INSTITUTO CARLOS I
FÍSICA TEÓRICA Y COMPUTACIONAL

FÍSICA LEJOS DEL EQUILIBRIO

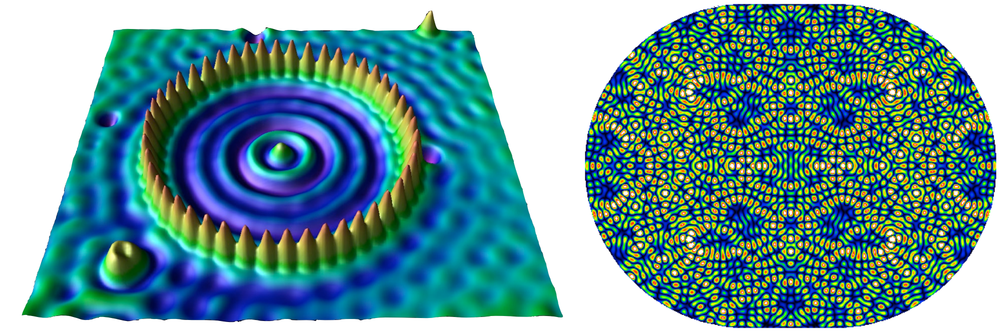
Daniel Manzano

Grupo de Física Estadística
Instituto Carlos I de Física Teórica y Computacional
Departamento de Electromagnetismo y Física de la Materia
Universidad de Granada

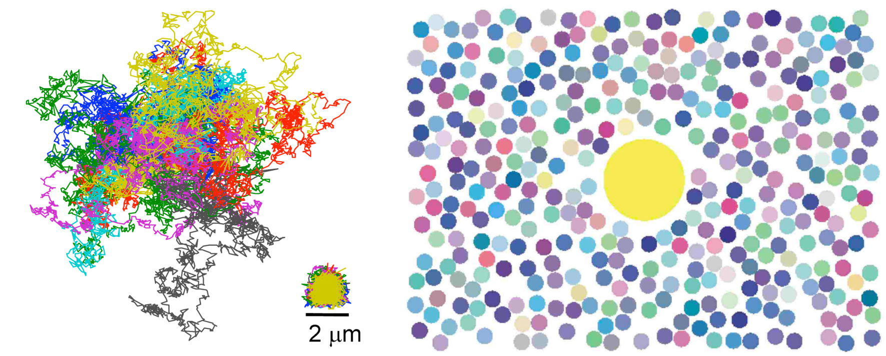
Jornadas de Orientación
Granada, 17 de Marzo de 2017

FÍSICA ESTADÍSTICA

- Las leyes de la física son sencillas
- Sin embargo, **la naturaleza es compleja**
- **¿Cómo emerge el mundo complejo que nos rodea de las leyes simples de la física?**

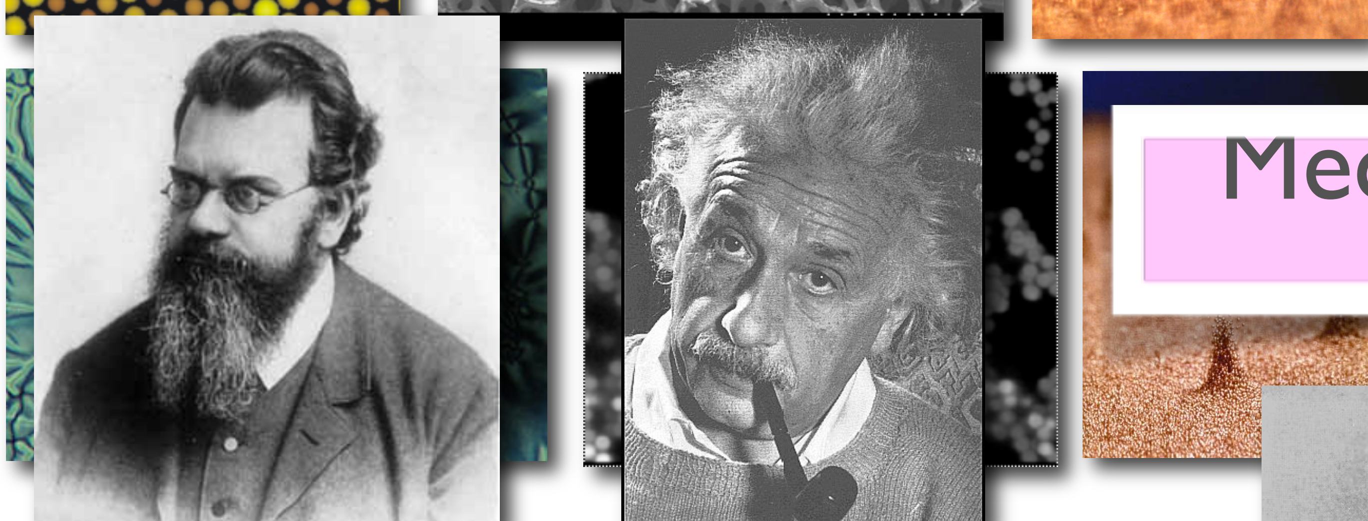


Caos en corrales cuánticos



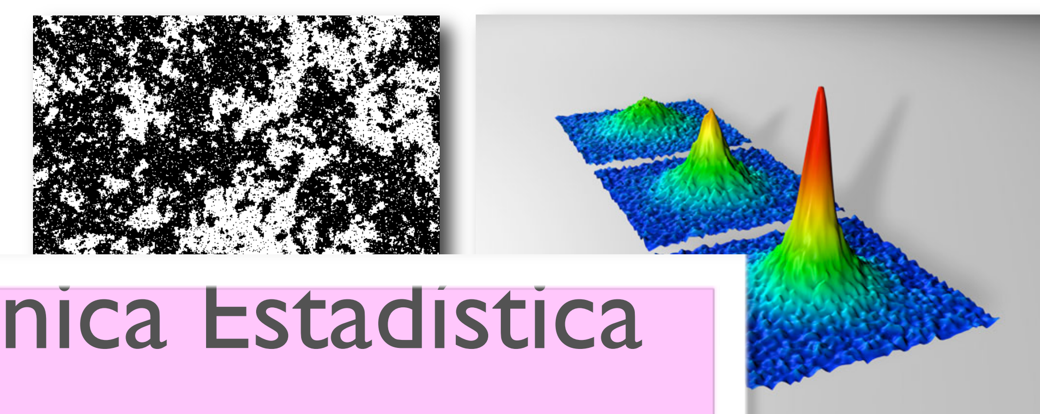
Einstein & movimiento Browniano

Materiales complejos



Boltzmann

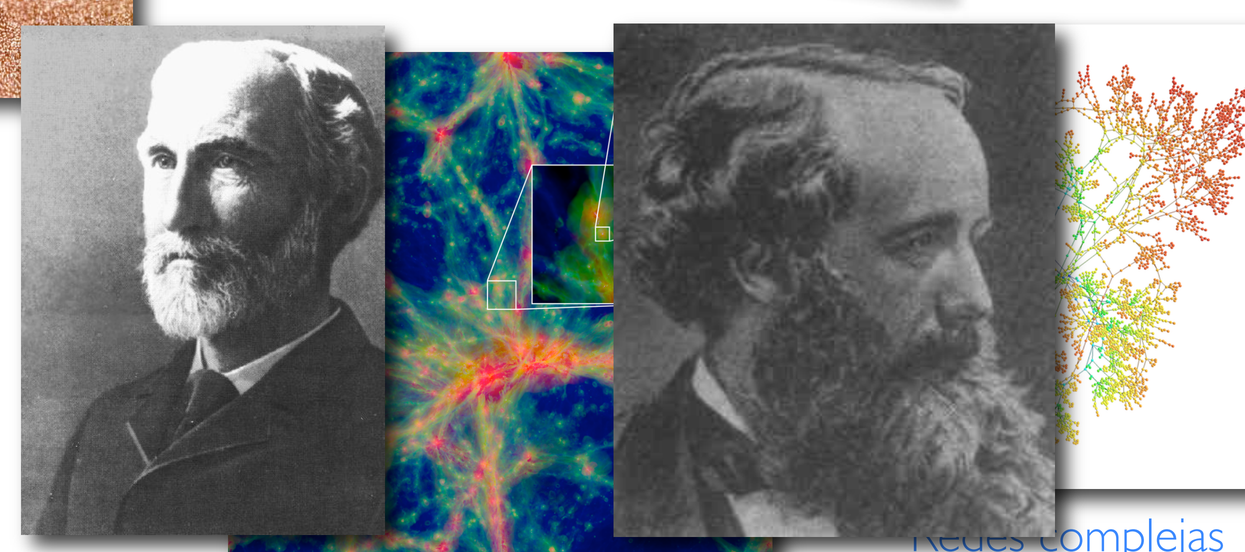
Einstein



Mecánica Estadística

Transiciones de fase & fenómenos críticos

Auto-organización



Redes complejas

Gibbs

Estructura a gran escala

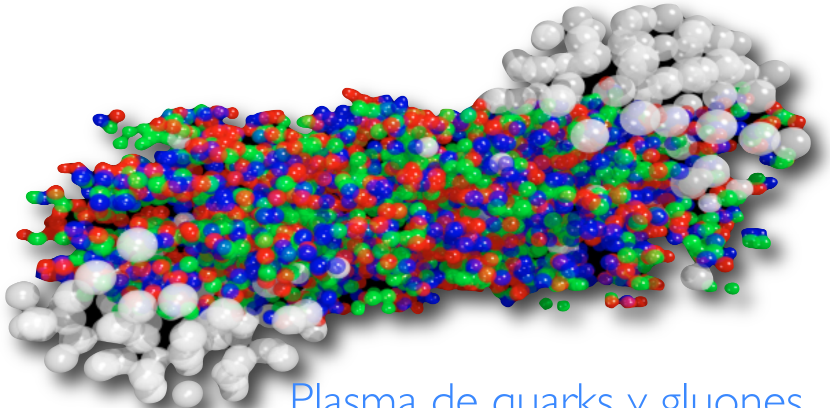
Maxwell

EQUILIBRIO VS NO-EQUILIBRIO

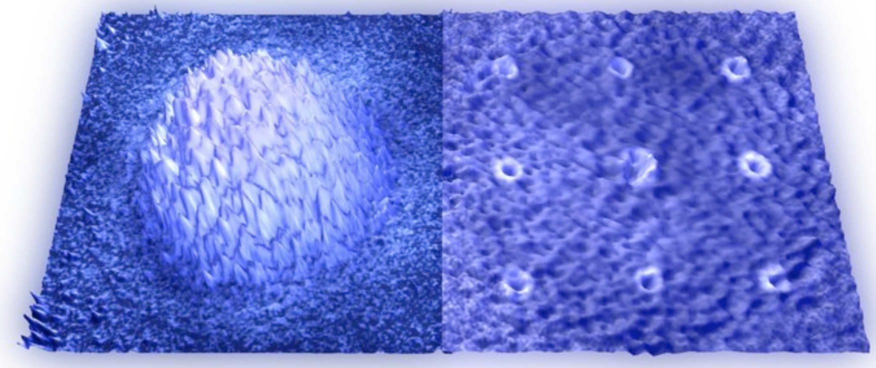
- **En equilibrio**: la teoría de colectividades nos ofrece una conexión simple entre la física microscópica y la macroscópica

Equilibrium: $\mathcal{H}(C) \longrightarrow Z = \sum e^{-\beta \mathcal{H}(C)} \longrightarrow F = -k_B T \ln Z$

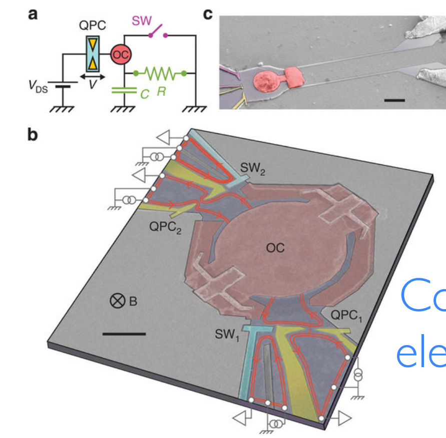
- Sin embargo, muchos sistemas naturales están **fuera del equilibrio**



