An economic model of the Covid-19 pandemic with young and old agents: Behavior, testing and policies

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Introduction

Covid-19: global pandemic

- age-specific: death rates, behavior, externalities, policy impact
- testing seems to work (uncertainty about infectious status)
- behavioral change through social distancing even w/o policy

Insights: Equilibrium

- simple way to model *behavior*, *incomplete information* & *age*
- benchmark
  - old shield themselves a lot; young less

    (death -50%, GDP -5%)
  - positive externality: risk-taking of young preferred by old

    (w/o bed constraints)

Insights: Policy

- mild lockdown for all: can back fire to more deaths
  - different from homogeneous agent models

    (Chen 2012, Eichenbaum et al 2020a, Farboodi et al 2020, Garibaldi et al 2020,...)
  - the young wait, so the old have to shield themselves longer

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  - little within-old externality as small and careful group:
  - 16% of population
  - 7% of steady-state interaction
  - 1.5% of peak interaction

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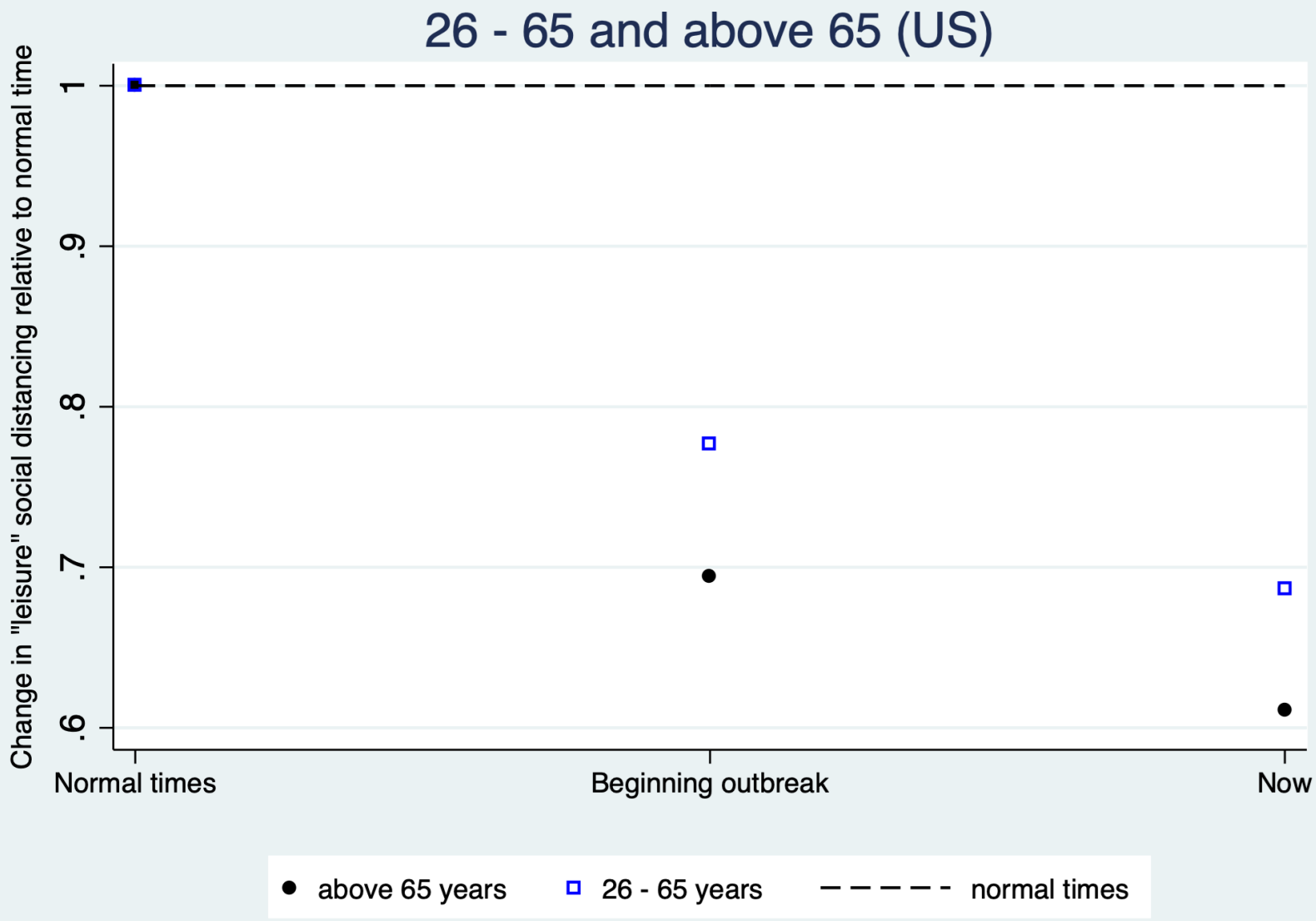
  - little within-old externality as small and careful group:
  - 16% of population
  - 7% of steady-state interaction
  - 1.5% of peak interaction
- separating activites by age works (death -10%)
- testing all works (death -35%)
- testing+quarantines better (death -35% to -100%, young suffice)

Behavioral Change in Non-Work Social Distance (Belot et al 2020)



Literature

Theory papers adding equ behavior to epidemiology: too much risk

Kremer (1996, SI), Quercioli & Smith (2006, SIR), Chen (2012, SIR), Rowthorn and Toxvaerd (2015), Toxvaerd (2019), Galleotti & Rogers (2012, 2015), Acemoglu et al (2016)...

Pre-existing calibrated econ-epidemiology: not much

Greenwood, Kircher, Santos & Tertilt (2019, 2017, 2013), Papageorge (2016), Keppo, Quercioli, Kudlyak, Smith & Wilson (2020)

New Covid Papers: little testing

- behavior but no age heterogeneity
- age heterogeneity but no behavior

Optimal containment policies: Alvarez, Argente & Lippi (2020), Eichenbaum, Rebelo & Trabandt (2020a), Farboodi, Jarosch & Shimer (2020), Garibaldi, Moen & Pissarides 2020, McAdams (2020), etc, *Unknown health status and testing*: Berger, Herkenhoff & Mongey (2020), Piguillem & Shi (2020), Eichenbaum, Rebelo & Trabandt (2020a), etc. *Heterogeneity*: Kaplan, Moll, Violante ('20), Glover, Heathcote, Krueger, Rios-Rull ('20), Favero, Ichino, Rustichini (2020), Acemoglu, Chernozhukov, Werning, Whinston ('20, tests), Gollier ('20)... *Macro stabilization policies*: Faria-e-Castro (2020), Guerrieri, Lorenzoni, Straub & Werning (2020)...

Model environment

Discrete time

Different ages (a): Young (y) and old (o)

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Health status (j):

- healthy (h)
- "fever" (f): unsure whether Covid or common cold
- infected (i): recovery ($\phi(0)$) or serious symptoms (α)
- symptoms (s): recovery ($\phi(1)$) or death (δ_t)
- recovered (r): immune forever

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Testing prob ξ_p (p for policy)

Death prob (δ_t): depends on availability of hospital beds

All of the above depend on age a

Households

Time: work n, leisure outside ℓ, leisure at home d

Time constraint (TC): $n + \ell + d = 1$

Leisure goods outside the house g:

$$g(x, \ell) = [\theta x^{\rho} + (1 - \theta)\ell^{\rho}]^{1/\rho}$$

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Preferences:

$$u(c, g, d; j, a, p) = \ln c + \gamma \ln g + [\underbrace{\lambda(j) + \lambda_p(j, a)}_{\text{altriusm/policy}}] \ln(d) + b$$

Discount factor (with natural death prob): $\beta(a)$

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Wages $w(a, n)$: wn for the young and $\overline{w}$ for the old

Budget constraint (BC): $c + x = w(a, n)$

Infections

Covid:

$$\pi(n+\ell, \Pi_t(a)) = \underbrace{(n+\ell)}_{\substack{\text{Prob. entering} \\ \text{common space}}} \quad \Pi_t(a)$$

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Infections

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Common cold:

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Covid transmission probability:

$$\hat{\Pi}_t(a) = \quad \Pi_0 \underbrace{\sum_{a', j \in \{f_i, i, s\}} \left(n_t(j, a') + \ell_t(j, a')\right) M_t(j, a')}_{\text{other infected per square meter}}$$

$$\Pi_t(a) = \underbrace{1 - e^{-\hat{\Pi}_t(a)}}_{\text{continuous time aggregation}}$$

Decision making

Healthy:

$$V_t(h,a) = \max_{c,x,n,\ell,d} u(c, g(x,\ell), d; h, a, p_t) +$$

$$\beta(a)[1 - \pi_f(n+\ell, \Pi_t(a)) + \pi^*(n+\ell, \Pi_t(a))\xi_{p_t}(a)]V_{t+1}(h,a) +$$

$$\beta(a)\xi_{p_t}(a)\pi(n+\ell, \Pi_t(a))V_{t+1}(i,a) +$$

$$\beta(a)(1-\xi_{p_t}(a))\pi_f(n+\ell, \Pi_t(a))V_{t+1}(f,a)$$

s.t. (TC) and (BC).

