The Shape of Mortality: Implications for Economic Analysis

Adriana Lleras-Muney

Flavien Moreau

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Question: What is the production function of health over lifetime?

1. What is the effect of economic conditions on mortality?
   - Puzzle in literature: Effect of GDP level and of deviations from trend.
   - Money in short and run long has different effects on health

2. Why is LE of women larger and growing faster than men's?
   - Biological differences versus social investments & innovation (how many missing women?)

3. What is the optimal sequence of health investments over the lifetime?
   - Health care expenditures by age?
   - SES gradients: Can initial conditions be overcome?

To answer these questions we need estimates of the "production" function of health over the lifetime.

Key insight here: Mortality rates by age reveal health process

This paper: A simple tractable model of cohort health and death

- **Model:** health = dynamic stock of "Frailty". Four "fundamental" forces affect stock and generate deaths
  1. Resources/investments increase stock
  2. Disease: random shocks. Can hit anyone but more likely kill the frail
  3. Depreciation: natural aging process.
  4. "External causes of death," mostly reproductive ages (M, war, etc)

- **Estimation of parameters**
  - Use newly available cohort life tables from Human mortality database
  - Use simulation method of moments
  - Study evolution of parameters over time their correlates, cost of war

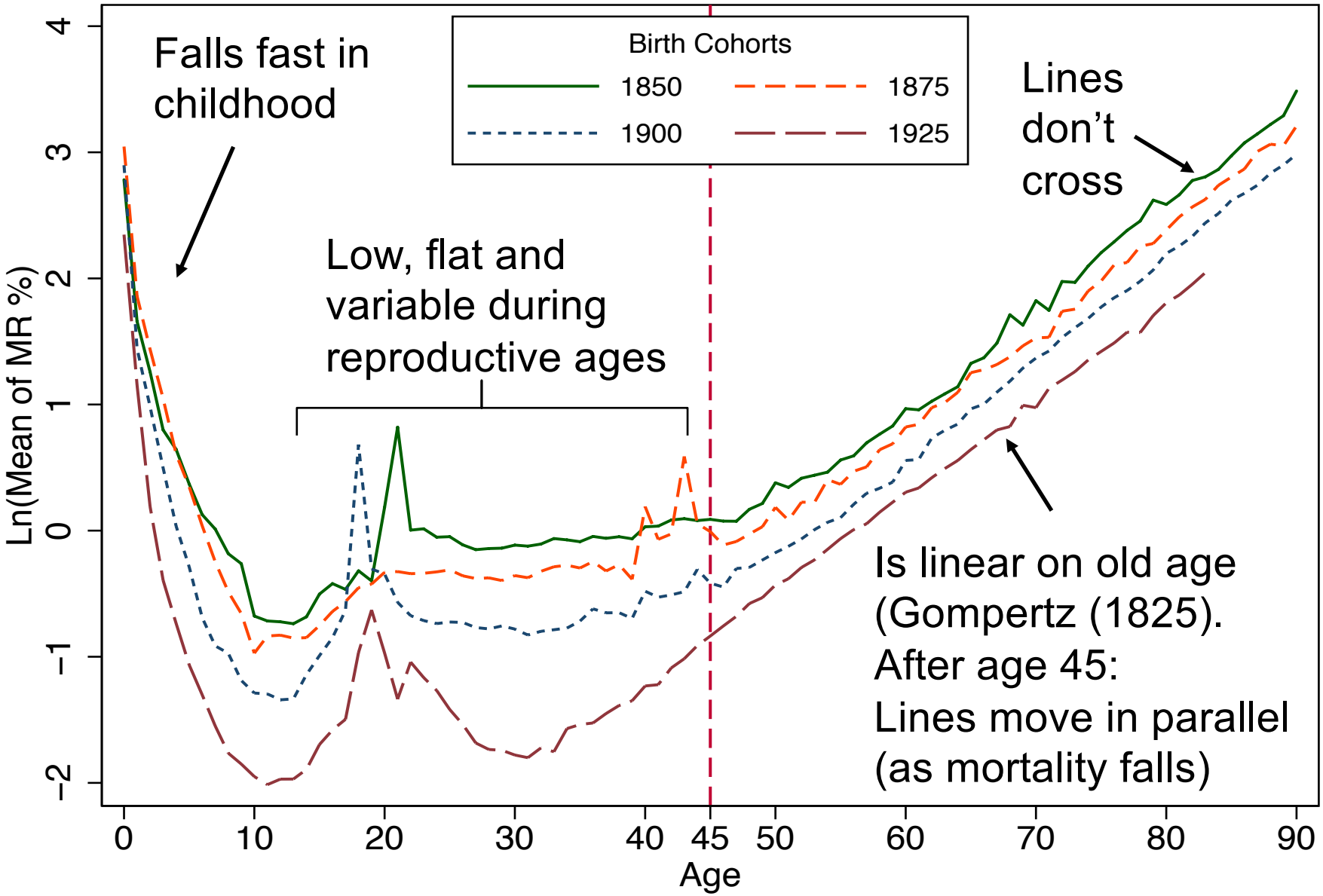
- **Investigate implications**
  - For economic decisions incorporating health and mortality
  - Interpret findings in empirical literature

Data: Human Mortality Database (HMD)

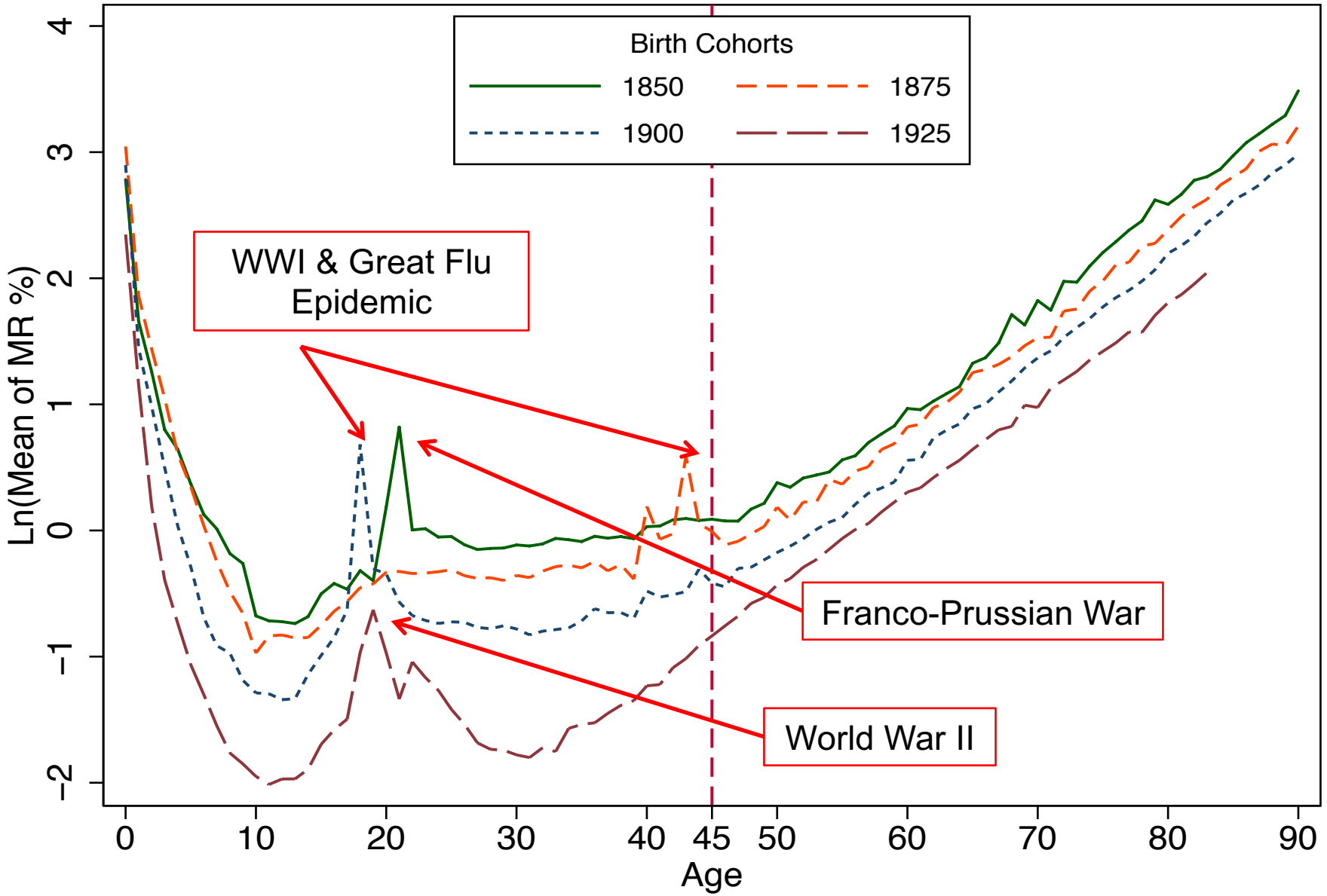
- Highest quality **cohort** life tables reporting mortality rates by year of birth, gender and age
- Use cohorts born 1860-1930 from 11 countries observed until 2010
  - Observe mortality from birth to age 90 (MR imputed after)

Country	Earliest fully observed birth cohort we use
Sweden	1860
France	1860
Denmark	1860
Iceland	1860
Belgium	1860
Norway	1860
Netherlands	1860
Italy	1872
Switzerland	1876
Finland	1878
Spain	1908
Australia	*1921*
Canada	*1921*
United Kingdom	*1922*

Log mortality is (almost) shaped like a check mark ✔



“External factors” matter most in reproductive ages



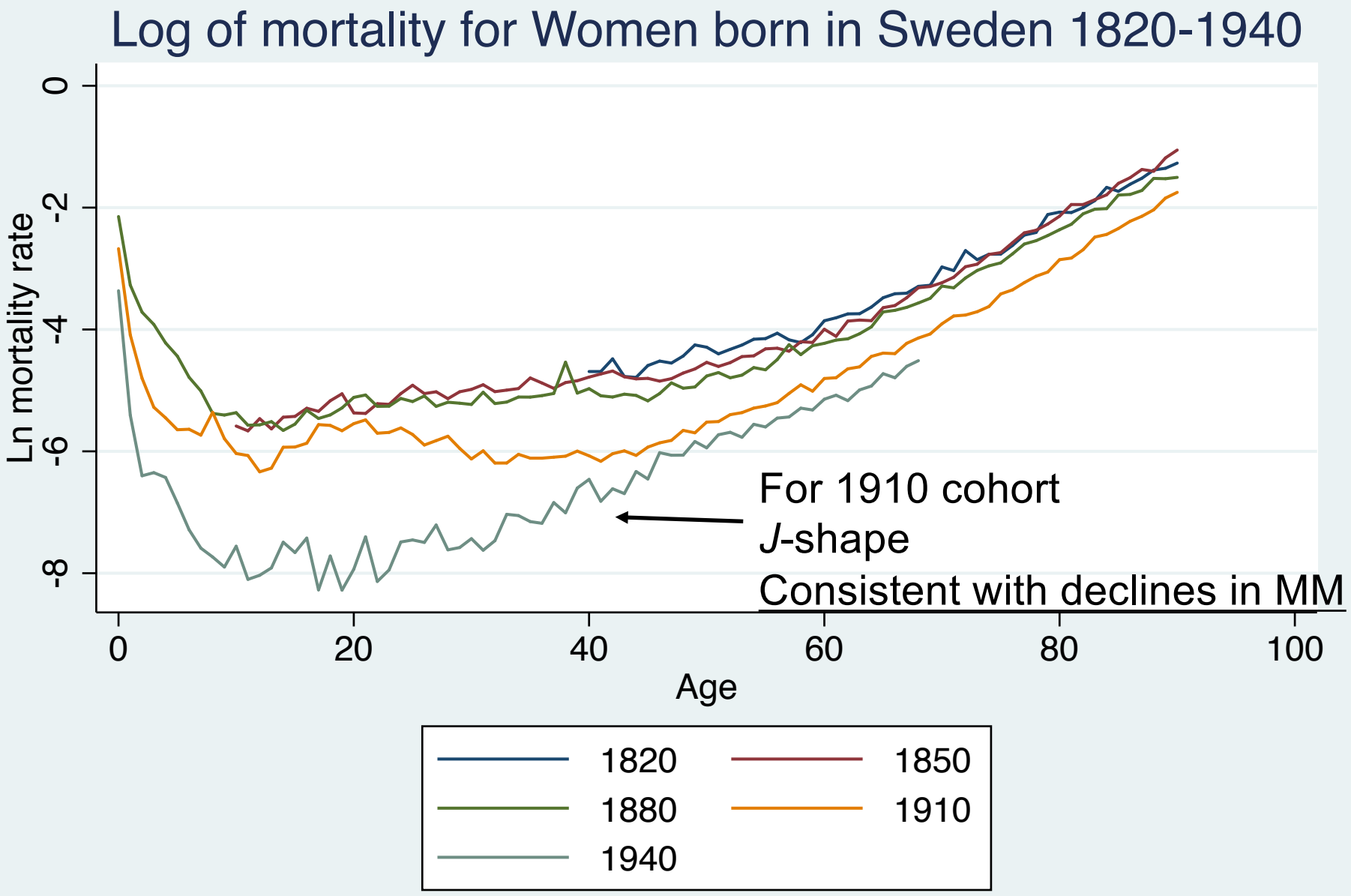
Weighted to a world population using samples present in that year.

Previous literature

- **Search for a unified model of mortality**: focus on modeling hazard rates
  - Gompertz (1825): log-linearity after age 40
  - Non-monotonic hazard: avoid by using Cox proportional hazard
  - Best parametric fit to date: Heligman and Pollard (1980)
- **Parametric approach here: model & estimate evolution of health consistent with shape of mortality**
  - Related to recent models of vitality models Li and Anderson (2013)
  - Grossman (1972) or Case & Deaton (2005): here add shocks
  - Heckman and Cuhna (2007): stochastic, applied to health/mortality
  - Make the stock a function of initial frailty as Vaupel et al (1979) but dynamic
  - Shocks shift distribution (Bozzoli et al, 2009; Bruckner et al. 2007) but every period.
- **Model biological processes & add shock to account for "Bump"**
  - Intuition from Carnes et al: eliminate "external" causes during reproductive ages

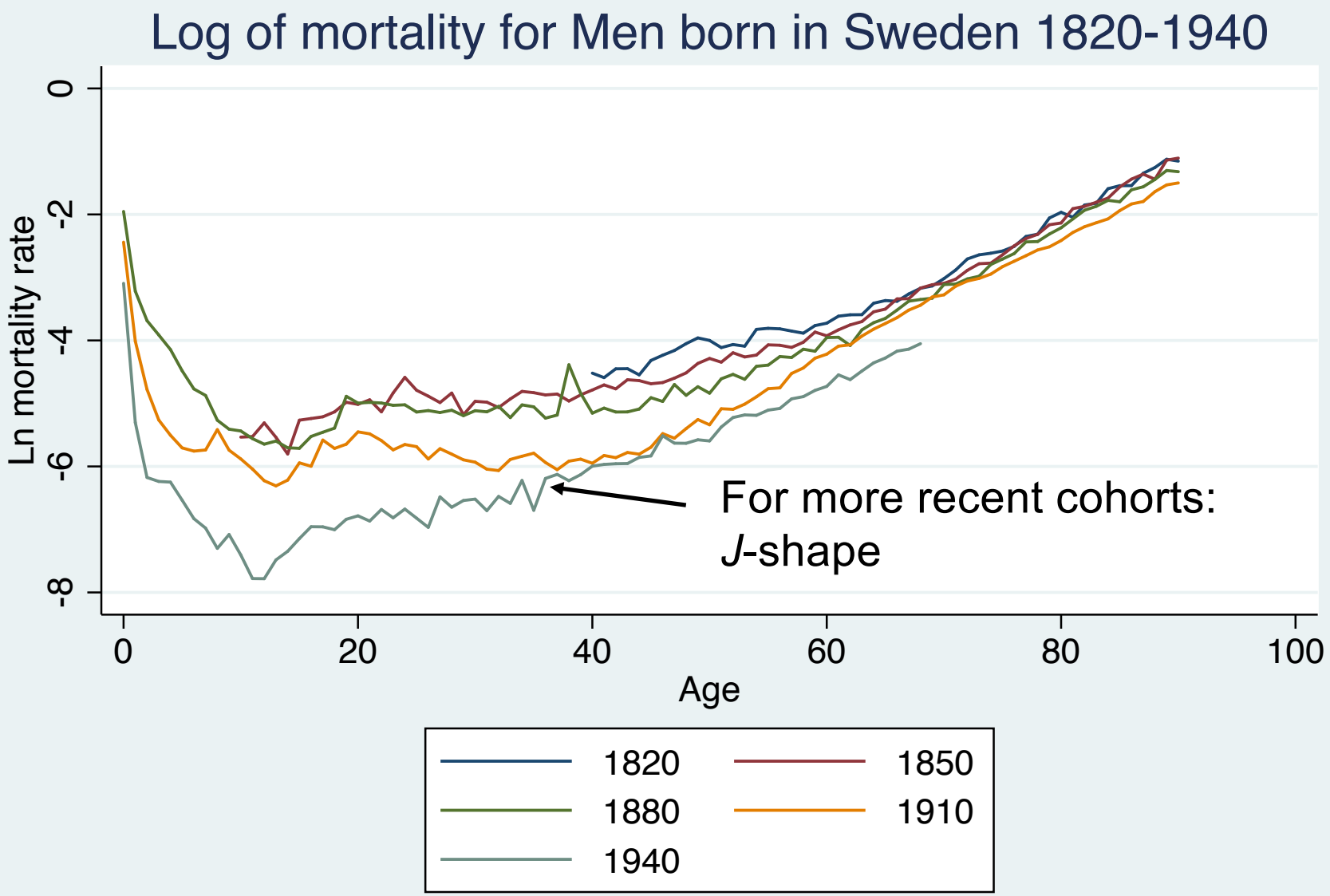
A MODEL OF “NATURAL” MORTALITY

What would female mortality look like without maternal mortality?



