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Inflation in the Great Recession and New Keynesian Models†

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Several prominent economists have argued that existing DSGE models cannot properly account for the evolution of key macroeconomic variables during and following the recent Great Recession. We challenge this argument by showing that a standard DSGE model with financial frictions available prior to the recent crisis successfully predicts a sharp contraction in economic activity along with a protracted but relatively modest decline in inflation, following the rise in financial stress in 2008:IV. The model does so even though inflation remains very dependent on the evolution of economic activity and of monetary policy. (*JEL* E12, E31, E32, E37, E44, E52, G01)

As dramatic as the recent Great Recession has been, it constitutes a potential test for existing macroeconomic models. Prominent researchers have argued that existing DSGE models cannot properly account for the evolution of key macroeconomic variables during and following the crisis. For instance, Hall (2011), in his Presidential Address, has called for a fundamental reconsideration of models in which inflation depends on a measure of slack in economic activity. He suggests that all theories based on the concept of the nonaccelerating inflation rate of unemployment, or NAIRU, predict deflation as long as the unemployment rate remains above a natural rate of, say, 6 percent. Since inflation declined somewhat in early 2009 but then remained positive, Hall (2011) argues that such theories based on a concept of slack must be wrong. Most notably, he states that popular DSGE models based on the simple New Keynesian Phillips curve, according to which prices are set on the basis of a markup over expected future marginal costs, "cannot explain the stabilization of inflation at positive rates in the presence of long-lasting slack" as they rely on a NAIRU principle. Hall (2011) thus concludes that inflation behaves in a nearly exogenous fashion.

Similarly, Ball and Mazumder (2011) argue that Phillips curves estimated over the 1960–2007 period in the United States cannot explain the behavior of inflation in

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the 2008–2010 period. Moreover, they conclude that the "Great Recession provides fresh evidence against the New Keynesian Phillips curve with rational expectations." They stress the fact that the fit of that equation deteriorates once data for the years 2008–2010 are added to the sample. One of the reasons for this is that the labor share, a proxy for firms' marginal costs, declines dramatically during the crisis, resulting in a change in the comovement with other measures of slack, such as the unemployment rate. A further challenge to the New Keynesian Phillips curve (henceforth, NKPC) is raised by King and Watson (2012), who find a large discrepancy between the inflation predicted by a popular DSGE model, the Smets and Wouters (2007) model, and actual inflation. They thus conclude that the model can successfully explain the behavior of inflation only when assuming the existence of large exogenous markup shocks. This is disturbing to the extent that such markup shocks are difficult to interpret and have small effects on variables other than inflation.

In this paper, we use such a standard DSGE model, which was available prior to the recent crisis and that is estimated with data up to 2008, to explain the behavior of output growth, inflation, and marginal costs since the crisis. The model used is the Smets and Wouters (2007) model, based on Christiano, Eichenbaum, and Evans (2005), extended to include financial frictions as in Bernanke, Gertler, and Gilchrist (1999) and Christiano, Motto, and Rostagno (2003, 2014). We show that as soon as financial stress jumps in the fall of 2008, the model successfully predicts a sharp contraction in economic activity along with a relatively modest and protracted decline in inflation. Price changes are projected to remain in the neighborhood of 1 percent. This result contrasts with the claim set forth by Hall (2011), Ball and Mazumder (2011), and others that New Keynesian models are bound to fail to capture the broad contours of the Great Recession and the near stability of inflation.

According to the NKPC, inflation is determined by the discounted sum of future expected marginal costs (fundamental inflation). The key to understanding our result is that inflation is more dependent on expected future marginal costs than on the current level of economic activity. Even though GDP and marginal costs contracted by the end of 2008, we show that monetary policy has in fact been sufficiently stimulative to ensure that marginal costs are expected to eventually rise. While—with hindsight—the DSGE model understates the observed drop in marginal costs, conditioning on the realized drop in marginal costs leads to a moderate downward revision of the inflation forecast, but not to a prediction of an extended period of deflation. This result stands in sharp contrast to an analysis based on backward-looking Phillips curve models, which indeed predict a strong deflation conditional on the observed slack in the economy.

From an ex post perspective, we decompose the forecast errors made by our DSGE models into errors due to markup shocks and nonmarkup shocks. While the nonmarkup shocks explain the observed drop in marginal costs, they contribute to a reduction in the inflation forecast by only about 0.8 percentage points, substantiating our argument that the absence of deflation after 2008 is broadly consistent with a DSGE model that is built around an NKPC.

Because the relationship between inflation and future marginal costs is the defining characteristic of the NKPC, we carefully document that, unlike in King and Watson (2012), the DSGE model with financial frictions generates a measure of fundamental inflation that has been accurately tracking the low- and medium-frequency movements of inflation since 1964, lending credibility to the NKPC relationship. Markup shocks are only needed to capture the high frequency movements of inflation, such as those attributable to temporary energy price changes. A key reason for the difference is that our estimated model involves a higher degree of price rigidities than is the case in Smets and Wouters (2007). This results in endogenous and more persistent marginal costs, which, in turn, allow our model to explain inflation with much smaller markup shocks. Yet, while the slope of the short-run Phillips curve is lower in our model than in Smets and Wouters (2007), monetary policy still has important effects on inflation.

Several recent papers provide alternative (and complementary) explanations in the context of New Keynesian models as to why inflation did not fall in the Great Recession. In Christiano, Eichenbaum, and Trabandt (2014), inflation does not decline much because their model features a working capital channel, implying that higher spreads feed directly into higher marginal costs. In addition, they assume a substantial drop in total factor productivity relative to prerecession trends that leads to higher inflation. In contrast, in our story, the shocks driving the Great Recession cause a large and persistent slack in the economy after 2008, with actual output being well below the corresponding level that would be obtained if prices and wages were flexible.[1] Gilchrist et al. (2013) describe a mechanism with heterogeneous firms where financial frictions affect pricing decisions, so that firms with a tightly binding credit constraint optimally choose to raise prices following an adverse credit shock. Instead of solving the NKPC forward, Coibion and Gorodnichenko (2013) replace the inflation-expectations term in the NKPC with household survey expectations, which rose sharply after 2009, in part in response to energy price movements. They argue that this rise in inflation expectations explains much of the "missing" deflation.

The remainder of this paper is organized as follows. Section I presents the DSGE model used for the empirical analysis, defines the concept of fundamental inflation, and discusses how we solve the model post 2008 to account for the zero lower bound on interest rates and the forward guidance. Forecasts of output growth, inflation, marginal costs, and interest rates for the period from 2009 to 2012 are presented in Section II. Section III examines the ex post forecast errors, demonstrating that nonmarkup shocks explain the drop in marginal costs but do not lead to a substantial downward revision of the inflation forecast, as expectations of future expansionary policy keeps inflation relatively anchored. In Section IV, we examine various aspects of the relationship between inflation and marginal cost forecasts, such as the sensitivity of marginal cost forecasts to the level of price rigidity and to the strength of the central bank's reaction to inflation fluctuations. We show that the DSGE model-implied fundamental inflation is able to track actual inflation, and we assess the DSGE model's marginal cost forecasts over time. Finally, Section V concludes. Information on the construction of the dataset used for the empirical analysis, as

[1] Christiano, Eichenbaum, and Rebelo (2011) use the model in Altig et al. (2011), which is similar to the one used here but without financial frictions, to generate simulations of the Great Recession taking the zero lower bound on interest rates into account. While they focus on the effects of fiscal policy, they also find that inflation declines only modestly in their model, in part because, as is the case here, their estimated Phillips curve is relatively flat. In their model the flatness of the Phillips curve partly results from the assumption of firm-specific capital.

well as detailed estimation results and supplementary tables and figures, is available in the online Appendix.

I. The DSGE Model

The model considered in this paper is an extension of the model developed in Smets and Wouters (2007) (SW model), which is in turn based on earlier work by Christiano, Eichenbaum, and Evans (2005). The SW model is a medium-scale DSGE model that augments the standard neoclassical stochastic growth model with nominal price and wage rigidities as well as habit formation in consumption and investment adjustment costs. We extend the SW model by allowing for a time-varying target inflation rate and incorporating financial frictions as in Bernanke, Gertler, and Gilchrist (1999) and Christiano, Motto, and Rostagno (2003, 2014). The ingredients of our DSGE model were publicly available prior to 2008. As a result, the model does not include some of the mechanisms that have been developed more recently in response to the financial crisis. The specification of the model is presented in Section IA. An important concept for our empirical analysis is the so-called fundamental inflation, which is defined in Section IB. The dataset as well as the prior distribution used for the estimation is discussed in Section IC. Finally, Section ID discusses how the DSGE model is solved to generate forecasts as of 2008:IV and how it is solved to examine the 2009–2012 data in view of the zero lower bound on nominal interest rates and the forward guidance policy pursued by the Federal Reserve.

A. *DSGE Model Specification*

Since the derivation of the SW model is discussed in detail in Christiano, Eichenbaum, and Evans (2005) we only present a summary of the log-linearized equilibrium conditions. We first reproduce the equilibrium conditions for the SW model and then discuss the two extensions that underlie the DSGE model used for our empirical analysis. We refer to our model as SWFF, where FF highlights the presence of financial frictions.

