

# The Distributional Effects of COVID-19 and Optimal Mitigation Policies

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March 18, 2020

The views expressed herein are those of the author and not necessarily those of the Federal Reserve Bank of Dallas or the Federal Reserve System.

# Motivation

“Will some people[’s *health*] be affected badly? Yes ... but we have to get our country[’s *economy*] opened and we have to get it open soon”

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- Is there a tradeoff between public health and economic outcomes? **Not necessarily**

# Introduction

- ▶ To better understand the economic-health tradeoff (or lack thereof), I build a quantitative model to use as a laboratory for policy counterfactuals
- ▶ Key ingredients:
  - ▶ heterogeneity in age
    - ▶ old individuals face higher fatality risk
    - ▶ young individuals face worse labor market outcomes
  - ▶ heterogeneity in income and wealth
  - ▶ two-way feedback between economic activity and virus transmission

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- ▶ Key ingredients:
  - ▶ heterogeneity in age
  - ▶ heterogeneity in income and wealth
    - ▶ most low-wage workers cannot work from home
    - ▶ many low-wealth workers lack the resources to weather prolonged time away from work
  - ▶ two-way feedback between economic activity and virus transmission

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  - ▶ heterogeneity in age
  - ▶ heterogeneity in income and wealth
  - ▶ two-way feedback between economic activity and virus transmission
- ▶ Other ingredients:
  - ▶ endogenous labor with option to work from home
  - ▶ optimal outside/home consumption and saving decisions
  - ▶ hospital capacity constraints

# Preview of findings

- ▶ Without mitigation, young workers engage in too much economic activity, relative to the social optimum
  - ▶ especially true for young low-wage/wealth workers
  - ▶ leading to higher infection rates and deaths in the aggregate
- ▶ Mitigation policies
- ▶ Stay-at-home subsidy reduces deaths by more and output by less
- ▶ Welfare maximizing Pareto improvement
- ▶ Output maximizing policy

# Preview of findings

- ▶ Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- ▶ Mitigation policies
  - ▶ *stay-at-home subsidy* (e.g. FPUC)
  - ▶ *stay-at-home order* (lockdown) that imposes a cap on outside work hours  
(e.g. stay-at-home, shelter-at-home, safe-at-home orders)
- ▶ Stay-at-home subsidy reduces deaths by more and output by less
- ▶ Welfare maximizing Pareto improvement
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# Preview of findings

- ▶ Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- ▶ Mitigation policies
- ▶ Stay-at-home subsidy reduces deaths by more and output by less
  - ▶ lockdown benefits older individuals at the expense of low-wage workers
  - ▶ stay-at-home subsidy benefits all
- ▶ Welfare maximizing Pareto improvement
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# Preview of findings

- ▶ Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- ▶ Mitigation policies
- ▶ Stay-at-home subsidy reduces deaths by more and output by less
- ▶ Welfare-maximizing Pareto improvement
  - ▶ weekly subsidy of \$1050 (gradually phased out after 7 months)
  - ▶ no lockdown
  - ▶ reduces deaths by 60 percent and output by 2 percent, compared to no mitigation

# Preview of findings

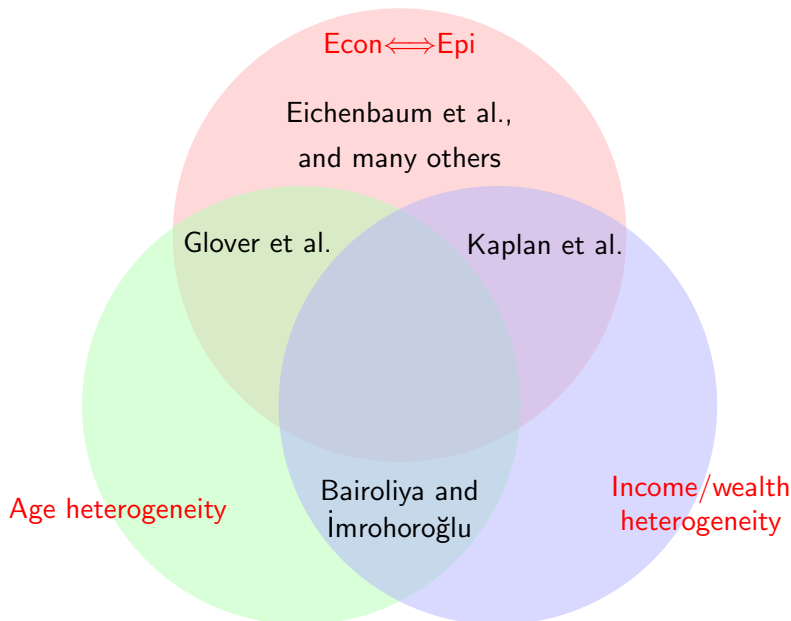
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- ▶ Mitigation policies
- ▶ Stay-at-home subsidy reduces deaths by more and output by less
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- ▶ Output maximizing policy
  - ▶ weekly subsidy of \$350 (gradually phased out after 13 months)
  - ▶ no lockdown
  - ▶ reduces deaths by 20 percent and *increases* output by 2 percent, compared to no mitigation