Data: Human Mortality Database

Similar for males as violence and accidents decline



Data: Human Mortality Database

A dynamic model of health

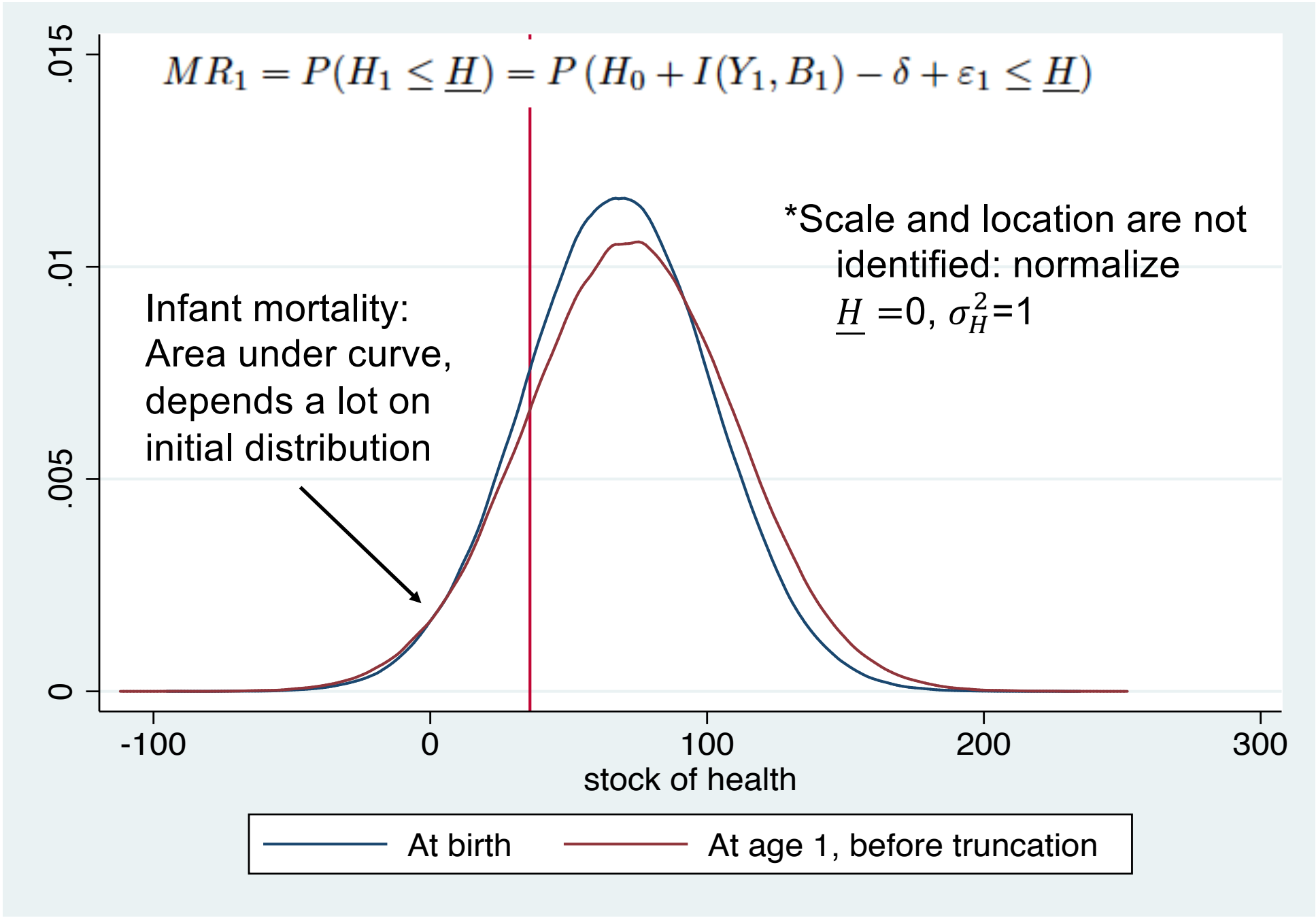
$$H_0 \sim N(\mu_H, \sigma_H^2)$$

$$H_t = H_{t-1} + I(Y_t, B_t) - \delta t^{\propto} + \varepsilon_t \qquad \varepsilon_t \sim i.i.d.N(0, \sigma_\varepsilon^2)$$

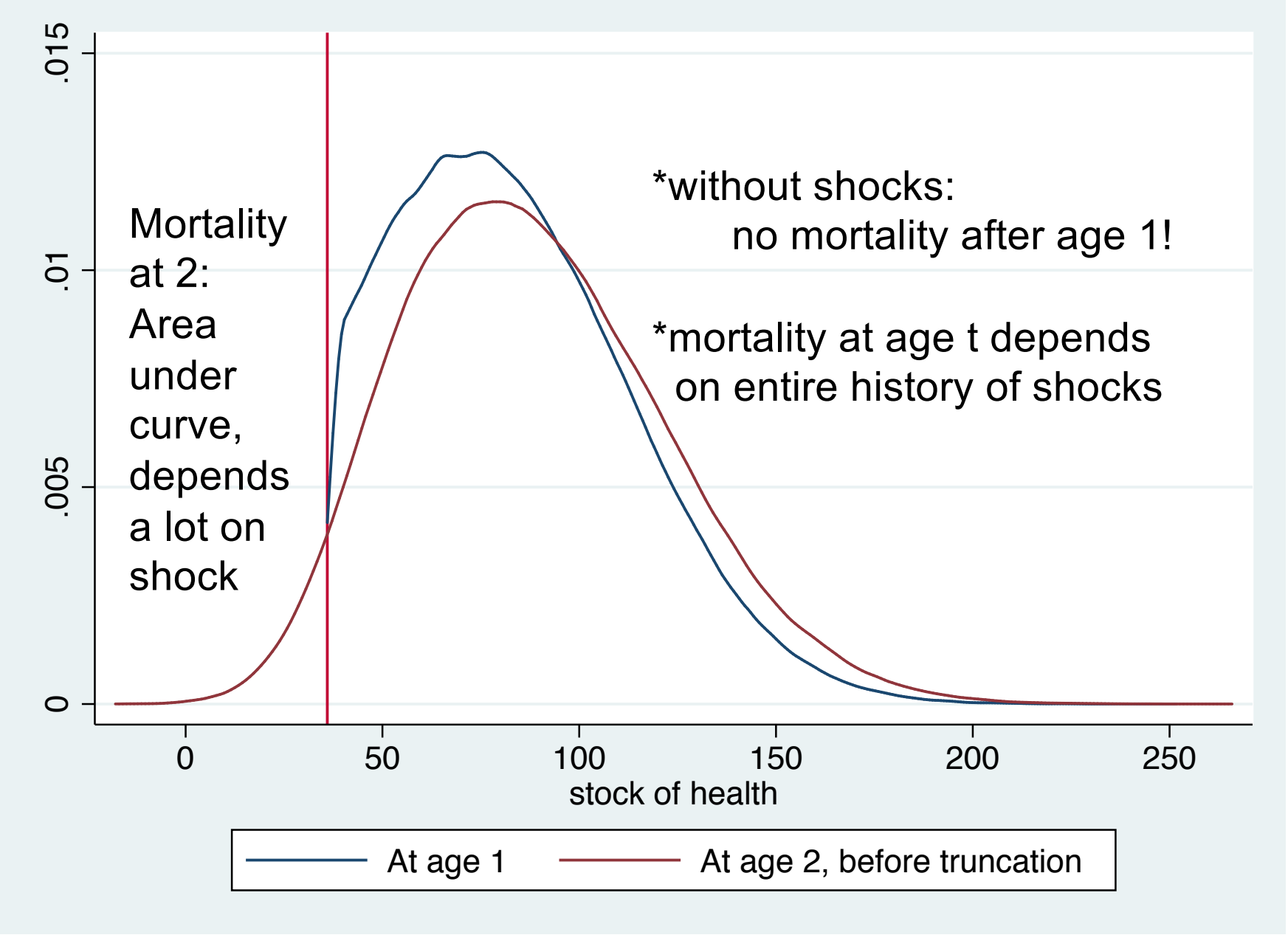
Die when $H_t < \underline{H}$

- **Initial conditions $\boldsymbol{\mu_H}$**: distance from death threshold at birth
- **Environment determines**
  - **Resources I**: Average annual investment. Can be zero. Can be affected by inputs like food *(Y)* and pollution *(B)*
  - **shocks $\boldsymbol{\sigma_\varepsilon^2}$**: random shock (rain drought, disease) hits individuals independently of their health, but is more likely to kill those with large unlucky shocks or who start with poor levels of health. Cannot be zero.
- **Aging $(\propto, \boldsymbol{\delta})$:** cannot be zero, cannot be constant over time.

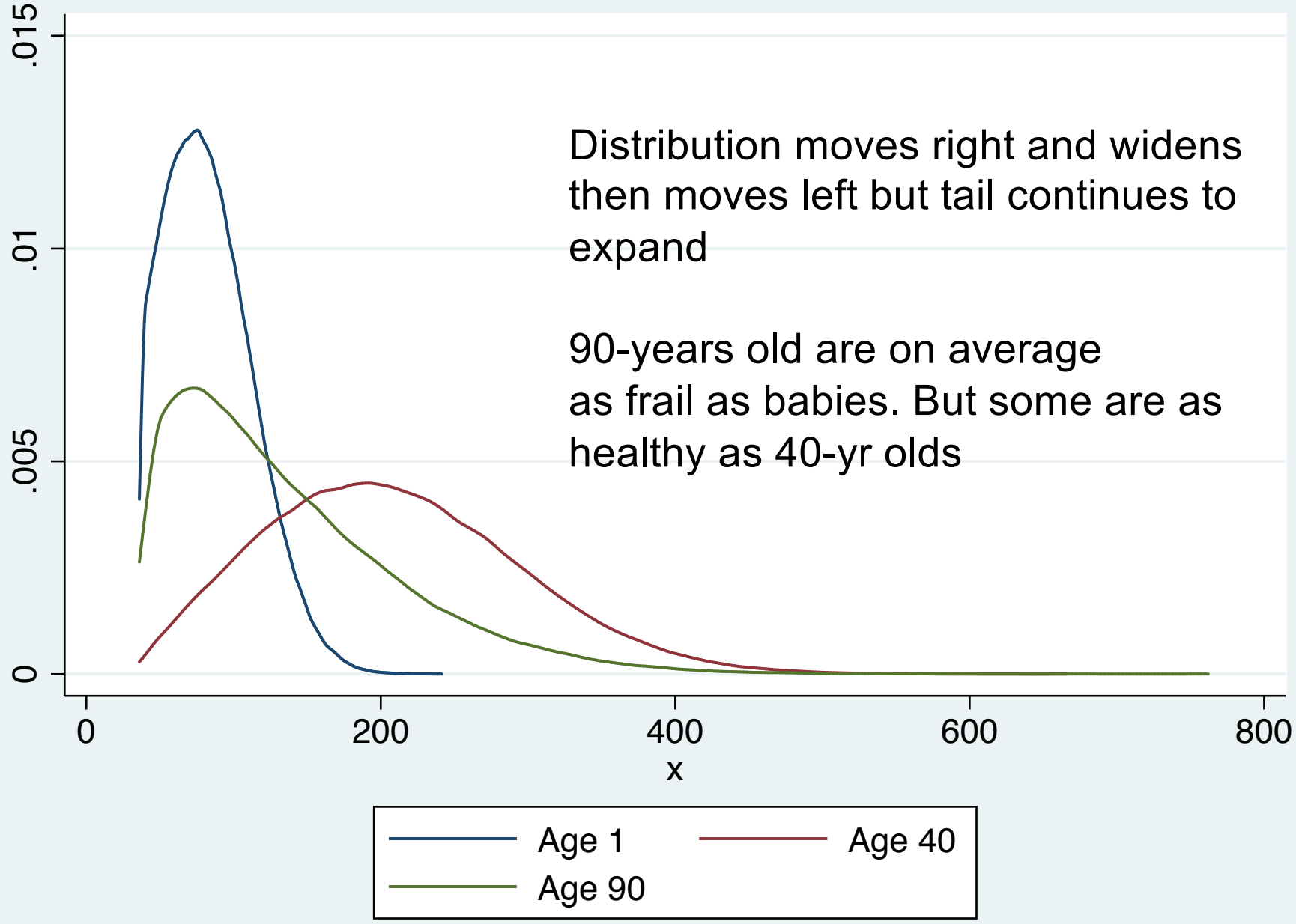
How is mortality determined?



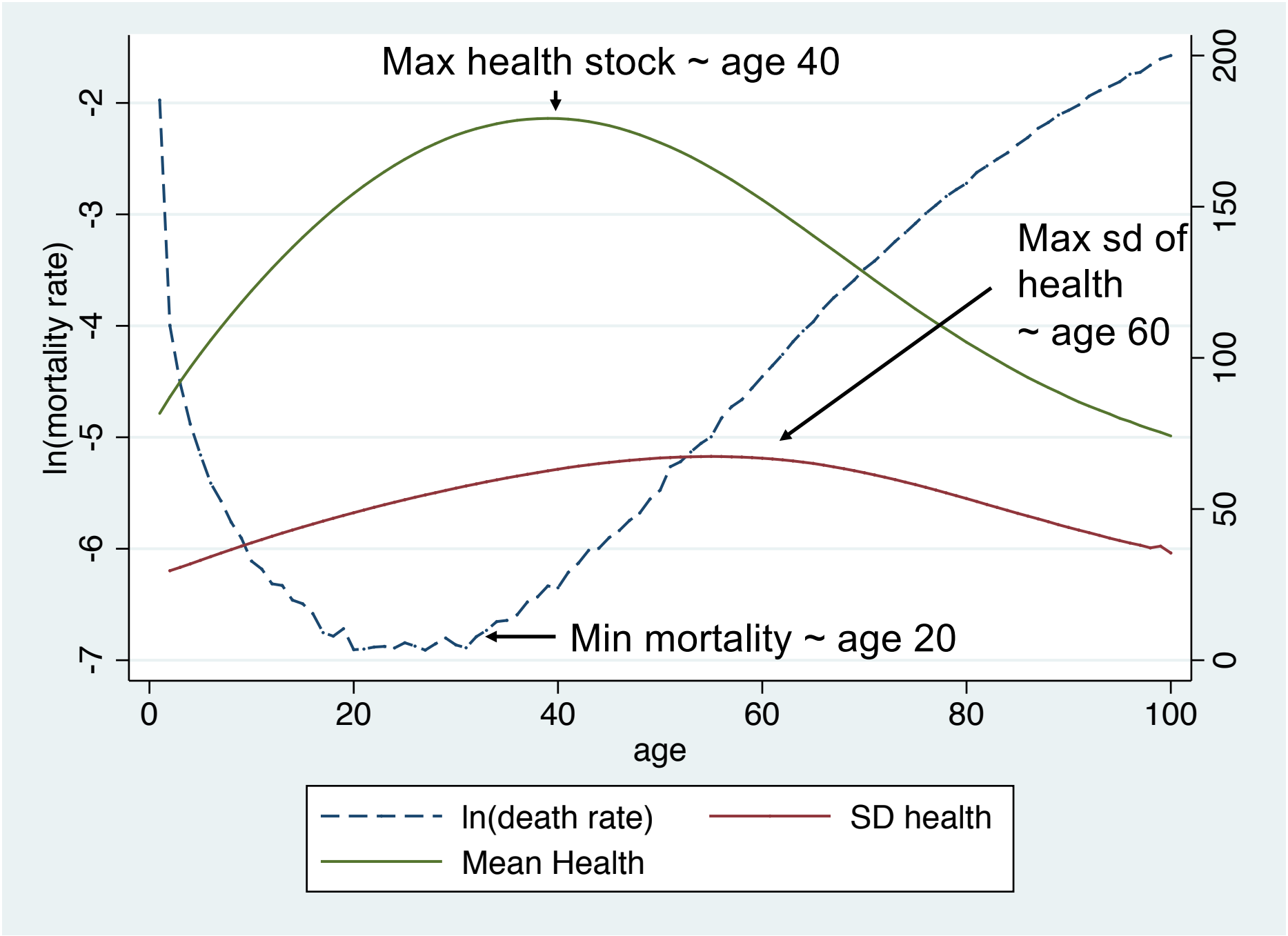
How is mortality determined? (cont'ed)



Evolution of health stock over the ages

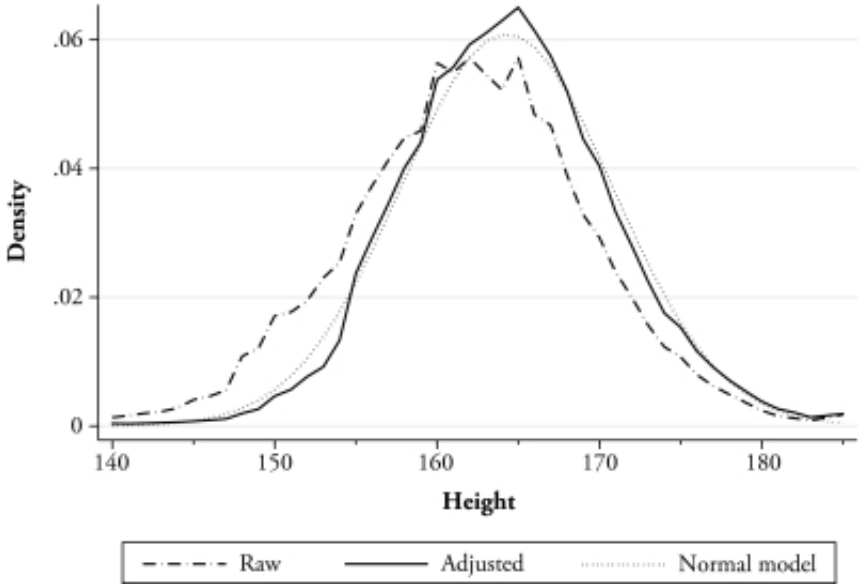


Simulated evolution of mortality and average stock



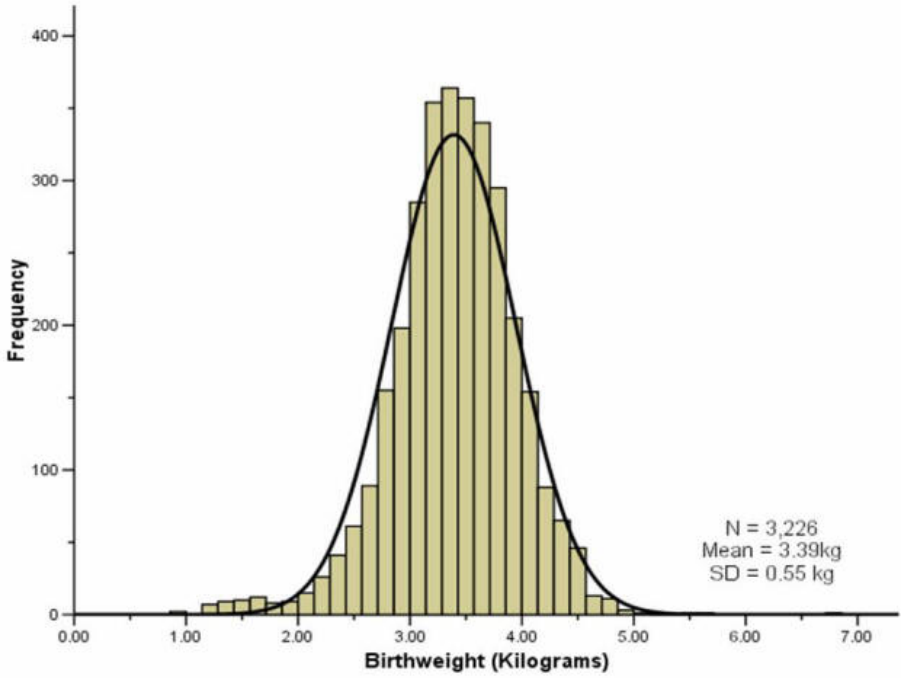
Despite truncation: H close to normal at most ages!

