The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964–2014

2583-7

Workshop on Coherent Phenomena in Disordered Optical Systems

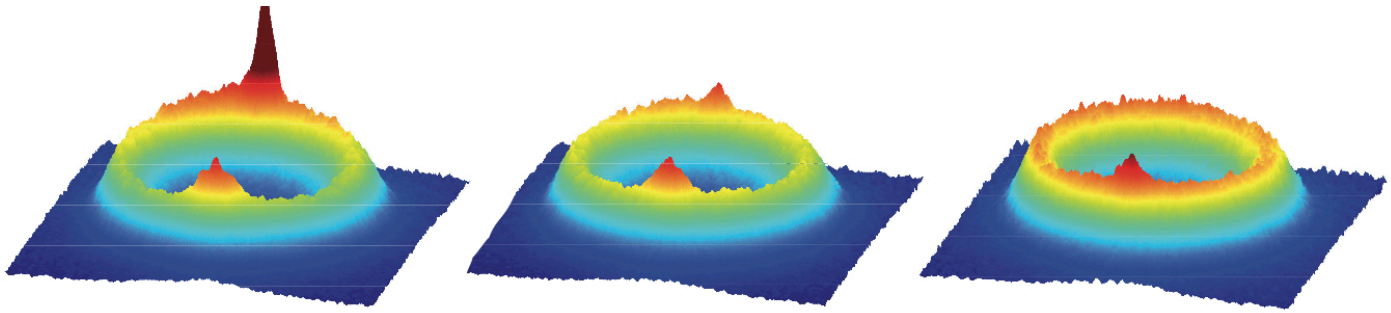
26 - 30 May 2014

Ultracold Atoms in Disorder: 3D Anderson Localization and Coherent Backscattering

Vincent JOSSE
Atom Optics Group, Institut d'Optique
Palaiseau
France

Ultracold Atoms in Disorder:

From 3D Anderson Localization to time reversal symmetry breaking in weak localization



Vincent Josse

Atom Optics Group – Institut d'Optique, Palaiseau, France

Workshop on Coherent Phenomena in Disordered Optical Systems
Trieste – May 27th 2014

PhDs

Fred Jendrzejewki
Kilian Müller
Jérémie Richard

Post Doc

Valentin Volchkov

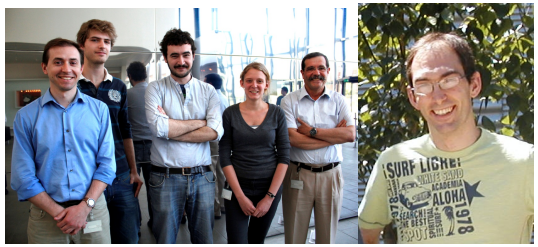
Former members

Juliette Billy (now Toulouse)
Alain Bernard (now at LENS)
Patrick Cheinet (now at LAC)
Stephan Seidel (Hannover)

Permanent

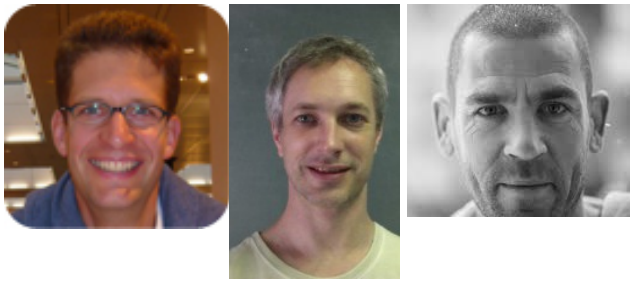
Vincent Josse
Philippe Bouyer
Alain Aspect

Collaborations :



AL 3D : Theory team IOGS
L. Sanchez-Palencia et al.

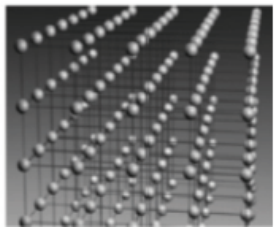
Time reversal symetry and localisation
T. Micklitz (Rio),
C. Müller (Konstanz)
A. Altland (Köln)



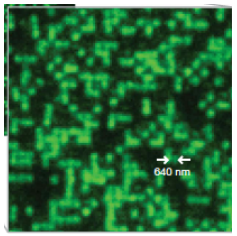
New approaches
M. Filoche (Polytechnique Palaiseau)
S. Mayroboda (US)

Ultracold atoms : « ideal » artificial systems

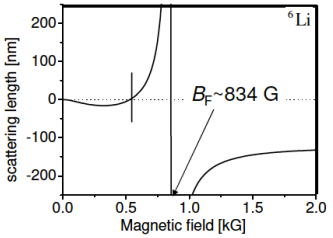
⇨ Controlled and tunable systems



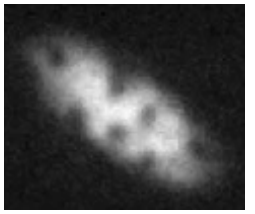
Geometries



Imaging

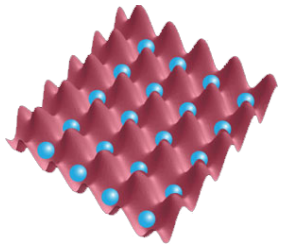


Interactions
(short and long range)

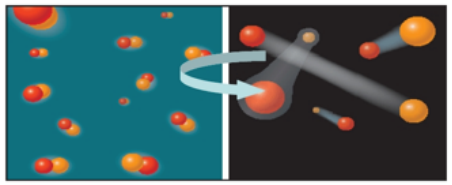


Artificial magnetic field

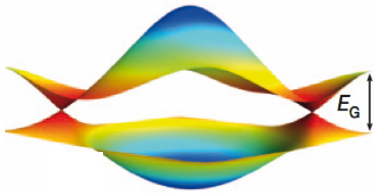
⇨ Systems in connection with condensed matter physics



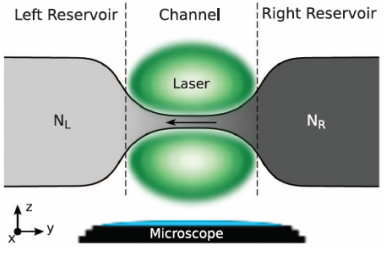
Mott Insulator



BEC-BCS and unitarity physics



Graphene



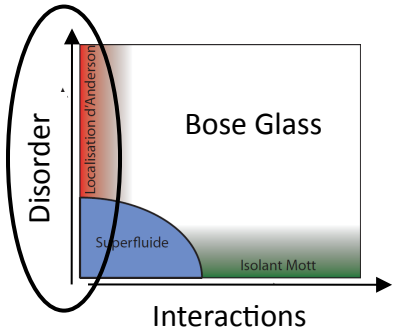
Conducting channel

⇨ Ultracold atoms in disorder

With interactions : superfluid – insulator transitions

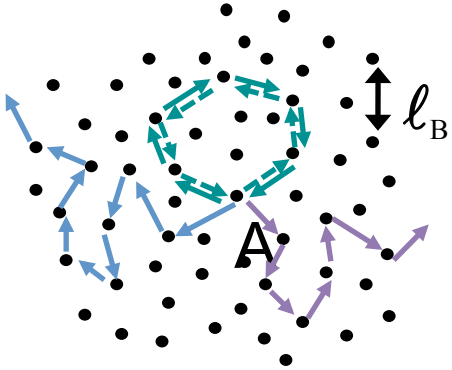
No interactions : Coherent effects on wave propagation

Weak localization and Anderson localization



Coherent propagation of (matter)waves in disorder

(Quantum) interferences on closed loops act against propagation



⇨ Weak localization : diffusion constant decreases
(e.g. magneto-negative resistance effect)

⇨ Strong localization (Anderson localization)
Complete halt of the wave (metal-insulator transition)

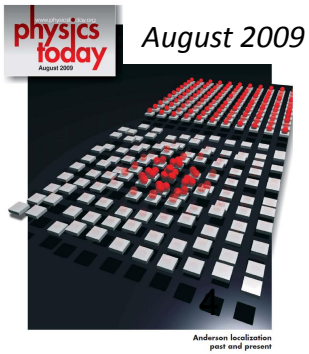
⇨ Dimensionnality

- *1D-2D : all states localize*
- *3D: a transition (diffusive – localized) with no exact theory yet*

A long history of research:

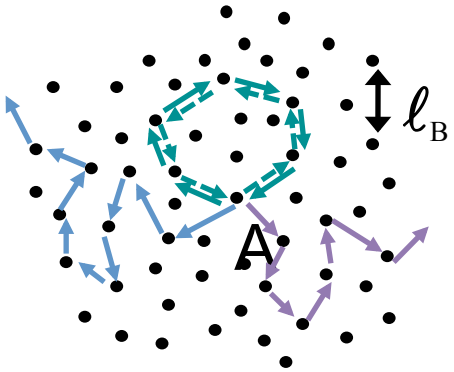
- Seminal paper of Anderson in 1958
- Electronic systems (80's)
- Classical waves (since 90')

…. *but open questions remain especially about the Anderson transition in 3D*



Coherent propagation of (matter)waves in disorder

(Quantum) interferences on closed loops act against propagation



⇨ Weak localization : diffusion constant decreases
(e.g. magneto-negative resistance effect)

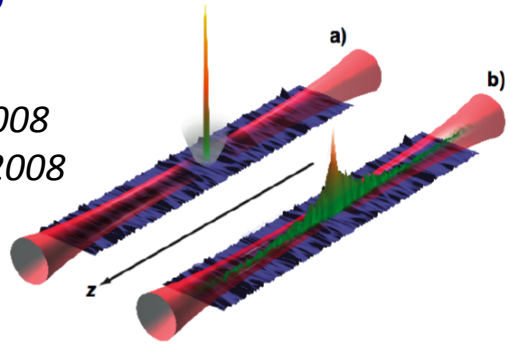
⇨ Strong localization (Anderson localization)
Complete halt of the wave (metal-insulator transition)

⇨ ultracold systems: good candidates to investigate AL

2008 : AL in 1D

Palaiseau, LENS

Billy et al. Nature 2008
Roati et al. Nature 2008



+ Dynamical localization (*p*-space)
in kicked rotor systems
Lille : J. Chabe et al. PRL 2008

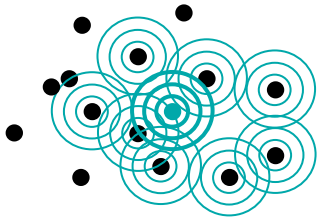
New Developments

Disorder + interactions
LENS : D'Errico arXiv:1405.1210 (2014)

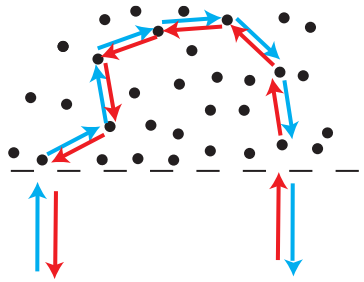
Higher dimensions (2D, 3D)
Looking for transition in 3D

Urbana Champaign (fermions): Kondov et al. Science (2011)
Palaiseau (bosons): Jendrzejewski et al. Nat. Phys. (2012)
LENS (bosons): Semeghini arXiv.1404.3528 (2014)

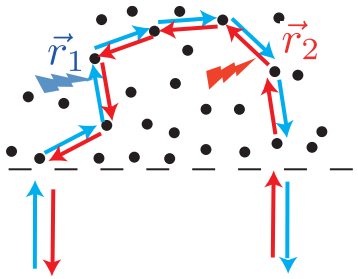
OUTLINE



I. 3D Anderson localization of ultracold atoms
in a laser speckle potential

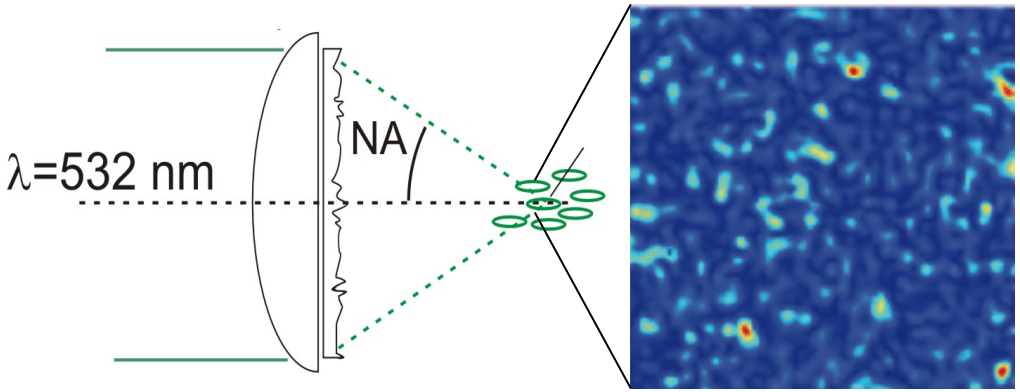


II. Coherent Backscattering of ultracold atoms



III. Time reversal symmetry on weak localization:
the CBS revival

Laser speckle disordered potential



$$V_{Random} \propto \frac{I(r)}{\Delta}$$

Blue detuned = repulsive potential
(^{87}Rb line : 780 nm)

Diffraction from a rough plate

⇒ *Exponential intensity distribution* $P(V) = \frac{1}{V_R} e^{-\frac{V}{V_R}}$

Well controlled properties

Large contrast *(high probability of zero intensity)*

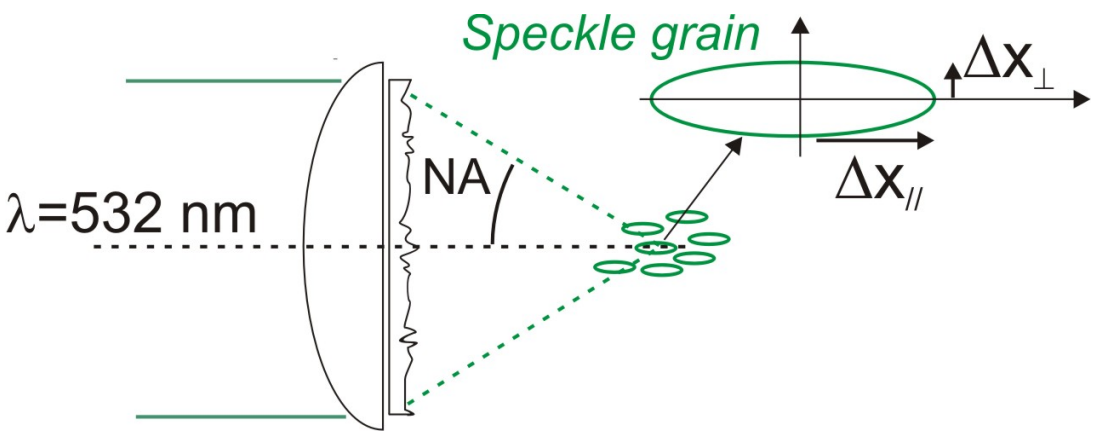
Goodman Speckle Phenomena in Optics
*Horak et al. PRA **58**, (1998)*
*Clément et al., NJP **8** (2006)*

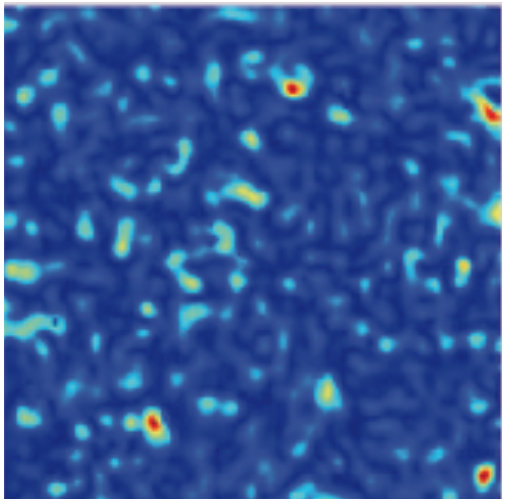
⇒ *« Speckle grain » = Finite correlation length controlled by numerical aperture (NA)*

Other possibilities : Bi-chromatic lattices, atomic impurities…

Damski et al. PRL (2003)
Gavish & Castin PRL (2005)
Esteve et al. PRA (2004)

Spatial correlation properties





Transverse correlation
the diffraction limit

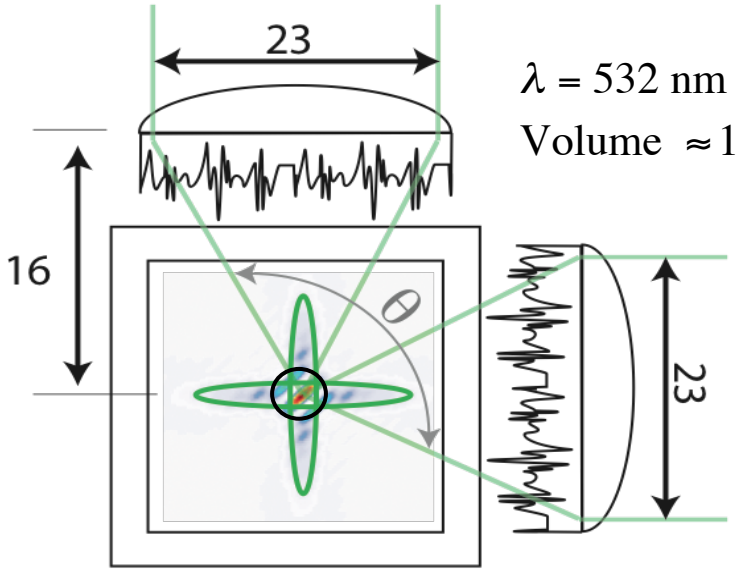
$$\Delta x_\perp = \frac{\lambda}{2\,\mathrm{NA}}$$

Longitudinal correlation
the Raileygh distance

$$\Delta x_{//} = \frac{\lambda}{2\,\mathrm{NA}^2} >> \Delta x_\perp$$

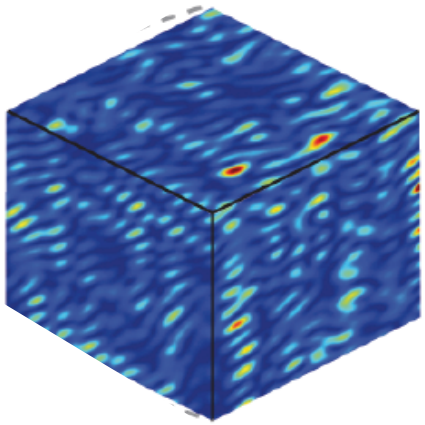
⇨ *Very elongated 3D speckle grain*

Our 3D disorder potential : crossing two speckle patterns at 90°



$\lambda = 532$ nm NA = 0.5

Volume ≈ 1 mm^3



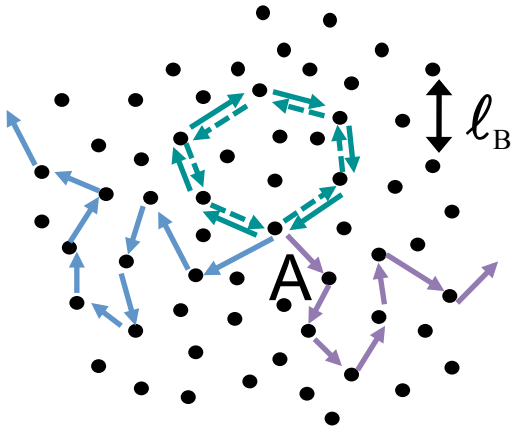
3D speckle realization

⇨ Short correlation length in all direction with moderate anisotropy

$\bar{\sigma}_R \approx 0.13\ \mu\text{m}$

⇨ Well controlled : properties fully taken into account for theoretical predictions

Naïve understanding of 3D Anderson transition



$k\ell_B \gg 1 \quad (\lambda_{dB} \ll \ell_B)$

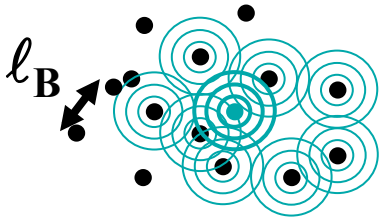
Propagation described by successive scattering events

In 3D : only weak corrections by the interferences (rare closed loops)

⇨ Diffusive behavior in weak disorder in 3D

$$D^\star \leq D_B$$

A phase transition in strong disorder : Anderson localization



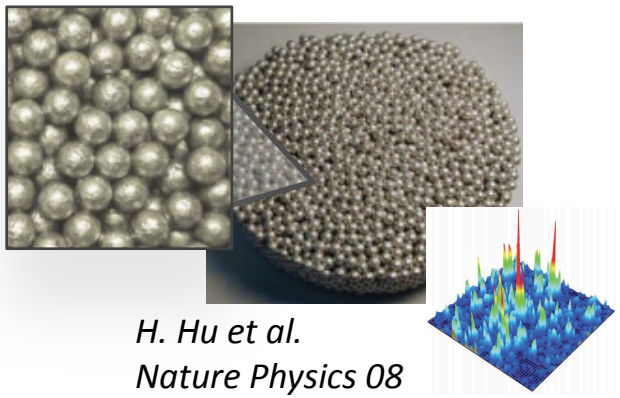
$k\ell_B \sim 1$

Ioffe Regel Criterion

⇨ *Localized wavefunctions*

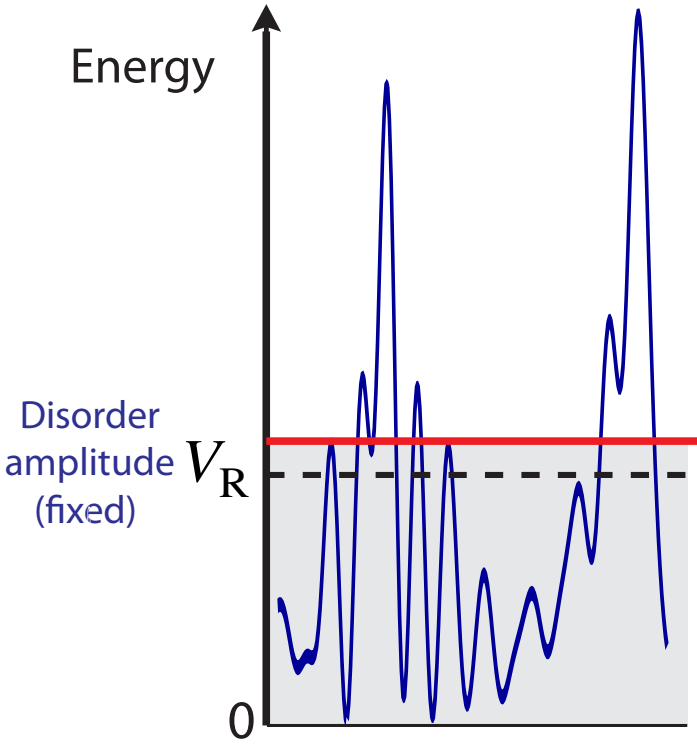
⇨ *No diffusion (insulating behavior)*

Hard to localize in 3D!

