The Effects and Origins of House Price Uncertainty Shocks *

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Abstract

This paper investigates the effects of house price uncertainty shocks on economic activity, and traces the origins of the shocks. A Markov-switching vector autoregression (MS-VAR) model shows that house price uncertainty shocks in expansionary regimes increase residential investment, housing prices, and mortgage debt, while they have the opposite effects in recessionary regimes. These empirical results are investigated in an estimated New-Keynesian dynamic stochastic general equilibrium (DSGE) model with a housing sector that allows for multiple structural uncertainty shocks. We show that uncertainty shocks to housing preference and the inflation target are the main sources of house price uncertainty shocks. Uncertainty shocks to investment-specific technology and the inflation target can reproduce the empirical impulse responses in recessionary regimes from the MS-VAR. By contrast, the responses to housing preference uncertainty shocks are consistent with the empirical impulse responses in expansionary regimes. House price uncertainty generated by these structural uncertainty shocks affects the housing market via both housing demand and real-options channels.

Keywords: House price uncertainty shocks, DSGE, Nonlinear estimation, Housing demand channel, Real-options channel
JEL Codes: E32, E44, E52, R21, R31

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1 Introduction

I think that the central issue in the economic situation right now is the housing market. It is the continued uncertainty about house prices and housing activity which is creating financial stress, is affecting consumer wealth and consumer expectations and causing the stress we are seeing in the economy. So my suggestion would be in the near term to focus on issues related to housing.

Ben S. Bernanke, JULY 15, 2008

Since the Great Recession of 2008-2009, which was partially driven by a collapse in the housing market, uncertainty surrounding housing has been an important issue for economists and policymakers. Recent studies have shown that uncertainty itself is a source of economic fluctuations and slows down economic activity. However, house price uncertainty has two different forces in the housing market (see Han, 2010, 2013); hence, these forces potentially have asymmetric impacts on economic activity over the business cycle. On the one hand, uncertainty about house prices makes home-owning and mortgage debt risky, and thus, reduces house prices due to a decrease in housing demand. On the other hand, households faced with house price uncertainty may use an early purchase strategy to hedge against future housing consumption risk. As a primary residence comprises about two-thirds of the median homeowner's assets, the unexpected change in house price uncertainty could have significant impacts on households' consumption through a wealth effects channel and a collateral constraints channel. In addition, changes in house price uncertainty can either positively or negatively affect the real-options values of residential investment projects, thereby affecting firms' decisions regarding residential investment in a different way.[1]

There have been extensive studies that have explored the uncertainty-return relationship in the finance literature using asset pricing models.[2] Importantly, some of the real estate literature in finance investigates the effects of house price uncertainty on homeowners' decision making in partial equilibrium (Banks et al., 2004; Sinai and Souleles, 2005; Han, 2010, 2013). However, there has been relatively little work on the effects and origins of house price uncertainty in a general equilibrium framework. Moreover, a large body of literature in macroeconomics that investigates

[1]The real-options channels are associated with the right to undertake a new investment project that is irreversible or partially irreversible when economic agents are faced with uncertainty about future cash flows, interest rates, and the price of capital (Bernanke, 1983). If the real call option to undertake investment in the future is more valuable than the real put option, then uncertainty has a negative effect on investment. However, partially irreversible investment could lead to uncertainty having a positive effect on the put option value, and thus, make more investment desirable. For the given predetermined capital, the real-options value may be associated with expected returns on capital in the housing sector, adjustment costs on capital and capacity utilization, and stochastic shocks. Moreover, the convex marginal revenue product of capital, regarding output prices and total factor productivity (TFP), is another channel that induces a positive relationship between uncertainty and investment (Oi, 1961; Hartman, 1972; Abel, 1983). This channel is known as the Oi-Hartman-Abel effect. However, it holds when firms freely expand to exploit good outcomes and contract to avoid bad outcomes without adjustment costs. The capacity utilization rate potentially allows flexibility to adjust capital inputs.

[2]Frank Knight (1921) distinguishes between risk and uncertainty. He describes risk as events for which the distribution is known over a set of events. On the other hand, he defines uncertainty as conditions in which economic agents are unable to predict the likelihood of events. In this paper, we will refer to uncertainty as a mixture of risk and uncertainty following Bloom (2014).

the relationship between the housing market and economic activity has focused on analyzing the direct effects of house price shocks on aggregate macroeconomic variables; however, the role played by changes in house price uncertainty is new to the literature. Our paper attempts to fill this gap by investigating the asymmetric effects of house price uncertainty on economic activity over the business cycle, finding its possible sources, and identifying transmission mechanisms.

We first estimate a house price process in the United States (U.S.) that is characterized by time-varying stochastic volatility in its shocks. This specification allows us to distinguish between house price shocks and house price uncertainty shocks. The estimated volatility, which we call house price uncertainty, shows time-variation and tends to increase in housing boom and bust periods. Following Fernández-Villaverde et al. (2015), we interpret the unexpected changes in the volatility as unexpected shocks to uncertainty about house prices. Next, we estimate a benchmark vector autoregression of the U.S. economy, augmented with the house price uncertainty that we extracted in the first step, and compute the impulse response functions (IRFs) of several macroeconomic variables to an identified house price uncertainty shock. We allow the benchmark VAR model to be regime-switching because of well-known business cycle asymmetries (Hamilton, 1989; Owyang et al., 2005). From this exercise, we find that the house price uncertainty shock has asymmetric impacts on the U.S. economy in that it leads to a decline in consumption, residential investment, house prices, and mortgage debt, but an increase in the rent to price ratio in recessionary regimes. However, the opposite responses occur in expansionary regimes for residential investment, house prices, mortgage debt, and the rent to price ratio.

The second step is to investigate uncertainty shocks in a nonlinear New Keynesian DSGE model with a housing sector (Iacoviello and Neri, 2010). The objective is to reproduce the asymmetric dynamic behaviors generated by the house price uncertainty shocks in the MS-VAR analysis. This model allows us to add a set of second-moment structural shocks that are interpreted as exogenous uncertainty shocks. We find the origins of house price uncertainty shocks by investigating the propagation mechanism of each structural uncertainty shock. The model is solved and estimated based on a third-order approximation. We first estimate the model without stochastic volatility processes by embedding the Central Difference Kalman filter (CDKF) into the Monte Carlo Markov Chain (MCMC) algorithm (Andreasen, 2013; Binning and Maih, 2015; Noh, 2019). As a second step, we match observations of the U.S. economy in terms of second moments and first- and second-order autocorrelations to estimate the parameters of the stochastic volatility processes. Consistent with the existing literature, the impulse responses for the given estimated parameters demonstrate that uncertainty shocks dampen economic activity. They reduce consumption, business investment, residential investment, housing prices, household debt, and output, although business investment initially increases after the shocks.

The variance decomposition analysis shows that uncertainty shocks to investment-specific technology, housing preference, and inflation objective play significant roles in explaining the variance in house prices, implying that these shocks could be the main sources of house price uncertainty shocks. The historical decomposition of house prices shows that housing preference uncertainty shocks increase house prices over the most recent housing boom periods, reflecting households' housing consumption hedging effect. However, they significantly decrease house prices over the recent housing bust periods. These findings explain empirical results in expansionary and recessionary regimes from the MS-VAR. The technology uncertainty shocks reduce house prices, mostly reflecting the financial and debt risk effects. Although monetary uncertainty shocks tend to play a small role in explaining the historical fluctuations of house prices, they reduce house prices over the 1982 recessionary periods and increase house prices over the recent housing boom periods.

The theoretical model illustrates that supply-side uncertainty shocks produce negative impacts on consumption, residential investment, housing prices, and household debt. The model implies that the supply-side uncertainty shocks induce precautionary motives, negative real-options effects on residential investment, and financial and debt risk effects on housing demand. These results are primarily driven by uncertainty shocks to investment-specific technology and technology in a nonhousing sector, capturing the key empirical findings obtained from the recessionary regimes in the MS-VAR analysis, except that they increase inflation and interest rates. The reason for the increase in inflation is that firms and labor unions optimally choose higher prices and wages due to upward pricing biases with sticky prices and wages (Fernández-Villaverde et al., 2015). The increase in inflation leads to an increase in interest rates. In contrast, we find that among demand-side uncertainty shocks, uncertainty shocks to housing preference have positive impacts on residential investment, house prices, and household debt. These results resemble the empirical findings when the economy is in expansionary regimes, reflecting a housing consumption hedging effect. However, the other demand-side uncertainty shocks, mainly driven by uncertainty shocks to inflation objective, have negative impacts on these variables.

Finally, we explore the demand-side transmission mechanisms of house price uncertainty by focusing on a financial risk effect, a housing consumption hedging effect, and a debt risk effect. The financial risk and debt risk effects are associated with the fact that when households have a strong desire for nonhousing consumption or when they face high borrowing costs, they tend to have a weak desire for housing and mortgage debt. This mechanism implies that higher uncertainty about housing prices lowers house prices in recessionary regimes. On the contrary, the hedging effect against future housing consumption risk implies that households faced with house price uncertainty are more likely to pay a higher price in expansionary regimes. All of these effects are related to decisions about home owning and hence housing prices. By deriving an analytic relationship between uncertainty and the returns to owning a home under simplifying assumptions, we show that model-simulated data generated by uncertainty shocks create the financial risk effect, the hedging effect, and the debt risk effect. The sign and magnitude of the relationship depend on the relative forces of these three effects. We also implement similar exercises to investigate real-options effects on business and residential investment.

The relationship between uncertainty and economic activity has been widely documented in a partial equilibrium framework (Leland, 1968; Hartman, 1976; Bernanke, 1983; Abel, 1983; Kimball, 1990; Carroll et al., 2006; Bloom, 2009). Building on this work, recent dynamic stochastic general equilibrium (DSGE) models investigate the effects of uncertainty on business cycle fluctuations in a general equilibrium setting (Fernández-Villaverde et al., 2011; Gómez-González et al., 2013; Born and Pfeifer, 2014a,b; Cesa-Bianchi and Corugedo, 2018; Fernández-Villaverde et al., 2015; Mumtaz and Theodoridis, 2015; Leduc and Liu, 2016; Bonciani and van Roye, 2016; Basu and Bundick, 2017). Most of these studies rely mainly on the markup channel with sticky prices, as emphasized by Fernández-Villaverde et al. (2015) and Basu and Bundick (2017). They show the contractionary effects of uncertainty on economic activity based on Rotemberg-type nominal rigidities. The effects are amplified through an increase in markups when nominal rigidities exist. The primary reasons for the increase in markups can be explained by an aggregate demand channel (or a precautionary savings channel) and an upward pricing bias channel (Fernández-Villaverde et al., 2015). The increase in markups leads to a decrease in output, and hence, a decrease in investment.[3] Based on this key mechanism, Born and Pfeifer (2014a) and Fernández-Villaverde et al. (2015) investigated policy uncertainty impacts on economic activity, Leduc and Liu (2016) proposed search frictions in the labor market, and Bonciani and van Roye (2016) and Cesa-Bianchi and Corugedo (2018) introduced financial frictions in the model.

We differ from previous studies in that: (1) we investigate house price uncertainty impacts on economic activity; we allow for (2) multiple sources of uncertainty (supply- and demand-side uncertainty); (3) a multi-sector structure with housing and nonhousing goods (durable and nondurable goods); and (4) nominal rigidities with financing frictions in the household sector. We conduct a structural estimation of a DSGE model solved up to the third order and analytically discuss the risk propagation channels of house price uncertainty. Our paper is related to Bianchi et al. (2018) who found the origins of macroeconomic uncertainty by investigating demand- and supply-side uncertainty. They introduced multiple risk propagation channels to illustrate the distinct roles of demand- and supply-side uncertainty. In contrast, we investigate the origins of house price uncertainty shocks based on a two-sector model with multiple structural uncertainty shocks. To the best of our knowledge, our paper is the first attempt to trace the structural sources of house price uncertainty shocks.

The paper is organized as follows. Section 2 estimates house price uncertainty and reports the MS-VAR evidence. Section 3 introduces the New Keynesian DSGE model with a housing market. Section 4 discusses the numerical implementation for the model solution and estimation. Section 5 presents the main results. Section 6 inspects the transmission mechanism, and Section 7 concludes the paper.

[3] Mumtaz and Theodoridis (2015) shows that uncertainty shocks with Calvo-type nominal rigidities increase price and wage dispersion, which creates less efficient aggregate production, requiring more labor input. This mechanism increases real wages, marginal costs, and inflation. In our paper, uncertainty shocks could be amplified through the markup of final goods over wholesale goods, and the markup between the wage costs for wholesale firms and households' wages.

2 House Price Uncertainty and Economic Activity

In this section, we estimate the time-varying uncertainty of U.S. housing prices in a model where economic agents form rational expectations of future housing prices using currently available information. We define house price uncertainty by the standard deviation of the unpredictable component of house price movements that is commonly considered as a measure of risk in the financial literature. Based on this measure of house price uncertainty, we investigate the evidence of its time-variation and a relationship between house price uncertainty and real economic activity.

2.1 House Price Uncertainty

The challenge in this empirical analysis is to measure house price uncertainty. First, we can directly use economic agents' expectations about future house prices obtained from surveys. Although the survey from the University of Michigan Survey of Consumers reports the expected changes in future home values with variances, the data span is not long enough for the analysis. As alternatives, it can be measured by either the cross-sectional variability or the time-series volatility of actual housing price data.

Micro-based financial studies for the housing market have proxied house price uncertainty in various ways. For example, uncertainty about housing prices is proxied by location indicators reflecting that housing prices in high-priced cities tend to have high standard deviations (Ioannides and Rosenthal, 1994; Green and Vandell, 1999). Others use variability in past house price history (Sinai and Souleles, 2005), or five-year conditional variance predicted by a GARCH model (Han, 2010). However, the location proxies and the variability approach based on past house price history are vulnerable to control market conditions and capture time-varying characteristics of house price uncertainty. Considering that economic agents make decisions on housing demand and supply based on the current and expected future economic conditions, a measure of house price uncertainty should vary over time. In addition, GARCH models do not distinguish between innovations to the level of house prices and to its volatility. Since house price uncertainty may be driven mainly by exogenous shocks, we consider estimating a stochastic volatility model that allows us to gauge the independent effect of shocks to house price uncertainty on economic activity.

To create the measure of house price uncertainty, we assume that economic agents make forecasts about future housing prices based on past housing prices, aggregate economic conditions, and policy information. Changes in the forecast error variance will then proxy for uncertainty. We use the one-period lagged Shiller real house price as past house price history.[4] The aggregate economic conditions include the real income and unemployment rates. Finally, the 3-month Treasury bill rate is assumed to be policy information. The real income is the real compensation per hour in the nonfarm business sector from FRED. The unemployment rate is the civilian unemployment

[4]Construction costs and expectations of future house price gains could be important determinants of future house price movements. We assume that the lagged house price contains information on these variables.

rate from FRED. The 3-month Treasury bill is also from FRED. We use quarterly-based data that cover the period from 1975Q2 to 2015Q4. The Shiller house price is deflated with the implicit price deflator for the nonfarm business sector from FRED.

Specifically, we define the detrended log of Shiller real house prices at time t, hp_t, as a function of the lagged detrended log of Shiller real house prices, hp_{t-1}, lagged 3-month Treasury bill rate, tb_{t-1}, lagged detrended log of real income, inc_{t-1}, lagged unemployment rate, $uemp_{t-1}$, and unpredicted shock, $\varepsilon_{hp,t}$. The volatility, $\sigma_{hp,t}$, is modeled as a function of one-period lagged volatility, $\sigma_{hp,t-1}$ and an exogenous shock $u_{\sigma,t}$. We detrend the log of real house prices and real income using the Hodrick-Prescott (HP) filter.[5] Based on the above specification, we estimate the following law of motion for the housing price and stochastic volatility process:

$$\begin{aligned} \mathrm{hp}_t - \bar{hp} &= \rho_{hp}(\mathrm{hp}_{t-1} - \bar{hp}) + \phi_r tb_{t-1} + \phi_{inc}(inc_{t-1} - \bar{inc}) \\ &\quad + \phi_u(uemp_{t-1} - ue\bar{m}p) + \exp(\sigma_{hp,t})\varepsilon_{hp,t} \quad , \varepsilon_{hp,t} \sim N(0,1), \end{aligned} \tag{1}$$

where $\bar{hp}$ is the mean detrended log of real house prices, $\bar{inc}$ is the mean detrended log of real income, $ue\bar{m}p$ is the mean unemployment rate, ρ_{hp} is the persistence of the log of real house prices, and $\sigma_{hp,t}$ is the log of the standard deviation of an innovation to the real house price. $\sigma_{hp,t}$ follows an AR(1) process:

$$\sigma_{hp,t} = (1-\rho_\sigma)\sigma_{hp} + \rho_\sigma \sigma_{hp,t-1} + (1-\rho_\sigma^2)^{1/2}\sigma_u u_{\sigma,t} \quad , u_{\sigma,t} \sim N(0,1), \tag{2}$$

where ρ_σ is the persistence of the log of the standard deviation of an innovation to the real house price, σ_{hp} determines the log of the average standard deviation of the house price shock, and σ_u is the standard deviation of the house price uncertainty. Note that, in each period, the house price shocks, captured by $\varepsilon_{hp,t}$, cause housing prices to deviate from expectations conditional on past house price history, aggregate economic conditions, and policy conditions. Although these sudden shocks could be driven by either the demand or the supply side, we cannot identify each side of the shock from the above specification. The shock $u_{\sigma,t}$ that affects house price volatility is considered to be the house price uncertainty shock.

2.2 Estimation

We estimate the parameters and stochastic volatility of equations (1) and (2) using particle MCMC (Fernández-Villaverde and Rubio-Ramírez, 2005; Andrieu et al., 2010). Since the model with the mean equation (1) and the stochastic volatility process (2) is not a linear state-space, we cannot obtain a closed form of the marginal likelihood. In such a case, we need to use an approximation method to evaluate the likelihood. The beauty of the particle filter with MCMC is that the difficult

[5]We tried other detrending methods, including linear detrending and the first log difference. However, the main results did not change.

problem of sampling from $p(\theta, \sigma_{hp,1:T}|hp_{1:T})$ can be reduced to sampling from $p(\theta|hp_{1:T})$, where θ is a set of parameters including coefficients and standard deviations of our mean equation and stochastic volatility process. By evaluating the approximately exact marginal likelihood $\hat{p}(hp_{1:T}|\theta)$ through the sequential Monte Carlo method and embedding them into the MCMC algorithm, we can sample θ and $\sigma_{hp,1:T}$ from $p(\theta, \sigma_{hp,1:T}|hp_{1:T})$. Under the random walk Metropolis-Hastings algorithm, we accept drawn samples of θ^* and $\sigma^*_{hp,1:T}$ with probability

$$\min\left[1, \frac{\hat{p}(hp_{1:T}|\theta^*)p(\theta^*)}{\hat{p}(hp_{1:T}|\theta)p(\theta)}\right], \quad \text{where } \theta \text{ is from previous samples.} \tag{3}$$

Table 1 reports prior distributions for the parameters of the house price process with posterior medians. For the persistence parameters, ρ_{hp} and ρ_σ, we impose a Beta prior with a mean of 0.8 and a standard deviation of 0.1. The shape of this prior restricts the parameter values to lie between 0 and 1. For the log of the mean standard deviation of the house price shock, σ_{hp}, we impose a Uniform prior ranging from -10 to 10. For each coefficient of control variables, we employ a Normal prior. The mean of the prior for each coefficient is set to the OLS estimate of equation (1) without stochastic volatility, and the standard deviation is set to 0.1. For the standard deviation of the house price uncertainty, σ_u, we use a Gamma prior with a mean of 1.0 and a standard deviation of 1.0 to ensure that the parameter is positive.

The posterior medians are obtained by using the random walk Metropolis-Hastings sampling algorithm. After the initial 10,000 burn-in draws, we use 40,000 draws to evaluate the posterior distribution of the parameters and uncertainty measures. The scaling matrix of the proposal density is adaptively adjusted following Vihola (2012) to achieve the appropriate acceptance rate.

