Macro-Finance Models with Nonlinear Dynamics*

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Abstract

We provide a review of macro-finance models featuring nonlinear dynamics. We survey the models developed recently in the literature, including models with amplification effects of financial constraints, models with households' leverage constraints, and models with financial networks. We also construct an illustrative model for those readers who are unfamiliar with the literature. Within this framework, we highlight several important limitations of local solution methods compared with global solution methods, including the fact that local-linearization approximations omit important nonlinear dynamics, yielding biased impulse-response analysis.

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1 Introduction

The Great Recession has called for attention from the academia, policy makers, and practitioners on the nonlinear impact of financial sector frictions on the macroeconomy. Such nonlinear impact poses tremendous risks to the economy as a whole. One emerging narrative is that macroeconomic models commonly employed at policy institutions lack the analytical specificity to account for important nonlinear influences of the financial sector on the aggregate economy. A new generation of enhanced models and advanced empirical and quantitative methodologies are needed by policymakers and need to be provided by researchers to better study the impact of shocks that are initially large or build endogenously over time.

This paper presents a review of these macro-finance models featuring nonlinear dynamics and their solution methods. Through this review, we hope to clarify the most important challenges faced by existing macro-finance models, and summarize some recent advances in new modeling and quantitative techniques. The primary goal of this paper is to provide insight, guidance, and motivation for the next generation of young scholars—especially those at the intersection of macroeconomics and financial economics.

There has been a remarkable evolution of macro-finance models, especially those used for policy analysis at major policy authorities around the world, in aspects such as model formulation, solution methods, and estimation approaches. Particularly, policy makers need a new generation of macroeconomic models with financial sector for both conventional and unconventional policies. For example, at the onset of the financial crisis, the zero lower bound for short-term nominal interest rates went from a remote possibility to reality with frightening speed. This led central banks to quickly develop unconventional measures to provide economic stimulus, including credit easing, quantitative easing, and extraordinary forward guidance. These unconventional measures require a proper platform to be analyzed. Furthermore, these measures have blurred the boundary between monetary policy and fiscal policy. Through these policies, central banks gave preference to some debtors over others (e.g., industrial companies, mortgage banks, governments), and some sectors over others (e.g., export versus domestic). In turn, the distributional effects of monetary policy were much stronger than in normal times; hence, these measures are sometimes referred to as quasi-fiscal policy. As emphasized, a reliable monetary policy experiment cannot ignore the effect of ongoing fiscal policy. In order to implement unconventional measures during the crisis, central banks put much more risk onto government balance sheets than ever before, which had the potential to lead to substantial losses. Thus the government balance sheets in these models should be forward-looking, and its interactions with financial sector and risk characteristics are crucial to the success of the model.

Methodological and empirical challenges have arisen along the way. First, advanced nonlinear solution methods and estimation approaches are necessary, if one wishes to guarantee that key nonlinear dynamics in the financial market and the macroeconomy are eventually captured in quantitative analysis (see, e.g., Brunnermeier and Sannikov, 2016; Miftakhova et al., 2019). Second, data availability and "tail risk" measurement are a central challenge in macro-finance modeling emphasizing nonlinear dynamics, but especially so in the wake of the global financial crisis and the subsequent global economic recession. Brunnermeier et al. (2012) pointed out that our current measurement systems are outmoded, leaving regulators, academics, and risk managers in a dangerous position. Assessing systemic risk requires viewing data on the financial sector through the lens of a macroeconomic model. However, macroeconomics in particular frames questions and builds models based on available data, and we have so far lacked the data to construct macro-financial models. New infrastructure for detailed micro-level financial data collection is necessary and critical for further risk measurement development and model construction. In fact, the Office of Financial Research (OFR) at the U.S. Department of the Treasury already has this mandate, and the first steps toward a new, comprehensive financial data collection system are already underway.

We start our review with the leading models that feature "financial constraint" as their core element, which leads to the failure of Modigliani-Miller (MM) theorem. Equilibrium macroeconomic models with funding liquidity frictions has the longest history, dating back to the early work by Bernanke and Gertler (1989). These models will be discussed extensively in section 2.1. As the first key function of the financial sector, it transforms riskless liabilities into risky assets and thus their net worth is exposed to macroeconomic risks. Funding liquidity frictions limit borrowers' debt capacity to be capped by the market value of the total assets they own while outside equity issuance is largely restrained. As a result, there is a spiral between the risky asset price and debt capacity amplifies shocks in the macroeconomy: when risky asset price is higher, borrowers have more debt capacity and the investment demand is higher. The higher investment demand pushes the risky asset price even higher. In this case, the decentralized competitive equilibrium is generally constrained inefficient due to the pecuniary externalities: agents do not take into account the effect on risky asset price when they adjust their balance sheets. Macroprudential policies can thus be welfare-improving.

The interaction between the risky asset price and debt capacity can potentially be highly nonlinear. When the economy experiences a good shock, the constraint is loose and the financial sector does not affect the real economy. However, in bad times when the constraint is binding, shocks can be greatly amplified and we may observe the realization of "rare disasters" or financial crises in the economy. In section 2.2, we specially discuss this feature in quantitative models.

The other fundamental feature of the financial sector is that it transforms the short-term liabilities into long-term assets. The liquidity transformation function makes the financial sector subject to liquidity problems. In section 2.3, we review models with market liquidity frictions, i.e., investors cannot sell their assets costlessly. In these models, liquid assets such as fiat money and government treasuries have an additional value. Therefore, these models are useful frameworks to evaluate the massive liquidity policies in the recent decade after the crisis.

Diamond and Dybvig (1983)'s classic work demonstrates that bank runs may arise as a result of liquidity mismatch. Due to the liquidity transformation function, the financial sector is subject to rollover risk. When creditors lose faith in the funding capacity of intermediaries, they will liquidate the financial sector's short-term liabilities and lead to a systemic run, even though the financial sector is in good health. In section 2.4, we review several recent papers that incorporate bank runs into dynamic macroeconomic analysis and show how we can understand the recent financial crisis as a realization of systematic bank run. We conclude section 2 by examining the empirical successes and challenges posed by the literature in section 2.5.

In section 3, we shift our attention to the behavior of households as borrowers of mortgage and review the literature on household leverage, mortgage, and housing prices. In the episodes before 2007, we witnessed booming housing prices and increased mortgage supply. The increased mortgage and the securitized products are considered as one of the major causes of the crisis. Particularly, the literature explores the potential causes of high housing price and the macro-financial consequences of the housing boom.

In section 4, we review the recent growing literature on financial networks. As we observe in most crises, trouble typically originates from a small set of entities and spills over to others. It is thus crucial to understand the underlying mechanisms of transmission and their welfare consequences.

Further, one relevant characteristic that introduces nonlinearities in macro-finance models is the zero lower bound (ZLB) of nominal interest rates (see, e.g., Christiano et al., 2014; Aruoba et al., 2017). We shall not discuss extensively on the nonlinear implications of zero lower bound or the solution methods designed to handle a DSGE model with zero lower bounds. Recent works including Miftakhova et al. (2019) provide useful discussions on how to solve DSGE models with zero lower bounds.

Many of the macro-finance models discussed in our article feature nonlinear dynamics, which poses challenges to standard techniques applied in macroeconomics. As an illustration, in sections 5 and 6, we propose a simple, benchmark macro-finance model and solve it using different solution methods, including the global method based on time iteration, perturbation method with the first and second order, and the more recent "OccBin" method. By comparing the solutions obtained using different methods, we are able to assess under which circumstances each method can be used.

2 Amplification Effects of Financial Constraints

2.1 Models with Funding Liquidity Constraints

In this section, we review the class of macroeconomic models with a financial sector that faces financing constraints (i.e. funding liquidity constraints). We focus on Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) and other related models highlighting debt and equity financing constraints. The details of the models are relegated to section 5, where we compare different solution methodologies.

We also discuss the models with a financial sector that highlight a particular type of constraints — the value-at-risk (VaR) models (see, e.g., Adrian and Shin, 2013; Adrian and Boyarchenko, 2017). VaR is a constraint imposed on the whole balance sheet of an intermediary. It is widely used as the major tool of risk management in the large financial institutions in practice.

The Key Features. This class of models explicitly specifies a financial sector that channels funds from savers to investors. There are two essential deviations from the standard frictionless models: first, households cannot directly invest in risky productive capital, and second, financial intermediaries are subject to a collateral constraint that impedes efficient intermediation of productive capital. Financial sector' intermediation capacity depends on their net worth and thus the capital price. The key feature of this class of models is to emphasize the importance of funding liquidity (i.e. intermediaries' net worth or the marginal value of intermediaries' net worth) as an inevitable state variable in macro-finance models.[1]

The market incompleteness and the price-dependent financing constraints lead to two distinct types of pecuniary externalities: distributive externalities that arise from incomplete insurance markets and collateral externalities that arise from price-dependent financing constraints (Dávila and Korinek, 2017).

This class of models offers two main economic insights. First, the price-dependent financing constraint plays an important role in amplifying economic fluctuations. Particularly, suppose a negative productivity shock hits the economy, the output, investment, and price of capital drops. Since intermediaries are the holders of productive capital with leverage, their net worth is destroyed with a greater amount, which further reduces the demand for capital because of the tightened financing constraints. The adverse feedback effect between price of capital and financing constraints amplifies the effect of the negative productivity shock. Second, this class of models emphasizes the important role of intermediary balance sheet in determining the intermediation capacity of the financial sector in an economy. When intermediary's net worth is scarce (i.e. leverage is excessive), its intermediation capacity is low. This insight highlights the importance of repairing bank balance sheet in financial disruption, justifying monetary authorities' unconventional monetary policies in the recent financial crisis. This insight also motivates the intermediary asset pricing literature where intermediary's leverage ratio is a crucial state variable priced in the cross section (see, e.g.,

[1] Research on corporate finance and asset pricing has increasingly emphasized the importance of corporate liquidity (or cash holdings) as an inevitable state variable in dynamic structural corporate models (see, e.g., Bolton et al., 2011, 2013, 2018; Dou et al., 2018). This increase is motivated by the empirical evidence showing that cash holdings are often large, but a more important reason is that liquidity management is crucial for corporate entities.

Adrian et al., 2014; He et al., 2017).

This class of models features the so-called "financial accelerator channel", which originates back to Bernanke and Gertler (1989), Kiyotaki and Moore (1997), Carlstrom and Fuerst (1997), and Bernanke et al. (1999), with the net worth of borrowers being the crucial state variables of the economy. The core idea of the "financial accelerator channel" is that the financial constraints imposed on the balance sheets of intermediaries and firms can adversely amplify the primitive economic shocks, such as productivity shocks, volatility shocks, and uncertainty shocks.[2]

Unlike the earlier literature which mostly focuses on firms' net worth, Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) explicitly model a financial sector and shed light on the role of financial intermediaries. As extensions, Gertler et al. (2012) enrich the model by allowing for outside equity injection into intermediaries from savers, which endogenously generates risky intermediary balance sheets. Gertler et al. (2013) study the effect of large-scale asset purchase program as central bank intermediation.

Welfare Analyses and Policy Implications. Compared to the first-best allocation, the presence of financing frictions leads to inefficient outcomes, but it is unclear whether the competitive equilibrium is constrained efficient. Lorenzoni (2008)'s theoretical study shows that the competitive equilibrium in an economy with financing frictions displays overborrowing compared to the constrained efficient level (i.e. the second best), even though the competitive equilibrium displays underbrorrowing relative to the first best. He points out that the reason for inefficiency is the pecuniary externality that individuals do not internalize in their decision making. Bianchi (2011) provides a quantitative analysis on the macroeconomic and welfare consequences of overborrowing, showing that the inefficient overborrowing substantially increases the frequency and severity of financial crisis. He also studies how various policies that restrict the amount of credit in the economy can restore the constrained efficiency. Bianchi et al. (2012) and Bianchi et al. (2016) extend macro-prudential policy analysis into models with financial innovation and news shocks.

[2]There have been recent efforts to show that the amplification effect of financial constraints on the impact of uncertainty shocks is particularly important to understand joint dynamics of macroeconomic quantities and financial variables (see, e.g., Christiano et al., 2014; Gilchrist et al., 2014; Di Tella, 2017; Dou, 2017).

Dávila and Korinek (2017) provide a general framework to distinguish the two types of pecuniary externalities: distributive externalities and collateral externalities. Distributive externalities arise when agents differ in their intertemporal marginal rate of substitution, while collateral externalities arise when the financing constraints depend on the market price of collateral assets. They show that collateral externalities lead to overborrowing relative to the second-best borrowing level, while it is ambiguous whether distributive externalities lead to overborrowing or underborrowing. Further, they show that the optimal corrective policies can be characterized by sufficient statistics that are invariant to the specific nature of the underlying financial frictions, such as uncontingent bonds, limited commitment, and market segmentation.

