ORIGINS

E.P. Wigner, Conference on Neutron Physics by Time of Flight, November 1956

P.W. Anderson, "*Absence of Diffusion in Certain Random Lattices*"; Phys.Rev., 1958, v.109, p.1492

L.D. Landau, "*Fermi-Liquid Theory*" Zh. Exp. Teor. Fiz., 1956, v.30, p.1058

J. Bardeen, L.N. Cooper & J. Schriffer, "*Theory of Superconductivity*"; Phys.Rev., 1957, v.108, p.1175.

Noncrossing rule (theorem) $P\left(s=0\right)=0$

Suggested by Hund (*Hund F. 1927 Phys. v.40, p.742*)

Justified by von Neumann & Wigner (*v. Neumann J. & Wigner E. 1929 Phys. Zeit. v.30, p.467*) . . . . .

Usually textbooks present a simplified version of the justification due to Teller (*Teller E., 1937 J. Phys. Chem 41 109).*

Arnold V. I., 1972 Funct. Anal. Appl.v. 6, p.94

Mathematical Methods of Classical Mechanics (Springer-Verlag: New York), Appendix 10, 1989

Arnold V.I., Mathematical Methods of Classical Mechanics (Springer-Verlag: New York), Appendix 10, 1989

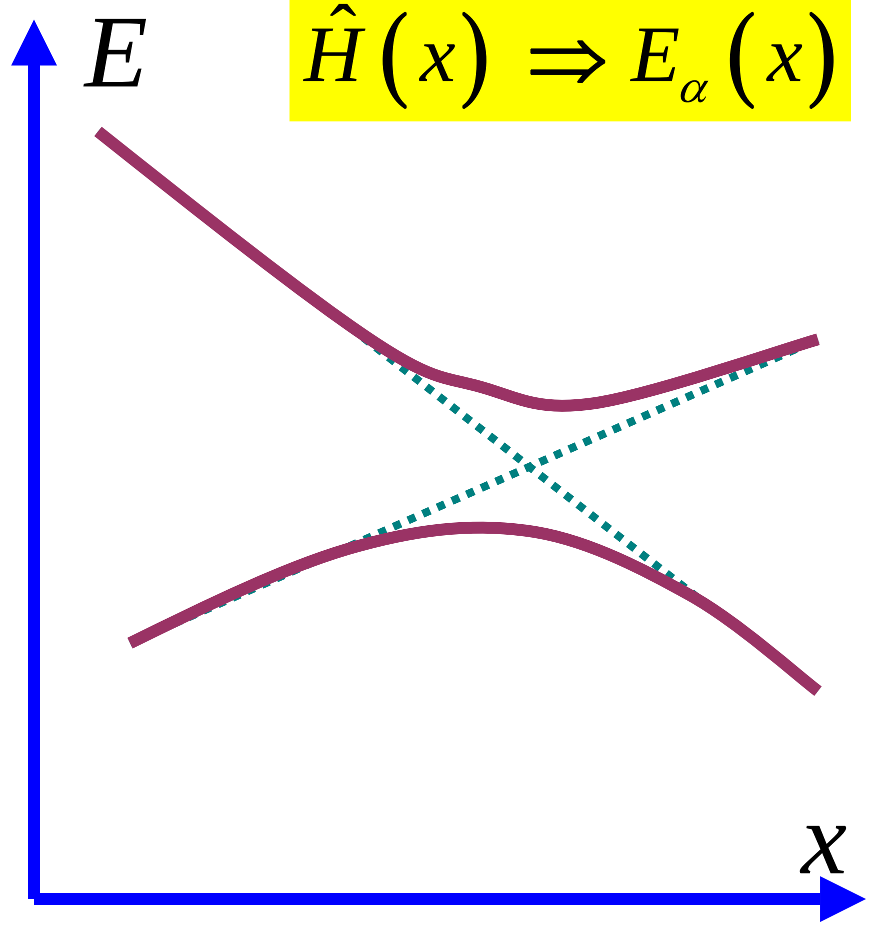
In general, a multiple spectrum in typical families of quadratic forms is observed only for two or more parameters, while in one-parameter families of general form the spectrum is simple for all values of the parameter. Under a change of parameter in the typical one-parameter family the eigenvalues can approach closely, but when they are sufficiently close, it is as if they begin to repel one another. The eigenvalues again diverge, disappointing the person who hoped, by changing the parameter to achieve a multiple spectrum.

$$\hat{H}(x) \Rightarrow E_\alpha(x)$$

Arnold V.I., Mathematical Methods of Classical Mechanics (Springer-Verlag: New York), Appendix 10, 1989

In general, a multiple spectrum in typical families of quadratic forms is observed only for two or more parameters, while in one-parameter families of general form the spectrum is simple for all values of the parameter. Under a change of parameter in the typical one-parameter family the eigenvalues can approach closely, but when they are sufficiently close, it is as if they begin to repel one another. The eigenvalues again diverge, disappointing the person who hoped, by changing the parameter to achieve a multiple spectrum.

$$\hat{H}(x) \Rightarrow E_{\alpha}(x)$$

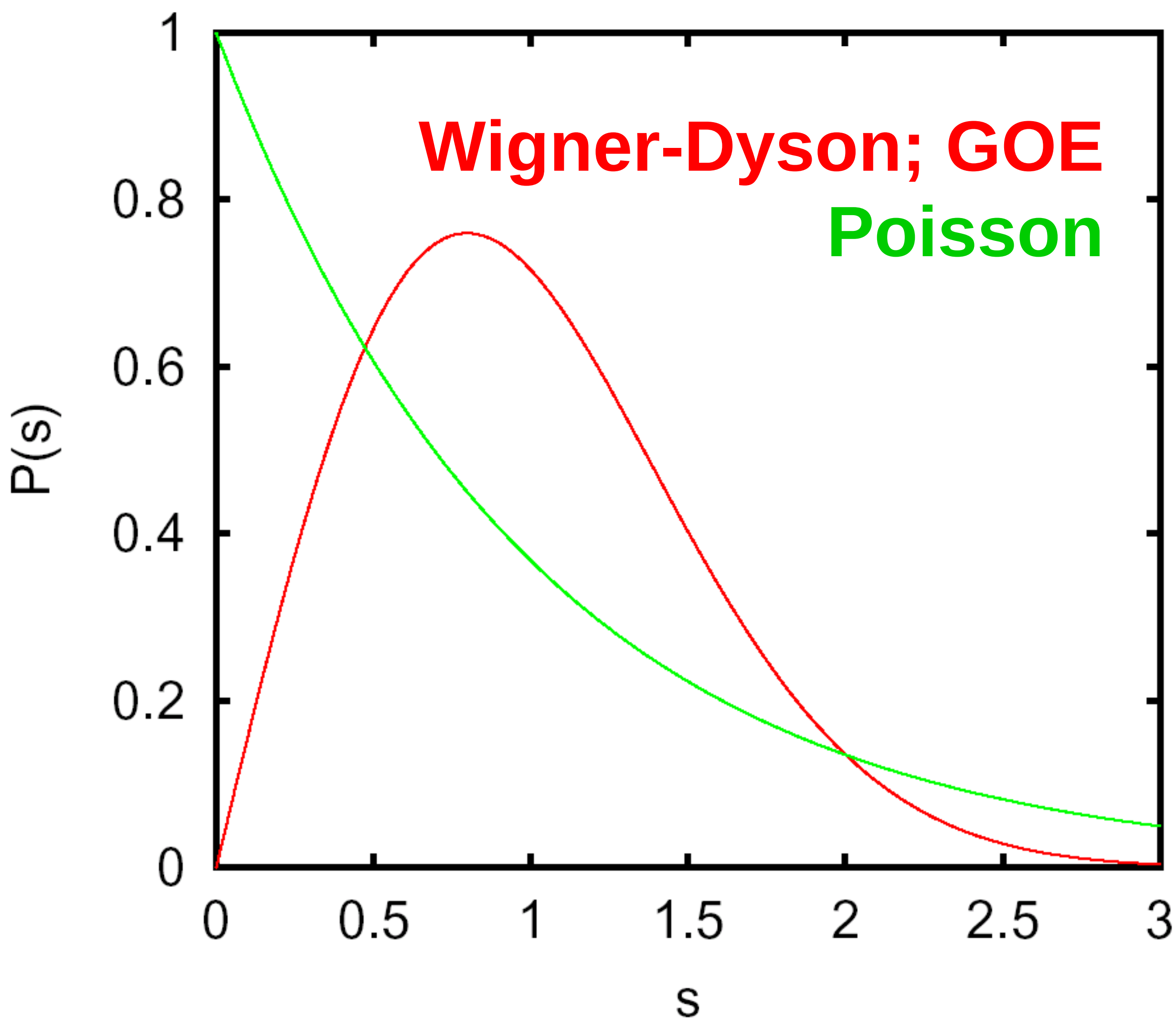


RANDOM MATRICES

$N \times N$ matrices with random matrix elements. $N \rightarrow \infty$

Dyson Ensembles

Matrix elements	Ensemble	β	realization
real	orthogonal	1	T-inv potential
complex	unitary	2	broken T-invariance (e.g., by magnetic field)
2×2 matrices	simplectic	4	T-inv, but with spin-orbital coupling

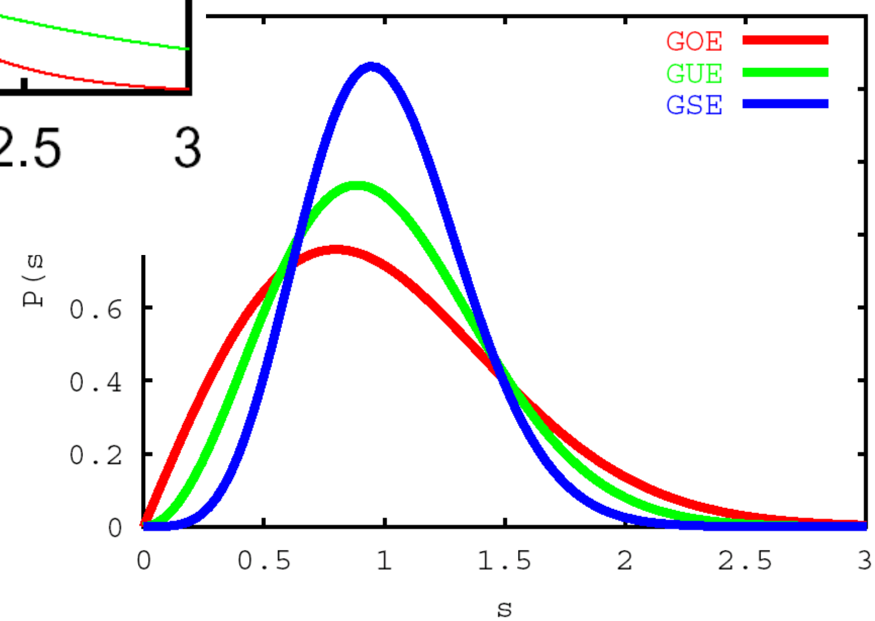


Gaussian
Orthogonal
Ensemble

Orthogonal
$\beta=1$

Unitary
$\beta=2$

Simplectic
$\beta=4$



Poisson – completely uncorrelated levels

ATOMS

Main goal is to classify the eigenstates in terms of the quantum numbers

NUCLEI

For the nuclear excitations this program does not work

E.P. Wigner:

Study spectral **statistics** of a **particular** quantum system – a given nucleus

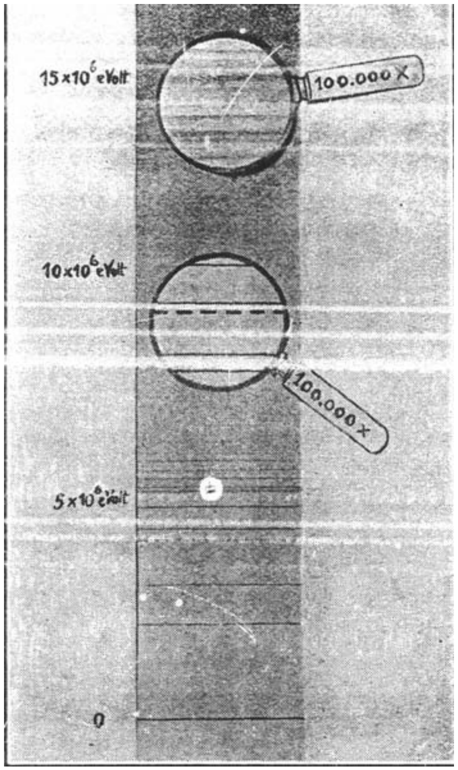
ATOMS Main goal is to classify the eigenstates in terms of the quantum numbers

