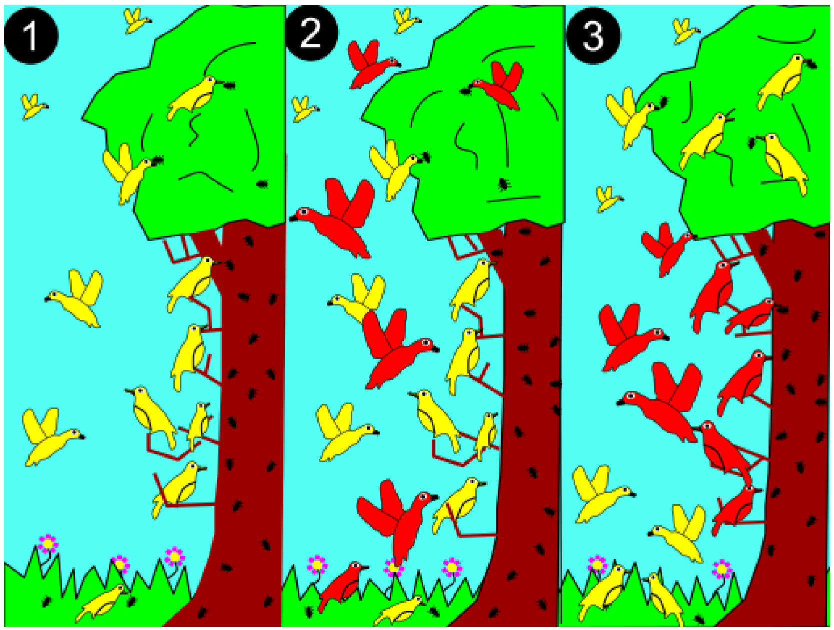
Revisiting community ecology in the age of microbes: What can statistical physics contribute?



BOSTON UNIVERSITY

Pankaj Mehta

Collaborators: Nanxi Lu, Alvaro Sanchez, Josh Goldford, Madhu Advani, Guy Bunin
Kirill Korolev, Daniel Segré

Statistical physics + community ecology

Ecology+ Statistical Physics of Disordered systems

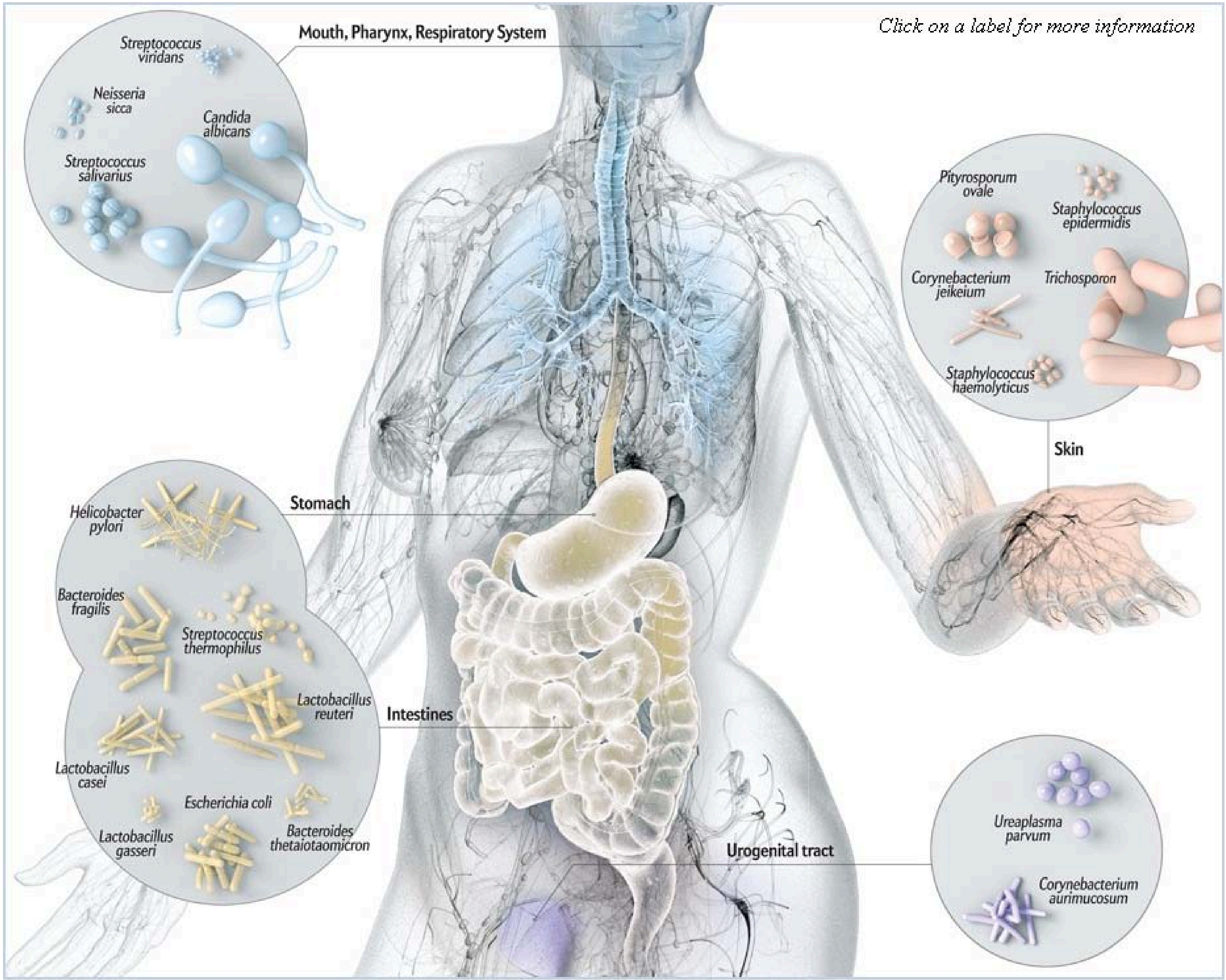
Fisher + Mehta PNAS 2014
Fisher+Mehta PLoS One 2014
Dickens+Fisher+Mehta PRE 2016
Tikhonov Elife 2016
Tikhonov +Monasson PRL 2016
Bunin PRE 2016
Kessler +Shnerb PRE 2015
Posfai+Wingreen PRL 2017

Neutral theory:

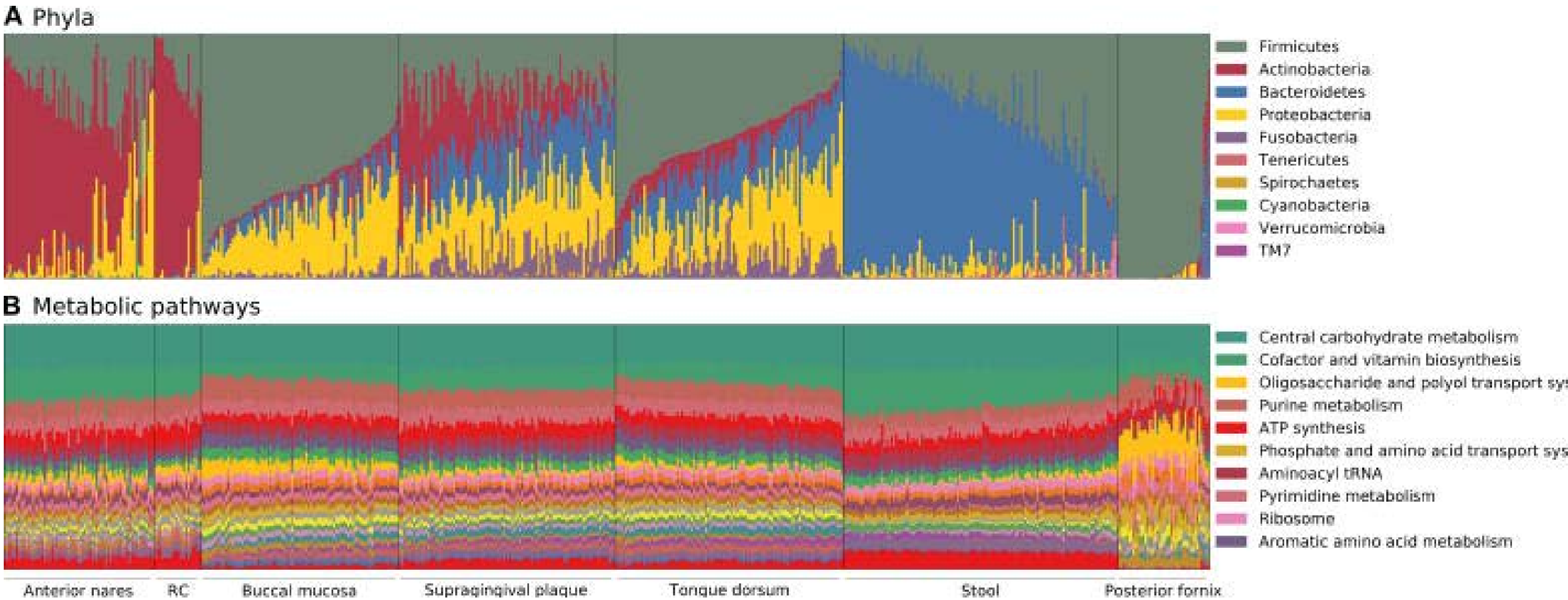
See review Azaele *et al.* Rev Mod Physics 88 (2016)
Shnerb group (Israel)
Volkov group (MD)
Maritan group (Padova, Italy)