Bianchi (2016) discusses the tradeoff between the ex-post bailout and ex-ante moral hazard. Although bailouts might be optimal ex post, the anticipation of such bailouts will lead to the moral hazard problem of excessive risk taking. Through a quantitative model, he shows that the excessive risk taking effect is limited if the bailout is systematic. On the contrary, when the bailout is idiosyncratic, it will make the economy more prone to crises. However, an unsolved key challenge is to separate "systematic" and "idiosyncratic" in practice given that the so-called "idiosyncratic" can be "systemic". An prominent example was the collapse of Lehman Brothers in the middle of the Great recession.

Bianchi and Mendoza (2018) show that the optimal macroprudential policies chosen by regulators are time inconsistent, and characterize the optimal time-consistent policies in a quantitative model. These macroprodential policies that can sharply reduce the frequency and magnitude of crises.

Phelan (2016) is another recent effort on the welfare implication of financing constraints. He shows that the competitive equilibrium is constrained inefficient in an economy similar with Brunnermeier and Sannikov (2014). Particularly, the paper emphasizes the common wisdom that the inefficient misallocation relative to the first-best ourcome can be constrained efficient. More specifically, it highlights that leverage of the most productive producers can reduce capital misallocation and increase output in the short run, with costs of increased frequency of crisis in the long run.

Other Related Models. There are closely related model in the continuous-time framework — He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014). Both models share the key feature that the market incompleteness and price-dependent financing constraints lead to adverse feedback between asset prices and intermediaries' financing constraints; such adverse feedback amplifies economic fluctuations and generates nonlinear dynamics of risk premia. Similarly, a critical implication is that intermediaries' net worth (or leverage) can serve as an informative state variable of the economy, and devastating crisis can be triggered as a consequence of a sequence of small negative primitive aggregate shocks.

More precisely, both models have two types of agents — households and experts. Experts own the expertise of investing in risky productive capital while the households do not.[3] Households and experts differ in their time discount rates so that there exists a borrowing-lending relationship between them[4]. Absent any frictions, productive capital should be all in the hands of the experts and experts distribute the share of investment return to the households. However, experts have limited capacity to invest on behalf of the households. In He and Krishnamurthy (2013), experts need at least a certain fraction of equity capital in their investment in the risky asset, which is motivated by "skin in the game" incentive constraint due to moral hazard (see, e.g., He and Krishnamurthy, 2011). Once experts' net worth becomes insufficient, the demand for productive capital is largely reduced and asset price plunges. In Brunnermeier and Sannikov (2014), the net worth of experts cannot fall below zero. Therefore, when experts have little wealth, households pick up the slackness despite being inefficient in investment with a lower price of capital. What's worse, the drop in asset price further reduces experts' wealth as they are levered investors, amplifying the negative shock. This is the same "financial accelerator" mechanism as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011).

The two-agent risk sharing models and their asset pricing implications have been studied in macro and finance literature for the past decades, dating back to Dumas (1989) and Longstaff and Wang (2012) with complete markets, and Mankiw and Zeldes (1991), Basak and Cuoco (1998), and Guvenen (2009) with incomplete markets. The main idea is that market incompleteness makes the aggregate risks born by a fraction of investors, and as

[3] In He and Krishnamurthy (2013) households are completely prohibited from investing in productive capital, while in Brunnermeier and Sannikov (2014), households are less efficient in investment.

[4] Technically, this assumption also prevents agents from perishing in the long run.

marginal pricers, their pricing kernel is much more volatile than the aggregate consumption process.

International Financial System. One unprecedented change in the financial market in the recent decades is the financial globalization and fast growth of cross-border capital flows. Financial institutions, especially the globally operated intermediaries, play a critical role in allocating capital across countries. As we have shown in previous sections, financial intermediaries face financing constraints, which in turn shape capital flows, global imbalances, and international financial system.

Miranda-Agrippino and Rey (2018) provide empirical evidence on the powerful financial transmission of US monetary policy through the financial intermediaries. They find that US tightening of monetary policy is associated with a sharp decline in capital flows in the banking sector, bank leverage, and risky asset prices on a global scale. Coimbra and Rey (2019) construct a dynamic equilibrium model that illustrates the financial transmission channel. Moreover, they incorporate heterogeneity in intermediaries' risk capacity and show that the effect of monetary policy shocks on financial stability depends on the distribution of wealth across the intermediaries. Jiang et al. (2019) link monetary policy transmission to the convenience yield and low interest rate of dollar. The low cost of dollar funding exposes firms in other countries to dollar exchange rate risk. As a consequence, a US monetary tightening and dollar appreciation deteriorates firms' balance sheet and contracts economic activities in other countries.

Bruno and Shin (2014) propose a model of international capital flows in the global banking system. Local banks get dollar funding from global banks and lend to entrepreneurs. Both local and global banks face credit risk and value-at-risk constraints. In the model, intermediaries play the centric role of driving capital flows. Moreover, the model features a risk-taking channel of exchange rates: since the entrepreneurs bear exchange rate risks, dollar depreciation lowers the cost of funding for entrepreneurs and increases the leverage of the banking system.

The heterogeneity in financing frictions across countries is also one of the main drivers of the global imbalances between the advanced economies (especially the US) and emerging countries. Mendoza et al. (2009) show that imbalance emerges as a transitional phenomenon when less financially developed emerging economies liberalize their financial account. The severe friction in the emerging financial markets keep their investment rate of return high, so that the developed countries tend to hold large portions of their assets. Maggiori (2017) attributes the global imbalances to the special status of US as a "global banker". Due to the superior financial development, US intermediaries face less frictions than other countries and they provide insurance to the rest of the world. In normal times, US intermediaries earn risk premia while in crisis times, resources are exported from the US to the rest of the world.

Different Forms of Financing Constraints. The financing constraints are defining characteristics of these models. External financing constraints (for debt and equity) focus on the liability side of the balance sheet, while value-at-risk (VaR) is a constraint on the whole balance sheet. One common important implication of all financing constraints is to generate a wedge between the marginal value of internal funds and that of external funds. However, different types of constraints have different micro foundations as well as different implications on leverage cyclicality.

Debt financing constraint (or leverage constraint) is prevalent in the literature, such as Bernanke et al. (1999), Kiyotaki and Moore (1997), Gertler and Kiyotaki (2010). In these models, firms and intermediaries are prevented from borrowing up to their desired level for various reasons. Bernanke et al. (1999) derive the constraint as an optimal contract between borrowers and lenders with costly state verification following Townsend (1979). In Gertler and Kiyotaki (2010), the constraint is a result of moral hazard between borrowers and lenders that borrowers can steal a fraction of their assets, as modeled by Holmstrom and Tirole (1997). Kiyotaki and Moore (1997) imposes an exogenous collateral constraint, under which the amount of borrowing cannot exceed a certain fraction of the market value of total assets. All these models share the common feature that financing with outside equity is not allowed.

He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014) are two models that focus equity financing constraints. In He and Krishnamurthy (2013), experts in risky investment must have enough equity stake (skin in the game) to ensure they do not seek for their private benefit. He and Krishnamurthy (2011) show that this constraint is the optimal contract. Brunnermeier and Sannikov (2014) introduce the constraint that the experts' net worth cannot go negative, which effectively means no outside equity issuance is allowed. Due to this constraint, experts will bear excessive concentrated aggregate risk, especially when their net worth is scarce.

Jermann and Quadrini (2012) assume that the two sources of funding – equity and debt– are imperfectly substitutable, and such imperfect substitutability helps explain the joint aggregate dynamics of financial variables and real quantities. When the debt constraint gets tighter, borrowers turn to equity financing, associated with a higher financing cost. More precisely, their model quantitatively match both the business cycles and the financial flows of debt and equity in the US in the past few decades.

Value-at-risk (VaR) is a more general constraint on the whole balance sheet of the borrowers. It is widely used as the major tool of risk management in large financial institutions. The VaR constraint states that the probability of the net worth dropping to zero (default) should be no more than a given probability threshold. The VaR constraint limits the amount of borrowing (leverage) as it amplifies the balance sheet risk and increases the probability of default. However, even if the investor does not borrow, VaR constraint limits the investment in certain high-risk securities. Adrian and Shin (2013) show empirical evidence on the relevance of VaR for large financial institutions and provide a moral hazard based micro foundation. Adrian and Boyarchenko (2017) extend the model into a richer environment and discuss the implications on leverage cycle and financial stability. Nuño and Thomas (2017) is a quantitative macroeconomic model with VaR constraint.

Different forms of constraints have different implications on the cyclicality of intermediary leverage. Models with debt and equity financing constraints imply countercyclical intermediary leverage. It means that the adjustment in debt is less than the change in net worth. By contrast, models with VaR constraints imply pro-cyclical intermediary leverage (see, e.g., Adrian and Shin, 2013). They argue that intermediaries actively adjust their balance sheet, especially the broker-dealers. Adrian and Shin (2010) show the important differences in balance sheet adjustment in different sectors, with broker-dealers exhibiting highly pro-cyclical leverage.

Solution Methods. Dynamic macroeconomic models typically rely on numerical solution methods, especially the perturbation method with log-linearized approximations around the deterministic steady state. Many leading models in this literature are solved in this way, for example, Bernanke et al. (1999), Gertler and Karadi (2011), with the assumption that the constraints always bind. The log-linearization procedure is simple and easy to extend without having to worry about the curse of dimensionality. However, the local approximation methods have very little capacity to analyze the models that primarily aim to generate occasionally-binding dynamics and sudden "jumps".

Guerrieri and Iacoviello (2015) develop a toolkit that allows for occasionally binding constraint (OccBin for short) yet relying on local approximations. The toolkit greatly improves the model solutions. However, they are still restricted to first-order approximations. In sections 5 and 6 of the paper, we write down a calibrated version of the canonical model in Gertler and Kiyotaki (2010) and provide detailed comparisons of global solution method and different versions of perturbation solution methods, including the OccBin toolkit.

Bocola (2016) is an example that uses global solution method to solve, estimate, and analyze the type of models similar to Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). He studies the pass-through of sovereign risk onto investment and output in a model with financing frictions. He highlights the "risk channel" that in bad times, investors will put higher probability weight on the sovereign default state with binding financing constraints, high marginal value of (liquid) wealth, and high risk premium. The perturbation method does not suffice to quantify this effect, which makes global solution method necessary.

The continuous-time models of He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014) are also solved globally. In these two papers, solving for the equilibrium requires numerically solving for a set of ordinary differential equations. The global method enables the authors to analyze the highly nonlinear dynamics for which the models are designed. For example, both models feature two regimes: the "normal times" when the constraint is slack, and the "crisis times" when the constraint binds. However, the solution method is subject to the curse of dimensionality: a full-fledged quantitative model requires many exogenous and endogenous state variables, which lead to a group of super complex partial differential equations of policy functions.

Mendoza (2010) is another example of globally-solved models in discrete time. He develops a model which quantitatively matches the frequency and the severity of financial crisis with an occasionally binding borrowing constraint. A key element in this model is the precautionary savings induced by incomplete market, which makes the financial crisis infrequent but severe.

The precautionary motives keep the economy fluctuating within the non-binding region most of the time; however, when the economy is pushed by a sequence of shocks to the region where the leverage of borrowers is higher than a critical value (i.e. the economy lies within the binding region), a small negative shock can lead to a large crisis. The OccBin toolkit is up to first order only and cannot capture this precautionary saving effect. In the next section, we will review this type of models in more detail.

In summary, perturbation methods have their advantages and limitations. They are simple to implement and can be easily extended, and work reasonably well in business cycle and policy analysis in normal times. However, when our research goal is to analyze the financial crisis and the related unconventional policies, we need the global solutions to accurately capture the large nonlinearities for useful quantitative guides in policy making. We conduct a comparison among local and global solution methodologies using the benchmark model of Gertler and Kiyotaki (2010). The comparison shows that global solution method is needed to obtain the accurate equilibrium policy functions featuring occasionally binding financial constraints and nonlinear dynamics.

2.2 Models with Endogenous "Disasters"

In this section, we review the class of models that feature endogenous infrequent and deep economic downturns. We first focus on the model proposed by Mendoza (2010). In this model, firms face occasionally binding constraints that limit debt to income/assets as collateral. When the economy is in the high leverage regime, tighter constraints shrink firms' investment and reduce the price of collateral sharply, which further tightens the constraint and reduces the collateral price. This mechanism is called "Fisherian deflation" (see Korinek and Mendoza (2014) for a literature review). On the other hand, in a recent paper by Petrosky-Nadeau et al. (2018). They show that labor market frictions play a crucial role in generating endogenous disasters.