NUCLEI For the nuclear excitations this program does not work

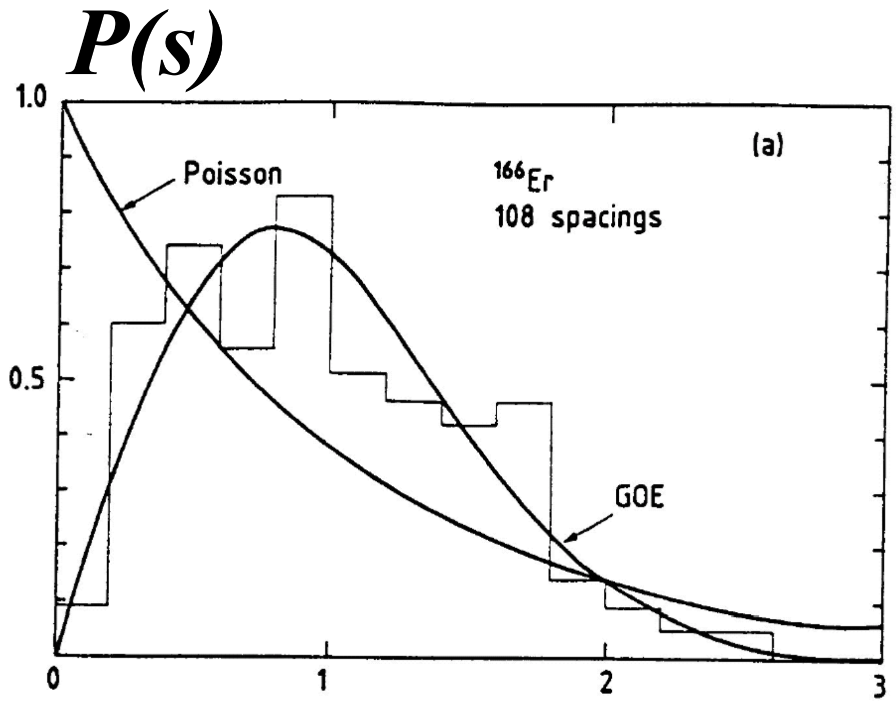
E.P. Wigner: Study spectral **statistics** of a **particular** quantum system – a given nucleus

Random Matrices	Atomic Nuclei
• *Ensemble*	• ***Particular quantum system***
• *Ensemble averaging*	• ***Spectral averaging (over α)***

Nevertheless Statistics of the nuclear spectra are almost exactly the same as the Random Matrix Statistics

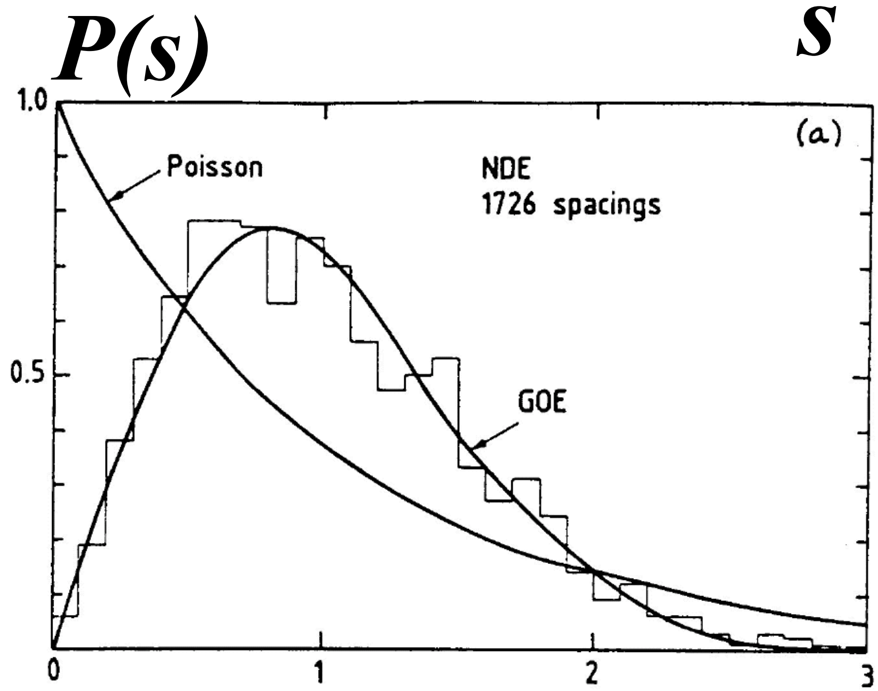


N. Bohr, Nature 137 (1936) 344.



Particular nucleus

^{166}Er



Spectra of several nuclei combined (after spacing) rescaling by the mean level

Q: *Why the random matrix theory (RMT) works so well for nuclear spectra* ?

Original answer:

These are systems with a large number of degrees of freedom, and therefore the “complexity” is high

Q: *Why the random matrix theory (RMT) works so well for nuclear spectra* ?

Original answer: *These are systems with a large number of degrees of freedom, and therefore the "complexity" is high*

Later it became clear that *there exist very "simple" systems with as many as 2 degrees of freedom* (d=2), *which demonstrate RMT - like spectral statistics*

Classical Dynamical Systems with d degrees of freedom

Integrable Systems

The variables can be separated and the problem reduces to d one-dimensional problems

⇒ d integrals of motion

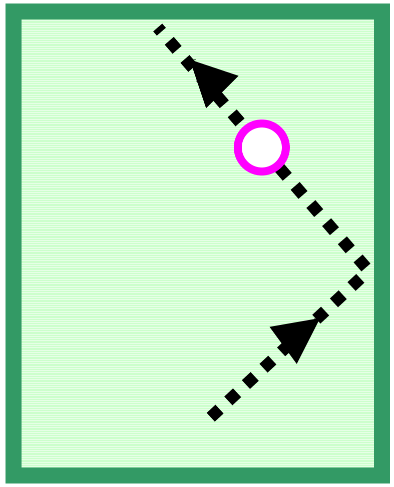
Classical ($\hbar$ =0) Dynamical Systems with d degrees of freedom

Integrable Systems

The variables can be separated and the problem reduces to d one-dimensional problems ⇒ d integrals of motion

Examples

1. A ball inside rectangular billiard; $d=2$



- Vertical motion can be separated from the horizontal one
- Vertical and horizontal components of the momentum, are both integrals of motion

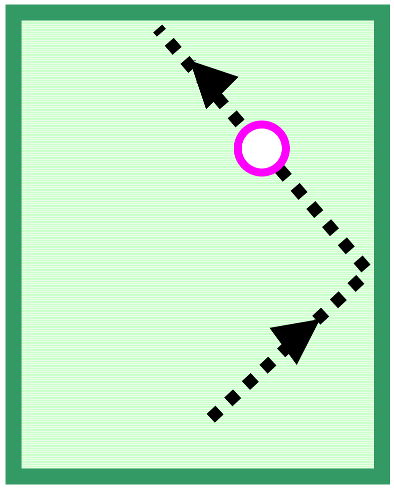
Classical ($\hbar$ =0) Dynamical Systems with *d* degrees of freedom

Integrable Systems

The variables can be separated and the problem reduces to *d* one-dimensional problems → *d* integrals of motion

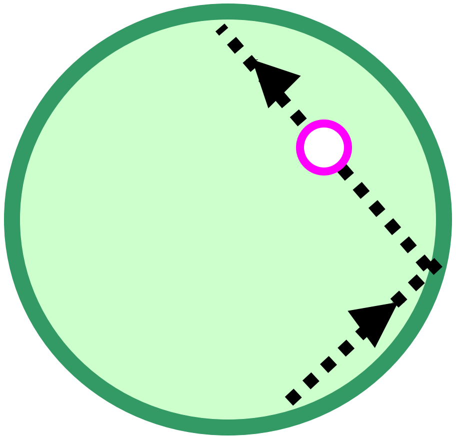
Examples

1. A ball inside rectangular billiard; $d=2$



- Vertical motion can be separated from the horizontal one
- Vertical and horizontal components of the momentum, are both integrals of motion

2. Circular billiard; $d=2$



- Radial motion can be separated from the angular one
- Angular momentum and energy are the integrals of motion

Classical Dynamical Systems with d degrees of freedom

Integrable Systems

The variables can be separated ⇨ d one-dimensional problems ⇨ d integrals of motion

Rectangular and circular billiard, Kepler problem, . . . ,
1d Hubbard model and other exactly solvable models, . .

Classical Dynamical Systems with d degrees of freedom

Integrable Systems

The variables can be separated ⇨ d one-dimensional problems ⇨ d integrals of motion

Rectangular and circular billiard, Kepler problem, . . . ,
1d Hubbard model and other exactly solvable models, . .

Chaotic Systems

The variables can not be separated ⇨ there is only one integral of motion - energy

Classical Dynamical Systems with d degrees of freedom

Integrable Systems

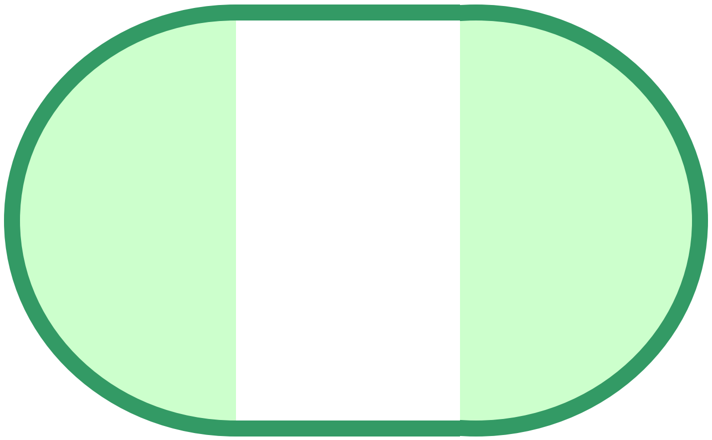
The variables can be separated ⇨ d one-dimensional problems ⇨ d integrals of motion

Rectangular and circular billiard, Kepler problem, . . . ,
1d Hubbard model and other exactly solvable models, . .

Chaotic Systems

The variables can not be separated ⇨ there is only one integral of motion - energy

Examples



Classical Dynamical Systems with *d* degrees of freedom

Integrable Systems

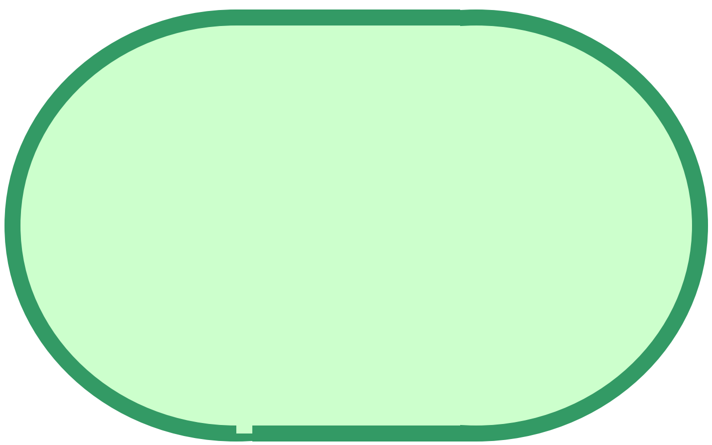
The variables can be separated ⇨ *d* one-dimensional problems ⇨ *d* integrals of motion

Rectangular and circular billiard, Kepler problem, . . . ,
1d Hubbard model and other exactly solvable models, . .