Table 1 shows that the parameter estimates for the persistence, ρ_{hp}, of the detrended log of real house prices and the persistence, ρ_σ, of the volatility are 0.966 and 0.948, respectively. They are highly persistent. The coefficients for other control variables are consistent with economic reasoning. For example, the parameter ϕ_r is negative, suggesting that house prices are negatively correlated with the monetary policy rate ($\phi_r < 0$). In addition, consistent with what one may expect, house prices are positively correlated with the detrended log of income ($\phi_{inc} > 0$), but negatively correlated with the unemployment rate ($\phi_u < 0$). Finally, the average standard deviation of the house price shock is 0.645 percentage points (exp(-0.439)), and the standard deviation of the house price uncertainty is 0.189. A positive one-standard deviation shock $u_{\sigma,t}$ increases the standard deviation of the house price shock to 0.886 percentage points $(\exp(-0.439+(1-0.948^2)^{(1/2)}))$.

Figure 1 displays the posterior median and the 90% posterior probability intervals of the smoothed house price volatility, $\exp(\sigma_{hp})$, over the sample. We also plot the percentage deviation of real house prices from the trend and shade NBER recessionary periods. The figure shows the time-varying evidence of house price uncertainty. The evolution of house price uncertainty corresponds to boom and bust cycles of house prices. It allows us to build an analytic narrative of house price uncertainty. House price uncertainty significantly increases in 1976-1978 and reaches a peak at nearly 0.9 percentage points in 1978. Case (1994) notes that there was a house price boom in California in the late 1970s; the growth rate of housing prices outpaced income growth. However, real house prices reach a low point in the early 1980s with an increase in house price uncertainty. The housing boom also occurred in California, the Northeast, Hawaii, Seattle, and Washington, D.C. in the late 1980s, creating an increase in house price uncertainty. Real house prices reach a trough in the early 1990s, creating slightly high uncertainty as shown in Figure 1. Figure 1 also shows that house price uncertainty has increased recently, reflecting the recent boom and bust cycles of the housing market. In 2001, real house prices appreciated much faster than before. The percentage deviation of real house prices from the trend reaches nearly double-digit levels in 2005. In addition, the 2008 financial crisis caused by the unprecedented collapse in the housing market created the highest uncertainty in housing prices over the sample periods. Consistent with other macroeconomic indicators of uncertainty, such as the volatility of stock markets, bond markets, exchange rates, and GDP growth, the volatility of housing prices tends to increase in recessions.

2.3 Empirical MS-VAR Evidence

To empirically investigate the macroeconomic consequences of house price uncertainty shocks, this section considers a quarterly two-lags MS-VAR model with time-varying coefficients and heteroskedastic errors.[6] It allows us to characterize macroeconomic fluctuations when our economy has structural changes, and to investigate the asymmetric effects of house price uncertainty shocks. The model is represented as follows:

$$Y_t = c_{s_t} + \sum_{i=1}^{2} \phi_{s_t,i} Y_{t-i} + \Sigma_{s_t}^{1/2} \varepsilon_t, \quad \varepsilon_t \sim N(0,1), \tag{4}$$

$$P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix},$$

where S_t indexes regimes, P denotes a transition probability matrix with components $p_{ij} = p(s_t = j|s_{t-1} = i)$. $\Sigma_{s_t} = A_{s_t}^{-1} A_{s_t}^{-1\prime}$ where A_{s_t} denotes the contemporaneous relationship between reduced-form shocks, c_{s_t} is a constant term, and Y_t is a vector of endogenous variables. This specification allows us to not only investigate the regime-dependent effects of house price uncertainty shocks on economic activities, but also improves the fit of the model. The Bayesian Deviance information criterion (DIC) of a non-regime-dependent VAR model is -2395.8, while the DIC with two regimes is -2632.4, implying that the MS-VAR model is preferred over the constant VAR model. The DIC

[6] We choose a lag length following Towbin and Weber (2015). The main results are robust regardless of the lag length. Increasing the number of lags from two to four does not change our main results. Although a large number of regressors allows us to use more information, the estimates could have large variances.

proposed in Spiegelhalter et al. (2002) is a generalization of the Akaike information criterion in the sense that it consists of the goodness of fit and the complexity of the model.[7] The number of regimes is restricted to a 2-state Markov chain. Although the model with three regimes is slightly preferred to the model with two regimes in terms of the DIC, we can use a large enough number of samples at each regime with two regimes and show clear asymmetric implications of house price uncertainty shocks.[8]

To estimate the model, we use quarterly data from 1975:1 to 2015:4 of nine endogenous variables in the following order: filtered real housing price volatility, real personal consumption expenditure, real private residential investment, consumer price index (CPI) inflation, real Shiller house price index, 3-month Treasury bill rate, mortgage rate, the size of mortgage debt, and the rent to price ratio. Since the smoothed house price volatility has information over all the sample periods so that it may be more likely to be endogenously determined, we use filtered volatility in this exercise (Fernández-Villaverde et al., 2015). We estimate the model using an MCMC algorithm and compute credible sets from the posterior. House price uncertainty shocks are identified by standard Cholesky decomposition. The ordering is based on the assumption that housing price uncertainty is exogenous, implying that it reacts to changes in the other variables only with a quarter lag. The main results are robust regardless of the ordering of house price uncertainty shocks. We also find no evidence that any of the endogenous variables Granger-cause the filtered house price uncertainty.

Consumption and residential investment are obtained from the Bureau of Economic Analysis (BEA). They are deflated with a GDP deflator. The Shiller's housing price index, CPI, Treasury bill rate, and mortgage debt are from FRED. We use the nominal contract rate on the purchases of existing single-family homes from the Federal Housing Financing Agency (FHFA) as the mortgage rate. The rent to house price ratio is computed as the ratio between the housing CPI component (BLS) and the nominal Shiller house price index. We take the log transformation for all variables, except for CPI inflation, the Treasury bill rate, and the mortgage rate, and linearly detrend them.

Figure 2 shows that regime 2 obtained by the MS-VAR model is associated with the NBER recessionary periods. It implies that regime 1 is likely to correspond to the stable and expansionary periods. Figure 3 and 4 plot the median of impulse responses in each regime to a two-standard-deviation house price uncertainty shock with a 68% confidence interval. Figure 4 shows that the house price uncertainty shock has negative effects on macroeconomic aggregates in regime 2. It initially reduces consumption by around 0.2% via a precautionary savings motive. Residential investment decreases by nearly 1.5%. This result can be explained by real-options channels, im-

[7] The DIC is calculated as $-2\bar{D} - 2p_D$, where the goodness of fit of the model $\bar{D}$ is the expected log of likelihood $E[\ln L(\theta_i)]$, and the complexity of the model p_D is the expected log of likelihood $E[\ln L(\theta_i)]$ minus the log of likelihood evaluated at the posterior mean $\ln L(E[\theta_i])$. $E[\ln L(\theta_i)]$ is approximated as $\frac{1}{N}\sum_i(\ln L(\theta_i))$, and $\ln L(E[\theta_i])$ is approximated as $\ln L(\frac{1}{N}\sum_i \theta_i)$.

[8] The DIC with two regimes is -2632.4, while the DIC with three regimes is -2729.4. However, the asymmetric effects of house price uncertainty shocks are robust regardless of the number of regimes.

plying that the house price uncertainty shock has a negative effect on the real-options value of a new residential investment project. Both of the responses are quite significant at the medium run with their peak responses occurring after about ten quarters. The peak decline in residential investment is around five times as large as the peak decline in consumption. Inflation decreases initially following the shock, as documented in other studies, although it is not statistically significant. The monetary policy rate reacts to the downturn in economic activities and inflation by lowering rates. However, mortgage rates increase, increasing the mortgage spread.

The shock in regime 2 generates positive co-movement between aggregate macroeconomic variables and housing market-related variables. Real house prices and mortgage debt decrease by 1.0% and 3.0% at the peak, respectively. These results imply that the financial and debt risk effect would be stronger than the hedging effect so that the demand for housing decreases, requiring a lower house price. Since mortgage debt is contemporaneously related to housing prices via collateral constraints, the decrease in house prices, driven by the financial and debt risk effect, leads to a decrease in mortgage debt with a high persistence level. Finally, the rent to price ratio increases and reverts back to the original level. This result suggests that the shock could lead to a decrease in renting houses to a smaller extent than the magnitude of the decrease in the demand for housing.

However, in regime 1, which contains the housing boom periods, house prices, residential investment, and mortgage debt increase in response to the house price uncertainty shock. These results are the notable differences between regime 1 and regime 2. Households in the expansionary regime are more likely to have a strong desire for more housing consumption to hedge against future housing consumption risks. A decrease in the rent to price ratio reflects these facts. The increase in house prices leads to an increase in mortgage debt. The magnitude of the decline in consumption is slightly larger in regime 2 (in Figure 4) than in regime 1 (in Figure 3). This result possibly reflects the fact that the recent financial crisis, with massive uncertainty about future economic conditions, is contained in this regime so that the precautionary motive in regime 2 is much more severe than in regime 1. Moreover, the decline in house prices could lead the response of aggregate consumption to be amplified by the wealth effects and collateral constraints channel.

Table 2 presents the fraction of forecast error variance explained by the house price uncertainty shock for the endogenous variables at each regime. The initial contribution of the uncertainty shock is small, with the maximum share being 8.62% and 4.28% for consumption, and the minimum share being 0.53% and 0.61% for CPI inflation in regime 1 and regime 2, respectively. However, as the forecast horizon increases, the house price uncertainty shock tends to account for a larger fraction of macroeconomic variables. The shock in regime 2 is more likely to explain fluctuations in consumption, residential investment, housing prices, and mortgage debt at longer horizons than the shock in regime 1; however, the shock in regime 1 accounts for a larger fraction of housing prices at shorter horizons than the shock in regime 2. This result implies that house price uncertainty shock plays a more significant role in explaining economic fluctuations in recessionary periods than in stable and expansionary periods at longer horizons. At a 40 quarter horizon, the shock explains 27% (30%) of consumption variation, 14% (16%) of residential investment variation, 10% (11%) of housing price variation, and 11% (24%) of mortgage debt variation in regime 1 (in regime 2). The significant increase in the contribution to consumption and mortgage debt at longer horizons may be driven by the wealth effects and collateral constraints channel.

3 Theoretical DSGE Model with a Housing Market

The MS-VAR model considered in Section 2 serves as a useful benchmark model by empirically capturing the asymmetric effects of house price uncertainty shocks on macroeconomic aggregates. However, it does not guarantee one-to-one mapping with a structural DSGE model due to nonlinear terms in a third-order approximation with stochastic volatility.[9] Moreover, the MS-VAR model can be thought of as a reduced-form version of a Markov-switching DSGE model. In this paper, however, we focus on linking potential sources of regime-dependent house price uncertainty shocks to two different types of structural volatility shocks (supply-side volatility shocks and demand-side volatility shocks) in a non-regime-dependent DSGE model. Since the house price uncertainty shocks are associated with second-moment shocks in the DSGE model, we assume that the house price uncertainty shocks are the combination of structural volatility shocks in the DSGE model, and their relationship is likely to change over time, depending on the phase of the business cycle. Although the recursive identification scheme allows us to identify the house price uncertainty shocks, it is difficult to identify structural volatility shocks that are possible sources of the house price uncertainty shocks. Following the spirit of sign restrictions as in Mumtaz and Theodoridis (2015), we find key sources of the house price uncertainty shocks based on model-implied impulse responses to structural volatility shocks.

This section describes a DSGE model for theoretical analysis. The model is based on Iacoviello and Neri (2010), but it allows for a rental housing market based on Mora-Sanguinetti and Rubio (2014); Gazzani (2016); Sun and Tsang (2017). Incorporating a rental housing market into the model leads us to better understand a transmission mechanism of the housing consumption hedging effect driven by house price uncertainty. We also consider multiple stochastic volatility shocks. The stochastic volatility process to each shock in the model plays a significant role in analyzing the heterogeneous effects of uncertainty shocks on the housing market and finding major sources of the house price uncertainty shocks.

In this economy, there are two types of households: lenders (patient households) and borrowers (impatient households). They mainly differ in terms of discount factors. Both consume nonhousing consumption goods and housing services and supply labors. Lenders rent capital to firms, lend to firms and borrowers, and rent out a part of the housing stock to borrowers. They benefit from

[9] To take volatility shocks into account in the DSGE model, it is required to approximate the optimized behaviors up to the third-order (Fernández-Villaverde et al., 2011, 2015).

a flow of housing services by owning the housing stock. On the other hand, borrowers benefit from consuming housing services by owning the housing stock and renting the housing stock from lenders. They can borrow against the value of the housing stock from lenders.

A representative household of lenders maximizes the discounted sum of expected utility:

$$E_0 \sum_{t=0}^{\infty} (\beta^L)^t z_t \{\Gamma_c^L \ln(c_t^L - \varepsilon^L c_{t-1}^L) + j_t \ln h_{t-1}^L - \frac{\tau_t}{1+\eta^L}((n_{c,t}^L)^{1+\xi^L} + (n_{h,t}^L)^{1+\xi^L})^{\frac{1+\eta^L}{1+\xi^L}}\}, \qquad (5)$$

where c_t^L is nonhousing consumption, h_t^L is the housing stock, and $n_{c,t}^L$ and $n_{h,t}^L$ are hours worked in the consumption and housing sectors. We assume that the housing stock purchased at the end of $t-1$ produces housing services at the beginning of t. z_t and τ_t are shocks to inter-temporal preferences and to labor supply, respectively, and j_t captures shocks to housing preference. ε^L measures habits in consumption, the parameter $\eta^L > 0$ is the inverse of the Frisch labor supply elasticity, ξ^L measures imperfect substitutability between work hours in the two sectors, and the scaling factor Γ_c^L ensures a simple form of marginal utility of consumption in the steady state $(1/c^L)$. All the shocks in the utility function follow AR(1) processes with normally distributed shocks and heteroskedastic standard deviations $\sigma_{z,t}$, $\sigma_{j,t}$, and $\sigma_{\tau,t}$. Lenders make optimal decisions based on the following budget constraint:

$$\begin{aligned}
& c_t^L + \frac{k_{c,t}}{A_{k,t}} + k_{h,t} + k_{b,t} + q_t[h_t^L - (1-\delta_h)h_{t-1}^L + h_t^r - (1-\delta_h)h_{t-1}^r] + p_{l,t}l_t - b_t^L \\
&= \frac{w_{c,t}^L n_{c,t}^L}{X_{wc,t}^L} + \frac{w_{h,t}^L n_{h,t}^L}{X_{wh,t}^L} + \Big(R_{c,t}z_{c,t} + \frac{1-\delta_{kc}}{A_{k,t}}\Big)k_{c,t-1} + (R_{h,t}z_{h,t} + 1 - \delta_{kh})k_{h,t-1} \qquad (6) \\
&+ p_{b,t}k_{b,t} - \frac{R_{t-1}b_{t-1}^L}{\pi_t} + (p_{l,t} + R_{l,t})l_{t-1} + q_t^r h_{t-1}^r + Div_t^L - \phi_t - \frac{a(z_{c,t})k_{c,t-1}}{A_{k,t}} - a(z_{h,t}),
\end{aligned}$$

where $k_{c,t}$ and $k_{h,t}$ are capital in the consumption and housing sectors with real rental rates $R_{c,t}$ and $R_{h,t}$, respectively. The term $A_{k,t}$ refers to investment-specific technology shocks. $k_{b,t}$ are intermediate inputs priced at $p_{b,t}$, h_t^r is the housing stock for rent, q_t is the price of housing in real terms, q_t^r captures real rental rates for one unit of housing, l_t is land priced at $p_{l,t}$ with real rental rates of $R_{l,t}$, b_t^L is the amount of lending with a riskless nominal return R_t, $w_{c,t}^L$ and $w_{h,t}^L$ are real wages paid in the two sectors of production, $X_{wc,t}^L$ and $X_{wh,t}^L$ are the markups that denote wages paid by the wholesale firms over wages paid to the households, $z_{c,t}$ and $z_{h,t}$ are capital utilization in the consumption and housing sectors, and π_t is gross inflation $(=\frac{P_t}{P_{t-1}})$. δ_h is the depreciation rate of houses, and δ_{kc} and δ_{kh} are the depreciation rates of capital in the consumption and housing sectors. Div_t^L are dividends paid from final goods retailers and from labor unions.[10] ϕ_t are capital adjustment costs and $a(z_{c,t})$ and $a(z_{h,t})$ are adjustment costs on capacity utilization

[10] Div_t^L are given as follows:

$$Div_t^L = \left(1 - \frac{1}{X_t}\right)Y_t + \left(1 - \frac{1}{X_{wc,t}^L}\right)w_{c,t}^L n_{c,t}^L + \left(1 - \frac{1}{X_{wh,t}^L}\right)w_{h,t}^L n_{h,t}^L,$$

(see the details of ϕ_t and $a(\cdot)$ in Appendix A).

The optimal conditions with respect to h_t^L and h_t^r are as follows:

$$u^L_{c^L,t} q_t = \beta^L E_t\Big[\frac{j_{t+1} z_{t+1}}{h_t^L}\Big] + \beta^L E_t[u^L_{c^L,t+1} q_{t+1}(1-\delta)], \tag{7}$$

$$u^L_{c^L,t} q_t = \beta^L E_t\Big[u^L_{c^L,t+1} q^r_{t+1}\Big] + \beta^L E_t[u^L_{c^L,t+1} q_{t+1}(1-\delta)]. \tag{8}$$

By combining (7) and (8), we obtain

$$E_t\Big[u^L_{c^L,t+1} q^r_{t+1}\Big] = \beta^L E_t\Big[\frac{j_{t+1} z_{t+1}}{h_t^L}\Big]. \tag{9}$$

If the equation (9) holds, then households are indifferent between consuming housing services and renting a part of the housing stock to borrowers. By iterating (7) and (8), we also obtain

$$q_t = E_t\Big[\sum_{i=1}^{\infty} (\beta^L)^i q^r_{t+i}\Big] = E_t\Big[\sum_{i=1}^{\infty} (\beta^L)^i \frac{j_{t+i}}{h_t^L}\Big]. \tag{10}$$

The equation (10) implies that real house prices are the infinite sum of discounted future real rental rates (or housing preference).

In a similar way, borrowers maximize the following discounted sum of expected utility:

$$E_0 \sum_{t=0}^{\infty} (\beta^B)^t z_t \{\Gamma_c^B \ln(c_t^B - \varepsilon^B c_{t-1}^B) + j_t \ln \hat{h}_{t-1}^B - \frac{\tau_t}{1+\eta^B}((n_{c,t}^B)^{1+\xi^B} + (n_{h,t}^B)^{1+\xi^B})^{\frac{1+\eta^B}{1+\xi^B}}\}, \tag{11}$$

where housing services $\hat{h}_t^B$ come from the housing stock h_t^B borrowers own and the housing stock h_t^r they rent from lenders. They are aggregated through the following CES function:

$$\hat{h}_t^B = [\kappa (h_t^B)^{\xi_h - 1} + (1-\kappa)(h_t^r)^{\xi_h - 1}]^{\frac{1}{\xi_h - 1}}. \tag{12}$$

Borrowers maximize their utility subject to the following budget constraint:

$$c_t^B + q_t[h_t^B - (1-\delta_h) h_{t-1}^B] + q_t^r h_{t-1}^r - b_t^B = \frac{w_{c,t}^B n_{c,t}^B}{X_{wc,t}^B} + \frac{w_{h,t}^B n_{h,t}^B}{X_{wh,t}^B} - \frac{R_{t-1} b_{t-1}^B}{\pi_t} + Div_t^B, \tag{13}$$

where Div_t^B are dividends from labor unions. Borrowers are allowed to borrow up to the expected present value of their houses times the loan-to-value (LTV) ratio

$$b_t^B \leq m E_t\Big[\frac{q_{t+1} \pi_{t+1} h_t^B}{R_t}\Big], \tag{14}$$

where X_t denotes the markup of final goods over wholesale goods. $X^L_{wc,t}$ and $X^L_{wh,t}$ are the markups between the wage costs for the wholesale firm and households' wages.

where m is the LTV ratio.

