The Propagation of Monetary Policy Shocks in a Heterogeneous Production Economy

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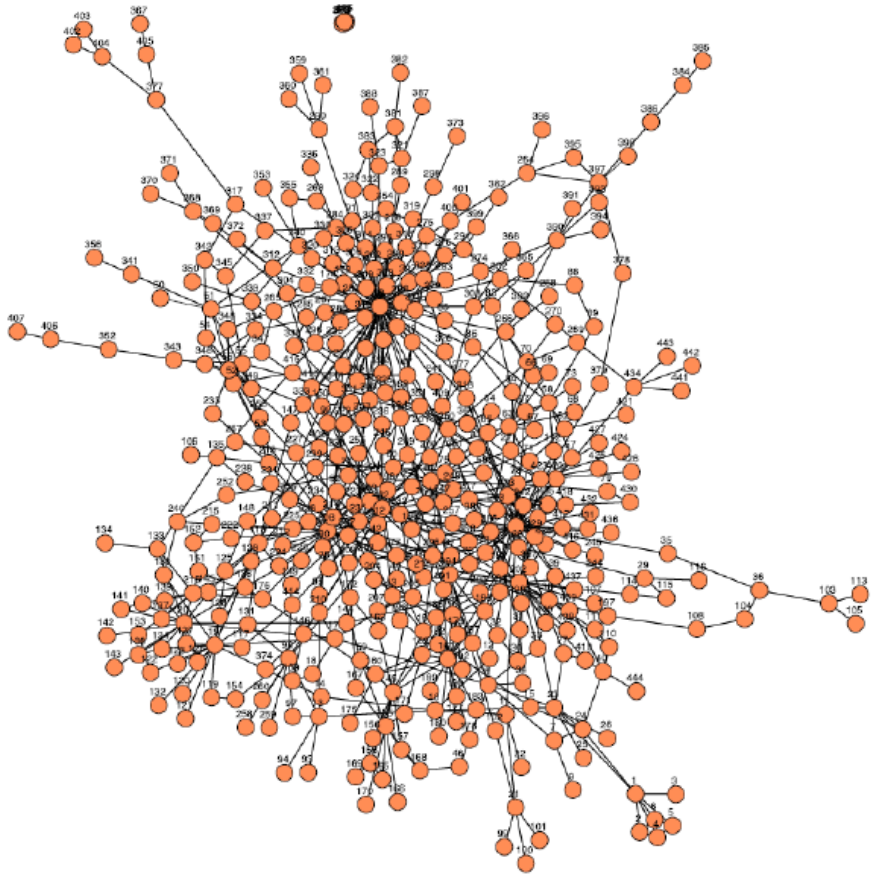
Federal Reserve Bank of Cleveland Inflation Conference

September 29, 2016

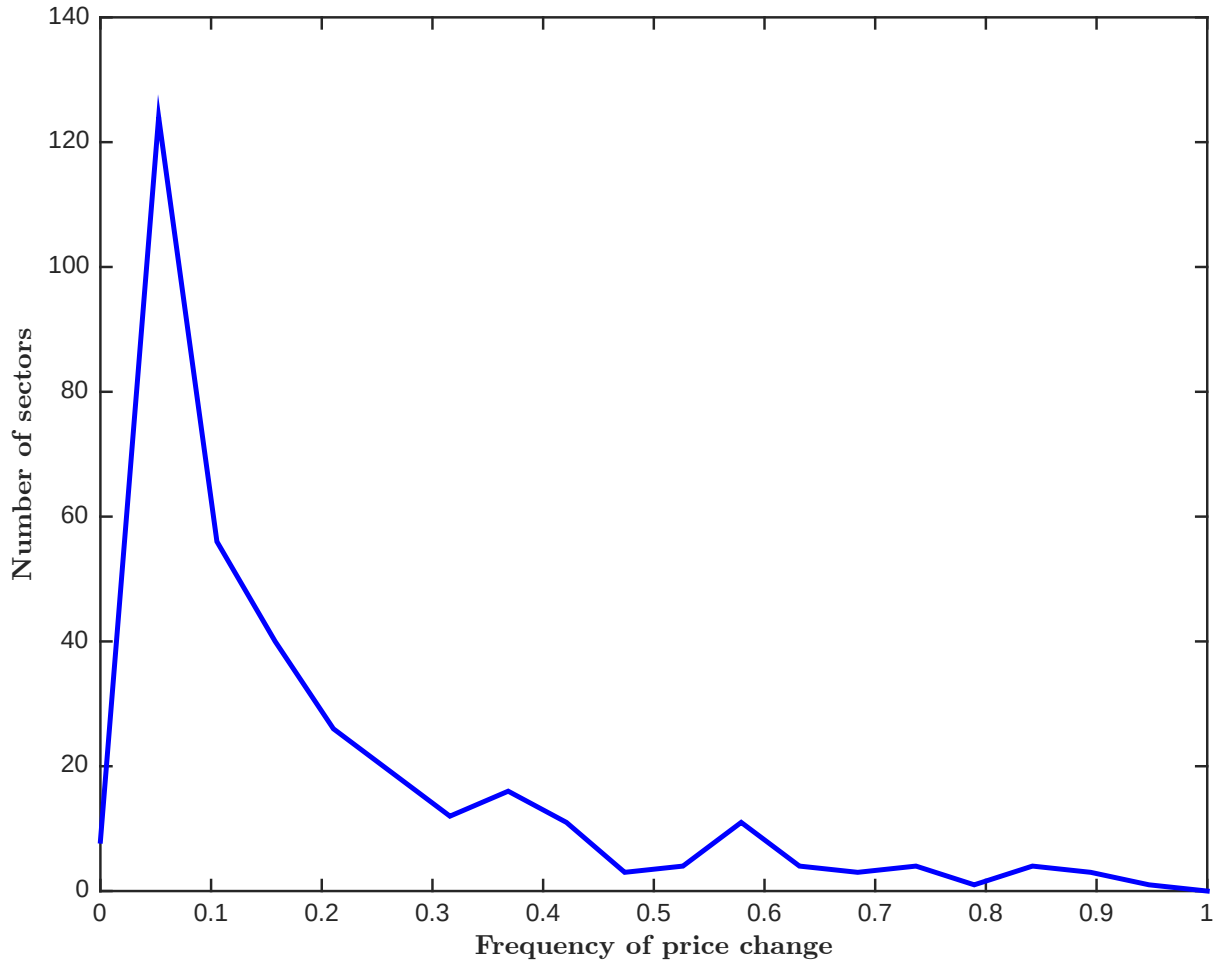
MOTIVATION

- Fact 1: Sectors are heterogeneous in their input-output linkages with other sectors.



