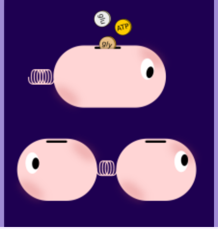

Scaling Laws in Cell Evolution

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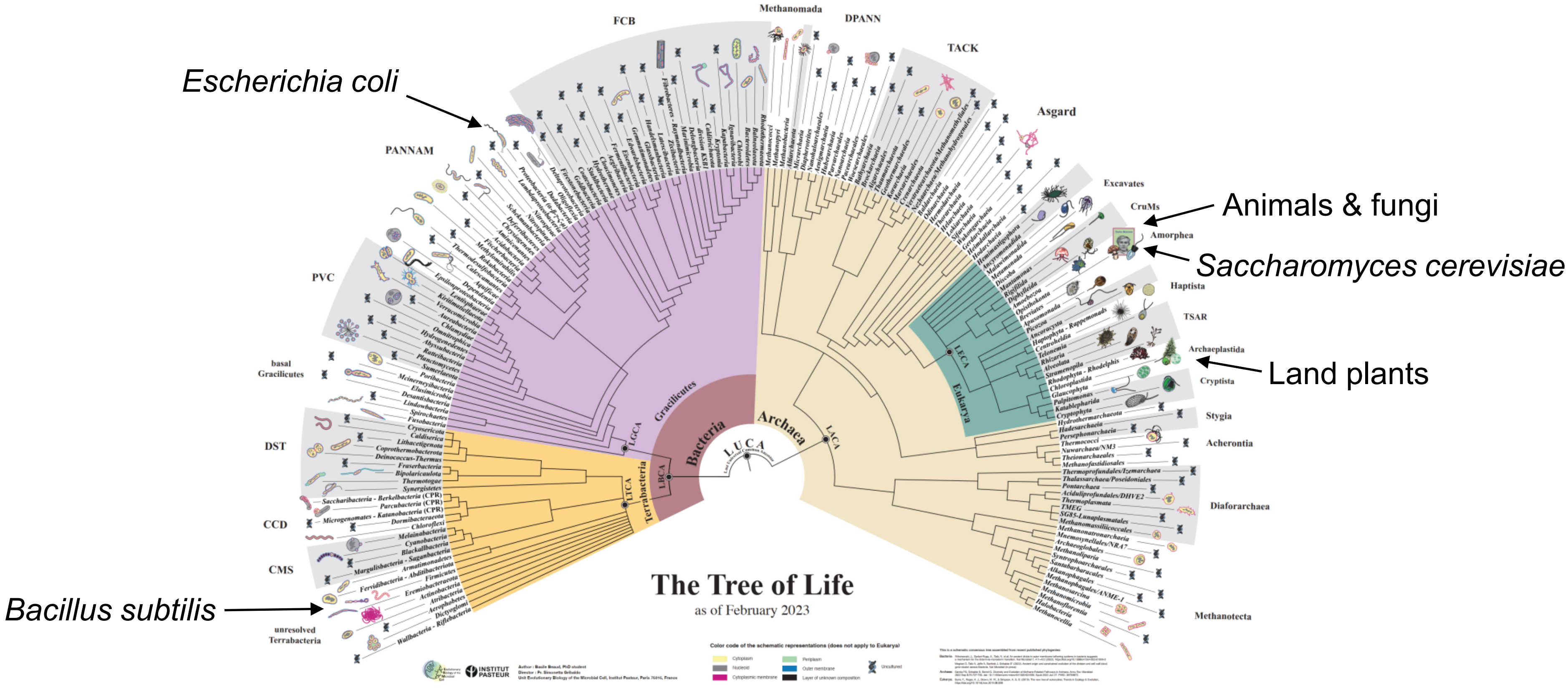
Contents

