ECEA 2019
5th International Electronic Conference on Entropy and Its Applications
18–30 November 2019
Chaired by Prof. Geert Verdoolaege
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Multispecies Emergence of Collective Behavior: Microbiome Connectome, Diversity and Services

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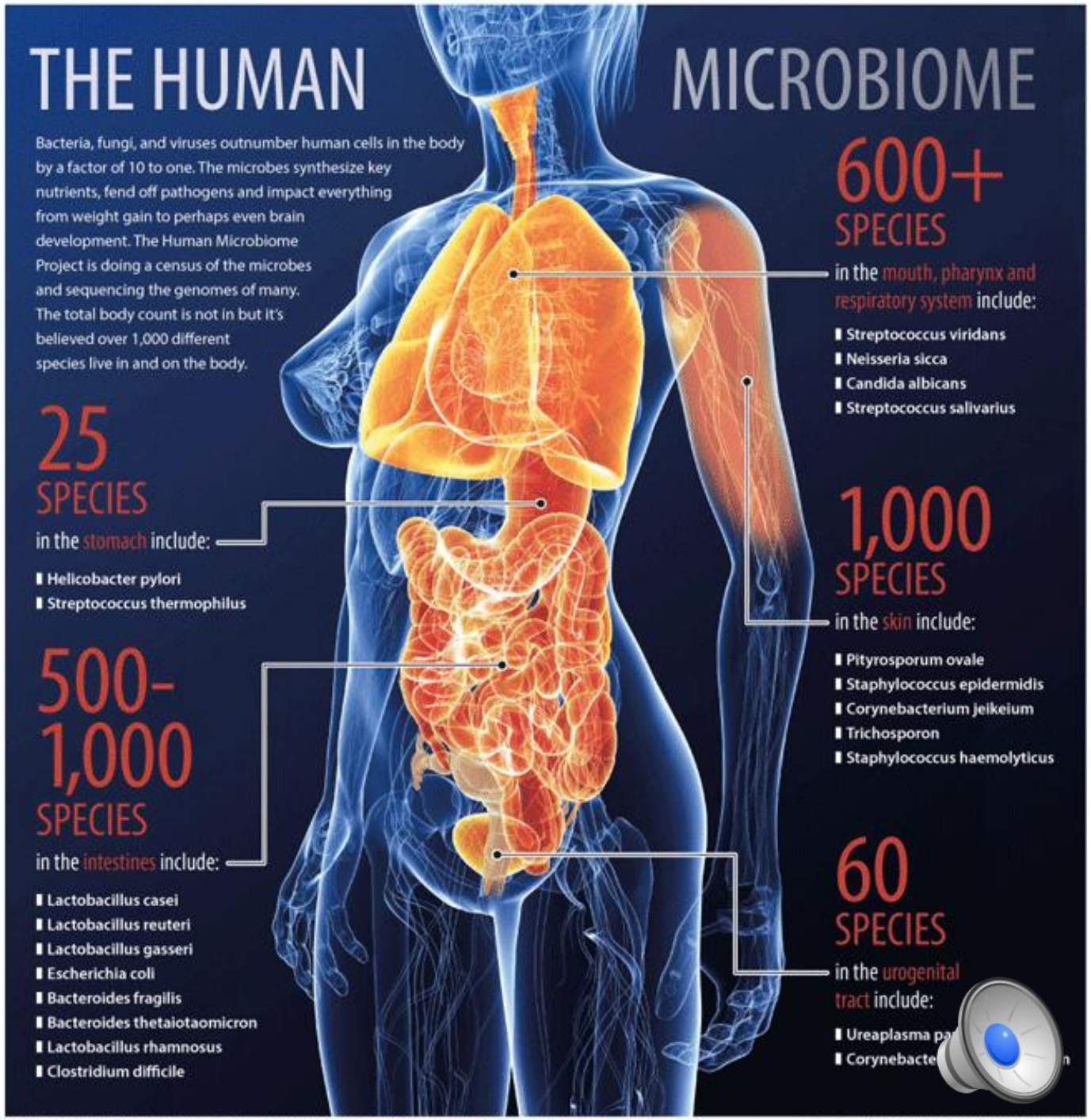
Hokkaido University, Sapporo, JP

Microbiome *Diversity (1.5 kg of Bacteria!): Unknown Connectome with the Environment*

& Health Outcomes -> an Entropic Challenge ☺



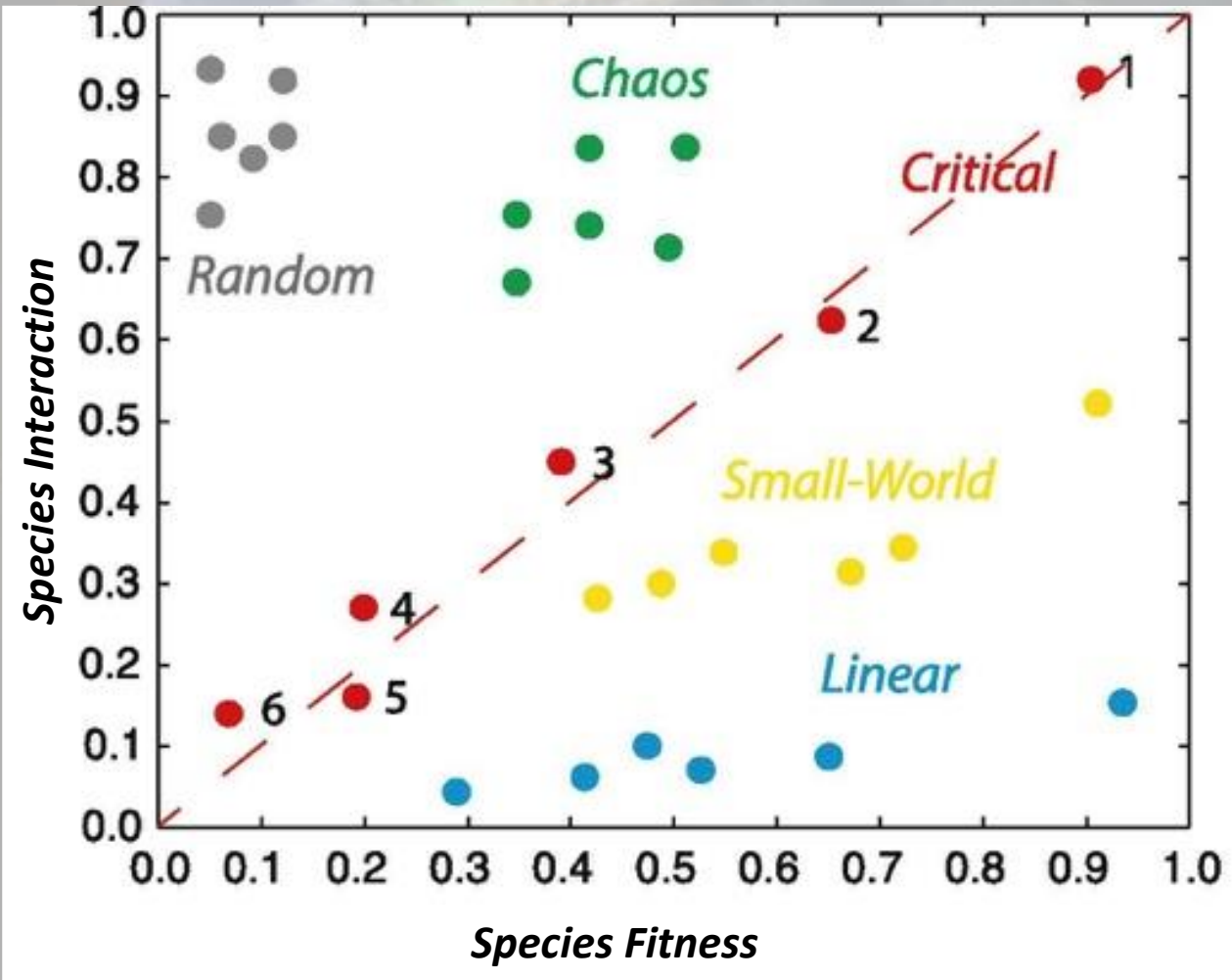
or better… the Holobiont

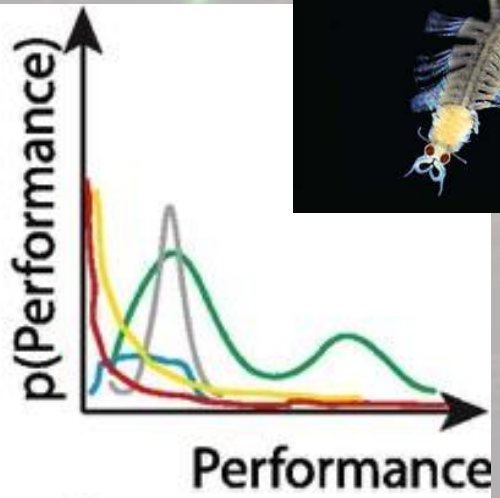
(Humans & the Environment)…

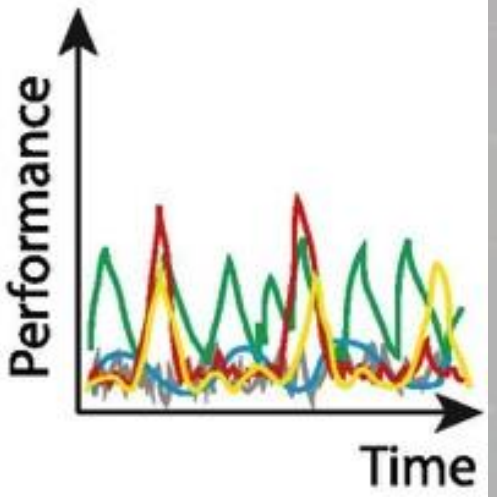
a much bigger Entropic Challenge ☺!

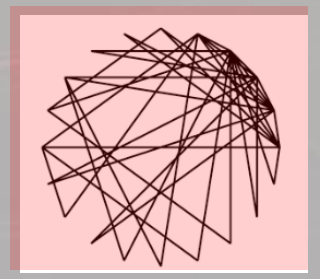
the best symbiosis is determined by an optimal cooperation that maximizes biodiversity growth

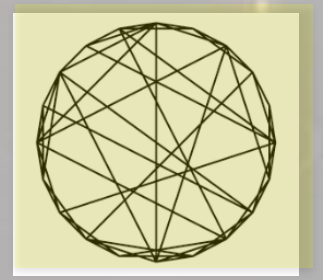
"Health" Imprinted into the Dynamics of Complex Systems

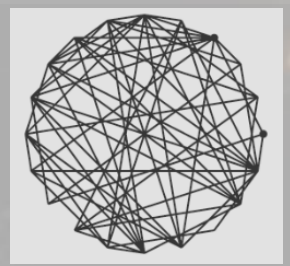












Convertino and Valverde (201 d. Servadio and Convertino (2018), Sci. Adv.

3 Pillars

Collective Information -> OTE as a measure of node importance for Topology Transitions ~ Metabolic Rate (Kleiber's Law connected top Zipf's and Taylor's Law)

Highly Interactive/Critical Nodes (high OTE and low k) are The Least Abundant; those promote State Transitions & Evolution

Network Topology -> Extreme "Positive" Interactions (Cooperative Bio-sensu <-> weakly Predictable), caused by External Multiplicative Noise affecting Microbiome Functional Network (SF/SW) -> Lead to Unstable Multimodal Dysbiotic States (Karenina principle) with Random Networks

Diversity -> Healthy States correspond to Max Diversity Growth (Principle of Optimal Heap's Evolution and Innovation Dec

Foundations

entropy

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Optimal Microbiome Networks: Macroecology and Criticality

by Jie Li [1,2] and Matteo Convertino [1,2,*]

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Entropy **2019**, *21*(5), 506; https://doi.org/10.339

RESEARCH ARTICLE | NETWORK SCIENCE

Optimal information networks: Application for data-driven integrated health in populations

Joseph L. Servadio[1] and Matteo Convertino[2,3,4,*]

+ See all authors and affiliations

Science Advances 02 Feb 2018:
Vol. 4, no. 2, e1701088
DOI: 10.1126/sciadv.1701088

ELSEVIER

Environmental Modelling & Software

Volume 51, January 2014, Pages 296-309

Untangling drivers of species distributions: Global sensitivity and uncertainty analyses of MaxEnt

M. Convertino [a, b, c], R. Muñoz-Carpena [d], M.L. Chu-Agor [e], G.A. Kiker [d], I. Linkov [f, g]

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Ecological Indicators

Volume 107, December 2019, 105510

Original Articles

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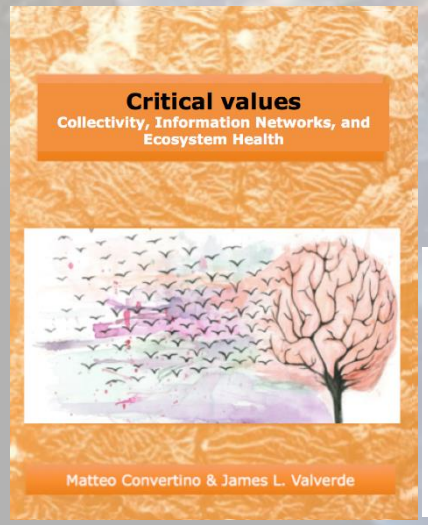
Matteo Convertino [a, b], L. James Valverde Jr. [c]



Taming Network Inference: Optimal Transfer Entropy Model

Jie Li[a], Matteo Convertino[a,b*]

Macroecology, Epigenetic Landscape, and Phase Transitions in the Gut Microbiome

M Convertino[a,b*], J Li[a]

Regular Article | Free Access

On neutral metacommunity patterns of river basins at different scales of aggregation

Matteo Convertino, Rachata Muneepeerakul, Sandro Azaele, Enrico Bertuzzo, Andrea Rinaldo, Ignacio Rodriguez-Iturbe

First published: 15 August 2009 | https://doi.org/10.1029/2009WR007799 | Cited by: 11

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Health and Disease Imprinted in the Time Variability of the Human Microbiome

Jose Manuel Martí, Daniel Martínez-Martínez, Teresa Rubio, César Gracia, Manuel Peña, Amparo Latorre, Andrés Moya, Carlos P. Garay
Jack A. Gilbert, Editor

DOI: 10.1128/mSystems.00144-16 Check for updates

Cooperation, competition and the emergence of criticality in communities of adaptive systems

Jorge Hidalgo[1,2], Jacopo Grilli[2,3], Samir Suweis[2], Amos Maritan[2] and Miguel A Muñoz[1]

Published 17 March 2016 • © 2016 IOP Publishing Ltd and SISSA Medialab srl

Journal of Statistical Mechanics: Theory and Experiment, Volume 2016, March 2016

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Neutral Theory and Scale-Free Neural Dynamics

Matteo Martinello, Jorge Hidalgo, Amos Maritan, Serena di Santo, Dietmar Plenz, and Miguel A. Muñoz
Phys. Rev. X **7**, 041071 – Published 26 December 2017

Stochastic models of evolution in genetics, ecology and linguistics

R A Blythe[1] and A J McKane[2]

Published 23 July 2007 • IOP Publishing Ltd

Journal of Statistical Mechanics: Theory and Experiment, Volume 2007, July 2007

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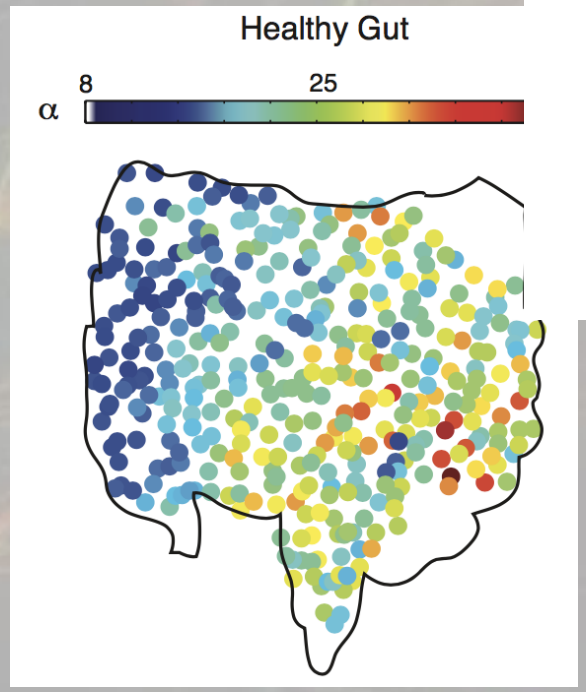
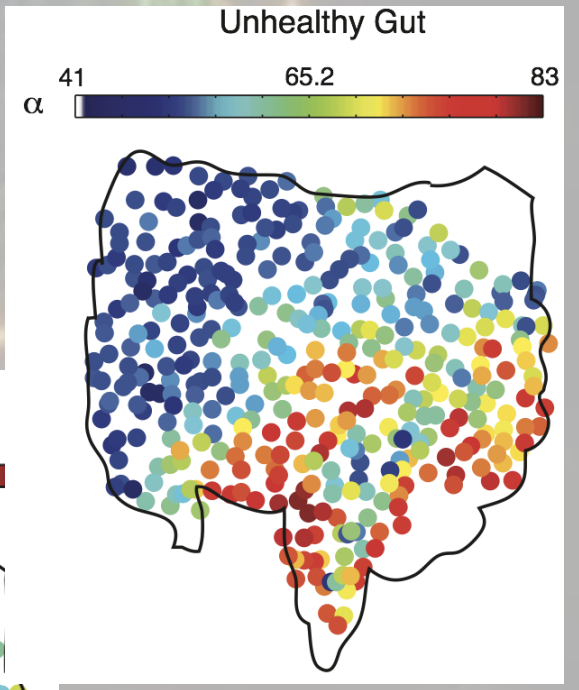
Inflammatory bowel disease (IBD)



