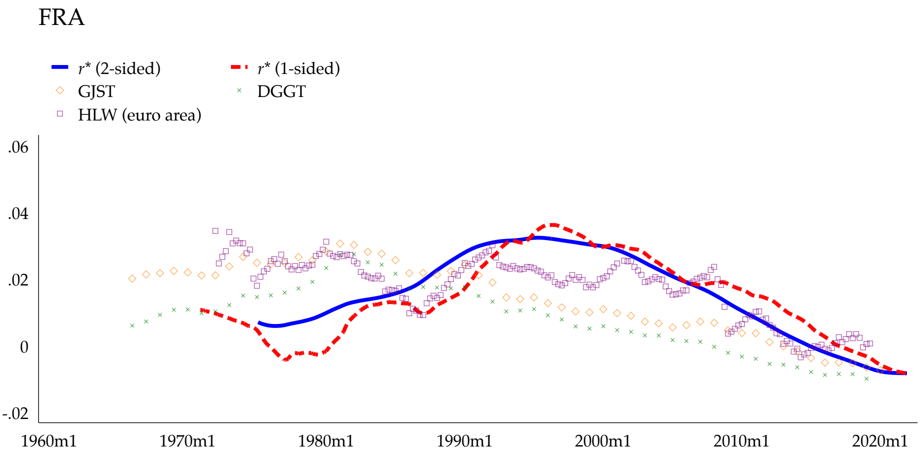
Main results: compared to others



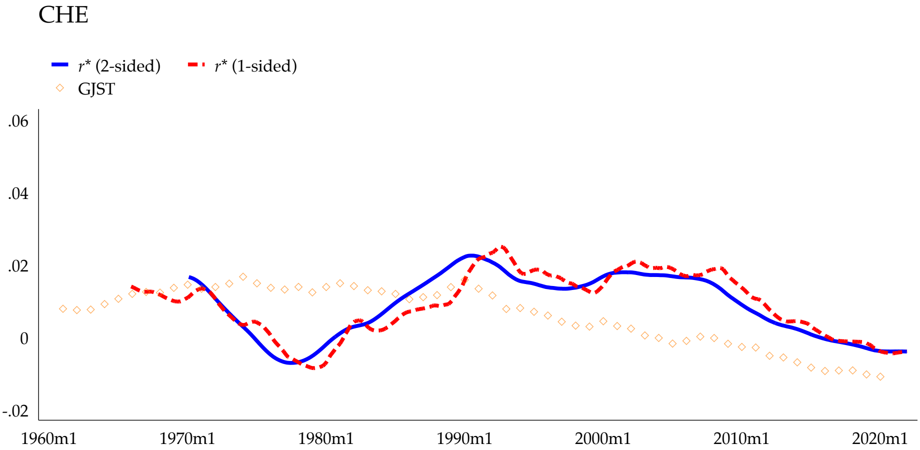
Main results: compared to others



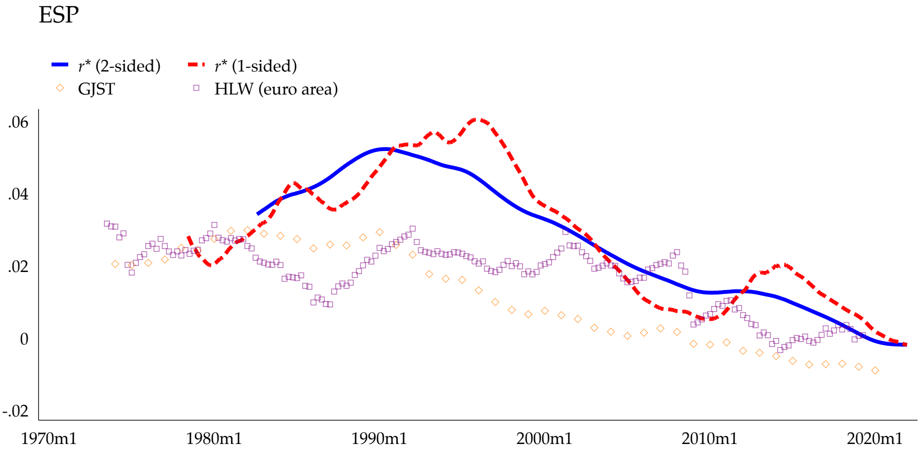
Main results: compared to others



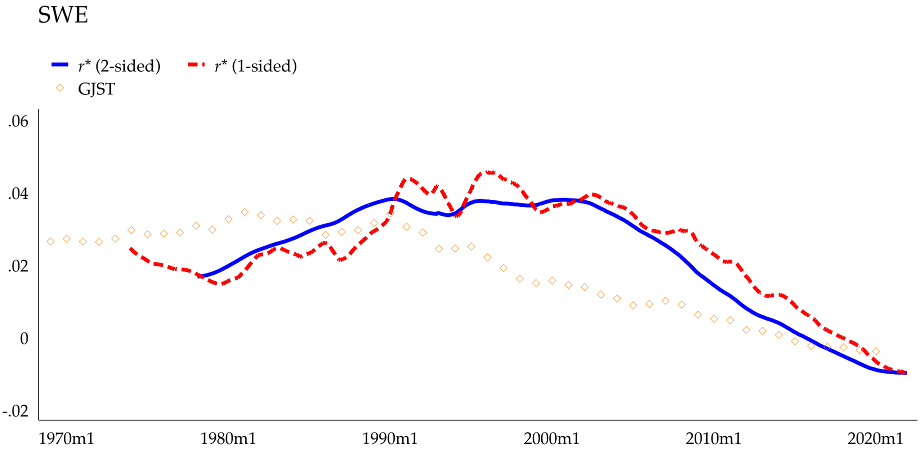
Main results: compared to others



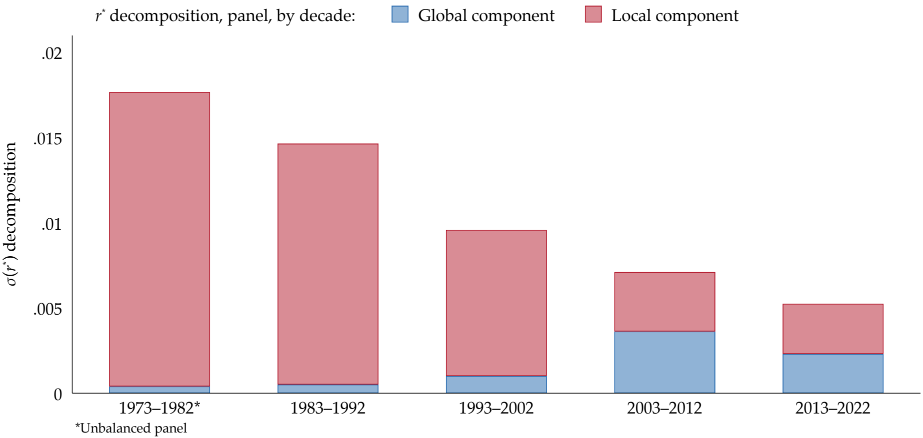
Main results: compared to others



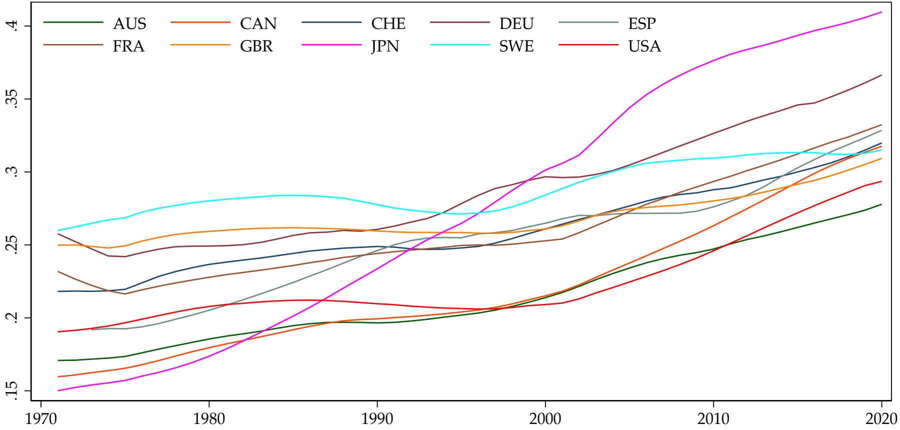
Main results: compared to others



Main results: local v global components of r^*