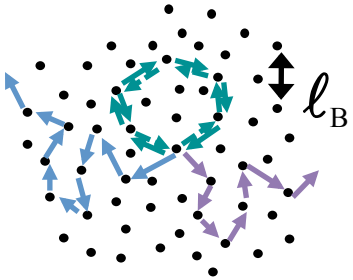


H. Hu et al.
Nature Physics 08

3D Anderson transition : energy diagram



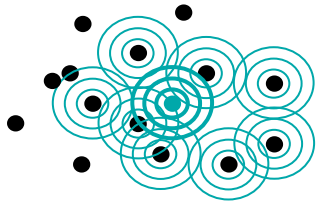
Diffusive states (high energy)

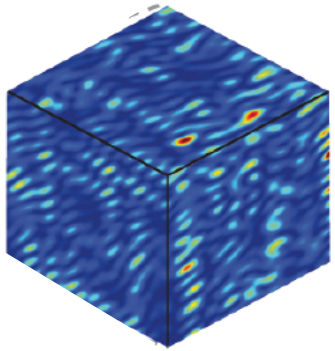


Mobility Edge

$k\ell_B \sim 1$

Localized states (low energy)

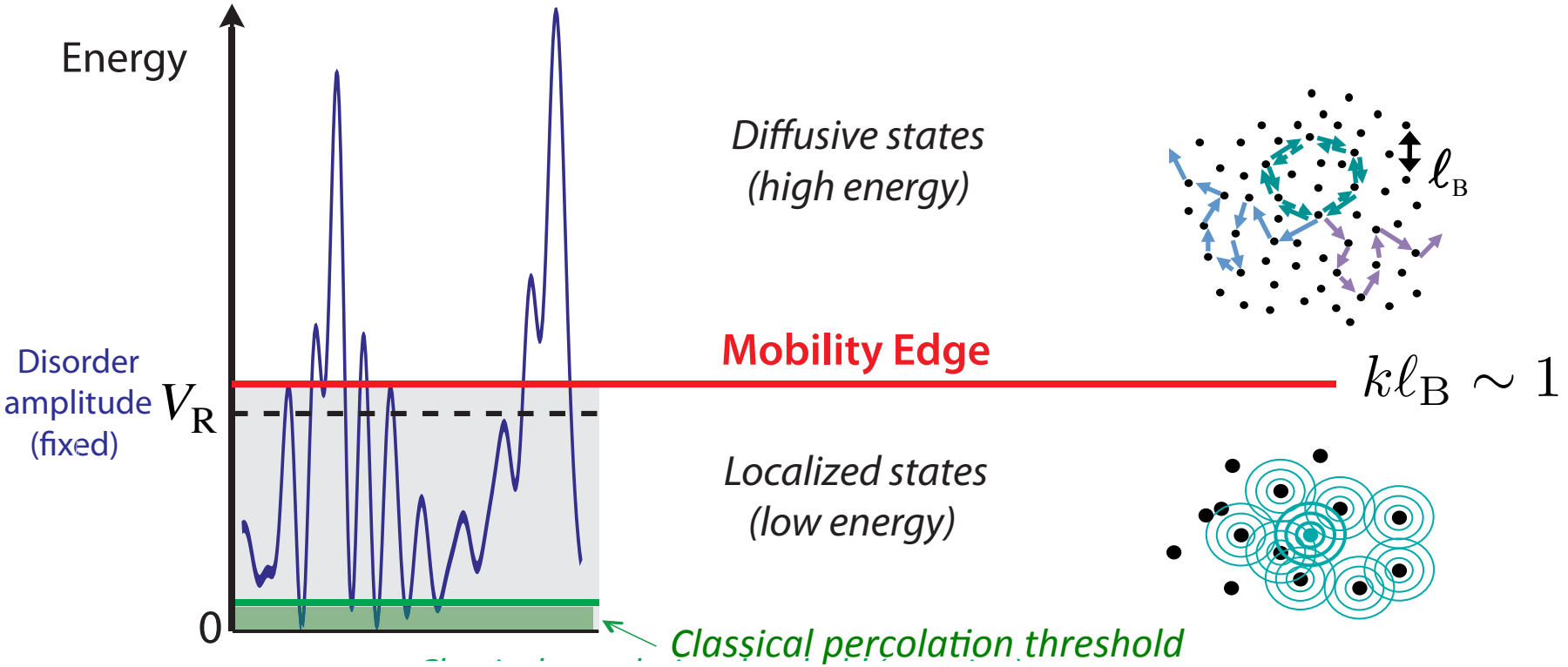


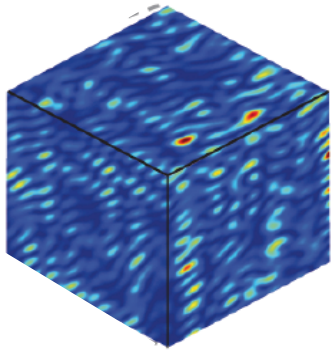


3D speckle disorder potential (repulsive potential)

⇨ *A critical energy: diffusive vs localized states*

3D Anderson transition : energy diagram





3D speckle disorder potential (repulsive potential)

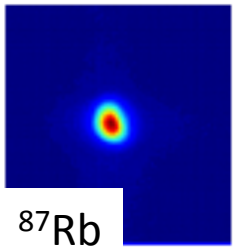
⇨ *A critical energy: diffusive vs localized states*

⇨ *Negligible classical trapping in laser speckle (less than 1%)*

Pilati et al. PRL (2009), NJP (2010)

Experimental scheme for 3D AL

1. Dilute ^{87}Rb BEC in a crossed optical trap

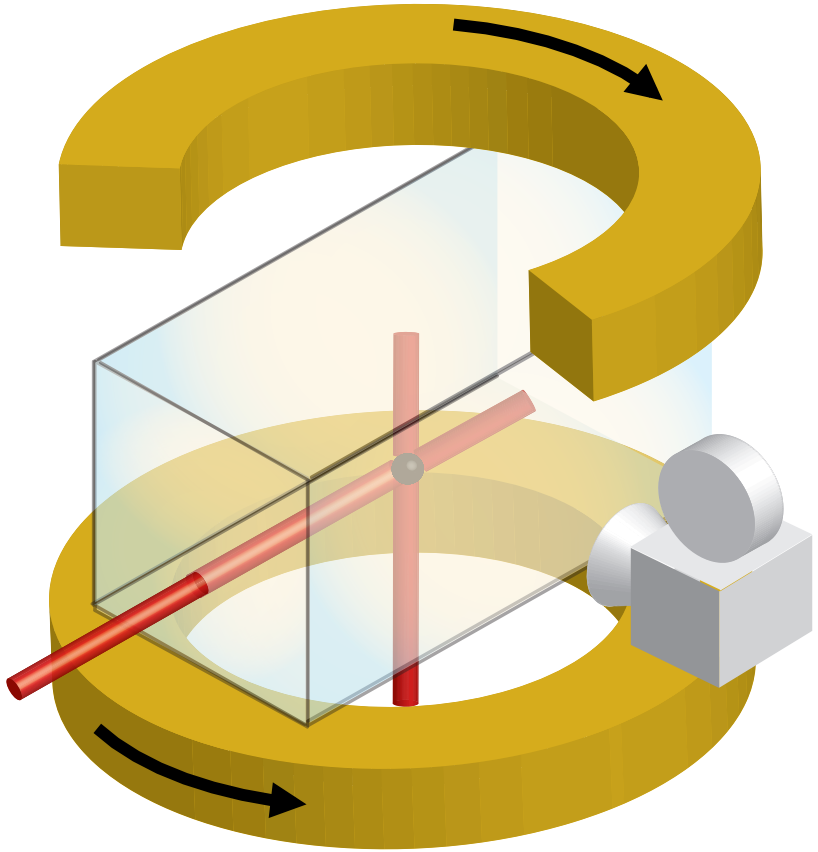


$\nu_{trap} \approx 5\ Hz$

$N_{at} \approx 3.10^4$

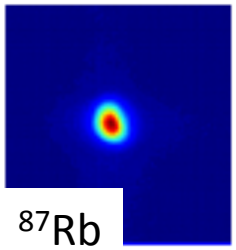
$T \approx 1\,\mathrm{nK}$

$\mu_{in} \approx 40\ \mathrm{Hz}$



Experimental scheme for 3D AL

1. Dilute ^{87}Rb BEC in a crossed optical trap



$\nu_{trap} \approx 5\ Hz$

$N_{at} \approx 3.10^4$

$T \approx 1\,\mathrm{nK}$

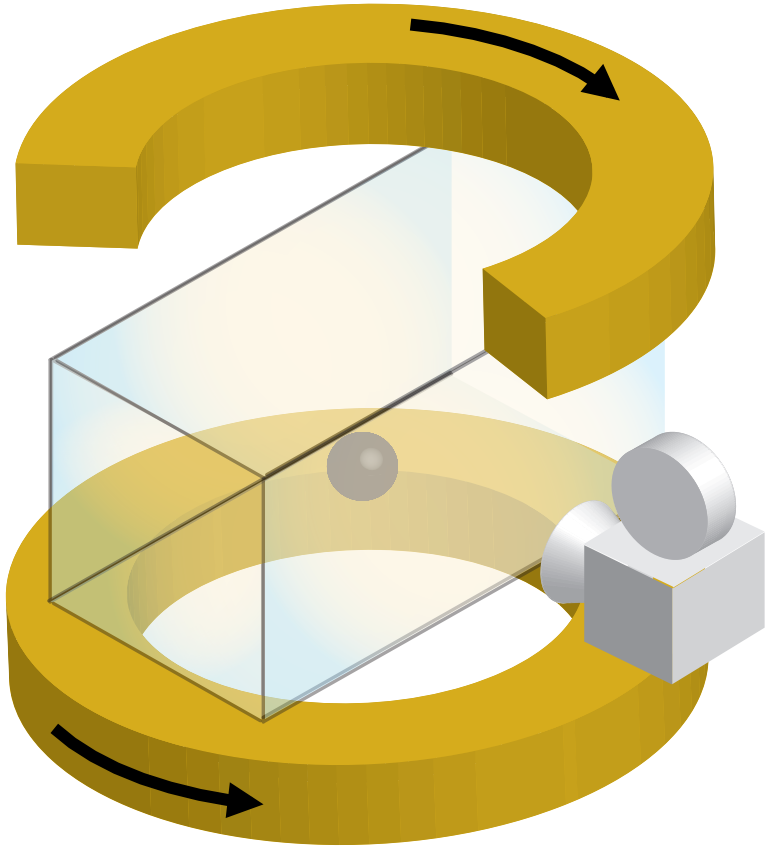
$\mu_{in} \approx 40\ \mathrm{Hz}$

2. « Free » expansion stage

⇨ *Initial interactions transform into kinetic energy*

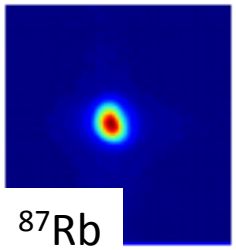
⇨ *A non-interacting matter wave with large* λ_{dB}

$\lambda_{dB} \sim 6\ \mu\mathrm{m}$



Experimental scheme for 3D AL

1. Dilute ^{87}Rb BEC in a crossed optical trap

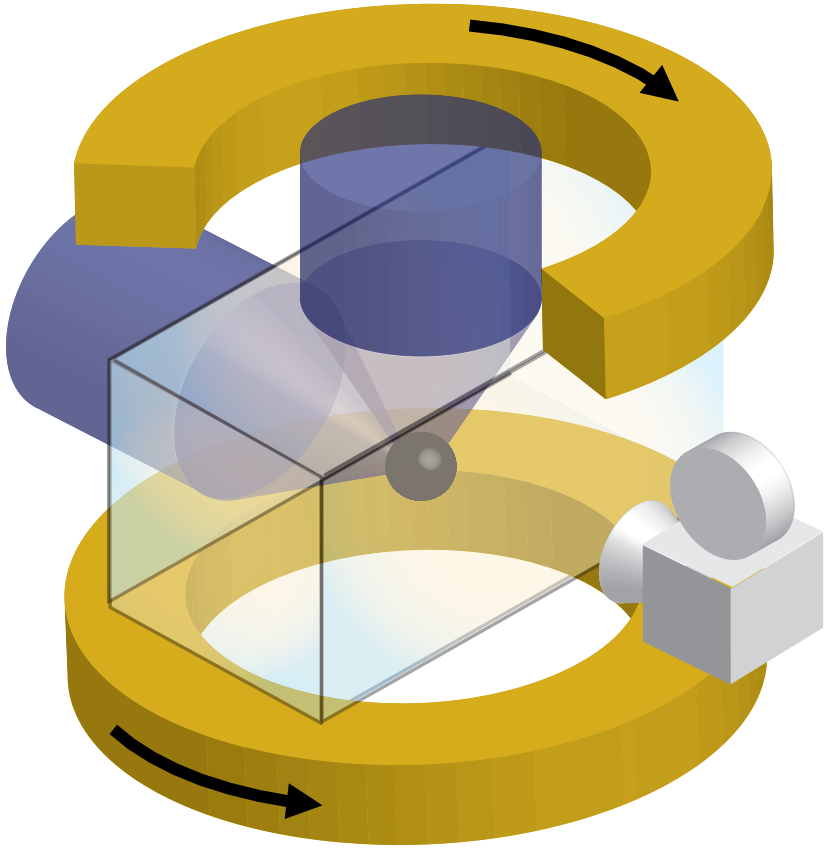


$\nu_{trap} \approx 5\ Hz$

$N_{at} \approx 3.10^4$

$T \approx 1\,\mathrm{nK}$

$\mu_{in} \approx 40\ \mathrm{Hz}$



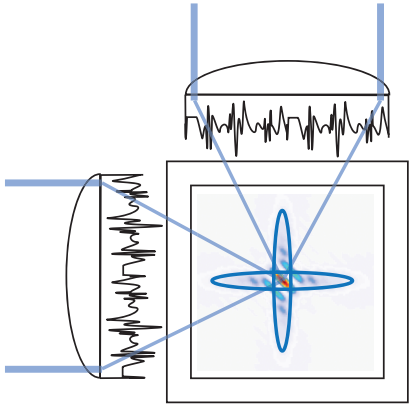
2. « Free » expansion stage

⇨ *Initial interactions transform into kinetic energy*

⇨ *A non-interacting matter wave with large λ_{dB}*

$\lambda_{dB} \sim 6\ \mu\mathrm{m}$

3. A 3D disorder by crossing two speckle fields

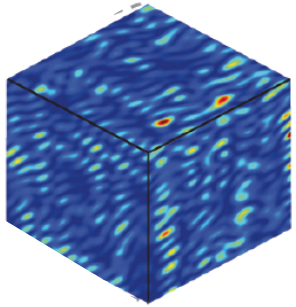


$\lambda = 532\ \mathrm{nm}$ NA = 0.5

Volume $\approx 1\ \mathrm{mm}^3$

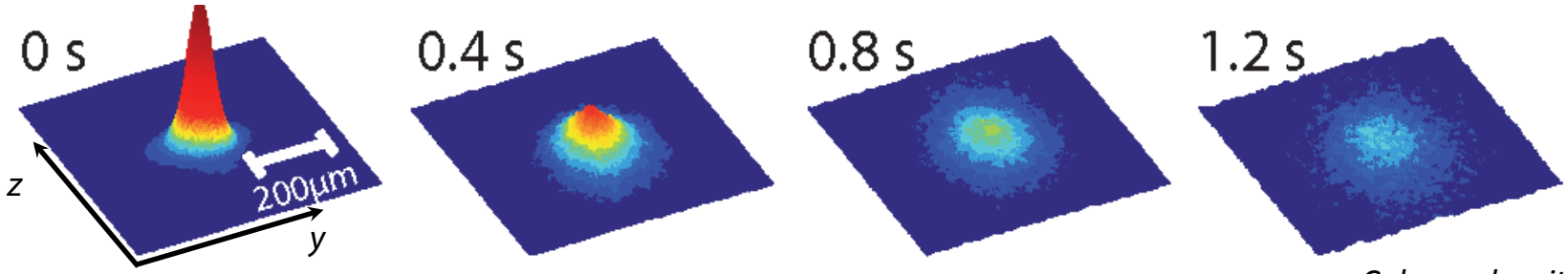
Short correlation length in all directions and moderate anisotropy