Microbial communities are diverse

Scientific American

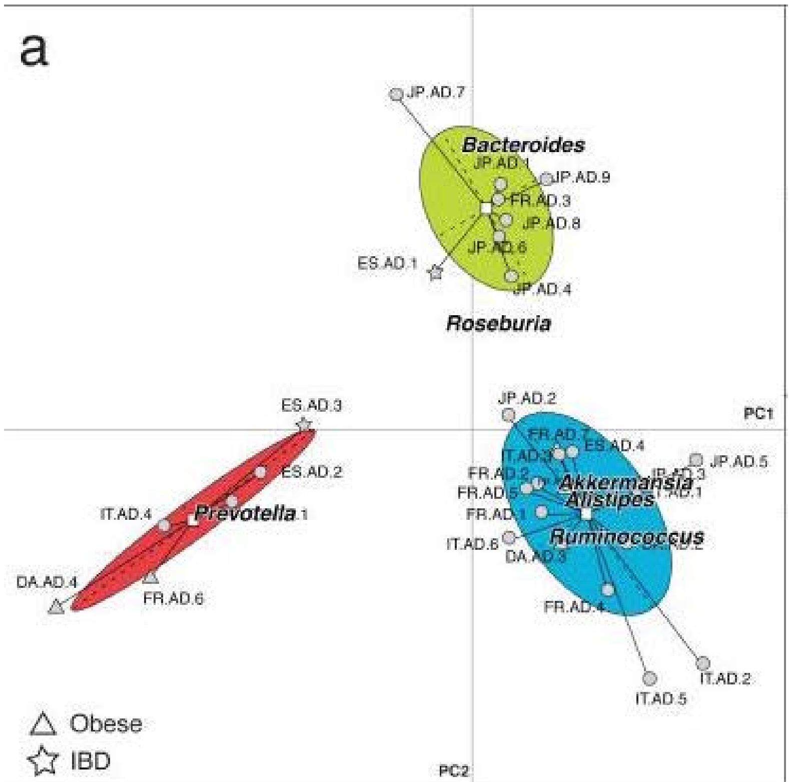


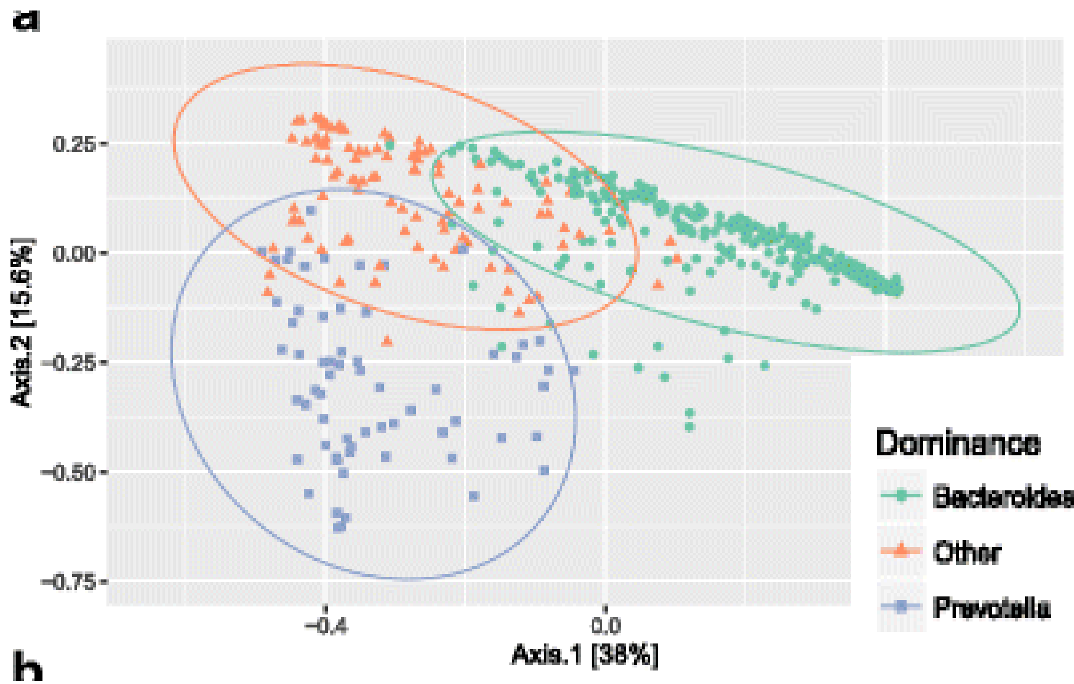
Functional Convergence



Human Microbiome Project (Nature 2011)

“Clustering
based on dominant family



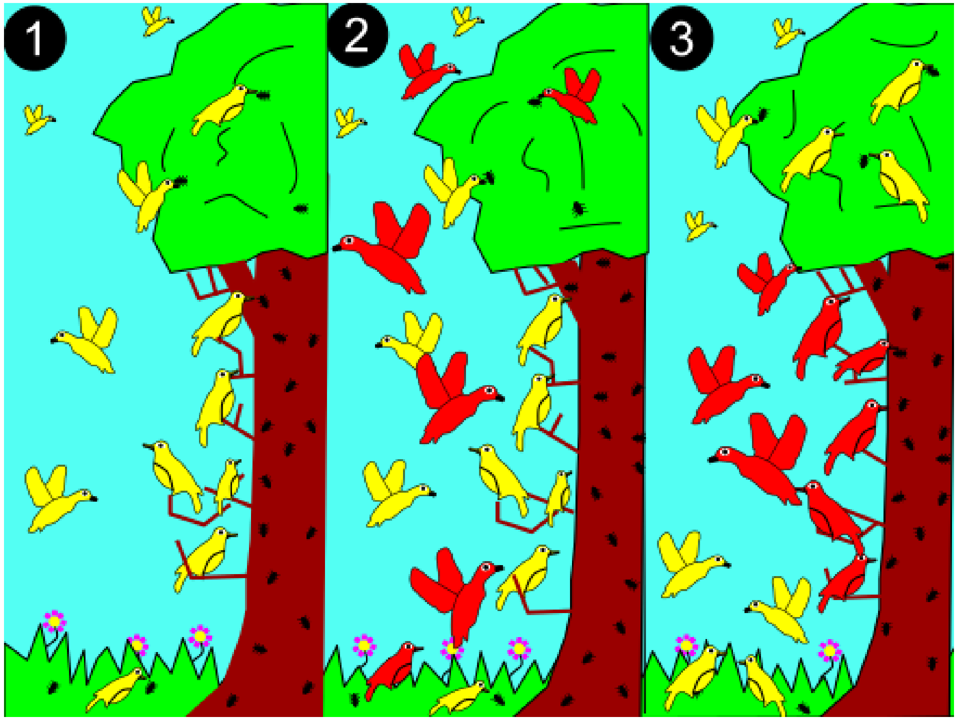


Nature 473, 174–180 (12 May 2011)

A Gorvitovskaia et al Microbiome 2016

How can we understand this mix between diversity and simplicity?

Niche-based Theories

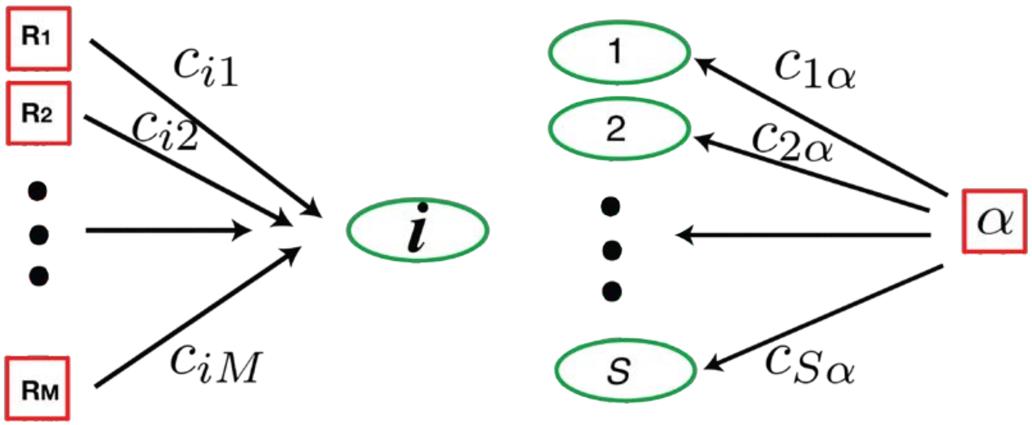


Niche theory- "Theory of competitive exclusion"; Tilmans R^* theory

Mathematics: Lotka –Volterra & MacArthur's consumer Resource model

Central intuition:
Number of species is strictly limited by number of limiting resources in environment

MacArthur Consumer Resource Model



Canonical model:

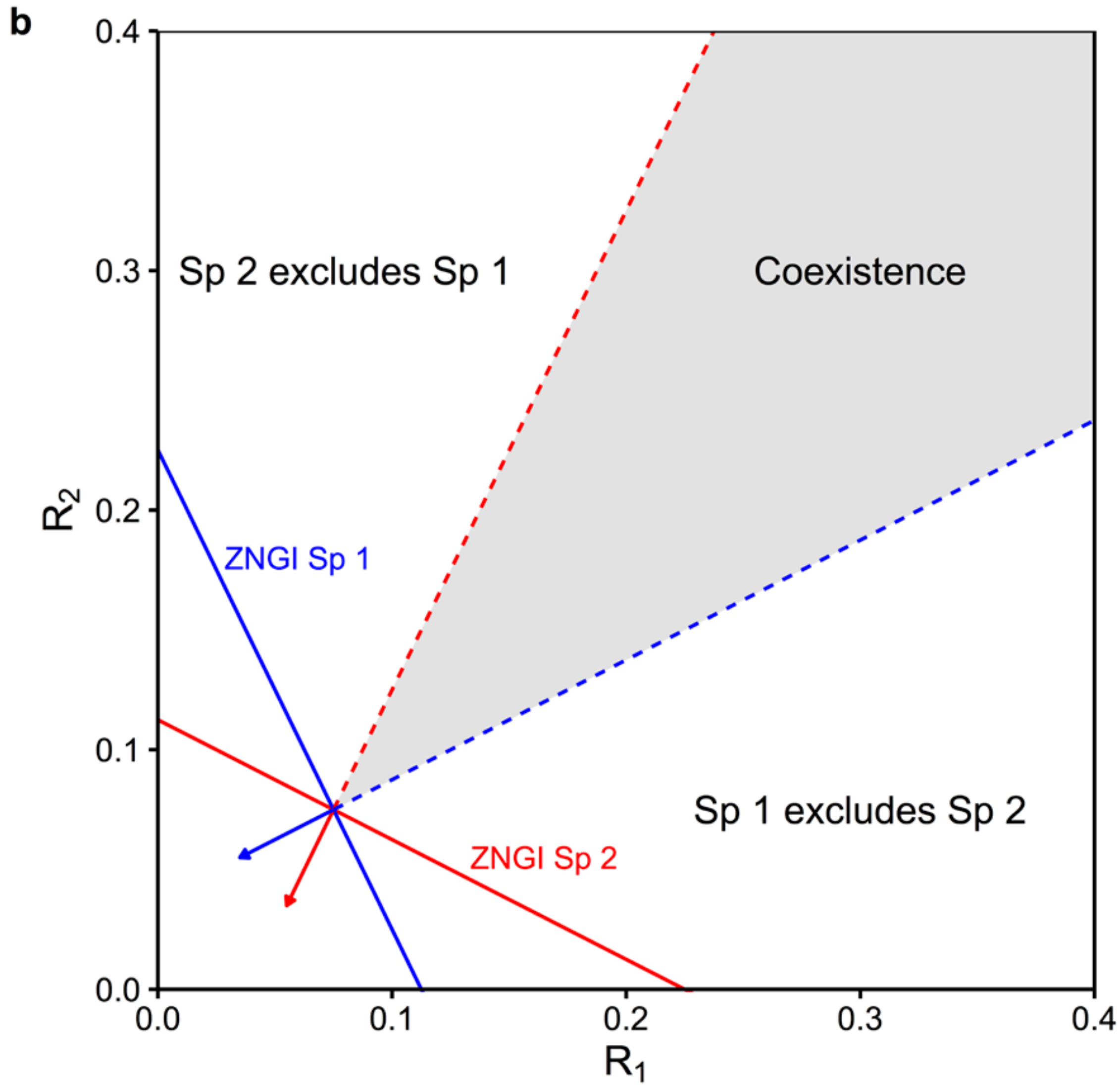
$$\frac{1}{N_i}\frac{dN_i}{dt} = b_i \sum_\alpha (w_\alpha c_{i\alpha} R_\alpha - m_i)$$

$$\frac{dR_\beta}{dt} = f_\beta(\mathbf{R}) - \sum_i c_{i\beta} R_\beta N_i$$

Fast dynamics: reduces to Lotka-Volterra equations

$$\frac{1}{N_i}\frac{dN_i}{dt} = K_i - N_i - \sum_j \alpha_{ij} N_j$$

Graphical intuitions from considering two species:



Letten, Ke, Fukami BioarXiv 2016

Each species must have its own “limiting resource” – (lowest R* wins)

Suggests we need complex environments for diversity

[SPACE, TIME, PREDATION, EVOLUTION, ETC….]

