MECÂNICA ESTATÍSTICA NÃO EXTENSIVA:

DESAFIOS ATUAIS

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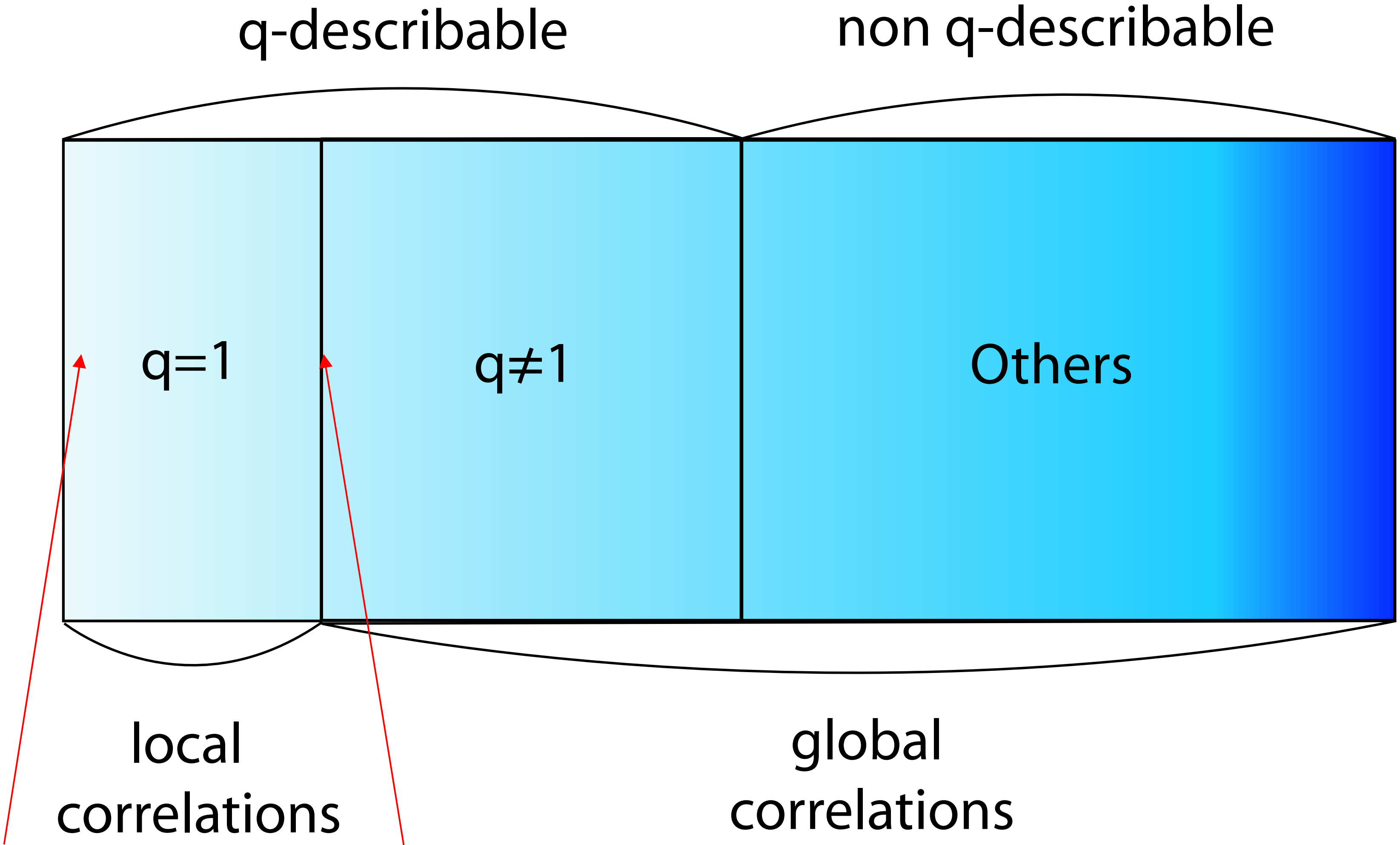
INCT-SC, Rio de Janeiro, Março 2009

Alguns conceitos

Algumas das verificações experimentais e computacionais

Alguns dos desafios



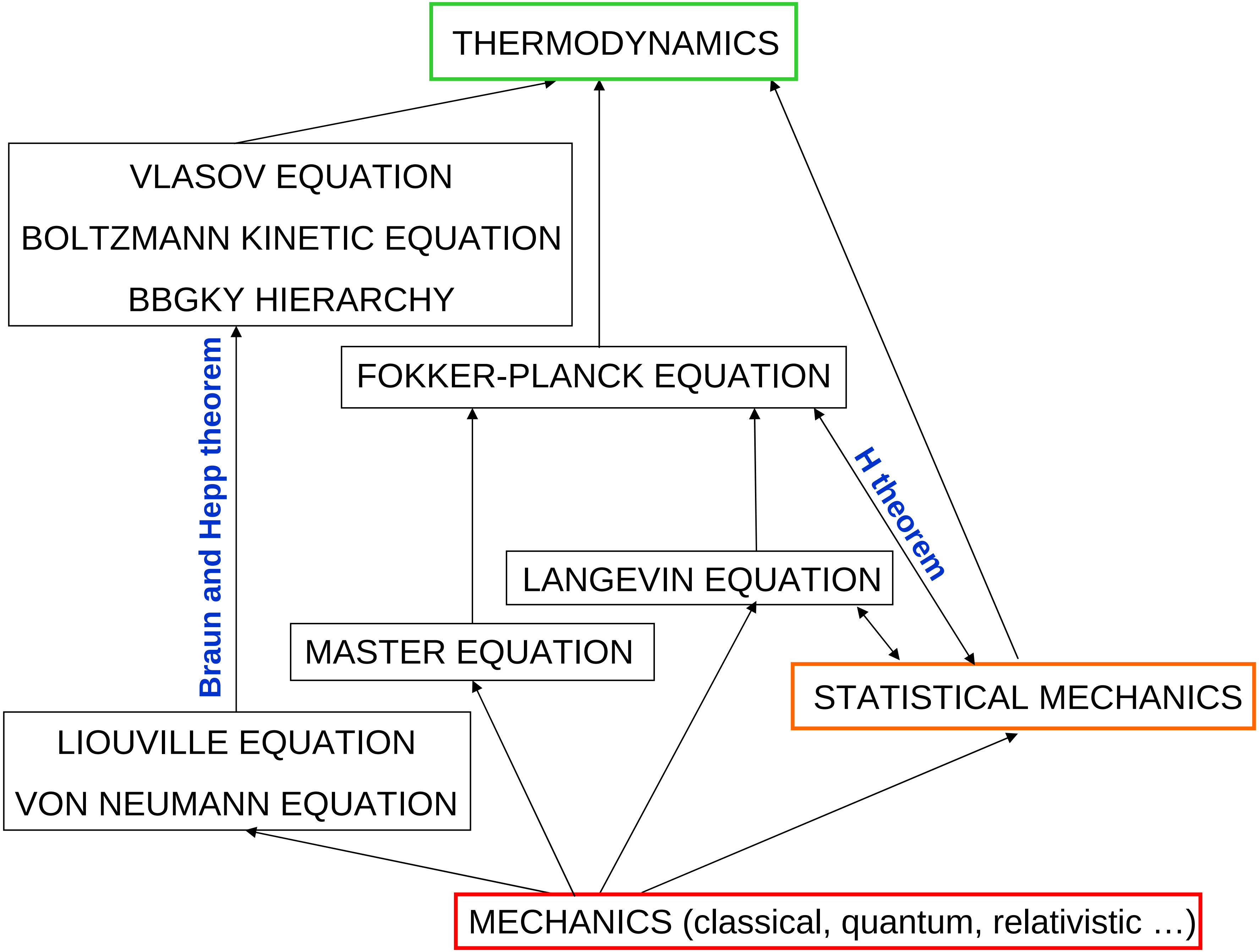
IDEAL GAS

CRITICAL PHENOMENA

$$q = \frac{1+\delta}{2}$$ [A. Robledo, Mol Phys 103 (2005) 3025]

$$q = \frac{\sqrt{9+c^2}-3}{c}$$ [F. Caruso and C. T., Phys Rev E 78 (2008) 021101]

C.T., M. Gell-Mann and Y. Sato
Europhysics News **36** (6), 186
(European Physical Society, 2005)



THERMODYNAMICS
VLASOV EQUATION
BOLTZMANN KINETIC EQUATION
BBGKY HIERARCHY
FOKKER-PLANCK EQUATION
Braun and Hepp theorem
H theorem
LANGEVIN EQUATION
MASTER EQUATION
STATISTICAL MECHANICS
LIOUVILLE EQUATION
VON NEUMANN EQUATION
MECHANICS (classical, quantum, relativistic …)

ADDITIVITY: O. Penrose, *Foundations of Statistical Mechanics: A Deductive Treatment* (Pergamon, Oxford, 1970), page 167

An entropy is additive if, for two probabilistically independent systems A and B,

$$S(A+B)=S(A)+S(B)$$

Hence, S_{BG} and $S_q^{Renyi}\ (\forall q)$ are additive, and $S_q\ (\forall q \neq 1)$ is nonadditive .

EXTENSIVITY:

Consider a system $\Sigma \equiv A_1 + A_2 + \ldots + A_N$ made of N (not necessarily independent) identical elements or subsystems A_1 and A_2, ..., A_N. An entropy is extensive if

$$0 < \lim_{N\to\infty} \frac{S(N)}{N} < \infty \ , \ i.e., \ S(N) \propto N \ \ (N \to \infty)$$

CONSEQUENTLY:

The additive entropies S_{BG} and S_q^{Renyi} are extensive if and only if the N subsystems are (strictly or asymptotically) independent; otherwise, S_{BG} and S_q^{Renyi} are nonextensive.

The nonadditive entropy $S_q\ (q \neq 1)$ is extensive for special values of q if the subsystems are specially (globally) correlated.

PHYSICAL REVIEW E **78**, 021102 (2008)

Nonadditive entropy reconciles the area law in quantum systems with classical thermodynamics

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(Received 16 March 2008; revised manuscript received 16 May 2008; published 5 August 2008)

The Boltzmann–Gibbs–von Neumann entropy of a large part (of linear size L) of some (much larger) d-dimensional quantum systems follows the so-called area law (as for black holes), i.e., it is proportional to L^{d-1}. Here we show, for $d=1,2$, that the (nonadditive) entropy S_q satisfies, for a special value of $q \neq 1$, the classical thermodynamical prescription for the entropy to be extensive, i.e., $S_q \propto L^d$. Therefore, we reconcile with classical thermodynamics the area law widespread in quantum systems. Recently, a similar behavior was exhibited in mathematical models with scale-invariant correlations [C. Tsallis, M. Gell-Mann, and Y. Sato, Proc. Natl. Acad. Sci. U.S.A. **102** 15377 (2005)]. Finally, we find that the system critical features are marked by a maximum of the special entropic index q.