$\bar{\sigma}_R \approx 0.13\ \mu\mathrm{m}$



Expansion in weak disorder

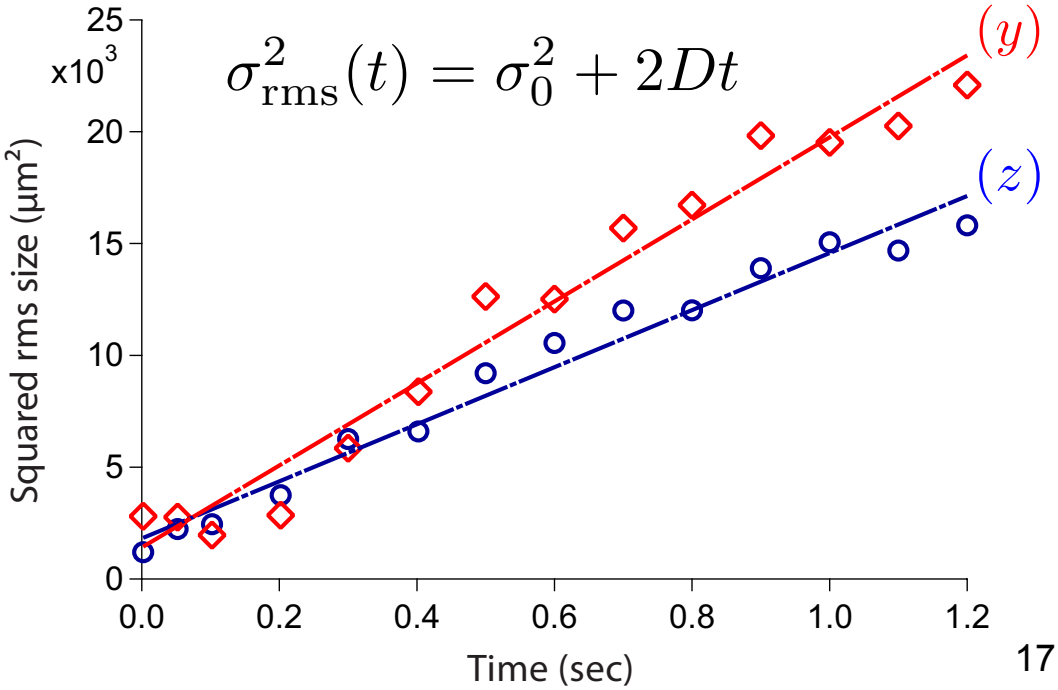
$V_R/h = 135$ Hz



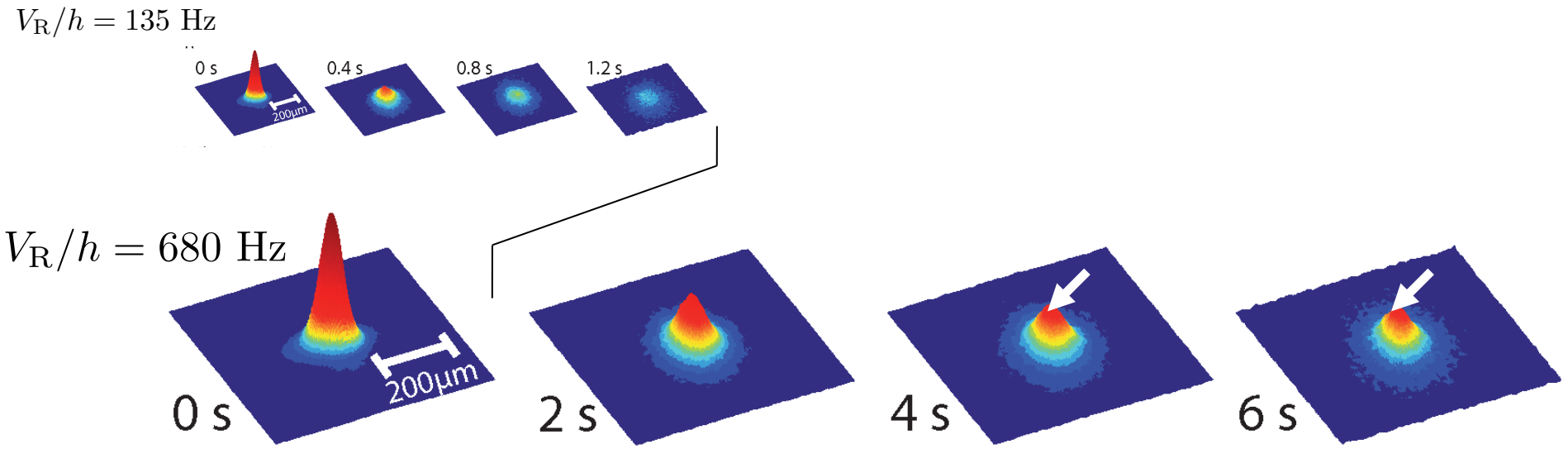
Column densities
by fluorescence imaging
(horizontal axis)

Weak disorder case :

- *Diffusive behavior is observed (with slight anisotropy)*
- *No localization (as expected in weak disorder)*



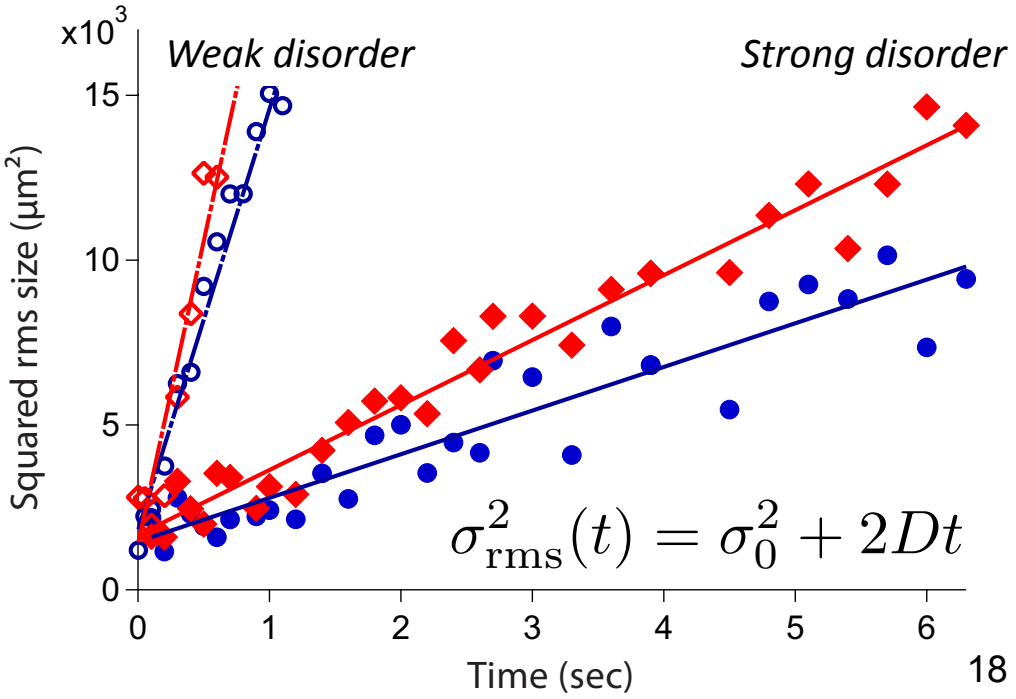
Expansion in strong disorder



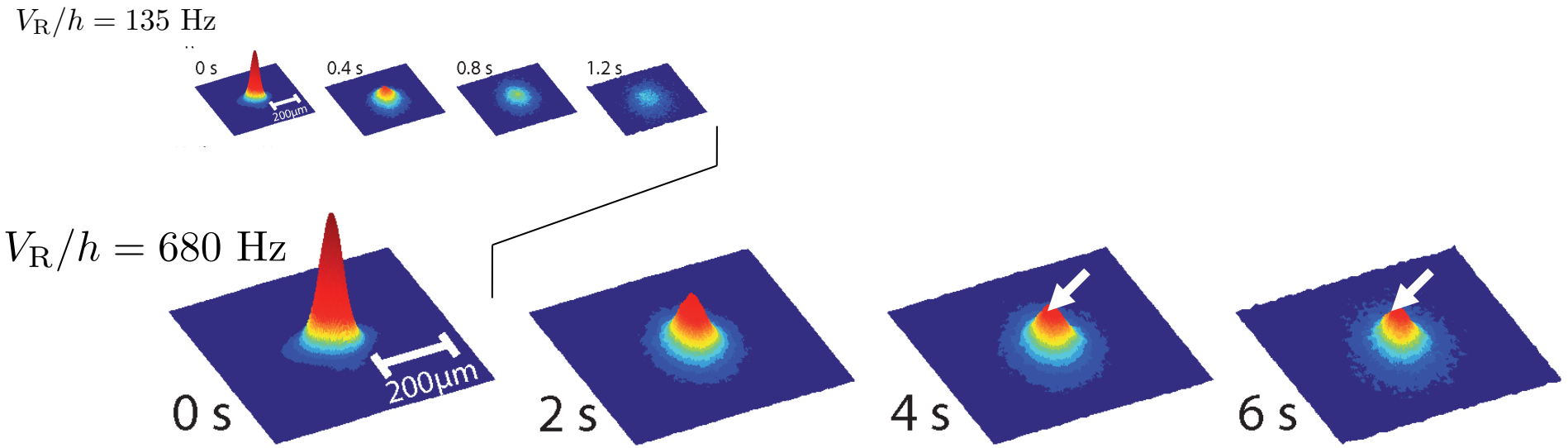
Strong disorder case :

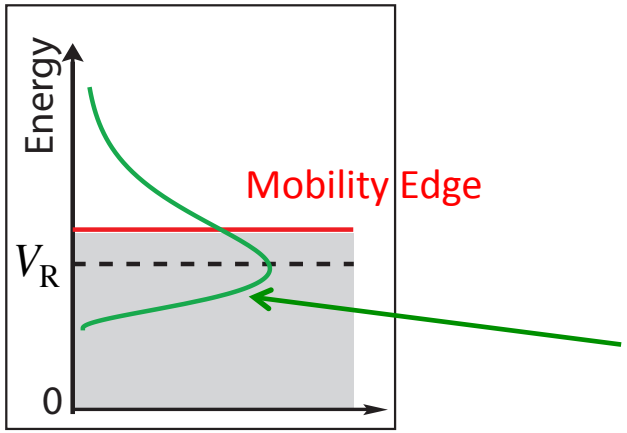
- *A much slower dynamics*
  But still a diffusive component !

- *A central peak persists at long time*
  A localized fraction



Expansion in strong disorder



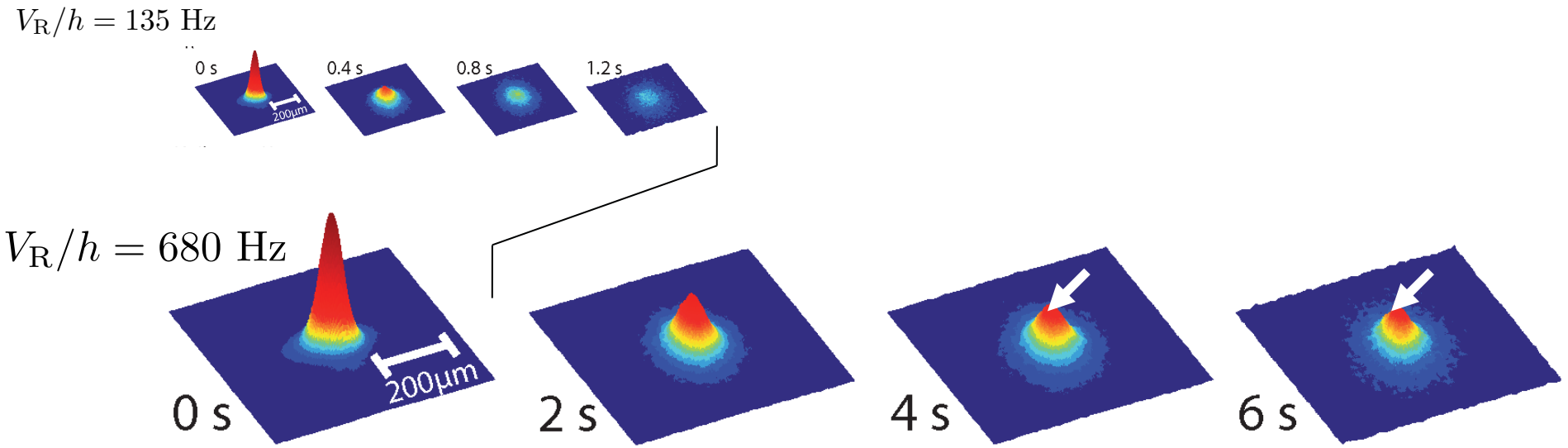


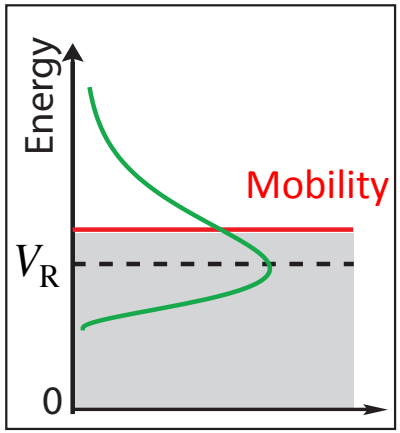
Existence of two components (diffusive and localized) :

Energy spreading at the disorder switch on
(projection of incoming k-waves into new eigenstates)

Kuhn et al., NJP (2007)
Skipetrov et al., PRL (2008)
Yedjour and van Tiggelen, EPJD (2010)
Piraud et al., arXiv.1112.2859

Expansion in strong disorder





Kuhn et al., NJP (2007)
Skipetrov et al., PRL (2008)
Yedjour and van Tiggelen, EPJD (2010)
Piraud et al., arXiv.1112.2859

⇨ Phenomenological analysis of the profiles :

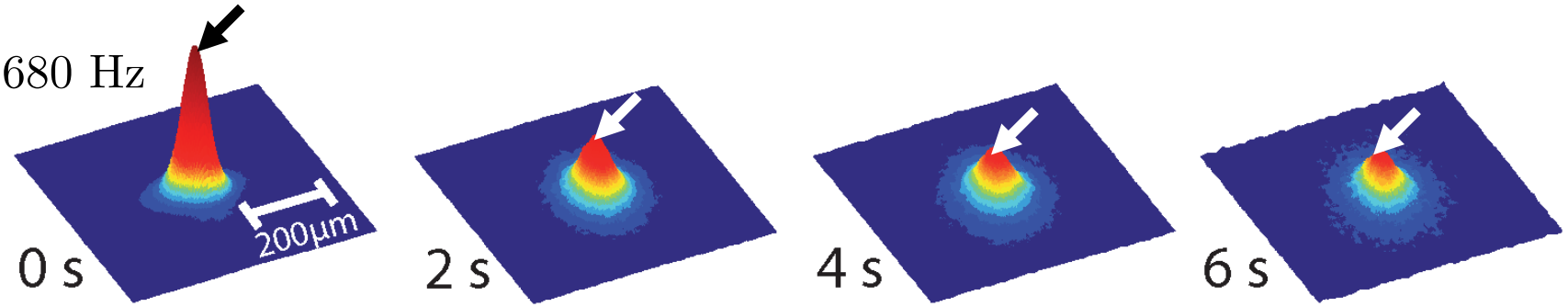
$$\tilde{n}(y,z,t) = f_{\mathrm{loc}} \times \tilde{n}_{\mathrm{i}}(y,z) + \tilde{n}_{\mathrm{D}}(y,z,t)$$

Steady localized part
= a replica of the inital shape
(very short L_{loc} << initial size)

Diffusive part

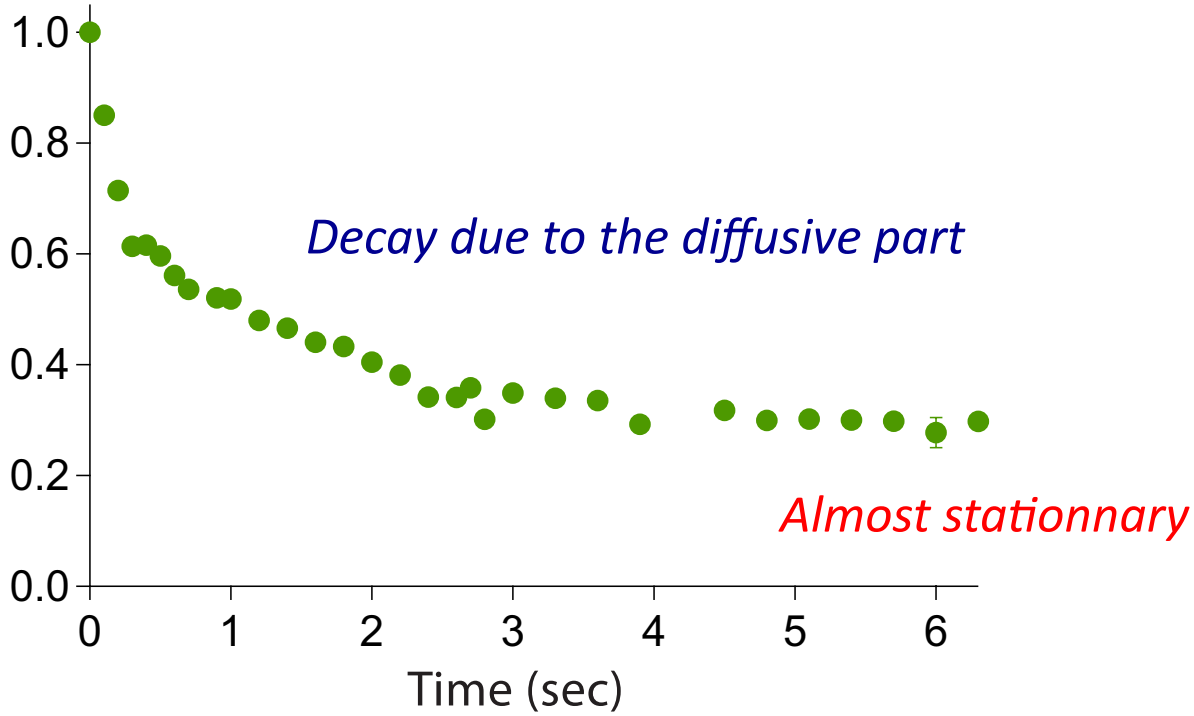
Evidence of a localized component

$V_{\mathrm{R}}/h = 680$ Hz



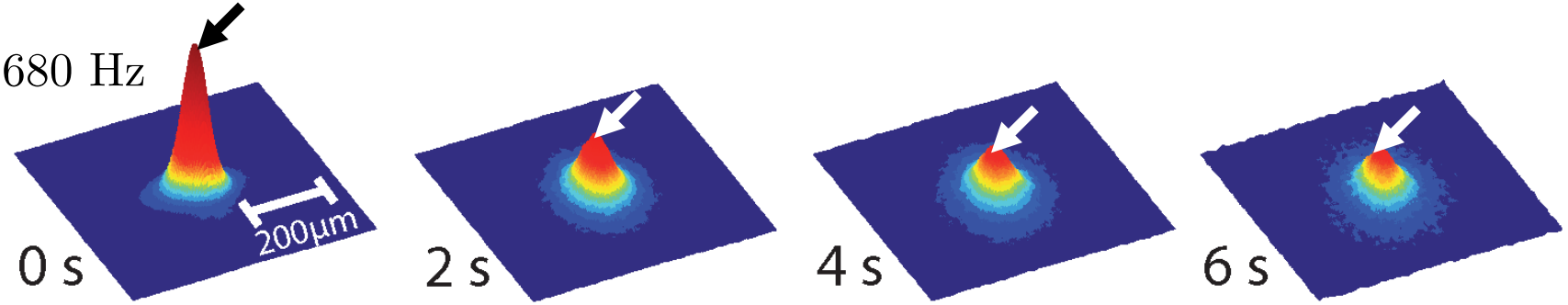
$$\tilde{n}(0,0,t) = f_{\mathrm{loc}} \times \tilde{n}_{\mathrm{i}}(0,0) + \tilde{n}_{\mathrm{D}}(0,0,t) \propto 1/t$$

