Prelude on the history of dissipative optical lattices: remember photon-photon correlations

Dissipative optical lattices: photon correlations a useful tool

Localization of Atoms in a Three-Dimensional Standing Wave

NIST Gaithersburg
PRL 65, 33 (1990)

Spectrum of scattered light

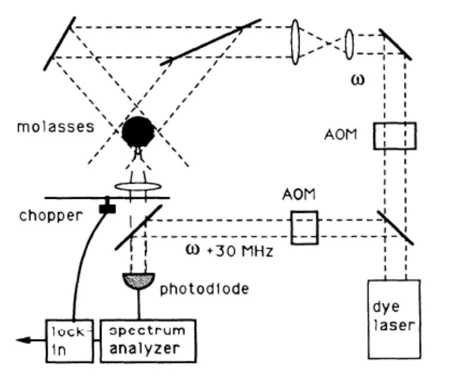
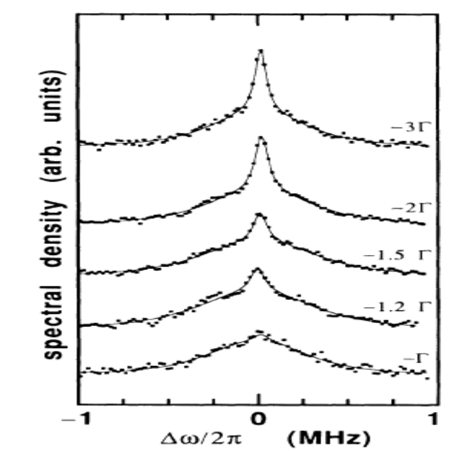


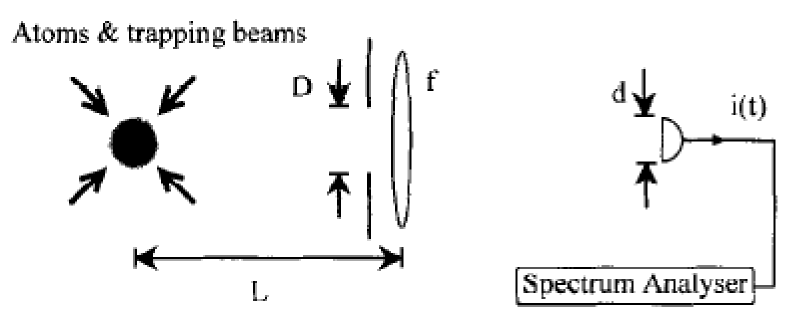
FIG. 1. Schematic diagram of the apparatus.

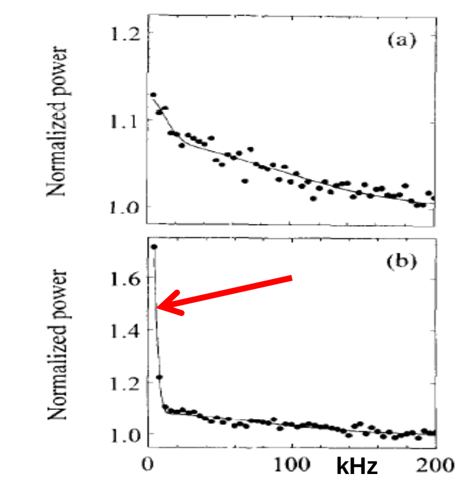


Observation of intensity correlations in the fluorescence from laser cooled atoms

Institut d'Optique
Optics comm. 115, 480 (1995)

Spectrum of photocurrent



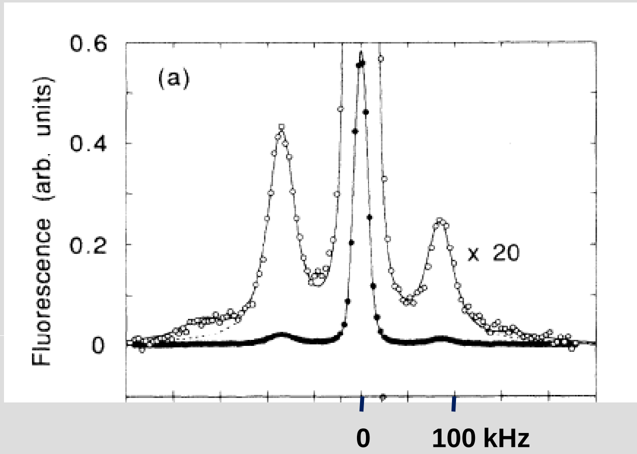


Dissipative optical lattices: photon correlations a sophisticated tool

Observation of Quantized Motion of Rb Atoms in an Optical Field

NIST Gaithersburg
PRL 69, 49 (1992)

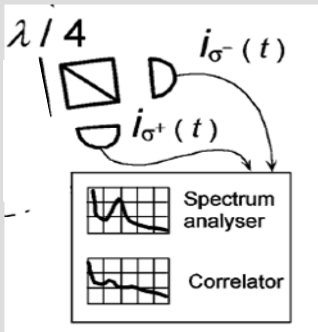
Spectrum of scattered light

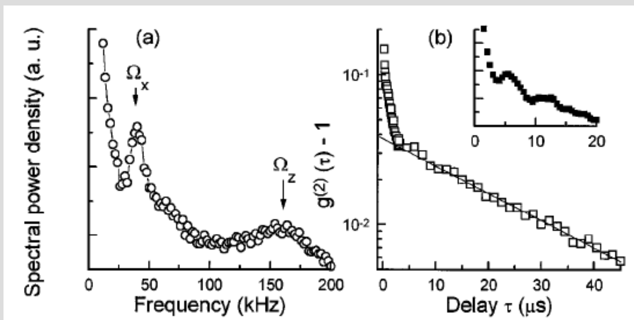


Atomic Transport in an Optical Lattice: An Investigation through Polarization-Selective Intensity Correlations

Institut d'Optique
PRL 77, 1727 (1996)

Intensity correlations in scattered light





See also Wisconsin -Madison (T.Walker)
PRA 53, 3469 (1996)

Anderson localization of ultracold atoms in a (laser speckle) disordered potential: from 1D to 2D and 3D

KITP, Santa Barbara, October 13th, 2010

Alain Aspect

Groupe d'Optique Atomique

Institut d'Optique - Palaiseau

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J. Billy et al. Nature, 453, 891 (2008)

A. Aspect M.Inguscio Physics today (August 2009)

Anderson localization of ultra cold atoms in a laser speckle disordered potential

1. Anderson localization: the naïve view of an AMO experimentalist: 1 particle quantum interference effect
2. Anderson localization with cold atoms in laser speckle
   A well controlled system
3. 1D Anderson localization: An energy mobility edge?
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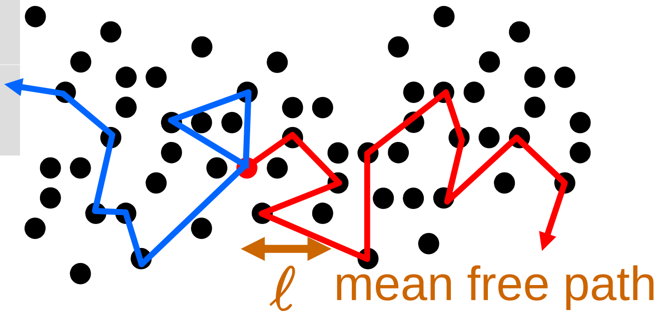
Anderson localization: a model for metal/insulator transition induced by disorder

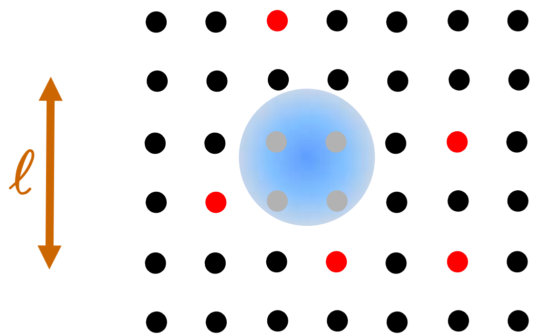
Classical model of metal: disorder hinders, does not cancel, ohmic conduction



Classical particles bouncing on impurities
$\Rightarrow$ diffusive transport (Drude)

Matter waves scattered on impurities $\Rightarrow$ incoherent addition
$\Rightarrow$ delocalized (extended) states (cf. radiative transfer): conductor