Heights among conscripts in Italy



https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2831262/

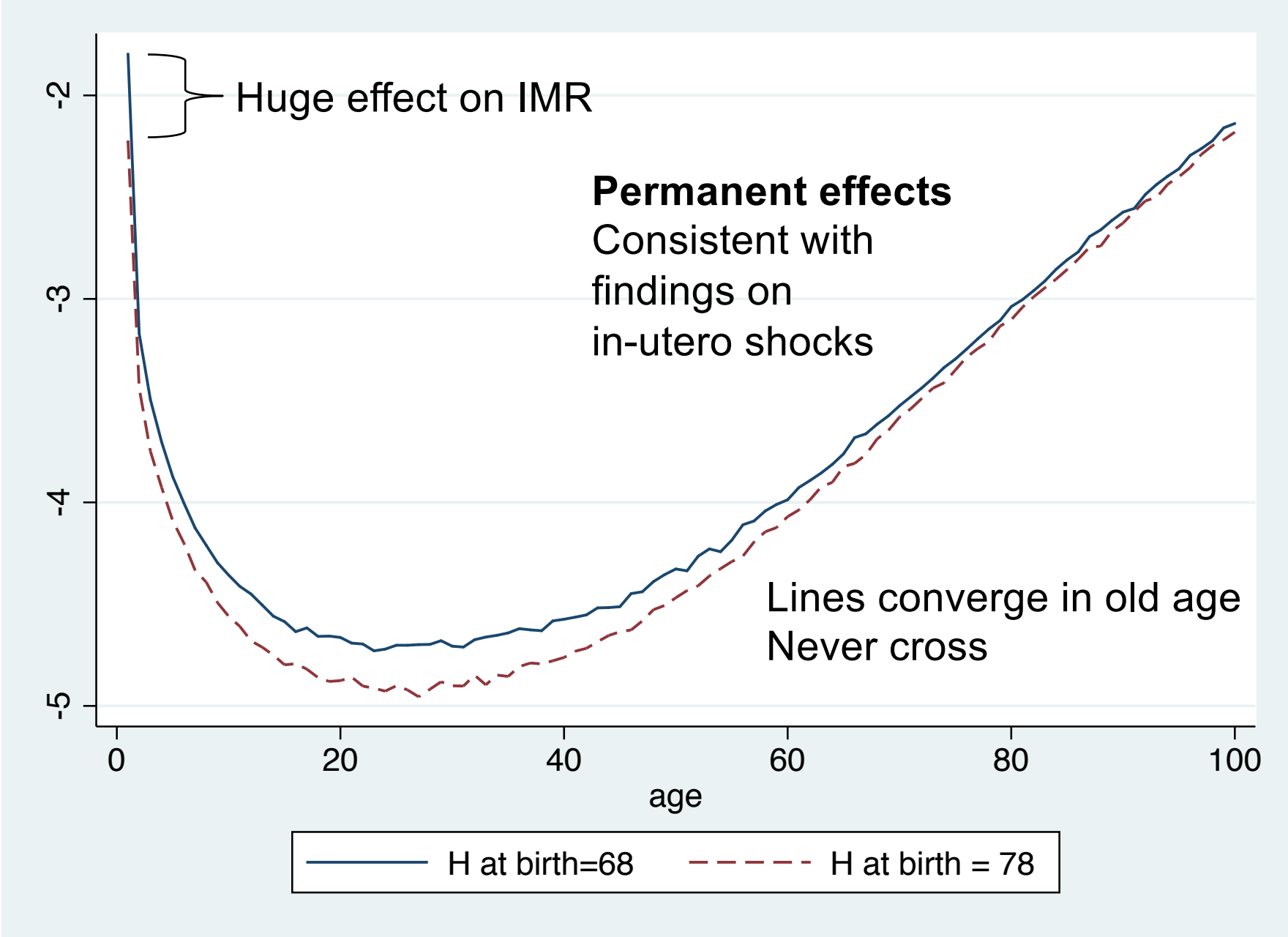
Birthweights US



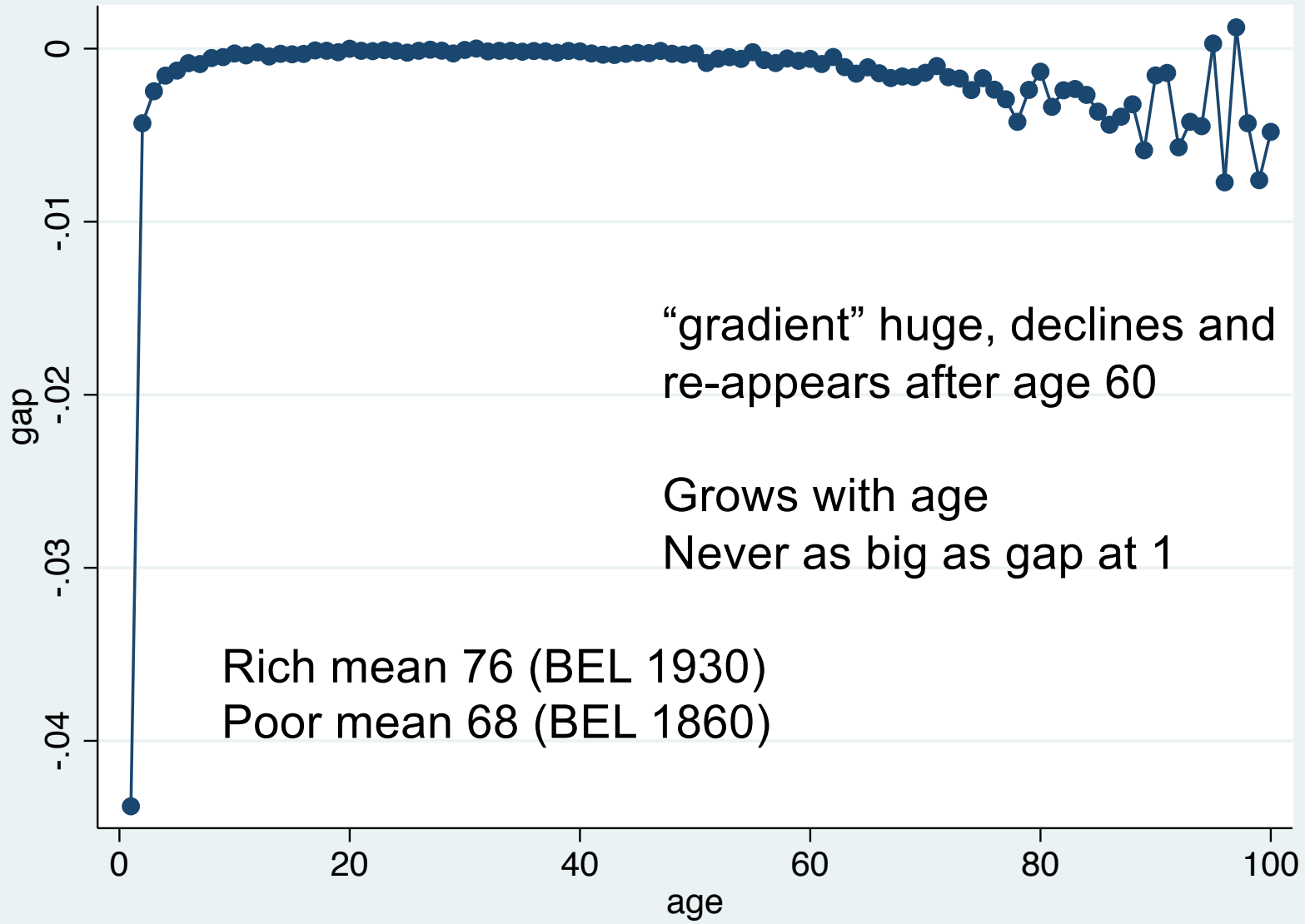
O' Cathain et al 2002)

COMPARATIVE STATICS (IDENTIFICATION)

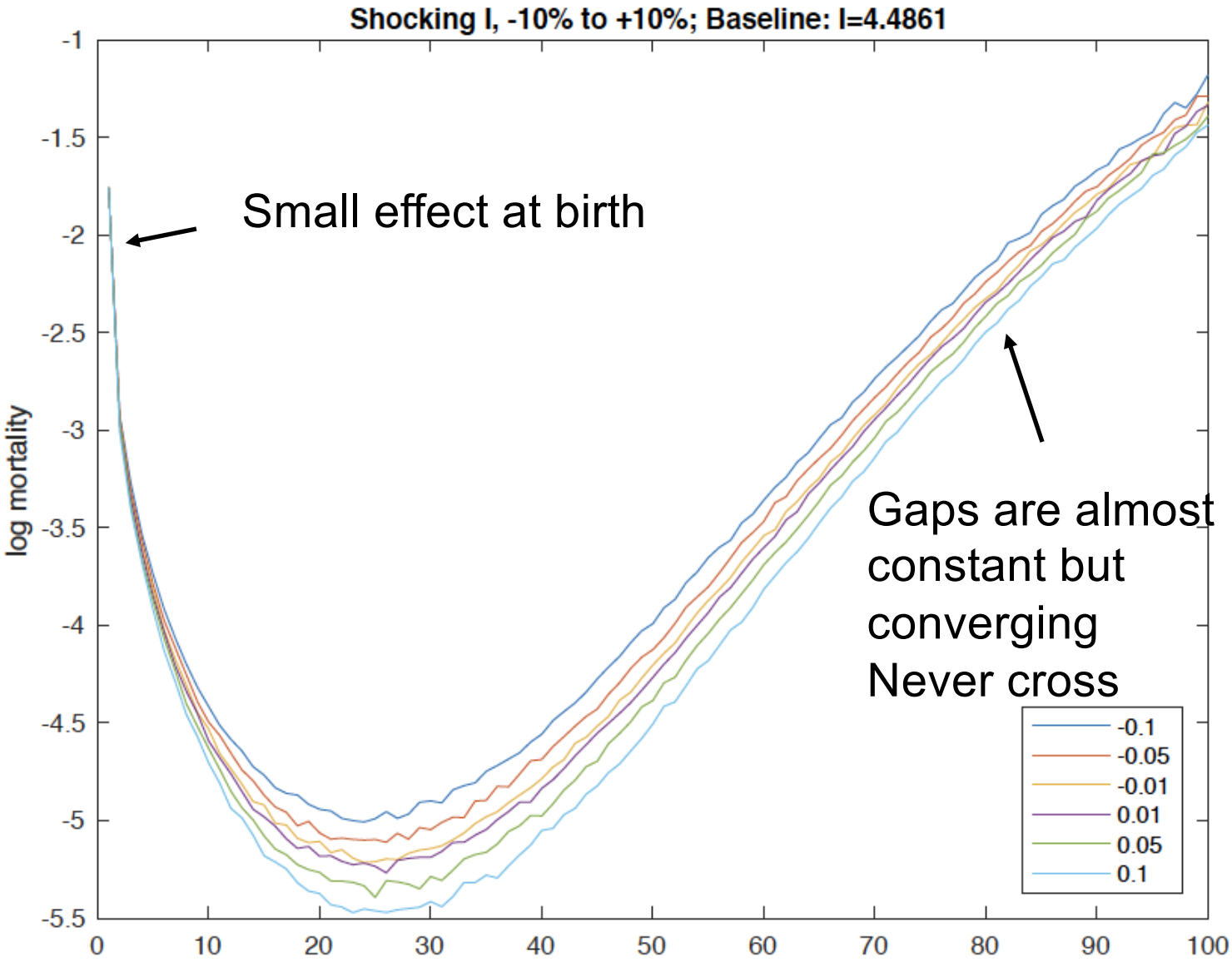
Changing initial conditions: effect in logs



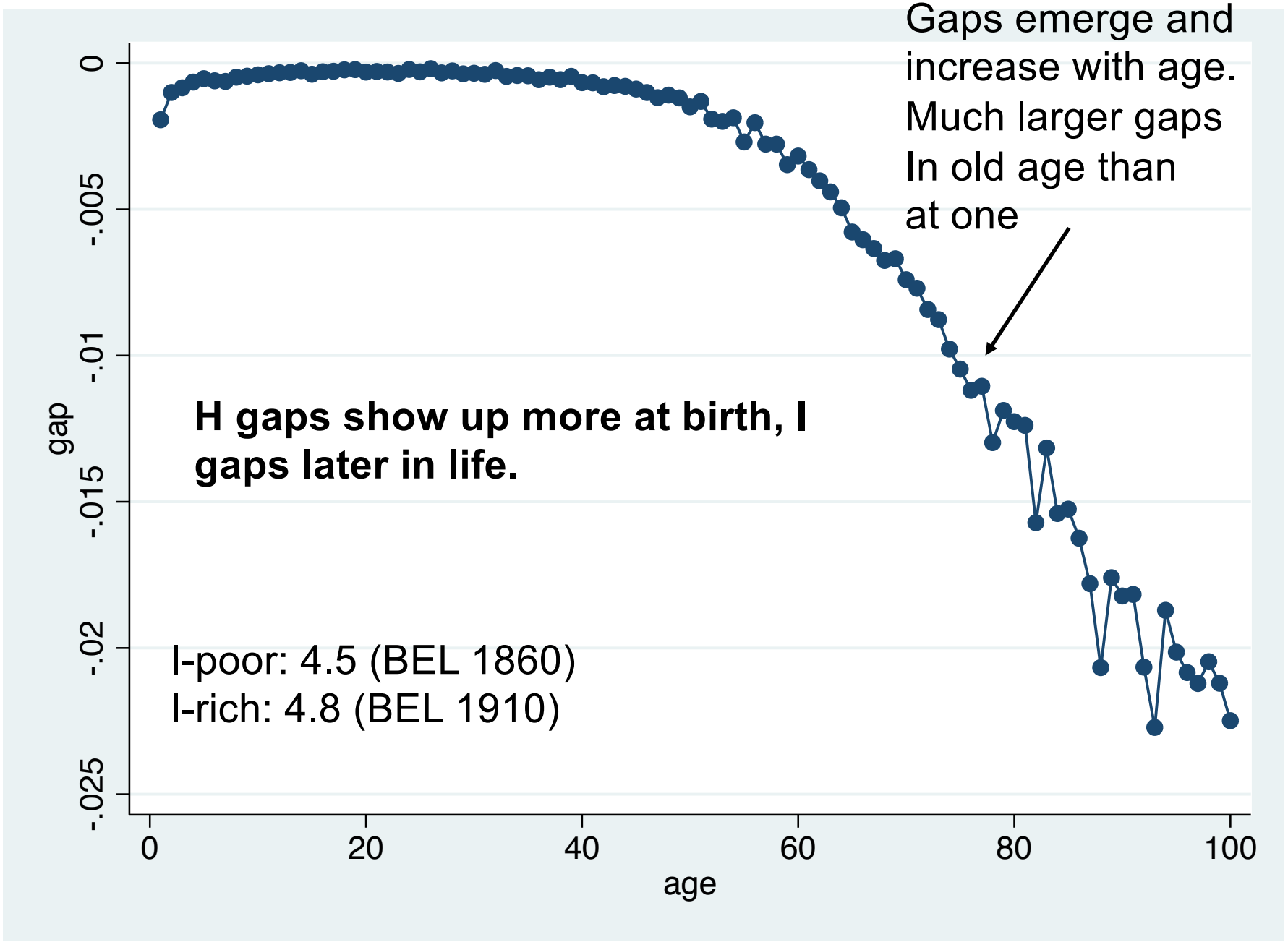
Gaps in mortality rates between H_0-rich and H_0-poor



