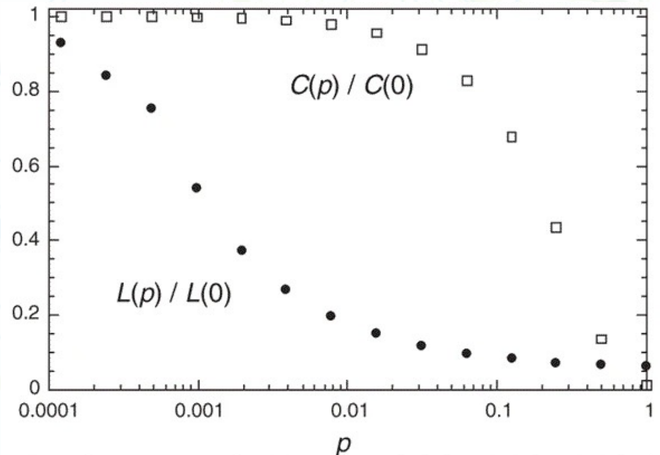
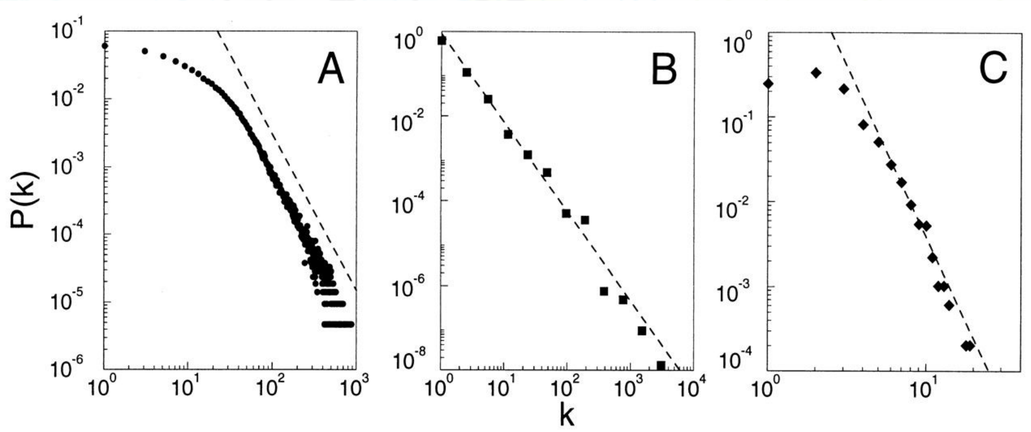
HIGHER-ORDER INTERACTIONS AND THE STABILITY OF COMPETITIVE ECOLOGICAL COMMUNITIES

Sandro Meloni

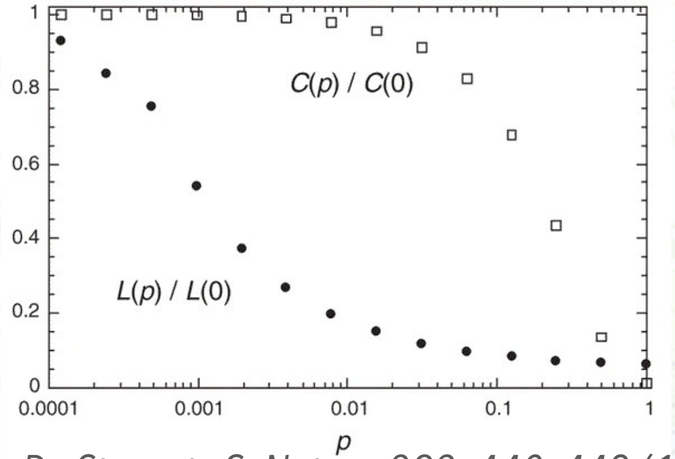
CCS/Italy 2025 - Bari, September 15th 2025



Watts D., Strogatz S. Nature 393, 440–442 (1998)



Barabási A.-L., Albert R. Science 286,509-512(1999)



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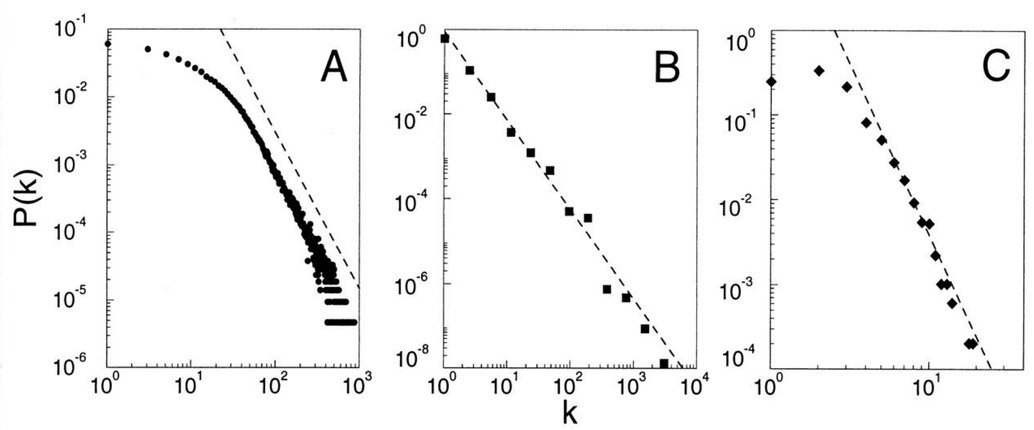
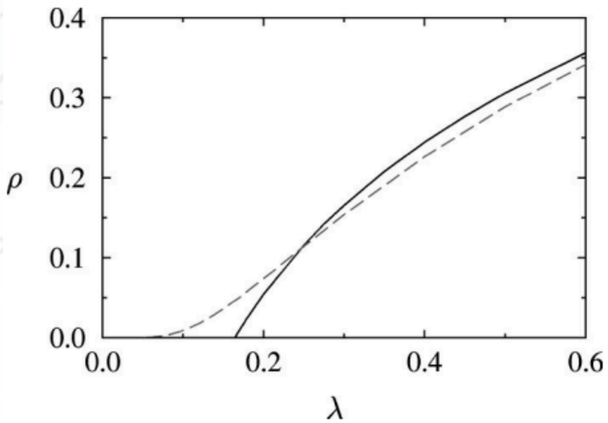
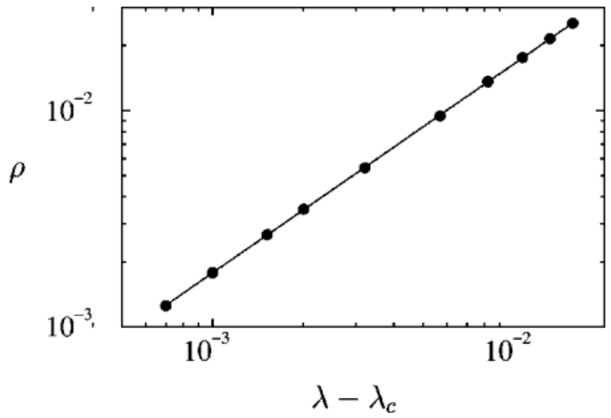


Barabási A.-L., Albert R. Science 286,509-512(1999)

New effects from topology

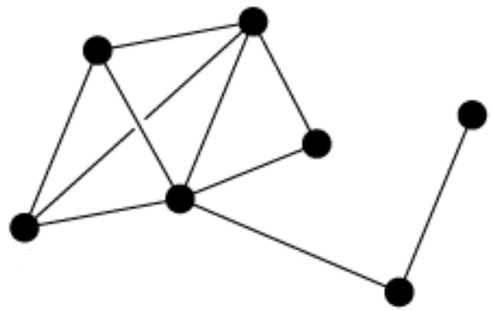




Pastor-Satorras R., Vespignani A. Physical Review E 63, 066117(2001)

BEYOND CLASSICAL NETWORKS

Extending classical graphs



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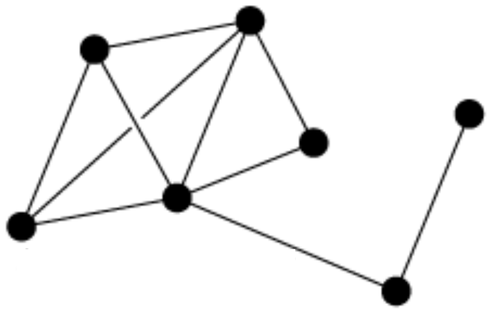
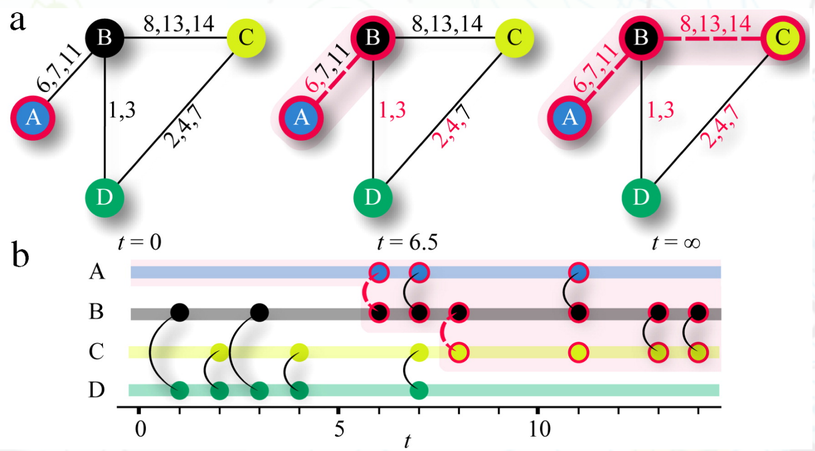
Extending classical graphs