Financial Market Frictions. Mendoza (2010) develops a business cycle model that can quantitatively account for the sudden, severe financial crises. The key ingredient of the model is a price-dependent financing constraint faced by firms; particularly, a proportion of productive capital held by firms needs to be pledged for borrowing. Mendoza (2010) is successful quantitatively both in accounting for the sudden stop nature of crises and replicating its low frequency, resolving the criticism by Kocherlakota (2000) on the quantitative importance of financial constraints. The precautionary motives keep the economy fluctuating within the non-binding region most of the time; however, when the economy is pushed by a sequence of shocks to the region where the leverage of borrowers is higher than a critical value (i.e. the economy lies within the binding region), a small negative shock can lead to a large crisis. This model also explains why private credit boom often precedes the occurrence of severe financial crisis, documented by Schularick and Taylor (2012) and Gourinchas and Obstfeld (2012).

There has been a strand of recent studies focusing on the similar mechanism. Mendoza (2010) matches the stylized facts of sudden stops in emerging economies on output, consumption, current account, and asset prices. Durdu and Mendoza (2006) show the role of asset price guarantees in preventing sudden stops. In Mendoza and Smith (2006), they derive the asset pricing implications of the Fisherian deflation with margin calls. Durdu et al. (2009) explore whether the fear of crises can account for the foreign reserve accumulation in emerging countries. They find that financial globalization and sudden stop risks rather than business cycle volatility explains the surge in foreign reserves. Boz and Mendoza (2014) relate the credit cycle to financial innovation and the gradual recovery of the true price of risk. Risk is underpriced initially when states with binding constraint does not occur. This phase is featured by a surge in asset price and credit. When the economy enters into a state with binding constraint, the abrupt change of belief leads to a collapse. Mendoza and Rojas (2018) study the effect of liability dollarization and currency mismatch on the frequency and severity of crises, as well as the macroprudential policy implications.

Labor Market Frictions. Petrosky-Nadeau et al. (2018) present a model with endogenous "disasters" (i.e., large and rapid economic downturns) originated from labor market frictions. They show that a textbook labor search model intrinsically features endogenous rare "disaster" when the model is solved nonlinearly with appropriate global method. A rare "disaster" here is an infrequent and deep economic downturn. The key ingredients that drive endogenous disaster are wage inertia, job destruction limit, and downward rigidity of job posting marginal cost. When a negative shock hits the labor-augmented productivity, the wage does not drop as much as in a frictionless economy since unemployment benefits are less affected. The real wage rigidity forces firms to lay off more aggressively and reduce job posting; however, the job destruction limit and the downward rigidity in job posting marginal cost prevent firms from optimally doing so. Such inefficient labor market illiquidity can lead to mismatch of labor and capital in corporate sector, which further causes endogenous rare “disasters”.

2.3 Models with Market Liquidity Frictions

For all the models discussed in Sections 2.1 and 2.2, the friction lies in the funding liquidity, i.e., the borrower has difficulty in obtaining funds for operation, investment, and even survival. In this section, we review another class of models in which the market liquidity of assets is imperfect. The market liquidity is defined as how easy an investor can sell the asset without affecting the asset price much (see, e.g., Pástor and Stambaugh, 2003; Brunnermeier and Pedersen, 2008; Hu et al., 2013). More precisely, the better the liquidity, the smaller the price effect of sales is. We categorize models with market liquidity frictions into two classes: those with exogenous market liquidity frictions, and those with endogenous market liquidity frictions.

Exogenous Market Liquidity Frictions. Kiyotaki and Moore (2005) and Kiyotaki and Moore (2012) are two macroeconomic models of monetary policy and business cycles with market liquidity frictions. In their model, money is a liquid asset that can be sold immediately without incurring a cost. Meanwhile, claims to productive capital (i.e., financial securities) is illiquid and only a fraction of it can be sold costlessly. The presence of liquidity friction incentivizes investors to hold money, and makes monetary policy have a real effect. They also provide a rationale on the liquidity source of fiat money’s value. Del Negro et al. (2017) incorporate the market liquidity friction into a standard DSGE model with nominal and real rigidities and show that shocks to the liquidity of private paper lead to nominal interest rate collapse and a recession. The role of liquidity facilities is assessed to be helpful in preventing crisis. Drechsler et al. (2018) analyze a model in which the market illiquidity of assets induce banks to hold liquid assets while forgoing the liquidity premium. In their model, monetary policy alters the risk taking behavior of banks by changing the liquidity premium of liquid assets, which in turn affects the risk premia.

Eisfeldt and Rampini (2006) study the time-series characteristics of capital's market liquidity. They provide empirical evidence on the procyclical capital reallocation and countercyclical reallocation gain measured by productivity dispertsion. To make sense of the two observations, the market liquidity of capital needs to be procyclical: in good times, the cost of capital reallocation is low.

Endogenous Market Liquidity Frictions. In the papers reviewed above, the market liquidity of assets is exogenously set, yet it remains unanswered what determines different assets' market liquidity. Cui and Radde (2016) uses a search model to endogenize the market liquidity of assets in the framework of Kiyotaki and Moore (2012). They show that under their model, asset prices positively comove with asset liquidity and the value of liquid assets increase in illiquid states. The variation of endogenous asset liquidity amplifies the aggregate fluctuations. Eisfeldt (2004) endogenizes the illiquidity of long-term risky assets with a different micro foundation of private information on the quality of risky projects. In her model, the resaleability of long-term risky assets depends on the pool of project quality, which in turn is a function of productivity of the economy. In good times, the pool of project quality is high so that assets have higher market liquidity. This theoretical result is consistent with Eisfeldt and Rampini (2006). The procyclical market liquidity amplifies the response of investment to productivity shocks.

Kurlat (2013) endogenizes the illiquidity of assets in a fully dynamic stochastic model. Entrepreneurs have stochastic investment opportunities so that there are incentives for financial transactions. The presence of adverse selection hampers the efficient transaction and introduces a wedge between investment return and cost of funding. This wedge depends on the proportion of low quality assets, or the severity of asymmetric information. In a calibrated version of his model, the effect of adverse selection on investment responses to aggregate shocks is quantitatively large. Bigio (2015) studies a similar model with endogenous illiquidity from adverse selection, and quantitatively explains the collapses in liquidity and other macro variables patterns observed during the Great Recession.

Funding versus Market Liquidity Frictions. Funding liquidity and market liquidity frictions are two major ways to introduce financial frictions into dynamic macroeconomic models. Both frictions impede the efficient allocation of capital, while they differ in many aspects, including the nature of the constraints, cyclicality of constraint tightness, and policy implications.

First, a typical model with funding liquidity frictions has countercyclical constraint tightness. When the aggregate economy is in a good state, the net worth of the borrower increases and the funding constraint is loosen. This is not necessarily true in models with market liquidity frictions, depending on how the friction is specified. In Kiyotaki and Moore (2012) with exogenous liquidity frictions, the tightness of the constraint is procyclical. When the aggregate economy is in good state, there is strong investment demand but the irresaleability prevents capital investment, so that the constraint is tighter. In models with endogenous liquidity frictions such as Eisfeldt (2004), the tightness of the constraint is countercyclical because in good times the average asset quality improves and the market liquidity of assets is higher.

Second, the two types of frictions differ in their policy implications. In models with funding liquidity frictions, the key state variable is the net worth of intermediaries or firms, and policy remedies should target at impairing net worth ex post and restricting excessive leverage and maintaining financial slackness ex ante. In models with market liquidity frictions, the introduction of liquid assets (such as fiat money, treasuries) improves the allocative efficiency (Del Negro et al., 2017).

Though having many differences, the two frictions are tightly linked. In Kiyotaki and Moore (2012), both funding liquidity and market liquidity frictions are incorporated into a unified framework. Funding liquidity frictions limit external financing, while market liquidity frictions limit the degree to which investment can be financed by liquidating financial securities held by entrepreneurs.

It's particularly important to understand that the two frictions interact and reinforce with each other. One outcome of funding liquidity friction is that the asset firesale of some investors suppresses prices dramatically, which adversely affects the market liquidity of the assets held by all other investors. Funding illiquidity can lead to market illiquidity. On the other hand, market illiquidity leads to excessive asset price volatility and price drops as selling pressure rises, and in turn the volatile asset price increases funding illiquidity. Brunnermeier and Pedersen (2008) illustrate this reinforcing interactions.

2.4 Models with Bank Runs

In this section, we review the macroeconomic models with bank runs. Bank run is one of the fundamental frictions in financial intermediation. The literture starts from Diamond and Dybvig (1983), which shows that liquidity mismatch of bank balance sheet may induce bank runs even when the bank has healthy balance sheet. The main friction is that long-term illiquid assets of banks cannot be liquidated at the fair price (market illiquidity) to meet the repayment obligations if creditors do not roll over their short term debt (funding illiquidity). However, bank runs have the unique feature of self-prophecy, and thus deserve a separate section of discussion. Gertler and Kiyotaki (2015) and Gertler et al. (2019) are the main models that integrate bank runs into macroeconomic analysis.

Self-fulfilling Prophecy. The distinct feature of bank run models is the self-fulfilling prophecy. In certain states of the aggregate economy, whether the banks run or not depend on borrowers' beliefs. If borrowers believe the banks cannot roll over their debt and withdrawal deposits, bank runs occur. On the other hand, if borrowers believe the banks can continue to operate, bank runs will not materialize.

The model of Gertler and Kiyotaki (2015) is built on the framework of Gertler and Kiyotaki (2010) with a few differences. In Gertler and Kiyotaki (2015), households are also allowed to hold productive capital, but they are less efficient in production than banks. Therefore, the price of capital depends on the share of capital held by banks. The economy features three regimes defined by the banks' solvency state: (i) Banks are solvent even if households own all capital; (ii) Banks are insolvent even if they own all capital; (iii) Banks are solvent if they own capital, but insolvent if households own capital.

If the economy is in the first two regimes, the economy has a unique equilibrium. In regime (i), banks are always solvent and households' know with certainty that banks are able to roll over the debt. In regime (ii), banks are always insolvent and are not able to roll over the debt for sure. In regime (iii), insolvency of banks are caused by households' pessimistic beliefs. More importantly, the beliefs are self-fulfilling. If households believe that banks are solvent, they provide funding to banks and thus banks can hold enough capital and maintain the capital price at a high level, so that banks are solvent ex post. On the other hand, if households believe that banks are insolvent, they will stop fund the banks so that capital will be reallocated to the hands of households and its price will be lower. As a result, the low price of capital induces banks to be insolvent.

With the possibility of multiple equilibria in regime (iii), Gertler and Kiyotaki (2015) use the sunspot criterion as equilibrium selection rule. Whenever multiple equilibria is possible, it is randomly determined which equilibrium occurs.

The equilibria of macroeconomic models with bank run have several special features. First, there exists a region with multiple self-fulfilling equilibria. Second, the macroeconomic quantities and asset prices are discontinuous when bank run occurs.

The self-fulfilling feature inherits the insight in the bank run literature of Diamond and Dybvig (1983). However, the Gertler and Kiyotaki (2015) model is different from Diamond and Dybvig (1983). In Diamond and Dybvig (1983), the recovery of deposit relies on the position of depositors in line, while in Gertler and Kiyotaki (2015) it does not. The reason is that the there exists two different prices of capital. It resembles the notion of "market illiquidity" that when banks sell off the asset, the price of capital will be sharply drop. This element of "market illiquidity" is missing in Diamond and Dybvig (1983).

Based on the theoretical work of Gertler and Kiyotaki (2015) and Gertler et al. (2019) develop a quantitative New Keynesian DSGE model with bank runs to characterize the recent financial crisis. The economy experiences sharp, nonlinear contractions when bank balance sheets are weak and banks are subject to runs. Their model studies how bank runs affect the real economy both qualitatively and quantitatively. Particularly, they show how optimistic beliefs about the economy leads to credit booms and excessive fragility that increases the bank run risk and drags the economy into crisis, as we have recently experienced.

Bank Run Risk. Bank runs change macro quantities and asset prices when they are realized (ex post bank runs). Moreover, they have an amplifying effect if there is an anticipation of bank runs in the economy. There are two forces at play: First, the probability of bank run is priced into the deposit rate, which raises the cost of borrowing for bankers. Second, the probability of getting into the bank run regime positively depends on the leverage; as a result, bankers' precautionary motives make them take less leverage. As banks earn a spread between their assets and liabilities, the severe leverage limit, endogenously caused by bank run risk, slows down the recovery rate of net worth in recessions.

