Quantum propagation of guided matter waves: Anderson localization and atom laser

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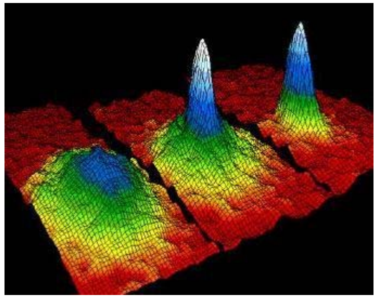
Ultracold atoms and condensed matter

Ultracold atoms

Bose -Einstein condensate

Anderson *et al.*
Science 1995

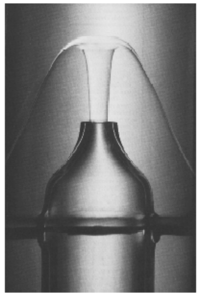


Matterwaves

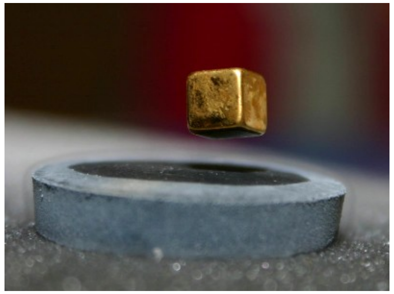
$$\lambda_{dB} \sim d$$

Condensed matter

Superfluid



Supraconductors



Geometries: 1D, 2D, 3D, lattices…

« clean » potentials without absorption

Observation tools:
wavefunction, momentum distribution…

Tunable interactions:
Feshbach resonances, BEC dilution

Conductivity measurement

Presence of phonons

Coulomb interactions between electrons

Ultracold atoms and condensed matter

Ultracold atoms

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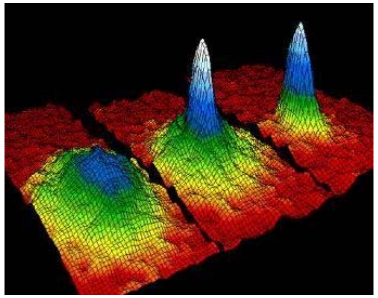
Anderson *et al.* Science 1995



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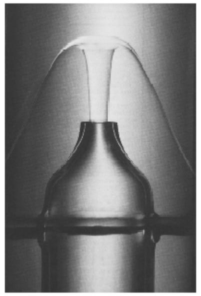

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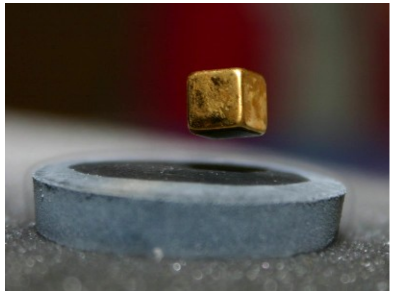


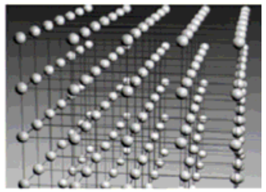
<u>Matterwaves</u>

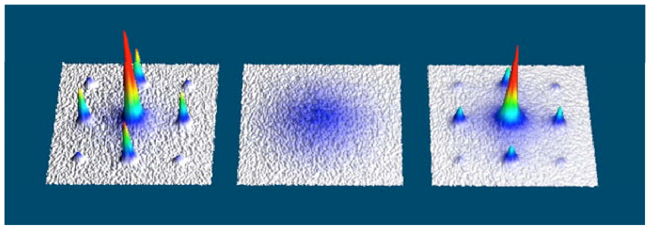
$$\lambda_{dB} \sim d$$

Ultracold atoms = « simple » and well controlled systems

$\Rightarrow$ condensed matter *simulators*

Mott transition (Superfluid – Insulator)





M. Greiner et al. Nature 2002

Quantum transport phenomena

Mainly studied in Condensed Matter $\rightarrow$ *Fondamental concept in physics*

(conduction of electrons)

Single particule effect (no interactions) : linear propagation

- *Tunneling effect / quantum reflection*
- *Fabry-Perot cavity effect*
- *Bloch oscillations in periodic potential*
- *Anderson localization through disorder*

Many body effect (interactions) : non linear propagation

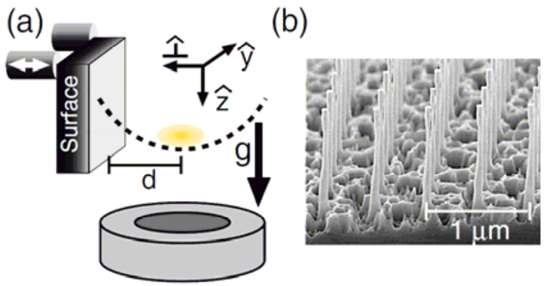
- *Superfluidity*
- *Atomic blockade (analog to Coulomb blockade)*
- *Solitonic propagation (Bright/ Dark)*

Quantum transport with Bose-Einstein Condensates

Linear propagation:

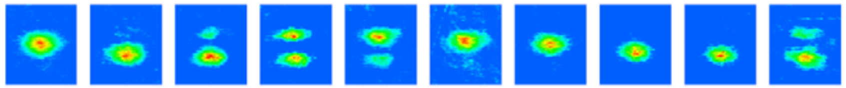
<u>Quantum reflection on surfaces:</u>

T. Pasquini *et al.*
PRL 2006



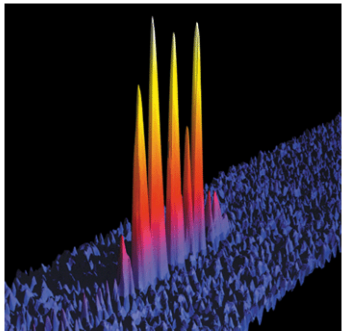
<u>Bloch oscillations:</u>

M. Ben Dahan *et al.*
PRL 1996



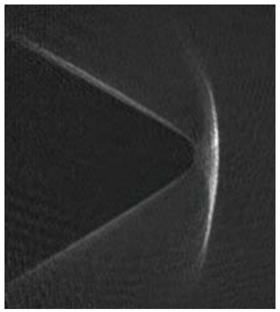
G. Roati *et al.* PRL 2004

Non linear : bright or dark solitons / shock waves



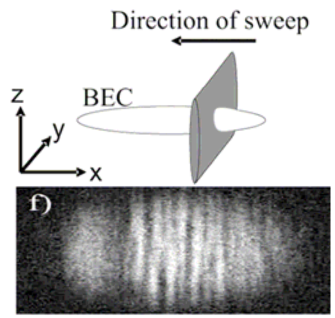
K Strecker *et al.* Nature 2002

L. Khaykovich *et al.* Science 2002



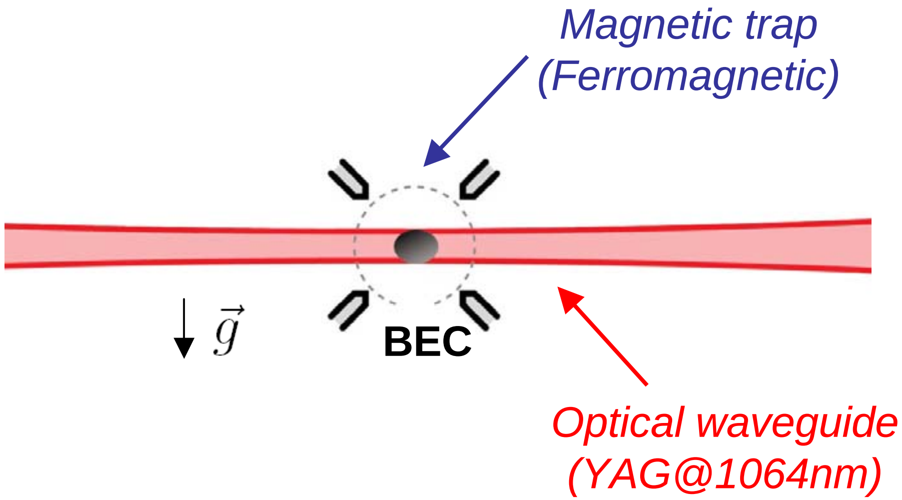
E. Cornell group
Jila, Boulder 2005

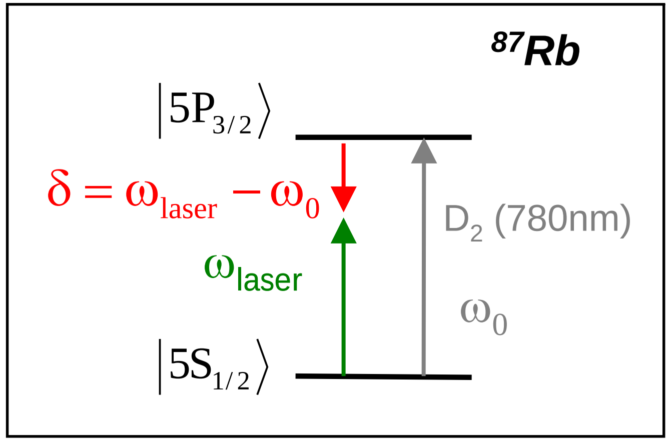
I. Carusotto *et al.* PRL 2006



P. Engels and C. Atherton
PRL 2007

Propagation of guided matterwaves (1D)





$$V_{dip} \propto \frac{I(r)}{\delta}$$

$\delta < 0$ ***attractive***

$\delta > 0$ ***repulsive***

BEC + horizontal guide
= guided matterwaves

$$\lambda_{dB} = \frac{h}{mv} \approx \mu m$$

$\Rightarrow$ Quantum propagation through optical potentials: size ~ µm

Propagation of guided matterwaves (1D)

BEC + horizontal guide
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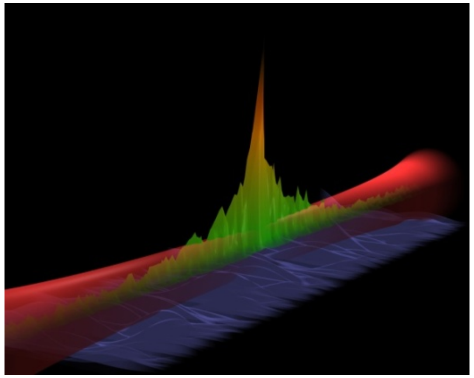
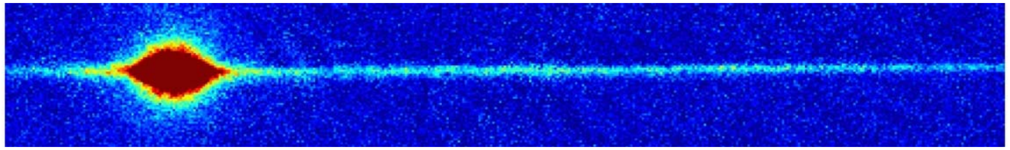
***1. Anderson localisation** of an expanding BEC in presence of disorder*



2.** Developpement of a new atomic source: **guided atom laser

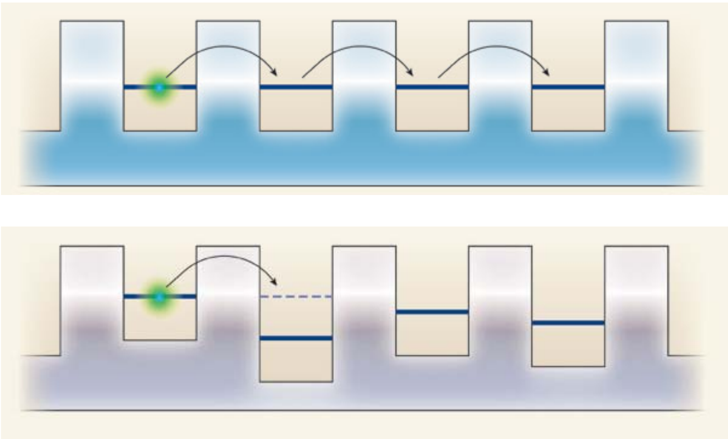


1. Anderson localization

Predicted for condensed matter *(electrons):*

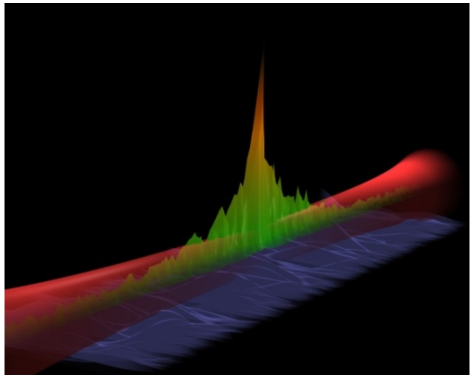
P.W. Anderson Phys. Rev. 1958

⇒Metal-Insulator transition
induced by disorder (no interactions)