The SW Model.—Let $\tilde{z}_t$ be the linearly detrended log productivity process that follows the autoregressive law of motion

$$(1) \qquad \tilde{z}_t = \rho_z \tilde{z}_{t-1} + \sigma_z \varepsilon_{z,t}.$$

Following Del Negro and Schorfheide (2013) we detrend all nonstationary variables by $Z_t = e^{\gamma t + \frac{1}{1-\alpha}\tilde{z}_t}$, where γ is the steady-state growth rate of the economy. The growth rate of Z_t in deviations from γ, denoted by z_t, follows the process:

$$(2) \qquad z_t = \ln(Z_t/Z_{t-1}) - \gamma = \frac{1}{1-\alpha}(\rho_z - 1)\tilde{z}_{t-1} + \frac{1}{1-\alpha}\sigma_z \epsilon_{z,t}.$$

All variables in the following equations are expressed in log deviations from their nonstochastic steady state. Steady-state values are denoted by $*$-subscripts and steady-state formulas are provided in the technical Appendix of Del Negro and

Schorfheide (2013), which is available online. The consumption Euler equation is given by

$$(3)\quad c_t = -\frac{(1 - he^{-\gamma})}{\sigma_c(1 + he^{-\gamma})}(R_t - E_t[\pi_{t+1}] + b_t) + \frac{he^{-\gamma}}{(1 + he^{-\gamma})}(c_{t-1} - z_t)$$

$$+ \frac{1}{(1 + he^{-\gamma})}E_t[c_{t+1} + z_{t+1}] + \frac{(\sigma_c - 1)}{\sigma_c(1 + he^{-\gamma})}\frac{w_* l_*}{c_*}(l_t - E_t[l_{t+1}]),$$

where c_t is consumption, l_t is labor supply, R_t is the nominal interest rate, and π_t is inflation. The exogenous process b_t drives a wedge between the intertemporal ratio of the marginal utility of consumption and the riskless real return $R_t - E_t[\pi_{t+1}]$, and follows an AR(1) process with parameters ρ_b and σ_b. The parameters σ_c and h capture the degree of relative risk aversion and the degree of habit persistence in the utility function, respectively. The following condition expresses the relationship between the value of capital in terms of consumption q_t^k and the level of investment i_t measured in terms of consumption goods:

$$(4)\quad q_t^k = S''e^{2\gamma}(1 + \bar{\beta})\left(i_t - \frac{1}{1 + \bar{\beta}}(i_{t-1} - z_t) - \frac{\bar{\beta}}{1 + \bar{\beta}}E_t[i_{t+1} + z_{t+1}] - \mu_t\right),$$

which is affected by both the investment adjustment cost (S'' is the second derivative of the adjustment cost function) and by μ_t, an exogenous process called the "marginal efficiency of investment," which affects the rate of transformation between consumption and installed capital (see Greenwood, Hercowitz, and Krusell 1997). The exogenous process μ_t follows an AR(1) process with parameters ρ_μ and σ_μ. The parameter $\bar{\beta} = \beta e^{(1-\sigma_c)\gamma}$ depends on the intertemporal discount rate in the utility function of the households β, the degree of relative risk aversion σ_c, and the steady-state growth rate γ.

The capital stock, $\bar{k}_t$, evolves as

$$(5)\qquad \bar{k}_t = \left(1 - \frac{i_*}{\bar{k}_*}\right)(\bar{k}_{t-1} - z_t) + \frac{i_*}{\bar{k}_*}i_t + \frac{i_*}{\bar{k}_*}S''e^{2\gamma}(1 + \bar{\beta})\mu_t,$$

where $i_*/\bar{k}_*$ is the steady-state ratio of investment to capital. The arbitrage condition between the return to capital and the riskless rate is

$$(6)\quad \frac{r_*^k}{r_*^k + (1 - \delta)}E_t[r_{t+1}^k] + \frac{1 - \delta}{r_*^k + (1 - \delta)}E_t[q_{t+1}^k] - q_t^k = R_t + b_t - E_t[\pi_{t+1}],$$

where r_t^k is the rental rate of capital, r_*^k its steady-state value, and δ the depreciation rate. Given that capital is subject to variable capacity utilization u_t, the relationship between $\bar{k}_t$ and the amount of capital effectively rented out to firms k_t is

$$(7)\qquad k_t = u_t - z_t + \bar{k}_{t-1}.$$

The optimality condition determining the rate of utilization is given by

$$(8) \qquad \frac{1-\psi}{\psi} r_t^k = u_t,$$

where ψ captures the utilization costs in terms of forgone consumption. Real marginal costs for firms are given by

$$(9) \qquad mc_t = w_t + \alpha l_t - \alpha k_t,$$

where w_t is the real wage and α is the income share of capital (after paying markups and fixed costs) in the production function. From the optimality conditions of goods producers, it follows that all firms have the same capital-labor ratio:

$$(10) \qquad k_t = w_t - r_t^k + l_t.$$

The production function is

$$(11) \qquad y_t = \Phi_p\big(\alpha k_t + (1-\alpha) l_t\big) + \mathcal{I}\{\rho_z < 1\}(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t,$$

if the log productivity is trend stationary. The last term $(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t$ drops out if technology has a stochastic trend, because in this case one has to assume that the fixed costs are proportional to the trend. Similarly, the resource constraint is

$$(12) \qquad y_t = g_t + \frac{c_*}{y_*}c_t + \frac{i_*}{y_*}i_t + \frac{r_*^k k_*}{y_*}u_t - \mathcal{I}\{\rho_z < 1\}\frac{1}{1-\alpha}\tilde{z}_t,$$

where again the term $-\frac{1}{1-\alpha}\tilde{z}_t$ disappears if technology follows a unit root process. Government spending g_t is assumed to follow the exogenous process

$$g_t = \rho_g g_{t-1} + \sigma_g \varepsilon_{g,t} + \eta_{gz}\sigma_z \varepsilon_{z,t}.$$

Finally, the price and wage Phillips curves are, respectively,

$$(13) \qquad \pi_t = \kappa\, mc_t + \frac{\iota_p}{1+\iota_p\bar{\beta}}\pi_{t-1} + \frac{\bar{\beta}}{1+\iota_p\bar{\beta}}E_t[\pi_{t+1}] + \lambda_{f,t},$$

and

$$(14) \qquad w_t = \frac{(1-\zeta_w\bar{\beta})(1-\zeta_w)}{(1+\bar{\beta})\zeta_w((\lambda_w - 1)\epsilon_w + 1)}\big(w_t^h - w_t\big) - \frac{1+\iota_w\bar{\beta}}{1+\bar{\beta}}\pi_t + \frac{1}{1+\bar{\beta}}\big(w_{t-1} - z_t + \iota_w\pi_{t-1}\big) + \frac{\bar{\beta}}{1+\bar{\beta}}E_t\big[w_{t+1} + z_{t+1} + \pi_{t+1}\big] + \lambda_{w,t},$$

where

$$\kappa = \frac{(1 - \zeta_p\bar{\beta})(1 - \zeta_p)}{(1 + \iota_p\bar{\beta})\zeta_p((\Phi_p - 1)\epsilon_p + 1)},$$

the parameters ζ_p, ι_p, and ϵ_p are the Calvo parameter, the degree of indexation, and the curvature parameter in the Kimball aggregator for prices, and ζ_w, ι_w, and ϵ_w are the corresponding parameters for wages. w_t^h measures the household's marginal rate of substitution between consumption and labor, and is given by

$$w_t^h = \frac{1}{1 - he^{-\gamma}}\left(c_t - he^{-\gamma}c_{t-1} + he^{-\gamma}z_t\right) + \nu_l l_t, \tag{15}$$

where ν_l characterizes the curvature of the disutility of labor (and would equal the inverse of the Frisch elasticity in the absence of wage rigidities). The markups $\lambda_{f,t}$ and $\lambda_{w,t}$ follow exogenous ARMA(1,1) processes

$$\lambda_{f,t} = \rho_{\lambda_f}\lambda_{f,t-1} + \sigma_{\lambda_f}\varepsilon_{\lambda_f,t} - \eta_{\lambda_f}\sigma_{\lambda_f}\varepsilon_{\lambda_f,t-1}, \text{ and}$$

$$\lambda_{w,t} = \rho_{\lambda_w}\lambda_{w,t-1} + \sigma_{\lambda_w}\varepsilon_{\lambda_w,t} - \eta_{\lambda_w}\sigma_{\lambda_w}\varepsilon_{\lambda_w,t-1},$$

respectively. Finally, the monetary authority follows a generalized feedback rule,

$$\begin{aligned} R_t = {} & \rho_R R_{t-1} + (1 - \rho_R)\left(\psi_1\pi_t + \psi_2\left(y_t - y_t^f\right)\right) \\ & + \psi_3\left(\left(y_t - y_t^f\right) - \left(y_{t-1} - y_{t-1}^f\right)\right) + r_t^m, \end{aligned} \tag{16}$$

where the flexible price/wage output y_t^f is obtained from solving the version of the model without nominal rigidities (that is, equations (3) through (12) and (15)), and the residual r_t^m follows an AR(1) process with parameters ρ_{r^m} and σ_{r^m}.

Time-Varying Target Inflation and Long-Run Inflation Expectations.—In order to capture the rise and fall of inflation and interest rates in the estimation sample, we replace the constant target inflation rate by a time-varying target inflation rate. While time-varying target rates have been frequently used for the specification of monetary policy rules in DSGE models (e.g., Erceg and Levin 2003 and Smets and Wouters 2003, among others), we follow the approach of Aruoba and Schorfheide (2008) and Del Negro and Eusepi (2011), and include data on long-run inflation expectations as an observable in the estimation of the DSGE model. At each point in time, the long-run inflation expectations essentially determine the level of the target inflation rate. To the extent that long-run inflation expectations at the forecast origin contain information about the central bank's objective function, e.g., the desire to stabilize inflation at 2 percent, this information is automatically included in the forecast.

More specifically, for the SW model the interest-rate feedback rule of the central bank (16) is modified as follows:

$$R_t = \rho_R R_{t-1} + (1 - \rho_R)\big(\psi_1(\pi_t - \pi_t^*) + \psi_2(y_t - y_t^f)\big) + \psi_3\big((y_t - y_t^f) - (y_{t-1} - y_{t-1}^f)\big) + r_t^m. \tag{17}$$

The time-varying inflation target evolves according to

$$\pi_t^* = \rho_{\pi^*}\pi_{t-1}^* + \sigma_{\pi^*}\varepsilon_{\pi^*,t}, \tag{18}$$

where $0 < \rho_{\pi^*} < 1$ and $\epsilon_{\pi^*,t}$ is an independently and identically distributed shock. We model π_t^* as a stationary process, although our prior for ρ_{π^*} forces this process to be highly persistent. The assumption that the changes in the target inflation rate are exogenous is, to some extent, a short cut. For instance, the learning models of Sargent (1999) or Primiceri (2006) imply that the rise in the target inflation rate in the 1970s and the subsequent drop are due to policy makers' learning about the output-inflation trade-off and trying to set inflation optimally. We are abstracting from such a mechanism in our specification.

