Localization of ultra-cold atoms in a laser speckle

Dynamics and thermodynamics
in Isolated Quantum Systems
KITP, August 21, 2012

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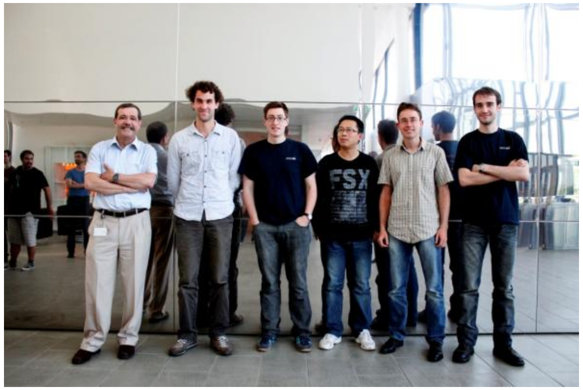
Post doc applications welcome

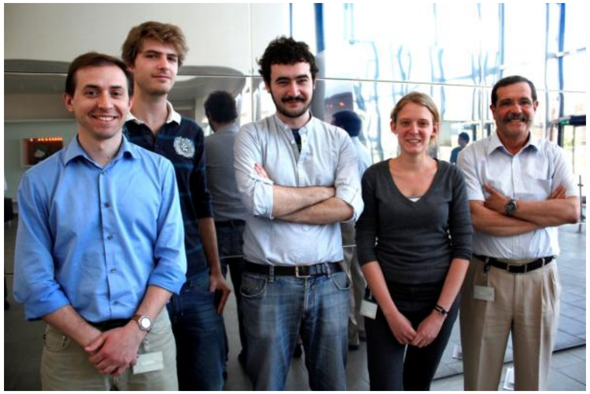
Photo Jean-François Dars

Ultra cold atoms in a laser speckle: from Anderson Localization to… Coherent Back Scattering

1. Anderson localization: the naïve view of an AMO experimentalist
2. Cold atoms in laser speckle?
3. 1D Anderson Localization?
4. 3D Anderson Localization?
5. Coherent Back Scattering?
6. Outllook and questions to experts in quantum dynamics

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





Experiments (Philippe Bouyer →Bordeaux)

1. **Vincent Josse,** J. Billy, A. Bernard, P. Cheinet, F. Jendrzejewski, K. Müller, J. Richard
2. **Thomas Bourdel,** J. P. Brantut, M. Robert dSV, B. Allard, T. Plisson , G. Salomon

and our electronic wizards: A.Villing, F. Moron

Theory (Laurent Sanchez Palencia): P. Lugan, M. Piraud, L.Pezze, G. Carleo, S Lellouch

Collaborations: M Lewenstein, G Shlyapnikov, Thierry Giamarchi, M Holzmann

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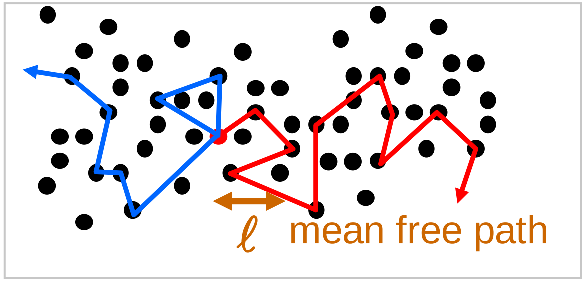
Anderson localization: a model for metal/insulator transition induced by disorder

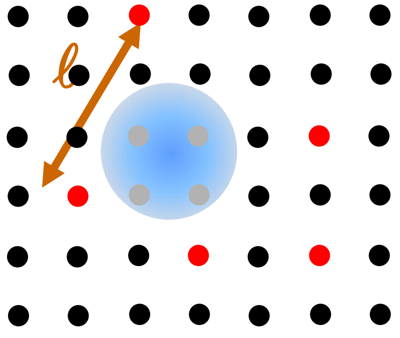
Classical model of metal: disorder hinders, does not cancel, conduction



- Classical particles bouncing on impurities
- Matter waves scattering on impurities + incoherent addition

$\Rightarrow$ delocalized (extended) states: conductor

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



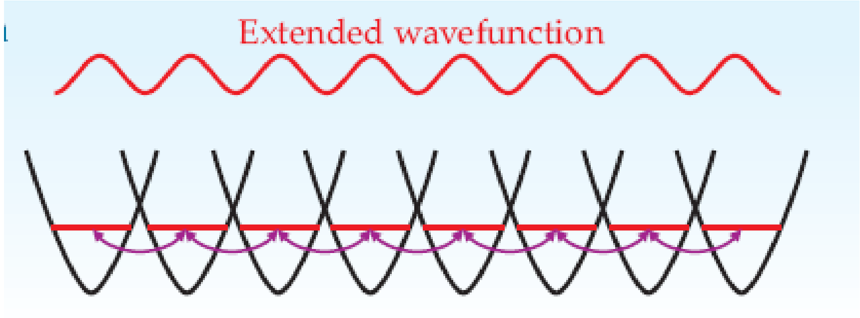
Tight binding model with disorder : $\Rightarrow$

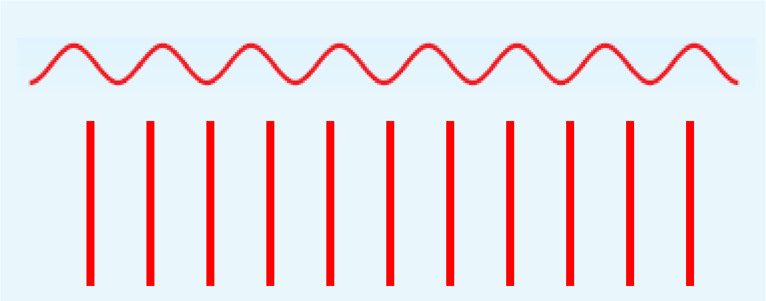
$\Rightarrow$ localized states: insulator

Quantum effect: addition of quantum amplitudes of hopping

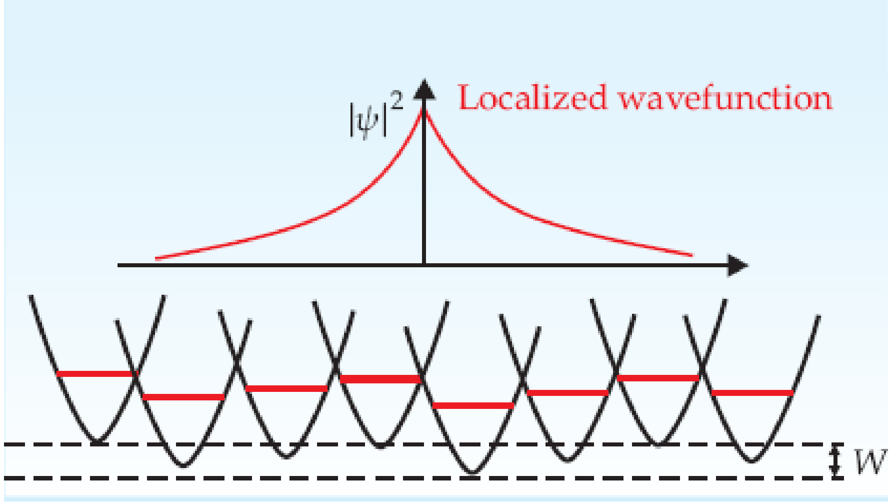
3D mobility edge (Ioffe Regel, Mott) $E \leq \dfrac{\hbar^2}{2m\ell^2}$

