THE BIOLOGY OF BUSINESS;SIZE MATTERS

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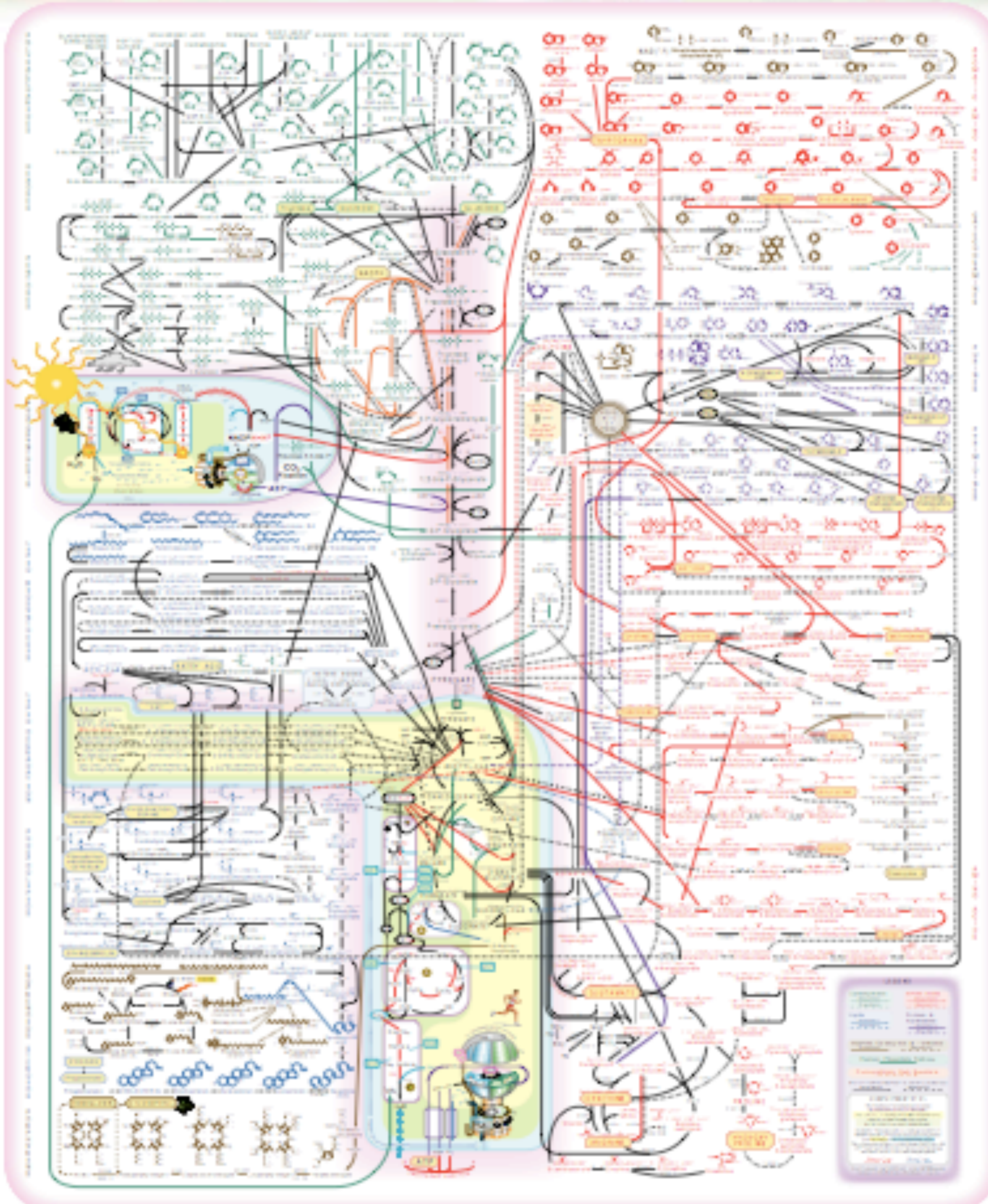
Time List of 100
Harvard Business Review

- LIVING/MAINTENANCE
- GROWTH
- REPRODUCTION
- AGING/DEATH
- EVOLUTION

- SLEEP/REPAIR
- DISEASE/CANCER
- ENERGY & RESOURCES
  vs. INFORMATION
- ***THE SEARCH FOR UNDERLYING LAWS AND PRINCIPLES LEADING TO A QUANTITATIVE PREDICTIVE CONCEPTUAL FRAMEWORK***

ARE BUSINESSES, CORPORATIONS AND CITIES JUST VERY LARGE ORGANISMS SATISFYING THE LAWS OF BIOLOGY?

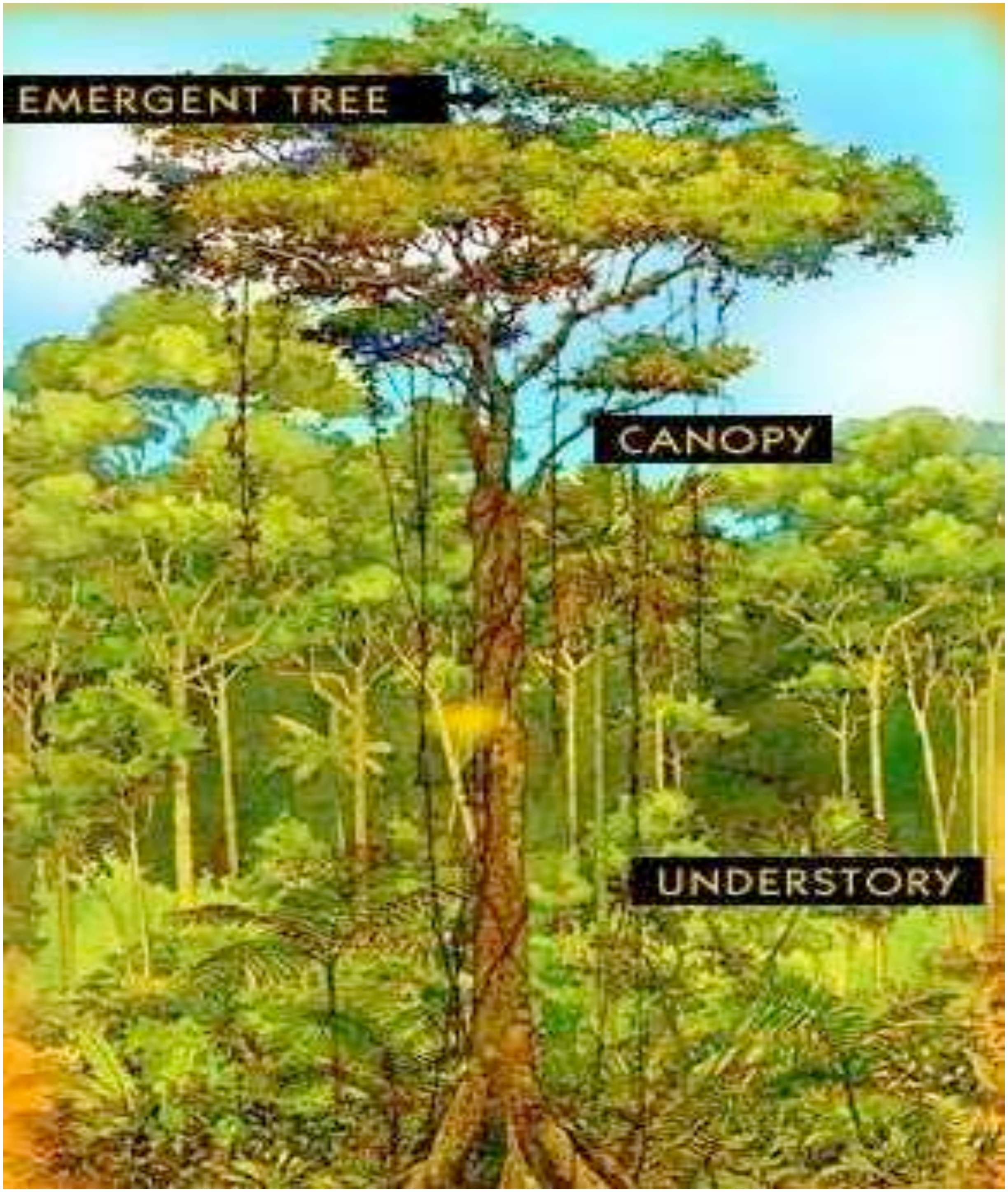
Metabolic Pathways



20th Edition Designed by Donald E. Nicholson, D.Sc., The University of Leeds, England – and Sigma-Aldrich

Relation between number and diameter of trees in a forest recapitulates the branches of the largest trees

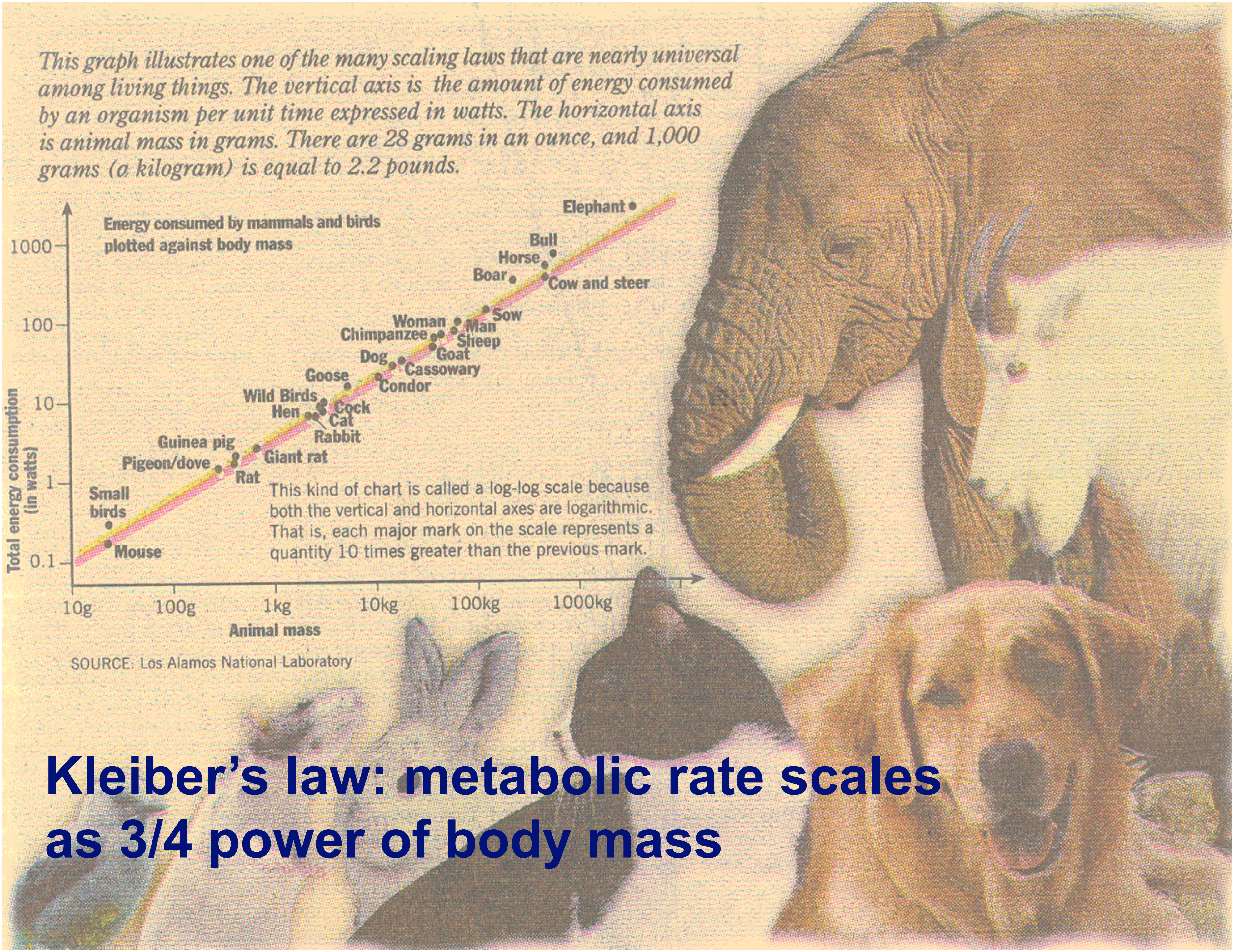
$N \propto D^{-2} \propto M^{-3/4}$



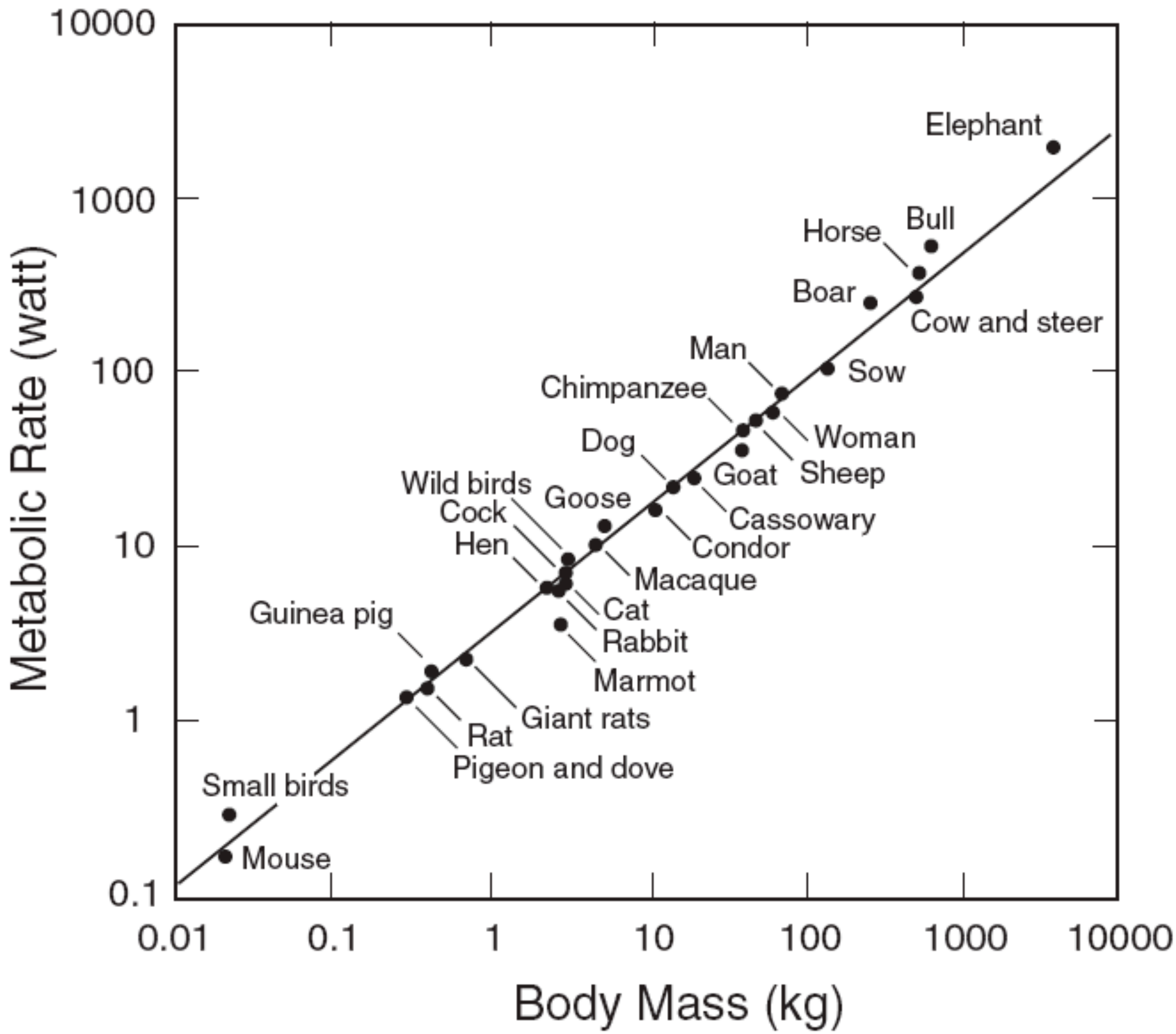

Scaling of economics with energy use


南 口
9

Mammals vary in size by 8 orders of magnitude

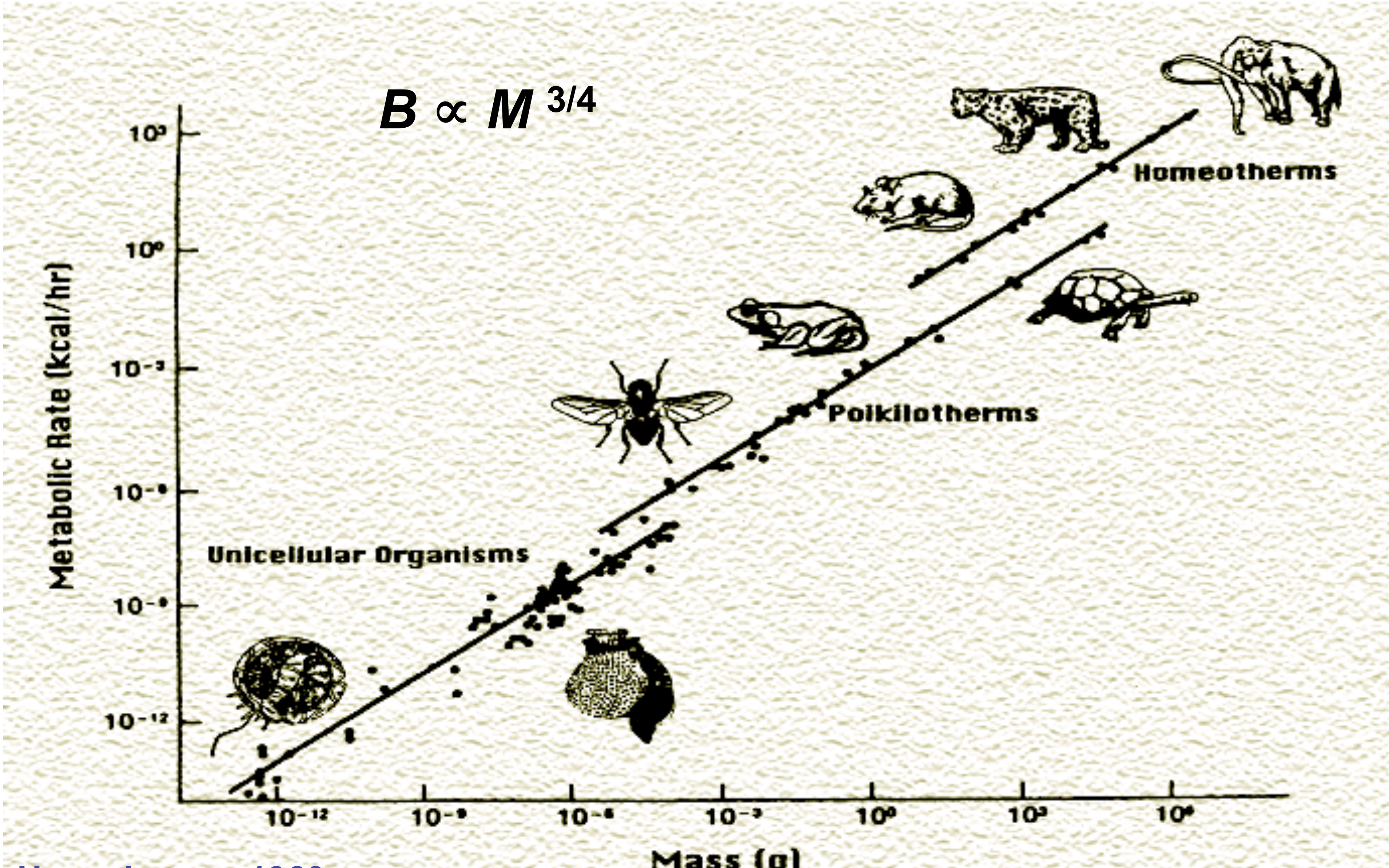


Kleiber's law: metabolic rate scales as 3/4 power of body mass

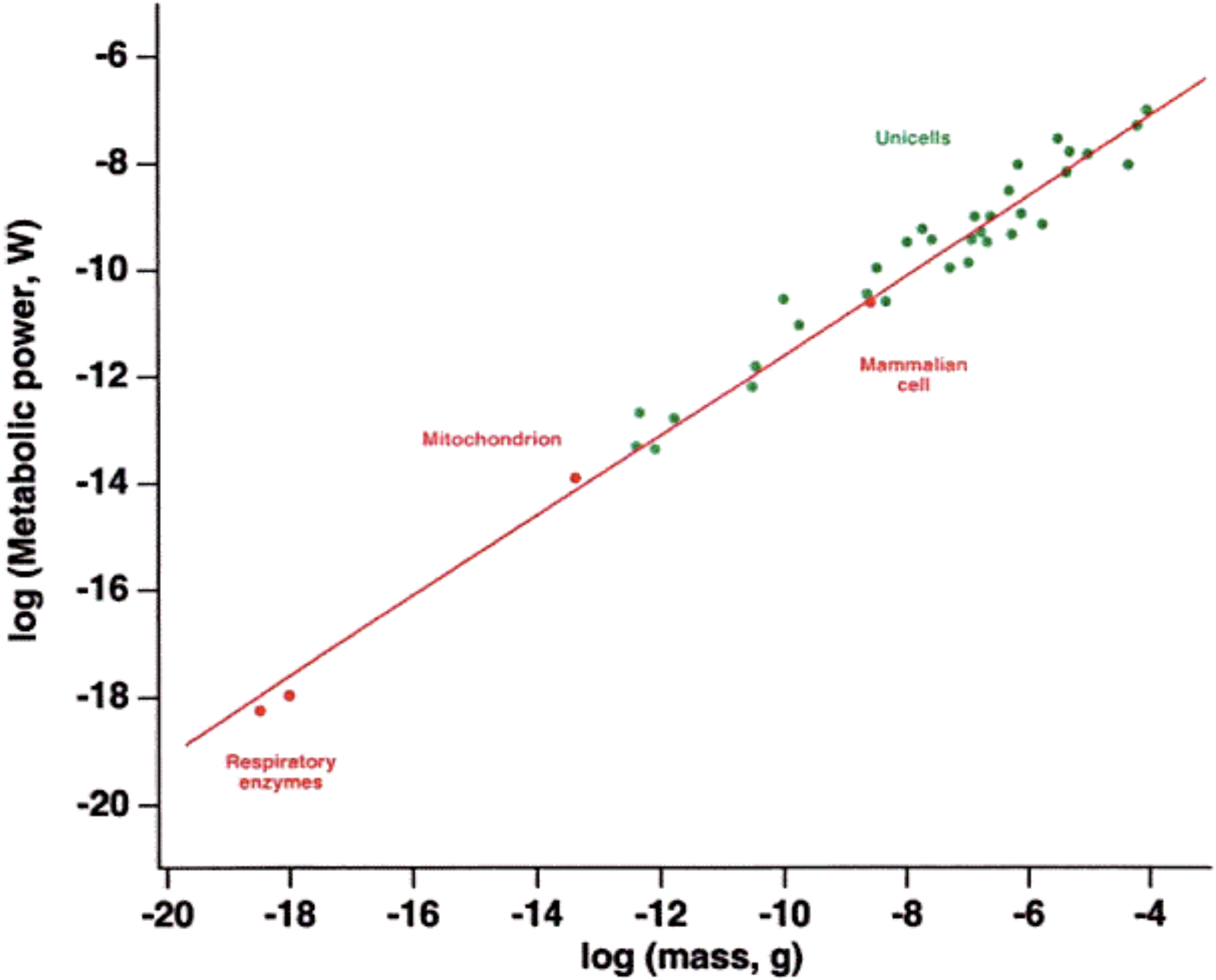


Metabolic Rate (watt)
Body Mass (kg)
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000
Elephant
Bull
Horse
Boar
Cow and steer
Man
Sow
Chimpanzee
Woman
Dog
Sheep
Goat
Wild birds
Goose
Cassowary
Cock
Condor
Hen
Macaque
Cat
Guinea pig
Rabbit
Marmot
Giant rats
Rat
Pigeon and dove
Small birds
Mouse

Whole-organism metabolic rate (*B*) scales as the 3/4 power of body mass (*M*)



Hemmingson 1960



log (Metabolic power, W)
-6
-8
-10
-12
-14
-16
-18
-20
Unicells
Mammalian cell
Mitochondrion
Respiratory enzymes
-20
-18
-16
-14
-12
-10
-8
-6
-4
log (mass, g)

METABOLIC RATE INCREASES NON-LINEARLY WITH SIZE

EXAMPLE

NAIVELY EXPECT THAT IF MASS (SIZE) INCREASES BY A FACTOR OF 10,000 (10^4)

THEN

METABOLIC RATE WOULD INCREASE BY A FACTOR OF 10,000 (10^4)

BUT

IN FACT,

METABOLIC RATE INCREASES BY A FACTOR OF ONLY 1,000 (10^3)

$$B \sim M^{3/4}$$

LIFE EXHIBITS AN EXTRAORDINARY SYSTEMATIC ECONOMY OF SCALE

TO SUSTAIN 1 gm MOUSE REQUIRES 3 TIMES THE POWER FOR 1 gm of DOG AND 9 TIMES THE POWER FOR 1 gm of ELEPHANT!!

