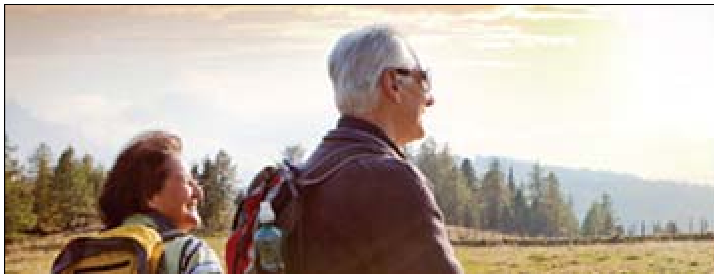


LIVING to 100
SOCIETY OF ACTUARIES INTERNATIONAL SYMPOSIUM

Jan. 4–6 , 2017
Orlando, FL

Session 1B, Late Life Mortality Curves

Moderator:
Jean-Marc Fix, FSA, MAAA

Presenters:
Jean-Marie Robine
Natalia S. Gavrilova
Leonid A. Gavrilov
Roland Rau

Historical Evolution of Old-Age Mortality and New Approaches to Mortality Forecasting

Dr. Leonid A. Gavrilov, Ph.D.
Dr. Natalia S. Gavrilova, Ph.D.

Center on Aging
NORC and The University of Chicago
Chicago, Illinois, USA

Using parametric models (mortality laws) for mortality projections

The Gompertz-Makeham Law

Death rate is a sum of age-independent component (Makeham term) and age-dependent component (Gompertz function), which increases exponentially with age.

$$\mu(x) = A + R e^{ax}$$

risk of death

A – Makeham term or background mortality

$R e^{ax}$ – age-dependent mortality; x - age

How can the Gompertz-Makeham law be used?

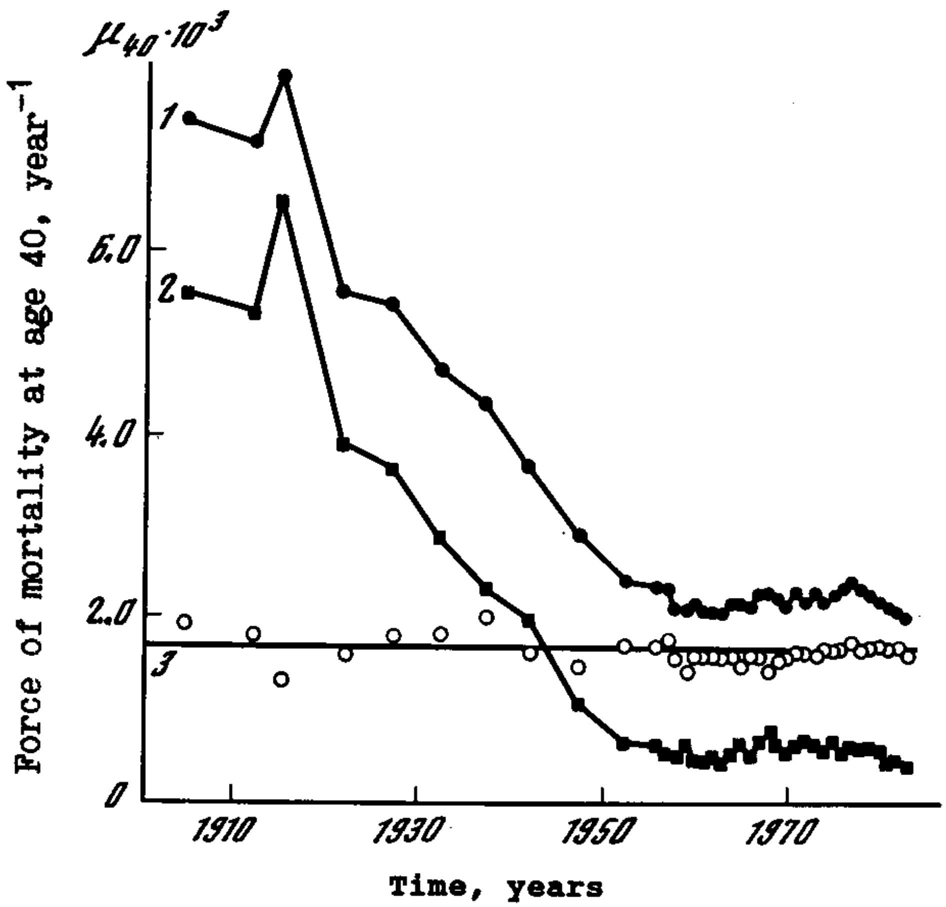
By studying the historical dynamics of the mortality components in this law:

$$\mu(x) = A + R\,e^{\alpha x}$$

Makeham component (A) Gompertz component ($R\,e^{\alpha x}$)

Historical Stability of the Gompertz Mortality Component

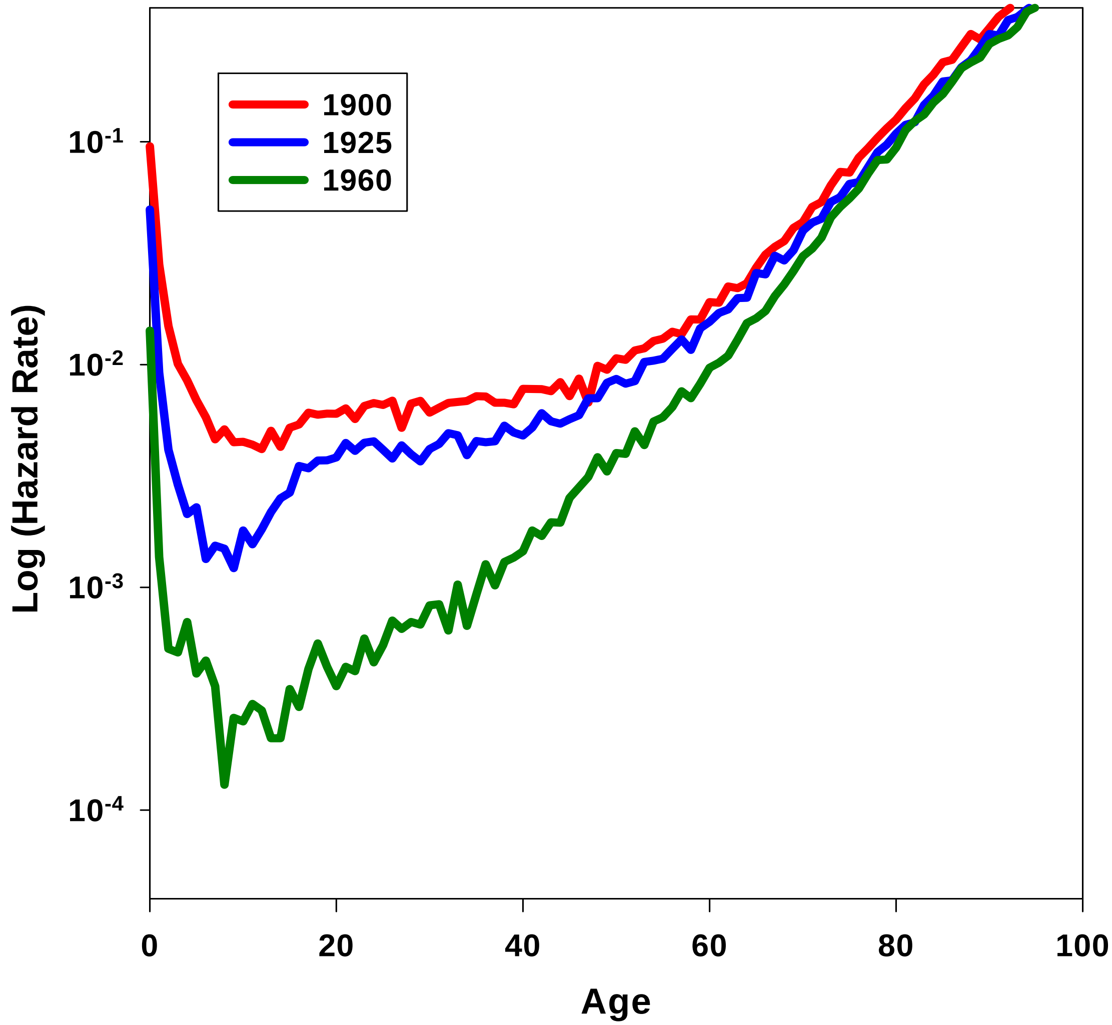
Historical Changes in Mortality for 40-year-old Swedish Males



1. Total mortality, μ_{40}
2. Background mortality (A)
3. Age-dependent mortality ($Re^{\alpha 40}$)

- Source: Gavrilov, Gavrilova, "*The Biology of Life Span*" 1991

Changes in Mortality, 1900-1960



Swedish females. *Data source*: Human Mortality Database

In the end of the 1970s it looked like there is a limit to further increase of longevity

Debate

Gerontology *29*: 176–180 (1983)

0304–324X/83/0293–0176$2.75/0

Human Life Span Stopped Increasing: Why?

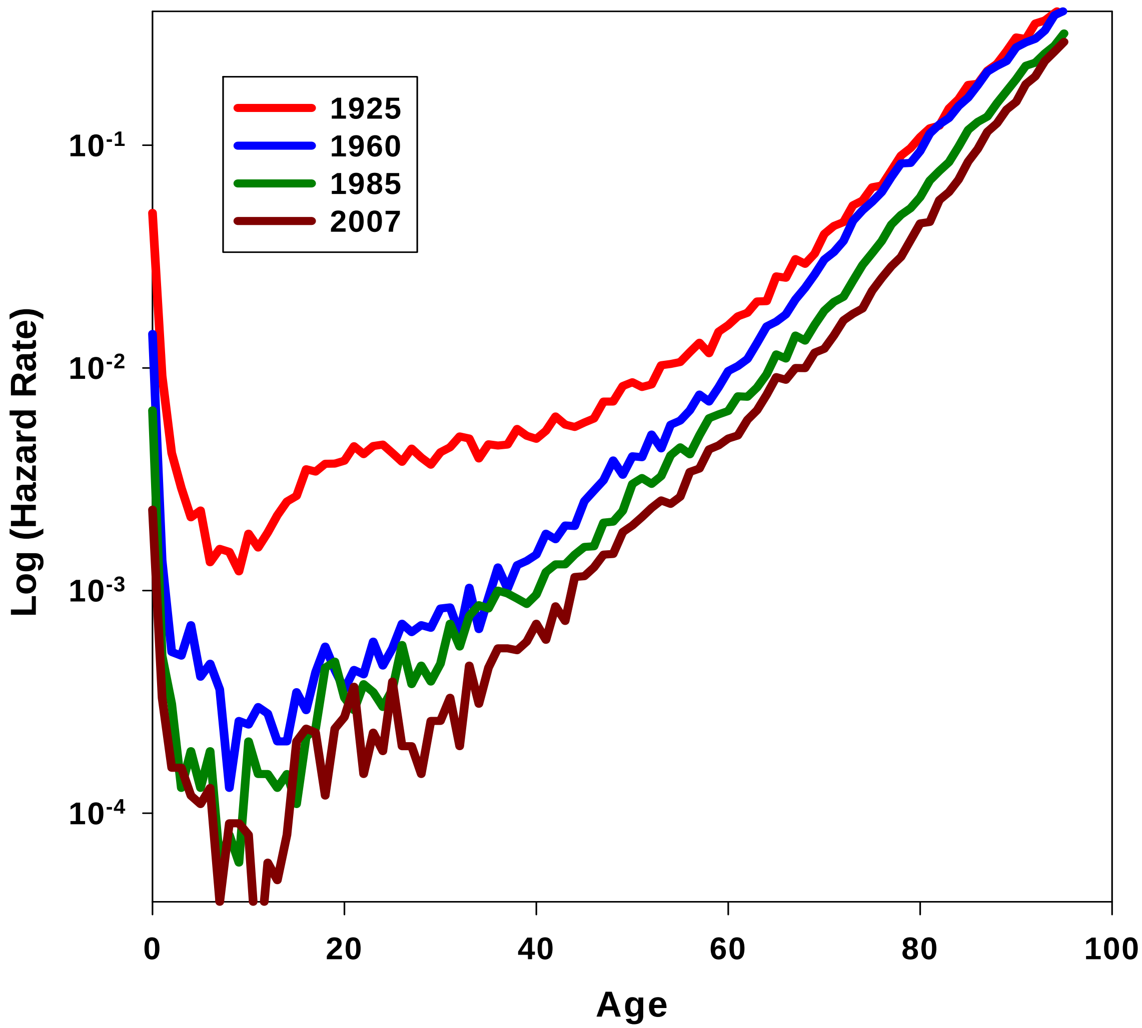
Leonid A. Gavrilov, Natalia S. Gavrilova, Victor N. Nosov

A.N. Belozersky Laboratory of Molecular Biology and Bioorganic Chemistry, and Department of Biology, Moscow State University, Moscow, USSR

Increase of Longevity after the 1970s:

Age-dependent mortality no longer is stable

Changes in Mortality, 1925-2007



Swedish Females. *Data source*: Human Mortality Database

Shifting model of mortality projection

Using data on mortality changes after the 1950s Bongaarts (2005) found that the slope parameter in the Gompertz-Makeham formula is stable in history. He suggested to use this property in mortality projections and called this method shifting mortality approach.

