Pablo Villegas

Critical Collective Phenomena

Renormalization, multiscale organization, and critical dynamics in heterogeneous systems

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Research Profile

Statistical physicist developing a unified multiscale framework for heterogeneous systems, based on renormalization, spectral methods, and geometric approaches to complex networks.

My research program focuses on establishing predictive principles for collective behavior, with particular emphasis on the Laplacian Renormalization Group and its applications to brain dynamics, ecology, and data-driven complex systems.

Research Vision

My research aims to establish a unified statistical-physics framework for heterogeneous systems, where geometry, topology, and dynamics are treated on equal footing.

The program focuses on: (i) developing renormalization principles for complex networks; (ii) identifying universality classes driven by structure and heterogeneity; and (iii) bridging theoretical advances with data-driven systems, including neuroscience, ecology, and learning architectures.

Research Themes

Renormalization and multiscale theory. Development of geometric and spectral frameworks to coarse-grain heterogeneous networks and reveal hidden organization across scales.

Criticality in complex systems. Statistical-physics approaches to phase transitions, synchronization, contagion, and collective dynamics on structured substrates.

Applications across natural systems. Brain networks, ecology, plant communities, collective behaviour, and related data-driven complex systems.

Appointments

2023–Present	**Research Scientist**, Enrico Fermi Research Center, Rome, Italy
2022–2023	**Postdoctoral Research Associate**, Enrico Fermi Research Center, Rome, Italy
2020–2022	**Postdoctoral Research Associate**, Networks Unit, IMT School for Advanced Studies, Lucca, Italy
2019–2020	**Postdoctoral Research Associate**, Institute for Complex Systems (ISC-CNR), Rome, Italy
2018–2019	**Postdoctoral Orientation Fellowship**, University of Granada, Spain
2015–2018	**PhD Fellowship**, Statistical Physics Group, University of Granada, Spain

Selected Contributions

2023	**Nature Physics**: Established the *Laplacian Renormalization Group* framework for heterogeneous networks. Cover article with accompanying *News & Views*.
2025	**Physical Review Letters**: Introduced a renormalization perspective on networks with multiple structural scales.
2018	**PNAS**: Developed a Landau–Ginzburg framework for cortical dynamics, showing that scale-free avalanches emerge at the edge of synchronization.
2024	**Physical Review E**: Revealed scale-free organization in tropical rainforests from a statistical-physics perspective. Editor's Suggestion; featured in *Physics*.
2025	**Physical Review E**: Demonstrated the emergence of strange attractors in complex networks (single-author).

Scientific Metrics

Publications	25+ peer-reviewed articles
Citations	1k+ citations (Google Scholar)
h-index	16

Full Publication List

1. L. Lucarini, G. Cimini, and P. Villegas, *Geometric Criticality in Scale-Invariant Networks*, **Physical Review Research 8**, 013330 (2025).
2. L. Falsi, P. Villegas, T. Gili, A. J. Agranat, and E. DelRe, *Topological protection breakdown: A route to frustrated ferroelectricity*, **Physical Review Research 7**, 043038 (2025).
3. P. Villegas, *Strange attractors in complex networks*, **Physical Review E 111**, L042301 (2025).
4. A. Poggialini, P. Villegas, M. A. Muñoz, and A. Gabrielli, *Networks with many structural scales: a Renormalization Group perspective*, **Physical Review Letters 134**, 057401 (2025).
5. P. Villegas, A. Gabrielli, A. Poggialini, and T. Gili, *Multi-scale Laplacian community detection in heterogeneous networks*, **Physical Review Research 7**, 013065 (2025).
6. G. Caldarelli, A. Gabrielli, T. Gili, and P. Villegas, *Laplacian renormalization group: an introduction to heterogeneous coarse-graining*, **Journal of Statistical Mechanics** 073202 (2024).
7. P. Villegas, T. Gili, G. Caldarelli, and A. Gabrielli, *Evidence of scale-free clusters of vegetation in tropical rainforests*, **Physical Review E 109**, L042402 (2024). Editor's Suggestion; featured in *Physics*.
8. P. Villegas, T. Gili, G. Caldarelli, and A. Gabrielli, *Laplacian Renormalization Group for heterogeneous networks*, **Nature Physics 19**, 445–450 (2023). Cover article; accompanied by a News & Views.
9. P. Villegas, A. Gabrielli, F. Santucci, G. Caldarelli, and T. Gili, *Laplacian paths in complex networks: information core emerges from entropic transitions*, **Physical Review Research 4**, 033196 (2022).
10. P. Villegas, T. Gili, A. Gabrielli, and G. Caldarelli, *Characterizing spatial point processes by percolation transitions*, **Journal of Statistical Mechanics** 073202 (2022).
11. V. Buendía, P. Villegas, R. Burioni, and M. A. Muñoz, *The broad edge of synchronization: Griffiths effects and collective phenomena in brain networks*, **Philosophical Transactions of the Royal Society A 380**, 20200424 (2022).