Financial Frictions.—Building on the work of Bernanke, Gertler, and Gilchrist (1999); Christiano, Motto, and Rostagno (2003, 2014); and De Graeve (2008), we also add financial frictions to our DSGE model. We assume that banks collect deposits from households and lend to entrepreneurs who use these funds as well as their own wealth to acquire physical capital, which is rented to intermediate goods producers. Entrepreneurs are subject to idiosyncratic disturbances that affect their ability to manage capital. Their revenue may thus be too low to pay back the bank loans. Banks protect themselves against default risk by pooling all loans and charging a spread over the deposit rate. This spread may vary as a function of the entrepreneurs' leverage and their riskiness. Adding these frictions to the SW model amounts to replacing equation (6) with the following conditions:

$$E_t\big[\tilde{R}_{t+1}^k - R_t\big] = b_t + \zeta_{sp,b}\big(q_t^k + \bar{k}_t - n_t\big) + \tilde{\sigma}_{\omega,t} \tag{19}$$

and

$$\tilde{R}_t^k - \pi_t = \frac{r_*^k}{r_*^k + (1-\delta)} r_t^k + \frac{(1-\delta)}{r_*^k + (1-\delta)} q_t^k - q_{t-1}^k, \tag{20}$$

where $\tilde{R}_t^k$ is the gross nominal return on capital for entrepreneurs, n_t is entrepreneurial equity, and $\tilde{\sigma}_{\omega,t}$ captures mean-preserving changes in the cross-sectional dispersion of ability across entrepreneurs (see Christiano, Motto, and Rostagno 2014) and follows an AR(1) process with parameters ρ_{σ_ω} and σ_{σ_ω}. The second condition defines the return on capital, while the first one determines the spread between the expected return on capital and the riskless rate. Note that if $\zeta_{sp,b} = 0$ and the financial friction shocks $\tilde{\sigma}_{\omega,t}$ are zero, (19) and (20) coincide with (6). The following condition describes the evolution of entrepreneurial net worth:

$$n_t = \zeta_{n,\tilde{R}^k}\left(\tilde{R}_t^k - \pi_t\right) - \zeta_{n,R}\left(R_{t-1} - \pi_t\right) + \zeta_{n,qK}\left(q_{t-1}^k + \bar{k}_{t-1}\right) + \zeta_{n,n}n_{t-1} - \frac{\zeta_{n,\sigma_\omega}}{\zeta_{sp,\sigma_\omega}}\tilde{\sigma}_{\omega,t-1} - \gamma_* \frac{v_*}{n_*}\hat{z}_t. \tag{21}$$

B. *Fundamental Inflation*

To understand the behavior of inflation, it will be useful to extract from the model-implied inflation series an estimate of "fundamental inflation" as in King and Watson (2012), and similar to Galí and Gertler (1999) and Sbordone (2005). To obtain this measure, we define $\Delta_{\iota_p}\pi_t = \pi_t - \iota_p\pi_{t-1}$, and rewrite the expression for the Phillips curve (13) as follows:

$$\Delta_{\iota_p}\pi_t = \bar{\beta}E_t[\Delta_{\iota_p}\pi_{t+1}] + (1 + \iota_p\bar{\beta})\left(\kappa\, mc_t + \lambda_{f,t}\right). \tag{22}$$

This difference equation can be solved forward to obtain

$$\Delta_{\iota_p}\pi_t = (1 + \iota_p\bar{\beta})\kappa \sum_{j=0}^{\infty} \bar{\beta}^j E_t[mc_{t+j}] + (1 + \iota_p\bar{\beta}) \sum_{j=0}^{\infty} \bar{\beta}^j E_t[\lambda_{f,t+j}]. \tag{23}$$

The first component captures the effect of the sum of discounted future marginal costs on current inflation, whereas the second term captures the contribution of future markup shocks. Defining

$$S_t^\infty = \sum_{j=0}^{\infty} \bar{\beta}^j E_t[mc_{t+j}], \tag{24}$$

we can decompose inflation into

$$\pi_t = \tilde{\pi}_t + \Lambda_{f,t}, \tag{25}$$

where

$$\tilde{\pi}_t = \kappa(1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1}S_t^\infty, \tag{26}$$

$$\Lambda_{f,t} = (1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1}\sum_{j=0}^{\infty}\bar{\beta}^j E_t[\lambda_{f,t+j}], \tag{27}$$

and L denotes the lag operator. We refer to the first term on the right-hand side of (25), $\tilde{\pi}_t$, as *fundamental inflation*. Fundamental inflation corresponds to the discounted sum of expected marginal costs (our measure differs slightly from that of Galí and Gertler 1999 and Sbordone 2005, who define fundamental inflation as $\tilde{\pi}_t = \iota_p\pi_t + \kappa(1 + \iota_p\bar{\beta})S_t^\infty$). Thus, our decomposition removes the direct effect of markup shocks from the observed inflation. Note, however, that the summands in (25) are not orthogonal. Fundamental inflation still depends on $\lambda_{f,t}$ indirectly, through the effect of the markup shock on current and future expected marginal costs.

C. *Data and Priors*

The estimation of the DSGE model is based on data on real output growth, consumption growth, investment growth, real wage growth, hours worked, inflation (as measured by the GDP deflator), interest rates, ten-year inflation expectations, and spreads. Measurement equations related the model variables that appeared in Section IA to the observables:

$$
\begin{aligned}
&\text{Output growth} &&= \gamma + 100(y_t - y_{t-1} + z_t)\\
&\text{Consumption growth} &&= \gamma + 100(c_t - c_{t-1} + z_t)\\
&\text{Investment growth} &&= \gamma + 100(i_t - i_{t-1} + z_t)\\
&\text{Real wage growth} &&= \gamma + 100(w_t - w_{t-1} + z_t)\\
&\text{Hours worked} &&= \bar{l} + 100 l_t\\
&\text{Inflation} &&= \pi_* + 100\pi_t\\
&\text{FFR} &&= R_* + 100 R_t\\
&\text{10y Infl Exp} &&= \pi_* + 100 E_t\left[\frac{1}{40}\sum_{k=1}^{40} \pi_{t+k}\right]\\
&\text{Spread} &&= SP_* + 100 E_t\left[\tilde{R}^k_{t+1} - R_t\right].
\end{aligned}
\tag{28}
$$

All variables are measured in percent. π_* and R_* measure the steady-state level of net inflation and short-term nominal interest rates, respectively, and $\bar{l}$ captures the mean of hours (this variable is measured as an index). The first seven series are commonly used in the estimation of the SW model. The Ten-year inflation expectations contain information about low-frequency inflation movements and are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters. As the spread variable we use a Baa Corporate Bond Yield spread over the Ten-Year Treasury Note Yield at constant maturity. Details on the construction of the dataset are provided in online Appendix AI.

We use Bayesian techniques in the subsequent empirical analysis, which require the specification of a prior distribution for the model parameters. For most of the parameters we use the same marginal prior distributions as Smets and Wouters (2007). There are two important exceptions. First, the original prior for the quarterly steady-state inflation rate π_* used by Smets and Wouters (2007) is tightly centered around 0.62 percent (which is about 2.5 percent annualized) with a standard deviation of 0.1 percent. We favor a looser prior, one that has less influence on the model's forecasting performance, that is centered at 0.75 percent and has a standard deviation of 0.4 percent. Second, for the financial frictions mechanism we specify priors for the parameters SP_*, $\zeta_{sp,b}$, ρ_{σ_ω}, and σ_{σ_ω}. We fix the parameters corresponding to the steady-state default probability and the survival rate of entrepreneurs, respectively. In turn, these parameters imply values for the parameters of (21). A summary of the priors is provided in Table A-1 in online Appendix AII.

D. *Forecasting and Ex Post Analysis*

Our empirical analysis essentially consists of two parts. In the first part, we are using the DSGE model to generate forecasts based on information that was available in 2008:IV, which is the quarter with the largest output growth drop during the Great Recession. These forecasts are generated from a version of the model that ignores the presence of the zero lower bound (ZLB) on nominal interest rates, which is partly justified on the grounds that the posterior mean prediction of the short-term interest rate does not violate the ZLB. The second part of the empirical analysis takes an ex post perspective and examines the shocks that have contributed to the errors associated with the 2008:IV forecasts. Ex post it turned out that the conduct of monetary policy changed after 2008. Policy was constrained by the ZLB, and, in order to alleviate this constraint, the central bank made announcements that it would deliberately keep the interest rate at zero for an extended period of time (forward guidance). In order to conduct the ex post analysis we use a solution method that accounts for the ZLB and forward guidance. Based on this solution we study the contributions of various types of aggregate shocks to macroeconomic fluctuations. In the remainder of this subsection we describe the information set used to generate the forecasts for the ex ante analysis as well as the solution method that is used for the ex post analysis. All of our analysis is based on modal forecasts. This is partly because a full-fledged characterization of the forecast distribution has already been conducted in Del Negro and Schorfheide (2013), and partly because explicitly considering parameter uncertainty would not change the main message of the paper.

Generating Forecasts of the Great Recession.—In order to generate forecasts using the information set of a DSGE-model forecaster in 2008:IV we use the method in Sims (2002) to solve the log-linear approximation of the DSGE model. We collect all the DSGE model parameters in the vector $\boldsymbol{\theta}$, stack the structural shocks in the vector ϵ_t, and derive a state-space representation for our vector of observables $\mathbf{y}_t$. The state-space representation is composed of a transition equation:

$$\mathbf{s}_t = \mathcal{T}(\boldsymbol{\theta})\mathbf{s}_{t-1} + \mathcal{R}(\boldsymbol{\theta})\epsilon_t, \tag{29}$$

which summarizes the evolution of the states $\mathbf{s}_t$, and a measurement equation

$$\mathbf{y}_t = \mathcal{Z}(\boldsymbol{\theta})\mathbf{s}_t + \mathcal{D}(\boldsymbol{\theta}), \tag{30}$$

which maps the states onto the vector of observables $\mathbf{y}_t$. This measurement equation expresses (28) in a more compact notation.

We use data from 1964:I to 2008:III to obtain posterior mode estimates of the DSGE model parameters $\boldsymbol{\theta}$. These estimates are reported in Table A-2 in online Appendix AII. We refer to the estimation sample as $\mathbf{Y}_{1:T} = \{\mathbf{y}_1, \ldots, \mathbf{y}_T\}$ and let $\hat{\boldsymbol{\theta}}$ be the mode of the posterior distribution $p(\boldsymbol{\theta} \mid \mathbf{Y}_{1:T})$. Our DSGE forecasts are made using information available to the econometrician in December 2008. Note that at this point the econometrician does not yet have access to NIPA data for 2008:IV. However, the forecaster already has information on the fourth quarter federal funds rate and the spread. We let $\mathbf{y}_{1,t}$ be the federal funds rate and the spread in period t and compute multi-step posterior mean forecasts based on the predictive distribution $p(\mathbf{Y}_{T+1:T_{full}} \mid \mathbf{Y}_{1:T}, \mathbf{y}_{1,T+1}, \hat{\boldsymbol{\theta}})$, where T_{full} corresponds to 2012:III.[2] For brevity, we will often refer to the information set

$$\mathbf{Y}_{1:T_+} = (\mathbf{Y}_{1:T}, \mathbf{y}_{1,T+1}, \hat{\boldsymbol{\theta}}).$$

Ex Post Accounting for the ZLB and Forward Guidance.—Starting in 2009:I nominal interest rates in the United States hit the ZLB. Moreover, the central bank engaged in forward guidance regarding the time horizon of the lift-off from the ZLB. Given the size of our DSGE model, the use of a fully nonlinear solution method as in Judd, Maliar, and Maliar (2010); Fernández-Villaverde et al. (2012); Gust, Lopez-Salido, and Smith (2012); and Aruoba and Schorfheide (2013) is beyond the scope of this paper. Instead, we use an approximation method proposed by Cagliarini and Kulish (2013) and Chen, Cúrdia, and Ferrero (2012) to capture the effect of the ZLB and forward guidance for post-2008:IV data ($t = T+1 : T_{full}$).