Anderson L. (1958): disorder can totally cancel ohmic conduction

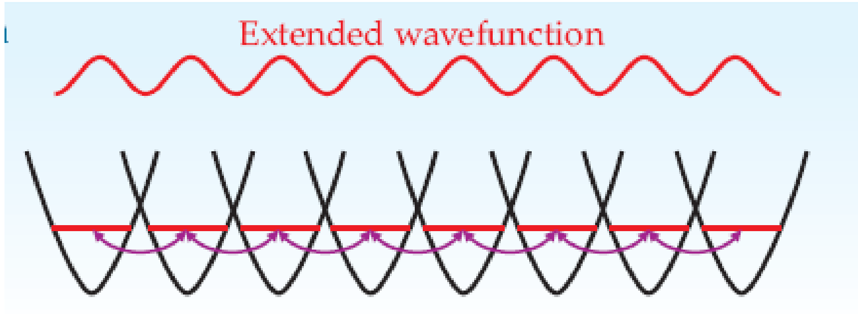


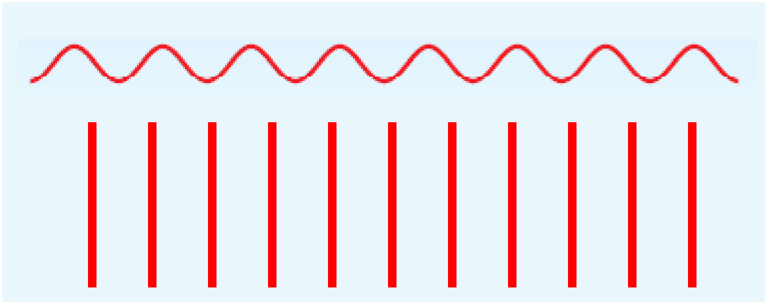
Tight binding model of electrons on a 3D lattice with disorder large enough: exponentially localized states: insulator

Quantum effect: addition of quantum amplitudes of hopping

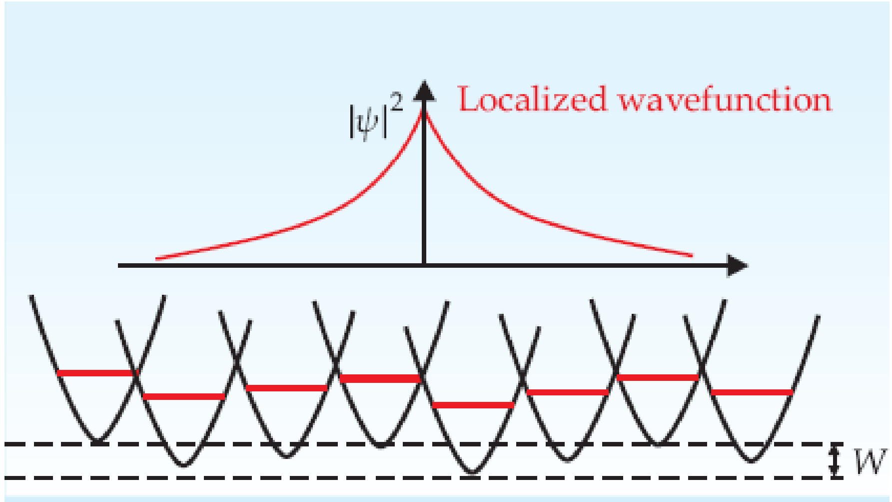
3D mobility edge (Ioffe Regel) $E \leq \dfrac{\hbar^2}{2m\ell^2}$

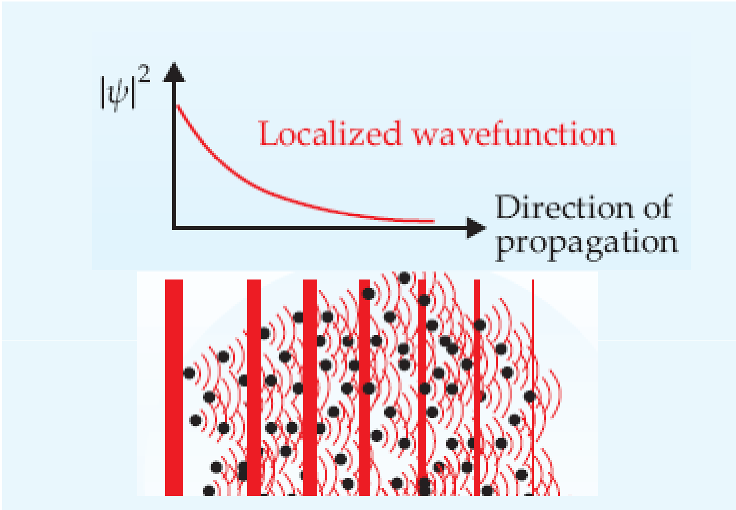
Tight binding model vs. wave model
From Condensed matter to AMO physics





Bloch wave in a perfect crystal ⇔ Freely propagating wave





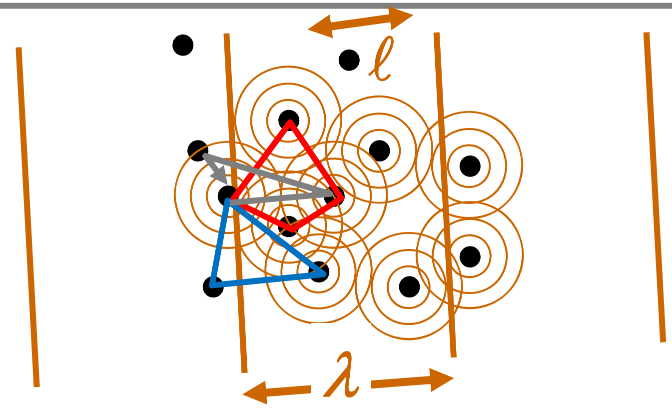
Disordered crystal ⇔ Scattering from impurities

Anderson localization: the point of view of an AMO physicist

Coherent addition of waves scattered on impurities. If mean free path ℓ smaller than de Broglie wavelength:

- coherent addition of trajectories returning to origin
- destructive interference in forward scattering, then in any direction

⇒ Localized states: insulator



3D mobility edge (Ioffe Regel) $\ell \leq \dfrac{\lambda}{2\pi}$

Main features:

- Interference of many scattered wavelets ⇒ localization
- Single particle quantum effect (no interaction)
- Role of dimensionality (probability of return to origin)

The experimental quest of AL in AMO physics

Electromagnetic waves scattering on non absorptive impurities: not easy to discriminate from ordinary absorption

Microwaves (cm) on dielectric spheres:

- discriminating localization from absorption by study of statistical fluctuations of transmission Chabonov et al., Nature 404, 850 (2000)

Light on dielectric microparticles (TiO_2):

- Exponential transmission observed; questions about role of absorption Wiersma et al., Nature 390, 671 (1997)
- Discriminating localization from absorption by time resolved transmission Störzer et al., Phys Rev Lett 96, 063904 (2006)

Difficult to obtain $\ell < \lambda / 2\pi$ (Ioffe-Regel mobility edge)
No direct observation of the exponential profile in 3D

Most of these limitations do not apply to the 2D or 1D localization of light observed in disordered 2D or 1D photonic lattices: T. Schwartz et al. (M. Segev), Nature 446, 52 (2007). Lahini et al. (Silberberg), PRL 100, 013906 (2008).

Anderson localization of ultra cold atoms in a laser speckle disordered potential

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Ultra cold atoms (matter waves) Good candidate to observe AL

Good features

- Controllable dimensionality (1D, 2D, 3D)
- Wavelength λ_{dB} "easily" controllable over many orders of magnitude (1 nm to 10 μm)
- Pure potentials (no absorption), with "easily" controllable amplitude and statistical properties
- Many observation tools: light scattering or absorption, Bragg spectroscopy, …

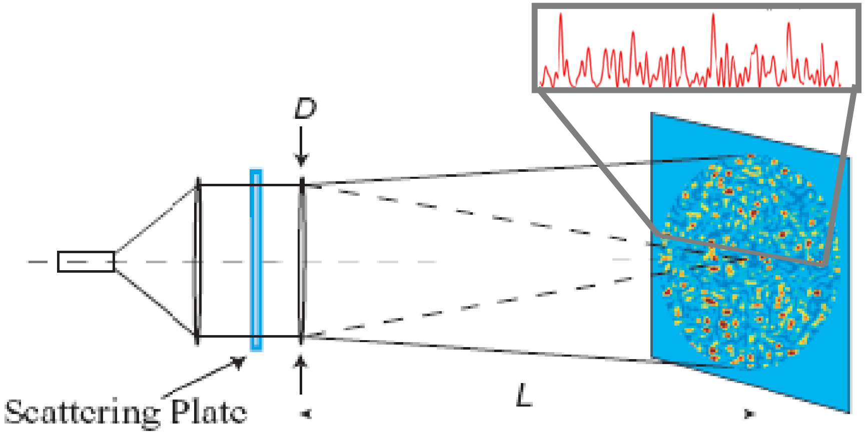
A new feature: interactions between atoms

- A hindrance to observe AL (pure wave effect for single particle)
- New interesting problems (many-body physics)

Laser speckle disordered potential

Blue detuned light creates a repulsive potential for atoms proportional to light intensity

$$V \propto \frac{I}{\delta} \propto \frac{|\mathcal{E}|^2}{\delta}$$



Laser speckle: very well controlled random pattern

(Complex electric field = Gaussian random process, central limit theorem)

Intensity (*i.e.* disordered potential) is NOT Gaussian:

$$P(I) = \frac{1}{\bar{I}} \exp\{-\frac{I}{\bar{I}}\}$$

Calibrated by RF spectroscopy of cold atoms (light shifts distribution)

Intensity inherits some properties of underlying Gaussian process

Autocorrelation function rms width (speckle size) controlled by aperture

$$\sigma_R \simeq \frac{\lambda L}{\pi D}$$

Calibrated for $\sigma_R > 1\,\mu m$

Extrapolated at $\sigma_R < 1\,\mu m$

D. Clément *et al.*, New J. Phys. 8, 165 (2006)

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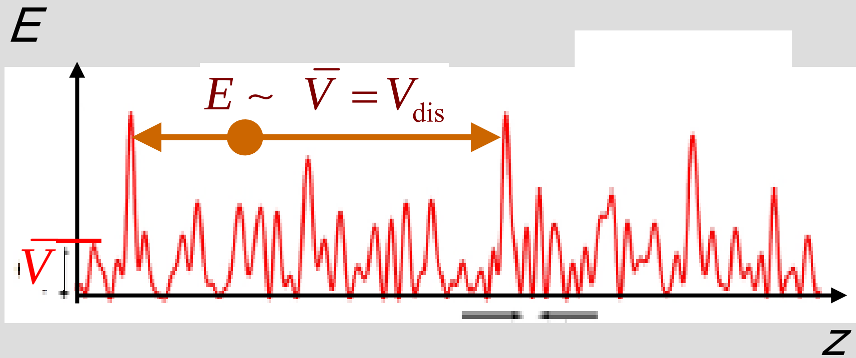
1D Anderson localization?