Main results: growth and demography as drivers of r^*



Main results: growth and demography as drivers of r^*

Fair and Dominguez (1991)

$$r^*_{it} = a_i + \phi\, g_{it} + \sum_{j=1}^{J} \alpha_j p_{j,it} + \theta X_{it} + \epsilon_{it}\,,$$

$$D_{1,it} = \left(\sum_{j=1}^{J} j\, p_{j,it} - \frac{1}{J} \sum_{j=1}^{J} j \right)\,,$$

$$D_{2,it} = \left(\sum_{j=1}^{J} j^2\, p_{j,it} - \frac{1}{J} \sum_{j=1}^{J} j^2 \right)\,,$$

$$D_{3,it} = \left(\sum_{j=1}^{J} j^3\, p_{j,it} - \frac{1}{J} \sum_{j=1}^{J} j^3 \right)\,.$$

$$r^*_{it} = a_i + \phi\, g_{it} + \sum_{k=1}^{3} \gamma_k D_{k,it} + \epsilon_{it}\,,$$

Main results: growth and demography as drivers of r^*

Fair and Dominguez (1991)

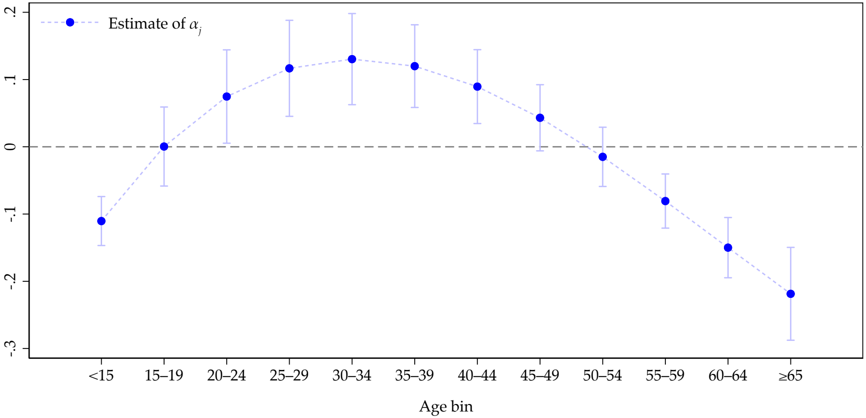
	(1) r^*	(2) r^*
g	0.594^{***}	0.573^{***}
	(0.055)	(0.053)
D_1	0.173129^{***}	0.172479^{***}
	(0.023356)	(0.022492)
D_2	-0.022371^{***}	-0.017606^{***}
	(0.004696)	(0.004581)
D_3	0.000687^{**}	0.000350
	(0.000254)	(0.000250)
Time trend		-0.000384^{***}
		(0.000059)
Constant	0.0334^{***}	0.0424^{***}
	(0.0028)	(0.0030)
N	543	543
R^2	0.674	0.698