Plasma de quarks y gluones

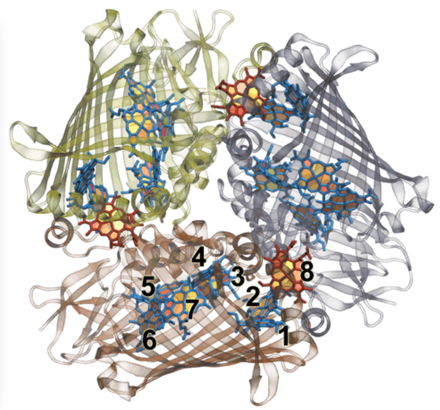


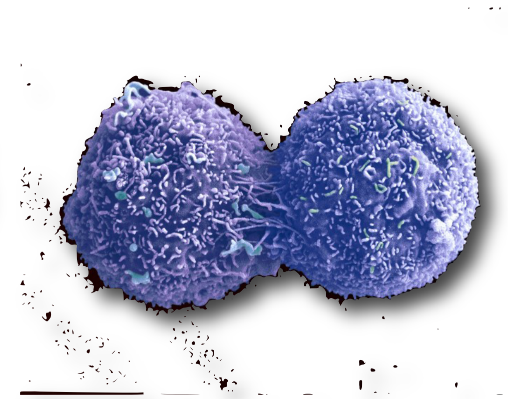
Expasión libre de un gas (cuántico)



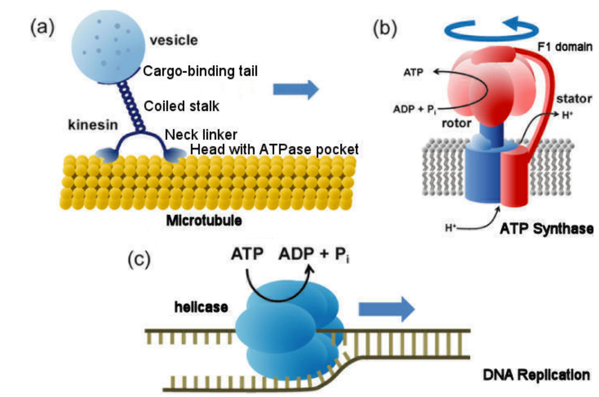
Corriente electrónica

Fotosíntesis





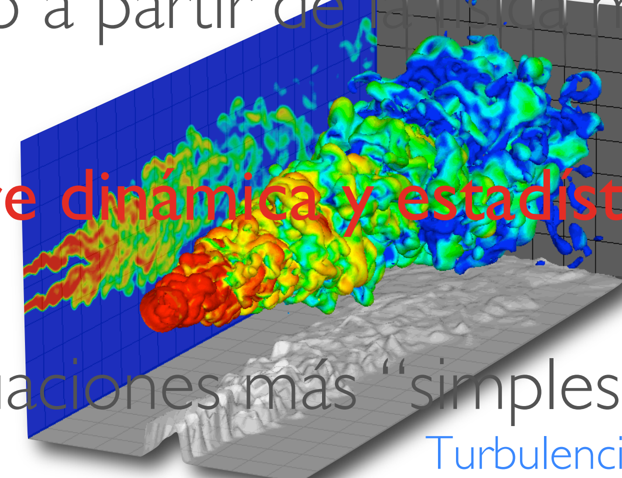
Funcionamiento celular



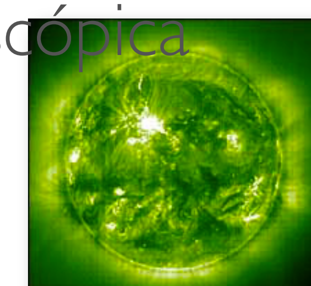
Motores moleculares

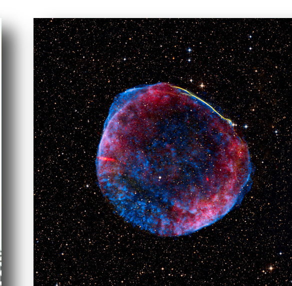
- **Fuera del equilibrio no existe un formalismo** capaz de predecir el comportamiento macroscópico de no-equilibrio a partir de la física microscópica

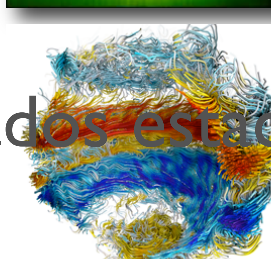
Reacciones químicas



Turbulencia







Física estelar

- Motivo: **conexión íntima entre dinámica y estadística**

- Esto sucede incluso en las situaciones más "simples": **estados estacionarios fuera del equilibrio**

CARACTERÍSTICAS DEL NO-EQUILIBRIO

- Los sistemas fuera del equilibrio **disipan constantemente energía** para mantener su estado, **generando entropía**.
- Están sujetos a **fuerzas externas y/o gradientes** que generan **corrientes**
- Física no local, correlaciones de largo alcance, invariancia de escala, topologías complejas, auto-organización, etc. **Principio unificador: fluctuaciones fuera del equilibrio**

PREGUNTAS QUE NOS HACEMOS

- **Origen de la irreversibilidad**: ¿Por qué las leyes de la física macroscópica son irreversibles mientras que las leyes microscópicas son reversibles?

- **Flecha del tiempo**: ¿por qué el tiempo fluye en una dirección determinada (la que marca el aumento de entropía)?

- ¿Cual es la probabilidad de diferentes **eventos raros**? ¿Cómo se organiza un sistema para generar esas fluctuaciones?

- **Simetrías ocultas y emergentes** en sistemas complejos. **Leyes de escala universales**.

- Transiciones de fase dinámicas y/o lejos del equilibrio

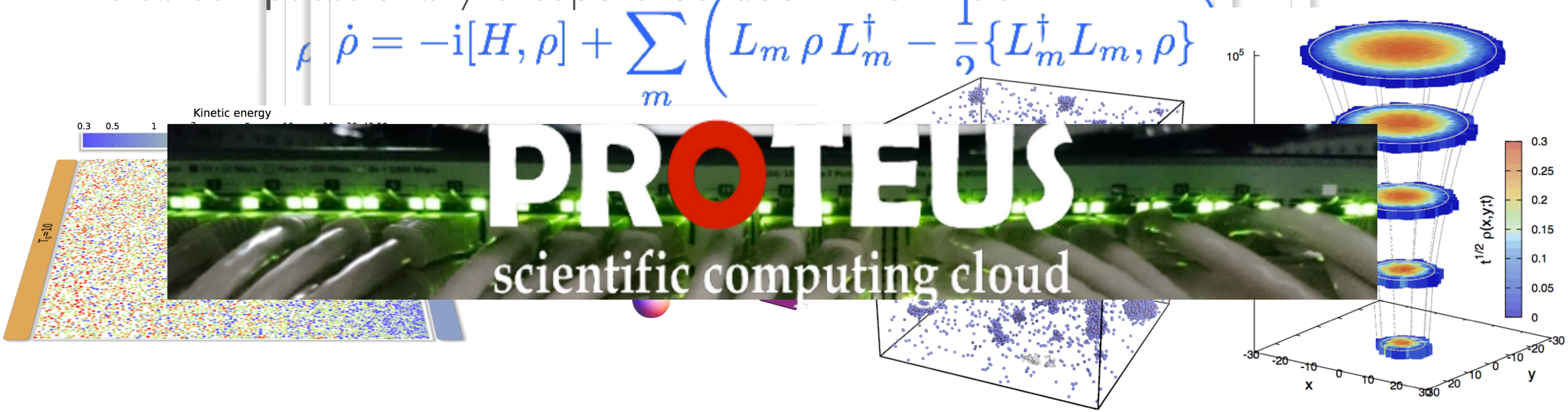
- ¿Podemos usar las herramientas de la física estadística para entender **fenómenos complejos y emergentes** en diferentes escalas?

- **Aplicaciones interdisciplinares** en biología, neurociencia, ecología, feología, sociología, economía, etc.

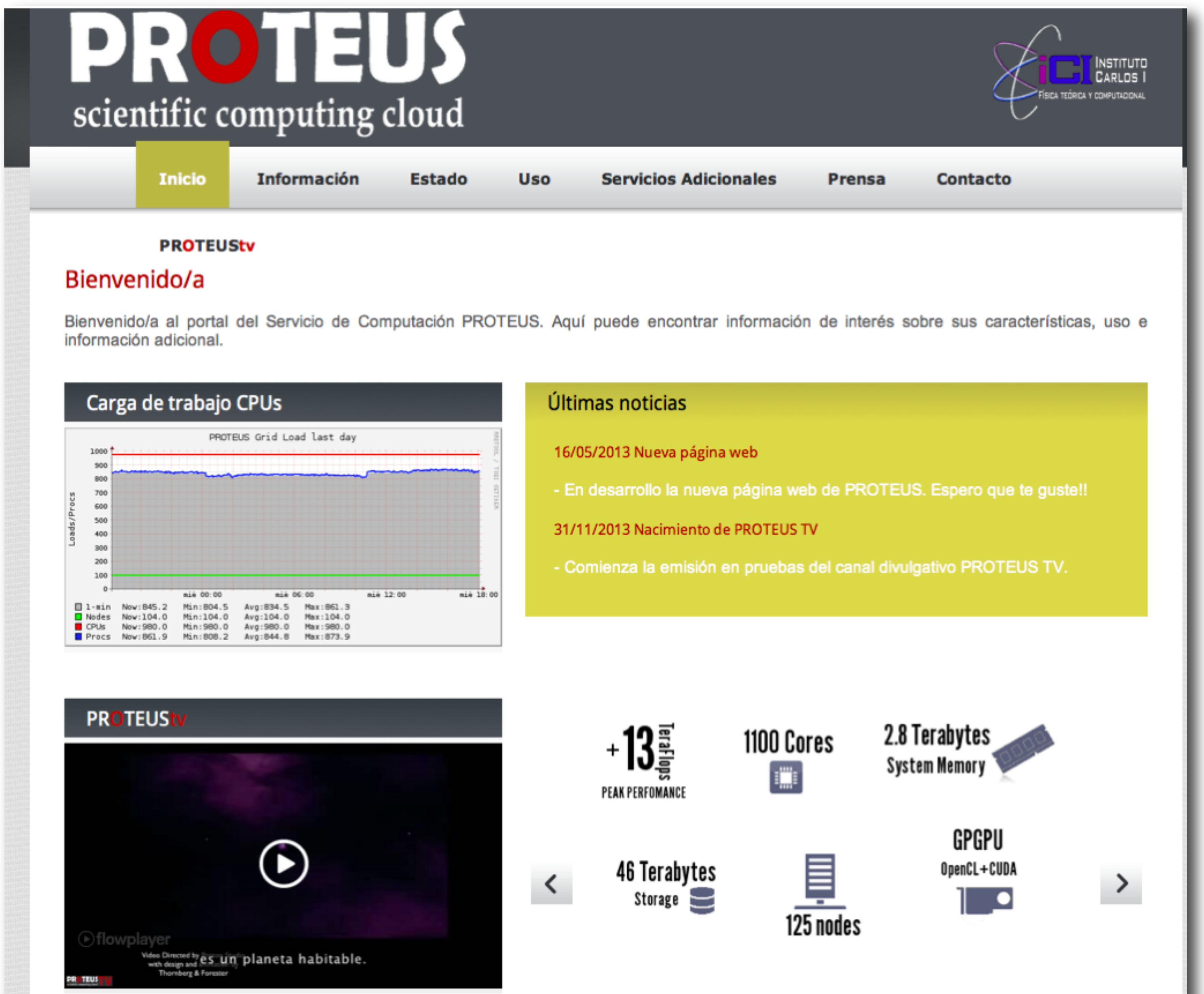
HERRAMIENTAS QUE UTILIZAMOS

- **Palabras clave**: Teorías de campos, ecuaciones de Langevin y Fokker-Planck, ecuación maestra, integrales de camino, teoría de grandes desviaciones, teoremas de fluctuación, hidrodinámica, leyes de escala, ecuación de Lindblad, redes complejas, métodos espectrales, etc.