Goal: To showcase how major cellular features scale with size across cells

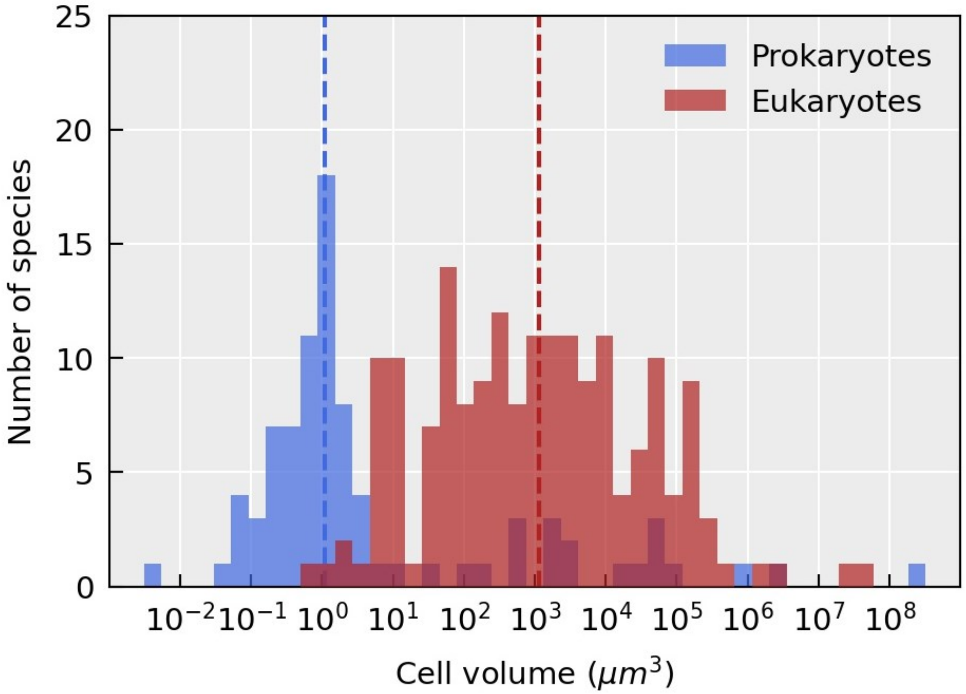
The tree of life



Phylogenetic diversity

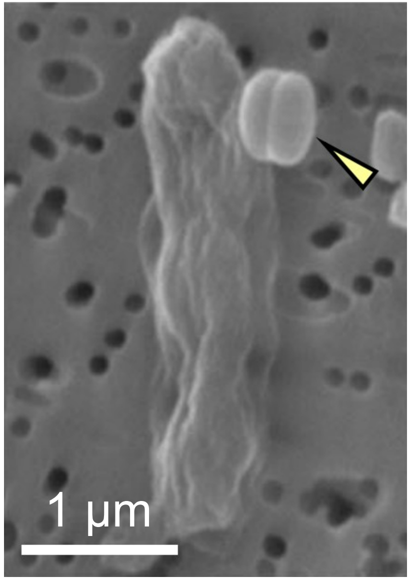
Cell volume

$\approx 1\ \mu m^3$ $\approx 1{,}000\ \mu m^3$

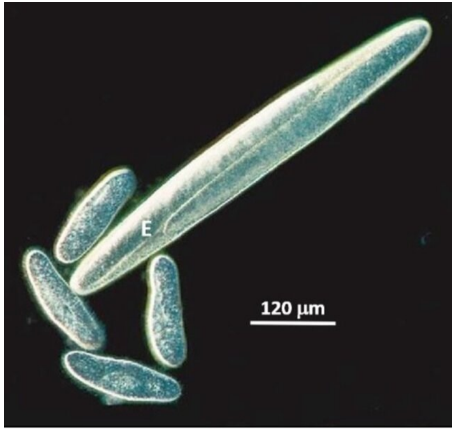


Phylogenetic diversity

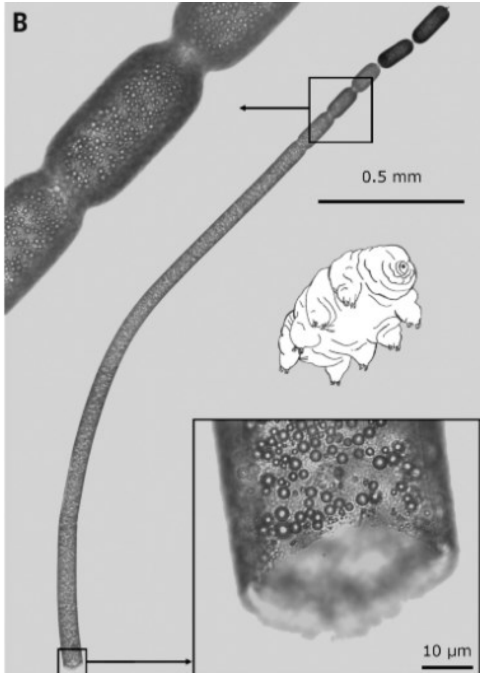
Prokaryotes



Vampirococcus sp.



Epulopiscium sp.

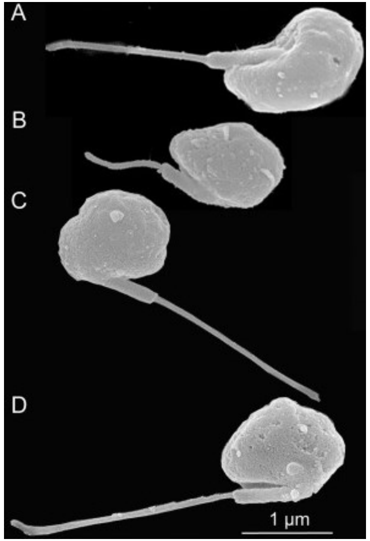


Ca. Thiomargarita magnifica

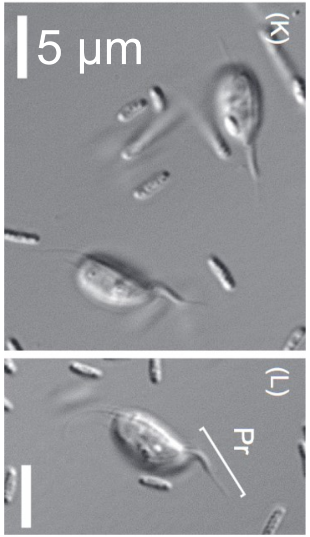
Stigonema spp.

Phylogenetic diversity

Eukaryotes



Micromonas spp.



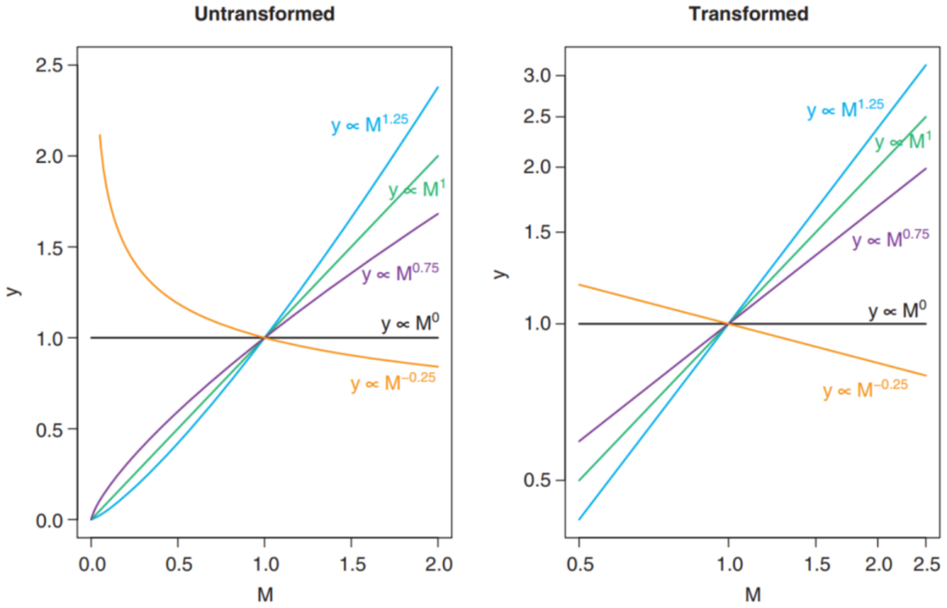
Apusomonads

Acetabularia sp.

Gromia sp.