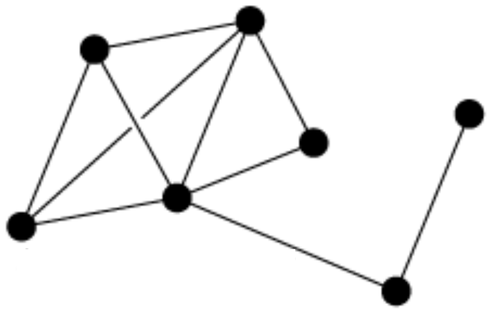


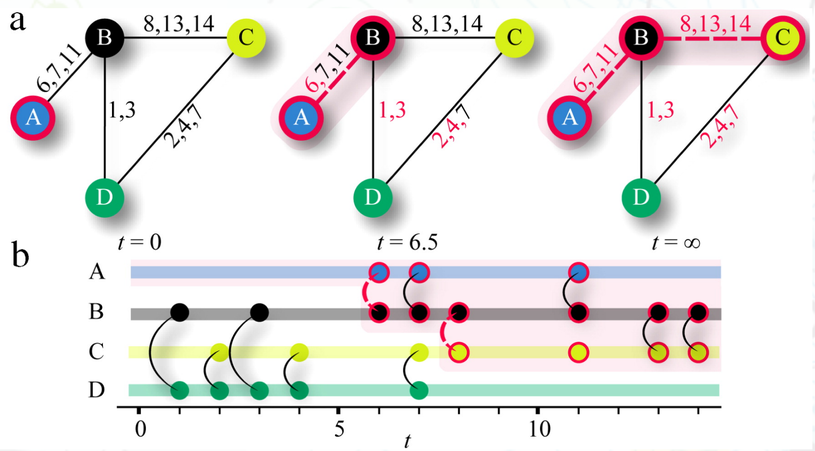


Temporal Networks

BEYOND CLASSICAL NETWORKS

Extending classical graphs





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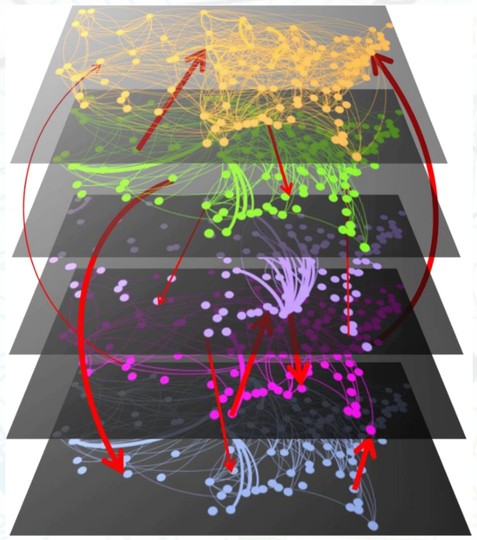


Multiplex/Multilayer Networks

BEYOND PAIRWISE INTERACTIONS

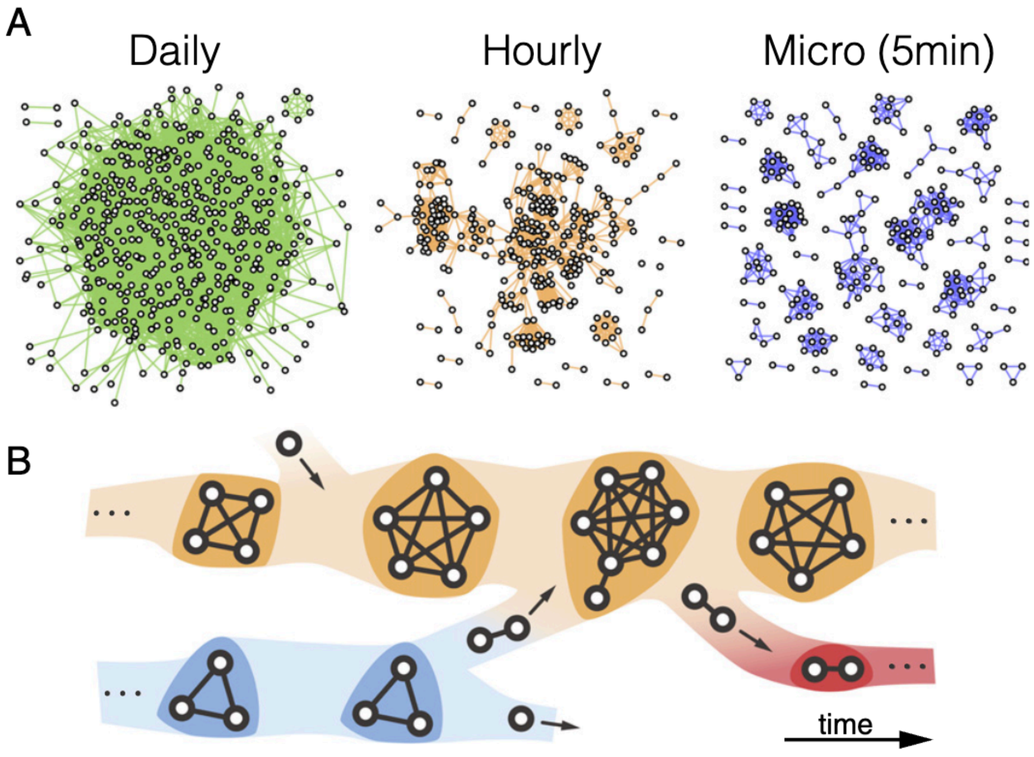
Fundamental structures of dynamic social networks

Vedran Sekara[a], Arkadiusz Stopczynski[a,b], and Sune Lehmann[a,c,1]

[a]Department of Applied Mathematics and Computer Science, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark, [b]Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139; and [c]The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

Edited by Albert-Laszlo Barabasi, Northeastern University, Boston, MA, and accepted by Editorial Board Member Kenneth W. Wachter July 12, 2016 (received for review March 9, 2016)

From pairwise to Higher-Order Interactions



BEYOND PAIRWISE INTERACTIONS

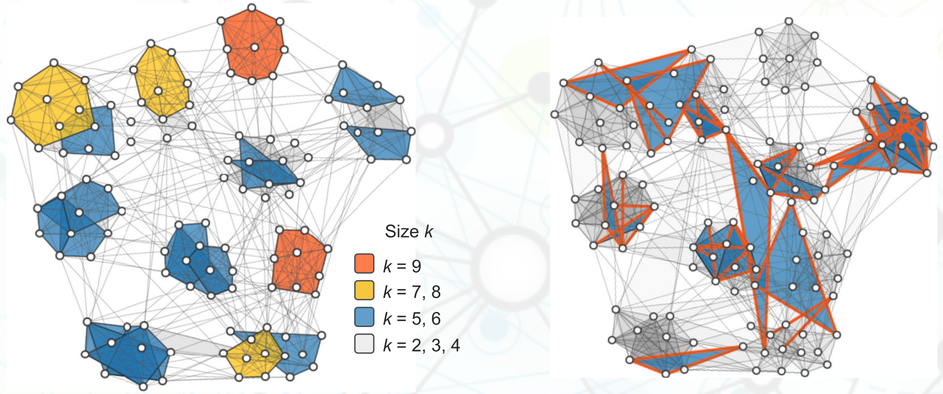
nature physics

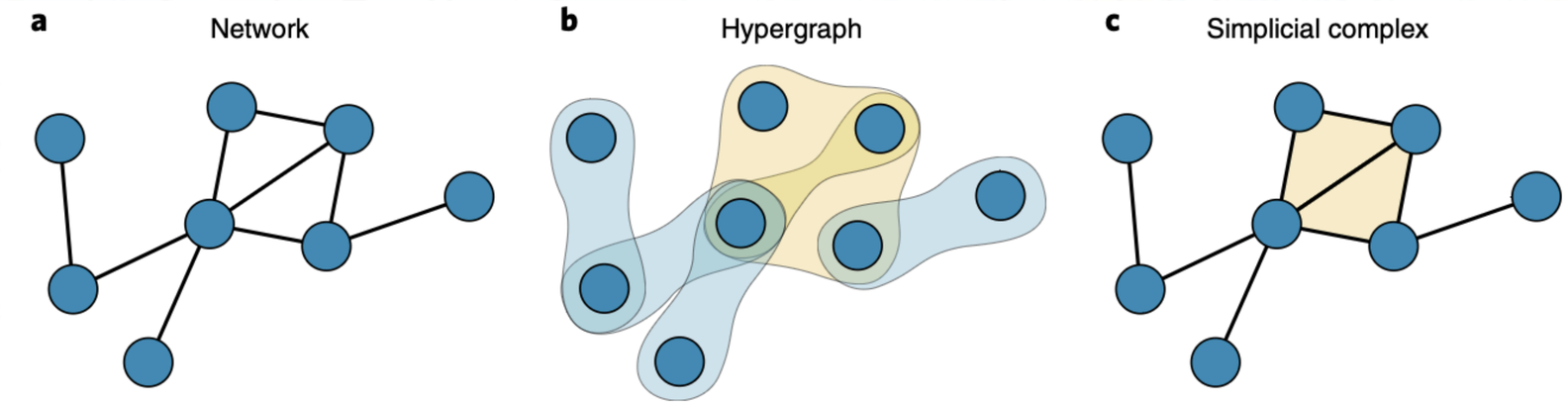
PERSPECTIVE

https://doi.org/10.1038/s41567-021-01371-4

The physics of higher-order interactions in complex systems

Federico Battiston[1]✉, Enrico Amico[2,3], Alain Barrat[4,5], Ginestra Bianconi[6,7], Guilherme Ferraz de Arruda[8], Benedetta Franceschiello[9,10], Iacopo Iacopini[1], Sonia Kéfi[11,12], Vito Latora[6,13,14,15], Yamir Moreno[8,15,16,17], Micah M. Murray[9,10,18], Tiago P. Peixoto[1,19], Francesco Vaccarino[20] and Giovanni Petri[8,21]✉





DYNAMICS WITH HIGHER ORDER INTERACTIONS

Social Contagion

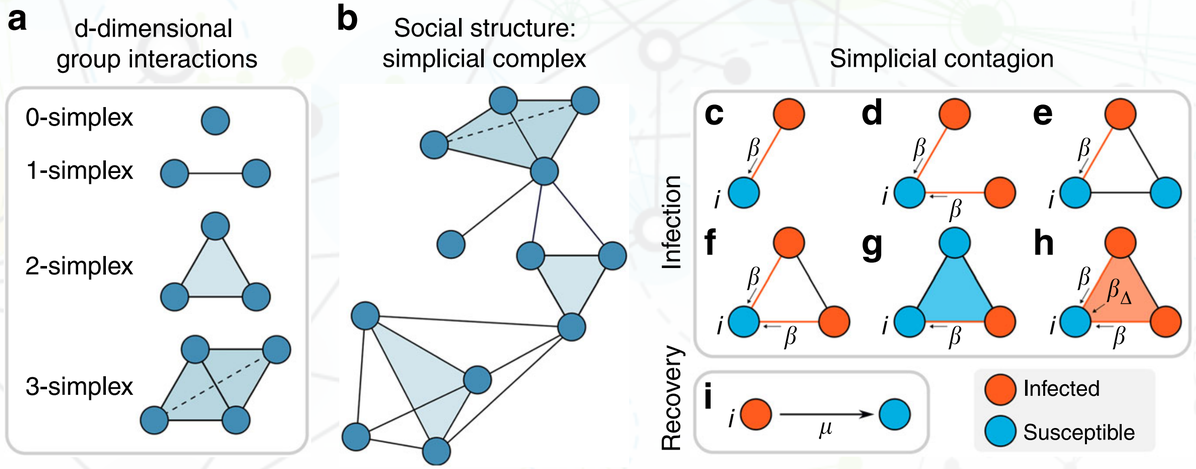
ARTICLE

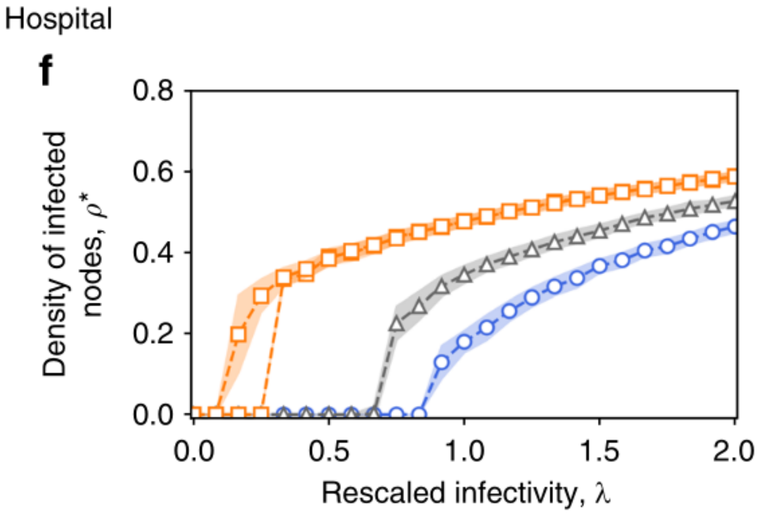
https://doi.org/10.1038/s41467-019-10431-6

