Giorgio Parisi

a Modern Theoretical Physicist
Complex Systems & Much More

Leticia F. Cugliandolo

Sorbonne Université

Institut Universitaire de France

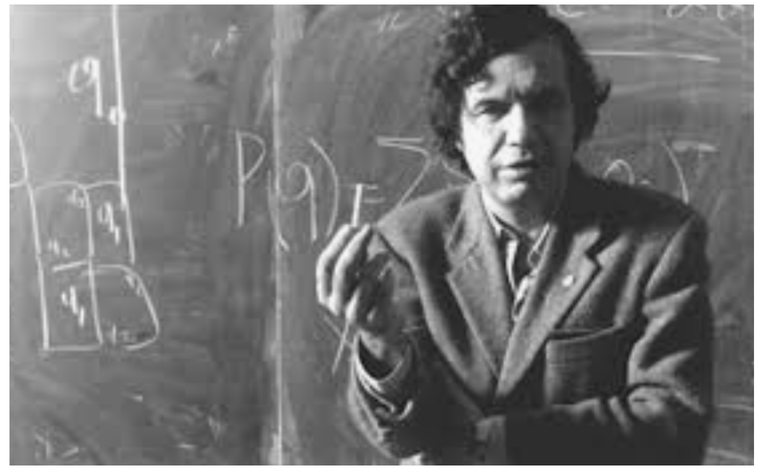
leticia@lpthe.jussieu.fr
www.lpthe.jussieu.fr/~leticia

GDR Matériaux, Etats ElecTroniques, Interactions et Couplages non-Conventionnels

Giorgio Parisi

Some pics






Giorgio Parisi

A renaissance man with so many interests

Theoretical physics & math

Particle physics – Statistical physics – Dynamical systems & turbulence...

Numerical methods – Mathematics

Technical

Computer architecture – Observation methods & data analysis

the beyond*

Neural nets, immunological system, optimisation, active matter, climate science...

Roman students' nickname of *Mézard, Parisi & Virasoso,** *Spin glass theory and beyond* (World Scientific 1987)

and a school of thought: a way of doing physics

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Roman students' nickname of *Mézard, Parisi & Virasoso,* *Spin glass theory and beyond* (World Scientific 1987)

it is not possible to cover all - let me tell you one story

Academic career

Rome - USA - France - Rome

Laurea at the Sapienza University of Rome (1970)

Researcher at the Laboratori Nazionali di Frascati (1971 - 1981)

Visiting scientist at Columbia University (1973 - 1974)

Visiting scientist at the Institut des Hautes Études Scientifiques (1976 - 1977)

Visiting scientist at École Normale Supérieure (1977 - 1978)

Full professor at the University of Rome Tor Vergata (1981 - 1992)

Full professor at the Sapienza University of Rome (1992 -)

Member of the Accademia Nazionale dei Lincei since 2009

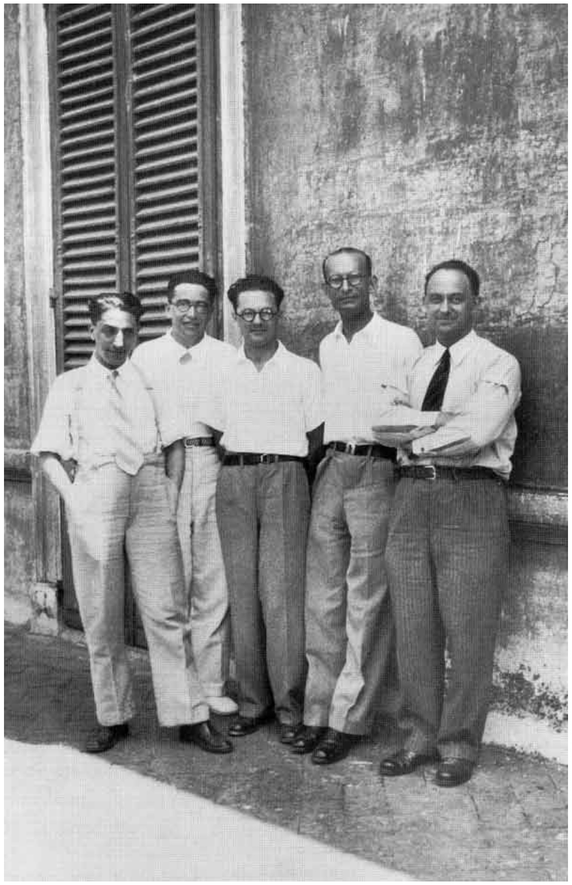
Rome

Central to modern physics since at least the 30s

I ragazzi di via Panisperna

1930, circa

Photo on the left from wikipedia



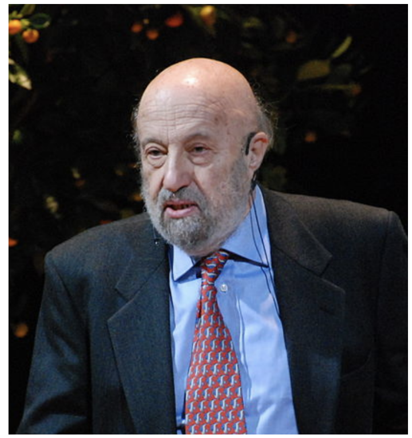
D’Agostino, Segrè, Amaldi, Rasetti & Fermi

Photo on the right, it’s mine

Rome

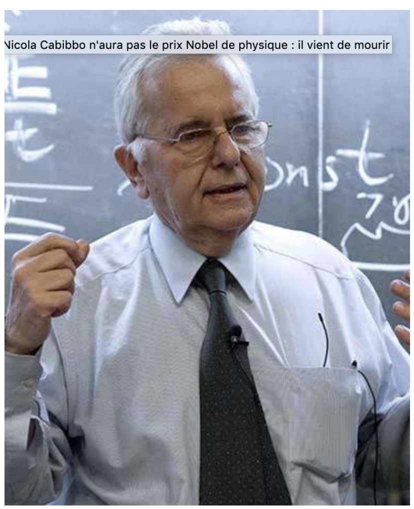
Late 60s - both cond-mat & particle physics

Giovanni Gallavotti

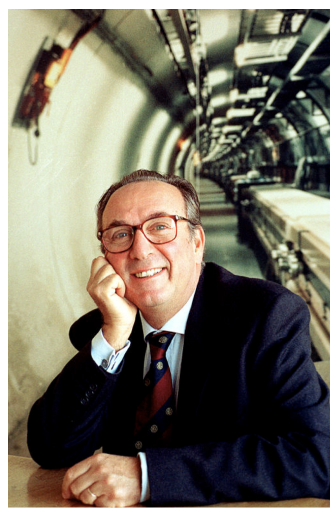


Giovanni Jona-Lasinio

Carlo Di Castro



Nicola Cabibbo



Luciano Maiani

Guido Altarelli

Research debuts

The early 70's: a great period for Theoretical Physics in Rome

Giorgio in **Nicola Cabibbo's** Theory Group

Quantum Field Theory (as opposed to S-Matrix) for **particle physics**

First papers*

5. Hadron Production in e+e- Collisions, with N. Cabibbo and M. Testa, Lettere al Nuovo Cimento 4 (1970) 35.
6. Deep Inelastic Scattering and the Nature of Partons, with N. Cabibbo, M. Testa and A. Verganelakis, Lettere al Nuovo Cimento 4 (1970) 569.
7. Gauge Invariance and Dynamical Symmetry Breaking, with M. Testa, Lettere al Nuovo Cimento 4 (1970) 71.
8. Generating Functionals, Ward Identities and Scalar Mesons, with M. Testa, Nuovo Cimento A67 (1970) 13.
9. Calculation of Critical Indices, with L. Peliti, Lettere al Nuovo Cimento 2 (1971) 627.
10. The s-Term and the Scale Breaking, with M. Testa, Lettere al Nuovo Cimento 2 (1971) 1154.