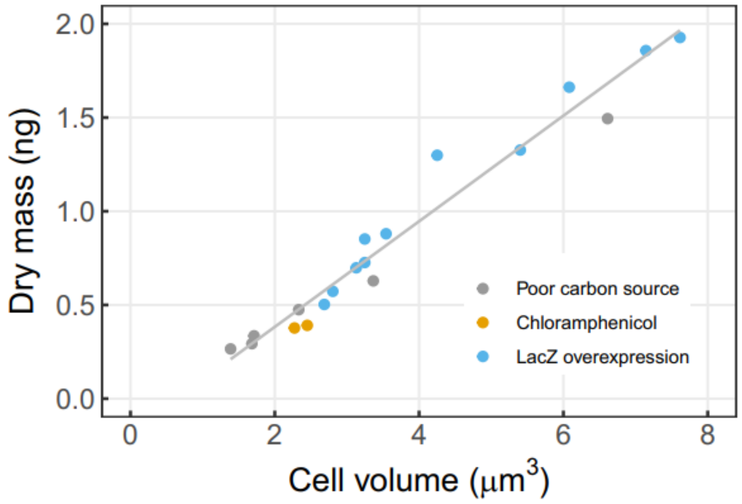
Power-law relationships

$$y = c \cdot M^{\alpha}$$
$$\log(y) = \alpha \cdot \log(M) + \log(c)$$
$$y = mx + b$$

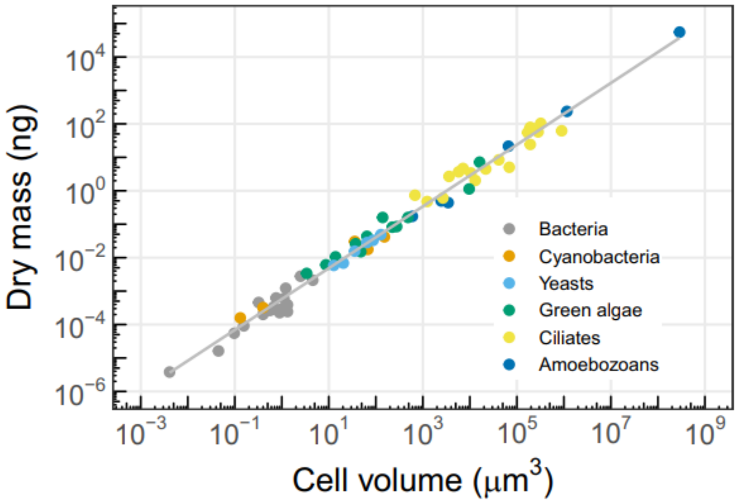


Developmental & evolutionary scaling laws

Within species

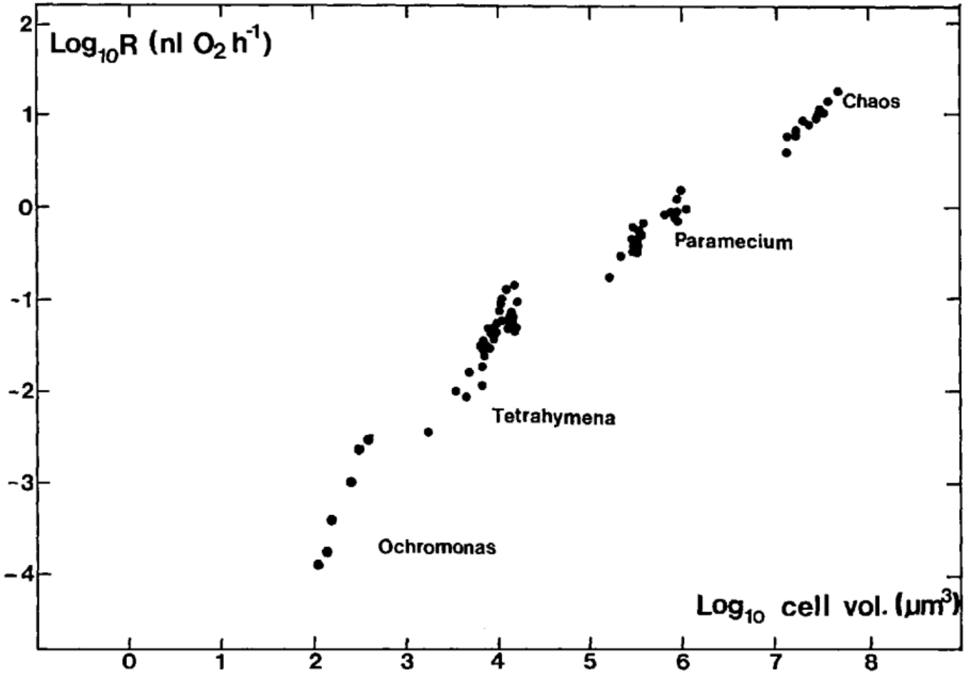


Across species



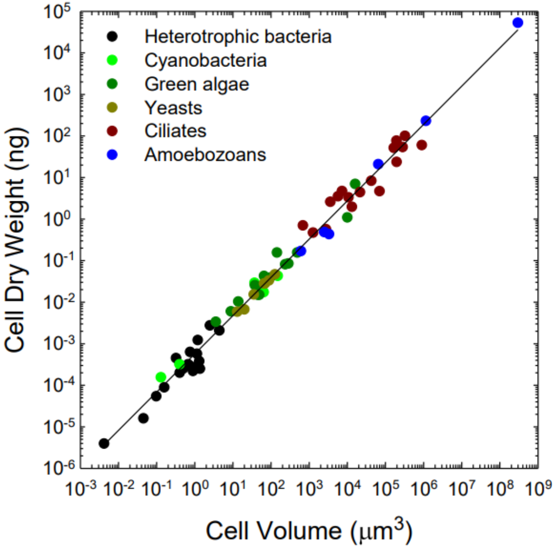
Developmental & evolutionary scaling laws

How do they relate to each other?

