ANNUAL REVIEWS

Annual Review of Financial Economics

Macro-Finance Models with Nonlinear Dynamics

Winston Wei Dou,[1,2] Xiang Fang,[3]
Andrew W. Lo,[2,4,5,6,7] and Harald Uhlig[2,8]

[1]Finance Department, The Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania, USA

[2]National Bureau of Economic Research, Cambridge, Massachusetts, USA

[3]HKU Business School, The University of Hong Kong, Hong Kong SAR, China

[4]Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA; email: alo-admin@mit.edu

[5]Laboratory for Financial Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

[6]Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

[7]Santa Fe Institute, Santa Fe, New Mexico, USA

[8]Kenneth C. Griffin Department of Economics, University of Chicago, Chicago, Illinois, USA

Annu. Rev. Financ. Econ. 2023. 15:407–32

The *Annual Review of Financial Economics* is online at financial.annualreviews.org

https://doi.org/10.1146/annurev-financial-110921-112053

JEL codes: G12, G29, C51

Keywords

DSGE models, dynamic stochastic general equilibrium models, systemic risk, endogenous jump risk, financial constraints, liquidity

Abstract

We review macro-finance models featuring nonlinear dynamics that have recently been developed in the literature, including models with funding liquidity constraints, market liquidity frictions, and bank run frictions, and discuss the empirical evidence and challenges of this class of models. We also construct an illustrative model featuring financial frictions and nonlinear dynamics for readers who are unfamiliar with the literature. We solve the model using different solution techniques, including both global and perturbation solution methods, and comprehensively compare the accuracy of these solutions. Within this framework, we highlight that local linearization approximations omit important nonlinear dynamics and yield biased impulse responses.

1. INTRODUCTION

The Great Recession of 2007–2009 spurred academics, policy makers, and practitioners to investigate the nonlinear effect of financial frictions on the macroeconomy. Since then, a new generation of enhanced models and advanced empirical and quantitative methodologies has been provided by researchers to better study the buildup of endogenous risk and the role of the financial sector. This article presents a review of macro-finance models featuring nonlinear dynamics and their solution methods. Through this review, we hope to summarize some recent advances in new modeling and quantitative techniques in the macro-finance literature and to clarify certain challenges of and reflections on these models. The primary goal of this article is to provide motivation, insight, and guidance for the next generation of young scholars, especially those at the intersection of macroeconomics and financial economics. This article complements the work of Dou et al. (2020), which focuses on macroeconomic models used for monetary policy from a finance perspective.

A remarkable advance in the macro-finance research is the development of macroeconomic models with a central role of the financial sector. Such models have been used for policy analysis by the major policy authorities around the world. For example, at the onset of the financial crisis, the zero lower bound on short-term nominal interest rates went from a remote possibility to a reality with frightening speed. In response, central banks quickly developed unconventional measures to stimulate the economy, including credit easing, quantitative easing, and extraordinary forward guidance. Macroeconomic models with financial sectors are needed for analyzing such unconventional measures.

Furthermore, the Great Recession was a manifestation of nonlinear fluctuations in macroeconomic and financial variables. If we consider other countries, especially the emerging markets, these nonlinear dynamics happen quite frequently. Numerous studies, including but not limited to those by Mendoza (2010), He & Krishnamurthy (2013), Brunnermeier & Sannikov (2014), Gertler & Kiyotaki (2015), and Gertler, Kiyotaki & Prestipino (2019), have highlighted the nonlinear dynamics as the defining feature of financial crises and large economic downturns. The presence of funding illiquidity, market liquidity freeze, and bank runs can be causes of nonlinear responses of macroeconomic quantities and financial variables to primitive economic shocks.

It is demanding to build tractable macroeconomic models featuring nonlinearities. 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 financial markets and the macroeconomy are eventually captured in quantitative analysis (e.g., Brunnermeier & Sannikov 2016; Miftakhova, Schmedders & Schumacher 2020). Second, data availability and tail risk measurement constitute a central challenge to the evaluation and validation of macro-finance models with nonlinear dynamics. Brunnermeier, Gorton & Krishnamurthy (2012) point out that our current measurement systems are outmoded, which leaves regulators, academics, and risk managers in a dangerous position. An assessment of systemic risk requires viewing data on the financial sector through the lens of a macroeconomic model and filtering out the latent risk level hidden behind the observables. New infrastructure for detailed microlevel financial data collection is necessary and critical for further risk measurement development and model construction. Furthermore, in a recent paper, Cheng, Dou & Liao (2022) show that robust inference under weak identification is important to the evaluation of many influential macro-finance models when their key nonlinear features are hard to detect directly in the fundamental data.

There have been closely related review articles of the literature at the intersection of macroeconomics and financial economics, such as those of Brunnermeier, Eisenbach & Sannikov (2012) and Gertler, Kiyotaki & Prestipino (2016). Our review adds to this prior work in the following aspects. First, our review covers the recent papers since the publication of these two articles. Second, we dissect the empirical evidence and the challenges faced by these models. Finally, we conduct a comprehensive comparison of global solution methods and local perturbation methods based on a canonical macro-finance model featuring nonlinear dynamics.

2. LIQUIDITY CONSTRAINTS AND NONLINEAR DYNAMICS

This section reviews topics including funding liquidity constraints, market liquidity constraints, and bank runs. We discuss other important topics in the literature, such as households' leverage constraint and financial networks, in the online **Supplemental Appendix**.

Supplemental Material >

2.1. Funding Liquidity Constraints

There is a large body of literature on macroeconomic models with a financial sector that faces funding liquidity constraints. Such models typically specify a financial sector that channels funds from savers to investors. There are two essential deviations from standard frictionless models. First, households are less efficient in (or prohibited from) investing in risky productive capital. Second, financial intermediaries are subject to a financing constraint that impedes efficient intermediation. The financial sector's intermediation capacity depends on its net worth, which in turn depends on the price of the risky assets it holds.

This class of models offers two main economic insights. First, the price-dependent financing constraint plays an important role in amplifying economic fluctuations. Suppose a negative productivity shock hits the economy and the price of capital drops. Since intermediaries are the holders of productive capital with leverage, their net worth is destroyed by a greater amount, which tightens financing constraints and further reduces the capital demand and suppresses the price of capital. The feedback effect between the price of capital and financing constraints amplifies the effect of the negative productivity shock. This mechanism is called the financial accelerator channel (Bernanke & Gertler 1989; Carlstrom & Fuerst 1997; Kiyotaki & Moore 1997; Bernanke, Gertler & Gilchrist 1999). Apart from productivity shocks, primitive economic shocks can also be volatility shocks and uncertainty shocks.[1]

Second, this class of models emphasizes the important role of the intermediary balance sheet in determining the intermediation capacity of the financial sector in an economy. When an intermediary's net worth is scarce (i.e., leverage is excessive), its intermediation capacity is low, which leads to a shortage of investment demand. This insight highlights the importance of repairing banks' balance sheets during periods of financial disruption, which justifies monetary authorities' unconventional monetary policies during the 2007–2008 financial crisis (e.g., Gertler & Kiyotaki 2010; Gertler & Karadi 2011, 2013).[2]

2.1.1. Endogenous nonlinear dynamics.

The financial accelerator mechanism potentially leads to strong amplification effects and thus nonlinear dynamics in the economy. The nonlinearity is particularly strong when the firm or intermediary that faces the constraint is highly levered, so that a negative shock wipes out a large fraction of its net worth, thereby leading to a substantial decline in asset prices and in real quantities such as investment. In a quantitative study,

[1]Recent attempts to show that the amplification effect of financial constraints on the impact of uncertainty shocks are particularly important in understanding the joint dynamics of macroeconomic quantities and financial variables (e.g., Romer 1990; Christiano, Motto & Rostagno 2014; Gilchrist, Sim & Zakrajsek 2014; Di Tella 2017; Dou 2017).

[2]Gomes, Jermann & Schmid (2016) propose a related but distinct channel of monetary policy transmission through nominal debt. In their paper, monetary tightening increases corporate debt burden and leads to debt overhang, which affects investments.

Mendoza (2010) presents a model of sudden stops that matches the frequency and severity of financial crises with an occasionally binding financing constraint, and the study resolves the criticism of Kocherlakota (2000) concerning the quantitative importance of financing constraints.[3]

Brunnermeier & Sannikov (2014) present a different model with strong nonlinearities. Similar to most models in the literature, market incompleteness and price-dependent financing constraints lead to a feedback effect between asset prices and intermediaries' financing capacity. Such feedback amplifies economic fluctuations and generates the nonlinear dynamics of risk premia. A devastating crisis can be triggered as a consequence of a sequence of negative primitive aggregate shocks.[4]

Models with strong nonlinearities can be fragile (Chen, Dou & Kogan 2021; Cheng, Dou & Liao 2022), since the models' implications are very sensitive to key parameters that are otherwise difficult to identify in the data. Therefore, researchers must consider model uncertainty when applying and assessing nonlinear models. For the sake of space, we leave out a detailed discussion of model uncertainty issues in this review. We refer readers to studies of model uncertainty, including those of Hansen & Sargent (2001) and Hansen et al. (2006), among others.

2.1.2. Welfare analyses and policy implications. The presence of funding liquidity constraints leads to inefficient outcomes compared with those from the social planner's constrained optimal solution. Lorenzoni's (2008) 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). The reason for the inefficiency is the pecuniary externality on the market price of assets that individuals do not internalize in their decision-making. Bianchi (2011) quantifies the welfare loss of the increased frequency and severity of financial crises due to overborrowing and studies the macroprudential policies that restore constrained efficiency. Bianchi, Boz & Mendoza (2012) and Bianchi, Liu & Mendoza (2016) extend macroprudential policy analysis to models with financial innovation and news shocks. Bianchi & Mendoza (2018) show that the optimal macroprudential policies chosen by regulators are time inconsistent. The authors characterize the optimal time-consistent policies in a quantitative model and show that optimal policies can sharply reduce the frequency and magnitude of crises. Phelan (2016) conducts welfare analyses in the context of Brunnermeier & Sannikov's (2014) model. Dávila & Korinek (2017) provide a general framework for macroprudential analysis that distinguishes the two types of pecuniary externalities: distributive externalities and collateral externalities. The authors show that collateral externalities lead to overborrowing compared to the second-best borrowing level, but it is ambiguous whether distributive externalities lead to overborrowing or underborrowing.[5]

The government can also use bailout policies when firms or intermediaries' net worth is scarce. However, bailout policies involve a trade-off between an ex post bailout benefit and ex ante moral hazard. Through a quantitative model, Bianchi (2016) shows that the excessive risk-taking effect is

[3] For a comprehensive literature review on the sudden stop mechanism, see Korinek & Mendoza (2014). This mechanism has been applied to study various important questions (e.g., Durdu & Mendoza 2006; Mendoza & Smith 2006; Durdu, Mendoza & Terrones 2009; Boz & Mendoza 2014; Mendoza & Rojas 2018).