Chaotic Systems

The variables can not be separated ⇨ there is only one integral of motion - energy

Examples



Stadium

Classical Dynamical Systems with *d* degrees of freedom

Integrable Systems

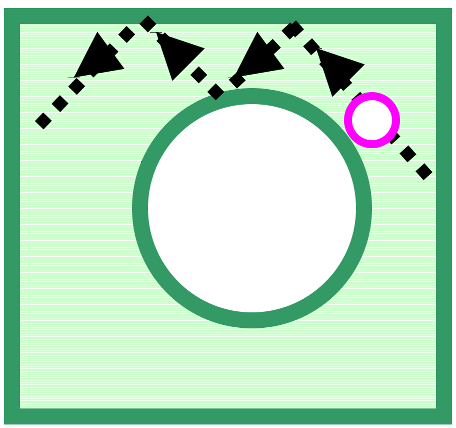
The variables can be separated ⇨ *d* one-dimensional problems ⇨ *d* integrals of motion

Rectangular and circular billiard, Kepler problem, . . . , 1d Hubbard model and other exactly solvable models, . .

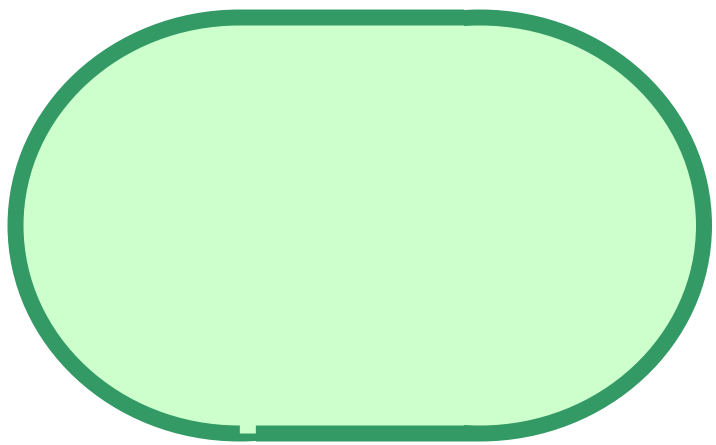
Chaotic Systems

The variables can not be separated ⇨ there is only one integral of motion - energy

Examples



Sinai billiard



Stadium

Classical Dynamical Systems with d degrees of freedom

Integrable Systems

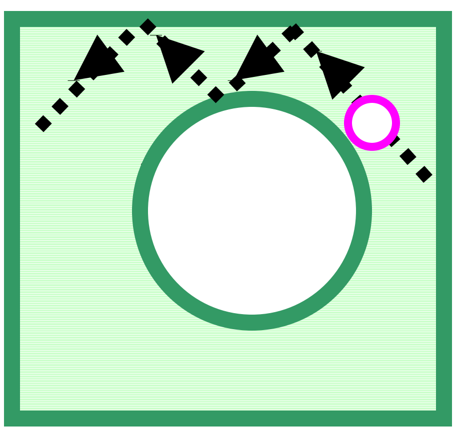
The variables can be separated ⇨ d one-dimensional problems ⇨ d integrals of motion

Rectangular and circular billiard, Kepler problem, . . . , 1d Hubbard model and other exactly solvable models, . .

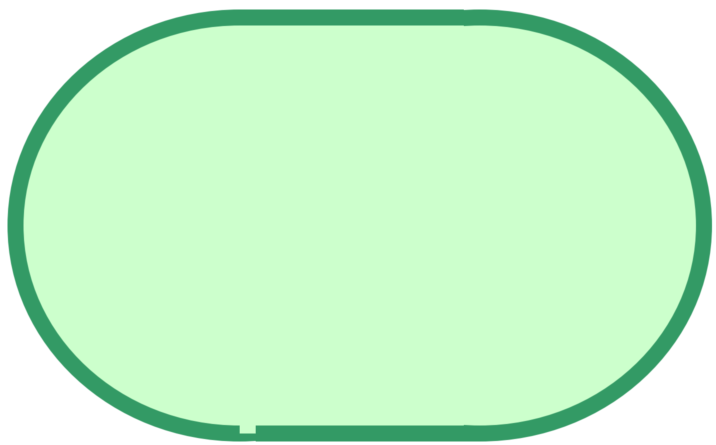
Chaotic Systems

The variables can not be separated ⇨ there is only one integral of motion - energy

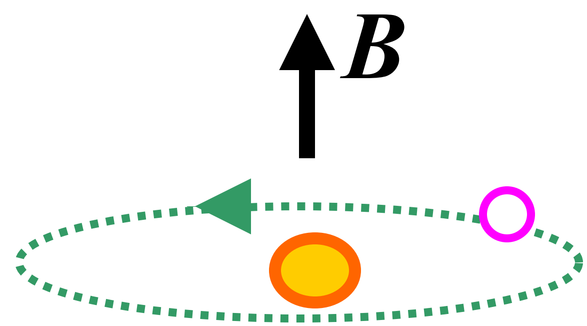
Examples



Sinai billiard



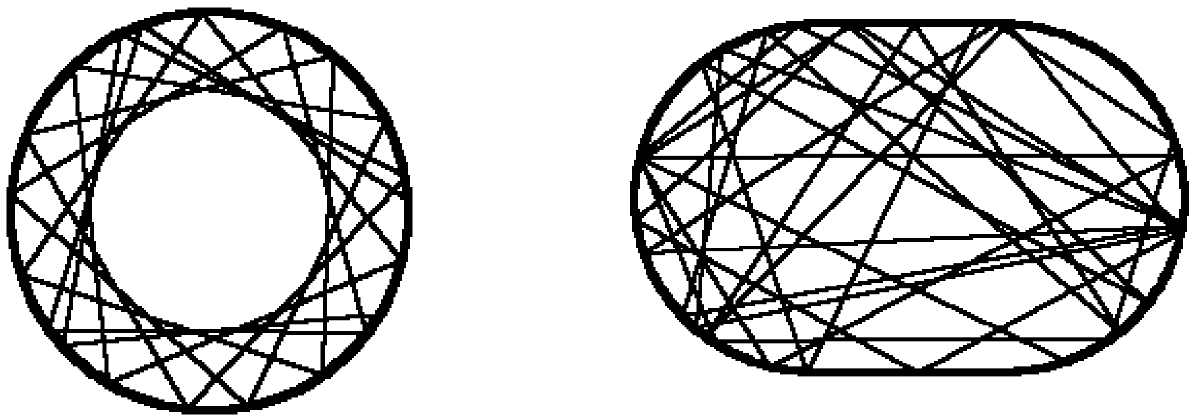
Stadium



Kepler problem in magnetic field

Classical Chaos
$\hbar = 0$

- *Nonlinearities*
- *Exponential dependence on the original conditions (Lyapunov exponents)*
- *Ergodicity*



Quantum description of any System with a finite number of the degrees of freedom is a linear problem – Shrodinger equation

Q: What does it mean Quantum Chaos ?

$\hbar \neq 0$ Bohigas – Giannoni – Schmit conjecture

VOLUME 52 2 JANUARY 1984 NUMBER 1

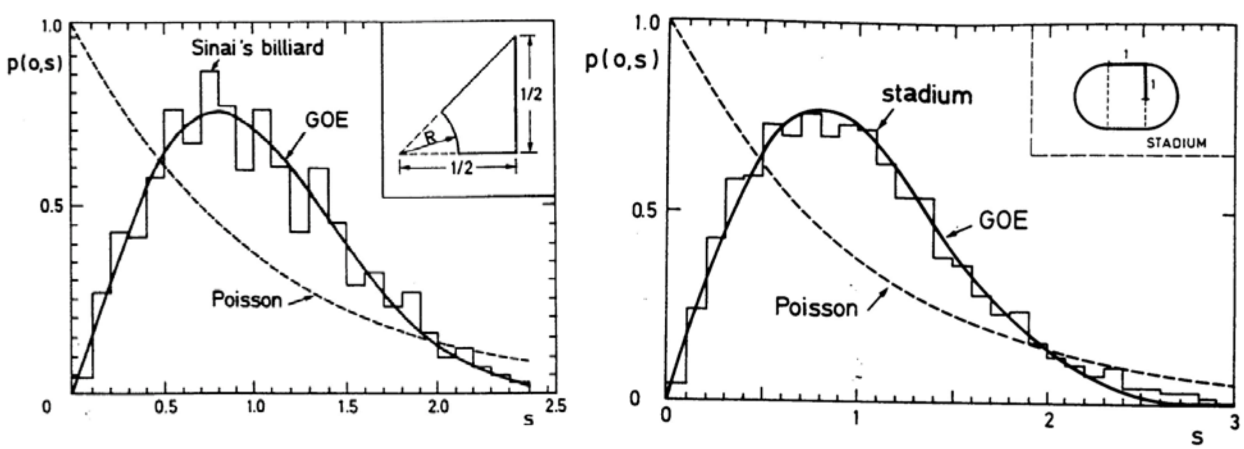
Characterization of Chaotic Quantum Spectra and Universality of Level Fluctuation Laws

O. Bohigas, M. J. Giannoni, and C. Schmit
Division de Physique Théorique, Institut de Physique Nucléaire, F-91406 Orsay Cedex, France

(Received 2 August 1983)

It is found that the level fluctuations of the quantum Sinai's billiard are consistent with the predictions of the Gaussian orthogonal ensemble of random matrices. This reinforces the belief that level fluctuation laws are universal.

In summary, the question at issue is to prove or disprove the following conjecture: Spectra of time-reversal-invariant systems whose classical analogs are K systems show the same fluctuation properties as predicted by GOE



Chaotic classical analog

Wigner- Dyson spectral statistics

No quantum numbers except energy

Q: What does it mean Quantum Chaos ?

Two possible definitions

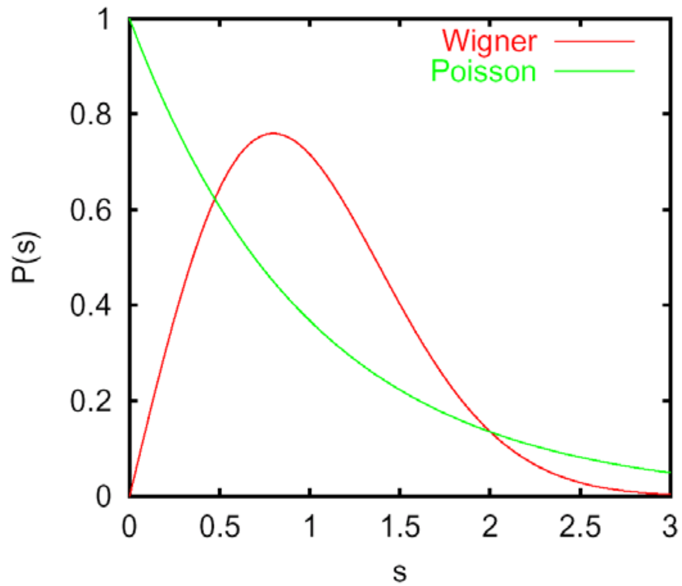
Chaotic classical analog

Wigner - Dyson-like spectrum

Classical Quantum

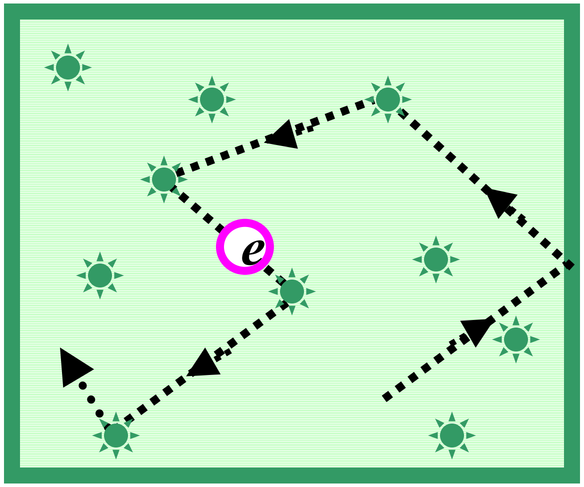
Integrable ? ⟺ Poisson

Chaotic ? ⟺ Wigner-Dyson



Poisson to Wigner-Dyson crossover

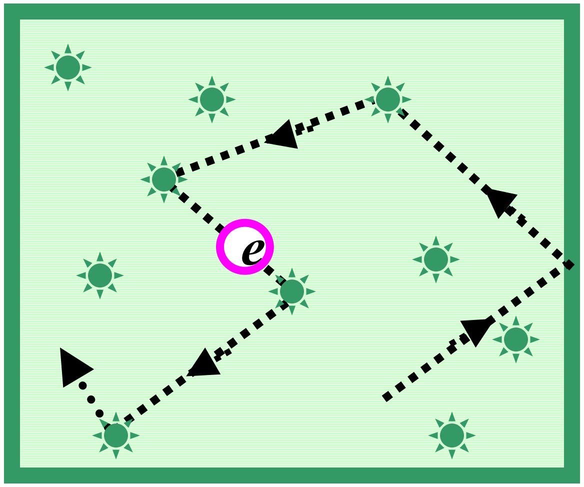
Important example: quantum particle subject to a random potential – disordered conductor



- Scattering centers, e.g., impurities

Poisson to Wigner-Dyson crossover

Important example: quantum particle subject to a random potential – disordered conductor



Scattering centers, e.g., impurities

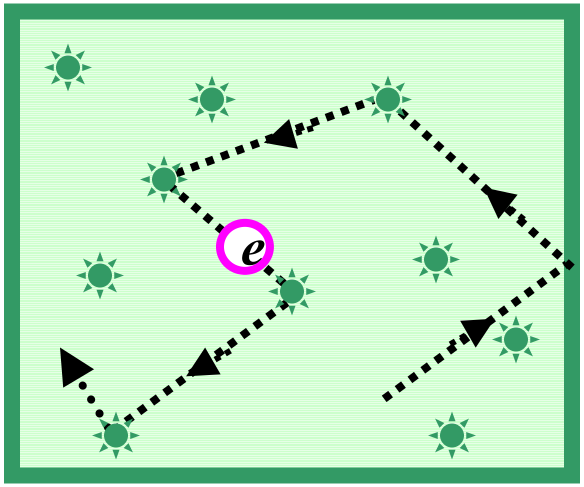
- As well as in the case of Random Matrices (RM) there is a luxury of ensemble averaging.
- The problem is much richer than RM theory
- There is still a lot of universality.