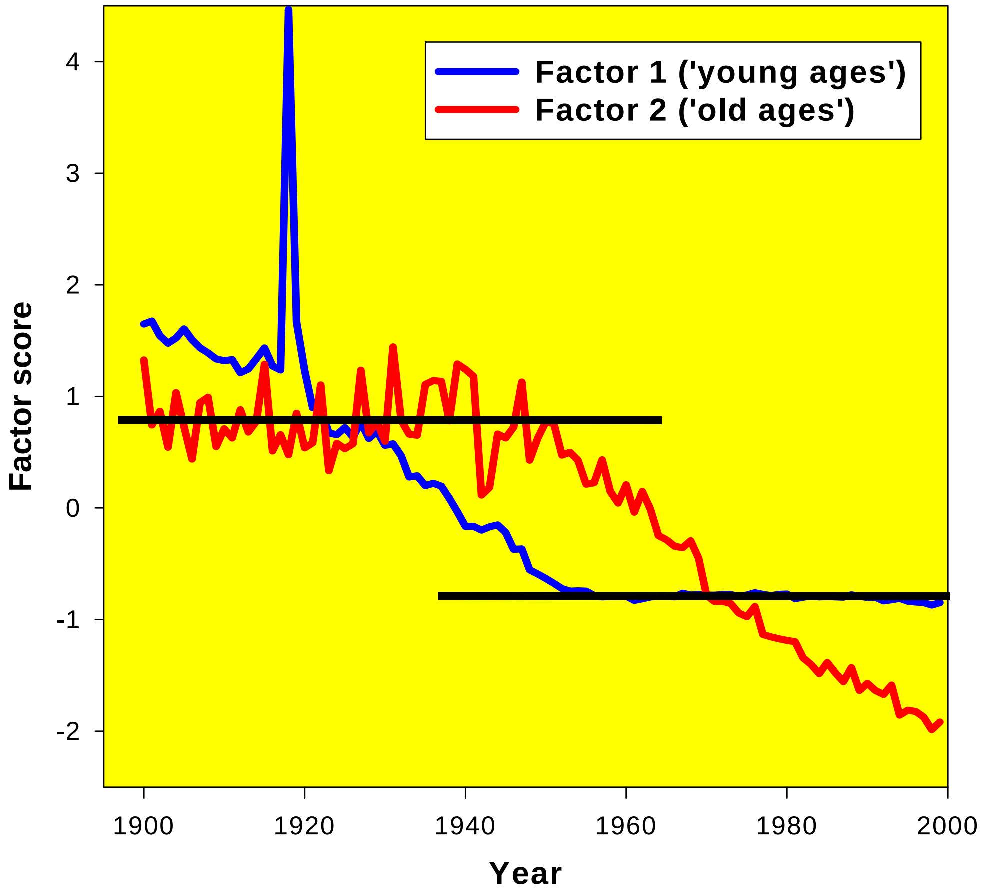
The main limitation of parametric approach to mortality projections is a dependence on the particular formula, which makes this approach too rigid for responding to possible changes in mortality trends and fluctuations.

Extension of the Gompertz-Makeham Model Through the Factor Analysis of Mortality Trends

Mortality force (age, time) =

$$= a_0(\text{age}) + a_1(\text{age}) \times F_1(\text{time}) + a_2(\text{age}) \times F_2(\text{time})$$

Factor Analysis of Mortality
Swedish Females



Data source: Human Mortality Database

Preliminary Conclusions

- **There was some evidence for ' biological' mortality limits in the past, but these 'limits' proved to be responsive to the recent technological and medical progress.**
- **Thus, there is no convincing evidence for absolute 'biological' mortality limits now.**
- **Analogy for illustration and clarification: There was a limit to the speed of airplane flight in the past ('sound' barrier), but it was overcome by further technological progress. Similar observations seems to be applicable to current human mortality decline.**

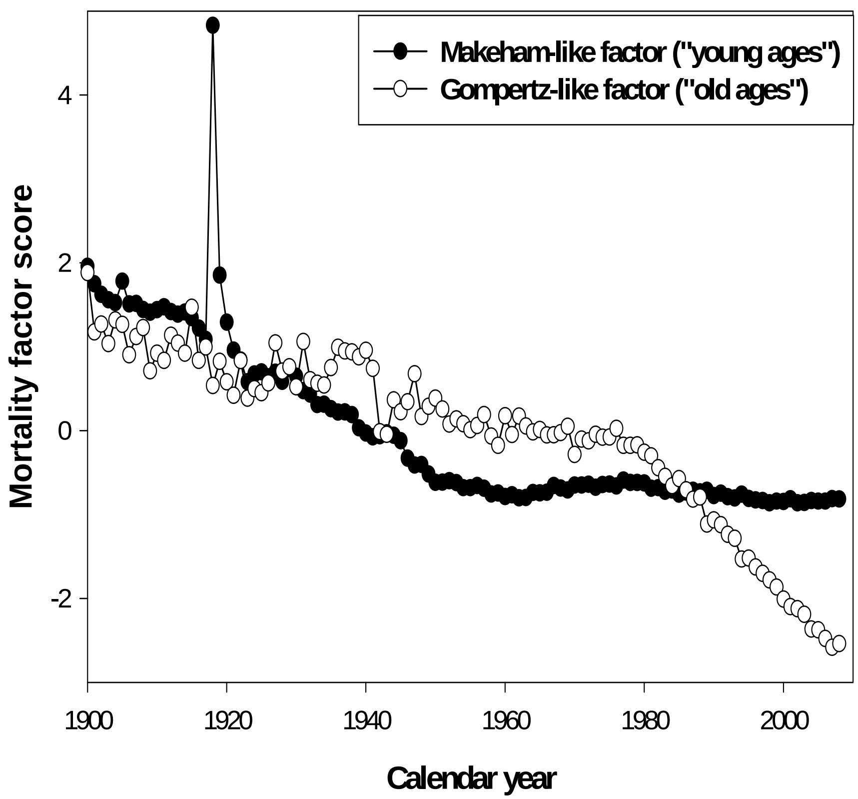
Implications

- **Mortality trends before the 1950s are useless or even misleading for current forecasts because all the “rules of the game” has been changed**