* from Giorgio's webpage https://chimera.roma1.infn.it/GIORGIO/papers.html

Nicola Cabibbo

Giorgio's supervisor laurea degree 1970

Blitz quotidiano > Scienza > Giorgio Parisi "vendica" il suo prof Nicola Cabibbo: "Il Nobel per la Fisica doveva vincerlo anche lui"

Giorgio Parisi "vendica" il suo prof Nicola Cabibbo: "Il Nobel per la Fisica doveva vincerlo anche lui"

Photo from Emilio Segrè's Visual Archives, Niels Bohr Library & Archives

Research debuts

... Statistical Physics was already meddling in

Giorgio in **Nicola Cabibbo's** Theory Group

Quantum Field Theory (as opposed to S-Matrix) for particle physics

First papers*

5. Hadron Production in e+e- Collisions, with N. Cabibbo and M. Testa, Lettere al Nuovo Cimento 4 (1970) 35.

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8. Generating Functionals, Ward Identities and Scalar Mesons, with M. Testa, Nuovo Cimento A67 (1970) 13.

9. $\boxed{\text{Calculation of Critical Indices, with L. Peliti, Lettere al Nuovo Cimento 2 (1971) 627.}}$

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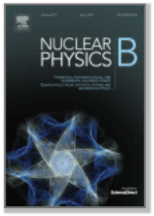
Particle Physics

in Paris

Nuclear Physics B

Volume 126, Issue 2, 8 August 1977, Pages 298-318



Asymptotic freedom in parton language

G. Altarelli *

Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, Paris, France

G. Parisi ***

Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977, Available online 26 October 2002.

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equations describe the variation of the parton distribution functions with varying energy scales

Parton: Pre-QCD name for hadron (protons, neutrons) constituents (quarks, gluons)

Particle Physics

the Altarelli-Parisi paper

Altarelli Yuri Parisi

EPS High Energy and Particle Physics Prize *"for having developed the scheme of a probabilistic field theory for the dynamics of quarks and gluons, enabling a quantitative understanding of high-energy collisions between hadrons"*

"... Guido liked to remark that it is the most cited French paper in the field of high energy physics."

Random matrices

Planar diagrams - 1978

Commun. math. Phys. 59, 35—51 (1978)

Communications in Mathematical Physics

Planar Diagrams

E. Brézin, C. Itzykson, G. Parisi*, and J. B. Zuber

Service de Physique Théorique, Centre d'Études Nucléaires de Saclay, F-91190 Gif-sur-Yvette, France

Abstract. We investigate the planar approximation to field theory through the limit of a large internal symmetry group. This yields an alternative and powerful method to count planar diagrams. Results are presented for cubic and quartic vertices, some of which appear to be new. Quantum mechanics treated in this approximation is shown to be equivalent to a free Fermi gas system.

Exploiting **'t Hoft**'s ideas to constrain the types of Feynman diagrams in gauge field theories & matrix models, *e.g.*

$$\mathcal{L} = \mathrm{Tr}(\partial_\mu M \partial_\mu M^\dagger) + \mathrm{Tr}(M M^\dagger) + \frac{g}{2N}\mathrm{Tr}(M M^\dagger M M^\dagger)$$

with $M(\vec{x})$ an $N \times N$ matrix, in the large N limit & thus **count planar diagrams**

Transition

Particle Physics $\mapsto$ Statistical Physics

"At the beginning of the 80's I became mostly interested in problems in statistical mechanics and my only residual activity in high energy physics was lattice QCD"

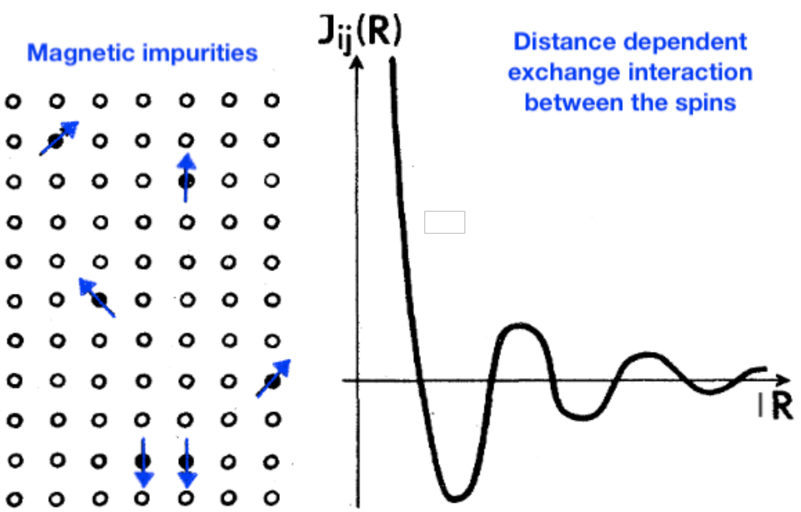
G. Parisi, *Historical and personal recollections of Guido Altarelli*,
EPJ Web of Conferences 164, 02001 (2017)

Disordered Systems

What are they ? Dirty materials

e.g. a crystal with magnetic impurities placed at fixed random positions,

a **spin-glass**



Finite d Heisenberg

$$\mathcal{H}_J = -\sum_{ij} J_{ij}(\mathbf{R})\, \mathbf{s}_i \cdot \mathbf{s}_j$$

Fully connected Ising **SK**

$$\mathcal{H}_J = -\sum_{i \neq j} J_{ij}\; s_i s_j$$

Exchanges chosen from a pdf

$P(J_{ij})$ typically Gaussian

Sketch from **Binder & Young**, Rev. Mod. Phys. 58, 801 (1986)

Disordered Systems

Self-averageness & the equilibrium Replica Method

Take a fully-connected spin $\{s_i\}, i = 1, \ldots, N$ model with quenched random interactions J_{ij} drawn from a probability distribution $P(J_{ij})$

$$\boxed{\mathcal{H}_J[\{s_i\}] = -\sum_{i \neq j} J_{ij} s_i s_j}$$

In the $N \to \infty$ limit, disorder averaged & typical free-energy densities, coincide

$$\boxed{f_J \underset{N\to\infty}{=} [f_J] = -k_B T N^{-1} [\ln \mathcal{Z}_J]}$$

self-averageness

The disorder average can be evaluated with the help of the **replica trick** which uses the identify $x^n = \exp(n \ln x)$ Taylor expanded around $n = 0$

$$x^n \underset{n\to 0}{=} 1 + n \ln x + \mathcal{O}(n^2) \quad \Rightarrow \quad \boxed{[\ln \mathcal{Z}_J] \underset{n\to 0}{=} \frac{[\mathcal{Z}_J^n] - 1}{n}}$$

Replica method

A sketch

$$\boxed{-\beta[f_J] = \lim_{N\to\infty} \frac{[\ln \mathcal{Z}_J]}{N} = \lim_{N\to\infty} \lim_{n\to 0} \frac{[\mathcal{Z}_J^n] - 1}{Nn}}$$

$\mathcal{Z}_J^n$ is the partition function of n independent copies of the system: the **replicas**

Gaussian $P(J_{ij})$ average over disorder $\Rightarrow$ **replica coupling**

$$\boxed{\sum_a \sum_{i\neq j} J_{ij} s_i^a s_j^a \;\Rightarrow\; \sum_{i\neq j} \sum_{ab} s_i^a s_j^a s_i b s_j^b}$$

Quadratic decoupling with the Hubbard-Stratonovich (Gaussian) trick

$$\boxed{Q_{ab} \sum_i s_i^a s_i^b + \frac{1}{2} Q_{ab}^2}$$

Q_{ab} is a 0×0 matrix but it admits an interpretation in terms of **overlaps**

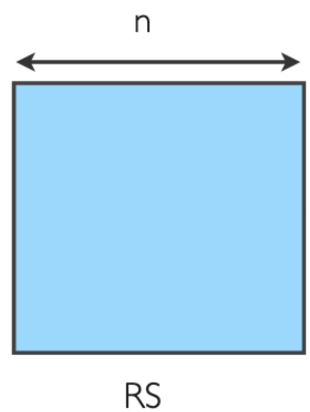
The elements of Q_{ab} can evaluated by saddle-point if one exchanges the limits

$$\lim_{N\to\infty} \lim_{n\to 0} \ldots \;\mapsto\; \lim_{n\to 0} \lim_{N\to\infty} \ldots$$

Disordered Systems

The structure of the matrix Q_{ab}

Replica Symmetry



Sherrington & Kirkpatrick, *Solvable model of a spin-glass*, PRL 35, 1792 (1975)

but $S(T=0) < 0$ and the saddle-point $Q_{ab} = q$ is not stable

de Almeida & Thouless , *Stability of the Sherrington-Kirkpatrick solution of a spin glass model*, J. Phys. A : Math. Gen. **11**, 983 (1978)

Fig. from **Morone, Caltagirone, Harrison & Parisi**, *Replica Theory and Spin Glasses,* Les Houches 2013

Disordered Systems

Why ? Answer : a nice open mathematical problem

VOLUME 43, NUMBER 23 PHYSICAL REVIEW LETTERS 3 DECEMBER 1979

Infinite Number of Order Parameters for Spin-Glasses

G. Parisi
Servizio Documentazione, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy
(Received 22 June 1979)

This Letter shows that in the mean-field approximation spin-glasses must be described by an infinite number of order parameters in the framework of the replica theory.