# Relation to literature

Econ  $\longleftrightarrow$  Epi

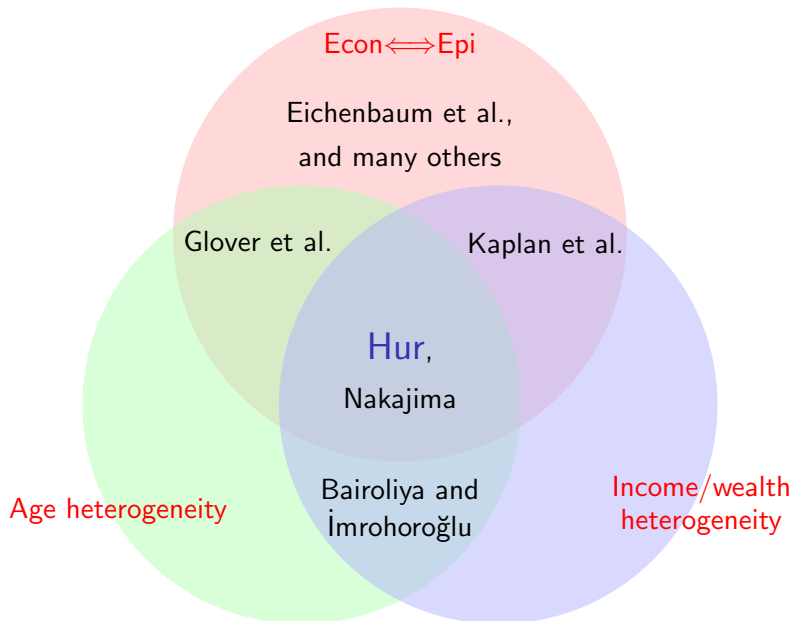
Eichenbaum et al.,  
and many others

# Relation to literature





# Relation to literature



Model

# Features of model

- ▶ Stochastic aging
- ▶ Income fluctuations + borrowing constraints + incomplete markets  $\longrightarrow$  precautionary savings
- ▶ Outside versus home consumption
- ▶ Endogenous labor supply with option to work from home
- ▶ Economic-Epidemiology model  
(economic activities  $\longleftrightarrow$  virus transmission)
- ▶ Hospital capacity constraints

# Demographics

- ▶ Individuals of age denoted by  $j \in J \equiv \{1, 2, \dots, \bar{J}\}$
- ▶ Stochastic aging
  - ▶  $\psi_j$ : probability of transitioning from age  $j$  to  $j + 1$
- ▶ Retirement at  $j = J^R$
- ▶ Health status  $h \in \{S, I, R, D\}$

# Demographics

- ▶ Individuals of age denoted by  $j \in J \equiv \{1, 2, \dots, \bar{J}\}$
- ▶ Stochastic aging
- ▶ Retirement at  $j = J^R$
- ▶ Health status  $h \in \{S, I, R, D\}$  for **S**usceptible, **I**nfectious, **R**ecovered, and **D**ead

# Epidemiological block

- ▶ Build on widely used SIR model
- ▶ Susceptible individuals get infected with probability  $\pi_{It}$ , which depends on individual outside consumption and labor ( $c_o, \ell_o$ ) and the measure of infected individuals ( $\mu_{It}$ ) and their outside consumption and labor ( $C_{It}^o, L_{It}^o$ )

$$\pi_{It}(c_o, \ell_o) = \beta_c c_o C_{It}^o + \beta_\ell \ell_o L_{It}^o + (\beta_e + \epsilon_t) \mu_{It}$$

where  $\epsilon_t$  captures time-varying transmissibility (e.g. seasonal factors)

- ▶ Infected individuals exit infection with probability  $\pi_\chi$
- ▶ Recovered individuals are assumed to be immune
- ▶ Let  $\Pi_{jhh't}(c_o, \ell_o)$  denote the transition matrix

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- ▶ Infected individuals exit infection with probability  $\pi_X$ , then
  - ▶ recover with prob.  $1 - \delta_j(\mu_{It})$
  - ▶ die with prob.  $\delta_j(\mu_{It})$
- ▶ Recovered individuals are assumed to be immune
- ▶ Let  $\Pi_{jhh't}(c_o, \ell_o)$  denote the transition matrix

# Labor income

- ▶ Each period, workers receive idiosyncratic productivity shocks  $\varepsilon \in E$ , which follows a Markov process, with trans. matrix  $\Gamma$
- ▶ Their labor income is given by  $w_t \eta_{jh} \varepsilon \ell$ , where
  - ▶  $w_t$ : efficiency wage
  - ▶  $\eta_{jh}$ : age-health-profile of efficiency units
- ▶ A fraction  $\bar{\theta}_j(\varepsilon)$  of labor can be done at home
- ▶ Retirees receive a fixed income of  $s$  each period
  - ▶ can easily depend on lifetime earnings as in Hur (2018)



# Retiree's problem

- ▶ Retirees with age  $j \geq J^R$ , wealth  $k$ , and health  $h$  choose inside and outside consumption  $c_i, c_o$  and savings  $k'$  to solve:

$$\begin{aligned} v_{jt}^R(k, h) = \max_{c_i, c_o, k' \geq 0} & \quad u(c_i, c_o) + \bar{u} + \hat{u}^h + \beta \sum_{h' \in H} \Pi_{jhh't}(\mathbf{c}_o, 0) \\ & \quad \times \left[ \psi_j v_{j+1,t+1}^R(k', h') + (1 - \psi_j) v_{j,t+1}^R(k', h') \right] \\ \text{s.t.} & \quad (1 + \tau_{ct})c + k' \leq s + k(1 + r_t) \end{aligned}$$

- ▶  $\bar{u}, \hat{u}_h$ : flow value of life, health
- ▶  $c = c_o + c_i$
- ▶  $v_{J+1}^R = 0$
- ▶  $\tau_{ct}$ : consumption tax
- ▶  $r_t$ : net return to capital

# Worker's problem

- Workers with age  $j < J^R$ , wealth  $k$ , productivity  $\varepsilon$ , and health  $h$  choose consumption  $c_i, c_o$ , inside and outside labor  $\ell_i, \ell_o$ , and savings  $k'$  to solve:

$$\begin{aligned}
 v_{jt}(k, \varepsilon, h) = \max_{\substack{c_i, c_o, \ell_i \\ \ell_o, k' \geq 0}} & \quad u(c_i, c_o) - g(\ell) + \bar{u} + \hat{u}^h + \beta \sum_{\varepsilon' \in E} \sum_{h' \in H} \Gamma_{\varepsilon, \varepsilon'} \Pi_{jh h' t}(c_o, \ell_o) \\
 & \quad \times [\psi_j v_{j+1, t+1}(k', \varepsilon', h') + (1 - \psi_j) v_{j, t+1}(k', \varepsilon', h')] \\
 \text{s.t.} \quad & (1 + \tau_{ct})c + k' \leq w_t \eta_{jh} (1 - \tau_{\ell t}) \varepsilon \ell + k(1 + r_t) + T_t(\ell) \\
 & \ell_i \leq \bar{\theta}_j(\varepsilon) \ell, \quad \ell_o \leq \bar{\ell}_{ot}
 \end{aligned}$$

