A Macroeconomic Model with a Financial Sector

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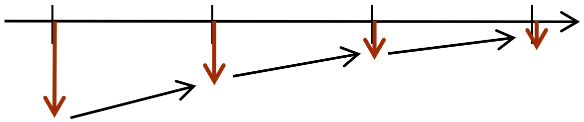
… so far

- Go to the (debt) limits
  - KM: Limit is exogenous - go to the limit
  - BruPed: Limit depends on future volatility
- "Safety cushion" – self-insurance
  - Bewley/Aiyagari: aggregate variables are deterministic
  - Krusell & Smith: add aggregate risk – no amplification (inv. is reversible)
  - …: add amplification in 3 period models
- BruSan10
  - Financial instability + Amplification + Persistence of shocks
  - Non-linear liquidity spirals - adverse feedback loops
    - Go beyond log-linearization
  - Endogenous risk
  - "Volatility paradox"
  - Asset pricing implications
    - Fat tails
    - Endogenous correlation structure

Amplification & Instability - Overview

- Bernanke & Gertler (1989), Carlstrom & Fuerst (1997)
  - Perfect (technological) liquidity, but persistence
  - Bad shocks erode net worth, cut back on investments, leading to low productivity & low net worth of in the next period



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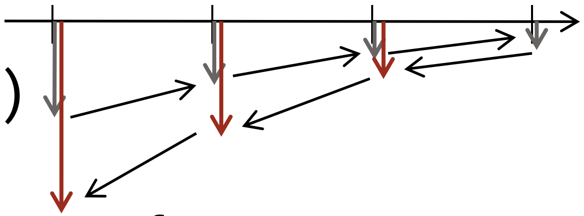

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  - Technological/market illiquidity
  - KM: Leverage bounded by margins; BGG: Verification cost (CSV)
  - Stronger amplification effects through prices (low net worth reduces leveraged institutions' demand for assets, lowering prices and further depressing net worth)

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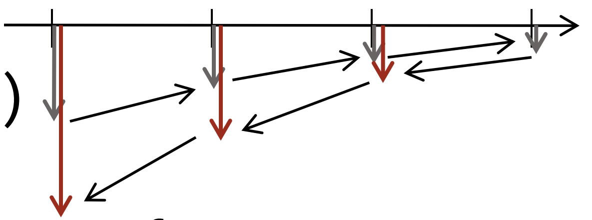

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- Brunnermeier & Sannikov (2010) *- only equity constraint*
  - Instability and volatility dynamics, volatility paradox

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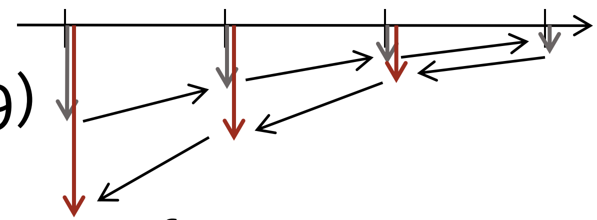

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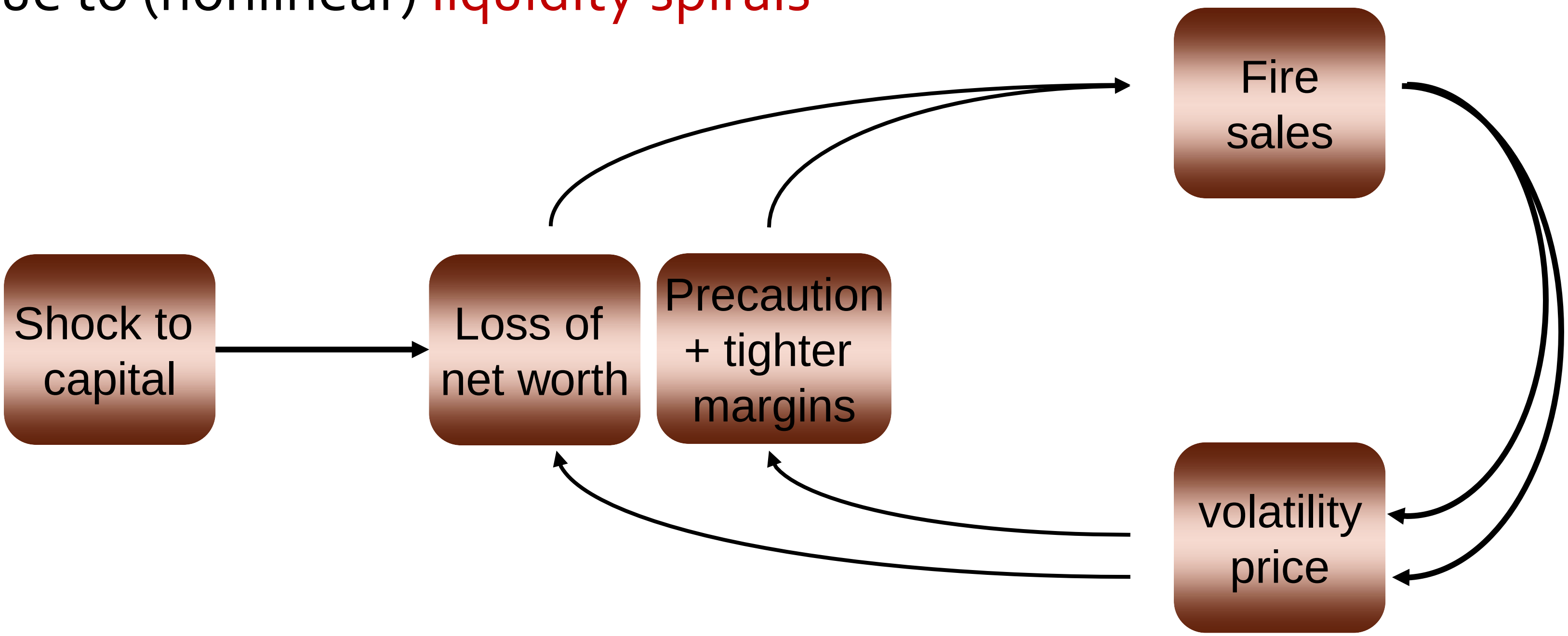
- Brunnermeier & Pedersen (2009), Geanakoplos
  - Volatility interaction with margins/haircuts (leverage) – *debt constraint*

Preview of results

- Full equilibrium dynamics + volatility dynamics
  - "Steady state" is endogenous depends on leverage, consumption etc.
  - Near "steady state"
    - (large) payouts balance profit making
    - intermediaries must be unconstrained and amplification is low
  - Below "steady state"
    - intermediaries constrained, try to preserve capital leading to high amplification and volatility → precaution
- Crises episodes have significant endogenous risk, correlated asset prices, larger spreads and risk premia
- SDF is driven by constraint & $c \geq 0$
- "Volatility paradox"
- Securitization and hedging of idiosyncratic risks can lead to higher leverage, and greater systemic risk

… with volatility dynamics + precaution

- Unstable dynamics away from steady state due to (nonlinear) liquidity spirals



- Volatility dynamics leads affects size of "safety cushion"
  - Note: log-linearization with zero probability shocks → no safety cushion

Model : Technology

$a \geq \underline{a},\ \delta \leq \underline{\delta}$

Experts

Output: $y_t = a k_t$

- Consumption rate c_t
- Investment rate ι_t
- $\frac{dk_t}{k_t} = \underbrace{(\Phi(\iota_t) - \delta)}_{=g} dt + \sigma dZ_t$

Less productive HH

Output: $y_t = \underline{a} k_t$

- Consumption rate $\underline{c}_t$
- Investment rate $\underline{\iota}_t$

$= (\Phi(\underline{\iota}_t) - \underline{\delta}) dt + \sigma dZ_t$

Model : Preferences

Experts

Output: $y_t = ak_t$

- Consumption rate c_t
- Investment rate ι_t
- $\frac{dk_t}{k_t} = \underbrace{(\Phi(\iota_t) - \delta)}_{=g} dt + \sigma dZ_t$

- U =E₀[$\int_0^\infty e^{-\rho t}\, dc_t$]
- $dc_t \geq 0$

$a \geq \underline{a},\ \delta \leq \underline{\delta}$

$\rho \geq r$

Less productive HH

Output: $y_t = \underline{a}k_t$

- Consumption rate $\underline{c}_t$
- Investment rate $\underline{\iota}_t$

$= (\Phi(\underline{\iota}_t) - \underline{\delta})dt + \sigma dZ_t$

- U =E₀[$\int_0^\infty e^{-rt}\, d\underline{c}_t$]
- $dc_t \in \mathbb{R}$

Model : Financial Frictions

Experts

$a \geq \underline{a},\ \delta \leq \underline{\delta}$

Output: $y_t = a k_t$

- Consumption rate c_t
- Investment rate ι_t
- $\frac{dk_t}{k_t} = \underbrace{(\Phi(\iota_t) - \delta)}_{=g} dt + \sigma dZ_t$
- U =E$_0$[$\int_0^\infty e^{-\rho t} dc_t$]
- $dc_t \geq 0$
- Can issue only risk-free debt + solvency constraint