J. Phys. A: Math. Gen. **13** (1980) L115–L121. Printed in Great Britain

LETTER TO THE EDITOR

A sequence of approximated solutions to the S–K model for spin glasses

G Parisi
Istituto Nazionale de Fisica Nucleare, Laboratori Nazionali di Frascati, Casella Postale 13, 0004 Frascati, Roma, Italy

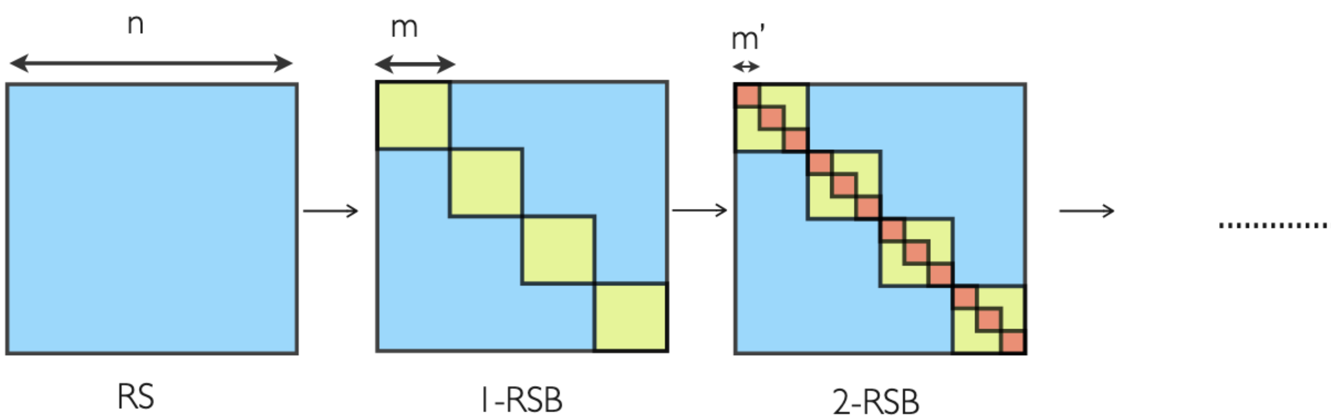
Received 4 January 1980

Abstract. In the framework of the new version of the replica theory, we compute a sequence of approximated solutions to the Sherrington–Kirkpatrick model of spin glasses.

Disordered Systems

The structure of the matrix Q_{ab}

Replica Symmetry Breaking



Now $S(T=0)=0$ and the saddle-point Q_{ab} is stable

Fig. from **Morone, Caltagirone, Harrison & Parisi**, *Replica Theory and Spin Glasses,* Les Houches 2013

Disordered Systems

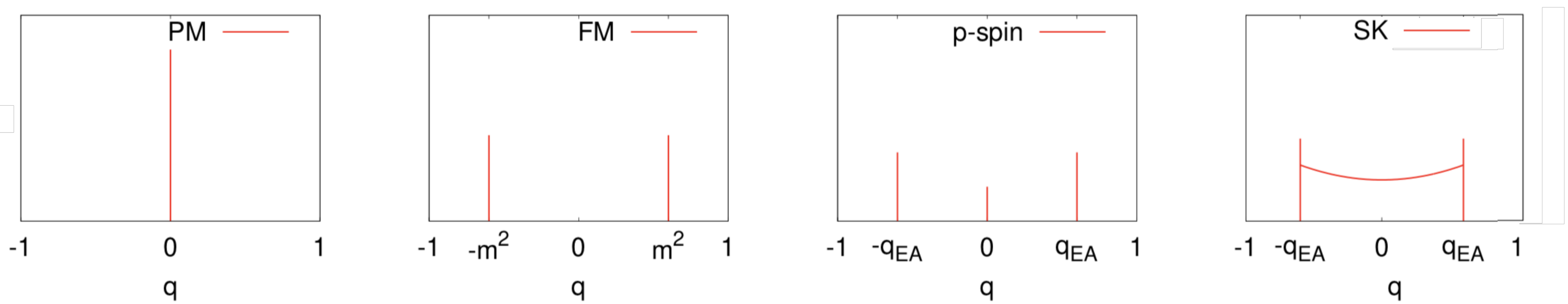
The disorder averaged overlap distribution function $P(q)$

The elements of the matrix Q_{ab} are overlaps between equilibrium states

$$Q_{ab} = \frac{1}{N} \sum_{i=1}^{N} s_i^a s_i^b$$

and are distributed according to $P_J(q = Q_{ab})$

Parisi's 79-82 a way to calculate $P(q) = [P_J(q)] \Rightarrow [f_J]$



High temperature FM Structural glasses Spin-glasses

The predicted equilibrium free-energy density $[f_J]$ was confirmed by **Guerra & Talagrand 00-04** with independent mathematical-physics methods

Disordered systems

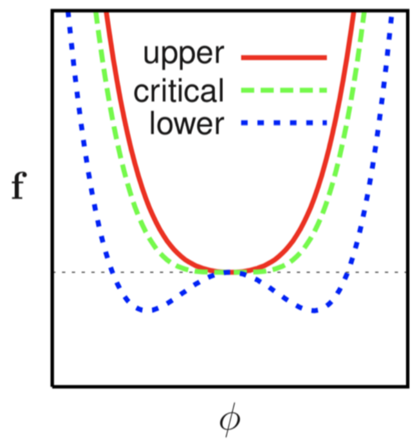
How to measure $P_J(q)$? Overlaps between real replicas

Take one sample and run it, with e.g. Monte Carlo, until it reaches **equilibrium**, measure the spin configuration $\{s_i\}$.

Re-initialize the same sample (same J_{ij}), run it again until it reaches again **equilibrium**, & measure the spin configuration $\{\sigma_i\}$.

Construct the overlap $q_{s\sigma} \equiv N^{-1} \sum_{i=1}^{N} s_i \sigma_i$.

In a **PM system** the overlap will typically vanish as, say, $N^{-1/2}$



Many repetitions

for a system with $N \gg 1$

$$\boxed{P(q_{s\sigma}) = \delta(q_{s\sigma})}$$

Disordered systems

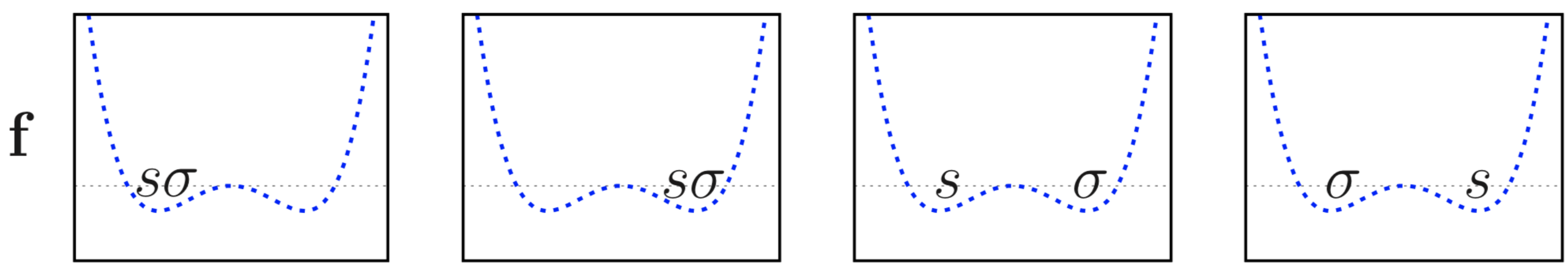
How to measure $P_J(q)$? Overlaps between real replicas

Take one sample and run it, with e.g. Monte Carlo, until it reaches **equilibrium**, measure the spin configuration $\{s_i\}$.