- $\ell = \ell_i + \ell_o$
- Let  $v_{jt}(k, \varepsilon, h) = v_{jt}^R(k, h)$  for  $j \geq J^R$
- $\tau_{\ell t}$ : labor income tax
- $g(\ell)$ : disutility of labor

# Optimality conditions ( $h = S$ )

$$\frac{\partial u}{\partial c_i} = \frac{\partial u}{\partial c_o} - \beta_c C_{it}^o \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} \times \underbrace{\left\{ \begin{aligned} &\psi_j [v_{j+1, t+1}(k', \varepsilon', S) - v_{j+1, t+1}(k', \varepsilon', I)] \\ &+ (1 - \psi_j) [v_{j, t+1}(k', \varepsilon', S) + v_{j, t+1}(k', \varepsilon', I)] \end{aligned} \right\}}_{\text{value of remaining susceptible}}$$

$$w_t \eta_{jS} \varepsilon \frac{\partial u}{\partial c_i} \frac{1 - \tau_{\ell t}}{1 + \tau_{ct}} = - \frac{\partial g}{\partial \ell} - (1 - \bar{\theta}_j(\varepsilon)) \beta_\ell L_{it}^o \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} \times \underbrace{\left\{ \begin{aligned} &\psi_j [v_{j+1, t+1}(k', \varepsilon', S) - v_{j+1, t+1}(k', \varepsilon', I)] \\ &+ (1 - \psi_j) [v_{j, t+1}(k', \varepsilon', S) + v_{j, t+1}(k', \varepsilon', I)] \end{aligned} \right\}}_{\text{value of remaining susceptible}}$$

# Production

- ▶ A representative firm solves

$$\max L_f^{1-\alpha} K_f^\alpha - w_t L_f - (r_t + \delta) K_f$$

where  $L_f$  are effective units of labor demanded

- ▶ Optimality conditions:

$$w_t = (1 - \alpha) \left( \frac{K_f}{L_f} \right)^\alpha$$
$$r_t = \alpha \left( \frac{K_f}{L_f} \right)^{\alpha-1} - \delta$$

# Rest of talk

1. Calibrate the model
  - ▶ pre-pandemic steady state ▶ Definition of equilibrium
  - ▶ transition path
2. Model fit
3. Welfare consequences of pandemic and U.S. mitigation policies
4. Optimal mitigation policies

# Calibration

# Environment

- ▶ Period length: 2 weeks
- ▶ Number of age cohorts: 3 (25–44, 45–64, 65+)
- ▶ Newborn endowments: 85% begin with zero wealth and 15% receive accidental bequests ( $\sim 28\times$  annual per capita cons.)
- ▶ Preferences

$$u(c_i, c_o) = \frac{(c_i^\gamma c_o^{1-\gamma})^{1-\sigma}}{1-\sigma}$$
$$g(\ell) = \varphi \frac{\ell^{1+\nu}}{1+\nu} + \mathbb{1}_{\ell=0} \tilde{u}$$

- ▶  $\tilde{u}$ : disutility from not working (e.g. administrative costs, stigma, or any other costs not modeled)

## Labor income

- ▶ Labor that can be done from home: set to match the Dingel and Neiman (2020) average share of jobs that can be done from home by occupations sorted into wage quintiles: 0.03, 0.21, 0.32, 0.47, 0.66
- ▶ Productivity shocks ( $\varepsilon$ ) follow a finite-state Markov process which approximates the continuous process,

$$\log \varepsilon_t = \rho_\varepsilon \log \varepsilon_{t-1} + \nu_t, \quad \nu_t \sim N(0, \sigma_\nu^2)$$

- ▶ Estimate using wage residuals constructed from PSID
  - ▶  $\rho_\varepsilon = 0.94$  and  $\sigma_\nu = 0.19$
  - ▶ Convert to higher frequency, following Krueger et al. (2016)



# Economic parameters

| Parameters                                 | Values | Targets / Source                       |
|--|--------|--|
| Discount factor, annualized, $\beta$       | 0.97   | Wealth-to-GDP: 4.8 (BOG, 2019)         |
| Risk aversion, $\sigma$                    | 2      | Standard value                         |
| Inside consumption share, $\gamma$         | 0.51   | Expenditure share (BEA, 2019)          |
| Disutility from labor, $\varphi$           | 22.64  | Average weekly hours: 34.4 (BEA, 2019) |
| Frisch elasticity, $1/\nu$                 | 0.50   | Standard value                         |
| Death prob., annualized, $\psi_3$          | 0.10   | 65+ share of population 25+: 0.2       |
| Aging prob., annualized, $\psi_1 = \psi_2$ | 0.05   | Expected duration: 20 years            |
| Efficiency units, $\eta_{1R} = \eta_{1S}$  | 1.00   | Wage ratio of age 45–64 to             |
| $\eta_{2R} = \eta_{2S}$                    | 1.35   | age 25–44 workers (PSID, 2014)         |
| Factor elasticity, $\alpha$                | 0.36   | Capital share                          |
| Depreciation, annualized, $\delta$         | 0.05   | Standard value                         |
| Retirement income, $s$                     | 1.00   | 30% of earnings per worker             |
| Labor income tax, $\tau_\ell$              | 0.07   | Gov't budget constraint                |
| Consumption tax, $\tau_c$                  | 0.00   |  |
| Transfer, $T$                              | 0.00   |  |

# Epidemiological parameters

- ▶ Death rates: as in Piguillem and Shi (2020) and other papers, I use the functional form

$$\delta_j(\mu_I) = \delta_j^u \min \left\{ 1, \frac{\kappa}{\mu_I} \right\} + \delta_j^c \max \left\{ 0, 1 - \frac{\kappa}{\mu_I} \right\}$$