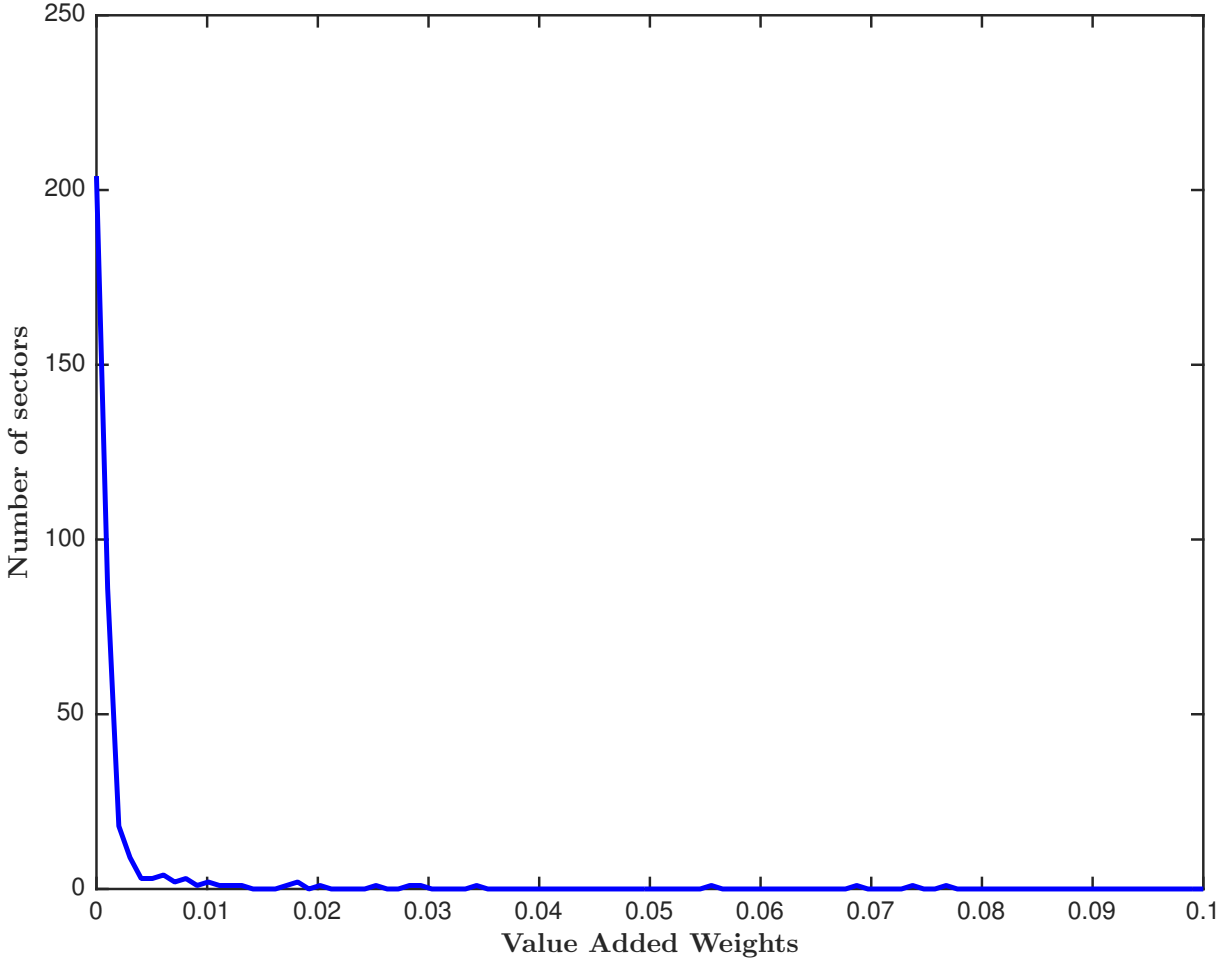
MOTIVATION

- Fact 2: Sectors are heterogeneous in their frequency of price changes, which is heavy-tailed.



MOTIVATION

- Fact 3: Sectors are heterogeneous in their importance for GDP.



Motivation (and literature review)

- How does the interaction of these three forms of heterogeneity affect the propagation of monetary policy shocks?
- Big picture:
  Interaction of heterogeneities with heterogeneous pricing frictions can change identity of sectoral effects on aggregate marginal cost.
- Companion paper: Propagation of idiosyncratic shocks.

Motivation (and literature review)

- Which heterogeneity matters the most for real output effects?
  - Price stickiness >> consumption shares >> input-output linkages.
- Does the choice of granularity matter? N=1? N=350?
  - Most disaggregated calibration yields 34% larger real effects
  - Similar impact response for inflation
- What is the role of heavy tail in frequency of adjustment?
- How does monetary policy rule interact with heterogeneities?

Motivation (and literature review)

- Relevant papers:
  - Monetary policy shocks and production networks: Basu (1995), Clark (1999), Huang and Liu (2002, 2004), Carvalho (2006), Nakamura and Steinsson (2010), Bouakez, Cardia, and Ruge-Murcia (2009, 2013), Carvalho and Lee (2011), Carvalho and Schwartzman (2015).
  - Asymmetry in sector size or input-output structure: Gabaix (2011), Acemoglu et al. (2012).
  - Many others on markups, real rigidities, trade linkages, etc.

Outline

Two parts:

- Theoretical results
- Empirical analysis

Abridged description of the setup 1/5

Households' utility:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma} - 1}{1-\sigma} - \sum_{k=1}^{K} g_k \frac{L_{kt}^{1+\varphi}}{1+\varphi} \right) \quad s.t. \;\; BC$$

where

$$C_t \equiv \left[\sum_{k=1}^{K} \omega_{ck}^{\frac{1}{\eta}} C_{kt}^{1-\frac{1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

$$C_{kt} \equiv \left[n_k^{-1/\theta} \int_{\Im_k} C_{kjt}^{1-\frac{1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}},$$

and $\eta < \theta$.

Abridged description of the setup 2/5

Firms' production function:

$$Y_{kjt} = L_{kjt}^{1-\delta} Z_{kjt}^{\delta},$$

where

$$Z_{kjt} \equiv \left[\sum_{r=1}^{K} \omega_{kr}^{\frac{1}{\eta}} Z_{kjt}(r)^{1-\frac{1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

$$Z_{kjt}(r) \equiv \left[n_r^{-1/\theta} \int_{\Im_r} Z_{kjt}\left(r, j'\right)^{1-\frac{1}{\theta}} dj' \right]^{\frac{\theta}{\theta-1}},$$

and $\eta < \theta$.