SPIN ½ XY FERROMAGNET WITH TRANSVERSE MAGNETIC FIELD:

$$\hat{\mathcal{H}} = -\sum_{j=1}^{N-1} \left[(1+\gamma)\hat{\sigma}_j^x \hat{\sigma}_{j+1}^x + (1-\gamma)\hat{\sigma}_j^y \hat{\sigma}_{j+1}^y + 2\lambda \hat{\sigma}_j^z \right]$$

$|\gamma| = 1 \quad \rightarrow \quad$ *Ising ferromagnet*

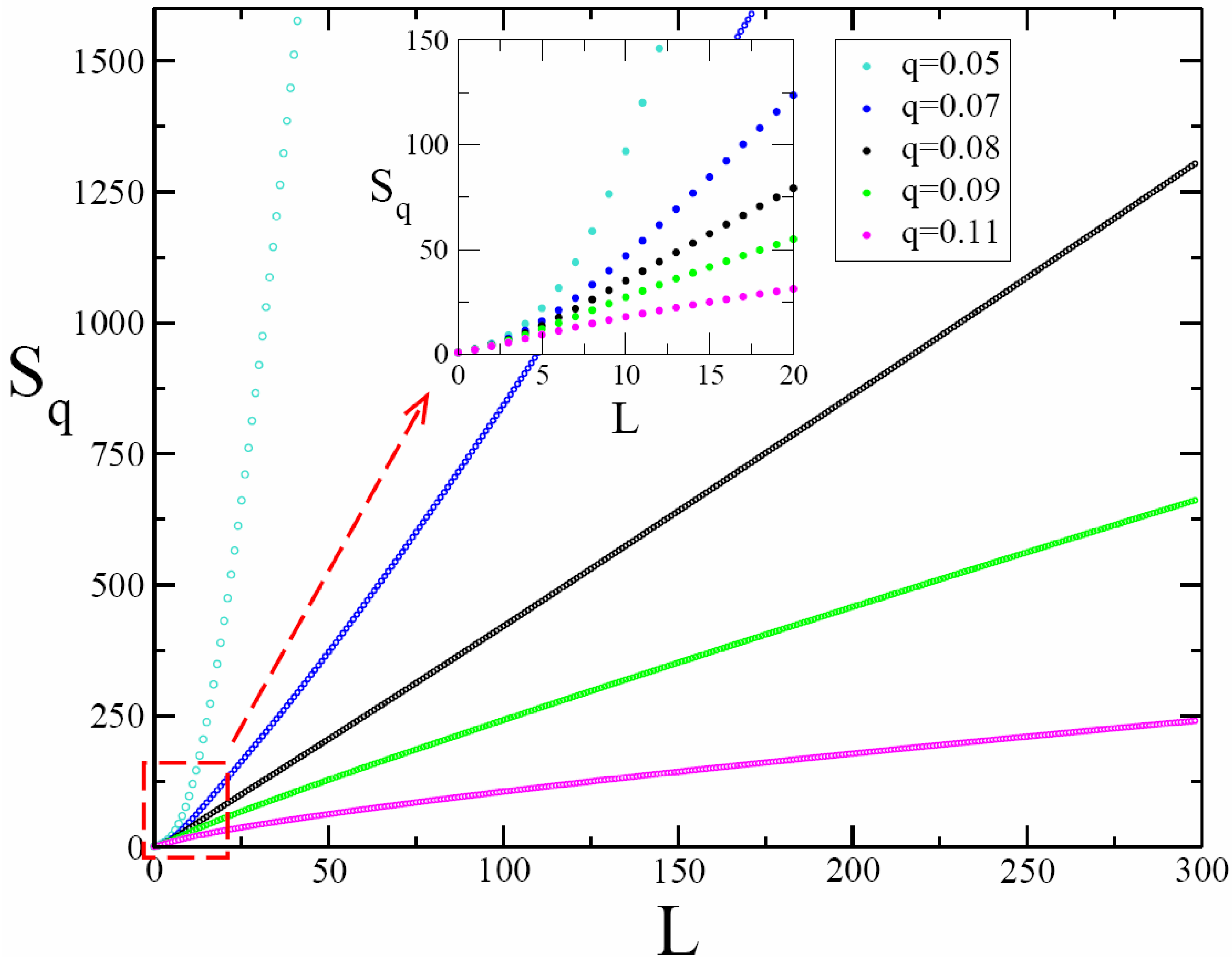
$0 < |\gamma| < 1 \quad \rightarrow \quad$ *anisotropic XY ferromagnet*

$\gamma = 0 \quad \rightarrow \quad$ *isotropic XY ferromagnet*

$\lambda \equiv$ *transverse magnetic field*

$L \equiv$ *length of a block within a* $N \rightarrow \infty$ *chain*

F. Caruso and C. T., Phys Rev E **78**, 021101 (2008)



F. Caruso and C. T., Phys Rev E **78**, 021101 (2008)

Using a Quantum Field Theory result

in P. Calabrese and J. Cardy, JSTAT P06002 (2004)

we obtain, at the critical transverse magnetic field,

$$q_{ent} = \frac{\sqrt{9+c^2}-3}{c}$$

with c ≡ central charge in conformal field theory

Hence

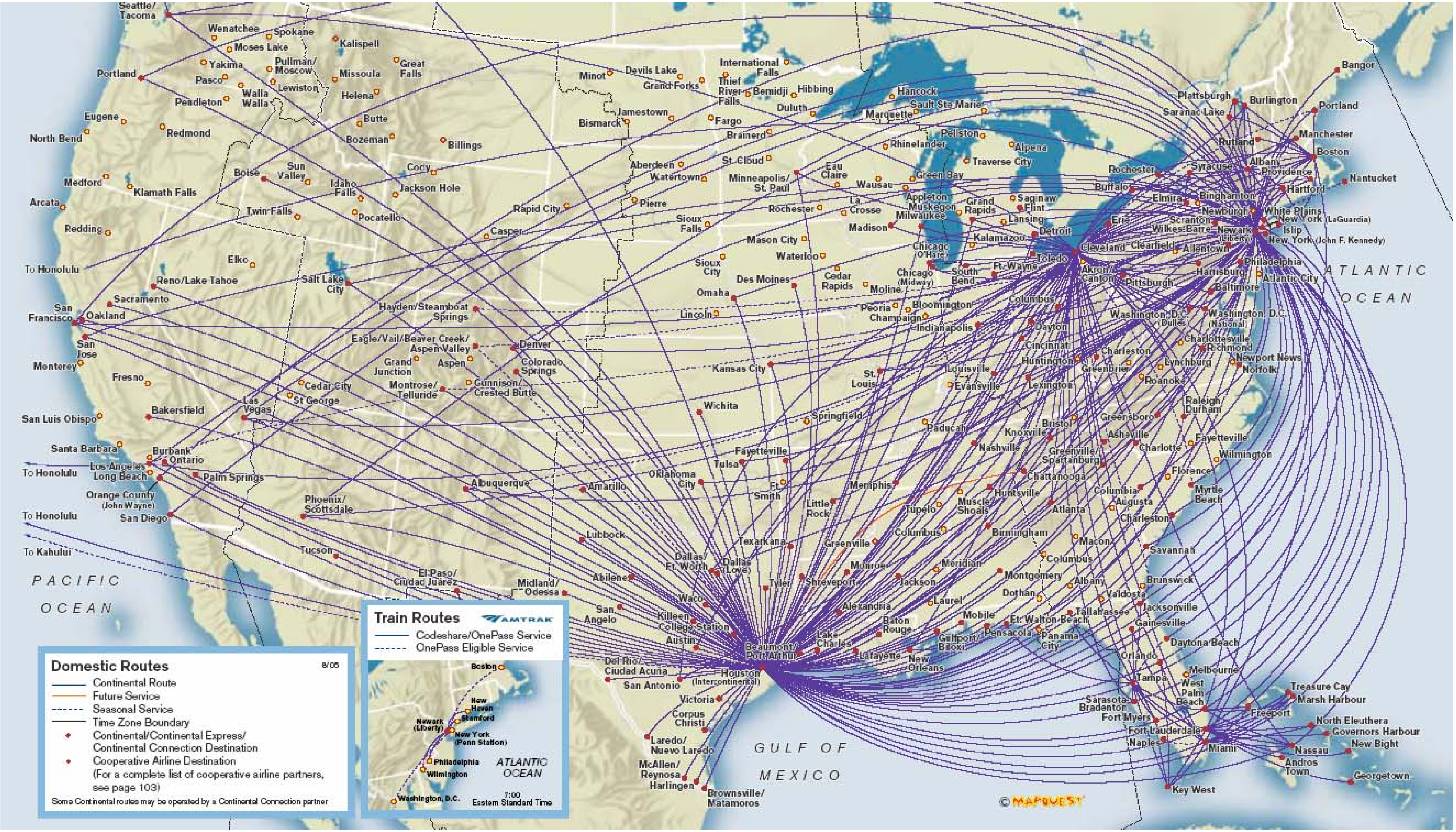
Ising and anisotropic XY ferromagnets $\Rightarrow \; c = \frac{1}{2} \; \Rightarrow \; q_{ent} = \sqrt{37} - 6 \; \approx 0.0828$

and

Isotropic XY ferromagnet $\Rightarrow \; c = 1 \; \Rightarrow \; q_{ent} = \sqrt{10} - 3 \; \approx 0.1623$

F. Caruso and C. T., Phys Rev E **78**, 021101 (2008)

SYSTEMS	ENTROPY S_{BG} (additive)	ENTROPY S_q (q<1) (nonadditive)
Short-range interactions, weakly entangled blocks, etc	EXTENSIVE	NONEXTENSIVE
Long-range interactions (QSS), strongly entangled blocks, etc	NONEXTENSIVE	EXTENSIVE



Continental Airlines

q - GENERALIZED CENTRAL LIMIT THEOREM:

S. Umarov, C.T. and S. Steinberg, Milan J Math **76,** 307 (2008)

q-Fourier transform:

$$F_q[f](\xi) \equiv \int_{-\infty}^{\infty} e_q^{ix\xi} \otimes_q f(x)\, dx = \int_{-\infty}^{\infty} e_q^{ix\xi[f(x)]^{q-1}} f(x)\, dx$$

$$(q \geq 1)$$

(nonlinear!)