- ▶  $\delta_j^u$ : unconstrained death rates
  - ▶  $\delta_j^c$ : untreated death rates
  - ▶  $\kappa$ : measure of infected individuals that can be treated
- ▶ 924 thousand hospital beds in the US (0.28% of population)

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- ▶ 924 thousand hospital beds in the US (0.28% of population)
    - ▶ not all infected cases require hospitalization  $\rightarrow \kappa = 0.01$

# Reproduction number

- ▶ Total new infections:

$$T_t = \beta_c C_{St}^o C_{It}^o + \beta_\ell L_{St}^o L_{It}^o + (\beta_e + \epsilon_t) \mu_{St} \mu_{It}$$

- ▶ The basic reproduction number, as  $\mu_I \rightarrow 0$  and  $\epsilon_t = 0$ , assuming  $C_I^o / \mu_I \rightarrow C_S^o / \mu_S$  and  $L_I^o / \mu_I \rightarrow L_S^o / \mu_S$ , is given by

$$R_0 = \frac{\beta_c (C_S^o)^2 + \beta_\ell (L_S^o)^2 + \beta_e}{\pi_X}$$

assuming that initially people are not working from home

- ▶ Most estimates range between 2.2 and 3.1. I use  $R_0 = 2.2$

- ▶ I assume that, initially, virus transmission equally likely between 3 channels (evidence from other infectious diseases: Ferguson et al. 2006, Mossong et al. 2008)

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## Epidemiological parameters (2)

| Parameters   | Values         | Targets / Source   |
|--|----------------|--|
| Infection exit rate, $\pi_X$                         | 0.78           | Expected infection duration: 18 days                           |
| Unconstrained death rate,<br>$\delta_1^u \times 100$ | 0.08           | Fatality rates in South Korea                                  |
| $\delta_2^u \times 100$                              | 0.85           |  |
| $\delta_3^u \times 100$                              | 8.47           |  |
| Untreated death rate, $\delta_j^c$                   | $2\delta_j^u$  | Piguillem and Shi (2020)                                       |
| Flow value of life, $\bar{u}$                        | 25.91          | VSL: \$7.4 mil. (EPA, 2006) <a href="#">► Derivation</a>       |
| Flow value of infection, $\hat{u}^I$                 | -12.48         | 50 percent reduction in flow<br>utility value of average agent |
| Disutility of not working, $\tilde{u}$               | 0.62           | 19 percent reduction in employment                             |
| Efficiency units, $\eta_{jI}$                        | $0.5\eta_{jS}$ |  |

# Transition path with pandemic

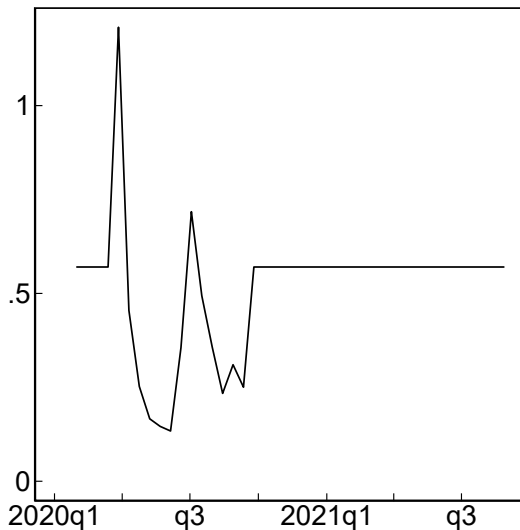
- ▶ COVID-19 introduced as an unanticipated MIT-shock
  - ▶ initial infections are set to 0.5 percent to match 17,982 deaths in the US during 3/27–4/9 ( $t = 1$ )
- ▶ Use first six months of the pandemic to fit  $\beta_e + \epsilon_t$  to biweekly deaths (capturing seasonal factors, etc.)
- ▶ Fiscal policies that are relevant for virus mitigation
- ▶ Transition path solved in partial equilibrium

# Transition path with pandemic

- ▶ COVID-19 introduced as an unanticipated MIT-shock
- ▶ Use first six months of the pandemic to fit  $\beta_e + \epsilon_t$  to biweekly deaths (capturing seasonal factors, etc.)
  - ▶ set  $\epsilon_t = 0$  after first six months
- ▶ Policies that are relevant for virus mitigation
- ▶ transition path solved in partial equilibrium



## Time-varying transmissibility ( $\beta_e + \epsilon_t$ )



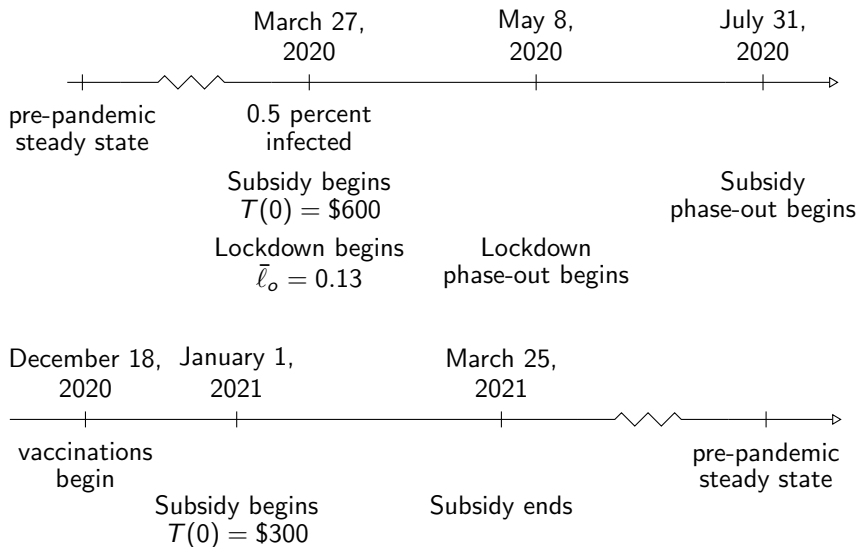
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- ▶ Policies that are relevant for virus mitigation
  1. *stay-at-home subsidy (subsidy)*: \$600 subsidy to individuals working 0 hours per week (e.g. FPUC)
  2. *stay-at-home order (lockdown)*: impose a cap of 15 outside work hours per week
- ▶ Transition path solved in partial equilibrium