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$$\beta(a)(1-\xi_{p_t}(a))\pi_f(n+\ell, \Pi_t(a))V_{t+1}(f,a)$$
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Infected:

$$V_t(i,a) = \max_{c,x,n,\ell,d} u(c, g(x,\ell), d; i, a, p_t) + \beta(a)\phi(0,a)V_{t+1}(r,a) +$$
$$\beta(a)(1-\phi(0,a))\alpha(a)V_{t+1}(s,a)$$
$$\beta(a)(1-\phi(0,a))(1-\alpha(a))V_{t+1}(i,a)$$
$$\text{s.t. (TC) and (BC).}$$

Decision making

Fever:

$$V_t(f,a) = \max_{c,x,n,\ell,d} \frac{\Pi^* \ \tilde{V}_t(c,x,n,\ell,d;h,a)}{\Pi_{t-1}(a)+\Pi^*} + \frac{\Pi_{t-1}(a) \ \tilde{V}_t(c,x,n,\ell,d;i,a)}{\Pi_{t-1}(a)+\Pi^*}$$

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Symptoms:

$$V_t(s,a) = \beta(a)\left[\phi(1,a)V_{t+1}(r,a) + (1-\phi(1,a))(1-\delta_t(a))V_{t+1}(s,a)\right]$$

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Recovered:

$$V_t(r,a) = \max_{c,x,n,\ell,h} u(c,g(x,\ell),d;r,a,p_t) + \beta(a)V_{t+1}(r,a)$$

$$\text{s.t. (TC) and (BC).}$$

Aggregation

Output: sum of wages

Laws of motion: as you would expect

Death prob : constant unless no hospital bed

Equilibrium concept: Rational expectations equilibrium

Summary: How age matters

- Old do not work - spend naturally more time at home.
- Higher probability of becoming critically ill.
- Once critically ill, higher chance of dying.
- Also higher chance of dying from natural causes.

Parameters

- $R_0 = 2.5$ from literature
- transition probabilities from CDC
- 3 common colds per year
- leisure outside: time use data
- bliss of living: mobility reductions in Sweden

◂ Details ◂ Fit

Non-targeted moments

Moment	Model	Data (ranges)
Infection fatality rate (CDC/Ferguson by age)	0.71	0.4-15
Daily growth of infections, outset of Covid-19, %	15	15-50
Deaths, old/all, %	34	$\approx$80

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Daily growth of infections, outset of Covid-19, %	15	15-50
Deaths, old/all, %	34	≈80

Week	1	2	3	4	5	6
Deaths, old/all, %	70.24	67.42	65.73	64.24	62.04	58.30

Benchmark results

	No disease	Benchmark	Epidem.
Wks to peak srsly ill (yng)	–	14.00	12.00
Wks to peak srsly ill (old)	–	12.00	12.00
Srsly ill p/ 1,000 @ peak (yng)	–	4.03	12.84
Srsly ill p/ 1,000 @ peak (old)	–	0.59	10.78
Dead p/ 1,000 1year (yng)	–	2.81	4.04
Dead p/ 1,000 1year (old)	–	7.81	30.07
Dead p/ 1,000 1year (all)	–	3.61	8.21
Dead p/ 1,000 LR (yng)	–	2.96	4.04
Dead p/ 1,000 LR (old)	–	9.00	30.07
Dead p/ 1,000 LR (all)	–	3.93	8.21
Immune in LR (yng), %	–	62.46	85.24
Immune in LR (old), %	–	12.00	39.45
Immune in LR (all), %	–	54.38	77.90
GDP at peak - rel to BM	1.22	1.00	1.21
GDP 1year - rel to BM	1.06	1.00	1.05
Cost p/ life saved, million $	–	–	–
Hrs @ home (yng) - peak	54.77	65.49	54.77
Hrs @ home (old) - peak	88.98	107.60	88.98
Hrs @ home (yng) - 6m	54.77	58.88	54.77
Hrs @ home (old) - 6m	88.98	100.73	88.98
Value - healthy (yng)	3753.35	3740.80	3736.30
Value - healthy (old)	1825.47	1802.00	1770.60
Value - healthy (all)	3444.50	3430.20	3421.40

Age ext. partial	Age ext. general
13.00	14.00
12.00	12.00
1.97	1.27
0.59	0.42
1.92	1.71
7.81	7.28
2.87	2.61
2.13	2.16
9.00	9.68
3.23	3.37
44.92	45.70
12.00	13.00
39.64	40.46
0.48	0.83
0.81	0.85
12.42	13.30
92.99	73.48
107.60	101.93
74.01	70.40
100.73	99.80
1610.30	1615.50
1802.00	1803.30
1641.00	1645.60

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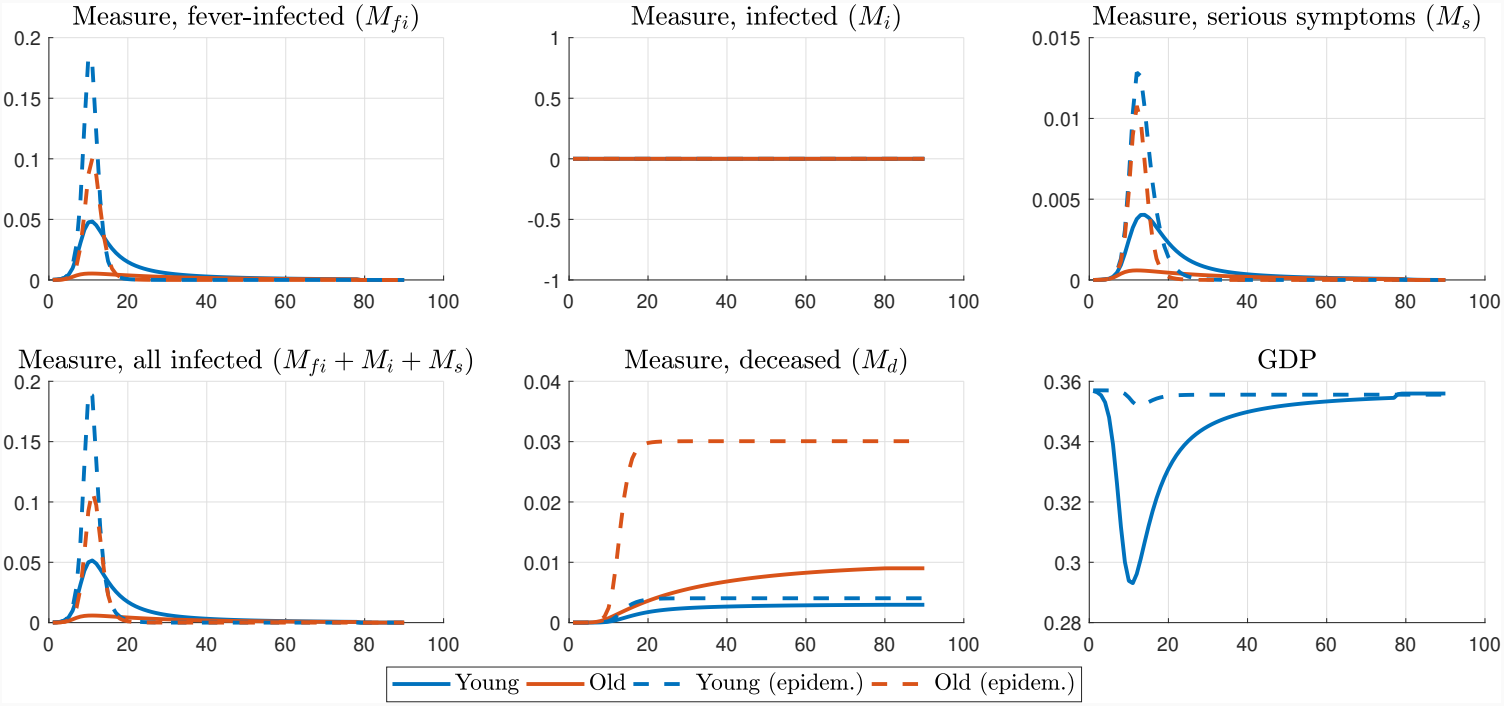
Srsly ill p/ 1,000 @ peak (old)	–	0.59	10.78	0.59	0.42
Dead p/ 1,000 1year (yng)	–	2.81	4.04	1.92	1.71
Dead p/ 1,000 1year (old)	–	7.81	30.07	7.81	7.28
Dead p/ 1,000 1year (all)	–	3.61	8.21	2.87	2.61
Dead p/ 1,000 LR (yng)	–	2.96	4.04	2.13	2.16
Dead p/ 1,000 LR (old)	–	9.00	30.07	9.00	9.68
Dead p/ 1,000 LR (all)	–	3.93	8.21	3.23	3.37
Immune in LR (yng), %	–	62.46	85.24	44.92	45.70
Immune in LR (old), %	–	12.00	39.45	12.00	13.00
Immune in LR (all), %	–	54.38	77.90	39.64	40.46
GDP at peak - rel to BM	1.22	1.00	1.21	0.48	0.83
GDP 1year - rel to BM	1.06	1.00	1.05	0.81	0.85
Cost p/ life saved, million $	–	–	–	12.42	13.30
Hrs @ home (yng) - peak	54.77	65.49	54.77	92.99	73.48
Hrs @ home (old) - peak	88.98	107.60	88.98	107.60	101.93
Hrs @ home (yng) - 6m	54.77	58.88	54.77	74.01	70.40
Hrs @ home (old) - 6m	88.98	100.73	88.98	100.73	99.80
Value - healthy (yng)	3753.35	3740.80	3736.30	1610.30	1615.50
Value - healthy (old)	1825.47	1802.00	1770.60	1802.00	1803.30
Value - healthy (all)	3444.50	3430.20	3421.40	1641.00	1645.60