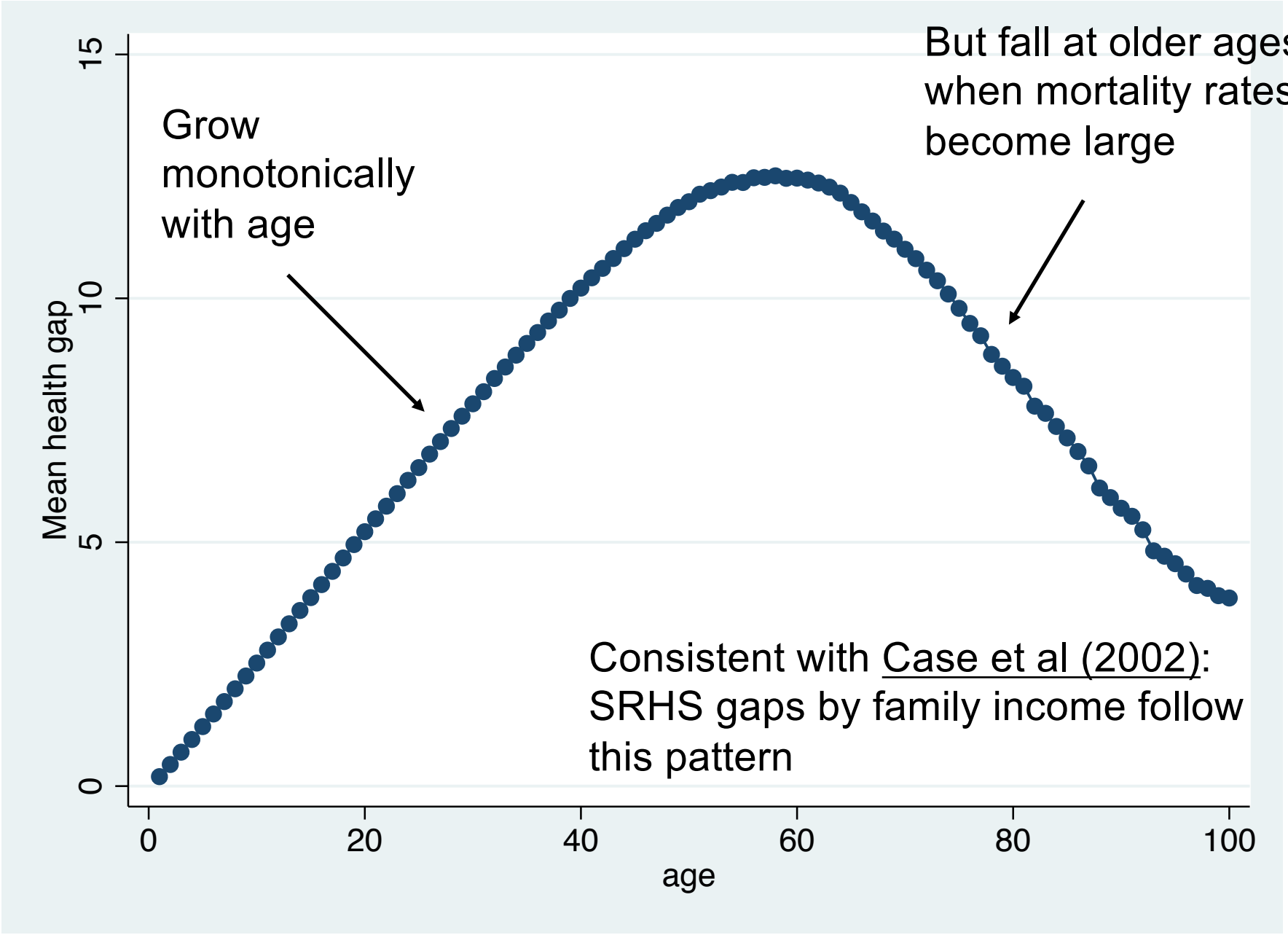
Changing Annual Investment: effect in logs



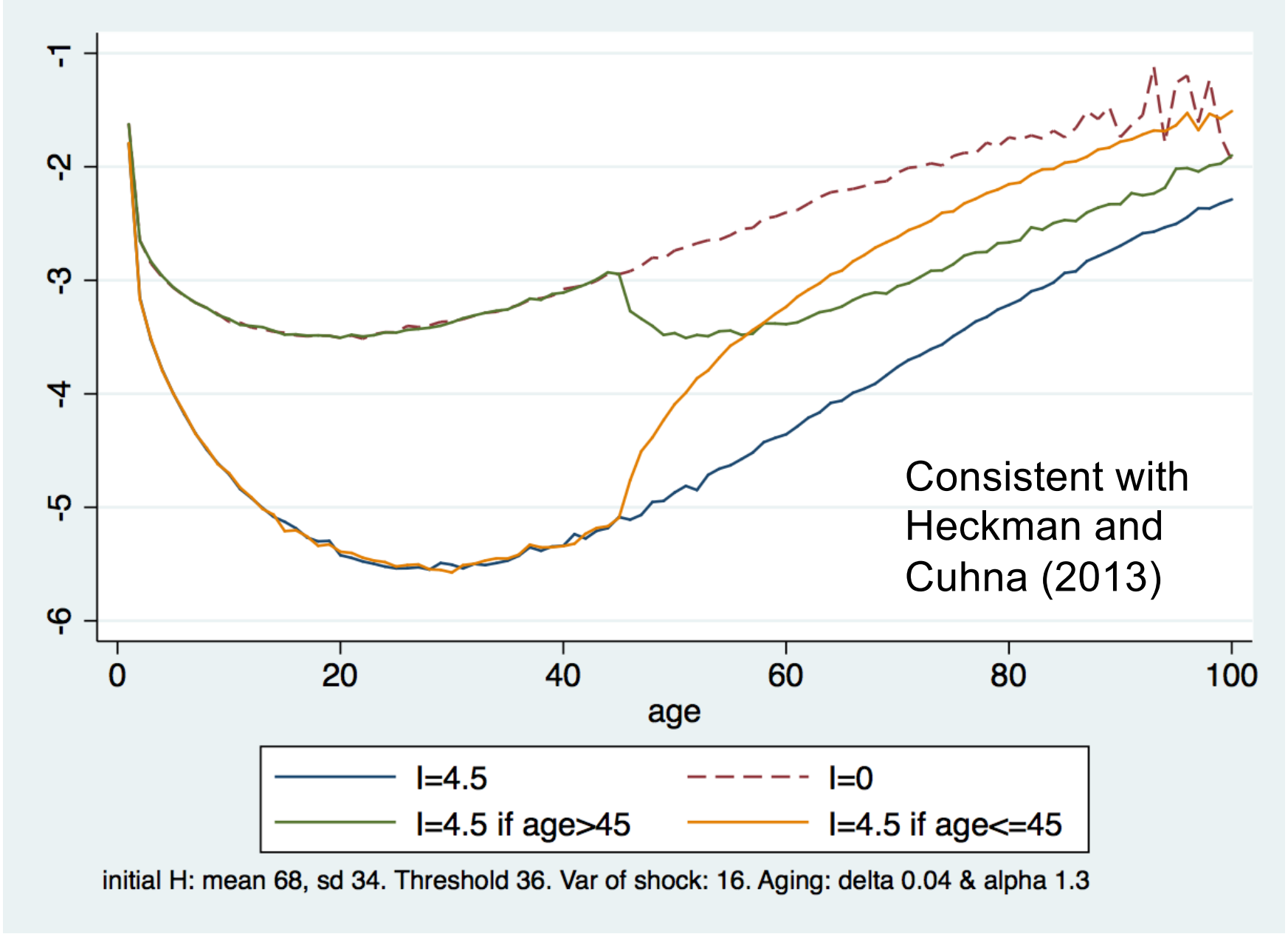
Gaps in mortality rates between I-rich and I-poor



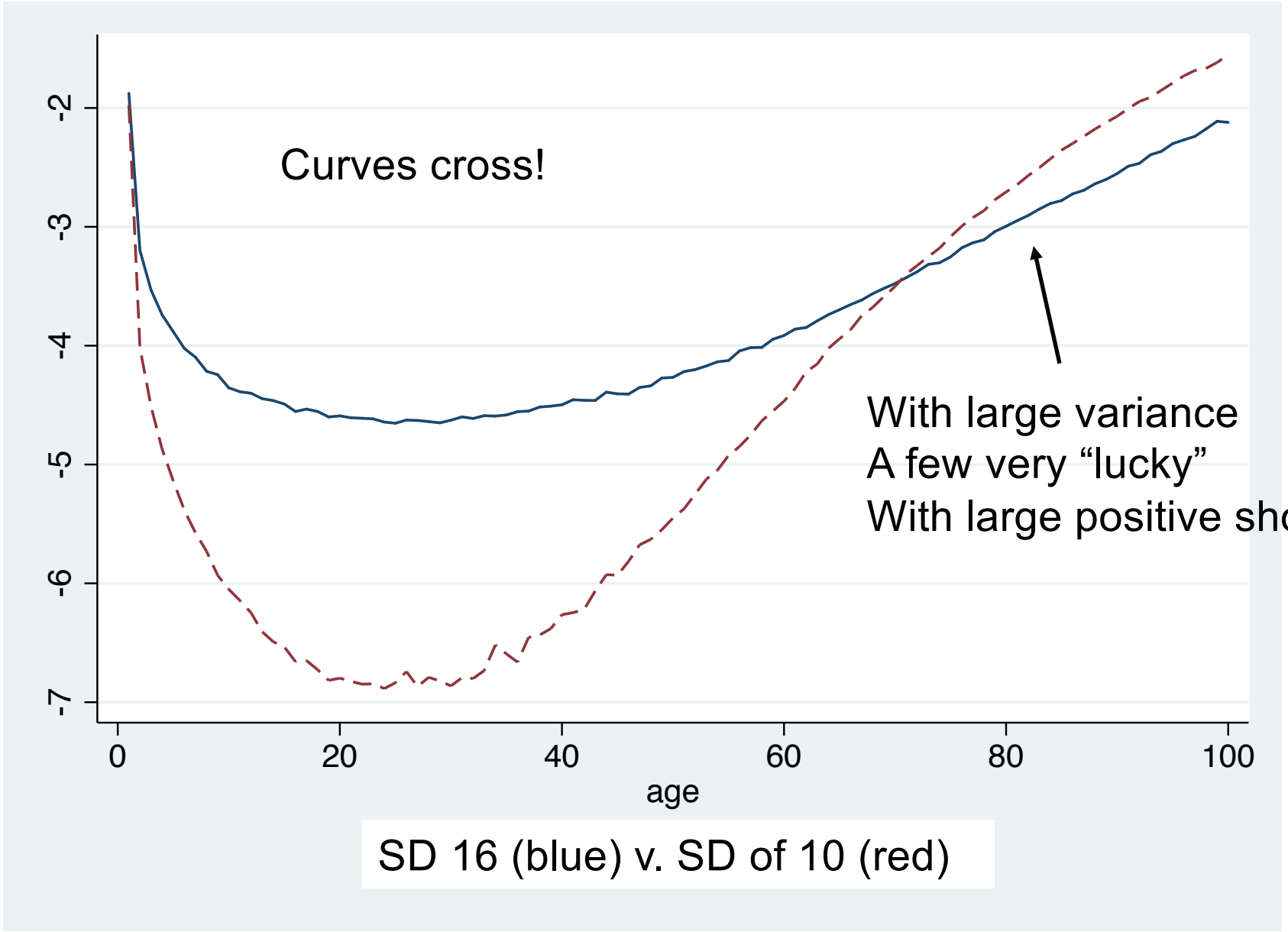
Health gaps among living between I-rich and I-poor



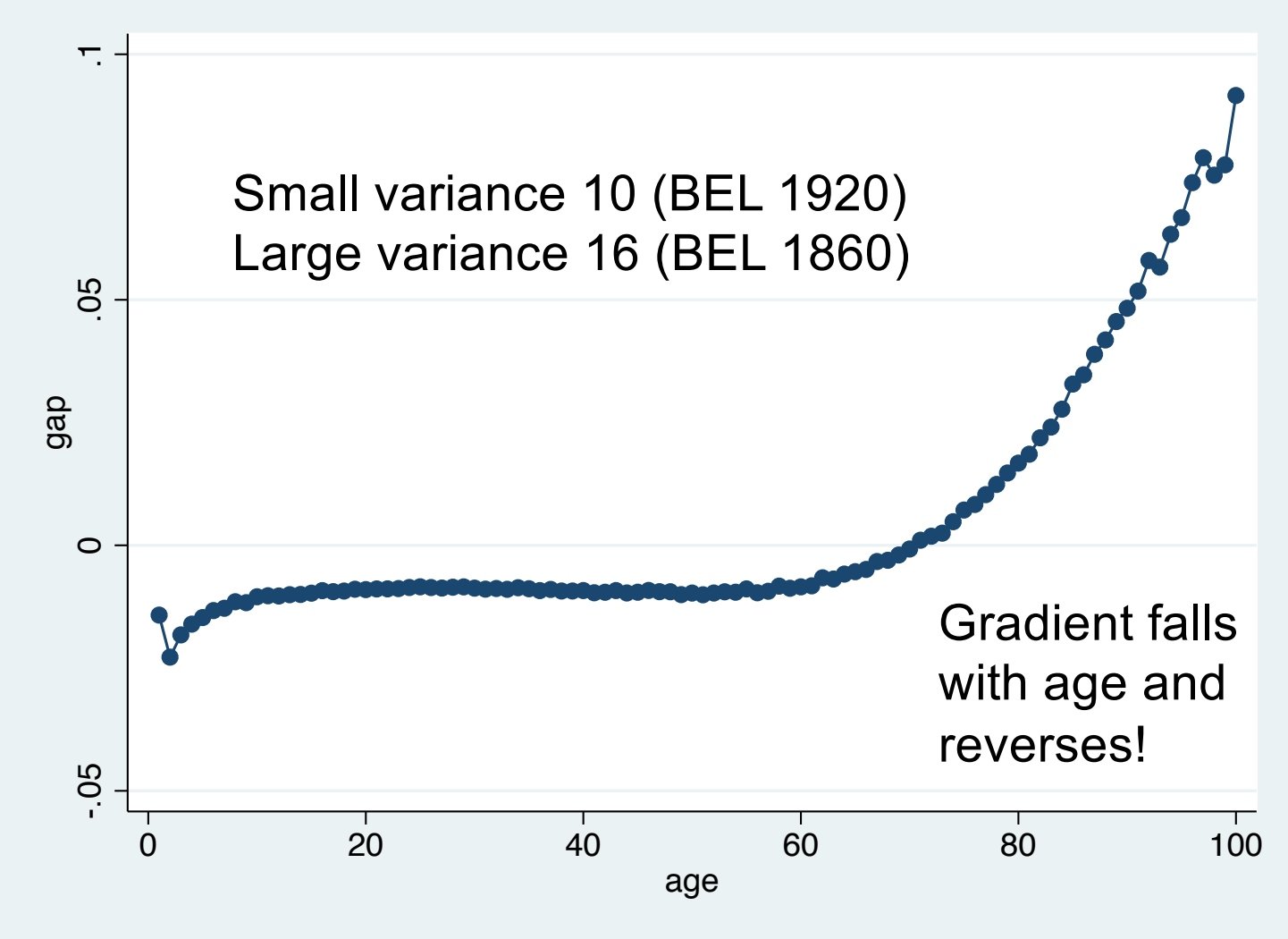
Investments over the lifetime are complementary



Changing standard deviation of disease shock: "what doesn't kill you makes you stronger" effect