- **Física computacional** y el superordenador PROTEUS



PROTEUS
scientific computing cloud



- Potencia de cómputo: ~13 Teraflops (13*1012 operaciones en doble precisión por segundo)
- Memoria principal: 2,8 Terabytes. Almacenamiento: 46 Terabytes (cuenta principal + backup)
- Núcleos de ejecución: 1100 núcleos (repartidos en nodos de 8 y 12 núcleos, a 2,33GHz y 3,45GHz, respectivamente)

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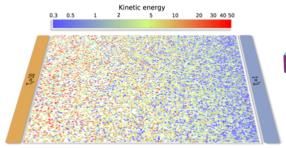
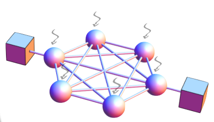
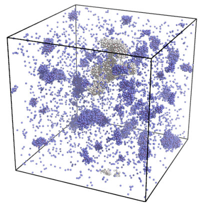
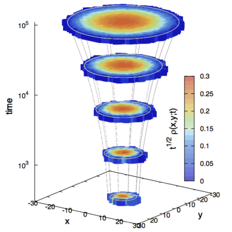
Física Teórica y Computacional

HERRAMIENTAS QUE UTILIZAMOS

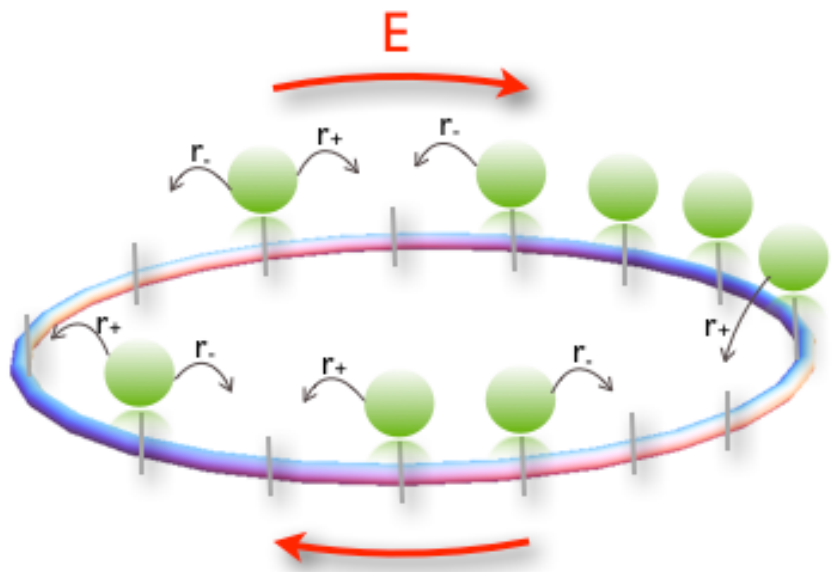
- **Palabras clave**: Teorías de campos, ecuaciones de Langevin y Fokker-Planck, ecuación maestra, integrales de camino, teoría de grandes desviaciones, teoremas de fluctuación, hidrodinámica, leyes de escala, ecuación de Lindblad, redes complejas, métodos espectrales.

- **Física computacional** y el superordenador **PROTEUS**

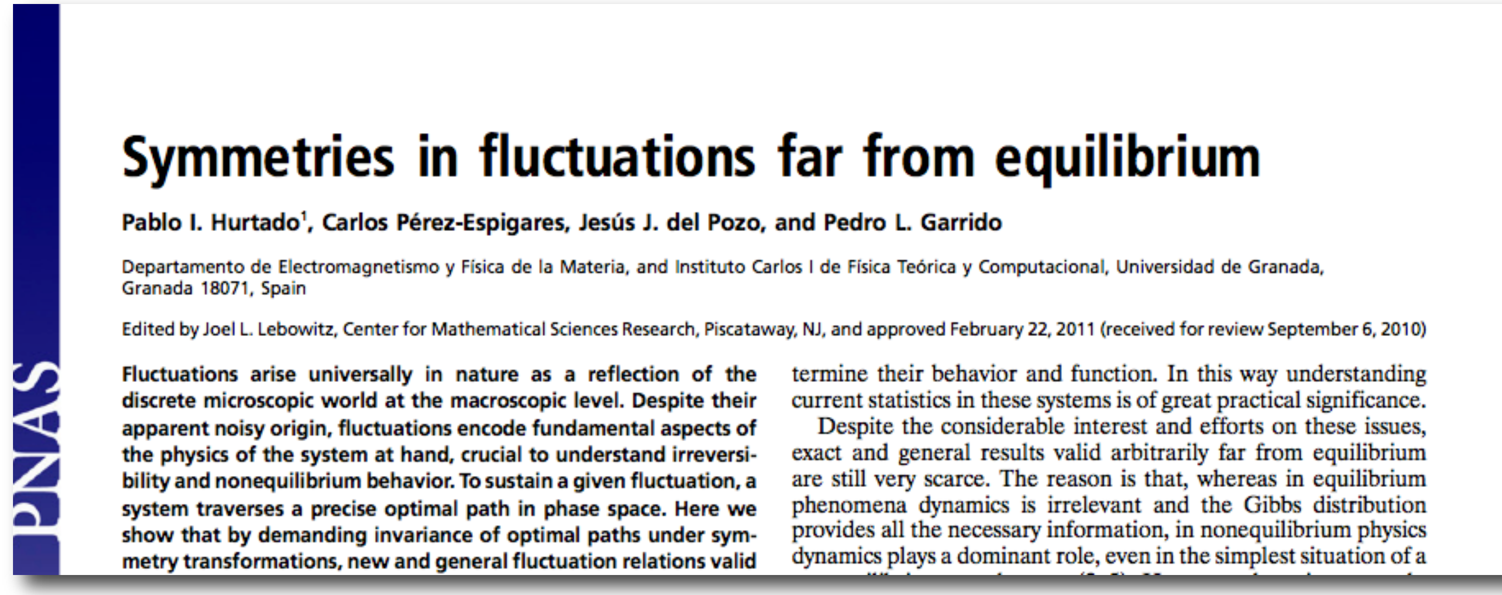





- **Modelos simplificados**

- E **imaginación**, mucha imaginación ...



GALERÍA DE RESULTADOS



PNAS

Symmetries in fluctuations far from equilibrium

Pablo I. Hurtado[1], Carlos Pérez-Espigares, Jesús J. del Pozo, and Pedro L. Garrido

Departamento de Electromagnetismo y Física de la Materia, and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Granada 18071, Spain

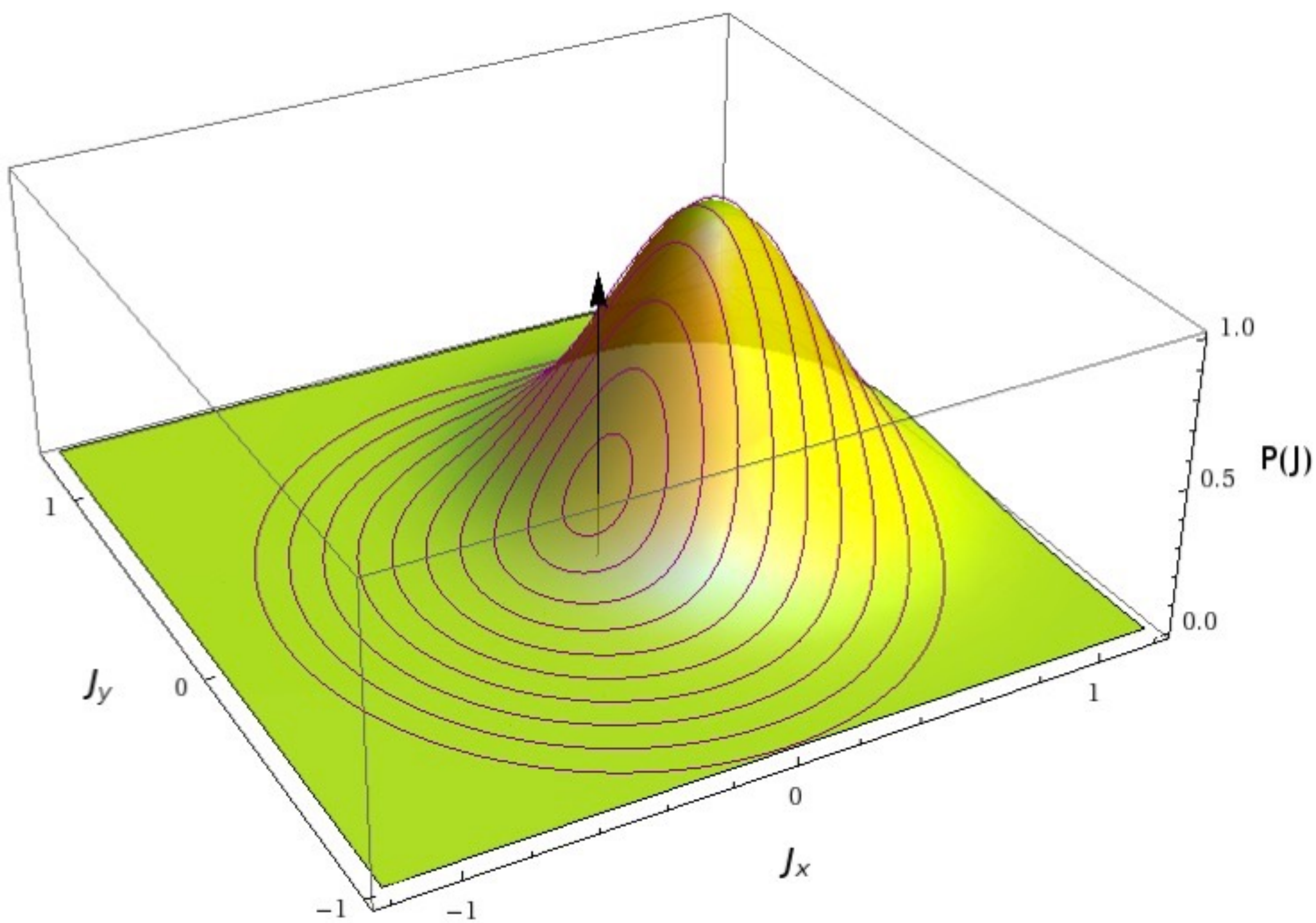
Edited by Joel L. Lebowitz, Center for Mathematical Sciences Research, Piscataway, NJ, and approved February 22, 2011 (received for review September 6, 2010)

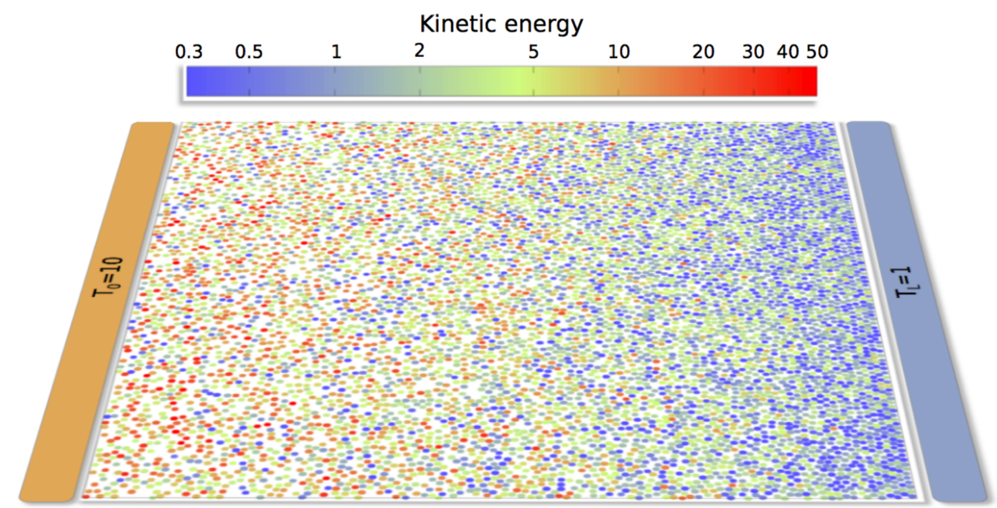
Fluctuations arise universally in nature as a reflection of the discrete microscopic world at the macroscopic level. Despite their apparent noisy origin, fluctuations encode fundamental aspects of the physics of the system at hand, crucial to understand irreversibility and nonequilibrium behavior. To sustain a given fluctuation, a system traverses a precise optimal path in phase space. Here we show that by demanding invariance of optimal paths under symmetry transformations, new and general fluctuation relations valid

termine their behavior and function. In this way understanding current statistics in these systems is of great practical significance.