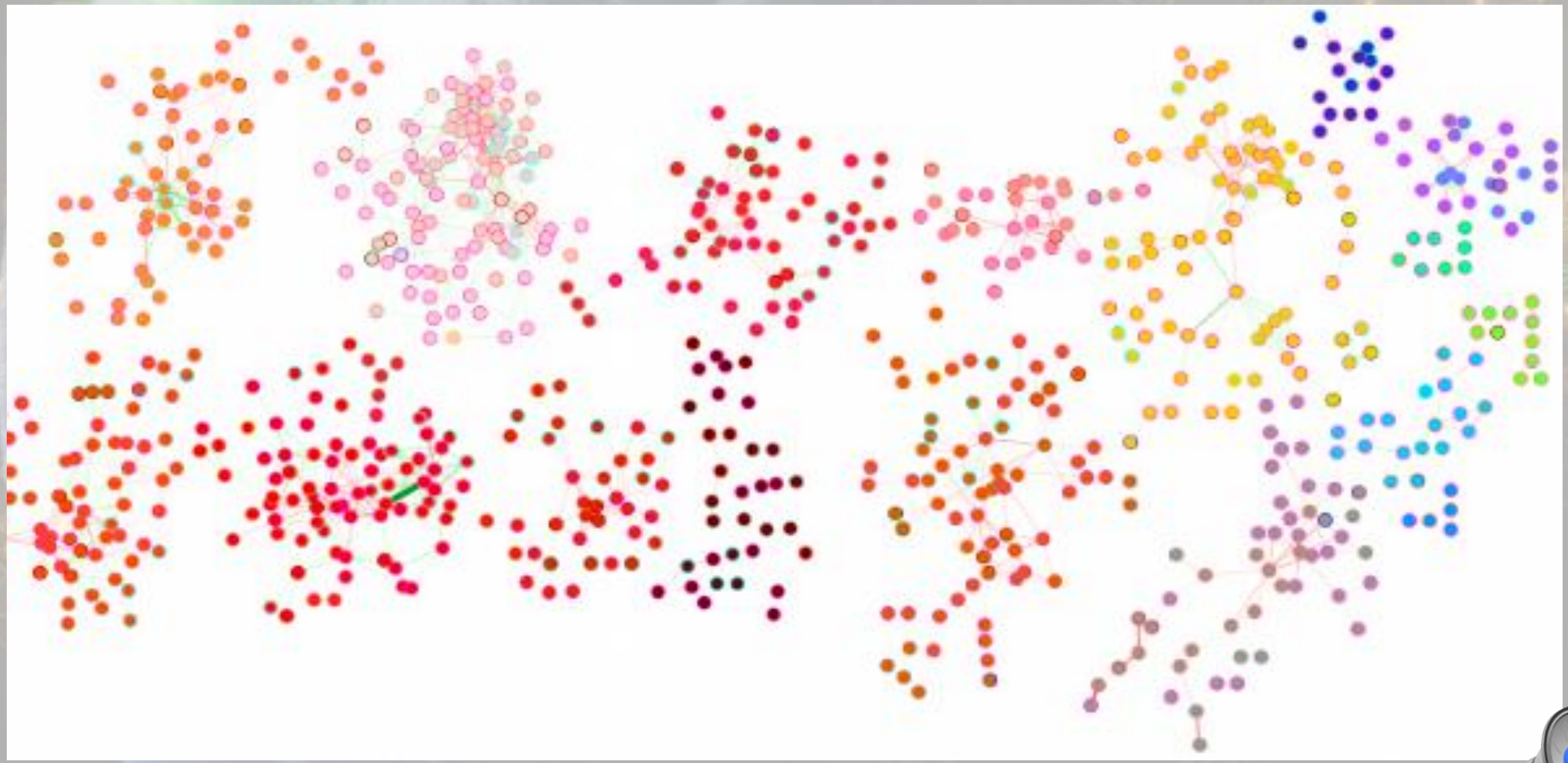


Inflammatory bowel disease (IBD) is an umbrella term used to describe disorders that involve chronic inflammation of your digestive tract.

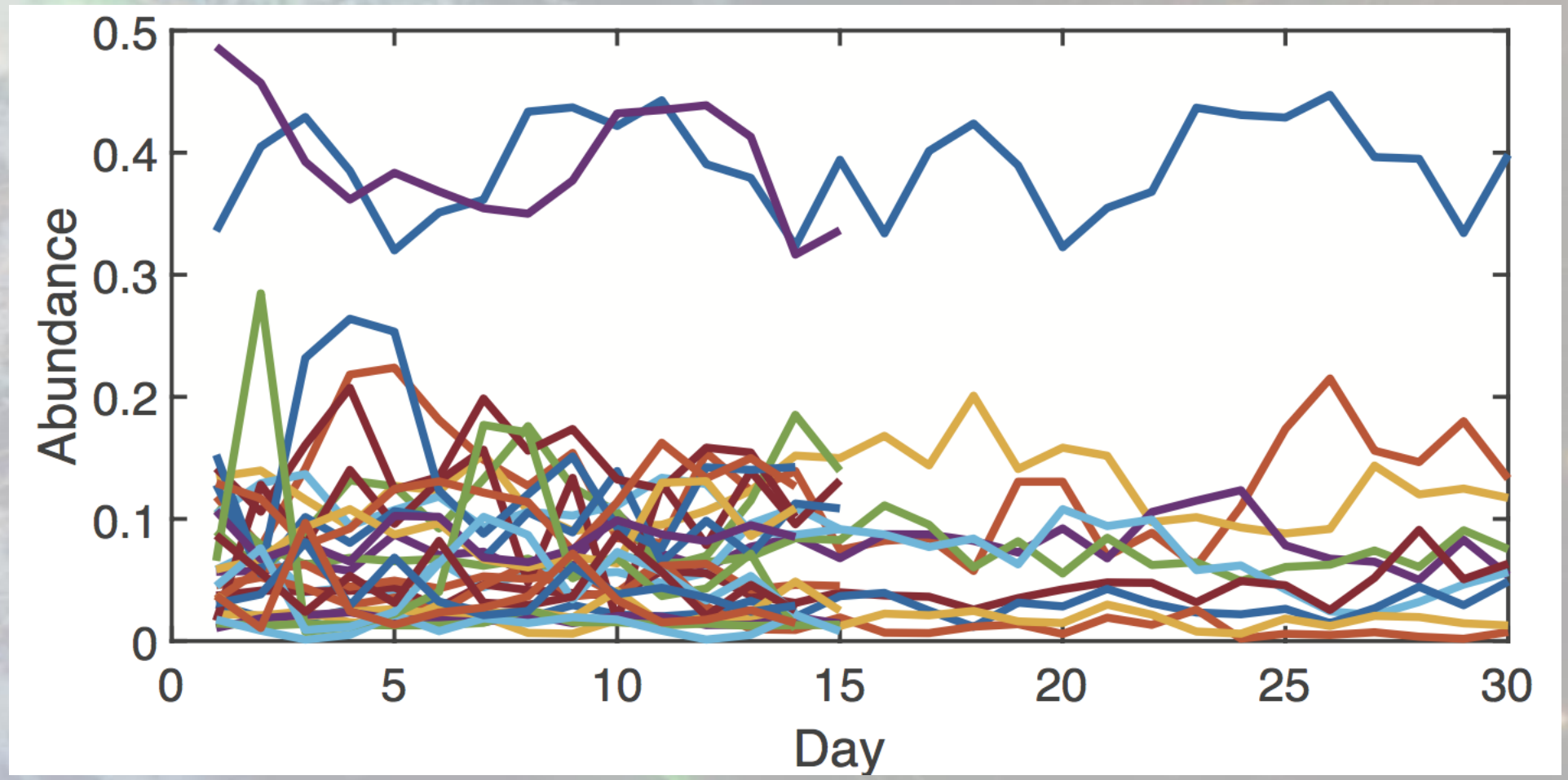
Symptoms:
Diarrhea
Fever and fatigue
Abdominal pain and cramping
Blood in your stool
Reduced appetite
Unintended weight loss

The ‘’exact cause’’ of inflammatory bowel disease remains unknown. One possible ‘’cause’’ is an immune system malfunction. When your immune system tries to fight off an invading virus or bacterium, *an abnormal immune response causes the immune system to attack the cells in the digestive tract*, too. However, the origin of this abnormal immune response is a *complex network of environmental factors*...

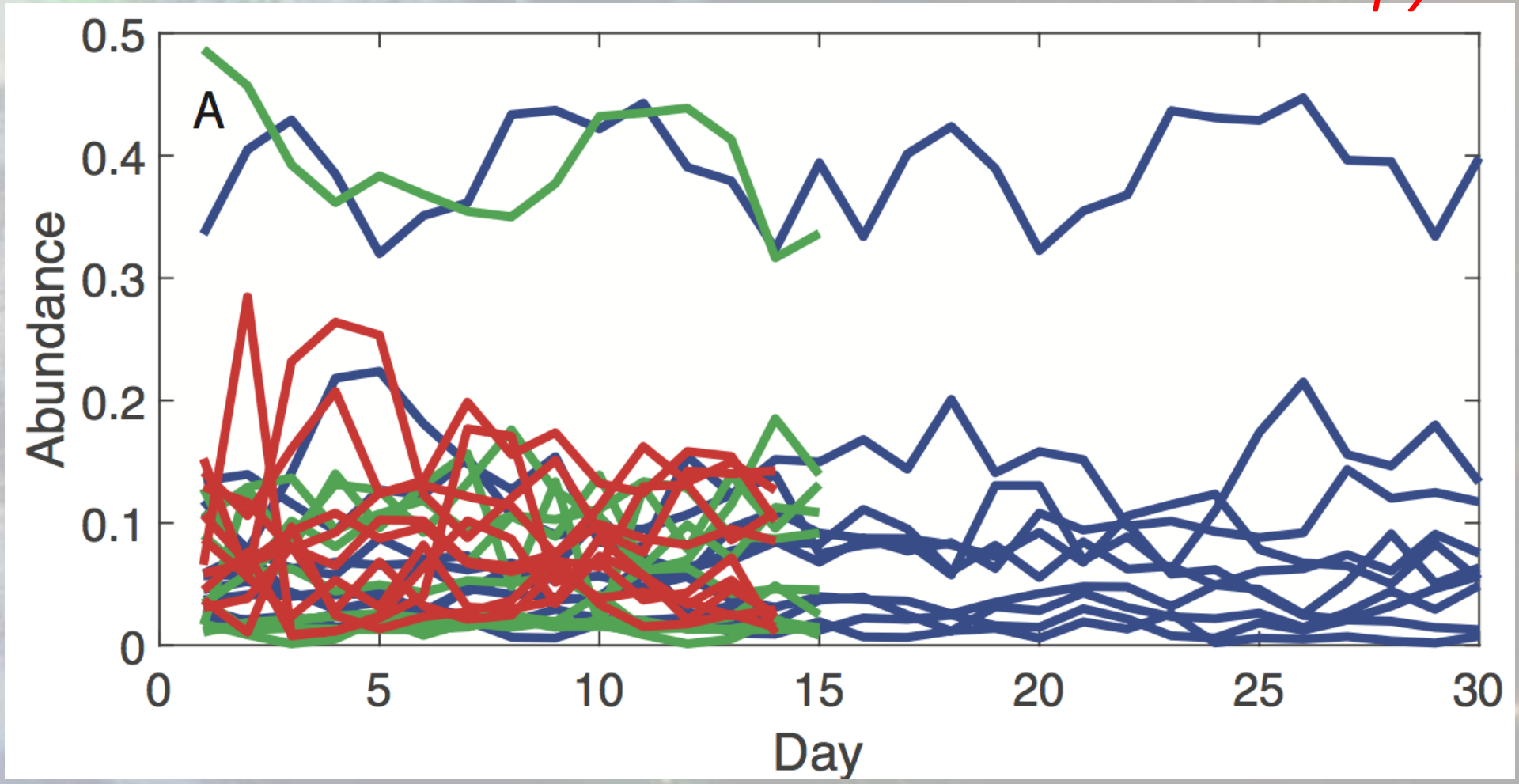
Old Statistical Approach does lead to poor Pattern Detection…

