

"Inference of coupling of waves in non linear disordered medium."

NETADIS

Statistical Physics Approaches
to
Networks Across Disciplines

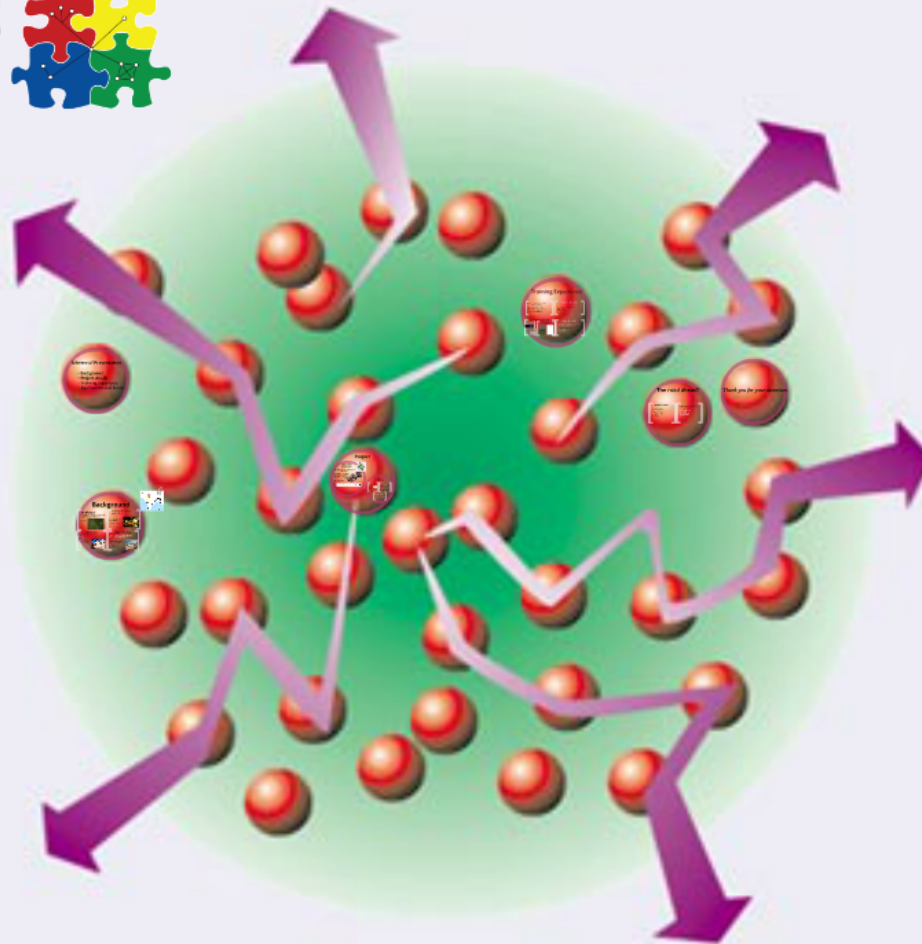


**MARIE CURIE
ACTIONS**



**SEVENTH FRAMEWORK
PROGRAMME**

**Supervisor :
Dr. Luca Leuzzi**



**SAPIENZA
UNIVERSITÀ DI ROMA**

**ESR :
Payal Tyagi**

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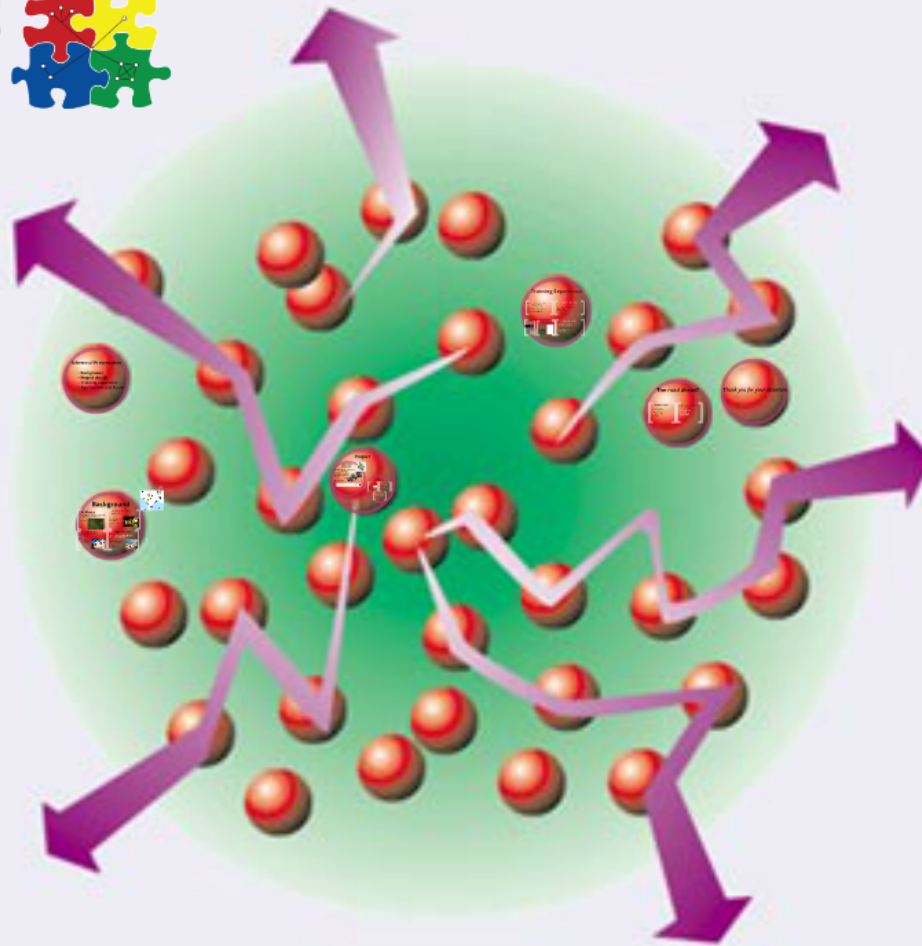
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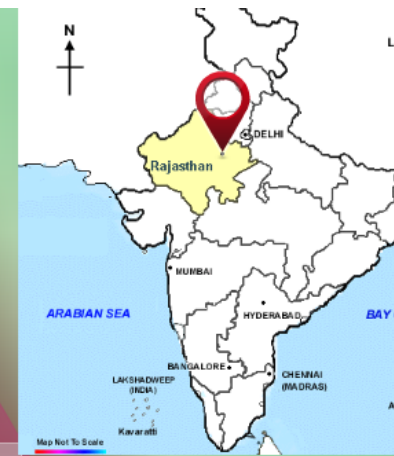


SAPIENZA
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ESR :
Payal Tyagi

Scheme of Presentation

- **Background**
- **Project details**
- **Training experience**
- **Applications and future**



Background

BS Physics

St. Stephen's College, University of Delhi, New Delhi, India

2007-10



Early Stage Researcher/ PhD student

IPCF-CNR/ Sapienza University, Rome

starting : Nov 2012



MSc Physics

Banasthali University, Rajasthan, India

2010-12

Focus : Condensed Matter Physics

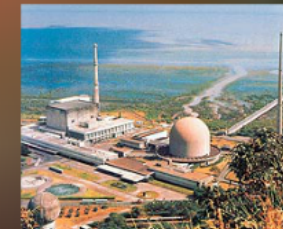


Project Trainee

" Crystal- chemical comparative study between naturally occurring shpene crystals."

