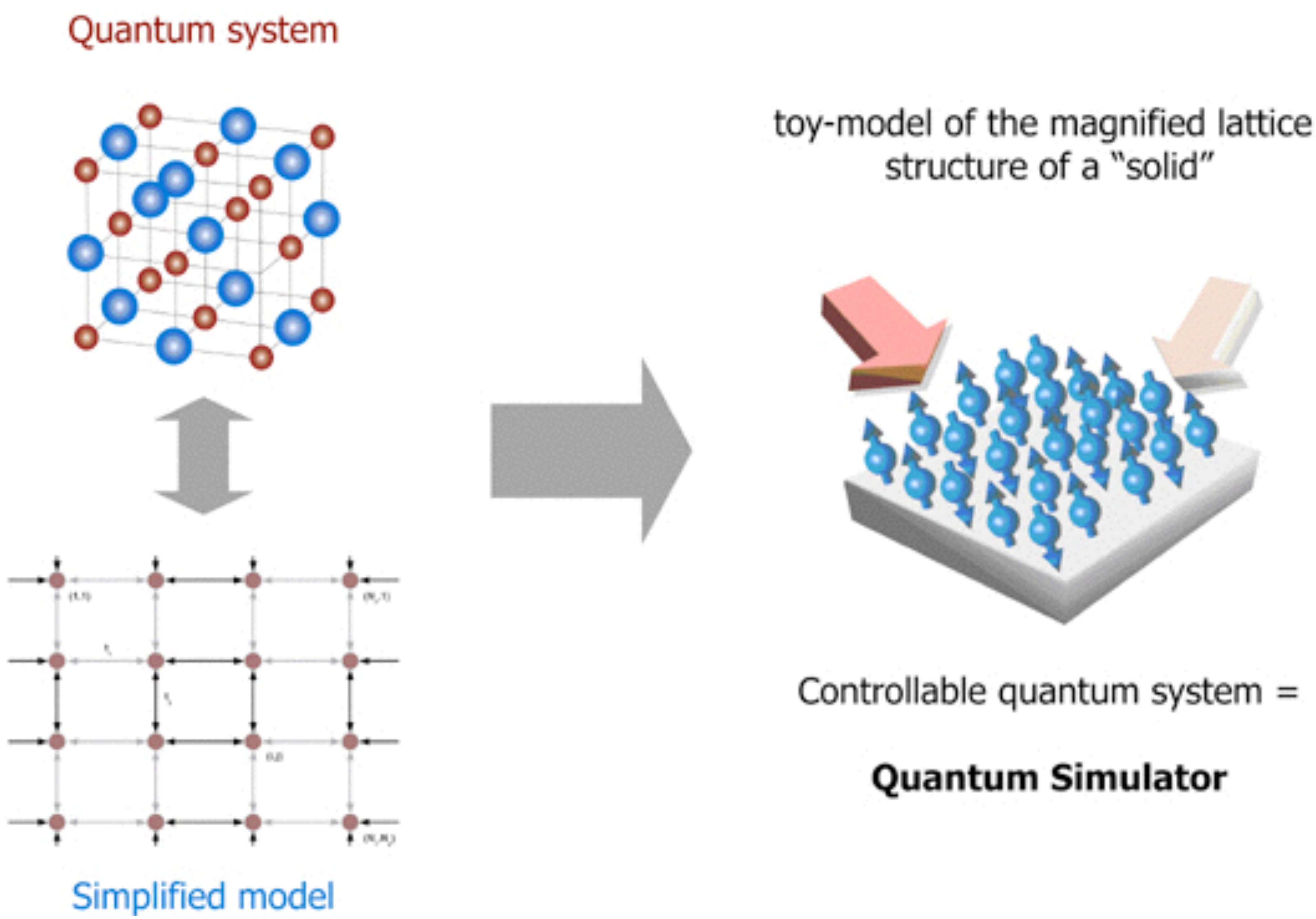
QUANTUM TRANSPORT OF ULTRA COLD ATOMS IN OPTICAL DISORDER

Philippe BOUYER

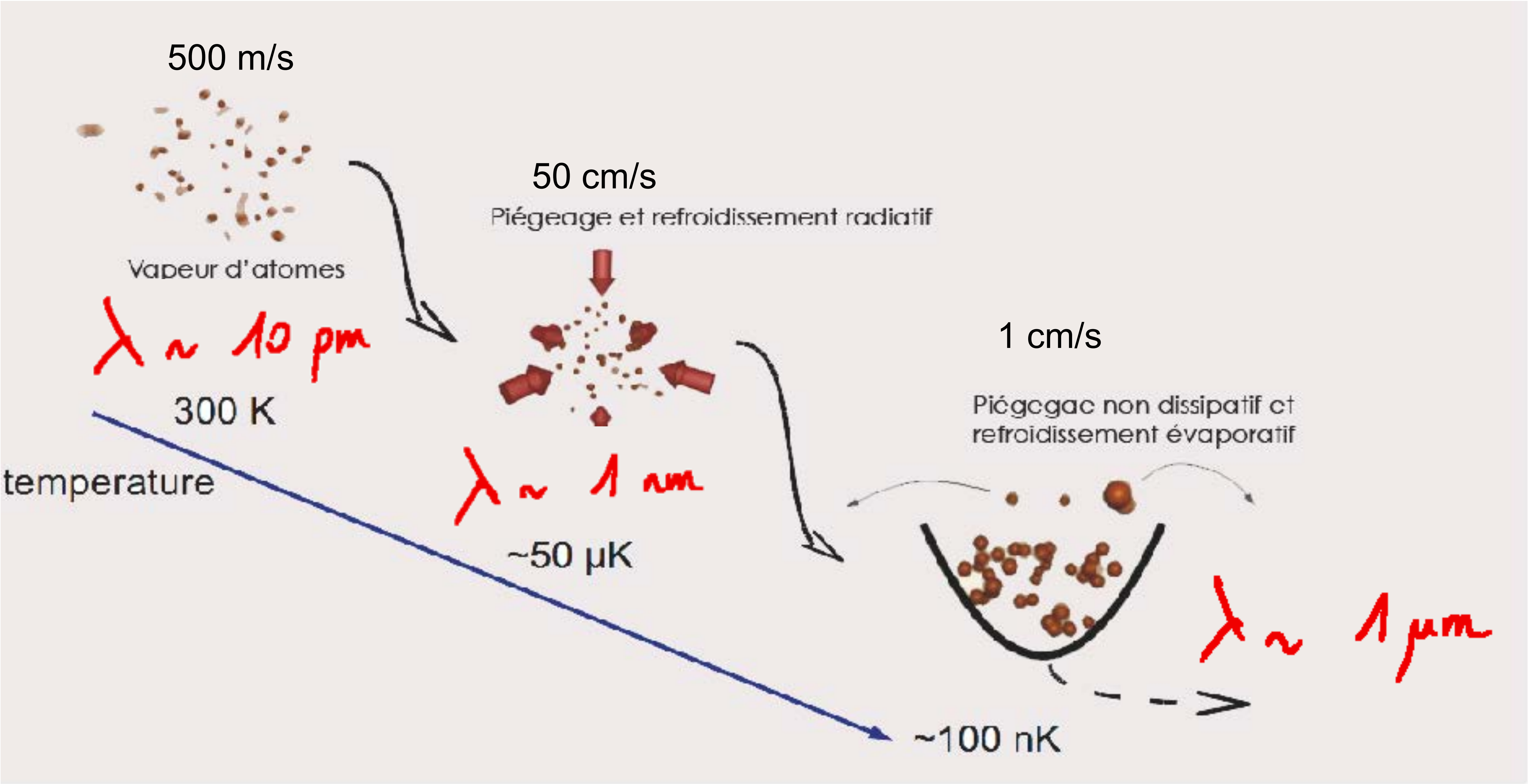
LP2N
Institut d'Optique d'Aquitaine
33400 TALENCE.

INSTITUT d'OPTIQUE GRADUATE SCHOOL
cnrs
université de BORDEAUX

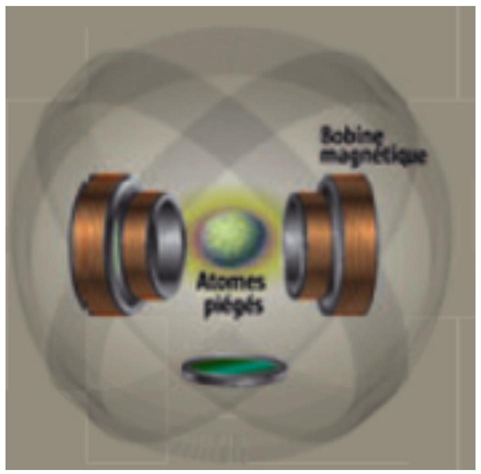
Using ultra cold atoms to build a controllable quantum system to simulate other quantum systems.

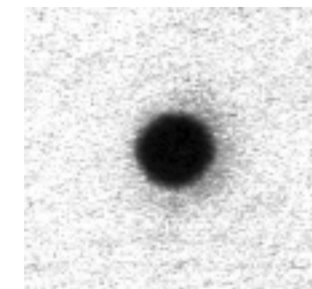


ULTRACOLD ATOMS : QUANTUM GAZ AND MATTER WAVE



MONITORING AND IMAGING ULTRACOLD ATOMS





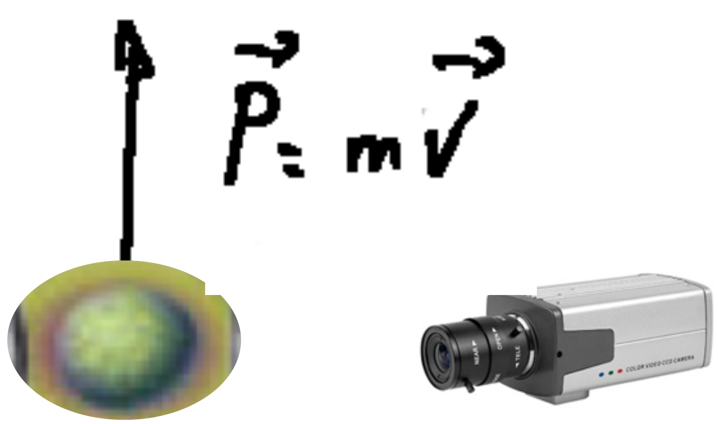
- *Cooled and trapped atoms can be directly observed with a camera*

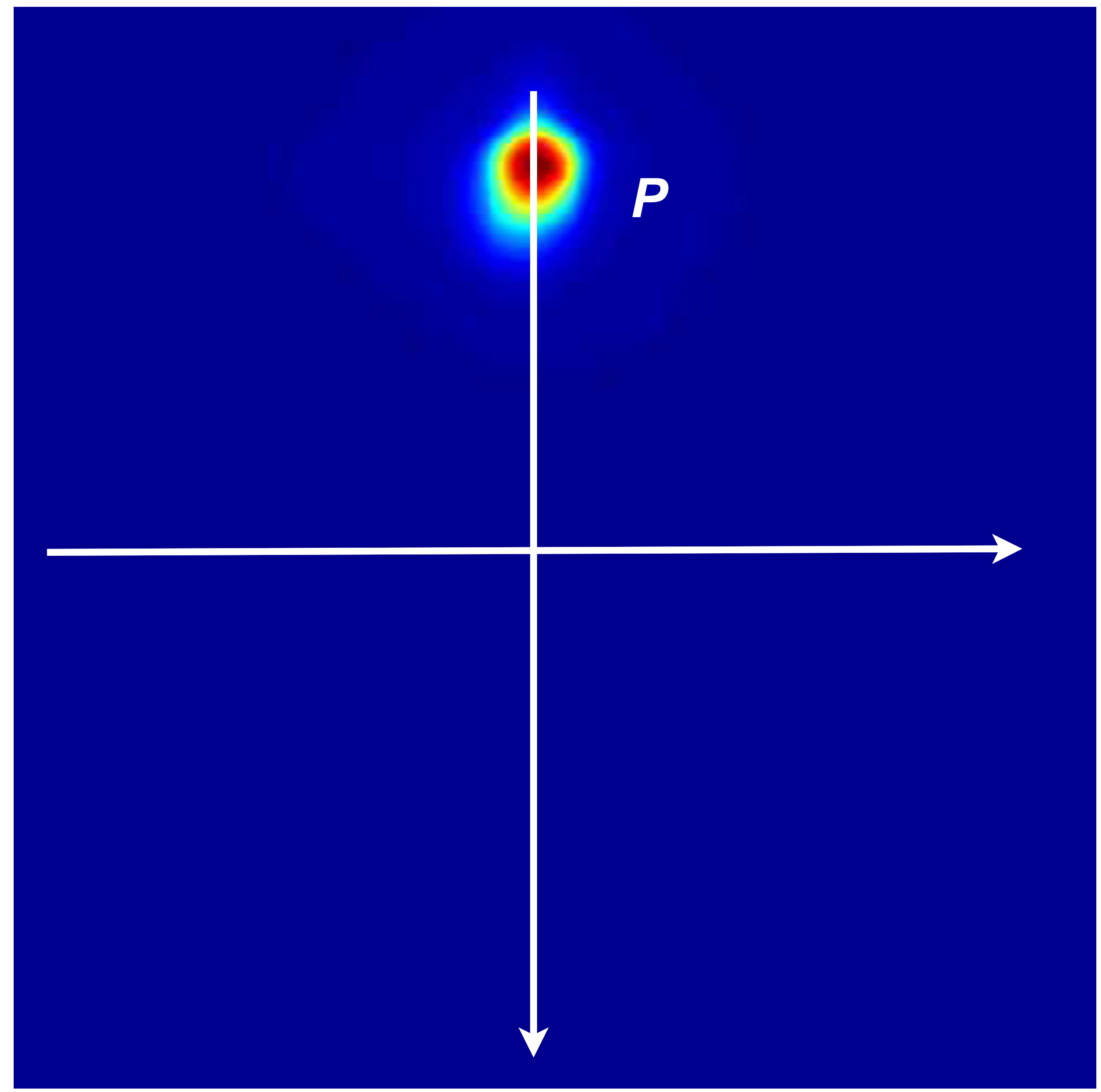
Monitoring and imaging ultracold atoms

- *Cooled and trapped atoms can be directly observed with a camera*
- *Direct imaging of matter wave functions*
- *Accessible time scales (particle velocities of mm/s)*

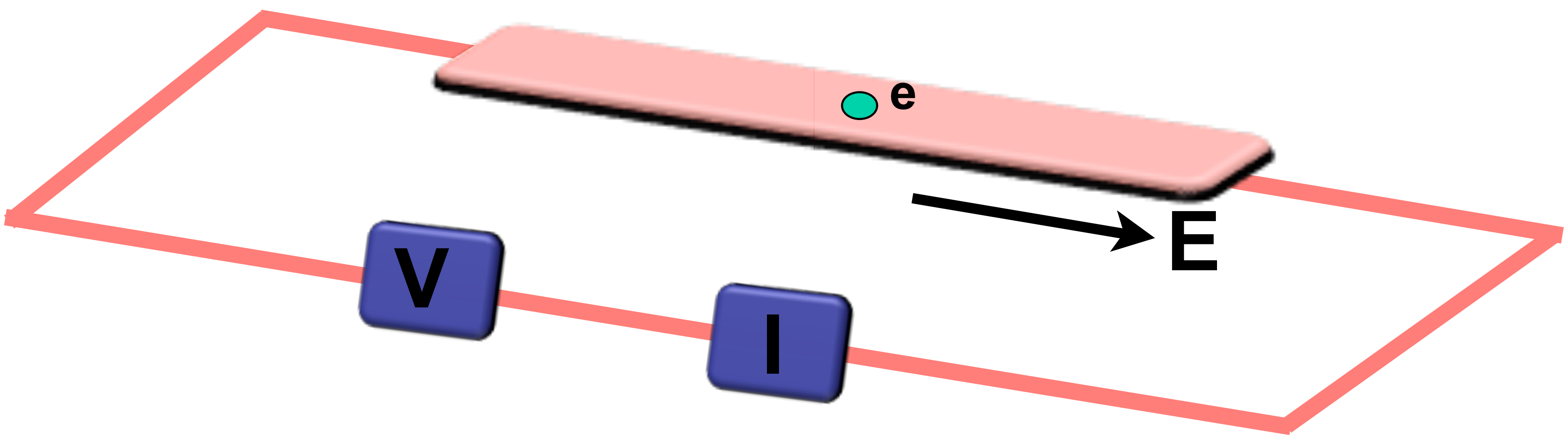
MONITORING AND IMAGING ULTRACOLD ATOMS

- When imaging atoms after they are ejected from the trap, we directly monitor the velocity and the velocity distribution (*time of flight*).





We can simulate transport and conduction properties of electrons in a solid with atoms : lattice, disorder, gauge fields …



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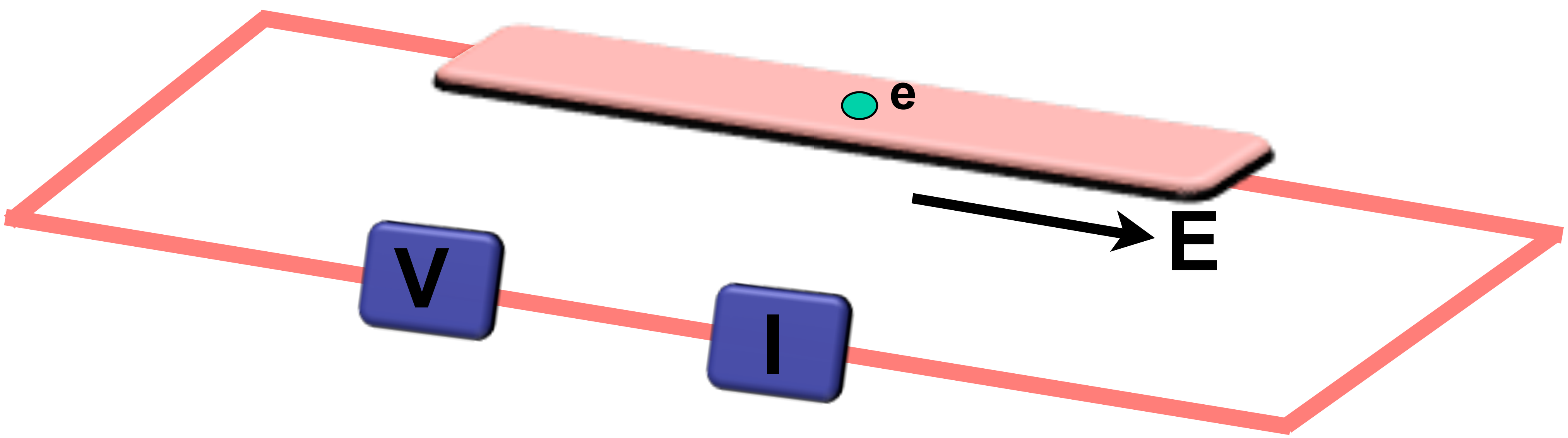

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ANDERSON LOCALISATION

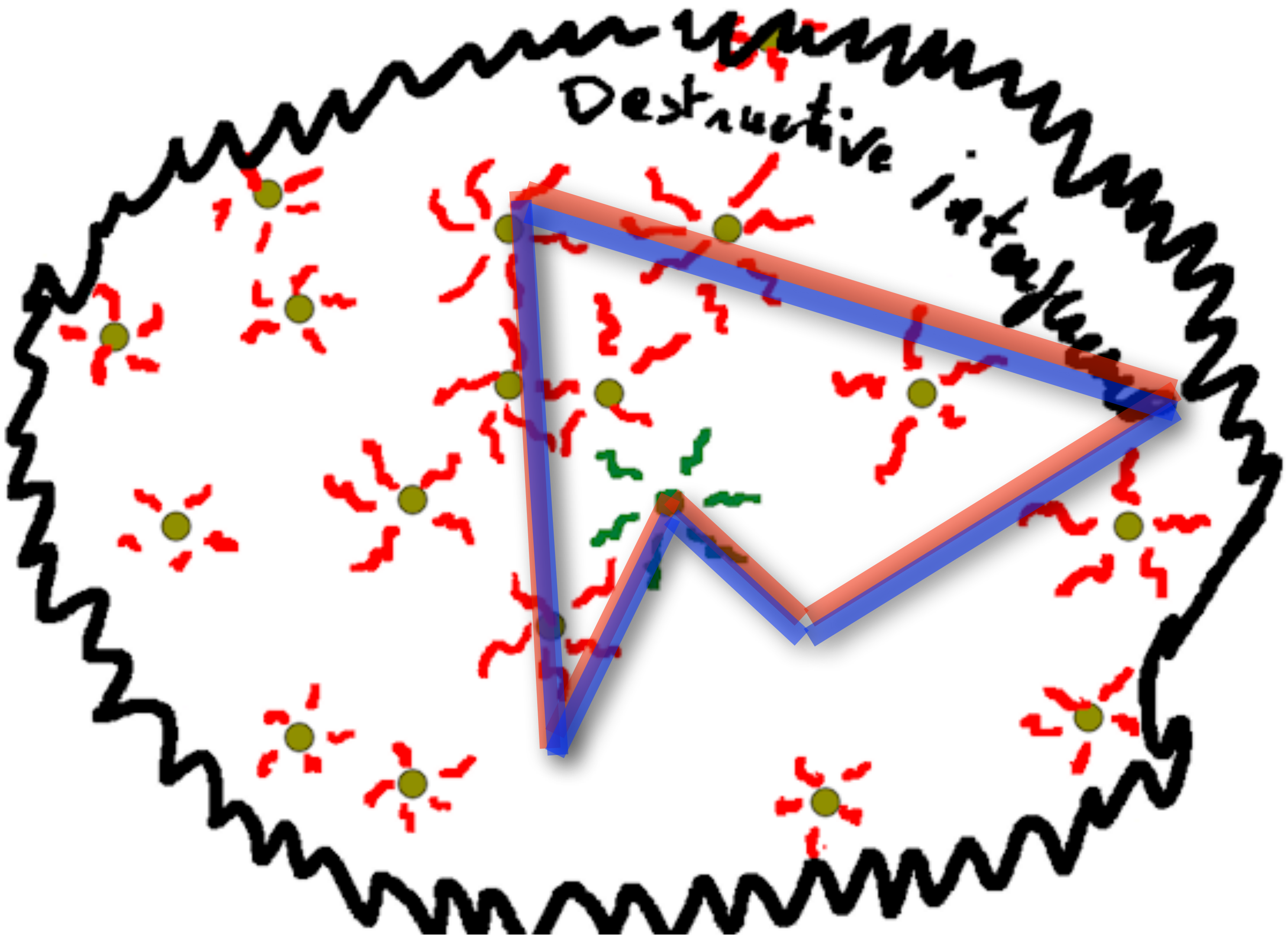
PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

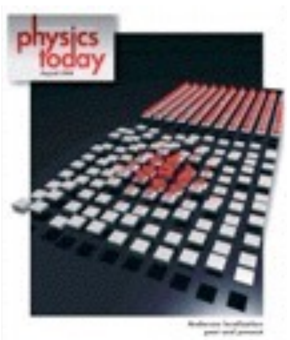
P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)

This paper presents a simple model for such processes as spin diffusion or conduction in the "impurity band." These processes involve transport in a lattice which is in some sense random, and in them diffusion is expected to take place via quantum jumps between localized sites. In this simple model the essential randomness is introduced by requiring the energy to vary randomly from site to site. It is shown that at low enough densities no diffusion at all can take place, and the criteria for transport to occur are given.