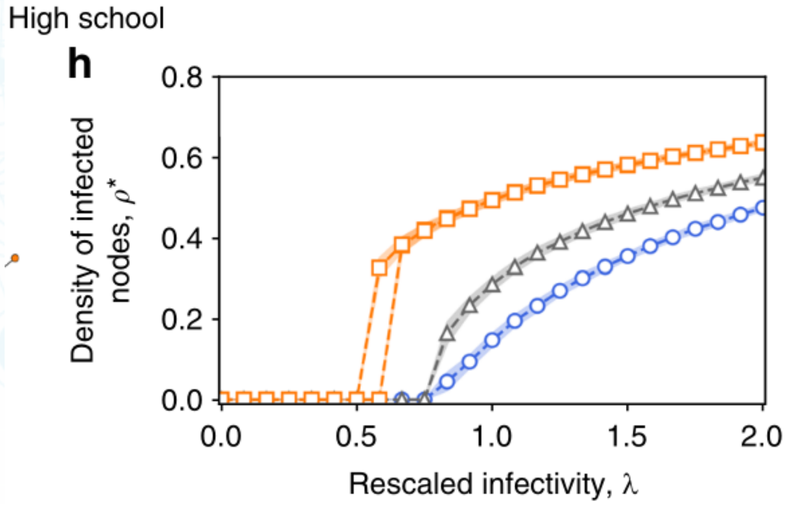
nature COMMUNICATIONS

Simplicial models of social contagion

Iacopo Iacopini [1,2], Giovanni Petri[3,4], Alain Barrat [3,5] & Vito Latora [1,2,6,7]







DYNAMICS WITH HIGHER ORDER INTERACTIONS

Synchronization

COMMUNICATIONS PHYSICS

ARTICLE

https://doi.org/10.1038/s42005-020-00485-0 OPEN

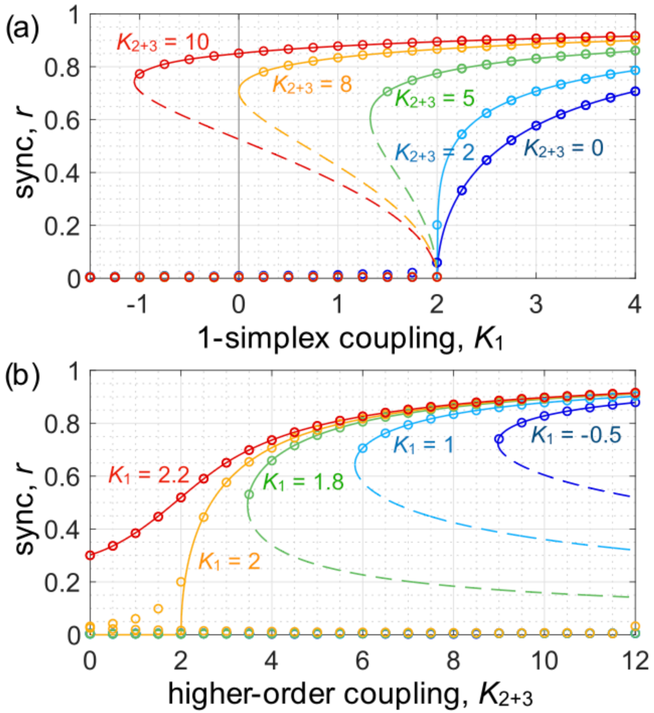
Higher order interactions in complex networks of phase oscillators promote abrupt synchronization switching

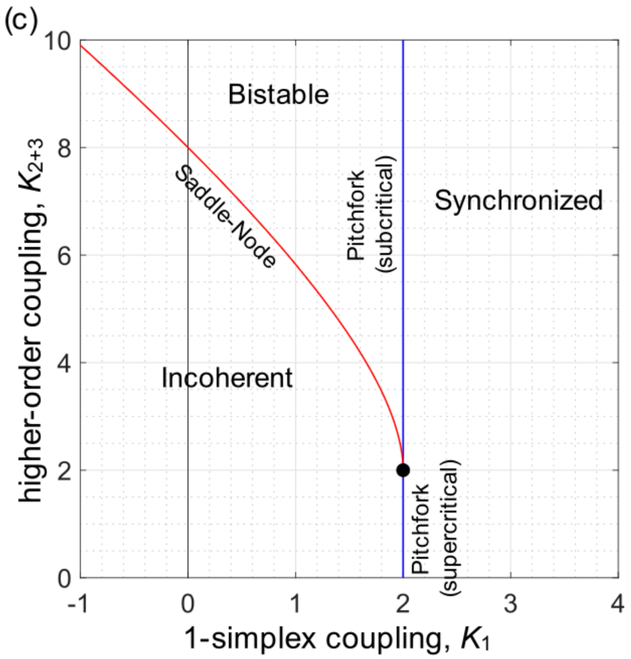
Per Sebastian Skardal [1]✉ & Alex Arenas [2]✉

$$\dot{\theta}_i = \omega_i + \frac{K_1}{\langle k^1 \rangle} \sum_{j=1}^{N} A_{ij} \sin(\theta_j - \theta_i)$$

$$+ \frac{K_2}{2\langle k^2 \rangle} \sum_{j=1}^{N} \sum_{l=1}^{N} B_{ijl} \sin(2\theta_j - \theta_l - \theta_i)$$

$$+ \frac{K_3}{6\langle k^3 \rangle} \sum_{j=1}^{N} \sum_{l=1}^{N} \sum_{m=1}^{N} C_{ijlm} \sin(\theta_j + \theta_l - \theta_m - \theta_i),$$





DYNAMICS WITH HIGHER ORDER INTERACTIONS

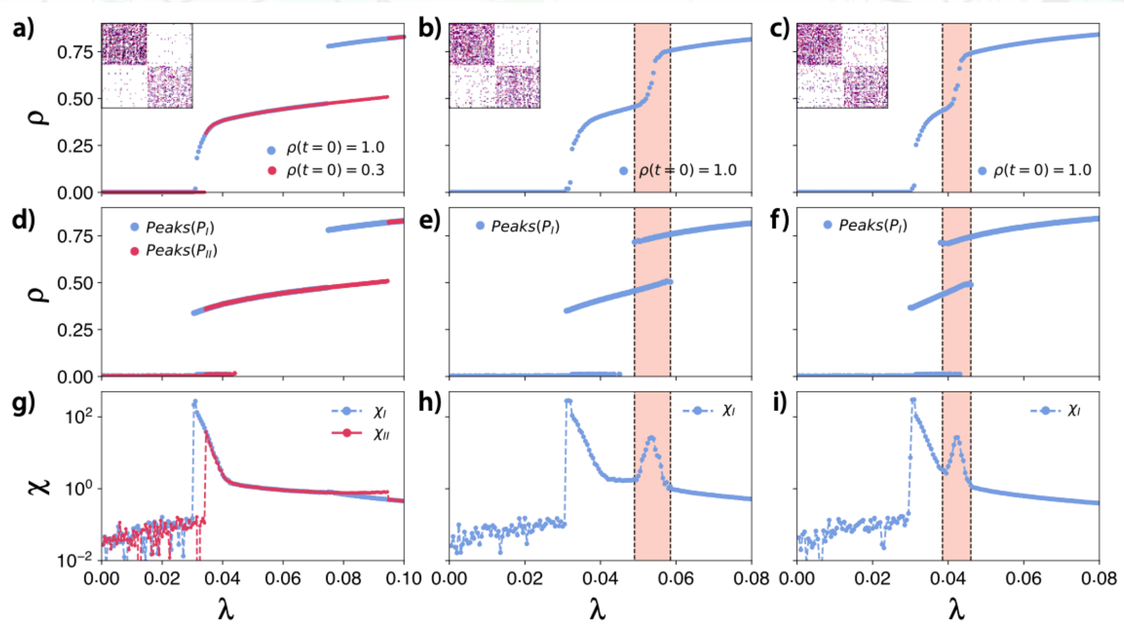
Rumor spreading

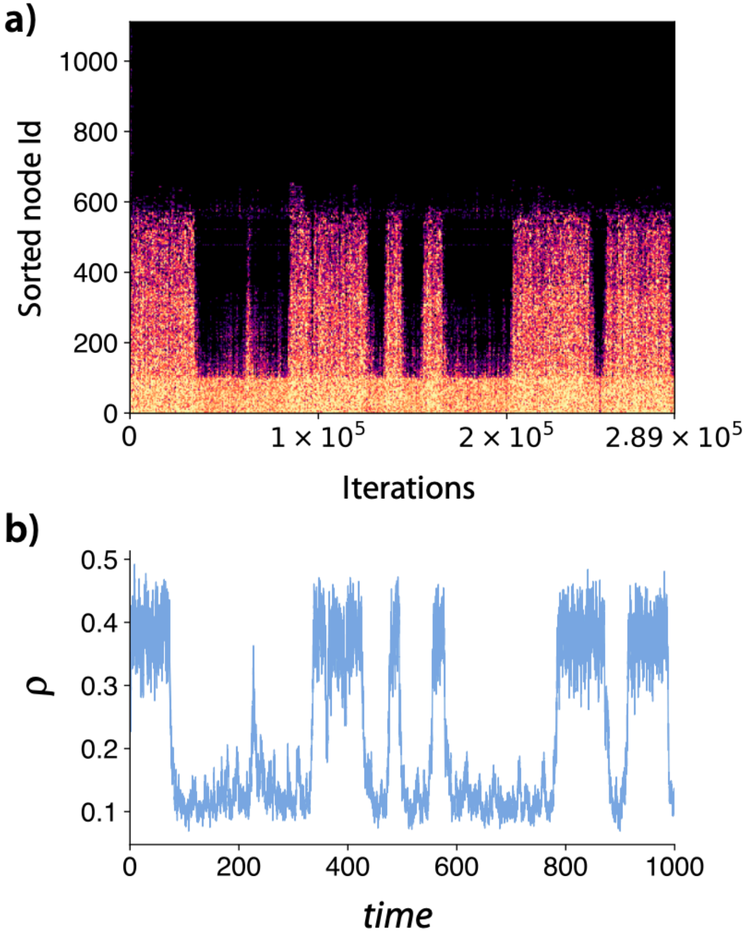
nature communications

Article

https://doi.org/10.1038/s41467-023-37118-3

Multistability, intermittency, and hybrid transitions in social contagion models on hypergraphs