$\rho \geq r$

Less productive HH

Output: $y_t = \underline{a} k_t$

- Consumption rate $\underline{c}_t$
- Investment rate $\underline{\iota}_t$

$= \left(\Phi\left(\underline{\iota}_t\right) - \underline{\delta}\right) dt + \sigma dZ_t$

- U =E$_0$[$\int_0^\infty e^{-rt}\, d\underline{c}_t$]
- $d\underline{c}_t \in \mathbb{R}$
- Financially unconstraint

Model : Market for Physical Capital

Experts

Output: $y_t = ak_t$

- Consumption rate c_t
- Investment rate ι_t
- $\frac{dk_t}{k_t} = \underbrace{(\Phi(\iota_t) - \delta)}_{=g} dt + \sigma dZ_t$
- U =E$_0$[$\int_0^\infty e^{-\rho t}\, dc_t$]
- $dc_t \geq 0$
- Can issue only risk-free debt + solvency constraint

$a \geq \underline{a}$, $\delta \leq \underline{\delta}$

$\rho \geq r$

Less productive HH

Output: $y_t = \underline{a}k_t$

- Consumption rate $\underline{c}_t$
- Investment rate $\underline{\iota}_t$

$= (\Phi(\underline{\iota}_t) - \underline{\delta})dt + \sigma dZ_t$

- U =E$_0$[$\int_0^\infty e^{-rt}\, d\underline{c}_t$]
- $d\underline{c}_t \in \mathbb{R}$
- Financially unconstraint

- Liquid markets for capital k_t with endogenous price process for capital

$$dq_t = \mu_t^q q_t dt + \sigma_t^q q_t dZ_t$$

First Best – No Frictions

- Experts
  - Manage capital forever
  - Issue equity to less productive HH
  - Consume entire net worth at $t = 0$
- Price of capital

$$\bar{q} = \max_{\iota} \frac{a - \iota}{r - \Phi(\iota) + \delta}$$

  - Earns a required return $= r$

  - Contrast: if HH were to manage capital forever

$$\underline{q} = \max_{\underline{\iota}} \frac{\underline{a} - \underline{\iota}}{r - \Phi(\underline{\iota}) + \underline{\delta}}$$

Definition of Equilibrium

- An equilibrium consists of functions that for each history of macro shocks $\{Z_s, s \in [0, t]\}$ specify
  - q_t the price of capital
  - $k_t, \underline{k}_t$ capital holdings
  - $dc_t \geq 0, d\underline{c}_t$ consumption of representative expert and households
  - $\iota_t, \underline{\iota}_t$ rate of internal investment, per unit of capital
  - r the risk-free rate
- such that
  - intermediaries and households maximize their utility, taking prices q_t as given and
  - markets for capital and consumption goods clear

Solution steps

1. Equilibrium conditions
   - Agents' optimization
     - Return from holding capital
     - Internal investment
     - Household's optimal portfolio choice
     - Experts optimal choice
       - Portfolio
       - Consumption
   - Market clearing conditions
2. Law of motion of state variable (wealth distribution)
3. Express in ODEs of state variable

Step 1: Equilibrium Conditions

- Return on Capital
  - dr_t^k = dividend yield + capital gains rate

- For experts:
  - $dr_t^k = \frac{a-\iota_t}{q_t}dt + \frac{d(k_t q_t)}{k_t q_t}$

- For less productive households
  - $d\underline{r}_t^k = \frac{\underline{a}-\underline{\iota}_t}{q_t}dt + \frac{d(\underline{k}_t q_t)}{\underline{k}_t q_t}$

1. Capital Gains Rate $d(k_t q_t)/k_t q_t$

- Capital
  - $dk_t = (\Phi(\iota_t) - \delta)k_t dt + \sigma k_t dZ_t$ "cash flow news"
- Price
  - $dq_t = \mu_t^q q_t dt + \sigma_t^q q_t dZ_t$ "SDF news"

- $k_t q_t$ value dynamics

1. Capital Gains Rate $d(k_t q_t)/k_t q_t$

- Capital
  - $dk_t = (\Phi(\iota_t) - \delta)k_t dt + \sigma k_t dZ_t$ exogenous risk
- Price
  - $dq_t = \mu_t^q q_t dt + \sigma_t^q q_t dZ_t$ endogenous risk
- $k_t q_t$ value dynamics
  - $d(k_t q_t) =$
    $\left(\Phi(\iota_t) - \delta + \mu_t^q + \sigma\sigma_t^q\right)(k_t q_t)dt + \left(\sigma + \sigma_t^q\right)(k_t q_t)dZ_t$

    exogenous risk, endogenous risk
  - Ito's Lemma product rule: $d(X_t Y_t) = dX_t Y_t + X_t dY_t + \sigma^X \sigma^Y dt$

1. Optimization

1. Internal investment — static

2. External investment x_t
   - Given price dynamics $dq_t/q_t = \mu_t^q dt + \sigma_t^q dZ_t$
   - Solvency constraint $n_t \geq 0$

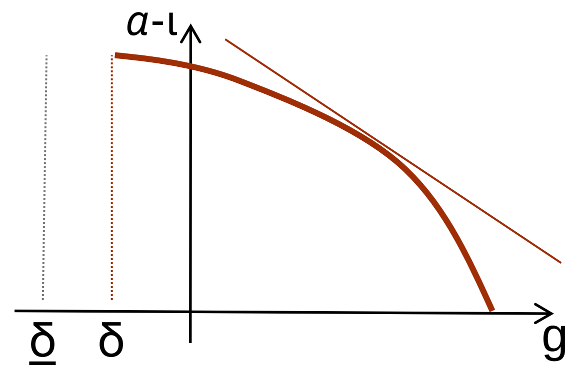
3. When to consume? dc_t

(2. and 3.: dynamic optimization)

- Bellman equation w/ value function $\theta_t n_t$

1. Internal investment – marginal Tobin's q

- Static problem



- Choose investment rate ι that solves

$$\max_{\iota} \Phi(\iota) - \iota / q_t$$

- FOC: $\Phi'(\iota) = \frac{1}{q_t}$ (marginal Tobin's q)

- Hence, optimal investment is

$$\iota_t = \underline{\iota}_t = \iota(q_t)$$

- Substitute in optimal investment rate

1. External Investment - Leverage

- Less productive HH
  - $\underline{x}_t$ fraction of net worth invested in capital
  - $\frac{d\underline{n}_t}{\underline{n}_t} = \underline{x}_t d\underline{r}_t^k + (1 - \underline{x}_t) r dt - \frac{d\underline{c}_t}{\underline{n}_t}$
  - Consumption can be negative

- Experts
  - x_t fraction of net worth invested in capital

$$\frac{dn_t}{n_t} = x_t dr_t^k + (1 - x_t) r dt - \frac{dc_t}{n_t}$$

Denote $d\zeta_t := dc_t / n_t$

  - If $x_t > 1$ then expert uses leverage

1. External Investment and Consumption

1. Households: risk free rate of r_t = households discount rate
   - Makes HH indifferent between consuming and saving, s.t. consumption market clears
   - Required return

$$\underbrace{\frac{\underline{a}-\iota(q_t)}{q_t} + \Phi(\iota(q_t)) - \underline{\delta} + \mu_t^q + \sigma\sigma_t^q}_{E_t[d\underline{r}_t^k]/dt} \leq r \text{ with equality if capital>o}$$

2. Experts choose $\{x_t, d\zeta_t\}$ - dynamic problem
   - Let future expected payoff under this strategy be

$$\theta_t n_t = E_t\left[\int_t^\infty e^{-\rho(s-t)} dc_s\right]$$

   - Value function is proportional to n_t, since
     - Price takers
     - Consumption is proportional to their wealth

1. Solving dynamic optimization

- Let value of extra \$, (Note, $\theta_t - 1$ = external funding premium)

$$d\theta_t = \mu_t^\theta \theta_t dt + \sigma_t^\theta \theta_t dZ_t$$

- Use Ito's lemma to expand the Bellman equation

$$\rho \theta_t n_t dt = \max_{x_t \geq 0, d\zeta_t \geq 0} n_t \, d\zeta_t + E[d(\theta_t n_t)]$$

  - Consumption: $\theta_t \geq 1$, and $d\zeta_t > 0$ only when $\theta_t = 1$
  - Risk free: $\underbrace{r}_{risk-free} + \underbrace{\mu_t^\theta}_{E[change\ of\ investment\ opportunities]} = \underbrace{\rho}_{required\ return}$
  - Capital:

$$\underbrace{\frac{a - \iota(q_t)}{q_t} + \Phi(\iota(q_t)) + \mu_t^q + \sigma\sigma_t^q - r}_{E[excess\ return\ of\ capital]} = \underbrace{-\sigma_t^\theta(\sigma + \sigma_t^q)}_{capital\ risk\ premium}$$