Anderson localization (1958)

At strong enough disorder all eigenstates are localized in space

Poisson to Wigner-Dyson crossover

Important example: quantum particle subject to a random potential – disordered conductor



✷ *Scattering centers, e.g., impurities*

Models of disorder:

Randomly located impurities

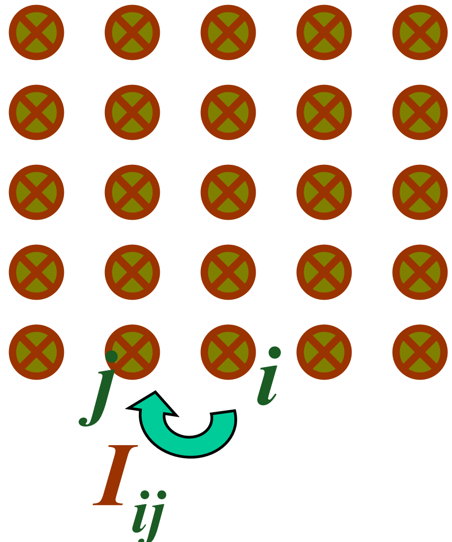
White noise potential

Lattice models

Anderson model

Lifshits model

Anderson Model

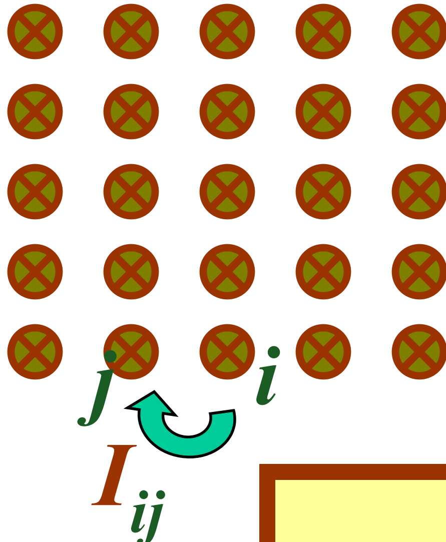


- *Lattice - tight binding model*
- *Onsite energies* ε_i - *random*
- *Hopping matrix elements* I_{ij}

$$-W < \varepsilon_i < W$$

uniformly distributed

Anderson Model



- *Lattice - tight binding model*
- *Onsite energies* ε_i *- random*
- *Hopping matrix elements* I_{ij}

$$-W < \varepsilon_i < W$$

uniformly distributed

$$I_{ij} = \begin{cases} I & i \text{ and } j \text{ are nearest neighbors} \\ 0 & \text{otherwise} \end{cases}$$

Anderson Transition

$$I < I_c$$

Insulator

All eigenstates are localized

Localization length ξ

$$I > I_c$$

Metal

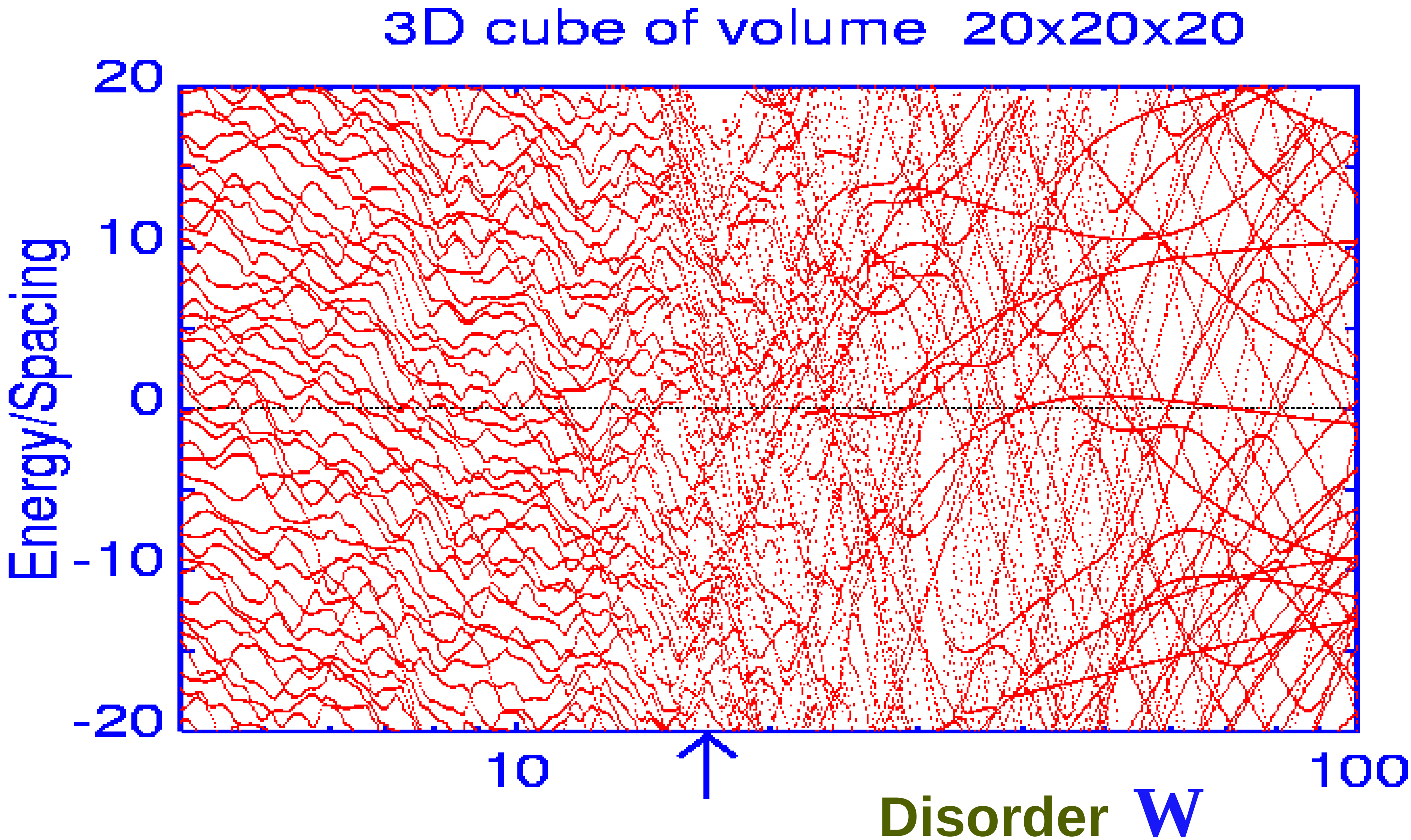
There appear states extended all over the whole system

Anderson Transition

Strong disorder	Weak disorder
$I < I_c$	$I > I_c$
Insulator	***Metal***
All eigenstates are localized	*There appear states extended all over the whole system*
Localization length ξ	
The eigenstates, which are localized at different places will not repel each other	*Any two extended eigenstates repel each other*
⇓	⇓
Poisson spectral statistics	*Wigner – Dyson spectral statistics*

Zharekeschev & Kramer.

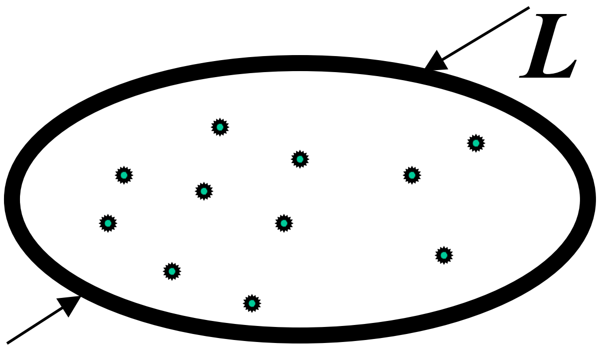
Exact diagonalization of the Anderson model

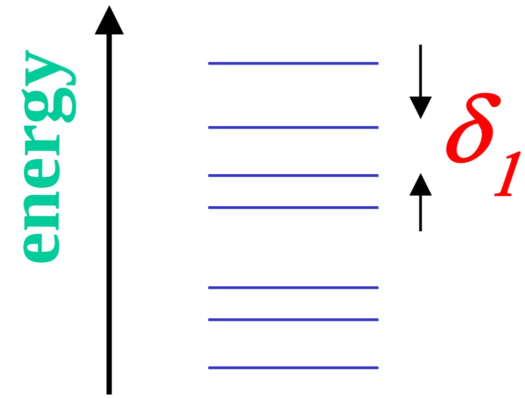


Energy scales (*Thouless, 1972*)

1. Mean level spacing

$$\delta_1 = 1/\nu \times L^d$$





L *is the system size;*

d *is the number of dimensions*

2. Thouless energy

$$E_T = hD/L^2$$

D *is the diffusion const*

E_T *has a meaning of the inverse diffusion time of the traveling through the system or the escape rate (for open systems)*