Evolution of the normalized central density



Evidence of a localized component

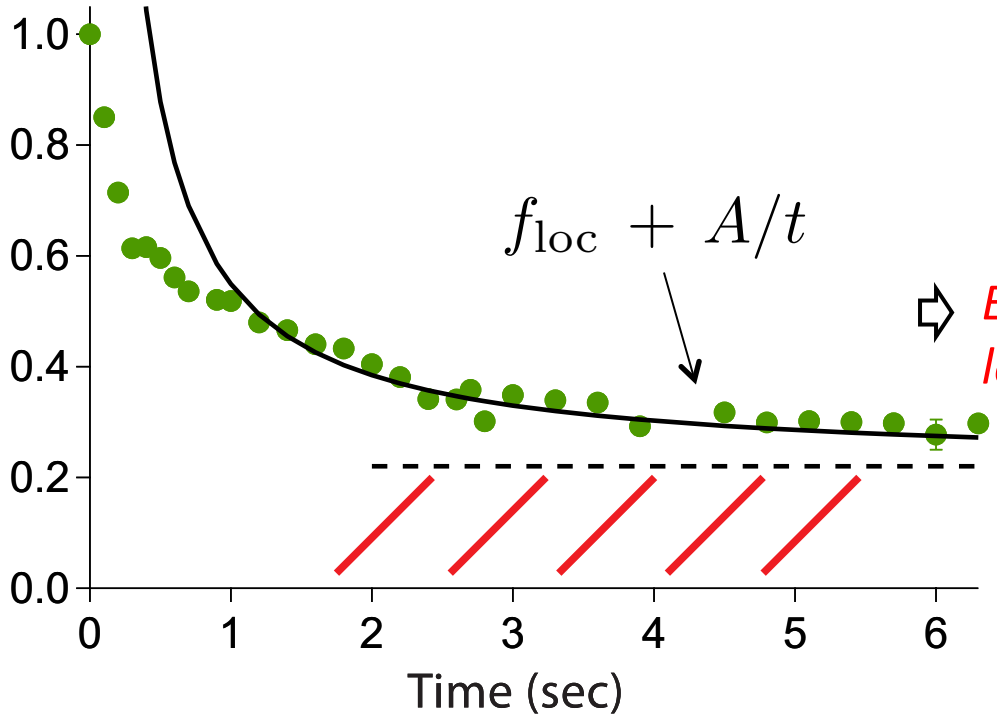
$V_R/h = 680$ Hz



$$\tilde{n}(0,0,t) = f_{\mathrm{loc}} \times \tilde{n}_{\mathrm{i}}(0,0) + \tilde{n}_{\mathrm{D}}(0,0,t)$$

$$\propto 1/t$$

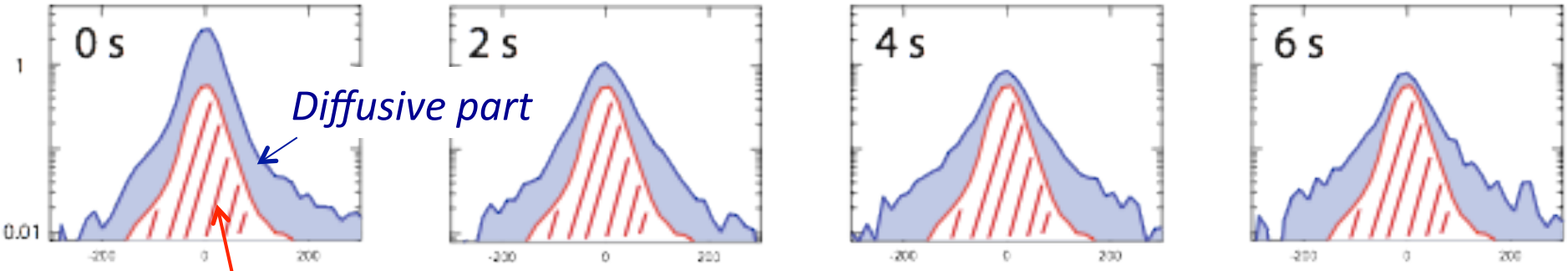
Evolution of the normalized central density



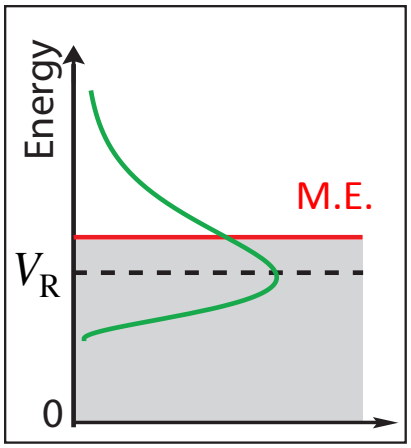
Estimation of the localized fraction

$f_{\mathrm{loc}} \sim 20\%$

Summary : How did we interpret the profiles ?



Horizontal cuts
in semi-log plots



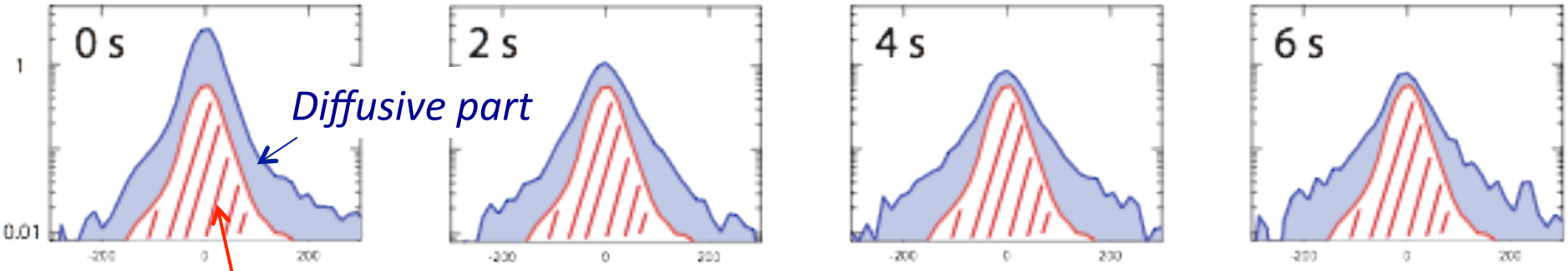
No classical trapping can explain the localized part

Diffusion constant have good order of magnitude

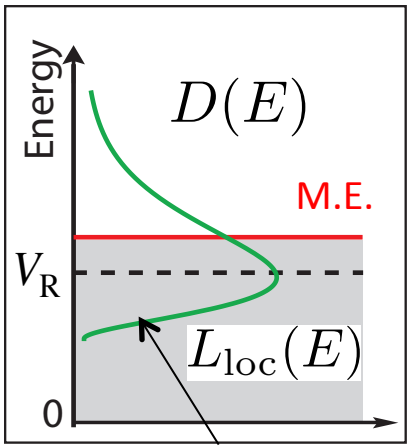
Comparison with theory of 3D Anderson localization ?

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

Summary : How did we interpret the profiles ?



Horizontal cuts
in semi-log plots



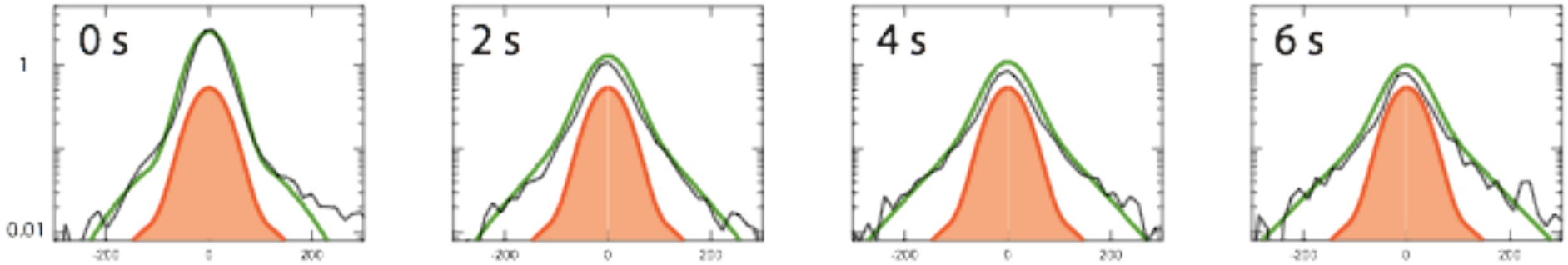
Numerical calculation of the energy distribution (independent of SC)

No exact theory but quantitative predictions based on the « Self-Consistent (SC) Theory »

Vollhardt and Wölfle PRL (1982)

Predictions adapted to our 3D speckle disorder
(theory team led by L. Sanchez-Palencia)

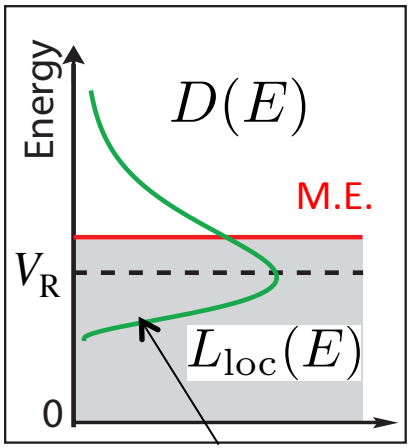
Comparison with 3D AL theory



Localized part

Total (Diffusive + Localized)

Horizontal cuts
in semi-log plots



Numerical calculation of the energy distribution (independent of SC)

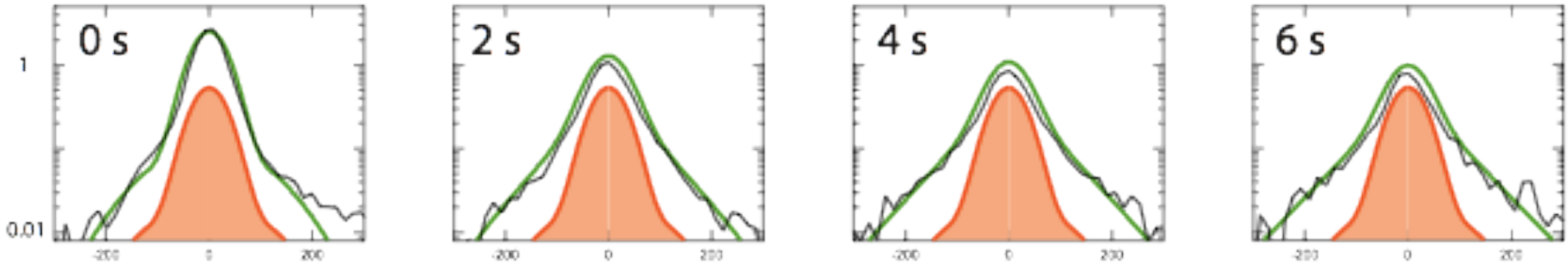
No exact theory but quantitative predictions based on the « Self-Consistent (SC) Theory »

Vollhardt and Wölfle PRL (1982)

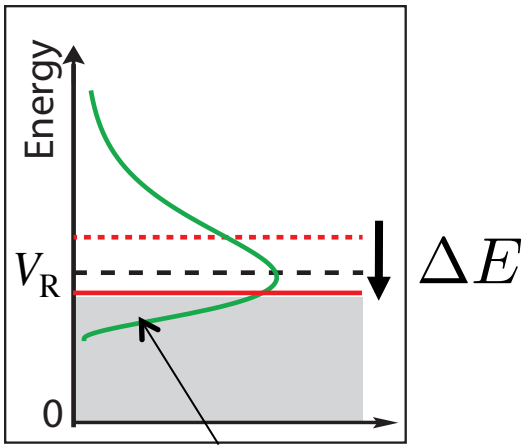
Predictions adapted to our 3D speckle disorder
(theory team led by L. Sanchez-Palencia)

Good agreement but…

Comparison with 3D AL theory



Horizontal cuts
in semi-log plots

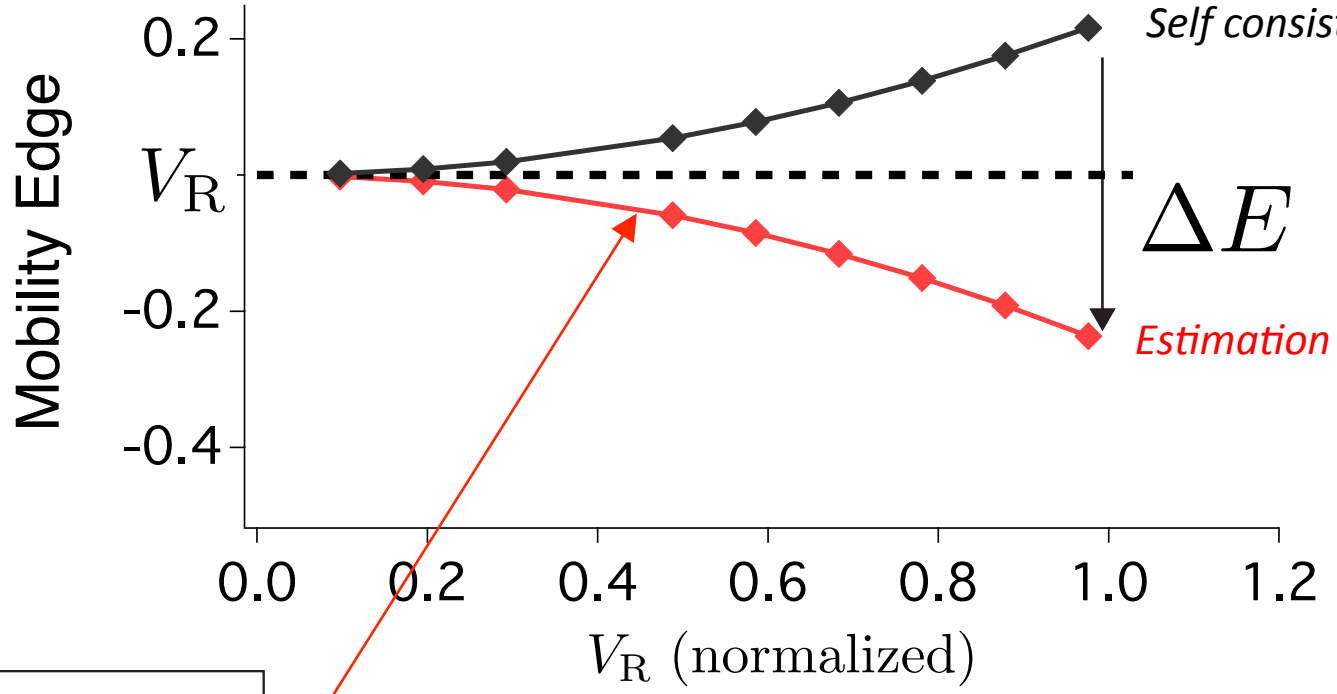


Numerical calculation of the energy distribution (independent of SC)

… an « ad hoc » shift in energy

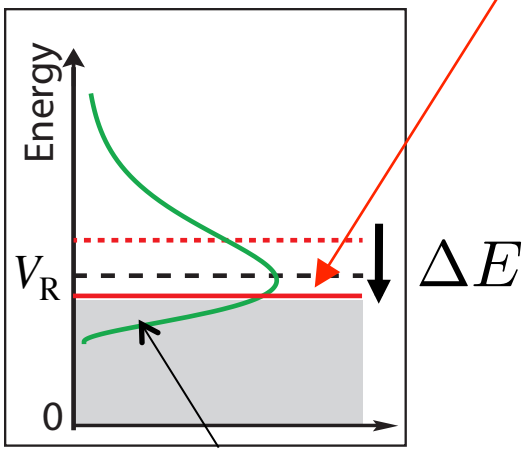
(a way to estimate the position of the mobility edge)

Comparison with 3D AL theory



Self consistent theory (version 1)

Estimation of mobility edge

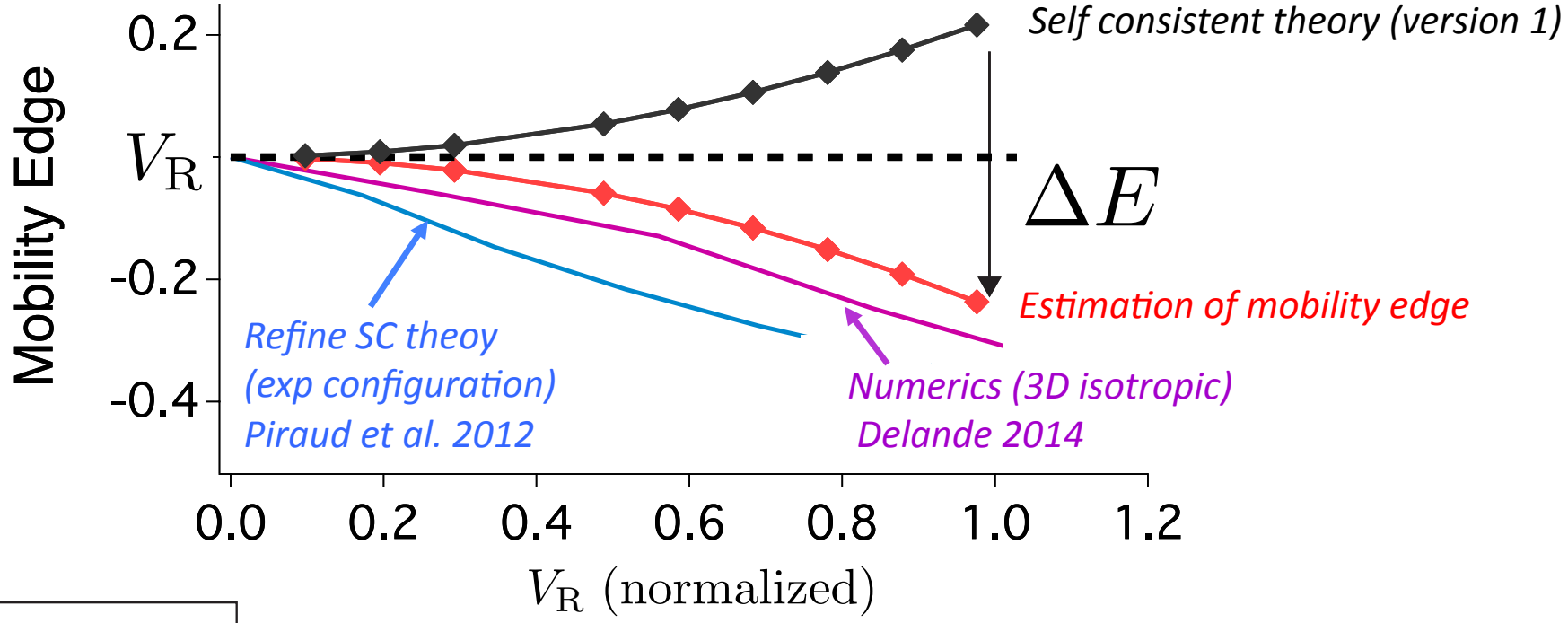


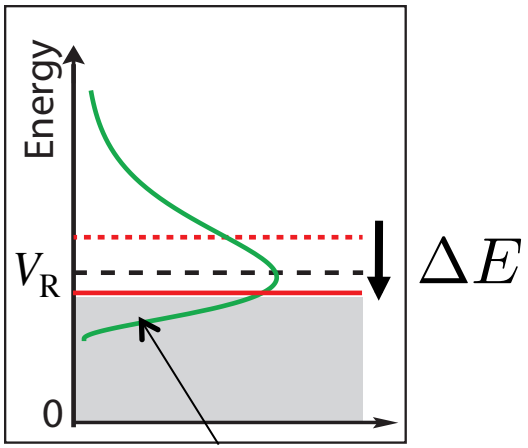
Numerical calculation of the energy distribution (independent of SC)

… an « ad hoc » shift in energy

(a way to estimate the position of the mobility edge)

Comparison with 3D AL theory





Numerical calculation of the energy distribution (independent of SC)

… an « ad hoc » shift in energy

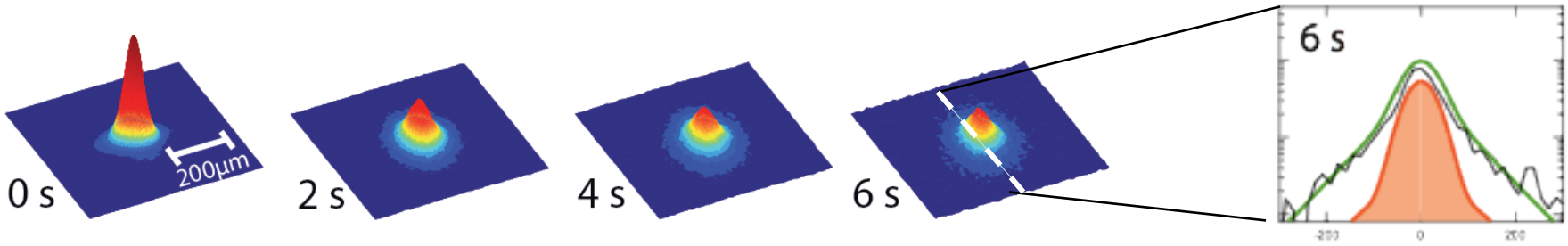
(a way to estimate the position of the mobility edge)

⇨ Shift in accordance with refined theoretical treatment and numerical simulations

Theory (SC): M. Piraud et al., EPL (2012)
Yedjour and van Tiggelen EPJD (2010)
Numerics: D. Delande and G. Orso, arXiv (2014)

Conclusion and perspectives (part I)

Evidences of 3D Anderson localization



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

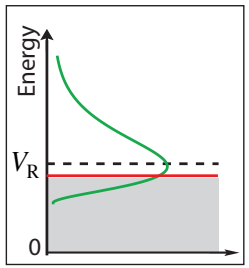
3D AL theory (SC) and ultracold atoms experiment come close together

A first step towards a « test bed » of SC theory

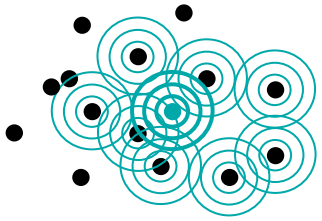
Towards the critical regime in 3D (mobility edge / critical exponents)

Need of

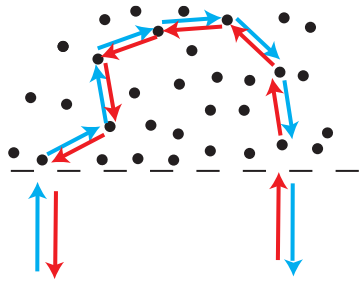
- Control and measure of the energy distribution *(See Talk of G. Modugno)*
- Other signatures of AL ?