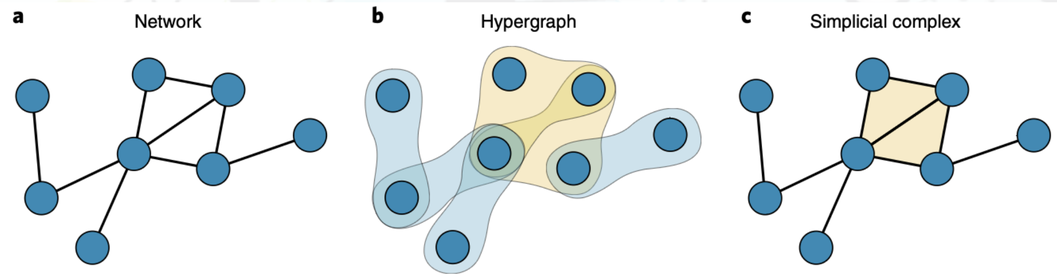
nature physics

PERSPECTIVE

https://doi.org/10.1038/s41567-021-01371-4

The physics of higher-order interactions in complex systems

Federico Battiston[1]✉, Enrico Amico[2,3], Alain Barrat[4,5], Ginestra Bianconi[6,7], Guilherme Ferraz de Arruda[8], Benedetta Franceschiello[9,10], Iacopo Iacopini[1], Sonia Kéfi[11,12], Vito Latora[6,13,14,15], Yamir Moreno[8,15,16,17], Micah M. Murray[9,10,18], Tiago P. Peixoto[1,19], Francesco Vaccarino[20] and Giovanni Petri[8,21]✉



The idea of higher-order interactions is well-known in the setting of many-body physics, for example in strong interactions[24,25] or van der Waals interactions[26], as well as in statistical mechanics[27]. However, in all these cases, representations of higher-order interactions are simple in the sense that they do not contribute to the emerging complexity of the problem. In complex systems, typically described as networks, the story is different, and in many cases these interactions must be taken into account using more advanced mathematical structures, such as hypergraphs and simplicial complexes[9]. Several investigations have already shown that the presence of higher-order interactions may substantially impact the dynamics on networked systems, from diffusion[28,29] and synchronization[30,31] to social[32–34] and evolutionary processes[35], possibly leading to the emergence of abrupt (explosive) transitions between states. Furthermore, although most research in complex systems focuses on the dynamical evolution of the states of the nodes, it is natural to consider that higher-order structures (described by hyperedges) could themselves possess a dynamical state, leading to a whole new panorama of dynamical processes. Finally, although many datasets can be easily visualized as networks, very few are readily described using a hypergraph representation. The challenge of going from the dynamics of units, and possibly information about their pairwise interactions, to a meaningful pattern of higher-order interactions between these units, remains substantial. In this Perspective, we outline the main signatures of new physics arising in higher-order systems, and we propose three key directions for future research.

NEW PHYSICS?

Questions:

- How these new results are related with classical theory?
- Are there equivalent pairwise models?
- Do we always need them?

UNDERSTANDING HOIS

Ref.

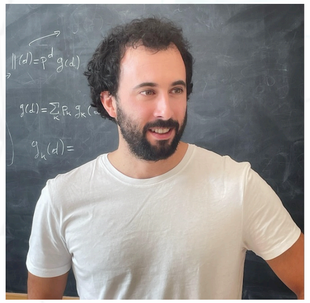
- "Higher-order contagion processes in 1.99 dimensions"
  SM, Andrea Gabrielli, Pablo Villegas
  arXiv:2502.18004
- "On the stability of competitive ecological communities with pairwise and higher-order interactions"
  Marc Duran-Sala, SM, Violeta Calleja-Solanas.
  arXiv:2501.09172
- "Demystifying HOI in ecology: is this description worth it?"
  Santiago Lamata-Otín, Carlos Gómez Ambrosi, Violeta Calleja-Solanas, Jesús Gómez Gardeñes, SM.
  in preparation

People

Carlos Gómez, UNIZAR

Jesús Gómez, UNIZAR

Santiago Lamata, UNIZAR



Pablo Villegas, CREF

Andrea Gabrielli, Roma TRE

Violeta Calleja, EBD CSIC

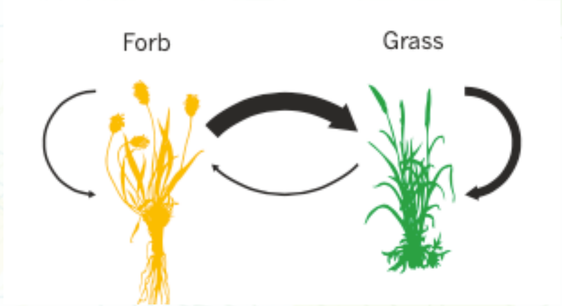
Marc Duran, EPFL

DO WE ALWAYS NEED THEM?

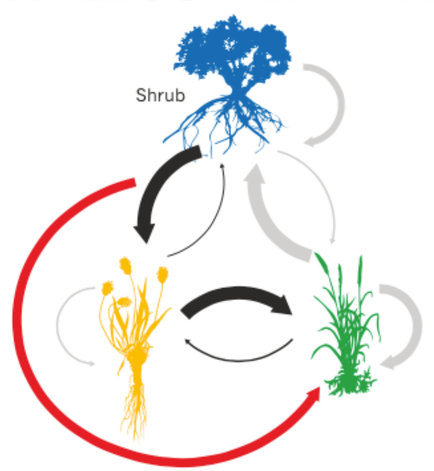
BEYOND PAIRWISE INTERACTIONS IN ECOLOGY

Ecological dynamics

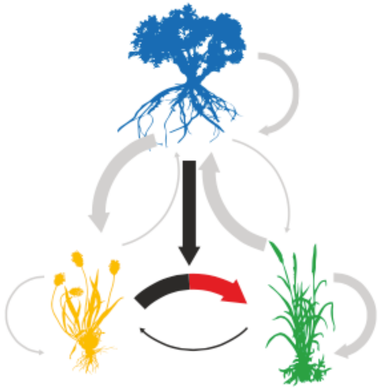
Pairwise



Interaction chain



Higher-Order Interaction



REVIEW

doi:10.1038/nature22898

Beyond pairwise mechanisms of species coexistence in complex communities

Jonathan M. Levine[1], Jordi Bascompte[2], Peter B. Adler[3] & Stefano Allesina[4]

Received: 2 December 2021 | Revised: 6 April 2022 | Accepted: 14 April 2022

DOI: 10.1111/ele.14022

ECOLOGY LETTERS WILEY

PERSPECTIVE

Detecting and interpreting higher-order interactions in ecological communities

Andrew R. Kleinhesselink[1] | Nathan J. B. Kraft[1] | Stephen W. Pacala[2] | Jonathan M. Levine[2]

Levine et al. Nature 546, 56–64 (2017)

ECOLOGICAL DYNAMICS WITH HOIS

HOIs and the stability of ecological communities

LETTER

doi:10.1038/nature23273

Higher-order interactions stabilize dynamics in competitive network models

Jacopo Grilli[1], György Barabás[1], Matthew J. Michalska-Smith[1] & Stefano Allesina[1,2,3]

nature ecology & evolution

ARTICLES

PUBLISHED: 17 FEBRUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0062

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Margaret M. Mayfield[1]* and Daniel B. Stouffer[2]*

ARTICLE

Received 16 Jan 2016 | Accepted 20 Jun 2016 | Published 2 Aug 2016

DOI: 10.1038/ncomms12285 OPEN

High-order species interactions shape ecosystem diversity

Eyal Bairey[1], Eric D. Kelsic[2,†] & Roy Kishony[2,3]

VOL. 203, NO. 4 THE AMERICAN NATURALIST APRIL 2024

Multitrophic Higher-Order Interactions Modulate Species Persistence

Lisa Buche,[1,*] Ignasi Bartomeus,[2] and Oscar Godoy[2,3]

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INTERFACE

royalsocietypublishing.org/journal/rsif

Ecological models: higher complexity in, higher feasibility out

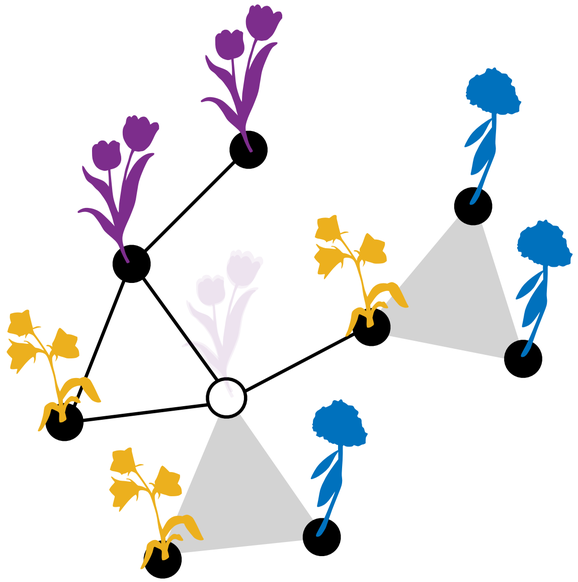
Mohammad AlAdwani and Serguei Saavedra

ECOLOGY LETTERS

Ecology Letters, (2019) **22**: 423–436 doi: 10.1111/ele.13211

The mechanistic basis for higher-order interactions and non-additivity in competitive communities