[4] There are other economic mechanisms from which nonlinear macroeconomic dynamics can arise. For example, Boissay et al. (2021) complement institution-based liquidity-driven mechanisms by proposing a novel channel for endogenous financial crises and nonlinear macro dynamics. They focus on the fragility of financial markets (as opposed to a focus on institutions) and highlight excess savings and capital accumulation (rather than excess bank leverage) as a source of fragility. In addition, Petrosky-Nadeau, Zhang & Kuehn (2018) present a textbook labor search model in which labor market frictions generate an endogenous rare disaster.

[5] A separate literature focuses on the optimal regulation of financial intermediaries, for example, capital requirements and liquidity requirements. See, for example, Begenau (2020), Elenev, Landvoigt & Van Nieuwerburgh (2021), and Begenau & Landvoigt (2022).

limited when the bailout is systematic. In contrast, an idiosyncratic bailout will make the economy more prone to crises. However, separating systematic from idiosyncratic remains an unsolved challenge, given that the so-called idiosyncratic can be systemic. A prominent example is the collapse of Lehman Brothers that occurred in the middle of the Great Recession.

The implementation of macroprudential polices is not a trivial task in practice. To tackle this challenge, Kilenthong & Townsend (2021) propose a market-based solution to achieve constrained efficiency when a pecuniary externality is at play. The key economic idea is to create a market of license for future asset trading in every period. This idea resembles that of the market of quotas for pollution and CO_2 emissions.

2.1.3. Asset pricing implications. The frictions that lie in the financial intermediation sector have rich asset pricing implications, and a growing literature of intermediary asset pricing theory has been pioneered by Shleifer & Vishny (1997) and He & Krishnamurthy (2013). As Shleifer & Vishny (1997) emphasize, professional arbitrage is conducted by a small number of highly specialized institutional investors using the delegated funds of other investors, involving agency conflicts and resulting in financial frictions.[6] Gabaix, Krishnamurthy & Vigneron (2007) provide empirical support for the limits of arbitrage asset pricing theory in the context of the mortgage-backed securities (MBS) market by showing that MBS market-specific risk, such as prepayment risk, carries a positive risk premium.

He & Krishnamurthy (2013) are among the first to highlight that the capital ratio of intermediaries determines the risk appetite of the economy and is the crucial state variable in the economy that drives asset prices. In a recent paper, Dou, Kogan & Wu (2021) highlight a different economic channel than the financing constraint (funding liquidity) channel, showing the importance of agency conflicts that are embedded in the delegation of asset management and fund flow risk in shaping asset prices. In particular, this paper shows that fund flows are informative about the stochastic discount factor in capital markets, as funds have strong hedging demands for fund flow shocks due to their assets-under-management–based revenues.

Theoretically, this class of intermediary asset pricing models is built on general two-agent models with limited risk sharing. The asset pricing implications of such two-agent models have been studied in the macro-finance literature for over three decades, dating back to Dumas (1989) and Longstaff & Wang (2012) with complete markets and Mankiw & Zeldes (1991), Basak & Cuoco (1998), and Guvenen (2009) with incomplete markets. These intermediary asset pricing models explicitly highlight the role of intermediary capital and focus on the nonlinearities that arise from the feedback effect between asset prices and intermediary capital.

Last, in a related work, Miao & Wang (2018) study stock price bubbles within a framework with financing constraints. In the presence of a constraint that depends on stock prices, higher stock value loosens the constraint and enables higher investment, which in turn supports a higher stock valuation. The additional shadow value of stocks causes stock prices to deviate from the present value of dividends, which the authors define as a bubble.

2.1.4. International finance implications. In recent decades, financial markets have seen unprecedented changes of fast financial globalization and rapid growth of cross-border capital flows.

---

[6]There have been extensions of the limits of arbitrage asset pricing theory (Shleifer & Vishny 1997) to highlight the fact that the marginal investor in a particular asset market is a small number of specialized arbitrageurs (usually institutional investors using delegated funds) rather than the diversified representative investors (e.g., Kyle & Xiong 2001, Gromb & Vayanos 2002). Beyond the funding liquidity constraints faced by intermediaries, Dou, Wang & Wang (2022) show that imperfect competition among highly specialized institutional investors exerts a significant impact on asset prices due to the market power of these institutional investors.

Financial institutions, and especially their funding liquidity constraints, play a critical role in jointly determining capital flows, asset prices, exchange rates, and some long-run phenomena such as global imbalances.[7]

Miranda-Agrippino & Rey (2020) document the global financial cycle driven by US monetary policy through financial intermediaries. The authors find that the tightening of US monetary policy is associated with a sharp decline in capital flows in the banking sector, bank leverage, and the prices of risky assets on a global scale. Jiang, Krishnamurthy & Lustig (2019) highlight the special role of dollar assets that provide convenience yields. The low cost of dollar funding induces more foreign borrowing in dollars and exposes borrowers to the dollar exchange rate and US monetary policy risk. Bruno & Shin (2014) model international credit as a consequence of credit provision through a double-tier banking system with global and local banks. Constraints faced by both global and local banks play a central role in driving capital flows. The intermediary frictions shed new light on our understanding of the foreign exchange market, inspiring a new literature of intermediary-determined exchange rates. Gabaix & Maggiori (2015) propose a canonical framework of studying exchange rates with capital flows intermediated by frictional global banks. Fang & Liu (2021) provide quantification and empirical evidence regarding the specific mechanism.

The intermediation view with funding liquidity constraints is helpful for understanding the long-run phenomenon of global imbalances. Advanced economies, especially the United States, have accumulated a large amount of external liabilities. Mendoza, Quadrini & Rios-Rull (2009) show that imbalance emerges as a consequence of the financial integration of advanced and emerging economies at different levels of financial development. Maggiori (2017) attributes global imbalances to the special status of the United States as a global banker that insures the rest of the world against global adverse shocks. Since the United States takes higher risk, it earns a risk premium, on average, which makes its external liabilities sustainable.

2.1.5. Different forms of financing constraints. One common, important feature of the models we have reviewed thus far is the presence of a wedge between the marginal value of internal and external funds induced by financing constraints. Different constraints have different microfoundations and different implications for leverage cyclicality, which we discuss in more detail.

Debt financing constraints (or leverage constraints) are prevalent in the literature. Bernanke, Gertler & Gilchrist (1999) derive such a constraint as an optimal contract between borrowers and lenders with costly state verification following Townsend (1979). In Gertler & Kiyotaki (2010), the constraint is the outcome of a moral hazard problem that borrowers can steal a fraction of their assets, as modeled by Holmstrom & Tirole (1997). None of these models have a role for external equity financing.[8]

In contrast, He & Krishnamurthy (2013) and Brunnermeier & Sannikov (2014) focus on equity financing constraints. In He & Krishnamurthy (2013), experts in risky investments must have a sufficiently large equity stake (i.e., skin in the game) to ensure they do not pursue their own private benefits.[9] Brunnermeier & Sannikov (2014) introduce the constraint that experts' net worth cannot go negative, which effectively means that no outside equity issuance is allowed. Because of this constraint, experts' risk-bearing capacity is dampened when their net worth is scarce.

---

[7] In standard models, it is extremely difficult to match data on both capital flow and asset price dimensions. Dou & Verdelhan (2017) show that systematic tail risk (i.e., disaster risk) can provide a joint quantitative explanation for the sizable volatility of both stock returns and international capital flows.

[8] Many models in the literature impose the lack of external equity financing as an exogenous assumption. Some models, including but not limited to that by Bernanke, Gertler & Gilchrist (1999), derive this feature endogenously as an outcome of optimal contracting.

[9] A contractual microfoundation of the friction is derived in He & Krishnamurthy (2011).

Jermann & Quadrini (2012) allow for both equity and debt financing that are imperfectly substitutable. When the debt constraint becomes tighter, borrowers turn to equity financing, which is associated with a higher financing cost. The model quantifies the effect of financial shocks on aggregate quantities and financial flows as sizable.

The Value-at-Risk (VaR) constraint is a different type of constraint imposed on the entire balance sheet, and it is widely used as a risk-management tool by 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. Effectively, the VaR constraint limits the amount of borrowing (leverage) as well as the holding of high-risk assets. Adrian & Shin (2013) provide empirical evidence on the relevance of the VaR constraint to large financial institutions and present a microfoundation for the constraint with moral hazard. Adrian & Boyarchenko (2017) extend the model to a richer environment and discuss implications for the leverage cycle and financial stability. Nuño & Thomas (2017) offer a quantitative macroeconomic model with a VaR constraint. Coimbra & Rey (2022) study the consequences of heterogeneous intermediaries facing different VaR constraints.

Different forms of constraints have different implications for the cyclicality of intermediary leverage. Models with external funding constraints mostly imply countercyclical intermediary leverage when intermediaries' net worth is more greatly affected by economic shocks than their assets. In contrast, models with VaR constraints imply procyclical intermediary leverage when net worth is stable and intermediaries actively adjust for the size of their balance sheets. Adrian & Shin (2010) uncover important differences across balance sheet adjustments in different sectors, with broker-dealers exhibiting highly procyclical leverage. Adrian, Colla & Shin (2013) document that intermediaries actively adjust their balance sheets, especially broker-dealers.

2.2. Market Liquidity Frictions

In this section, we review another class of models in which the market liquidity of assets is imperfect. Market liquidity is defined as how easily an investor can sell an asset without affecting the asset price (e.g., Pástor & Stambaugh 2003; Brunnermeier & Pedersen 2008; Hu, Pan & Wang 2013). The better the market liquidity, the smaller the price effect of sales. We categorize models with market liquidity frictions into two classes: those with exogenous market liquidity frictions and those with endogenous market liquidity frictions.

2.2.1. Exogenous market liquidity frictions. Kiyotaki & Moore (2005, 2019) offer two macroeconomic models of monetary policy and business cycles with market liquidity frictions. In these models, money is a liquid asset that can be immediately sold without incurring a cost. Meanwhile, claims to productive capital (i.e., financial securities) are illiquid, and only a fraction of claims can be sold costlessly. The presence of market liquidity frictions incentivizes investors to hold money, so that the monetary policy has a real effect. The friction then provides a rationale for the liquidity source of fiat money's value. Del Negro et al. (2017) incorporate the market liquidity friction into a standard dynamic stochastic general equilibrium (DSGE) model with nominal and real rigidities and show that shocks to the liquidity of private paper lead to a recession. To prevent such recessions, liquidity facilities are helpful. Drechsler, Savov & Schnabl (2018a) study a model in which the market illiquidity of assets induces banks to hold liquid assets while forgoing the liquidity premium.[10] 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.

[10]Drechsler, Savov & Schnabl (2018b) provide a review of the recent literature on the financial transmission of monetary policy shocks.

Empirically, Eisfeldt & Rampini (2006) study the time-series characteristics of market liquidity and provide evidence supporting the procyclical capital reallocation and countercyclical reallocation gain.