To better understand the mechanism of the financial risk effect, the hedging effect, and the debt risk effect of house price uncertainty, we describe the optimal decisions on housing stock for owning and renting. We will describe the details of the mechanism in section 6.

$$u^B_{c^B,t} q^r_t = \beta^B E_t\Big[\frac{j_{t+1} z_{t+1}}{\hat{h^B_t}}[\kappa(h^B_t)^{\xi_h - 1} + (1-\kappa)(h^r_t)^{\xi_h - 1}]^{\frac{2-\xi_h}{\xi_h - 1}}(1-\kappa)(h^r_t)^{\xi_h - 2}\Big], \tag{15}$$

$$\begin{aligned} u^B_{c^B,t} q_t = \beta^B E_t\Big[\frac{j_{t+1} z_{t+1}}{\hat{h^B_t}}[\kappa(h^B_t)^{\xi_h - 1} + (1-\kappa)(h^r_t)^{\xi_h - 1}]^{\frac{2-\xi_h}{\xi_h - 1}}\kappa(h^B_t)^{\xi_h - 2}\Big] \\ + \beta^B E_t[u^B_{c^B,t+1} q_{t+1}(1-\delta)] + E_t\Big[\frac{\lambda_t m q_{t+1}\pi_{t+1}}{R_t}\Big]. \end{aligned} \tag{16}$$

Wholesale firms that produce wholesale goods (Y) and new houses (IH) solve the following profit maximization problem:

$$\max \frac{Y_t}{X_t} + q_t IH_t - \Big(\sum_{i=c,h} w^L_{i,t} n^L_{i,t} + \sum_{i=c,h} w^B_{i,t} n^B_{i,t} + \sum_{i=c,h} R_{i,t} z_{i,t} k_{i,t-1} + R_{l,t} l_{t-1} + p_{b,t} k_{b,t}\Big), \tag{17}$$

where X_t is the markup between final goods and wholesale goods ($\frac{P_t}{P^W_t}$). Both the consumption and housing sectors face Cobb-Douglas production functions. The nonhousing consumption sector uses capital (k_c) and labor supplied by lenders (n^L_c) and borrowers (n^B_c) to produce wholesale goods. The housing sector uses capital (k_h), land (l), intermediate inputs (k_b), and labor (n^L_h and n^B_h) as production inputs.

$$Y_t = (A_{c,t}((n^L_{c,t})^{\alpha}(n^B_{c,t})^{1-\alpha}))^{1-\mu_c}(z_{c,t} k_{c,t-1})^{\mu_c}, \tag{18}$$

$$IH_t = (A_{h,t}((n^L_{h,t})^{\alpha}(n^B_{h,t})^{1-\alpha}))^{1-\mu_h-\mu_b-\mu_l}(z_{h,t} k_{h,t-1})^{\mu_c} k^{\mu_b}_{b,t} l^{\mu_l}_{t-1}, \tag{19}$$

where $A_{c,t}$ and $A_{h,t}$ are productivity in the consumption and housing sectors. The parameter μ_c is the share of capital in the production function for the nonhousing sector, the parameters, μ_h, μ_b, and μ_l are, respectively, the shares of capital, intermediate inputs, and land in the production function for the housing sector, and α measures the labor income share of lenders and $1-\alpha$ of borrowers.

A continuum of retailers of mass 1, indexed by z, purchase wholesale goods Y_t and differentiate them by adding a unique feature to the product. They sell the differentiated product $Y_t(z)$ at the price $P_t(z)$. Monopolistic competition occurs at the retail level following Bernanke et al. (1999). Prices are adjusted with probability $1-\theta_\pi$ in every period based on a Calvo scheme, while a fraction θ_π indexes prices to lagged inflation at ι_π. Retailers take this constraint into account when maximizing the following expected profits with respect to $P_t(z)$,

$$\sum_{k=0}^{\infty}(\beta^L\theta_\pi)^k E_t\Big\{\frac{\lambda_{t+k}^L}{\lambda_t^L}\{\frac{\pi_{t-1,t+k-1}^{\iota_\pi}P_t(z)}{P_{t+k}}Y_{t+k}(z)-\frac{1}{X_{t+k}}Y_{t+k}(z)\}\Big\}, \tag{20}$$

where λ_t^L is the marginal utility of consumption for lenders ($u_{c^L,t}^L$) and $Y_{t+k}(z)$ is an individual demand $\Big(=(\frac{\pi_{t+k-1}^{\iota_\pi}P_t(z)}{P_{t+k}})^{-\varepsilon_p}Y_{t+k}\Big)$ that the retailers face.[11] Under the assumption that the retailers face the same optimization problem, all firms choose the following price level P_t^*.

$$\begin{aligned} P_t^* &= \frac{\varepsilon_p}{\varepsilon_p-1}\frac{X_{1t}}{X_{2t}},\\ X_{1t} &= \lambda_t^L\frac{1}{X_t}P_t^{\varepsilon_p}Y_t+\beta\theta\pi_t^{-\iota_\pi\varepsilon_p}E_tX_{1t+1},\\ X_{2t} &= \lambda_t^L P_t^{\varepsilon_p-1}Y_t+\beta\theta\pi_t^{\iota_\pi(1-\varepsilon_p)}E_tX_{2t+1}. \end{aligned} \tag{21}$$

To express the optimal pricing conditions in terms of inflation rates, we divide P_t^* by P_{t-1}.

$$\begin{aligned} \pi_t^* &= \frac{P_t^*}{P_{t-1}} = \frac{\varepsilon_p}{\varepsilon_p-1}\pi_t\frac{x_{1t}}{x_{2t}},\\ x_{1t} &= \lambda_t^L\frac{1}{X_t}Y_t+\beta\theta\pi_t^{-\iota_\pi\varepsilon_p}E_t\pi_{t+1}^{\varepsilon_p}x_{1t+1},\\ x_{2t} &= \lambda_t^L Y_t+\beta\theta\pi_t^{\iota_\pi(1-\varepsilon_p)}E_t\pi_{t+1}^{\varepsilon_p-1}x_{2t+1}. \end{aligned} \tag{22}$$

Since a fraction θ_π of the prices is unchanged, the gross inflation of the aggregate price is given by

$$\pi_t^{1-\varepsilon_p} = (1-\theta_\pi)\pi_t^{*(1-\varepsilon_p)}+\theta_\pi\pi_{t-1}^{\iota_\pi(1-\varepsilon_p)}. \tag{23}$$

In a similar way, wages are set in a monopolistic way based on a Calvo scheme with a given probability $1-\theta_{w,i}$ in every period. Households supply labor to the labor unions who differentiate labor services. The unions sell the differentiated labor $N_{i,t}^j(z)$ to wholesale labor packers at $w_{i,t}^j(z)$. The packers aggregate labor services based on the CES aggregates and provide labor services to

[11]As described in Iacoviello (2005), under a linear aggregation, total final goods sold by retailers equal wholesale goods Y_t within a local region of the steady state. Thus, we consider total final goods as Y_t. The demand function is derived from the assumption that the differentiated goods are aggregated by the CES function:

$$Y_t = \left(\int_0^1 Y_t(z)^{(\varepsilon_p-1)/\varepsilon_p}dz\right)^{\varepsilon_p/(\varepsilon_p-1)}.$$

The aggregate price index is given by

$$P_t = \left(\int_0^1 P_t(z)^{(1-\varepsilon_p)}dz\right)^{1/(1-\varepsilon_p)}.$$

wholesale firms.

$$\sum_{k=0}^{\infty}(\beta^j\theta_{w,i})^k E_t\Big\{\frac{\lambda_{t+k}^j}{\lambda_t^j}\{\pi_{t-1,t+k-1}^{\iota_{w,i}}\pi_{t,t+k}^{-1}w_{i,t}^j(z)N_{i,t+k}^j(z)-\frac{w_{t+k}}{X_{i,t+k}^j}N_{i,t+k}^j(z)\}\Big\}, \tag{24}$$

where $N_{i,t+k}^j(z)$ is the demand function $\Big(=(\frac{\pi_{t-1,t+k-1}^{\iota_{w,i}}\pi_{t,t+k}^{-1}w_{i,t}^j(z)}{w_{i,t+k}^j})^{-\varepsilon_{i,w}^j}n_{i,t+k}^j\Big)$ that the labor union faces, $X_{i,t+k}^j$ is the markup, and λ_t^j is the marginal utility of consumption $(u_{c^j,t}^j)$. The sticky wage leads to the following optimal real wage:

$$\begin{aligned}
w_{i,t}^{*j} &= \frac{\varepsilon_{i,w}^j}{\varepsilon_{i,w}^j-1}\frac{f_{i,1t}^j}{f_{i,2t}^j},\\
f_{i,1t}^j &= \lambda_t^j\frac{(w_{i,t}^j)^{1+\varepsilon_{i,w}^j}}{X_{i,t}^j}n_{i,t}^j+\beta^j\theta_{w,i}\pi_t^{-\iota_{w,i}\varepsilon_{i,w}^j}E_t\pi_{t+1}^{\varepsilon_{i,w}^j}f_{i,1t+1}^j,\\
f_{i,2t}^j &= \lambda_t^j(w_{i,t}^j)^{\varepsilon_{i,w}^j}n_{i,t}^j+\beta^j\theta_{w,i}\pi_t^{\iota_{w,i}(1-\varepsilon_{i,w}^j)}E_t\pi_{t+1}^{\varepsilon_{i,w}^j-1}f_{i,2t+1}^j.
\end{aligned} \tag{25}$$

where i=consumption sector (C) or housing sector (H) and j=Borrowers (B) or lenders (L). Since a fraction $\theta_{w,i}$ of wages is unchanged, the aggregate real wage is given by

$$(w_{i,t}^j)^{1-\varepsilon_{i,w}}=(1-\theta_{w,i})(w_{i,t}^{*j})^{(1-\varepsilon_{i,w}^j)}+\theta_{w,i}\pi_{t-1}^{\iota_{w,i}(1-\varepsilon_{i,w}^j)}\pi_t^{\varepsilon_{i,w}^j-1}(w_{i,t-1}^j)^{(1-\varepsilon_{i,w}^j)}. \tag{26}$$

Monetary authority follows a Taylor-type rule:

$$R_t=R_{t-1}^{r_R}\pi_t^{(1-r_R)r_\pi}\Big(\frac{GDP_t}{GDP_{t-1}}\Big)^{(1-r_R)r_Y}\bar{rr}^{1-r_R}\frac{\sigma_{R,t}u_{R,t}}{A_{s,t}} \quad \text{where } \ u_{R,t}\sim N(0,1), \tag{27}$$

where $\bar{rr}$ is the steady state real interest rate, r_R, r_π, and r_Y are the responses of the interest rate to changes in the lagged interest rate, inflation, and GDP growth, respectively, the inflation objective shock $(A_{s,t})$ follows the AR(1) process with stochastic volatility $\sigma_{s,t}$, and the shock to the monetary policy $u_{R,t}$ is assumed to have time-varying volatility $\sigma_{R,t}$.

In the equilibrium,

$$C_t+IK_{c,t}/A_{k,t}+IK_{h,t}+k_{b,t}=Y_t-\phi_t, \tag{28}$$

$$H_t-(1-\delta_h)H_{t-1}=IH_t, \tag{29}$$

$$b_t^L+b_t^B=0, \tag{30}$$

$$l_t=1, \tag{31}$$

where

$$IK_{c,t} = k_{c,t} - (1 - \delta_{kc})k_{c,t-1}, \tag{32}$$

$$IK_{h,t} = \frac{k_{h,t} - (1 - \delta_{kh})k_{h,t-1}}{A_{k,t}}. \tag{33}$$

Finally, productivity in the consumption ($A_{c,t}$), investment ($A_{k,t}$), and housing sectors ($A_{h,t}$) follows:

$$\ln(A_{i,t}) = \rho_{A,i}\ln(A_{i,t-1}) + exp(\sigma_{i,t})u_{i,t} \quad \text{where } \ u_{i,t} \sim N(0,1), \tag{34}$$

where $i = \{c, k, h\}$ and $u_{i,t}$ are the innovation. All of the stochastic volatility processes follow:

$$\sigma_{j,t} = (1 - \rho_{\sigma_j})\sigma_j + \rho_{\sigma_j}\sigma_{j,t-1} + \sigma_{\sigma_j}v_{j,t} \quad \text{where } \ v_{j,t} \sim N(0,1), \tag{35}$$

where $j \in \{c, h, j, k, \tau, z, s, R\}$, $\sigma_{j,t}$ is the j-th stochastic volatility, σ_j is the unconditional mean of $\sigma_{j,t}$, ρ_{σ_j} is the level of persistence, and σ_{σ_j} is the standard deviation of the volatility shock $v_{j,t}$. All of the equilibrium conditions are given in Appendix A.

4 Solution and Estimation

We solve the model based on a third-order approximation that allows time-varying volatility to be an independent component of the decision rules. This approximation is crucial when we investigate the direct effects of uncertainty shocks on economic activity. However, higher-order approximations that consist of polynomials of state variables have multiple steady states and can yield unbounded solutions. As explained by Kim et al. (2008), simulated sample paths of the approximated policy function could explode when the accumulation of higher-order effects is significantly large, generating unstable steady states. To solve this problem, they suggest applying a pruning procedure to a second-order approximation that eliminates terms of higher-order effects than the approximation order. Andreasen et al. (2017) extend this logic to any order and provide closed-form expressions of first and second moments and IRFs. Although Den Haan and De Wind (2012) question the suitability of this approach, it has been widely accepted as an efficient and reliable way to get the solution of a higher-order approximated DSGE model.

The model solved using a third-order approximation with pruning is given by the following state space representation:

$$\begin{aligned} \mathbf{Y_t} &= \mathbf{G}(\mathbf{X_t}, \sigma) + \boldsymbol{\epsilon_t}, \\ \mathbf{X_{t+1}} &= \mathbf{H}(\mathbf{X_t}, \sigma) + \sigma\boldsymbol{\eta_{t+1}}, \end{aligned} \tag{36}$$

where $\mathbf{X_t}$ denotes a set of state variables that contain pre-determined endogenous and exogenous variables, $\mathbf{Y_t}$ is a set of observable variables, $\boldsymbol{\epsilon_{t+1}} \sim i.i.dN(0, \mathbf{R}_\epsilon)$, and $\boldsymbol{\eta_{t+1}} \sim i.i.dN(0, \mathbf{R}_\eta)$.

The detailed expression is given in Appendix B.

We calibrate some parameters based on Iacoviello and Neri (2010). Table 3 describes our calibration. The calibrated parameters $\varepsilon_p, \varepsilon^L_{c,w}, \varepsilon^L_{h,w}, \varepsilon^B_{c,w}$, and $\varepsilon^B_{h,w}$ in the CES aggregator allow price and wage markups to be 1.2 in the steady state. Additionally, we calibrate κ. The parameter κ is set to match the U.S. homeownership rate of households whose income is below the median as in Gazzani (2016). For ease of implementation, we solve the model using Dynare (Adjemian et al., 2011).

We use a two-step procedure to estimate the structural parameters that are not calibrated.[12] First, we use the random-walk Metropolis-Hastings algorithm to estimate the model without stochastic volatility processes. Since approximately exact likelihood evaluation methods such as the particle filter and the Gaussian mixture filter are infeasible for a practical purpose due to a huge dimension of state variables, we use the CDKF for the evaluation of the likelihood within the MCMC algorithm. Although the CDKF is based on Gaussian-based approximation, it is computationally efficient and reasonably accurate (Andreasen, 2013; Noh, 2019). Most of the priors are based on Iacoviello and Neri (2010). We allow for a normal distribution for a parameter that determines the elasticity of substitutions between home-owning and renting (ξ_h). The prior mean for that parameter is set to 1.5 with a loose standard deviation.

In the second step, we use the Simulated Method of Moments (SMMs) to estimate the parameters in the stochastic volatility processes. The reason for applying this two-step procedure is two-fold. First, the solution with pruning involves a large number of state variables so that the CDKF is burdensome when estimating the model with stochastic volatility processes. Second, by focusing on the parameters in volatility processes to match the actual data moments, we can gauge the impacts of volatility shocks on economic activity. The model is estimated using eight observable variables: real consumption, real residential investment, real business investment, real Shiller house price index, nominal interest rates, inflation, wage inflation in the consumption sector, and wage inflation in the housing sector. The data span from 1977Q1 to 2008Q4.

Although this two-step procedure does not guarantee efficiency, it allows us not only to use full information maximum likelihood to estimate key structural parameters, but also to capture the role of stochastic volatility processes in explaining fluctuations of the main macroeconomic variables with a reasonable computational burden. The details of the data are given in Appendix C.

[12] We use the pruning package provided by Andreasen et al. (2017) to transform the Dynare notation into the one used in Andreasen et al. (2017), and then take the approximated solution to the data.

5 Estimation Results

5.1 Parameter Estimates

The posterior means and 90% credible sets are reported in Table 4 with the prior distributions. The estimated labor income share of borrowers is 0.34 in the third-order approximation, which is larger than the value implied by the linearized model in Iacoviello and Neri (2010). The estimated degree of habit formation in consumption is marginally larger for lenders than the degree for borrowers ($\varepsilon^L = 0.48$ and $\varepsilon^B = 0.40$). Although lenders can smooth consumption by saving (capital adjustment and lending to firms and borrowers), they have to take the risks of saving into account and may have high capital adjustment costs. These facts imply that lenders are required to have a large habit persistence to smooth consumption. The parameters (ξ^L and ξ^B) for labor mobility are 0.94 and 1.01, respectively, implying imperfect substitutes between the consumption-good market and the housing market. The inverse of the Frisch labor supply elasticity is 0.40 (η^L) and 0.50 (η^B) for lenders and borrowers, respectively. The estimated nominal stickiness for prices and wages is in line with Sun and Tsang (2017), except that price and wage indexation coefficients (ι_π, $\iota_{w,c}$, $\iota_{w,h}$) are different from their estimates. $\theta_\pi = 0.91$ implies that retailers reoptimize prices every eleven quarters. We also find that stickiness in the housing sector ($\theta_{w,h} = 0.97$) is higher than in the consumption sector ($\theta_{w,c} = 0.76$). All shock processes are persistent, ranging from 0.76 to 0.98.

Table 5 summarizes the estimated parameter values for the stochastic volatility processes. A degree of persistence of the volatility processes ranges from 0.63 to 0.91, with inflation objective and intertemporal preference having 0.91 and 0.63, respectively. The standard deviations of volatility shocks to technology in the nonhousing sector, investment-specific technology, inflation objective, and monetary policy are relatively larger than the other shocks. The standard deviation of the volatility shock for monetary policy shows the largest value. A one-standard-deviation volatility shock increases the standard deviation of technology in the nonhousing and housing sectors, housing preference, investment-specific technology, labor supply, intertemporal preference, inflation objective, and monetary policy by 19.6%, 5.7%, 8.2%, 28.5%, 0.5%, 7.5%, 23.1%, and 36.5%, respectively. These values are calculated by $(\exp(\sigma_{\sigma_j}) - 1)\times 100$. The small standard deviation of the labor supply volatility shock implies that the labor supply shock process is close to the one of constant volatility. The moments presented in Table 6 show that the DSGE model does a good job of matching the standard deviations. In particular, the model approximately captures the volatilities of consumption, business investment, inflation, monetary policy rate, and wage inflation in the consumption and housing sectors. However, it does a relatively poor job of reproducing fluctuations in residential investment and housing prices and of matching the auto-correlations.

5.2 Impulse Response Analysis

For the impulse response analysis, we calculate stochastic steady states and generate IRFs around the stochastic steady states of model variables to a composite uncertainty shock following Born and Pfeifer (2014a). We define an uncertainty shock as a two-standard deviation increase in the shock's volatility while keeping level shocks constant. Figure 5 shows the impulse responses to two-standard deviation shocks for all volatility processes in the model. To test the role of the third-order approximation, we plot the responses based on both the second- and third-order approximations. The figure shows that uncertainty shocks play no significant role in the second-order solution, but the impacts are significantly amplified through the third-order terms of the solution.

Consistent with the existing literature, uncertainty shocks tend to dampen economic activity. Consumption and business investment decrease, reaching a trough of 0.06% at around the five-quarter horizon. Housing prices follow a similar pattern, decreasing by about 0.03%. There is a sharp decrease in residential investment in response to the shock, reaching a trough of 0.2% at around the five-quarter horizon. A composite uncertainty shock has initial countervailing impacts on business and residential investment. The shock initially increases the option value of business investment but reduces the option value of residential investment. The increase in exogenous uncertainty shocks leads households to reduce consumption due to precautionary motives and to decrease the demand for housing due to the financial risk and debt risk effect.

Although the model tends to reproduce most of the average impulse responses obtained from the constant VAR model, it mainly fails to capture the empirical responses of inflation and the nominal interest rate.[13] Under a sticky price and wage, an upward pricing bias channel leads firms and labor unions to optimally choose higher prices and wages, respectively (Fernández-Villaverde et al., 2015). This channel induces an increase in inflation. In addition, the Taylor rule in the model fails to replicate the VAR results. The model-implied reaction of the monetary authority does not offset the negative effects of the uncertainty shocks because of the increase in inflation. A decrease in output can be explained by an increase in markups between wholesale good prices and final good prices ($\frac{P_t}{P_t^W}$) with the presence of nominal rigidities.[14]

[13]The house price uncertainty shocks in the constant VAR model initially reduce consumption and residential investment by 0.2% and 0.9%, respectively. Both of the responses are quite persistent, with their peak responses occurring after about 20 quarters. The peak decline in residential investment is around four times as large as the peak decline in consumption. Inflation decreases, although it is not statistically significant. The monetary policy rate decreases and remains below the trend for about three years. The decrease in the monetary policy rate leads to a decrease in mortgage rates, but to a smaller extent, reducing the mortgage spread. Real house prices and mortgage debt decrease by 1.0% and 2.5% at the peak, respectively. These results are available upon request.