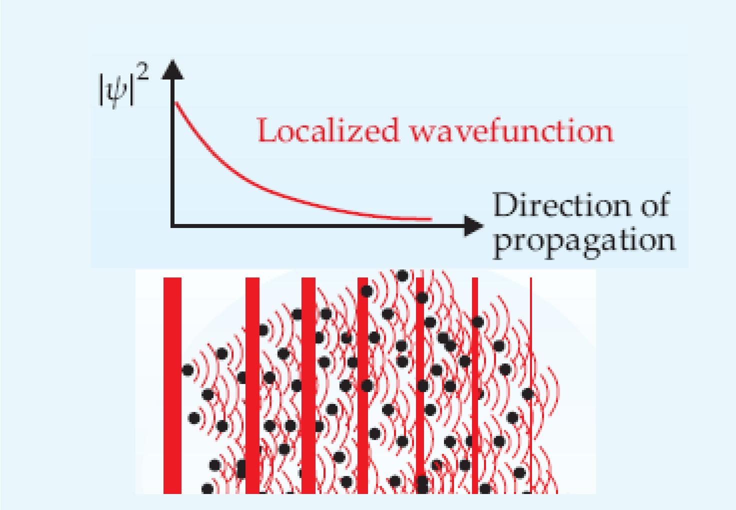
Tight binding model vs. wave model
Condensed matter vs. AMO physics





Bloch wave in a perfect crystal ⇔ Freely propagating wave





Disordered crystal ⇔ Scattering from impurities

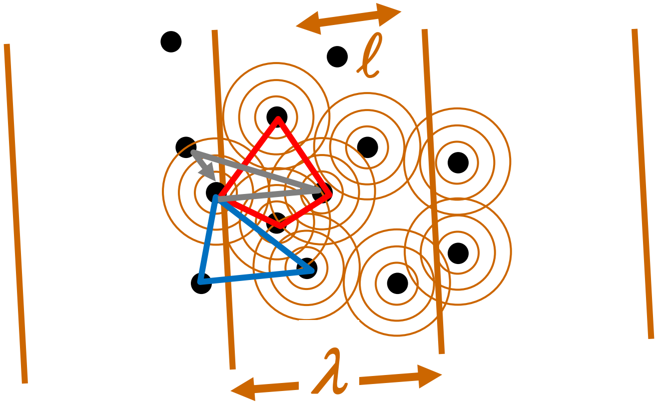
A.A, M Inguscio, Physics today August 2009

Anderson localization: the point of view of an AMO physicist

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

- coherent addition of trajectories returning to origin
- destructive interference in any direction

$\Rightarrow$ Localized states: insulator



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

Akkermans&Montambaux, B. Van Tiggelen (Les Houches 1999)

Main features:

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

The quest of AL with classical waves

Electromagnetic waves scattering on impurities:

AL not easy to discriminate from ordinary absorption

Microwaves (cm) on dielectric spheres:

- Chabonov et al., Nature 404, 850 (2000)

Light on dielectric microparticles (TiO_2):

- Wiersma et al., Nature 390, 671 (1997)
- 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

Convincing experiments with light on 2D or 1D photonic lattices:

- T. Schwartz et al. (M. Segev), Nature 446, 52 (2007)
- Lahini et al. (Silberberg), PRL 100, 013906 (2008).

Acoustic (and seismic) waves:

RL Weaver (1990… 2008)

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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 (1 nm to 10 μm)
- Pure potentials (no absorption), controllable disorder
- Many observation tools: absorption or fluorescence imaging, time of flight, Bragg spectroscopy, …

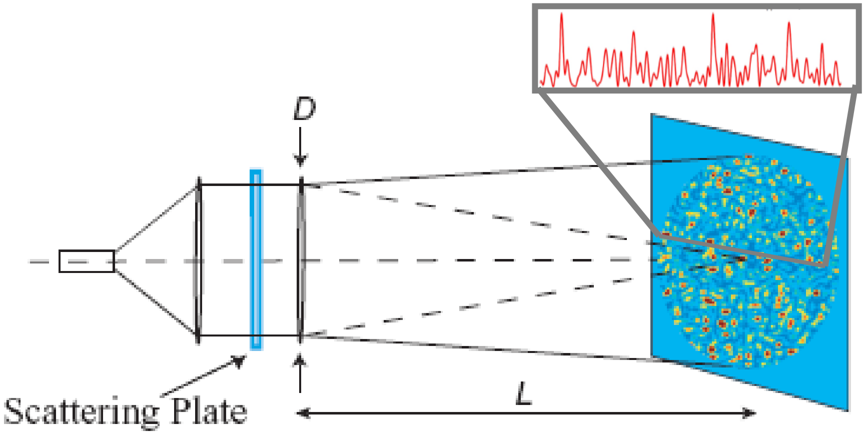
A new feature: interactions between atoms

- A hindrance to observe AL (pure wave effect for single particle)
- New interesting problems, many-body physics (T. Giamarchi, B. Altshuler, S. Skipetrov, D. Shepelyansky…)

Laser speckle: a well controlled disorder

Blue detuned ($\delta > 0$) light creates a repulsive potential for atoms, proportional to light intensity

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



Laser speckle: well controlled random pattern
(Complex electric field = Gaussian random process, central limit theorem)

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

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

Intensity inherits some properties of underlying Gaussian process

Easy to calculate autocorrelation function

Speckle grain size $\sigma_R \simeq \frac{\lambda L}{\pi D}$

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

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1D Anderson localization?

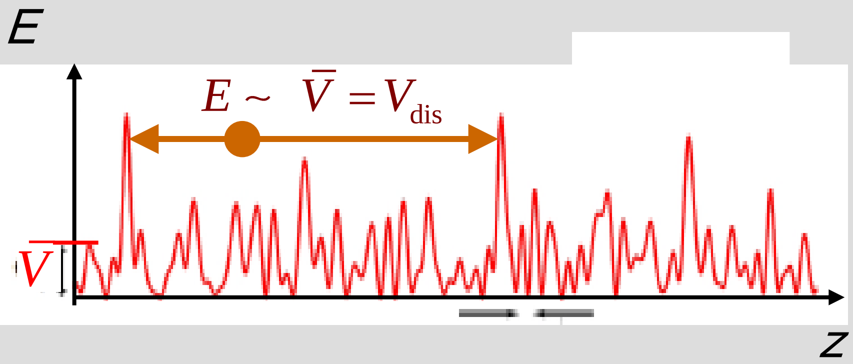
Theorist statement: all states localized in 1D. Why bother?

Abrahams, Anderson, Licciadello, Ramakkrishnan, PRL 1979

Experimentalist: Can we observe Anderson-like localization?