12. A. Cavagna, A. Culla, X. Feng, I. Giardina, T. S. Grigera, W. Kion-Crosby, S. Melillo, G. Pisegna, L. Postiglione, and P. Villegas, *Marginal speed confinement resolves the conflict between correlation and control in natural flocks of birds*, **Nature Communications 13**, 2315 (2022).

13. P. Villegas, T. Gili, and G. Caldarelli, *Emergent spatial patterns of coexistence in species-rich plant communities*, **Physical Review E 104**, 034305 (2021).

14. V. Buendía, P. Villegas, R. Burioni, and M. A. Muñoz, *Hybrid-type synchronization transitions: Where incipient oscillations, scale-free avalanches, and bistability live together*, **Physical Review Research 3**(2), 023224 (2021).

15. A. Cavagna, X. Feng, S. Melillo, L. Parisi, L. Postiglione, and P. Villegas, *CoMo: A novel co-moving 3D camera system*, **IEEE Transactions on Instrumentation and Measurement 70**, 1–16 (2021).

16. P. Villegas, A. Cavagna, M. Cencini, H. Fort, and T. S. Griguera, *Joint assessment of density correlations and fluctuations for analysing spatial tree patterns*, **Royal Society Open Science 8**(1), 202200 (2021).

17. V. Buendía, S. di Santo, P. Villegas, R. Burioni, and M. A. Muñoz, *Self-organized bistability and its possible relevance for brain dynamics*, **Physical Review Research 2**, 013318 (2020).

18. P. Villegas, M. A. Muñoz, and J. A. Bonachela, *Evolution in the Debian GNU/Linux software network: analogies and differences with gene regulatory networks*, **Journal of the Royal Society Interface 17**(163), 20190845 (2020).

19. V. Buendía, P. Villegas, S. di Santo, A. Vezzani, R. Burioni, and M. A. Muñoz, *Jensen's force and the statistical mechanics of cortical asynchronous states*, **Scientific Reports 9**, 15183 (2019).

20. P. Villegas, S. di Santo, R. Burioni, and M. A. Muñoz, *Time-series thresholding and the definition of avalanche size*, **Physical Review E 100**, 012133 (2019).

21. S. di Santo, P. Villegas, R. Burioni, and M. A. Muñoz, *Non-normality, reactivity, and intrinsic stochasticity in neural dynamics: a non-equilibrium potential approach*, **Journal of Statistical Mechanics** 073402 (2018).

22. S. di Santo*, P. Villegas*, R. Burioni, and M. A. Muñoz, *Landau-Ginzburg theory of cortex dynamics: scale-free avalanches emerge at the edge of synchronization*, **Proceedings of the National Academy of Sciences USA 115**(7), E1356–E1365 (2018). *Joint first authors.