Abridged description of the setup 3/5

Demand for sector k, variety producer j :

from households:	from other firms:
$C_{kt} = \omega_{ck} \left(\frac{P_{kt}}{P_t^c}\right)^{-\eta} C_t,$	$Z_{k'j't}(k) = \omega_{k'k} \left(\frac{P_{kt}}{P_t^{k'}}\right)^{-\eta} Z_{k'j't},$
$C_{kjt} = \frac{1}{n_k} \left(\frac{P_{kjt}}{P_{kt}}\right)^{-\theta} C_{kt}.$	$Z_{k'j't}(k,j) = \frac{1}{n_k} \left(\frac{P_{kjt}}{P_{kt}}\right)^{-\theta} Z_{k'j't}(k)$

where price aggregators are:

for households:	for other firms:
$P_t^c = \left[\sum_{r=1}^{K} \omega_{cr} P_{rt}^{1-\eta}\right]^{\frac{1}{1-\eta}},$	$P_t^{k'} = \left[\sum_{r=1}^{K} \omega_{k'r} P_{rt}^{1-\eta}\right]^{\frac{1}{1-\eta}},$
$P_{rt} = \left[\frac{1}{n_r} \int_{\Im_r} P_{rjt}^{1-\theta} dj\right]^{\frac{1}{1-\theta}}.$	$P_{rt} = \left[\frac{1}{n_r} \int_{\Im_r} P_{rjt}^{1-\theta} dj\right]^{\frac{1}{1-\theta}}.$

Abridged description of the setup 4/5

Sectoral heterogeneity of price stickiness:

$$\sum_{s=0}^{\infty} Q_{t,t+s} \alpha_k^s Y_{kjt+s} \left[P_{kjt}^* - \frac{\theta}{\theta - 1} MC_{kjt+s} \right] = 0$$

where

$$MC_{kjt} = \frac{1}{1-\delta} \left(\frac{\delta}{1-\delta} \right)^{-\delta} W_{kt}^{1-\delta} \left(P_t^k \right)^{\delta}$$

and sectoral prices follow

$$P_{kt} = \left[(1 - \alpha_k) P_{kt}^{*1-\theta} + \alpha_k P_{kt-1}^{1-\theta} \right]^{\frac{1}{1-\theta}}$$

Abridged description of the setup 5/5

Equilibrium conditions:

$$Y_{kjt} = C_{kjt} + \sum_{k'=1}^{K} \int_{\Im_{k'}} Z_{k'j't}(k,j)\, dj',$$

$$Y_t = C_t + Z_t$$

+ the usual equations:

- sectoral labor supply,
- Euler equation,
- production efficiency condition,
- Taylor rule, and
- standard equilibrium conditions.

Mechanism: Intuition

The effect of monetary policy shocks depends on the properties of marginal cost:

- Highlight individual feedback mechanisms
- Analytical expressions from simplified model

Mechanism: Intuition

Defining aggregate price indices:

$$CPI: \quad p_t^c = \sum_{k=1}^{K} \omega_{ck} p_{kt},$$

$$\text{sectoral input price index:} \quad p_t^k = \sum_{k'=1}^{K} \omega_{kk'} p_{k't}$$

Sectoral participation in total production (note: $\psi = Z/Y$):

$$n_k = (1-\psi)\,\omega_{ck} + \psi \left(\sum_{k'=1}^{K} n_{k'} \omega_{k'k} \right) \text{ for all } k.$$

$$\rightarrow \aleph = (1-\psi) \left[\mathbb{I} - \psi \Omega' \right]^{-1} \Omega^c$$

Mechanism: Intuition

Feedback at the sectoral level:

$$mc_{kt} = (1-\delta)\, w_{kt} + \delta p_t^k$$

and w_{kt} solves

$$\begin{aligned}
\text{(labor sup)} \quad w_{kt} &= \varphi l_{kt} + \sigma c_t + p_t^c, \\
\text{(sect prod. fn)} \quad y_{kt} &= l_{kt} + \delta \left(w_{kt} - p_t^k \right), \\
\text{(sect demand)} \quad y_{kt} &= y_t - \eta \left[p_{kt} - (1-\psi)\, p_t^c - \psi \widetilde{p}_t \right]
\end{aligned}$$

where $\widetilde{p}_t = \sum_{k=1}^{K} \left(\sum_{k'=1}^{K} n_{k'} \omega_{k'k} \right) p_{kt}$.

Mechanism: Intuition

Overall, sectoral prices follow

$$\begin{aligned} \beta \mathbb{E}_t \left[p_{kt+1} \right] - (1+\beta) p_{kt} + p_{kt-1} &= -\kappa_k \left(mc_{kt} - p_{kt} \right) \\ \beta E_t \left[\pi_{kt+1} \right] - \pi_{kt} &= \kappa_k x_{kt} \end{aligned}$$

where $\kappa_k \equiv (1-\alpha_k)(1-\alpha_k\beta)/\alpha_k$ and

$$\begin{aligned} x_{kt} = & (1+\varphi\eta)\,\gamma_1(\delta)\,(p_t^c - p_{kt}) + \gamma_2(\delta)\left(p_t^k - p_t^c\right) + \gamma_3(\delta)\left(\widetilde{p}_t - p_t^c\right) \\ & + (\sigma+\varphi)\,\gamma_4(\delta)\,c_t \end{aligned}$$

Compare to $\delta = 0$:

$$x_{kt}^{\delta=0} = (1+\varphi\eta)\,(p_t^c - p_{kt}) + (\sigma+\varphi)\,c_t$$

Analytical Results

Simplified model:

- utility log in consumption, linear in leisure
- exogenous nominal demand, one-time permanent shock
- future fully discounted: $p^*_{kt} = mc_{kt}$

Intuition carries through in full model, and calibration.

Analytical Results

Three propositions on effect of monetary policy:

- Homogeneous price stickiness
- Heterogeneous price stickiness but irrelevance of heterogeneity in I/O linkages
- Heterogeneous price stickiness and no restriction on I/O linkages

Two propositions on effect of granularity

Analytical Results: Monetary Policy Shock

- Assume that $\alpha_k = \alpha$ for all k, so $\kappa_k = \kappa$ for all k (homogeneous stickiness)
- Unrestricted consumption shares $\{\omega_{ck}\}$and I/O linkages $\{\omega_{kk'}\}$

Proposition

Following a permanent monetary shock m at time t^*, heterogeneity of $\{\omega_{ck}\}$ and $\{\omega_{kk'}\}$ is irrelevant for the response of output. The existence of I/O linkages amplifies the response of output.

Proof.

Follows directly from

$$\widetilde{p}_t^c(\alpha) = \left[1 - \left(\frac{\alpha}{1-\delta(1-\alpha)}\right)^{t-t^*+1}\right] m \text{ for } t \geq t^* \qquad (1)$$

□

Analytical Results: Monetary Policy Shock

- Assume that $\omega_{ck} = \omega_{kk'}$ (no price wedge), otherwise unrestricted.
- Assume that $\{\alpha_k\}$ are heterogeneous, $E[\alpha_k] = \alpha$

Proposition

Following a permanent monetary shock,

1. *The sectoral heterogeneity of price stickiness and consumption shares are irrelevant for the response of output to the monetary shock on impact.*
2. $p_t^c \leq p_t^c(\alpha)$ *for* $t > t^*$. *The response of the aggregate consumption prices for* $t \geq t^*$ *is weakly decreasing in the dispersion of price stickiness.*

Analytical Results: Monetary Policy Shock

- No restrictions, allowing for $\omega_{ck} \neq \omega_{kk'}$ (price wedge)

