Simulating quantum transport with atoms and light

Philippe Bouyer

▶ **To cite this version:**

Philippe Bouyer. Simulating quantum transport with atoms and light. HYBRID QUANTUM SYSTEMS: NEW PERSPECTIVES ON QUANTUM STATE CONTROL, May 2010, Heidelberg, Germany. hal-00502398

HAL Id: hal-00502398
https://hal.science/hal-00502398

Submitted on 14 Jul 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

INSTITUT d'OPTIQUE GRADUATE SCHOOL

Simulating quantum transport with atoms and light

P. BOUYER

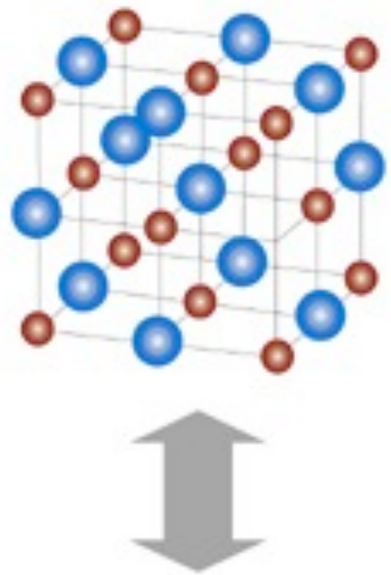
Laboratoire Charles Fabry de l'Institut d'Optique
Palaiseau, France

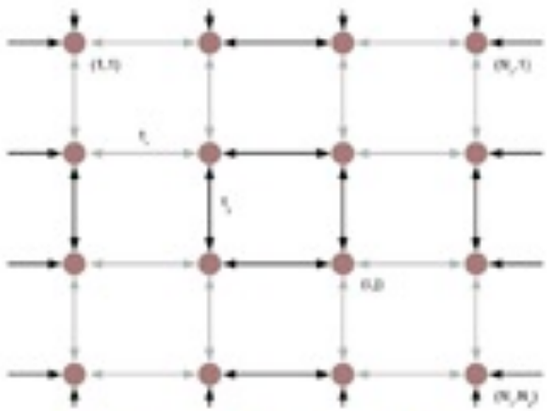
Physics Department, Stanford University

Stanford, USA

«Quantum simulators» : building a controllable quantum system to simulate other quantum systems.

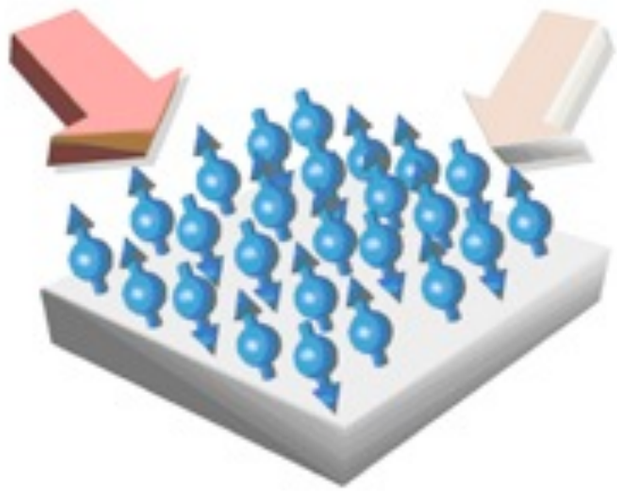
Quantum system





Simplified model

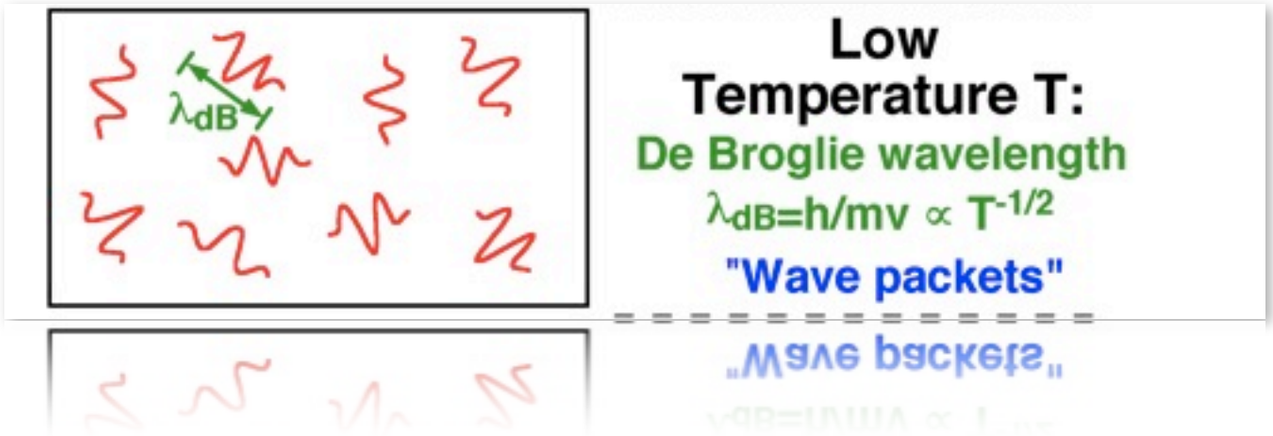
toy-model of the magnified lattice structure of a "solid"



Controllable quantum system =

Quantum Simulator

USING COLD ATOMS AND LIGHT FIELDS

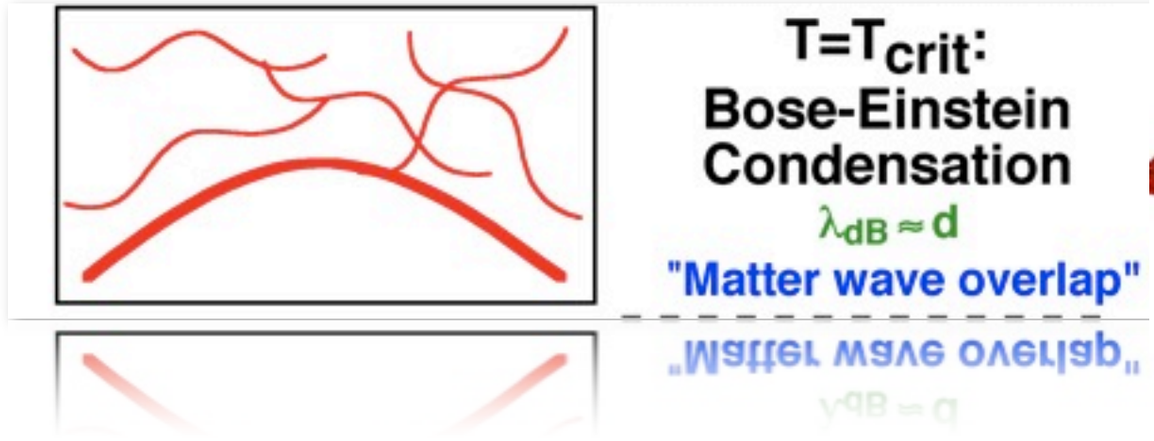


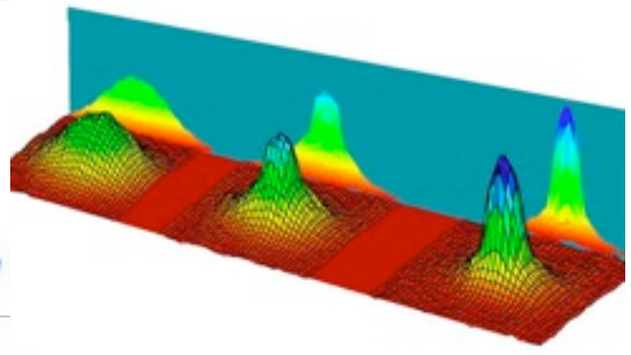
Atoms cooled below 1 μK

Distribution of particles with velocities around mm/s

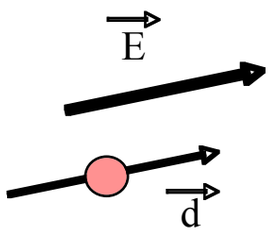
Distribution on matter waves with de Broglie wavelength ≈ 1 μm

Degenerate gases



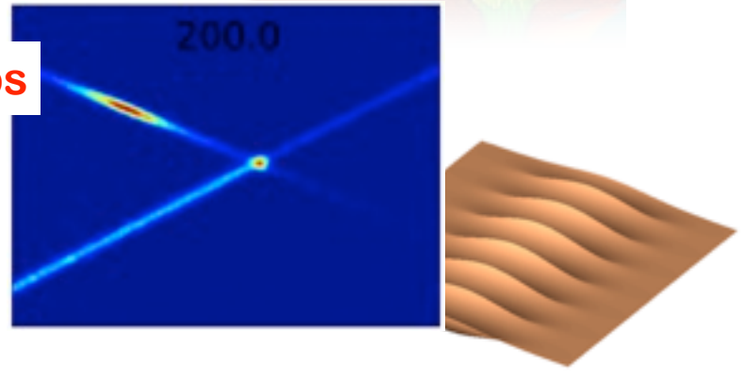


- Non-dissipative potentials made with light
  - No photon scattering (coherent)
  - Dispersive (dephasing) part of radiative force



$$U = -\mathbf{d}\cdot\mathbf{E} = -\alpha(\omega)E^2$$

Optical traps



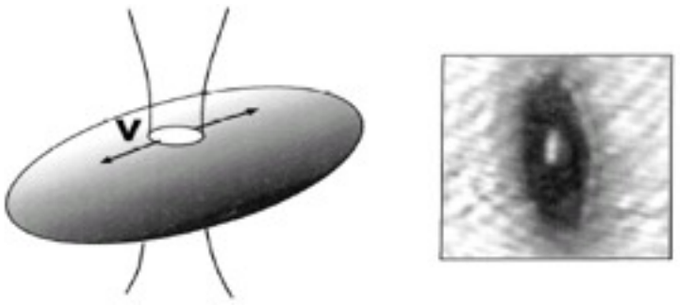
INSTITUT d'OPTIQUE GRADUATE SCHOOL

CONDENSED MATTER AND DEGENERATE GASES

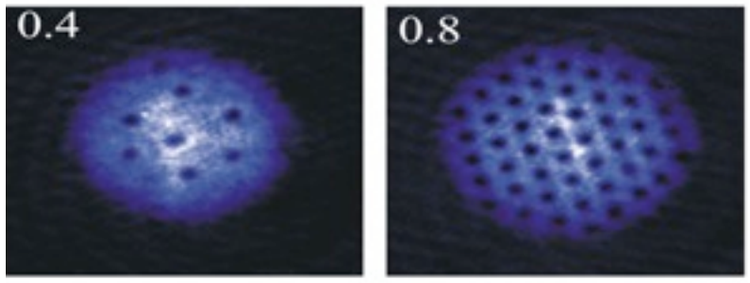
UNIVERSITÉ PARIS-SUD 11

IFRAF

Superfluidity



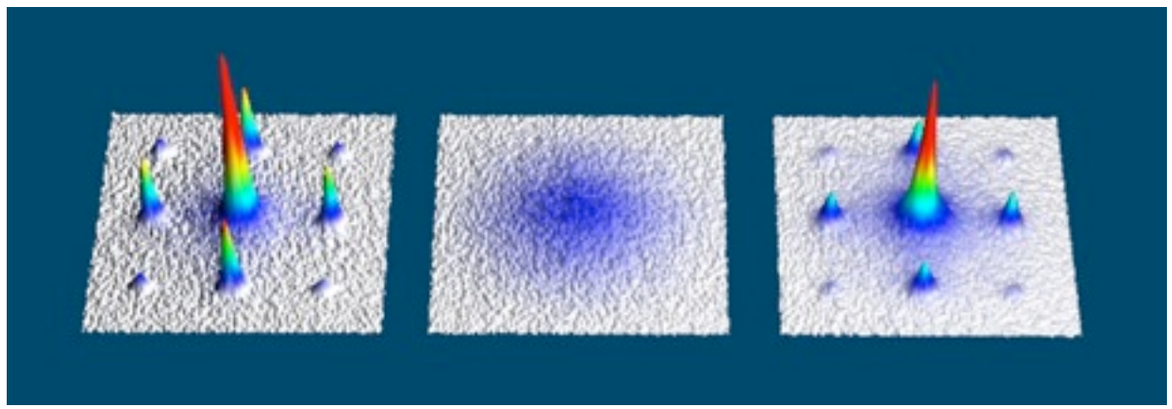
C. Raman et al., PRL. **83**, 2502-2505 (1999).



Degenerate mixtures (bosons,fermions).