SMALL BE BEAUTIFUL BUT LARGE IS MORE EFFICIENT

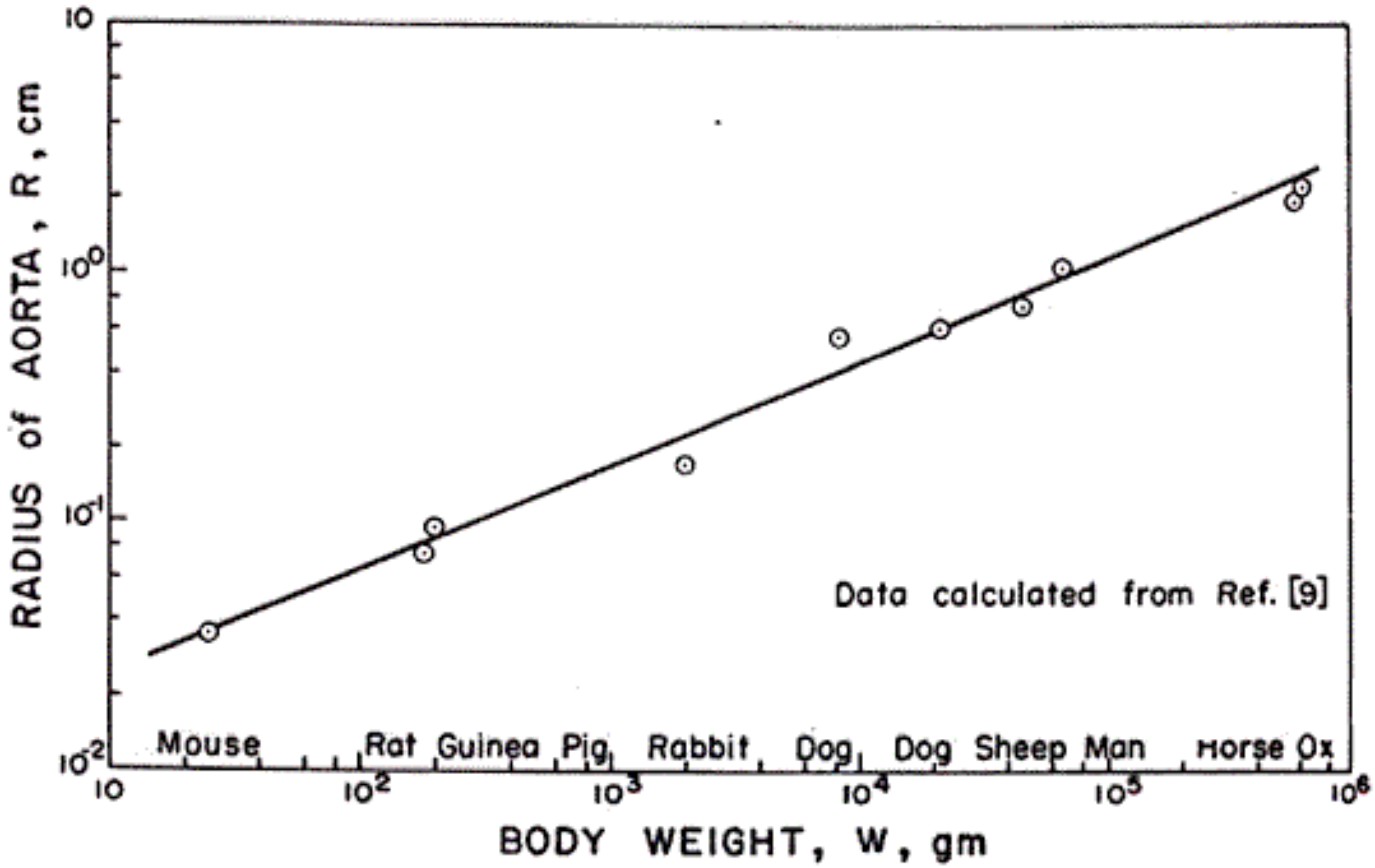
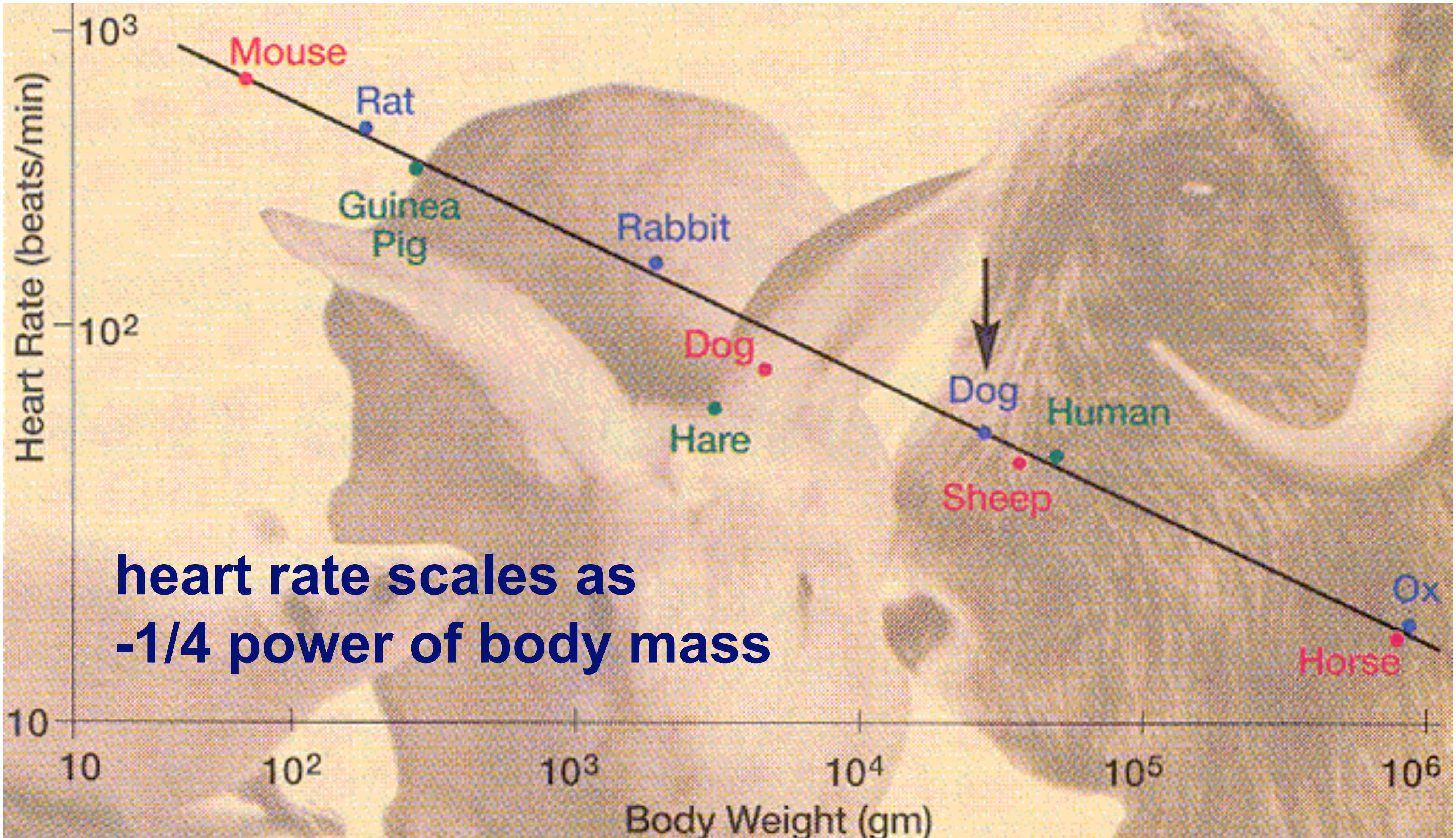


FIG. 4 – VARIATION IN RADIUS OF AORTA WITH BODY WEIGHT

$r \sim M^{3/8}$

SAME SCALING FOR TREE TRUNKS

Metabolic rate sets the pace of life
small animals live fast and die young



LIFESPAN

$$T \sim M^{1/4}$$

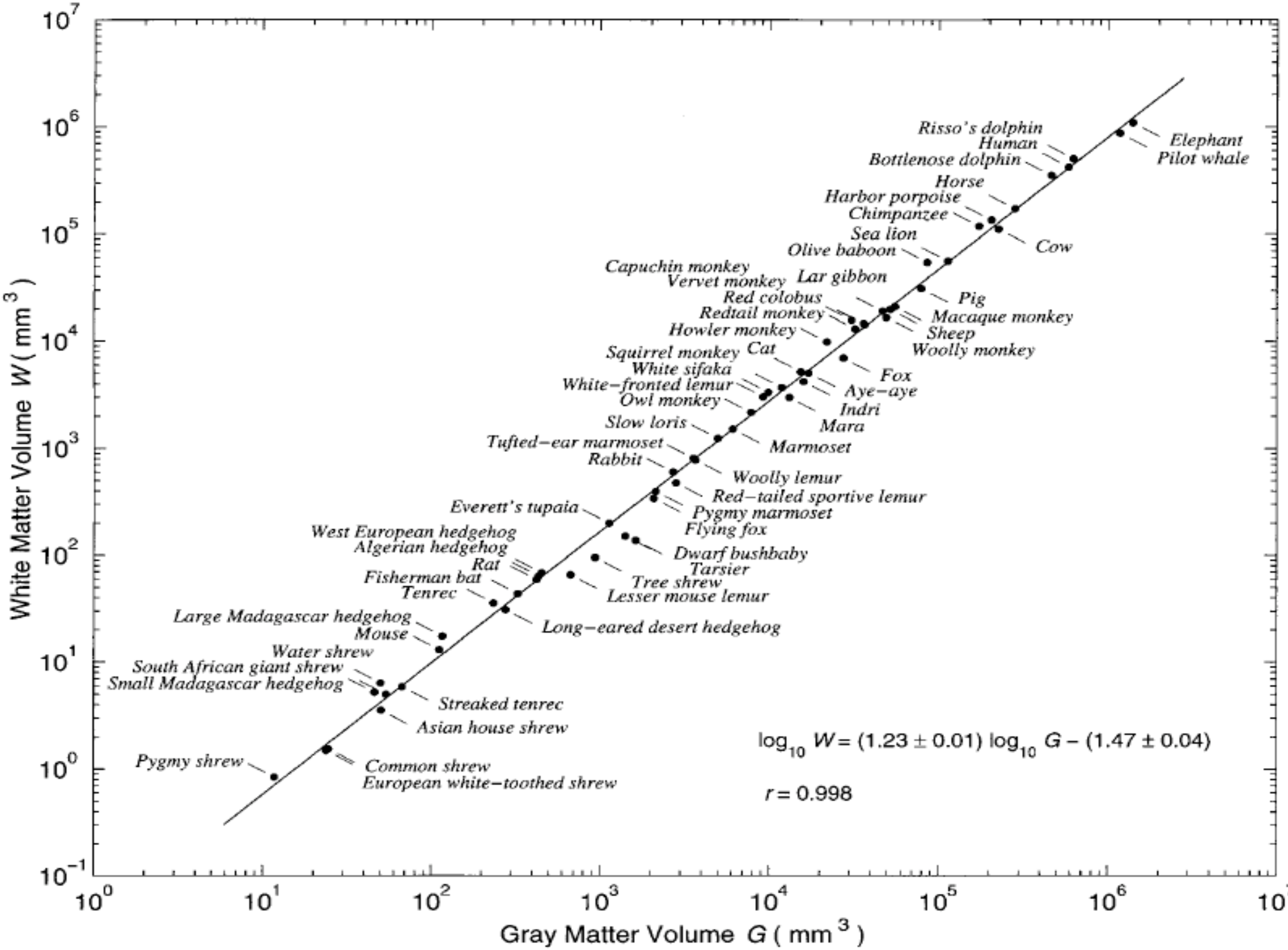
IF HEART-RATE (NUMBER OF BEATS PER SEC.)

$$\sim M^{-1/4}$$

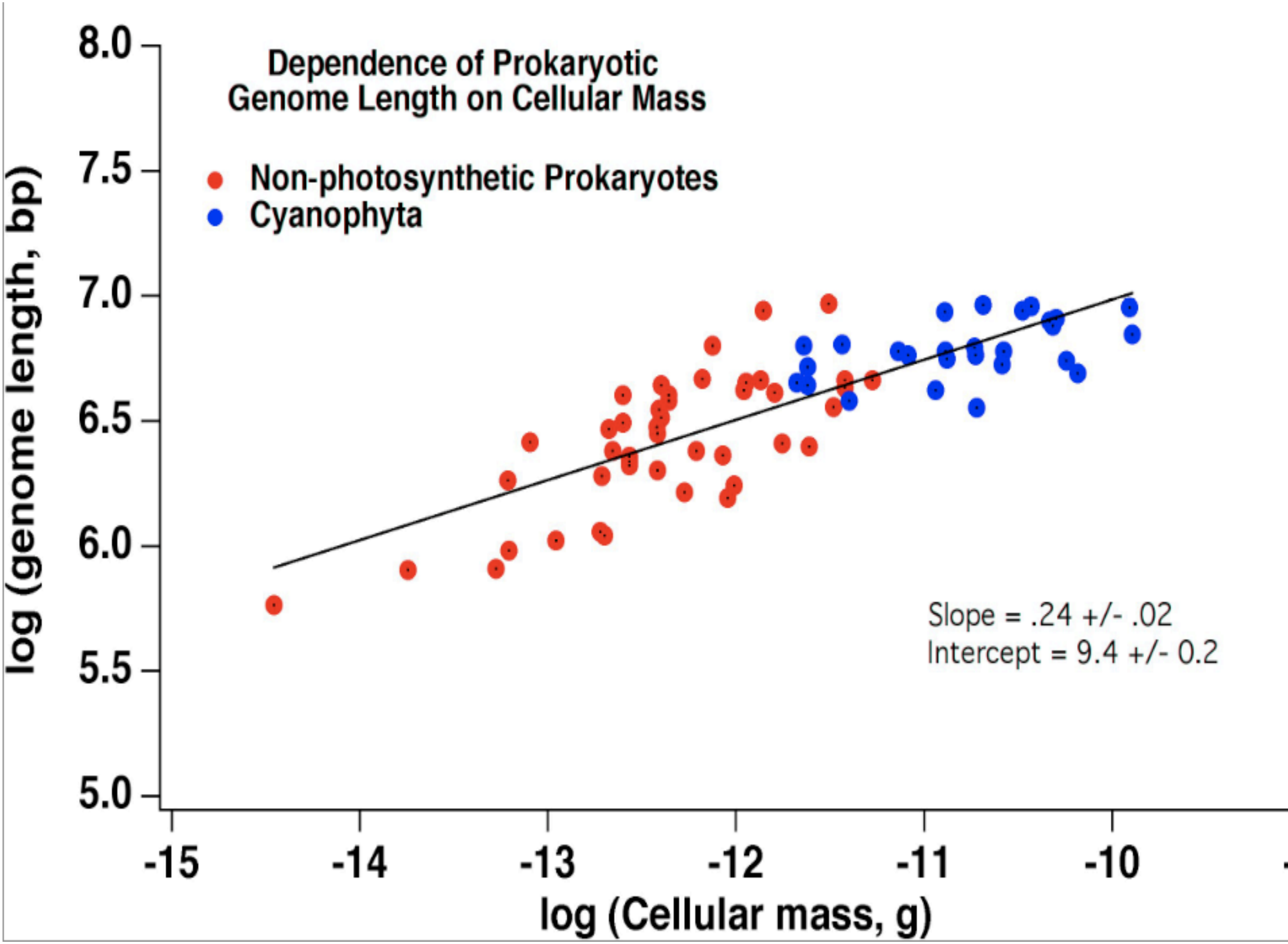
$\Rightarrow$ TOTAL NUMBER OF HEART-BEATS IN A TYPICAL LIFE-TIME IS INDEPENDENT OF SIZE!

$$\approx 1.5 \times 10^9$$

EACH ANIMAL SPECIES REGARDLESS OF SIZE HAS APPROXIMATELY THE SAME NUMBER OF HEART-BEATS IN ITS LIFE-TIME (ROUGHLY 1 BILLION)



White Matter Volume W (mm 3)
Gray Matter Volume G (mm 3)
log10 W = (1.23 ± 0.01) log10 G – (1.47 ± 0.04)
r = 0.998
Risso's dolphin
Human
Bottlenose dolphin
Elephant
Pilot whale
Horse
Harbor porpoise
Chimpanzee
Cow
Sea lion
Olive baboon
Capuchin monkey
Vervet monkey
Lar gibbon
Pig
Red colobus
Redtail monkey
Macaque monkey
Sheep
Howler monkey
Woolly monkey
Squirrel monkey
Cat
Fox
White sifaka
White–fronted lemur
Aye–aye
Owl monkey
Indri
Mara
Slow loris
Marmoset
Tufted–ear marmoset
Rabbit
Woolly lemur
Red–tailed sportive lemur
Pygmy marmoset
Everett's tupaia
Flying fox
West European hedgehog
Algerian hedgehog
Dwarf bushbaby
Rat
Tarsier
Tree shrew
Fisherman bat
Tenrec
Lesser mouse lemur
Large Madagascar hedgehog
Long–eared desert hedgehog
Mouse
Water shrew
South African giant shrew
Small Madagascar hedgehog
Streaked tenrec
Asian house shrew
Pygmy shrew
Common shrew
European white–toothed shrew


Dependence of Prokaryotic
Genome Length on Cellular Mass
Non-photosynthetic Prokaryotes
Cyanophyta
Slope = .24 +/- .02
Intercept = 9.4 +/- 0.2
log (genome length, bp)
log (Cellular mass, g)
8.0
7.5
7.0
6.5
6.0
5.5
5.0
-15
-14
-13
-12
-11
-10

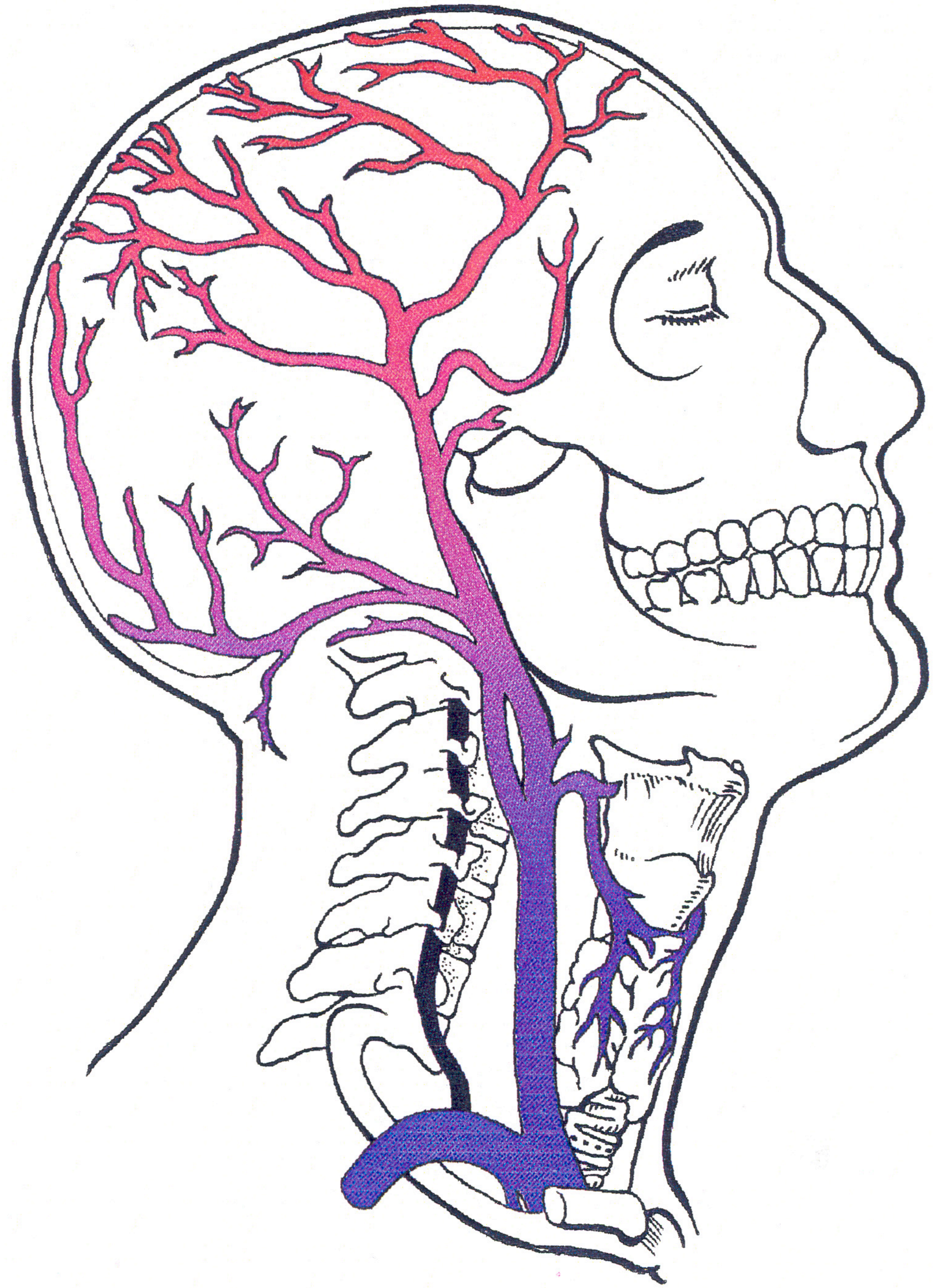
NETWORKS!!!

