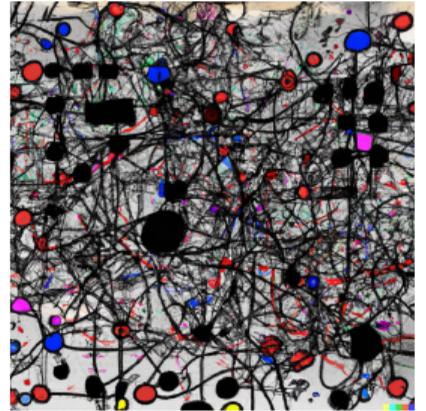


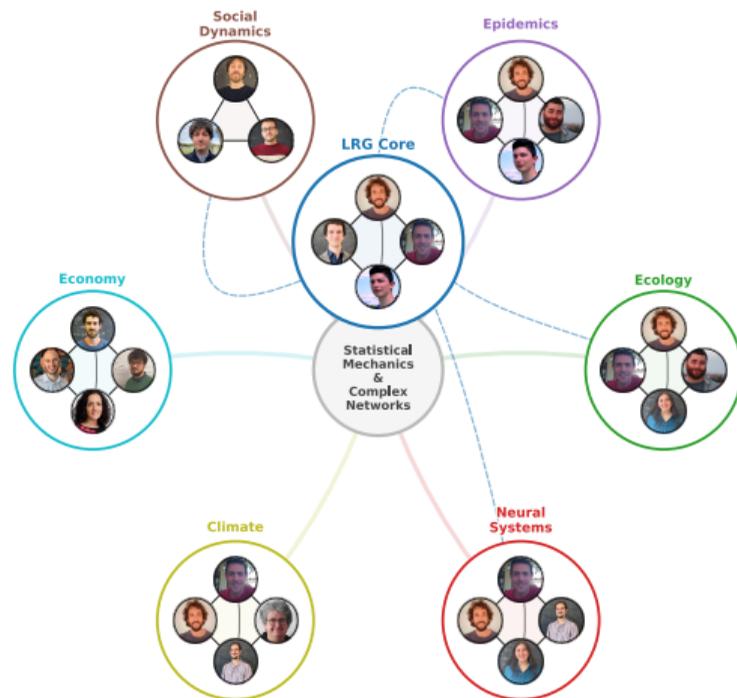
STATISTICAL PHYSICS AND COMPLEX SYSTEMS IN NATURAL SCIENCES

Pablo Villegas
CREF Scientific Council
02/2026 Rome



A Research Line with Modular Structure

A modular team sharing a common theoretical toolbox across domains.