Anderson Localization with expanding BEC in disorder

First experiments in 2005

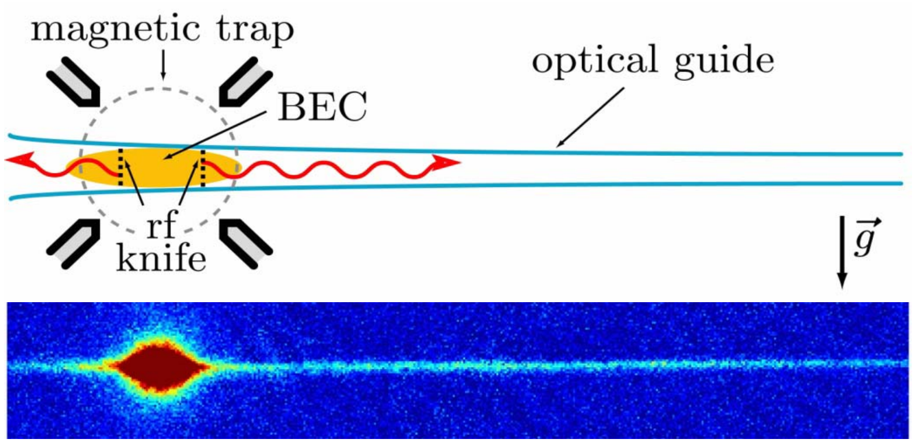


General context: disorder + interactions

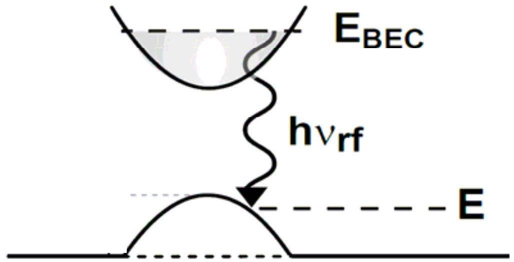
New quantum phase (Bose Glass…)

B. Damski et al. PRL 2003

2. Guided Atom Laser



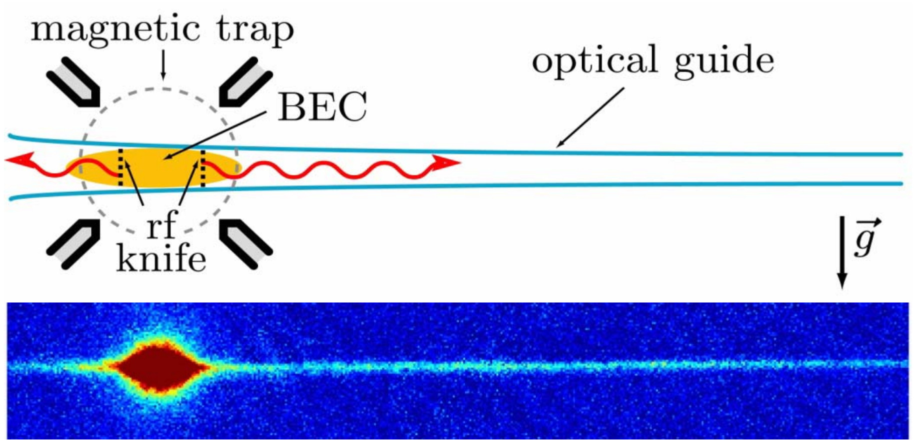
W. Guerin *et al.* PRL (2006)



Well defined energy E
Controlled flux ⇒ interactions

$\lambda_{dB} \simeq \mu m$

2. Guided Atom Laser



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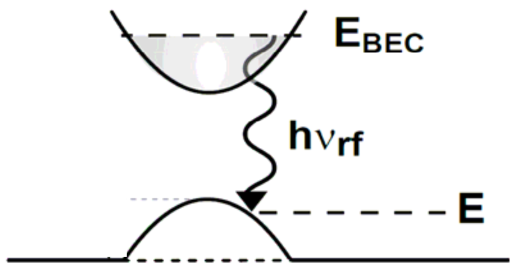

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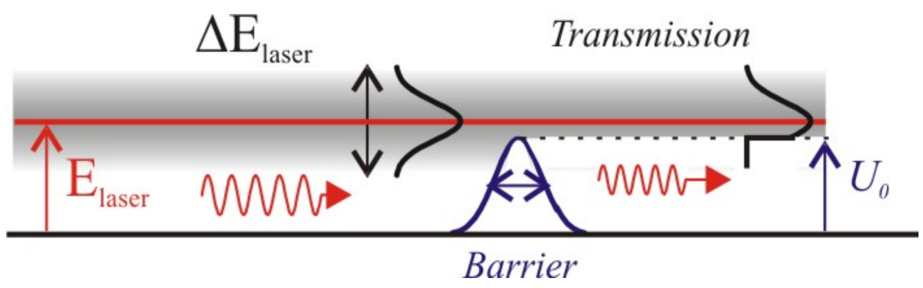
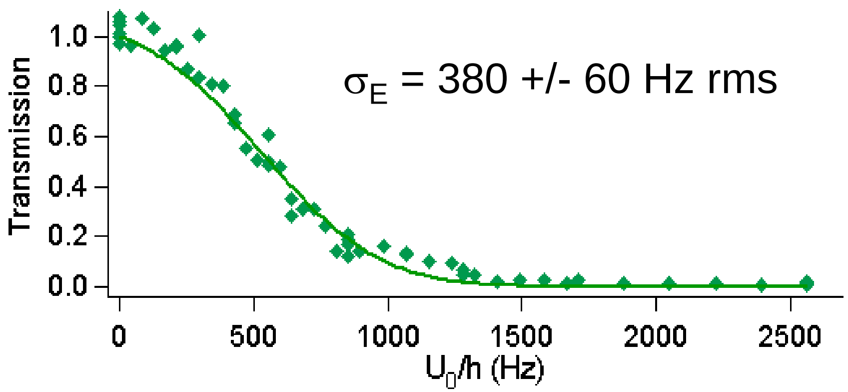
Spectral linewidth measurement:





Outline

1. Anderson Localization (AL)

P.W. Anderson
Phys. Rev. 1958

- *Introduction and motivations*
- *Scheme of 1D Anderson localization in laser speckle*
- *Experimental realization and results*
- *Conclusion*

2. Perspectives

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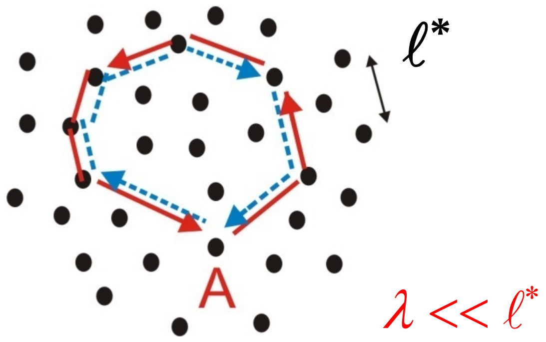
Localization of waves

Weak disorder : weak localization



Interferences on closed loops

$\Rightarrow$ Enhanced (x2) return probability

$\Rightarrow$ Decrease of diffusion constant

Localization of waves

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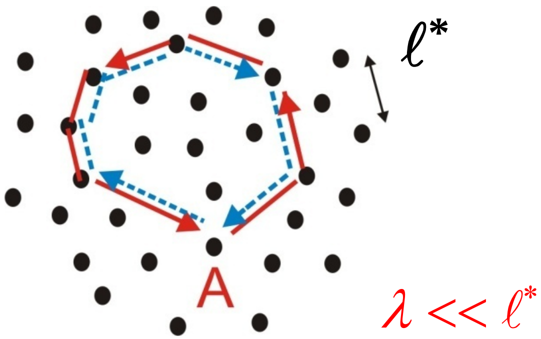

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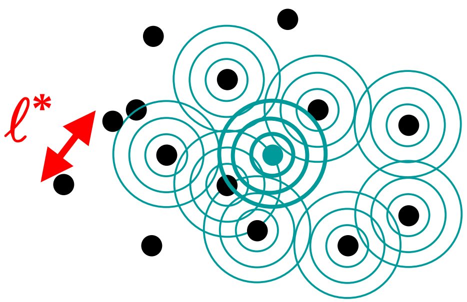
Strong disorder : localized – extended states transition



Mobility edge (Ioffe Regel)
$\lambda \approx \ell^*$

$\Rightarrow$ **wavefunction are exponentially localized**

$\Rightarrow$ **Dimensionality**

1D, 2D : all states localized

3D : transition (mobility edge)

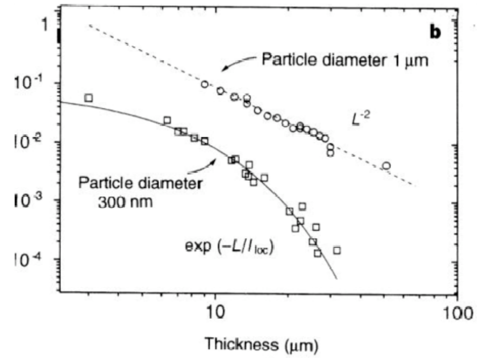
Strong localization with classical waves

Problematic :
Discrimination absorption / localization

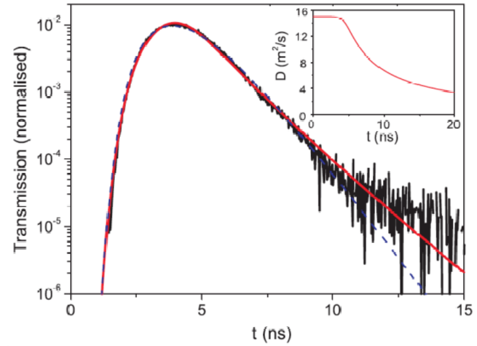
Classical waves :
Ultrasound, µ-waves, light

Geometries :
- quasi-1D, 2D, 3D
- Photonic crystals

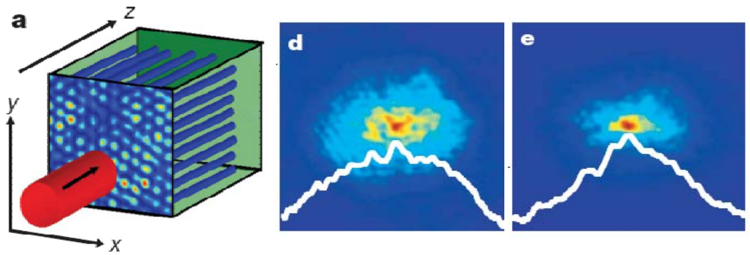
Signatures :
- Transmission (static / time resolved)
- Fluctuations
- Wavefunction imaging



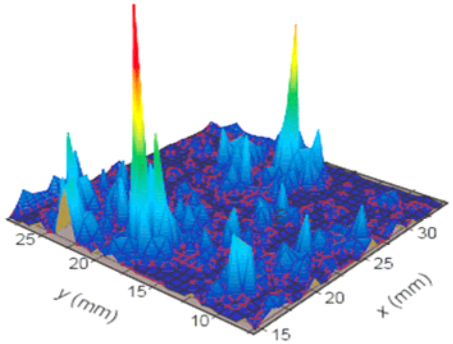
D. Wiersma et al. Nature 97



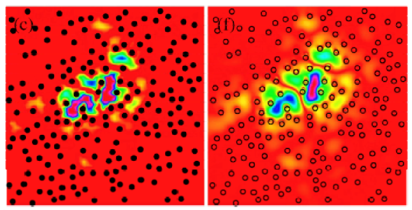
C.M. Aegerter et al. EPL 06



T. Schwartz et al. Nature 07



H. Hu et al. Nature Physics 08



D. Laurent et al. PRL 08

Anderson localization: still an active field !

Remaining challenges

Behavior of the transition (3D) ? (critical exponents)

C.M. Aegerter et al. EPL 2006

Effects of non-linearities ? (interaction)

1D : Y. Lahini et al. PRL 2008
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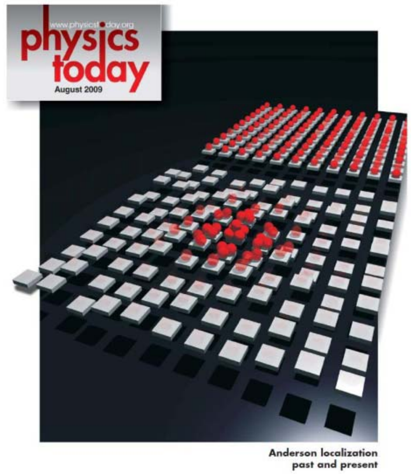

Experiments with matterwaves ?

