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February 2021

Working Paper 2019-27

https://www.frbsf.org/economic-research/publications/working-papers/2019/27/

**Suggested citation:**

Jørgensen, Peter Lihn, Kevin J. Lansing. 2021. "Anchored Inflation Expectations and the Slope of the Phillips Curve," Federal Reserve Bank of San Francisco Working Paper 2019-27. https://doi.org/10.24148/wp2019-27

# Anchored Inflation Expectations and the Slope of the Phillips Curve*

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February 8, 2021

**Abstract**

We estimate a New Keynesian Phillips curve that allows for changes in the degree of anchoring of agents' subjective inflation forecasts. The estimated slope coefficient in U.S. data is highly significant and stable over the period 1960 to 2019. Out-of-sample forecasts with the model resolve both the "missing disinflation puzzle" during the Great Recession and the "missing inflation puzzle" during the subsequent recovery. Using a simple New Keynesian model, we show that if agents solve a signal extraction problem to disentangle temporary versus permanent shocks to inflation, then an increase in the policy rule coefficient on inflation serves to endogenously anchor agents' inflation forecasts. Improved anchoring reduces the correlation between *changes* in inflation and the output gap, making the backward-looking Phillips curve appear flatter. But at the same time, improved anchoring increases the correlation between the *level* of inflation and the output gap, leading to a resurrection of the "original" Phillips curve. Both model predictions are consistent with U.S. data since the late 1990s.

Keywords: *Inflation expectations, Phillips curve, Inflation puzzles, Unobserved component time series model.*
JEL Classification: E31, E37

*An earlier version of this paper was titled "Anchored Expectations and the Flatter Phillips Curve." For helpful comments and suggestions, we thank Michael Bauer, Olivier Blanchard, Roger Farmer, Yuriy Gorodnichenko, Henrik Jensen, Òscar Jordà, Albert Marcet, Emi Nakamura, Gisle Natvik, Ivan Petrella, Søren Hove Ravn, Emiliano Santoro, and Jon Steinsson. We also thank participants at numerous seminars and conferences. The views in this paper are our own and not necessarily those of the Federal Reserve Bank of San Francisco or the Board of Governors of the Federal Reserve System. Jørgensen acknowledges financial support from the Independent Research Fund Denmark.

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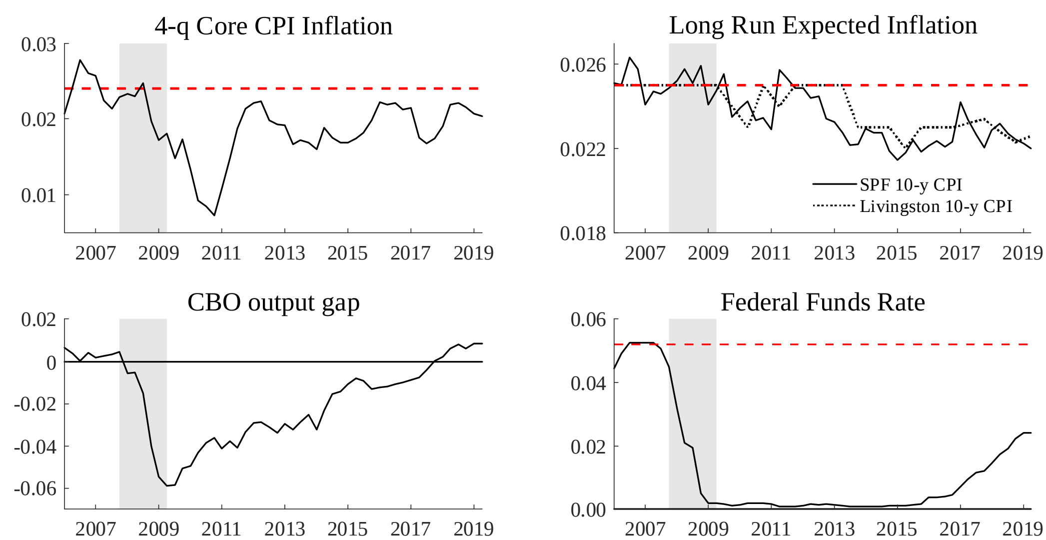
# 1 Introduction

The original Phillips curve dates back to Phillips (1958) who documented an inverse relationship between wage inflation and unemployment in the United Kingdom. Following the contributions of Phelps (1967) and Friedman (1968), the expectations-augmented Phillips curve (which links inflation to expected inflation and economic activity) has become a cornerstone in monetary economic models. But over the past decade, U.S. inflation appears to have deviated from the behavior predicted by the expectations-augmented Phillips curve. First, the absence of a persistent decline in inflation during the Great Recession (the "missing disinflation," Coibion and Gorodnichenko 2015a), and, subsequently, the absence of re-inflation during the recovery (the "missing inflation," Constâncio 2015), has led some to argue that the Phillips curve relationship has weakened or even disappeared (Hall 2011, Powell 2019).

In this paper, we estimate a New Keynesian Phillips curve that allows for changes in the degree of anchoring of agents' subjective inflation forecasts. The estimated slope coefficient on the output gap is highly significant and stable over the period 1960 to 2019. In an out-of-sample forecast from 2007.q4 to 2019.q2, we show that our estimated Phillips curve can account for the behavior of inflation and long-run expected inflation in U.S. data, thereby resolving the two inflation puzzles noted above. The model also resolves a third inflation puzzle in U.S. data—one that has received surprisingly little attention in the literature. The third puzzle is the observation of a "flatter" backward-looking Phillips together with the re-emergence of a positive correlation between the level of inflation and the output gap. Using a simple New Keynesian model, we show that if agents solve a signal extraction problem to disentangle temporary versus permanent shocks to inflation, then an increase in the policy rule coefficient on inflation serves to endogenously anchor agents' inflation forecasts. Improved anchoring reduces the correlation between *changes* in inflation and the output gap, making the backward-looking Phillips curve appear flatter. But at the same time, improved anchoring increases the correlation between the *level* of inflation and the output gap, leading to a resurrection of the "original" Phillips curve. Both model predictions are consistent with U.S. data since the late 1990s.

Figure 1 shows the evolution of key macroeconomic variables from 2006 onward. During the Great Recession from 2007.q4 to 2009.q2, the output gap estimated by the Congressional Budget Office (CBO) declined by around 6 percentage points. From a historical perspective, a recession of this magnitude should have delivered substantial disinflationary pressures. But in the wake of the Great Recession, core Consumer Price Index (CPI) inflation declined by less than 2 percentage points. The absence of a large disinflation has been labeled "the missing disinflation puzzle." Figure 1 shows that long-run expected inflation, as measured by 10-year ahead forecasts of CPI inflation from either the Survey of Professional Forecasters (SPF) or the Livingston Survey, remained nearly constant during the Great Recession. But more recently, long-run expected inflation from surveys has gradually declined; the end-of-sample values in Figure 1 are about 25 basis points (bp) below their pre-recession levels. Core CPI inflation is about 50 bp below its pre-recession level. The Fed's preferred inflation measure, the 4-quarter headline Personal Consumption Expenditures (PCE) inflation rate, has remained mostly below the Fed's 2 percent target since 2012. The absence of re-inflation during the recovery from the Great Recession has been labeled the "missing inflation puzzle."

Figure 1: *Key Macroeconomic Variables 2006.q1 to 2019.q2*

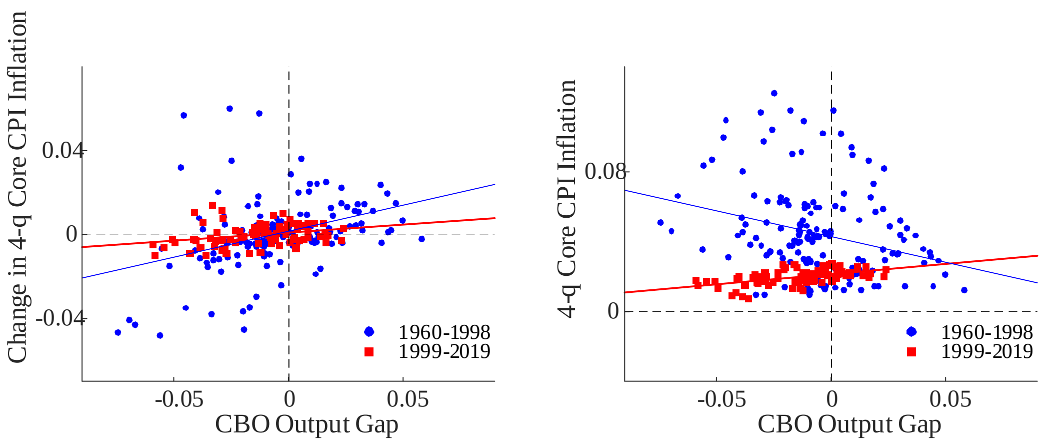



Notes: Gray bars indicate the Great Recession from 2007.q4 to 2009.q2. Dashed red lines indicate pre-recession levels as measured by the average level of each variable over the four quarters prior to the start of recession, i.e., from 2006.q4 to 2007.q3. Data sources are described in Appendix A

The two inflation puzzles have led some to conclude that the historically-observed statistical relationship between inflation and economic activity has changed. The left panel of Figure 2 provides reduced-form evidence that the expectations-augmented Phillips curve has become "flatter" over time. The figure plots the CBO output gap against the 4-quarter change in the 4-quarter core CPI inflation rate, both before and after 1999. The slope of each fitted line can be interpreted as measuring the slope of a typical backward-looking Phillips curve. *Changes* in inflation have become less sensitive to the output gap over the past 20 years, making the backward-looking Phillips curve appear flatter. Numerous studies have argued that the flatter curve can be fully or partially attributed to a decline in the structural slope parameter of the Phillips curve (Ball and Mazumder 2011, IMF 2013, Blanchard, Cerutti, and Summers 2015).

The right panel of Figure 2 plots the CBO output gap against the *level* of 4-quarter core CPI inflation. The slope of the fitted line can be interpreted as measuring the slope of the "original" Phillips curve which does not include any measure of expected inflation on the right side. For the period from 1960 to 1998, the slope is negative, but not statistically significant. However, since the late 1990s, a positive relationship between inflation and the output gap has emerged. This positive relationship is statistically significant at the 1 percent level. The $R^2$ value of the regression is 0.28, indicating a relatively strong link between inflation and the output gap in recent decades.[1]

Figure 2: *Has the Phillips Curve Become "Flatter"?*




Note: The left panel plots fitted lines of the form: $\pi_{4,t} - \pi_{4,t-4} = c_0 + c_1 y_t$, where $\pi_{4,t}$ is the 4-quarter core CPI inflation rate and $y_t$ is the CBO output gap. The right panel plots fitted lines of the form: $\pi_{4,t} = c_0 + c_1 y_t$.

Table 1 shows that the correlation between changes in inflation and the output gap has declined over time. But in contrast, the correlation between the level of inflation and the

[1] Along similar lines, Blanchard, Cerutti, and Summers (2015) and Blanchard (2016) point out that the U.S. Phillips curve has shifted from an "accelerationist" Phillips curve in which economic activity affects the change in inflation to one in which activity affects the level of inflation. Campbell, Pflueger, and Viceira (2020) identify a statistically significant break in the correlation between inflation and the output gap (going from negative to positive) around the date 2001.q2.

output gap has increased.[2] The table also shows that the volatility and persistence of inflation have declined over time. The right-most panel of the table shows that these patterns were present in the data prior to the onset of the Great Recession. Our aim in this paper is to provide a coherent explanation for the shifting inflation behavior summarized in Table 1.

Table 1: Moments of U.S. inflation

| | 1960.q1 to 1998.q4 | 1999.q1 to 2019.q2 | 1999.q1 to 2007.q3 |
|---|---|---|---|
| $Corr\,(\pi_t, y_t)$ | $-0.10$ | 0.36 | 0.28 |
| $Corr\,(\Delta\pi_t, y_t)$ | 0.14 | 0.03 | 0.07 |
| $Std.\ Dev.\,(4\pi_t)$ | 2.91 | 0.80 | 0.77 |
| $Corr\,(\pi_t, \pi_{t-1})$ | 0.75 | 0.20 | 0.20 |

Note: $\pi_t$ is quarterly core CPI inflation, $y_t$ is the CBO output gap, and $\Delta\pi_t = \pi_t - \pi_{t-1}$. Standard deviations are in percent. Data sources are described in Appendix A.

We estimate four versions of a New Keynesian Phillips curve (NKPC) that vary according to the way in which inflation expectations are formed. First, under rational expectations, we do not find a positive and statistically significant relationship between inflation and economic activity in any of our empirical specifications. Second, under a simple backward-looking setup in which expected inflation is given by the average inflation rate over the past four quarters, we obtain the standard result that the Phillips curve has become flatter over time. For the third version, we postulate that expected inflation evolves according to the following law of motion

$$\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t), \tag{1}$$

where $\lambda_\pi \in (0,1]$ is a gain parameter that governs the sensitivity of expected inflation to short-run inflation surprises. For the fourth version, we estimate the NKPC using survey-based measures of expected inflation.

Equation (1) is the optimal forecast rule when inflation is governed by an unobserved-component time series model along the lines of Stock and Watson (2007, 2010). This type of forecast rule is also motivated by survey data on actual expectations, including inflation expectations, as measured by the Survey of Professional Forecasters.[3] Coibion and Gorodnichenko (2015b) show that ex-post mean inflation forecast errors from the SPF can be predicted using

[2] Similar results are obtained using core PCE inflation rather than core CPI inflation.

[3] A large body of empirical evidence suggests that survey expectations are well described by forecast rules of the type (1). The evidence includes investors' expectations about future stock returns (Vissing-Jørgensen 2003, Greenwood and Shleifer 2014, Barberis, et al. 2015, Adam, Marcet, and Beutelet 2017), economists' long-run productivity growth forecasts (Edge, Laubach, and Williams 2011), inflation forecasts of households and professionals (Mankiw, Reis, and Wolfers 2003, Lansing 2009, Kozicki and Tinsley 2012, Coibion and Gorodnichenko 2015b, 2018), and forecasts of other key macroeconomic variables (Coibion and Gorodnichenko 2012, Bordalo, et al. 2020).

ex-ante mean forecast revisions, consistent with a forecast rule of the form (1). The gain parameter $\lambda_\pi$ can be viewed as measuring the degree of anchoring in agents' inflation forecasts, with lower values of $\lambda_\pi$ implying that expectations are more firmly anchored. This interpretation is consistent with the definition provided by Bernanke (2007): *"I use the term 'anchored' to mean relatively insensitive to incoming data. So, for example, if the public experiences a spell of inflation higher than their long-run expectation, but their long-run expectation of inflation changes little as a result, then inflation expectations are well anchored."*

When expected inflation in the NKPC is given by equation (1), the estimated value of $\lambda_\pi$ declines substantially over the Great Moderation period, indicating that inflation expectations have become more firmly anchored since the mid-1980s. The estimated coefficient on the output gap is highly statistically significant and stable over the period 1960 to 2019.[4] If instead the NKPC is estimated using survey data on long-run expected inflation in place of equation (1), then we obtain very similar slope coefficients, confirming that the structural Phillips curve relationship in the data is alive and well.

We use the estimated Phillips curves to generate out-of-sample forecasts from 2007.q4 onward. Neither the rational or the backward-looking versions of the NKPC can explain the observed inflation paths in the data. However, the version that employs equation (1) can largely account for the behavior of inflation and long-run expected inflation from surveys from 2007.q4 onward. The estimated value of $\lambda_\pi$ implies that agents' inflation forecasts were well-anchored (but not perfectly anchored) prior to the start of the Great Recession. The well-anchored forecasts deliver a muted response of inflation to the highly-negative output gap observed during the Great Recession. Nevertheless, the persistent negative gap episode brings about a gradual downward drift in the model-predicted path for long-run expected inflation. As a result, the model-predicted path for actual inflation persistently undershoots the Fed's inflation target. According to the third version of the NKPC, there is no missing disinflation puzzle in the wake of the Great Recession and no missing inflation puzzle during the subsequent recovery.[5]

Motivated by the empirical evidence, we use a simple three-equation New Keynesian model to demonstrate how expected inflation can become more firmly anchored via an endogenous

[4] This result is related to the findings of Stock and Watson (2010) and Stock (2011) who employ measures of expected inflation derived from the unobserved components-stochastic volatility (UC-SV) model of Stock and Watson (2007). Specifically, they find that improved anchoring of expected inflation can help explain the decline in the estimated slope coefficient in backward-looking Phillips curve regressions.