COMPETITIVE COMMUNITY MODEL



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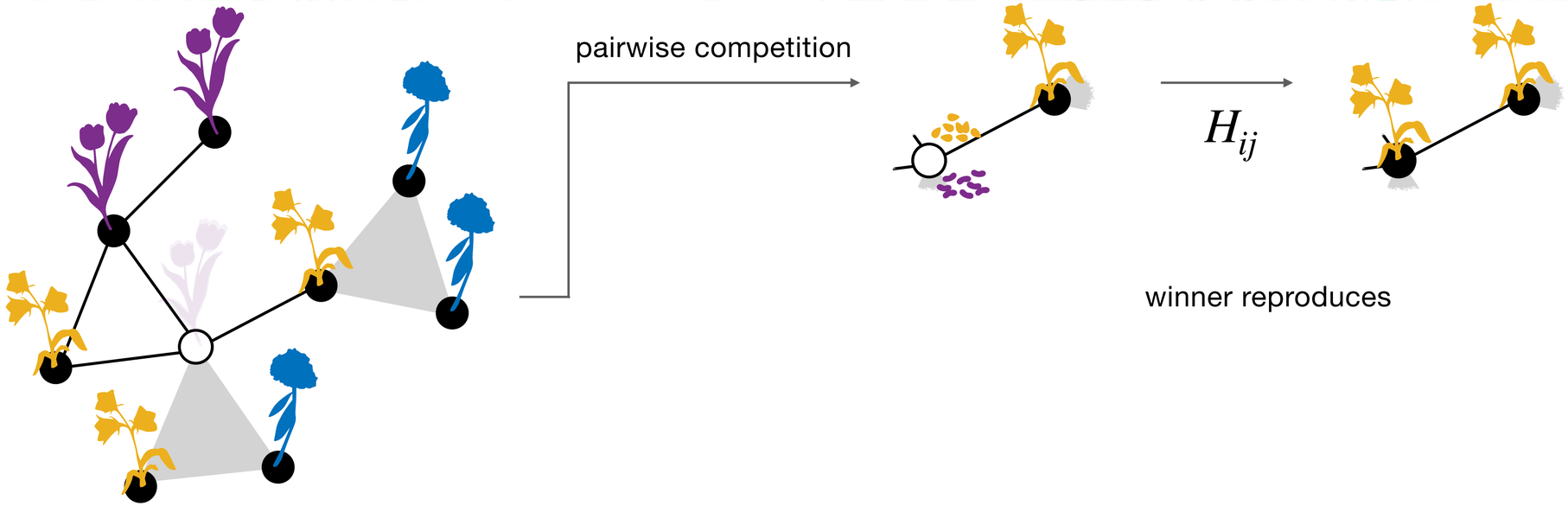

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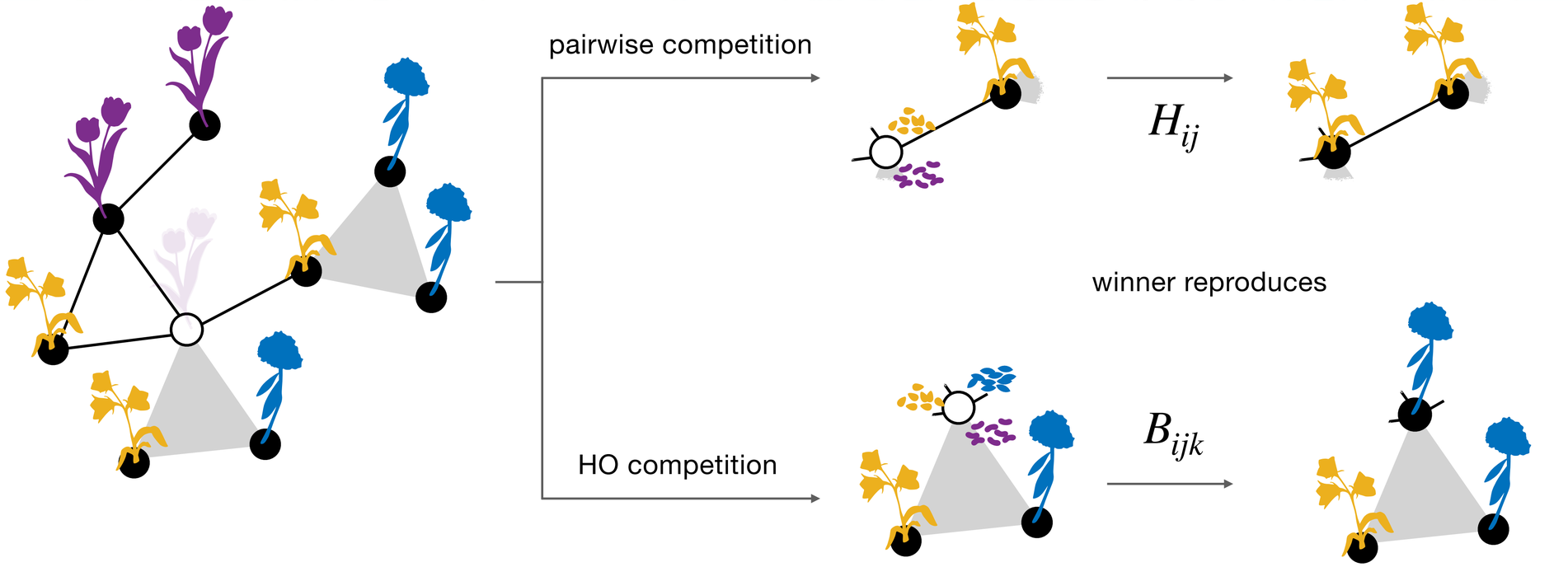


HOIS AND THE STABILITY OF ECOLOGICAL COMMUNITIES

LETTER

doi:10.1038/nature23273

Higher-order interactions stabilize dynamics in competitive network models

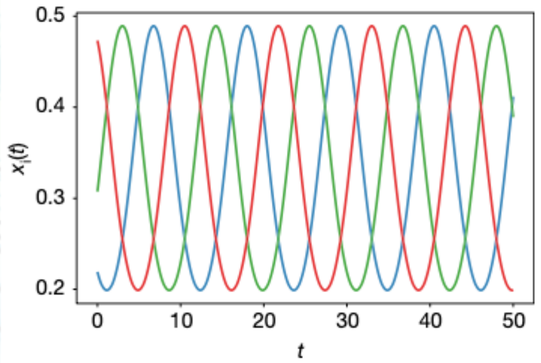
Jacopo Grilli[1], György Barabás[1], Matthew J. Michalska-Smith[1] & Stefano Allesina[1,2,3]

Described by a Replicator Equation (well mixed case)

Pairwise interactions

$$\frac{dx_i}{dt} = x_i \left(\frac{D(x)}{F(x)^2} f_i \sum_j 2H_{ij} f_j x_j - d_i \right)$$

Neutral circles



With:

f_i birth rate

d_i death rate

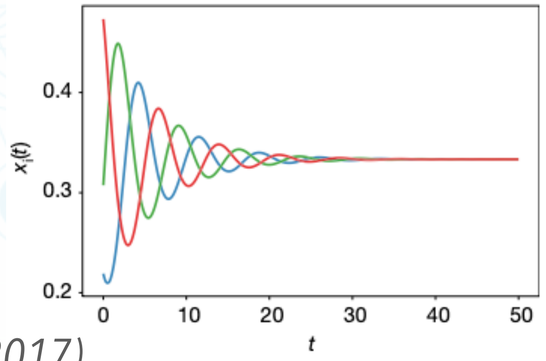
$$F(x) = \sum_i f_i x_i$$

$$D(x) = \sum_i d_i x_i$$

Higher-order interactions

$$\frac{dx_i}{dt} = x_i \left(\frac{D(x)}{F(x)^3} f_i \sum_{j,k} B_{ijk} f_j x_j f_k x_k - d_i \right)$$

Fixed point



Grilli et al. Nature 548, 210–213 (2017)

HOIS AND THE STABILITY OF ECOLOGICAL COMMUNITIES

LETTER

doi:10.1038/nature23273

Higher-order interactions stabilize dynamics in competitive network models

Jacopo Grilli[1], György Barabás[1], Matthew J. Michalska-Smith[1] & Stefano Allesina[1,2,3]

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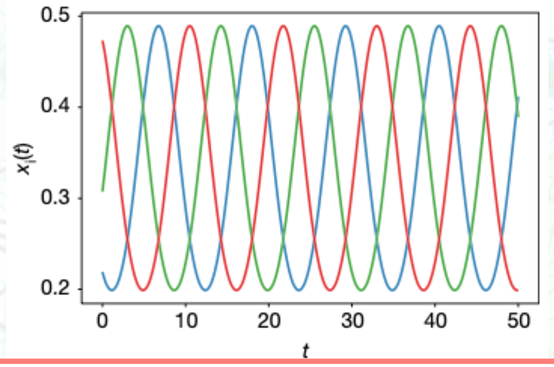
Neutral circles



With:

f_i birth rate

d_i death rate

$$F(x) = \sum_i f_i x_i$$

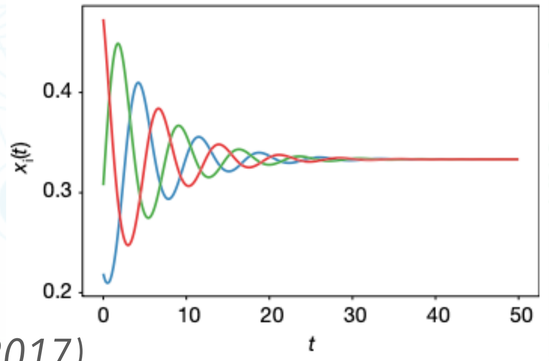
$$D(x) = \sum_i d_i x_i$$

What happens in more realistic scenarios?

Higher-order interactions

$$\frac{dx_i}{dt} = x_i \left(\frac{D(x)}{F(x)^3} f_i \sum_{j,k} B_{ijk} f_j x_j f_k x_k - d_i \right)$$

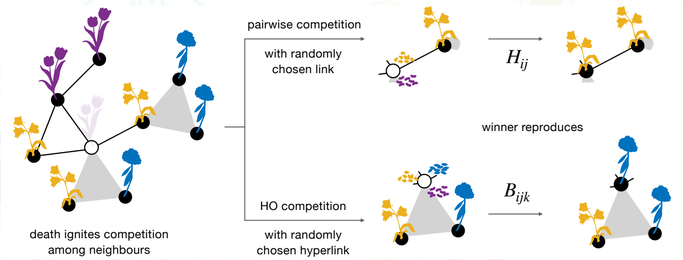
Fixed point



Grilli et al. Nature 548, 210–213 (2017)

COMPETITIVE COMMUNITY MODEL

Described by a Replicator Equation (well mixed case)



Full model

$$\frac{dx_i}{dt} = (1-\alpha)\left[x_i\left(\frac{D(x)}{F(x)^2}f_i\sum_j 2H_{ij}f_jx_j - d_i\right)\right] + \alpha\left[x_i\left(\frac{D(x)}{F(x)^3}f_i\sum_{j,k} B_{ijk}f_jx_jf_kx_k - d_i\right)\right]$$

With:

f_i birth rate

d_i death rate

$$F(x) = \sum_i f_i x_i$$

$$D(x) = \sum_i d_i x_i$$

α intensity of HOIs

IDENTICAL PHYSIOLOGICAL RATES

Special case:

Identical physiological rates

f_i birth rate = 1

d_i death rate =1

$$F(x) = \sum_i f_i x_i = 1$$

$$D(x) = \sum_i d_i x_i = 1$$

It reduces to:

$$\frac{dx_i}{dt} = (1-\alpha)\left(-x_i + 2\sum_j H_{ij} x_i x_j \right) + \alpha\left(-x_i + \sum_{j,k} B_{ijk} x_i x_j x_k \right)$$