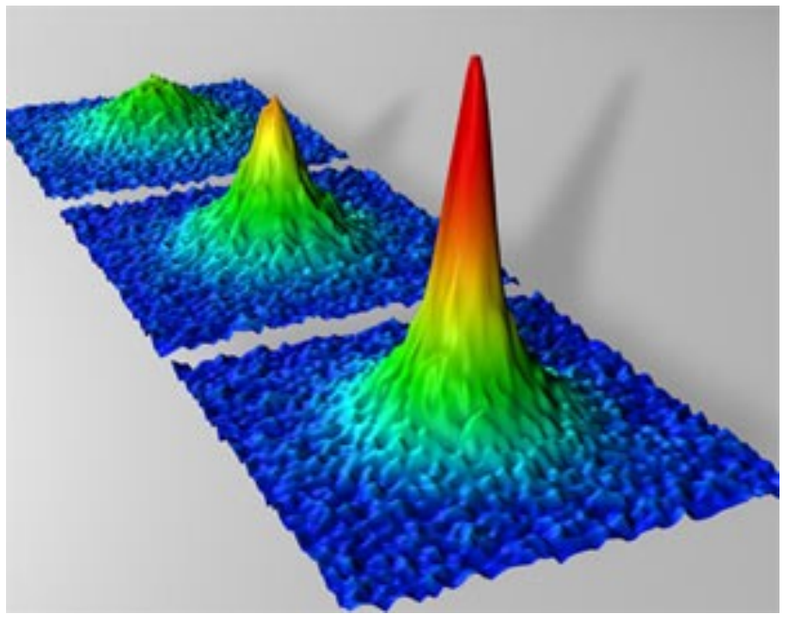
Controllable configurations and interactions

Mott transition



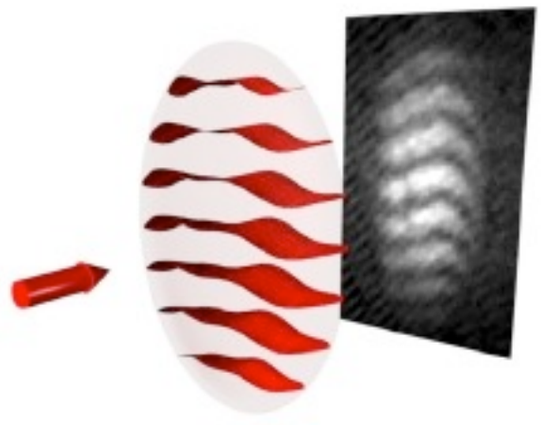
M. Greiner et al.,
Nature **415**, 39-44, 2002

BEC-BCS crossover



C.A. Regal & D.S. Jin.,
PRL **90**, 230404, 2003

BKT transition



Z. Hadzibabic et al.,
Nature **441**, 1118-1121 (2006)

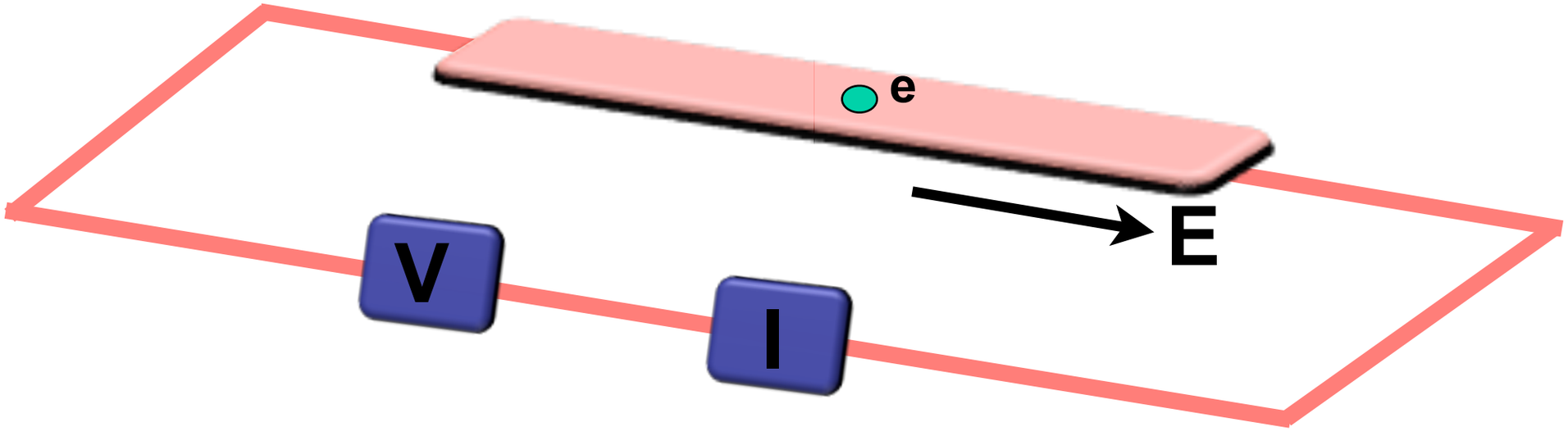
INSTITUT d'OPTIQUE GRADUATE SCHOOL

SIMULATION OF CONDENSED MATTER PHYSICS

UNIVERSITÉ PARIS-SUD 11

IFRAF

One of the key topics in condensed matter physics is to study the response of electrons to an electromagnetic field

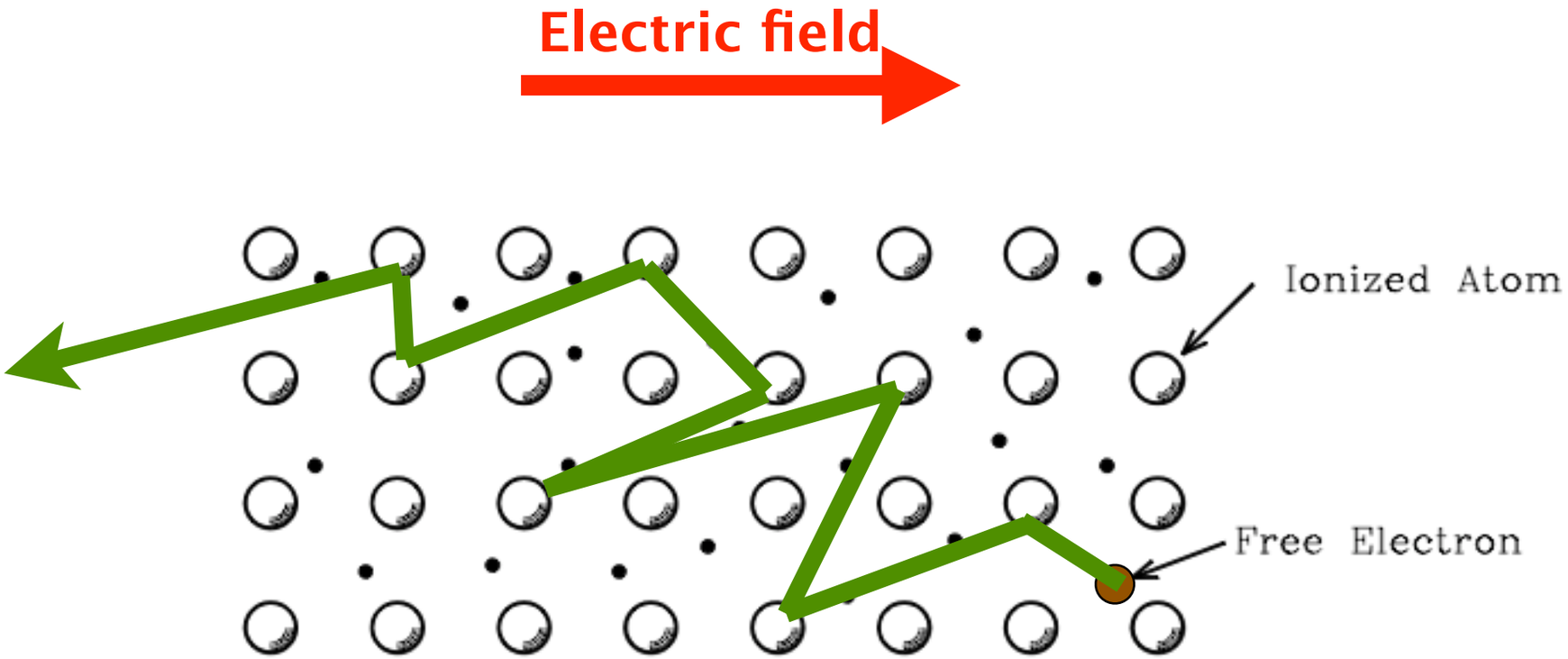


Can we simulate transport and conduction of electrons with atoms.

What is the role of disorder ...

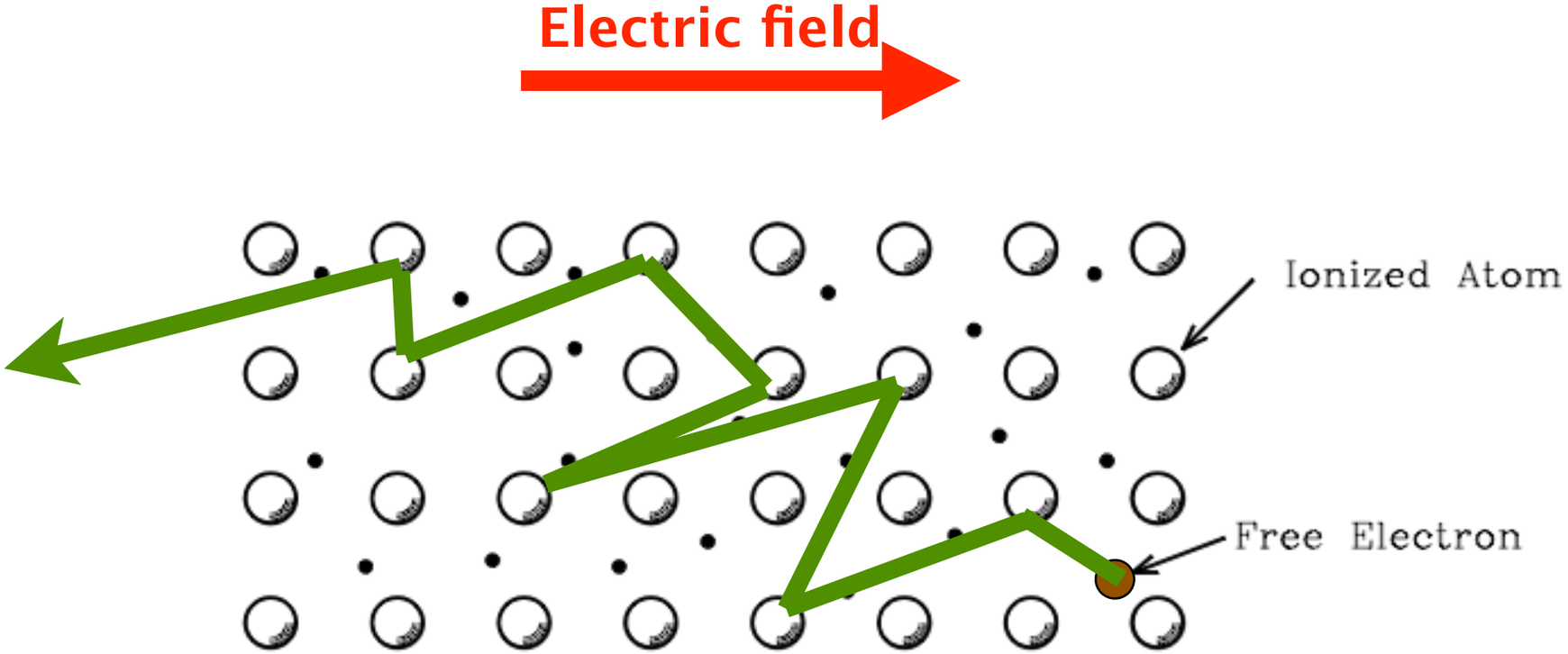
ELECTRONIC CONDUCTION

In a perfectly ordered metal



Diffusive transport caused by scattering on lattice defects (Drude model)

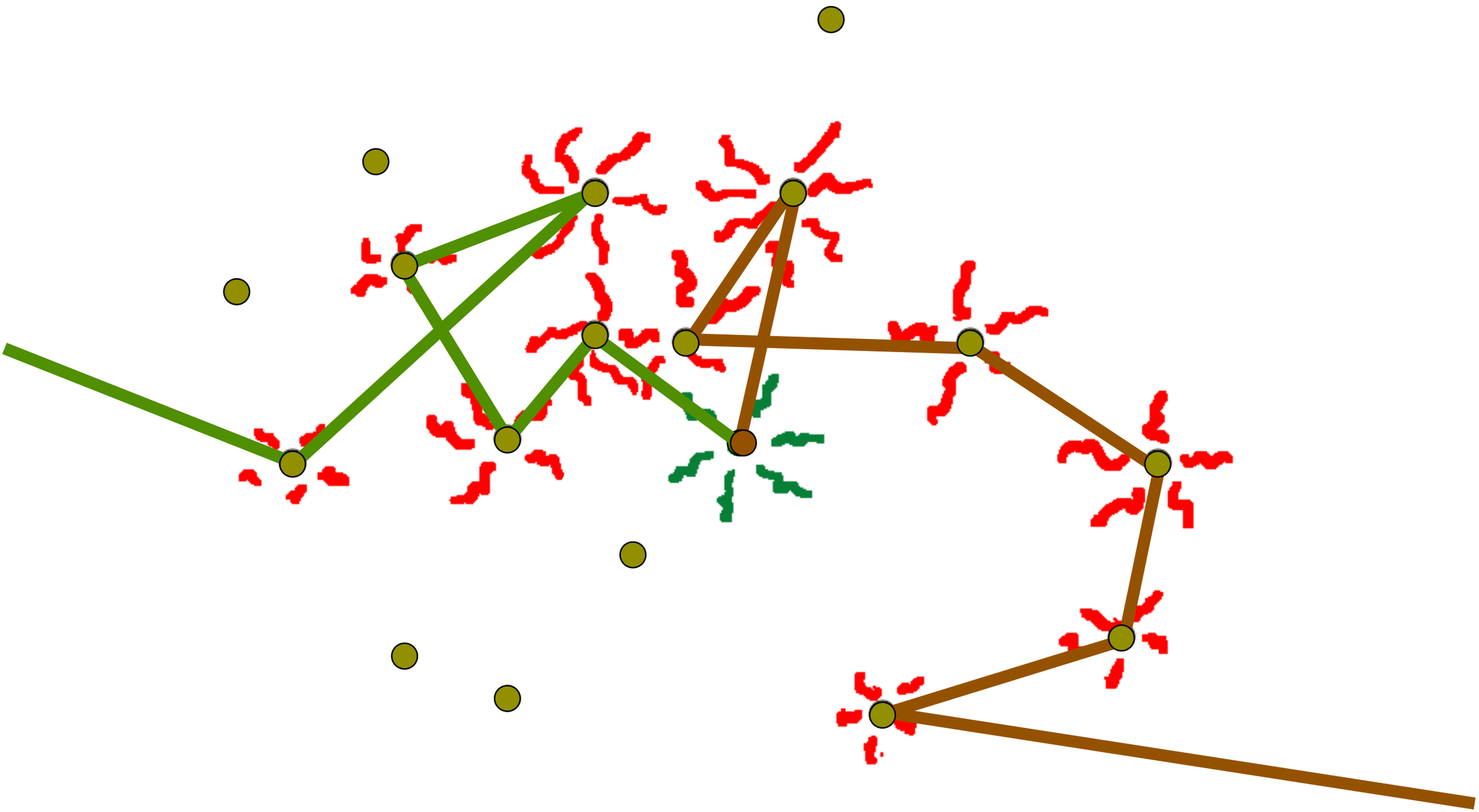
In a perfectly ordered metal



Diffusive transport caused by scattering on lattice defects (Drude model)