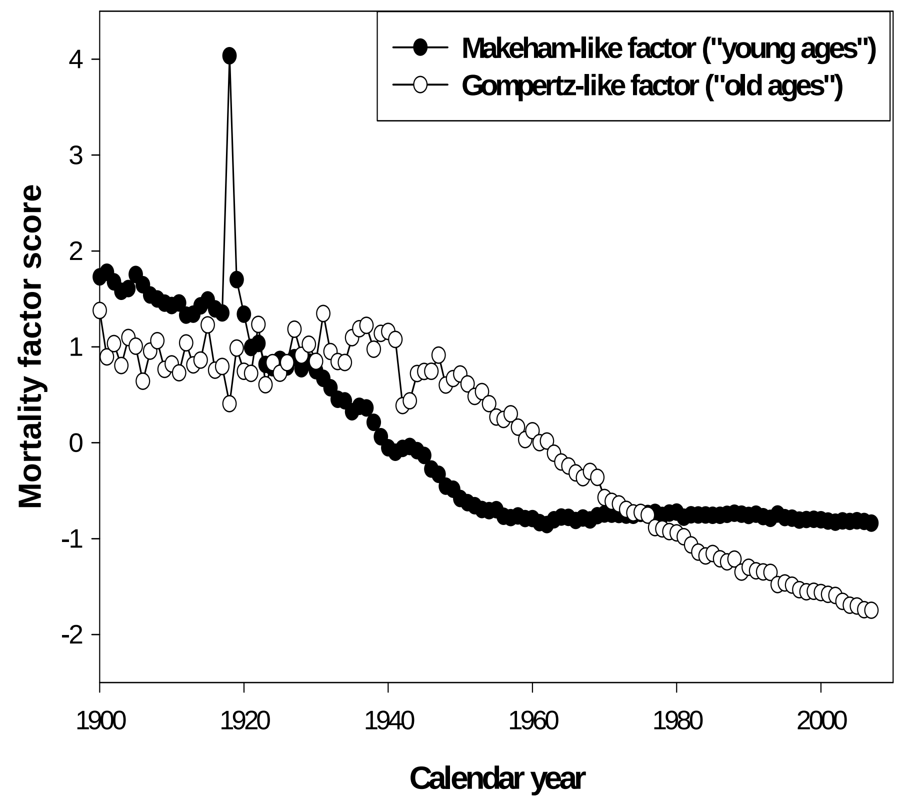
Factor Analysis of Mortality

Data for Swedish men and women

Men

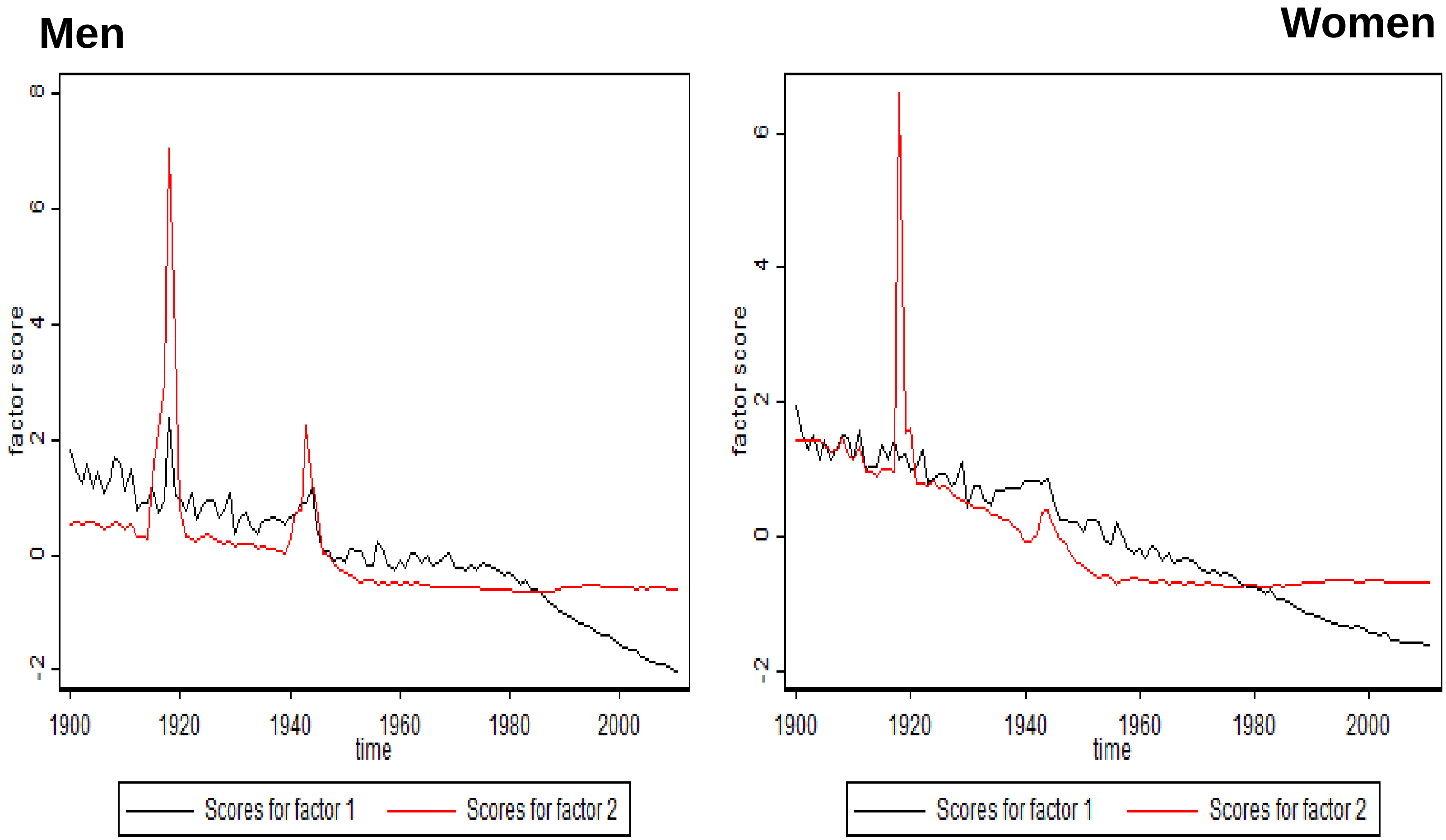


Women



Data source: Human Mortality Database

Country participated in WWII
Data for Italian men and women

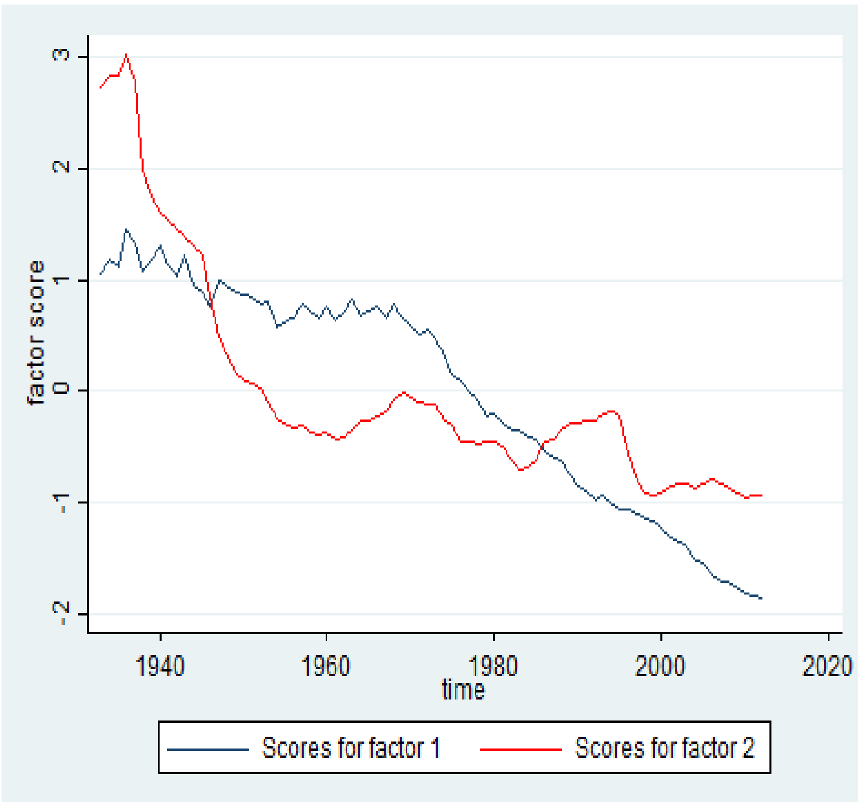


Red color - Young-age factor . Black color – old-age factor

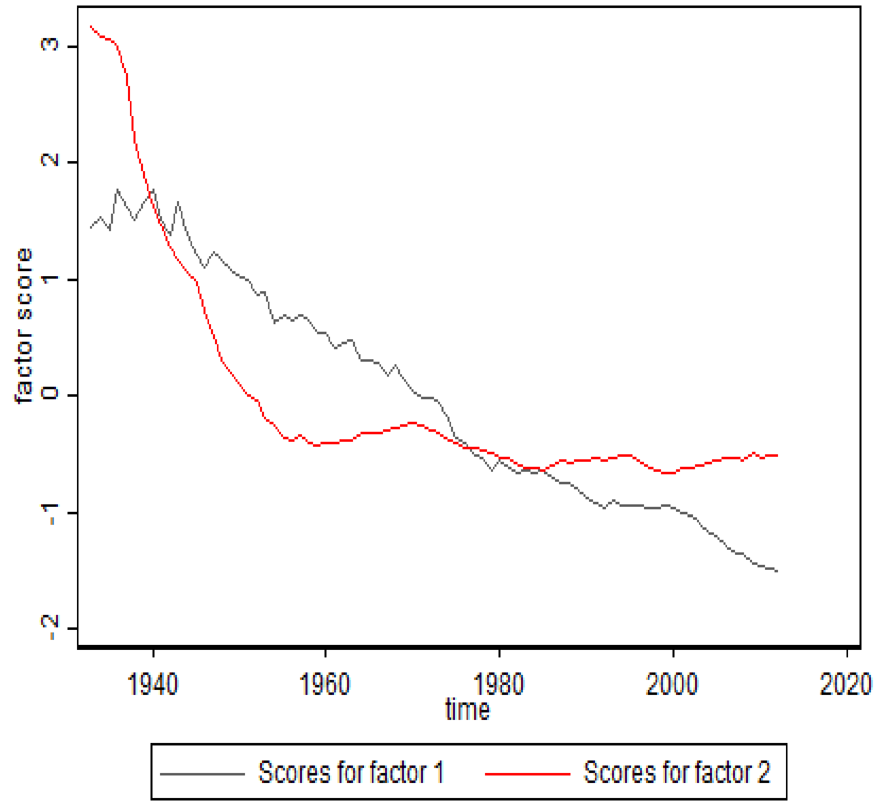
Data source: Human Mortality Database

Factor analysis of the U.S. data

Men



Women



Red color - Young-age factor . Black color – old-age factor

Data source: Human Mortality Database

Advantages of factor analysis of mortality

First, it is able to determine the number of factors (latent variables) affecting mortality changes over time.

Second, this approach allows researchers to determine the time interval, in which underlying factors remain stable or undergo rapid changes.

Simple model of mortality projection

Taking into account the shifting model of mortality change it is reasonable to assume that mortality after 1980 can be modeled by the following log-linear model with similar slope for all adult age groups:

$$\ln(\mu_{x,t}) = a(x) - kt$$

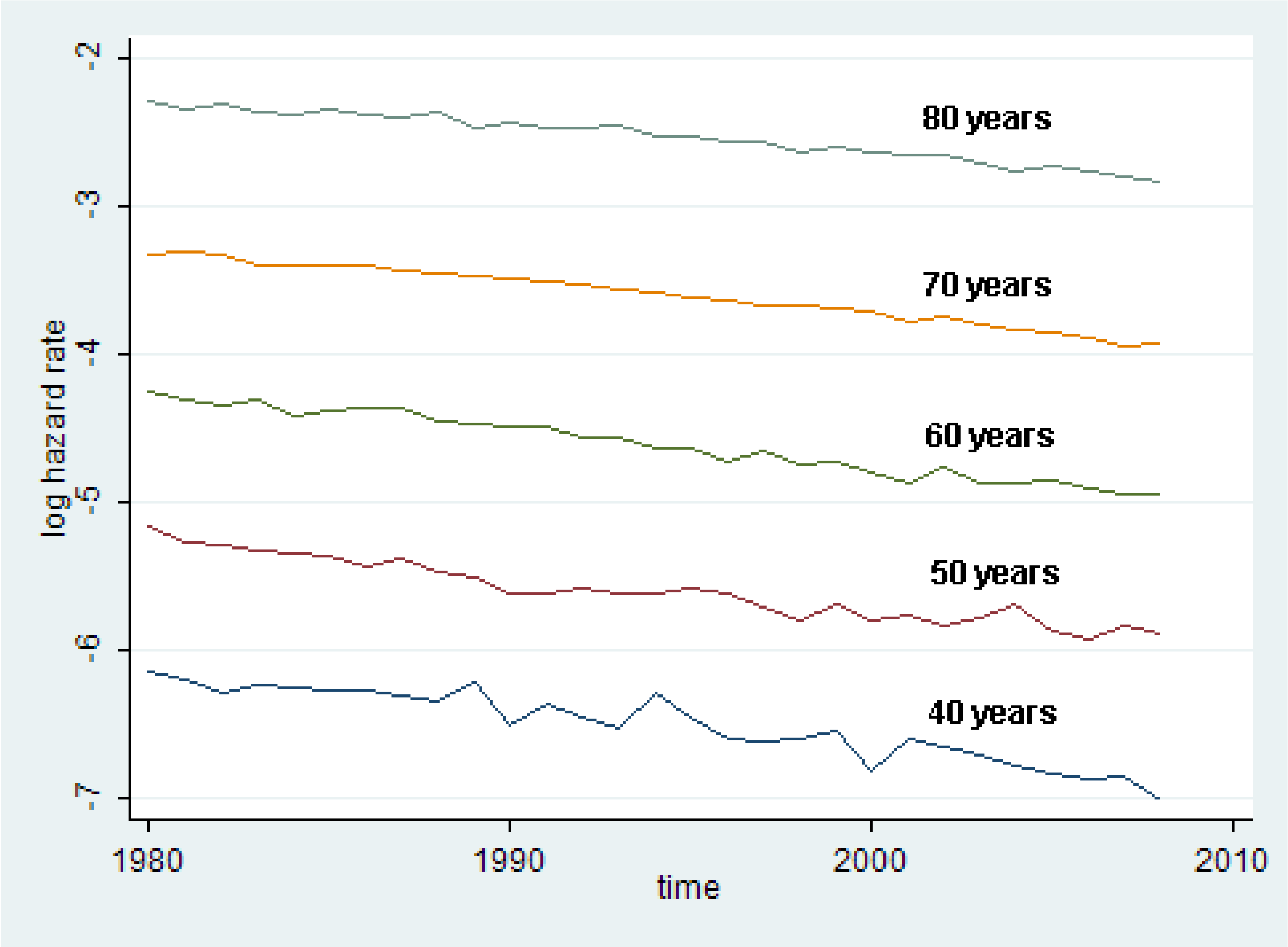
Lee-Carter model is similar but somewhat more complex:

$$\ln(\mu_{x,t}) = a(x) + b(x)k(t)$$

$$\sum_t k(t) = 0; \quad \sum_x b(x) = 1$$

Mortality modeling after 1980

Data for Swedish males



Data source: Human Mortality Database

Factor analysis of mortality at advanced ages

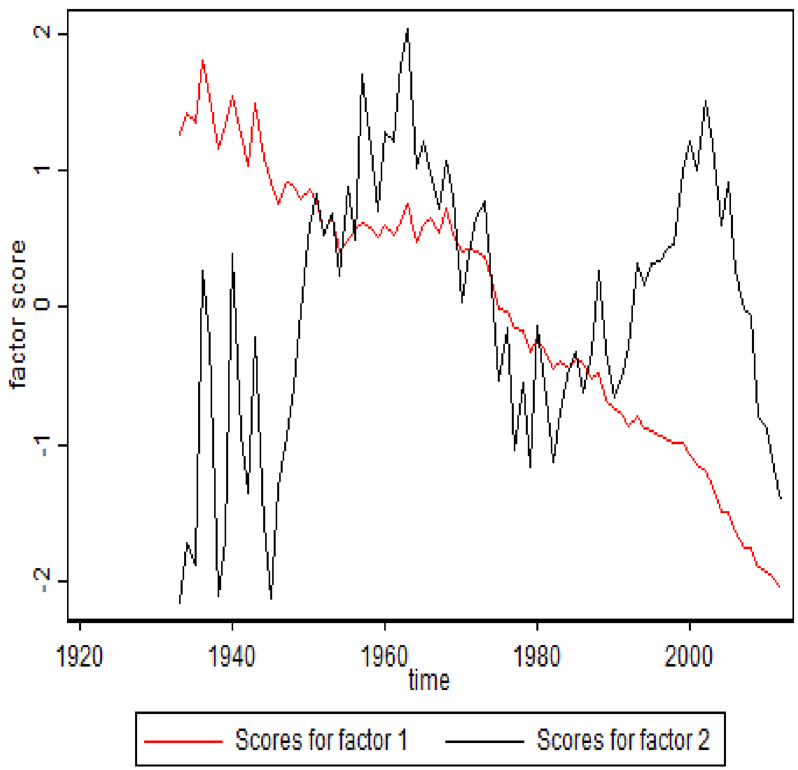
Mortality at advanced ages is explained by specific oldest-old factor.

This factor shows variability but no decline over time.