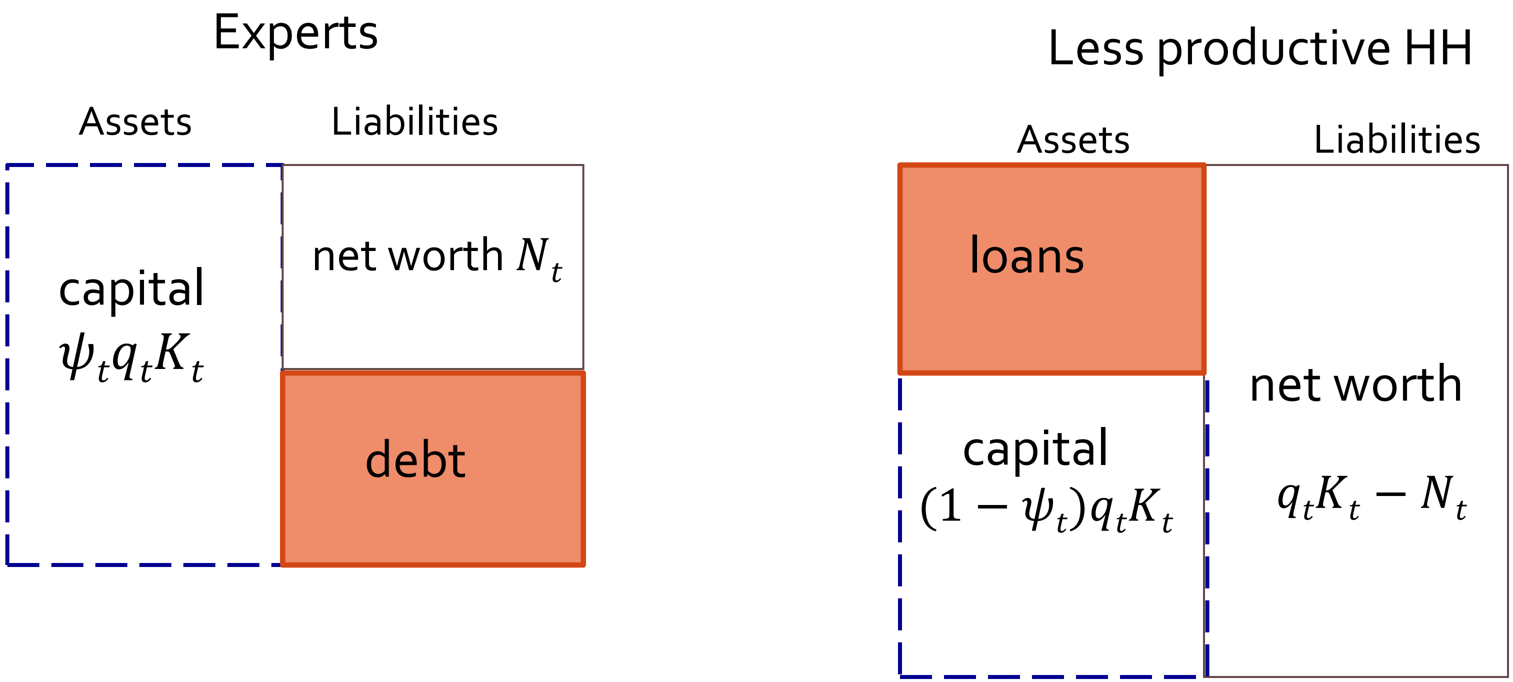
with (in) equality if $x_t > (=)0$

1. Intuition – main forces at work

- Investment
  - *Scale up*
    - Scalable profitable investment opportunity
    - Higher leverage (borrow at r)
  - *Scale back*
    - Precaution: - don't exploit full (GE) debt capacity – "dry powder"
      - Ultimately, stay away from fire-sales prices
      - Debt can't be rolled over if $d > k_t \underline{q}$ (note, price is depressed)
      - Solvency constraint
- Consumption
  - Consume *early* and borrow $r < \rho$
  - Consume *late* to overcome investment frictions

aggregate leverage!

1. Aggregate Balance Sheets



- Wealth distribution is summarized by $\eta_t = N_t/(q_t K_t)$ "experts' wealth share"
- In equilibrium everything (prices, capital allocation, investment) will be functions of η_t

Step 2: Law of Motion of η

- $dN_t = \psi_t q_t K_t dr_t^k - (\psi_t q_t K_t - N)rdt - dC_t$
  - $dr_t^k = \cdots,$
- Recall $\frac{d(q_t K_t)}{q_t K_t} = \cdots$
  - Use Ito to derive $\frac{d(1/q_t K_t)}{1/q_t K_t} = \ldots$
- Again Ito
- $d\eta_t =$

$$(dN_t)\frac{1}{q_t K_t} + N_t d\left(\frac{1}{q_t K_t}\right) + \psi_t q_t K_t(\sigma + \sigma_t^q)\frac{-1}{q_t K_t}(\sigma + \sigma_t^q)dt$$

$$= \quad \ldots$$

2. Law of Motion of η

$$\frac{d\eta_t}{\eta_t} = \mu_t^\eta dt + \sigma_t^\eta dZ_t - d\zeta_t$$

where

$$\sigma_t^\eta = \frac{\psi_t - \eta_t}{\eta_t}\left(\sigma + \sigma_t^q\right)$$

$$\mu_t^\eta = \sigma_t^\eta\left(\sigma + \sigma_t^q + \sigma_t^\theta\right) + \frac{a - \iota(q_t)}{q_t} + (1 - \psi_t)\left(\underline{\delta} - \delta\right)$$

Step 3: Express as functions of η

- Use Ito's formula (extensively) to replace terms such as $\mu_t^{\theta}, \sigma_t^{q}$, ... with expressions $q', q'', \theta', \theta''$ → ODEs
- Simplified example: Leland (1994). Value equity, $E(V)$
  - Firm's asset value follow $\frac{dV_t}{V_t} = rdt + \sigma dZ_t$ (state variable)
  - Debt coupon payment rate of C
  - Default when V_B is hit – liquidation value αV_B with $\alpha \in (0,1)$
  - Postulate equity follows: $dE_t = \mu_t^E E_t dt + \sigma_t^E E_t dZ_t$ (q-measure)
  - $r = \mu^E - C/E$, since any asset expected return under q is r.
  - Using Ito's lemma on $E(V)$, $\mu_t^E E_t = rV_t E' + \frac{1}{2}\sigma^2 V_t^2 E''$
  - So $r = \frac{rVE' + 1/2\sigma^2 V^2 E''}{E} - \frac{C}{E}$, boundaries $E(V_B) = 0$, $\lim_{V\to\infty} V - E(V) \to C/r$

Step 4: Numerical algorithm

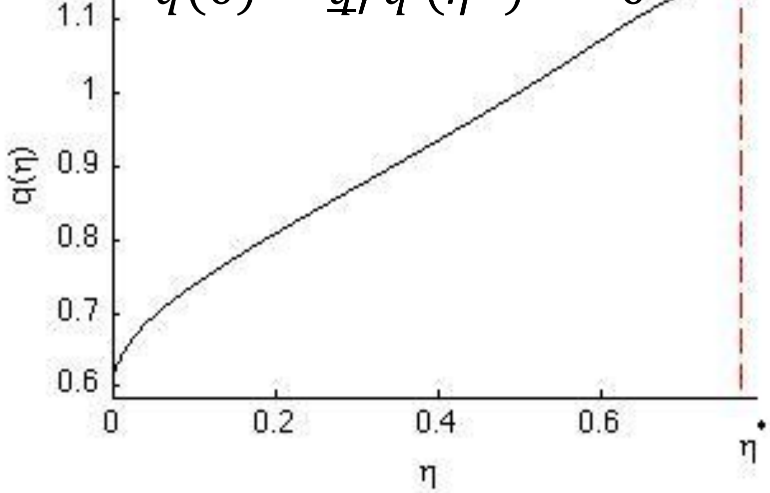
- Algorithm 1: Compute $q''(\eta)$ and $\theta''(\eta)$ from $\eta, \mathrm{q}(\eta), q'(\eta), \theta(\eta), \theta'(\eta)$