2.2.2. Endogenous market liquidity frictions. Cui & Radde (2020) use a search model to endogenize the market liquidity of assets in the framework of Kiyotaki & Moore (2019). The variation in endogenous asset liquidity amplifies the aggregate fluctuations. Eisfeldt (2004) endogenizes the market liquidity of long-term illiquid assets in a model with adverse selection. Kurlat (2013) endogenizes the illiquidity of assets in a quantitative dynamic stochastic model, in which entrepreneurs have incentives for financial transactions that are induced by stochastic investment opportunities. Adverse selection introduces a wedge between investment return and the cost of funding, leading to inefficient transactions. The market liquidity wedge depends on the proportion of low-quality assets (i.e., the severity of asymmetric information). Bigio (2015) studies a similar model with endogenous illiquidity from adverse selection and quantitatively explains the collapses in liquidity and other patterns of macro variables observed during the Great Recession.

2.2.3. Funding versus market liquidity frictions. Both funding liquidity and market liquidity frictions impede the efficient allocation of capital. However, they differ in many aspects, including the 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 loosens. This is not necessarily true in models with market liquidity frictions, depending on how the friction is specified. In Kiyotaki & Moore (2019), with exogenous liquidity frictions, market liquidity is countercyclical. When the aggregate economy is in a good state, investment demand is strong but irresaleability prevents capital investment, so that the constraint is tighter. In contrast, in models of market illiquidity driven by adverse selection only, such as that in Uhlig (2010), market liquidity is countercyclical. In Uhlig's (2010) model, sellers have private information about the quality of assets sold and a lemons problem emerges. When the market has more sellers under liquidity pressure, the average quality of assets on sale improves and market liquidity is higher. A crucial driver of market liquidity cyclicality is whether the distribution of asset quality changes with time. If the distribution of asset quality does not change, market liquidity is driven by the composition of assets for sale and becomes countercyclical. Otherwise, for example, in Eisfeldt (2004), there are more financial trades of assets in the secondary market when aggregate productivity is high. This force alleviates adverse selection and makes market liquidity procyclical.

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. Policies should aim to impair net worth ex post and restrict excessive leverage ex ante. In models with market liquidity frictions, the introduction of information-insensitive liquid assets such as fiat money and US Treasuries improves allocative efficiency (Del Negro et al. 2017).

It is particularly important to understand how the two types of frictions interact with and reinforce each other. Brunnermeier & Pedersen (2008) develop a model to illustrate the interaction and reinforcement. One outcome of funding liquidity friction is that the asset fire sale of some investors dramatically suppresses prices, which adversely affects the market liquidity of the assets held by all other investors. In this way, funding illiquidity leads to market illiquidity. In the meantime, market illiquidity leads to excessive asset price volatility. Asset price drops sharply as selling pressure rises, which in turn increases funding illiquidity.

2.3. Bank Runs

In this section, we discuss bank run models in a macroeconomic context. A bank run, one major concern for financial fragility, is primarily explained by fundamentals and panics. Panic-based bank runs are pure self-fulfilling phenomena, while fundamental-based bank runs are related to economic fundamentals.

2.3.1. Panic-based and fundamental-based explanations. Panic-based explanations originate in the seminal work of Diamond & Dybvig (1983). In their model, early depositors have liquidity needs and thus need to withdraw their deposits from banks in the interim period, while late depositors can wait until the final period. Optimally, banks hold enough short-term liquid assets to satisfy early depositors. However, if late depositors believe banks are running out of funds, they will withdraw from banks in the interim period as well. As a result, banks will be forced to liquidate their long-term illiquid assets at a discount and unable to repay all of their depositors, and bank runs ensue.

Empirically, Calomiris & Gorton (1991) show that bank runs are more likely to happen in bad times, a finding that challenges the pure panic view of bank runs. Fundamental-based explanations of bank runs argue that negative economic conditions make depositors pessimistic about banks' asset returns and thus incite bank runs (Allen & Gale 1998, Uhlig 2010).

2.3.2. Sunspot and global games: Why do depositors feel panic? In panic-based explanations, bank runs are self-fulfilling and multiple equilibria exist. Diamond & Dybvig (1983) select equilibria with sunspot realizations. The literature also adopts the global games approach to select the equilibrium. A global games approach, introduced into bank run analysis by Rochet & Vives (2004) and Goldstein & Pauzner (2005), assumes a small amount of asymmetric information to eliminate multiple equilibria. With the global games approach, depositors differ by types (i.e., private signals about the aggregate state), and they decide whether or not to withdraw based on a trigger strategy (i.e., they decide to withdraw if and only if their types are higher or lower than an equilibrium threshold). Depositors can infer the aggregation of other depositors' beliefs only from their own private signals and the aggregate outcomes. In this case, even a tiny amount of ex ante uncertainty (i.e., asymmetric information) about the private signals of other investors will lead to a unique equilibrium.

2.3.3. Systemic bank runs: Why are bank assets sold at large discounts? An important assumption of bank run theories is that banks find it difficult to liquidate their long-term assets. In reality, there are always investors who have the capacity to purchase assets sold by banks. It is unclear why buyers are only willing to do so by charging large discounts. To understand these large discounts in equilibrium, Uhlig (2010) compares two different microfoundations: adverse selection and uncertainty-averse investors. He concludes that the uncertainty-averse investor microfoundation is consistent with the observation that banks' assets are sold at deeper discounts when troubled banks have larger market shares.

A version of a systemic bank run can even affect the monetary system as a whole when households run away from currency and into goods. Real-life versions are hyperinflations: though they typically occur in episodes of fast money growth, this is not a precondition. The evaporation of trust suffices. Frost, Shin & Wierts (2020) have shown this using the case of the Bank of Amsterdam. Schilling, Fernández-Villaverde & Uhlig (2020) argue that this issue may become particularly acute with the introduction of a central bank digital currency: A spending run is then effectively a run on the central bank itself.

2.3.4. Bank runs in dynamic macroeconomic models. Gertler & Kiyotaki (2015) embed the bank run feature into the dynamic framework of Gertler & Kiyotaki (2010). The economy is subject to self-fulfilling bank runs. When households believe there will be a run on banks, they liquidate their deposits and it becomes a self-fulfilling prophecy. On the other hand, if the households are confident in the solvency of banks, the price of capital will be higher and there will not be a bank run. In this model, bank runs occur through both panic and fundamental channels. The macroeconomic condition determines the cutoffs of the self-fulfilling run region. In a follow-up paper, Gertler, Kiyotaki & Prestipino (2019) develop a fully specified dynamic quantitative model with bank runs. The economy experiences sharp, nonlinear contractions when bank balance sheets are weak, and as a result, banks are subject to runs. The model studies how bank runs affect the real economy both qualitatively and quantitatively. In particular, they show how optimistic beliefs about the economy lead to credit booms, which in turn increase the risk of bank runs.

2.4. Critical Reflections

In this section, we review empirical evidence and challenges faced by the existing macro-finance models. In doing so, we discuss possible future research directions.

2.4.1. Supporting evidence. The empirical banking literature shows that macroeconomic shocks, particularly monetary policy shocks, affect the credit supply when the banking sector faces financial frictions (e.g., Kashyap & Stein 2000, Jiménez et al. 2014).

After the financial crisis in 2007–2008, extensive empirical research has studied the interactive relationship between macro and financial variables. Gilchrist & Zakrajsek (2012) construct a credit spread index (i.e., the excess bond premium) that strongly predicts future macroeconomic activities. The index is now widely used to measure the financial sector's risk capacity (e.g., Christiano, Eichenbaum & Trabandt 2015; Gertler & Karadi 2015). Schularick & Taylor (2012) and Gourinchas & Obstfeld (2012) use historical data to show that, conditional on the occurrence of a crisis, leverage is built up and a credit boom precedes the crisis. Gorton & Ordoñez (2016) find that not all credit booms end in crises and categorize credit booms into good and bad booms. They find that credit booms with large productivity declines are more likely to be bad booms that end in crises. Aruoba, Bocola & Schorfheide (2017) provide supportive empirical evidence for nonlinearities of macroeconomic variables.

Models with financing frictions shed light on the critical role of financial sector health in determining asset prices. The net worth of financial intermediaries is found to have important pricing implications for a wide set of assets (e.g., Adrian, Etula & Muir 2014; He, Kelly & Manela 2017; Muir 2017; Haddad & Muir 2021). Du, Tepper & Verdelhan (2018) rationalize deviation from the covered interest rate parity (CIP) based on the financial constraint channel. They provide compelling evidence that CIP deviation spikes at the quarter end when banks need to report their leverage to regulatory authorities. Dou, Kogan & Wu (2021) rely on the well-documented fact that fund managers care about fund size, which in turn is driven by fund returns and fund flows. They provide a rich set of evidence showing that active equity funds hedge against fund flow fluctuations by tilting their portfolios toward stocks with low-flow betas. The resultant hedging demand boosts the valuation of low-flow beta stocks.

2.4.2. Empirical challenges. Chari, Christiano & Kehoe (2008) show that, at the aggregate level, US corporations have excess internal funds and can cover their capital expenses using retained earnings. This poses a challenge to the literature: If firms have ample internal funds, then why do financial constraints matter?[11]

[11] Research on corporate finance and asset pricing increasingly emphasizes the importance of corporate liquidity (or cash holdings) as an inevitable state variable in dynamic structural corporate models (e.g., Bolton, Chen

One potential resolution to this challenge is to look at the cross-sectional heterogeneity in firms and banks. Zetlin-Jones & Shourideh (2017) provide a model in which only some firms are constrained and the shocks spill over from constrained firms to unconstrained firms. They find that financial shocks only generate moderate declines in economic activities in aggregate. In a related work, Khan & Thomas (2013) evaluate the role of financial shocks in a general equilibrium model with default and productivity heterogeneity. They find large and persistent reductions in aggregate total factor productivity (TFP) that are due to financial shocks. In their model, financial shocks are amplified and propagated due to distortions in the cross-sectional distribution of capital.[12] Instead of focusing on firm heterogeneity, Boissay, Collard & Smets (2016) provide a model of heterogeneous banks with credit booms and banking crises.

Baron & Xiong (2017) pose another challenge to this literature. They find that credit expansion raises the crash risk for banks in subsequent periods but that the increased risk is not compensated for by higher subsequent bank equity returns. This feature cannot be explained by the models we review in this article.

2.4.3. Managing the risk of financing constraints. A related challenge to the literature is that if financial frictions have serious consequences such as a financial crisis, why do firms not effectively manage such risks? Firms may hold cash to address the possible distress. Even firms without enough internal funds may retain their earnings and quickly grow out of the financing constraint. Midrigan & Xu (2014) quantitatively assess the different channels through which financial frictions affect capital allocation. They find that new entrants and technology adoption are distorted by a lack of funding. The effect of financial frictions on the intensive margin is small as firms quickly grow out of financing constraints with retained earnings. Moll (2014) studies to what degree firms' self-financing can undo the distortions caused by financial frictions in a neoclassical growth model. He analyzes both the steady state effect and the transitional effect, the relative importance of which depends on the persistence of the TFP shocks.

