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Abstract

We develop a parsimonious New Keynesian macro-finance model with downward nominal rigidities to understand secular and cyclical movements in Treasury bond premia. Downward nominal rigidities create state-dependence in output and inflation dynamics: a higher level of inflation makes prices more flexible, leading output and inflation to be more volatile, and bonds to become more risky. The model matches well the relation between the level of inflation and a number of salient macro-finance moments. Moreover, we show that empirically, inflation and output respond more strongly to productivity shocks when inflation is high, as predicted by the model.

JEL classification: E31, E32, E43, E44, G12.
Keywords: Term Premium, Bond premium, Phillips curve, Inflation, Asymmetry, Skewness.

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1 Introduction

Yields on long-term bonds exhibit large secular and cyclical components, but understanding what drives yield changes is difficult. A large literature documents violations of the expectation hypothesis: long-term yields are not simply the expectation of future short rates. Rather yields, comprise a substantial time-varying term premium, or bond premium, which represents the compensation required by investors to hold nominal long-term bonds. But what are the economic forces driving the variation in this bond premium?

In this paper, we develop a parsimonious New Keynesian macro-finance asset pricing model with asymmetric nominal rigidities: prices are easier to raise than to cut. We show that this single, realistic ingredient can go some way towards understanding fluctuations in the bond premium, and more generally in the association of inflation or bond returns with consumption or stock returns. In particular, we show that our model, despite its simplicity, can account for a significant fraction of the decline in the bond premium since the 1980s, as documented in Wright (2011), as well a number of other salient macro-finance moments.

Our mechanism is best understood in two steps. First, in our model, as in most New Keynesian models, an increase in productivity leads to higher consumption and lower inflation, as real marginal costs falls. Intuitively, productivity shocks act as "supply shock". As a result, nominal bonds are risky since nominal yields rise in "bad times" when productivity drops and inflation rises. In short, bonds are exposed to "stagflation risk". This is a standard result, that has been used in previous work to understand the bond premium.[1]

The novelty of our model is that the extent of nominal rigidities depends on the level of inflation - when inflation is low, prices become effectively "stickier" given the stronger downward rigidities. As a result, the behavior of the economy is state-dependent: the same productivity impulse has different effects depending on whether inflation is initially high or low. In particular, the response of inflation is weaker when inflation is low - since prices are "stickier", inflation is less responsive to a productivity shock. The response of output is also weaker when inflation is low. That is because, when prices more rigid, the economy does not benefit from the productivity shock.[2] Overall, in times of low inflation, the output-inflation covariance is smaller (in absolute value, i.e. less negative),

[1] See, among others, Piazzesi et al. (2006), Bansal and Shaliastovich (2013), Song (2017).

[2] If productivity rises, demand must rise for the higher supply to be exploited; lower inflation allows demand to rise, as it generates lower interest rates through the Taylor rule, but when prices are stickier, this channel is weaker.

which reduces the nominal bond premium. Hence, in our model, the *level* of inflation is one determinant of bond premia. In contrast, we show that if nominal rigidities are symmetric, bond premia are independent of the level of inflation.

The same mechanism affects a number of other key covariances, such as that between stock and bond returns, or stock returns and inflation. When we calibrate our model to replicate the asymmetry of inflation as well as basic moments of U.S. data, we find that the mechanism accounts well for the secular changes in macro-finance moments since the 1950s. Our model also matches the predictability evidence of Fama and Bliss (1987), as well as other macroeconomic and finance observations such as the correlation between the term spread and GDP growth or the skewness of output.

We use the model to perform counterfactual policy analysis, and find that monetary policy affects not just the volatility of output and inflation, as is usually the focus of the macroeconomics literature, but also the level and volatility of bond premia. Due to the asymmetry of fluctuations, monetary policy can even increase the average level of output by reducing inefficient fluctuations.

Finally, in the last section, we provide some direct evidence for state-dependence in the response of both output and inflation to productivity shocks. Consistent with our theory, we find that when inflation is initially high, an increase in total factor productivity (TFP) increases real GDP and reduces inflation, more than when inflation is initially low.

Our model extends the canonical three-equation New Keynesian model (Gali (2008), Woodford (2003)) in two ways. First, we incorporate recursive preferences (as in Epstein and Zin (1989), Weil (1990)) so as to match the level of bond premia. Second, we incorporate downward nominal rigidities in a tractable way by assuming asymmetric price adjustment (as in Kim and Ruge-Murcia (2009)). We do not attempt to provide a deep micro-foundation for the asymmetry in this paper, but rather focus on its implications, in our case for macro-finance moments and how they evolve with the level of inflation.[3] Two parameters - the level of risk aversion and the degree of asymmetry in price adjustment costs - govern the differences with the standard New Keynesian model and allow us to cleanly demonstrate its properties.

Why do we focus on downward nominal rigidities? First, it is a realistic ingredient: prices and wages are more rigid on the downside, as has been emphasized for a long

[3]One potential explanation for downward nominal rigidities is simply money illusion (nominal anchoring) on the part of workers or shoppers. Another is that asymmetry in prices stem from asymmetry in wages, which itself come from regulations or other labor market frictions (e.g., limited commitment). Motivated by this idea, we develop an extension of our model with wage and price asymmetry (see internet appendix 3). The appendix shows that incorporating wage asymmetries reduces the need for price asymmetries, but overall does not change any of the main conclusions, and hence we stick to the simpler model.

time,[4] and used in recent research modeling macroeconomic fluctuations.[5] Second, from an empirical viewpoint, downward rigidities are attractive as they can rationalize two salient features of inflation illustrated in figure 1: (i) inflation exhibits a positive skew; (ii) it is almost never negative. We calibrate our model to replicate these two features.

More broadly, the asymmetry is appealing in light of the recent history of inflation. In the United States, after the Great Financial Crisis, economists were puzzled by the absence of deflation. The same patterns have been observed in Japan or Europe, where the feared deflation trap did not materialize: inflation stayed stable at very low levels for many years. Conversely, economists are now trying to understand why inflation rose so quickly during the Covid recovery after being so stable in the previous decades.[6] The simple asymmetry in price setting in our model can readily explain both why inflation was stable when it was low, and why it could rise quickly.[7]

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Overall, our contribution is to offer a simple economic mechanism to generate time-variation in variances and covariances of macroeconomic quantities and asset returns, and consequently in bond premia, and to provide some evidence for time variation in these covariances in a manner consistent with the model. While much work in finance has documented variation in bond premia or related macro-finance moments, there is a limited number of explanations offered in the literature.[8] In contrast to some studies that assume exogenous shifts in parameters or macroeconomic regimes, our model generates the changes endogenously through nonlinearities. Finally, while the relevance of downward nominal rigidities is largely acknowledged by macroeconomists and policymakers, their implications for asset prices have been overlooked. One of our contributions is to close this gap.

The paper is organized as follows. The rest of the introduction reviews the related

[4] See Keynes (1936), Tobin (1972), Friedman (1977).

[5] For instance, Schmitt-Grohé and Uribe (2016), and more broadly the New Keynesian literature, which focuses on the failure of prices to *fall* in recessions, e.g. Krugman (1998), Eggertsson and Woodford (2003).

[6] On the post-GFC lack of deflation, see among others Del Negro et al. (2015), Gilchrist et al. (2017), Jørgensen and Lansing (2019), and Harding et al. (2022). On the post-Covid inflation, see among others Benigno and Eggertsson (2023), Gagliardone and Gertler (2023), Harding et al. (2023), Pfäuti (2023).

[7] We motivated our assumptions by the behavior of inflation (because this is our object of interest). Another way to motivate downward nominal rigidities is to use microeconomic evidence on price-setting: there is a large body of empirical evidence in favor of downward stickiness. In particular, nominal wages are sticky at zero (for two recent studies using high-quality data, see Grigsby et al. (2021) or Hazell and Taska (2020)). Prices do occasionally decline, but most declines are temporary sales that reflect different motives and obey different dynamics (Nakamura and Steinsson (2008), Klenow and Malin (2010)). Prices also tend to rise faster than they fall, consistent with an asymmetry (Peltzman (2000)).

[8] We review the related work below. We view the alternatives explanations, such as changes in the conduct of monetary policy or in the size and composition of shocks hitting the economy, as complementary, and future work should try and disentangle them empirically.

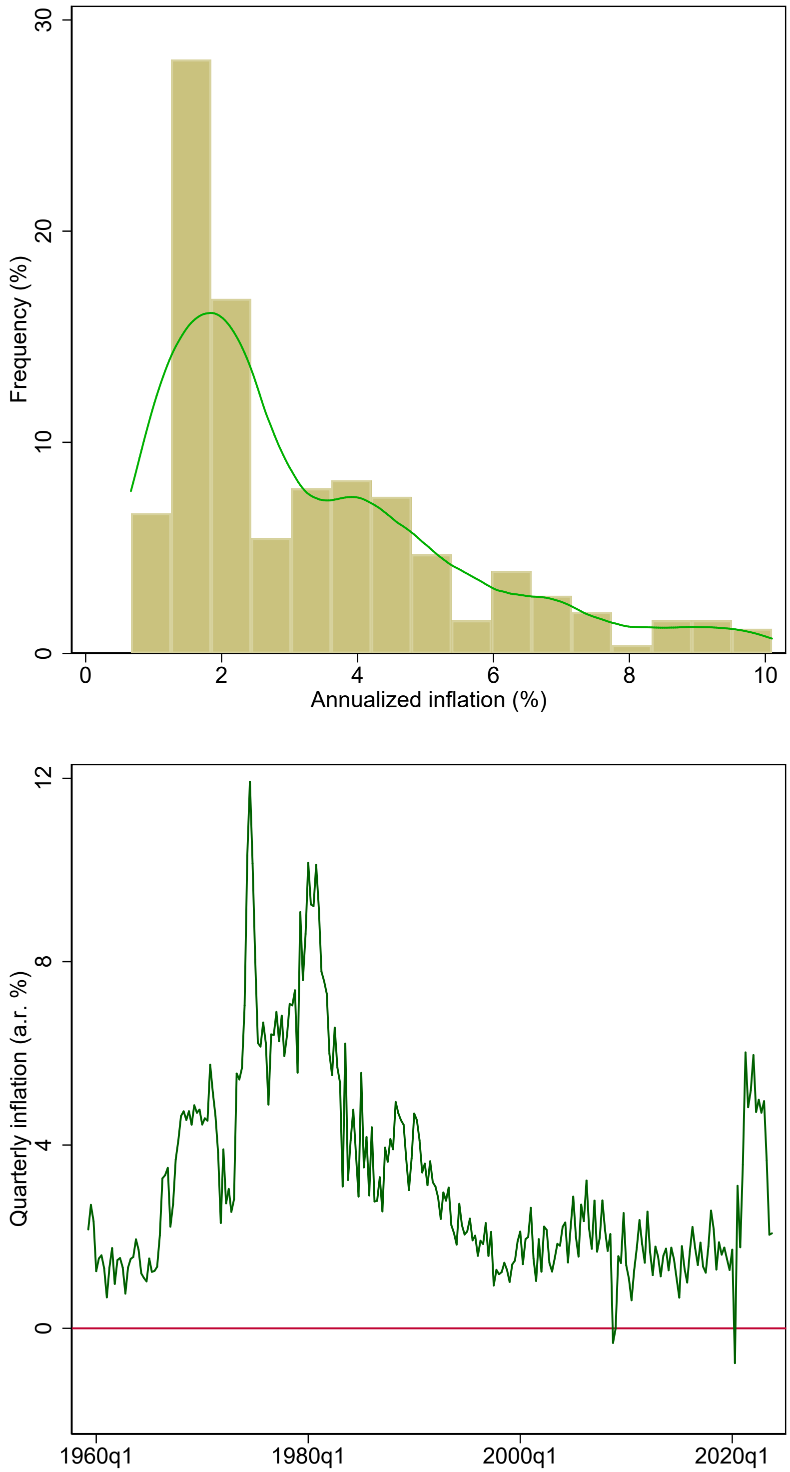

Figure 1: The top panel is a histogram of quarterly inflation together with a smoothed (Epanchikov) kernel density estimate. The bottom panel graphs quarterly inflation. Inflation is measured as the change in the Personal Consumption Expenditures (PCE) index exclusive of food and energy (i.e., the "core" PCE inflation) and is expressed at an annual rate. Data is from the Bureau of Economic Analysis (BEA) and covers the period 1959q1 through 2023q4.

literature. Section 2 documents a positive association between the level of inflation and proxies for bond premia as well as macro-finance (co)variances. Section 3 introduces our model, and Section 4 calibrates it and presents the key quantitative results. Section 5 discusses some additional implications and robustness. Finally, Section 6 presents additional empirical evidence in favor of the key mechanism, and Section 7 concludes. An internet appendix presents some additional results and robustness.