Bhabha Atomic Research Centre(BARC), Mumbai, India

May-June 2011



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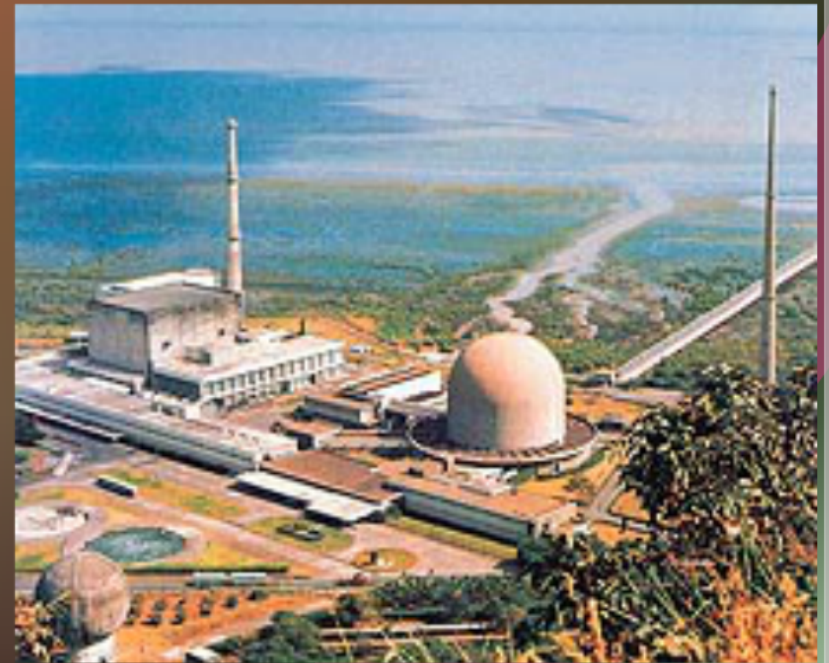


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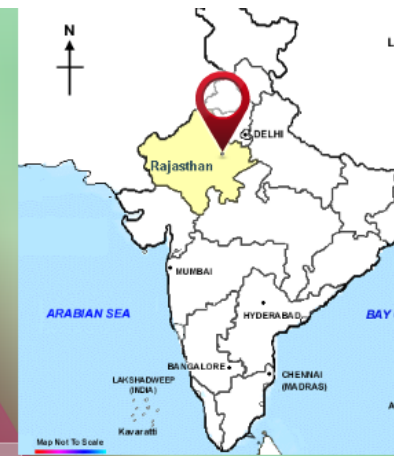


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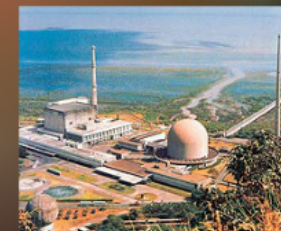


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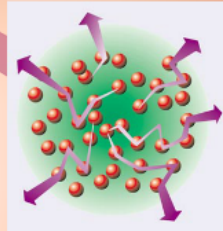
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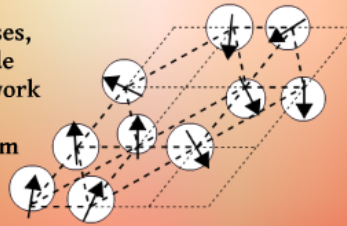


Project

System under consideration



- Statistical mechanics of disordered system
-->Random Laser
- Spins(continous) -> mode phases, mode amplitude
- Graph (various) -> modes network
- Non linear interaction -> laser medium



Generic Hamiltonian :

$$\mathcal{H} = -\Re \left[\sum_{j < k} G_{jk}^{(2)} a_j a_k^* + \sum_{\omega_j + \omega_k = \omega_l + \omega_m} G_{jklm}^{(4)} a_j a_k a_l^* a_m^* \right]$$

Details

Part 1

Various spin glass models:
- 2-SV and 0-SV model
- NKSAT model

Techniques:
- Cavity Method
- Self-Organization
- Population dynamics
using C++/ also python using
CUDA on GPUs

Expect:
- Characterize phase transitions
continuous
- random vs order phase transition/
discontinuous with phase coexistence
- Relationship between phase and frequency
- Various thermodynamic variables