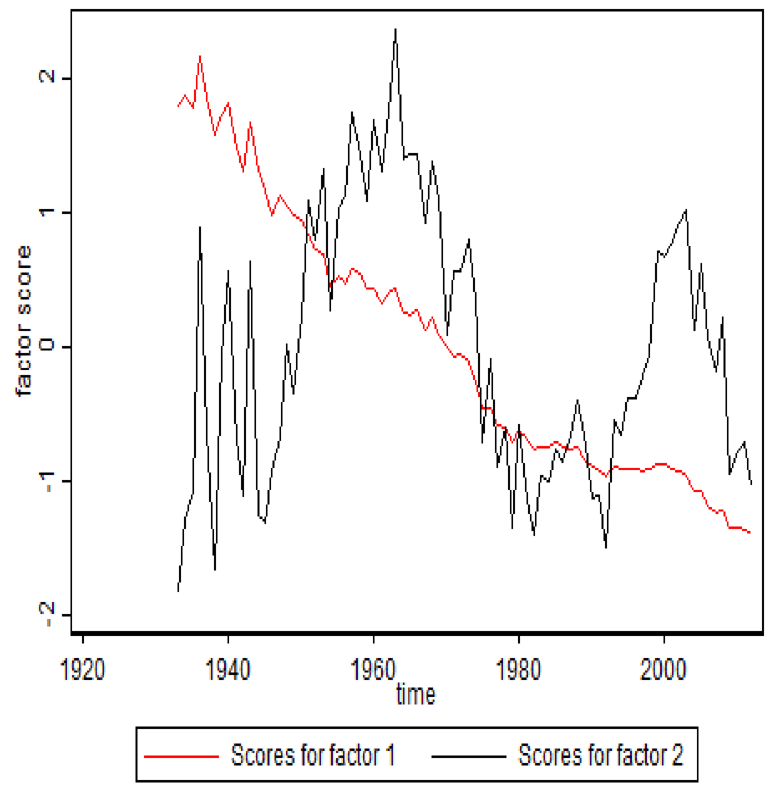
Factor analysis of the U.S. data

Mortality analyzed in age interval 65-100 years

Men



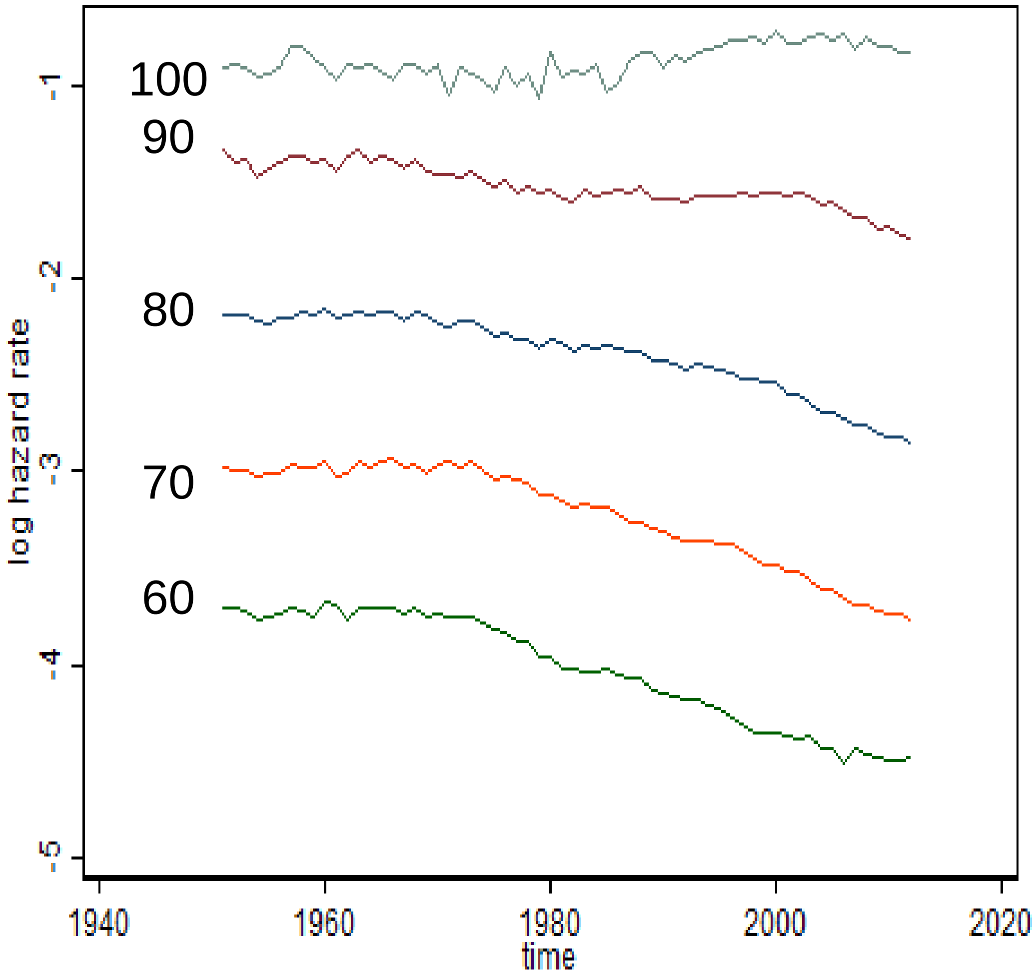
Women



Red color - Old-age factor . Black color – Oldest-old-age factor

Data source: Human Mortality Database

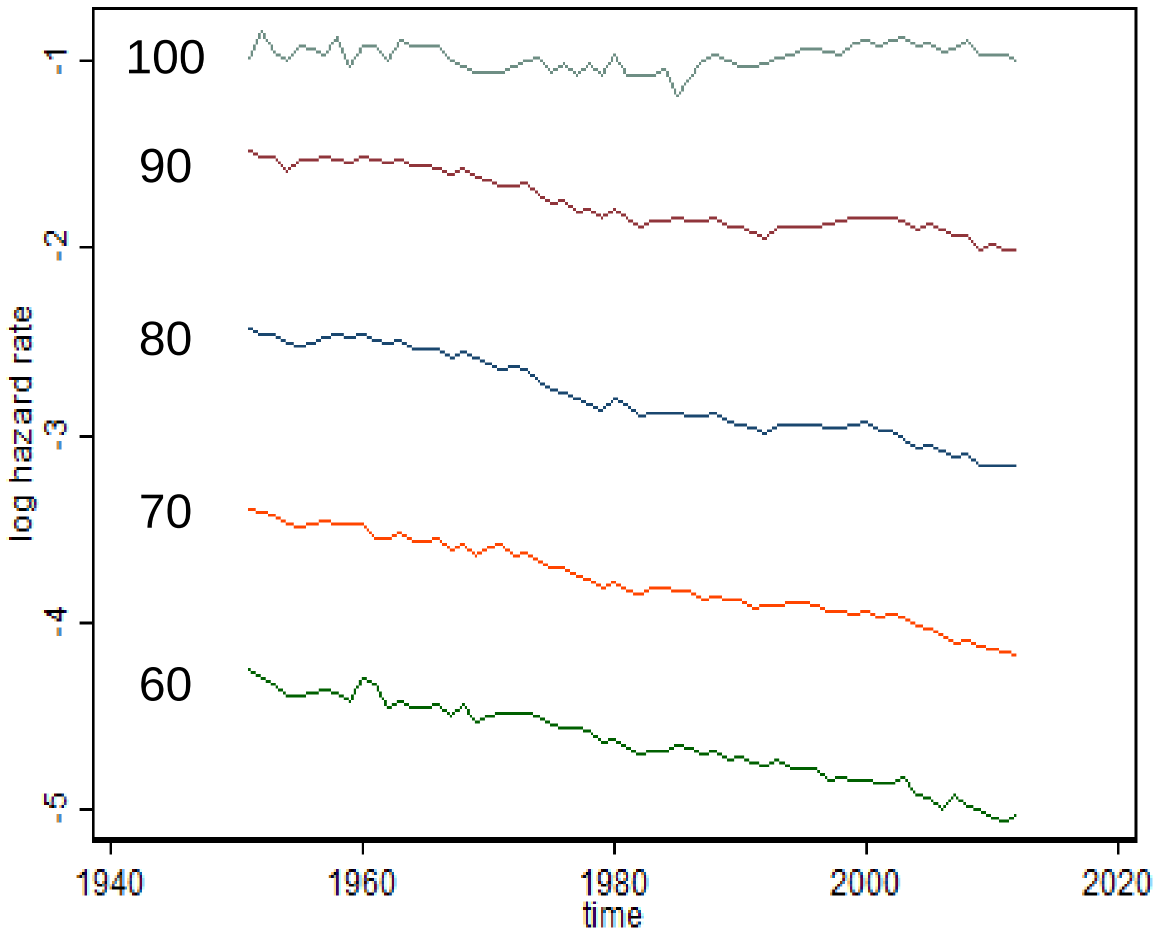
Mortality of Male Centenarians Does Not Decline Over Time



Mortality of U.S. Men at 60, 70, 80, 90 and 100 years

Based on data from the Human Mortality Database

Mortality of Female Centenarians Does Not Decline Over Time



Mortality of U.S. Women at 60, 70, 80, 90 and 100 years

Based on data from the Human Mortality Database

Conclusions

- Factor analysis of mortality trends allows researchers to find the most optimal base period for adult mortality forecasting when the background factor remains constant and the senescent factor shows steady decline over time.
- This one-factor model, however, cannot be applied to extreme old ages (over 96 years) when the oldest-old mortality is driven by its own factor with specific behavior over time.

Acknowledgments

This study was made possible thanks to:

generous support from the

- National Institute on Aging
- NORC at the University of Chicago

For More Information and Updates Please Visit Our Scientific and Educational Website on Human Longevity:

- **http://longevity-science.org**

And Please Post Your Comments at our Scientific Discussion Blog:

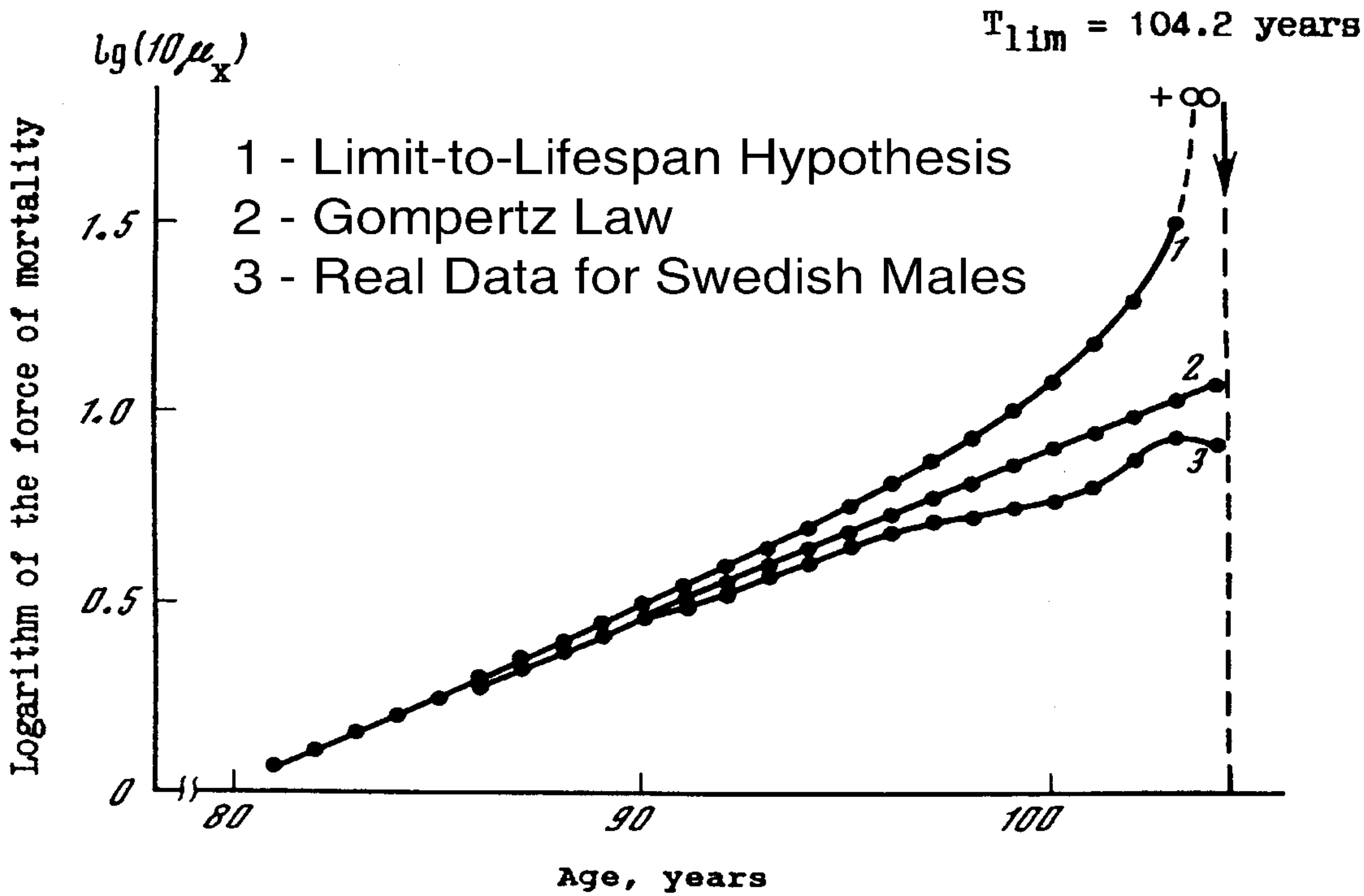
- **http://longevity-science.blogspot.com/**

Mortality of Supercentenarians: Does It Grow with Age?

Natalia S. Gavrilova, Ph.D.
Leonid A. Gavrilov, Ph.D.