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

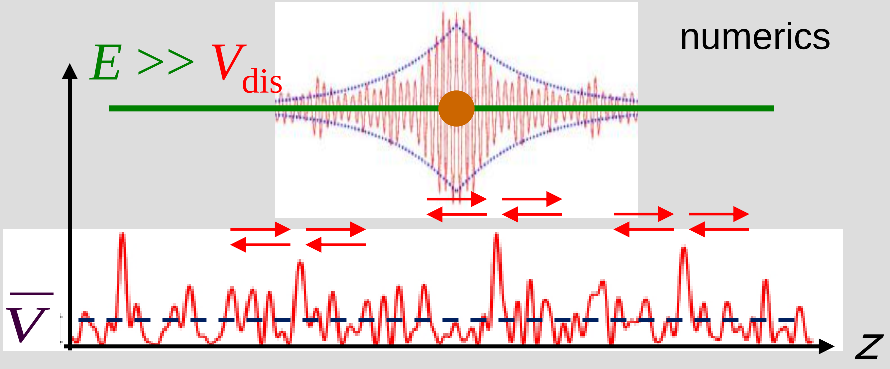
Classical localization, not Anderson



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

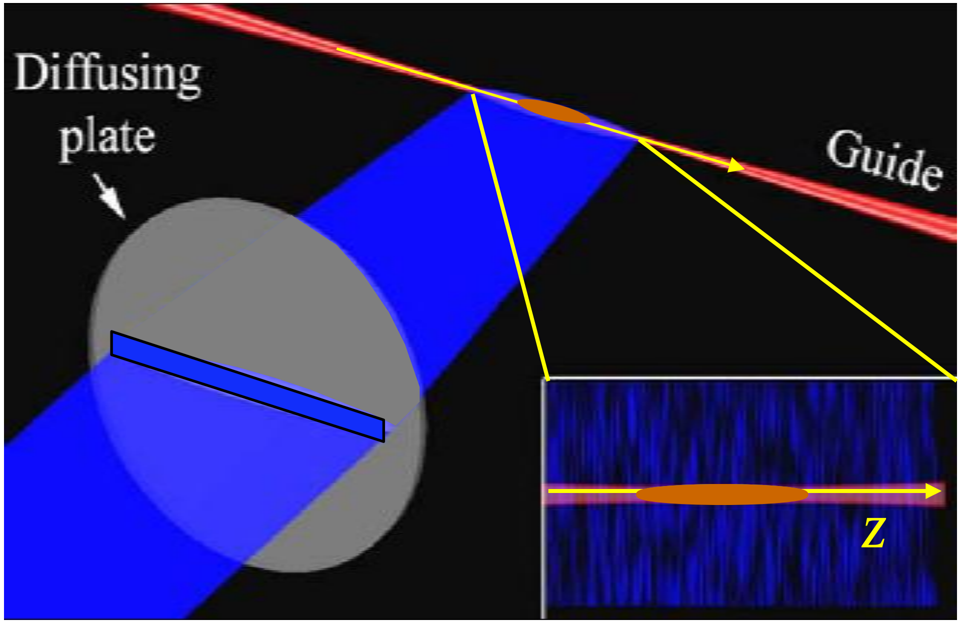
Looks like Anderson localization!

Worth testing it



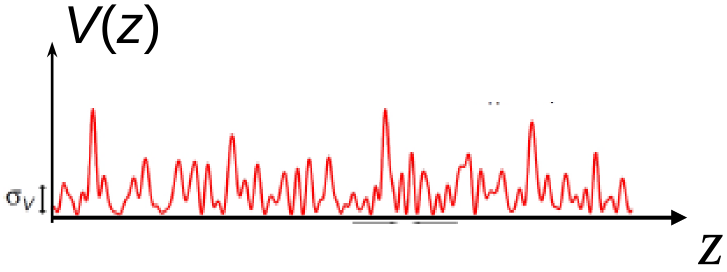
A 1D random potential for 1D guided atoms

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



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 and guided along *z* (focused laser, $\delta < 0$)

$$2R_z^{\mathrm{TF}} \approx 300\,\mu\text{m} \;;\; 2R_\perp^{\mathrm{TF}} \approx 3\,\mu\text{m}$$

Imaged with resonant light: many times single atom observation

1 D situation for the elongated BEC.

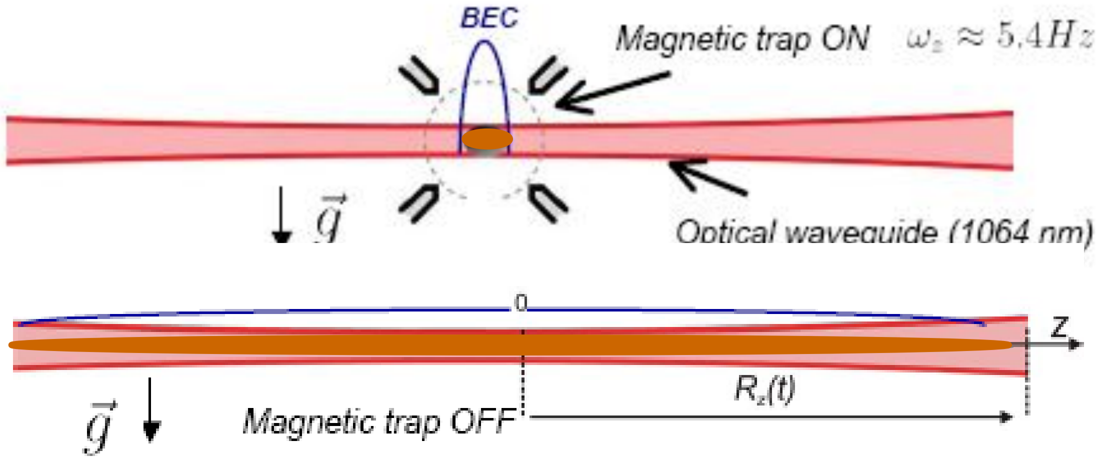
Many speckle grains covered (self averaging system = ergodic)

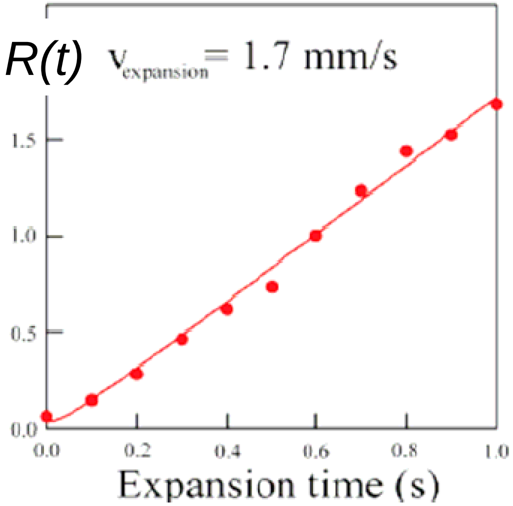
1D situation: invariant transversely to z