Part 2

Statistical inference of interaction couplings

- No complete knowledge of modes (localization and interaction)
- couplings -> representative of spatial interaction or overlap among light modes
- Determine interaction couplings (J) using data of magnetisation & Correlation functions
- MC simulations and from experiments.
- MATLAB

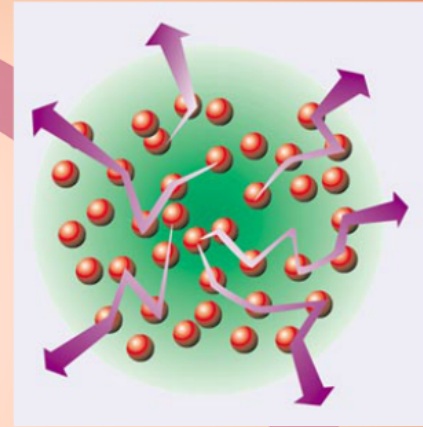
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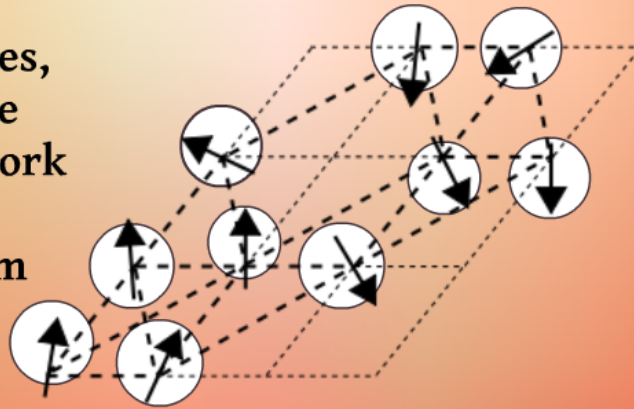
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- MC simulations on various generic graphs from short to long range
- Continuous variables -> CUDA programming on GPU -> effective implementation
- Data can be used for statistical inference until we have experimental data.

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Various spin glass model
2-XY and 4-XY model
4 - XORSAT model

Techniques :
• Cavity Method
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• Population dynamics using C/C++/ also optimization CUDA on GPU's

Expect :
• Characterize phase transition continuous/random 1st order phase discontinuous with p
• Relationship between
• Various thermodynamic

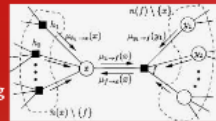
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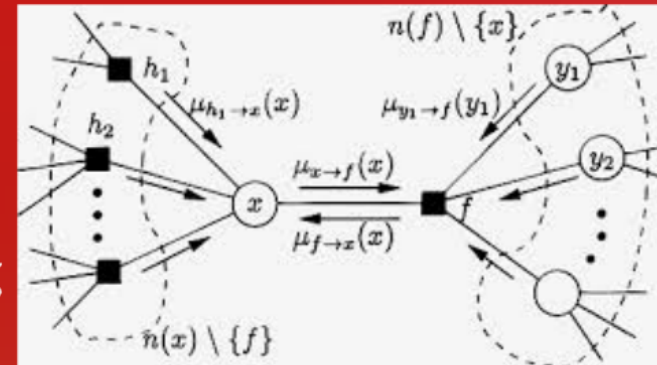
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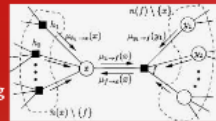
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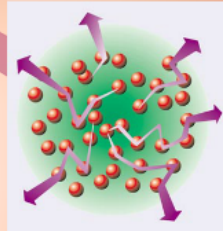
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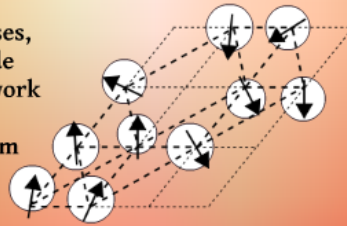
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Training Experience

Courses at Sapienza University, Roma

January 2013 - July 2013

- Theory and phenomenology of Structural Glass
- Random Graphs
- Spin Glass Theory
- Introduction to Information, physics and computation

Passed the required examinations and granted promotion to 2nd year of PhD physics at the university.