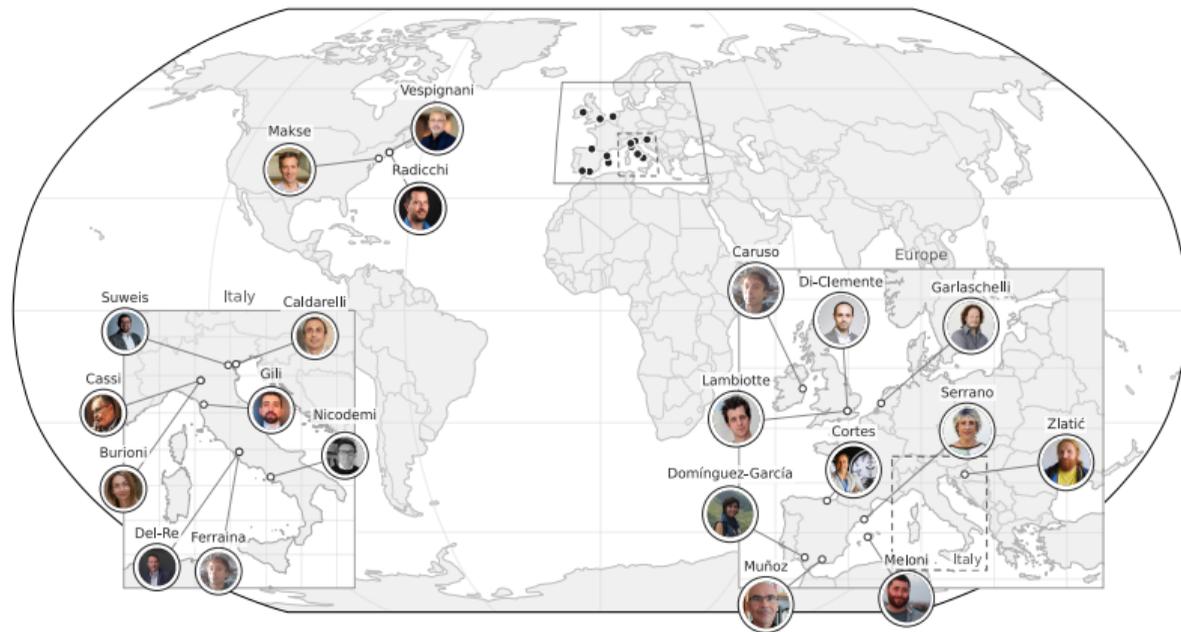
10 senior researchers, 5 PhD/Postdocs

International Research Network

Positioning CREF as an international hub for multiscale complex systems.

International collaborators

Geographical footprint & network of collaborations



40+ joint papers and long-term collaborations

From multiscale physics to LRG

Why multiscale

What LRG changes

Where this leads

Renormalization group & universality classes

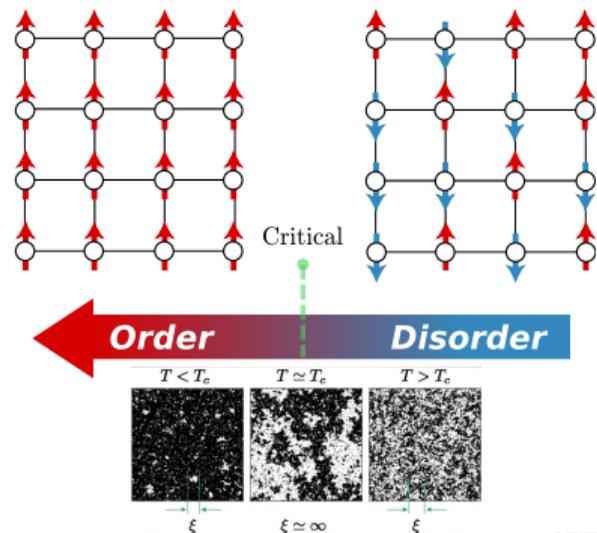
The Ising model

→ Kadanoff (1966) & Wilson (1971). RG: Coarse-graining + rescaling + redefinition of coupling constants

Problems in Physics with Many Scales of Length

Physical systems as varied as magnets and fluids are alike in having fluctuations in structure over a vast range of sizes. A novel method called the renormalization group has been invented to explain them

by Kenneth G. Wilson



CENTRO RICERCHE
ENRICO FERMI

! “A substantial number of unsolved problems in physics trace their difficulty to a multiplicity of scales.”

Criticality is ubiquitous in Nature...

Bird flocking in Rome

Firing of cortical neurons

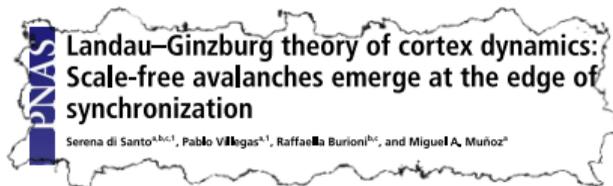
Percolation in bacterial communities

Criticality hypothesis

“Operating near criticality may provide functional advantages in biological systems.”

Selected evidence of criticality in living systems:

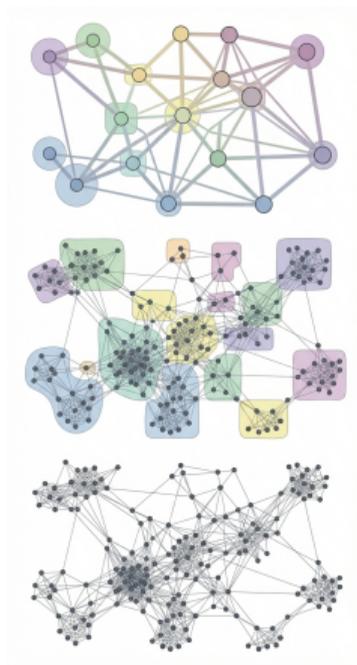
- Starling flocks – Cavagna, PNAS (2010)
- Bacterial communities – Larkin, Cell (2018)
- Cortex dynamics – di Santo, PNAS (2018)
- Review – Muñoz, RMP (2018)