Despite the considerable interest and efforts on these issues, exact and general results valid arbitrarily far from equilibrium are still very scarce. The reason is that, whereas in equilibrium phenomena dynamics is irrelevant and the Gibbs distribution provides all the necessary information, in nonequilibrium physics dynamics plays a dominant role, even in the simplest situation of a

- Simetrías en fluctuaciones fuera del equilibrio





$$\lim_{\tau\to\infty} \frac{1}{\tau L^d} \ln\left[\frac{P_\tau(\boldsymbol{J})}{P_\tau(\boldsymbol{J}')}\right] = \boldsymbol{\epsilon}\cdot(\boldsymbol{J}-\boldsymbol{J}')$$

$$\boldsymbol{J}' = \hat{\mathcal{R}}_d \boldsymbol{J} \;\Rightarrow\; |\boldsymbol{J}| = |\boldsymbol{J}'|$$

GALERÍA DE RESULTADOS

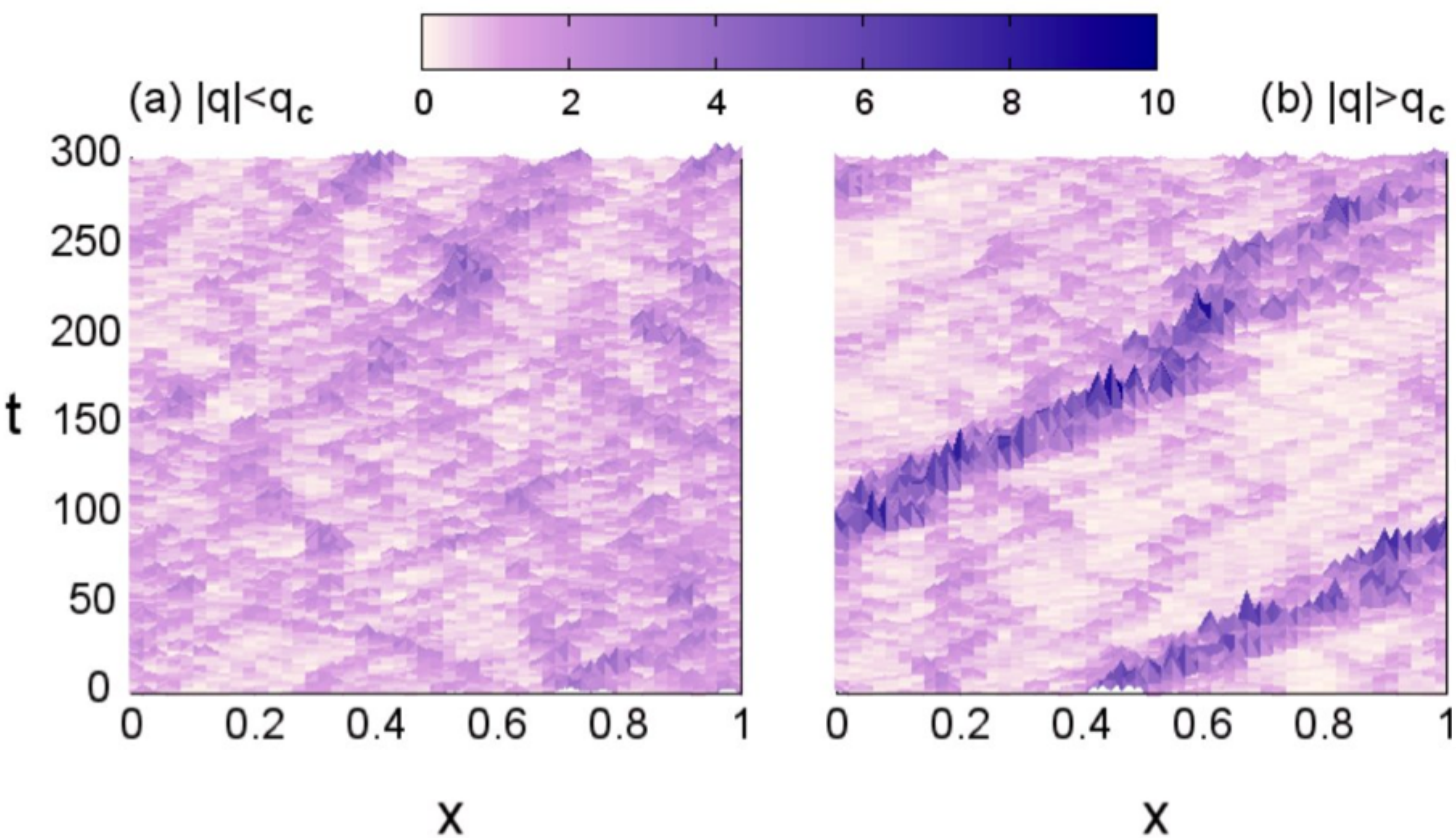
PRL 107, 180601 (2011) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2011

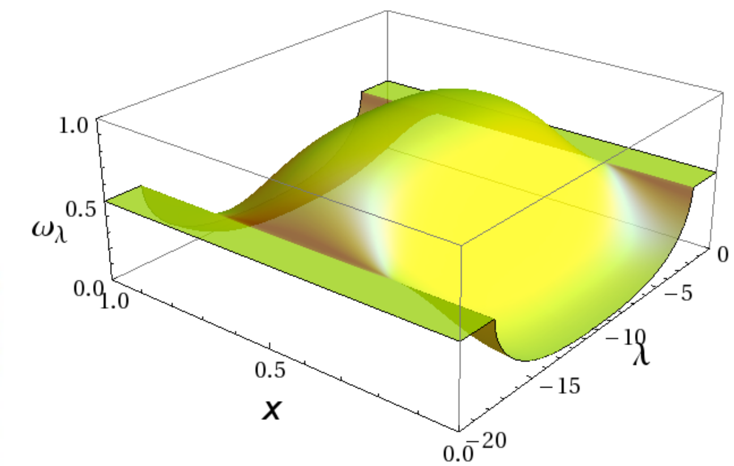
Spontaneous Symmetry Breaking at the Fluctuating Level

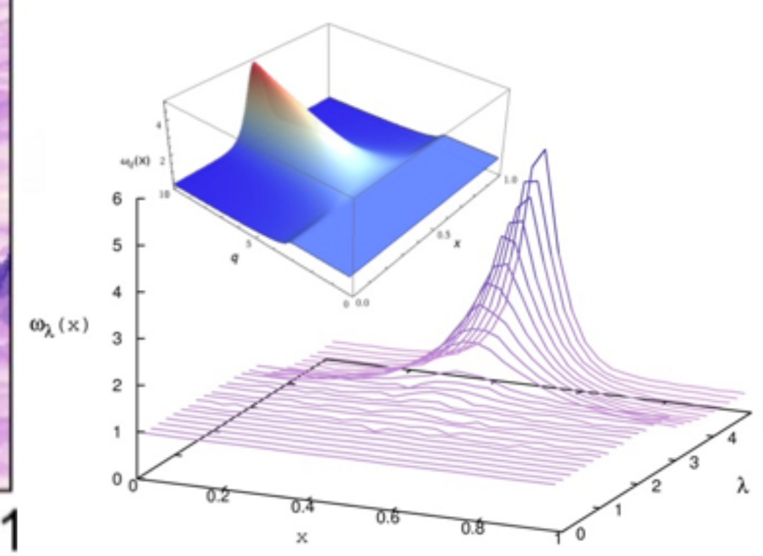
Pablo I. Hurtado and Pedro L. Garrido
Departamento de Electromagnetismo y Física de la Materia,
and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Granada 18071, Spain
(Received 3 June 2011; published 27 October 2011)

Phase transitions not allowed in equilibrium steady states may happen, however, at the fluctuating level. We observe for the first time this striking and general phenomenon measuring current fluctuations in an isolated diffusive system. While small fluctuations result from the sum of weakly correlated local events, for currents above a critical threshold the system self-organizes into a coherent traveling wave which facilitates the current deviation by gathering energy in a localized packet, thus breaking translation

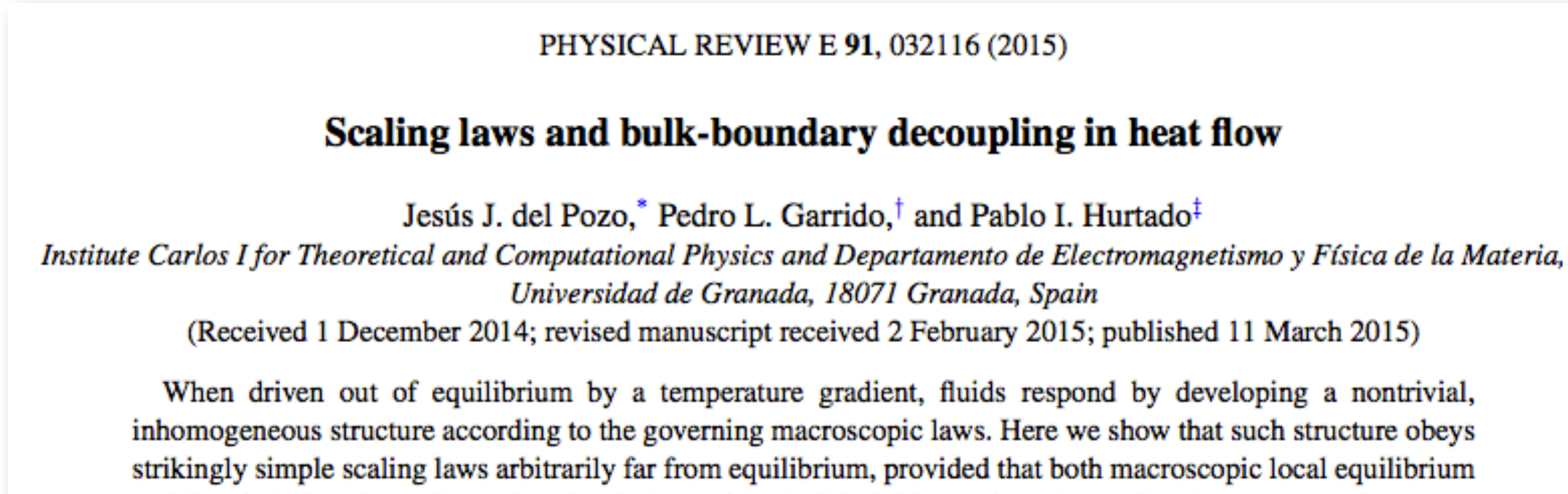
- Ruptura espontánea de simetría a nivel fluctuante







GALERÍA DE RESULTADOS

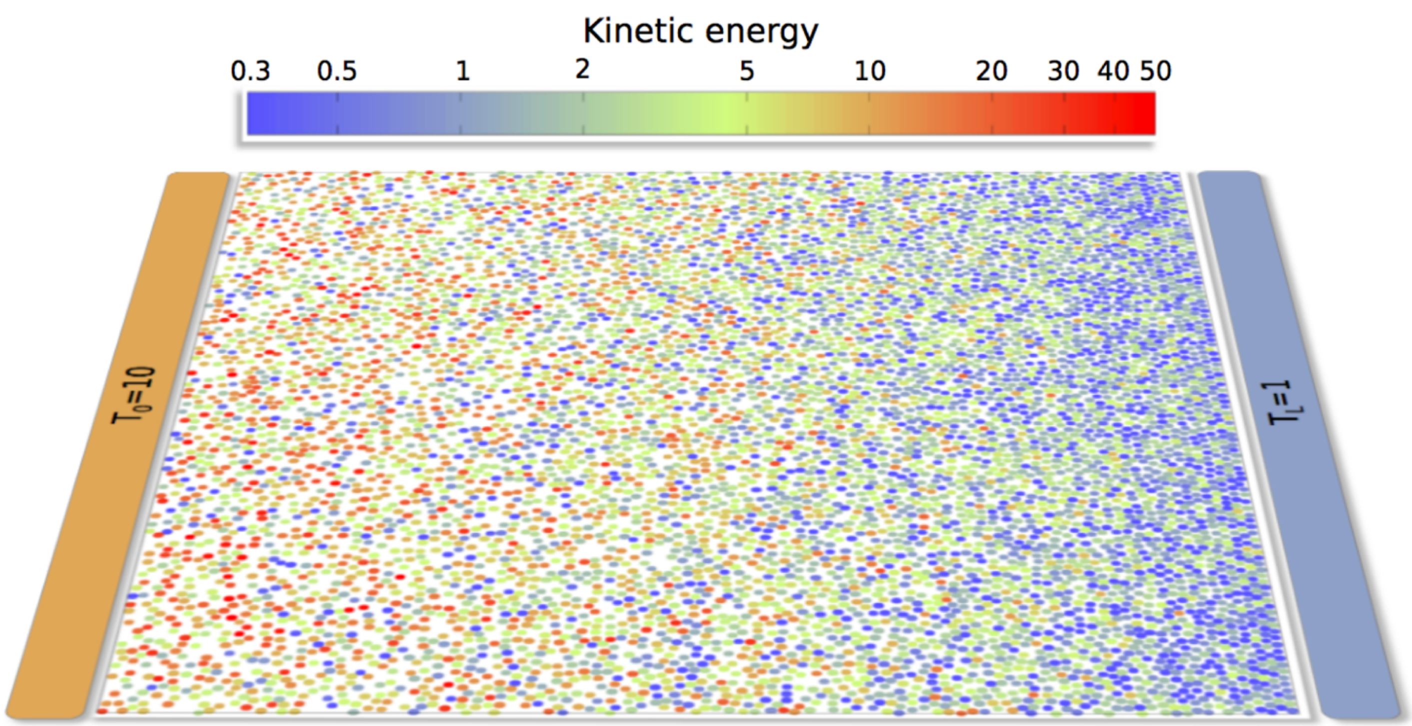

PHYSICAL REVIEW E **91**, 032116 (2015)