[14]The upward pricing channels with sticky prices and wages tend to increase P_t initially. In addition, a decrease in wages driven by the precautionary labor supply reduces P_t^W so that markups are increased in the long run.

5.3 Source of House Price Uncertainty

5.3.1 Shock decomposition

In this section, we measure the contribution of each of the eight volatility shocks in our model to fluctuations of the main aggregate variables. In particular, we focus on house price fluctuations. By measuring the contribution of each uncertainty shock to house price fluctuations, we can identify a potentially significant source of house price uncertainty shocks. Since it is difficult to correctly divide the total variance among the eight shocks as implemented in the linearized model because of the second- and third-order terms in the third-order approximation, we calculate the standard deviations of the main aggregate variables generated from the following specifications, turning on: (1) eight uncertainty shocks; (2) supply-side uncertainty shocks; (3) demand-side uncertainty shocks; and (4) an individual uncertainty shock. We investigate five macro-aggregates: consumption (C), business investment (IK), residential investment (IH), housing prices (q), and rent to house price ratio (q^r/q).

Table 7 shows that a simultaneous one-standard-deviation shock for all sources of uncertainty has significant impacts on business and residential investment and has relatively small impacts on consumption, housing prices, and the rent to price ratio. The fluctuations of business investment are more driven by supply-side uncertainty shocks than demand-side uncertainty shocks. However, residential investment is more affected by demand-side uncertainty shocks. In particular, shifts in uncertainty about investment-specific technology and inflation target have the largest impacts on business and residential investment, respectively. Moreover, house price fluctuations are more likely to be explained by demand-side uncertainty shocks than supply-side uncertainty shocks. Among all the uncertainty shocks, uncertainty shocks to investment-specific technology, technology in the nonhousing sector, housing preference, and inflation objective are the key drivers of the variance in housing prices. Uncertainty shocks to both the technology in the housing sector and the monetary policy play a moderate role in explaining the variance in housing prices.

To highlight the role of structural uncertainty shocks in accounting for the historical fluctuations of housing prices, Figure 6 decomposes house prices in terms of the underlying level shocks with/without uncertainty shocks: housing preference shocks, technology shocks, and monetary shocks. The solid line displays the detrended historical house prices. The other lines show the historical contribution of the level shocks(dashed lines) and the level and uncertainty shocks (dashed-dotted lines) under our estimated parameters. In the upper panel of Figure 6, the decomposition for house prices shows that housing preference level shocks explain a large share of the movements in house prices. In addition, housing preference uncertainty shocks increase house prices over the most recent housing boom periods, reflecting households' housing consumption hedging effect. However, they significantly reduce house prices over the recent housing bust periods. These findings explain the empirical results in expansionary and recessionary regimes from the MS-VAR. The figure also highlights that technology uncertainty shocks reduce house prices, mostly reflecting the financial and debt risk effects. Monetary uncertainty shocks reduce house prices over the 1982 recessionary periods, but they increase house prices over the recent housing boom periods.

5.3.2 Supply-side uncertainty shocks

We examine how economic agents respond to supply-side uncertainty shocks. Figure 7 shows impulse responses to (1) uncertainty shocks to investment-specific technology (black solid line); (2) uncertainty shocks to investment-specific technology and technology in the housing sector (black dashed line); (3) uncertainty shocks to investment-specific technology and technology in the nonhousing and housing sectors (black dashed-dotted line); and (4) uncertainty shocks to investment-specific technology, technology in the nonhousing and housing sectors, and labor supply (black dotted line).

The supply-side uncertainty shocks have negative impacts on consumption, residential investment, housing prices, and household debt. Among them, uncertainty shocks to investment-specific technology and technology in the nonhousing sector generate large impacts on these variables. Due to precautionary motives, consumption initially decreases below its steady state and then reverts to the steady state. Residential investment is also affected by the supply-side uncertainty shocks. It initially declines by 0.15% because of a decrease in the demand for housing, and hence a decrease in the real-options value of investing in new housing construction. The decrease in demand for housing may be induced by the financial risk and debt risk effect, which implies that households who face greater house price uncertainty require a lower housing price. It leads house prices to decrease below the steady state by 0.04% initially, and the rent to price ratio to increase by 0.04%. Although the uncertainty shocks to technology in the housing sector increase house prices, its impact is not significant. The level of household debt is diminished through the channel of collateral constraint. Most of these results are closely linked to the key features of the empirical impulse responses in recessionary regimes obtained from the MS-VAR model.

However, the supply-side uncertainty shocks initially increase business investment by 0.25%, which is mostly driven by the investment-specific uncertainty shock. This result supports the idea that the investment-specific uncertainty shock increases the real-options value of a new business investment project. Although the uncertainty shocks to technology in the nonhousing sector and labor supply reduce business investment, the magnitude is much smaller than those generated by the investment-specific uncertainty shock. Investment-specific uncertainty leads output to increase after the shock. It implies that the positive real-options effect on business investment dominates the negative effects of markup channels. The supply-side uncertainty shocks increase inflation because the upward pricing channels lead to a higher price and wage. The nominal interest rate is elevated by the increase in inflation and output.

5.3.3 Demand-side uncertainty shocks

In this section, we examine how economic agents respond to demand-side uncertainty shocks. Figure 8 shows impulse responses to (1) housing preference uncertainty shocks (black solid line); (2) housing preference and intertemporal preference uncertainty shocks (black dashed line); (3) housing preference, intertemporal preference, and inflation objective uncertainty shocks (black dashed-dotted line); and (4) housing preference, intertemporal preference, inflation objective, and monetary policy uncertainty shocks (black dotted line). The impulse responses are mainly driven by both the housing preference uncertainty shocks and the inflation objective uncertainty shocks. They have countervailing impacts on residential investment, housing prices, household debt, and the rent to price ratio. Interestingly, the responses of these variables to the housing preference uncertainty shocks, when compared with the responses to the supply-side uncertainty shocks, are the opposite. However, the inflation objective uncertainty shocks generate similar responses to those obtained from the supply-side uncertainty shocks.

The housing preference uncertainty shocks lead households to demand more housing consumption through a hedging effect. When households face higher house price uncertainty, induced by the housing preference uncertainty shocks, the costs for future housing consumption increase. Households can hedge against future housing consumption risk by holding onto their current house, implying that they will pay higher housing prices. The increase in housing prices induced by the housing preference uncertainty shocks leads households to borrow more debt and consume more due to the collateral constraint and wealth effect. Since housing prices see a larger increase than rental rates, the rent to price ratio falls below its steady state. The collateral constraint channels and the wealth effect channels tend to dominate the households' precautionary behavior so that they initially increase consumption; however, it marginally responds to the house price uncertainty shocks and reverts back to the steady state in the long-run. Inflation and the nominal interest rate increase due to the upward pricing bias channels with sticky prices and wages. As in the case of the supply-side uncertainty shocks, the housing preference uncertainty shocks initially increase output, but for different reasons. The initial increase in output to the housing preference uncertainty shocks is driven by the initial jumps in consumption, business investment, and residential investment. It implies that they initially dominate the negative effects of markup channels.

Contrary to the housing preference uncertainty shocks, shocks to inflation objective uncertainty and monetary policy uncertainty have negative impacts on economic activities. The shocks reduce consumption, business investment, residential investment, housing prices, household debt, and output. In particular, the shocks to inflation target uncertainty show significant impacts on these variables. The results obtained from the housing preference uncertainty shocks are closely related to the VAR impulse responses in expansionary regimes, but the shocks to inflation target uncertainty reproduce the VAR impulse responses in recessionary regimes. In the housing boom periods, when there was prevalent housing preference uncertainty, the hedging effect may increase housing prices. However, in recessionary periods, high inflation objective uncertainty and monetary policy uncertainty may decrease housing prices.

6 Inspecting the Mechanism

6.1 Housing demand channels

Why do house prices increase or decrease after uncertainty shocks? Housing demand is impacted by financial risk, housing consumption hedging, and debt risk effects, which are all driven by uncertainty shocks. These effects have countervailing effects on households' demands for housing. In this section, we analyze the Euler equation to understand how the supply- and demand-side uncertainty shocks affect the housing demand differently through a channel of the financial risk effect, the hedging effect, and the debt risk effect. Since borrowers' equilibrium conditions are more general, in the sense that they face borrowing constraints, we focus on the Euler equations for borrowers and also discuss lenders' behavior. The equilibrium conditions, (15) and (16), for borrowers can be simplified as:

$$1 = E_t[\Lambda_{t+1} R_{t+1}], \tag{37}$$

where $R_{t+1} = \frac{(1-\delta)q_{t+1} + \frac{\kappa}{1-\kappa}\left(\frac{h_t^B}{h_t^r}\right)^{\xi_h - 2} q_{t+1}^r + m q_{t+1} D_{t+1}}{q_t}$ denotes the returns to owning houses, $\Lambda_{t+1} = \beta^B \frac{u^B_{c^B,t+1}}{u^B_{c^B,t}}$ indicates the present value of marginal utility of future consumption, $D_{t+1} = \frac{\pi_{t+1} u^B_{b,t}}{R_t \beta^B u^B_{c^B,t+1}}$ is the present value of borrowing costs relative to the present value of future consumption, q_{t+1} are housing prices, and q_{t+1}^r represent the housing rental rates.

The structural uncertainty shocks propagate through this equilibrium condition, implying that they could be the possible sources of uncertainty surrounding housing prices, housing rental rates, inflation rates, and the intertemporal marginal rate of substitution. These shocks create the relationship between returns to owning housing stock and uncertainty. Since the model is too complicated to provide insight as to how the financial risk effect, the hedging effect, and the debt risk effect work, we make assumptions about the stochastic process and the distribution of the intertemporal marginal rate of substitution, the growth rate of house prices, the growth rate of rent, and the relative value of debt over the value of consumption based on Han (2013).

For convenience, the intertemporal marginal rate of substitution is assumed to follow

$$\Lambda_{t+1} = exp\Big(-r_t^f - \frac{1}{2}\sigma^2_{\Lambda,t} + \epsilon_{\Lambda,t+1}\Big), \tag{38}$$

where $\epsilon_{\Lambda,t+1}|I_t \sim N(0, \sigma^2_{\Lambda,t})$ and r_t^f denotes the riskless return at time t. The growth rate of housing prices ($x_{t+1}^q = \ln\frac{q_{t+1}}{q_t}$), the growth rate of rent ($x_{t+1}^{q^r} = \ln\frac{q_{t+1}^r}{q_t^r}$), and the relative value of debt over the value of consumption ($x^D_{t+1} = \ln D_{t+1}$) are assumed to follow the AR(1) process.

$$x^j_{t+1} = \alpha^j_0 + \alpha^j_1 x^j_t + \epsilon^j_{t+1}, \tag{39}$$

where $\epsilon^j_{t+1}|I_t \sim N(0, \sigma^2_{j,t})$ and j indexes housing price (q), rent (q^r), and borrowing cost (D). Under these assumptions, we can derive the analytic form of the uncertainty-return relationship for borrowers. The details of the derivation are provided in Appendix D.

$$\frac{\partial E^B_t(r_{t+1})}{\partial Var^B_t(r_{t+1})} = -\frac{\frac{1}{2}B + \rho^B_{q\Lambda} + D\rho^B_{qq^r} + F\rho^B_{qD}}{B + 2D\rho^B_{qq^r} + 2F\rho^B_{qD}}, \tag{40}$$

where $r_{t+1} = \ln R_{t+1}$, $B = \left((1-\delta) + m\left(\frac{\beta^L}{\beta^B} - 1\right)\right)$, $D = \frac{\kappa}{1-\kappa}\left(\frac{h^B}{h^r}\right)^{\xi_h - 2}\left(\frac{q^r}{q}\right)$, $F = m\left(\frac{\beta^L}{\beta^B} - 1\right)$, $\rho^B_{q\Lambda}$ is the correlation between the growth rate of housing prices and the intertemporal marginal rate of substitution, $\rho^B_{qq^r}$ is the correlation between the growth rate of housing prices and the growth rate of the rental rate, and ρ^B_{qD} is the correlation between the growth rate of housing prices and the log of borrowing cost. Equation (40) shows the relationship between the expected return to owning housing stock and the associated uncertainty. The relationship is determined by $\rho^B_{q\Lambda}$, $\rho^B_{qq^r}$, and ρ^B_{qD}, implying that house price uncertainty may affect house prices to the extent that it affects nonhousing consumption, housing consumption, and the debt level.

In the financial asset pricing literature, the following assumptions are generally accepted: (1) the growth rate of housing prices is negatively correlated with the intertemporal marginal rate of substitution ($\rho^B_{q\Lambda} < 0$), but (2) it is positively correlated with the growth rate of the rental rate ($\rho^B_{qq^r} > 0$). With a negative $\rho^B_{q\Lambda}$, the growth rate of housing prices decreases when the future nonhousing consumption is more valuable. It implies that households are reluctant to buy a house as a financial asset when they want more nonhousing consumption. In this case, faced with greater house price uncertainty and hence higher uncertainty about future nonhousing consumption, households require more compensation to induce themselves to buy a house which reduces housing prices. This mechanism, based on a negative $\rho^B_{q\Lambda}$, describes the financial risk effect, which is common to all financial assets. On the other hand, a positive $\rho^B_{qq^r}$ implies that a housing price increases when households face a high rental rate, which can be thought of as future costs for housing. In this case, households want to buy a house to hedge against uncertain future housing costs, and thus house price uncertainty increases house prices. This mechanism, with a positive $\rho^B_{qq^r}$, is associated with the hedging effect. The size of the hedging effect depends on the portion of homeowners relative to the portion of renters. Although negative values of $\rho^B_{q\Lambda}$ and positive values of $\rho^B_{qq^r}$ are generally supported by empirical evidence (Sinai and Souleles, 2005; Davidoff, 2006), it is not clear that individual uncertainty shock induces similar implications. In addition, we assume $\rho^B_{qD} < 0$. The negative value of ρ^B_{qD} is associated with the debt risk effect, implying that households reduce their demand for housing to reduce their exposure to risk in debt.

In a similar way, the uncertainty-return relationship for lenders is expressed as

$$\frac{\partial E_t^L(r_{t+1})}{\partial Var_t^L(r_{t+1})} = -\frac{\frac{1}{2}B + \rho_{q\Lambda}^L + C\rho_{qq^r}^L}{B + 2C\rho_{qq^r}^L}, \tag{41}$$

where $r_{t+1} = \ln\left(\frac{(1-\delta)q_{t+1}+q_{t+1}^r}{q_t}\right)$, $B = (1-\delta)\bar{r}$ and $C = \frac{k}{1-k}\left(\frac{h_t^L}{h_t^r}\right)^{\xi-2} q\Lambda$. This relationship is derived by the lenders' equilibrium conditions (7) and (8).

We now investigate the above-described housing demand channels through which house price uncertainty affects house prices. To measure the magnitude and sign of the financial risk effect ($\rho_{q\Lambda}$), the hedging effect (ρ_{qq^r}), and the debt risk effect (ρ_{qD}) for borrowers and lenders, we simulate q_t, q_t^r, Λ_t, and D_t, and estimate the following equations for borrowers

$$x_t^q = \beta_0^B + \beta_{q\Lambda}^B \Lambda_{B,t} + \beta_{qq^r}^B x_t^{q^r} + \beta_{qD}^B x_{B,t}^D + v_{B,t}, \tag{42}$$

and for lenders

$$x_t^q = \beta_0^L + \beta_{q\Lambda}^L \Lambda_{L,t} + \beta_{qq^r}^L x_t^{q^r} + v_{L,t}, \tag{43}$$

where the coefficients $\beta_{q\Lambda}^i$, $\beta_{qq^r}^i$, and β_{qD}^i correspond to the financial risk effect $\rho_{q\Lambda}^i$, the hedging effect $\rho_{qq^r}^i$, and the debt risk effect ρ_{qD}^i, respectively.

These equations can be interpreted as a reduced-form way of capturing the financial risk effect, the hedging effect, and the debt risk effect. Specifications of this kind are similar to those in standard financial asset pricing models that are used to investigate risk-return relationships. For example, the estimated $\beta_{q\Lambda}^i$ is often defined as market risk. Empirically, market risk, $\beta_{q\Lambda}^i$, is simply the regression coefficient of the asset return on the marginal rate of substitution, which is a function of nonhousing consumption growth. An important advantage of our exercises, based on the simulated data, relative to the actual data-based regressions, is that the structural model-based regressions can avoid problems associated with poor quality consumption data. Financial economists often model consumption growth in terms of a set of market factors, such as the return on a broad-based stock portfolio. In this paper, we use the simulated marginal rate of substitution between future and current nonhousing consumption instead of using a proxy variable.

We simulate the variables with four possible combinations for borrowers and lenders: (1) the benchmark case with eight uncertainty shocks; (2) the supply-side uncertainty shocks; (3) the demand-side uncertainty shocks; and (4) the individual uncertainty shock. Using 2000 simulated samples, we estimate the coefficients 100 times and obtain the average coefficients. We normalize simulated data for the estimation. Table 8 shows that most of the cases satisfy the financial risk effect ($\rho_{q\Lambda}^B < 0$), the hedging effect ($\rho_{qq^r}^B > 0$), and the debt risk effect ($\rho_{qD}^B < 0$), except that the uncertainty shocks do not seem to generate the financial risk effects for borrowers.[15] For

[15] As a robustness exercise, we experimented with several specifications that included interest rates and wage

lenders, the supply-side uncertainty shocks have a larger effect on the financial risk effect than the demand-side uncertainty shocks, but the demand-side uncertainty shocks have a stronger effect on the hedging effect. Specifically, lenders give more weight to uncertainty about investment-specific technology and technology in the nonhousing sector for the financial risk effect and to housing preference uncertainty for the hedging effect. Although borrowers give significant weight to uncertainty about housing preference for the financial risk effect, this effect is diluted by other uncertainty shocks so that it plays a small role in explaining the financial risk effect for borrowers. Moreover, uncertainty about monetary shocks generates the hedging effects for borrowers. Most of the uncertainty shocks, including uncertainty about technology, housing preference, and intertemporal preference, have debt risk effects. On average, demand-side uncertainty shocks have a larger effect on the debt risk effect than supply-side uncertainty shocks.

6.2 Real-options channels

To illustrate the mechanism through which uncertainty shocks affect investment, we conduct an additional investigation about the relationship between uncertainty and returns on (business or residential) investment. For simplicity, we close adjustment costs for capital and capacity utilization. Based on lenders' optimal decision making on capital in the nonhousing and housing sectors, we can derive the following relationship:

$$\frac{\partial E_t^L(r_{i,t+1})}{\partial Var_t^L(r_{i,t+1})} = -\frac{\frac{1}{2}R_i + \rho^L_{R_i\Lambda}}{R_i} \qquad \text{for } i = c, h, \tag{44}$$

where $r_{i,t+1} = \ln(R_{i,t+1}z_{i,t+1} + 1 - \delta_k)$ for i = nonhousing sector (c) or housing sector (h). It implies that investment decisions are determined by a correlation, $\rho^L_{R_i\Lambda}$, between gross returns to investment i and the intertemporal marginal rate of substitution, describing real option channels. If this correlation is positive, it has a positive real option effect on investment. On the other hand, if it is negative, it has a negative real option effect on investment. Based on the same procedure in section 6.1, we estimate the following equation,

$$x^{R_i}_{L,t} = \beta^L + \beta^L_{R_i\Lambda}\Lambda_{L,t} + v_{L,t} \qquad \text{for } i = c, h, \tag{45}$$

where $x^{R_i}_{L,t} = \ln R_{i,t}$, the coefficient $\beta^L_{R_c\Lambda}$ corresponds to a real option effect on business investment ($\rho^L_{R_c\Lambda}$), and the coefficient $\beta^L_{R_h\Lambda}$ corresponds to a real option effect on residential investment ($\rho^L_{R_h\Lambda}$). As Table 9 shows, a composite uncertainty shock has a positive real option effect on business investment. This result is mainly driven by supply-side uncertainty shocks, especially investment-specific technology uncertainty shocks. However, a composite uncertainty shock has a negative real option effect on residential investment. This result is mainly driven by supply-side uncertainty shocks, especially uncertainty about investment-specific technology.

growth as controls. We found that the results were robust to this exercise.