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





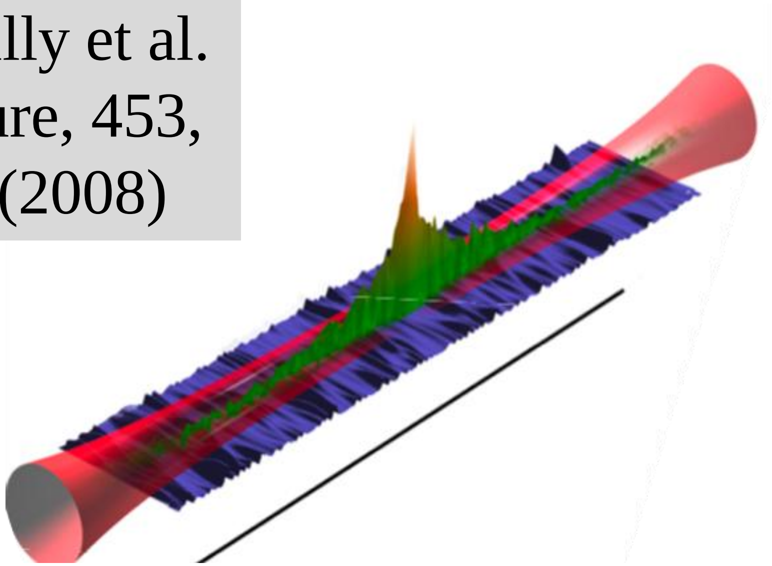
Initial interaction energy μ_{in} converted into kinetic energy

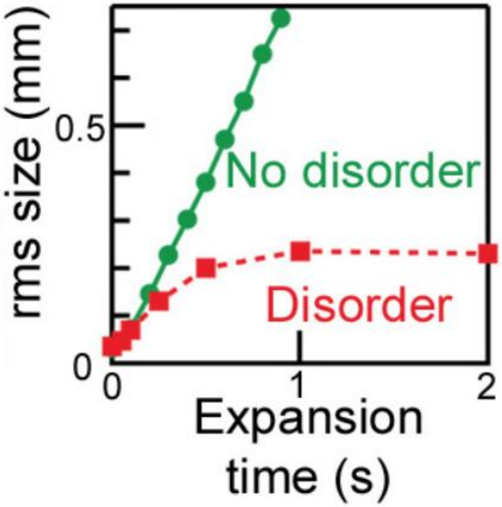
$\Rightarrow$ After a while, interaction free ballistic expansion

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

1D Anderson localization in a weak speckle

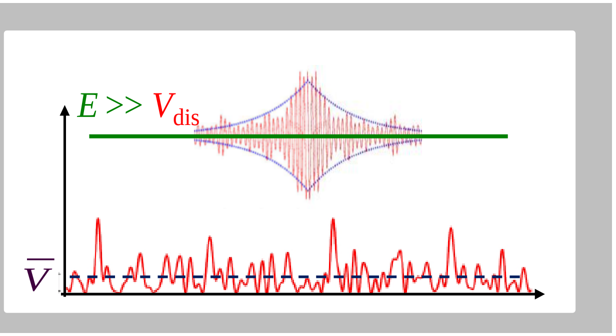
J. Billy et al.
Nature, 453,
891 (2008)





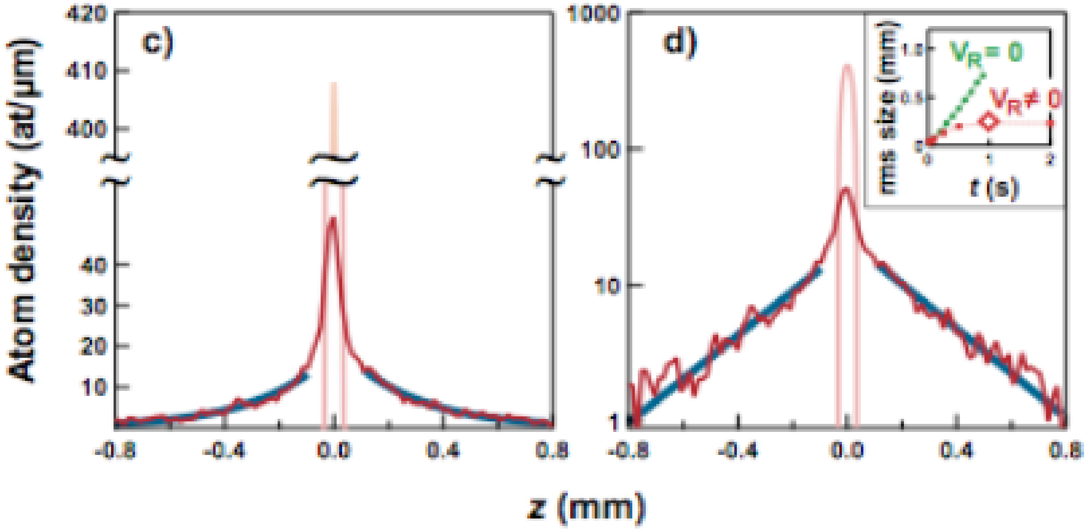
Expansion stops. Exponential localization?

Weak
disorder
regime
$V_R = 0.1\ \mu_{\mathrm{ini}}$

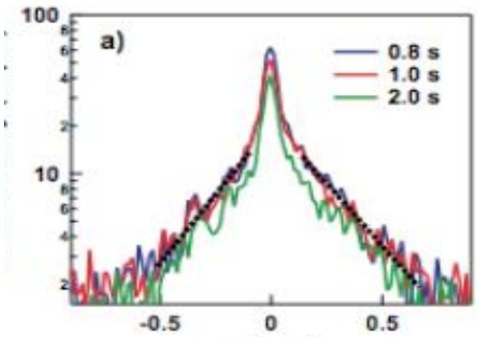


1D Anderson localization in a weak speckle

Direct observation of the wave function (squared modulus)



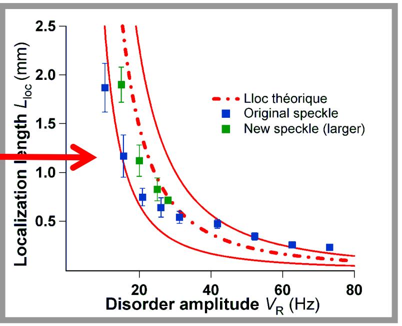
Profile stops evolving



Exponential fit in the wings ⇒ Localization length agreement with (Born 1^{rst} order) calculation

Speckle 1D disorder: effective mobility edge

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



Related results in Florence (Inguscio), Austin (Raizen), Lille (Garreau), Hannover (Ertmer), Rice (Hulet)

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

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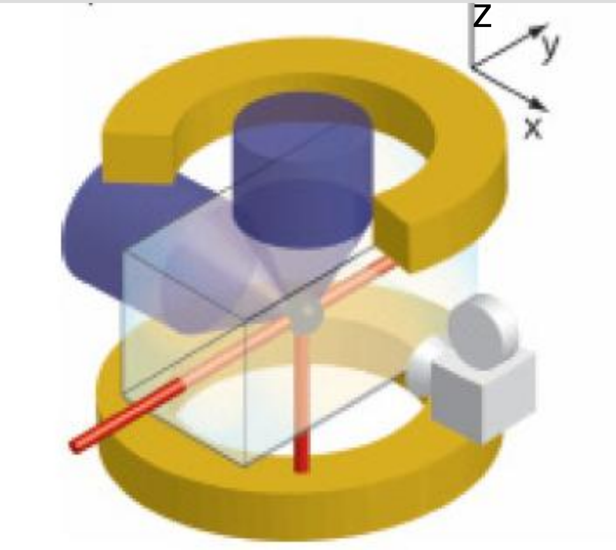
3D localization of ultra-cold atoms in a laser speckle disordered potential: apparatus