Communication skills

- Presentations, seminars and workshops
- Report writing
- Article writing
- Poster presentation

Advanced schools and training workshops

• Spring College on physics of complex systems,
20 May - 14 June 2013,
ICTP, Trieste, Italy



• Advanced Workshop on Nonlinear Photonics,
Disorder and Wave Turbulence,
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• Introduction to GPGPU and CUDA programming,
9-10 May 2013,
CINECA, Bologna

NETADIS summer school,
8 - 22 September 2013,
Hillerod, Denmark



Secondments

1) HuGeF Torino, 18 November - 20 December 2013

Dr. Andrea Pagnani, Prof. Riccardo Zecchina

"Statistical inference on XY model"

2) TU Berlin - 2014

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Investigating random laser through study of disordered systems.
 Papi Tigris and Luca Letteri
 ICTP-CNR, Dep. of Physics, University of Roma, P.le A. Moro 2, I-00185, Roma, Italy

<p>Abstract</p> <p>Disordered systems have been the subject of intense research in the last few years. In this paper we study the properties of random lasers in the presence of disorder. We consider a system of coupled oscillators and study the properties of the eigenvalues and eigenvectors of the system. We show that the system exhibits a transition from a localized state to a delocalized state as the disorder is increased. This transition is characterized by a change in the distribution of the eigenvalues and eigenvectors. We also study the properties of the system in the presence of disorder and show that the system exhibits a transition from a localized state to a delocalized state as the disorder is increased.</p>	<p>Fig. 1: Distribution of eigenvalues</p> <p>The distribution of eigenvalues is shown in the figure. The x-axis represents the real part of the eigenvalue and the y-axis represents the imaginary part. The distribution is shown for a system of coupled oscillators with disorder. The distribution is characterized by a transition from a localized state to a delocalized state as the disorder is increased.</p>	<p>Fig. 2: Distribution of eigenvectors</p> <p>The distribution of eigenvectors is shown in the figure. The x-axis represents the real part of the eigenvector and the y-axis represents the imaginary part. The distribution is shown for a system of coupled oscillators with disorder. The distribution is characterized by a transition from a localized state to a delocalized state as the disorder is increased.</p>
<p>Fig. 3: Distribution of eigenvalues</p> <p>The distribution of eigenvalues is shown in the figure. The x-axis represents the real part of the eigenvalue and the y-axis represents the imaginary part. The distribution is shown for a system of coupled oscillators with disorder. The distribution is characterized by a transition from a localized state to a delocalized state as the disorder is increased.</p>	<p>Fig. 4: Distribution of eigenvectors</p> <p>The distribution of eigenvectors is shown in the figure. The x-axis represents the real part of the eigenvector and the y-axis represents the imaginary part. The distribution is shown for a system of coupled oscillators with disorder. The distribution is characterized by a transition from a localized state to a delocalized state as the disorder is increased.</p>	<p>Fig. 5: Distribution of eigenvalues</p> <p>The distribution of eigenvalues is shown in the figure. The x-axis represents the real part of the eigenvalue and the y-axis represents the imaginary part. The distribution is shown for a system of coupled oscillators with disorder. The distribution is characterized by a transition from a localized state to a delocalized state as the disorder is increased.</p>

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Fig. 3: Random laser in a conventional laser

Starting from the Haus master equation for mode locking

laser is disordered cavity

So the Hamiltonian has a body invariant when the spin

mode amplitude:

Hence, the Hamiltonian with 2-body and 4-body terms is

where coupling has in both quadratures and modes

are required to satisfy the following mode locking condition

→ being the width of the peak in amplitude spectrum.



Objective

4 spin glass models with a continuous variables is a master field model for spin glass random optical systems or random lasers which has been studied in [22] under the framework of replica method. But we need to generalize the system since mode locking random system, disorder in the graph connectivity. In the previous case in fully connected system, all the modes are selected and showing at frequency ω_0 but in random laser when disorder occurs because of the mode locking condition. In this regard we need to study an equivalent system of 4 body spin glass model with continuous variables on a diluted or sparsely connected system.