6.3 Additional Analysis

6.3.1 The role of price and wage stickiness

There have been several prominent studies emphasizing the markup channels based on nominal rigidities (Born and Pfeifer, 2014a; Fernández-Villaverde et al., 2015; Leduc and Liu, 2016; Bonciani and van Roye, 2016; Basu and Bundick, 2017; Cesa-Bianchi and Corugedo, 2018). Contractionary effects of uncertainty on economic activity are amplified through an increase in markups when the nominal rigidities exist. The primary reasons for the increase in markups can be explained by an aggregate demand channel and an upward pricing bias channel (Fernández-Villaverde et al., 2015). The aggregate demand channel implies that price and wage stickiness hinder fully accommodating the lower demand driven by households' precautionary saving behavior. The upward pricing bias says that firms faced with higher uncertainty optimally choose a high price when nominal rigidities are strong. These channels increase markups, and hence decrease output. Figure 9 and 10 illustrate the role of nominal rigidities for the supply- and demand-side uncertainty shocks, respectively. The red-circled line plots the IRFs when we allow flexible prices. The blue-circled line plots the IRFs when we reduce wage stickiness. As the figure shows, wage stickiness is crucial for the responses of residential investment to both supply- and demand-side uncertainty shocks. This result is in line with the findings in Iacoviello and Neri (2010). They document that sticky wages are necessary for the fluctuations of residential investment, making them sensitive to changes in demand conditions. The responses of output to both the supply- and demand-side uncertainty shocks are driven by business investment rather than residential investment. Moreover, price stickiness plays a significant role in amplifying demand-side uncertainty shocks, although it has little impact on supply-side uncertainty shocks. It also tends to reduce the housing consumption hedging effects of demand-side uncertainty shocks.

6.3.2 The role of collateral constraints

As illustrated in Iacoviello and Neri (2010), collateral effects are the key feature that generate a significant response of consumption following a change in housing prices. Since households are limited to borrowing money equal to the value of housing collateral, the change in house prices not only affect the household's balance sheet, but also affect borrowing capacity and consumption levels. Figure 11 and 12 show impulse responses to the supply- and demand-side uncertainty shocks, respectively. Both figures show that the effects of uncertainty shocks on consumption are amplified in the presence of strong collateral constraint channels. This finding is in line with several papers that show a positive effect of housing prices on consumption (Case et al., 2005; Campbell and Cocco, 2007; Iacoviello and Neri, 2010).

6.3.3 The role of perfect factor mobility

In this section, we examine how uncertainty shocks affect the economy as we relax the assumption of imperfect labor factor mobility. We allow factors of production to move freely across sectors. In our model, higher uncertainty has a differential impact on sectoral price markups because of asymmetric price rigidity between the consumption sector and the housing sector. Higher uncertainty increases the price markups in the consumption sector with sticky prices through the precautionary labor supply effect, causing the production of the consumption sector to decrease. However, firms in the housing sector maintain their markups by flexibly adjusting prices when higher uncertainty induces the precautionary labor supply effect, and hence a decrease in marginal costs. The asymmetric price rigidity across sectors makes factor prices in the consumption sector lower than those in the housing sector. Thus, an increase in uncertainty leads to an increase in real housing prices in the two-sector model, with the combination of flexible housing prices and sticky prices in the consumption sector (Katayama and Kim, 2016). However, if factors can flow freely across sectors, the factor prices will equalize across sectors, and thus real housing prices will decrease. Figure 14 shows that the responses of housing prices to demand-side uncertainty shocks are reduced. Also, the responses of residential investment are less pronounced in the economy with perfect labor factor mobility between the consumption sector and the housing sector. It is because perfect labor factor mobility induces a fall in the factor price in the housing sector.

7 Conclusion

Since the 2008 financial crisis, there has been a surge of uncertainty surrounding the economy. Macroeconomists have been interested in the relationship between uncertainty and economic activity. However, there has been little examination of the effects of house price uncertainty on economic activity, despite considerable house price uncertainty over the past decade, along with huge changes in housing prices and dramatic economic fluctuations. This paper investigates the asymmetric effects of U.S. house price uncertainty shocks on economic activity using a reduced-form MS-VAR model. The impulse responses to the house price uncertainty shocks in our VAR analysis show that residential investment, housing prices, and mortgage debt decrease by 4%, 1%, and 3%, respectively, at the peak in recessionary periods. However, they increase by 1%, 0.95%, and 0.85% at the peak in expansionary periods.

We then use a theoretical DSGE model with a housing sector to find significant structural uncertainty shocks that reproduce empirical impulse responses. In particular, we consider an increase in composite supply- and demand-side uncertainty shocks. We find that the supply-side uncertainty shocks produce negative impacts on consumption, residential investment, housing prices, and household debt. The results imply that the supply-side uncertainty shocks induce precautionary motives, a negative real-options effect on residential investment, and a financial risk and debt risk effect on housing demand. These results are mainly driven by the uncertainty shocks to investment-specific technology and technology in the nonhousing sector, replicating the empirical findings in recessionary regimes obtained from the VAR analysis. In contrast, we find that among the demand-side uncertainty shocks, the housing preference uncertainty shocks have positive impacts on residential investment, housing prices, and household debt that resemble the empirical findings when the economy is in expansionary regimes; however, the inflation objective uncertainty shocks have significant opposite impacts on these variables, reproducing the empirical impulse responses in recessionary regimes.

Overall, uncertainty about investment-specific technology and technology in the nonhousing sector, housing preference uncertainty, and inflation target uncertainty play a significant role in explaining housing price fluctuations, implying that the shocks to these uncertainties could be the main sources of house price uncertainty shocks.

Appendix A Equilibrium Conditions

Budget constraint for lenders

$$
\begin{aligned}
&c_t^L + \frac{k_{c,t}}{A_{k,t}} + k_{h,t} + k_{b,t} + q_t[h_t^L - (1-\delta_h)h_{t-1}^L + h_t^r - (1-\delta_h)h_{t-1}^r] + p_{l,t}l_t - b_t^L \\
&= \frac{w_{c,t}^L n_{c,t}^L}{X_{wc,t}^L} + \frac{w_{h,t}^L n_{h,t}^L}{X_{wh,t}^L} + \Big(R_{c,t}z_{c,t} + \frac{1-\delta_{kc}}{A_{k,t}}\Big)k_{c,t-1} + (R_{h,t}z_{h,t} + 1 - \delta_{kh})k_{h,t-1} \\
&+ p_{b,t}k_{b,t} - \frac{R_{t-1}b_{t-1}^L}{\pi_t} + (p_{l,t} + R_{l,t})l_{t-1} + q_t^r h_{t-1}^r + Div_t^L - \phi_t - \frac{a(z_{c,t})k_{c,t-1}}{A_{k,t}} - a(z_{h,t})
\end{aligned}
\tag{A.1}
$$

where

$$
\begin{aligned}
Div_t^L &= \left(1 - \frac{1}{X_t}\right)Y_t + \left(1 - \frac{1}{X_{wc,t}^L}\right)w_{c,t}^L n_{c,t}^L + \left(1 - \frac{1}{X_{wh,t}^L}\right)w_{h,t}^L n_{h,t}^L \\
\phi_t &= \frac{\phi_{kc}}{2}\left(\frac{k_{c,t}}{k_{c,t-1}} - 1\right)^2 k_{c,t-1} + \frac{\phi_{kh}}{2}\left(\frac{k_{h,t}}{k_{h,t-1}} - 1\right)^2 k_{h,t-1} \\
a(z_{c,t}) &= R_c\left(\frac{1}{2}\bar{w}z_{c,t}^2 + (1-\bar{w})z_{c,t} + \Big(\frac{\bar{w}}{2} - 1\Big)\right) \\
a(z_{h,t}) &= R_h\left(\frac{1}{2}\bar{w}z_{h,t}^2 + (1-\bar{w})z_{h,t} + \Big(\frac{\bar{w}}{2} - 1\Big)\right)
\end{aligned}
$$

Optimal conditions for lenders

$$
u_{c^L,t}^L q_t = \beta^L E_t\Big[\frac{j_{t+1}z_{t+1}}{h_t^L}\Big] + \beta^L E_t[u_{c^L,t+1}^L q_{t+1}(1-\delta)] \tag{A.2}
$$

$$
u_{c^L,t}^L q_t = \beta^L E_t\Big[u_{c^L,t+1}^L q_{t+1}^r\Big] + \beta^L E_t[u_{c^L,t+1}^L q_{t+1}(1-\delta)] \tag{A.3}
$$

$$
u_{c^L,t}^L = \beta^L E_t\left(\frac{u_{c^L,t+1}^L R_t}{\pi_{t+1}}\right) \tag{A.4}
$$

$$
u_{c^L,t}^L\left(\frac{1}{A_{k,t}} + \frac{\partial\phi_{c,t}}{\partial k_{c,t}}\right) = \beta^L E_t u_{c^L,t+1}^L\left(R_{c,t+1}z_{c,t+1} - \frac{a(z_{c,t+1}) + 1 - \delta_{kc}}{A_{k,t+1}} - \frac{\partial\phi_{c,t+1}}{\partial k_{c,t}}\right) \tag{A.5}
$$

$$
u_{c^L,t}^L\left(1 + \frac{\partial\phi_{h,t}}{\partial k_{h,t}}\right) = \beta^L E_t u_{c^L,t+1}^L\left(R_{h,t+1}z_{h,t+1} - a(z_{h,t+1}) + 1 - \delta_{kh} - \frac{\partial\phi_{h,t+1}}{\partial k_{h,t}}\right) \tag{A.6}
$$

$$
u_{c^L,t}^L w_{c,t}^L = u_{nc^L,t}^L X_{wc,t}^L \tag{A.7}
$$

$$u^L_{c^L,t} w^L_{h,t} = u^L_{nh^L,t} X^L_{wh,t} \tag{A.8}$$

$$u^L_{c^L,t}(p_{b,t} - 1) = 0 \tag{A.9}$$

$$R_{c,t} A_{k,t} = a'(z_{c,t}) \tag{A.10}$$

$$R_{h,t} = a'(z_{h,t}) \tag{A.11}$$

$$u^L_{c^L,t} p_{l,t} = \beta^L E_t u^L_{c^L,t+1}(p_{l,t+1} + R_{l,t+1}) \tag{A.12}$$

Budget and borrowing constraint for borrowers

$$c^B_t + q_t[h^B_t - (1-\delta_h)h^B_{t-1}] + q^r_t h^r_{t-1} - b^B_t = \frac{w^B_{c,t} n^B_{c,t}}{X^B_{wc,t}} + \frac{w^B_{h,t} n^B_{h,t}}{X^B_{wh,t}} - \frac{R_{t-1} b^B_{t-1}}{\pi_t} + Div^B_t \tag{A.13}$$

$$b^B_t = m E_t \frac{q_{t+1}\pi_{t+1} h^B_t}{R_t} \tag{A.14}$$

Optimal conditions for borrowers

$$u^B_{c^B,t} q^r_t = \beta^B E_t\Big[\frac{j_{t+1} z_{t+1}}{\hat{h}^B_t}[\kappa(h^B_t)^{\xi_h - 1} + (1-\kappa)(h^r_t)^{\xi_h - 1}]^{\frac{2-\xi_h}{\xi_h - 1}}(1-\kappa)(h^r_t)^{\xi_h - 2}\Big] \tag{A.15}$$

$$\begin{aligned} u^B_{c^B,t} q_t = {} & \beta^B E_t\Big[\frac{j_{t+1} z_{t+1}}{\hat{h}^B_t}[\kappa(h^B_t)^{\xi_h - 1} + (1-\kappa)(h^r_t)^{\xi_h - 1}]^{\frac{2-\xi_h}{\xi_h - 1}}\kappa(h^B_t)^{\xi_h - 2}\Big] \\ & + \beta^B E_t[u^B_{c^B,t+1} q_{t+1}(1-\delta)] + E_t\Big[\frac{\lambda_t m q_{t+1}\pi_{t+1}}{R_t}\Big] \end{aligned} \tag{A.16}$$

$$u^B_{c^B,t} = \beta^B E_t\left(u^B_{c^B,t+1}\frac{R_t}{\pi_{t+1}}\right) + \lambda_t \tag{A.17}$$

$$u^B_{c^B,t} w^B_{c,t} = u^B_{nc^B,t} X^B_{wc,t} \tag{A.18}$$

$$u^B_{c^B,t} w^B_{h,t} = u^B_{nh^B,t} X^B_{wh,t} \tag{A.19}$$

$$Div_t^B = \left(1 - \frac{1}{X_{wc,t}^B}\right) w_{c,t}^B n_{c,t}^B + \left(1 - \frac{1}{X_{wh,t}^B}\right) w_{h,t}^B n_{h,t}^B \tag{A.20}$$

Intermediate goods firms

$$Y_t = (A_{c,t}((n_{c,t}^L)^\alpha (n_{c,t}^B)^{1-\alpha}))^{1-\mu_c} (z_{c,t} k_{c,t-1})^{\mu_c} \tag{A.21}$$

$$IH_t = (A_{h,t}((n_{h,t}^L)^\alpha (n_{h,t}^B)^{1-\alpha}))^{1-\mu_h-\mu_l-\mu_b} (z_{h,t} k_{h,t-1})^{\mu_h} k_{b,t}^{\mu_b} l_{t-1}^{\mu_l} \tag{A.22}$$

$$(1-\mu_c)\alpha Y_t = X_t w_{c,t}^L n_{c,t}^L \tag{A.23}$$

$$(1-\mu_c)(1-\alpha) Y_t = X_t w_{c,t}^B n_{c,t}^B \tag{A.24}$$

$$(1-\mu_h-\mu_b-\mu_l)\alpha q_t IH_t = w_{h,t}^L n_{h,t}^L \tag{A.25}$$

$$(1-\mu_h-\mu_b-\mu_l)(1-\alpha) q_t IH_t = w_{h,t}^B n_{h,t}^B \tag{A.26}$$

$$\mu_c Y_t = X_t R_{c,t} z_{c,t} k_{c,t-1} \tag{A.27}$$

$$\mu_h q_t IH_t = R_{h,t} z_{h,t} k_{h,t-1} \tag{A.28}$$

$$\mu_l q_t IH_t = R_{l,t} l_{t-1} \tag{A.29}$$

$$\mu_b q_t IH_t = p_{b,t} k_{b,t} \tag{A.30}$$

Price Stickiness

$$\begin{aligned} \pi_t^* &= \frac{P_t^*}{P_{t-1}} = \frac{\varepsilon_p}{\varepsilon_p - 1} \pi_t \frac{x_{1t}}{x_{2t}} \\ x_{1t} &= \lambda_t \frac{1}{X_t} Y_t + \beta^L \theta \pi_t^{-\iota_\pi \varepsilon_p} E_t \pi_{t+1}^{\varepsilon_p} x_{1t+1} \\ x_{2t} &= \lambda_t Y_t + \beta^L \theta \pi_t^{\iota_\pi (1-\varepsilon_p)} E_t \pi_{t+1}^{\varepsilon_p - 1} x_{2t+1} \end{aligned} \tag{A.31}$$

$$\pi_t^{1-\varepsilon_p} = (1-\theta_\pi) \pi_t^{*(1-\varepsilon_p)} + \theta_\pi \pi_{t-1}^{\iota_\pi (1-\varepsilon_p)} \tag{A.32}$$

Wage Stickiness

$$w_{i,t}^{*j} = \frac{\varepsilon_{i,w}^{j}}{\varepsilon_{i,w}^{j}-1}\frac{f_{i,1t}^{j}}{f_{i,2t}^{j}}$$
$$f_{i,1t}^{j} = \lambda_t^j \frac{(w_{i,t}^{j})^{1+\varepsilon_{i,w}^{j}}}{X_{i,t}^{j}} n_{i,t}^{j} + \beta^j \theta_{w,i} \pi_t^{-\iota_{w,i}\varepsilon_{i,w}^{j}} E_t \pi_{t+1}^{\varepsilon_{i,w}^{j}} f_{i,1t+1}^{j} \tag{A.33}$$
$$f_{i,2t}^{j} = \lambda_t^j (w_{i,t}^{j})^{\varepsilon_{i,w}^{j}} n_{i,t}^{j} + \beta^j \theta_{w,i} \pi_t^{\iota_{w,i}(1-\varepsilon_{i,w}^{j})} E_t \pi_{t+1}^{\varepsilon_{i,w}^{j}-1} f_{i,2t+1}^{j}$$

$$(w_{i,t}^{j})^{1-\varepsilon_{i,w}} = (1-\theta_{w,i})(w_{i,t}^{*j})^{(1-\varepsilon_{i,w}^{j})} + \theta_{w,i}\pi_{t-1}^{\iota_{w,i}(1-\varepsilon_{i,w}^{j})}\pi_t^{\varepsilon_{i,w}^{j}-1}(w_{i,t-1}^{j})^{(1-\varepsilon_{i,w}^{j})} \tag{A.34}$$

where i=consumption sector (C) or housing sector (H) and j=Borrowers (B) or lenders (L).

Taylor-type rule

$$R_t = R_{t-1}^{r_R}\pi_t^{(1-r_R)r_\pi}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{(1-r_R)r_Y}\bar{rr}^{1-r_R}\frac{\sigma_{R,t}u_{R,t}}{A_{s,t}} \quad \text{where } u_{R,t} \sim N(0,1) \tag{A.35}$$

where $\bar{rr}$ is the steady state real interest-rate, r_R, r_π, r_Y are the responses of the interest rate to changes in the lagged interest rate, inflation and GDP growth, respectively, the inflation objective shock ($A_{s,t}$) follows AR(1) process with stochastic volatility $\sigma_{s,t}$, and the shock to the monetary policy $u_{R,t}$ is assumed to have time-varying volatility $\sigma_{R,t}$.

Market Clearing

$$C_t + IK_{c,t}/A_{k,t} + IK_{h,t} + k_{b,t} = Y_t - \phi_t \tag{A.36}$$

$$H_t - (1-\delta_h)H_{t-1} = IH_t \tag{A.37}$$

$$b_t^L + b_t^B = 0 \tag{A.38}$$

$$l_t = 1 \tag{A.39}$$

Shock processes

Productivity in the consumption ($A_{c,t}$), investment ($A_{k,t}$), and housing sector ($A_{h,t}$) follows:

$$\ln(A_{i,t}) = \rho_{A,i}\ln(A_{i,t-1}) + \sigma_{i,t}u_{i,t} \quad \text{where } u_{i,t} \sim N(0,1) \tag{A.40}$$

where $i = \{c,k,h\}$ and $u_{i,t}$ is the innovation. All of the stochastic volatility processes follow:

$$\sigma_{j,t} = (1-\rho_{\sigma_j})\sigma_j + \rho_{\sigma_j}\sigma_{j,t-1} + \sigma_{\sigma_j}v_{j,t} \quad \text{where } v_{j,t} \sim N(0,1) \tag{A.41}$$

where $j = \{c, h, j, k, \tau, z, s, R\}$, $\sigma_{j,t}$ is the j-th stochastic volatility, σ_j is the unconditional mean of $\sigma_{j,t}$, ρ_{σ_j} is the level of persistence, and σ_{σ_j} is the standard deviation of the volatility shock $v_{j,t}$.

Appendix B Third-order Approximation

The model solved using third-order approximation with pruning is given by the following state space representation

$$\begin{aligned} \mathbf{Y_t} &= \mathbf{G}(\mathbf{X_t}, \sigma) + \boldsymbol{\epsilon_t} \\ \mathbf{X_{t+1}} &= \mathbf{H}(\mathbf{X_t}, \sigma) + \sigma \boldsymbol{\eta_t} \end{aligned} \tag{B.1}$$

where $\mathbf{X_t}$ denotes a set of state variables that contain pre-determined endogenous and exogenous variables, $\mathbf{Y_t}$ is a set of observable variables, $\boldsymbol{\epsilon_{t+1}} \sim i.i.d N(0, \mathbf{R}_\epsilon)$, and $\boldsymbol{\eta_{t+1}} \sim i.i.d N(0, \mathbf{R}_\eta)$.