(FRACTALS!!)

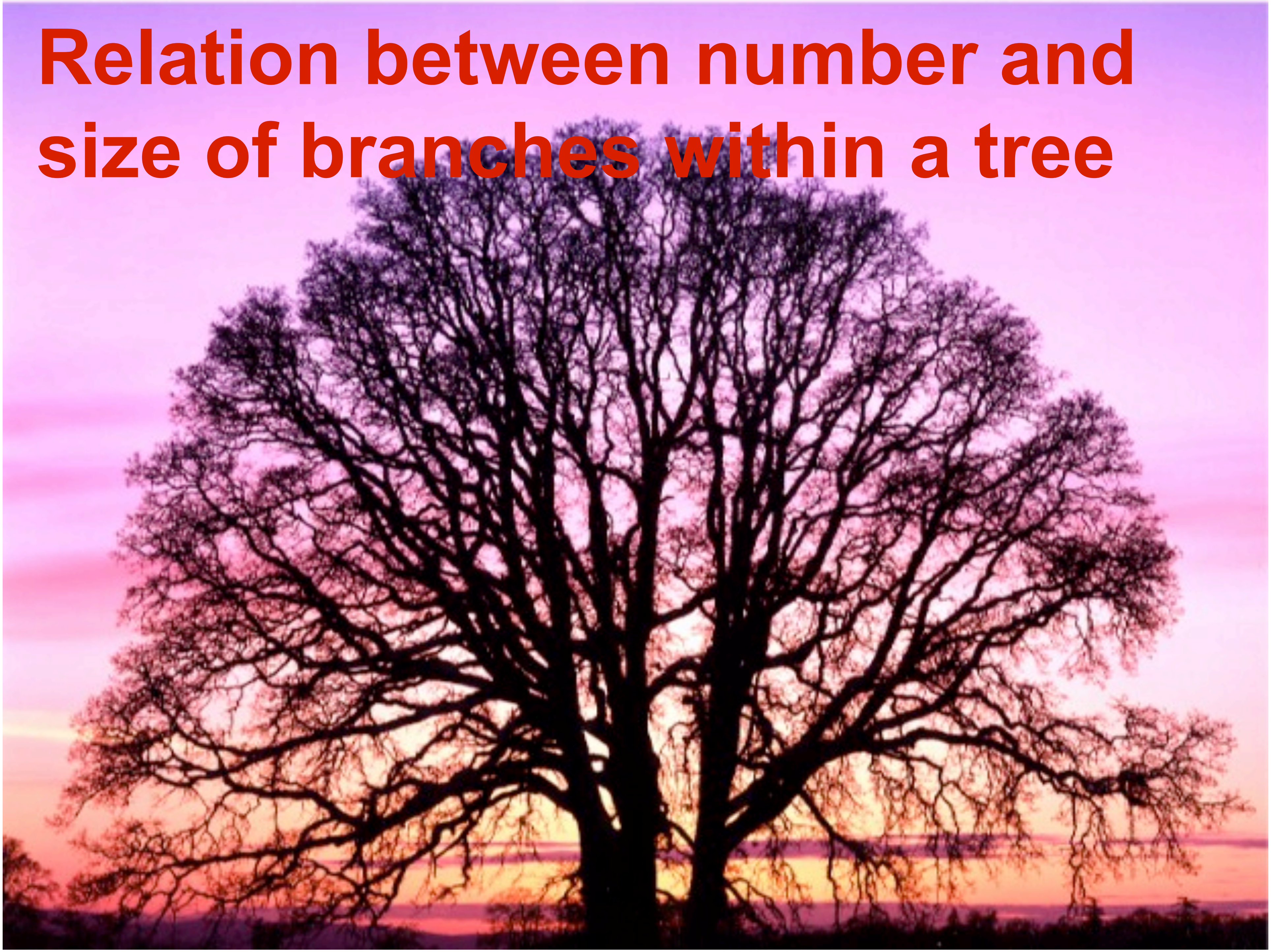
Large vessels branch into smaller ones

Beating heart

Pulse wave propagates through elastic vessels

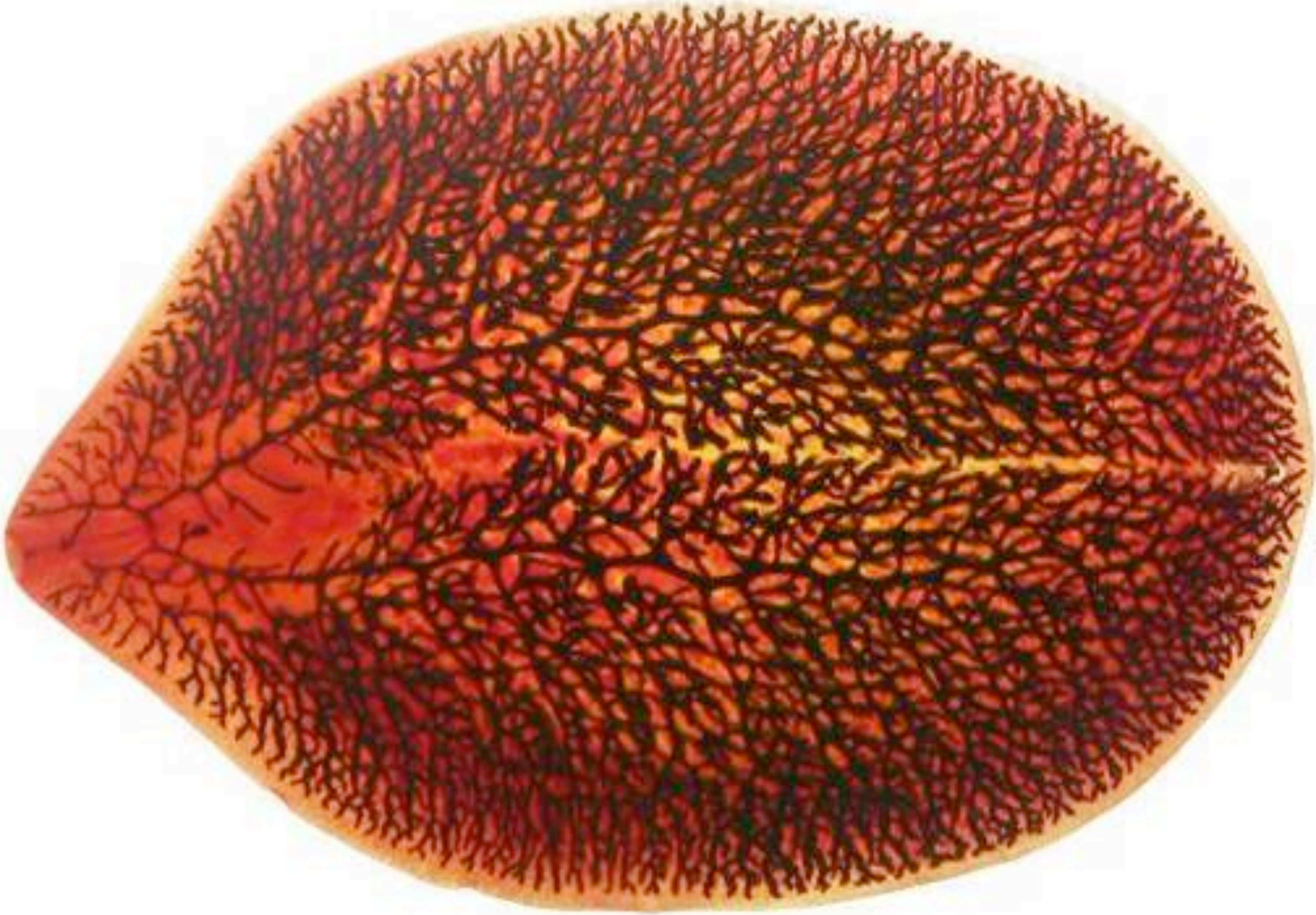


Relation between number and size of branches within a tree

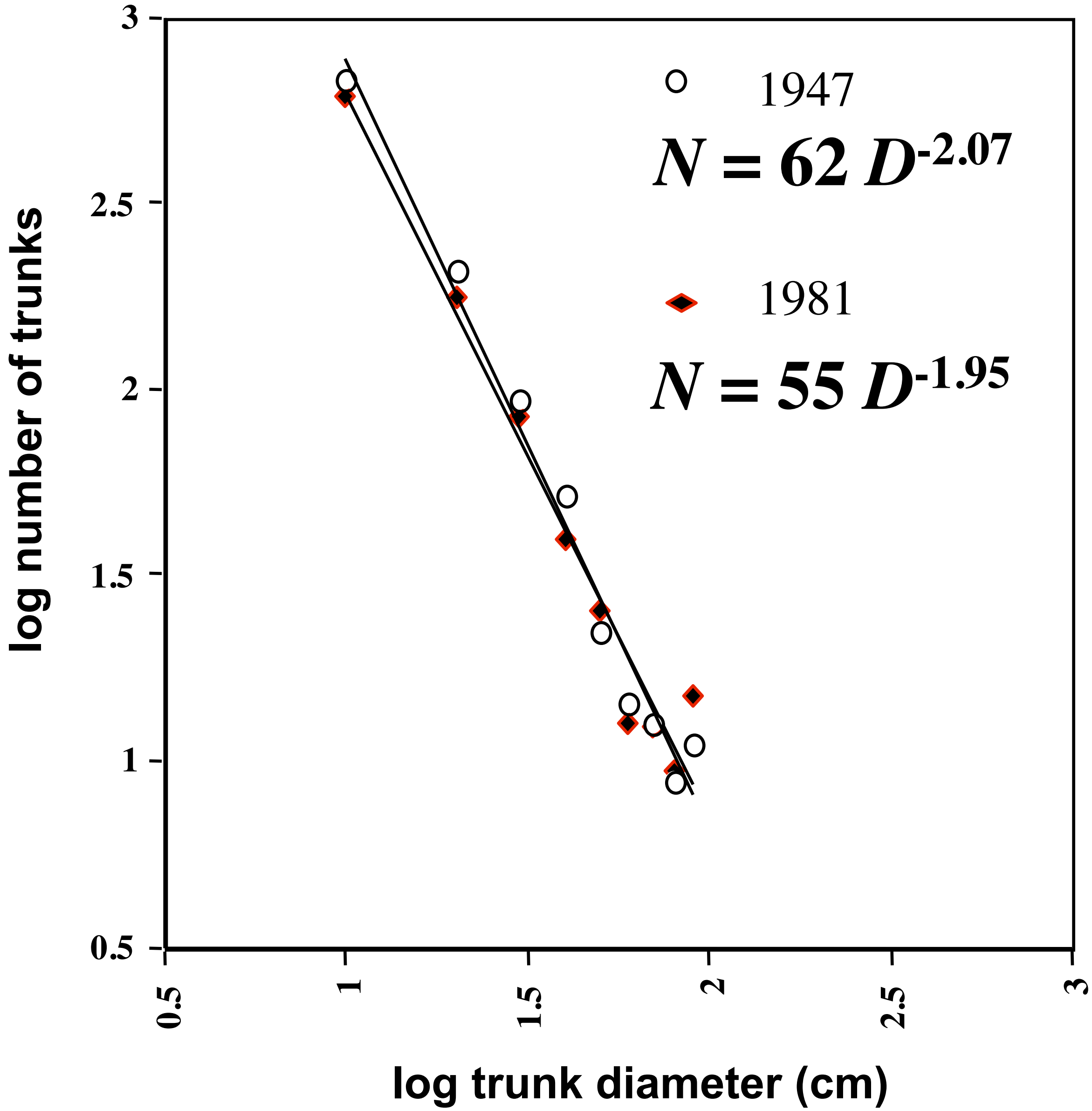



Microcapillary tubes follow branching
architecture from trunk to leaves

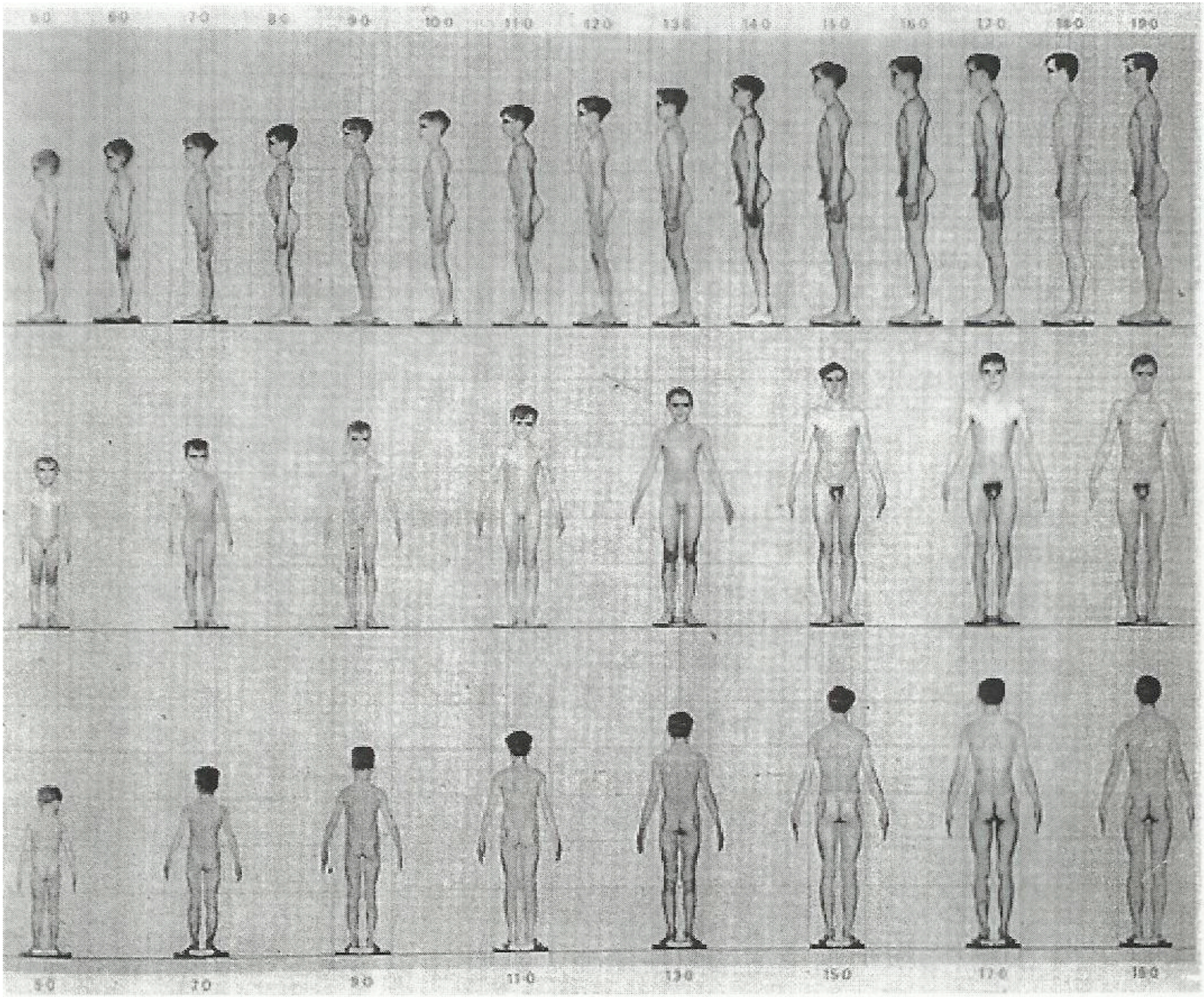
What is this?



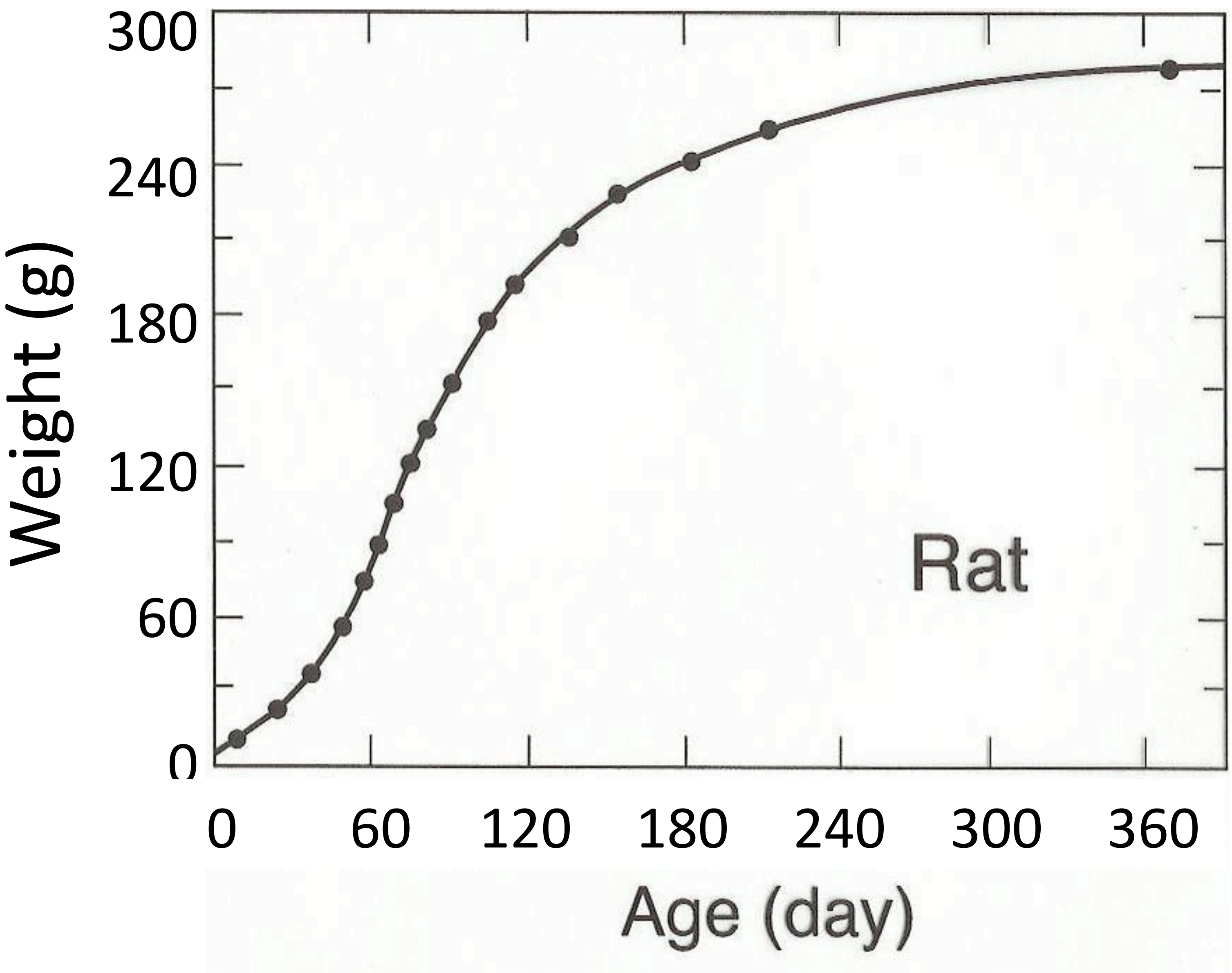
INTERSPECIFIC SIZE DISTRIBUTION
All species in a Malaysian Rainforest



Manokaran and Kochummen (1987)


5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0


Food
"fire of life"
Energy


Weight (g)
300
240
180
120
60
0
Rat
0
60
120
180
240
300
360
Age (day)