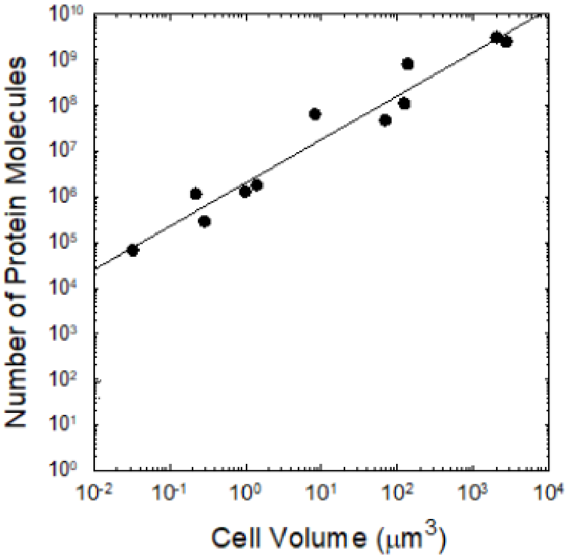


Cell density

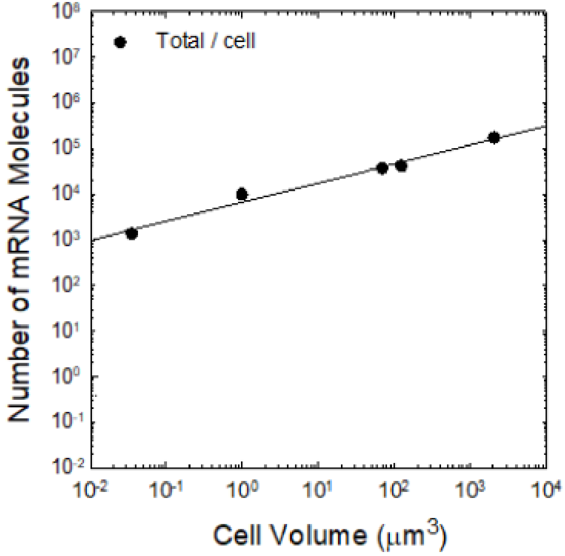
$$M = 0.00057 \cdot V^{0.92}$$



$$N_{tot,p} = (2.0 \times 10^6) \cdot V^{0.95}$$

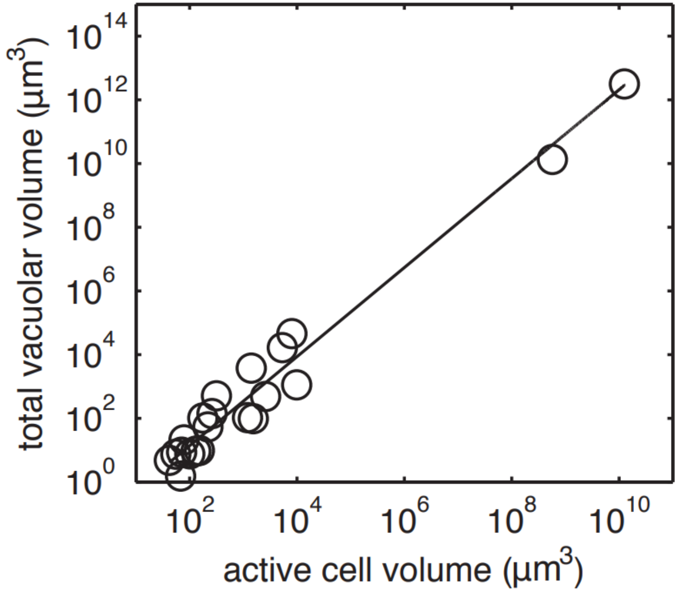


$$N_{tot,mRNA} = 6760 \cdot V^{0.42}$$



Cell density

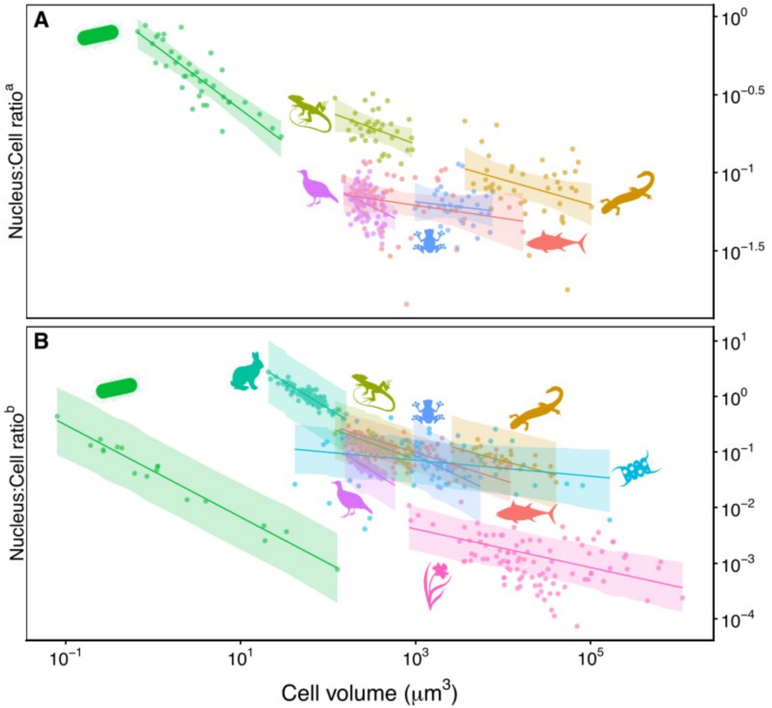
$$V_v = 8.36 \cdot V_a^{1.4}$$

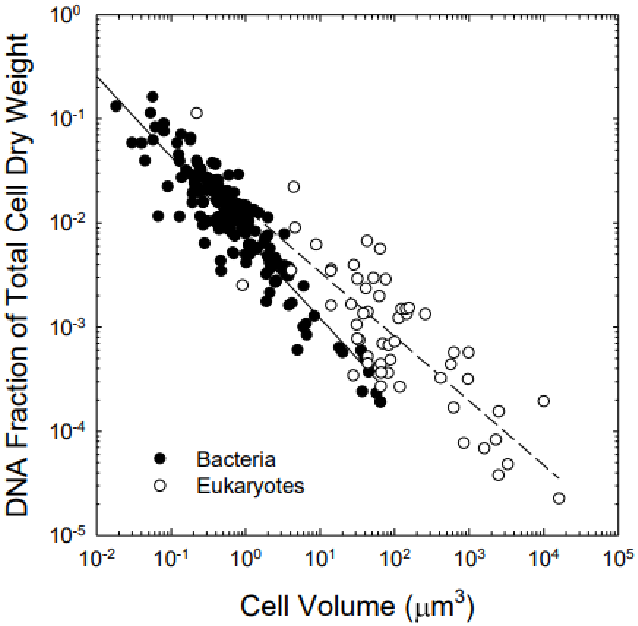


Nucleoid and nucleus size, and DNA fraction

$N{:}C \propto V^{-0.3}$

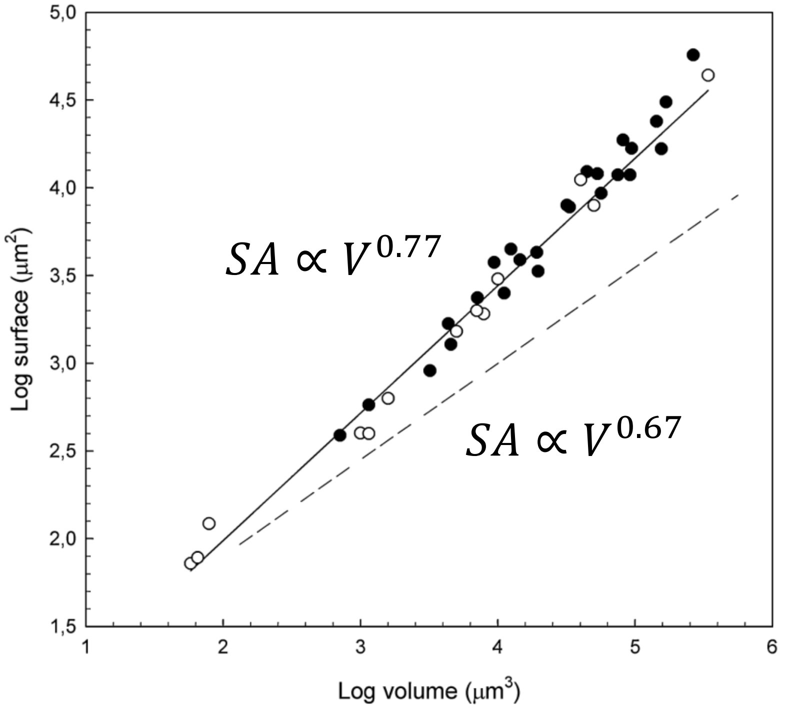