[5] Alternative accounts of the missing inflation puzzle have invoked the role played by the zero lower bound (ZLB) on nominal interest rates. See for example Hills, Nakata, and Schmidt (2019), Mertens and Williams (2019), and Lansing (2021).

mechanism. We postulate that agents have an imperfect understanding of the inflation process but nevertheless behave as econometricians in a boundedly-rational manner. Along the lines of Stock and Watson (2007, 2010), agents in our model forecast inflation using equation (1) where $\lambda_\pi$ is pinned down within the model as the perceived optimal gain value that minimizes the one-step-ahead mean squared forecast error. The gain value, in turn, depends on the perceived "signal-to-noise ratio" which measures the relative variances of the perceived permanent and temporary shocks to inflation.[6] We show that a stronger response to inflation in the monetary policy rule serves to reduce the perceived optimal value of $\lambda_\pi$, making expected inflation more firmly anchored. This result is consistent with a popular view among economists that a more "hawkish" monetary policy accounts for the improved anchoring of U.S. inflation expectations starting with the Volcker disinflation of the early 1980s.

Next, we show that our model of endogenous anchoring can account for the shifts in the reduced-form Phillips curve relationships shown in Figure 2. Previously, Bullard (2018) and McLeay and Tenreyro (2020) have argued that a flatter reduced-form Phillips curve is the predicted outcome from a simple model of optimal monetary policy. Specifically, in the presence of cost-push shocks, a monetary response to inflation will impart a *negative* correlation between inflation and the output gap, making it more difficult to identify a positively-sloped Phillips curve in the data. But importantly, as documented in Table 1, the correlation between the level of inflation and the output gap has *increased* in recent decades. The strong positive correlation between inflation and the output gap since 1999 suggests that the explanation proposed by Bullard (2018) and McLeay and Tenreyro (2020) does not fit the evidence. Our model offers an alternative explanation. The improved anchoring of expected inflation induced by a stronger policy response to inflation reduces the correlation between *changes* in inflation and the output gap. But at the same time, improved anchoring increases the correlation between the *level* of inflation and the output gap. Intuitively, improved anchoring reduces the sensitivity of actual inflation to both lagged inflation rates and cost-push shocks. To the extent that these sensitivities impart negative comovement between the level of inflation and the output gap, improved anchoring serves to "steepen" the original Phillips curve, as shown in the right panel of Figure 2. A stronger policy rule response to inflation also allows our model to account for the observed declines in U.S. inflation volatility and persistence, as documented in Table 1.

The apparent flattening of the Phillips curve is an important issue for U.S. monetary policy

[6] Our theoretical framework extends the model of Lansing (2009) who develops a partial equilibrium model in which the concept of central bank credibility, or anchored inflation expectations, is linked to agents' signal extraction problem for unobserved trend inflation.

(Yellen 2019, Clarida 2019). If the Phillips curve is believed to be structurally flat when in fact it is not, then policymakers could allow the economy to run too hot, eventually risking a surge in inflation. Our empirical results indicate that the underlying structural relationship between inflation and economic activity remains alive and well. Attempts to exploit a flat Phillips curve could eventually de-anchor agents' inflation expectations, leading to a more volatile and persistent inflation environment.

Our paper is related to a large and growing literature on the anchoring of expected inflation and its implications for the Phillips curve relationship (Stock 2011, IMF 2013, Blanchard, Cerutti, and Summers 2015, Blanchard 2016, Ball and Mazumder 2019, Bundick and Smith 2020, Barnichon and Mesters 2021). In particular, our results are in line with those of Hazell, et al. (2020) who estimate a Phillips curve using state-level data. They find that: (1) the slope of the Phillips curve has been roughly stable over time, and (2) changes in inflation dynamics are mostly due to the improved anchoring of expected inflation.

The remainder of the paper proceeds as follows. Section 2 demonstrates how improved anchoring of expected inflation may change the slope of reduced-form Phillips curves. In Section 3, we estimate four versions of the NKPC that vary according to the way that inflation expectations are formed. Section 4 contains out-of-sample inflation forecasts for the period from 2007.q4 to 2019.q2. Section 5 uses a simple New Keynesian equilibrium model to examine the theoretical links between the policy rule response to inflation and the degree of endogenous anchoring in agents' inflation forecasts. We show that a shift towards a more hawkish monetary policy can explain the observed changes in U.S. inflation behavior, as summarized in Table 1. Section 6 concludes. The Appendix describes our data sources and provides numerous robustness checks of our empirical results.

# 2 Anchored expectations and the Phillips curve slope

The starting point for our analysis is the standard New Keynesian Phillips curve:

$$\pi_t = \beta \widetilde{E}_t \pi_{t+1} + \kappa y_t + u_t, \qquad \kappa > 0, \;\; \beta \in [0,1), \;\; u_t \sim N\left(0, \sigma_u^2\right), \tag{2}$$

where $\pi_t$ is the quarterly inflation rate (log difference of the price level), $y_t$ is the output gap (the log deviation of real output from potential output), $u_t$ is an *iid* cost-push shock, $\beta$ is the agent's subjective discount factor, and $\kappa$ is the structural slope parameter. The symbol $\widetilde{E}_t$ represents the agent's subjective expectations operator. Under rational expectations, $\widetilde{E}_t$ becomes the mathematical expectations operator $E_t$. Equation (2) can be derived from the sticky price model of Calvo (1983) or the menu cost model of Rotemberg (1982) (Clarida, Galí, and Gertler 2000, Woodford 2003).[7]

Equation (2) implies that the covariance between inflation and the output gap is given by:

$$Cov\left(\pi_t, y_t\right) = \beta Cov(\widetilde{E}_t \pi_{t+1}, y_t) + \kappa Var\left(y_t\right) + Cov\left(u_t, y_t\right). \tag{3}$$

Numerous empirical studies have concluded that changes in the Phillips curve relationship can be fully or partially attributed to a decline in the structural slope parameter $\kappa$ (Ball and Mazumder 2011, IMF 2013, Blanchard, Cerutti and Summers 2015, Del Negro, et al. 2020). In contrast, Bullard (2018) and McLeay and Tenreyro (2020) argue that the "flatter" reduced-form Phillips curve is the predictable outcome of improved monetary policy that induces a negative co-movement between the output gap and the cost-push shock, such that $Cov\left(u_t, y_t\right) < 0$. All else equal, either a decline in $\kappa$ or a decline in $Cov\left(u_t, y_t\right)$ would serve to reduce $Cov\left(\pi_t, y_t\right)$, leading to a flatter "original" Phillips curve. But as we showed earlier in Figure 2 and Table 1, this prediction is counterfactual; the original Phillips curve since 1999 is now steeper than in the previous four decades.

Improved anchoring of expected inflation offers an alternative explanation for the observed changes in U.S. inflation behavior. To illustrate the basic intuition, we first substitute the subjective forecast rule (1) into the NKPC (2) with $\beta = 1$, yielding

$$\begin{aligned} \pi_t &= \widetilde{E}_{t-1}\pi_t + \frac{\kappa}{1-\lambda_\pi} y_t + \frac{1}{1-\lambda_\pi} u_t, \\ &\simeq \lambda_\pi \pi_{t-1} + \frac{\kappa}{1-\lambda_\pi} y_t + \frac{1}{1-\lambda_\pi} u_t, \end{aligned} \tag{4}$$

where we have eliminated $\widetilde{E}_{t-1}\pi_t$ in the first line using the lagged version of the subjective forecast rule and then imposed $\widetilde{E}_{t-2}\pi_{t-1} \simeq 0$.

From equation (4), we can see that a lower value of $\lambda_\pi$, implying improved anchoring, can affect inflation dynamics through three distinct channels. First, improved anchoring will make $\pi_t$ less sensitive to lagged inflation $\pi_{t-1}$. Second, for any given value of $\kappa$, improved anchoring will reduce the sensitivity of $\pi_t$ to the output gap $y_t$. Third, improved anchoring will make $\pi_t$ less sensitive to the cost-push shock $u_t$.

[7] The derivation makes use of the Law of Iterated Expectations, which may not be satisfied under subjective expectations. However, as shown by Adam and Padula (2011), if agents are unable to predict revisions to their own or other agents' forecasts, then subjective expectations will satisfy the Law of Iterated Expectations, thereby recovering a Phillips curve that resembles equation (2). Coibion and Gorodnichenko (2018) show that SPF inflation forecasts do in fact appear to satisfy the Law of Iterated Expectations.

Equation (4) implies the following covariance relationship:

$$Cov\left(\pi_t, y_t\right) \simeq \lambda_\pi Cov\left(\pi_{t-1}, y_t\right) + \frac{\kappa}{1-\lambda_\pi} Var\left(y_t\right) + \frac{1}{1-\lambda_\pi} Cov\left(y_t, u_t\right). \tag{5}$$

Since $Var\left(y_t\right) > 0$, a lower value of $\lambda_\pi$ will reduce the positive contribution of the second term to $Cov\left(\pi_t, y_t\right)$, helping to make the original Phillips curve appear flatter. But in contrast, when $Cov\left(\pi_{t-1}, y_t\right) < 0$ and $Cov\left(y_t, u_t\right) < 0$, then a lower value of $\lambda_\pi$ will serve to reduce the negative contributions of the first and third terms to $Cov\left(\pi_t, y_t\right)$, helping to make the original Phillips curve appear steeper. Indeed, as we verify in Section 5.5, embedding the subjective forecast rule (1) in a standard New Keynesian model with a Taylor-type rule implies $Cov\left(\pi_{t-1}, y_t\right) < 0$ and $Cov\left(y_t, u_t\right) < 0$.

The following definitional relationship helps to explain the observed changes in the slope of the backward-looking Phillips curve relative to the slope of the original Phillips curve:

$$Cov\left(\Delta\pi_t, y_t\right) - Cov\left(\pi_t, y_t\right) = -Cov\left(\pi_{t-1}, y_t\right). \tag{6}$$

If monetary policy induces a negative co-movement between lagged inflation rates and the output gap such that $Cov\left(\pi_{t-1}, y_t\right) < 0$, then we have $Cov\left(\Delta\pi_t, y_t\right) > Cov\left(\pi_t, y_t\right)$. This result implies that slope of the backward-looking Phillips curve exceeds the slope of the original Phillips curve. However, if improved anchoring makes $Cov\left(\pi_{t-1}, y_t\right)$ *less* negative, this effect will serve to flatten the slope of the backward-looking Phillips curve relative to the slope of the original Phillips curve. At the same time, a less negative value of $Cov\left(\pi_{t-1}, y_t\right)$ will help to steepen the original Phillips curve via the first term in equation (5). Indeed, the value of $Cov\left(\pi_{t-1}, y_t\right)$ in U.S. data is negative for the sample period from 1960.q1 to 1998.q4 but positive for the sample period from 1999.q1 to 2019.q2.

In Section 4, we use a simple New Keynesian model to show that a shift towards a more hawkish monetary policy serves to reduce agents' perceived optimal value of $\lambda_\pi$, making expected inflation more firmly anchored. This result, in turn, allows the model to account for the observations of a flatter backward-looking Phillips curve, a steeper original Phillips curve, and declines in the volatility and persistence of inflation.

# 3 Estimation of the NKPC

In this section, we examine the empirical question of whether the structural slope parameter of the NKPC has declined over time. We consider four versions of equation (2) that vary according to the way that inflation expectations are formed. For simplicity, we set $\beta = 1$ in all specifications, but none of our results are sensitive to this assumption.

## 3.1 Four specifications of expected inflation

The four specifications of expected inflation that we employ are given by

$$\begin{aligned} \widetilde{E}_t\pi_{t+1} &= \gamma_f \, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}, \qquad 0 \le \gamma_f \le 1, && (7) \\ \widetilde{E}_t\pi_{t+1} &= \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4, && (8) \\ \widetilde{E}_t\pi_{t+1} &= \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t), && (9) \\ \widetilde{E}_t\pi_{t+1} &= \widetilde{E}_t^s\pi_{t+h}. && (10) \end{aligned}$$

Equation (7) is the model of expected inflation employed by Galí and Gertler (1999) in estimating a so-called "hybrid" NKPC, where expected inflation is a weighted average of a rational expectations (RE) component $E_t\pi_{t+1}$ and a backward-looking component $\pi_{t-1}$. The backward-looking component can be motivated by the assumption that a fraction of firms index their prices to past inflation each period (Christiano, Eichenbaum, and Evans 2005). Equation (8) is the purely backward-looking specification employed by Ball and Mazumder (2011). Equation (9) is the optimal forecast rule when inflation is governed by an unobserved-component time series model along the lines of Stock and Watson (2007, 2010). For this time series model, the optimal value of the gain parameter $\lambda_\pi$ depends on the signal-to-noise ratio which measures the relative variances of the permanent and temporary shocks to inflation. We will refer to equation (9) as the "signal-extraction" model of expected inflation. In equation (10), $\widetilde{E}_t^s\pi_{t+h}$ is a survey-based measure of expected inflation at horizon $h$.

## 3.2 Empirical methodology

Following Galí and Gertler (1999), we estimate the NKPC using the Generalized Method of Moments (GMM) with lagged variables as instruments. This estimation strategy attempts to resolve two endogeneity problems in the NKPC: (1) the output gap $y_t$ may be correlated with the cost-push shock $u_t$, and (2) the term $E_t\pi_{t+1}$ in the hybrid RE forecast rule (7) is endogenous. Substituting the hybrid RE forecast rule into the NKPC (2) yields

$$\pi_t = \gamma_f \, \pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1} + \kappa y_t + \widetilde{u}_t, \qquad (11)$$

where $\widetilde{u}_t \equiv u_t + \gamma_f \left(E_t\pi_{t+1} - \pi_{t+1}\right)$ is *iid* under rational expectations. Additionally, to help control for the impacts of cost-push shocks on inflation, we use core inflation as our baseline inflation measure and include current and lagged oil price inflation as regressors.[8]

[8] Following Hooker (2002), we include lagged oil price inflation as a regressor because the pass-through from oil prices to core inflation may occur with a lag.

We estimate the hybrid RE version of the NKPC using the following orthogonality condition:

$$E_t \left\{ \vartheta_{RE} \mathbf{z}_{t-1} \right\} = 0, \tag{12}$$

where

$$\vartheta_{RE} = \pi_t - \gamma_f \, \pi_{t+1} - \left(1 - \gamma_f\right) \pi_{t-1} - \kappa y_t - \delta \pi_t^{oil} - \varphi \pi_{t-1}^{oil}, \tag{13}$$

is the residual, $\mathbf{z}_{t-1}$ is a vector of instruments dated $t-1$ and earlier, $\pi_t^{oil}$ is quarterly oil price inflation, and $\gamma_f$, $\kappa$, $\delta$, and $\varphi$ are the parameters to be estimated.[9]

Similarly, we estimate the backward-looking and signal-extraction versions of the NKPC using the following orthogonality conditions

$$\vartheta_{BL} = \pi_t - \left(\pi_{t-1} + \pi_{t-2} + \pi_{t-3} + \pi_{t-4}\right)/4 - \kappa y_t - \delta \pi_t^{oil} - \varphi \pi_{t-1}^{oil}, \tag{14}$$

$$\vartheta_{SE} = \pi_t - \widetilde{E}_{t-1} \pi_t - \frac{1}{1 - \lambda_\pi} (\kappa y_t + \delta \pi_t^{oil} + \varphi \pi_{t-1}^{oil}), \tag{15}$$

where $\widetilde{E}_{t-1} \pi_t$ in equation (15) is updated using the lagged version of the signal-extraction forecast rule (9).[10]

When estimating the NKPC using expected inflation from surveys, the orthogonality condition becomes

$$\vartheta_S = \pi_t - c - \widetilde{E}_t^s \pi_{t+h} - \kappa y_t - \delta \pi_t^{oil} - \varphi \pi_{t-1}^{oil}, \tag{16}$$

where $\widetilde{E}_t^s \pi_{t+h}$ is a survey-based measure of expected *headline* inflation at horizon $h$ and $c$ is a constant. The constant is included to account for historical differences between the levels of headline and core inflation and to account for potential systematic biases in survey forecasts (Coibion and Gorodnichenko 2015a).