Benchmark results



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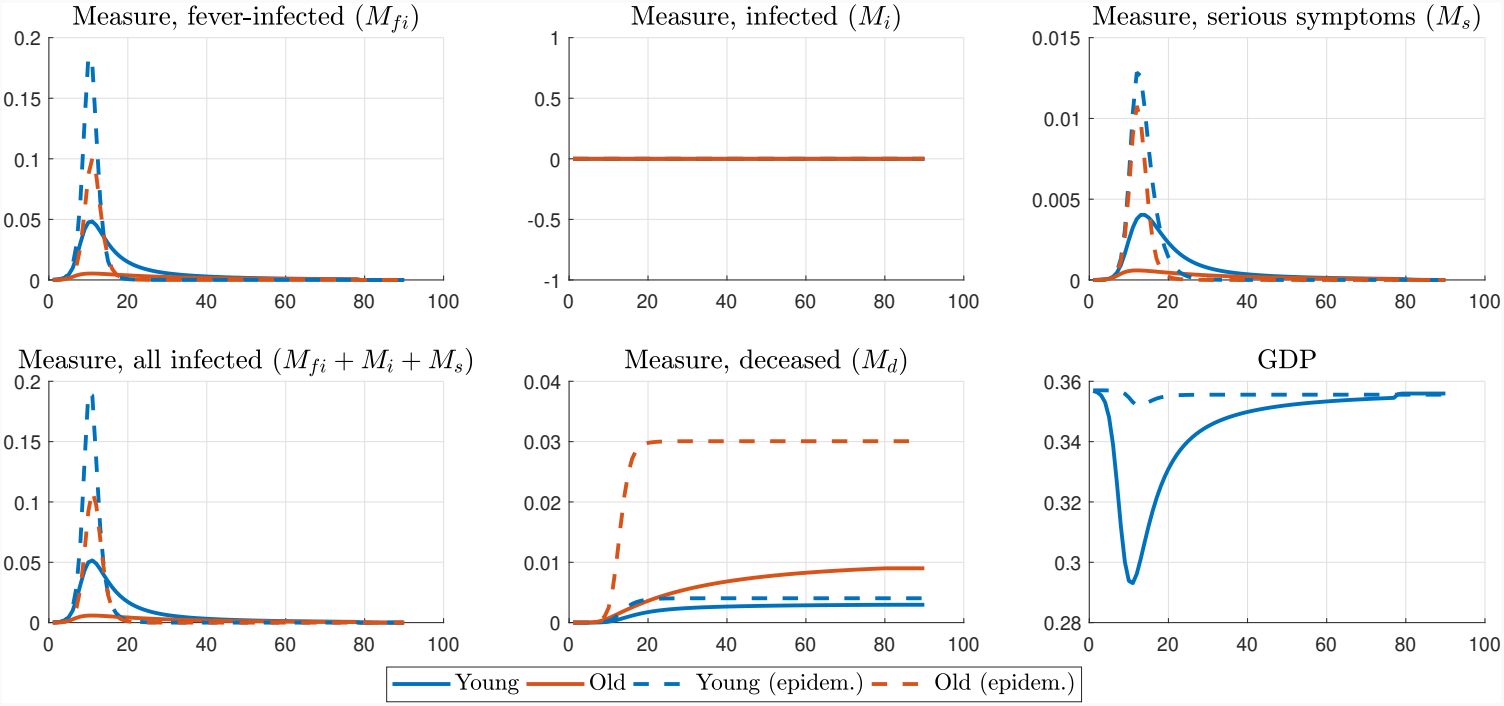
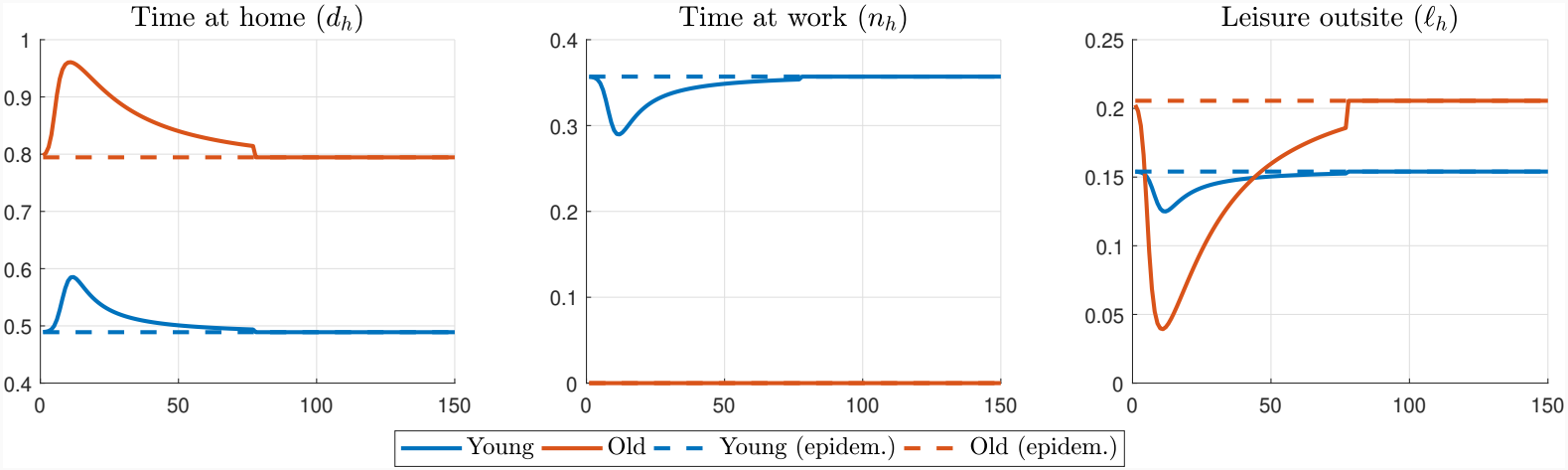




Benchmark results - hospital constraints

	Benchmark	Epidem.	Age ext. partial	Age ext. general
Wks to peak srsly ill (yng)	11.00	11.00	11.00	12.00
Wks to peak srsly ill (old)	12.00	12.00	12.00	12.00
Srsly ill p/ 1,000 @ peak (yng)	2.02	6.42	2.02	1.99
Srsly ill p/ 1,000 @ peak (old)	1.34	9.19	1.34	1.33
Dead p/ 1,000 1year (yng)	11.21	18.99	11.07	10.78
Dead p/ 1,000 1year (old)	15.21	31.97	15.20	14.82
Dead p/ 1,000 1year (all)	11.85	21.07	11.73	11.43
Dead p/ 1,000 LR (yng)	11.32	18.99	11.19	10.93
Dead p/ 1,000 LR (old)	16.14	31.97	16.14	15.98
Dead p/ 1,000 LR (all)	12.09	21.07	11.98	11.73
Immune in LR (yng), %	63.51	82.88	62.92	62.26
Immune in LR (old), %	20.41	38.40	20.41	20.24
Immune in LR (all), %	56.61	75.75	56.11	55.53
GDP at peak - rel to BM	1.00	1.20	1.00	1.00
GDP 1year - rel to BM	1.00	1.03	0.99	0.99
Cost p/ life saved, million $	–	–	3.90	1.17
Hrs @ home (yng) - peak	64.57	54.77	64.74	64.69
Hrs @ home (old) - peak	100.56	88.98	100.56	100.47
Hrs @ home (yng) - 6m	56.67	54.77	58.55	58.26
Hrs @ home (old) - 6m	93.58	88.98	93.58	93.28
Value - healthy (yng)	559.80	555.08	240.45	240.58
Value - healthy (old)	405.07	399.50	405.07	405.18
Value - healthy (all)	535.01	530.15	266.82	266.95

Policy experiments

Stylized Policies:

- Shelter at home
- Selective mixing by age (supermarket times for the old)
- Testing
- Testing and quarantining