In addition, firms can use financial instruments to hedge against and overcome the financing constraints, so a key question is: Why do they not do so? Rampini & Viswanathan (2010, 2013) argue that hedging requires resources and firms face a trade-off between risk management and investment. When debt capacity is limited, spending resources on hedging means forgoing investment opportunities. Rampini, Sufi & Viswanathan (2014) provide evidence to support these implications.

The market illiquidity of assets can be another reason why borrowers cannot easily manage the risk of a financing constraint (Uhlig 2010, Kurlat 2013, Bigio 2015). Even though borrowers hold assets to deal with a binding constraint, they might not be able to easily sell the assets once the constraint materializes.

2.4.4. Banks and capital markets. While most studies in the literature highlight how banks transform risk-free and liquid liabilities into risky and illiquid assets, they abstract away capital markets. It is natural to ask why banks and capital markets coexist and whether they have different implications for the macroeconomy.

& Wang 2011, 2013; Bolton, Wang & Yang 2019; Dou et al. 2021). Increased interest in corporate liquidity is motivated by empirical evidence showing that cash holdings are often large. More importantly, liquidity management is crucial for corporate entities.

[12] Along this line, Gomes & Schmid (2021) develop a quantitative general equilibrium model of heterogeneous firms and default, and they study the joint determination of leverage, investment, credit spread, equity premium, and value premium.

Gersbach & Uhlig (2007) develop a model with the coexistence of banks and capital markets, in which banks have a comparative advantage in monitoring and capital markets are better at screening projects. In a related work, De Fiore & Uhlig (2011) present a quantitative model with both bank and bond financing. Banks have access to private information, while bond investors can only obtain public information about the quality of projects. The difference leads to endogenous financing choices. De Fiore, Hoerova & Uhlig (2022) examine the interplay between funding constraints and liquidity constraints for the banking sector as well as the impact of policy responses.

3. A CANONICAL MACRO-FINANCE MODEL

In this section, we narrow down and present a benchmark model in the spirit of Gertler & Kiyotaki (2010) to formally illustrate the key mechanism of financial amplification. More importantly, using this transparent benchmark model, we compare the performance of various solution methods that are widely used in the literature. Additional details about the model and solutions are in the online **Supplemental Appendix**.

Supplemental Material >

3.1. Households

There is a continuum of representative households with workers and bankers that consume together. The full set of Arrow–Debreu securities is available to the members within each household (but not across households), so that idiosyncratic consumption risks can be fully insured. Labor supply is inelastic and normalized to 1.

Each banker within a household manages a financial intermediary. Workers deposit funds into these intermediaries. Intermediaries hold equity claims on capital. In each period, $1 - \theta$ bankers and workers switch their roles. Exiting bankers rebate the net worth of banks to their households, while new bankers receive start-up funds from their households.

The households solve the optimization problem:

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

subject to the dynamic budget constraint:

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

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

3.2. 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.

$$Y_t = A_{c,t} K_t^{\alpha} L_{c,t}^{1-\alpha}, \quad 0 < \alpha < 1, \tag{3.}$$

where $A_{c,t}$ is an exogenous TFP process that follows

$$\ln A_{c,t} = \ln A_{c,t-1} + \sigma_a \epsilon_{a,t}, \tag{4.}$$

where $\epsilon_{a,t}$ are independent and identically distributed (i.i.d.) standard normal variables.

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

$$K_{t+1} = I_t + (1-\delta)K_t. \tag{5.}$$

There are convex adjustment costs for the rate of investment as follows:

$$\Upsilon_t = \Upsilon(I_t; K_t) \equiv I_t + g(I_t, K_t), \quad \text{where } g(I_t, K_t) \equiv \frac{\vartheta}{2}\left(\frac{I_t}{K_t}\right)^2 K_t. \tag{6.}$$

Denote the price of investment goods as P_t and the price of capital as Q_t. We define the dividend of firms as

$$D_t \equiv Y_t - W_t L_{c,t} - P_t \Upsilon(I_t, K_t). \tag{7.}$$

Given the capital stock, K_t, the price of capital, Q_t, and the dividend, D_t, the stock return can be written as

$$1 + R_{k,t+1} = \underbrace{\frac{D_{t+1}}{Q_t K_{t+1}}}_{\text{total dividend return}} + \underbrace{\frac{Q_{t+1} K_{t+2}}{Q_t K_{t+1}}}_{\text{total capital gains return}}. \tag{8.}$$

Given the prices and wages, the optimal investment decision solves

$$\max_{I_{t+1}} Q_{t+1} I_{t+1} - P_{t+1} \Upsilon(I_{t+1}; K_{t+1}), \tag{9.}$$

and the optimal labor demand solves

$$\max_{L_{c,t}} A_{c,t} K_t^{\alpha} L_{c,t}^{1-\alpha} - W_t L_{c,t}. \tag{10.}$$

Consumption goods are distributed as either wages or dividends, so it holds that

$$Y_t = D_t + W_t L_{c,t} + W_t L_{\iota,t}, \tag{11.}$$

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

3.3. Investment Goods Sector

There is a continuum of representative investment goods firms that produce investment goods using labor. Their production function is as follows:

$$\Upsilon_t = A_{\iota,t} L_{\iota,t}, \tag{12.}$$

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 the labor market requires the following:

$$L_{c,t} + L_{\iota,t} = L_t \equiv 1. \tag{13.}$$

3.4. Financial Intermediaries

Financial intermediaries borrow funds from households at a risk-free rate, pool those 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 as follows:

$$Q_t K_{t+1} S_{j,t} = N_{j,t} + B_{j,t}, \tag{14.}$$

where $S_{j,t}$ is the quantity of equity held by the intermediary, $N_{j,t}$ is the net worth, and $B_{j,t}$ represents 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

$$N_{j,t+1} = (R_{k,t+1} - R_{f,t})Q_t K_{t+1} S_{j,t} + (1 + R_{f,t})N_{j,t}. \tag{15}$$

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

$$V_{j,t} = \max_{S_{j,t+1},B_{j,t+1}} \mathbb{E}_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \left[(1-\theta)N_{j,t+1} + \theta V_{j,t+1} \right] \right\}, \tag{16}$$

subject to the incentive compatibility constraint,

$$V_{j,t} \geq \lambda_t Q_t K_{t+1} S_{j,t}. \tag{17}$$

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

The economy has one single endogenous state variable, the total net worth share defined as

$$n_t \equiv \frac{N_t}{Q_t K_{t+1}}, \quad \text{where } N_t \equiv \int_j N_{j,t} \mathrm{d}j. \tag{18}$$

3.5. Net Worth Evolution

After integrating Equation 15 over all intermediaries and accounting for the net fund transfer, the aggregate net worth share defined in Equation 18 evolves as

$$n_{t+1} = \theta \left[(R_{k,t+1} - R_{f,t})S_{p,t} + (1 + R_{f,t})n_t \right] / G_{k,t+1} + \aleph, \tag{19}$$

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, $S_{p,t} \equiv \int S_{j,t}\mathrm{d}j$ is the total share of equity held privately, and $\aleph Q_{t+1} K_{t+2}$ is the total start-up funds received by new bankers.

3.6. Government Policies

In our model, the government buys a fraction $S_{g,t}$ of the total outstanding shares of firms (normalized to 1), so that

$$1 = S_{p,t} + S_{g,t}. \tag{20}$$

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 as $\Xi^* = \gamma\sigma_a^2 - \frac{1}{2}\sigma_a^2$. The government credit policy rule is as follows:

$$S_{g,t} = 1 - \frac{1}{1 + \nu_g \times (\Xi_t - \Xi^*)} \approx \nu_g \times (\Xi_t - \Xi^*). \tag{21}$$

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

3.7. Resource and Government Budget Constraints

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

$$Y_t = C_t + \bar{g}Y_t + \tau S_{g,t} Q_t K_{t+1}. \tag{22.}$$

Finally, the government budget constraint is

$$\bar{g}Y_t + (1+\tau)S_{g,t}Q_tK_{t+1} = T_t + S_{g,t-1}Q_{t-1}K_t(R_{k,t} - R_{f,t-1}) + B_{g,t}. \tag{23.}$$

Since taxation effectively takes up any slack on the government balance sheet, the intertemporal budget constraint of a representative household and the intertemporal budget constraint of the government can be combined, leaving out taxes. Intuitively, then, by Walras's law, both budget constraints are redundant in determining the equilibria. The size and composition of the government balance sheet matter for pinning down the equilibrium, because not all investors can purchase an arbitrary amount of the same assets at the same market prices as the government in this model. Unlike private financial intermediation, government intermediation is not constrained by the balance sheet.

The model can be applied to analyzing the stabilizing effect of government's unconventional monetary policies. The government policy specified in Equation 21 is fixed as a component of the model, rather than a choice variable of the government in the model. The parameter ν_g is calibrated in the quantitative experiments. A higher ν_g reflects a more aggressive government credit policy. The optimal design of government credit policy to stabilize the economy by battling against the nonlinear downturn caused by financial frictions is an important research question but beyond the scope of this review article.

3.8. Optimality Conditions

Solving households' optimization problem (Equation 1) with respect to the debt holding leads to the intertemporal Euler equation:

$$1 = \mathbb{E}_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}(1+R_{f,t})\right], \quad \text{where } \Lambda_t \equiv \beta^t C_t^{-\gamma}. \tag{24.}$$

The solution to consumption goods producers' optimal investment problem (Equation 9) is characterized by the first-order condition:

$$Q_{t+1}/P_{t+1} = 1 + \vartheta i_{t+1}, \quad \text{where } i_{t+1} \equiv \frac{I_{t+1}}{K_{t+1}}. \tag{25.}$$

The solution to the firms' optimal labor demand problem (Equation 10) is characterized by the first-order condition:

$$L_{c,t+1} = \left[(1-\alpha)\frac{A_{c,t+1}}{W_{t+1}}\right]^{1/\alpha} K_{t+1}. \tag{26.}$$

Following the literature of Gertler & Kiyotaki (2010), we conjecture that the value of financial intermediary j is linear in its net worth, as

$$V_{j,t} = \Omega_t N_{j,t}, \tag{27.}$$

where Ω_t is the marginal value of net worth for financial intermediaries.

To solve the intermediaries' problem (Equation 16), we take first-order conditions with respect to $B_{j,\,t+1}$ and $S_{j,\,t+1}$ and then obtain the following intermediary-based Euler equations for risk-free rates and equity returns:

$$1 \geq 1 - \mu_t = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1} (1 + R_{f,t}) \right] \quad \text{and} \tag{28.}$$

$$1 \geq 1 - \mu_t (1 - \lambda_t \Omega_t^{-1}) = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1} (1 + R_{k,t+1}) \right], \quad \text{respectively.} \tag{29.}$$

The effective intertemporal marginal rate of substitution of intermediaries is $\mathcal{M}^{\mathcal{I}}_{t,t+1} \equiv \frac{\Lambda_{t+1}}{\Lambda_t} \frac{1-\theta+\theta\Omega_{t+1}}{\Omega_t}$, where Ω_t is the marginal value of net worth for financial intermediaries defined in Equation 27. The variable $\mu_{j,t}$ is the Lagrangian multiplier on the constraint for intermediary j. We consider the symmetric equilibrium: $\mu_{j,t} = \mu_t$.

