Energy, Growth, Sustainability and the Underlying Threat of Urbanization

SIZE MATTERS

GEOFFREY WEST

SOME CHARACTERISTICS OF COMPLEX SYSTEMS

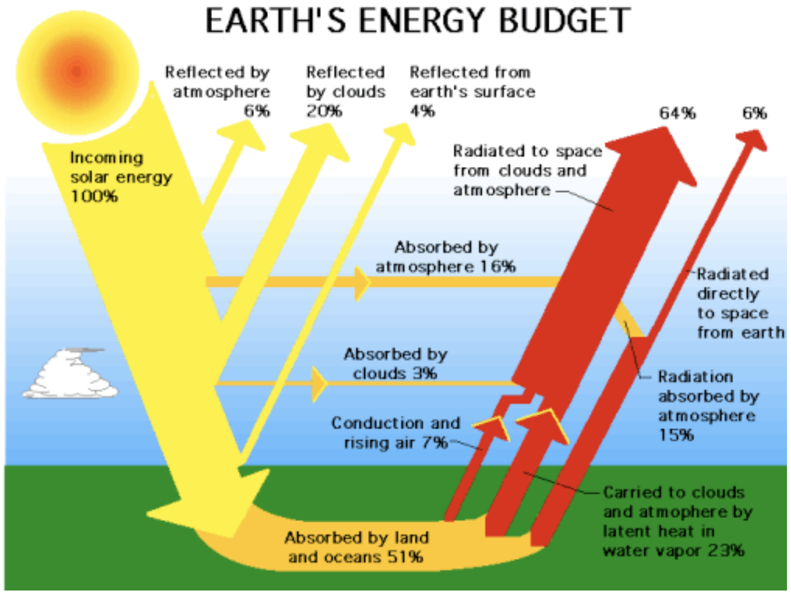
- MANY COMPONENTS
- MANY INDIVIDUAL ACTORS / AGENTS
- MULTI SPATIAL AND TEMPORAL SCALES
- STRONGLY COUPLED / INTERACTING
- NON-LINEAR
- SENSITIVITY TO BOUNDARY CONDITIONS (CHAOS)
- EMERGENT PHENOMENA / MULTIPLE PHASES
- UNINTENDED CONSEQUENCES
- ADAPTIVE / EVOLVING
- HISTORICALLY CONTINGENT / PATH DEPENDENT
- ROBUST / RESILIENT
- NON-EQUILIBRIUM
- UNDERLYING SIMPLICITY
- COMPLICATED vs COMPLEX

- ***COARSE- GRAINED DESCRIPTION***

- ***KINETIC THEORY***

- ***QUARK MODEL***

- ***LONGEVITY***


EARTH'S ENERGY BUDGET
Reflected by atmosphere 6%
Reflected by clouds 20%
Reflected from earth's surface 4%
64%
6%
Incoming solar energy 100%
Radiated to space from clouds and atmosphere
Absorbed by atmosphere 16%
Radiated directly to space from earth
Absorbed by clouds 3%
Radiation absorbed by atmosphere 15%
Conduction and rising air 7%
Carried to clouds and atmophere by latent heat in water vapor 23%
Absorbed by land and oceans 51%


lonelyplanetimages.com


THALDEN•BOYD ARCHITECTS
A Native American Firm

Scaling of economics with energy use

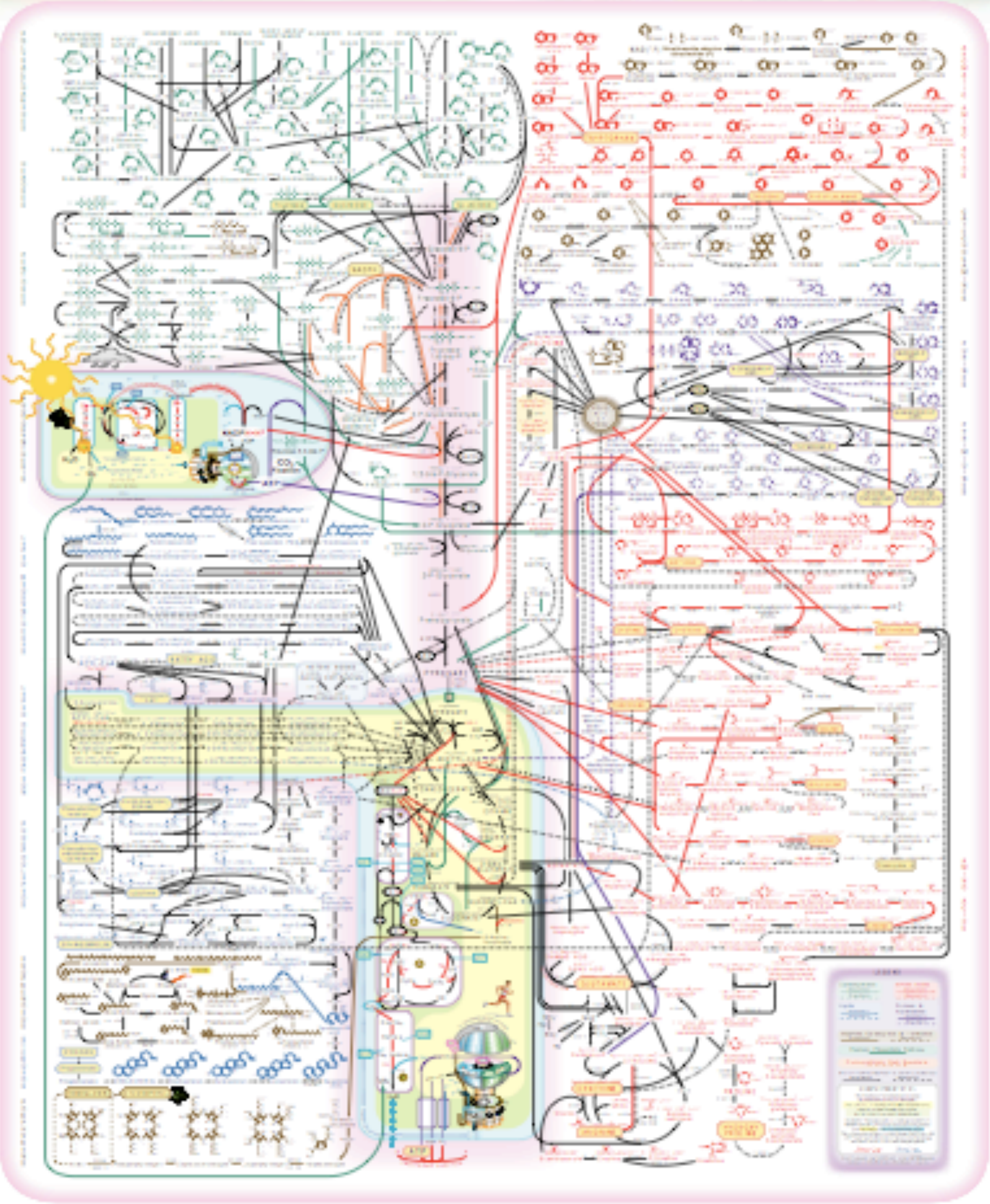

南 口
9

- 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



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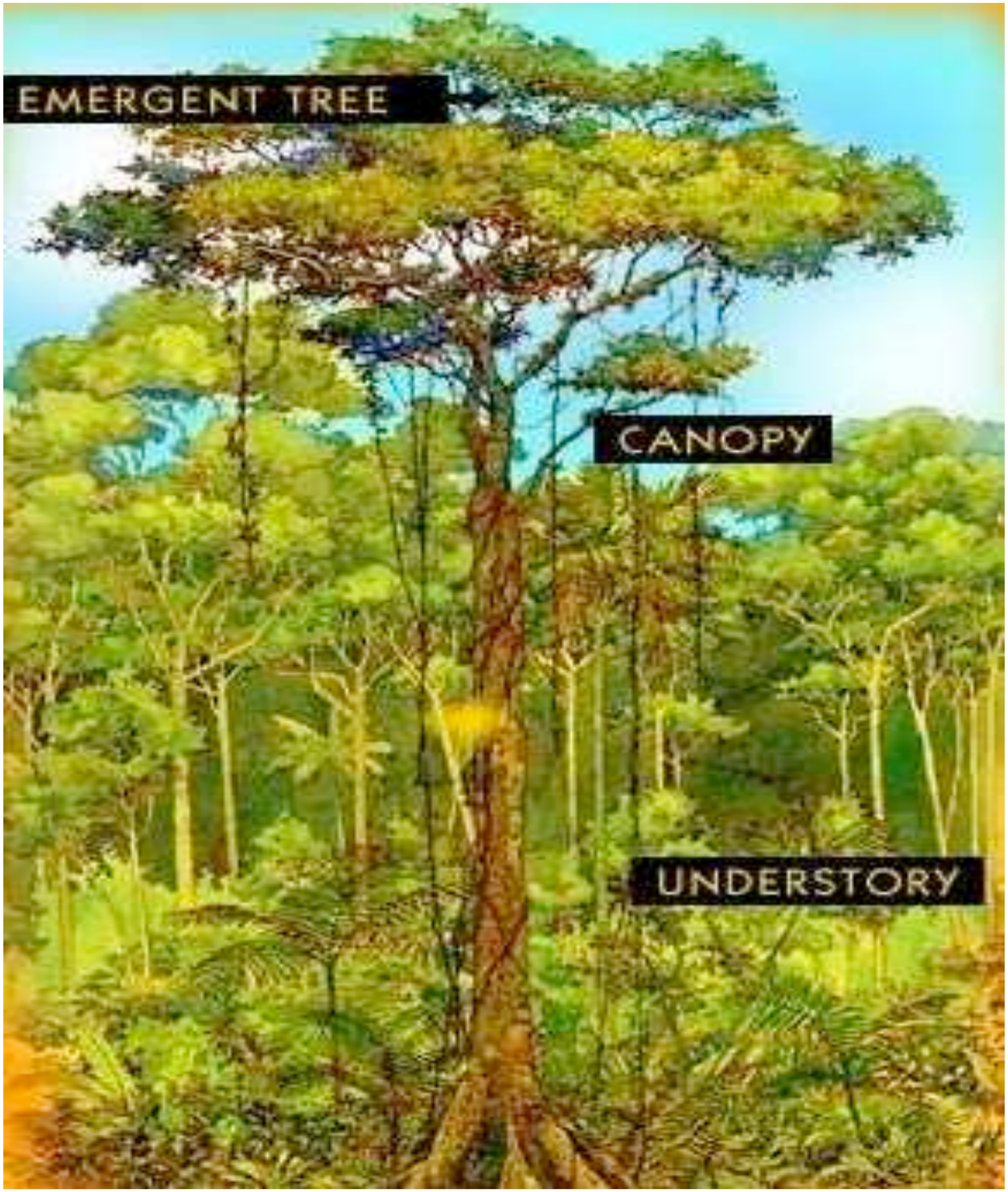
20th Edition Designed by Donald E. Nicholson, D.Sc., The University of Leeds, England – and Sigma-Aldrich

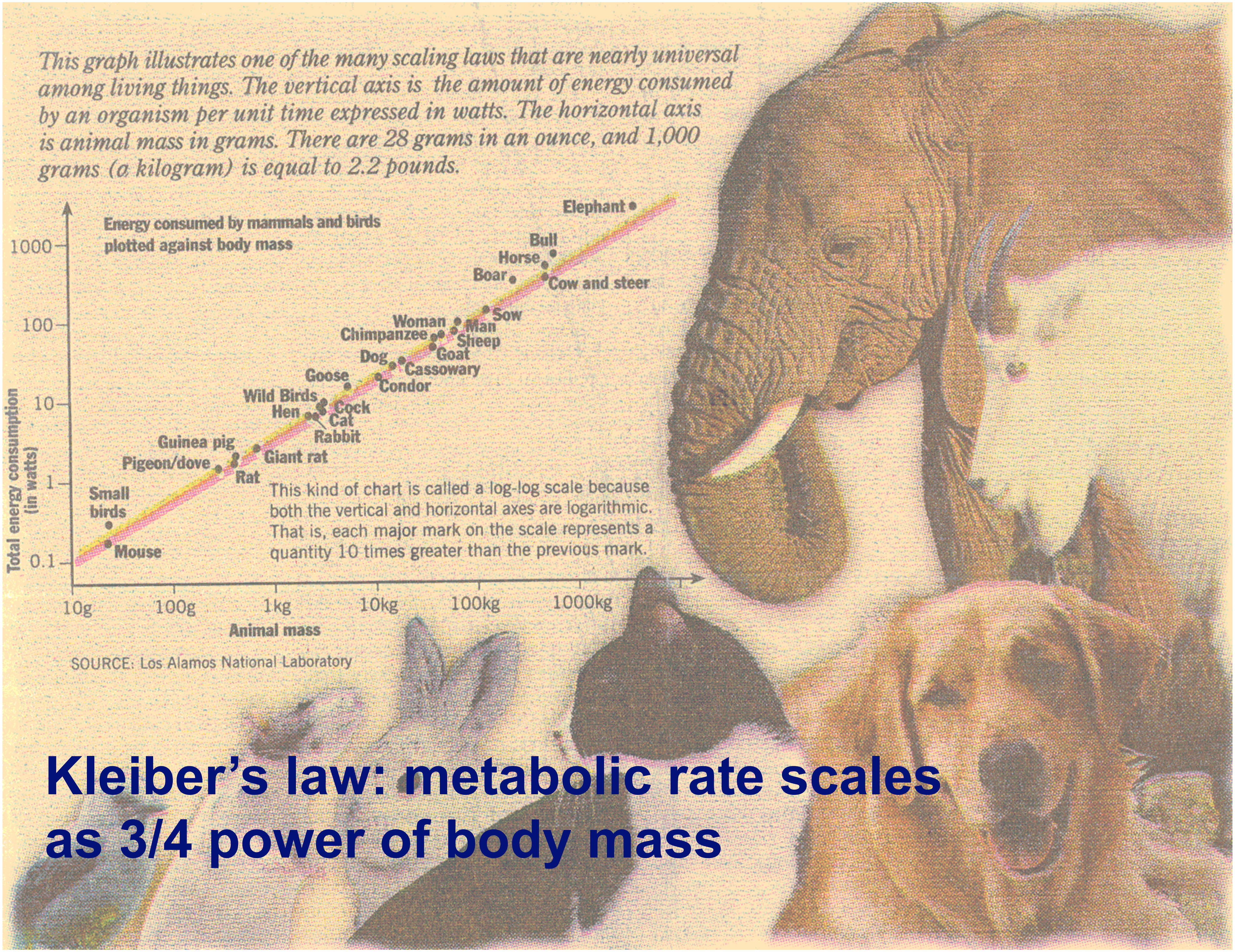
Relation between number and diameter of trees in a forest recapitulates the branches of the largest trees

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



Mammals vary in size by 8 orders of magnitude

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

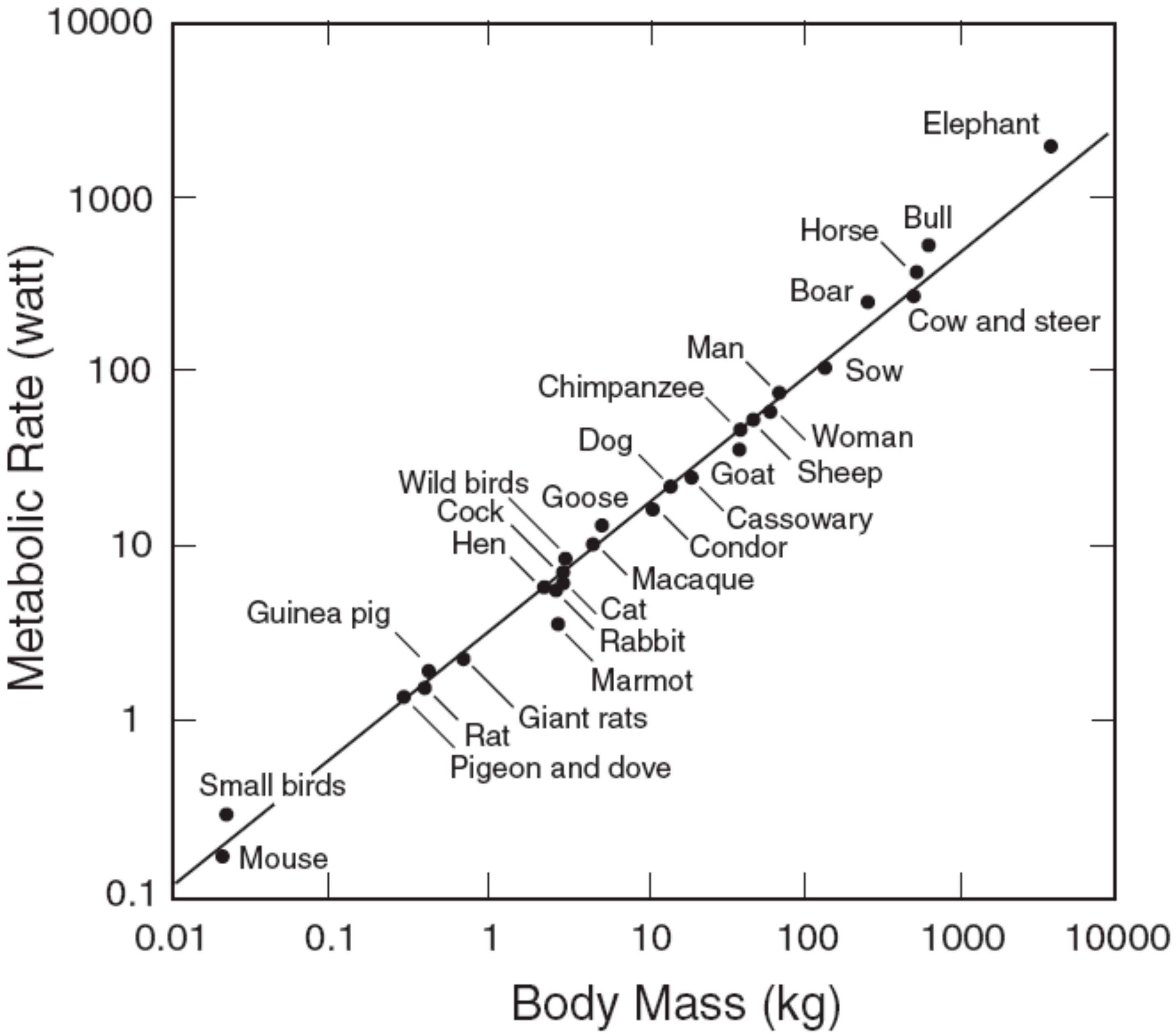


This graph illustrates one of the many scaling laws that are nearly universal among living things. The vertical axis is the amount of energy consumed by an organism per unit time expressed in watts. The horizontal axis is animal mass in grams. There are 28 grams in an ounce, and 1,000 grams (a kilogram) is equal to 2.2 pounds.

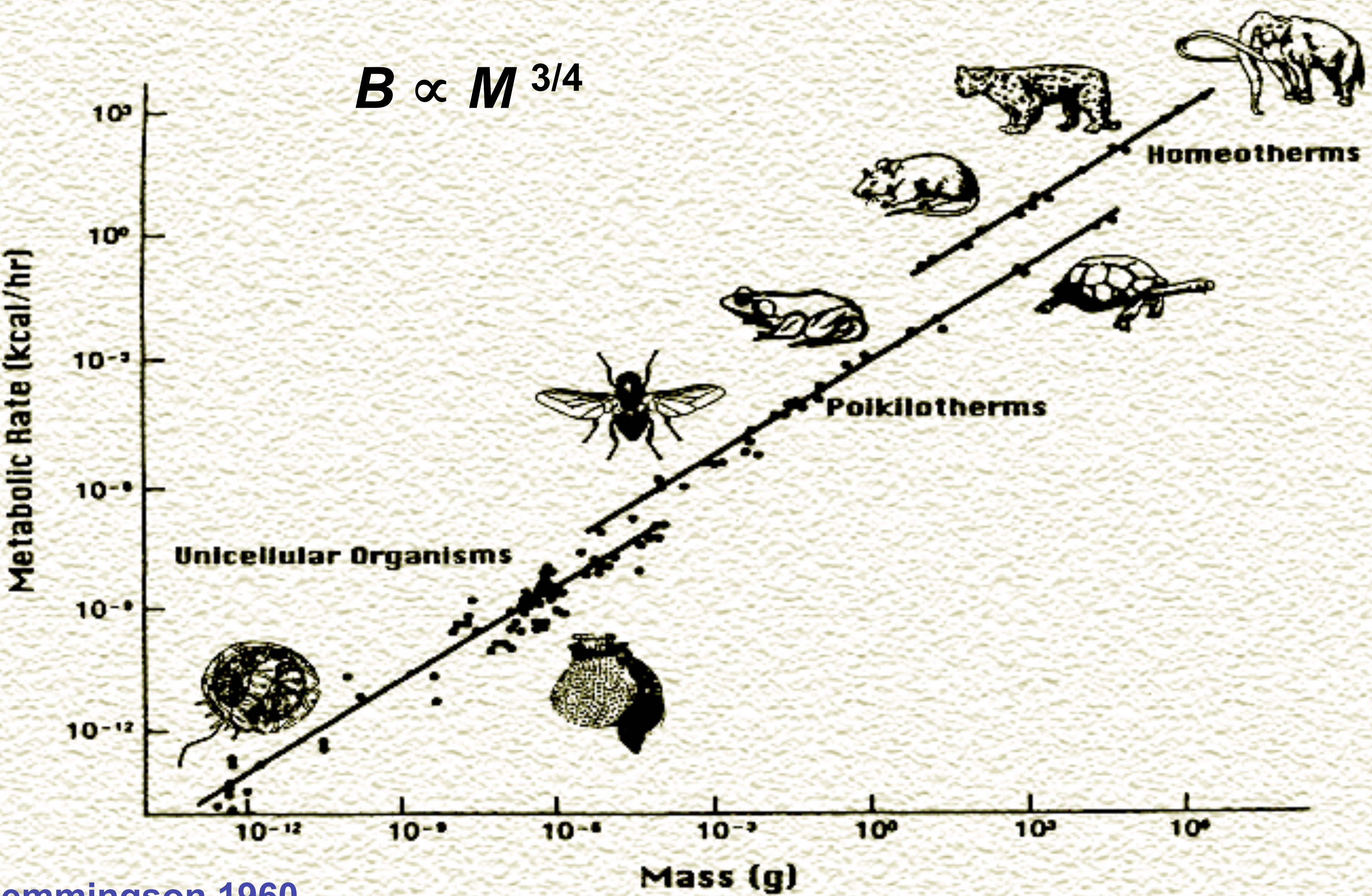
Energy consumed by mammals and birds plotted against body mass

This kind of chart is called a log-log scale because both the vertical and horizontal axes are logarithmic. That is, each major mark on the scale represents a quantity 10 times greater than the previous mark.

SOURCE: Los Alamos National Laboratory

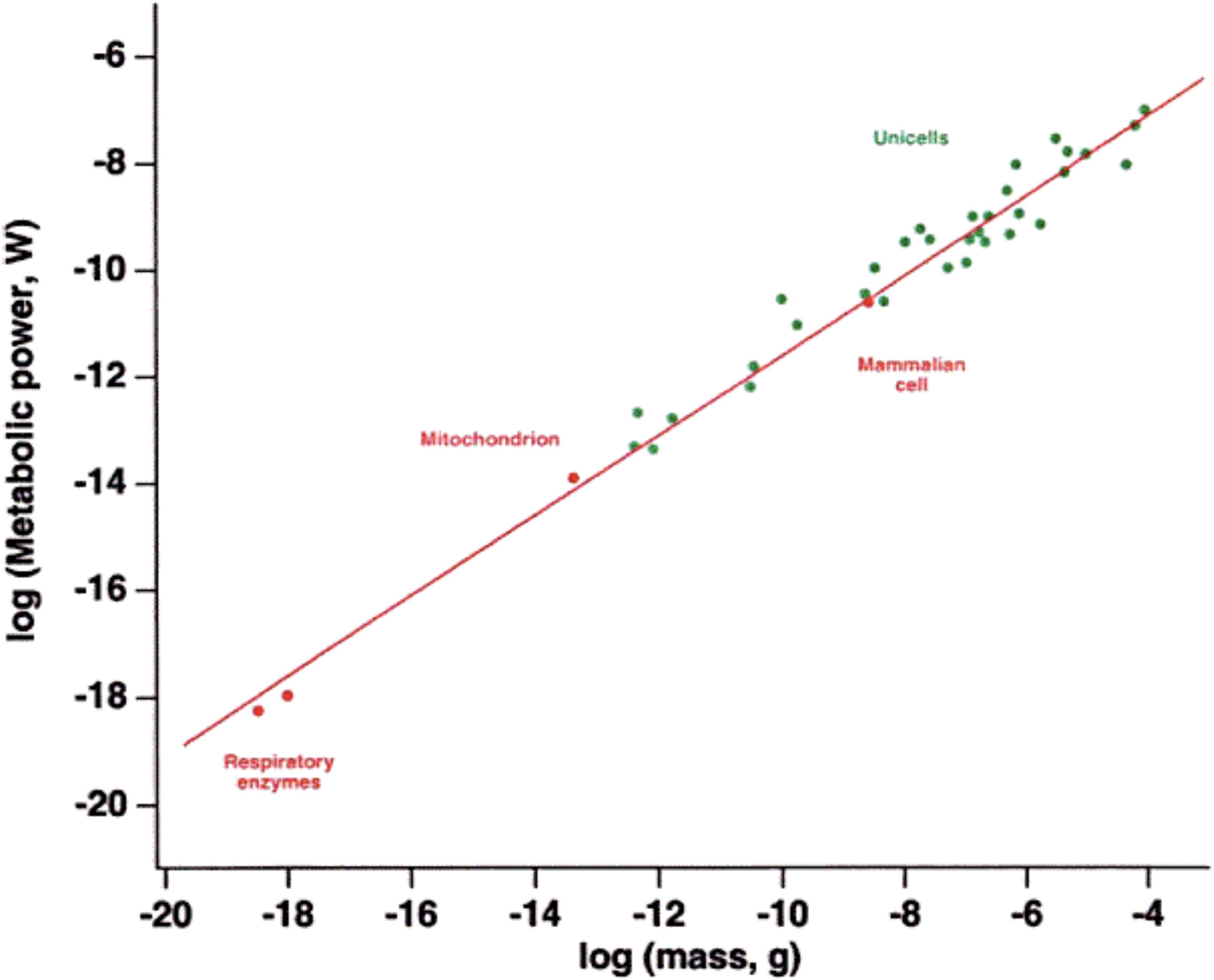

Metabolic Rate (watt)
Body Mass (kg)
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000
Elephant
Bull
Horse
Boar
Cow and steer
Man
Sow
Chimpanzee
Woman
Dog
Goat
Sheep
Wild birds
Goose
Cassowary
Cock
Condor
Hen
Macaque
Cat
Rabbit
Marmot
Guinea pig
Giant rats
Rat
Pigeon and dove
Small birds
Mouse

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



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

Hemmingson 1960


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

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)

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

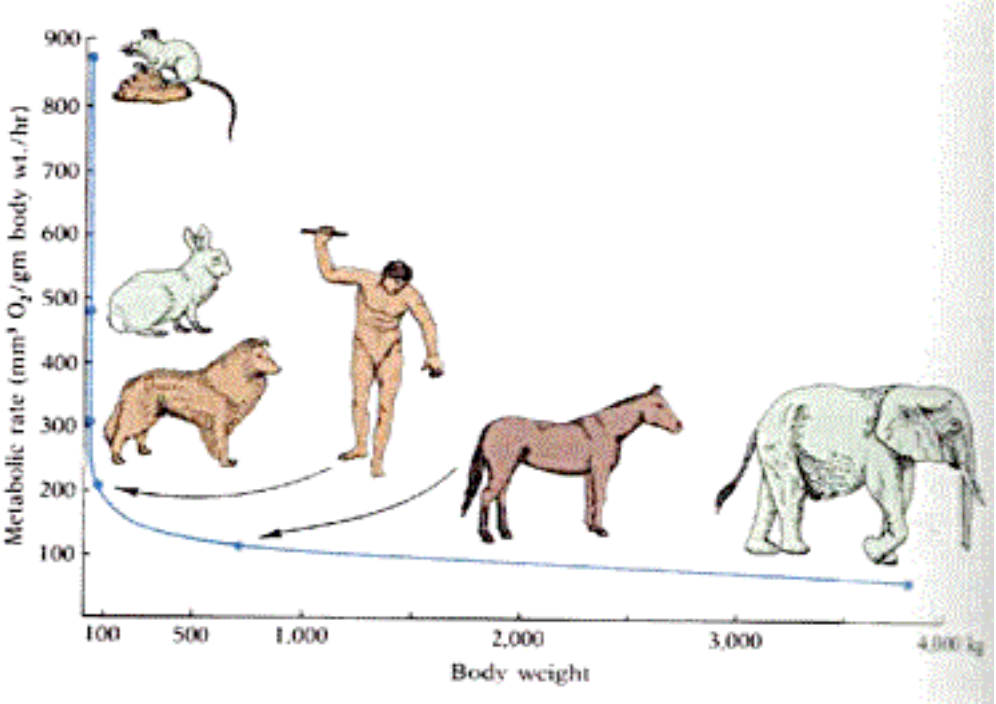
SPECIFIC METABOLIC RATE (PER UNIT MASS)

$$\frac{B}{M} \propto M^{-1/4}$$

SO METABOLIC RATE OF AVERAGE CELL

$$B_{cell} \propto M^{-1/4}$$

LIFE EXHIBITS A 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 MAY BE BEAUTIFUL BUT LARGE IS MORE EFFICIENT

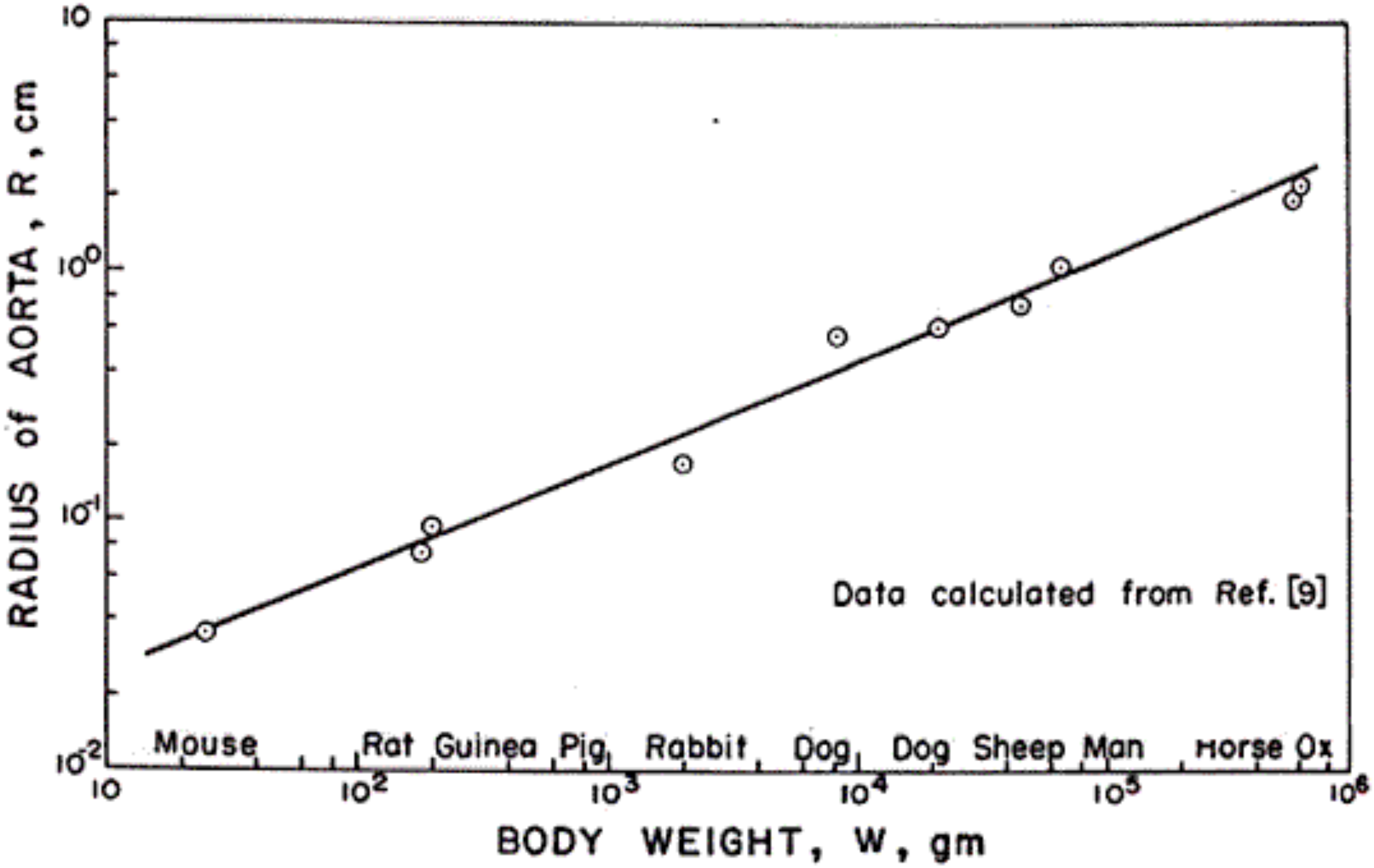
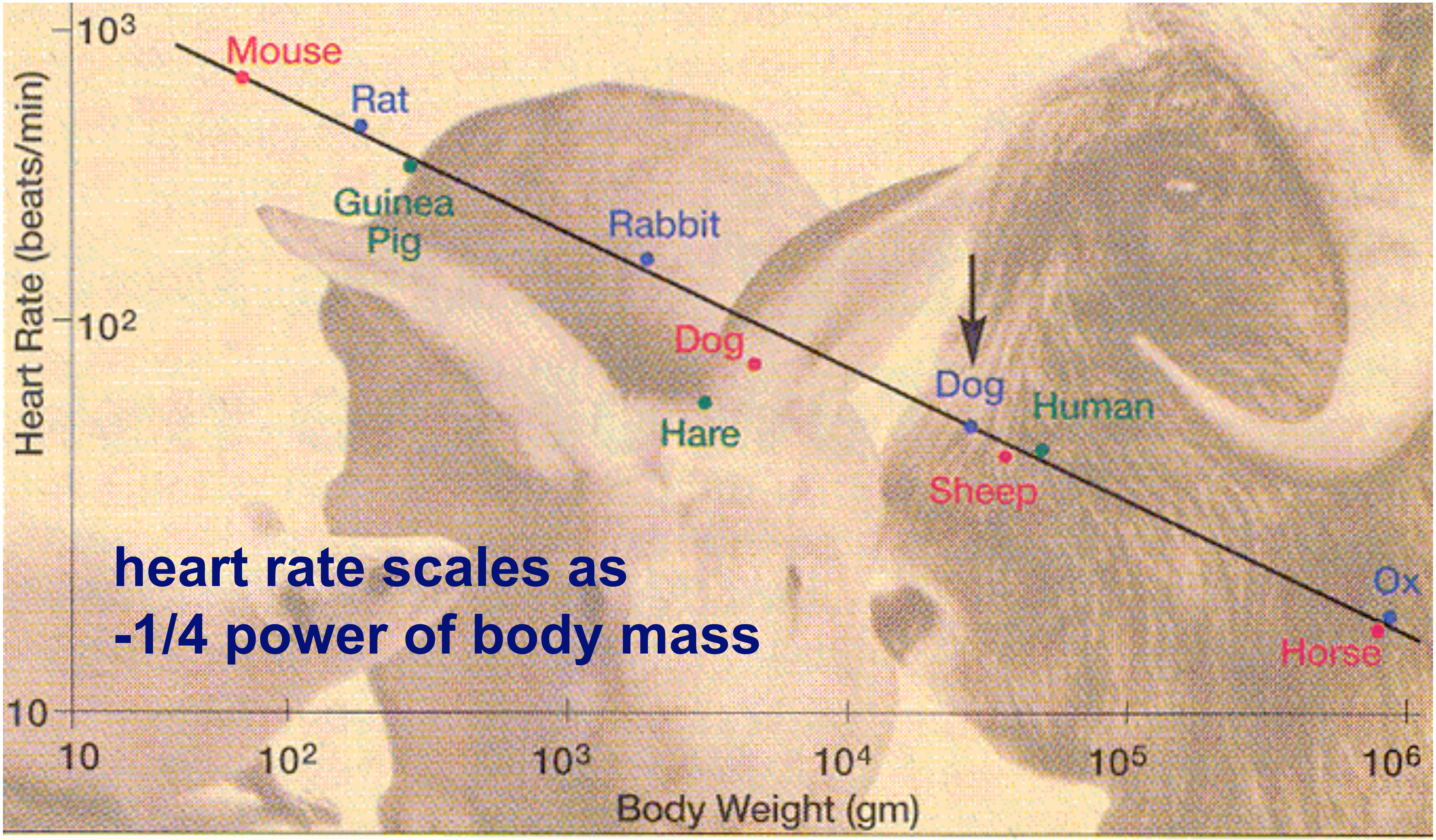