Policy Implications. Models with bank runs provide us new insights on the design of prudential policies of ex-ante capital requirement policy and ex-post lender of last resort policy. The ex-ante capital requirement policy reduces bankers' leverage choice and make them less prone to runs. However, there is a tradeoff between less fragility and less intermediation activity. The ex-post lender of last resort policy can raise the price of capital when funding dries up in the market, thus reducing the possibility of the economy getting into the bank run regime. The policy of lender of last resort can strengthen households' beliefs that bank run would not happen and reduce the probability of bank runs. In these cases, the government does not even need to inject real resources to bail out the banks.

These two papers successfully incorporate the insight of bank runs into a dynamic macroeconomic model. One shortcut that is shared by both papers is the sunspot determination of bank runs. The probability of run is linked to the economic fundamentals in a reduced-form way. We may seek to microfound the occurence of bank runs as well as its probability in a richer economic environment, for example, using the global game technique proposed by Goldstein and Pauzner (2005). It will potentially open up more insightful discussions on the general equilibrium effect of bank runs on real economic activities.

2.5 Critical Reflections

Empirical Successes and Challenges. A vast literature has provided empirical support to the macroeconomics literature with financing frictions. Bernanke and Gertler (1995) summarize the early empirical literature on the effect of financing frictions in firms' decisions. The empirical literature also offers plentiful evidence for the impact of macroeconomic shocks (monetary policy, particularly) on the credit supply when the banking sector faces financial frictions, e.g., Kashyap and Stein (2000) and Jiménez et al. (2014).

After the financial crisis, burgeoning empirical evidence is provided on the interactive relationship between macro and financial variables. Gilchrist and Zakrajsek (2012) construct a credit spread index (excess bond premium) that excludes the firms' expected default premium. They show that this financial variable has strong predictive power on future macroeconomic activities. The excess bond premium is now widely used as a risk capacity of the economy, especially the financial sector. In terms of macroeconomic quantities, aggregate credit expansion is viewed as the most significant predictor of financial crisis (see, e.g., Schularick and Taylor, 2012; Gourinchas and Obstfeld, 2012). Moreover, Reinhart and Rogoff (2011) empirically show the tight intrinsic connection between private debt spike, banking crisis, and sovereign default.

The models with financing frictions motivate empirical studies of asset prices that shed light on the critical role of financial sector health. The US broker-dealers' net worth is found to price a set of cross-sectional assets (see, e.g., He et al., 2017; Adrian et al., 2014). Muir (2017) shows that standard consumption-based models cannot explain the asset price drop and risk premium spike during the finanicial crisis, which indicates the specialty of financial crisis.

The macroeconomics literature with financing frictions also face some empirical challenges. In a recent paper, Baron and Xiong (2017) empirically show that credit expansion raises crash risk for banks in subsequent periods. Moreover, the increased crash risk is not compensated by higher subsequent bank equity return. Instead, credit expansion is associated with a lower subsequent bank equity returns. It is a puzzling finding through the lens of the models we reviewed before. All models indicate that the increased fragility is requires higher risk premium while in the data the additional premium does not exist in the data.

Growing Out of Financing Constraint and the Role of Heterogeneity. Chari et al. (2008) criticize the literature of macroeconomics with financial frictions by showing that the US corporations can repay all their debt burdens using their retained earnings in aggregate. In other words, corporations in the US have excess internal funds. This poses a challenge for models with financial frictions to account for: If firms have ample internal wealth, why do the financial constraints matter?

One potential solution is to look at the cross-sectional heterogeneity in firms. In the speech at the Nobel Symposium of Money and Banking, V.V.Chari showed that most of the firms that are affected by financial frictions are private firms while public firms mostly have enough internal funds. Zetlin-Jones and Shourideh (2017) provide a model in which only some firms are constrained, and the constraints are spilled over to other unconstrained firms. Moreover, they find financial shocks only generate moderate declines in economic activities in aggregate. On the contrary, Khan and Thomas (2013) find large and persistent reductions in aggregate TFPs due to financial shocks. They evaluate the role of financial shocks in a general equilibrium model of default and idiosyncratic productivity heterogeneity. Financial shocks are amplified and propogated due to distortions in the cross sectional distribution of capital. Gomes and Schmid (2016) develop a quantitative model with heterogenous firms and default that study the joint determination of leverage, investment, credit spread, equity premium, and value premium. Buera and Moll (2015) show that different models with heterogeneity maps into different aggregate distortions and the Euler equations are not distorted. The comparison indicates limitations on the use of representative models to identify the source of fluctuations.

A related challenge to the literature is that if the frictions have serious consequences such as financial crises, why don't firms precautionarily save to prevent it from happening? Rampini and Viswanathan (2010) argue that hedging the financial crisis takes resources and firms face a tradeoff between risk management and investment. When debt capacity is limited, firms face the tradeoff to allocate the limited capital: Hedging forgoes investment opportunities. The model has several implications. First, more productive firms exhaust debt capacity and downsize their investment more easily in economic downturns, and thus leads to more severe capital allocation. Second, small firms choose less risk management because they have little net worth. Rampini et al. (2014) provide empirical evidence while Rampini et al. (2017) provide evidence on financial institution risk management that better capitalized financial institutions hedge more. Rampini and Viswanathan (2013) develop a full dynamic model with endogenous firm net worth.

Financial frictions are also seen as one main driving forces of misallocation, especially in developing countries. Midrigan and Xu (2014) quantitatively assess the different channels that financial frictions affect misallocation and find that the effect mainly takes place on the extensive margin. The new entrants and technology adoption are distorted for lack of funding. On the other hand, the intensive margin effect for given firms is small, because firms can quickly save out of retained earnings to get out of the financial constraints. The importance of extensive margin also requires models with heterogeneous firms in the cross-section.

Moll (2014) study how much firms' self-financing can undo the distortions brought by financial frictions in a neoclassical growth model. He analyzes both the steady-state effect and the transitional effect with transitory and highly persistent shocks. Persistent TFP shocks enable self-financing so that the steady state distortionary effect is small, but the transition can be very slow. On the contrary, when TFP shocks are transitory, the steady state distortions are large while the transition is faster.

On the other hand, Boissay et al. (2016) construct a model of heterogeneous banks with credit booms and banking crisis. Banks differ in their intermediation efficiencies, which are banks' private information. Moreover, banks also have moral hazard problems that they have the ability to divert away their assets for private benefits. When the cost of funding is low in booms, the moral hazard problem is more severe, especially for those less efficient banks. However, market participants do not observe the intermediation efficiency of each bank, so that it exacerbates the interbank market frictions. As a result, the interbank freezes endogenously when the cost of funding is below a critical value and a banking crisis takes place. This model also implies that credit booms precede banking crises, and the bank heterogeneity and interbank market play critical roles.

Financial Shocks and Corporate Behavior. In most of the models with financing frictions, the financial sector serves as an amplifier that propagates the fundamental macroeconomic shocks. However, the financial sector itself may be the origin of the shock. Jermann and Quadrini (2012) quantitatively show that shocks in the tightness of financing constraint (or the margins) are important in accounting for the US business cycle and more importantly the financial flows in the corporate sector.

Jermann and Quadrini (2012) deliver the main insight that understanding shocks originated from the financial sector is important in understanding the corporate financial behaviors, such as debt and equity financing. While they model the financial shocks are completely exogenous processes, it is interesting future research to explore the micro foundation and cyclical dynamics of the financial shocks.

3 Models with Households' Leverage Constraints

The episode before the Great Recession witnessed a boom in housing prices and a substantial expansion of subprime mortgages. An empirical study by Mian and Sufi (2009) shows at the ZIP code level that the martgage default rates are highly correlated with the amount of subprime mortgages. Moreover, regions that receive higher subprime mortgage credit have lower income growth in the past 20 years abd thus lower credit demand. These two observations indicate a credit supply effect from easing mortgage financing. Mian and Sufi (2011) find a strong link between housing price and household borrowing, especially those that facen tighter borrowing constraints. These empirical findings lead us to study the important roles of housing and household leverage in driving macroeconomic quantities and asset prices. In this section, we briefly review the related macro-finance literature about households' leverage, mortgage, and housing. For a more complete survey on this topic, see Guerrieri and Uhlig (2016).

The focus of the literature is centered around two themes: (i) what are the main drivers of housing demand, default, and house prices; and (ii) the macro-financial consequences of the housing boom and bust? Particularly, the literature is interested in whether the easing credit can account for the subsequent crisis. The literature can be split into partial equilibrium and general equilibrium models. Partial equilibrium models take real estate prices as given, while general equilibrium models endogenously solve for prices of real estate as well as other assets.

Housing Demand, Default, and House Prices. Campbell and Cocco (2003) provide a benchmark life-cycle portfolio choice model on housing and mortgages. The model incorporates various sources of risks, including labor income, interest rate, inflation, and house price risk, as well as a borrowing constraint. Campbell and Cocco (2015) study the default decision within a similar modeling framework. Ortalo-Magne and Rady (2006) propose a life-cycle model with property ladder and credit constraints. They show that income volatility of the young households and the relaxation of their credit constraints explains the housing price volatility. Landvoigt (2017) estimates a structural model with credit constraints and beliefs about future prices. He emphasizes on the key driving force of the expectation of future housing prices and its uncertainty on housing demand. He also finds that the sensitivity of housing demand with credit conditions and future expectations and especially high for constrained households. Favara and Imbs (2015) provide empirical evidence on mortgage supply as a cause of housing price booms. In a quantitative model context, Chatterjee and Eyigungor (2015) stress the role of favorable tax treatment of housing in understanding the patterns of the housing market.

Corbae and Quintin (2015) explore whether the foreclosure crisis can be explained by the increased high-leverage mortgage origination during the housing boom in the context of a partial equilibrium quantitative model with exogenous housing prices. In the model, heterogenous agents with idiosyncratic age, income, and house-specific price risks choose between high and low down payment fixed-rate mortgages. Structural shocks include housing prices and relaxation of mortgage approval standard. Two effects are at play. When housing prices drop, highly levered households run out of net equity and default (the "leverage effect"). On the other hand, the lower approval standard attract more households with low income and low assets into the mortgage market. These borrowers are more likely to default in adverse scenarios (the "selection effect"). The model's quantitative experiment suggests that relaxed financing constraint can account for 62 percent of the rise in foreclosures. In a related paper, Huo and Ríos-Rull (2016) also show that financial shocks can generate large drops in housing prices in a heterogeneous agent setting. Other general equilibrium model with similar results include Kermani (2012) and He et al. (2015). Hatchondo et al. (2015) show the prudential policies that limit the loan-to-value ratios can lower default rate while boost housing demand. Garriga et al. (2019) provide a quantitative general equilibrium model in which housing market is segmented from other asset classes. In the model context, mortgage rate reductions increase housing price while the effect of loosening leverage constraint is ambiguous. In a recent empirical paper, Cox and Ludvigson (2018) examine direct measures of credit conditions and investors' beliefs. They find that looser credit conditions contribute to both contemporaneous higher risky debt fraction and future housing price spikes.

Favilukis et al. (2017) study a quantitative general equilibrium production model of two sectors. The model includes aggregate risk and production, and generates a realistic wealth distribution that is highly skewed with the presumption of bequest heterogeneity. In their study, the relaxation and tightening of collateral constraints explains the housing boom-bust cycle.

Another set of the papers in the literature find a limited effect of the relaxation of households' collateral constraint. In Kiyotaki et al. (2011), housing prices mainly react to exogenous changes in expected productivity or the world interest rate, but responds very little to changing financing constraint. Sommer et al. (2013) also find that changing financing constraint can only have small effect on housing prices.

Favilukis et al. (2017) analyze the potential reasons for the different conclusions in the literature. In Favilukis et al. (2017), they highlight the important role of aggregate risk and bequest heterogeneity, which are absent in much of the literature that find small effect of easing financial constraints. Aggregate risk is important because it affects risk premium in housing, while bequest heterogeneity is important because it raises the fraction of agents that are constrained.

In Justiniano et al. (2015), they distinguish the two types of constraints: the borrowing constraint, i.e., the collateral requirement, and the lending constraint, i.e., the technology that allows savings to flow into the mortgage market. They find that the ease of borrowing constraint alone is not enough to acccount for the salient features of the US housing market, and the ease of lending constraint plays a crucial role. Greenwald (2018) argues that it is the debt-to-income ratio, instead of the loan-to-value ratio that is the crucial indicator of credit conditions.

The Macro-Financial Consequences of the Housing Boom and Bust. With models of exogenous housing prices, Campbell and Hercowitz (2005) and Iacoviello and Pavan (2013) study the macroeconomic effect of loosing the financing constraint with lower down payment rate. They find that the declines in down payment reduces macroeconomic volatility.