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

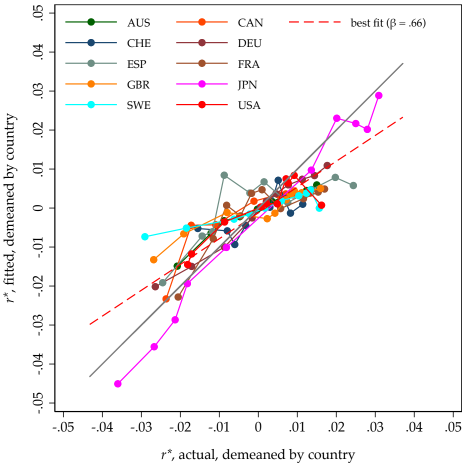
Main results: growth and demography as drivers of r^*

Fair and Dominguez (1991)

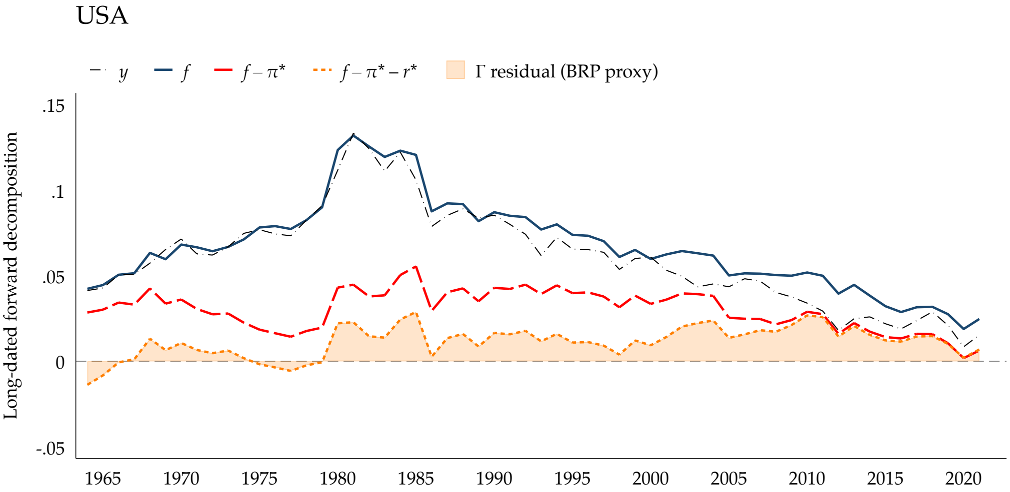


Main results: growth and demography as drivers of r^*

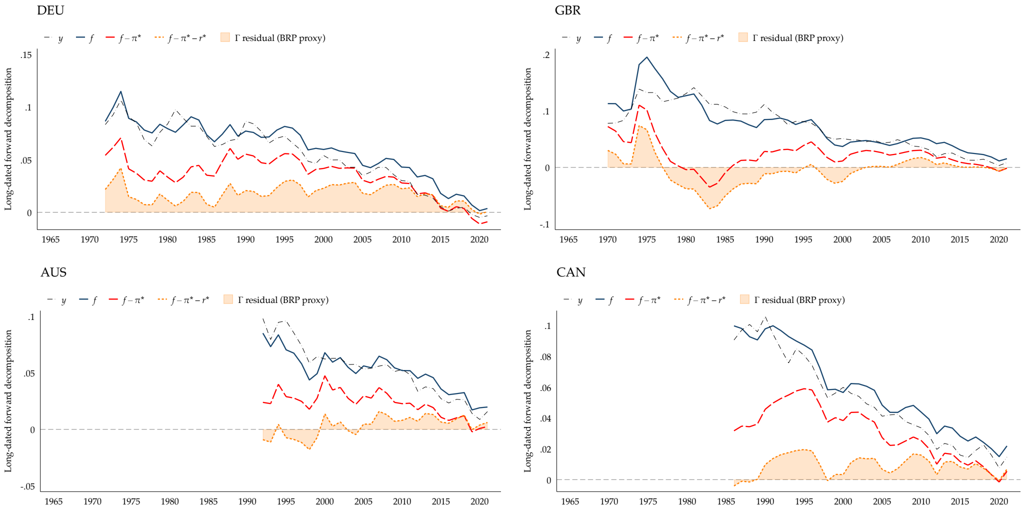
fitted v actual



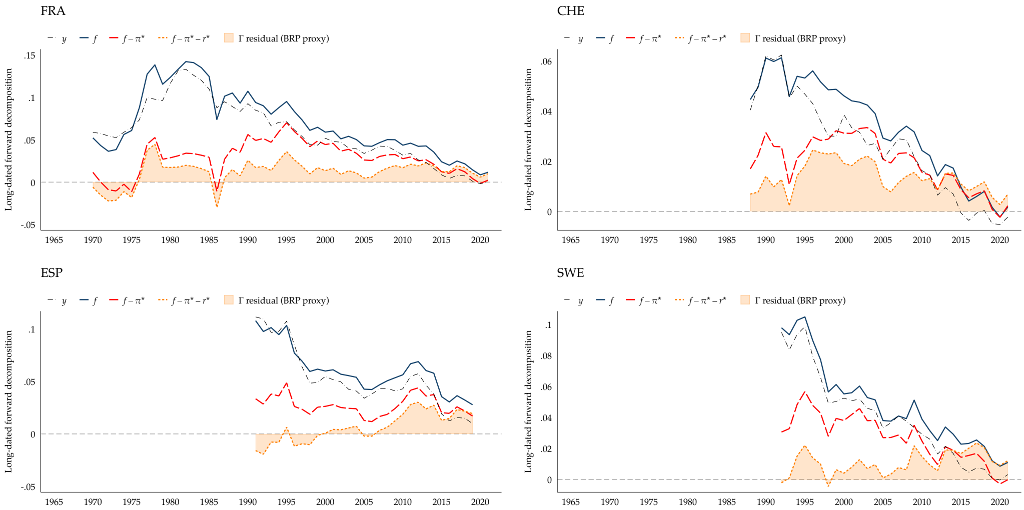
Main results: puzzle



Main results: puzzle



Main results: puzzle



Summary

Summary

Main contributions

- Natural rate puzzle
- New hybrid macro-finance estimation
- More data (larger N, T)
- Improved estimates of BRP, in and out of sample
- Puzzle resolved... but a revisionist history of BRP
- New r^* estimates plausible
- Growth and demography $\rightarrow$ 2/3 of long-run decline
- Even lower for even longer?

Model Appendix: Bayesian Estimation of the Model

- We estimate the state-space model using the RWMH algorithm for each country separately.
- The initial particles are drawn from the prior distribution $\theta_0 \sim p(\theta)$.