$$f_{DNA,prok} = 0.0072 \cdot V^{-0.77}$$
$$f_{DNA,euk} = 0.014 \cdot V^{-0.62}$$





Cell shape

Shape-shifting



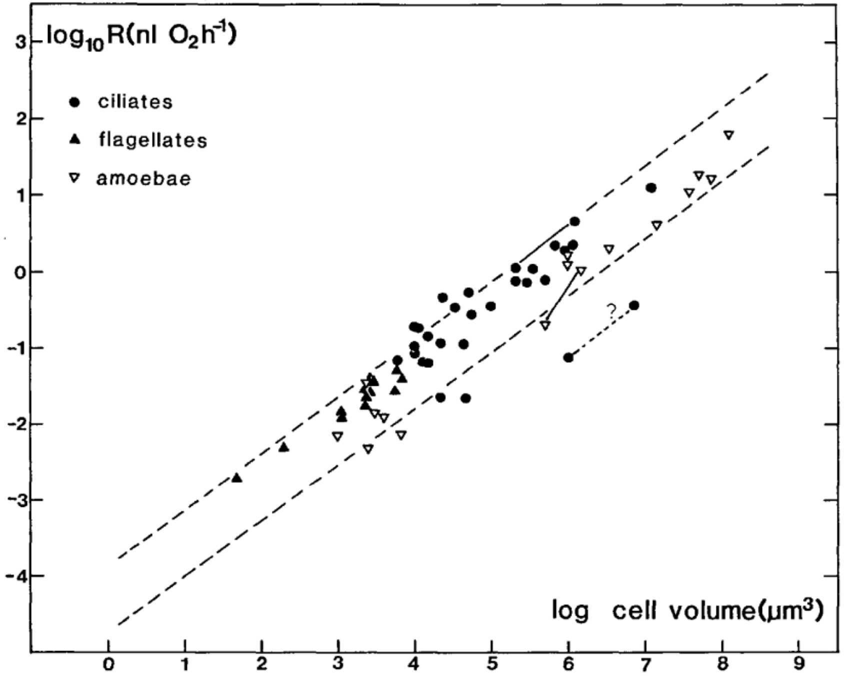
Metabolic rate

- "Pace (or speed) of living and interacting with the environment"
- The rate at which energy and matter are transformed within a cell
- Energy consumed or produced per unit of time
  - Joules per time (seconds or hours)
  - nL O_2 per time
  - ATP hydrolyses per time
- Controversy on the scaling exponent with body mass/volume

