Houses as ATMs? Mortgage Refinancing and Macroeconomic Uncertainty*

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Abstract

Can liquidity constraints explain the dramatic build-up of household leverage during the housing boom of mid-2000s? To answer this question we estimate a structural model of household liquidity management in the presence of long-term mortgages and short-term home equity loans. Households face counter-cyclical idiosyncratic labor income uncertainty and borrowing constraints, which affect optimal choices of leverage, precautionary saving in liquid assets and illiquid home equity, debt repayment, mortgage refinancing, and default. Taking the observed historical path of house prices, aggregate income, and interest rates as given, the model quantitatively accounts for the run-up in household debt and consumption boom prior to the financial crisis, their subsequent collapse, and weak recovery following the Great Recession, especially among the most constrained households.

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1 Introduction

Both the origins of the recent financial crisis and the severity of the Great Recession are often attributed to the increase in consumer indebtedness during the period of house price run-up in mid-2000s and the subsequent deterioration of household balance sheets with the sharp decline in house prices (e.g., Dynan (2012), Mian, Rao, and Sufi (2013)). There is less consensus about the structural forces driving both the borrowing boom and the consumption slump that followed (e.g., see Cooper (2012)). In particular, the expansion of household leverage and growth of consumer expenditures financed with extracted home equity over the period of house price boom as documented by Mian and Sufi (2010) is *qualitatively* consistent with liquidity-constrained households taking advantage of relaxed housing collateral constraints, but also with consumers' lack of self-control (e.g., Laibson (1997)), over-optimistic expectations, and/or lender moral hazard (e.g., Keys, Mukherjee, Seru, and Vig (2010)).

We show that a rational model of home equity-based borrowing by liquidity-constrained households can *quantitatively* account for the empirical patterns in household leverage and consumption over the last decade. In the aggregate, taking the observed historical path of house prices, aggregate household income, and interest rates as exogenously given, such a model can reproduce both the dramatic run-up in the housing debt over the period 2000-2006, and the sharp contraction in consumption that followed, most pronounced among the highly-levered households. In the cross section, the interaction of idiosyncratic labor income shocks with liquidity constraints, absent any ex ante heterogeneity, generates wide dispersion in liquid assets, debt holdings, and the ability of households to refinance their mortgages. This dispersion implies diverging paths of consumption following the Great Recession for households with different boom-time leverage.

We build a model of consumption, saving, and financing decisions of households who are subject to idiosyncratic labor income risk and liquidity constraints that incorporates key institutional features of the U.S. mortgage markets (such as long-term fixed rate mortgages), following the partial-equilibrium approach of Campbell and Cocco (2003).[1] Our analysis focuses on households' optimal choices of leverage, precautionary savings in liquid assets and illiquid home equity, as well as the dynamic decisions in debt repayment, mortgage refinancing, home equity extraction, and default.[2] The model captures the relevant frictions impacting the households' ability to smooth consumption over time and across states of nature when borrowing collateralized with housing wealth is the main source of consumer credit. We estimate the structural parameters of the model by targeting the key moments of household consumption, asset and debt holdings, and the aggregate dynamics of mortgage refinancing and equity extraction in relation to macroeconomic conditions.

While much of the existing literature treats mortgage refinancing and home-equity-backed borrowing in isolation, our analysis indicates that an integrated approach is important for understanding both.[3] Specifically, the decision to

[1]We abstract from the choice between adjustable and fixed-rate mortgages analyzed by Campbell and Cocco (2003) and Koijen, Van Hemert, and Van Nieuwerburgh (2009).

[2]Our approach is also closely related to models of consumption smoothing in the presence of transaction costs, e.g. Bertola, Guiso, and Pistaferri (2005), Alvarez, Guiso, and Lippi (2010), and Kaplan and Violante (2011).

[3]The wealth and collateral effects of housing on consumption have been studied empirically (e.g. Caplin, Freeman, and Tracy (1997), Campbell and Cocco (2007), Carroll, Otsuka, and Slacalek (2011), Lustig and Van Nieuwerburgh (2010), Case, Quigley, and Shiller (2011), and Calomiris, Longhofer, and Miles (2012)), as well as theoretically (e.g., Campbell and Hercowitz (2005), Fernandez-Villaverde and Krueger (2011), Attanasio, Leicester, and Wakefield (2011), Favilukis, Ludvigson, and Van Nieuwerburgh (2011), and Midrigan and Philippon (2011)).

refinance trades off the benefits, in the form of lower interest rates and/or access to liquidity, against the costs of originating a new loan, both financial and non-pecuniary. Our model also incorporates two sets of realistic borrowing constraints that restrict the ratios of loan size to home value (LTV) and to current household income (LTI) to be not too high at the time of loan origination. Another important feature of our model is counter-cyclical idiosyncratic labor income risk (Meghir and Pistaferri (2004), Storesletten, Telmer, and Yaron (2004), Guvenen, Ozkan, and Song (2012)). This property of the labor income process implies that a macroeconomic downturn not only can make more households become liquidity constrained, but also make households more concerned about the increased uncertainty of future income.

Together, these ingredients generate a set of new predictions about household consumption and borrowing decisions. First, because households do not have access to complete financial markets, the embedded options to default, prepay, or refinance the mortgage can no longer be analyzed in the standard option-pricing framework (e.g., Chen, Miao, and Wang (2010)). In particular, interest rates are not the only consideration in refinancing. The ability to convert some of the home equity into liquid assets can generate refinancing even when the costs of borrowing are high, especially among the most constrained households (e.g., see evidence in Hurst and Stafford (2004)). The model implies that such behavior spikes at the beginning of a recession, when income shock dispersion rises, which is consistent with the data (a puzzle for traditional models that consider lowering the interest rate as the only reason to refinance).

Second, the interactions between labor income risk and liquidity constraints can cause households to preemptively refinance before actually becoming constrained.

Because idiosyncratic labor income risk jumps up significantly in recessions, households may refinance "early" to build up a buffer stock of liquid assets preemptively, in order to avoid being caught by a binding loan-to-income constraint in the future. Households build up precautionary savings using both liquid assets and home equity. Since liquid assets provide limited returns while home equity is itself illiquid due to the refinancing costs and the limits on loan-to-income and loan-to-value ratios, households dynamically balance these two types of savings, holding more home equity when labor income risk is relatively low, and switching to stockpiling liquidity when labor income risk is high or following bad shocks that tighten the constraints. Under these conditions households are particularly sensitive to an increase in house prices, which relaxes the collateral constraints. Compared to models of one period debt and/or frictionless access to borrowing, our model generates greater accumulation of debt by financially constrained households as borrowing and liquid assets are imperfect substitutes. It also generates a more prolonged "deleveraging" following a drop in house prices, since households are not required to pay back their debt at the end of each period but rather rebalance it optimally in response to changing conditions. We show that even in the presence of long-term debt the effect of deleveraging on consumption is substantial, with households in the top quintile of the leverage distribution experiencing real consumption drops of 10% more than the average.

Third, even though households in the model face identical schedules of refinancing costs, their refinancing decisions can differ significantly due to idiosyncratic labor income risk and the resulting dispersion in balance sheet positions, which might appear suboptimal according to standard theory.[4] The model thus helps to

[4] Campbell (2006) surveys evidence of apparently suboptimal refinancing behavior.

connect aggregate refinancing activity with the cross section of household characteristics. Crucially, it helps explain the divergent paths of consumption during the Great Recession across households with different prior levels of indebtedness.

By feeding in the actual time series of macroeconomic shocks into the model, we show that it successfully replicates the significant run-up in household leverage for households experiencing large house price appreciation, compared to the situation of relatively stable house prices. Since our simulated moments estimation only targets a few reduced-form correlations between aggregate variables but not their realizations, such a test presents a high hurdle for the model.

In our simulations we assume that the lending standards remain constant over time, so that only realizations of income and house price shocks affect the tightness of collateral constraints. Relaxation of mortgage lending standards in the early 2000s, e.g. via expansion of subprime and low-documentation loans, would imply that our results provide a lower bound for the expansion of leverage as more marginal households would see their constraints relaxed than our model allows (e.g., as in Corbae and Quintin (2013)); similarly, the subsequent consumption drop could be even more drastic if lending standard were tightened (e.g., Guerrieri and Lorenzoni (2011)).[5] At the same time, while our model takes the evolution of house prices as given, a number of authors have attributed much of the house price run-up to the easing of lending standards (e.g., Landvoigt, Piazzesi, and Schneider (2012)), and some of the subsequent crash to an exogenous tightening (e.g., Favilukis, Ludvigson, and Van Nieuwerburgh (2011) and Midrigan and

[5] Carroll, Slacálek, and Sommer (2012) argue that an increase in labor income uncertainty, rather than the tightening of credit constraints by themselves, was the main driver of the consumption decline during the Great Recession.

Philippon (2011)).[6] Similarly, our model shows that relaxing lending standards is necessary to explain the rise in foreclosure following the crash (e.g., Corbae and Quintin (2013)), as the benchmark estimates based on the traditionally conservative credit limits imply very low default rates.[7]

Our simulation-based evidence also demonstrates that the interaction between interest rates and household liquidity constraints is important for assessing the effect of monetary policy on refinancing activity. When many households are liquidity constrained, their refinancing behavior becomes insensitive to changes in interest rates, especially in the face of depressed values of housing collateral or high debt service ratios. At the same time, our analysis suggests that a monetary easing in the early stages of an economic downturn, when both aggregate income falls and its cross-sectional dispersion rises, elicits stronger refinancing activities than what standard models would predict based solely on interest rate changes.

2 The Model

In this section, we present a dynamic model of household consumption, saving, and borrowing decisions with incomplete markets. Households are confronted with idiosyncratic shocks to income and aggregate shocks to interest rates, income growth, and house value. Since our focus is to capture households' behavior in the face of realistic macroeconomic risks and constraints, we try to model the key

[6] Rios-Rull and Sanchez-Marcos (2008), Ortalo-Magné and Rady (2006), and He, Wright, and Zhu (2012) analyze endogenous evolution of house prices in environments with collateral constraints.

[7] Chatterjee and Eyigungor (2011) study mortgage default in a model with both long-term loans and endogenous pricing of debt and housing collateral, but without the possibility of refinancing. Jeske, Krueger, and Mitman (2011) evaluate the aggregate implications of the government guarantees against mortgage default risk.

elements of the institutional environment of the U.S. housing finance while taking asset prices (including house prices) as exogenous.

2.1 Model specification

The economy is populated by ex-ante identical, infinitely lived households, indexed by i. We assume households have recursive utility over real consumption as in Epstein and Zin (1989) and Weil (1990),

$$U_{i,t} = \left[(1-\delta)\, X_{i,t}^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E}_t \left[U_{i,t+1}^{1-\gamma}\right]^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{1}$$

where δ is the time discount rate, γ is the coefficient of relative risk aversion, ψ is the intertemporal elasticity of substitution (IES), $\theta = \frac{1-\gamma}{1-\frac{1}{\psi}}$, and $X_{i,t}$ is a Cobb-Douglas aggregator of housing services $s_{i,t}$ and real non-housing consumption $c_{i,t}$,[8]

$$X_{i,t} = s_{i,t}^{\nu} c_{i,t}^{1-\nu}.$$

In the special case with $\theta = 1$, we recover CRRA utility.

The nominal price level at time t is P_t. For tractability, we assume the (gross) inflation rate is constant, $P_{t+1}/P_t \equiv \pi$. Each household is endowed with one unit of labor supplied inelastically, which generates before-tax nominal income y_{it}. The income tax rate is τ. We assume y_{it} has an aggregate real income component, Y_t,

[8] Piazzesi, Schneider, and Tuzel (2007) argue for a preference structure that is close to Cobb-Douglas based on the joint behavior of the U.S. housing expenditure shares and asset prices over time, while Davis and Ortalo-Magne (2011) show that a Cobb-Douglas specification is broadly consistent with the cross-sectional U.S. data.

an idiosyncratic component, $\tilde{y}_{it}$, as well as adjustment for inflation:

$$y_{it} = P_t \; Y_t \; \tilde{y}_{it}. \tag{2}$$

The growth rate of aggregate real income is $Z_{t+1} = Y_{t+1}/Y_t$. The idiosyncratic labor income component, $\tilde{y}_{it}$, follows an autoregressive process with state-dependent conditional volatility,

$$\log \tilde{y}_{it} = \log \mu_y(Z_t) + \rho_y \log \tilde{y}_{i,t-1} + \sigma(Z_t)\epsilon^y_{it}, \quad \epsilon^y_{it} \sim \mathcal{N}(0,1). \tag{3}$$

The counter-cyclical nature of idiosyncratic labor income risk, which is captured here by having $\sigma(Z_t)$ decreasing in Z_t, is emphasized by Storesletten, Telmer, and Yaron (2004). We set $\log \mu_y(Z) = -\frac{1}{2}\frac{\sigma^2(Z)}{1+\rho_y}$, so that the cross-sectional mean of $\tilde{y}_{it}$ is normalized to 1.

Next, we specify households' assets, liabilities, and the financing constraints.

Liquid assets Households have access to a riskless savings account with balance a_{it}, which earns the nominal short rate r_t. Interest income is taxed at the same rate τ as labor income. We also refer to the savings account as the households' liquid assets, in contrast to the illiquid housing assets.

Houses A household can choose to own h_{it} units of housing, which generates housing service flow $s_{i,t} = h_{it}Y_t$. Indexing per-unit housing service to real aggregate income Y_t ensures that aggregate housing and non-housing consumption are consistent with balanced growth.