Since 80's: indirect observations (conductivity) with electrons

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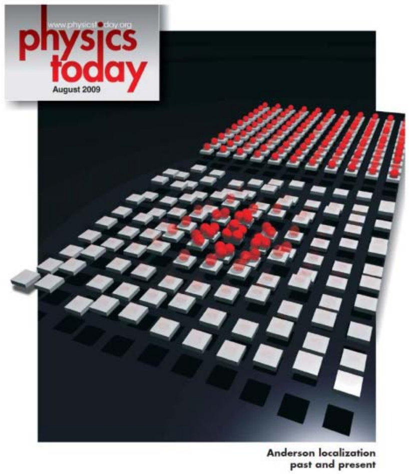

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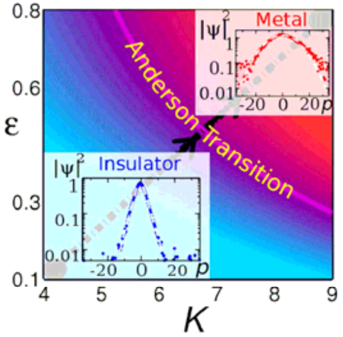
Dynamical localisation
with cold atoms

J. Chabé et al. PRL 2009



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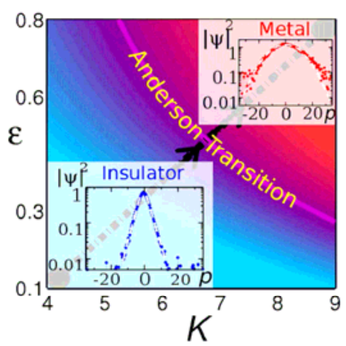


Since 2005: experimental activity with cold atoms

D. Clément et al. PRL 2005
C. Fort et al. PRL 2005
T. Schulte et al. PRL 2005

Anderson localization with cold atoms ?

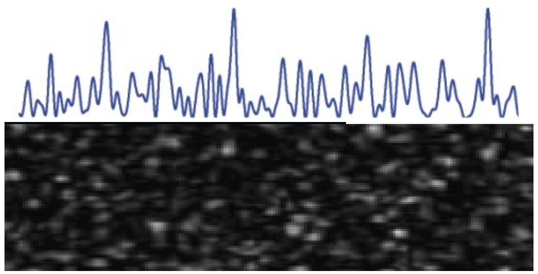
→ Cold atoms = controlled systems

→ Direct observation of localized wavefunctions

→ Critical exponents in 3D ?

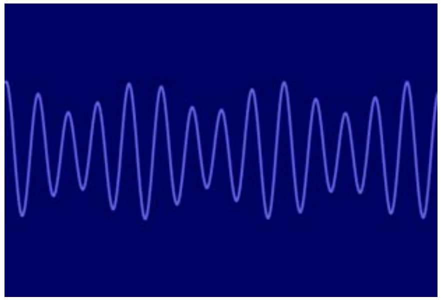
Controlled random optical potentials:

Speckle pattern



Horak et al. PRA 1998

Bi-chromatic lattice



Damski et al. PRL 2003

+

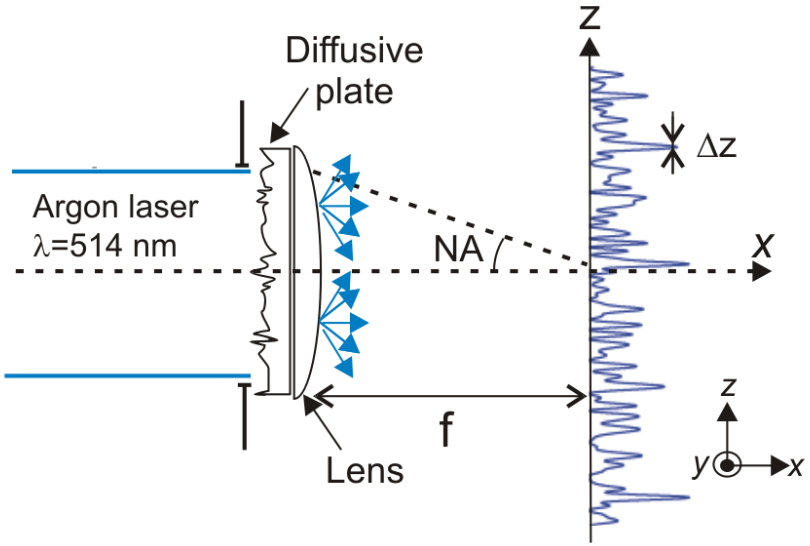
Impurities in optical lattice

Gavish & Castin PRL 2005

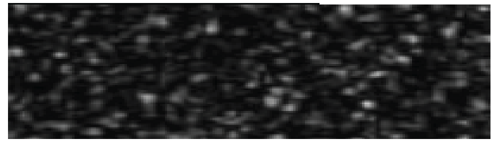
Atomic chips

Esteve et al. PRA 2004

Our disordered potential: laser speckle



Laser speckle : diffraction from a rough plate



$$V_{random} \propto \frac{I(r)}{\delta}$$

Blue detuned (atomic transition @ 780 nm)
= repulsive potential

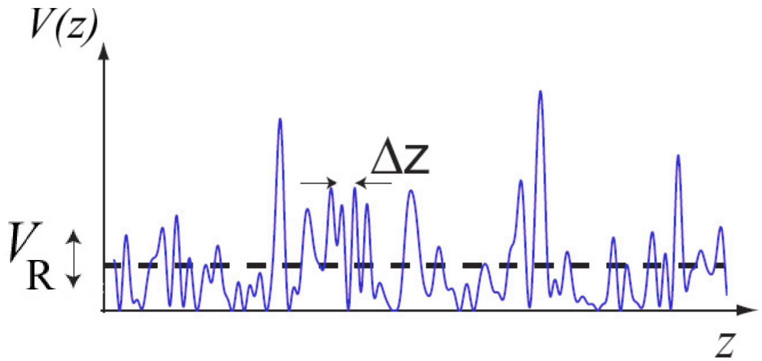
A controlled disorder:

$\Rightarrow$ *Disorder strength = laser intensity*

$$\sigma_V = \langle V \rangle \equiv V_R$$

$\Rightarrow$ *Correlation length = numerical aperture*

$$\Delta z = \frac{\lambda}{2(N.A.)}$$



D. Clément et al. NJP 2006

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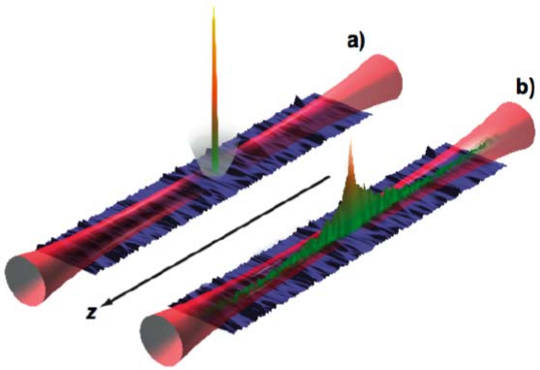

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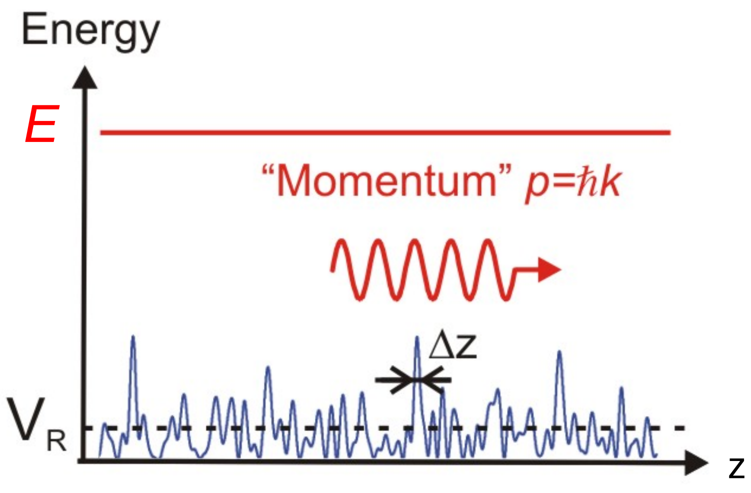
1D Anderson localization of matterwave



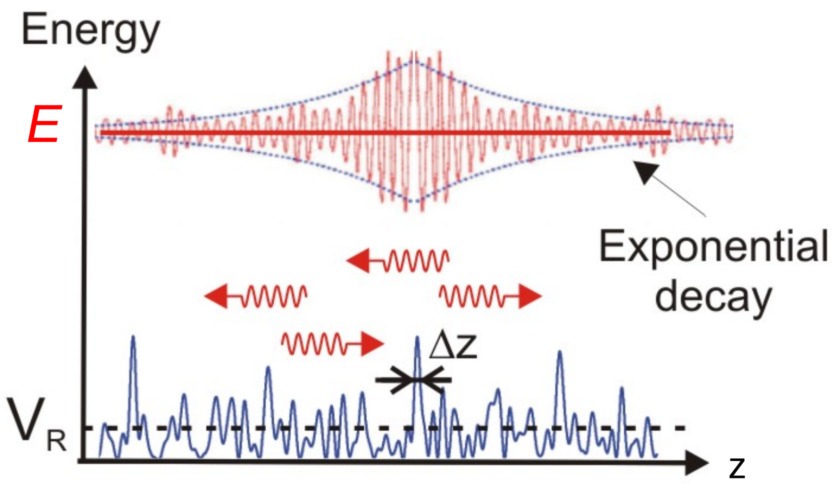
Classical : atoms « fly » above disorder

Propagation in weak disorder

$$\boxed{E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} >> V_R}$$

No classical trapping

1D Anderson localization of matterwave



Classical : atoms « fly » above disorder

Quantum : - destructive multiples interferences

- *single particule effect* **(no interaction)**

Propagation in weak disorder

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} >> V_R$$

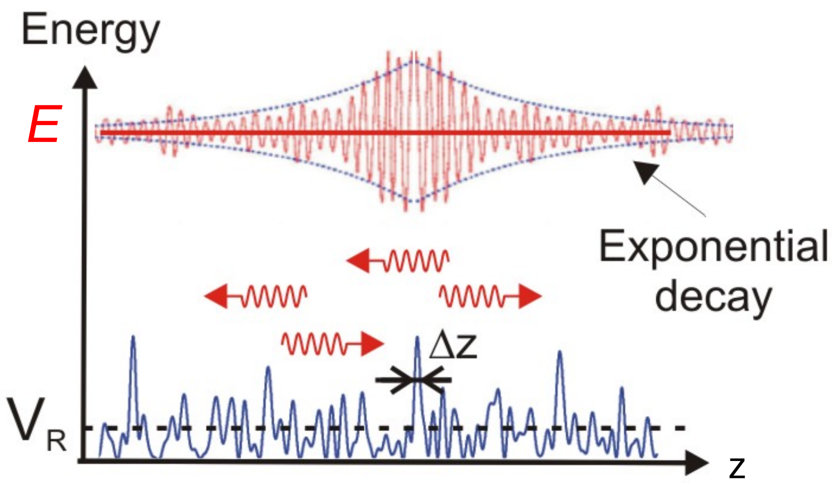
No classical trapping

1D: All wavefunction are exponentially localized

Lyapunov exponent:

$$\frac{1}{L_{loc}(k)} = \gamma(k) = -\lim_{|z|\to+\infty} \left\langle \frac{\log\{r(z)\}}{|z|} \right\rangle \qquad (p = \hbar k)$$

Weak disorder regime

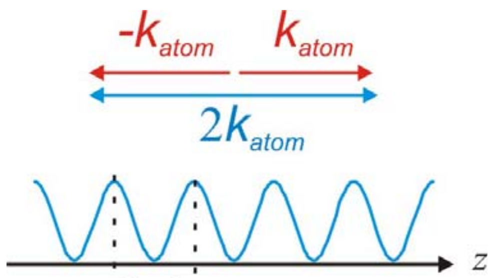


1st order calculation (Born approximation) :

$$\gamma(k_{atom}) \propto C(\,2k_{atom}\,) \quad \left(p = \hbar k\right)$$

Frequency distribution of disorder

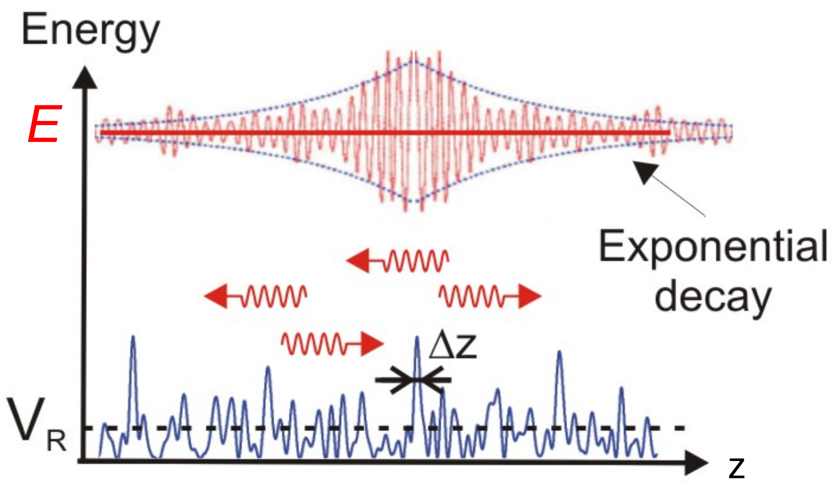
Bragg condition (momentum conservation)



Localization at 1st order:

Disorder contains the spatial componant $2k_{atom}$

Weak disorder regime



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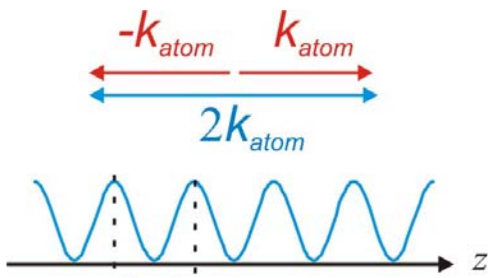


Localization at 1st order:

Disorder contains the spatial componant $2k_{atom}$

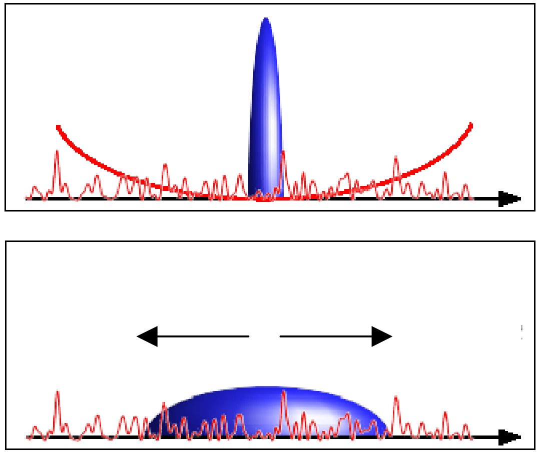
⇒ 2 important distributions

- Atomic momentum distribution : $D(k_{atom})$
  (↔ expansion from a BEC)
- Spatial frequency distribution : $C(2k_{atom})$
  (↔ speckle caracteristics)

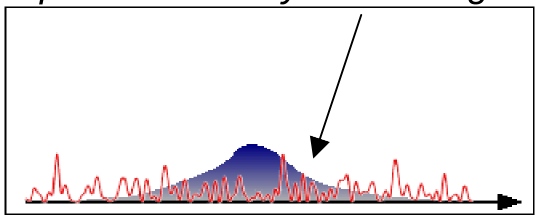
Scheme for localization of an expanding BEC

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

1D expansion of BEC in
weak disorder (V_R<< μ_{in})



Exponential decay in the wings ?