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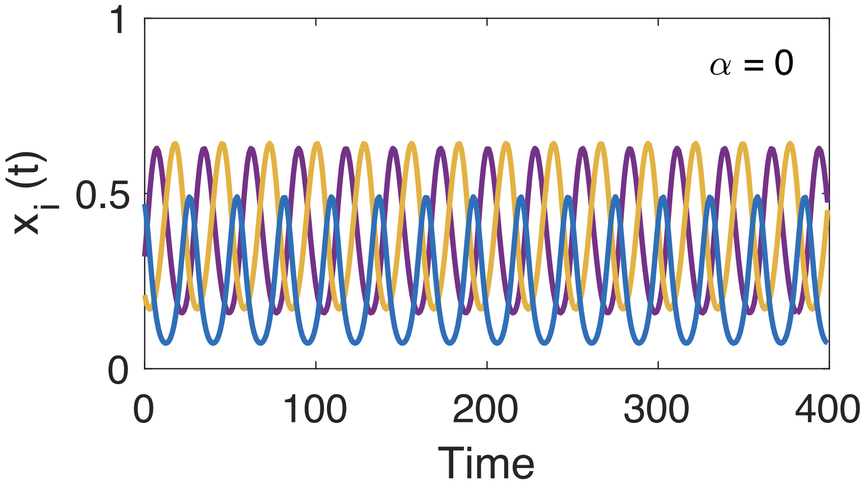

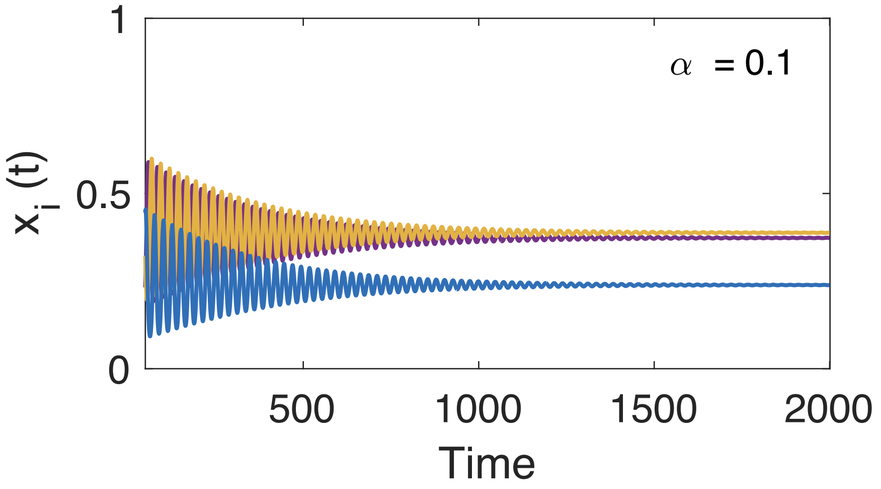

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Lyapunov function

$$V(x) = -\sum_i x_i^* \log \frac{x_i}{x_i^*}$$

$$\frac{dV}{dt} = \alpha \left[-2 \sum_i x_i^* \left(\sum_j H_{ij} \xi_j \right)^2 \right]$$

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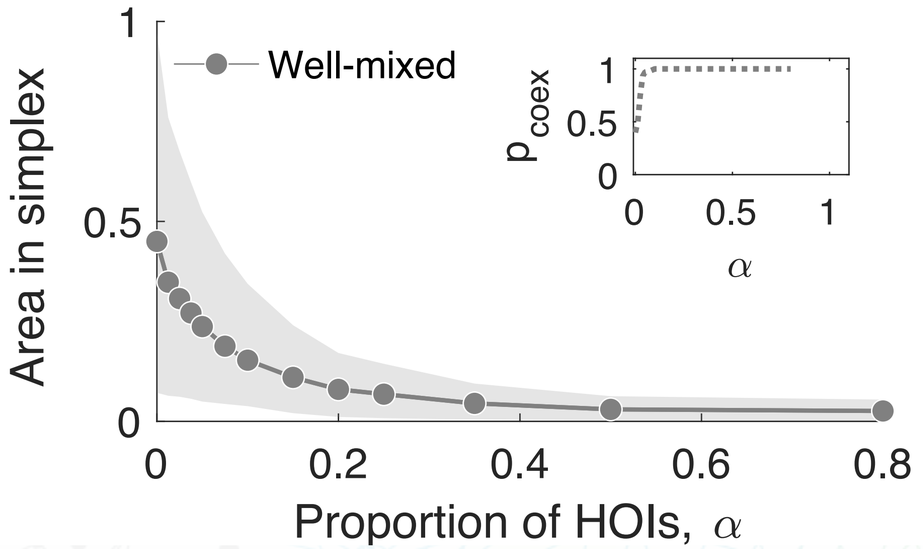


$\alpha_c = 0$. Any amount of HOIs stabilizes the dynamics

DIFFERENT PHYSIOLOGICAL RATES

General case (well mixed)

$$\frac{dx_i}{dt} = (1-\alpha)\left[x_i\left(\frac{D(x)}{F(x)^2} f_i \sum_j 2H_{ij} f_j x_j - d_i\right)\right] + \alpha\left[x_i\left(\frac{D(x)}{F(x)^3} f_i \sum_{j,k} B_{ijk} f_j x_j f_k x_k - d_i\right)\right]$$

The equilibrium depends of the fraction of HOIs

$$\alpha_c = \frac{-\frac{1}{F^2 D^*}(F^* D - F D^*)^2}{2D\frac{F^*}{F} - \sum_i x_i^* T_2 - \frac{F^{*2}}{F^2}\frac{D}{D^*}\sum_i x_i T_2^*}$$

With:

f_i birth rate

d_i death rate

$$F(x) = \sum_i f_i x_i$$

$$D(x) = \sum_i d_i x_i$$

With $T_2(\vec{x}) = \frac{D}{F^3} f_i \sum_j \sum_k f_j f_k (2H_{ij}H_{ik} + H_{ij}H_{jk} + H_{ik}H_{kj}) x_j x_k$

DIFFERENT PHYSIOLOGICAL RATES

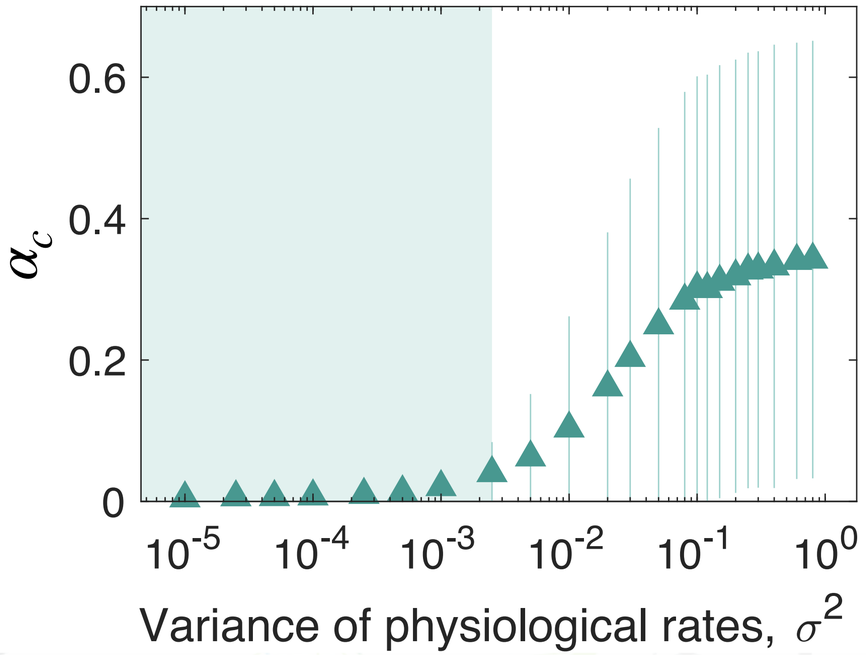
Adding noise:

f_i and d_i normally distributed with mean $\mu = 1$

DIFFERENT PHYSIOLOGICAL RATES

Adding noise:

f_i and d_i normally distributed with mean $\mu = 1$



DIFFERENT PHYSIOLOGICAL RATES

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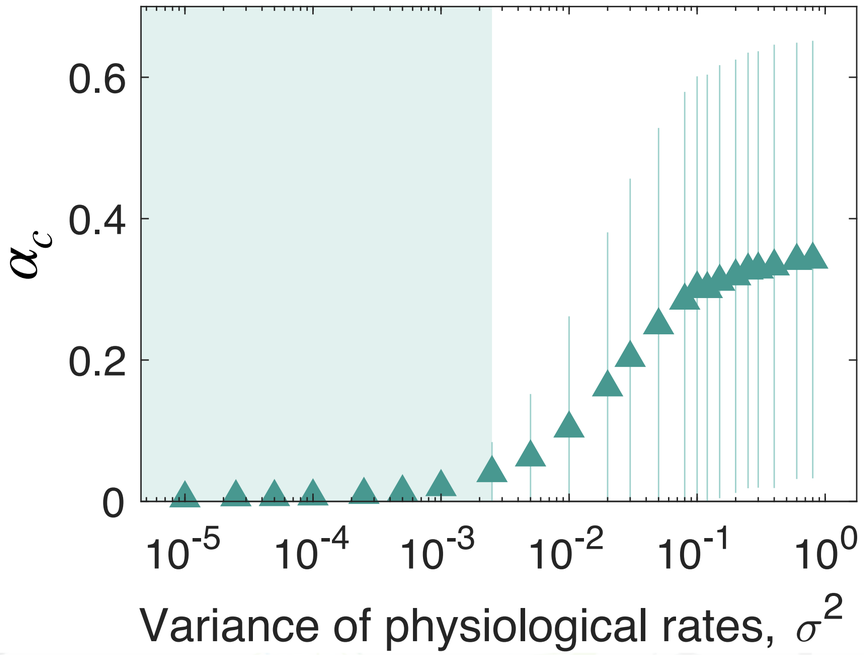
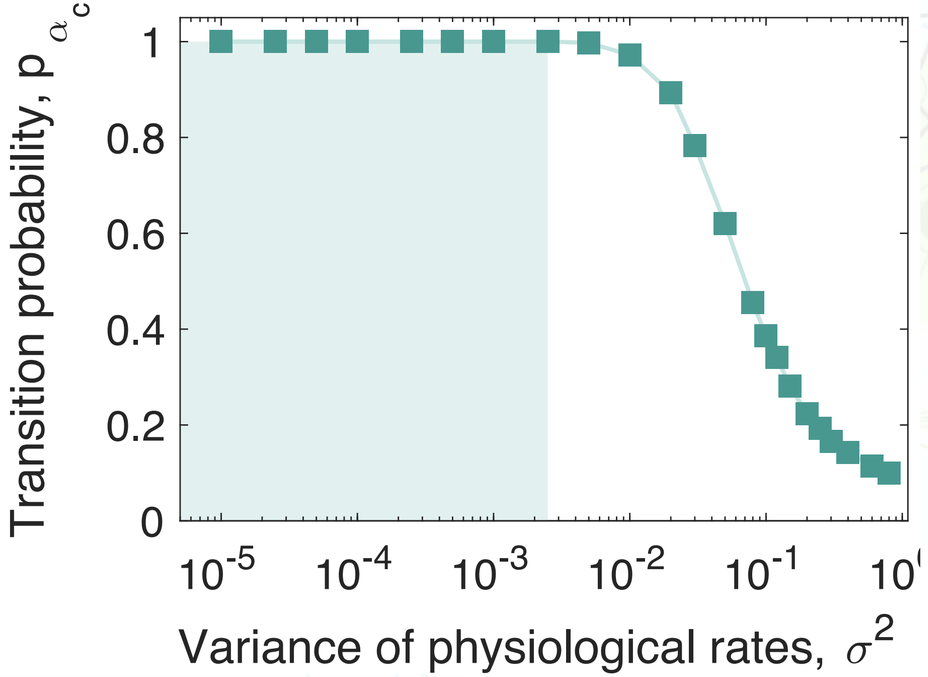
f_i and d_i normally distributed with mean $\mu = 1$