Houses are valued proportionally at price P^H_t per unit. We assume that the nominal house price level P^H_t is co-integrated with the nominal aggregate income,

$P_t Y_t$. Specifically,

$$P_t^H = \bar{H}\ P_t\ Y_t\ p_t^H, \tag{4}$$

where $\bar{H}$ is the long-run house price-to-income ratio, while p^H is a stationary process that represents the aggregate risk inherent in the housing market's transitory deviations from the trend in aggregate income. Finally, the sale or purchase of a home incurs a proportional transaction cost ϕ_h.[9]

Debt There are two types of borrowing allowed for households, both of which are collateralized by the house: long-term fixed-rate mortgages and short-term home equity lines of credit (HELOC). For simplicity, long-term mortgage contracts are assumed to be perpetual interest-only mortgages. The coupon rate for mortgages originated in period t is R_t, which can be different from the coupon rate for existing mortgages, k_{it}. Based on the beginning-of-period mortgage balance b_{it} and coupon rate k_{it}, the mortgage payment in period t is $k_{it} b_{it}$. Households can deduct the mortgage interest expense, which is the full mortgage payment for an interest-only mortgage, from their taxable income y_{it}.

The HELOC is modeled as a one-period debt with floating interest rate benchmarked to the riskfree rate r_t, $r_t^{HL} = r_t + \vartheta$, with spread $\vartheta > 0$ over the short rate r_t. It is costless to adjust the HELOC balance, although the balance is subject to a set of borrowing constraints every period, which we specify below. Due to the interest rate spread ϑ and the borrowing constraints, it is never optimal to simultaneously hold non-zero balances in HELOC and liquid assets. Thus,

[9] Our approach implicitly treats house size as fundamentally limited by the availability of fixed factors such as land, similarly to the approaches in Ortalo-Magné and Rady (2006) and Corbae and Quintin (2013). Alternatively, one can model housing stock as fully adjustable through investment and depreciation, e.g. as in Favilukis, Ludvigson, and Van Nieuwerburgh (2011) and Iacoviello and Pavan (2013). Kiyotaki, Michaelides, and Nikolov (2011) consider the combination of both fixed and adjustable factors in the total value of the housing stock.

we can capture the HELOC and liquid asset balance with the same variable $a_{i,t}$. Specifically, the balance of HELOC and liquid assets are $-a^-_{i,t}$ and $a^+_{i,t}$, respectively, with $a^+_{i,t} = \max(a_{i,t}, 0)$ and $a^-_{i,t} = \min(a_{i,t}, 0)$.

When a homeowner sells the home and become a renter, it immediately repays all the outstanding debt – including the current period mortgage coupon payment, the remaining mortgage balance, and the HELOC balance – using the net proceeds of house sale and its stock of liquid assets.

Mortgage refinancing and repayment Households have the option to refinance the long-term mortgage, which results in a reset of the coupon rate $k_{i,t+1}$ from $k_{i,t}$ to the current market mortgage rate R_t, as well as a possibly different mortgage balance $b_{i,t+1}$. In particular, a cash-out refinancing is one that results in a higher mortgage balance, $b_{i,t+1} > b_{i,t}$.

When a household refinances into a new loan with balance $b_{i,t+1}$, they will incur a cost equal to $\phi(b_{i,t+1}; S_t)$. Therefore, the net proceeds from refinancing will be $b_{i,t+1} - b_{i,t} - \phi(b_{i,t+1}; S_t)$. The refinancing costs include the opportunity cost of time spent on the refinancing process, which does not depend on the loan amount, as well as direct fees associated with issuing a new mortgage, which tend to scale with the loan size. The cost of refinancing has both a quasi-fixed component (indexed to nominal aggregate income) and a proportional component:

$$\phi(b_{i,t+1}; S_t) = \phi_0 \; P_t Y_t + \phi_1 \; b_{i,t+1}. \tag{5}$$

Besides refinancing, households can also reduce their mortgage balance costlessly at any time by repaying the mortgage, i.e., choosing $b_{i,t+1} < b_{i,t}$, which does not change the existing coupon rate, $k_{i,t+1} = k_{i,t}$.

Collateral and debt service constraints When households apply for new loans, they face a pair of borrowing constraints: the *loan-to-value constraint* (LTV) and the *loan-to-income constraint* (LTI). Specifically, these constraints are imposed when the new HELOC balance is non-zero ($a^{-}_{i,t+1} < 0$), or when the household obtains a new mortgage, which occurs when they buy a new house or refinance the existing mortgage.

The LTV constraint restricts the new combined balances of all loans, including mortgage and HELOC, relative to the house value:

$$b_{i,t+1} - a^{-}_{i,t+1} \leq \xi_{LTV} \; P^{H}_{t} h_{it}, \tag{6}$$

with $\xi_{LTV} \geq 0$. Similarly, the LTI constraint restricts the new combined balances of all loans relative to household nominal income:

$$b_{i,t+1} - a^{-}_{i,t+1} \leq \xi_{LTI} \; y_{i,t}, \tag{7}$$

with $\xi_{LTI} \geq 0$. The constraints (6) and (7) mimic the loan-to-value and debt-to-income constraints widely used in practice by mortgage lenders, in particular, for conforming loans.

In addition, we impose an upper bound on the HELOC balance (or a lower bound on $a_{i,t}$) as a fraction $-\underline{a}$ of permanent income,

$$- a^{-}_{i,t+1} \leq -\underline{a} P_t Y_t. \tag{8}$$

This constraint is motivated by the common practice that limits the size of HELOCs and home equity loans to reduce the risk of default.

Default Homeowners have the option to default on their mortgages and HELOCs. When a household defaults on any of its debt, its home is ceased and it becomes a renter. Furthermore, the defaulted household will be excluded from the housing market for a stochastic period of time. With probability ω each period, it will regain eligibility for becoming a homeowner, at which point the household can choose to buy a house or remain a renter. This approach of modeling homeownership and default decision broadly follows Campbell and Cocco (2010).

Renting Unlike homeowners, a renter household can freely adjust the amount of housing services it consumes each period. For simplicity, we assume the ratio of rent per unit of housing relative to nominal aggregate income is a constant ϖ. The parameter ϖ can also capture the disutility of renting relative to owning a home. An unrestricted renter (not excluded from the housing market due to default) can become a homeowner by purchasing a house, using savings and borrowing.

2.2 Summary of exogenous shocks

In total, there are three aggregate state variables, summarized in the aggregate state vector $V_t = (Z_t, p_t^H, r_t)$. We assume that V_t follows a first-order vector autoregressive process (VAR) in logarithms:

$$\log V_{t+1} = \mu_V + \Phi_V \log V_t + \sqrt{\Sigma_V}\epsilon_{t+1}^V. \tag{9}$$

We assume that the mortgage rate R_t is a function of the aggregate state variables. We choose the following linear-quadratic specification for R_t, which is motivated empirically (see Section 3.1):

$$\log R(V_t) = \kappa_0 + \kappa_1' \log V_t + \kappa_2 \left(\log p_t^H\right)^2. \tag{10}$$

For an individual household, the vector of exogenous state variables, denoted by v_{it}, contains the individual labor income and the aggregate state vector: $v_{it} \equiv (y_{it}, V_t)$.[10]

We characterize the intertemporal optimization problem for homeowners and renters using standard dynamic programming tools, as detailed in Appendix A.

3 Structural Estimation

This section describes the empirical implementation of the model in Section 2. To solve the model, we discretize the state space and apply standard numerical dynamic programming techniques. We estimate the model parameters in three steps. First, we specify the dynamics of the exogenous state variables based on empirical estimates. Second, we set the institutional parameters to broadly represent the environment faced by U.S. households. Third, we estimate the preference and transaction cost parameters by matching the model-implied moments (computed from the simulation of a large panel of households) of household assets, liabilities, and consumption, as well as the dynamics of mortgage refinancing, with the data, taking the pre-estimated state variable dynamics and pre-set institutional parameters as given. Thus, our approach is essentially a version of the simulated

[10] We assume that all households bear the same aggregate risks since we focus on the "average" household that is likely to need to use home equity to smooth consumption. There is some evidence in the recent literature that wealthier households are disproportionately affected by aggregate fluctuations, see e.g., Parker and Vissing-Jørgensen (2009).

Table 1: Aggregate State Variables

Panel A: VAR Parameters

	μ	Φ_s			$\Sigma_s \times 10^{-3}$		
GDP	0.013	0.420	0	0	0.492	0.576	0.006
p_t^H	-0.015	0	0.888	0	0.576	6.525	0.440
r_t	0.002	0	0	0.844	0.006	0.440	0.192

Panel B: Mortgage Rate Parameters

κ_0	κ_Z	κ_{p^H}	κ_r	$\kappa_{(p^H)^2}$	R^2
0.049	0.094	0.011	0.684	-0.270	0.949
(0.001)	(0.023)	(0.004)	(0.025)	(0.022)	

method of moments (e.g., Duffie and Singleton (1993)) where a set of "nuisance" parameters are pre-specified before the structural parameters are estimated.[11] Details of the procedure can be found in Appendix B.

3.1 Exogenously specified parameters

Aggregate state variable dynamics We first estimate the VAR for the aggregate state variables in (9) using annual data. To reduce the degrees of freedom, we impose the restriction that Φ_V is diagonal. We use the U.S. real GDP growth rate as proxy for the real growth rate in aggregate income Z_t in the model, the one-year Treasury bill rate as proxy for the nominal short rate r_t, and the demeaned log house price-GDP ratio (computed using the S&P Case-Shiller house price index

[11] Dridi, Guay, and Renault (2007) provide a formal justification of this approach based on the indirect inference methodology (Smith (1993), Gallant and Tauchen (1996), and Gourieroux, Monfort, and Renault (1993)). Laibson, Repetto, and Tobacman (2007) follow a similar strategy for estimating the structural parameters in a household consumption and liquidity management model with hyperbolic discounting. Gourinchas and Parker (2002) pioneered structural estimation of household consumption-saving models. Hennessy and Whited (2005) apply structural estimation in corporate debt and investment models.

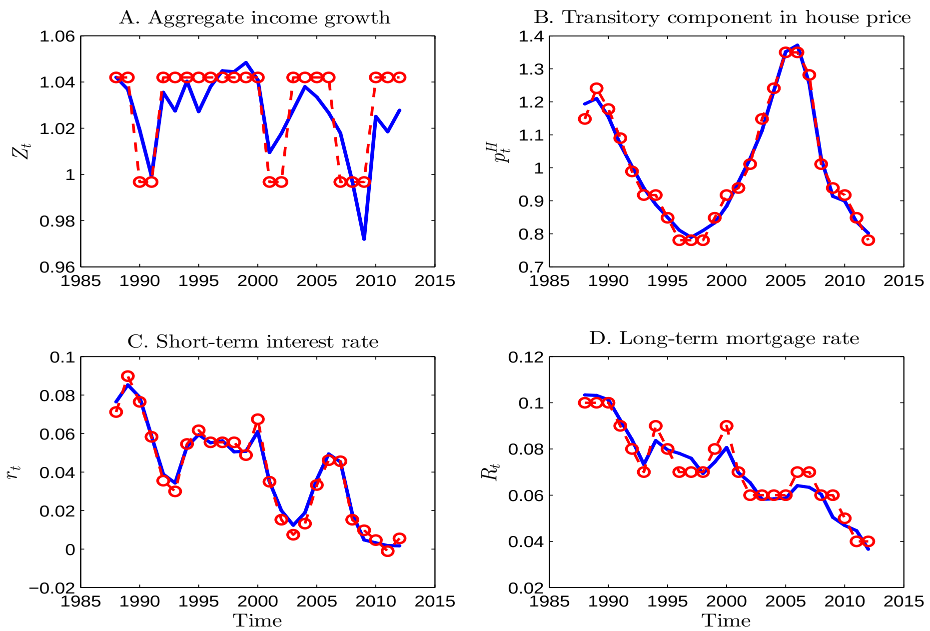

Figure 1: **Time series of exogenous state variables.**

and GDP data) as proxy for the transitory component in house price h_t. The estimated parameters of the VAR are reported in Table 1. We then approximate the VAR with a discrete-state Markov chain using the method of Tauchen and Hussey (1991). The state variables (Z, p^H, r) are discretized using 2, 10, and 10 grid points, respectively.

Panels A-C of Figure 1 compares the actual time series of the three aggregate state variables (blue solid lines) against the Markov chain approximation (red circle lines) for the period 1987-2012. Panel A shows that the 2-state approximation tracks the history of real income growth well over all, but it understates the severity of the Great Recession and slightly overstates the extent of the recovery thereafter. Panel B and C show that our model captures closely the highly persistent deviations of house prices from the trend of real economic growth and the paths of nominal short-term rates.

For tractability, we specify the mortgage rate R_t as an exogenous quadratic function of all the aggregate state variables as in Equation (10). Panel C of Table 1 reports the regression estimates of this relation based on the 30-year conforming mortgage rate (our empirical proxy for R). We obtain an R-square of 95% with just 4 explanatory variables $(Z_t, p_t^H, r_t, (p_t^H)^2)$, suggesting that this exogenous function $R(V)$ captures most of the time variation in the long-term mortgage rate. Since the household's fixed mortgage rate k_{it} is part of the endogenous state variables that spans the same states as R_t, in order to keep the size of the state space manageable we use a coarser grid for the latter with 7 points based on the implied distribution of $R(V)$. Panel D of Figure 1 plots the long-term mortgage rate in the data and the corresponding value on the grid. The discretized process for R_t tracks the history of the mortgage rates closely throughout the sample.