Suppose in period t the policy rate is expected to be at the ZLB for $\bar{H}$ periods, that is,

$$R_\tau = -R_*, \quad \text{for } \tau = t, \ldots, t + \bar{H}, \tag{31}$$

and is determined by the feedback rule (17) afterward (for $\tau > t + \bar{H}$). We can write the DSGE model's equilibrium conditions as (omitting the dependence on $\boldsymbol{\theta}$ to simplify the notation)

$$\boldsymbol{\Gamma}_{2,\tau} E_\tau[\mathbf{s}_{\tau+1}] + \boldsymbol{\Gamma}_{0,\tau}\mathbf{s}_\tau = \boldsymbol{\Gamma}_{c,\tau} + \boldsymbol{\Gamma}_{1,\tau}\mathbf{s}_{\tau-1} + \boldsymbol{\Psi}_\tau \boldsymbol{\varepsilon}_\tau, \tag{32}$$

where $\mathbf{s}_\tau$ includes all endogenous and exogenous variables and where the matrices $\boldsymbol{\Gamma}_{2,\tau}$, $\boldsymbol{\Gamma}_{0,\tau}$, $\boldsymbol{\Gamma}_{c,\tau}$, $\boldsymbol{\Gamma}_{1,\tau}$, and $\boldsymbol{\Psi}_\tau$ differ depending on whether $\tau \leq t + \bar{H}$ (in fact, only the row corresponding to the policy rule differs across τs in this application).

[2] We are taking two short cuts. First, we do not reestimate the model with the additional information contained in $\mathbf{y}_{1,T+1}$. Given the size of our sample $\mathbf{Y}_{1:T}$, the two additional observations have no noticeable effect on the posterior. Second, we condition on the posterior mode rather than integrating with respect to the posterior distribution of $\boldsymbol{\theta}$. Since we mostly focus on point estimates in this paper, the conditioning has only small effects on the results but speeds up the computations considerably.

For $\tau > t + \bar{H}$ the solution of (32) is given by the transition equation (29). For $\tau = t, \ldots, t + \bar{H}$ the solution takes the time-varying form

$$\mathbf{s}_\tau = \mathcal{C}_\tau^{(\tau,\bar{H})} + \mathcal{T}_\tau^{(t,\bar{H})}\mathbf{s}_{\tau-1} + \mathcal{R}_\tau^{(t,\bar{H})}\varepsilon_\tau. \tag{33}$$

We use the superscript $(t, \bar{H})$ to indicate that the solution was obtained under the assumption that the announcement of zero interest rates for a duration of $\bar{H}$ periods was made in period t. The matrices $\mathcal{C}_\tau^{(t,\bar{H})}$, $\mathcal{T}_\tau^{(t,\bar{H})}$, and $\mathcal{R}_\tau^{(t,\bar{H})}$ can be computed using the recursion

$$\begin{aligned}
\mathcal{C}_\tau^{(t,\bar{H})} &= \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\left(\Gamma_{c,\tau} - \Gamma_{2,\tau}\,\mathcal{C}_{\tau+1}^{(t,\bar{H})}\right), \\
\mathcal{T}_\tau^{(t,\bar{H})} &= \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\Gamma_{1,\tau}, \\
\mathcal{R}_\tau^{(t,\bar{H})} &= \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\Psi_\tau,
\end{aligned} \tag{34}$$

starting from $\mathcal{T}_{t+\bar{H}+1}^{(t,\bar{H})} = \mathcal{T}, \mathcal{C}_{t+\bar{H}+1}^{(t,\bar{H})} = 0$.

We use overnight index swap (OIS) rates available from the Board of Governors to measure the duration that the federal funds rate is expected to remain at the ZLB, denoted by $\bar{H}_t$. In order to construct a time-varying coefficient state-space model for the post-2008 period, in each period $t > T$ we use the matrices $\left(\mathcal{C}_t^{(t,\bar{H}_t)}, \mathcal{T}_t^{(t,\bar{H}_t)}, \mathcal{R}_t^{(t,\bar{H}_t)}\right)$. We assume that agents are myopic in the sense that they do not attempt to forecast changes in the length of the central bank's zero-interest-rate policy. This assumption is comparable to the anticipated utility approach in the learning literature, e.g., Sargent, Williams, and Zha (2006). Thus, the transition equation (29) is replaced by

$$\mathbf{s}_t = \mathcal{C}_t^{(t,\bar{H}_t)} + \mathcal{T}_t^{(t,\bar{H}_t)}\mathbf{s}_{\tau-1} + \mathcal{R}_t^{(t,\bar{H}_t)}\epsilon_t. \tag{35}$$

When applying the Kalman filter and smoother to extract the ex post states and shocks, we assume that the time t system matrices are known at the end of period $t - 1$.

II. Forecasts during the Great Recession

We begin the empirical analysis by examining forecasts of inflation, output growth, and marginal costs during the 2007–2009 recession. We show that the New Keynesian DSGE model introduced in Section I predicts a deep recession and a subsequent weak recovery, just as observed in the data, and yet it does not predict deflation.

A. *Inflation and Output Growth*

The output growth forecasts (quarter-on-quarter percentages) made with information $\mathbf{Y}_{1:T_+}$ available to the econometrician as of December 31, 2008, are depicted

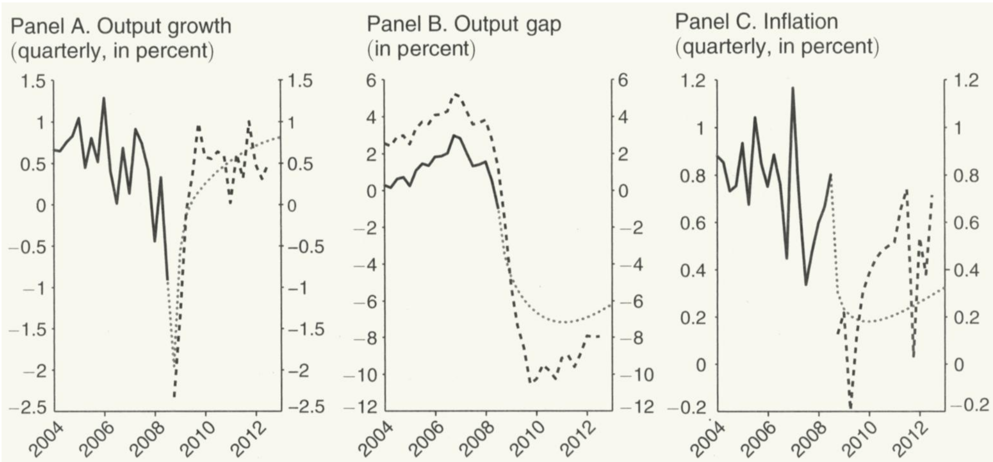

FIGURE 1. FORECASTS OF OUTPUT GROWTH, OUTPUT GAP, AND INFLATION

Notes: Output growth and inflation: actual data until 2008:III (solid black); forecast paths (dotted); actual data starting 2008:IV (dashed). Output gap: ex ante smoothed $E[gap_t | \mathbf{Y}_{1:T_+}, \hat{\theta}]$ until 2008:III (solid black); forecast path (dotted); ex post smoothed $E[gap_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ (dashed).

in the left panel of Figure 1. Similar forecasts, as well as a detailed description on how to compute them, were reported in Del Negro and Schorfheide (2012).[3]

When the sudden rise in interest rate spreads, following the Lehman default, are incorporated into the forecast, the DSGE model with financial frictions predicts a sharp drop in GDP growth and a very sluggish recovery.[4] Indeed, the model's forecast for the log *level* of output in 2012:III (shown in the online Appendix) is remarkably close to the actual value. This implies that based on the $\mathbf{Y}_{1:T_+}$ information available right after the Lehman collapse, the DSGE model predicts that output will remain well below trend four years after the financial crisis.

The center panel of Figure 1 depicts the DSGE model-implied output gap, that is the gap between actual output and counterfactual output in an economy without nominal rigidities, markup shocks, and financial frictions. The figure illustrates that the low level of output after 2008:IV is not an efficient outcome for the economy. Because the counterfactual output is unobserved, actual values of the output gap have to be replaced by smoothed values. The solid line is based on $\mathbf{Y}_{1:T_+}$ information and corresponds to $E[gap_t | \mathbf{Y}_{1:T_+}]$. The dotted line depicts forecasts conditional on $\mathbf{Y}_{1:T_+}$ information and the dashed line marks ex post smoothed values $E[gap_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$. In order to obtain the ex post smoothed values we use the time-varying coefficient state-space representation described in Section ID, accounting for the ZLB and the forward guidance after 2008. In 2008:IV the model forecasts large and persistent gaps, up to -7 percent, which are only slightly smaller by the end of the sample (about -6 percent). The ex post output gap is somewhat larger

[3] The forecasts in Del Negro and Schorfheide (2012) were based on real-time data, whereas the forecasts in this paper are based on the 2012:III vintage of data. Although revised and unrevised data are somewhat different as of 2008:III, the forecasts turn out to be very similar.

[4] This is consistent with the findings of Gilchrist and Zakrajšek (2012), who use a reduced-form approach (and a different measure of spreads).

in absolute terms than the forecasted one: it falls below -10 percent by the end of 2009, and recovers only gradually.

The right panel of Figure 1 shows the inflation forecasts (quarter-on-quarter percentages). The DSGE model prediction misses the deflation in 2009:I partly caused by the collapse in commodity prices and the subsequent reversal in inflation in 2010 and at beginning of 2011, which coincides with the Arab Spring and the associated surge in commodity prices. But aside from these high frequency movements, the model arguably produces reasonable inflation forecasts. In terms of the cumulative price change between 2008:IV and 2012:III, the model underpredicts the price *level* at the end of the sample by about 2 percent.

To summarize, using information available at the end of 2008, the DSGE model predicts a drop in output growth of roughly the same magnitude as the actual one as well as the subsequent sluggish recovery, and large and persistent output gaps. However, unlike Hall's (2011) and Ball and Mazumder's (2011) conjecture, the model-implied Phillips curve does not generate negative inflation forecasts.