Age-specific policies as well

Shelter at home - mild

	Benchmark	SH25-a-4	SH25-a-26	SH25-y-26
Wks to peak srsly ill (yng)	14.00	16.00	34.00	34.00
Wks to peak srsly ill (old)	12.00	14.00	33.00	33.00
Srsly ill p/ 1,000 @ peak (yng)	4.03	4.04	2.34	2.27
Srsly ill p/ 1,000 @ peak (old)	0.59	0.59	0.48	0.47
Dead p/ 1,000 1year (yng)	2.81	2.79	2.48	2.49
Dead p/ 1,000 1year (old)	7.81	7.64	7.52	8.12
Dead p/ 1,000 1year (all)	3.61	3.56	3.29	3.39
Dead p/ 1,000 LR (yng)	2.96	2.95	2.87	2.87
Dead p/ 1,000 LR (old)	9.00	8.93	9.76	10.34
Dead p/ 1,000 LR (all)	3.93	3.91	3.97	4.07
Immune in LR (yng), %	62.46	62.31	60.60	60.60
Immune in LR (old), %	12.00	11.93	13.14	13.89
Immune in LR (all), %	54.38	54.24	53.00	53.12
GDP at peak - rel to BM	1.00	1.00	1.08	1.08
GDP 1year - rel to BM	1.00	0.98	0.88	0.88
Cost p/ life saved, million $	–	40.40	–	–
Hrs @ home (yng) - peak	65.49	65.36	62.57	62.43
Hrs @ home (old) - peak	107.60	107.60	105.68	105.57
Hrs @ home (yng) - 6m	58.88	59.57	70.59	70.58
Hrs @ home (old) - 6m	100.73	101.80	102.74	101.00
Value - healthy (yng)	3740.80	3740.40	3738.50	3738.40
Value - healthy (old)	1802.00	1802.00	1799.80	1800.00
Value - healthy (all)	3430.20	3429.90	3427.90	3427.90

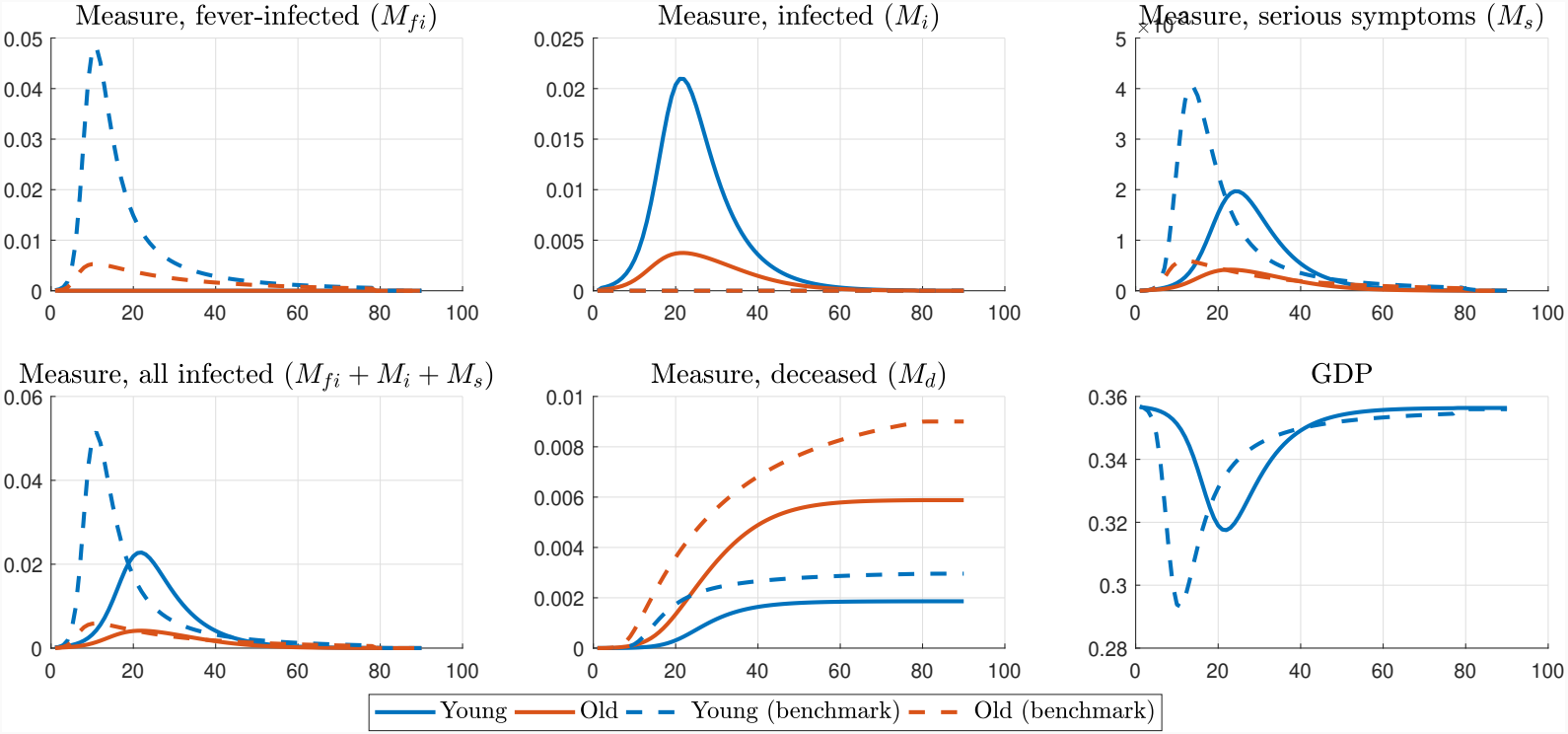
Shelter at home - strong

	Benchmark	SH75-a-12	SH75-a-35	SH90-a-26	SH90-o-26
Wks to peak srsly ill (yng)	14.00	33.00	66.00	54.00	14.00
Wks to peak srsly ill (old)	12.00	32.00	64.00	53.00	30.00
Srsly ill p/ 1,000 @ peak (yng)	4.03	3.96	3.50	3.78	4.02
Srsly ill p/ 1,000 @ peak (old)	0.59	0.57	0.51	0.54	0.30
Dead p/ 1,000 1year (yng)	2.81	2.46	0.00	0.32	2.80
Dead p/ 1,000 1year (old)	7.81	5.71	0.00	1.07	4.39
Dead p/ 1,000 1year (all)	3.61	2.98	0.00	0.44	3.06
Dead p/ 1,000 LR (yng)	2.96	2.87	2.23	2.62	2.96
Dead p/ 1,000 LR (old)	9.00	8.10	4.64	6.35	5.73
Dead p/ 1,000 LR (all)	3.93	3.71	2.62	3.22	3.40
Immune in LR (yng), %	62.46	60.57	47.15	55.33	62.47
Immune in LR (old), %	12.00	10.98	6.43	8.74	7.70
Immune in LR (all), %	54.38	52.63	40.62	47.86	53.70
GDP at peak - rel to BM	1.00	1.00	0.97	0.98	1.00
GDP 1year - rel to BM	1.00	0.83	0.55	0.58	1.00
Cost p/ life saved, million $	–	29.63	13.53	23.28	0.00
Hrs @ home (yng) - peak	65.49	65.18	67.19	66.08	65.33
Hrs @ home (old) - peak	107.60	107.55	107.41	107.53	110.12
Hrs @ home (yng) - 6m	58.88	57.56	95.85	104.06	58.76
Hrs @ home (old) - 6m	100.73	101.76	106.14	109.09	109.42
Value - healthy (yng)	3740.80	3727.00	3702.70	3685.10	3740.80
Value - healthy (old)	1802.00	1799.50	1799.00	1789.40	1792.60
Value - healthy (all)	3430.20	3418.20	3397.70	3381.40	3428.70

Selective mixing: half of activities separated (ΔDeath=-10%)

	Benchmark	Sel. mix.
Wks to peak srsly ill (yng)	14.00	13.00
Wks to peak srsly ill (old)	12.00	12.00
Srsly ill p/ 1,000 @ peak (yng)	4.03	4.61
Srsly ill p/ 1,000 @ peak (old)	0.59	0.50
Dead p/ 1,000 1year (yng)	2.81	2.95
Dead p/ 1,000 1year (old)	7.81	5.75
Dead p/ 1,000 1year (all)	3.61	3.40
Dead p/ 1,000 LR (yng)	2.96	3.07
Dead p/ 1,000 LR (old)	9.00	6.43
Dead p/ 1,000 LR (all)	3.93	3.61
Immune in LR (yng), %	62.46	64.89
Immune in LR (old), %	12.00	8.55
Immune in LR (all), %	54.38	55.86
GDP at peak - rel to BM	1.00	0.97
GDP 1year - rel to BM	1.00	1.00
Cost p/ life saved, million $	–	0.10
Hrs @ home (yng) - peak	65.49	66.79
Hrs @ home (old) - peak	107.60	105.82
Hrs @ home (yng) - 6m	58.88	58.88
Hrs @ home (old) - 6m	100.73	97.09
Value - healthy (yng)	3740.80	3740.20
Value - healthy (old)	1802.00	1809.80
Value - healthy (all)	3430.20	3431.00