Thermal excitation increases diffusion = reduced conductivity

CLASSICAL TRANSPORT THROUGH IMPURITIES

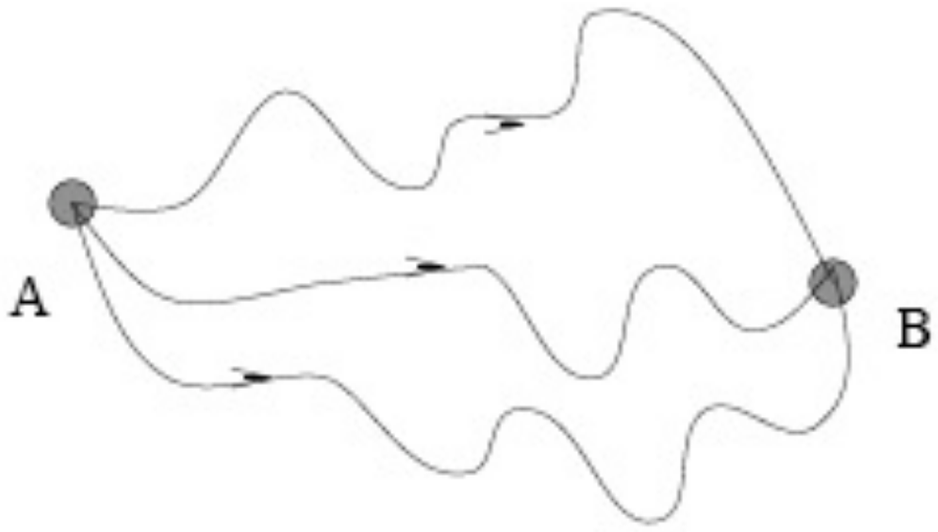


Waves but no coherence bouncing on impurities = diffusion

QUANTUM TRANSPORT

If the length scales become small compare to the de Broglie wavelength and/or the phase coherence length, then quantum mechanics will rule the transport properties.

The probability for a particle to go from point A to point B is the sum of the amplitudes of all possible trajectories.



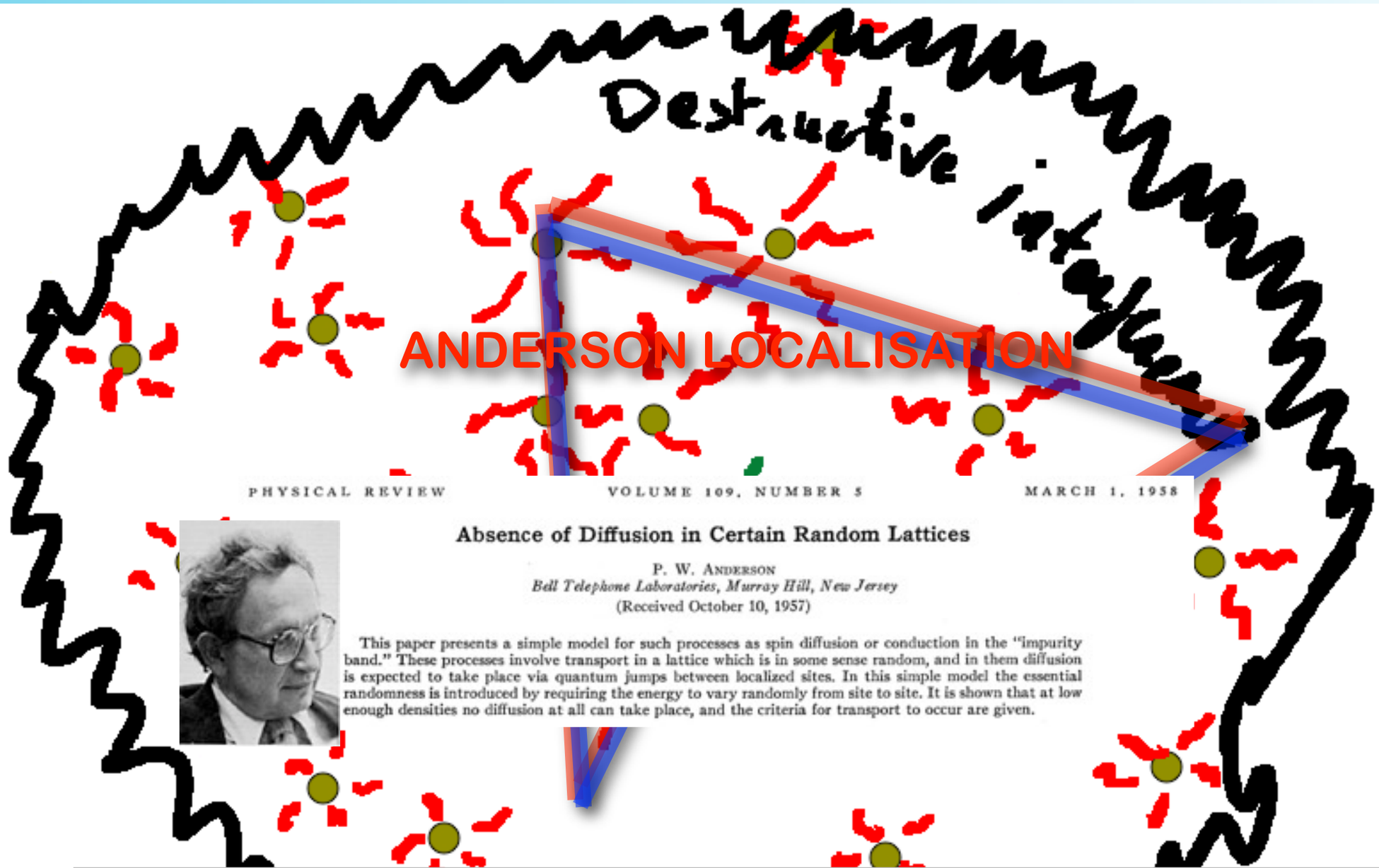
Interference terms can appear and the transport properties can be modified

INSTITUT d'OPTIQUE GRADUATE SCHOOL

QUANTUM TRANSPORT THROUGH IMPURITIES

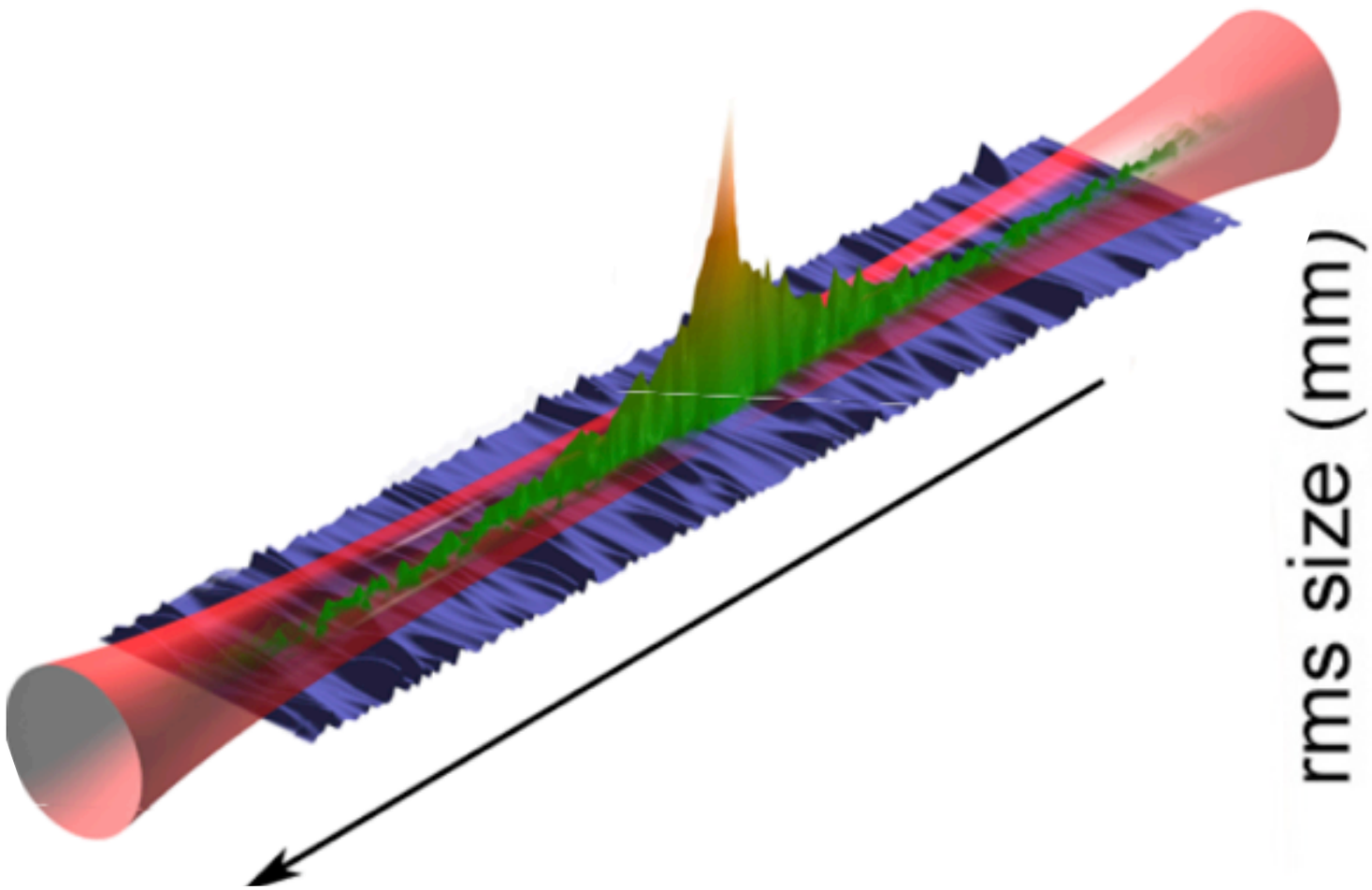
UNIVERSITÉ PARIS-SUD 11

IFRAF



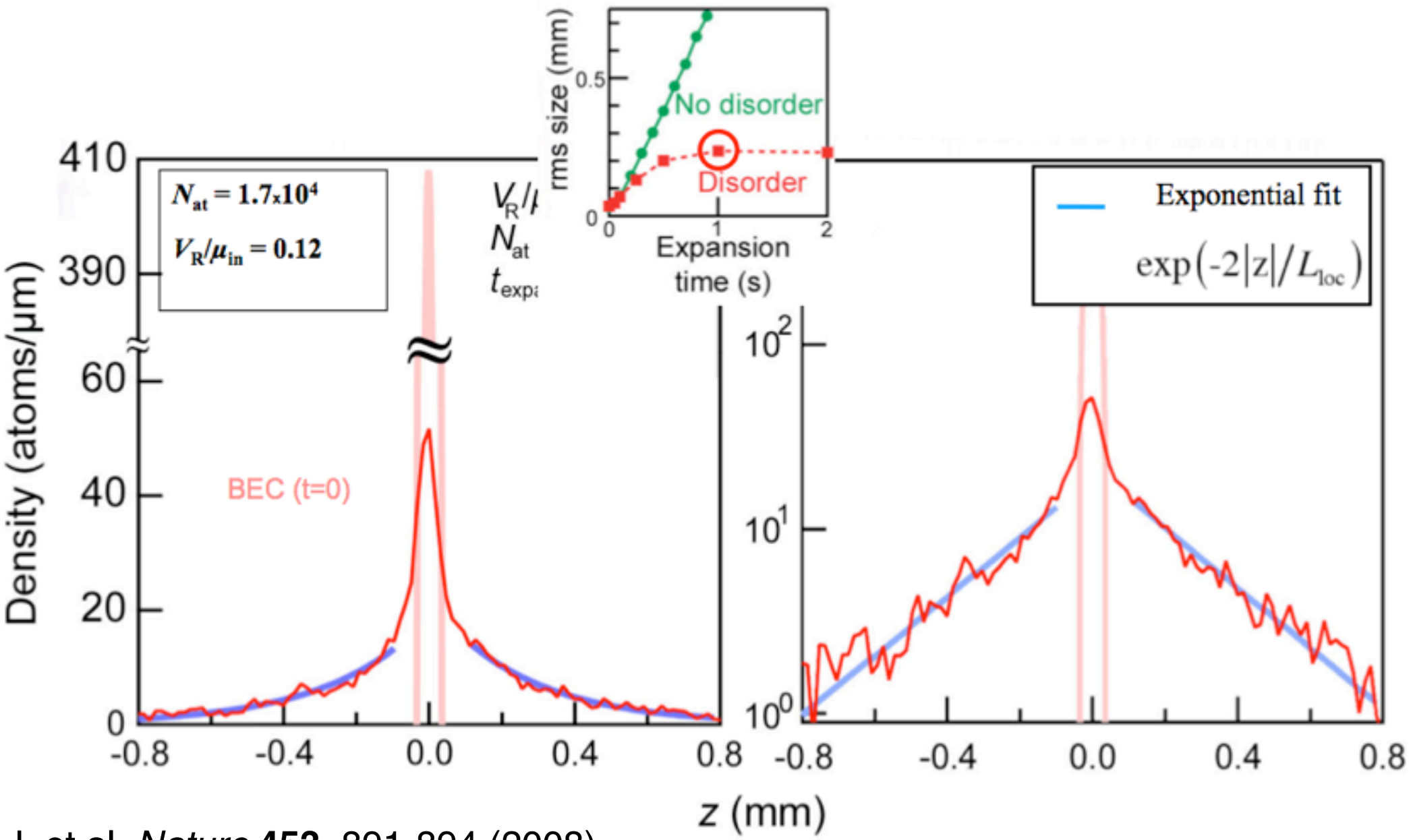
If mean free path smaller than de Broglie wavelength: constructive interference of trajectories returning to origin: localized states: insulator