Theorist answer: all states localized in 1D

Experimentalist question: Anderson like localization? AL: Interference effect between many scattered wavelets ⇒ exponential wave function

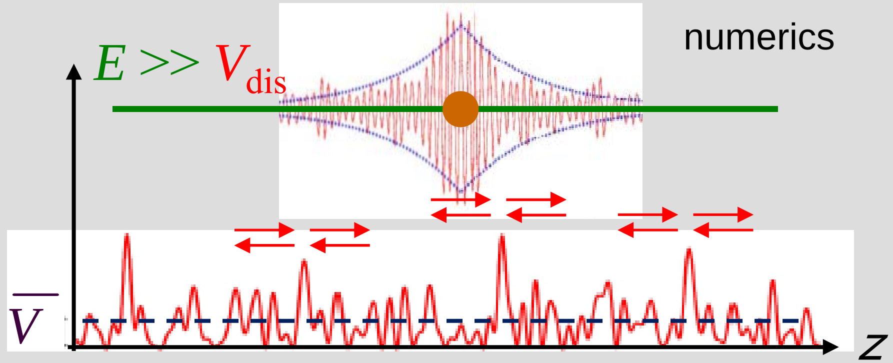
Localization in a strong disorder: particle trapped between two large peaks

Classical localization, not Anderson

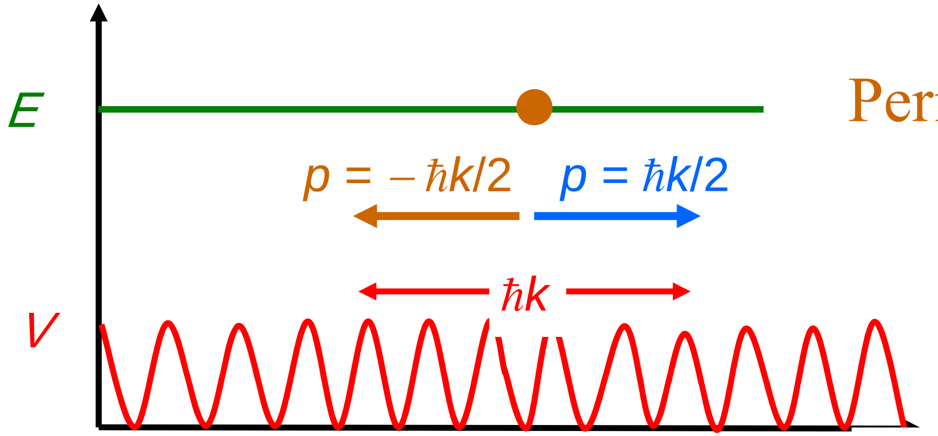


Localization in weak disorder (numerics): interference of many scattered wavelets

Looks like Anderson localization



1D localization in a weak disorder as Bragg reflection



Periodic potential $V = V_0 \cos kz$

No propagation of matter wave

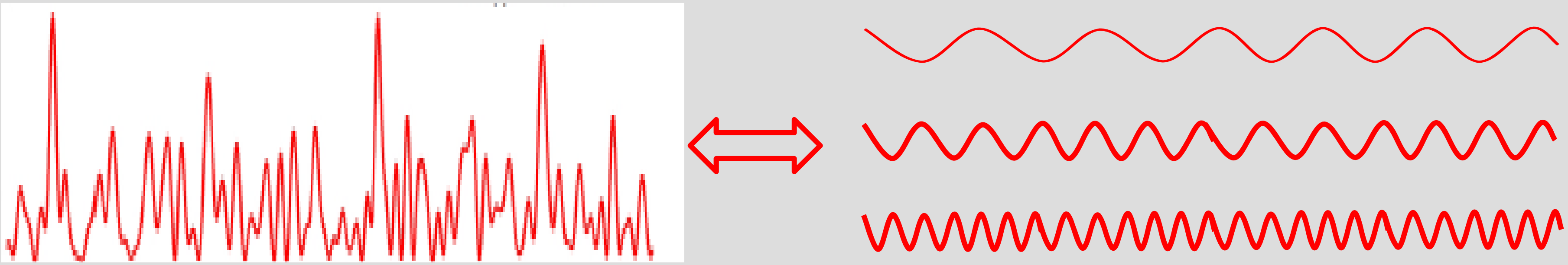
$$\psi = A \exp\left(\pm i \frac{p}{\hbar} z \right) \quad \text{if } p \sim \hbar k/2$$

even in the case of $E = \dfrac{p^2}{2M} >> V_0$ (weak perturbation)

- Bragg reflection of $p \sim \hbar k/2$ on $\cos kz$
- No propagation in a gap around $E = \dfrac{\hbar^2 k^2}{8M}$

although $E >> V_0$

1D localization in a weak disorder as Bragg reflection

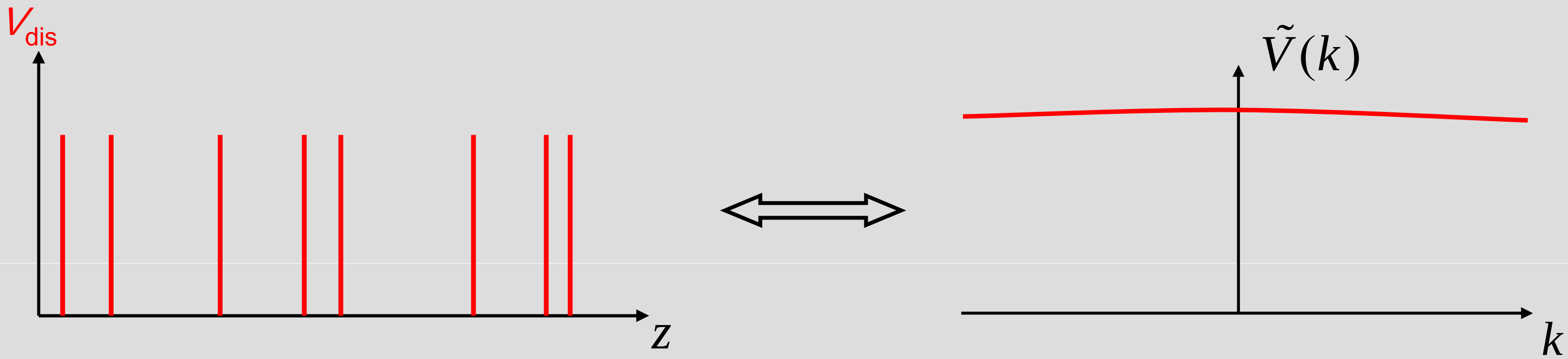


Disordered potential: many independents *k* components, acting separately on various p components (Born approximation) .

Anderson localization: all p components Bragg reflected.
Demands broad spectrum of disordered potential

1D Anderson localization in a weak uncorrelated disorder

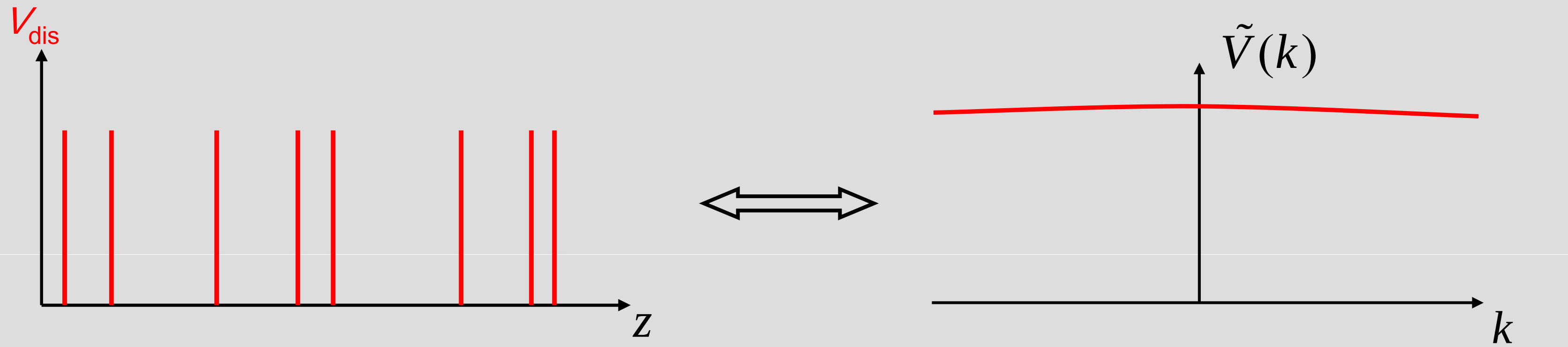
Disordered potential with a white spectrum of *k* vectors