Limitations of Approaches

1. Not clear intuitions from few species scale up to complex ecosystems with many species --- emergence of new behaviors

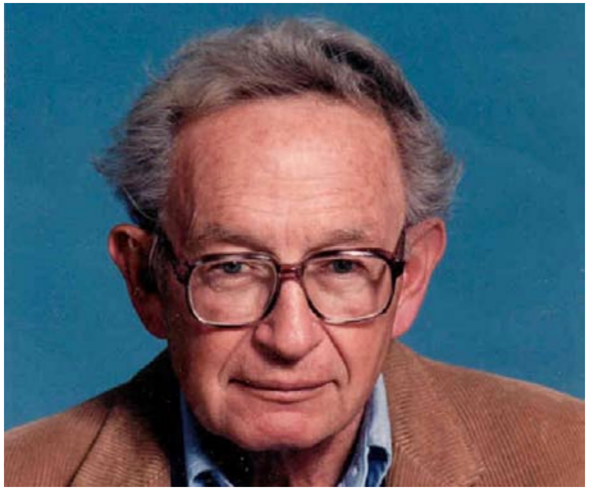
4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

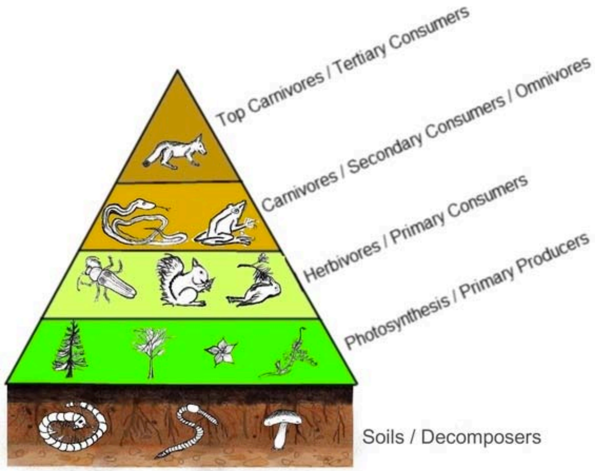


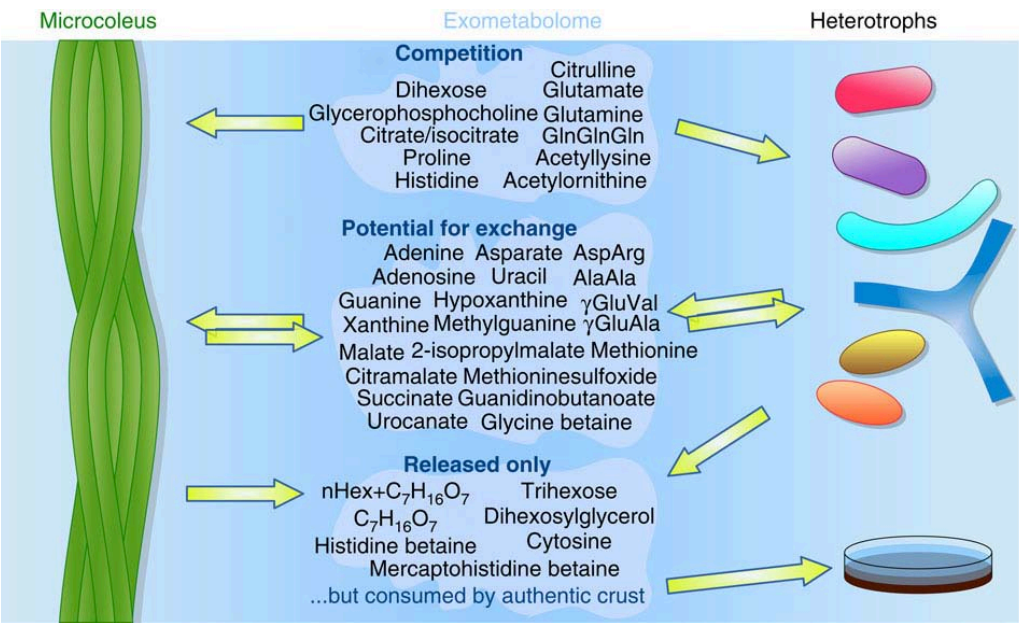
The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

PNAS 2014, PRE 2016, Arxiv 2017

Limitations of Approaches for Microbial Systems

2. Niche-based models assume trophic layer separation- no longer true in microbial world





Statistical physics of MacArthur Consumer Resource Model

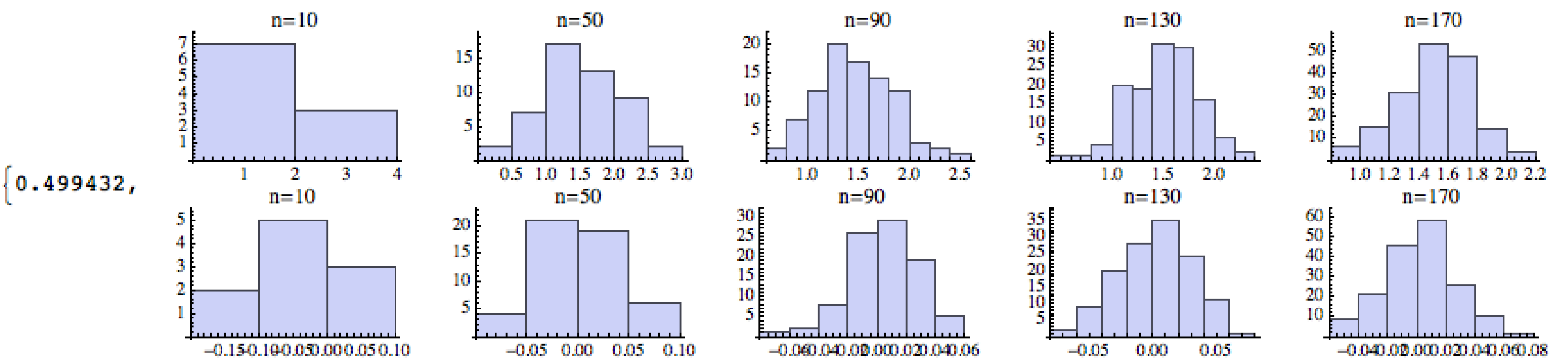
Madhu Advani
Harvard

Guy Bunin
Technion

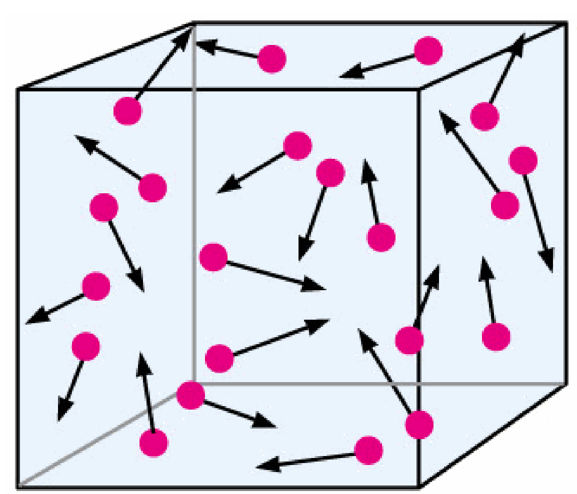
arXiv:1707.03957 / BioRxiv 162966

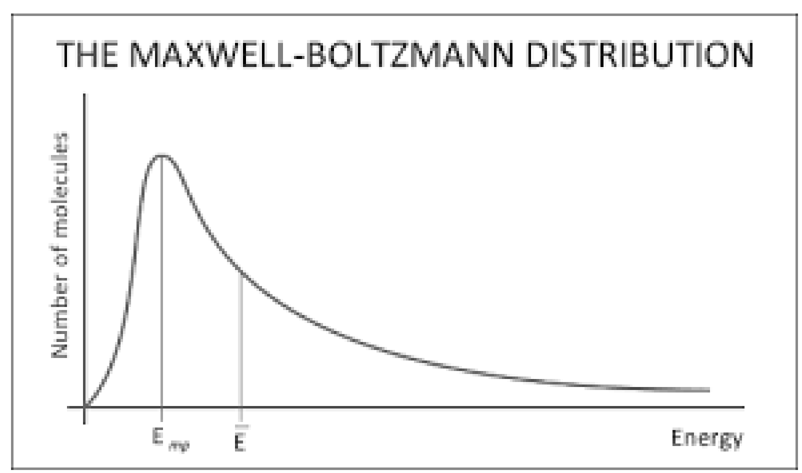
Things are actually simpler for large systems

Central limit theorem applied to large systems with many degrees of freedom.



Price you pay: Talk about macroscopic quantities (pressure) and distributions



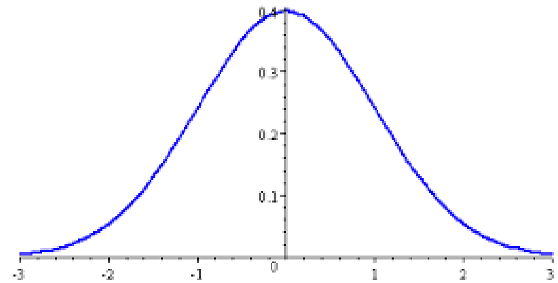


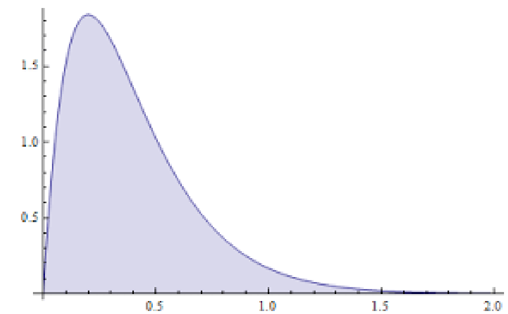
A theory of large "typical ecosystems"

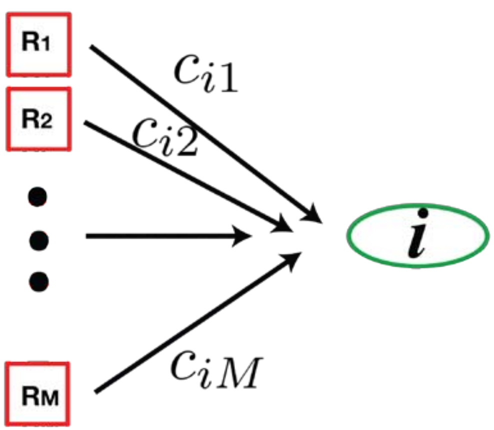
We will consider large ecosystems where S, M >>1. Draw parameters from random distribution (May 1973).

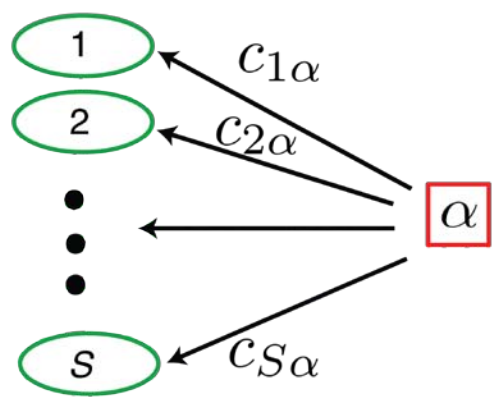
$$\frac{1}{N_i}\frac{dN_i}{dt} = b_i \sum_\alpha (w_\alpha c_{i\alpha} R_\alpha - m_i)$$

$$\frac{1}{R_\alpha}\frac{dR_\alpha}{dt} = K_\alpha - R_\alpha - \sum_i c_{i\alpha} N_i$$









A theory of large "typical ecosystems"

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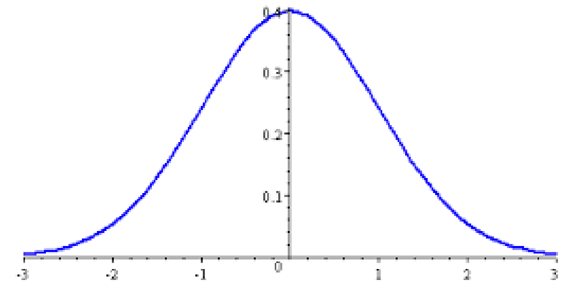
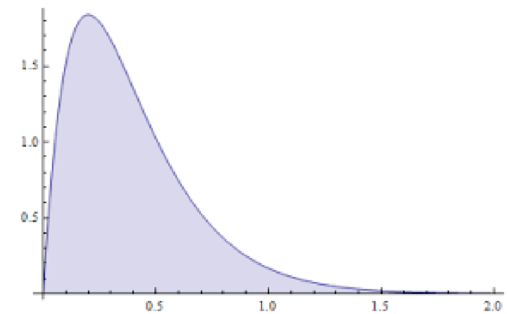
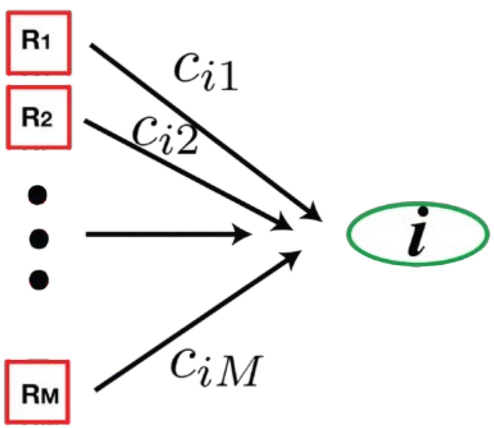
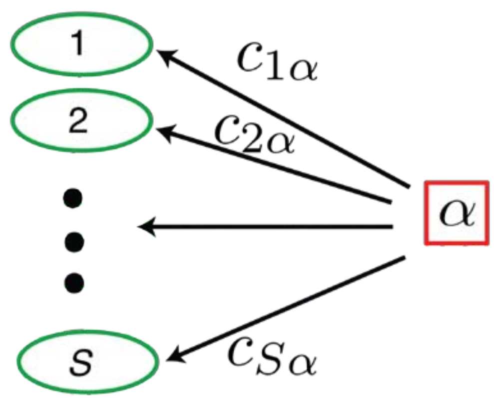
$$\frac{1}{N_i}\frac{dN_i}{dt} = g_i(\mathbf{R})$$

$$\frac{1}{R_\alpha}\frac{dR_\alpha}{dt} = K_\alpha^{eff}(\mathbf{N}) - R_\alpha$$



