Estimating Macroeconomic Models of Financial Crises: An Endogenous Regime-Switching Approach

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The views expressed herein are solely those of the authors and do not necessarily reflect the views of the Federal Reserve Banks of Kansas City or St. Louis, or the Federal Reserve System.
Motivation

- Global Financial Crisis Proved Costly to Resolve
- Long History of Painful Financial Crises in Emerging Markets
- Large Theoretical Literature in Response
  - Models of Collateral Constraints for Amplification of Shocks
  - Normative Analyses of Inefficiencies from Collateral Constraints
  - *Ex-ante* versus *Ex-post* Policies
  - Which Instruments Most Effective
- Still Lack a Concrete Explanation of Why Countries Fall into Crisis
  - Which Shocks (Interest Rate, Technology, Collateral) Trigger Crises?
  - This is an Empirical Issue
  - Can then Return to Policy Questions
- Issue: Models with Occasionally Binding Constraints Hard to Solve
  - Usually Requires Slow Global Solution Methods
  - Makes Likelihood-Based Estimation Infeasible
The Objective of this Paper

- Formulate a Model with Occasionally Binding Constraint
- Quantitative Analysis of Financial Crises in Mexico
- Address Several Questions
  - Which Shocks Drive Crises? The Same Ones that Drive Normal Cycle?
  - Is there Time Variation in the Importance of those Shocks?
  - How do the Dynamic Responses to Shocks Change between Crises and Normal Times?
- Enables Future Steps: Return to the Theoretical Questions
  - Which Instruments Best Address which Shocks?
  - Counterfactuals: Given Shocks that Drove Crisis in Past, would Policy have Helped?
Pre-Crisis and Post-Crisis Consensus on Methodology

- Pre-Crisis: Medium Scale Estimated DSGE Models
  - Estimate Importance of Shocks and Frictions
  - Analyze Policy Questions in this Fully Specified Empirical Framework
- Post-Crisis: Calibrated Models featuring Non-Linear Dynamics
  - Focus on Event-Study Type Analysis
  - Occasionally Binding Borrowing Constraints
- This Paper Bridges the Two Approaches
  - Providing an Empirical Framework: Estimation of Shocks and Frictions
  - Incorporating the Non-Linearities Associated with Financial Crises
This Paper

- New Approach to Specifying, Solving, Estimating Models of Crises
  - Financial Crises Rare but Large Events, so Model Must be Non-Linear
  - Provide a Tractable Formulation of Collateral Constraint
  - Develop Methods to Solve and Estimate such a Model

- Kiyotaki-Moore Type Collateral Constraint
  - Limit Total Debt to a Fraction of the Market Value of Physical Capital
  - Unconstrained to Constrained a Stochastic Function of the LTV Ratio
  - Write as Endogenous Regime-Switching Process
    - Two Regimes: Crisis (Constraint Binds) and Normal (Doesn’t Bind)
    - Probability of Crisis Rises with Leverage (More Debt or Less Collateral)
    - Agents in Model have Rational Expectations

- Estimate via Full-Information Bayesian Methods
  - Estimated Crisis Regime Corresponds to Sudden Stop Narrative Dates
  - Fluctuations in Normal Regime Driven by Real Shocks
  - Leverage Shocks most Important in Crisis Regime
Output and Debt in Mexico

Output

Debt-to-Output Ratio
Introduction

Model
- Standard Open Economy Preferences and Production
- Collateral Constraint as Endogenous Regime-Switching

Solution and Estimation
- Solving the Endogenous Switching Model
- Importance of Non-Linear Methods
- Estimation Methodology

Results
- Crises Dates
- Which Shocks Drive Crises and Standard Fluctuations

Conclusion
Model Overview

- Small Open Economy that Borrows from Abroad
- Imported Goods used in Production
- Working Capital Constraint for Labor and Import Payments
- Value of Capital Serves as Collateral
- Pecuniary Externality and Overborrowing
- Regime-Specific Borrowing Constraints
- Endogenously Switch Between Regimes
- Four Types of Shocks: 3 Real, 1 Financial
Preferences and Production