$$g = E_T / \delta_1$$

dimensionless Thouless conductance

$$g = Gh/e^2$$

Thouless Conductance and One-particle Spectral Statistics

Localized states
Insulator

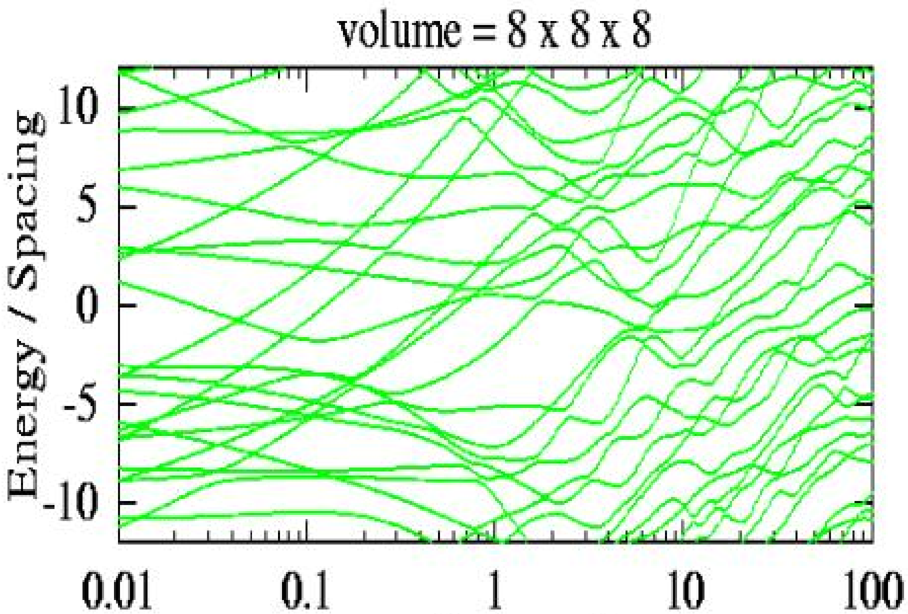
Poisson spectral statistics

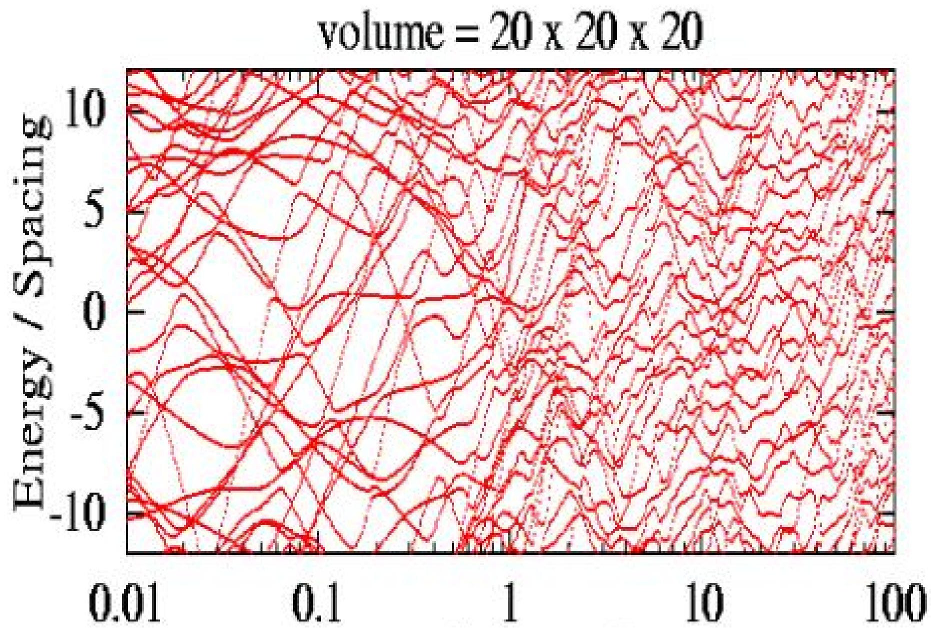
Extended states
Metal

Wigner-Dyson spectral statistics

Transition at $g\sim 1$.

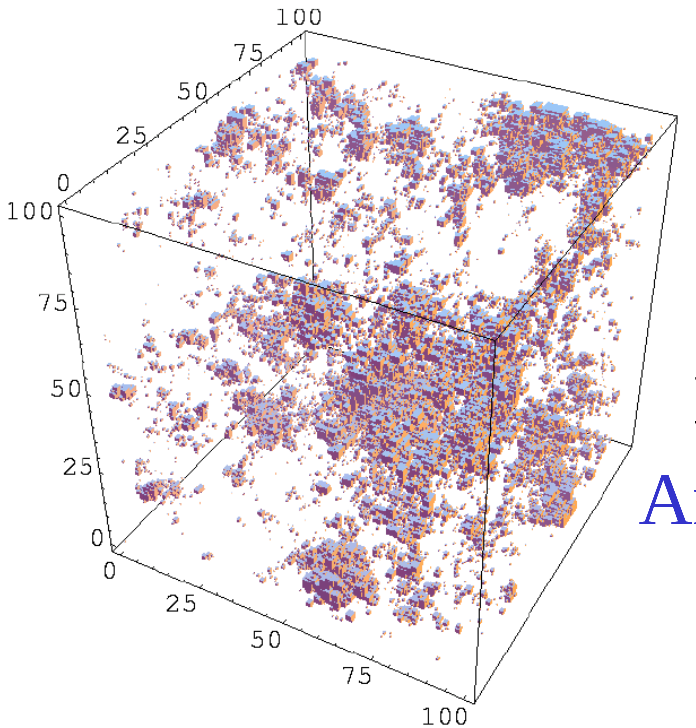
Is it sharp?





Conductance ***g***

Critical electron eigenstate at the Anderson transition

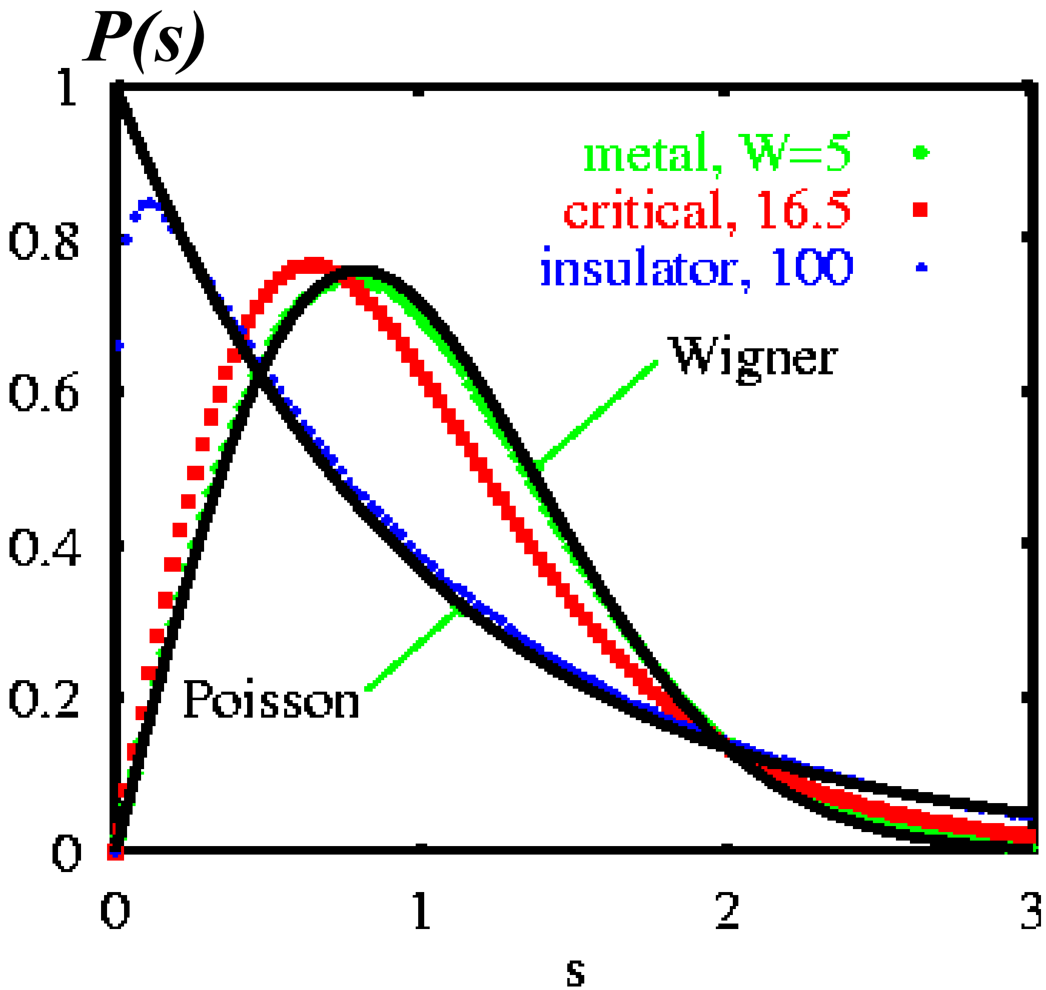


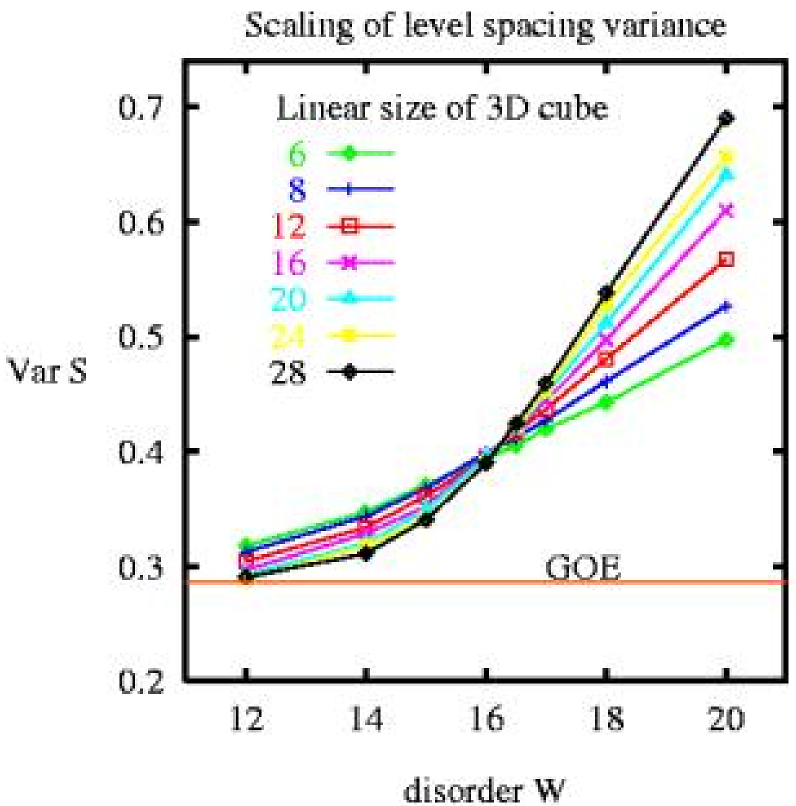
Zharekeshev, Computer Phys. Commun. 1999

$100 \times 100 \times 100$

Anderson model cube

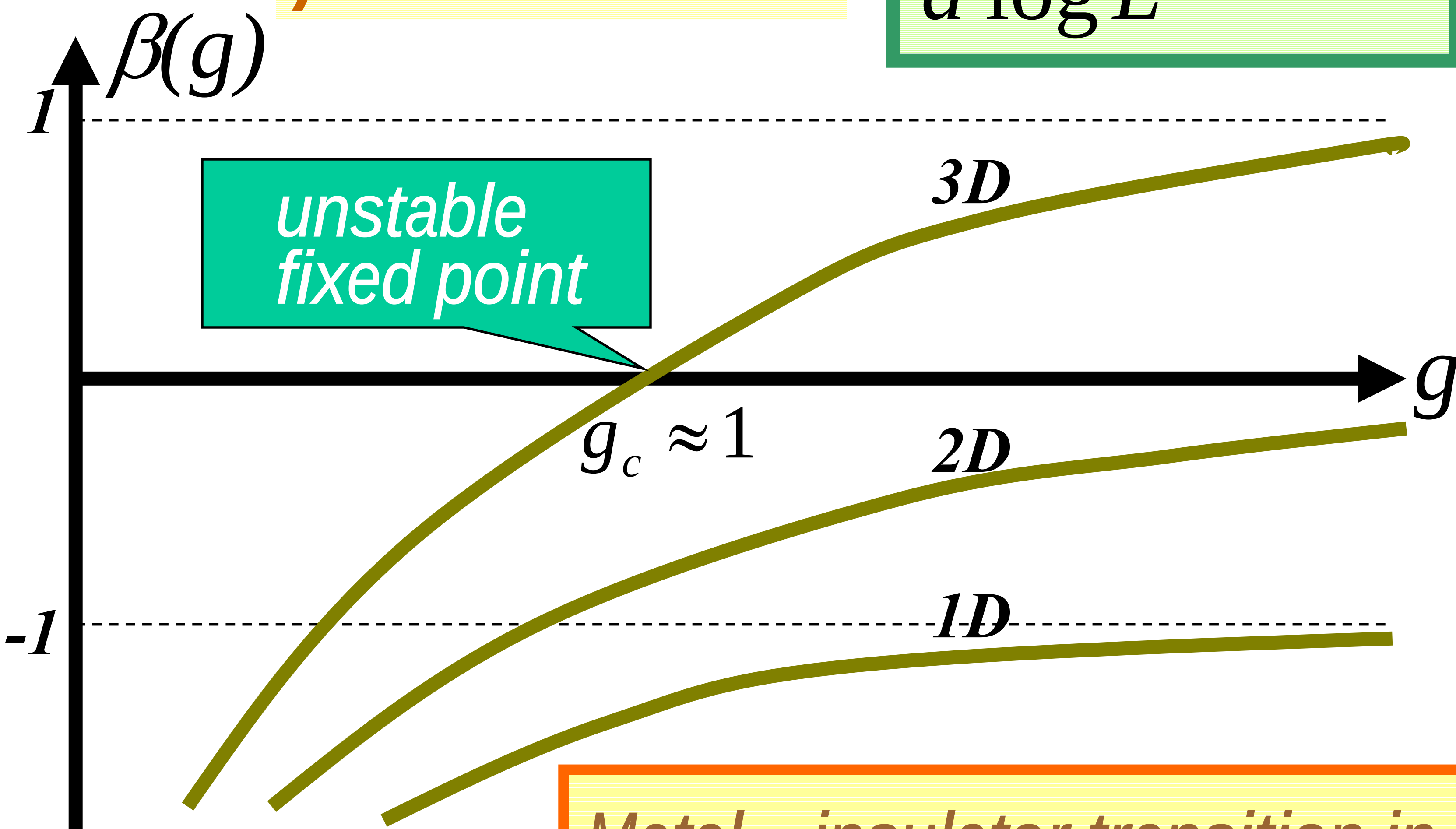
Anderson transition in terms of pure level statistics