ARTICLE
Marginal speed confinement resolves the conflict between correlation and control in collective behaviour

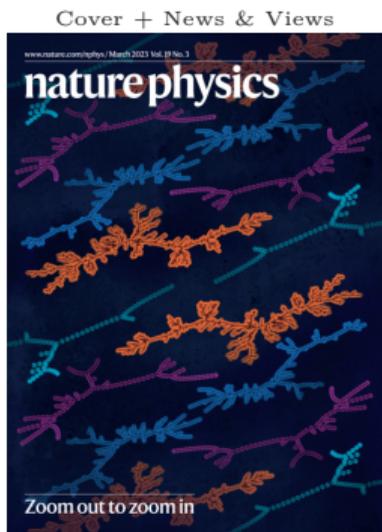
CENTRO RICERCHE
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The missing RG for heterogeneous systems



- Complex systems are intrinsically multiscale
- Heterogeneity fundamentally shapes dynamics
- Statistical physics provides predictive principles

Laplacian Renormalization Group for heterogeneous networks



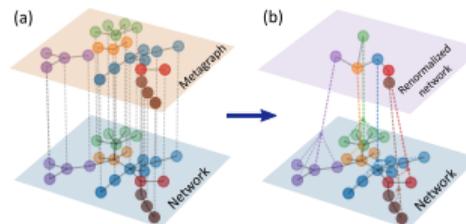
nature physics

Article

<https://doi.org/10.1038/s41567-022-01868-8>

Laplacian renormalization group for heterogeneous networks

Pablo Villegas¹, Tommaso Gill², Guido Caldarelli^{3,4,5,6,7} & Andrea Gabrielli^{1,6}



News & views

Renormalization group

<https://doi.org/10.1038/s41567-022-01842-0>

A zoom lens for networks

Konstantin Klemm

Check for updates

Laplacian renormalization for complex networks: Information new emerges from network transitions
Pablo Villegas¹, Tommaso Gill², Guido Caldarelli^{3,4,5,6,7} & Andrea Gabrielli^{1,6}

PHYSICAL REVIEW RESEARCH 5, 031001 (2023)

PHYSICAL REVIEW RESEARCH 5, 031001 (2023)

CENTRO RICERCHE
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The LRG framework positions CREF as a global reference in multiscale network theory.

Vision and Objectives

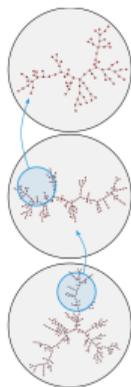
LRG provides a unifying language across disciplines.

Scientific goals

- Develop a geometric theory of disordered systems
- Understand memory and non-ergodicity
- Deliver multiscale tools for brain, climate, ecology and AI

Strategic impact for CREF

- Position CREF at the frontier of statistical physics
- Strengthen links across physics, neuroscience, climate and AI
- Delivering high-visibility publications
- Positioning CREF for ERC-level funding



→ Characterization of LRG fixed points

PHYSICAL REVIEW LETTERS **134**, 057401 (2025)

Networks with Many Structural Scales: A Renormalization Group Perspective

Anna Poggialini^{1,2}, Pablo Villegas^{2,3,*}, Miguel A. Muñoz^{4,3} and Andrea Gabrielli^{2,5,6}

→ Characterization of basin stability

PHYSICAL REVIEW RESEARCH **10**, 010109 (2020)

Geometric criticality in scale-invariant networks

Luca de Luca^{1,2}, Giulio Cimini^{3,4} and Pablo Villegas^{2,5,6}

¹Physics Department and INFN, University of Rome Tor Vergata, 00133 Rome, Italy

²Enrico Fermi Research Center (CFE), 00198 Rome, Italy

³Antonio Caiani I de Física Teórica y Computacional, Universidad de Granada, 18071 Granada, Spain

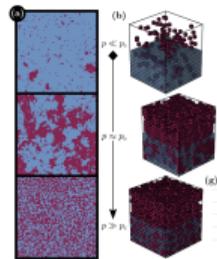
⁴ (Received 19 July 2020; accepted 28 January 2021; published 10 October 2020)

⁵ (Received 19 July 2020; accepted 28 January 2021; published 10 October 2020)

→ Short-range spin-glasses framework (under review in Nat. Comm.)