Iacoviello (2005) provides the workhorse dynamic general equilibrium model of household debt and mortgage. It features nominal debt and households' collateral constraints within a new Keynesian model framework. In this model, the author contrasts the different effects of collateral constraint on demand and supply shocks. Collateral constraint amplifies demand shock and dampens supply shocks. Positive demand shocks and negative supply shocks lead to aggregate price level increase and reduces the real debt burden, which in turn increases the borrowing capacity and increases the aggregate demand.

Lustig and Van Nieuwerburgh (2006) examine the effect of housing price on other asset price movements, and find that housing price boom loosens the collateral constraints and boosts up other risky asset prices. Lustig and Van Nieuwerburgh (2010) show that the loosen constraints induced by increases in housing prices improves risk sharing across regions. Piazzesi and Schneider (2012) link the increase in demand of houses as an asset to the changing demographic structure and inflation of the economy. The structures changes make real estates more attractive than equities and bonds to investors.

4 Models with Financial Networks

Typically, in a financial crisis, trouble orinigates in a limited set of institutions and is transmissed across the whole system through the linkages across institutions (financial network). In this section, we review the literature related to shock transmission, stability, and efficiency of a financial network.

The literature on how network propogates shocks has been long in business cycle analysis, dating back to Long and Plosser (1983)'s multisector real business cycle model. Sectors are interdependent because of input-output linkage, so that a shock to one sector is propogated to sectors that use its product as input and sectors that provide intermediate inputs to the shocked sector. In a world with financial network, institutions are connected through cross-holding of each other's financial claims. This section is organized based on three themes of the literature: (i) What is the mechanism of shock transmission from one single institution to others? (ii) How is the structure of the network related to the stability of the system? (iii) Are financial networks efficient and what is the optimal network structure?

The Transmission Mechanisms Across the Network. Allen and Gale (2000) illustrate a bank-run based mechanism of financial contagion. The economy features a number of regions facing idiosyncratic liquidity shocks while the aggregate liquidity demand is constant. An interbank market (financial network) provides liquidity risk sharing for banks in different regions by holding deposits in other regions. However, when one region has a slightly larger liquidity demand, banks in that region will have to liquidate the long-term, illiquid assets and trigger bank run in the troubled region. In turn, the bankruptcy of banks in the troubled region lowers the value of their deposits, which triggers a run in banks that hold their deposits. By induction, a small liquidity shock to one region can lead to large economywide crisis.

Elliott et al. (2014) present an alternative model of contagion. In that model, there is a loss of the value of productive asset held by a certain institution when the market value of this institution falls below a certain point. Therefore, other institutions that directly hold the productive asset are exposed to the shock, which also affects their asset values. By induction, even though some institution does not directly hold the same productive asset as the initial institution in trouble, it is indirectly affected through the network.

Private information also makes contagion prevalent in financial networks. For example, Kodres and Pritsker (2002) show that portfolio rebalancing across markets in the presence of private information can lead to severe contagion even between economies with weak macroeconomic links. In their model, informed and uninformed investors make portfolio choices among the N countries' assets in the economy. The informed investors receive signals on the fundamentals of these economies. When investors rebalance their holdings of all countries' assets in response to news in one country. Uninformed investors will perceive the order flow as containing news. This portfolio rebalancing effect is particularly strong for countries where private information is severe, such as emerging economies.

Caballero and Simsek (2013) consider a model with complex financial network and information asymmetry. Banks borrow from and lend to each other but all banks only have information about the their closest neighbors. Each bank chooses the the composition of balance sheet: holding the productive asset gives higher return while holding liquid assets enables payment on demand. When a liquidity shock hits some random bank in the network, banks precautionarily choose to have a liquid balance sheet due to their limited information on which bank is hit by the liquidity shock. The liquidation of productive asset lowers the asset price and worsen the balance sheet of all the banks, even those distant from the bank that is hit by the liquidity shock.

Network Structure and Stability. In the early literature, for example, Allen and Gale (2000) and Freixas et al. (2000), contagion is weaker when the structure of the network is more condense, because the liquidation cost is burdened by more institutions n the network. The recent literature uncovers a tradeoff between risk sharing and contagion effect of the financial network. Elliott et al. (2014) show that the benefit of risk sharing outweighs the cost of contagion when the network is segmented. When the network gets more connected, the cost exceeds benefit beyond a certain point. With the similar logic, Acemoglu et al. (2015) discuss the relationship between network structure and stability regarding different nature of shocks. With small shocks, the benefit is larger than the cost, while contagion makes the system fragile when the shock is large.

Efficiency and Optimal Network. Generally, financial network cannot achieve the first-best allocation of risk due to network externalities: When one institution makes decisions, it does not take into account its effect on other institutions. For example, in Caballero and Simsek (2013), when banks liquidate their productive asset, they do not consider their liquidation's effect on the asset price. Moreover, complexity of the network and limited information amplifies to inefficiency in their model.

Wang (2015) identifies two sources of ineffiency when firms that differ in distress risk endogenously form networks. Links between non-distressed firms create gains for risk sharing, while links with distressed firms are socially costly as it raises the systemic risk. When firms can choose the counterparty, the most liquid firms form too many links with distressed firms because they do not take into account its effect on other network players. Excessive links with distressed firms dampen risk sharing gains and the links between non-distressed firms are fewer than optimal.

Cabrales et al. (2017) obtain the optimal design of network under different conditions. In most cases, the optimal network is between a fully integrated or segmented one. They provide a guidance for designing network policy: Institutions should optimally form network with the ones that have similar risk distributions. In contrast, Leitner (2005) shows the optimality of a complete network (when all institutions are linked to each other) when the contagion threat leads to private bailout.

Based on the argument of network externality and its inefficiency, Acharya et al. (2017) propose an explanation of the observed large dividend payout of banks in crisis. When institutions make dividend payment decisions, they do not take into account the increased probability of default of their creditors induced by their dividend payment. Therefore, the dividend policy is suboptimal and excessive.

5 A Canonical Macro-Finance Model

In this section, we provide a benchmark model in the spirit of Gertler and Kiyotaki (2010), and compare solutions obtained using different solution methods. More details about the model and solutions are relegated to the appendix.

5.1 Households

There is a continuum of representative households, with workers and bankers that consume together. Each banker within a household manages a financial intermediary. Workers deposit funds into these intermediaries. Intermediaries hold equity claims on capital. In each period,

$1-\theta$ of bankers and workers switch their roles. Exiting bankers rebate the net worth of banks to their households, while the new bankers receive start-up funds from their households.

The households solve the optimization problem:

$$\max_{C_{t+\tau},B_{t+\tau},B_{g,t+\tau}} \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} \beta^{\tau} \frac{C_{t+\tau}^{1-\gamma}}{1-\gamma} \right], \tag{1}$$

$$s.t.: C_t = W_t L_t + \Pi_t - T_t + (1+R_{f,t-1})(B_{t-1} + B_{g,t-1}) - (B_t + B_{g,t}), \tag{2}$$

where C_t, W_t, T_t, Π_t are household consumption, real wage, tax, and profits from exiting intermediaries, respectively. B_t denotes bank deposit, and $B_{g,t}$ denotes government debt $R_{f,t}$ is the real interest rate to deposit and government debt. Bank deposit and government are perfect substitutes. The intertemporal Euler equation is

$$1 = \mathbb{E}_t \left[\frac{\Lambda_{t+1}}{\Lambda_t}(1+R_{f,t}) \right], \quad \text{where } \Lambda_t \equiv \beta^t (C_t)^{-\gamma}. \tag{3}$$

5.2 Consumption Goods Sector

There is a continuum of representative firms in the consumption goods sector. Each firm produces its output using Cobb-Douglas technology with capital and labor.

$$Y_t = A_{c,t} K_t^{\alpha} L_{c,t}^{1-\alpha}, \quad 0 < \alpha < 1, \tag{4}$$

where $A_{c,t}$ is an exogenous total factor productivity (TFP) process that follows:

$$\ln A_{c,t} \quad = \quad \ln A_{c,t-1} + \sigma_a \epsilon_{a,t} \tag{5}$$

where $\epsilon_{a,t}$ are i.i.d. standard normal variables.

There is no friction between firms and intermediaries. Firms hire labor $L_{c,t}$ and use the capital K_t to produce, and make investment decisions I_t. Denote depreciation rate δ, the law of motion for aggregate capital stock is given by

$$K_{t+1} = I_t + (1-\delta)K_t. \tag{6}$$

There are convex adjustment costs for the rate of investment:

$$\Upsilon_t = \Upsilon(I_t; K_t) \equiv I_t + g(I_t, K_t), \quad \text{where } g(I_t, K_t) \equiv \frac{\vartheta}{2}\left(\frac{I_t}{K_t}\right)^2 K_t, \tag{7}$$

Denote P_t the price of investment goods, and Q_t the price of capital. Define the dividend of firms:

$$D_t \equiv Y_t - W_t L_{c,t} - P_t \Upsilon(I_t, K_t). \tag{8}$$

The stock return can be written as

$$1 + R_{k,t+1} = \underbrace{\frac{D_{t+1}}{Q_t K_{t+1}}}_{\text{total dividend return}} + \underbrace{\frac{Q_{t+1} K_{t+2}}{Q_t K_{t+1}}}_{\text{total capital gains return}}. \tag{9}$$

The optimal investment decision solves:

$$\max_{I_{t+1}} Q_{t+1} I_{t+1} - P_{t+1} \Upsilon(I_{t+1}; K_{t+1}). \tag{10}$$

The first-order condition with respect to I_{t+1}:

$$Q_{t+1}/P_{t+1} = 1 + \vartheta i_{t+1}, \quad \text{where } \; i_{t+1} \equiv \frac{I_{t+1}}{K_{t+1}}. \tag{11}$$

The optimal labor demand by consumption goods sector satisfies:

$$L_{c,t+1} = \left[(1-\alpha)\frac{A_{c,t+1}}{W_{t+1}}\right]^{1/\alpha} K_{t+1}. \tag{12}$$

Consumption goods are either distributed as wage or dividend, so the following equation holds:

$$Y_t = D_t + W_t L_{c,t} + W_t L_{\iota,t}. \tag{13}$$

where $L_{\iota,t}$ is labor allocated to investment good firms.

5.3 Investment Goods Sector

There is a continuum of representative investment good firms which produce investment goods using labor. Their production function is:

$$\Upsilon_t = A_{\iota,t} L_{\iota,t} \tag{14}$$

where $A_{\iota,t}$ is the productivity of investment goods production. We assume that $A_{\iota,t} = Z_\iota K_t$, with Z_ι being a constant.

The market clearing condition for labor market requires

$$L_{c,t} + L_{\iota,t} = L_t \equiv 1 \tag{15}$$

5.4 Financial Intermediaries

Financial intermediaries borrow funds from households at a risk-free rate, pool the funds with their own net worth and invest the sum in the equity of the representative consumption good firm. The balance sheet equation of intermediary j is:

$$Q_t K_{t+1} S_{j,t} = N_{j,t} + B_{j,t}, \tag{16}$$

where $S_{j,t}$ is the quantity of equity held by the intermediary, $N_{j,t}$ is the net worth, and $B_{j,t}$ is the deposits raised from households. The intermediary earns a return $R_{k,t+1}$ from the equity investment at time $t+1$, and must pay the interest, $R_{f,t}$, on the deposit. Intermediary net worth evolves as:

$$N_{j,t+1} \quad = \quad (R_{k,t+1} - R_{f,t})Q_t K_{t+1} S_{j,t} + (1 + R_{f,t})N_{j,t} \tag{17}$$

The intermediaries face a constraint on raising deposits that the franchise value of intermediaries cannot be smaller than λ_t fraction of their assets. The value of the financial intermediary j can be expressed as:

$$V_{j,t} = \max_{S_{j,t+1},B_{j,t+1}} \mathbb{E}_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \left[(1-\theta)N_{j,t+1} + \theta V_{j,t+1}\right] \right\}. \tag{18}$$

$$s.t. : V_{j,t} \geq \lambda_t Q_t K_{t+1} S_{j,t}. \tag{19}$$

The log of margin parameter, $\ln \lambda_t$ follows a first-order Markov chain.

The value of the financial intermediary j is linear in its net worth:

$$V_{j,t} = \Omega_t N_{j,t} \tag{20}$$

where Ω_t is the marginal value of net worth for financial intermediaries. The total net worth share $n_t \equiv \dfrac{N_t}{Q_t K_{t+1}}$ is the only endogenous state variable, with $N_t \equiv \int_j N_{j,t} \mathrm{d}j$. Denote $S_{p,t} \equiv \int_j S_{j,t} \mathrm{d}j$ be the shares of firms held by private financial intermediaries.