FIG. 4 – VARIATION IN RADIUS OF AORTA WITH BODY WEIGHT

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

SAME SCALING FOR TREE TRUNKS

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



heart rate scales as -1/4 power of body mass

LIFESPAN

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

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

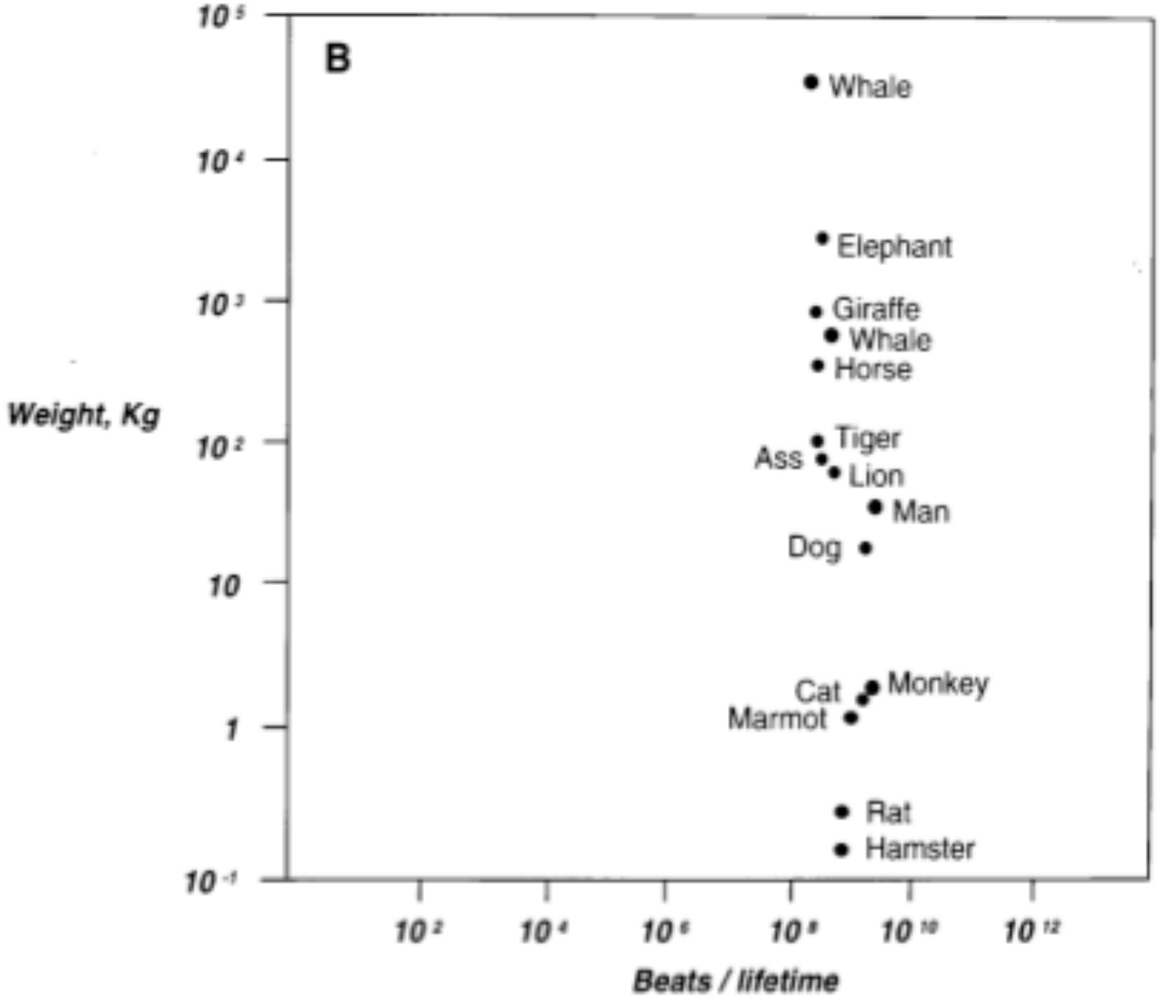
$$\sim M^{-1/4}$$

$\Rightarrow$ 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)

MORE FUNDAMENTALLY, ACROSS AEROBIC METABOLISM: THE NUMBER OF TURNOVERS IN A LIFETIME OF CytO ENZYMES (RESPIRATORY COMPLEX) IS AN APPROXIMATE INVARIANT (~ 10^{16})



RECALL SPECIFIC METABOLIC RATE

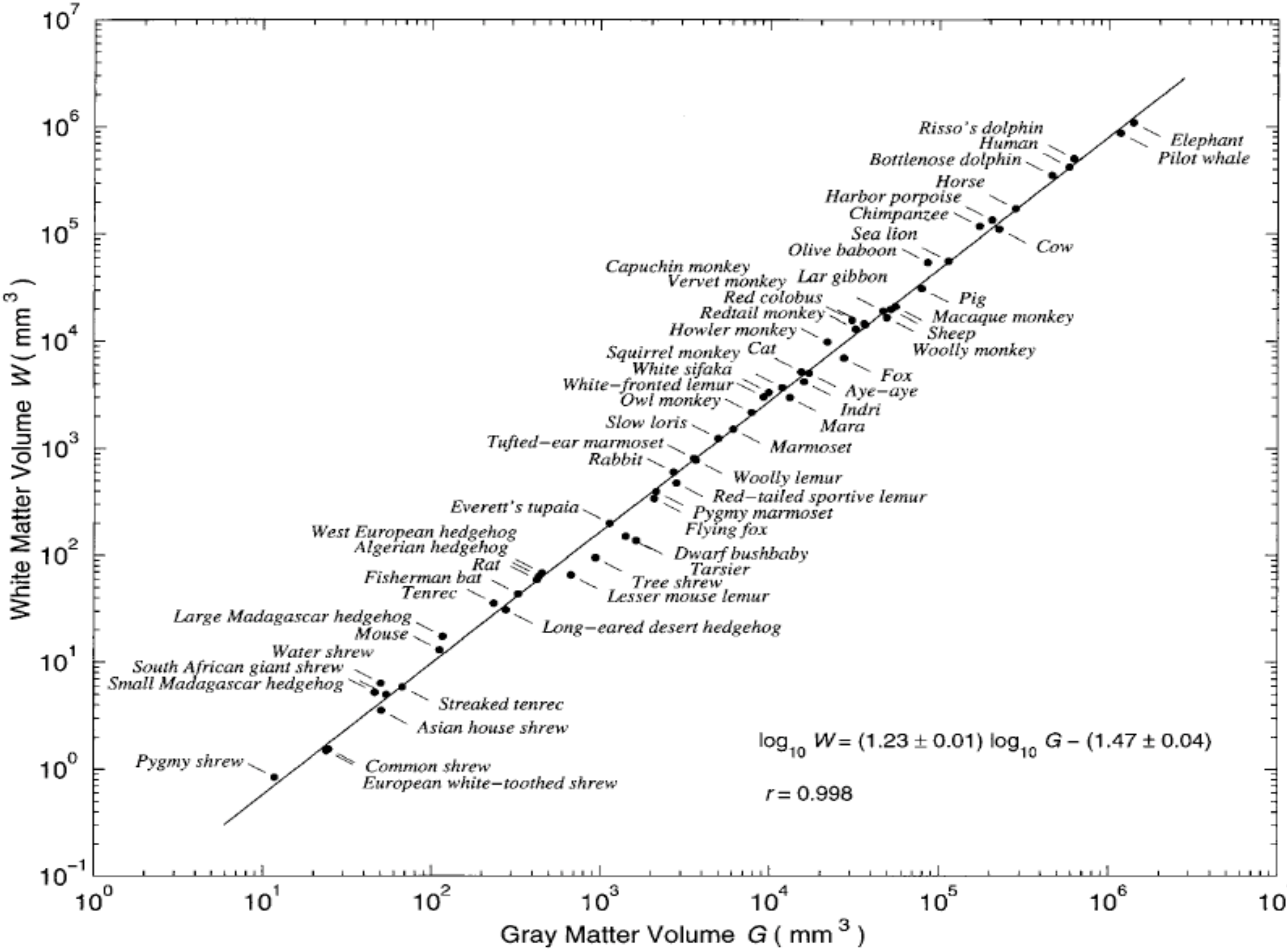
$$\bar{B} = \frac{B}{M} \propto M^{-1/4}$$

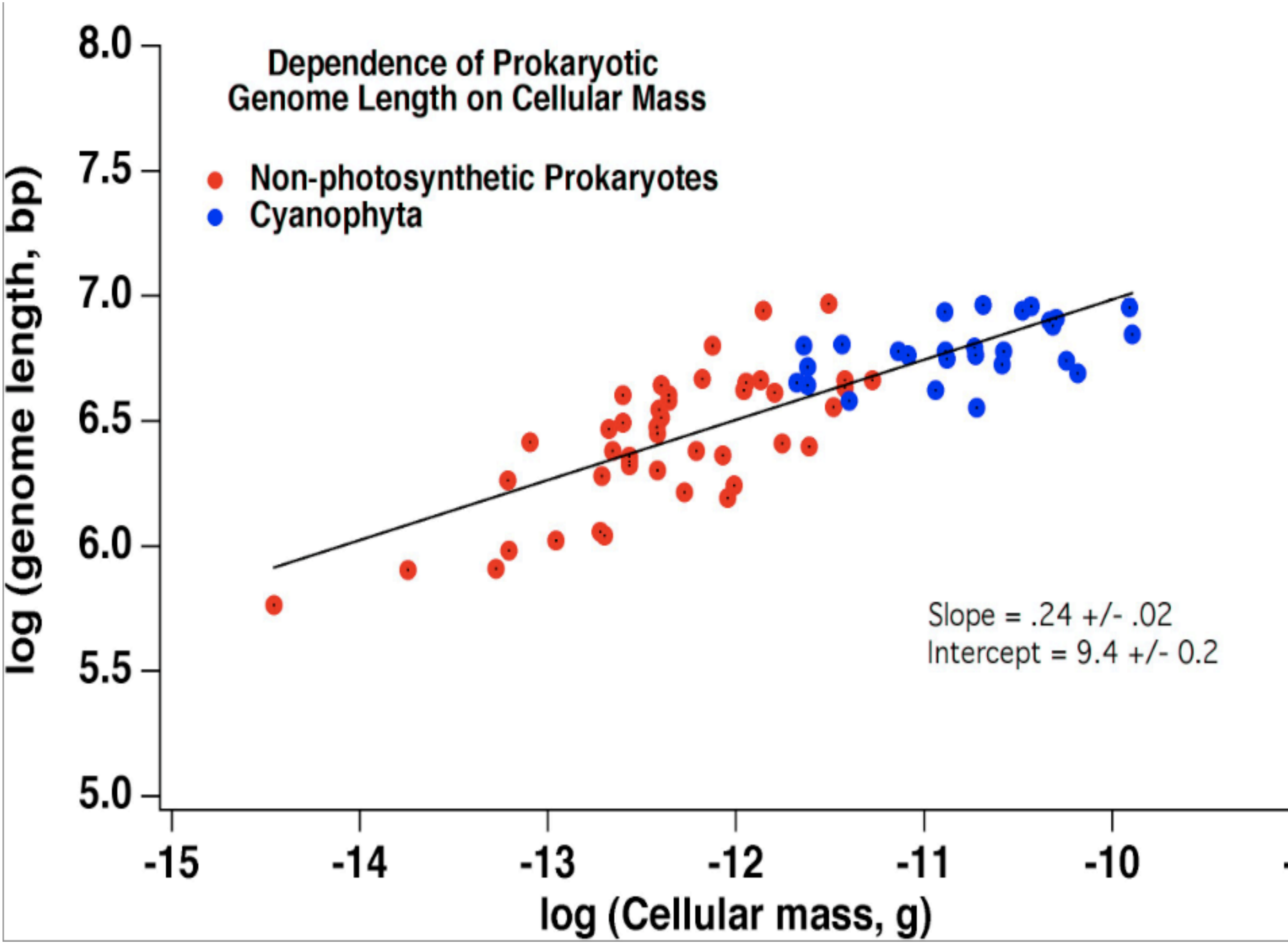
$\Rightarrow$ TOTAL ENERGY NEEDED TO SUPPORT UNIT MASS OF AN ANIMAL DURING A LIFETIME IS THE SAME FOR ALL ANIMALS REGARDLESS OF SIZE :

$$E_{TOT} \approx 1.2 \times 10^{6} \text{ JOULES} / \text{gm}$$

$$\approx 300 \text{ kcals} / \text{gm}$$

≈ 5.2 moles


White Matter Volume W (mm 3)
Gray Matter Volume G (mm 3)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
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
log10 W = (1.23 ± 0.01) log10 G − (1.47 ± 0.04)
r = 0.998


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

LIFE IS THE MOST COMPLEX SYSTEM

SCALING LAWS ARE REMARKABLE BECAUSE

i) THEY EXIST

ii) THEY ARE VERY SIMPLE

iii) THEY ARE UNIVERSAL

} DOMINANCE OF 1/4 POWER

iv) ⇒ BIGGER IS MORE EFFICIENT

v) FEW QUANTITATIVE "LAWS" IN BIOLOGY

NETWORKS!!!

(FRACTALS!!)

FUNDAMENTAL PRINCIPLES (NATURAL SELECTION)

I. AT ALL SCALES ORGANISMS ARE SUSTAINED BY THE TRANSPORT OF ENERGY AND ESSENTIAL MATERIALS THROUGH HIERARCHICAL BRANCHING NETWORK SYSTEMS IN ORDER TO SUPPLY ALL LOCAL PARTS OF THE ORGANISM

II. THESE NETWORKS ARE SPACE-FILLING

III. THE TERMINAL BRANCHES OF THE NETWORK ARE INVARIANT UNITS

IV. ORGANISMS HAVE EVOLVED BY NATURAL SELECTION SO AS TO

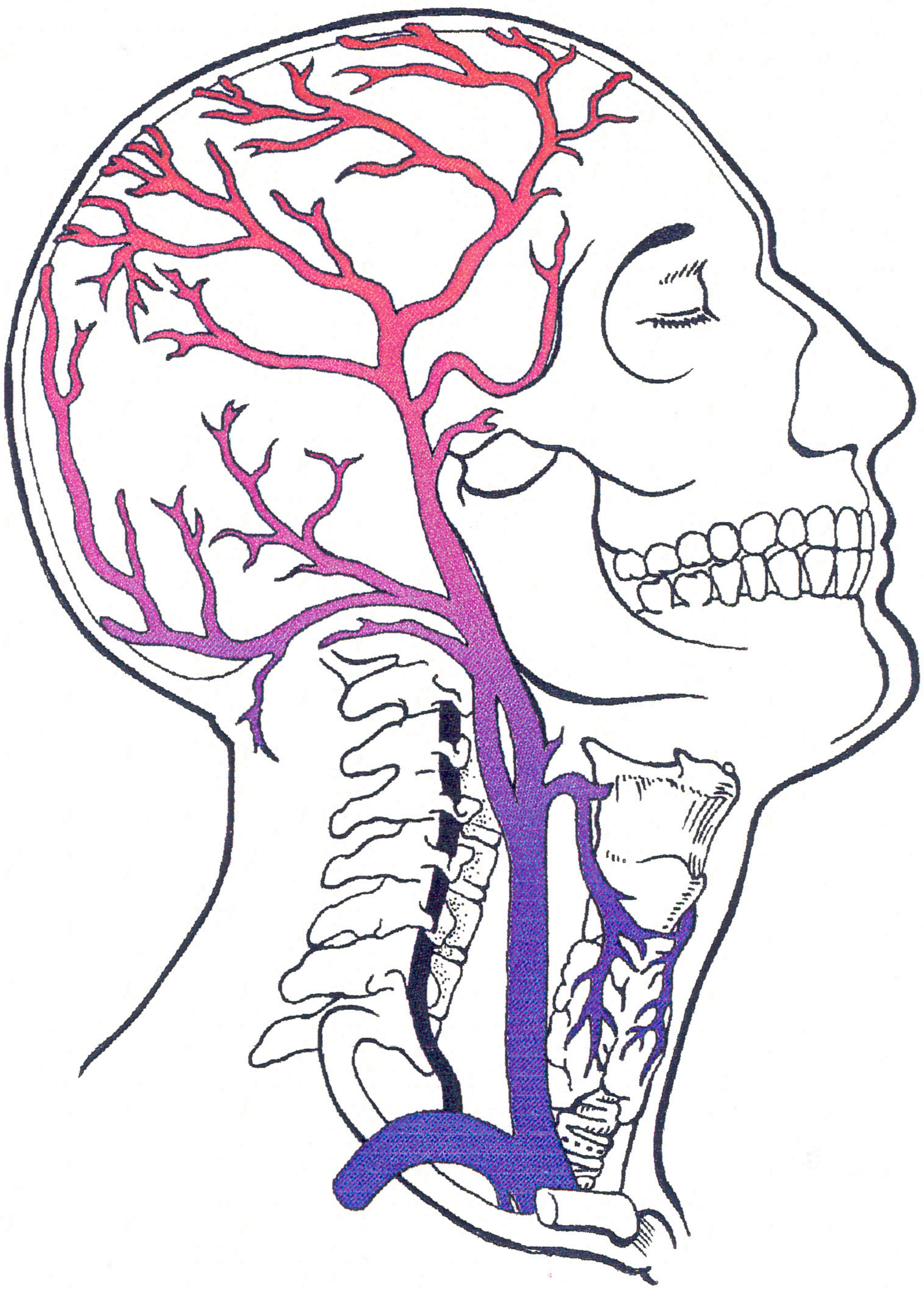
i) MINIMISE ENERGY DISSIPATED IN THE NETWORKS

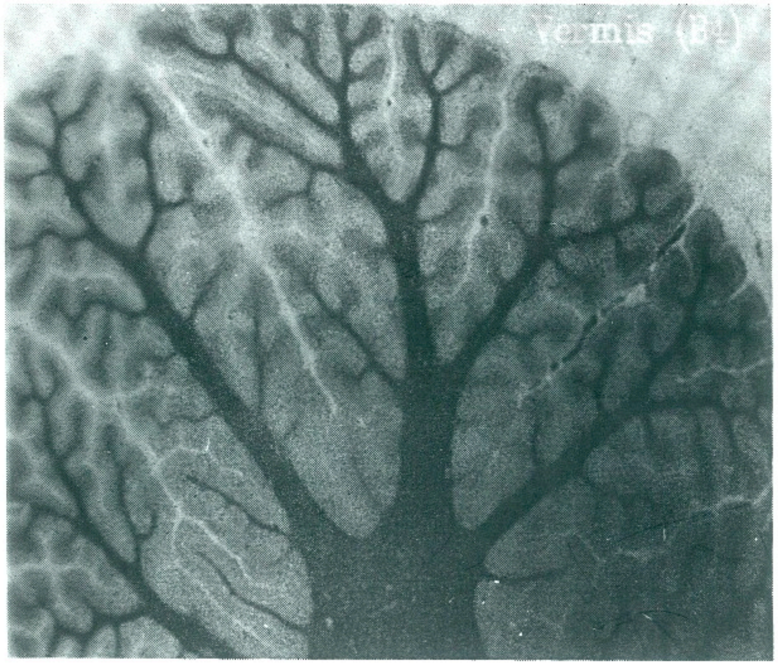
AND/OR ii) MAXIMISE THE SCALING OF THEIR AREA OF INTERFACE WITH THEIR RESOURCE ENVIRONMENT

Large vessels branch into smaller ones

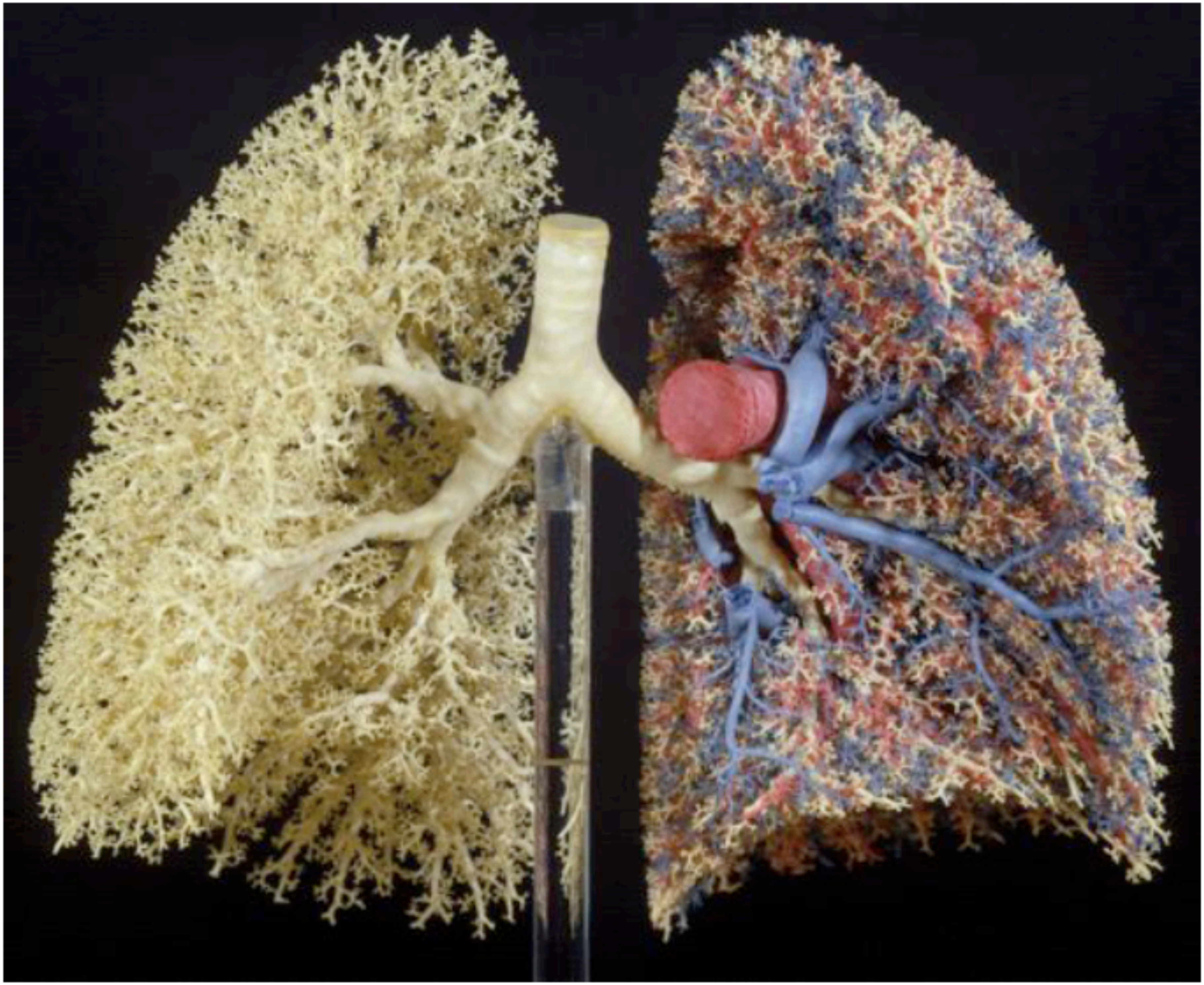
Beating heart

Pulse wave propagates through elastic vessels

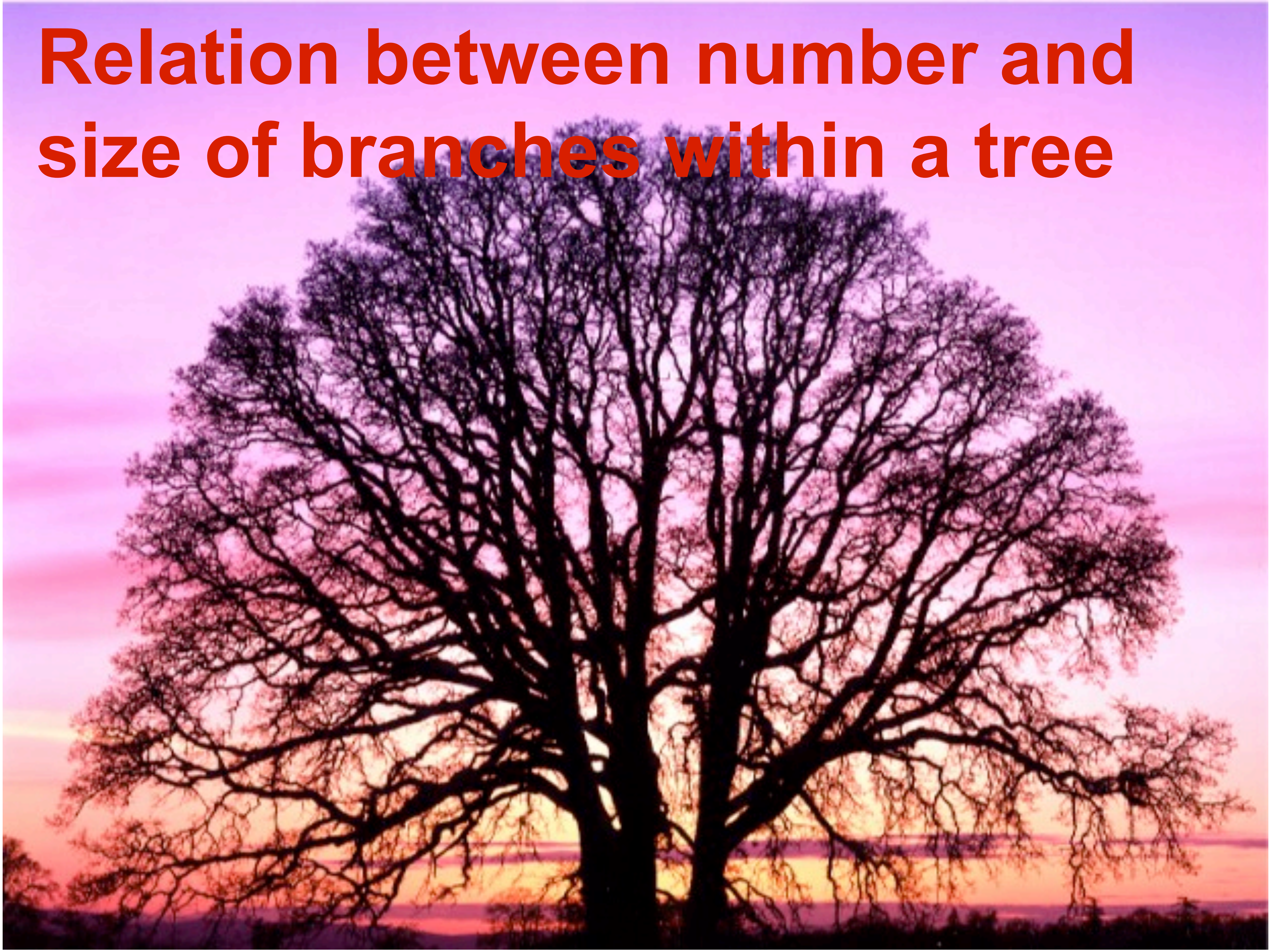




5 A slice through the cerebellum showing the progressive branching structure vhite matter is distributed throughout the cerebellar volume. The geometric ity of these structures provides for rapid dissemination of information (or) via a large surface area in a compact space. This feature is a hallmark of tructures which maximize the surface area within a finite volume.

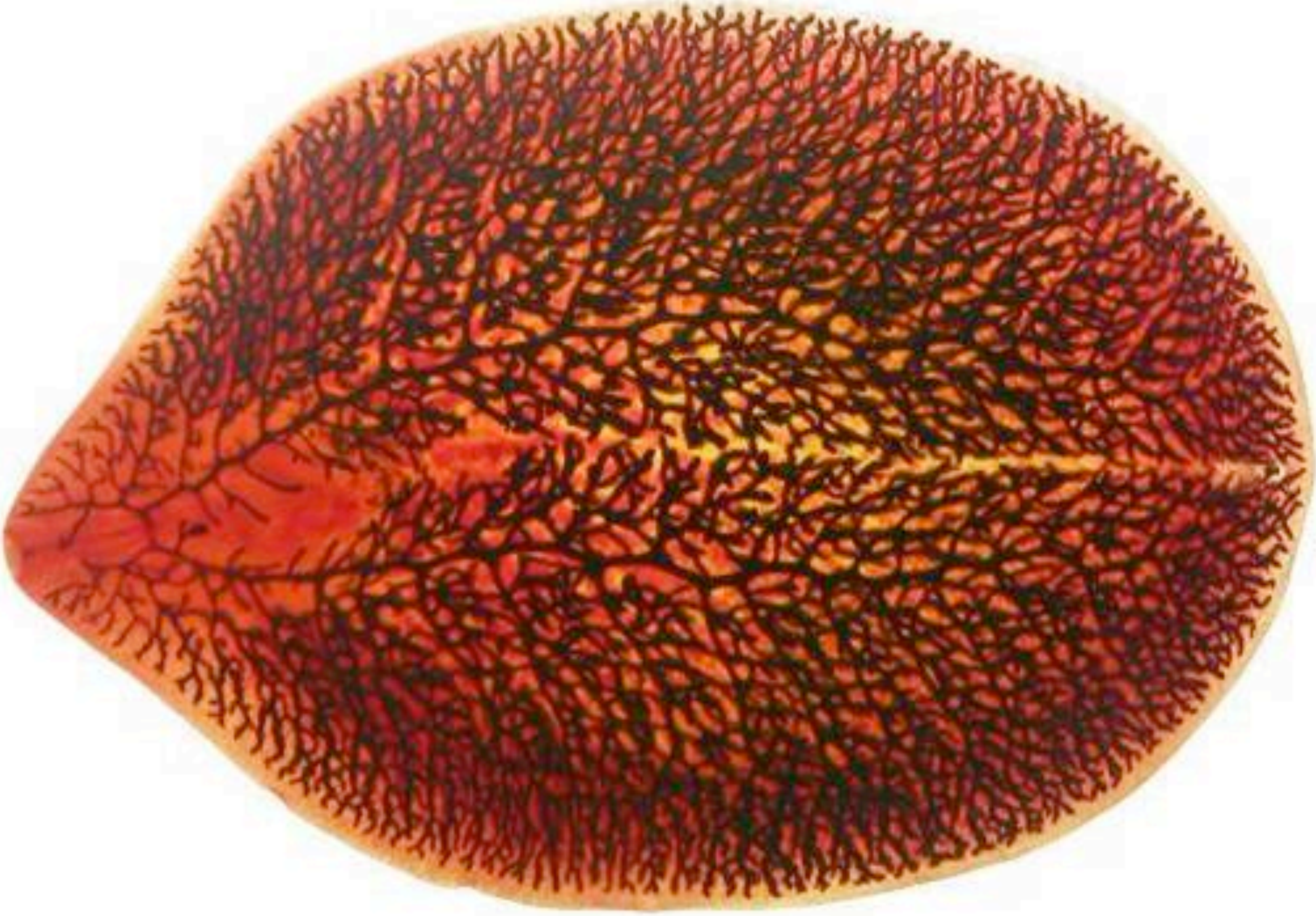


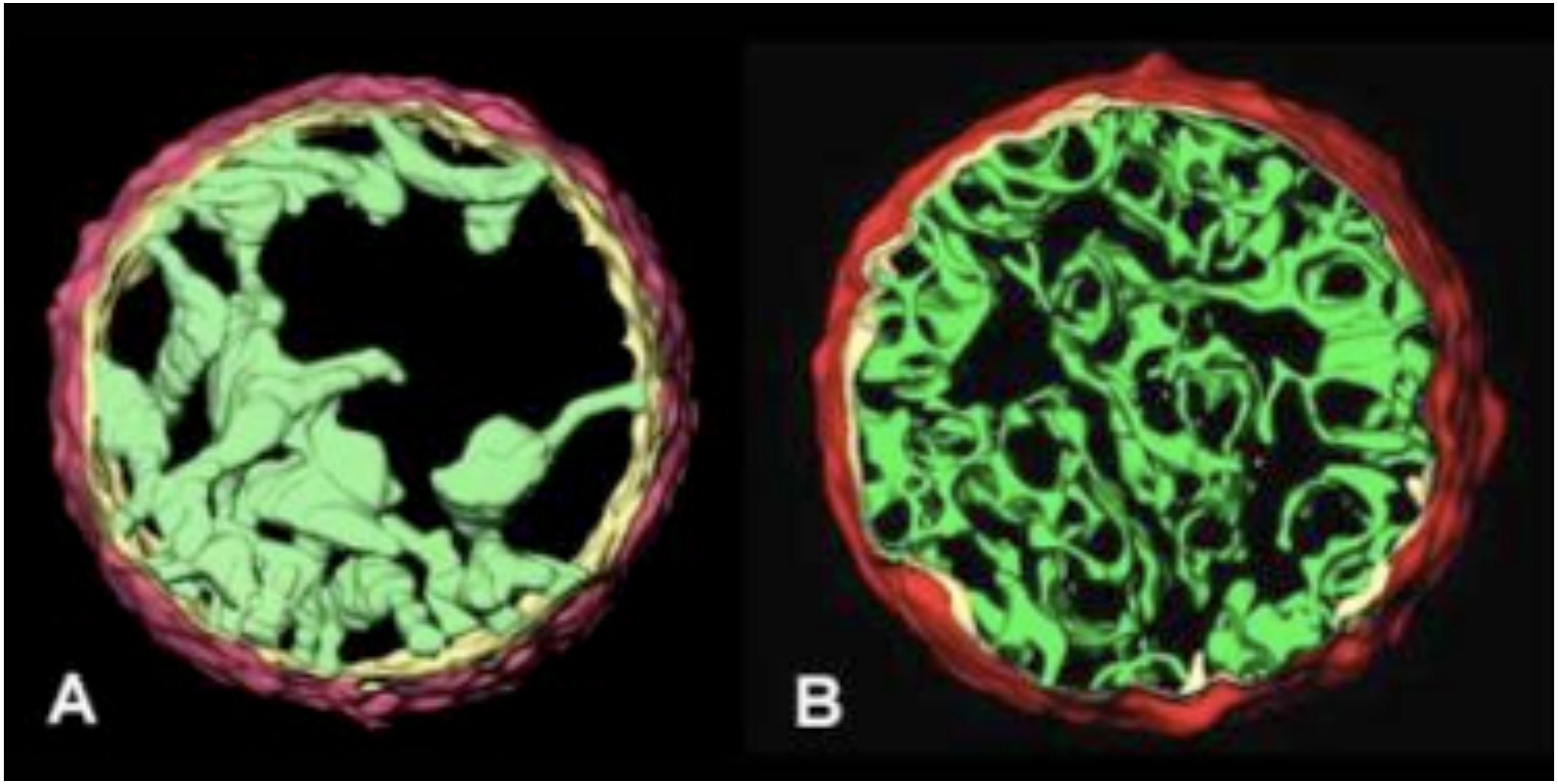
Relation between number and size of branches within a tree



Microcapillary tubes follow branching architecture from trunk to leaves

What is this?