INCOMING METABOLISED ENERGY

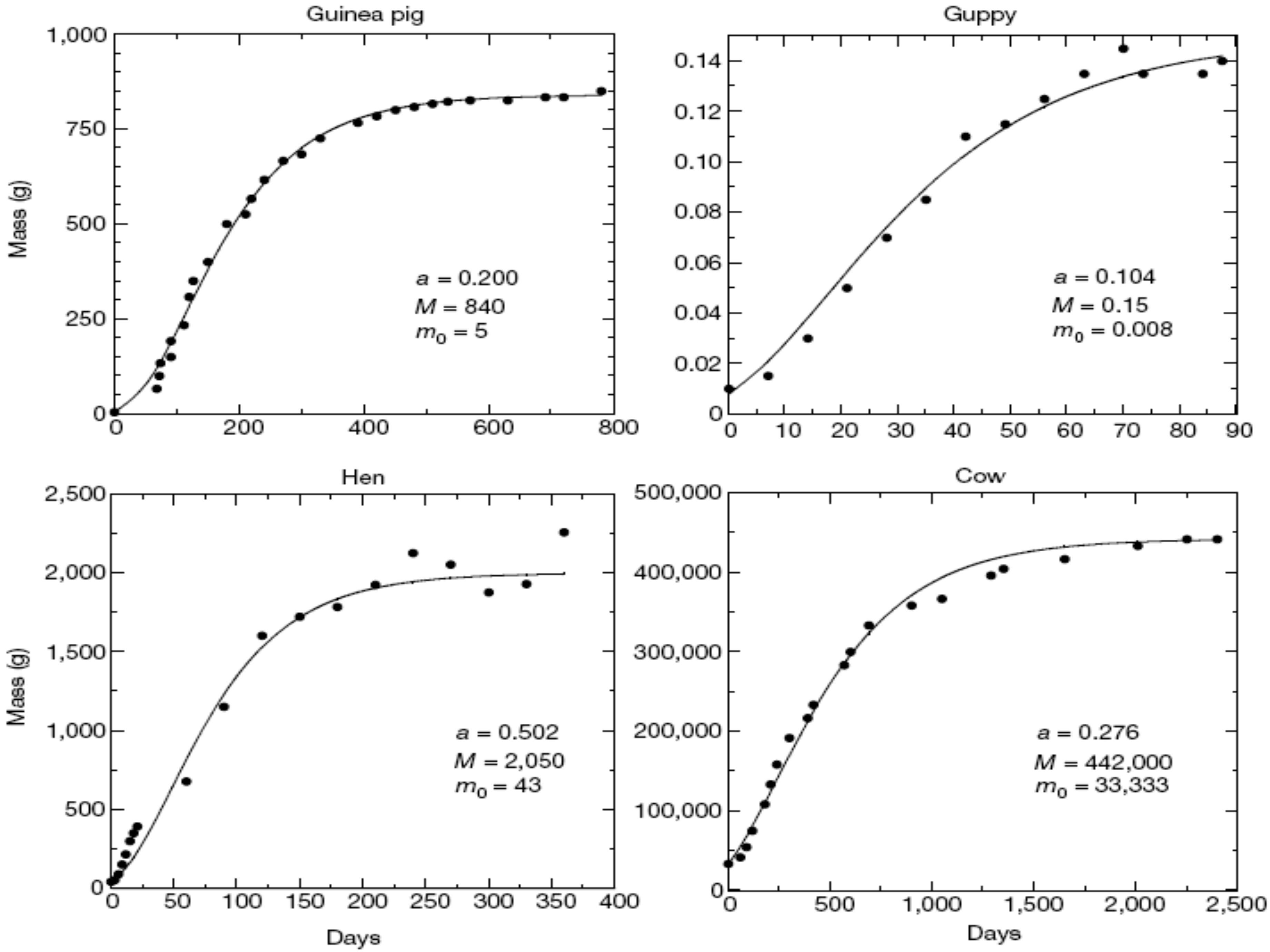
↓

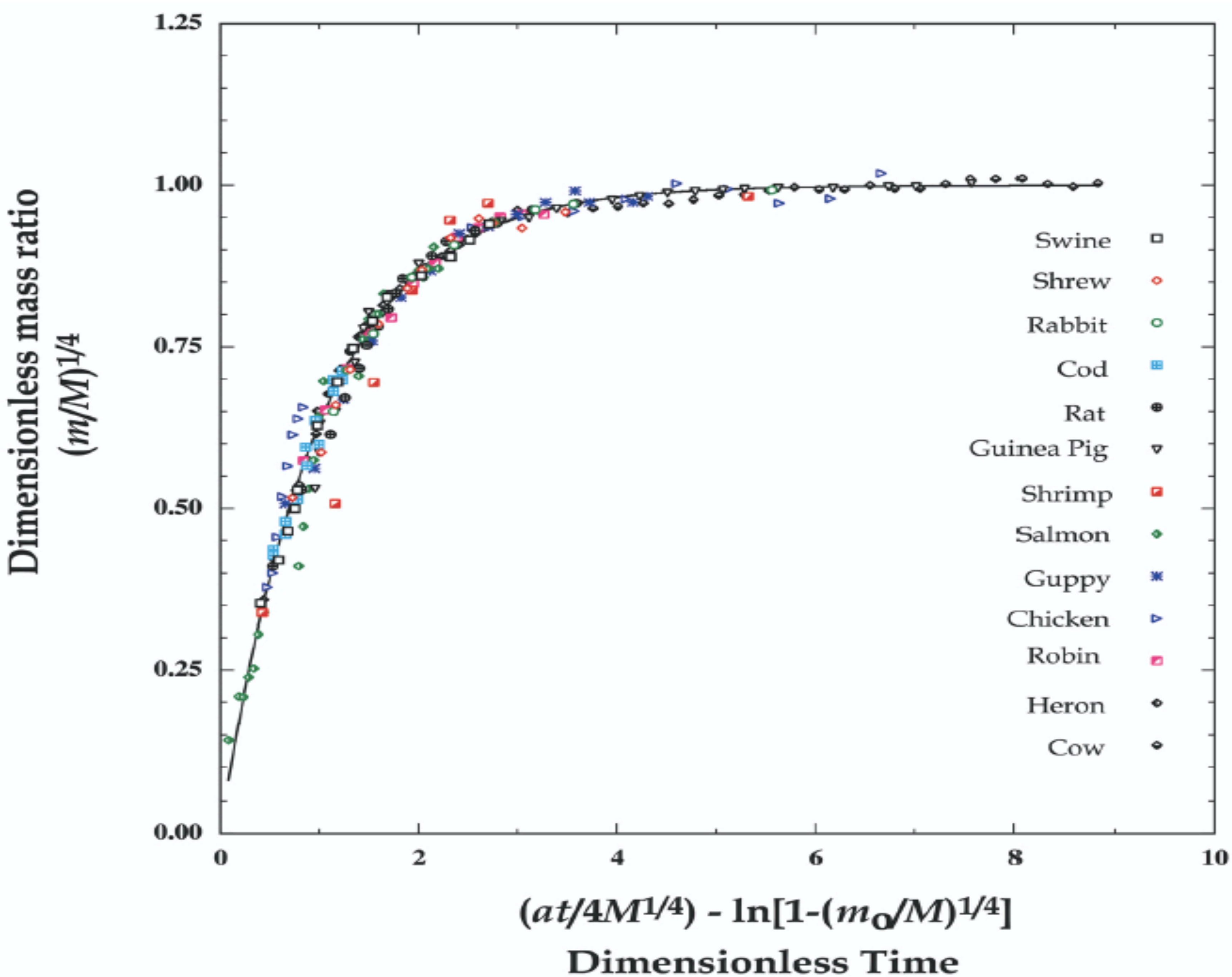
MAINTENANCE
(of existencing cells)

+

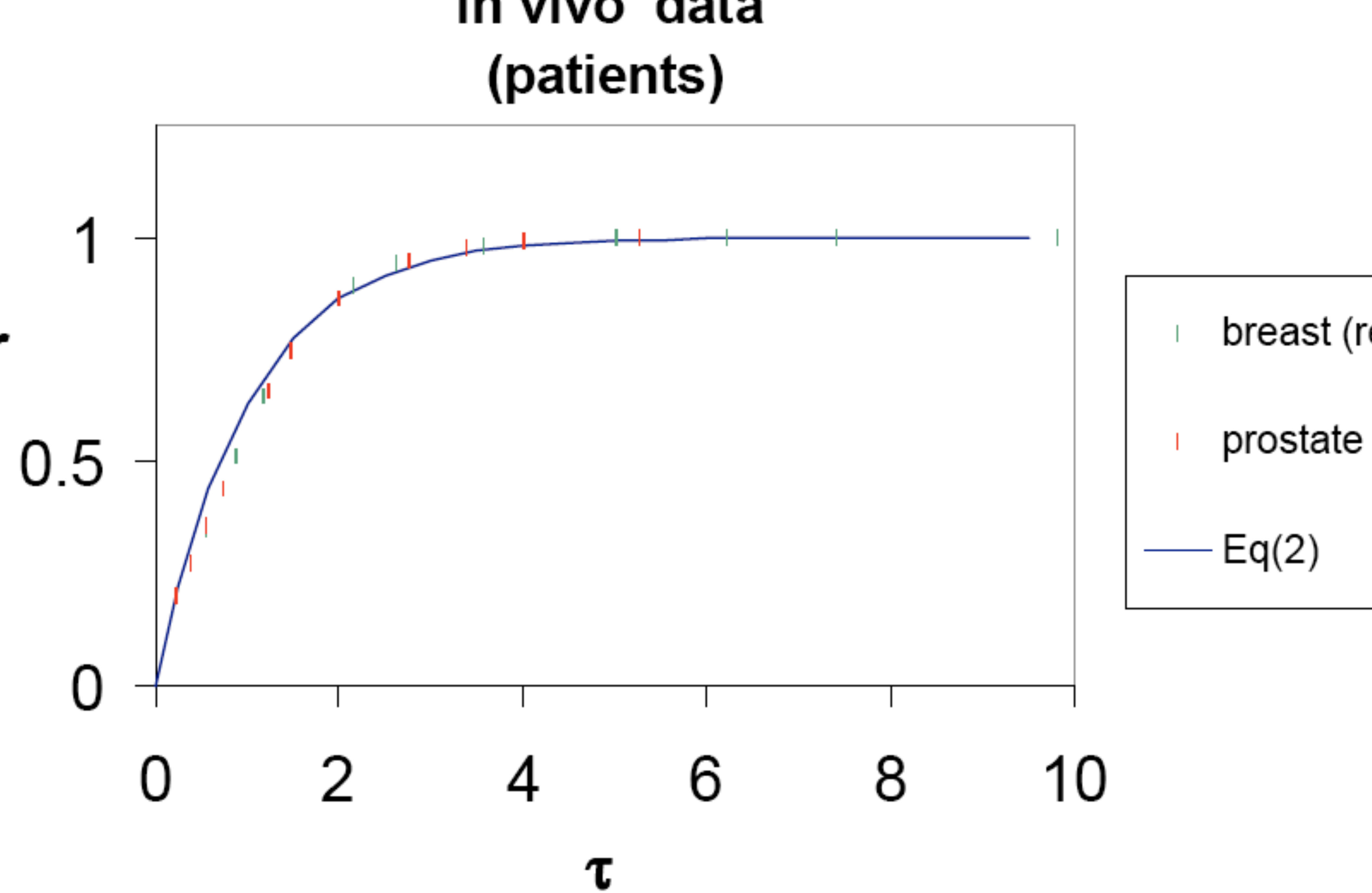
GROWTH
(of new cells)

$$B = N_{cells} B_{cell} + E_{cell} \frac{dN_{cell}}{dt}$$


Guinea pig
Mass (g)
a = 0.200
M = 840
m0 = 5
Guppy
a = 0.104
M = 0.15
m0 = 0.008
Hen
Mass (g)
a = 0.502
M = 2,050
m0 = 43
Days
Cow
a = 0.276
M = 442,000
m0 = 33,333
Days



Dimensionless mass ratio
$(m/M)^{1/4}$
1.25
1.00
0.75
0.50
0.25
0.00
0
2
4
6
8
10
$(at/4M^{1/4}) - \ln[1-(m_o/M)^{1/4}]$
Dimensionless Time
Swine
Shrew
Rabbit
Cod
Rat
Guinea Pig
Shrimp
Salmon
Guppy
Chicken
Robin
Heron
Cow



in vivo data
(patients)
1
0.5
0
0
2
4
6
8
10
τ
breast (r
prostate
Eq(2)

Biology   Life

- ***NON-LINEAR SCALING LAWS***
- ***UNIVERSAL QUARTER POWERS***
- ***SUB-LINEAR EXPONENTS (< 1)***
- ***ECONOMIES OF SCALE (~ $M^{-1/4}$)***
- ***PACE OF LIFE DECREASES WITH SIZE:***

  TIMES ~ $M^{1/4}$

  RATES ~ $M^{-1/4}$
- ***SIGMOIDAL GROWTH CURVES***
- ***STABLE ASYMPTOTE***
- ***SUSTAINABLE***
- ***GOVERNED BY NETWORKS (~ FRACTAL)***

Social Organizations
(Urban/Corporate Structures)

- Can one construct a **general theory of social organizations** that is quantitative and predictive?
- Are there **“universal” scaling laws** that reveal underlying principles?
- Are there **average idealized social organizations**?
- Did they evolve under **“natural selection”** in a **“free market”** environment via competition?
- What is the nature of their **hierarchies and generic network structure**?

Social Organizations
(Urban/Corporate Structures)

- Are there **universality classes of networks**?
- Is there an **optimal** maximum (or minimum) **size?**
- What drives **mergers**?
- Growth, mortality, aging, evolution, …
- **Energy** (resources) **vs. information**: which dominates?

Are Cities Approximate Scaled Versions of Each Other?

Do They Obey Power Law Scaling? β

Do Exponents Manifest "Universality" (analogous to quarter powers in Biology)?

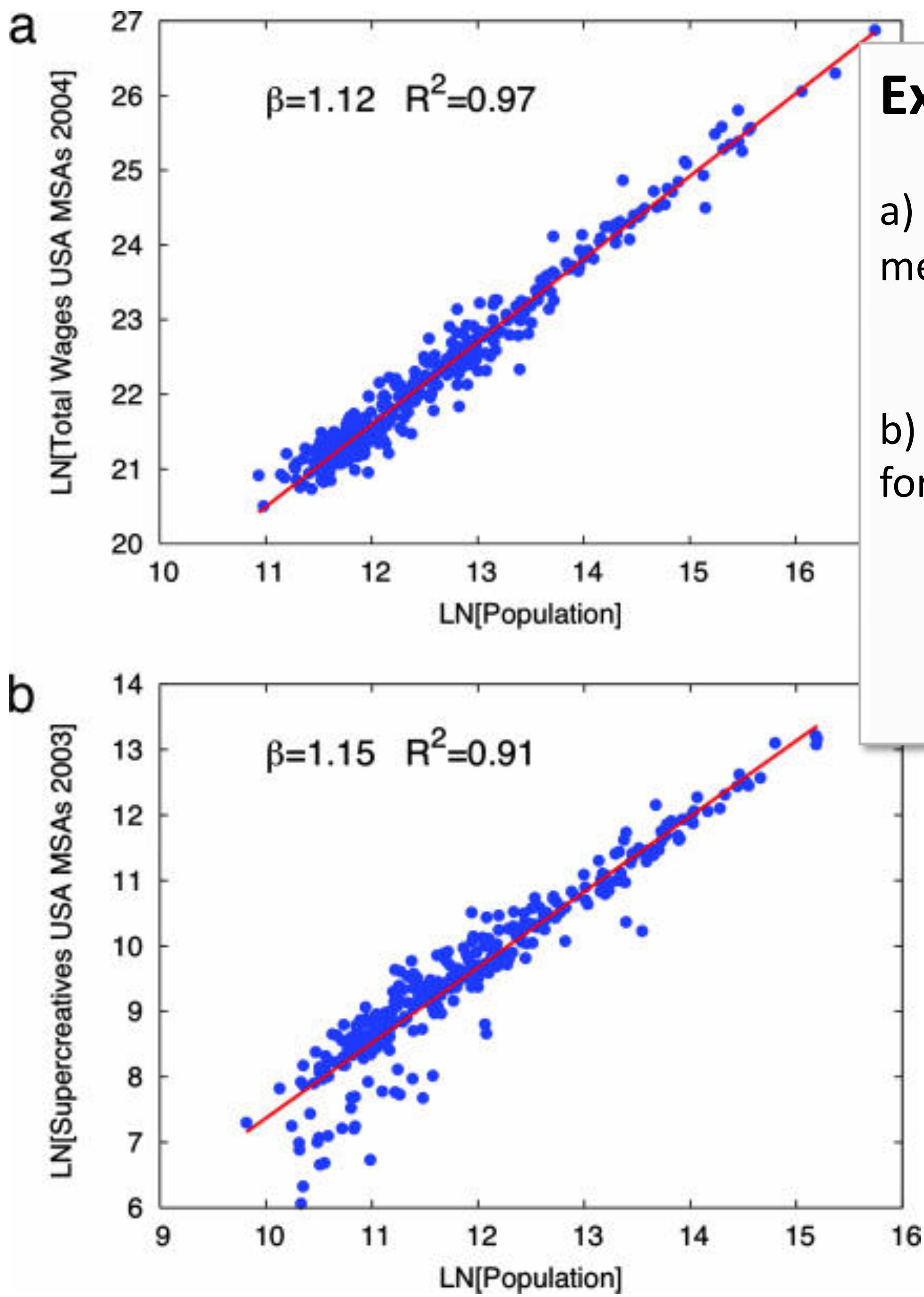
$$R \sim N^b$$

NETWORK DYNAMICS IMPLIES THAT THE PACE OF LIFE IS DETERMINED BY

$$RATES \sim N^{b-1}$$

$b < 1$ PACE OF LIFE SLOWS DOWN

$b > 1$ PACE OF LIFE SPEEDS UP

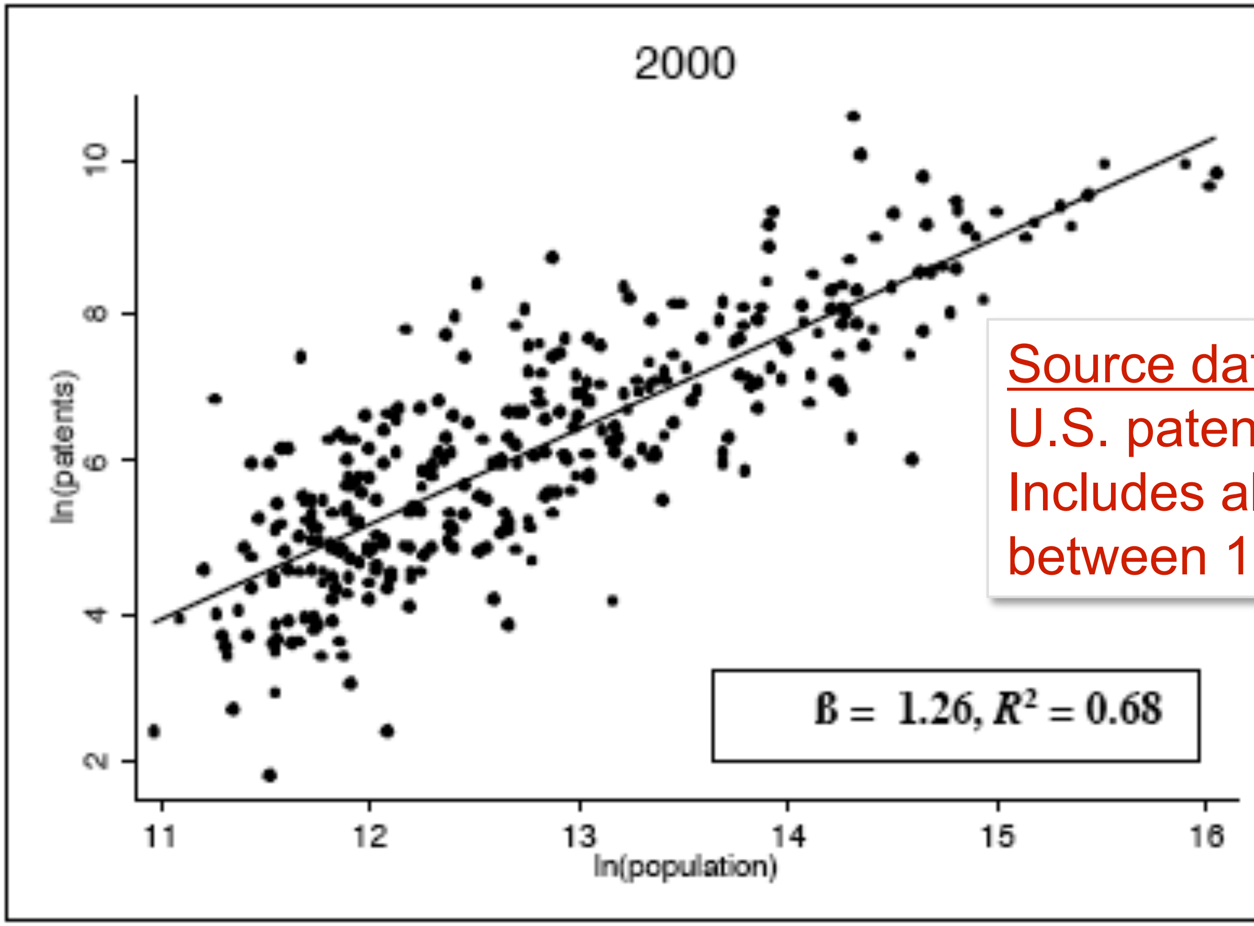


Example of scaling relationships

a) Total wages per MSA in 2004 for the USA vs. metropolitan population.

b) Supercreative employment per MSA in 2003, for the USA vs. metropolitan population.