CENTRAL LIMIT THEOREM

$N^{1/[\alpha(2-q)]}$*-scaled attractor* $\mathbb{F}(x)$ *when summing* $N \to \infty$ q*-independent identical random variables*

with symmetric distribution $f(x)$ *with* $\sigma_Q \equiv \int dx\, x^2 [f(x)]^Q / \int dx\, [f(x)]^Q$ $\left(Q \equiv 2q-1,\; q_1 = \frac{1+q}{3-q} \right)$

	$q=1$ [*independent*]	$q \neq 1$ (*i.e.*, $Q \equiv 2q-1 \neq 1$) [*globally correlated*]
$\sigma_Q < \infty$ $(\alpha = 2)$	$\mathbb{F}(x) =$ *Gaussian* $G(x)$, *with same* σ_1 *of* $f(x)$ Classic CLT	$\mathbb{F}(x) = G_q(x) \equiv G_{(3q_1-1)/(1+q_1)}(x)$, *with same* σ_Q *of* $f(x)$ $G_q(x) \sim \begin{cases} G(x) & \text{if } \lvert x \rvert \ll x_c(q,2) \\ f(x) \sim C_q / \lvert x \rvert^{2/(q-1)} & \text{if } \lvert x \rvert \gg x_c(q,2) \end{cases}$ *with* $\lim_{q \to 1} x_c(q,2) = \infty$ S. Umarov, C. T. and S. Steinberg, Milan J Math 76, 307 (2008)
$\sigma_Q \to \infty$ $(0 < \alpha < 2)$	$\mathbb{F}(x) =$ *Levy distribution* $L_\alpha(x)$, *with same* $\lvert x \rvert \to \infty$ *behavior* $L_\alpha(x) \sim \begin{cases} G(x) \\ \quad \text{if } \lvert x \rvert \ll x_c(1,\alpha) \\ f(x) \sim C_\alpha / \lvert x \rvert^{1+\alpha} \\ \quad \text{if } \lvert x \rvert \gg x_c(1,\alpha) \end{cases}$ *with* $\lim_{\alpha \to 2} x_c(1,\alpha) = \infty$ Levy-Gnedenko CLT	$\mathbb{F}(x) = L_{q,\alpha}$, *with same* $\lvert x \rvert \to \infty$ *asymptotic behavior* $L_{q,\alpha} \sim \begin{cases} G_{\frac{2(1-q)-\alpha(1+q)}{2(1-q)-\alpha(3-q)},\,\alpha}(x) \sim C^*_{q,\alpha} / \lvert x \rvert^{\frac{2(1-q)-\alpha(3-q)}{2(1-q)}} \\ \text{(intermediate regime)} \\ G_{\frac{2\alpha q-\alpha+3}{\alpha+1},\,2}(x) \sim C^L_{q,\alpha} / \lvert x \rvert^{(1+\alpha)/(1+\alpha q-\alpha)} \\ \text{(distant regime)} \end{cases}$ S. Umarov, C. T., M. Gell-Mann and S. Steinberg cond-mat/0606038v2 and cond-mat/0606040v2 (2008)

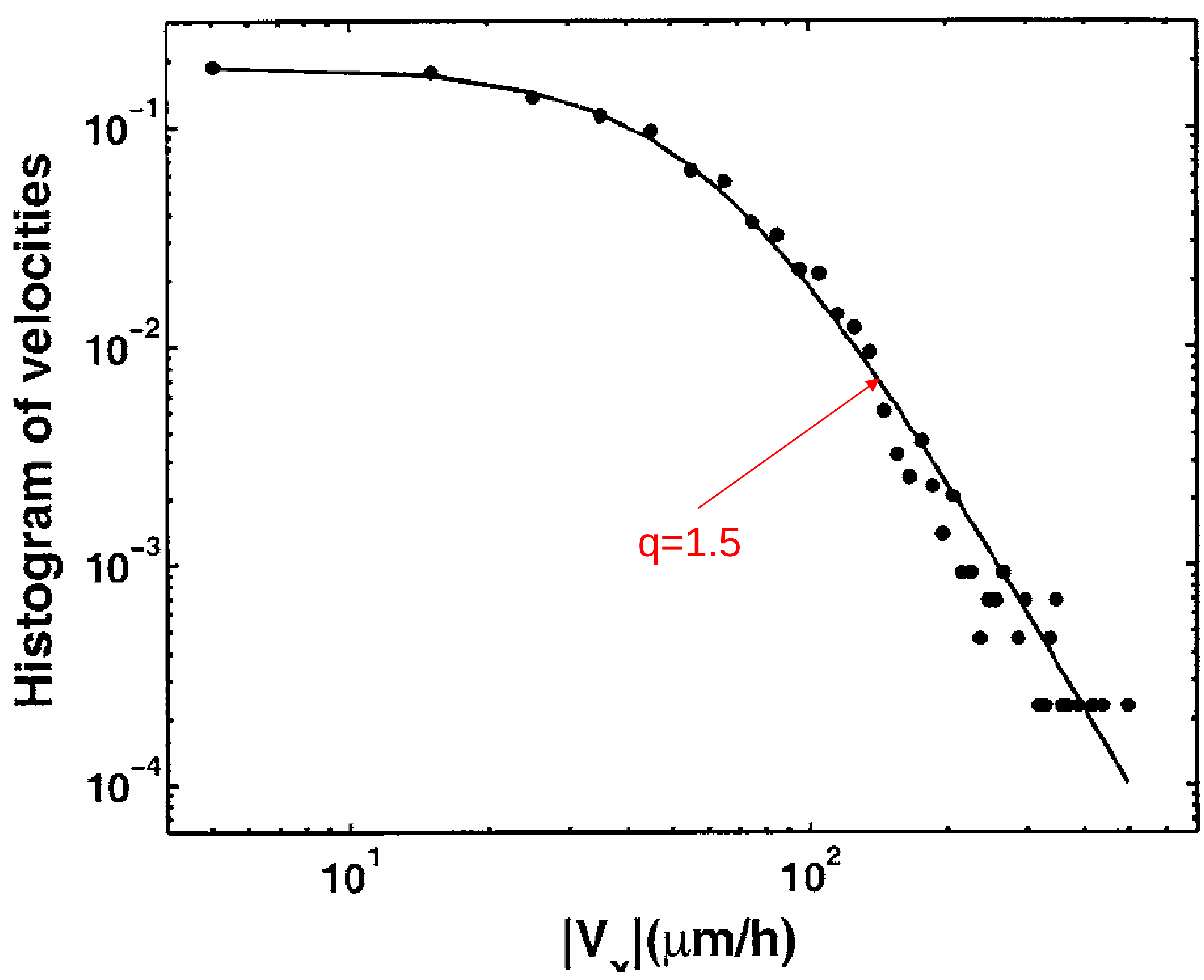
Alguns conceitos

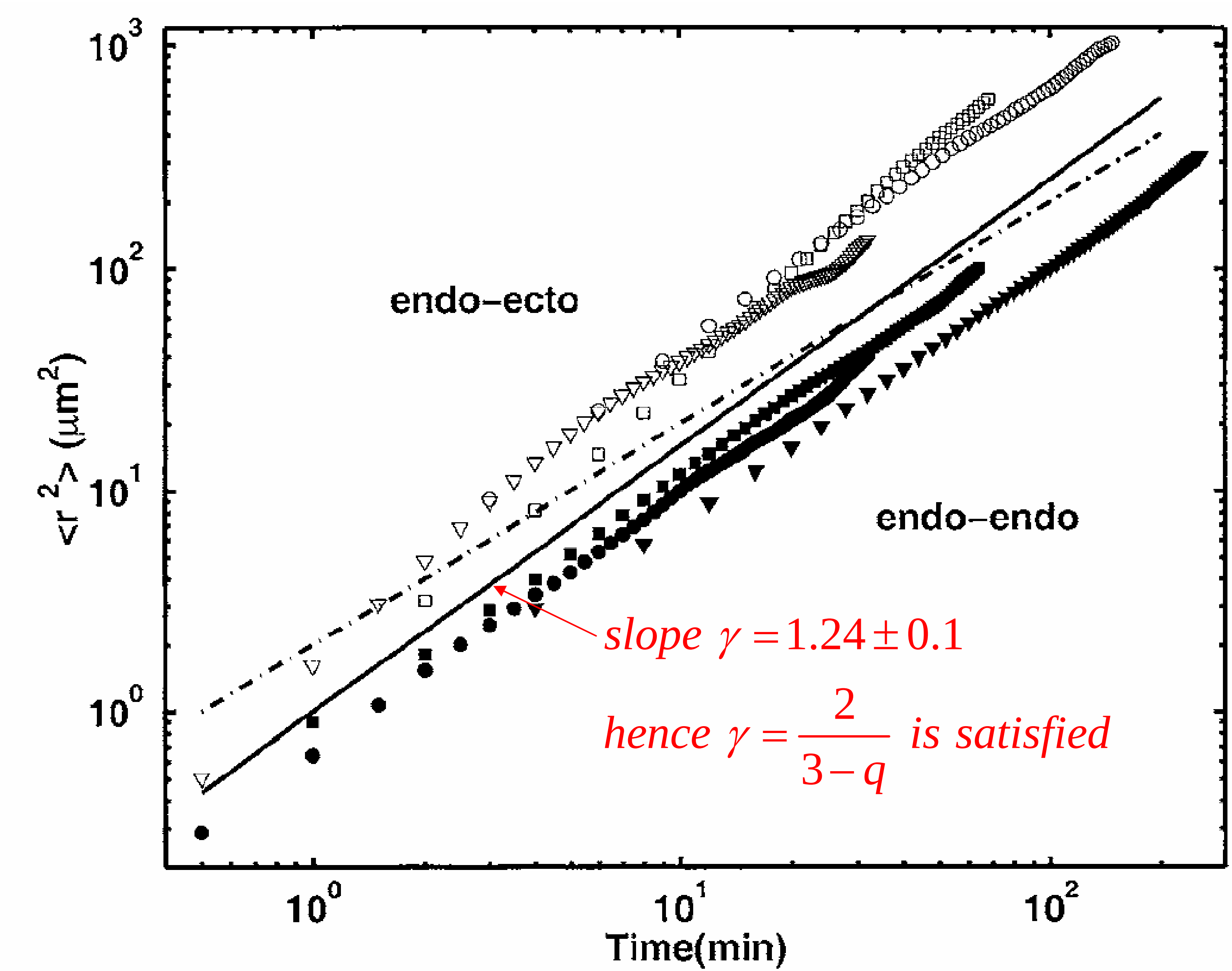
Algumas das verificações experimentais e computacionais

Alguns dos desafios

Hydra viridissima:

A Upadhyaya, J-P Rieu, JA Glazier and Y Sawada, Physica A **293**, 549 (2001)





A Upadhyaya, J-P Rieu, JA Glazier and Y Sawada, Physica A **293**, 549 (2001)

COLD ATOMS IN DISSIPATIVE OPTICAL LATTICES:

RAPID COMM

PHYSICAL REVIEW A **67**, 051402(R) (2003)

Anomalous diffusion and Tsallis statistics in an optical lattice

Eric Lutz

Sloane Physics Laboratory, Yale University, P.O. Box 208120, New Haven, Connecticut 06520-8120

(Received 26 February 2003; published 27 May 2003)

We point out a connection between anomalous transport in an optical lattice and Tsallis' generalized statistics. Specifically, we show that the momentum equation for the semiclassical Wigner function which describes atomic motion in the optical potential, belongs to a class of transport equations recently studied by Borland [Phys. Lett. A **245**, 67 (1998)]. The important property of these ordinary linear Fokker-Planck equations is that their stationary solutions are exactly given by Tsallis distributions. An analytical expression of the Tsallis index q in terms of the microscopic parameters of the quantum-optical problem is given and the spatial coherence of the atomic wave packets is discussed.

