Coherence of Photons in Disordered Media

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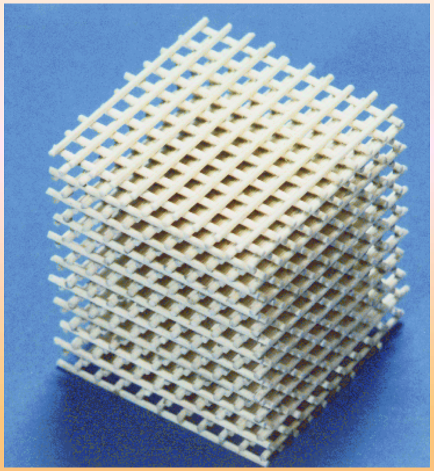
Quantum Engineering with Photons, Atoms and Molecules
Les Houches, February 14-17, 2005

Wave propagation in random media

Mesoscopic regime :
Interferences alter diffusion process

Propagation of light waves
/
Propagation of matter waves

Photonic crystals



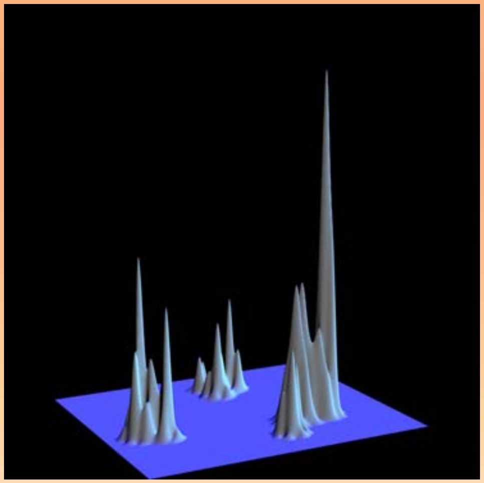
Interferences in 1D, 2D and 3D

Energy bandgaps

Localized modes

much more on http://ab-initio.mit.edu/

Anderson localization in random media



Random equivalent of photonic crystals

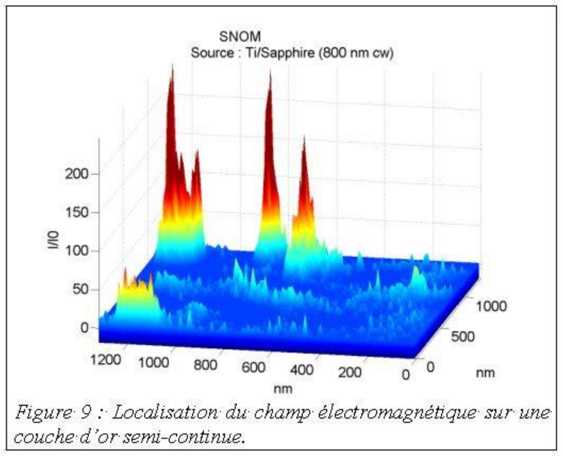


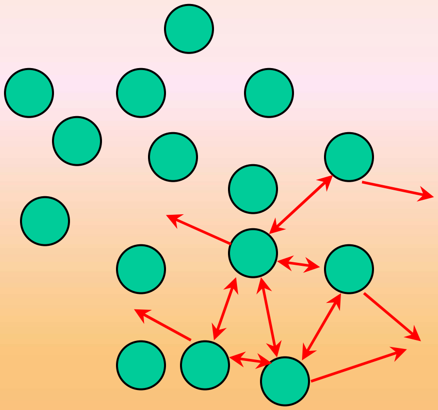
Figure 9 : Localisation du champ électromagnétique sur une couche d'or semi-continue.

Coherent transport :

in 1D and 2D : localization for any disorder

in 3D : threshold for localization ?

Photons ...

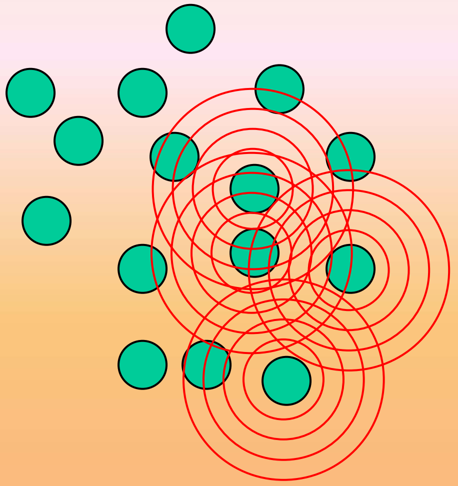


Random walk :

Diffusion coefficient

$D_0 \approx \ell^2 / \tau$

... are waves



Interference correction to

Diffusion coefficient

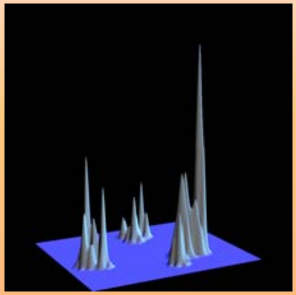
$D \approx D_0 \,(1 - 3/k\ell\,)$

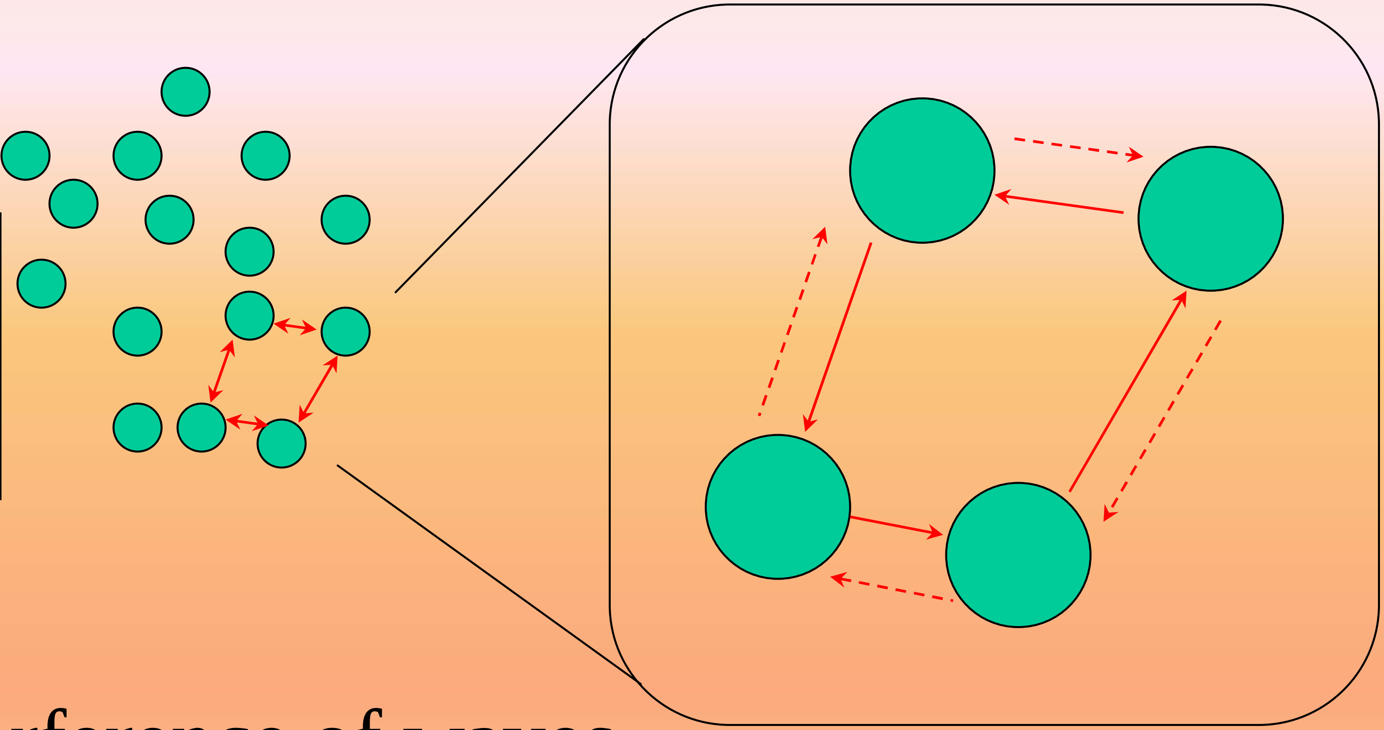
Strong Localization (D=0) :

Ioffe-Regel criterium : $k\ell \approx 1$

(on resonance $n_{at} \approx 10^{14}$ at/cm^3)