23. S. di Santo, P. Villegas, R. Burioni, and M. A. Muñoz, *Simple unified view of branching process statistics: Random walks in balanced logarithmic potentials*, **Physical Review E 95**(3), 032115 (2017).

24. P. Villegas, J. M. Ruiz, J. Hidalgo, and M. A. Muñoz, *Intrinsic noise and deviations from criticality in Boolean gene-regulatory networks*, **Scientific Reports 6**, 34743 (2016).

25. P. Villegas, J. Hidalgo, P. Moretti, and M. A. Muñoz, *Complex synchronization patterns in the human connectome network*, in *Proceedings of ECCS 2014: European Conference on Complex Systems*, 69–80 (Springer International Publishing, 2016).

26. B. Moglia, E. Albano, P. Villegas, and M. A. Muñoz, *Interfacial depinning transitions in disordered media: revisiting an old puzzle*, **Journal of Statistical Mechanics** P10024 (2014).

27. P. Villegas, P. Moretti, and M. A. Muñoz, *Frustrated hierarchical synchronization and emergent complexity in the human connectome network*, **Scientific Reports 4**, 5990 (2014).

Talks and Conference Activity

Jul 2025	Complex Networks and Their Applications – StatPhys29 Satellite Workshop, Venice, Italy. Talk.
Jul 2025	StatPhys29 – The 29th International Conference on Statistical Physics, Florence, Italy. Talk.
Jul 2024	Complex networks: from socio-economic systems to biology and the brain, Lipari, Italy. Talk.
Jan 2024	NetSciX 2024 – International School and Conference on Network Science, Venice, Italy. Talk.
Sep 2023	Granada Seminar: Machine Learning and Physics, Granada, Spain. Talk.
Jul 2023	Complex networks: from socio-economic systems to biology and the brain, Lipari, Italy. Talk.
Oct 2022	Conference on Complex Systems, Mallorca, Spain. Talk.
Jul 2022	Complex networks: from socio-economic systems to biology and the brain, Lipari, Italy. Talk.
Jun 2022	II Conference of the Italian Society of Statistical Physics (SIFS), Parma, Italy. Talk.
Sep 2019	15th Granada Seminar: Stochastic and Collective Effects in Neural Systems, Granada, Spain. Talk.
Jul 2019	StatPhys27, Buenos Aires, Argentina. Participant.
Jul 2019	Workshop: Statistical Mechanics of Swarming Behaviour, La Plata, Argentina. Talk.
Jun 2019	24th National Conference on Statistical Physics and Complex Systems, Parma, Italy. Poster.
Jun 2019	Statistical mechanics of active matter, L'Aquila, Italy. Participant.
Jun 2018	23rd National Conference on Statistical Physics and Complex Systems, Parma, Italy. Poster.
Apr 2017	FISES 2017, Sevilla, Spain. Poster.
Nov 2016	III Scientific Conferences of the "Carlos I" Institute of Theoretical and Computational Physics, Granada, Spain. Poster.
Jun 2016	Quantitative Laws II: From physiology to ecology, from interaction structures to collective behavior, Como, Italy. Talk.
May 2016	I Conferences for young researchers: fostering interdisciplinarity, Granada, Spain. Talk.
Oct 2015	II Scientific Conferences of the "Carlos I" Institute of Theoretical and Computational Physics, Granada, Spain.
Oct 2015	FISES 2015, Badajoz, Spain. Talk.
Sep 2015	Net-Works 2015: Complex networks and their interdisciplinary applications, Granada, Spain. Local organizing committee.
Jun 2015	13th Granada Seminar on Computational and Statistical Physics, La Herradura, Spain. Talk. Local organizing committee.
May 2015	BIOMAT: Emergence and self-organization in social and biological systems, Granada, Spain. Participant.
Sep 2014	Summer School on Statistical Physics of Complex Systems, IFISC, Palma de Mallorca, Spain. Poster and talk.