Our task is to study coupling of modes in such a system using cavity method. To accomplish this task we first consider several studies already done in the regard on spin glasses.

- cavity method on spin glass system with firing variables in a fully connected model.
- XORSAT problem equivalent to spin glass system with firing spins studied on a diluted graph.
- spin glass with continuous variables on a diluted graph.
- XORSAT with continuous variables on a sparsely connected graph.

Investigating random laser through study of disordered systems.

Payal Tyagi and Luca Leuzzi

IPCF-CNR, Dep. of Physics, Sapienza University of Rome, Piazzale A. Moro 2, I-00185, Rome, Italy

Motivation

Step 1: firing spin fully connected graph

Cavity method on Boolean firing spin glass model in a fully connected system. Cavity method is used to solve a given random instance from the wide variety of ensembles of random graphs. It is in principle a formalism equivalent to replica method but comes out to have a much clear and more direct interpretation that enables us to solve for systems and find solutions of some problems which are difficult to understand from standpoint of replica method. It works on random graphs under the Debye approximation when cavity mode loops are rare and in the thermodynamic limit it can be considered as a loop where neighboring spins can be considered to be uncorrelated. If a spin is removed from the graph, free energy is needed. Free energy can be calculated using the free energy shifts due to removal or addition of a spin in the graph. Observables are calculated if we add the cavity spin back to graph and study for all the messages passed to this spin via belief propagation.

Hamiltonian:

The cavity field which is propagated along the tree

More precisely if spin i is removed and except one spin j

Free energy will have both site and bond contribution:

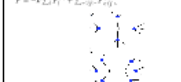


Fig. 2: site and bond contribution

The system can be solved by cavity method using population dynamics of the level equivalent to replica symmetry and replica symmetry breaking case where approximation for presence of lowered order states is considered. Here various observables like free energy, magnetization, order parameter are calculated.

Step 2: XORSAT firing spin diluted graph

XOR-SAT is a constraint satisfaction problem to solve a system of linear equations which involves finding a vector \mathcal{I} of boolean variables satisfying the linear equations $A\mathcal{I} = \mathcal{B}$ with A and \mathcal{B} $(N \times M)$ and \mathcal{I} $(M \times 1)$ resulting in Hamiltonian which tells us about the number of satisfied constraints.

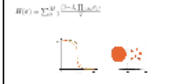


Fig. 3: XOR-SAT below percolation threshold SAT/UNSAT transition using fast SAT phase and complexity graph

Solutions for such a system can be obtained and it can be checked whether the system is SAT or UNSAT. Such a transition between SAT/UNSAT is not uniquely determined, the system is SAT i.e. system has solution or it has only one pure state. Ideally there are many ways in which the system can be solved. Using the fast formal algorithm to solve the system we find that there occurs a point when system is stuck and we are no more able to find a solution. We have seen several classes of solutions and the system is stuck in one of these classes and unable to reach other class of solutions and not able to traverse whole of the space of solutions, due to which complexity arises. Alternatively, such a system can be solved using cavity method.

Alternatively, such a system can be solved using cavity method under certain assumptions.

Step 3: continuous spin diluted graph

Finite connectivity is more realistic than fully connected and same argument applies for vector spins over firing spins. Dilutely connected connected spin sites investigated spin vector spins live on a sphere S^{N-1} with random matrix interaction.

all where σ_i are unitary matrices representing rotations in S^2 which will draw randomly and independently from random matrix ensemble $P(\sigma)$ and $P(\sigma') = P(\sigma)$ and $\langle \sigma_i \sigma_j \rangle$ is the cavity potential.

and having quenched disorder with:

where $\mathcal{Z}^2(\sigma)$ is $\int \prod_{\alpha} \delta(\sigma_{\alpha} - \sigma_{\alpha}')$

where this partition function can be used to find free energy which takes both site and bond contribution as in previous case. Working in the one parameter approximation phase transition can be found using replica analysis on a suitable graph like Erdos-Renyi graph. Writing the above partition function for cavity potential, Hamiltonian $\mathcal{H}(\sigma)$ and defining order parameter to be length of distribution

Order parameter is a functional and hence functional moment expansion is required to find phase transitions. Population dynamics in this case requires finding functional which is numerically challenging to perform. Also, numerical simulations requires to generate suitable random instances.