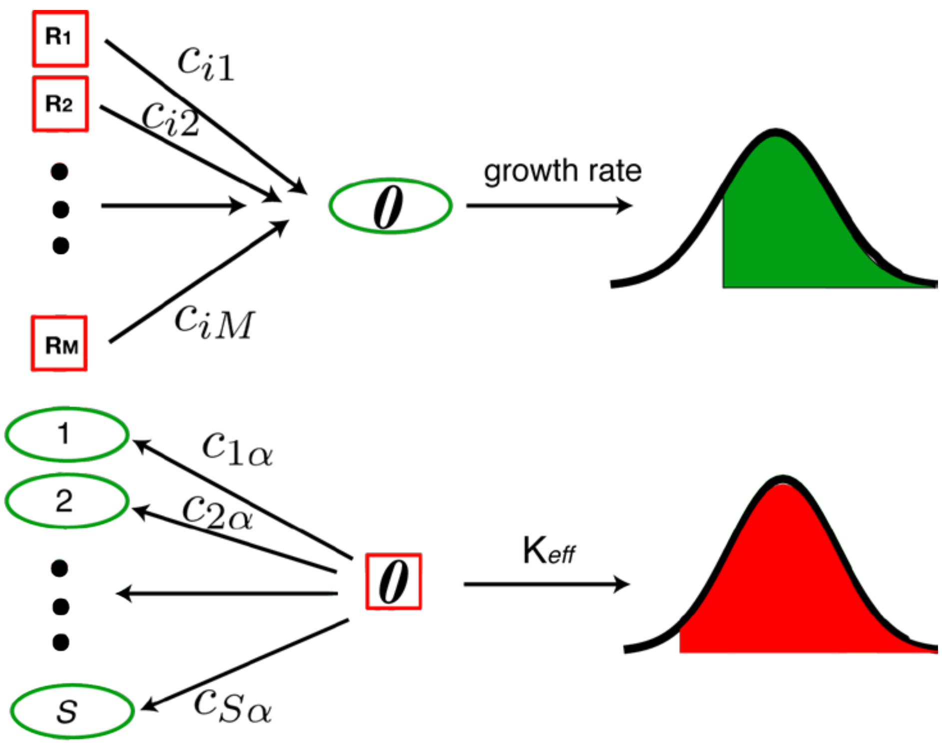






Things are actually simpler for large ecosystems

Pictorial of basic idea: Ask what happens when you add new species to the ecosystem (Levins + MacArthur 1967)



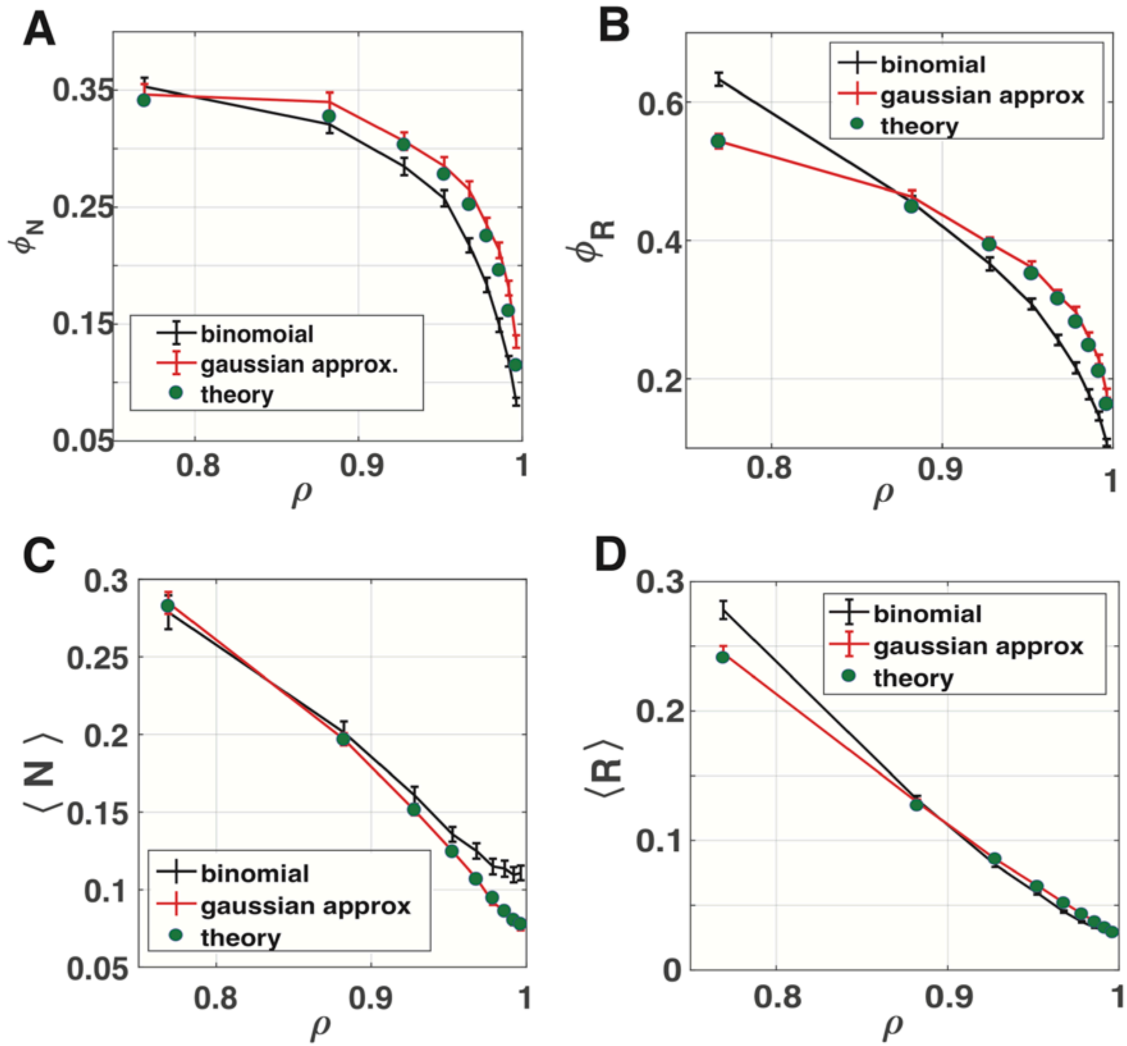
$$\frac{1}{N_i}\frac{dN_i}{dt} = g_i(\mathbf{R})$$

$$\frac{1}{R_\alpha}\frac{dR_\alpha}{dt} = K_\alpha^{eff}(\mathbf{N}) - R_\alpha$$

Use two-step cavity method to solve for “self-consistency” equations

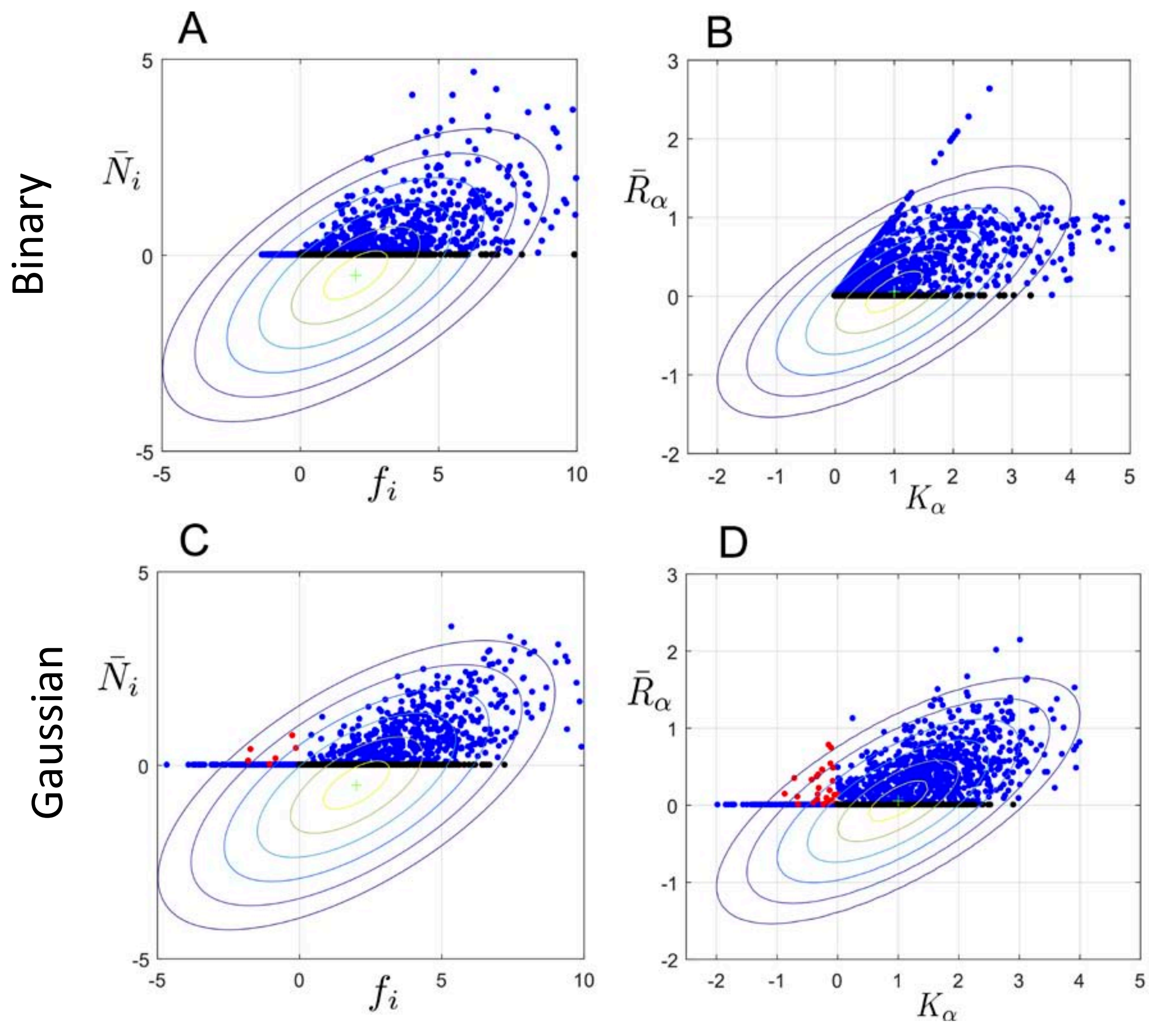
Theory can predict numerical simulations

Various quantities as a function of the typical niche overlap

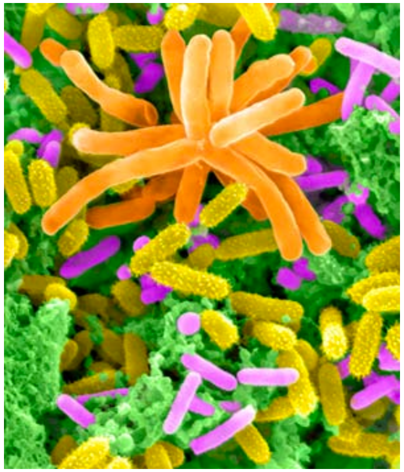


Environmental engineering is a generic feature of large ecosystems

Properties in a diverse ecosystem are not the same as those of isolated individuals.