B. *Forecasts of Marginal Costs*

According to the NKPC, inflation is determined by expectations of future marginal costs. We therefore inspect the marginal costs forecasts for the Great Recession period. In the absence of fixed costs in the DSGE model, marginal costs mc_t are proportional to the labor share. Moreover, changes in the labor share are spanned by the set of observables used in the estimation because our dataset includes the growth rates of output and real wages as well as the level of hours worked. The presence of fixed costs in our model breaks the direct proportionality between marginal costs and the labor share and we have to treat marginal costs as a latent variable. The left panel of Figure 2 shows three objects: the smoothed marginal costs $E[mc_t | \mathbf{Y}_{1:T_+}]$ using data up to the forecast origin (black solid line), forecasts conditional on $\mathbf{Y}_{1:T_+}$ information (solid grey line), and ex post smoothed values $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ (dashed black line).

The left panel of Figure 2 makes clear that the DSGE model grossly overpredicts marginal costs. At first sight, Figure 2 presents damning evidence against this New Keynesian model. Even if the model captured the decline in output growth, it did not forecast the decline in marginal costs. One might think that if it had, the forecasts of inflation would have been substantially lower. This is essentially the point made by Ball and Mazumder (2011). The right panel of Figure 2 reproduces the model's baseline forecast of inflation (dotted line) from Figure 1 and depicts an alternative inflation forecast that is obtained by conditioning on the ex post path of marginal costs (dashed with circles).[5] This conditioning ensures that the model's predictions match actual marginal costs over the period 2008:IV to 2012:III. The resulting forecast for inflation is of course lower than the baseline forecast, but not dramatically so.

[5]The ex post marginal costs are obtained using a Kalman smoother based on the time-varying state-space model described in Section ID (Ex Post Accounting for the ZLB and Forward Guidance). The conditional forecasts are generated based on the fixed-coefficient state-space model described in Section ID (Generating Forecasts of the Great Recession) using a generalized version of Algorithm 3 in Del Negro and Schorfheide (2012).

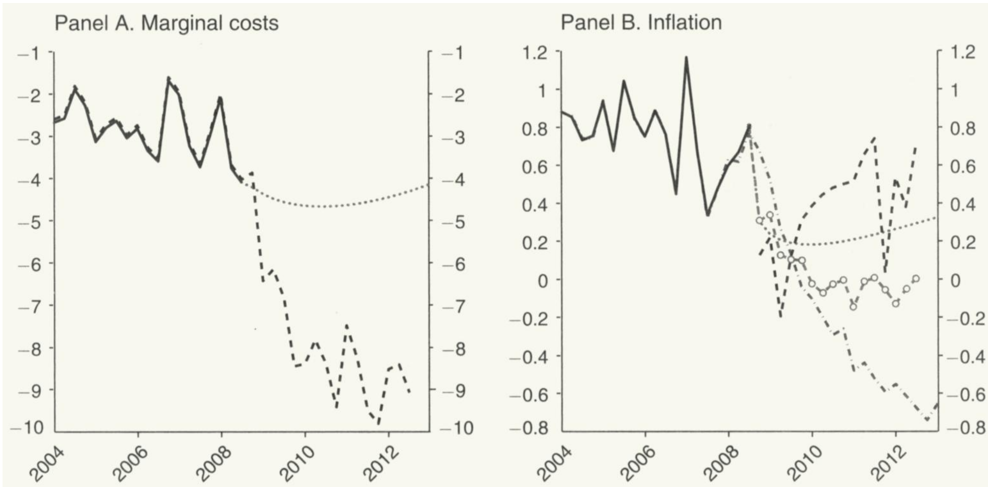

Figure 2. Marginal Cost and Conditional Inflation Forecasts

Notes: Left panel: ex ante smoothed $E[mc_t | \mathbf{Y}_{1:T_+}]$ until 2008:III (solid black); forecast path (dotted); ex post smoothed $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ starting 2008:IV (dashed black). Right panel: actual inflation until 2008:III (solid black); actual inflation starting 2008:IV (dashed); forecasts (dotted); forecasts conditional on ex post marginal costs $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ (dashed with circles); forecasts from a reduced-form Phillips curve conditional on realized unemployment (dashed-dotted).

Why doesn't inflation fall by more, given the large drop in marginal costs? The answer is that actual inflation is largely determined by fundamental inflation, which is defined as the expected present discounted value of future marginal costs (see Section IB). Thus, even if *current* marginal costs are low and the current output gap is well below steady state (as in Figures 1 and 2), as long as the marginal costs are expected to revert back to steady state in the future, the present value of marginal costs, and therefore inflation, may not fall dramatically. This naturally raises the question of what determines the expected reversion of marginal costs. Section IVB addresses this question in detail and shows that if price rigidities are sufficiently large, monetary policy has a considerable impact on the dynamics of marginal costs. When inflation is below steady state or output below potential, the policy rule promises to lower the real rate for an extended period of time (due to interest rate smoothing). This promise stimulates consumption and investment demand by reducing the discounted sum of the expected future real rates and, in turn, raises marginal costs. Because inflation is determined by the sum of expected discounted values of future marginal costs, a dramatic fall in inflation is prevented.

For comparison, the right panel of Figure 2 also shows inflation forecasts from a backward-looking Phillips curve obtained by feeding in actual realizations of unemployment (dash-and-dotted line).[6] The backward-looking Phillips curve does forecast deflation (about -2 percent annualized), which may not be surprising given

[6] Our version of the backward-looking Phillips curve is taken from Stock and Watson (2008, equation (9)), with four lags for both inflation and unemployment and no other regressor), estimated with quarterly data on the GDP deflator and unemployment up to 2008:III. We also tried a version of the Phillips curve in differences (equation (10) in Stock and Watson 2008, again with four lags), and obtained very similar results.

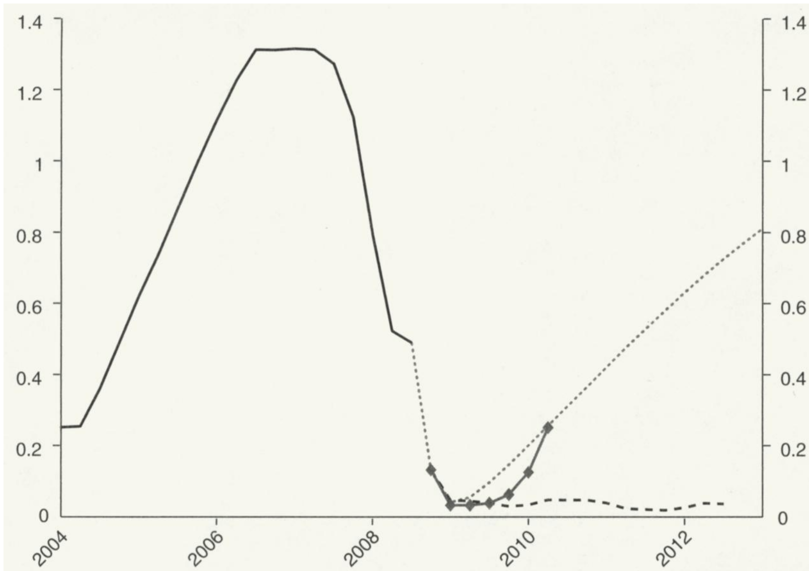

FIGURE 3. FORECASTS OF THE FEDERAL FUNDS RATE

Note: Actual FFR data until 2008:III (solid black); FFR forecast path (dotted); actual FFR data starting in 2008:IV (dashed black); Blue Chip forecasts (solid with diamonds).

the amount of slack suggested by the level of unemployment. Marginal costs are also well below steady state, yet the NKPC's forecasts are not nearly as much at odds with ex post outcomes as those from the backward-looking Phillips curve. Ironically, it is precisely the forward-looking nature of the NKPC that keeps its forecasts afloat.

C. *Interest Rate Forecasts*

Figure 3 depicts the DSGE model's forecasts of the federal funds rate (FFR). As of the end of 2008, the model's interest rate forecasts do not fall below zero. The predicted interest rate path is not just a feature of our DSGE model. It is very much in line with the January 10, 2009 Blue Chip FFR forecasts—the diamonds in Figure 3—at least for the first six quarters (the horizon for which Blue Chip forecasts are available). Ex post it turned out that interest rates stayed at the ZLB, as revealed by the dashed line, and the Taylor rule mechanism of reducing the current interest rate in response to below-target inflation and output was replaced by a policy of forward guidance and quantitative easing (not directly modeled here). In the subsequent ex post analysis of the forecast errors we approximate the effect of the ZLB and the forward guidance policy using the solution method described in Section ID2.

III. What Explains the Ex Post Forecast Errors?

Thus far, we have shown that as of the end of 2008 the SWFF model could successfully predict the output and inflation behavior during the Great Recession and its aftermath. Marginal costs and interest rates, however, turned out to be substantially lower than initially forecast. Why is that? As we now discuss, this reflects both adverse shocks and considerable monetary policy accommodation. The policy accommodation sufficiently compensated for the averse shocks such that output growth and inflation did not differ too much, ex post, from their path predicted in 2008.

Figure 4 shows the paths of inflation and marginal costs, comparing actuals (black), the baseline forecasts made in 2008:IV and discussed in Section II (dotted), and forecasts that are computed conditional on the ZLB, the forward guidance provided after 2008 and, in addition, ex post realized shocks (dashed with circles). Specifically, the dashed lines with circles in the left panels show the paths computed using the solution described in Section ID (Ex Post Accounting for the ZLB and Forward Guidance) and setting all shocks to zero ("No Shocks"). The difference between these paths and the baseline forecasts is due to the fact that ex post policy is different from the anticipated one. The other two panels show the impact of the realized shocks. Given that one of the main questions this paper wants to address is "Does the model need strong positive markup shocks in the postrecession period to explain why we did not observe deflation?" We focus our discussion on the effect of markup versus nonmarkup shocks. The forecasts conditional on realized shocks are obtained as follows. We condition on the full-sample smoothed vector of states $E[\mathbf{s}_T | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$, the additional interest rate and spread information $\mathbf{y}_{1,T+1}$ that is available at the end of 2008:IV, and the set of smoothed shock innovations $E[\epsilon_{j,T+1:T_{full}} | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$.[7] Here, $\epsilon_{j,t}$ corresponds to either the markup shock or the vector of nonmarkup shocks. Because post-2008 policy is different from that assumed in the baseline forecasts, the contribution of markup and nonmarkup shocks does not add up to the difference between realized data and the baseline forecasts.