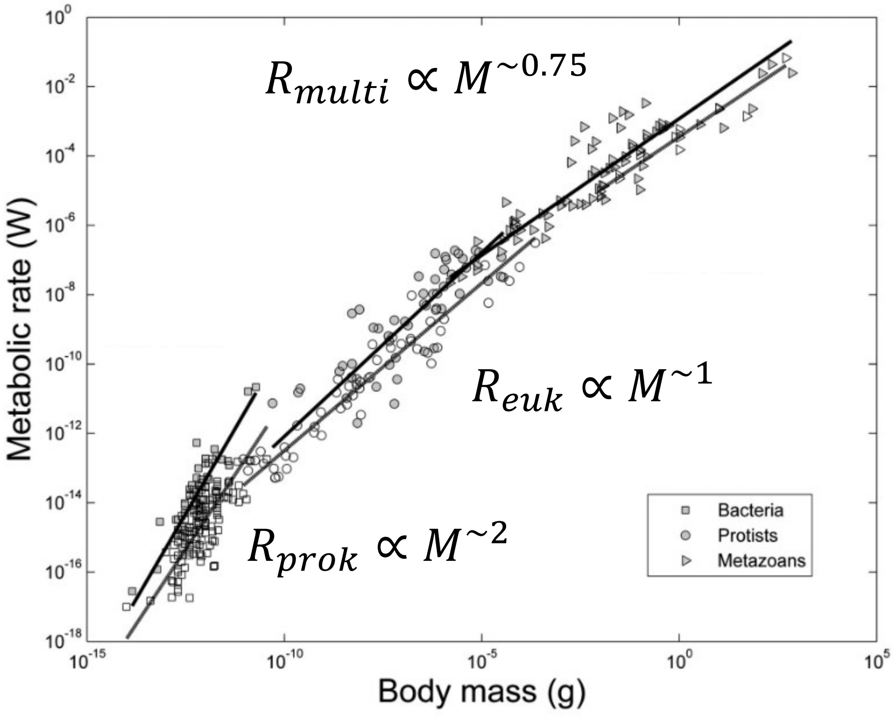
Metabolic rate

Fenchel & Finlay

$$R = 0.123 \cdot V^{0.75}$$



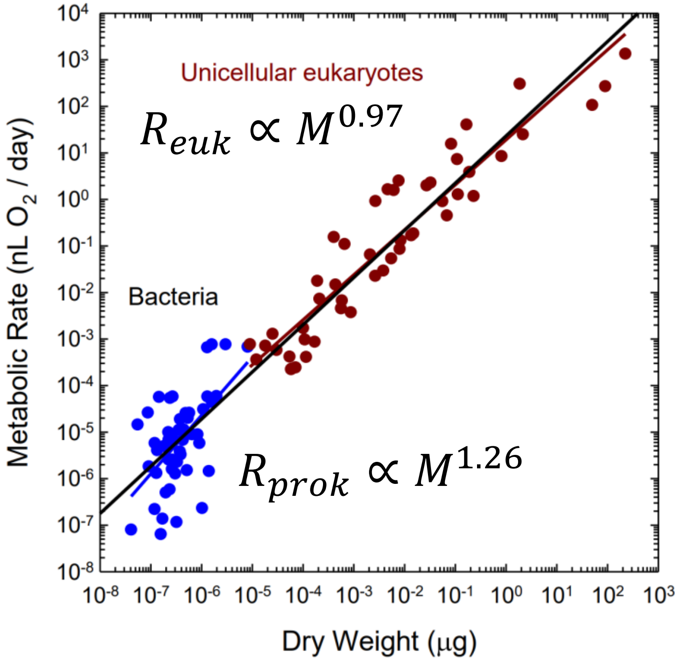
Metabolic rate
DeLong *et al*.



Metabolic rate

Lynch

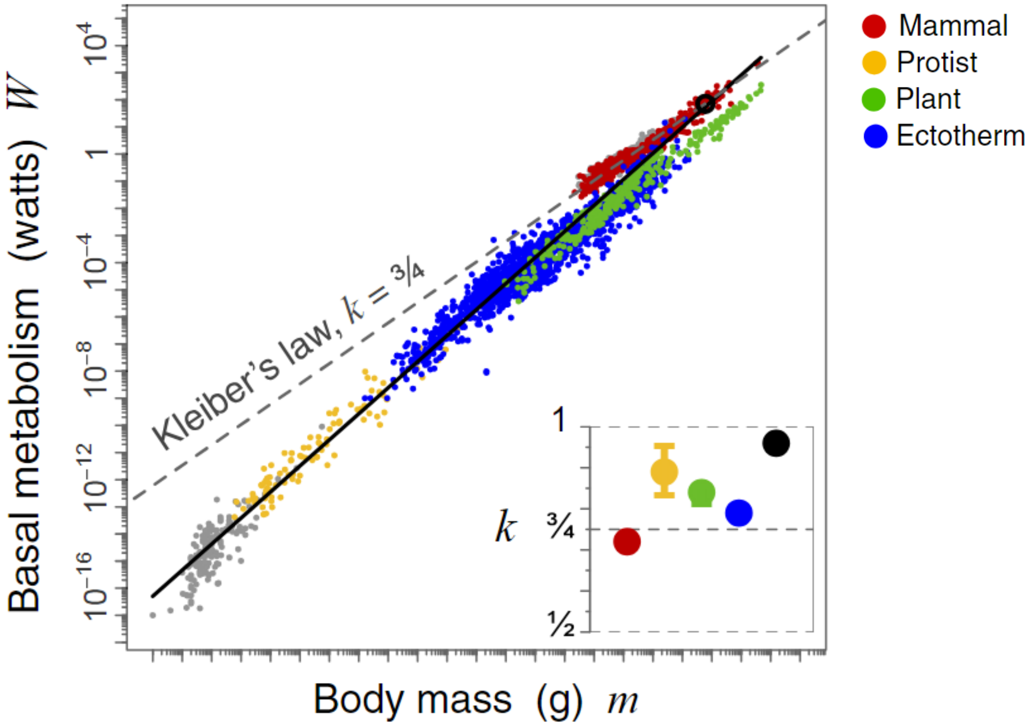
$$R = 23.3 \cdot M^{1.01}$$



Metabolic rate

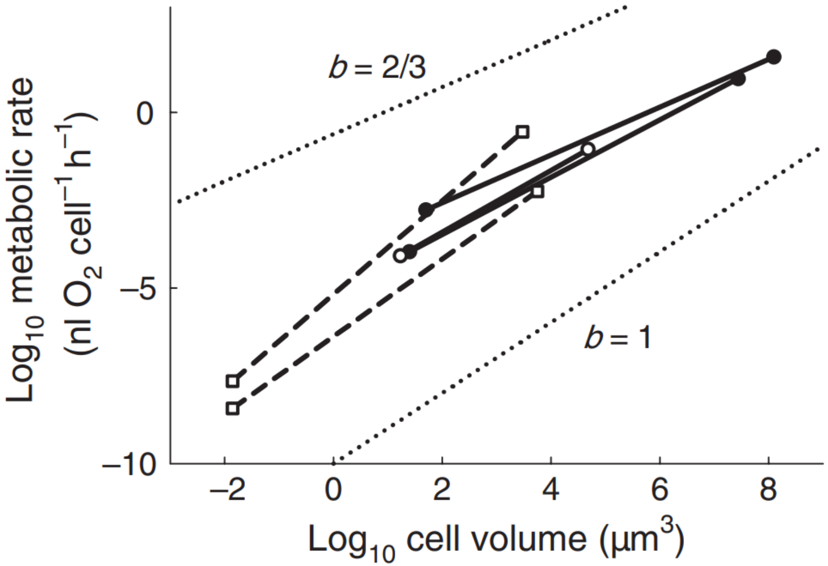
Hatton *et al*.