Supervision

Master's theses	Lorenzo Lucarini and Ottavia Falconi (2023–2024).
PhD supervision	Giulio Iannelli (2022–2025), CREF; Gabriele Poidomani (2022–Present), CREF; Lorenzo Grimaldi (2023–Present), CREF; Lorenzo Lucarini (2024–Present), CREF; Ottavia Falconi (2024–Present), CREF.

Grants, Awards, and Projects

2020	**Seal of Excellence**, MSCA-IF High Quality Project: *Statistical Mechanics of Tropical Rainforests* (87.0/100), ISC-CNR, Rome.
2017	**Mobility Grant**, University of Strathclyde, funded by MINECO. Advisor: J. A. Bonachela.
2015–2018	**Doctoral Grant** (FPI Programme), University of Granada, funded by MINECO. Advisor: Miguel Á. Muñoz.
Projects	Participation in funded projects: *Structure and function of cortex neural networks: Connecting fundamental, biomedical and computational aspects* (P20_00173, 2021–2023); *Advances in statistical physics: from fundamentals to the physics of living systems* (PID2020-113681GB-I00, 2021–2024); *Collective Response from Individual Behavior in Groups and Ecosystems (CRIB)* (ELAC2015/T01-0593, 2019–2020); *Frontiers of statistical physics and complex systems* (FIS2017-84256-P, 2018–2021); *Statistical physics of complex systems* (FIS2013-43201-P, 2015–2018).

Teaching and Service

Teaching	Teaching support at the University of Granada in computational physics, statistical physics, physics of complex systems, and complementary training in physics and chemistry (2016–2019).
Detailed teaching	Complementary training in physics and chemistry (0.75 cr, 2018–2019); Physics of complex systems (1.5 cr, 2017–2018); Computational physics (1.5 cr, 2017–2018; 2.2 cr, 2016–2017); Statistical physics (1.5 cr, 2016–2017), University of Granada.
Reviewing	Referee for *Physical Review Letters*, *Physical Review X*, *Science Advances*, *Nature Communications*, *Physical Review E*, *PLoS One*, *Physica D: Nonlinear Phenomena*, *Neurocomputing*, *Scientific Reports*, *Journal of Physics: Complexity*, and *Cambridge Elements*.
Training	Scientific disclosure for researchers: press, TV and radio (2018); Supervision of academic works: PhDs, Master theses and graduate theses (2018); Educational tools for peer production (2016); Initiation to University Teaching for FPU and FPI PhD students (2016).

Education

2014–2018	**PhD in Physics**, University of Granada, Spain. *Magna cum laude*. Dissertation: *Phases and phase transitions in living matter*. Advisor: Miguel Á. Muñoz.
2014–2015	**MSc in Teaching Compulsory and Pre-University Secondary Education, Vocational Training and Language Teaching**, University of Granada. Grade: 9.1/10. Thesis: *Educational applications in Vpython employing cooperative learning*. Advisors: Pablo I. Hurtado and Francisco de los Santos.
2013–2014	**MSc FisyMat: Biomathematics**, University of Granada. Grade: 9.7/10. Thesis: *Synchronization: Study and applications of the Kuramoto model*. Advisors: Miguel Á. Muñoz and Paolo Moretti.
2008–2013	**BSc+MSc in Physics (Licenciado en Física)**, University of Granada. Grade: 7.5/10.

Visits, Languages, and Technical Skills

Visits	Department of Materials Science, University of Erlangen–Nürnberg, Germany (2019, invited seminar); IFLYSIB, University of La Plata, Argentina (2019); Department of Mathematics, Physics and Computer Science, University of Parma, Italy (2018); MASTS Marine Population Modelling Group, University of Strathclyde, Glasgow, UK (2017).
Languages	Spanish (native), Italian (near-native), English (fluent working proficiency).
Technical skills	Programming and scientific computing: Python, C, Fortran, R, LaTeX, OpenMP, GNU/Linux, Matlab, Mathematica, Maxima. Document processing: LyX, LibreOffice Writer, Word.