Strong Localization of light

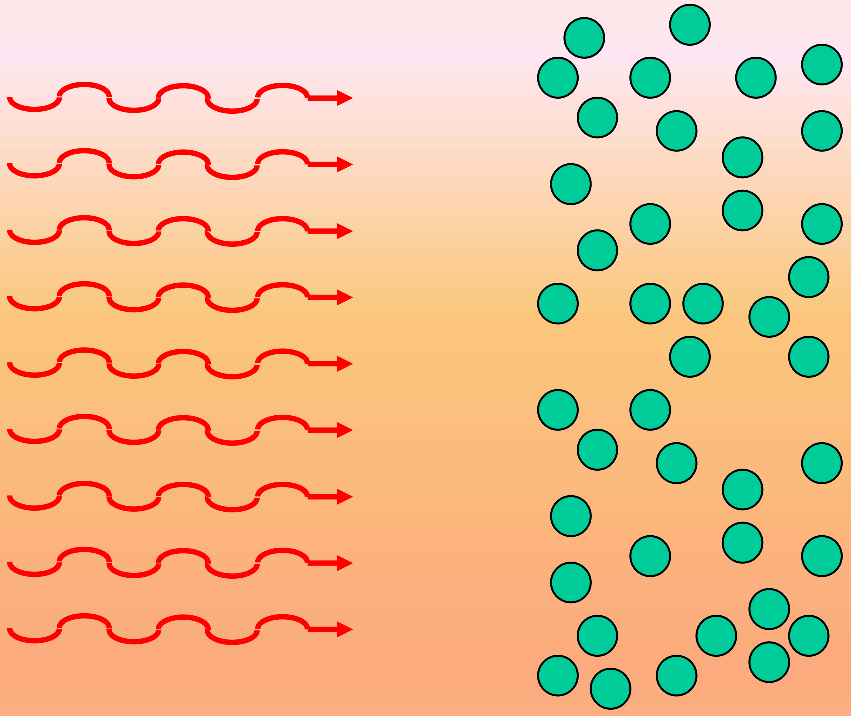




- Interference of waves
  propagating along closed loops?

- ‘random cavities’ : ‘precursor’ modes ?
  ⇒ random laser

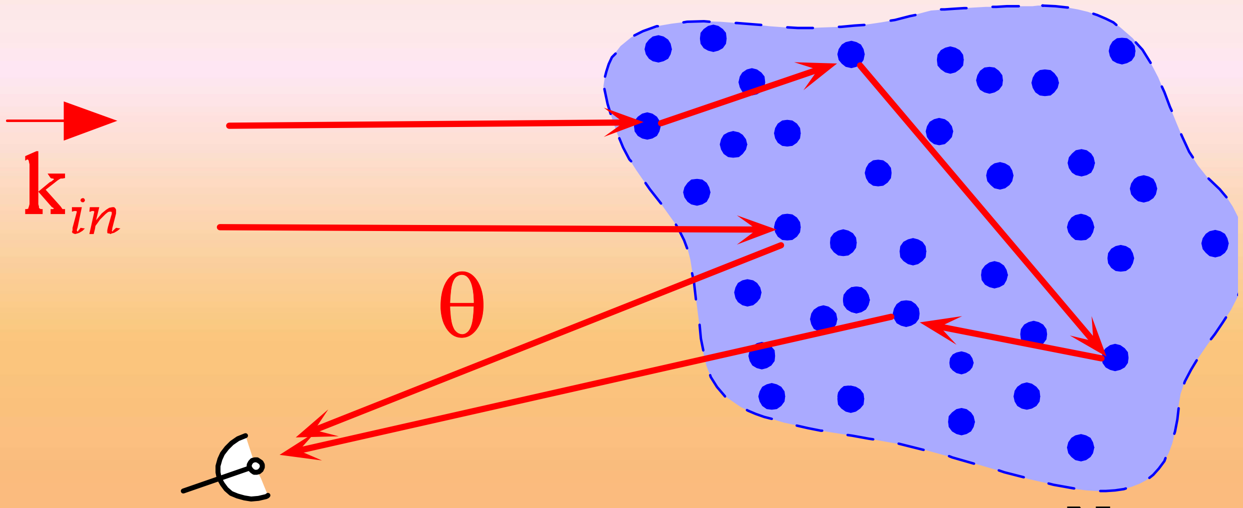
Scattering Experiments



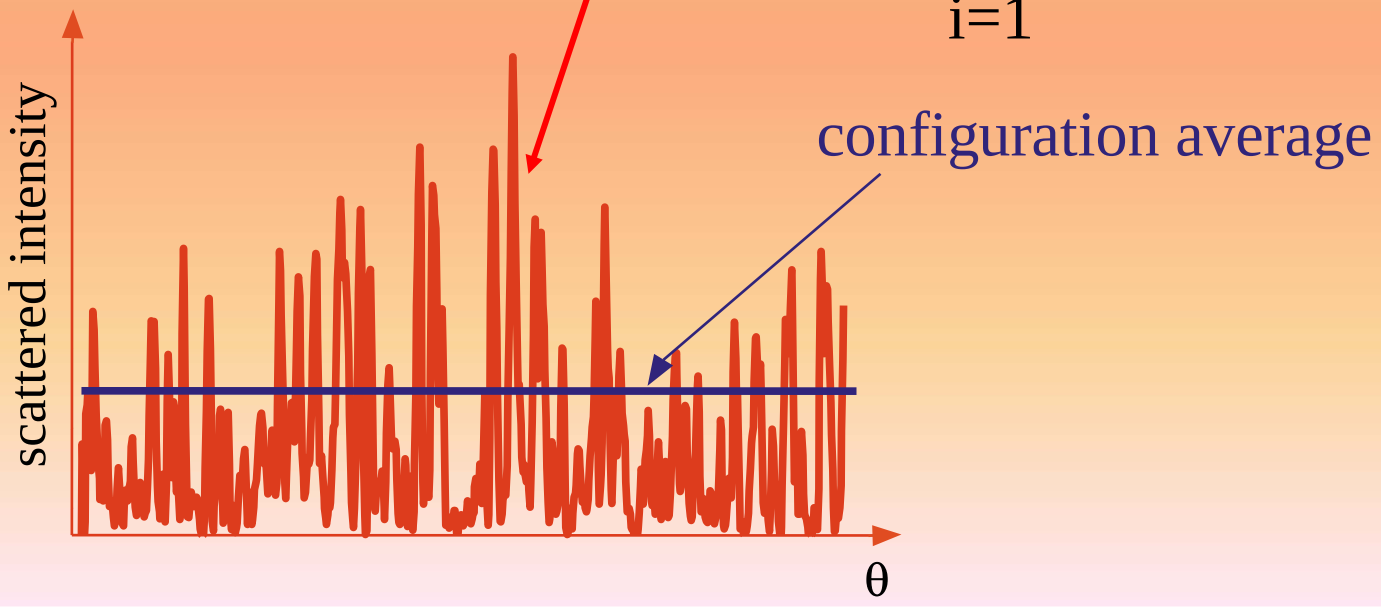
* coherent transmission, diffuse transmission / reflection