We use quarterly data for core CPI inflation, the CBO output gap, and oil price inflation for the sample period 1960.q1 to 2019.q2. Throughout the paper, we split the data into three subsamples. We use a smaller set of instruments than is used by Galí, Gertler, and López-Salido (2005). This is done to minimize the potential small sample bias that may arise when there are too many over-identifying restrictions, as discussed by Staiger and Stock (1997). Our baseline set of instruments includes two lags each of core CPI inflation and oil price inflation, and one lag each of the CBO output gap and wage inflation. Our survey-based measure of short-run expected inflation is the mean 1-quarter ahead forecast of headline CPI inflation

[9] We use iterated GMM with a weight matrix computed using the Newey and West (1987) heteroskedasticity- and autocorrelation-consistent estimator with automatic lag truncation.

[10] For the first period of the estimation sample ($t = t_0$), we use the initial condition $\widetilde{E}_{t_0-1} \pi_{t_0} = 0.125 \sum_{k=1}^{8} \pi_{t_0-k}$.

from the Survey of Professional Forecasters (SPF). Our survey-based measures of long-run expected inflation are the mean 5-year ahead inflation forecast from the Michigan Survey of Consumers (MSC) and the mean 10-year ahead forecast of headline CPI inflation from the SPF. When estimating the NKPC with survey data, we add one lag of survey-expectations to the baseline instrument set noted above. Appendix A contains a detailed description of our data sources.

### 3.3 Estimation results

Table 2 reports the baseline parameter estimates from the four empirical specifications of the NKPC.[11] In Appendix C, we show that all of our main empirical findings are robust to changes in the inflation measure (use of core PCE inflation instead of core CPI inflation), changes in the measure of economic slack (use of detrended GDP instead of the CBO output gap), use of an alternative instrument set, and the exclusion of oil price inflation from the estimation.

Panel A in Table 2 shows that the estimated slope parameter $\widehat{\kappa}$ in the hybrid RE model is never statistically significant. Even worse, the slope coefficient has the wrong sign in the first two subsamples. Galí and Gertler (1999) argue that labor's share of income should be used as the driving variable in the NKPC instead of the output gap. We repeat the estimation using labor's share of income in Appendix C.3 but still do not recover a statistically significant slope parameter. Our results for the hybrid RE model are consistent with previous findings in the literature, as surveyed by Mavroeidis, Plagborg-Møller, and Stock (2014).[12]

Panel B shows that $\widehat{\kappa}$ in the backward-looking model exhibits a clear downward trend over time, consistent with the idea that the backward-looking Phillips curve has become flatter. The estimated slope is quite steep during the Great Inflation Era ($\widehat{\kappa} = 0.08$) but it has since declined to level around 0.02 in the Great Recession Era. While the estimated slope parameter has declined over time, it remains statistically significant at the 1 percent level in all three subsamples.

Panel C shows that $\widehat{\kappa}$ in the signal-extraction model remains stable and highly statistically significant across all three subsamples. But in contrast, the estimated value of the gain parameter $\widehat{\lambda}_\pi$ declines over time, going from around 0.3 during the Great Inflation Era to around 0.1 during the Great Moderation Era. In the Great Recession Era, $\widehat{\lambda}_\pi$ is not statistically

[11] The estimated oil price inflation coefficients are reported in Appendix B, Table B2. All specifications pass $J$-tests of overidentifying restrictions. The $J$-test results are available upon request.

[12] These authors point to weak instruments as the main problem driving the results. A growing literature attempts to overcome this problem by estimating RE versions of the NKPC using regional data (McLeay and Tenreyro 2020, Hooper, Mishkin and Sufi 2019, and Hazell, et al. 2020).

different from zero. According to the signal-extraction model, a decline in the gain parameter implies that expected inflation has become more firmly anchored.

The hybrid RE model implies that the Phillips curve always been flat whereas the backward-looking model implies that the curve has become flatter over time. The signal-extraction model implies that the Phillips curve slope parameter has remained positive and relatively constant. Which of these conclusions is correct? To help answer this question, we estimate the NKPC using direct measures of expected inflation from surveys. Panel D in Table 2 reports estimation results using survey-based measures of expected inflation for the Great Moderation Era and the Great Recession Era.[13]

In Panel D, all three survey-based measures of expected inflation deliver a highly statistically significant slope coefficient in the most recent subsample. Moreover, the values of $\widehat{\kappa}$ all increase when going from the Great Moderation Era to the Great Recession Era. These results contradict notions that the NKPC has always been flat or that it has become flatter over time. If anything, the results suggest that the NKPC has become steeper over time.

Panel D further shows that the Phillips curve relationship in the data is substantially stronger when longer-run expected inflation is used in the estimation. Notably, when we use the 10-year ahead inflation forecast from the SPF, the resulting values of $\widehat{\kappa}$ are nearly identical to those obtained from the signal-extraction model. This result may indicate that agents in the economy set prices and wages with reference to their longer-run inflation forecasts—a hypothesis put forth by Bernanke (2007). Overall, the results in Table 2 do not support the idea that the NKPC has become structurally flatter over time.

[13] Survey-based measures of expected inflation are not available for the Great Inflation Era.

Table 2: Baseline NKPC parameter estimates

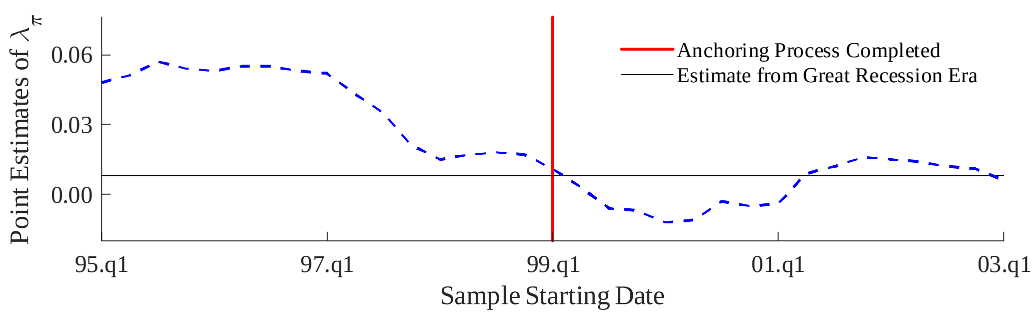
| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f \, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | | |
| $\widehat{\kappa}$ | $-0.013$ | $-0.003$ | 0.010 |
| | (0.019) | (0.010) | (0.013) |
| $\widehat{\gamma}_f$ | 0.862*** | 1.003*** | 0.743*** |
| | (0.123) | (0.179) | (0.173) |
| | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | 0.080*** | 0.033*** | 0.020*** |
| | (0.022) | (0.010) | (0.010) |
| | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | | |
| $\widehat{\kappa}$ | 0.066*** | 0.042*** | 0.063*** |
| | (0.115) | (0.015) | (0.013) |
| $\widehat{\lambda}_\pi$ | 0.280*** | 0.119** | 0.008 |
| | (0.021) | (0.059) | (0.010) |
| | D. Survey Data: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}^s_t\pi_{t+h}$ | | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | 0.006 | 0.026** |
| | | (0.020) | (0.011) |
| | | 5-y MSC[2] | |
| $\widehat{\kappa}$ | | 0.024** | 0.070*** |
| | | (0.011) | (0.015) |
| | | 10-y SPF[3] | |
| $\widehat{\kappa}$ | | 0.041*** | 0.065*** |
| | | (0.010) | (0.019) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation of both $y_t$ and $\pi_t^{oil}$ in each subsample. [2]Great Moderation sample starts in 1990.q3. [3]Great Moderation sample starts in 1992.q1.

# 4 Out-of-sample forecasts: Resolving inflation puzzles

In this section, we show that the signal-extraction version of the NKPC can account for the "puzzling" behavior of inflation observed since 2007. For this exercise, we re-estimate the three versions of the NKPC in Panels A, B and C of Table 2 using data from 1999.q1 to 2007.q3. The date 1999.q1 is approximately when the anchoring process for expected inflation appears to have been completed. We illustrate this idea below in Figure 3 which plots point estimates of $\widehat{\lambda}_\pi$ from the signal-extraction NKPC using a rolling series of sample start dates, but keeping the sample end date fixed at 2019.q2.[14] Figure 3 shows that from 1991.q1 onward, the estimated value of $\widehat{\lambda}_\pi$ fluctuates around the value obtained for the entire Great Recession Era. Mishkin (2007) and Bernanke (2007) reach similar conclusions regarding the timing of the anchoring process.

Figure 3: *Point Estimates of the Gain Parameter for Subsamples Ending in 2019.q2*




Notes: The figure shows point estimates of the gain parameter $\widehat{\lambda}_\pi$ from the signal-extraction NKPC using a rolling series of sample start dates, but keeping the sample end date fixed at 2019.q2. The anchoring process for expected inflation appears to have been completed around 1999.q1.

The NKPC estimates for the out-of-sample forecasting exercise are shown in Table 3. The point estimates are broadly similar to those in Table 2 for the Great Recession Era.[15]

[14] Using 2019.q2 as the fixed sample end date instead of 2007.q3 yields more stable point estimates without changing the conclusions regarding the completion of the anchoring process.

[15] The full set of estimates for the period 1999.q1 to 2007.q3, including the oil price inflation coefficients, are provided in Appendix B, Table B1.

Table 3: NKPC estimates for out-of-sample forecasts

| | Hybrid RE | Backward-looking | Signal-extraction |
|---|---|---|---|
| $\widehat{\kappa}$ | 0.002 | 0.046*** | 0.048*** |
| | (0.009) | (0.012) | (0.019) |
| $\widehat{\gamma}_f$ | 0.636*** | – | – |
| | (0.101) | | |
| $\widehat{\lambda}_\pi$ | – | – | 0.024 |
| | | | (0.177) |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. The estimation period is 1999.q1 to 2007.q3.

Figure 4 plots the out-of-sample forecasts of inflation from the three NKPC versions along with the 95% confidence bands. For this exercise, we use the CBO output gap as the only driving variable.[16] For the hybrid RE model, we construct the inflation forecast using the closed-form solution of equation (11) and assume perfect foresight with respect to future values of the driving variable $y_t$.[17]

The out-of-sample inflation forecast from the hybrid RE model exhibits very wide confidence bands compared to the other two models. Conditional on the path of the CBO output gap, one cannot statistically reject forecasted deflation rates in the neighborhood of $-20\%$ during the Great Recession. Put another way, the hybrid RE model is largely uninformative about the out-of-sample path of inflation.[18] On average, inflation declines by around 3 percentage points between 2007.q4 and 2009.q2 despite a near-zero value of the estimated slope coefficient ($\widehat{\kappa} = 0.002$). From 2009.q3 onward, the CBO output gap starts to recover, causing the hybrid RE model to predict a large increase in inflation relative to the value observed at recession trough. But this did not happen in the data.

The confidence bands around the out-of-sample inflation forecast from the backward-looking model are much narrower, reflecting the higher precision of the point estimates in

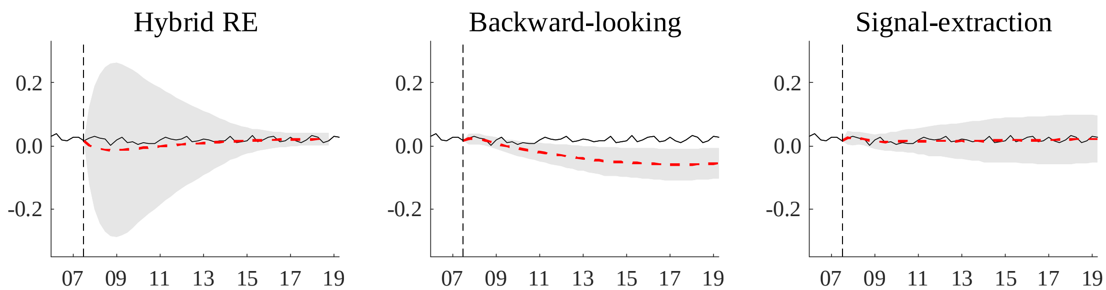
[16] Specifically, we drop the oil price inflation terms from the three estimated versions of the NKPC. In Appendix B.3, we show that including oil price inflation as an additional driving variable in the out-of-sample forecasting exercise does not significantly improve the signal-extraction model's ability to resolve the inflation puzzles.

[17] Our methodology is described in detail in Appendix B.2. The assumption of perfect foresight ensures that rational agents do not make systematic forecast errors with respect to the driving variable.

[18] The confidence bands begin to narrow from 2009.q3 onward because the CBO output gap starts to recover.

Table 3. But the backward-looking model predicts a pronounced deflation episode during and after the Great Recession; forecasted inflation declines by around 7 percentage points between 2007.q4 and 2019.q2.

Figure 4: *Out-of-Sample Inflation Forecasts: 2007.q4 to 2019.q2*




Notes: Gray areas indicate 95% confidence bands. Model-implied paths for inflation are expressed as annualized quarterly rates.

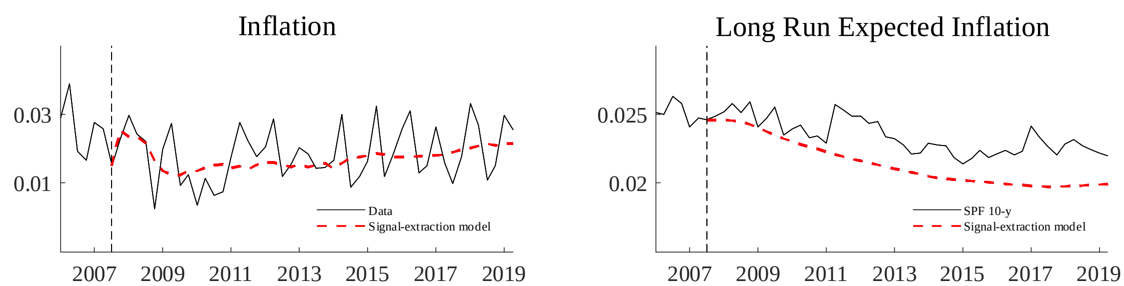
In contrast with the other two models, the right-most panel of Figure 4 shows that the out-of-sample inflation forecast from the signal-extraction model is closely aligned with the data. Figure 5 provides a more detailed view of the results and includes a comparison between the median model path for expected inflation and the path of long-run expected inflation from the SPF.[19] Despite the signal-extraction model's relatively large estimated slope parameter ($\widehat{\kappa} = 0.048$), forecasted inflation declines by only about 1 percentage point during the Great Recession. This modest decline is followed by persistently low inflation rates, consistent with the data. By the end of the simulation in 2019.q2, the predicted inflation rate is only around 40 bp below its pre-recession level. Thus, according to the signal-extraction model, there is no missing disinflation during the Great Recession and no missing inflation during the subsequent recovery.

The right panel of Figure 5 shows that the signal-extraction model accurately captures the behavior of long-run expected inflation in the SPF. As noted earlier, a low value of the estimated gain parameter $\widehat{\lambda}_{\pi}$ (implying well-anchored inflation expectations) implies a low sensitivity of inflation to the output gap. This feature of the signal-extraction model explains the absence of a persistent decline in inflation during the Great Recession. However, because inflation expectations are not perfectly anchored ($\widehat{\lambda}_{\pi} = 0.024 > 0$), the model-implied path

[19] The time series process for inflation that motivates the signal-extraction forecast rule (9) implies that the optimal forecast for inflation is the same at all future horizons. This is because the permanent component of inflation is modeled as a driftless random walk, as can be seen from equation (18).

for long-run expected inflation will gradually decline when inflation remains persistently low, as it does in the data. While the decline in long-run expected inflation is modest (around 50 bp in the model and 25 bp in the SPF), it is highly persistent.[20] The low level of expected inflation in the signal-extraction model serves to keep actual inflation low, even after the CBO output gap has fully recovered. This feature allows the signal-extraction model to account for the "missing inflation" during the recovery from the Great Recession.