The choice of $\bar{H} = 4$ is based on estimates obtained using micro data (in the Survey of Consumer Finances for 2001, a year when the house price to GDP ratio is close to its long-run mean, the average ratio of housing assets to income among homeowners with positive income equals approximately 3.95). Finally, given the relatively smooth evolution of inflation over the sample period, we assume a constant inflation rate equal to its historical average $\pi = 2.85\%$ per annum.

Idiosyncratic state variable dynamics We calibrate the process for the idiosyncratic component of labor income $\tilde{y}_{it}$ (3) following Storesletten, Telmer, and Yaron (2007). With two states for the growth rate of real aggregate income, we set the conditional volatility of $\tilde{y}_{it}$ to $\sigma(Z_G) = 12\%$ and $\sigma(Z_B) = 21\%$. The autocorrelation parameter is $\rho_y = 0.95$. This process is then discretized as a

Table 2: Parameter Values

This table reports the exogenously-fixed parameters and the estimated parameters of the model. For the estimated parameters, the values in parentheses are the standard errors.

Panel A. Exogenously-fixed parameters

ρ_y	$\sigma(Z_G)$	$\sigma(Z_B)$	τ	$\bar{H}$	ξ_{LTV}	ξ_{LTI}	$-\underline{a}$	ω	ζ	ϑ
0.95	0.12	0.21	0.25	4.00	0.80	3.50	0.30	0.15	1.0	0.04

Panel B. Estimated parameters

δ	γ	ψ	ν	ϖ	ϕ_0	ϕ_1	ϕ_h
0.920	3.036	0.301	0.134	1.324	0.154	0.014	0.135
(0.007)	(0.347)	(0.020)	(0.004)	(0.100)	(0.020)	(0.008)	(0.017)

Markov chain with 12 grid points.

Institutional parameters Several exogenously set parameters reflect the main institutional features of the U.S. economy for homeowners and renters. The personal income tax rate is $\tau = 25\%$. The set of borrowing constraints includes (i) the constraint on the loan-to-value ratio $\xi_{LTV} = 80\%$, (ii) the constraint on the loan-to-income ratio $\xi_{LTI} = 3.5$, both of which are broadly consistent with the conforming loan requirements, and (iii) the upper bound on HELOC balances is $-\underline{a} = 30\%$ of aggregate income. The period of exclusion from debt markets for defaulted households is on average 7 years, as represented by the annual probability of $\omega = 0.15$ for returning to the housing market. Finally, we set $\zeta = 1$, so that a household does not lose any of its liquid assets at default. Most of these parameter choices closely follow Campbell and Cocco (2010).

The idiosyncratic labor income and institutional parameters are summarized in Panel A of Table 2.

3.2 Simulated moments estimation

Taking as given the set of prespecified parameters described above, we then estimate the remaining structural parameters $\Theta \equiv (\delta, \gamma, \psi, \nu, \varpi, \phi_0, \phi_1, \phi_h)$ by minimizing a standard objective function:

$$\hat{\Theta} = \arg\min_{\Theta} \left(M - m(\Theta, \Theta_0)\right)' \mathbf{W} \left(M - m(\Theta, \Theta_0)\right),$$

where $m(\Theta, \Theta_0)$ is the vector of reduced-form statistics of the simulated variables, M are their empirical counterparts, and W is a weighting matrix.

For a given set of parameter values, we first solve for the optimal policies from the household problem numerically. Then, we simulate a panel of households, which are initialized by randomly drawing pairs of liquid assets a_i and mortgage balance b_i over the state space for all N households in the cross section. We use a cross section of $N = 1000$ households and compute all of the statistics m along the aggregate time path of $T = 2000$ (annual) periods, after burn-in.

Data moment targets We estimate the preference and transaction cost parameters by targeting 14 moments of the data (sources detailed in Appendix C). These include 3 unconditional means applying to the whole population: (1) aggregate ratio of nondurable and non-housing services consumption to income, (2) average household-level consumption growth volatility (based on the Consumer Expenditure Survey estimates reported by Wachter and Yogo (2010)), and (3) the average homeownership rate.

There are 6 moments relevant to the homeowner subset of the population: (4) average ratio of liquid asset holdings to income, and (5) average ratio of household mortgage debt to income; (6) the average ratio of HELOC balances to income; (7) the average number of refinance loans relative to the number of homeowner households; (8) the average loan-to-income ratio upon refinancing; (9) dollar cash-out as a share of aggregate refinancing volume. There is also one moment for the renter population: (10) the average ratio of liquid asset holdings to income for the renter subset of the population.

All of the cross-sectional moments are based on the truncated sample from the 2001 Survey of Consumer Finances, whereby we exclude the top 20% of households sorted on liquid assets (similarly to the approach of Gomes and Michaelides (2005)). In the data, the wealth distribution is heavily skewed to the right, which implies that its mean is much higher than the median (1.33 vs. 0.10 for the liquid asset holdings) and therefore not representative of a typical household that our model aims to replicate, whereas the mean of the bottom 80% of the distribution is close to the median of the entire sample.[12]

The remaining 4 moments describe the dynamics of refinancing and cash-out behavior estimated via linear regressions of these variables on aggregate income growth and house price growth rates as documented in the Appendix. Table 3 reports both the target empirical moments and the simulated moments corresponding to the minimized objective function, as well as several additional moments that were not targeted in the estimation.

Since we use more moments than parameters, the model is over-identified. We use a diagonal weighing matrix that is scaled by the empirical moments in

[12]In our model all households are ex ante identical, and all of the heterogeneity is due to idiosyncratic shocks, which are transitory. Moreover, in our model household preferences are homothetic, while explaining the large amount of asset holdings by the wealthy households typically requires non-homotheticities, e.g. Carroll (2000), DeNardi (2004), Roussanov (2010).

question as a normalization, that is, $\mathbf{W} = \text{diag}(M)^{-1}\mathbf{S}\,\text{diag}(M)^{-1}$, where $\text{diag}(M)$ is a diagonal matrix with the empirical moments as the diagonal elements. The diagonal matrix $\mathbf{S}$ has elements of ones corresponding to all of the moments, except: (i) average debt balances and the refinancing rate have the weight equal 6, (ii) liquid asset holdings and average consumption growth volatility for homeowners each have the weight of 4, (iii) the 4 regression coefficients, which have the weight of 3, and (iv) the mean liquid assets of renters have the weight of 0.1. These weights reflect the fact that we are most interested in capturing the leverage and liquidity choices of homeowners. We use this pre-specified weighting matrix rather than a matrix that is based on the estimated variance-covariance matrix of moments (such as the efficient GMM weighting matrix of Hansen (1982)) in order to make sure that the information in some of the economically important but relatively poorly estimated moments (like the regression coefficients) is not down-weighed too much, as it is important for identification.

In order to conduct statistical inference we compute the variance-covariance matrix of sample moments Ξ using simulation under the null of the model, as described in Appendix B.

3.3 Estimation results

The targeted empirical moments and their model counterparts are reported in Panel A of Table 3 along with the simulated standard errors.

In our model, the average ratio of consumption to income at 0.71 is slightly above the 0.66 in the aggregate data (using both nondurable and durable goods expenditures, as well as non-housing services); according to the model this moment is estimated very precisely, with a standard error of 1%, which implies that statistically this difference is significant, even though it is economically small. The model-implied annual household-level consumption growth volatility of 16.4% is much higher than the 9% target estimated by Wachter and Yogo (2010), which is constructed to reduce measurement error, but it is consistent with the estimate of Brav, Constantinides, and Geczy (2002) based on the CEX data (16-18% for households with total assets exceeding $2,000). The model implies an average homeownership rate of 67.4%, quite close to the 66% average homeownership rate in the data.

The 16.4% household-level consumption growth volatility is only slightly below the unconditional labor income growth volatility of 16.6%, implying limited consumption smoothing on average. The model tries to match simultaneously a low level of average liquid asset holdings, a high level of average debt holdings (both of which require low risk aversion), and a moderate consumption volatility (which requires high risk aversion). Although home equity can help homeowners smooth income shocks in bad times, the financial leverage tends to raise consumption volatility on average.

The model does a good job matching the average liquid asset holding and mortgage balances for homeowners in the data. Mortgage debt is a fraction 0.96 of household income on average, compared to 0.98 in the SCF data. Households pay down a part of the mortgage balances over time for two reasons. First, mortgage borrowing is generally a costly way to finance consumption due to the interest rate differential between mortgage loans and personal savings. Except when the term structure of interest rates is sufficiently flat that the effective (after-tax) borrowing rate is equal to or lower than the short rate, households optimally choose to repay part of their mortgage debt rather than holding too much in liquid assets. Second, by partially repaying the mortgage debt, households can maintain some home equity "for the rainy day." Since accessing housing collateral is costly, home equity is an illiquid form of saving that can be tapped for consumption purposes infrequently, e.g., following large negative income shocks. The model also matches the average holdings of second-lien loans reasonably well (0.07 of household income in the data vs. 0.08 in the model, insignificantly different statistically given the standard error of 0.01).

Despite the low return on liquid assets, households still hold liquid assets equal to 24% of income in the model, which is close to the amount observed in the SCF data (28%). It is more efficient to use liquid assets to buffer small fluctuations in income due to the costs of accessing home equity via cash-out refinancing. Liquid assets also become highly valuable in cases when the borrowing constraints (LTV or LTI) bind.[13] The model implies a reasonable level of liquid asset holdings for renters at 15% of annual household income vs. 18% in the SCF data.

About 11.3% of homeowners per year refinance their mortgages in the model, compared to 8% in the data. The average loan-to-income ratio for the new loans originated from refinancing in the model (2.74) is significantly higher than the average value in the 2001 SCF (1.41) and the HMDA data for 1993-2009 (1.90). Accordingly, the amount cashed out conditional on refinancing is also high, equaling to 51% of new loan balances, compared to 12% in the data. Estimates

[13] Using 2004 SCF data, Vissing-Jørgensen (2007) estimates that by using their lower-return liquid assets to accelerate the repayment of higher-cost housing debt U.S. consumers would have saved $16.3 billion - see discussion in Guiso and Sodini (2013). Telyukova (2013) analyzes the role of liquidity in explaining the related puzzle of concurrent credit card debt and savings account holdings documented by Gross and Souleles (2002), while Laibson, Repetto, and Tobacman (2003) argue that consumer self-control problems may be necessary to explain quantitatively the extent of the puzzle.

from the data are based on the average cash-out share of refinance originations for prime, conventional loans, and average loan-to-income (for all refinance loans). To the extent that these estimates are representative of the U.S. homeowners, the model predicts too much cash-out as well as too frequent refinancing into large mortgages in general, with the differences being both economically and statistically significant. It is a challenge for the model to simultaneously match the refinancing rate and the dollar amounts of cashed-out home equity. While raising the fixed cost of loan origination helps reduce the frequency of refinancing, it makes households cash out even more each time they refinance.

On the set of moments from the refi and cash-out regressions, the model matches the signs and approximately the magnitudes of all the coefficients on income growth (β_Z) and on house price growth (β_H), especially in the case of cash-out regression. Both the refinancing rate and the dollar cash-out to income ratio comove positively with house price growth, and negatively with income growth, as we find in the data. While these regression coefficients are estimated quite imprecisely, as evidenced by the large standard errors that we report, targeting these coefficients is important for capturing the cyclical dynamics of household demand for liquidity, which helps to identify some of our key structural parameters.

Next, the estimated values of the preference and transaction cost parameters are reported in panel B of Table 2, accompanied with the standard errors in the parentheses. The preference parameters implied by the moments above are the subjective discount factor $\delta = 0.920$, the coefficient of relative risk aversion $\gamma = 3.036$, and the intertemporal elasticity of substitution $\psi = 0.301$. These parameters imply a moderate degree of risk aversion and a limited willingness to substitute consumption intertemporally, i.e. a desire for a smooth consumption profile over time. These parameter estimates are driven largely by the low target level of liquid asset holdings, high debt levels, and the observed sensitivity to changes in interest rates and economic conditions embedded in the refinancing frequency and the regression coefficients. In particular, our estimate of the IES is close to the estimate obtained by Vissing-Jørgensen (2002) using stockholder household-consumption data from the CEX (0.299).[14]

While a number of studies that estimate the IES using the aggregate log-linearized Euler equation following Hall (1988) find values very close to zero, such an approach would not be valid in an economy that conforms to our model, given the substantial heterogeneity and frictions.[15] As Table 3 Panel B reports, the estimated slope coefficient from the regression of consumption growth on the lagged risk-free rate based on the simulated data from the benchmark model is only 0.09, while the coefficient from the regression of consumption growth on the lagged long-term mortgage rate R is 0.10, both about a third of the true value.

The estimated implied average rent/income ratio parameter is $\varpi = 1.324$. This parameter is identified jointly by the average consumption-income ratio and the share of homeowners as well as the balance sheet moments, since the benefit of homeownership is in large part the avoidance of rental expenses but also the asset and collateral value of housing.