(i) The distribution of atomic velocities is a *q*-Gaussian;

(ii) $q = 1 + \frac{44 E_R}{U_0}$ where $E_R \equiv$ recoil energy

$U_0 \equiv$ potential depth

Experimental and computational verifications in optical lattices:

PRL 96, 110601 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Tunable Tsallis Distributions in Dissipative Optical Lattices

P. Douglas, S. Bergamini, and F. Renzoni

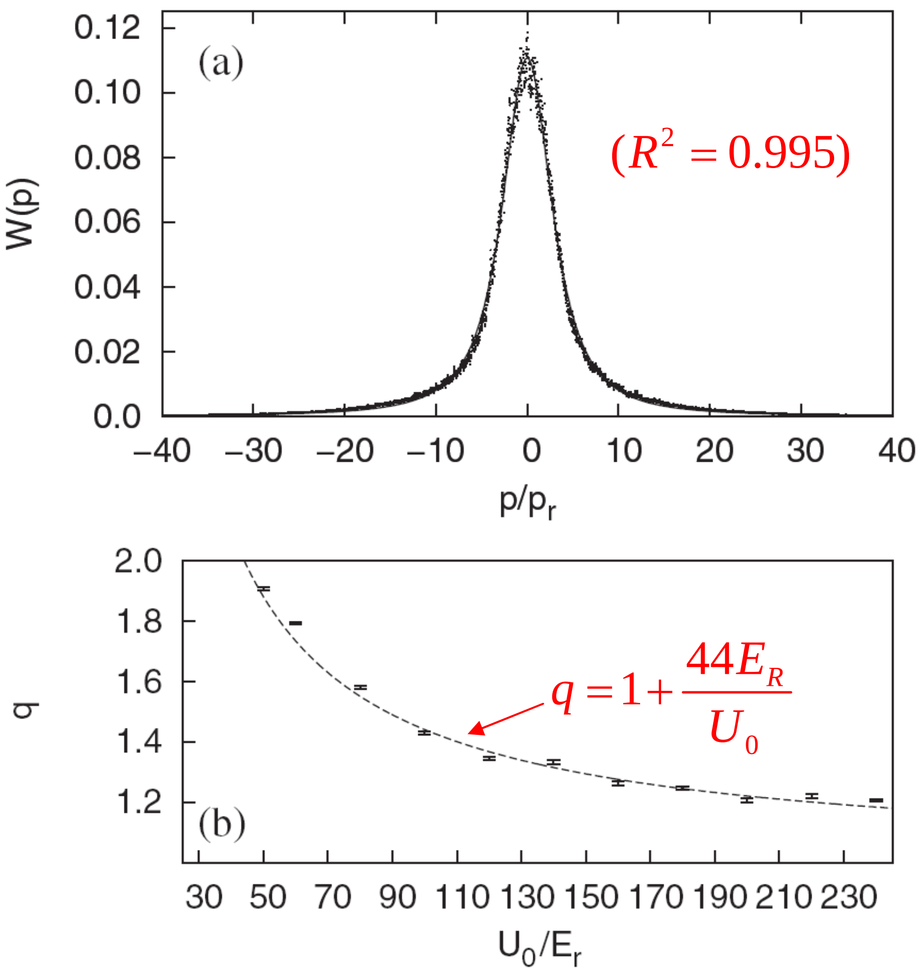
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 10 January 2006; published 24 March 2006)

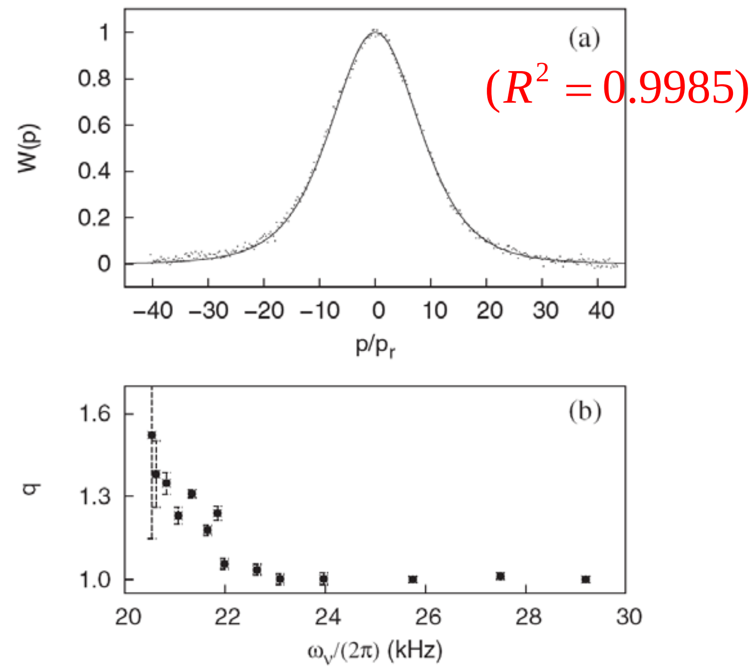
We demonstrated experimentally that the momentum distribution of cold atoms in dissipative optical lattices is a Tsallis distribution. The parameters of the distribution can be continuously varied by changing the parameters of the optical potential. In particular, by changing the depth of the optical lattice, it is possible to change the momentum distribution from Gaussian, at deep potentials, to a power-law tail distribution at shallow optical potentials.

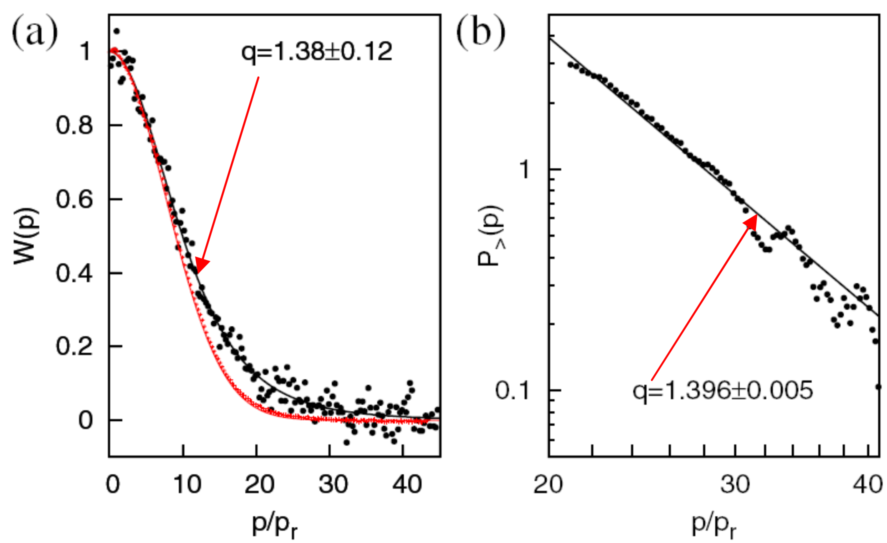
Experimental and computational verifications

by P. Douglas, S. Bergamini and F. Renzoni, Phys Rev Lett **96**, 110601 (2006)



(Computational verification: quantum Monte Carlo simulations)





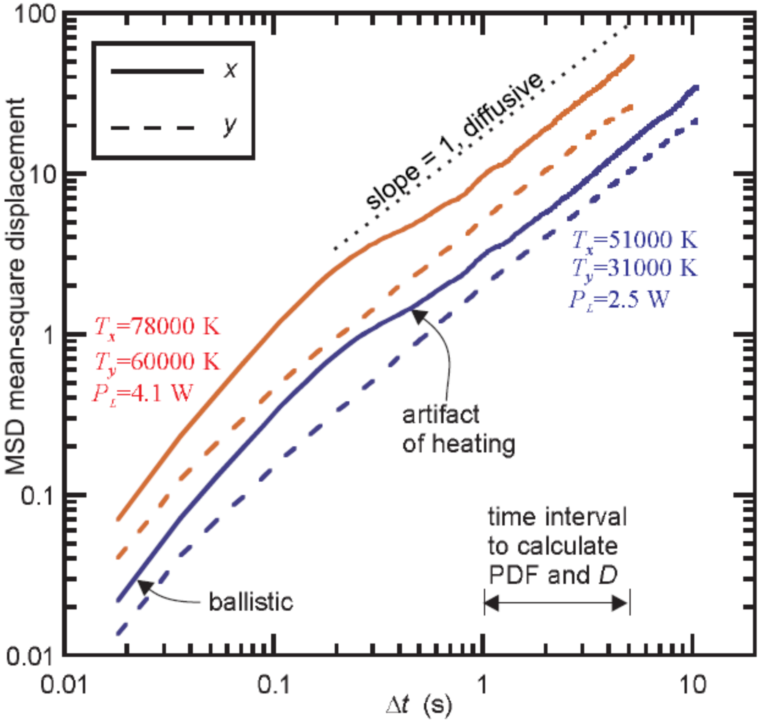
(Experimental verification: Cs atoms)

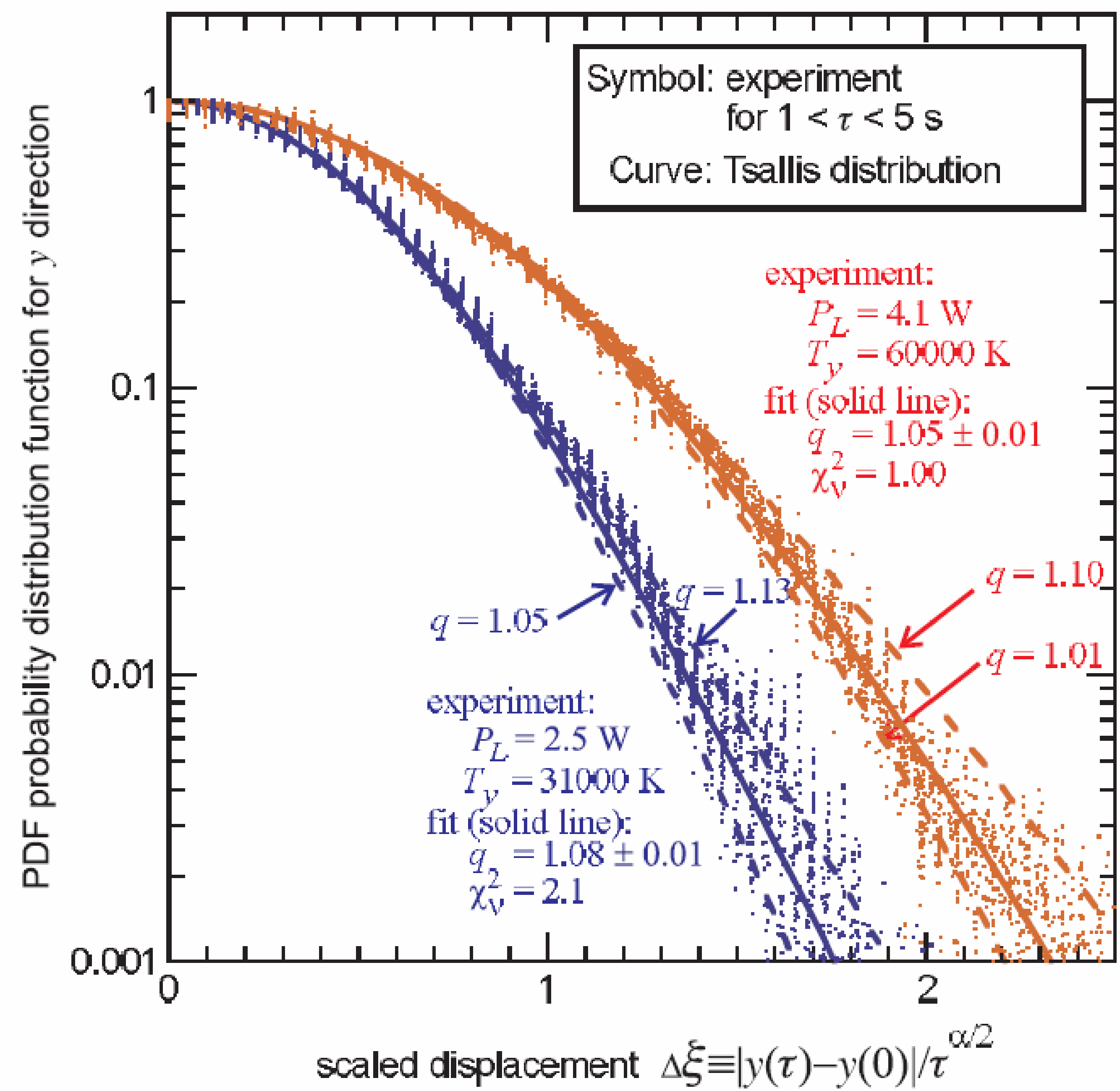
Superdiffusion and Non-Gaussian Statistics in a Driven-Dissipative 2D Dusty Plasma