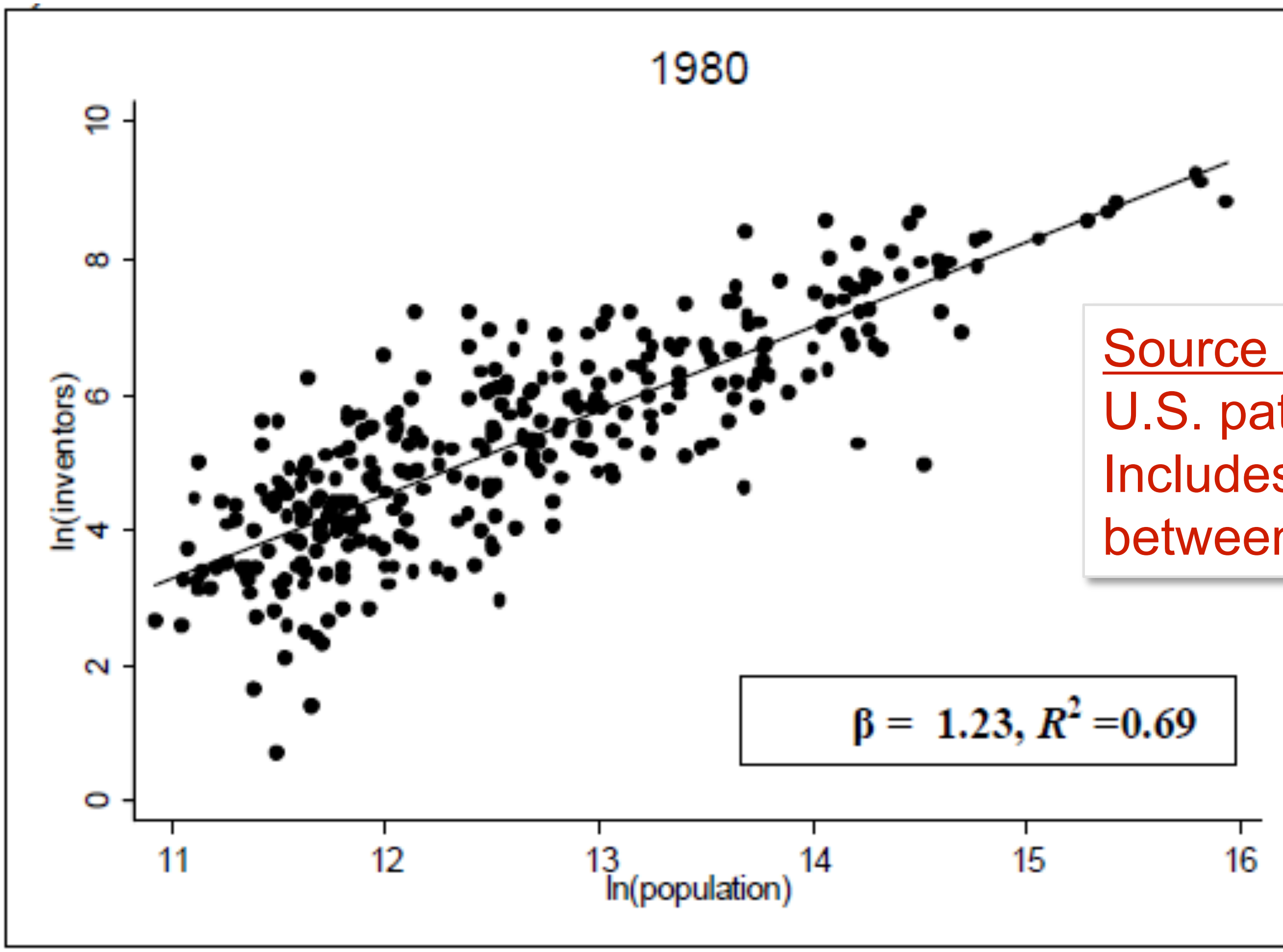
Innovation measured by Patents



Source data:
U.S. patent office
Includes all patents
between 1980 – 2001

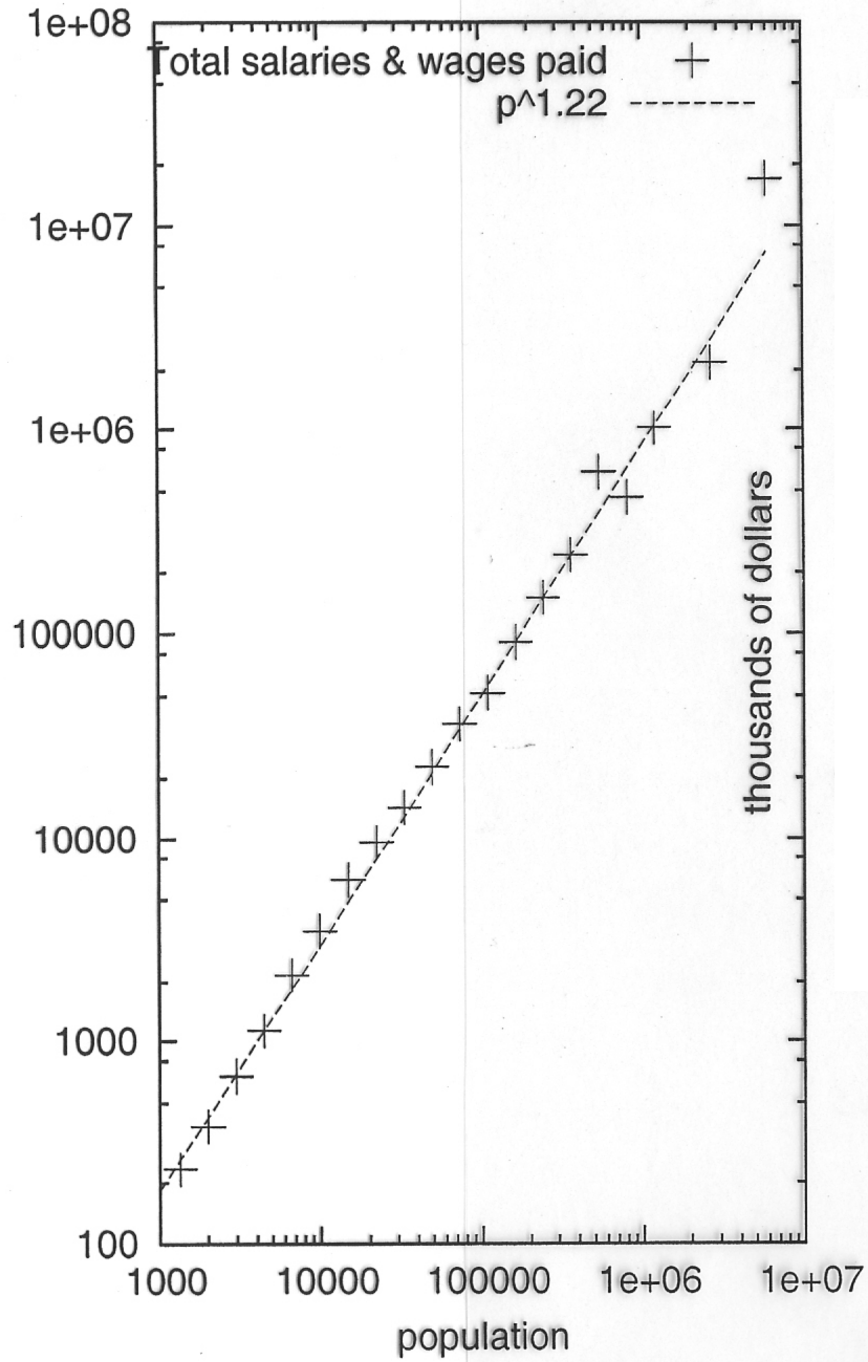
From "**Innovation in the city: Increasing returns to scale in urban patenting**"
Bettencourt, Lobo and Strumsky
Data courtesy of Lee Fleming, Deborah Strumsky

Or to a disproportionate agglomeration of inventors with urban size?



<u>Source data</u>:
U.S. patent office
Includes all patents between 1980 – 2001

Data courtesy of Lee Fleming, Deborah Strumsky



Total salaries & wages paid
p^1.22
thousands of dollars
population
1e+08
1e+07
1e+06
100000
10000
1000
100
1000
10000
100000
1e+06
1e+07

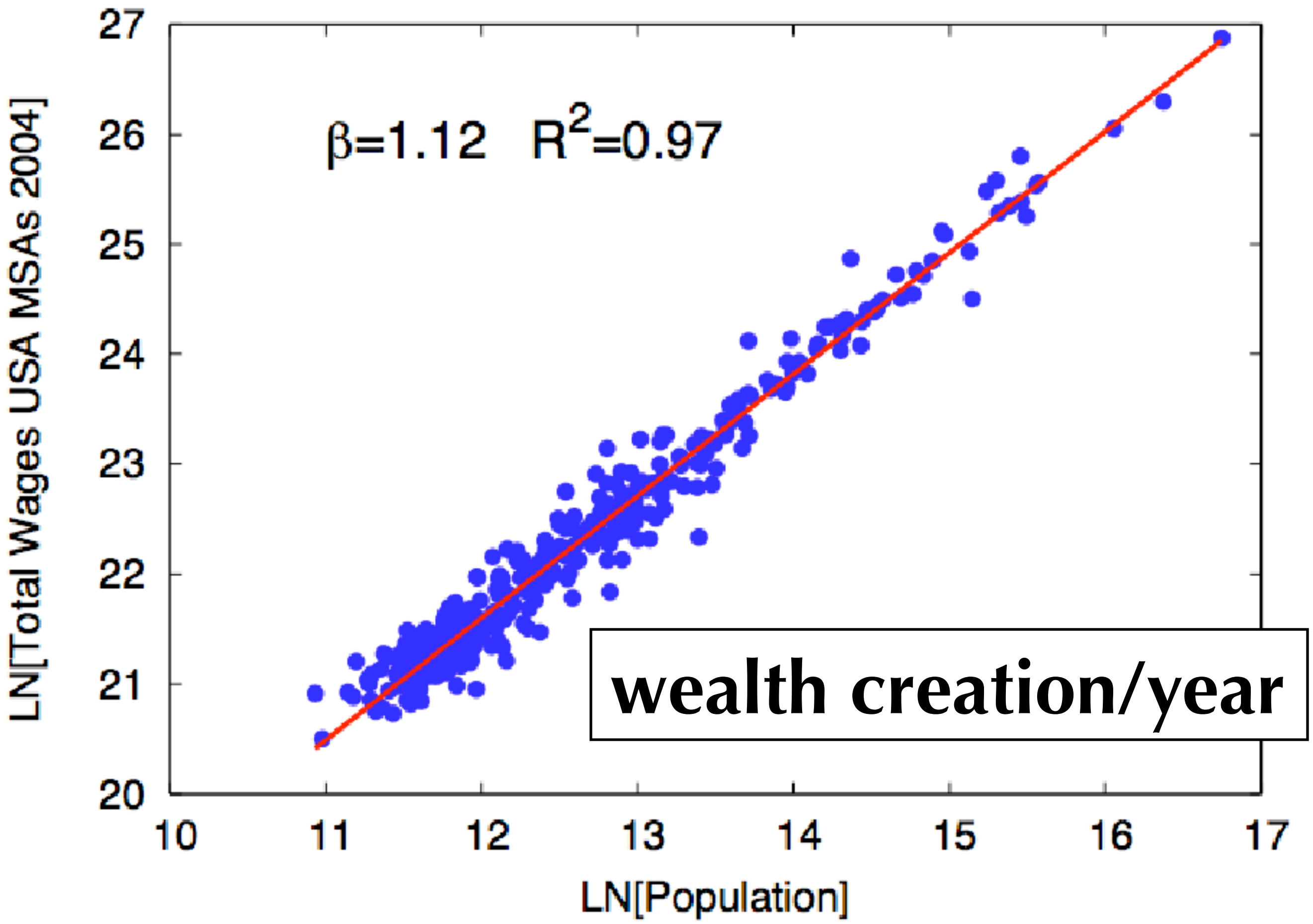
Table 1. Scaling exponents for urban indicators vs. city size

Y	β	95% CI	Adj-R^2	Observations	Country–year
New patents	1.27	[1.25,1.29]	0.72	331	U.S. 2001
Inventors	1.25	[1.22,1.27]	0.76	331	U.S. 2001
Private R&D employment	1.34	[1.29,1.39]	0.92	266	U.S. 2002
"Supercreative" employment	1.15	[1.11,1.18]	0.89	287	U.S. 2003
R&D establishments	1.19	[1.14,1.22]	0.77	287	U.S. 1997
R&D employment	1.26	[1.18,1.43]	0.93	295	China 2002
Total wages	1.12	[1.09,1.13]	0.96	361	U.S. 2002
Total bank deposits	1.08	[1.03,1.11]	0.91	267	U.S. 1996
GDP	1.15	[1.06,1.23]	0.96	295	China 2002
GDP	1.26	[1.09,1.46]	0.64	196	EU 1999–2003
GDP	1.13	[1.03,1.23]	0.94	37	Germany 2003
Total electrical consumption	1.07	[1.03,1.11]	0.88	392	Germany 2002
New AIDS cases	1.23	[1.18,1.29]	0.76	93	U.S. 2002–2003
Serious crimes	1.16	[1.11, 1.18]	0.89	287	U.S. 2003
Total housing	1.00	[0.99,1.01]	0.99	316	U.S. 1990
Total employment	1.01	[0.99,1.02]	0.98	331	U.S. 2001
Household electrical consumption	1.00	[0.94,1.06]	0.88	377	Germany 2002
Household electrical consumption	1.05	[0.89,1.22]	0.91	295	China 2002
Household water consumption	1.01	[0.89,1.11]	0.96	295	China 2002
Gasoline stations	0.77	[0.74,0.81]	0.93	318	U.S. 2001
Gasoline sales	0.79	[0.73,0.80]	0.94	318	U.S. 2001
Length of electrical cables	0.87	[0.82,0.92]	0.75	380	Germany 2002
Road surface	0.83	[0.74,0.92]	0.87	29	Germany 2002

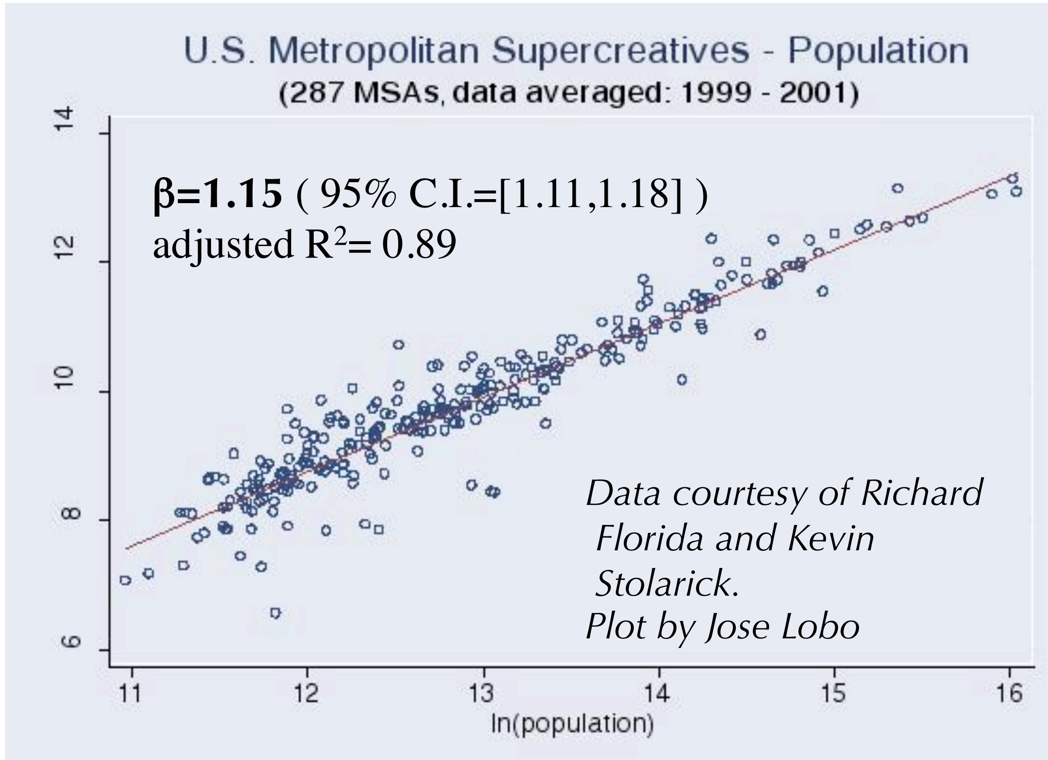
Data sources are shown in *SI Text*. CI, confidence interval; Adj-R^2, adjusted R^2; GDP, gross domestic product.

See supplementary online materials for further details and data sources.

Increasing returns in cities

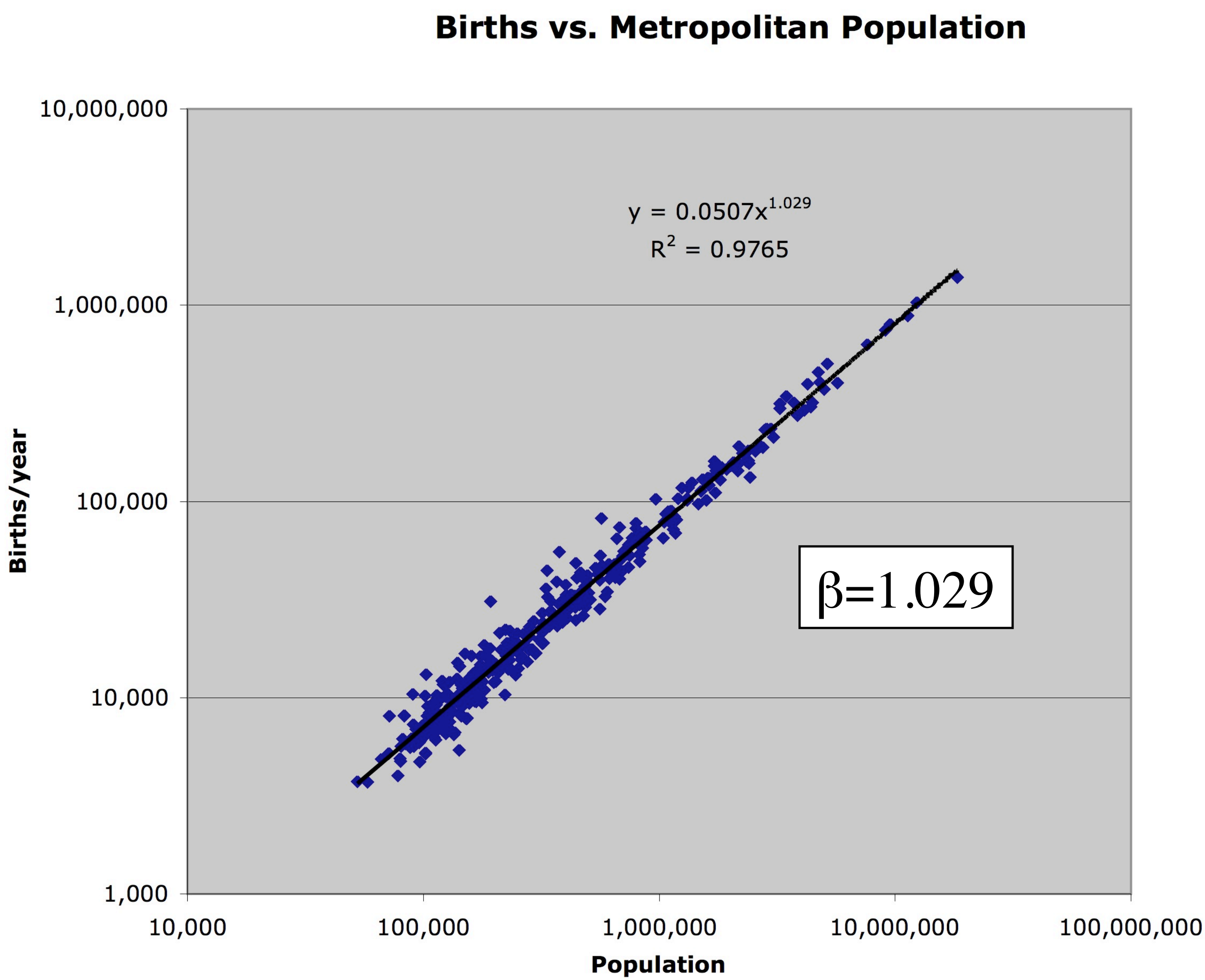


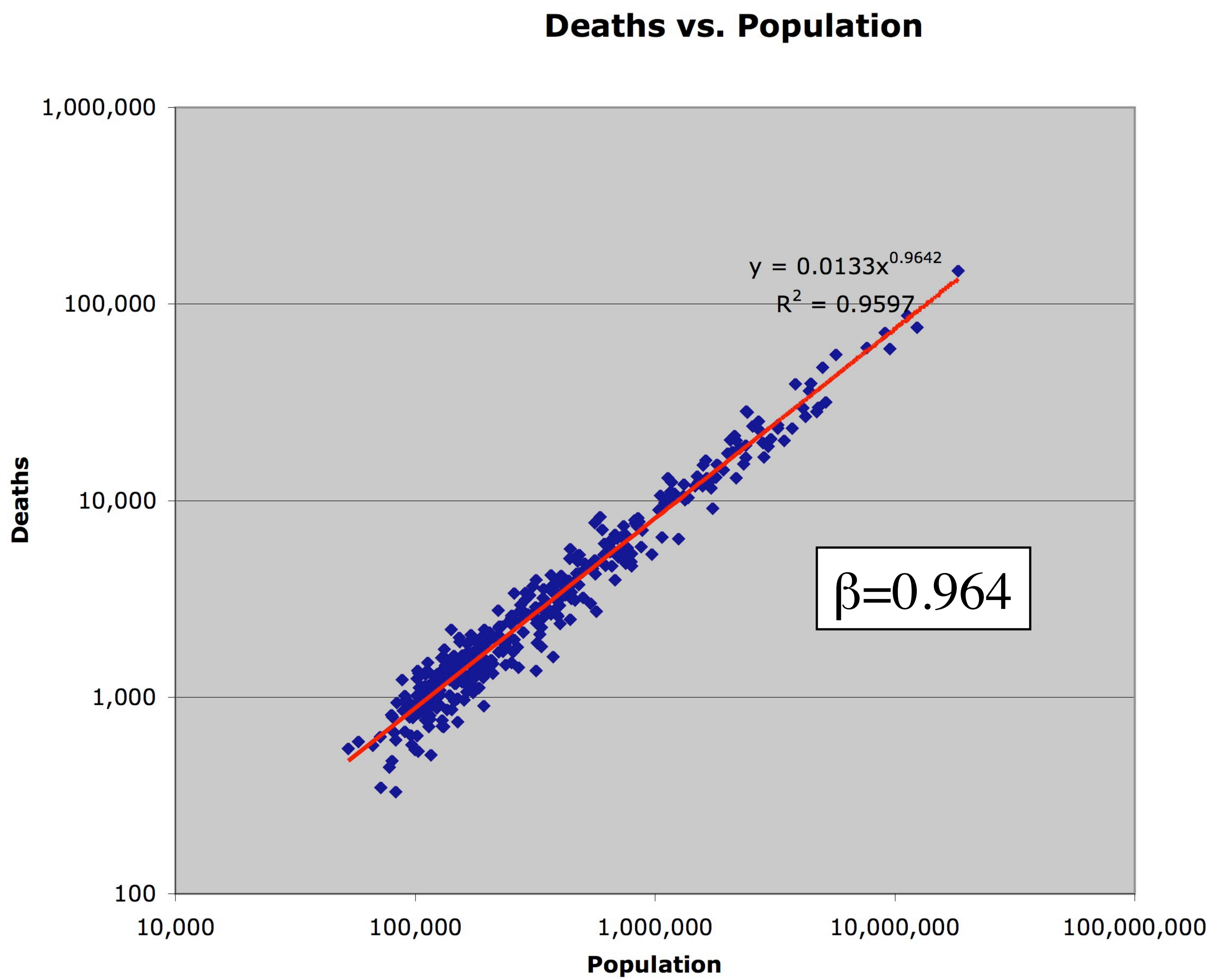
Employment patterns

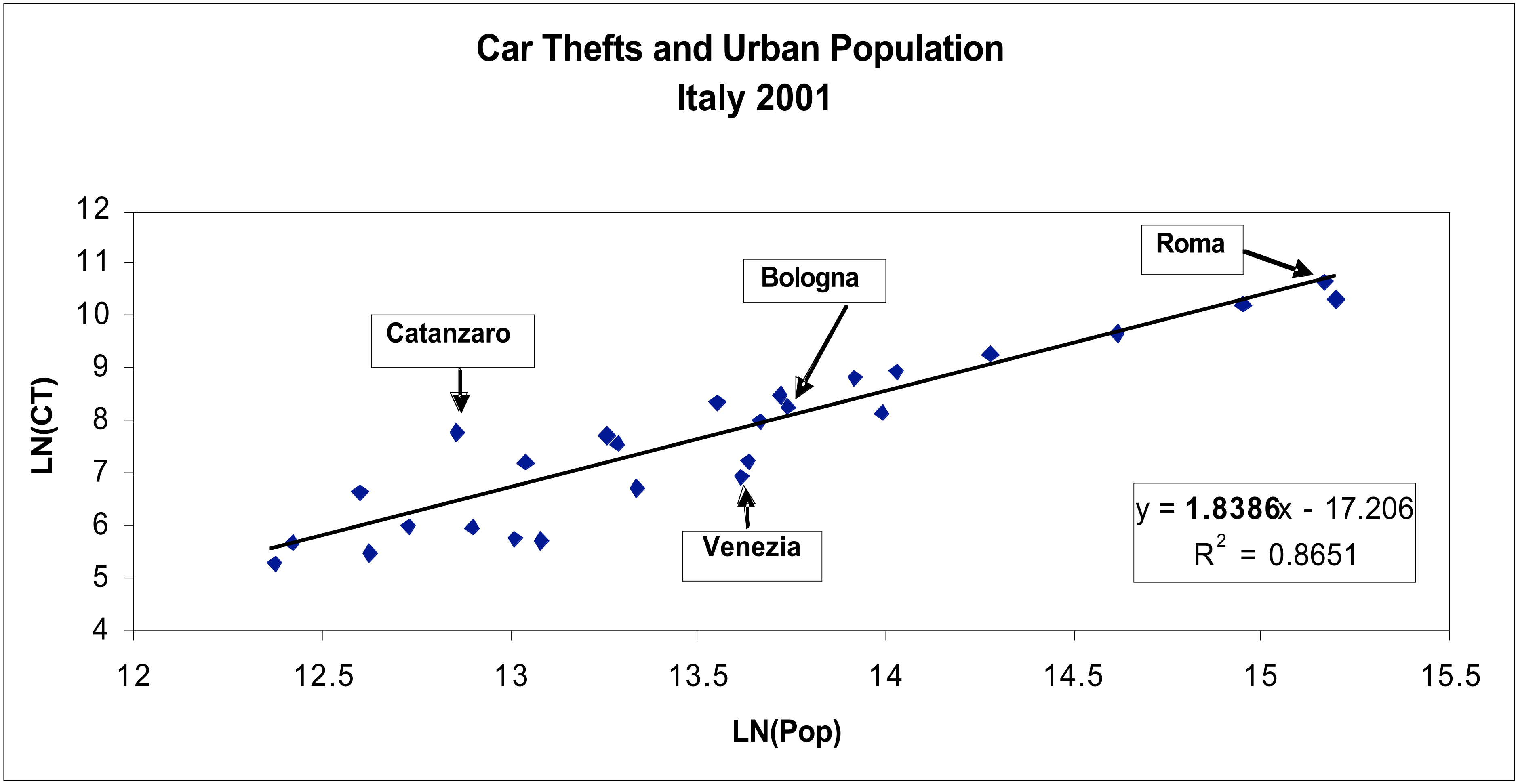


Supercreative professionals [Florida 2002, pag. 327-329] are *"Computer and Mathematical, Architecture and Engineering, Life Physical and Social Sciences Occupations, Education training and Library, Arts, Design, Entertainment, Sports and Media Occupations".*