Related Literature We make contact with a number of literatures in macroeconomics and finance. First, we contribute to the connection between inflation and asset returns, a classic topic in asset pricing at least since Fama and Schwert (1977) and Modigliani and Cohn (1979).[9] Our work is also closely related to macro-finance models that study the term structure of interest rates, for instance endowment economy models such as Piazzesi et al. (2006), David and Veronesi (2013), Bansal and Shaliastovich (2013), and Song (2017), who also study the different regimes in bond premia.

More closely related to our work are studies that endogenize consumption and inflation using production models with nominal rigidities in the New Keynesian tradition, such as Rudebusch and Swanson (2008), Rudebusch and Swanson (2012), Li and Palomino (2014), Andreasen (2012), Palomino (2012), Kung (2015), Swanson (2021), and, more recently, Pflueger and Rinaldi (2022), Kekre and Lenel (2022), Caballero and Simsek (2022), Bianchi et al. (2022). In particular, most closely related are those studies that also use a macroeconomic model to understand the variation in various macro-finance moments, notably Campbell et al. (2020), Pflueger (2023). These papers emphasize structural breaks in monetary policy rules or the structure of the economy, and in the structure of shocks, rather than endogenous change in the propagation of productivity shocks as in our model.[10]

We also build on a small macroeconomic literature that studies the effect of downward rigidities. We follow closely the model of Kim and Ruge-Murcia (2009), but focus on very different mechanisms and questions. Other recent studies that emphasize asymmetry in nominal rigidities include Benigno and Antonio-Ricci (2011), Abbritti and Fahr (2013), Daly and Hobijn (2014), Jo and Zubairy (2022). We also relate to the literature emphasizing asymmetries over the business cycle (Neftci (1984), Dupraz et al. (2019), Dew-Becker

[9] For some more recent work, see Fleckenstein et al. (2017), Fang et al. (2022) or Cieslak and Pflueger (2023) for a review.

[10] Some related work focuses on the role of the zero lower bound (ZLB) (for instance including our previous paper Gourio and Ngo (2020) and Nakata and Tanaka (2016)), which is another mechanism for the changing responsiveness, with somewhat different implications, and which explains different periods and phenomena.

et al. (2021)). Like Ascari and Sbordone (2014), Ascari and Rossi (2012), Ascari (2004), we are interested in the implications of trend inflation, which is often ignored in New Keynesian models that focus on dynamics around a zero inflation steady-state.

Finally, our paper also makes contacts with a number of big-picture macroeconomic topics: the causes of the Great Moderation (e.g. Stock and Watson (2002), Benati and Surico (2009) among many others); changes in the dynamics of inflation (e.g. Stock and Watson (2007) among many others); and the changes in the slope of the Phillips curve (on top of the papers cited in the introduction, see Boehm and Pandalai-Nayar (2022), Cerrato and Gitti (2022), Costain et al. (2022)). Our paper also proposes an explanation for the relation between the level and volatility of inflation, which is an oft-noted regularity (Okun (1971), Foster (1978), Ball et al. (1990), Golob et al. (1994) among others), but for which there is no clear explanation (See Ball (1992) and Nirei and Scheinkman (2021) for some related work).

2 Motivating Evidence

In this section, we document a positive association between the *level* of inflation and several macro-finance moments, in particular the riskiness of bonds and inflation. In a first part, we use as proxy for the riskiness of bonds the term premium estimated by affine term structure models. In a second part, we use time-varying volatilities and covariances of inflation, bond returns, and other macro-finance variables using rolling windows. While these facts are not new, we present them in a novel way. In section 4, we will evaluate our structural model by its ability to replicate these facts.

2.1 Term premia implied by affine models

A large literature has developed sophisticated affine term structure models to infer term premia from bond prices and other observables.[11] Figure 2 presents a variety of estimates, from Kim and Wright (2005), Christensen et al. (2011), Adrian et al. (2013), and D'Amico et al. (2018). Each estimate relies on a different statistical model and may use different data. Overall, these estimates are broadly similar, both along the cyclical margin and along the secular margin. In particular, the low frequency movements appear to follow those of inflation or nominal interest rates during this period. To confirm this, in table 1

[11] Recall that the term premium is the average excess return per year obtained by buying a long-term bond and holding it to maturity, over the expected return from buying short-term bonds and rolling them over at future (unknown) short-term rates. Calculating the term premium hence requires a statistical model to forecast future short-term interest rates. See section 3.4 for more details.

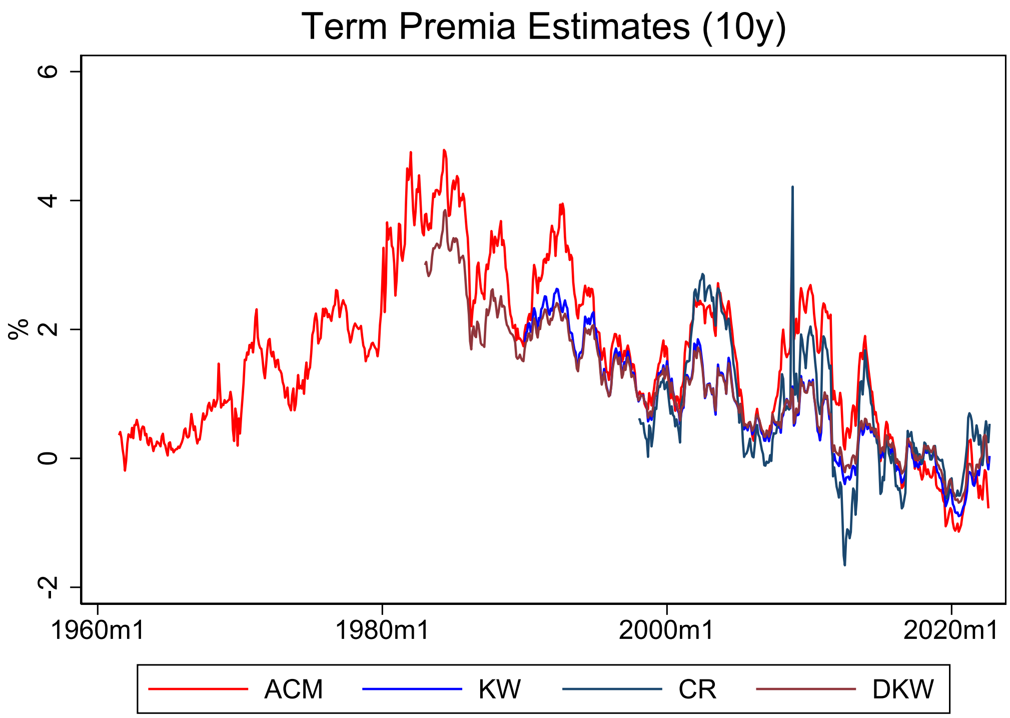

Figure 2: Estimates of 10-year nominal term premium from affine term structure models. ACM denotes Adrian et al. (2013), KW is Kim and Wright (2005), DKW is D'Amico et al. (2018), and CR is Christensen et al. (2011). Monthly data 1961m6-2022m10.

we measure the association using the regression:

$$TP_t = \beta_0 + \beta_1 \pi_t + \beta_2 t + \varepsilon_t,$$

where TP_t is the Adrian et al. (2013) estimate of the 10-year nominal term premium,[12] π_t is either PCE or core PCE inflation (year-over-year), and we may include a linear trend as control. According to the table, a 1pp decrease in inflation is associated with a decrease in the term premium of 15-26bps. This result is in line with the findings of Wright (2011) who documents a reduction in term premia across many developed countries during the 1980s and 1990s.

[12]We use the Adrian et al. (2013) estimate because it has the longest available history - covering the low-inflation periods that precede, and follow, the "Great Inflation" of the 1970s.

Dependent variable: 10-year ACM Term Premium				
Core PCE inflation	0.259***		0.248***	
	(0.080)		(0.089)	
PCE inflation		0.174**		0.151**
		(0.067)		(0.080)
Time Trend	N	N	Y	Y
Obs.	733	733	733	733

Table 1: Association between Adrian et al. (2013) 10-year term premium and inflation. Standard errors are Newey-West with 36 monthly lags. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively. The data range from 1961m1-2022m10.

2.2 Time-varying Covariances

Another approach to measuring the riskiness of bonds is to estimate the covariance of bond returns with macroeconomic proxies for marginal utility, such as consumption or the market stock return (corresponding, respectively to the consumption or market CAPM measure of riskiness). Since bonds are highly exposed to inflation, we will also look at the riskiness of inflation itself, measured as the covariance with consumption or the market. Even more simply, we can look at the volatility of inflation or yields.

We estimate these moments at each point in time by using a simple rolling window.[13] Figures 3 and 4 display the results. In these figures, each dot is a date between 1963q2 and 2013q1, for which we calculate the mean and volatility of inflation using the corresponding 13-year centered rolling window; we then add a fitted regression line to the scatter plot to visualize the overall association.

The top-left panel shows that a higher level of inflation is associated with more volatile inflation - a well-known empirical regularity in the applied macroeconomics literature.[14] The top right panel of figure 3 shows that higher inflation is associated with higher volatility of GDP, reflecting not just the so-called "Great moderation" but also the fact that growth was smoother in the 1950s-1960s. The last two panels show that high inflation is also associated with higher volatility of long-term interest rates (the 10-year yield; results are similar for the short-term (Tbill) yield), and a more negative covariance of GDP

[13]We obtain similar results if we estimate conditional moments by calculating the volatility or covariance of the residuals from a monthly VAR.

[14]See Okun (1971), Foster (1978), Ball et al. (1990), Golob et al. (1994) among others.

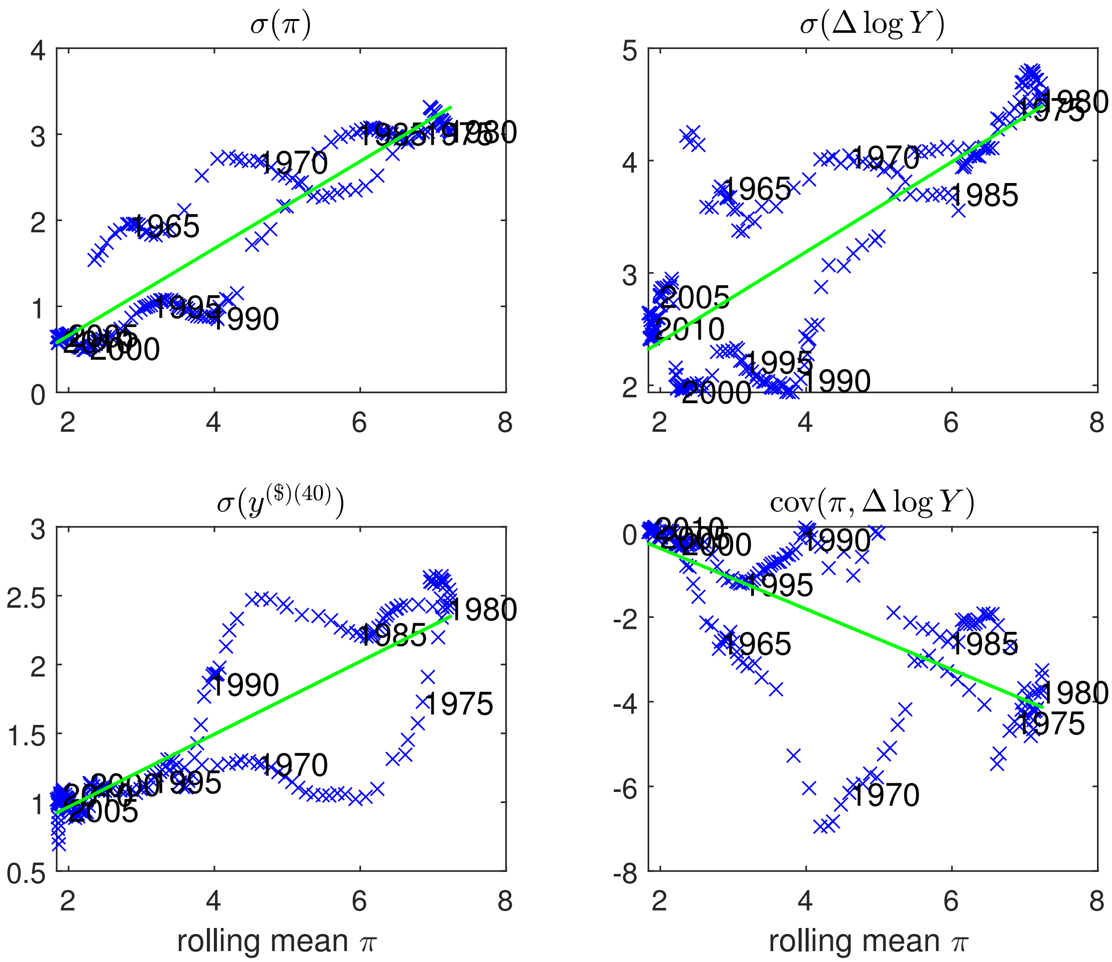

Figure 3: **Data moments, 1/2.** Each panel is a scatter plot (together with a fitted regression line) of a macro-finance moment against the mean of inflation, where both the moment and the mean are estimated on a 13-year centered rolling window. The moments depicted here are the volatility of (core) inflation (top left), of GDP growth (top right), of the 10-year Treasury yield (bottom left), and the covariance of GDP growth and (core) inflation (bottom right). The sample is 1957q1-2019q4.