* far field analysis

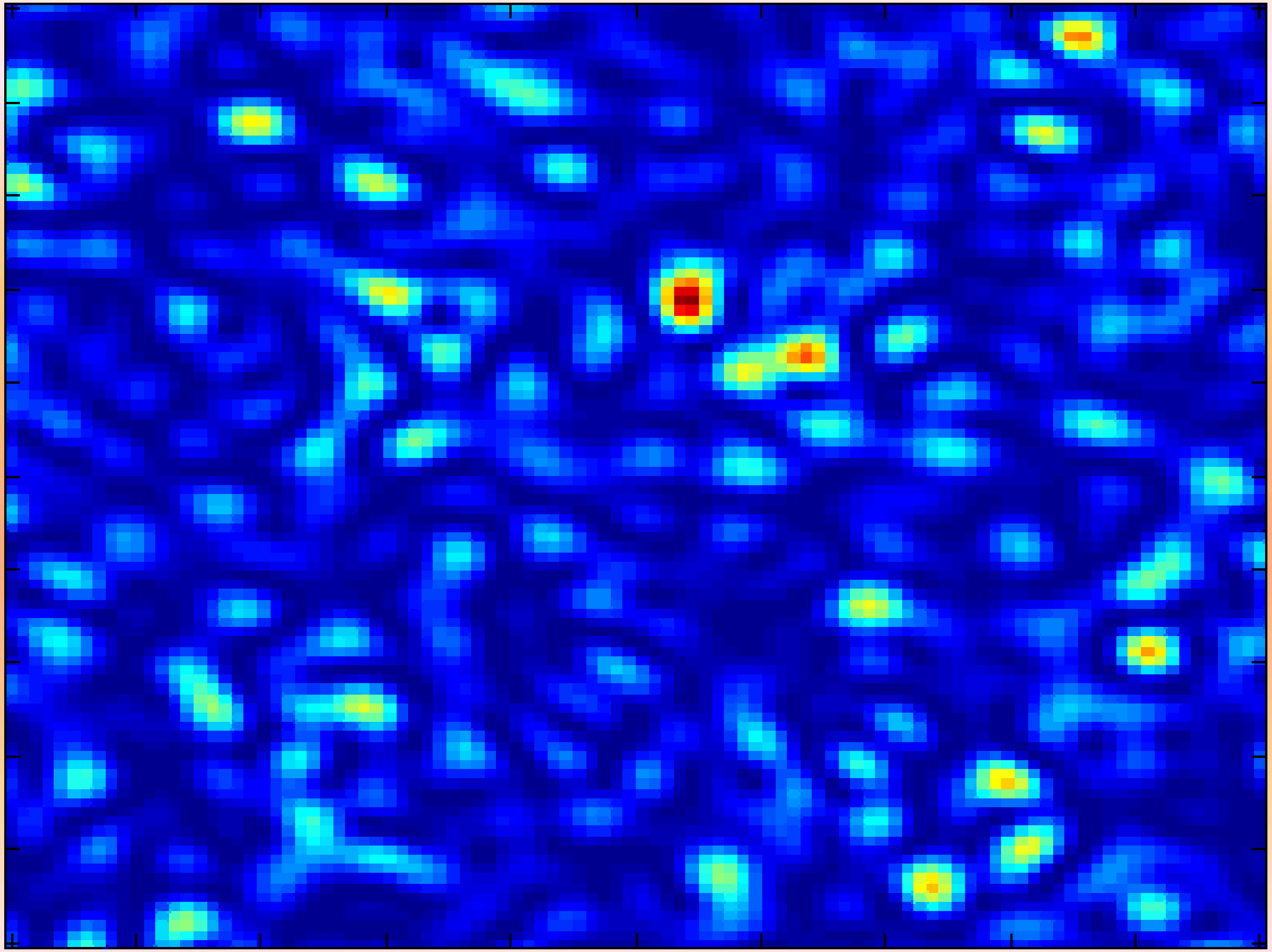
Interferences and speckle



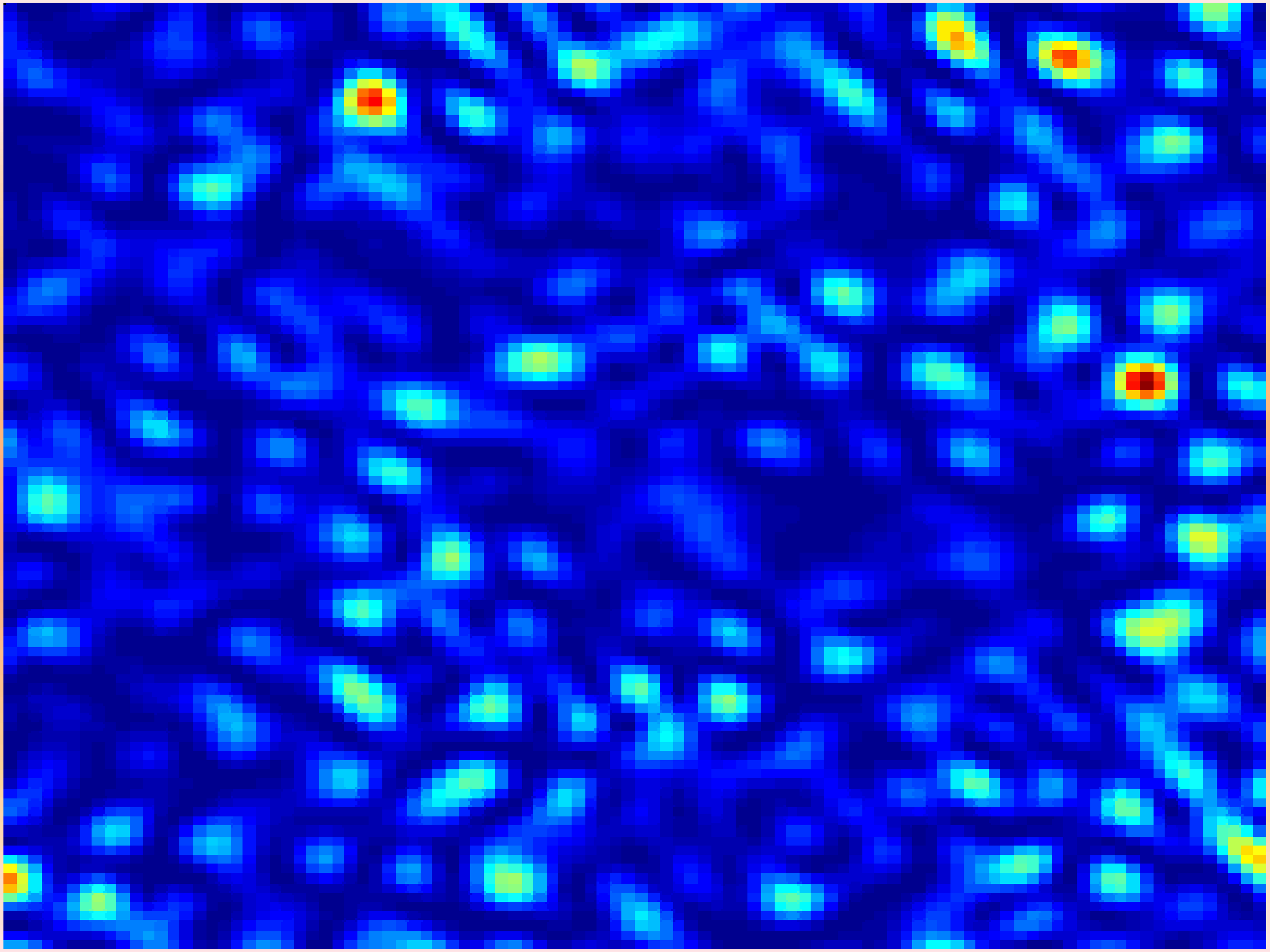
fixed scatterers : speckle pattern $\vec{E} = \sum_{i=1}^{N} \vec{E}_i$



Fluctuating Speckle Pattern

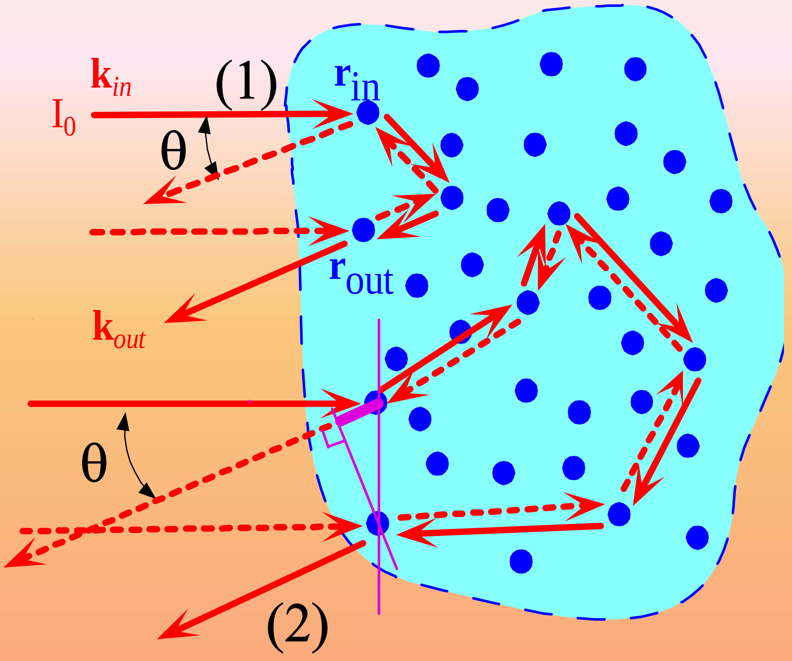


Integrated signal (configuration average)