- Algorithm 2: solve system of ODE's numerically
  - Use Matlab ode45 solver

Numerical example

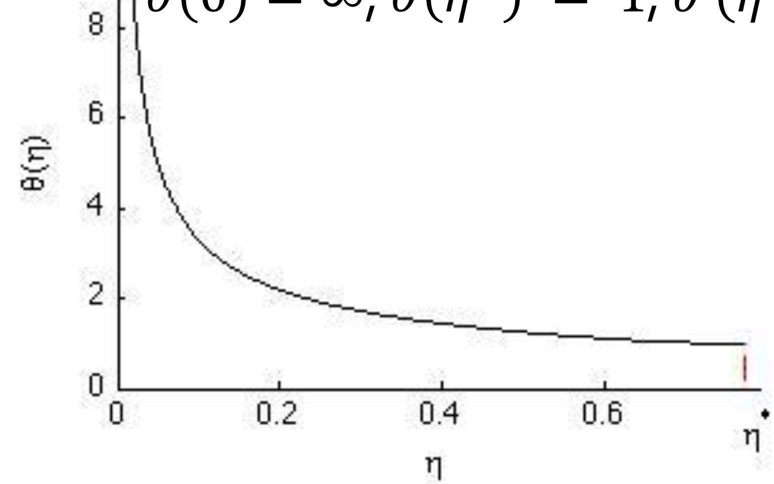
boundary conditions

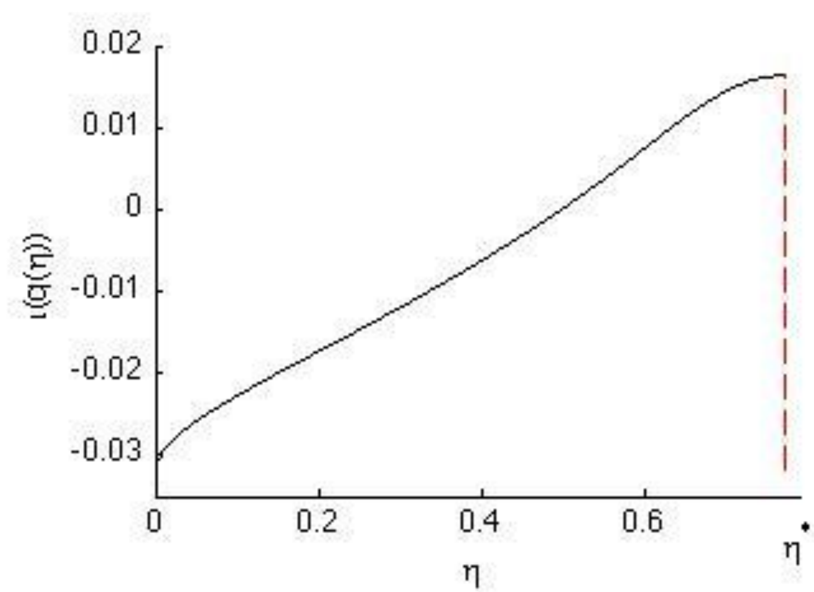
$q(0) = \underline{q},\ q'(\eta^*) = 0$

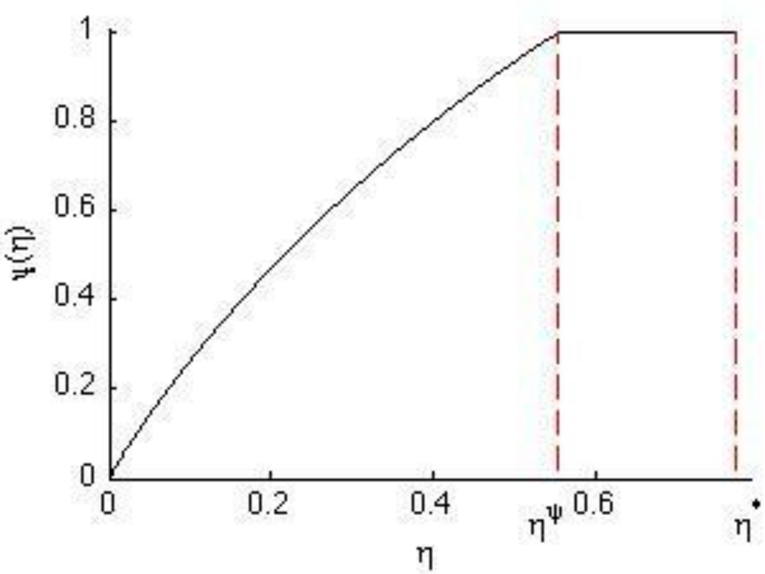


boundary conditions

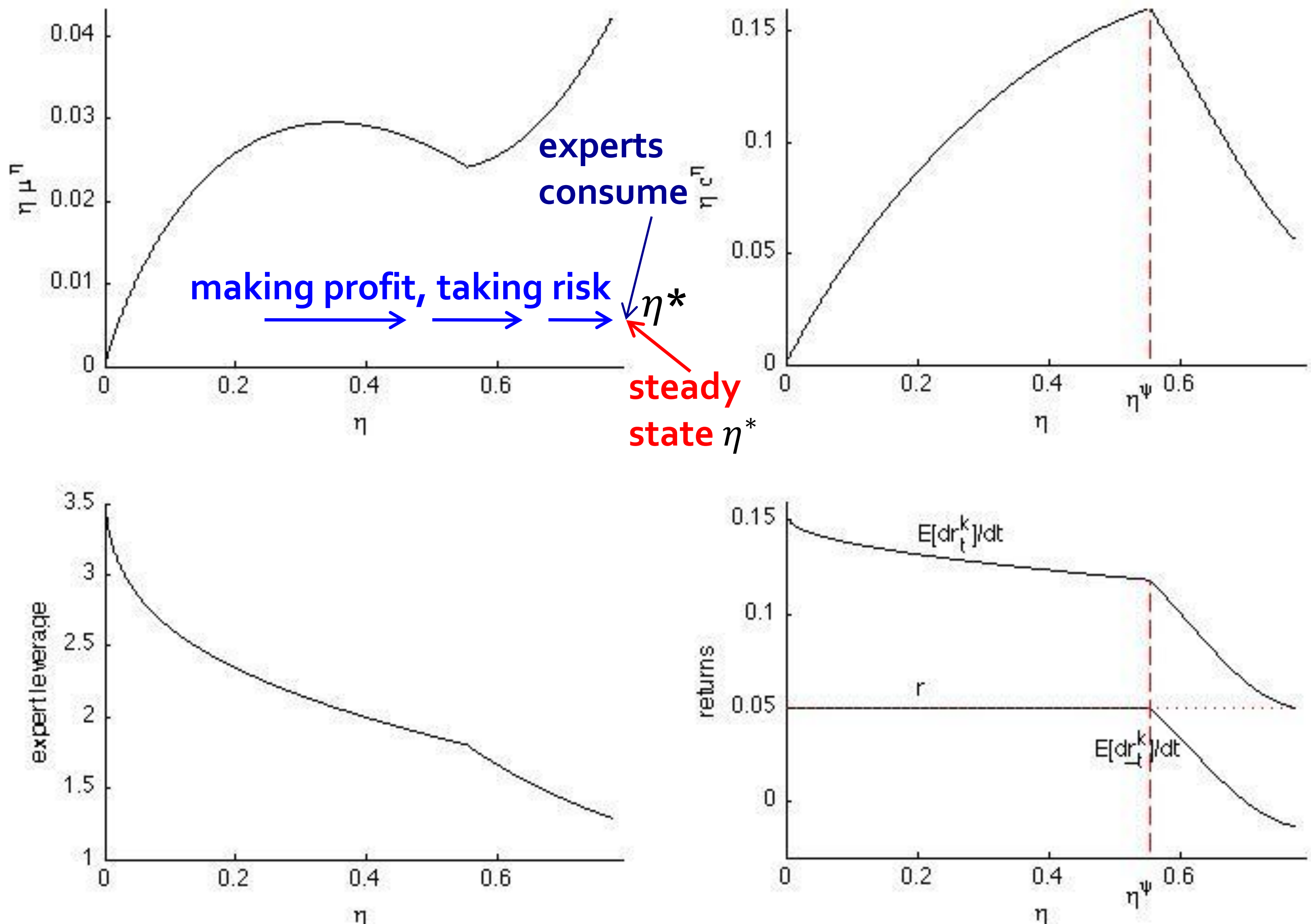
$\theta(0) = \infty,\ \theta(\eta^*) = 1,\ \theta'(\eta^*) = 0$