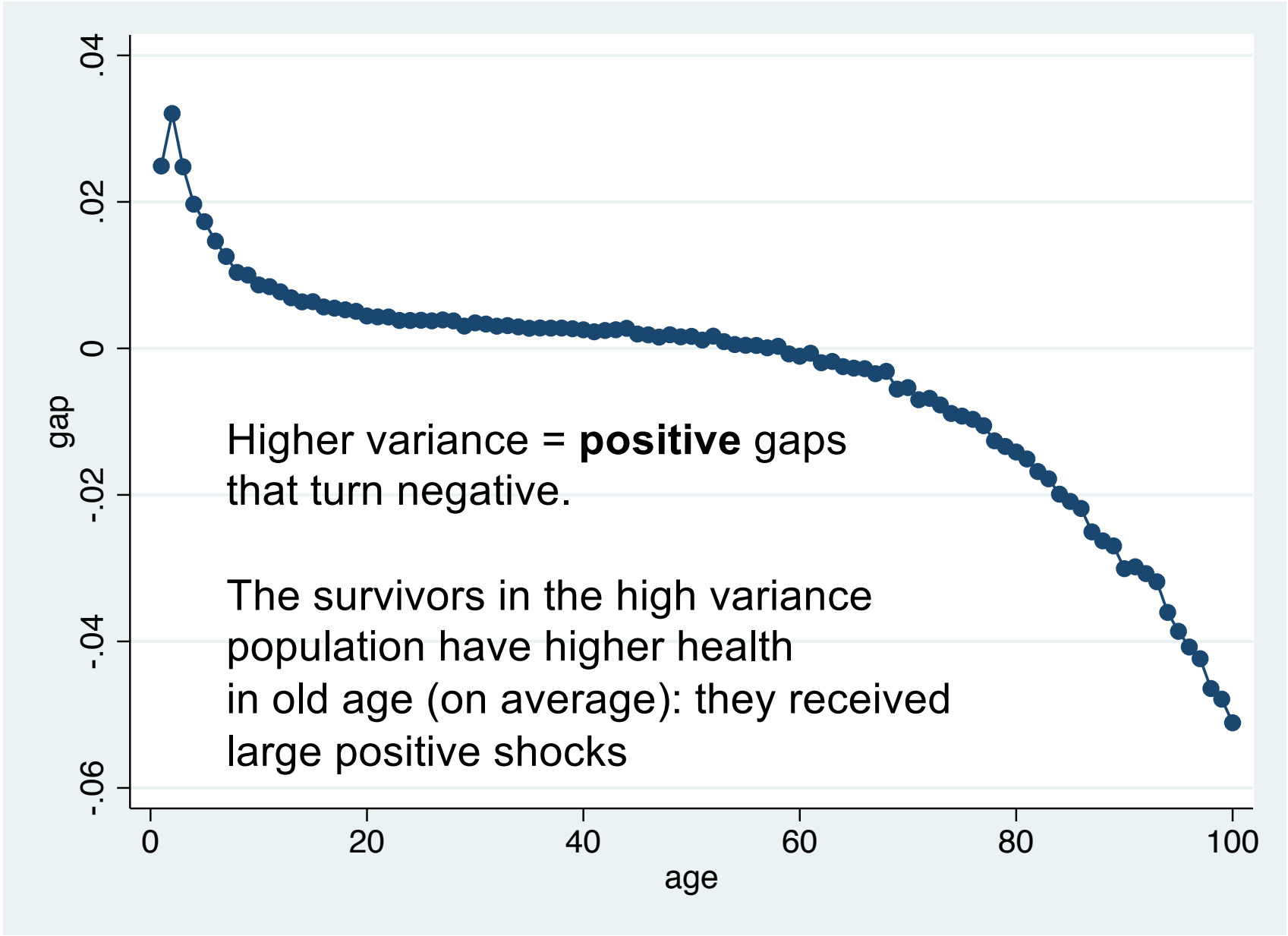


Mortality gap reverses

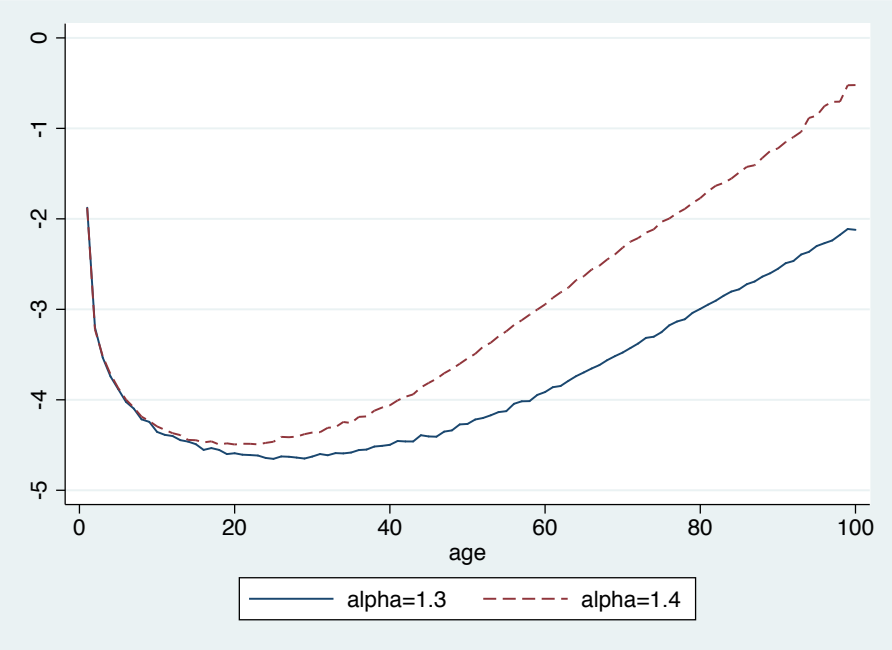


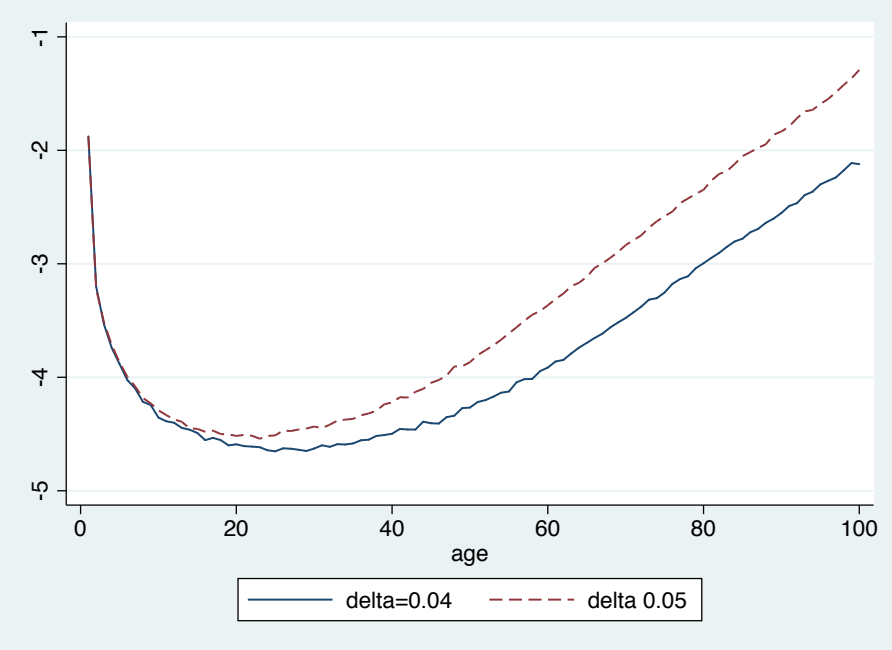
Similar to cross over for blacks relative to whites in US

health gaps for different variances: opposite pattern



Delta and alpha affect line after 40

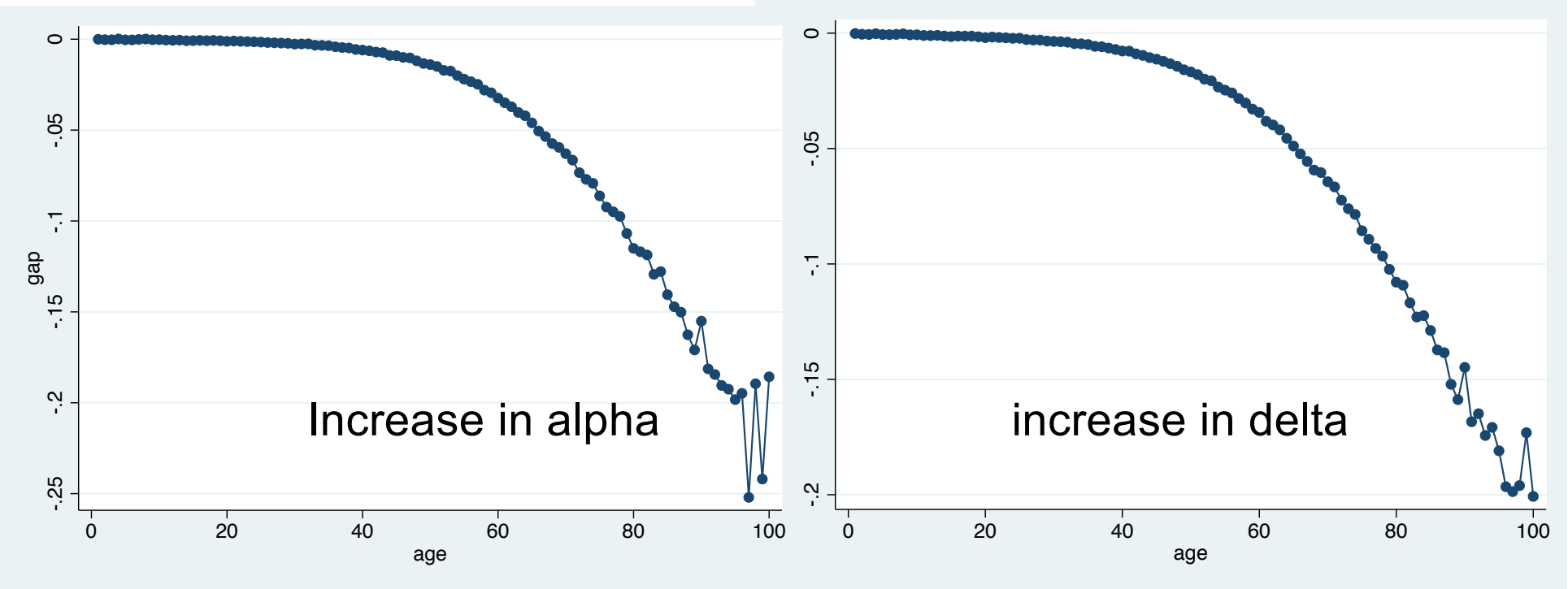




- Could we use only1 parameter to describe aging? No, they govern the starting point (intercept) and slope of aging

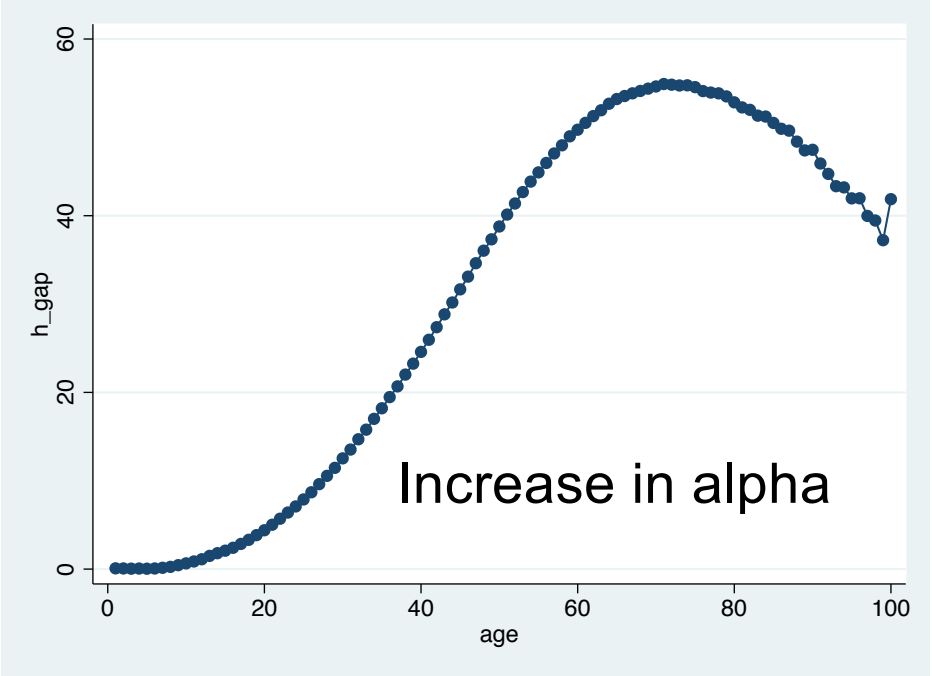
- These “dominate” mortality in old age but the slope in old age is a function of ALL the parameters in the model.

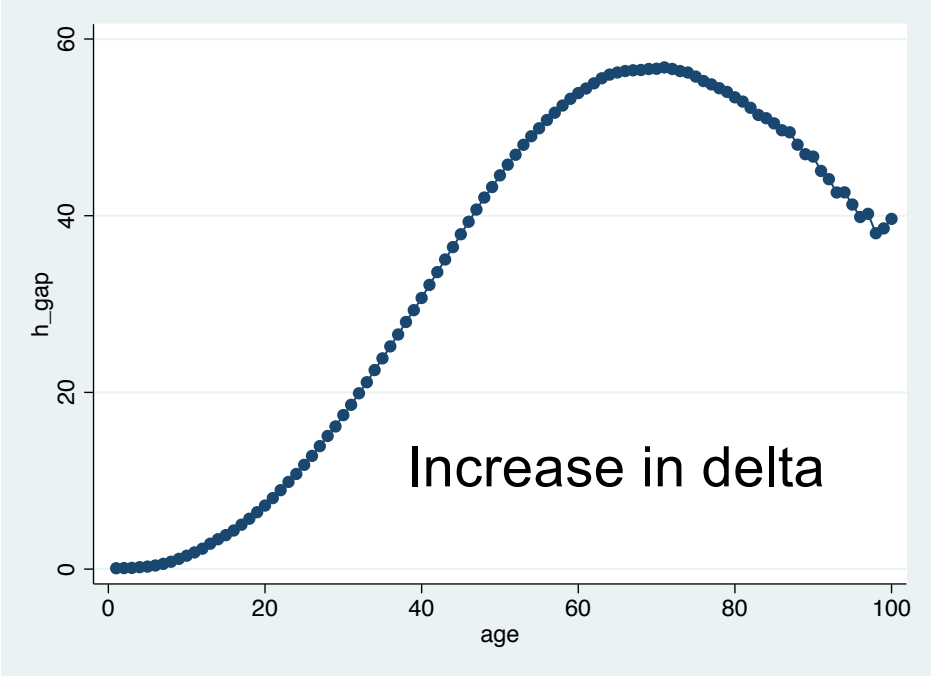
Gaps in mortality when aging parameters vary



Increase in either parameter results in gaps that
*are almost zero before age 45
*grow with age thereafter

Gaps in health when aging varies





Increase in either parameter results in gaps that grow and then fall with age.

Initial H_0, I and Aging parameter changes all have similar effects
They can only be separated by effects at younger ages
***H shows up a lot at birth**
***I shows throughout**
***aging only after 45**

Final comment: Selection forces are weak

- Selection effects never dominate, curves do not cross

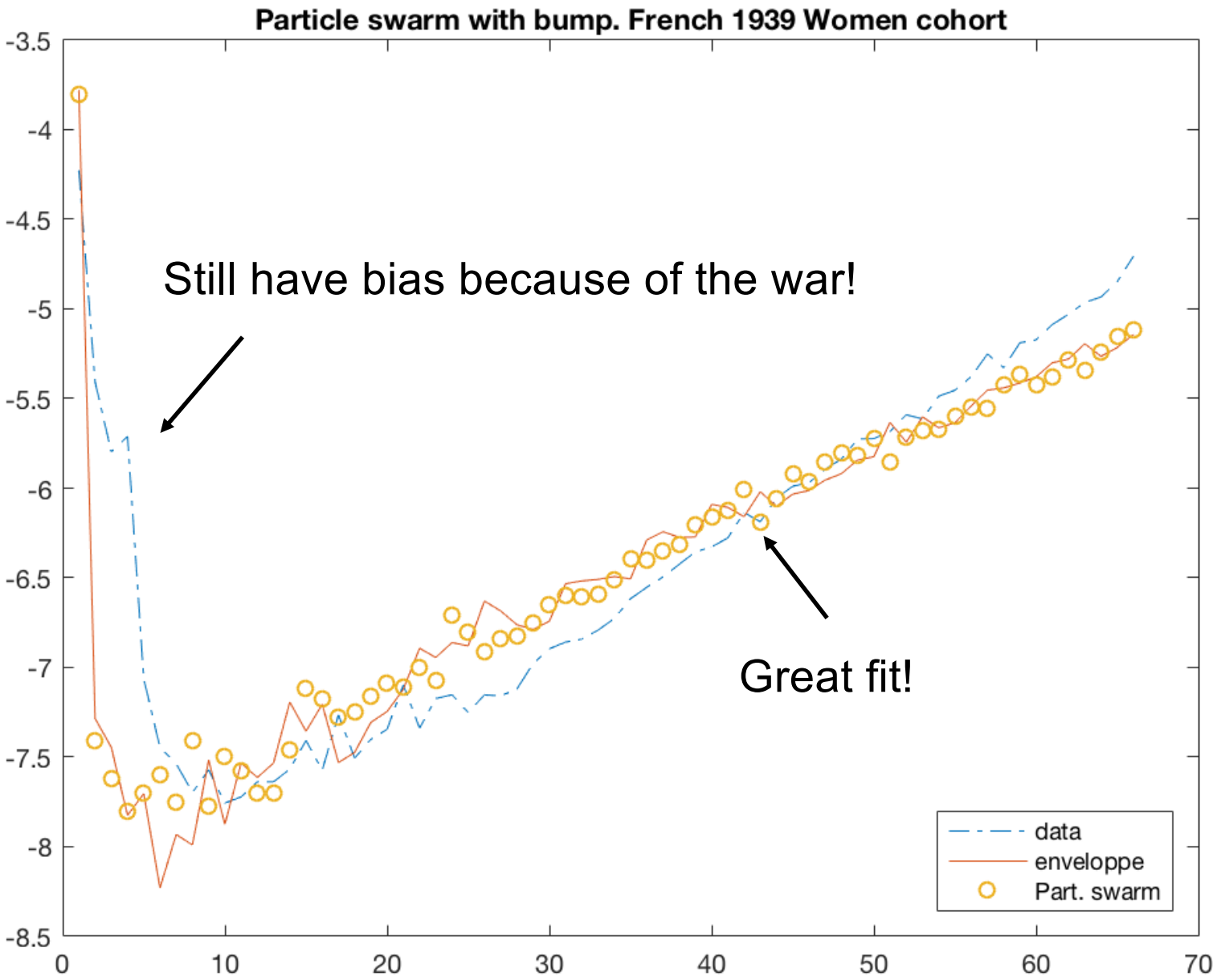
- For changes in SD they do, but not because of selection (trimming of weakest). Rather because some lucky individuals receive a sequences of large positive shocks.

ESTIMATION

Estimating parameters

- Use simulated method of moments
  - Find parameters that make simulated mortality closest to actual mortality
    - Specifically: Minimize sum of absolute errors in ln(MR)
    - Estimate using particle swarm (initial guess matters)
- Recover parameters for each cohort. Estimate for all cohorts
- Standard Errors: under construction.
  - Use bootstrap
  - Preliminary results: very small se (because we have population data)

Does the model fit? A cohort without a bump



HOW TO ACCOUNT FOR MORTALITY DURING REPRODUCTIVE AGES?

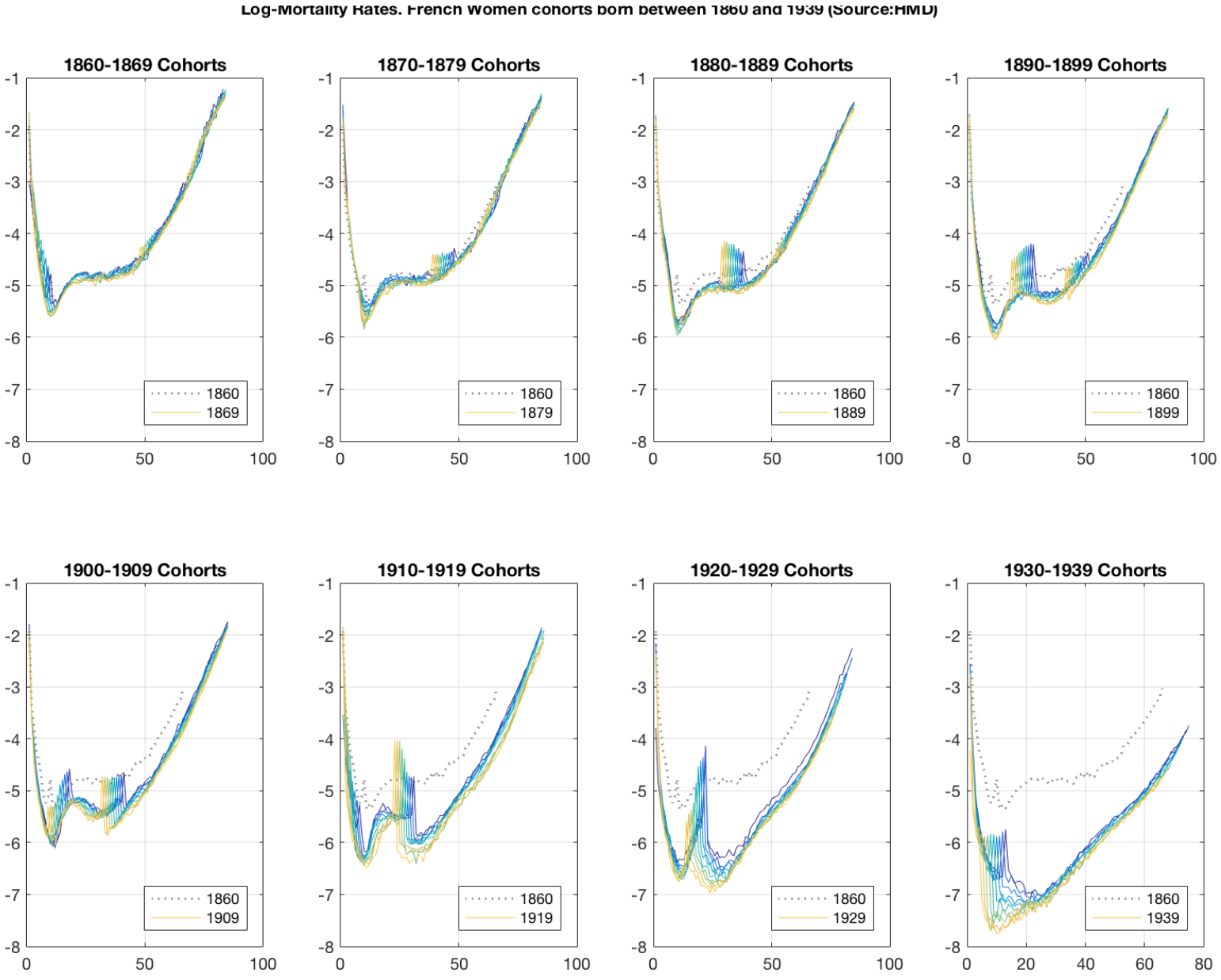
What are the main causes of death 15-45?