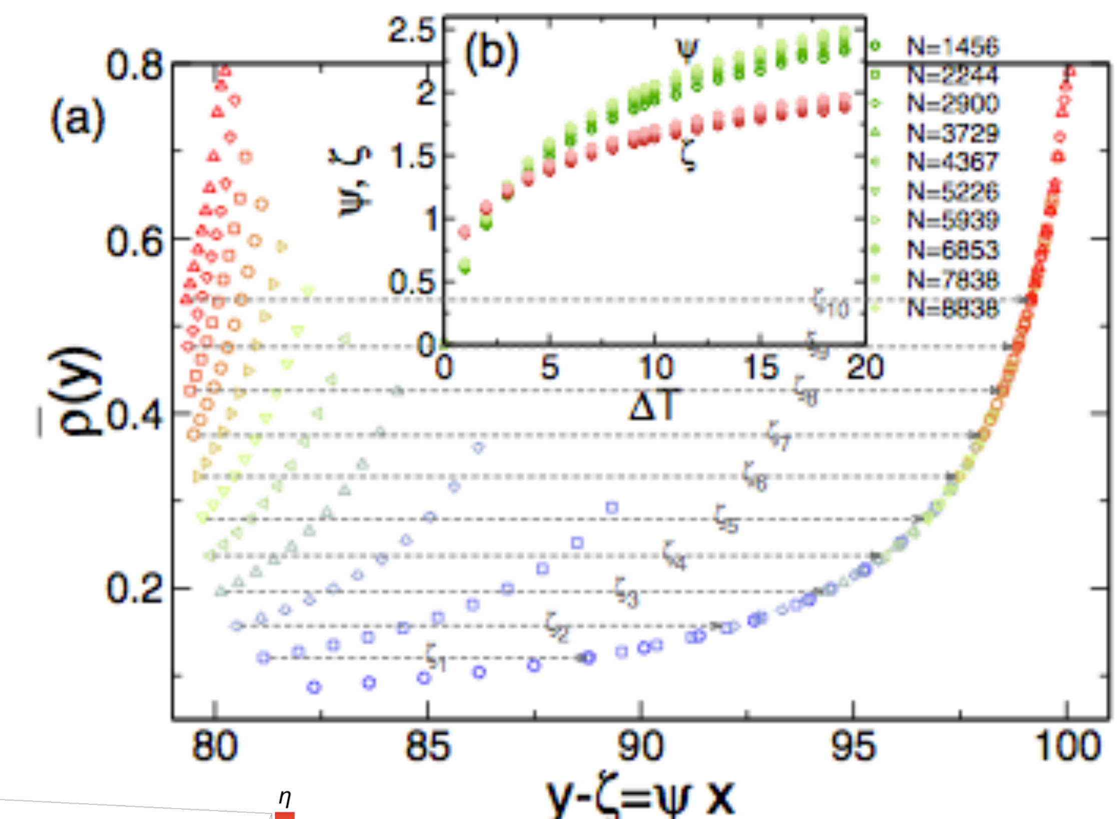
Scaling laws and bulk-boundary decoupling in heat flow

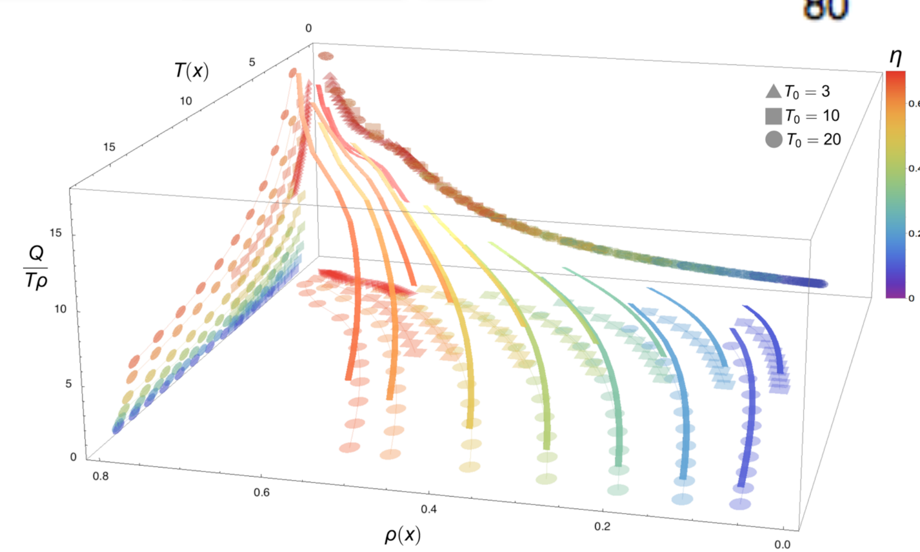
Jesús J. del Pozo,* Pedro L. Garrido,† and Pablo I. Hurtado‡
Institute Carlos I for Theoretical and Computational Physics and Departamento de Electromagnetismo y Física de la Materia, Universidad de Granada, 18071 Granada, Spain
(Received 1 December 2014; revised manuscript received 2 February 2015; published 11 March 2015)

When driven out of equilibrium by a temperature gradient, fluids respond by developing a nontrivial, inhomogeneous structure according to the governing macroscopic laws. Here we show that such structure obeys strikingly simple scaling laws arbitrarily far from equilibrium, provided that both macroscopic local equilibrium

- Leyes de escala universales para el transporte de energía







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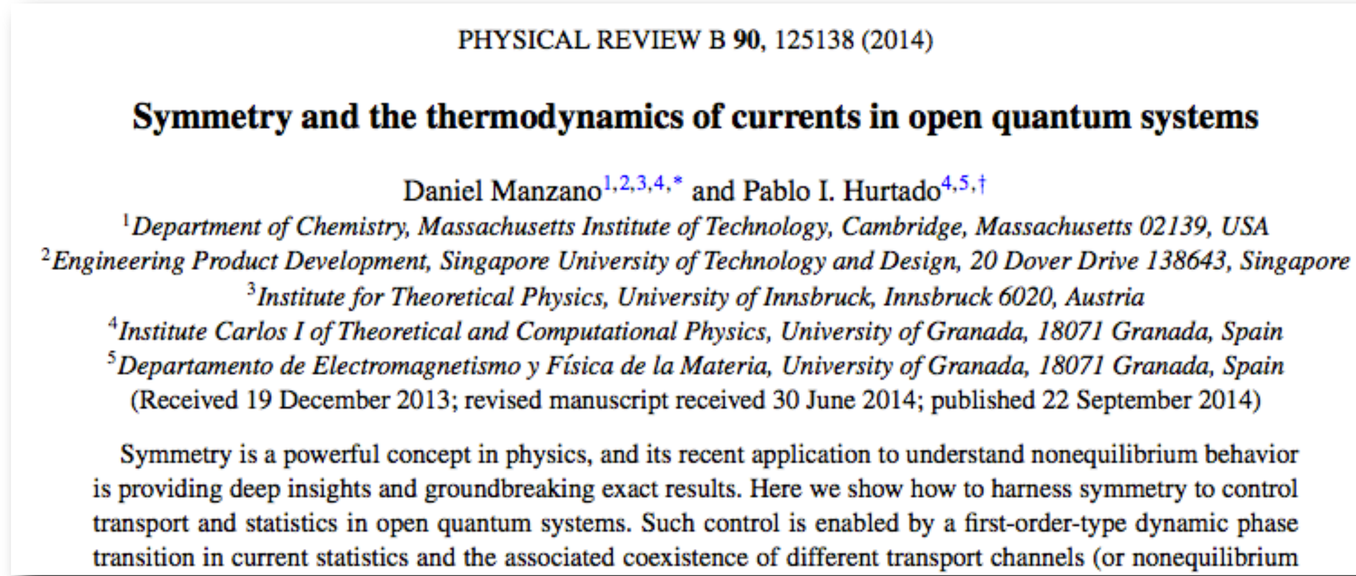
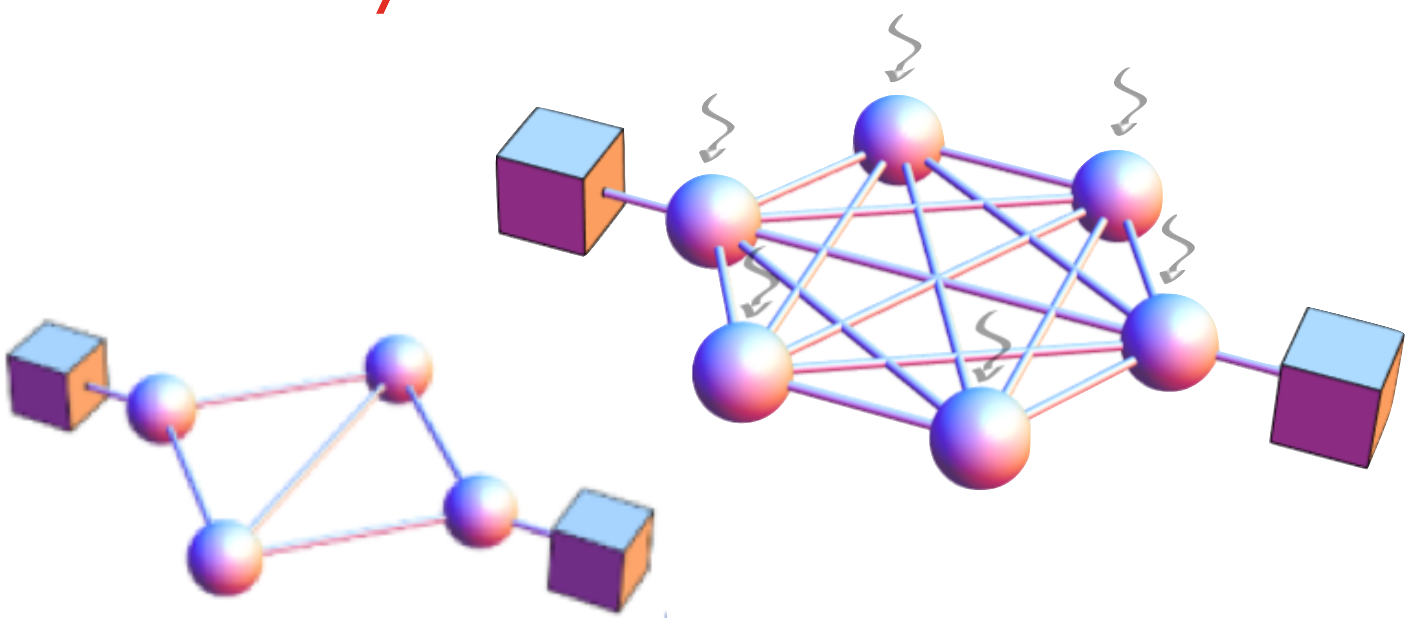

PHYSICAL REVIEW B **90**, 125138 (2014)

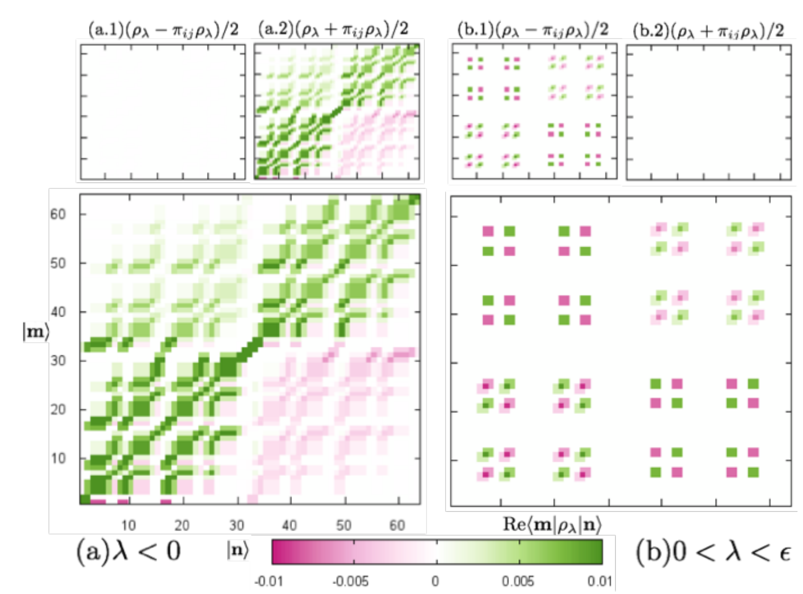
Symmetry and the thermodynamics of currents in open quantum systems