A
B

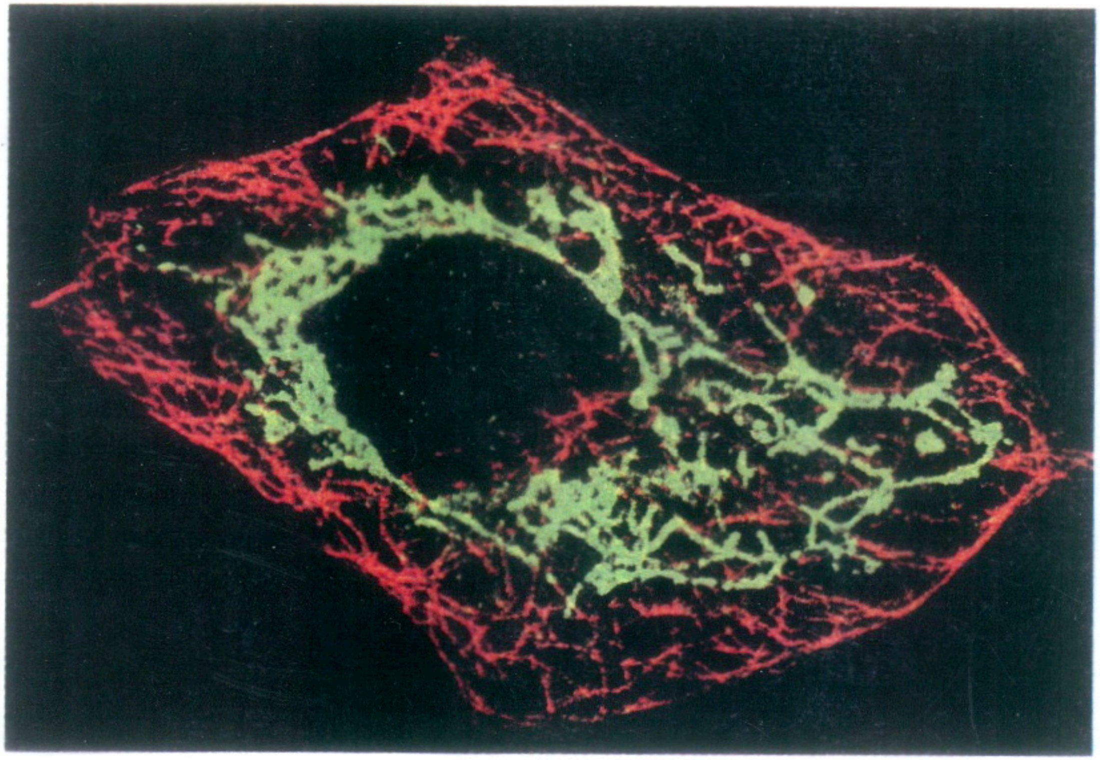
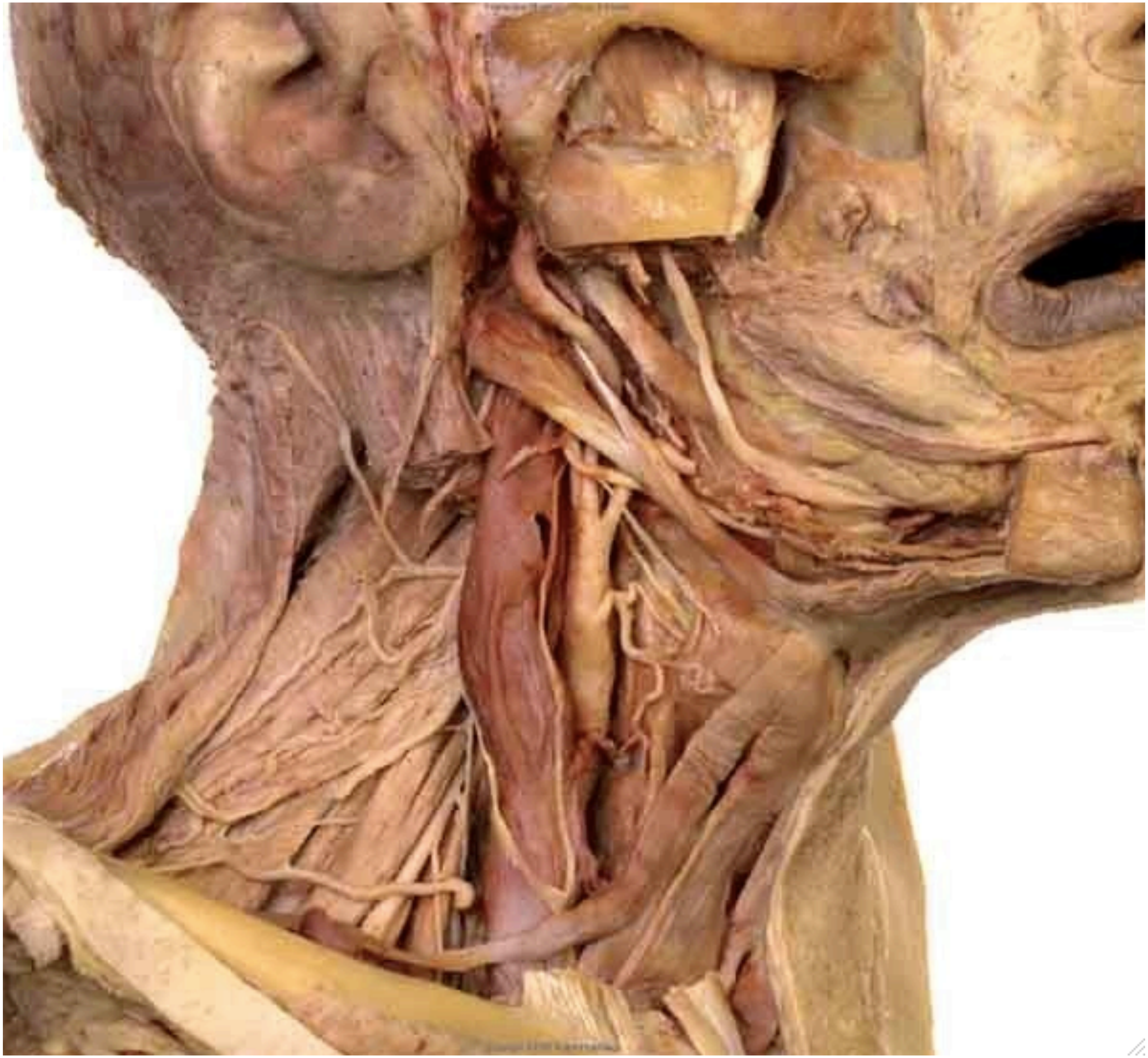
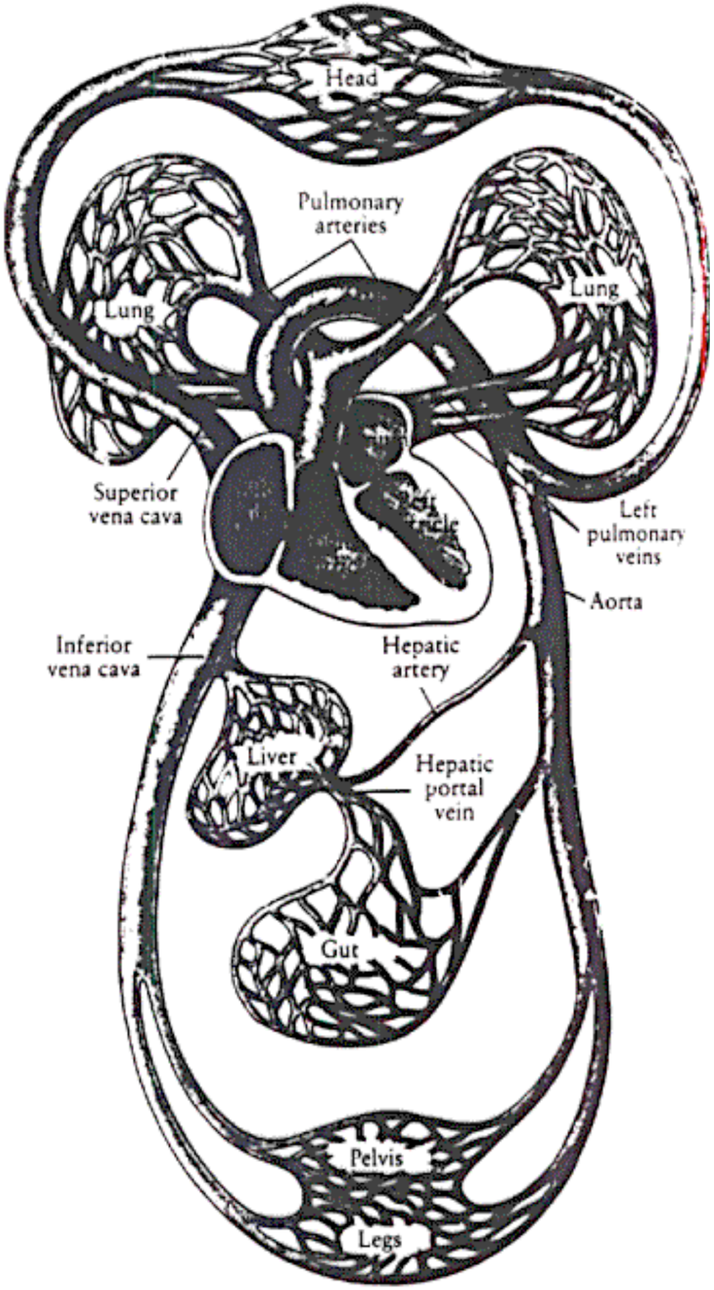


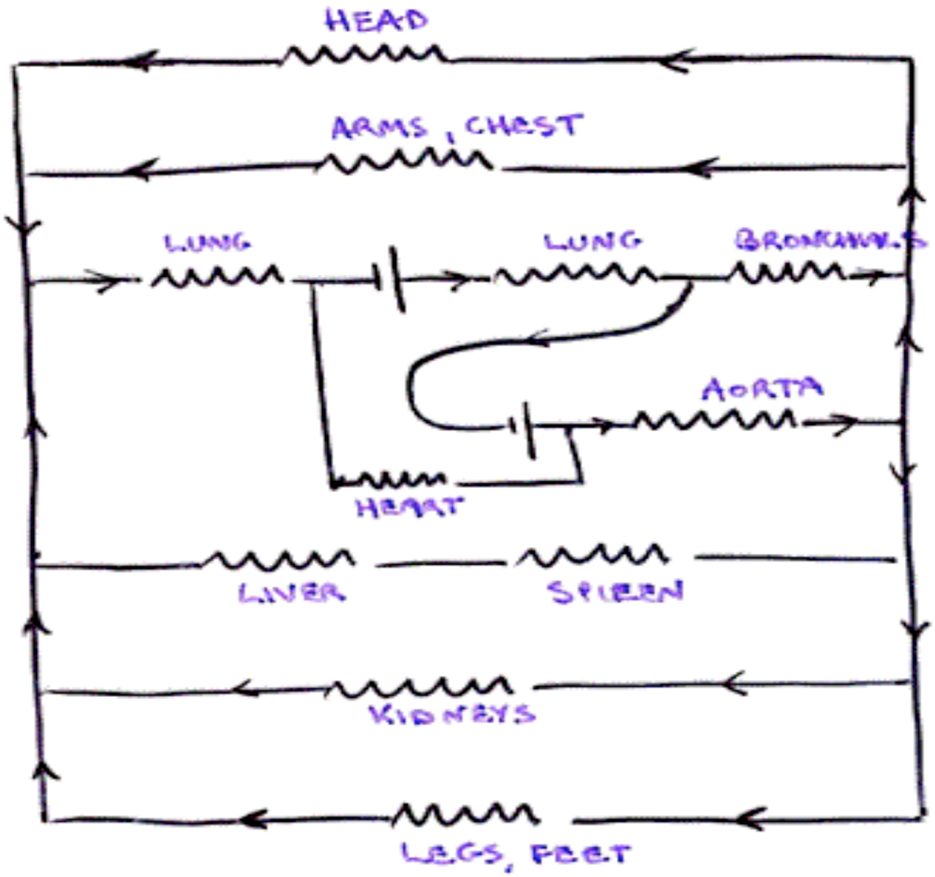
Fig. 1. Mitochondrial network in a mammalian fibroblast. A COS-7 cell labeled to visualize mitochondria (green) and microtubules (red) was analyzed by indirect immunofluorescence confocal microscopy. Mitochondria were labeled with antibodies to the β subunit of the F_1-ATPase and a rhodamine-conjugated secondary antibody. Microtubules were labeled with antibody to tubulin and a fluorescein-conjugated secondary antibody. Pseudocolor was added to the digitized image. Scale: 1 cm = 10 μm.

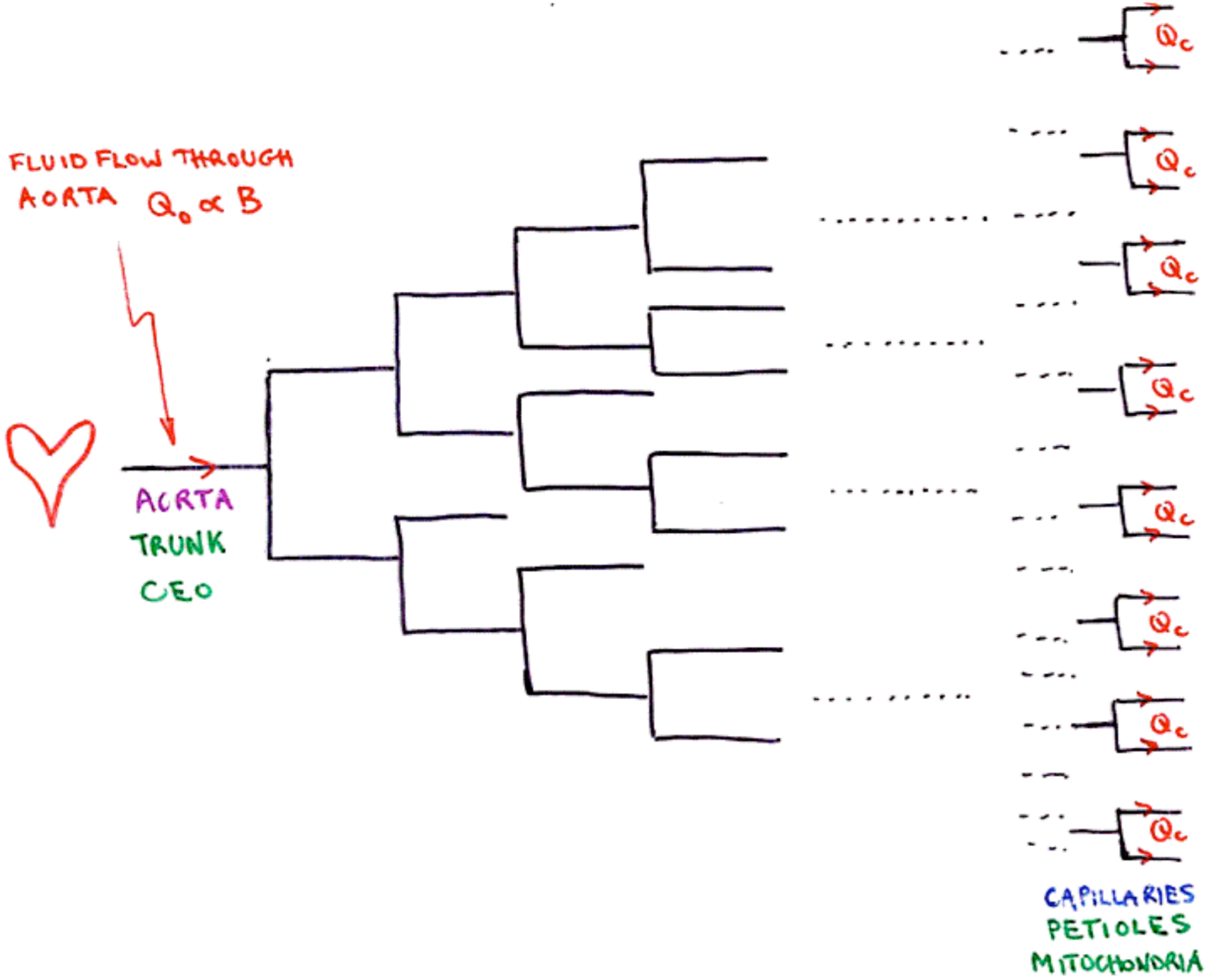
From M. P. Yaffe, *Science,* **283,** 1493 (1999).





THE VASCULAR CIRCUITRY


HEAD
ARMS, CHEST
LUNG
LUNG
BRONCHIALS
AORTA
HEART
LIVER
SPLEEN
KIDNEYS
LEGS, FEET


FLUID FLOW THROUGH
AORTA $Q_0 \propto B$
AORTA
TRUNK
CEO
Q_c
CAPILLARIES
PETIOLES
MITOCHONDRIA

SINCE THE FLUID (BLOOD) TRANSPORTS OXYGEN, NUTRIENTS, ETC FROM THE AORTA TO THE CAPILLARIES

METABOLIC RATE $\propto$ VOLUME FLOW RATE

$$B \propto Q_0$$

BUT THE CONSERVATION OF FLUID (BLOOD)

$$\Rightarrow \quad Q_0 = N_c Q_c$$

TOTAL NUMBER OF CAPILLARIES

VOLUME FLOW RATE IN AVERAGE CAPILLARY

CAPILLARY IS AN INVARIANT UNIT

(Q_c IS SAME FOR ALL MAMMALS)

$\Rightarrow$ NUMBER OF CAPILLARIES (N_c) MUST SCALE IN SAME WAY AS THE METABOLIC RATE ($B \propto Q_0$)

SO, <u>IF</u> $B \sim M^{3/4}$ THEN

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

(<u>NOT</u> $N_c \sim M$)

TOTAL NUMBER OF CELLS

$N_{cell} \sim M$ (LINEAR)

TOTAL NUMBER OF CAPILLARIES

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

MISMATCH!

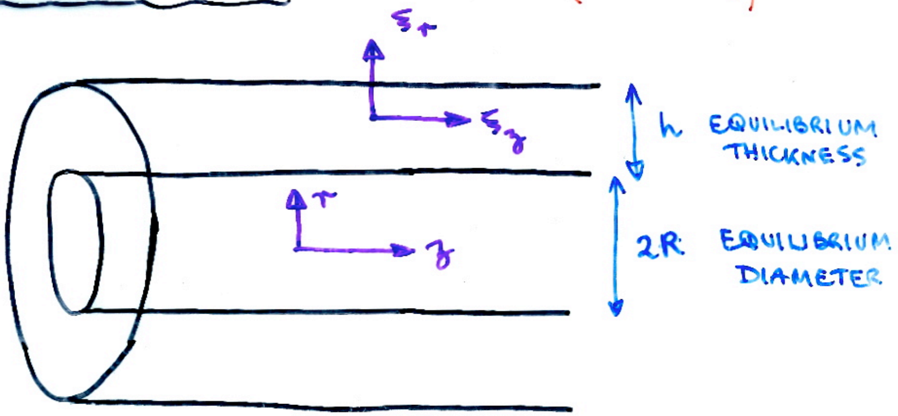
$\Rightarrow$ NUMBER OF CELLS FED BY A SINGLE CAPILLARY INCREASES AS $M^{1/4}$

(ANOTHER MANIFESTATION THAT EFFICIENCY INCREASES WITH SIZE)

IMPORTANT IMPLICATIONS FOR GROWTH AND DEATH!

) PULSATILE TREATMENT

(WOMERSLEY)



a) FLUID :

COEFFICIENTS OF VISCOSITY

STRESS TENSOR : $\theta_{ij} = \lambda e_{kk} \delta_{ij} + 2\mu e_{ij} - p \delta_{ij}$

(NEWTONIAN)

PRESSURE

STRAIN TENSOR : $e_{ij} = \frac{1}{2} (\partial_i v_j + \partial_j v_i)$

VELOCITY

EQ^N. OF MOTION : $\rho \frac{D v_i}{D t} = \partial_j \theta_{ij}$

NAVIER - STOKES EQ^N.

COVARIANT DERIVATIVE $\frac{D}{Dt} = \frac{\partial}{\partial t} + v_i \partial_i$

EQ^N. OF CONTINUITY : $\frac{\partial \rho}{\partial t} + \partial_i (\rho v_i) = 0$

b) WALLS :

ELASTIC MODULI

$$\theta^{W}_{ij} = \lambda e^{W}_{kk}\delta_{ij} + 2B e^{W}_{ij} - p\,\delta_{ij}$$ HOOKE'S LAW

$$e^{W}_{ij} = \tfrac{1}{2}(\partial_i \xi_j + \partial_j \xi_i)$$

$$\rho_W \frac{Du_i}{Dt} = \partial_j \theta^{W}_{ij} \quad ; \quad u_i \equiv \frac{\partial \xi_i}{\partial t}$$ NAVIER EQ^NS/.

$$\partial_i \xi_i = 0$$

NEGLECT NON-LINEARITIES :

$$\rho_W \frac{\partial^2 \xi_i}{\partial t^2} = B\,\partial^2 \xi_i - \partial_i p$$

SOLVE USING FOURIER AS WITH FLUID, WALLS AND FLUID COUPLED VIA BOUNDARY CONDITIONS : CONTINUITY OF VELOCITY AND FORCE : $u_r = \dfrac{\partial \xi_r}{\partial t}$

AND $\displaystyle\int_{\text{SURFACE}} \theta_{ij}\, dS_j$ CONTINUOUS

CAN BE SOLVED : BIG MESS!

SIMPLIFY USING THIN WALL APPROXIMATION

IE. $\dfrac{h}{R} << 1$

"EVERYTHING" FOLLOWS FROM THE 4 BASIC PRINCIPLE'

I. HIERARCHICAL "FRACTAL-LIKE" BRANCHING NETWORKS

II. SPACE - FILLING

III. INVARIANT TERMINAL UNITS

IV. ENERGY DISSIPATED IS MINIMISED

"AVERAGE IDEALISED ORGANISM OR SYSTEM"

II ⇒ i) SPACE-FILLING $\frac{l_{k+1}}{l_k} = \frac{1}{2^{1/3}}$ $\frac{1}{n^{1/d}}$

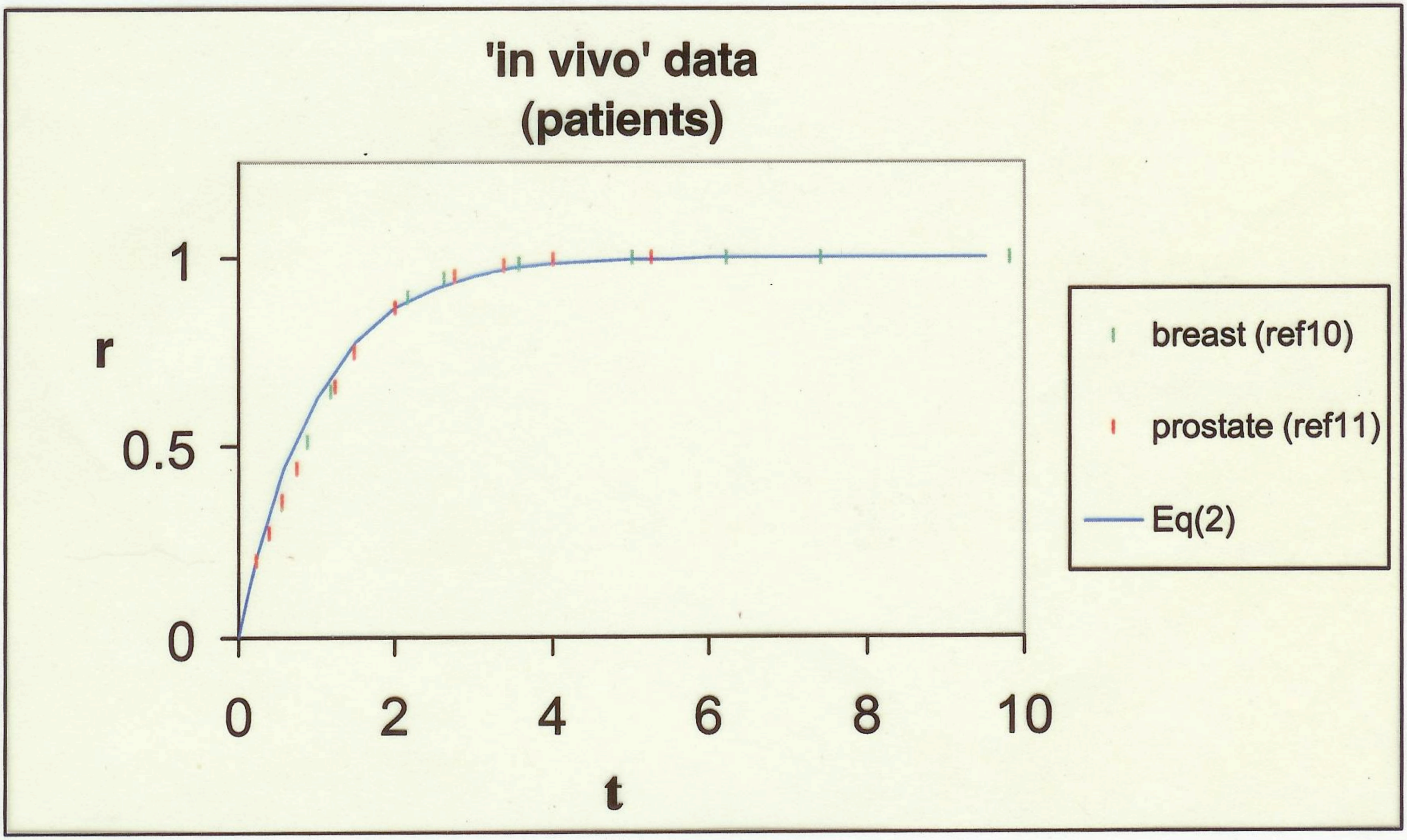
III ⇒ ii) INV. TERMINAL UNITS

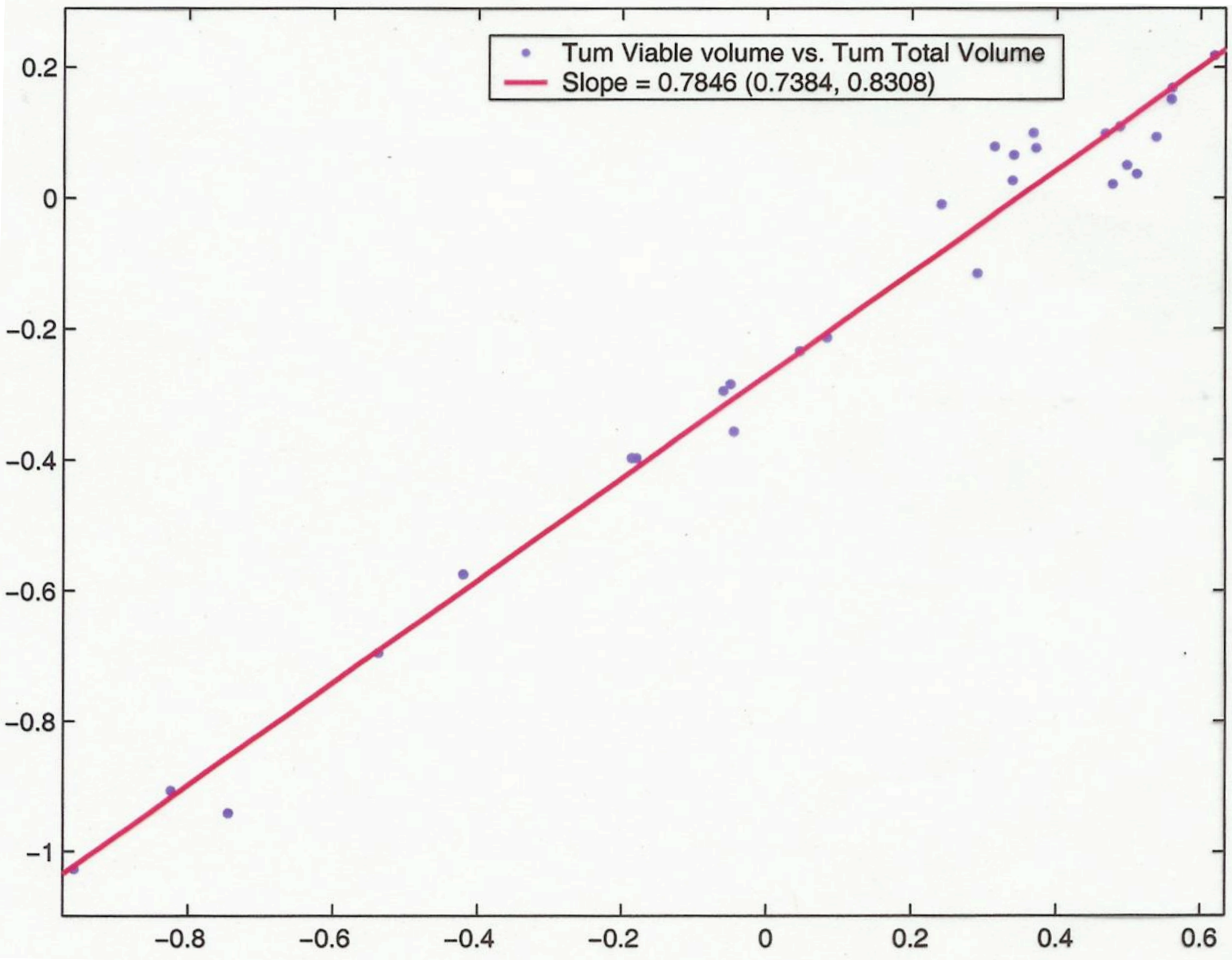
IV ⇒ iii) AREA-PRESERVING BRANCHING $\frac{r_{k+1}}{r_k} = \frac{1}{2^{1/2}}$