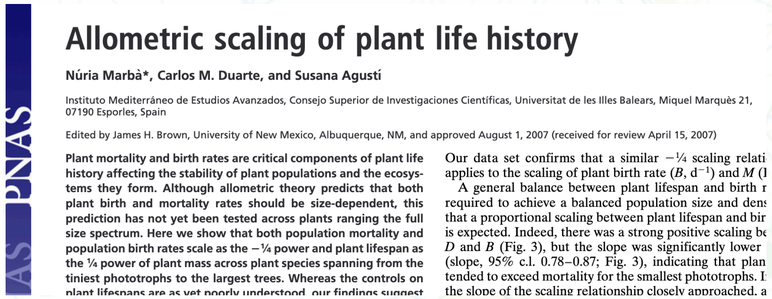




Heterogeneity affects stability

REAL PHYSIOLOGICAL RATES

Real data



PNAS

Allometric scaling of plant life history

Núria Marbà*, Carlos M. Duarte, and Susana Agustí

Instituto Mediterráneo de Estudios Avanzados, Consejo Superior de Investigaciones Científicas, Universitat de les Illes Balears, Miquel Marquès 21, 07190 Esporles, Spain

Edited by James H. Brown, University of New Mexico, Albuquerque, NM, and approved August 1, 2007 (received for review April 15, 2007)

Plant mortality and birth rates are critical components of plant life history affecting the stability of plant populations and the ecosystems they form. Although allometric theory predicts that both plant birth and mortality rates should be size-dependent, this prediction has not yet been tested across plants ranging the full size spectrum. Here we show that both population mortality and population birth rates scale as the −¼ power and plant lifespan as the ¼ power of plant mass across plant species spanning from the tiniest phototrophs to the largest trees. Whereas the controls on plant lifespans are as yet poorly understood, our findings suggest

Our data set confirms that a similar −¼ scaling relati
applies to the scaling of plant birth rate (B, d^{-1}) and M (

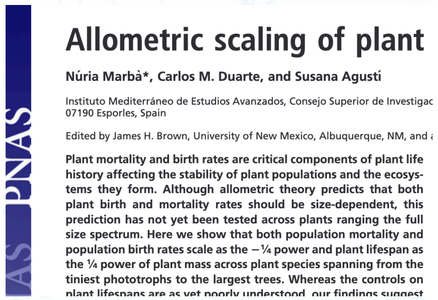
A general balance between plant lifespan and birth r
required to achieve a balanced population size and dens
that a proportional scaling between plant lifespan and bir
is expected. Indeed, there was a strong positive scaling be
D and B (Fig. 3), but the slope was significantly lower
(slope, 95% c.l. 0.78–0.87; Fig. 3), indicating that plan
tended to exceed mortality for the smallest phototrophs. I
the slope of the scaling relationship closely approached, a

Plant type	*n*	Individual mass, grams dry weight	Mortality rate, d^{-1}	Life span, d	Birth rate, d^{-1}
Phytoplankton	48	$3.5 \pm 2.4 \times 10^{-9}$ (3.4×10^{-15}–8.3×10^{-8})	$39 \pm 7.0 \times 10^{-2}$ (1.2×10^{-3}–2.5)	$2.3 \pm 1.2 \times 10^{1}$ (2.8×10^{-1}–5.8×10^{2})	$15 \pm 2.5 \times 10^{-1}$ (4.0×10^{-2}–3.7)
Macroalgae	37	$7.2 \pm 4.6 \times 10^{1}$ (7.3×10^{-4}–1.5×10^{3})	$7.6 \pm 1.8 \times 10^{-3}$ (2.2×10^{-4}–5.8×10^{-2})	$4.0 \pm 1.2 \times 10^{2}$ (1.2×10^{-1}–3.1×10^{3})	$1.4 \pm 0.63 \times 10^{-2}$ (2.6×10^{-4}–3.8×10^{-2})
Mosses	7	$2.1 \pm 0.26 \times 10^{-2}$ (1.6×10^{-2}–3.3×10^{-2})	$1.8 \pm 0.27 \times 10^{-3}$ (6.7×10^{-4}–2.8×10^{-3})	$4.8 \pm 1.0 \times 10^{2}$ (2.5×10^{2}–1.0×10^{3})	
Ferns	3		$2.6 \pm 1.0 \times 10^{-4}$ (1.3×10^{-4}–4.6×10^{-4})	$3.4 \pm 1.1 \times 10^{3}$ (1.5×10^{3}–5.2×10^{3})	$2.0 \pm 0.32 \times 10^{-4}$ (1.2×10^{-4}–2.8×10^{-4})
Seagrasses	151	$3.1 \pm 0.37 \times 10^{-1}$ (7.0×10^{-3}–2.5)	$2.5 \pm 0 - 35 \times 10^{-3}$ (5.6×10^{-5}–4.1×10^{-2})	$13 \pm 1.4 \times 10^{2}$ (1.7×10^{1}–1.2×10^{4})	$1.9 \pm 0.20 \times 10^{-3}$ (3.9×10^{-5}–1.2×10^{-2})
Land and salt marsh herbs	190	4.9 ± 2.4 (1.8×10^{-2}–1.2×10^{2})	$5.8 \pm 1.5 \times 10^{-3}$ (1.4×10^{-5}–2.2×10^{-1})	$16 \pm 3.0 \times 10^{2}$ (3.2–5.0×10^{4})	$2.1 \pm 0.44 \times 10^{-3}$ (1.1×10^{-5}–2.0×10^{-2})
Succulent plants	12	$2.9 \pm 1.4 \times 10^{3}$ (4.4×10^{2}–6.1×10^{3})	$8.9 \pm 2.2 \times 10^{-3}$ (2.6×10^{-5}–2.0×10^{-2})	$7.6 \pm 3.3 \times 10^{3}$ (3.5×10^{1}–2.7×10^{4})	$2.1 \pm 0.8 \times 10^{-5}$ (6.7×10^{-6}–3.6×10^{-5})
Shrubs and lianas	20	$5.9 \pm 3.2 \times 10^{1}$ (4.5–1.8×10^{2})	$1.1 \pm 0.6 \times 10^{-2}$ (1.1×10^{-4}–1.2×10^{-1})	$14 \pm 4.1 \times 10^{2}$ (6.0–6.5×10^{3})	
Mangroves	30	$2.8 \pm 1.3 \times 10^{1}$ (6.4×10^{-1}–3.2×10^{2})	$3.5 \pm 0.94 \times 10^{-3}$ (2.4×10^{-5}–2.3×10^{-2})	$1.8 \pm 0.94 \times 10^{3}$ (3.0×10^{1}–2.8×10^{4})	
Trees	230	$7.7 \pm 1.2 \times 10^{5}$ (11–11×10^{6})	$2.9 \pm 0.53 \times 10^{-4}$ (2.8×10^{-7}–5.2×10^{-3})	$1.1 \pm 0.2 \times 10^{5}$ (1.3×10^{2}–2.5×10^{6})	$4.1 \pm 0.65 \times 10^{-5}$ (3.0×10^{-6}–3.1×10^{-4})
Overall	728	$23 \pm 4.2 \times 10^{4}$ (3.4×10^{-15}–11×10^{6})	$2.9 \pm 0.58 \times 10^{-2}$ (2.8×10^{-7}–2.5)	$37 \pm 6.7 \times 10^{3}$ (2.8×10^{-1}–2.5×10^{6})	$1.3 \pm 0.32 \times 10^{-1}$ (3.0×10^{-6}–3.7)

From N. Marbà, et al. , Proc. Natl. Acad. Sci. U.S.A. 104 (40) 15777-15780 (2007)