Combining these two optimality conditions in Equations 28 and 29, we obtain the intermediary-based Euler equation for the excess return of equity relative to the risk-free rate:

$$0 \leq \mu_{j,t} \lambda_t \Omega_t^{-1} = \mathbb{E}_t \left[\mathcal{M}^{\mathcal{I}}_{t,t+1} (R_{k,t+1} - R_{f,t}) \right]. \tag{30.}$$

Equation 30 shows that $\mathbb{E}_t[\mathcal{M}^{\mathcal{I}}_{t,t+1}(R_{k,t+1} - R_{f,t})] > 0$ when the constraint is binding and $\mathbb{E}_t[\mathcal{M}^{\mathcal{I}}_{t,t+1}(R_{k,t+1} - R_{f,t})] = 0$ when the constraint is slack. The occasionally binding constraint (OccBin) feature leads to nonlinearities in the solution of the model.

4. COMPARING SOLUTION METHODS

In this section, we solve the model introduced in Section 3 using both local and global methods and compare these solutions. In practice, many studies solve dynamic macroeconomic models with local methods that rely 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."

Despite being simple and easy to handle, 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 those of He & Krishnamurthy (2013) and Brunnermeier & Sannikov (2014), show that the nonlinearity of the amplification effect is a key aspect of systemic risk. Second, first-order approximations are not 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, 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 to study asset prices.[13] Third, Fernández-Villaverde, Rubio-Ramirez & Santos (2006) consider log-linearization approximation to be unsatisfactory, as second-order approximation errors in the solution of the model can have first-order effects on the likelihood function approximation. Ackerberg, Geweke & Hahn (2009) made important asymptotic corrections to a theoretical result in Fernández-Villaverde, Rubio-Ramirez & Santos (2006), arguing that the approximation error on the classical maximum likelihood

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

estimation of the approximate likelihood function has the same magnitude as that 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. Fourth, a log-linearization approximation with large errors can potentially lead to misleading theoretical predictions in the presence of highly nonlinear true dynamics. For example, Pohl, Schmedders & Wilms (2018, 2021) and Lorenz, Schmedders & Schumacher (2020) argue that the log-linearization solution method can lead to severe errors in the approximation of return, volatility, and price–dividend ratio dynamics for macro asset pricing models featuring highly nonlinear dynamics [namely, those macro asset pricing models whose key asset pricing implications rely heavily upon dark matter, as emphasized by Chen, Dou & Kogan (2021)], such as the seminal long-run risk models (with jumps) (Bansal & Yaron 2004) that have become a standard workhorse model in recent macro-finance literature. Furthermore, the model solution based on log-linearization approximations may even lead to the opposite time-series patterns as those generated by the true nonlinear solution.

Specific to the model we present, the log-linearization approximation requires a constraint that always binds, which may not hold in the true solution of the model. To address this issue, Guerrieri & Iacoviello (2015) develop a toolkit that allows for an OccBin yet relies on local approximations. The toolkit improves the model's solutions and has been adopted in the literature (see, e.g., Holden, Levine & Swarbrick 2020). However, the toolkit is restricted to first-order approximations, so that any higher-order effect, such as precautionary saving, cannot be captured. For the purpose of capturing highly nonlinear dynamics and systematic risks in the model, the OccBin toolkit is still insufficient. For example, Bocola (2016) highlights that investors' perceived uncertainty regarding whether or not the constraint binds has a first-order effect quantitatively, which cannot be captured by the OccBin solution method.[14]

4.1. Calibration

The calibration of the model is fairly standard and follows the literature (e.g., Smets & Wouters 2007, Gertler & Karadi 2011). The exogenous autoregressive processes are discretized according to Rouwenhorst (1995). To save space, the details of calibration can be found in the online **Supplemental Appendix**.

Supplemental Material >

4.2. Policy Function Analysis

We solve the model using four different solution methods: the first-order perturbation method, the second-order perturbation method with pruning, the OccBin method proposed by Guerrieri & Iacoviello (2015), and the global solution method based on the time-iteration projection procedure. When using perturbation, 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. **Figures 1** to **3** display the policy functions at different states of the constraint margin. In **Figure 3*d***, we show the histogram of the ergodic distribution of net worth share n. Policy functions with the OccBin method are plotted based on a simulation of 50,000 periods of the economy that are conditional on the corresponding values of λ.

The economy features occasionally binding financial constraints, which lead to nonlinearities in the solution. For any value of λ, low intermediary net worth share n is associated with a binding

[14]It is even more challenging to estimate OccBin models. In a recent study, Aruoba et al. (2021) propose a method for estimation.

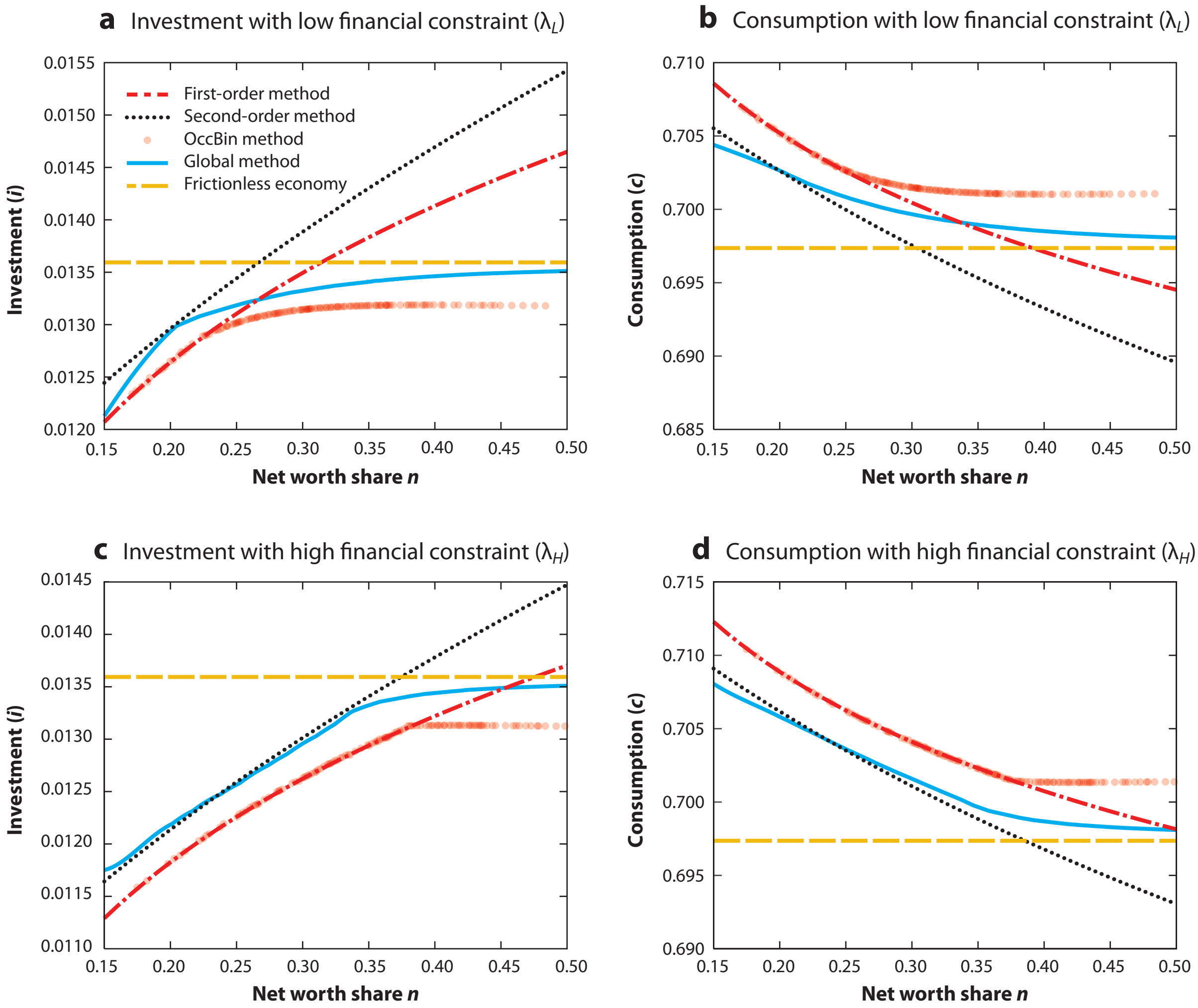

Figure 1

Policy functions of real variables. 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 and λ_H. The variable n is defined in Equation 18, and the parameter λ is the marginal parameter defined in Equation 17. The lines indicate the policy function obtained through the first-order perturbation method (*red dot-dashed line*), the second-order perturbation method with pruning (*black dotted line*), the OccBin method (*orange dots*), and the global method (*blue solid line*). The yellow dashed line indicates values of corresponding variables in a frictionless economy.

constraint, a larger multiplier, and a higher marginal value of net worth. This, in turn, corresponds to a lower price of capital q, higher risk premium Ξ, and lower investment i. The government implements an aggressive credit policy. When n is large enough that the constraint is slack, n does not matter for the price of capital and investment. On the other hand, λ indicates how tight the constraint is. Larger values of λ are associated with a higher risk premium and lower investment for the same level of n.