Proposition

1. *The response of p_t^c is now weaker on impact when $u_k \equiv \sum_{k'=1}^{K} \omega_{ck'} (1-\alpha_{k'}) \omega_{k'k} > (1-\overline{\alpha}) \omega_{ck}$ for the sectors with the most sticky prices.*
2. *The response of p_t^c for $t > t^*$ is now more persistent when for sectors with the most sticky prices either of the following conditions hold: (i) $\overline{\omega}_k \equiv \frac{1}{K} \sum_{k'=1}^{K} \omega_{k'k} > \omega_{ck}$, (ii) $u_k > (1-\overline{\alpha}) \omega_{ck}$, (iii) $COV(\omega_{ck'} \alpha_{k'}^{\tau} (1-\alpha_{k'}), \omega_{k'k}) > 0$.*

where first-order and second-order outdegrees are

$$u_k \equiv \sum_{k'=1}^{K} \omega_{ck'} (1-\alpha_{k'}) \omega_{k'k}, v_k \equiv \sum_{k'=1}^{K} u_{k'} (1-\alpha_{k'}) \omega_{k'k}.$$

Summary of Results: Monetary Policy Shock

The real effects of monetary policy shocks are bigger if

- share of intermediate inputs is high,
- sticky-price sectors are important suppliers to the rest of the economy,
- sticky-price sectors are important suppliers to flexible-price sectors,
- sticky-price sectors are important suppliers to large sectors,
- sticky-price sectors have large covariance of connectedness with function of customer size and price stickiness.

Analytical Results: Effect of Aggregation

What is the effect of sectoral aggregation?

- Granularity matters for the real effects of monetary policy
  - Convexification of price stickiness
  - Size heterogeneity and I/O linkages can amplify effect

Analytical Results: Effect of Aggregation

Theoretical results from comparison of two economies

- Finely disaggregated economy:
  - K sectors, $\{\alpha_k, \omega_{ck}, \omega_{ks}\}$
  - $p_t^c = \sum_{k=1}^{K} \omega_{ck} p_{kt}$
- Coarse, aggregated economy:
  - $K/2$ sectors, $\{\bar{\alpha}'_k, \bar{\omega}_{ck'}, \bar{\omega}_{k's'}\}$
  - $\bar{p}_t^c = \sum_{k'=1}^{K/2} \bar{\omega}_{ck'} \bar{p}_{k't}$
- Sectors randomly combined, with appropriate weights.

$\Rightarrow$Two propositions.

Analytical Results: Effect of Aggregation

Proposition

Given no I/O linkages ($\delta = 0$), the difference of consumption prices

$$\overline{p}_t^c - p_t^c = \sum_{k'=1}^{K/2} \overline{\omega}_{ck'} \left[\lambda_{k'} \alpha_{2k'-1}^{t-t^*+1} + (1-\lambda_{k'}) \alpha_{2k'}^{t-t^*+1} - \overline{\alpha}_{k'}^{t-t^*+1} \right] m$$

is such that

1. $p_t^c = \overline{p}_t^c$ *for* $t = t^*$
2. $p_t^c < \overline{p}_t^c$ *for* $t > t^*$
3. $\overline{p}_t^c - p_t^c$ *is increasing in the dispersion of Calvo parameters among merged sectors*
4. $\overline{p}_t^c - p_t^c$ *is increasing in* $\bar{\omega}_{ck'}$ *for merged sectors with the highest dispersion of Calvo parameters*

Analytical Results: Effect of Aggregation

Proposition

When $\delta \in (0,1)$ and $\omega_{sk} = \omega_{ck}\ \forall s,k$, the amplification effect of monetary non-neutrality introduced by intermediate inputs is stronger in the finely-disaggregated economy relative to the coarsely-disaggregated economy when the dispersion of frequency of price changes is higher among the merged sectors.

$$p_t^c - \overline{p}_t^c = -\frac{1-\delta}{1-\delta\left(1-\overline{\alpha}\right)} \sum_{k'=1}^{K/2} \overline{\omega}_{ck'} \left(\lambda_{k'}\, \alpha_{2k'-1}^{t-t^*+1} + \left(1-\lambda_{k'}\right) \alpha_{2k'}^{t-t^*+1} - \overline{\alpha}_{k'}^{t-t^*+1}\right) m$$

$$+\frac{\delta}{1-\delta\left(1-\overline{\alpha}\right)} \sum_{\tau=1}^{t-t^*} \left(\sum_{k'=1}^{K/2} \overline{\omega}_{ck'} \left[\begin{array}{c} \lambda_{k'} \left(1-\alpha_{2k'-1}\right) \alpha_{2k'-1}^{\tau} + \left(1-\lambda_{k'}\right)\left(1-\alpha_{2k'}\right) \alpha_{2k'}^{\tau} \\ -\left(1-\overline{\alpha}_{k'}\right) \overline{\alpha}_{k'}^{\tau} \end{array} \right] \right) p_{t-\tau}^c \qquad (2)$$

Analytical Results: Effect of Aggregation

Allowing for full, unrestricted heterogeneity such that $\omega_{sk} \neq \omega_{ck}$ can lead to even larger amplification.

How large are these effects? Empirical question.

Calibration

Calibration goal:

- Which type of heterogeneity matters most?
  - 6 cases with incremental degrees of heterogeneity
- Role of monetary policy?
- Does the level of aggregation matter?
  - Decrease aggregation from 350 to 8 sectors
  - Value-added sectoral output shares from BEA
  - 2002 I-O tables from BEA to get industry-to-industry linkages
  - Stickiness from BLS PPI micro data
- What is the role of heavy-tailed price stickiness?

Calibration

$K \in (8, 350)$	: Number of sectors
$\beta = .9975$	: Monthly discount factor to get 3% annual risk-free rate
$\sigma = 1$	: Relative risk aversion
$\varphi = 2$	: Inverse of Frisch elasticity
$\delta = .7$	: Intermediate inputs share in production function
$\eta = 2$	: Elasticity of substitution across sectors
$\theta = 6$	: Elasticity of substitution across firms within sectors
$\phi_\pi = 1.24$	: Responsiveness of monetary policy to inflation
$\phi_c = .33/12$	: Responsiveness of monetary policy to GDP variations
$\rho = .9$	: Persistence of shocks

Monetary shock: $\mu_t = 1$

Calibration

Overview of Calibration Cases

	Prices	Consumption Weights	Input-Output Linkages
Case 1	flexible	homogeneous	homogeneous
Case 2	sticky, homogeneous	homogeneous	homogeneous
Case 3	sticky, heterogeneous	homogeneous	homogeneous
Case 4	sticky, heterogeneous	heterogeneous	heterogeneous (size weights)
Case 5	sticky, heterogeneous	heterogeneous	homogeneous
Case 6	sticky, heterogeneous	heterogeneous	heterogeneous