Anderson L.: all *p* components Bragg reflected

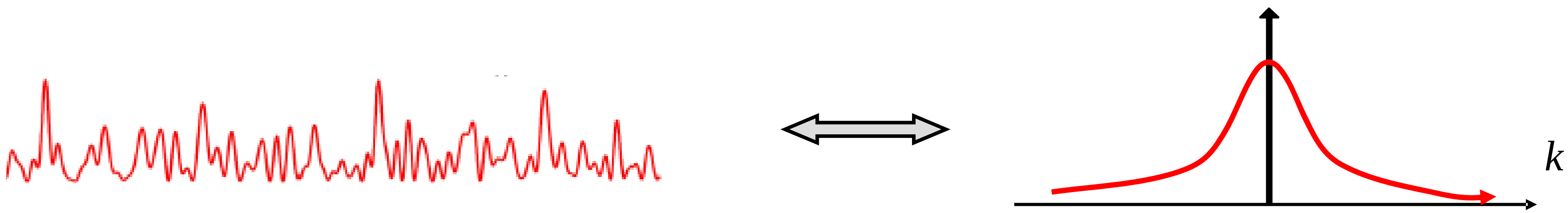
1D Anderson localization in a weak uncorrelated disorder

Disordered potential with a white spectrum of k vectors

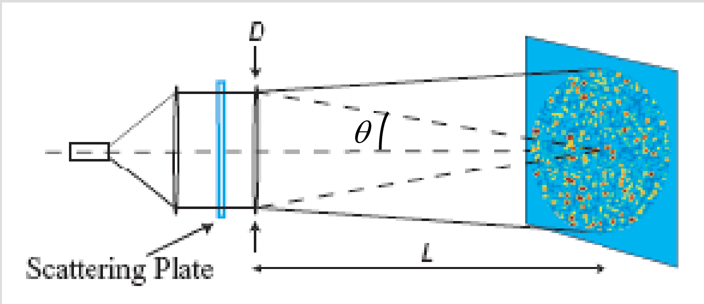


Anderson L.: all p components Bragg reflected

What happens for a correlated potential (finite spectrum)?

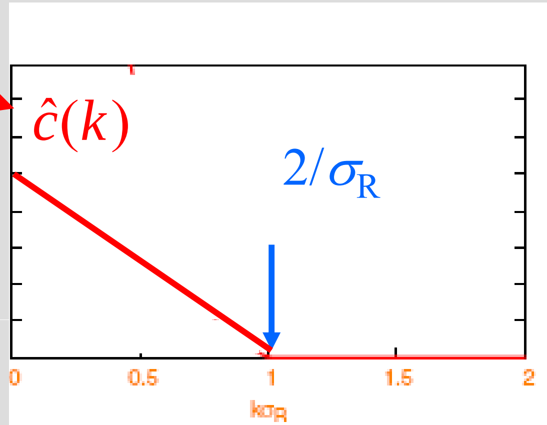


Case of a speckle disorder: cut off in the spatial frequency spectrum



Spatial frequencies spectrum of speckle potential

FT of auto correlation $\langle V(z)V(z+\Delta z)\rangle$



Speckle potential, created by diffraction from a scattering plate: no k component beyond a cut off $\frac{2}{\sigma_R} = \frac{\sin\theta}{k_{\text{light}}}$

Only matter waves with $E < \hbar^2/2m\sigma_R^2$ $\left(p < \hbar/\sigma_R\right)$ localize

Effective (Born approx.) mobility edge

First order perturbative calculation (second order in V)

Lyapunov coefficient $\gamma(p) = \frac{1}{L_{\text{loc}}(p)} \propto \hat{c}(2\frac{p}{\hbar}) \Rightarrow \gamma(p) = 0$ for $p > \frac{\hbar}{\sigma_R}$

L. Sanchez-Palencia et al., PRL 98, 210401 (2007)

1D Anderson localization in a weak speckle potential?

First order calculations*: exponentially localized wave functions provided that $p < \hbar / \sigma_R$

- Localization results from interference of many scattered wavelets (not a classical localization, weak disorder)
- Effective mobility edge

Same features as genuine (3D) Anderson localization

Worth testing it

* What happens beyond Born approximation? Ask question!

Anderson localization of ultra cold atoms in a laser speckle disordered potential

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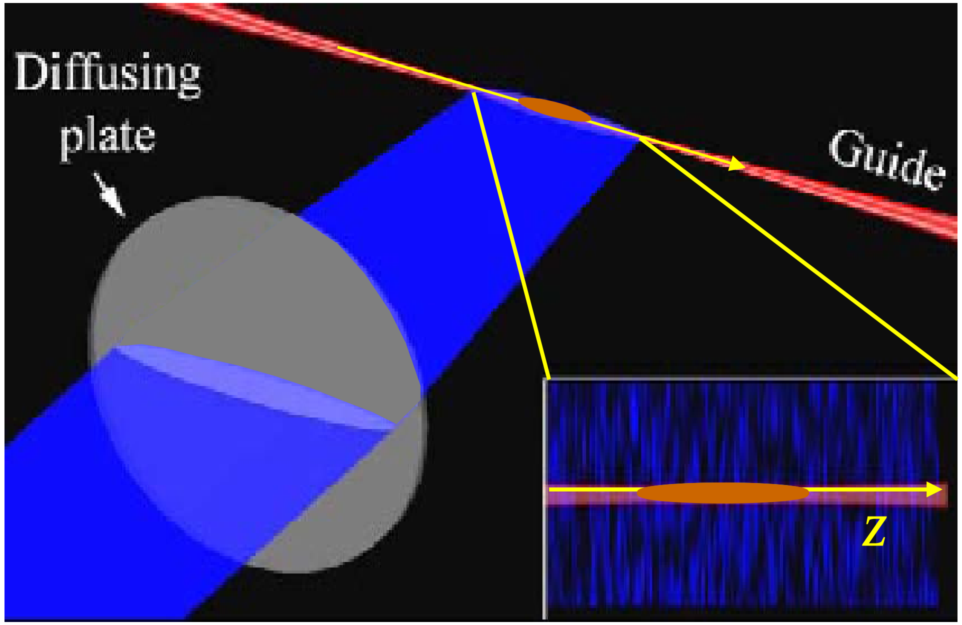
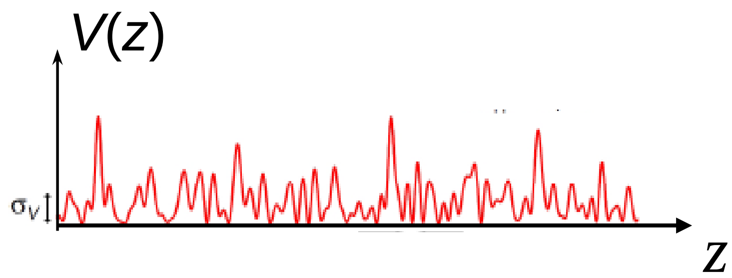
A 1D random potential for 1D guided atoms

Atoms tightly confined in x-y plane, free along z: 1D matterwaves



Cylindrical lens = anisotropic speckle, elongated along *x*-*y* fine along *z*



$\sigma_x, \sigma_y \approx 50\,\mu\text{m}\ ;\ \sigma_z \approx 1\ \mu\text{m}$

BEC elongated along z and confined (focussed laser) transversely to *z*

$2R_z^{TF} \approx 300\,\mu\text{m}\ ;\ 2R_\perp^{TF} \approx 3\,\mu\text{m}$ Imaged with resonant light

1 D situation for the elongated BEC.

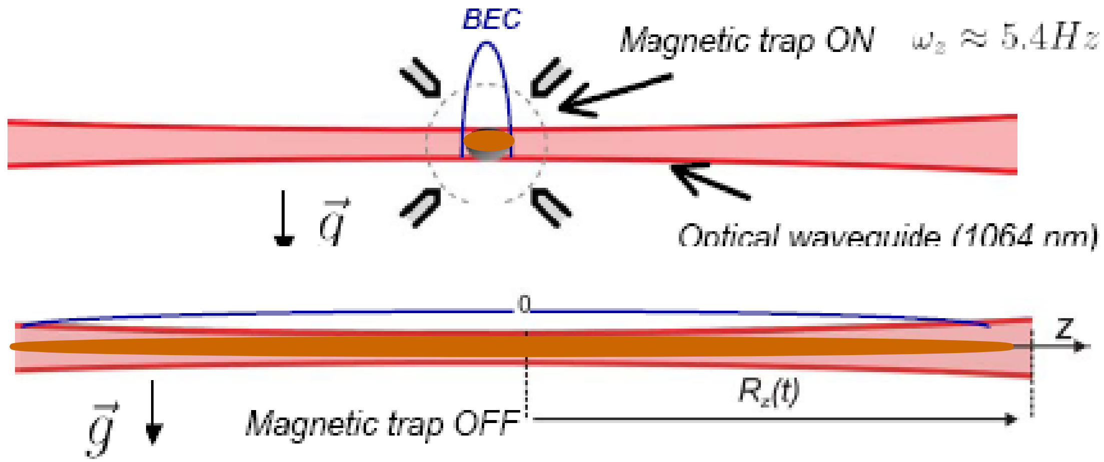
Many speckle grains covered (self averaging system = ergodic)