If mean free path smaller than de Broglie wavelength: constructive interference of trajectories returning to origin: localized states: insulator

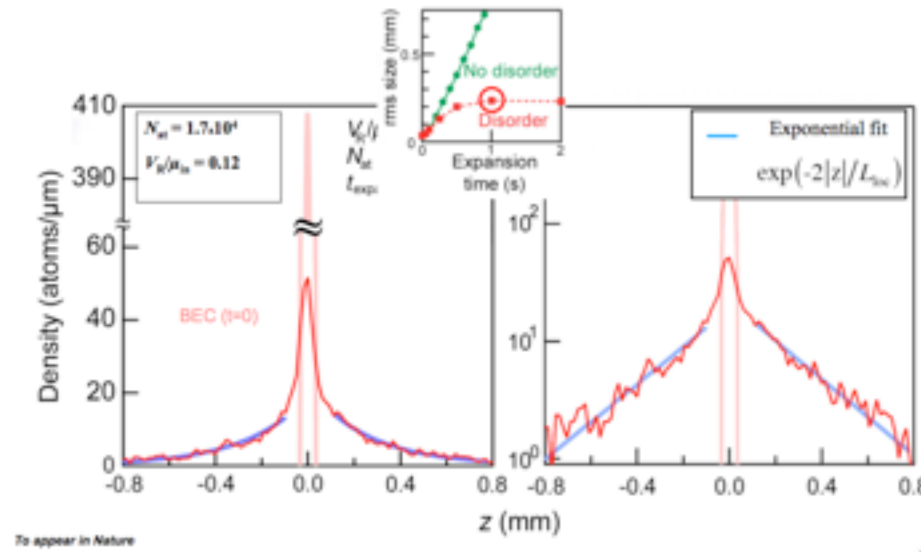


ANDERSON LOCALIZATION



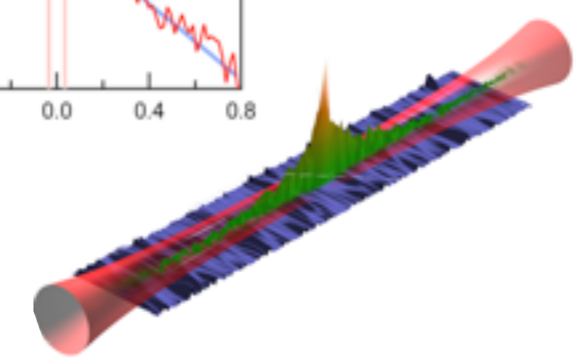
Studied in a wide variety of systems

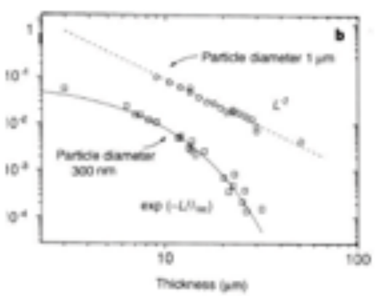
- Electronic conductivity
- Classical waves (since 90')
- Ultracold atoms (first proposal 2003)



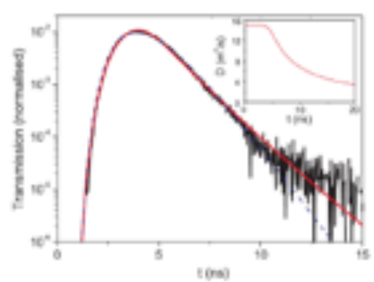
Texte

Billy, J. et al. *Nature* **453**, 891-894 (2008).

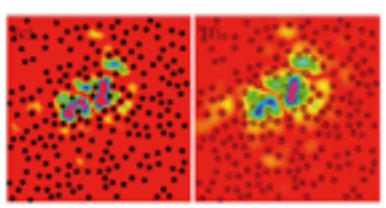




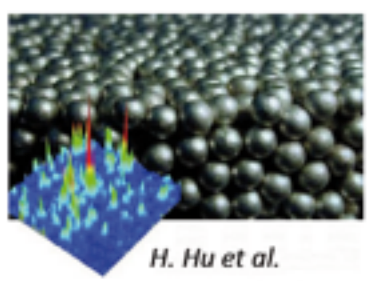
D. Wiersma et al. Nature 97



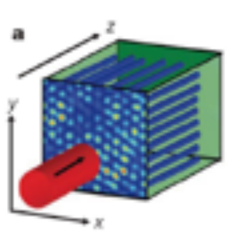
C. M. Aegerter et al. EPL 06



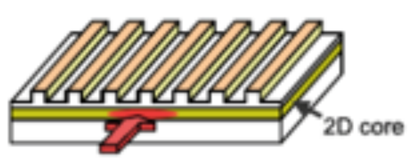
D. Laurent et al. PRL 08



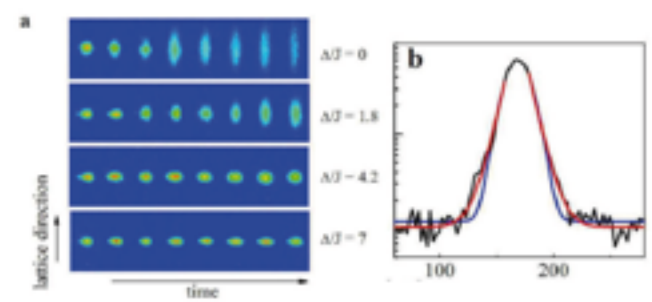
H. Hu et al. Nature Physics 08



T. Schwartz et al. Nature 07



Y. Lahini et al. PRL 08 / PRL 09



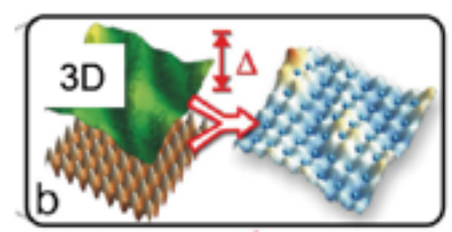
Disorder : bi-chromatic lattices

G. Roati et al. Nature 2008

Deissler et al., Nat. Phys

Lucioni et al., arXiv 2010

LENS, Florence

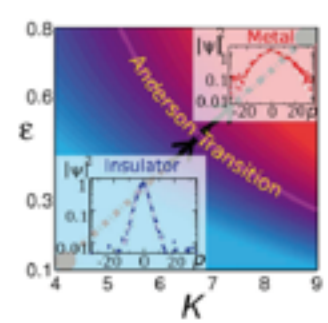


White et al. PRL (2009)

Pasienski et al. Nat. Phys (2010)

Urbana Champaign

Strongly interacting regime in disordered lattice : Towards a Bose Glass



Raizen PRL 94

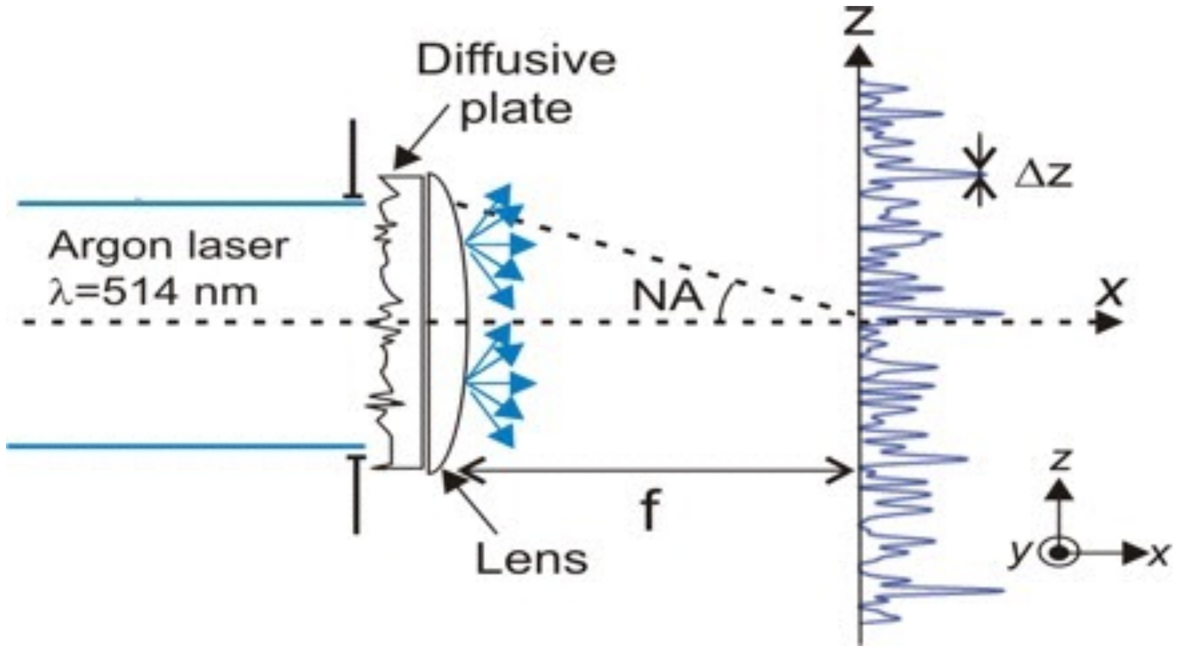
Mapping the 3D transition in momentum space

J. Chabé et al. PRL 08

Observation of the critical state

G. Lemarié et al. PRL 2010

DISORDER FOR ULTRACOLD ATOMS



Well controlled disorder

Clément et al. NJP (2006)

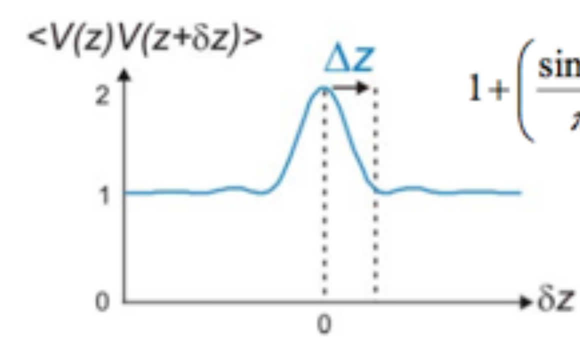
⇒ *Disorder strength* = *laser intensity* $\sigma_V = \langle V \rangle \equiv V_R$

Exponential law distribution

⇒ *Correlation length* = *numerical aperture* $\Delta x_\perp = \dfrac{\lambda}{2\,\mathrm{NA}}$

transverse « grain » speckle size = diffraction limit

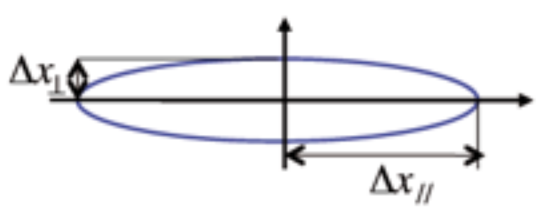
Spatial autocorrelation : C(δz)= <V(z)V(z+δz)>



$1+\left(\dfrac{\sin(\pi\delta z/\Delta z)}{\pi\delta z/\Delta z}\right)^2$

$$\Delta z = \frac{\lambda}{2(N.A.)} = 0.8\ \mu m$$

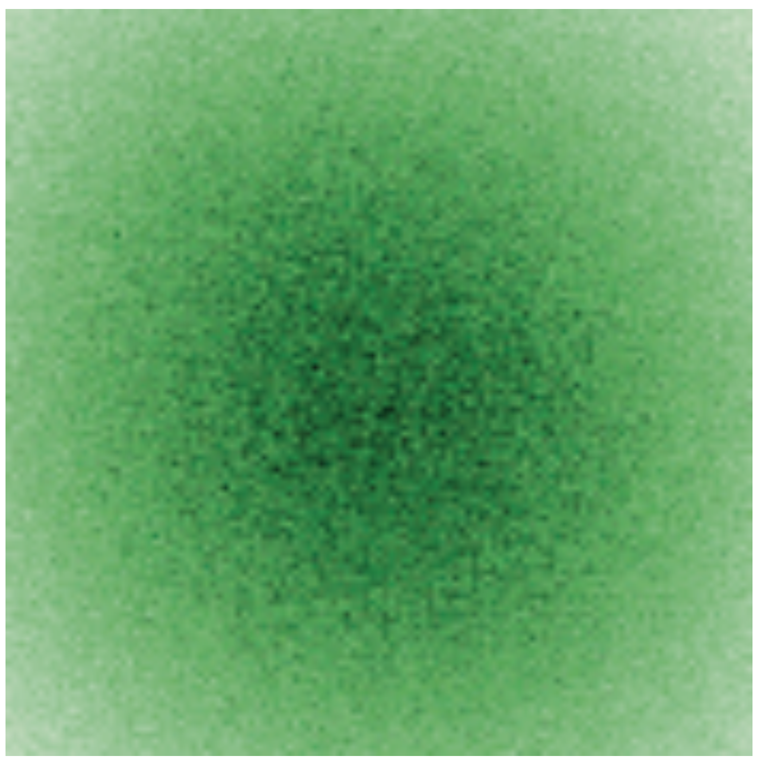
Speckle from a diffusing plate
= an anisotropic disorder

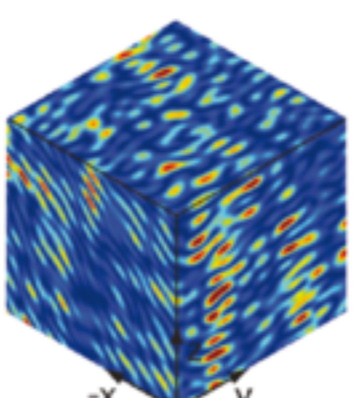


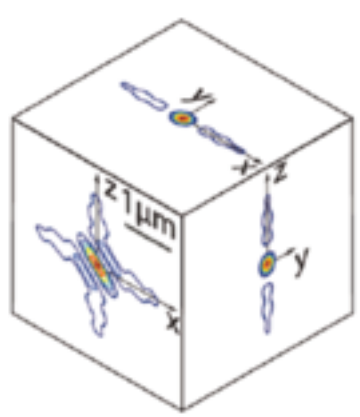
$\Delta x_{//} = \dfrac{\lambda}{2\,\mathrm{NA}^2} >> \Delta z$

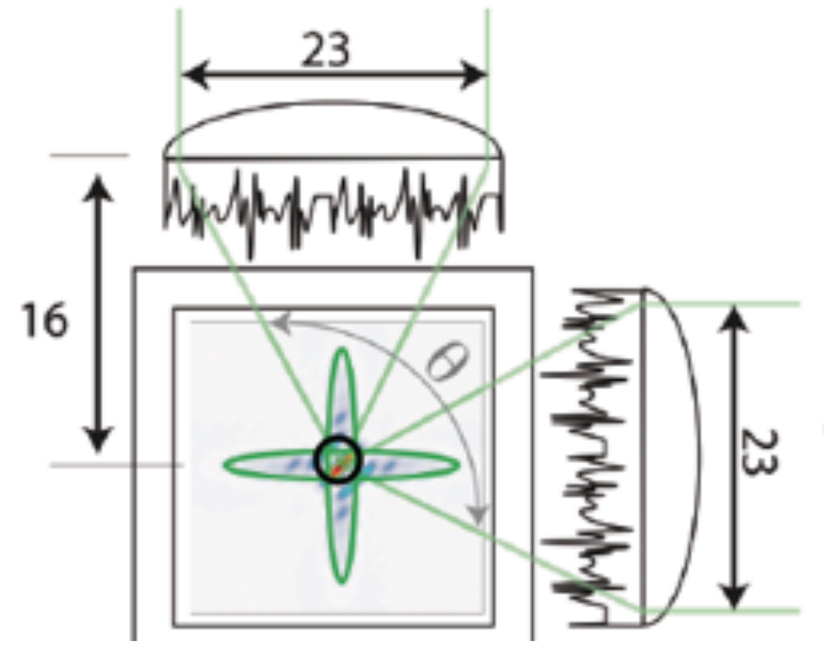
Longitudinal correlation length = Rayleigh distance

LASER SPECKLE : OPTICAL DISORDER







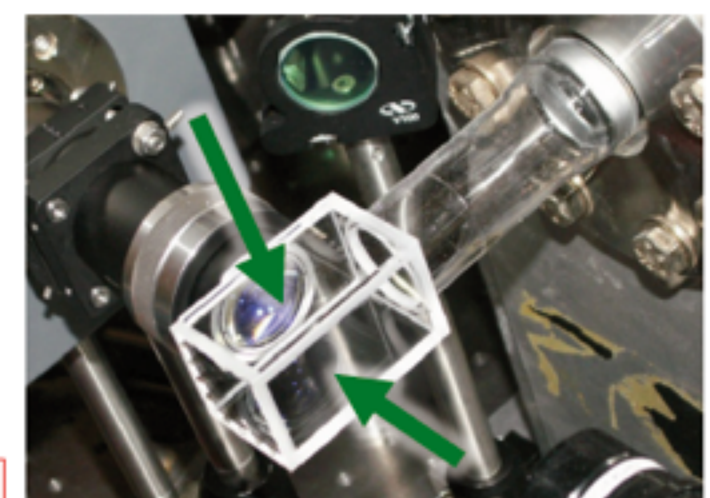


Coherent or incoherent superposition of two speckle field

(Complex correlation functions)

$$\Delta x_{max} \approx 0.8\ \mu m$$

$$k_{c,min} = \frac{\pi}{\Delta x_{max}} \approx 4\ \mu m^{-1}$$



Glass cell = large optical access available (NA=0.5)

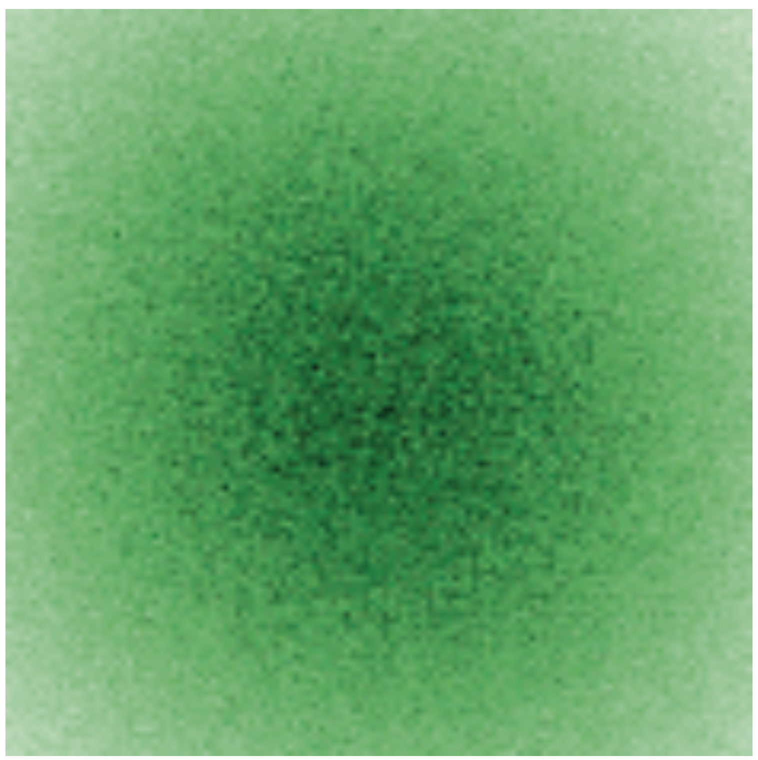
Extension: w= 1.2 mm

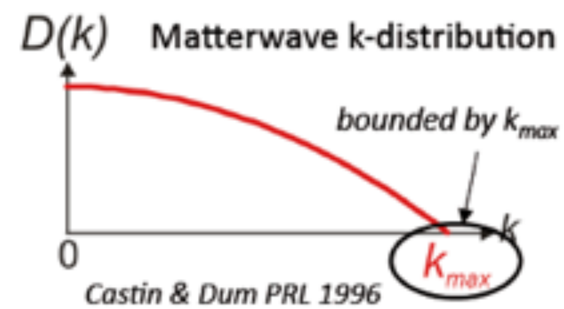
Disorder volume ≈ mm^3

Amplitude of disorder : 2+2=4 kHz

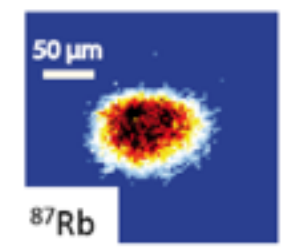
LASER SPECKLE : OPTICAL DISORDER

Start with a low energy BEC (or ultra low temperature coud).