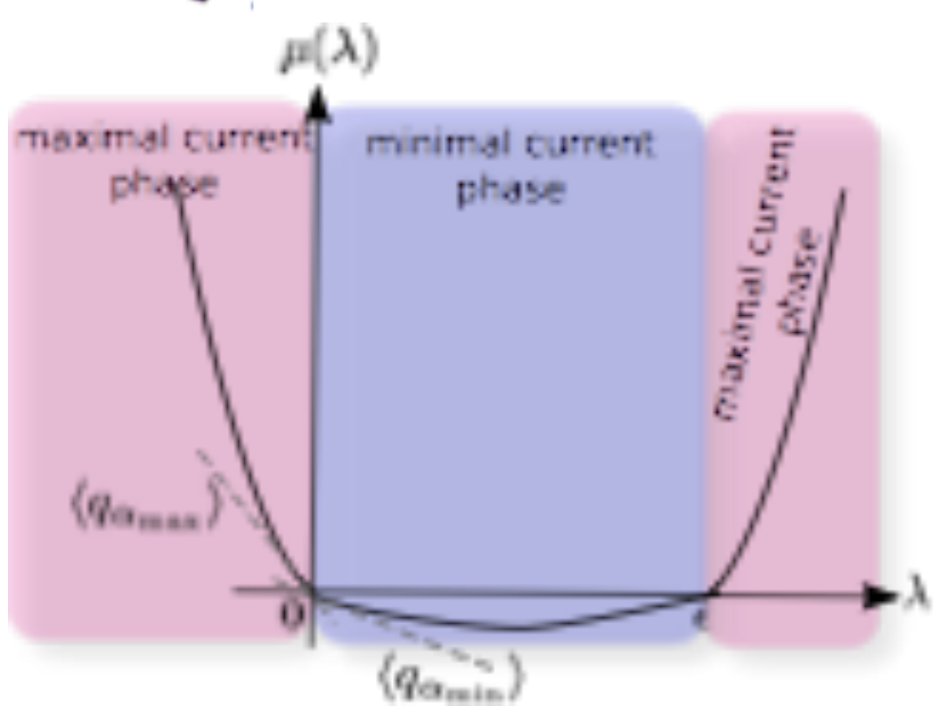
Daniel Manzano[1,2,3,4,*] and Pablo I. Hurtado[4,5,†]
[1]*Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Engineering Product Development, Singapore University of Technology and Design, 20 Dover Drive 138643, Singapore*
[3]*Institute for Theoretical Physics, University of Innsbruck, Innsbruck 6020, Austria*
[4]*Institute Carlos I of Theoretical and Computational Physics, University of Granada, 18071 Granada, Spain*
[5]*Departamento de Electromagnetismo y Física de la Materia, University of Granada, 18071 Granada, Spain*
(Received 19 December 2013; revised manuscript received 30 June 2014; published 22 September 2014)

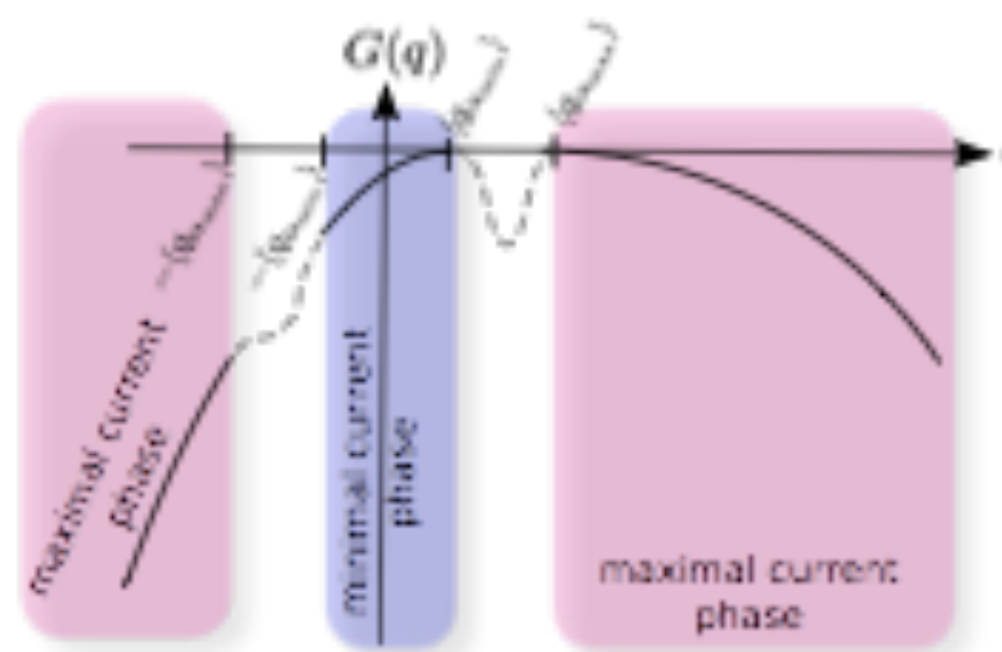
Symmetry is a powerful concept in physics, and its recent application to understand nonequilibrium behavior is providing deep insights and groundbreaking exact results. Here we show how to harness symmetry to control transport and statistics in open quantum systems. Such control is enabled by a first-order-type dynamic phase transition in current statistics and the associated coexistence of different transport channels (or nonequilibrium

- Simetría y termodinámica de corrientes en sistemas cuánticos abiertos









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SCIENTIFIC REPORTS

OPEN

An atomic symmetry-controlled thermal switch

Daniel Manzano[1,2,3] & Elica Kyoseva[1]

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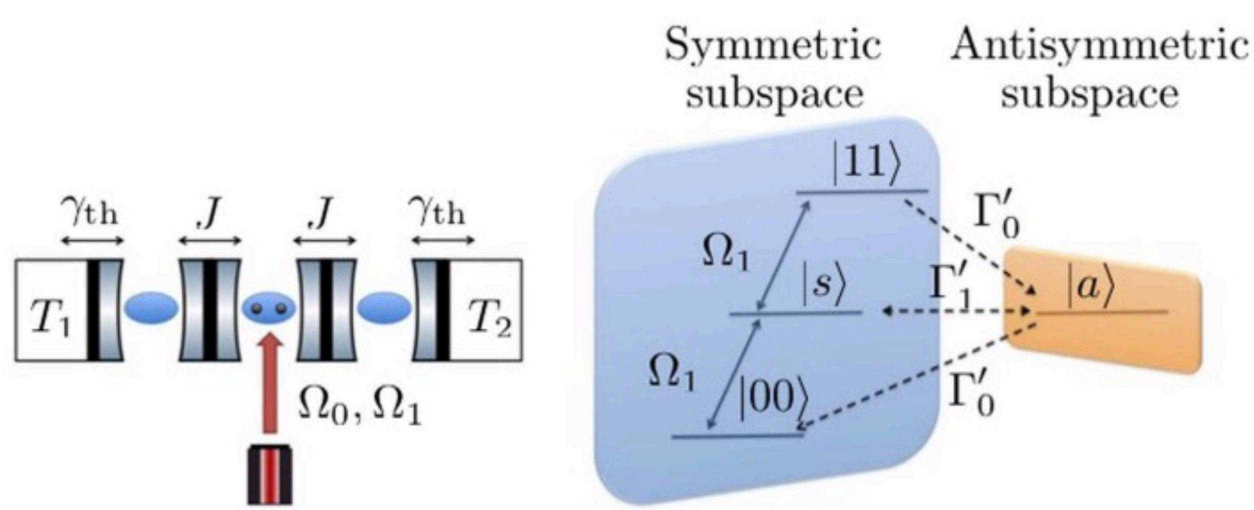
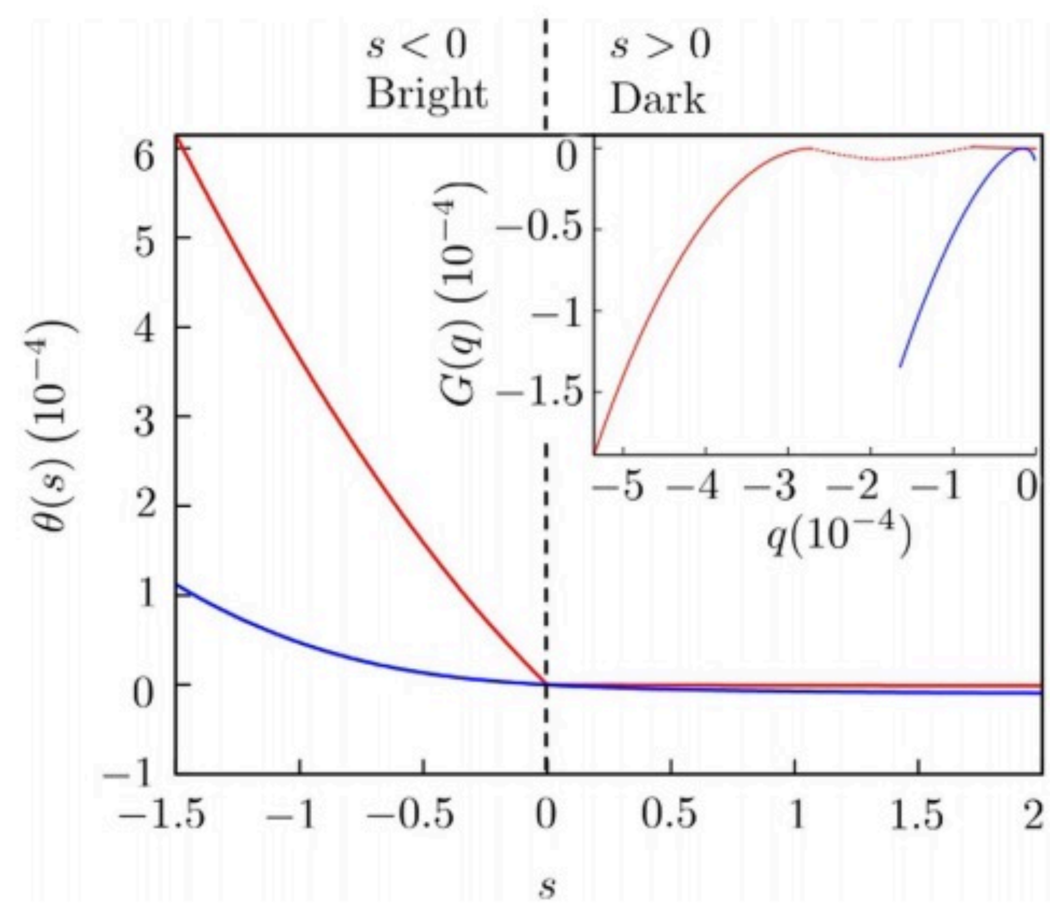
Accepted: 05 May 2016
Published: 09 August 2016

We propose a simple diatomic system trapped inside an optical cavity to control the energy flow between two thermal baths. Through the action of the baths the system is driven to a non-equilibrium steady state. Using the Large Deviation theory we show that the number of photons flowing between the two baths is dramatically different depending on the symmetry of the atomic states. Here we present a deterministic scheme to prepare symmetric and antisymmetric atomic states with the use of external driving fields, thus implementing an atomic control switch for the energy flow.