Figure 5: *Median Out-of-Sample Forecasts: 2007.q4 to 2019.q2*




Notes: Model-implied paths for inflation and expected inflation are expressed as annualized quarterly rates. Inflation in the data is the annualized quarterly core CPI inflation rate. Long-run expected inflation in the data is the 10-year ahead forecast of headline CPI inflation from the Survey of Professional Forecasters.

# 5 Policy and anchored expectations in equilibrium

Many economists believe that the start of the expectations anchoring process can be traced to a shift in monetary policy under Fed Chairman Paul Volcker in the early-1980s. Indeed, at the peak of the Great Inflation, Volcker himself (1979), pp. 888-889 emphasized the crucial importance of inflation expectations: *"Inflation feeds in part on itself, so part of the job of returning to a more stable and more productive economy must be to break the grip of inflationary expectations."*

In this section, we use a three-equation New Keynesian model to show that a more "hawkish" monetary policy can serve to endogenously anchor agents' inflation expectations. The policy-induced change in the degree of anchoring allows the model to explain the observed changes in U.S. inflation behavior since the mid-1980's, including: (1) the flattening of the

[20]Similarly, Reis (2020) finds that long-run expected inflation in the data has been imperfectly anchored and steadily declining since 2014.

backward-looking Phillips curve, (2) the resurrection of the original Phillips curve, and (3) declines in the volatility and persistence of inflation.

## 5.1 Formalizing anchored inflation expectations

Our empirical results in Sections 3 and 4 show that the signal-extraction forecast rule (9) captures the behavior of long-run expected inflation from surveys quite well. Moreover, there is considerable evidence that univariate forecasting models of inflation outperform Phillips curve-based forecasts, at least since the mid 1980s (Atkeson and Ohanian 2001, Stock and Watson 2009). Motivated by these ideas, we postulate that agents in our New Keynesian model employ the following univariate time series model for inflation:

$$\pi_t = \overline{\pi}_t + \zeta_t, \qquad \zeta_t \sim N\left(0, \sigma_\zeta^2\right), \tag{17}$$

$$\overline{\pi}_t = \overline{\pi}_{t-1} + \eta_t, \qquad \eta_t \sim N\left(0, \sigma_\eta^2\right), \quad Cov\left(\zeta_t, \eta_t\right) = 0, \tag{18}$$

where $\overline{\pi}_t$ is the unobservable inflation trend, $\zeta_t$ is a transitory shock that pushes $\pi_t$ away from trend, and $\eta_t$ is permanent shock (uncorrelated with $\zeta_t$) that shifts the trend over time. In the following, we assume that agents compute the signal-to-noise ratio $\sigma_\eta^2/\sigma_\zeta^2$ using the observed moments of inflation in the model economy. These moments may change in response to a shift in the monetary policy regime, thereby affecting agents' perceived signal-to-noise ratio.[21]

For the time series model given by equations (17) and (18), the signal-extraction forecast rule (9) minimizes the one-step-ahead mean squared forecast error when the gain parameter $\lambda_\pi$ is given by

$$\lambda_\pi = \frac{-\phi_\pi + \sqrt{\phi_\pi^2 + 4\phi_\pi}}{2}, \tag{19}$$

where $\phi_\pi \equiv \sigma_\eta^2/\sigma_\zeta^2$ is the signal-to-noise ratio.[22] As $\phi_\pi \rightarrow \infty$, we have $\lambda_\pi \rightarrow 1$. Intuitively, a high signal-to-noise ratio implies that inflation is driven mostly by the permanent shock $\eta_t$. Consequently, agents are quick to revise their inflation forecast in response to the most recent forecast error, implying that expectations are poorly anchored. In contrast, a low signal-to-noise ratio implies that inflation is driven mostly by the transitory shock $\zeta_t$. As $\phi_\pi \rightarrow 0$, we have $\lambda_\pi \rightarrow 0$. In this case, agents do not revise their inflation forecast at all in response to the most-recent forecast error, implying that expectations are perfectly-anchored.[23]

[21] The unobserved component, stochastic volatility (UC-SV) time series model for inflation employed by Stock and Watson (2007, 2010) allows the variances of $\zeta_t$ and $\eta_t$ to evolve as exogenous stochastic processes.

[22] For details of the derivation, see Nerlove (1967), pp. 141-143.

[23] Along these lines, Lansing (2009) notes that the perceived signal-to-noise ratio can be viewed as an inverse measure of the central bank's credibility for maintaining a stable inflation target.

We now consider whether the optimal value of $\lambda_\pi$ computed directly from U.S. inflation data has changed over time. Table 4 shows the values of $\lambda_\pi$ that minimize the 1-quarter ahead mean squared forecast error for quarterly core CPI inflation across three subsamples. Specifically, we compute the value of $\lambda_\pi$ that solves:

$$\min_{\lambda_\pi} \sum_{k=0}^{n} \frac{1}{n} (\pi_{t-k} - \widetilde{E}_{t-k-1}\pi_{t-k})^2, \tag{20}$$

where $\pi_t$ is the observed quarterly inflation rate, $n$ is the number of observations in the subsample, and $\widetilde{E}_{t-k-1}\pi_{t-k}$ is constructed using lagged versions of the signal extraction forecast rule (9).[24]

Table 4 shows that the ex post optimal value of $\lambda_\pi$ has declined substantially from around 0.5 in the Great Inflation Era to near-zero in the Great Recession Era. This pattern is driven by a decline in the inflation signal-to-noise ratio. Put another way, unexpected changes in core CPI inflation are much less persistent now than in earlier decades. Consequently, inflation expectations, as governed by the signal-extraction forecast rule (9), should have become more anchored over the past 30 to 40 years. This result is consistent with our NKPC estimation results in Table 2 which documented a clear downward drift in $\widehat{\lambda}_\pi$ over time. Similarly, Stock and Watson (2007) and Coibion and Gorodnichenko (2015b) find that their estimated versions of $\lambda_\pi$ have declined over time. Other papers that find empirical evidence of more firmly anchored inflation expectations over the Great Moderation Era include Williams (2006), Lansing (2009), IMF (2013), Blanchard, Cerutti, and Summers (2015), and Carvalho, et al. (2020), among others.

Table 4: Ex-post optimal gain parameter

| | Great Inflation Era<br>1960.q1 to 1983.q4 | Great Moderation Era<br>1984.q1 to 2007.q3 | Great Recession Era<br>2007.q4 to 2019.q2 |
|---|---|---|---|
| $\lambda_\pi$ | 0.491*** | 0.221*** | 0.058 |
| | (0.104) | (0.061) | (0.068) |

Notes: The asterisks *** denote significance at the 1% level. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses.

[24] In the first two subsamples, we use the following initial condition for $k = 0$: $\widetilde{E}_{t-1}\pi_t = 0.125 \sum_{i=1}^{8} \pi_{t-i}$. In the third subsample, we set $\widetilde{E}_{t-1}\pi_t$ equal to the mean 10-year ahead forecast for headline CPI inflation from the SPF, adjusted downward by 40 annualized basis points. The downward adjustment corresponds to the estimated constant $\widehat{c}$ for the Great Moderation Era, as shown in Appendix C, Table C2.

## 5.2 New Keynesian model

We employ a three-equation New Keynesian model consisting of the NKPC (2), an IS equation, and a monetary policy rule. The IS equation (which is derived from the agent's consumption Euler equation) is given by:

$$y_t = \widetilde{E}_t y_{t+1} - \alpha(i_t - \widetilde{E}_t \pi_{t+1}) + v_t, \qquad \alpha > 0, \;\; v_t \sim N\left(0, \sigma_v^2\right), \tag{21}$$

where $i_t$ is the deviation of the nominal policy interest rate from its steady state value, $\alpha$ is the inverse of the coefficient of relative risk aversion, and $v_t$ is an *iid* demand shock that is uncorrelated with the cost-push shock.

Monetary policy is governed by the following Taylor-type rule (Taylor 1993):

$$i_t = \mu_\pi \widetilde{E}_t \pi_{t+1} + \mu_y \widetilde{E}_t y_{t+1}, \tag{22}$$

where $\mu_\pi > 1$ and $\mu_y > 0$ determine the response of the policy interest rate to the central bank's forecasts of inflation and the output gap. For simplicity, we assume that the central bank's forecasts coincide with the forecasts of the private sector agents. Equation (22) implies that the central bank will respond less aggressively to cost-push shocks when inflation expectations become well-anchored. This feature of the model is consistent with the findings of Kilian and Lewis (2011) who show that there is no evidence of a systematic monetary policy response to oil price shocks after 1987.

The model contains two subjective forecasts, namely $\widetilde{E}_t \pi_{t+1}$ and $\widetilde{E}_t y_{t+1}$. As before, $\widetilde{E}_t \pi_{t+1}$ is computed using equation (9) which is the perceived optimal forecast rule when inflation is governed by the time series process described by equations (17) and (18). We postulate that agents employ an analogous time series process for the output gap, as given by

$$y_t = \overline{y}_t + \chi_t, \qquad \chi_t \sim N\left(0, \sigma_\chi^2\right), \tag{23}$$

$$\overline{y}_t = \overline{y}_{t-1} + \varphi_t, \qquad \varphi_t \sim N\left(0, \sigma_\varphi^2\right), \;\; Cov\left(\chi_t, \varphi_t\right) = 0, \tag{24}$$

where $\overline{y}_t$ is the perceived long-run output gap, $\chi_t$ is a transitory shock and $\varphi_t$ is permanent shock (uncorrelated with $\chi_t$). A technical point worth noting is that while the CBO output gap appears to be stationary, it is highly persistent. For example, the CBO output gap remained in negative territory for nearly a decade from 2008.q1 through 2017.q3. The autoregressive coefficient in quarterly data from 1984.q1 to 2019.q2. is 0.95. Agents' use of a time series process for the output gap that exhibits a unit root can be viewed as a local approximation that is convenient for forecasting purposes.

Conditional on the time series process described by equations (23) and (24), the perceived optimal forecast rule for the output gap is

$$\widetilde{E}_t y_{t+1} = \widetilde{E}_{t-1} y_t + \lambda_y (y_t - \widetilde{E}_{t-1} y_t), \tag{25}$$

where the gain parameter is given by

$$\lambda_y = \frac{-\,\phi_y + \sqrt{\phi_y^2 + 4\phi_y}}{2}, \tag{26}$$

with $\phi_y \equiv \sigma_\varphi^2 / \sigma_\chi^2$. Our model specification is consistent with the findings of Coibion and Gorodnichenko (2015b) who identify different degrees of information rigidity in the mean professional forecasts of different macroeconomic variables. Different degrees of information rigidity would imply different perceived signal-to-noise ratios and hence different gain parameters when forecasting these different macroeconomic variables.

## 5.3 Equilibrium values of gain parameters

Rational expectations are sometimes called "model consistent expectations." A more precise term would be "true-model consistent expectations," because the maintained assumption is that agents know the true model of the economy. In reality, agents do not know the true model of the economy, but they can observe economic data. In this section, we solve for a "consistent expectations equilibrium" in which the parameters of the representative agent's forecast rules are consistent with: (1) the perceived laws of motion for $\pi_t$ and $y_t$, and (2) the observed moments of $\Delta\pi_t$ and $\Delta y_t$ in the model-generated data.[25]

**Proposition 1.** *If the representative agent's perceived law of motion for inflation is given by equations* (17) *and* (18)*, then the perceived optimal value of the gain parameter* $\lambda_\pi$ *is uniquely pinned down by the autocorrelation of observed inflation changes,* $Corr\,(\Delta\pi_t, \Delta\pi_{t-1})$.

*Proof*: From equations (17) and (18), we have $\Delta\pi_t = \eta_t + \zeta_t - \zeta_{t-1}$. Since $\eta_t$ and $\zeta_t$ are perceived to be independent, we have $Cov\,(\Delta\pi_t, \Delta\pi_{t-1}) = -\sigma_\zeta^2$ and $Var\,(\Delta\pi_t) = \sigma_\eta^2 + 2\sigma_\zeta^2$. Combining these two expressions and solving for the signal-to-noise ratio yields

$$\phi_\pi = \frac{-1}{Corr\,(\Delta\pi_t, \Delta\pi_{t-1})} - 2, \tag{27}$$

where $\phi_\pi \equiv \sigma_\eta^2 / \sigma_\zeta^2$ and $Corr\,(\Delta\pi_t, \Delta\pi_{t-1}) = Cov\,(\Delta\pi_t, \Delta\pi_{t-1}) / Var\,(\Delta\pi_t)$. The above expression shows that $Corr\,(\Delta\pi_t, \Delta\pi_{t-1})$ uniquely pins down the value of $\phi_\pi$. The value of

[25] This type of boundedly-rational equilibrium concept was developed by Hommes and Sorger (1998). A closely-related concept is the "restricted perceptions equilibrium" described by Evans and Honkopohja (2001), Chapter 13.

$\phi_\pi$, in turn, uniquely pins down $\lambda_\pi$ from equation (19). From the agent's perspective, the shocks $\zeta_t$ and $\eta_t$ are not directly observable, but the signal-to-noise ratio can be inferred from observed data on inflation changes. ■

Proposition 1 shows that the observed statistic $Corr\left(\Delta\pi_t, \Delta\pi_{t-1}\right)$ can be used by the agent to pin down the perceived optimal value of $\lambda_\pi$ which, in turn, governs the weights assigned to current and past rates of inflation in the signal-extraction forecast rule (9). This result is reminiscent of the "accelerationist controversy" identified by Sargent (1971) p. 35 who argued that any forecast weighting scheme involving past rates of inflation should "be compatible with the observed evolution of the rate of inflation." Analogous to equation (27), the perceived signal-to-noise ratio for the output gap $\phi_y$ can be inferred from the observed statistic $Corr\left(\Delta y_t, \Delta y_{t-1}\right)$. The value of $\phi_y$, in turn, uniquely pins down $\lambda_y$ from equation (26).

Given the values of $\phi_\pi$, $\phi_y$, $\lambda_\pi$, and $\lambda_y$ together with the agent's perceived optimal forecast rules (9) and (25), the actual law of motion (ALM) for the economy is governed by the three model equations (2), (21), and (22). The ALM can written in the following matrix form:

$$\mathbf{Z}_t = \mathbf{A}\mathbf{Z}_{t-1} + \mathbf{B}\mathbf{U}_t, \tag{28}$$

where $\mathbf{Z}_t \equiv \left[\begin{array}{ccccc} \pi_t & y_t & i_t & \widetilde{E}_t\pi_{t+1} & \widetilde{E}_t y_{t+1} \end{array}\right]'$ and $\mathbf{U}_t \equiv \left[\begin{array}{cc} u_t & v_t \end{array}\right]'$. The variance-covariance matrix $\mathbf{V}$ of the left-side variables in equation (28) can be computed using the formula:

$$vec\left(\mathbf{V}\right) = \left[\mathbf{I} - \mathbf{A}\otimes\mathbf{A}\right]^{-1} vec(\mathbf{B}\mathbf{\Omega}\mathbf{B}'), \tag{29}$$

where $\mathbf{\Omega}$ is the variance-covariance matrix of the two fundamental shocks $u_t$ and $v_t$. Given the theoretical moments of $\pi_t$ and $y_t$ from equation (29), we can derive analytical expressions for $Corr\left(\Delta\pi_t, \Delta\pi_{t-1}\right)$ and $Corr\left(\Delta y_t, \Delta y_{t-1}\right)$ in terms of $\phi_\pi$, $\phi_y$, $\lambda_\pi$, and $\lambda_y$.