Initial BEC in the dipole trap



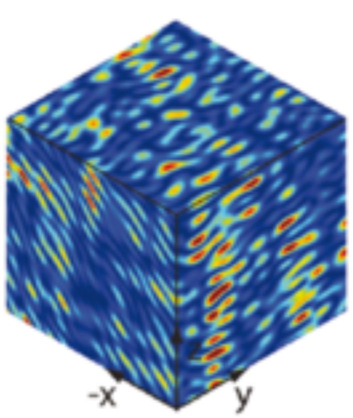
$\omega_{PO} / 2\pi = 50$ Hz

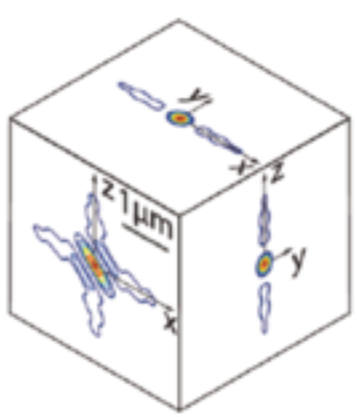
$N_{at} \approx 2.10^4$

$\mu_{in} \approx 700$ Hz

$$k_{max} \approx 2,2\ \mu\text{m}^{-1}$$

$$v_{max} \approx 1,5\ \text{mm/s}$$

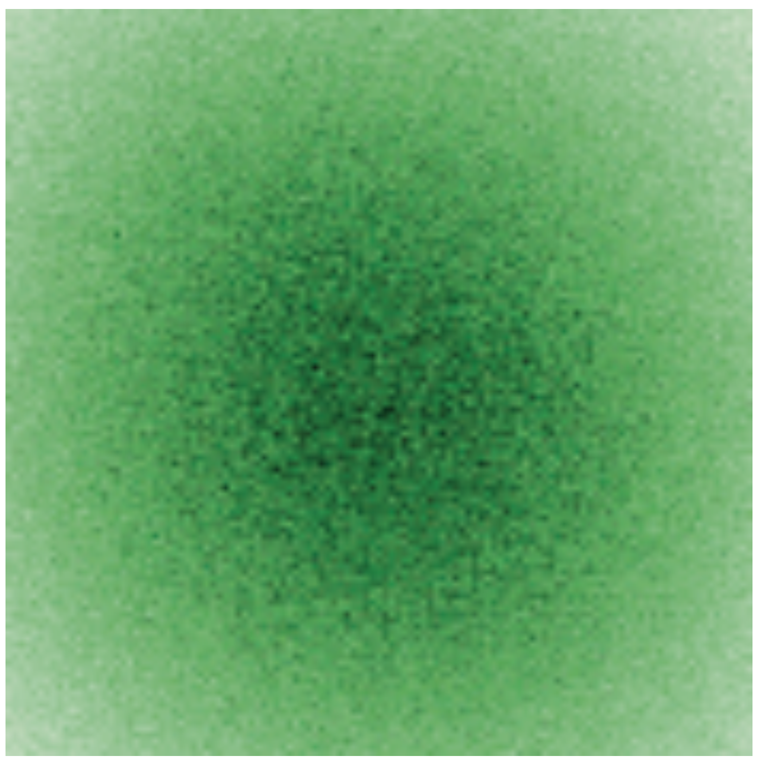




Need to keep the atomic velocities low in all directions

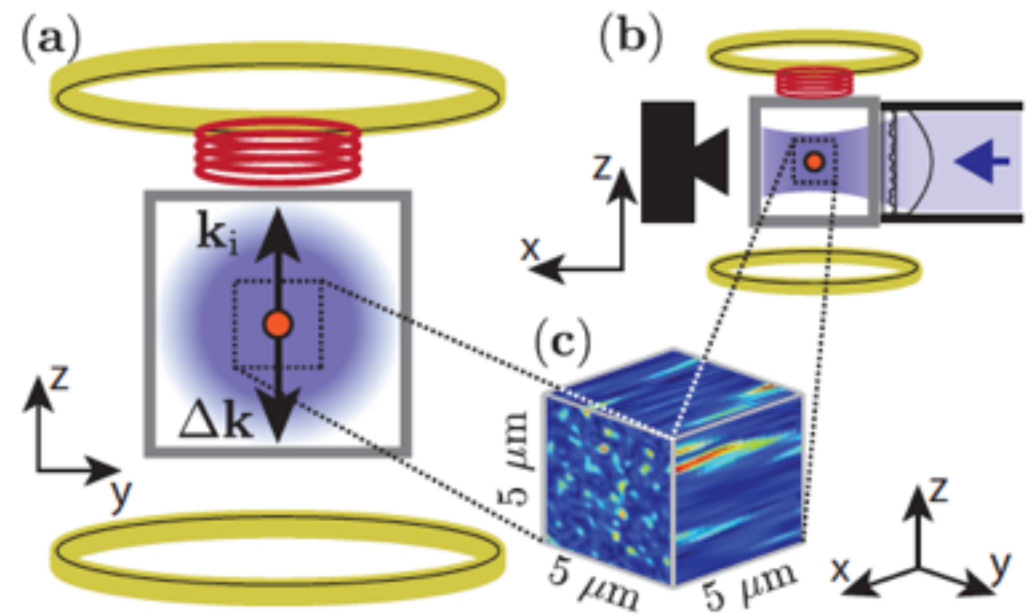
LASER SPECKLE : OPTICAL DISORDER

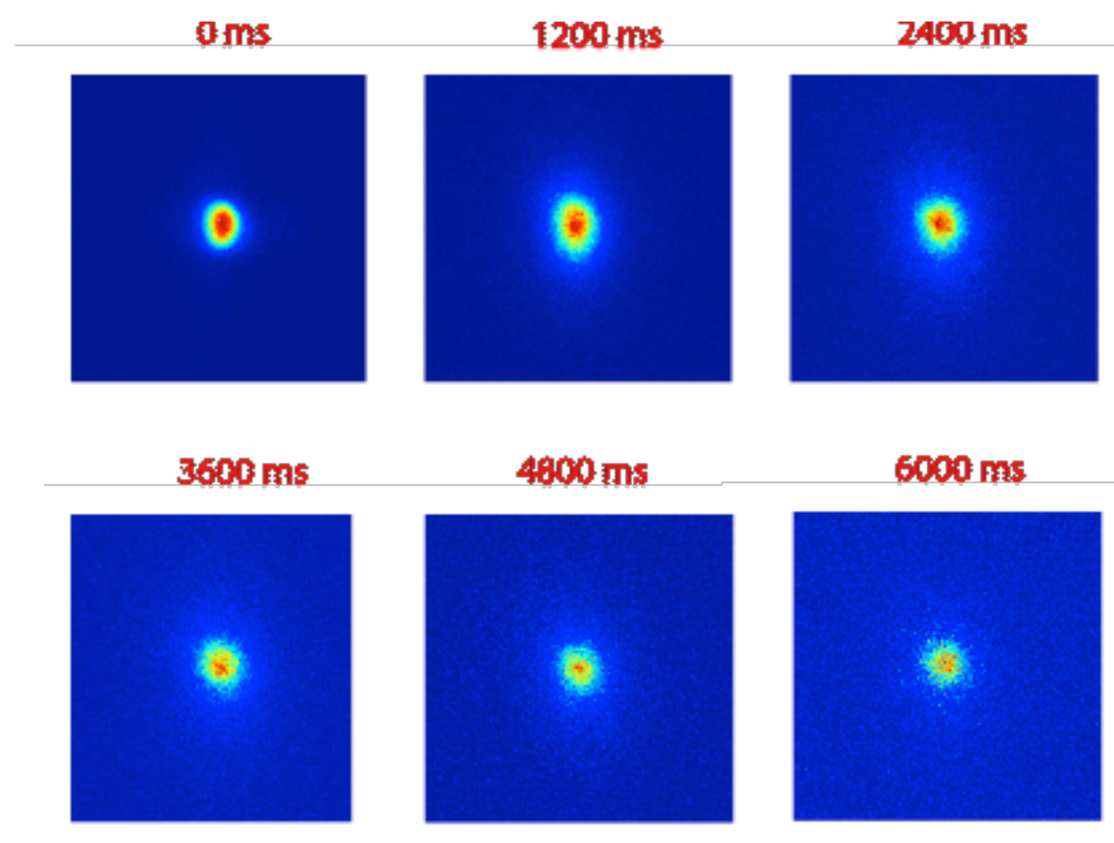
Need to compensate for gravity for long expansion time (1.5 mm/s in 17 ms)



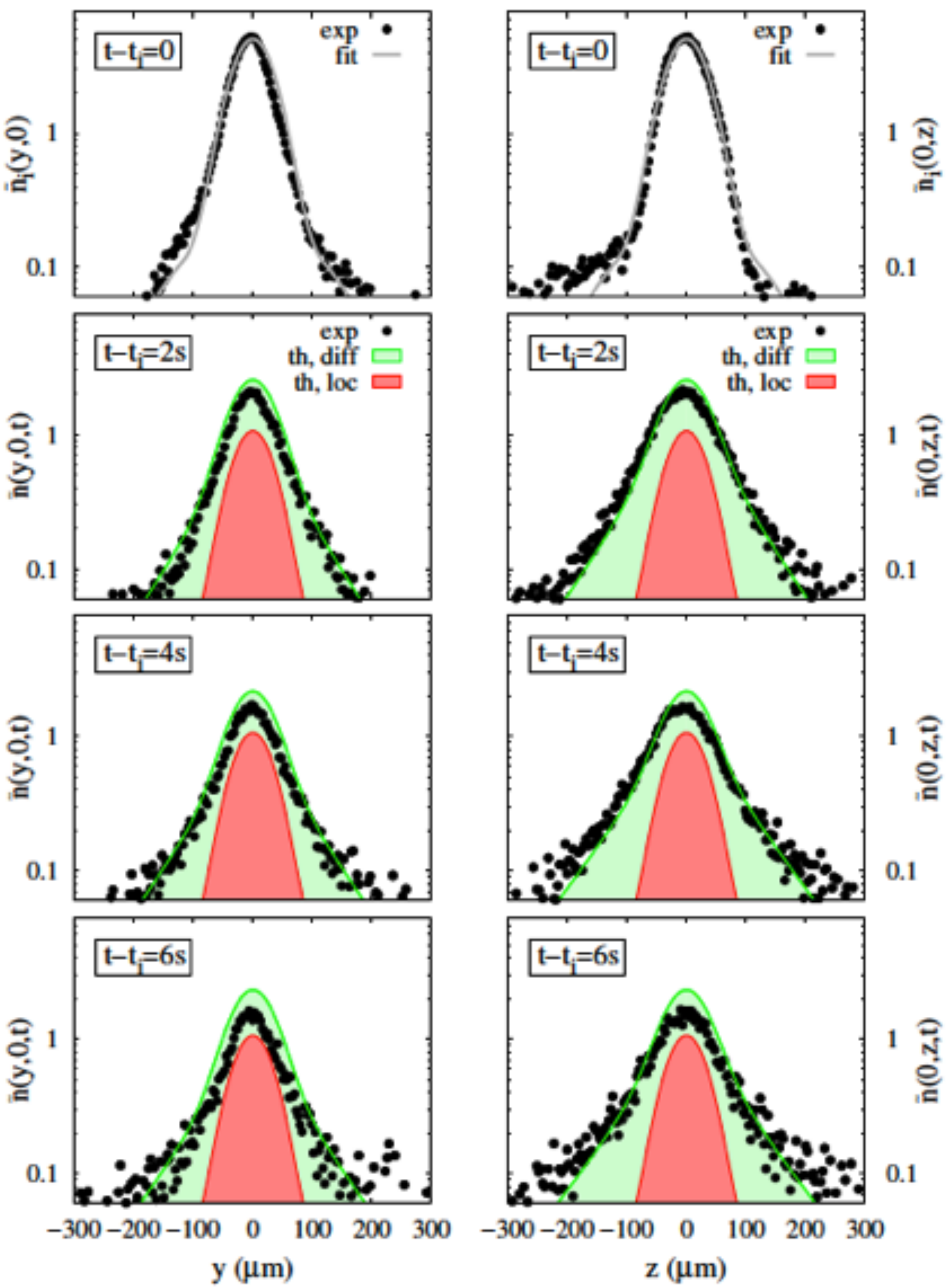
B_0 up to 2000 G: minimal residual trapping (trapping or anti- trapping configuration)

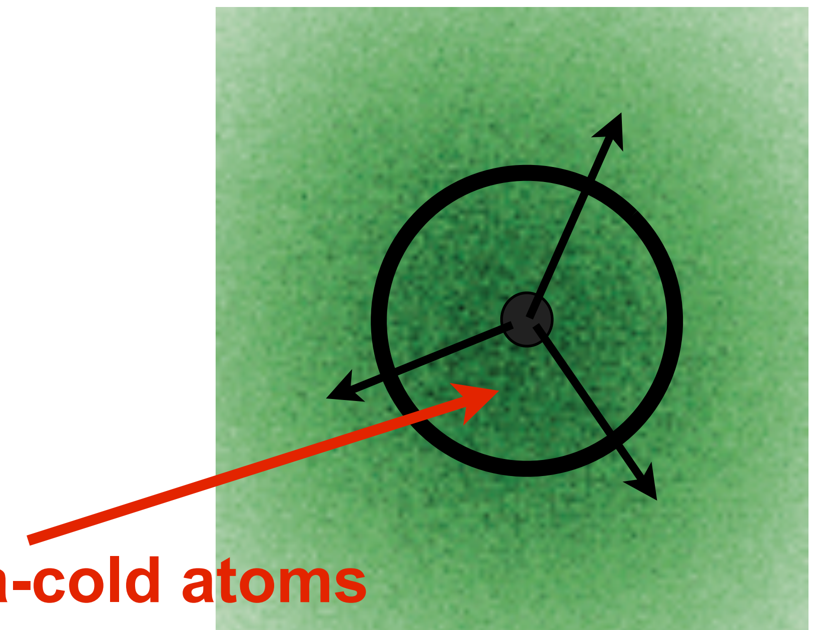
$$\omega_{LEV}^{\min} \approx 0.2\ \text{Hz}$$