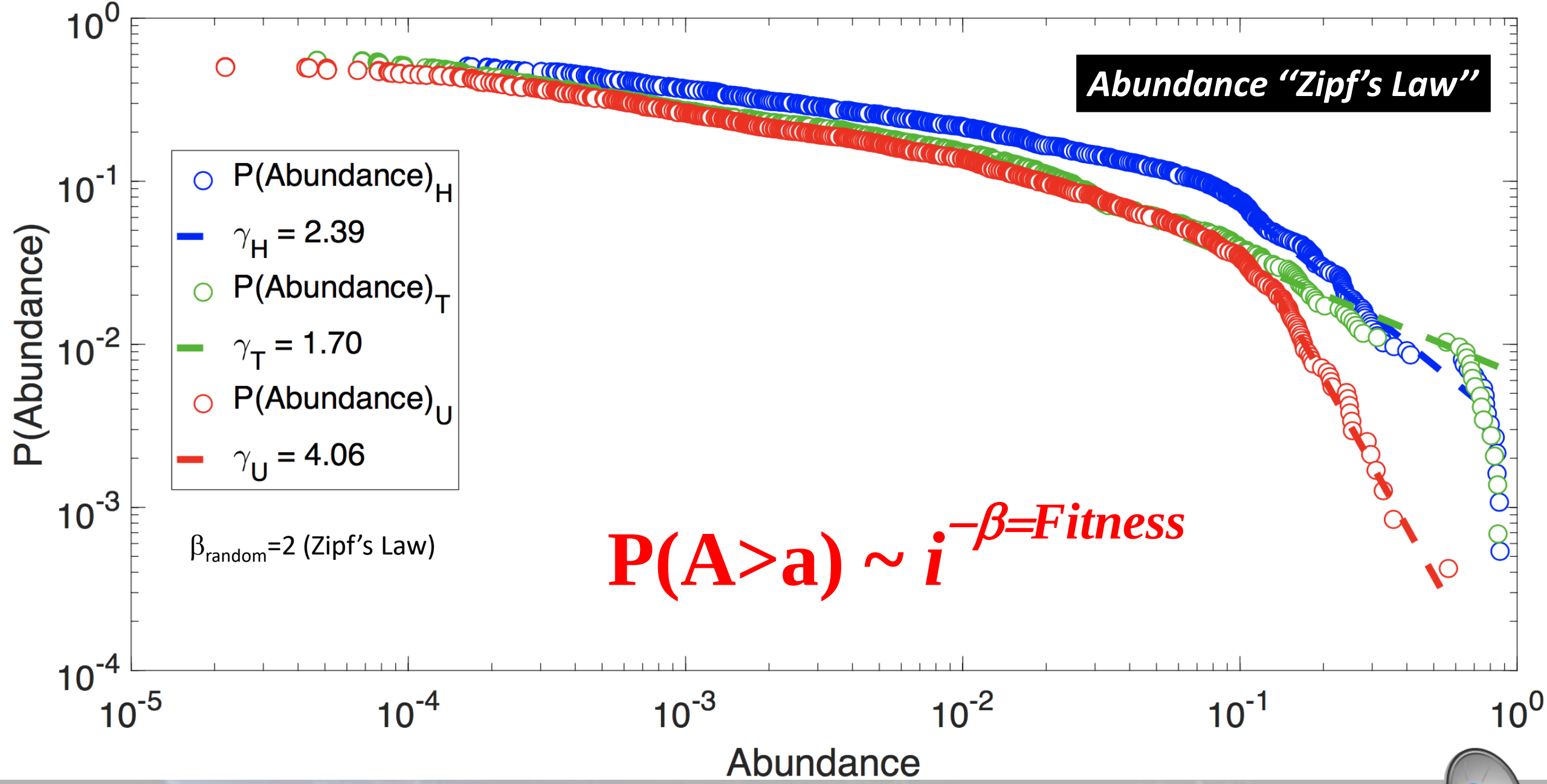


Species ''Speech'': basic Information

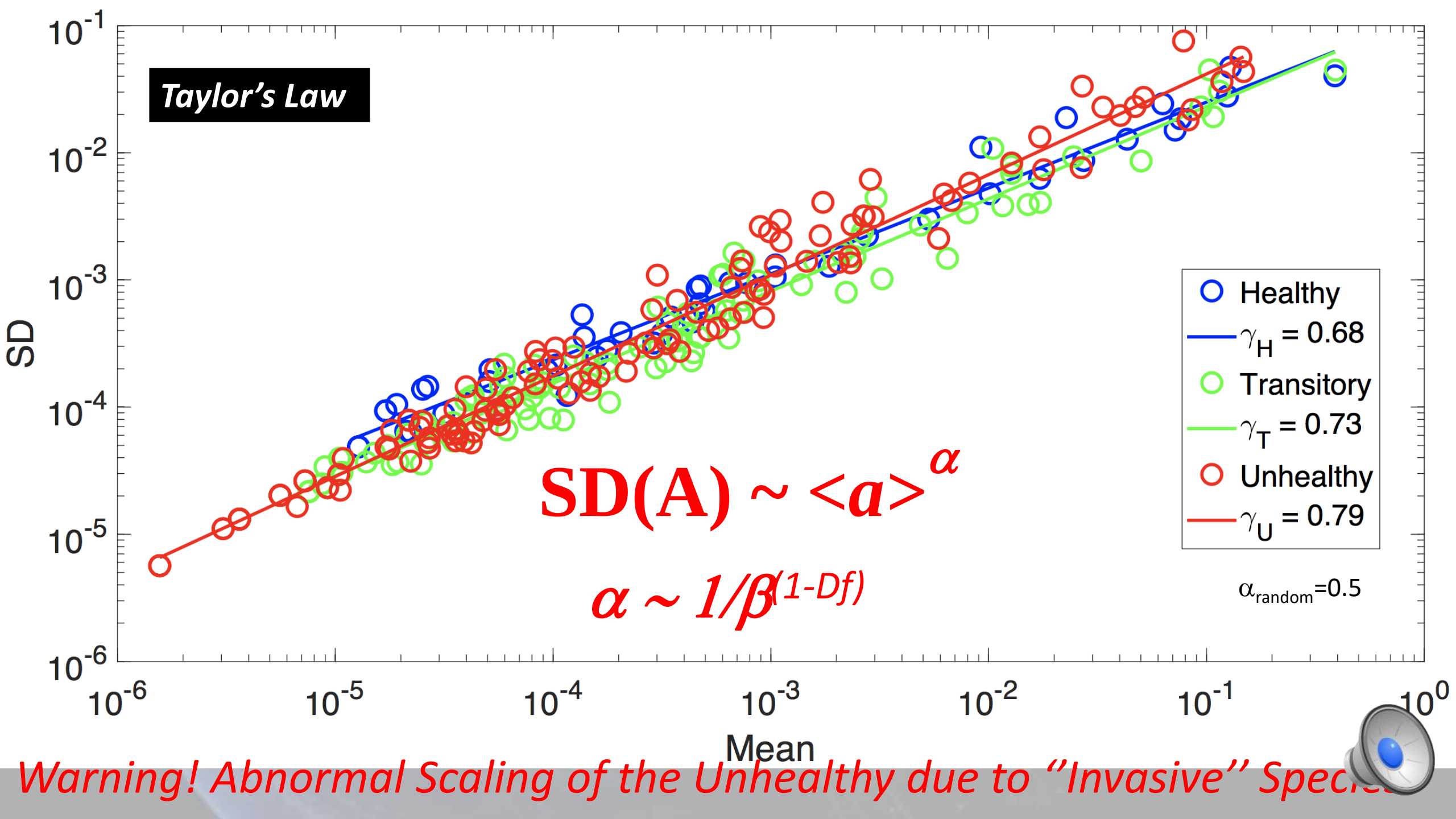


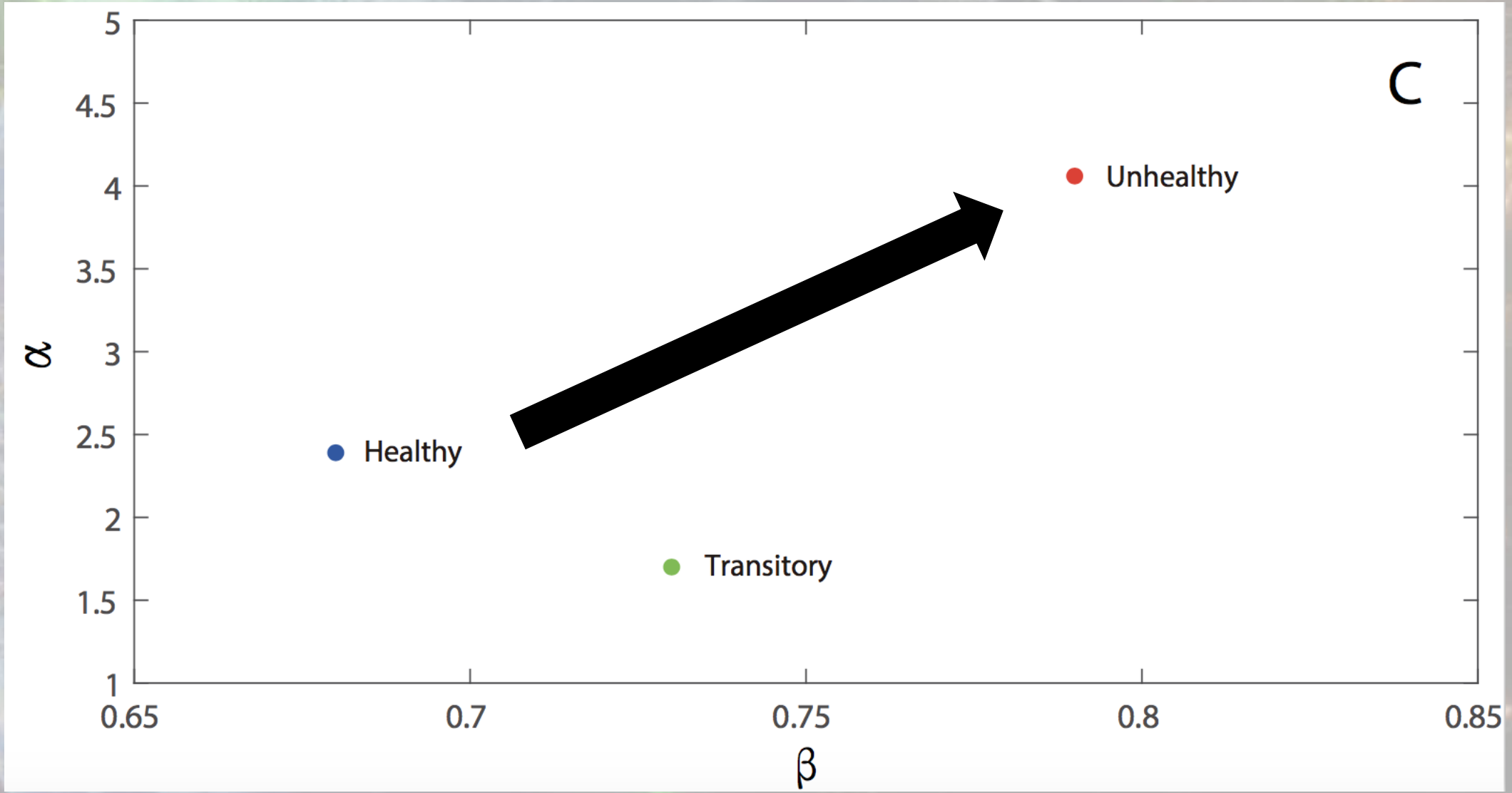
Species "Speech": clustering based on pdf of species abundance -> Entropy clustering





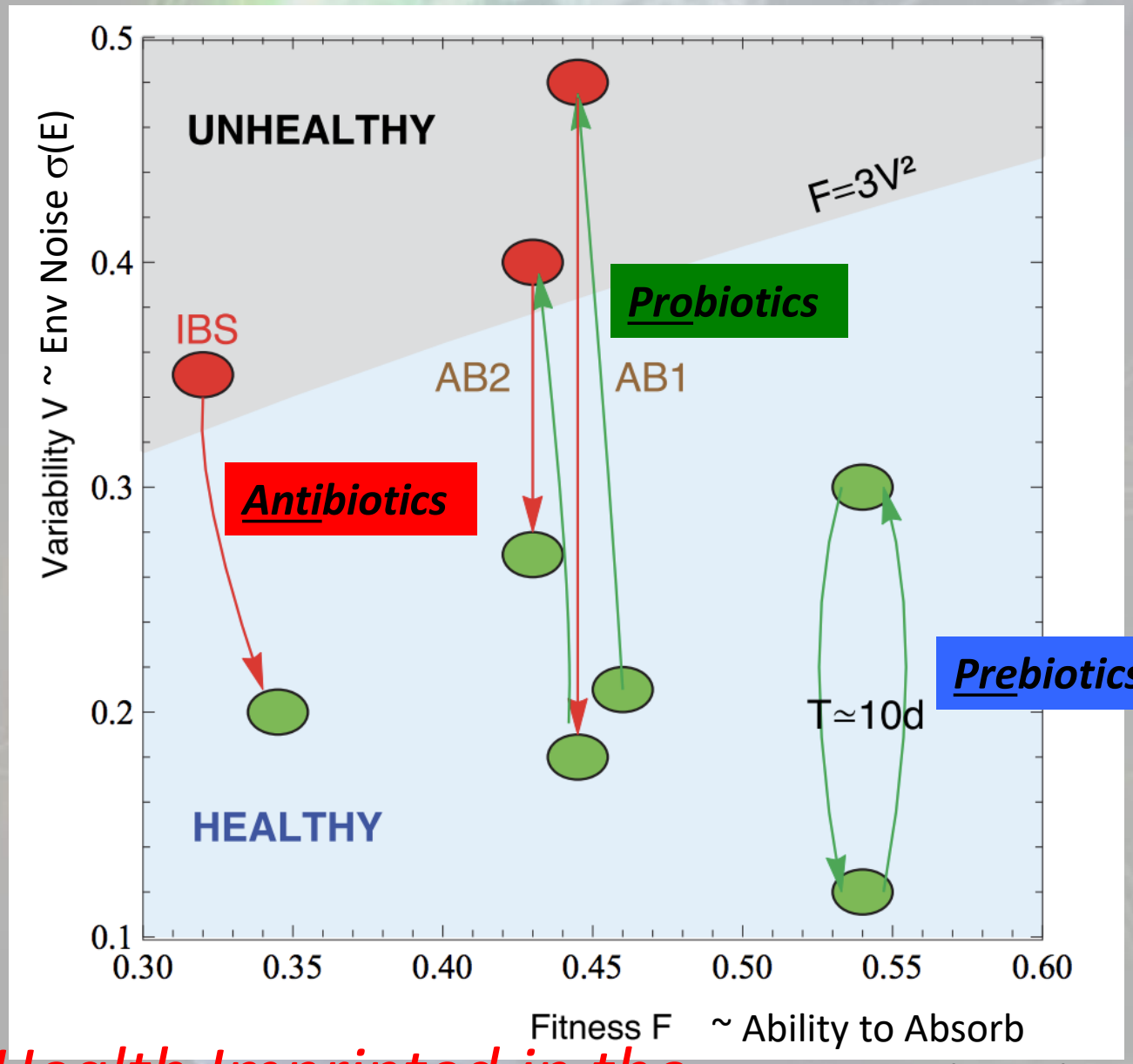
Population Patterns as Fingerprint of Species Network Topology


Taylor's Law
SD
Mean
Healthy
γ_H = 0.68
Transitory
γ_T = 0.73
Unhealthy
γ_U = 0.79
α_{random}=0.5
$SD(A) \sim \langle a \rangle^{\alpha}$
$\alpha \sim 1/\beta^{(1-Df)}$
Warning! Abnormal Scaling of the Unhealthy due to "Invasive" Species

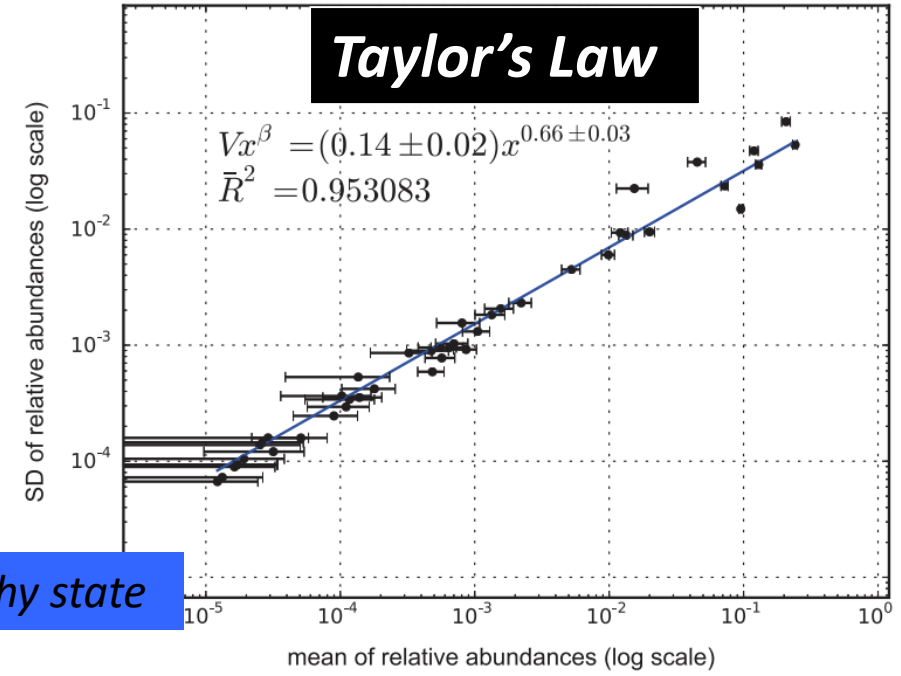


Taylor's – Zipf's Macroecological State Indicators

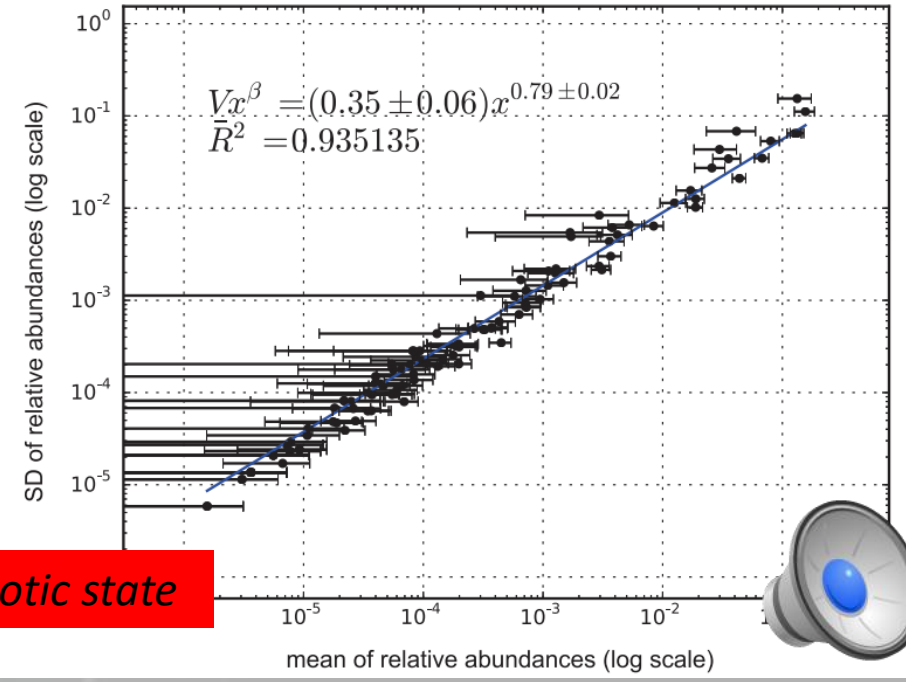
Marti et al. (2017), mSystems; Convertino and Li (2018), in preparation



Taylor's Law



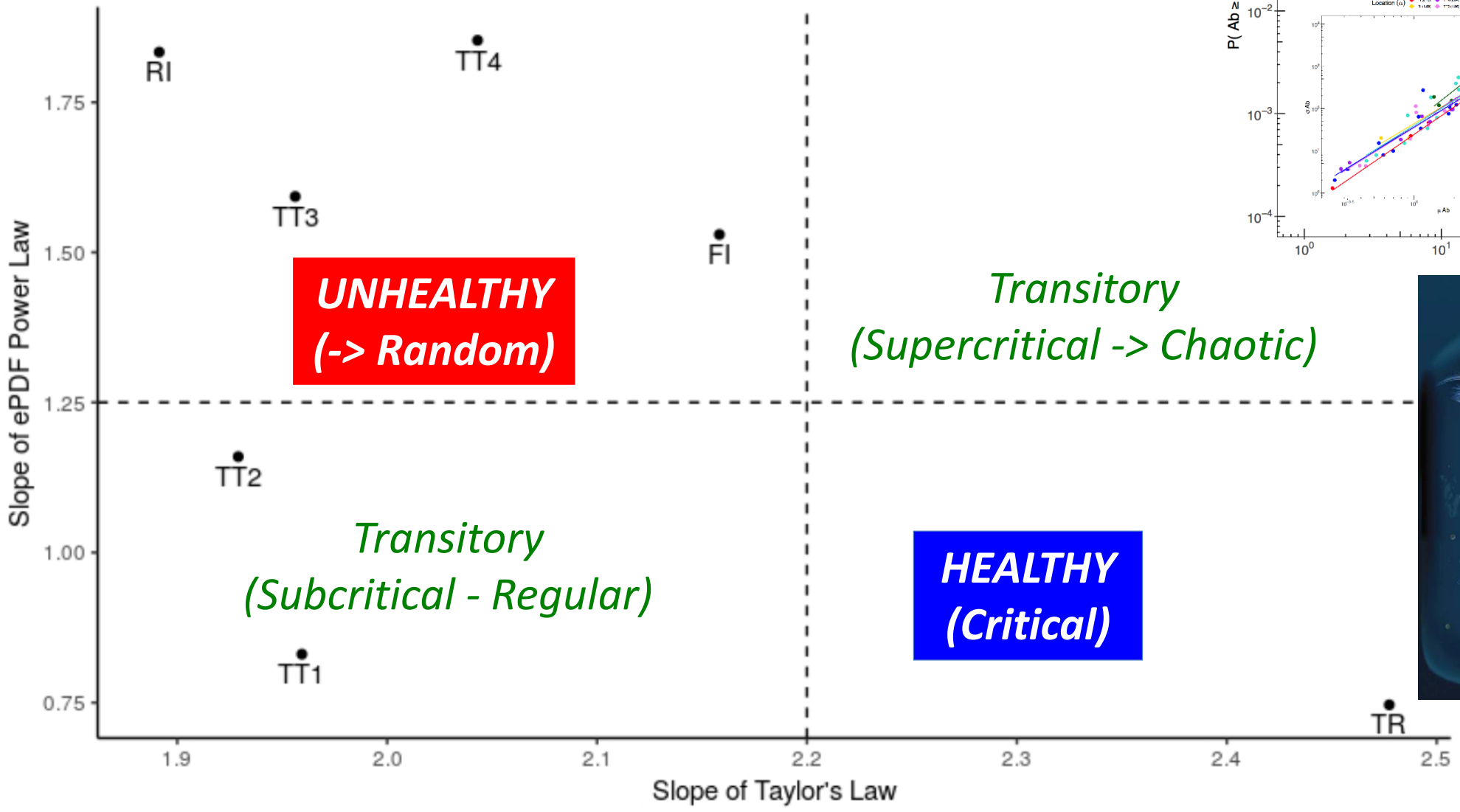
Healthy state

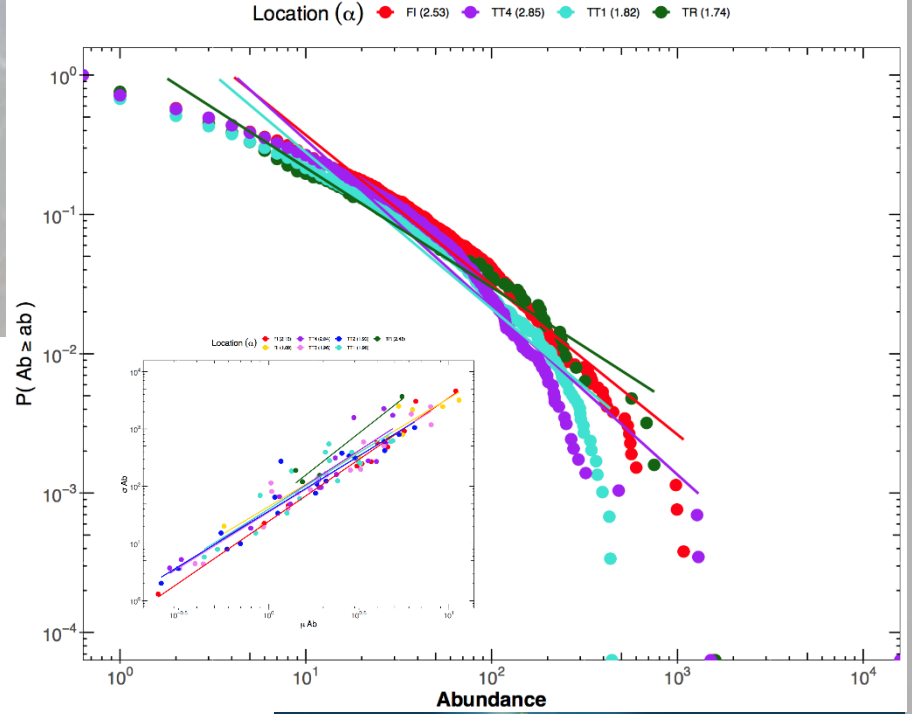


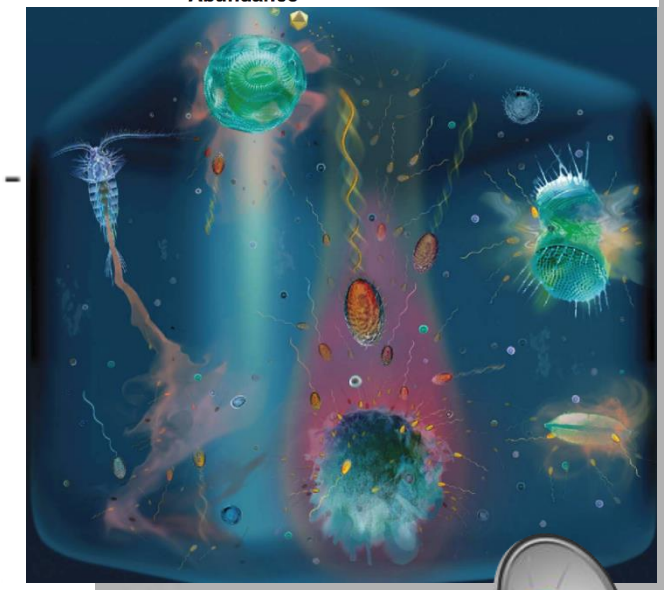
Dysbiotic state

Health Imprinted in the Temporal Dynamics

Macroecological Classification: Optimal Metabolic Function for Open Systems and Endemic Species