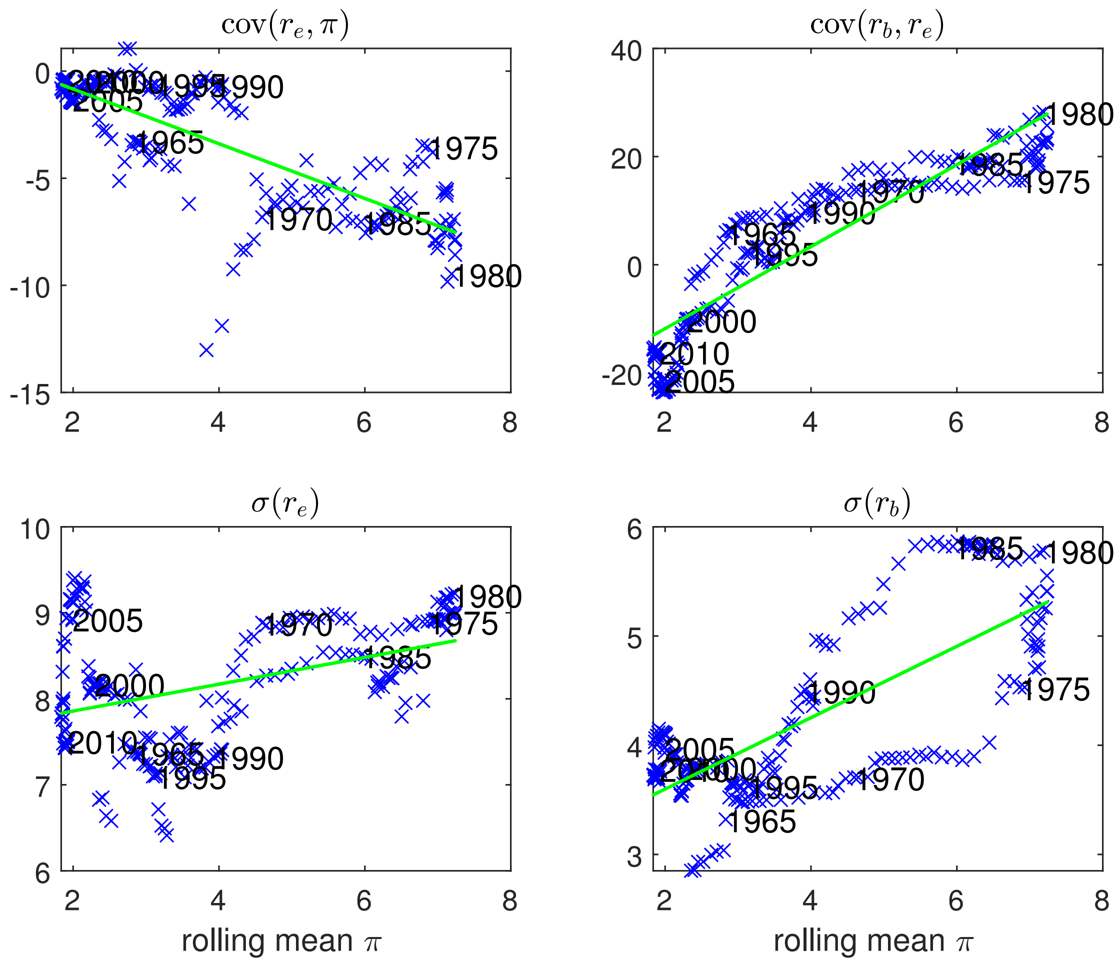

Figure 4: **Data moments, 2/2.** Each panel is a scatter plot (together with a fitted regression line) of a macro-finance moment against the mean of inflation, where both the moment and the mean are estimated on a 13-year centered rolling window. The moments depicted here are the covariance of the real equity return and (core) inflation (top left), the covariance of the real equity return with the real return on the 10-year Treasury note (top right), the volatility of the real equity return (bottom left), and the volatility of the real return on the 10-year Treasury note (bottom right). The sample is 1957q1-2019q4.

growth and inflation. That moment suggests that inflation was more "risky" in the 1970s with a higher stagflation risk.

Continuing in table 4, we see that higher inflation happens simultaneously with (i) a more negative covariance of real stock returns and inflation, also suggestive that inflation was more risky in the "CAPM" sense; (ii) a more positive covariance of real stock returns and the real return on a 10-year Treasury - a higher "CAPM beta" on bonds; (iii) a slightly higher volatility of real stock returns; (iv) a higher volatility of the real 10-year Treasury return. Overall, these moments suggest that inflation is more risky when it is high - and hence, bonds are more risky - consistent with the term premia estimates, which use a very different identification.

These results are not new - they confirm the findings of a large literature that documents changes over time in these associations.[15] One dimension in which we differ from some of the existing literature is that we incorporate data from the low-inflation 1950s and 1960s, before the Great Inflation, and show that, for, the most part, they line up relatively well with the low-inflation period from 1985 through 2020. This suggests that the changes observed in these associations are not simply due to one of the many structural changes that occurred during the 1980s - but rather, the actual level of inflation might be, in itself, an important factor.[16]

While the idea that a high level of inflation is associated with (and perhaps causes) volatile inflation, is intuitive, it is not a prediction of standard monetary models, which typically explain the *average* level of inflation, on the one hand, by the *average* growth of money growth or the average interest rate (the inflation target), and the volatility of inflation, on the other hand, by the volatility of underlying shocks and their propagation - factors which in principle have no relation to each other. For this reason, the relation between level and volatility of inflation is a longstanding puzzle. We now explore one potential explanation: asymmetric nominal rigidities, and its implications for asset prices.

3 Model

Our model builds on the standard three-equation New Keynesian model (Gali (2008), Woodford (2003)). We depart from this standard model in two ways. First, we use recursive preferences (Epstein and Zin (1989), Weil (1990)) with high risk aversion to match

[15] See among many papers Piazzesi et al. (2006), Campbell et al. (2017), Campbell et al. (2020), David and Veronesi (2013), Cieslak and Pflueger (2023), and the references therein.

[16] We abstract from the Covid period because macroeconomic data is extremely volatile - and potentially less reliable - in 2020.

the observed level of risk premia. Second, we introduce asymmetric nominal rigidities following the work of Kim and Ruge-Murcia (2009).

3.1 Household

The representative household works, consumes, and decides how much to save in various assets. Following the simplest New Keynesian model, there is no capital. Because the equilibrium is not affected by the number and type of assets available, we simplify the exposition of the household problem by using only a short-term nominal risk-free bond.[17] We discuss later in section 3.4 the other assets we consider.

We use the formulation of recursive preferences introduced by Rudebusch and Swanson (2012). The flow utility of consumption is:

$$u\left(C_t, N_t\right) = \frac{C_t^{1-\sigma}}{1-\sigma} - \chi \frac{N_t^{1+\nu}}{1+\nu}, \tag{1}$$

and the intertemporal utility is:[18]

$$V_t = (1-\beta)\, u(C_t, N_t) + \beta E_t \left(V_{t+1}^{1-\alpha}\right)^{\frac{1}{1-\alpha}}. \tag{2}$$

The household budget constraint is:

$$P_t C_t + B_t = W_t N_t + H_t + R_{t-1} B_{t-1} - T_t. \tag{3}$$

Here B_t is the quantity of one-period risk-free bonds bought, $R_t \equiv Y_t^{\$(1)}$ is the gross nominal yield on these bonds (set in period t, paid in period $t+1$), H_t are firms' profits, T_t are lump-sum taxes, P_t is the price level, and W_t is the nominal wage rate.

Denote by $w_t = W_t / P_t$ the real wage; labor supply is governed by the usual condition:

$$w_t = -\frac{u_2\left(C_t, N_t\right)}{u_1\left(C_t, N_t\right)} = \chi C_t^{\sigma} N_t^{\nu}, \tag{4}$$

[17] Agents are Ricardian, i.e. they recognize that government debt is not net wealth, since it comes with future tax liabilities, and hence the quantity and types of bonds issued by the government has no effect on the equilibrium: the bonds, *together* with the associated tax liabilities, are in zero net supply.

[18] Note that, if the parameters lead to a negative flow utility $u(C_t, N_t)$, we define utility as:

$$V_t = (1-\beta)\, u(C_t, N_t) - \beta E_t \left(\left(-V_{t+1}\right)^{1-\alpha}\right)^{\frac{1}{1-\alpha}}.$$

and optimal consumption is determined by the Euler equation linking the nominal short-term interest rate to the nominal stochastic discount factor:

$$E_t\left[R_t M^{\$}_{t+1}\right] = 1. \tag{5}$$

The nominal SDF is

$$M^{\$}_{t+1} = \frac{M_{t+1}}{\Pi_{t+1}}, \tag{6}$$

where Π_{t+1} is gross inflation P_{t+1}/P_t, and M_{t+1} is the real stochastic discount factor:

$$M_{t+1} = \beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma}\left(\frac{V_{t+1}}{E_t\left(V_{t+1}^{1-\alpha}\right)^{\frac{1}{1-\alpha}}}\right)^{-\alpha}. \tag{7}$$

3.2 Production and price-setting

There is a measure one of identical monopolistically competitive firms, each of which operates a constant return to scale, labor-only production function:

$$Y_{it} = Z_t N_{it}, \tag{8}$$

where Z_t is aggregate productivity, which follows an exogenous stochastic process. The household consumes a Dixit-Stiglitz CES aggregator of these firms:

$$C_t = \left(\int_0^1 Y_{it}^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}},$$

where the elasticity of substitution is ε. As a result, each firm faces a downward-sloping demand curve with elasticity of demand ε:

$$Y_{it} = Y_t\left(\frac{P_{it}}{P_t}\right)^{-\varepsilon}, \tag{9}$$

where P_t is the price aggregator:

$$P_t = \left(\int_0^1 P_{it}^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}}.$$

Following Rotemberg (1982) and Ireland (1997) we assume that each intermediate goods firm i faces costs of adjusting prices. The adjustment cost is proportional to aggregate output, and a function of the size of the price change:

$$AC_{it} = G\left(\frac{P_{it}}{P_{it-1}}\right) Y_t,$$

where G is a convex function, to be discussed below. The problem of firm i is to maximize the present discounted value of real profits, net of adjustment costs:

$$\max_{\{P_{it+j}\}} E_t \sum_{j=0}^{\infty} M_{t,t+j} \left[\left(\frac{P_{it+j} Y_{it+j} - w_{t+j} Nit + j}{P_{t+j}} \right) - G\left(\frac{P_{it+j}}{P_{it+j-1}}\right) Y_{t+j} \right] \tag{10}$$

subject to its demand curve (9) and its production function (8). The first term in this expression reflects the real profit per unit sold, and the second term the cost of changing prices, and $M_{t,t+j}$ is the real SDF between periods t and $t+j$:

$$M_{t,t+j} = \prod_{k=1}^{j} M_{t+k}$$

In equilibrium, all firms choose the same price and produce the same quantity (i.e., $P_{it} = P_t$ and $Y_{it} = Y_t$). Taking first-order conditions to (10) and imposing this equilibrium condition yields the optimal pricing rule:

$$J(\Pi_t) = 1 - \varepsilon + \varepsilon \frac{w_t}{Z_t} + E_t \left[M_{t+1} J(\Pi_{t+1}) \frac{Y_{t+1}}{Y_t} \right], \tag{11}$$

where $J(x) = xG'(x)$ captures the marginal cost of adjusting prices. Note that w_t / Z_t is the (real) marginal cost of production. If there are no costs to adjusting prices, this formula reduces to the Lerner rule, i.e. the markup equals the inverse elasticity of demand. With adjustment costs, this equation yields a relation between inflation and current (and future) marginal costs, i.e. a Phillips curve.