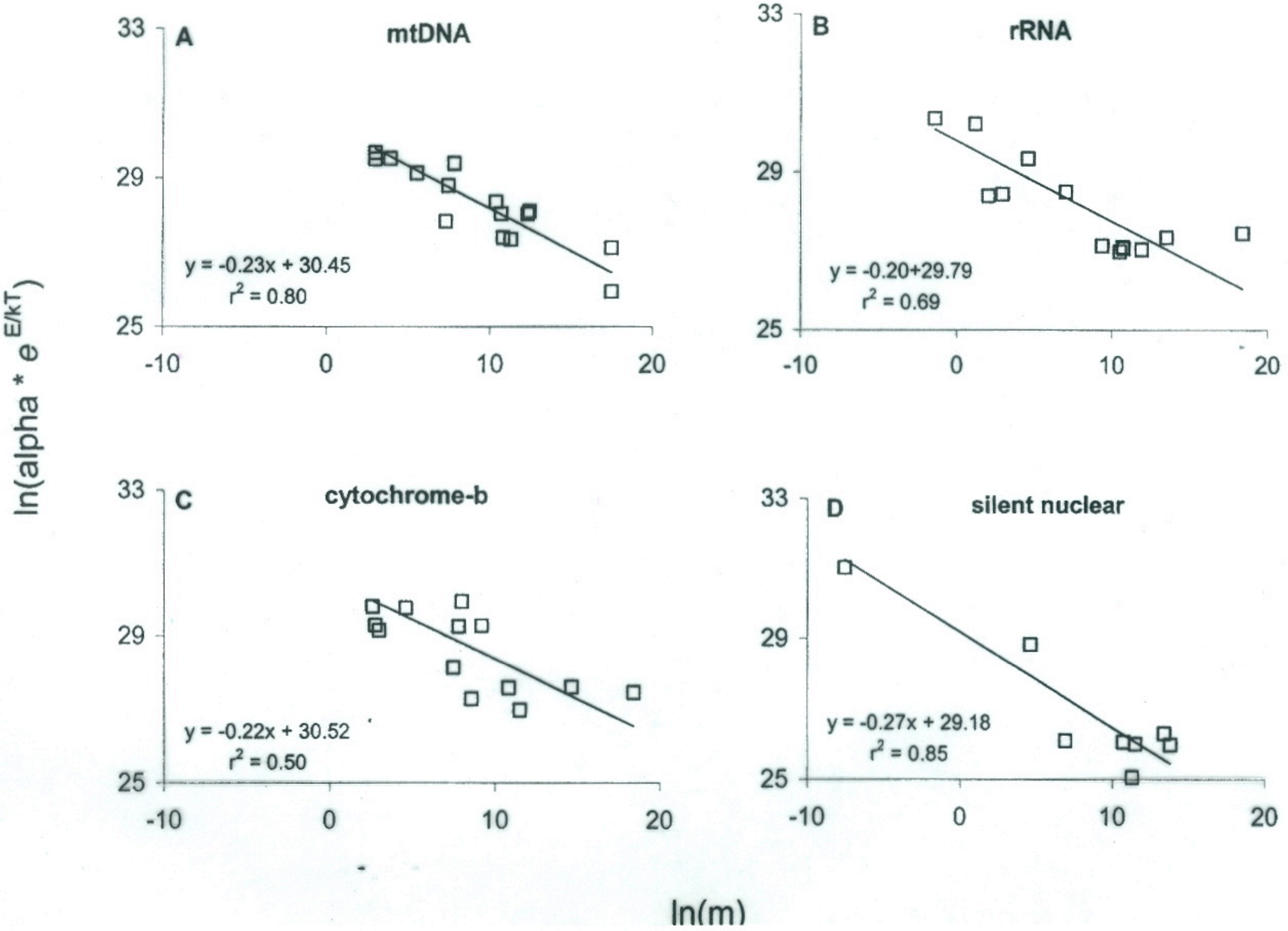
iv) VOLUME OF NETWORK (BLOOD) $\sim$ VOLUME OF WHOLE BODY $\sim M$

$\Rightarrow B \propto M^{3/4}$ (AND MUCH MORE)

[MORE GENERALLY : $B \sim M^{b(M)}$ WITH $b(M) \approx 3/4$ M LARGE
$< 3/4$ M SMALL
NOT A STRICT POWER LAW! ≈ 1 $M < \mu$]


'in vivo' data
(patients)
r
1
0.5
0
0
2
4
6
8
10
t
breast (ref10)
prostate (ref11)
Eq(2)


Tum Viable volume vs. Tum Total Volume
Slope = 0.7846 (0.7384, 0.8308)
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6


ln(alpha * e E/kT)
A
mtDNA
y = -0.23x + 30.45
r2 = 0.80
B
rRNA
y = -0.20+29.79
r2 = 0.69
C
cytochrome-b
y = -0.22x + 30.52
r2 = 0.50
D
silent nuclear
y = -0.27x + 29.18
r2 = 0.85
33
29
25
-10
0
10
20
ln(m)

IN d DIMENSIONS

$$B \propto M^{\frac{d}{d+1}}$$

WE LIVE IN 3 SPATIAL DIMENSIONS SO $B \propto M^{3/4}$

$\Rightarrow$ "3" REPRESENTS DIMENSIONALITY OF SPACE

"4" INCREASE IN DIMENSIONALITY DUE TO FRACTAL-LIKE SPACE FILLING

LIFE HAS TAKEN ADVANTAGE OF THE POSSIBILITY OF USING SPACE-FILLING FRACTAL-LIKE SURFACES (WHERE ENERGY AND RESOURCES ARE EXCHANGED) TO MAXIMISE ENERGY TRANSFER FROM THE ENVIRONMENT

AREA

NON-FRACTAL : $M^{2/3}$ ← DIMENSIONALITY OF SPACE (VOLUME)

BIOLOGICAL (FRACTAL) $M^{3/4}$

BY ANALOGY : LIFE EFFECTIVELY OPERATES IN FOUR SPATIAL DIMENSIONS

[FIVE IF TIME IS INCLUDED]

Cardiovascular

Variable	Exponent	
	Predicted	Observed
Aorta radius r_o	3/8 = 0.375	0.36
Aorta pressure Δp_o	0 = 0.00	0.032
Aorta blood velocity u_o	0 = 0.00	0.07
Blood volume V_b	1 = 1.00	1.00
Circulation time	1/4 = 0.25	0.25
Circulation distance l	1/4 = 0.25	ND
Cardiac stroke volume	1 = 1.00	1.03
Cardiac frequency ω	−1/4 = −0.25	−0.25
Cardiac output $\dot{E}$	3/4 = 0.75	0.74
Number of capillaries N_c	3/4 = 0.75	ND
Service volume radius	1/12 = 0.083	ND
Womersley number α	1/4 = 0.25	0.25
Density of capillaries	−1/12 = −0.083	−0.095
O_2 affinity of blood P_{50}	−1/12 = −0.083	−0.089
Total resistance Z	−3/4 = −0.75	−0.76
Metabolic rate B	3/4 = 0.75	0.75

Respiratory

Variable	Exponent	
	Predicted	Observed
Tracheal radius	3/8 = 0.375	0.39
Interpleural pressure	0 = 0.00	0.004
Air velocity in trachea	0 = 0.00	0.02
Lung volume	1 = 1.00	1.05
Volume flow to lung	3/4 = 0.75	0.80
Volume of alveolus V_A	1/4 = 0.25	ND
Tidal volume	1 = 1.00	1.041
Respiratory frequency	−1/4 = −0.25	−0.26
Power dissipated	3/4 = 0.75	0.78
Number of alveoli N_A	3/4 = 0.75	ND
Radius of alveolus r_A	1/12 = 0.083	0.13
Area of alveolus A_A	1/6 = 0.083	ND
Area of lung A_L	11/12 = 0.92	0.95
O_2 diffusing capacity	1 = 1.00	0.99
Total resistance	−3/4 = −0.75	−0.70
O_2 consumption rate	3/4 = 0.75	0.76

Table 1 Predicted values of scaling exponents for physiological and anatomical variables of plant vascular systems.

Variable	Plant mass		Branch radius		
	Exponent predicted	Symbol	Symbol	Exponent	
				Predicted	Observed
Number of leaves	$\frac{3}{4}$(0.75)	n_0^L	n_k^L	2 (2.00)	2.007 (ref. 12)
Number of branches	$\frac{3}{4}$(0.75)	N_0	N_k	–2 (–2.00)	–2.00 (ref. 6)
Number of tubes	$\frac{3}{4}$(0.75)	n_0	n_k	2 (2.00)	n.d.
Branch length	$\frac{1}{4}$(0.25)	l_0	l_k	$\frac{2}{3}$(0.67)	0.652 (ref. 6)
Branch radius	$\frac{3}{8}$(0.375)	r_0			
Area of conductive tissue	$\frac{7}{8}$(0.875)	A_0^{CT}	A_k^{CT}	$\frac{7}{3}$(2.33)	2.13 (ref. 8)
Tube radius	$\frac{1}{16}$(0.0625)	a_0	a_k	$\frac{1}{6}$(0.167)	n.d.
Conductivity	1 (1.00)	K_0	K_k	$\frac{8}{3}$(2.67)	2.63 (ref. 12)
Leaf-specific conductivity	$\frac{1}{4}$(0.25)	L_0	L_k	$\frac{2}{3}$(0.67)	0.727 (ref. 17)
Fluid flow rate			$\dot{Q}_k$	2 (2.00)	n.d.
Metabolic rate	$\frac{3}{4}$(0.75)	$\dot{Q}_0$			
Pressure gradient	$-\frac{1}{4}$(–0.25)	$\Delta P_0/l_0$	$\Delta P_k/l_k$	$-\frac{2}{3}$(–0.67)	n.d.
Fluid velocity	$-\frac{1}{8}$(–0.125)	u_0	u_k	$-\frac{1}{3}$(–0.33)	n.d.
Branch resistance	$-\frac{3}{4}$(–0.75)	Z_0	Z_k	$-\frac{1}{3}$(–0.33)	n.d.
Tree height	$\frac{1}{4}$(0.25)	h			
Reproductive biomass	$\frac{3}{4}$(0.75)				
Total fluid volume	$\frac{25}{24}$(1.0415)				

Table 1. Similarity of predicted scaling relations for branches within a tree [quantities denoted by uppercase symbols and subscripts *i* (20)], and for trees within a forest (denoted by lowercase symbols and subscripts *k*)*

Scaling quantity	Individual tree	Entire forest
Area preserving	$\frac{R_{i+1}}{R_i} = \frac{1}{n^{1/2}}$	$\frac{r_{k+1}}{r_k} = \frac{1}{\lambda^{1/2}}$
Space filling	$\frac{L_{i+1}}{L_i} = \frac{1}{n^{1/3}}$	$\frac{l_{k+1}}{l_k} = \frac{1}{\lambda^{1/3}}$
Biomechanics	$R_i^2 = L_i^3$	$r_k^2 = l_k^3$
Size distribution*	$\Delta N_i \propto R_i^{-2} \propto M_i^{-3/4}$	$\Delta n_k \propto r_k^{-2} \propto m_k^{-3/4}$
Energy and material flux*	$B_i \propto R_i^2 \propto N_i^L \propto M_i^{3/4}$	$B_k \propto r_k^2 \propto n_k^L \propto m_k^{3/4}$

Stand property	Predicted stem radius, r_k, based scaling function
Size class neighbor separation	$d_k \propto r_k$
Canopy scaling	$r_k^{\mathrm{can}} \propto r_k^{2/3}$
Canopy spacing	$d_k^{\mathrm{can}} = c_1 r_k \left[1 - \left(\frac{r_{\bar{k}}}{r_k} \right)^{1/3} \right]$
Energy Equivalence	$\Delta n_k B_k \propto r_k^0$
Total forest resource use	$B_{\mathrm{Tot}} \propto \Sigma \Delta n_k r_k^2 \leq \dot{R}$
Mortality rate	$\mu_k \approx A r_k^{-2/3}$
Size distribution	$N_k \approx \frac{\dot{R}}{(K+1) b_0} r_k^{-2}$

HYDRODYNAMIC RESISTANCE OF THE NETWORK

$$\sim \frac{1}{M^{3/4}}$$

TOTAL RESISTANCE DECREASES WITH SIZE !!

SMALL MAY BE BEAUTIFUL BUT LARGE IS MORE EFFICIENT !!

BLOOD PRESSURE $\sim M^0$

AORTA BLOOD VELOCITY $\sim M^0$

$\}$ INVARIANT !

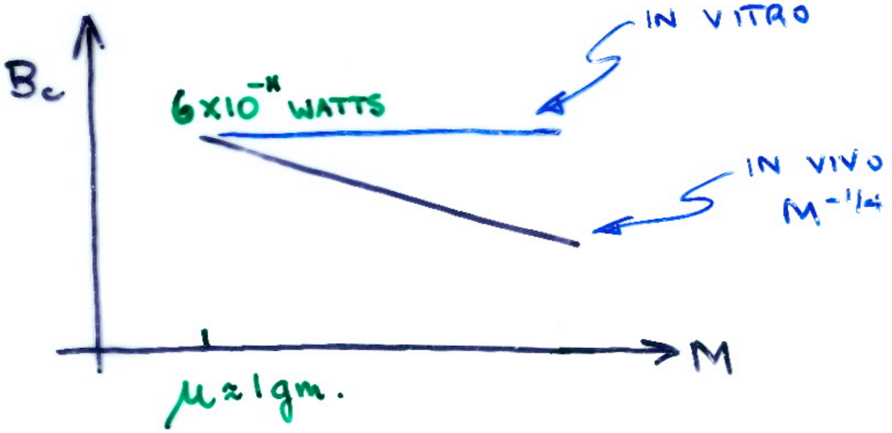
RADIUS OF A WHALE'S AORTA ~ 30 cm

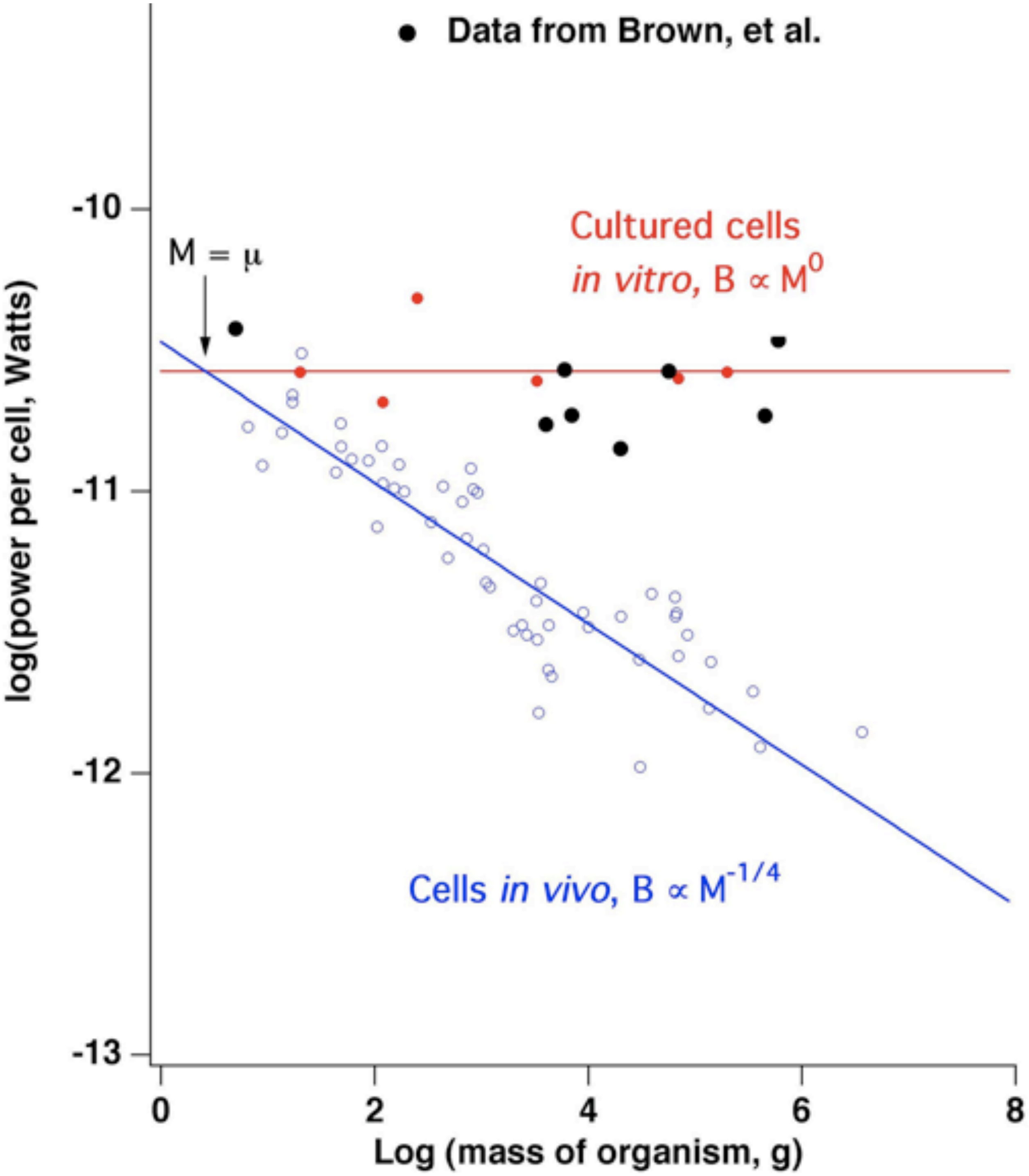
RADIUS OF A SHREW'S AORTA $\sim \frac{1}{10}$ mm

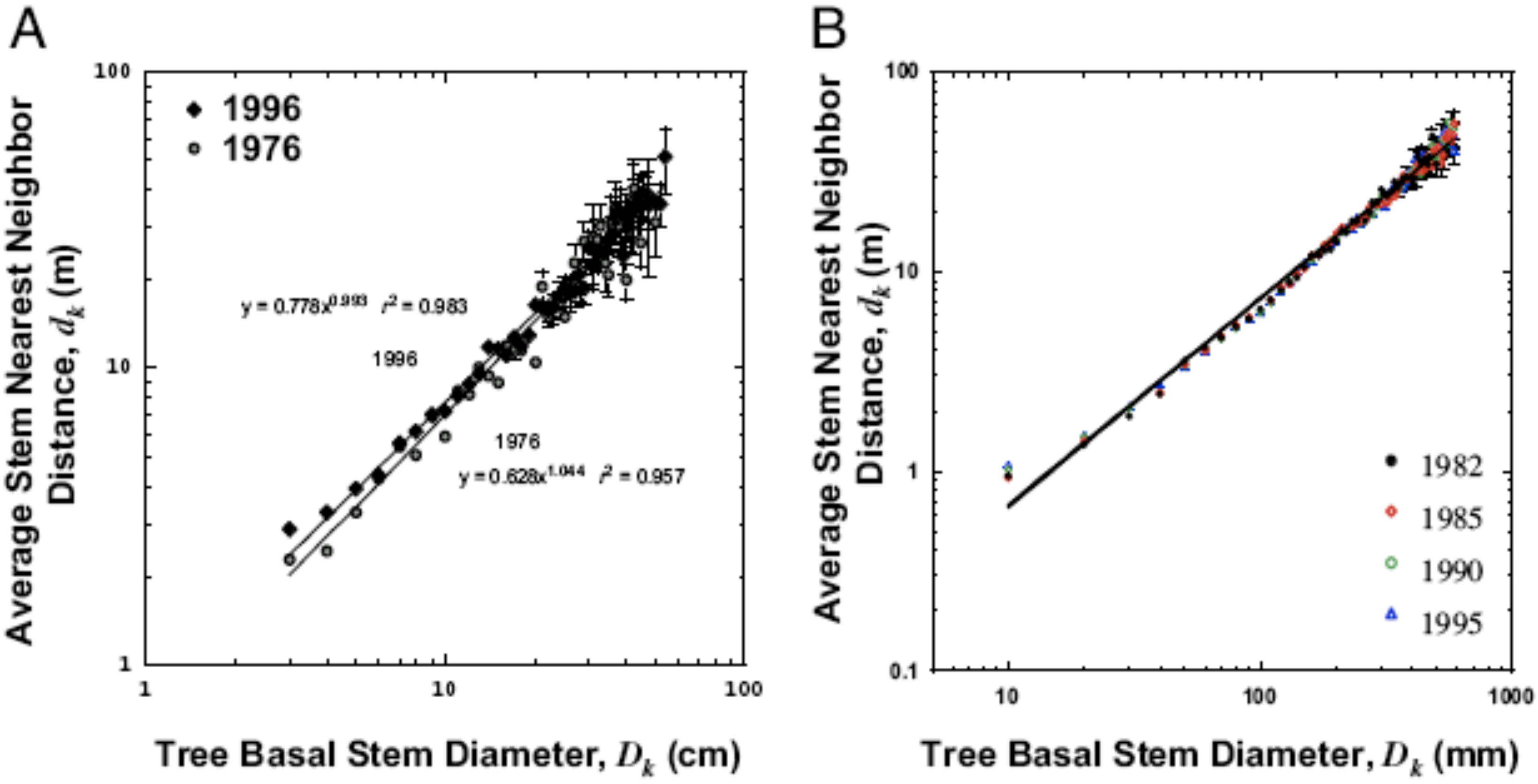
YET THEY HAVE THE SAME BLOOD PRESSURE

THIS DECREASE OF B_c WITH SIZE IS DRIVEN BY THE HEGEMONY OF THE NETWORK (CONTROLS FUNDAMENTAL BIOCHEMICAL RATES)

⇒ IF THE NETWORK WERE REMOVED SO CELLS BECOME FREE (IN VITRO) B_c SHOULD BECOME INDEPENDENT OF WHAT MAMMAL THEY ORIGINATED IN: PREDICT

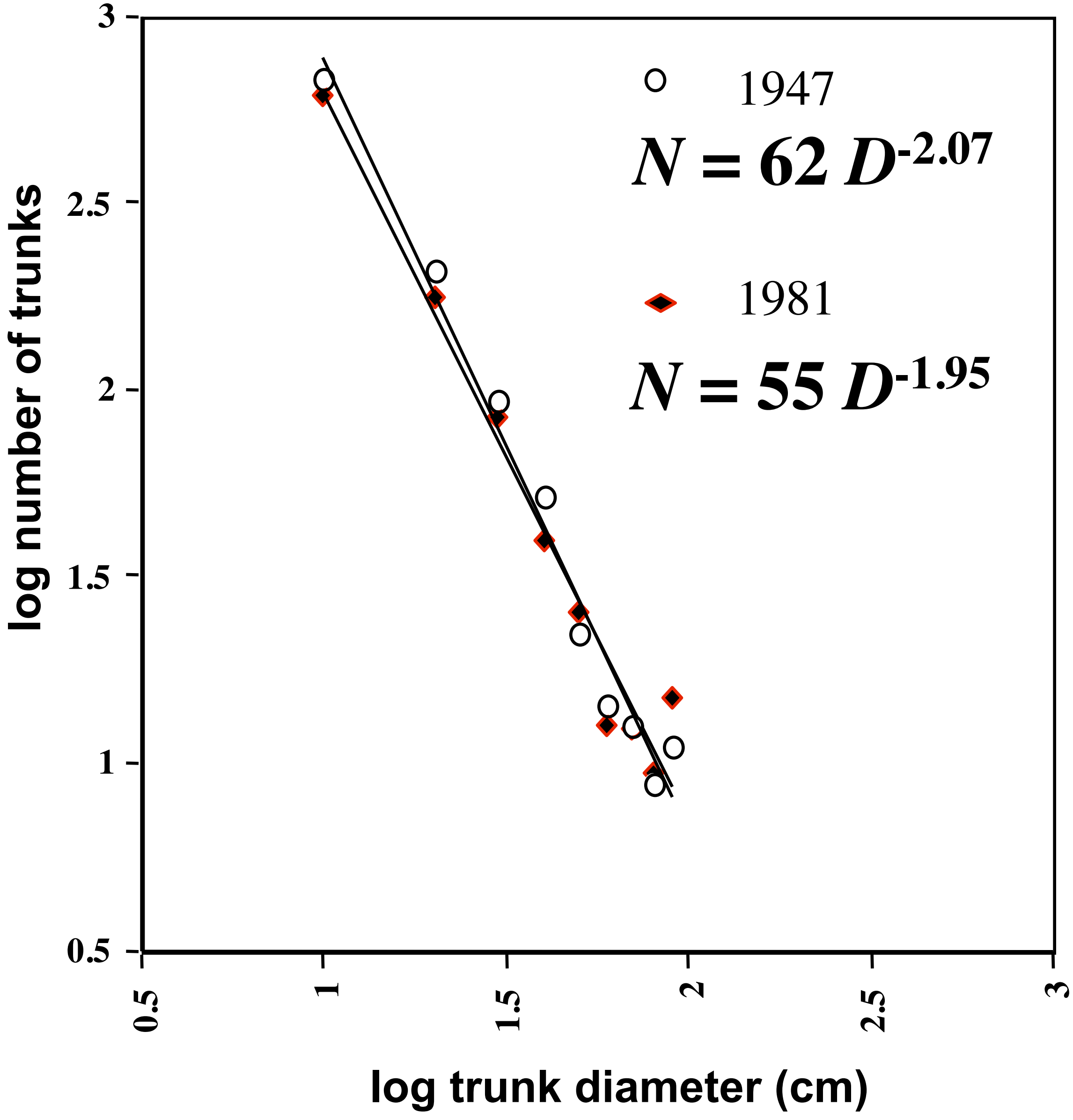



● Data from Brown, et al.
Cultured cells
in vitro, B ∝ M^0
M = μ
Cells in vivo, B ∝ M^-1/4
log(power per cell, Watts)
-10
-11
-12
-13
0
2
4
6
8
Log (mass of organism, g)

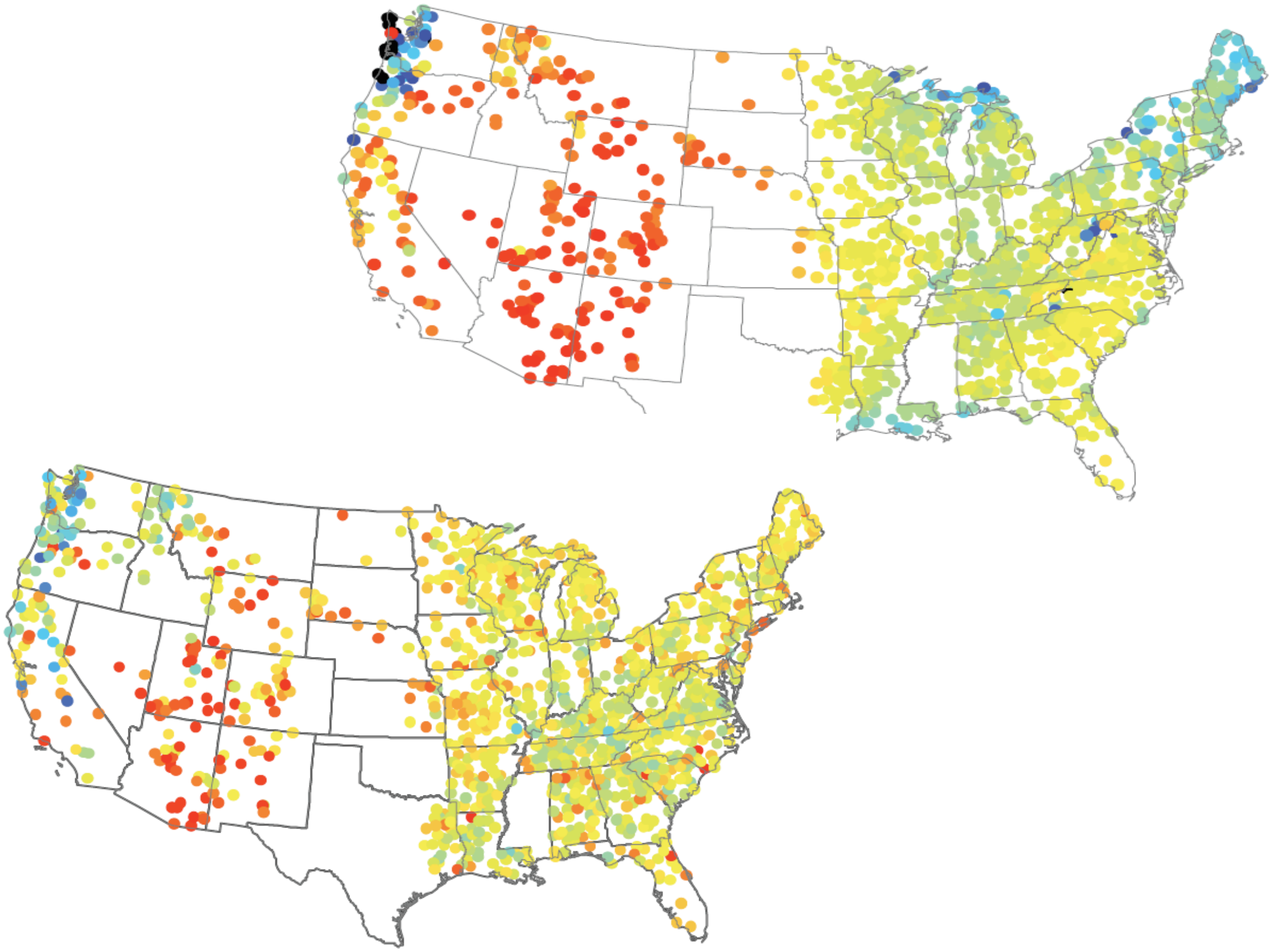

A
1996
1976
y = 0.778x^0.993 r^2 = 0.983
1996
1976
y = 0.628x^1.044 r^2 = 0.957
100
10
1
1
10
100
Average Stem Nearest Neighbor Distance, d_k (m)
Tree Basal Stem Diameter, D_k (cm)
B
1982
1985
1990
1995
100
10
1
0.1
10
100
1000
Average Stem Nearest Neighbor Distance, d_k (m)
Tree Basal Stem Diameter, D_k (mm)

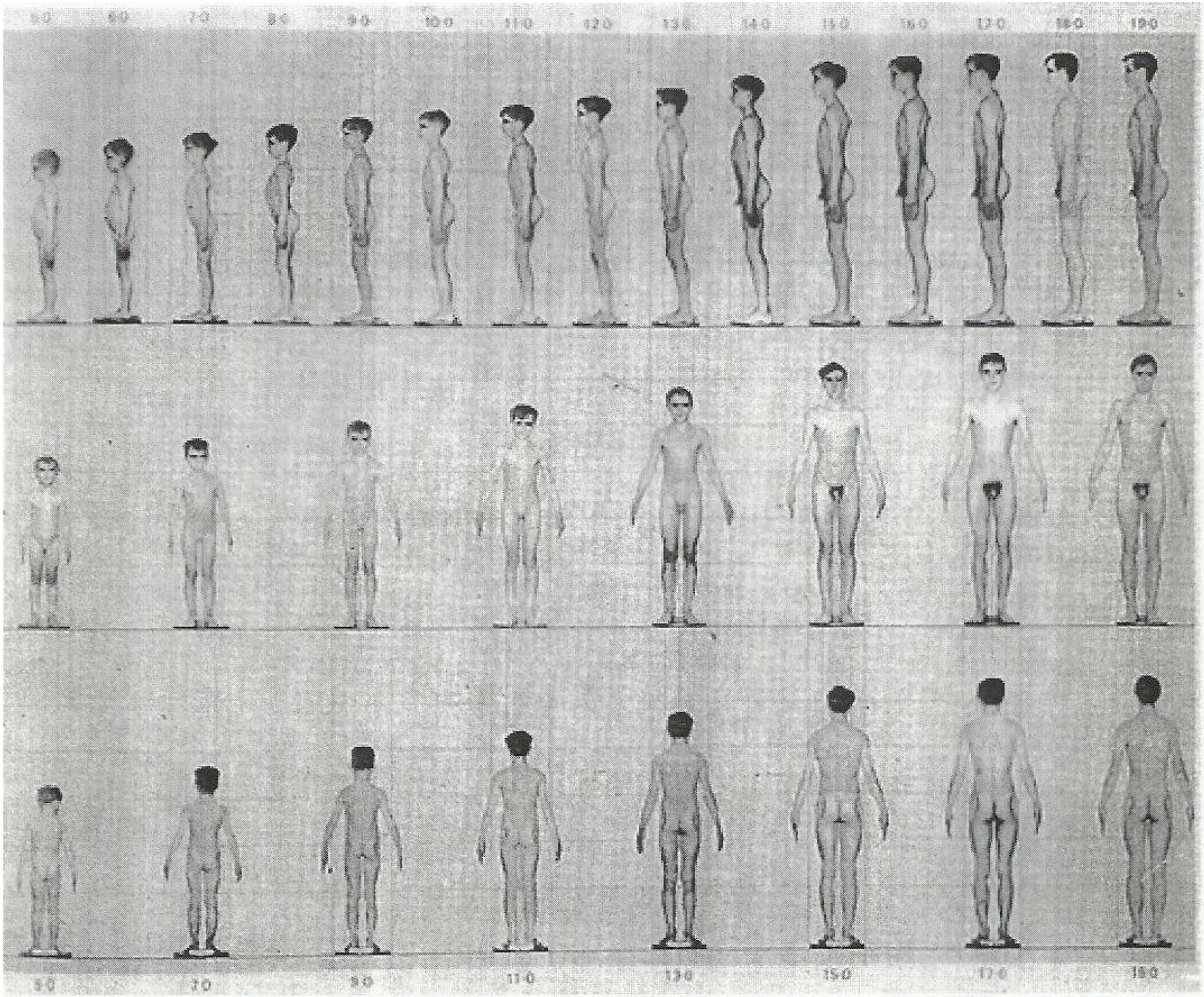
INTERSPECIFIC SIZE DISTRIBUTION

All species in a Malaysian Rainforest

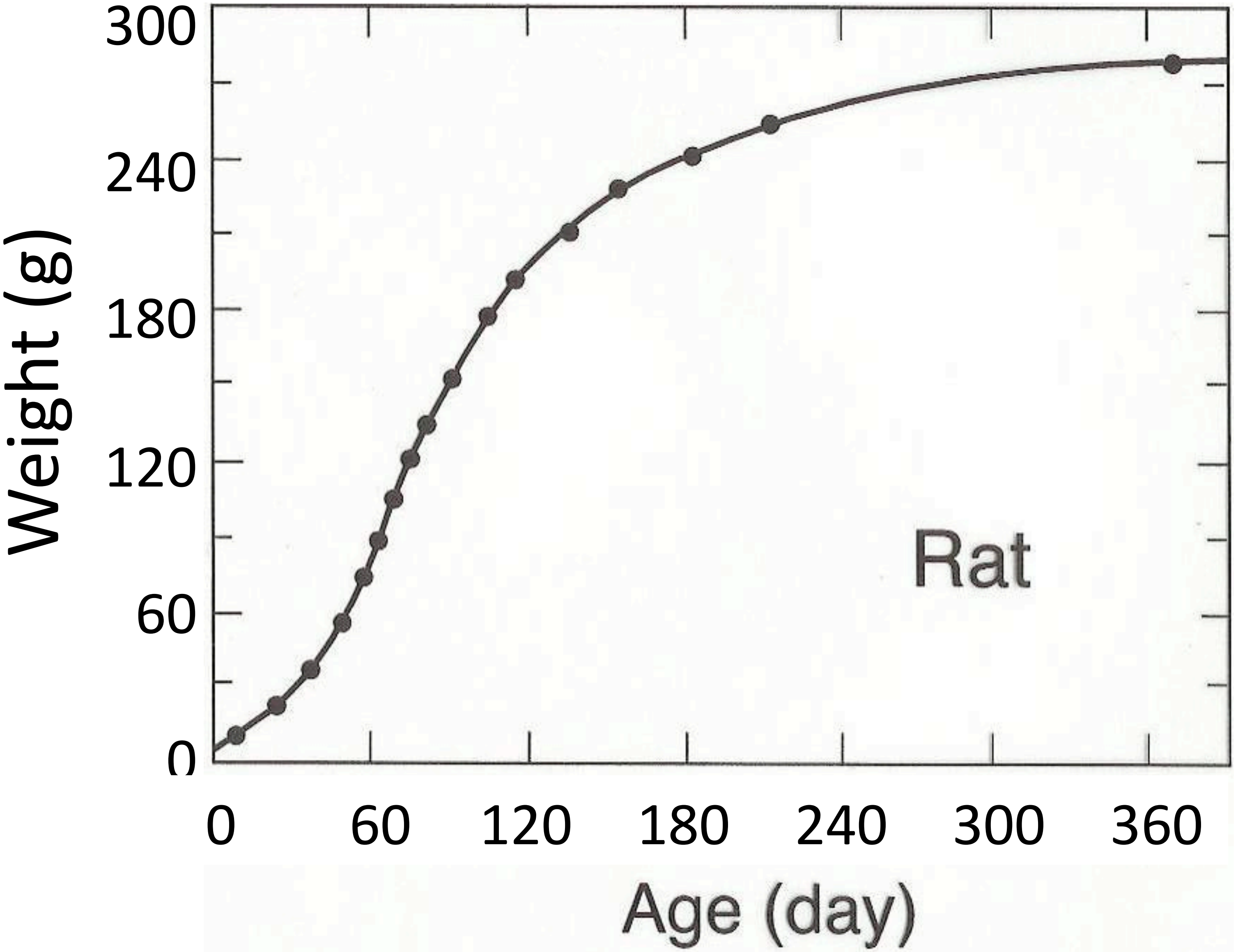


Manokaran and Kochummen (1987)