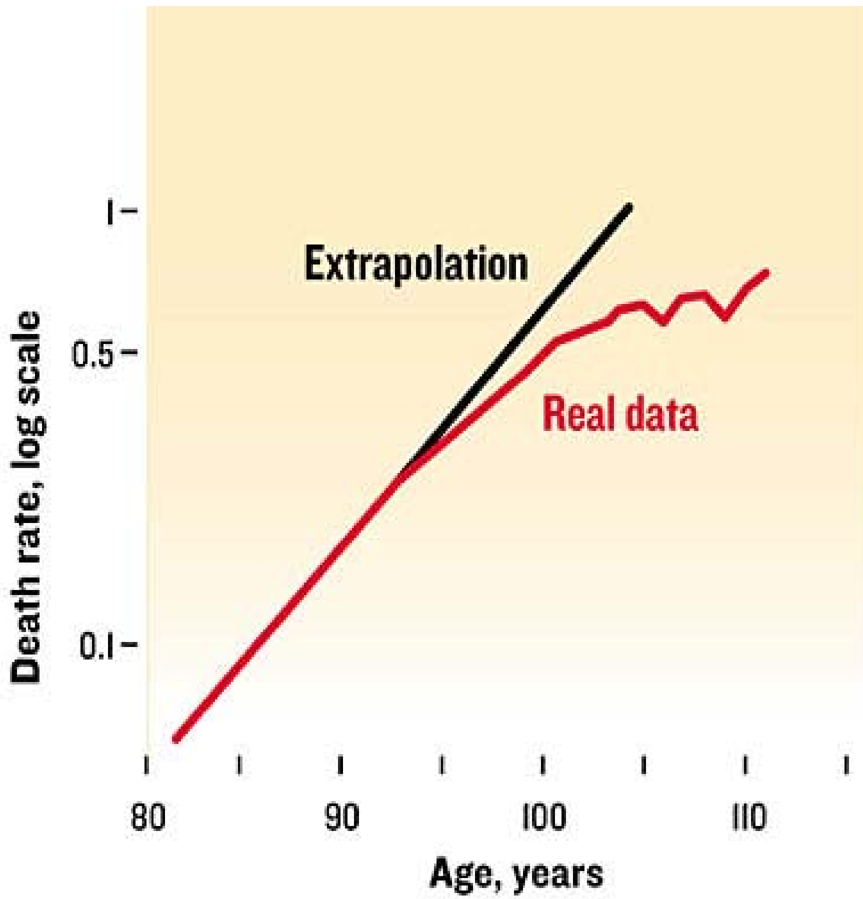
Center on Aging
NORC and The University of Chicago
Chicago, Illinois, USA

Possible scenarios for mortality after age 80



Source: **Gavrilov L.A., Gavrilova N.S. The Biology of Life Span: A Quantitative Approach, NY: Harwood Academic Publisher, 1991**

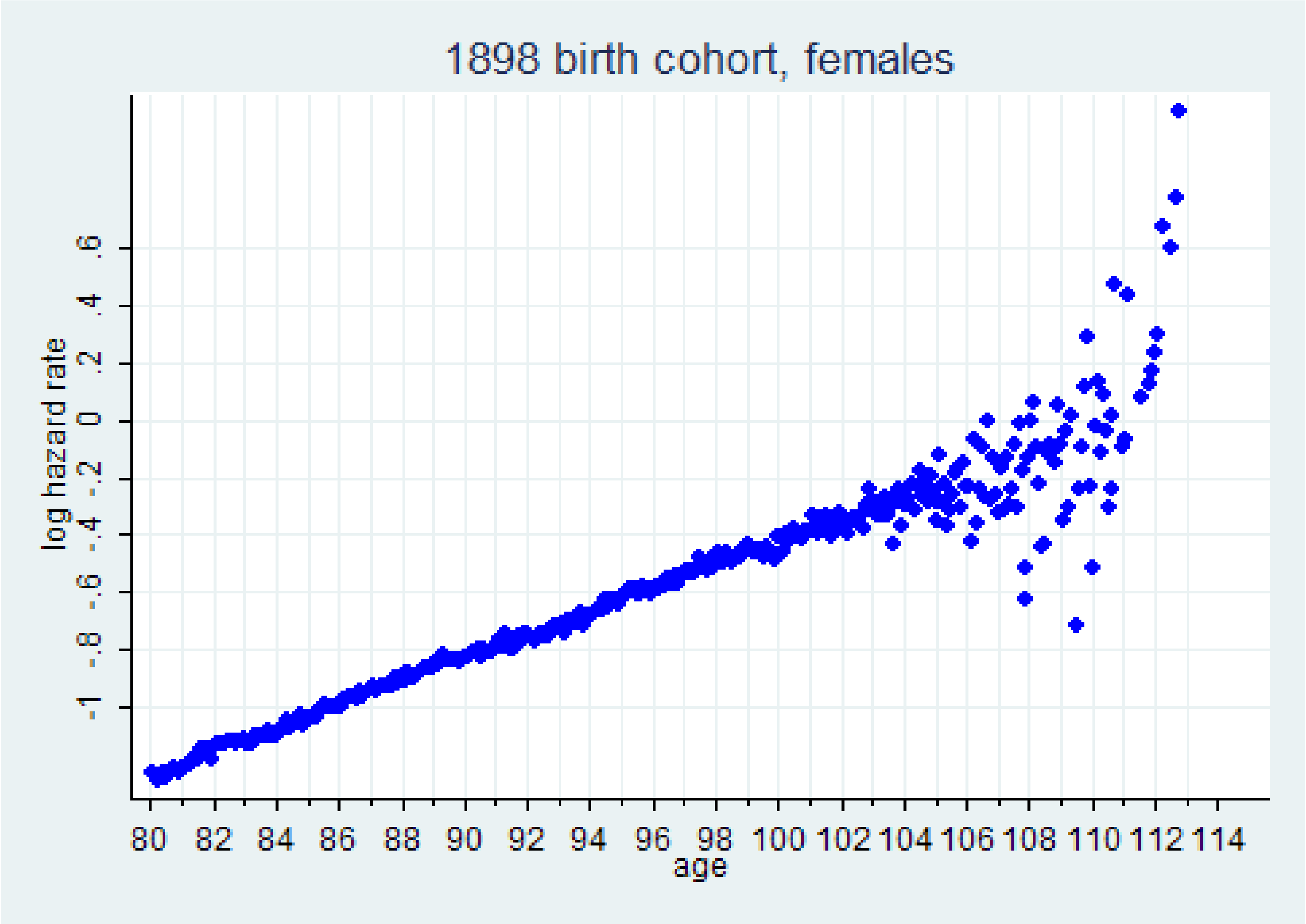
Mortality deceleration at advanced ages.



- **After age 95, the observed risk of death [red line] deviates from the values predicted by the Gompertz law [black line].**
- Mortality of Swedish women for the period of 1990-2000 from the Kannisto-Thatcher Database on Old Age Mortality
- Source: Gavrilov, Gavrilova, "Why we fall apart. Engineering's reliability theory explains human aging". *IEEE Spectrum*. 2004.

Gompertz model of old-age mortality (2011)

- **Study of 20 single-year extinct U.S. birth cohorts based on the Social Security Administration Death Master File found no mortality deceleration up to ages 105-106 years (Gavrilov, Gavrilova, NAAJ, 2011).**
- **However, data quality problems did not allow us to study mortality trajectories after age 107 or 110 years using this source of data.**



Mortality of 1898 U.S. cohort. Data Source: DMF full file obtained from the National Technical Information Service (NTIS). Last deaths occurred in September 2011.

Nelson-Aalen monthly estimates of hazard rates using Stata 11

Study of the Social Security Administration Death Master File

Mortality Measurement at Advanced Ages: A Study of the Social Security Administration Death Master File

Leonid A. Gavrilov* and Natalia S. Gavrilova†

Abstract

Accurate estimates of mortality at advanced ages are essential to improving forecasts of mortality and the population size of the oldest old age group. However, estimation of hazard rates at extremely old ages poses serious challenges to researchers: (1) The observed mortality deceleration

North American Actuarial Journal, Volume 15, Number 3

- ***North American Actuarial Journal*, 2011, 15(3):432-447**

Study of the U.S. cohort death rates taken from the Human Mortality Database

Journals of Gerontology: BIOLOGICAL SCIENCES
Cite journal as: J Gerontol A Biol Sci Med Sci
doi:10.1093/gerona/glu009

Biodemography of Old-Age Mortality in Humans and Rodents

Natalia S. Gavrilova and Leonid A. Gavrilov

Center on Aging, NORC at the University of Chicago, Chicago, Illinois.

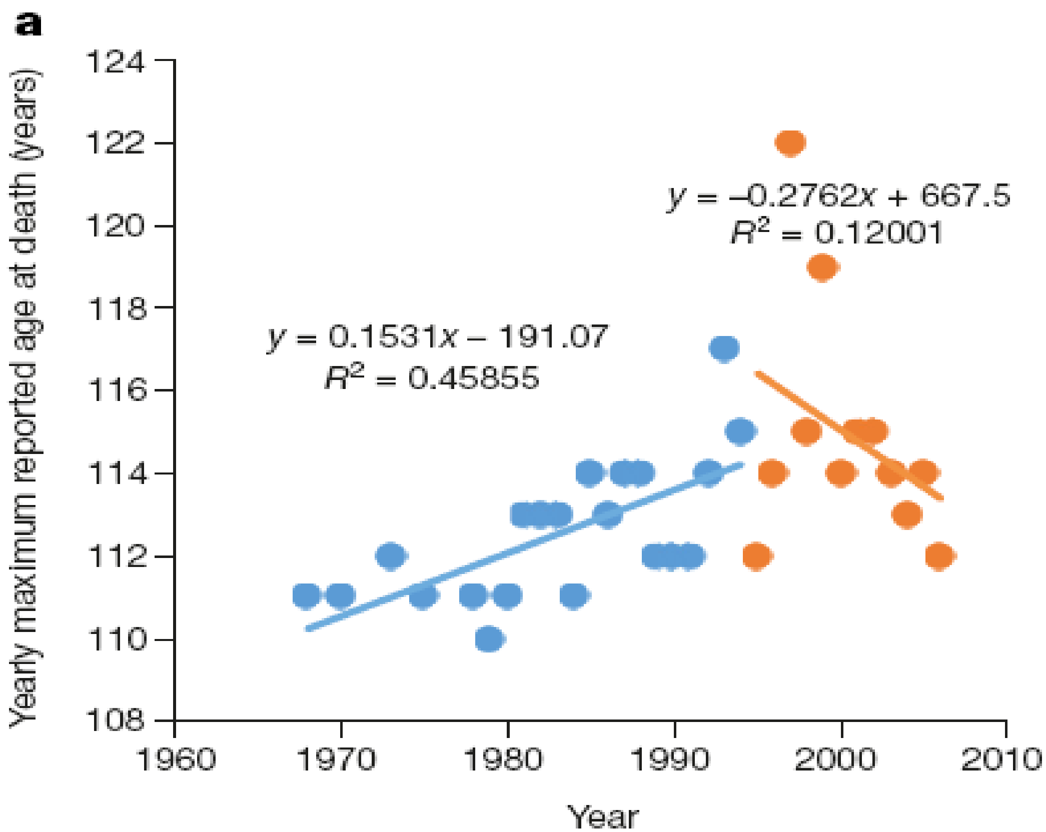
Address correspondence to Natalia S. Gavrilova, PhD, Center on Aging, NORC at the University of Chicago, 1155 East 60th Street, Chicago, IL 60637. Email: gavrilova@longevity-science.org

The growing number of persons living beyond age 80 underscores the need for accurate measurement of mortality at advanced ages and understanding the old-age mortality trajectories. It is believed that exponential growth of mortality

Nature (2016)

Evidence for a limit to human lifespan

Xiao Dong[1]*, Brandon Milholland[1]* & Jan Vijg[1,2]



Based on data from the International Database on Longevity (IDL)

Note: After 2000 number of supercentenarians exposed to death rapidly declines

International Database on Longevity (IDL)

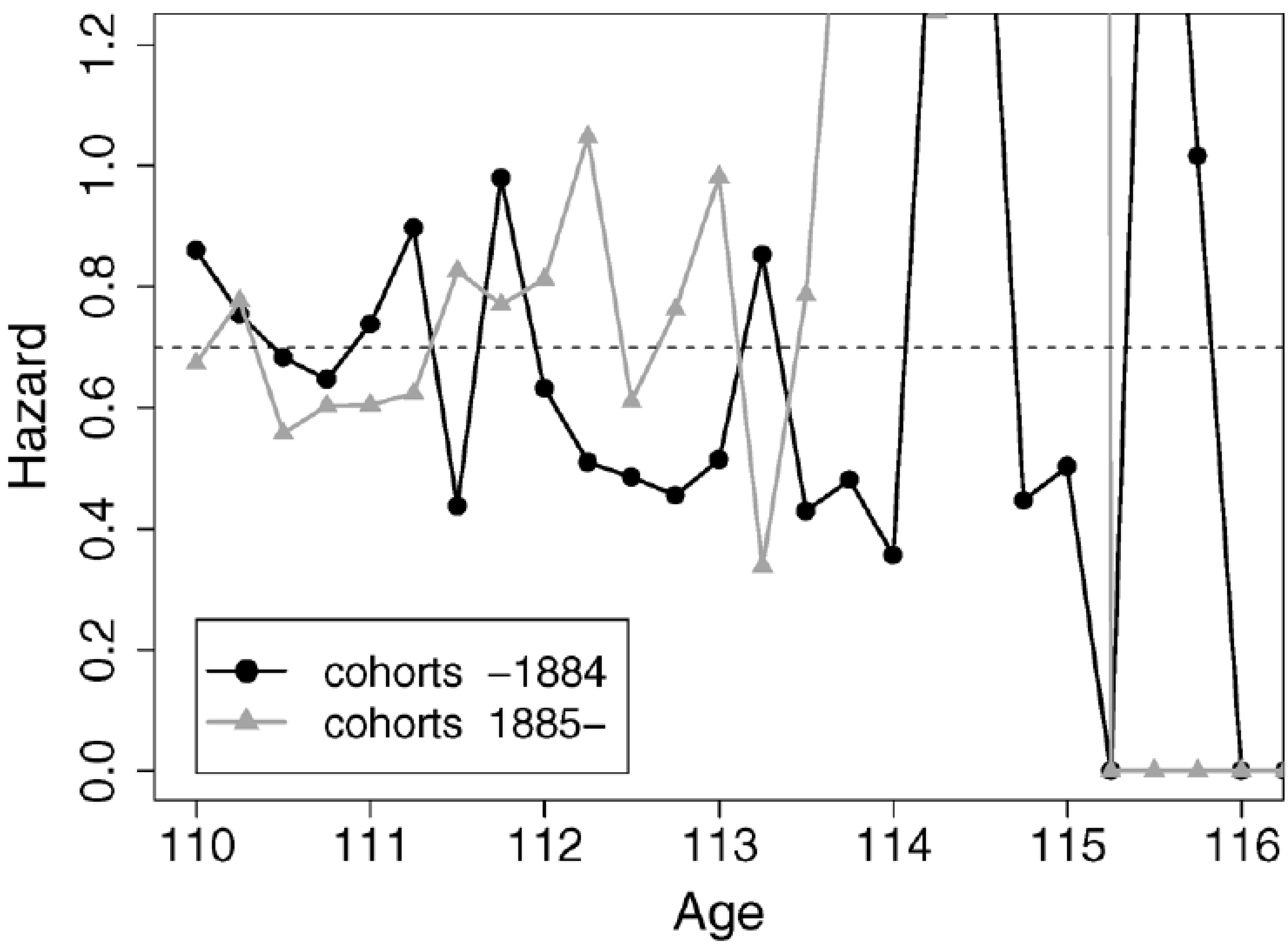
- This database contains validated records of 637 persons aged 110 years and more from 15 countries with good quality of vital records.
- The contributors to IDL performed data collection in a way that avoided age-ascertainment bias, which is essential for demographic analysis.
- The database was last updated in March 2010.
- Available at www.supercentenarians.org

Previous studies of mortality using IDL

- Robine and Vaupel, 2001.
- Robine et al. (2005). Used IDL data, calculated age-specific probabilities of death.
- Gampe, 2010. Used IDL data. Wrote her own program to estimate hazard rates, which adjusts for censored and truncated data.