# Transition path with pandemic

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- ▶ Policies that are relevant for virus mitigation
- ▶ Transition path solved in partial equilibrium
  - ▶ prices fixed
  - ▶ retirement benefits and contributions fixed
  - ▶ newborn distribution fixed

# Timeline



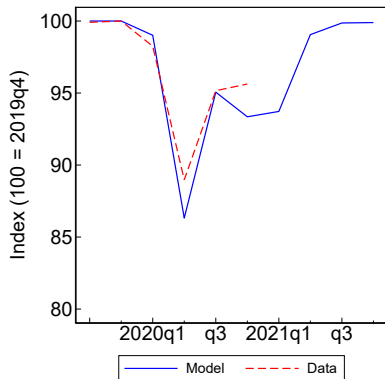
## Model validity

## Pre-pandemic steady state

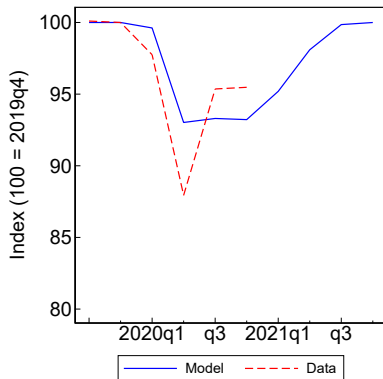
|                                       | Data  | Model |
|---------------------------------------|-------|-------|
| <i>Targeted moments</i>               |       |       |
| wealth/GDP                            | 4.8   | 4.8   |
| average weekly hours                  | 34.4  | 34.4  |
| average VSL (annual cons. per capita) | 238.8 | 238.8 |
| <i>Nontargeted moments</i>            |       |       |
| disposable earnings gini              | 0.37  | 0.36  |
| consumption gini                      | 0.33  | 0.25  |
| wealth gini                           | 0.74  | 0.59  |
| wealth p75/p25                        | 11.9  | 13.2  |

# Aggregates during the pandemic

(a) Output



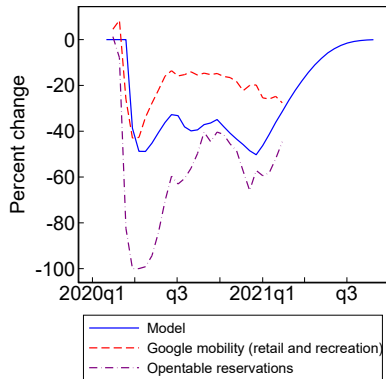
(b) Consumption



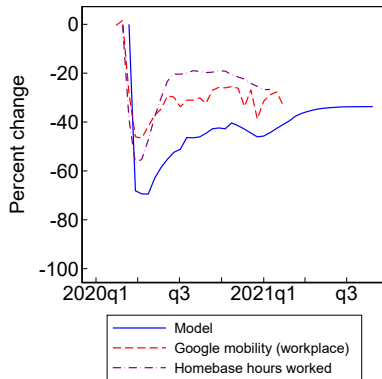
Notes: Both consumption and output in the data are linearly detrended at 2 percent per year.

# Aggregates during the pandemic (2)

(a) Outside consumption



(b) Outside hours

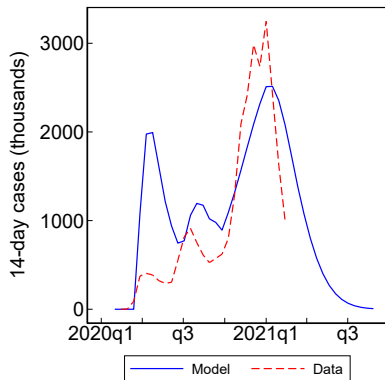


Notes: Outside consumption and hours in the model is relative to the pre-pandemic steady state. Google mobility and Opentable reservations are year over year percent changes. Homebase hours are relative to the median for each day of the week during January 4–31, 2020.

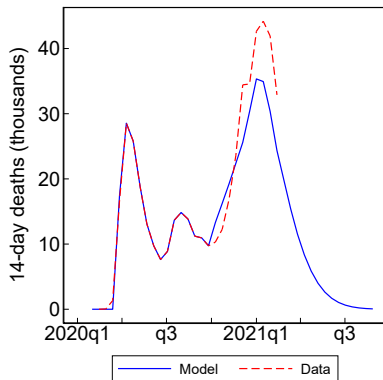


# Aggregates during the pandemic (3)

(a) Cases



(b) Deaths



## Quantitative exercises

# Quantitative exercises

- ▶ Use the calibrated model to investigate the aggregate and distributional effects of the pandemic and mitigation policies
- ▶ First, explore how the economic-epi model of virus transmission differs from an exogenous one ( $\beta_c = \beta_\ell = 0$ )
  - ▶ private mitigation is very heterogeneous across age, income, and wealth
- ▶ Second, explore optimal mitigation policies

# Quantitative exercises

- ▶ Use the calibrated model to investigate the aggregate and distributional effects of the pandemic and mitigation policies
- ▶ First, explore how the economic-epi model of virus transmission differs from an exogenous one ( $\beta_c = \beta_\ell = 0$ )
- ▶ Second, evaluate US mitigation policies
  - ▶ stay-at-home subsidies (e.g. FPUC)
  - ▶ stay-at-home orders
- ▶ Third, explore optimal mitigation policies

# Quantitative exercises

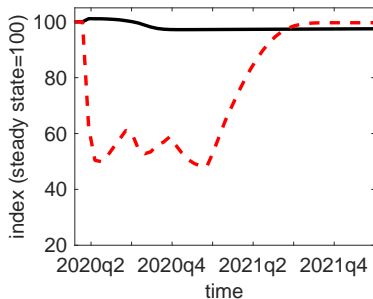
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- ▶ Second, evaluate US mitigation policies
- ▶ Third, explore optimal mitigation policies