β - function

$$\frac{d\log g}{d\log L} = \beta(g)$$



Metal – insulator transition in ***3D***

All states are localized for ***d=1,2***

Thouless Conductance and One-particle Spectral Statistics

0 **1** ***g***

Localized states
Insulator

Extended states
Metal

Poisson spectral statistics

Wigner-Dyson spectral statistics

$N \times N$
Random Matrices

$N \to \infty$

Quantum Dots with Thouless conductance ***g***

$g \to \infty$

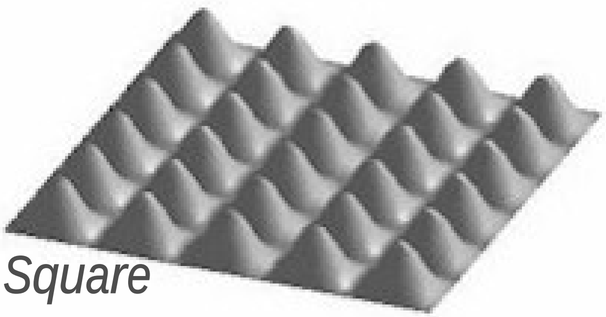
The same statistics of the random spectra and one-particle wave functions (eigenvectors)

VOLUME 85, NUMBER 11 PHYSICAL REVIEW LETTERS 11 SEPTEMBER 2000

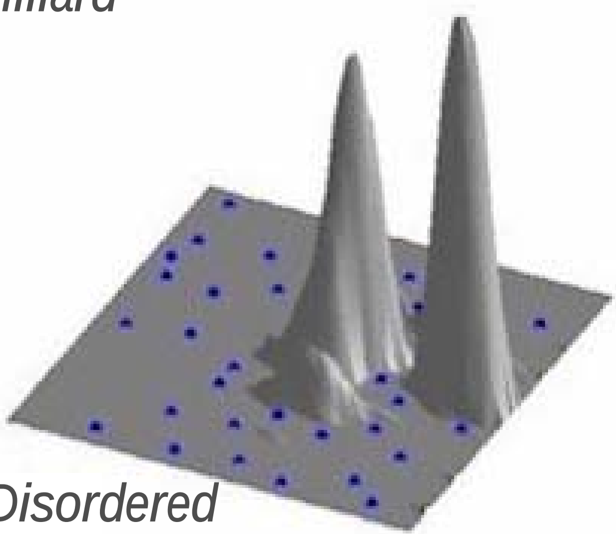
Correlations due to Localization in Quantum Eigenfunctions of Disordered Microwave Cavities

Prabhakar Pradhan and S. Sridhar
Department of Physics, Northeastern University, Boston, Massachusetts 02115
(Received 28 February 2000)

Integrable

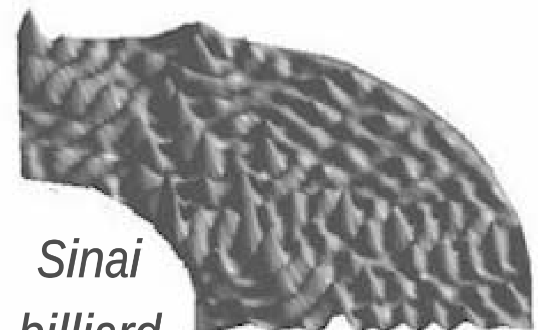


Square billiard

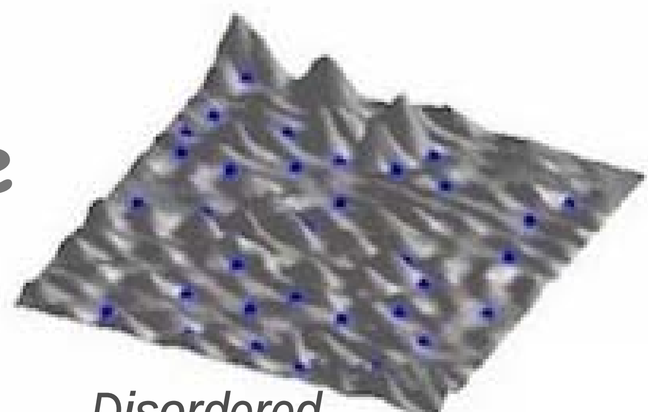


Disordered
localized

Chaotic



Sinai billiard



Disordered
extended

All chaotic systems resemble each other.

All integrable systems are integrable in their own way

Disordered Systems:

Anderson ***metal;***
Wigner-Dyson *spectral statistics*

Anderson ***insulator;***
Poisson *spectral statistics*

Q: *Is it a generic scenario for the Wigner-Dyson to Poisson crossover* **?**

Speculations

Consider an ***integrable*** *system. Each state is characterized by a* ***set of quantum numbers.***

It can be viewed as a point in the ***space of quantum numbers****. The whole set of the states forms a* ***lattice*** *in this space.*

A ***perturbation*** *that violates the integrability provides matrix elements of the* ***hopping*** *between different sites (****Anderson model !?****)*

Q: ***Does Anderson localization provide a generic scenario for the Wigner-Dyson to Poisson crossover*** **?**

Consider an integrable system. Each state is characterized by a set of quantum numbers.

It can be viewed as a point in the space of quantum numbers. The whole set of the states forms a lattice in this space.

A perturbation that violates the integrability provides matrix elements of the hopping between different sites (Anderson model !?)

Weak enough hopping - Localization - Poisson
Strong hopping - transition to Wigner-Dyson

The very definition of the localization is **not invariant** – one should specify in which space the eigenstates are localized.

Level statistics **is invariant**:

Poissonian statistics $\exists$ basis where the eigenfunctions are localized

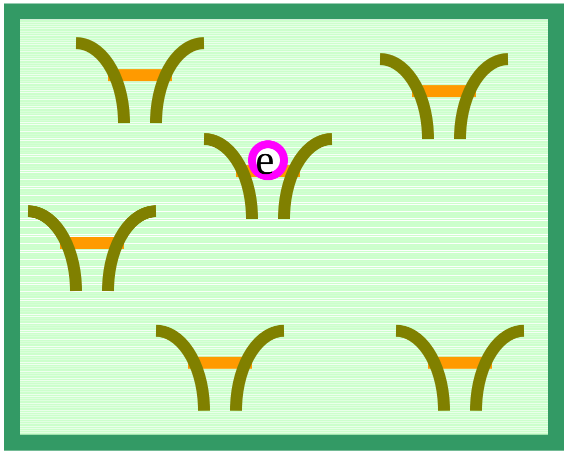
Wigner -Dyson statistics $\forall$ basis the eigenfunctions are extended

Example 1

Doped semiconductor

Low concentration of donors → Electrons are localized on donors ⇨ Poisson

Higher donor concentration → Electronic states are extended ⇨ Wigner-Dyson

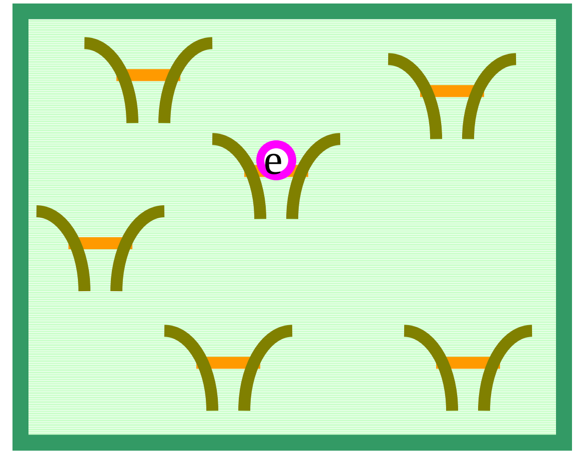


Example 1

Doped semiconductor

Low concentration of donors ⇒ Electrons are localized on donors ⇨ Poisson

Higher donor concentration ⇒ Electronic states are extended ⇨ Wigner-Dyson

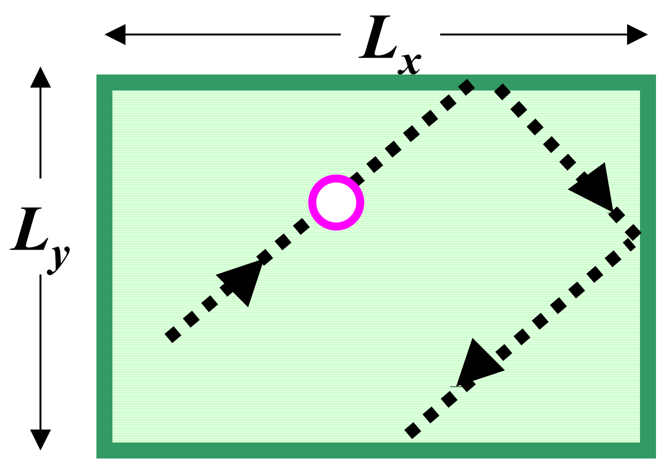


Example 2

Rectangular billiard

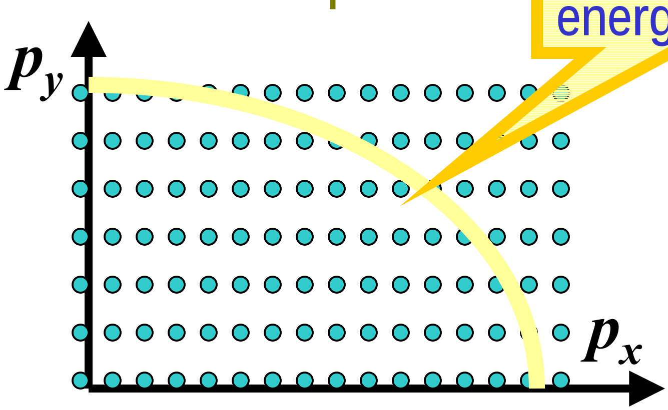
Two integrals of motion

$$p_x = \frac{\pi n}{L_x}; \quad p_y = \frac{\pi m}{L_x}$$



Lattice in the momentum space

Line (surface) of constant energy



Ideal billiard – localization in the momentum space ⇨ Poisson

Deformation or smooth random potential – delocalization in the momentum space ⇨ Wigner-Dyson

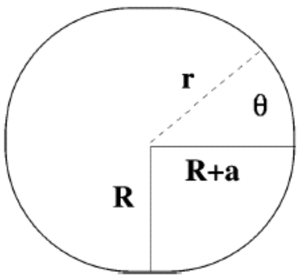
Localization and diffusion in the angular momentum space

VOLUME 77, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1996

Diffusion and Localization in Chaotic Billiards

Fausto Borgonovi,[1,3,4] Giulio Casati,[2,3,5] and Baowen Li[6,7]
[1] *Dipartimento di Matematica, Università Cattolica, via Trieste 17, 25121 Brescia, Italy*
[2] *Università di Milano, sede di Como, Via Lucini 3, Como, Italy*
[3] *Istituto Nazionale di Fisica della Materia, Unità di Milano, via Celoria 16, 22100, Milano, Italy*
[4] *Instituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy*
[5] *Instituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy*
[6] *Department of Physics and Centre for Nonlinear and Complex Systems, Hong Kong Baptist University, Hong Kong*
[a7] *Center for Applied Mathematics and Theoretical Physics, University of Maribor, Krekova 2, 2000 Maribor, Slovenia*
(Received 29 July 1996)

$$\varepsilon \equiv \frac{a}{R}$$



$\varepsilon > 0$ Chaotic stadium

$\varepsilon \to 0$ Integrable circular billiard

Angular momentum is the integral of motion

$$\hbar = 0; \quad \varepsilon << 1$$

Angular momentum is not conserved

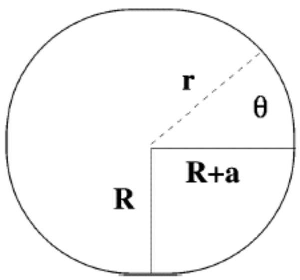
VOLUME 77, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1996

