A Macroeconomic Framework for Quantifying Systemic Risk

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University of Chicago & NBER

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Northwestern University & NBER

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Systemic Risk and Nonlinearity

- The economy occasionally can arrive in a state where
  - financial intermediation is disrupted
  - small fundamental shocks can have quantitatively large effects on macro economy
- This is **systemic risk**; for example, as in the recent crisis
The economy occasionally can arrive in a state where
- financial intermediation is disrupted
- small fundamental shocks can have quantitatively large effects on macro economy

This is **systemic risk**; for example, as in the recent crisis

Goal: Write down a calibratable DSGE model with nonlinearity, in which
- much of the time the link between financial intermediation and macro economy is small
- but at (crisis) times the effects are greatly amplified

Quantitatively evaluate the model predictions, including the transition between normal and systemic states
Innovation Relative to Much of Literature

- We study a model with occasionally binding financial constraint
- Typical models (e.g., Kiyotaki-Moore (1997),...) linearize around steady state where constraint binds.
  - Cannot talk about 1) likelihood that intermediation is disrupted (it's always disrupted...) and 2) how severe it is disrupted
- Our model solution has stochastic steady state, with fully solved equilibrium prices and policies
  - Main drawback: need to reduce state variables
  - Have to leave out some common DSGE elements
- Similar methodology to Mendoza (2010) and Brunnermeier-Sannikov (2011)
- Model elements adopted from He-Krishnamurthy (2012), with real investment and housing
Crisis: $e_{crisis} = 0.65$, binding capital constraint

Distress: $e_{distress} = 4$ so that $Pr(e_{distress}) = 33\%$ as in data
Crisis: $e_{crisis} = 0.65$, binding capital constraint

Distress: $e_{distress} = 4$ so that $\Pr(e \leq e_{distress}) = 33\%$ as in data
Evidence of Non-Linearity

- **Excess bond premium** (EBP): the risk premium part of credit spread (removing default part), Gilchrist and Zakrajsek (2010). Correlates with measures of intermediary health.

- Use EBP to classify distress periods (33%) and non-distress periods (the rest)

<table>
<thead>
<tr>
<th>Distress Periods</th>
<th>NBER Recessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975Q1 - 1975Q3</td>
<td>11/73 - 3/75</td>
</tr>
<tr>
<td>1982Q2 - 1982Q4</td>
<td>7/81 - 11/82</td>
</tr>
<tr>
<td>1985Q4 - 1987Q3</td>
<td></td>
</tr>
<tr>
<td>1988Q4 - 1990Q1</td>
<td>7/90 - 3/91</td>
</tr>
<tr>
<td>1992Q4 - 1993Q2</td>
<td></td>
</tr>
<tr>
<td>2001Q2 - 2003Q1</td>
<td>3/01 - 11/01</td>
</tr>
<tr>
<td>2007Q3 - 2009Q3</td>
<td>12/07 - 6/09</td>
</tr>
</tbody>
</table>

- Caveat: distress periods are much “milder” relative to 07/08 crisis
State-Dependent Covariances (1)

- Equity = Total market value of equity of finance, insurance and real estate sectors. (works as well if only include banks + broker/dealers)
- All variables are growth, except Sharpe ratio constructed from EBP

<table>
<thead>
<tr>
<th></th>
<th>Distress</th>
<th>Non Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cov</td>
<td>Corr</td>
</tr>
<tr>
<td>Equity, Investment</td>
<td>1.31%</td>
<td>51.48</td>
</tr>
<tr>
<td>Equity, Consumption</td>
<td>0.25%</td>
<td>45.85</td>
</tr>
<tr>
<td>Equity, Sharpe</td>
<td>-6.81%</td>
<td>-35.96</td>
</tr>
<tr>
<td>Equity, Landprice</td>
<td>4.06%</td>
<td>60.65</td>
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</tbody>
</table>
State-Dependent Covariances (2)

All variables are growth, except Sharpe ratio constructed from EBP

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<tr>
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<th>Distress</th>
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<tr>
<td></td>
<td>NBER+2</td>
<td>Excl-Crisis</td>
</tr>
<tr>
<td>Equity, Investment</td>
<td>31.78%</td>
<td>22.10</td>
</tr>
<tr>
<td>Equity, Consumption</td>
<td>0.13%</td>
<td>0.04</td>
</tr>
<tr>
<td>Equity, Sharpe</td>
<td>-7.57%</td>
<td>-2.12</td>
</tr>
<tr>
<td>Equity, Landprice</td>
<td>4.39%</td>
<td>-0.63</td>
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Note: Similar numbers if only use NBER dates, but sample is only 20% of observations.
VAR Evidence of Non-Linearity (3)