Testing - all (or young): ΔGDP=+1%, ΔDeath= - 35%



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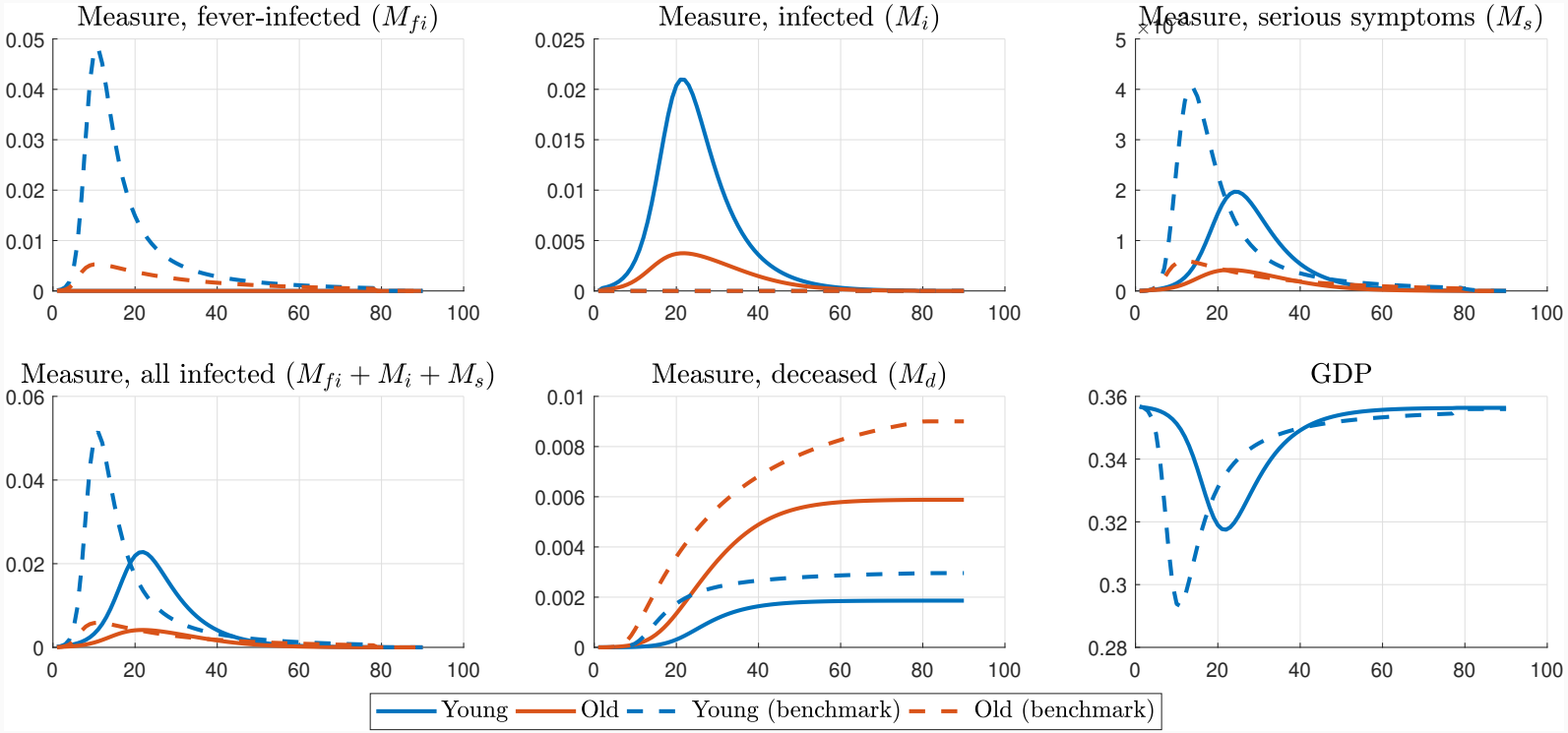
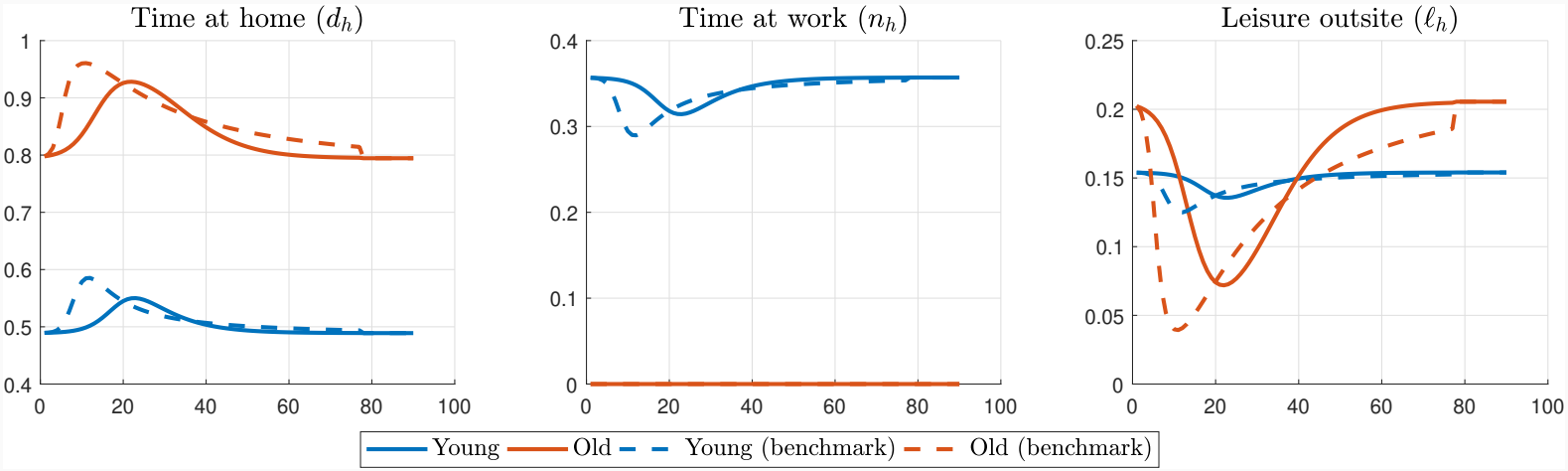
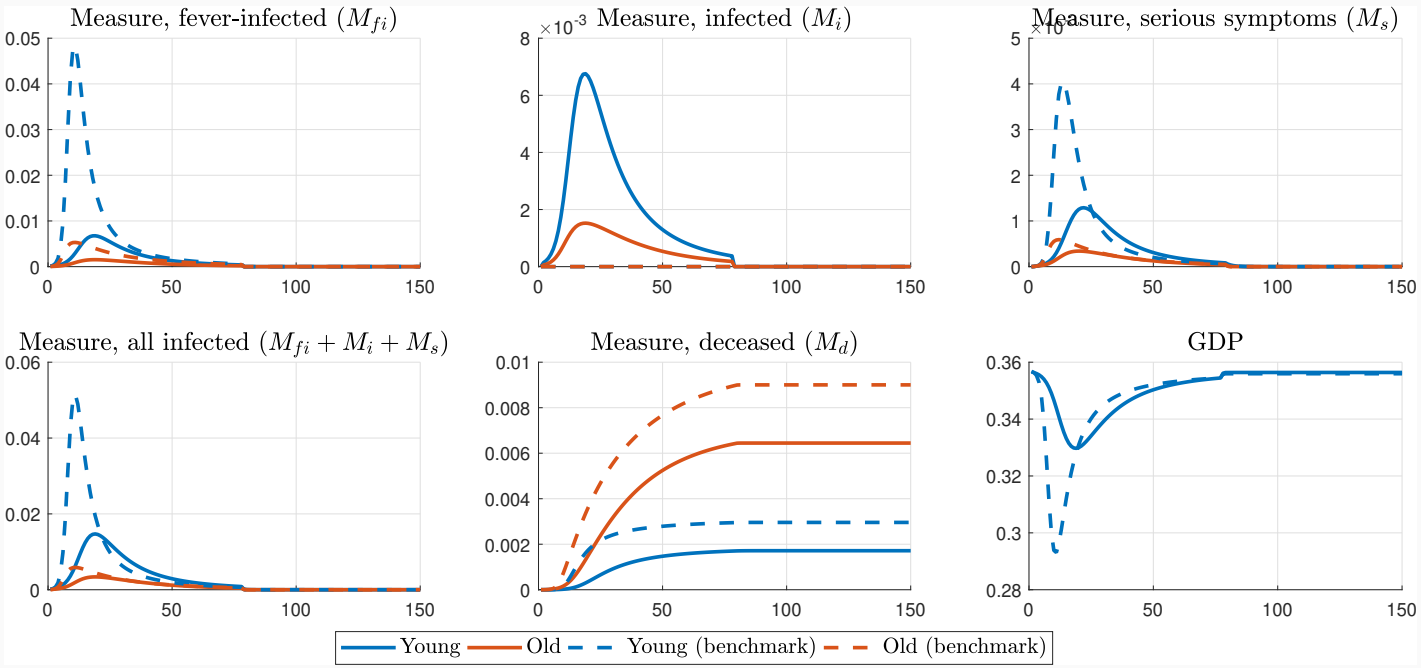