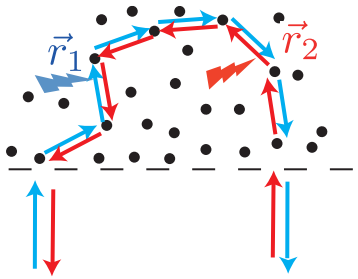
OUTLINE



I. 3D Anderson localization of ultracold atoms
in a laser speckle potential



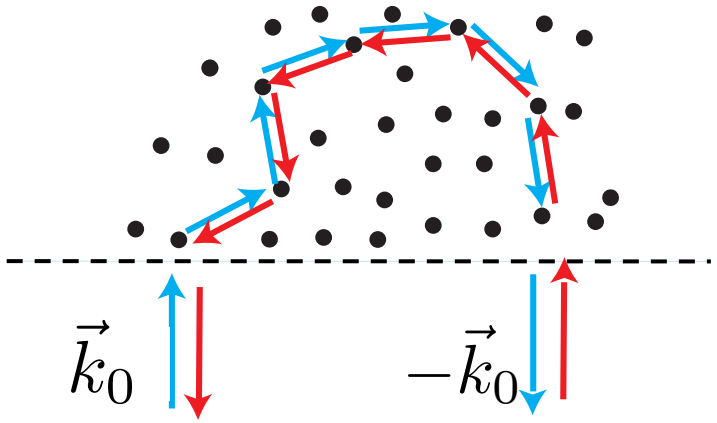
II. Coherent Backscattering of ultracold atoms



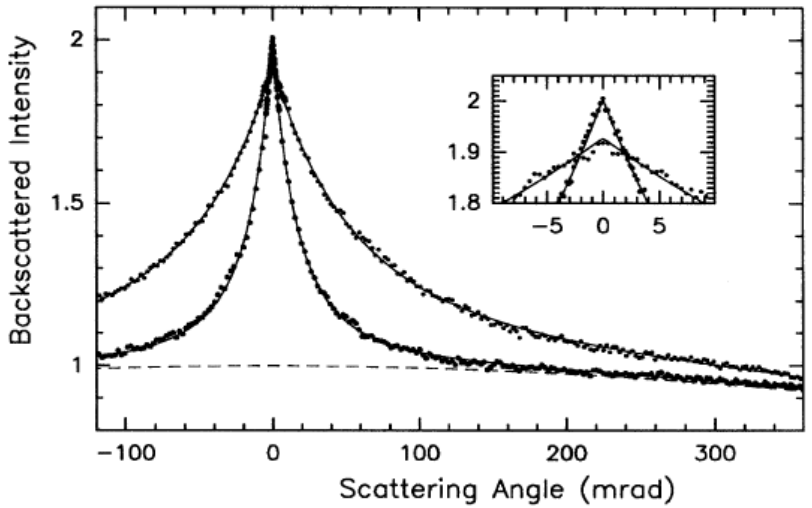
III. Time reversal symmetry on weak localization:
the CBS revival

Coherent backscattering of waves

Retro-diffusion enhanced by (quantum) interferences between time-reversed paths



Ex: Wiersma et al. PRL 1995



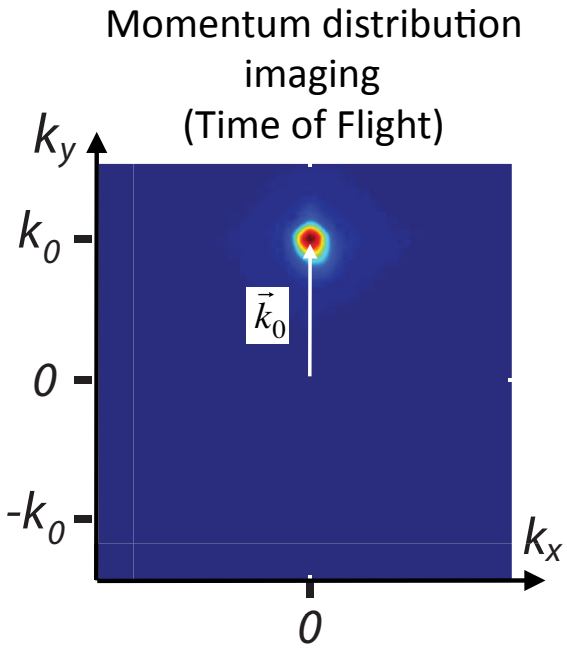
⇨ *A direct signature of phase coherence in presence of disorder*

E. Akkermans and G. Montambaux, Cambridge University Press 2007

⇨ Observation with ultracold atoms : study momentum space dynamics

N. Cherroret et al. PRA 2012

Experimental scheme for CBS : study momentum dynamics

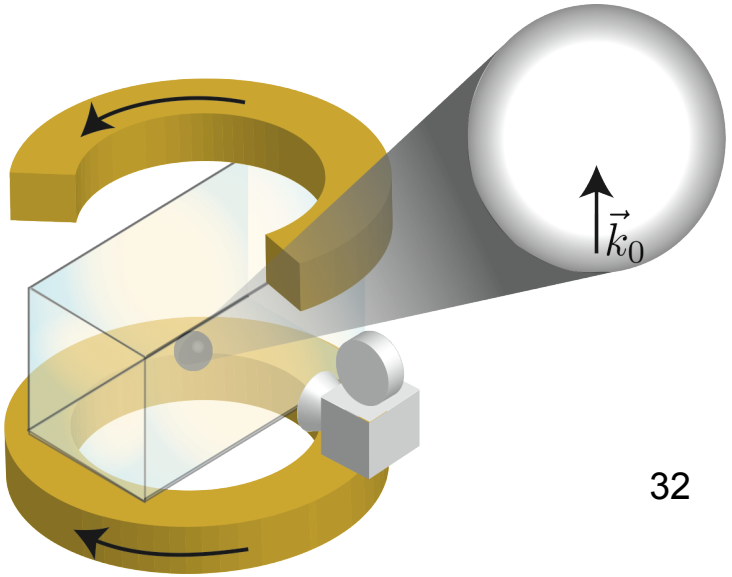


1. Initial state (no disorder) : a well defined momentum
   (same BEC procedure + a magnetic kick)

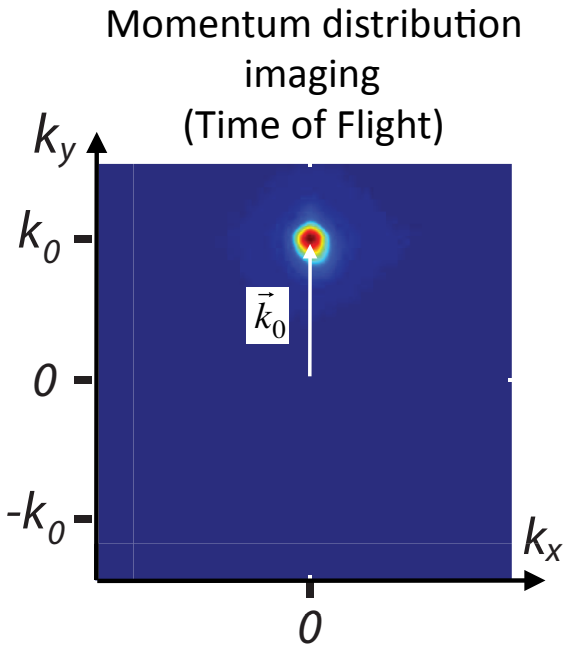
$$v_0 = 3.3\ \mathrm{mm/s} \quad \text{and} \quad \Delta v = 0.12\ \mathrm{mm/s}$$

$$(T \sim 150\ \mathrm{pK})$$

Ultra-ultra cold atoms !



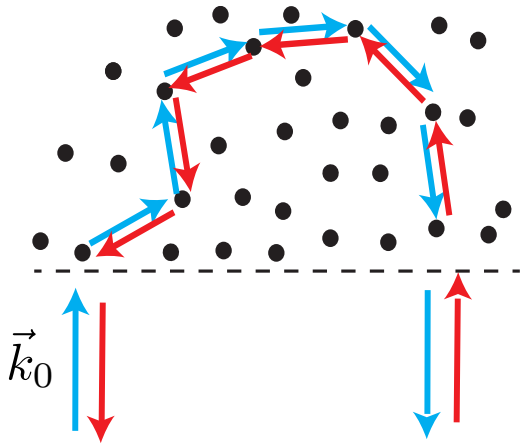
Experimental scheme for CBS : study momentum dynamics

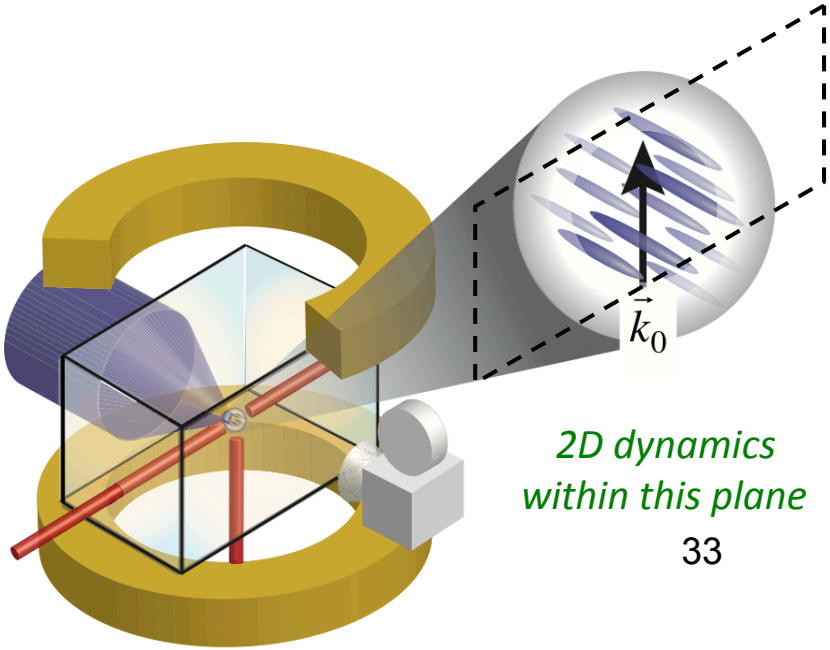


2. Shine the disorder (before Time of Flight imaging) and let the atoms scatter (Quasi-2D geometry)

Elongated speckle grains

Kick in transverse direction

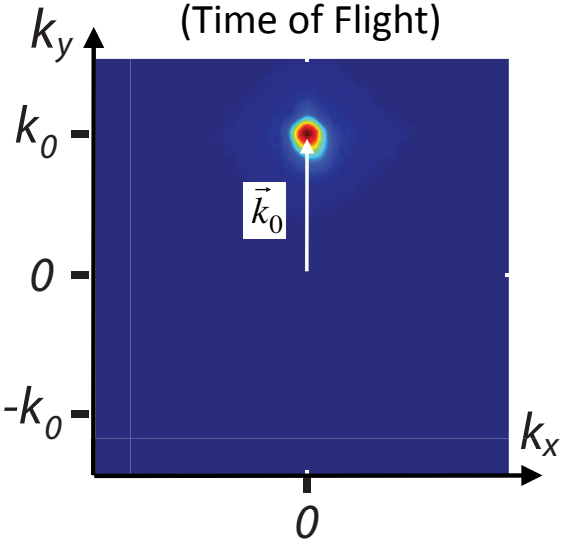


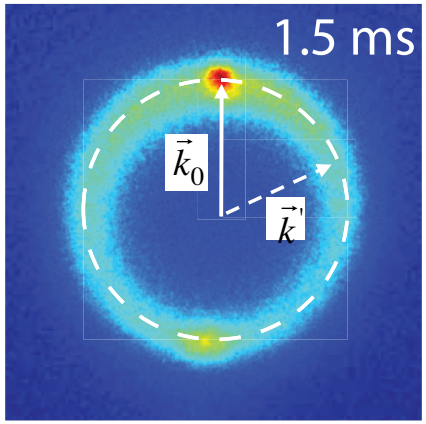


2D dynamics within this plane

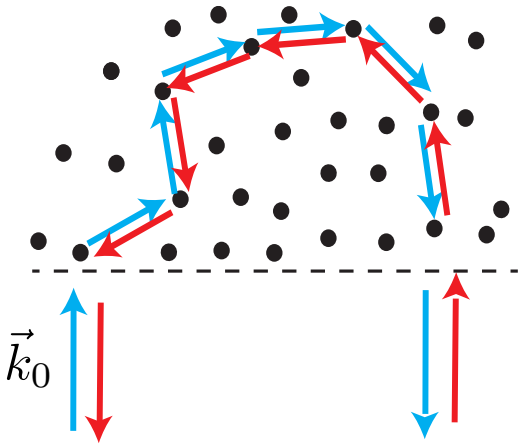
Experimental scheme for CBS : study momentum dynamics

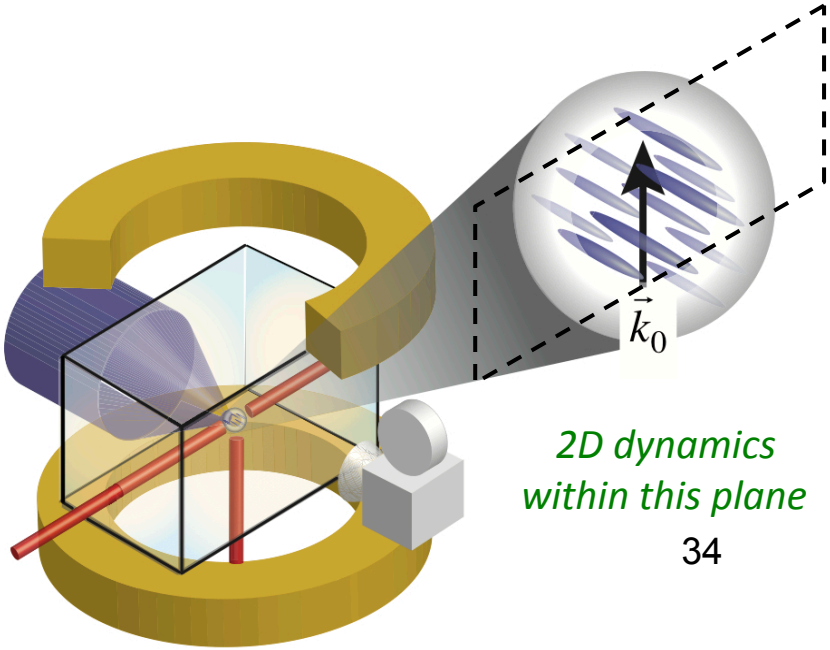
Momentum distribution imaging (Time of Flight)





3. Monitor the isotropization of the momentum distribution by elastic scattering

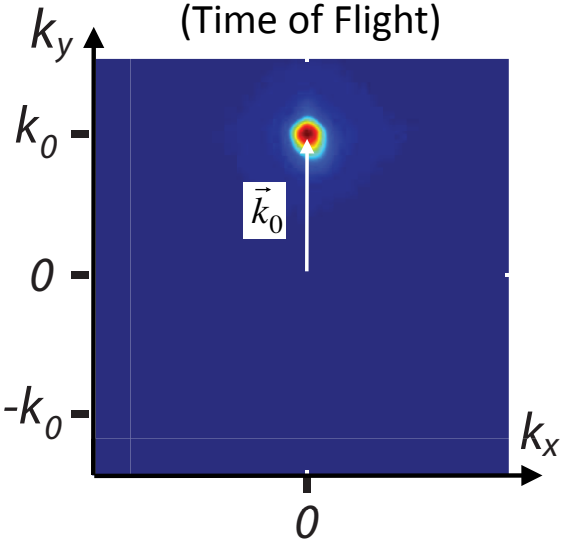


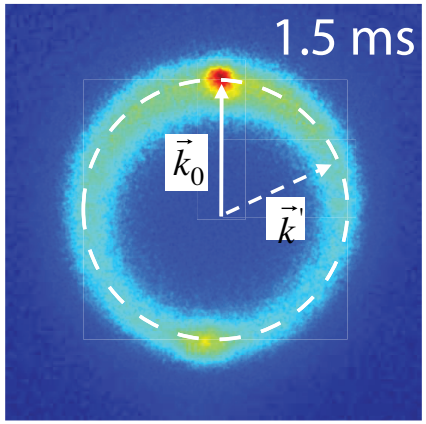


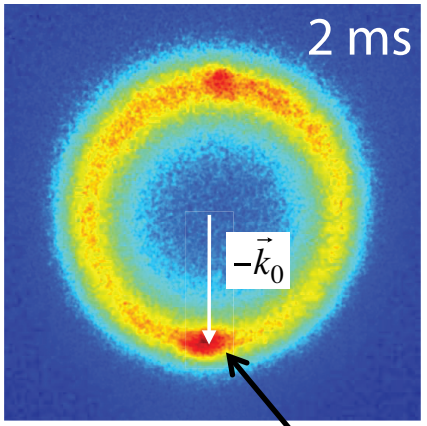
2D dynamics within this plane

Experimental scheme for CBS : study momentum dynamics

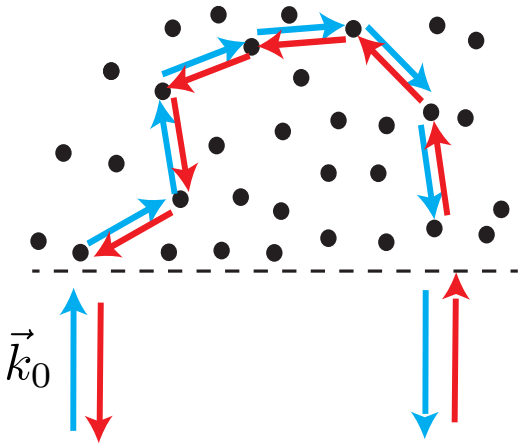
Momentum distribution imaging (Time of Flight)