Configuration Averaged Intensity

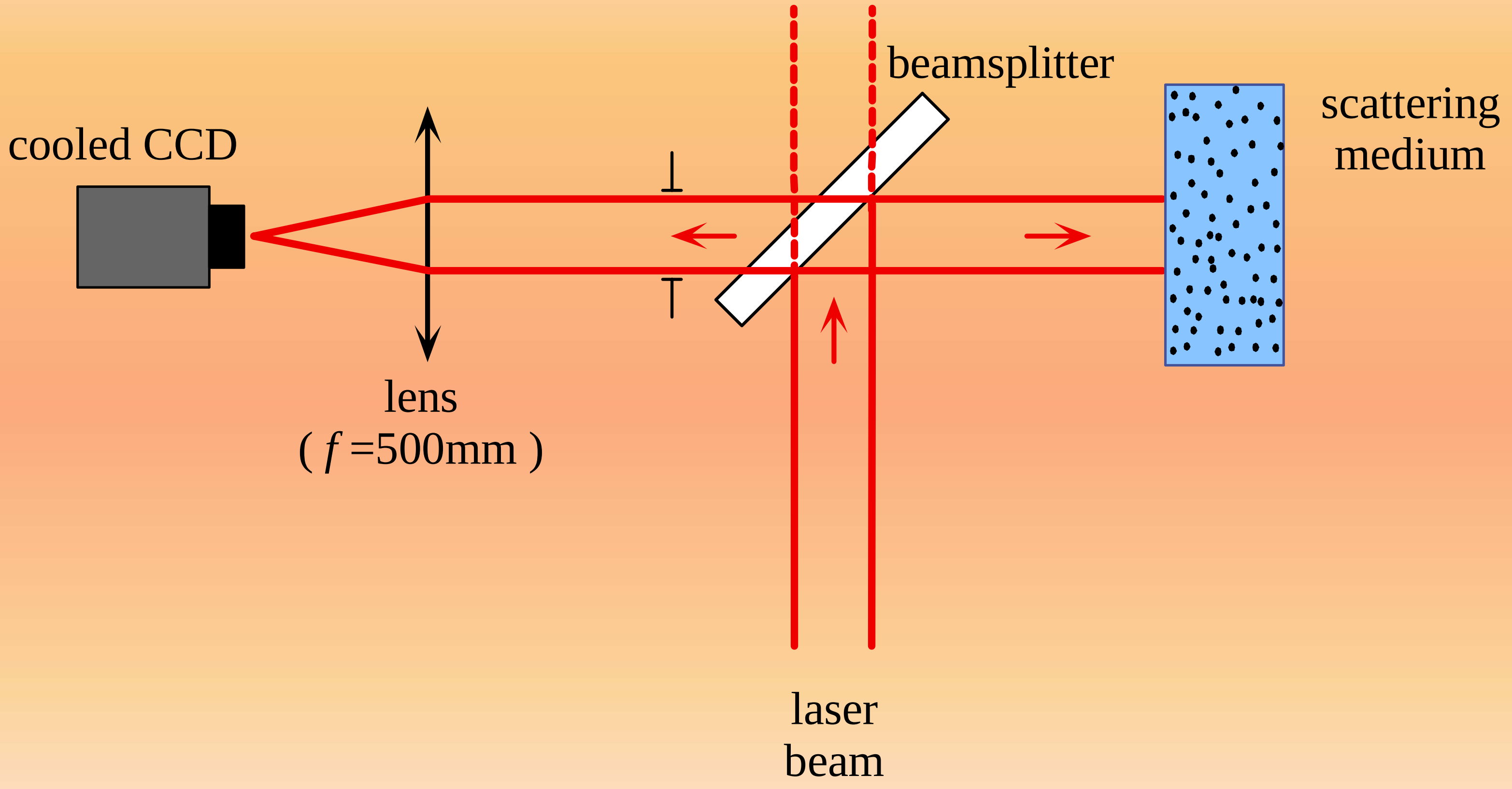
- **uncorrelated paths add incoherently**
- **correlated (i.e. reciprocal) paths add coherently**



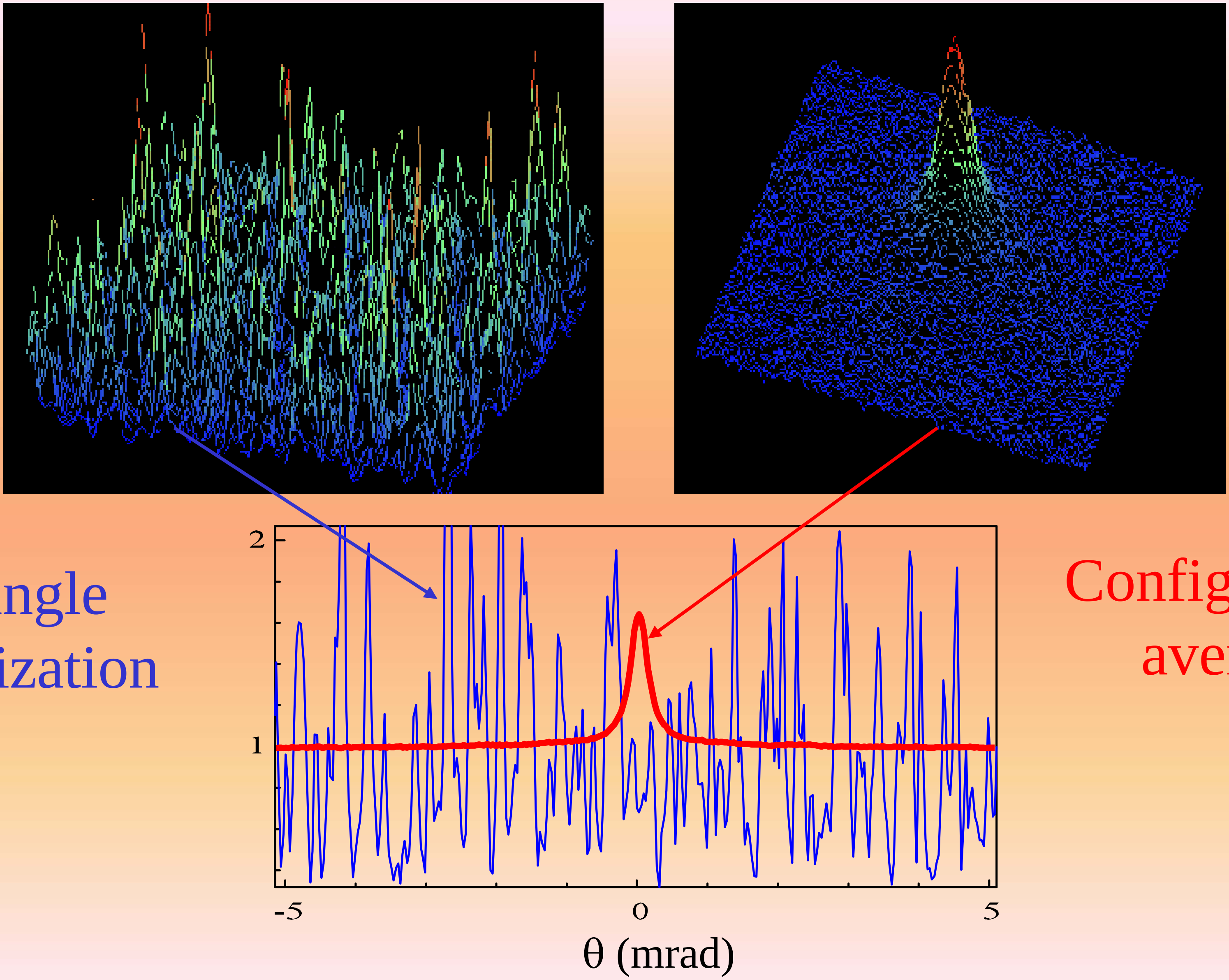
$\Delta\varphi=(k_{in}+k_{out}).(r_{in}-r_{out})$ $\theta=0 \Rightarrow \Delta\varphi = 0$ for any path