1D BEC EXPANDING IN AN OPTICAL GUIDE



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

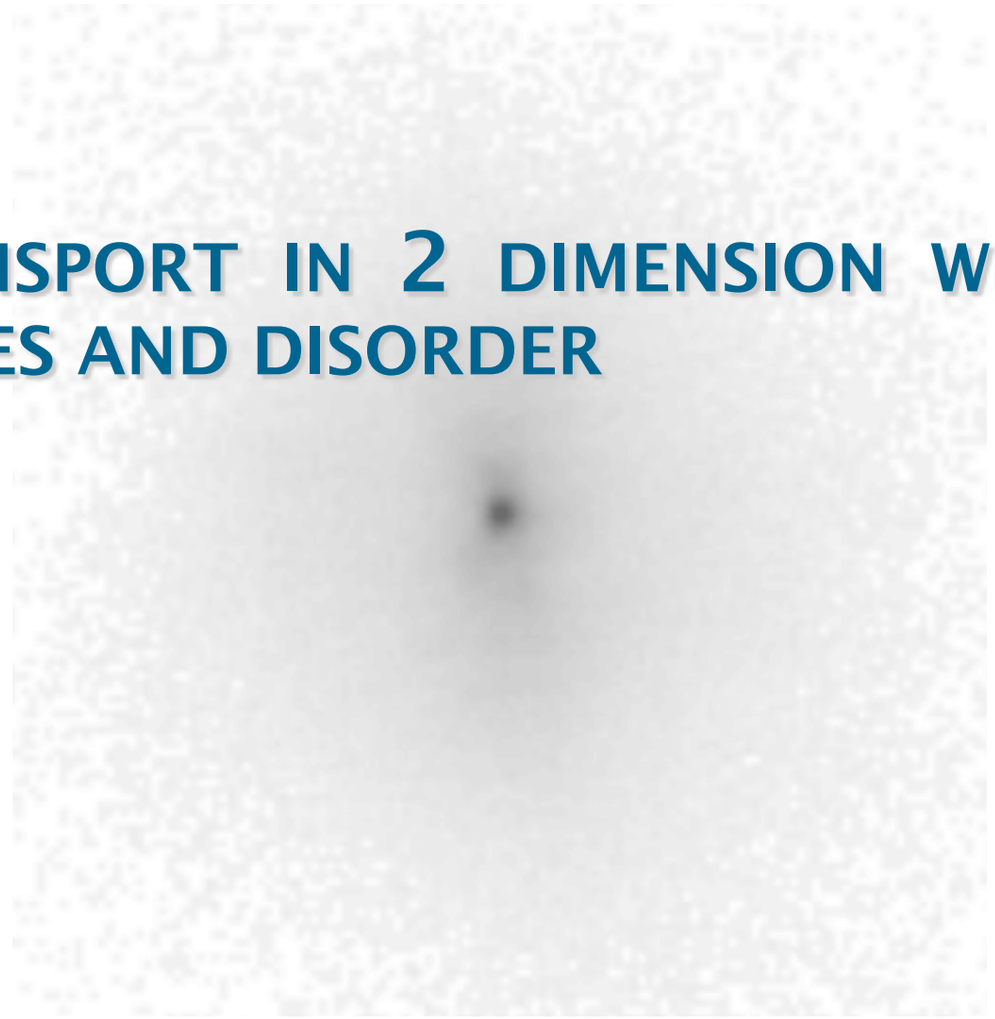
OBSERVATION OF LOCALISED WAVEFUNCTION



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

INSTITUT d'OPTIQUE GRADUATE SCHOOL

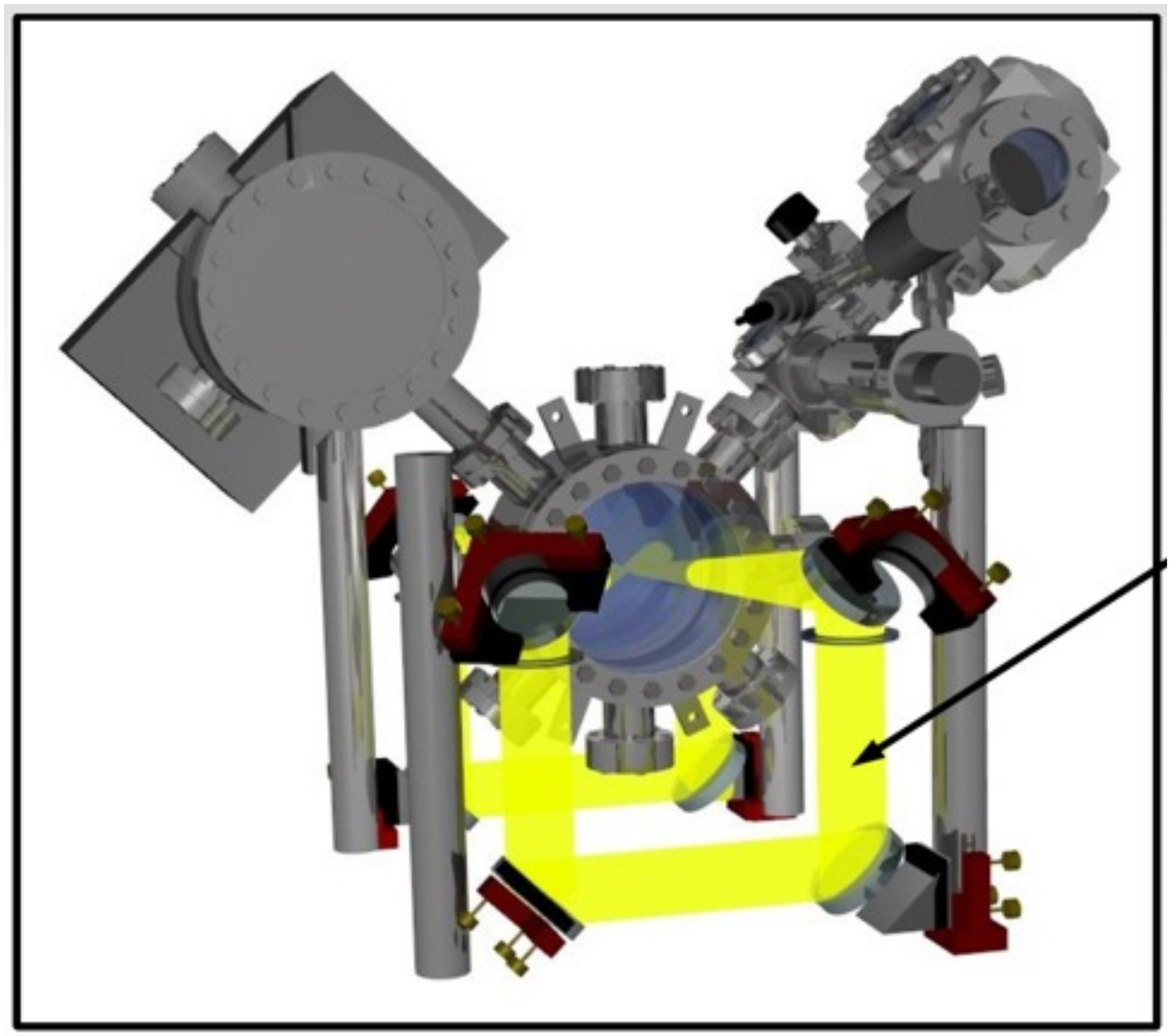
TRANSPORT IN 2 DIMENSION WITH MATTER WAVES AND DISORDER

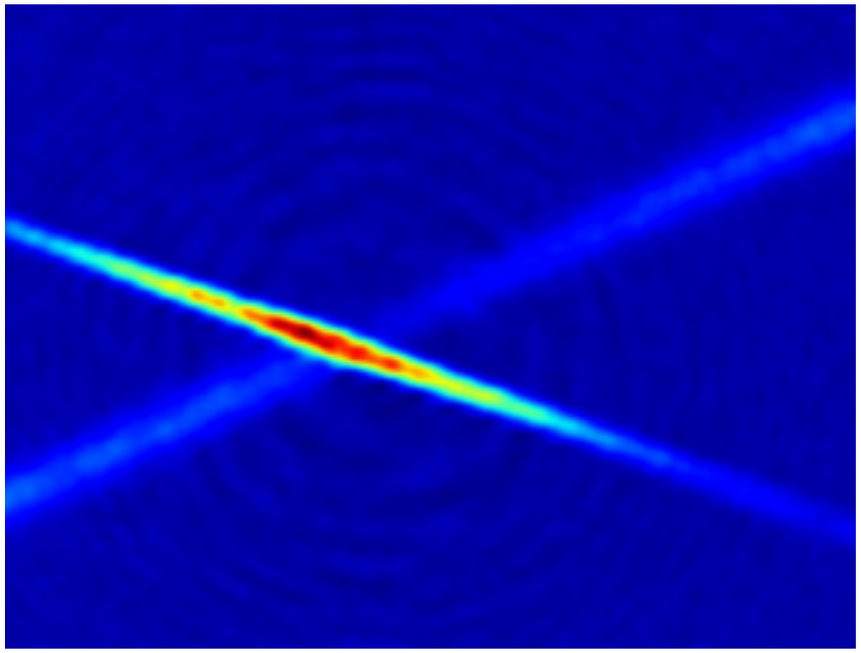


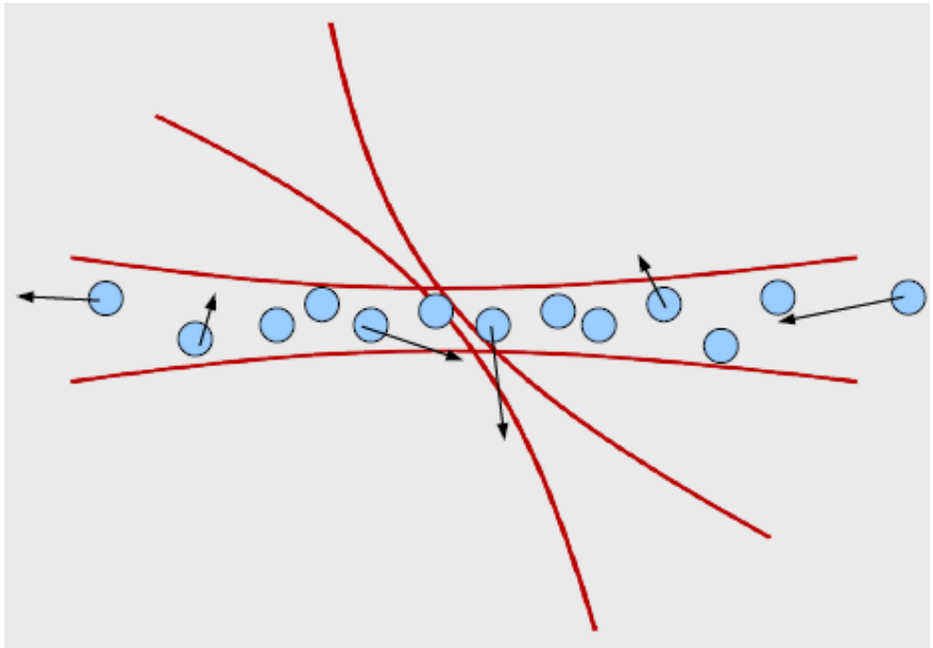
EXPANSION OF MATTER WAVE

EXPERIMENTAL IMPLEMENTATION

Crossed dipole trap with 1 small beam