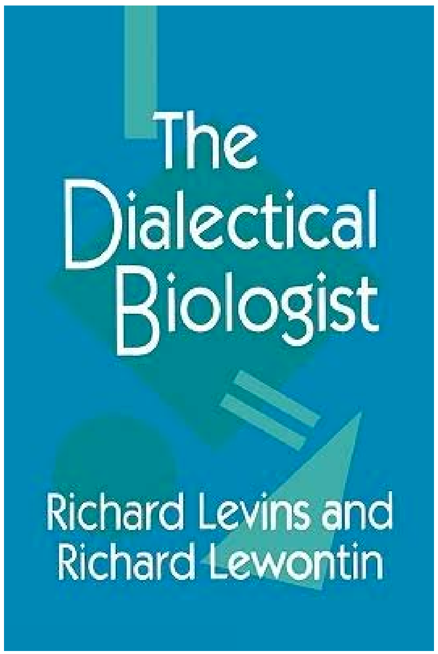
Statistical physics of MacArthur Consumer Resource Model

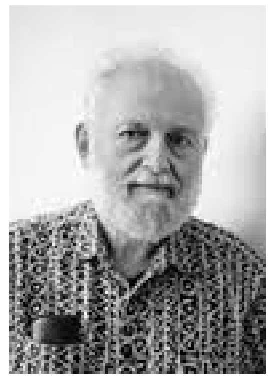


- Developed statistical mechanics of MacArthur Consumer Resource Model.
- Environmental engineering is a generic feature of diverse ecosystems.
- Properties of isolated individuals in isolation can differ significantly from those in complex ecosystems.
- Practical implication: Maybe its much easier to work directly with large ecosystems where you see "average" environment.

Microbial Consumer Resource Model

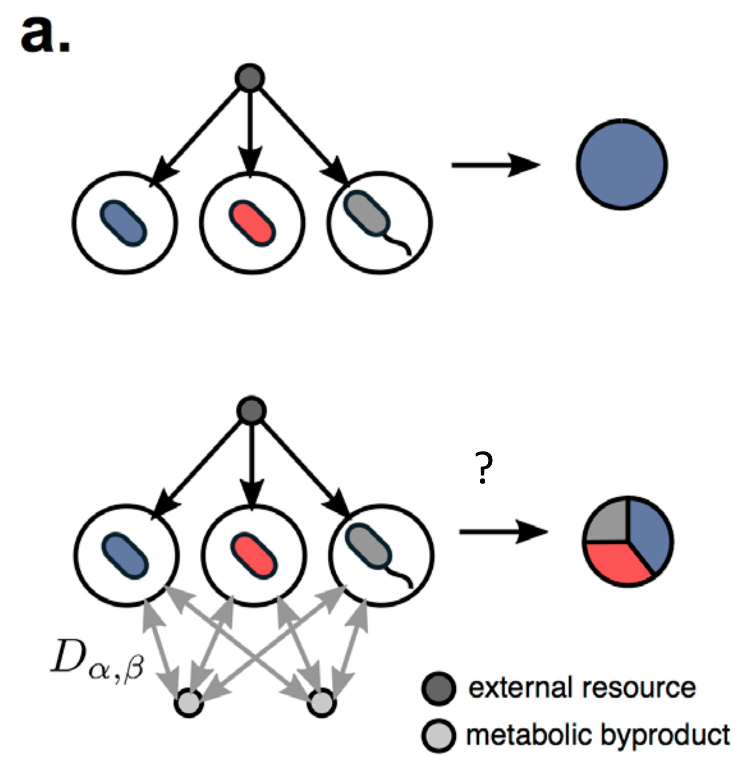
Cross-feeding means microbes construct their own environment.
Implies we no longer think of organisms in fixed external environment





The incorporation of the organism as an active subject in its own ontogeny and in the construction of its own environment leads to a complex dialectical relationship of the elements in the triad of gene, environment, and organism. We have seen that the organism enters directly

Microbial Consumer Resource Model



When microbes consume small molecule – they produce other molecules that can be consumed.

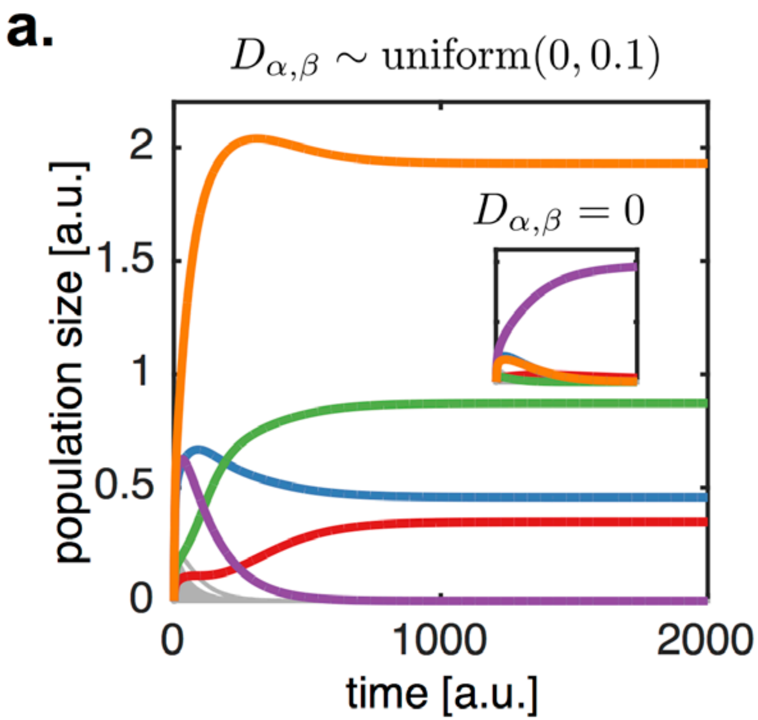
$$\frac{1}{N_i}\frac{dN_i}{dt} = b_i\left[\sum_{\alpha,\beta} D^i_{\alpha\beta} c_{i\beta} R_\beta w_{\alpha\beta} - m_i\right]$$

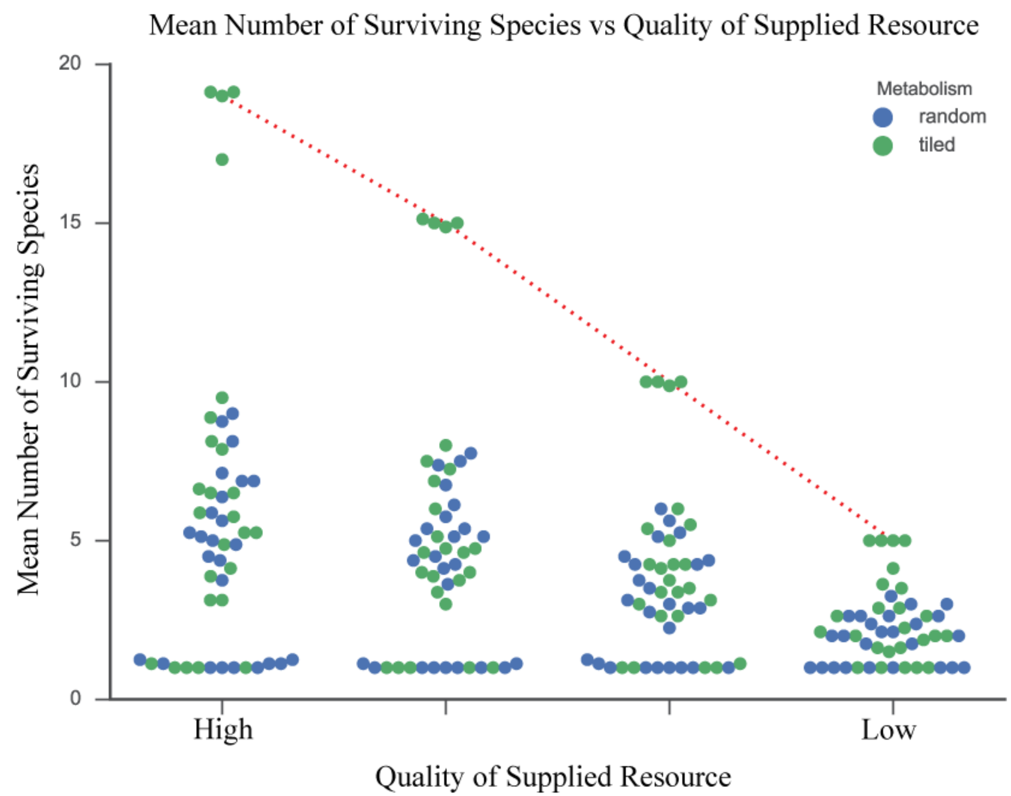
$$\frac{dR_\beta}{dt} = f_\beta(\vec{R}) - \sum_{i,\alpha} N_i D^i_{\alpha\beta} c_{i\beta} R_\beta + \sum_{i,\alpha} N_i D^i_{\beta\alpha} c_{i\alpha} R_\alpha$$

Depletion due to consumption

Production of resource (metabolic products)

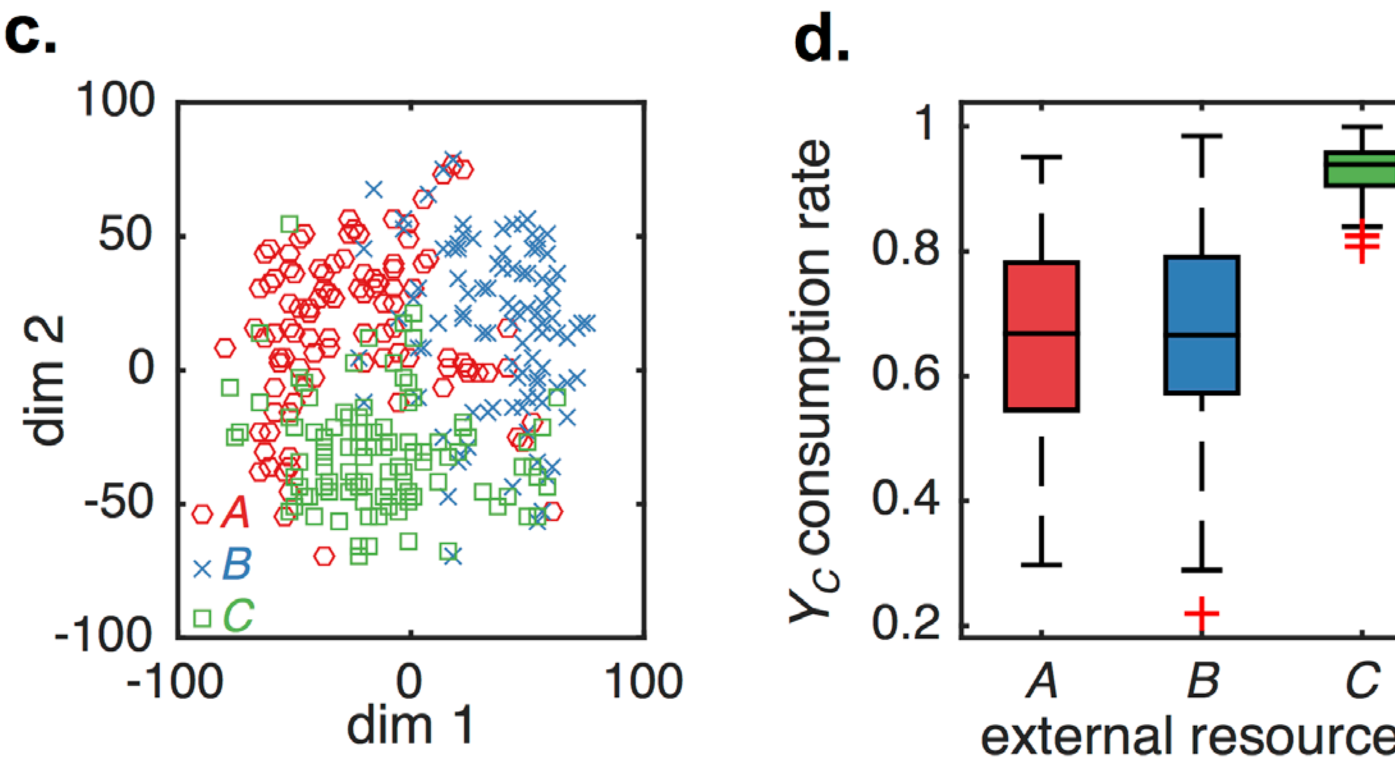
Complex communities can coexist on a single resource





Structure of community shaped by external resource

The structure and “metagenomics” of community is shaped by external resource.