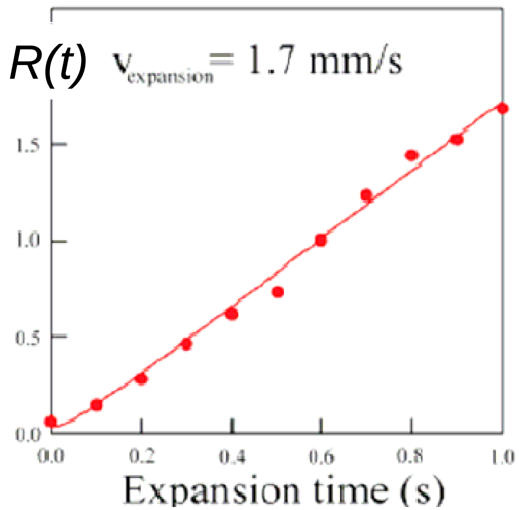
1D situation: invariant transversely to *z*

Ballistic expansion of a 1D BEC

Cloud of trapped ultracold atoms (dilute BEC) observable on a single shot: N atoms with the same confined wave function.

Release of trapping potential along z: expansion in the 1D atom guide



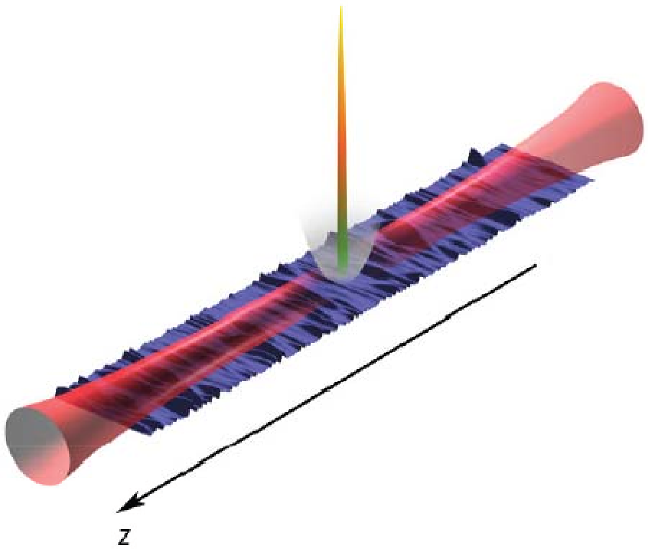


Initial interaction energy μ_{in} converted into kinetic energy

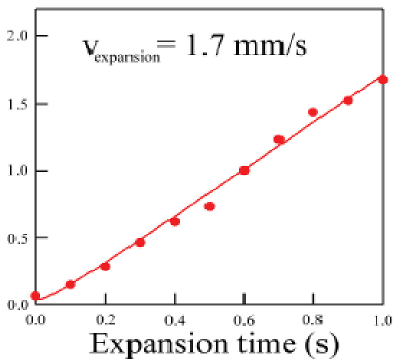
$\Rightarrow$ After a while, interaction free ballistic expansion

$\Rightarrow$ Superposition of plane waves with $p \leq p_{\max} = \sqrt{2M\mu_{\text{in}}}$

Search for Anderson localization in a weak speckle potential: a demanding experiment

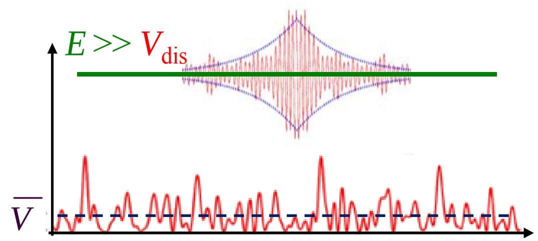


Residual longitudinal potential well compensated: balistic expansion over 4 mm



Requirements:

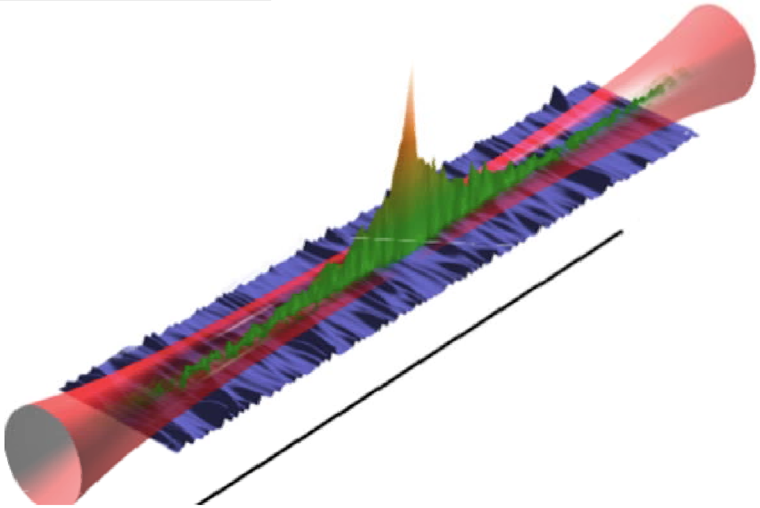
- Good optical access for fine speckle $(\sigma_R = 0.26\ \mu m)$
- Initial density small enough for max velocity well below the effective mobility edge
  $p_{max} = 0.65\ \hbar / \sigma_R$
  (fluorescence imaging: 1 at / µm)
- Deep in weak disorder regime
  $V_R = 0.1\ \mu_{ini}$

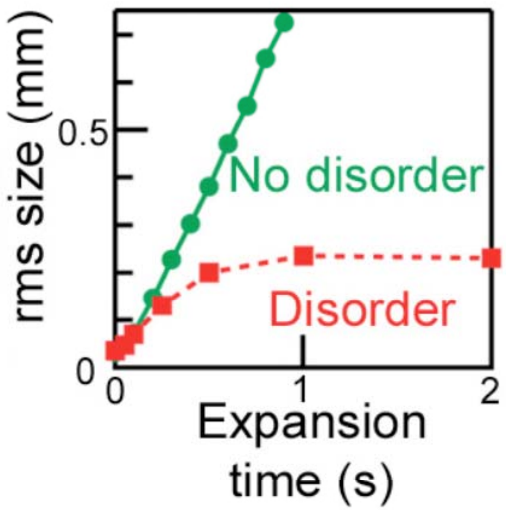


Anderson localization in a weak speckle: below the effective mobility edge

J. Billy et al.
Nature, 453,
891 (2008)

$p_{\max}\, \sigma_R = 0.65\, \hbar$

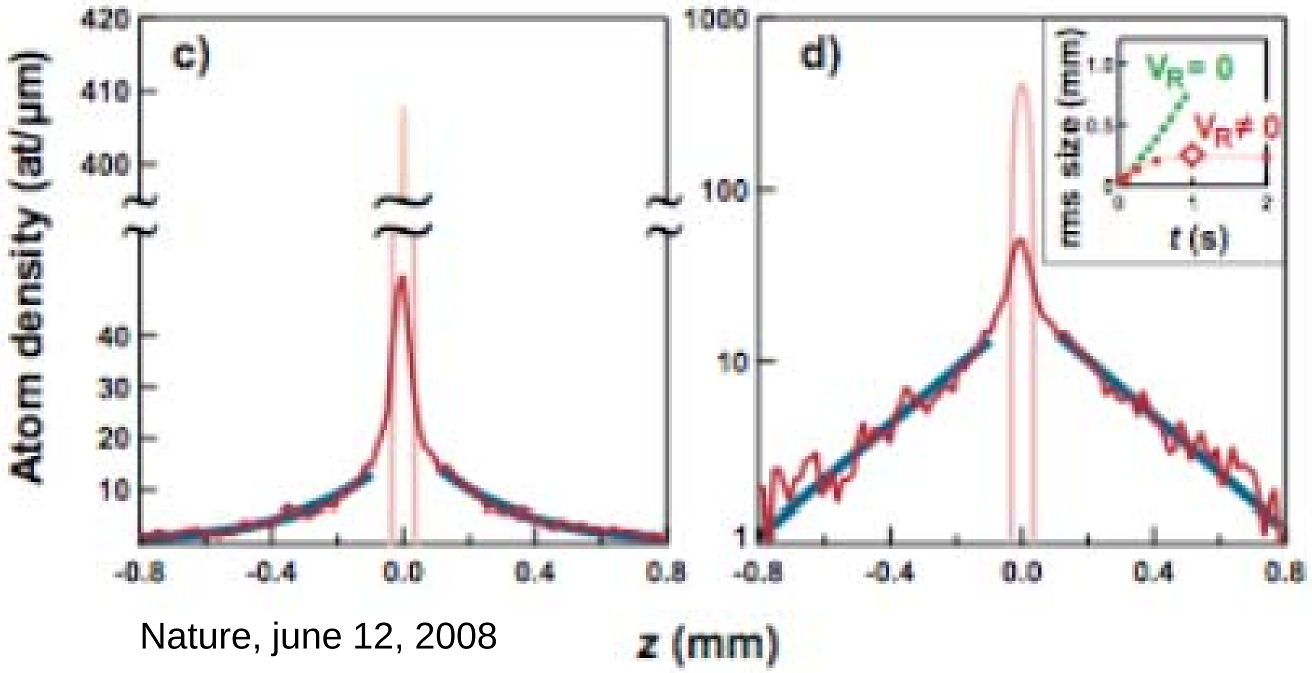




Expansion stops. Exponential localization?