Re-initialize the same sample (same J_{ij}), run it again until it reaches again **equilibrium**, & measure the spin configuration $\{\sigma_i\}$.

Construct the overlap $q_{s\sigma} \equiv N^{-1} \sum_{i=1}^{N} s_i \sigma_i$.

In a **FM system** there are four possibilities



$q_{s\sigma} = m^2$ $\qquad m^2 \qquad -m^2 \qquad -m^2$

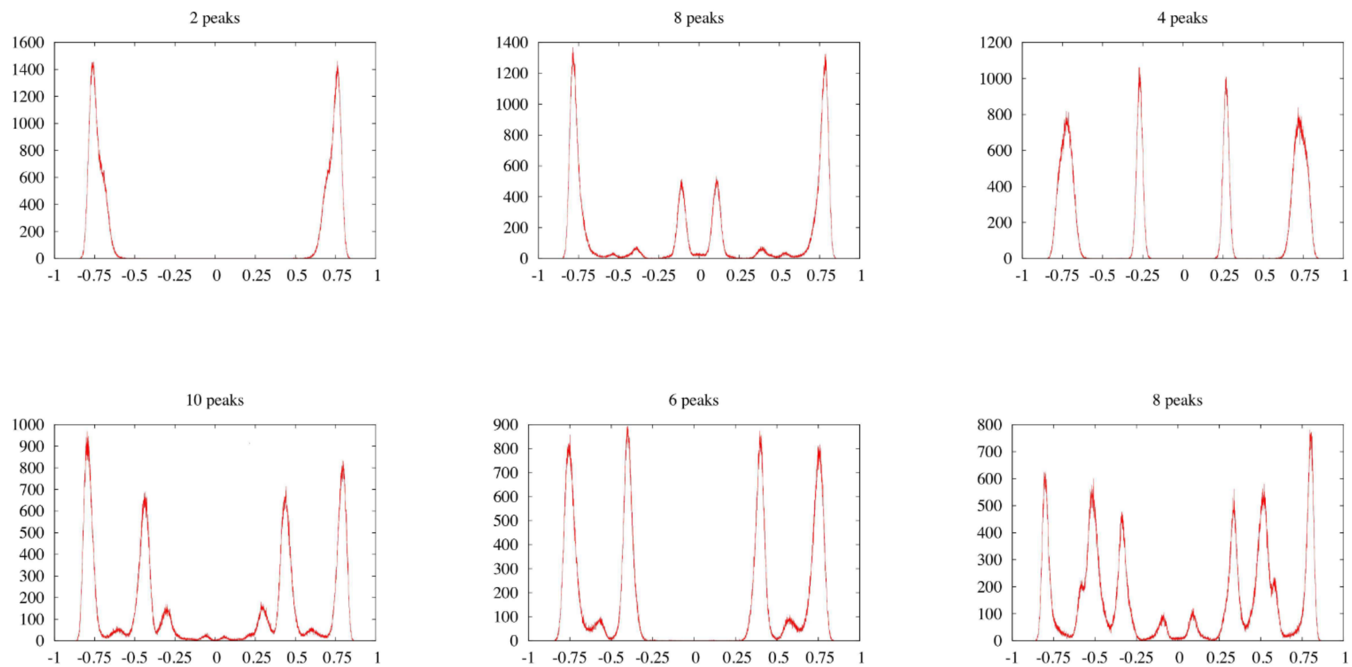
Many repetitions $\boxed{P(q_{s\sigma}) = \frac{1}{2}\delta(q_{s\sigma} - m^2) + \frac{1}{2}\delta(q_{s\sigma} + m^2)}$

Disordered Systems

How to measure $P_J(q)$? Overlap between real replicas

SK model with $N = 4096$ at $T = 0.4\,T_c$ and six J_{ij}, one per panel

$$\mathcal{H}_J[\{s_i\}] = -\sum_{i\neq j} J_{ij} s_i s_j \qquad q = \frac{1}{N}\sum_i s_i \sigma_i \qquad P_J(q)$$



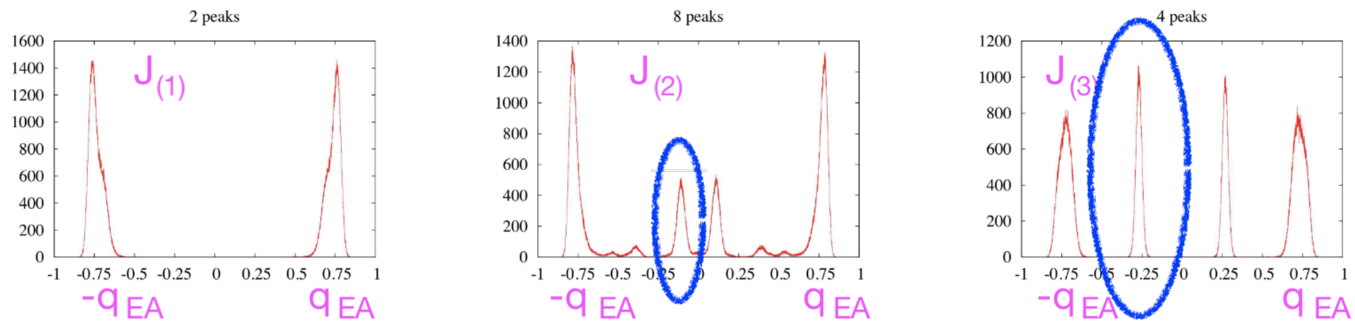
Aspelmeier, Billoire, Marinari & Moore, *Finite size corrections in the Sherrington-Kirkpatrick model*, J. Phys. A 41, 324008 (2008)

Real replicas

How to measure $P_J(q)$? Overlap between real replicas

SK model with $N = 4096$ at $T = 0.4\,T_c$ and six J_{ij}, one per panel

$$\mathcal{H}_J[\{s_i\}] = -\sum_{i \neq j} J_{ij} s_i s_j \qquad q = \frac{1}{N}\sum_i s_i \sigma_i \qquad P_J(q)$$



$J_{ij}^{(1)}$ $\qquad J_{ij}^{(2)}$ $\qquad J_{ij}^{(3)}$

Data in each panel for a different realization of the random couplings

> Most samples have peaks at $|q| < q_{\mathrm{EA}}$:
>
> replicas $\{s_i\}$ and $\{\sigma_i\}$ falling in different states

Disordered systems

Thouless-Anderson-Palmer

SK model

$$\boxed{\mathcal{H}_J = -\sum_{i \neq j} J_{ij} s_i s_j}$$

(Naive) free-energy function of the **local order parameters** $m_i = \langle s_i \rangle$

$$\boxed{N f_J(\{m_i\}) = -\sum_{i \neq j} J_{ij} m_i m_j + k_B T \sum_{i=1}^{N} \frac{1+m_i}{2} \ln \frac{1+m_i}{2} + \frac{1-m_i}{2} \ln \frac{1-m_i}{2}}$$

and the (naive) TAP equations

$$\boxed{m_i = \tanh \sum_{j(\neq i)} 2\beta J_{ij} m_j}$$

that determine the m_i at the saddle-point level

Thouless, Anderson, Palmer, *Solution of 'Solvable model of a spin glass'*, Phil. Mag. 35, 593 (1977). **De Dominicis & Young**, *Weighted averages and order parameters for the infinite range Ising spin glass*, J. Phys. A : Math. Gen. 16, 2063 (1983)