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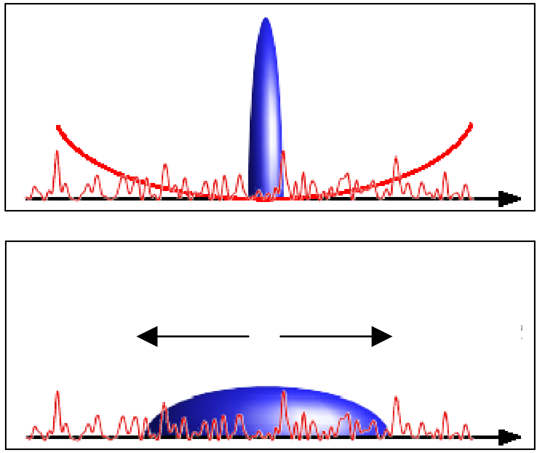
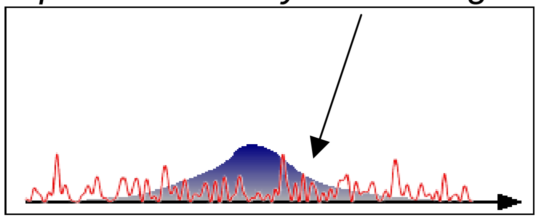
1D expansion of BEC in
weak disorder ($V_R \ll \mu_{in}$)

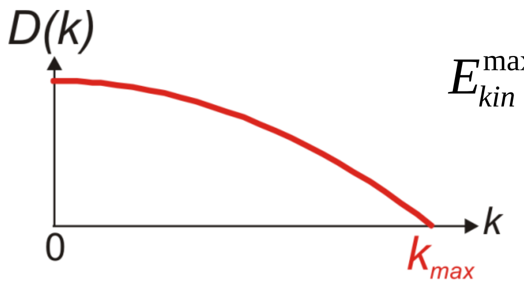


Exponential decay in the wings ?



Matterwave k-distribution:

Interaction energy (~ μ_{in}) converted into kinetic energy

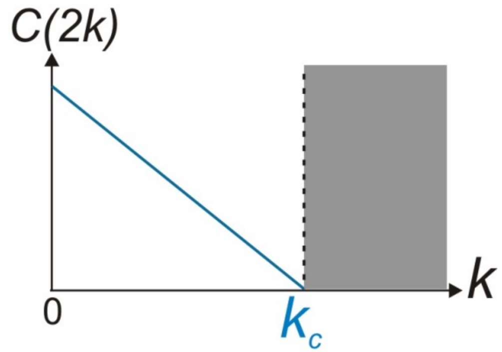


$$E_{kin}^{\max} = \frac{\hbar^2 k_{\max}^2}{2m} = 2\mu_{in}$$

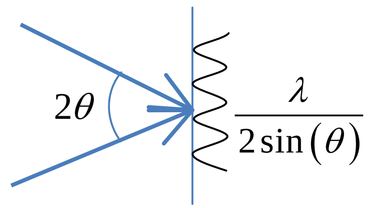
Castin & Dum PRL 1996

Disorder k-distribution:

High frequency cut-off k_c given by diffraction limit



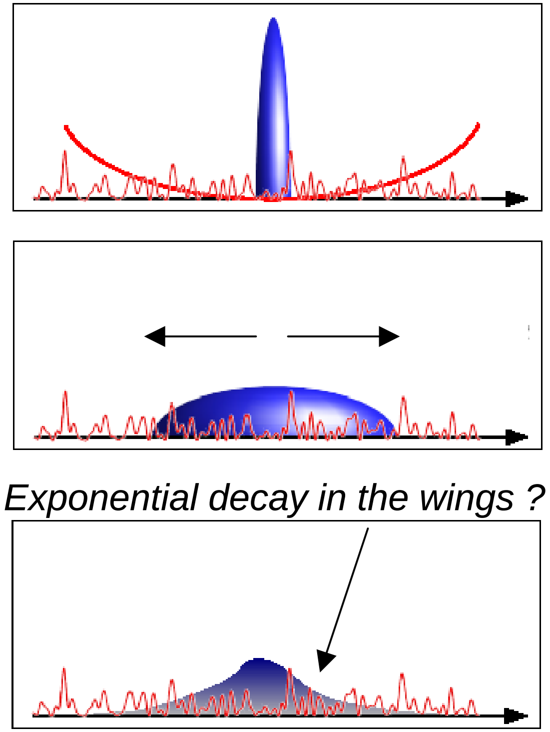
$$\boxed{k_c = \frac{\pi}{\Delta z}} = \frac{2\pi}{\lambda}(N.A.)$$



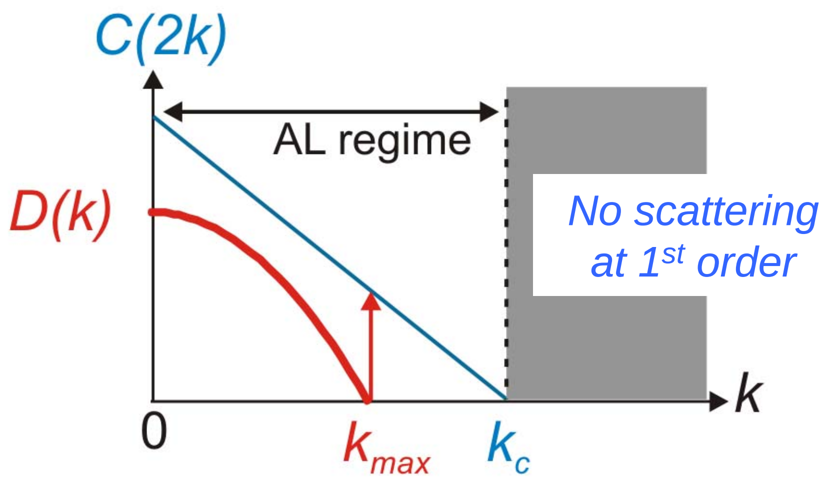
Scheme for localization of an expanding BEC

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

1D expansion of BEC in
weak disorder (V_R<< μ_{in})



Exponential localization of matterwave:
All k-components localize



$$\boxed{k_{\max} < k_c}$$

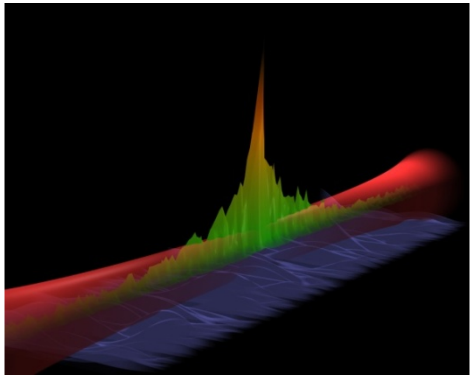
Preliminary experiments:

- ***k_{max} >> k_c***
- ***interactions***

D. Clément et al. PRL 2005
C. Fort et al. PRL 2005
T. Schulte et al. PRL 2005

Outline

1. Anderson Localization (AL)



- *Introduction and motivations*
- *Scheme of 1D Anderson localization in laser speckle*
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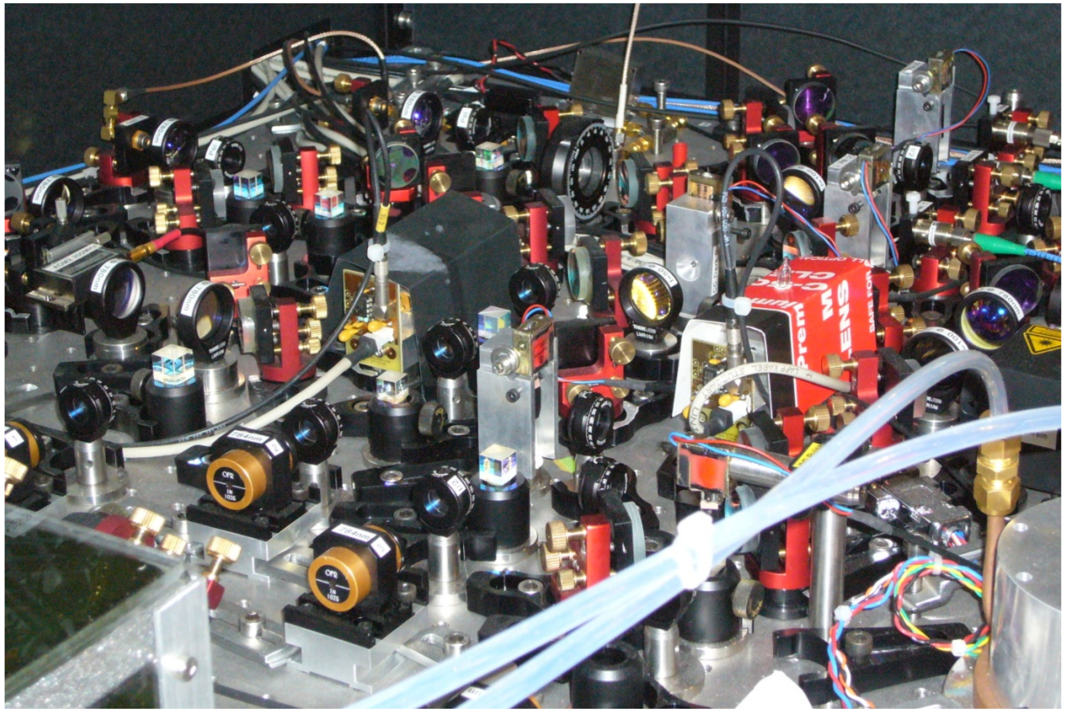
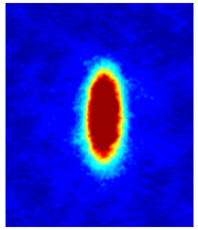
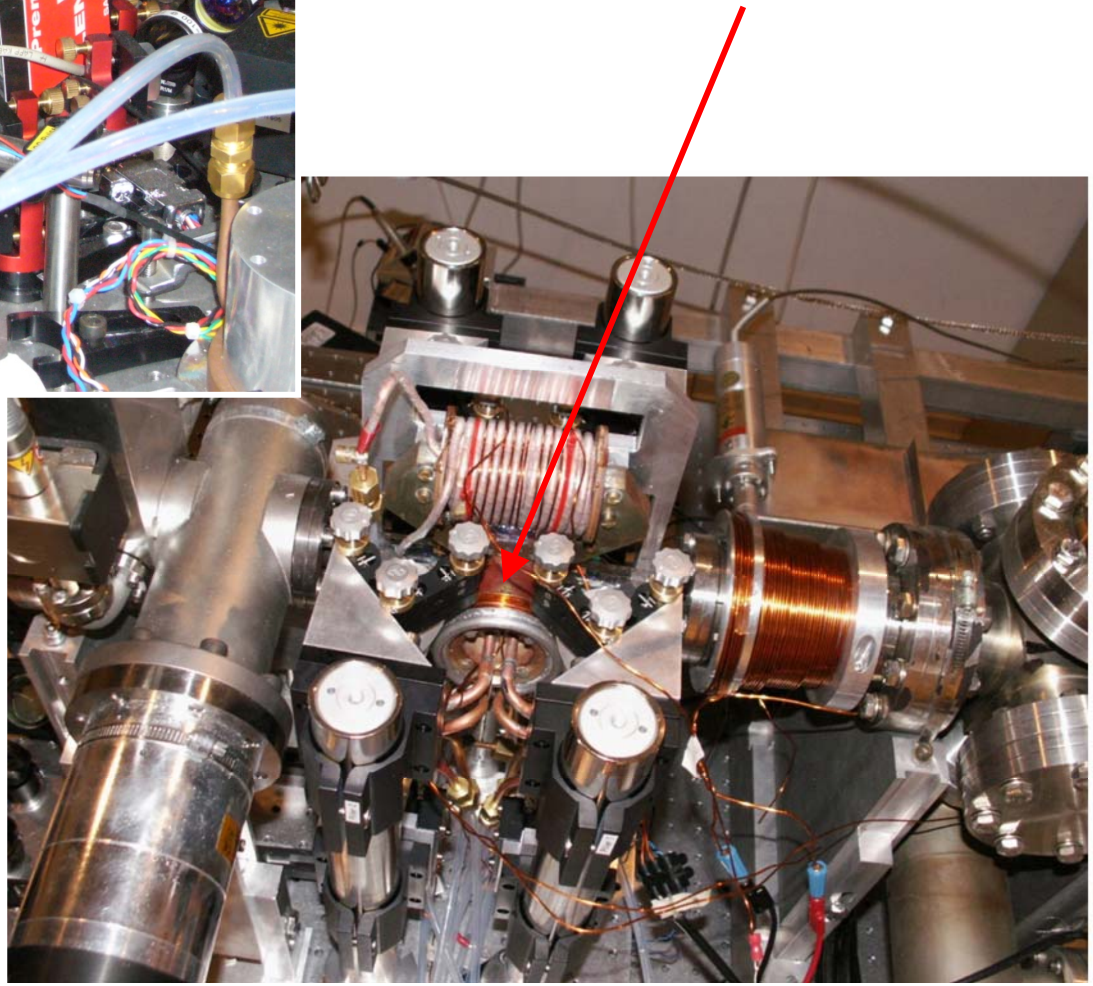
- *Conclusion*