The first-order condition gives

$$0 \leq \mu_{j,t} \lambda_t \Omega_t^{-1} = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1}(R_{k,t+1} - R_{f,t})\right], \tag{21}$$

The effective IMRS of intermediaries is $\mathcal{M}^{\mathcal{I}}_{t,t+1} \equiv \mathcal{M}_{t,t+1} \dfrac{1-\theta+\theta\Omega_{t+1}}{\Omega_t}$. The condition shows that $\mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1}(R_{k,t+1} - R_{f,t})\right] > 0$ when the credit constraint is binding. $\mu_{j,t}$ is the Lagrangerian multiplier on the constraint for intermediary j. We consider the symmetric equilibrium: $\mu_{j,t} = \mu_t$.

The pricing rules for risk-free bonds and firm equity are:

$$1 \geq 1 - \mu_t = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1}(1 + R_{f,t}) \right], \quad \text{and} \tag{22}$$

$$1 \geq 1 - \mu_t(1 - \lambda_t \Omega_t^{-1}) = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1}(1 + R_{k,t+1}) \right]. \tag{23}$$

5.5 Net Worth Evolution

After integrating the dynamic equations in (17) over all intermediaries and accounting for the net fund transfer, the aggregate net worth share evolves as:

$$n_{t+1} = \theta \left[(R_{k,t+1} - R_{f,t}) S_{p,t} + (1 + R_{f,t}) n_t \right] / G_{k,t+1} + \aleph \tag{24}$$

where $G_{k,t+1} \equiv \frac{Q_{t+1}K_{t+2}}{Q_t K_{t+1}}$ is the total capital gain of equity, ane $\aleph Q_{t+1}K_{t+2}$ is the total startup funds received by new bankers.

5.6 Government Policies

In our model, the government buys a fraction $S_{g,t}$ of the total outstanding shares of firms (normalized to one), so that

$$1 = S_{p,t} + S_{g,t} \tag{25}$$

where $S_{p,t} \equiv \int S_{j,t} \mathrm{d}j$ is the total share of equity held privately. The government credit has an efficiency cost of $\tau > 0$ units per unit of credit supplied, but the government is not financially constrained.

We define the risk premium in a frictionless economy $\Xi^* = \gamma \sigma_a^2 - \frac{1}{2}\sigma_a^2$. The government credit policy rule follows:

$$S_{p,t} = \frac{1}{1 + \nu_g \times (\Xi_t - \Xi^*)} \approx \nu_g \times (\Xi_t - \Xi^*), \tag{26}$$

The government expands credit as the risk premium Ξ_t increases, $\nu_g > 0$ is a constant.

5.7 Resource and Government Budget Constraints

Suppose government expenditure is a fixed proportion $\overline{g}$ of total output. The resource constraint for the final good is given by

$$Y_t = C_t + \overline{g}Y_t + \tau S_{g,t}Q_t K_{t+1}. \tag{27}$$

Finally, the government budget constraint is

$$\overline{g}Y_t + (1+\tau)S_{g,t}Q_t K_{t+1} = T_t + S_{g,t-1}Q_{t-1}K_t(R_{k,t} - R_{f,t-1}) + B_{g,t}. \tag{28}$$

6 Comparing Solution Methods

In this section, we solve the model introduced in the previous section using both local and global methods. Solving the DSGE model with heterogeneous agents in incomplete markets and severe nonlinearity is mathematically equivalent to solving a large system of nonlinear equations. The nonlinearity and infinite dimensionality of the model makes the problem challenging.

In local methods, the solution relies on log-linearization around the steady state. First-order approximations have been, until recently, the main tool employed for numerically solving and empirically evaluating DSGE models. However, as Judd (1997, p. 911) observes, "If theoretical physicists insisted on using only closed-form solutions or proofs of theorems to study their models, they would spend their time examining the hydrogen atom, universes with one star, and other highly simplified cases and ignore most interesting applications of physical theories."

The log-linearization approximation method has several important drawbacks. First, the solution methodology makes it impossible to model and study systemic risk. The most recent papers on modeling financial intermediaries, such as He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014), show that the nonlinearity of the amplification effect is a key aspect of systemic risk. Second, first-order approximations fail to be appropriate for evaluating welfare across policies that do not affect the steady state of the economy, e.g., when asset prices and the risk premium are taken into consideration. Log-linearization around a constant steady state is not applicable to asset pricing because, by construction, it eliminates all risk premia in the model. In fact, the risk premium is zero in a first-order approximation, and constant in the case of a second-order approximation, therefore higher-order approximations are required.[5] Third, Fernández-Villaverde et al. (2006) consider log-linearization approximation to be unsatisfactory as they argue that second-order approximation errors in the solution of the model can have first-order effects on the likelihood function approximation. Ackerberg et al. (2009) made important asymptotic corrections to a theoretical result in Fernández-Villaverde et al. (2006), arguing that the approximation error on the classical maximum likelihood estimation of the approximate likelihood function has the same magnitude as the approximation error of equilibrium policy functions. When exact yet highly nonlinear policy functions are approximated by local linear ones, the likelihood implied by the linearized model can diverge greatly from that implied by the exact model, and similarly the likelihood-based point estimation.

6.1 Calibration

We use a calibrated version of the model, basing our parameter choices mainly on those in Gertler and Karadi (2011) and standard choices or estimates in the literature (e.g. Smets and Wouters, 2007). The exogenous autoregressive processes are discretized according to Rouwenhorst (1995). Table 1 shows the calibrated parameters.

6.2 Policy Function Analysis

We solve the model using four different solution methods: first-order perturbation method, second-order perturbation method with pruning [6], the OccBin method proposed by Guerrieri and Iacoviello (2015), and the global solution method based on time-iteration projection procedure. When using pertubation, the model is always perturbed around the deterministic steady state where the constraint binds. In this economy, there are two state variables: constraint margin λ, and intermediary net worth share n. Figure 1 to Figure 4 display the

[5] See, for example, Schmitt-Grohé and Uribe (2004) and Kim et al. (2005), and An and Schorfheide (2007) for a discussion of second-order approximations.

[6] It is important to use pruning to kill the explosive higher order term. Otherwise, the system will explode.

Table 1: Baseline Parameters (Monthly)

Parameter	Symbol	Value	Source
Household preference			
Discount rate	β	$0.99^{\frac{1}{12}}$	Standard
Relative risk aversion	γ	6	Standard
Total labor supply	$\bar{L}$	1	Standard
Financial intermediaries			
Steady-state fraction of divertible capital	$\overline{\lambda}$	0.381	GK (2011)
Proportional transfer to new bankers	$\aleph$	$0.002 \times \frac{1}{12}$	GK (2011)
Survival rate of bankers	θ	$1 - 0.24 \times \frac{1}{12}$	Non-degenerate condition
Consumption-good firms			
Effective capital share	α	0.33	Standard
Depreciation rate	δ	$0.06 \times \frac{1}{12}$	Standard
Adjustment cost coefficient	ϑ	20	Standard
Investment-good firms			
Efficiency of investment good production	Z_ι	$1 \times \frac{1}{12}$	Standard
Government policies			
Government expenditure ratio	$\overline{g}$	20%	Standard
Government efficiency loss	τ	$10\% \times \frac{1}{12}$	Calibration
Sensitivity coefficient	ν_g	5	Calibration
Dynamic			
Volatility of TFP	σ_a	$0.03 \times \sqrt{\frac{1}{12}}$	Standard
Persistence of margin	ρ_λ	$0.6^{\frac{1}{12}}$	GK (2011)
Volatility of margin	σ_λ	$0.267 \times \sqrt{\frac{1-\rho_\lambda^2}{1-\rho_\lambda^{24}}}$	GK (2011)

NOTE: All parameters are standard except the credit-policy related parameters τ, ν_g. We pick ν_g and τ here to provide reasonable private holding shares of risky assets and average risk premia. The closest comparison in the literature is Gertler and Karadi (2011); however, their model is solved using log-linearization techniques. The local approximation significantly understates the magnitude and the volatility of the conditional risk premium, even though the model is capable of generating both quantitatively. The implication of biased asset pricing makes quantitative discussion of unconventional monetary policies itself biased. For example, the suppressed risk premium and its nonlinear dynamics require extremely sensitive unconventional monetary policy in order to have a quantitatively significant stabilization effect on the aggregate quantities. In Gertler and Karadi (2011), the credit policy sensitivity parameter ν_g is chosen about 100 and the cost parameter of the intervention τ is chosen at an extremely small value 0.1%. Parameters on the intermediary side θ, ρ_λ, $\bar{\lambda}$, and $\bar{\sigma}_\lambda$ are calibrated monthly.

policy functions for three possible states of the constraint margin: λ_L, λ_M, and λ_H. Each row in the figures corresponds to λ_L, λ_M, and λ_H respectively. In Panel D of Figure 4, we show the histogram of the ergodic distribution of net worth share n. Policy functions with OccBin method are plotted based on a simulation of 50,000 periods of the economy, with observations corresponding to λ values close to λ_L, λ_M, and λ_H. Therefore, the simulation based policy functions only covers the range of simulated net worth share.

First, we understand the mechanism of the model. The economy features occasionally-binding financial constraints. For any value of λ, low intermediary net worth share n is is associated with a binding constraint with larger multiplier, and a higher marginal value of net worth. It in turn corresponds to lower price of capital q, higher risk premium Ξ, and lower investment i. The government conducts aggressive credit policy. When n is large enough so that the constraint is slack, n does not matter for price of capital and investment. On the other hand, λ indicates how severe the constraint is. Larger values of λ are associated with higher risk premium and lower investment, for the same level of n.

Figure 1 to Figure 4 plot the policy functions of the key variables obtained using different solution methods. Four observations stand out: (1) First and second order perturbation methods work well when n is small and the constraint binds; (2) First and second order perturbation methods work better for larger values of λ; (3) With second order perturbation, policy functions are closer to the global solution; (4) The OccBin method solutions capture the change of constraint slackness.

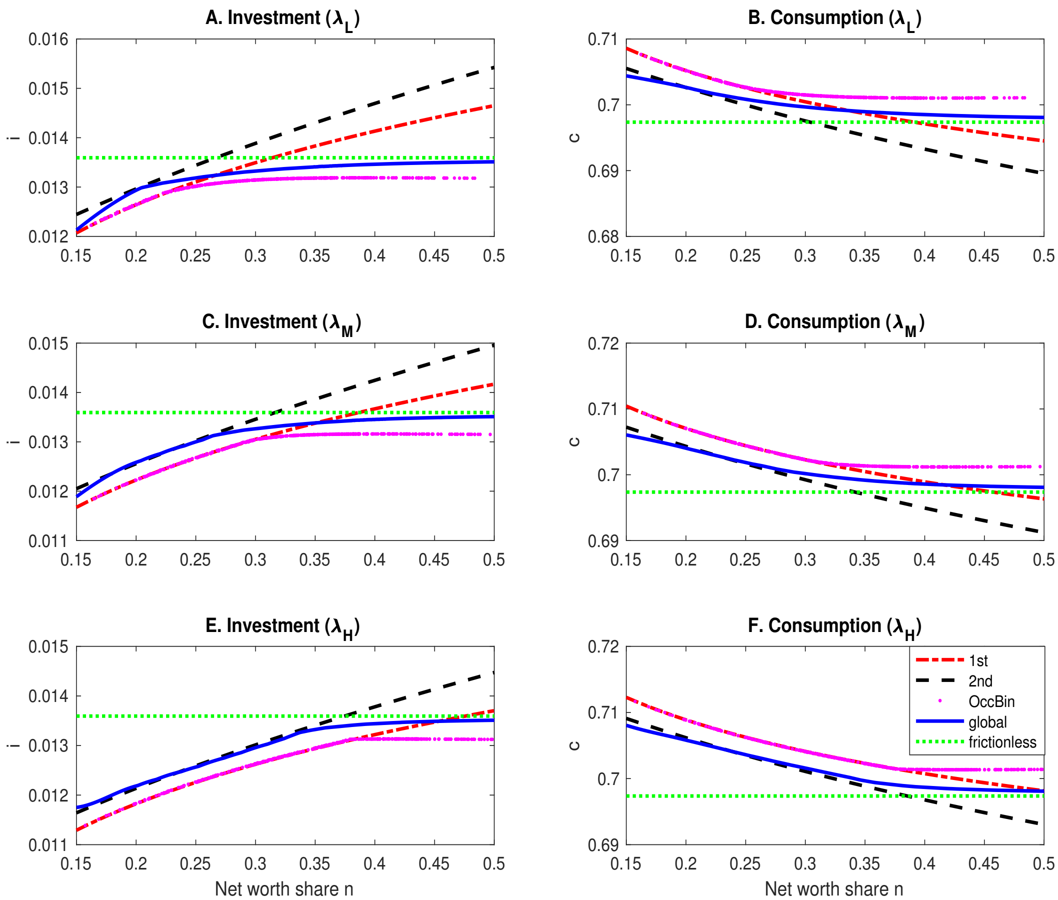
From these observations, we conclude standard pertubation method does a poor job when the constraint is slack. Though OccBin method can capture the change of regime, it is limited to first order and thus ignores the role of risk premium.