Disordered systems

Many solutions : complex landscapes

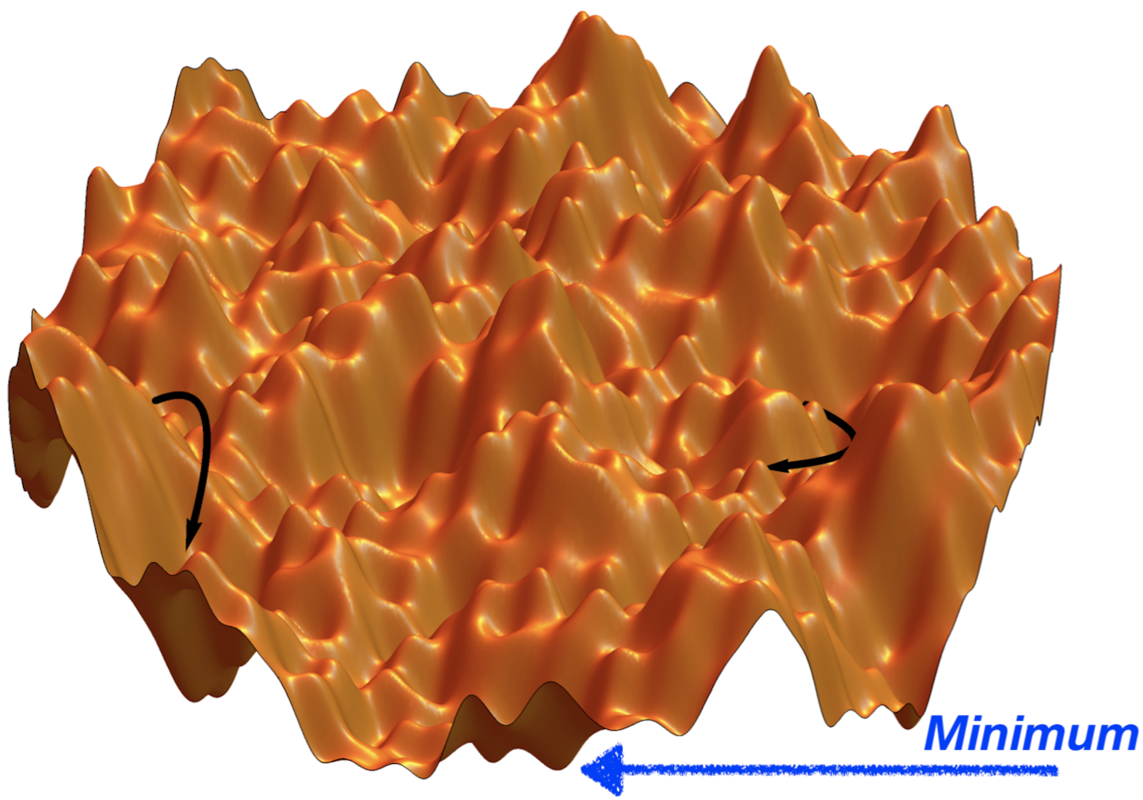


Fig. from **C. Cammarota**

Much more

Opened so many areas of research

and more or less simultaneously !

Stochastic resonance

Stochastic processes & climate science - 1981

Tellus (1982) ***34***, 10–16

Stochastic resonance in climatic change

By ROBERTO BENZI, *Istituto di Fisica dell'Atmosfera, C.N.R., Piazza Luigi Sturzo 31, 00144, Roma, Italy,*
GIORGIO PARISI, *I.N.F.N., Laboratori Nazionali di Frascati, Frascati, Roma, Italy,*
ALFONSO SUTERA, *The Center for the Environment and Man, Hartford, Connecticut 06120, U.S.A.*
and ANGELO VULPIANI, *Istituto di Fisica "G. Marconi", Università di Roma, Italy*

(Manuscript received November 12, 1980; in final form March 13, 1981)

ABSTRACT

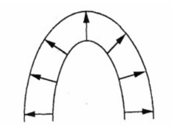
An amplification of random perturbations by the interaction of non-linearities internal to the climatic system with external, orbital forcing is found. This stochastic resonance is investigated in a highly simplified, zero-dimensional climate model. It is conceivable that this new type of resonance might play a role in explaining the 10^5 year peak in the power spectra of paleoclimatic records.

$$\frac{\mathrm{d}T(t)}{\mathrm{d}t} = [\underbrace{T(t)(a - T^2(t))}_{\text{non}-\text{linear}} + \underbrace{A\cos\Omega t}_{\text{periodic}}] + \underbrace{\xi(t)}_{\text{white noise}}$$

Kardar-Parisi-Zhang

Surface growth - 1986

$$\underbrace{\partial_t h(\vec{x},t) \;=\; \nu \nabla^2 h(\vec{x},t)}_{\text{Edwards}-\text{Wilkinson}} \underbrace{+\,\lambda(\vec{\nabla} h(\vec{x},t))^2}_{\text{KPZ}} \;+\; \underbrace{\xi(\vec{x},t)}_{\text{white noise}}$$

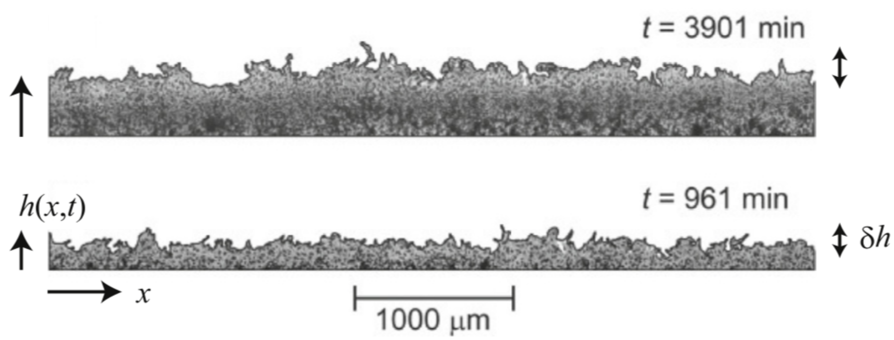


Kardar, Parisi & Zhang, *Dynamic Scaling of Growing Interfaces*, **PRL 56, 889 (1986)**

Square of the surface slope

non-linear equation

non-Gaussian statistics



(a) Proliferating cancer cells.

Mathematics

M. Hairer, Fields Medal 2014

Experiments Takeuchi, Physica A 504, 77 (2018)

IUPAP Young Scientist Award 2013

Array processor with emulator

APE: a computer for lattice QCD — since 1984

Università di Roma "La Sapienza"
Dipartimento di Fisica
Nota Interna n.839 del 13.12.1984

IFUP – TH 84/40

The APE project: a computer for lattice QCD

P. Bacilieri
INFN-CNAF, Bologna, Italy

N. Cabibbo, E. Marinari, G. Parisi
Dipartimento di Fisica, II Università di Roma "Tor Vergata"
INFN – Sezione di Roma, Roma, Italy

F. Costantini, G.Fiorentini, S.Galeotti, D.Passuello, R.Tripiccione
Dipartimento di Fisica, Università di Pisa
INFN – Sezione di Pisa, Pisa, Italy

A. Fucci, R. Petronzio, F. Rapuano
CERN, Geneva, Switzerland

F. Marzano, S. Petrarca, G. Salina
Dipartimento di Fisica, Università di Roma "La Sapienza"
INFN – Sezione di Roma, Roma, Italy

D. Pascoli
Dipartimento di Fisica, Università di Padova
INFN – Sezione di Padova, Padova, Italy

E. Remiddi
Dipartimento di Fisica, Università di Bologna
INFN – Sezione di Bologna, Bologna, Italy

Abstract

We propose to build a special computer for studying lattice QCD. Although it can be used as a general purpose array processor controlled by the 3081/E, the hardware is optimized for lattice QCD. The theoretical speed is 1 Giga-Flop and the memory can be expanded up to 0.5 Giga-byte.

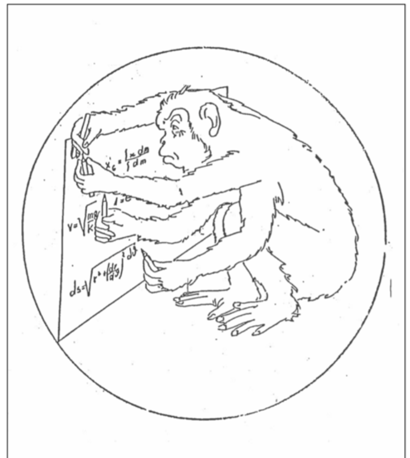


fig.0.0: A.P.E.: Schema Funzionale

A.P.E.: Functional Diagram

Ape Proposal

APE images & photos courtesy of Gaetano Salina

Array processor with emulator

APE: a computer for lattice QCD — since 1984

Enzo Marinari - Gaetano Salina - Nicola Cabibbo

Giorgio Parisi - G. Salina

APE images & photos courtesy of Gaetano Salina

More later on computer design: SUE-Janus collaboration for spin-glasses

Disordered Systems

Late 80s - early 90s in Rome

Daniel Amit   Miguel Virasoro   Giorgio Parisi

Neural Nets   Disordered Systems

Roma I   Roma II

My Roman times

1991 - 1994

My Roman times

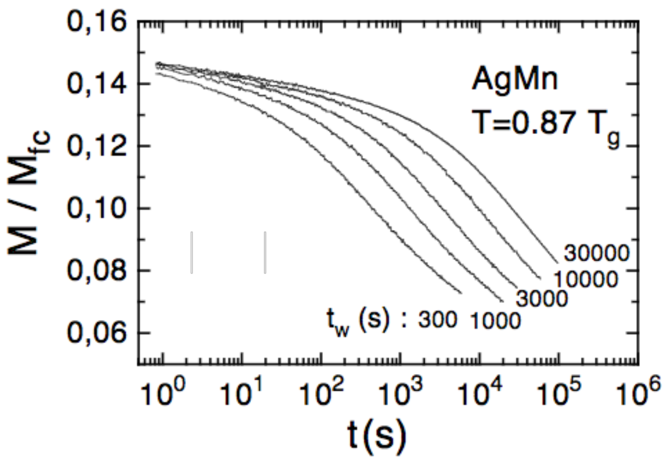
Out of equilibrium dynamics of spin glasses & glasses