- Un interruptor atómico controlado por simetría





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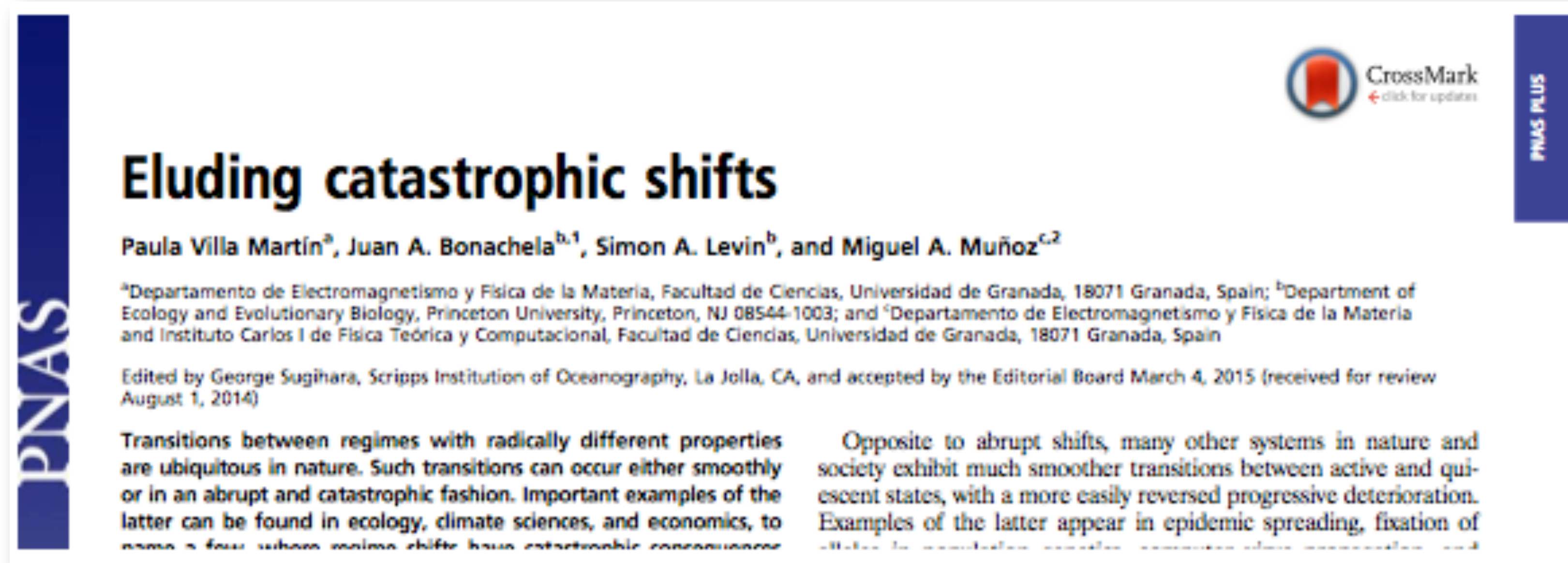

PNAS

PNAS PLUS

CrossMark

Eluding catastrophic shifts

Paula Villa Martín[a], Juan A. Bonachela[b,1], Simon A. Levin[b], and Miguel A. Muñoz[c,2]

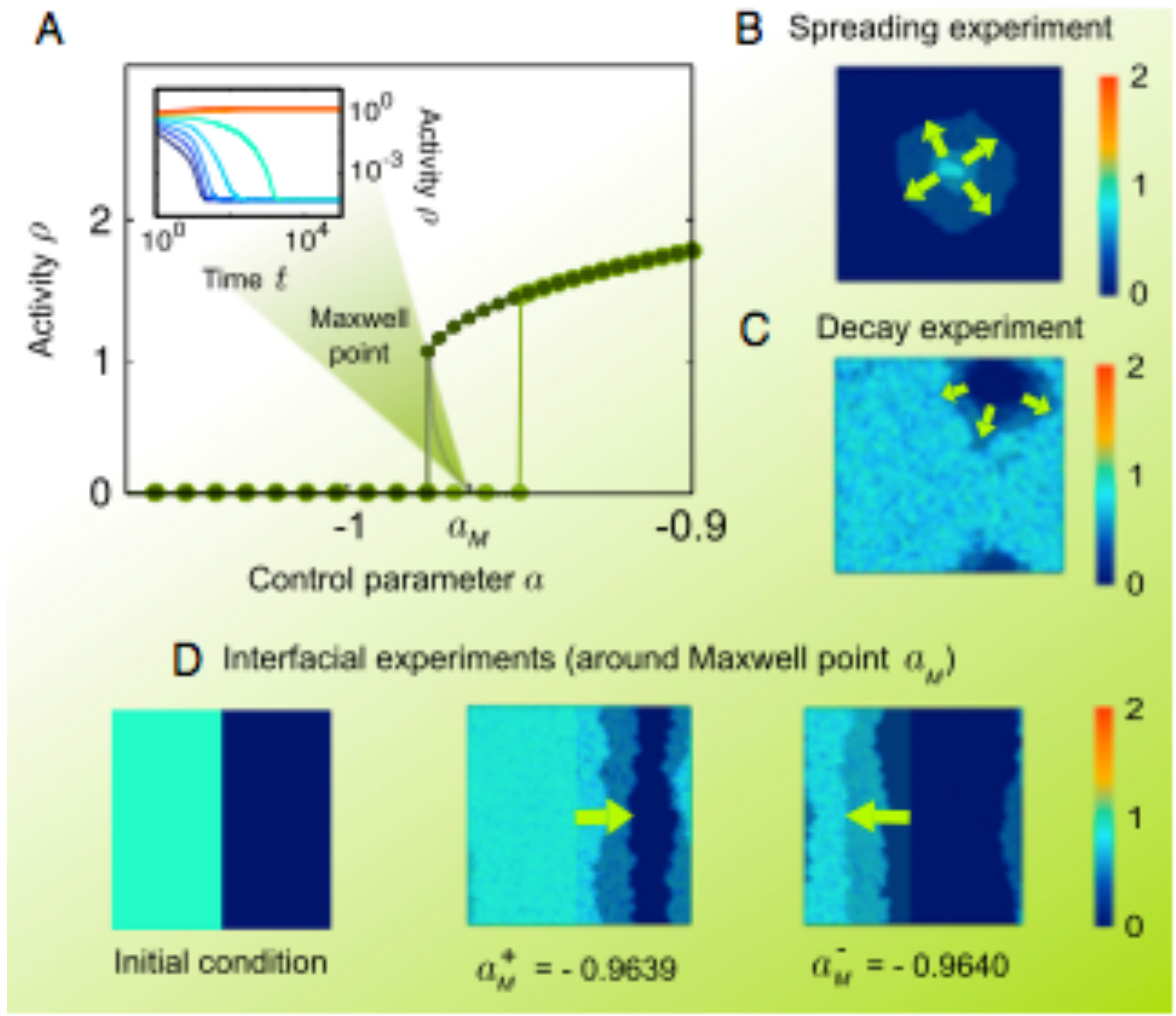
[a]Departamento de Electromagnetismo y Física de la Materia, Facultad de Ciencias, Universidad de Granada, 18071 Granada, Spain; [b]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544-1003; and [c]Departamento de Electromagnetismo y Física de la Materia and Instituto Carlos I de Física Teórica y Computacional, Facultad de Ciencias, Universidad de Granada, 18071 Granada, Spain

Edited by George Sugihara, Scripps Institution of Oceanography, La Jolla, CA, and accepted by the Editorial Board March 4, 2015 (received for review August 1, 2014)

Transitions between regimes with radically different properties are ubiquitous in nature. Such transitions can occur either smoothly or in an abrupt and catastrophic fashion. Important examples of the latter can be found in ecology, climate sciences, and economics, to

Opposite to abrupt shifts, many other systems in nature and society exhibit much smoother transitions between active and quiescent states, with a more easily reversed progressive deterioration. Examples of the latter appear in epidemic spreading, fixation of

- Eludiendo cambios catastróficos



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nature COMMUNICATIONS

ARTICLE

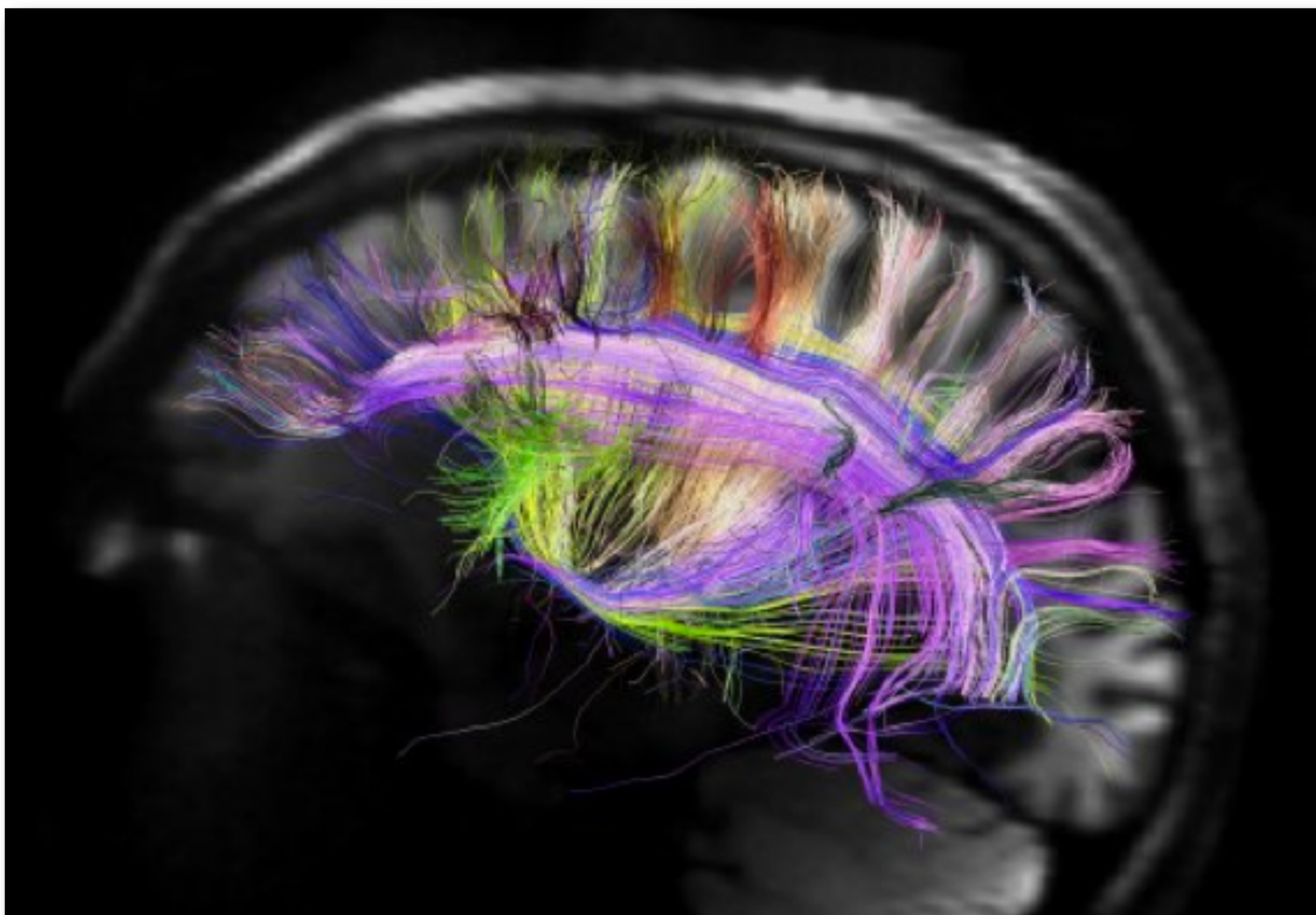
Received 15 Apr 2013 | Accepted 28 Aug 2013 | Published 3 Oct 2013

DOI: 10.1038/ncomms3521

Griffiths phases and the stretching of criticality in brain networks

Paolo Moretti[1] & Miguel A. Muñoz[1]

- Estudio del estado fundamental del cerebro



SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
COMPLEX NETWORKS
COMPUTATIONAL SCIENCE

Frustrated hierarchical synchronization and emergent complexity in the human connectome network

Pablo Villegas, Paolo Moretti & Miguel A. Muñoz

GALERÍA DE RESULTADOS

SCIENTIFIC REPORTS

OPEN

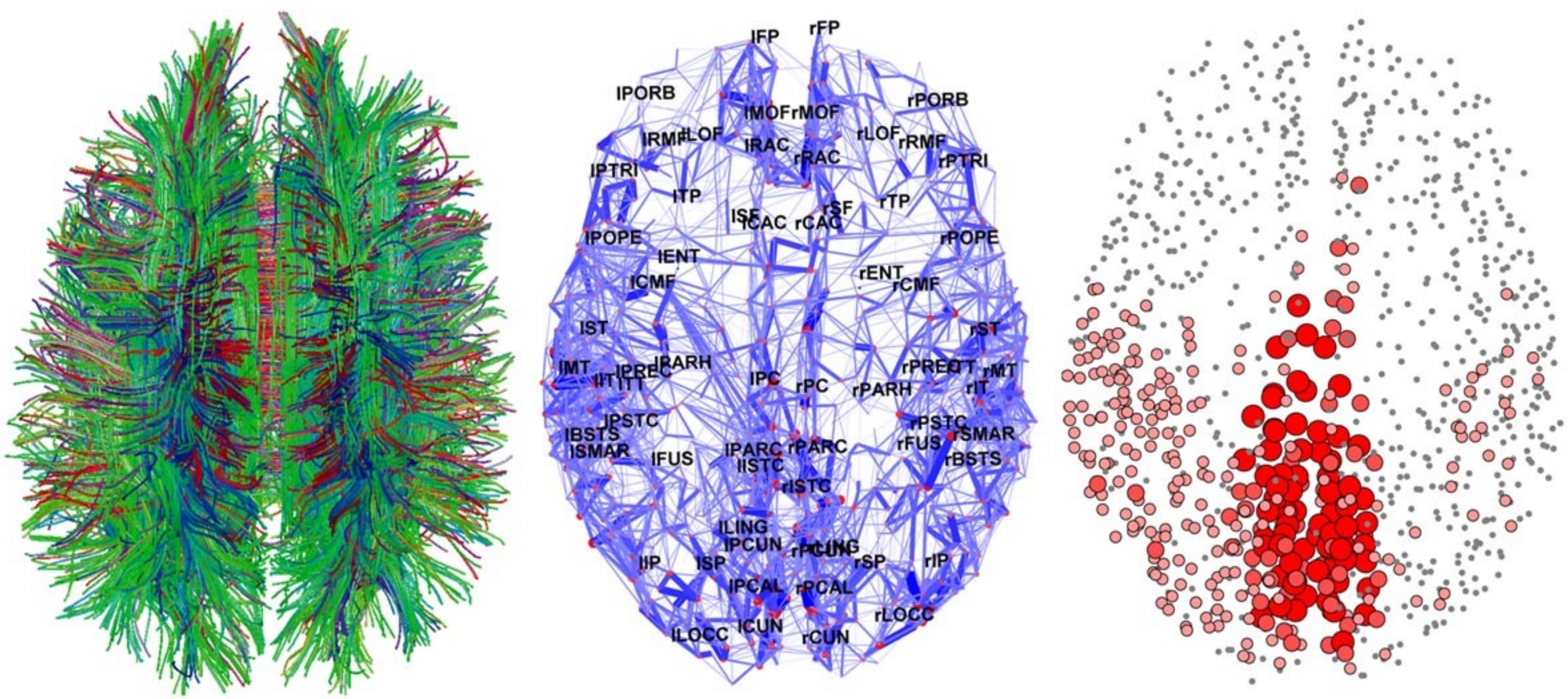
Brain Performance *versus* Phase Transitions