- **Men**: Injury (War, violent deaths and accidents).
  - (Mostly) Unrelated to health, income?
  - In peace times greatly influenced by by alcohol consumption & vehicle use (normal goods), gun availability, violence (related to SES)
  - War might or might not kill on the basis of H

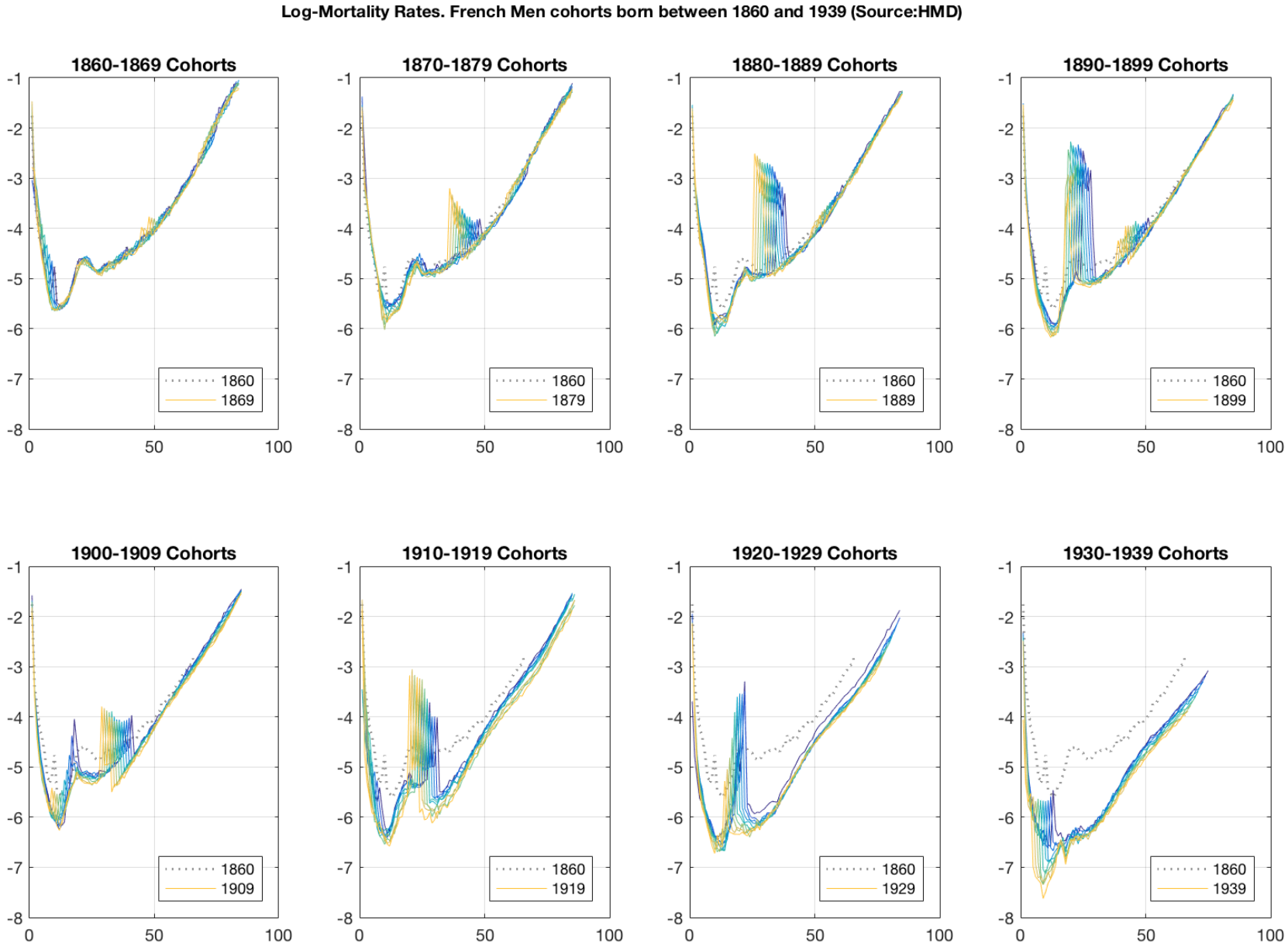
- **Women**: Maternal Mortality
  - Sepsis (puerperal fever) main cause ~40%, hemorrhage second.
  - SES & nutrition play small role relative to hygiene and "intervention" not H
    - Historical evidence Loudon (2000).
    - Complications at birth very difficult to predict

- **Generic model likely will fail:**
  - Timing and deadliness of war by age vary over time and place
  - MM a function of fertility rates and conditions at birth

Examining bumps for French women



Examining bumps for French men



Adding External Causes to the model

Four possibilities that involve ONE more parameter

1. **I-shock**: Lower I during reproductive ages
   - $H_t = H_{t-1} + I(Y_t, B_t) - \kappa * D(= 1\ if\ 15 < t < 45) - \delta t^{\propto} + \varepsilon_t$

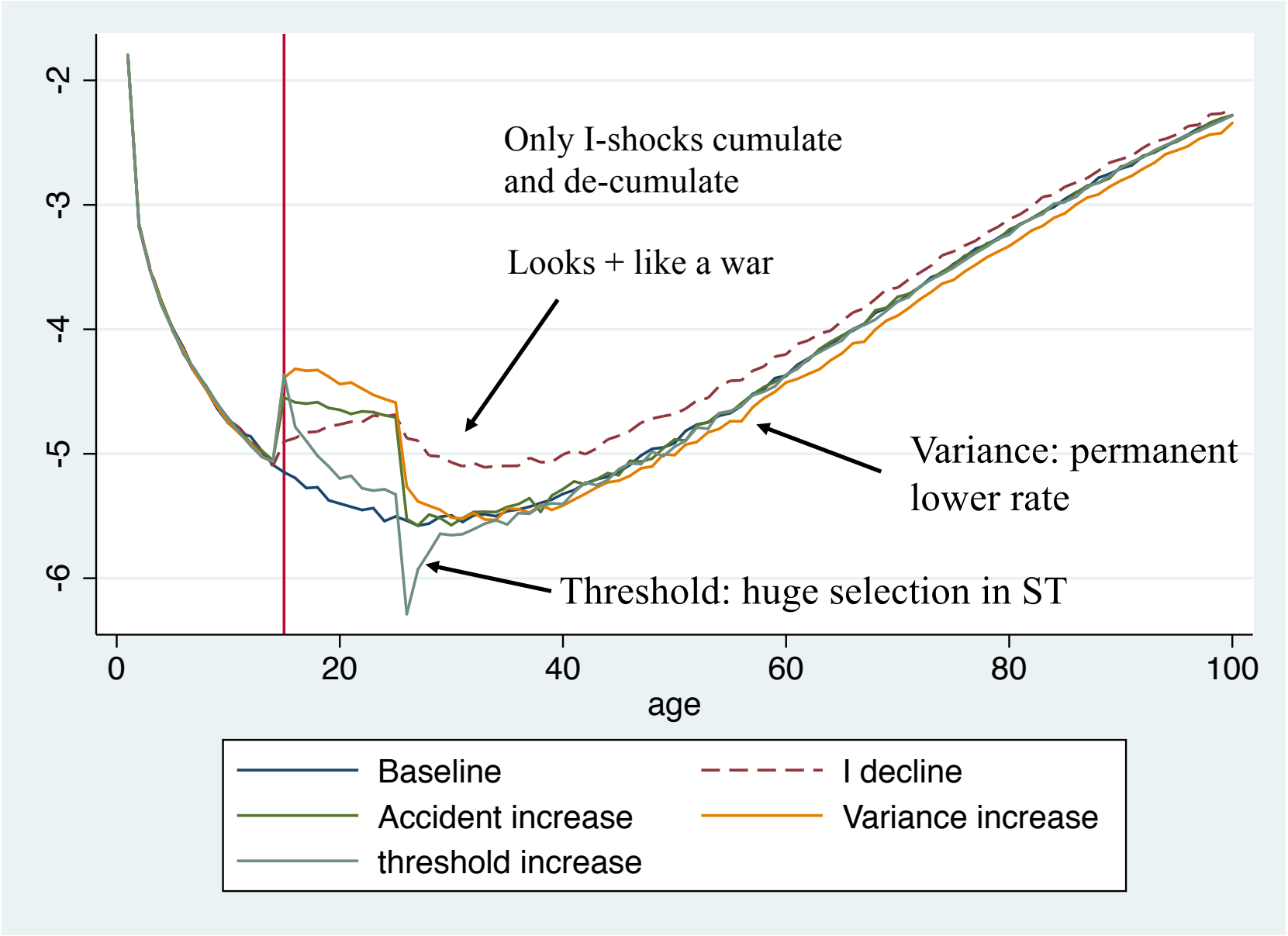
2. **Accident**: Random death shock, healthy and sick equally likely to die
   - Die when $H_t < \underline{H}$ OR when new i.i.d. term U[0-1]$< \kappa\ if\ 15 < t < 45$

3. Change in death **threshold**: $\underline{H} = \underline{H} + \kappa\ if\ 15 < t < 45$

4. Increases in **variance:**
   - $\varepsilon_t \sim N(0, \sigma_\varepsilon^2)\ if\ 15 > t\ or\ t > 45$
   - $\varepsilon_t \sim N(0, \sigma_\varepsilon^2 + \kappa)\ if\ 15 < t < 45$

- Assumes ages (15-45) are fixed and known, otherwise 3 new parameters

Simulated shock between ages 15 and 25



Suggests additional empirical tests

- Regression-based test, for mortality after ages 45 regress:

$$\ln MR_t = c_0 + b_0 * \text{age} + c_1 * \ln MR_{1-14} + b_1 * \text{age} * \ln MR_{1-14} + c_2 * \ln MR_{15-45} + b_2 * \ln MR_{15-45} * \text{age} + e_t$$

  - If initial conditions matter, c_1 and b_1 will be non-zero
  - If shocks during reproductive ages are
    - "accidents" then c_2 and b_2 will be equal to zero
    - variance changes then $c_2 < 0$ and $b_2 = 0$
    - I-shocks then $c_2 > 0$ and $b_2 < 0$
    - Threshold shocks: $c_2 < 0$ and $b_2 > 0$
  - Alternative test: if observe H can do AR estimation?

Women in HMDB: Bump is not random

VARIABLES	Basic Women	Add reproductive mortality	Add child mortality	Separate under age 2-14 mortality	Individual 2-14 mortality	country FE	Birth year FE
Constant	-4.889***	-3.852***	-3.853***	-5.341***	-5.271***	-5.329***	-5.335***
	[0.0137]	[0.0186]	[0.0272]	[0.0720]	[0.0660]	[0.0728]	[0.0616]
Age	0.0865***	0.0789***	0.0764***	0.0909***	0.0893***	0.0894***	0.0892***
	[0.000198]	[0.000270]	[0.000395]	[0.00105]	[0.000960]	[0.000913]	[0.000895]
Ln(MR 15-45)		1.213***	1.212***	1.137***	1.176***	1.092***	1.165***
		[0.0198]	[0.0514]	[0.0514]	[0.0561]	[0.0547]	[0.0540]
Ln(MR 15-45)*Age		-0.00881***	-0.0146***	-0.0146***	-0.0152***	-0.0150***	-0.0149***
		[0.000288]	[0.000747]	[0.000746]	[0.000813]	[0.000773]	[0.000758]
Observations	16,461	16,461	16,461	16,061	13,497	13,497	13,497
R-squared	0.920	0.970	0.973	0.976	0.982	0.984	0.984

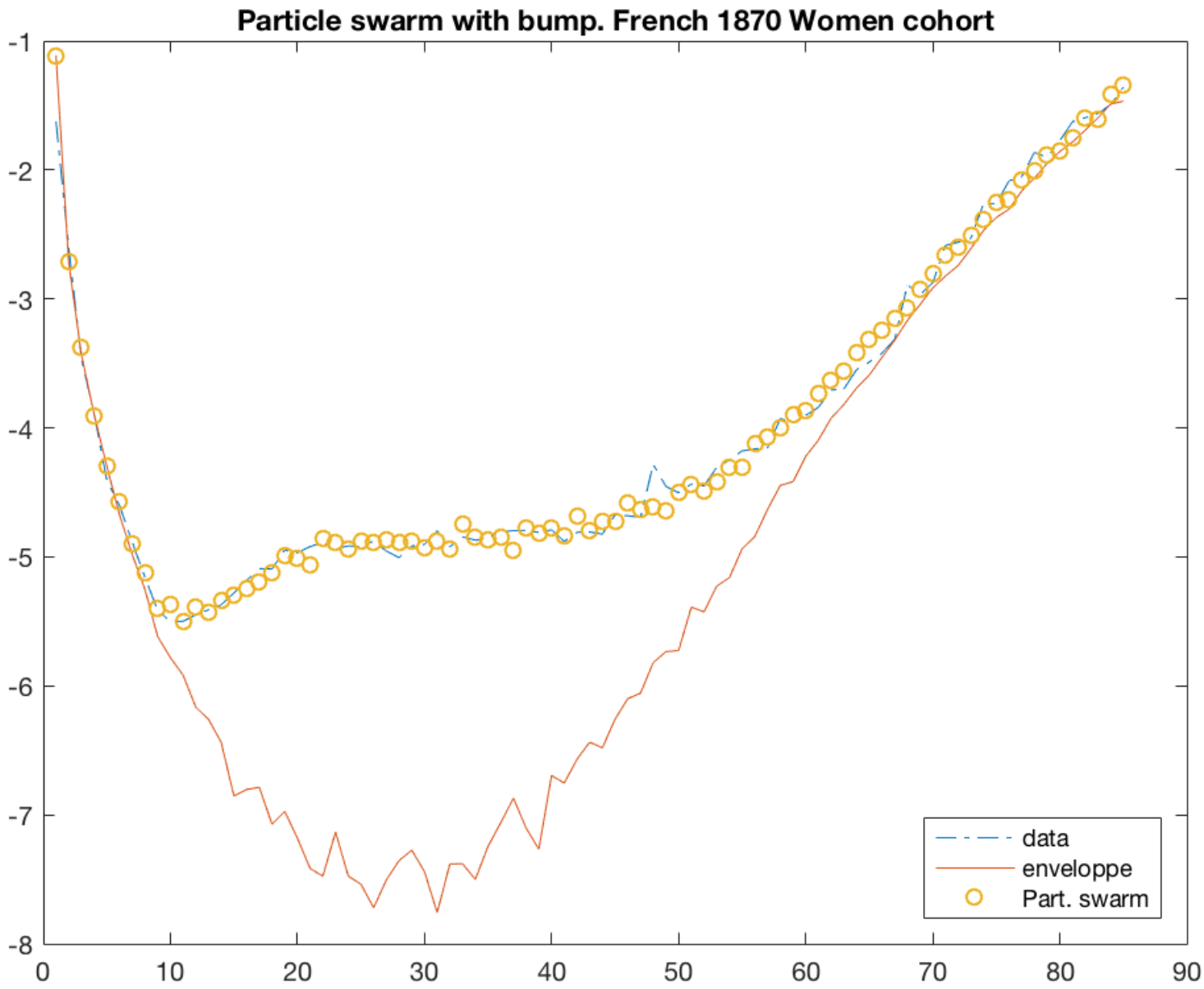
Higher intercept and flatter slope: looks like I-shock

Men in HMDB: Bump is not random

VARIABLES	Basic Men	Add reproductive mortality	Add child mortality	Separate under age 2-14 mortality	Individual 2-14 mortality	Country FE	Birth year FE
Constant	-4.889***	-3.638***	-3.559***	-5.628***	-5.449***	-4.888***	-5.595***
	[0.0137]	[0.0143]	[0.0149]	[0.0601]	[0.0619]	[0.0608]	[0.0585]
Age	0.0865***	0.0764***	0.0751***	0.0957***	0.0930***	0.0932***	0.0930***
	[0.000198]	[0.000207]	[0.000215]	[0.000873]	[0.000899]	[0.000776]	[0.000846]
Ln(MR 15-45)		1.083***	1.484***	1.566***	1.466***	1.224***	1.560***
		[0.0174]	[0.0294]	[0.0270]	[0.0328]	[0.0307]	[0.0311]
Ln(MR 15-45)*Age		-0.0116***	-0.0182***	-0.0191***	-0.0174***	-0.0174***	-0.0173***
		[0.000253]	[0.000425]	[0.000391]	[0.000472]	[0.000408]	[0.000444]
Observations	16,461	16,461	16,461	16,061	13,497	13,497	13,497
R-squared	0.92	0.976	0.977	0.982	0.984	0.988	0.986