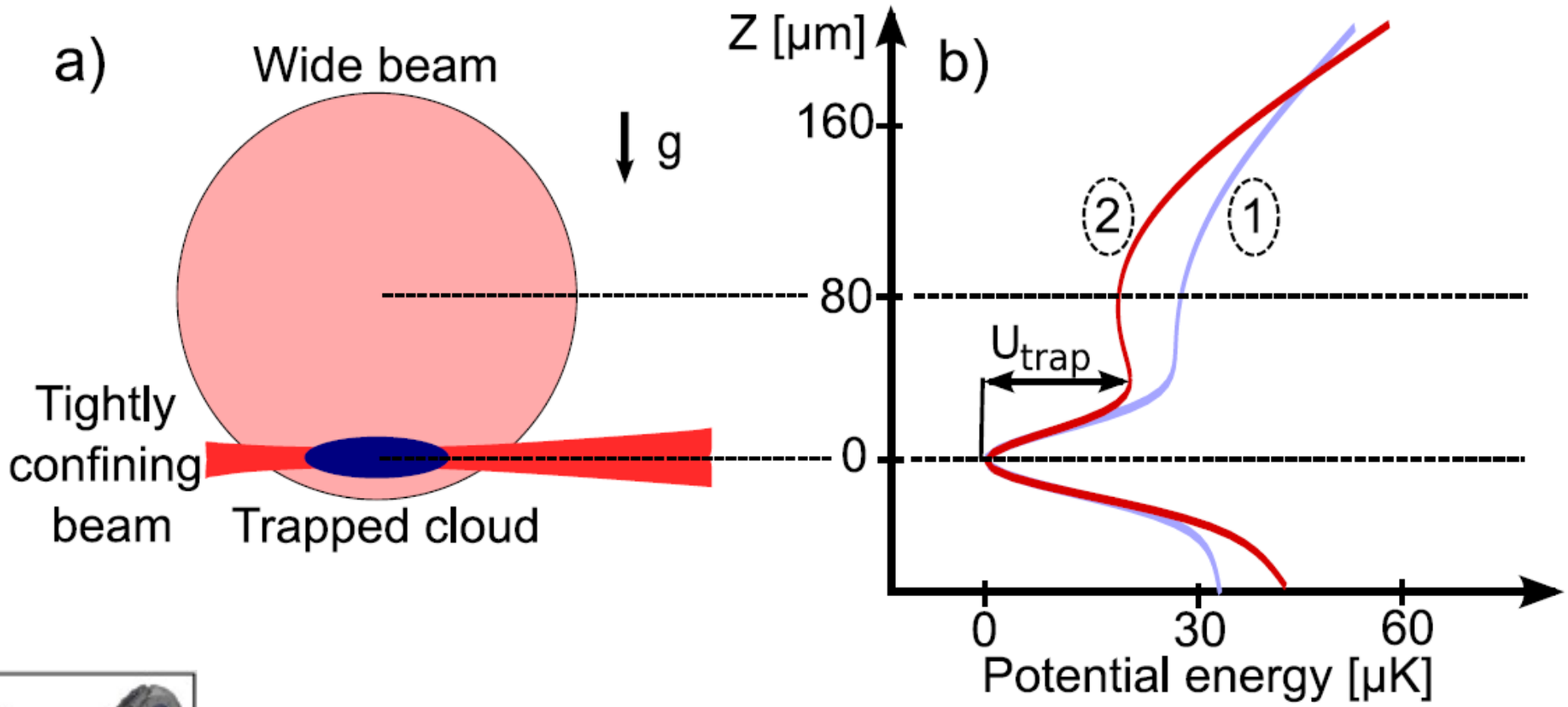


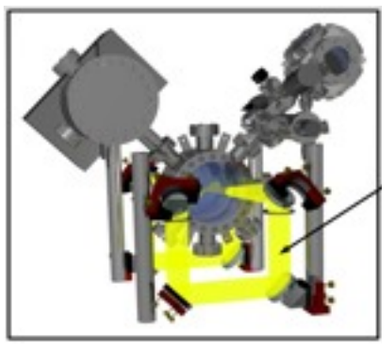




J.-F. Clément, *et al.*, Phys. Rev. A **79**, 061406(R) (2009).

FAST ALL OPTICAL BEC

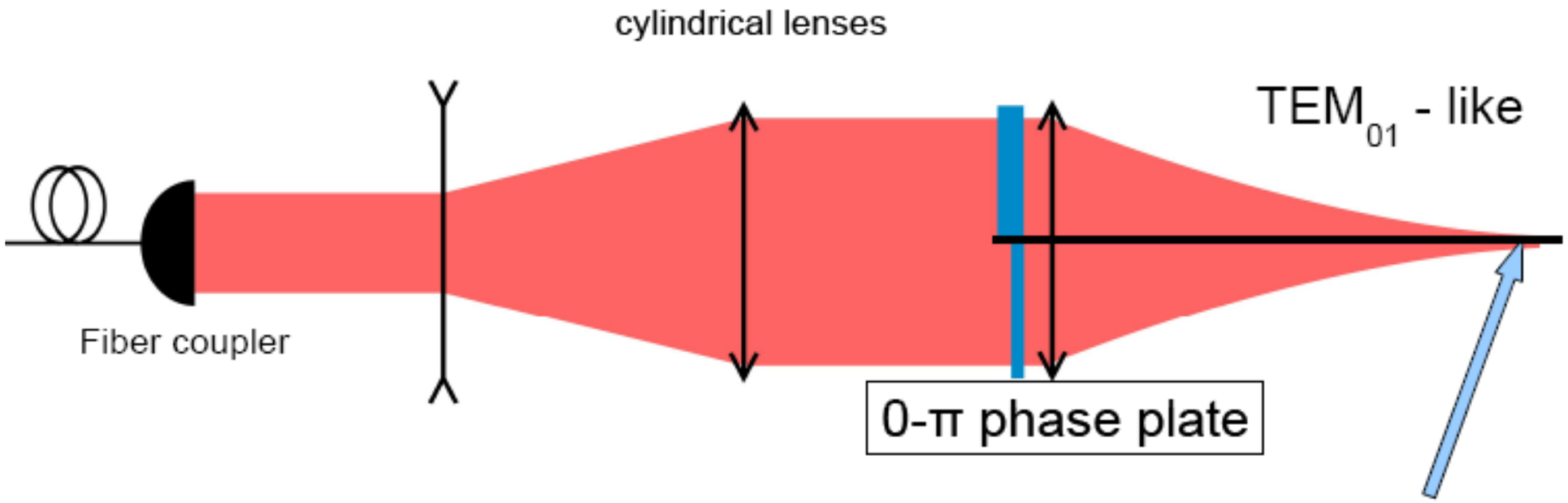




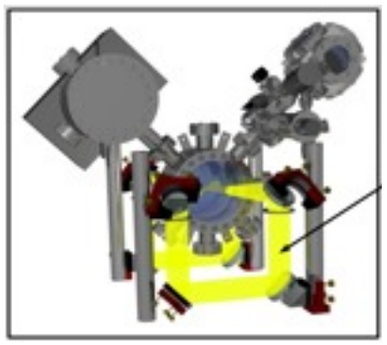
J.-F. Clément, *et al.*, Phys. Rev. A **79**, 061406(R) (2009).

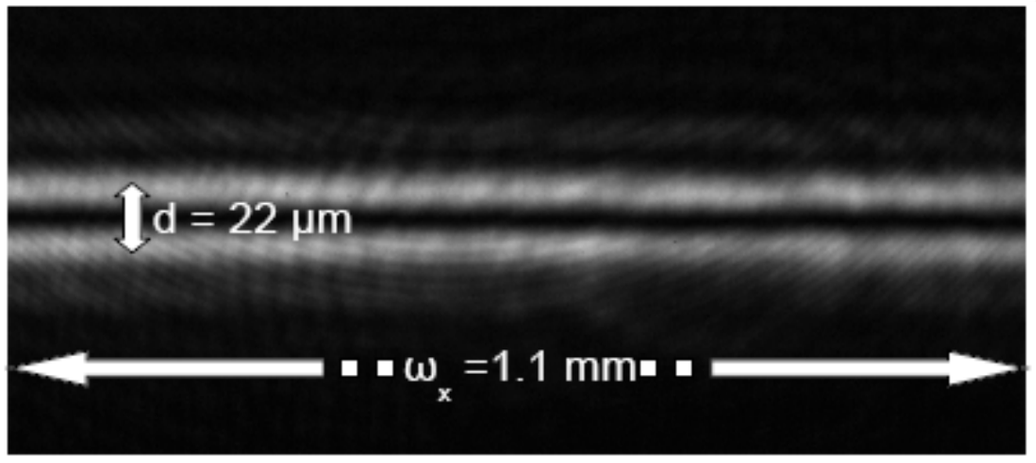
Tc with 10^6 atoms
Pure spinor condensates
few 10^5 atoms
3 seconds of evaporation
BEC achieved in 650 ms

2D TRAP



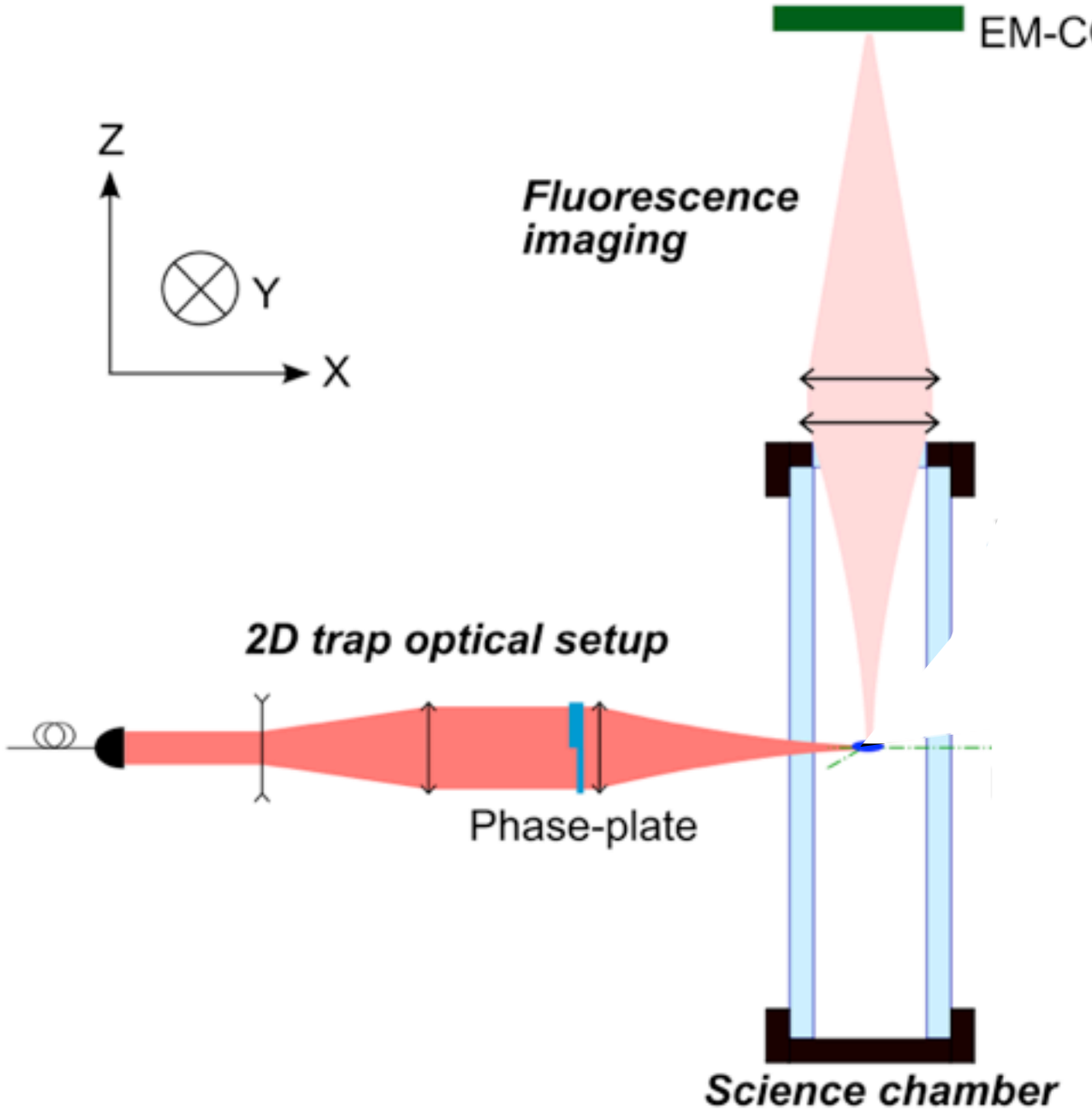
λ=767nm BLUE DETUNED
P=150mW
f_z = 600 Hz