Calibration

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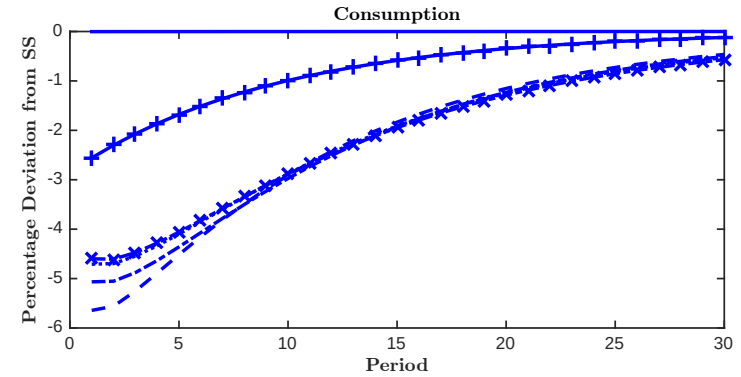
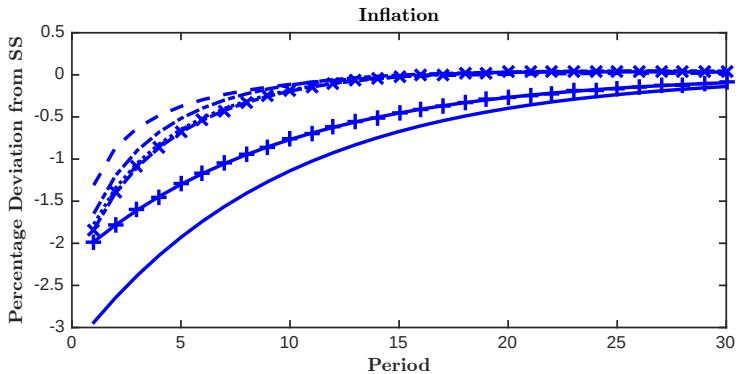
Case 6	sticky, heterogeneous	heterogeneous	heterogeneous

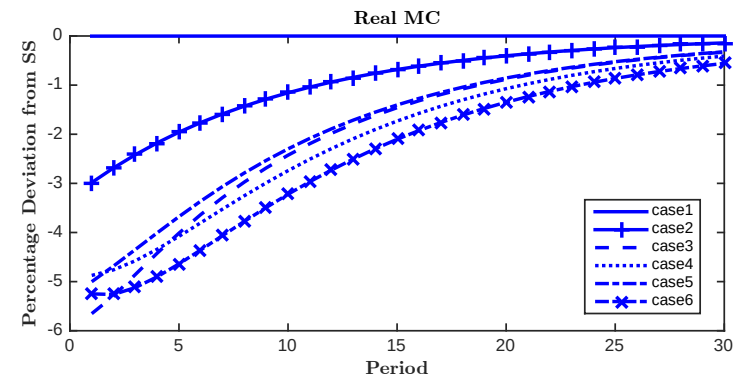
Calibration

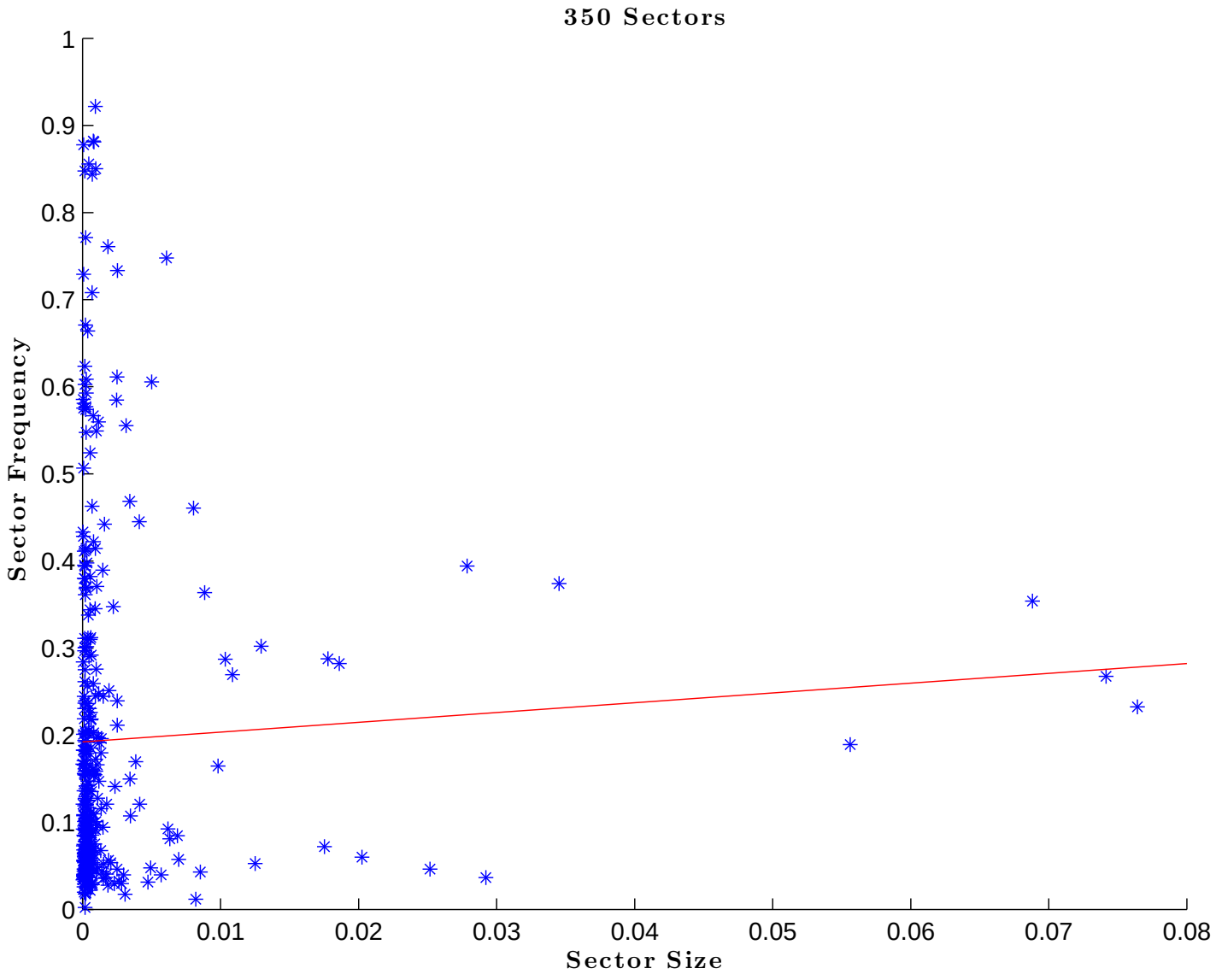
Which heterogeneity matters most?