Anderson localization in a weak speckle below the effective mobility edge

Direct observation of the wave function (squared modulus)



Nature, june 12, 2008

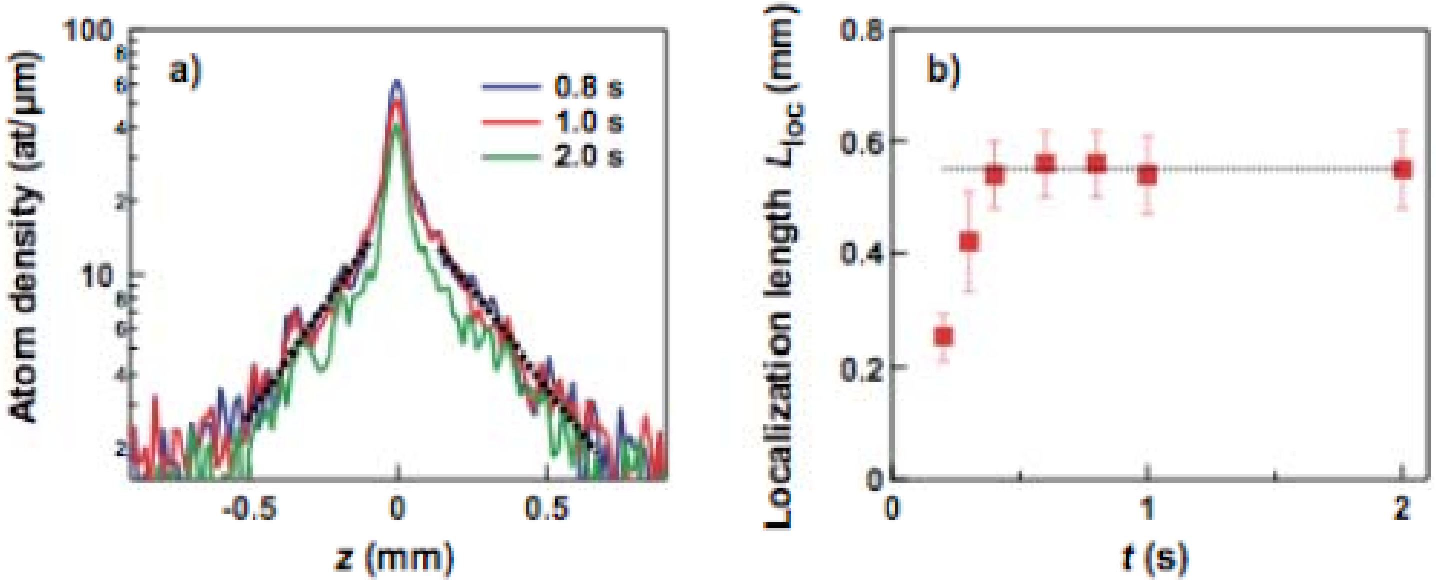
$p_{\max}\ \sigma_R = 0.65\ \hbar$

Exponential localization in the wings

Exponential fit ⇒ Localization length

Is this measured localization length meaningful?

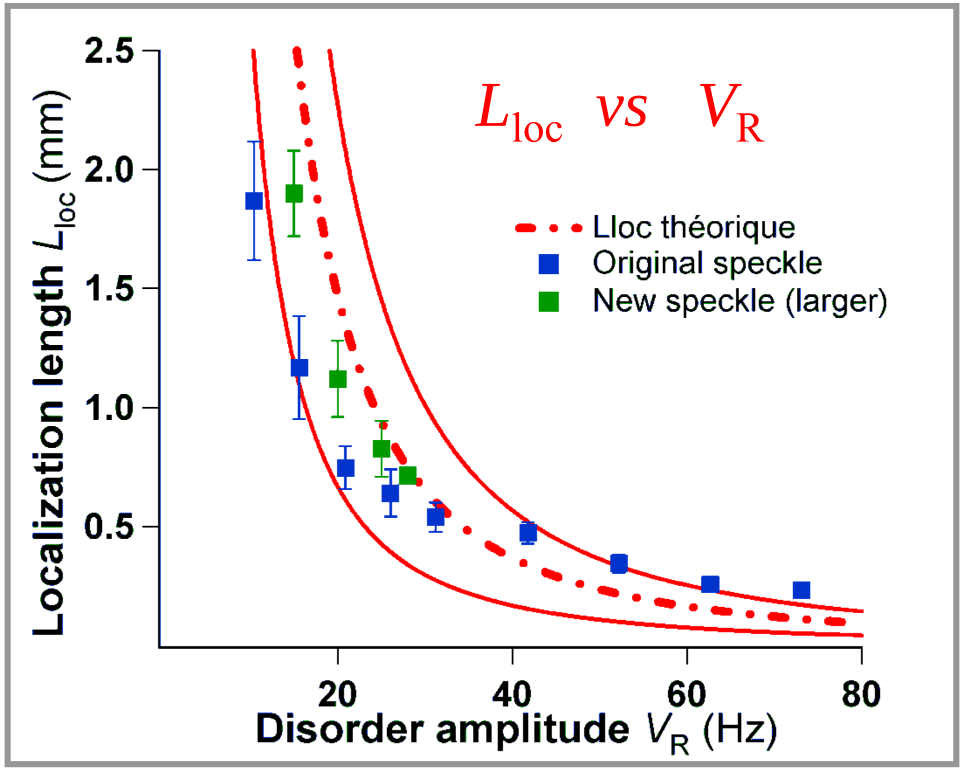
Anderson localization in a weak speckle potential below the effective mobility edge



Profile stops evolving: wings well fitted by an exponential

Fitted localization length stationary: meaningful

Comparison to perturbative calculation



$$L_{loc} = \frac{2\hbar^4 k_{max}{}^2}{\pi m^2 V_R{}^2 \sigma_R (1 - k_{max}\sigma_R)}$$

$$k_{max}\ \sigma_R = 0.65\ \hbar$$

$$\mu_{ini} = 220 \text{ Hz}$$

Magnitude and general shape well reproduced by perturbative calculation without any adjustable parameter

What happens beyond the mobility edge?

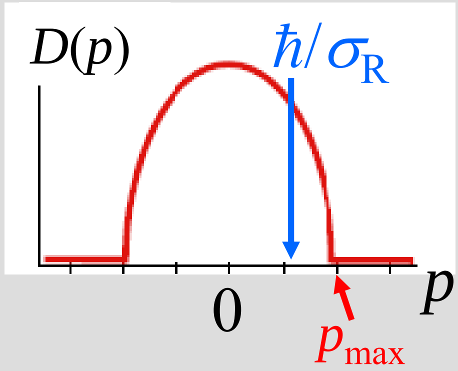
Theoretical prediction (1rst order Born approximation):

BEC with large initial interaction energy

$\Rightarrow$ Waves with p values between $\hbar/\sigma_R$ and $p_{max} = \sqrt{2M\mu_{in}}$ do not localize

$\Rightarrow$ Waves with p values below $\hbar/\sigma_R$ localize with different L_{loc}

$\Rightarrow$ power law wings ~ z^{-2}



L. Sanchez-Palencia et al., PRL 98, 210401 (2007)

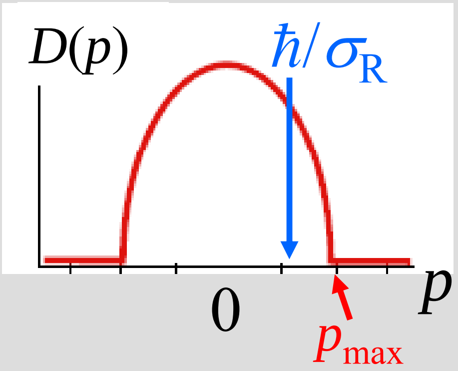
What happens beyond the mobility edge?