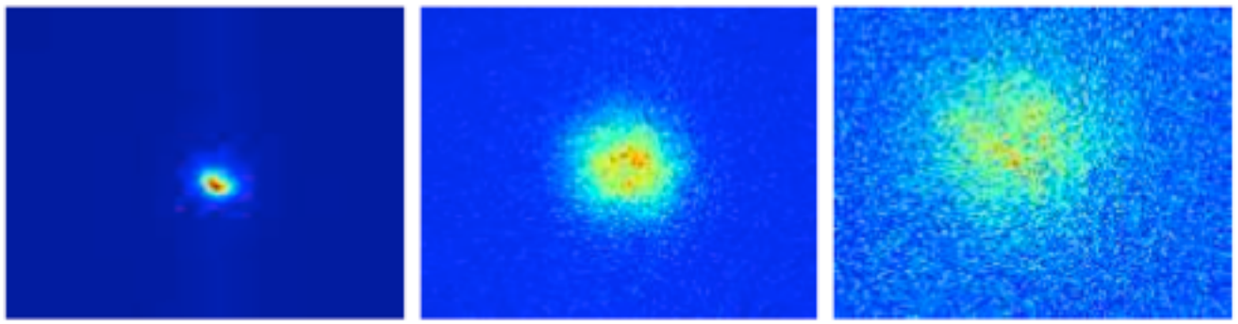


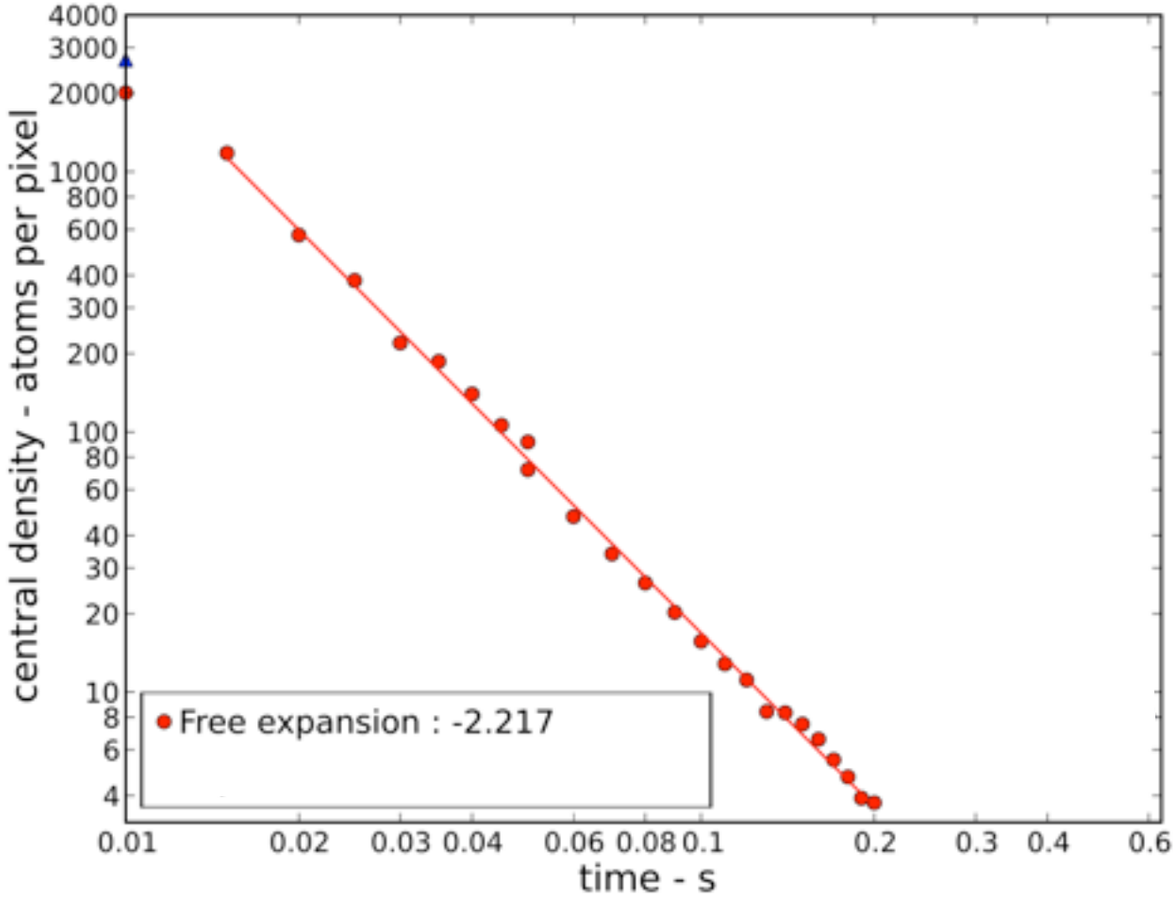
G. Stern et al., arXiv:1003.4761

2D TRAP


EM-CCD
Z
Y
X
Fluorescence imaging
2D trap optical setup
Phase-plate
Science chamber

EXPANSION

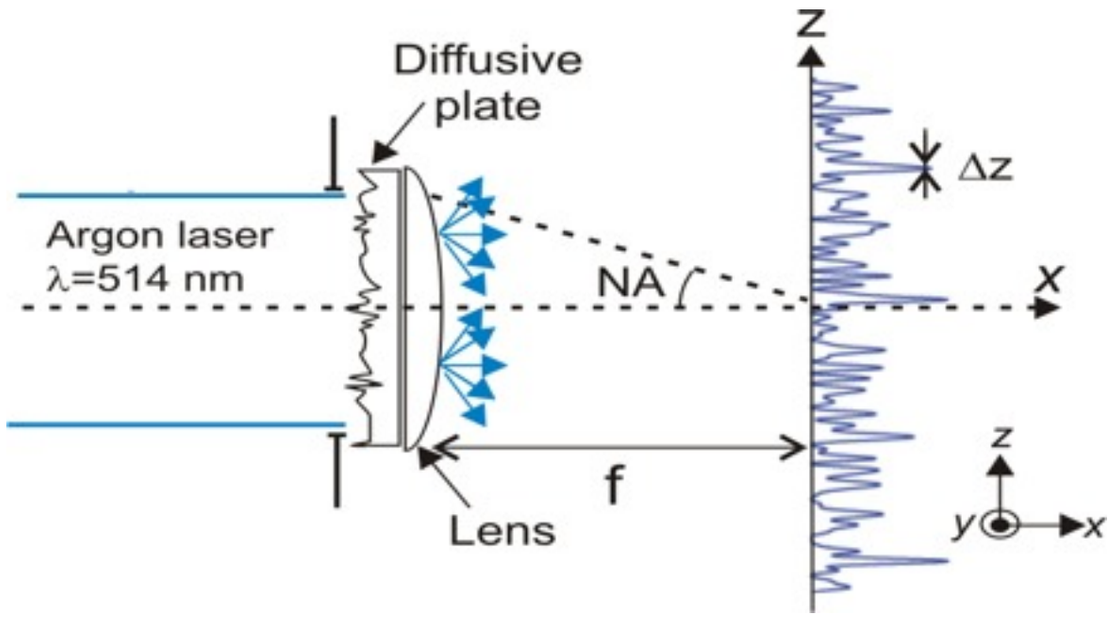


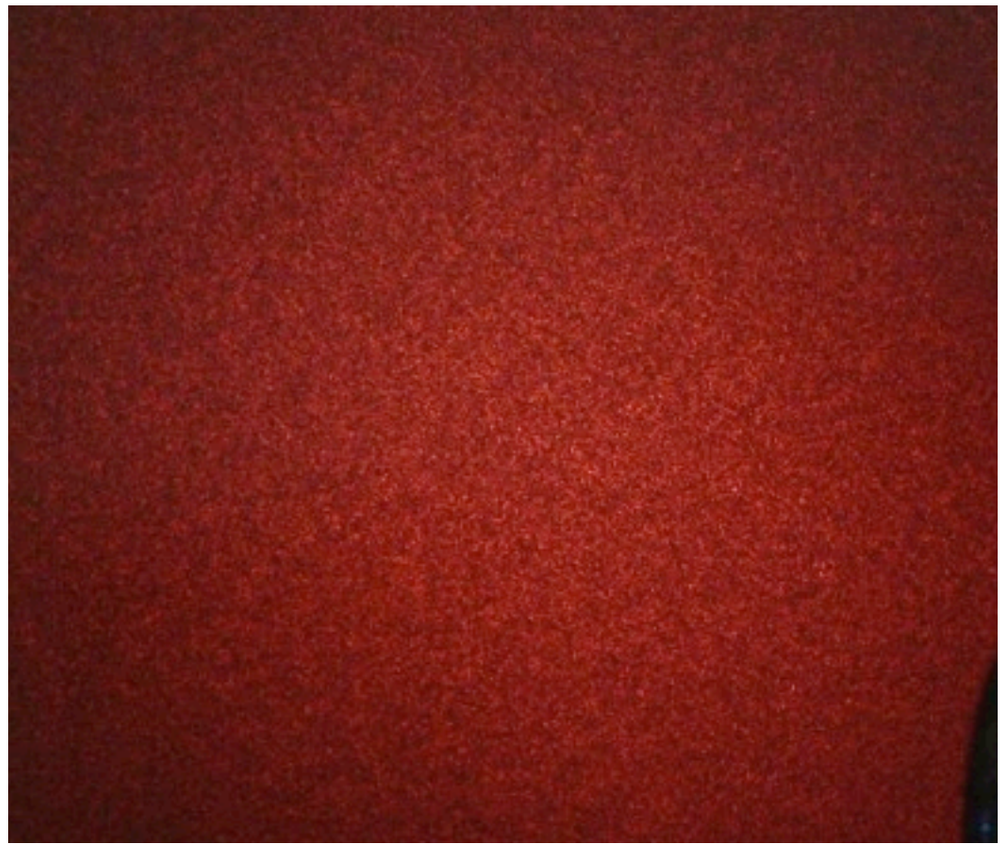


$$r^2(t) = r^2(0) + \frac{k_B T}{M} t^2$$

2D density scales as $1/r^2$

OPTICAL DISORDER FOR ATOMS : SPECKLE PATTERN





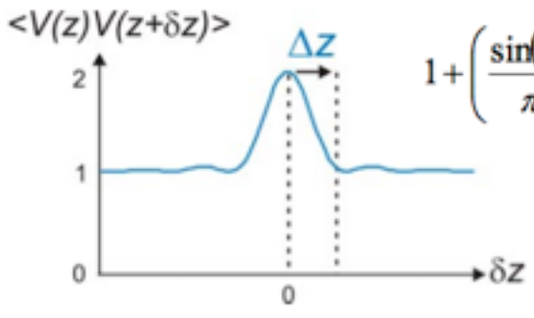
Depth of the optical wells

Indirect (CCD) and direct (using HF spectroscopy) measurements
Statistical properties verified $\sigma_I \sim < I >$
Potential depth σ_V calculated from σ_I

$$\sigma_V = \frac{2}{3}\frac{\Gamma^2}{2\delta}\frac{\sigma_I}{I_S}$$

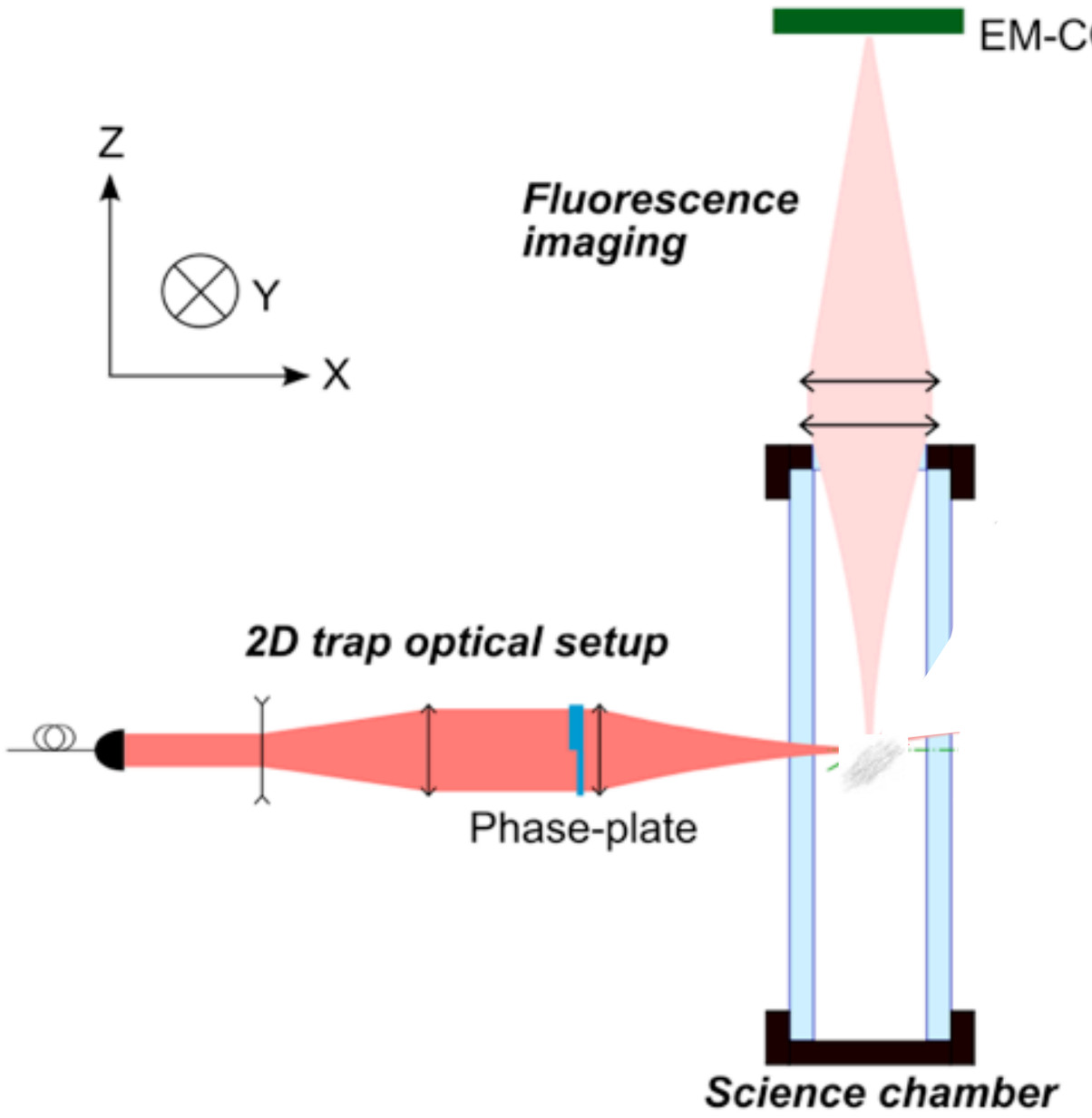
Good agreement with HF measurements (calibration)
Disorder amplitude definition γ : $\gamma = \sigma_V/\mu$