- Representative Household-Firm with Preferences

\[ U \equiv E_0 \sum_{t=0}^{\infty} \left\{ \beta^t \frac{1}{1-\rho} \left( C_t - \frac{H_t^\omega}{\omega} \right)^{1-\rho} \right\} \]

- Production uses Capital, Labor, and Imported Intermediate Goods

\[ Y_t = A_t K_{t-1}^\eta H_t^\alpha V_t^{1-\alpha-\eta} \]

- Investment with Adjustment Costs

\[ I_t = \delta K_{t-1} + (K_t - K_{t-1}) \left( 1 + \frac{\iota}{2} \left( \frac{K_t - K_{t-1}}{K_{t-1}} \right)^2 \right) \]

- Budget Constraint, with \( B_t < 0 \) as Debt

\[ C_t + I_t = Y_t - P_t V_t - \phi r_t (W_t H_t + P_t V_t) - \frac{1}{1 + r_t} B_t + B_{t-1} \]
Collateral Constraint: Motivation

- The Agent Faces a Regime-Specific Collateral Constraint
  - When $s_t = 1$, in the Crisis Regime and Borrowing is Constrained
  - When $s_t = 0$, in the Normal Regime and Borrowing is Unconstrained
- International Lenders have Stochastic Monitoring
  - In Crisis, Actively Monitor and Enforce Borrowing Constraint
  - In Normal, Don’t Actively Monitor and Allow Borrowing
  - Decision to Monitor or Not Depends on Previous Borrowing and Monitoring Shock
  - Key Timing: Monitoring Shock Orthogonal to Structural Shocks
Collateral Constraint: Crisis Regime

- In Crisis Regime, Total Borrowing is a Fraction of Value of Collateral

\[
\frac{1}{(1 + r_t)} B_t - \phi (1 + r_t) (W_t H_t + P_t V_t) = -\kappa_t q_t K_t
\]

- Debt and Working Capital Restricted
- Collateral in the Model is Defined over the Value of Capital
- Pecuniary Externality: Price and Quantity of Collateral are Endogenous
- Multiplier Associated with Constraint is \( \lambda_t \)
Collateral Constraint: Normal Regime

- In Normal Regime, Borrowing is Unconstrained
  - Collateral Value is Sufficient for International Lenders to Finance all Desired Borrowing
  - No Explicit Constraint on Borrowing
  - Two Forces Limiting Infinite Borrowing
    - Debt Elastic Interest Rate Premium
    - Expectations
- The “Borrowing Cushion” is Debt Less the Collateral Value
  \[ B_t^* = \frac{1}{(1 + r_t)} B_t - \phi (1 + r_t) (W_t H_t + P_t V_t) + \kappa_t q_t K_t \]
- Small Borrowing Cushion Implies High Leverage Ratio
Endogenous Switching

• In Normal Regime, Probability that Constraint Binds or Not Next Period Depends on Borrowing Cushion and Monitoring Shock

\[ s_{t+1} = \Gamma \left( e^{M}_{t+1} | s_t = 0, B^*_t \right) \]

• In Crisis Regime, Probability that Constraint Binds or Not Next Period Depends on Multiplier

\[ s_{t+1} = \Gamma \left( e^{M}_{t+1} | s_t = 1, \lambda_t \right) \]

• Reformulates Kiyotaki-Moore Idea that Increased Leverage Leads to Binding Collateral Constraints as a Probabilistic Statement

• Note the Difference in Timing
### Endogenous Switching

- Assume that $\epsilon_{t+1}^M$ Distributed to Induce Logistic Distributions

\[
\Pr(s_{t+1} = 1 | s_t = 0) = \frac{\exp(-\gamma_0 B_t^*)}{1 + \exp(-\gamma_0 B_t^*)}
\]

\[
\Pr(s_{t+1} = 0 | s_t = 1) = \frac{\exp(-\gamma_1 \lambda_t)}{1 + \exp(-\gamma_1 \lambda_t)}
\]