Our results are as follows. First, the two left panels of Figure 4 show that monetary policy has provided considerable accommodation through forward guidance, especially in the post-2010 period. In the absence of shocks this policy would have implied a sharp increase in marginal costs, relative to the baseline forecast, and an associated increase in inflation after 2010. Second, the sharp decline in marginal costs is almost completely explained by nonmarkup shocks (upper middle panel of Figure 4). We will show in Section IV that given the high degree of estimated price rigidities in the SWFF model, marginal costs are largely endogenous and not very much affected by markup shocks.

Third, nonmarkup shocks cause only a modest fall in inflation relative to the baseline forecast—about 20 basis points (quarter-on-quarter, lower middle panel). This finding is consistent with that shown in Figure 2 even conditional on a set of shocks that imply accurate predictions for marginal costs, the model does not predict a deflationary episode. The intuition behind this result is the one discussed in Section IIB—by being accommodative, monetary policy is expected to push marginal costs up, which prevents inflation from declining too much.

Fourth, ex post markup shocks essentially explain all of the high frequency movements in inflation, but have little effect on marginal costs (upper and lower

[7] Recall that the baseline forecast was conditioned on time T filtered states $E[\mathbf{s}_T | \mathbf{Y}_{1:T}, \hat{\theta}]$ as well as $\mathbf{y}_{1,T+1}$.

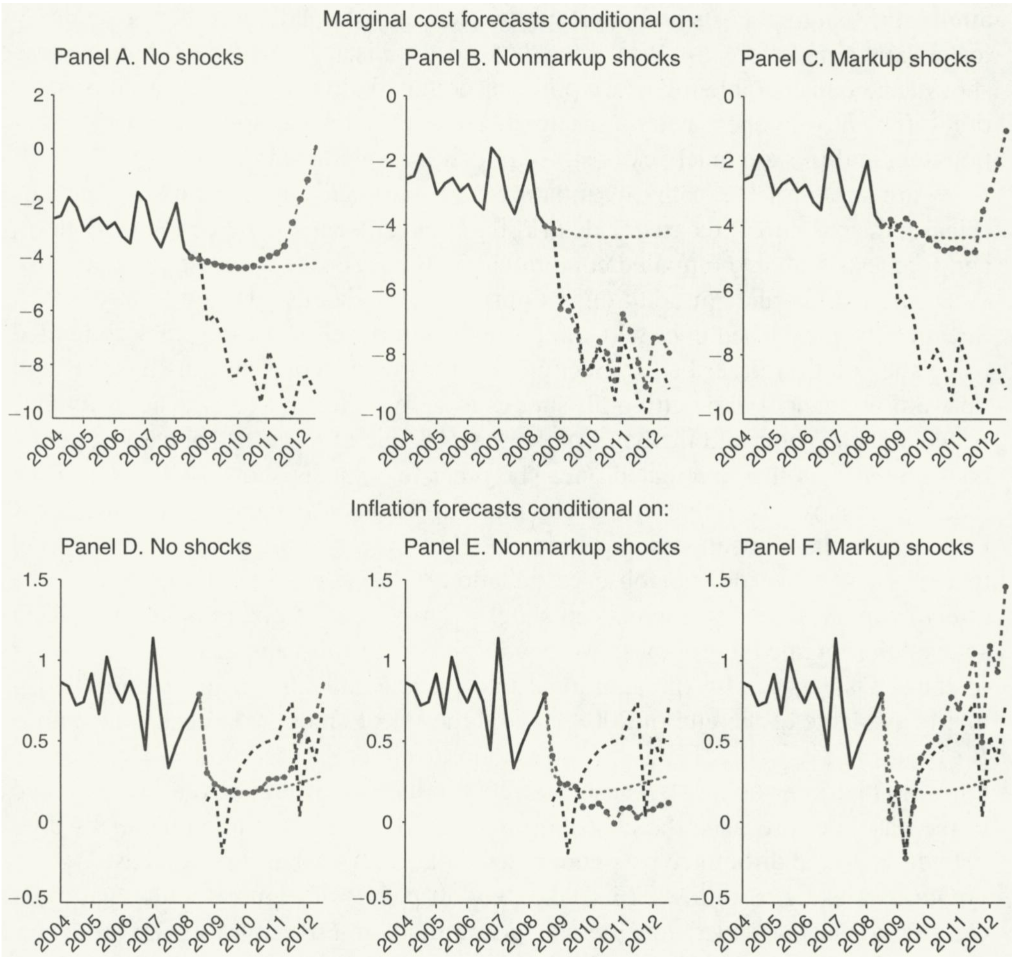

Figure 4. Forecasts Conditional on (Ex Post) Smoothed Shocks

Note: Actual smoothed marginal cost $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ and actual GDP deflator inflation until 2008:III (solid); Actual smoothed marginal cost $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ and actual GDP deflator inflation from 2008:IV on (dashed); unconditional forecasts based on $\mathbf{Y}_{1:T_+}$ (dotted); forecasts conditional on $(E[\mathbf{s}_T | \mathbf{Y}_{1:T_{full}}, \hat{\theta}], \mathbf{y}_{1,T+1}, E[\epsilon_{j,T+1:T_{full}} | \mathbf{Y}_{1:T_{full}}, \hat{\theta}])$ where $j \in$ {No shock; Markup; Nonmarkup} (dashed with circles).

right panels of Figure 4). The model holds markup shocks responsible for the large but short-lived swings in inflation registered between 2009 and 2011. These swings arguably reflect movements in energy prices, which collapsed in the last quarter of 2008 before jumping again in early 2011, during the Arab Spring.[8]

On balance, we conclude that the economy experienced generally negative shocks that pushed inflation, activity and marginal costs down. At the same time, monetary policy counteracted these shocks by deviating from the historical rule and providing more stimulus. This stimulus resulted in a much lower interest rate path than initially forecasted.

[8] This is consistent with the findings of Coibion and Gorodnichenko (2013), who emphasize the rise in inflation expectations due to increases in oil prices during this time period.

IV. Why Didn't Inflation Collapse?

We emphasized in Section II that according to the NKPC, expectations about future marginal costs are a key determinant of inflation. We will now take a closer look at this relationship. Quantitatively, our empirical analysis relies on a fairly high estimate of the price rigidity (the estimate of the Calvo parameter is $\hat{\zeta}_p = 0.87$) for the model with financial frictions. Our $\hat{\zeta}_p$ is higher than the one obtained for a version of the DSGE model without financial frictions (that is, the SW model).[9] We discuss in Section IVA how the introduction of credit spreads as an observable affects these estimates.

Subsequently, in Section IVB we show that if price rigidities are relatively high, marginal costs have three important features: they are persistent; they are largely endogenous, meaning that they fluctuate in response to shocks other than markup shocks; and their dynamics are strongly influenced by the degree to which the central bank is committed to stabilizing inflation. One contribution of this paper is thus to show that the higher degree of price rigidities is key not only because it yields a flatter Phillips curve, but also because it implies that the behavior of marginal costs in this model is largely endogenous. This endogeneity is important, since it makes it possible for policy to play a role in the determination of inflation. This supports our argument that inflation did not fall dramatically during the Great Recession because monetary policy managed to maintain expectations of rising future marginal costs, so that inflation expectations remained anchored.

In Section IVC, we extend our analysis of the NKPC relationship to the rest of the sample, prior to 2009. We document that the present value of marginal costs has historically been able to track low- and medium-frequency movements in inflation very well. Finally, in Section IVD, we examine the historical accuracy of the SWFF-model-based marginal cost forecasts.

A. *Financial Frictions and Estimates of Price Rigidities*

Our quantitative results are sensitive to the estimate of the price rigidity parameter ζ_p and are based on a value that is larger than the one reported in Smets and Wouters (2007). Why does the model with financial frictions and spreads as an observable yield a higher estimate of ζ_p?

The argument can be explained using Figure 5. Imagine that we knew for sure that we just observed a negative demand shock (a leftward shift in the AD curve), and that as a result of this shock output dropped a lot but inflation fell only a little. A model with a steep Phillips curve (AS curve) would have to rationalize this chain

[9] Our $\hat{\zeta}_p$ implies that prices are re-optimized on average every $1/(1 - 0.87) = 7.7$ quarters in the SWFF model. This may appear large when compared to microeconomic evidence about the frequency of price changes reported, e.g., in Bils and Klenow (2004) or Nakamura and Steinsson (2008). However, recall that prices change in every quarter in this model, as prices that are not re-optimized are indexed to past inflation. Furthermore, as argued by Boivin, Giannoni, and Mihov (2009), while individual or sectoral prices may vary frequently in response to sector-specific disturbances, they appear much more sluggish in response to aggregate shocks, which are arguably more relevant for our purposes. Finally, as shown in Woodford (2003) and Altig et al. (2011), a relatively flat slope of the NKPC can alternatively be obtained without large price rigidities by assuming that firms use firm-specific capital, or by assuming a larger curvature parameter in the Kimball aggregator for prices, ϵ_p.

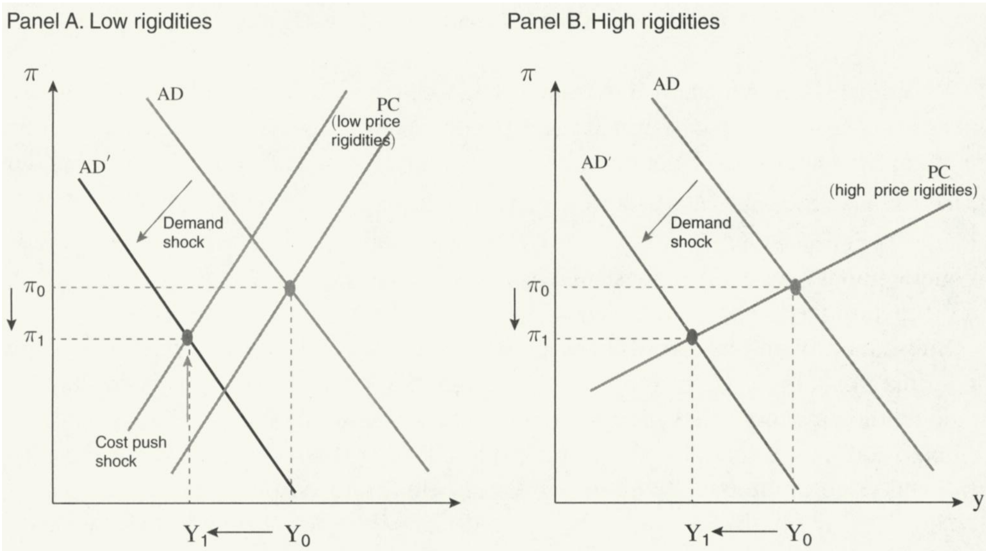

FIGURE 5. DEMAND SHOCKS AND THE SLOPE OF THE PHILLIPS CURVE (AS)

of events with a joint shift of the AD and the AS curve (left panel), the latter caused by a positive markup shock—given that an AD shift would only cause a large fall in inflation. Conversely, a model with a flat Phillips curve would have no problem explaining this with a simple shift in the AD curve only (right panel). The first explanation would involve a negative correlation of demand and markup shocks—one that is at odds with the model's assumptions. The second explanation would be more natural, in that the outcomes can be explained as the result of one shock only.