[14] Our estimate of the IES differs from values typically used to reconcile asset pricing facts with consumption dynamics in representative-agent models. For example, Bansal, Kiku, and Yaron (2012) estimate IES of around 2 using aggregate consumption and asset price data, while their estimate of the coefficient of relative risk aversion is twice as large as ours. This is not surprising since the only risky asset that we target in the data is housing (and mortgage). Moreover, we target households in the bottom 80% of the wealth distribution, who exhibit low rates of stock market participation. Vissing-Jørgensen (2002) obtains estimates of the IES above one for households in the upper tail of the wealth distribution who participate in financial markets; see also Attanasio and Weber (1995) and Vissing-Jørgensen and Attanasio (2003).

[15] Carroll (2001) and Hansen, Heaton, Lee, and Roussanov (2007) discuss some of the issues associated with the standard approaches to estimating the IES.

Households use debt primarily as a way of smoothing consumption and financing new home purchases. Existing debt balances are refinanced either to reduce the coupon rate k, or to cash-out equity. The quasi-fixed and proportional costs of refinancing, ϕ_0 and ϕ_1, are primarily identified by targeting empirically observed average refinancing rates, in terms of both frequency and loan size. They are also influenced by the average level of mortgage debt, since higher transaction costs make higher balances less attractive by effectively lowering the value of the refinancing option, as well as by making home-equity withdrawal via cash-out more expensive. Anecdotal evidence suggests that explicit costs of roughly $2\% - 5\%$ of loan amount are paid when refinancing a mortgage loan of average size, in addition to non-pecuniary information processing costs and the opportunity cost of time required to process the transaction. In the estimation, we obtain a quasi-fixed cost of 15.4% of permanent income (or 3.9% of the house value on average) and a proportional cost of 1.4%, which is comparable to the costs calibrated by Campbell and Cocco (2003).[16]

The model implies that the cost of buying (or selling) a house ϕ_h is 13.5% of the house value. This parameter is identified primarily by the average homeownership rate but also by the asset holding levels among homeowners and renters, since this parameter controls the cost of transition from one group to another. This estimated cost is high, although it is meant to capture the psychic and physical costs of moving, besides the actual pecuniary transaction costs (such as transfer taxes and realtor commissions).

[16]Empirically the bulk of explicit cost of refinancing can be attributed to title insurance, which is proportional to house value, whereas the non-monetary costs such as the opportunity cost of time spend searching for an attractive mortgage rate and preparing the necessary documents are likely quasi-fixed.

As indicated by the standard errors, most of the parameters are estimated fairly precisely in the sense that the sampling uncertainty about the data moments, under the null of the model, translates into tight confidence bands for the point estimates. All of the parameters are statistically significantly different from zero. The discount factor δ is statistically significantly lower than unity. Interestingly, the coefficient of relative risk aversion cannot be distinguished from the inverse of the IES, suggesting that the standard separable utility function with constant relative risk aversion provides a reasonable description of household preferences.

Finally, Panel B of Table 3 reports several moments that are not targeted in the structural estimation. Checking the ability of the model to match these moments is a form of out-of-sample test. The volatility of aggregate consumption growth in the model is 3.9%, compared to 2.7% in the data. The model matches reasonably well the sensitivities of the total refinancing rate and dollar cash-out to the fluctuations in the mortgage rate. In the refinancing regression, the coefficient on mortgage rate, β_R^{REFI}, is -1.09 in the model, compared to -1.91 in the data. In the cash-out regression, $\beta_R = -0.83$ in the model vs. -0.43 in the data.

4 Model Implications

Having examined the aggregate moments of the estimated model, we now turn to its implications for the dynamics of household financing and consumption in the cross section and over time.

4.1 Cross-sectional implications

Having examined the aggregate implications of the estimated model, we now turn to its cross-sectional predictions. We focus on the behavior of homeowners with respect to their use of mortgage debt as a key tool of balance sheet adjustment.

Figure 2 presents the key variables capturing the household refinancing behavior for the quintiles of households sorted on income relative to the aggregate (i.e., on the idiosyncratic component $\tilde{y}$), conditional on homeownership (panels in the left column) and on the ratio of debt to income (panels in the right column). In the model, liquidity needs drive much of the refinancing behavior. Consequently, conditional on refinancing, the average dollar cash-out to income ratio is decreasing in income (Panel A), from close to 1.5 in the bottom quintile to about 0.25 in the top. At the same time, it is also decreasing in debt to income ratios, largely due to the LTI constraint, from just under 3.5 in the bottom two quintiles (households who go from essentially zero debt all the way up to the constraint) down to approximately 1 in the top quintile.

The average refinancing households in all the income quintiles have nonzero HELOC balances before refinancing, as evidenced by negative average asset holdings before refinancing in panels C and D. This suggests that liquidity-constrained households first borrow using short-term HELOCs, which have no transaction costs, and then switch to cashing out home equity when the liquidity needs become sufficiently strong. The asset-to-income ratio is increasing in income (Panel C), ranging from -0.32 for the bottom quintile to 0.02 for the top quintile. After refinancing, the cashed-out home equity not only helps pay down the HELOC balances, but substantially boosts the liquid asset positions, up to around 80%

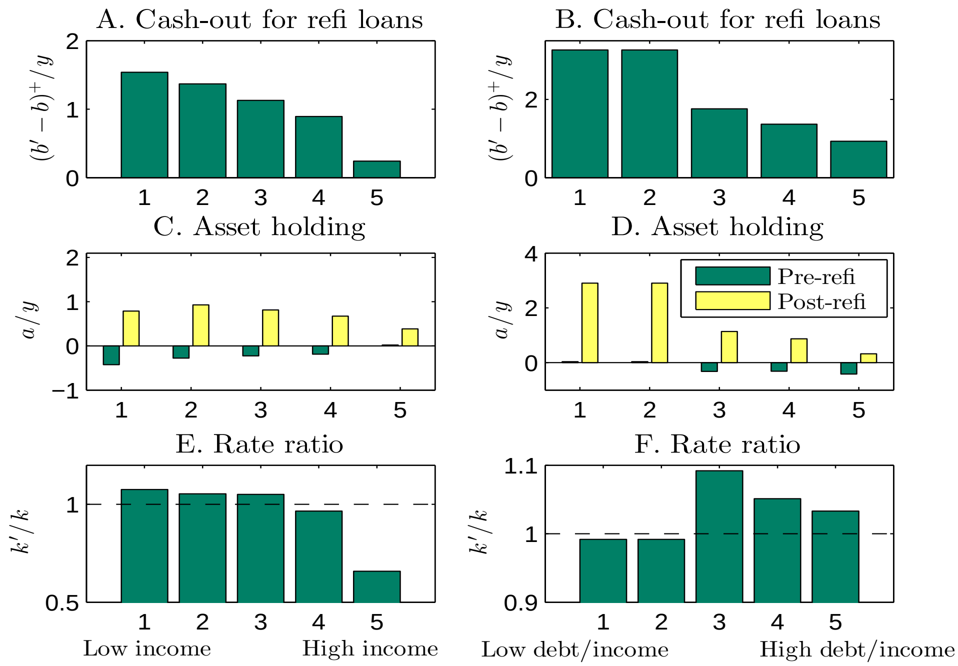

Figure 2: **Cross-sectional features of refinancing: model.**

of annual income for the bottom two quintiles, and about 50% for the fourth quintile. Similarly for the debt/income sort (Panel D), high debt households repay HELOC balances, leaving relatively little of the cashed-out funds available for consumption (roughly one half of income in the top quintile and just above one year's income in the middle quintile), where as the 40% households with no debt enter the period in which they refinance with on average a tiny amount of liquid assets, leaving with over 3 times one year's income.

As a clear indication that it is liquidity demands that drive much of the refinancing for relatively low income homeowners, the ratio of the new mortgage rate obtained upon refinancing k' to the old rate k is above unity for the bottom three quintiles, and significantly below unity (at 0.7) for the top income quintile

(Panel E). The low income households are willing to *increase* their average debt service cost in order to access liquidity. On the other hand, the high income households tend to have lower mortgage balances, which means that they will require a significant drop in mortgage rate to be willing to incur the fixed cost for refinancing. However, since larger debt holdings increase the incentive to lower financing costs, the rate ratio declines as a function of debt relative to income across the top three deciles of debt/income ratio, where households enter the period with substantial debt holdings.

Next, we confront the model's cross-sectional predictions with empirical evidence in Figure 3. We use data from SCF for years 1998, 2001, 2004, 2007, and 2010, which contain questions about mortgage refinancing. In the model, we sort households into quintiles based on relative income and on the ratio of debt to income as before (conditional on homeownership); in the data, we sort households based on income relative to the value of their primary residence (panels in the left column) and based on debt relative to income (panels in the right column); we sort within each year and then average the values over all years.

The model matches the cross-sectional distribution of mortgage debt-to-income ratios remarkably well (Panels A and B). The bottom quintile of income on average has mortgage balances that are about twice as large as annual income on average (slightly above in the model, slightly below in the data); these decline to just over a single year's worth of income in the second quintile, and down to about a quarter of annual income in the top quintile (other than for the bottom group, the model undershoots these levels somewhat). The increase in loan balances relative to income across quintiles of its own distributions is of a similar magnitude.

The model's ability to match the unconditional distribution of loan-to-value

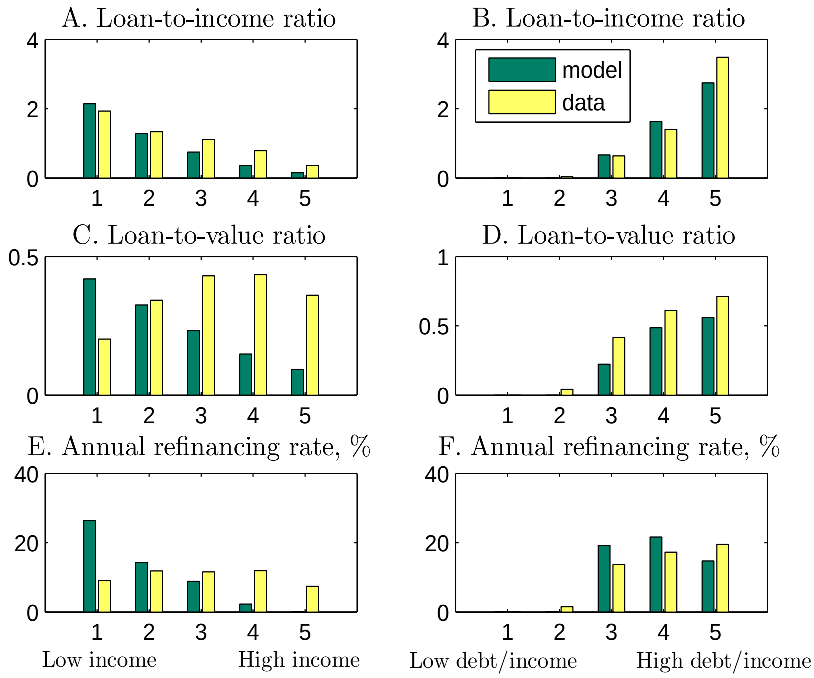

Figure 3: **Comparing the cross-sectional implication of the model with the data.**

ratios (LTV) is weaker when sorted on income (Panel C) than when sorted on debt relative to income (Panel D). In the data, the average mortgage debt relative to home value is hump-shaped in income/house ratio, ranging from about 0.2 in the bottom quintile, peaking at about 0.4 in quintiles 3 and 4, and declining slightly in the top quintile. In the model, the ratio is monotonically decreasing from 0.4 to about 0.1. The bottom 40% of the LTV distribution have exactly zero debt in the model and essentially zero debt in the data, and both increase monotonically to about 0.5 in the model vs. 0.7 in the data.

Finally, the model matches reasonably well the rates of refinancing for the middle of the income distribution (quintiles 2 and 3, Panel E), where they are close to the average. For the bottom quintile of income, the model dramatically overshoots the fraction of household refinancing – over 25% in the model but just under 10% in the data, on average. In the top quintile, very few households in the model refinance, where as about 8% of those in the data do. This can be attributed to the fact that our model undershoots the magnitude of mortgage liabilities of the high-income households, especially relative to house value. When sorted on debt relative to income, the model matches the empirical refinancing rates fairly well, since households with little debt rarely refinance and a large fraction of refinance loans involves cash-out, which raises loan balances ex-post (in the data, we sort households based on current debt balance, while the refinancing indicator is naturally backward-looking).

The discrepancy between the rates of refinancing as a function of income in the model and in the data could also be driven by the fact that cognitive costs associated with understanding the refinancing process are decreasing with household income, which our model does not capture. Woodward and Hall (2010) report that many consumers overpay their mortgage brokers during their mortgage transactions, which effectively increases their cost of refinancing. If these costs are a function of financial sophistication, which likely rises with income, our model should overshoot refinancing among low income households, and undershoot it at the top of the distribution.

4.2 Historical time series

In order to evaluate the model's ability to match the observed history of household consumption behavior, we simulate a panel of 1000 households, who face random idiosyncratic labor income shocks generated within the model as well as the time series of realized shocks to the exogenous state variables in the data (discretized accordingly) for the period 1988–2012. We report the time-series aggregates of the model-generated variables along with their data counterparts in Figure 4. Panel A depicts the annual series for real consumption growth. The model-generated series of consumption growth tracks the data closely both in direction and in the magnitude of variations. The model overstates the fluctuations in consumption growth in 1990-1991 (both the recession-induced drop and the subsequent recovery), but matches closely the rapid and smooth growth in consumption boom in the late 1990s, somewhat exaggerates the "consumption boom" of mid-2000s, matches well the large consumption drop during the Great recession, with three consecutive years of consumption declines close to 2% per year (2007-2009), and somewhat overshoots the subsequent recovery.