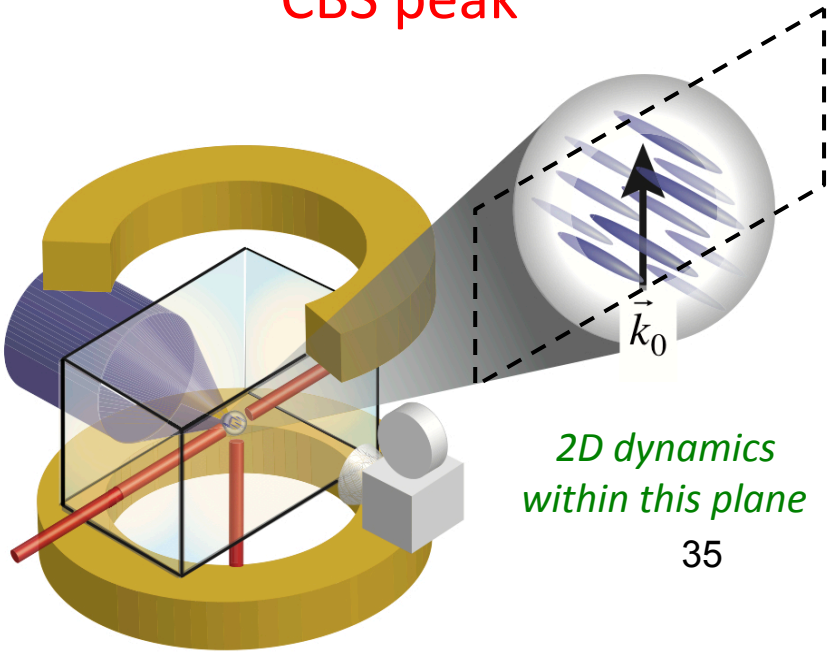






CBS peak

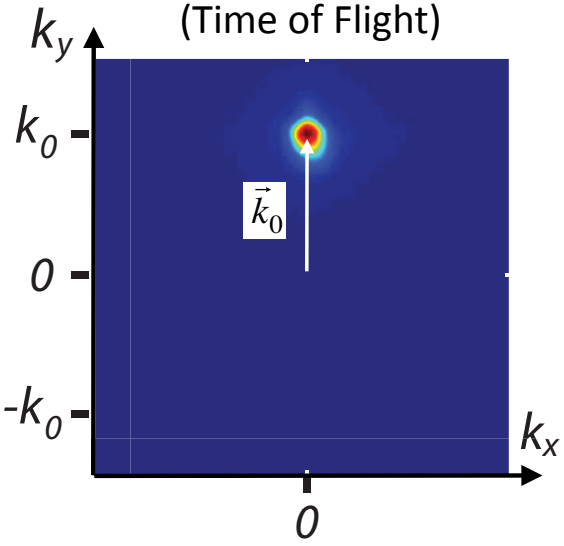


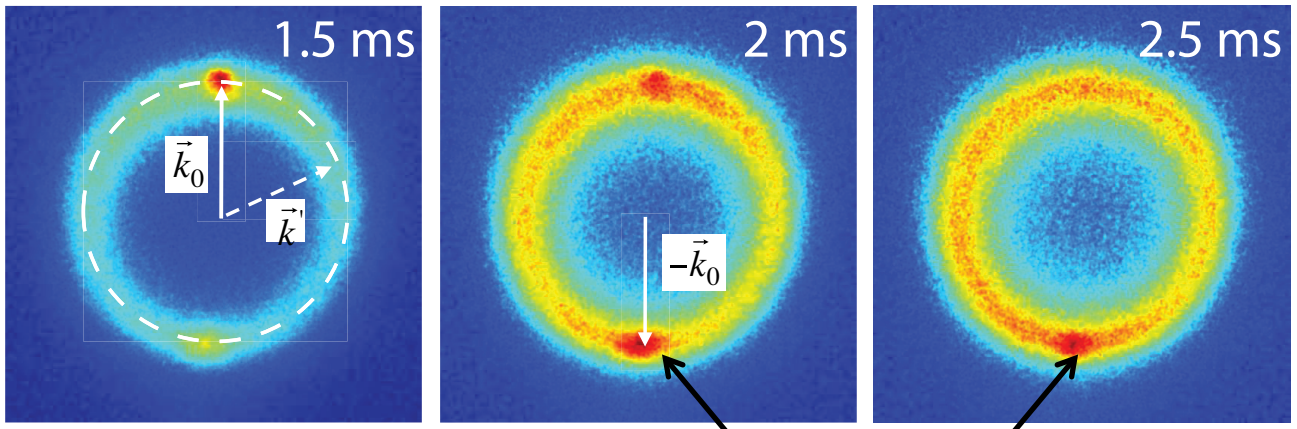


2D dynamics within this plane

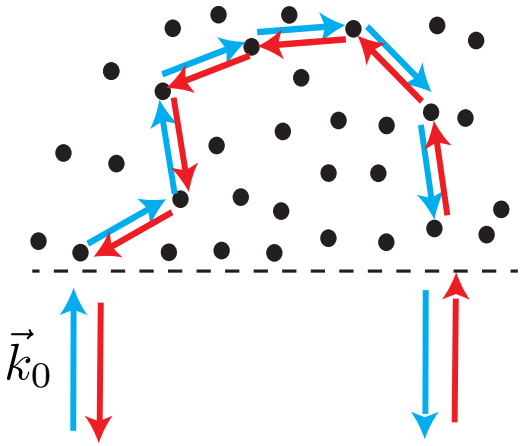
Experimental scheme for CBS : study momentum dynamics

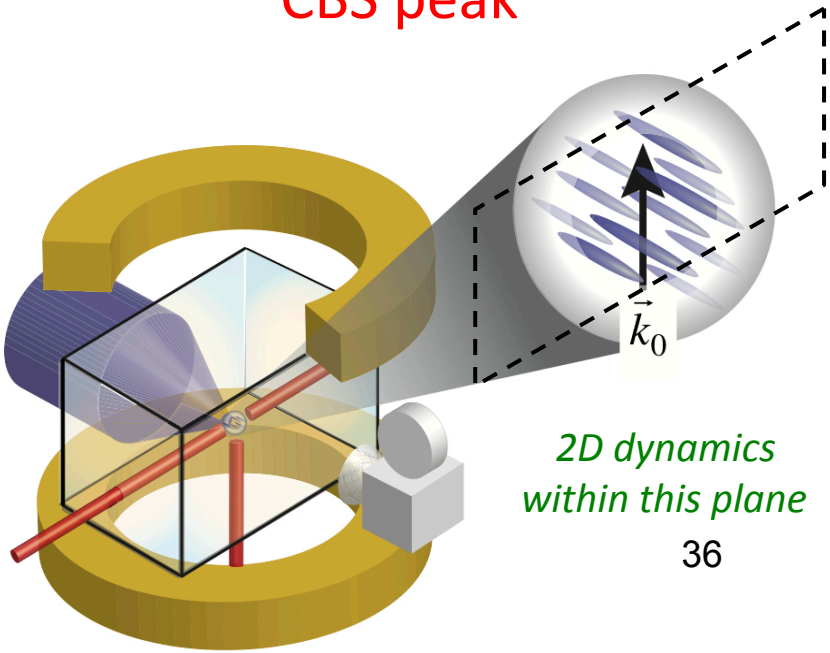
Momentum distribution imaging (Time of Flight)





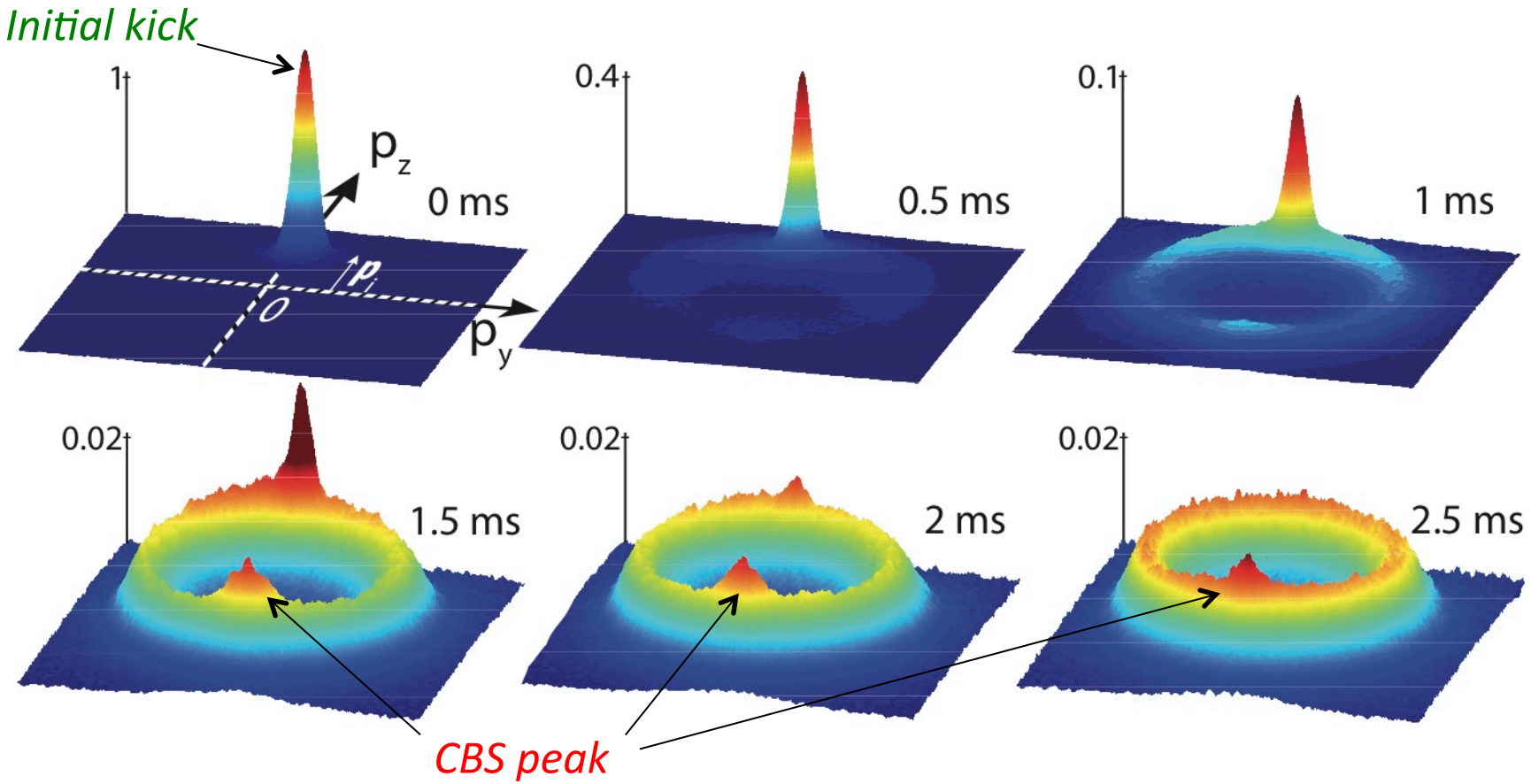
CBS peak





2D dynamics within this plane

Coherent backscattering of ultracold atoms



➪ Measure microscopic quantities

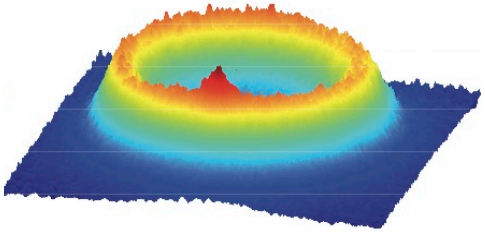
N. Cherroret et al. PRA 2012
C. Müller et al. arXiv:1209.1477

- *Elastic scattering time :* $\tau_s = 0.33\,\mathrm{ms}$
- *Mean transport time :* $\tau_B = 0.4\,\mathrm{ms}$

➪ Study the time resolved CBS dynamics (in very good agreement with predictions)

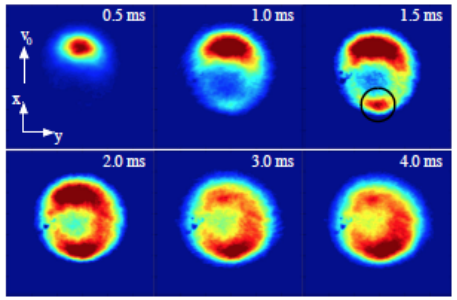
Conclusion and perspectives (part II)

Direct demonstration of CBS with ultra cold atoms (weak localization)



F. Jendrzejewski et al. *Phys. Rev. Lett.* **109**, 195302 (2012)

Also observation of an incoherent backscattering echo:



G. Labeyrie *et al.*, *EPL* **100**, 66001 (2012)

Momentum space analysis : powerful tool to study phase coherence in disordered media

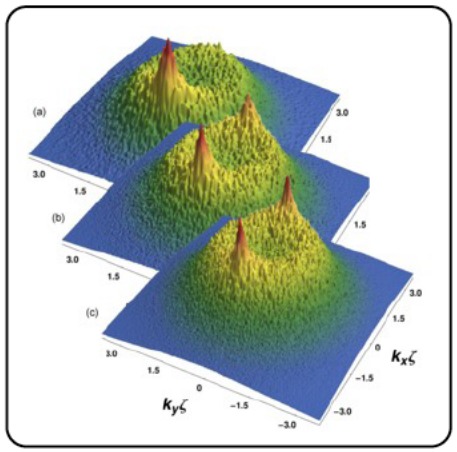
- *New signatures of Anderson localization (Coherent Forward Scattering peak)*

  T. Karpiuk *et al.*, *PRL* . **109**, 190601 (2012)

- *Effects of interactions?*

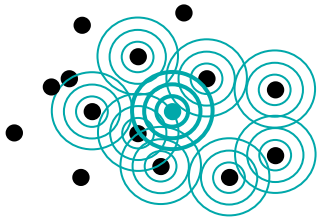
  Agranovich and Kravtsov *et al.*, *PRB* . **43**, 13691 (1991)

- Playing with time reversal invariance *(gauge fields, time dependent potentials)*

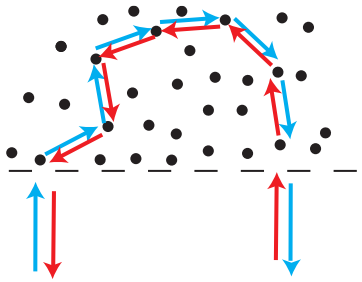


See Talk of C. Müller

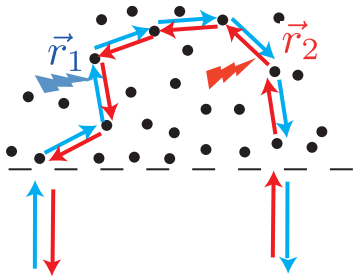
OUTLINE



I. 3D Anderson localization of ultracold atoms
in a laser speckle potential



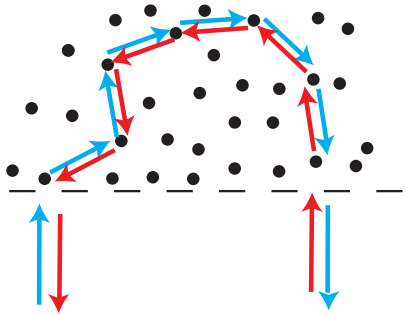
II. Coherent Backscattering of ultracold atoms



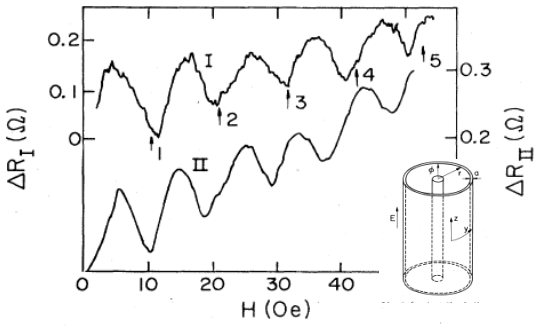
III. Time reversal symmetry on weak localization:
the CBS revival

Some motivations

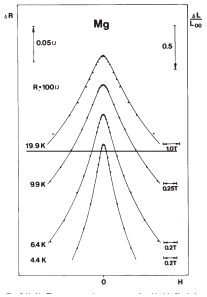
Fundamental : Time reversal symmetry (reciprocity) at the heart of weak localization



- Dephasing with magnetic fields in CM systems (80's)



Sharvin & Sharvin (1981)



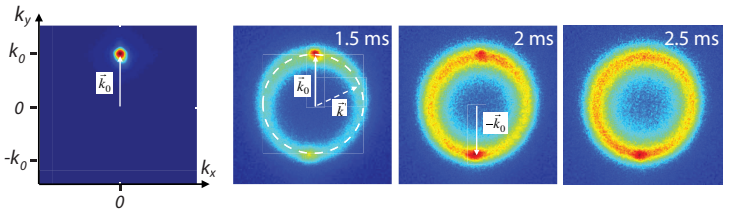
Magneto-resistance in thin films
Bergman (1984)

- Also in optics with faraday rotation in optics

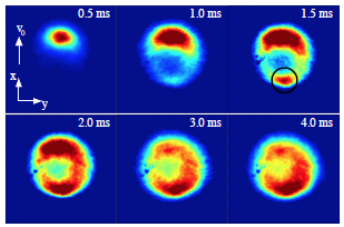
Lenke and Maret
EPJD (2000)

More pratical interest

Coherent vs incoherent backscattering ?
(enhanced backscattering is not enough)

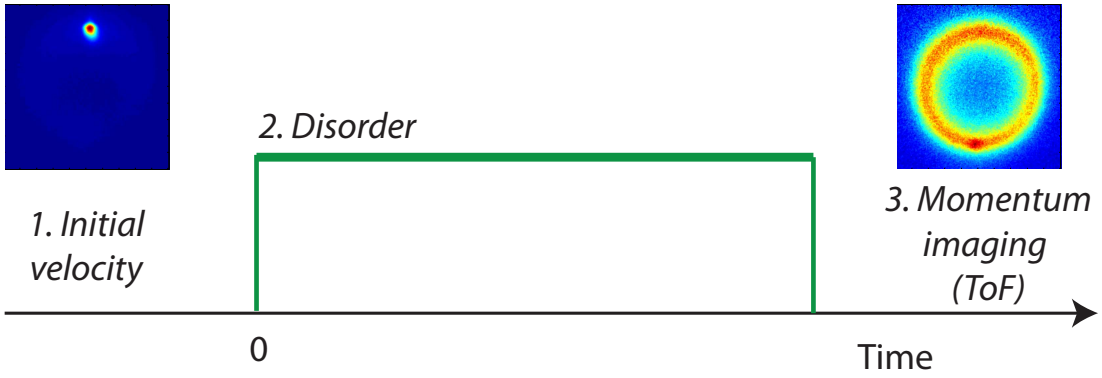


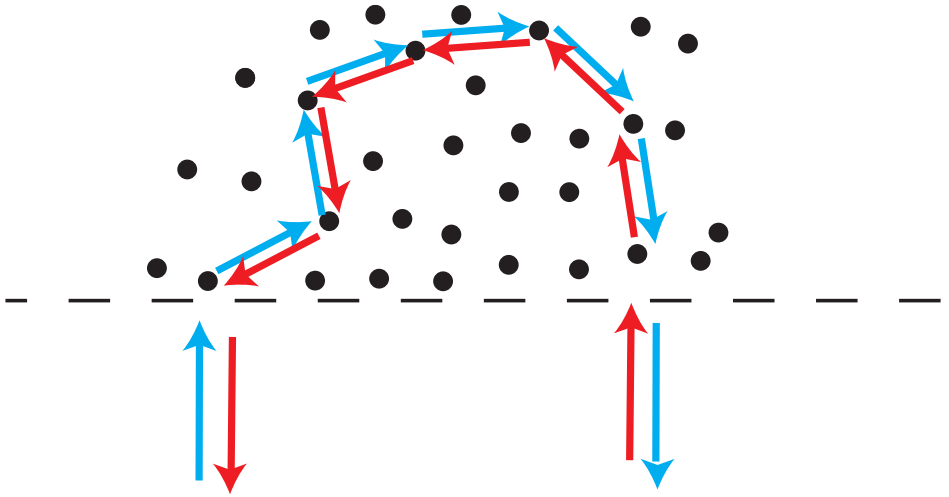
Palaiseau
(2012)



Nice
(2012)

Manipulating time reversal symmetry : the CBS revival





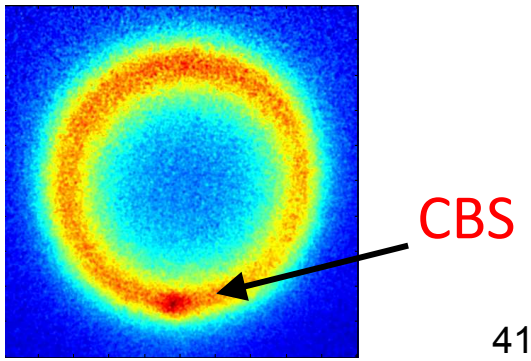
« Usual » methods for dephasing :

- Modulation of the disorder (e.g. amplitude)

  B. Altshuler et al., Solid. State. Comm. 1981
  J. Wei et al. Phys. Rev. Lett. 2005

- Artificial gauge field (in the spirit of C.M. experiments)