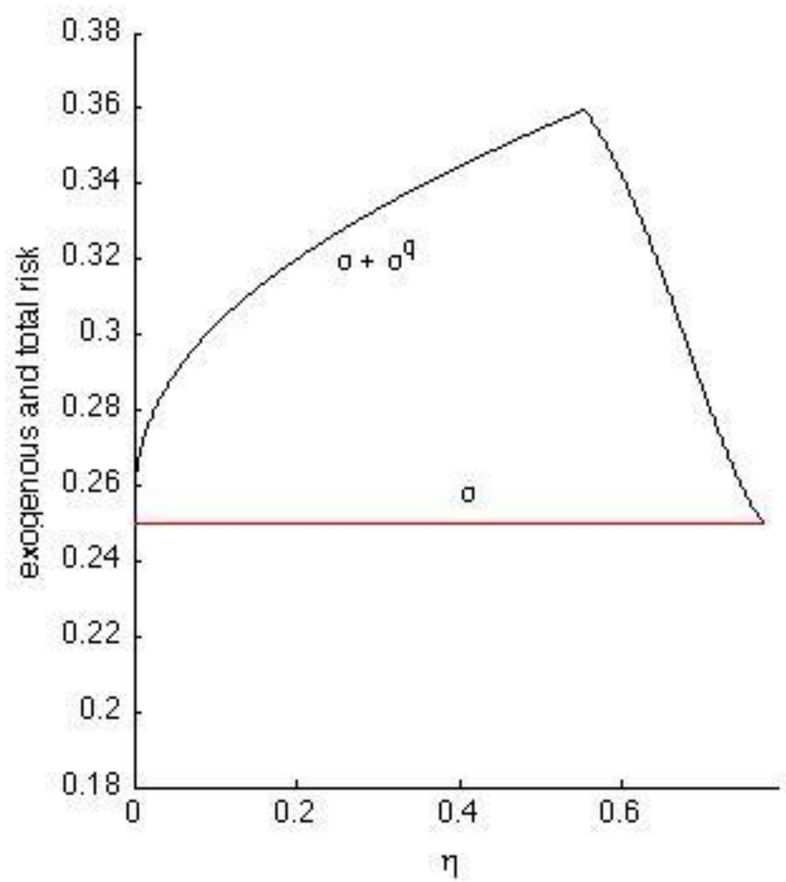


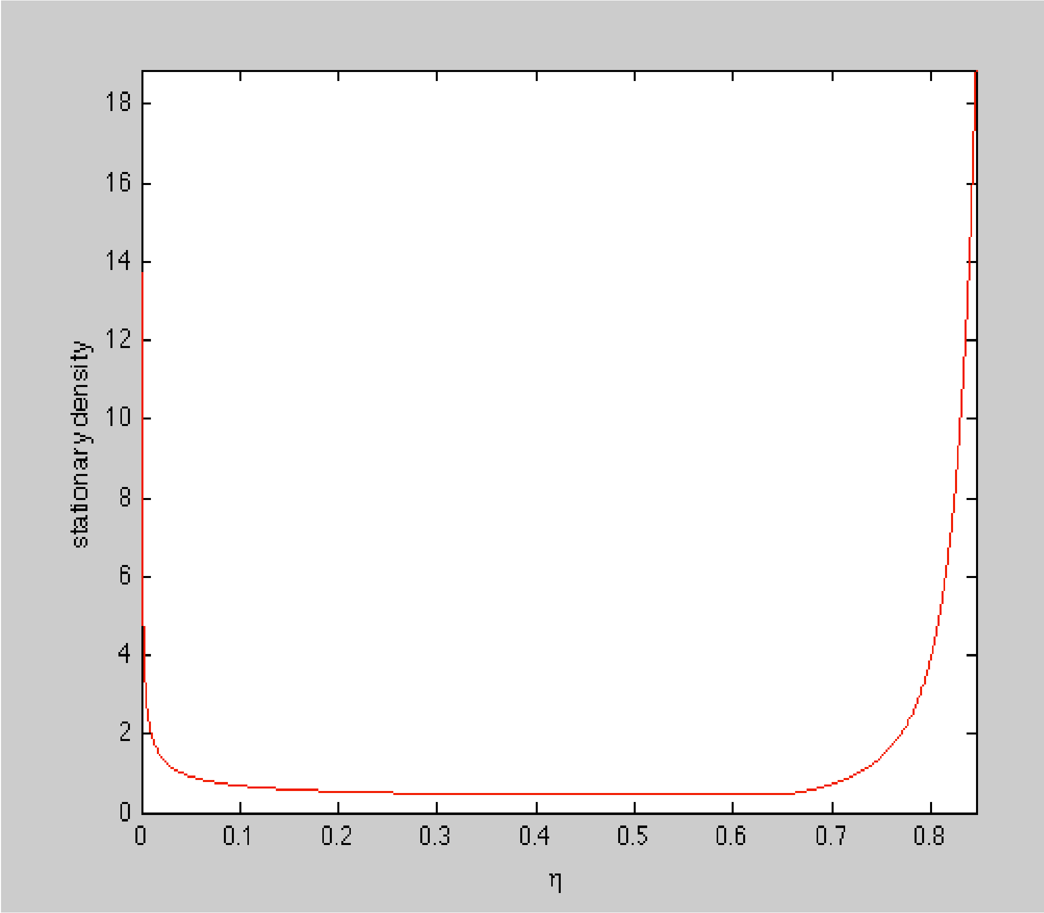


Drift and Volatility of η



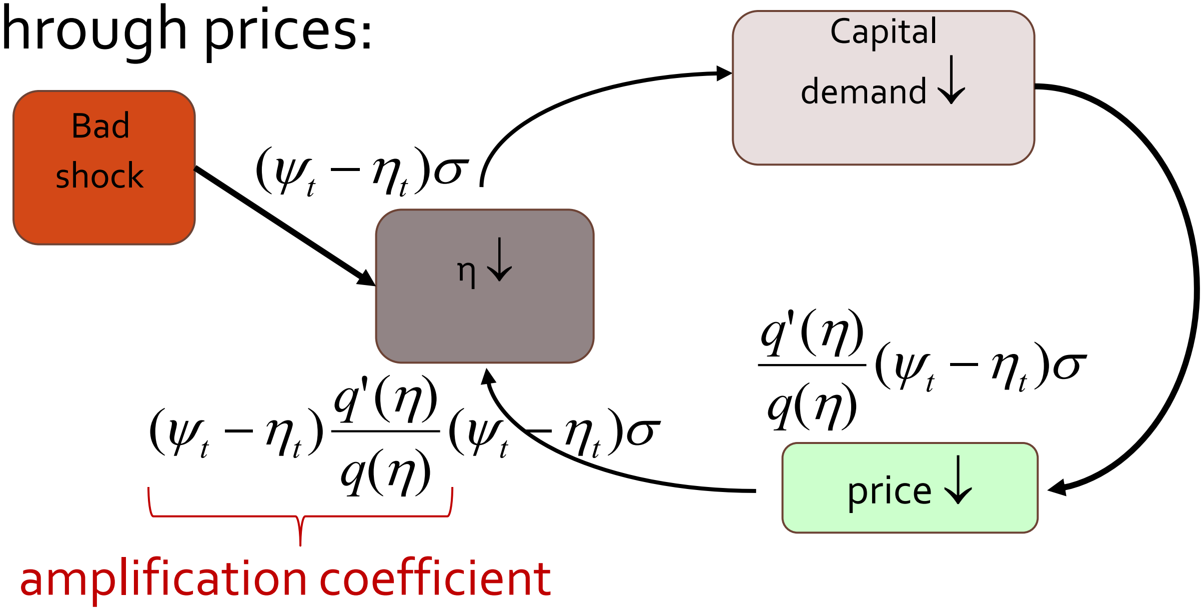
Stationary Density





Endogenous Risk Through Amplification

- Amplification through prices:



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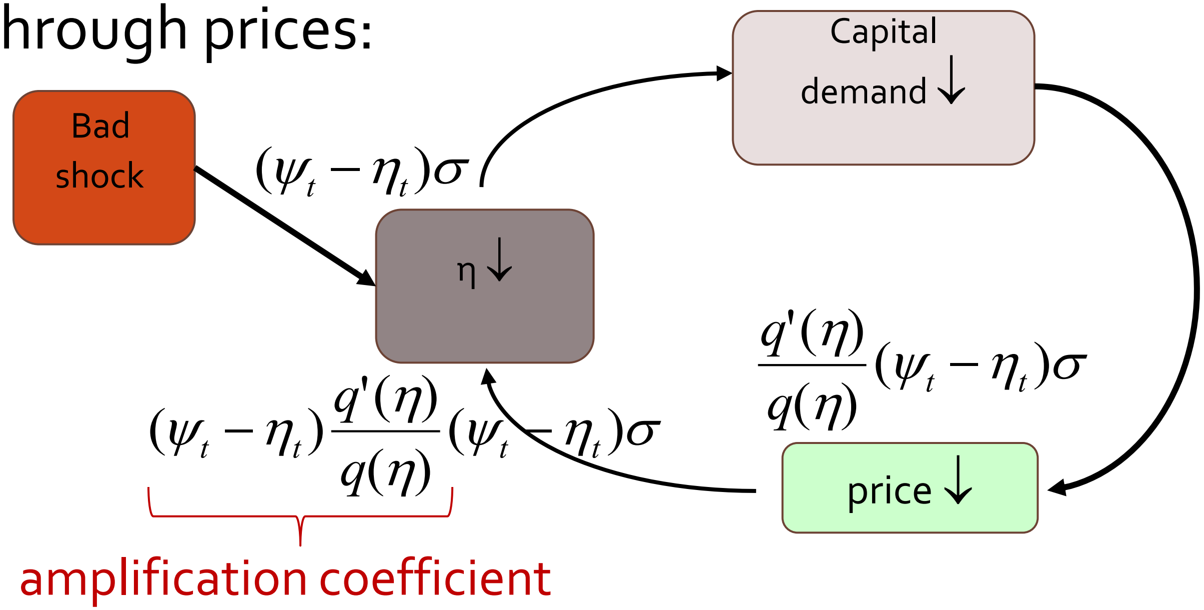


- Endogenous risk
  - zero near the steady state
  - large below steady state

$$\sigma_t^q = \frac{\frac{q'(\eta)}{q(\eta)}(\psi_t - \eta_t)\sigma}{1 - (\psi_t - \eta_t)\frac{q'(\eta)}{q(\eta)}}$$