VAR order: [intermediary equity, EBP, investment]. Coefficients depend on distress state

Panel A: Distress Periods

Panel B: Non Distress Periods
Road Map of the Rest of Talk

- Model, mechanism, and solution
- Calibration
  - Baseline parameters
  - Prices and polices, comparative statics
- Matching data on distress and non-distress (i.e. mild crises)
- Systemic crisis
  - Extrapolate to crisis state
  - Uncover fundamental shocks in the recent crisis
  - How likely are crises?
- Advantage of structural models: we have essentially one data point with deep systemic crisis
Agents and Technology

- Two classes of agents: households and bankers
  - Households own the entire economy, but subject to frictions related to bankers who control intermediaries (next slide)
- Two types of capital: productive capital $K_t$ and housing capital $H$. Fixed supply of housing $H \equiv 1$
  - Price of capital $q_t$ and price of housing $P_t$ determined in equilibrium
Agents and Technology

- Two classes of agents: households and bankers
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- Two types of capital: productive capital $K_t$ and housing capital $H$. Fixed supply of housing $H \equiv 1$
  - Price of capital $q_t$ and price of housing $P_t$ determined in equilibrium
- Production $Y = AK_t$, with $A$ being constant
- Fundamental shocks: stochastic capital quality shock $dZ_t$

$$\frac{dK_t}{K_t} = i_t dt - \delta dt + \sigma dZ_t$$

- Investment/Capital $i_t$, quadratic adjustment cost

$$\Phi(i_t, K_t) = i_t K_t + \frac{\kappa}{2} (i_t - \delta)^2 K_t$$
Aggregate Balance Sheet

\[ W_t = q_t K_t + P_t H \]
Aggregate Balance Sheet

Loans to Capital Producers $i_t$

Intermediary Sector

Capital $q_t K_t$

Equity $E_t$

Debt $W_t - E_t$

Housing $P_t H$

Aggregate bank reputation $\mathcal{E}_t$

Household Sector

Financial Wealth

Constraint: $E_t \leq \mathcal{E}_t$

$W_t = q_t K_t + P_t H$

No constraint
## Single Bank/Banker

<table>
<thead>
<tr>
<th>Capital $q_t k_t$</th>
<th>Equity $e_t$</th>
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<tbody>
<tr>
<td>Housing $P_t h_t$</td>
<td>Debt $d_t$</td>
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</table>

**Portfolio share in capital:** $\alpha^k_t = \frac{q_t k_t}{e_t}$

**Portfolio share in housing:** $\alpha^h_t = \frac{P_t h_t}{e_t}$

**Borrowing (no constraint):** $d_t = q_t k_t + P_t h_t - e_t = (\alpha^k_t + \alpha^h_t - 1)e_t$

**Return on bank equity:** $d\tilde{R}_t = \alpha^k_t dR^k_t + \alpha^h_t dR^h_t - (\alpha^k_t + \alpha^h_t - 1)r_t dt$

**Banker (log preference) solves:** $\max_{\alpha^k_t, \alpha^h_t} E[d\tilde{R}_t - r_t dt] - \frac{m}{2} \text{Var}_t[d\tilde{R}_t]$
**Single Bank/Banker**

<table>
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<th>Capital $q_t k_t$</th>
<th>Equity $e_t$</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing $P_t h_t$</td>
<td>Debt $d_t$</td>
<td>· $(k, h)$ scale up with $e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· $(k, h)$ increasing in $E_t [dR - r]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· $(k, h)$ decreasing in $Var[dR]$</td>
</tr>
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Portfolio share in capital: $\alpha^k_t = \frac{q_t k_t}{e_t}$

Portfolio share in housing: $\alpha^h_t = \frac{P_t h_t}{e_t}$

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### General Equilibrium (1)

**Intermediary Sector**

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<th>Equity $E_t$</th>
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<tbody>
<tr>
<td>Housing $p_t H$</td>
<td>Debt $W_t - E_t$</td>
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</table>

**Constraint:** $E_t \leq \mathcal{E}_t$

- **Financial Wealth**
  
  $W_t = q_t K_t + p_t H$

**Portfolio shares**

- Portfolio share in capital: $\alpha^k_t = \frac{q_t K_t}{E_t}$
- Portfolio share in housing: $\alpha^h_t = \frac{p_t H}{E_t}$

- Given a particular state $(K_t, \mathcal{E}_t)$, the portfolio shares are pinned down by GE.