$$R = 0.001 \cdot M^{0.96}$$

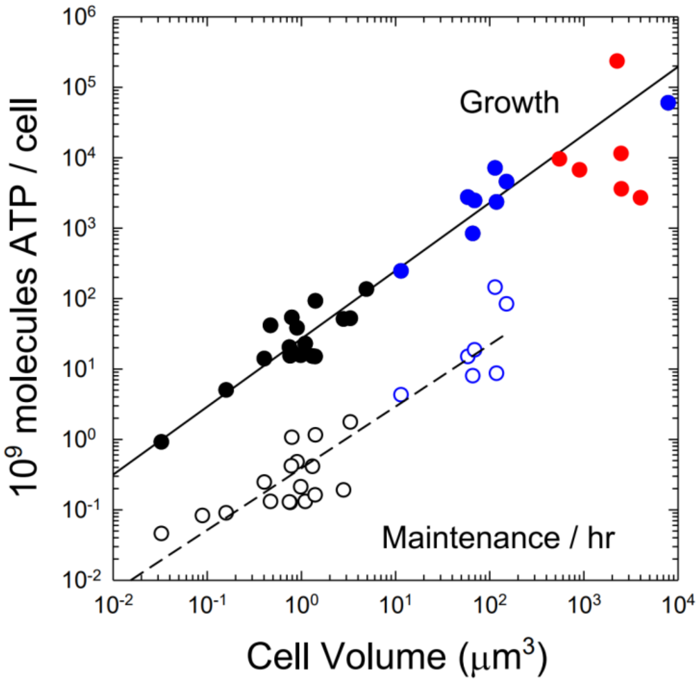


Metabolic rate

Glazier



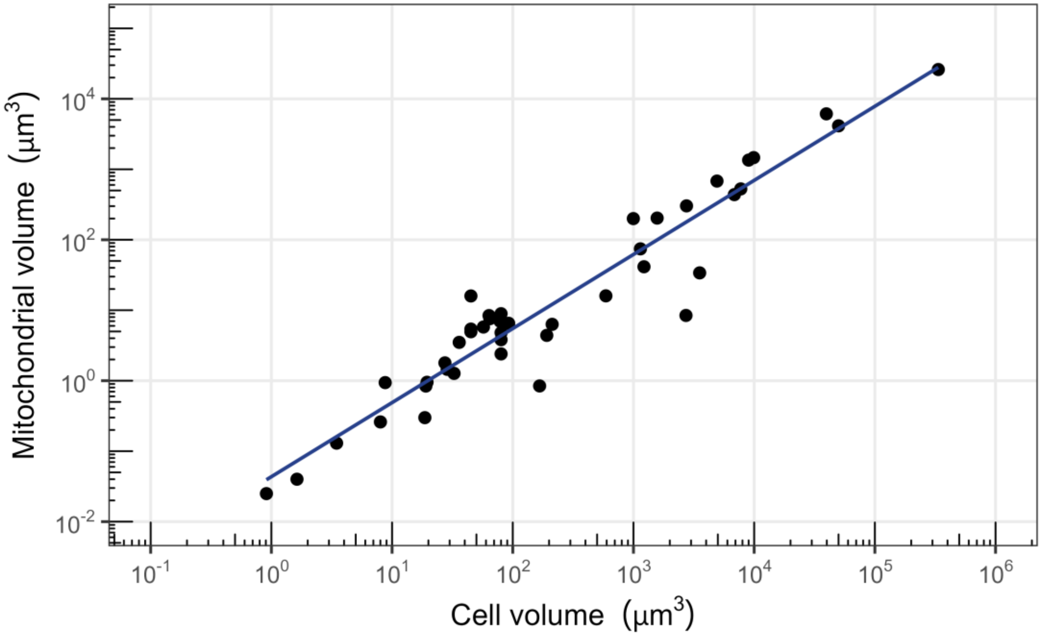
Lifetime ATP requirements



$$C_g = 26.9 \cdot V^{0.96}$$
$$C_m = 0.39 \cdot V^{0.88}$$
$$C_T \cong C_g + C_m \cdot t_d$$