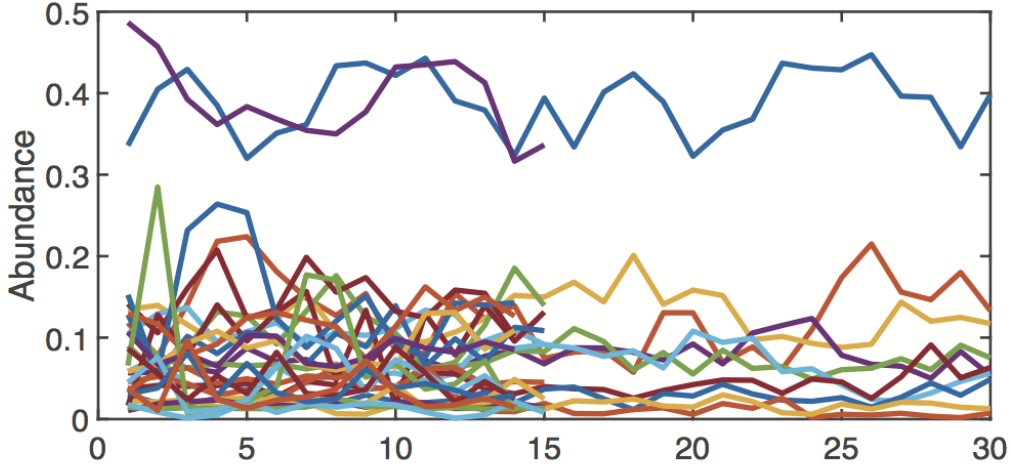




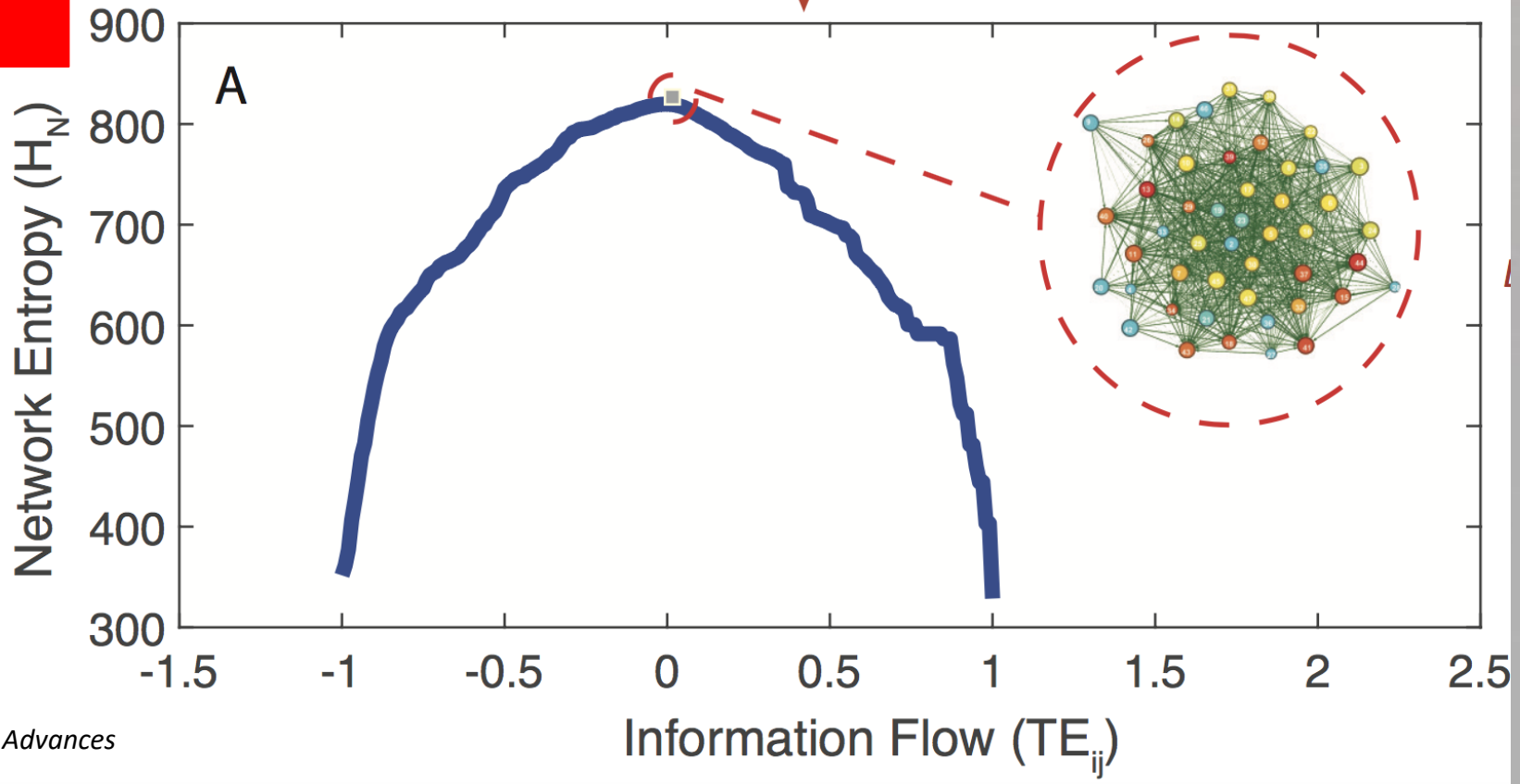
Galbraith et al (2019), GCB, submitted

Species Functional Interaction Network Inference

***OINs**: the minimum directed functional and/or structural networks useful for predicting a systemic indicator*



MICROBIOME NETWORK INFERENCE



Li and Convertino, 2019, Entropy
Servadio and Convertino, 2017, Sci Advances

Inferring Interdependency

$$H_{c,d} \sim \sum_i \Gamma(1+d, 1-c\ ln(p_i)) \qquad H = \sum_i p_i\ log(p_i)$$

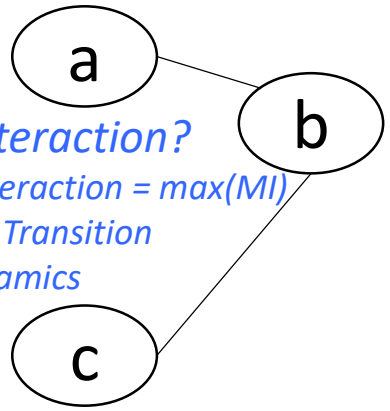
Hanel and Thurner, (2013), Entropy

Mutual Information

$$I(X,Y) = \sum_x \sum_y p(x,y) \log \frac{p(x,y)}{p(x)p(y)}$$

The amount of information that one variable contains about another variable. High I, d small.

$$d(X,Y) = e^{-I(X,Y)}$$



Is there an interaction?

Focus on Max Interaction = max(MI)

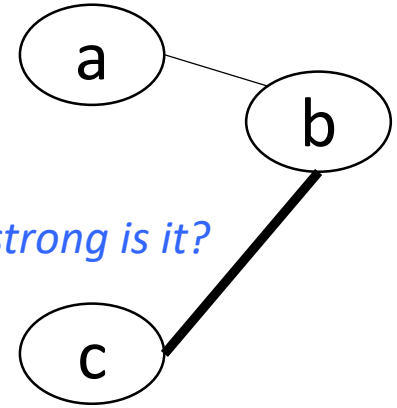
→ Prediction of Transition

vs Collective Dynamics

Conditional Entropy

$$H(Y|X^*) = -\sum_x \sum_y p(x^*, y) \log p(y|x^*)$$

The amount of information that one variable contains *conditional* on the knowledge of other variables. Entropy ``Reduction''.

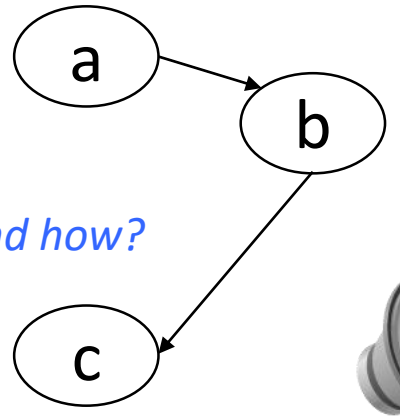


How strong is it?

Transfer Entropy

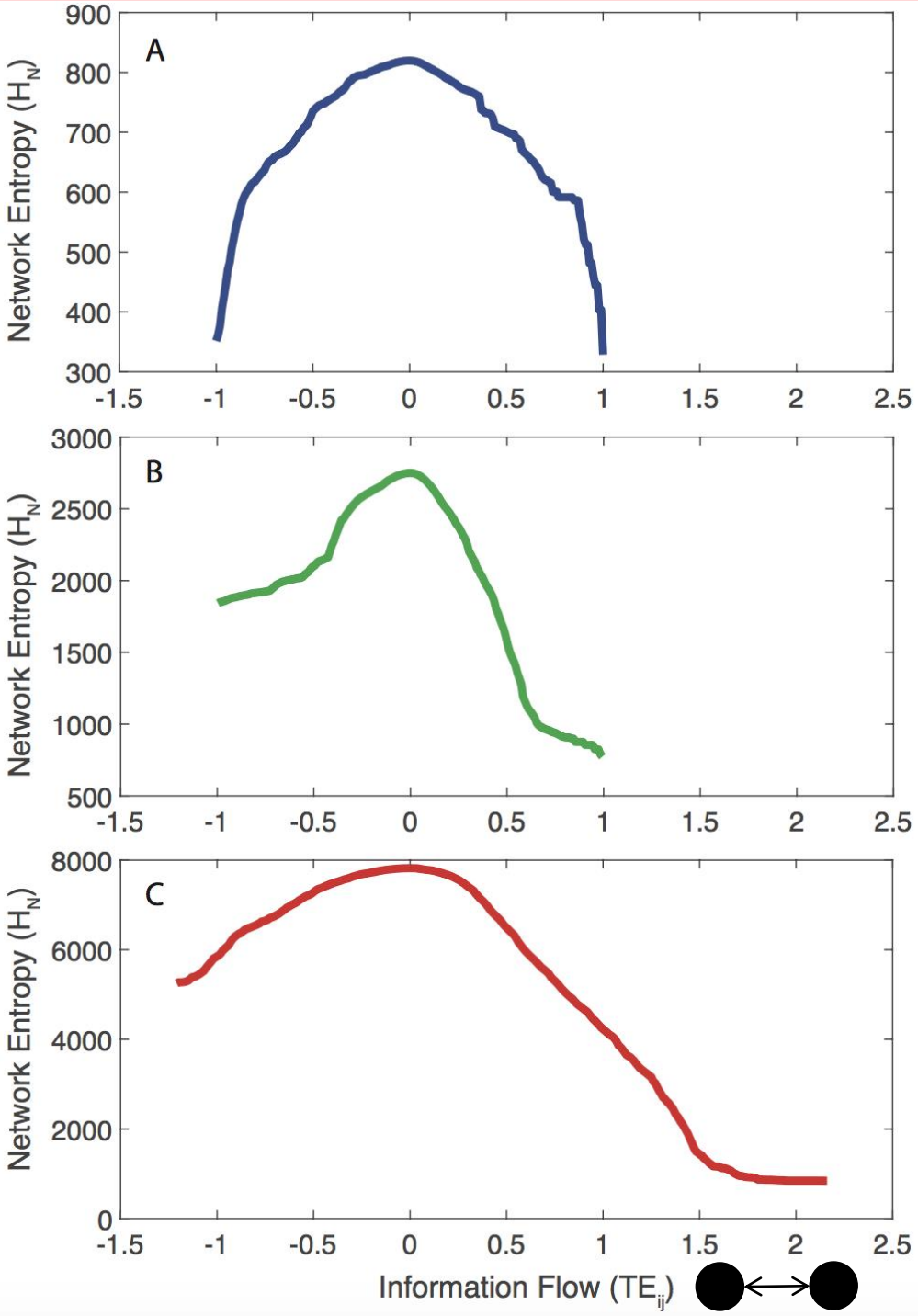
$$T_{X\to Y} = H(Y^\tau|Y^{t-\tau}) - H(Y^\tau|Y^{t-\tau}, X^{t-\tau})$$

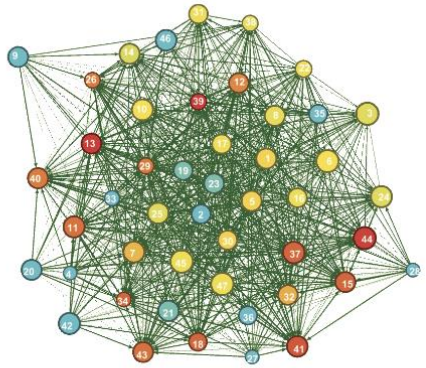
The amount of information that one variable contains based on the knowledge of the *history* of another variable. After Entropy Reduction. TE~Causal Info Flow.

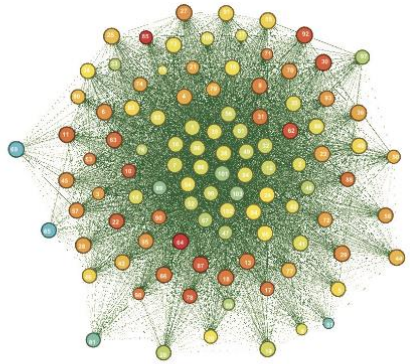


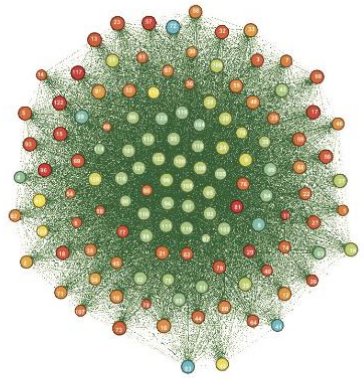
When does it occur and how?

Villaverde et al., 2014, PLoS ONE, Servadio and Convertino, 2018, Sci. Adv.









Information Network Landscape

→ Negative TE as Misinformation
→ Extreme TE for increased Divergence & Asynchronicity

Neutral & critical

Non-ne

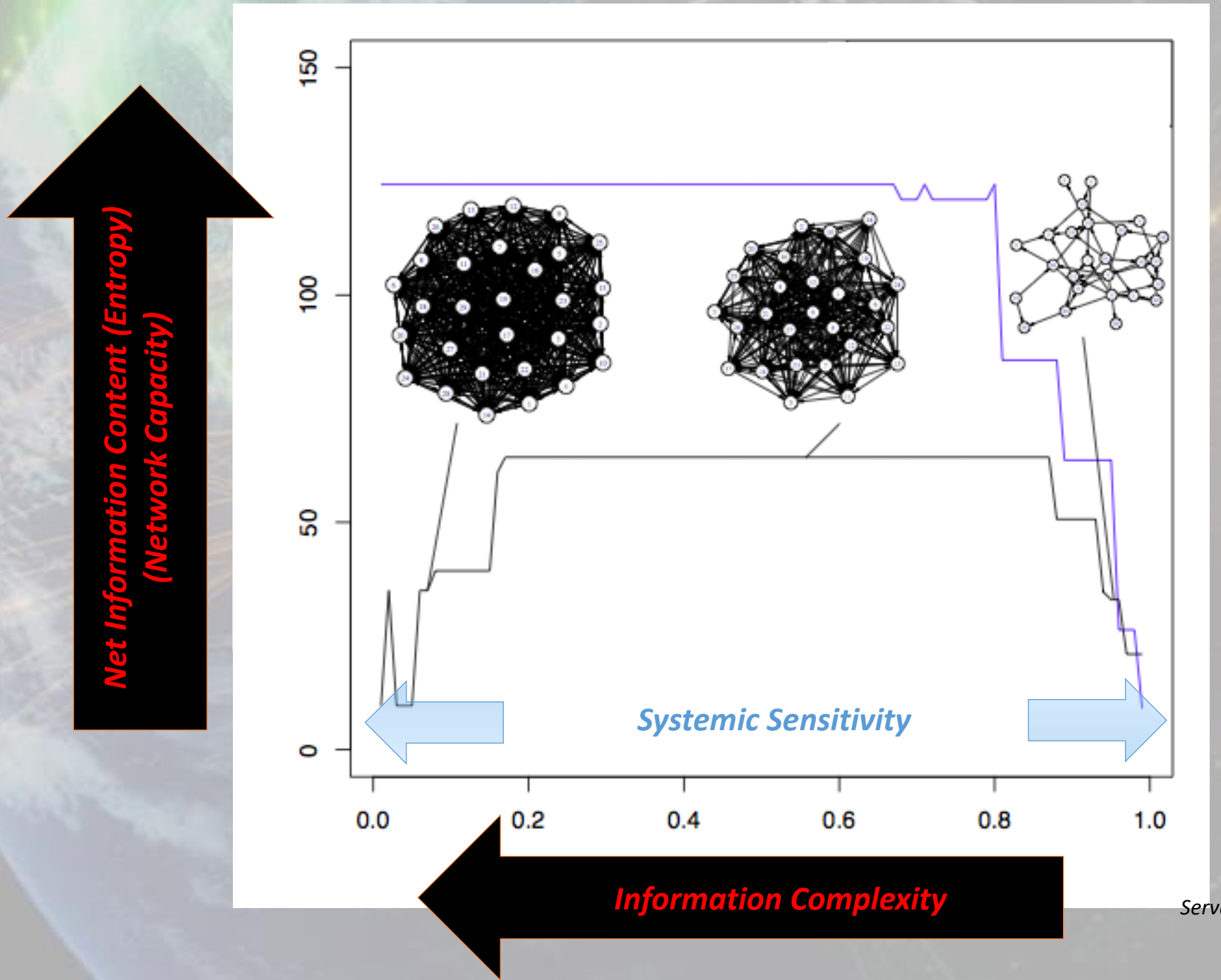
Env Variations (e.g. Infections, Stormwater, extreme Climate Change) are the cause of the environmental shift