- Logistic is Common, Parsimonious Formulation
  - Fiscal Policy and Default

- Evidence for $\gamma_0, \gamma_1$ Key in Estimation
Form of the Logistic Function

\[ \text{Prob}(s_{t+1} = 0 | s_t = 0, B_t^*) \]

- \( \gamma_0 = 1000 \)
- \( \gamma_0 = 100 \)
- \( \gamma_0 = 0 \)
Regime Switching Slackness Condition

- “Typical” Slackness Condition is $B_t^* \lambda_t = 0$
- Need to Adapt to Regime-Switching Framework
- Introduce Indicator Variables $\varphi(s_t) = \nu(s_t) = s_t$
- Regime Switching Slackness Condition

$$\varphi(s_t) B_{ss}^* + \nu(s_t) (B_t^* - B_{ss}^*) = (1 - \varphi(s_t)) \lambda_{ss} + (1 - \nu(s_t)) (\lambda_t - \lambda_{ss})$$

- Slackness Constraint Becomes
  - In Normal Regime, $\varphi(0) = \nu(0) = 0$, so $\lambda_t = 0$
  - In Crisis Regime, $\varphi(1) = \nu(1) = 1$, so $B_t^* = 0$
Timing of the Model

Agents enter knowing lagged states and a probability distribution over regimes, \(Pr(s_t|s_{t-1})\).

Realize the regime \(s_t\) which determines whether the constraint binds or not.

Realize shocks to exogenous processes, which are orthogonal to regime realization.

Make decisions that pin down \(B_t^*\) and \(\lambda_t\), which in turn imply a probability distribution over whether the constraint binds in \(t+1\).
Interest Rates and Exogenous Processes

• Interest Rate Process

\[ r_t = r^* + \psi_r \left( e^{\bar{B} - B_t - 1} \right) + \sigma_r (s_t) \varepsilon_{r,t} \]

• Productivity

\[ \log A_t = (1 - \rho_A (s_t)) a^* (s_t) + \rho_A (s_t) \log A_{t-1} + \sigma_A (s_t) \varepsilon_{A,t} \]

• Terms of Trade

\[ \log P_t = (1 - \rho_P (s_t)) p^* (s_t) + \rho_P (s_t) \log P_{t-1} + \sigma_P (s_t) \varepsilon_{P,t} \]

• Regime-Specific Process for Flexibility in Estimation
Leverage Shocks

- Interested in Role of Leverage Shocks
  - Importance as a Cause of Crises
  - Relative Importance in and Out of Crisis

Stochastic, Regime-Dependent Restrictions on Leverage

\[ \kappa_t = \left(1 - \rho_{\kappa} (s_t)\right) \kappa^* (s_t) + \rho_{\kappa} (s_t) \kappa_{t-1} + \sigma_{\kappa} (s_t) \epsilon_{\kappa,t} \]

- Binding Regime

\[ \frac{1}{(1 + r_t)} B_t - \phi (1 + r_t) (W_t H_t + P_t V_t) = -\kappa_t q_t K_t \]

- Non-binding regime

\[ B_t^* = \frac{1}{(1 + r_t)} B_t - \phi (1 + r_t) (W_t H_t + P_t V_t) + \kappa_t q_t K_t \]
Solution

- Full Set of Equilibrium Conditions
  - First-Order Conditions
  - Constraints
  - Regime-Switching Slackness Condition
  - Exogenous Processes
- Nonlinear Model that Can in Principle be Solved with Global Methods
- This Paper: Compute an Approximate Solution via Perturbation
  - Very Fast Solution that Allows for Likelihood-Based Estimation
  - Endogenously Determined Approximation Point between Regimes
- Extend Perturbation Method of Foerster, et. al. (2016)
Properties of the Solution

• Approximation Point Ergodic Mean of Regimes

\[ P_{ss} = \begin{bmatrix} 1 - \frac{\exp(-\gamma_0 B_{ss}^*)}{1 + \exp(-\gamma_0 B_{ss}^*)} & \frac{\exp(-\gamma_0 B_{ss}^*)}{1 + \exp(-\gamma_0 B_{ss}^*)} \\ \frac{\exp(-\gamma_1 \lambda_{ss})}{1 + \exp(-\gamma_1 \lambda_{ss})} & 1 - \frac{\exp(-\gamma_1 \lambda_{ss})}{1 + \exp(-\gamma_1 \lambda_{ss})} \end{bmatrix} \]