$$\mathcal{H}_J[\{s_i\}] = - \sum_{i_1 \neq \dots \neq i_p} J_{i_1 \dots i_p} s_{i_1} \dots s_{i_p}$$

p-psin spherical model

random coupling exchanges drawn from $P[J_{i_1 \dots i_p}]$

Langevin dynamics (coupling to a bath) $\gamma \frac{ds_i}{dt} = -\frac{\delta \mathcal{H}}{\delta s_i} + \xi_i$



Analytic solution *vs.*

Experiments @ Uppsala, Saclay, UCLA

out of equilibrium relaxation

Aging effects & violations of FDT

LFC & Kurchan, *Analytic Solution of the Off-Equilibrium Dynamics of a Long-Range Spin-Glass Model*, PRL 71, 173 (1993)

My Roman times

La Sapienza

My Roman times

Laurea at Tor Vergata (after PhD)

REPUBBLICA ITALIANA
IN NOME DELLA LEGGE
Noi Professor Aldo Brancati
RETTORE DELL'UNIVERSITÀ DEGLI STUDI DI ROMA
TOR VERGATA
VEDUTI GLI ATTESTATI DEGLI STUDI COMPIUTI ED IL RISULTATO DELL'ESAME DI LAUREA
SUPERATO con lode IN QUESTA UNIVERSITÀ ADDÌ 10 Marzo 1995
ABBIAMO CONFERITO A
Leticia Fernanda Cugliandolo
nata a Mar del Plata (Argentina) addì 11 Febbraio 1965
LA LAUREA DI DOTTORE IN
Fisica
IL PRESENTE DIPLOMA VIENE RILASCIATO A TUTTI GLI EFFETTI DI LEGGE
DATO A ROMA IL 22 Aprile 1996 REG. 002 FGL. N. 154
IL RETTORE
IL DIRETTORE AMMINISTRATIVO
IL PRESIDE DELLA FACOLTÀ
№ 01768

Benzi & Parisi

J. Phys. I France **4** (1994) 1641–1656 NOVEMBER **1994**, PAGE 1641

Off equilibrium dynamics and aging in unfrustrated systems

L. F. Cugliandolo, J. Kurchan and G. Parisi

Dipartimento di Fisica, Università di Roma I, *La Sapienza*, I-00185 Roma, Italy
INFN Sezione di Roma I, Roma, Italy

(Received 21 June 1994, accepted 18 July 1994)

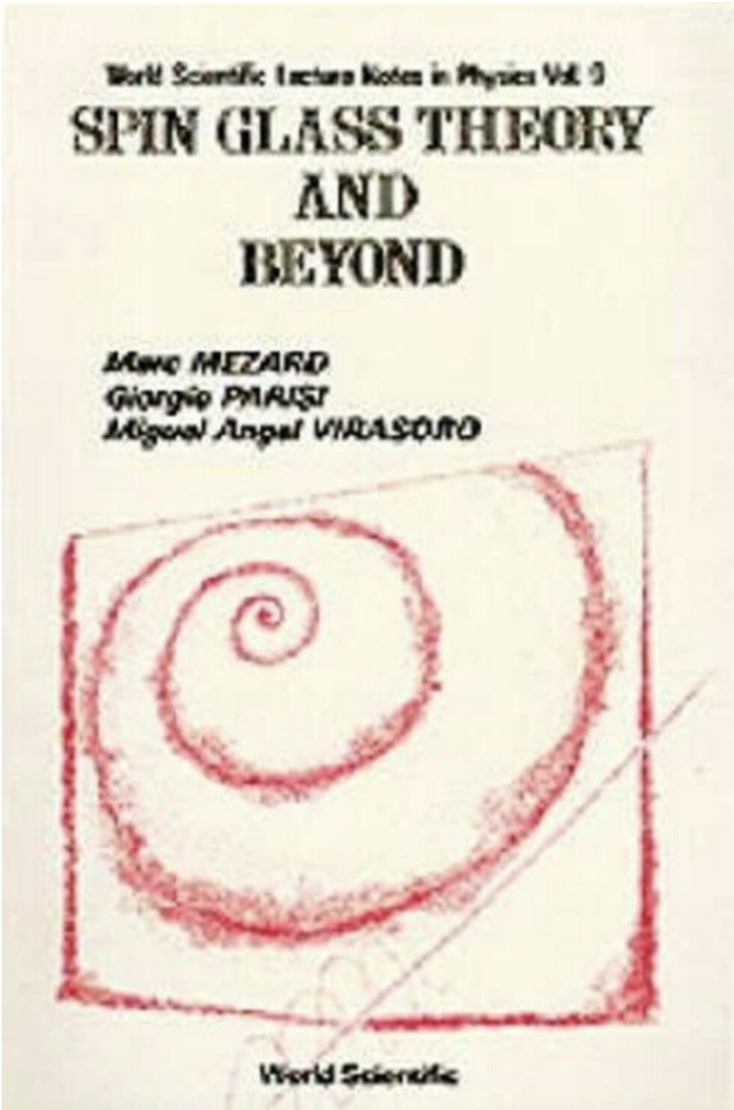
Abstract. — We analyse the Langevin dynamics of the random walk, the scalar field, the X-Y model and the spinoidal decomposition. We study the deviations from the equilibrium dynamics theorems (FDT and homogeneity), the asymptotic behaviour of the systems and the aging phenomena. We compare the results with the dynamical behaviour of (random) spin-glass mean-field models.

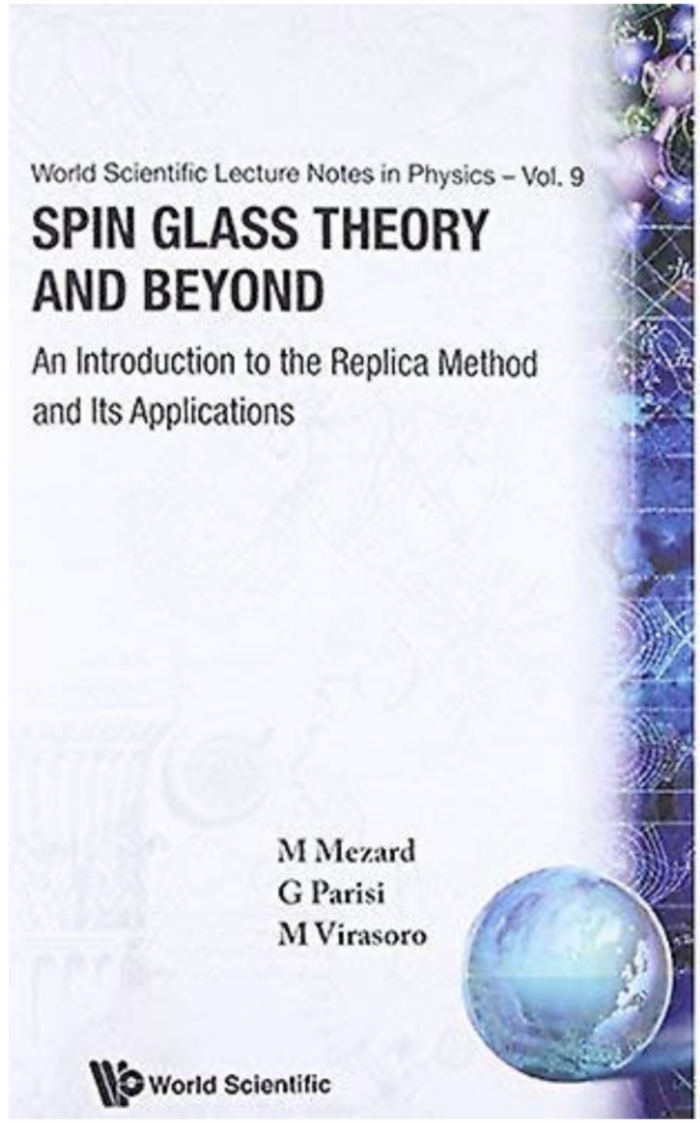
e.g. $\mathcal{H} = \int d^dx \left[\frac{1}{2}(\nabla\phi)^2 + \frac{r}{2}\phi^2\right]$

with $\gamma \frac{\partial\phi}{\partial t} = -\frac{\delta\mathcal{H}}{\delta\phi} + \xi$