For XY spins $\sigma = (\cos \theta, \sin \theta)$ with $\theta \in [0, 2\pi)$. Probability distribution $P(\sigma)$ can be parameterized both angle θ and so the rotations in the plane. Hence, we can write similar equation for order parameter and solve for it.

The basic Hamiltonian of N dimensional angular variables σ_i is given by:

where $\sigma_i = (\cos \theta_i, \sin \theta_i)$ is the state of the spin for our investigation. We solve for the ground state XOR-SAT problem corresponding state of the set for the quadrants on a sparsely connected graph in order to investigate coupling of modes in a random laser module. In a first system of equations with 4 non vanishing solutions in each row and with quadruple coupling possible Hamiltonian might be:

where quadruple coupling $\langle \sigma_i \sigma_j \sigma_k \sigma_l \rangle$ is given name as in the first equation.

References

- [1] Introduction physics and computation by Marc Mezard and Andrea Montanari, Oxford University Press, 2009.
- [2] G. Candolfi, L. Leuzzi, Phys. Rev. B, 84, 134404(2011).
- [3] M. Mezard and G. Parisi, Phys. Rev. Lett., 76, 217-220(1996).
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<p>Abstract</p> <p>Disorder is a key feature of many physical systems. In this paper, we study the properties of random lasers, which are disordered systems that emit light in a random direction. We discuss the theory of random lasers and the experimental setup used to study them. We also present our results on the properties of random lasers and the implications for the theory of disordered systems.</p>	<p>Key 1: random laser</p> <p>The study of random lasers is a topic that has attracted much attention in the last few years. In this paper, we discuss the theory of random lasers and the experimental setup used to study them. We also present our results on the properties of random lasers and the implications for the theory of disordered systems.</p>	<p>Key 2: disordered systems</p> <p>Disordered systems are systems that lack long-range order. In this paper, we study the properties of disordered systems and the implications for the theory of disordered systems. We also present our results on the properties of disordered systems and the implications for the theory of disordered systems.</p>
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Fig. 1: Random laser

Fig. 2: Disordered system

Fig. 3: Random laser

Fig. 4: Disordered system

Fig. 5: Random laser

Fig. 6: Disordered system

Fig. 7: Random laser

Fig. 8: Disordered system

Fig. 9: Random laser

Fig. 10: Disordered system

Fig. 11: Random laser

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Fig. 98: Disordered system

Fig. 99: Random laser

Fig. 100: Disordered system

Secondments

1) HuGeF Torino, 18 November - 20 December 2013

Dr. Andrea Pagnani, Prof. Riccardo Zecchina

"Statistical inference on XY model"

2) TU Berlin - 2014

Communication skills

- **Presentations, seminars and workshops**
- **Report writing**
- **Article writing**
- **Poster presentation**

Training Experience

Courses at Sapienza University, Roma

January 2013 - July 2013

- Theory and phenomenology of Structural Glass
- Random Graphs
- Spin Glass Theory
- Introduction to Information, physics and computation

Passed the required examinations and granted promotion to 2nd year of PhD physics at the university.