Bin Liu and J. Goree
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA
(Received 1 June 2007; published 6 February 2008)

Anomalous diffusion and non-Gaussian statistics are detected experimentally in a two-dimensional driven-dissipative system. A single-layer dusty plasma suspension with a Yukawa interaction and frictional dissipation is heated with laser radiation pressure to yield a structure with liquid ordering. Analyzing the time series for mean-square displacement, superdiffusion is detected at a low but statistically significant level over a wide range of temperatures. The probability distribution function fits a Tsallis distribution, yielding q, a measure of nonextensivity for non-Gaussian statistics.

$$< r^2 > \;\propto\; t^{\alpha}$$





B. Liu and J. Goree, Phys Rev Lett **100**, 055003 (2008)

LASER COOLING:

PRL **102,** 063001 (2009) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2009

Power-Law Distributions for a Trapped Ion Interacting with a Classical Buffer Gas

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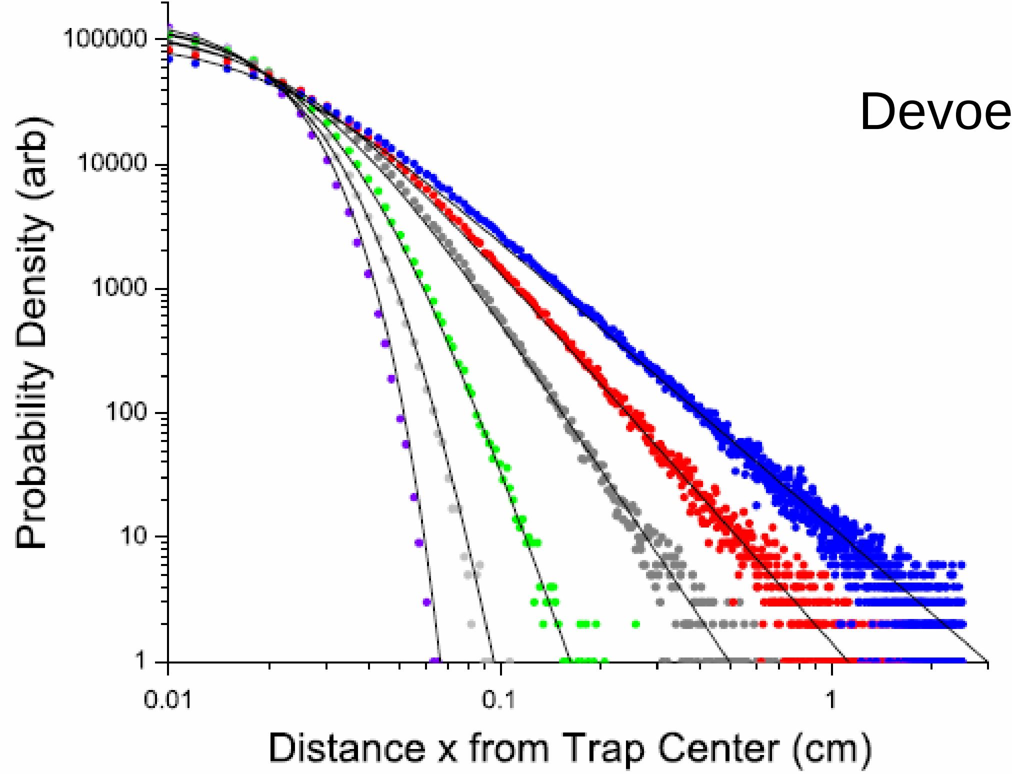
(Received 3 November 2008; published 10 February 2009)

Classical collisions with an ideal gas generate non-Maxwellian distribution functions for a single ion in a radio frequency ion trap. The distributions have power-law tails whose exponent depends on the ratio of buffer gas to ion mass. This provides a statistical explanation for the previously observed transition from cooling to heating. Monte Carlo results approximate a Tsallis distribution over a wide range of parameters and have *ab initio* agreement with experiment.



Devoe, Phys Rev Lett **102** (2009) 063001

$$T(x) = \frac{T(0)}{\left[1+(q-1)\left(\frac{x}{\sigma}\right)^2\right]^{\frac{1}{q-1}}}$$

FIG. 1 (color online). Monte Carlo distributions for a single $^{136}Ba^+$ ion cooled by six different buffer gases at 300 K ranging from $m_B = 4$ (left) to $m_B = 200$ (right). Note the evolution from Gaussian to power law (straight line) as the mass increases. The solid lines are Tsallis functions [Eq. (7)] with fixed $\sigma = 0.0185$ cm and the exponents of Table I.

TABLE I. Tsallis parameters n and q_T fit from Fig. 1.

Buffer gas	m_I/m_B	n	q_T
He	34.5	>60	1.03
Ar	3.40	8.2	1.12
Kr	1.70	3.8	1.26
Xe	1.0	1.98	1.51
170	0.80	1.50	1.80
200	0.68	1.15	1.87

SPIN RELAXATION IN SPIN GLASSES (NEUTRON SPIN ECHO):

PRL **102,** 097202 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

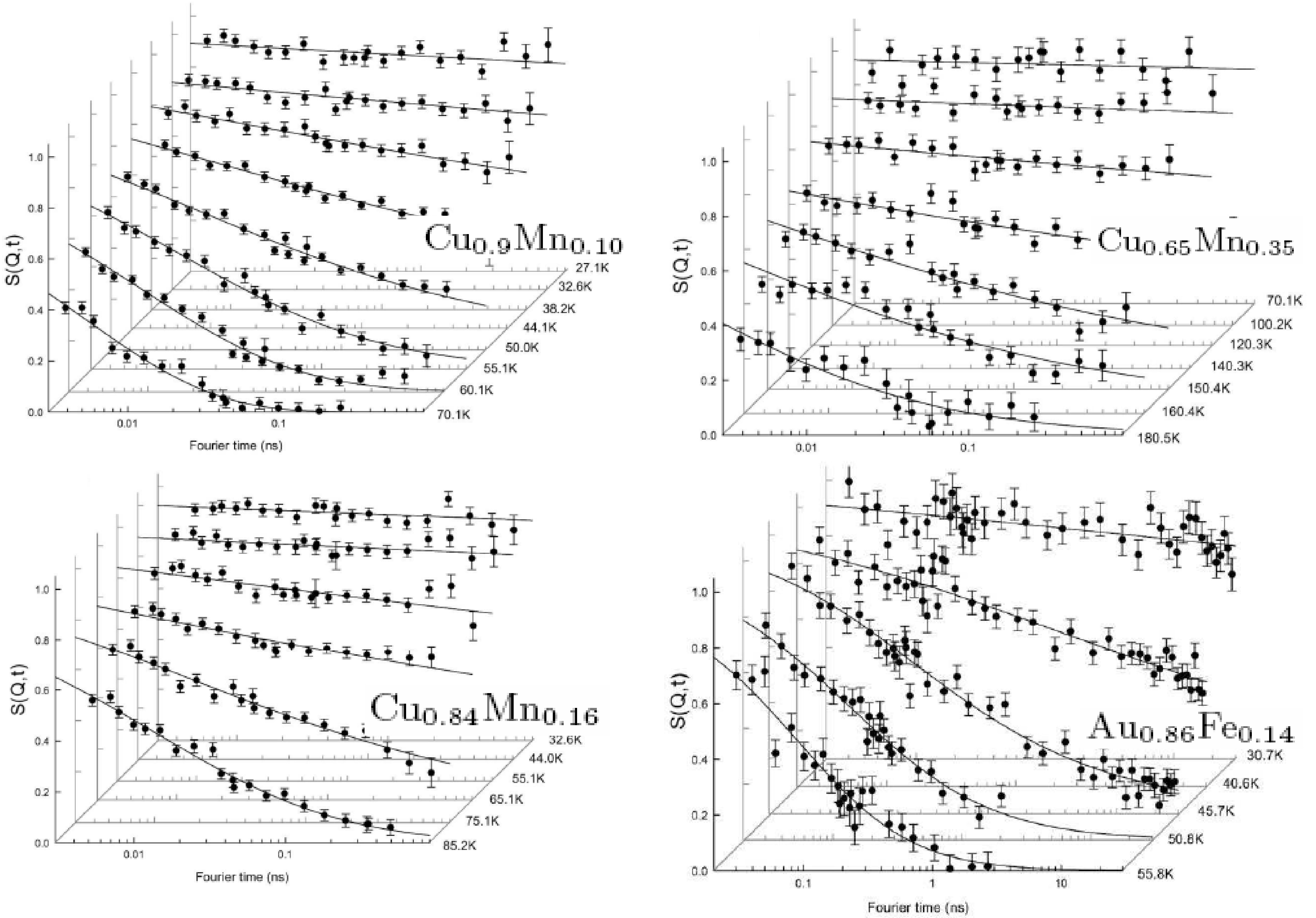
Generalized Spin-Glass Relaxation

R. M. Pickup,[1] R. Cywinski,[2,*] C. Pappas,[3] B. Farago,[4] and P. Fouquet[4]

[1]*School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom*
[2]*School of Applied Sciences, University of Huddersfield, Huddersfield HD1 3DH, United Kingdom*
[3]*Helmholtz Center Berlin for Materials and Energy, Glienickerstrasse 100, 14109, Berlin, Germany*
[4]*Institut Laue Langevin, 6 rue Jules Horowitz, 38000 Grenoble, France*

(Received 18 July 2008; published 4 March 2009)

Spin relaxation close to the glass temperature of CuMn and AuFe spin glasses is shown, by neutron spin echo, to follow a generalized exponential function which explicitly introduces hierarchically constrained dynamics and macroscopic interactions. The interaction parameter is directly related to the normalized Tsallis nonextensive entropy parameter q and exhibits universal scaling with reduced temperature. At the glass temperature $q = 5/3$ corresponding, within Tsallis' q statistics, to a mathematically defined critical value for the onset of strong disorder and nonlinear dynamics.