Theoretical prediction (1rst order):

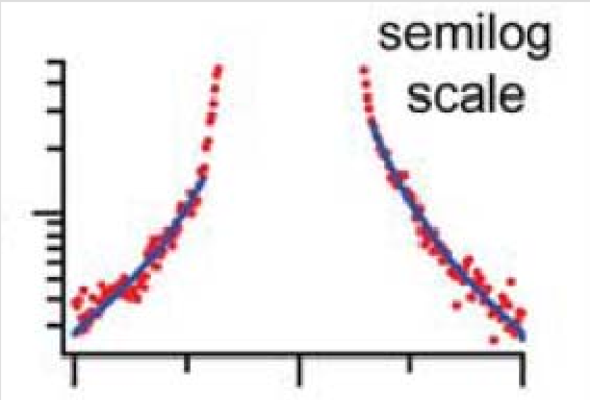
BEC with large initial interaction energy

$p_{\max} > \hbar / \sigma_R \quad \Rightarrow$ power law wings ~ z^{-2}

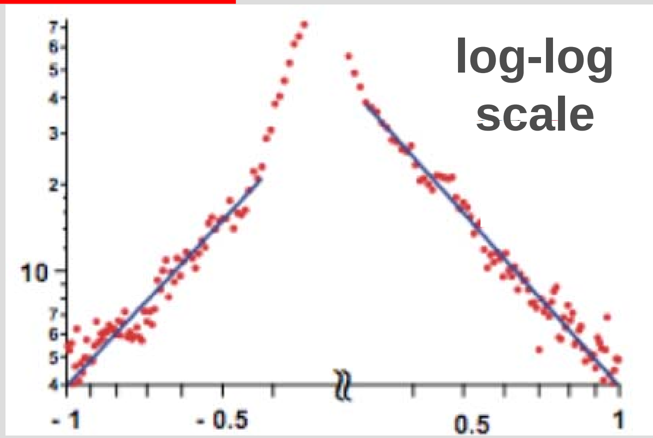
L. Sanchez-Palencia et al., PRL 98, 210401 (2007)



Experiment at $p_{\max} \sigma_R = 1.15\, \hbar$



Not exponential wings



Power law wings ~ z^{-2}

We can tell the difference between exponential and z^{-2}

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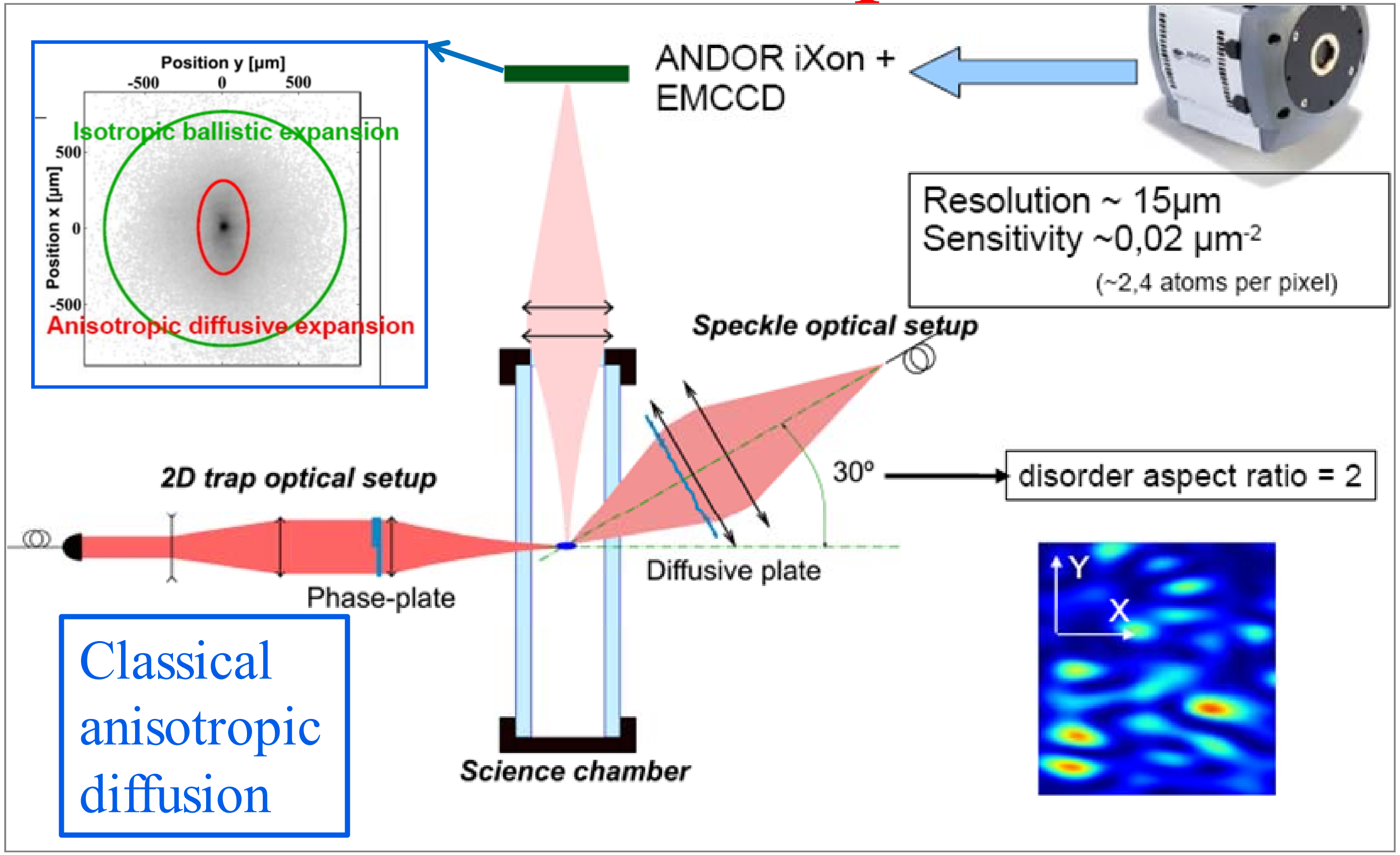
First results on 2D diffusion of ultra-cold atoms in a disordered potential

200 nK thermal sample released in a speckle potential with average 50 mK

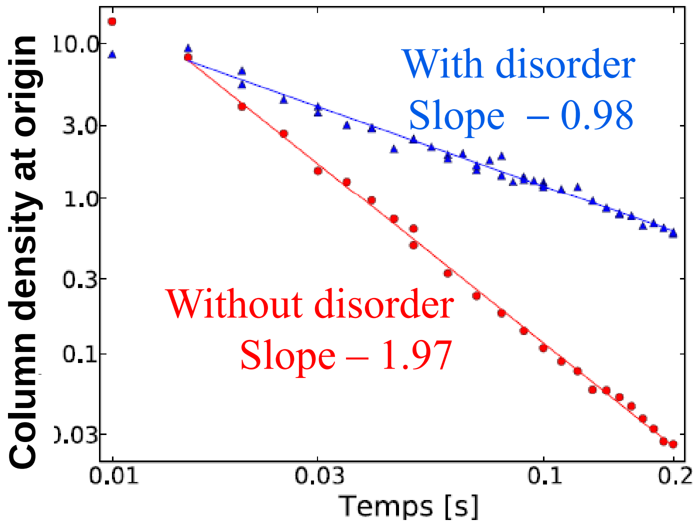


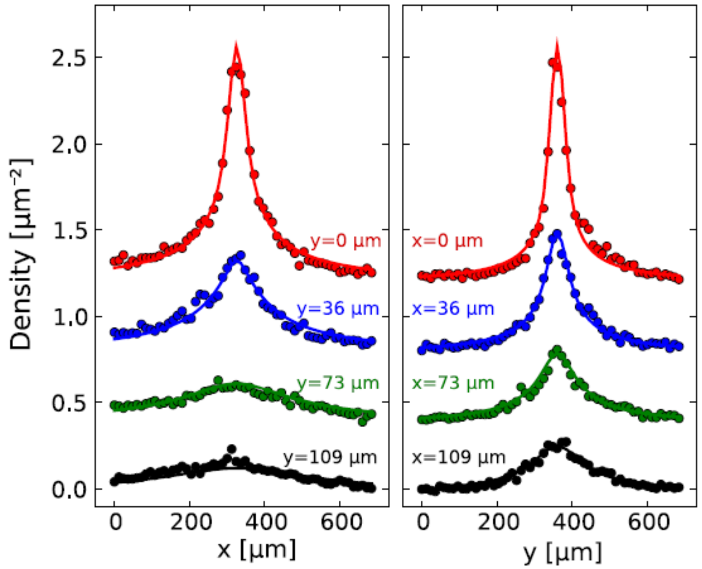
PRL **104,** 220602 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Anisotropic 2D Diffusive Expansion of Ultracold Atoms in a Disordered Potential

M. Robert-de-Saint-Vincent, J.-P. Brantut,[†] B. Allard, T. Plisson, L. Pezzé, L. Sanchez-Palencia, A. Aspect, T. Bourdel,[*] and P. Bouyer