Figures 1 to **3** plot the policy functions of the key variables obtained using different solution methods. The global solutions are used as a benchmark, since they deliver the smallest

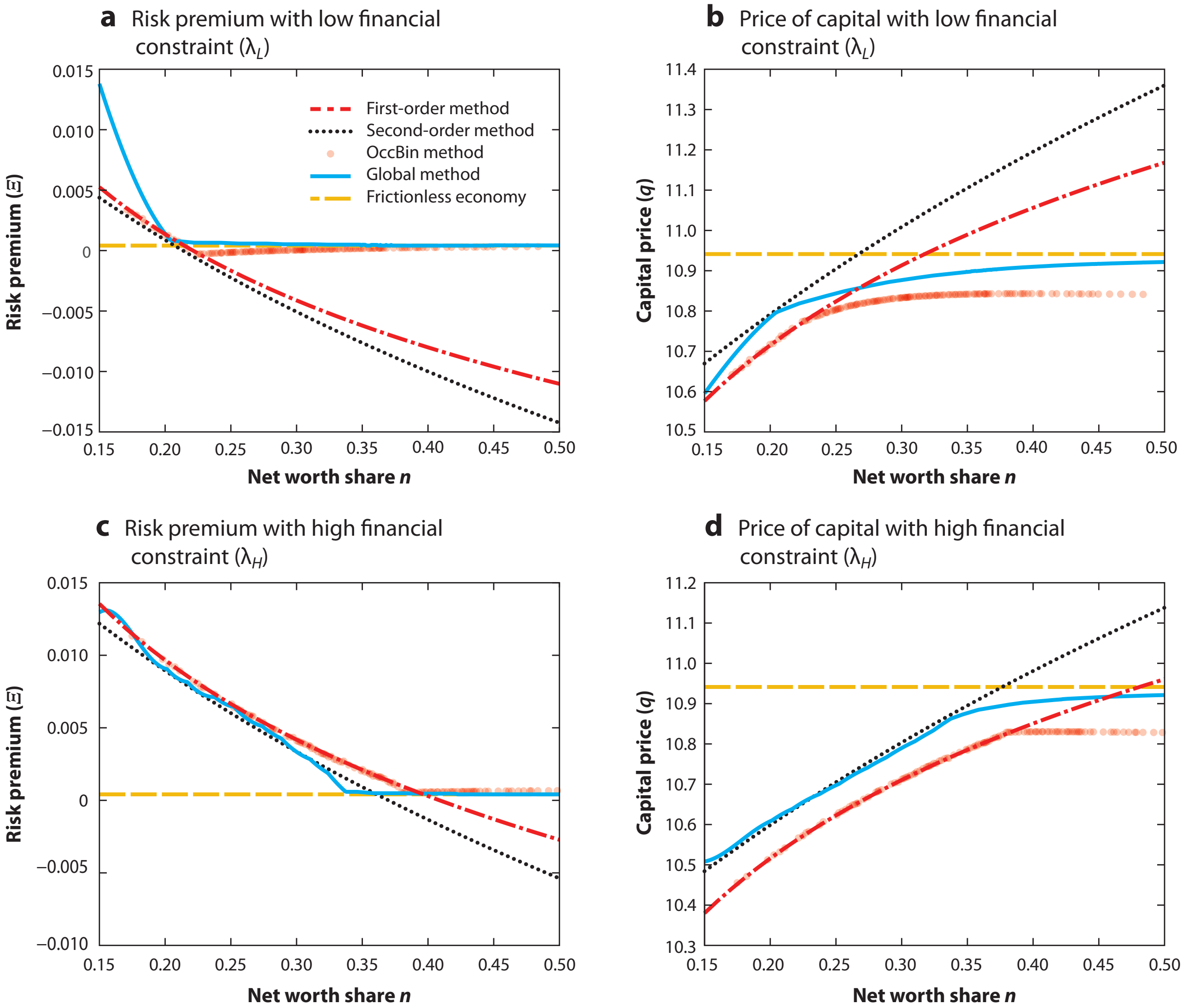

Figure 2

Policy functions of financial variables. 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 and λ_H. The variable n is defined in Equation 18, and the parameter λ is the marginal parameter defined in Equation 17. The lines indicate the policy function obtained through the first-order perturbation method (*red dot-dashed line*), the second-order perturbation method with pruning (*black dotted line*), the OccBin method (*orange dots*), and the global method (*blue solid line*). The yellow dashed line indicates values of corresponding variables in a frictionless economy.

Euler equation errors, as shown in the online **Supplemental Appendix**. All other solutions are compared to the global solution to assess their accuracy.

Supplemental Material >

Four observations stand out: (*a*) First- and second-order perturbation methods work well when n is small and the constraint binds; (*b*) first- and second-order perturbation methods work better for larger values of λ; (*c*) with second-order perturbation, policy functions are closer to the global solution; and (*d*) the OccBin method solutions capture the change in constraint slackness. In terms of economic magnitude, the solution error is nonnegligible. Take investment in **Figure 1** as an example. The discrepancy between the global solution and the first-order perturbation solution

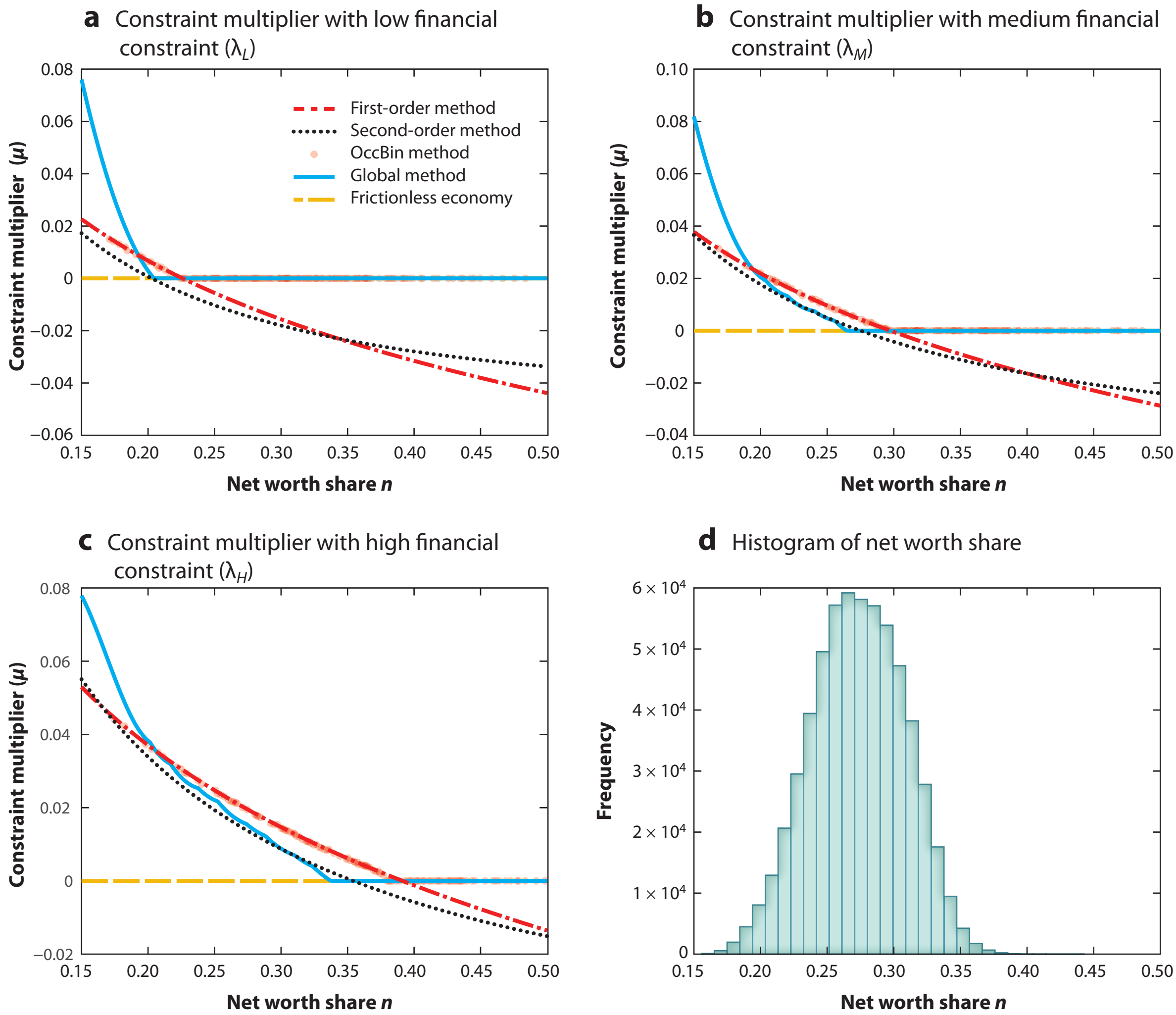

Figure 3

Policy functions of financial constraint variables. Panels *a* through *c* in this figure show the policy function of variables of the constraint (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 variable n is defined in Equation 18, and the parameter λ is the marginal parameter defined in Equation 17. The lines indicate the policy function obtained through the first-order perturbation method (*red dot-dashed line*), the second-order perturbation method with pruning (*black dotted line*), the OccBin method (*orange dots*), and the global method (*blue solid line*). The yellow dashed line indicates values of corresponding variables in a frictionless economy. Panel *d* shows the ergodic distribution of net worth share.

when the constraint is slack can be as large as 5 percentage points for investment when $n = 0.35$ and the financial constraint is low. Intuitively, when the financial constraint is slack, the perturbation method that assumes an always-binding constraint has large errors.

A key feature of the model is that the effect of the leverage constraint is asymmetric. When the constraint binds, a tighter constraint depresses investment and asset prices. But such effect is absent if the constraint is slack. Intrinsically, the model features nonlinearity and asymmetry, which is captured by the global solution. From the comparisons, we conclude that the standard perturbation method does a poor job when the constraint is slack. Although the OccBin method can capture the change in regime, it is limited to the first-order approximation and thus ignores the role of the risk premium.

Due to space limitations, a more detailed discussion of model solution comparisons is in the online **Supplemental Appendix**. This discussion includes impulse response analyses, error analyses, and additional cases where the local perturbation method can fail.

Supplemental Material >

5. 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, distilling complex phenomena into macroscopic narratives that can be grasped and managed by human cognition is the very essence of macroeconomics. 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. Although there have been 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 of the nexus of financial markets and the macroeconomy in the modern world.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank Lars Peter Hansen and Laura Veldkamp for detailed suggestions and comments. We also thank Tobias Adrian, Richard Berner, Michael Binder, Marco Del Negro, Fernando Duarte, Mark Gertler, Nobuhiro Kiyotaki, Nellie Liang, Debbie Lucas, Johannes Pfeifer, David Romer, Karl Schmedders, David Skeie, and Volker Wieland and seminar participants at the Macro Financial Modeling Group 2013 Meeting in Chicago, the Macro Financial Modeling Group 2015 Meeting in New York, and the Research Conference of the Centre for Economic Policy Research Network on Macroeconomic Modeling and Model Comparison for helpful discussion and comments. We thank Jayna Cummings for editorial assistance. We appreciate the generous support from the Macro Financial Modeling Group, the Alfred P. Sloan Foundation, and the Massachusetts Institute of Technology Laboratory for Financial Engineering. All errors are our own.