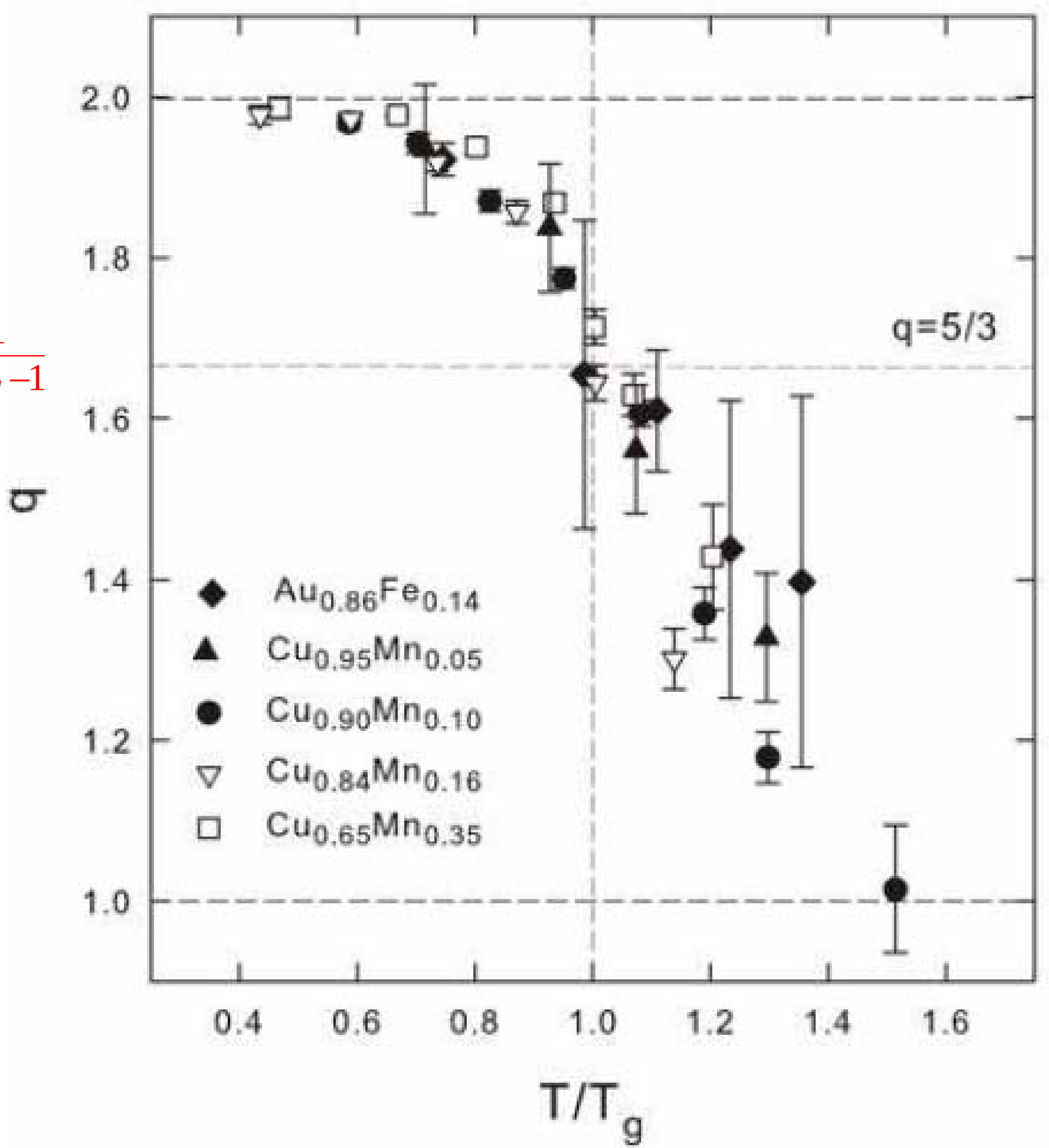
Pickup, Cywinski, Pappas, Farago, Fouquet, Phys Rev Lett **102** (2009) 097202

SPIN RELAXATION IN SPIN GLASSES (NEUTRON SPIN ECHO):

$$\phi(t) = \left[1 + \frac{q-1}{2-q}\left(\frac{t}{\tau}\right)^{\beta}\right]^{-\frac{2-q}{q-1}}$$

$$\equiv \left[1 + (q_{rel}-1)\left(\frac{t}{\tau}\right)^{\beta}\right]^{-\frac{1}{q_{rel}-1}}$$

$$q_{rel} \equiv \frac{1}{2-q}$$



Pickup, Cywinski, Pappas, Farago, Fouquet, Phys Rev Lett **102** (2009) 097202

Alguns conceitos

Algumas das verificações experimentais e computacionais

Alguns dos desafios

Available online at www.sciencedirect.com
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ELSEVIER
Physica A 356 (2005) 375–384
PHYSICA A
www.elsevier.com/locate/physa

Triangle for the entropic index q of non-extensive statistical mechanics observed by Voyager 1 in the distant heliosphere

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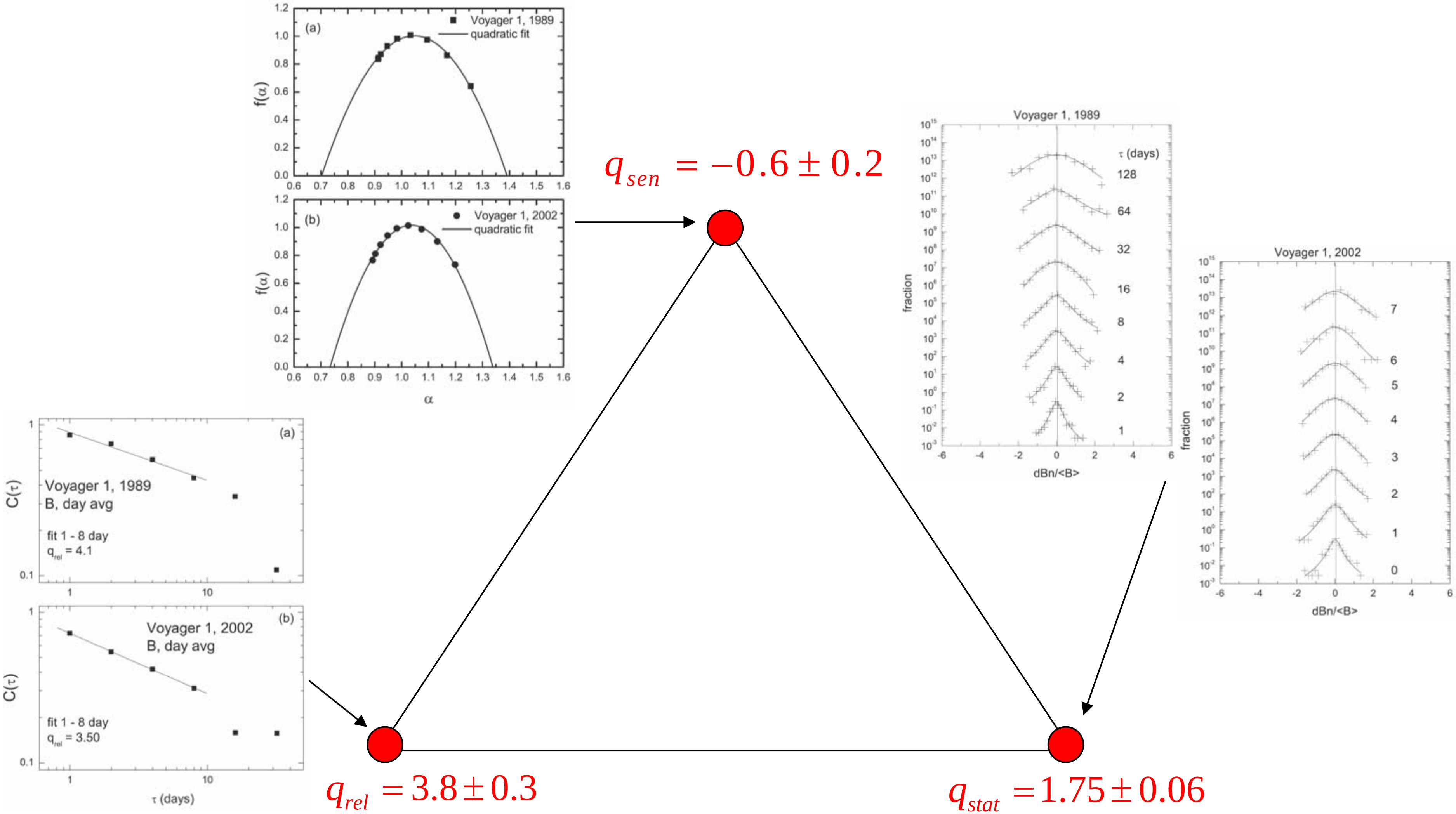
Received 10 June 2005
Available online 11 July 2005

SOLAR WIND: Magnetic Field Strength

L.F. Burlaga and A. F.-Vinas (2005) / NASA Goddard Space Flight Center; Physica A **356**, 375 (2005)

[Data: Voyager 1 spacecraft (1989 and 2002); 40 and 85 AU; daily averages]



Playing with additive duality $(q \to 2-q)$

and with multiplicative duality $(q \to 1/q)$

(*and using numerical results related to the* $q-$*generalized central limit theorem*)

we conjecture

$$q_{rel} + \frac{1}{q_{sen}} = 2 \qquad \text{and} \qquad q_{stat} + \frac{1}{q_{rel}} = 2$$

hence $$1- q_{sen} = \frac{1-q_{stat}}{3-2\,q_{stat}}$$

hence only one independent!

Burlaga and Vinas (NASA) most precise value of the $q-$*triplet is*

$$q_{stat} = 1.75 = 7/4$$

hence $q_{sen} = -\,0.5 = -\,1/2$ (*consistent with* $q_{sen} = -0.6 \pm 0.2$!)

and $q_{rel} = 4$ (*consistent with* $q_{rel} = 3.8 \pm 0.3$!)

C.T., M. Gell-Mann and Y. Sato, Proc Natl Acad Sc USA **102**, 15377 (2005)

$$\varepsilon_{sen} \equiv 1 - q_{sen} = 1 - (-1/2) = 3/2$$

$$\varepsilon_{rel} \equiv 1 - q_{rel} = 1 - 4 = -3$$

$$\varepsilon_{stat} \equiv 1 - q_{stat} = 1 - 7/4 = -3/4$$

We verify

$$\varepsilon_{stat} = \frac{\varepsilon_{sen} + \varepsilon_{rel}}{2} \quad \text{(arithmetic mean!)}$$

$$\varepsilon_{sen} = \sqrt{\varepsilon_{stat}\ \varepsilon_{rel}} \quad \text{(geometric mean!)}$$