Communication skills

- Presentations, seminars and workshops
- Report writing
- Article writing
- Poster presentation

Advanced schools and training workshops

• Spring College on physics of complex systems,
20 May - 14 June 2013,
ICTP, Trieste, Italy



• Advanced Workshop on Nonlinear Photonics,
Disorder and Wave Turbulence,
15-19 July 2013,
ICTP, Trieste, Italy



• Introduction to GPGPU and CUDA programming,
9-10 May 2013,
CINECA, Bologna

NETADIS summer school,
8 - 22 September 2013,
Hillerod, Denmark



Secondments

1) HuGeF Torino, 18 November - 20 December 2013

Dr. Andrea Pagnani, Prof. Riccardo Zecchina

"Statistical inference on XY model"

2) TU Berlin - 2014

The road ahead!

Applications of RL

- speckle free imaging
- cryptography
- medical diagnostic
- biomedical imaging
- laser paints

Future possible fields

- GPU computing
- Photonics
- Experimental laser
- Neuroscience
- Biophysics

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Thank you for your attention.

"Inference of coupling of waves in non linear disordered medium."

NETADIS

Statistical Physics Approaches
to
Networks Across Disciplines



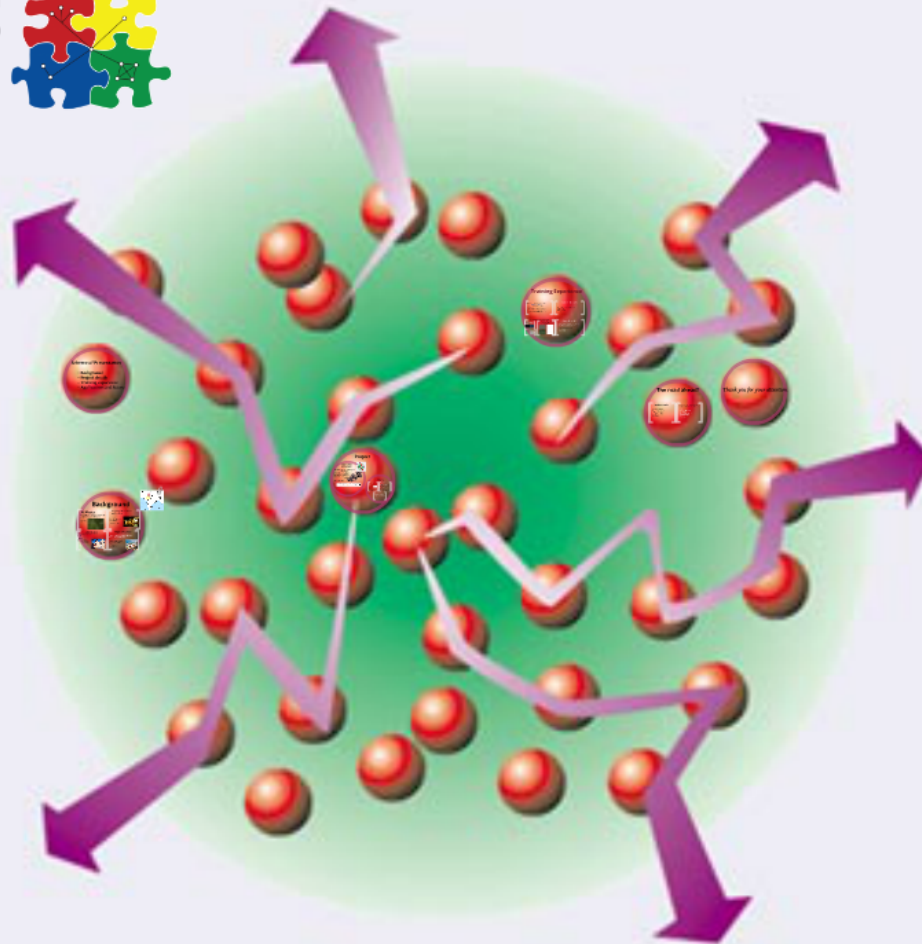
MARIE CURIE

ACTIONS



SEVENTH FRAMEWORK
PROGRAMME

Supervisor :
Dr. Luca Leuzzi



Consiglio
Nazionale delle
Ricerche



SAPIENZA
UNIVERSITÀ DI ROMA

ESR :
Payal Tyagi