6.3 Impulse Response Analysis

In this subsection, we turn to look at the responses of various economic variables when λ has a one-time deviation from λ_M to λ_L. In this case, the constraint is becoming looser, so we highlight how different solution methods can deliver different impulse responses in this scenario. The appendix also reports the impulse responses to positive λ shock.

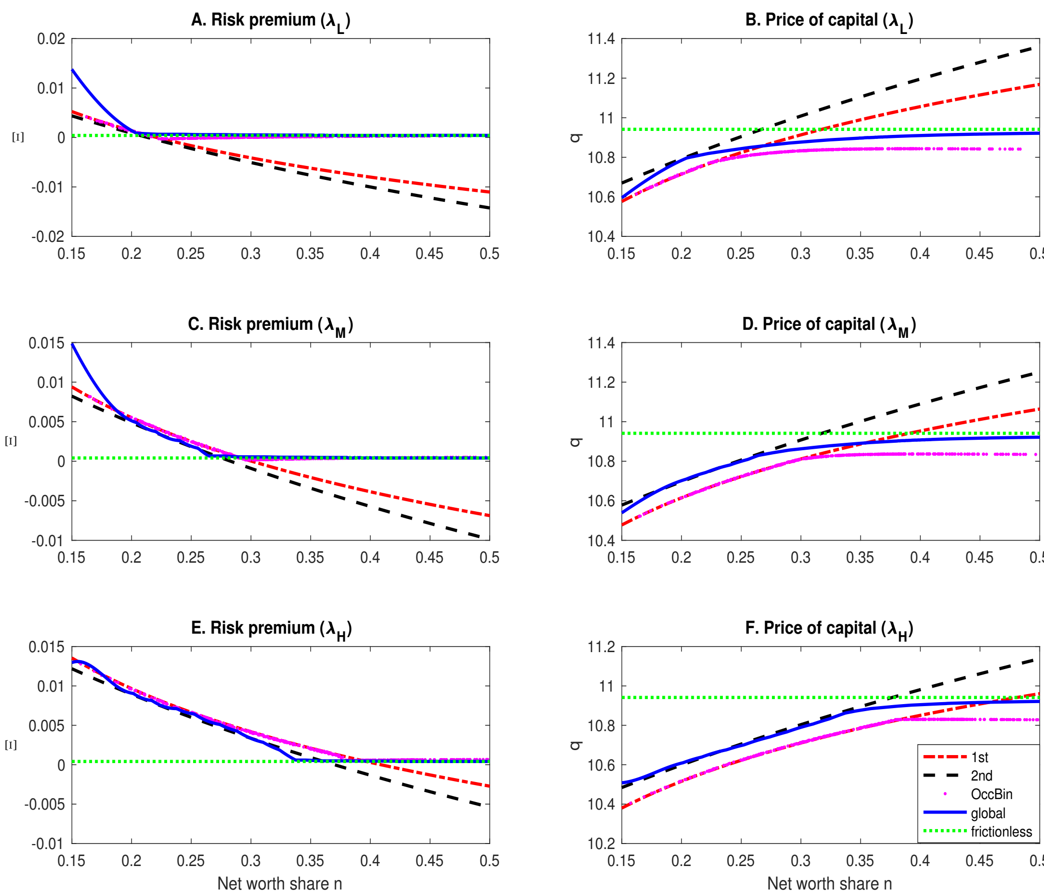
To compute the impulse response functions with global solution, we first simulate N parallel economies ($N = 1000$) for T_1 periods ($T_1 = 200$) when fixing $\lambda = \lambda_M$. Then we let

Figure 1: Policy Functions of Real Variables



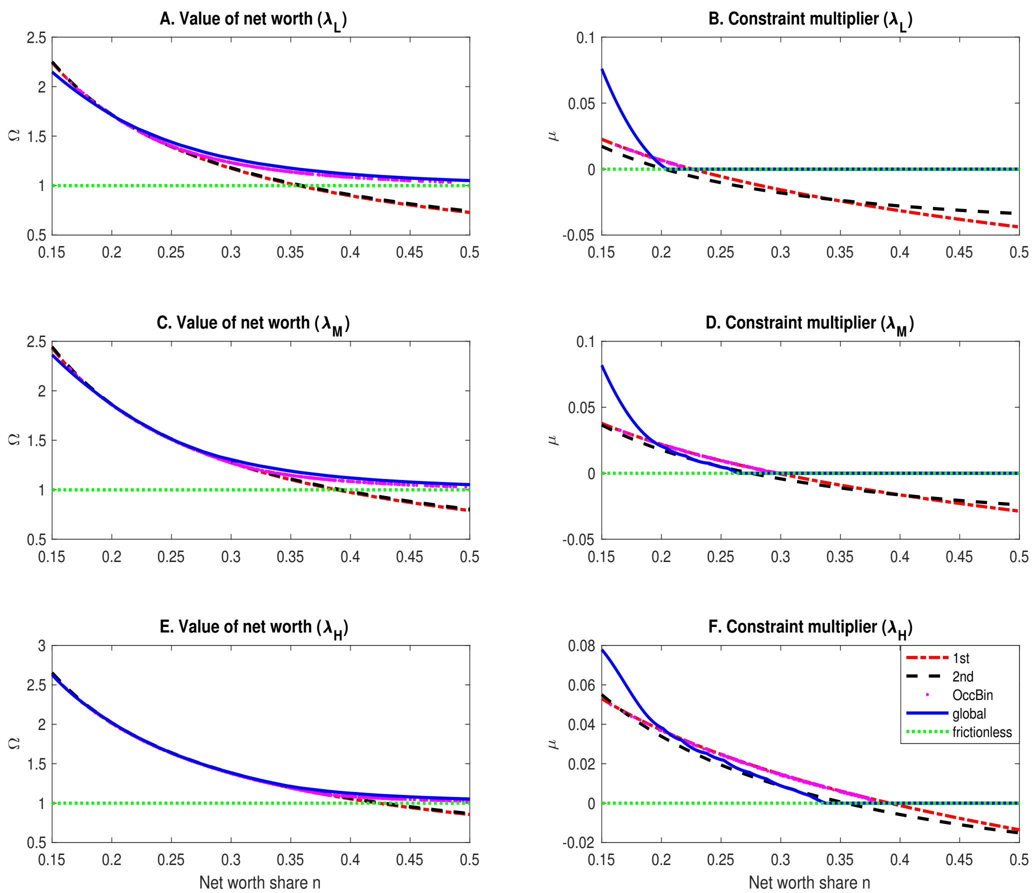
NOTE: This figure shows the policy function of real variables (investment i and consumption c) as a function of intermediary net worth share n for different states λ_L, λ_M, and λ_H. The dot-dashed red line shows the policy function obtained through first order perturbation method. The dashed black line displays the policy function obtained through second order perturbation method with pruning. The dotted pink line shows the policy function obtained through the OccBin method. The solid blue line plots the policy function obtained using global method. The green dots are values of corresponding variables in a frictionless economy.

Figure 2: Policy Functions of Financial Variables



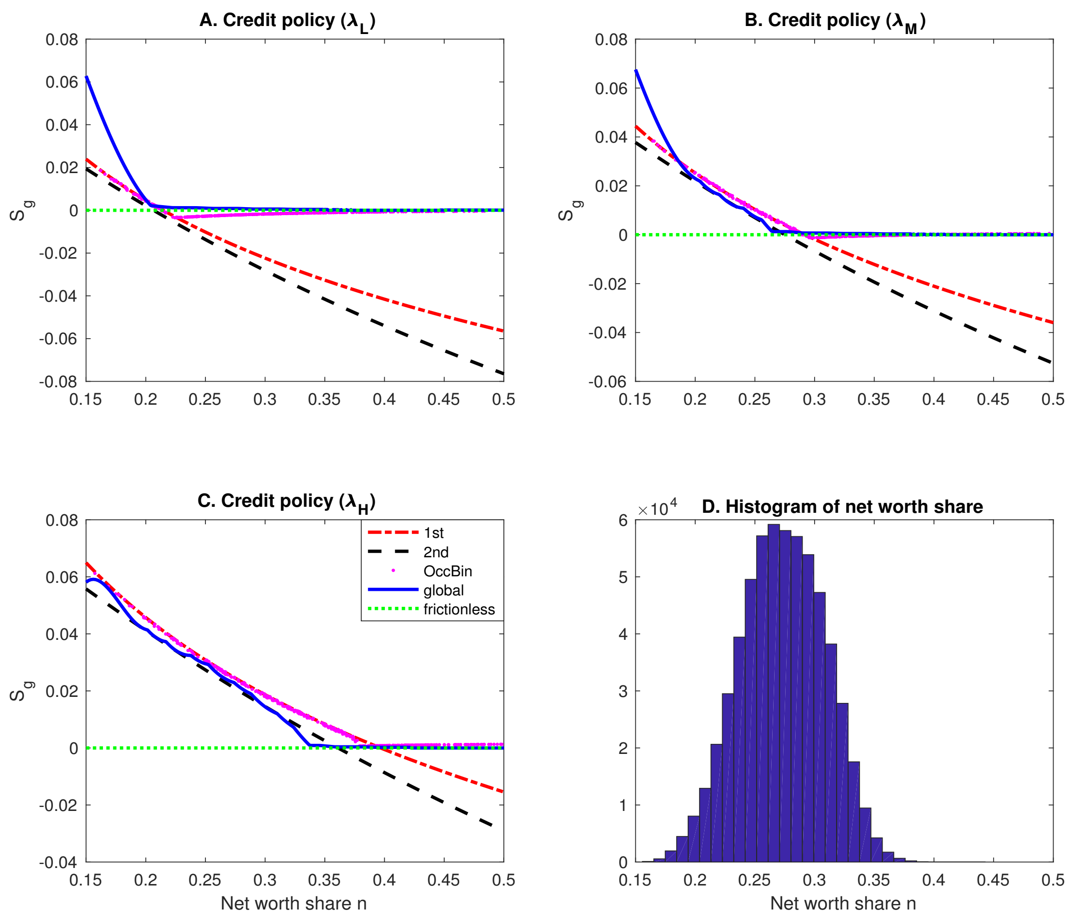
NOTE: This figure shows the policy function of financial variables (risk premium Ξ and capital price q) as a function of intermediary net worth share n for different states λ_L, λ_M, and λ_H. The dot-dashed red line shows the policy function obtained through first order perturbation method.The dashed black line displays the policy function obtained through second order perturbation method with pruning.The dotted pink line shows the policy function obtained through the OccBin method. The solid blue line plots the policy function obtained using global method. The green dots are values of corresponding variables in a frictionless economy.

Figure 3: Policy Functions of Financial Constraint Variables



Note: This figure shows the policy function of variables of the constraint (value of net worth Ω and multiplier of the constraint μ) as a function of intermediary net worth share n for different states λ_L, λ_M, and λ_H. The dot-dashed red line shows the policy function obtained through first order perturbation method.The dashed black line displays the policy function obtained through second order perturbation method with pruning. The dotted pink line shows the policy function obtained through the OccBin method. The solid blue line plots the policy function obtained using global method. The green dots are values of corresponding variables in a frictionless economy.

Figure 4: Credit Policy and Stationary Distribution



NOTE: This figure shows the policy function of credit policy S_g as a function of intermediary net worth share n for different states λ_L, λ_M, and λ_H. The dot-dashed red line shows the policy function obtained through first order perturbation method.The dashed black line displays the policy function obtained through second order perturbation method with pruning. The dotted pink line shows the policy function obtained through the OccBin method. The solid blue line plots the policy function obtained using global method. The green dots are values of corresponding variables in a frictionless economy. We also show the histogram of the stationary distribution of net worth share.

$\lambda = \lambda_L$ for all parallel economies at period $T_1 + 1$, and let the economy evolve afterwards for T_2 periods ($T_2 = 120$, 10 years) with λ drawn randomly from the discretized state space. We compute the mean of various variables after the shock from the N parallel economies.

Figure 5 shows the impulse responses. n is determined by the response of both intermediary net worth and the total value of capital in the economy. Upon a negative shock on λ, both intermediary net worth and total value of λ increase, but intermediary net worth increases more due to leverage, so n increases at first. When the economy reverts back, net worth drops faster than price of capital for the same reason. As time goes by, n converges back to its ergodic mean.

Other variables' direction of impulse responses are then intuitive. When λ decreases, the constraint gets slacker, so risk premium drops, price of capital increases, and investment rate increases. Consumption decreases due to labor reallocation from the consumption good sector to the investment good sector, and wage increases as a result. The government credit policy is less aggressive because of the lowerer risk premium.