Photo on the left Rosa Zaldivia (mamma)

The beyond


World Scientific Lecture Notes in Physics Vol. 9
SPIN GLASS THEORY AND BEYOND
Marc MEZARD
Giorgio PARISI
Miguel Angel VIRASORO
World Scientific


World Scientific Lecture Notes in Physics – Vol. 9
SPIN GLASS THEORY AND BEYOND
An Introduction to the Replica Method and Its Applications
M Mezard
G Parisi
M Virasoro
World Scientific

Attractor Neural Networks

Hopfield models

$$H = \sum_{i \neq j} J_{ij} s_i s_j \text{ (Hopfield 1982) with } J_{ij} = \frac{1}{M} \sum_{\mu=1}^{M} \xi_i^{(\mu)} \xi_j^{(\mu)} \text{ (Hebb 1949)}$$

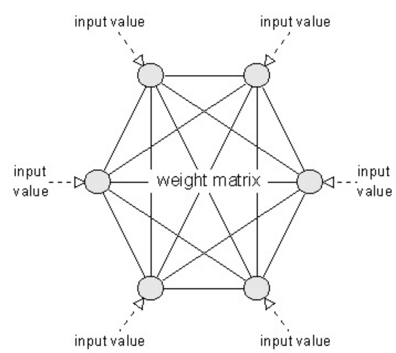
N neurons s_i and M patterns $\xi_i^{(\mu)}$ learnt

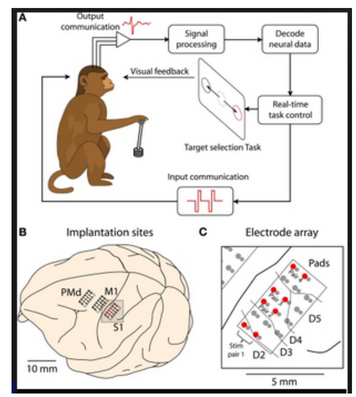
Neuron activity

$s_i = 1$ active $s_i = -1$ inactive

Symmetric couplings

Fully connected network





Replica Method used to find the maximal (storage) capacity $\alpha = M/N$

of such neural networks **Amit, Gutfreund & Sompolinsky**, PRL 55, 1530 (1985)

Physics & biology

42 Physics World September 1993

Physics began with the study of simple models that became more complicated as they became more realistic. Biology has followed the opposite path but the two disciplines are now converging in the study of complex systems

Statistical physics and biology

GIORGIO PARISI

The relationship between biology and physics has often been close and, at times, uneasy. During this century many physicists have moved to work in biology. Amongst the most famous are Francis

have a satisfactory formulation of the laws.

However, a knowledge of the laws that govern the behaviour of the constituent elements of the system does not necessarily imply an understanding of the

Parisi, Physics World 1993

Optimization problems

Constrained satisfaction problems

Problems involving variables which must satisfy some constraints

e.g. equalities, inequalities or both

studied in computer science to

compute their complexity or develop algorithms to most efficiently solve them

Typically, N variables, which have to satisfy M constraints.

e.g. the variables could be the weights of a neural network, and each constraint imposes that the network satisfies the correct input-output relation on one of M training examples (e.g. distinguishing images of cats from dogs).

Statistical physics approach

thermodynamic limit $N \to \infty$ and $M \to \infty$ with $\alpha = M/N$ finite

Optimization problems

K-Satisfiability

Hard to decide formulæ are made of M clauses involving k literals required to take the true value (x) or the false value ($\overline{x}$) each, these taken from a pool of N variables. An example in $k = 3$-SAT is

$$F = \begin{cases} C_1 & : \; x_1 \text{ OR } \overline{x}_2 \text{ OR } x_3 \\ C_2 & : \; \overline{x}_5 \text{ OR } \overline{x}_7 \text{ OR } x_9 \\ C_3 & : \; x_1 \text{ OR } \overline{x}_4 \text{ OR } x_7 \\ C_4 & : \; x_2 \text{ OR } \overline{x}_5 \text{ OR } x_8 \end{cases}$$

All clauses have to be satisfied simultaneously so the formula has to be read

$$\text{F} : C_1 \text{ AND } C_2 \text{ AND } C_3 \text{ AND } C_4$$

When $\alpha \equiv M/N \gg 1$ the problems typically become unsolvable while many solutions exist for $\alpha \ll 1$. A sharp **threshold** at α_c for $N, M \to \infty$

Random optisation problems

_e.g._, Random K-sat

Optimisation problems,

e.g. **random K-SAT**

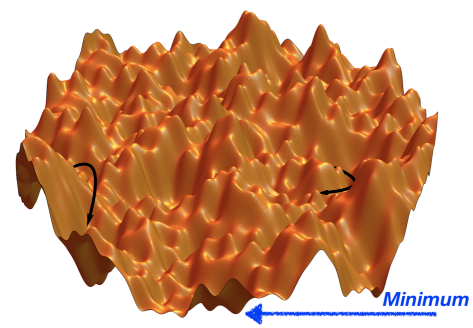
$$\text{Formula} = \wedge_{k=1}^{M} C_k(\{B_i\})$$

Boolean $B_i = 1, 0$ with $i = 1, \ldots, N$

Spin-glass on a random graph

Complex (free)energy - cost function

landscape



Disordered systems techniques (replicas, cavity methods) characterise these landscapes in great detail $\Rightarrow$ guidelines to develop

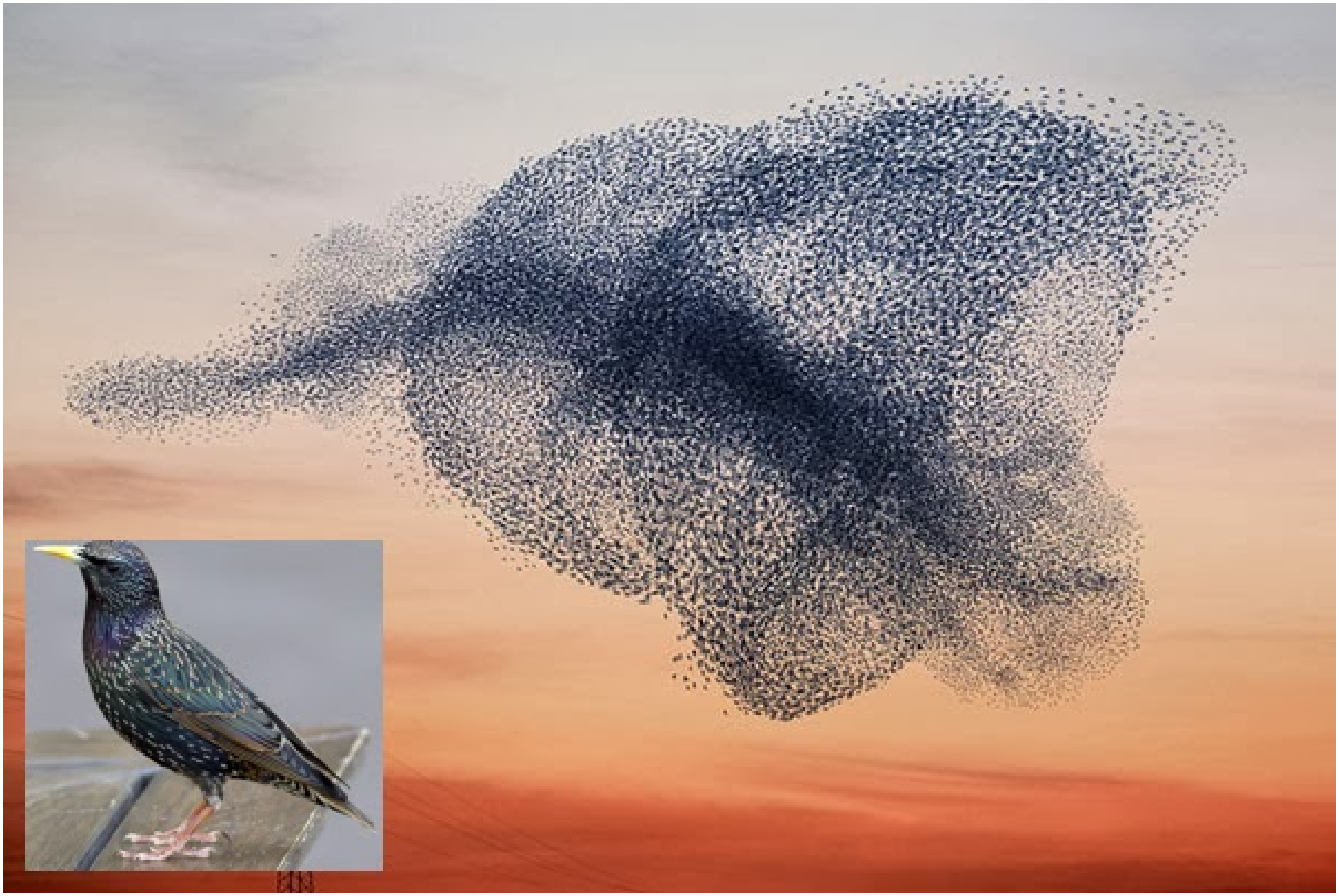
smart algorithms to solve F (**find minimum**) in hard phases (M/N control)