Quarantine (50%): ΔGDP=+2%, ΔDeath= - 35%
(similar: only young; 100%: very few deaths)



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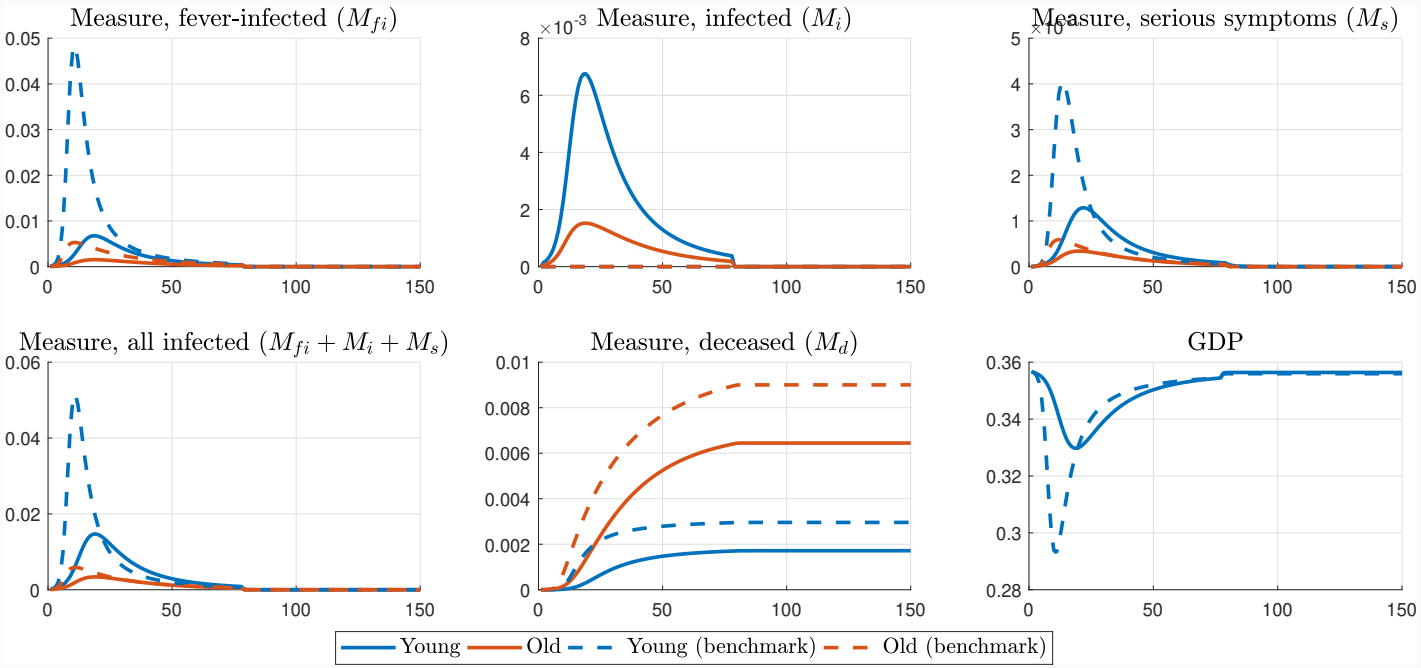
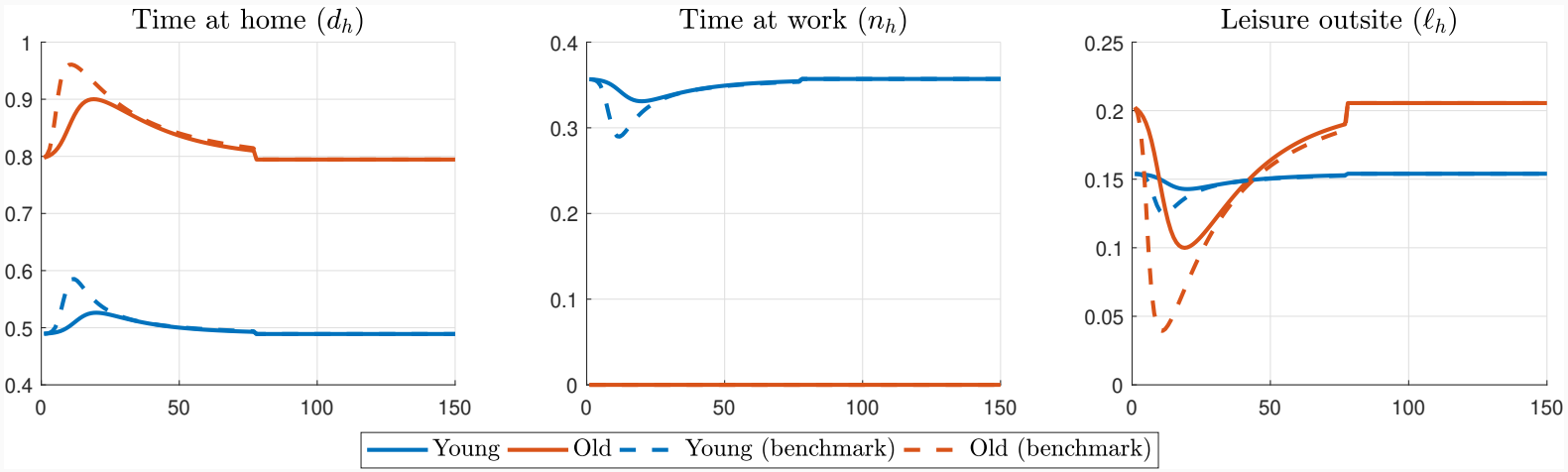




More on the counterfactuals

Hospital bed (ICU) constraints:

- Qualitatively similar
- Quantitatively more powerful

More on the counterfactuals

Hospital bed (ICU) constraints:

- Qualitatively similar
- Quantitatively more powerful

Caveats and next steps:

- Uncertainty regarding calibration
- Immediate test results
- Immediate start of policies
- Teleworking; middle-aged workers

Conclusions

Choice-theoretic equilibrium model of Covid-19 epidemic:

- Different age/risk groups
- Different behavior
- Partial uncertainty about health status

Results:

- Large behavioral adjustments without policy (by old)
- Shelter at home can backfire/hurt the old, but potential
  - if hospital beds are scarce
  - if in place until a vaccine is widely available

- Testing/quarantine: important if massive (suffices on young)
- Hospital bed constraints: quantitatively important

Conclusions

Choice-theoretic equilibrium model of Covid-19 epidemic:

- Different age/risk groups
- Different behavior
- Partial uncertainty about health status

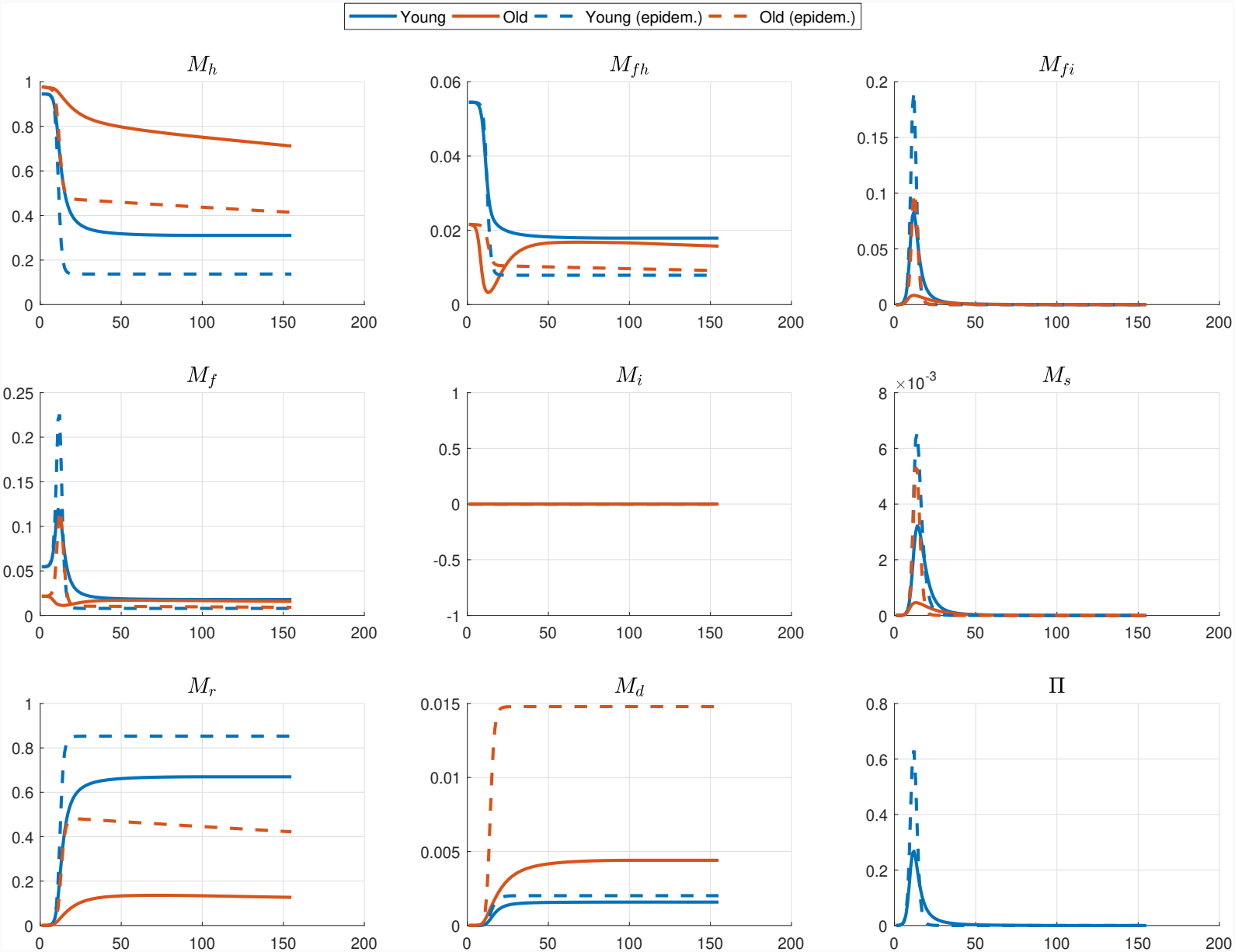
Results:

- Large behavioral adjustments without policy (by old)
- Shelter at home can backfire/hurt the old, but potential
  - if hospital beds are scarce
  - if in place until a vaccine is widely available
  - if buys time to learn about masks, dexamethasone,...
  - if people have wrong beliefs about mortality rates
- Testing/quarantine: important if massive (suffices on young)
- Hospital bed constraints: quantitatively important

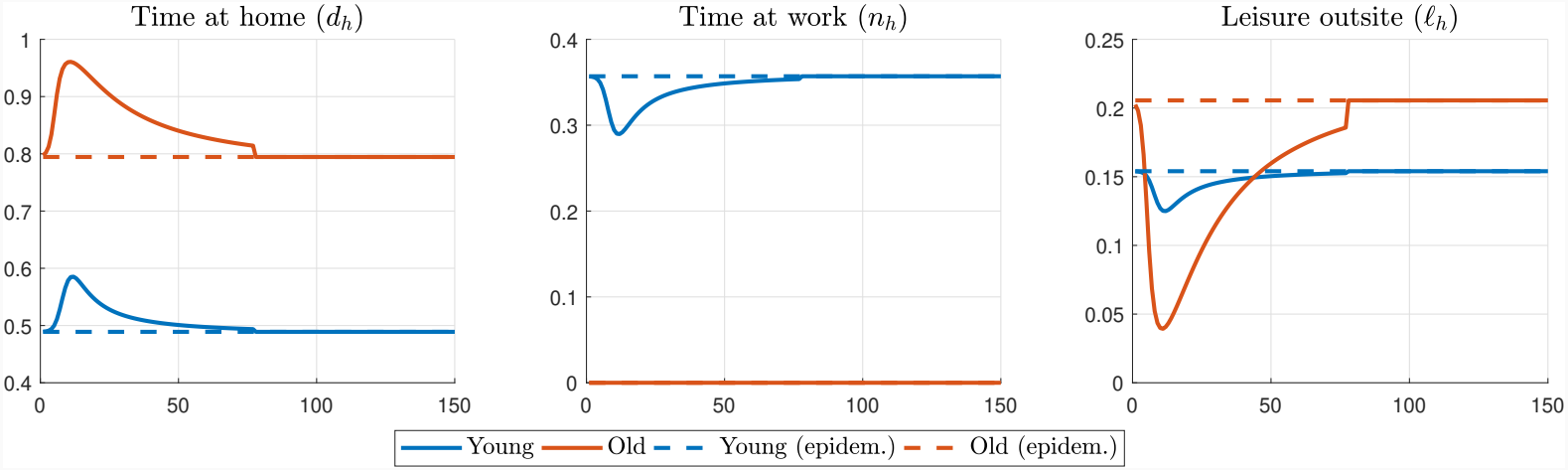
Work in progress: many steps to go...

Appendix

Benchmark results



Benchmark results



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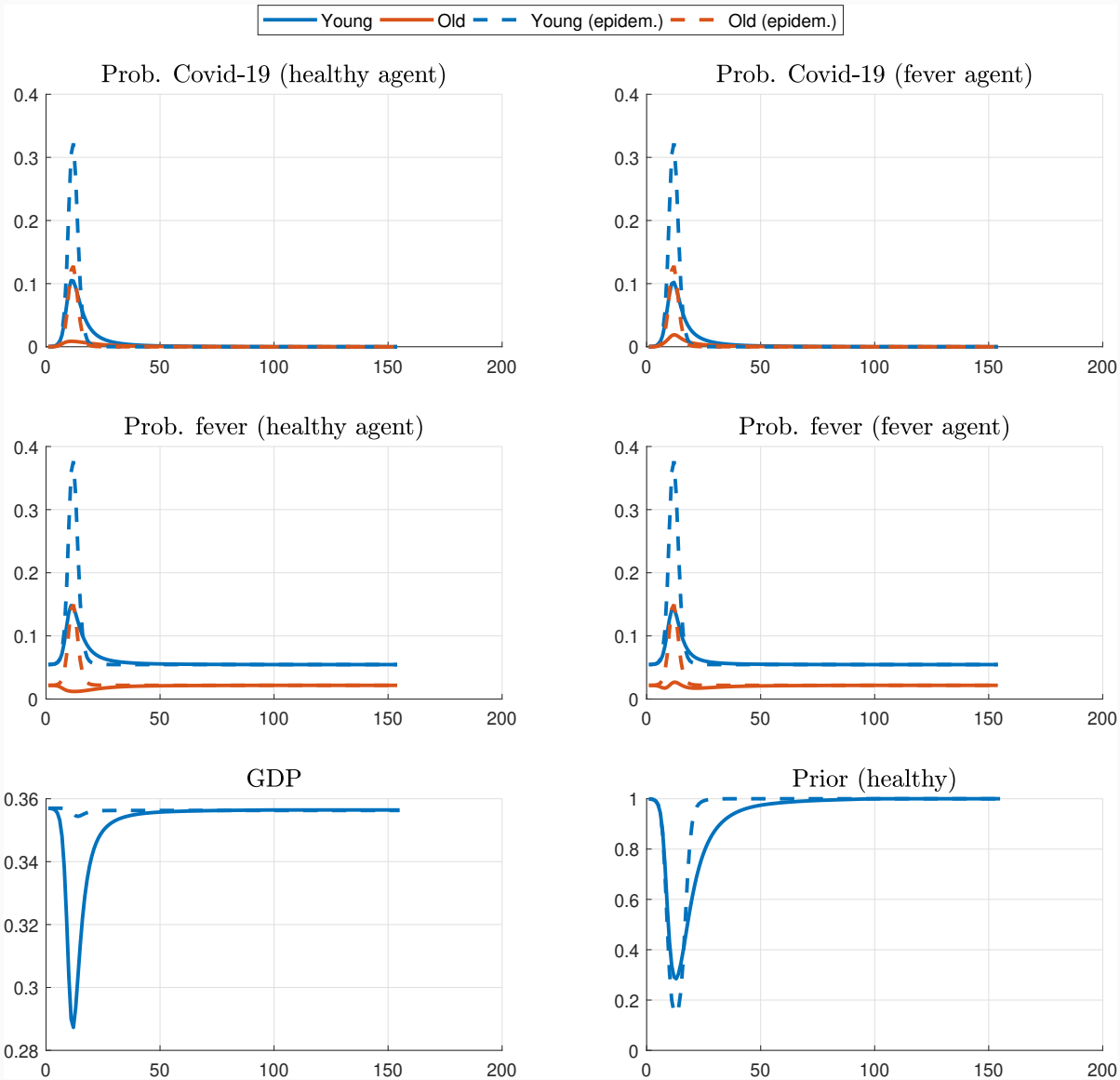
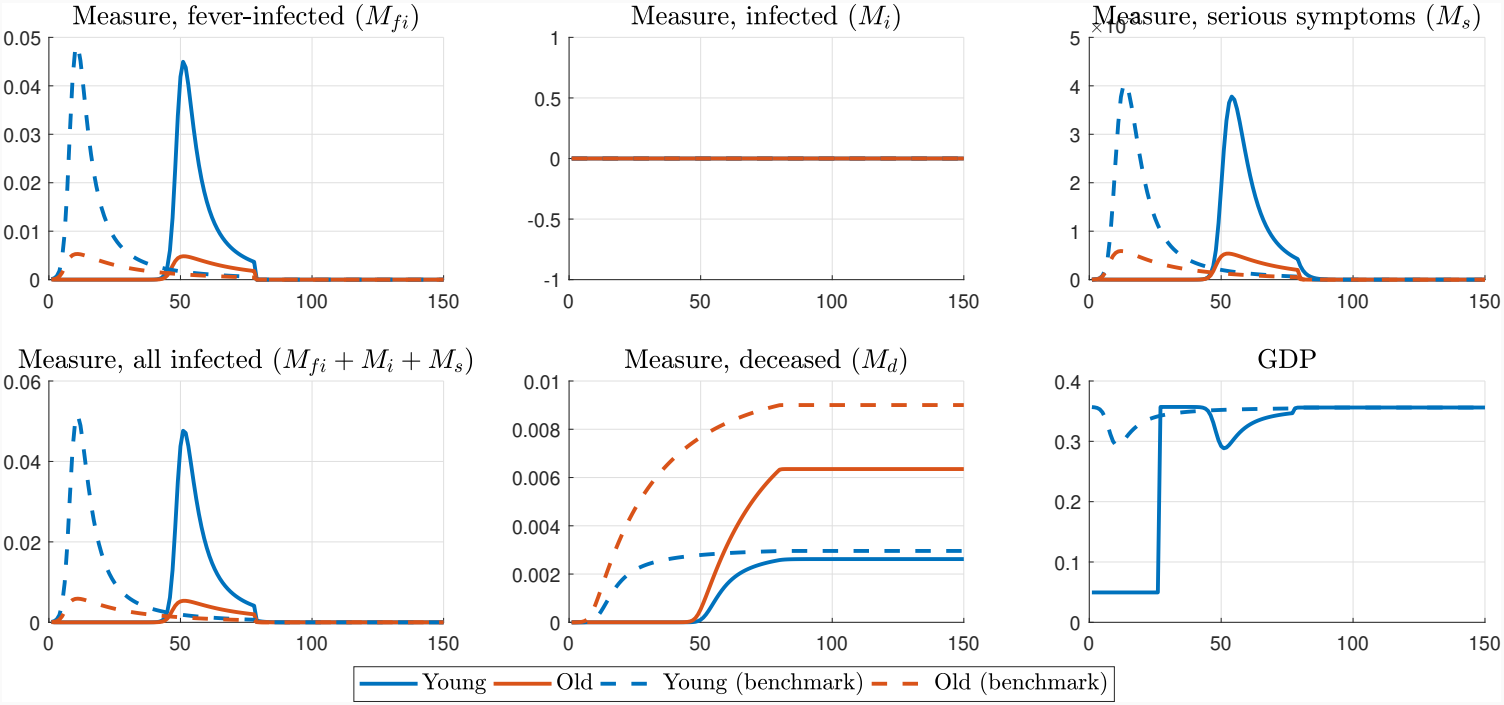