These are re-expressed in a more specific way:

$$\begin{aligned} \mathbf{X_{t+1}} &= \begin{bmatrix} \hat{\mathbf{x}}_{t+1}^f \\ \hat{\mathbf{x}}_{t+1}^s \\ \hat{\mathbf{x}}_{t+1}^{th} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{h_x}\hat{\mathbf{x}}_t^f + \sigma\boldsymbol{\eta}\boldsymbol{\epsilon}_{t+1} \\ \mathbf{h_x}\hat{\mathbf{x}}_t^s + \frac{1}{2}\mathbf{H_{xx}}\left(\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f\right) + \frac{1}{2}\mathbf{h}_{\sigma\sigma}\sigma^2 \\ \mathbf{h_x}\hat{\mathbf{x}}_t^{th} + \mathbf{H_{xx}}\left(\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^s\right) + \mathbf{H_{xxx}}\left(\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f\right) + \frac{3}{6}\mathbf{h}_{\sigma\sigma\mathbf{x}}\sigma^2\hat{\mathbf{x}}_t^f + \frac{1}{6}\mathbf{h}_{\sigma\sigma\sigma}\sigma^3 \end{bmatrix} \end{aligned} \tag{B.2}$$

$$\begin{aligned} \mathbf{Y_t} =& \mathbf{g_x}(\hat{\mathbf{x}}_t^f + \hat{\mathbf{x}}_t^s + \hat{\mathbf{x}}_t^{th}) + \frac{1}{2}\mathbf{G_{xx}}\Big((\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f) + 2(\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^s)\Big) \\ &+ \frac{1}{6}\mathbf{G_{xxx}}\left(\hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f \otimes \hat{\mathbf{x}}_t^f\right) + \frac{1}{2}\mathbf{g}_{\sigma\sigma}\sigma^2 + \frac{3}{6}\mathbf{g}_{\sigma\sigma\mathbf{x}}\sigma^2\hat{\mathbf{x}}_t^f + \frac{1}{6}\mathbf{g}_{\sigma\sigma\sigma}\sigma^3 \end{aligned} \tag{B.3}$$

where we eliminate the terms of higher-order effects than the third-order by using a pruning method (see, in particular Kim et al. (2008) and Andreasen et al. (2017)).

Appendix C Data Sources over 1977Q1-2008Q4

1. Civilian Noninstitutional Population, BLS, CNP160V
2. Real Personal Consumption Expenditure (divided by CNP160V and deflated with GDP deflator), BEA, NIPA
3. Real Private Nonresidential Fixed Investment (divided by CNP160V and deflated with GDP deflator), BEA, NIPA

4. Real Private Residential Fixed Investment (divided by CNP160V and deflated with GDP deflator), BEA, NIPA

5. Inflation: Log differences in the implicit price deflator for the nonfarm business sector, Demeaned, BLS

6. Nominal interest rate: 3-month Treasury Bill Rate, Demeaned, FRED

7. Real Shiller House Price Index: Shiller House Price Index (FERD) deflated with the implicit price deflator for the nonfarm business sector.

8. Wage Inflation in Consumption-good Sector: Quarterly changes in Average Hourly Earnings of Production/Nonsupervisory Workers on Private Nonfarm Payrolls , Demeaned, BLS

9. Wage Inflation in Housing Sector: Quarterly changes in Average Hourly Earnings of Production/Nonsupervisory Workers in the Construction Industry, Demeaned, BLS

Appendix D Uncertainty-Return Relationship

The optimal conditions with respect to h_t^B and h_t^r can be simplified as:

$$1 = E_t\left[\Lambda_{t+1}\Big(\frac{(1-\delta)q_{t+1} + \frac{\kappa}{1-\kappa}\left(\frac{h_t^B}{h_t^r}\right)^{\xi_h - 2} q_{t+1}^r + mq_{t+1}D_{t+1}}{q_t}\Big)\right] \tag{D.1}$$

where $\Lambda_{t+1} = \beta^B \frac{u^B_{c^B,t+1}}{u^B_{c^B,t}}$ indicates the present value of marginal utility of future consumption, $D_{t+1} = \frac{\pi_{t+1}u^B_{b,t}}{R_t\beta^B u^B_{c^B,t+1}}$ is the present value of borrowing costs relative to the present value of future consumption, q_{t+1} is house price, and q_{t+1}^r represents rental rate of housing.

The intertemporal marginal rate of substitution is assumed to follow

$$\Lambda_{t+1} = exp\Big(-r_t^f - \frac{1}{2}\sigma^2_{\Lambda,t} + \epsilon_{\Lambda,t+1}\Big) \tag{D.2}$$

where $\epsilon_{\Lambda,t+1}|I_t \sim N(0,\sigma^2_{\Lambda,t})$ and r_t^f denotes the riskless return at time t. The growth rate of house price and rent is assumed to follow the AR(1) process.

$$x_{t+1}^j = \alpha_0^j + \alpha_1^j x_t^j + \epsilon_{j,t+1} \tag{D.3}$$

where $\epsilon_{j,t+1}|I_t \sim N(0,\sigma^2_{j,t})$ and j indexes housing price (q), rent (q^r), and present value of marginal utility of future consumption (D). For example, $x_{t+1}^q = \ln\frac{q_{t+1}}{q_t}$, $x_{t+1}^{q^r} = \ln\frac{q^r_{t+1}}{q^r_t}$, and $x_{t+1}^D = \ln\frac{\pi_{t+1}u^B_{b,t}}{R_t\beta^B u^B_{c^B,t+1}}$.

The equation (D.1) can be re-expressed as:

$$1 = E_t[\Lambda_{t+1}R_{t+1}] \tag{D.4}$$

where $R_{t+1} = \frac{(1-\delta)q_{t+1}+\frac{\kappa}{1-\kappa}\left(\frac{h_t^B}{h_t^r}\right)^{\xi_h-2}q^r_{t+1}+mq_{t+1}D_{t+1}}{q_t}$. By applying Campbell and Shiller's (1988) approximation, we derive the following equation.

$$\begin{aligned} r_{t+1} &= \ln R_{t+1} \\ &= A + Bx^q_{t+1} + Cx^H_t \\ &+ Dx^{q^r}_{t+1} + Ex^Q_{t+1} + Fx^D_{t+1} \end{aligned} \tag{D.5}$$

where $A = (1-\delta) + \frac{\kappa}{1-\kappa}\left(\frac{h^B}{h^r}\right)^{\xi_h-2}\left(\frac{q^r}{q}\right) + m\left(\frac{\beta^L}{\beta^B}-1\right)$, $B = \left((1-\delta)+m\left(\frac{\beta^L}{\beta^B}-1\right)\right)$, $C = \frac{\kappa}{1-\kappa}(\xi_h-2)\left(\frac{h^B}{h^r}\right)^{\xi_h-2}\left(\frac{q^r}{q}\right)$, $D = \frac{\kappa}{1-\kappa}\left(\frac{h^B}{h^r}\right)^{\xi_h-2}\left(\frac{q^r}{q}\right)$, $E = \frac{\kappa}{1-\kappa}\left(\frac{h^B}{h^r}\right)^{\xi_h-2}\left(\frac{q^r}{q}\right)$, $F = m\left(\frac{\beta^L}{\beta^B}-1\right)$, $x^H_t = \ln\left(\frac{h^B_t}{h^r_t}\right)$ and $x^Q_t = \ln\left(\frac{q^r_t}{q_t}\right)$. Assume that a solution to the log of rent to house price ratio takes the following form:

$$x^Q_{t+1} = c_0 + c_1x^q_t + c_2x^H_t + c_3x^{q^r}_t + c_4x^D_t + c_5\sigma^2_{qt} + c_6\sigma^2_{q^rt} + c_7\sigma^2_{Dt} \tag{D.6}$$

Substituting equations (D.5) and (D.6),

$$1 = E_t exp[A(\cdot)] \tag{D.7}$$

where

$$\begin{aligned} A(\cdot) &= (-r^f_t + A + B\alpha^q_0 + D\alpha^{q^r}_0 + Ec_0 + F\alpha^D_0) - \frac{1}{2}\sigma^2_{\Lambda t} + \varepsilon_{\Lambda t+1} \\ &+ (B\alpha^q_1 + Ec_1)x^q_t + (C + Ec_2)x^H_t + (D\alpha^{q^r}_1 + Ec_3)x^{q^r}_t + (F\alpha^D_1 + Ec_4)x^D_t \\ &+ Ec_5\sigma^2_{qt} + Ec_6\sigma^2_{q^rt} + Ec_7\sigma^2_{Dt} + B\varepsilon_{qt+1} + D\varepsilon_{q^rt+1} + F\varepsilon_{Dt+1} \end{aligned} \tag{D.8}$$

The first and second moments are as follows:

$$\begin{aligned} E_tA(\cdot) &= (-r^f_t + A + B\alpha^q_0 + D\alpha^{q^r}_0 + Ec_0 + F\alpha^D_0) - \frac{1}{2}\sigma^2_{\Lambda t} \\ &+ (B\alpha^q_1 + Ec_1)x^q_t + (C + Ec_2)x^H_t + (D\alpha^{q^r}_1 + Ec_3)x^{q^r}_t + (F\alpha^D_1 + Ec_4)x^D_t \\ &+ Ec_5\sigma^2_{qt} + Ec_6\sigma^2_{q^rt} + Ec_7\sigma^2_{Dt} \end{aligned} \tag{D.9}$$

$$\begin{aligned} Var_tA(\cdot) &= \sigma^2_{\Lambda t} + B^2\sigma^2_{qt} + D^2\sigma^2_{q^rt} + F^2\sigma^2_{Dt} + 2B\rho_{q\Lambda}\sigma^2_{qt} \\ &+ 2BD\rho_{qq^r}\sigma^2_{qt} + 2BF\rho_{qD}\sigma^2_{qt} \end{aligned} \tag{D.10}$$

Since $A(\cdot)$ follows a normal distribution, the (D.7) leads to

$$E_t A(\cdot) + \frac{1}{2} Var_t A(\cdot) = 0 \tag{D.11}$$

By substituting the equations (D.9) and (D.10), this leads to

$$\begin{aligned} 0 =& (-r_t^f + A + B\alpha_0^q + D\alpha_0^{q^r} + Ec_0 + F\alpha_0^D) \\ &+ (B\alpha_1^q + Ec_1)x_t^q + (C + Ec_2)x_t^H + (D\alpha_1^{q^r} + Ec_3)x_t^{q^r} + (F\alpha_1^D + Ec_4)x_t^D \\ &+ \Big(\frac{1}{2}B^2 + B\rho_{q\Lambda} + BD\rho_{qq^r} + BF\rho_{qD} + Ec_5\Big)\sigma_{qt}^2 \\ &+ \Big(\frac{1}{2}D^2 + Ec_6\Big)\sigma_{q^r t}^2 + \Big(\frac{1}{2}F^2 + Ec_7\Big)\sigma_{Dt}^2 \end{aligned} \tag{D.12}$$

This equation holds when the terms in the eight brackets must be equal to zero. Based on this result, we derive the following rent to house price ratio:

$$x_{t+1}^Q = q_t^r - q_t = c_0 + c_1 x_t^q + c_2 x_t^H + c_3 x_t^{q^r} + c_4 x_t^D + c_5\sigma_{qt}^2 + c_6\sigma_{q^r t}^2 + c_7\sigma_{Dt}^2 \tag{D.13}$$

where

$$\begin{aligned} c_0 &= -\frac{-r_t^f + A + B\alpha_0^q + D\alpha_0^{q^r} + F\alpha_0^D}{E} \\ c_1 &= -\frac{B\alpha_1^q}{E} \\ c_2 &= -\frac{C}{E} \\ c_3 &= -\frac{D\alpha_1^{q^r}}{E} \\ c_4 &= -\frac{F\alpha_1^D}{E} \\ c_5 &= -\frac{\frac{1}{2}B^2 + B\rho_{q\Lambda} + BD\rho_{qq^r} + BF\rho_{qD}}{E} \\ c_6 &= -\frac{\frac{1}{2}D^2}{E} \\ c_7 &= -\frac{\frac{1}{2}F^2}{E} \end{aligned}$$

By substituting the (D.13) into (D.5), we get

$$\begin{aligned} r_{t+1} &= r_t^f + B\varepsilon_{qt+1} + D\varepsilon_{q^r t+1} + F\varepsilon_{Dt+1} \\ &\quad - \Big(\frac{1}{2}B^2 + B\rho_{q\Lambda} + BD\rho_{qq^r} + BF\rho_{qD}\Big)\sigma_{qt}^2 - \frac{1}{2}D^2\sigma_{q^r t}^2 - \frac{1}{2}F^2\sigma_{Dt}^2 \end{aligned} \tag{D.14}$$

We obtain the following first and second moments of r_{t+1}

$$
\begin{aligned}
&E_t r_{t+1} = r_t^f - \Big(\frac{1}{2}B^2 + B\rho_{q\Lambda} + BD\rho_{qq^r} + BF\rho_{qD}\Big)\sigma_{qt}^2 - \frac{1}{2}D^2\sigma_{q^r t}^2 - \frac{1}{2}F^2\sigma_{Dt}^2 \\
&Var_t r_{t+1} = B^2\sigma_{qt}^2 + D^2\sigma_{q^r t}^2 + F^2\sigma_{Dt}^2 + 2BD\rho_{qq^r}\sigma_{qt}^2 + 2BF\rho_{qD}\sigma_{qt}^2
\end{aligned} \tag{D.15}
$$

This leads to

$$
\frac{\partial E_t r_{t+1}}{\partial Var_t r_{t+1}} = -\frac{\frac{1}{2}B + \rho_{q\Lambda} + D\rho_{qq^r} + F\rho_{qD}}{B + 2D\rho_{qq^r} + 2F\rho_{qD}} \tag{D.16}
$$

The above derivation applies to the uncertainty-return relationship for lenders and the real-options channel (equation (41) and equation (42)).

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Table 1: Prior and Posterior Distribution

	Posterior		Prior	
	Median	90% credible set	Distribution	(mean, std.)
ρ_{hp}	0.966	(0.934,0.988)	Beta	(0.8, 0.1)
ϕ_r	-0.218	(-0.318,-0.114)	Normal	($\hat{\phi}_r^{OLS}$, 0.1)
ϕ_{inc}	0.075	(0.011,0.141)	Normal	($\hat{\phi}_{inc}^{OLS}$, 0.1)
ϕ_u	-0.009	(-0.058,0.039)	Normal	($\hat{\phi}_u^{OLS}$, 0.1)
ρ_σ	0.948	(0.890,0.983)	Beta	(0.8, 0.1)
σ_{hp}	-0.439	(-0.854,-0.011)	Uniform	(0, 2.9)
σ_u	0.189	(0.122,0.281)	Gamma	(1.0, 1.0)

Notes: We report the priors with means and standard deviations in parenthesis. For σ_{hp}, we impose a Uniform prior ranging from -10 to 10.

Table 2: Forecast Error Variance Decomposition

Regime 1

Horizon	Consumption	Residential Investment	CPI	Housing Price	3 Month TBill Rate	Mortgage Rate	Mortgage Debt	Rent/Price
1Q	8.62	0.61	0.53	1.96	3.42	1.75	1.78	1.39
10Q	27.16	4.18	4.46	14.60	6.12	8.60	12.77	9.44
20Q	28.98	5.88	6.95	10.85	11.48	9.98	18.64	8.89
30Q	28.06	9.73	8.35	8.83	18.32	14.71	13.72	6.76
40Q	26.72	13.99	9.08	9.92	19.24	16.85	10.81	7.64

Regime 2

Horizon	Consumption	Residential Investment	CPI	Housing Price	3 Month TBill Rate	Mortgage Rate	Mortgage Debt	Rent/Price
1Q	4.28	2.28	0.61	3.04	1.58	0.99	1.17	3.30
10Q	31.37	14.34	3.78	5.69	3.54	4.86	19.28	2.91
20Q	33.76	14.89	4.89	8.53	5.18	6.63	25.43	5.02
30Q	31.86	15.07	5.65	10.03	6.95	8.45	25.38	7.11
40Q	30.32	15.75	6.19	11.43	8.69	10.59	24.29	8.65

Table 3: Calibrated Parameters

Parameter		Value
β^L	discount factor, lenders	0.9925
β^B	discount factor, borrowers	0.97
j	weight on housing	0.12
μ_c	capital share in the goods production function	0.35
μ_h	capital share in the housing production function	0.1
μ_l	land share	0.1
μ_b	intermediate goods share	0.1
δ_h	depreciation rates for housing	0.01
δ_{kc}	depreciation rates for capital in the consumption	0.025
δ_{kh}	depreciation rates for capital in the housing	0.03
$\varepsilon_p, \varepsilon^L_{c,w}, \varepsilon^L_{h,w}, \varepsilon^B_{c,w}, \varepsilon^B_{h,w}$	steady-state gross price and wage markups	6
m	loan to value ratio (LTV)	0.85
ρ_s	correlation of the inflation objective shock	0.975
κ	preference for owning home	0.6

Table 4: Prior and Posterior Distribution

		Prior	Posterior
Parameter		Dist.(mean,std)	Mode(5%,95%)
ε^L	habit in consumption, lenders	Beta(0.5,0.075)	0.4849 (0.3689,0.59)
ε^B	habit in consumption, borrowers	Beta(0.5,0.075)	0.3994 (0.2892,0.5224)
η^L	labor supply elasticity, lenders	Gamma(0.5,0.1)	0.3986 (0.2522,0.5805)
η^B	labor supply elasticity, borrowers	Gamma(0.5,0.1)	0.5009 (0.3319,0.7248)
ξ^L	labor mobility, lenders	Normal(1,0.1)	0.9384 (0.7295,1.1317)
ξ^B	labor mobility, borrowers	Normal(1,0.1)	1.014 (0.7958,1.2092)
$\phi_{k,c}$	investment adj. cost, consumption	Gamma(10,2.5)	17.6362 (13.9717,21.526)
$\phi_{k,h}$	investment adj. cost, housing	Gamma(10,2.5)	12.5146 (7.5724,18.4359)
α	labor share in production	Beta(0.65,0.05)	0.6617 (0.5867,0.7397)
r_R	inertia Taylor rule	Beta(0.75,0.1)	0.4182 (0.3211,0.5133)
r_π	inflation resp. Taylor rule	Normal(1.5,0.1)	1.6308 (1.5069,1.7726)
r_Y	output response Taylor rule	Normal(0,0.1)	0.3297 (0.2453,0.4324)
θ_π	Calvo parameters, prices	Normal(0.667,0.05)	0.9107 (0.8843,0.9293)
ι_π	price indexation	Beta(0.5,0.2)	0.6028 (0.3955,0.7567)
$\theta_{w,c}$	Calvo parameters, wages in consumption	Normal(0.667,0.05)	0.7575 (0.7147,0.7979)
$\iota_{w,c}$	wage indexation in consumption	Beta(0.5,0.2)	0.6469 (0.2096,0.9366)
$\theta_{w,h}$	Calvo parameters, wages in housing	Normal(0.667,0.05)	0.9667 (0.954,0.9773)
$\iota_{w,h}$	wage indexation in housing	Beta(0.5,0.2)	0.7945 (0.5868,0.9454)
ζ	utilization parameter	Beta(0.5,0.2)	0.9106 (0.8054,0.9828)
ξ_h	elasticity of sub. between owning home and rent	Normal(1.5,0.5)	1.3661 (1.0175,1.9437)
ρ_{AC}	AR(1) consumption tech. shock	Beta(0.8,0.1)	0.8097 (0.7257,0.8724)
ρ_{AH}	AR(1) housing tech. shock	Beta(0.8,0.1)	0.983 (0.9654,0.9953)
ρ_{AK}	AR(1) investment tech. shock	Beta(0.8,0.1)	0.9236 (0.8974,0.9461)
ρ_j	AR(1) housing preference. shock	Beta(0.8,0.1)	0.9704 (0.9513,0.9863)
ρ_z	AR(1) intertemporal shock	Beta(0.8,0.1)	0.7617 (0.6315,0.8706)
ρ_τ	AR(1) labor supply shock	Beta(0.8,0.1)	0.9839 (0.9662,0.9953)
σ_{AC}	std. consumption tech. shock	I.G(0.001,0.01)	0.0305 (0.0175,0.0455)
σ_{AH}	std. housing tech. shock	I.G(0.001,0.01)	0.0125 (0.011,0.0141)
σ_{AK}	std. investment tech. shock	I.G(0.001,0.01)	0.0105 (0.0085,0.0132)
σ_j	std. housing preference. shock	I.G(0.001,0.01)	0.047 (0.0322,0.0672)
σ_R	std. interest rate shock	I.G(0.001,0.01)	0.0016 (0.0013,0.002)
σ_z	std. intertemporal shock	I.G(0.001,0.01)	0.0086 (0.0056,0.0123)
σ_τ	std. labor supply shock	I.G(0.001,0.01)	0.016 (0.012,0.0216)
σ_s	std. inflation objective shock	I.G(0.001,0.01)	0.0004 (0.0003,0.0006)
$\sigma_{m,c}$	std. measurement err, consumption	I.G(0.001,0.01)	0.0024 (0.0014,0.0032)
$\sigma_{m,p}$	std. measurement err, inflation	I.G(0.001,0.01)	0.003 (0.0026,0.0035)
$\sigma_{m,wh}$	std. measurement err, wage in housing	I.G(0.001,0.01)	0.0058 (0.005,0.0068)

Table 5: Estimated Parameter Values

Parameters	Descriptions	Value
ρ_{σ_c}	Persistence: technology in nonhousing sector	0.692
ρ_{σ_h}	Persistence: technology in housing sector	0.891
ρ_{σ_j}	Persistence: housing preference shock	0.862
ρ_{σ_k}	Persistence: investment-specific technology	0.769
ρ_{σ_τ}	Persistence: labor supply shock	0.806
ρ_{σ_z}	Persistence: intertemporal preference shock	0.626
ρ_{σ_s}	Persistence: inflation objective shock	0.910
ρ_{σ_R}	Persistence: monetary policy shock	0.875
σ_{σ_c}	STD: technology in nonhousing sector	0.179
σ_{σ_h}	STD: technology in housing sector	0.055
σ_{σ_j}	STD: housing preference shock	0.079
σ_{σ_k}	STD: investment-specific technology	0.251
σ_{σ_τ}	STD: labor supply shock	0.005
σ_{σ_z}	STD: intertemporal preference shock	0.073
σ_{σ_s}	STD: inflation objective shock	0.208
σ_{σ_R}	STD: monetary policy shock	0.311

Notes: STD refers to standard deviation.