Ultra-cold atoms (BEC), suspended against gravity (mag field gradient) ; released in repulsive disordered potential

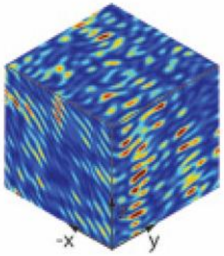


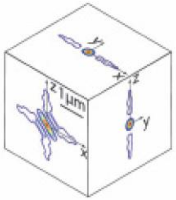
F. Jendrzejewski et al., Nature Physics 8, 398 (2012)

Fluorescence integrated along *x*: column density *n*(*y*,*z*)

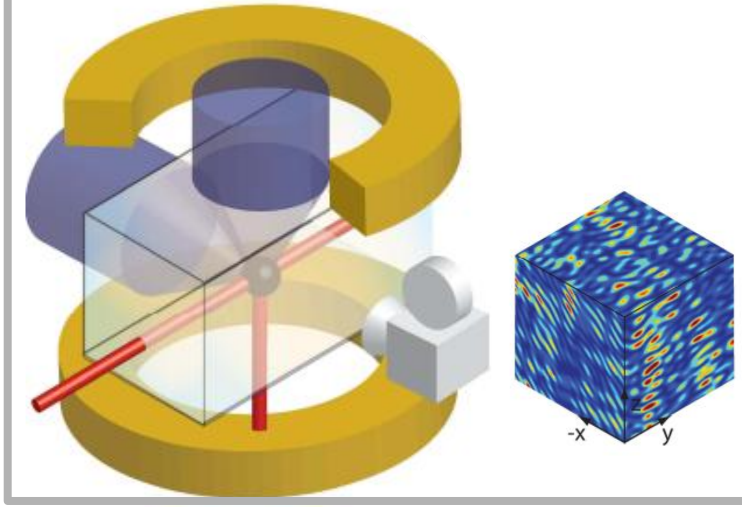
Disordered optical potential: Two crossed coherent speckle fields, with same polarization:

- Tunable amplitude of disorder $(0 < \overline{V_{\mathrm{dis}}}/h < 1.1\mathrm{kHz})$
- Small correlation lengths in all directions (σ_u = 0.11, 0.27, 0.08 µm), but not isotropic
- Low classical percolation threshold $(< 10^{-2}\,\overline{V_{\mathrm{dis}}})$

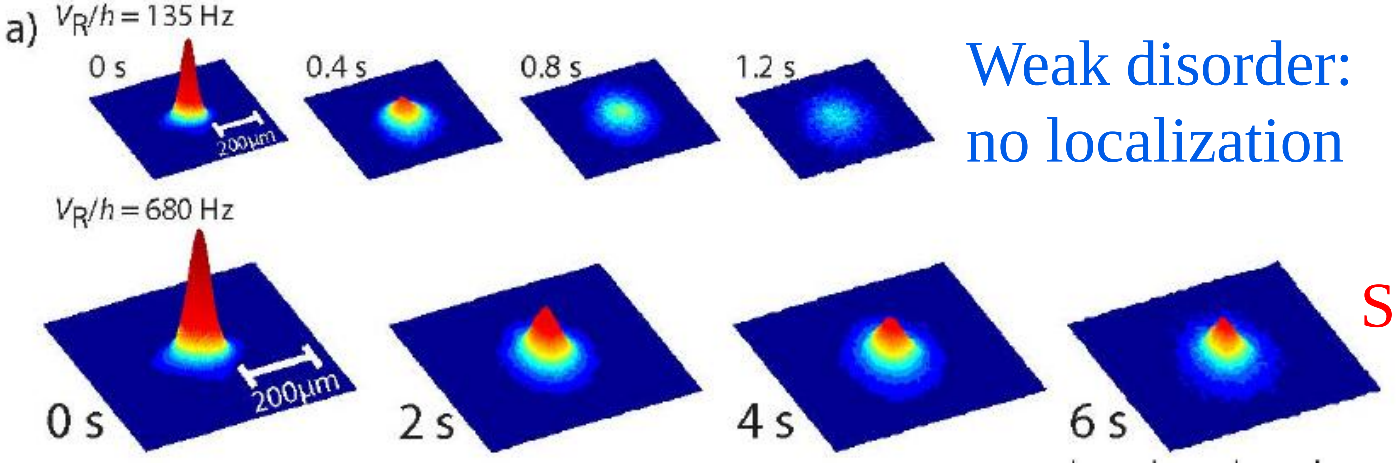




3D localization of ultra-cold atoms in a laser speckle disordered potential



- Ultra-cold atoms (BEC, $\mu_{ini} / h = 40$ Hz; T = 1nK) released
- Disordered ramped up rapidly
- Cloud of atoms observed after variable delay