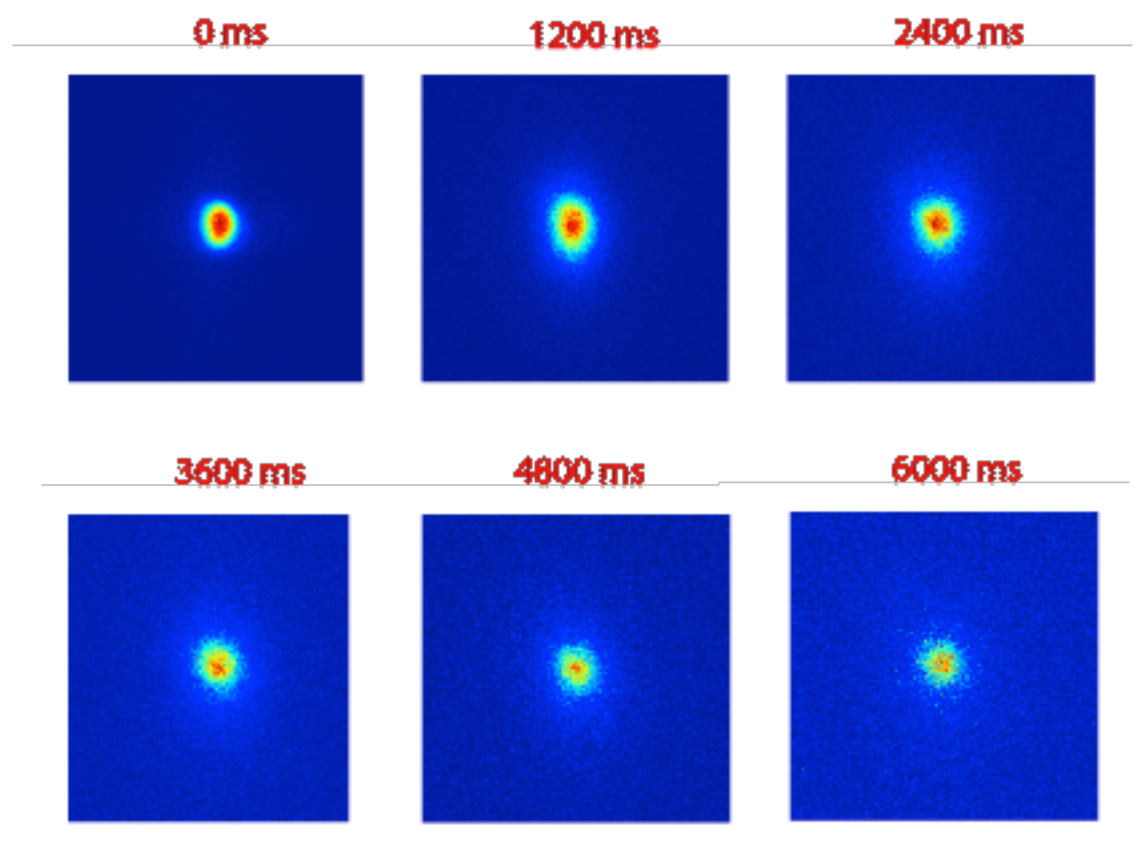
LASER SPECKLE : OPTICAL DISORDER



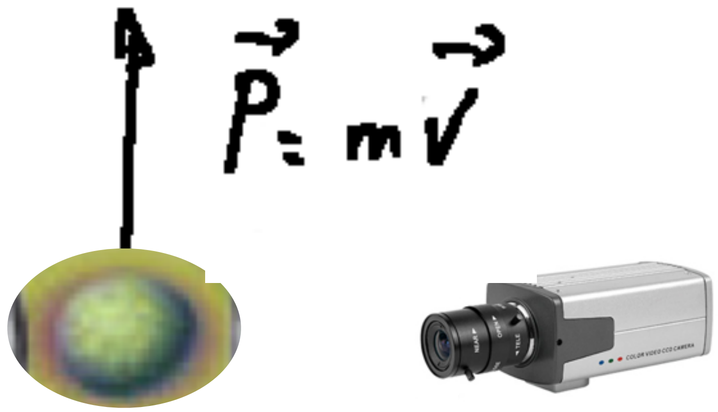


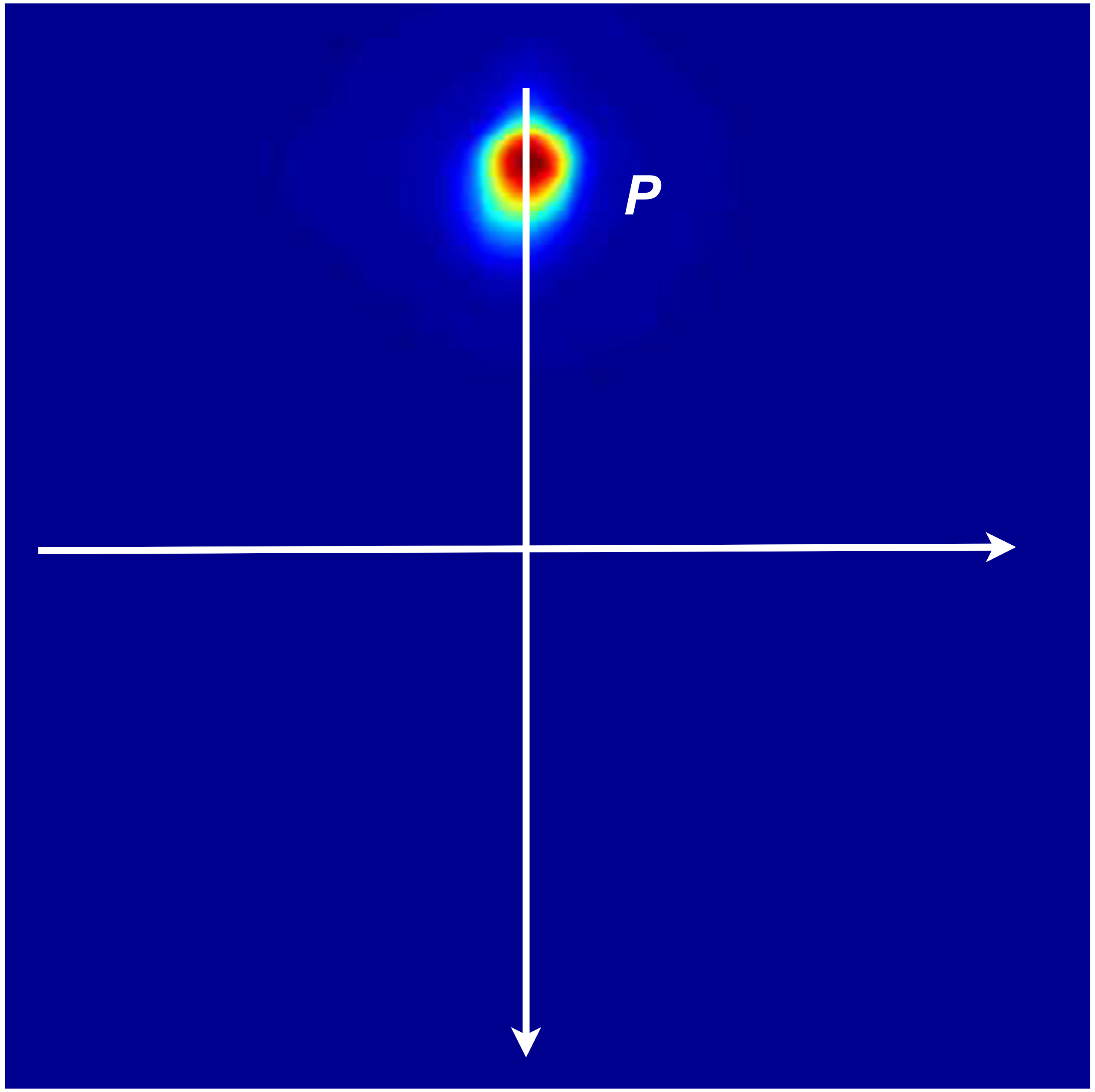
Ultra-cold atoms

^{87}Rb BEC, T < 50 nK, E ≈ kHz

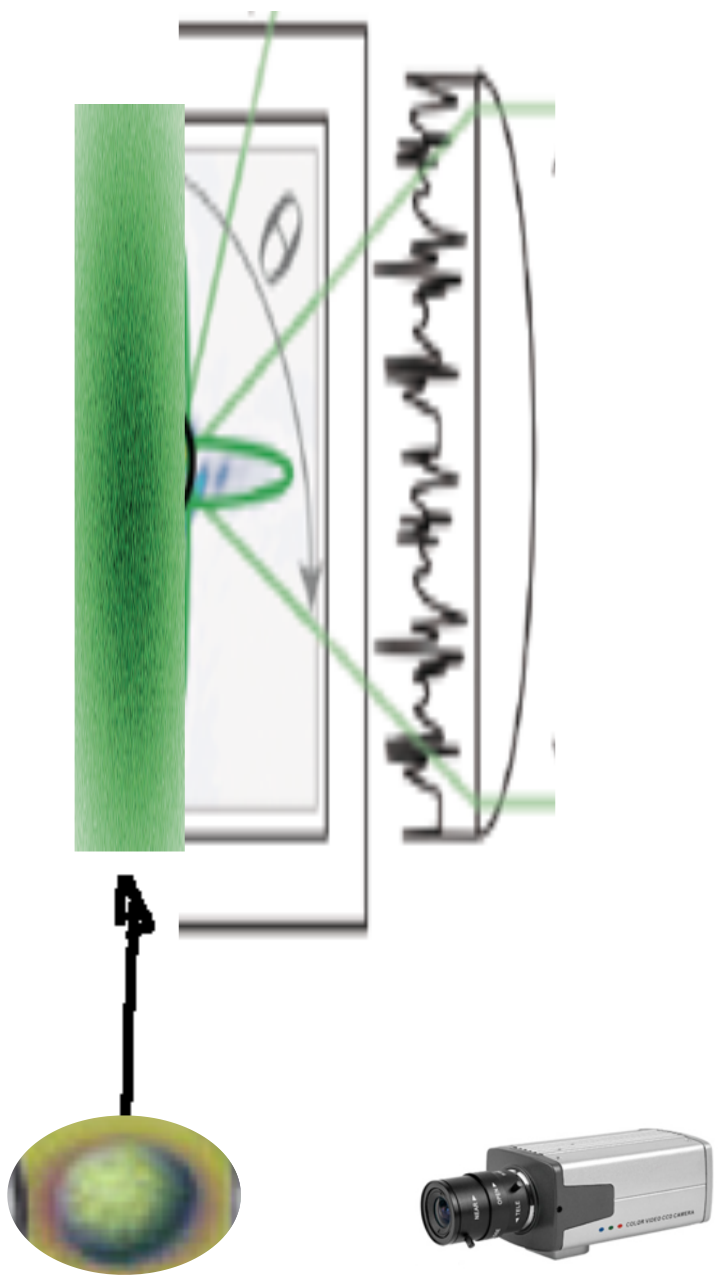


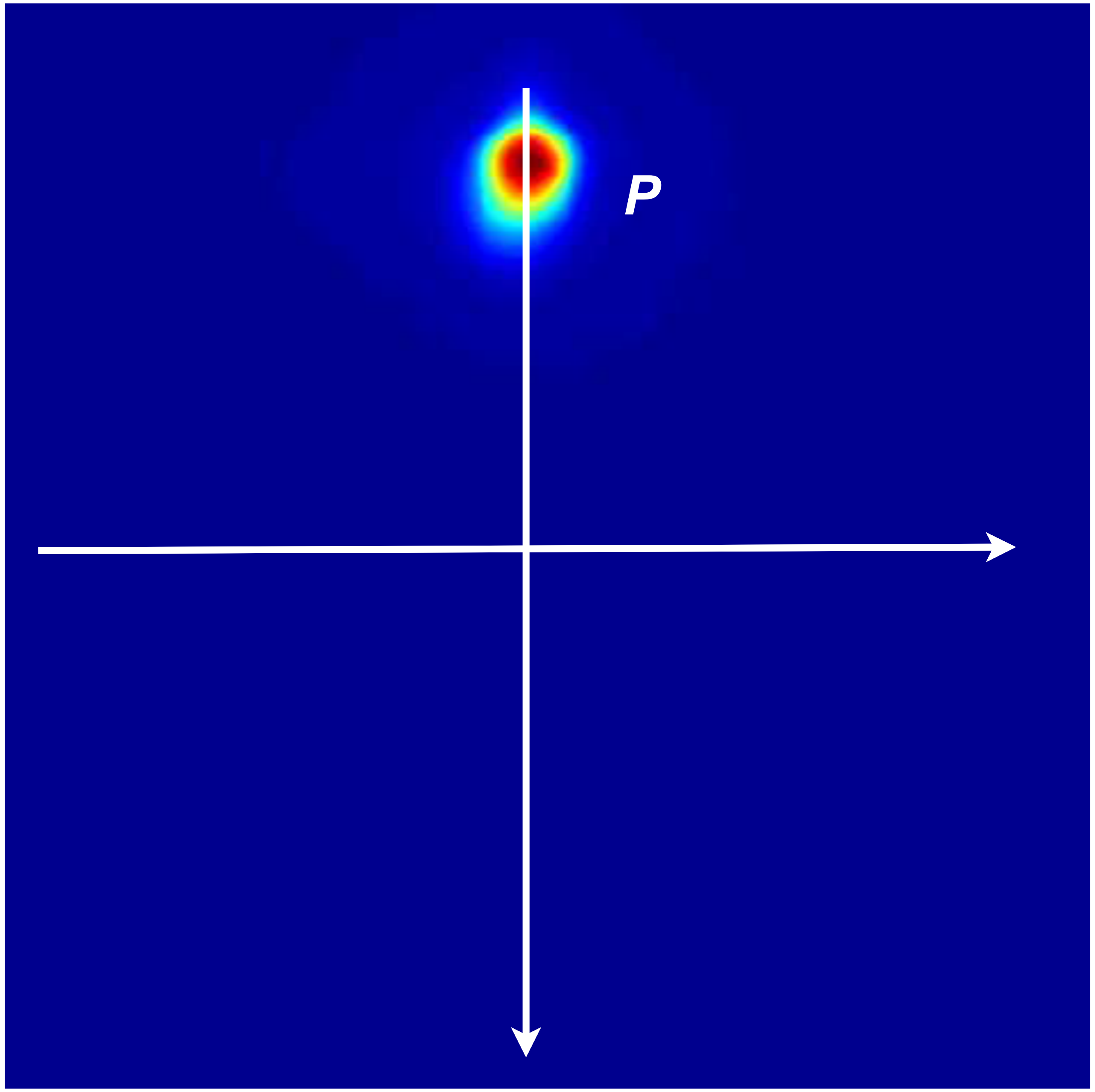
- **When imaging atoms after they are ejected from the trap, we directly monitor the velocity and the velocity distribution (*time of flight*).**





- **Adding arbitrarily placed *obstacles* that will deflect the atoms.**





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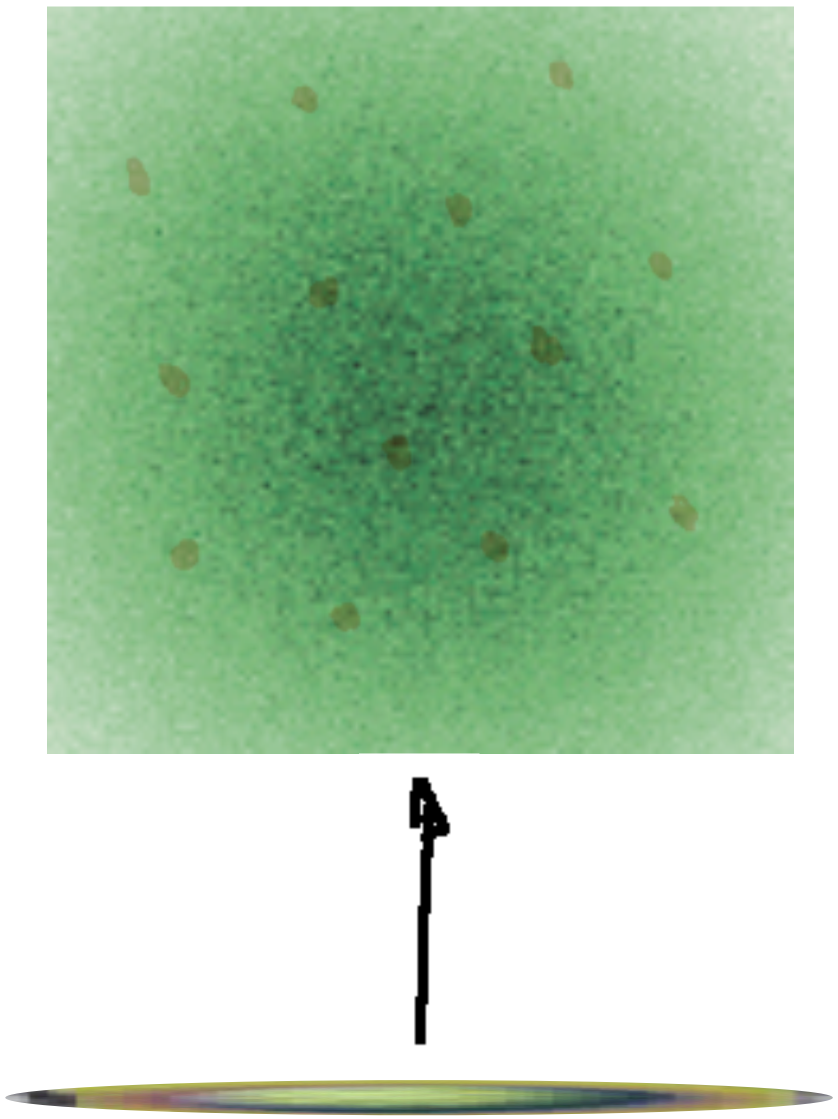
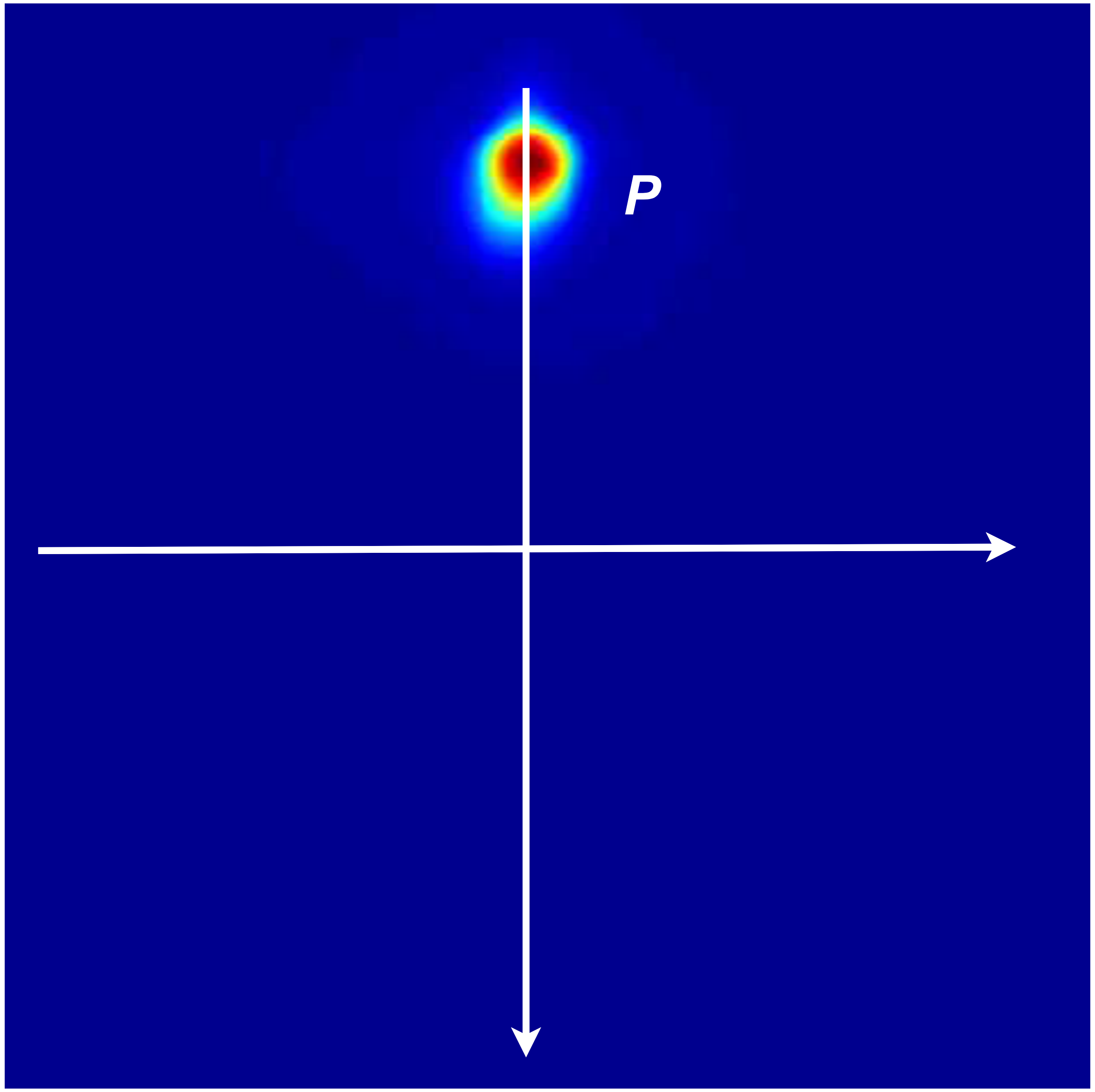
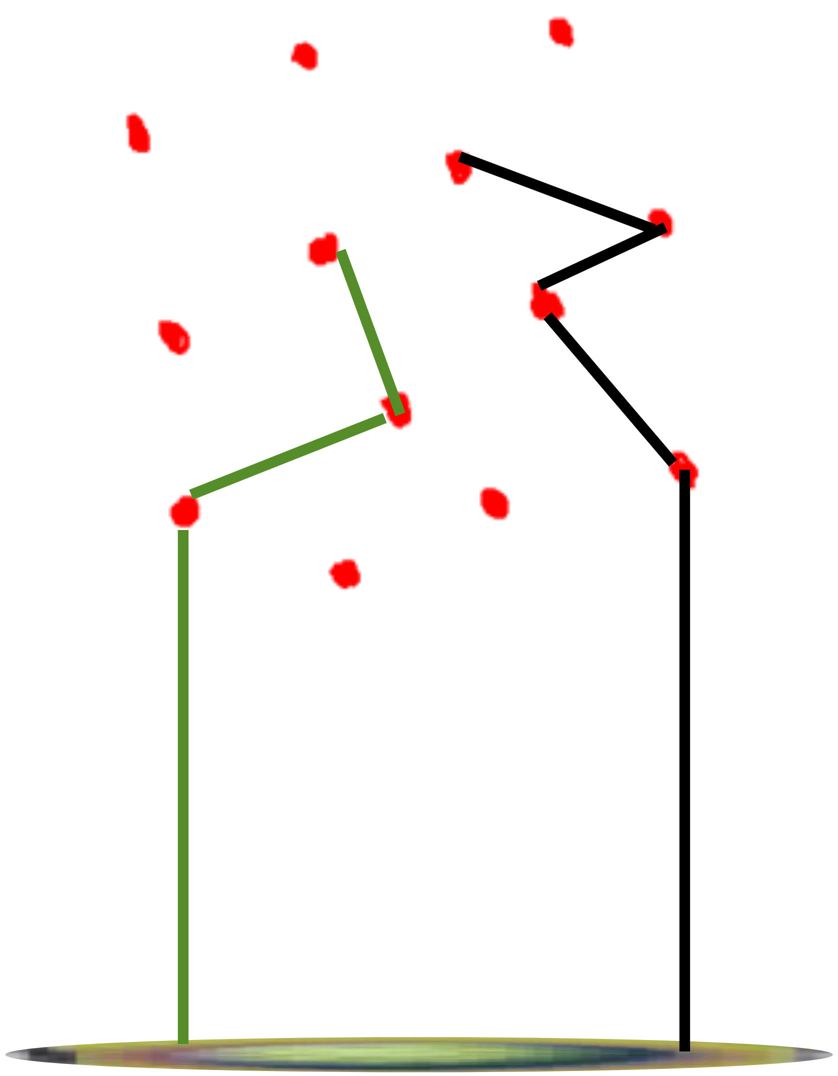
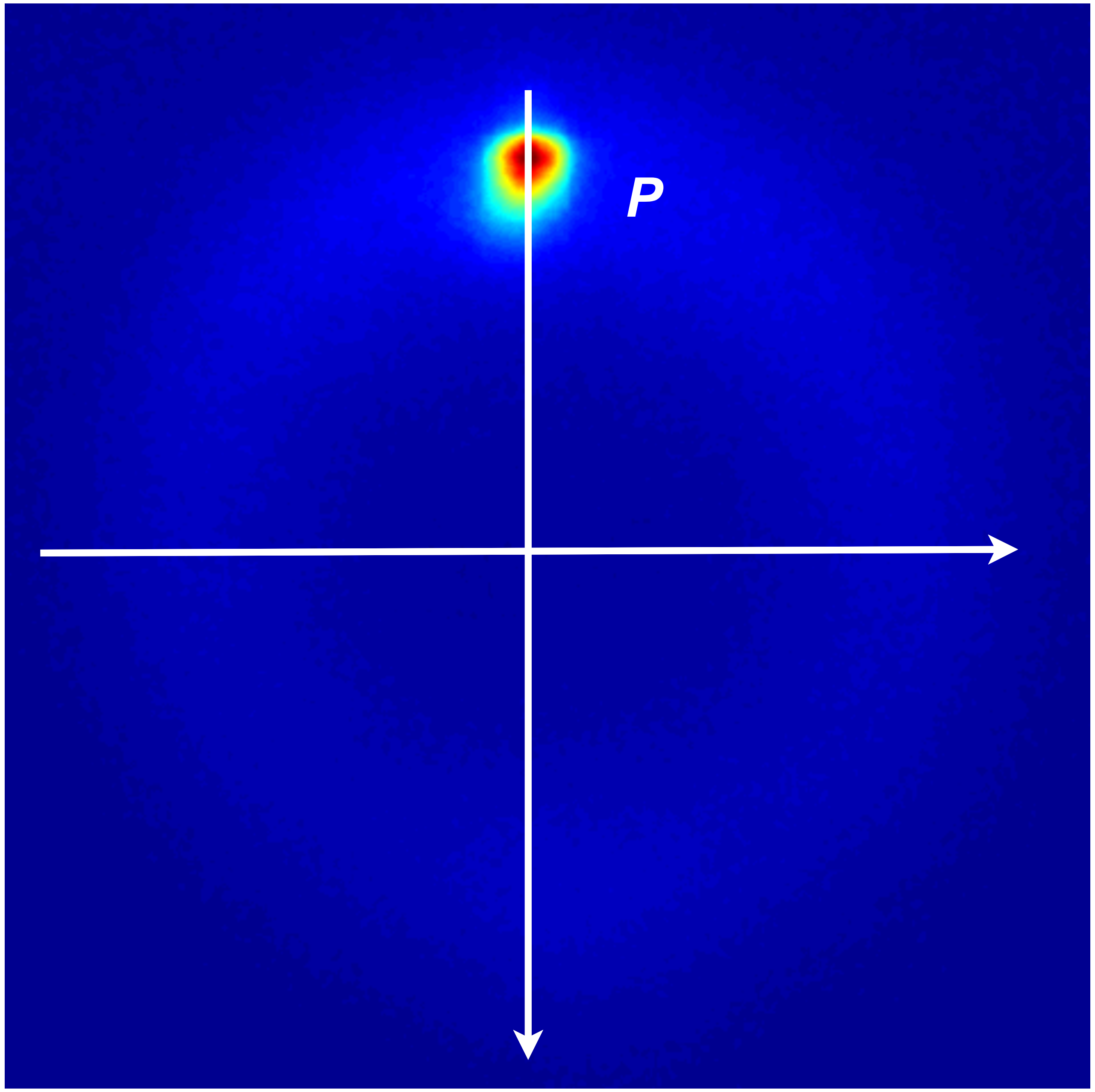