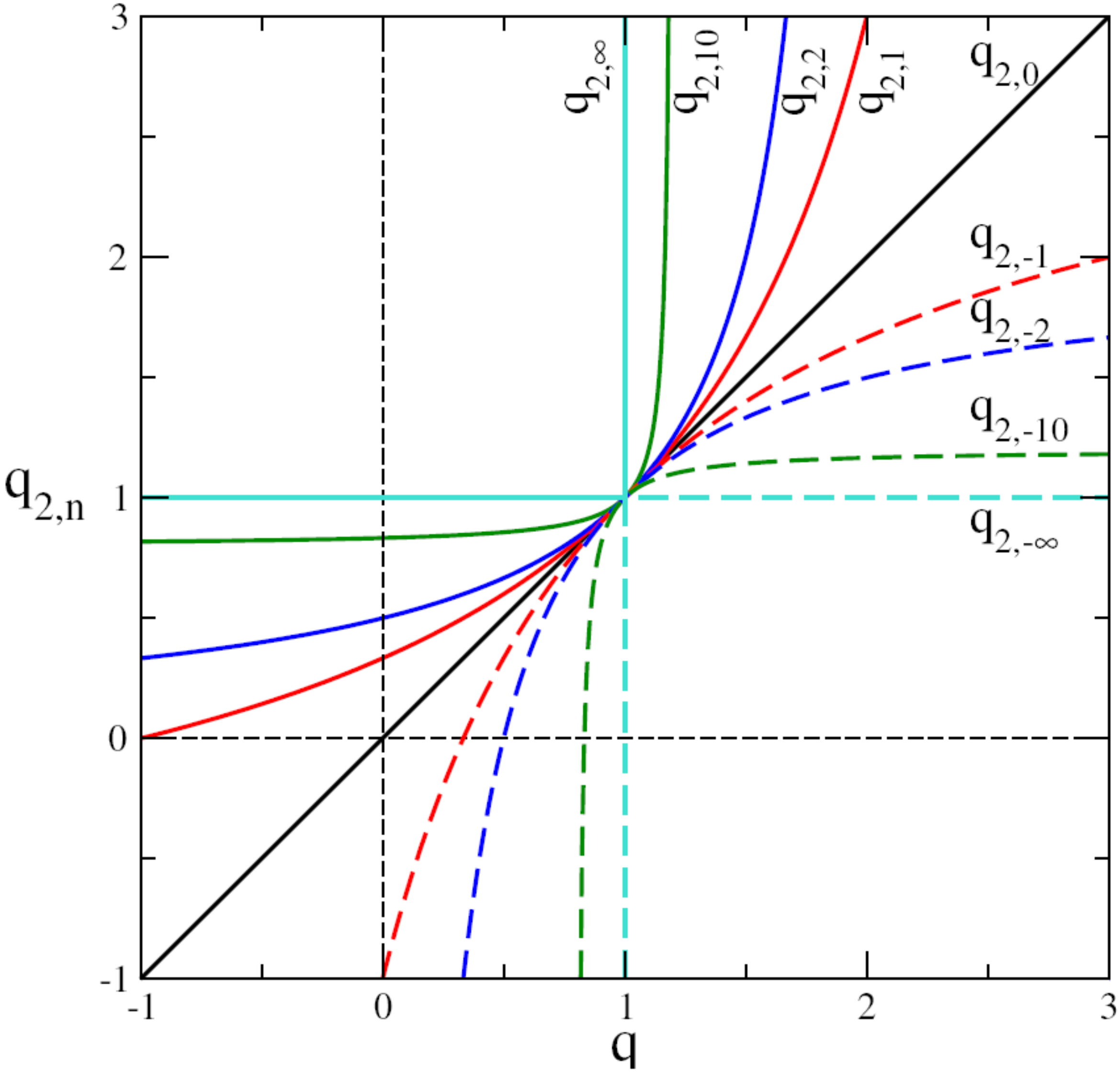
$$\varepsilon_{rel}^{-1} = \frac{\varepsilon_{sen}^{-1} + \varepsilon_{stat}^{-1}}{2} \quad \text{(harmonic mean!)}$$

N.O. Baella (2008)

ALGEBRA ASSOCIATED WITH *q* -GENERALIZED CENTRAL LIMIT THEOREMS:

$$\frac{\alpha}{1-q_{\alpha,n}} = \frac{\alpha}{1-q} + n$$

$$(n = 0, \ \pm 1, \ \pm 2, \ldots)$$



S. Umarov, C.T. and S. Steinberg, Milan J Math **76**, 307 (2008)

EDGE OF CHAOS OF THE LOGISTIC MAP:

$$
q\text{-triplet}
\begin{cases}
q_{sensitivity} = q_{ent\ production} = 0.2444877013412820661 98... \\
q_{relaxation} = 2.249784109... \\
q_{stationary\ state} = 1.65 \pm 0.05
\end{cases}
$$

WHAT IS THE PHYSICAL MEANING OF *q*-INDEPENDENCE?

IS IT CONSISTENT WITH (STRICT OR ASYMPTOTIC) SCALE INVARIANCE? IF YES, IS IT SUFFICIENT? NECESSARY?

CANDIDATE MODELS FOR *q*-INDEPENDENCE:

1) *N* compact-support continuous variables with correlation introduced through a *N*-variate covariance matrix **(strictly scale-invariant)**

W. Thistleton, J.A. Marsh, K. Nelson and C. T., unpublished (2007)

(see H.J. Hilhorst and G. Schehr, J Stat Mech (2007) P06003)

2) *N* binary variables with correlation introduced through the *q*-product **(strictly scale-invariant)**

L.G. Moyano, C. T. and M. Gell-Mann, Europhys Lett **73** (2006) 813

(see H.J. Hilhorst and G. Schehr, J Stat Mech (2007) P06003)

3) *N* binary variables with correlation introduced through a family of triangles generalizing the Leibnitz one **(strictly scale-invariant)**

A. Rodriguez, V. Schwammle and C. T., J Stat Mech (2008) P09006

R. Hanel, S. Thurner and C. T. (2008)

4) N-binary-discretized *q*-Gaussians **(asymptotically scale-invariant)**

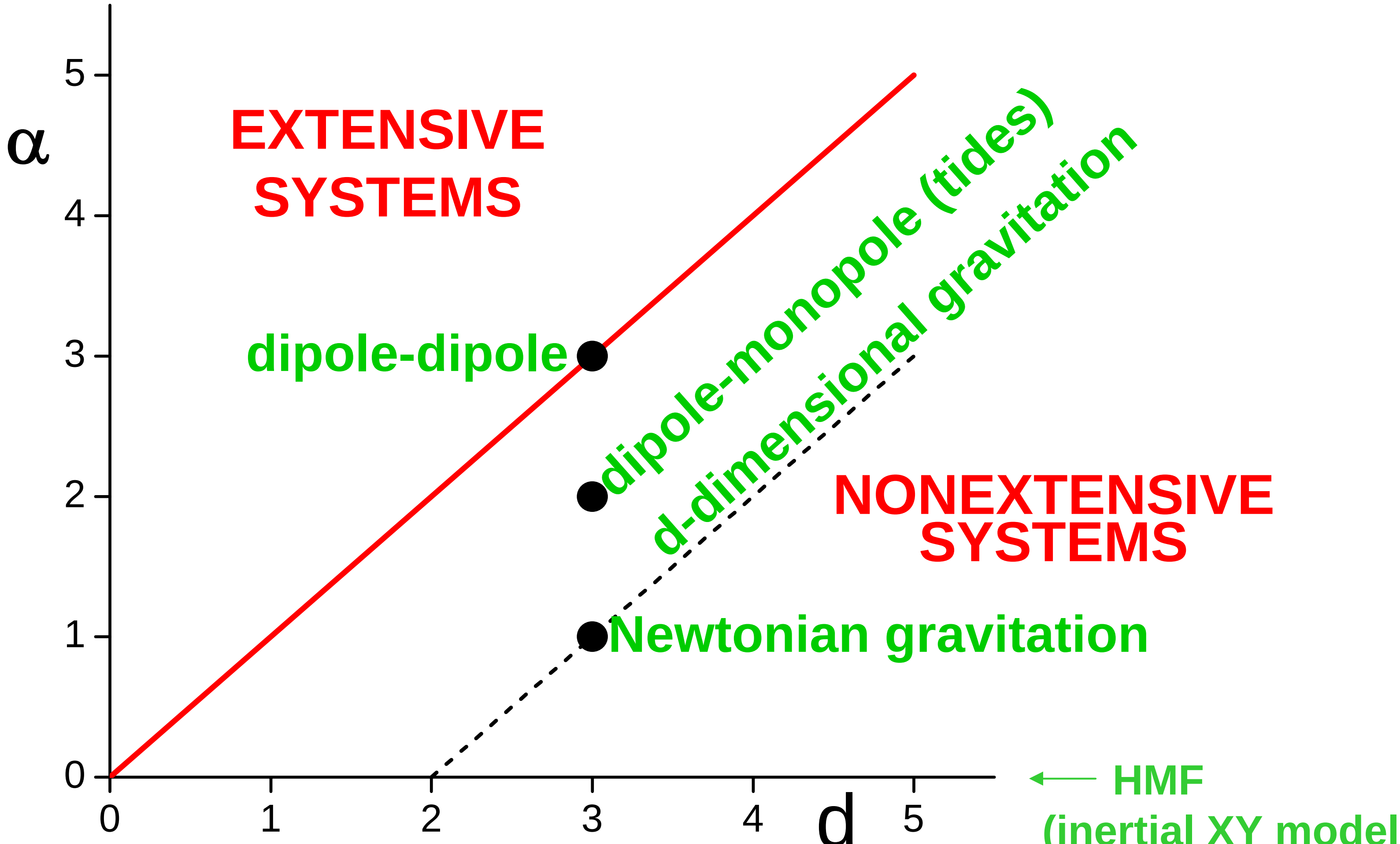
A. Rodriguez, V. Schwammle and C. T., J Stat Mech (2008) P09006

CLASSICAL LONG-RANGE-INTERACTING MANY-BODY HAMILTONIAN SYSTEMS

$$V(\vec{r}) \sim -\frac{A}{r^{\alpha}} \qquad (r \to \infty) \qquad (A > 0, \quad \alpha \geq 0)$$

integrable if $\alpha / d > 1$ *(short-ranged)*

non-integrable if $0 \leq \alpha / d \leq 1$ *(long-ranged)*



d-DIMENSIONAL CLASSICAL INERTIAL *XY* FERROMAGNET:

(We illustrate with the *XY* (i.e., *n=2*) model; the argument holds however true for any *n>1* and any *d*-dimensional Bravais lattice)

$$H = K + V = \frac{1}{2I}\sum_{i=1}^{N} L_i^2 + \frac{J}{\mathfrak{A}}\sum_{i,j}\frac{1-\cos(\vartheta_i - \vartheta_j)}{r_{ij}^{\alpha}} \qquad (I>0,\ J>0)$$

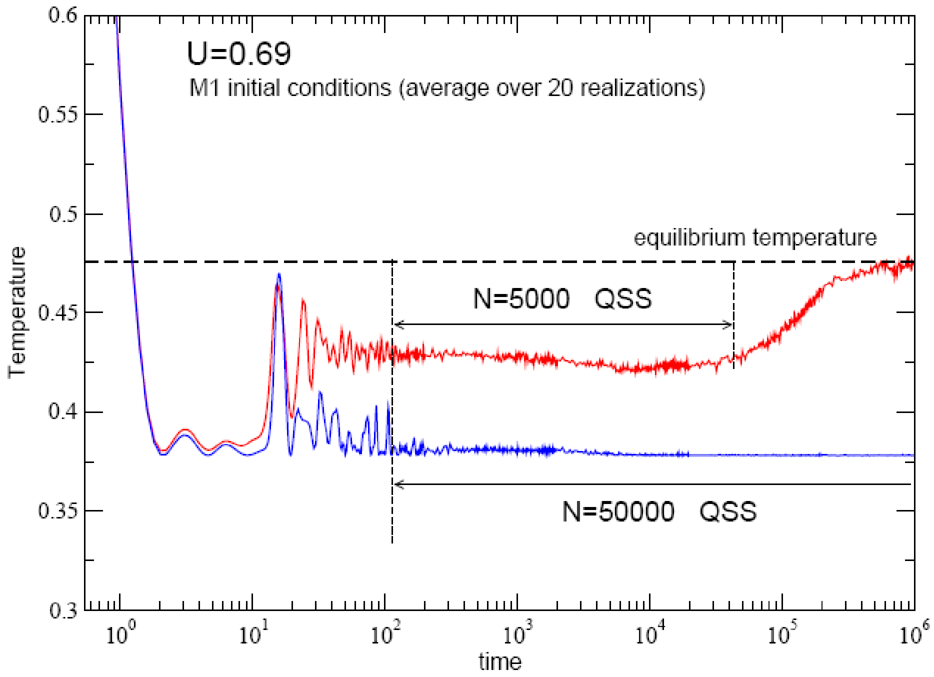
$$with \ \ \mathfrak{A} \equiv \sum_{j=1}^{N} r_{ij}^{-\alpha} \propto \begin{cases} N^{1-\alpha/d} & if \quad 0 \le \alpha/d < 1 \\ \ln N & if \quad \alpha/d = 1 \\ constant & if \quad \alpha/d > 1 \end{cases}$$