Non-neutral (niche) & chaotic

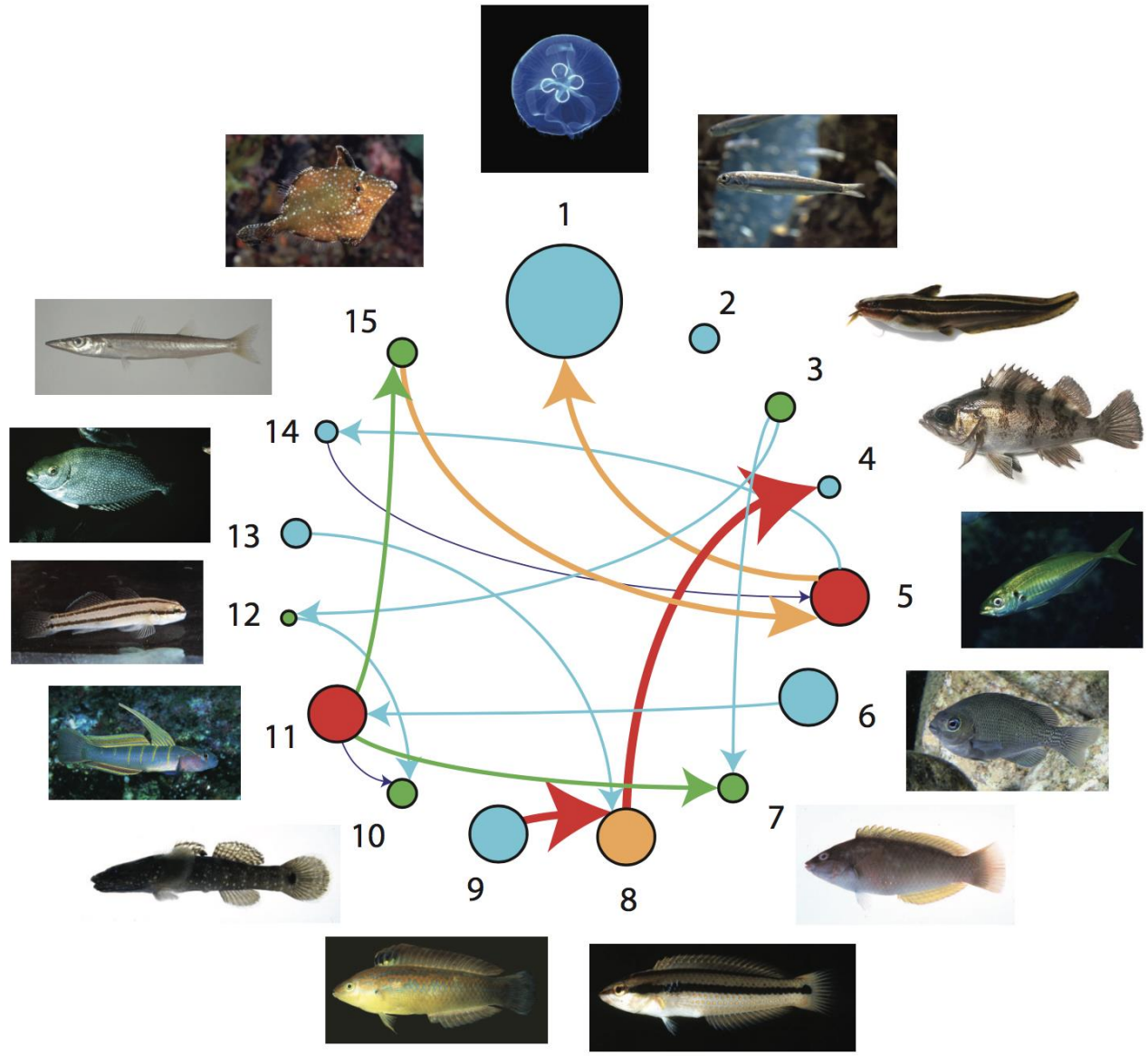
Li and Convertino, 2 py
Servadio and Convertino, 2017, Sci Advances

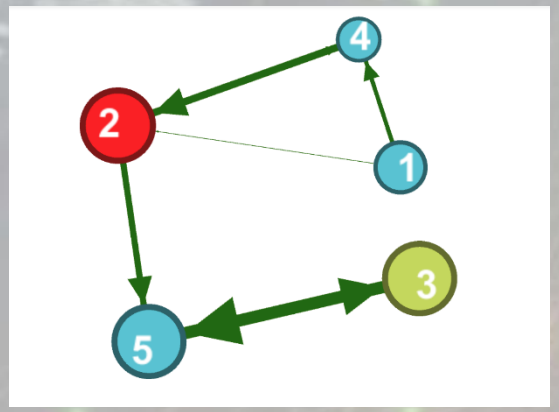
Complexity & OINs

The ambiguity of simplicity … between order and chaos…



Servadio and Convertino, 2017, Sc
Crutchfield, 2012,



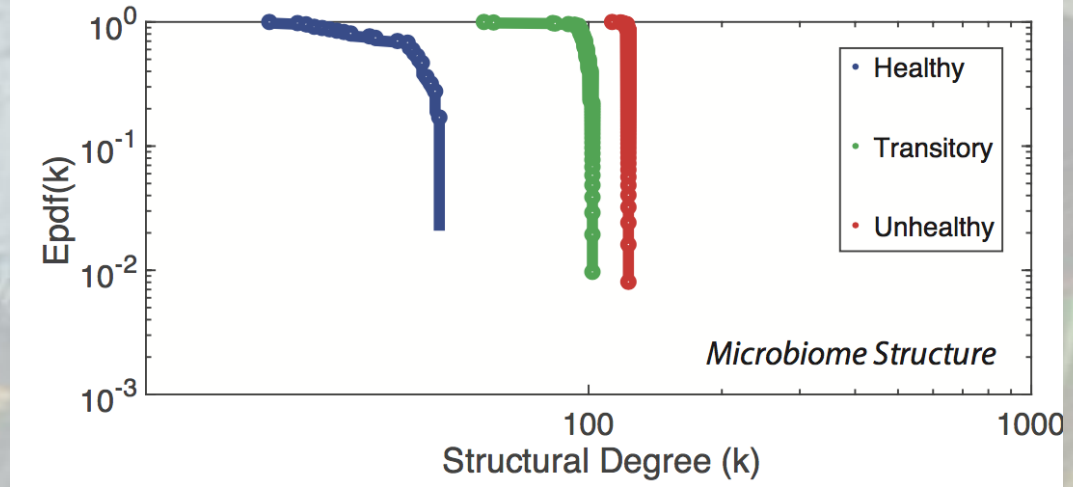


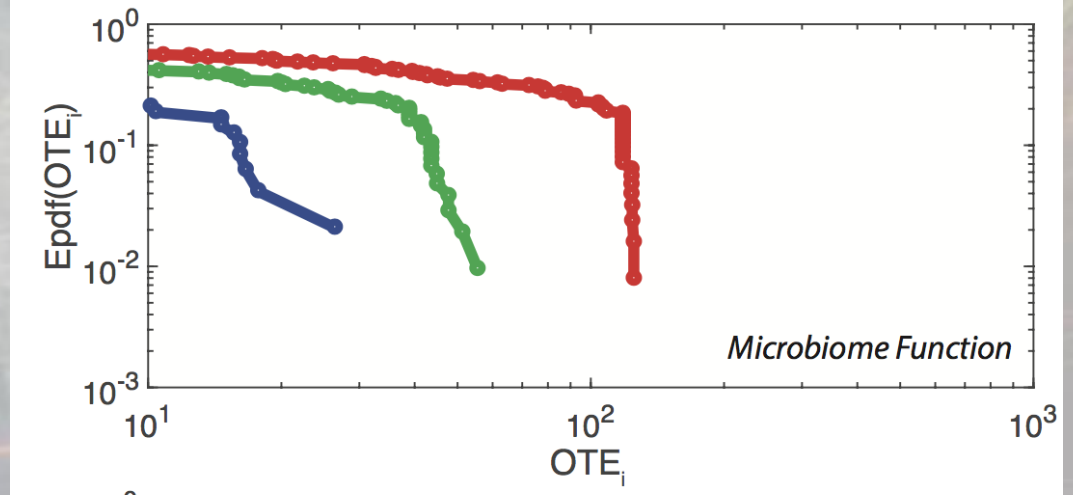
Network Viz for MaxEnt Interactions

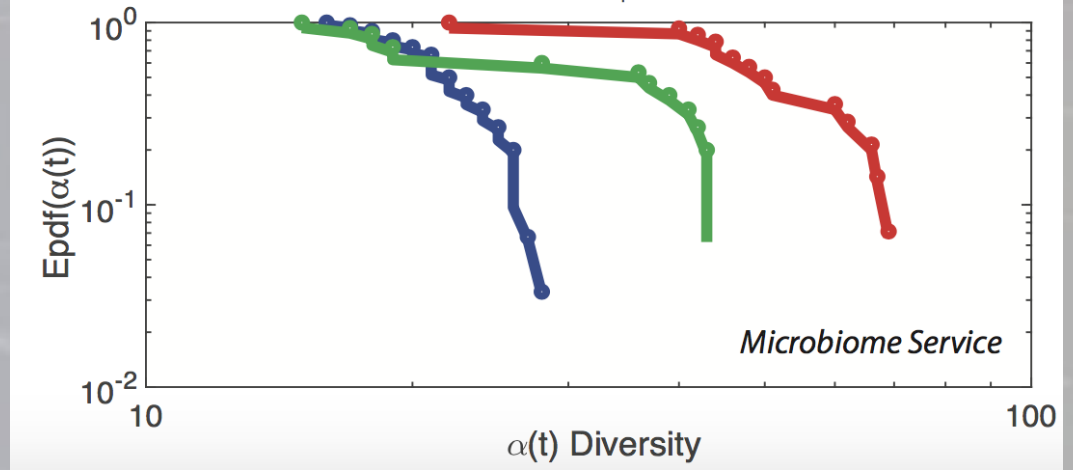
(1) the *size of each node* is proportional to the *Shannon Entropy* of the species (AIS)
(2) the color of each node is prop to the sum of total Outgoing TE of the node (OTE). The higher OTE, the warmer the color
(3) distance = min(exp(-I(X,Y))) where I(X,Y) is the mutual information between variables x and y.
(4) the width of each edge is proportional to the pairwise Transfer Entropy/Info Flow
(5) the direction is related to TE(i->j); the direction of this edge is from i to j.

Structure is not precisely reflecting Function; therefore assessing the Information Exchange is crucial to guarantee Eco Services! Function-Service Nexus much stronger

It seems however possible to alter structure (if spatially defined, e.g. a dispersal net) and have an effect on function. Relationships between structure and function can be mapped!