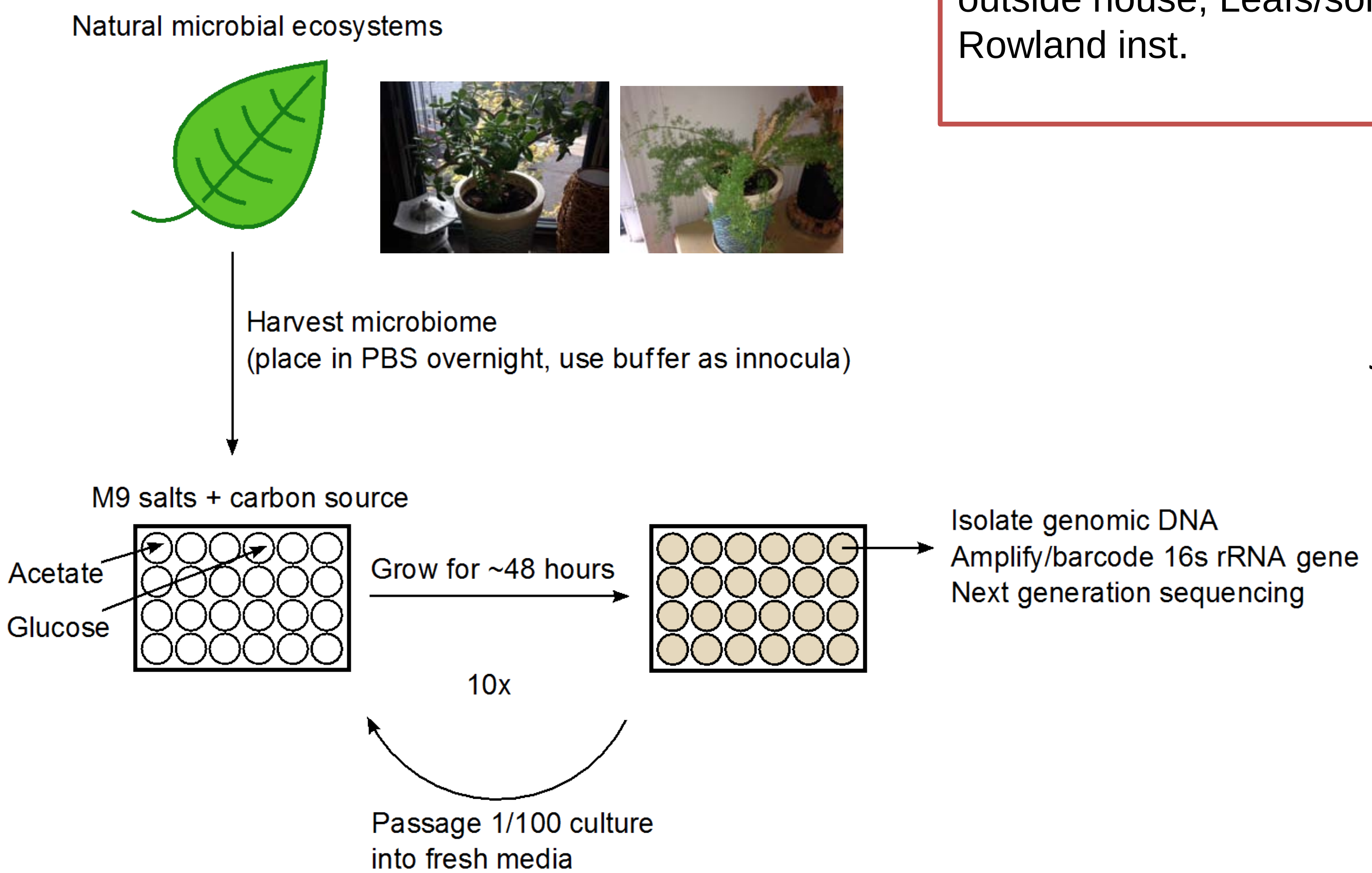
PCA of community coefficients

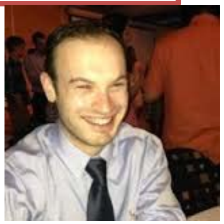
$$\vec{\mathbf{R}}_\alpha^{\mathrm{comm}} = \sum_{i\alpha} c_{i\alpha} \bar{N}_i$$

Multiple communities in minimal environments

Experimental tests:

Samples included:
Leafs/soil of house plants, Soil outside house, Leafs/soil inside Rowland inst.





Josh Goldford

Nanxi Lu

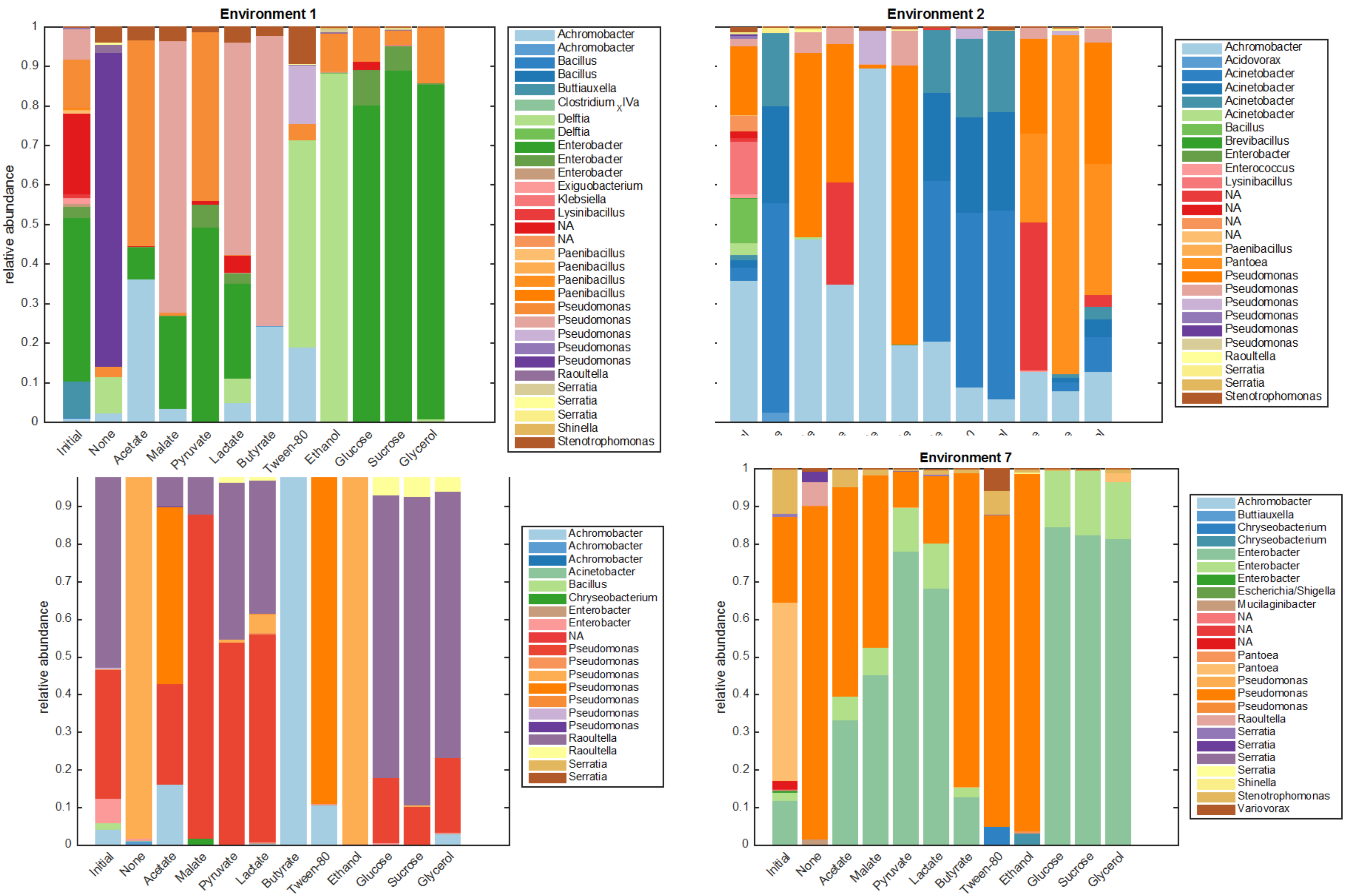
Alvaro Sanchez

Grow different natural communities in minimal environments with a single carbon sources

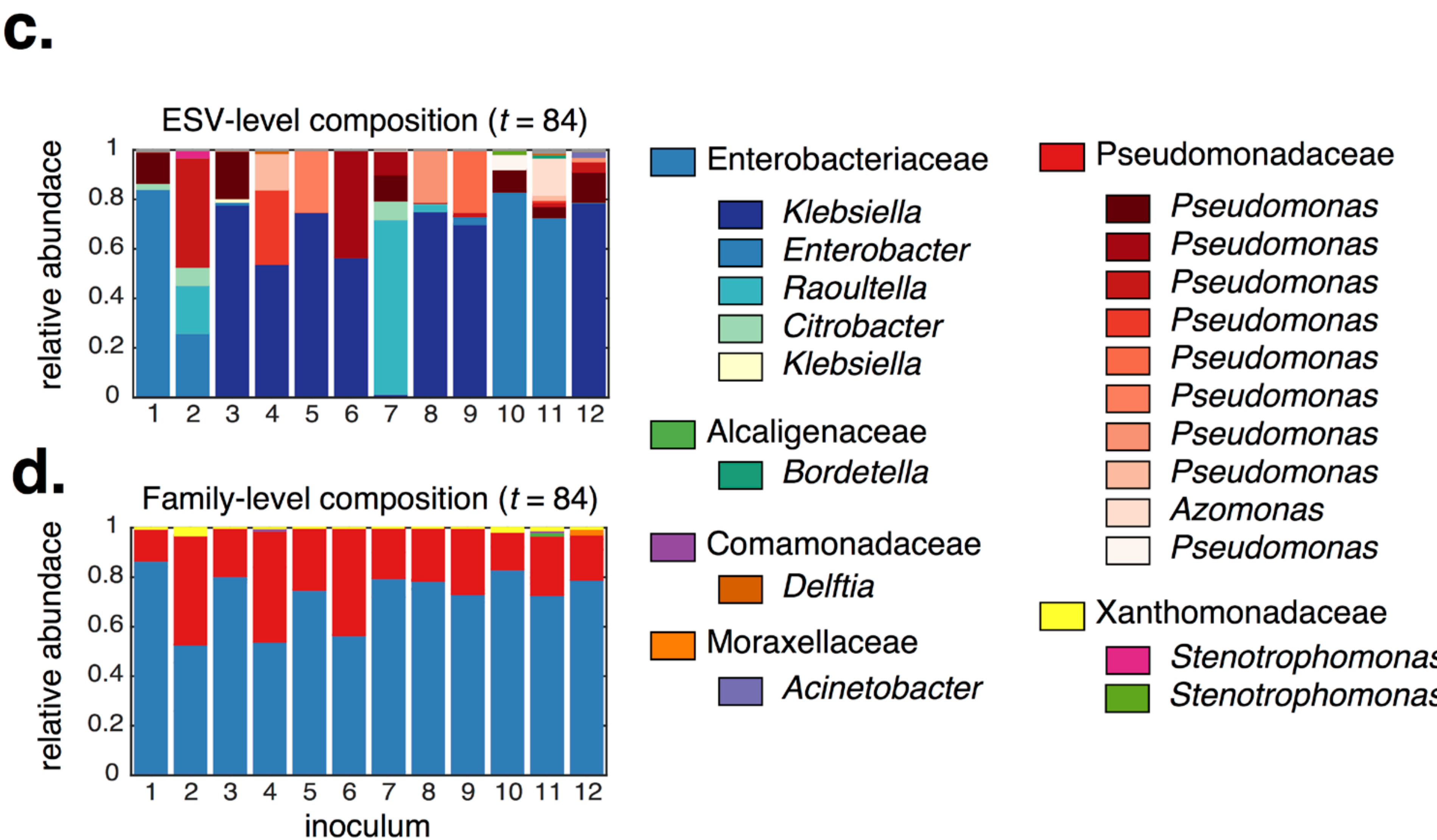
Acetate	Lactose	Melibiose	Tartrate	**Glycerol**
Benzoate	**Malate**	Trehalose	Decanoate	**Tween-80**
Formate	Mannitol	Raffinose	Dodecanoate	Methanol
Cellobiose	2-oxogutarate	Succinate	Myristate	**Ethanol**
Arabinose (D)	Maltose	Citrate	Hexanoate	1-Propanol
Arabinose (L)	Propionate	**Glucose**	**Butyrate**	1-Butanol
Glycolic acid	Inositol	Fructose	Ribose	Isoproponal
Glyxoxylic acid	Fumerate	**Sucrose**	D-Sorbitol	**None**
Dulicitol	**Pyruvate**	Galactose	D-Salicin	
Oxalate	Rhamnose	**Lactate**	Adonitol	

Complex consortia in single resource environment

Complex consortia can grow on a single carbon source (seems to be generic!)