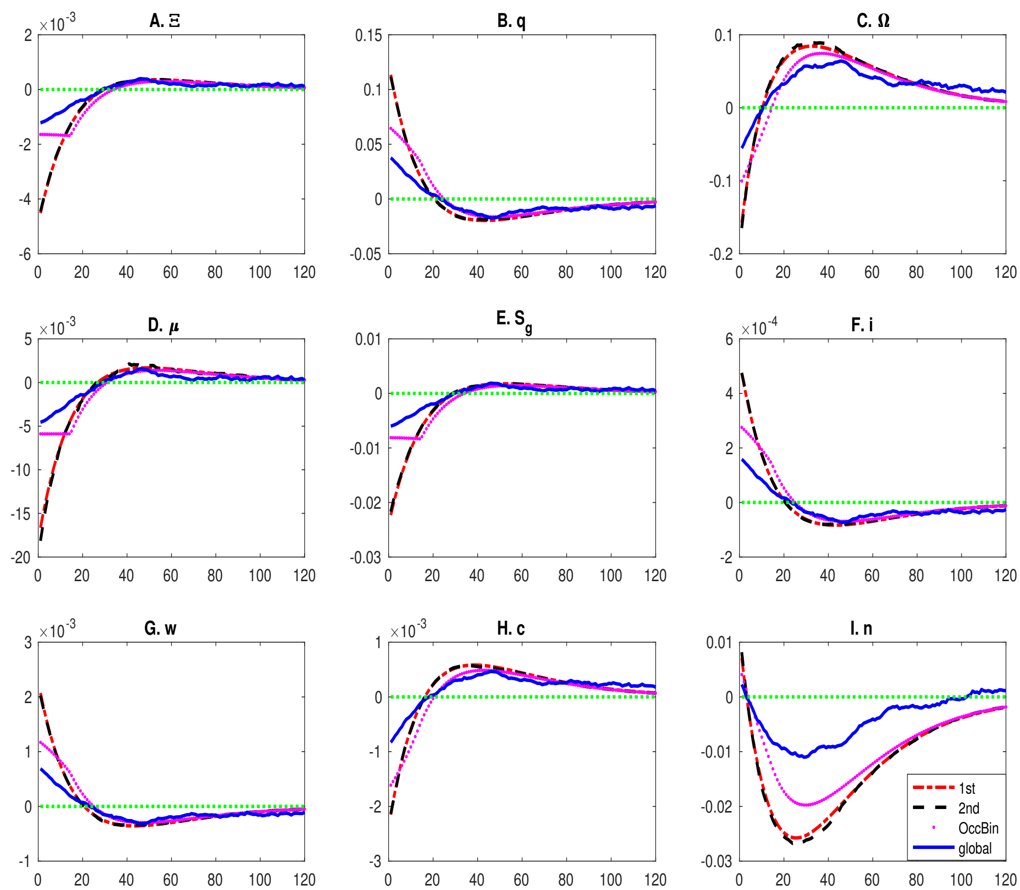
We note that the global solution delivers different responses to solutions from pertubation methods. When λ is lower, the constraint may be slack. Pertubation solutions tend to obtain excessive reaction while assuming the constraint still binds. OccBin method captures the switch of regime, but it misses the role of risk premium so that the responses still do not coincide with the global solution.

6.4 Error Analysis

In this section, we evaluate the accuracy of different solution methods by calculating the errors of equilibrium conditions using our policy functions. The key informative equations are intertemporal Euler equations and market clearing conditions. Figure 6 to Figure 7 present the errors to the intertemporal Euler equations (one for household and two for intermediaries), and market clearing conditions (consumption good, investment good, and security). Errors to market clearing conditions are shown, because they crucially pin down the prices in the economy.

We show the errors to three Euler equations in the most relevant range of $n \sim [0.2, 0.4]$ in Figure 6. First order perturbation solution has significantly larger approximation errors than global solution, while second order pertubation solutions perform better when $\lambda = \lambda_H, \lambda_M$.

Figure 5: Impulse Response Functions to a Negative Shock on λ



NOTE: This figure shows the impulse response functions of various variables upon a negative shock on λ, from λ_M to λ_L. The dot-dashed red line shows the impulse response function obtained through first order pertubation method.The dashed black line displays the impulse response function obtained through second order pertubation method with pruning. The dotted pink line shows the impulse response function obtained through the OccBin method. The solid blue line plots the impulse response function obtained using global method.

The slackness of the constraint determines how accurate perturbation solutions are. When $\lambda = \lambda_L$, the constraint is less likely to bind so the pertubation approximation error is larger. Also, we find that the approximation to households Euler equation is more accurate than intermediary Euler equations. The three market clearing conditions all hold relatively well with different methods.

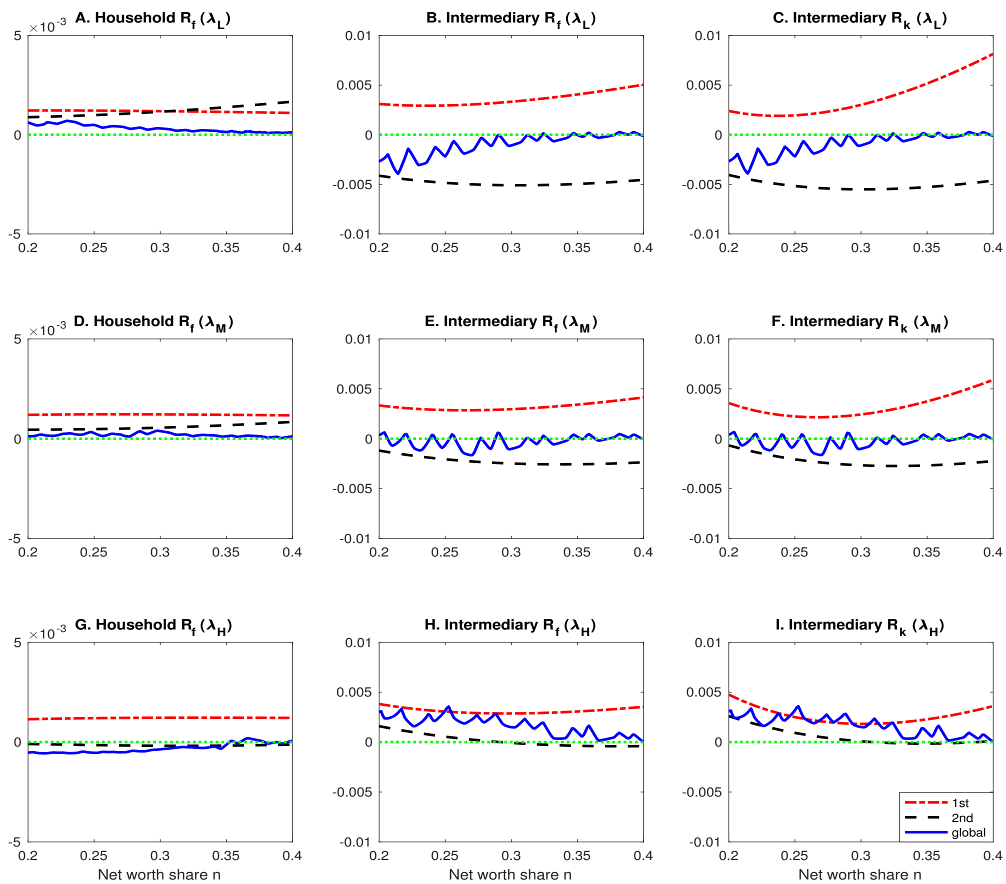
The errors to Euler equations to OccBin method are not included in the figure. Due to the nonlinear feature of policy functions, it is hard to back out parametric policys that can be applied to evaluating expectations in the Euler equations. In the appendix, we show a comparison of unconditional Euler errors with these methods.

Finally, we note that for pertubation methods to work, we have to ensure a deterministic steady state when the constraint binds. It imposes a stringent restriction on the parameter we choose. For example, if we lower the productivity of investment good sector Z_ι to be 0.4, there will not exist a steady state with binding constraint. In that case, the pertubation method cannot be used. The appendix provides a detailed analysis of this scenario.

7 Conclusion

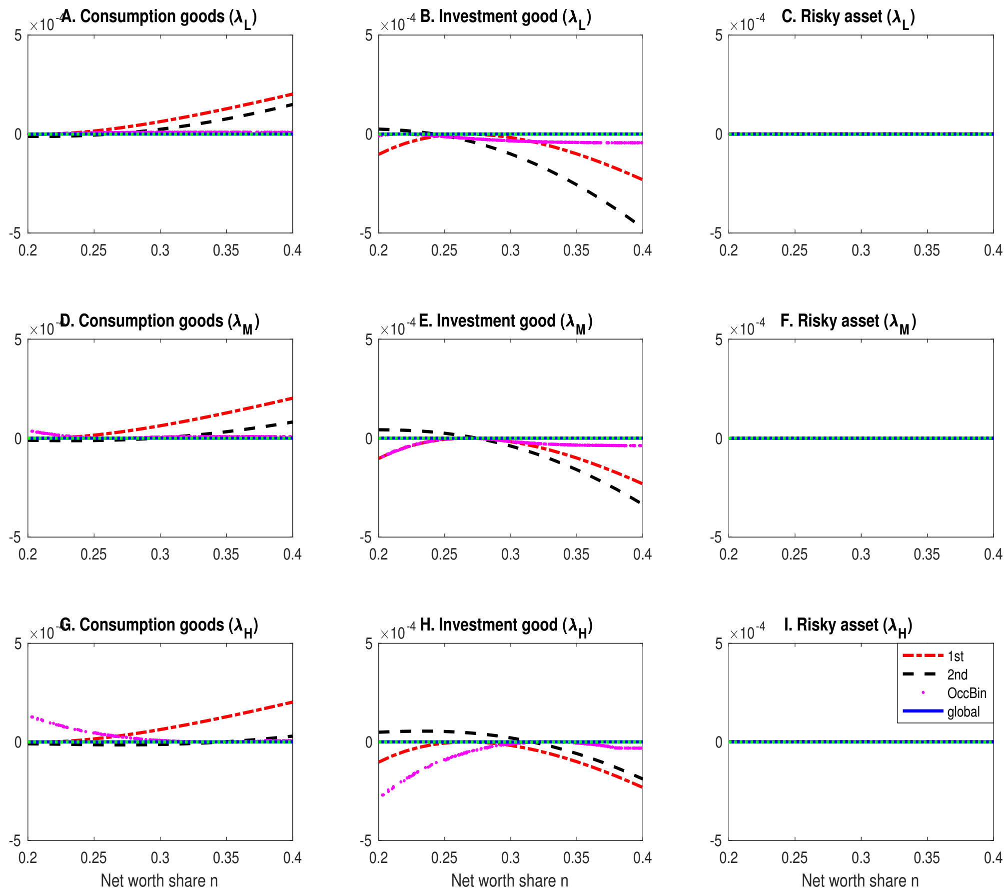
The complexity of the modern financial system makes it seemingly hopeless and naive to incorporate the intricacies of the financial sector effectively into macroeconomic analysis. However, the very essence of macroeconomics is to distill complex phenomena into macroscopic narratives that can be grasped and managed by human cognition. This article reviews the vast literature on how the financial sector shapes the nonlinear joint dynamics of macroeconomic quantities and asset prices, as well as their interactions. The literature provides new theoretical underpinnings, quantitative guidance, and empirical validation for policy analysis. Though with plentiful advances in accounting for recent macro-financial phenomena, this literature still faces many challenges and criticisms. We hope the challenges and criticisms can guide us to explore further and provide a more precise and clearer picture on the nexus of finance and macroeconomy in the modern world.

Figure 6: Error to Euler Equations



NOTE: This figure shows the errors to three Euler equations: households Euler equations, intermediary Euler equation with risk free rate, and intermediary Euler equation with capital. Each column represents a state of λ. Column 1 corresponds to λ_L, column 2 corresponds to λ_M, and column 3 corresponds to λ_H. The dot-dashed red line shows the errors of first order perturbation solution.The dashed black line displays the errors of second order perturbation method with pruning. The solid blue line plots the errors of global solution.

Figure 7: Error to Market Clearing Conditions



NOTE: This figure shows the errors to three market clearing conditions: consumption good, investment good, and security. Each column represents a state of λ. Column 1 corresponds to λ_L, column 2 corresponds to λ_M, and column 3 corresponds to λ_H. The dot-hased red line shows the errors of first order perturbation solution.The dashed black line displays the errors of second order perturbation method with pruning. The dotted pink line shows the errors of OccBin method. The solid blue line plots the errors of global solution.

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