• General Result: Endogenous Switching Doesn’t Appear in First Order
  • First-Order Dynamics Same with Endogenous and Exogenous Probabilities of \( P_{ss} \)
  • Precautionary Behavior in the Second Order Solution is Critical

• Expectational Effects Matter for Response to Shocks in Normal Regime
  • Sensitivity of Crises to Debt Cushion
  • Crisis Regime Parameters
  • Helps with Identification in Estimation
  • Note that this Makes Policy Implications Interesting/Relevant
Approximation and IRF to TFP Shock

\[ B^* \text{ (level)} \]

\[ A \]

- \( B^* \) (level)
- \( A \)
- Second Order
- First Order
Estimating the Nonlinear Model

- Second-Order plus Endogenous Probabilities Complicates Estimation
- Rational Expectations
  - Links Parameters Across Regimes and Economic Behavior
  - Two-Step Procedures Inappropriate
  - Agents in the Model Fully Understand Crises Occur and Adjust Behavior
  - Estimated Model Useful for Normative Analysis
- Procedure for Simultaneous Estimation of Regimes and Parameters
  - Metropolis-Hastings Algorithm
  - Binning and Maih (2015): Unscented Kalman Filter with Sigma Points
- Bayesian Estimation with Uniform Priors
Data for Estimation

- Data for Mexico from 1981Q1 to 2016Q4
  - Also Periods of Expansion and Recession
- Observables
  - Real GDP Growth
  - Investment Growth
  - Consumption Growth
  - Interest Rate
  - Trade-Balance-to-Output Ratio
- Measurement Errors for all Observables
Quick Recap

- Set up a Small Open Economy Model
  - Hit with 4 Types of Shocks
  - Borrow to Smooth Consumption, Pay for Inputs
  - As Debt Increases Relative to Capital, Probability of a Crisis Increases
  - Crisis Constrains Borrowing

- Developed Solution and Estimation Procedures
  - Endogenous Regime Switching
  - Second Order Solution and Estimation