What is driving these consumption patterns in the data? Clearly, the empirically observed processes for aggregate income and house prices that we feed into the model play a role. But the model provides households with opportunities to endogenously adjust their decisions on consumption, savings, homeownership vs. renting, as well as the decisions related to mortgage refinancing.

The role of refinancing in particular is apparent from Panel B of Figure 4, which depicts the median ratio of the mortgage rate obtained as a result of refinancing to the rate on the original (prepaid) loan. The model matches the dynamics of the median ratio of the new mortgage rate to the old rate closely, including the peaks when the ratio goes above unity, capturing the effect of liquidity demand by constrained households at the onset of a recession. The rate ratio series appear to be moving in the opposite direction of the consumption growth plotted in Panel A,

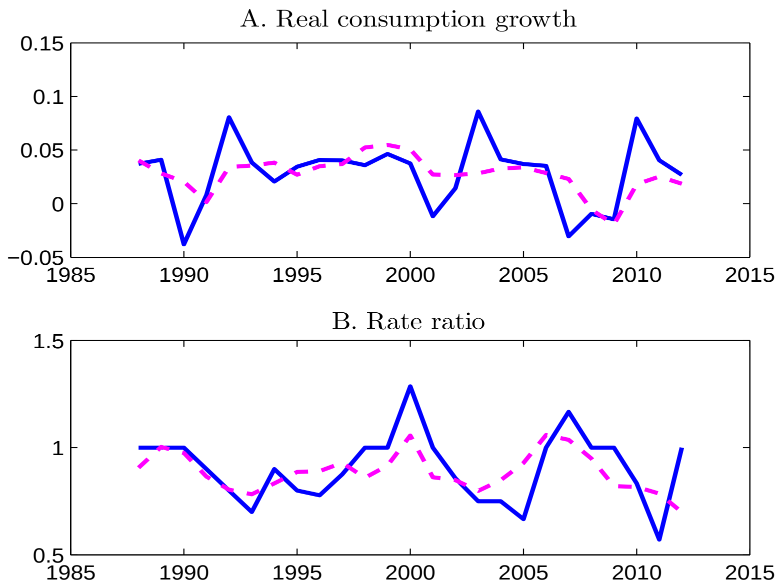

Figure 4: **Model-implied aggregate time series.** This figure plots the model-implied aggregate time series (solid lines) for real consumption growth (all households) and the median rate ratio of refinance loans, and their data counterparts (dashed lines), from 1988 to 2012.

suggesting that absent the opportunity to refinance (and cash-out) consumption would fall even more in recessions. The rate ratio in the model is somewhat more variable than it is in the data.

In sum, our model successfully replicates the main dynamics in consumption, debt, and the cash-out share and rate ratio of refinance loans in the period 1998–2012. In particular, it captures the relaxation of liquidity constraints due to the rise in house prices in the 2000s, which allowed households to rationally withdraw home equity via cash-out refinancing (and second-lien borrowing), driving up household leverage and generating (in part) the consumption boom of the mid-2000s. The fall in house prices and income starting in 2007 following the dramatic expansion of leverage tightened households' balance sheets, causing a sharp and protracted consumption drop. Despite the fact that in the model households are given an opportunity to "ride out" bad times by only paying interest on long-maturity loans, the tightening of the collateral constraints, combined with an increased uncertainty about future labor income (and a lower expected growth rate) lead households to reduce their leverage and improve their asset position, which entails cutting consumption. This mechanism is consistent with the evidence of depressed consumption by highly-indebted households as documented by Dynan (2012) and Mian, Rao, and Sufi (2013).

4.3 Cross-sectional analysis of the housing boom and bust

In this section, we examine our model's predictions about the cross-sectional household behavior during the recent housing boom and bust. We focus on two types of heterogeneity. First, we compare households that have experienced different degrees of house price appreciation but otherwise similar macroeconomic conditions during the housing boom. Second, we compare how households with different amount of leverage in 2007 behave differently following the housing bust.

Mian and Sufi (2010) document an important piece of empirical evidence in support of the effect of house prices on household borrowing. They use a measure of elasticity of housing supply developed by Saiz (2010) to show that U.S. MSAs with relatively inelastic supply of housing, which experienced fast house price growth prior to the Great Recession, saw a dramatic increase in household leverage due to home equity withdrawal, while MSAs with more elastic housing supply that had not experienced such a run-up in prices did not.

Since there is no heterogeneity in house price dynamics built into our model, we approach this evidence by conducting a counterfactual experiment. Specifically, along with our baseline model we consider two scenarios that are broadly representative of the "inelastic" and the "elastic" areas. Specifically, we solve the model using the same set of parameters as in the baseline model but a different stochastic process of house prices. In particular, in the "inelastic" case we let the volatility of transitory innovations to house prices be twice as large as our baseline. In the "elastic" case we instead assume that the ratio of real house price to real income is constant, i.e. $p_t^H = 1$. This assumption captures the notion that in areas with elastically supplied housing prices are closely aligned with construction costs (e.g., see Glaeser, Gyourko, and Saiz (2008)). Since labor wages are a large component of these costs, we expect house prices to be roughly proportional to income in the elastic areas.

We plot the simulated total debt growth and changes in debt-to-income ratio over the decade 1998-2008 in Figure 5, analogous to Figure 1 in Mian and Sufi (2010). Panel A depicts the cumulative growth in house prices under the "inelastic" scenario and under the "elastic" scenario, as well as the baseline model. The inelastic case exhibits a much more rapid rise in house prices and a sharper drop than the baseline, where as the elastic case shows only moderate growth in house prices, driven by the increase in aggregate income, consistent with the Mian-Sufi data.

Panels B and C depict the evolution of the total housing debt and the debt-to-income ratio under the two scenarios. Under the inelastic scenario with significant house price appreciation, household debt grows dramatically, especially during the latter part of the period 2005-2008, both in total amount and relative to income,

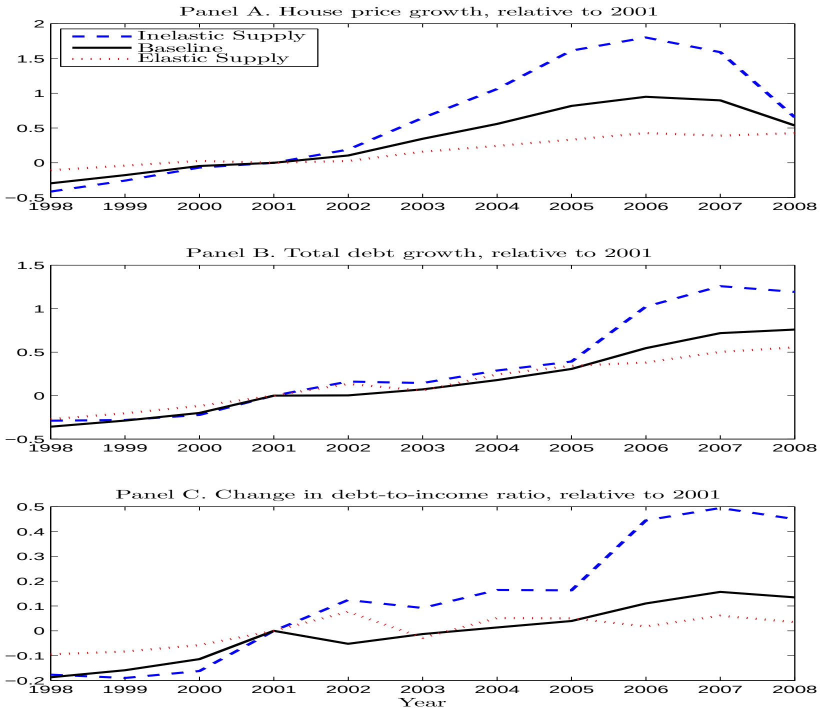

Figure 5: **Replicating Mian and Sufi (2010) evidence on household leverage.** The solid line represents the case with the house price path from the baseline model. The dash line represents the case with the ratio of real house price to real income being constant, which mimics the effect of elastic housing supply.

(although the model overstates the former and understates the latter increase compared to the Mian-Sufi data). In contrast, under the "elastic" scenario, total debt and debt-to-income ratio stay relatively flat over the entire period, broadly in line with the evidence documented by Mian and Sufi (2010). Therefore, according to our model, relaxation of the liquidity constraints as a result of house price run up can account for the observed increase in household leverage in a rational framework, insofar as it can be consistent with the observed path of house prices.

What about the cross-sectional evidence of household behavior following the housing bust of 2007 and the ensuing Great Recession? Mian, Rao, and Sufi

(2013) document evidence of "debt overhang" whereby households whose leverage grew the most during the boom period experienced the sharpest declines in consumption subsequently.[17] We use the simulated artificial panel based on the aggregate historical time-series described in Section 4.2 above to analyze the model's cross-sectional implications in this period. Figure 6 plots several key variables aggregated over groups of households in the model: the top (dashed line) and bottom (dash-dotted line) quintile based on debt relative to income in 2006, and the average of all homeowners (solid line). We plot the simulated series for the years 2007-2012 to illustrate the heterogeneity in households' responses to aggregate economic conditions.

Panel A depicts the cumulative consumption growth (relative to 2006) for the three groups. The high-leverage households experience a sharper drop in consumption during the Great Recession than an average household, with a cumulative decline of about 10% by 2009 (vs. 5% for the average homeowner). In contrast, low leverage households experience essentially the same consumption drop than the average. This pattern is broadly consistent with evidence in Mian, Rao, and Sufi (2013). In the model, consumption recovers starting in 2010 for all groups. In fact the average household consumes 10% more by 2012 than in 2006 (in part because the highly levered households are those that experience particularly bad transitory income shocks, so that their income and consumption grows over time the most due to mean reversion).

Panel B plots the liquid asset positions of the three groups. The high-leverage group enters the recession with substantial cash holdings, of about one year's

[17] Cooper (2012) debates the direct role of leverage and argues that the evidence is more consistent with a standard wealth effect.

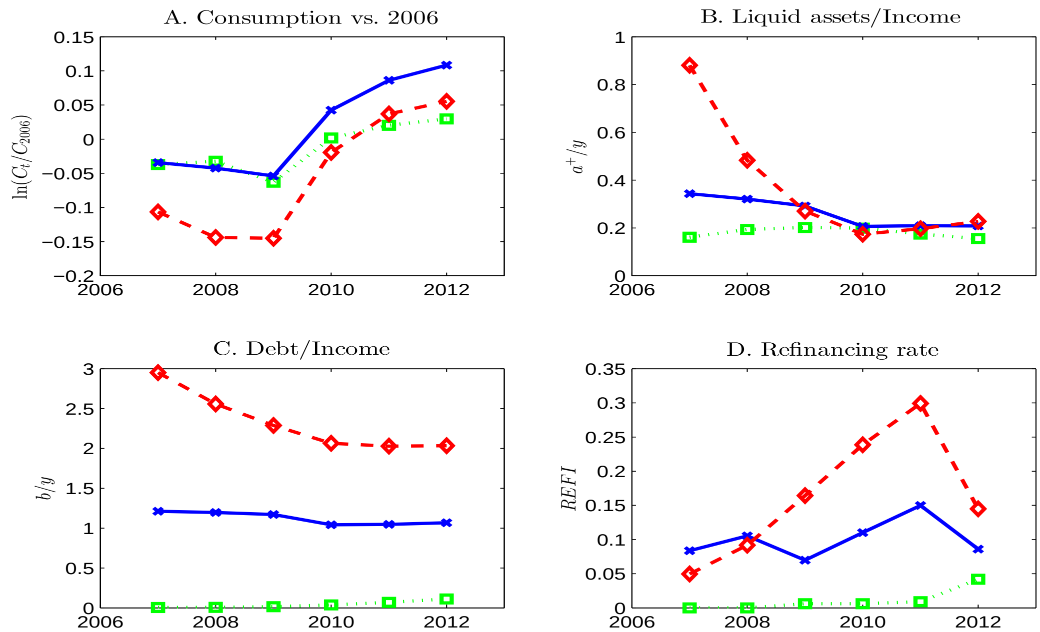

Figure 6: **Consumption, balance sheet, and refinancing behavior for households with different amount of leverage.** The dash-diamond line and the dot-square line represent the top and bottom quintile of the distribution of debt-to-income ratio in 2006, respectively. The solid-cross line represents the average homeowner.

worth of income on average: this is the result of the cash-out over the preceding boom period, which led to the high leverage in the first place. This endogenous link between leverage and liquid asset holding will be important for assessing the impact of income shocks on consumption. In contrast, the low leverage group has one tenth as much in assets relative to income at the beginning of the recession, whereas the average homeowner's asset holding is just under 40% of income. In the recession, the high- and average-leverage households draw down their liquid assets over time, while the low-leverage homeowners accumulate liquid assets due to elevated income uncertainty (and demand for precautionary savings). The high-leverage households also significantly reduce their leverage over 2007-2010 as a result of debt repayment and (in the later period) the rebound in income (Panel C).

The households' refinancing behaviors in this period are also quite revealing. In Panel D we plot the refinancing rates for the three groups. The high-leverage group initially experiences lower refinancing rates than average (essentially zero in 2007 and 2008), as the LTI and LTV constraints are binding for most of the households in this group. Refinancing activity rises significantly for this group after 2008, surpassing that of the average households and reaching 33% of loans in 2011, compared to the corresponding peak at 15% for the average household. This jump in refinancing is in part due to decline in debt, which relaxed the collateral constraints, but can be largely attributed to the prolonged period of lower mortgage rates. The model may be overstating refinancing by the constrained households, however, due to the tightening of lending standards following the subprime mortgage crisis.