Much of the literature assumes a symmetric, quadratic adjustment cost:

$$G(x) = \frac{\phi}{2} \left(x - \overline{\Pi}\right)^2, \tag{12}$$

where ϕ is the adjustment cost parameter which determines the degree of nominal price rigidity, and $\overline{\Pi}$ the level of inflation which implies zero costs, which can be thought of as the "indexation" trend for the economy.

Instead of using a quadratic G, we follow Kim and Ruge-Murcia (2009) who use a linex function to model adjustment costs:

$$G\left(x\right)=\frac{\phi}{\psi^{2}}\left(e^{-\psi\left(x-\overline{\Pi}\right)}+\psi\left(x-\overline{\Pi}\right)-1\right). \tag{13}$$

This function implies that changing prices at a rate below $\overline{\Pi}$ is more costly than changing prices at a rate above $\overline{\Pi}$. The linex functional form, which has been used in various contexts to model asymmetry, is attractive for two reasons. First, it neatly separates the role of the *size* of adjustment costs (governed by the parameter ϕ) from that of the *asymmetry* (governed by ψ). Second, it nests the standard quadratic specification: when $\psi \to 0$, the specification converges to the usual quadratic one.[19] This will allow us to demonstrate clearly the role of the asymmetry by varying ψ while holding ϕ fixed.

To understand intuitively some of the differences between our model (13) and the quadratic model (12), it is useful to approximate the Phillips curve (equation (11)). To a first-order (and around a zero inflation steady-state, that is assuming both that $\overline{\Pi}=1$ and an average inflation rate of zero), the quadratic model implies:

$$\pi_t=\kappa\widehat{mc}_t+\beta E_t(\pi_{t+1}), \tag{15}$$

where π_t is the (net) inflation rate, and hats denote log-deviations from (nonstochastic) steady-state.[20] This equation is the canonical New Keynesian Phillips Curve, with slope

$$\kappa=\frac{\varepsilon-1}{\phi}. \tag{16}$$

The Phillips curve is flatter (lower κ) when prices are more sticky (higher ϕ) or demand is less elastic (lower ε).[21]

[19]The second point can be seen easily using L'Hospital rule, and the intuition for the first point can be gleaned from a Taylor expansion:

$$G\left(x\right)\approx\frac{\phi}{2}\left(\left(x-\overline{\Pi}\right)^{2}-\frac{\psi}{3}\left(x-\overline{\Pi}\right)^{3}\right), \tag{14}$$

which shows that a larger ψ makes the costs lower for positive adjustments (above $\overline{\Pi}$) and higher for negative adjustments (below $\overline{\Pi}$), while a larger ϕ increases adjustment costs for all adjustments.

[20]That is $\pi_t=\Pi_t-1$ and $\widehat{mc}_t=mc_t/mc^*-1$ where mc^* is the steady-state real marginal cost.

[21]This equation is typically derived using the Calvo model. In that model, firms are assumed to face a random cost of changing prices. The cost is *iid* over time and firms, and equals zero with probability λ each period, and is infinite with probability $1-\lambda$. As is well known (e.g. Roberts (1995)), in the quadratic case, and around a zero inflation steady-state, the (Calvo) Phillips curve is equivalent (to a first-order) to that implied by the Rotemberg model. See Miao and Ngo (2021) for a detailed comparison of Rotemberg and Calvo models of price stickiness. We use the Rotemberg framework for two reasons: most importantly, it is easy to introduce asymmetry in price-setting; second, it is easier to solve non-linearly as there is one fewer

By contrast, for a general (i.e. non-quadratic) adjustment cost function G, the first-order approximation to the Phillips curve around a given level of inflation Π^* is:

$$\pi_t = \kappa \widehat{mc}_t + \frac{\beta J(\Pi^*)}{J'(\Pi^*)} E_t \left(\widehat{M}_{t+1} + \widehat{Y}_{t+1} - \widehat{Y}_t \right) + \beta E_t(\pi_{t+1}). \tag{17}$$

This equation is similar to the standard NKPC, but for two features - first, there is a new term that involves discounting and growth; second, the slope κ is now given by a different formula:

$$\kappa = \frac{\varepsilon - 1}{J'(\Pi^*)} + \frac{J(\Pi^*)(1-\beta)}{J'(\Pi^*)}. \tag{18}$$

In particular, this slope depends on the level of inflation Π^*: the higher the level of inflation, the larger the slope. This naturally arises because higher inflation leads prices to be less sticky, which in turns increases the slope (as discussed above in equation (16)).

3.3 Shocks, monetary policy, and equilibrium

Productivity Process We assume that productivity follows an AR(1) process with normal innovations:

$$\log Z_t = \rho_z \log Z_{t-1} + \varepsilon_{z,t}, \tag{19}$$

with $\varepsilon_{z,t}$ i.i.d $N(0, \sigma_z^2)$. By imposing normal shocks, we force all skewness or higher moments to be generated endogenously through the model. We abstract from other fundamental disturbances for now in the interest of simplicity.[22] In internet appendix 2 we study an extension of the model that incorporates demand shocks as well.

Monetary policy We assume that monetary policy is well described by the following rule:

$$\log R_t = \log R^* + \phi_\pi(\log \Pi_t - \log \Pi^*) + \phi_y(\log Y_t - \log Y^*), \tag{20}$$

where R_t is the (gross) short-term nominal interest rate, ϕ_π and ϕ_y are the responsiveness to inflation and GDP respectively; and R^*, Π^* and Y^* are constants.[23] We abstract from

state variable. Another strand of the literature studies fixed costs of adjusting prices (so-called "menu cost models"). These models have also the potential to generate interesting asymmetries (e.g., Ball and Mankiw (1994), Ball and Mankiw (1995)).

[22] Of course, other shocks are also relevant in reality, for instance fiscal shocks (e.g., Bretscher et al. (2020)), monetary shocks (e.g., Kekre and Lenel (2022)), but also uncertainty shocks, news shocks, etc. However, many of these shocks typically induce negative, rather than positive, term premia, making it difficult to rationalize the observed positive slope of the yield curve.

[23] Clearly, only the overall intercept $\log R^* - \phi_\pi \log \Pi^* - \phi_y \log Y^*$ is relevant. In our quantitative work, we will only vary R^*, which will generate variation in average inflation as moving the intercept is akin to

the zero lower bound, and from unconventional policies, and hence will focus on periods where the zero lower bound was not a relevant constraint for monetary policy.[24]

The original Taylor rule assumes that the central bank responds to the deviation of GDP from potential GDP (i.e., the "output gap"). Often, researchers assume that potential GDP is the level of GDP that would prevail in an economy without price stickiness (the so-called natural level of output).[25] In practice, potential GDP is difficult to estimate, especially in real time. Indeed, the Fed has often been slow to recognize changes in trend growth or in the natural rate of unemployment (Orphanides (2001), Orphanides (2004)). Hence, we follow Fernandez-Villaverde et al. (2015) and Swanson (2021) and assume that the central bank responds to the deviation of GDP from a statistical "trend"; given that our model abstracts from long-run growth, it is natural to define the trend simply as a constant. In section 5, we study the impact of alternative monetary policy rules on bond premia and the macroeconomy.

Government Budget constraint The government uses taxes to service its debt (or, if taxes are negative, finances transfers through government borrowing):

$$T_t = B_t - R_{t-1}B_{t-1}. \tag{21}$$

Equilibrium Finally, following Miao and Ngo (2021), we assume that price adjustment costs are transfers that are rebated to households, rather than real resource costs.[26] With no investment or government spending, the aggregate resource constraint is simply:

$$C_t = Y_t. \tag{22}$$

Formally, an equilibrium is a collection of stochastic processes $(C_t, Y_t, w_t, N_t, R_t, M_{t+1}, \Pi_t)$ that satisfy equations ((4),(5),(7),(8),(11),(20),(22)) given that Z_t follows process (19).

moving the "inflation target" Π^*. Note that, despite the name, R^* is not the "neutral rate of interest" (often denoted r^*) - that is, the rate of interest that would prevail in a frictionless economy - but simply a monetary policy choice.

[24] Gourio and Ngo (2020) or Nakata and Tanaka (2016) analyze the effect of the zero lower bound.

[25] In our model, the natural level of output $\overline{Y}_t$ is obtained as the solution of equations (4), (8), and (11), specialized to the case $G(x) = J(x) = 0$, which leads to

$$\overline{Y}_t = \left(\frac{\varepsilon - 1}{\varepsilon\chi} Z_t^{1+v}\right)^{\frac{1}{\sigma+v}}.$$

[26] This allows us to abstract from uninteresting wealth effects stemming from the resource costs of price adjustment.

3.4 Asset prices

This section defines the assets that we consider in the model. While our model description only included a short-term bond, we can allow the government to issue any type of bond (see footnote (17)), by simply adjusting the government budget constraint (21) and the household budget constraint (3), which cancel out in the resource constraint (22), and hence do not affect the equilibrium described above. We can hence price any asset using the stochastic discount factor (7) and the nominal stochastic discount factor $M^{\$}_{t+1}$, which is generated by the equilibrium (stochastic process) for (C_t, N_t, Π_t).

We start by pricing a full term structure of zero-coupon nominal and real bonds using the standard recursions. The price of a n-period nominal bond satisfies

$$P_t^{\$(n)} = E_t\left[M^{\$}_{t+1} P^{\$(n-1)}_{t+1}\right], \tag{23}$$

with $P_t^{\$(0)} = 1$. From these bond prices, we deduce log yields as

$$y_t^{\$(n)} \equiv \log Y_t^{\$(n)} = -\frac{1}{n}\log P_t^{\$(n)}, \tag{24}$$

and log real holding period return as

$$r_{t+1}^{\$(n)} = \log \frac{P_{t+1}^{\$(n-1)}}{P_t^{\$(n)}\Pi_{t+1}} = n y_t^{\$(n)} - (n-1) y_{t+1}^{\$(n-1)} - \log \Pi_{t+1}. \tag{25}$$

Similarly, we obtain the prices, yields and returns of real bonds, and we define inflation compensation (or breakeven) as the difference between the log nominal and real yields for a given maturity:

$$IC_t^n \equiv y_t^{\$(n)} - y_t^{(n)}. \tag{26}$$

We define the risk-neutral nominal log yield as the average expected future short-term (log) nominal yields over the remaining lifetime of a bond:

$$y_t^{Q\$(n)} \equiv \frac{1}{n} E_t \sum_{k=0}^{n-1} y_{t+k}^{\$(1)},$$

and similarly for real bonds. With this in hand, the (log) term premium of a maturity n-bond is defined the difference between actual and risk-neutral yields:

$$tp_t^{\$(n)} \equiv y_t^{\$(n)} - y_t^{Q\$(n)}.$$

The term premium measures the expected return per year on a bond of maturity n if it is held to maturity, over holding short-term bonds and rolling them over. On average, the term premium equals the slope of the yield curve. Term premia and expected holding period returns are two related ways to measure the riskiness of bonds - the term premium is an average of the expected excess returns over the remaining lifetime of the bond, as its maturity continuously decreases. We can also break out the nominal term premium into the real term premium

$$tp_t^{(n)} \equiv y_t^{(n)} - y_t^{\mathbb{Q}(n)},$$

and the inflation term premium:

$$itp_t^{(n)} \equiv tp_t^{\$(n)} - tp_t^{(n)}.$$

Last, we also price a stock, which we define, following Abel (1999), as an asset with payoff $D_t = C_t^{\lambda}$, where $\lambda \geq 1$ reflects leverage.[27] The real stock price P_t^s satisfies the usual recursion

$$P_t^s = E_t \left[M_{t+1} \left(P_{t+1}^s + D_{t+1} \right) \right].$$

3.5 Solution method

The model, while highly stylized, does not admit an analytical solution, and hence we solve it numerically. Due to the presence of asymmetric adjustment costs, and given our focus on asset prices, we solve the model using global methods. We verified our numerical approximation by using two independent approaches to solve the model: projection of the first-order conditions using cubic splines, on the one hand, and policy iteration after discretizing the exogenous shock using a Markov chain. The two approaches yielded nearly identical results.