- Portfolio shares must also be optimally chosen by banks.

Given the portfolio shares, the expected utility is maximized as follows:

$$\max_{\alpha^k_t, \alpha^h_t} \mathbb{E}_t[d \tilde{R}_t - r_t dt] - \frac{m}{2} \text{Var}_t[d \tilde{R}_t]$$
**General Equilibrium (2)**

<table>
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<tr>
<th>Intermediary Sector</th>
<th>Household Sector</th>
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</thead>
<tbody>
<tr>
<td>Capital $q_tK_t$</td>
<td>Financial Wealth</td>
</tr>
<tr>
<td>Housing $p_tH$</td>
<td>$W_t = q_tK_t + p_tH$</td>
</tr>
<tr>
<td>Equity $E_t$</td>
<td></td>
</tr>
<tr>
<td>Debt $W_t - E_t$</td>
<td></td>
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</table>

**Constraint:** $E_t \leq \mathcal{E}_t$

**Portfolio share in capital:** $\alpha^k_t = \frac{q_tK_t}{E_t}$

**Portfolio share in housing:** $\alpha^h_t = \frac{P_t}{E_t}$

- Prices (returns) have to adjust for optimality:
  - $\mathbb{E}_t[dR^h_t - r_t dt], \mathbb{E}_t[dR^k_t - r_t dt] \Rightarrow$ equations for $\mathbb{E}_t[dP_t], \mathbb{E}_t[dq_t]$
- Rewrite to get ODEs for $P(K, \mathcal{E})$ and $q(K, \mathcal{E})$
- Scale invariance: Define $e \equiv \mathcal{E}/K$; then $P = Kp(e)$ and $q(e)$
Reputations and Capital Constraint

- Single bank has reputation $\epsilon_t$ linked to intermediary performance (constant $m$)

\[
\frac{d\epsilon_t}{\epsilon_t} = m\bar{R}_t.
\]

- Poor returns reduce reputation!

- Households invest a maximum of $\epsilon_t$ dollars of equity capital with this banker
Reputations and Capital Constraint

- Single bank has reputation $\epsilon_t$ linked to intermediary performance (constant $m$)
  \[
  \frac{d\epsilon_t}{\epsilon_t} = m\tilde{R}_t.
  \]
  \[\text{Poor returns reduce reputation!}\]

- Households invest a maximum of $\epsilon_t$ dollars of equity capital with this banker

- Death rate $\eta$, and entry $d\psi_t > 0$ of new bankers in extreme states (modeled later)

- $\mathcal{E}_t$: aggregate reputation. Identical banks, aggregate dynamics of $\mathcal{E}_t$
  \[
  \frac{d\mathcal{E}_t}{\mathcal{E}_t} = md\tilde{R}_t - \eta dt + d\psi_t
  \]
Bankers’ Problem

- Banker may die at a Poisson rate of $\eta$ which is effective discount rate.
- Banker maximizes his expected reputation: $\mathbb{E} \left[ \int_0^\infty e^{-\eta t} \ln \epsilon_t dt \right]$
  - Bankers do not consume goods – preserves some “representative household” features.
- With log preferences, banker makes portfolio decision (for intermediary) to

$$\max_{\alpha^k_t, \alpha^h_t} \mathbb{E}_t [d\tilde{R}_t - r_t dt] - \frac{m}{2} \text{Var}_t [d\tilde{R}_t]$$

Here, $m$ parameterizes banker’s “risk aversion.”
Capital Producers and Investment

- Capital goods producers (owned by households) undertake real investment
- Producers must sell the capital stock to intermediaries at price $q_t$
  - Risk averse intermediaries bear aggregate fundamental shocks
  - Real investment is affected by financial condition of intermediaries to capture "credit crunch"
- Possible interpretations:
  - Entrepreneurs raise capital from VC/PE at the price of $q_t$
  - Commercial banks make collateralized loans
- Investment decision

$$\max_{i_t} q_t i_t K_t - \Phi(i_t, K_t) \Rightarrow i_t = \delta + \frac{q_t - 1}{\kappa}$$
Households’ Problem (1)

- Choose consumption $c_t^y$ and housing $c_t^h$ to maximize

$$
\mathbb{E} \left[ \int_0^\infty e^{-\rho t} \left( (1 - \phi) \ln c_t^y + \phi \ln c_t^h \right) dt \right]
$$