Topological Symmetry Breaking in Antagonistic Dynamics

Giulio Iannelli^{1,2}, Pablo Villegas^{1,3,*}, Tommaso Gili⁴, and Andrea Gabrielli^{1,5}



→ Metrical network embeddings

PHYSICAL REVIEW E **111**, L042301 (2025)

Letter

Strange attractors in complex networks

Pablo Villegas^{*}

^{*}Enrico Fermi^{*} Research Center (CFE), Via Pasubio 39A, 00198 Rome, Italy

and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, E-18071 Granada, Spain

^{*} (Received 16 December 2024; accepted 31 March 2025; published 15 April 2025)

→ Review on LRG on Nature Review Physics

nature reviews physics

Technical review

<https://doi.org/10.1038/s42254-025-00817-5>

check for updates

Network renormalization

Andrea Gabrielli^{1,2,3}, Diego Garlaschelli^{4,5,6}, Subodh P. Patil⁷ & M. Angeles Serrano^{8,9,10}

Actual results

Ecology & Social & Climate applications

→ Analyzing ecological systems



Physics

Uncovering Networks in Rainforest Plants

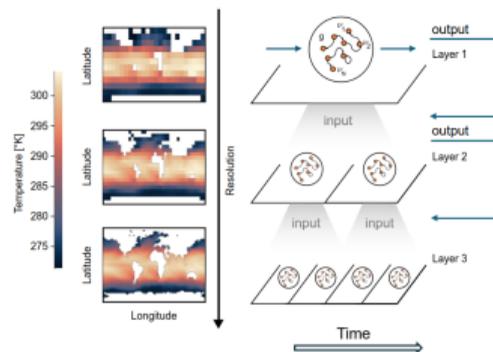
The spatial arrangement of plants in a rainforest corresponds to a special "critical" state that could be vital for ecosystem robustness.

By Philip Ball



BCI, Panama

→ Climate change multi-scale predictions



→ Epidemic and social contagion

scientific reports



Higher-order contagion processes in 1.99 dimensions

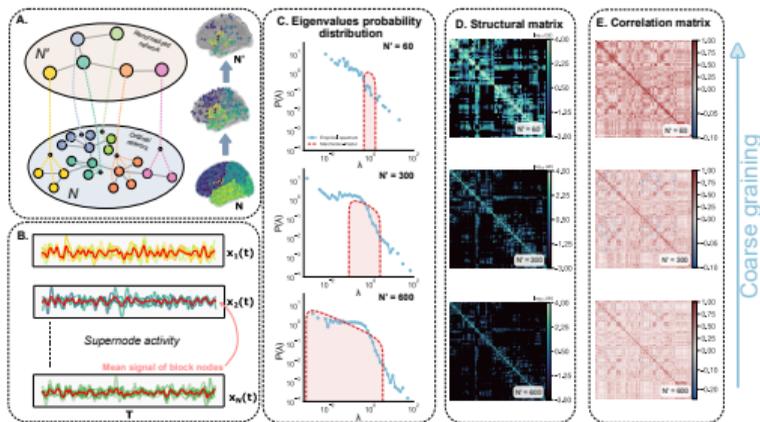
Sandro Meloni^{1,2,3,*}, Andrea Gabrielli^{3,4,5} and Pablo Villegas^{3,6,†}

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ENRICO FERMI

On-going research

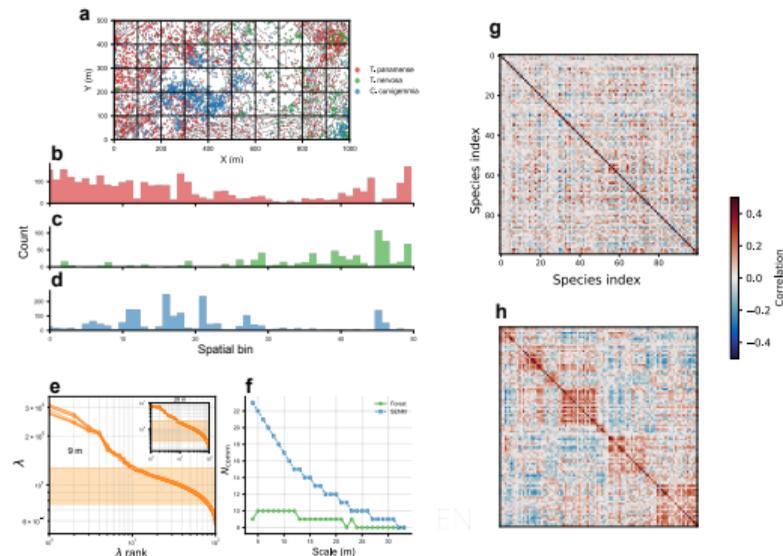
Neural & Ecological data-driven applications