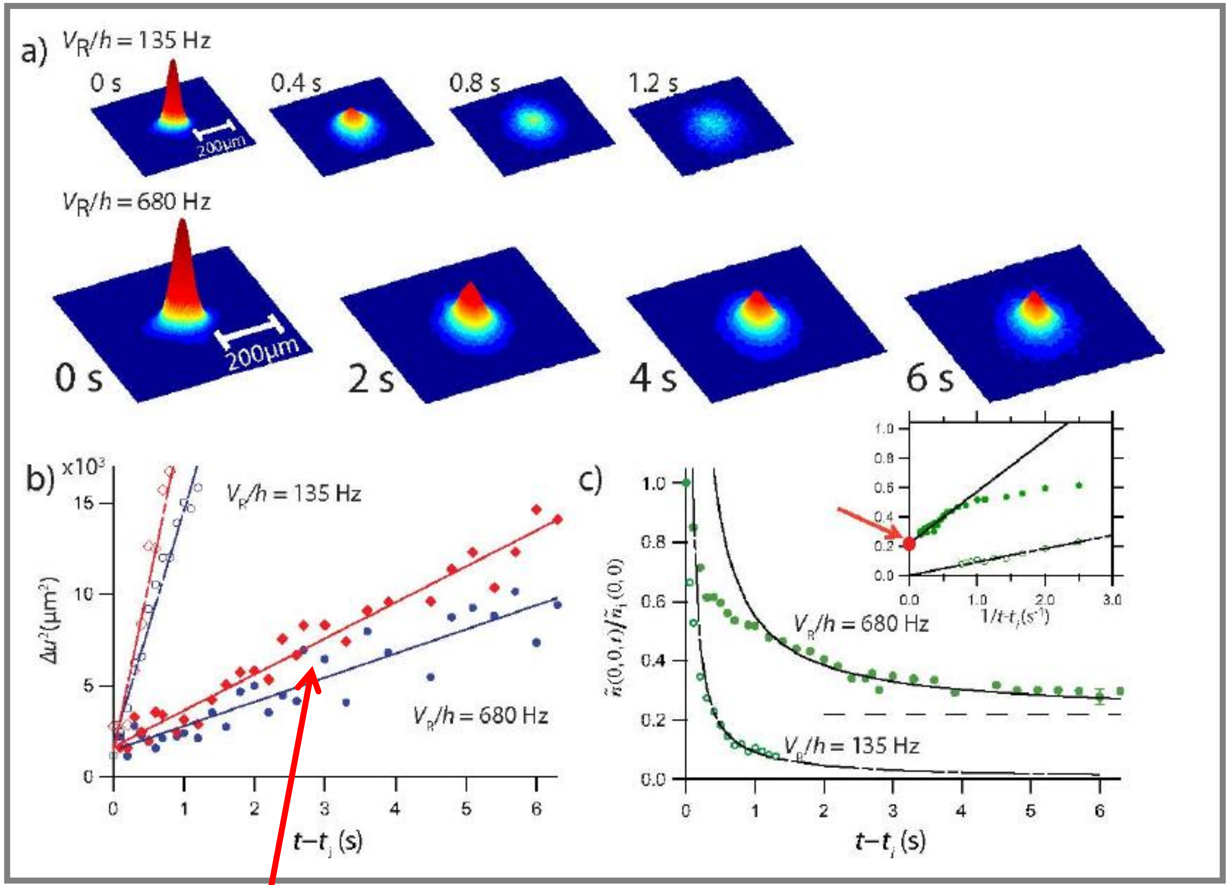
Weak disorder: no localization

F. Jendrzejewski et al., Nature Physics 8, 398 (2012)

Strong disorder: localization

Related experiment in DeMarco’s group: Kondov et al., Science 334, 66 (2011)

Diffusive and localized components: phenomenological analysis



Column density taken as sum of:

$\Rightarrow$ localized peak, replica of initial profile

$\Rightarrow$ diffusing component

$\tilde{n}_D(0,0,t)$ decays as $1/t$ $\Rightarrow$ localized fraction

Mean squared radii grow linearly with time: $\Rightarrow$ determination of the diffusion coefficients

$$\tilde{n}(y,z,t) = f_{\mathrm{loc}} \times \tilde{n}_{\mathrm{i}}(y,z) + \tilde{n}_{\mathrm{D}}(y,z,t)$$

stationary

diffusing

Theoretical analysis

Sudden application of the (strong) disorder

⇒ wide energy distribution of the atoms.

Results of calculation (self-consistent theory of localization)

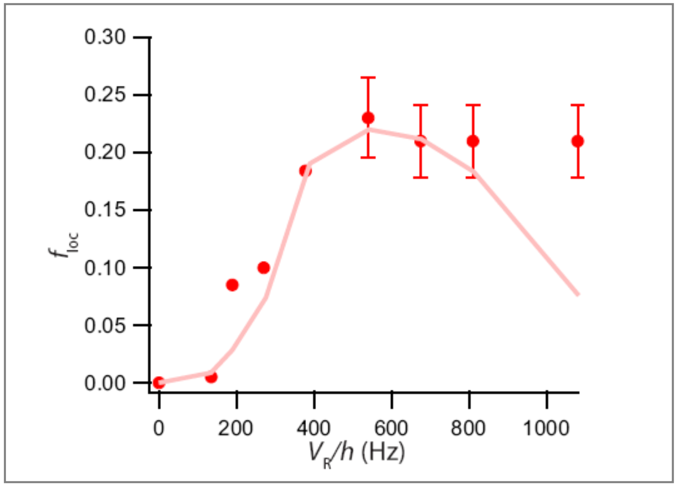
⇒ Always a fraction of the atoms above mobility edge

⇒ Localization lengths too small to be oberved (⇒ localized part a replica of the initial distribution)

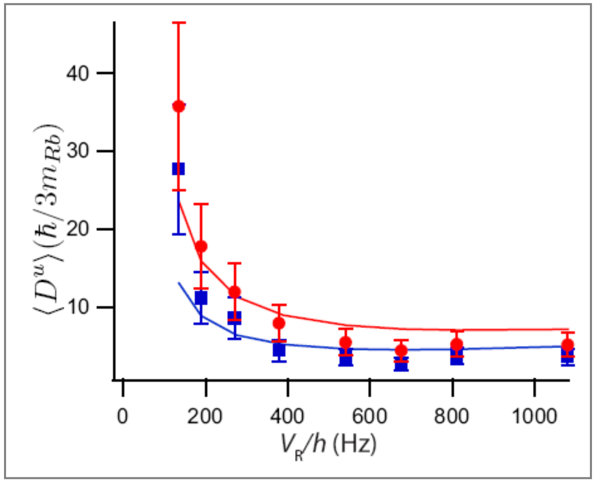
Theory

(one adjustable parameter, partly understood):

solid curves



Localized fraction



Diffusion coefficients

M. Piraud, L. Pezzé, L. Sanchez-Palencia, arXiv1112.2859,
Matterwave transport and AL in anisotropic 3D disorder

Localization of ultra cold atoms in 3D disordered potential: summary

- Direct observation of localized and diffusing components
- Phenomenological measurements (not theory dependent) of localized fraction and diffusion coefficients.

Localization cannot be explained

  - by classical trapping below the classical percolation threshold
  - by quantum trapping in local minima of the disorder

Convincing theoretical description of the observations

Hard to conclude that it is not Anderson Localization

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Still missing: a smoking gun of the role of coherence in the observed localisation

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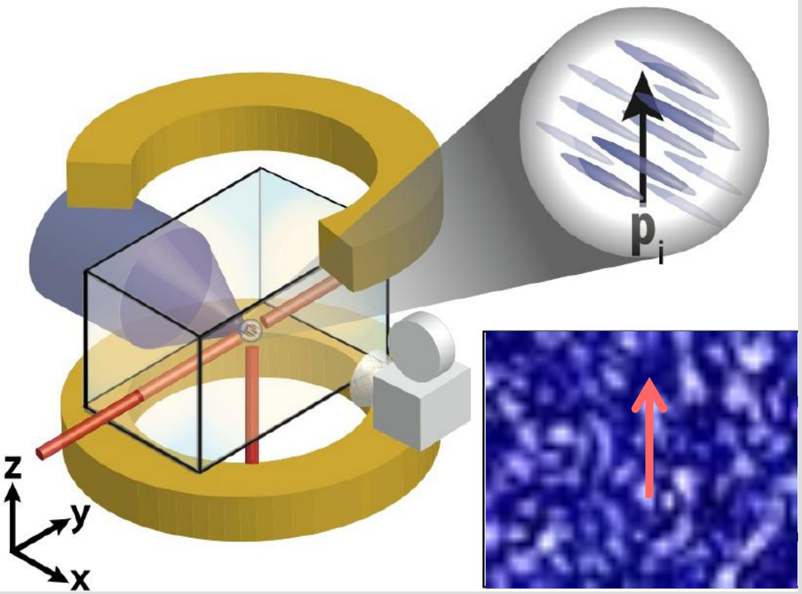
Ultra cold atoms with well defined momentum launched in 2D disorder

Atoms launched with a momentum **$\mathbf{p}_i$** in a quasi 2D speckle* (elongated)

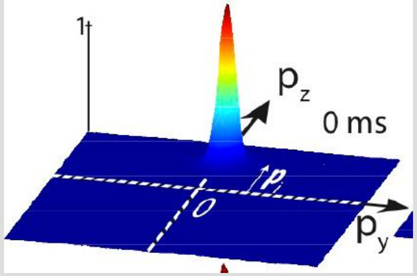
Narrow momentum distribution :

- Harmonic kick on expanding BEC→ stopped atoms
- Magnetic kick



Time of flight ⇒ initial velocities distribution:

$V_i = 3.3 \pm 0.2$ mm / s

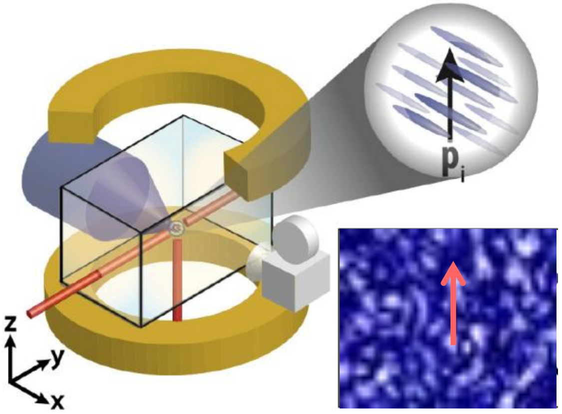


F. Jendrzejewski et al., arXiv 1207, 4775

* Theoretical proposal: Cherroret et al., PRA85, 01604 (2012)

Evolution of momentum distribution in the disordered potential

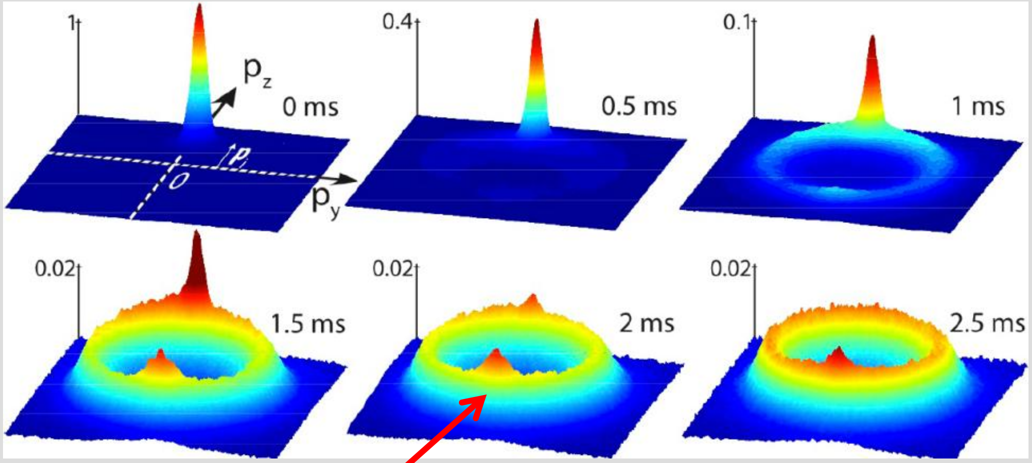
Atoms launched in 2D disorder with well defined momentum **p_i**



F. Jendrzejewski et al., arXiv 1207, 4775

Momentum distribution after diffusion time *t*

- Elastic scattering ring: determination of scattering and transport times
- Coherent Back Scattering peak

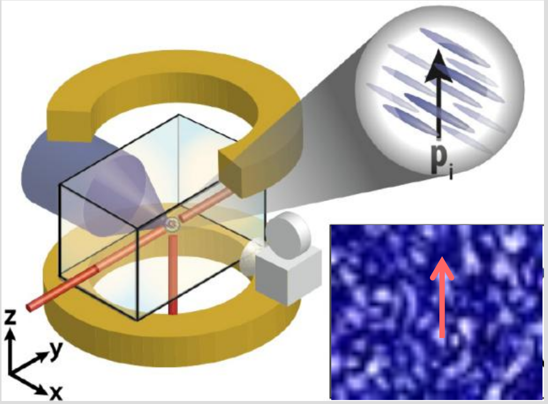


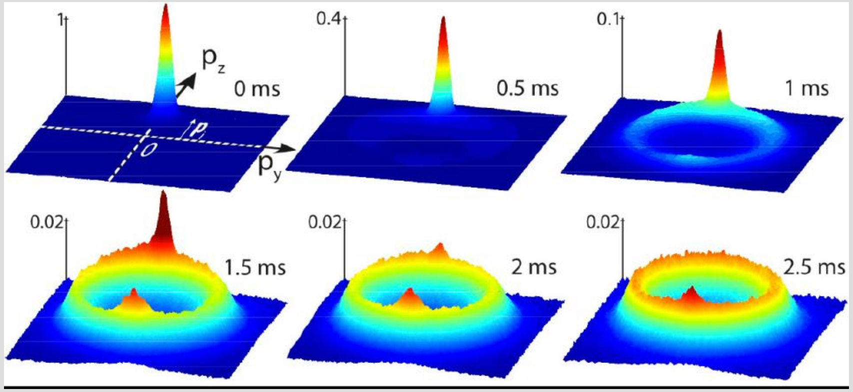
Related results G. Labeyrie et al., arXiv 1206.0845

Atomic Coherent Back Scattering as an evidence of coherence

Atoms launched with $\mathbf{p}_i$

Momentum distribution after diffusion time *t*

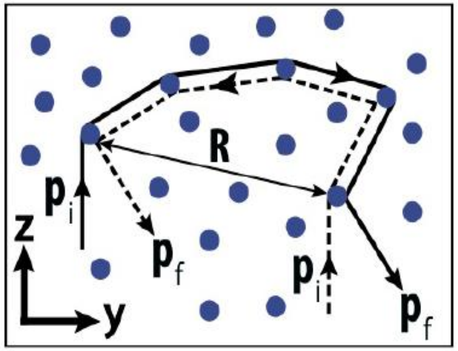




- Elastic scattering ring: determination of scattering and transport times
- Coherent Back Scattering peak

CBS peak: interference between counter propating multiple scattering paths for $\mathbf{p}_f = -\mathbf{p}_i$

Width decreases as $R^{-1} = (2Dt)^{-1/2}$



F. Jendrzejewski et al., arXiv 1207, 4775

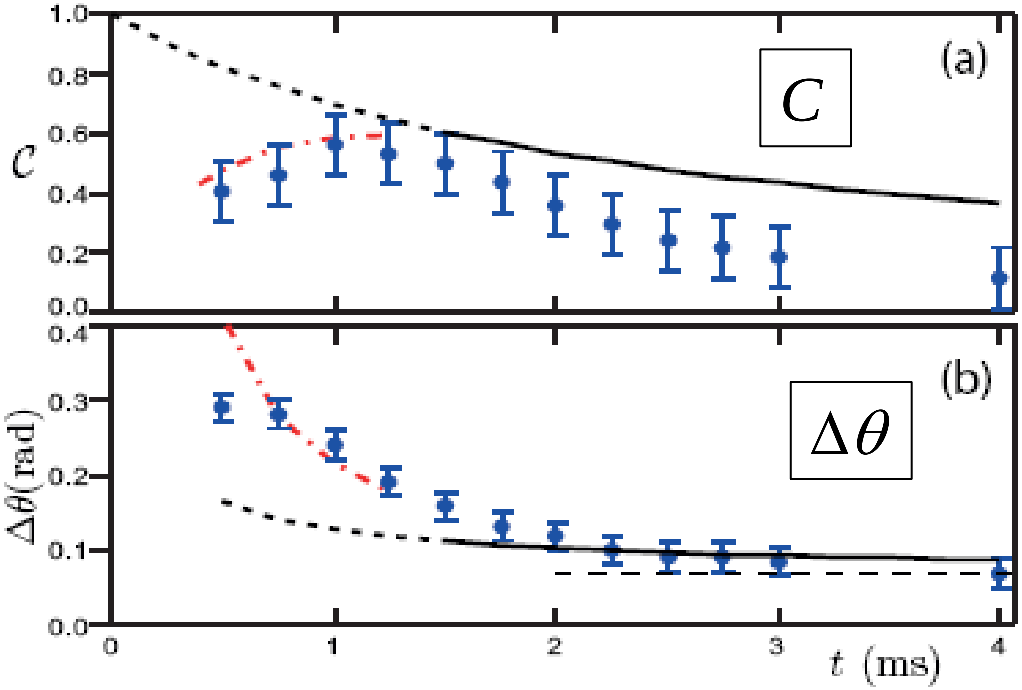
Peak width evolution agrees with model (no adjust. parameter)