**Definition 1.** *A consistent expectations equilibrium is defined as the actual law of motion* (28) *and the associated perceived optimal gain parameters* $\lambda_\pi^*$, and $\lambda_y^*$, *such that the pair* $(\lambda_\pi^*, \lambda_y^*)$ *is the fixed point of the following multidimensional nonlinear maps:*

$$\lambda_\pi^* = \frac{-\,\phi_\pi(\lambda_\pi^*, \lambda_y^*) + \sqrt{\phi_\pi(\lambda_\pi^*, \lambda_y^*)^2 + 4\phi_\pi(\lambda_\pi^*, \lambda_y^*)}}{2},$$

$$\text{where} \qquad \phi_\pi(\lambda_\pi^*, \lambda_y^*) = \frac{-1}{Corr\left(\Delta\pi_t, \Delta\pi_{t-1}\right)} - 2, \tag{30}$$

$$\lambda_y^* = \frac{-\phi_y(\lambda_\pi^*, \lambda_y^*) + \sqrt{\phi_y(\lambda_\pi^*, \lambda_y^*)^2 + 4\phi_y(\lambda_\pi^*, \lambda_y^*)}}{2},$$

$$\text{where} \qquad \phi_y(\lambda_\pi^*, \lambda_y^*) = \frac{-1}{Corr\,(\Delta y_t, \Delta y_{t-1})} - 2, \tag{31}$$

*and where the statistics* $Corr\,(\Delta\pi_t, \Delta\pi_{t-1})$ *and* $Corr\,(\Delta y_t, \Delta y_{t-1})$ *are computed from the actual law of motion* (28).

To obtain a graphical representation of the equilibrium, it is useful to express the nonlinear maps (30) and (31) in terms of the following functions:

$$\mathrm{f}_\pi(\lambda_\pi^*, \lambda_y^*) \equiv \lambda_\pi^* - \frac{-\phi_\pi(\lambda_\pi^*, \lambda_y^*) + \sqrt{\phi_\pi(\lambda_\pi^*, \lambda_y^*)^2 + 4\phi_\pi(\lambda_\pi^*, \lambda_y^*)}}{2}, \tag{32}$$

$$\mathrm{f}_y(\lambda_\pi^*, \lambda_y^*) \equiv \lambda_y^* - \frac{-\phi_y(\lambda_\pi^*, \lambda_y^*) + \sqrt{\phi_y(\lambda_\pi^*, \lambda_y^*)^2 + 4\phi_y(\lambda_\pi^*, \lambda_y^*)}}{2}. \tag{33}$$

A consistent expectations equilibrium must therefore satisfy the following two conditions:

$$\mathrm{f}_\pi(\lambda_\pi^*, \lambda_y^*) = 0, \tag{34}$$

$$\mathrm{f}_y(\lambda_\pi^*, \lambda_y^*) = 0. \tag{35}$$

If only one pair $(\lambda_\pi^*, \lambda_y^*)$ satisfies both equilibrium conditions (34) and (35) with $\phi_\pi$ and $\phi_y$ as defined in equations (30) and (31), then the equilibrium is unique.

## 5.4 Numerical solution for equilibrium

The complexity of the equilibrium conditions (34) and (35) necessitates a numerical solution for the equilibrium. We consider a standard calibration of the model using the parameter values shown in Table 5. Following our empirical methodology in Section 3, we set $\beta = 1$. We set $\kappa = 0.065$, which roughly corresponds to the average estimated NKPC slope parameter for the signal-extraction model during the Great Inflation and Great Recession subsamples, as shown in Table 2. We employ a coefficient of relative risk aversion $(1/\alpha)$ equal to 1, a typical value. The coefficients in the Taylor-type rule are $\mu_\pi = 1.5$ and $\mu_y = 0.5$ (Taylor 1993). The shock volatility measures $\sigma_v$ and $\sigma_u$ are set to 1 percent and 0.1 percent, respectively. These values allow the model to roughly reproduce the standard deviations of core CPI inflation and the CBO output gap over the Great Moderation Era from 1984.q1 to 2007.q3.[26]

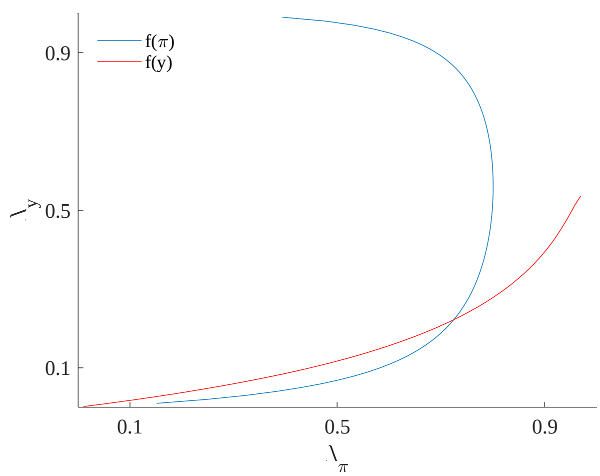
[26] The model-implied standard deviations are *Std. Dev.* $(4\pi_t) = 3.0\%$ and *Std. Dev.* $(y_t) = 1.2\%$.

Figure 6 plots the two equilibrium conditions (34) and (35) in $(\lambda_\pi, \lambda_y)$ space. As shown, the model has a unique fixed point equilibrium at $(\lambda_\pi, \lambda_y) = (0.7253, 0.222)$. At the fixed point, we have $Corr\,(\triangle\pi_t, \triangle\pi_{t-1}) = -0.256$ and $Corr\,(\triangle y_t, \triangle y_{t-1}) = -0.485$, which in turn imply $\phi^*_\pi = 1.915$ and $\phi^*_y = 0.064$.[27]

Table 5: Baseline parameter values

| Parameter | Value | Description |
|---|---|---|
| $\beta$ | 1 | Subjective time discount factor. |
| $\kappa$ | 0.065 | Slope parameter in NKPC. |
| $1/\alpha$ | 1 | Coefficient of relative risk aversion. |
| $\mu_\pi$ | 1.5 | Policy rule response to inflation. |
| $\mu_y$ | 0.5 | Policy rule response to output gap. |
| $\sigma_u$ | 0.1 | Std. dev. of cost push shock in percent. |
| $\sigma_v$ | 1.0 | Std. dev. of aggregate demand shock in percent. |

Figure 6: *Uniqueness of the Consistent Expectations Equilibrium*




Note: The figure plots the two equilibrium conditions (34) and (35) in $(\lambda_\pi, \lambda_y)$ space. The model has a unique fixed point equilibrium at $(\lambda_\pi, \lambda_y) = (0.7253, 0.222)$.

[27] Although not plotted here, we have verified that the model's consistent expectations equilibrium is convergent under a real time learning algorithm in which the agent's estimates of the population statistics $Corr\,(\triangle\pi_t, \triangle\pi_{t-1})$ and $Corr\,(\triangle y_t, \triangle y_{t-1})$ are computed using past data generated by the model itself. Details are available upon request.

## 5.5 Monetary policy regime change

A large literature has identified shifts in the conduct of U.S. monetary policy starting with the Volcker disinflation of the early 1980s (Clarida, Galí, and Gertler 2000, Orphanides 2004). Around the same time, inflation volatility and persistence both started to decline. More recently, the backward-looking Phillips curve has become flatter while the original Phillips curve has re-emerged in U.S. data. In this section, we show that a shift towards a more hawkish monetary policy can explain all of these stylized facts in the context of our signal-extraction equilibrium model.

### 5.5.1 Exogenous anchoring

We first demonstrate how an exogenous reduction in $\lambda_\pi$ affects the slopes of the backward-looking and original Phillips curves. To build intuition, consider a simplified version of the our model with $\lambda_y \to 0$ and $\widetilde{E}_{t-2}\pi_{t-1} \simeq 0$. As shown in Appendix D.1, the simplified version of the model implies the following expression for the covariance between inflation and the output gap

$$
\begin{aligned}
Cov\left(\pi_t, y_t\right) \quad = \quad & -\frac{\alpha\left(\mu_\pi - 1\right)\widehat{\beta}\left(1-\lambda_\pi\right)^2\lambda_\pi^2}{(1-\widehat{\beta}\lambda_\pi)^2}\, Var\left(\pi_{t-1}\right) + \frac{\kappa\left(1-\beta\lambda_\pi\right)}{(1-\widehat{\beta}\lambda_\pi)^2}\,\sigma_v \\
& -\frac{\alpha\left(\mu_\pi - 1\right)\lambda_\pi}{(1-\widehat{\beta}\lambda_\pi)^2}\,\sigma_u, \qquad (36)
\end{aligned}
$$

where $\widehat{\beta} \equiv \beta - \kappa\alpha\left(\mu_\pi - 1\right)$.

The first term in equation (36) shows that movements in lagged inflation induce a negative co-movement between current inflation and the output gap. The presence of lagged inflation derives from expected inflation. Intuitively, if inflation has been higher in the recent past, then expected inflation will tend to be higher. Higher expected inflation contributes to higher value of $\pi_t$ through the NKPC. To combat higher expected inflation, the central bank's policy rule calls for an increase in the real interest rate, thus lowering the output gap and generating negative co-movement between $\pi_t$ and $y_t$. Similarly, the third term in equation (36) shows that movements in the cost-push shock induce a negative co-movement between $\pi_t$ and $y_t$, also working through the policy rule. In contrast, the second term in equation (36) shows that movements in the demand shock $v_t$ induce a positive co-movement between $\pi_t$ and $y_t$. This occurs because the demand shock does not create a trade-off for the central bank as it seeks to stabilize both expected inflation and the expected output gap.

Consider how an exogenous decline in $\lambda_\pi$ will affect $Cov\left(\pi_t, y_t\right)$ as given by equation

(36).When $\lambda_\pi \to 0$ such that expected inflation becomes perfectly anchored, the coefficients on $Var(\pi_{t-1})$ and $\sigma_u$ both become zero. Hence, perfect anchoring eliminates the negative contributions to $Cov(\pi_t, y_t)$ coming from the first and third terms of equation (36). Intuitively, when $\lambda_\pi \to 0$, expected inflation becomes constant so that current inflation no longer responds to movements in lagged inflation. In addition, because the central bank responds to expected inflation, perfect anchoring eliminates the sensitivity of the policy interest rate and the output gap to lagged inflation. Similarly, cost-push shocks will no longer blur the statistical correlation between $\pi_t$ and $y_t$ because perfect anchoring eliminates the sensitivity of the policy interest rate and the output gap to cost-push shocks. As $\lambda_\pi \to 0$, the coefficient on $\sigma_v$ in equation (36) will converge to $\kappa$, the true structural slope parameter in the NKPC. Consequently, perfect anchoring ensures that $Cov(\pi_t, y_t) > 0$.

Now consider the implications of improved anchoring for the slope of the backward-looking Phillips curve versus the slope of the original Phillips curve. The relationship between the two slopes can be understood using the following definitional relationship

$$Cov(\Delta\pi_t, y_t) - Cov(\pi_t, y_t) = -Cov(\pi_{t-1}, y_t). \tag{37}$$

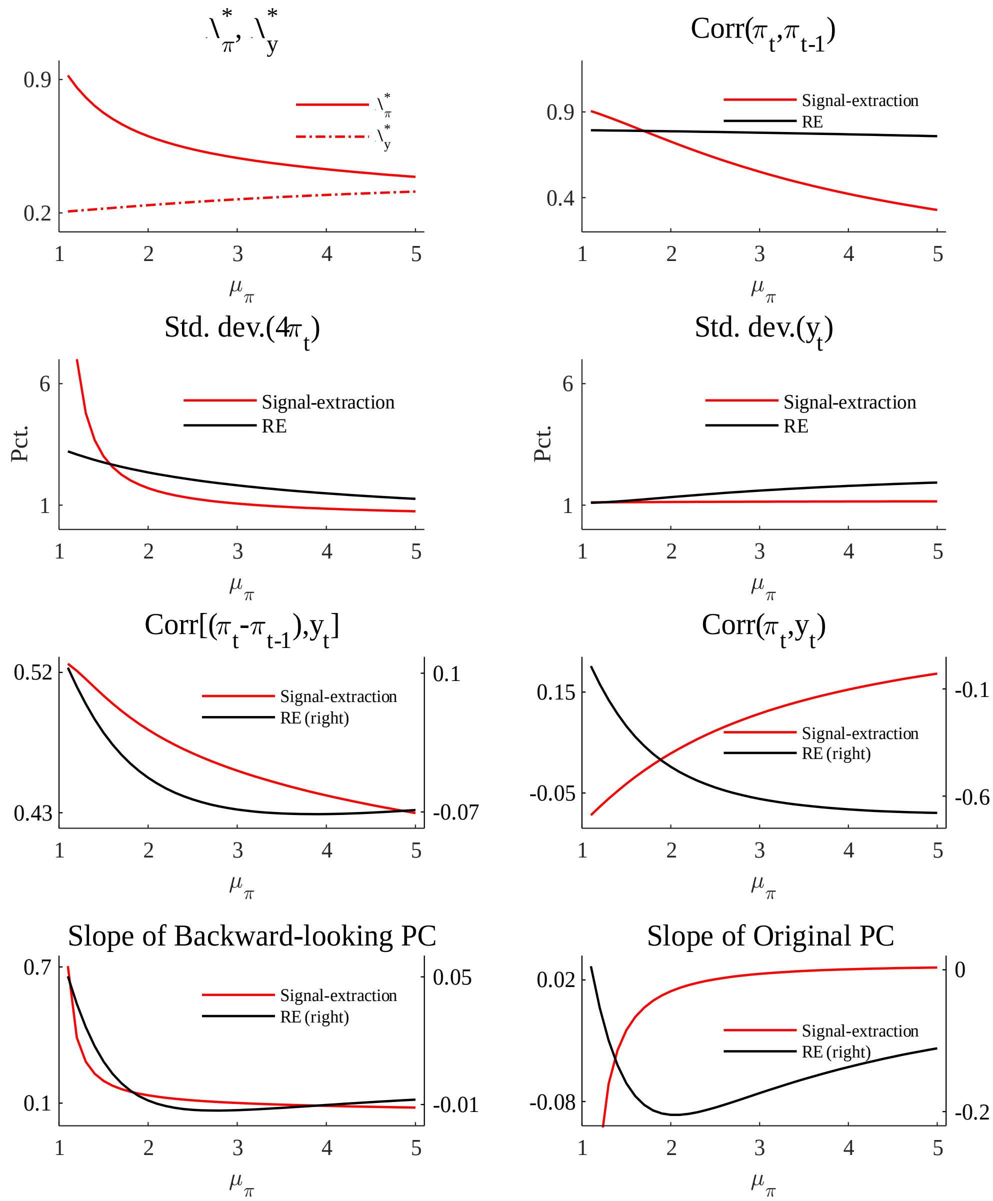
The above expression shows that relative movements in the two slopes will be governed by movements in the value of $-Cov(\pi_{t-1}, y_t)$. It is straightforward to verify that $Cov(\pi_{t-1}, y_t)$ is strictly negative in our simplified model with $\lambda_y \to 0$ and $\widetilde{E}_{t-2}\pi_{t-1} \simeq 0$. As a result, the backward-looking Phillips curve will appear steeper than the original Phillips curve. However, in the empirically relevant case when $\lambda_\pi$ is relatively low, we demonstrate numerically in Appendix D.2 that lower values of $\lambda_\pi$ will cause $Cov(\pi_{t-1}, y_t)$ to become *less negative*, leading to a flattening of the backward-looking Phillips curve relative to the original Phillips curve.

### 5.5.2 Endogenous anchoring

Now let us consider the implications of an endogenous reduction in $\lambda_\pi$ that is caused by an increase in the policy rule coefficient $\mu_\pi$. It is straightforward to verify from equation (36), that an increase in $\mu_\pi$, holding $\lambda_\pi$ constant, will serve to reduce $Cov(\pi_t, y_t)$, making the original Phillips curve appear flatter. But this prediction is counterfactual, as shown earlier in the right panel of Figure 2. We show below that our signal-extraction equilibrium model can overturn this counterfactual prediction. In our model, an increase in $\mu_\pi$ will cause agents to choose a lower value of $\lambda_\pi^*$. This endogenous anchoring mechanism serves to increase $Cov(\pi_t, y_t)$, thus making the original Phillips curve appear steeper, consistent with the data since 1999.