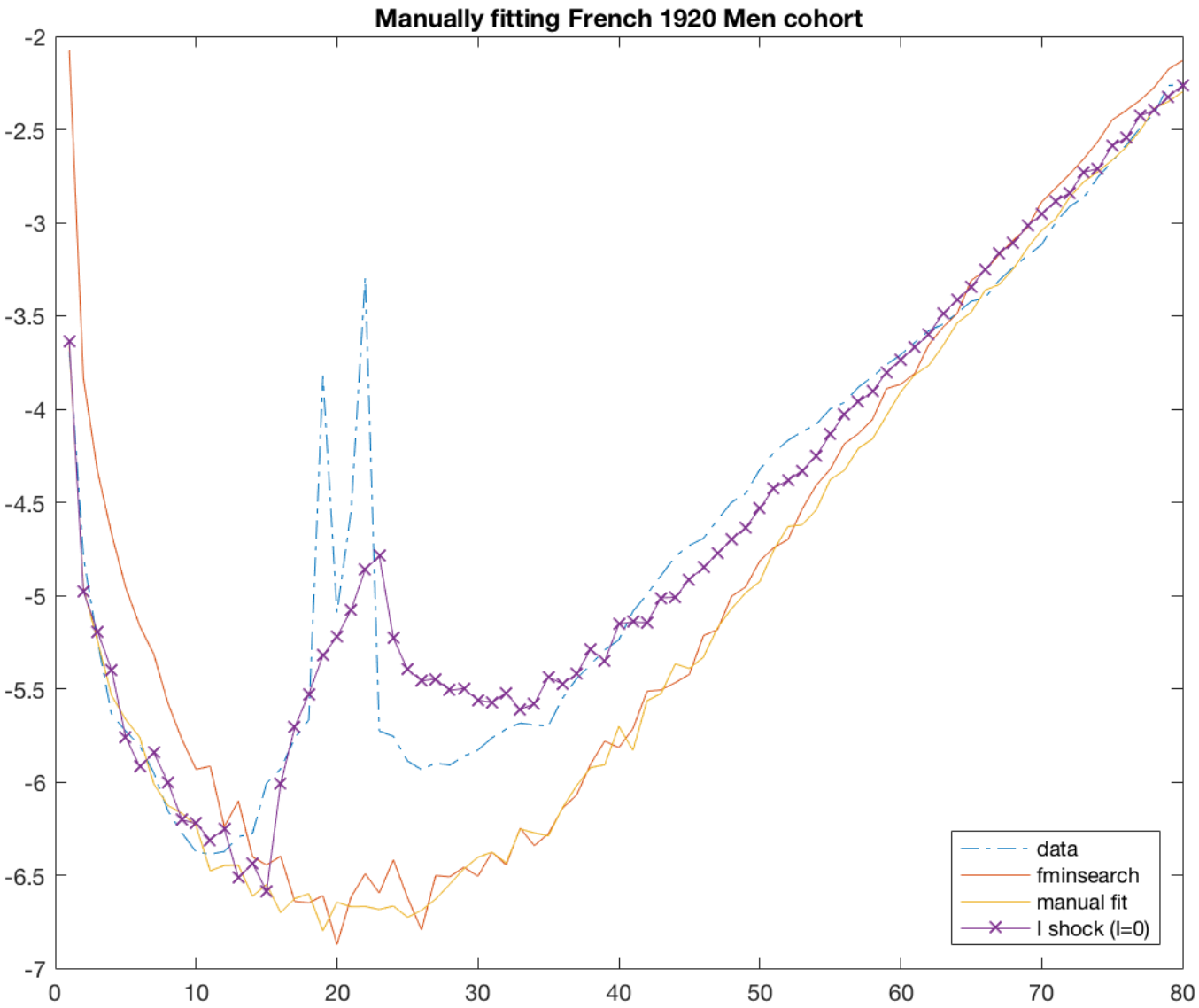
Higher intercept and flatter slope: looks like I-shock

Estimating “bump” in non-war times: accident fits!



Note: Start time is normally distributed to get smoothness, no end.

Estimating War spike: I-shock fits!

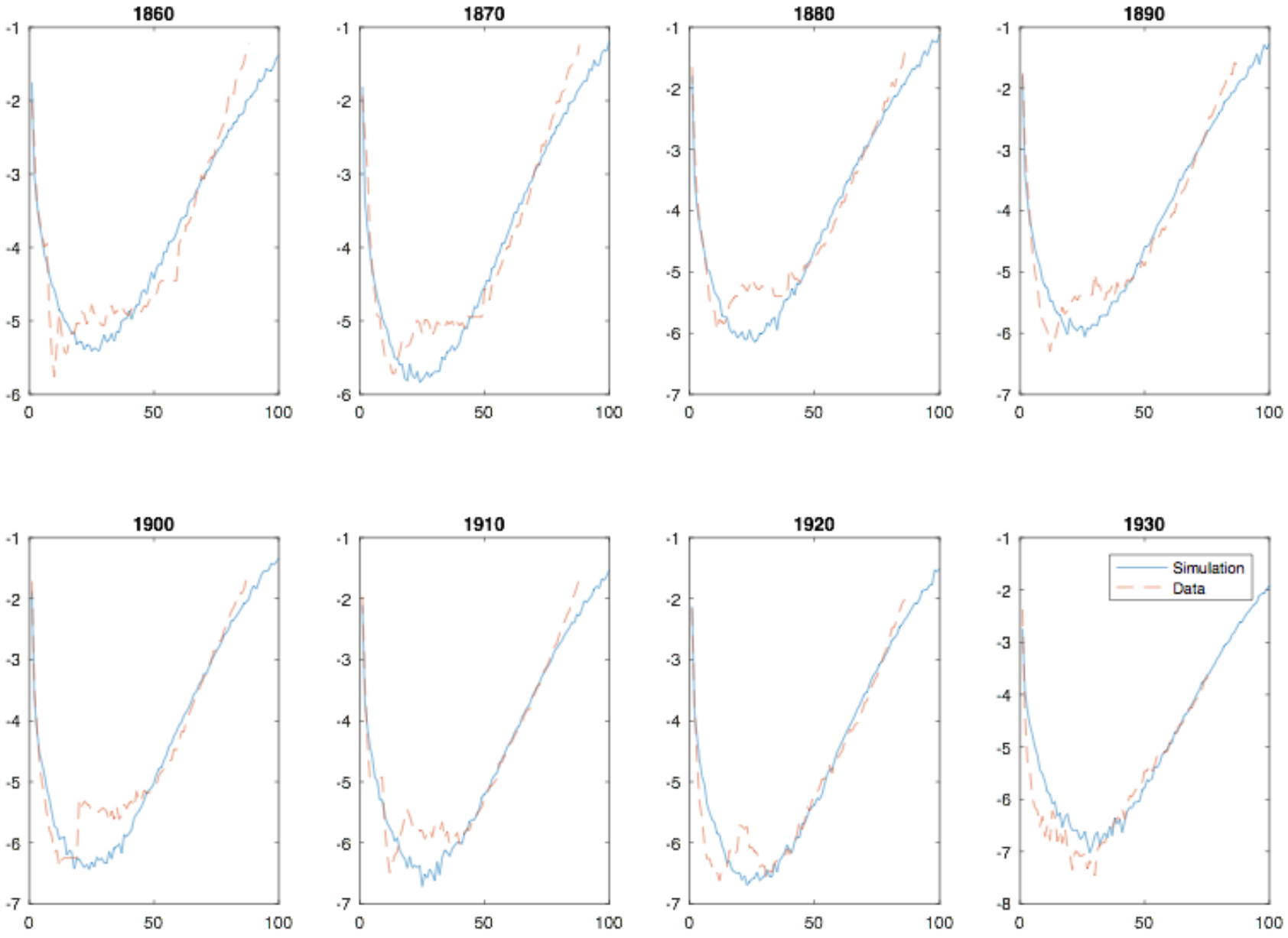


Some comments

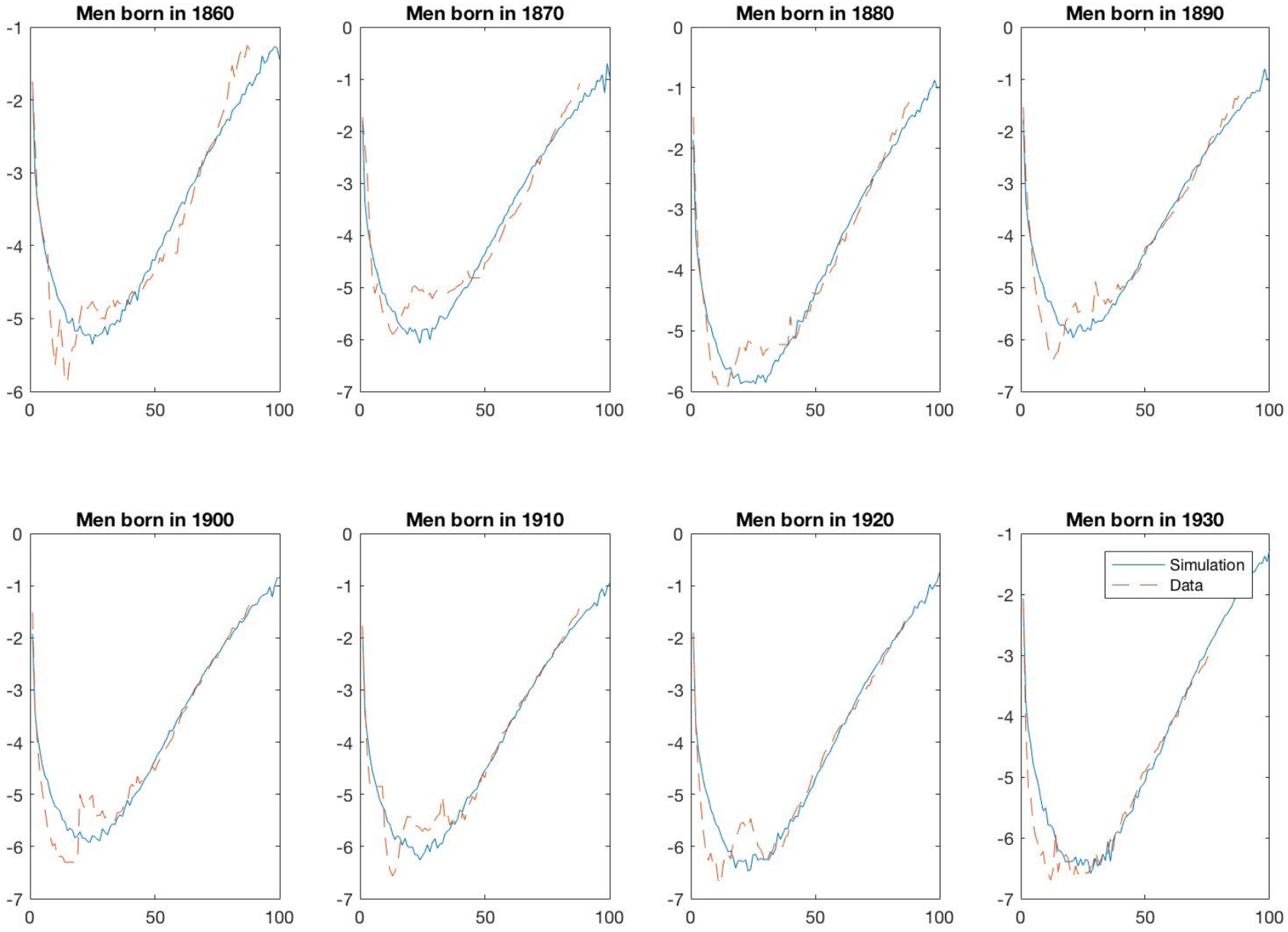
- Why are war spikes I-shocks?
  - War spikes for both men and women, and visible before reproductive ages: war deaths are not just combat deaths
  - Nutrition falls drastically for all individuals in population during war times. Dutch famine, rations, price of food: all evidence in favor of lower investments during war.
  - Disease rates increase because of poor sanitary conditions. Eg: influenza pandemic
- Model that accounts for bump &/or spike: greater level of I estimated. Bias is significant
- Cohorts have both bumps and spikes.
  - Next we will estimate a model with both.

SOME PRELIMINARY (BIASED) RESULTS WITHOUT BUMPS (EXCLUDE 15-45)

Belgian women: 1860-1930



Belgian men: 1860-1930



The sources of progress: Belgian males 1860-1910

Birth cohort	**1860**	**1870**	**1880**	**1890**	**1900**	**1910**
Mean health at birth	0.941	0.963	1.011	0.963	1.061	0.973
Variance of shocks	0.460	0.378	0.368	0.386	0.391	0.355
Average investment	0.129	0.138	0.130	0.138	0.140	0.135
Depreciation rate	0.0012	0.0012	0.0011	0.0013	0.0012	0.0012
Aging rate	1.348	1.356	1.356	1.342	1.358	1.334

Largest changes in variance of shocks (-23%), investment (5%) and mean at birth (3%)

No changes in depreciation or aging rate

The sources of progress: Belgian females1860-1910

Birth cohort	**1860**	**1870**	**1880**	**1890**	**1900**	**1910**
Mean health at birth	0.939	0.983	0.973	0.973	1.025	1.160
Variance of shocks	0.464	0.393	0.355	0.364	0.327	0.367
Average investment	0.135	0.134	0.131	0.129	0.130	0.143
Depreciation rate	0.0012	0.0012	0.0012	0.0011	0.0011	0.0011
Aging rate	1.342	1.334	1.335	1.333	1.320	1.340

Largest changes in mean at birth (24%). variance of shocks (-21%), investment (6%). Depreciation decline 11%
No change in aging rate.

Across countries: Males Belgium, Norway and France

Cohort	Country	Annual investment	Delta	sd of shocks	Gamma	H_0 mean
1860	Belgium	0.129	1.145E-03	0.471	1.3400	0.964
	France	0.129	1.235E-03	0.453	1.3715	0.972
	Norway	0.130	1.188E-03	0.444	1.3337	0.957
1910	Belgium	0.133	1.100E-03	0.354	1.3073	0.999
	France	0.142	1.129E-03	0.403	1.3778	1.077
	Norway	0.153	1.052E-03	0.337	1.3700	1.991
1920	Belgium	0.131	1.320E-03	0.321	1.3080	1.155
	France	0.123	1.106E-03	0.358	1.3381	1.051
	Norway	0.160	1.123E-03	0.370	1.3636	1.186

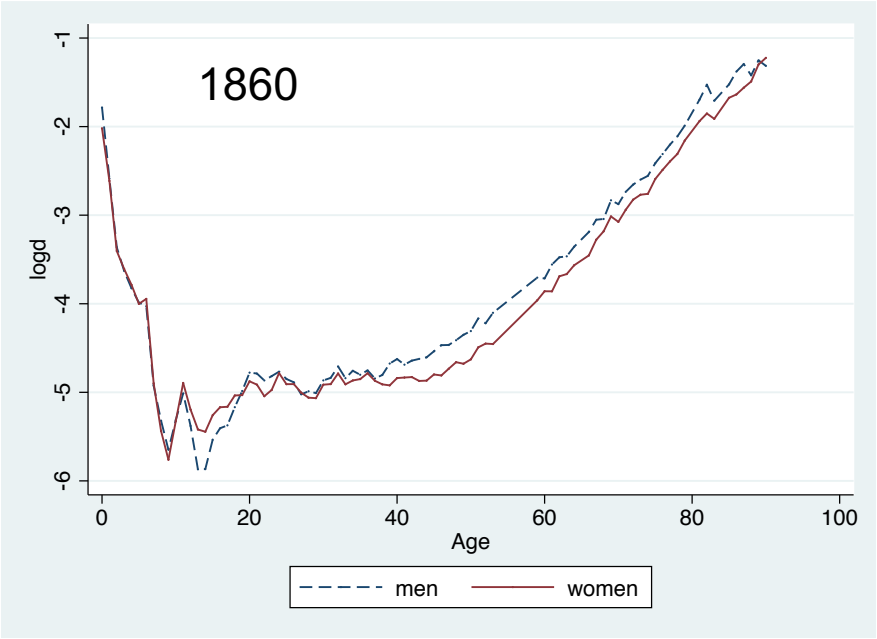
- In all cases health at birth & investment has increased substantially up to 1910
- Standard deviation of shock declines range from 17-32%: huge!
- Slope of again: almost identical across countries & periods.
- WW2: BIG shock

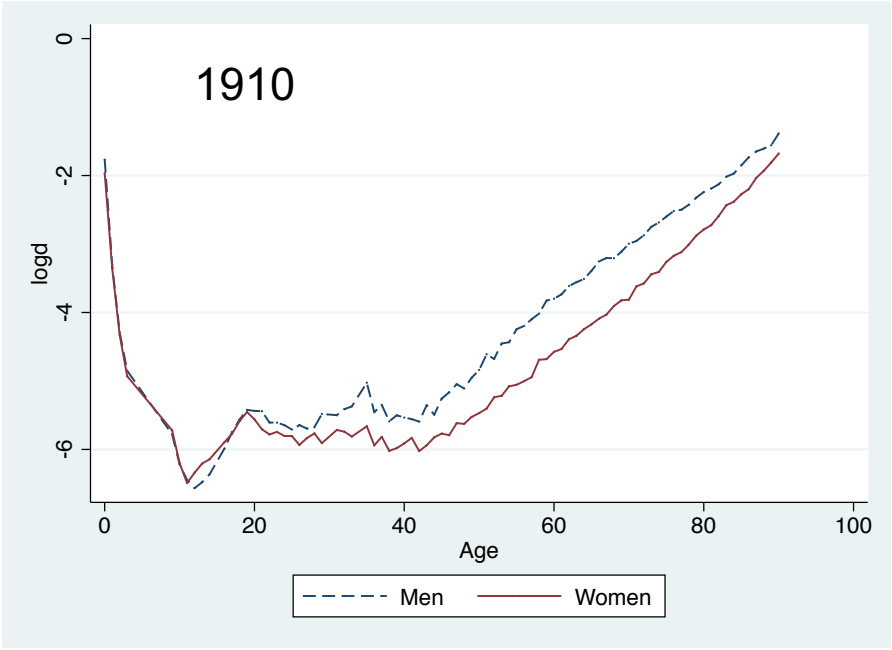
Females in Belgium, Norway and France

Cohort	Country	Annual investment	Delta	sd of shocks	Gamma	H_0 mean
1860	Belgium	0.135	1.219E-03	0.464	1.3420	0.939
	France	0.130	1.201E-03	0.418	1.3512	1.112
	Norway	0.132	1.189E-03	0.470	1.3294	1.001
1910	Belgium	0.143	1.071E-03	0.367	1.3155	1.160
	France	0.147	1.291E-03	0.345	1.3039	1.043
	Norway	0.164	7.241E-04	0.378	1.4528	1.459
1920	Belgium	0.132	9.769E-04	0.329	1.3440	1.176
	France	0.134	1.094E-03	0.359	1.3155	1.194
	Norway	0.166	1.292E-03	0.348	1.3073	1.340

- Patterns for women identical

Explaining gender gaps: Belgium 1860 and 1910





cohort		**H_0 mean**	sd of shocks	**Annual investment**	Delta	Gamma	**Actual LE**	**Predicted LE**
1860	M	0.941	0.460	0.129	0.0012	1.348	37.71	38.52
	F	0.939	0.464	0.135	0.0012	1.342	40.4	40.24
1910	M	0.973	0.355	0.135	0.0012	1.334	45.13	45.98
	F	1.160	0.367	0.143	0.0011	1.340	51.07	53.7

Female advantage: **initial H has increased a lot more for women** (I a bit too)
Either more inputs or women are more responsive to inputs

Across countries: 1870-1920 as % of 1870

Gender	Country	Annual investment	Delta	sd of shocks	Gamma	H_0 mean
Male	Belgium	2.22%	19.86%	29.09%	-0.15%	-25.24%
	France	-3.08%	8.91%	14.11%	2.64%	-7.37%
	Norway	-25.76%	-8.66%	25.96%	1.66%	-33.87%
Female	Belgium	-1.55%	-15.28%	31.85%	2.39%	-19.81%
	France	4.65%	10.45%	20.97%	2.44%	-8.13%
	Norway	-23.08%	5.47%	16.67%	-2.24%	-23.93%

- In all cases health at birth increased more for women
- In all cases standard deviation of shock fell more for women
- Investment results depend a lot on country
- Changes in aging slope close to zero.