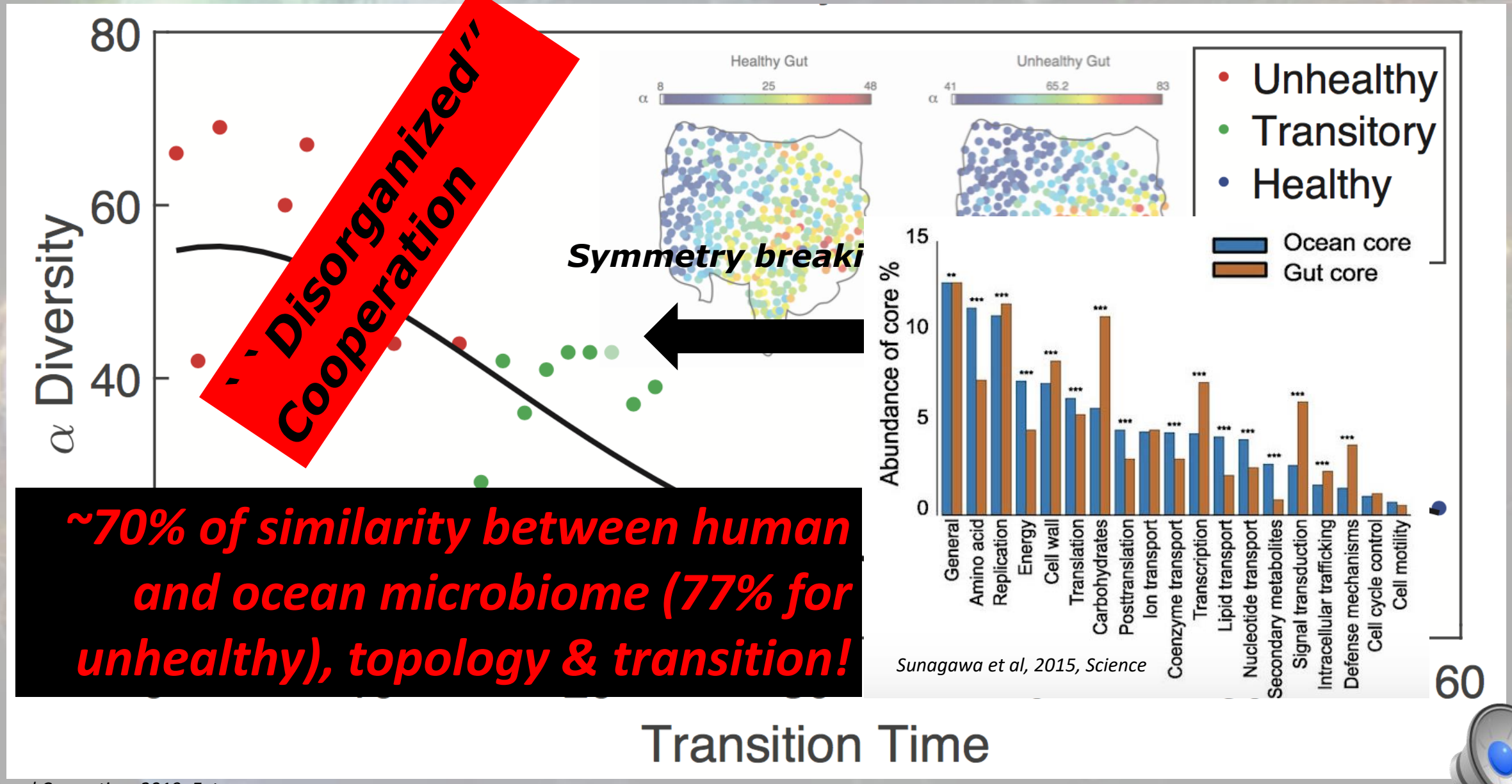






Syntax, Communication, and Semantic

Second Order Phase Transition in the Human Gut

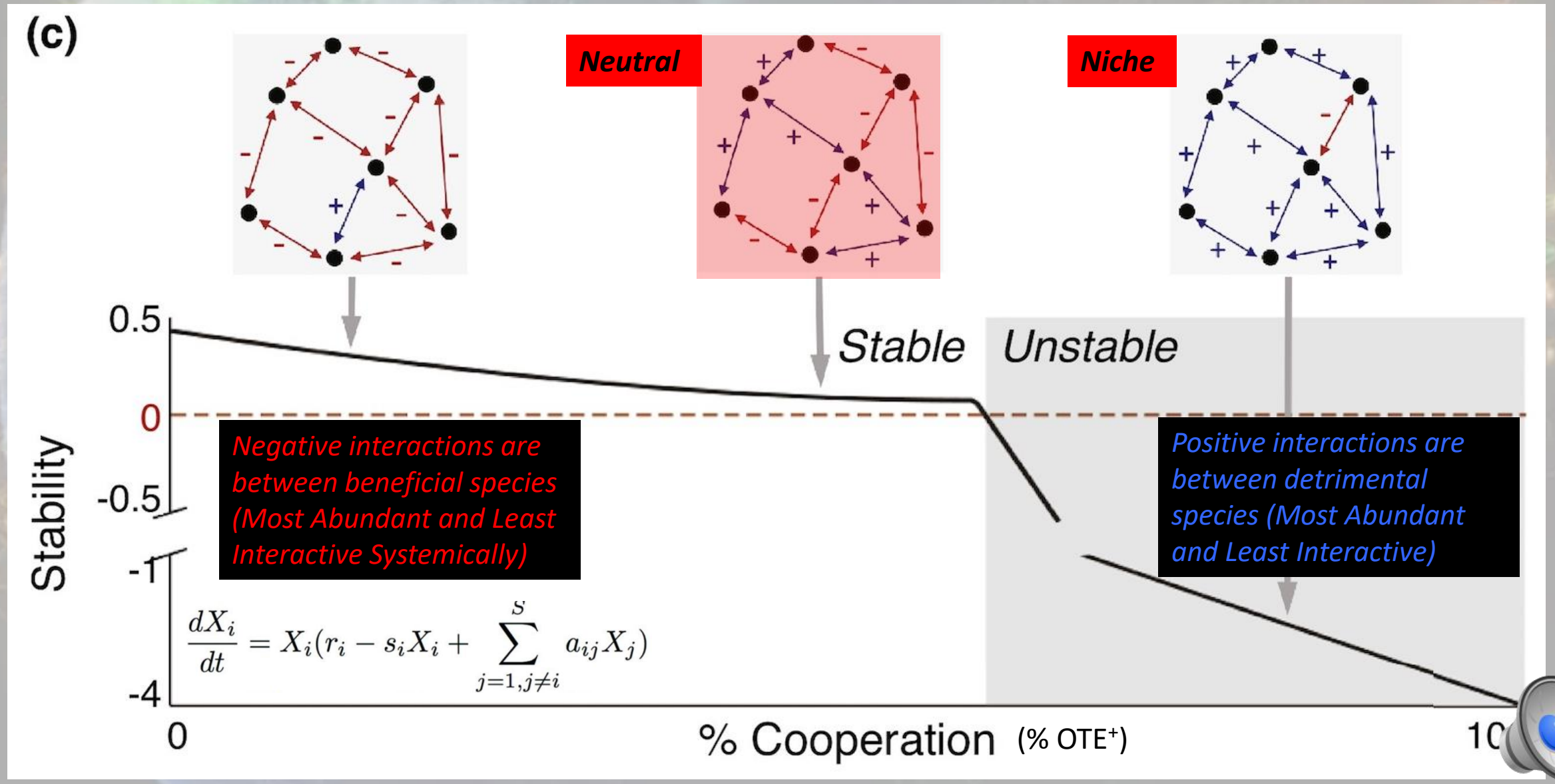


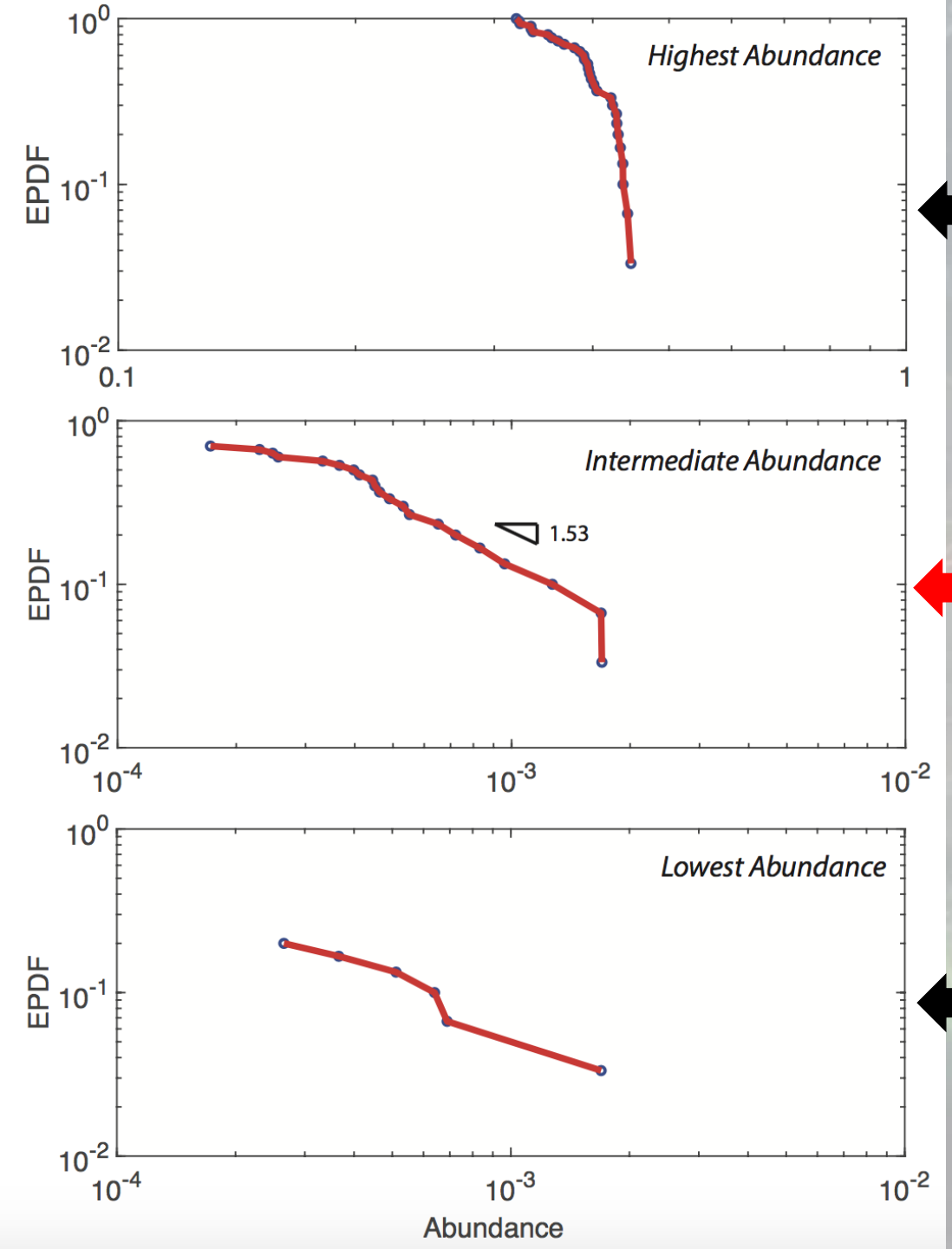
~70% of similarity between human and ocean microbiome (77% for unhealthy), topology & transition!

Sunagawa et al, 2015, Science

Li and Convertino, 2019, Entropy

Network Function (as Predictable Dynamics vs Bio-causality) and Ecosystem Stability. Positive Interaction Bio-sensu -> Low predictability / Max Cooperation





Species Abundance Distribution

The Common, "Dominant" (Low Fitness)

Most stable (High Fitness, Globally Stable)

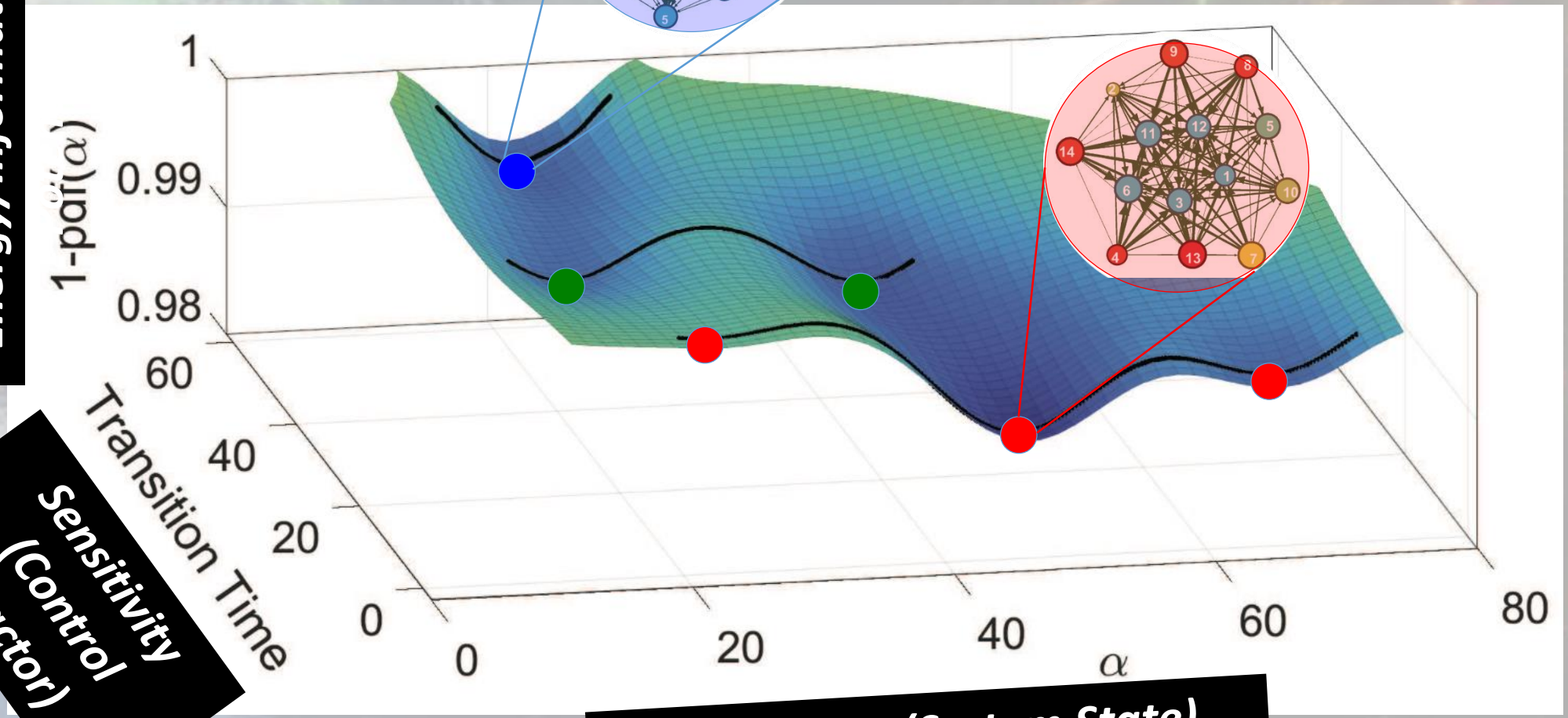
The Uncommon, Causing the "Butterfly Effect", the Tipping

*The dominant make the norm, but the uncommon produce the spiky evolution (those are the ones that "talk" the most) … **the Tragedy of the Commons,** & on the diminishing role of network hubs*

Convertino and Li (20…

Ecosystem Potential Landscape

$$E_F = E_{T\ (dissipation)} - H$$

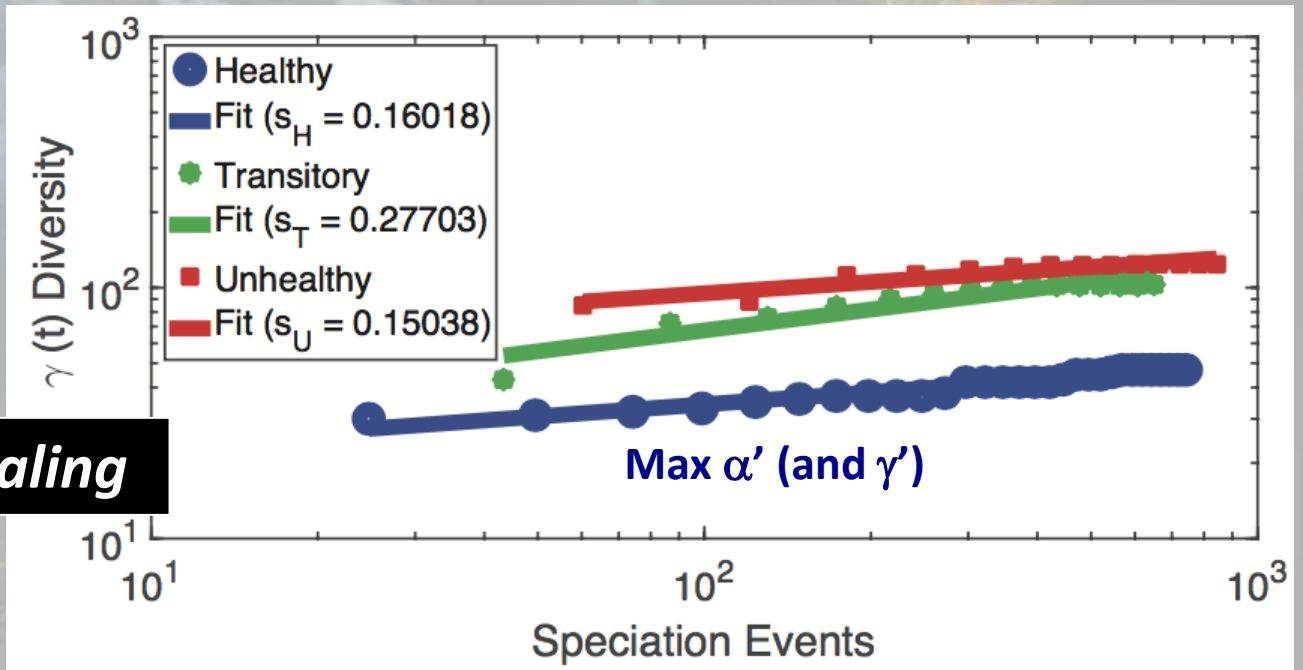


Li and Convertino, 2019, Entropy

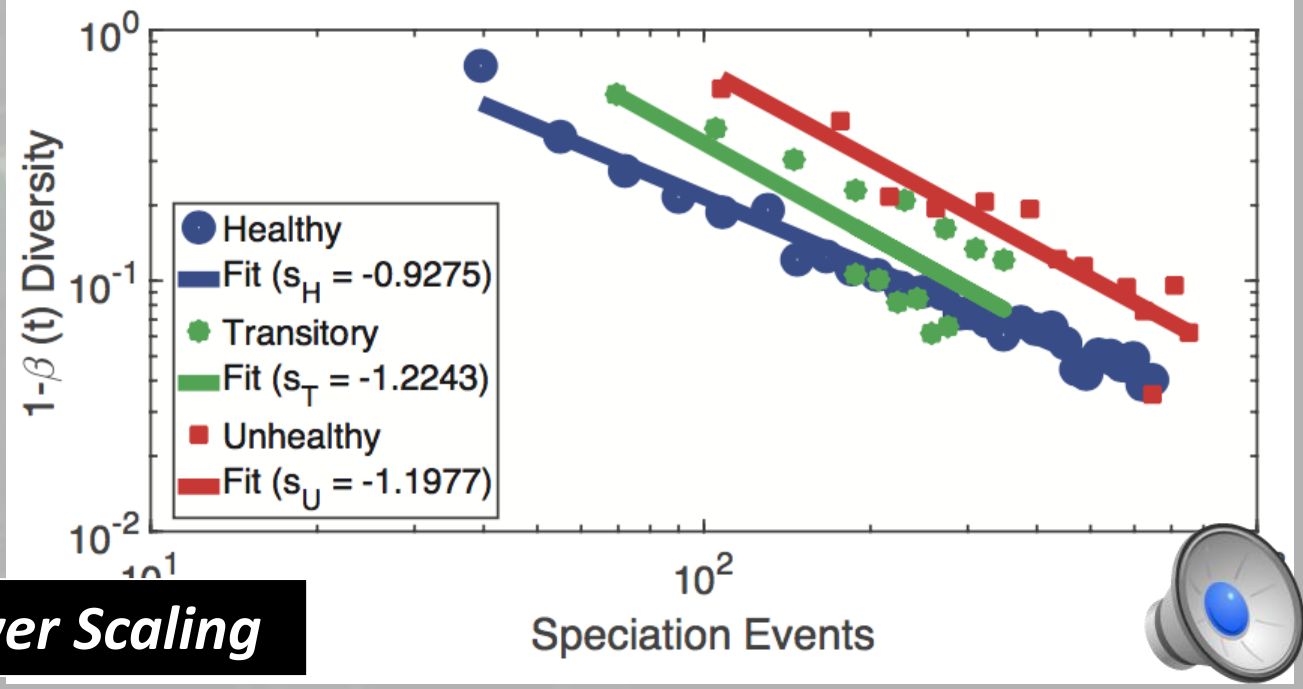
Macroecological Patterns

Principle of Optimal Evolution and Diversity Decay

Species-Area Scaling



Species Turnover Scaling

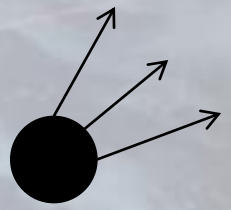


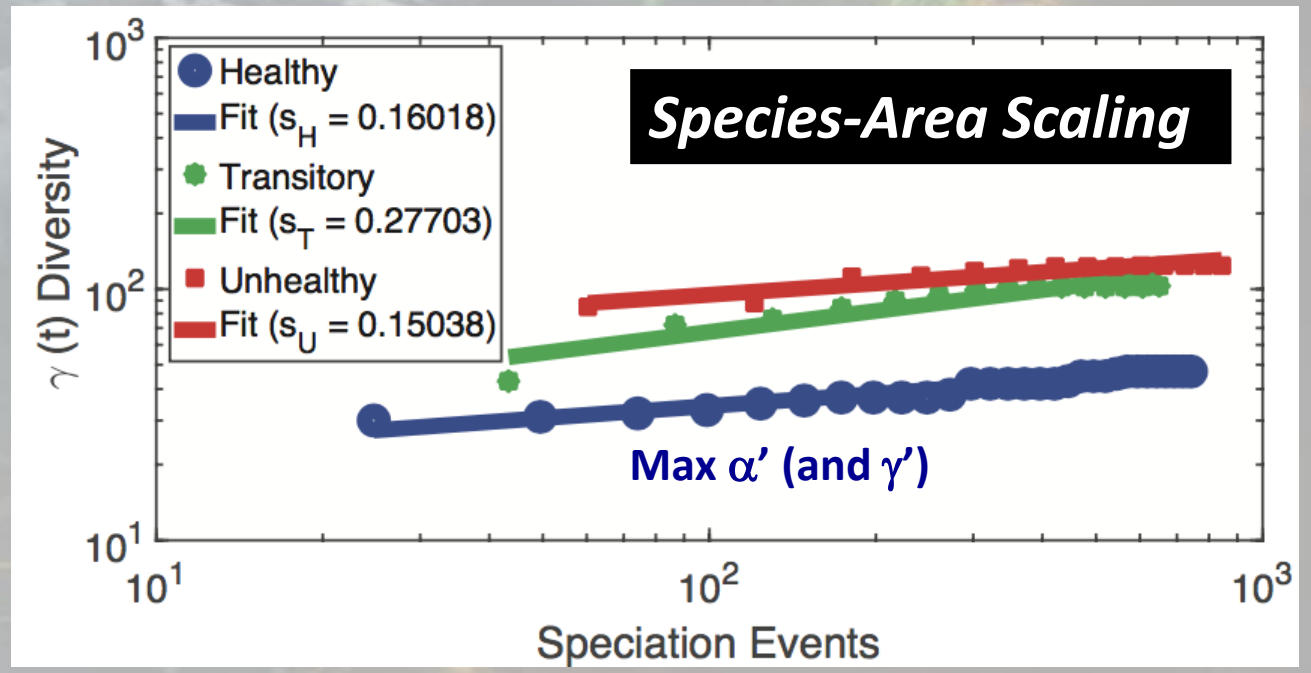
Li and Convertino, 2019, Entropy

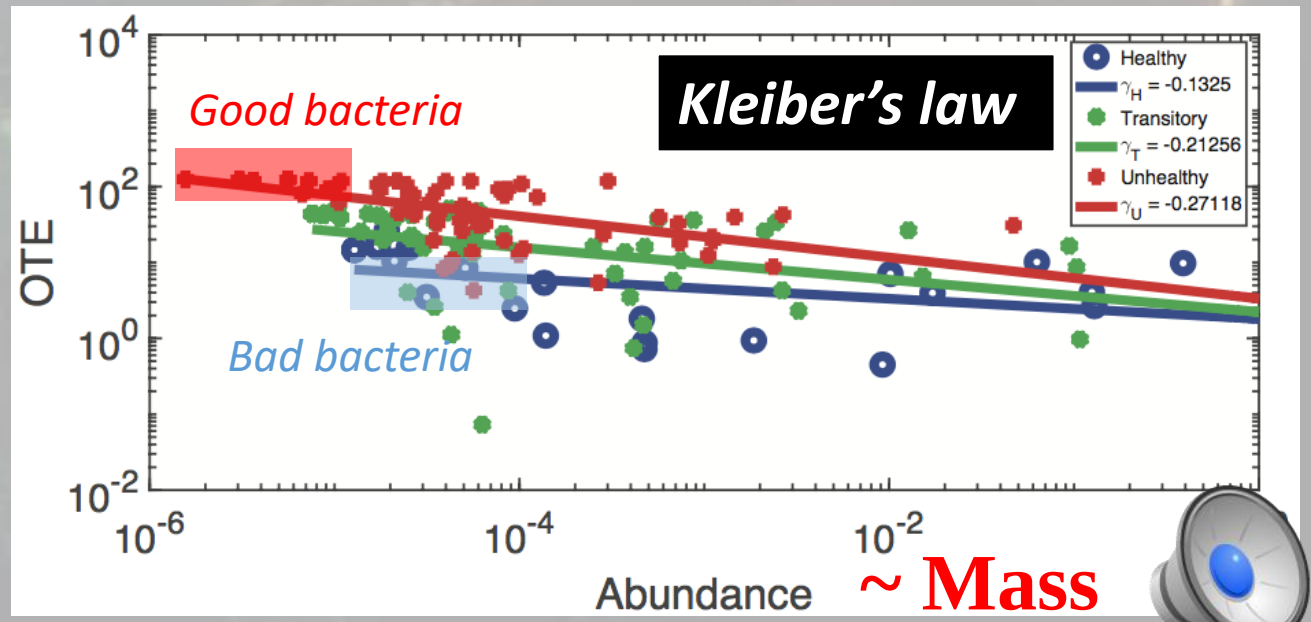
Macroecological Patterns & Network Function