Figure 7 shows how higher values of $\mu_\pi$ influence the equilibrium gain parameters $\lambda_\pi^*$ and

Figure 7: *Effects of an Increase in the Policy Rule Coefficient on Inflation*




Notes: Increasing the value of $\mu_\pi$ in the signal-extraction equilibrium model leads to lower equilibrium gain parameter $\lambda_\pi^*$. The lower value of $\lambda_\pi^*$ helps to reduce $Cov\left(\Delta\pi_t, y_t\right)/Var\left(y_t\right)$, making the backward-looking Phillips curve appear flatter. At the same time, the lower value of $\lambda_\pi^*$ helps to raise $Cov\left(\pi_t, y_t\right)/Var\left(y_t\right)$, making the original Phillips curve appear steeper.

$\lambda_y^*$ and numerous model-implied moments.[28] All other parameters take on the values shown in Table 5. We compare the results from the signal-extraction model with the predictions of an RE version of the same model but with persistent shocks.[29] The persistence parameters of the shocks are calibrated to deliver roughly the same autocorrelation coefficients for $\pi_t$ and $y_t$ as our signal-extraction equilibrium model.[30]

Increasing the value of $\mu_\pi$ in the RE version of the model has essentially no effect on inflation persistence and volatility, as measured by $Corr\,(\pi_t, \pi_{t-1})$ and $Std.\ Dev.\,(4\pi_t)$. At the same time, the increase in $\mu_\pi$ serves to lower of the reduced-form slope coefficients $Cov\,(\Delta\pi_t, y_t)\,/Var\,(y_t)$ and $Cov\,(\pi_t, y_t)\,/Var\,(y_t)$, making the backward-looking Phillips curve and the original Phillips curve both appear flatter.[31] These results are consistent with those of Bullard (2018) and McLeay and Tenreyro (2020).

For the signal-extraction equilibrium model, the top left panel of Figure 7 shows that increasing the value of $\mu_\pi$ serves to reduce the equilibrium gain parameter $\lambda_\pi^*$, resulting in more firmly anchored inflation expectations. This occurs because higher values of $\mu_\pi$ move the statistic $Corr\,(\triangle\pi_t, \triangle\pi_{t-1})$ further into negative territory, implying a lower perceived signal-to-noise ratio for inflation and faster reversion of inflation to steady state in response to a shock.[32] Figure 7 shows that the lower value of $\lambda_\pi^*$ contributes to a substantial decline in both $Corr\,(\pi_t, \pi_{t-1})$ and $Std.\ Dev.\,(4\pi_t)$ , as observed in U.S. data.

Importantly, our signal-extraction equilibrium model can help explain the observed changes in the slopes of the reduced-form Phillips curves shown in Figure 2. The bottom left panels show that an increase in $\mu_\pi$ serves to reduce $Corr\,(\Delta\pi_t, y_t)$ and $Cov\,(\Delta\pi_t, y_t)\,/Var\,(y_t)$, making the backward-looking Phillips curve appear flatter. The bottom right panels show that an increase in $\mu_\pi$ serves to *raise* $Corr\,(\pi_t, y_t)$ and $Cov\,(\pi_t, y_t)\,/Var\,(y_t)$, making the original Phillips curve appear steeper. If instead we hold $\lambda_\pi$ fixed while increasing $\mu_\pi$, then $Corr\,(\pi_t, y_t)$ will counterfactually decline. Hence, the endogenous anchoring mechanism that is built into our signal-extraction equilibrium model is the crucial element that is needed to

[28] For these computations, we make use of the full equilbrium model of Section 5.2, without the simplifying assumptions of $\lambda_y \to 0$ and $\widetilde{E}_{t-2}\pi_{t-1} \simeq 0$.

[29] Introducing persistence in the RE version of the model via indexation in the NKPC or habit formation in the IS equation would yield similar results.

[30] The persistence parameters for the shocks $v_t$ and $u_t$ in the RE version of the model are set to 0.8 and 0.2, respectively.

[31] But as shown in bottom right panel Figure 7, the slope of the original Phillips curve in the RE version of the model starts to increase with $\mu_\pi$ when $\mu_\pi > 2$. This pattern is driven by a counterfactual increase in $Var\,(y_t)$ which makes the slope less negative. Nevertheless, the slope remains negative even for very large values of $\mu_\pi$.

[32] The equilibrium gain parameter $\lambda_y^*$ and the volatility of the output gap are largely unaffected by changes in $\mu_\pi$.

explain the Phillips curve slope patterns in Figure 2.

# 6 Conclusion

The volatility and persistence of U.S. inflation have significantly declined since the mid-1980s. Over the same period, the backward-looking Phillips curve (which relates the change in inflation to the output gap) has become flatter while the original Phillips curve (which relates the level of inflation to the output gap) has re-emerged in U.S. data. This last observation contrasts sharply with views that either the structural slope parameter of the Phillips curve has declined (Ball and Mazumder 2011, IMF 2013, Blanchard, Cerutti, and Summers 2015, Del Negro, et al. 2020), or alternatively, that Federal Reserve policy has broken the reduced-form Phillips curve relationship (Bullard 2018, McLeay and Tenreyro 2020). This paper shows that a shift towards a more hawkish monetary policy can trigger an endogenous anchoring of agents' subjective inflation forecasts, thus providing a coherent explanation for all of the observed changes in U.S. inflation behavior.

We estimate an NKPC that allows for changes in the degree of anchoring of agents' subjective inflation forecasts. Our estimation results show that expected inflation has become more firmly anchored since the mid-1980s. Accounting for this improved anchoring, the estimated structural slope parameter in the NKPC is highly statistically significant and stable over the period 1960 to 2019. We obtain nearly identical estimated slope parameters using survey-based measures of long-run expected inflation, confirming that the structural Phillips curve relationship in the data is alive and well. Out-of-sample forecasts constructed using our estimated NKPC can resolve both the "missing disinflation puzzle" during the Great Recession and the "missing inflation puzzle" during the subsequent recovery.

We show that improved anchoring of expected inflation influences the behavior of inflation through three distinct channels. First, improved anchoring makes inflation less sensitive to lagged inflation. Second, for any given value of the structural slope parameter, improved anchoring reduces the sensitivity of inflation to the output gap. Third, improved anchoring makes inflation less sensitive to cost-push shocks. The second channel helps to resolve the inflation puzzles mentioned above. But all else equal, a reduced sensitivity of inflation to the output gap will serve to weaken the statistical relationship between these two variables. This prediction is at odds with the stronger statistical relationship between inflation and the output gap observed in U.S. data since 1999. The first and third channels explain the re-emergence of the original Phillips curve in the data. The presence of lagged inflation and cost push shocks in the NKPC induces negative co-movement between current inflation and the output gap. Improved anchoring serves to dampen these negative co-movement forces, thereby allowing a positive statistical relationship between current inflation and the output gap to re-emerge.

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# A Appendix: Data Description

With the exception of the survey-based measures of expected inflation, all data series are from the Federal Reserve Economic Database (FRED) maintained by the Federal Reserve Bank of St. Louis. The series are described below with series names indicated in parentheses. Monthly data is converted into quarterly data by taking quarterly averages.

CBO output gap: 100*(GDPC1-GDPPOT)/GDPPOT, 100*(Bil. of Chn. 2012 $-Bil. of Chn. 2012 $)/Bil. of Chn. 2012 $, Quarterly (GDPC1_GDPPOT)

Core CPI index: Consumer price index for all urban consumers: All items less food and energy, monthly (CPILFENS, not seasonally adjusted, 1982-1984=100).

Core PCE index: Personal consumption expenditures: Chain-type price index less food and energy, quarterly (CPILFENS, seasonally adjusted, 2012=100).

Federal funds rate: Effective federal funds rate, percent, monthly (FEDFUNDS, not seasonally adjusted).

Labor share of income: Nonfarm business sector, labor share, quarterly, (PRS85006173, seasonally adjusted, Index 2012=100)

Oil prices: Spot crude oil price, West Texas Intermediate (WTI), dollars per barrel, monthly, (WTISPLC, not seasonally adjusted).

Real GDP: Real gross domestic product, billions of chained 2012 dollars, quarterly (GDPC1, seasonally adjusted, 2012=100). We detrend real GDP using a two-sided Hodrick-Prescott filter with a smoothing parameter of 1600.

Wage index: Nonfarm business sector compensation per hour, quarterly (HCOMPBS, seasonally adjusted, 2012=100).

Survey-based expected inflation: The 1-quarter ahead and 10-year ahead mean CPI inflation forecasts are from the Survey of Professional Forecasters (quarterly).[33] The 5-year ahead mean inflation forecasts are from the Michigan Survey of Consumers (quarterly).[34] The 10-year ahead mean CPI inflation forecasts are from the Livingston Survey (semi-annual).[35]

[33] https://www.philadelphiafed.org/research-and-data/real-time-center/survey-of-professional-forecasters/data-files.

[34] https://data.sca.isr.umich.edu/data-archive/mine.php.

[35] https://www.philadelphiafed.org/research-and-data/real-time-center/livingston-survey/historical-data

# B Appendix: Details of out-of-sample forecasts

## B.1 NKPC estimates for out-of-sample forecasts

Table B1: NKPC estimates for out-of-sample forecasts

| | Hybrid RE | Backward-looking | Signal-extraction |
|---|---|---|---|
| $\widehat{\kappa}$ | 0.002 | 0.046*** | 0.048*** |
| | (0.009) | (0.012) | (0.019) |
| $\widehat{\delta}$ | 0.003 | 0.000 | 0.012** |
| | (0.003) | (0.004) | (0.006) |
| $\widehat{\varphi}$ | −0.004* | −0.003** | −0.007** |
| | (0.003) | (0.002) | (0.004) |
| $\widehat{\gamma}_f$ | 0.636*** | – | – |
| | (0.101) | | |
| $\widehat{\lambda}_\pi$ | – | – | 0.024 |
| | | | (0.177) |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates. (not annualized) Newey-West standard errors are shown in parentheses. Sample period is 1999.q1-2007.q3.

## B.2 Out-of-sample forecast in the hybrid RE model

The closed form solution of equation (11) can be written as:

$$\pi_t = \delta_1 \pi_{t-1} + \frac{\kappa}{\delta_2 \gamma_f} \sum_{k=0}^{T-1} \left(\frac{1}{\delta_2}\right)^k E_t y_{t+k} + E_t \left[ \left(\frac{1}{\delta_2}\right)^T (\pi_{t+T} - \delta_1 \pi_{t+T-1}) \right], \tag{B.1}$$

where $\delta_1 = \frac{1-\sqrt{1-4(1-\gamma_f)\gamma_f}}{2\gamma_f}$ and $\delta_2 = \frac{1+\sqrt{1-4(1-\gamma_f)\gamma_f}}{2\gamma_f}$ are, respectively, the stable and unstable roots of the second order difference equation (11).

We assume perfect foresight and replace the expectations $E_t y_{t+k}$ and $E_t \pi_{t+k}$ with the realizations $y_{t+k}$ and $\pi_{t+k}$, yielding:

$$\pi_t = \delta_1 \pi_{t-1} + \frac{\kappa}{\delta_2 \gamma_f} \sum_{k=0}^{T-1} \left(\frac{1}{\delta_2}\right)^k y_{t+k} + \left(\frac{1}{\delta_2}\right)^T (\pi_{t+T} - \delta_1 \pi_{t+T-1}), \tag{B.2}$$

where $T = 2019.q2$ is the final period of the simulation. Equation (B.2) shows that inflation at time $t$ is a function of current and future realizations of $y_{t+k}$ through 2019.q1 plus a terminal condition that depends on the realized inflation rates in 2019.q2 and 2019.q1.

## B.3 Can oil prices help explain the missing disinflation puzzle?

Here we examine how movements in oil prices affect the out-of-sample inflation forecast of the signal-extraction version of the estimated NKPC. In a prominent paper, Coibion and Gorodnichenko (2015a) argue that the missing disinflation puzzle during the Great Recession can be explained by a rise in households' inflation expectations, which, in turn, can be traced to a simultaneous increase in oil prices. To evaluate this hypothesis within the context of the signal-extraction NKPC, we construct an out-of-sample inflation forecast using both the CBO output gap and oil price inflation as driving variables. As in the baseline out-of-sample forecast shown in Figure 5, the NKPC parameters are estimated using data from 1999.q1 to 2007.q3.

Table B2 compares the estimated oil price inflation coefficients for the signal-extraction NKPC with the corresponding estimates using survey data. The left panel shows the results using data from 1999.q1 to 2007.q3 while the right panel shows the results using data from 2007.q4 to 2019.q2. Two observations are worth noting. First, the estimated oil price inflation coefficients for the signal-extraction NKPC are very similar to those obtained using survey data. This result suggests that the signal-extraction NKPC accurately captures the oil price pass-through to core CPI inflation implied by the survey data. Second, the estimated oil price inflation coefficients for the signal-extraction NKPC are nearly the same across the two subsamples. This result suggests that oil price pass-through to core CPI inflation was similar in the years before and after the Great Recession.

Table B2: Estimated oil price inflation coefficients

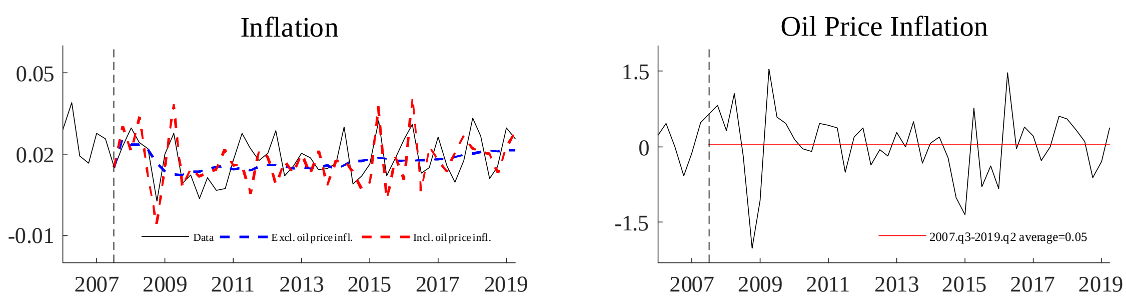
| | Pre-Great Recession Period 1999.q1 to 2007.q3 | | | Great Recession Era 2007.q4 to 2019.q2 | | |
|---|---|---|---|---|---|---|
| | Signal-extraction | 5-y MSC | 10-y SPF | Signal-extraction | 5-y MSC | 10-y SPF |
| $\widehat{\delta}$ | 0.012** | 0.012* | 0.008 | 0.016* | 0.017* | 0.023** |
| | (0.006) | (0.008) | (0.006) | (0.011) | (0.011) | (0.013) |
| $\widehat{\varphi}$ | −0.007** | −0.005** | −0.006*** | −0.005*** | −0.005*** | −0.006*** |
| | (0.004) | (0.003) | (0.002) | (0.002) | (0.002) | (0.002) |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses.

Figure 8 compares our baseline out-of-sample inflation forecast from the signal-extraction NKPC with an alternative forecast that uses realized oil price inflation as a driving variable in addition to the CBO output gap. Compared to the baseline out-of-sample forecast, the version that includes oil price inflation accounts quite well for the high frequency movements in core CPI inflation since 2007. However, oil price inflation does not appear to be important in explaining the low frequency movements in core CPI inflation since 2007.

The right panel of Figure 8 shows that oil price inflation exhibits very low persistence.[36] While average oil price inflation from 2007.q4 to 2019.q2 is around 5%, including it as a driving variable increases the average out-of-sample predicted CPI inflation rate by only 0.01 percentage points. These results show that including oil price inflation in the out-of-sample forecasting exercise does not significantly improve the signal-extraction NKPC's ability to account for the missing disinflation puzzle.