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
19.0

Food
"fire of life"
Energy


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

INCOMING METABOLISED ENERGY

↓

MAINTENANCE
(of existencing cells)

+

GROWTH
(of new cells)

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

IN TERMS OF MASS AT AGE t

$$\Rightarrow \frac{dm}{dt} = am^{3/4} - bm$$

where

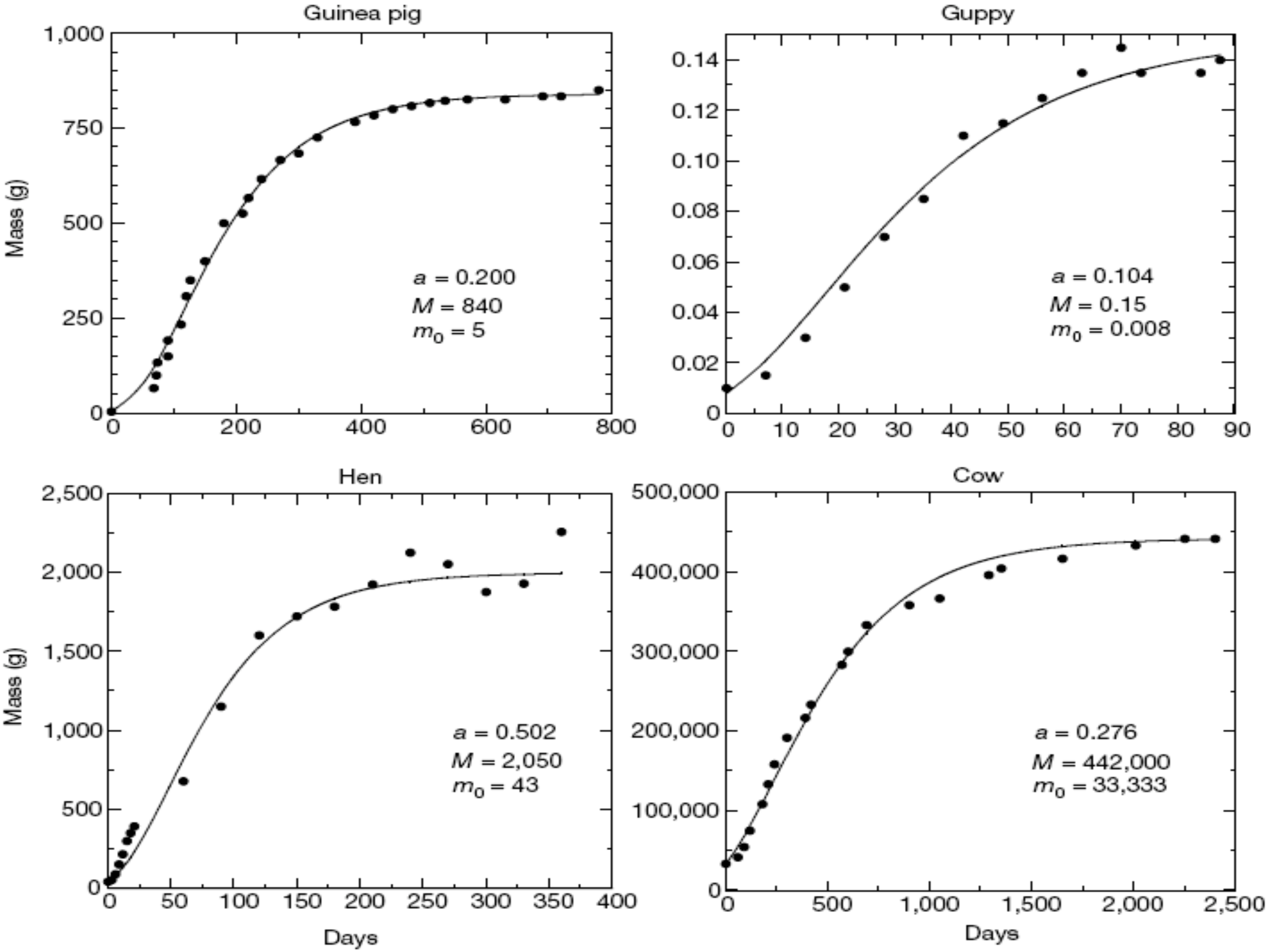
$$a \equiv \frac{B_0 m_c}{E_c}$$

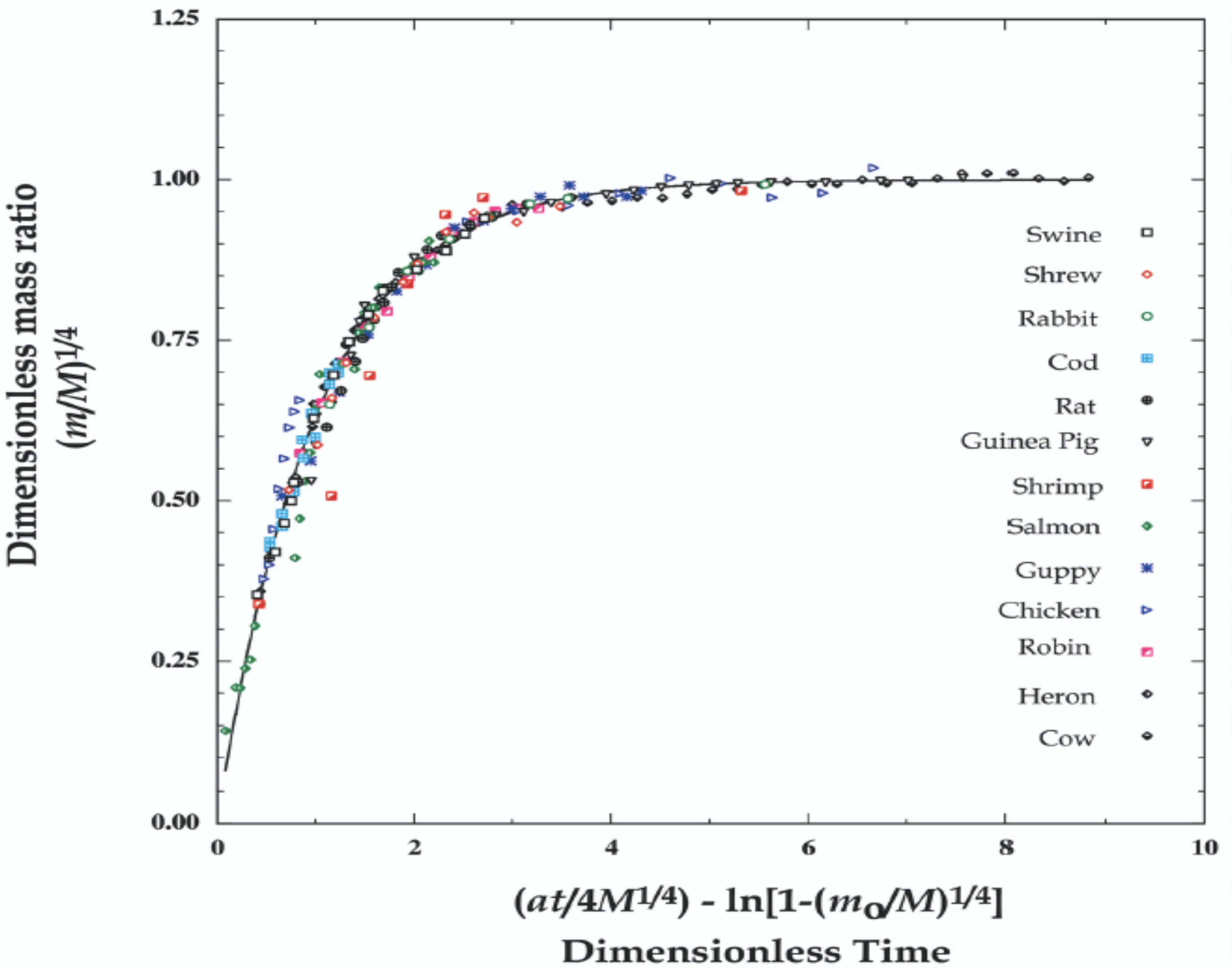
$$b \equiv \frac{B_c}{E_c}$$

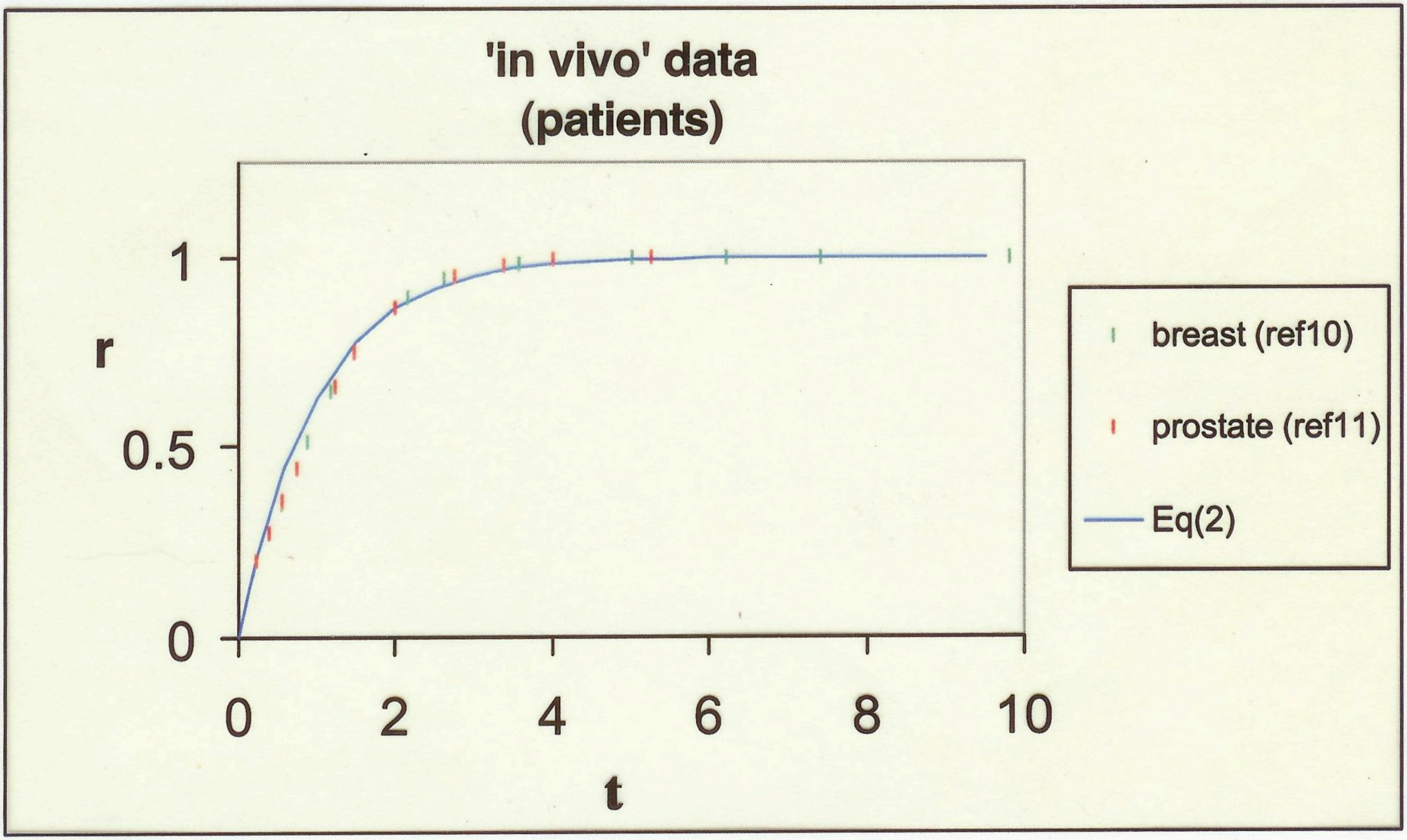
SOLUTION:

$$\left(\frac{m}{M}\right)^{1/4} = 1 - \left[1 - \left(\frac{m_0}{M}\right)^{1/4}\right] e^{-at/4M^{1/4}}$$

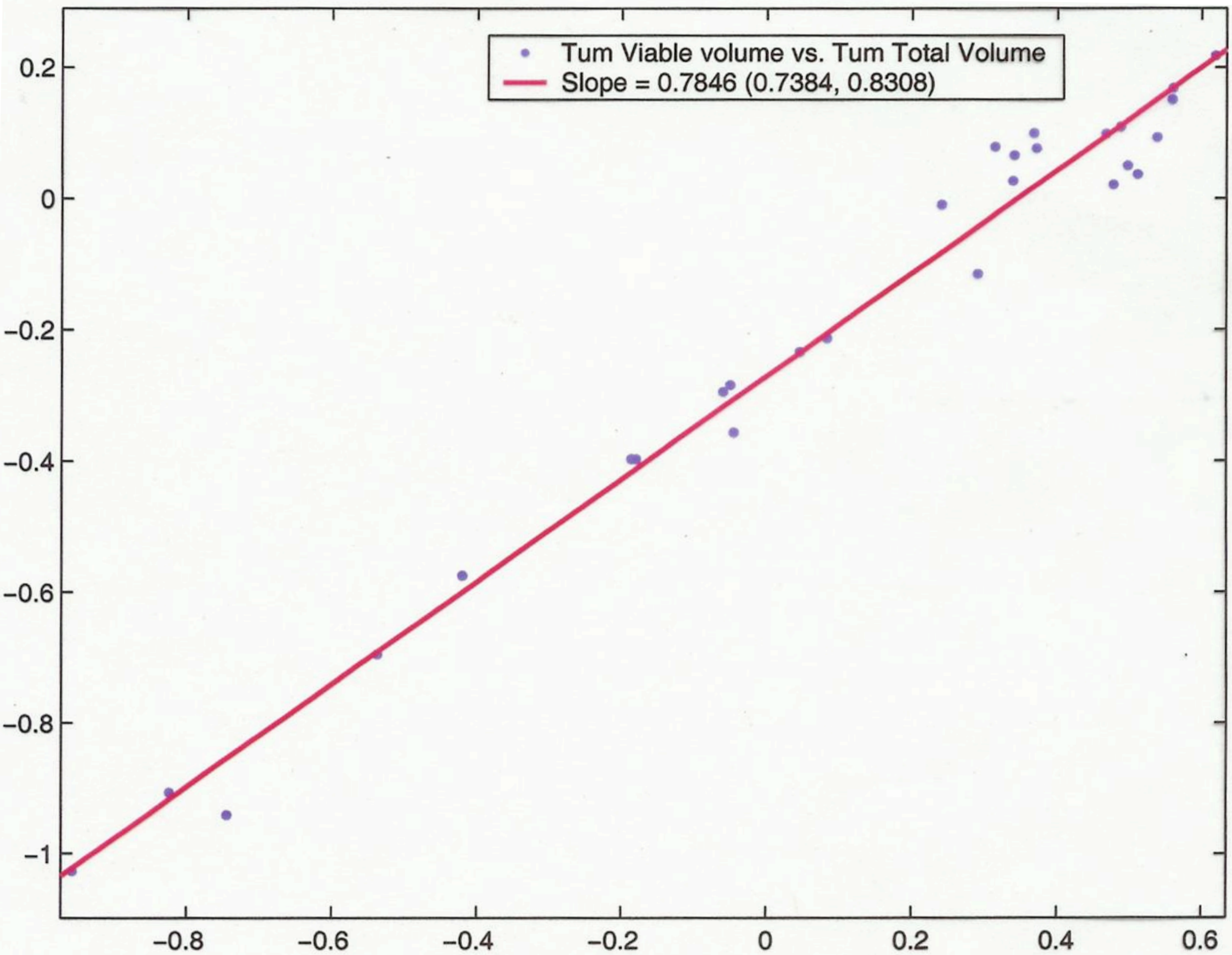
WHERE m_0 = MASS AT BIRTH ($m = m_0$ WHEN $t = 0$)

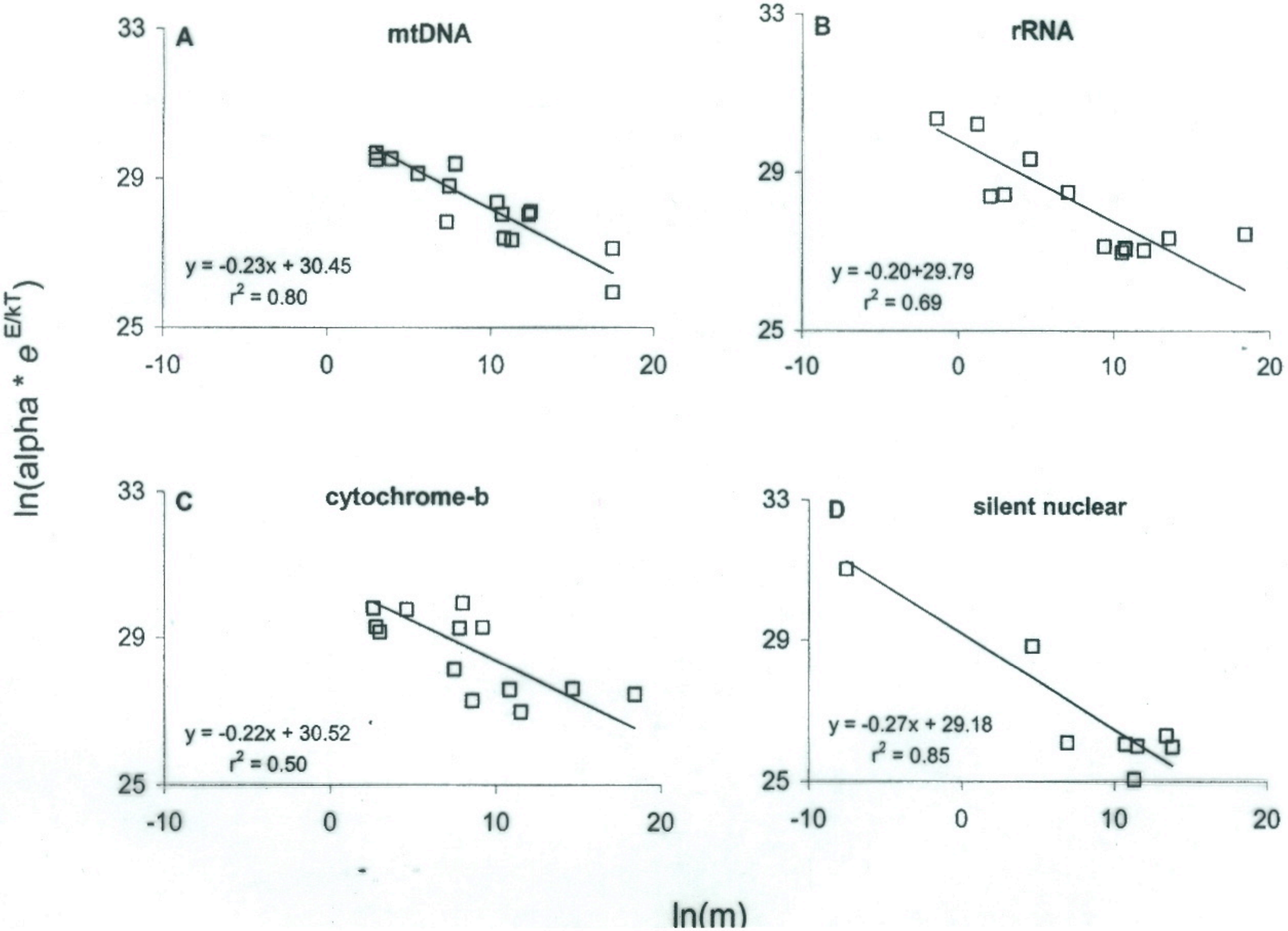

Guinea pig
Mass (g)
1,000
750
500
250
0
0
200
400
600
800
$a = 0.200$
$M = 840$
$m_0 = 5$
Guppy
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0
10
20
30
40
50
60
70
80
90
$a = 0.104$
$M = 0.15$
$m_0 = 0.008$
Hen
Mass (g)
2,500
2,000
1,500
1,000
500
0
0
50
100
150
200
250
300
350
400
Days
$a = 0.502$
$M = 2,050$
$m_0 = 43$
Cow
500,000
400,000
300,000
200,000
100,000
0
0
500
1,000
1,500
2,000
2,500
Days
$a = 0.276$
$M = 442,000$
$m_0 = 33,333$


1.25
1.00
0.75
0.50
0.25
0.00
Dimensionless mass ratio
$(m/M)^{1/4}$
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)


Tum Viable volume vs. Tum Total Volume
Slope = 0.7846 (0.7384, 0.8308)
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6


A
mtDNA
y = -0.23x + 30.45
$r^2 = 0.80$
B
rRNA
y = -0.20+29.79
$r^2 = 0.69$
C
cytochrome-b
y = -0.22x + 30.52
$r^2 = 0.50$
D
silent nuclear
y = -0.27x + 29.18
$r^2 = 0.85$
33
29
25
-10
0
10
20
$\ln(\text{alpha} * e^{E/kT})$
ln(m)

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)?

$$R \sim N^b$$

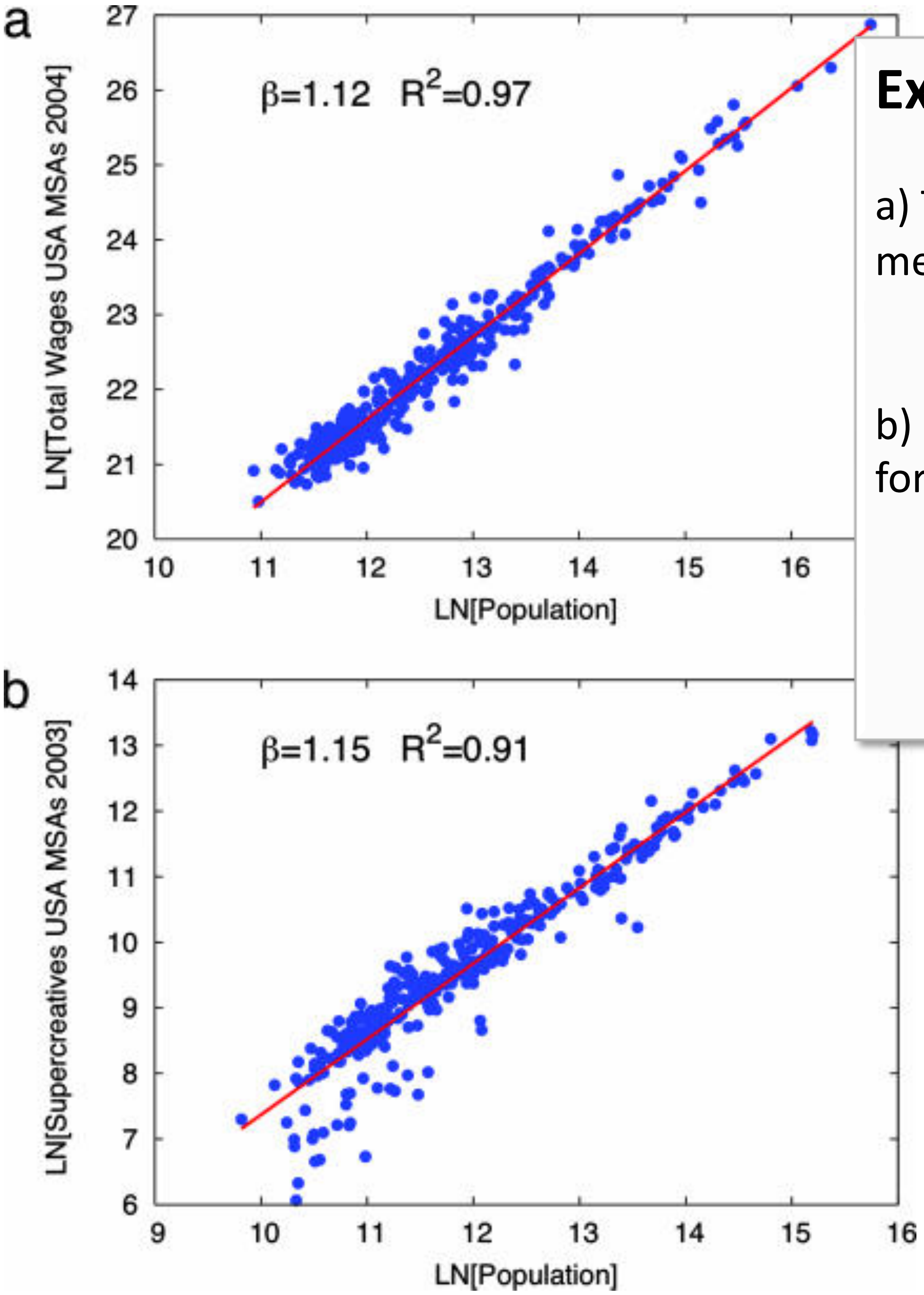
NETWORK DYNAMICS IMPLIES THAT THE PACE OF LIFE IS DETERMINED BY

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

$b < 1$ *PACE OF LIFE SLOWS DOWN*

$b > 1$ *PACE OF LIFE SPEEDS UP*

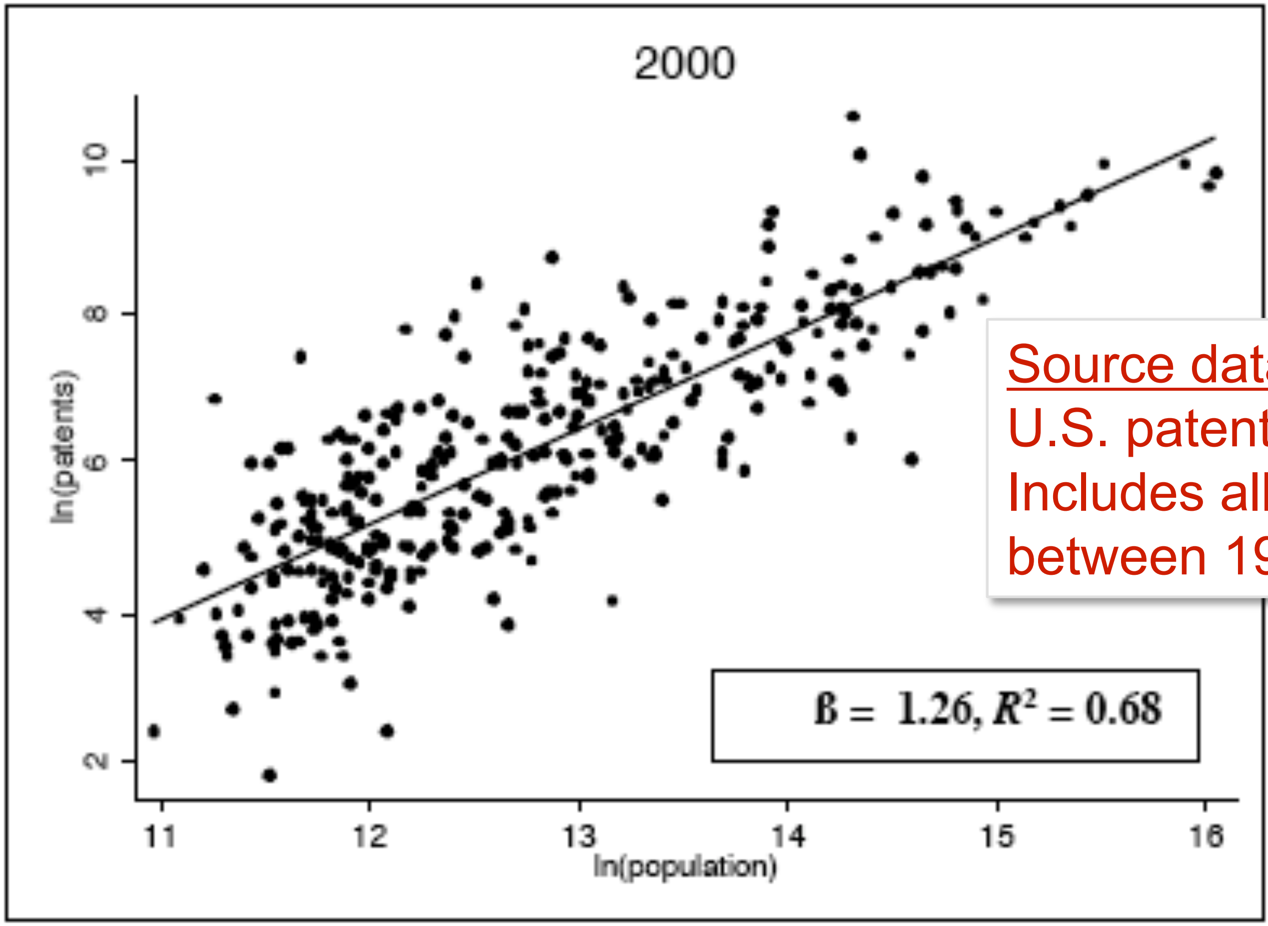
Example of scaling relationships



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.