2. Perspectives

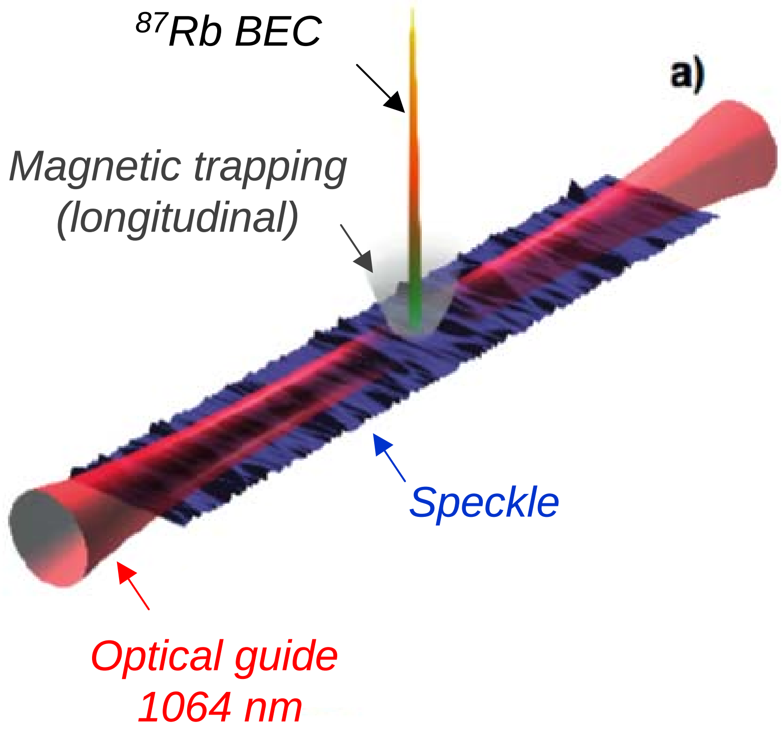


^{87}Rb BEC



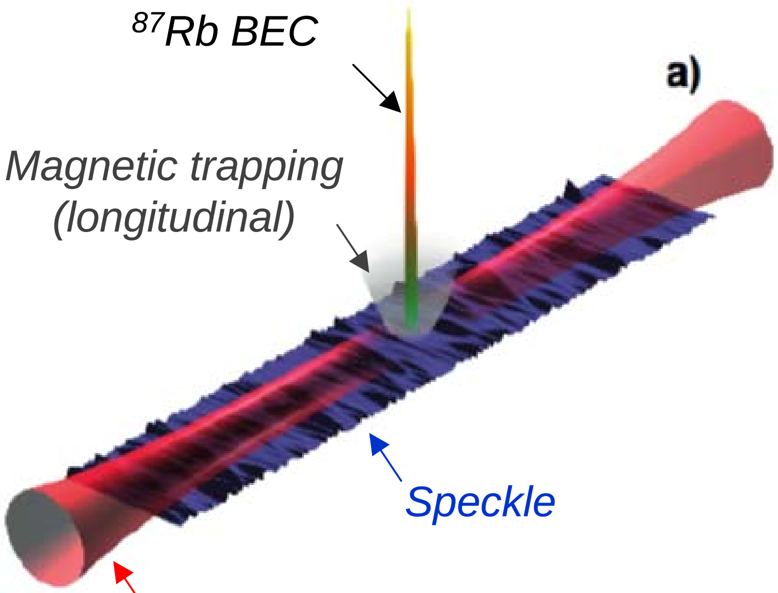


Experimental « road map »



Condition : $\boxed{k_{\max} < k_c}$

Experimental « road map »



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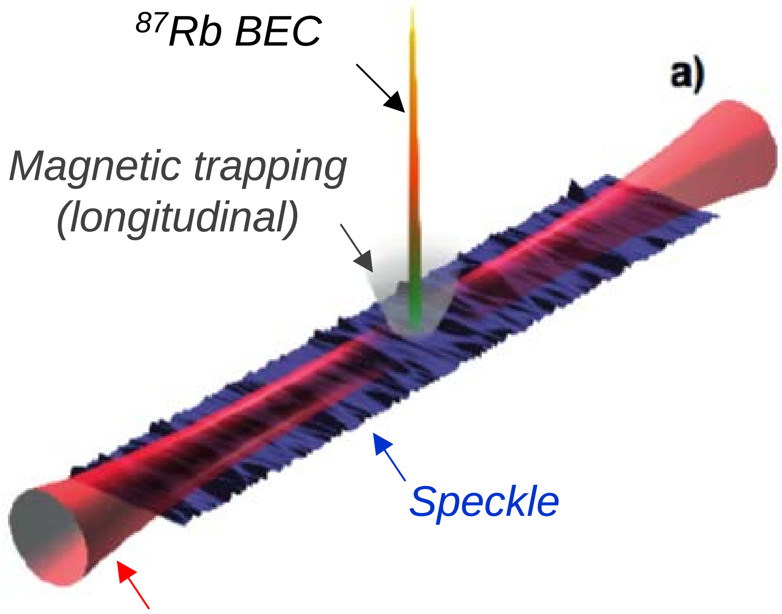
1. large $k_c \rightarrow$ Very thin speckle

Experimental « road map »

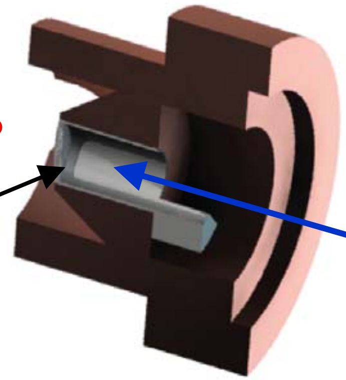


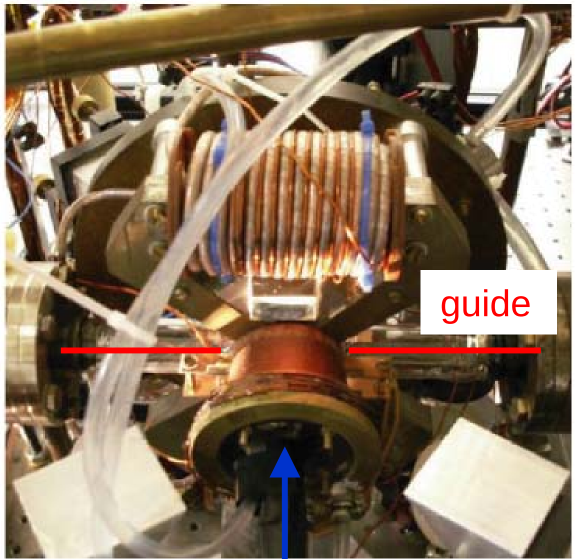
Condition : $\boxed{k_{\max} < k_c}$

1. large $k_c \rightarrow$ Very thin speckle $k_c = 3.85\mu m^{-1}$

Blue light @ 514 nm
High N.A. = 0.3

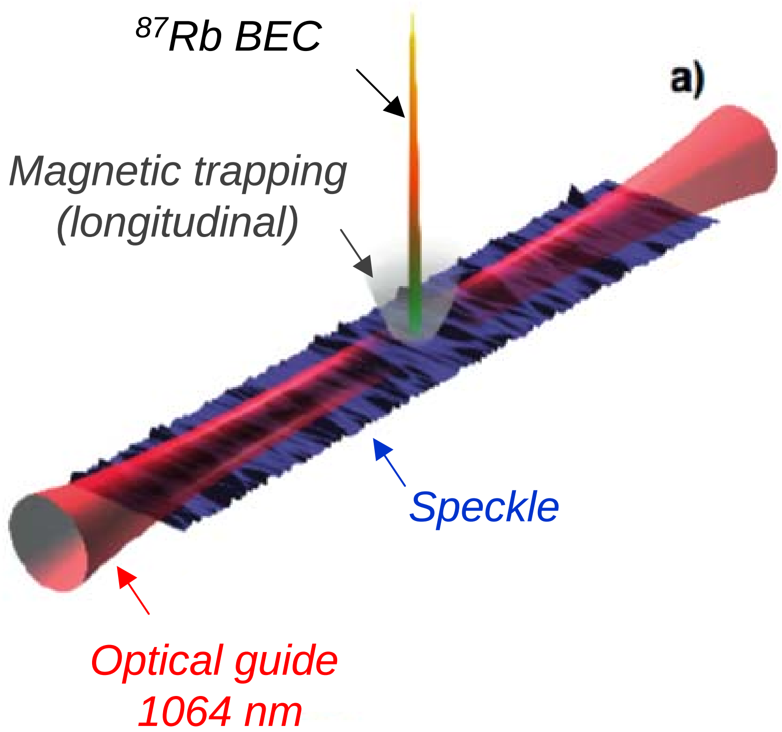
$\Delta z = 0.8\mu m$





Beam @ 514nm

Experimental « road map »

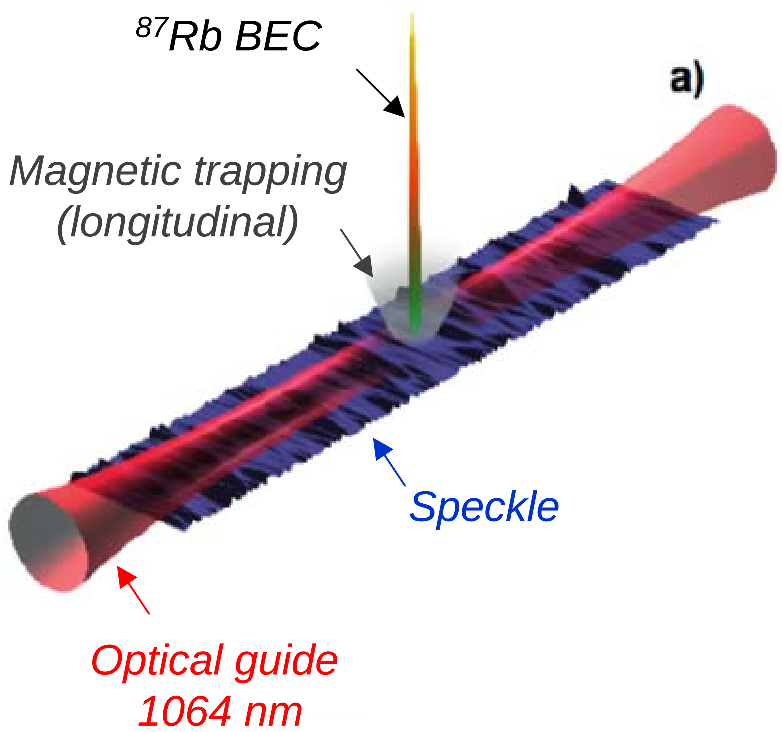


Condition : $\boxed{k_{\max} < k_c}$

1. large k_c $\rightarrow$ Very thin speckle $k_c = 3.85 \mu m^{-1}$

2. small k_{max} $\rightarrow$ Dilute BEC

Experimental « road map »