- We then build a Markov chain of the model parameters θ recursively: For $n = 1, ..., N$
  1. Draw step n proposal particles $\hat{\theta}_n$ from the proposal distribution $q\left(\hat{\theta}_n | \theta_{n-1}\right)$
  2. Accept the new draw with probability $\alpha\left(\hat{\theta}_n | \theta_{n-1}\right)$
  3. Update the particle sequence: If accepted $\theta_n = \hat{\theta}_n$, else $\theta_n = \theta_{n-1}$
- Standard proposal distribution $q\left(\cdot | \theta_{n-1}\right)$ and acceptance probability $\alpha\left(\cdot | \theta_{n-1}\right)$
- We target an acceptance rate of 23.4 percent

Main Estimation

Model Appendix: Prior Specification

Parameter	Distribution	Mean	Variance
ρ_z	Beta	0.997	2.00×10^{-6}
ρ_y	Normal	0.9	0.025
σ_z	Log-Normal	1.00×10^{-4}	$\bar{\sigma}_z^2$
σ_y	Log-Normal	1.00×10^{-3}	5.00×10^{-4}
a_y	Normal	0.00	7.50×10^{-4}
b_π	Normal	1.25	0.10
b_{r*}	Normal	0.50	0.05

where $\bar{\sigma}_z^2 \in \left[10^{-5}, 10^{-6}\right]$ is country-specific

Main Estimation