If we knew that a good portion of business cycle fluctuations is explained by such demand shocks, we would arguably be more comfortable with the second, simpler, explanation (flat AS curve) than with the first one (steep AS curve and correlated markup shocks). It turns out that by including spreads as observables, the shocks that are predominantly responsible for explaining the variation in spreads, namely the "discount rate" (b) and the "spread" (σ_w) shocks, play a more important role for aggregate fluctuations, overall. These shocks by and large operate like the demand shocks described above. We substantiate this claim as follows. First, we reestimate the SW model using spreads as an additional observable. This raises the estimate of ζ_p from 0.65 to 0.81.[10] Second, we computed the correlation between demand and markup shocks in the SWFF and SW models. As suggested by the left panel of Figure 5, this correlation is negative for the SW model (-0.37), implying that adverse demand shocks are associated with positive markup shocks, and are slightly positive for the SWFF model (0.18).

[10] It has been documented, e.g., in Schorfheide (2008) that DSGE model-based estimates of the slope of the Phillips curve can vary widely across studies. The variation can be caused by a combination of model specification, dataset, and choice of the prior distribution. Del Negro and Schorfheide (2008) document that reasonable changes in the prior distribution can generate estimates of ζ_p ranging between 0.54 and 0.84, well within the range reported here. In addition, Herbst and Schorfheide (forthcoming) document that under a diffuse prior the SW model can generate a posterior distribution with two modes, one with $\zeta_p = 0.59$ and another one with $\zeta_p = 0.70$. Including the spread data as an additional observable contributes to shifting the posterior mass from one modal region to another.

B. *Price Rigidities and Marginal Cost Dynamics*

In this section we illustrate the dependence of marginal costs dynamics on the degree of price stickiness as well as the conduct of monetary policy. First, we compare marginal cost forecasts based on our posterior mode estimate of $\hat{\zeta}_p = 0.87$ to forecasts obtained based on Smets and Wouters' (2007) estimate of $\hat{\zeta}_p^{SW} = 0.65$. Second, we illustrate the effect of lowering the central bank's response to inflation from the estimated value of $\hat{\psi}_1 = 1.37$ to the counterfactual value of 1.1. The results are summarized in Figure 6.

The left panel of Figure 6 illustrates the effect of changing the degree of nominal rigidity. The solid black line corresponds to smoothed estimates of marginal costs in deviations from the steady state $E[mc_t \,|\, \mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$ for the post-2005 period. The dotted and dashed lines departing at two points in time from the black line are the projected path of future marginal costs. Formally, we are depicting

$$E[mc_{t+h} \,|\, \hat{\mathbf{s}}_{t|T_{full}}, \hat{\boldsymbol{\theta}}], \qquad \text{where} \qquad \hat{\mathbf{s}}_{t|T_{full}} = E[\mathbf{s}_t \,|\, \mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}].$$

Thus, the marginal cost forecasts are conditional on the smoothed value of the state $\mathbf{s}_t$. The dotted lines are forecasts using our estimated value of $\hat{\zeta}_p = 0.87$, whereas the dashed lines are based on the SW value $\hat{\zeta}_p^{SW} = 0.65$.

Figure 6 shows that marginal costs revert quickly to their state value if prices are relatively flexible. To understand this result, suppose that the prices are essentially fully flexible. In this case, firms would set their prices at a markup over the nominal marginal costs. As a consequence, real marginal costs would only move in response to exogenous markup shocks and would have no endogenous persistence.[11] Similarly, in Figure 6 when prices are relatively flexible, real marginal costs revert quickly to the steady state (to the extent that exogenous markup shocks are not very persistent) so that the present discounted value of future marginal costs

$$S_t^{\infty} = \sum_{j=0}^{\infty} \bar{\beta}^j E_t[mc_{t+j}],$$

defined in (24) essentially coincides with *current* real marginal costs mc_t (see Figure A3 in online Appendix AIII). This is essentially what happens for the dashed lines. In contrast, if prices are rigid, firms meet a persistent decline in the demand for goods with a decline in the supply of goods, which results in a persistent fall in marginal costs. It follows that the present discounted value of future marginal costs, S_t^{∞}, may differ substantially from current real marginal costs mc_t.

To substantiate the claim that monetary policy also affects future marginal costs, we depict in the right panel of Figure 6 marginal cost forecasts under the estimated policy rule coefficient $\hat{\psi}_1 = 1.3$ and the counterfactual value $\psi_1 = 1.1$. The graph shows that a lower policy response to inflation makes little difference to the expected path of marginal costs for $\hat{\zeta}_p^{SW} = 0.65$ as marginal costs are essentially exogenous,

[11] This can be seen by taking the limit as prices become fully flexible in the linearized NKPC (13). Noting that $\lambda_{f,t}$ is a renormalized version of the markup shock (i.e., $\lambda_{f,t} = \kappa\tilde{\lambda}_{f,t}$, following SW), this equation implies that $0 = mc_t + \tilde{\lambda}_{f,t}$, as $\zeta_p \to 0$.

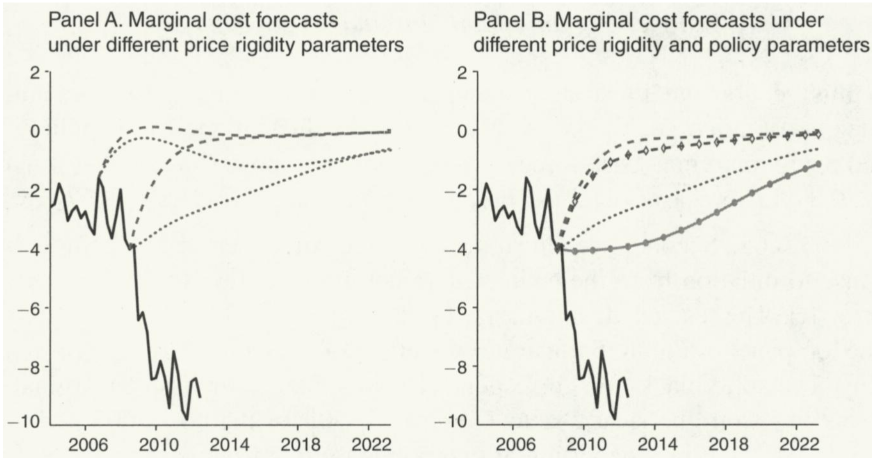

FIGURE 6. PRICE RIGIDITIES AND FORECASTS OF MARGINAL COSTS

Notes: Left panel: ex post smoothed $E[mc_t|\mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$ (solid); forecasts based on $\hat{\zeta}_p = 0.87$ (dotted); forecasts based on $\hat{\zeta}_p^{SW} = 0.65$ (dashed). Right panel: ex post smoothed $E[mc_t|\mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$ (solid); forecasts based on ($\hat{\zeta}_p = 0.87$; $\hat{\psi}_1 = 1.3$) (dotted); forecasts based on ($\hat{\zeta}_p^{SW} = 0.65$; $\hat{\psi}_1 = 1.3$) (dashed); forecasts based on ($\hat{\zeta}_p = 0.87$; $\psi_1 = 1.1$) (solid with circles); forecasts based on ($\hat{\zeta}_p^{SW} = 0.65$; $\psi_1 = 1.1$) (dashed with diamonds).

and quickly revert back to the steady state regardless of the conduct of monetary policy. However, under $\hat{\zeta}_p = 0.87$, the marginal cost forecasts are very sensitive to the central bank's reaction to inflation movements. Thus, if nominal rigidities are strong, marginal costs have a strong endogenous component that can be dampened by a monetary policy that reacts strongly to inflation. In turn, monetary policy is able to anchor current and future inflation.

The point that policy can exert control on inflation even with a flat Phillips curve (i.e., high nominal rigidities) is relevant for the current policy debate. Box 3.1 of the 2013 World Economic Outlook (International Monetary Fund 2013) asks, "Does Inflation Targeting Still Make Sense with a Flatter Phillips Curve?" The premise of this question is that with anchored inflation expectations and a flat Phillips curve, it has become harder for central banks to affect inflation. Seen from the perspective of our model, the anchoring of inflation expectations is part and parcel of policy's influence on expected future marginal costs. In fact, to the extent that the dynamics of marginal costs are more affected by policy when the Phillips curve is relatively flat than when it is steep, policy may have more control over inflation under the former than under the latter.

C. *Price Rigidities and Fundamental Inflation*

The analysis in Section IVB focused on the effect of price rigidities and monetary policy on the persistence of marginal costs. While policy affects inflation dynamics through the NKPC, a change in nominal rigidities not only affects the persistence of marginal costs, hence S_t^∞, but also the slope κ of the Phillips curve. Recall that in Section IB we decomposed inflation into fundamental inflation defined as

$$\tilde{\pi}_t = \kappa(1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1} S_t^\infty$$

and $\Lambda_{f,t}$, which is the exogenous present discounted value of markup shocks. It is well understood that a larger value of ζ_p implies a flatter Phillips curve, i.e., a smaller slope coefficient κ, as more rigid prices are less responsive to given changes in marginal costs. Our estimate of $\hat{\zeta}_p = 0.87$ and the Smets and Wouters (2007) estimate of $\hat{\zeta}_p^{SW} = 0.65$ offer two competing explanations for the historical US inflation dynamics: $\hat{\zeta}_p = 0.87$ implies a relatively flat Phillips curve in conjunction with large movements in S_t^{∞}. The SW value, on the other hand, implies a steep Phillips curve but little movement in S_t^{∞}. Which one is the most plausible? In order to address this question we will examine the behavior of fundamental inflation.

Figure 7 compares fundamental inflation $\tilde{\pi}_t$ (dotted line) to actual GDP deflator inflation (solid black line). For the NKPC to be a compelling model of inflation, fundamental inflation should explain a substantial portion of the variation in actual inflation. We can see that this is indeed the case for $E[\tilde{\pi}_t \,|\, \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ computed from our SWFF model.[12] Fundamental inflation from the SWFF model captures the low-frequency variation of GDP deflator inflation. We also compared fundamental inflation to core PCE inflation, and it turns out that the time paths of these two series are very similar (see online Appendix AIII for details). The difference between core PCE and GDP deflator inflation typically reflects abrupt changes in commodity prices, which are attributed to markup shocks in our estimation results. We deduce that the NKPC of the SWFF model is successful in capturing the low- and medium-frequency movements of inflation, not just during the Great Recession and its aftermath but also over the historical period from 1964 to 2008.