First results on 2D diffusion of ultra-cold atoms in a disordered potential



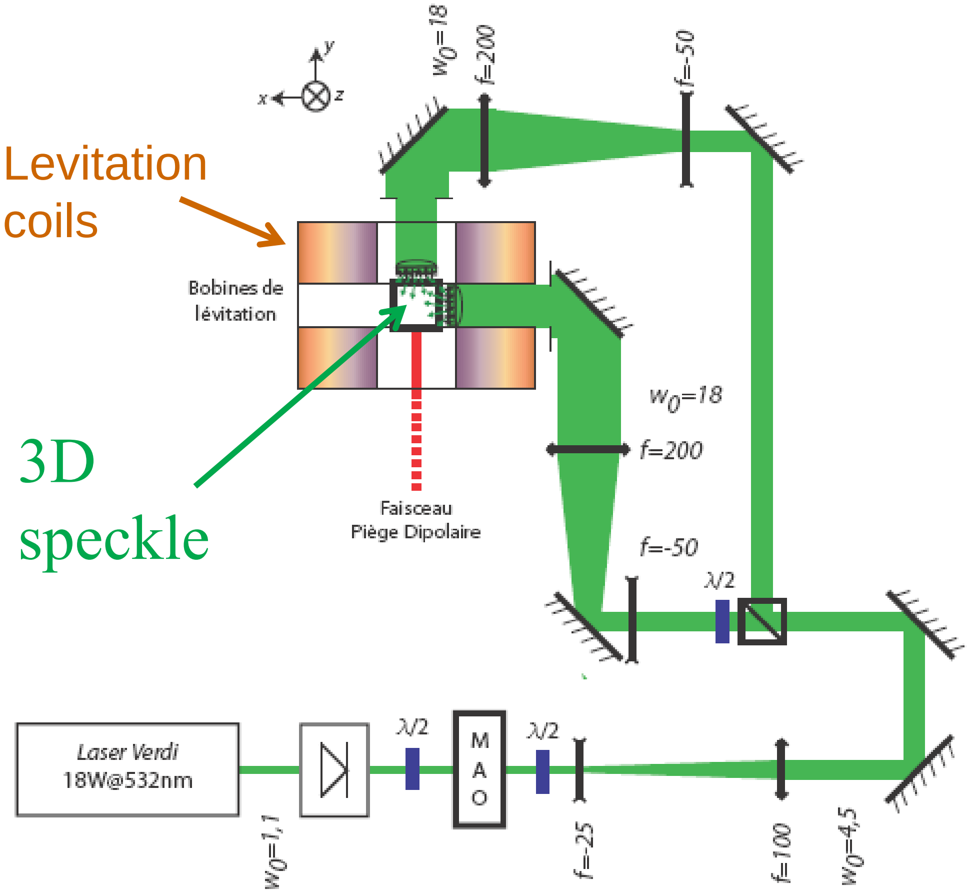


Ballistic vs.diffusive 2D expansion

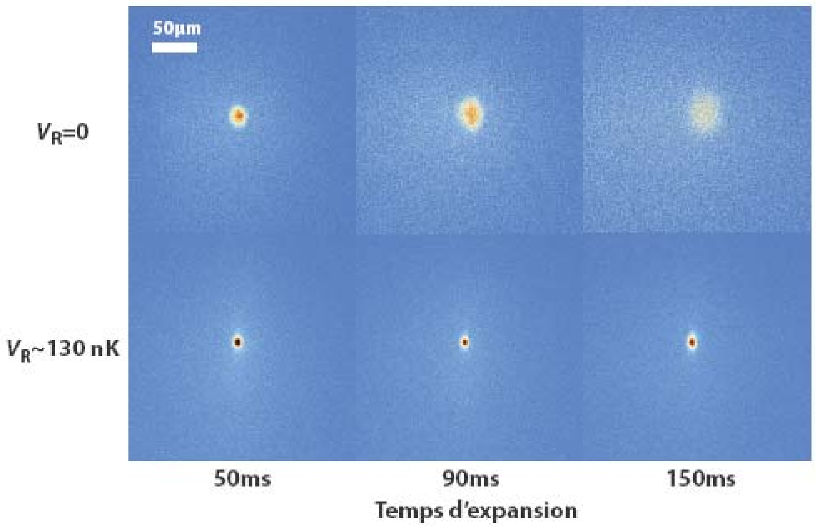
Determination of 2D (energy depending) diffusion coefficients by fits of profiles at various expansion times

M. Robert-de-Saint-Vincent et al., PRL 104, 220602 (2010)

Preliminary results on 3D diffusion of ultra-cold atoms in a disordered potential



Ultra cold atoms at 10 nK, released in a suspending magnetic gradient, without or with a 3D speckle



The disordered potential freezes the expansion

Conclusion: 1D localization

Evidence of Anderson localization of Bosons in 1D laser speckle disordered potential

- Crossover from exponential to algebraic profiles (effective mobility edge)
- Good agreement with perturbative ab initio calculations (no adjustable parameter)

Related results

Florence (Inguscio): Localization in a bichromatic potential with incommensurate periods (Aubry-André model), interaction control

Austin (Raizen), Lille (Garreau): Dynamical localization in momentum space for a kicked rotor

Hannover (Ertmer): lattice plus speckle

Rice (Hulet): Localization in speckle with controlled interactions

Urbana-Champaign (DiMarco): 3D lattice plus speckle, interactions

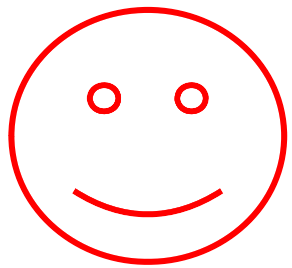
Outlook

Assets of our system

- Well controlled and well understood disordered potential (laser speckle = gaussian process)
- Cold atoms with controllable kinetic and interaction energy
- Direct imaging of atomic density (~wave function)
- Unambiguous distinction between algebraic and exponential

Future plans:

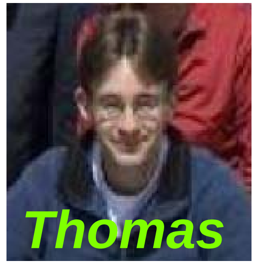
- more 1D studies (tailored disorder)
- role of interactions
- 2D & 3D studies
- fermions and bosons



Theory far from complete.

A quantum simulator!

Anderson localisation in the Atom Optics group at Institut d'Optique



Experimental teams (Philippe Bouyer)

1. David Clément, A. Varon, Jocelyn Retter
2. **Vincent Josse,** Juliette Billy, Alain Bernard, Patrick Cheinet
3. **Thomas Bourdel,** J. P. Brantut, M. Robert de SV, B. Allard, T. Plisson

   and our electronic wizards: André Villing and Frédéric Moron

Theory team (Laurent Sanchez Palencia): P. Lugan, L. Pezze, M. Piraud

Collaborations: Dima Gangardt, Gora Shlyapnikov, Maciej Lewenstein

Anderson localization of ultra cold atoms in a laser speckle disordered potential

1. Anderson localization: the naïve view of an AMO experimentalist: 1 particle quantum interference effect
2. Anderson localization with cold atoms in laser speckle
   A well controlled system
3. 1D Anderson localization: An energy mobility edge?
4. 1D Anderson localization of ultra cold atoms in a speckle disordered potential: the experimental answer
5. 2D and 3D experiments: in progress…

No localization beyond the effective 1D mobility edge?

Localization beyond the effective 1D mobility edge

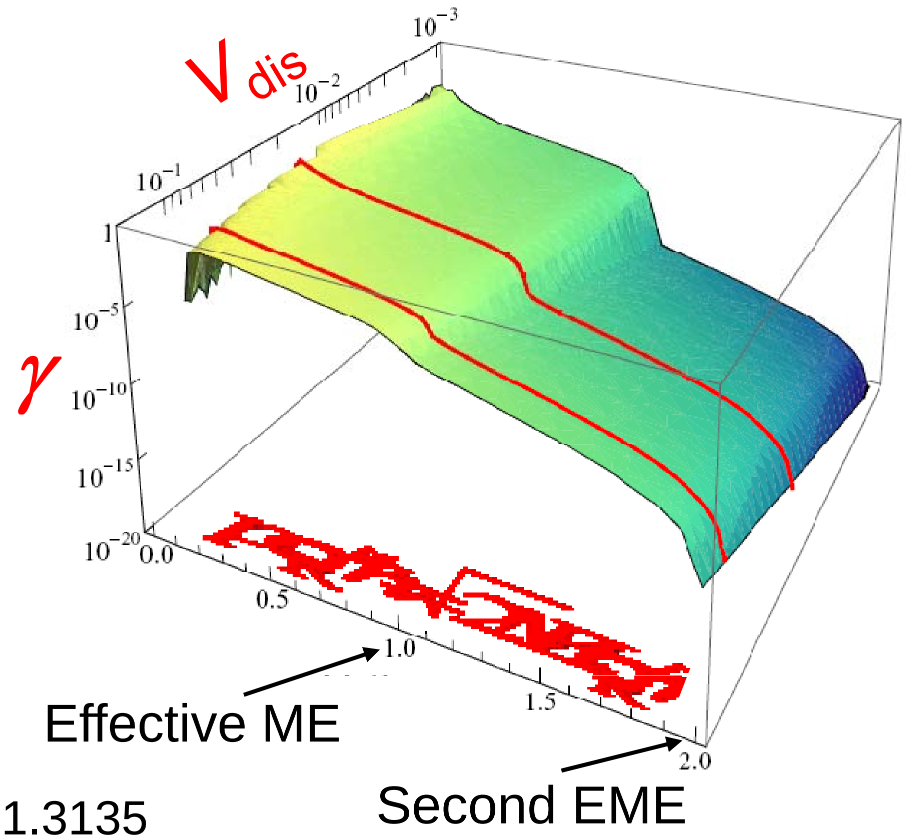
Calculations (P. Lugan, L. Sanchez-Palencia) beyond the Born approximation (4th order) (agreement with numerics, D. Delande, and diagrams, C. Müller)

Pierre Lugan et al. PRA 80, 023605 (2009)

Lyapunov coefficient γ not exactly zero but crossover to a much smaller value at effective mobility edge

Sharper crossover for weaker disorder

Effective transition in a finite size system



* analogous results by E. Gurevich, 0901.3135

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