Coherent Backscattering $$\frac{<I(0)>}{<I(\theta)>} = 2$$

Experimentel Setup



Configuration Average

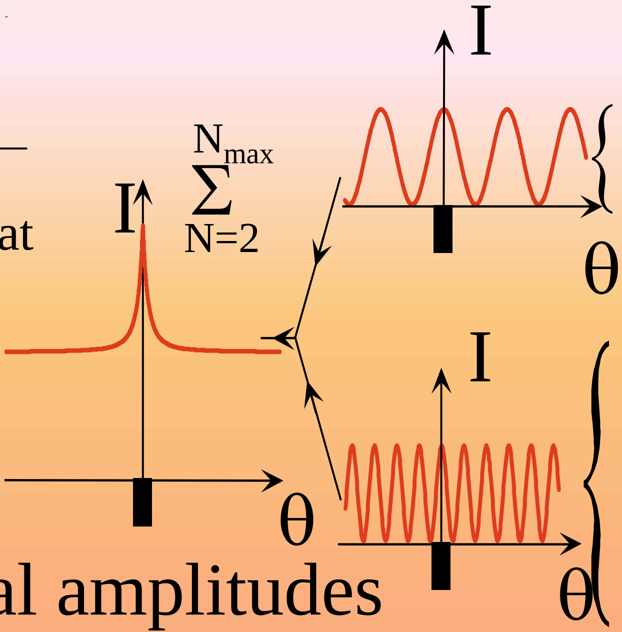


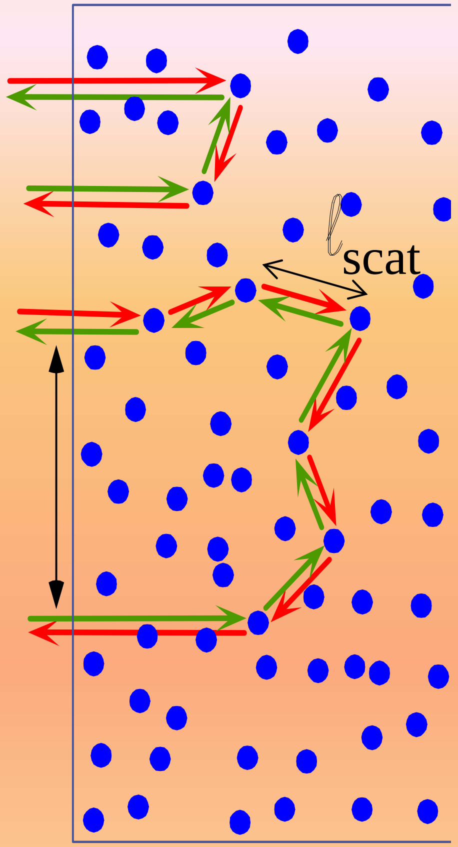
Single realization

Configuration average

Coherent backscattering

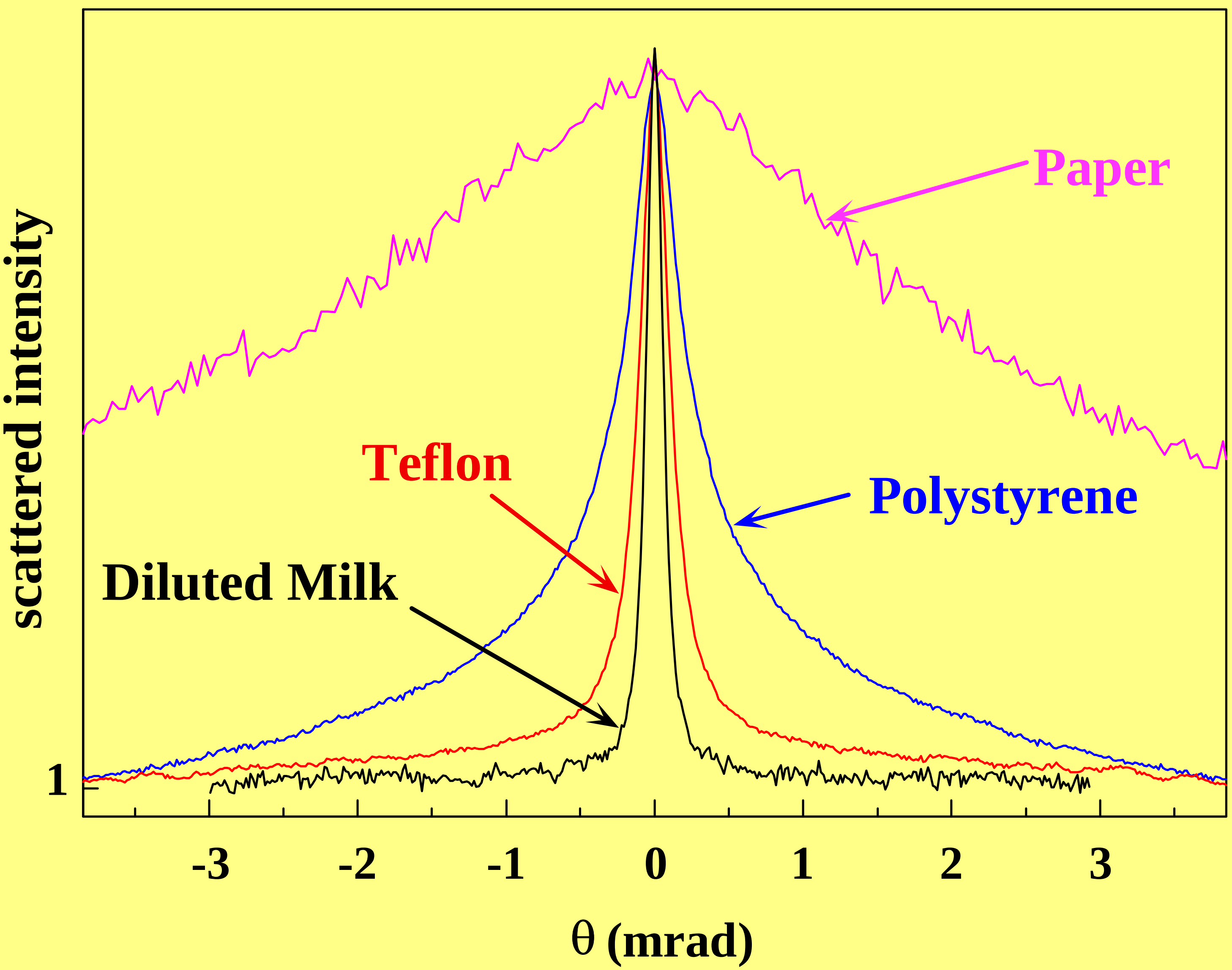
- <u>cone with</u> : $\Delta\theta = 2\pi \dfrac{\lambda}{\ell_{\text{scat}}}$





- <u>cone height</u> : reciprocal amplitudes
(phase, intensity)

**Young double slits /
self-aligned multiple
Sagnac interferometer**

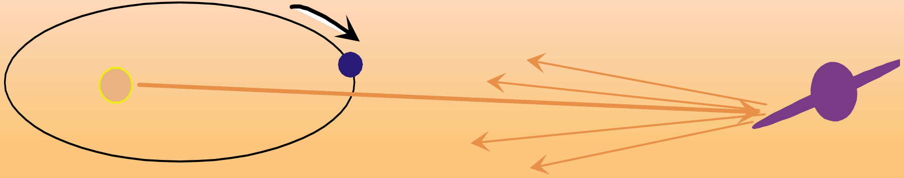

Paper
Polystyrene
Teflon
Diluted Milk
scattered intensity
1
-3
-2
-1
0
1
2
3
θ (mrad)

Coherent Backscattering

Light waves :

white paint (TiO_2), teflon, milk, paper, tissue

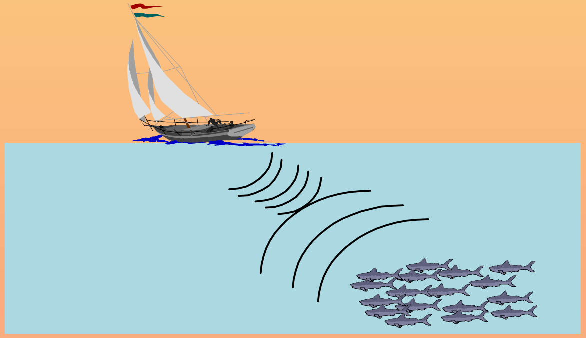
rings of Saturn



Acoustic waves :

metal rods

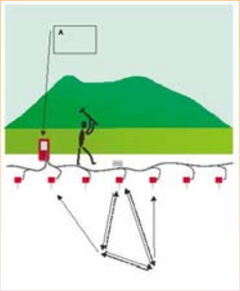
fish (?)



Matter waves :

electrons : negative magneto-resistance

Seismic waves :



Why cold atoms ?

- spontaneous emission :

  ⇒ coherent process?

  ⇒ role of quantum fluctuations?