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

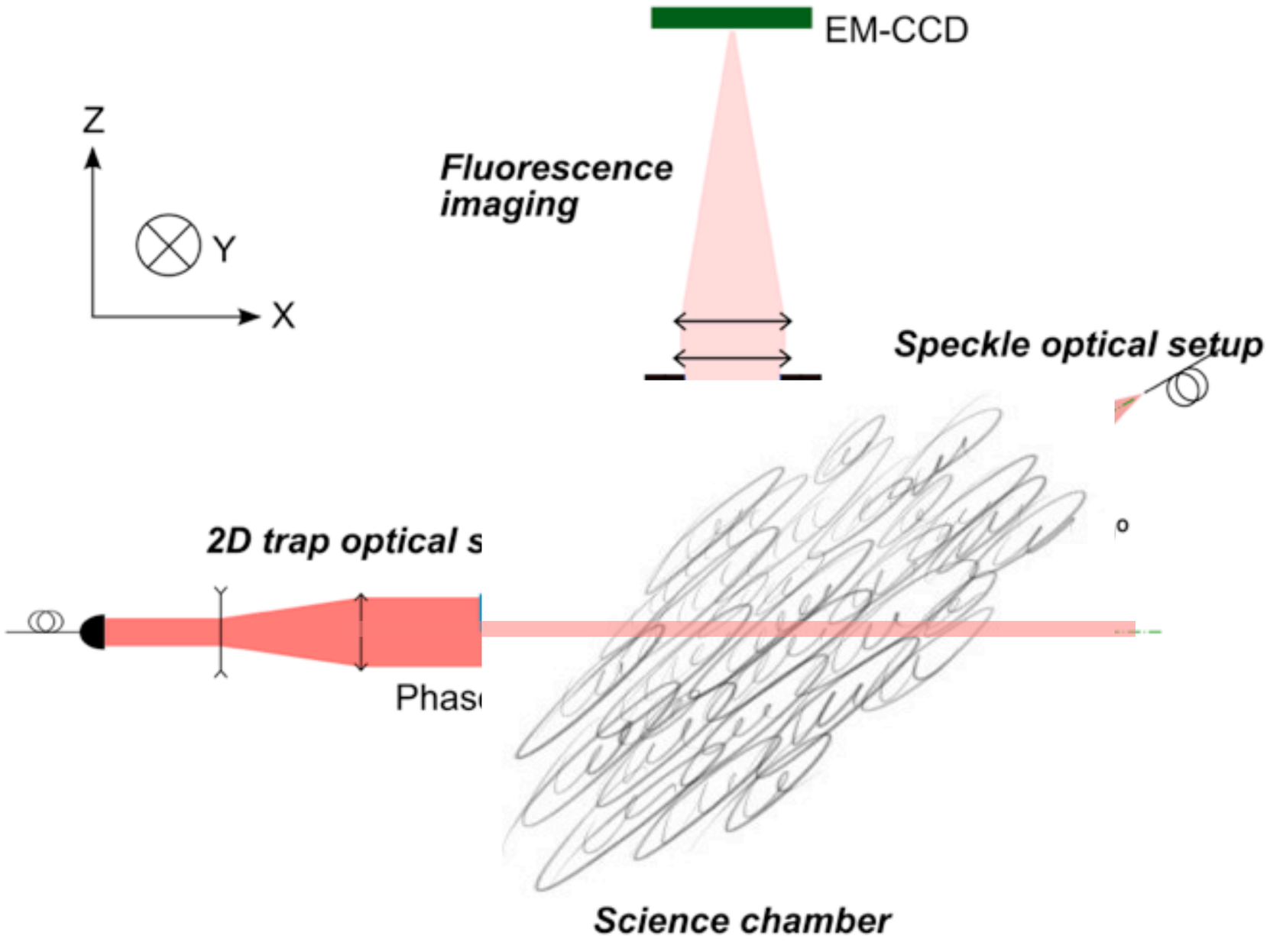


$$\Delta z = \frac{\lambda}{2(N.A.)} = 0.8\ \mu m$$

2D TRAP + DISORDER

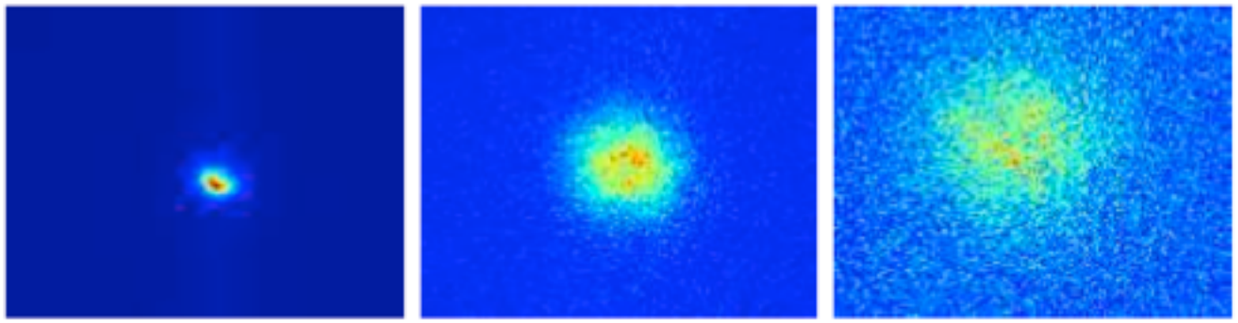


EXPERIMENTAL IMPLEMENTATION

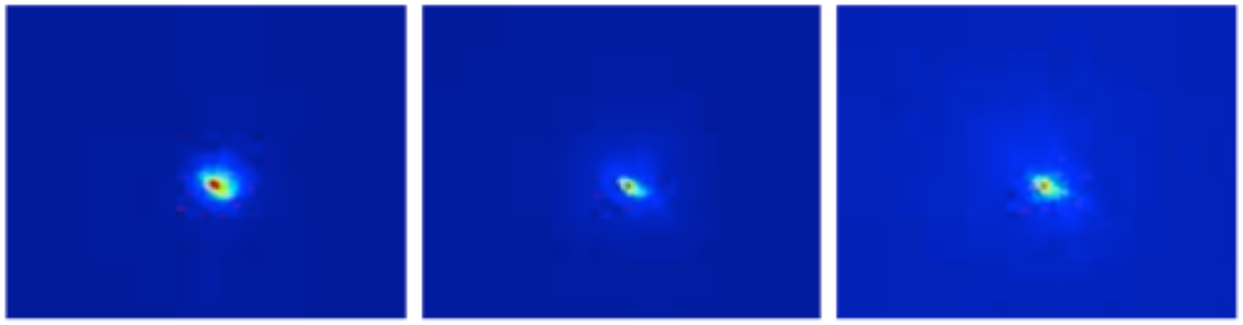


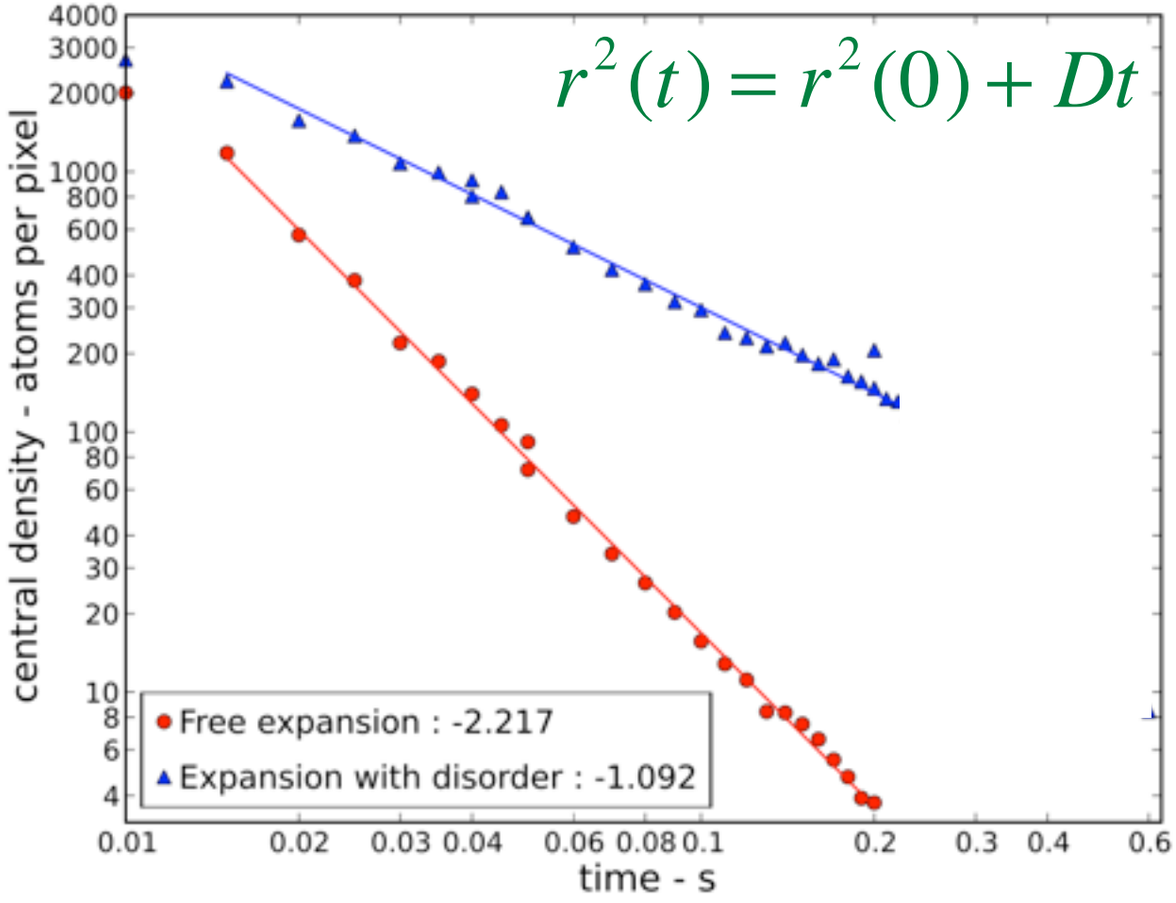
DIFFUSION

without disorder



with disorder





$$r^2(t) = r^2(0) + \frac{k_B T}{M} t^2$$

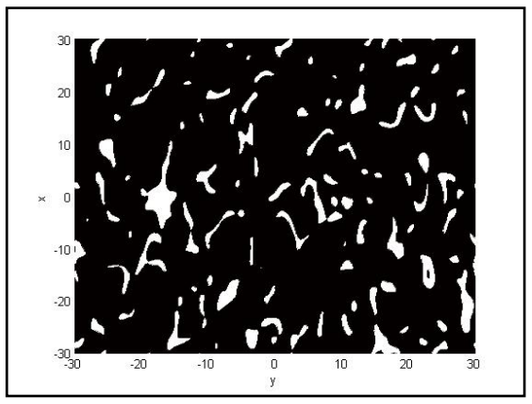
2D density scales as 1/r

EXPANSION, DIFFUSION, TRAPPING ...