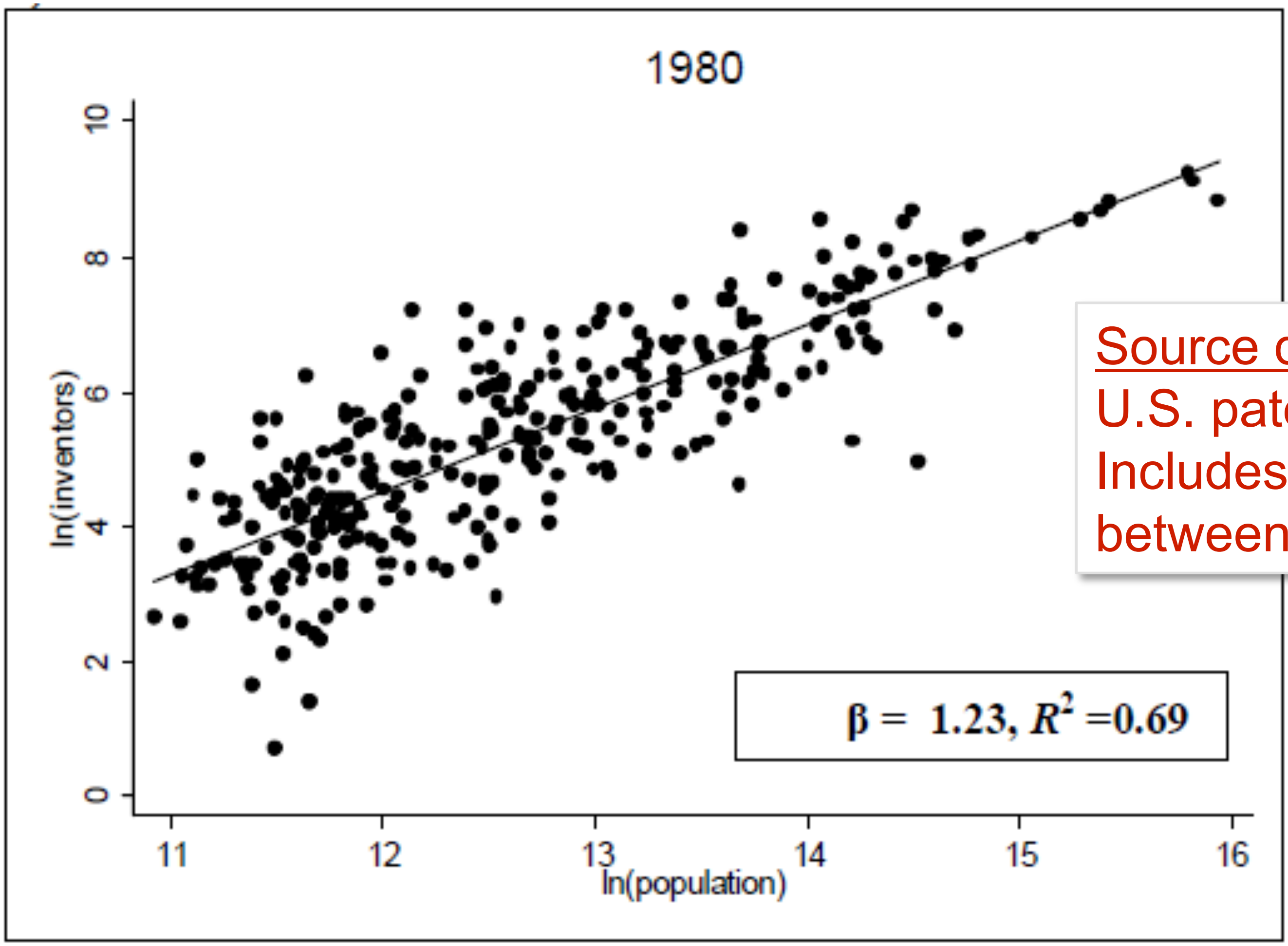
Innovation measured by Patents



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

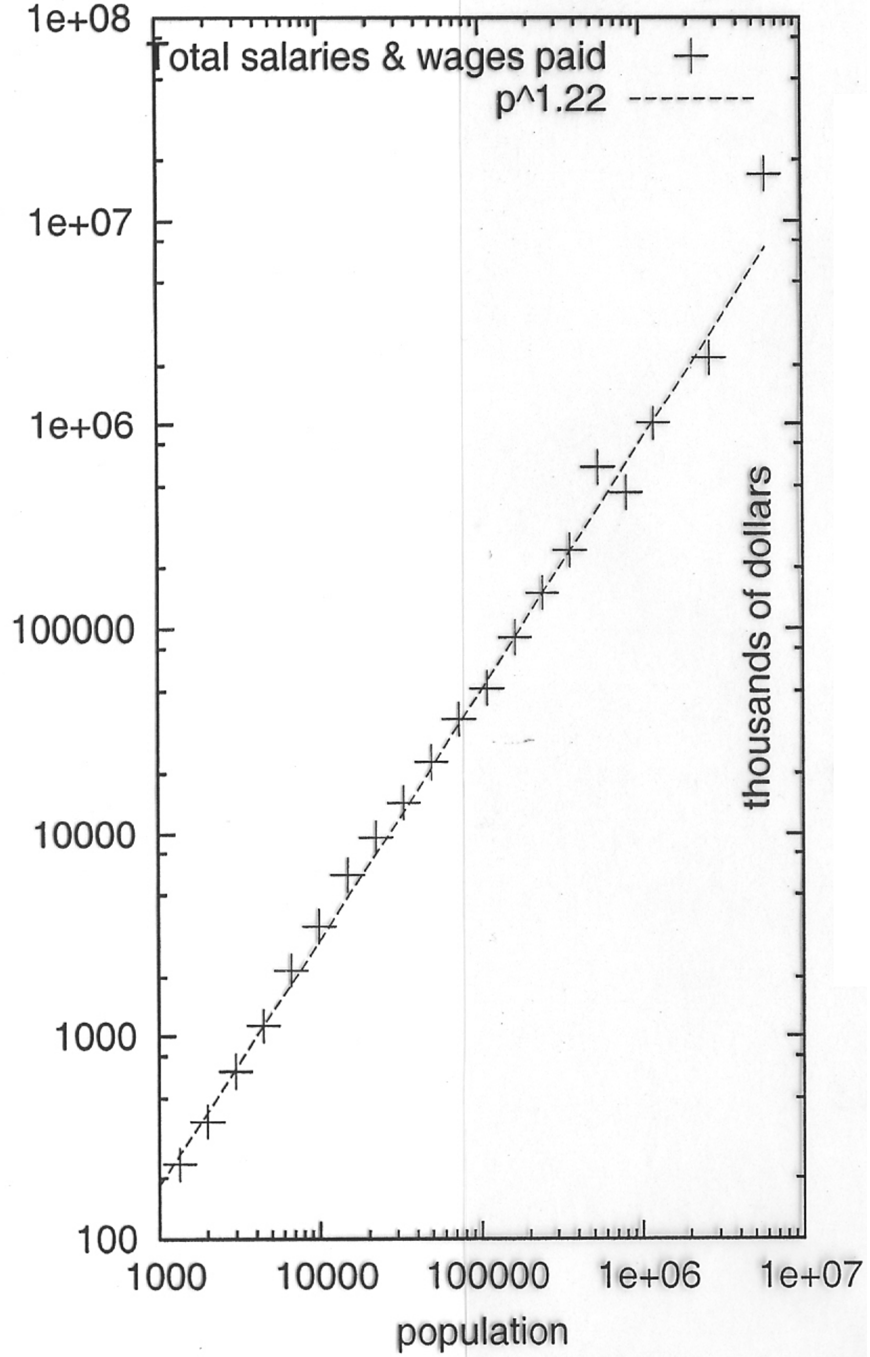
From “**Innovation in the city: Increasing returns to scale in urban patenting**”
Bettencourt, Lobo and Strumsky
Data courtesy of Lee Fleming, Deborah Strumsky

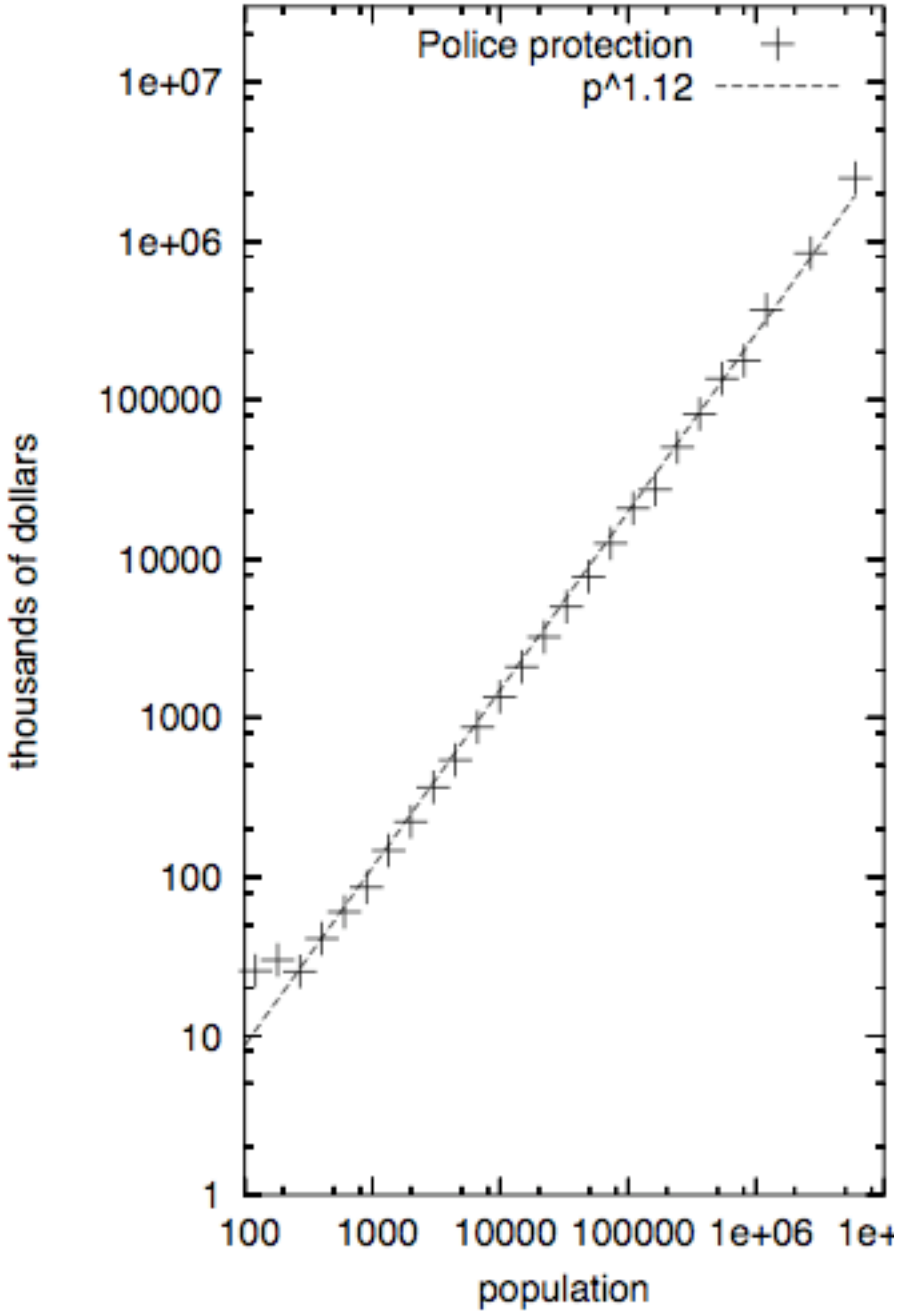
Or to a disproportionate agglomeration of inventors with urban size?

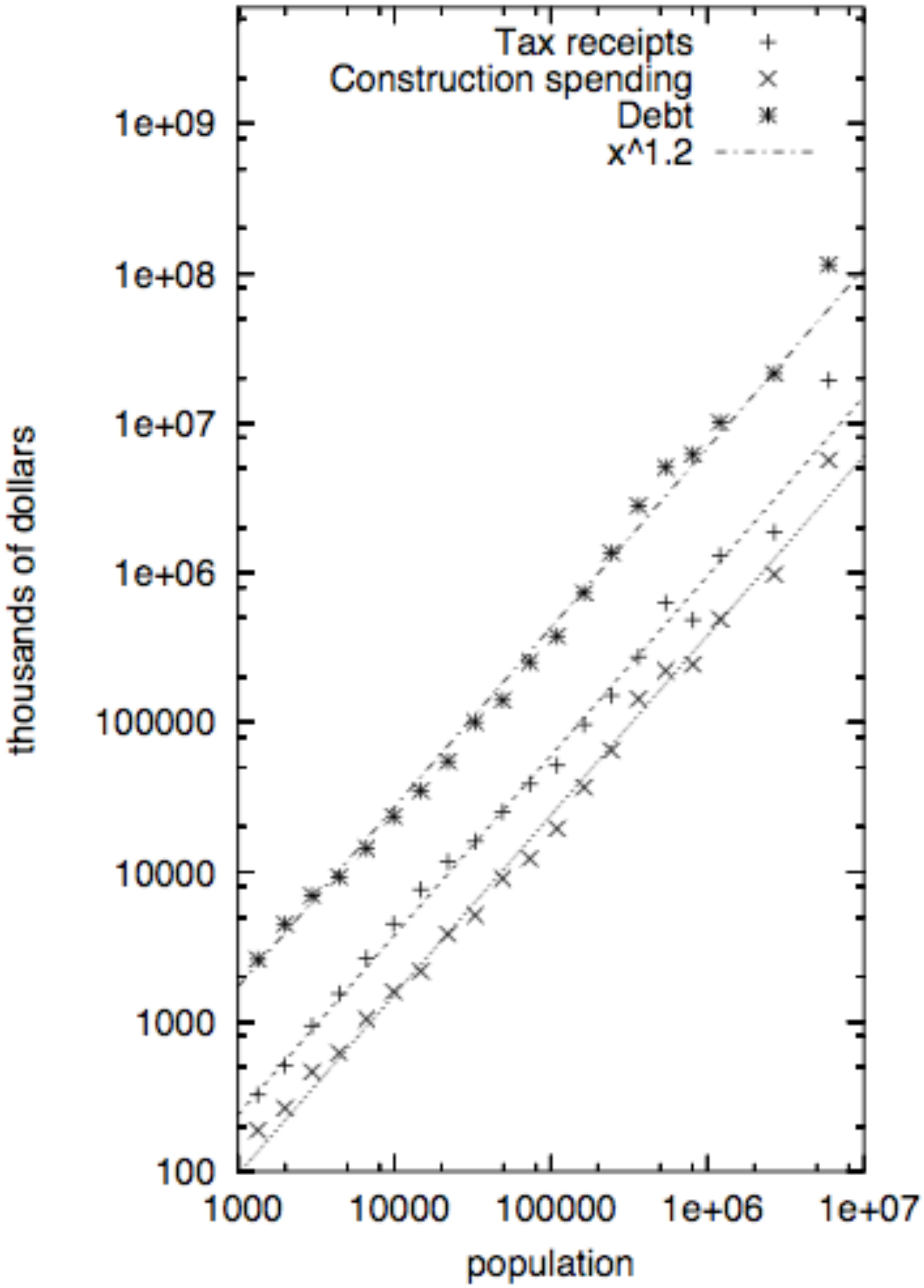


Source data:
U.S. patent office
Includes all patents
between 1980 – 2001

Data courtesy of Lee Fleming, Deborah Strumsky


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


Police protection
p^1.12
thousands of dollars
1e+07
1e+06
100000
10000
1000
100
10
1
100
1000
10000
100000
1e+06
1e+
population


Tax receipts
Construction spending
Debt
x^1.2
thousands of dollars
1e+09
1e+08
1e+07
1e+06
100000
10000
1000
100
1000
10000
100000
1e+06
1e+07
population

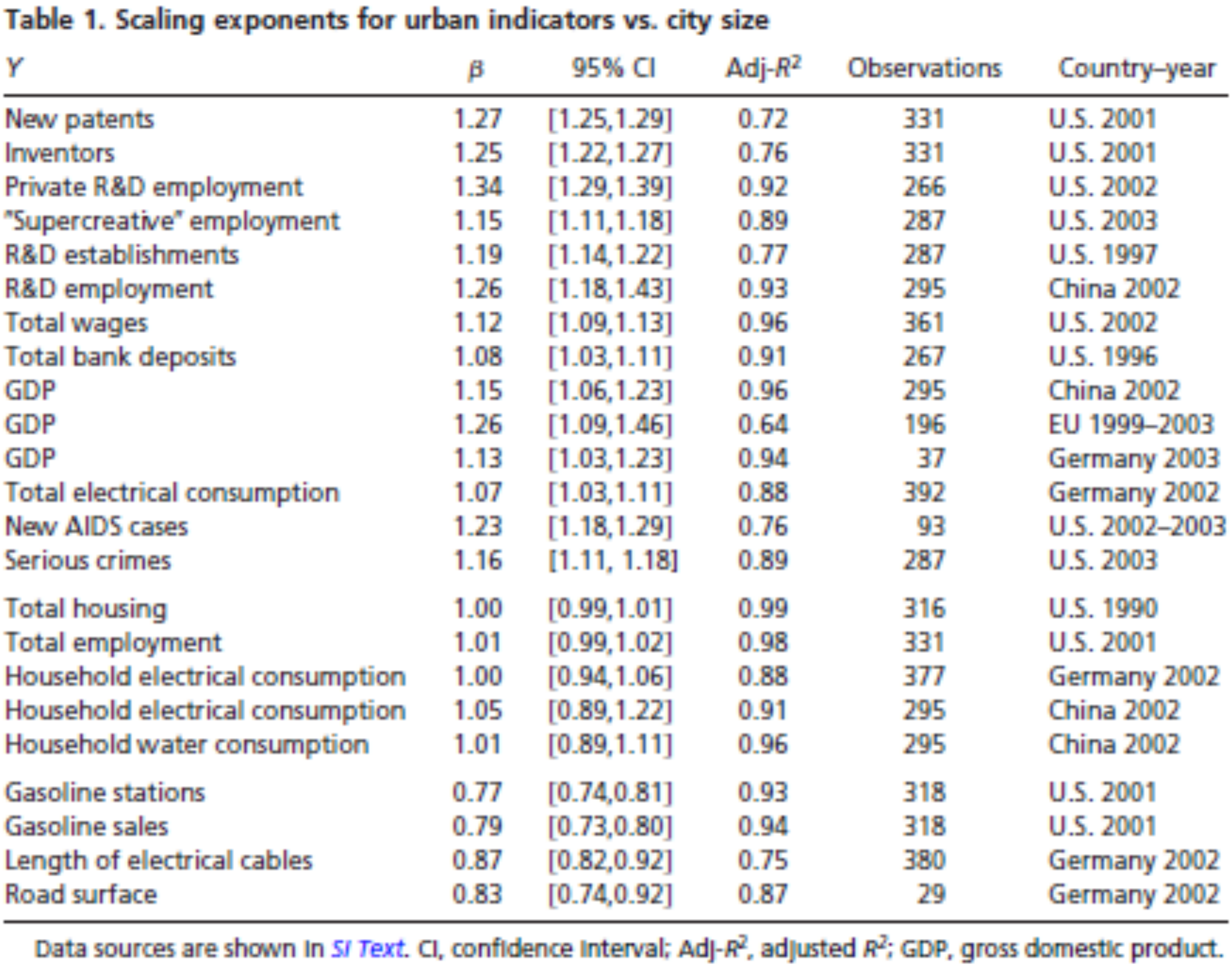


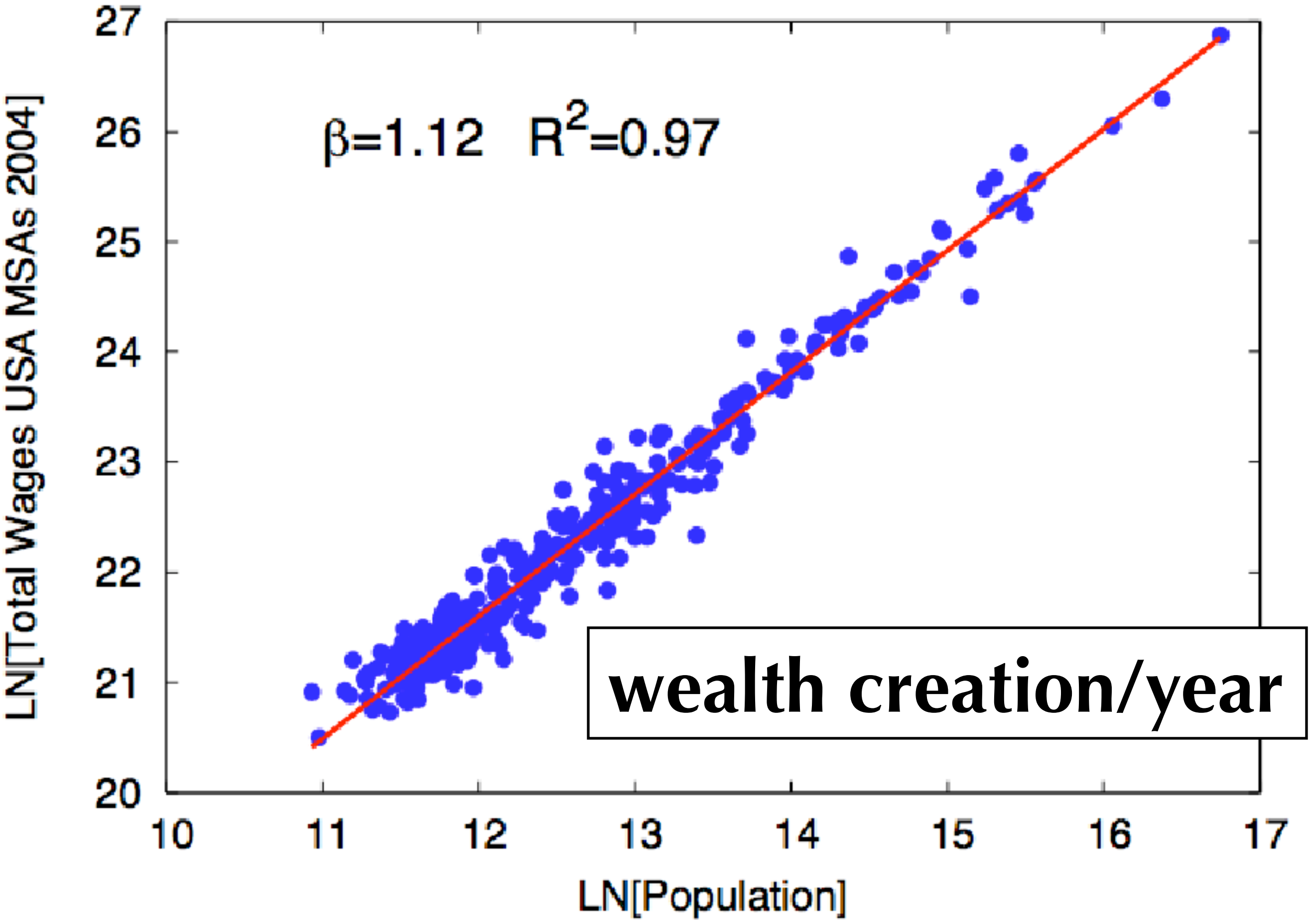
Table 1. Scaling exponents for urban indicators vs. city size

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.

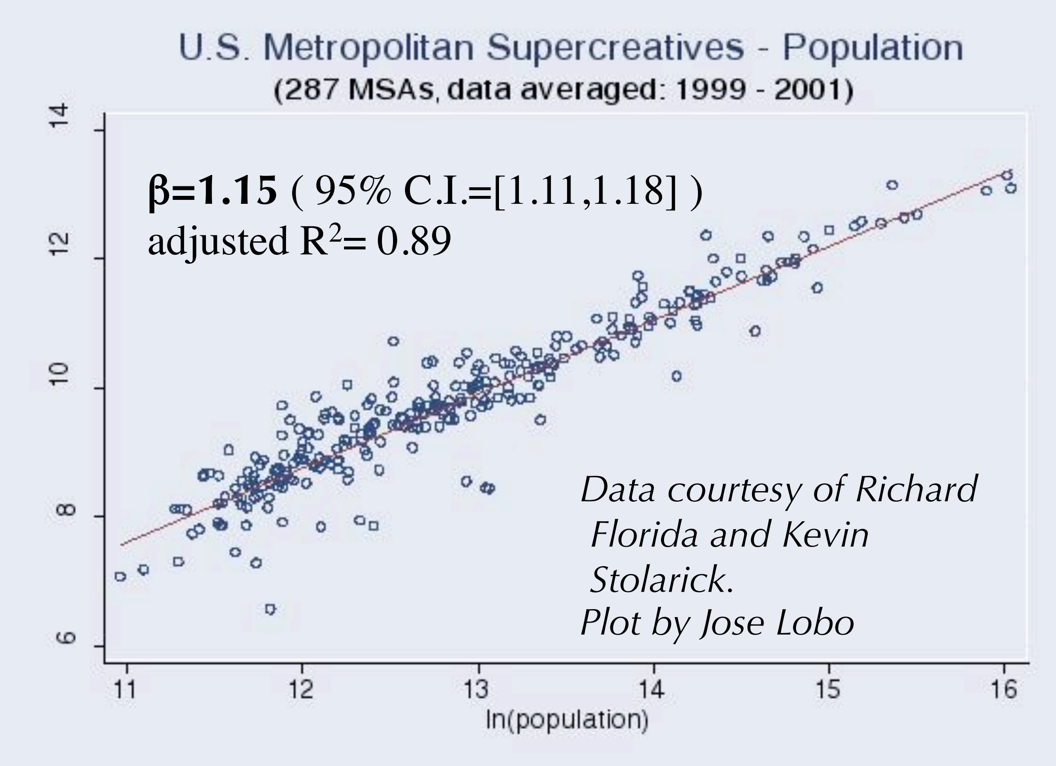
See supplementary online materials for further details and data sources.

Increasing returns in cities



wealth creation/year

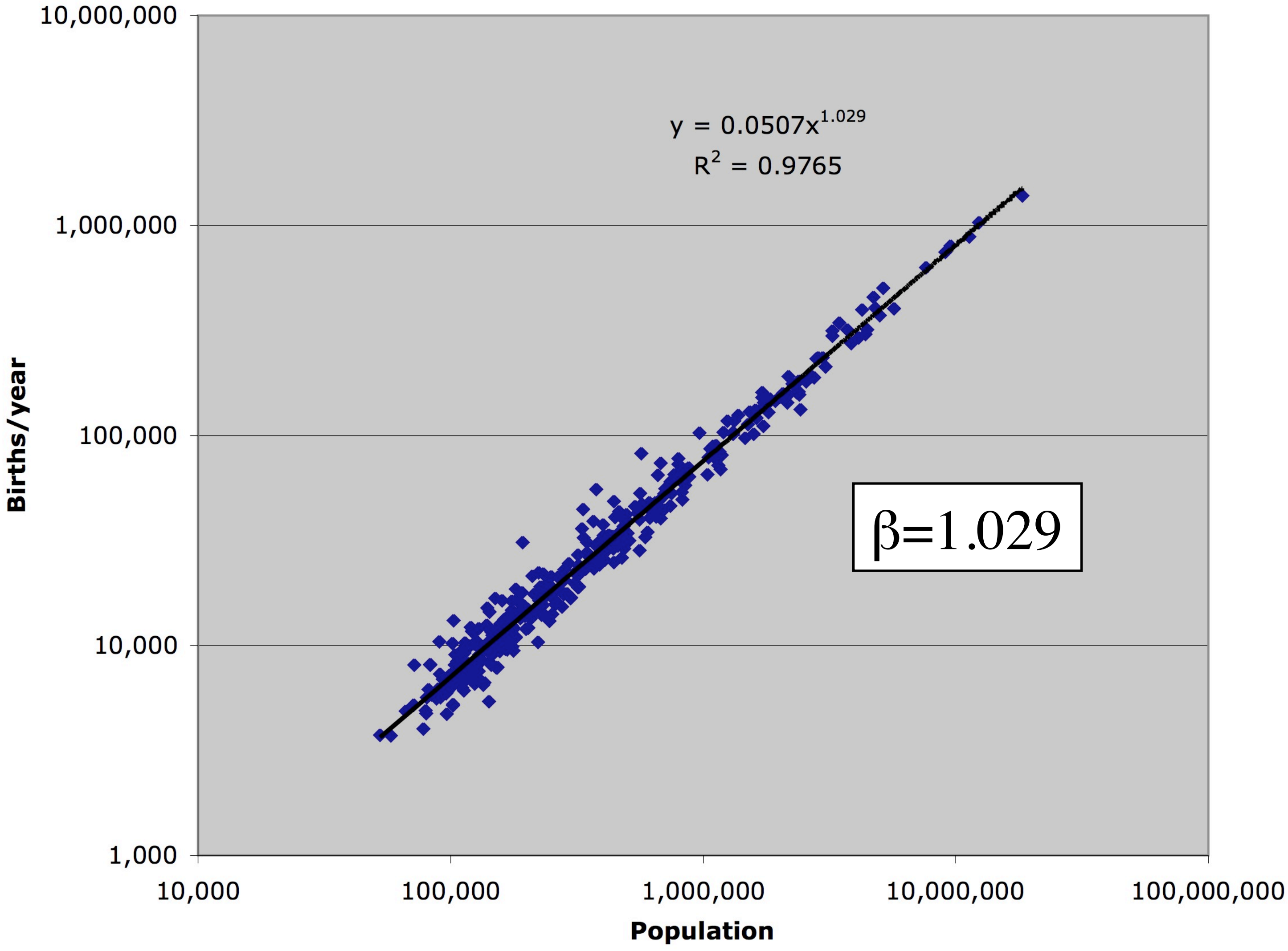
Employment patterns



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"*.

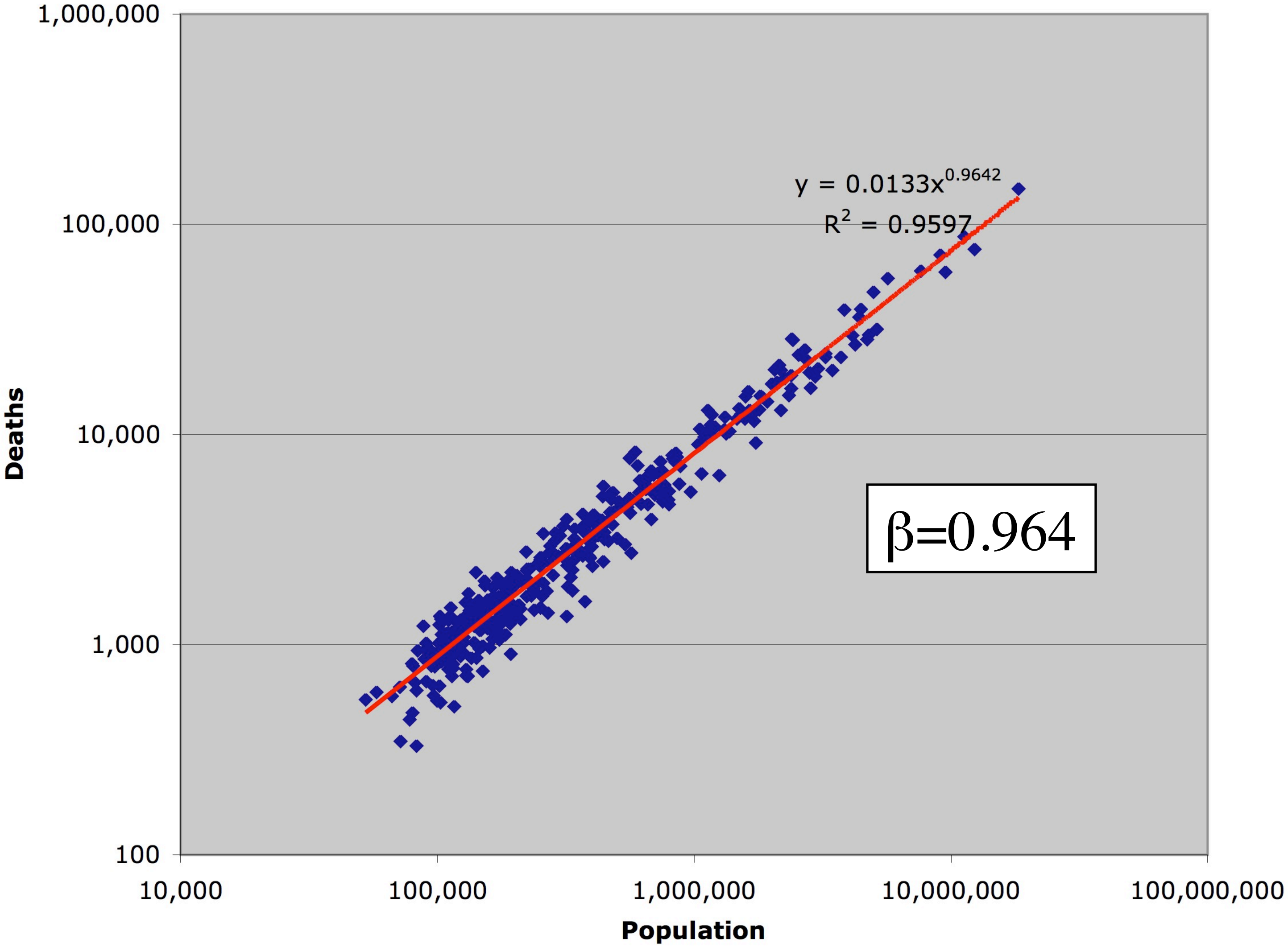
Derived from Standard Occupation Classification System of the U.S. Bureau of Labor Statistics

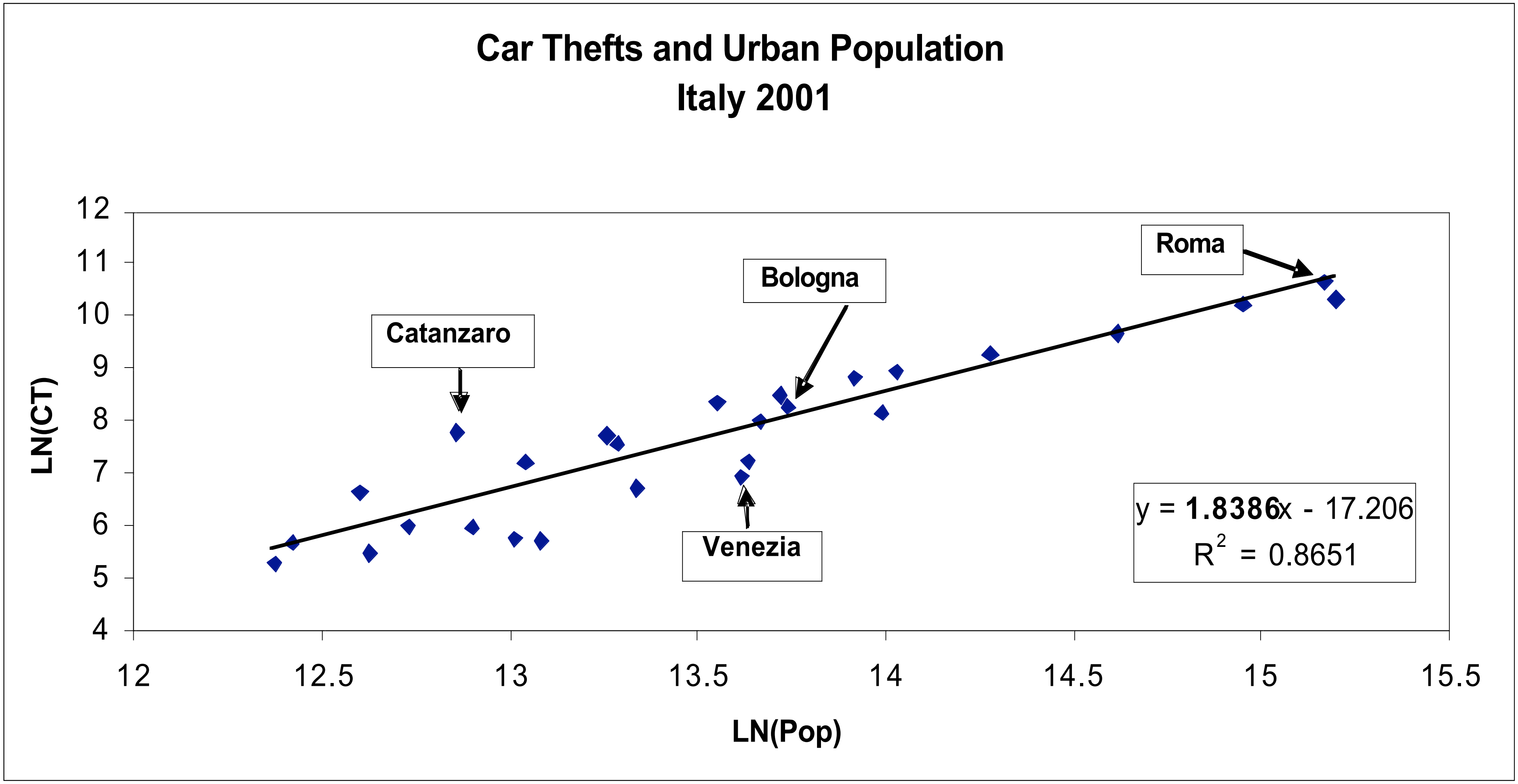
Births vs. Metropolitan Population



$\beta=1.029$

Deaths vs. Population




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

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

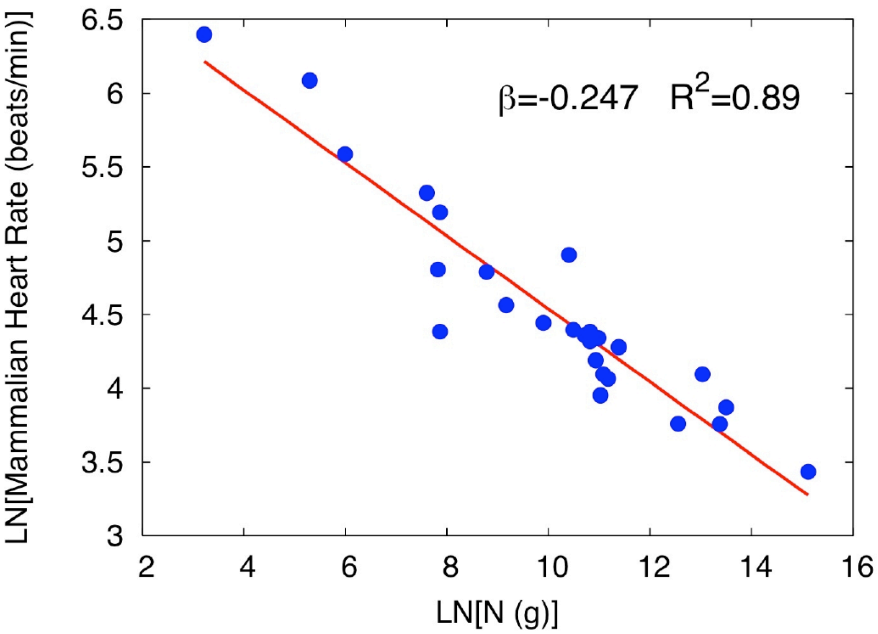
ii) $b = 1$

LINEAR ➔ NON-INNOVATIVE

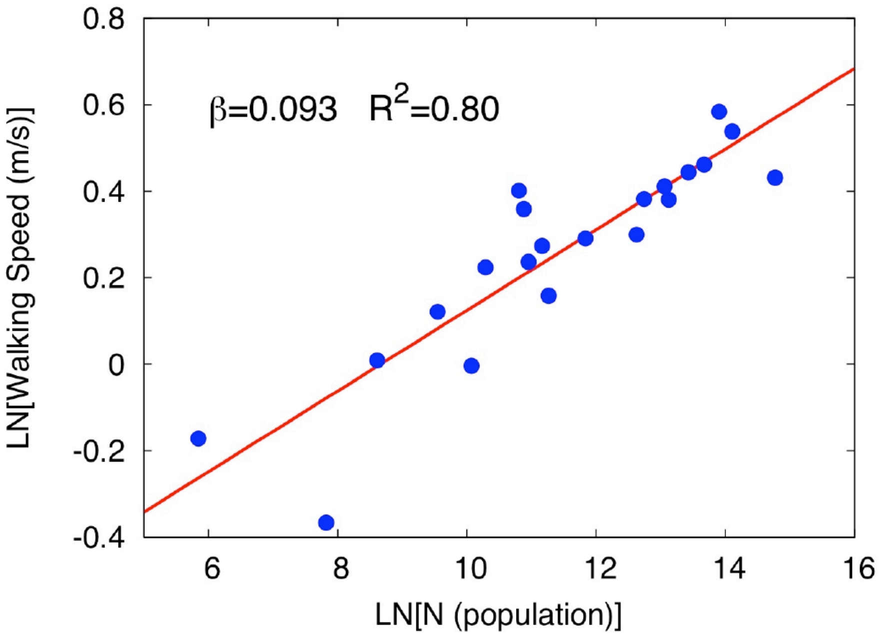
iii) $b \sim 1.15$ >1 ➔ **SOCIO-ECONOMIC**