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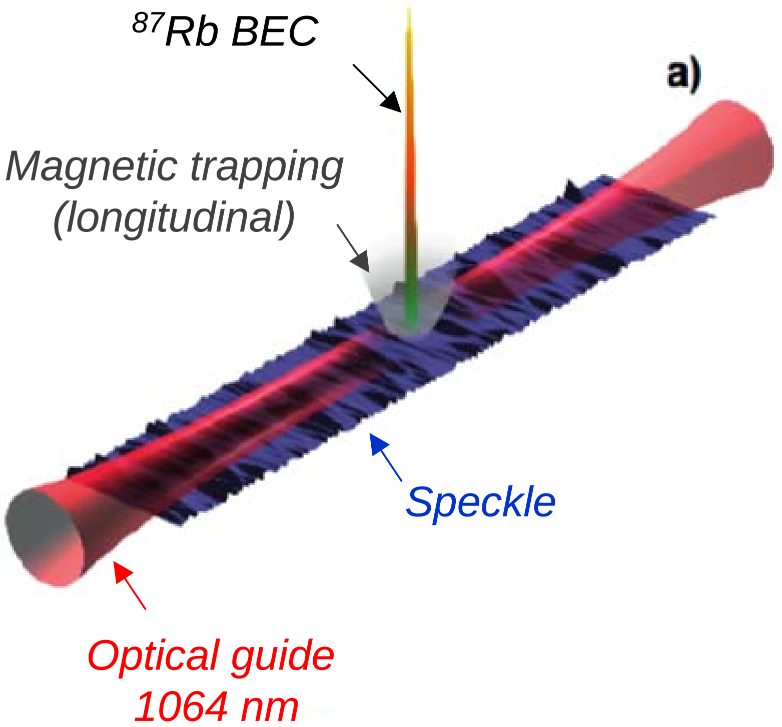
2. small $k_{max} \rightarrow$ Dilute BEC

Low number of atoms: 1.7 10^4
Weak trap frequencies

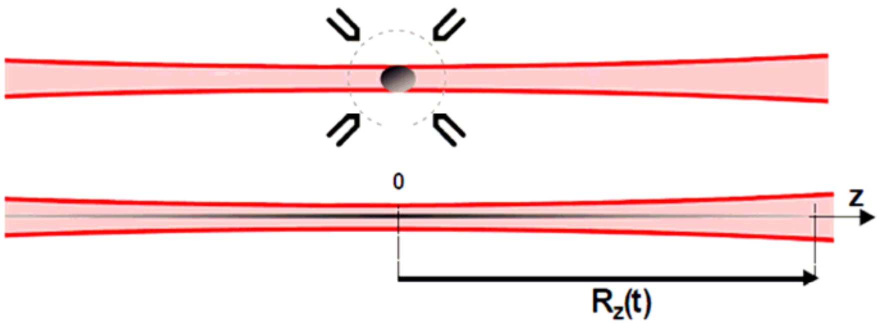
$$\mu_{in} = 220\ Hz$$

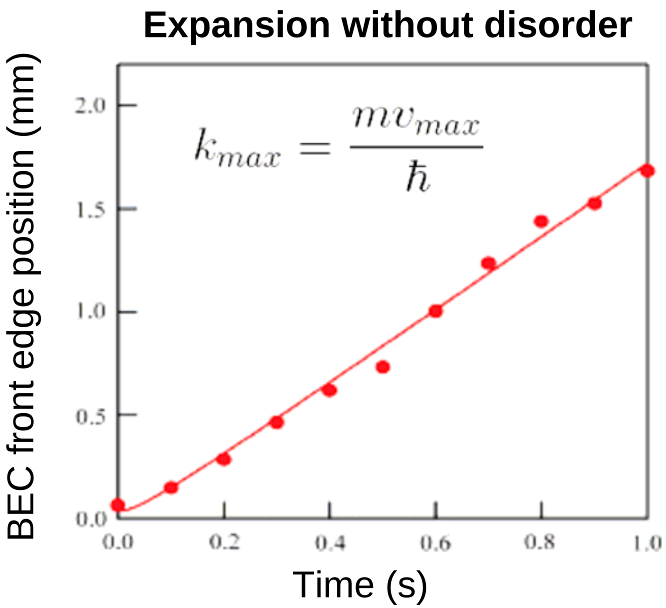
Experimental « road map »



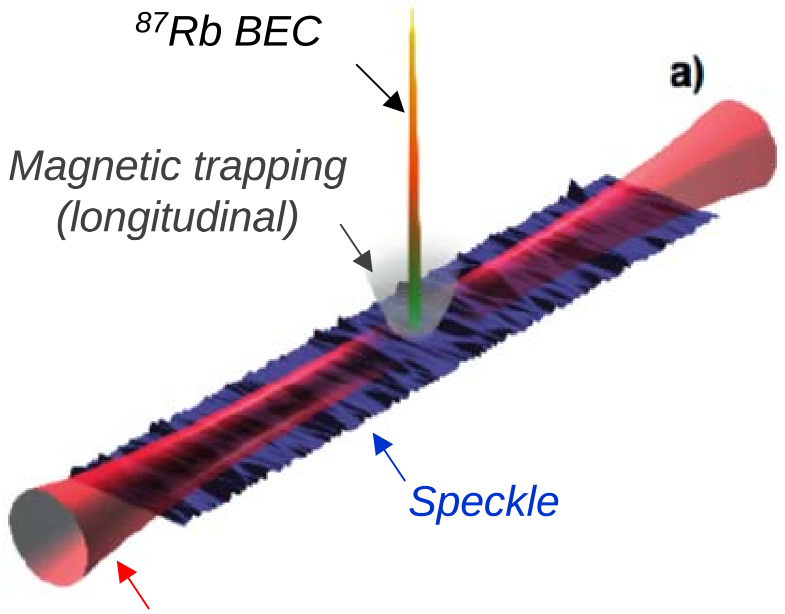
Condition : $\boxed{k_{\max} < k_c}$

1. large k_c $\rightarrow$ Very thin speckle $k_c = 3.85\mu m^{-1}$
2. small k_{max} $\rightarrow$ Dilute BEC
3. large L_{loc} $\rightarrow$ Expansion over few millimeters





Experimental « road map »



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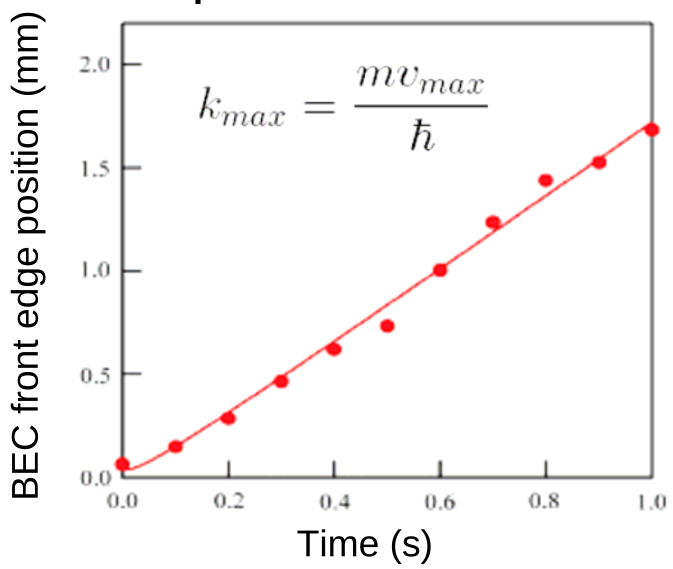


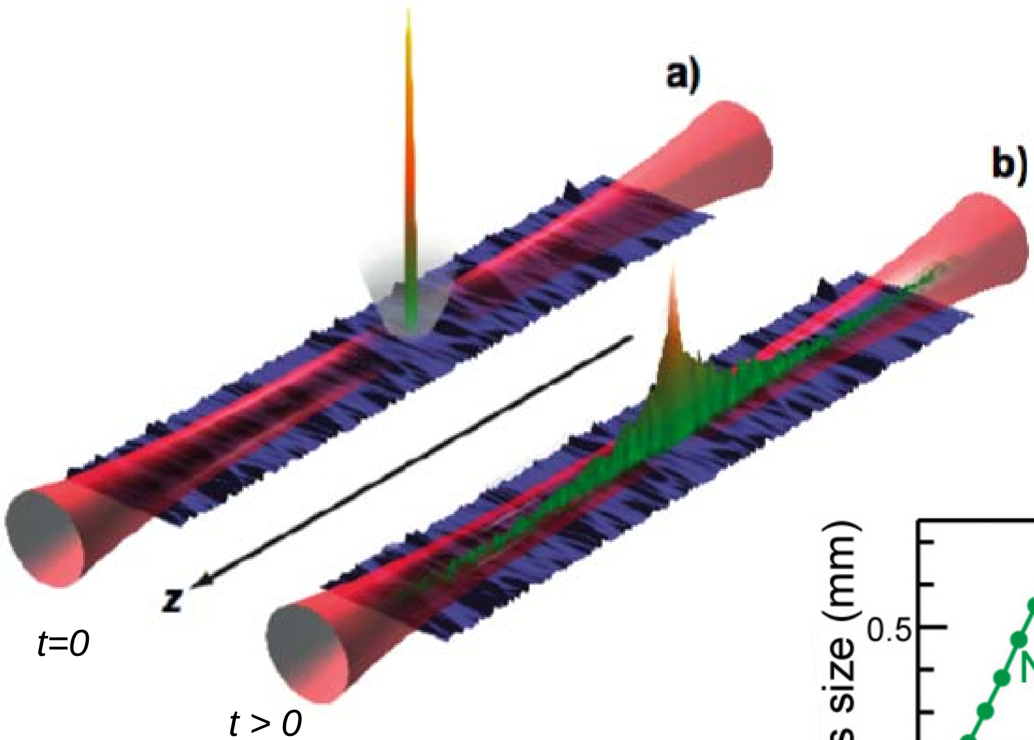
$$k_{\max} = 2.47\mu m^{-1} < k_c = 3.85\mu m^{-1}$$

$\Rightarrow$ ***Condition for AL satisfied !***

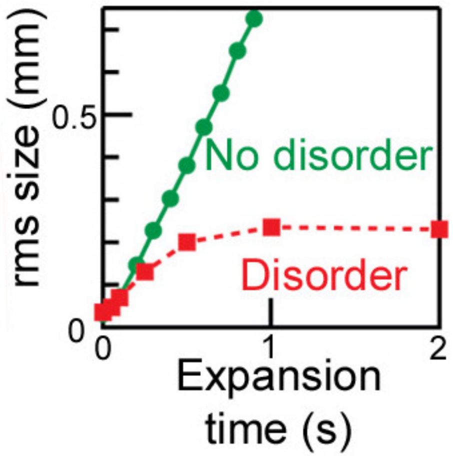
Expansion in disorder

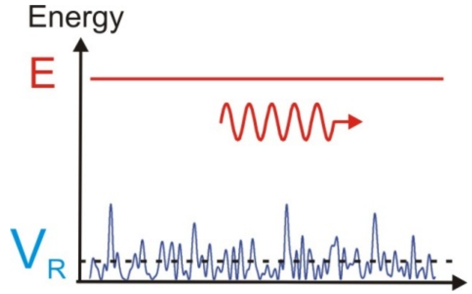
$$\boxed{k_{max} < k_c}$$

+ *weak disorder* $V_R/\mu_{in} = 0.12 \ll 1$



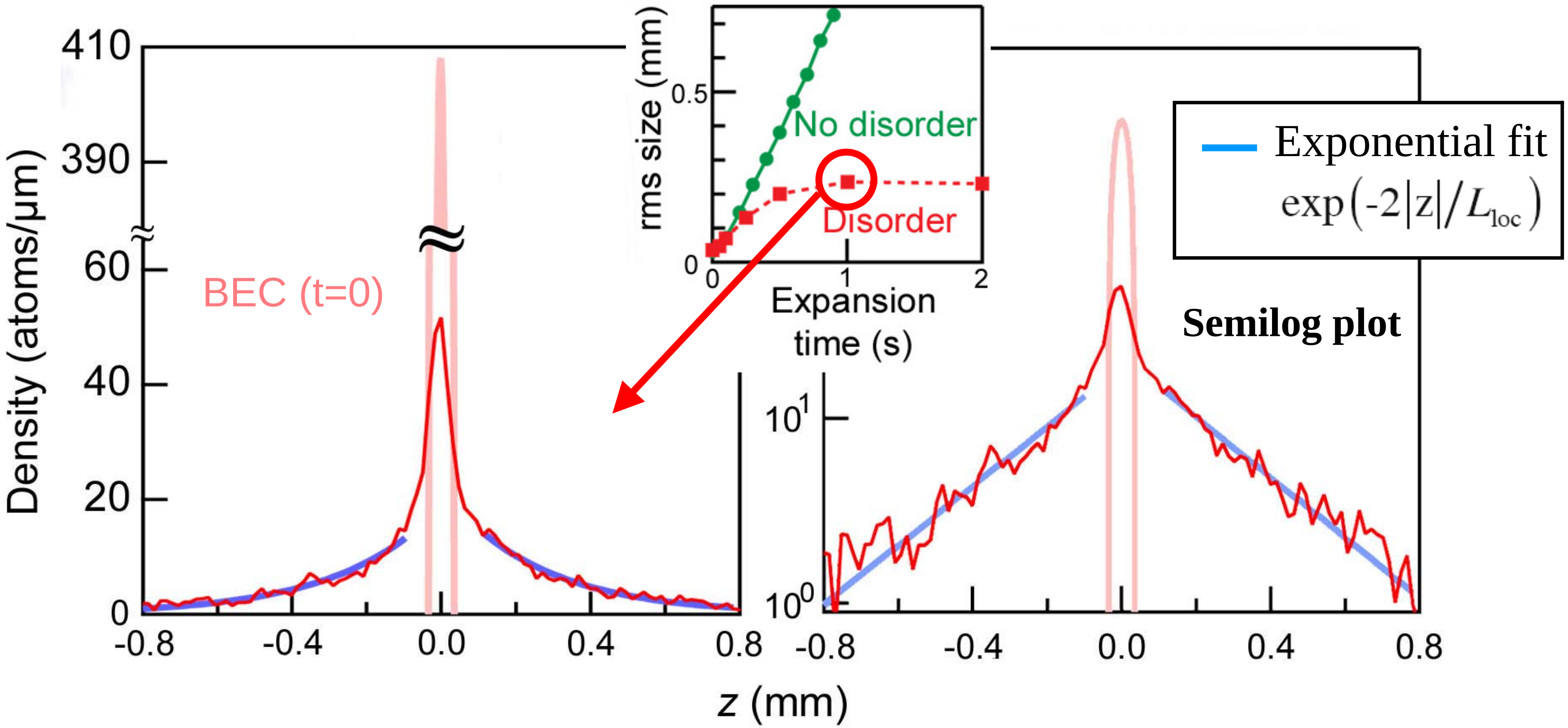
Fluorescence imaging
(Camera EMCCD ↔ 1at/µm)