4 Main Quantitative Results

In this section, we first discuss our calibration and show that the model matches some basic moments of the macroeconomic and yield curve data. We then explain the key economic mechanisms by showing how the economy responds to a productivity shock, and how this response changes with the level of inflation. We then present our main

[27] We do not define a stock as a claim to profits, because profits tend to be countercylical in this model. A number of extensions have been proposed to explain this cyclicality, for instance fixed costs, sticky wages, or financial leverage (see, for instance, Li and Palomino (2014)). We do not incorporate these extensions in the interest of simplicity.

Parameter	Description	Value
	A. Taken from the literature	
σ	Preferences: inverse IES	2
υ	Preferences: labor supply	1.5
χ	Preferences: labor supply	40.66
ε	Preferences: substitution across goods	7.66
ϕ_π	Monetary policy rule: weight on inflation	2
ϕ_y	Monetary policy rule: weight on output	0.125
ρ_z	Shock: persistence of TFP	0.99
ϕ	Adj. cost of prices: size parameter	78
	B. Calibrated to match key moments	
R^*	Monetary policy rule: intercept	1.0101
σ_z	Shock: std. dev. of TFP innovation	0.0112
ψ	Adj. cost of prices: asymmetry parameter	884
$\overline{\Pi}$	Adj. cost of prices: location parameter	1.0091
β	Preferences: subjective discount factor	0.991
α	Preferences: Epstein-Zin curvature (note: CRRA=59)	-82

Table 2: Model parameters. The time period is one quarter.

result: the model reproduces well the association between the level of inflation and the macro-finance moments documented in section 2.

4.1 Calibration and unconditional moments

Table 2 presents the (quarterly) parameters we use as baseline values. (In section 5 we present some comparative statics to illustrate the role of some important parameters.) A first set of parameters, shown in Panel A, are pretty standard, and so we set them a priori based on the usual values in the literature ("external calibration"). A second set of parameters, that are more novel or important for our results, are shown in panel B, and are estimated to match selected moments (i.e., an exactly-identified SMM, or "internal calibration"). Because our model uses a standard Taylor rule to describe monetary policy, we use the post-Volcker, pre-ZLB sample (1979q4-2008q4) as target.

For the first set of parameters (externally calibrated), we follow Woodford (2003) and

Swanson (2021) among many others. The intertemporal elasticity of substitution (IES) $1/\sigma$ is 0.5, the Frisch elasticity of labor supply $1/v$ is 2/3, the gross markup is $\varepsilon/(\varepsilon-1)$ is 1.15. The price adjustment cost parameter is $\phi = 78$, corresponding to a half-year duration of price stickiness. We set the weight on inflation in the Taylor rule to $\phi_\pi = 2$ and the weight on output $\phi_y = 0.125$ (which translates into the usual 0.5 response once the interest rate is annualized), consistent with standard values for the sample that we target. Finally, we assume that the TFP process is highly persistent (0.99 quarterly); this fits with the high persistence of inflation and interest rates.

The second set of parameters ("internally calibrated") includes the novel parameters governing the asymmetry of the price adjustment cost. In order to identify these, we target the two striking features of U.S. inflation data that we noted in the introduction: (1) inflation is significantly skewed (1.55 in our data), so that the "upside risk" to inflation is much larger than the "downside risk"; and (2) low inflation is rare: the probability of inflation below 1% is 1.7% (corresponding to 2 observations out of 117 quarters in our sample). Together, these two features allow us to identify the magnitude (ψ) and location ($\overline{\Pi}$) of the asymmetry.[28] The other parameters that we estimate are those that directly impact some features of the data that we want to match perfectly: the mean and volatility of inflation, and the mean short-term (one-quarter) and long-term (ten-year) nominal interest rates.[29] Finally, we choose the stock leverage parameter λ to match the volatility of real stock returns in the data. By construction, this parameter has no impact on the allocation or prices except for that of stocks.

Table 3 compares the data moments to the model moments for our benchmark calibration. (The table also reports the moments if we remove asymmetry by setting ψ to zero, while keeping all other parameters unchanged. We will discuss these later.) The table shows that we can match the targeted moments (identified with asterisks) almost perfectly. Table 2 reports the parameters we obtain from this calibration: the asymmetry ψ is large, at 884, as can be seen from the estimated adjustment cost function that we depict in figure 5. The baseline inflation $\overline{\Pi}$ is 3.64% (annualized), which is also fairly high. This is because the model must generate inflation that falls regularly in the 2-3% range, but rarely below. Unsurprisingly, risk aversion is high, since we need to match the slope

[28] It might seem natural to locate the asymmetry at zero, i.e. impose $\overline{\Pi} = 1$ a priori, but because the cost of changing prices G is a continuous function, this would lead to a nontrivial share of observations with deflation, unlike the data. It seems more appropriate to let the data govern the location.

[29] Heuristically, the identification works as follows. The Taylor rule intercept R^* determines the average level of inflation, since it fixes the "inflation target". (We normalize the other Taylor rule constants as $\Pi^* = 1.005$, and set Y^* equal to the nonstochastic steady-state value of Y.) The volatility of exogenous productivity shocks σ_z pins down the volatility of inflation, the subjective discount factor β pins down the average short-term interest rate, and the risk aversion α pins down the average long-term interest rate.

	Data		Model		$\psi = 0$	
	Mean	Sd	Mean	Sd	Mean	Sd
$\Delta \log Y$	–	3.03	0.00	2.37	0.00	3.17
π	3.14*	1.97*	3.14*	1.97*	2.03	3.19
$y^{\$(1)}$	5.63*	3.20	5.63*	1.97	4.04	3.61
$y^{\$(40)}$	7.36*	2.97	7.36*	2.12	6.65	2.98
$y^{(1)}$	–	–	2.37	0.34	1.85	0.43
$y^{(40)}$	–	–	2.42	0.19	2.19	0.36
Stock return	8.12	16.32*	8.98	16.08*	10.53	19.34
$tp^{(40)}$	–	–	0.02	0.21	0.34	0.00
$tp^{\$(40)}$	–	–	1.67	0.68	2.63	0.02
Skewness(π)	1.55*	–	1.55*	–	0.03	–
Prob($\pi < 1\%$) (in %)	1.71*	–	1.78*	–	37.3	–

Table 3: Data and model moments. Columns 2 and 3 report the mean and standard deviation from U.S. data over the sample 1979q4-2008q4. Columns 4 and 5 report the mean and standard deviation for the benchmark model, and columns 6 and 7 for the model with no asymmetry ($\psi = 0$). Asterisks denote targeted moments. All statistics are reported in annualized terms.

of the yield curve, which averages a substantial 1.73% in our data (the difference between the average 10-year Treasury yield (7.36%) and the average of the T-bill yield (5.63%)): we obtain $\alpha = -82$, which corresponds to a relative risk aversion to consumption (CRRA) of 59 (Swanson (2012)). Finally, we require a high $\lambda = 15.5$ to generate the volatility of stock returns. Interestingly, given this leverage parameter, the model succeeds at generating a reasonable equity premium - reflecting that the market price of risk in the model is reasonable.

Our model is a stylized New Keynesian model, so it requires a high risk aversion to generate a sizable slope for the yield curve, or more generally high market price of risk.[30] Clearly, this parameter does not reflect the preferences of any single individual. Rather, it captures the aversion of the macroeconomy to fairly small fluctuations in aggregate consumption, as inferred from asset prices. As such, it could reflect robustness concerns (e.g. Barillas et al. (2009)) or the compensation of marginal investors who bear a disproportionate share of macroeconomic risk - for instance, wealthy stockholders (e.g. Malloy et al. (2009)).[31]

[30] The value we obtain is comparable to that used by other studies: Swanson (2021) has CRRA equal 60, and Rudebusch and Swanson (2012) has CRRA equal to 75 in the baseline.

[31] One approach to match the data with lower risk aversion is to introduce long-run risk to growth and, perhaps, to inflation. We should also note that, given our choice to target the volatility of inflation, the model undershoots the volatility of GDP (2.37% vs. 3.03% in our data). This is another reason why the level

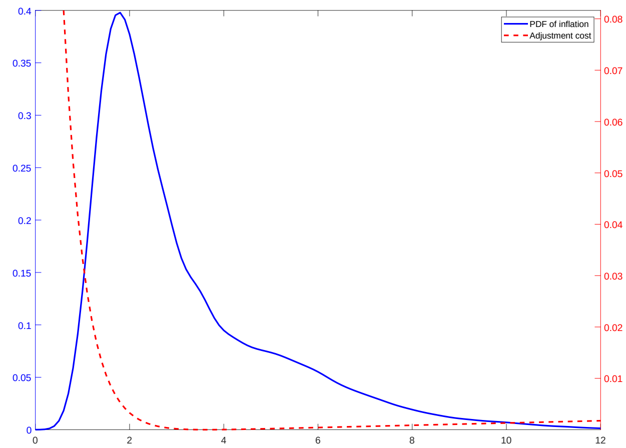

Figure 5: The red line depicts the adjustment cost function we estimate, and the blue line plots the (ergodic) distribution of inflation in the model.

Volatility of long-term rates and of bond premia The first success of the model (that is, an important untargeted moment) is the volatility of the long-term interest rate: while still below the data (2.97%), it is relatively high (2.12%). In particular, the volatility of the long-term interest rate is slightly higher than that of the short-term interest rate (1.97%). This property contrasts with many models where the short-term interest rate is a mean-reverting process, and the weak form of the expectation hypothesis approximately holds (e.g., Vasicek (1977)). In these models, the long-term interest rate is approximately equal to a constant premium plus an average of the future short-term rates, and since these are mean-reverting, it is less (and often much less) volatile than the short-term interest rate. There are two reasons why our model does well in this dimension. First, the shock is highly persistent, so the mean-reversion is effectively muted. Second, and most interestingly, the bond premia (or term premia) are volatile, and hence generate movements in long-term bond yields above and beyond those implied by the expectation component. As we will document in section 5, the model does indeed capture reasonably well the predictability of bond returns.

We can also measure the predictability directly in the model: the 10-year nominal term premium has a mean of 167bps (which equals the average slope of the yield curve), with a substantial volatility of 68bps. In the model, this variation in term premium is largely driven by the inflation component: the real term premium is on average very small (2bps) and fairly stable (21bps).[32] The low average real term premium is due to

of risk aversion (and stock leverage) is so high.

[32]Because TIPS were not traded during much of our sample, we do not have a data counterpart to the

the high persistence of shocks, which implies that there is little predictability in future consumption growth, and hence little variation in the real interest rate (the volatility of the short-term real interest rate is only 0.34%).[33]

4.2 Impulse responses in a high vs. low inflation environment

To understand the mechanics of the model, it is useful to study how the economy responds to a productivity shock, and how this response depends on the level of inflation. Figure 6 displays a simple "impulse response function" to a one-standard deviation innovation to TFP, for two parametrizations of the model. In the first one, we set R^* (i.e., the "inflation target") so that long-term average inflation equals 2% (red line); in the other one, 4%.[34]

First, note that a higher productivity leads to higher GDP and lower inflation - that is, they are "stagflationary". Intuitively, higher productivity expands the potential of the economy, allowing larger production. Lower marginal costs leads to lower inflation, which in turns leads to a lower short-term nominal interest rate per the Taylor Rule. The interest rate cut increases aggregate demand (i.e., consumption through the Euler equation), which enables the economy to take advantage of the supply shock. However, in equilibrium, given the Taylor rule, aggregate demand does not expand quite enough to align with the newly available supply: actual GDP expands less that potential GDP, so that "slack" in the economy increases, which decreases inflation. This is the standard New Keynesian model result.[35]

The novel result of the paper is the *difference* in the responses in economies with high vs. low average inflation. When average inflation is high, GDP responds more positively to a TFP shock, and inflation more negatively. As a result, the economy is more volatile, inflation covaries more negatively with output, and bonds are riskier.

Where does this result come from? Intuitively, given our adjustment cost for prices,

real term premium, and target only the overall term premium.

[33]Variation in economic uncertainty also generates real interest rate volatility, and our model does have some heteroskedasticity, but the effect on the real interest rate appears to be quantitatively small.

[34]By "impulse response function" we simply mean here the path that variables take if the economy is initially at the nonstochastic steady-state and there is a one-standard deviation innovation to productivity at time 0, followed by no shocks thereafter. This notion of impulse response is the one familiar from linear models, but in nonlinear models it is also common to construct "generalized impulse response functions" (GIRF). It turns out that in this instance, the two are fairly close, so we stick to the simpler, more intuitive measure.