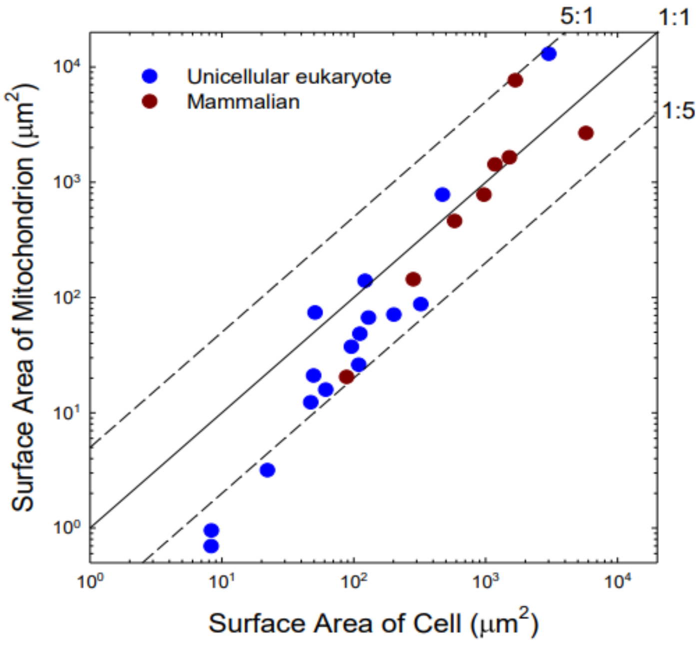
Mitochondrial volume

$$V_{mt} \propto \sim 0.1 \cdot V^{\approx 1.0}$$

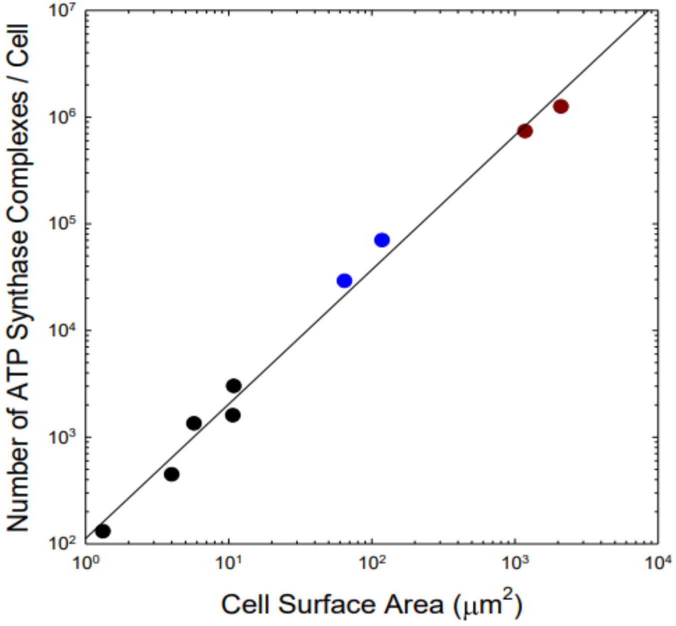


Mitochondrial membranes and ATP synthases

$$N_{MOM} = 0.4 \cdot SA^{1.30}$$



$$N_{F1FO} = 113 \cdot SA^{1.31}$$

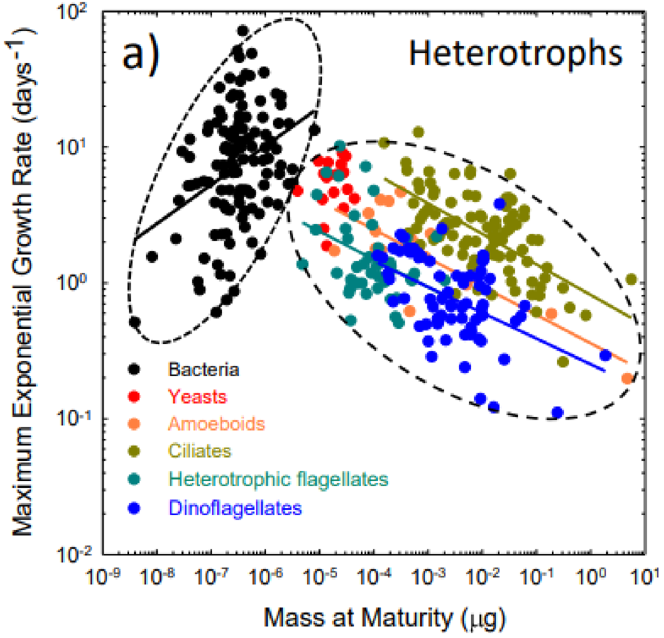


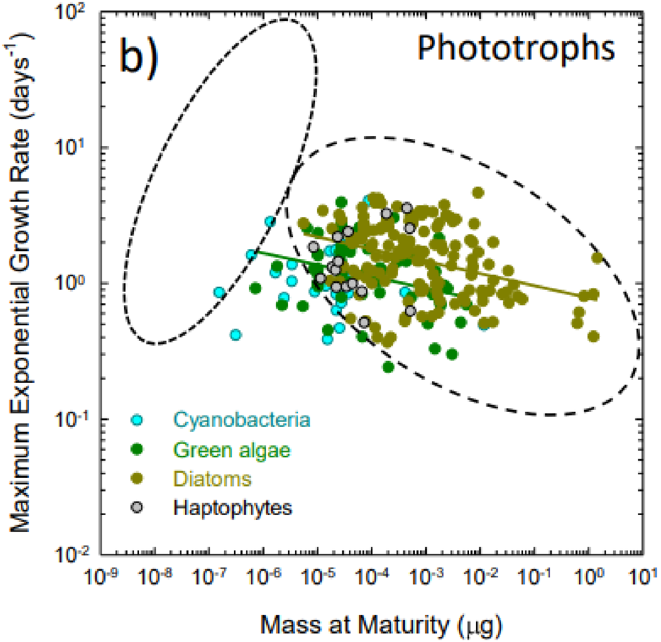
Growth rate

$$\mu_{max,prok} \propto V^{\sim 0.28}$$

$$\mu_{max,euk} \propto V^{\sim -0.2}$$

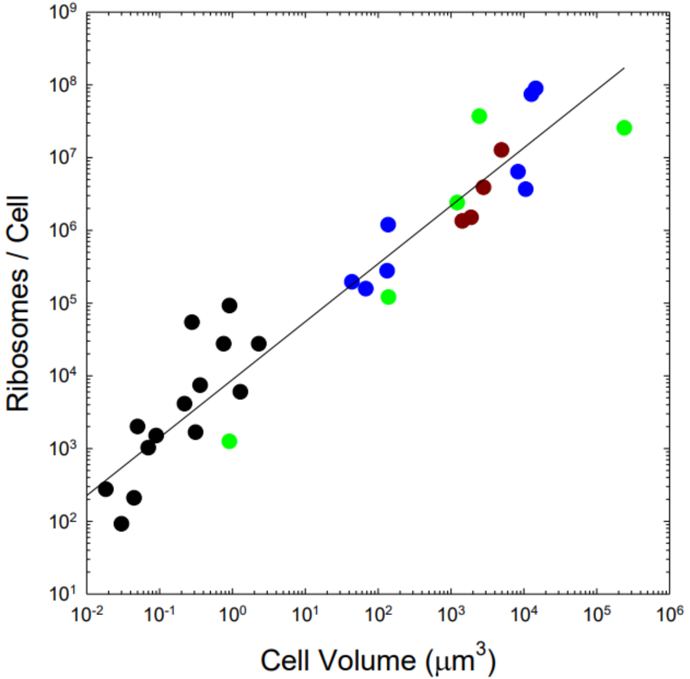
$$\mu_{max,photo} \propto V^{\sim -0.09}$$





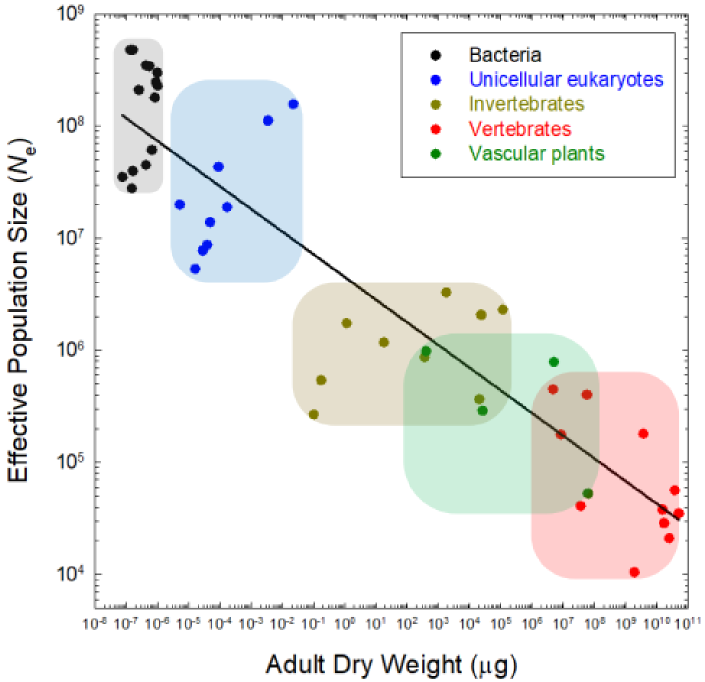
Biosynthetic capacity

$$N_{ribo} = 8810 \cdot V^{0.8}$$



Effective population size

$$N_e \propto M^{\sim -0.2}$$



Summary

- Cells become less dense as they increase in size in evolution
- Cells evolve adaptations to overcome biophysical and physiological constraints
- Evolutionary innovations can alter scaling relationships
- Energetic features scale linearly but biosynthetic capabilities scale sublinearly with cell size
- Size is a major factor in cell evolution
- The efficiency of natural selection decreases as cells get larger

Open questions

- What are the causes of the scaling laws?
- How do they emerge from developmental scaling laws?
- How do evolutionary and developmental scaling laws interact with each other?
- Are scaling laws the result of biophysical constraints?
- Are scaling laws the outcome of optimal adaptive strategies?