Joaquín J. Torres* & J. Marro*

Received: 21 January 2015
Accepted: 11 June 2015
Published: 20 July 2015

We here illustrate how a well-founded study of the brain may originate in assuming analogies with phase-transition phenomena. Analyzing to what extent a weak signal endures in noisy environments, we identify the underlying mechanisms, and it results a description of how the excitability associated to (non-equilibrium) phase changes and criticality optimizes the processing of the signal. Our setting is a network of *integrate-and-fire* nodes in which connections are heterogeneous with rapid time-varying intensities mimicking *fatigue* and *potentiation*. Emergence then becomes quite robust against wiring topology modification—in fact, we considered from a fully connected network to the Homo sapiens connectome—showing the essential role of synaptic flickering on computations. We also suggest how to experimentally disclose significant changes during actual brain operation.

- Estudio del estado fundamental del cerebro



GALERÍA DE RESULTADOS


PNAS

CrossMark

Trophic coherence determines food-web stability

Samuel Johnson[a,1,2], Virginia Domínguez-García[b,1], Luca Donetti[c], and Miguel A. Muñoz[b]

[a]Warwick Mathematics Institute, and Centre for Complexity Science, University of Warwick, Coventry CV4 7AL, United Kingdom; [b]Departamento de Electromagnetismo y Física de la Materia, and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, 18071 Granada, Spain; and [c]Departamento de Electrónica y Tecnología de Computadores and Centro de Investigación en Tecnologías de la Información y de las Comunicaciones, Universidad de Granada, 18071 Granada, Spain

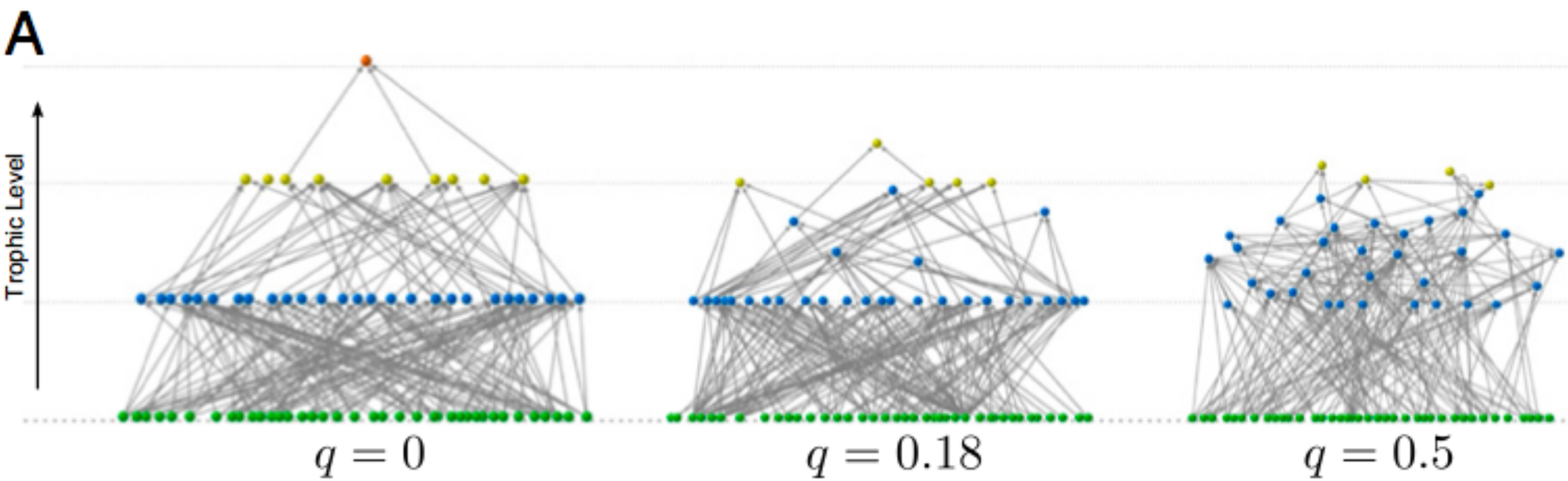
Edited* by Robert M. May, University of Oxford, Oxford, United Kingdom, and approved November 3, 2014 (received for review May 16, 2014)

Why are large, complex ecosystems stable? Both theory and simulations of current models predict the onset of instability with growing size and complexity, so for decades it has been conjectured that ecosystems must have some unidentified structural property exempt-

Results

Trophic Coherence and Stability. Each species in an ecosystem is generally influenced by others, via processes such as predation, parasitism, mutualism, or competition for various resources (11–

- Estabilidad de redes tróficas



GALERÍA DE RESULTADOS

PNAS

Information-based fitness and the emergence of criticality in living systems

Jorge Hidalgo[a,1], Jacopo Grilli[b,1], Samir Suweis[b], Miguel A. Muñoz[a,2], Jayanth R. Banavar[c], and Amos Maritan[b,2]

[a]Departamento de Electromagnetismo y Física de la Materia and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, 18071 Granada, Spain; [b]Dipartimento di Fisica "G. Galilei", Consorzio Nazionale Interuniversitario per le Scienze Fisiche della Materia and Istituto Nazionale di Fisica Nucleare, Università di Padova, 35131 Padua, Italy; and [c]Department of Physics, University of Maryland, College Park, MD 20742

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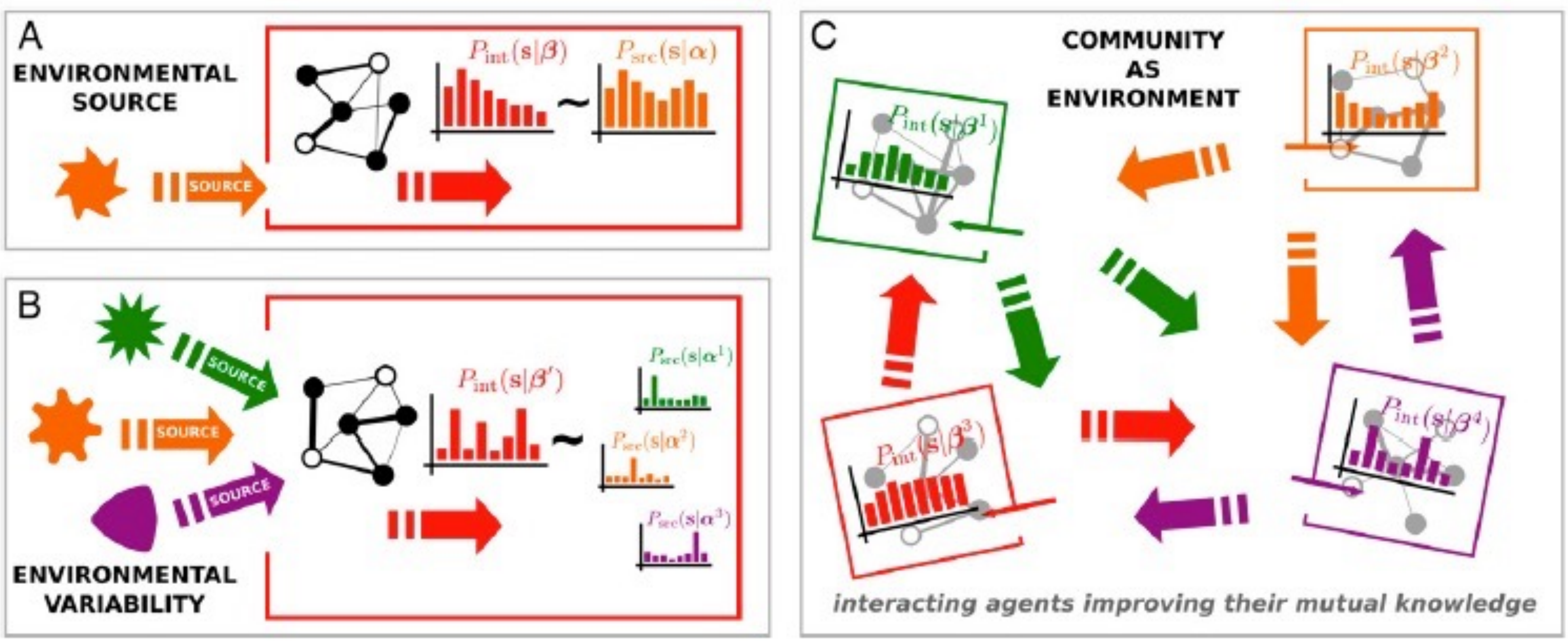

GALERÍA DE RESULTADOS

- Y otros muchos resultados interesantes

PRL **95,** 188701 (2005) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2005

PRL **98,** 135503 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2007

PRL **102,** 250601 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009

Test of the Additivity Principle for Current Fluctuations in a Model of Heat Conduction

Pablo I. Hurtado and Pedro L. Garrido
Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Granada 18071, Spain
(Received 23 September 2008; published 23 June 2009)

The additivity principle allows to compute the current distribution in many one-dimensional (1D) nonequilibrium systems. Using simulations, we confirm this conjecture in the 1D Kipnis-Marchioro-Presutti model of heat conduction for a wide current interval. The current distribution shows both

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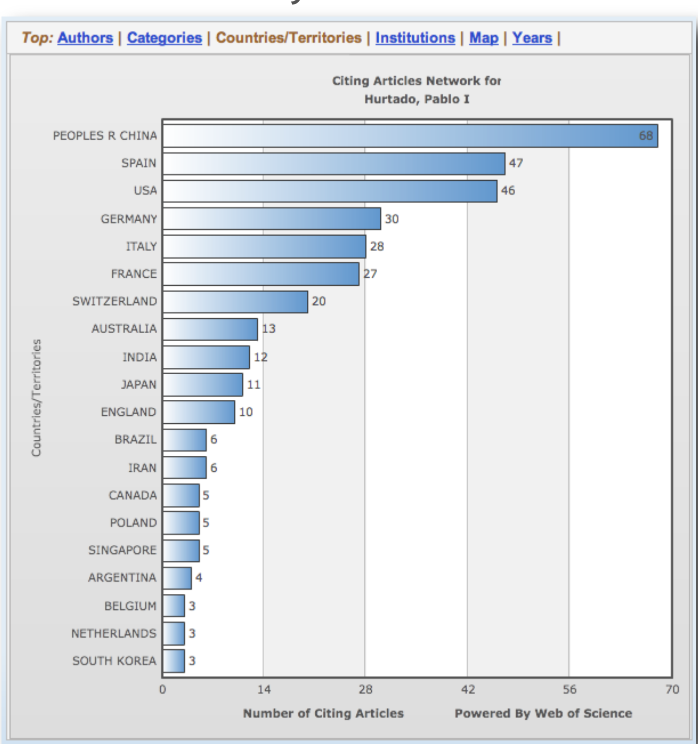
- Trabajamos codo con codo con investigadores de todo el mundo

- Y nuestros trabajos son citados ampliamente



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MUCHAS GRACIAS POR LA ATENCIÓN

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