- LRG-RMT noise filtering to make fMRI analysis statistically well-posed under realistic scan durations

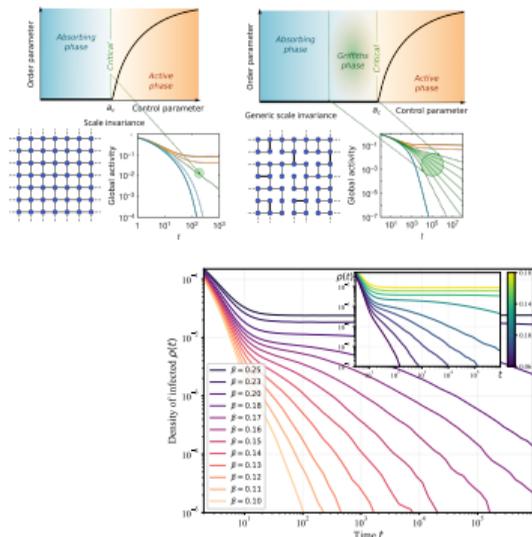


- Collaborations with CREF & Sapienza on biomarkers and multiscale LRG

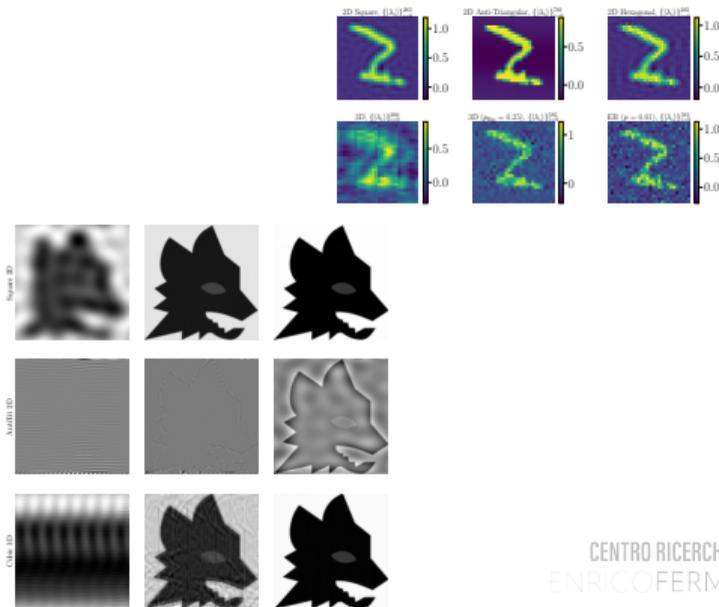
- Neutral-niche debate: scale limits from Barro Colorado data



→ Theory of Griffiths phases in complex systems



→ Developing a new class of heterogeneous topological autoencoders





Building a unifying geometric theory of complexity at CREF

- Theory: geometry-driven criticality
- Data: multiscale biomarkers in brain & ecology
- AI: memory and learning in disordered networks

Track records and funded projects

- The research line has produced more than 30 papers in the last 3 years, including Nat. Phys., Nat.Comm., PRL, Nat.Rev.Phys and receiving attention in covered media.

Funded Projects

- 2022-2026 PRIN PNRR. With IAC-CNR & Politecnico di Milano. 32 k€. PI: Fabio Saracco
- 2024-2025 PNRR. MNESYS SINVAS. 249k€. PI: Federico Giove. Participant: Pablo Villegas

Future Project Request

- ERC Starting Grant 2026. PI: Pablo Villegas. Disentangling topology from dynamics in non-ergodic systems.
- PRIN Projects 2026.