⇒ Matterwave is stopped by weak disorder (after around 1s of propagation)

Signature of Anderson Localization



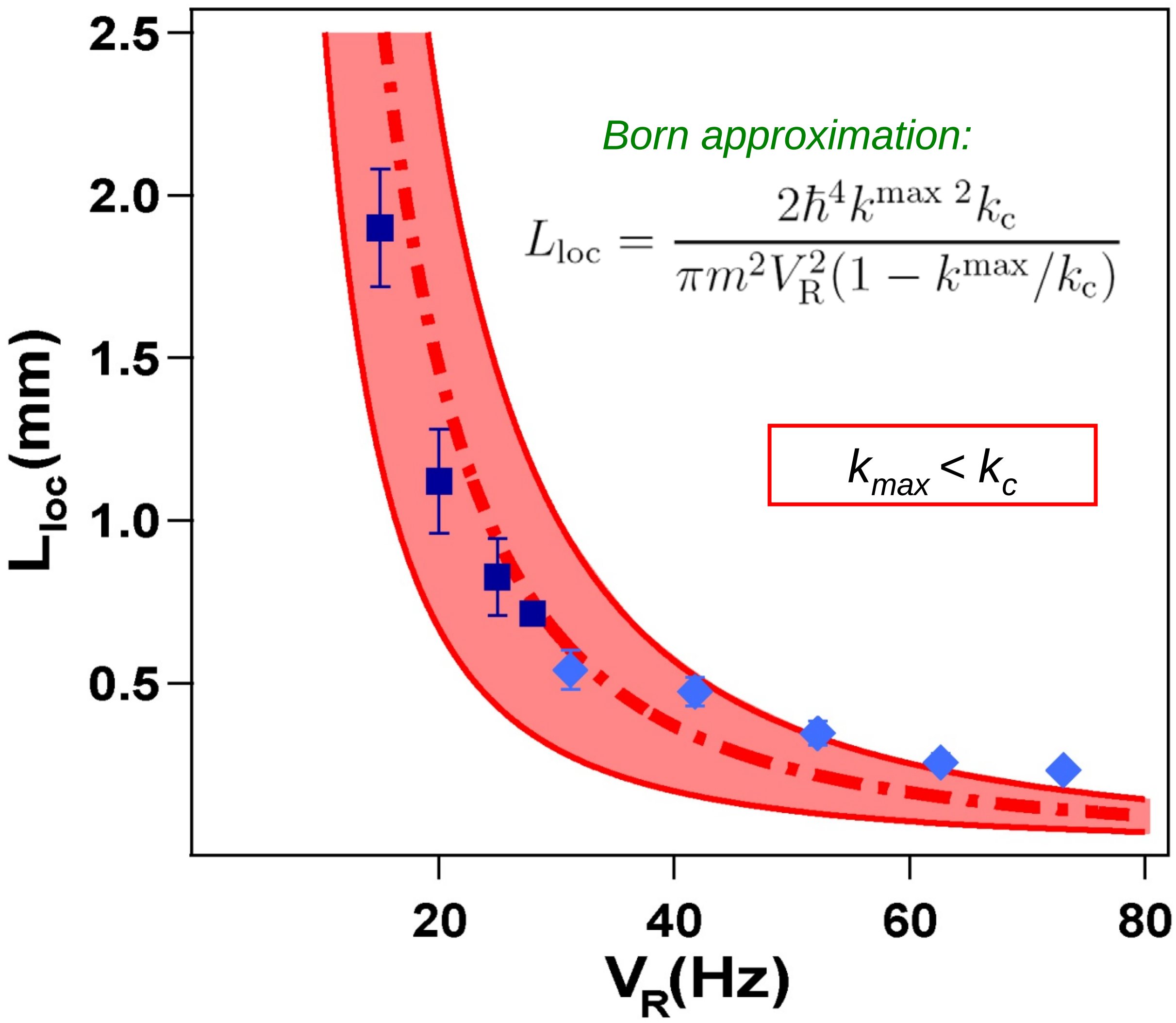
⇒ *Exponential decay in the wings* ***(no interactions)***

⇒ *Stationary profiles (not shown)*

Localization length

L_{Loc}=530 +/- 80 µm

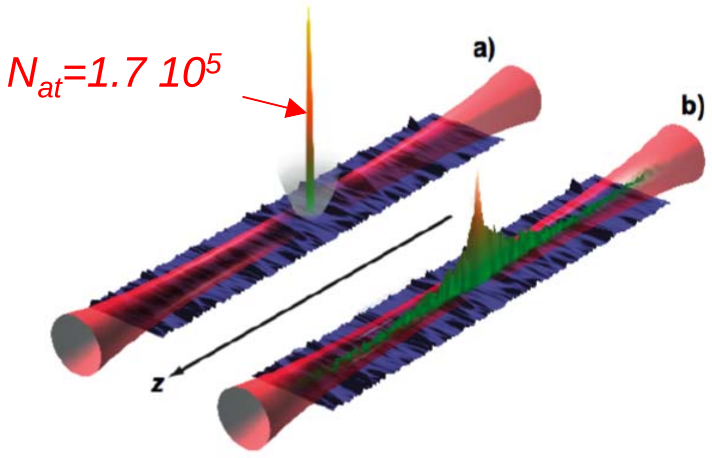
Localization length vs disorder amplitude



$\Rightarrow$ *Good agreement with no adjustable parameters*

Beyond the effective mobility edge ($k_{max} > k_c$)

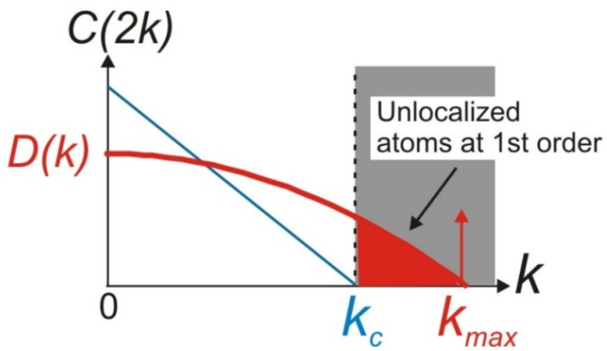
Same scheme with N_{at} (x10):



k_{max} *increases* $\Rightarrow$ $\boxed{k_{max} > k_c}$

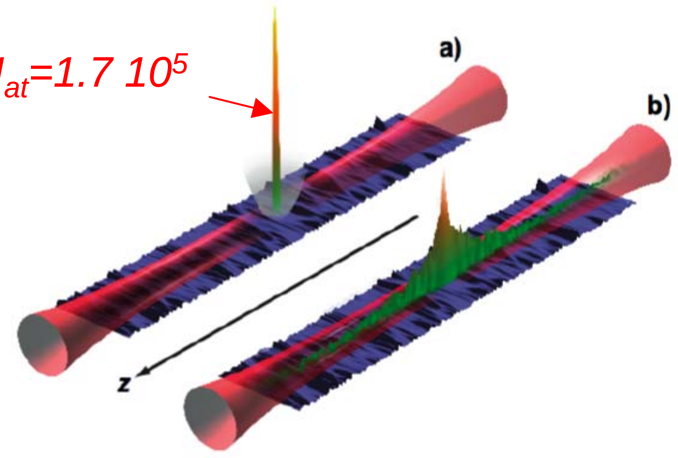
Theory : algebraic decay
LSP et al. PRL 2007

$$\boxed{n_{1D} \propto 1/z^2}$$



Beyond the effective mobility edge ($k_{max} > k_c$)

Same scheme with N_{at} (x10):



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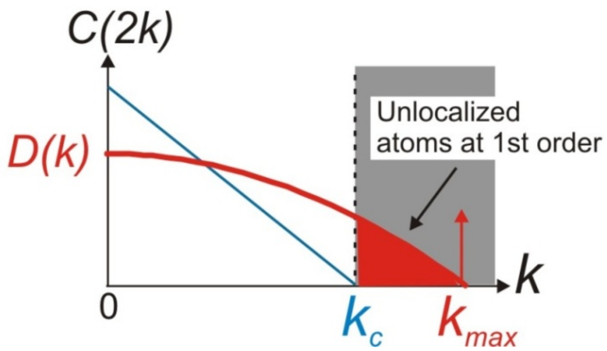
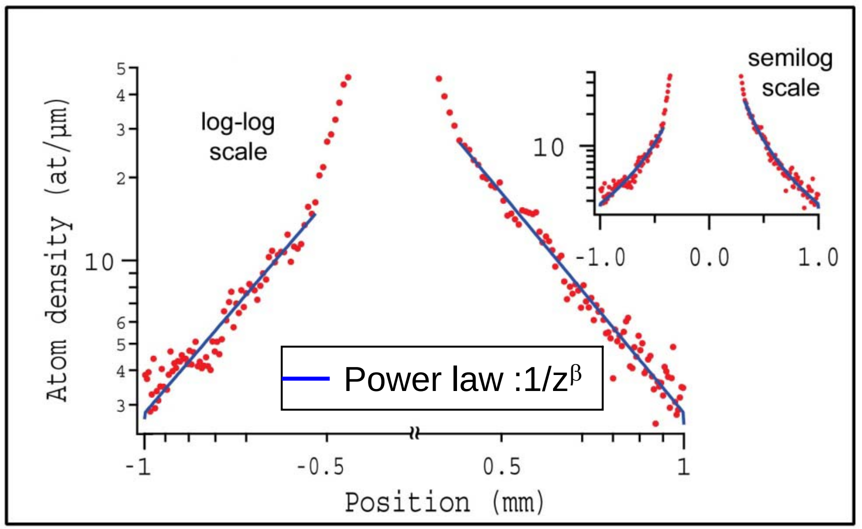
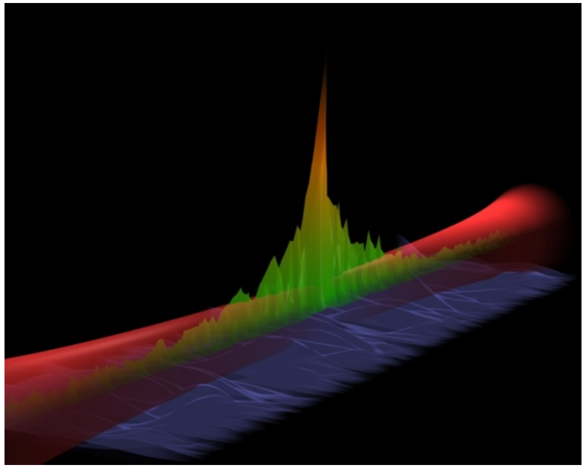




Observation of stationnary localized profiles

$$n_{1D} \propto 1/z^{\beta} \quad \text{with} \quad \boxed{\beta = 1.96 +/- 0.06}$$

Conclusion

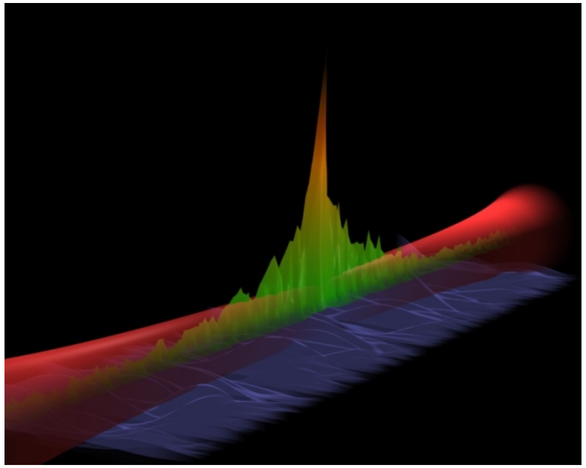


• 1D Anderson localization of matterwaves without interaction

• Speckle disorder: two localization regimes (exponentiel & algebraic)