Twelve distinct starting communities in glucose



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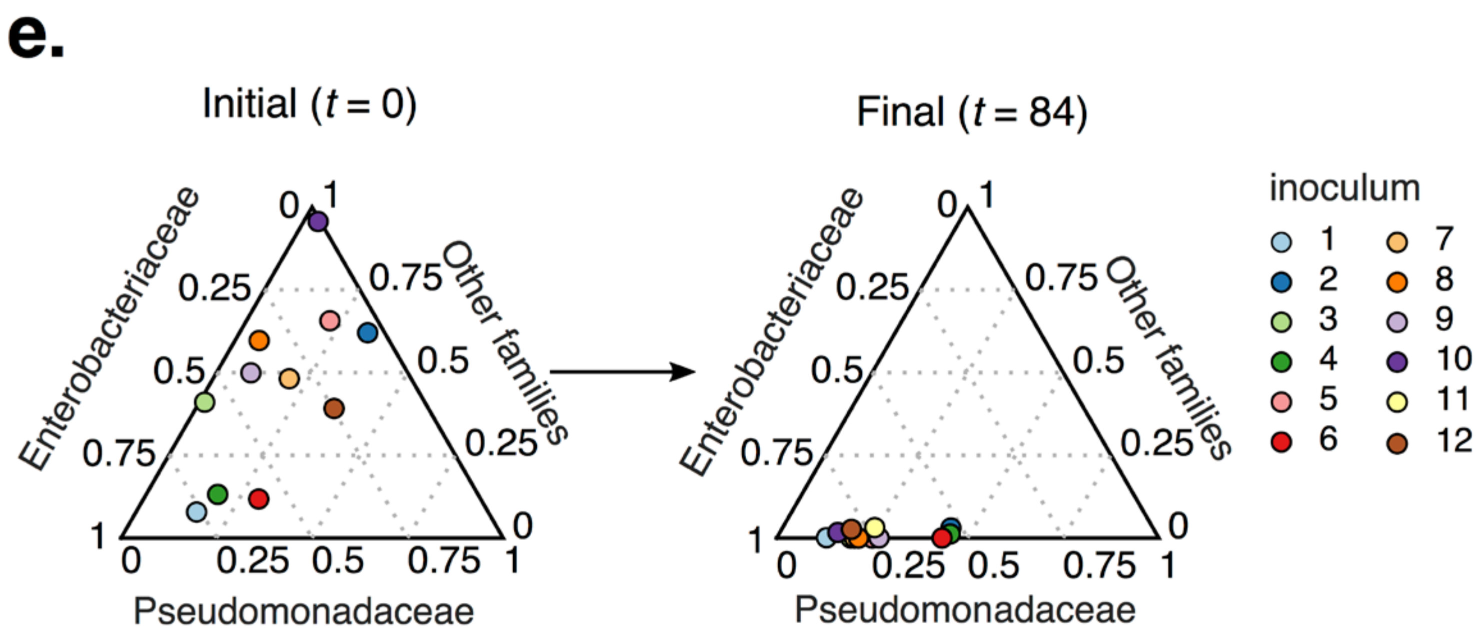
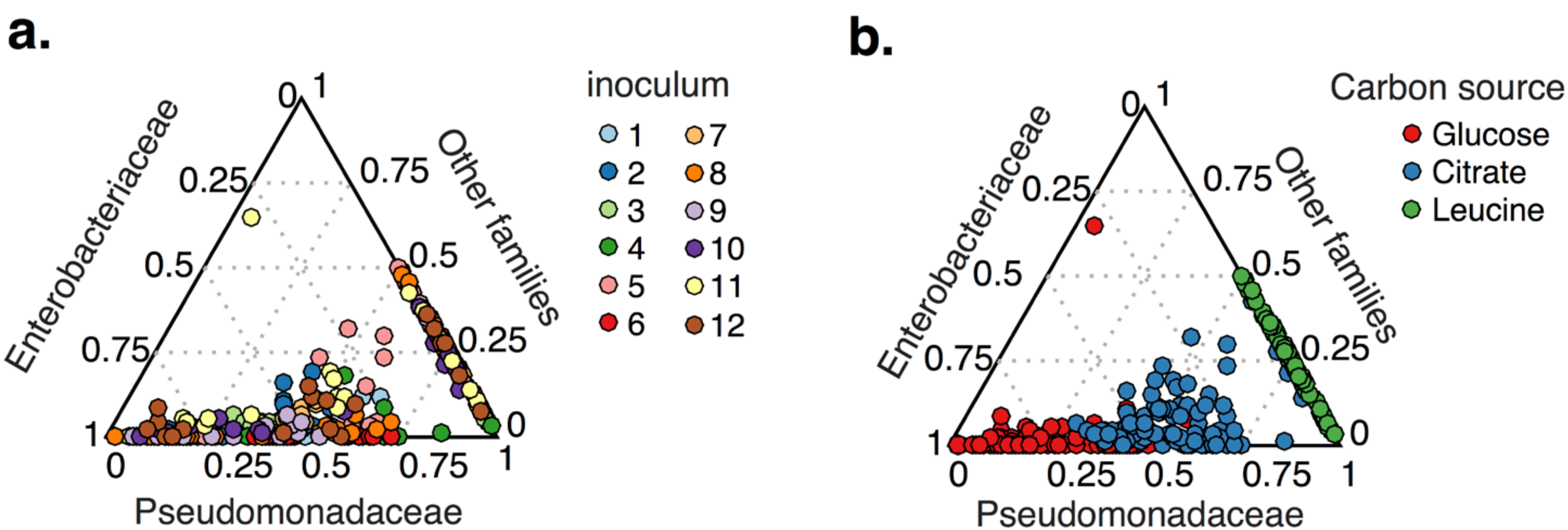
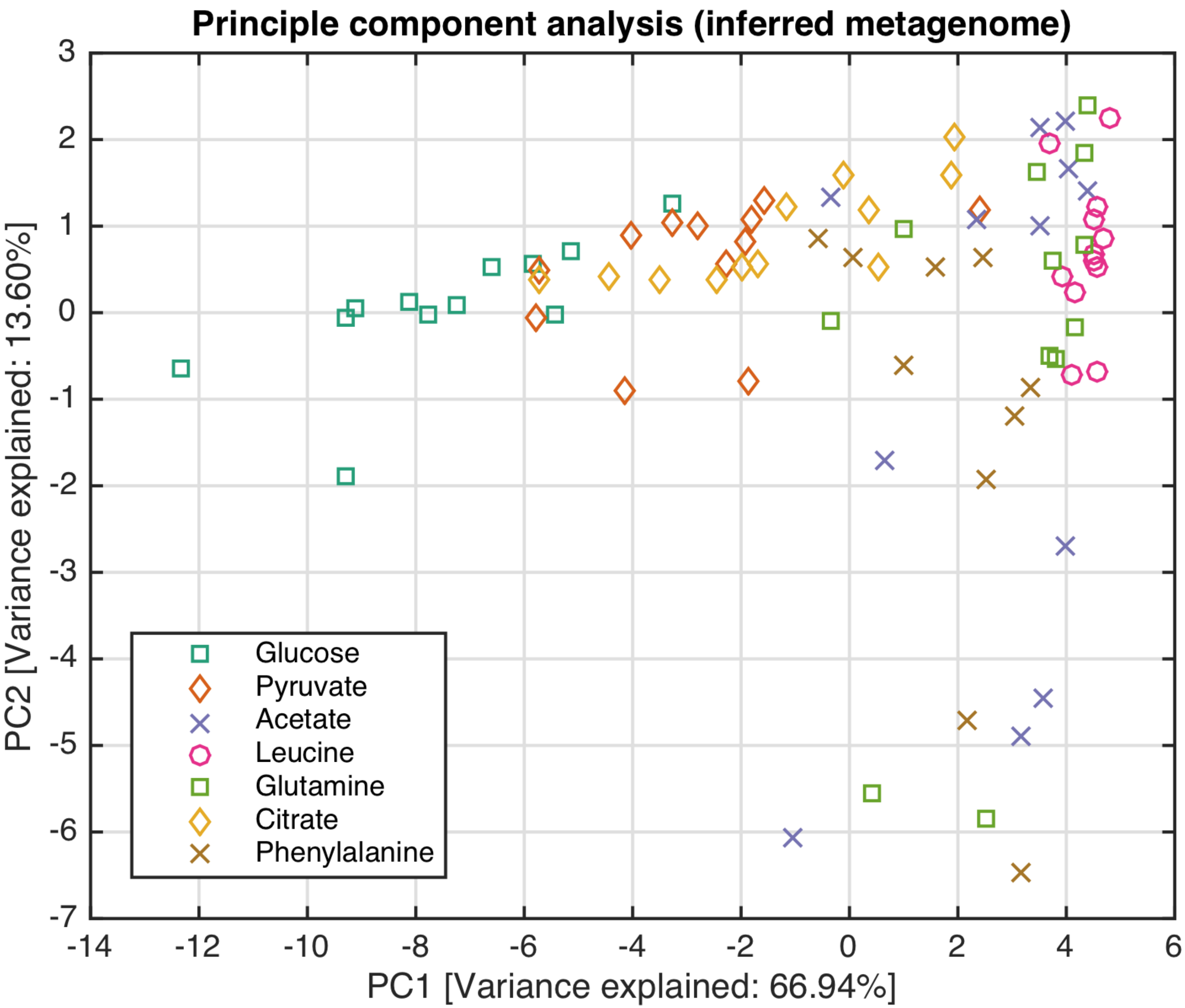