Table 6: Second Moments in the Model and Data

Variables	Model		Data	
	STD	AR(1)	STD	AR(1)
Consumption	0.014	0.888	0.012	0.901
Business Investment	0.047	0.803	0.043	0.933
Residential Investment	0.094	0.764	0.101	0.947
Inflation	0.005	0.963	0.006	0.832
Monetary Policy Rate	0.007	0.928	0.008	0.921
Housing Price	0.024	0.796	0.039	0.985
Wage Inflation in Consumption Sector	0.006	0.834	0.005	0.824
Wage Inflation in Housing Sector	0.005	0.955	0.007	0.469

Notes: STD refers to standard deviation, and AR(1) is the first-order autocorrelation.

Table 7: Variance Decomposition

	Uncertainty shocks	C	IK	IH	q	q^r/q
Supply	Investment tech.	0.0152	0.1773	0.0745	0.0245	0.0185
	Tech. in housing	0.0003	0.0005	0.0244	0.0048	0.0033
	Tech. in nonhousing	0.0169	0.0235	0.0439	0.0110	0.0076
	Labor supply	0.0001	0.0002	0.0003	0.0001	0.0001
	Supply-side uncertainty shocks	0.0228	0.1808	0.0906	0.0275	0.0204
Demand	Housing pref.	0.0116	0.0072	0.1426	0.0428	0.0305
	Intertemporal pref.	0.0005	0.0009	0.0013	0.0004	0.0004
	Inflation objective	0.0863	0.1486	0.1868	0.0412	0.0432
	Monetary policy	0.0025	0.0052	0.0113	0.0020	0.0026
	Demand-side uncertainty shocks	0.0865	0.1489	0.2342	0.0599	0.0528
All uncertainty shocks		0.0897	0.2335	0.2523	0.0662	0.0571

Notes: To measure the contribution of each of the eight volatility shocks, we calculate the standard deviations of the main aggregate variables generated from the following specifications, turning on: (1) eight uncertainty shocks; (2) supply-side uncertainty shocks; (3) demand-side uncertainty shocks; and (4) an individual uncertainty shock.

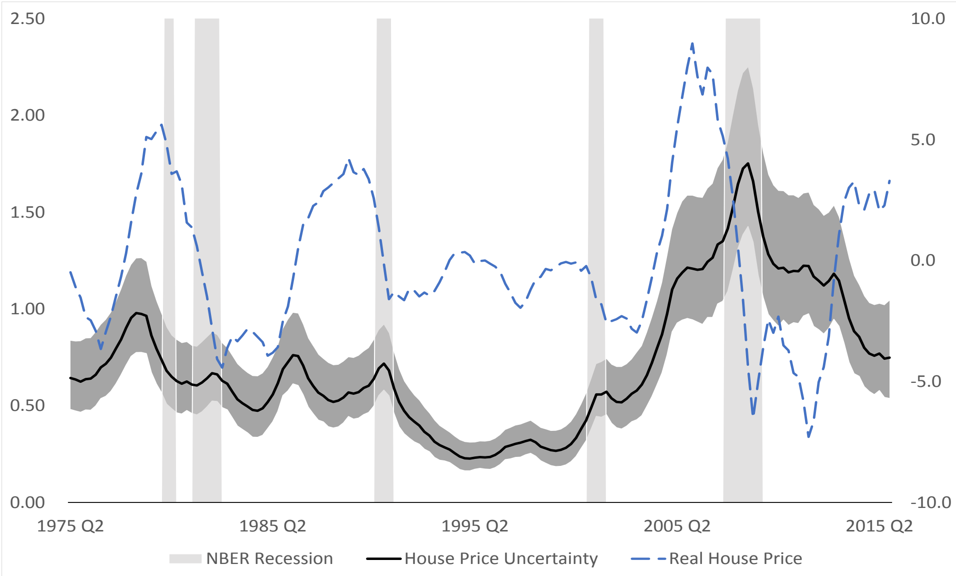
Table 8: Uncertainty and housing demand channels

Borrowers				
	Uncertainty shocks	$\beta^B_{q\Lambda}$	$\beta^B_{qq^r}$	β^B_{qD}
Supply	Investment tech.	0.032	1.056	-0.266
	Tech. in housing	0.531	0.202	-0.497
	Tech. in nonhousing	2.041	2.973	-0.077
	Labor supply	0.839	1.735	0.177
	Supply-side uncertainty shocks	0.364	0.931	-0.065
Demand	Housing pref.	-2.800	-1.694	-0.336
	Intertemporal pref.	-1.290	-0.056	-0.494
	Inflation objective	-0.273	0.569	0.228
	Monetary policy	-0.016	1.015	0.005
	Demand-side uncertainty shocks	0.233	1.221	-0.133
	All uncertainty shocks	0.819	1.631	-0.100
Lenders				
	Uncertainty shocks	$\beta^L_{q\Lambda}$	$\beta^L_{qq^r}$	
Supply	Investment tech.	-0.952	0.050	
	Tech. in housing	0.475	0.531	
	Tech. in nonhousing	-1.736	-0.763	
	Labor supply	-0.554	0.523	
	Supply-side uncertainty shocks	-1.062	-0.069	
Demand	Housing pref.	-0.367	1.211	
	Intertemporal pref.	-1.047	0.209	
	Inflation objective	-0.841	0.169	
	Monetary policy	-0.077	0.923	
	Demand-side uncertainty shocks	-0.025	0.927	
	All uncertainty shocks	-0.410	0.670	

Table 9: Uncertainty and real-options channels

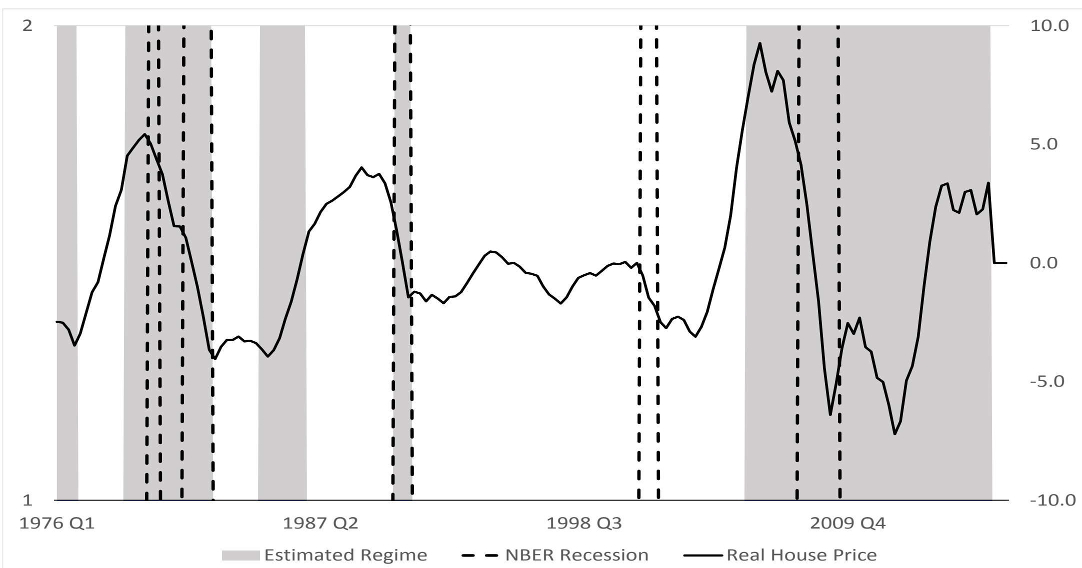
Real-option channels			
	Uncertainty shocks	$\beta^L_{R_c\Lambda}$	$\beta^L_{R_h\Lambda}$
Supply	Investment tech.	0.404	-0.465
	Tech. in housing	-0.300	-0.139
	Tech. in nonhousing	0.011	-0.164
	Labor supply	0.048	-0.420
	Supply-side uncertainty shocks	0.342	-0.406
Demand	Housing pref.	-0.411	-0.255
	Intertemporal pref.	0.265	-0.216
	Inflation objective	-0.171	-0.248
	Monetary policy	-0.171	-0.212
	Demand-side uncertainty shocks	-0.176	-0.218
	All uncertainty shocks	0.031	-0.244

Figure 1: House Price Uncertainty



Notes: The blue dashed line is the HP-filtered real house price. The left y-axis measures $exp(\sigma_{hp,t})$, and the right y-axis measures percent deviation from the trend.

Figure 2: Regime Indicator



Notes: The black solid line is the HP-filtered real house price. The left y-axis denotes regimes, and the right y-axis measures percent deviation from the trend.

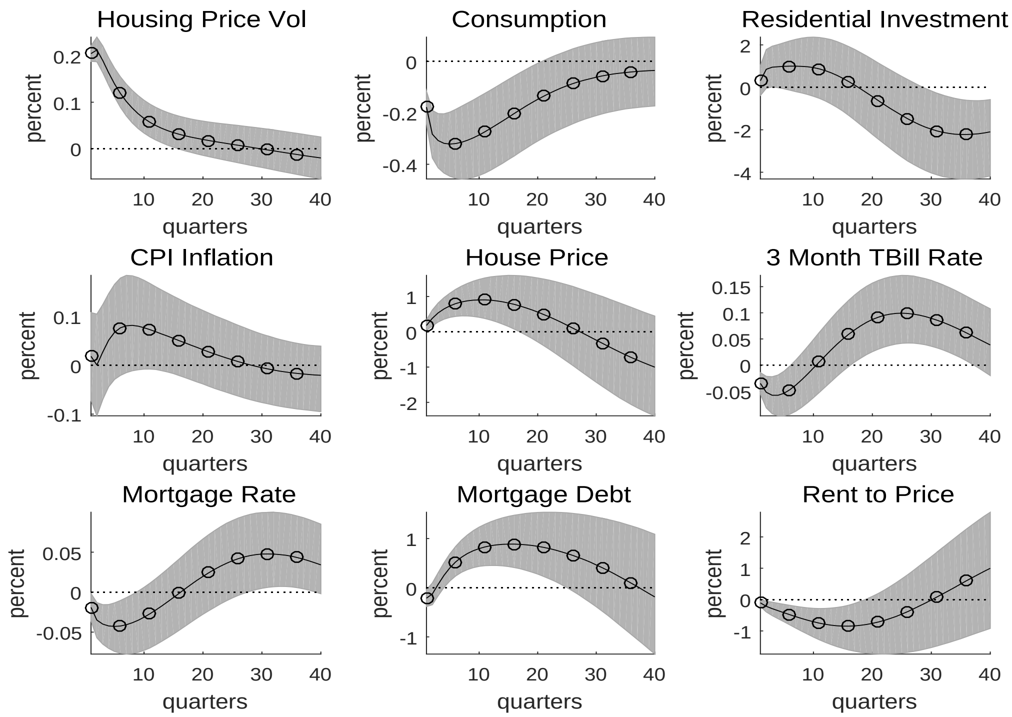


Figure 3: Responses to House Price Uncertainty Shock in Regime1 (Expansionary)

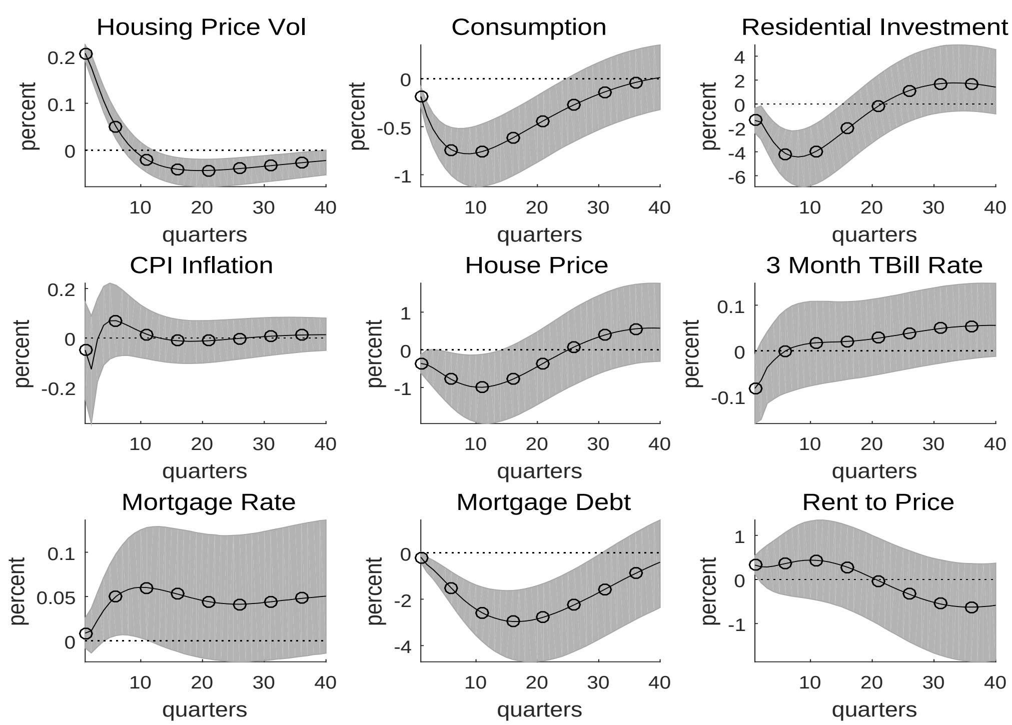
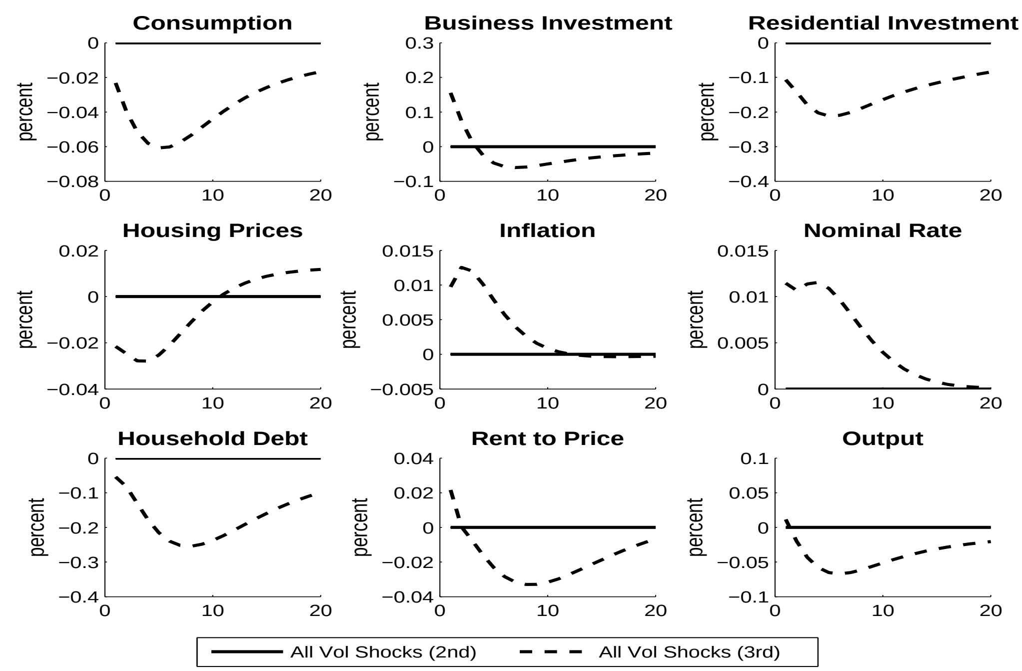


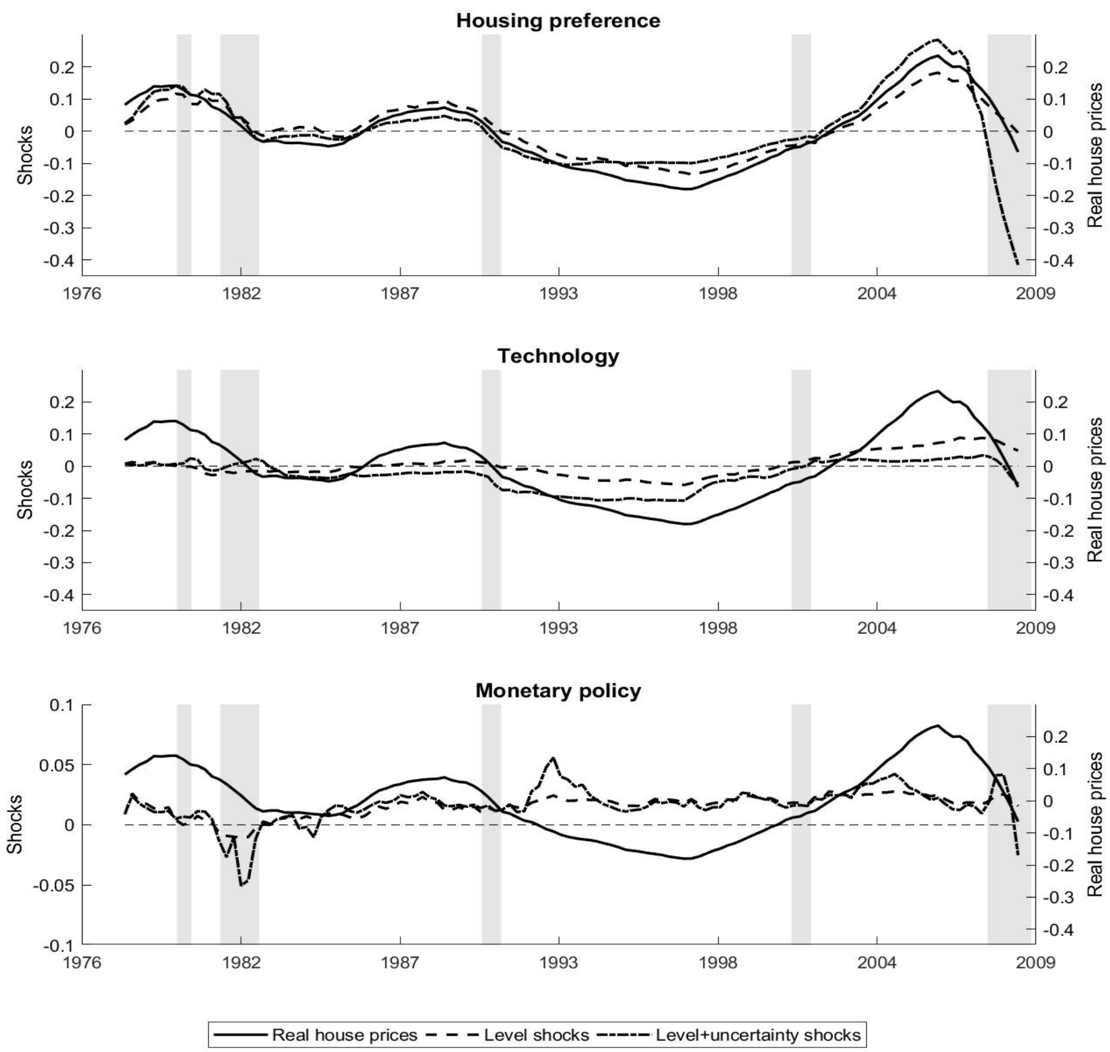
Figure 4: Responses to House Price Uncertainty Shock in Regime2 (Recessionary)

Figure 5: Responses to a Composite Uncertainty Shock



Notes: The black solid line is the response to a composite uncertainty shock based on the second-order approximation. The black dashed line is the response to a composite uncertainty shock based on the third-order approximation.