# Private mitigation

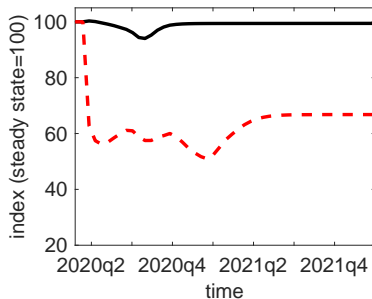
- ▶ To understand the magnitude and properties of private mitigation, compare
  - ▶ calibrated model without mitigation policy (i.e.  $T(0) = 0, \bar{\ell}_o \gg 0$ )
  - ▶ exogenous SIR model ( $\beta_c = \beta_\ell = 0$ )

# Private mitigation is large ...

(a) Outside consumption

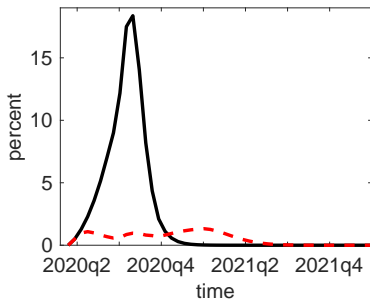


(b) Outside hours

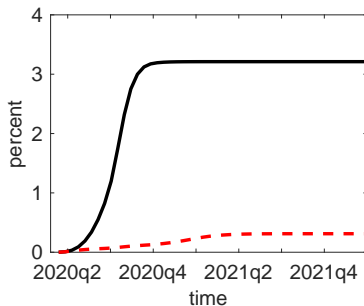


.. leading to less deaths

(a) Current infections



(b) Cumulative deaths



Notes: Percent of population 25+

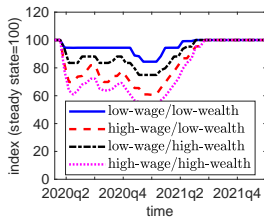


# Private mitigation is heterogeneous

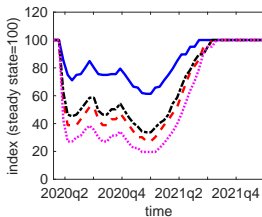
- ▶ Private mitigation is increasing in
  - ▶ age
  - ▶ income
  - ▶ wealth

# Policy functions of susceptible individuals

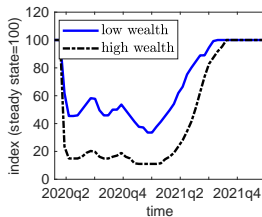
(a) Outside cons.  
(young)



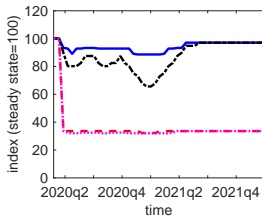
(b) Outside cons.  
(middle)



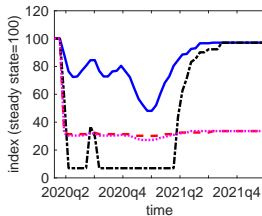
(c) Outside cons.  
(old)



(d) Outside hours  
(young)



(e) Outside hours  
(middle)



# US Mitigation Policies

# COVID-19 and US mitigation policies

|                | no<br>mitigation | US<br>mitigation | subsidy<br>only | lockdown<br>only |
|----------------|------------------|------------------|-----------------|------------------|
| welfare        | -8.0             | -6.4             | -6.4            | -7.8             |
| working-age    | -4.9             | -3.8             | -3.8            | -4.9             |
| retired        | -20.4            | -16.8            | -16.9           | -19.8            |
| low-wage       | -3.1             | -2.2             | -2.2            | -3.2             |
| high-wage      | -6.8             | -5.4             | -5.4            | -6.5             |
| low-wealth     | -6.0             | -4.6             | -4.6            | -6.0             |
| high-wealth    | -10.0            | -8.2             | -9.2            | -9.7             |
| policy support |                  | 100.0            | 100.0           | 81.4             |
| 2-year output  | 95.6             | 95.8             | 96.6            | 95.0             |
| deaths per 10k | 20.6             | 16.0             | 16.2            | 19.8             |

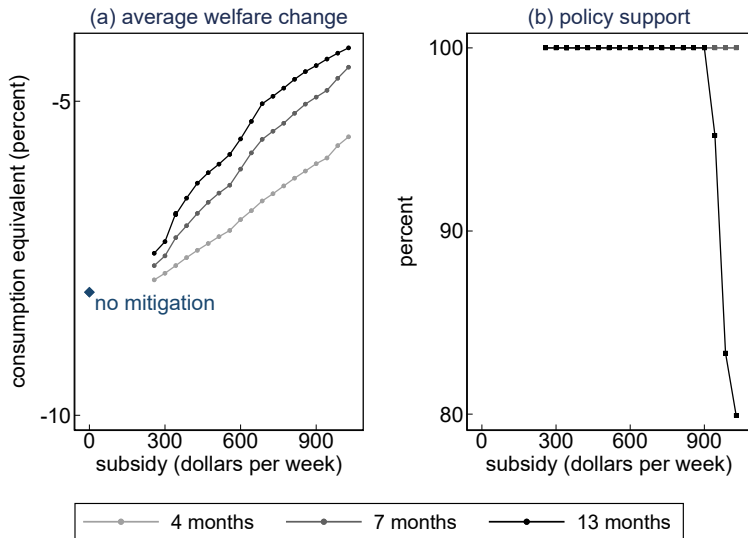
Notes: Low- and high-wage (wealth) correspond to below and above the median wage (wealth), respectively. Welfare reports consumption equivalents (percent). 2-year output is indexed to 2-year output in the pre-pandemic steady state