Diffusion and Localization in Chaotic Billiards

Fausto Borgonovi,[1,3,4] Giulio Casati,[2,3,5] and Baowen Li[6,7]
[1] *Dipartimento di Matematica, Università Cattolica, via Trieste 17, 25121 Brescia, Italy*
[2] *Università di Milano, sede di Como, Via Lucini 3, Como, Italy*
[3] *Istituto Nazionale di Fisica della Materia, Unità di Milano, via Celoria 16, 22100, Milano, Italy*
[4] *Instituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy*
[5] *Instituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy*
[6] *Department of Physics and Centre for Nonlinear and Complex Systems, Hong Kong Baptist University, Hong Kong*
[a7] *Center for Applied Mathematics and Theoretical Physics, University of Maribor, Krekova 2, 2000 Maribor, Slovenia*
(Received 29 July 1996)

Localization and diffusion in the angular momentum space

$$\varepsilon \equiv \frac{a}{R}$$



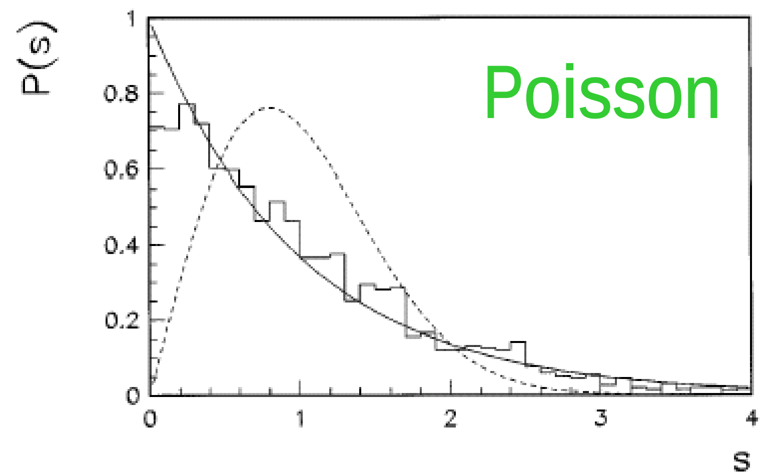
$\varepsilon > 0$ Chaotic stadium

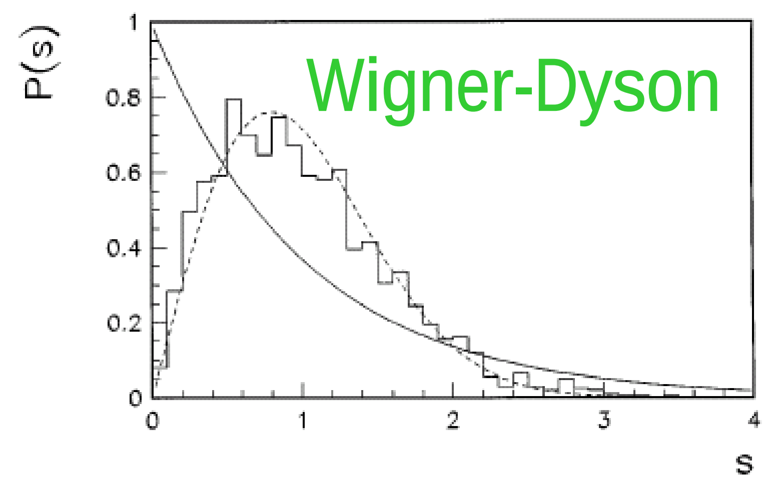
$\varepsilon \to 0$ Integrable circular billiard

Angular momentum is the integral of motion

$\hbar = 0; \quad \varepsilon << 1$

Angular momentum is not conserved





D.Poilblanc, T.Ziman, J.Bellisard, F.Mila & G.Montambaux
Europhysics Letters, v.22, p.537, 1993

1D Hubbard Model on a periodic chain

$$H = t\sum_{i,\sigma}\left(c^{+}_{i,\sigma}c_{i+1,\sigma} + c^{+}_{i+1,\sigma}c_{i,\sigma}\right) + U\sum_{i,\sigma} n_{i,\sigma}n_{i,-\sigma} + V\sum_{i,\sigma,\sigma'} n_{i,\sigma}n_{i+1,\sigma'}$$

Onsite interaction

n. neighbors interaction

$V = 0$ Hubbard model integrable

$V \neq 0$ extended Hubbard model nonintegrable

D.Poilblanc, T.Ziman, J.Bellisard, F.Mila & G.Montambaux

Europhysics Letters, v.22, p.537, 1993

1D Hubbard Model on a periodic chain

$$H = t\sum_{i,\sigma}\left(c^{+}_{i,\sigma}c_{i+1,\sigma} + c^{+}_{i+1,\sigma}c_{i,\sigma}\right) + U\sum_{i,\sigma} n_{i,\sigma}n_{i,-\sigma} + V\sum_{i,\sigma,\sigma'} n_{i,\sigma}n_{i+1,\sigma'}$$

Onsite interaction

n. neighbors interaction

$V = 0$ Hubbard model — integrable

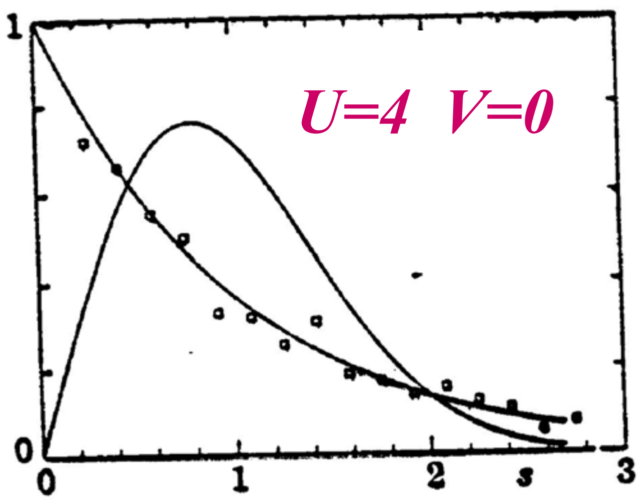
$V \neq 0$ extended Hubbard model — nonintegrable

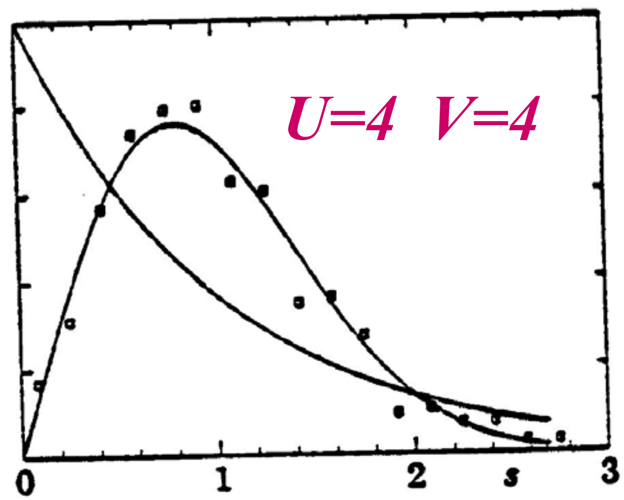
12 sites

3 particles

Zero total spin

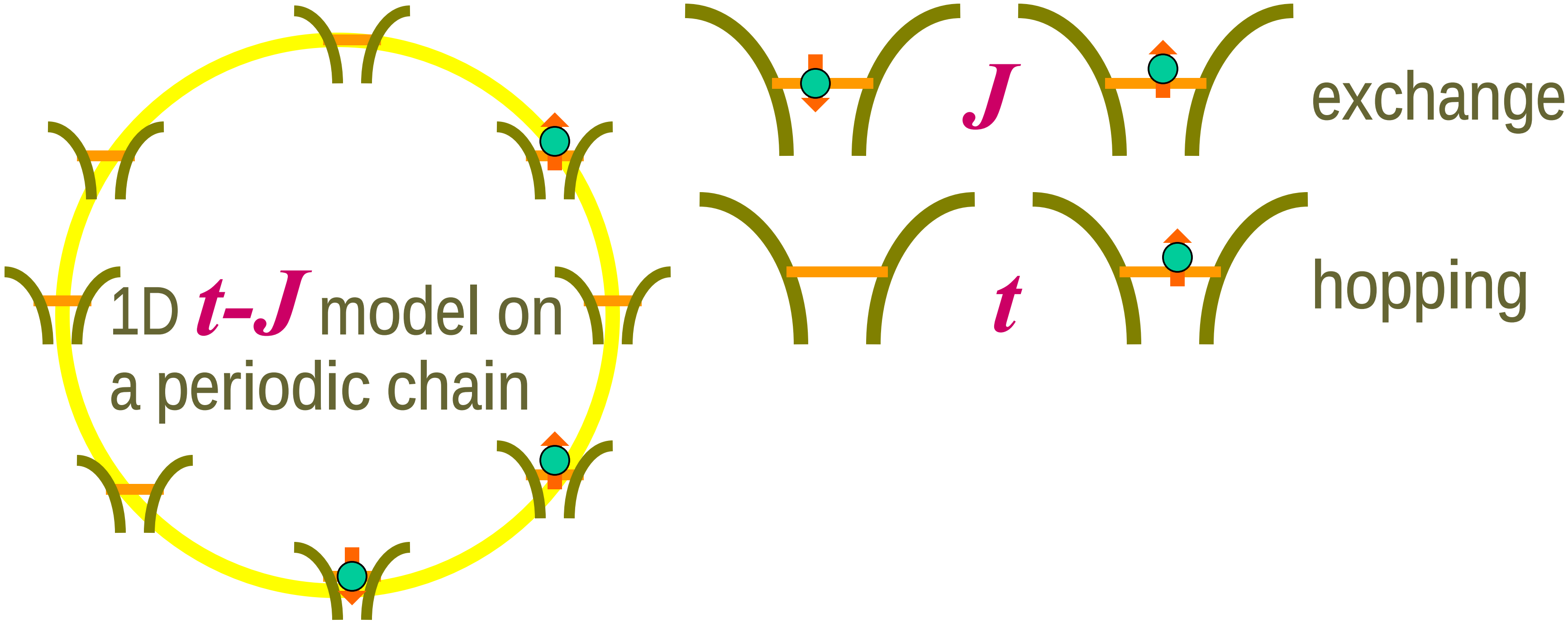
Total momentum $\pi/6$





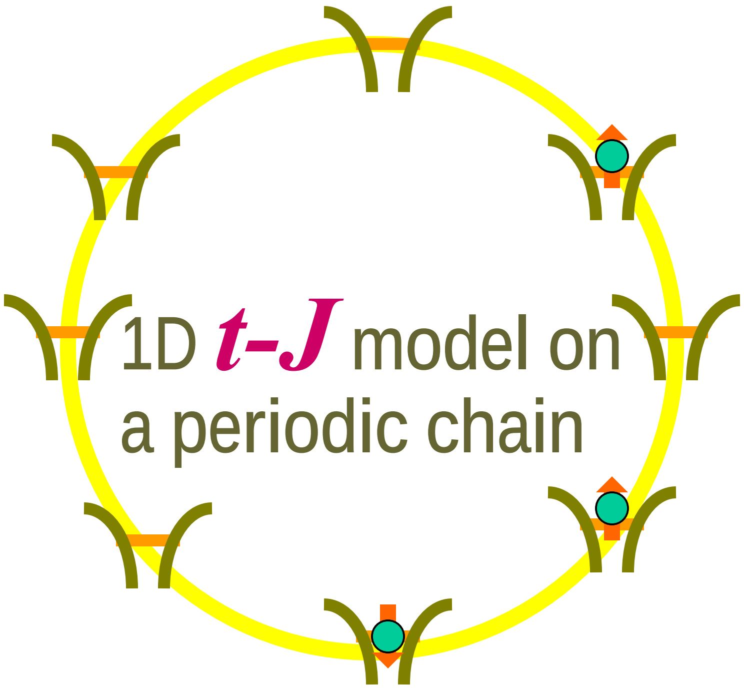
D.Poilblanc, T.Ziman, J.Bellisard, F.Mila & G.Montambaux