Dynamics near and away from SS

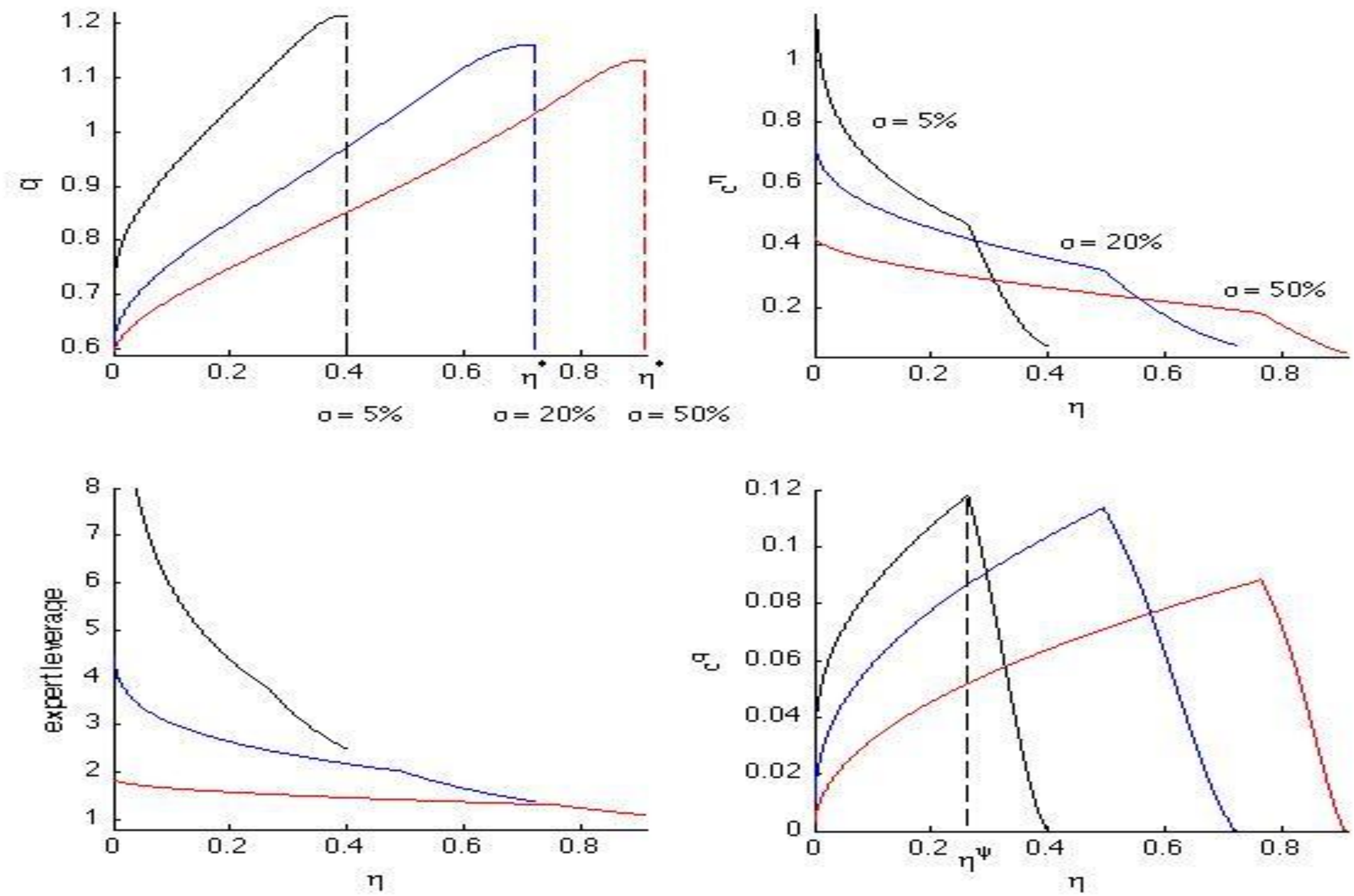
- Intermediaries choose payouts endogenously
  - Exogenous exit rate in BGG/KM
  - Payouts occur when intermediaries are least constrained

$$q'(\eta^*) = 0$$

- Steady state: experts unconstrained
  - Bad shock leads to lower payout rather than lower capital demand
  - $q'(\eta^*) = 0, \sigma_t^q(\eta^*) = 0$
- Below steady state: experts constrained
  - Negative shock leads to lower demand
  - $q'(\eta)$ is high, strong amplification, $\sigma_t^q(\eta)$ is high

Note difference to BGG/KM

"Volatility Paradox" … σ (.05, .2 , .5)



Ext1: asset pricing (cross section)

- **Capital:** Correlation increases with σ^q
  - Extend model to many types i of capital

$$\frac{dk_t^i}{k_t^i} = \left(\Phi\left(\iota_t^i\right) - \delta\right)dt + \sigma dZ_t + \sigma' dz_t^i$$

aggregate shock   uncorrelated shock

  - Experts hold diversified portfolios
    - Equilibrium looks as before, (all types of capital have same price) but
    - Volatility of $q_t k_t$ is $\sigma + \sigma' + \sigma^q$
    - Endogenous risk is perfectly correlated, exogenous risk not
    - For uncorrelated z^i and z^j
      correlation $(q_t^i k_t^i, q_t^j k_t^j)$ is $(\sigma + \sigma^q)/(\sigma + \sigma' + \sigma^q)$
      which is increasing in σ^q

Ext1: asset pricing (cross section)

- **Outside equity:** (in an extended version with outside equity)
  - Negative skewness
  - Excess volatility
  - Pricing kernel: e^{-rt}
    - Needs risk aversion!

- **Derivatives:**
  - Volatility smirk (Bates 2000)
  - More pronounced for index options (Driessen et al. 2009)

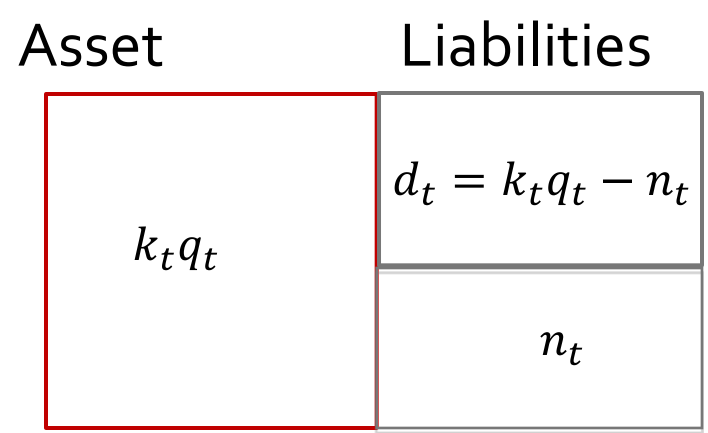
Ext2: Idiosyncratic jump losses

$$dk_t^i = gk_t^i dt + \sigma k_t^i dZ_t + k_t^i dJ_t^i$$

- J_t^i is an idiosyncratic compensated Poisson loss process, loss distribution $F(y)$, $y \in [-1,0]$ (per \$ of total assets) and intensity λ
- $q_t k_t^i$ drops below debt d_t, costly state verification
- Debt holders' loss rate $L(x) = \lambda \int_{-1}^{x} \left(\frac{1}{x} + y\right) dF(y)$

$$\frac{n_t}{k_t q_t} = \frac{1}{x_t}$$

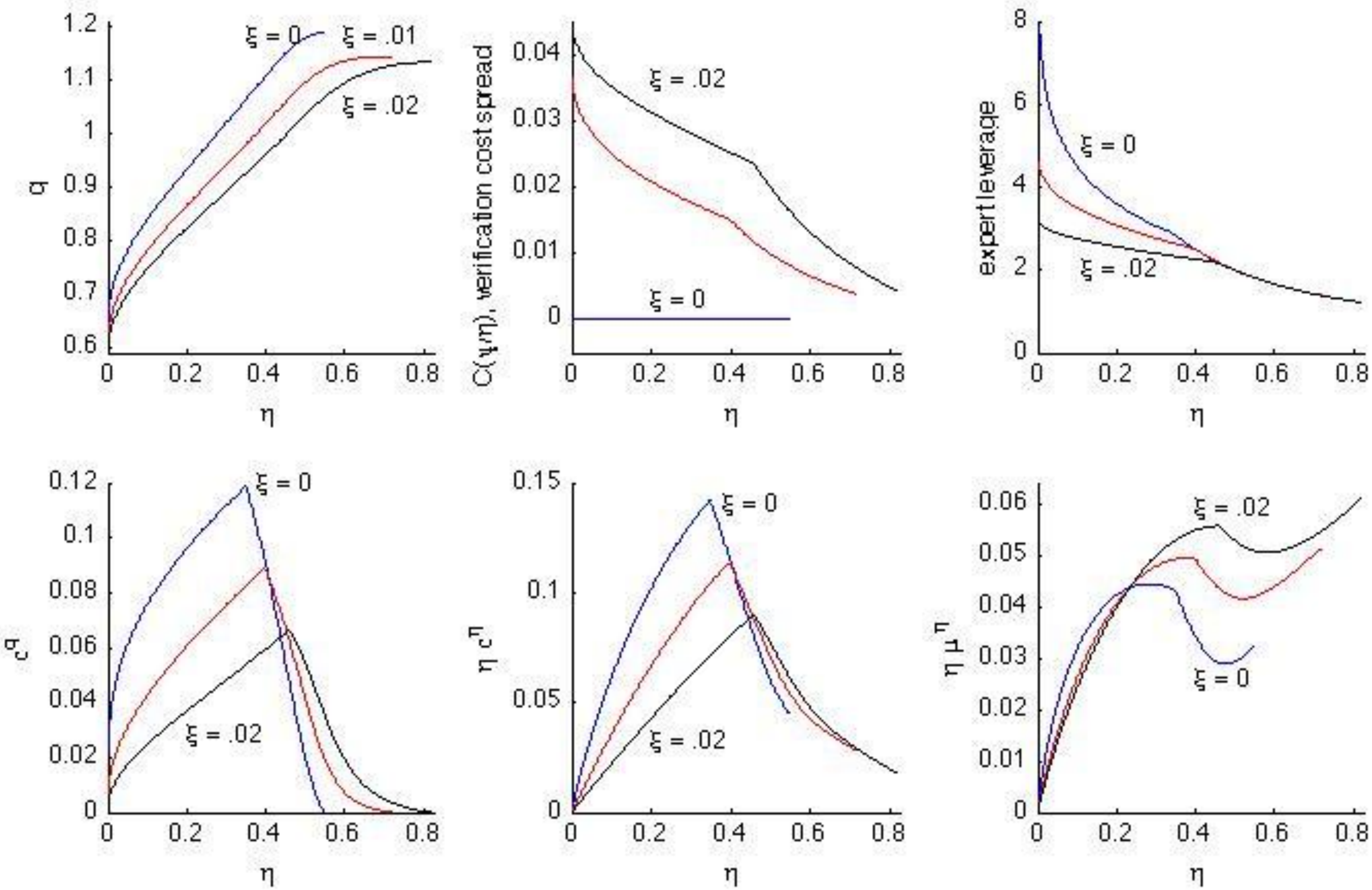
- Borrowing cost rate $C(x)$
  - E.g. : $C(x) = \xi(x-1)$
  - BGG: verification costs
  - KM: $C(x) = 0$ on $[0, \underline{x}]$ and ∞ otherwise
- Leverage bounded not only by precautionary motive, but also by the cost of borrowing