REAL PHYSIOLOGICAL RATES

Real data



Allometric scaling of plant

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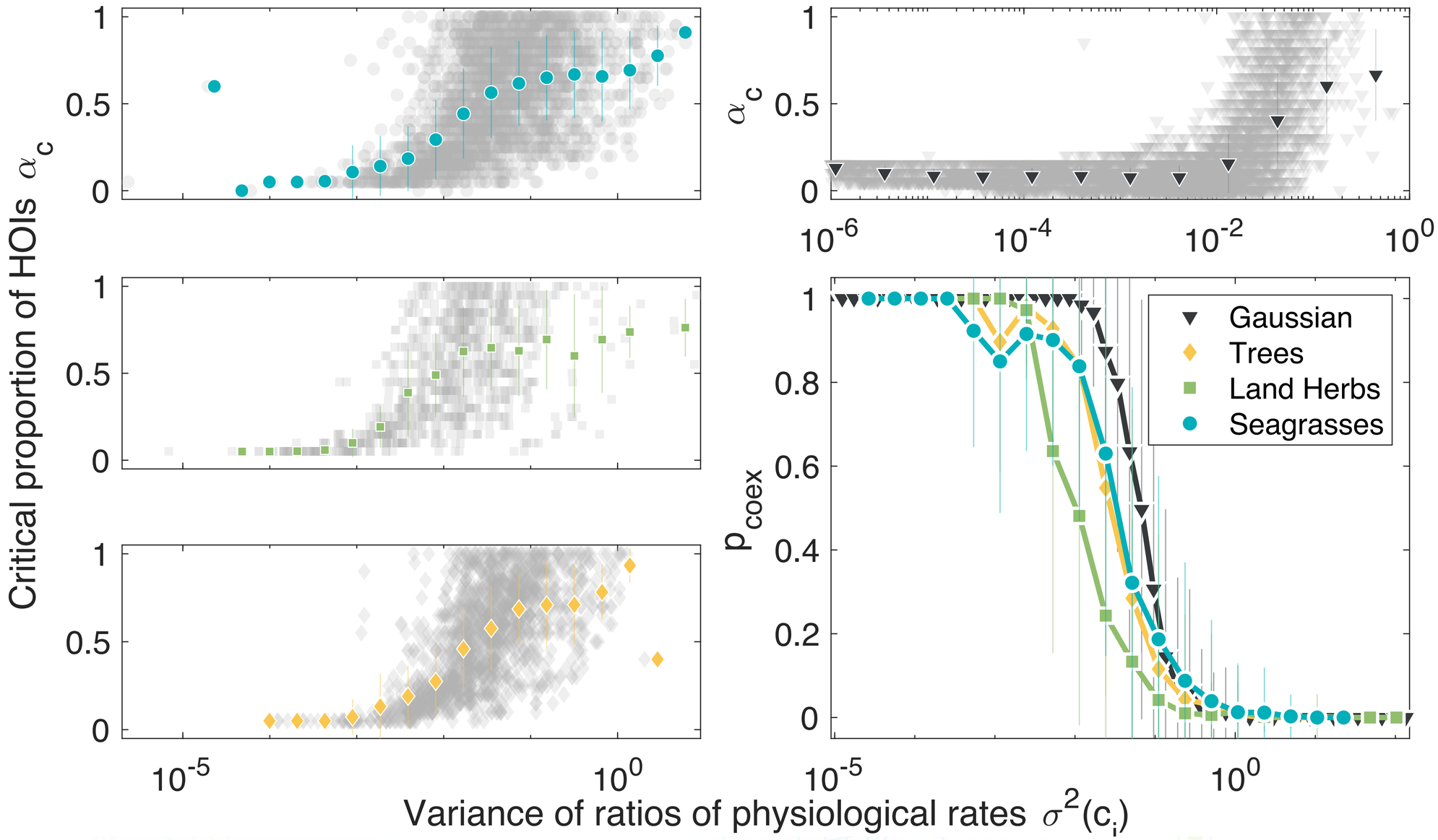

Special case:

Identical physiological rates

Random networks (Erdös-Rényi) with tunable fraction of HOIs

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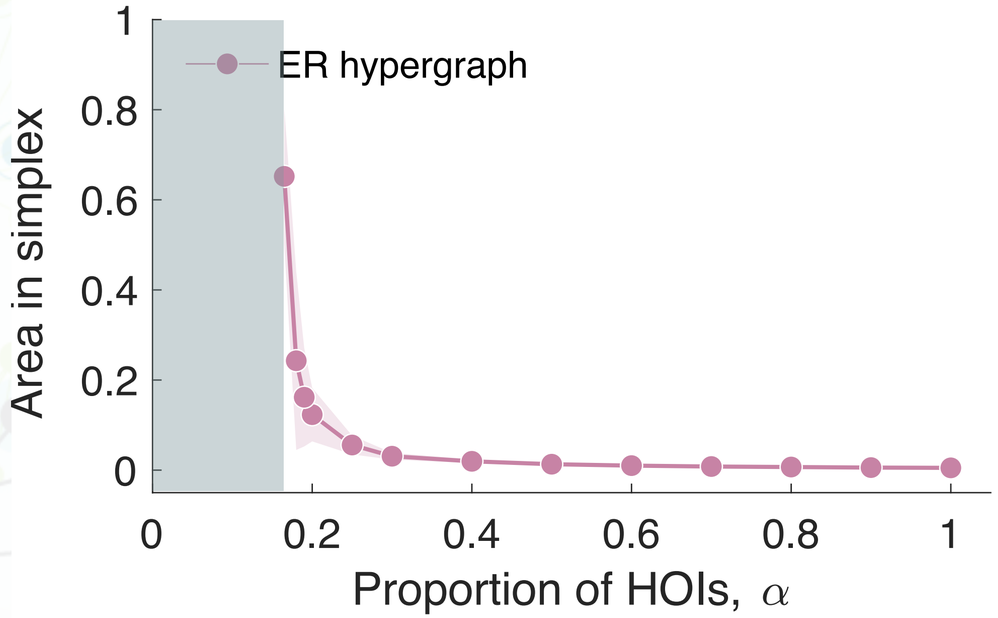
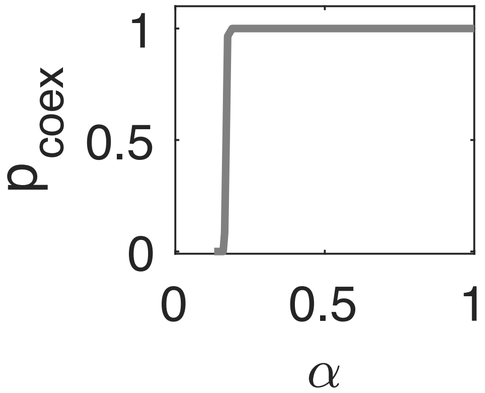
Random networks (Erdös-Rényi) with tunable fraction of HOIs





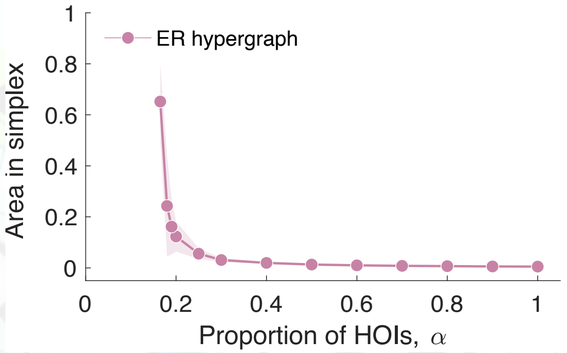
Sharp transition in Coexistence

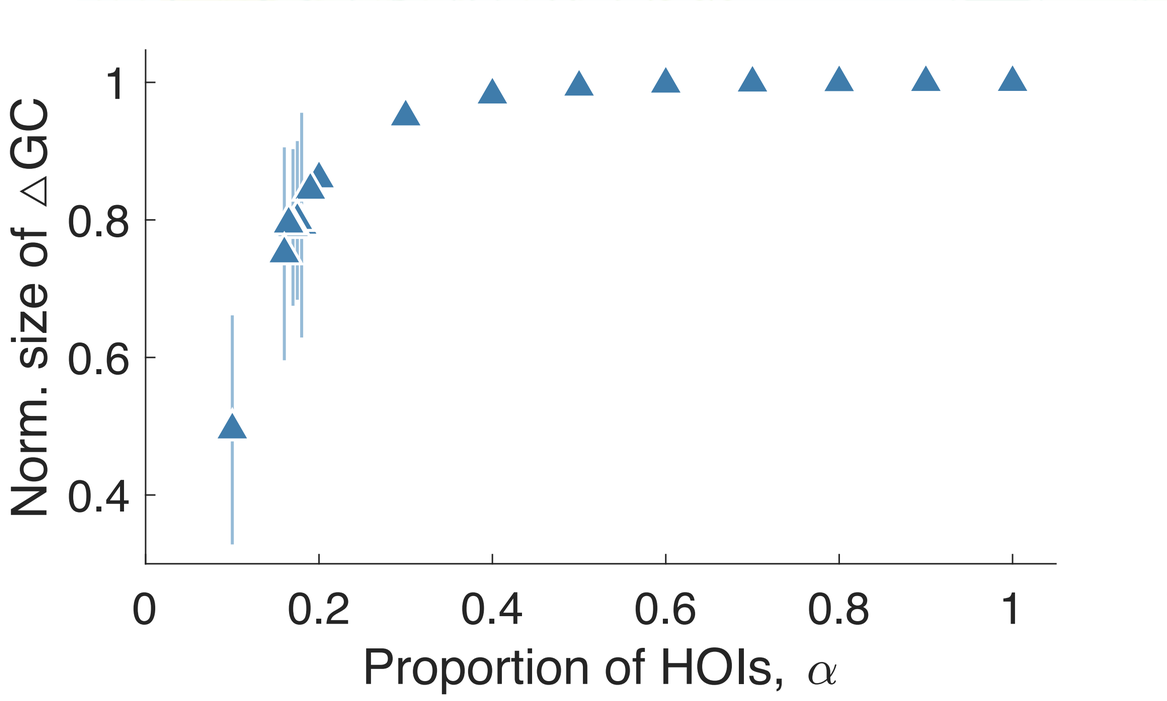
Special case:

Identical physiological rates

Random networks (Erdös-Rényi) with tunable fraction of HOIs

Sharp transition in coexistence: how?





$\triangle GC$

size of the giant component
considering only HO connections

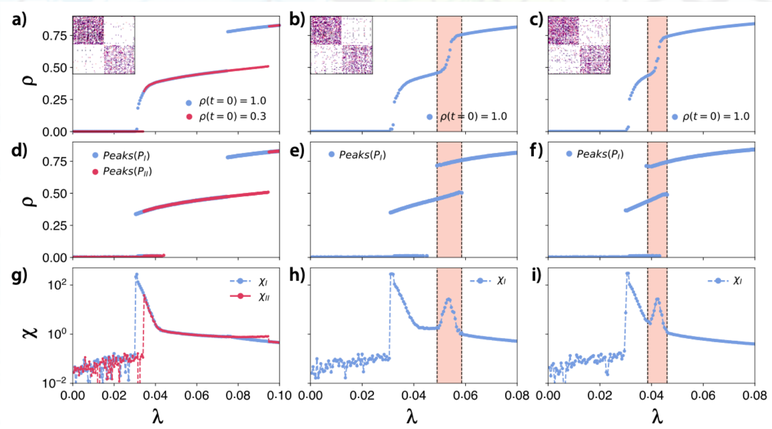
Percolating cluster of HOIs

SUMMING UP

Higher-order interactions can be a framework to study dynamical systems on networks

However:

- Rethink their study at the light of Network Theory and Statistical Mechanics
- Leave the "new physics" behind and put efforts in systematize these new results



SUMMING UP

Ref.

- "Higher-order contagion processes in 1.99 dimensions"
  SM, Andrea Gabrielli, Pablo Villegas
  arXiv:2502.18004
- "On the stability of competitive ecological communities with pairwise and higher-order interactions"
  Marc Duran-Sala, SM, Violeta Calleja-Solanas.
  arXiv:2501.09172
- "Demystifying HOI in ecology: is this description worth it?"
  Santiago Lamata-Otín, Carlos Gómez Ambrosi, Violeta Calleja-Solanas, Jesús Gómez Gardeñes, SM.
  in preparation

Acks.

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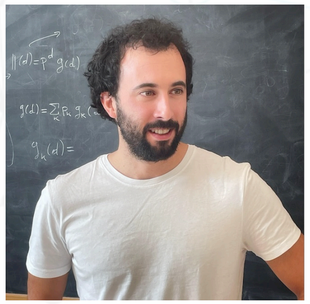

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