Figure 8: *Median Out-of-Sample Forecasts: The Role of Oil Prices*




Notes: The left panel compares the baseline out-of-sample inflation forecast from the estimated signal-extraction NKPC with an alternative out-of-sample forecast that uses realized oil price inflation as a driving variable in addition to the CBO output gap. The right panel shows that oil price inflation exhibits very low persistence. Inflation is expressed as annualized quarterly rates.

[36]Oil price inflation is the annualized quarterly growth rate of the spot price for West Texas Intermediate crude oil. For details, see Appendix A.

# C Appendix: Robustness of NKPC estimates

## C.1 Baseline estimates: All coefficients

Table C1: Baseline NKPC estimates (1 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f\, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | | |
| $\widehat{\kappa}$ | $-0.013$ | $-0.003$ | 0.010 |
| | (0.019) | (0.010) | (0.013) |
| $\widehat{\gamma}_f$ | 0.862*** | 1.003*** | 0.743*** |
| | (0.123) | (0.179) | (0.173) |
| $\widehat{\delta}$ | 0.001 | 0.001 | 0.018 |
| | (0.009) | (0.006) | (0.017) |
| $\widehat{\varphi}$ | $-0.003$ | $-0.002$ | $-0.003$* |
| | (0.003) | (0.002) | (0.002) |
| | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | 0.080*** | 0.033*** | 0.020*** |
| | (0.022) | (0.010) | (0.010) |
| $\widehat{\delta}$ | $-0.027$* | $-0.005$ | 0.009** |
| | (0.020) | (0.005) | (0.005) |
| $\widehat{\varphi}$ | 0.026*** | 0.002 | $-0.004$*** |
| | (0.009) | (0.002) | (0.001) |
| | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | | |
| $\widehat{\kappa}$ | 0.066*** | 0.042*** | 0.063*** |
| | (0.115) | (0.015) | (0.013) |
| $\widehat{\lambda}_\pi$ | 0.280*** | 0.119** | 0.008 |
| | (0.021) | (0.059) | (0.010) |
| $\widehat{\delta}$ | $-0.022$* | $-0.010$* | 0.016* |
| | (0.015) | (0.007) | (0.011) |
| $\widehat{\varphi}$ | 0.022*** | 0.003* | $-0.005$*** |
| | (0.009) | (0.002) | (0.002) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation of both $y_t$ and $\pi_t^{oil}$ in each subsample. Newey-West standard errors are shown in parentheses.

Table C2: Baseline NKPC estimates (2 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | | D. Survey Data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | 0.006 | 0.026** |
| | | (0.020) | (0.011) |
| $\widehat{\delta}$ | | −0.016*** | 0.010 |
| | | (0.006) | (0.009) |
| $\widehat{\varphi}$ | | 0.000 | −0.006*** |
| | | (0.002) | (0.001) |
| $\widehat{c}$ | | 0.000 | 0.000 |
| | | (0.000) | (0.000) |
| | | 5-y MSC[1] | |
| $\widehat{\kappa}$ | | 0.024** | 0.070*** |
| | | (0.011) | (0.015) |
| $\widehat{\delta}$ | | 0.007* | 0.017* |
| | | (0.005) | (0.012) |
| $\widehat{\varphi}$ | | −0.004** | −0.005*** |
| | | (0.002) | (0.002) |
| $\widehat{c}$ | | −0.003*** | −0.002*** |
| | | (0.000) | (0.000) |
| | | 10-y SPF[2] | |
| $\widehat{\kappa}$ | | 0.041*** | 0.065*** |
| | | (0.010) | (0.019) |
| $\widehat{\delta}$ | | 0.006 | 0.022** |
| | | (0.005) | (0.013) |
| $\widehat{\varphi}$ | | −0.008*** | −0.006*** |
| | | (0.002) | (0.002) |
| $\widehat{c}$ | | −0.001** | 0.000 |
| | | (0.000) | (0.001) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Great Moderation subsample starts in 1990.q3. [2]Great Moderation subsample starts in 1992.q1. Newey-West standard errors are shown in parentheses.

## C.2 Excluding oil price inflation

Table C3: NKPC estimates excluding oil price inflation.

| | Great Inflation Era<br>1960.q1 to 1983.q4 | Great Moderation Era<br>1984.q1 to 2007.q3 | Great Recession Era<br>2007.q4 to 2019.q2 |
|---|---|---|---|
| | | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f\, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | |
| $\widehat{\kappa}$ | $-0.009$ | $-0.005$ | 0.002 |
| | (0.015) | (0.010) | (0.005) |
| $\widehat{\gamma}_f$ | 0.783*** | 0.978*** | 0.716*** |
| | (0.149) | (0.170) | (0.075) |
| | | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | |
| $\widehat{\kappa}$ | 0.081*** | 0.030*** | 0.013* |
| | (0.018) | (0.009) | (0.010) |
| | | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | |
| $\widehat{\kappa}$ | 0.052*** | 0.034*** | 0.066*** |
| | (0.017) | (0.013) | (0.010) |
| $\widehat{\lambda}_\pi$ | 0.346*** | 0.175** | 0.000 |
| | (0.108) | (0.083) | (0.005) |
| | | D. Survey Data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | $-0.005$ | 0.042*** |
| | | (0.010) | (0.011) |
| $\widehat{c}$ | | 0.000 | 0.001** |
| | | (0.000) | (0.000) |
| | | 5-y MSC[2] | |
| $\widehat{\kappa}$ | | 0.008 | 0.077*** |
| | | (0.012) | (0.013) |
| | | $-0.003$*** | $-0.002$*** |
| | | (0.000) | (0.000) |
| | | 10-y SPF[3] | |
| $\widehat{\kappa}$ | | 0.020** | 0.078*** |
| | | (0.011) | (0.010) |
| $\widehat{c}$ | | $-0.001$*** | 0.001** |
| | | (0.000) | (0.000) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. [1]Due the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation of $y_t$ in each subsample. [2]Great Moderation subsample starts in 1990.q3. [3]Great Moderation subsample starts in 1992.q1.

## C.3 Alternative Driving Variable: Labor Share

Table C4: NKPC estimates using labor share (1 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t \pi_{t+1} = \gamma_f \, E_t \pi_{t+1} + \left(1 - \gamma_f\right) \pi_{t-1}$ | | |
| $\widehat{\kappa}$ | 0.042 | −0.033 | 0.007 |
| | (0.083) | (0.054) | (0.056) |
| $\widehat{\gamma}_f$ | 0.829*** | 1.040*** | 0.729*** |
| | (0.108) | (0.210) | (0.166) |
| $\widehat{\delta}$ | 0.006 | −0.006 | 0.016 |
| | (0.015) | (0.013) | (0.014) |
| $\widehat{\varphi}$ | −0.003 | −0.000 | −0.003** |
| | (0.003) | (0.003) | (0.002) |
| | B. Backward-looking: $\widetilde{E}_t \pi_{t+1} = \left(\pi_{t-1} + \pi_{t-2} + \pi_{t-3} + \pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | −0.097 | 0.025 | 0.051 |
| | (0.136) | (0.052) | (0.062) |
| $\widehat{\delta}$ | −0.012 | −0.004 | 0.016* |
| | (0.019) | (0.006) | (0.012) |
| $\widehat{\varphi}$ | 0.017*** | 0.000 | −0.005*** |
| | (0.005) | (0.002) | (0.002) |
| | C. Signal-extraction: $\widetilde{E}_t \pi_{t+1} = \widetilde{E}_{t-1} \pi_t + \lambda_\pi (\pi_t - \widetilde{E}_{t-1} \pi_t)$ | | |
| $\widehat{\kappa}$ | 0.002 | 0.169 | 0.049 |
| | (0.177) | (0.161) | (0.082) |
| $\widehat{\lambda}_\pi$ | 0.118** | 0.061* | 0.096 |
| | (0.055) | (0.044) | (0.153) |
| $\widehat{\delta}$ | −0.001 | −0.012* | 0.019* |
| | (0.018) | (0.008) | (0.013) |
| $\widehat{\varphi}$ | 0.023*** | 0.003* | −0.005** |
| | (0.007) | (0.002) | (0.002) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation of both $y_t$ and $\pi_t^{oil}$ in each subsample. Newey-West standard errors are shown in parentheses..

Table C5: NKPC estimates using labor share (2 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | | D. Survey Data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | 0.415 | 6.02 |
| | | (2.749) | (6.454) |
| $\widehat{\delta}$ | | $-0.016^{***}$ | 0.023 |
| | | (0.006) | (0.019) |
| $\widehat{\varphi}$ | | 0.000 | $-0.007^{**}$ |
| | | (0.002) | (0.004) |
| $\widehat{c}$ | | 0.002 | 0.034 |
| | | (0.013) | (0.036) |
| | | 5-y MSC[1] | |
| $\widehat{\kappa}$ | | $4.458^{**}$ | $-8.676$ |
| | | (2.110) | (9.507) |
| $\widehat{\delta}$ | | $-0.001$ | $0.015^{*}$ |
| | | (0.005) | (0.010) |
| $\widehat{\varphi}$ | | 0.000 | $-0.003$ |
| | | (0.002) | (0.002) |
| $\widehat{c}$ | | $0.018^{**}$ | $-0.052$ |
| | | (0.010) | (0.054) |
| | | 10-y SPF[2] | |
| $\widehat{\kappa}$ | | 5.090 | $-2.547$ |
| | | (4.423) | (3.945) |
| $\widehat{\delta}$ | | $0.019^{**}$ | $0.018^{*}$ |
| | | (0.011) | (0.012) |
| $\widehat{\varphi}$ | | $-0.006^{**}$ | $-0.004^{**}$ |
| | | (0.003) | (0.002) |
| $\widehat{c}$ | | 0.024 | -0.016 |
| | | (0.021) | (0.022) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. [1]Great Moderation subsample starts in 1990.q3. [2]Great Moderation subsample starts in 1992.q1.

## C.4 Alternative Driving Variable: Detrended GDP

Table C6: NKPC estimates using detrended GDP (1 of 2)

| | Great Inflation Era<br>1960.q1 to 1983.q4 | Great Moderation Era<br>1984.q1 to 2007.q3 | Great Recession Era<br>2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f \, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | | |
| $\widehat{\kappa}$ | $-0.000$ | $-0.002$ | 0.073 |
| | (0.025) | (0.019) | (0.082) |
| $\widehat{\gamma}_f$ | 0.809*** | 0.972*** | 0.823*** |
| | (0.097) | (0.140) | (0.226) |
| $\widehat{\delta}$ | $-0.002$ | 0.002 | 0.021 |
| | (0.008) | (0.007) | (0.018) |
| $\widehat{\varphi}$ | $-0.002$ | $-0.002$ | $-0.004$** |
| | (0.002) | (0.002) | (0.002) |
| | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | 0.130*** | 0.050** | 0.070** |
| | (0.041) | (0.024) | (0.035) |
| $\widehat{\delta}$ | $-0.004$ | $-0.005$ | 0.011** |
| | (0.012) | (0.004) | (0.006) |
| $\widehat{\varphi}$ | 0.010*** | 0.000 | $-0.006$*** |
| | (0.001) | (0.002) | (0.001) |
| | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | | |
| $\widehat{\kappa}$ | 0.157*** | 0.061** | 0.153** |
| | (0.040) | (0.027) | (0.085) |
| $\widehat{\lambda}_\pi$ | 0.162** | 0.218** | 0.079 |
| | (0.077) | (0.112) | (0.087) |
| $\widehat{\delta}$ | $-0.014$ | $-0.004$ | 0.016** |
| | (0.014) | (0.005) | (0.009) |
| $\widehat{\varphi}$ | 0.016*** | 0.000 | $-0.006$*** |
| | (0.004) | (0.002) | (0.002) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation less of both $y_t$ and $\pi_t^{oil}$ in each subsample. Newey-West standard errors are shown in parentheses. Real GDP is detrended using a two-sided HP filter with $\lambda = 1600$.

Table C7: NKPC estimates using detrended GDP (2 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | | D. Survey data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | 0.050** | 0.072* |
| | | (0.026) | (0.047) |
| $\widehat{\delta}$ | | −0.013** | 0.011 |
| | | (0.006) | (0.009) |
| $\widehat{\varphi}$ | | −0.001 | −0.007*** |
| | | (0.002) | (0.001) |
| $\widehat{c}$ | | 0.000 | 0.000 |
| | | (0.000) | (0.000) |
| | | 5-y MSC[1] | |
| $\widehat{\kappa}$ | | 0.041*** | 0.166*** |
| | | (0.016) | (0.067) |
| $\widehat{\delta}$ | | 0.005 | 0.014** |
| | | (0.005) | (0.007) |
| $\widehat{\varphi}$ | | −0.003** | −0.006*** |
| | | (0.002) | (0.002) |
| $\widehat{c}$ | | −0.003*** | −0.003*** |
| | | (0.000) | (0.000) |
| | | 10-y SPF[2] | |
| $\widehat{\kappa}$ | | 0.057*** | 0.151** |
| | | (0.017) | (0.007) |
| $\widehat{\delta}$ | | 0.006 | 0.020** |
| | | (0.005) | (0.011) |
| $\widehat{\varphi}$ | | −0.007*** | −0.007*** |
| | | (0.001) | (0.002) |
| $\widehat{c}$ | | −0.001*** | −0.001*** |
| | | (0.000) | (0.000) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively. The estimation uses quarterly inflation rates (not annualized).[1]Great Moderation subsample starts in 1990.q3. [2]Great Moderation subsample starts in 1992.q1. Newey-West standard errors are shown in parentheses. Real GDP is detrended using a two-sided HP filter with $\lambda = 1600$.

## C.5 Alternative Inflation Measure: Core PCE Inflation

Table C8: NKPC estimates using core PCE inflation (1 of 2)

| | Great Inflation Era 1961.q3 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f \, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | | |
| $\widehat{\kappa}$ | $-0.026^{*}$ | $-0.002$ | $-0.002$ |
| | (0.017) | (0.006) | (0.006) |
| $\widehat{\gamma}_f$ | $1.004^{***}$ | $0.994^{***}$ | $0.984^{***}$ |
| | (0.259) | (0.221) | (0.226) |
| $\widehat{\delta}$ | 0.002 | 0.001 | $-0.004$ |
| | (0.007) | (0.003) | (0.006) |
| $\widehat{\varphi}$ | $-0.003$ | 0.000 | $0.004^{*}$ |
| | (0.003) | (0.001) | (0.003) |
| | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | $0.044^{***}$ | $0.014^{**}$ | 0.008 |
| | (0.010) | (0.007) | (0.009) |
| $\widehat{\delta}$ | $-0.005$ | $-0.002$ | $0.017^{*}$ |
| | (0.008) | (0.005) | (0.010) |
| $\widehat{\varphi}$ | $0.011^{***}$ | 0.001 | 0.002 |
| | (0.003) | (0.002) | (0.002) |
| | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | | |
| $\widehat{\kappa}$ | $0.018^{**}$ | 0.019 | $0.024^{*}$ |
| | (0.009) | (0.024) | (0.017) |
| $\widehat{\lambda}_\pi$ | $0.538^{***}$ | 0.243 | 0.071 |
| | (0.180) | (0.233) | (0.066) |
| $\widehat{\delta}$ | $-0.007^{*}$ | $-0.003$ | $0.008^{*}$ |
| | (0.005) | (0.007) | (0.006) |
| $\widehat{\varphi}$ | $0.007^{**}$ | 0.001 | $0.002^{*}$ |
| | (0.004) | (0.003) | (0.001) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation less of both $y_t$ and $\pi_t^{oil}$ in each subsample Newey-West standard errors are shown in parentheses. Due to limited data availability, the estimation for the Great Inflation Era starts in 1961.q3.