Households in the low-leverage group have almost no mortgage debt. A few of these households "refinance"starting in 2010 by taking out a new loan with a 100% cash-out. However, such behavior is rare: even though liquidity is valuable, these households do not possess the interest rate option embedded in the mortgage (i.e., they do not benefit from lower mortgage payments by refinancing when interest rates are low), which makes it less worthwhile to incur the fixed costs of refinancing. In contrast, for households with non-zero mortgage balances, the exercising of the interest rate option complements the liquidity needs in their refinancing decisions. In fact, the wave of refinancing activity in the model contributes to the stronger recovery of consumption for levered households considered to those with little or no debt in 2006, since low interest rates represent a wealth effect that boosts consumption but only for those who can realize the savings by refinancing existing debt. The fact that empirically observed refinancing behavior among highly constrained households did not respond nearly as strongly to the refinancing incentives following the financial crisis, as documented by Fuster and Willen (2010), suggests that tightening of lending standards could play an important role in limiting the effectiveness of monetary policy on stimulating consumption.

5 Concluding Remarks

We present an estimated structural model of household mortgage debt and liquidity management that accounts for a range of key features of both the historical time-series and the cross-sectional facts on mortgage refinancing, household leverage, and consumption. The model can be useful for quantitative evaluation of economic policies aimed at supporting household balance sheets via the mortgage market.

Our model could be extended in a number of ways in order to investigate a set of closely related issues. While our focus is on understanding household decisions in response to the empirically observed prices of houses and financial assets, an evaluation of welfare and distributional implications would require closing the model by clearing both housing and asset markets. First, a fully specified model of the housing market would require not only a careful consideration of supply and its elasticity, but also a richer set of preferences over housing and the decision of whether to rent or own. Second, it would be useful to endogenize the interest rates on mortgages and HELOCs. One could endogenize mortgage rates within our framework using a partial equilibrium setting by introducing an exogenous stochastic discount factor, which would allow an evaluation of the welfare impact of refinancing costs by incorporating the equilibrium response of mortgage spreads to slower prepayment speeds.

Understanding the impact of securitization on mortgage borrowing, as well as its welfare implications, requires a general equilibrium analysis (e.g., as in Landvoigt (2013)). While Gerardi, Rosen, and Willen (2010) show empirically that mortgage securitization improved households' ability to smooth their housing consumption over time, the net effect on total consumption and welfare can only be ascertained in a structural model that captures all of the relevant frictions. Our framework should prove useful in pursuing this line of research.

Table 3: Target Moments for the Estimation and Model Outputs

Moment	Variable	Data	Model	s.e.
	Panel A. Targeted Moments			
All Households:				
1. Consumption/Income	c_i/y_i	0.66	0.71	0.01
2. Consumption growth volatility, %	$\sigma(\Delta \log c_{i,t+1})$	12.0	16.4	0.01
3. Homeownership rate, %	$E[I^h]$	66.0	67.5	0.08
Homeowners:				
4. Liquid assets/Income	a_i^+/y_i	0.28	0.24	0.04
5. Mortgage/Income	b_i/y_i	0.98	0.96	0.08
6. HELOC/Income	$-a_i^-/y_i$	0.07	0.08	0.01
7. Refinancing rate, % of homeowners	$REFI$	8.0	11.3	0.02
8. Refi loan/Income	b_i'/y_i	1.41	2.74	0.14
9. Dollar cash-out/Refi loan	$(b_i' - b_i)^+/b_i'$	0.12	0.51	0.03
Renters:				
10. Liquid assets/Income	a_i^+/y_i	0.18	0.15	0.06
Refinancing Regression:				
11. Coefficient on Z	β_Z^{REFI}	-0.25	-0.24	0.41
12. Coefficient on $\Delta \log H$	β_H^{REFI}	0.15	0.08	0.14
Cashout Regression:				
13. Coefficient on Z	β_Z	-0.12	-0.23	0.43
14. Coefficient on $\Delta \log H$	β_H	0.06	0.11	0.15
	Panel B. Additional Moments			
Volatility of aggregate consumption growth, %	$\sigma(\Delta \log C_{t+1})$	2.7	3.9	0.01
Sensitivity of consumption to Z shocks	β_Z^C	0.46	1.30	0.20
Sensitivity of consumption to H shocks	β_H^C	0.06	0.09	0.05
Sensitivity of consumption to lagged r	β_r^C	0.07	0.09	0.43
Sensitivity of consumption to lagged R	β_R^C	0.09	0.10	0.65
Refinancing regression coefficient on R	β_R^{REFI}	-1.91	-1.09	0.67
Cashout regression coefficient on R	β_R	-0.43	-0.83	0.73

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Appendix
For Online Publication

A Household problem

In this section, we specify the problem for homeowners and renters. In order to simplify notation, we drop subscripts t and use primes to denote next period variables.

Homeowner problem The problem for homeowner i is to choose real non-housing consumption c_i, house size h_i, the position in the liquid asset (or HELOC) a_i', as well as the decision to refinance or repay early (both of which result in a new mortgage balance b_i'), sell the house, or default on the debt, so as to maximize the expected lifetime utility of real consumption. Denoting the refinancing decision by the indicator I_{it}^{RF} (with $I_{it}^{RF} = 1$ for refinancing at time t and 0 otherwise), the dynamics of the mortgage rate k_{it} can be written as

$$k_{i,t+1} = k_{it}\ (1 - I_{it}^{RF}) + R_t I_{it}^{RF}. \tag{A.1}$$

The household problem can be formalized as follows,

$$U_i^h(a_i, b_i, k_i, h_i, v_i) = \max_{a_i', b_i', h_i', I_i^{RF}} \left[(1-\delta)\left((h_i Y)^{\nu}\, c_i^{1-\nu} \right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E}\left[\max\left(U_i^{h'}, U_i^{hr'}, U_i^{hd'} \right)^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}} \tag{A.2}$$

subject to a

$$\begin{aligned} c_i P + \frac{a_i^{+\prime}}{1+(1-\tau)r} + \frac{a_i^{-\prime}}{1+r^{HL}} + b_i = (1-\tau)(y_i - k_i b_i) + a_i + b_i' - \phi(b_i'; V)\ I_i^{RF} \\ + I_i^M P^H \left((1-\phi_h)\, h_i - (1+\phi_h)\, h_i' \right) \qquad \text{(A.3)} \\ (b_i' - b_i)\ (1 - I_i^{RF}) \leq 0, \\ c_i, b_i' \geq 0, \end{aligned}$$

along with the law of motion for mortgage rate k_i (A.1), the LTV and LTI constraints (6) and (7), and the upper bound on HELOC (8). We denote the value function of the household in the homeowner state by $U_i^h(a_i, b_i, k_i, h_i, v_i)$, by $U_i^{hr}(a_i, b_i, k_i, h_i, v_i)$ in a state of transition from homeowner to renter by selling the home, and by $U_i^{hd}(a_i, b_i, k_i, h_i, v_i)$ in a state of transition from homeowner to renter by defaulting on the mortgage.

Upon transition from homeownership to renter state the proceeds from selling the house $(1-\phi_h)h_i P^H$ are added to the resource constraint while the mortgage and HELOC borrowing must be repaid. The problem for the household making the transition from the homeowner to the renter state by selling its home is then given by

$$U_i^{hr}(a_i, b_i, k_i, h_i, v_i) = \max_{a_i'} \left[(1-\delta) \left((h_i Y)^{\nu} c_i^{1-\nu} \right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E} \left[U_i^r(a_i', v_i')^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}}, \tag{A.4}$$

subject to

$$\begin{aligned} c_i P + \frac{a_i'}{1+(1-\tau)r} &= (1-\tau)(y_i - k_i b_i) + a_i + (1-\phi_h) h_i P^H - b_i, \quad (A.5) \\ a_i', c_i &\geq 0, \end{aligned}$$

where $U_i^r(a_i, v_i)$ denotes the value function of an unrestricted renter who is allowed to buy a house immediately.

If a household defaults on its mortgage, it also becomes a renter, but with the added restriction that it will be excluded from the housing market for a period of time. This transition problem is given by

$$U_i^{hd}(a_i, b_i, k_i, h_i, v_i) = \max_{a_i'} \left[(1-\delta) \left((h_i Y)^{\nu} c_i^{1-\nu} \right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E} \left[U_i^d(a_i', v_i')^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}} \tag{A.6}$$

subject to

$$\begin{aligned} c_i P + \frac{a_i'}{1+(1-\tau)r} &= (1-\tau) y_i + \zeta a_i^+, \quad (A.7) \\ a_i', c_i &\geq 0, \end{aligned}$$

where $U_i^d(a_i, v_i)$ denotes the value function of a restricted renter who is currently excluded from the housing market due to defaulting on its mortgage. In both (A.6) and (A.7), the constraint $a_i \geq 0$ is due to the fact that HELOC is unavailable to renters.

Renter problem For convenience, we define three different types of renters: unrestricted renter, restricted renter, and a renter in transition to become a homeowner, with value functions $U_i^r(a_i, v_i)$, $U_i^d(a_i, v_i)$, and $U_i^{rh}(a_i, v_i)$, respectively. The problem for an unrestricted renter is to choose the size of the rental house h_i^r, the non-housing consumption c_i, and the liquid assets for the next period a', such that

$$U_i^r(a_i,v_i) = \max_{h_i^r, a_i' \geq 0} \left[(1-\delta) \left((h_i^r Y)^\nu \, c_i^{1-\nu} \right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E} \left[\max \left(U_i^{rh}(a_i', v_i'), U_i^r(a_i', v_i') \right)^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}} \tag{A.8}$$

subject to the positivity of consumption and the budget constraint:

$$h_i^r \varpi P Y + c_i P = (1-\tau) y_i + a_i - \frac{a_i'}{1+(1-\tau)r}. \tag{A.9}$$

The intra-temporal optimization implies

$$\frac{h_i^r \varpi P Y}{c_i P} = \frac{\nu}{1-\nu}.$$

That is, the ratio of rental expense and non-housing consumption is constant. This condition helps simplify the Bellman equation (A.8) and the renter budget constraint (A.9) into

$$U_i^r(a_i,v_i) = \max_{a_i' \geq 0} \left[(1-\delta) \left(\overline{\eta} c_i \right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E} \left[\max \left(U_i^{rh}(a_i', v_i'), U_i^r(a_i', v_i') \right)^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}} \tag{A.10}$$

and

$$\frac{c_i P}{1-\nu} = (1-\tau) y_i + a_i - \frac{a_i'}{1+(1-\tau)r}, \tag{A.11}$$

where

$$\overline{\eta} \doteq \left(\frac{\nu}{(1-\nu)\varpi} \right)^\nu. \tag{A.12}$$

The transition problem for the household from the renter to the homeowner state is given by

$$U_i^{rh}(a_i,v_i) = \max_{a_i', b_i', h_i'} \; \left[(1-\delta) \left(\overline{\eta} c_i \right)^{\frac{1-\gamma}{\theta}} + \delta \; \mathbb{E} \left[U_i^h(a_i', b_i', k_i, h_i, s_i')^{1-\gamma} \right]^{\frac{1}{\theta}} \right]^{\frac{\theta}{1-\gamma}}, \tag{A.13}$$

subject to

$$\frac{c_i P}{1-\nu} = (1-\tau) y_i + a_i - \frac{a_i'}{1+(1-\tau)r} + b_i' - \phi(b_i'; V) - (1+\phi_h) h_i' P^H, \tag{A.14}$$
$$c_i, b_i' \geq 0,$$

as well as the LTV and LTI constraints (6) and (7), and the constraint on HELOC (8).

The problem of a restricted (post-default) renter is given by

$$\begin{aligned} U_i^d(a_i, v_i) &= \max_{a_i' \geq 0} \Bigg[(1-\delta)\left(\overline{\eta} c_i\right)^{\frac{1-\gamma}{\theta}} + \delta \mathbb{E}\left[(1-\omega)\left(U_i^d(a_i', v_i')\right)^{1-\gamma}\right]^{\frac{1}{\theta}} \\ & + \delta \mathbb{E}\left[\omega \max\left(U_i^{rh}(a_i', v_i'), U_i^r(a_i', v_i')\right)^{1-\gamma}\right]^{\frac{1}{\theta}} \Bigg]^{\frac{\theta}{1-\gamma}}, \end{aligned} \tag{A.15}$$

subject to the positivity of consumption as well as the renter budget constraint (A.11).

Since households have homothetic preferences, we rescale the problem with respect to the price level P_t and the permanent aggregate income Y_t in order to make it stationary.