- resonant scattering :

$$\delta = \omega_{las} - \omega_{at}$$

$$\sigma = \frac{3\lambda^{\mathbf{2}}}{2\pi}\frac{1}{1+(2\delta/\Gamma)^2} >> (\mathbf{a}_0)^2$$

$$\Gamma/2\pi = 6 \text{ MHz}$$

$$\lambda = 780\text{nm}$$

⇒ quality factor ~ 10^8

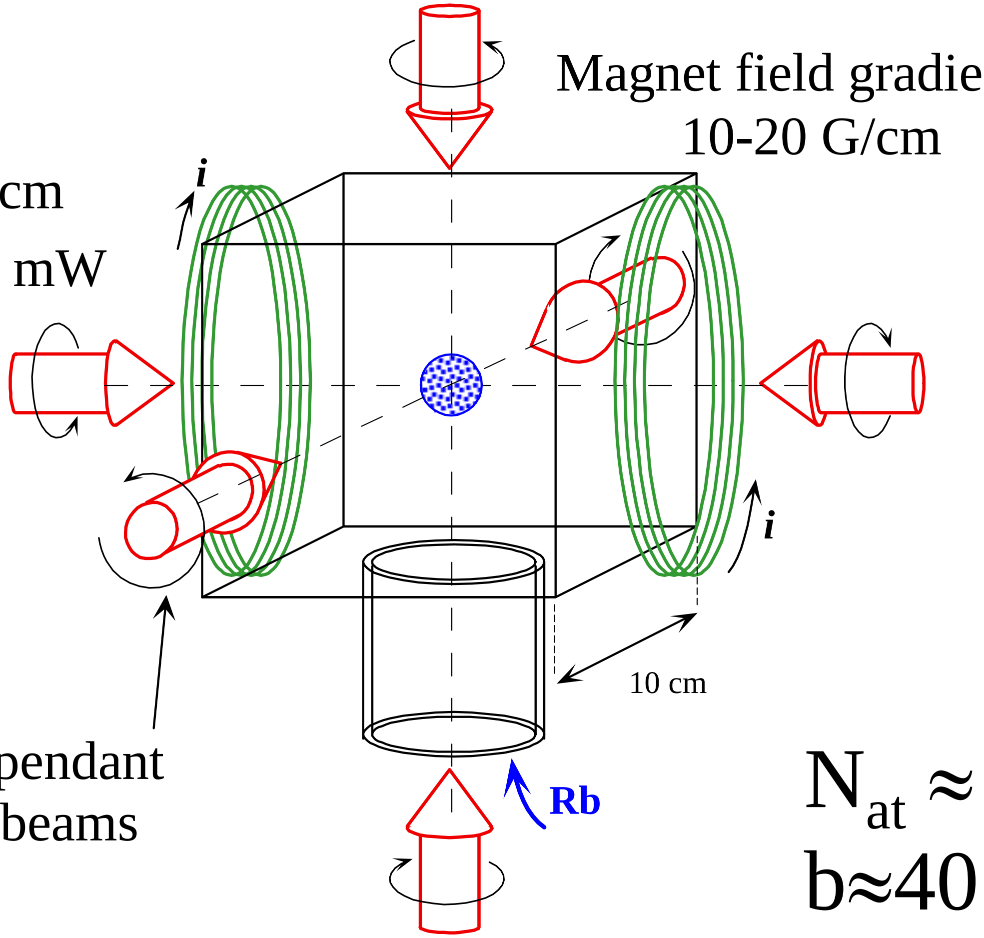
⇒ ‘monodisperse’ sample : cold atoms

⇒ ‘delay time’ at resonance : τ_d ~50ns

- ⇒ matter waves

Magneto-optical trap (MOT)