Derived from Standard Occupation Classification System of the U.S. Bureau of Labor Statistics


Births vs. Metropolitan Population
10,000,000
1,000,000
100,000
10,000
1,000
Births/year
y = 0.0507x^1.029
R^2 = 0.9765
β=1.029
10,000
100,000
1,000,000
10,000,000
100,000,000
Population


Deaths vs. Population
1,000,000
100,000
10,000
1,000
100
Deaths
10,000
100,000
1,000,000
10,000,000
100,000,000
Population
y = 0.0133x^0.9642
R^2 = 0.9597
β=0.964



Car Thefts and Urban Population
Italy 2001
Roma
Bologna
Catanzaro
Venezia
y = 1.8386x - 17.206
R2 = 0.8651
12
11
10
9
8
7
6
5
4
12
12.5
13
13.5
14
14.5
15
15.5
LN(CT)
LN(Pop)

Material Infrastructure

optimized global design for economies of scale

Y	β	95% CI	adj.- R^2	observations	Country/ year
Gasoline Stations	0.77	[0.74,0.81]	0.93	318	USA/2001
Gasoline Sales	0.79	[0.73,0.80]	0.94	318	USA/2002
Length of electrical cables	0.88	[0.82,0.94]	0.82	387	Germany/2001
Road surface	0.83	[0.74,0.92]	0.87	29	Germany/2002

Note that although there are economies of scale in cables the network is still delivering energy at a superlinear rate:

<u>Social rates drive energy consumption rates, not the opposite</u>

Basic Individual needs

proportionality to population

Y	β	95% CI	adj.- R^2	observations	Country/ year
Total establishments	0.98	[0.95,1.02]	0.95	331	USA/2001
Total employment	1.01	[0.99,1.02]	0.98	331	USA/2001
Total Household electrical consumption	1.00	[0.94,1.06]	0.70	387	Germany/2001
Total Household electrical consumption	1.05	[0.89,1.22]	0.91	295	China/2002
Total Household water consumption	1.01	[0.89,1.11]	0.96	295	China/2002

Also true for the scaling of <u>number of housing units</u>

The urban economic miracle

across time, space, level of development or economic system

Y	β	95% CI	adj.- R^2	observations	Country/ year
Total Wages/yr	1.12	[1.09,1.13]	0.96	361	USA/2002
GDP/yr	1.15	[1.06,1.23]	0.96	295	China/2002
GDP/yr	1.13	[1.03,1.23]	0.94	37	Germany/2003
GDP/yr	1.26	[1.03,1.46]	0.64	196	EU/2003

Innovation as the engine

Y	β	95% CI	adj.- R^2	observations	Country/year
New Patents/yr	1.27	[1.25,1.29]	0.72	331	USA/2001
Inventors/yr	1.25	[1.22,1.27]	0.76	331	USA/2001
Private R&D employment	1.34	[1.29,1.39]	0.92	266	USA/2002
"Supercreative" Professionals	1.15	[1.11,1.18]	0.89	287	USA/2003
R&D employment	1.26	[1.18,1.43]	0.93	295	China/2002

Social Side Effects

Y	β	95% CI	adj.- R^2	observations	Country/year
Total elect. consumption	1.09	[1.03,1.15]	0.72	387	Germany/2001
New AIDS cases	1.23	[1.18,1.29]	0.76	93	USA/2002
Serious Crime	1.16	[1.11,1.18]	0.89	287	USA/2003
Walking Speed	0.09	[0.07,0.11]	0.79	21	Several/1979

Disease transmission is a social contact process:

$$\frac{dT}{dt} = \beta_c SI$$ Standard Incidence

TAXONOMY OF EXPONENTS FALL INTO THREE “UNIVERSAL” CLASSES

i) $b \sim 0.8 < 1$ **INFRASTRUCTURE (BIOLOGICAL)**

SUB-LINEAR ➔ ECONOMIES OF SCALE DRIVEN BY EFFICIENCY

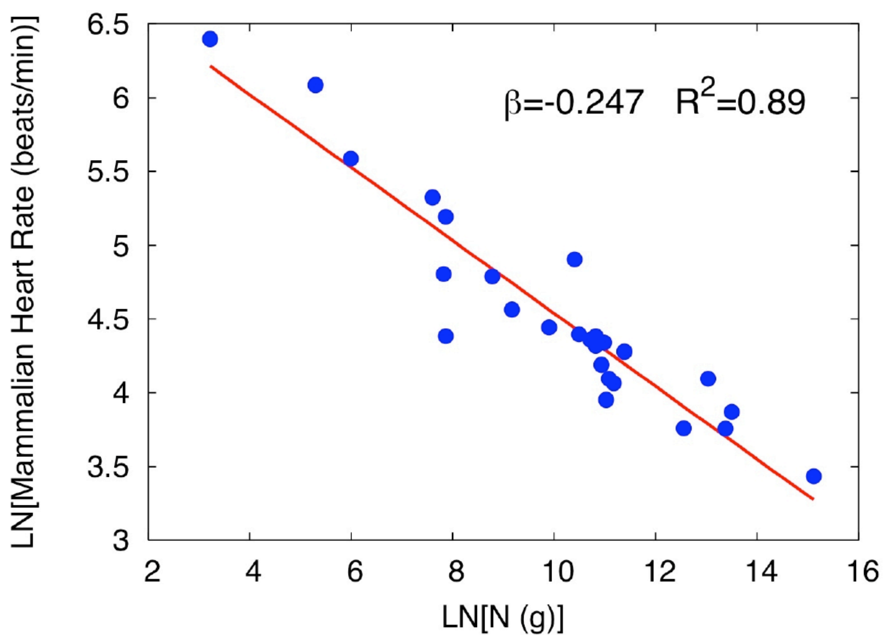
ii) $b = 1$

LINEAR ➔ NON-INNOVATIVE

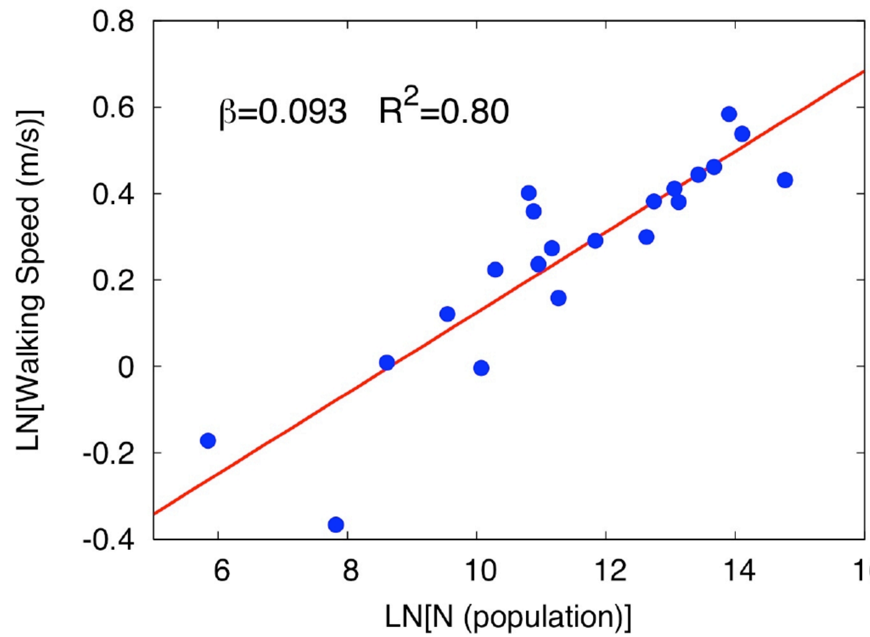
iii) $b \sim 1.15 > 1$ ➔ **SOCIO-ECONOMIC**

SUPER-LINEAR ➔ INNOVATIVE DRIVEN BY WEALTH CREATION

Pace of biological life vs. Pace of social life



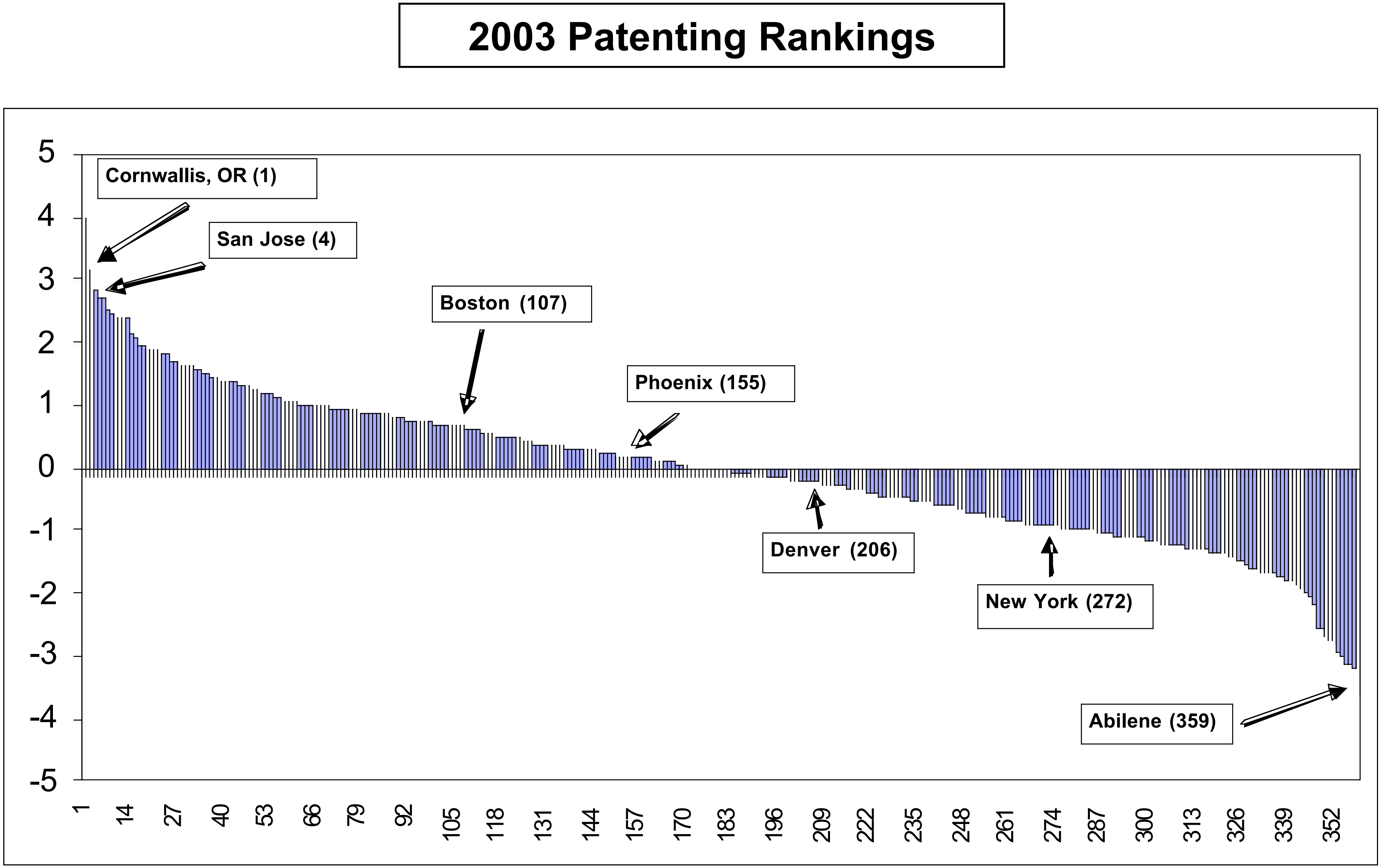
Heart Rate vs. Body Size



Walking Speed vs. Population Size

Urban exponents and the dynamics of growth

Scaling Exponent	Driving Force	Organization	Growth
$\beta<1$	Optimization, Efficiency	Biological	Sigmoidal long-term population limit
$\beta>1$	Creation of Information, Wealth and Resources	Sociological	Boom / Collapse finite-time singularity/unbounded growth accelerating growth rates / discontinuities
$\beta=1$	Individual Maintenance	Individual	Exponential


2003 Patenting Rankings
Cornwallis, OR (1)
San Jose (4)
Boston (107)
Phoenix (155)
Denver (206)
New York (272)
Abilene (359)
5
4
3
2
1
0
-1
-2
-3
-4
-5
1
14
27
40
53
66
79
92
105
118
131
144
157
170
183
196
209
222
235
248
261
274
287
300
313
326
339
352

Growth Equation

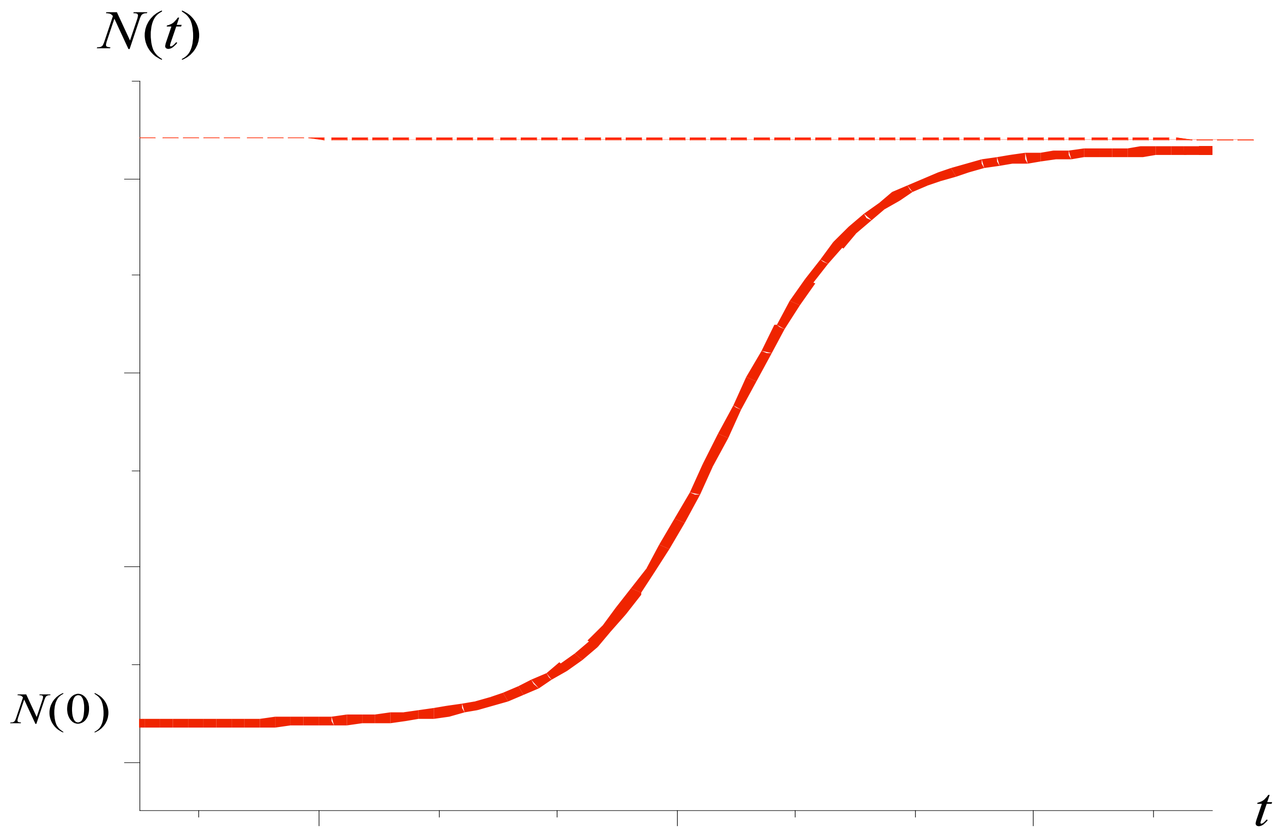
Total incoming rate (Resources, Products, … "Energy" or "Dollar" equivalent)

≈ **Maintenance** (Repair, Replacement, Sustenance, …) + **Growth**

$$R \approx NR_o + E_o \frac{dN}{dt}$$

Energy/resources, etc. needed to create new individual

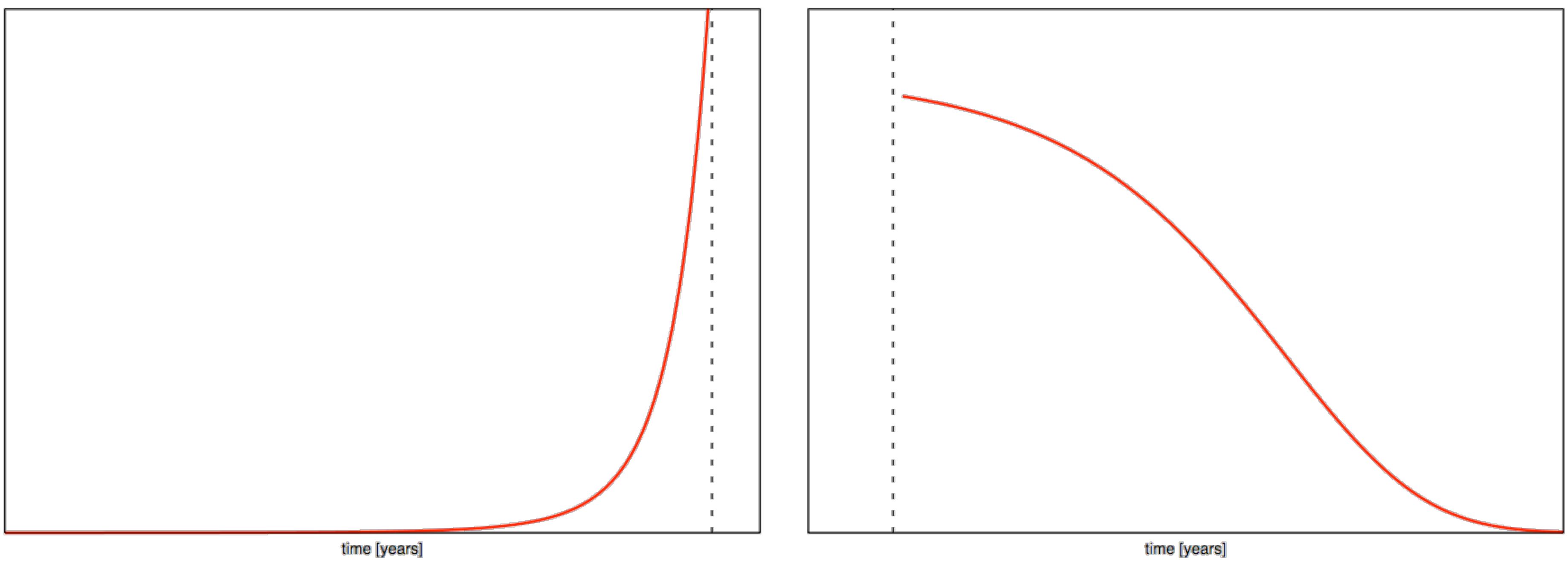
Resources, etc. needed to maintain individual



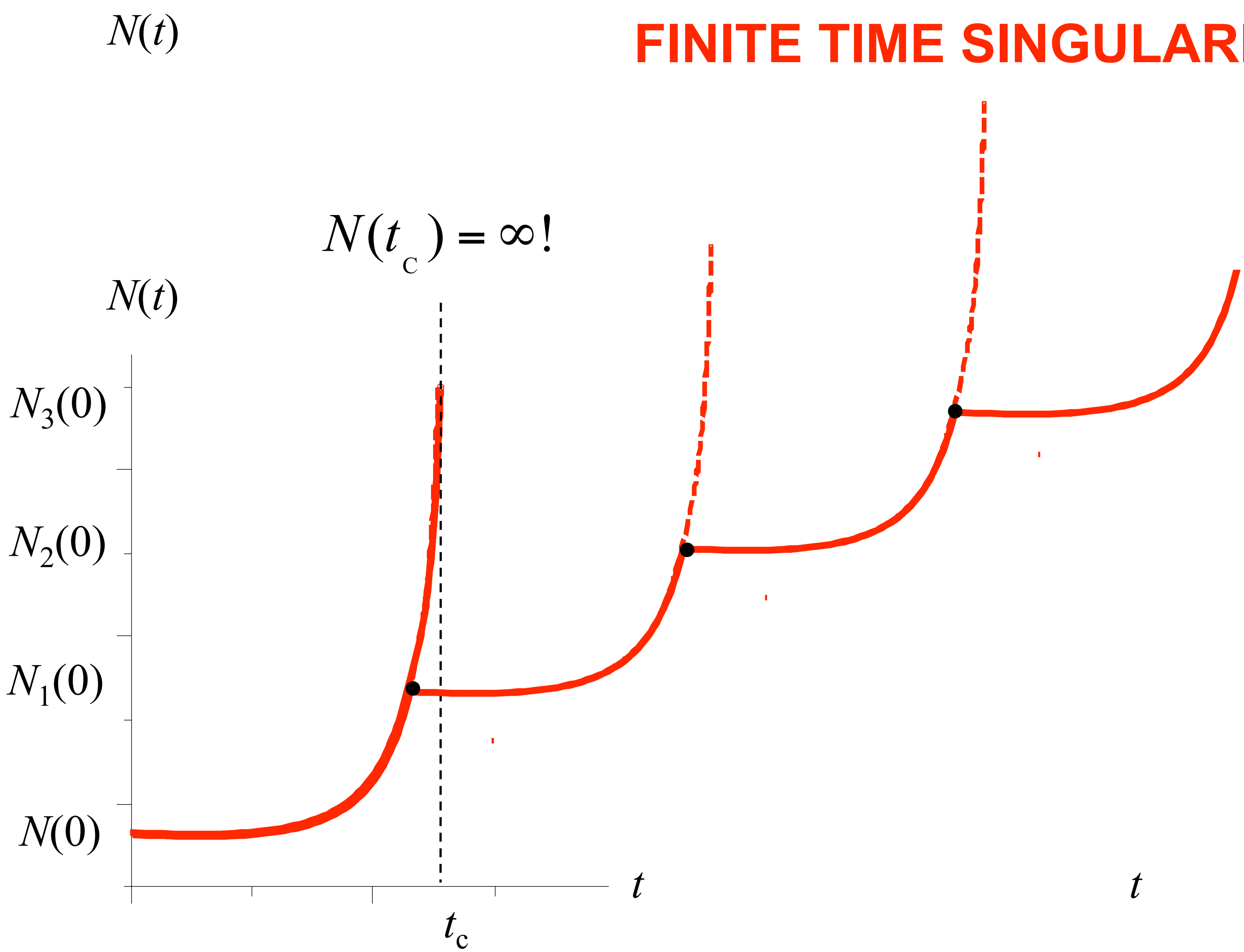
b < 1

SIGMOIDAL BOUNDED GROWTH

b>1 : Finite time Boom and Collapse



b> 1 UNBOUNDED GROWTH UP TO FINITE TIME SINGULARITY



TO MAINTAIN CONTINUOUS GROWTH, MUST HAVE:

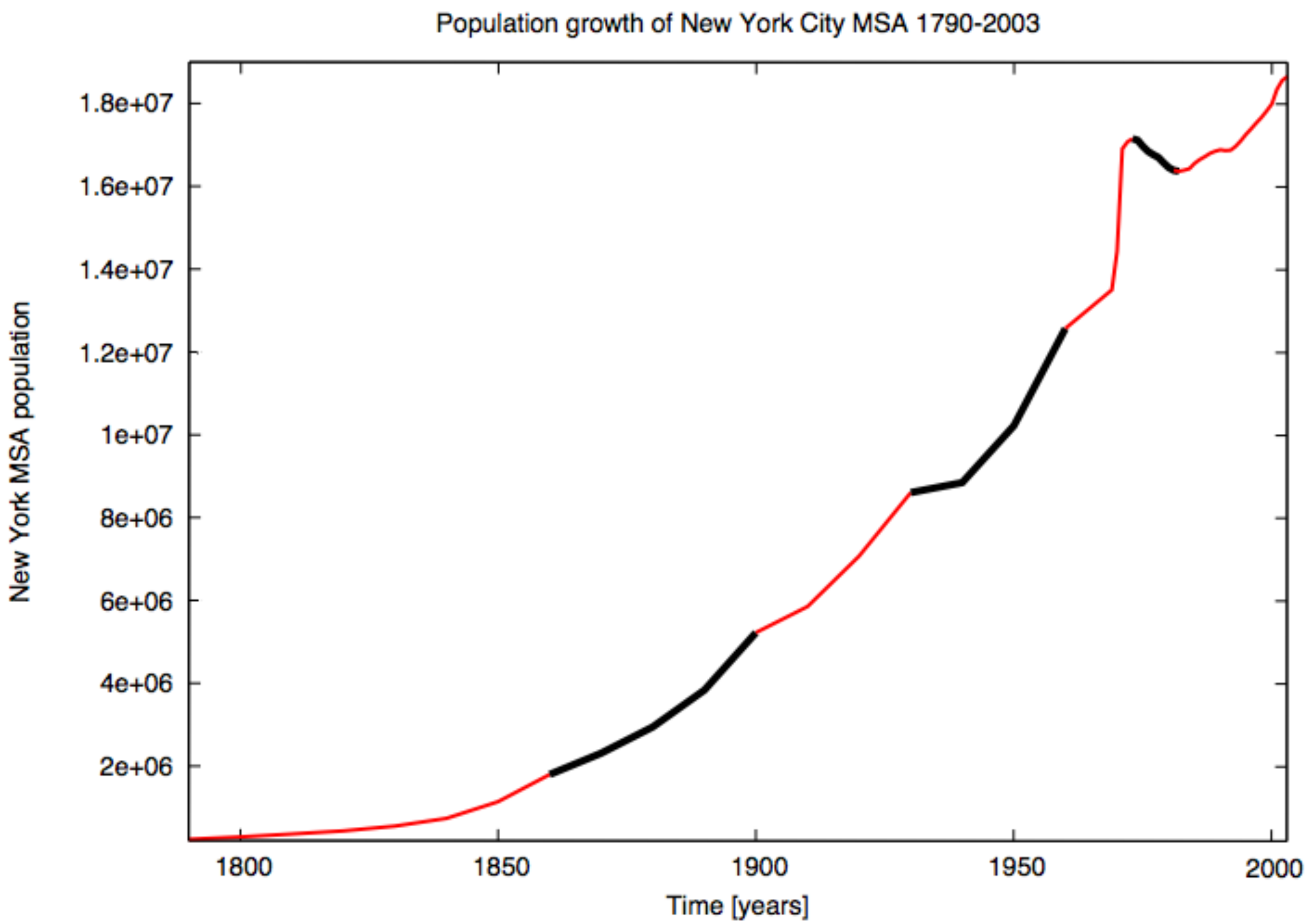
i) $b > 1$ **AND**

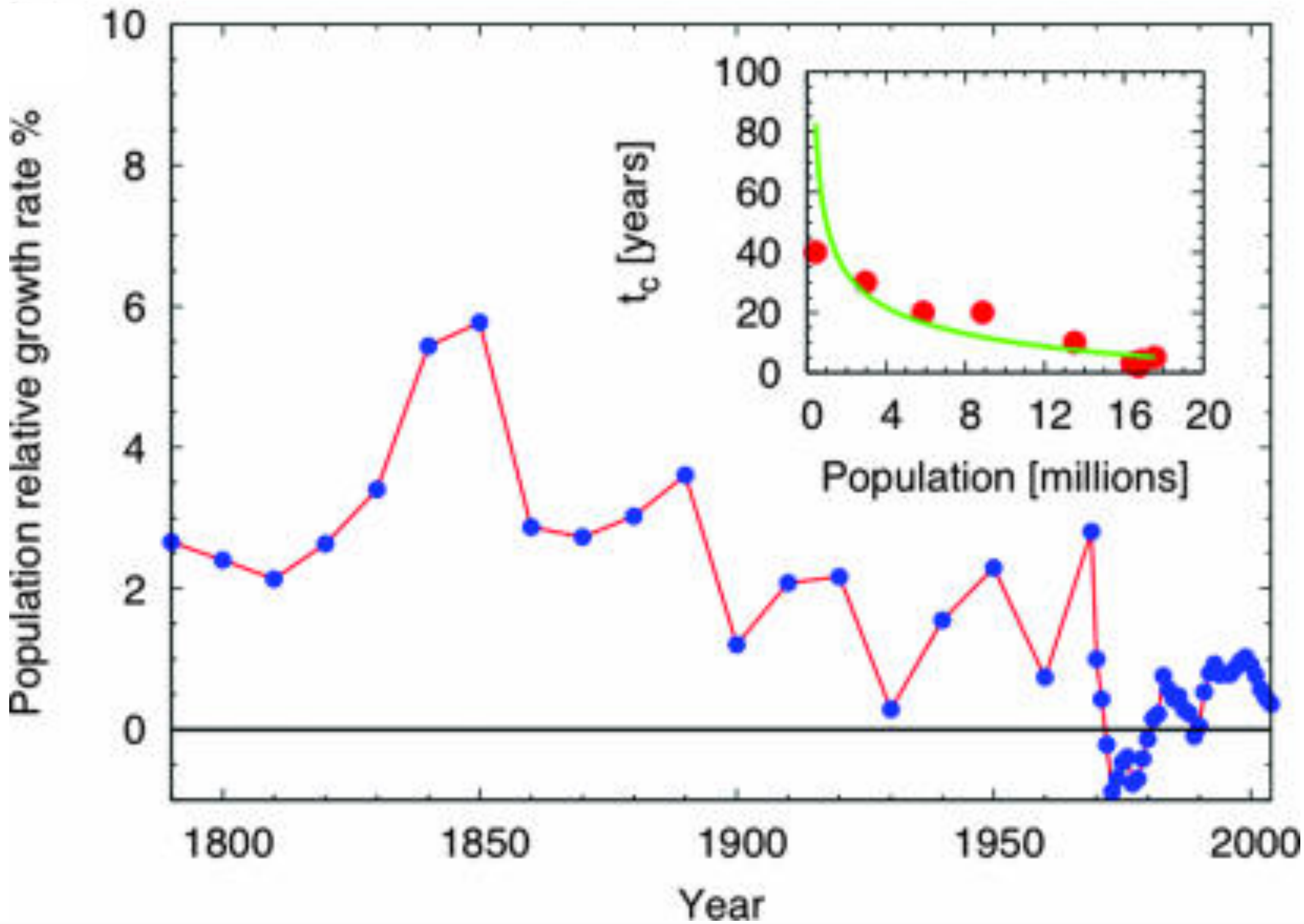
ii) **CONTINUOUS MAJOR INNOVATIONS OR PARADIGM SHIFTS AT AN ACCELERATING RATE**

iii) TIME BETWEEN INNOVATIONS DECREASES SYSTEMATICALLY WITH GROWTH:

$$t_c \sim N^{1-b} \sim N^{-0.15} \sim 1/t$$

Population growth for New York City
1790 - 2003





Successive cycles of superlinear innovation reset the singularity and postpone instability and subsequent collapse. The relative population growth rate of New York City over time reveals periods of accelerated (super-exponential) growth. Successive shorter periods of super exponential growth appear, separated by brief periods of deceleration. (Inset) t_c for each of these periods vs. population at the onset of the cycle. Observations are well fit with $\beta = 1.09$ (green line).

Social Corporate Urban

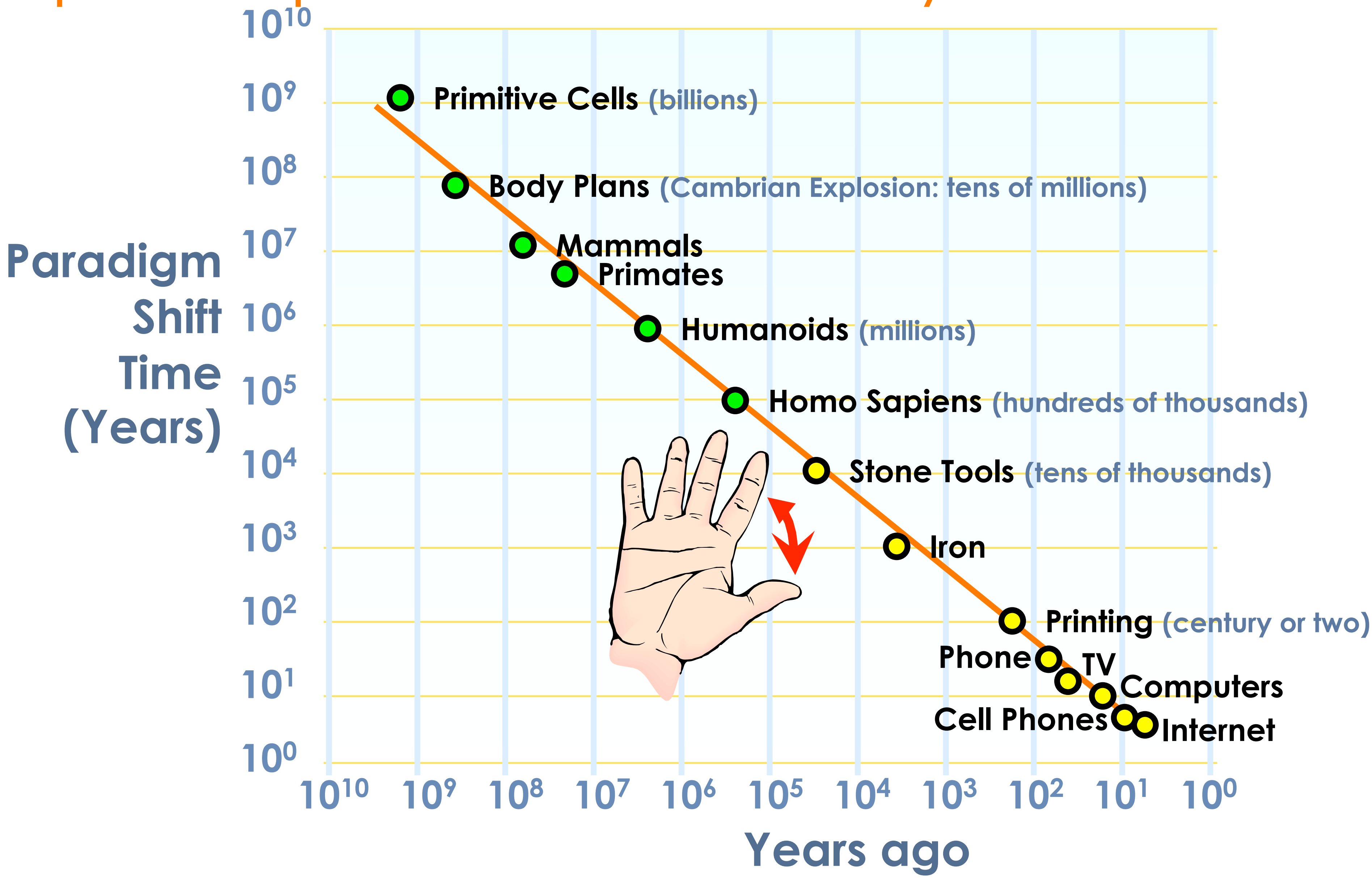
- ***NON-LINEAR SCALING LAWS***
- ***THREE UNIVERSAL CLASSES***
- ***SUPER-LINEAR EXPONENTS (> 1)***
- ***WEALTH CREATION INNOVATION ($\sim N^{0.15}$)***
- ***PACE OF LIFE INCREASES WITH SIZE:***

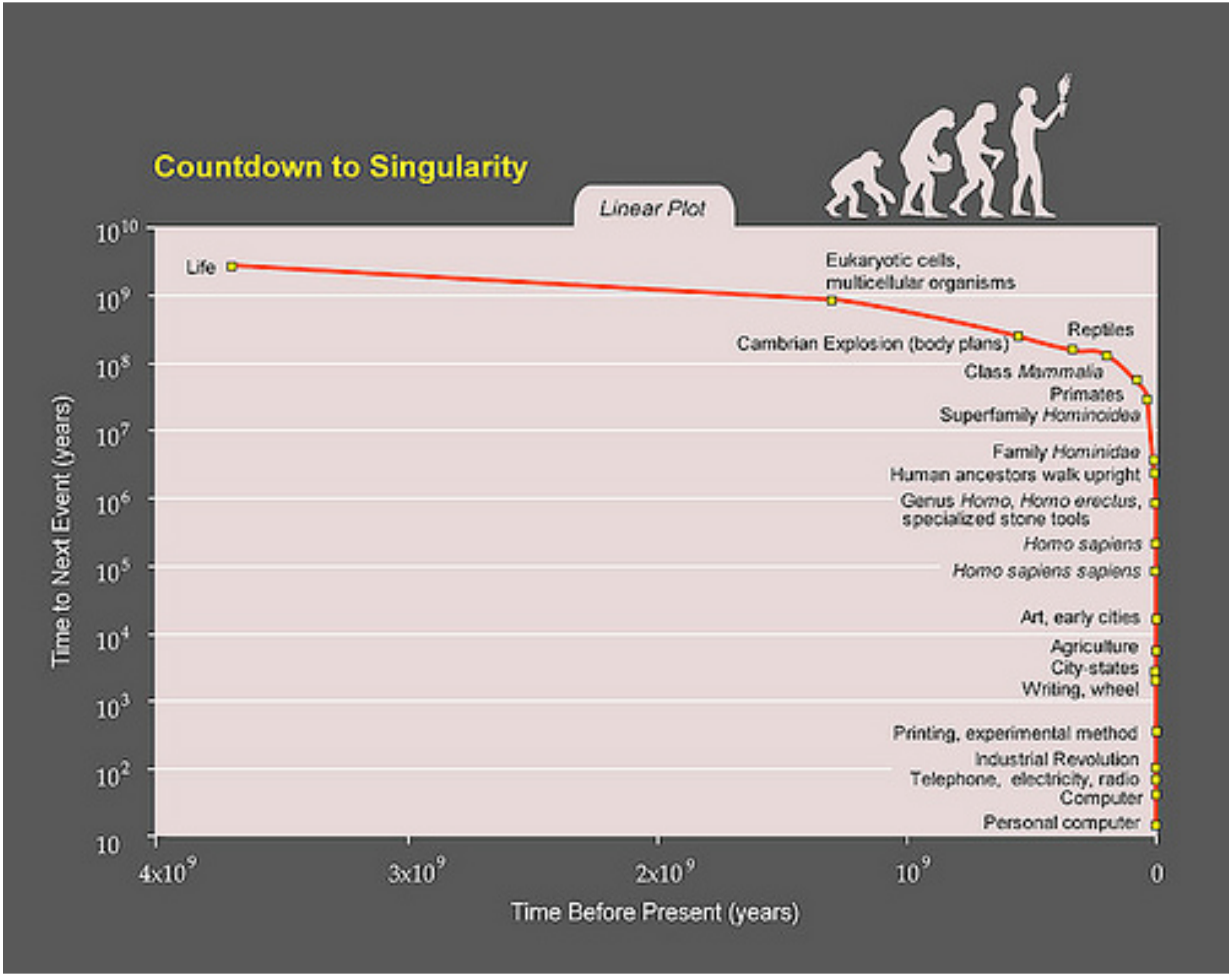
  TIMES $\sim N^{-0.15}$

  RATES $\sim N^{0.15}$
- ***UNBOUNDED SUPER-EXPONENTIAL GROWTH***
- ***FINITE TIME SINGULARITY***
- ***ACCELERATING CYCLES OF INNOVATION***
- ***SUSTAINABLE?***
- ***GOVERNED BY NETWORKS (FRACTALS?)***

Countdown to singularity

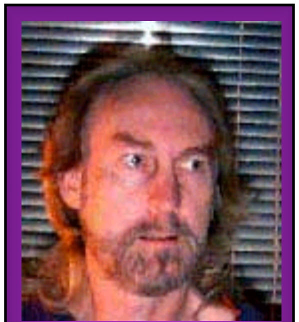
Singularity is technological change so rapid and so profound that is represents a rupture in the fabric of human history



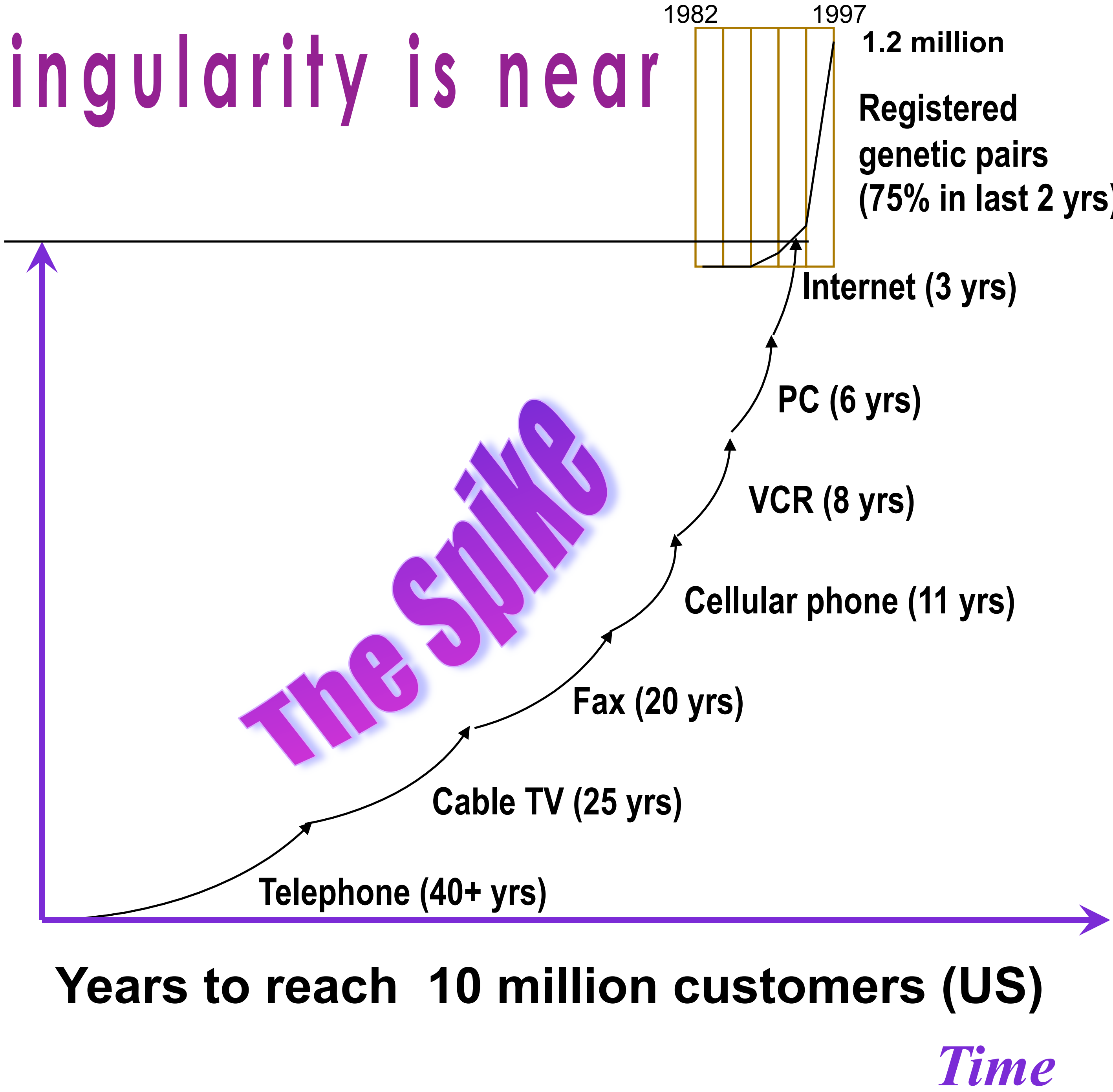


Countdown to Singularity
Linear Plot
Life
Eukaryotic cells, multicellular organisms
Cambrian Explosion (body plans)
Reptiles
Class Mammalia
Primates
Superfamily Hominoidea
Family Hominidae
Human ancestors walk upright
Genus Homo, Homo erectus, specialized stone tools
Homo sapiens
Homo sapiens sapiens
Art, early cities
Agriculture
City-states
Writing, wheel
Printing, experimental method
Industrial Revolution
Telephone, electricity, radio
Computer
Personal computer
Time to Next Event (years)
Time Before Present (years)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
$4x10^9$
$3x10^9$
$2x10^9$
10^9
0

Singularity is near



Damien Broderick

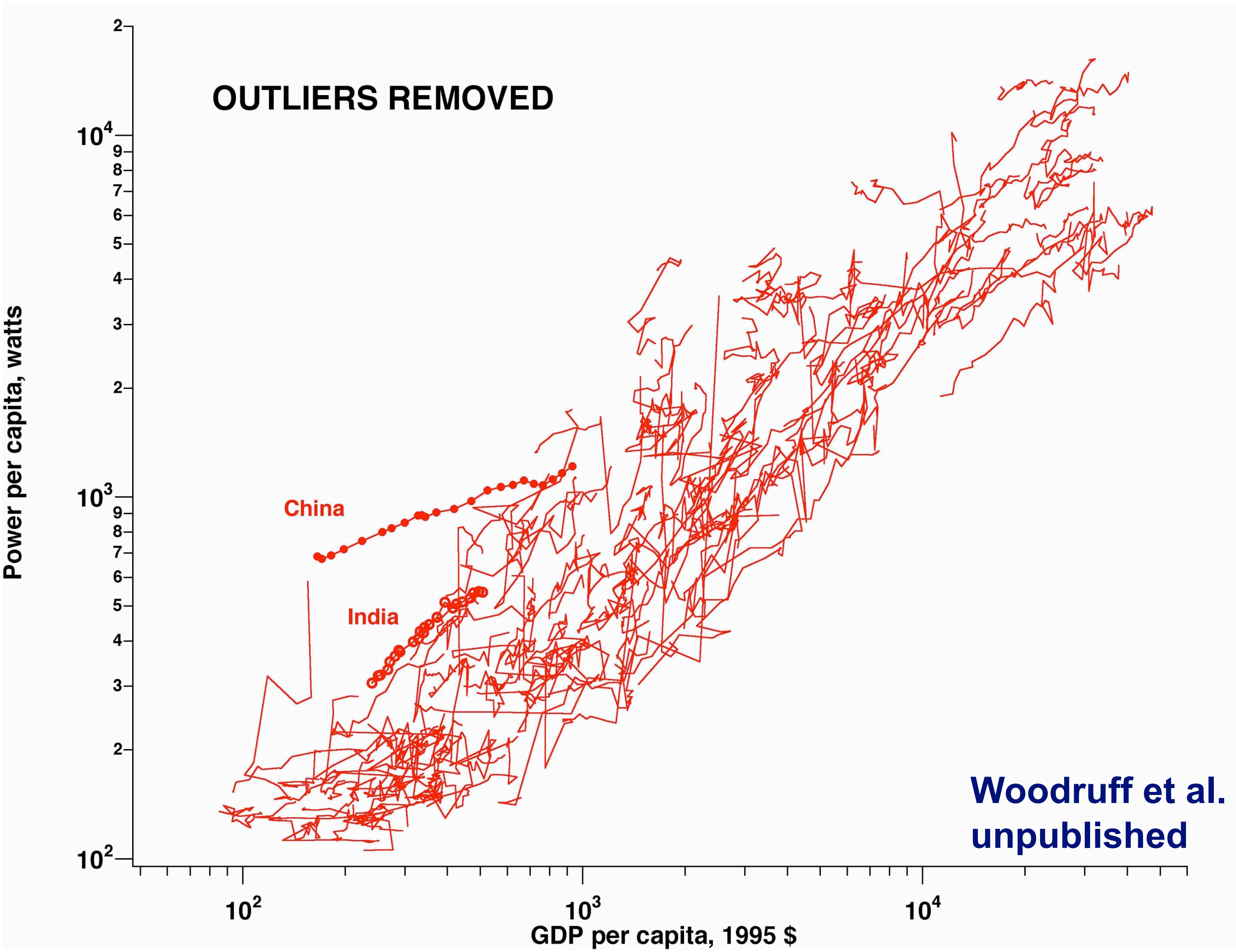


Singularity is near

The ever accelerating progress of technology….gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue.