Back

Shelter at home: shifts peak (here all - 26 weeks)



Back

Parameters - disease

Parameter	Value	Interpretation
	0.16	Fraction of old in Population
Π^*	0.107	Weekly infectiousness of common cold/flu
Π_0	11.56	Infectiousness of Covid-19
α	1	Prob(serious symptoms | no recovery from mild)
$\phi(0,y)$	0.983	Prob of recovering from mild Covid-19, young
$\phi(0,o)$	0.954	Prob of recovering from mild Covid-19, old
$\phi(1,y)$	0.284	Prob of recovering from serious Covid-19, young
$\phi(1,o)$	0.284	Prob of recovering from serious Covid-19, old
$\bar{\ell}$	0.158	Infections through the health care system
$\delta(y)$	0.065	Weekly death rate (among critically ill), young
$\delta(o)$	0.738	Weekly death rate (among critically ill), old
$\Delta(y)$	1	Weekly survival (natural causes), young
$\Delta(o)$	0.999	Weekly survival (natural causes), old

◂ Back

Parameters - others

Parameter	Value	Interpretation
ρ	-1.72	Elasticity of subst. bw leisure time and goods
θ	0.033	Production of leisure goods
γ	0.636	Rel. utility weight - leisure goods
λ_d	1.56	Rel. utility weight - leisure at home
$\lambda(i)$	2.937	Rel. utility weight - leisure at home (infected)
b	6.5	Value of being alive
$\tilde{\beta}$	$0.96^{1/52}$	Discount factor
w	1	Wage per unit of time
$\overline{w}$	0.214	Retirement income
τ	0	Productivity of telework

◂ Back

Model fit

Moment	Model	Data (ranges)
Common colds per year	3	2-4
R_0, Covid-19	2.5	1.6-4
% of infected in critical care, young	3.33	3.33
% of infected in critical care, old	9.10	9.10
% in critical care that dies, young	14.2	5-24
% in critical care that dies, old	65.0	40-73
Weeks in critical care, young	3.5	3-6
Weeks in critical care, old	3.5	3-6
Hours/day interacting while in ICU	3.8	7.6 (controlled)
Life expectancy (natural), young	∞	79
Life expectancy (natural), old	20	20

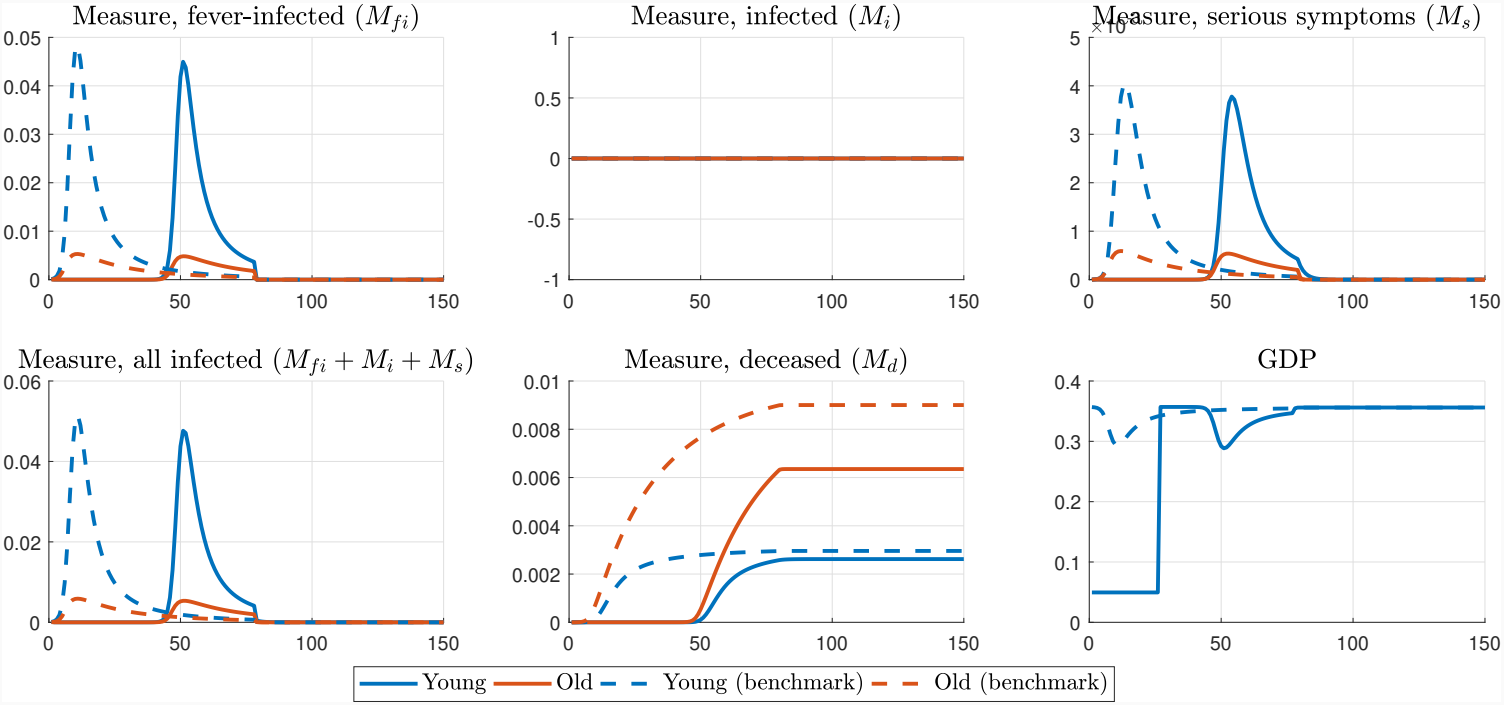
◂ Back

Model fit - cont.

Moment	Model	Data (ranges)
Hours of work per week	40	
Hours of outside activities per week	17.3	17.3
% of income on goods outside	12.5	11.1-16.1
% ↑ in time @ home - outset of Covid-19	15.7	15.7% (Sweden)
% ↑ in time @ home - mild symptoms	50	50 (H1N1)
Replacement rate - social security, %	60	46-64

◂ Back

Shelter at home: shifts peak (here all - 26 weeks)



Back