- Rb^{85} MOT from background

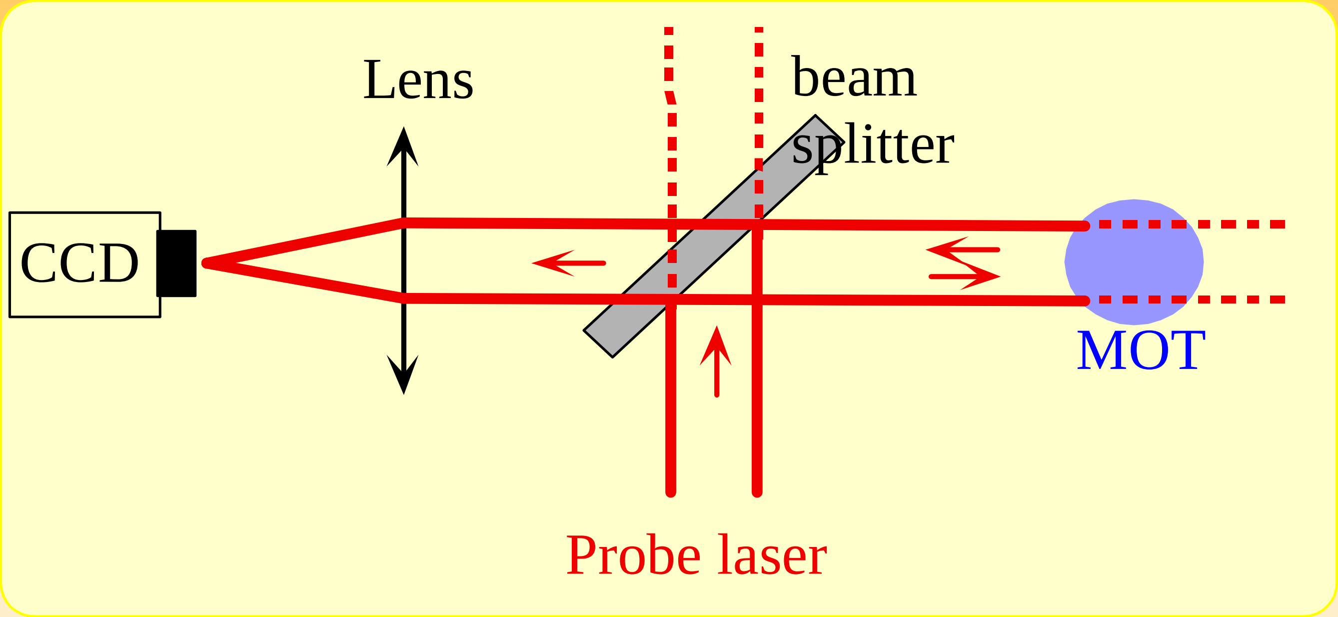


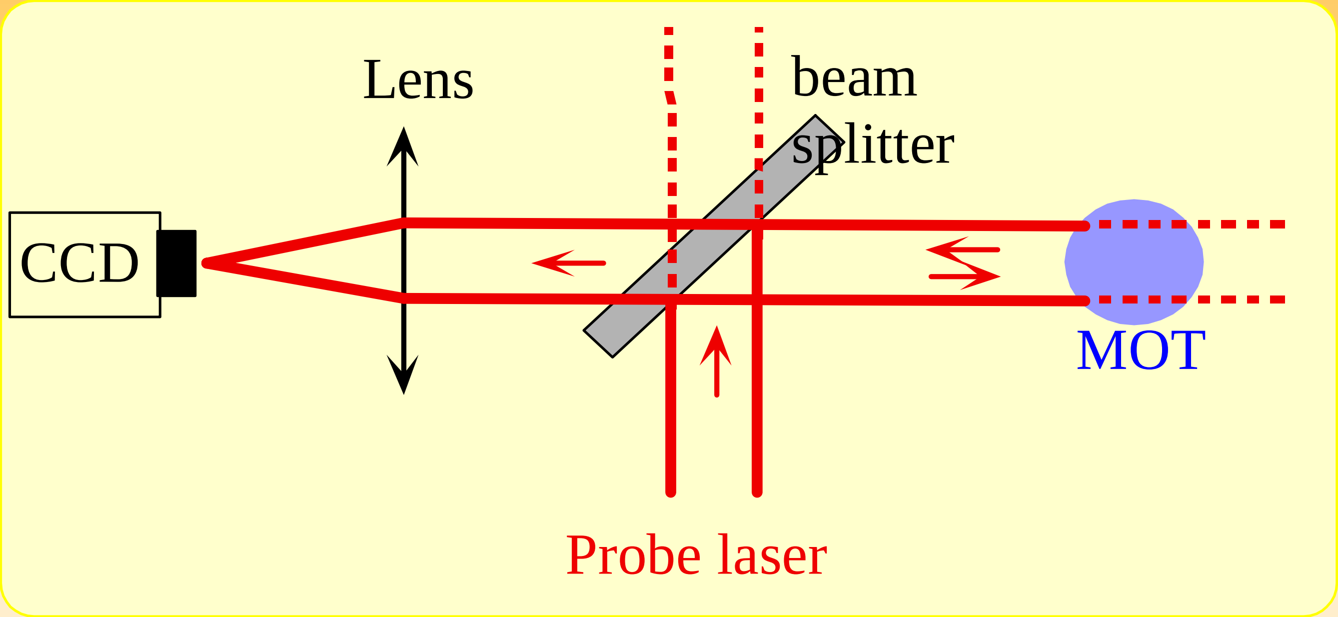
Magnet field gradient :
10-20 G/cm

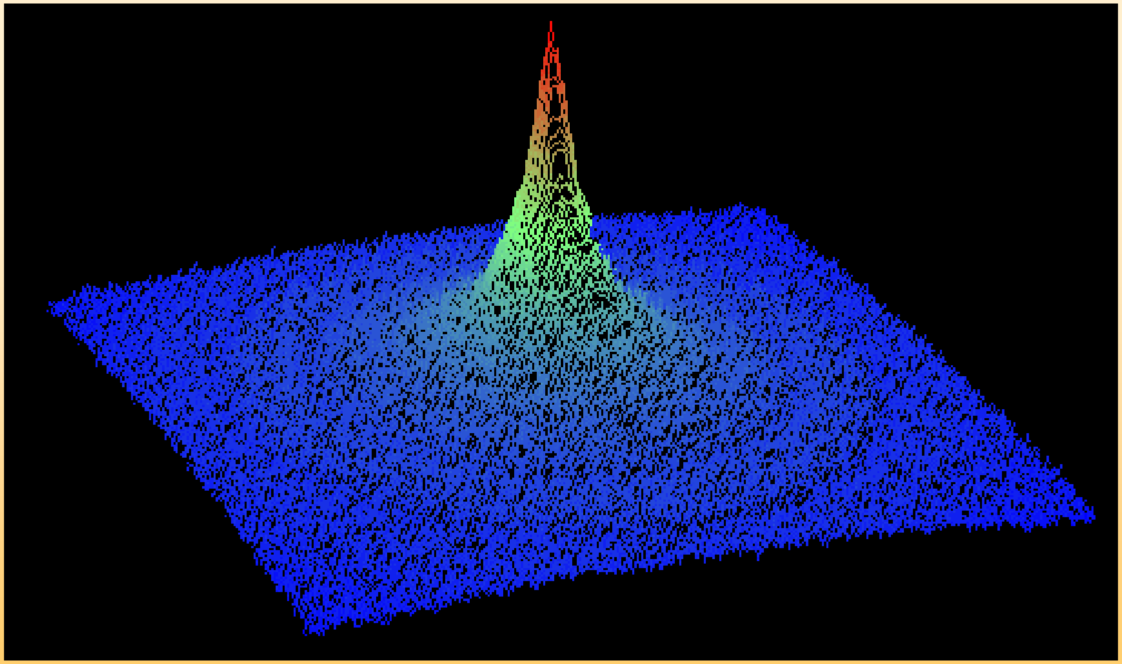
w = 3 cm
P = 30 mW

6 independant
laser beams

$N_{at} \approx 10^{10}$
$b \approx 40$


Lens
beam splitter
CCD
MOT
Probe laser

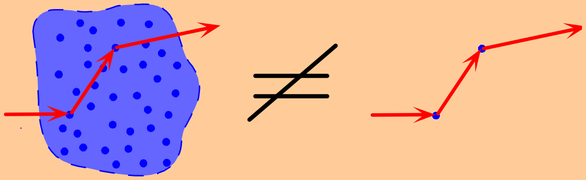




Phys. Rev. Lett. **83**, 5266 (1999)

Probing and manipulating the coherence of photons in disordered systems

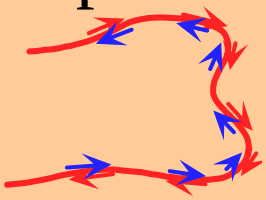
- scattering effect (cross section)
  vs propagation effect (index of refraction)



- time dependant / dynamic analysis

- interference contrast : amplitude vs phase effect
  (geometrical phase compensated)

$E_I \, e^{i\phi_I} + E_{II} \, e^{i\phi_{II}}$

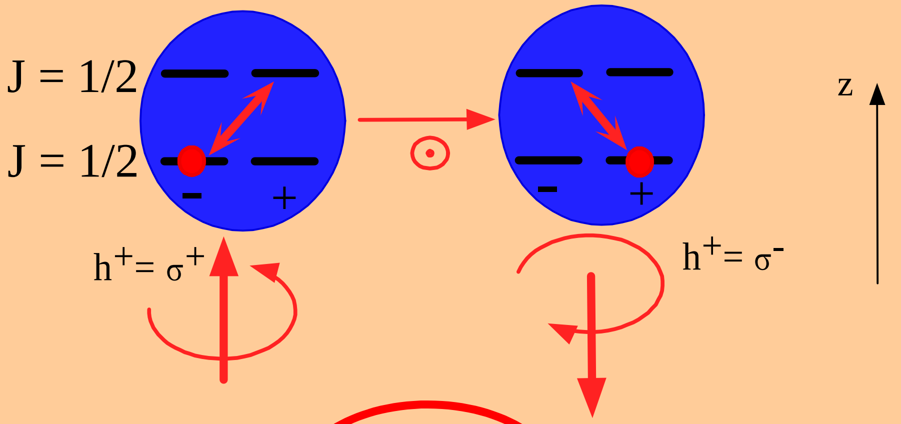


- coherence length

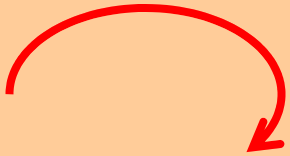
Influence of internal structure

- **Amplitude** effect : an example :

  Rayleigh scattering on J=1/2 → J'=1/2

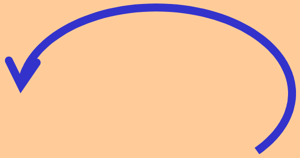


direct path :



amplitude $E_I \neq 0$

reverse path :



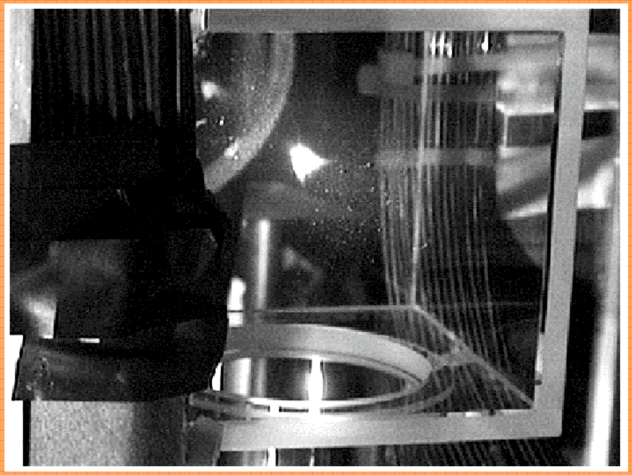
amplitude $E_I = 0$

degenerated ground state :

⇒ reduced contrast !

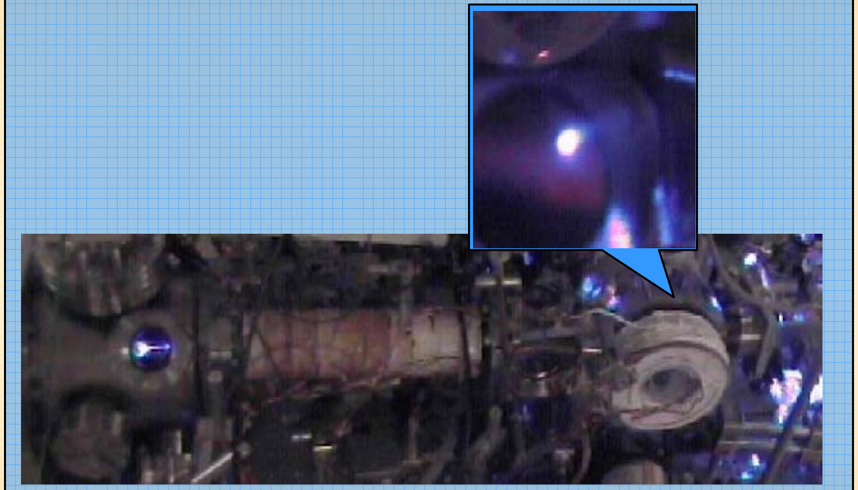
2 MOT in Nice

Rubidium (F=3 → F'=4)