- Objectives for Estimation
  - Estimate Key Structural Parameters
  - Characterize When in Crisis Regime
  - Determine which Shocks Drive Fluctuations
  - How Frequent are Crises?
  - Bonus: Preview Effect of Capital Controls
## Calibrated Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount Factor</td>
<td>$\beta = 0.97959$</td>
</tr>
<tr>
<td>Risk Aversion</td>
<td>$\rho = 2$</td>
</tr>
<tr>
<td>Labor Share</td>
<td>$\alpha = 0.592$</td>
</tr>
<tr>
<td>Capital Share</td>
<td>$\eta = 0.306$</td>
</tr>
<tr>
<td>Wage Elasticity of Labor Supply</td>
<td>$\omega = 1.846$</td>
</tr>
<tr>
<td>Capital Depreciation</td>
<td>$\delta = 0.022766$</td>
</tr>
<tr>
<td>Interest Rate Elasticity</td>
<td>$\psi_r = 0.05$</td>
</tr>
<tr>
<td>Debt-to-GDP Ratio</td>
<td>$B_{ss} / Y_{ss} = -0.86$</td>
</tr>
<tr>
<td>Mean of TFP Process, Normal Regime</td>
<td>$a^*(0) = 0$</td>
</tr>
<tr>
<td>Mean of Import Price Process, Normal Regime</td>
<td>$p^*(0) = 0$</td>
</tr>
<tr>
<td>Mean of Leverage Process, Normal Regime</td>
<td>$\kappa^*(0) = 0.15$</td>
</tr>
</tbody>
</table>
### Estimation Results: Key Structural Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Mean</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>Uniform(0,100)</td>
<td>2.8233</td>
<td>2.8144</td>
<td>2.8360</td>
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<td>$\phi$</td>
<td>Uniform(0,100)</td>
<td>0.3036</td>
<td>0.2697</td>
<td>0.3217</td>
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<tr>
<td>$\gamma_0$</td>
<td>Uniform(0,1000)</td>
<td>89.0076</td>
<td>73.2143</td>
<td>108.1845</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>Uniform(0,1000)</td>
<td>1.9676</td>
<td>0.0892</td>
<td>5.8921</td>
</tr>
<tr>
<td>$\rho_a(0)$</td>
<td>Uniform(0,1)</td>
<td>0.8134</td>
<td>0.7208</td>
<td>0.8843</td>
</tr>
<tr>
<td>$\rho_a(1)$</td>
<td>Uniform(0,1)</td>
<td>0.7746</td>
<td>0.5543</td>
<td>0.8968</td>
</tr>
<tr>
<td>$\rho_p(0)$</td>
<td>Uniform(0,1)</td>
<td>0.9637</td>
<td>0.9340</td>
<td>0.9876</td>
</tr>
<tr>
<td>$\rho_p(1)$</td>
<td>Uniform(0,1)</td>
<td>0.9260</td>
<td>0.8258</td>
<td>0.9941</td>
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<tr>
<td>$\rho_\kappa(0)$</td>
<td>Uniform(0,1)</td>
<td>0.6656</td>
<td>0.4152</td>
<td>0.8946</td>
</tr>
<tr>
<td>$\rho_\kappa(1)$</td>
<td>Uniform(0,1)</td>
<td>0.7804</td>
<td>0.6728</td>
<td>0.8872</td>
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<tr>
<td>$a^*(1)$</td>
<td>Uniform(-10,0)</td>
<td>-0.0059</td>
<td>-0.0072</td>
<td>-0.0047</td>
</tr>
<tr>
<td>$p^*(1)$</td>
<td>Uniform(0,10)</td>
<td>0.0005</td>
<td>0.0000</td>
<td>0.0013</td>
</tr>
<tr>
<td>$\kappa^*(1)$</td>
<td>Uniform(0,1)</td>
<td>0.2305</td>
<td>0.2203</td>
<td>0.2440</td>
</tr>
</tbody>
</table>

Posterior of Logistic Function

\[ \text{Prob}(s_{t+1} = 0|s_t = 0, B^*_t) \]
Crisis Estimates vs. Reinhart-Rogoff Currency Crisis Dates

Smoothed Probability of Binding
Crises Estimates vs. OECD Recession Dates
Transition Prob. vs. Reinhart-Rogoff Currency Crisis Dates

![Graph showing transition probabilities over time with shaded areas indicating crisis dates.](graph.png)
### Estimation Results: Shock Standard Deviations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Mean</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_r(0)$</td>
<td>Uniform(0,1)</td>
<td>0.0007</td>
<td>0.0001</td>
<td>0.0015</td>
</tr>
<tr>
<td>$\sigma_r(1)$</td>
<td>Uniform(0,1)</td>
<td>0.0438</td>
<td>0.0332</td>
<td>0.0496</td>
</tr>
<tr>
<td>$\sigma_a(0)$</td>
<td>Uniform(0,1)</td>
<td>0.0056</td>
<td>0.0043</td>
<td>0.0068</td>
</tr>
<tr>
<td>$\sigma_a(1)$</td>
<td>Uniform(0,1)</td>
<td>0.0091</td>
<td>0.0062</td>
<td>0.0123</td>
</tr>
<tr>
<td>$\sigma_p(0)$</td>
<td>Uniform(0,1)</td>
<td>0.0401</td>
<td>0.0338</td>
<td>0.0478</td>
</tr>
<tr>
<td>$\sigma_p(1)$</td>
<td>Uniform(0,1)</td>
<td>0.0487</td>
<td>0.0218</td>
<td>0.0766</td>
</tr>
<tr>
<td>$\sigma_K(0)$</td>
<td>Uniform(0,1)</td>
<td>0.0012</td>
<td>0.0001</td>
<td>0.0030</td>
</tr>
<tr>
<td>$\sigma_K(1)$</td>
<td>Uniform(0,1)</td>
<td>0.0248</td>
<td>0.0072</td>
<td>0.0419</td>
</tr>
</tbody>
</table>
## Variance Decomposition