Europhysics Letters, v.22, p.537, 1993

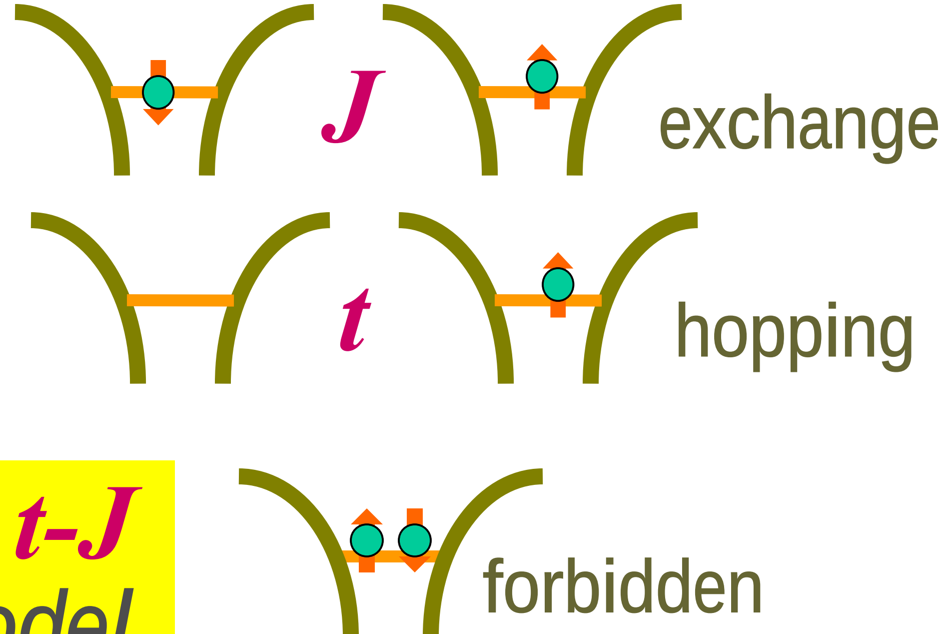


D.Poilblanc, T.Ziman, J.Bellisard, F.Mila & G.Montambaux

Europhysics Letters, v.22, p.537, 1993

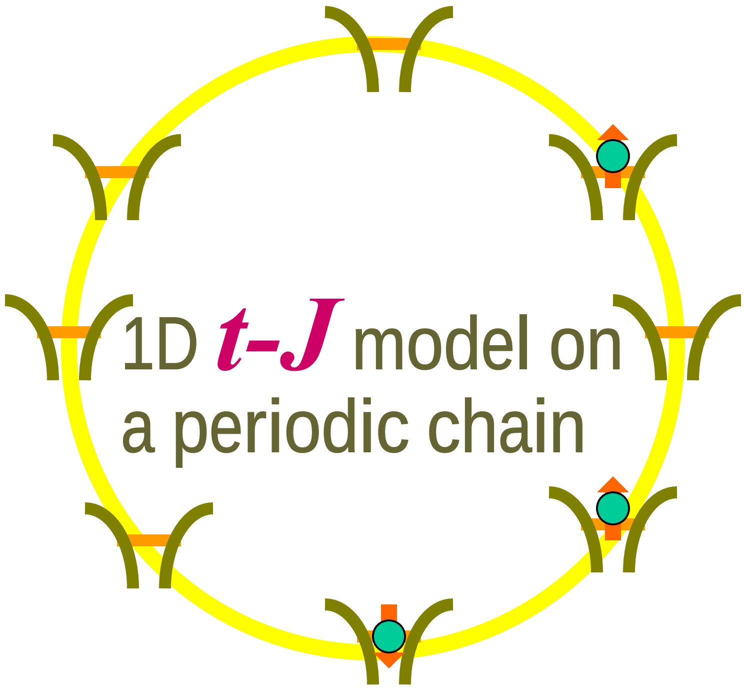


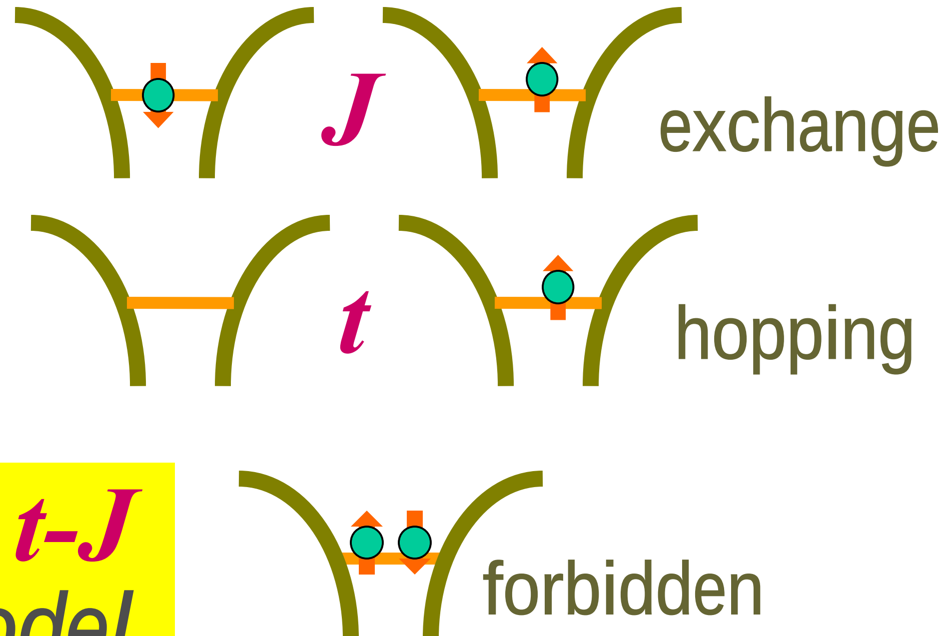
1d *t-J*
model



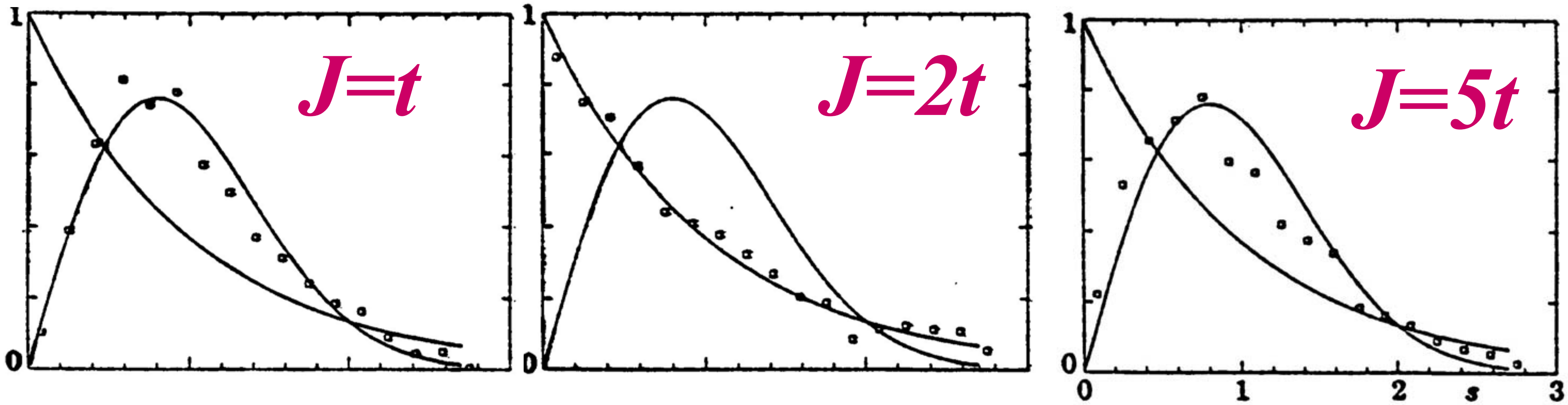
D.Poilblanc, T.Ziman, J.Bellisard, F.Mila & G.Montambaux

Europhysics Letters, v.22, p.537, 1993





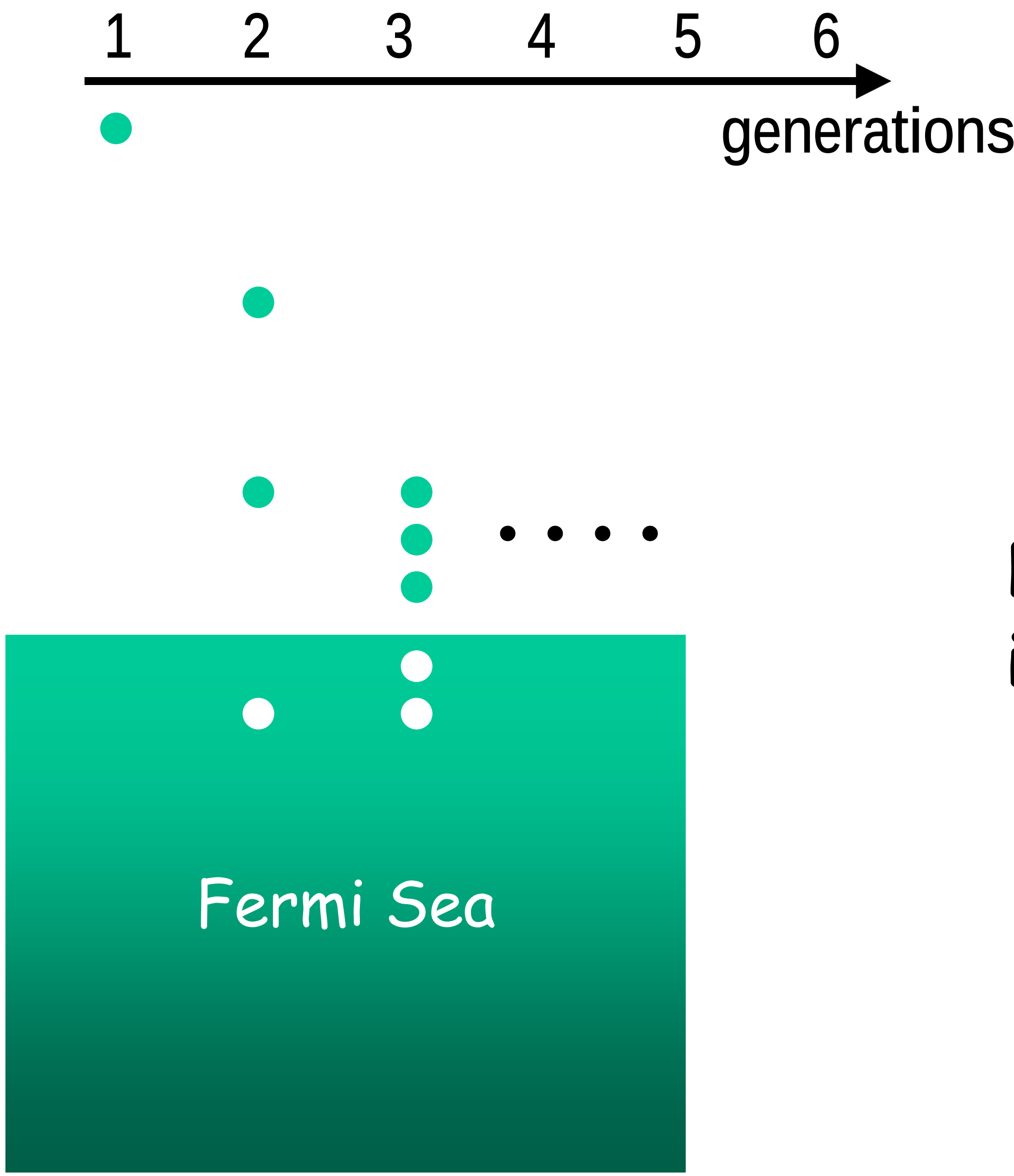
1d *t-J*
model



***N=16*; one hole**

Q: ***Why the random matrix theory (RMT) works so well for nuclear spectra*** **?**

Chaos in Nuclei – Delocalization



Delocalization in Fock space