- Equilibrium rental price $D_t$ (housing asset dividend), FOC

$$
\frac{c_t^h D_t}{\phi} = \frac{c_t^y}{1 - \phi}.
$$

In equilibrium ($C_t^h = H = 1$)

$$
D_t = \frac{\phi}{1 - \phi} C_t^y
$$

- $\phi$: expenditure share in housing, or the relative size of housing sector

- Interest rate $r_t = \rho + \mathbb{E}_t \left[ dC_t^y / C_t^y \right] - Var_t \left[ dC_t^y / C_t^y \right]$
Households’ Problem (2)

- Representative household enters time $t$ with financial wealth $W_t$
- The household splits wealth: $(1 - \lambda) W_t$ to “equity households,” $\lambda W_t$ to “bond households”
  - Equity households invest their portion of wealth as equity of intermediaries, **subject to capital frictions**
  - Bond households invest in riskless bonds
- Once returns are realized, both members pool their wealth again (as in Lucas 1990)
- The only role of bond households (i.e. parameter $\lambda$) is to introduce intermediary’s leverage in normal time
Model Scheme

Loans to Capital Producers $i_t$

Intermediary Sector

Capital $q_t K_t$

Equity $E_t$

Constraint: $E_t \leq \mathcal{E}_t$

Debt $W_t - E_t$

No constraint

Housing $P_t H$

Aggregate bank reputation $\mathcal{E}_t$

Household Sector

Financial Wealth

$W_t = q_t K_t + p_t H$

$(1 - \lambda) W_t$

$\lambda W_t$
Equity Capital Constraint

- Equity households wish to buy equity of at most \((1 - \lambda)W_t\)
- Intermediary equity capital \(E_t\) is given by
\[
E_t = \min \left[ E_t, (1 - \lambda)W_t \right]
\]
- If \(E_t > (1 - \lambda)W_t\) then equity capital constraint is slack
Equity Capital Constraint

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- Intermediary equity capital \(E_t\) is given by
  \[
  E_t = \min [E_t, (1 - \lambda)W_t]
  \]
- If \(E_t > (1 - \lambda)W_t\) then equity capital constraint is slack
- How can capital constraint come to bind, if now \(E_t > (1 - \lambda)W_t\)?
- Suppose a \(-10\%\) shock to real estate and price of capital, so that \(W_t \downarrow 10\%\) (Household wealth = aggregate wealth)
- Reputation follows \(\frac{dE_t}{E_t} = md\tilde{R}_t + \ldots\) Two forces make \(E_t \downarrow\) more than \(10\%\):
  - If \(m > 1\)
  - \(d\tilde{R}_t < -10\%\): \(d\tilde{R}_t\) is a levered claim on assets (bond households)
Boundary Conditions

- When $e = \infty$, $\mathcal{E}_t > (1 - \lambda) W_t$ frictionless economy
  - We solve for $p(\infty), q(\infty)$ analytically
- As $e \rightarrow 0$, intermediaries' portfolio volatility, i.e. Sharpe ratio, rises
- New bankers enter if $e = e$ (Sharpe ratio hits $\gamma$, exogenous constant)
  - Entry increases aggregate $\mathcal{E}$ but requires physical capital $K$ at conversion rate of $\beta$
  - $e$ is a reflecting boundary
- Boundary conditions at the entry point $e$

$$q'(e) = 0, \quad p'(e) = \frac{p(e) \beta}{1 + e \beta}, \quad \text{and} \quad \text{Sharpe Ratio (e)} = \gamma$$
## Calibration: Baseline Parameters

<table>
<thead>
<tr>
<th>Parameter Choice</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A: Intermediation</strong></td>
<td></td>
</tr>
<tr>
<td>$m$ Performance sensitivity</td>
<td>2.5</td>
</tr>
<tr>
<td>$\lambda$ Debt ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta$ Banker exit rate</td>
<td>13%</td>
</tr>
<tr>
<td>$\gamma$ Entry trigger</td>
<td>5.5</td>
</tr>
<tr>
<td>$\beta$ Entry cost</td>
<td>1.9</td>
</tr>
</tbody>
</table>

| **Panel B: Technology** |
| $\sigma$ Capital quality shock | 5% | Investment and Consumption volatilities |
| $\delta$ Depreciation rate | 10% | Literature |
| $\kappa$ Adjustment cost | 2 | Literature |
| $A$ Productivity | 0.14 | Investment-to-capital ratio |

| **Panel C: Others** |
| $\rho$ Time discount rate | 2% | Literature |
| $\phi$ Housing share | 0.5 | Housing-to-wealth ratio |
Equilibrium Prices and Policies (1)