Main conclusion from Gampe (2010) study is that hazard rate after age 110 years is flat.

From study by Gampe (2010)



It is believed now that mortality of supercentenarians is flat

INSIGHT REVIEW NATURE|Vol 464|25 March 2010|doi:10.1038/nature08984

Biodemography of human ageing

James W. Vaupel[1,2,3]

“Mortality for humans seems to level off after age 110” (Vaupel, *Nature*, 2010, p.539)

Our study of supercentenarians based on IDL data

- IDL database as of January, 2015. Last update in 2010, last deaths in 2007.
- Two extinct birth cohorts (<1885 and 1885-1892), so no censored or truncated records were used.
- Hazard rate was estimated using standard Stata package (procedure *ltable*).
- Hazard rate was calculated using actuarial estimate of hazard rate (mortality rate):

$$\mu_{x+\frac{\Delta x}{2}} = \frac{2}{\Delta x} \frac{l_x - l_{x+\Delta x}}{l_x + l_{x+\Delta x}}$$

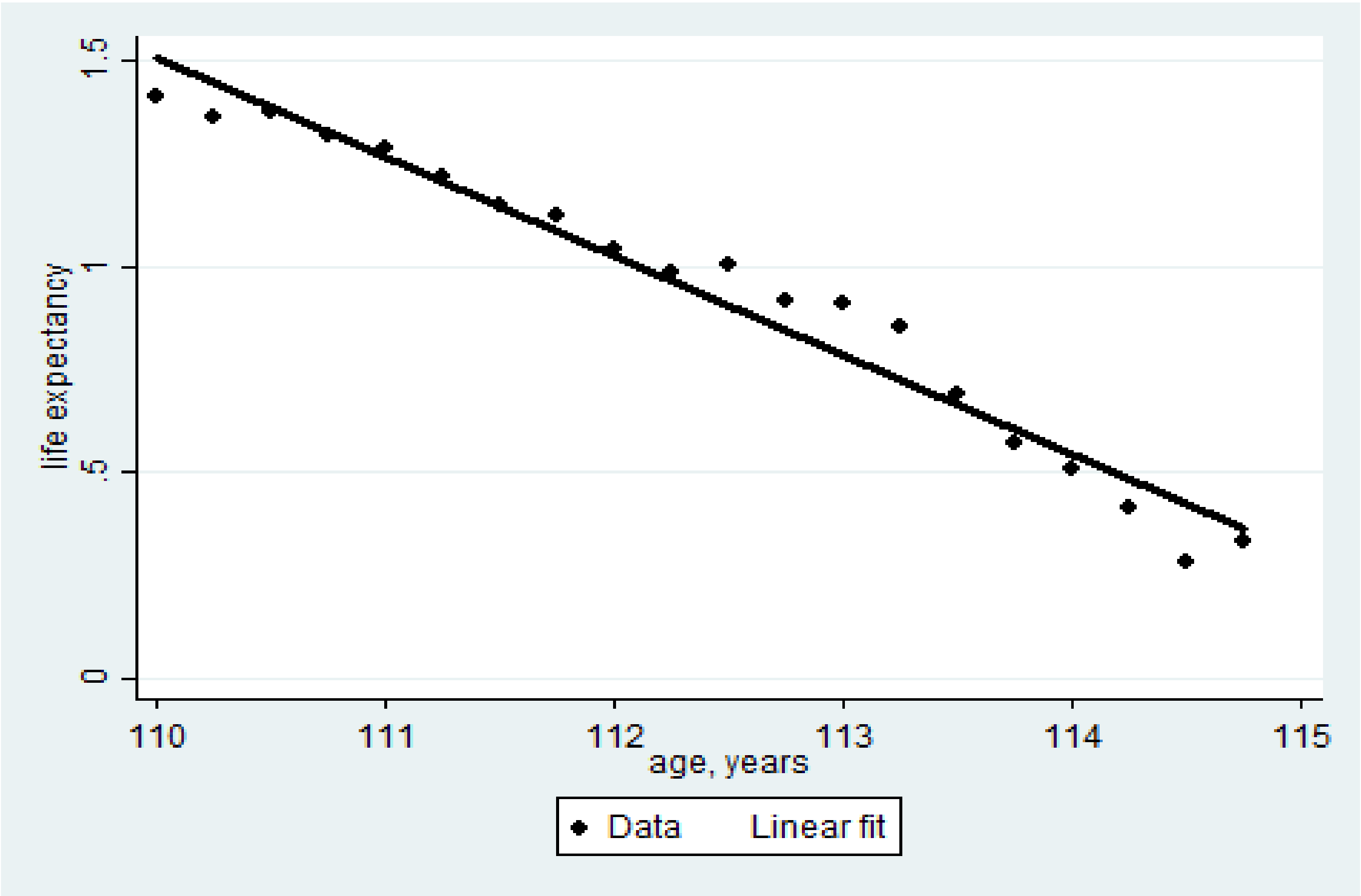
Testing assumption about flat hazard rate after age 110

- **Direct estimates of hazard rates at advanced ages are subjected to huge variations.**
- **More robust ways of testing this assumption come from the properties of exponential distribution:**

1. **Hazard rate, $\mu = const$**
2. **Mean life expectancy (LE) = $1/\mu = const$**
3. **Coefficient of variation for LE = $SD/mean=1$**