To put the SWFF fundamental inflation into perspective, we also compute it for the SW model (dashed line in Figure 7). Our SW-model-based estimate of fundamental inflation essentially reproduces the estimate reported by King and Watson (2012), henceforth KW.[13] The discrepancy with actual inflation is staggering. In the first part of the sample, the SW/KW measure grossly overestimates actual inflation, whereas in the second part of the sample, it underestimates GDP-deflator inflation, in particular since 2007. Were inflation to coincide with the SW/KW fundamental inflation, it would be of the order of -12 percent annualized in the aftermath of the Great Recession. The difference between our estimate of fundamental inflation and the KW estimate is mainly driven by the degree of price rigidity ζ_p. If we replace our modal estimate of $\hat{\zeta}_p = 0.87$ with $\hat{\zeta}_p^{SW} = 0.65$, we obtain results that are very similar to the ones depicted by the dashed line in Figure 7.

Recall from the analysis in Section IVB that for $\hat{\zeta}_p^{SW} = 0.65$ marginal costs are strongly mean reverting and mostly driven by exogenous markup shocks. This implies that fundamental inflation under the SW estimate of ζ_p mainly tracks *current* marginal costs. Markup shocks now play two roles. First, they are the main driver of marginal costs and fundamental inflation. Second, the present discounted value of markup shocks has to explain the discrepancy between actual inflation and fundamental inflation. Figure A4 in online Appendix AIII illustrates these points.

[12] In computing these smoothed estimates, we are using the time-varying coefficient solution described in Section ID (Ex Post Accounting for the ZLB and Forward Guidance) that accounts for the ZLB and forward guidance.

[13] We use a different vintage of data from KW, so the smoothed series are not identical, but this makes little difference.

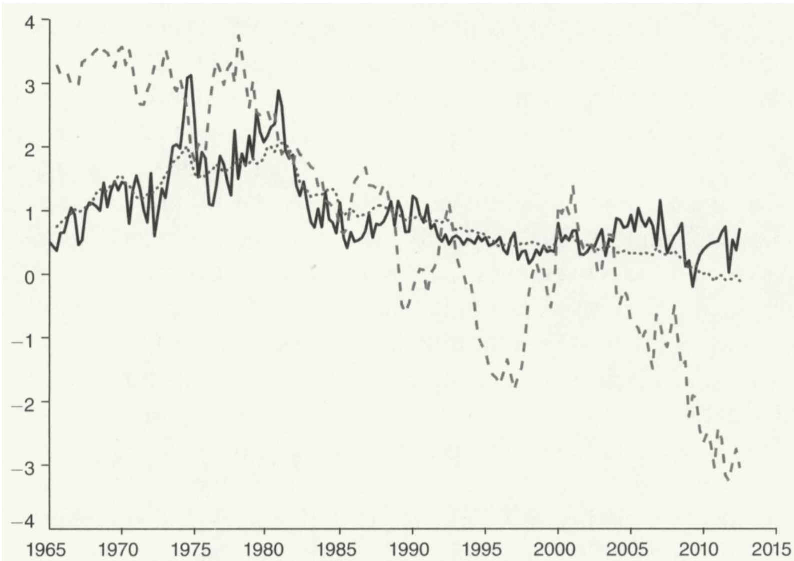

FIGURE 7. INFLATION AND FUNDAMENTAL INFLATION

Note: GDP deflator inflation (solid black); fundamental inflation $E[\tilde{\pi}_t | \mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$ from SWFF model (dotted); fundamental inflation from SW model (dashed).

Conversely, under the high estimate of $\hat{\zeta}_p = 0.87$ associated with the SWFF model, markup shocks are only important in matching high-frequency movements in inflation, and play only a small role in driving fluctuations in marginal costs and fundamental inflation. Fluctuations in marginal costs and in S^{∞} are mostly explained endogenously by changes in economic activity.

D. *How Accurate Were Agents' Marginal Cost Forecasts?*

Our argument as to why inflation did not fall in the Great Recession hinges crucially on the (model-implied) expectations of future marginal costs. To assess the accuracy of agents' (and econometricians') marginal cost forecasts in the SWFF model, we depict in Figure 8 for the full sample what we previously showed in Figure 6 for only two periods toward the end of the sample: smoothed historical marginal costs in deviations from the steady state ($E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$, solid) and for each period t the projected path of future marginal costs ($E[mc_{t+h} | \hat{\mathbf{s}}_{t|T_{full}}, \hat{\boldsymbol{\theta}}]$, thin "hairs"). The forecasts are strongly mean-reverting, more so than the ex post realized path of marginal costs. While there were some historical episodes in which the forecasts seem to systematically miss the prolonged fall in marginal costs, e.g., 1987 to 1995, there are other periods, e.g., 1995 to 2005, in which the forecasts captured the future movements of marginal costs quite well. To put the model's marginal cost forecasts into perspective, we compare them with forecasts from two reduced-form alternatives: a random walk model and an AR(2) model.[14] While the marginal cost forecasts differ across specifications, the root mean squared errors

[14] The AR(2) model is estimated recursively using data on $E[mc_{1:t} | \mathbf{Y}_{1:T_{full}}, \hat{\boldsymbol{\theta}}]$.

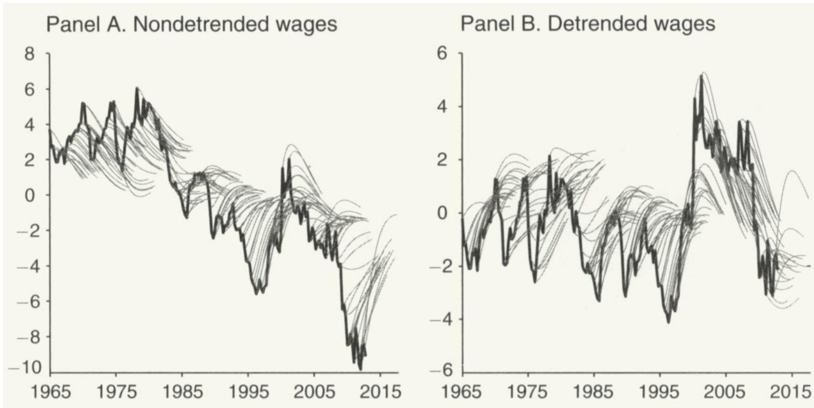

FIGURE 8. MARGINAL COSTS AND FORECASTS OF FUTURE MARGINAL COSTS

Notes: Smoothed marginal costs $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$ (solid black); forecasts of future marginal costs (thin "hairs"). The left panel is based on the raw wage growth series used for the estimation. The right panel is based on an adjusted wage series (see text for details).

(RMSEs) of the three types of forecasts are quite similar, with the AR(2) model performing slightly worse than the SWFF and the random walk model (details are reported in online Appendix AIII). In sum, even if the marginal cost forecasts for the most recent years have been consistently over-optimistic, the historical forecast record of the model (and the agents in the model) is comparable with alternative reduced-form specifications.

The SWFF model assumes that marginal costs eventually return to their original steady-state level. The left panel of Figure 8 may, however, cast some doubts on that assumption as the historical path of marginal costs suggests the presence of a possible long-run downward trend in addition to the business cycle fluctuations. This trend captures a downward trend in the labor share since the early 1980s.[15] The decline in the labor share reflects two separate phenomena: a long-term decline in the labor share attributable to a slower growth of per capita labor compensation relative to per capita output from 1985 to 2000, and a sharp drop in employment during the Great Recession.

To make sure that our results are not sensitive to the assumption of stationary marginal costs, we consider a robustness exercise in which we reproduce our calculations with the same model parameters, but we use an alternative wage series that is corrected to offset the drop in the wage-output ratio that occurred in the mid 1980s. We refer to this alternative wage series as "detrended." This detrending is achieved by changing the long-run growth rate of labor compensation so that it is equal to that of output from 1980 on.[16] The right panel of Figure 8 depicts marginal costs and their forecasts obtained by replacing actual real wage growth with the growth rate of detrended real wages when computing the smoothed estimate $E[mc_t | \mathbf{Y}_{1:T_{full}}, \hat{\theta}]$.

[15] While ex post smoothed marginal costs in the SWFF model are not exactly equal to the labor share, the time paths of the two series are very similar.

[16] Altering the compensation data in this way also addresses in part the measurement issues identified by Elsby, Hobijn, and Sahin (2013) regarding the compensation data. Indeed, they argue that around one third of the decline in the published labor share is an artifact of a progressive understatement of the labor income of the self-employed. However, they point out that offshoring of the labor-intensive component of the US supply chain may also have contributed to the decline in the US labor share over the past 25 years.

We find that the output growth and inflation forecasts for the Great Recession generated based on the detrended wage series are almost identical to those reported for the raw wage series in Figure 1 (see online Appendix AIII for further details), except that now the model's marginal cost forecasts for the Great Recession period appear much more in line with ex post outcomes. The fact that the inflation forecast remains broadly unchanged reflects two offsetting forces: as evident from the right panel of Figure 8, smoothed marginal costs are higher than in the baseline case, which tends to push inflation up, but the marginal costs are not expected to revert back to the steady state as quickly, which contributes to keeping inflation at the level that was predicted with the nondetrended data.

V. Conclusions

In this paper, we examined the behavior of inflation forecasts generated from a standard, medium-sized DSGE model, augmented with a time-varying target inflation rate and financial frictions. The model embodies a New Keynesian Phillips curve relating current inflation to expected future real marginal costs. Several authors recently argued that the Phillips curve relationship seemed to have broken down during the Great Recession. The basis for this argument is the observation that real activity dropped sharply without generating a corresponding drop in inflation. We challenge this argument by showing that this observation can be reconciled with predictions of a standard DSGE model. As of 2008:III, our DSGE model is able to predict a sharp decline in output without forecasting a large drop in inflation. The model predicts that marginal costs will revert back to the steady state after the crisis, which, through the forward-looking Phillips curve, prevents a prolonged deflationary episode. While the underlying marginal cost forecasts turned out to be overly optimistic ex post, we show that even taking into account the ex post realizations of marginal costs, the model does not imply deflation. We also document that our DSGE model generates a plausible measure of fundamental inflation for the post-1964 era, which explains the low- to medium-frequency fluctuations of inflation and tracks core PCE inflation without relying on markup shocks.

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