Time resolved observation of atomic CBS

Evolution of CBS peak contrast C and width $\Delta\theta$, from short times to long times regime

Cross over

- from short times regime, where single scattering dominates (no CBS)
- to long times regime where multiple scattering dominates ($\Rightarrow$ pure CBS)



Excellent agreement, without adjustable parameter: direct evidence of the role of coherence in quantum transport

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Outlook and questions

3D AL

- measure the exact value of the mobility edge
- measure the localization lengths vs energy
- measure critical exponents

Demands a better control of the atom energy in disorder.

Adiabatic ramping of the disorder?

2D: AL will not be easy to observe, interesting results already obtained (PRL **104** 220602, NJP **13** 095015; PRA **84** 061606, **85** 033602)

Add controlled interactions: a big challenge for theorists

More evidence of role of coherence in quantum transport:
Scrambling disorder to destroy coherence between loops: **Heating?**

A quantum simulator?

Outlook and questions

3D AL
- measure the exact value of the mobility edge
- measure the localization lengths vs energy
- measure critical exponents

Demands a better conrol of the atom energy in disorder.
Adiabatic ramping of the disorder?

2D: AL will not be easy to observe, interesting results already obtained (PRL **104** 220602, NJP **13** 095015; PRA **84** 061606, **85** 033602)

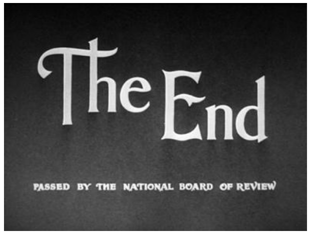
Add controlled interactions: a big challenge for theorists

More evidence of role of coherence in quantum transport:
Scrambling disorder to destroy coherence between loops: **Heating?**

Many challenges for theorists:
genuine **quantum theorists stimulator**

Ultra cold atoms in a laser speckle: from Anderson Localization to… Coherent Back Scattering

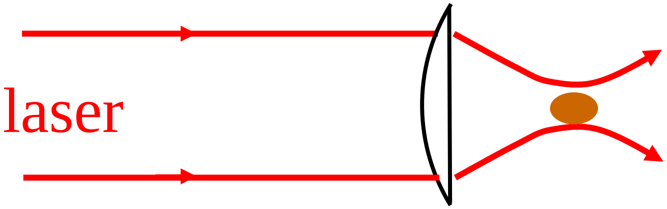
1. Anderson localization: the naïve view of an AMO experimentalist: single particle interference effect
2. Cold atoms in laser speckle? A well controlled system
3. 1D Anderson Localization? More interesting than expected
4. 3D Anderson Localization? Yes we can
5. Coherent Back Scattering? Evidence for coherence
6. Outllook: more to come, many open questions



Optical dipole potential

Inhomogeneous light field: $\mathbf{E}(\mathbf{r},t)=\mathbf{E_0}(\mathbf{r})\cos[\omega t-\varphi(\mathbf{r})]$

Induced atomic dipole: $\langle \mathbf{D}_{\mathrm{at}}(t)\rangle_{\mathbf{r}_{\mathrm{at}}} = \alpha\,\mathbf{E}(\mathbf{r}_{\mathrm{at}},t)$



Far from atomic resonance, α real

- $\alpha < 0$ above resonance
- $\alpha > 0$ below resonance

Interaction energy: $W=-\overline{\mathbf{E}(\mathbf{r}_{\mathrm{at}},t)\langle \mathbf{D}_{\mathrm{at}}(t)\rangle_{\mathbf{r}_{\mathrm{at}}}} = -\alpha\dfrac{[\mathbf{E}_0(\mathbf{r}_{\mathrm{at}})]^2}{2}$

Atoms experience a (mechanical) potential proportional to light intensity

$$U_{\mathrm{dip}}(\mathbf{r})=-\alpha I(\mathbf{r})$$

- Attracted towards large intensity regions below resonance
- Repelled out of large intensity regions above resonance

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)

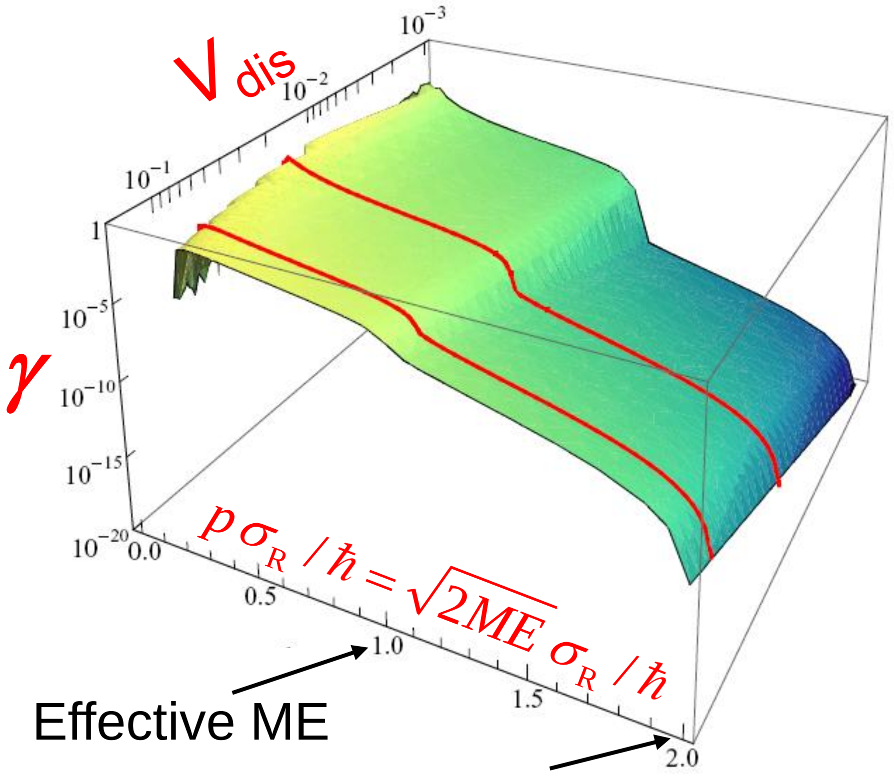
Pierre Lugan et al. PRA 80, 023605 (2009)

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



Effective ME

Second EME

* analogous results by E. Gurevich, 0901.3135