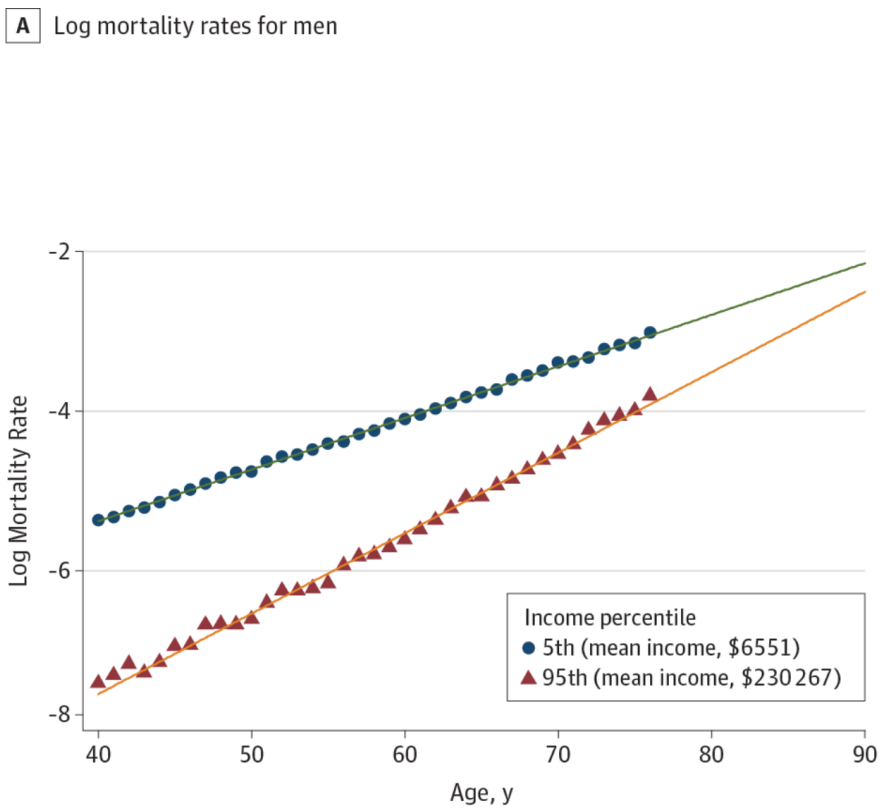
Some observations

- Large decreases in variance of shocks:
  - public health improvements: decline of **infectious disease** level and cyclicality of morbidity (eg flu)
  - Larger "social insurance" rates: savings, public spending, decrease in famine mortality
    - Improvements in data collection (smaller measurement error in MR)?

- H_0 going up: like birth weight and other measures of health at birth
  - Intergenerational component might be important too
  - in-utero shocks and nutrition matter (Barker 1975)

- Increases in H and I consistent with large secular increases in GDP (in BEL and many other countries during this period)—and associated increases in food and public health investments.

Understanding parameter sizes: SES gradients



Chetty et al (2016)

How big is the gap?

"the gap in life expectancy between individuals in the top and bottom 1% of the income distribution in the United States is 15 years for men and 10 years for women"

Suggest main differences by income at age 40 driven by pre-age 40 Conditions: either H_0 or I

Differences here much larger than changes in initial conditions or I in Belgium from 1860-1930. (combined?)

WHAT'S NEXT?

How to characterize entire curve?

Estimation in four steps:

1. Estimate model "outside reproductive ages": obtain initial guesses.

2. Estimate bumps and spikes
   - Taking the parameters from step 1 as given

3. Re-estimate full model allowing all parameters to move
   - Also allow for begining and end point of bump to be estimated.
   - Allow for spikes during war years (for any cohort/age)

4. Bootstrap standard errors

Explore various implications

1. **Explaining progress:** Does GDP predict changes in parameters? What else correlates with progress?
   - Re-estimate for all cohorts between 1850-1930: 80 estimates for each parameter
   - Regress each parameter on GDP at birth, or GDP at age 20, or GDP at age 40, or GDP at age 60

2. **Estimate Cost of War and Accidents**

3. **Estimate intergenerational correlation in health implied by estimates**

4. **Predict future changes in LE, by SES: Currie v Chetty**

Investigate optimal investments

- Compute ST and LT rate of return at each age
- Solve investment allocation problem
  - Maximize years lived in the population under fixed budget
  - Consumption and health investment, with health affecting wages and probability of dying

EXTRA SLIDES

Heligman and Pollard's function 1980

- Model log odds of dying at age a (ratio of the probability of dying at age x to that of the probability of not dying at age x), i.e.

$$Qx/px = (1 - px) / px$$

$$= A^{((x+B)C)} + D.\exp\left(- E.(\ln(x) - \ln(F))^2 \right) + GH^x$$

- A, B and C: capture the rapid decline in child mortality at younger ages.
- G and H: Gompertz mortality function in old age
- D, E and F: reflects the 'accident hump' or the effects of maternal mortality among women.

Back

Consistent with trends in maternal mortality

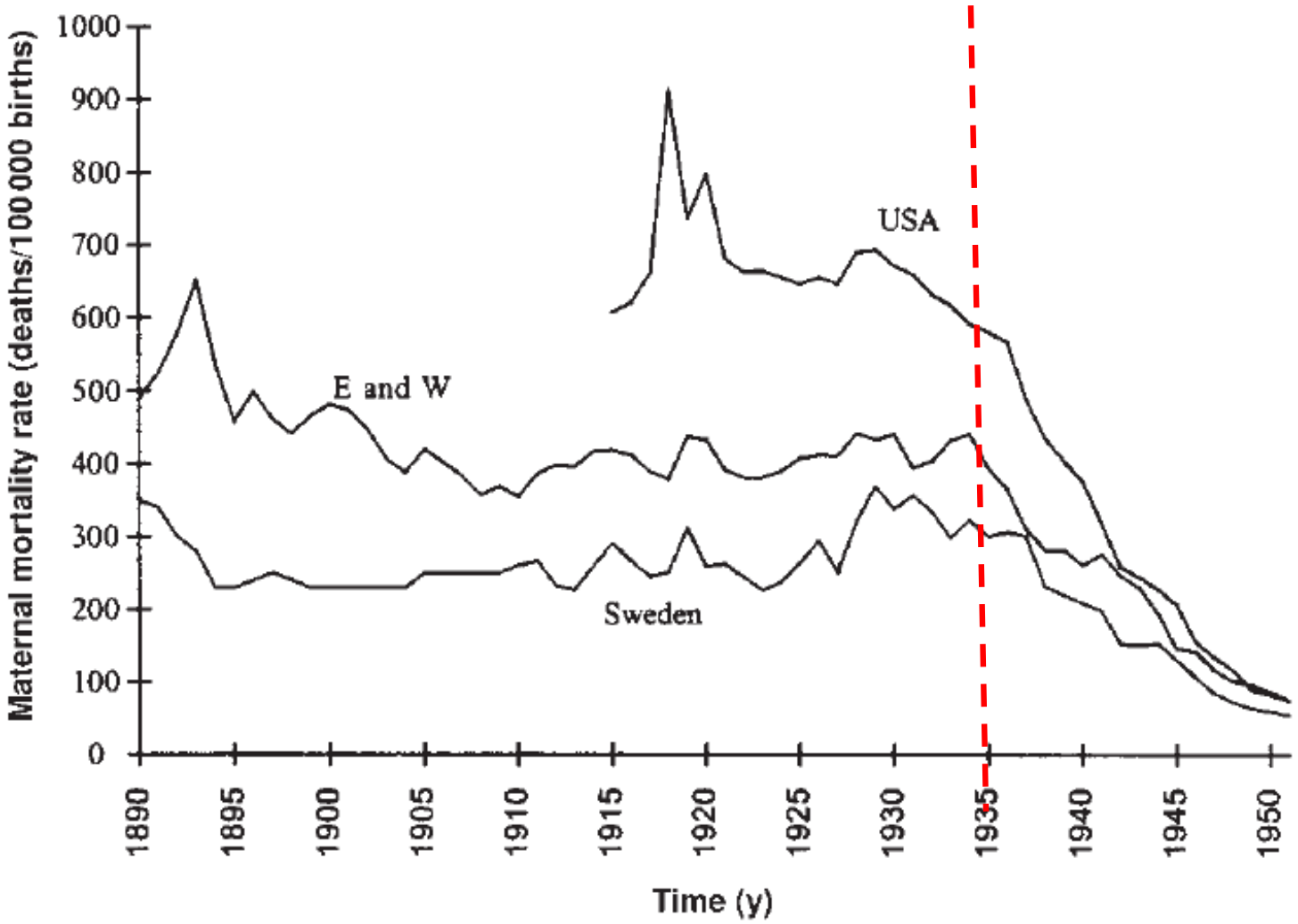


Figure 2, Loudon (2000)

Follows findings in Case, Paxson and Lubotsky

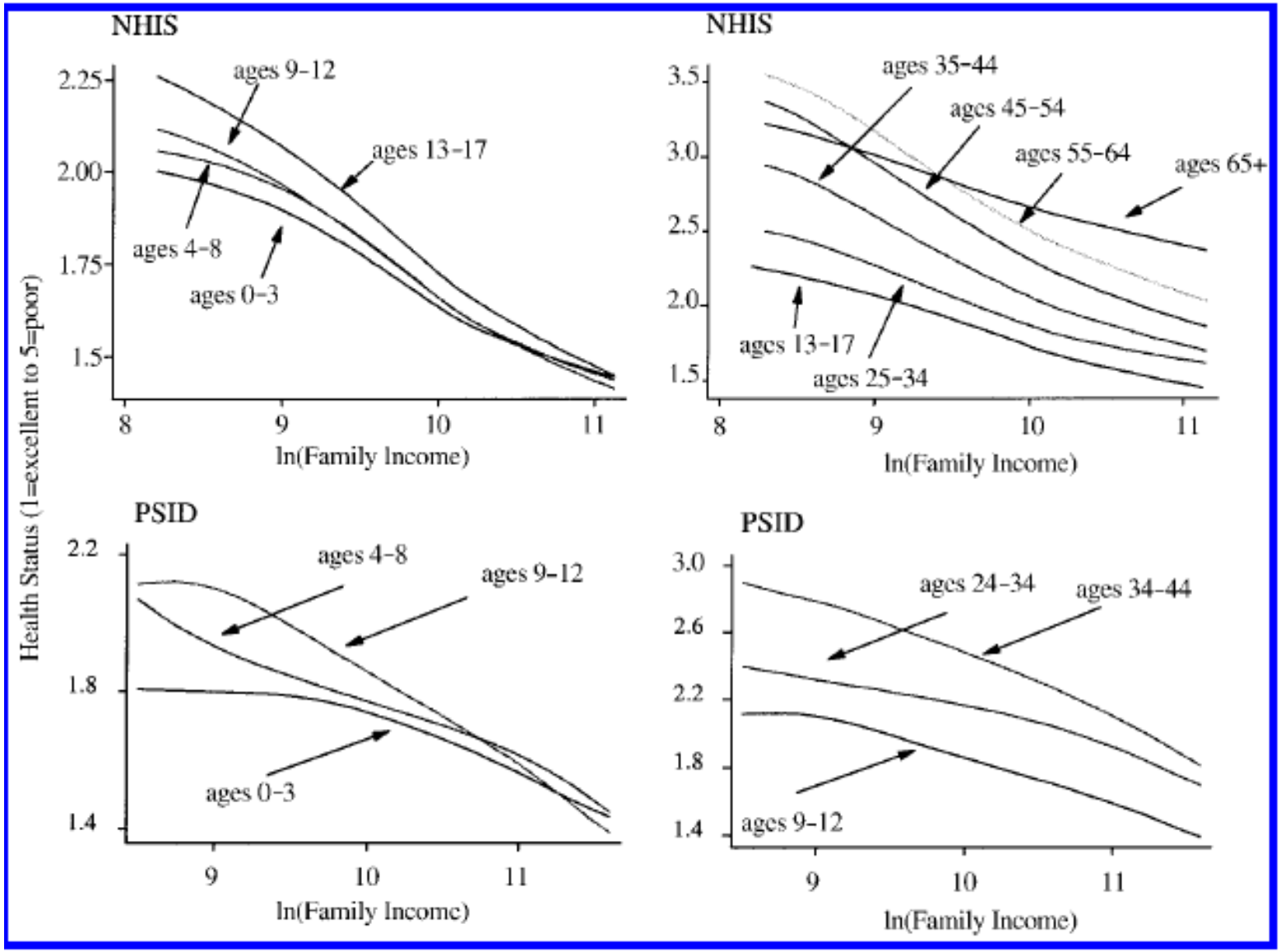
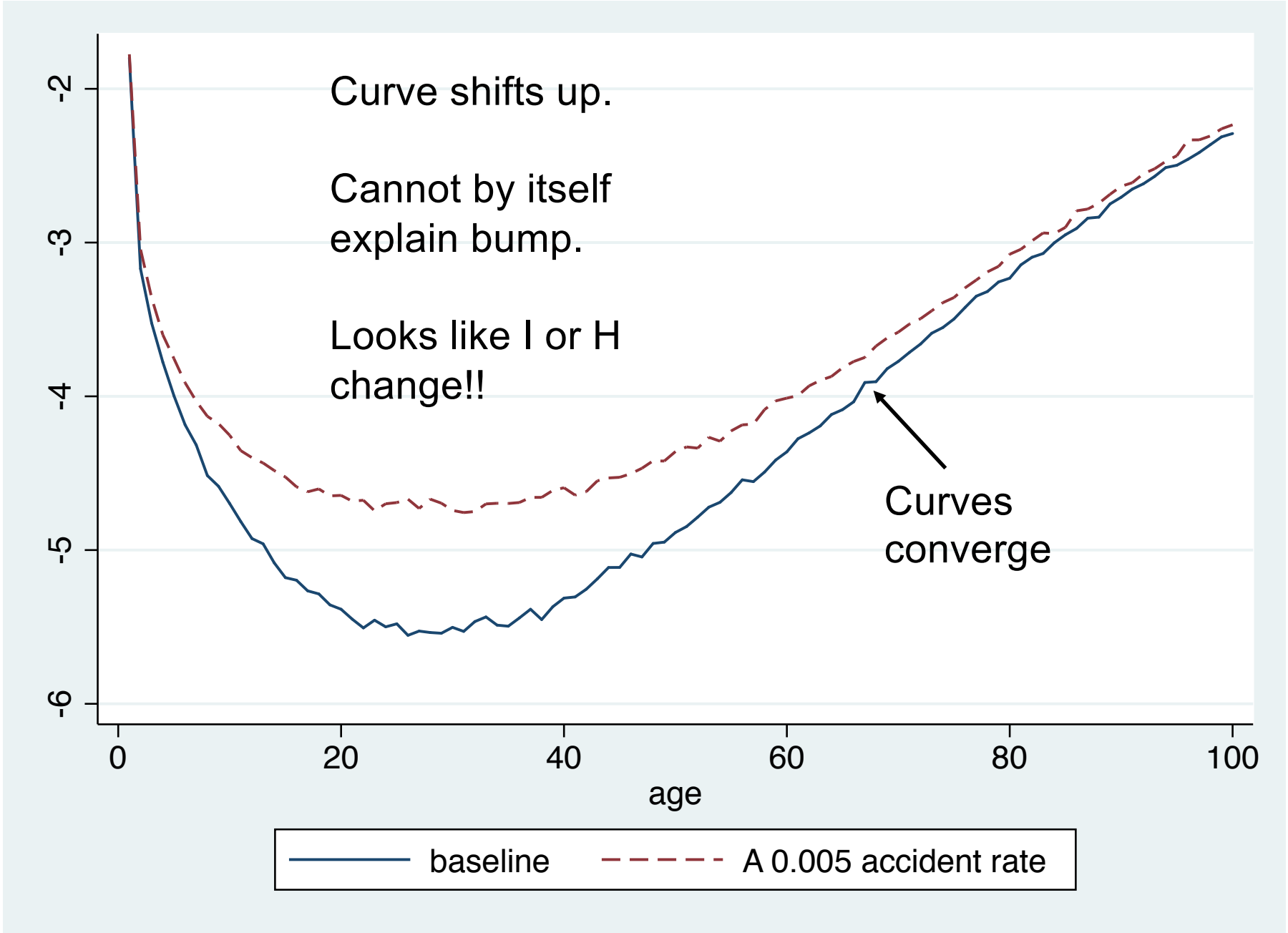


FIGURE 1. HEALTH AND INCOME FOR CHILDREN AND ADULTS: NHIS (1986–1995) AND PSID

Higher "Accident" risk throughout life: higher MR



BUT mortality gaps are constant by construction