Mézard, Parisi & Zecchina, *Analytic and Algorithmic Solution of Random Satisfiability Problems*, Science 297, 812 (2002)

Onsager prize APS 2016

Animal behaviour

Collective motion of starlings



Animal behaviour

Observation and data collection in Rome

Reconstruction of the $3d$ positions of individual birds in airborne flocks of a few thousand members

Opened the way to unprecedented data analysis

e.g., proof that the **interaction depends on the topological distance**

Six-to-seven neighbour range

Importance for **cohesive reaction** against predators

Ballerini, Cabibbo, Candelier, Cavagna, Cisbani, Giardina, Lecomte, Orlandi, Parisi, Procaccini, Viale & Zdravkovic, *Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study*, PNAS 105, 1232 (2008)

The SUE & Janus collaborations

Special Purpose Computers for spin glass simulations - 2000

Roma - Ferrara (Italia) Badajoz - Madrid - Zaragoza (España)

Discrete spins & couplings

($Fe_{0.5}Mn_{0.5}TiO_3$)

Field Programmable Gate Arrays

$\sim 5 \times 10^5$ PCs

Monte Carlo Simulations

$3d$ **Edwards-Anderson Model**

Equilibration of $\sim 10^3 - 10^4$ samples

$L = 32$ down to $T \sim 0.65\, T_c$

Out of equilibrium $\sim 10^2$ samples

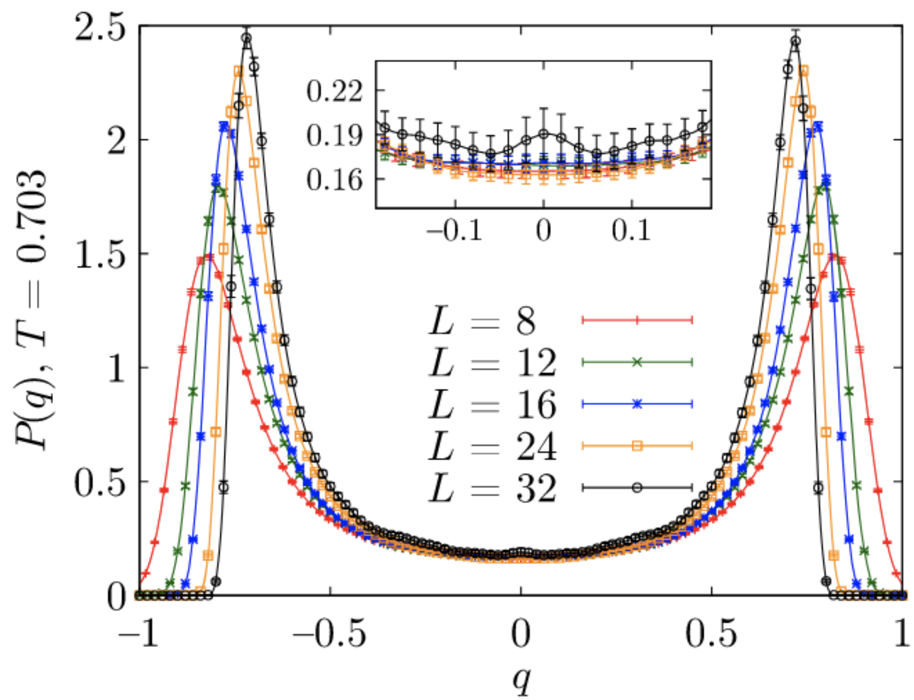
$L = 80,\ 10^{12}\,\mathrm{MCs} \sim 1s$

time-scales comparable to

experimental ones

The SUE & Janus collaborations

Three dimensional Edwards-Anderson model



Álvarez Baños *et al*, *Nature of the spin-glass phase at experimental length scales*

J. Stat. Mech. P06026 (2010)

& so much more

just in Statistical Physics

Stochastic Quantisation (with **Y-S Wu**)

Langevin equations & Supersymmetric Quantum Mechanics (with **N Sourlas**)

Multifractality (with **R Benzi, G Paladin & A Vulpiani**)

Random matrices for glasses (with **LFC, J Kurchan & F Ritort**)

Effective potential for random first order phase transitions (with **S Franz**)

Large d theory for glasses (with **J Kurchan, P-F Urbani, F Zamponi**)

etc

The school

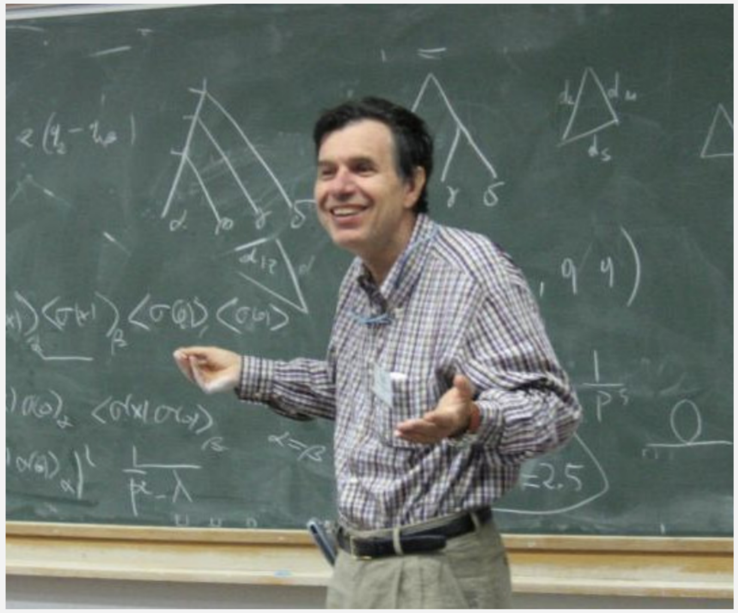
Map of co-authors ~ 300

The school

Map of co-authors

Responsabilities

Lecturer & scientific advisor* at Les Houches



NOBEL LAUREATE GIORGIO PARISI

Oct. 2021

Congratulations to Giorgio Parisi, the 2021 Physics Nobel Laureate who was a member of the board of Ecole de Physique and was in les Houches in 2013, 2020 and will be one of the speakers in May 2022 for the celebration of the 71th anniversary of the School of Physics.

From the Les Houches School website

***All my gratitude**

RSB40


ISTITUTO FISICO
GUGLIELMO MARCONI
FISICA
40 years of
Replica Symmetry Breaking
SIMONS
©MaurizioPerciballi2019

70th birthday

Juan Ruiz-Lorenzo LFC GP Miguel Virasoro Daniel Stariolo