B Computation and Estimation

Prespecified parameters The parameters controlling the dynamics of the exogenous state variables as well as describing the institutional features of the model environment are summarized as

$$\Theta_0 \equiv (\mu_S, \Phi_S, \Sigma_S, \pi, \mu_y, \rho_y, \sigma_y(\cdot), \bar{H}, \tau, \kappa_0, \kappa_1, \kappa_2, \xi_{LTI}, \xi_{LTV}, \underline{a}, \zeta, \omega, \vartheta).$$

Numerical Implementation The household problem is solved numerically using a standard value function iteration (VFI) procedure on a very large grid (more than 1.9 million total grid points, with 1920 points for the exogenous states and 960 points for the endogenous states). Moreover, we need to solve the model repeatedly in the estimation. These requirements make the computational problem rather challenging. To make the estimation feasible, we programmed the numerical solution in CUDA language and ran the VFI on a Nvidia C2050 (Fermi) graphics card (with 448 CUDA cores). Since the objective function is highly nonlinear, we use a global search algorithm to ensure that the resulting estimates are not due to local minima. The estimation was implemented with a global optimization routine capable of using up to 8 graphics cards simultaneously. This (software and hardware) implementation yields a significant improvement in speed, allowing us to estimate the model in less than one week. The same estimation problem will take 400 times as long on a standard desktop computer.

Simulation-based inference In order to be able to evaluate the statistical significance of the mismatch between the target and simulated moments, as well as the uncertainty about the estimated parameter values, we need to estimate the variance-covariance matrix of the sample moments, Ξ. Since we use a combination of time-series and cross-sectional moments, using data directly is not feasible. Instead, we construct the variance-covariance matrix of the *simulated* moments under the null that the model is true (with the parameters set at the estimated values). In order to estimate this matrix we simulate $N_A = 80$ paths of aggregate variables and generate a panel of $N = 1000$ households using these aggregate shocks and simulated idiosyncratic shocks so that it matches the small sample length $T_D = 25$ years available in the data. For each of the aggregate paths we compute the full set of moments, and estimate the variance-covariance matrix of these moment vectors across simulations. While the simulated moments used in estimation are based on long samples of length T, i.e. are essentially population moments, the variance-covariance matrix estimated using the short-sample simulated moments measures the sampling uncertainty about the moments estimated in the data under the null of the model.

In addition, we construct standard errors for the estimated parameters from the Ξ matrix using the standard delta method,

$$var(\hat{\Theta}) = \frac{1}{T_D}(d'Wd)^{-1}d'W\Xi Wd(d'Wd)^{-1},$$

where the derivatives of the moments with respect to the parameters $d = \frac{\partial m(\Theta_0,\Theta)}{\Theta}$ are approximated using numerical finite differences.

C Data Targets

C.1 Aggregates

Aggregate consumption, personal income, and gross domestic product are from the U.S. *National Income and Product Accounts*; house price index is from $S\&P$/Case-Shiller; one-year Treasury Bill rate from FRED; 30-year fixed mortgage rate is from Freddie Mac Primary Mortgage Market Survey (PMMS). Homeownership rate is from the U.S. Census (average over the time period 1990-2010 is 66.54%). The number and volume of mortgage refinancing originations, as well as the average ratio of the loan amount to income, by state, per quarter, is based on the Home Mortgage Disclosure Act (HMDA) reporting for the time period 1993-2009. Total dollar cash-out relative to total dollar refinancing volume for prime, conventional loans, as well as the fraction of loans that involve cash-out and the median ratio of new to old rate are from Freddie Mac for the time period 1993-2010.

The target regression coefficients are based on the auxiliary model. For total refinancing we estimate

$$REFI_t = \beta_0^{REFI} + \beta_Z^{REFI} Z_t + \beta_H^{REFI} \Delta HPI_t + \beta_R^{REFI} R_t^{M30} + \beta_r^{REFI} r_t^{1Y} + \epsilon_t, \quad \text{(A.16)}$$

where $REFI_t$ is the monthly mortgage applications index constructed by the Mortgage Bankers Association (MBA Refi Index), $Z = \Delta IP_t$ is the monthly year-on-year growth in the Industrial Production index, ΔHPI_t is the year-on-year growth in the Case-Shiller housing price index, R_t^{M30} is the 30-year fixed mortgage rate, and r_t^{1Y} is the 1-year Treasury rate. To make the coefficients easier to interpret, we rescale the MBA Refi Index to have a mean of 8%, which is the average annual refinancing rate for homeowners according to the HMDA and Census data.

For cash-out, we estimate

$$CASHOUT_t = \beta_0 + \beta_Z Z_t + \beta_H \Delta HPI_t + \beta_R R_t^{M30} + \beta_r r_t^{1Y} + \epsilon_t. \quad \text{(A.17)}$$

where $CASHOUT$ is the total dollar amount of home equity withdrawn in a year via cash-out refinancing, scaled by the total personal income in the previous year, $Z_t = \Delta PI_t$ is the one-year growth rate in real personal income, and the other variables are the same as defined in (A.16).

C.2 Survey of Consumer Finances

We use the SCF public data set available from the Federal Reserve Board of Governors for the year 2001 in constructing empirical targets. The survey is representative of the U.S. population and is designed to oversample the wealthy households. Each household is represented in the data set by 5 replicates (implicates) constructed in order to compensate for omitted information about households assets, etc; thus, there are 22,210 observations produced from the 4,442 households actually surveyed. We use sampling weights provided by the SCF to allow aggregation to population totals.

The survey contains detailed information on household demographics, income, debt, and asset holdings. We define liquid assets in the SCF data as the total value of checking/savings accounts, bonds, and public equity holdings, including both directly-held stocks and mutual funds. Kaplan and Violante (2011) use a similar definition. For mortgage debt we use the first lien loan collateralized by the primary residence of the household, whereas the combined balance of all of the junior lien loans on the same residence (including second/third mortgages and home equity lines of credit) is classified as HEL(OC). Income is total family income in the calendar year (prior to the survey year). House value is based on the total value of the primary residence (for homeowners). Refinancing statistics are constructed based on mortgages that are identified as refinance loans originated during the year of the survey or the prior year.

For the cross-sectional evaluation of the model we combine data from the 1995, 1998, 2001, 2004, 2007, and 2010 SCF waves, which contain information about mortgage refinancing, averaging quantile values across years (data from all of the waves is treated similarly to that described above, with quantiles based on the truncated distributions).

D Estimated model: inspecting the mechanism

D.1 Sensitivity analysis

Here analyze the sensitivity of the simulated moments to the estimated parameters, which underpins our structural identification. Table A.1 displays the values of simulated moments for different values of the key parameters in Θ, compared to the baseline case. For each of the seven estimated parameters we consider two values equidistant from the point estimates in either direction. Our discussion focuses on the key effect of each of the parameters.

Subjective discount factor δ Making households more patient via a larger δ increases the prevalence of homeownership, and increases household savings in the form of liquid asset holdings and home equity while lowering average mortgage balances). HELOC balances stay essentially the same (even though HELOC is more expensive than the mortgage on average in terms of the interest rate, it can be cheaper to access when liquidity is needed). As mortgage balances decline with higher δ, so does the frequency of refinancing and the sensitivity of refinancing to interest rates (β_R^{REFI} closer to 0). When the benefit of interest savings from refinancing is small, only those suffering from large income shocks find it worthwhile to pay the fixed costs of refinancing, as evidenced by the higher loan-to-income ratios and cash-out share for the new loans after refinancing. Moreover, under higher δ, while households cash-out more following negative aggregate income shocks (more negative β_Z), the consumption growth is still more affected by income shocks (larger β_Z^C), suggesting that households save the cashed-out home equity rather than consuming it. Finally, the average consumption/income ratio is higher with more patient households, again due to the fact that they have accumulated more savings via liquid assets and home equity.

Coefficient of relative risk aversion γ Increasing the risk aversion leads to more precautionary savings in the forms of liquid asset holdings and home equity (through both higher homeownership and lower mortgage balances), but also reduces the usage of HELOC as households accumulate enough liquid assets.

Refinancing is mainly driven by the need to withdraw home equity rather than the purely financial incentive of lowering the mortgage rate, as cash-out/refi ratios increase in risk aversion and the sensitivity of refinancing to mortgage rate β_R^{REFI} moves closer to 0. Like the patient households, risk-averse households also cash-out more following negative aggregate consumption shocks (more negative β_Z) and shocks to mortgage rates (more negative β_R).

Intertemporal elasticity of substitution ψ A higher IES lowers liquid asset holdings, increases mortgage balances, and raises consumption volatility. This is due to the reason that households are less concerned with smoothing consumption over time, and the effects are qualitatively similar to those of a lower risk aversion. However, while a lower risk aversion coefficient reduces homeownership (which is driven by weaker precautionary savings motive), a higher IES raises homeownership. This is because the higher IES makes the refinancing option associated with owning a house more valuable, whereby households can better take advantage of house price appreciation and drop in interest rate.

The IES is also important for the dynamics of refinancing and cash-out. With a higher ψ, households are more willing to substitute consumption over time, therefore both cash-out and consumption are responding more to the changes in interest rates, as shown in a more negative β_R and a larger β_R^C.

Cost of refinancing ϕ_0, ϕ_1 Raising the quasi-fixed cost ϕ_0 of refinancing reduces the frequency of refinancing while increasing the new loan size and its cash-out component. Since costly refinancing makes mortgages effectively more expensive, average mortgage balances decline, as does homeownership. Its effect on the total leverage is partly offset by higher HELOC balances. Since lower mortgage balance reduces the risk in the household balance sheet, the precautionary holding of liquid assets is also lower. Raising the proportional cost parameter ϕ_1 has very similar effects. It might appear surprising that higher proportional refinancing cost increases the average new loan size and the cash-out share. This is driven by the composition effect: households are less likely to refinance for the purpose of lowering mortgage rates (β_R^{REFI} is -0.83 with high ϕ_1, compared to -1.09 in baseline case) but more likely to refinance to cash out home equity.

D.2 Comparative statics

In order to analyze the model's mechanism we compute a range of comparative statics for its key structural elements. We report the simulated moments from the model for each of the model specification alongside the baseline that uses the estimated parameter values, similarly to the sensitivity analysis described above.

Labor income risk Table D.2 displays the comparative statics that pertain to the underlying dynamics and the key frictions faced by the households in the model. Specifications in columns (2) and (3) shut down heteroscedasticity in the idiosyncratic labor income process and vary amount of uncertainty faced by households via setting $\sigma(Z_G) = \sigma(Z_B) = 8\%$ in column (2) and $\sigma(Z_G) = \sigma(Z_B) = 17\%$ in column (3). In the latter case, the reduction in risk due to the removal of the counter-cyclical variation in income uncertainty leads households to choose slightly higher leverage than in the baseline (mortgage-to-income ratio rises from 0.94 to 0.97), while the consumption growth volatility at both the individual and aggregate level change very little, the latter being somewhat lower due to the reduction in the sensitivity of consumption to aggregate income shocks, even though the sensitivity of cash-out activity to Z shocks actually increases, presumably due to the fact that in downturns fewer households receive such large shocks that they are prevented from extracting equity by the debt service constraint.

Reducing the overall level of idiosyncratic uncertainty by eliminating the high-risk state (as displayed in column (2)) has a substantially greater effect on most of the moments. Household leverage increases dramatically, with mortgage debt at 1.63 times annual income, conditional on homeownership. This higher leverage dramatically increases idiosyncratic consumption growth volatility, to 21.1% annually. This may appear surprising given a much lower level of idiosyncratic income volatility, but is in fact a direct consequence of lower level of exogenous risk faced by the households. Aggregate consumption volatility remains essentially unchanged, however, indicating that most of the increase in idiosyncratic volatility is driven by idiosyncratic labor income shocks rather than aggregate shocks to household balance sheets via house prices and interest rates.

With higher mortgage balances, homeowners also refinance their mortgages substantially more frequently (at rate 22.6% per year). In fact, interest rate savings become the dominant motive for refinancing, as evidenced by lower levels of cash-out (34% of annual income compared to 51% in the baseline). In particular, refinancing becomes more sensitive to fluctuations in the mortgage rate (β_R^{REFI} changing from -0.97 to -1.98), while cash-out becomes essentially insensitive to changes in aggregate income (β_Z changing from -0.18 to -0.01) and mortgage rates (β_R changing from -0.57 to -0.17).

In specification (4) we magnify the time-varying labor income uncertainty by increasing the value of $\sigma(Z_B)$ from 21% in the baseline case to 30%, while keeping the "good state" volatility $\sigma(Z_G) = 12\%$, the same as in the baseline. In response, homeowner households reduce their leverage (mortgage debt to income ratio drops to 0.81) and all households accumulate more liquid assets (asset to income ratio rises from 0.24 to 0.31 for homeowners and from 0.15 to 0.22 for renters), yet the consumption volatility at at the aggregate level is higher, at 4.5% (even though individual consumption growth volatility is slightly lower on average, at 15.6%). Homeownership rate increases from 67.7% under the baseline to 71.7%, pointing to the consumption-smoothing role of home equity. Given lower mortgage balances, refinancing is less frequent, at 9.5%, but households withdraw slightly more equity upon refinancing, with the ratio of cash-out amount to new loan balance increasing marginally, from 0.51 to 0.54, as households are more likely to encounter large negative shocks that require them to access housing collateral for consumption smoothing but are reluctant to accumulate large debt balances. Furthermore, refinancing becomes less sensitive to interest rates (β_R^{REFI} changes from -0.97 to -0.8) as consumption smoothing is the dominant incentive for refinancing.

Relaxing the constraints Specifications (5-10) consider the cases where the borrowing constraints imposed on mortgage origination and refinancing are relaxed.