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

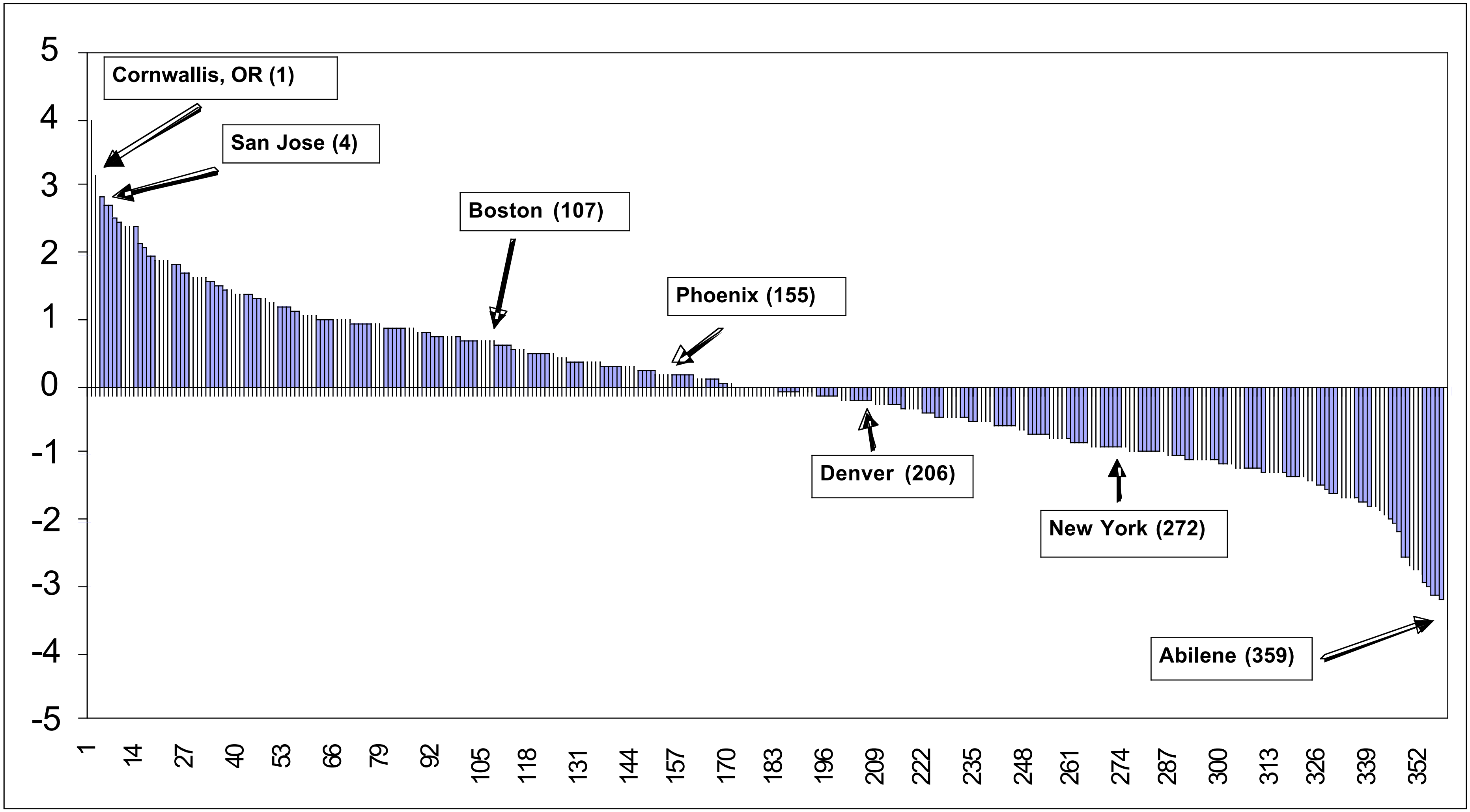
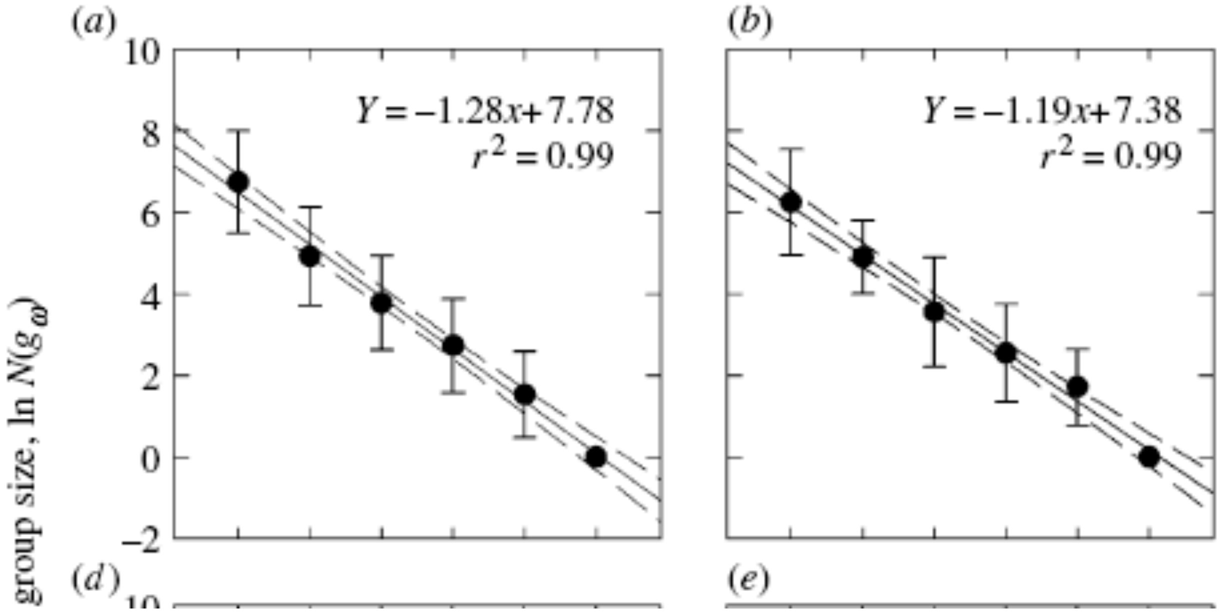


Table 1. Hunter-gatherer group sizes and frequencies.

organizational level	Horton order	sample size	ln mean	s.d.	geometric mean
group size (g)	ω	n	$\langle \ln g \rangle$	s_g	$\bar{g}$
individual	1	—	0	—	1
family	2	114	1.50	0.23	4.48
dispersed group	3	227	2.75	0.46	15.60
aggregated group	4	297	3.98	0.71	53.66
periodic aggregation	5	213	5.11	0.66	165.32
population size	6	339	6.73	1.25	839.19
frequency, $N(g)$	ω	n	$\langle \ln N(g) \rangle$	$s_{N(g)}$	$\bar{N}(g)$



Growth Equation

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

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

Energy/resources, etc. needed to create new individual

$$R \approx NR_{O} + E_{O}\frac{dN}{dt}$$

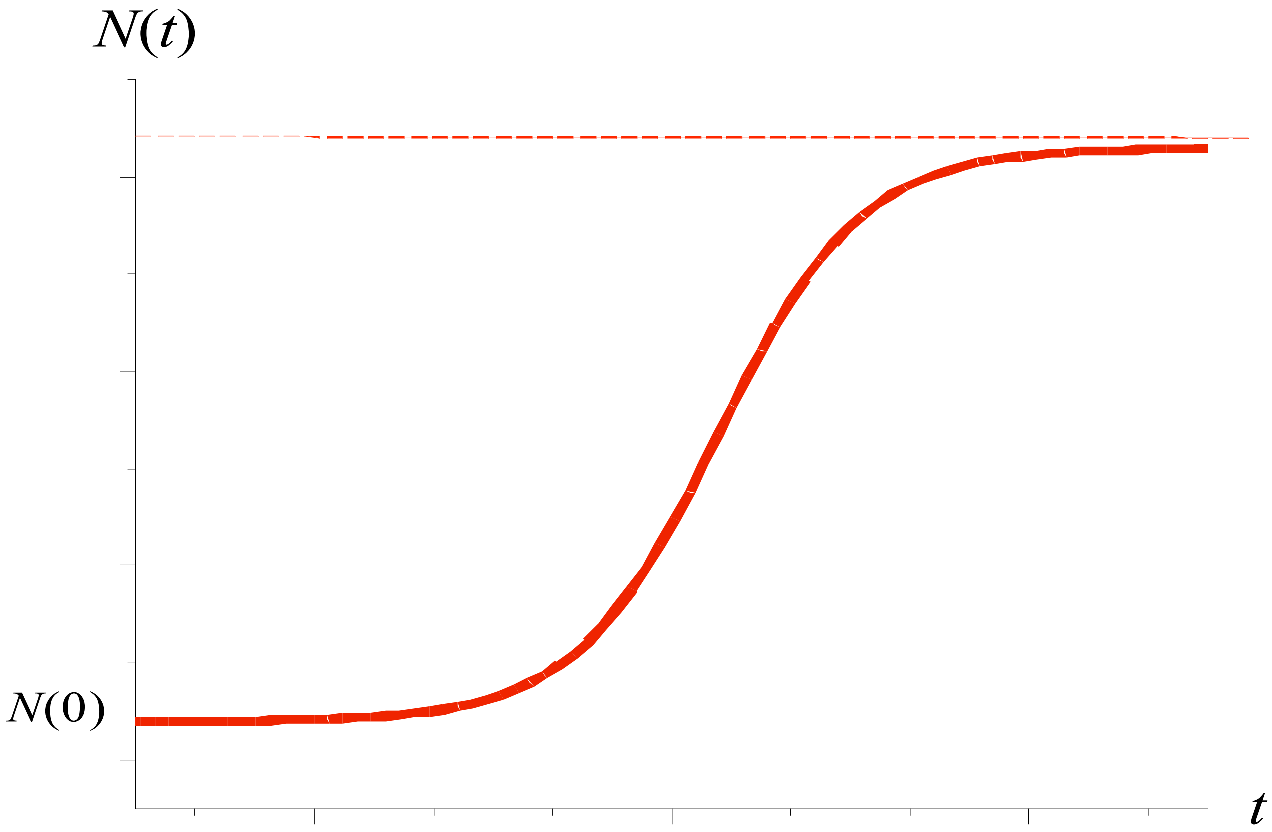
Resources, etc. needed to maintain individual

$$\frac{dN}{dt} = \left(\frac{R_1}{E_0}\right)\left[N^{\beta} - \left(\frac{R_0}{R_1}\right)N\right]$$

SOLUTION:

$$N^{1-\beta} = \frac{R_1}{R_0} + \left[N^{1-\beta}(0) - \frac{R_1}{R_0}\right]e^{-\frac{R_0}{E_0}(1-\beta)t}$$

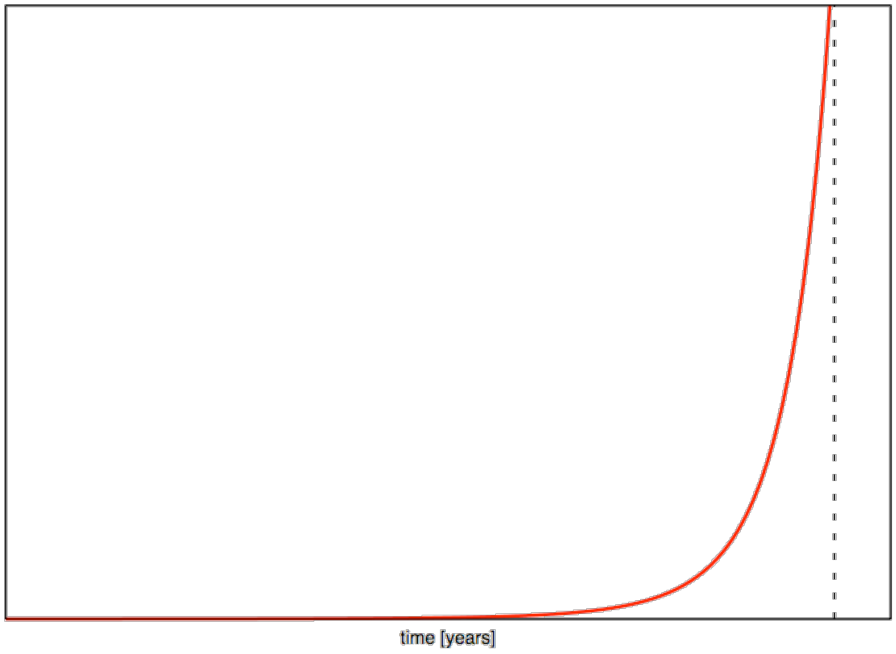
CHARACTER OF SOLUTION SENSITIVE TO $\beta >,=,< 1$

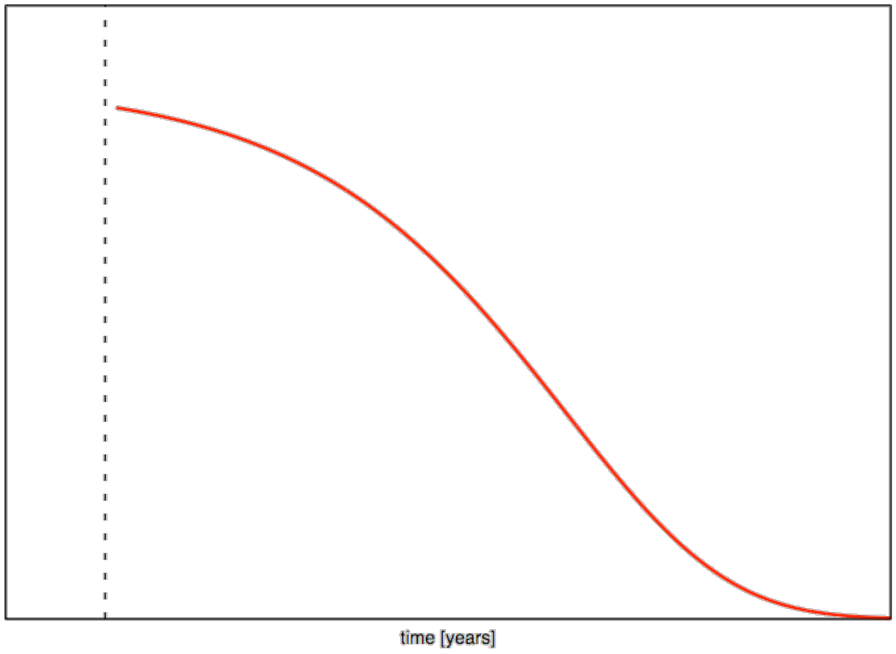


b < 1

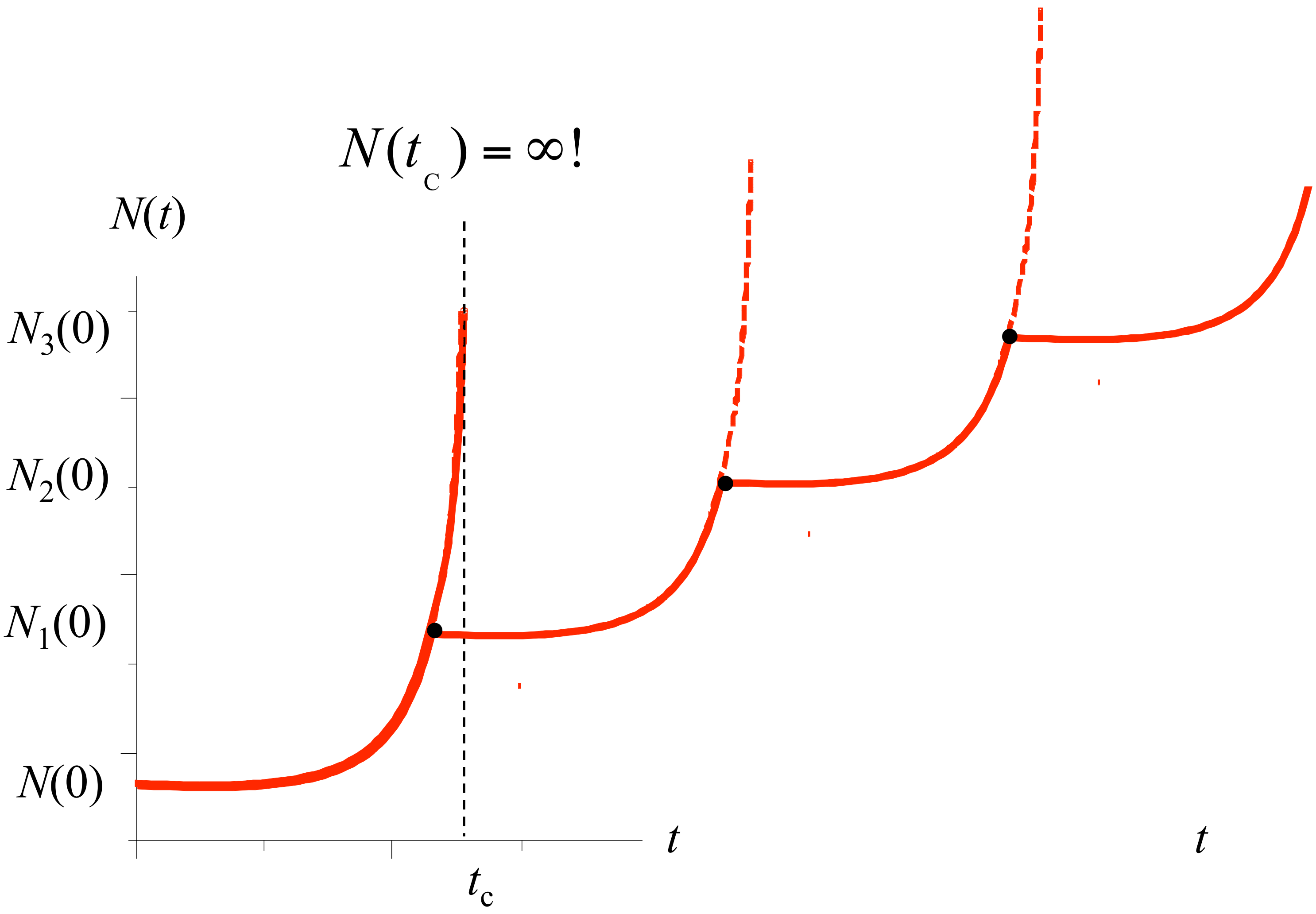
SIGMOIDAL BOUNDED GROWTH

b>1 : Finite time Boom and Collapse

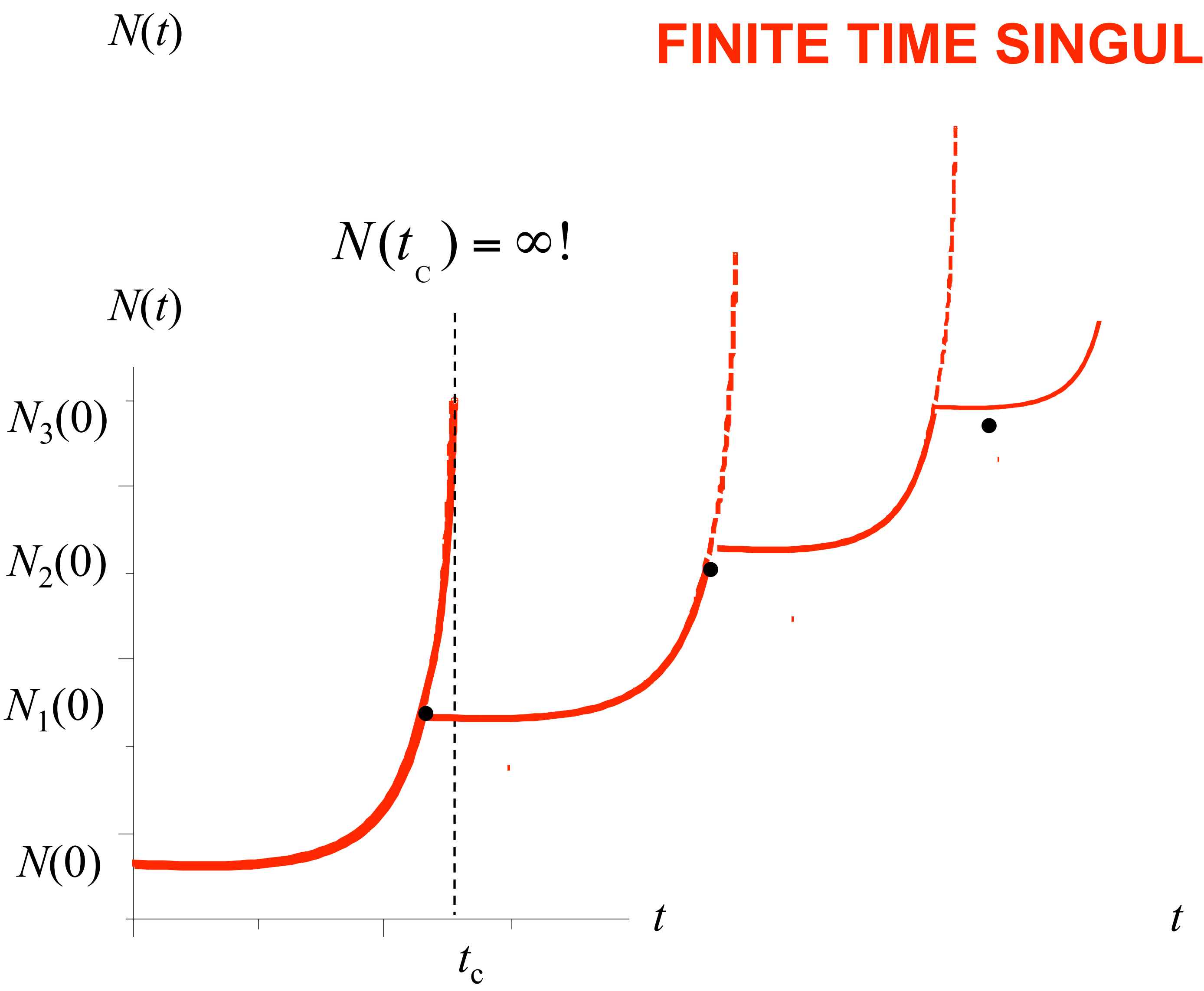




b> 1 UNBOUNDED GROWTH UP TO FINITE TIME SINGULARITY



b> 1 UNBOUNDED GROWTH UP TO FINITE TIME SINGULARITY



TO MAINTAIN CONTINUOUS GROWTH, MUST HAVE:

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

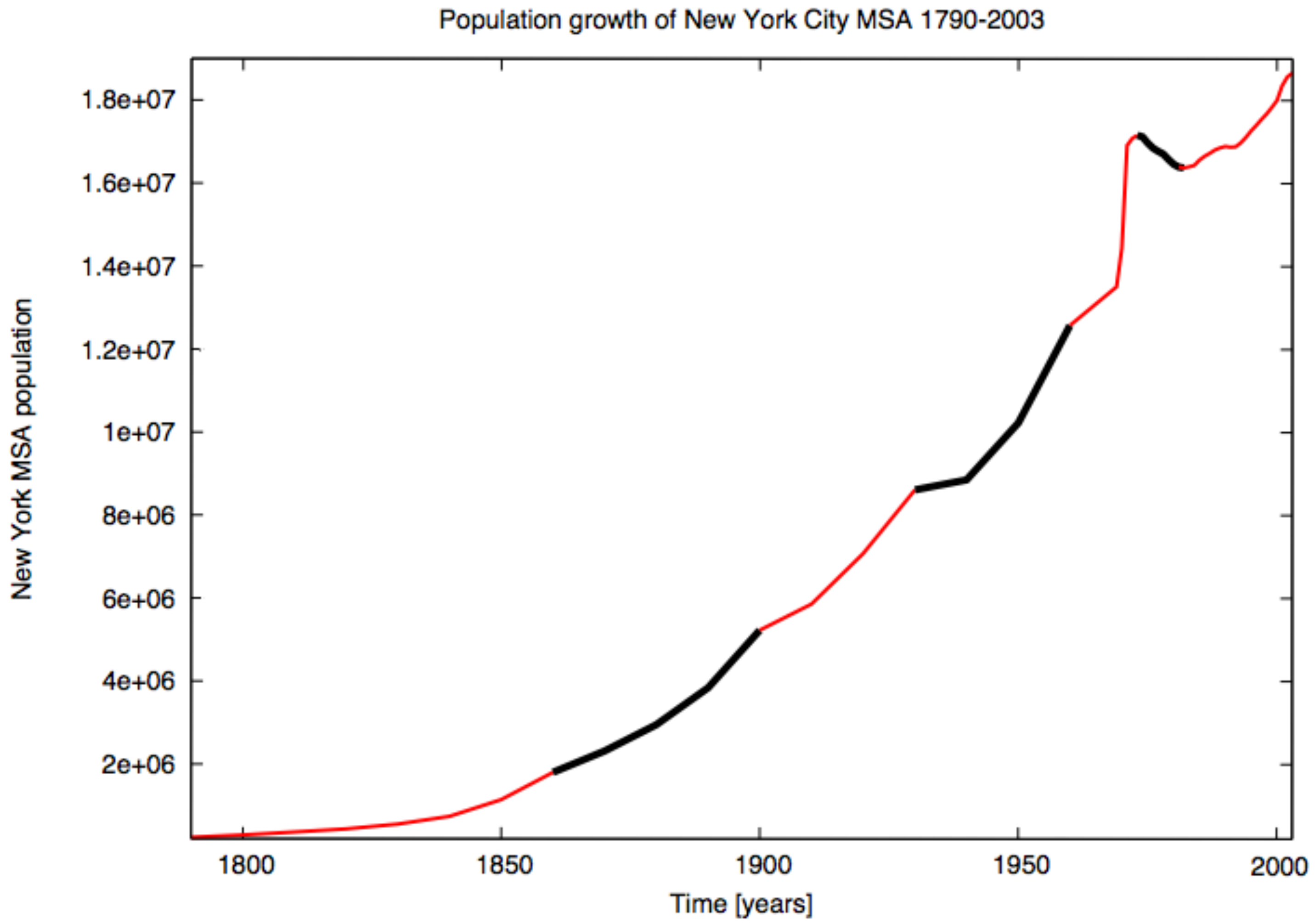
ii) CONTINUOUS MAJOR INNOVATIONS OR PARADIGM SHIFTS AT AN ACCELERATING RATE

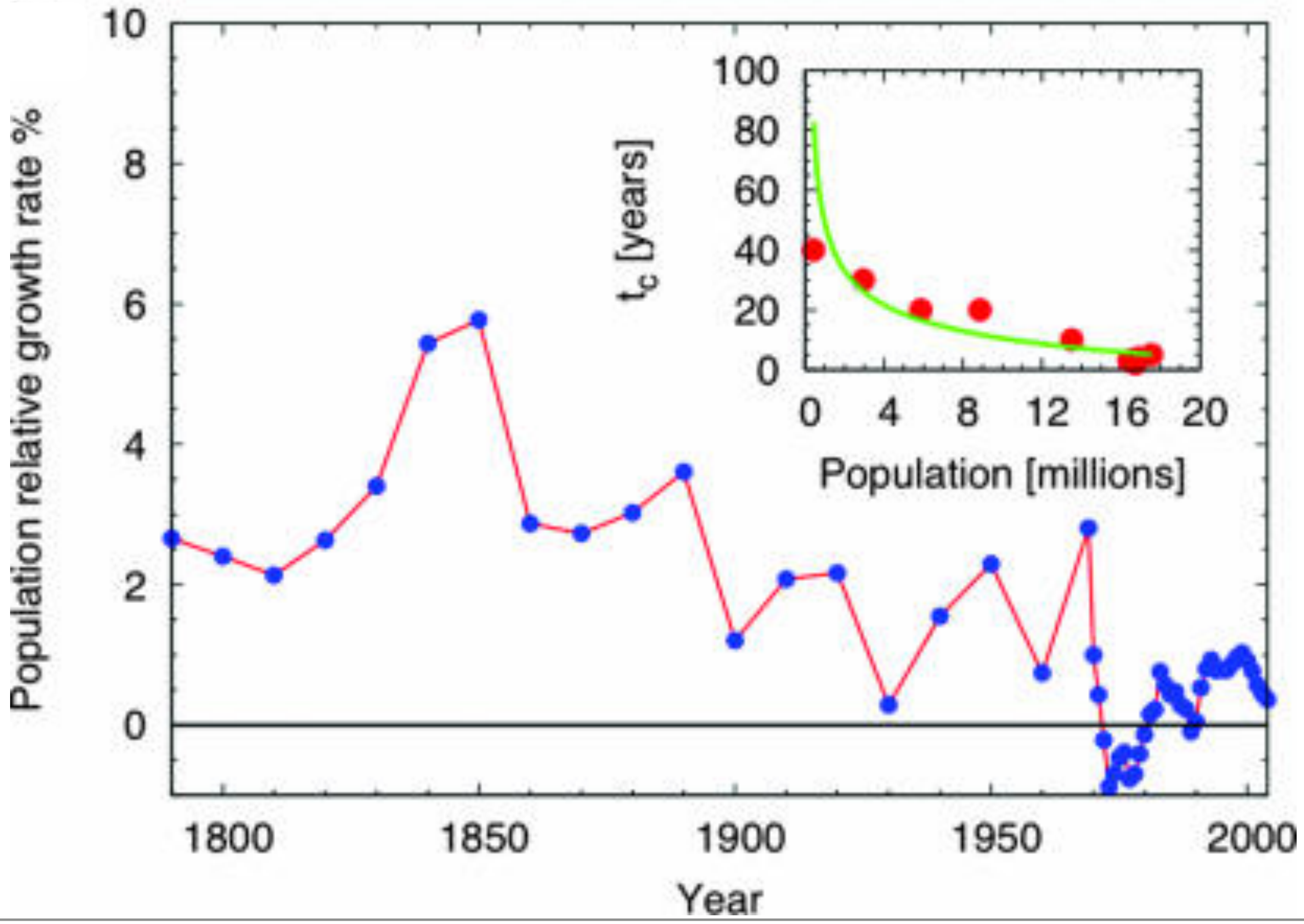
iii) TIME BETWEEN INNOVATIONS DECREASES SYSTEMATICALLY WITH GROWTH:

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

Population growth for New York City

1790 - 2003





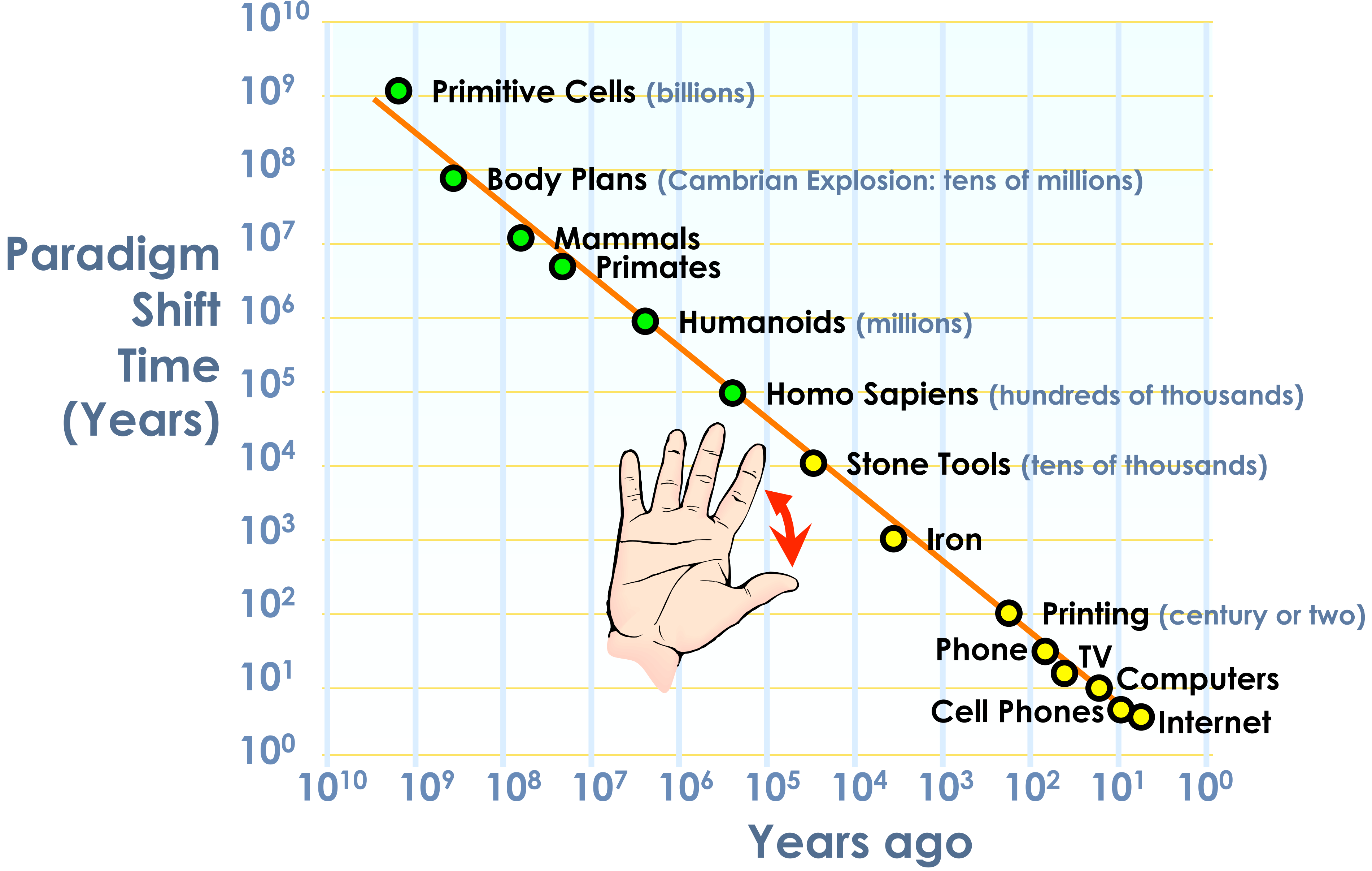
Successive cycles of superlinear innovation reset the singularity and postpone instability and subsequent collapse. The relative population growth rate of New York City over time reveals periods of accelerated (super-exponential) growth. Successive shorter periods of super exponential growth appear, 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).