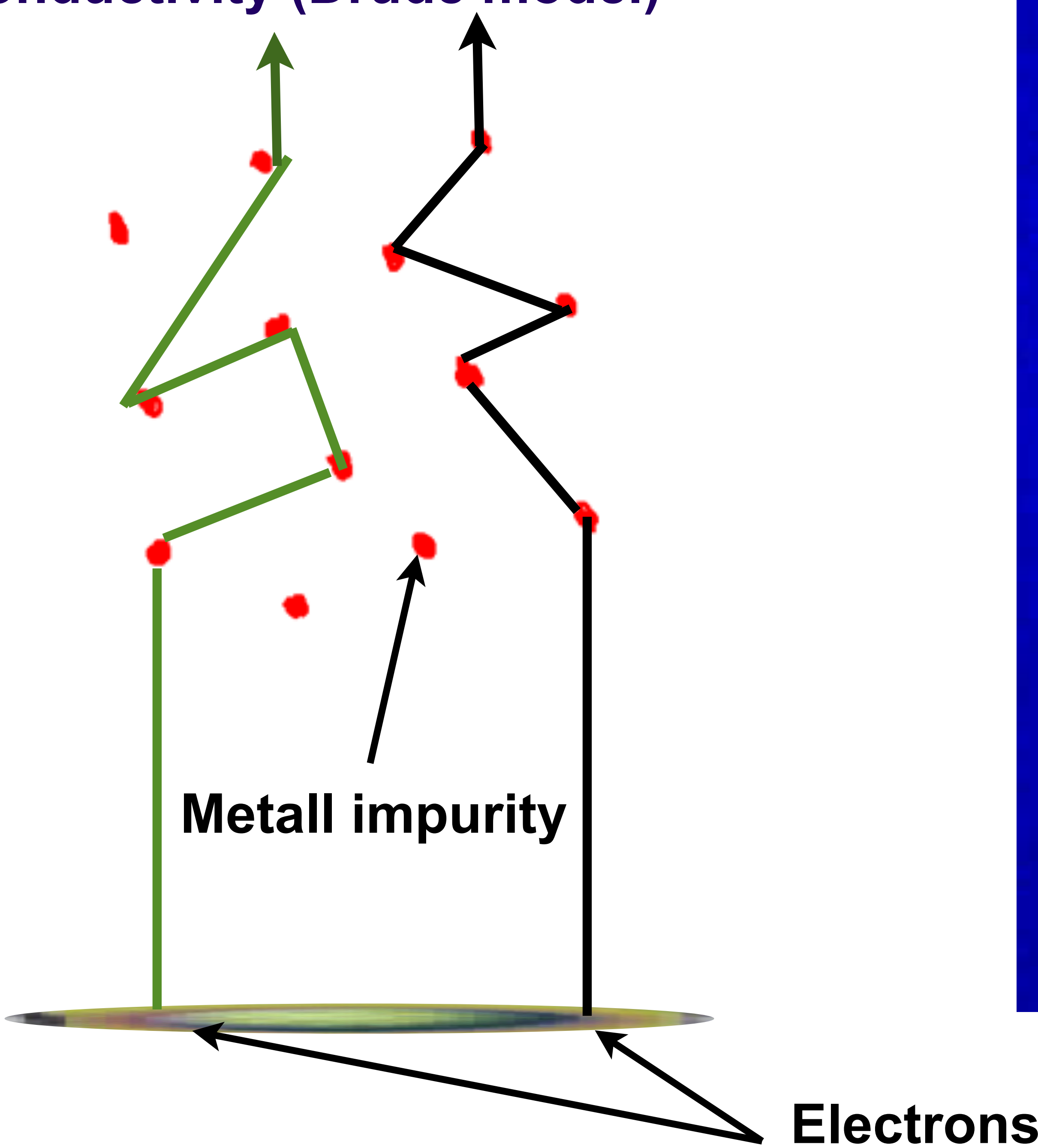
- ***The atoms will have a random walk because of scattering***

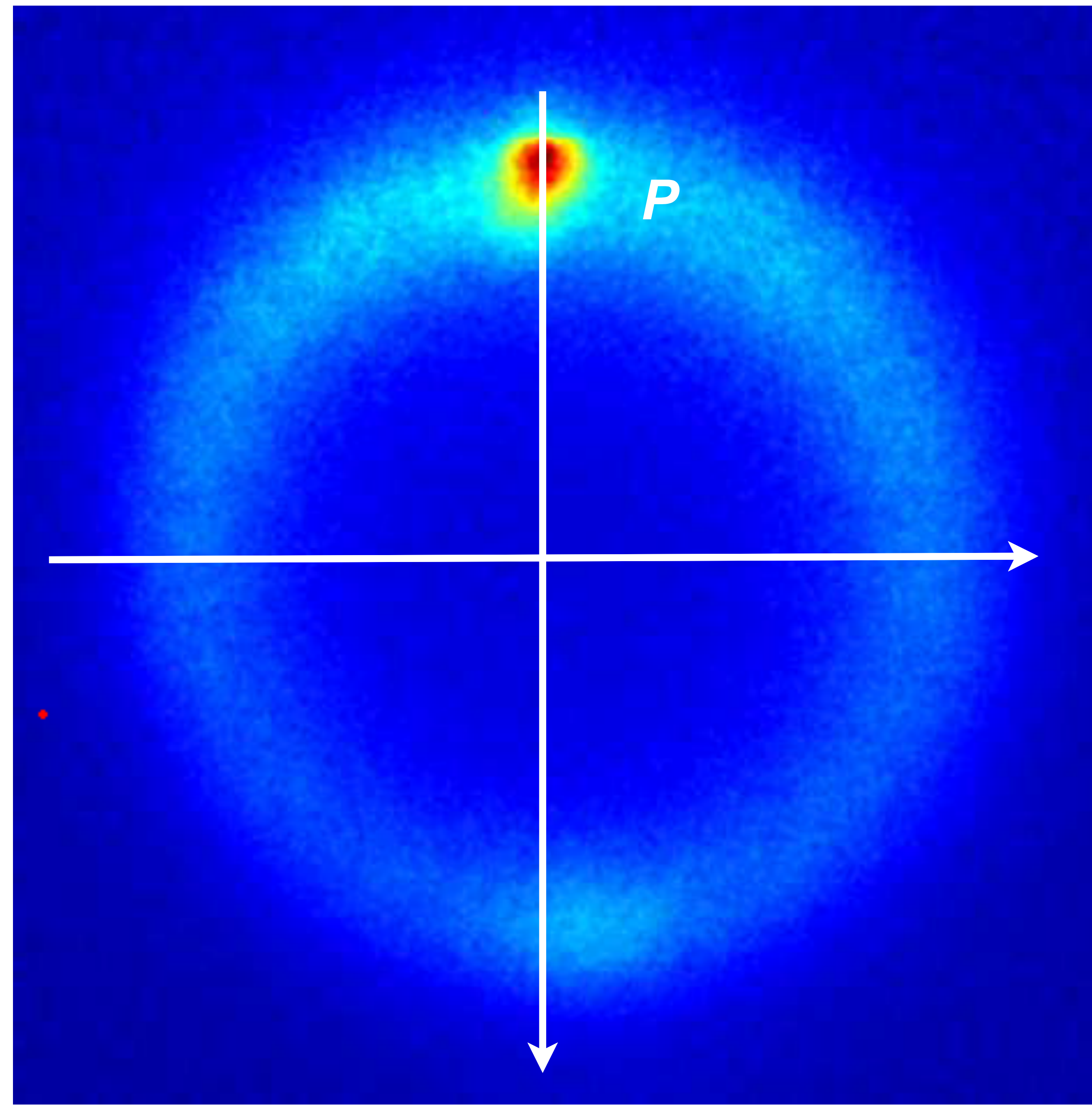




WEAK LOCALIZATION FOR ULTRACOLD ATOMS

- **We observe a transport phenomenon mimicking conventional electrical conductivity (Drude model)**





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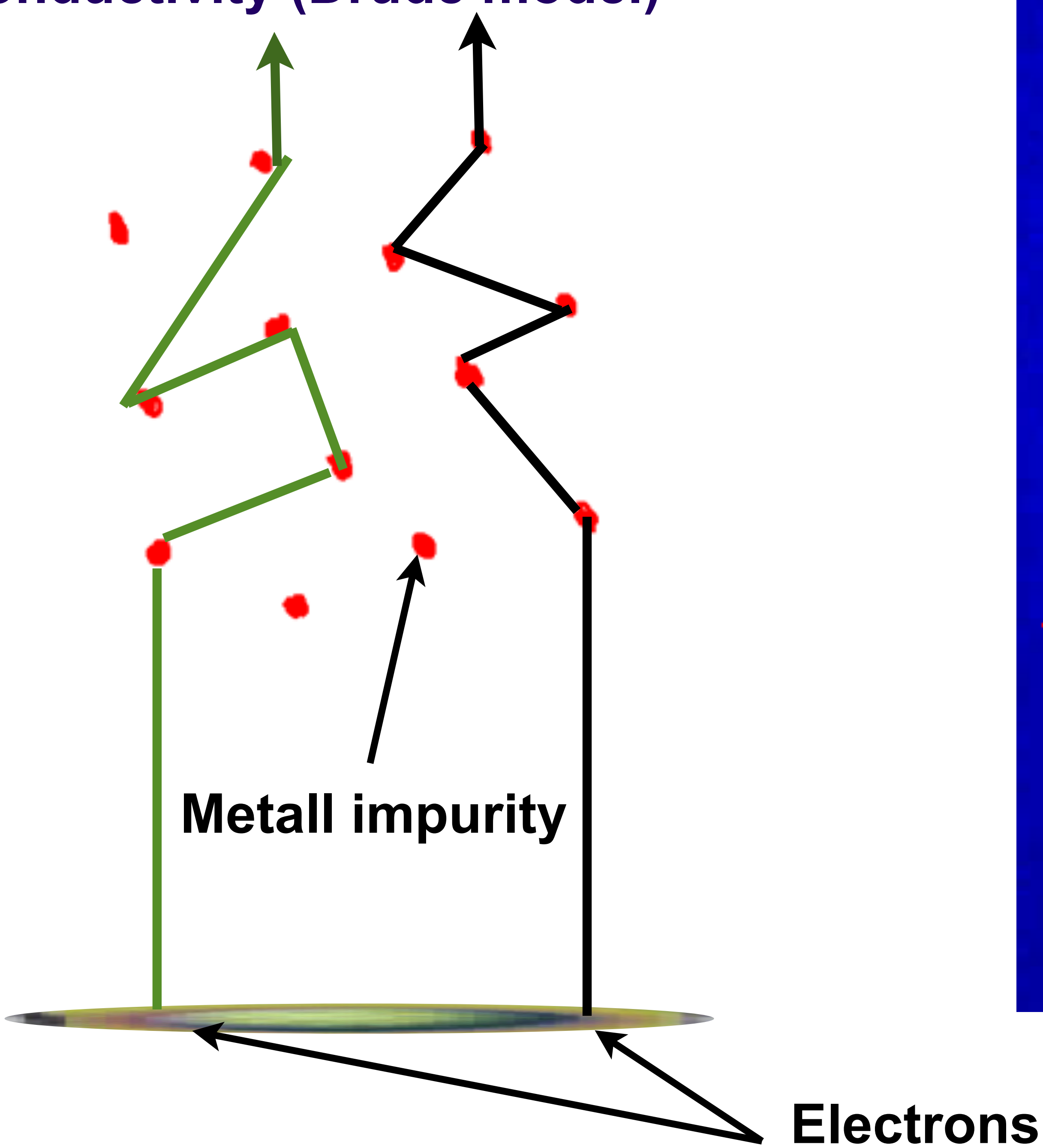
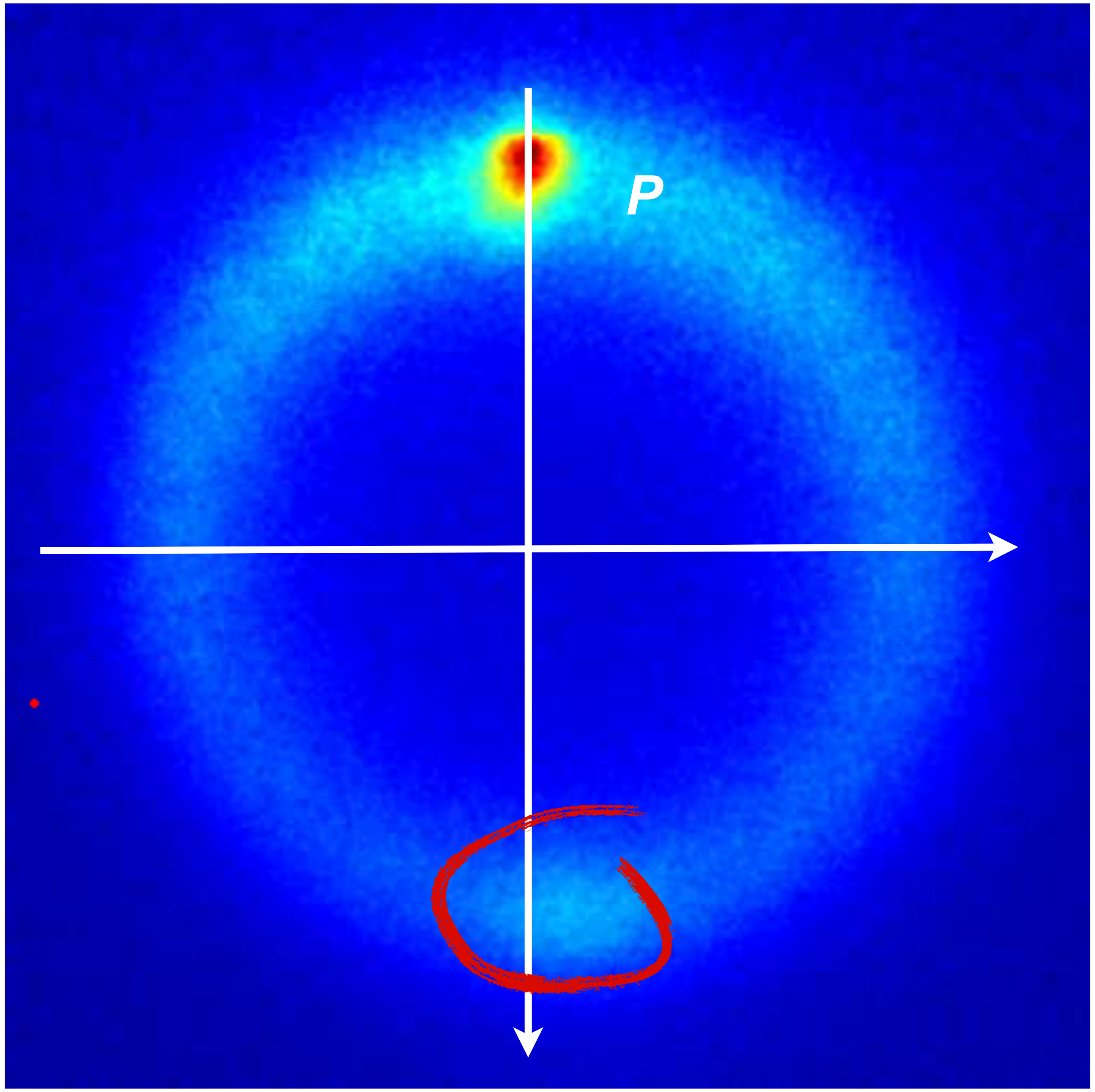
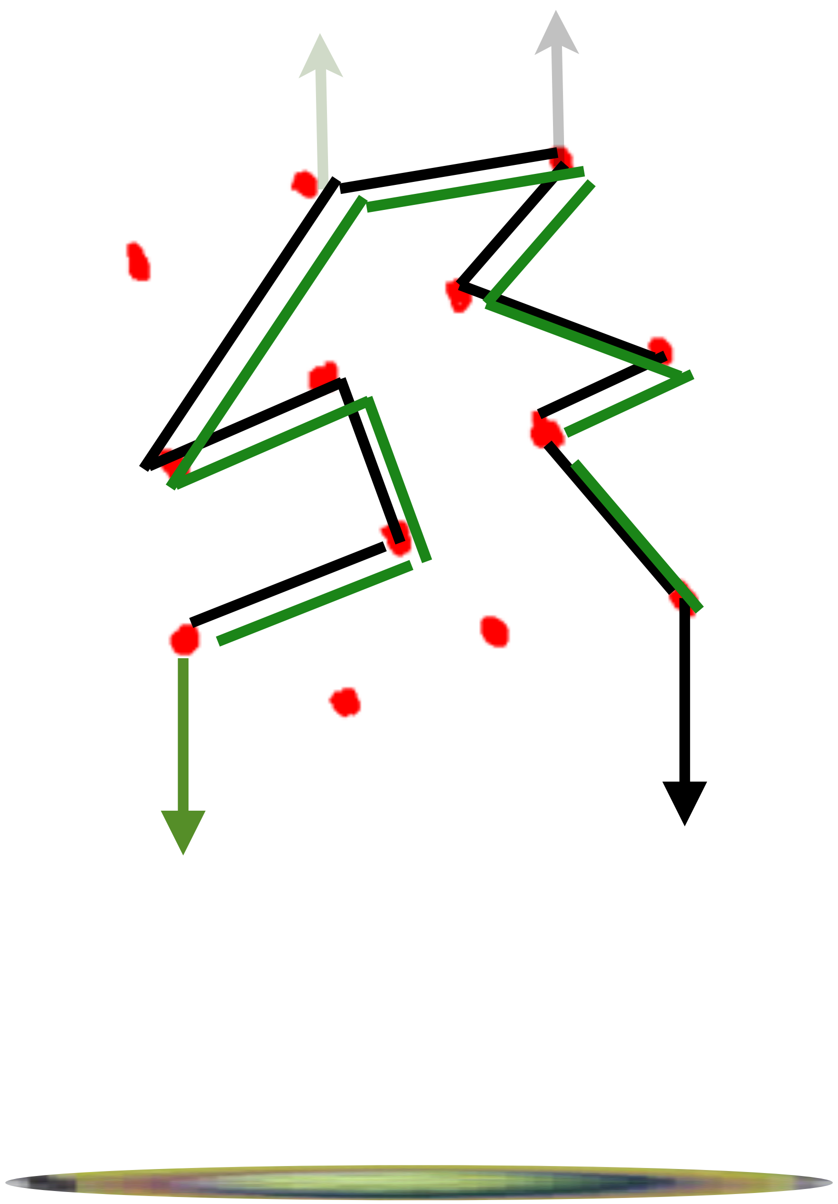
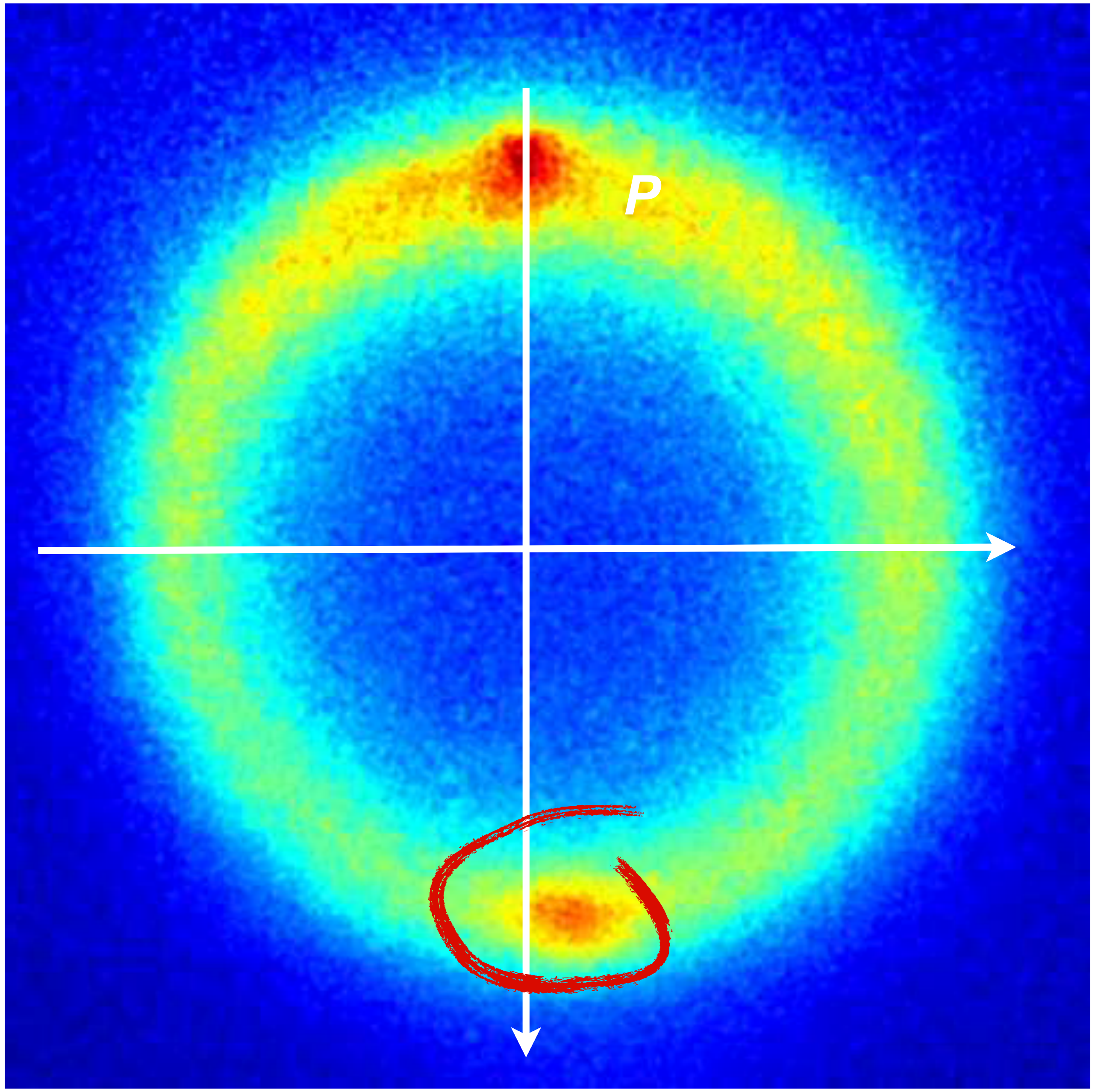