Table C9: NKPC estimates using core PCE inflation (2 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | | D. Survey data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | $-0.019^{*}$ | $-0.009$ |
| | | (0.012) | (0.012) |
| $\widehat{\delta}$ | | 0.000 | $0.013^{*}$ |
| | | (0.005) | (0.008) |
| $\widehat{\varphi}$ | | $-0.002^{**}$ | 0.000 |
| | | (0.001) | (0.002) |
| $\widehat{c}$ | | $-0.001^{***}$ | $-0.001^{***}$ |
| | | (0.000) | (0.000) |
| | | 5-y MSC[1] | |
| $\widehat{\kappa}$ | | 0.008 | $0.042^{***}$ |
| | | (0.009) | (0.011) |
| $\widehat{\delta}$ | | 0.000 | 0.004 |
| | | (0.003) | (0.004) |
| $\widehat{\varphi}$ | | 0.000 | $0.003^{***}$ |
| | | (0.001) | (0.001) |
| $\widehat{c}$ | | $-0.005^{***}$ | $-0.003^{***}$ |
| | | (0.000) | (0.000) |
| | | 10-y SPF[2] | |
| $\widehat{\kappa}$ | | 0.015 | $0.026^{***}$ |
| | | (0.016) | (0.008) |
| $\widehat{\delta}$ | | 0.011 | $0.005^{*}$ |
| | | (0.006) | (0.003) |
| $\widehat{\varphi}$ | | 0.000 | $0.002^{***}$ |
| | | (0.003) | (0.000) |
| $\widehat{c}$ | | $-0.002$ | $-0.002^{***}$ |
| | | (0.000) | (0.000) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. [1]Great Moderation subsample starts in 1990.q3. [2]Great Moderation subsample starts in 1990.q3. Due to limited data availability, the estimation for the Great Inflation Era starts in 1961.q3.

## C.6 Alternative Instruments Set

Tables C10 and C11 show the estimation results when we replace our baseline instruments set from Section 3 with a larger set of instruments, consisting of four lags of core CPI inflation, two lags of wage inflation, the CBO output gap, and oil price inflation. For the specifications using survey data, we add one lag of survey expectations to the set of instruments. As shown, the use of a larger set of instruments does not change any of our basic results.

Table C10: NKPC estimates using alternative instruments (1 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | A. Hybrid RE[1]: $\widetilde{E}_t\pi_{t+1} = \gamma_f\, E_t\pi_{t+1} + \left(1-\gamma_f\right)\pi_{t-1}$ | | |
| $\widehat{\kappa}$ | $-0.071^{***}$ | $-0.003$ | $0.009^{*}$ |
| | (0.020) | (0.012) | (0.006) |
| $\widehat{\gamma}_f$ | $1.235^{***}$ | $0.694^{***}$ | $0.789^{***}$ |
| | (0.148) | (0.113) | (0.122) |
| $\widehat{\delta}$ | $0.037^{**}$ | $-0.015^{***}$ | $0.013^{***}$ |
| | (0.021) | (0.006) | (0.005) |
| $\widehat{\varphi}$ | $-0.016^{***}$ | 0.000 | $-0.003^{***}$ |
| | (0.006) | (0.002) | (0.001) |
| | B. Backward-looking: $\widetilde{E}_t\pi_{t+1} = \left(\pi_{t-1}+\pi_{t-2}+\pi_{t-3}+\pi_{t-4}\right)/4$ | | |
| $\widehat{\kappa}$ | $0.080^{***}$ | $0.036^{***}$ | $0.022^{***}$ |
| | (0.018) | (0.010) | (0.008) |
| $\widehat{\delta}$ | $-0.021^{*}$ | $-0.015^{***}$ | $0.011^{***}$ |
| | (0.015) | (0.005) | (0.003) |
| $\widehat{\varphi}$ | $0.017^{***}$ | $0.004^{**}$ | $-0.003^{***}$ |
| | (0.004) | (0.002) | (0.001) |
| | C. Signal-extraction: $\widetilde{E}_t\pi_{t+1} = \widetilde{E}_{t-1}\pi_t + \lambda_\pi(\pi_t - \widetilde{E}_{t-1}\pi_t)$ | | |
| $\widehat{\kappa}$ | $0.075^{***}$ | $0.036^{**}$ | $0.061^{***}$ |
| | (0.014) | (0.017) | (0.009) |
| $\widehat{\lambda}_\pi$ | $0.232^{***}$ | $0.101^{**}$ | 0.000 |
| | (0.058) | (0.052) | (0.006) |
| $\widehat{\delta}$ | $-0.022^{*}$ | $-0.020^{***}$ | $0.012^{***}$ |
| | (0.014) | (0.006) | (0.003) |
| $\widehat{\varphi}$ | $0.009^{***}$ | $0.006^{***}$ | $-0.003^{**}$ |
| | (0.001) | (0.002) | (0.001) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). [1]Due to the lead term $\pi_{t+1}$, the hybrid RE model uses one less observation of both $y_t$ and $\pi_t^{oil}$ in each subsample. Newey-West standard errors are shown in parentheses.

Table C11: NKPC estimates using alternative instruments (2 of 2)

| | Great Inflation Era 1960.q1 to 1983.q4 | Great Moderation Era 1984.q1 to 2007.q3 | Great Recession Era 2007.q4 to 2019.q2 |
|---|---|---|---|
| | | D. Survey data | |
| | | 1-q SPF | |
| $\widehat{\kappa}$ | | 0.001 | 0.021** |
| | | (0.023) | (0.010) |
| $\widehat{\delta}$ | | −0.021*** | 0.003* |
| | | (0.004) | (0.002) |
| $\widehat{\varphi}$ | | 0.000 | −0.004*** |
| | | (0.002) | (0.001) |
| $\widehat{c}$ | | 0.000 | 0.000** |
| | | (0.000) | (0.000) |
| | | 5-y MSC[1] | |
| $\widehat{\kappa}$ | | 0.014 | 0.048*** |
| | | (0.016) | (0.011) |
| $\widehat{\delta}$ | | −0.015*** | 0.008*** |
| | | (0.004) | (0.003) |
| $\widehat{\varphi}$ | | 0.006*** | −0.005*** |
| | | (0.002) | (0.000) |
| $\widehat{c}$ | | −0.003*** | −0.002*** |
| | | (0.000) | (0.000) |
| | | 10-y SPF[2] | |
| $\widehat{\kappa}$ | | 0.049*** | 0.059*** |
| | | (0.012) | (0.010) |
| $\widehat{\delta}$ | | 0.000 | 0.012*** |
| | | (0.003) | (0.003) |
| $\widehat{\varphi}$ | | −0.008*** | −0.004*** |
| | | (0.002) | (0.001) |
| $\widehat{c}$ | | 0.000 | 0.000 |
| | | (0.000) | (0.000) |
| Obs. | 96 | 95 | 47 |

Notes: The asterisks ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. The estimation uses quarterly inflation rates (not annualized). Newey-West standard errors are shown in parentheses. [1]Great Moderation subsample starts in 1990.q3. [2]Great Moderation subsample starts in 1992.q1.

# D Appendix: Exogenous anchoring

## D.1 Simplified model

The signal-extraction model is given by

$$\begin{aligned}
\pi_t &= \beta \widetilde{E}_t \pi_{t+1} + \kappa y_t + u_t, && \text{(D.1)}\\
y_t &= \widetilde{E}_t y_{t+1} - \alpha(i_t - \widetilde{E}_t \pi_{t+1}) + v_t, && \text{(D.2)}\\
i_t &= \mu_\pi \widetilde{E}_t \pi_{t+1} + \mu_y \widetilde{E}_t y_{t+1}, && \text{(D.3)}\\
\widetilde{E}_t \pi_{t+1} &= \widetilde{E}_{t-1} \pi_t + \lambda_\pi (\pi_t - \widetilde{E}_{t-1} \pi_t), && \text{(D.4)}\\
\widetilde{E}_t y_{t+1} &= \widetilde{E}_{t-1} y_t + \lambda_y (y_t - \widetilde{E}_{t-1} y_t). && \text{(D.5)}
\end{aligned}$$

Assuming $\lambda_y \to 0$ and $\widetilde{E}_{t-2}\pi_{t-1} \simeq 0$, the simplified signal-extraction model can be written as:

$$\pi_t = \frac{\widehat{\beta}\,(1-\lambda_\pi)\,\lambda_\pi}{1-\widehat{\beta}\lambda_\pi}\,\pi_{t-1} + \frac{\kappa}{1-\widehat{\beta}\lambda_\pi}\,v_t + \frac{1}{1-\widehat{\beta}\lambda_\pi}\,u_t \tag{D.6}$$

$$y_t = -\frac{\alpha\,(\mu_\pi-1)\,(1-\lambda_\pi)\,\lambda_\pi}{1-\widehat{\beta}\lambda_\pi}\,\pi_{t-1} + \frac{1-\beta\lambda_\pi}{1-\widehat{\beta}\lambda_\pi}\,v_t - \frac{\alpha\,(\mu_\pi-1)\,\lambda_\pi}{1-\widehat{\beta}\lambda_\pi}\,u_t, \tag{D.7}$$

where $\widehat{\beta} \equiv \beta - \kappa\alpha\,(\mu_\pi - 1)\,.$

Starting from equations (D.6) and (D.7), we have

$$Cov\,(\pi_t, y_t) = -\tfrac{\alpha(\mu_\pi-1)\widehat{\beta}(1-\lambda_\pi)^2\lambda_\pi^2}{(1-\widehat{\beta}\lambda_\pi)^2}\,Var\,(\pi_{t-1}) + \tfrac{\kappa(1-\beta\lambda_\pi)}{(1-\widehat{\beta}\lambda_\pi)^2}\,\sigma_v - \tfrac{\alpha(\mu_\pi-1)\lambda_\pi}{(1-\widehat{\beta}\lambda_\pi)^2}\,\sigma_u \tag{D.8}$$

$$Var\,(\pi_{t-1}) = \tfrac{\kappa^2}{(1-\widehat{\beta}\lambda_\pi)^2-[\widehat{\beta}(1-\lambda_\pi)\lambda_\pi]^2}\,\sigma_v + \tfrac{1}{(1-\widehat{\beta}\lambda_\pi)^2-[\widehat{\beta}(1-\lambda_\pi)\lambda_\pi]^2}\,\sigma_u, \tag{D.9}$$

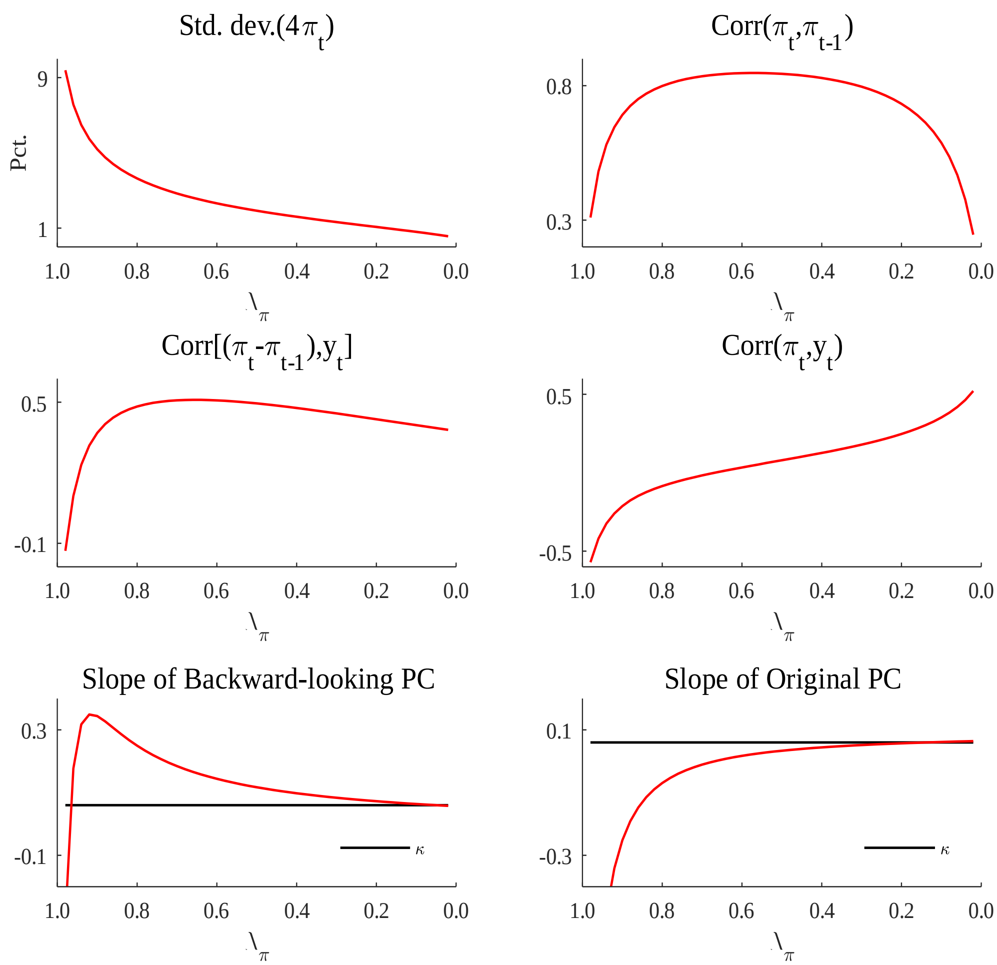
## D.2 Full model

Figure 9 plots inflation moments for different values of $\lambda_\pi \in (0,1]$. Other parameters are held fixed at the baseline values shown in Table 5 with $\lambda_y = 0.222$. The top left panel shows that improved anchoring will unambiguously reduce inflation volatility. The top right panel of Figure 9 shows that an exogenous decline in $\lambda_\pi$ can have nonmonotonic effects on inflation persistence, as measured by $Corr\,(\pi_t, \pi_{t-1})$. Intuitively, as $\lambda_\pi \to 1$, the weight on lagged inflation rates in the signal-extraction forecast rule (9) will approach zero and inflation persistence will be low. On the other hand, as $\lambda_\pi \to 0$, expected inflation becomes constant, causing inflation persistence to be low. Away from these limits, inflation persistence will be higher, giving rise to the hump-shaped pattern in $Corr\,(\pi_t, \pi_{t-1})$.

The bottom four panels of Figure 9 plot the correlation coefficients $Corr\,(\Delta\pi_{t,}y_t)$ and $Corr\,(\pi_{t,}y_t)$ and the reduced-form slope coefficients $Cov\,(\Delta\pi_{t,}y_t)\,/Var\,(y_t)$ and $Cov\,(\pi_{t,}y_t)\,/Var\,(y_t)$ as $\lambda_\pi$ declines from 1 to 0. The empirically-relevant case for the recent U.S. economy is characterized by relatively low values of $\lambda_\pi$. In this case, lower values of $\lambda_\pi$ serve to decrease $Corr\,(\Delta\pi_{t,}y_t)$ and $Cov\,(\Delta\pi_{t,}y_t)\,/Var\,(y_t)$, making the backward-looking Phillips curve appear flatter. At the same time, lower values of $\lambda_\pi$ serve to increase $Corr\,(\pi_{t,}y_t)$ and $Cov\,(\pi_{t,}y_t)\,/Var\,(y_t)$, making the original Phillips curve appear steeper.

When $\lambda_\pi \to 0$, the slope of the original Phillips curve will converge to the true structural slope parameter such that $Cov\,(\pi_{t,}y_t)\,/Var\,(y_t) = \kappa$. This occurs because $\lambda_\pi \to 0$ serves to eliminate the negative contributions to $Cov\,(\pi_t, y_t)$ that derive from the first and third terms in equation (D.8). At the same time, $\lambda_\pi \to 0$ causes the slope of the backward-looking Phillips curve to converge to a level that is *below* the true structural slope parameter such that $Cov\,(\Delta\pi_{t,}y_t)\,/Var\,(y_t) < \kappa$.

Figure 9: *Effects of an Exogenous Improvement in the Anchoring of Expected Inflation*




The figure plots the effects of exogenous changes in the degree of anchoring of expected inflation, as measured by $\lambda_\pi$. Other parameters are held fixed at the baseline values shown in Table 5 with $\lambda_y = 0.222$.