Mean life expectancy vs age

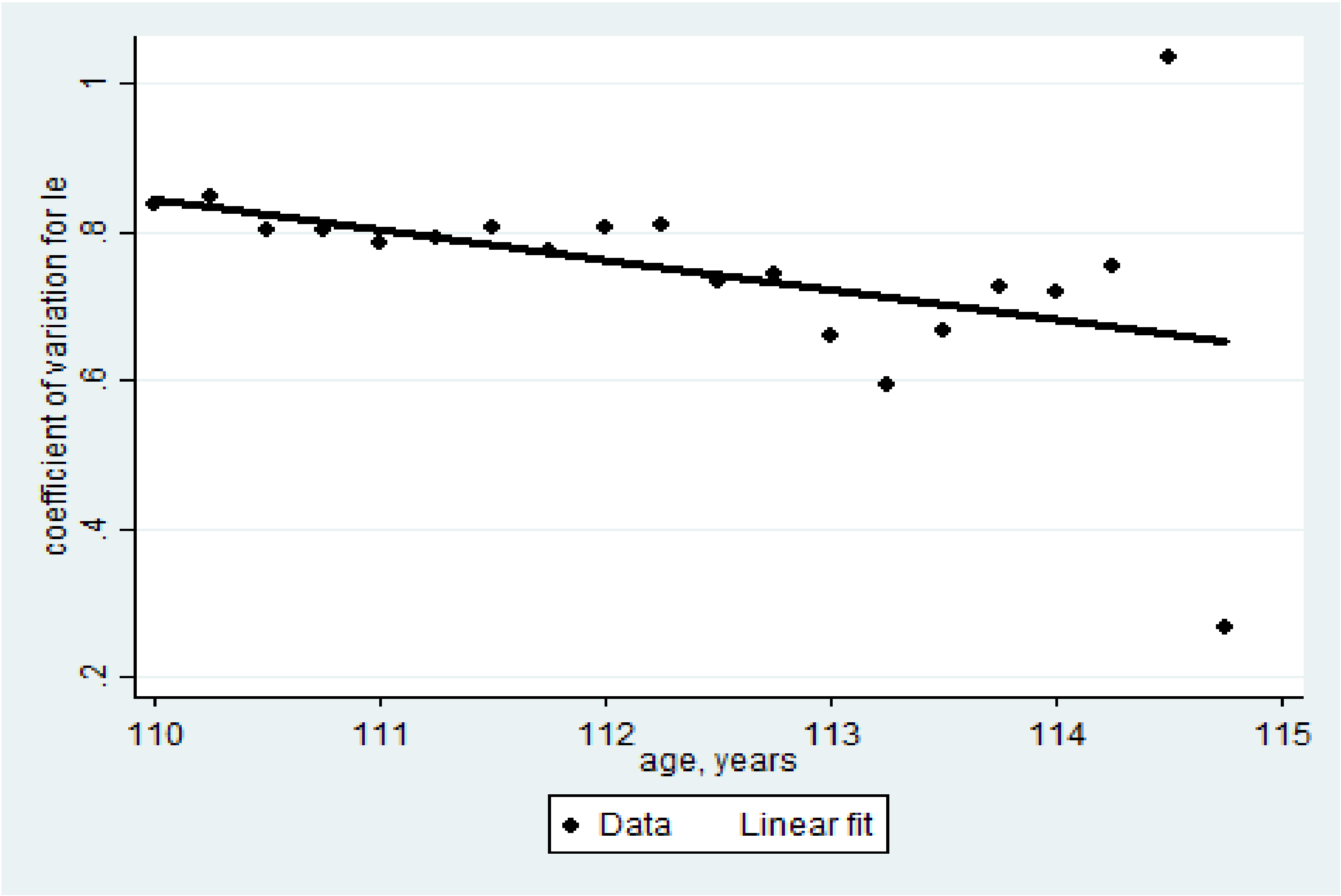
Cohort born in 1885-1892



Slope coefficient = -0.24 ($p<0.001$). Quarterly age intervals

Coefficient of variation for LE vs age

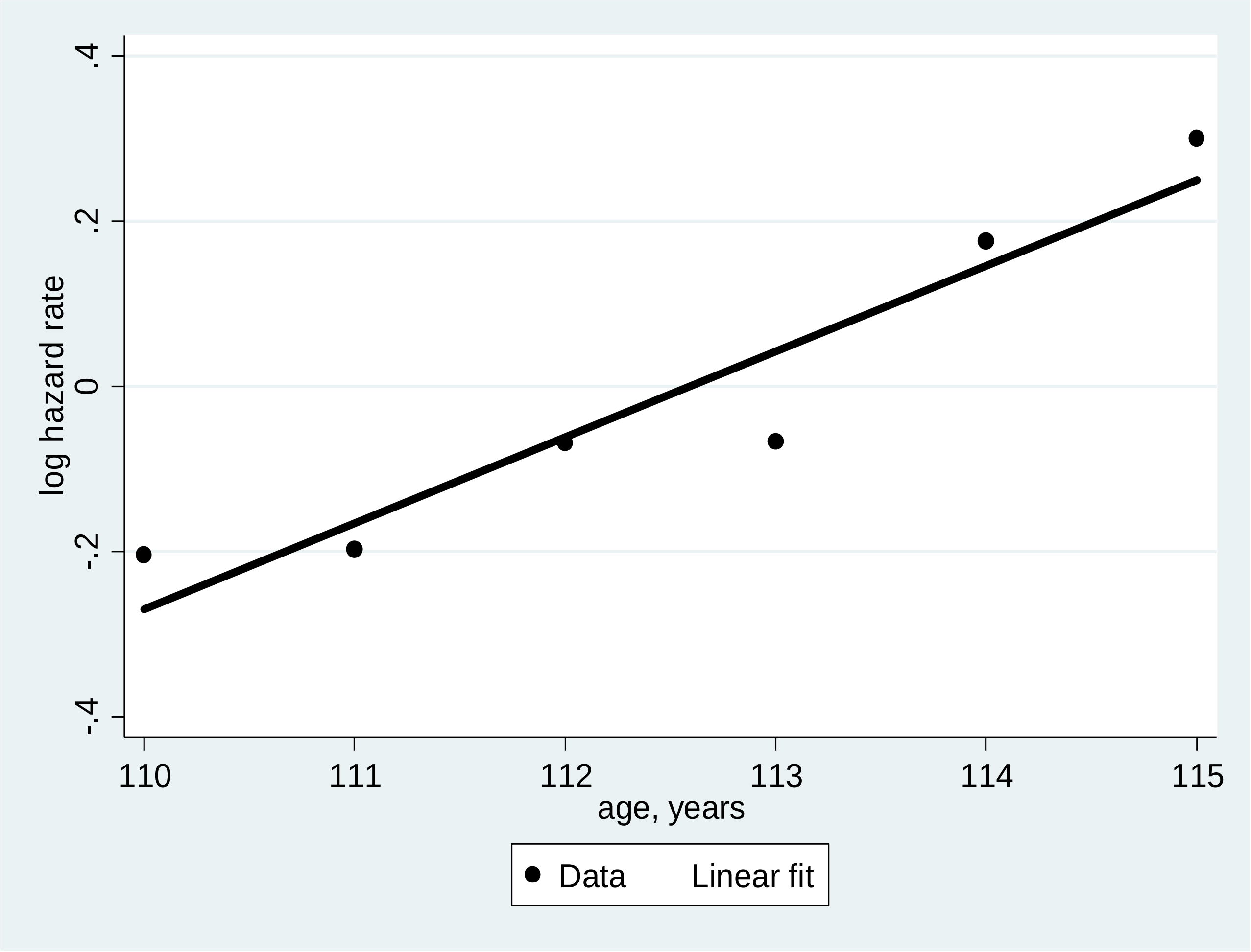
Cohort born in 1885-1892



Slope coefficient = -0.041 (p=0.066). Quarterly age intervals

Mortality of supercentenarians increases with age

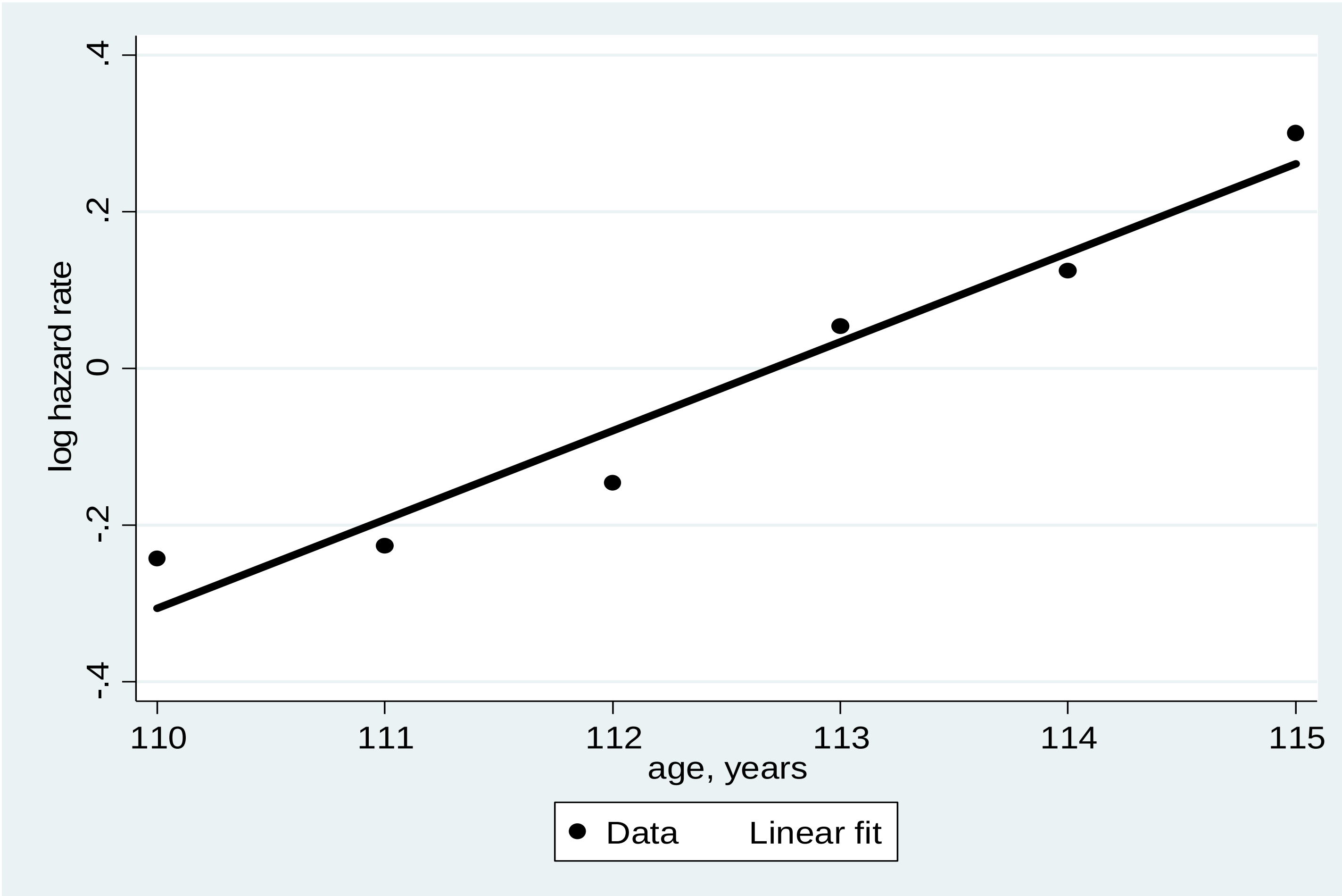
Cohort born in 1885-1892



Yearly age intervals

Mortality of U.S. supercentenarians

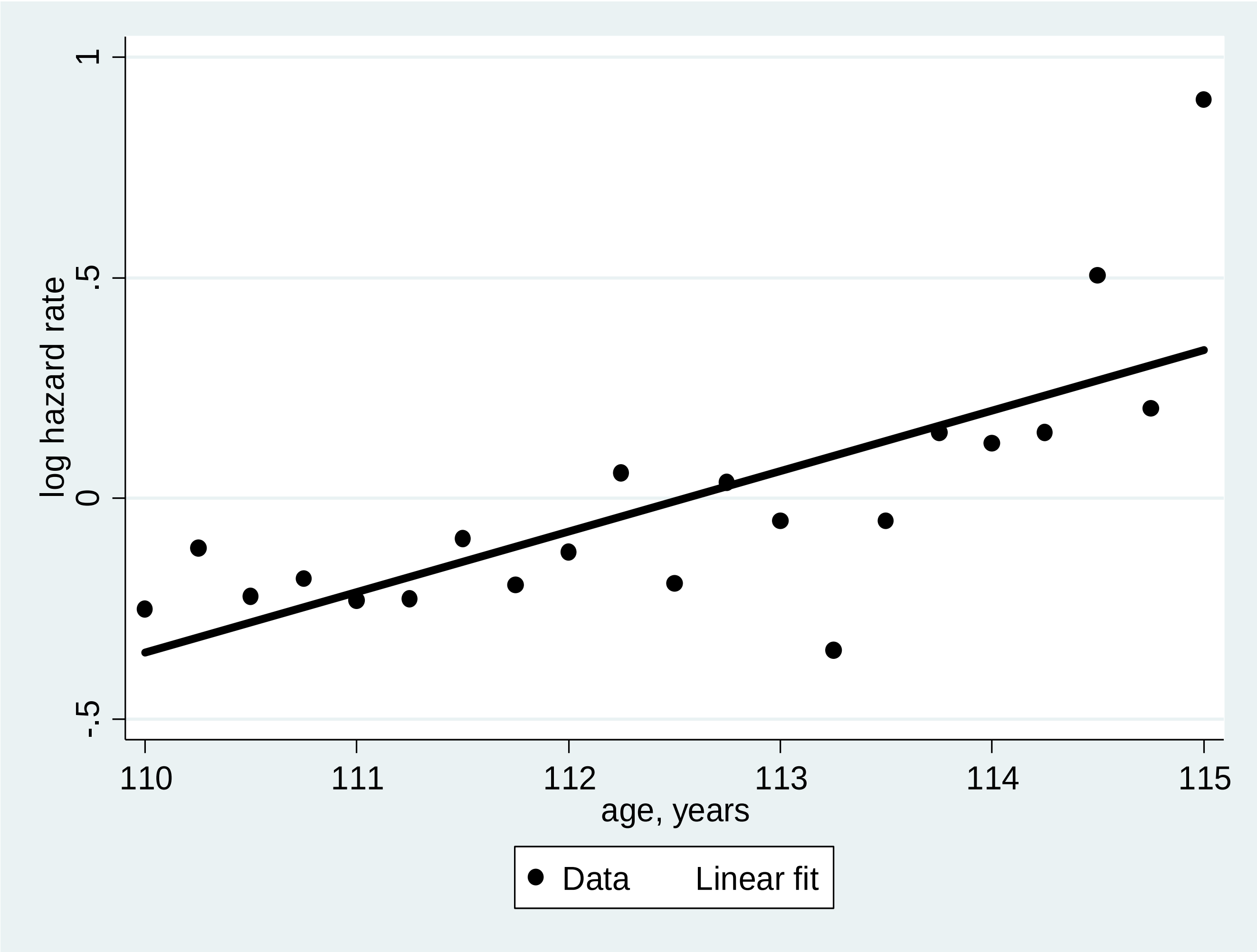
U.S. cohort born in 1885-1892



Yearly age intervals

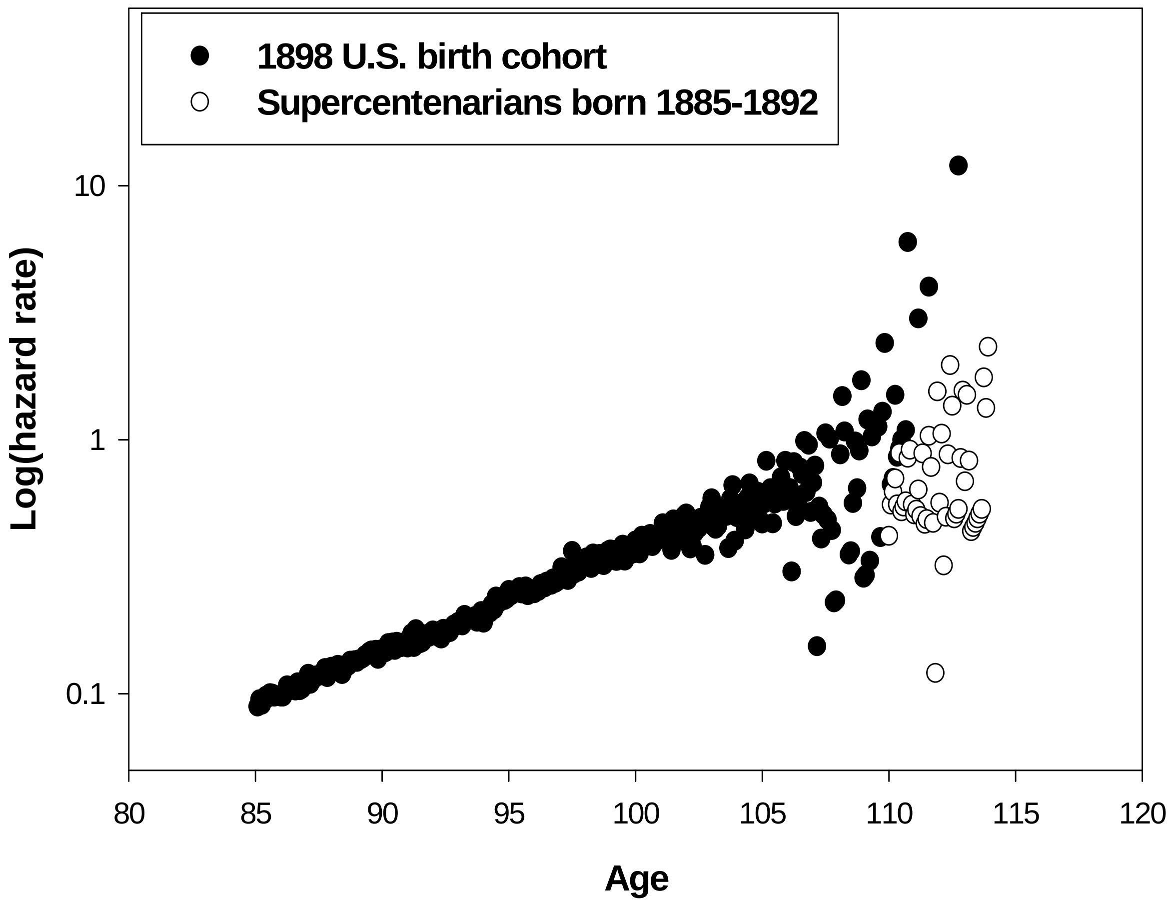
Mortality of supercentenarians

Cohort born in 1885-1892



Quarterly age intervals

Mortality after age 85 years



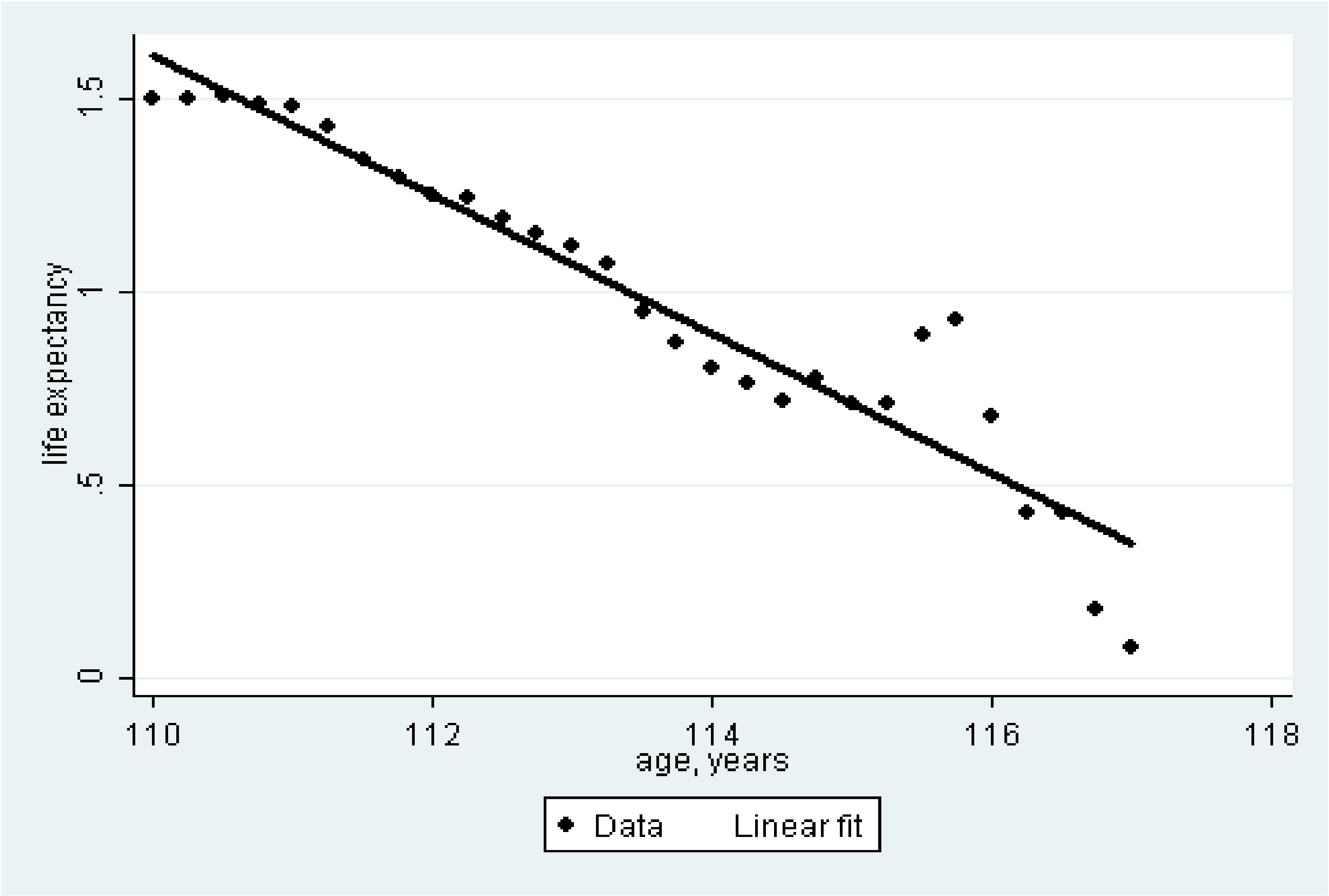
Monthly age intervals

More up-to-date records: GRG database

- Database is maintained by the Gerontology Research Group (GRG).
- Collects information on alleged supercentenarians and validates their birth dates with at least 3 documentary sources.
- The last deaths occurred in 2016.
- The 1898 birth cohort in GRG database has no living individuals and therefore can be considered to be extinct. So we analyzed data for 1885-1898 birth cohorts (over 800 records)

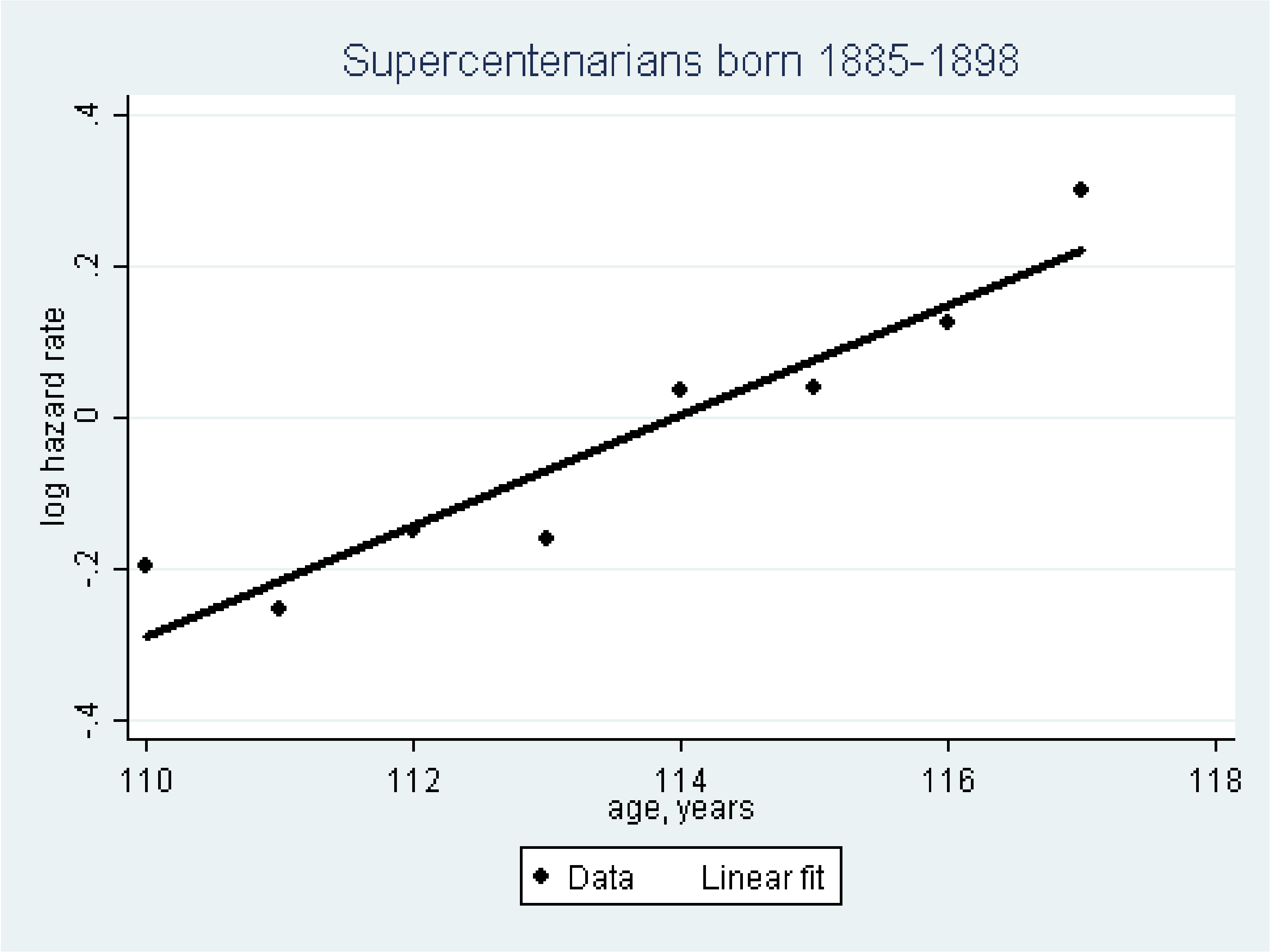
Mean remaining life expectancy vs age

834 supercentenarians born in 1885-1898