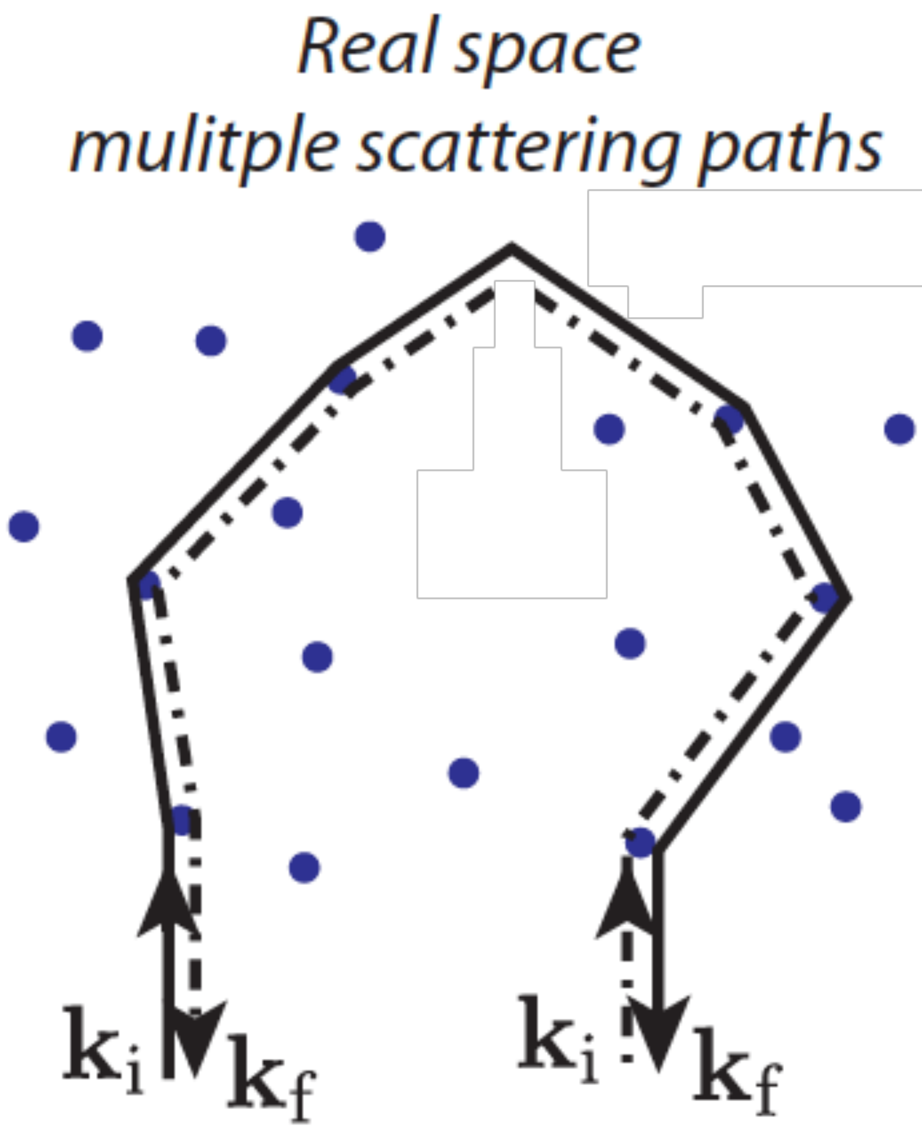


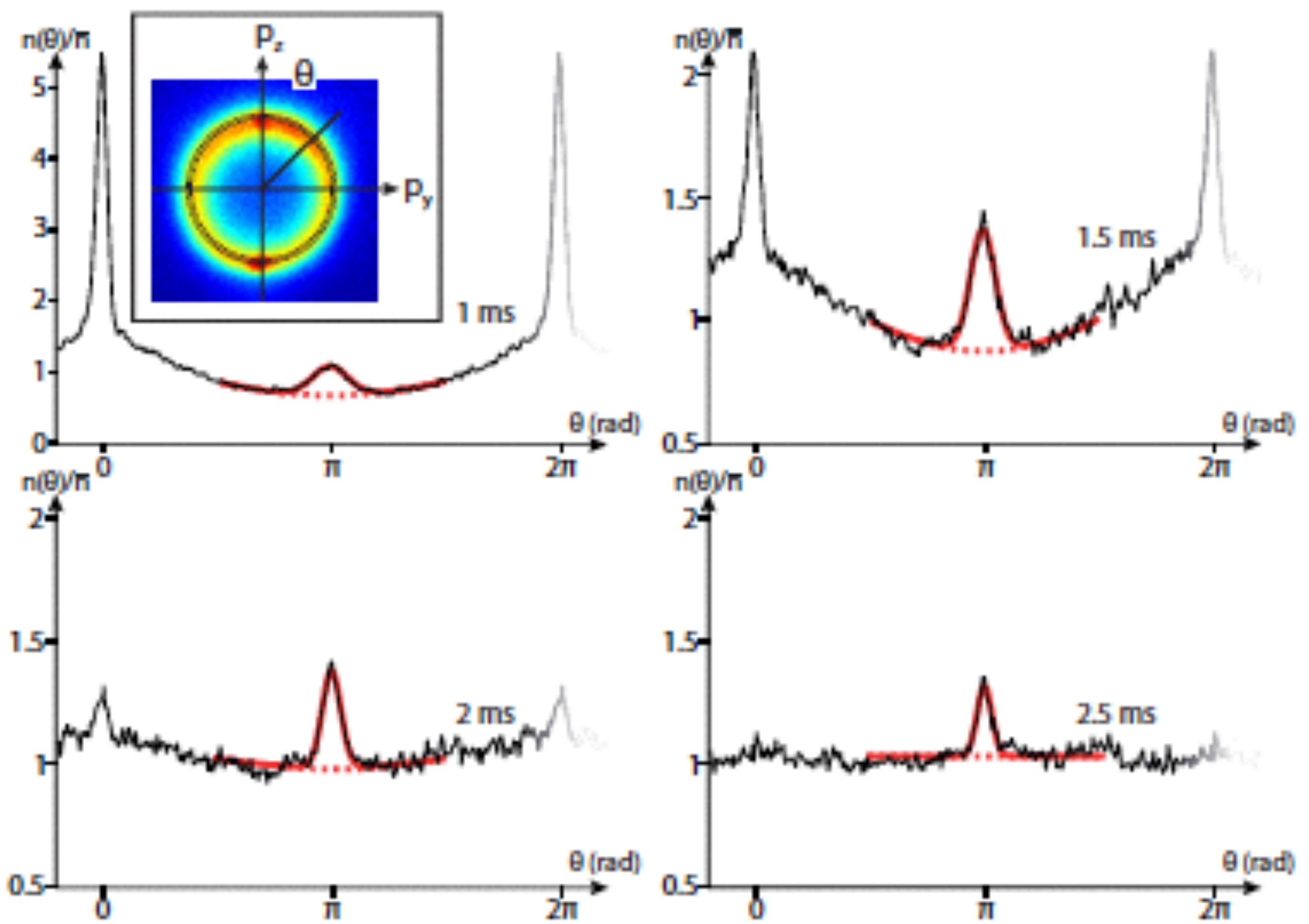
- **Observation of enhanced retroreflection**





- **Observation of weak localisation induced by Time Reversal Symmetry of the atomic paths : coherent back scattering**





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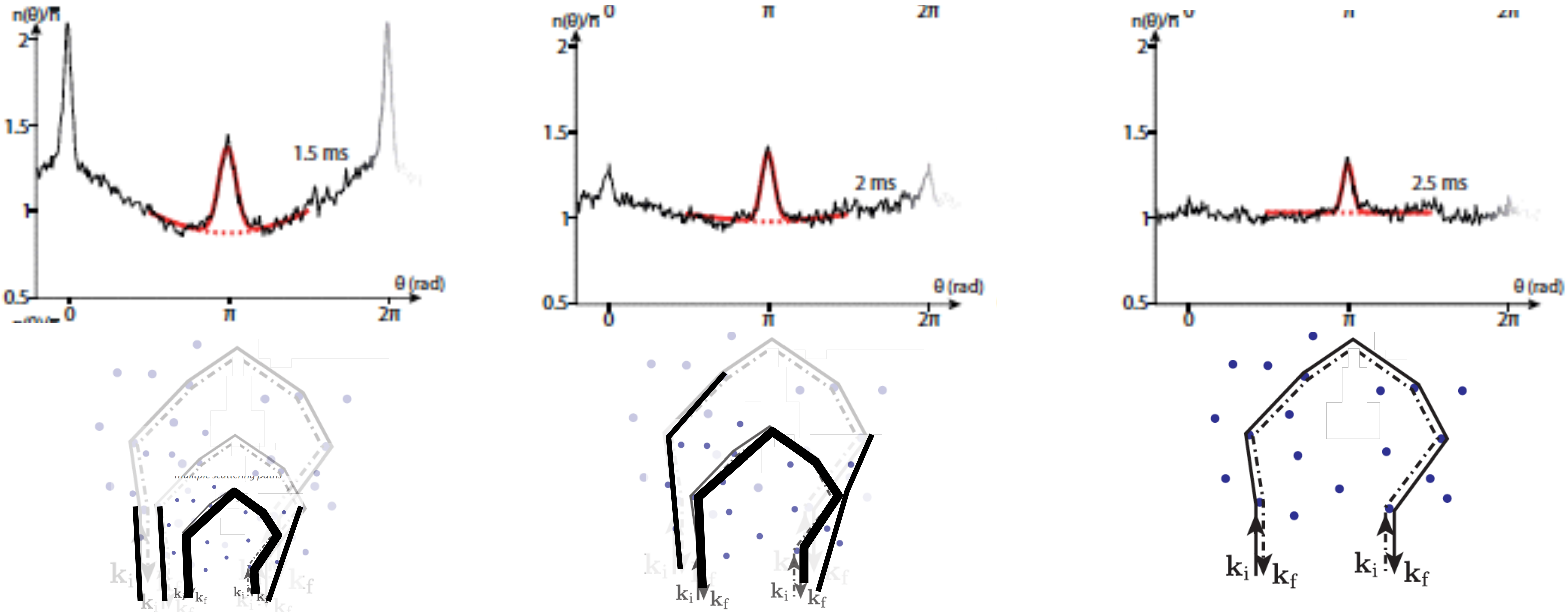
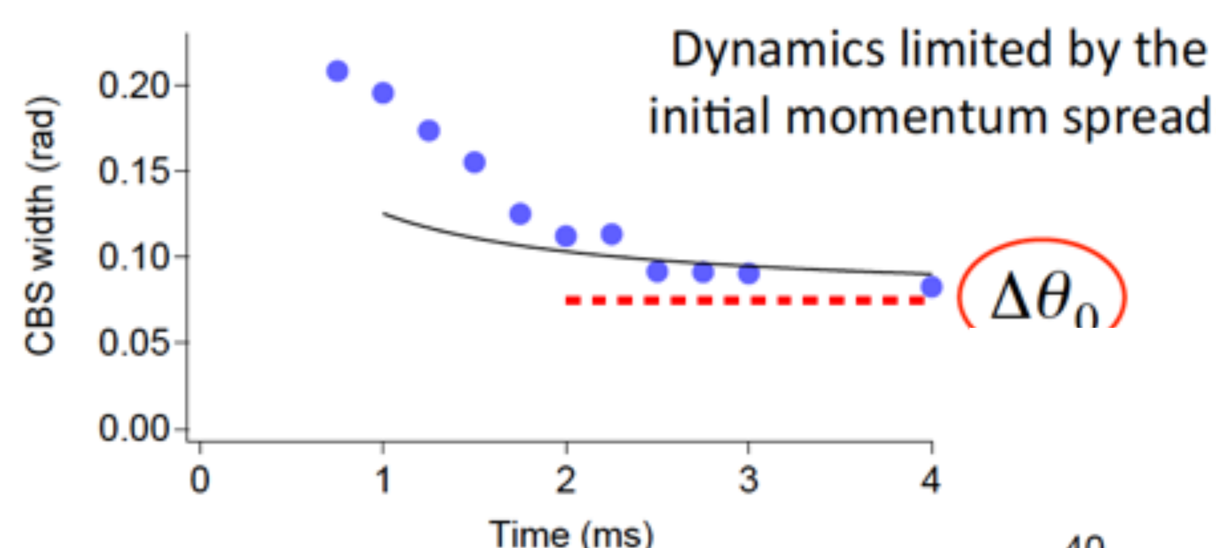
Coherent back scattering of matter waves

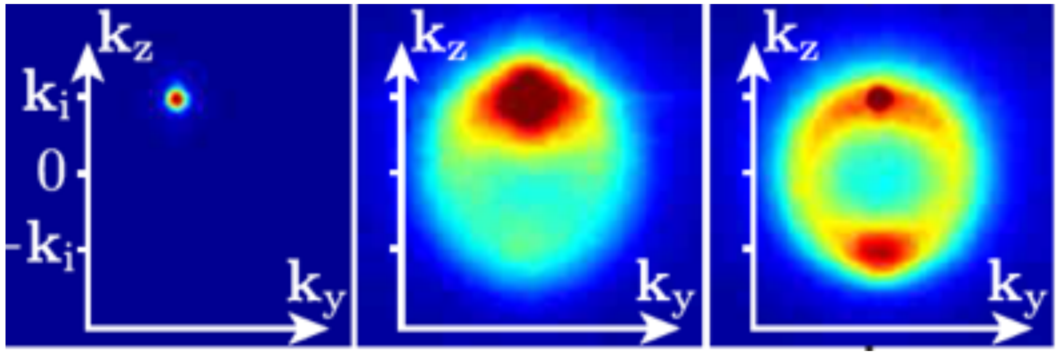


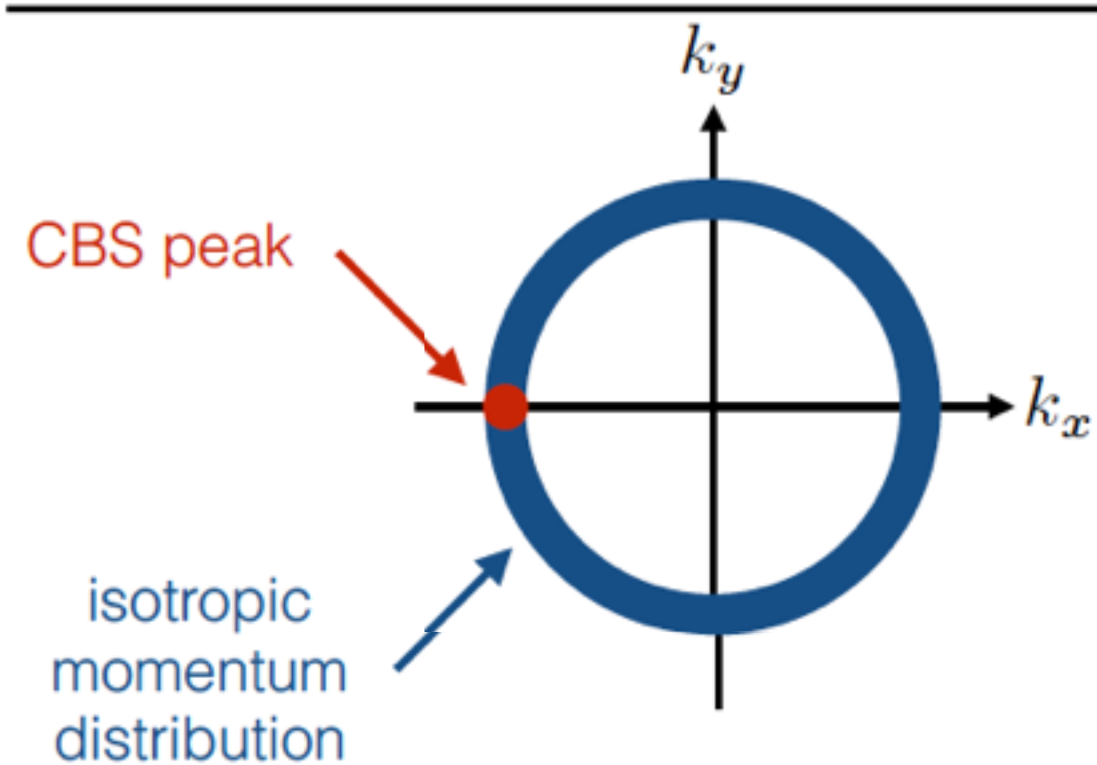
$$\Delta\theta_{CBS}(t) \propto \frac{1}{\langle|\vec{r}_1 - \vec{r}_2|\rangle} \propto \frac{1}{\sqrt{2Dt}}$$