Ext2: Idiosyncratic losses

- Experts borrowing rate $> r$
  - Compensates for verification cost
- $d\eta_t$ = diffusion process (without jumps) because losses cancel out in aggregate
- Results:
  - Borrowing costs (even in downturn) make system more stable --- note difference to KM!
  - Non-degenerated deterministic steady state $x^0 = 1/\eta^0$
    - $\rho - r = x^0(x^0 - 1)C'(x^0) + C(x^0)$
    - If $C(x)$ large as $x \to \infty$, then experts cannot hold capital η close to zero

Ext2: Idiosyncratic losses



- Borrowing costs (even in downturns) stabilize system

Ext3: Securitization

- Experts can contract on shocks Z_t and dJ_t^i directly among each other, zero contracting costs
- In principle, good thing (avoid verification costs)
- Equilibrium
  - experts fully hedge idiosyncratic risks
  - experts hold their share (do not hedge) aggregate risk Z_t, market price of risk depends on $\sigma_t^\theta(\sigma + \sigma_t^q)$
  - with securitization experts lever up more (as a function of η_t) and bonus payments occur "sooner"
  - financial system becomes less stable
  - risk taking is endogenous (Arrow 1971, Obstfeld 1994)

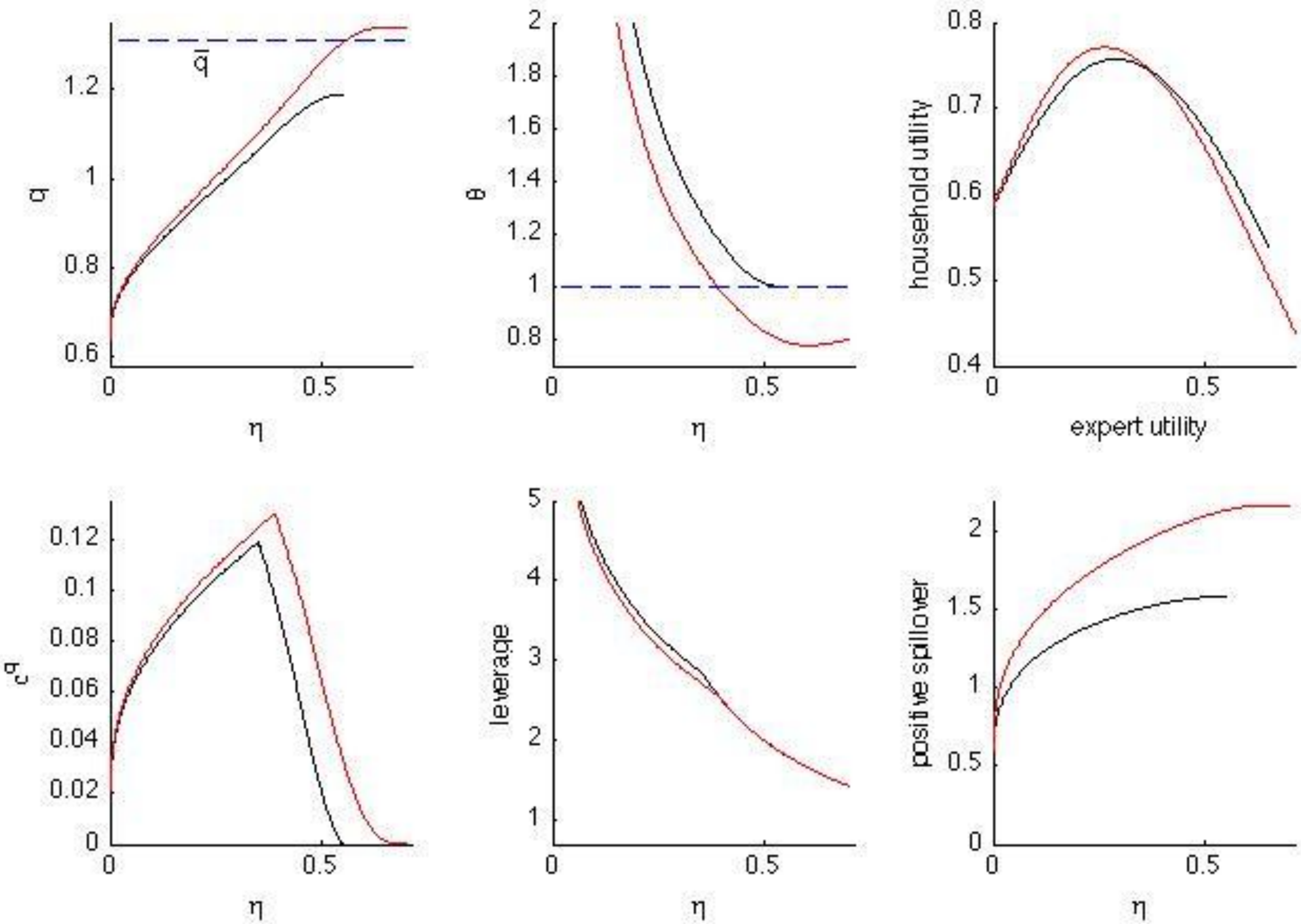
Ext4: Policy measures

- Policy 1: Capital requirement (leverage constraint) $x \leq \bar{x}(\eta)$
  - Increases η^* ➡ stabilizing effect
    - Small effect, e.g. $\bar{x}(\eta) = \bar{x}$ which binds on 70% in downturns increases η^* only by 2%
  - Depresses price, more misallocation ➡ inefficient

  ➡ Overall, mostly inefficient

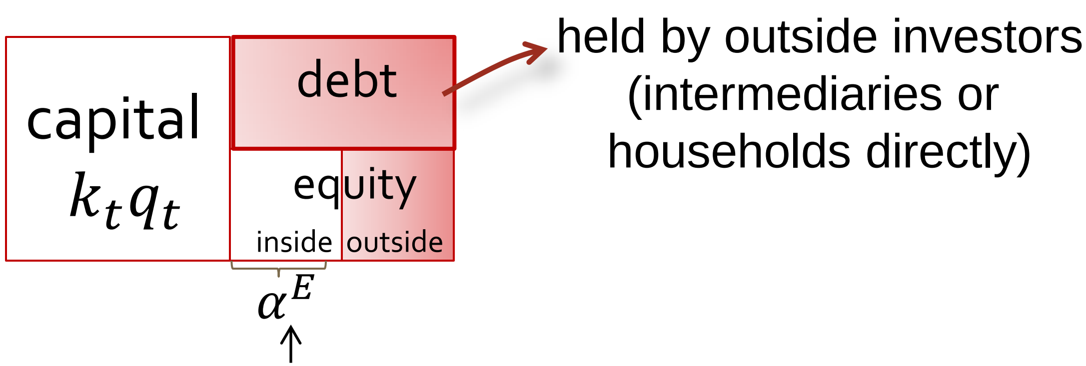
- Policy 2: Forced retained earnings until $\eta^* = 0.7$
  - Improves welfare
  - Price of q rises, θ non-continuous and risk premia negative around η^*
  - Less frequent, but more severe crisis, low speed of recovery

Ext4: Policy measures



Microfoundation: Contracting friction

- Focus on contracts in which agents is required to hold sufficient levered equity stake in projects