• Good agreement theory / experiment

Conclusion



• 1D Anderson localization of matterwaves without interaction

• Speckle disorder: two localization regimes (exponentiel & algebraic)

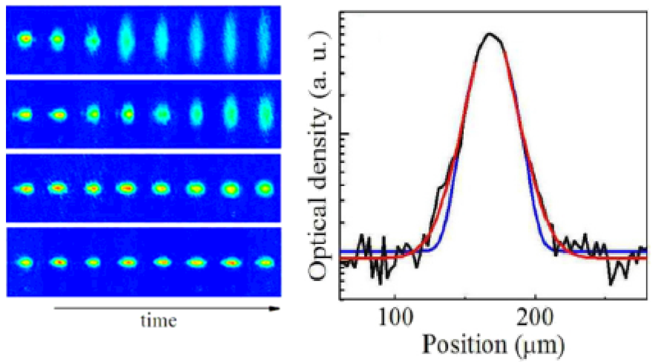
• Good agreement theory / experiment

• Related results in Florence (M. Inguscio group)

G. Roati et al. Nature 2008

Disorder : bi-chromatic lattice

No interactions : Feshbach resonance ^{39}K



Cold atoms = « good candidate » to study disordered systems

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- *Introduction and motivations*
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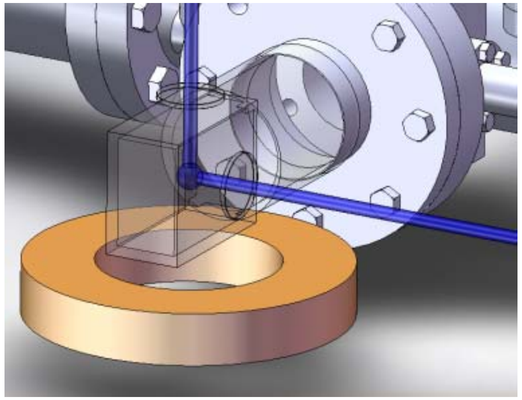
Anderson localization in higher dimensions

2D: critical dimensionality

3D: real transition (critical exponant, mobility edge position)

R.C. Kuhn et al. NJP 2007
S. Skipetrov et al. PRL 2008



On the experiment: 3D Anderson localisation

→ *3D expansion of matterwaves in laser speckle*

Anderson localization in higher dimensions

2D: critical dimensionality

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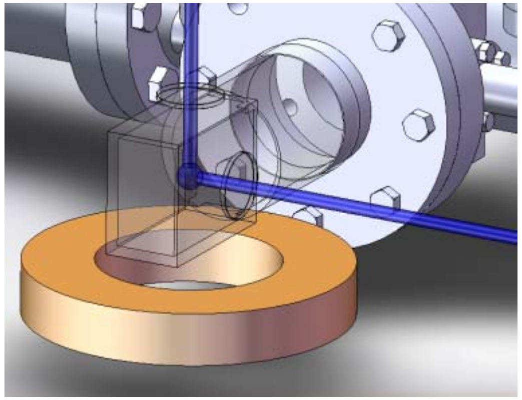
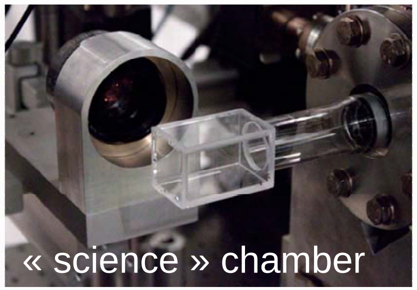
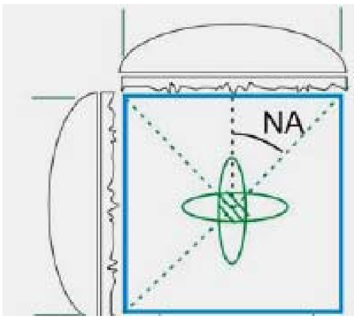


On the experiment: 3D Anderson localisation

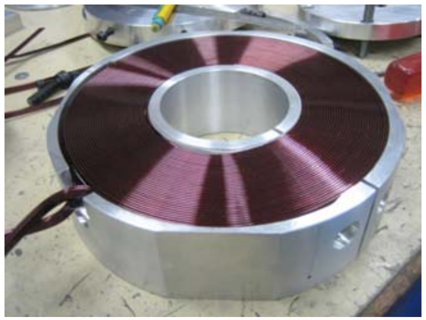
→ 3D expansion of matterwaves in laser speckle

→ 3D speckle realisation: crossed speckles



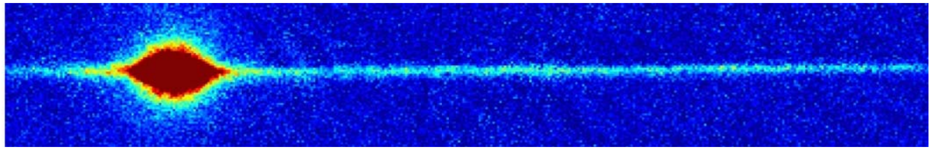


→ 3D expansion of BEC:
magnetic levitation to compensate gravity



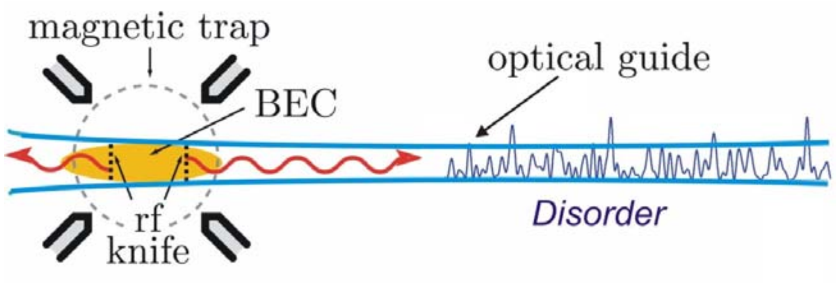
1D Anderson localization with guided atom laser

Localization of the guided atom laser in presence of disorder:



Transport experiment:
linear and non-linear propagation

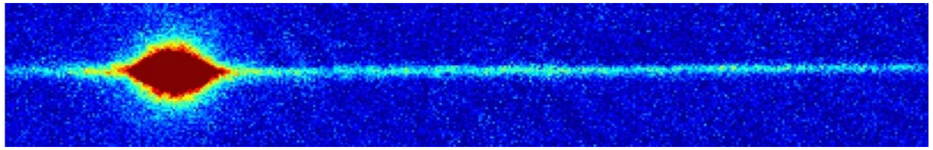
T. Paul *et al.* PRA 2009



→ **Effects of interactions on AL: localization in « real systems »**

1D Anderson localization with guided atom laser

Localization of the guided atom laser in presence of disorder:



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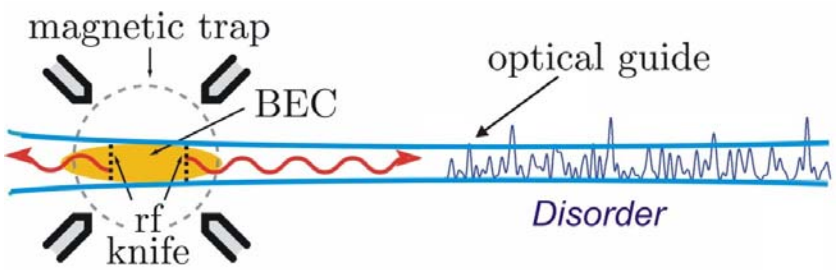
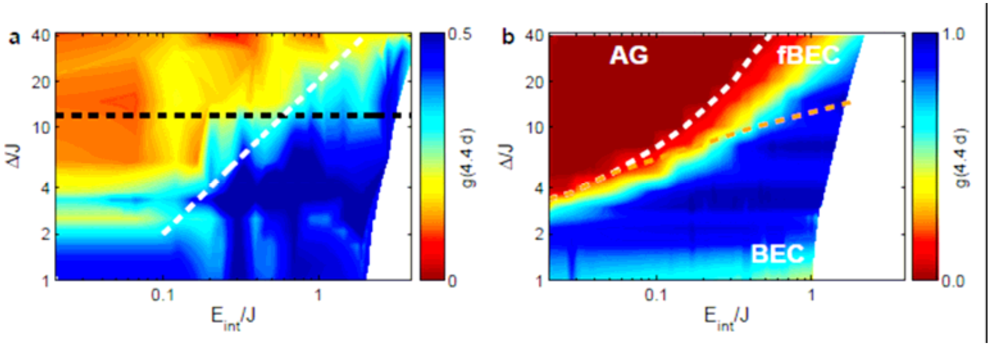


→ Effects of interactions on AL: localization in « real systems »

Florence (1D)

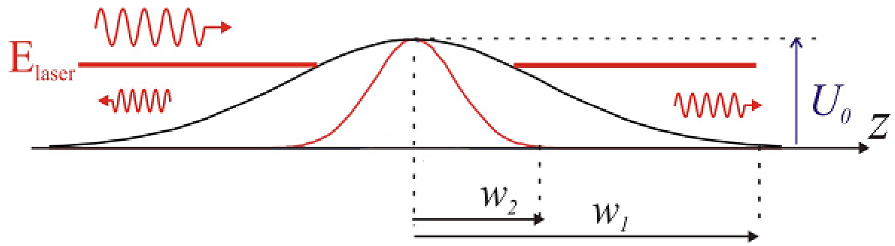
Feshbach resonance ^{39}K

B. Deissler *et al. arxiv* 2009

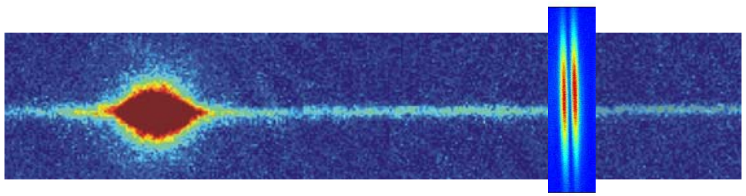


Quantum propagation with guided atom laser

Quantum tunneling through a single thin optical barrier



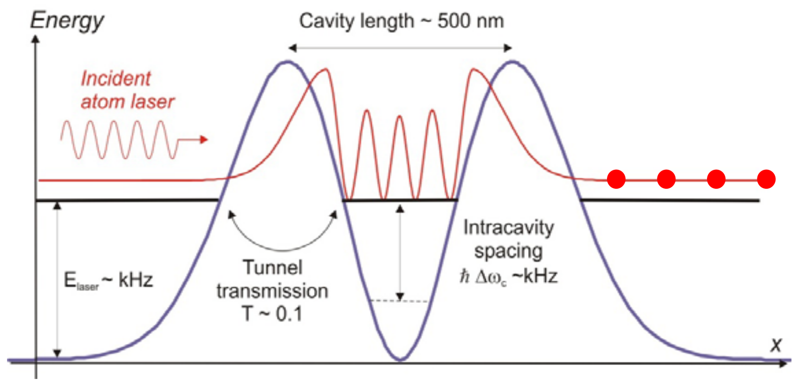
Atomic Fabry-Pérot cavity: transport through a double barrier



- *Frequency filtering*
- *Atom interactions → non classical atomic state*

Towards blockade effect

I. Carusotto PRA **2001**

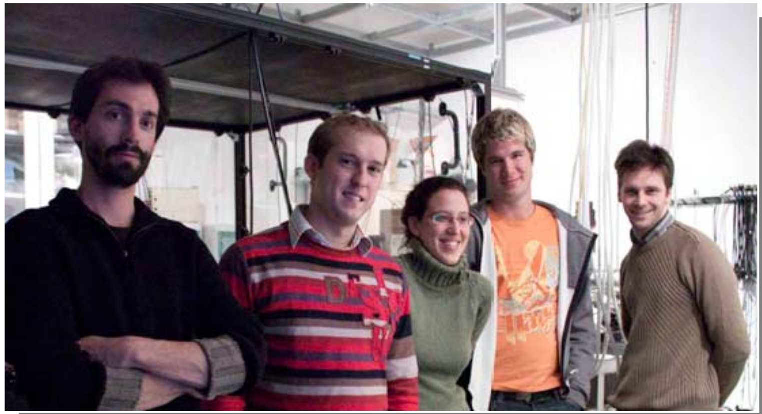


Thanks…

Pierre Chavel
Alain Aspect
Philippe Bouyer
Vincent Josse

Eric Willemenot

Marie-Lise Duplaquet



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André Willing and Frédéric Moron

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Ben Hambrecht, Pierre Lugan and David Clément

Thanks…

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« TP » Supoptique: Lionel, Thierry and Cédric

To all members of Institut d'Optique !