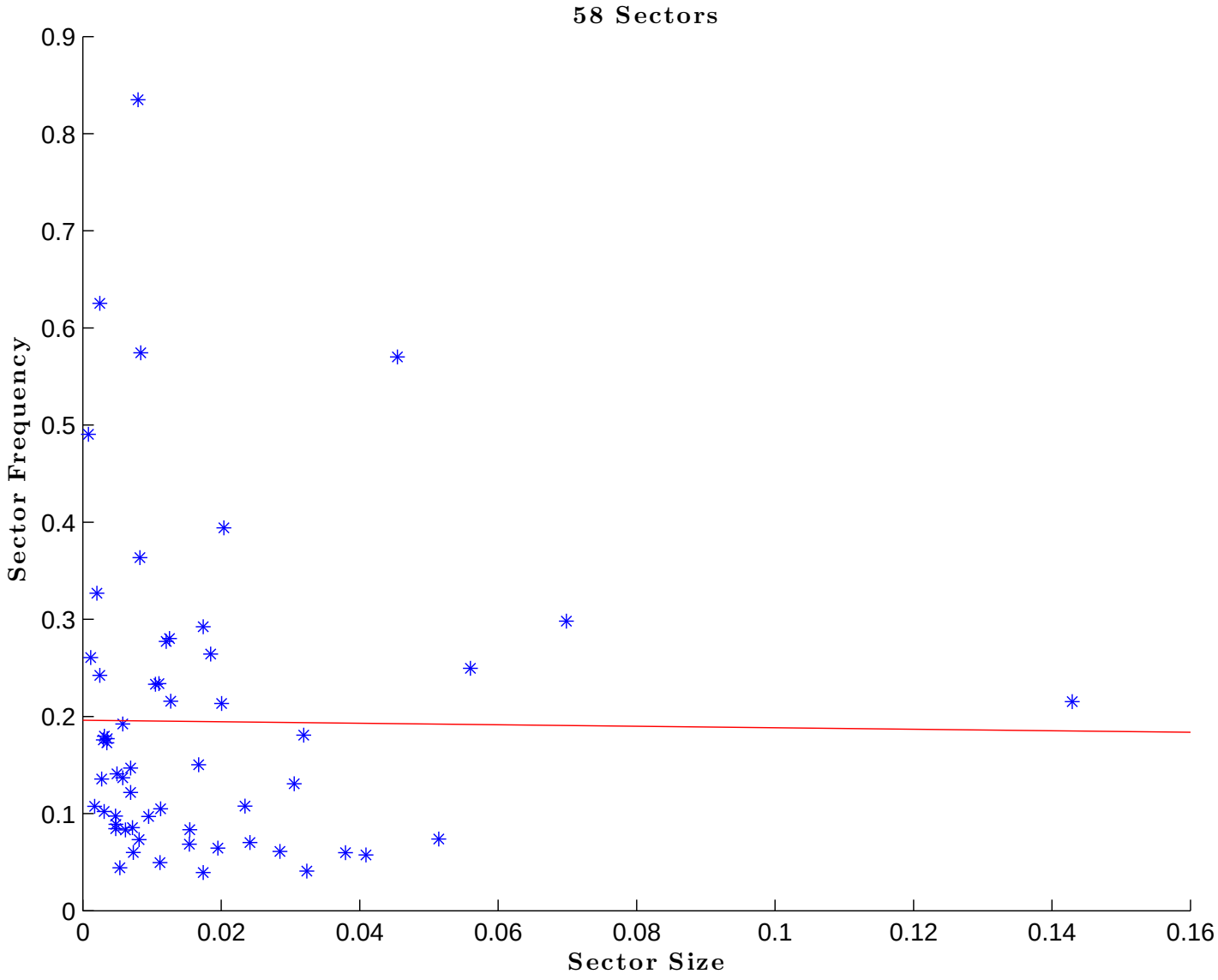
- Heterogeneity of price stickiness most important driver of real effects.
- Lesser role for heterogeneous consumption shares and even less for input-output linkages.


Consumption
Percentage Deviation from SS
Period
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30


Inflation
Percentage Deviation from SS
Period
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
5
10
15
20
25
30

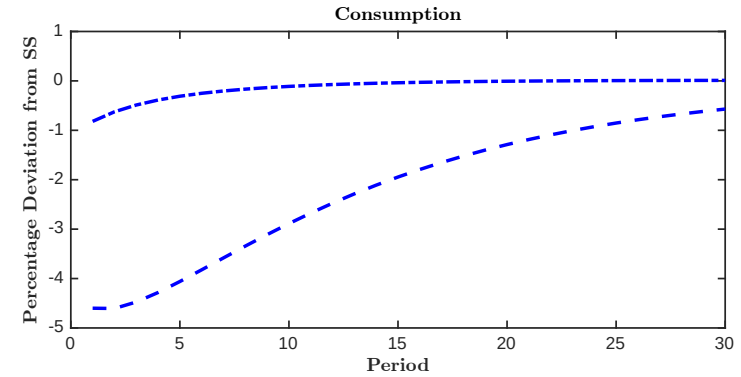

Real MC
Percentage Deviation from SS
Period
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30
case1
case2
case3
case4
case5
case6


350 Sectors
Sector Frequency
Sector Size
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08


58 Sectors
Sector Frequency
Sector Size
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16

Role of monetary policy:

- Large effect of endogenizing demand through monetary policy.
- Large effect of more systematic response to inflation.


Consumption
Percentage Deviation from SS
Period
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-3
-4
-5
0
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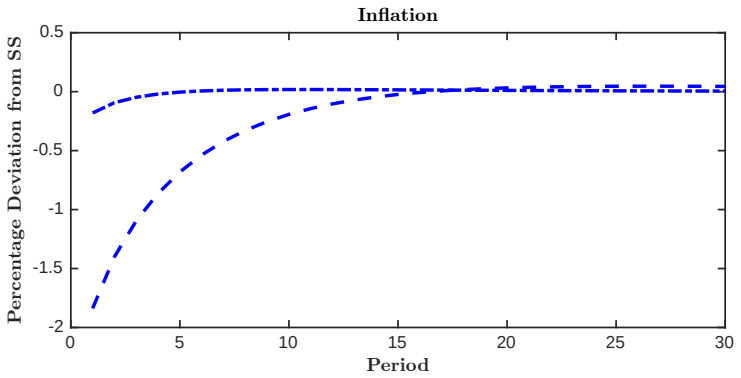
25
30


Inflation
Percentage Deviation from SS
Period
0.5
0
-0.5
-1
-1.5
-2
0
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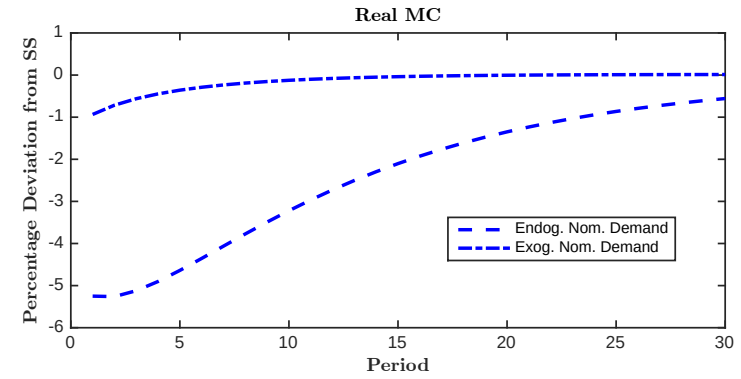
Real MC
Percentage Deviation from SS
Period
1
0
-1
-2
-3
-4
-5
-6
0
5
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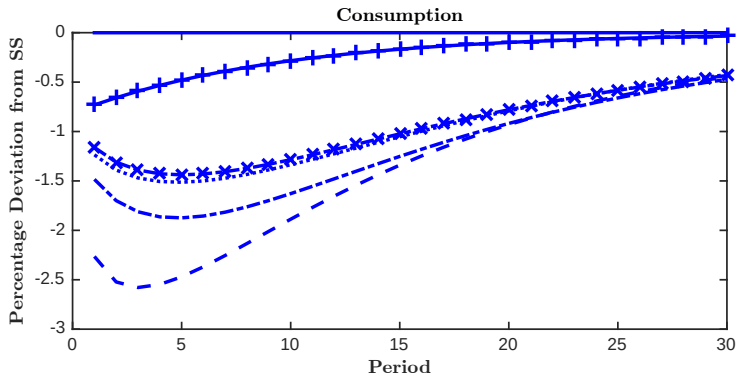
15
20
25
30
Endog. Nom. Demand
Exog. Nom. Demand