- $e_{\text{crisis}} = 0.65$: binding capital constraint
- $e_{\text{distress}} = 4$ so that $Pr(e \leq e_{\text{distress}}) = 33\%$ as in data

![Graphs showing $p(e)$, scaled housing price, and $q(e)$, capital price, as well as return volatilities of housing and capital.](image-url)
Equilibrium Prices and Policies (2)

- $e_{\text{crisis}} = 0.65$: binding capital constraint
- $e_{\text{distress}} = 4$ so that $\Pr(e \leq e_{\text{distress}}) = 33\%$ as in data
### Matching State-Dependent Covariances: Baseline

<table>
<thead>
<tr>
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<th>Distress</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data</td>
<td>Baseline</td>
</tr>
<tr>
<td>$vol \ (Eq)$</td>
<td>31.48%</td>
<td>26.13</td>
</tr>
<tr>
<td>$vol \ (I)$</td>
<td>8.05%</td>
<td>5.74</td>
</tr>
<tr>
<td>$vol \ (C)$</td>
<td>1.71%</td>
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</tr>
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<td>21.24%</td>
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<td>0.81</td>
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<td>0.35</td>
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<td>4.06%</td>
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<tr>
<td>$cov \ (Eq, EB)$</td>
<td>-6.81%</td>
<td>-6.86</td>
</tr>
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### Matching State-Dependent Covariances: lower $\sigma$

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Matching State-Dependent Covariances: No Housing

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Uncovering Shocks in the Recent Crisis

Data

Model
Based on realized equity return we uncover fundamental shocks to $K$

<table>
<thead>
<tr>
<th></th>
<th>07QIII</th>
<th>07QIV</th>
<th>08QI</th>
<th>08QII</th>
<th>08QIII</th>
<th>08QIV</th>
<th>09QI</th>
<th>09QII</th>
<th>09QIII</th>
<th>09QIV</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>-3.69%</td>
<td>-7.06</td>
<td>-6.46</td>
<td>-2.78</td>
<td>-0.52</td>
<td>-3.05</td>
<td>-2.34</td>
<td>-1.26</td>
<td>-0.14</td>
<td>-0.80</td>
</tr>
</tbody>
</table>

Total -25%. Capital constraint binds after 08QII—systemic crisis

- In the model (data), land price fall by 71% (55%)
Economic variables in systemic crisis. Recall $e_{\text{crisis}} = 0.65$

<table>
<thead>
<tr>
<th></th>
<th>At mean e</th>
<th>X4</th>
<th>X8</th>
<th>X16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharpe Ratio</td>
<td>0.327</td>
<td>1.308</td>
<td>2.616</td>
<td>5.232</td>
</tr>
<tr>
<td>Prob Sharpe being higher</td>
<td>71.79%</td>
<td>0.31</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>Equity ($E/K$)</td>
<td>0.87</td>
<td>0.40</td>
<td>0.26</td>
<td>0.13</td>
</tr>
<tr>
<td>Housing ($P/K$)</td>
<td>0.74</td>
<td>0.24</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>Capital ($q$)</td>
<td>1.0068</td>
<td>0.9943</td>
<td>0.9936</td>
<td>0.9933</td>
</tr>
<tr>
<td>Investment ($I/K$)</td>
<td>10.34%</td>
<td>9.71</td>
<td>9.68</td>
<td>9.66</td>
</tr>
<tr>
<td>Interest rate</td>
<td>2.44%</td>
<td>-2.61</td>
<td>-7.76</td>
<td>-19.98</td>
</tr>
<tr>
<td>Consumption growth</td>
<td>0.40%</td>
<td>-4.57</td>
<td>-9.72</td>
<td>-21.68</td>
</tr>
</tbody>
</table>
Probability of Crisis

- Conditional probability of hitting crisis (left) or distress (right)

2007Q2, Prob(crisis occurs in the next 2 years) = 0.13%
Conclusion

We develop a fully stochastic model of systemic crisis, with two major frictions:

- Equity capital constraint on intermediary sector
- Intermediaries have substantial holdings in real assets (physical capital or housing)

We find that the model

- not only qualitatively delivers the nonlinearity observed in the data
- but also quantitatively matches the differential comovements in distress and non-distress periods

Recent 07/08 crisis requires a cumulative negative shock around -25%

Things we are working on: more on model-based measure of systemic risk