John von Neumann
(1903 - 1957)

PER CAPITA POWER CONSUMPTION AS A FUNCTION OF PER CAPITA GDP 1980-2000



Human ecology: reproductive rate in modern nations

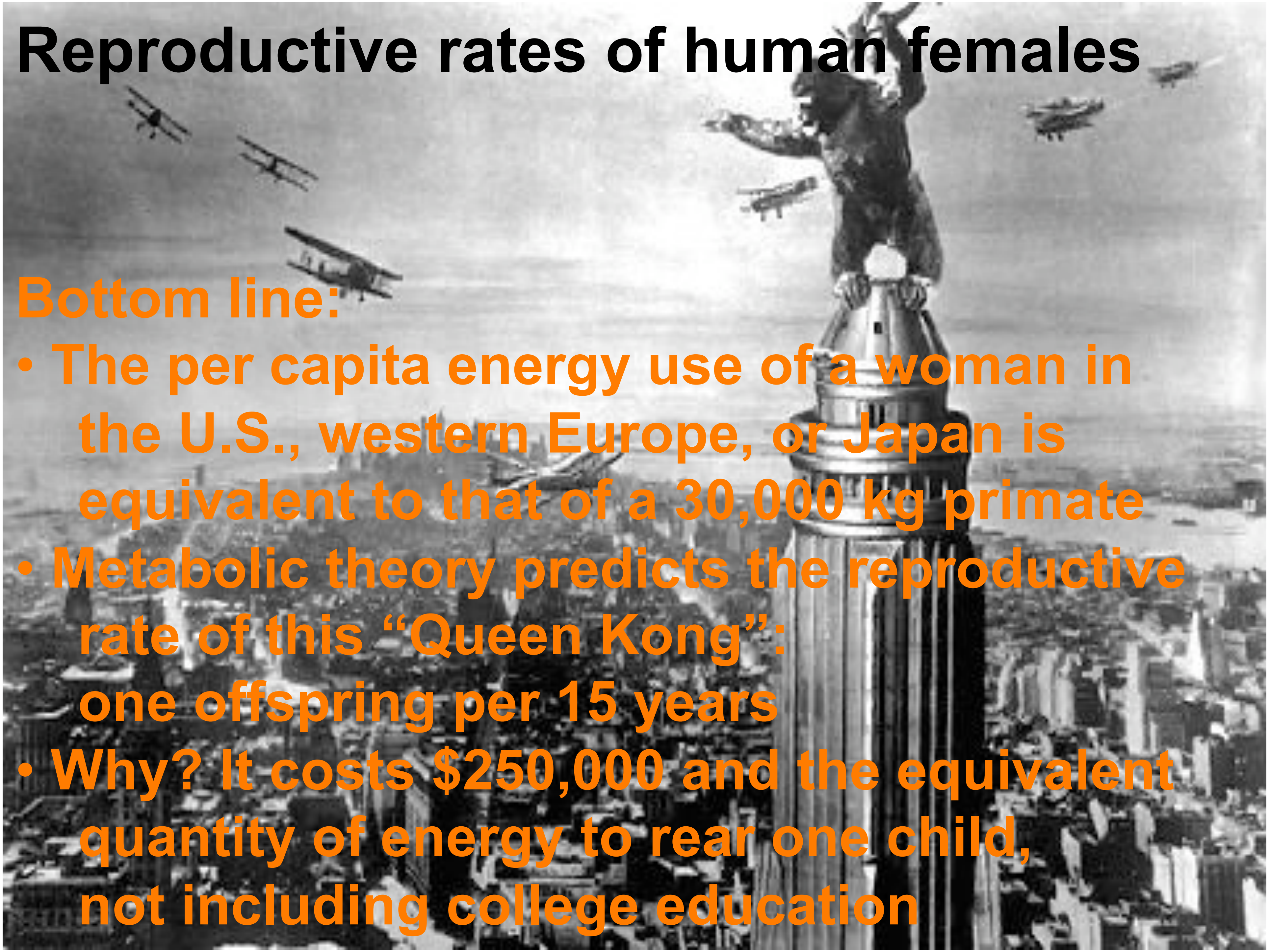
- Biological metabolic rate (*B*) is 100 watts
- Per capita rate of total energy use, including fossil fuels, varies

  from 300 watts in developing nations

  to 11,000 watts in developed nations
- Predicted fecundity rate (*F*)

  $F \propto M^{-1/4}$ and $B \propto M^{3/4}$,

  so $F \propto B^{-1/3}$



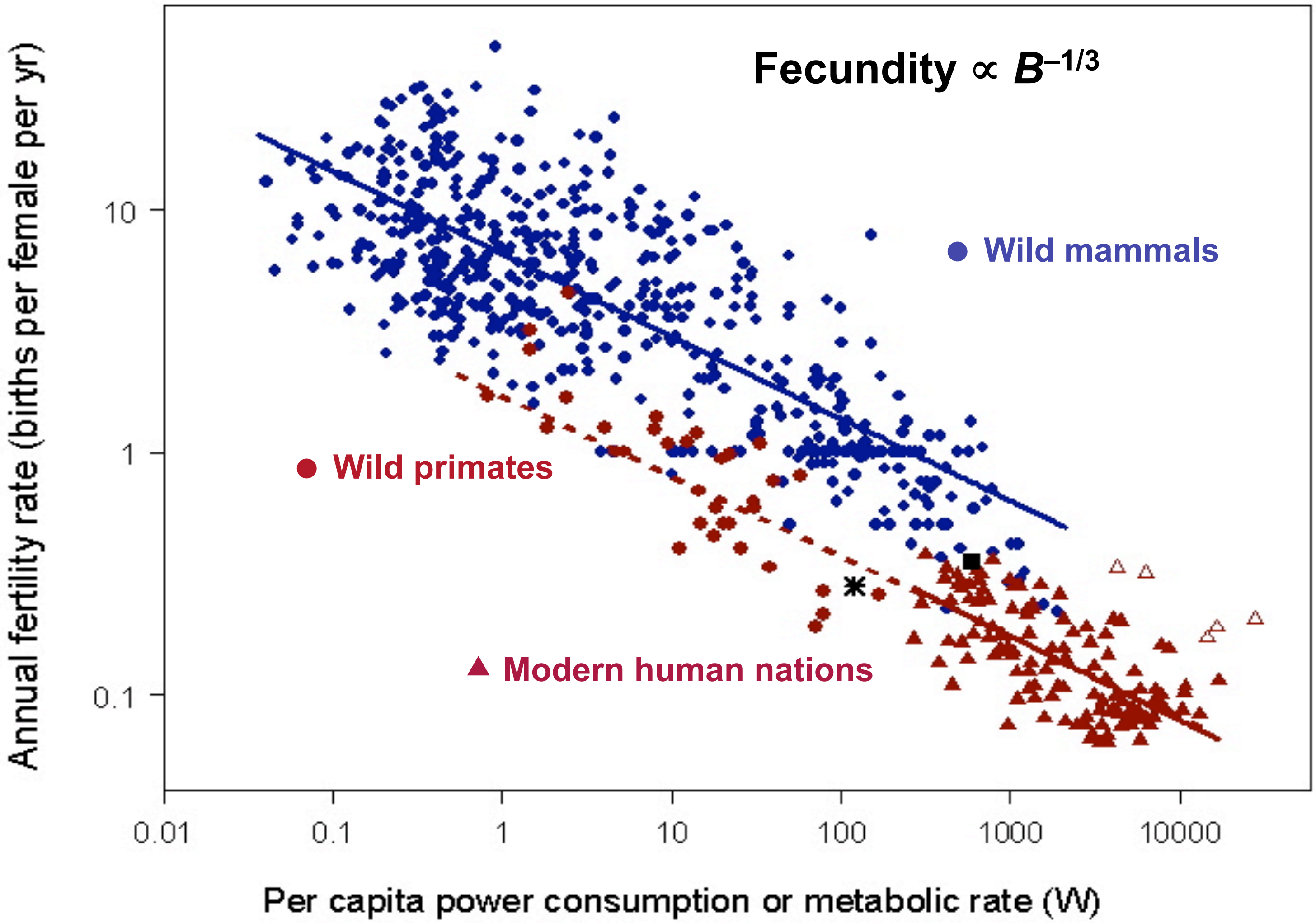
Reproductive rates of human females

Bottom line:

- The per capita energy use of a woman in the U.S., western Europe, or Japan is equivalent to that of a 30,000 kg primate
- Metabolic theory predicts the reproductive rate of this “Queen Kong”: one offspring per 15 years
- Why? It costs $250,000 and the equivalent quantity of energy to rear one child, not including college education

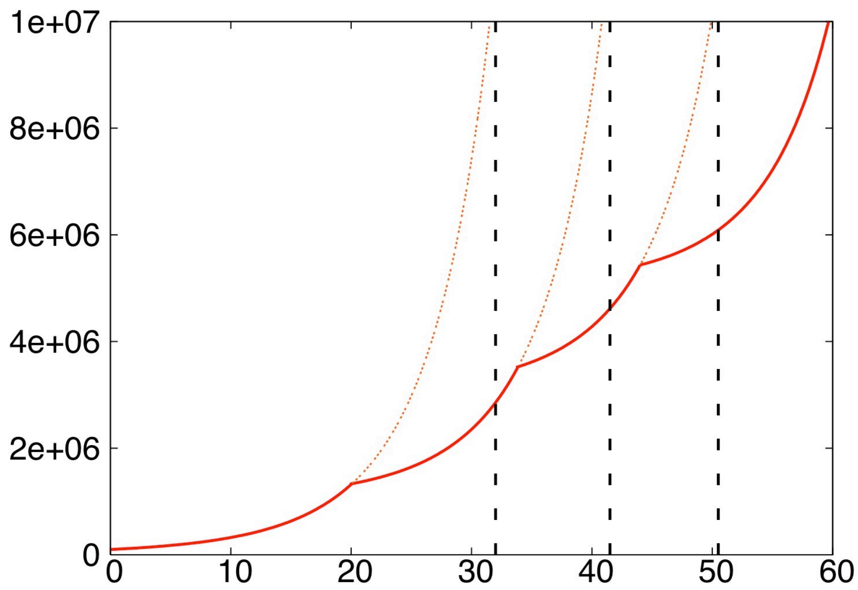
Reproductive rates of mammals, primates, and humans

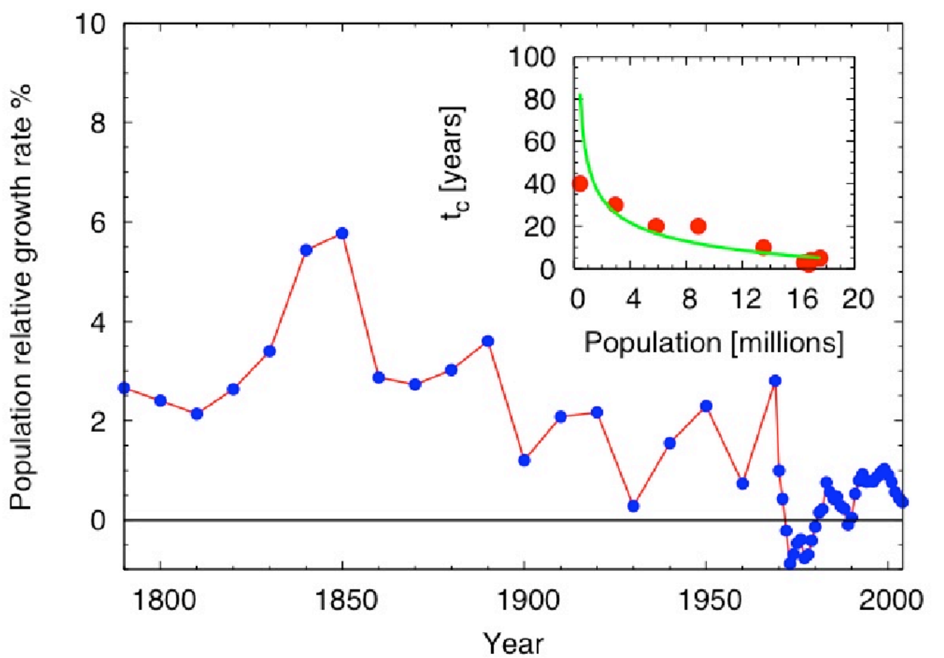
Moses and Brown 2002



Escaping the singularity with β>1:

cycles of successive growth & innovation

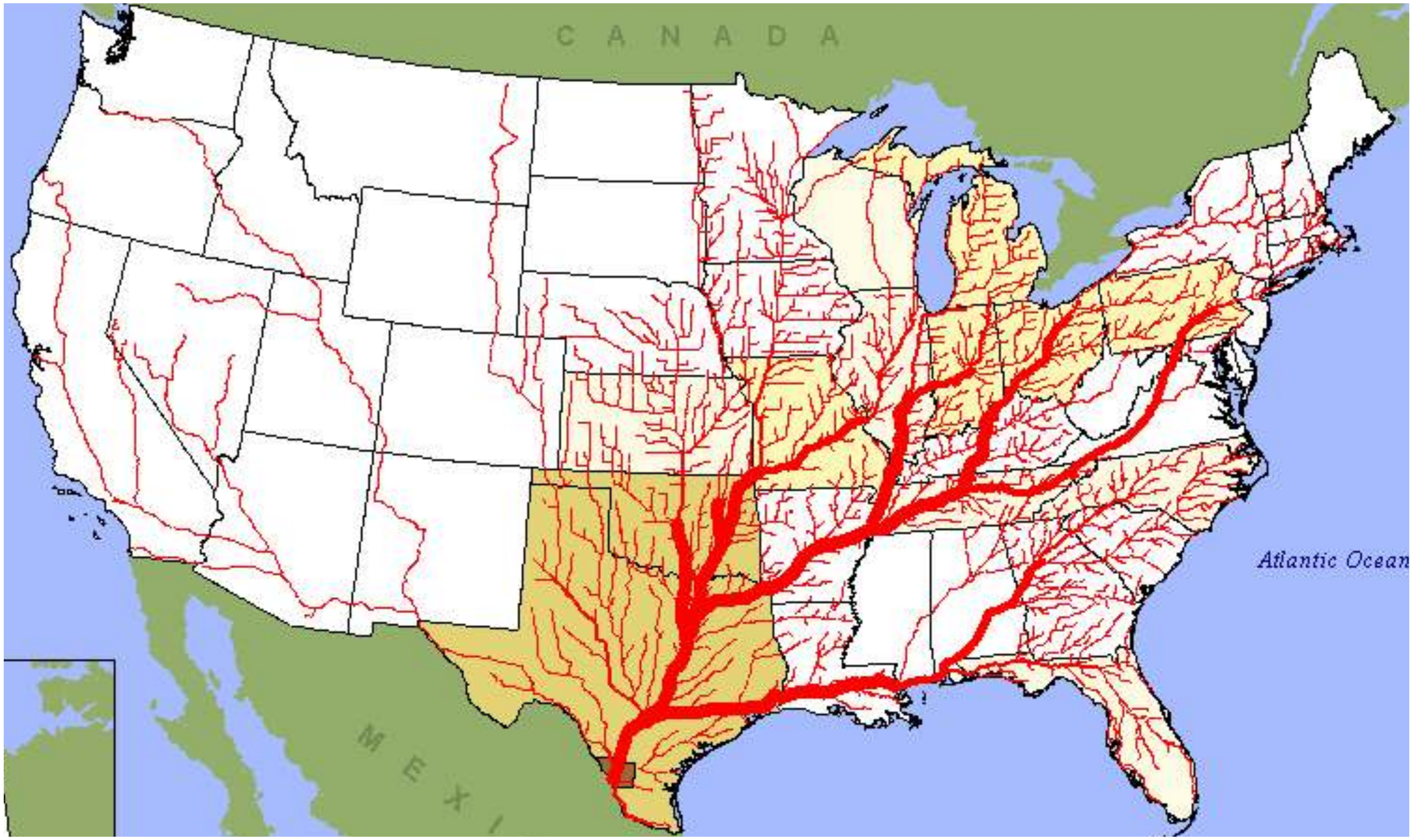




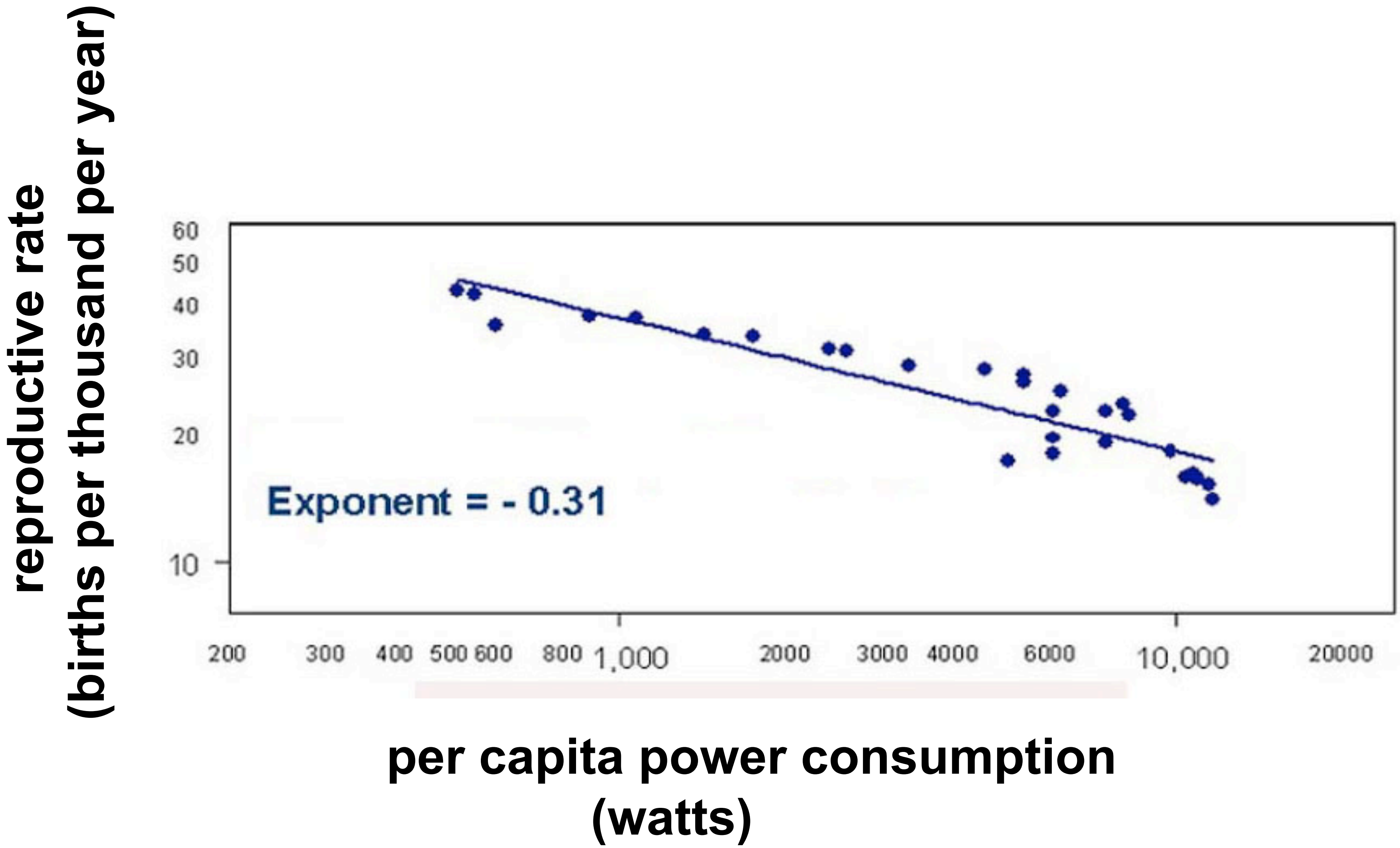
$$t_{crit} \approx \frac{E_0}{(\beta - 1)R_a} N^{1-\beta}(0) \cong 50 \frac{T}{n^{\beta-1}} \, years.$$

➡ t_{crit} shortens with population size N

Combined truck traffic through the Laredo area



Reproductive rates of U.S. females: Temporal change 1870-2000



Moses and Brown 2002