# Optimal Policies

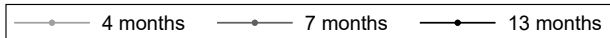
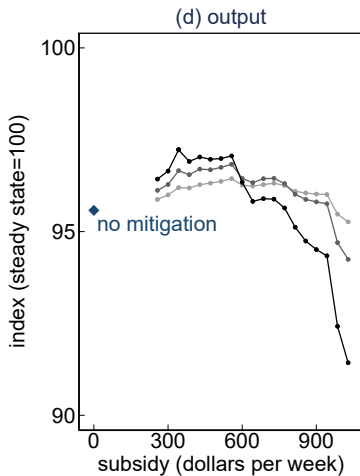
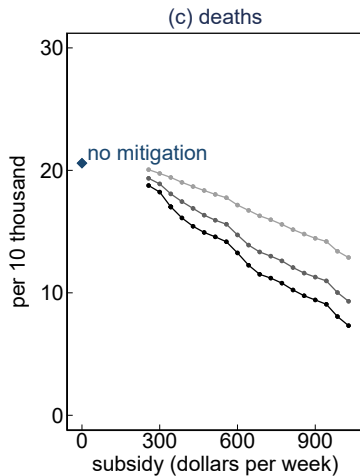
# Optimal Policies

- ▶ Investigate the properties of optimal mitigation policies, within a limited set of instruments
  - ▶ subsidy amount
  - ▶ duration
  - ▶ speed of phase-out
  - ▶ lockdown, with varying intensities
- ▶ Characterize:
  - ▶ Constrained optimal policy (welfare-maximizing Pareto improvement)
  - ▶ Output maximizing policy

# Larger & longer subsidies improve welfare ...



... lead to less deaths and *possibly* lower output





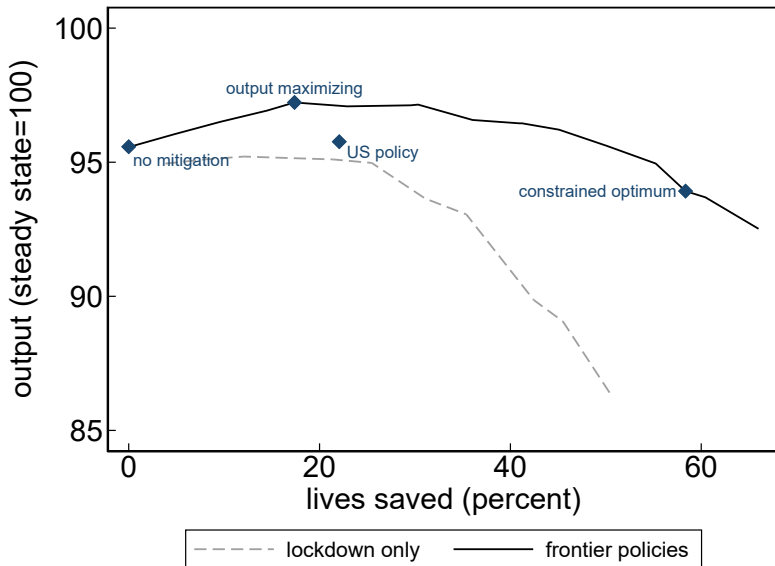
# How mitigation policies can increase output

- ▶ Mitigation policies can increase output (relative to no mitigation)
- ▶ This is due to two opposing effects
  1. **Direct effect:** subsidy reduces labor supply, holding fixed the severity of the pandemic
  2. **Indirect effect:** subsidy attenuates the pandemic, leading to increased labor supply
- ▶ For moderate subsidy amounts (less than \$600), only low-wage workers reduce their hours, leading to a small decline in output
- ▶ Because low-wage hours are almost exclusively outside, almost all of the reduction in hours contribute to mitigating the virus, making it safer to engage in more economic activities

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## Not necessarily a trade-off between lives and output



# Optimal policy breakdown

|                   | no<br>mitigation | maximizing<br>policy | optimal<br>policy | subsidy<br>only | tax<br>only |
|-------------------|------------------|----------------------|-------------------|-----------------|-------------|
| subsidy (\$/week) | 0                | 350                  | 1050              | 1050            | 0           |
| duration (months) | 0                | 13                   | 7                 | 7               | 7           |
| cons. tax (pct)   | 0                | 0.4                  | 36.5              | 0               | 36.5        |
| lockdown          | no               | no                   | no                | no              | no          |
| welfare           | -8.0             | -6.8                 | -4.3              | -4.3            | -8.2        |
| working-age       | -4.9             | -4.1                 | -2.3              | -2.0            | -5.3        |
| retired           | -20.4            | -17.7                | -11.8             | -13.4           | -19.6       |
| low-wage          | -3.1             | -2.5                 | -0.8              | -0.1            | -3.7        |
| high-wage         | -6.8             | -5.7                 | -3.9              | -4.0            | -6.8        |
| low-wealth        | -6.0             | -4.9                 | -2.7              | -2.2            | -6.4        |
| high-wealth       | -10.0            | -8.6                 | -5.7              | -6.4            | -9.8        |
| policy support    |                  | 100.0                | 100.0             | 100.0           | 37.9        |
| 2-year output     | 95.6             | 97.2                 | 93.9              | 93.7            | 96.0        |
| deaths per 10k    | 20.6             | 17.0                 | 8.6               | 12.0            | 18.0        |

Notes: Welfare reports consumption equivalents (percent). 2-year output is indexed to 2-year output in the pre-pandemic steady state.

# Conclusion

- ▶ Quantitative life-cycle economic-epidemiology model
  - ▶ measure the heterogeneous welfare effects of COVID-19
  - ▶ evaluate mitigation policies
- ▶ Stay-at-home subsidies dominate stay-at-home orders
- ▶ Optimal mitigation policies involve large subsidies and no lockdowns
- ▶ There need not be a tradeoff between saving lives and output

# Appendix

# Equilibrium [▶ back](#)

- ▶ Let  $X = K \times E \times H$  denote the state space over wealth, productivity, and health
- ▶ Let a  $\sigma$ -algebra over  $X$  defined by the Borel sets,  $\mathcal{B}$ , on  $X$ .
- ▶ A *steady-state recursive equilibrium*, given fiscal policies  $\{\tau_c, \tau_\ell, s\}$ , is
  - ▶ value functions  $\{v_j\}_{j \in J}$ ,
  - ▶ policy functions  $\{c_{ji}, c_{jo}, \ell_{ji}, \ell_{jo}, k'_j\}_j$ ,
  - ▶ producer plans  $\{Y_f, L_f, K_f\}$
  - ▶ prices  $\{w, r\}$ ,
  - ▶ distribution of newborns  $\omega$
  - ▶ invariant measures  $\{\mu_j\}_j$

such that:

## Equilibrium (2)

► back

1. Given prices, workers and retirees optimize
2. Given prices, firms optimize
3. Goods and factor markets clear
4. Government budget holds:

$$\begin{aligned} s \int_X \sum_{j \geq J^R} d\mu_j(k, \varepsilon, h) = \\ \tau_\ell \int_X \sum_{j < J^R} w \eta_{jh} \varepsilon [\ell_{ji}(k, \varepsilon, h) + \ell_{jo}(k, \varepsilon, h)] d\mu_j(k, \varepsilon, h) \\ + \tau_c \int_X \sum_{j \in J} [c_{ji}(k, \varepsilon, h) + c_{jo}(k, \varepsilon, h)] d\mu_j(k, \varepsilon, h) \end{aligned}$$



## Equilibrium (3) [▶ back](#)

5. for any  $(\mathcal{K}, \mathcal{E}, \mathcal{H}) \in \mathcal{B}$ , the **invariant measure**  $\mu_j$  satisfies

$$\begin{aligned}\mu_j(\mathcal{K}, \mathcal{E}, \mathcal{H}) &= \int_X \psi_{j-1} \mathbb{1}_{\{k'_{j-1}(k, \varepsilon, h) \in \mathcal{K}\}} \sum_{\varepsilon' \in \mathcal{E}} \sum_{h' \in \mathcal{H}} \Gamma_{\varepsilon, \varepsilon'} \Pi_{jhh'} d\mu_{j-1}(k, \varepsilon, h) \\ &\quad + \int_X (1 - \psi_j) \mathbb{1}_{\{k'_{j+1}(k, \varepsilon, h) \in \mathcal{K}\}} \sum_{\varepsilon' \in \mathcal{E}} \sum_{h' \in \mathcal{H}} \Gamma_{\varepsilon, \varepsilon'} \Pi_{jhh'} d\mu_j(k, \varepsilon, h)\end{aligned}$$

and

$$\begin{aligned}\mu_1(\mathcal{K}, \mathcal{E}, \mathcal{H}) &= \int_X (1 - \psi_1) \mathbb{1}_{\{k'_1(k, \varepsilon, h) \in \mathcal{K}\}} \sum_{\varepsilon' \in \mathcal{E}} \sum_{h' \in \mathcal{H}} \Gamma_{\varepsilon \varepsilon'} \Pi_{hh'} d\mu_1(k, \varepsilon, h) \\ &\quad + \omega(\mathcal{K}, \mathcal{E}, \mathcal{H})\end{aligned}$$

## Equilibrium (4)

[▶ back](#)

6. The newborn distribution satisfies:

$$\int_X k d\omega(k, \varepsilon, h) = \int_X \psi_{\bar{J}} k'_{\bar{J}}(k, \varepsilon, h) d\mu_{\bar{J}}(k, \varepsilon, h)$$

# Derivation of $\bar{u}$ [▶ back](#)

## ► Pre-pandemic steady-state value

$$\begin{aligned} v_j(k, \varepsilon) = & \frac{((c_i^*)^\gamma (c_o^*)^{1-\gamma})^{1-\sigma}}{1-\sigma} - \varphi \frac{(\ell_i^* + \ell_o^*)^{1+\nu}}{1+\nu} + \bar{u} \\ & + \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} [\psi_j v_{j+1}(k', \varepsilon') + (1 - \psi_j) v_j(k', \varepsilon')] \end{aligned}$$

- $c_i^*, c_o^*, \ell_i^*, \ell_o^*$ : pre-pandemic steady-state policy functions

## Derivation of $\bar{u}$ (2) [▶ back](#)

- ▶ Imposing optimality conditions

$$v_j(k, \varepsilon) = \frac{[(c^* + \Delta_c) \gamma^\gamma (1 - \gamma)^{1-\gamma}]^{1-\sigma}}{1 - \sigma} - \varphi \frac{(\ell_i^* + \ell_o^*)^{1+\nu}}{1 + \nu} + \bar{u} \\ + \beta(1 + \Delta_s) \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} [\psi_j v_{j+1}(k', \varepsilon') + (1 - \psi_j) v_j(k', \varepsilon')]$$

- ▶  $c^* = c_i^* + c_o^*$
- ▶  $\Delta_c, \Delta_s$ : small one-time deviations to consumption and survival probability

## Derivation of $\bar{u}$ (3) [▶ back](#)

$$\blacktriangleright \frac{\partial v}{\partial \Delta_s} = \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} [\psi_j v_{j+1}(k', \varepsilon') + (1 - \psi_j) v_j(k', \varepsilon')]$$

$$\blacktriangleright \frac{\partial v}{\partial \Delta_c} = (c^* + \Delta_c)^{-\sigma} \left( \gamma^\gamma (1 - \gamma)^{1-\gamma} \right)^{1-\sigma}$$

- ▶ The VSL—defined as the marginal rate of substitution between survival and consumption—can be expressed as

$$VSL = \left. \frac{\frac{\partial v}{\partial \Delta_s}}{\frac{\partial v}{\partial \Delta_c}} \right|_{\Delta_c=0, \Delta_s=0} = \frac{\beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon, \varepsilon'} [\psi_j v_{j+1}(k', \varepsilon') + (1 - \psi_j) v_j(k', \varepsilon')]}{c^{*- \sigma} \left( \gamma^\gamma (1 - \gamma)^{1-\gamma} \right)^{1-\sigma}}$$

$$\blacktriangleright \text{Set } \bar{u} \text{ such that } \frac{E(VSL)}{\bar{c}} = \frac{\$11.5e6}{\$44271 \times 14/365} = 6772 \text{ or}$$

$$\frac{\$7.4e6}{\$30989 \times 14/365} = 6226$$