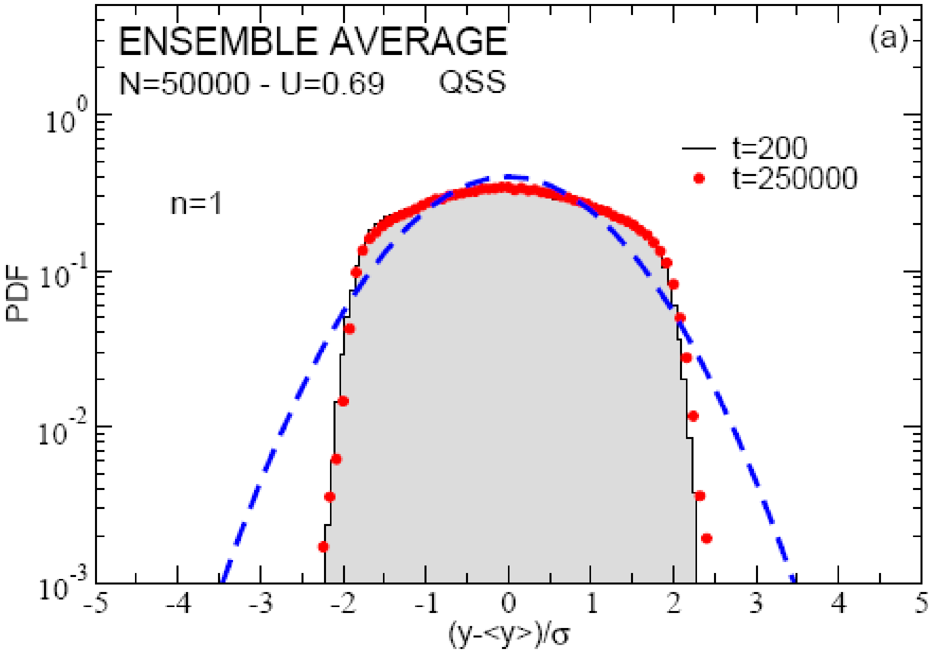
and periodic boundary conditions.

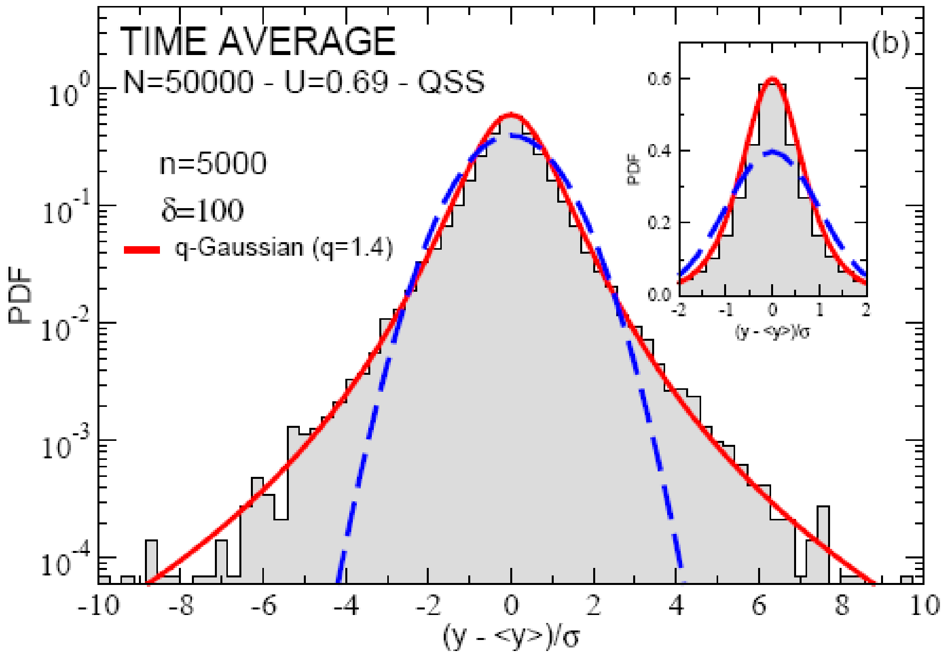
$[The\ HMF\ \ model\ corresponds\ to\ \alpha/d = 0]$

C. Anteneodo and C. T., Phys Rev Lett **80**, 5313 (1998)

HMF MODEL







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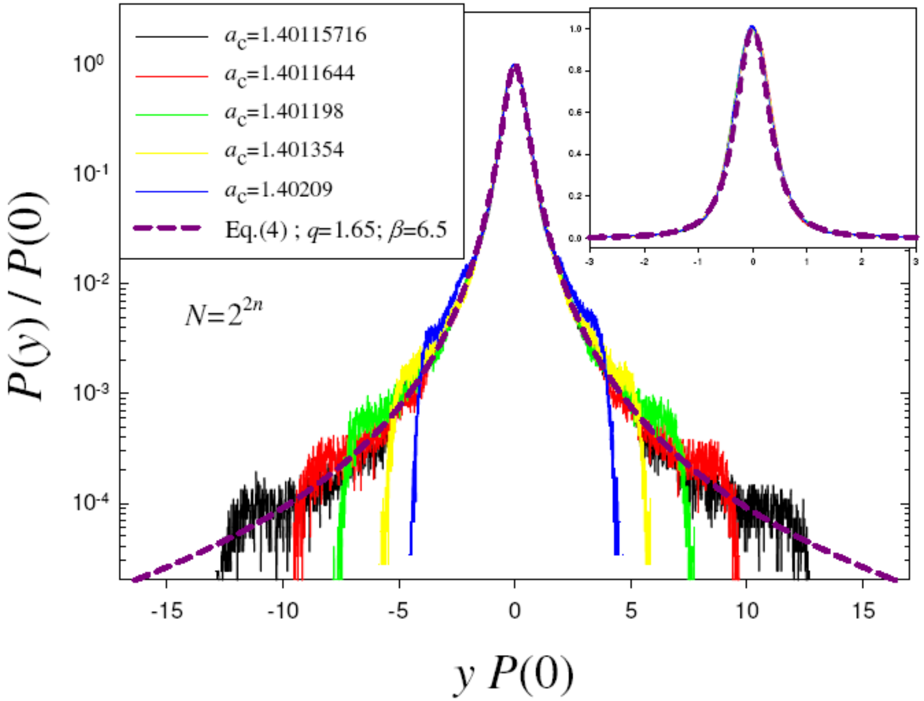
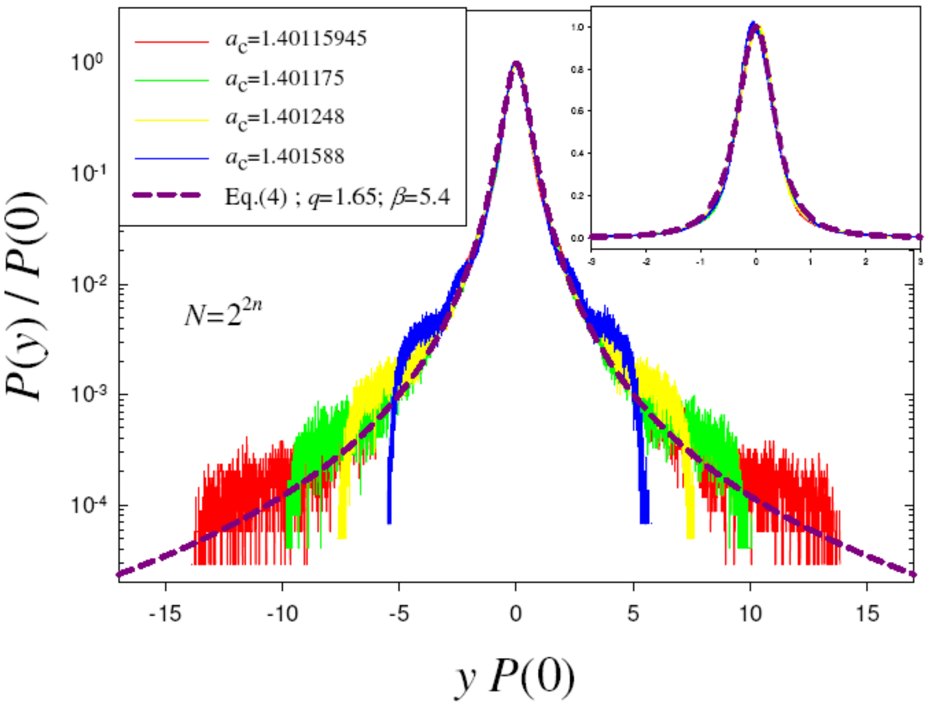


odd 2n

***q*=1.65**

beta=6.5



even 2n

***q*=1.65**

beta=5.4

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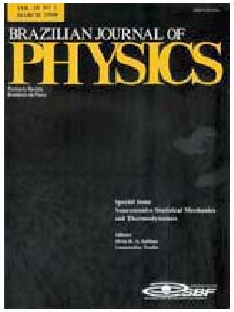

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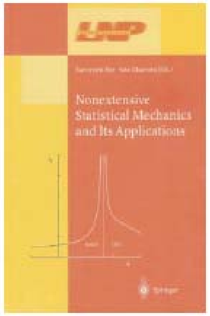

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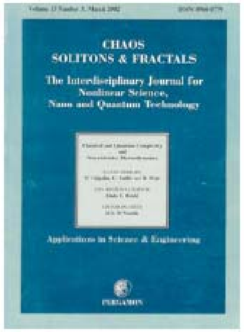

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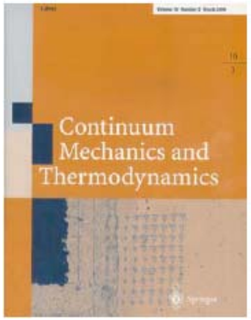

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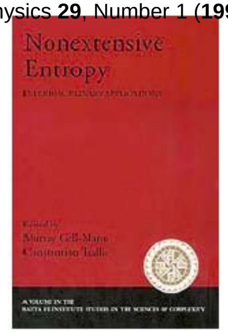

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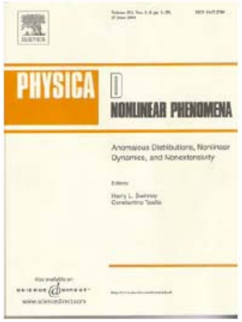

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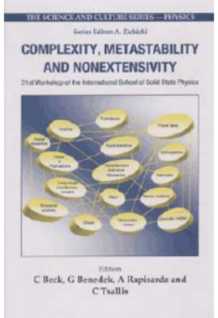

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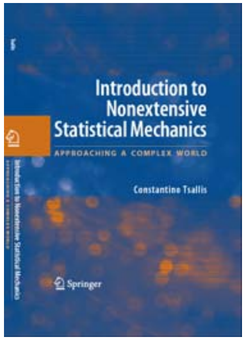

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