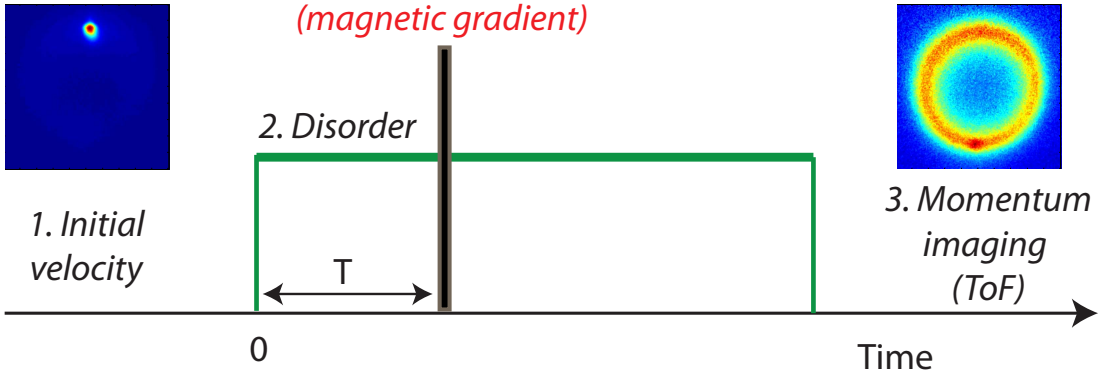
  J. Towers, S. C. Cormack, and D. A. W. Hutchinson, PRA 2013

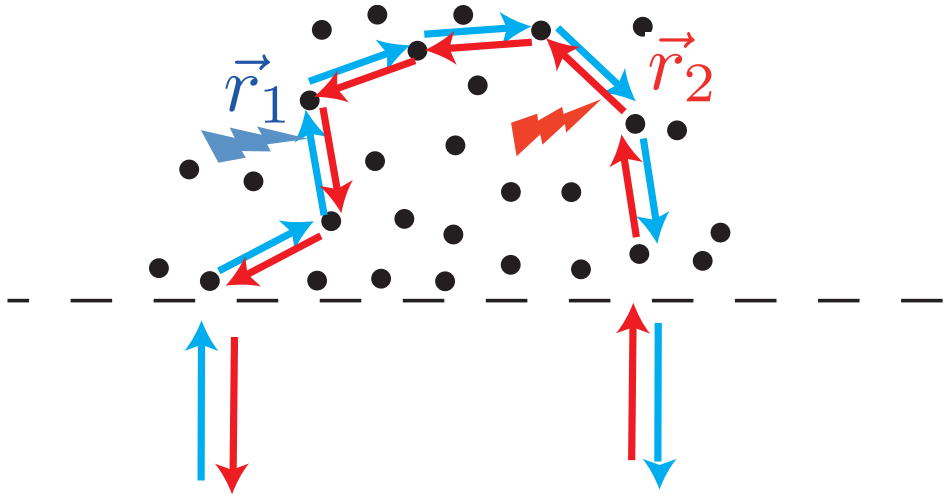


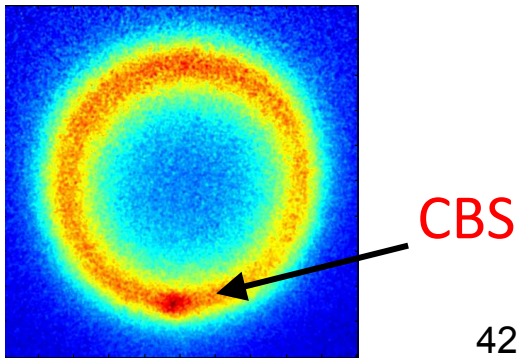
Manipulating time reversal symmetry : the CBS revival

Proposal by T. Micklitz, C. Müller and A. Altland

A perturbation, at a given time T, that induces a spatially dependent dephasing



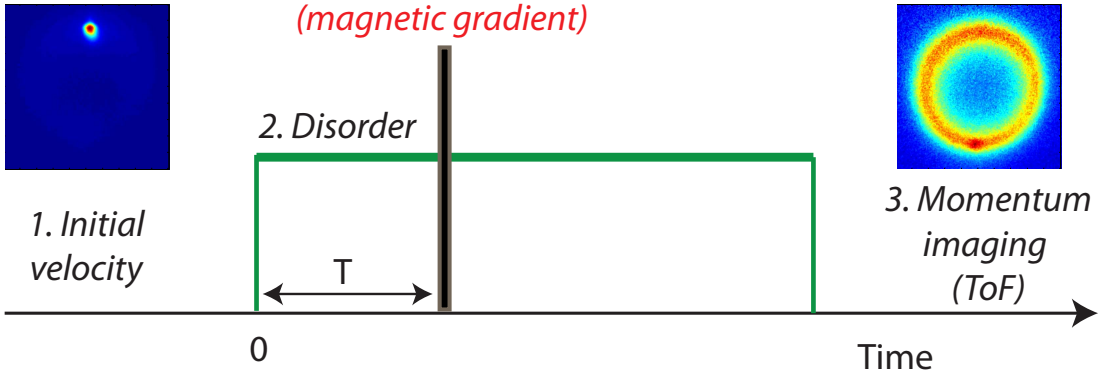


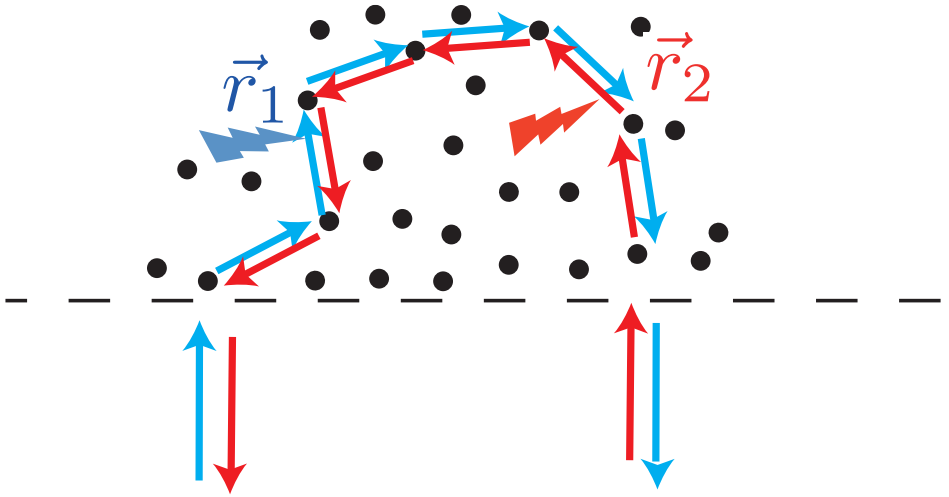


Manipulating time reversal symmetry : the CBS revival

Proposal by T. Micklitz, C. Müller and A. Altland

A perturbation, at a given time T, that induces a spatially dependent dephasing

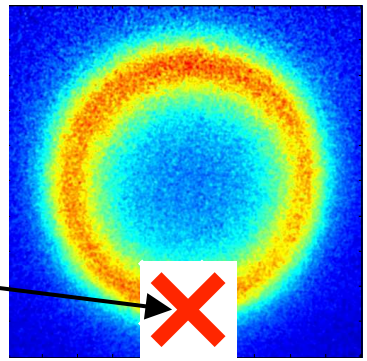




Different phases picked up at different positions :

$$\phi_{\text{magnetic}}(r) = \frac{\mu B(r)\Delta t}{\hbar} \quad \Rightarrow \quad \boxed{\Delta\phi \neq 0}$$

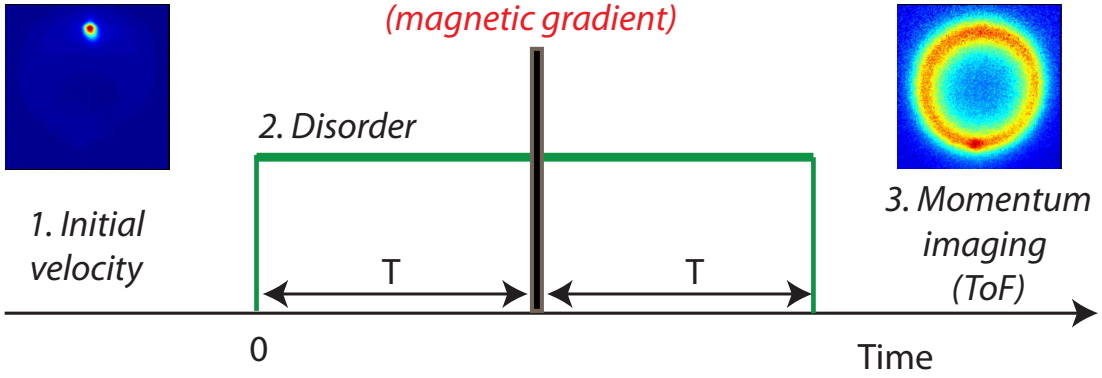
⇨ *Disparition of the CBS*

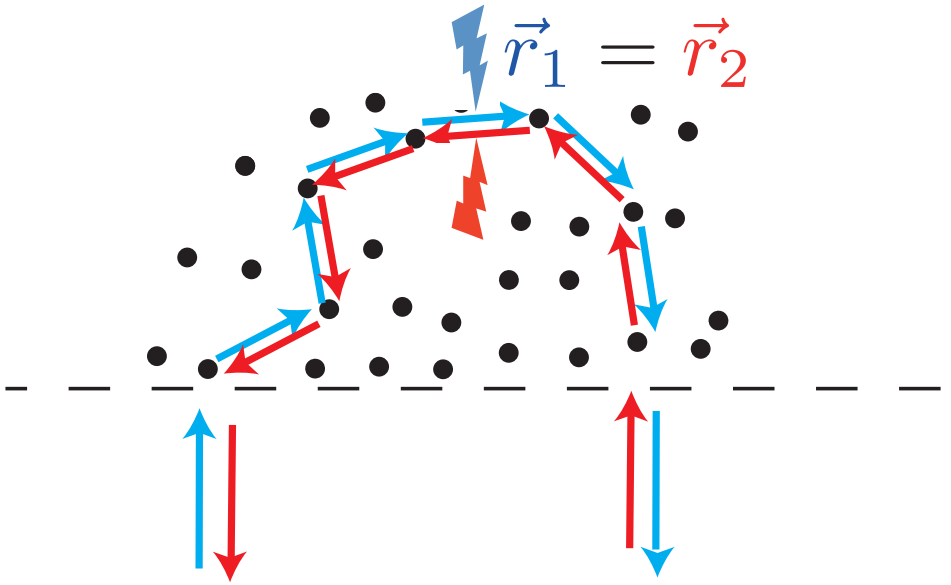


Manipulating time reversal symmetry : the CBS revival

Proposal by T. Micklitz, C. Müller and A. Altland

A perturbation, at a given time T, that induces a spatially dependent dephasing

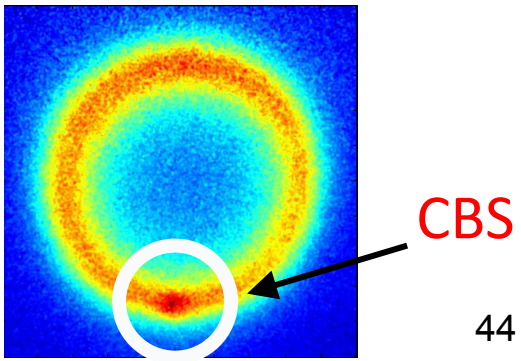




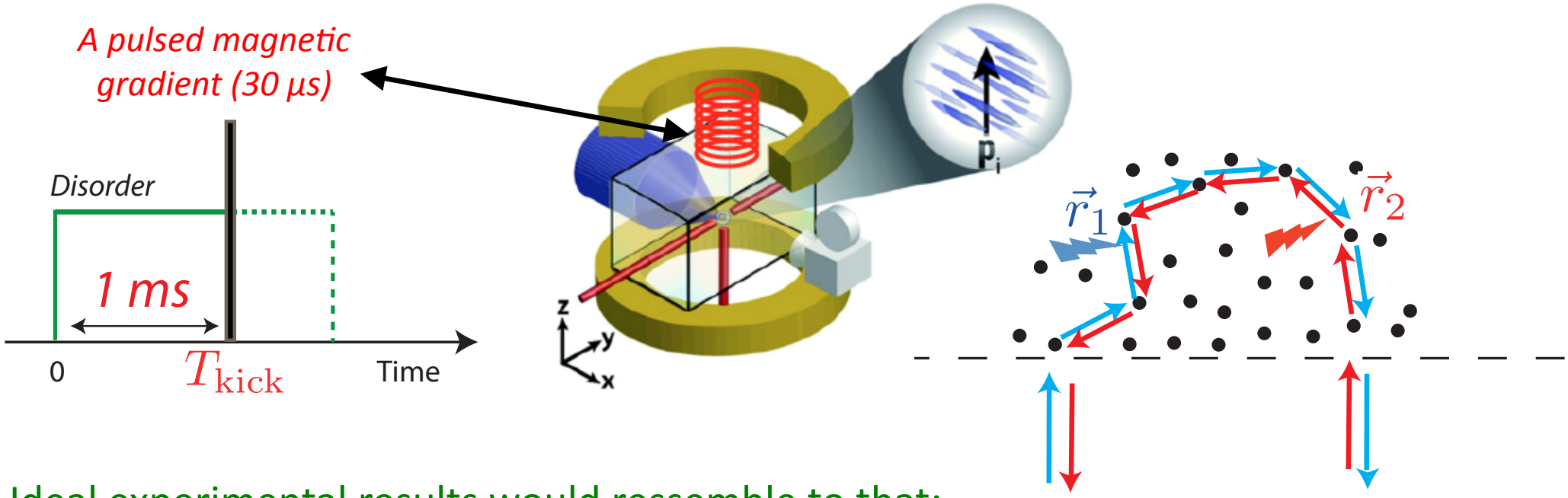
$$\Delta\phi = 0$$

⇨ *A revival of the CBS peak at time 2T*

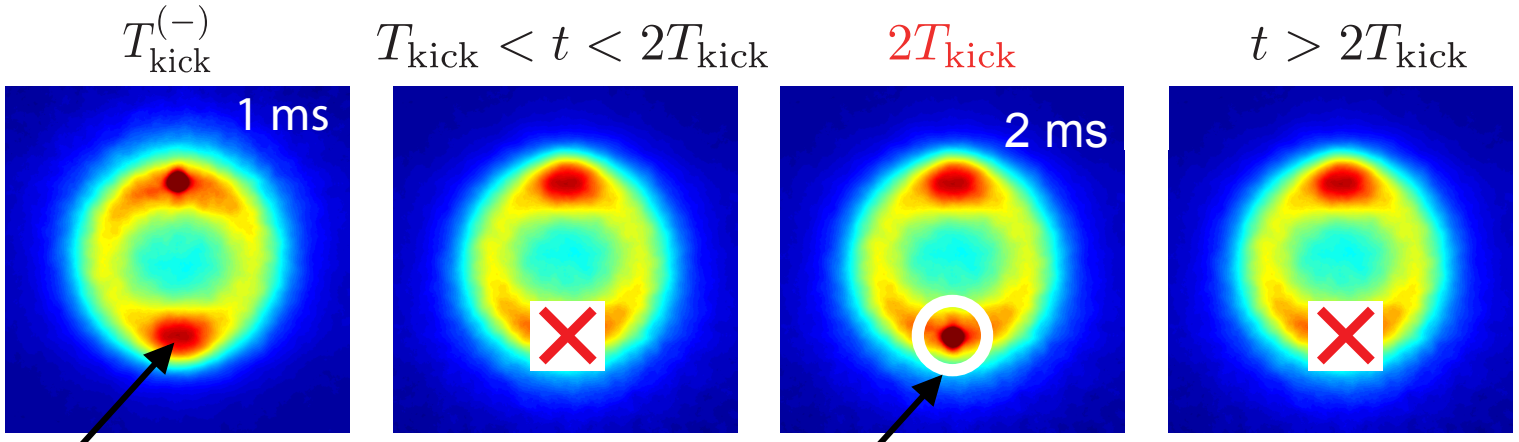
(Time reversal symmetry re-established)



Experimental implementation



Ideal experimental results would ressemble to that:

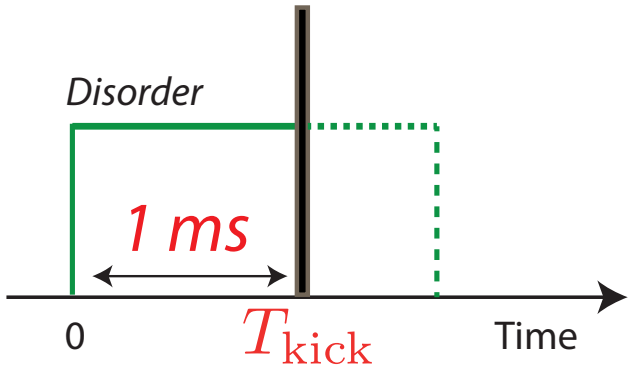


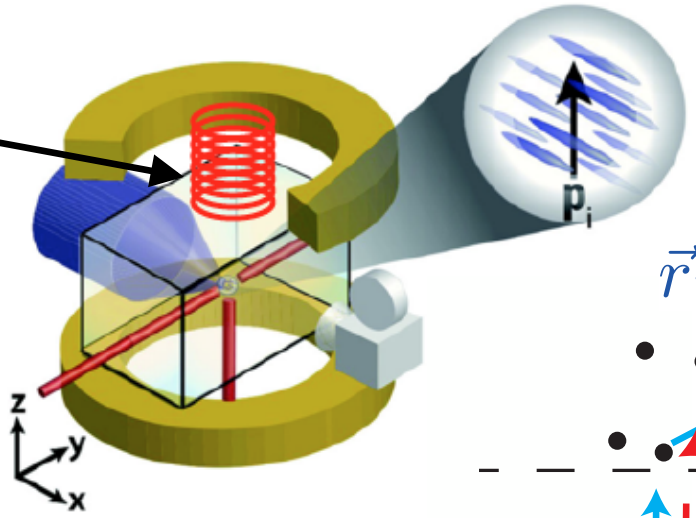
CBS

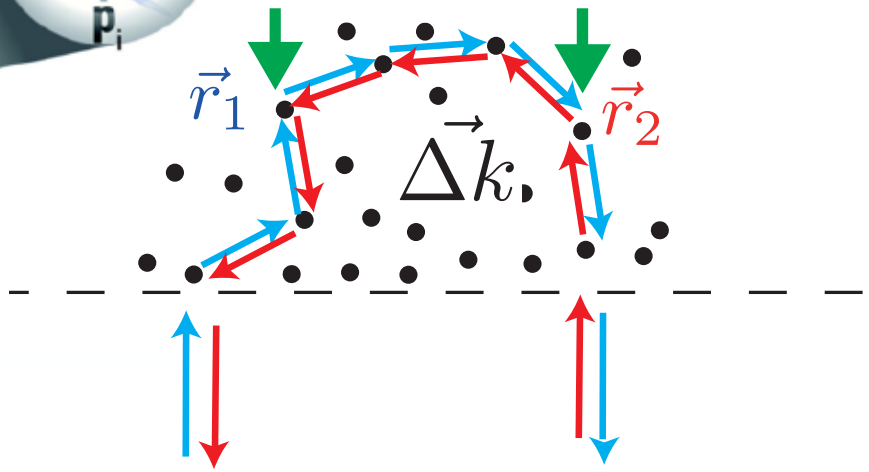
CBS revival expected at 2 ms

Experimental implementation

A pulsed magnetic gradient (30 µs)