Principle of Pareto Optimal Evolution
("Heaps' law")

Each Abundance class defines a *Function* (OTE) ~ Hydrolisis Rate



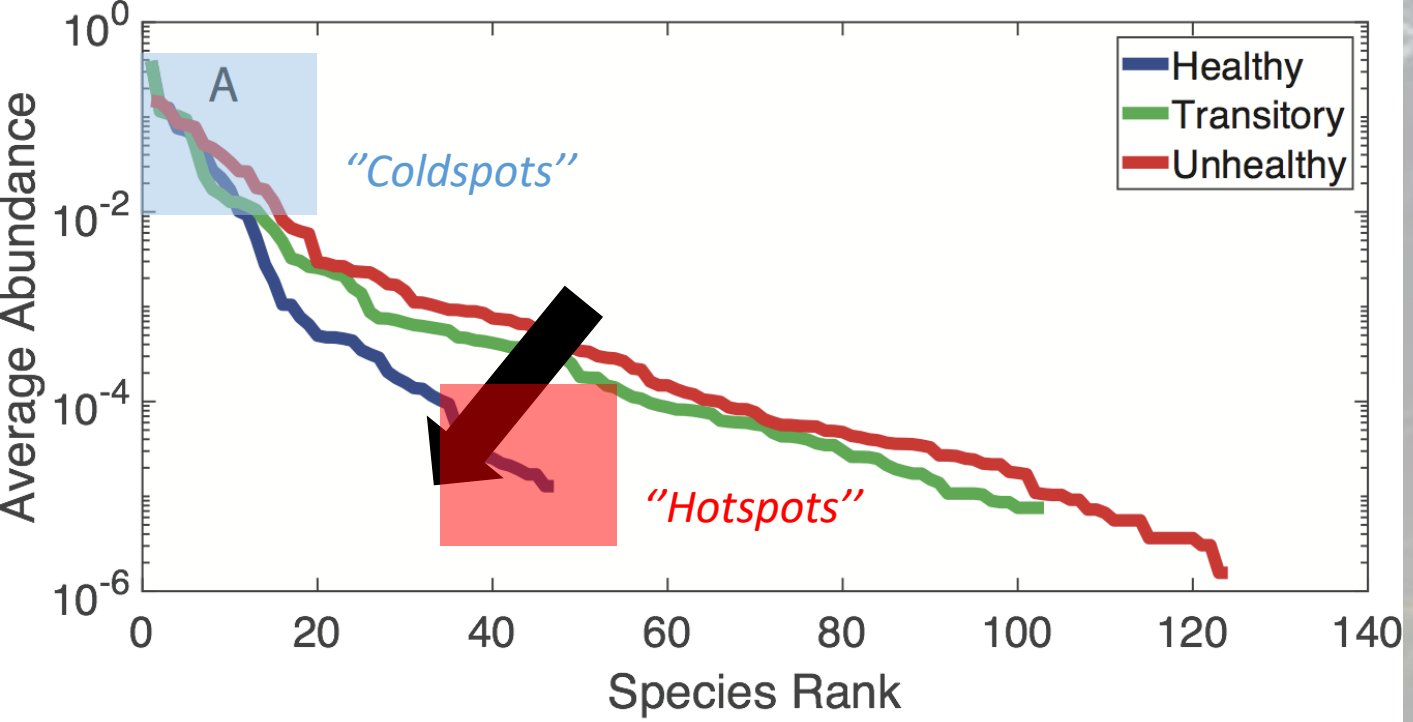


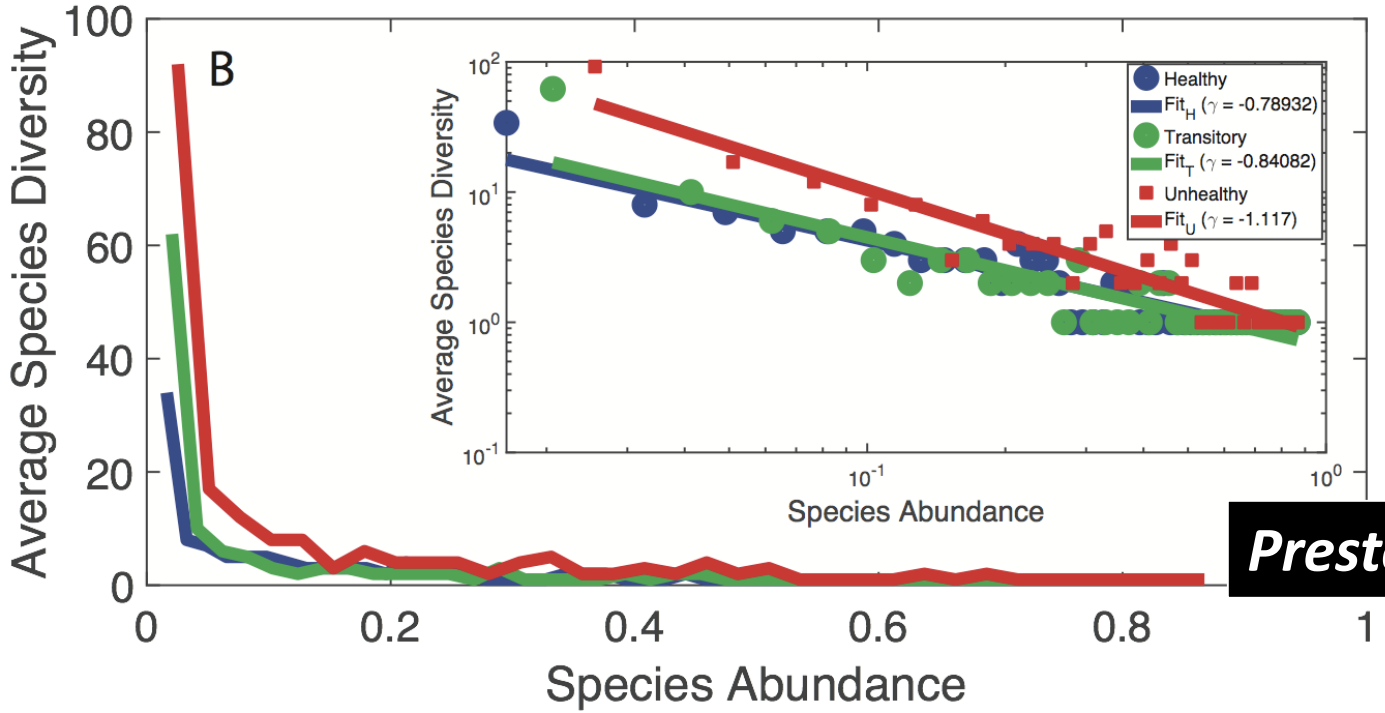


~ Metabolic Rate$_{\text{mass spec}}$

~ Mass

Li and Convertino, 2019, Entropy

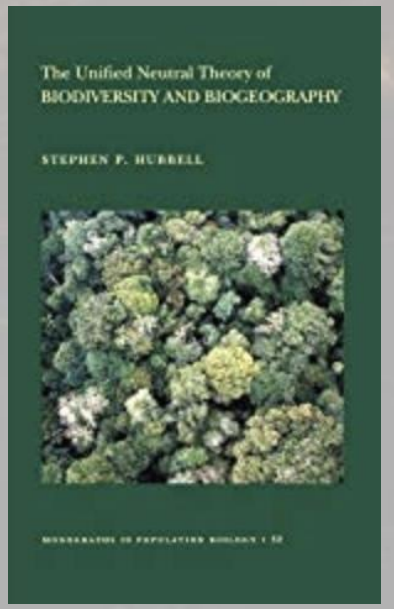


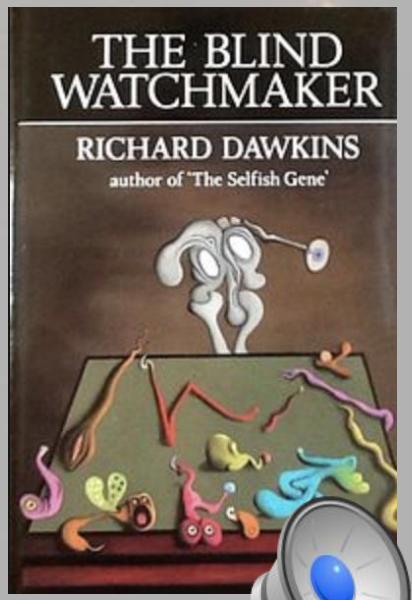


Preston Plot

Universal Pattern and Singular Variations: Transitions from Simple Patterns

A power-law decay of the Relative Species Abundance (RSA) for the unhealthy microbiome is what we desire (!) vs. the expected neutral and Poissonian pattern of the healthy RSA





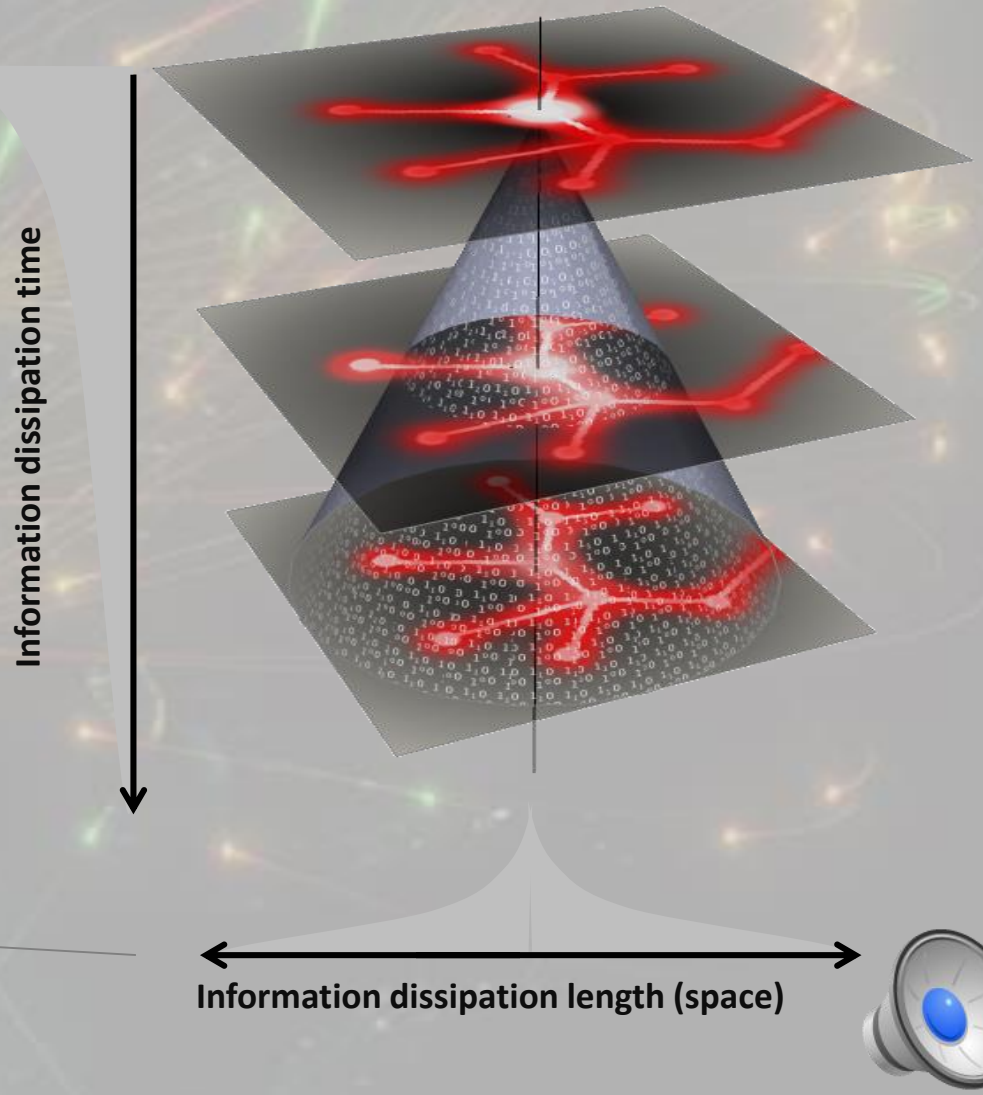
Convertino and Li (2015), E[illegible]

Information Dissipation for Info-based Species Rank

How long is the information
about a node's state
retained in the network? (Active Information Storage)

measures of influence of a single node (or of a stressor) to the dynamics of the entire network!

How far can the information
about a node's state reach
before it is lost? (Transfer Entropy)



Info Balance -> Info-theoretic Global Sensitivity Analysis

Ludtke et al., 2008, JRSI
Saltelli et al., 2008, JWS
Convertino et al., 2013, EM&S

Information Balance Eq.

Local Variability

Functional and/or Structural Systemic Variability

$$H(IH) \approx \sum_i H(x_i) + \sum_i \sum_{j \neq i} TE_i(x_i, x_j) + \sigma(IH)$$

Noise

General Collective sensitivity indices

$$\mu_i = \frac{H(x_i) \cdot g(x_{i,t})}{H(OIN)}$$

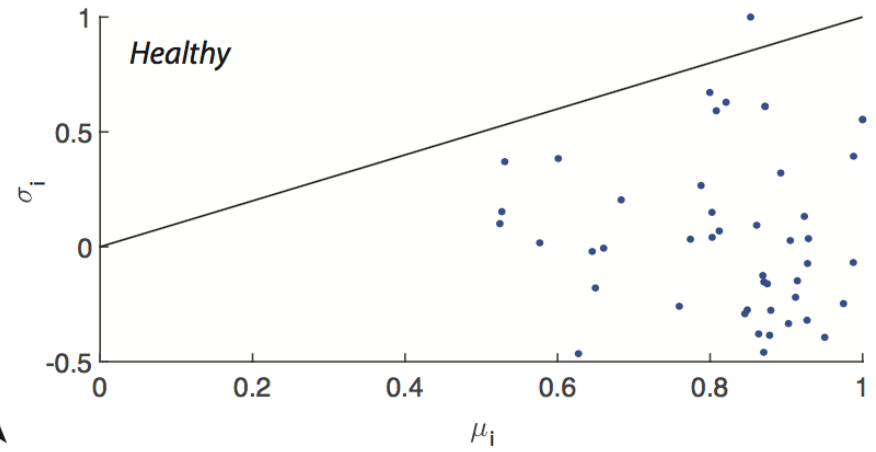
$$\sigma_i = \frac{OTE(j) = \sum_i TE_{j \to i}}{H(OIN)}$$

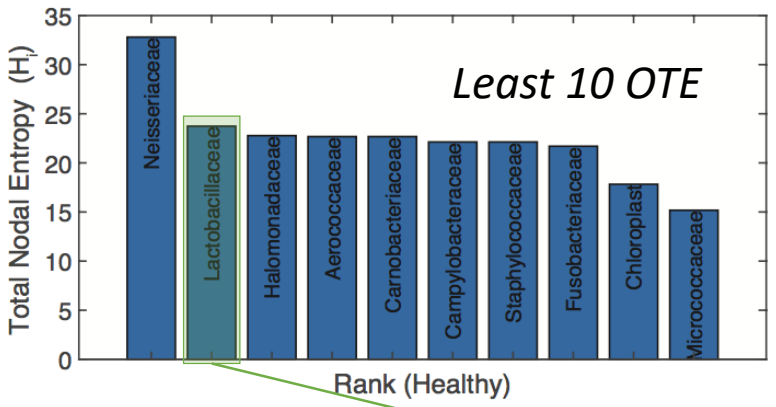
Collective sensitivity indices (constrained to predictability of ecoservices Y, e.g. α)

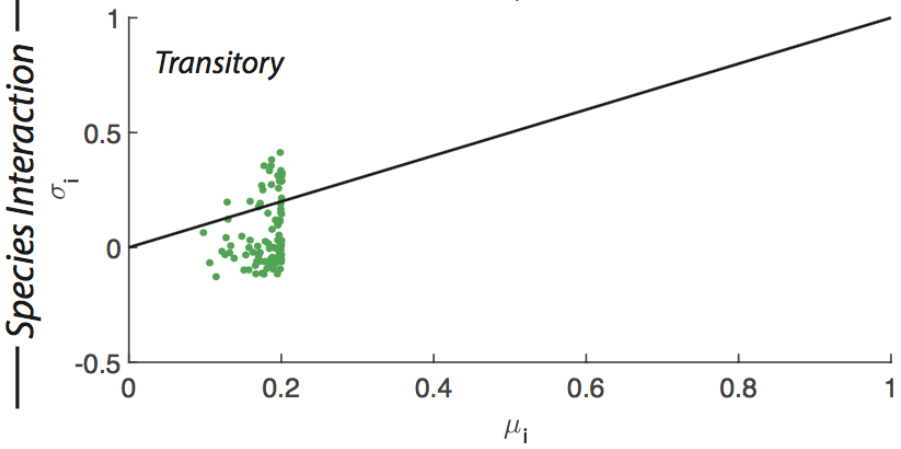
S_i - first-order sensitivity index $I(X_i; Y)/H(Y)$

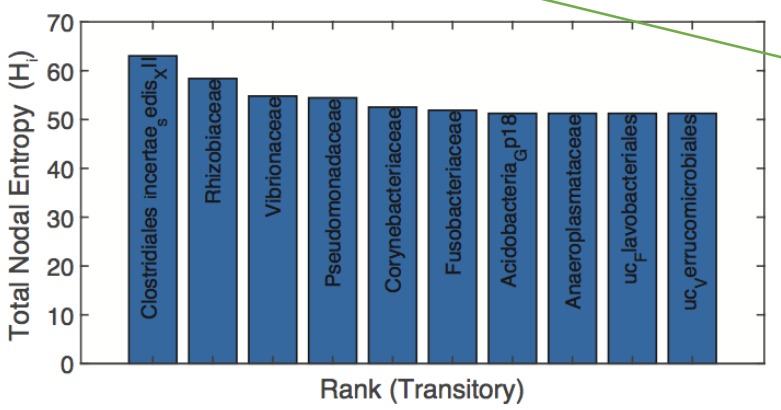
S_{ij} - 2nd ord. sensitivity index $I(X_i, X_j; Y)/H(Y)$