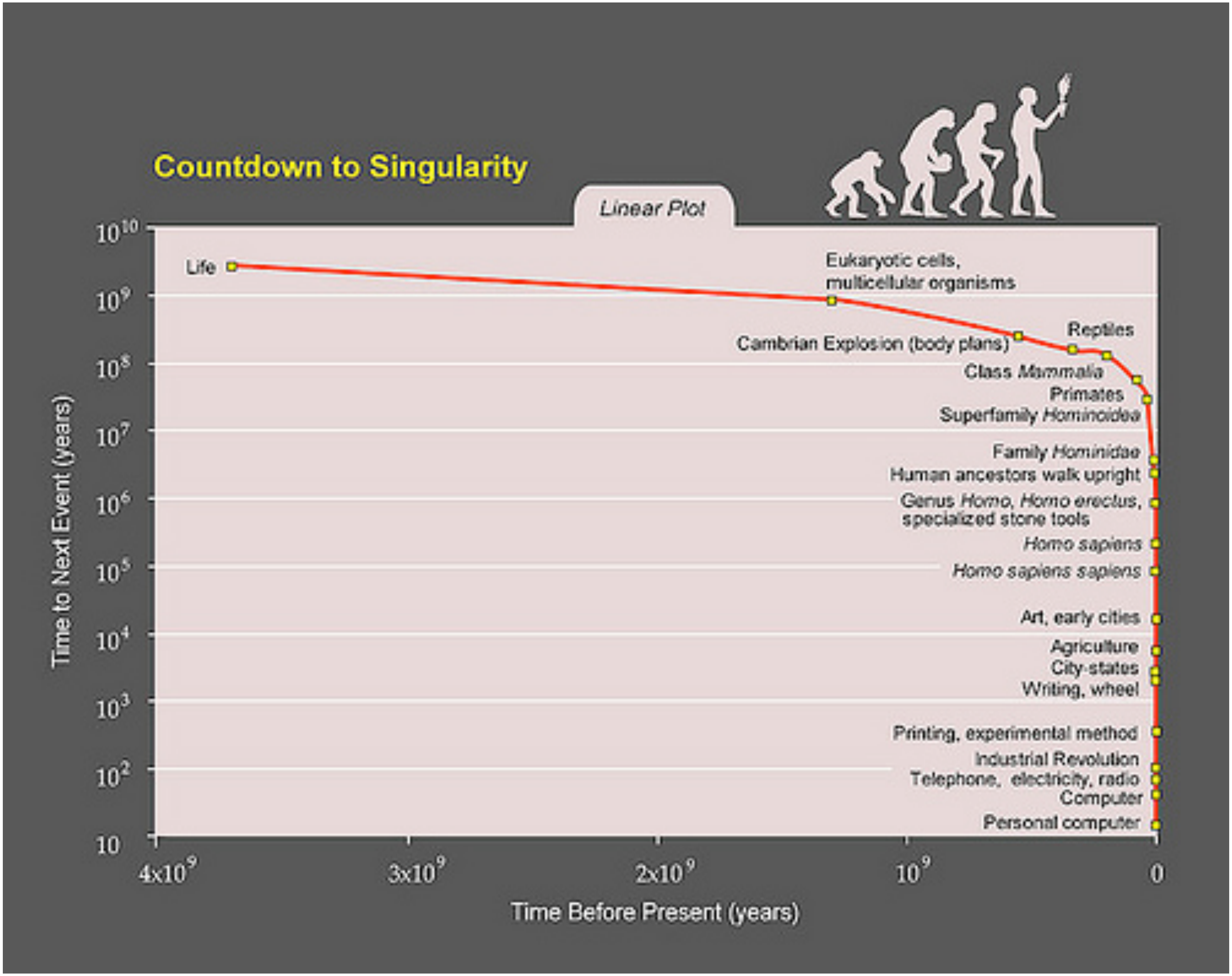
Social Corporate Urban

- *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

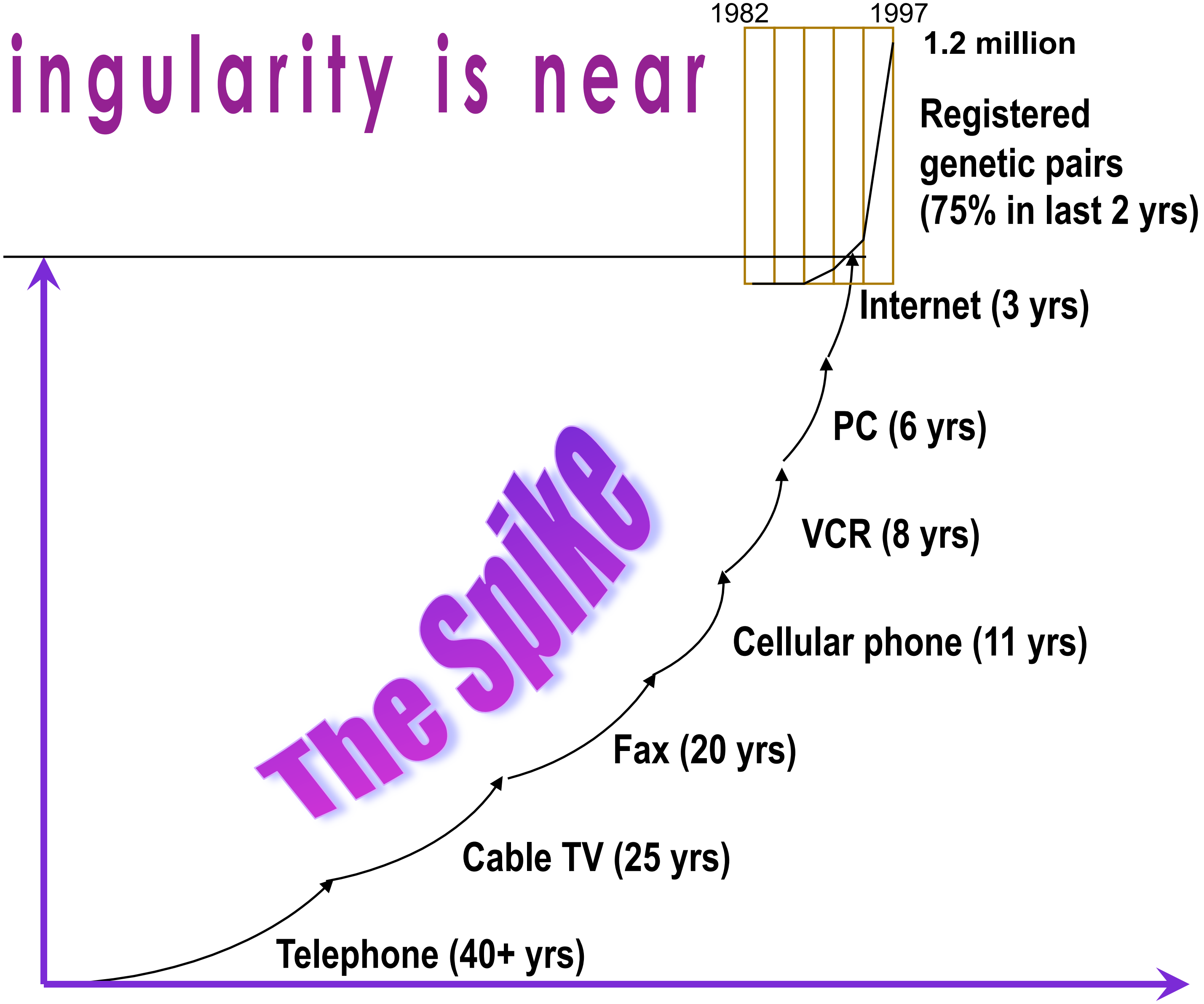
Singularity is technological change so rapid and so profound that is represents a rupture in the fabric of human history




Countdown to Singularity
Linear Plot
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
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

Singularity is near

Damien Broderick



1982

1997

1.2 million

Registered genetic pairs (75% in last 2 yrs)

Internet (3 yrs)

PC (6 yrs)

VCR (8 yrs)

Cellular phone (11 yrs)

Fax (20 yrs)

Cable TV (25 yrs)

Telephone (40+ yrs)

The Spike

Years to reach 10 million customers (US)

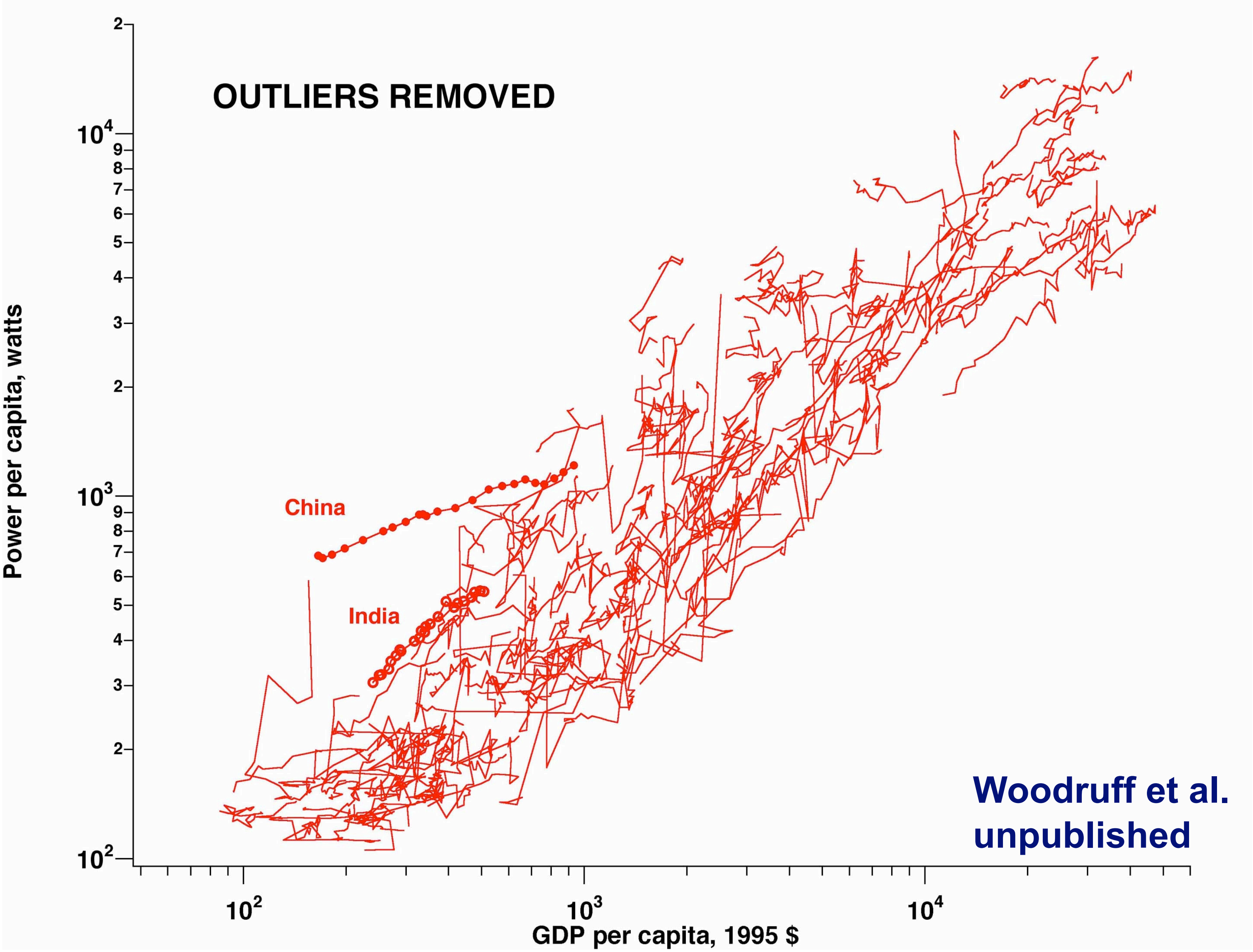
Time

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

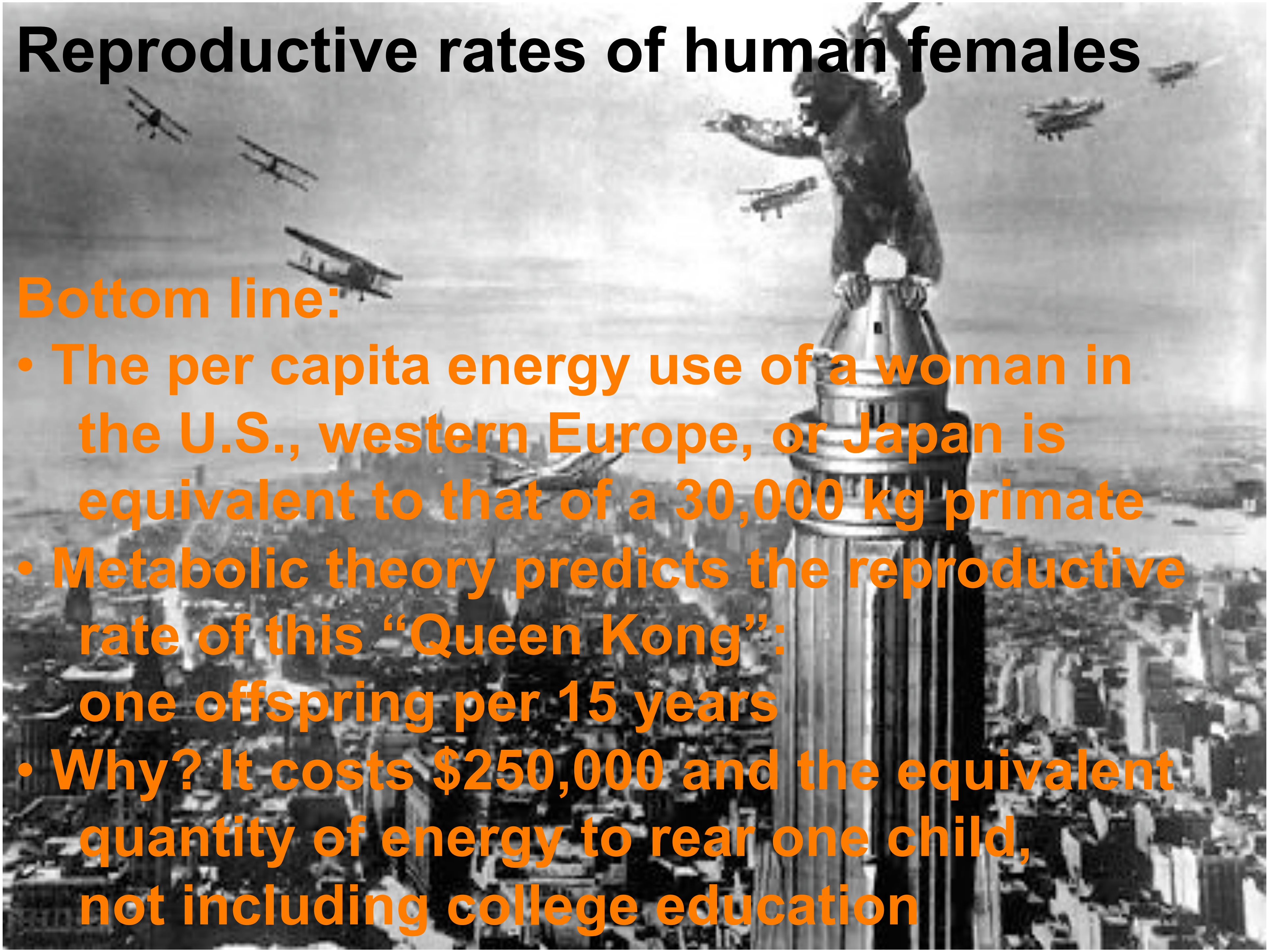
  from 300 watts in developing nations

  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

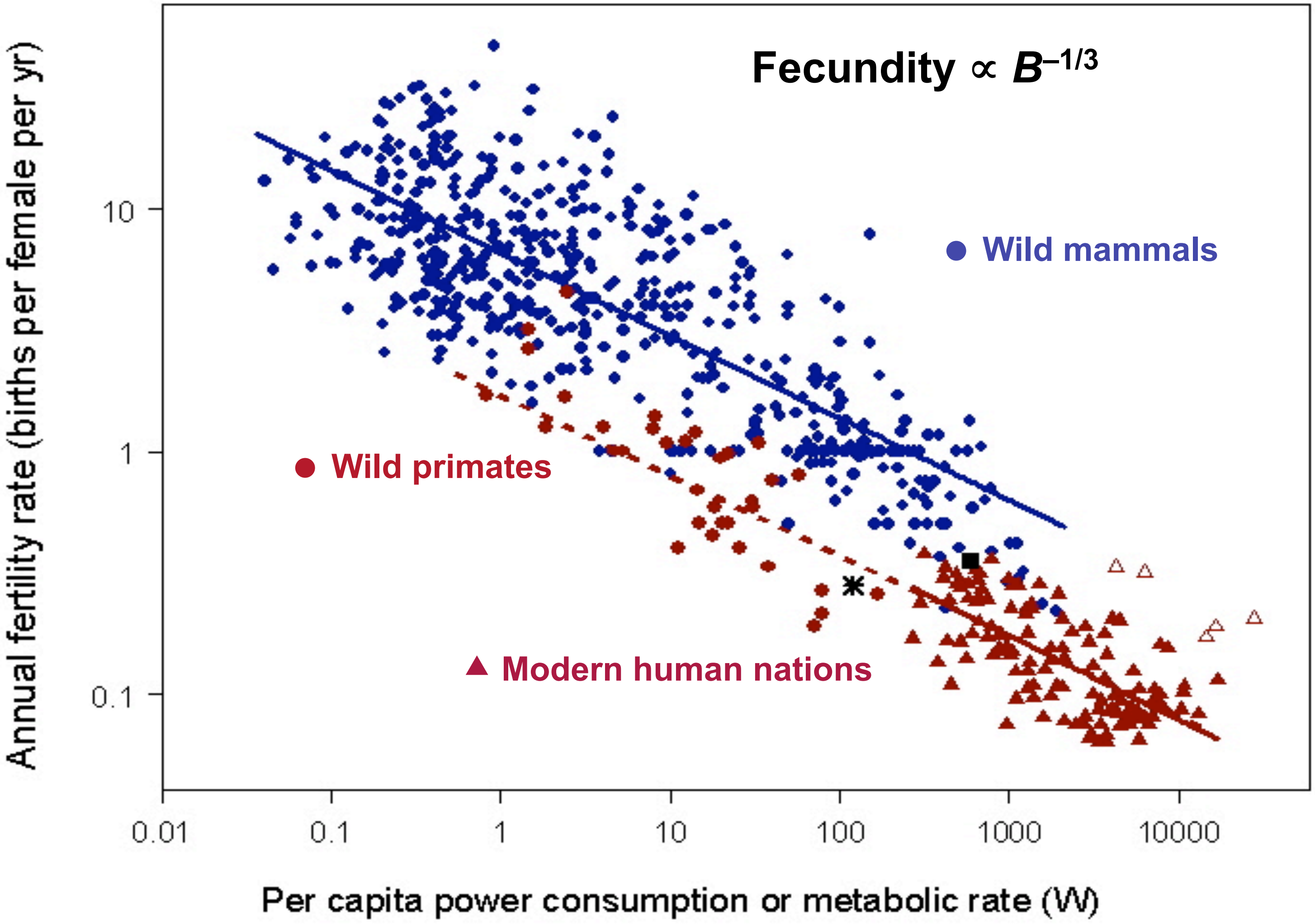


Bottom line:

- 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

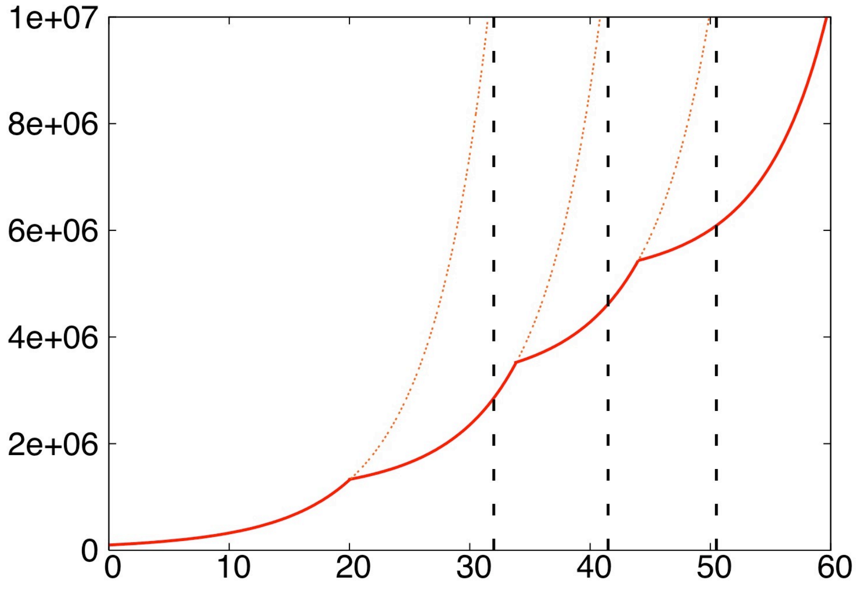
Reproductive rates of mammals, primates, and humans

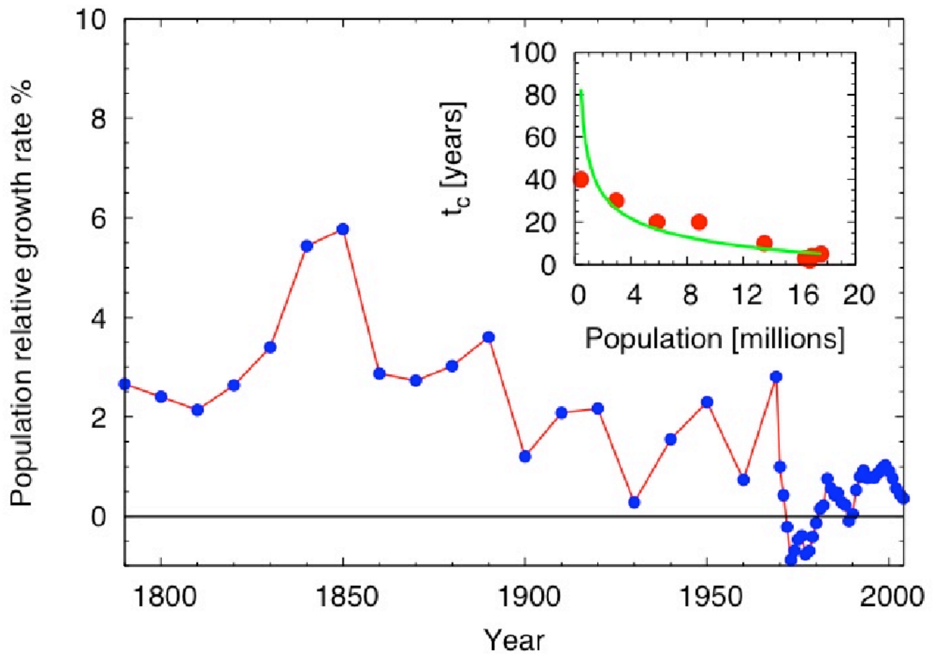
Moses and Brown 2002



Escaping the singularity with β>1:

cycles of successive growth & innovation

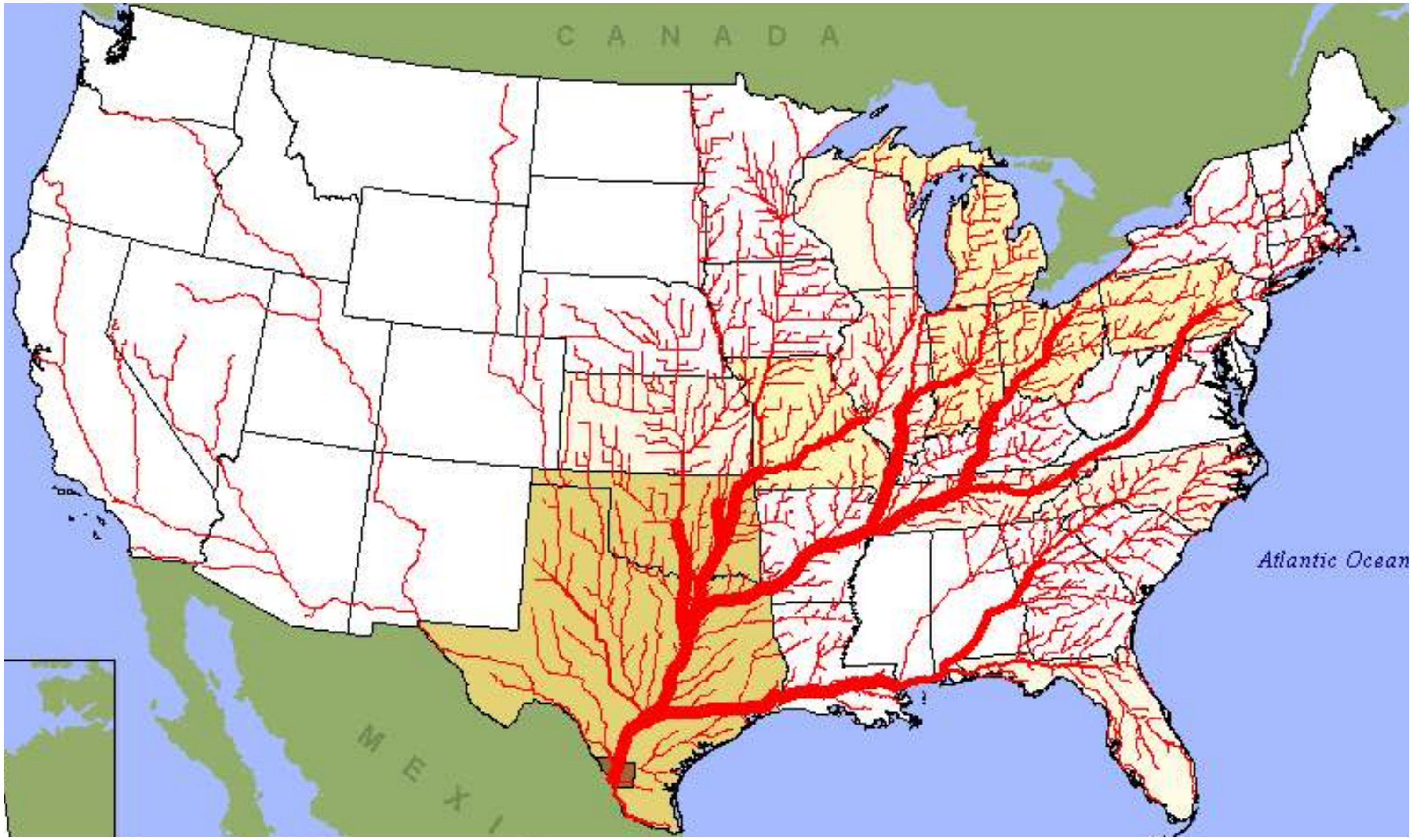




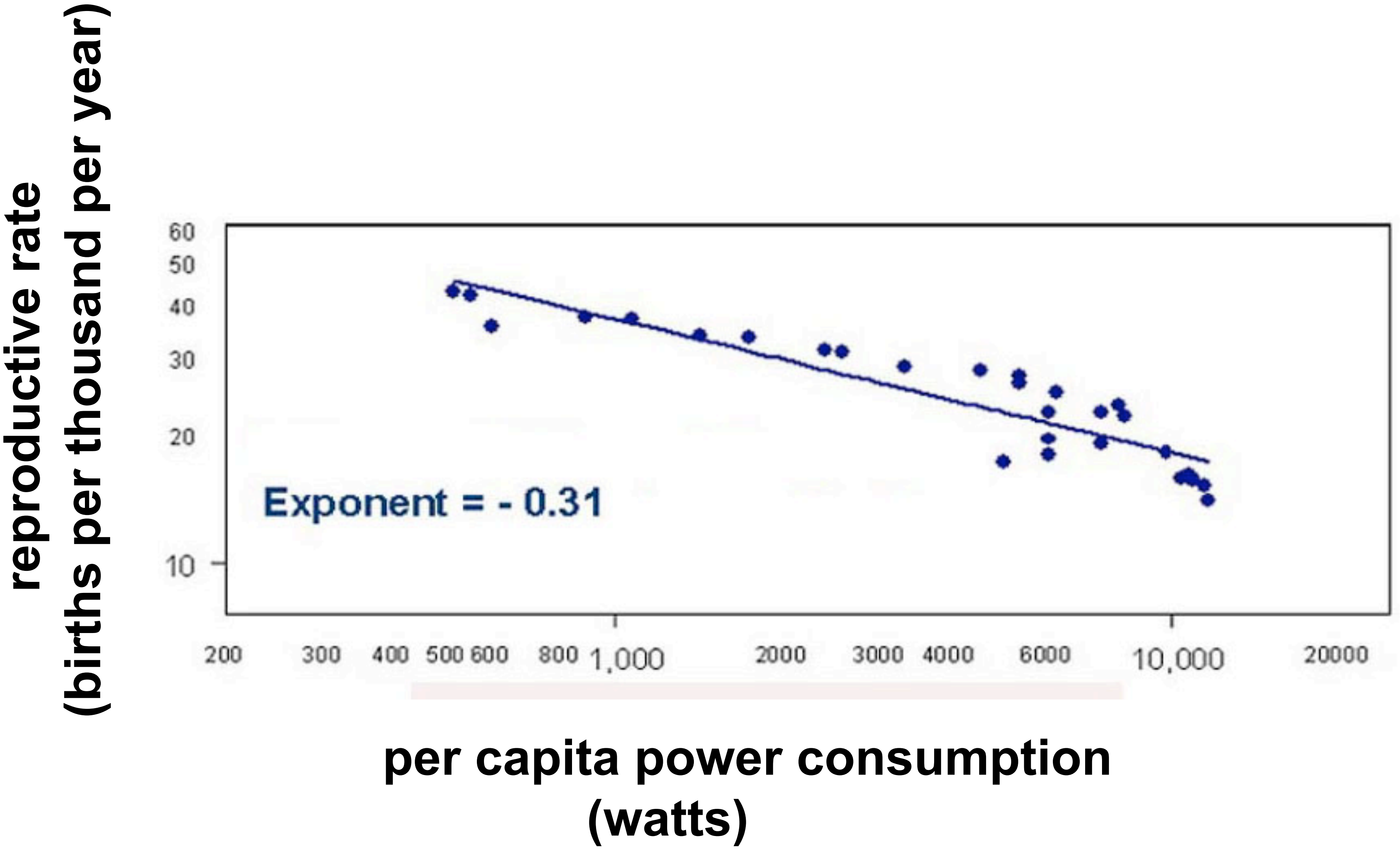
$$t_{crit} \approx \frac{E_0}{(\beta - 1)R_a} N^{1-\beta}(0) \cong 50 \frac{T}{n^{\beta-1}} \, years.$$

→ 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

Energy, Urbanization and Sustainability; Lessons from Biology

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Energy, Sustainability and the Underlying Threat of Urbanization

SIZE MATTERS

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