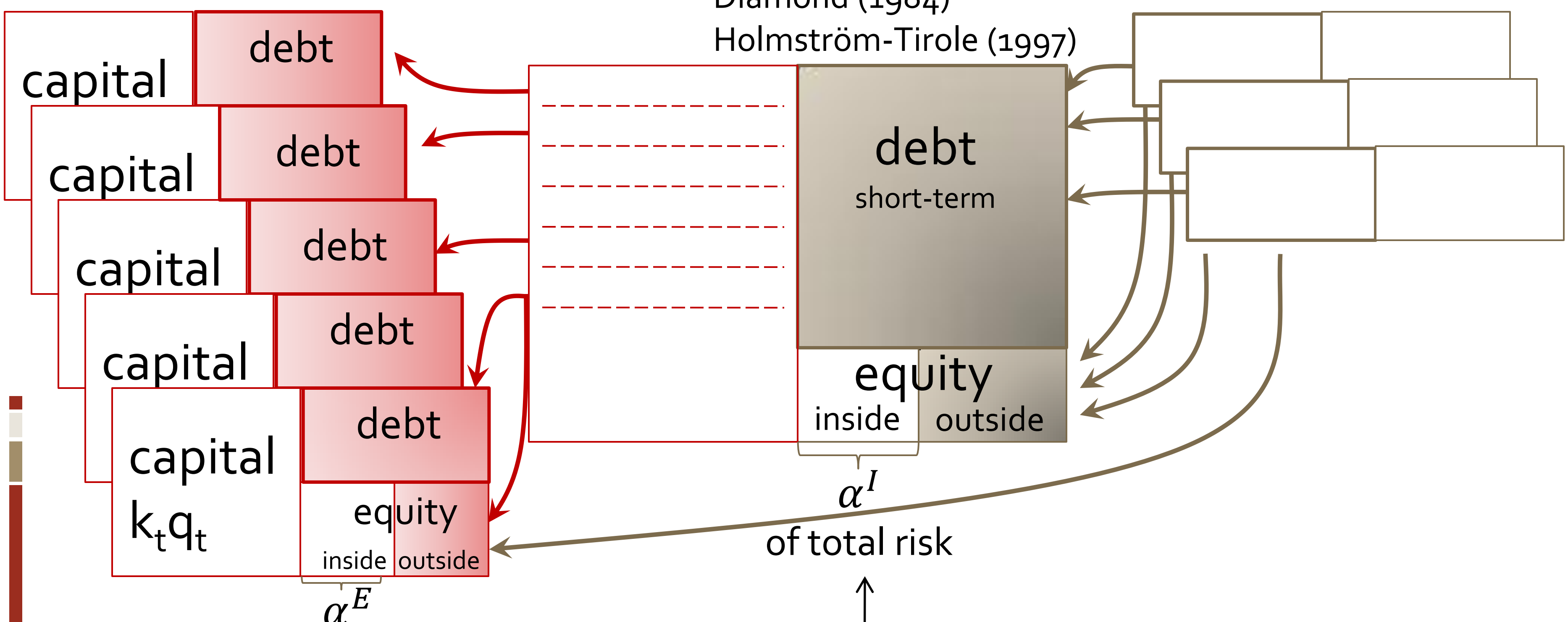
- The more risk entrepreneur wants to unload, the more they have to be monitored (by someone who takes on exposure)

Microfoundation of contracts (extra)

- Agency problem of entrepreneur
  - Increase capital depreciation rate, private benefit b per \$1 destroyed
  - Incentive constraint: entrepreneur equity stake $\geq b$
- Are these contracts optimal? No
  - Entrepreneur reward depends on $k_t q_t$, but q_t is determined by market – why not hedge q_t to get a better performance?
  - Shocks to k_t are common across entrepreneurs, why not hedge those and get first best?
  - In practice markets aggregate information to determine $k_t q_t$, but hard to distinguish between shocks to k_t (cash flow news) and q_t (SDF news)
- Optimal contracts get first-best, but miss important phenomena
- Same as in Kiyotaki & Moore, BGG, He & Krishnamurthy

Interlinked balance sheets

- Productive
- Intermediary
  - Monitoring
    Diamond (1984)
    Holmström-Tirole (1997)
- Less productive



incentive for entrepreneur to exert effort

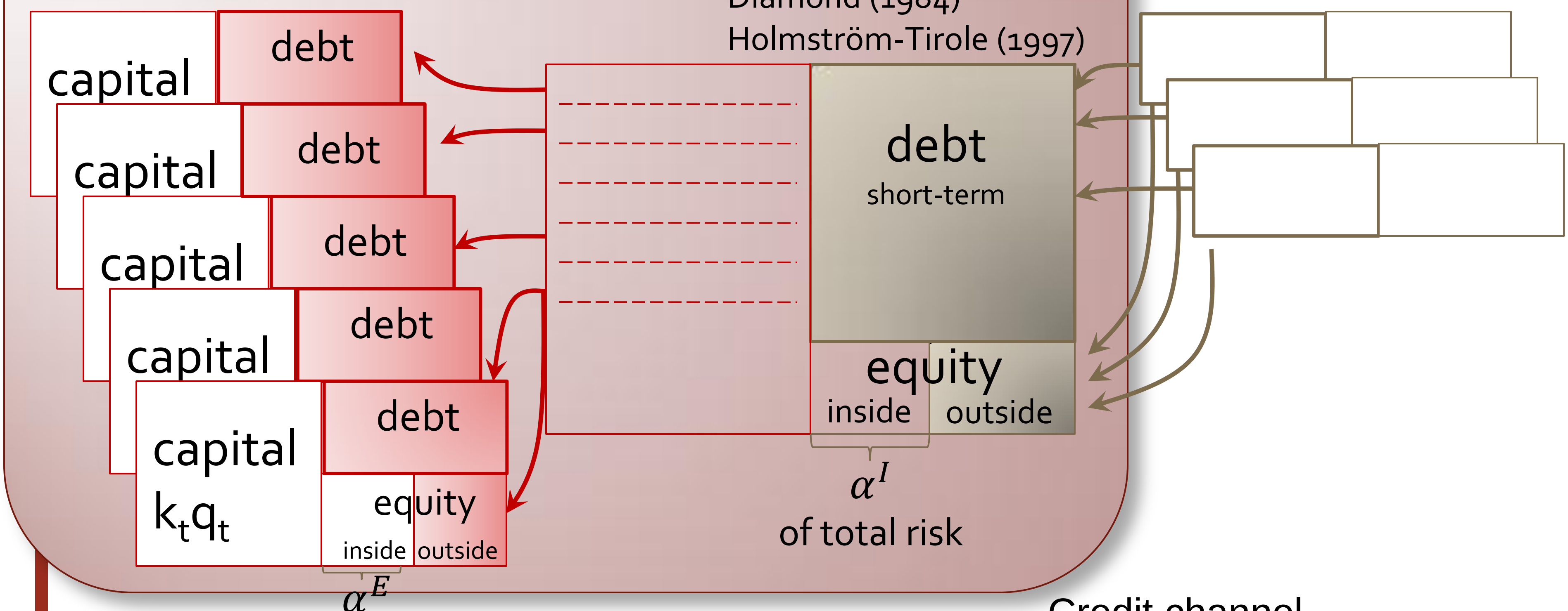
incentive for intermediaries to monitor (have to hold outside equity)

Microfoundation of capital structures

- *Assumption:* value of assets $q_t k_t^i$ is contractable, k_t^i not
- Agency problem of entrepreneur
  - Can take projects w/ NPV<0, private benefit $b(m) < 1$ per $ destroye
  - m is amount of monitoring by intermediary
  - Incentive constraint: $\alpha^E \geq b(m)$, binds in equ. $\Rightarrow \alpha^{E(m)}$
- Agency problem of intermediary
  - Save monitoring cost $c(m)$ per $1 if shirking
  - Incentive constraint: $\alpha^I \geq c(m)$
- Solvency constraint: $n \geq 0$ (implied by IC constraints)
- Assume $c(m) + b(m)$ is a constant for all m
  entrepreneurs' & intermediaries' net worth are substitutes
  - Special case: if entrepreneurs' net worth =0, then m s.t. $b(m) = 0$

Merging productive HH & Intermediaries

- Productive
- Intermediary
  - Monitoring
    Diamond (1984)
    Holmström-Tirole (1997)
- Less productive



$$\alpha := \alpha^E + \alpha^I \geq b(m) + c(m)$$

"merged experts"

Credit channel

- Lending channel
- Borrowers' balance sheet channel

Conclusion

- Incorporate financial sector in macromodel
  - Higher growth
  - Exhibits instability
    - similar to existing models (BGG, KM) in term of persistence/amplification, but
    - non-linear liquidity spirals (away from steady state) lead to instability
- Risk taking is endogenous
  - "Volatility paradox:" Lower exogenous risk leads to greater leverage and may lead to higher endogenous risk
  - Correlation of assets increases in crisis
  - With idiosyncratic jumps: countercyclical credit spreads
  - Securitization helps share idiosyncratic risk, but leads to more endogenous risk taking and amplifies systemic risk
- Welfare: (Pecuniary) Externalities
  - excessive exposure to crises events

Thank you! ☺