Figure 6: Historical decomposition



Notes: The black solid line is the linearly detrended real house price. Technology shocks include housing, nonhousing, and investment-specific technology shocks. Monetary shocks include independently and identically distributed monetary policy shocks and changes in the inflation objective. The estimated shocks are normalized, and all series are in deviation from the trend. Shaded areas denote the NBER recession periods.

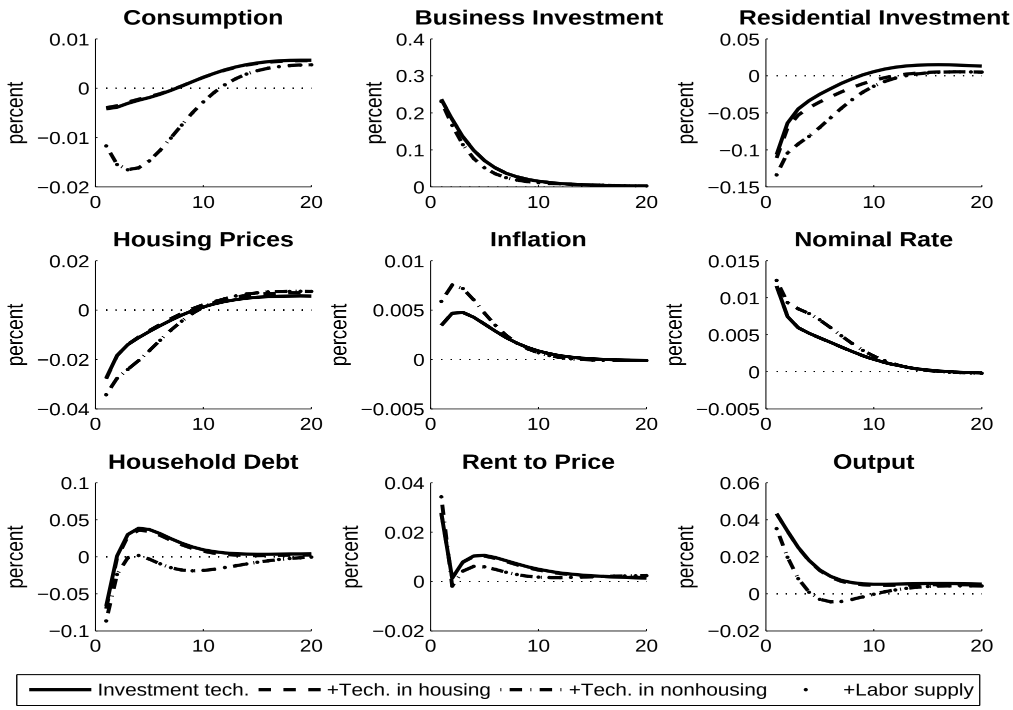


Figure 7: Responses to Supply-side Uncertainty Shock

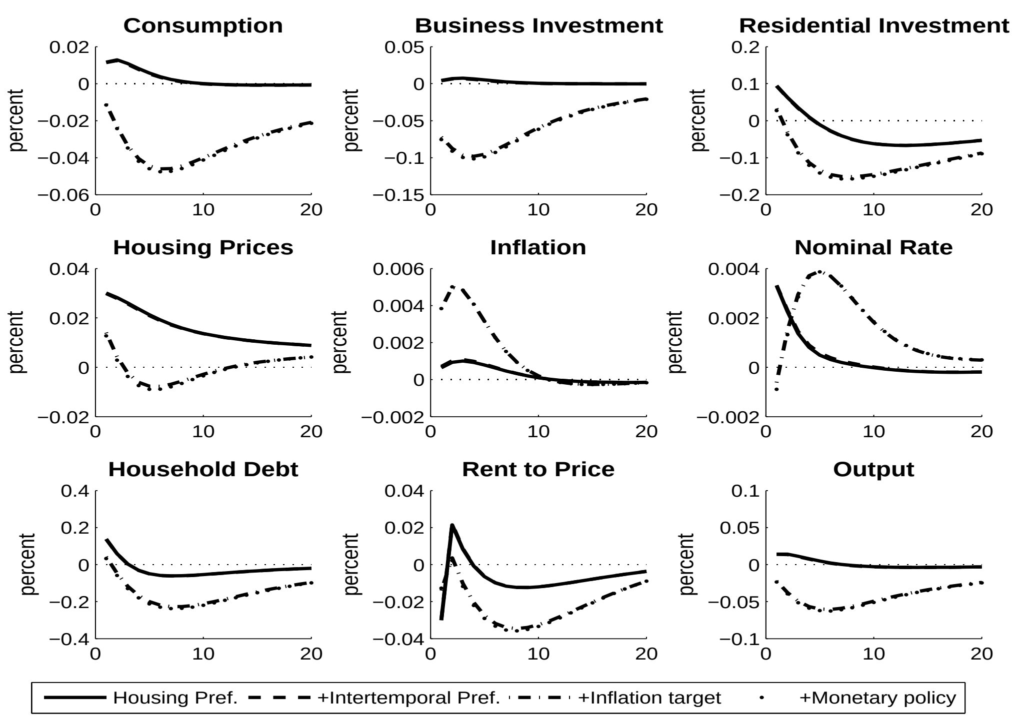


Figure 8: Responses to Demand-side Uncertainty Shock

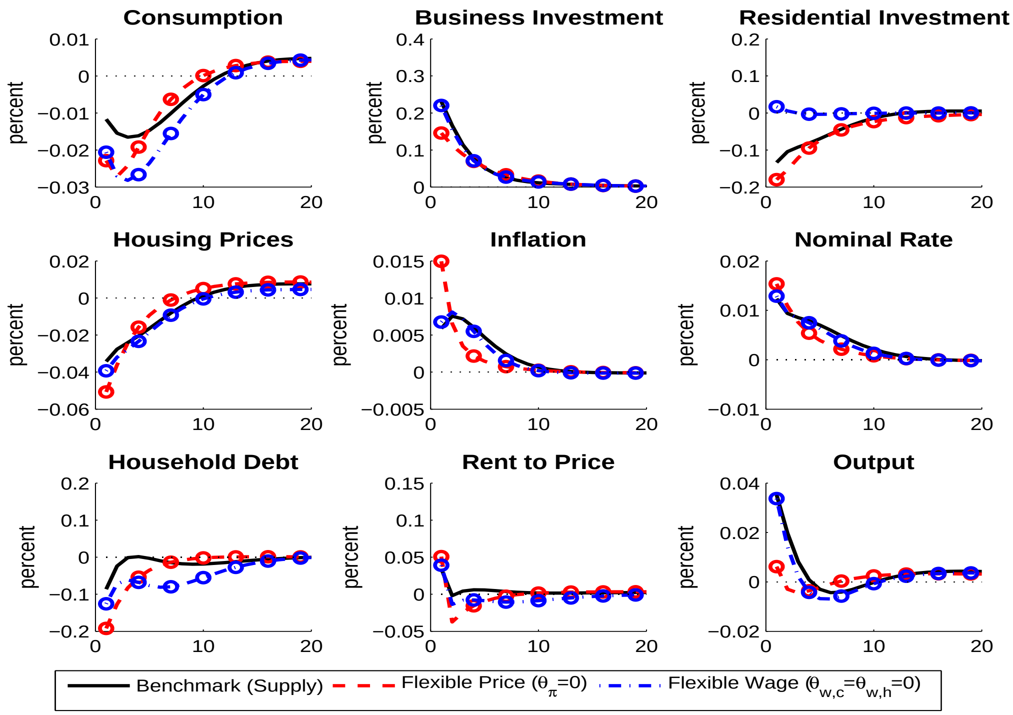


Figure 9: Supply-side Uncertainty Shock: Role of price and wage stickiness

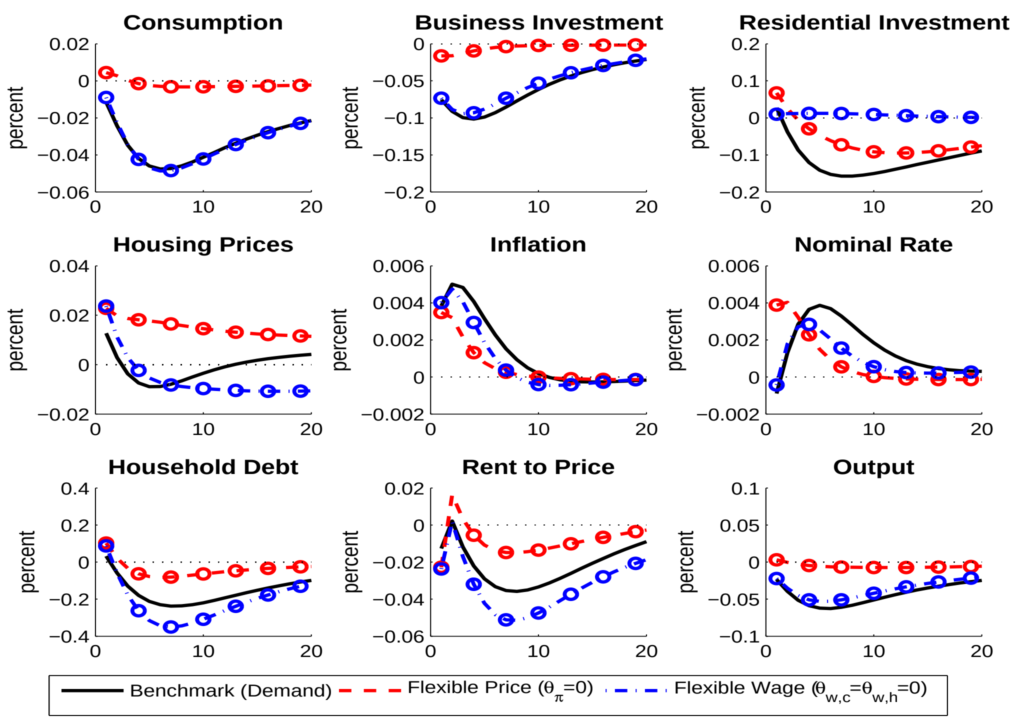


Figure 10: Demand-side Uncertainty Shock: Role of price and wage stickiness

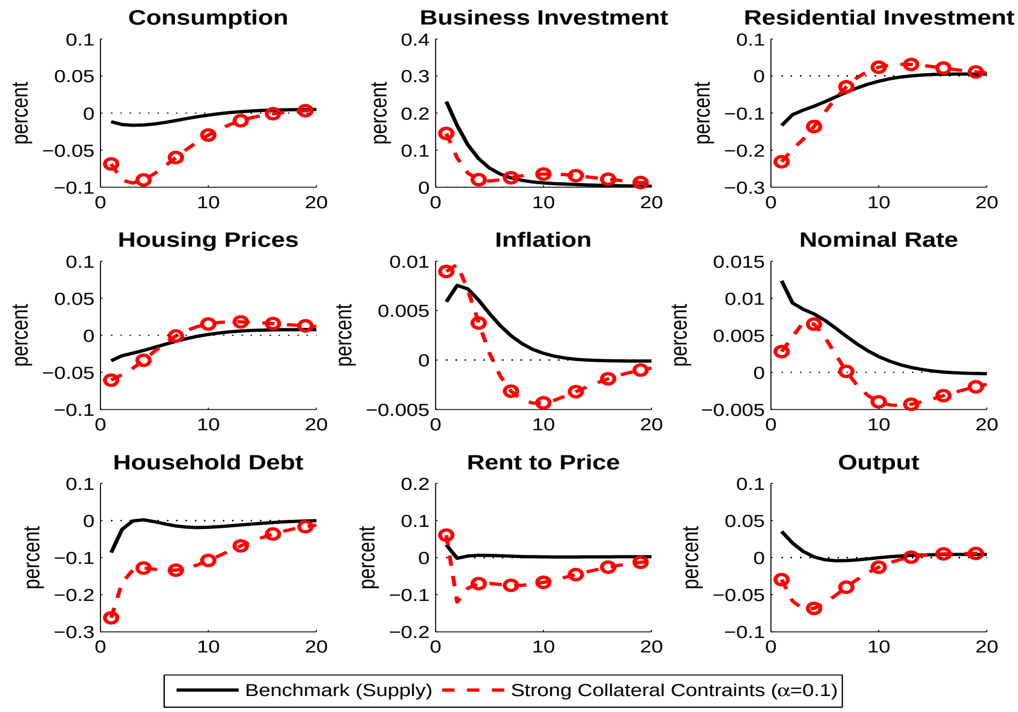


Figure 11: Supply-side Uncertainty Shock: Role of collateral constraints

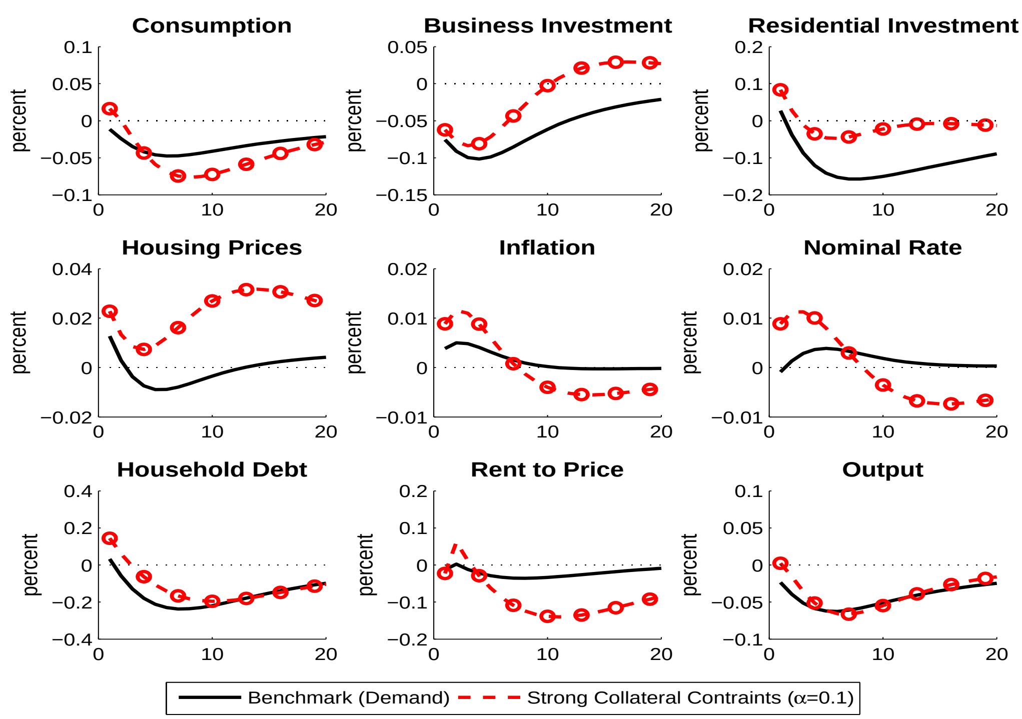


Figure 12: Demand-side Uncertainty Shock: Role of collateral constraints

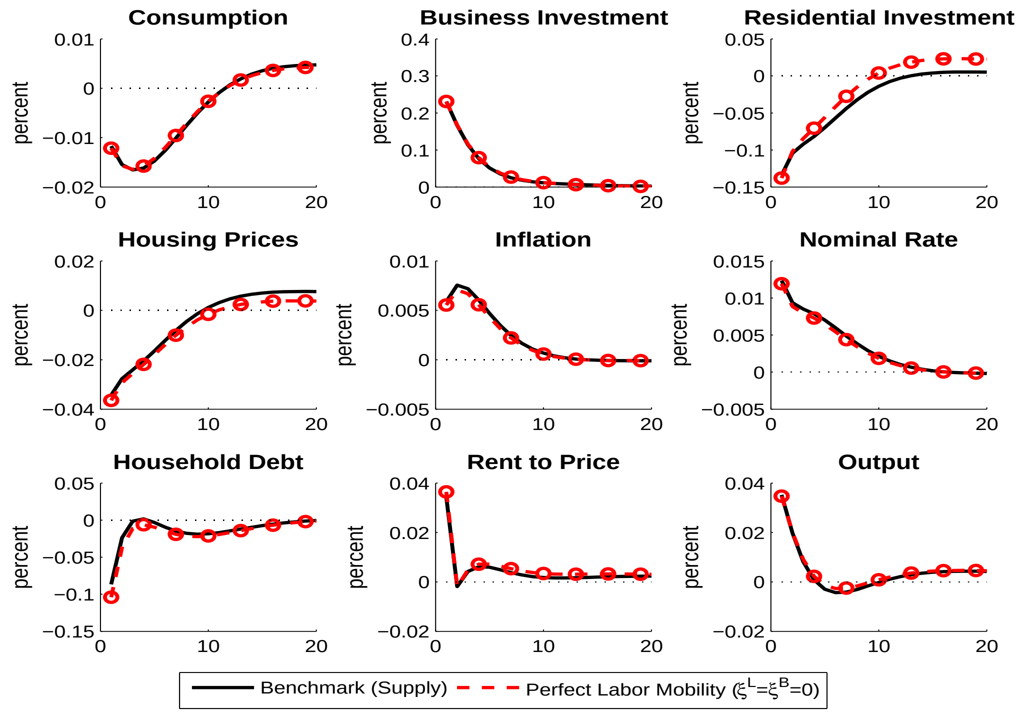


Figure 13: Supply-side Uncertainty Shock: Role of perfect factor mobility

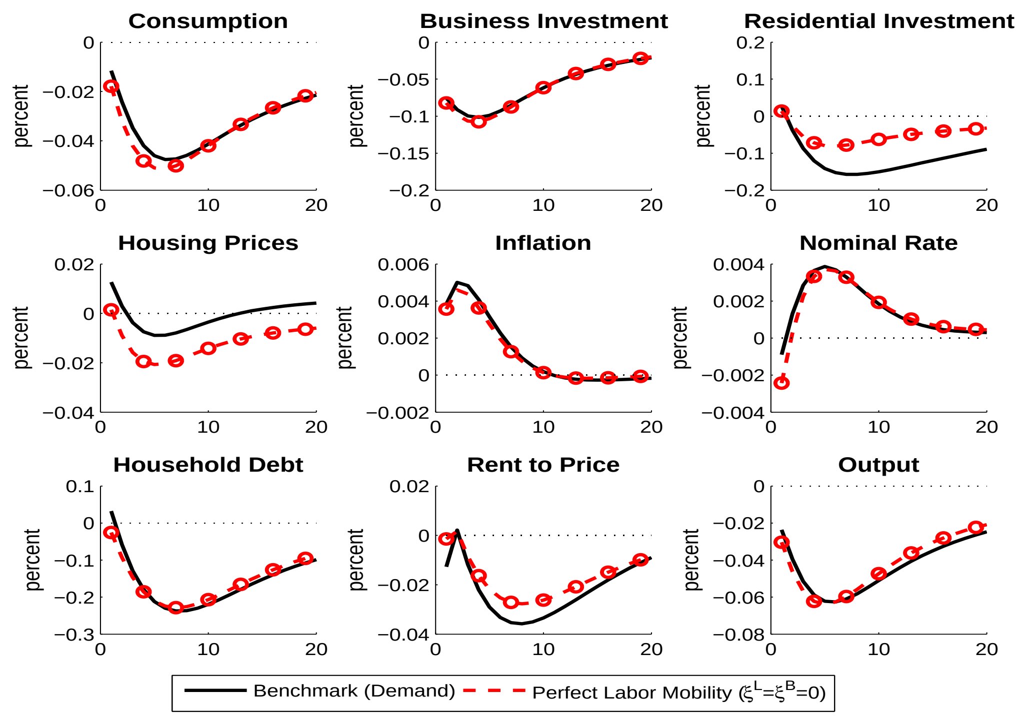


Figure 14: Demand-side Uncertainty Shock: Role of perfect factor mobility