Slope coefficient = -0.18 (p<0.001). Quarterly age intervals

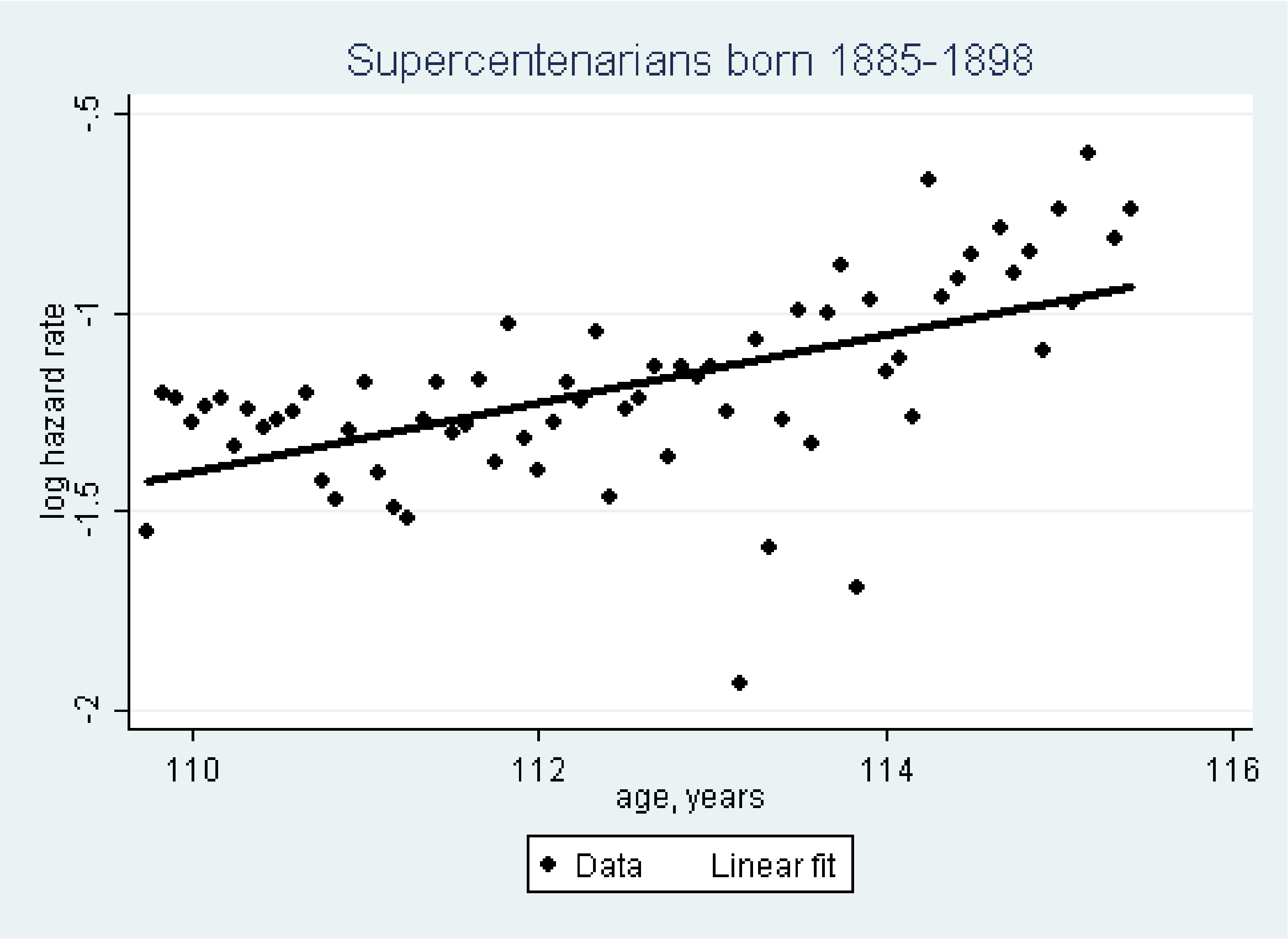
Mortality of supercentenarians
834 supercentenarians born in 1885-1898



GRG database. Yearly age intervals

Mortality of supercentenarians

834 supercentenarians born in 1885-1898



GRG database. Monthly age intervals

Conclusions

- Assumption about flat hazard rate after age 110 years is not supported by the study of age trajectory for mean remaining life expectancy (LE). LE after age 110 continues to decline, which suggests that actuarial aging does not stop.
- Coefficient of variation for LE is lower than one and declines rather than increases with age, which does not support the assumption about flat hazard rate.
- Hazard rate estimates (mortality rates) after age 110 continue to grow with almost linear trajectory in semi-log coordinates suggesting that Gompertz law is still valid at this age.

Acknowledgments

This study was made possible thanks to:

generous support from the

- National Institute on Aging (R01 AG028620)
- Stimulating working environment at NORC/University of Chicago

For More Information and Updates Please Visit Our Scientific and Educational Website on Human Longevity:

- **http://longevity-science.org**

And Please Post Your Comments at our Scientific Discussion Blog:

- **http://longevity-science.blogspot.com/**