Increase systematic response of monetary policy ($\phi_\pi = 2.5$) :


Consumption
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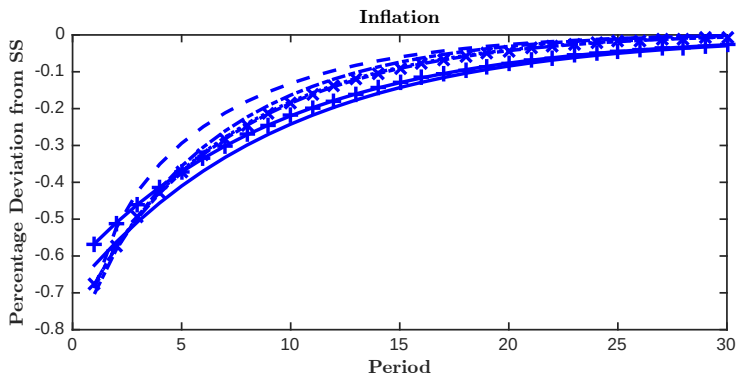
Inflation
Percentage Deviation from SS
Period
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
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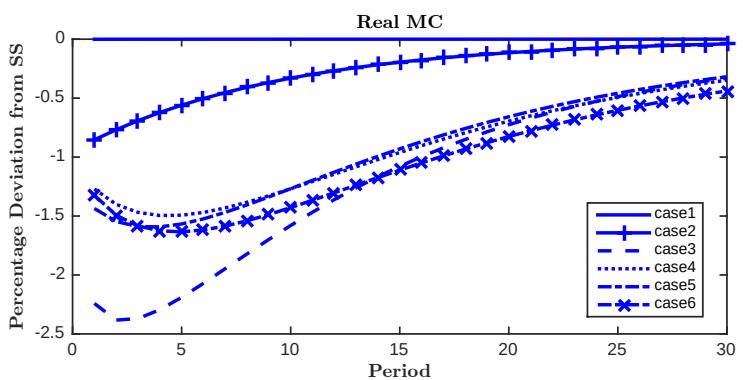
Real MC
Percentage Deviation from SS
Period
0
-0.5
-1
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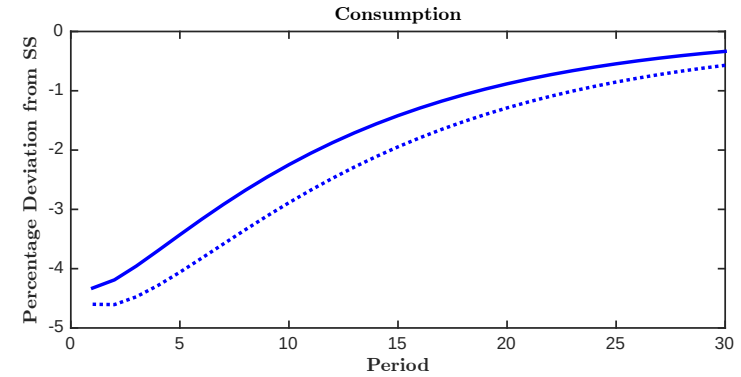
-2
-2.5
0
5
10
15
20
25
30
case1
case2
case3
case4
case5
case6

Finer granularity of calibration increases real effects:

- 25% (34%) larger cumulative consumption response for 350 vs. 58 (8) sectors
- Steepest gradient between 148/60, and 60/20 sector aggregations

Similar impact response for inflation.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Percentage Deviation from SS
0
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-2
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-4
-5
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5
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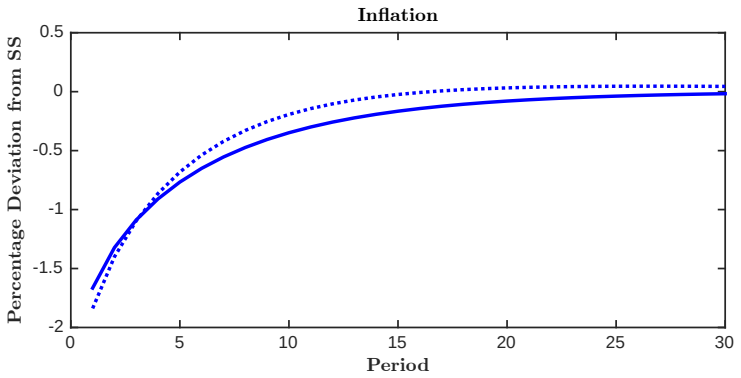
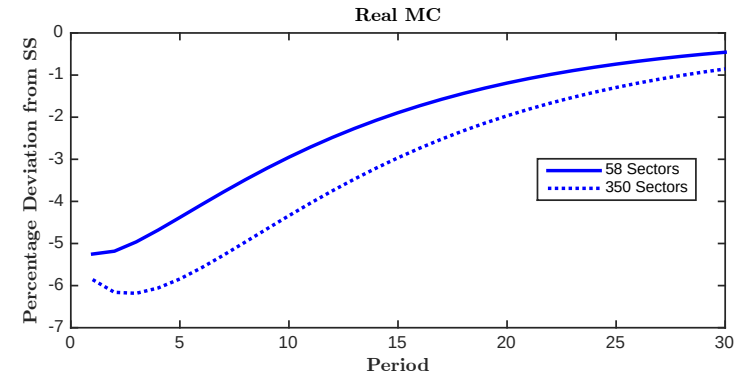
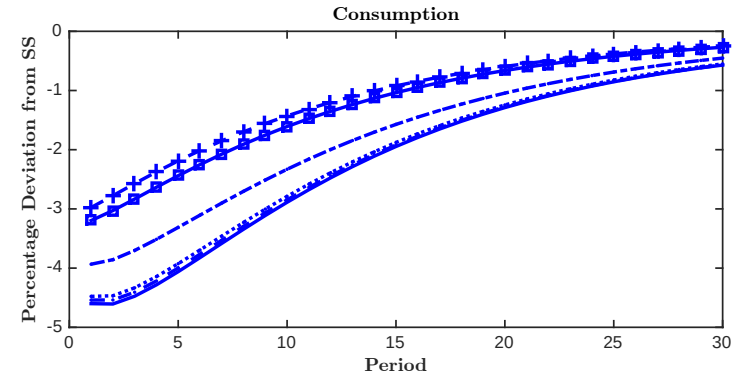
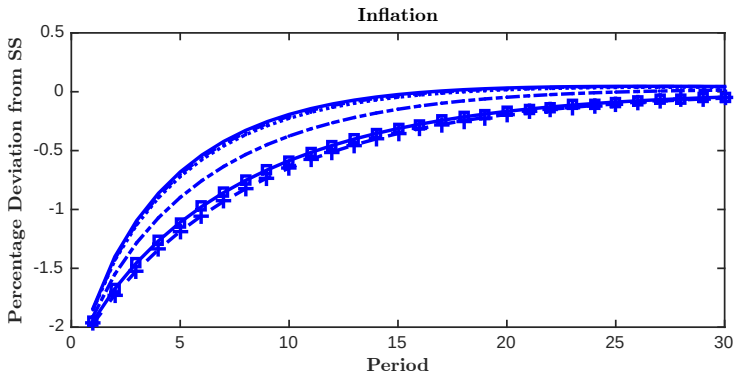
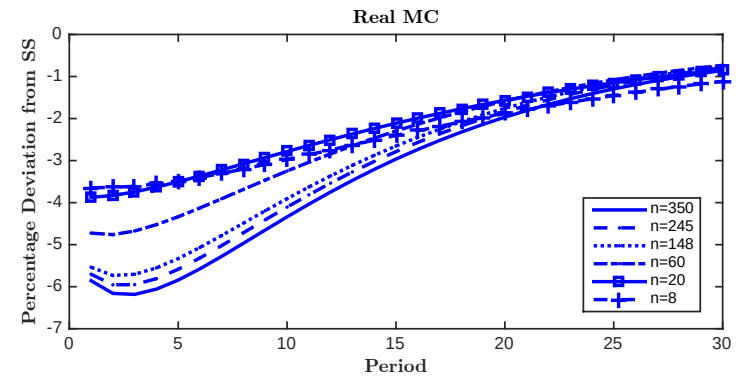
15
20
25
30
Period