[35]In New Keynesian models, output is demand-determined (as long as the markup stays positive, that is, firms make profits). Higher productivity increases the "potential" or "natural" output that the economy can achieve without inflation, but whether the actual output achieves this "potential" depends on whether aggregate demand is available to match the supply.

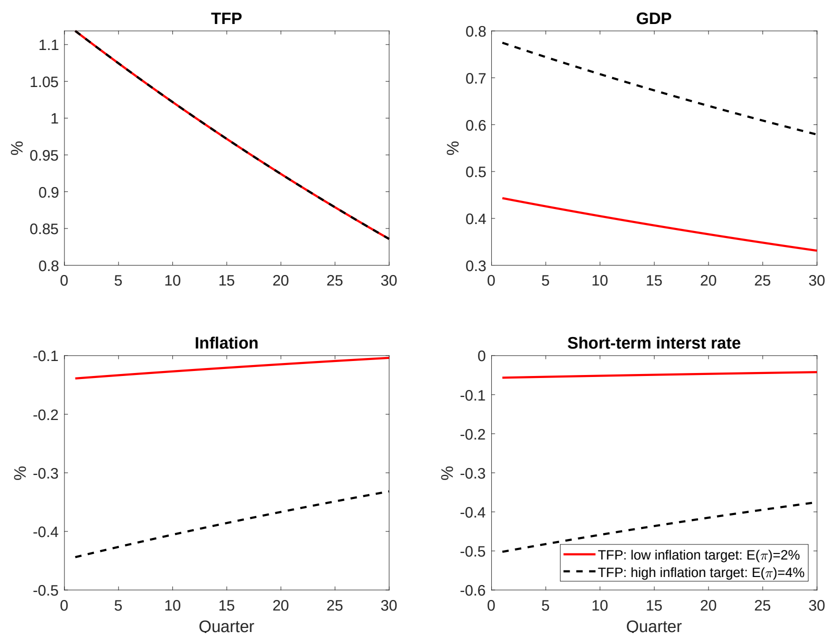

Figure 6: Impulse response function to a productivity shock. The figure presents the evolution of TFP, real GDP, inflation, and the short-term (1-quarter) interest rate in response to a one-standard deviation productivity shock. The full (resp. dashed) line corresponds to the response when the Taylor rule parameter R^* is chosen such that average inflation is 2% (resp. 4%).

at high levels of inflation, prices are less sticky. Hence, inflation reacts more to the higher productivity. This stronger response of inflation in turns allows a stronger response of output, because lower inflation leads to lower interest rates through the Taylor rule, which stimulates output. Conversely, when inflation is low, prices are more sticky, so inflation and the interest rate do not react much, and output expands less.[36] We will test directly this empirical prediction in section 5.

This exercise illustrates how the *average long-run* level of inflation affects the response to a productivity impulse; but what about the *current* level of inflation? It turns out that the same mechanism is at work. For instance, suppose that a series of negative productivity shocks leads inflation to be high; then a further shock (positive or negative) will have a larger impact on the economy, since with high inflation, the marginal cost of adjusting prices is now low. (In internet appendix (1.1.1), we present the corresponding impulse responses.) As a result, bond premia are time-varying, owing to endogenous heteroskedasticity in inflation and output growth.

4.3 The level and inflation and macro-finance moments

We now evaluate the ability of our model to explain the changes in macro-finance moments documented in section 2, moments that measure how volatility and covariances have changed over the past 60 years in the US. As explained above, we calibrated the model to match a subset of these moments over 1979q4-2008q4. We now ask: how does the model fit the other moments? And more importantly, how does the model predict these moments change with the level of inflation? Does this fit the experience of, for instance, the 1970s?

To conduct this experiment in the model requires us to take a stand on why inflation rose in the 1970s. There are two natural approaches in the model, that correspond to two different interpretation of the 1970s.[37] The first interpretation is that inflation rose because the Fed accepted it (or, perhaps, resigned itself to it, due to political pressure). Mathematically, the inflation target (i.e., the Taylor rule intercept R^*) changed. The second interpretation is that inflation rose because of "bad luck", i.e. a number of adverse shocks (for instance the energy shocks, the productivity slowdown, and perhaps other events besides the Fed's purview, such as poor fiscal policies and price controls). Mathematically,

[36] This is related to Bhattarai et al. (2018) who argue, like us, that larger price flexibility makes the economy more volatile in response to productivity shocks (and show that this result holds even without a Taylor rule). Two important differences with our paper is that we focus on asset prices, and that in our case, price flexibility varies endogenously over time due to the asymmetry in the adjustment cost (whereas they study comparative statics with respect to the Calvo parameter).

[37] For a recent authoritative review of the history and research on the topic, see Bernanke (2022).

this would correspond to a sequence of low realizations of z.[38]

In the main text, we present the results corresponding to the first interpretation, i.e. changes in inflation target $R^{\$}$ drive inflation. In the internet appendix (1.1.2), we show that similar results obtain under the second interpretation (shocks to productivity z). Hence, in the end the question of what drove inflation appears somewhat secondary for our result.[39]

Figures 7 and 8 depict the same data we presented in section 2, together with the model implied moments. (To calculate these moments, we calculate the equilibrium of our model for different values of the inflation target R^{*}, which then lead to different average inflation, and we plot the corresponding (ergodic) macro-finance moment against average inflation.) The figure shows that, as the level of inflation rises, the volatility of inflation and GDP rise, in a manner quantitatively comparable to the data. The mechanism is that discussed in the previous section: with higher average inflation, prices are less sticky and the economy is more responsive to productivity impulses. The decent fit of this untargeted moment is supportive of the model mechanism. Similarly, the model does well on the volatility of long-term yields (and also, not shown, short-term yields). The model underpredicts significantly the relation between average inflation and the output growth-inflation covariance, and to a lower extent the stock return-inflation covariance. However, it does well on the stock-bond covariance - capturing the magnitude of the change, if not the sign switch. (Given that our model has only one shock, it is difficult to generate a switch in the sign of covariance.) The model underpredicts a bit the volatility of bonds, but match the increase well, while it overpredicts that of stocks.

Given the parsimony of the model it is surprising, and encouraging, that it is roughly consistent with such a diverse set of (mostly untargeted) macro-finance moments, and their (always untargeted) evolution over a long period of time. We should note a key maintained assumption: the price adjustment cost function stays stable as the level of inflation changes.[40]

[38] These two possibilities correspond to the two exercises with impulse responses discussed in the previous section - one compares two economies with different parameters - the other the same economy in two different initial states owing to past history.

[39] Another interpretation of the 1970s, popularized by Clarida et al. (2000), is that, during this period, the Fed did not react strongly enough to inflation (i.e. the Taylor rule coefficient on inflation was too small), leading to more inflation volatility and perhaps even indeterminacy. (That explanation, however, does not account for the stagflation pattern, i.e. the negative correlation of output and inflation.) Another related interpretation is that of Orphanides (2001), that the Fed overestimated potential output (underestimated the natural rate of unemployment) and hence was overall excessively loose. At a high level, these interpretations are similar to our interpretation that the Fed simply resigned itself to a high level of inflation. In our model, changes in the rule as suggested by these authors would also have somewhat similar implications for the macro-finance moments that we are interested in.

[40] Given that we do not have a deep microfoundation for the source of asymmetry, it is difficult to evaluate

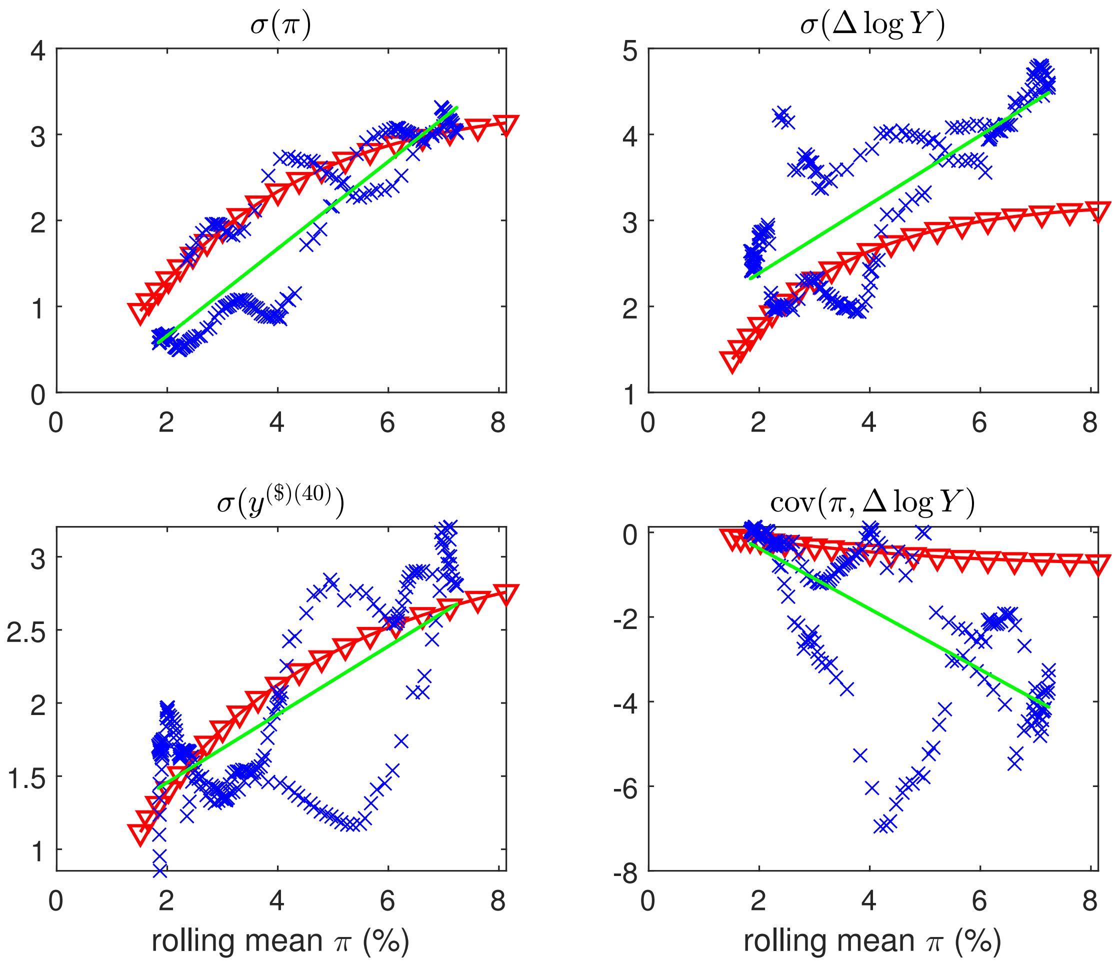

Figure 7: **Model and data moments, 1/2.** Each panel plots a model moment against the model mean of inflation (in red), together with the data local moment against the local mean of inflation (in blue), where the local moments and mean are both estimated on a 13-year centered rolling window, as in Section (2). The moments depicted here are the volatility of (core) inflation (top left), of GDP growth (top right), of the 10-year Treasury yield (bottom left), and the covariance of GDP growth and (core) inflation (bottom right). The sample is 1959q1-2019q4.