LITERATURE CITED

Ackerberg D, Geweke J, Hahn J. 2009. Comments on "Convergence Properties of the Likelihood of Computed Dynamic Models." *Econometrica* 77(6):2009–17

Adrian T, Boyarchenko N. 2017. Liquidity policies and systemic risk. *J. Financ. Intermed.* 35(B):45–60

Adrian T, Colla P, Shin HS. 2013. Which financial frictions? Parsing the evidence from the financial crisis of 2007 to 2009. *NBER Macroecon. Annu.* 27(1):159–214

Adrian T, Etula E, Muir T. 2014. Financial intermediaries and the cross-section of asset returns. *J. Finance* 69(6):2557–96

Adrian T, Shin HS. 2010. Liquidity and leverage. *J. Financ. Intermed.* 19(3):418–37

Adrian T, Shin HS. 2013. Procyclical leverage and value-at-risk. *Rev. Financ. Stud.* 27(2):373–403

Allen F, Gale D. 1998. Optimal financial crises. *J. Finance* 53(4):1245–84

An S, Schorfheide F. 2007. Bayesian analysis of DSGE models. *Econom. Rev.* 26(2–4):113–72
Aruoba SB, Bocola L, Schorfheide F. 2017. Assessing DSGE model nonlinearities. *J. Econ. Dyn. Control* 83(C):34–54
Aruoba SB, Cuba-Borda P, Higa-Flores K, Schorfheide F, Villalvazo S. 2021. Piecewise-linear approximations and filtering for DSGE models with occasionally-binding constraints. *Rev. Econ. Dyn.* 41:96–120
Bansal R, Yaron A. 2004. Risks for the long run: a potential resolution of asset pricing puzzles. *J. Finance* 59(4):1481–509
Baron M, Xiong W. 2017. Credit expansion and neglected crash risk. *Q. J. Econ.* 132(2):713–64
Basak S, Cuoco D. 1998. An equilibrium model with restricted stock market participation. *Rev. Financ. Stud.* 11(2):309–41
Begenau J. 2020. Capital requirements, risk choice, and liquidity provision in a business-cycle model. *J. Financ. Econ.* 136(2):355–78
Begenau J, Landvoigt T. 2022. Financial regulation in a quantitative model of the modern banking system. *Rev. Econ. Stud.* 89(4):1748–84
Bernanke B, Gertler M. 1989. Agency costs, net worth, and business fluctuations. *Am. Econ. Rev.* 79(1):14–31
Bernanke BS, Gertler M, Gilchrist S. 1999. The financial accelerator in a quantitative business cycle framework. In *Handbook of Macroeconomics*, Vol. 1, ed. JB Taylor, M Woodford, pp. 1341–93. Amsterdam: Elsevier
Bianchi J. 2011. Overborrowing and systemic externalities in the business cycle. *Am. Econ. Rev.* 101(7):3400–26
Bianchi J. 2016. Efficient bailouts? *Am. Econ. Rev.* 106(12):3607–59
Bianchi J, Boz E, Mendoza EG. 2012. Macroprudential policy in a Fisherian model of financial innovation. *IMF Econ. Rev.* 60(2):223–69
Bianchi J, Liu C, Mendoza EG. 2016. Fundamentals news, global liquidity and macroprudential policy. *J. Int. Econ.* 99:S2–15
Bianchi J, Mendoza E. 2018. Optimal time-consistent macroprudential policy. *J. Political Econ.* 126(2):588–634
Bigio S. 2015. Endogenous liquidity and the business cycle. *Am. Econ. Rev.* 105(6):1883–927
Bocola L. 2016. The pass-through of sovereign risk. *J. Political Econ.* 124(4):879–926
Boissay F, Collard F, Gali J, Manea C. 2021. *Monetary policy and endogenous financial crises*. NBER Work. Pap. 29602
Boissay F, Collard F, Smets F. 2016. Booms and banking crises. *J. Political Econ.* 124(2):489–538
Bolton P, Chen H, Wang N. 2011. A unified theory of Tobin's *q*, corporate investment, financing, and risk management. *J. Finance* 66(5):1545–78
Bolton P, Chen H, Wang N. 2013. Market timing, investment, and risk management. *J. Financ. Econ.* 109(1):40–62
Bolton P, Wang N, Yang J. 2019. Optimal contracting, corporate finance, and valuation with inalienable human capital. *J. Finance* 74(3):1363–429
Boz E, Mendoza EG. 2014. Financial innovation, the discovery of risk, and the US credit crisis. *J. Monet. Econ.* 62:1–22
Brunnermeier MK, Eisenbach TM, Sannikov Y. 2012. *Macroeconomics with financial frictions: a survey*. NBER Work. Pap. 18102
Brunnermeier MK, Gorton G, Krishnamurthy A. 2012. Risk topography. *NBER Macroecon. Annu.* 26(1):149–76
Brunnermeier MK, Pedersen LH. 2008. Market liquidity and funding liquidity. *Rev. Financ. Stud.* 22(6):2201–38
Brunnermeier MK, Sannikov Y. 2014. A macroeconomic model with a financial sector. *Am. Econ. Rev.* 104(2):379–421
Brunnermeier MK, Sannikov Y. 2016. Macro, money, and finance: a continuous-time approach. In *Handbook of Macroeconomics*, Vol. 2, ed. JB Taylor, H Uhlig, pp. 1497–545. Amsterdam: Elsevier
Bruno V, Shin HS. 2014. Cross-border banking and global liquidity. *Rev. Econ. Stud.* 82(2):535–64
Calomiris CW, Gorton G. 1991. The origins of banking panics: models, facts, and bank regulation. In *Financial Markets and Financial Crises*, ed. RG Hubbard, pp. 109–74. Chicago: Univ. Chicago Press
Carlstrom CT, Fuerst TS. 1997. Agency costs, net worth, and business fluctuations: a computable general equilibrium analysis. *Am. Econ. Rev.* 87(5):893–910

Chari VV, Christiano L, Kehoe PJ. 2008. *Facts and myths about the financial crisis of 2008*. Work. Pap. 666, Fed. Reserve Bank Minneap.

Chen H, Dou WW, Kogan L. 2021. Measuring the "dark matter" in asset pricing models. *J. Finance*. Forthcoming

Cheng X, Dou WW, Liao Z. 2022. Macro-finance decoupling: robust evaluations of macro asset pricing models. *Econometrica* 90(2):685–713

Christiano LJ, Eichenbaum MS, Trabandt M. 2015. Understanding the Great Recession. *Am. Econ. J. Macroecon.* 7(1):110–67

Christiano LJ, Motto R, Rostagno M. 2014. Risk shocks. *Am. Econ. Rev.* 104(1):27–65

Coimbra N, Rey H. 2022. Financial cycles with heterogeneous intermediaries. *Rev. Econ. Stud.* In press. **https://doi.org/10.1093/restud/rdad039**

Cui W, Radde S. 2020. Search-based endogenous asset liquidity and the macroeconomy. *J. Eur. Econ. Assoc.* 18(5):2221–69

Dávila E, Korinek A. 2017. Pecuniary externalities in economies with financial frictions. *Rev. Econ. Stud.* 85(1):352–95

De Fiore F, Hoerova M, Uhlig H. 2022. *Money markets, collateral and monetary policy*. Work. Pap. 997, Bank Int. Settl., Basel, Switz.

De Fiore F, Uhlig H. 2011. Bank finance versus bond finance. *J. Money Credit Bank.* 43(7):1399–421

Del Negro M, Eggertsson G, Ferrero A, Kiyotaki N. 2017. The great escape? A quantitative evaluation of the Fed's liquidity facilities. *Am. Econ. Rev.* 107(3):824–57

Di Tella S. 2017. Uncertainty shocks and balance sheet recessions. *J. Political Econ.* 125(6):2038–81

Diamond DW, Dybvig PH. 1983. Bank runs, deposit insurance, and liquidity. *J. Political Econ.* 91(3):401–19

Dou WW. 2017. *Embrace or fear uncertainty: growth options, limited risk sharing, and asset prices*. Work. Pap., Univ. Pa., Philadelphia

Dou WW, Ji Y, Reibstein D, Wu W. 2021. Inalienable customer capital, corporate liquidity, and stock returns. *J. Finance* 76(1):211–65

Dou WW, Kogan L, Wu W. 2021. *Common fund flows: flow hedging and factor pricing*. Work. Pap., Univ. Pa., Philadelphia

Dou WW, Lo AW, Muley A, Uhlig H. 2020. Macroeconomic models for monetary policy: a critical review from a finance perspective. *Annu. Rev. Financ. Econ.* 12:95–140

Dou WW, Verdelhan A. 2017. *The volatility of international capital flows and foreign assets*. Work. Pap., Univ. Pa., Philadelphia

Dou WW, Wang W, Wang W. 2022. *The cost of intermediary market power for distressed borrowers*. Tech. Rep., Wharton School, Univ. Pa., Philadelphia

Drechsler I, Savov A, Schnabl P. 2018a. A model of monetary policy and risk premia. *J. Finance* 73(1):317–73

Drechsler I, Savov A, Schnabl P. 2018b. Liquidity, risk premia, and the financial transmission of monetary policy. *Annu. Rev. Financ. Econ.* 10:309–28

Du W, Tepper A, Verdelhan A. 2018. Deviations from covered interest rate parity. *J. Finance* 73(3):915–57

Dumas B. 1989. Two-person dynamic equilibrium in the capital market. *Rev. Financ. Stud.* 2(2):157–88

Durdu CB, Mendoza EG. 2006. Are asset price guarantees useful for preventing Sudden Stops? A quantitative investigation of the globalization hazard–moral hazard tradeoff. *J. Int. Econ.* 69(1):84–119

Durdu CB, Mendoza EG, Terrones ME. 2009. Precautionary demand for foreign assets in Sudden Stop economies: an assessment of the New Mercantilism. *J. Dev. Econ.* 89(2):194–209

Eisfeldt AL. 2004. Endogenous liquidity in asset markets. *J. Finance* 59(1):1–30

Eisfeldt AL, Rampini AA. 2006. Capital reallocation and liquidity. *J. Monet. Econ.* 53(3):369–99

Elenev V, Landvoigt T, Van Nieuwerburgh S. 2021. A macroeconomic model with financially constrained producers and intermediaries. *Econometrica* 89(3):1361–418

Fang X, Liu Y. 2021. Volatility, intermediaries, and exchange rates. *J. Financ. Econ.* 141(1):217–33

Fernández-Villaverde J, Rubio-Ramirez JF, Santos MS. 2006. Convergence properties of the likelihood of computed dynamic models. *Econometrica* 74(1):93–119

Frost J, Shin HS, Wierts P. 2020. *An early stablecoin? The Bank of Amsterdam and the governance of money*. Work. Pap. 902, Bank Int. Settl., Basel, Switz.