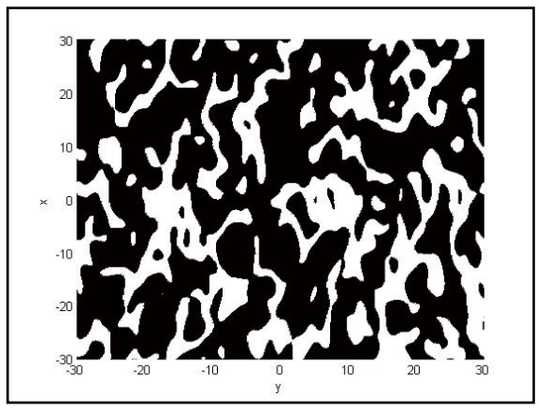
Since $k_{\mathrm{B}}T/\hbar\omega \approx 6$ and $k\sigma_y \approx 5$,we expect classical dynamics

3 regimes present during the expansion :

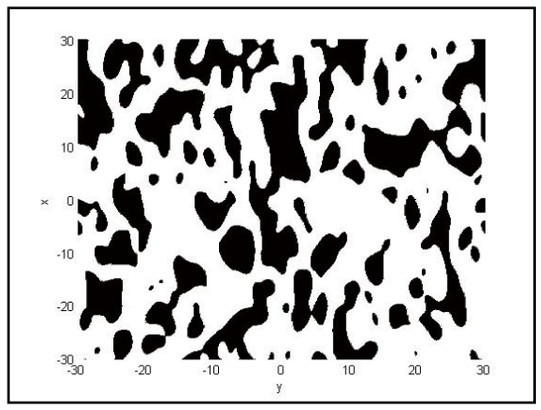
Below percolation threshold (E ≈ 0.5 V) : trapping



E/V=0.1



E/V=0.4



E/V=1

L.N. Smith and C.J. Lobb, PRB 1979

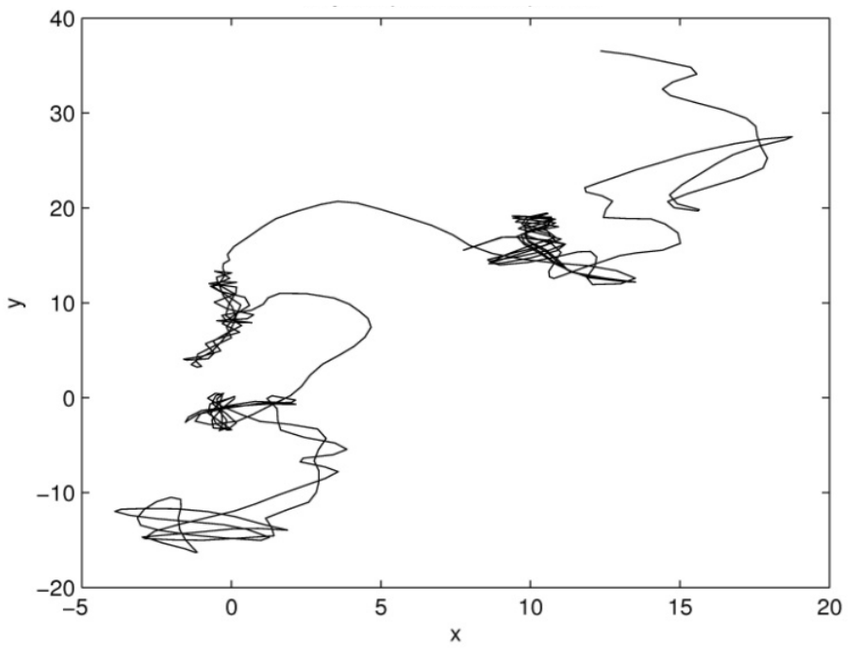
A. Weinrib PRB 1982

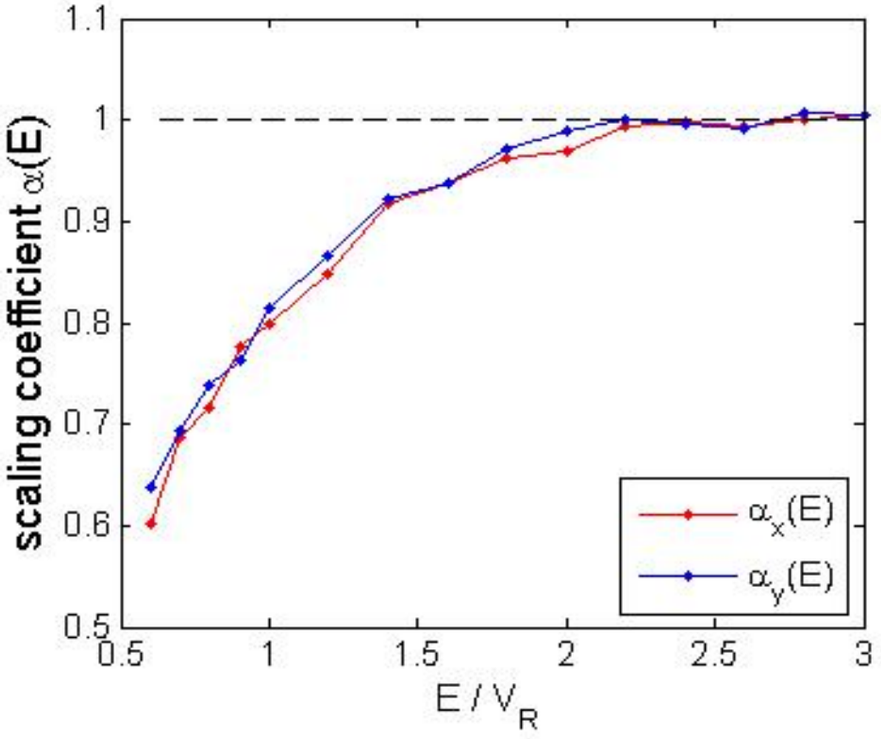
EXPANSION, DIFFUSION, TRAPPING ...

Since $k_{\mathrm{B}}T/\hbar\omega \approx 6$ and $k\sigma_y \approx 5$,we expect classical dynamics

3 regimes present during the expansion :

Below diffusion threshold (E ≈ 2 V) : sub-diffusion



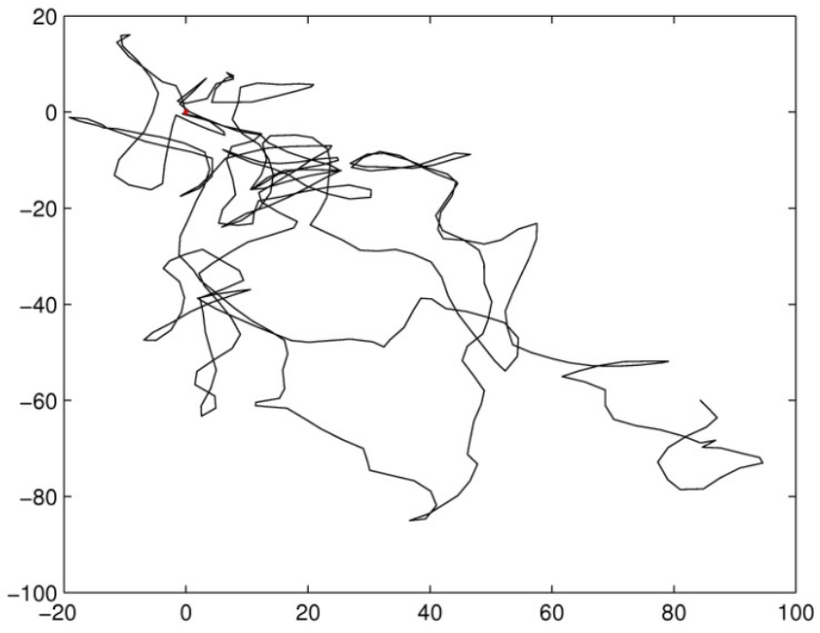


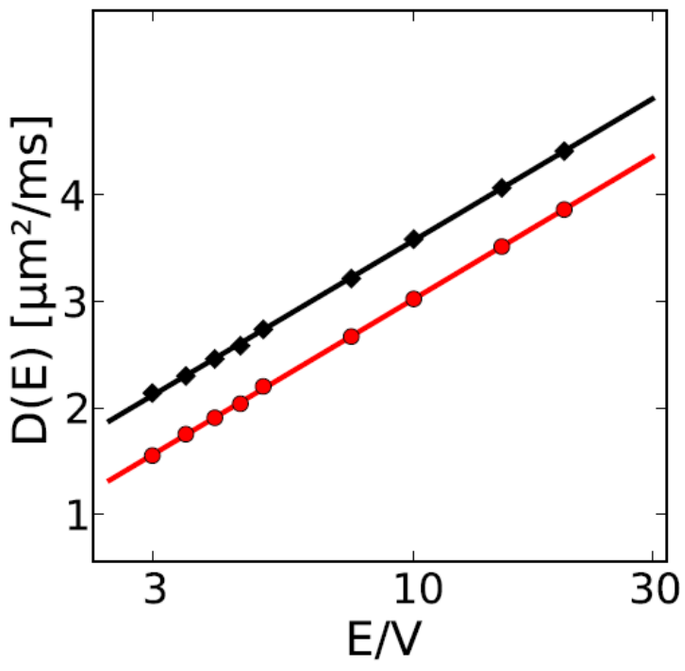
EXPANSION, DIFFUSION, TRAPPING ...

Since $k_{\mathrm{B}}T/\hbar\omega \approx 6$ and $k\sigma_y \approx 5$,we expect classical dynamics

3 regimes present during the expansion :

Diffusion



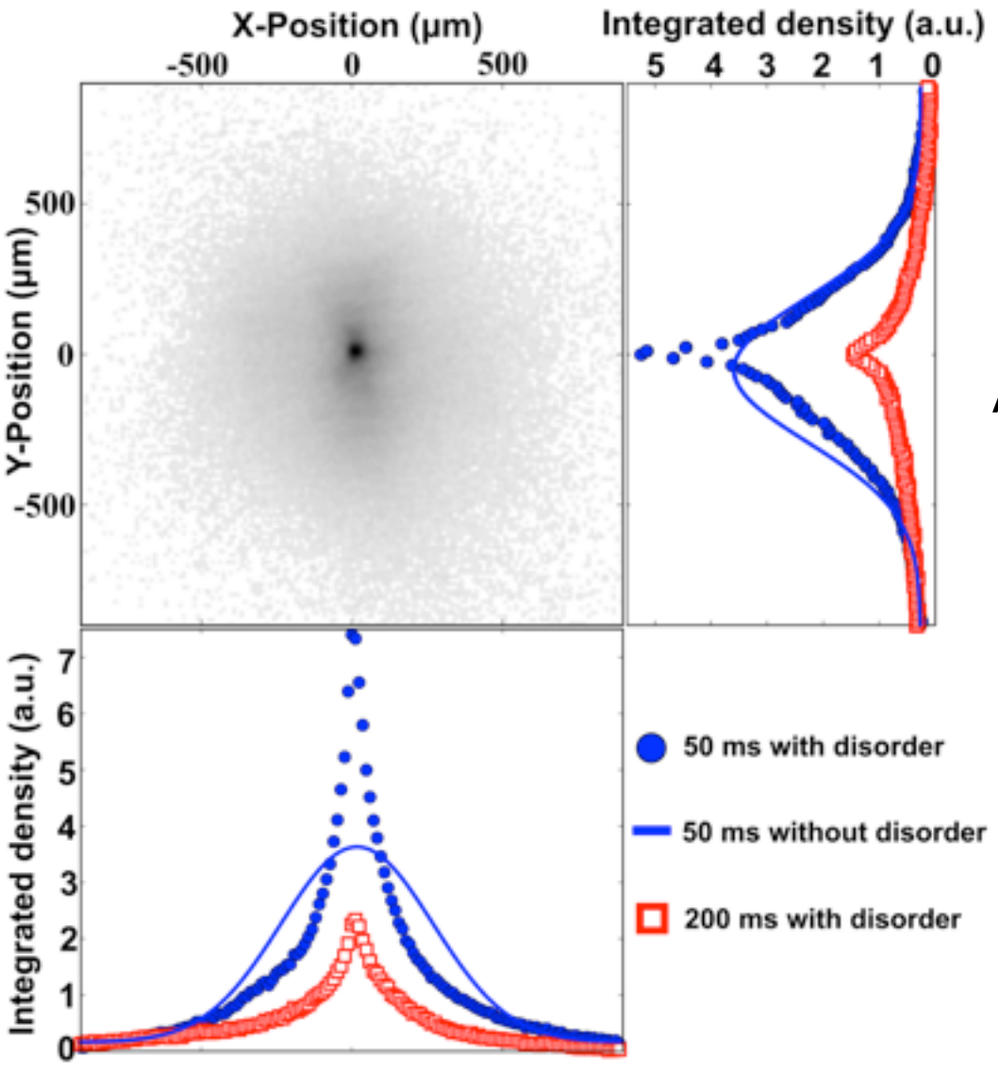


γ_ξ=2.8

$$D_\xi(E) = D_\xi^0(E/\bar{V})^{\gamma_\xi}$$

anisotropy of 3.7

MEASURING DIFFUSION COEFFICIENTS



Exp: γ=3.3(3)

Th: γ_{th}=2.8

Anisotropy ratio:
Exp: 3.45(15)
Th: 3.7

Profiles contain ballistic wings
+ diffusive central part

Diffusion coefficients : $D_{x,y}(E)$

Profile = $\mathrm{sum}_E\left(e^{\frac{-r^2}{D(E)t}}\right)$

Pb : what is $D(E)$?

weak scattering : $D(E) \sim D_0 E^{\alpha}$

$D_0 \sim 0.13\ \mathrm{mm^2 s^{-1}}$; $\alpha \sim 3$

M. Robert-de-saint-Vincent, et al.
arXiv:1004.0312, to appear in PRL

Understanding the rôle of disorder is fundamental in many field :

- **Optics (wave propagation, random lasers ...), electrons, ...** Storzer et al. Phys. Rev. Lett. 96, 063904 (2006), Schwartz et al. Nature 446, 52 (2007), Lahini, Y. et al. Phys. Rev. Lett. 100, 013906 (2008) ...
- **On cold atoms, many experiment using the "mapping" from quantum chaos (dynamical localisation) has been used :** Moore et al. PRL (1994), Chabé et al. (2007) ...
- **There are now many experiments studying BEC and disorder, adressing various aspects (propagation, lattice ...) :** Billy et al. Nature 453, 891(2008), Roati et al., Nature 453, 896 (2008), Chen et al. Physical Review A 77, 033632 (2008), Schulte et al., PRL 95, 170411(2005), White et al arxiv:0807.0446 (2008)

With atoms and disorder we can simulate transport in various configurations:

- **Possibility to control all matter-wave parameter (velocity, density, interactions ...)**
- **Very good control and understanding on the disorder model (Speckle pattern well characterized ...)**

Direct observation of wavefunction, correlation functions ...

Anderson localisation in the atom optics group (A. Aspect, www.atomoptic.fr)

Theory : L. Sanchez Palencia,

P. Lugan, B. Hambrecht, L. Pezze

Experiments : P. Bouyer

1D and 3D : V. Josse

J. Billy, A. Bernard, P. Cheinet, F. Jendrzejewski, S. Seidel

2D and controllable interactions : T. Bourdel

J-P Brantut, M. Robert de Saint Vincent, JF Clément, T. Plisson, B. Allard

web site : www.atomoptic.fr