Twelve distinct starting communities in multiple carbon sources



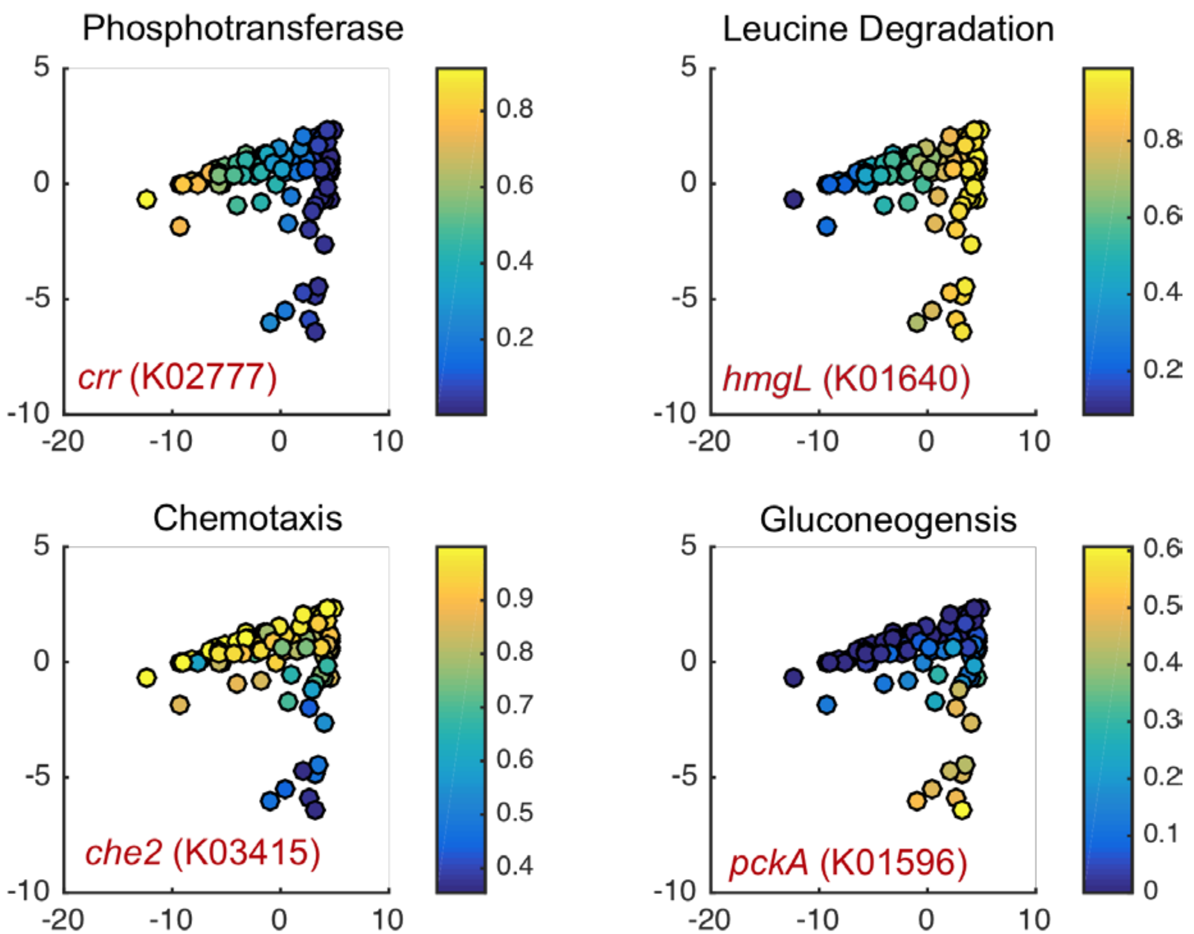
Co-existence is metabolically mediated



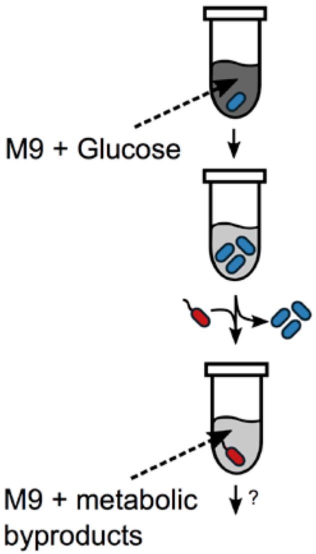
Co-existence is metabolically mediated

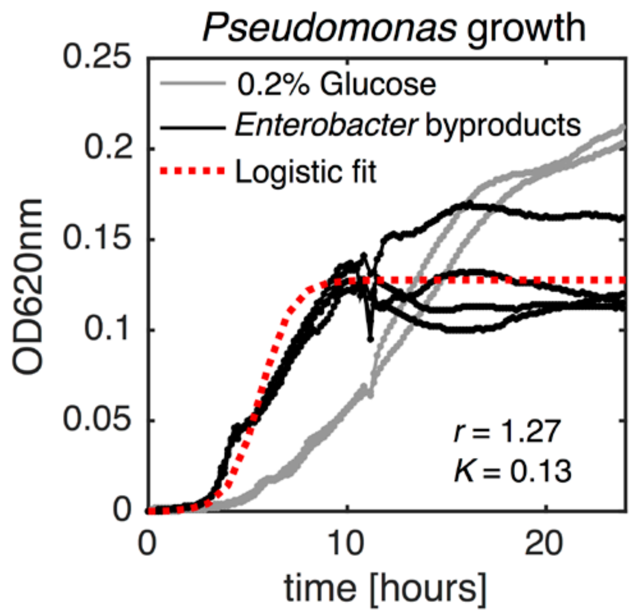
PCA 1- Glycolysis versus fermentation

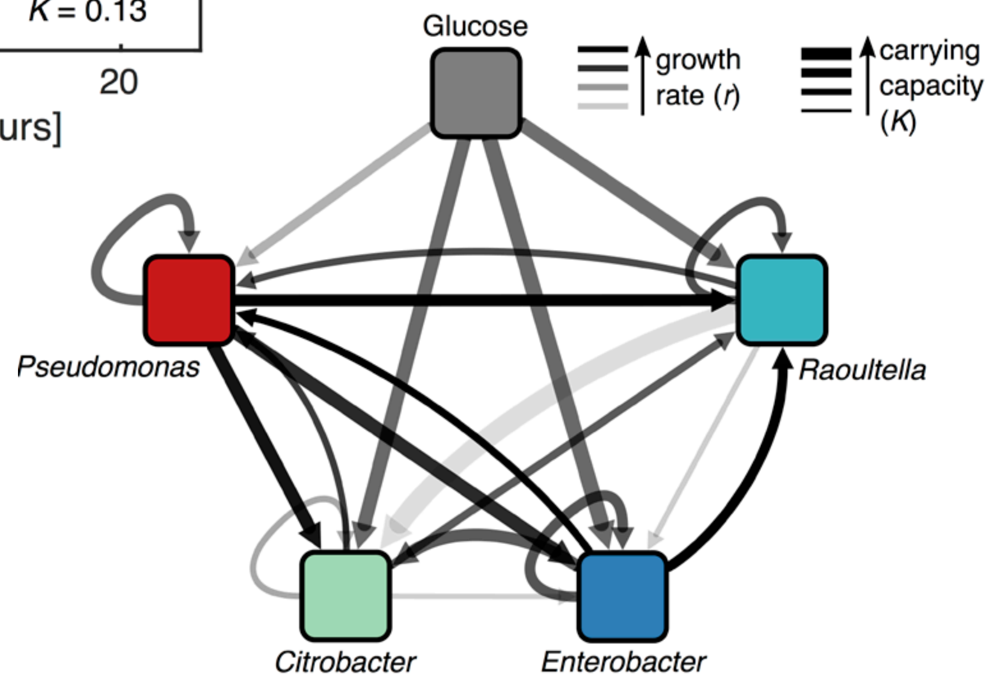
PCA 2- Gluconeogenesis (Biofilm formation?)



Cross-feeding is generic between species

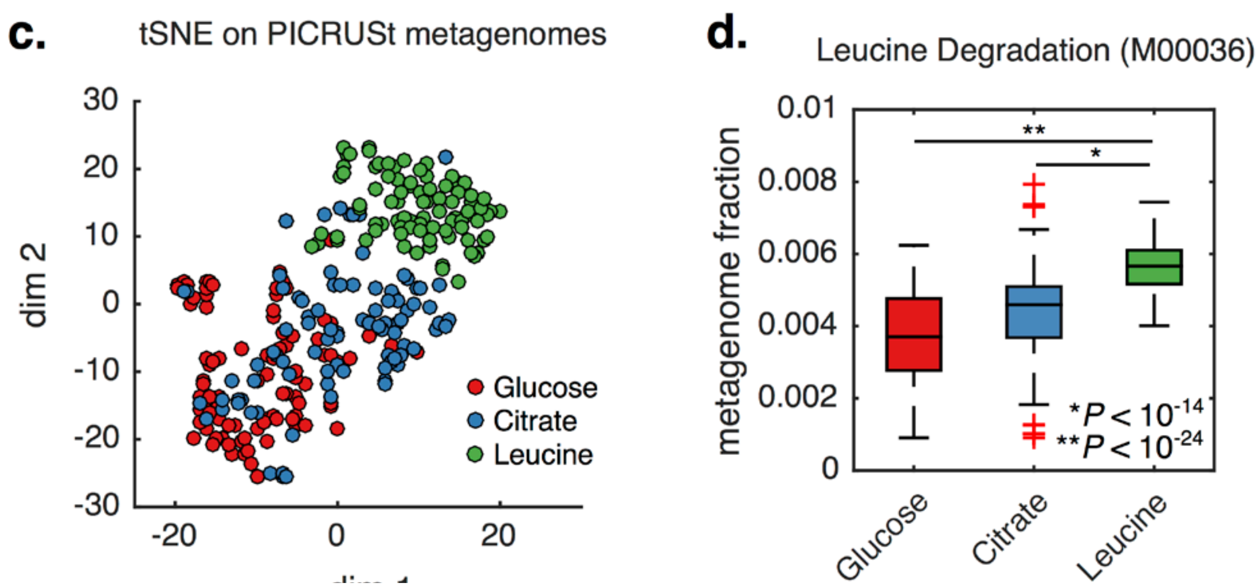




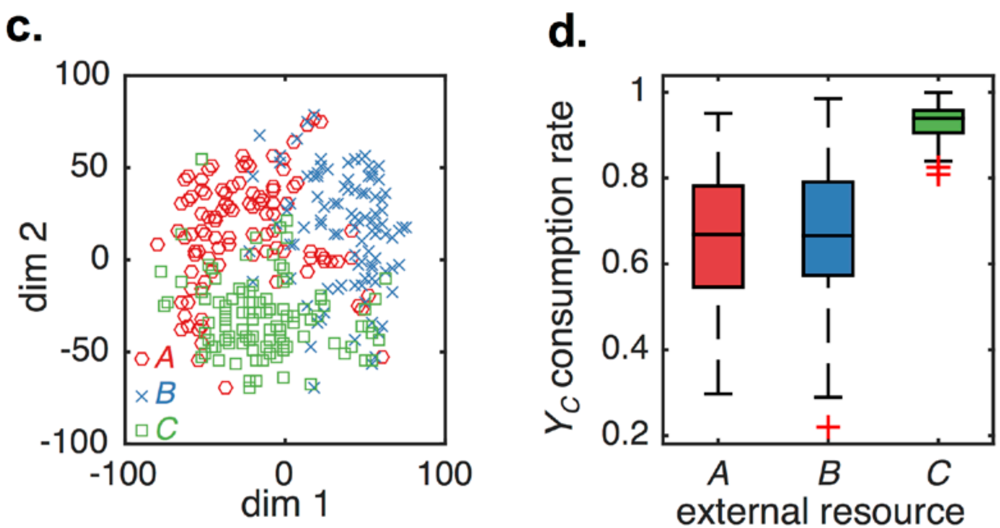


External resources shape community structure

Experiments



Theory



Microbial Consumer Resource Model

- Introduce Microbial Consumer Resource Model to include cross-feeding
- Leads to qualitatively different behaviors — single externally supplied resource can sustain multispecies microbial ecosystems
- Bacteria construct their “own niches”— need to think about environment and species together on equal footing
- “Emergent Simplicty” – all these properties seem to be typical.
- Much more: thermodynamic limitations, ecological principles, what sets limits on diversity etc. and of course experimental analysis.

Acknowledgements

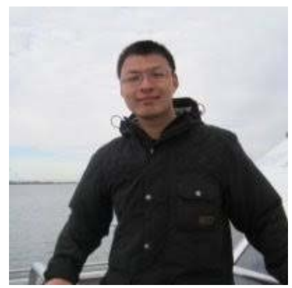
POSTDOC OPENINGS !!!

Joshua Goldford

Alvaro Sanchez

Nanxi Lu

Kirill Korolev



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Daniel Segrè

Mehta Group

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RESEARCH CORPORATION for SCIENCE ADVANCEMENT

GORDON AND BETTY MOORE FOUNDATION

ALFRED P. SLOAN FOUNDATION 1934

NATIONAL INSTITUTES OF HEALTH

Co-existence is metabolically mediated

PCA by log-relative abundance shows clustering by sugar source