In specification (5) we examine whether our results are sensitive to the availability of HELOCs by setting $\underline{a} = 0$. This change has a direct effect of reducing homeownership somewhat, to 61.6%, by effectively tightening the collateral constraint and therefore restricting the ability of households to purchase homes with debt, as well as by indirectly reducing the attractiveness of homes as a saving vehicle, via removing the least costly way of liquefying home equity. The natural consequence of this change also is the increase of the average liquid asset balances, from 0.24 to 0.34 (as a fraction of annual income), since the inability to costlessly draw on home equity in response to shocks creates a need for greater precautionary liquidity buffer. As discussed before, HELOCs are used mainly to smooth small idiosyncratic income shocks. Without HELOCs, households simply substitute into liquid assets, and their consumption and mortgage financing behaviors are not significantly altered.

In specifications (6-8) we relax the LTV constraint by setting $\xi_{LTV} = 90\%$ in column (6), $\xi_{LTV} = 100\%$ in column (7), both capturing the perception that mortgage lending standards were dramatically relaxed over the course of the housing boom, and$\xi_{LTV} = 125\%$ in column (8), mimicking the Homeowner Affordable Refinance Program (HARP) instituted by the U.S. government in 2011, which was intended to allow underwater homeowners who are current on their mortgage payments and whose loans were guaranteed by the government-sponsored enterprizes (GSEs) Fannie Mae and Freddie Mac to refinance. Relaxing the LTV constraint leads to higher leverage, in a form of simultaneously higher mortgage balances and higher liquid asset holdings. The former increases much more than the latter (from .94 to 1.22 vs. from 0.24 to 0.28), leading to slightly higher consumption volatility. Homeownership rate increases to 77.4% in the least constrained case, as more "marginal" households are able to access the housing market.

Refinancing also becomes slightly more frequent, and cash-out is more sensitive to shocks to aggregate income as well as interest rates. However, as collateral constraints are relaxed, sensitivity of cash-out to house prices declines (β_H changes from 0.10 in the baseline case to 0.04 in column (6)). In fact, as LTV constraint approaches (and crosses) 100%, households cash-out more, not less, following drops in house prices (β_H changes to -0.05 and -0.27 in columns (7) and (8), respectively). Two effects are at work in determining how cash-out responds to house price shocks. On the one hand, a rise in house price relaxes the LTV constraint, which helps generating a positive relation between cash-out and house price changes. On the other hand, to the extent that house prices comove with the business cycle, the demand for extracting liquidity from home equity is greater in "bad" times. If the collateral constraint is relatively tight, as in our baseline scenario, the former effect dominates. If the constraint is relatively slack, however, as in scenarios (7) and (8), the former effect generates negative comovement between house prices and cash-out.

Most notably, relaxing the housing collateral constraint raises the default rate sharply, from essentially zero to 0.4% and 1.9% of homeowners per year in specifications (7) and (8), respectively. This is not surprising, as with higher leverage it is more likely that a household would find its home equity negative after a decline in house prices, which is a necessary (but not sufficient) condition for a strategic default to be optimal (Corbae and Quintin (2013) analyze the effect of the loosening and subsequent tightening of leverage constraints on mortgage default following the decline in house prices; see also Campbell and Cocco (2010) for a detailed analysis of household default decisions in the presence of labor income shocks and different mortgage products).

In case (9) instead of relaxing the collateral constraint we remove the LTI constraint ($\xi_{LTI} = \infty$). Naturally, the average mortgage balances are almost 66% higher, at 1.56 (relative to income), compared to 0.94 in the baseline. Consequently, refinancing becomes more frequent (15.8% per year) and more sensitive to interest rate changes ($\beta_R^{REFI} = -1.30$). Removing the LTI constraint also enables households to cash-out more following aggregate income shocks, as β_Z becomes over twice as large as in the baseline case at -0.45. As a result, despite the fact that consumption growth becomes more volatile at the aggregate level, its sensitivity to aggregate income shocks β_Z^C remains essentially the same as in the baseline case.

The dynamics of cash-out in response to house prices are very different than when the collateral constraint is relaxed however, as the positive correlation between cash-out and house prices even strengthens in the absence of the debt service constraint, with $\beta_H = 0.37$. This is intuitive, since in the absence of the LTI constraint more households hit with bad income shocks are able to extract liquidity at a given level of home equity, and since LTV is the only constraint, it becomes relatively more important than when both constraints operate, raising the comovement between cash-out and house prices.

Greater leverage also leads to a slight increase in the default rate, albeit it is still just less than one percent of homeowner households per year. This result is also in sharp contrast to the case of relaxing the LTV constraint. In the presence of the LTV constraint, relaxing the LTI constraint has very limited impact on mortgage default, but it can already help facilitate consumption smoothing by boosting cash-out refinancing in bad times. In this sense, a program that relaxes the LTI constraint instead of the LTV constraint (like the HARP) might be able to relax the household financial constraints without causing as much of a rise in default risk. Moreover, the different sensitivity of default risk to the LTI and LTV constraints as captured in our model will also be important for mortgage pricing and mortgage contract design.

Not surprisingly, relaxing either the LTI constraint also increases the rate of homeownership substantially, to 81.9%. Since houses are valued for their housing services as well as potential saving vehicles, lowering barriers to entry into housing markets increases demand.

Finally, in specification (10) we simultaneously relax the collateral and debt service constraint, by setting maximum LTV to 100% as in specification (7) and removing the LTI limit as in specification (9). This change has a dramatic effect on almost all of the moments, illustrating how the two constraints reinforce each other: homeownership rate increases to 88.4% percent, average mortgage balances more than double relative to the baseline, to 2.07 times the annual income, with liquid assets increasing less dramatically to 0.29 for homeowners, as there is less need for a liquidity cushion with home equity is relatively easy to access, which average liquid assets of renters are much lower, at 7% of annual income (vs. 15% in the baseline), as only the poorest cannot afford to own. Refinancing rate rises to 17.6%, with more of the refinancing activity driven by rate savings, as evidenced by the lower ratio of cash-out to refinanced loan size (at 0.34 vs 0.51 in the baseline) and much more negative coefficient of refinancing on the mortgage rate, $\beta_R^{REFI} = -1.56$. Cash-out is less sensitive to interest rates but more sensitive to aggregate fluctuations in income and house prices, the former correlation strongly negative ($\beta_Z = -0.52$) and the latter strongly positive ($\beta_H = 0.23$), indicating that the effect of relaxing the debt service constraint dominates in the presence of the collateral constraint, albeit a loose one.

Finally, the amount of risk in the economy increases despite the greater ability to smooth fluctuations, through the endogenous response of households of choosing greater leverage and higher investment in (risky) housing. While household-level consumption volatility increases only slightly, to 17% per annum, aggregate consumption growth volatility is the highest among all specifications, at 5%, with sensitivities to all of the aggregate state variables displaying moderate increases. Most importantly, the rate of mortgage default is also the highest, at 2.1$ of homeowners per annum, suggesting that relaxation of both LTI and LTV constraints simultaneously can have a dramatic effect on default.

Table A.1: Sensitivity Analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Baseline	δ		γ		ψ		ν		ϕ_0		ϕ_1	
		0.874	0.966	1.518	6.071	0.151	0.603	0.067	0.268	0.077	0.309	0.007	0.028
All Households:													
Consumption/Income	0.71	0.68	0.74	0.69	0.74	0.71	0.72	0.73	0.70	0.72	0.71	0.71	0.71
Cons. growth vol, %	16.5	17.2	15.7	17.6	15.2	15.5	19.3	15.8	19.2	16.9	16.3	16.6	16.4
Homeownership rate, %	67.4	43.6	96.3	51.6	88.0	58.5	86.2	53.6	100.0	76.0	64.3	68.3	66.0
Homeowners:													
Liquid assets/Income	0.24	0.20	0.31	0.20	0.35	0.30	0.20	0.24	0.28	0.26	0.15	0.25	0.22
Mortgage/Income	0.94	1.34	0.56	1.34	0.51	0.92	1.07	0.91	1.43	1.22	0.45	1.00	0.84
HELOC/Income	0.09	0.08	0.09	0.08	0.07	0.07	0.11	0.08	0.09	0.08	0.12	0.08	0.09
Refinancing rate, %	11.1	17.4	6.6	17.2	6.2	11.5	12.5	11.0	15.9	17.2	4.8	12.0	9.7
Refi loan/Income	2.73	2.39	2.97	2.47	2.91	2.57	2.81	2.64	2.83	2.51	2.97	2.71	2.76
Dollar cash-out/Refi loan	0.51	0.42	0.56	0.41	0.60	0.52	0.49	0.51	0.46	0.43	0.62	0.50	0.54
Renters:													
Liquid assets/Income	0.15	0.07	0.38	0.08	0.34	0.18	0.19	0.13	0.09	0.16	0.14	0.15	0.15
Refinancing Regression:													
Coefficient on R, β_R^{REFI}	-0.97	-1.40	-0.66	-1.46	-0.56	-0.61	-1.54	-0.80	-1.35	-1.57	-0.26	-1.03	-0.83
Cashout Regression:													
Coefficient on R, β_R	-0.57	-0.25	-0.84	-0.32	-0.71	-0.26	-1.14	-0.35	-1.08	-0.72	-0.24	-0.54	-0.59
Coefficient on Z, β_Z	-0.19	-0.09	-0.24	-0.09	-0.20	-0.12	-0.38	-0.25	0.13	-0.18	-0.38	-0.18	-0.25
Coefficient on H, β_H	0.10	0.14	0.01	0.15	0.04	0.06	0.17	0.10	0.05	0.08	0.06	0.11	0.08
Aggregate Consumption:													
Growth volatility, %	3.9	3.9	4.0	4.0	4.1	4.0	4.5	3.6	5.3	4.2	3.7	3.9	3.8
Sensitivity to Z, β_Z^C	1.30	1.25	1.37	1.28	1.36	1.34	1.40	1.22	1.72	1.41	1.26	1.30	1.28
Sensitivity to H, β_H^C	0.09	0.14	0.04	0.13	0.06	0.10	0.08	0.10	0.06	0.08	0.08	0.09	0.09
Sensitivity to lagged r, β_r^C	0.13	0.06	0.20	0.09	0.18	0.07	0.26	0.09	0.24	0.15	0.12	0.13	0.13
Sensitivity to lagged R, β_R^C	0.17	0.08	0.26	0.12	0.23	0.07	0.39	0.12	0.33	0.22	0.15	0.18	0.17

Table A.2: Comparative Statics

	(1) Baseline	(2) $\sigma_{G,B} = 8\%$	(3) $\sigma_{G,B} = 17\%$	(4) $\sigma_B = 30\%$	(5) $\underline{a} = 0$	(6) $\xi_{LTV} = 90\%$	(7) $\xi_{LTV} = 100\%$	(8) $\xi_{LTV} = 125\%$	(9) $\xi_{LTI} = \infty$	(10) (7) + (9)
<u>All Households:</u>										
Consumption/Income	0.73	0.70	0.73	0.74	0.73	0.73	0.73	0.72	0.72	0.71
Cons. growth vol, %	16.6	21.1	16.8	15.6	16.6	16.7	16.9	17.2	16.9	17.0
Homeownership rate, %	67.4	46.3	67.1	71.7	61.6	70.6	74.7	77.4	81.9	88.4
<u>Homeowners:</u>										
Liquid assets/Income	0.24	0.16	0.23	0.31	0.34	0.25	0.27	0.28	0.27	0.29
Mortgage/Income	0.94	1.63	0.97	0.81	0.91	1.02	1.10	1.22	1.56	2.07
HELOC/Income	0.09	0.08	0.09	0.08	0.00	0.08	0.08	0.08	0.08	0.08
Refinancing rate, % of homeowners	11.1	22.6	11.5	9.5	11.8	11.1	11.3	11.5	15.8	17.6
Refi loan/Income	2.73	2.26	2.71	2.82	2.71	2.82	2.87	2.94	3.19	3.65
Cash-out $/Refi loan	0.51	0.34	0.50	0.54	0.45	0.51	0.50	0.48	0.40	0.34
Default rate, % of homeowners	0.0	0.1	0.0	0.0	0.0	0.1	0.4	1.9	0.6	2.1
<u>Renters:</u>										
Liquid assets/Income	0.15	0.07	0.15	0.22	0.15	0.16	0.19	0.20	0.09	0.07
<u>Refinancing Regression:</u>										
Coefficient on R, β_R^{REFI}	-0.96	-1.98	-1.06	-0.80	-0.83	-1.01	-1.10	-1.19	-1.30	-1.56
<u>Cashout Regression:</u>										
Coefficient on R, β_R	-0.59	-0.17	-0.59	-0.61	-0.45	-0.85	-1.10	-1.67	-0.22	-0.18
Coefficient on Z, β_Z	-0.18	-0.01	-0.25	-0.18	-0.20	-0.16	-0.31	-0.31	-0.45	-0.52
Coefficient on H, β_H	0.11	0.19	0.10	0.07	0.10	0.04	-0.05	-0.27	0.37	0.23
<u>Aggregate Consumption:</u>										
Growth volatility, %	3.9	4.0	3.4	4.5	3.7	4.0	4.0	4.1	4.6	5.0
Sensitivity to Z, β_Z^C	1.30	1.20	1.21	1.41	1.24	1.33	1.35	1.39	1.36	1.50
Sensitivity to H, β_H^C	0.09	0.16	0.07	0.11	0.10	0.08	0.09	0.07	0.17	0.16
Sensitivity to lagged r, β_r^C	0.13	0.08	0.13	0.14	0.10	0.13	0.14	0.16	0.13	0.16
Sensitivity to lagged R, β_R^C	0.17	0.11	0.20	0.16	0.13	0.19	0.19	0.23	0.16	0.19