Inflation
Percentage Deviation from SS
0.5
0
-0.5
-1
-1.5
-2
0
5
10
15
20
25
30
Period


Real MC
Percentage Deviation from SS
0
-1
-2
-3
-4
-5
-6
-7
0
5
10
15
20
25
30
Period
58 Sectors
350 Sectors

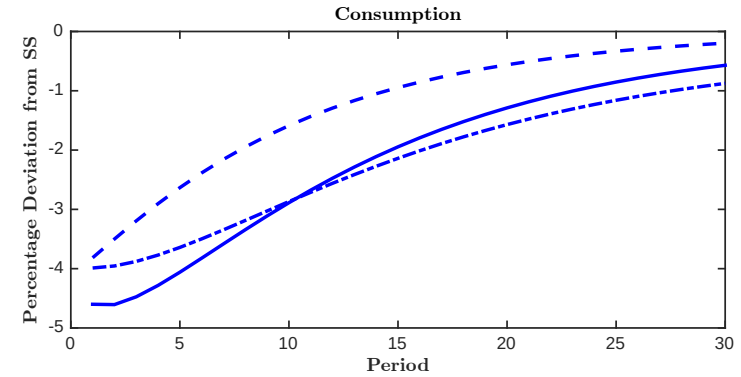

Consumption
Percentage Deviation from SS
Period
0
-1
-2
-3
-4
-5
0
5
10
15
20
25
30

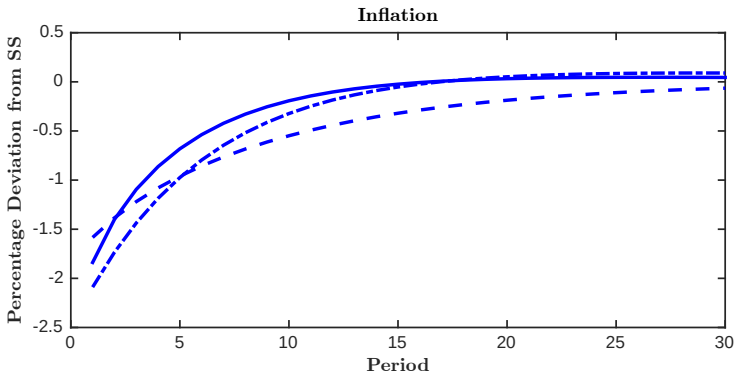

Inflation
Percentage Deviation from SS
Period
0.5
0
-0.5
-1
-1.5
-2
0
5
10
15
20
25
30

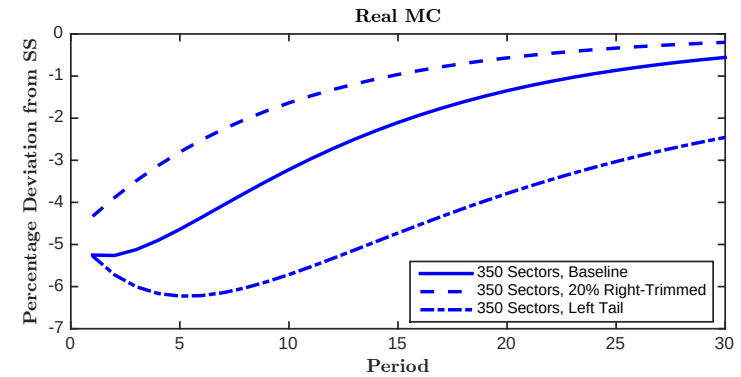

Real MC
Percentage Deviation from SS
Period
0
-1
-2
-3
-4
-5
-6
-7
0
5
10
15
20
25
30
n=350
n=245
n=148
n=60
n=20
n=8

Role of fat tails in frequency of price changes:

- Experiment 1: cut right tail
  - Censor 20% of upper tail
  - Assign mean to the right censored sectors
  - Shift entire distribution to the right to preserve mean
- Experiment 2: heavier left tail
  - Right-censor at f=18%
  - Mirror at 0.18
  - Put uniform mass to the left to preserve mean


Consumption
Percentage Deviation from SS
0
-1
-2
-3
-4
-5
0
5
10
15
20
25
30
Period


Inflation
Percentage Deviation from SS
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
Period


Real MC
Percentage Deviation from SS
0
-1
-2
-3
-4
-5
-6
-7
0
5
10
15
20
25
30
Period
350 Sectors, Baseline
350 Sectors, 20% Right-Trimmed
350 Sectors, Left Tail

Conclusion:

- Convolution of heterogeneity of price stickiness with sector size and intput-output linkages creates rich set of theoretical predictions.
- Empirically:
  - Heterogeneity of price stickiness most important driver of real effects; lesser role for heterogeneous consumption shares and even less for input-output linkages.
  - More granular calibration yields up to 34% larger real effects but similar impact response for inflation, steep gradient.
  - Results highly sensitive to monetary policy specification.
  - Heavy tails of frequency of price changes affect real effects.
- Ongoing work: idiosyncratic shocks, oil price shocks, optimal monetary policy.