Gabaix X, Krishnamurthy A, Vigneron O. 2007. Limits of arbitrage: theory and evidence from the mortgage-backed securities market. *J. Finance* 62(2):557–95
Gabaix X, Maggiori M. 2015. International liquidity and exchange rate dynamics. *Q. J. Econ.* 130(3):1369–420
Gersbach H, Uhlig H. 2007. On the coexistence of banks and markets. *Scand. J. Econ.* 109(2):225–43
Gertler M, Karadi P. 2011. A model of unconventional monetary policy. *J. Monet. Econ.* 58(1):17–34
Gertler M, Karadi P. 2013. QE 1 vs. 2 vs. 3...: A framework for analyzing large-scale asset purchases as a monetary policy tool. *Int. J. Cent. Bank.* 9(1):5–53
Gertler M, Karadi P. 2015. Monetary policy surprises, credit costs, and economic activity. *Am. Econ. J. Macroecon.* 7(1):44–76
Gertler M, Kiyotaki N. 2010. Financial intermediation and credit policy in business cycle analysis. In *Handbook of Monetary Economics*, Vol. 3, ed. BM Friedman, M Woodford, pp. 547–99. Amsterdam: Elsevier
Gertler M, Kiyotaki N. 2015. Banking, liquidity, and bank runs in an infinite horizon economy. *Am. Econ. Rev.* 105(7):2011–43
Gertler M, Kiyotaki N, Prestipino A. 2016. Wholesale banking and bank runs in macroeconomic modeling of financial crises. In *Handbook of Macroeconomics*, Vol. 2, ed. JB Taylor, H Uhlig, pp. 1345–425. Amsterdam: Elsevier
Gertler M, Kiyotaki N, Prestipino A. 2019. A macroeconomic model with financial panics. *Rev. Econ. Stud.* 87(1):240–88
Gilchrist S, Sim JW, Zakrajsek E. 2014. *Uncertainty, financial frictions, and investment dynamics*. NBER Work. Pap. 20038
Gilchrist S, Zakrajsek E. 2012. Credit spreads and business cycle fluctuations. *Am. Econ. Rev.* 102(4):1692–720
Goldstein I, Pauzner A. 2005. Demand–deposit contracts and the probability of bank runs. *J. Finance* 60(3):1293–327
Gomes J, Jermann U, Schmid L. 2016. Sticky leverage. *Am. Econ. Rev.* 106(12):3800–28
Gomes JF, Schmid L. 2021. Equilibrium asset pricing with leverage and default. *J. Finance* 76(2):977–1018
Gorton G, Ordoñez G. 2016. Good booms, bad booms. *J. Eur. Econ. Assoc.* 18(2):618–65
Gourinchas PO, Obstfeld M. 2012. Stories of the twentieth century for the twenty-first. *Am. Econ. J. Macroecon.* 4(1):226–65
Gromb D, Vayanos D. 2002. Equilibrium and welfare in markets with financially constrained arbitrageurs. *J. Financ. Econ.* 66(2):361–407
Guerrieri L, Iacoviello M. 2015. OccBin: a toolkit for solving dynamic models with occasionally binding constraints easily. *J. Monet. Econ.* 70:22–38
Guvenen F. 2009. A parsimonious macroeconomic model for asset pricing. *Econometrica* 77(6):1711–50
Haddad V, Muir T. 2021. Do intermediaries matter for aggregate asset prices? *J. Finance* 76(6):2719–61
Hansen LP, Sargent TJ. 2001. Acknowledging misspecification in macroeconomic theory. *Rev. Econ. Dyn.* 4(3):519–35
Hansen LP, Sargent TJ, Turmuhambetova G, Williams N. 2006. Robust control and model misspecification. *J. Econ. Theory* 128(1):45–90
He Z, Kelly B, Manela A. 2017. Intermediary asset pricing: new evidence from many asset classes. *J. Financ. Econ.* 126(1):1–35
He Z, Krishnamurthy A. 2011. A model of capital and crises. *Rev. Econ. Stud.* 79(2):735–77
He Z, Krishnamurthy A. 2013. Intermediary asset pricing. *Am. Econ. Rev.* 103(2):732–70
Holden TD, Levine P, Swarbrick JM. 2020. Credit crunches from occasionally binding bank borrowing constraints. *J. Money Credit Bank.* 52(2–3):549–82
Holmstrom B, Tirole J. 1997. Financial intermediation, loanable funds, and the real sector. *Q. J. Econ.* 112(3):663–91
Hu GX, Pan J, Wang J. 2013. Noise as information for illiquidity. *J. Finance* 68(6):2341–82
Jermann U, Quadrini V. 2012. Macroeconomic effects of financial shocks. *Am. Econ. Rev.* 102(1):238–71
Jiang Z, Krishnamurthy A, Lustig HN. 2019. *Dollar safety and the global financial cycle*. SSRN Work. Pap. 3328808
Jiménez G, Ongena S, Peydró JL, Saurina J. 2014. Hazardous times for monetary policy: What do twenty-three million bank loans say about the effects of monetary policy on credit risk-taking? *Econometrica* 82(2):463–505

Judd KL. 1997. Computational economics and economic theory: Substitutes or complements? *J. Econ. Dyn. Control* 21(6):907–42
Kashyap AK, Stein JC. 2000. What do a million observations on banks say about the transmission of monetary policy? *Am. Econ. Rev.* 90(3):407–28
Khan A, Thomas JK. 2013. Credit shocks and aggregate fluctuations in an economy with production heterogeneity. *J. Political Econ.* 121(6):1055–107
Kilenthong WT, Townsend RM. 2021. A market-based solution for fire sales and other pecuniary externalities. *J. Political Econ.* 129(4):981–1010
Kim H, Kim J, Schaumburg E, Sims CA. 2005. *Calculating and using second order accurate solutions of discrete time dynamic equilibrium models.* Tech. Rep., Dep. Econ., Tufts Univ., Medford, Mass.
Kiyotaki N, Moore J. 1997. Credit cycles. *J. Political Econ.* 105(2):211–48
Kiyotaki N, Moore J. 2005. Liquidity and asset prices. *Int. Econ. Rev.* 46(2):317–49
Kiyotaki N, Moore J. 2019. Liquidity, business cycles, and monetary policy. *J. Political Econ.* 127(6):2926–66
Kocherlakota NR. 2000. Creating business cycles through credit constraints. *Q. Rev. Fed. Res. Bank Minneap.* 24(3):2
Korinek A, Mendoza EG. 2014. From Sudden Stops to Fisherian deflation: quantitative theory and policy. *Annu. Rev. Econ.* 6:299–332
Kurlat P. 2013. Lemons markets and the transmission of aggregate shocks. *Am. Econ. Rev.* 103(4):1463–89
Kyle AS, Xiong W. 2001. Contagion as a wealth effect. *J. Finance* 56(4):1401–40
Longstaff FA, Wang J. 2012. Asset pricing and the credit market. *Rev. Financ. Stud.* 25(11):3169–215
Lorenz F, Schmedders K, Schumacher M. 2020. *Nonlinear dynamics in conditional volatility.* Work. Pap., Univ. Münster, Ger.
Lorenzoni G. 2008. Inefficient credit booms. *Rev. Econ. Stud.* 75(3):809–33
Maggiori M. 2017. Financial intermediation, international risk sharing, and reserve currencies. *Am. Econ. Rev.* 107(10):3038–71
Mankiw NG, Zeldes SP. 1991. The consumption of stockholders and nonstockholders. *J. Financ. Econ.* 29(1):97–112
Mendoza EG. 2010. Sudden stops, financial crises, and leverage. *Am. Econ. Rev.* 100(5):1941–66
Mendoza EG, Quadrini V, Rios-Rull JV. 2009. Financial integration, financial development, and global imbalances. *J. Political Econ.* 117(3):371–416
Mendoza EG, Rojas E. 2018. Positive and normative implications of liability dollarization for Sudden Stops models of macroprudential policy. *IMF Econ. Rev.* 67:174–214
Mendoza EG, Smith KA. 2006. Quantitative implications of a debt-deflation theory of sudden stops and asset prices. *J. Int. Econ.* 70(1):82–114
Miao J, Wang P. 2018. Asset bubbles and credit constraints. *Am. Econ. Rev.* 108(9):2590–628
Midrigan V, Xu DY. 2014. Finance and misallocation: evidence from plant-level data. *Am. Econ. Rev.* 104(2):422–58
Miftakhova A, Schmedders K, Schumacher M. 2020. Computing economic equilibria using projection methods. *Annu. Rev. Econ.* 12:317–53
Miranda-Agrippino S, Rey H. 2020. US monetary policy and the global financial cycle. *Rev. Econ. Stud.* 87(6):2754–76
Moll B. 2014. Productivity losses from financial frictions: Can self-financing undo capital misallocation? *Am. Econ. Rev.* 104(10):3186–221
Muir T. 2017. Financial crises and risk premia. *Q. J. Econ.* 132(2):765–809
Nuño G, Thomas C. 2017. Bank leverage cycles. *Am. Econ. J. Macroecon.* 9(2):32–72
Pástor L, Stambaugh RF. 2003. Liquidity risk and expected stock returns. *J. Political Econ.* 111(3):642–85
Petrosky-Nadeau N, Zhang L, Kuehn LA. 2018. Endogenous disasters. *Am. Econ. Rev.* 108(8):2212–45
Phelan G. 2016. Financial intermediation, leverage, and macroeconomic instability. *Am. Econ. J. Macroecon.* 8(4):199–224
Pohl W, Schmedders K, Wilms O. 2018. Higher order effects in asset pricing models with long-run risks. *J. Finance* 73(3):1061–111
Pohl W, Schmedders K, Wilms O. 2021. Asset pricing with heterogeneous agents and long-run risk. *J. Financ. Econ.* 140(3):941–64

Rampini AA, Sufi A, Viswanathan S. 2014. Dynamic risk management. *J. Financ. Econ.* 111(2):271–96
Rampini AA, Viswanathan S. 2010. Collateral, risk management, and the distribution of debt capacity. *J. Finance* 65(6):2293–322
Rampini AA, Viswanathan S. 2013. Collateral and capital structure. *J. Financ. Econ.* 109(2):466–92
Rochet JC, Vives X. 2004. Coordination failures and the Lender of Last Resort: Was Bagehot right after all? *J. Eur. Econ. Assoc.* 2(6):1116–47
Romer CD. 1990. The Great Crash and the onset of the Great Depression. *Q. J. Econ.* 105(3):597–624
Rouwenhorst KG. 1995. Asset pricing implications of equilibrium business cycle models. In *Frontiers of Business Cycle Research*, Vol. 1, ed. TF Cooley, pp. 294–330. Princeton, NJ: Princeton Univ. Press
Schilling L, Fernández-Villaverde J, Uhlig H. 2020. *Central bank digital currency: When price and bank stability collide*. NBER Work. Pap. 28237
Schmitt-Grohé S, Uribe M. 2004. Solving dynamic general equilibrium models using a second-order approximation to the policy function. *J. Econ. Dyn. Control* 28(4):755–75
Schularick M, Taylor AM. 2012. Credit booms gone bust: monetary policy, leverage cycles, and financial crises, 1870–2008. *Am. Econ. Rev.* 102(2):1029–61
Shleifer A, Vishny RW. 1997. The limits of arbitrage. *J. Finance* 52(1):35–55
Smets F, Wouters R. 2007. Shocks and frictions in US business cycles: a Bayesian DSGE approach. *Am. Econ. Rev.* 97(3):586–606
Townsend RM. 1979. Optimal contracts and competitive markets with costly state verification. *J. Econ. Theory* 21(2):265–93
Uhlig H. 2010. A model of a systemic bank run. *J. Monet. Econ.* 57(1):78–96
Zetlin-Jones A, Shourideh A. 2017. External financing and the role of financial frictions over the business cycle: measurement and theory. *J. Monet. Econ.* 92:1–15