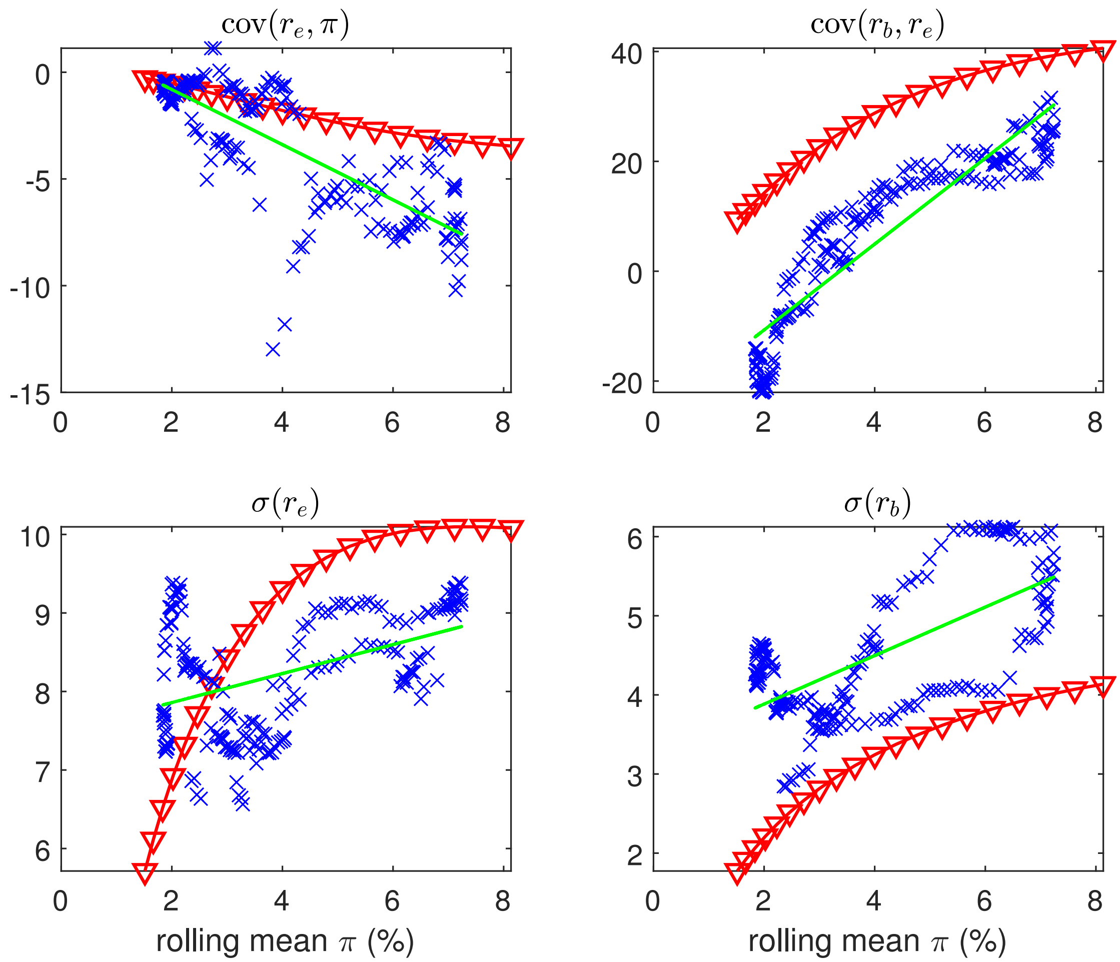

Figure 8: **Model and data moments, 2/2.** Each panel plots a model moment against the model mean of inflation (in red), together with the data local moment against the local mean of inflation (in blue), where the local moments and mean are both estimated on a 13-year centered rolling window, as in Section (2). The moments depicted here are the covariance of the real equity return and (core) inflation (top left), the covariance of the real equity return with the real return on the 10-year Treasury note (top right), the volatility of the real equity return (bottom left), and the volatility of the real return on the 10-year Treasury note (bottom right). The sample is 1959q1-2019q4.

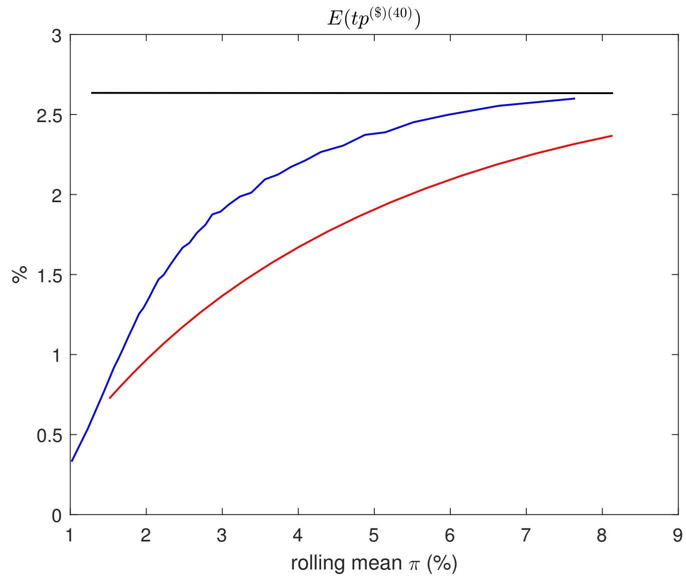

Figure 9: **Model-implied term premia, as a function of inflation.** The red (black) line shows the (average) 10-year term premium in the model for different values of R^*, corresponding to different average inflation, in the baseline (symmetric) model. The blue line shows the 10-year term premium in the model as a function of inflation, where inflation is driven by productivity shocks, using rolling windows as in section 2.

Table 4 quantifies more precisely the effect of a change in average inflation. When the long-run inflation increases from 1.51% to 8.13%, the term premium increases from 75bps to 257bps. In other words, a 1% decrease in the long-run inflation is associated with 27bps decrease in the term premium of the 10-year bonds, which is at the upper boundary of the range of 15-26bps that we estimated in the data in 1. This is another untargeted moment that is in line with the model. To visualize this, figure 9 shows the model-implied term premium as a function of inflation. It also shows the term premium implied when inflation is driven by z and not R^*, which is broadly similar, as noted above and shown in more detail in internet appendix (1.1.2), and for the symetric model ($\psi = 0$), when it is constant.

5 Additional Implications & Robustness

This section first illustrates the importance of asymmetry in adjustment costs for our results, and some further implications of asymmetry. Next, we presents some additional implications of the model, regarding the predictability of bond returns, and the forecast-

directly the validity of this assumption. In its defense, it is a single assumption that delivers a number of empirically validated predictions.

	Lower IT		Baseline		Higher IT	
	Mean	Std	Mean	Std	Mean	Std
$\Delta \log(Y)$	0.00	1.39	0.00	2.37	0.00	3.13
π	1.51	0.95	3.14	1.97	8.13	3.13
$y^{(\$)(1)}$	4.60	0.80	5.63	1.97	10.19	3.51
$y^{(\$)(40)}$	5.37	1.15	7.36	2.12	12.65	2.93
$y^{(1)}$	3.03	0.30	2.37	0.34	1.86	0.39
$y^{(40)}$	2.88	0.18	2.42	0.19	2.18	0.34
$tp^{(40)}$	-0.15	0.11	0.02	0.21	0.31	0.08
$tp^{(\$)(40)}$	0.75	0.56	1.67	0.68	2.57	0.21

Table 4: The table reports model moments for different values of the parameter R^*, i.e. the inflation target.

ing power of the term spread. Finally, we discuss the implications of the monetary policy rule. In the appendix, we offer additional comparative statics (section 1.5), and present extensions of the model to incorporate demand shocks (section 2) and to introduce wage asymmetry as well as price asymmetry (section 3).

5.1 The role of asymmetry

Asymmetry in price setting is the key parameter We have emphasized in our discussion of the results the role played by the asymmetry of the price adjustment cost, which we argued was the source of state dependence in the response of the economy to productivity shocks. To verify this intuition, we use the fact that our model nests the symmetric model: we solve the model for the exact same parameters we used, but removing the asymmetry by setting the parameter ψ equal to zero. This allows a clear comparison between our model and a similar model with high risk aversion but now symmetric adjustment costs. What does this model miss?

Table 3 shows that in the symmetric model, risk premia are high, as risk aversion is high and output and inflation volatility are even more volatile than in the baseline model (since there are no downward rigidities). However, the risk premia are also nearly constant: the term premium volatility goes from 68bps to 2bps (and the real term premium volatility from 21bps to 0bps) even as the average goes up. This shows that the symmetric model has no state-dependence. Figure 9 confirms that as a result, the term premium is constant. In the appendix (1.2), we also show that the impulse response functions are nearly identical, irrespective of the level of inflation, and that all macro-finance moments discussed above are essentially constant. This set of experiments unequivocally demonstrates that average inflation is not relevant in the symmetric model.

Mechanics of state-dependence vs. asymmetry Given our focus on asymmetric nominal rigidities, one might expect that the responses to positive and negative shocks are very different, or, more broadly that the key testable implications have to do with asymmetry rather than state-dependence. Here we want to explain why that is not the case.

In the equilibrium of our model, inflation depends on current (log) productivity: $\pi_t = f(z_t)$, where $z_t = \rho z_{t-1} + \varepsilon_t$ follows an AR(1) process. The function f is smooth, decreasing and convex, reflecting the nonlinearity in the price adjustment cost function G. As a result, the *marginal effect of a positive innovation equals that of a negative innovation*:

$$\Delta\pi_t = f'(z_t)\Delta\varepsilon_t,$$

so that positive and negative shocks have similar effects.[41] But note how the *magnitude* of the response to a shock, $f'(z_t)$, depends on z_t. With f convex, the response to a shock becomes smaller in absolute value as z_t rises. (The exception is if f is linear, which turns out to be the case when the adjustment cost is symmetric: in this instance, the responsiveness to a shock is nearly constant.) As a result, the model implies state-dependence: as the value of z endogenously changes, so does the response of inflation to a shock.

Asymmetry of output A natural question is whether the asymmetry has additional implications that can be used to discipline its magnitude. We have already used one such implication - the skewness of inflation - to calibrate the model. Conversely, the distribution of output is negatively skewed in the model, because large negative productivity shocks are accommodated by inflation, but large positive productivity shocks are not (as deflation is highly limited). As a result, very low output is relatively more likely than very high output, and the skewness of the log output gap is -0.85. This is comparable to the skewness of the output gap in the data, which ranges from -0.6 to -1.0, depending on the measure.[42] This suggests that the magnitude of asymmetry we assume is reasonable.

[41] Still, while this result is true in the limit as the size of shock goes to zero, it does not hold in general. In appendix (1.3), we compare the impulse response functions to positive and negative shocks, which are different, but not dramatically so.

[42] We measure the skewness of the output gap in our sample (1979q4-2008q4) either using the CBO output gap (-1.05), or the cyclical component of real GDP, calculated using either the Hodrick-Prescott filter (-0.93) or its alternative suggested by Hamilton (2018) (-0.59).

5.2 Fama-Bliss predictability of bond returns

A classic result in the bond premium literature is the result by Fama and Bliss (1987) that the excess return on a bond of maturity n can be predicted by the spread between the n-periods-ahead forward rate and the spot rate, i.e.

$$r_{t+1}^{\$(n)} - y_t^{\$(1)} = \alpha_n + \beta_n (f_t^{\$(n)} - y_t^{\$(1)}) + \varepsilon_{t,n},$$

where $r_{t+1}^{\$(n)} - y_t^{\$(1)}$ is the excess holding period return from t to $t+1$ of a bond maturity n over a short-term bond, $f_t^{\$(n)}$ is the (log) forward rate ($f_t^{\$(n)} = ny_t^{\$(n)} - (n-1)y_t^{\$(n-1)}$) and $y_t^{\$(1)}$ the spot rate. (Equivalently, the excess return is higher when the slope is higher, as in Campbell and Shiller (1991).) Table 5 shows the results of running this regression using U.S. data (top panel), running the regression in the benchmark model (middle panel), and in the model with symmetric adjustment costs (i.e. $\psi = 0$), respectively. With asymmetric adjustment costs, the model is able to qualitatively replicate the data. However, this is not the case for the model with symmetric adjustment costs.

Where does this comes from? Intuitively, a negative shock to productivity, that leads inflation to go up, increases the short-term rate, and also increases expected future short-term interest rates, because the shock is persistent. This, alone, would make the term spread go down, because, as explained in section 4, the long-term rates increases less than the short-term rate. But in our model, the bond premium also goes up because inflation goes up. Given the muted mean-reversion (due to high persistence), the term spread actually goes up - i.e., the long-term rate goes up more than the short-term rate, or the forward rate goes up more than the short rate. Overall, a negative shock to productivity leads both to higher expected excess returns on long-term bonds *and* a higher forward-spot spread (or slope), generating the correct correlation. In the symmetric model, there is no variation in the term premium, and as a result the only effect at work is the mean-reversion, generating the opposite sign.

5.3 The term spread forecasts growth

It is well known that the term spread forecasts GDP growth. To evaluate the ability of the model to match this evidence, we run the regression:

$$\log \frac{Y_{t+4}}{Y_t} = \alpha + \beta TS_t + \varepsilon_t, \tag{27}$$

Panel A: Data	β	std	R^2
n=8	0.697	0.059	0.060
n=16	0.916	0.123	0.049
n=24	1.152	0.206	0.046
n=32	1.302	0.313	0.038
n=40	1.384	0.443	0.029
Panel B: Benchmark model	β	std	R^2
n=8	1.003	0.000	0.103
n=16	1.039	0.000	0.073
n=24	1.046	0.000	0.049
n=32	1.024	0.000	0.032
n=40	0.963	0.000	0.020
Panel C: Symmetric model	β	std	R^2
n=8	-0.073	0.001	0.000
n=16	-0.070	0.001	0.000
n=24	-0.067	0.001	0.000
n=32	-0.064	0.001	0.000
n=40	-0.062	0.001	0.000

Table 5: Fama-Bliss predictability of bond returns. The table reports slope coefficients and standard errors, and R^2 of the regression.