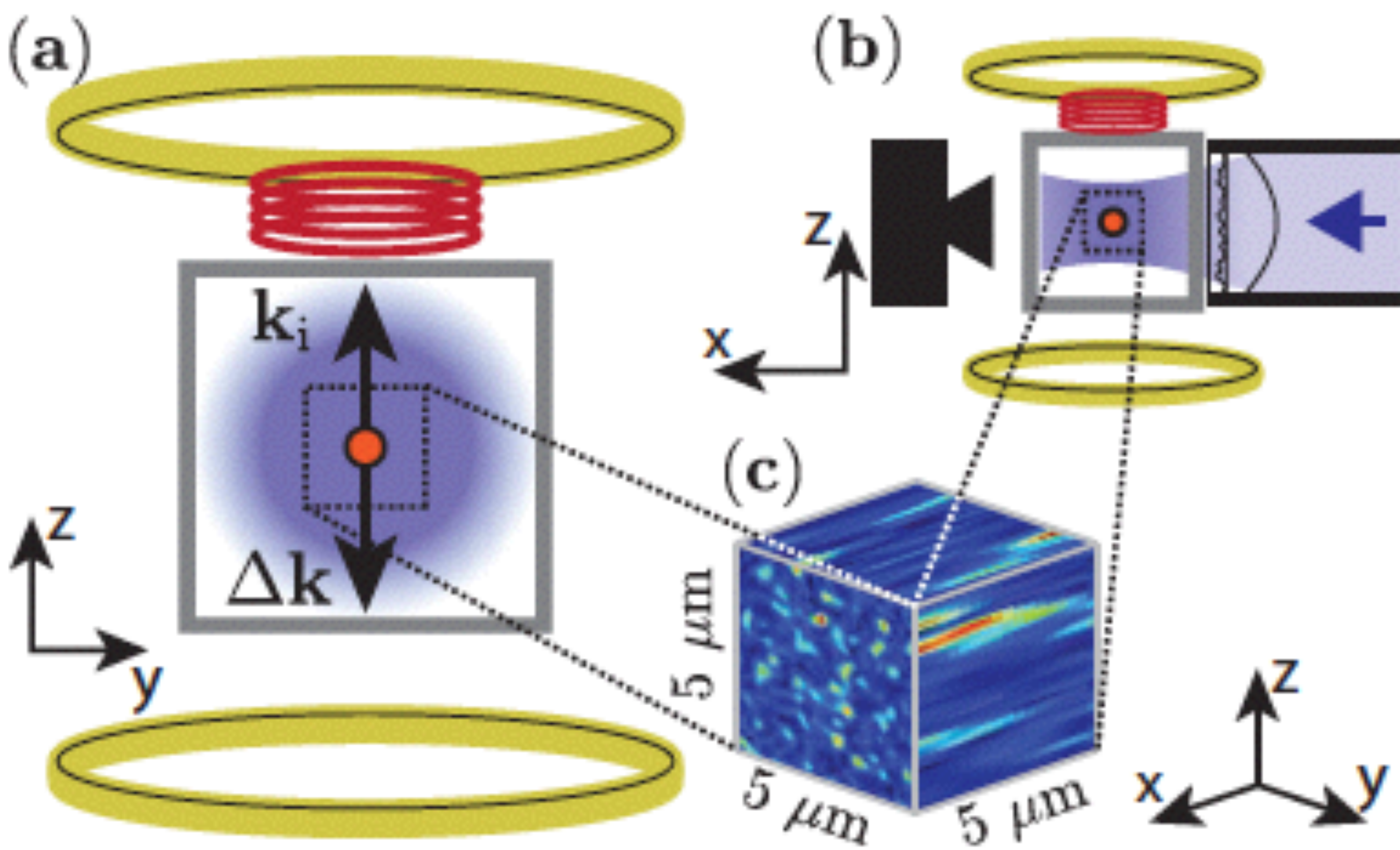


KILLING AND RECOVERING TIME REVERSAL SYMMETRY

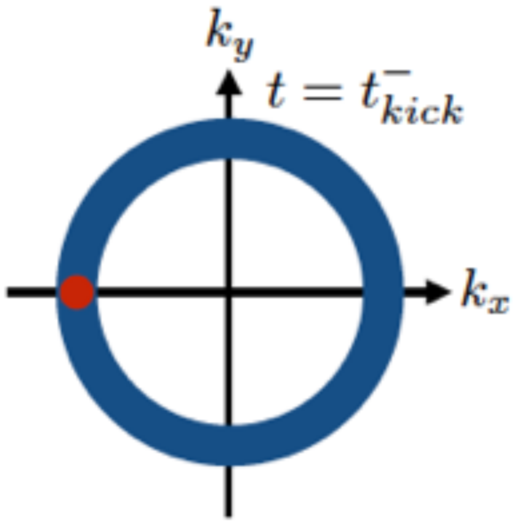
1 ms



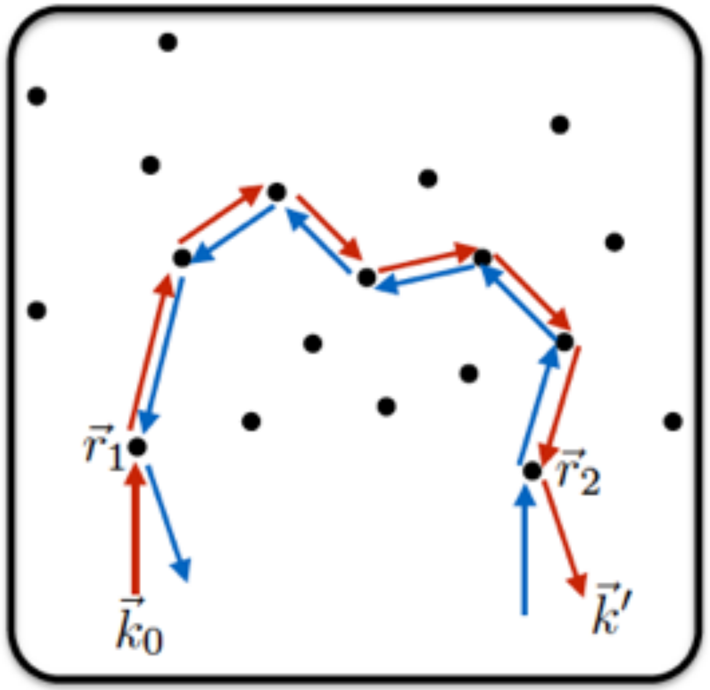


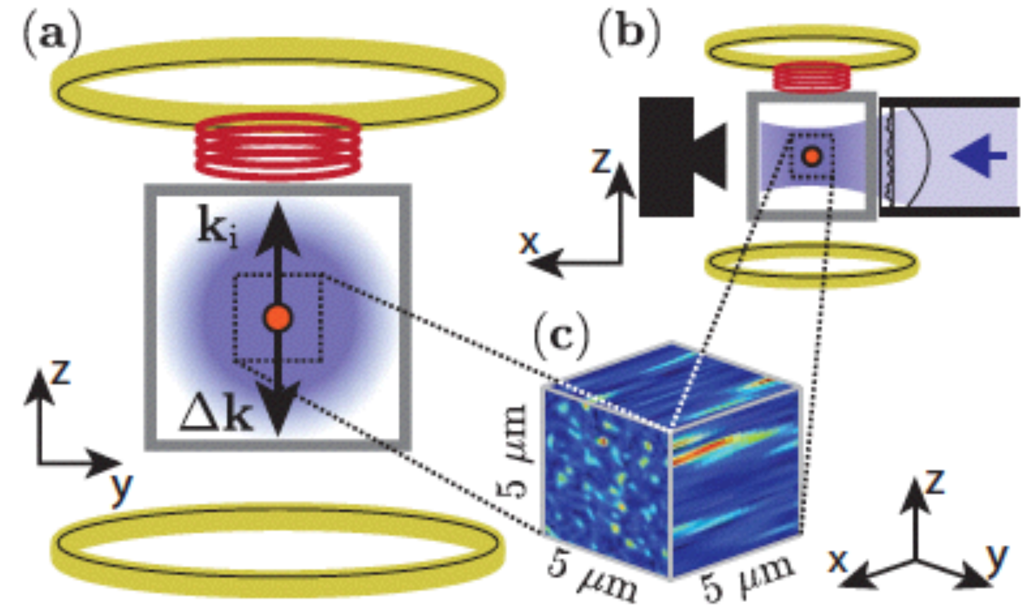


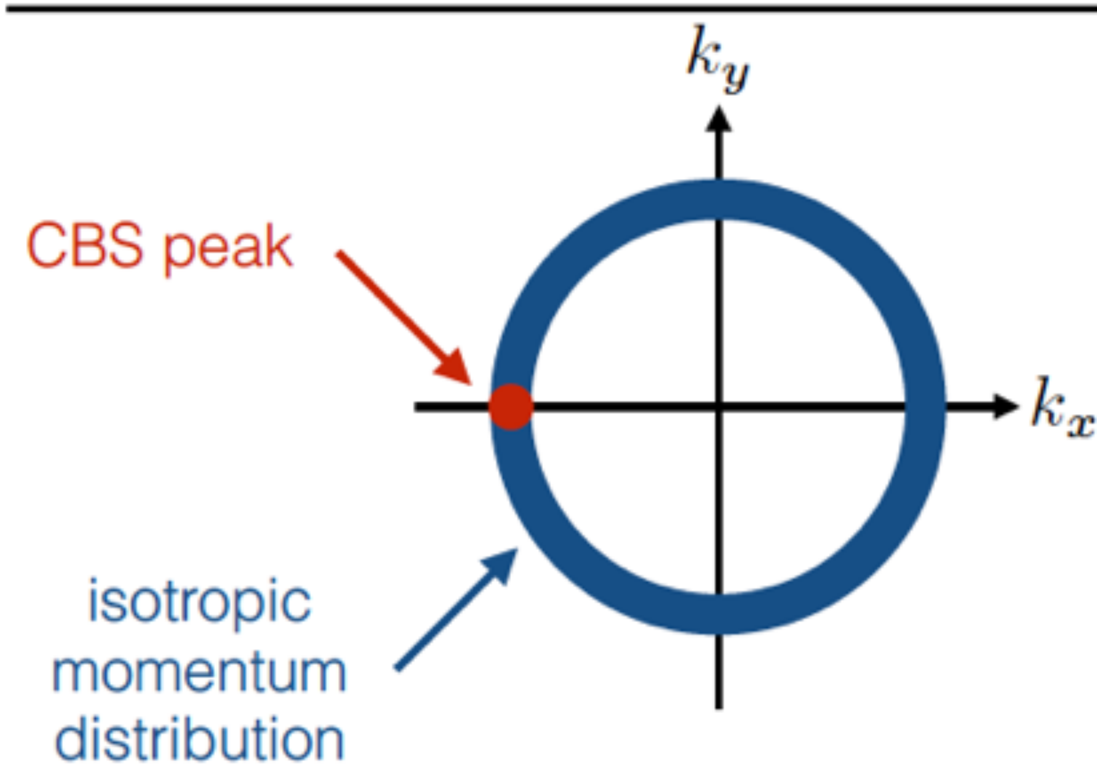
KILLING AND RECOVERING TIME REVERSAL SYMMETRY



just before the dephasing kick

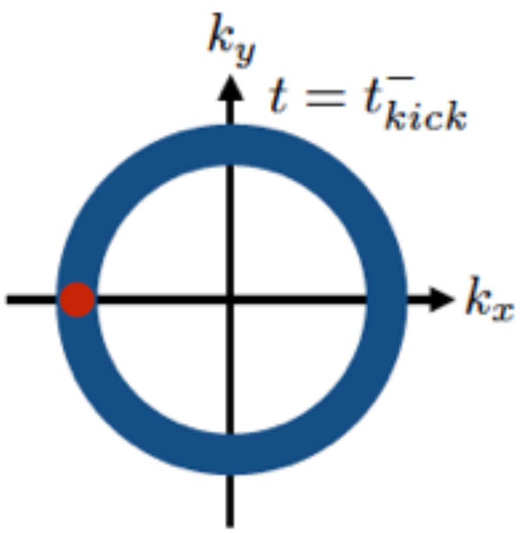




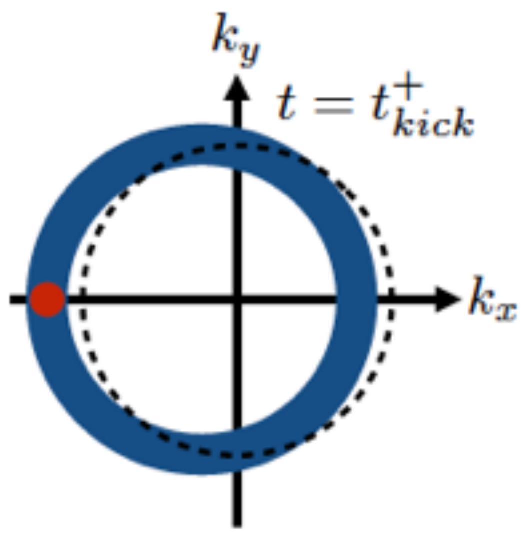


We have the normal CBS dynamics before we apply the dephasing kick.

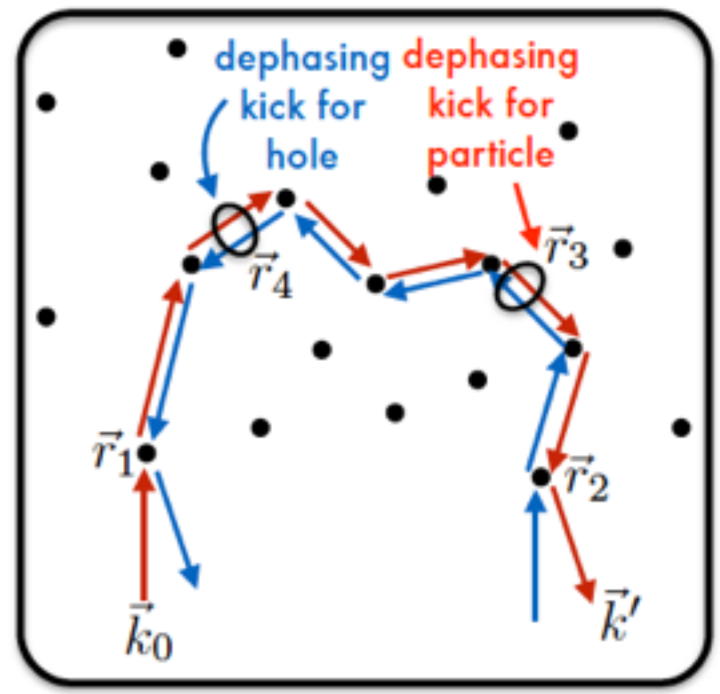
Killing and Recovering Time Reversal Symmetry

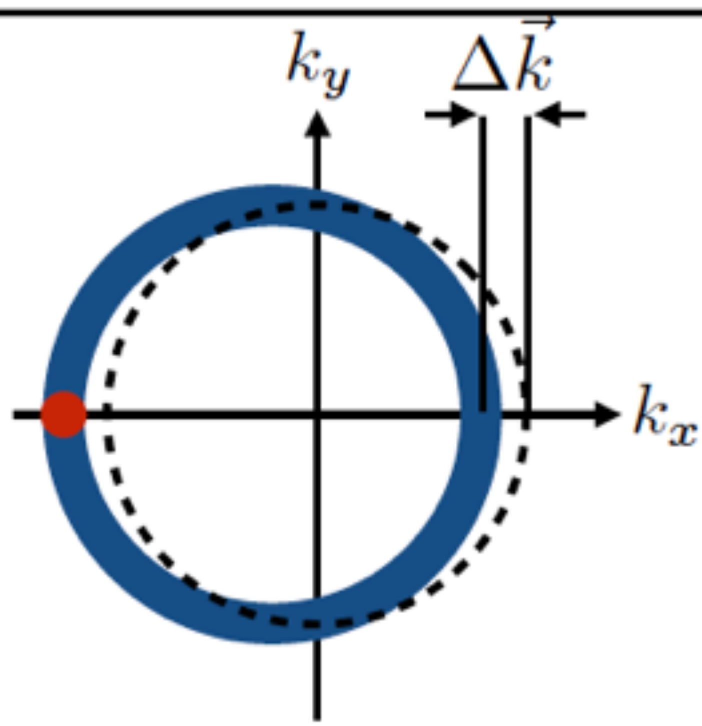


just before the dephasing kick



just after the dephasing kick

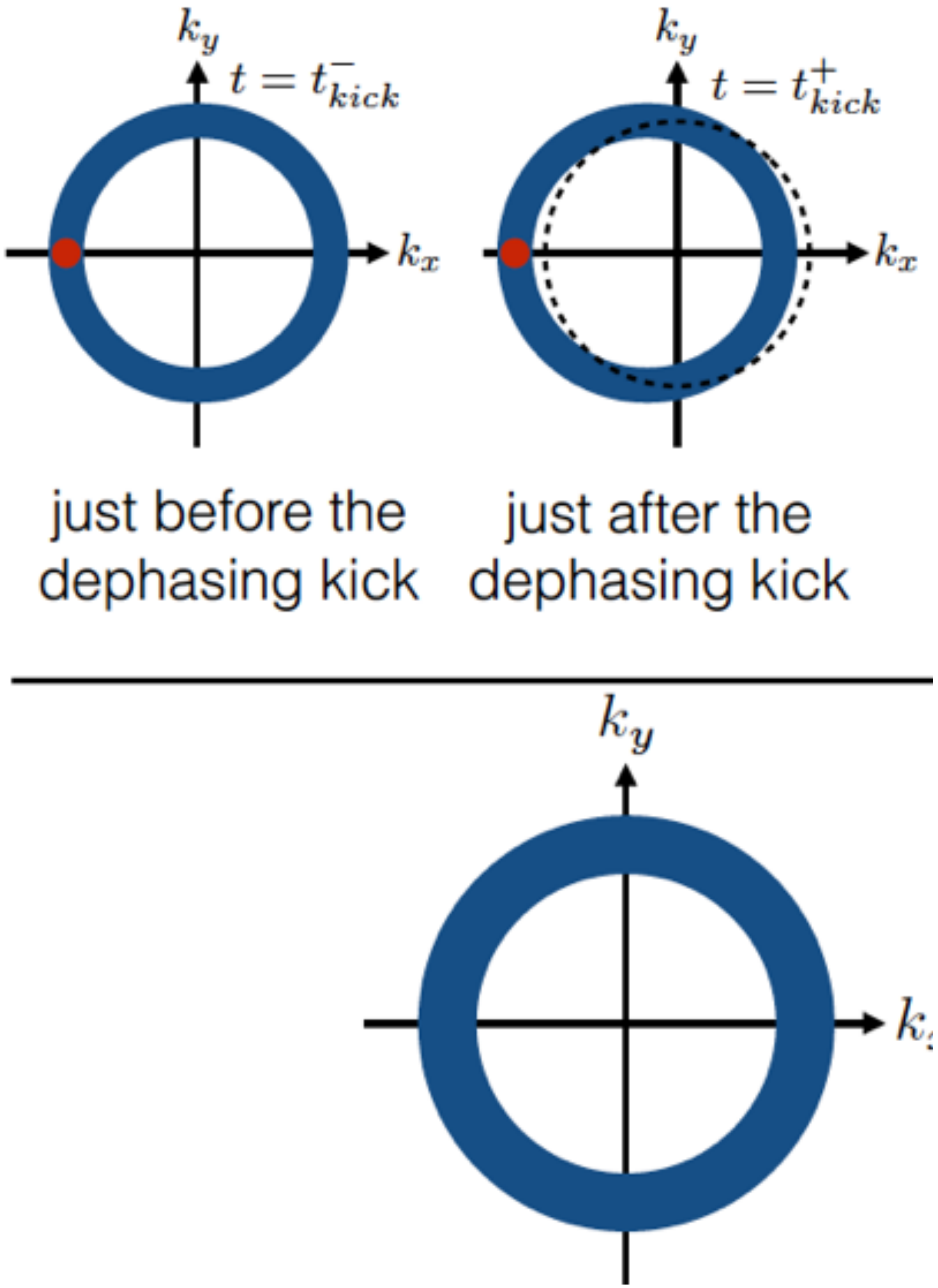


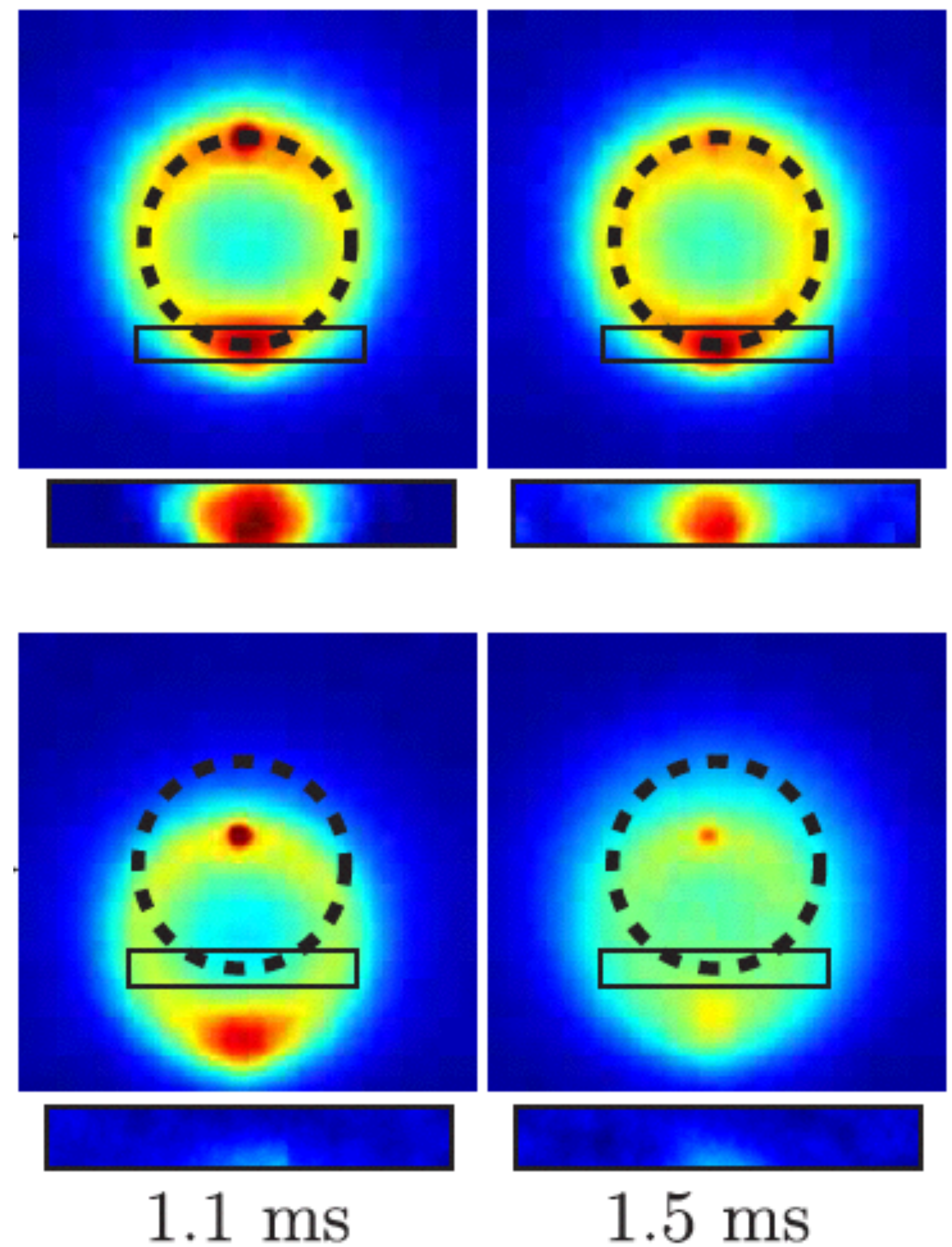


The magnetic gradient field gives a momentum $\Delta\vec{k}$ to the atoms.

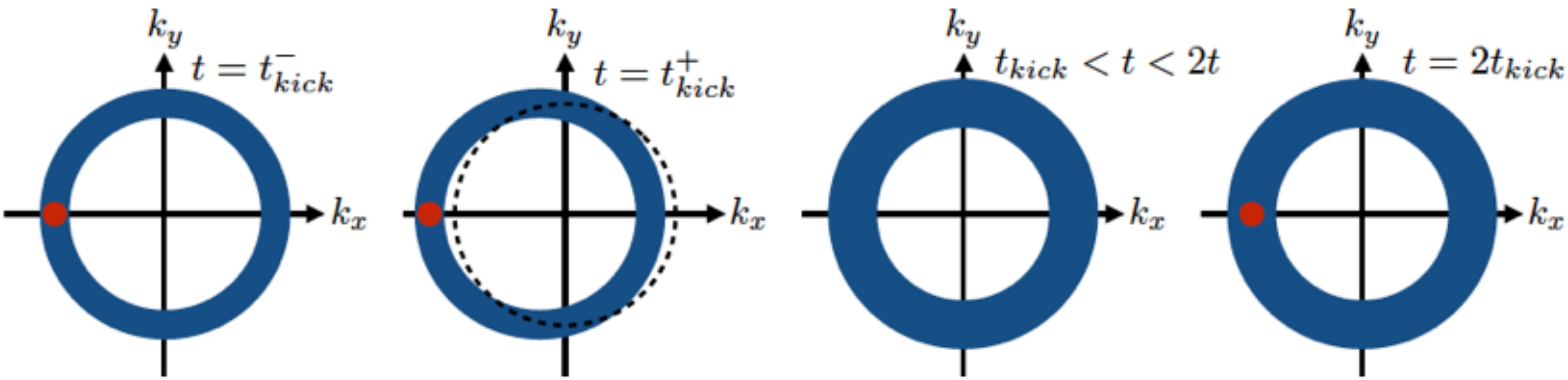
=> The whole momentum distribution is briefly shifted by $\Delta\vec{k}$.