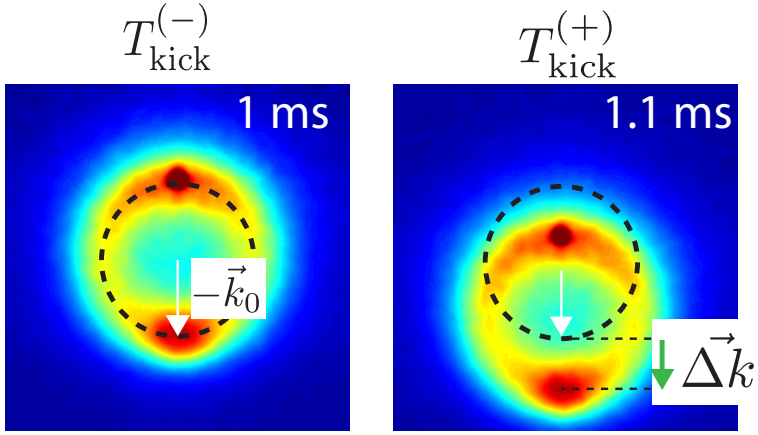




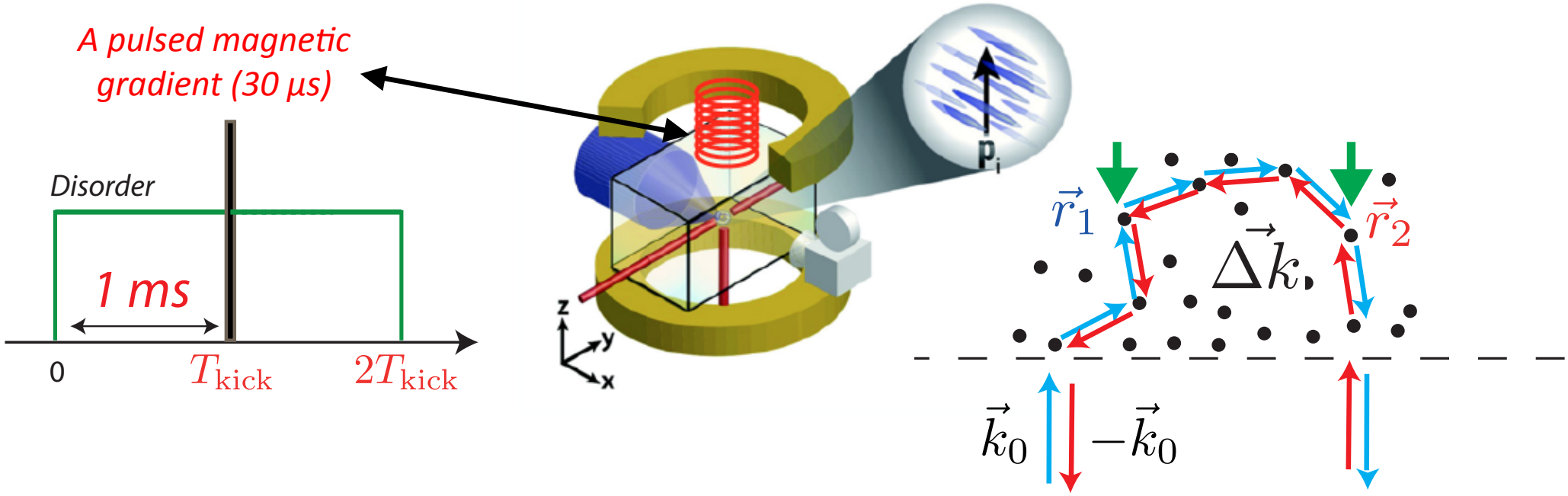


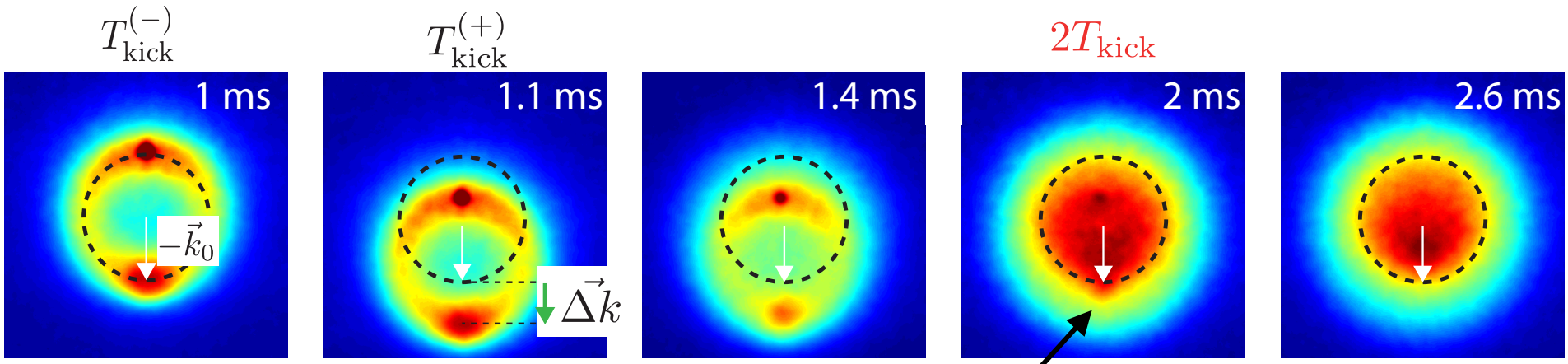
A magnetic gradient = a force !!
Transfer a momentum (downwards) of :

$$\vec{\Delta k}$$



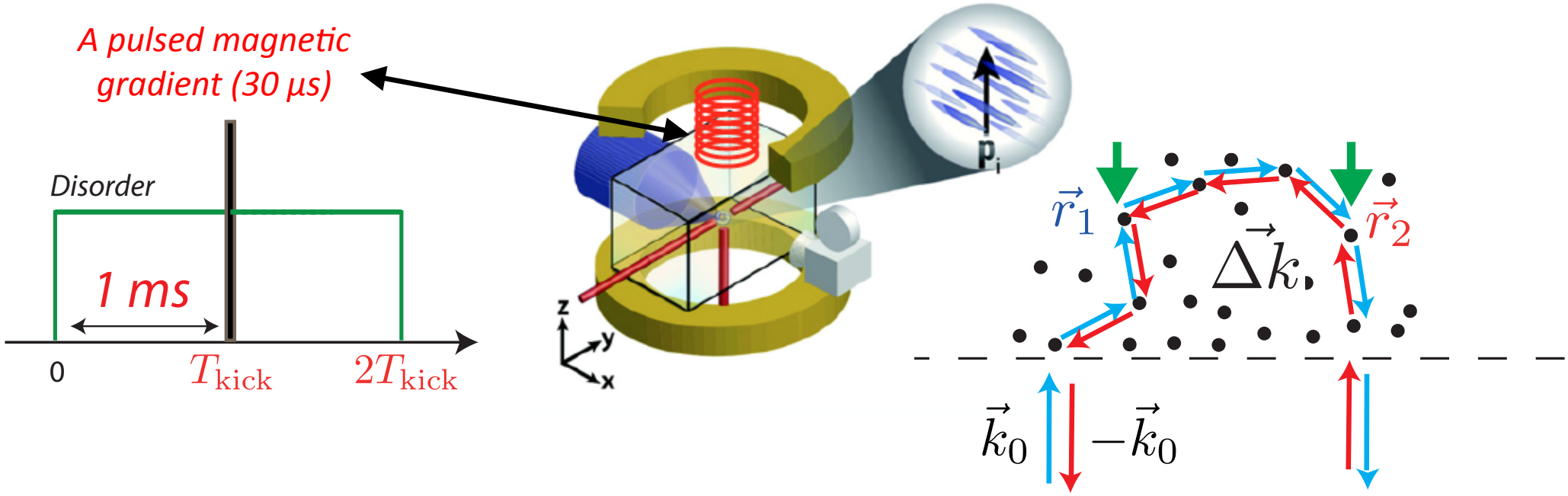
Experimental implementation

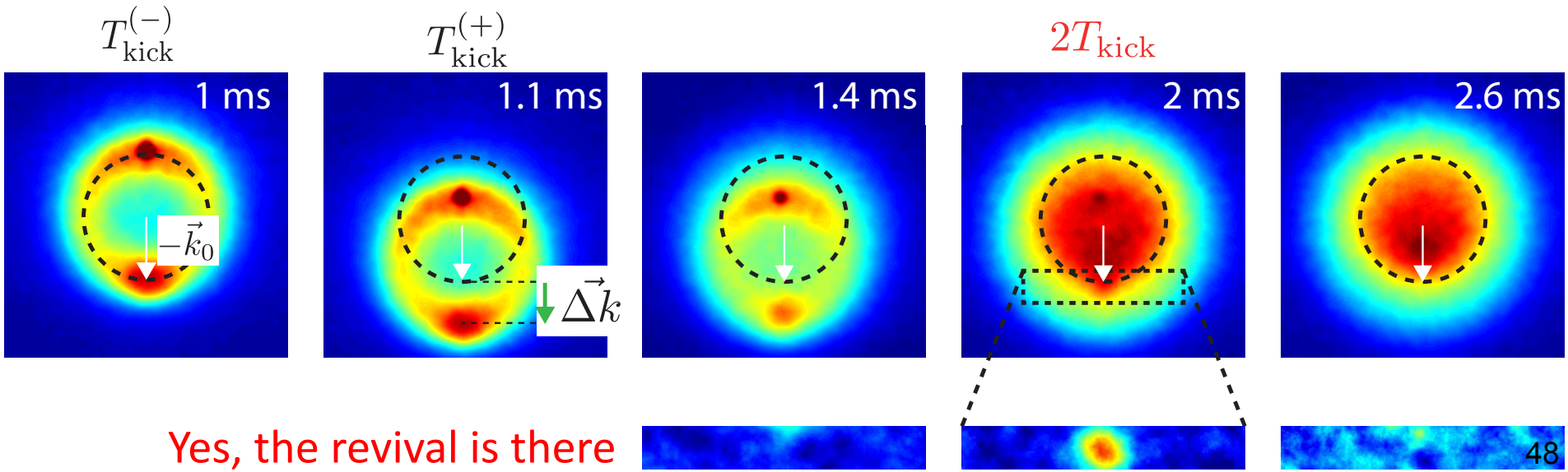




CBS revival here ($-\vec{k}_0$) ??

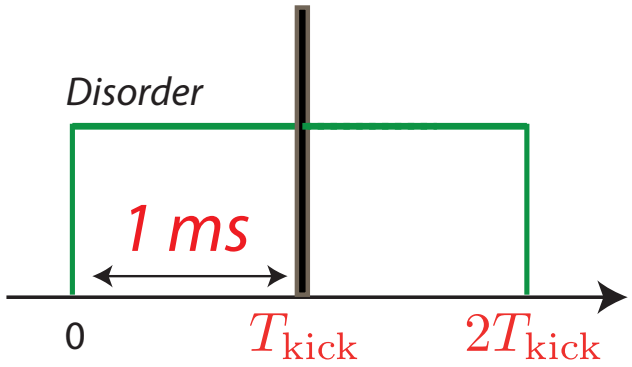
Experimental implementation

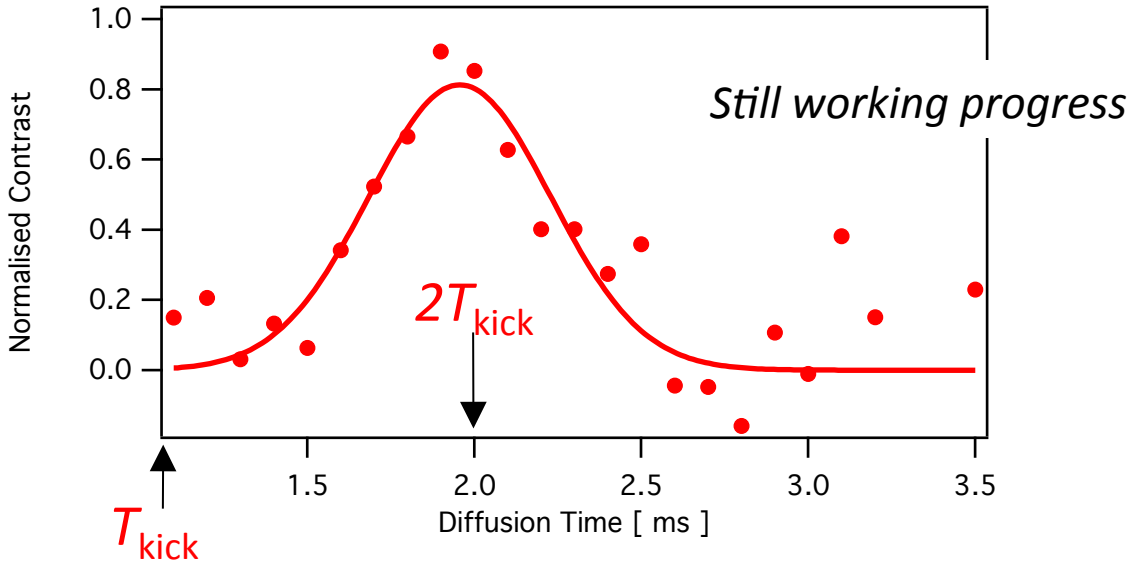


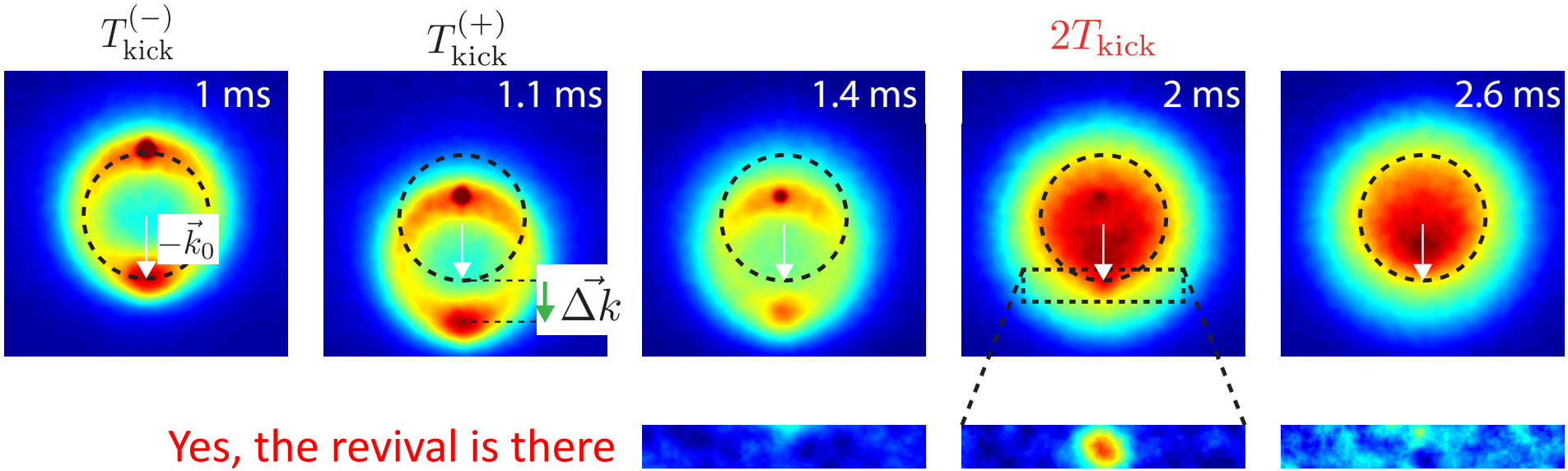


Yes, the revival is there

Observation of the CBS revival





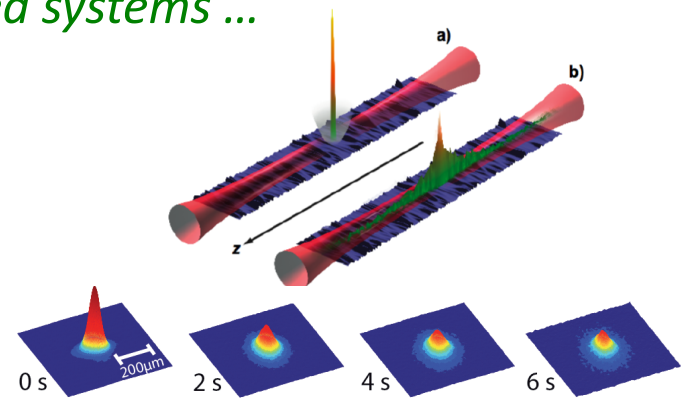


Yes, the revival is there

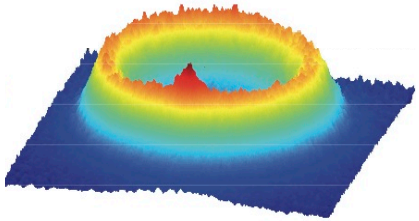
Conclusion

Ultracold atoms for precise investigations of « standard problems » in disordered systems …

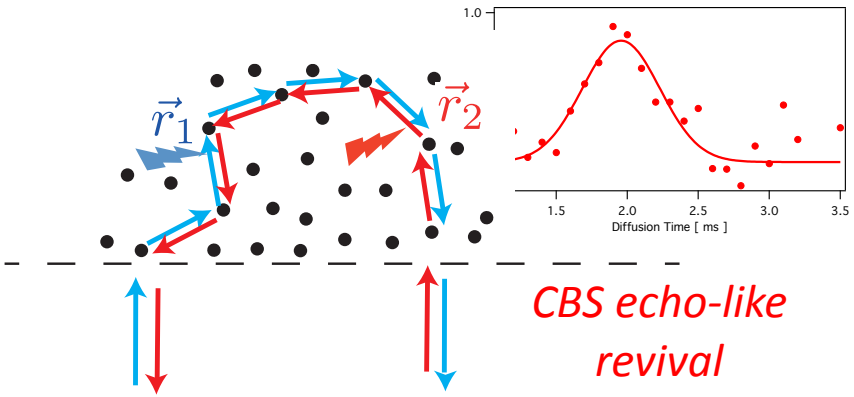
Anderson localization (1D, 3D)



Weak localization (CBS)

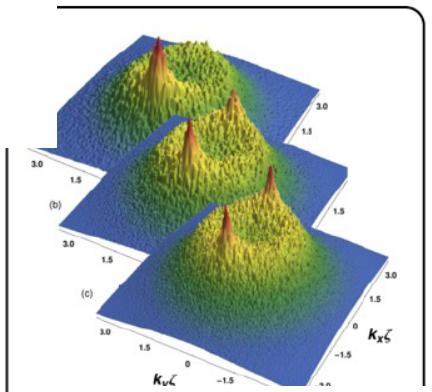


… but also stimulate new ideas



CBS echo-like revival

Coherent forward scattering



See Talk of C. Müller

Proposal by T. Micklitz, C. Müller and A. Altland

Experiments to be published…

T. Karpiuk et al., *Phys. Rev. Lett.* **109**, 190601 (2012)

T. Micklitz et al., *Phys. Rev. Lett.* **112,** 110602(2014)

Lee et al. , arXiv:1405.2979 (2014)

PhDs

Fred Jendrzejewki
Kilian Müller
Jérémie Richard

Post Doc

Valentin Volchkov

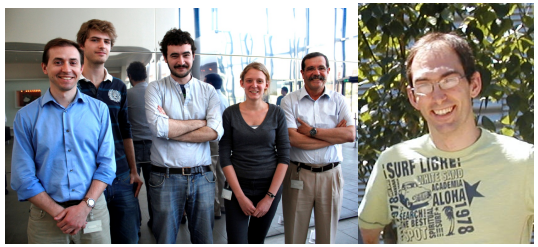
Former members

Juliette Billy (now Toulouse)
Alain Bernard (now at LENS)
Patrick Cheinet (now at LAC)
Stephan Seidel (Hannover)

Permanent

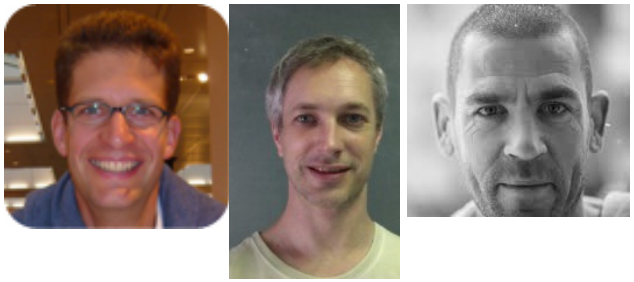
Vincent Josse
Philippe Bouyer
Alain Aspect

Collaborations :



AL 3D : Theory team IOGS
L. Sanchez-Palencia et al.

Time reversal symetry and localisation
T. Micklitz (Rio),
C. Müller (Konstanz)
A. Altland (Köln)



New approaches
M. Filoche (Polytechnique Palaiseau)
S. Mayroboda (US)