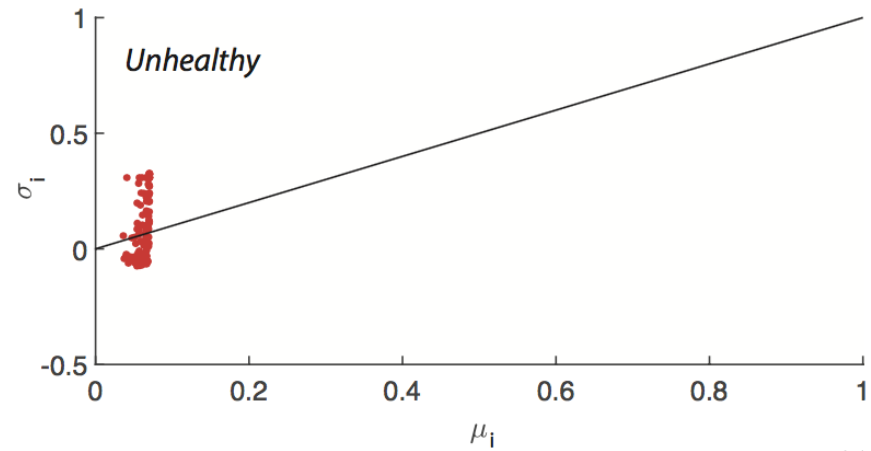
Pinpointing Causes for Microbiome Engineering: TEI

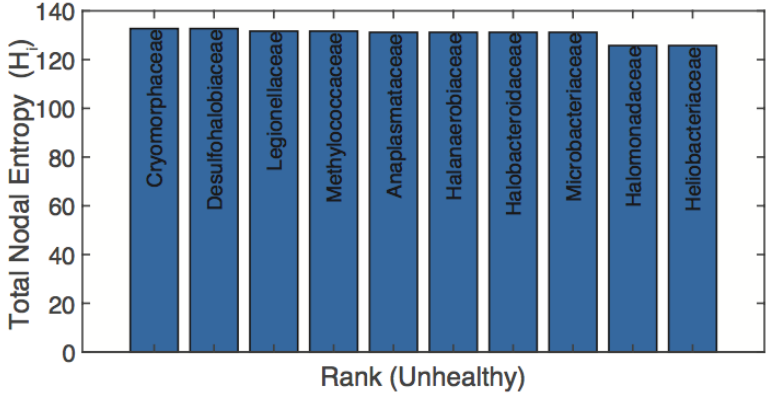












$$\sigma_i = \frac{OTE(j)=\sum_i TE_{j\to i}}{H(OIN)}$$

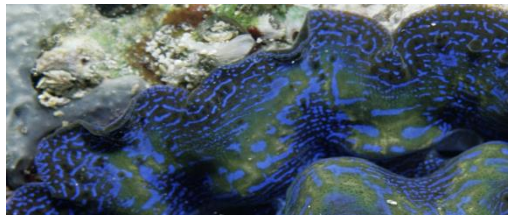
— Species Interaction →

— Species Singular Importance →

$$\mu_i = \frac{H(x_i)\cdot g(x_{i,t})}{H(OIN)}$$

Probiotics (Bacteria Inoculation)

Eco-engineering (e.g. symbiotic algae) with potential for nutrient filtering



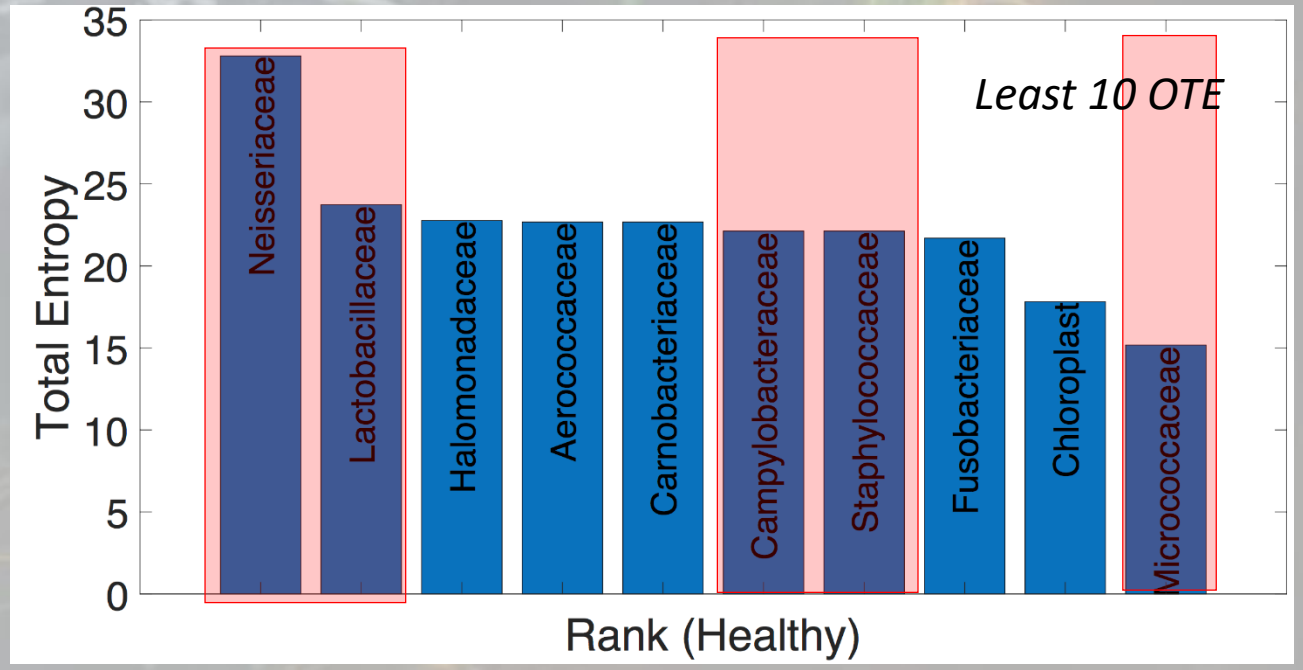
Geomorphic Engineering (Temp & hydro protection)

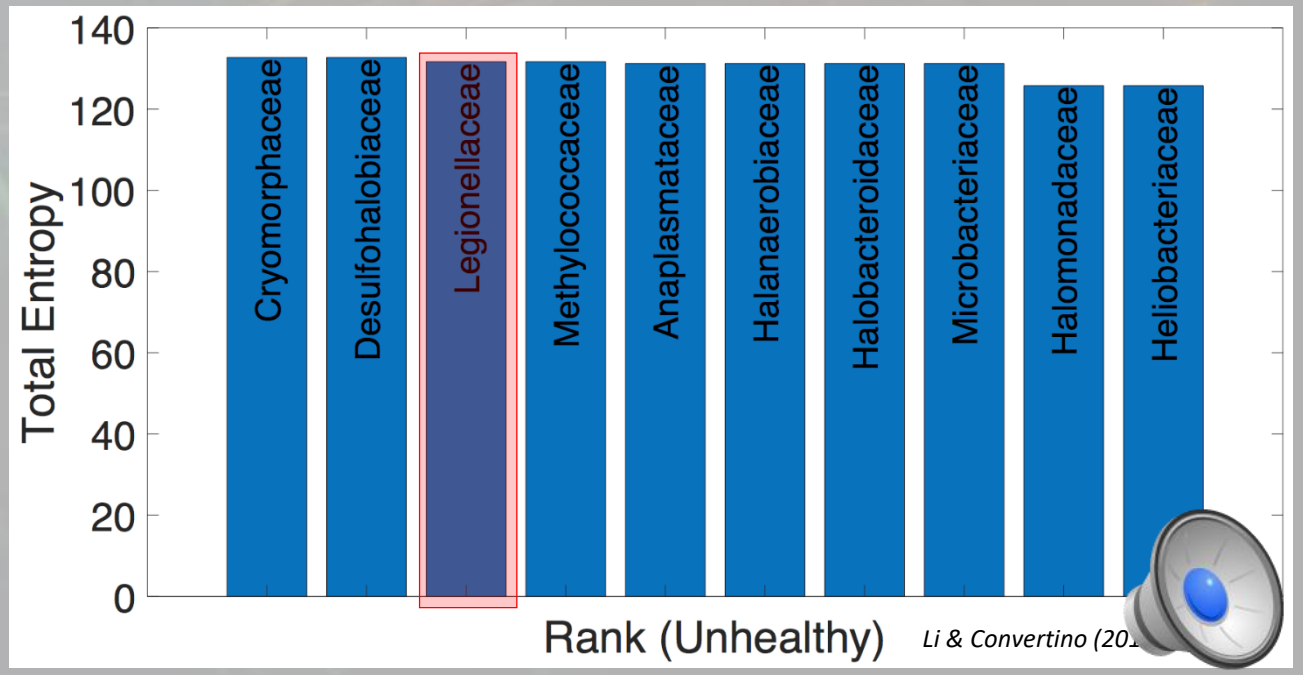
Detection of Top Species contributing to Health States for Population / Personalized Control

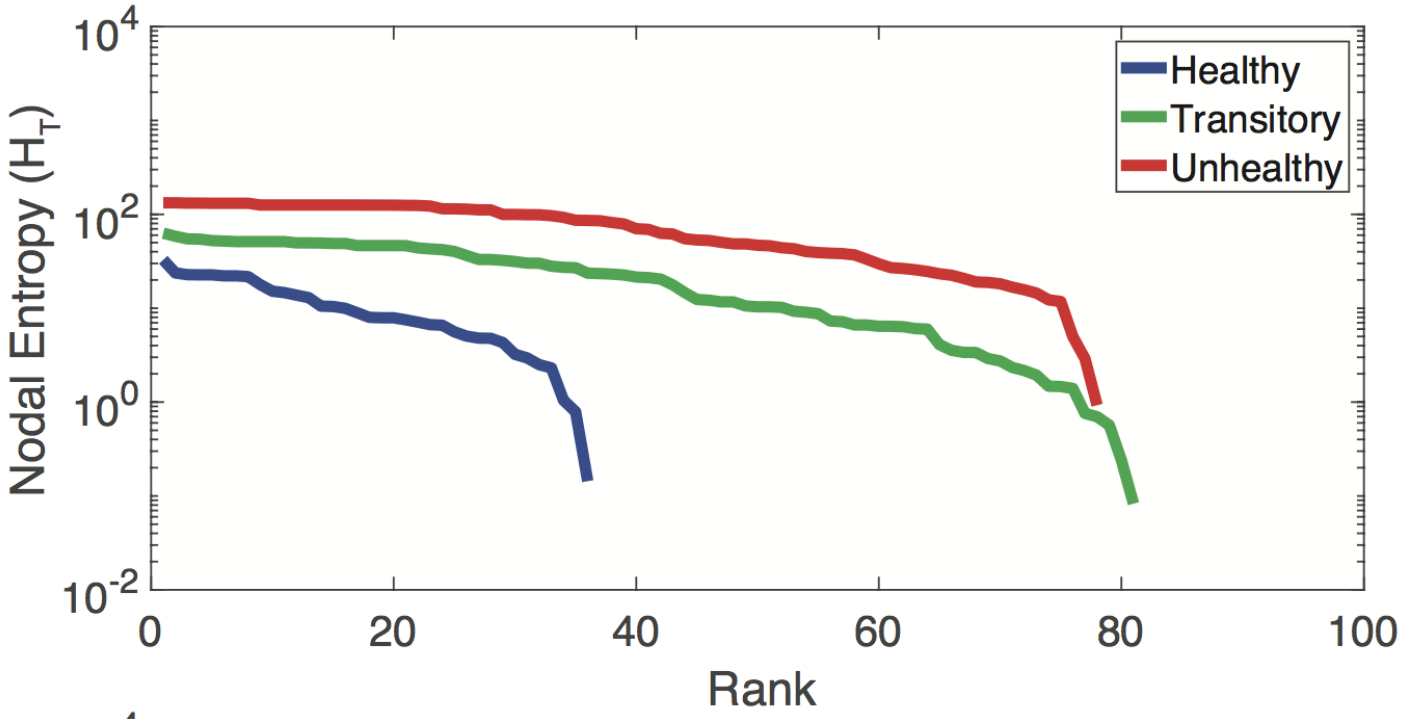
The top ten active nodes (competitive, predictability sensu) in the healthy state are the least abundant and the most dangerous species; however they are kept under control by the ''good'' nodes!

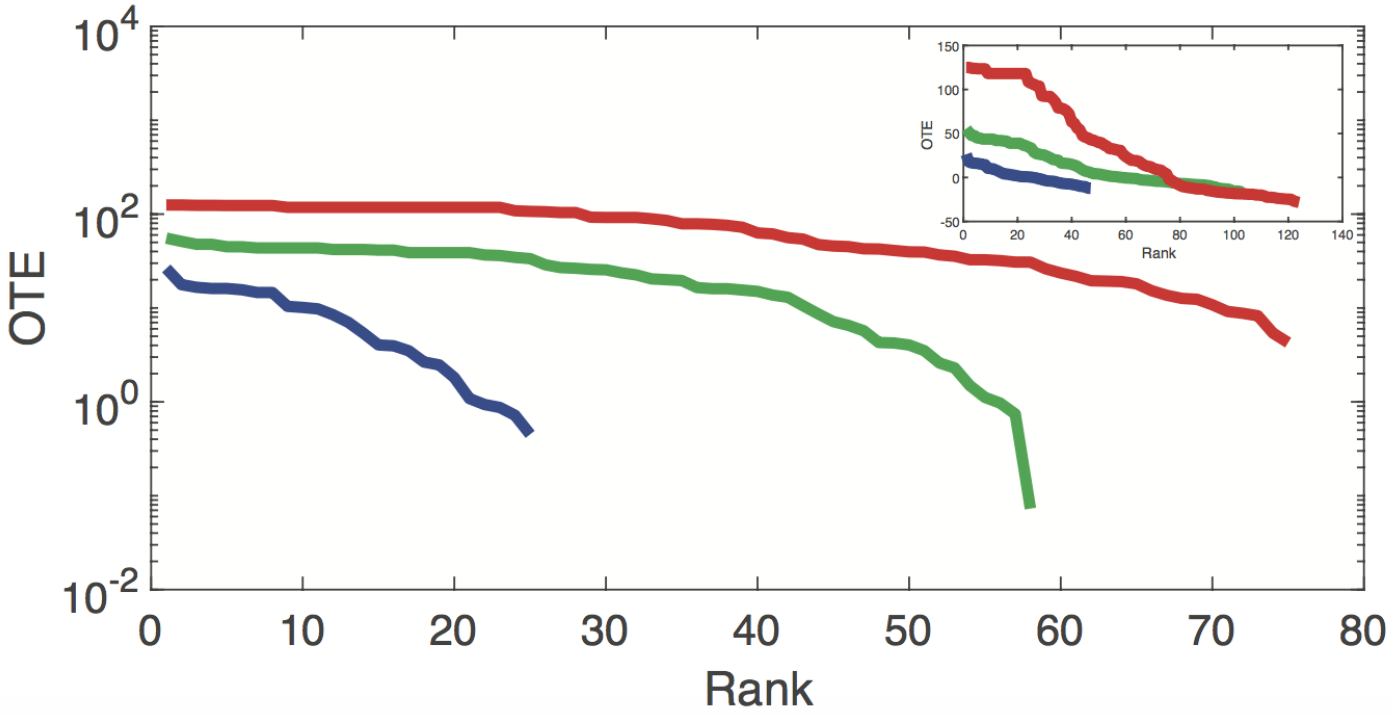
The top ten active nodes (competitive, predictability sensu) in the unhealthy state are the least abundant and the least harmful species; unfortunately they are controlled by the ''bad'' nodes!

''Hubs'' (or better CRITICAL NODES!) have fewer active interactions and they are **competitive** (positive feedbacks biological sensu, TE is high). On the diminishing role of network hubs (based on k) … vs ''weak'' ties (Granovetter) for predictability & health









OTE Importance

OTE = total Outgoing Transfer Entropy

TE = pairwise Transfer Entropy

NIS: Net Information Storage = Sum of Incoming TE – Outgoing TE

OTE is controlling the dynamics of the network (in terms of network topology)!

Unhealthy: Random Nets
Healthy: SW Nets with tendency SF

Convertino and Li (2018), in

Specific Findings

Neutral symmetrical patterns correspond to healthy states; this corresponds to small-world states that has a tendency toward a scale-free (fractal) optimal state; SW is optimal against random and targeted attacks

The critical state correspond to the neutral state where + and – interactions are balanced; criticality is not at the phase transition (of second order in this case) and is not caused by instantaneous external trigger (Criticality conferring Resilience)

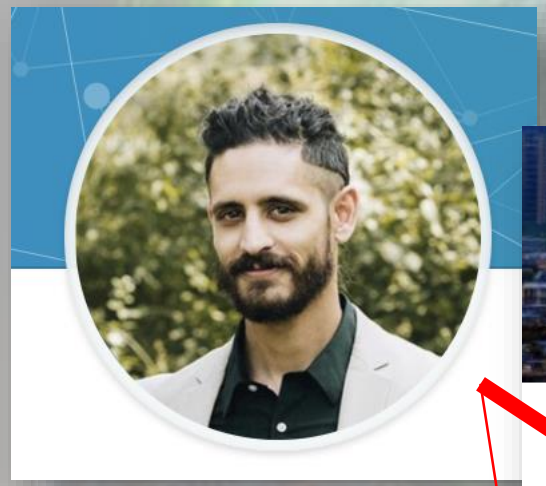
The Highest Diversity Growth Rate is The Healthiest, yet suboptimal State; Max Feasible Entropy across the Info Landscape. Unhealthy State with Non-native Diversity

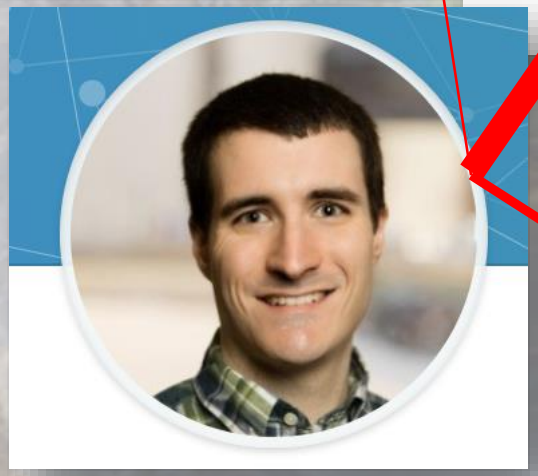
The most abundant are the most beneficial and the least interacting species in the healthy state (Endemic State). Most Competitive systemically -> Highest Predictability.

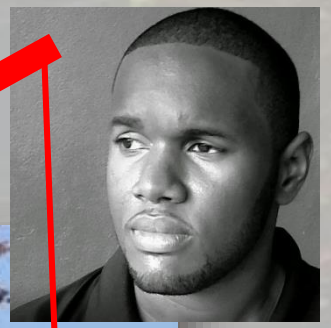
New Definition of Network Hubs (CRITICAL NODES!) based on OTE v

OTE Ranking Focused on Species Causing Transiti

Pareto Decisions are Critical for Health!







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WHO

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Driven to Discov

THANKS!

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