	Data	Model
β	1.55	1.22
s.e.	(0.34)	(0.17)
t-stat	[4.6]	[7.2]

Table 6: Estimates from equation 27 of GDP growth on the term spread in the model and in the data.

where TS_t is the term spread, which in the spirit of Engstrom and Sharpe (2019) we take to be the difference between the 2-year yield and the 1-quarter yield, $TS_t = y_t^{\$(8)} - y_t^{\$(1)}$, as these authors have shown that the forecasting power comes from the short-end of the yield curve. As table 6 illustrates, the model is able to reproduce this relationship: a steep yield curve is indicative of high expected growth.

Why is that? Here too, a higher spread reflects, in the end, primarily a higher risk premium, which comes from higher inflation, i.e. lower productivity. But lower productivity is associated with higher expected growth due to mean-reversion. Hence, higher spreads forecast higher growth.

5.4 The role of monetary policy

One important advantage of general equilibrium models with production is that they can be used to study the effects of adopting alternative policies. This is what we do in this section. Table 7 presents model moments for two extreme policy rules - a rule that increases the weight on inflation stabilization to $\phi_\pi = 5$ (from $\phi_\pi = 2$ in the baseline), and a rule that puts no weight on output stabilization, $\phi_y = 0$ (from $\phi_y = 0.125$ in the baseline).

Macroeconomic theory typically focuses on the trade-off between inflation and output stabilization. Consistent with this, in our model, a monetary policy that emphasizes stabilizing inflation (i.e., $\phi_\pi = 5$) will reduce dramatically the volatility of inflation, from 1.97% to 0.60%, but at the cost of slightly higher output volatility (2.63% vs. 2.37%). But there are some additional lessons from our model, which are more novel. First, as ϕ_π rises, the average term premium falls dramatically from 1.67% to 0.66%. The volatility of the term premium also falls concomitantly with the decline of inflation volatility. Hence, this monetary policy rule has the advantage - typically not considered in the macro literature - of lowering bond premia and their volatility.[43]

A second advantage of a higher focus on inflation stabilization is that it not only reduces the volatility of inflation, but also its mean, from 3.14% to 2.16%. Intuitively, given that inflation has a strong right skew, reducing inflation volatility implies reducing its mean, as the central bank effectively "truncates" the worst (highest inflation) outcomes.

Finally, a third lesson is that higher inflation stabilization increases the average level of output - by 0.36% in this case [not shown in table]. This is a consequence of the asymmetry: a more reactive monetary policy allows output to rise more in booms when productivity is high, and to fall more in busts when productivity is low, but with asymmetric price rigidities the benefits in the boom outweight the costs in the bust.[44]

Overall, this counterfactual validates the analysis of Clarida et al. (2000) who argued that a less reactive policy (lower ϕ_π) could explain the patterns observed in the 1970s - with a higher average and volatility of inflation as well as higher and more volatile bond premia.

Our second policy experiment involves abstracting from output stabilization. Because the central bank is assumed to completely mismeasure potential, such an abstraction is actually a net positive in the model. Specifically, setting $\phi_y = 0$ leads to much lower

[43] Interestingly, the average real term premium rises when ϕ_π increases, as the volatility of consumption growth rises.

[44] Kim and Ruge-Murcia (2009) and Kim and Ruge-Murcia (2011) also study optimal policy in a model with asymmetries.

	Data		Model		$\phi_\pi = 5$		$\phi_y = 0$	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
$\Delta \log Y$	–	3.03	0.00	2.37	0.00	2.63	0.00	2.93
π	3.14	1.97	3.14	1.97	2.16	0.60	1.97	0.32
$y^{\$(1)}$	5.63	3.20	5.63	1.97	4.38	0.74	3.99	0.65
$y^{\$(40)}$	7.36	2.97	7.36	2.12	5.04	0.77	4.52	0.59
$y^{(1)}$	–	–	2.37	0.34	2.17	0.18	1.99	0.32
$y^{(40)}$	–	–	2.42	0.19	2.34	0.21	2.27	0.30
Stock return	8.12	16.32	8.98	16.08	12.42	62.28	11.4	66.38
$tp^{(40)}$	–	–	0.02	0.21	0.15	0.11	0.27	0.03
$tp^{\$(40)}$	–	–	1.67	0.68	0.66	0.18	0.54	0.06
Skewness(π)	1.55	–	1.55	–	0.69	–	0.56	–
Prob($\pi < 1\%$)	1.71	–	1.78	–	0.45	–	0.00	–

Table 7: Comparative statics. As in table (3), columns 2-3 report the mean and standard deviation from U.S. data over the sample 1979q4-2008q4, and columns 4-5 report the mean and standard deviation for the benchmark model. Columns 6-7 and 8-9 report the same statistics respectively if $\phi_\pi = 5$ and if $\phi_y = 0$, respectively, (while keeping all other parameters at the benchmark values).

inflation volatility (0.32% vs. 1.97%) at the cost of moderately higher output volatility (2.93% vs. 2.37%). But even this higher volatility is not a real cost: some output volatility is desirable with productivity shocks. In this instance too, the average level of inflation falls, the term premia plummet, and the average level of output rises. This experiment illustrates the costs of misestimating potential GDP. Hence, this experiment is consistent with the argument of Orphanides (2001) and Orphanides (2004) that mismeasurement of potential can also explain some of the patterns observed in the 1970s.

6 State-Dependent Impulse Responses in the data

In this last section, we provide some direct evidence in favor of the key mechanism of the paper: when inflation is high, output reacts more positively, and inflation more negatively, to a positive productivity shock, than when inflation is low. It is straightforward to test this prediction using interaction regressions. Specifically, we estimate local projections of an outcome variable y on TFP growth Z and an interaction term with the level of inflation π_t:

$$y_{t+h} = \alpha_h + \sum_{i=1}^{L} \beta_{i,h} y_{t-i} + \beta_{z,h} Z_t + \beta_{\pi,h} \pi_t + \gamma_h Z_t \pi_t + \varepsilon_{t,h} \tag{28}$$

where h is the horizon, y is log of GDP or the log of the core PCE price index, and Z_t is utilization adjusted (Fernald (2014)) TFP growth, i.e.

$$Z_t = \log(TFP_t / TFP_{t-4}) g$$

and finally π_t is measured as PCE inflation over the past 2 years (in order to smooth out short-run fluctuations). We estimate this equation on sample of quarterly data 1953q1:2019q4 - so that we include the low inflation periods both before and after the "Great Inflation" of the 1970s, and present the regression results in table 8, and the associated impulse responses in figure 10.[45]

Figure 10 illustrates the state-dependence by calculating the effect of a 1% increase in TFP on the level of GDP (left panel) and the level of prices (right panel), first when inflation is at its average value during the sample (blue full line), i.e. 3.1%, and second when inflation is 3pp higher than average, i.e. 6.1%. Clearly, GDP rises following an increase in productivity, and more so when inflation is initially high. Similarly, inflation falls, following an increase in productivity, and the effect is larger when inflation is initially high.

To assess the statistical significance, it is easiest to look at table 8. Regarding the baseline effect, the first row shows that a 1pp increase in TFP increases GDP after $h = 4$ quarters by 0.25%, and by 0.47% after $h = 8$ quarters, and reduces inflation by an insignificant 6bps after $h = 4$ quarters. Regarding the interaction effect, the fourth row shows that the interaction term for output is positive, statistically significant, and economically meaningful: going from 3% to 6% annual inflation increases the response at $h = 4$ quarters goes from 0.25% to 0.64%. Moreover, the coefficient on inflation is negative, and economically and statistically significant: the response at $h = 4$ quarters goes from -6bps to -33bps. Overall, these results, which appear new to the vast literature on the effects of technology shocks, are consistent with our mechanism.[46]

[45] We demean π_t to facilitate the interpretation. All equations include $L = 4$ lags, as well as a quadratic time trend, which reduces standard errors by purging some low-frequency variation. The appendix (4) presents results without the quadratic time trend, which are similar, and using alternative measures for π_t.

[46] Much of the literature debates the impact of productivity shocks on employment and its importance in accounting for macroeconomic fluctuations, e.g. Gali (1999), Basu et al. (2006), and the survey by Ramey (2016). We are not aware of work studying the state-dependence of TFP shocks. Perhaps the most closely related study is Galı et al. (2003), who argue that the response to TFP depends on the monetary policy regime.

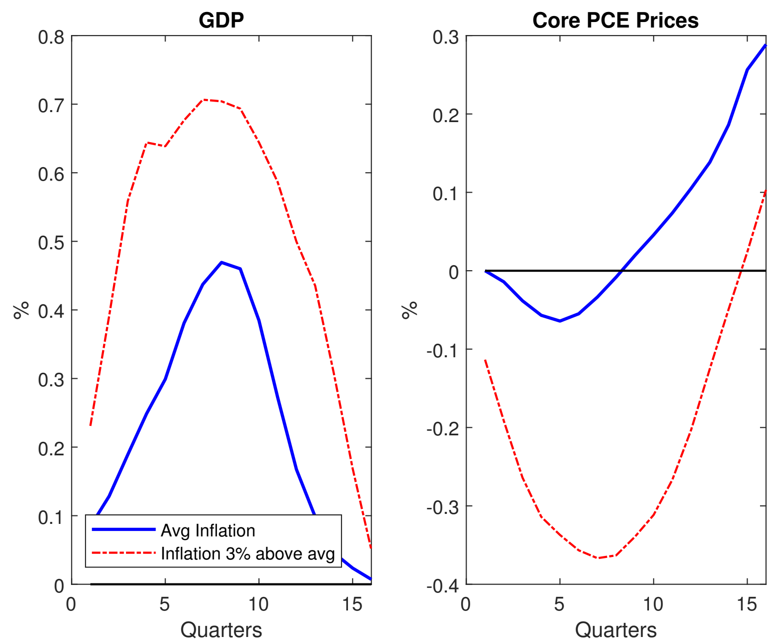

Figure 10: The figure depicts the estimated responses of the (log-level of) GDP and the (Core PCE) price index to a 1% increase in utilization-adjusted TFP, for two cases: (i) the initial inflation equals the average inflation in our sample (3.1%), (ii) the initial inflation equals the average inflation in our sample plus 3%. The estimates are constructed using the results of equation 28.

	Real GDP			Core PCE price index		
Horizon h	4	8	12	4	8	12
$\beta_{z,h}$	0.25**	0.47***	0.17	-0.06	-0.01	0.11
s.e.	(0.12)	(0.16)	(0.17)	(0.06)	(0.09)	(0.16)
t-stat	2.13	3.03	0.98	-0.92	-0.09	0.67
γ_h	0.13***	0.08	0.11	-0.09***	-0.12**	-0.10
s.e.	(0.03)	(0.06)	(0.08)	(0.03)	(0.05)	(0.07)
t-stat	4.75	1.36	1.44	-3.40	-2.58	-1.55
Obs.	256	252	248	236	232	228

Table 8: The table reports the estimates of $\beta_{z,h}$ and γ_h from equation (28), for $h = 4, 8, 12$ quarters, for $y = \log$ GDP (left panel) or the log core PCE index (right panel). The sample is 1953q1:2019q4 for GDP and 1959q1:2019q4 for Core PCE. Standard errors are Newey-West with 8 lags.

7 Conclusion

This paper develops a simple production asset pricing model with downward nominal rigidities, and shows that it creates state-dependence in the response to productivity shocks. This, in turn, generates secular and cyclical changes in bond premia and in a number of macro-finance moments. Despite its highly stylized nature (one shock, no state variable, and tightly constrained parameters), the model does surprisingly well in matching the broad patterns of the data. For instance, in the model, a 1pp higher inflation is associated with approximately 25bps higher 10-year term premium, which is similar to the data. Moreover, we provide time-series evidence supporting the key mechanism. The model highlights the risks for the central bank of mismeasuring potential output, or of putting a lower weight on inflation - generating not just more volatility in inflation, as in standard models, but also higher average inflation, lower average output, as well as higher and more volatile bond premia.

The current paper has focused on how macroeconomic dynamics and monetary policy generate term premia, but a natural next step is to study how bond premia affect the macroeconomy. This would likely require abandoning the representative agent framework, and would allow studying the new trade-offs that monetary policy confronts when it affects bond premia.

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