<table>
<thead>
<tr>
<th>Shock</th>
<th>Regime</th>
<th>C</th>
<th>I</th>
<th>r</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest Rate Shock $\varepsilon_{r,t}$</td>
<td>Non-Binding</td>
<td>0.0001</td>
<td>0.0128</td>
<td>0.0066</td>
<td>0.0000</td>
</tr>
<tr>
<td>Technology Shock $\varepsilon_{a,t}$</td>
<td>Non-Binding</td>
<td>0.3087</td>
<td>0.2670</td>
<td>0.6390</td>
<td>0.3158</td>
</tr>
<tr>
<td>Import Price Shock $\varepsilon_{p,t}$</td>
<td>Non-Binding</td>
<td>0.6817</td>
<td>0.3777</td>
<td>0.1971</td>
<td>0.6814</td>
</tr>
<tr>
<td>Leverage Shock $\varepsilon_{\kappa,t}$</td>
<td>Non-Binding</td>
<td>0.0095</td>
<td>0.3424</td>
<td>0.1572</td>
<td>0.0027</td>
</tr>
<tr>
<td>Interest Rate Shock $\varepsilon_{r,t}$</td>
<td>Binding</td>
<td>0.0074</td>
<td>0.0044</td>
<td>0.3701</td>
<td>0.0145</td>
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<tr>
<td>Technology Shock $\varepsilon_{a,t}$</td>
<td>Binding</td>
<td>0.0106</td>
<td>0.0003</td>
<td>0.0004</td>
<td>0.0705</td>
</tr>
<tr>
<td>Import Price Shock $\varepsilon_{p,t}$</td>
<td>Binding</td>
<td>0.0124</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0630</td>
</tr>
<tr>
<td>Leverage Shock $\varepsilon_{\kappa,t}$</td>
<td>Binding</td>
<td>0.9696</td>
<td>0.9951</td>
<td>0.6291</td>
<td>0.8520</td>
</tr>
</tbody>
</table>
Crisis Frequency

![Crisis Frequency Graph](chart.png)
What Drives the Crisis Frequency?

<table>
<thead>
<tr>
<th>Shock</th>
<th>Mean</th>
<th>70%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Shocks</td>
<td>10.99</td>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>Individual</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest Rate Only</td>
<td>ε_{r,t}</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>Technology Only</td>
<td>ε_{a,t}</td>
<td>2.07</td>
<td>0</td>
</tr>
<tr>
<td>Import Price Only</td>
<td>ε_{p,t}</td>
<td>4.81</td>
<td>4</td>
</tr>
<tr>
<td>Leverage Only</td>
<td>ε_{κ,t}</td>
<td>3.26</td>
<td>0</td>
</tr>
</tbody>
</table>
The Research Agenda: Capital Controls and Crises

• Would Different Capital Control Policies help Avoid or Mitigate Crises?
• Given Estimated Shocks and Frictions, Regenerate Data with Counterfactual Policy
• Consider Specific Rules or Find Optimal Rules
• Example: Tax on Debt that is Returned Lump-Sum

\[ T_t = \tau_t^B B_t \]

• Outstanding Issue: What about Observed Crises?
Crisis Frequency with 1% Tax

Mean Crisis Frequency = 1.7592
Crisis Frequency with Various Tax Rates

The graph shows the relationship between crisis frequency and tax rate. The x-axis represents the tax rate (%) ranging from 0 to 1, while the y-axis represents crisis frequency ranging from 0 to 12. As the tax rate increases, the crisis frequency decreases significantly, indicating a negative correlation between tax rate and crisis frequency.
Conclusion

• New Approach to Specifying, Solving, Estimating Models of Financial Crises
• Probability Regime Switch Depends on State of Economy
• Endogenous Switching Impacts the Economic Behavior in Qualitatively and Quantitatively Important Ways
• Crisis Regime Corresponds to Narrative Dates
• Leverage Shocks Drive Fluctuations during Financial Crises
• Real Shocks Drive Fluctuations in Normal Regime
• Future Work: Conditional Policy Counterfactuals