Killing and recovering Time Reversal Symmetry





Killing and recovering Time Reversal Symmetry

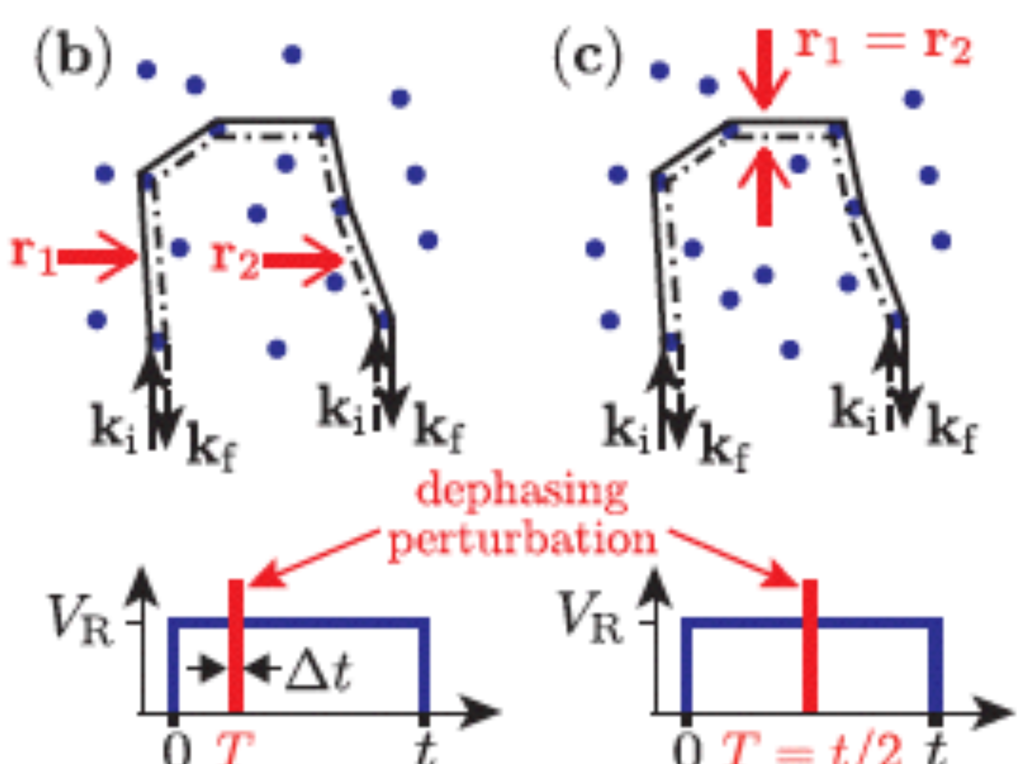


just before the dephasing kick

just after the dephasing kick

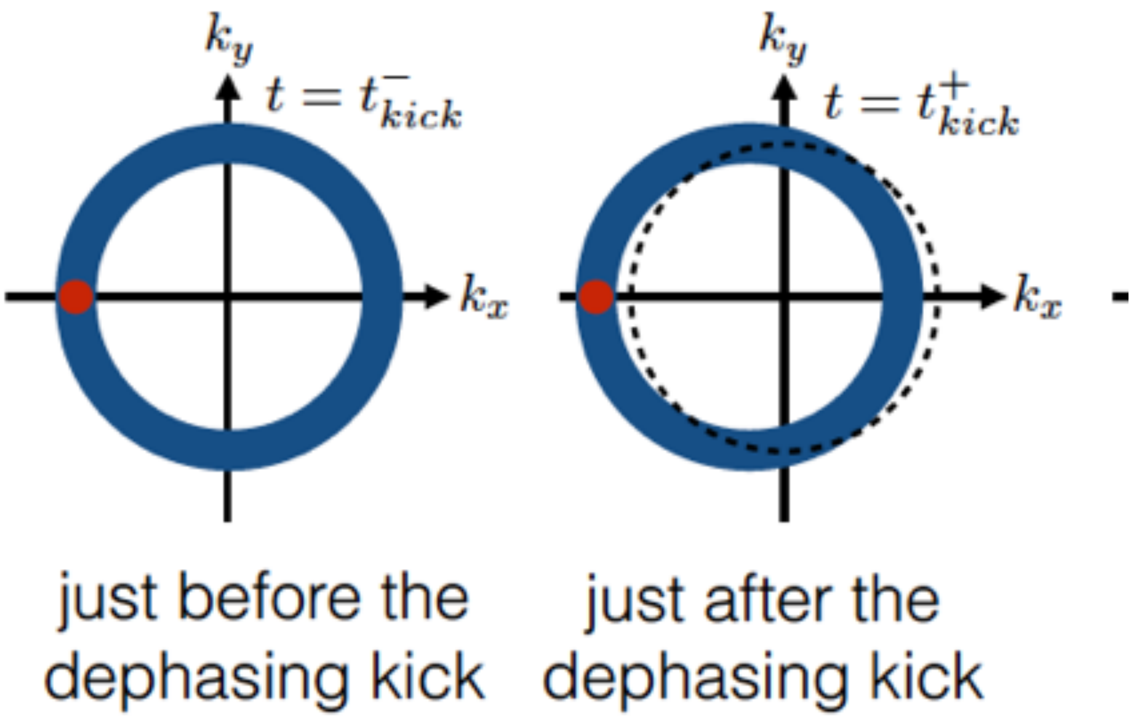
between dephasing kick and revival

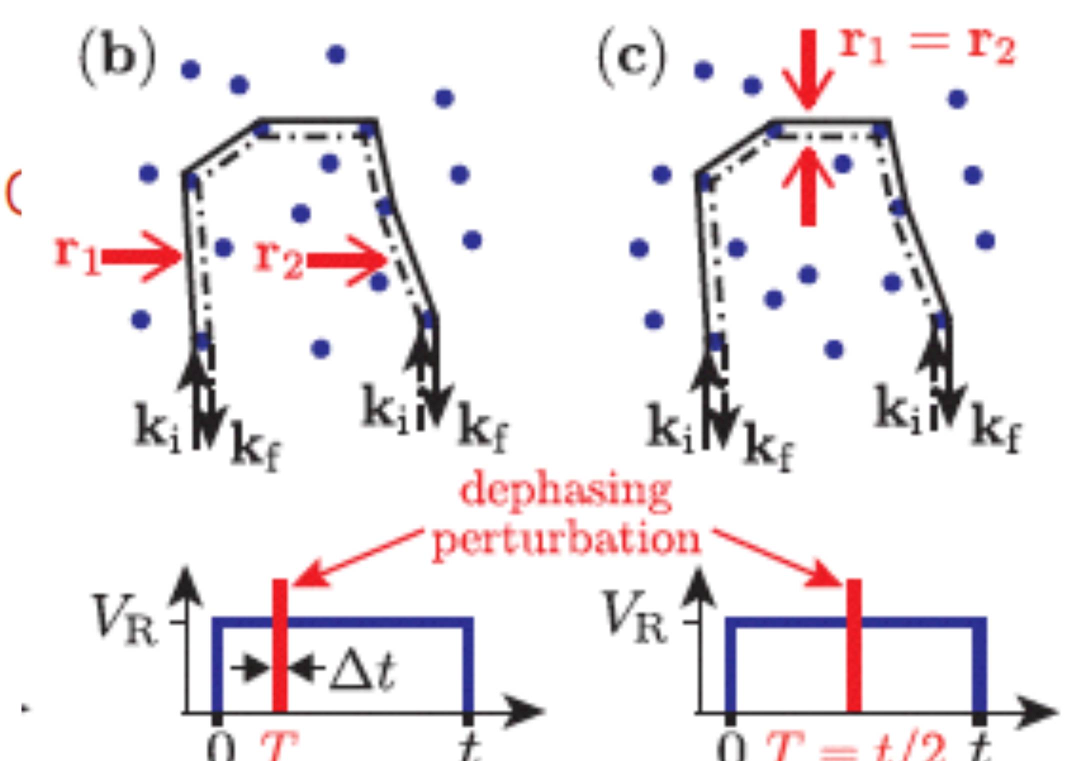
Revival of the coherent peak (CBSE)

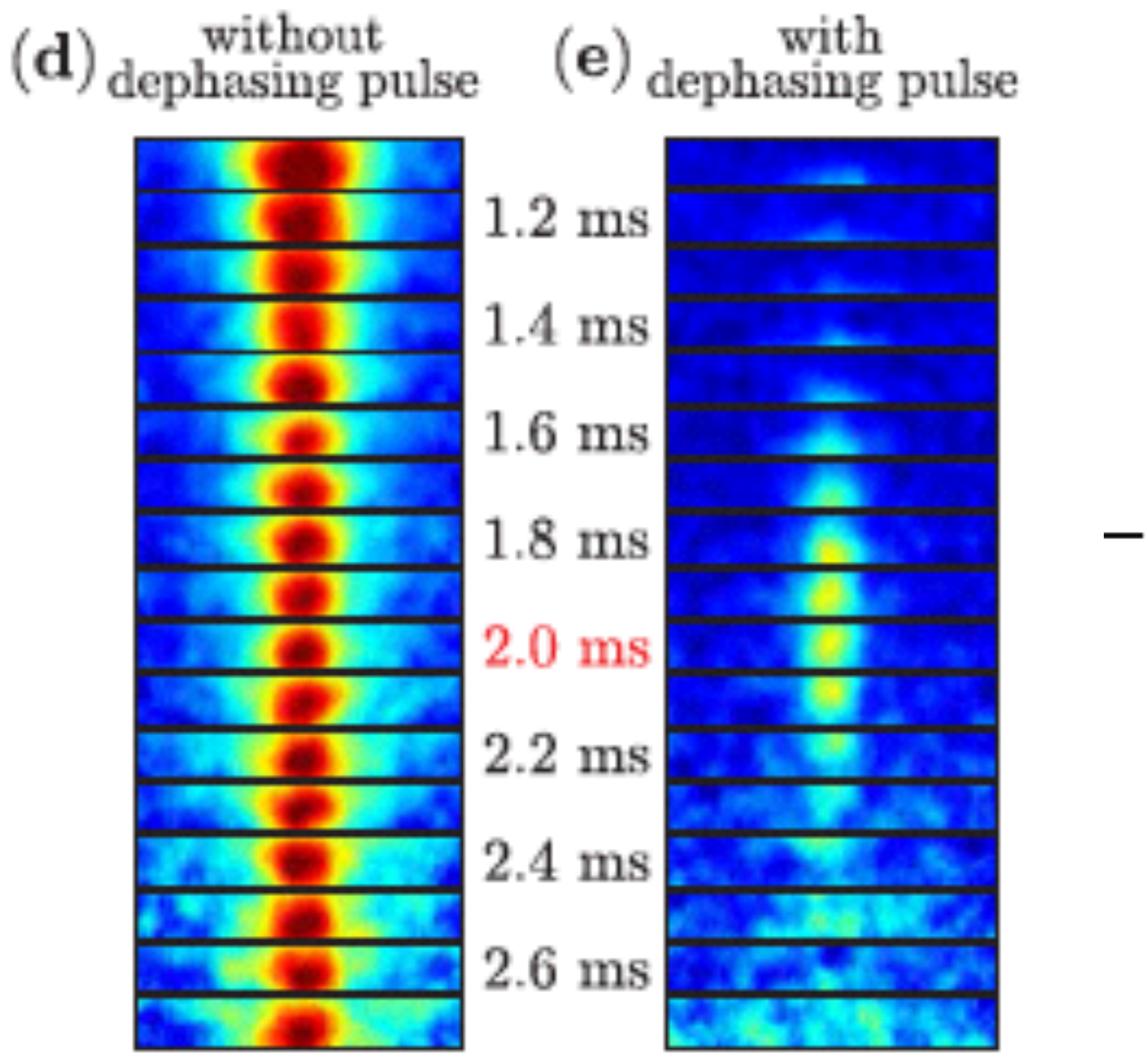


At a diffusion time of TDiff=2tkick time-reversal symmetry is briefly reestablished and the coherent peak reappears (CBSE).

KILLING AND RECOVERING TIME REVERSAL SYMMETRY







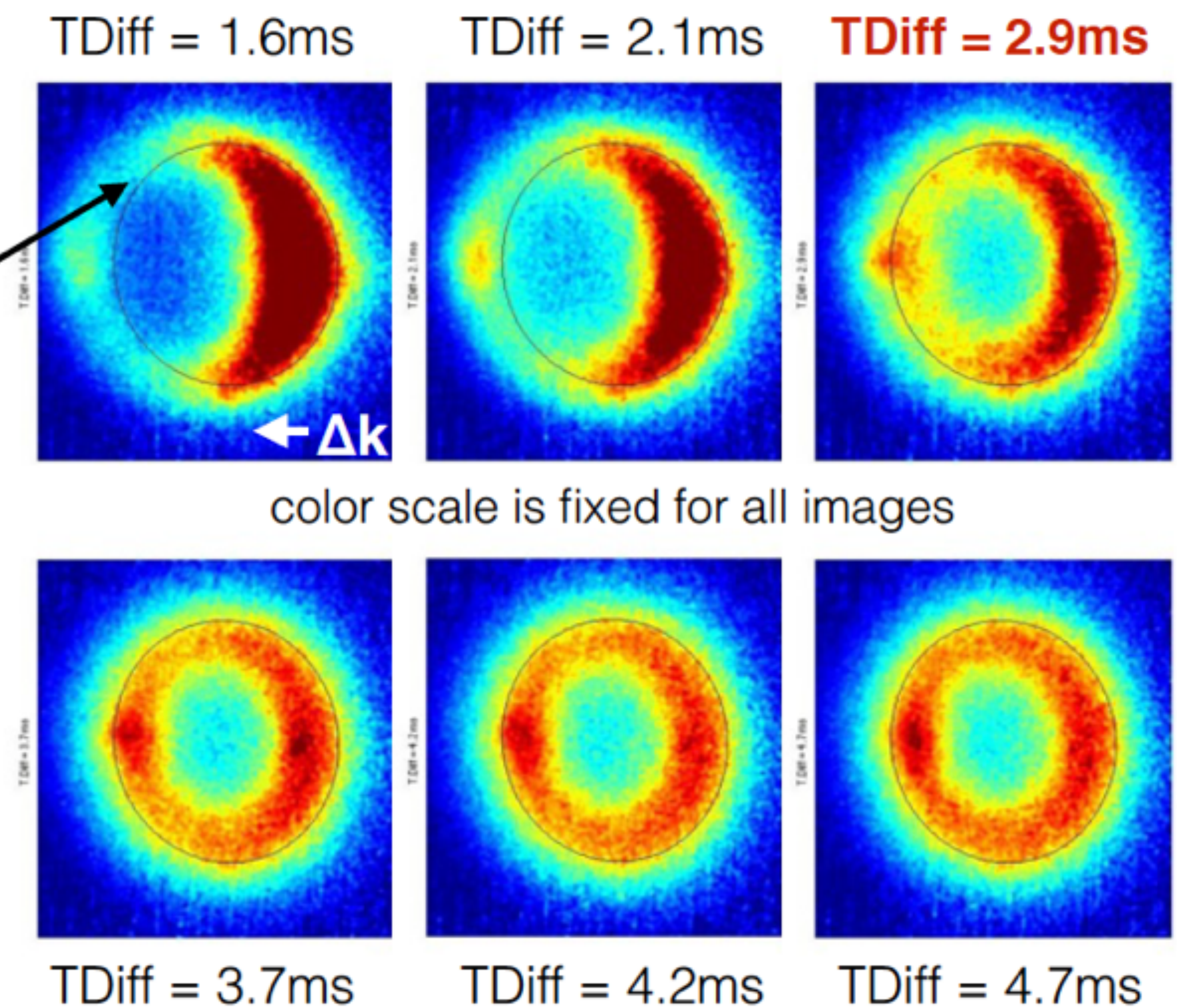
KILLING AND RECOVERING TIME REVERSAL SYMMETRY

Dephasing kick is applied at TDiff = 1.45ms
=> We expect the CBSE at **2.9ms**

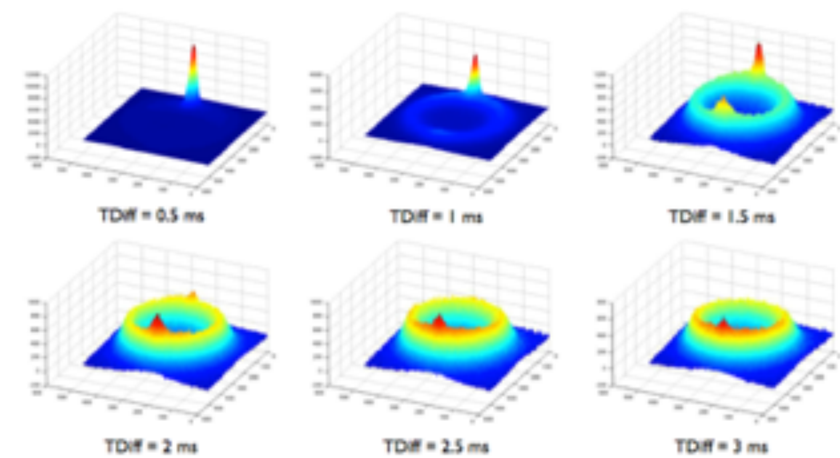
Thin black line marks the position of the ring without the dephasing kick.

Transport parameters for this configuration:

- $k_0\boldsymbol{\sigma} \approx 1.3$
- $\tau_S \approx 0.72$ms
- $\tau_B \approx 1.22$ms
- $k_0 \approx 3.76/\mu$m
- $\Delta k \approx k_0/3$
- $\Delta k\ l_B \approx 4.2$



Conclusions

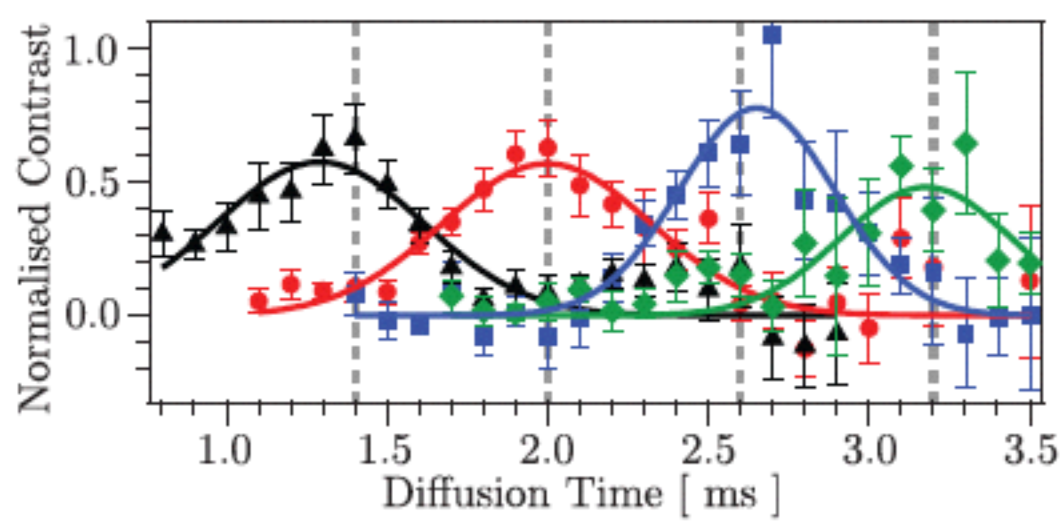


Observation of weak localisation

- Time resolved diffusion
- Time resolved CBS and weak localisation

Observation of TRS with ultra cold atoms in disorder

- It is possible to “kill” and “recover” the time reversal symmetry by changing the atomic trajectories.



Experiments performed in Palaiseau with **A. Aspect, V.Josse, P.B.**

K. Muller, J. Richard, V. Volchkov, V. Denechaud

New teams :

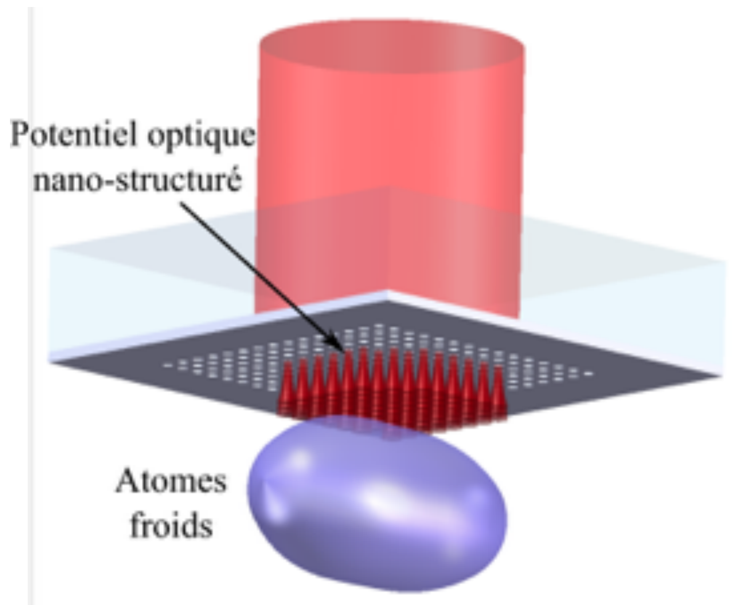
Cold atom in Bordeaux

P.B., S. Bernon, A. Bertoldi,

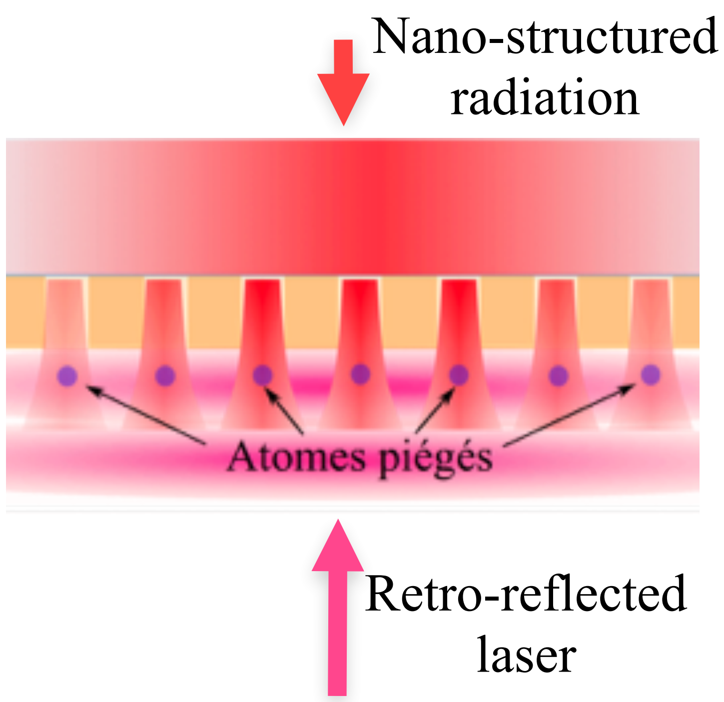
H. Vasquez, J. Zhang,

C. Busquet

Nano structured potentials



A new setup for new regime in 2D electron gas quantum simulation

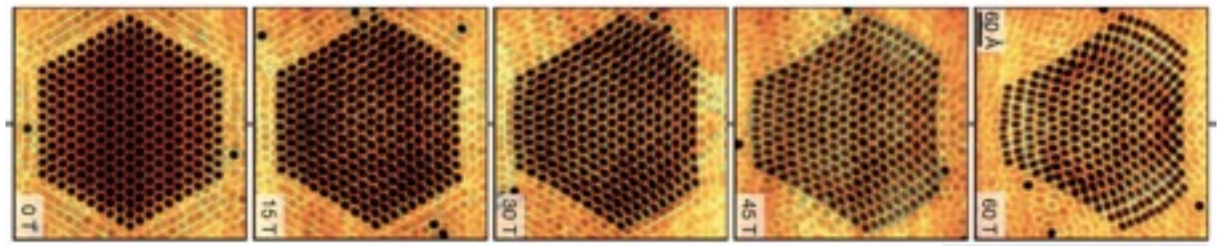


- Atome-surface interaction
  - Casimir Polder with nano-structured surfaces

- New geometry for the potential
  - hexagonal : graphene including on demand impurities
  - triangular : Spin liquid physics
  - *exotic : topological insulators*

- High energy physics : quantum anti-ferromagnetism

- From graphene to a topological insulator



Nature 483, 308 (2012)

<u>Collaboration :</u> *J.Cayssol*

Thank you

you are welcome to joint us in Bordeaux