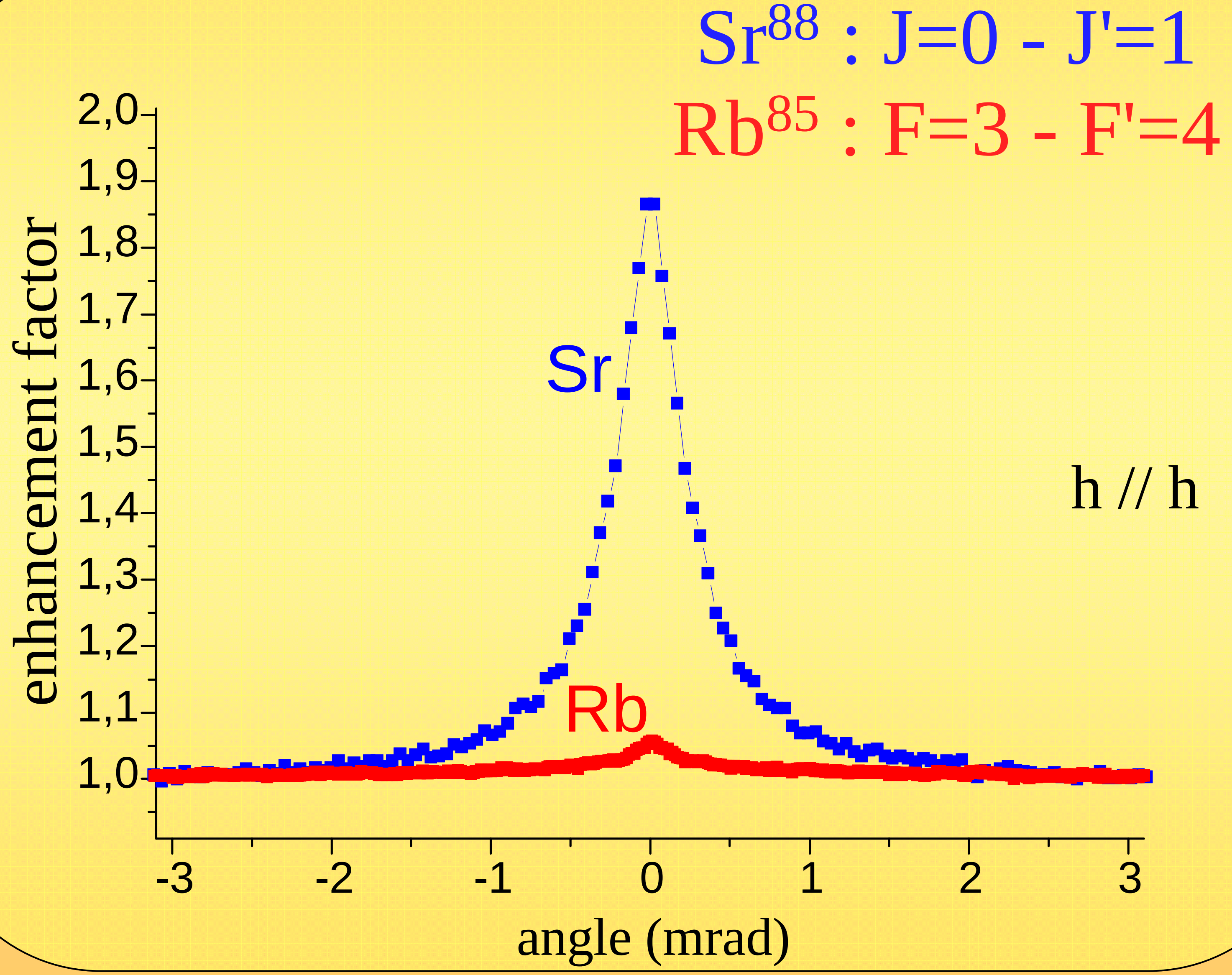
vapor trap :
optical thickness : 40

Strontium (J=0→J'=1)

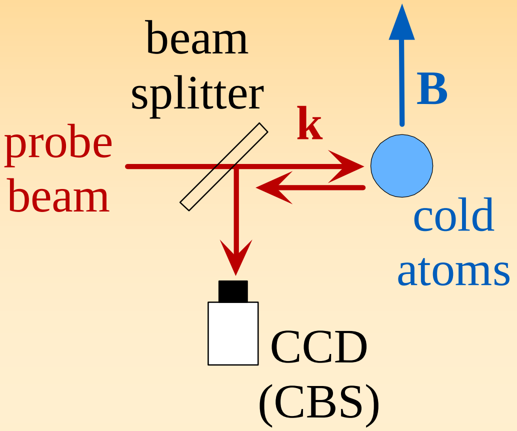


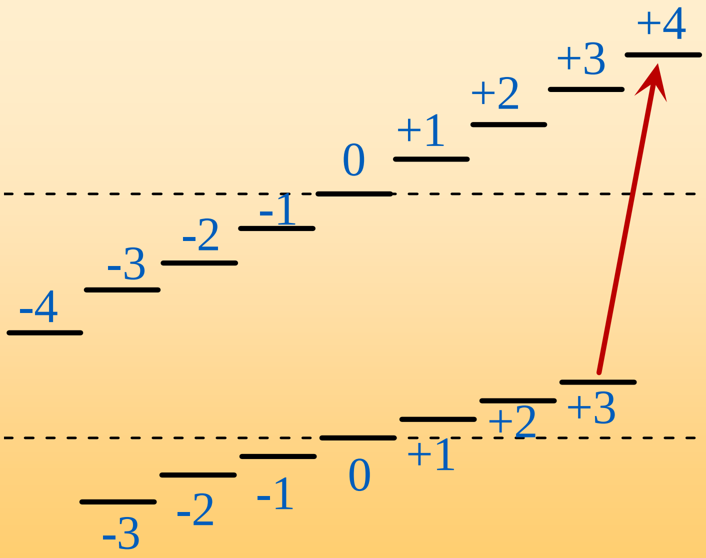
Zeeman slower :
optical thickness : 3

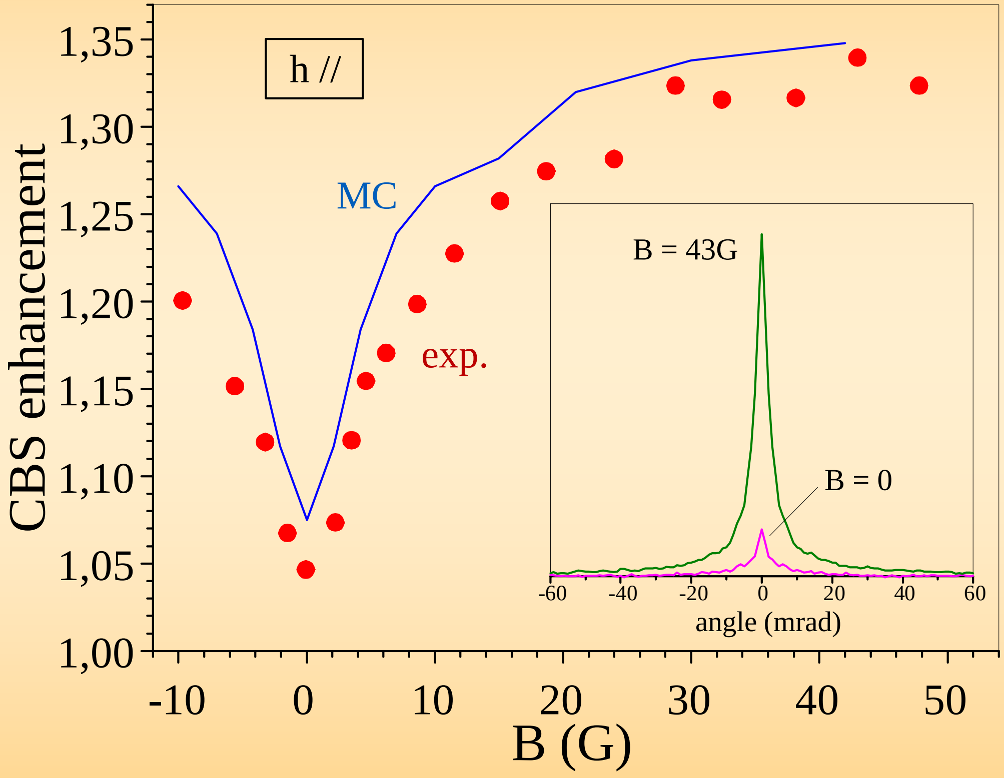
Influence of internal structure



Restoring Coherent Backscattering with Magnetic Fields



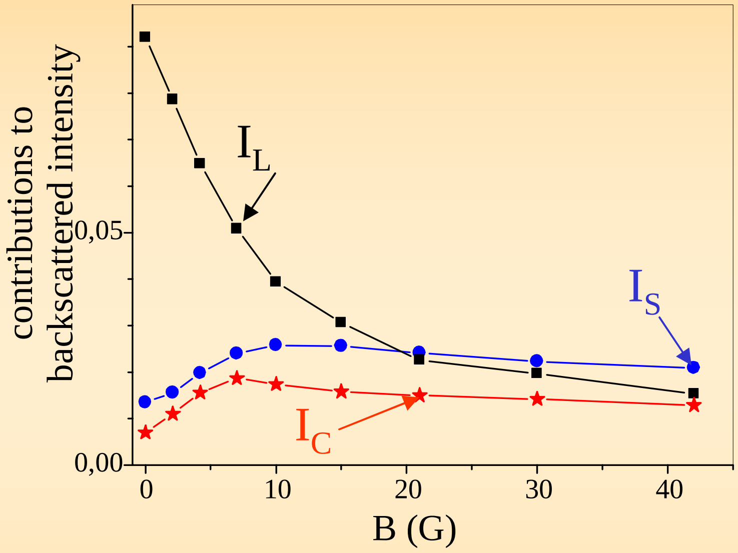


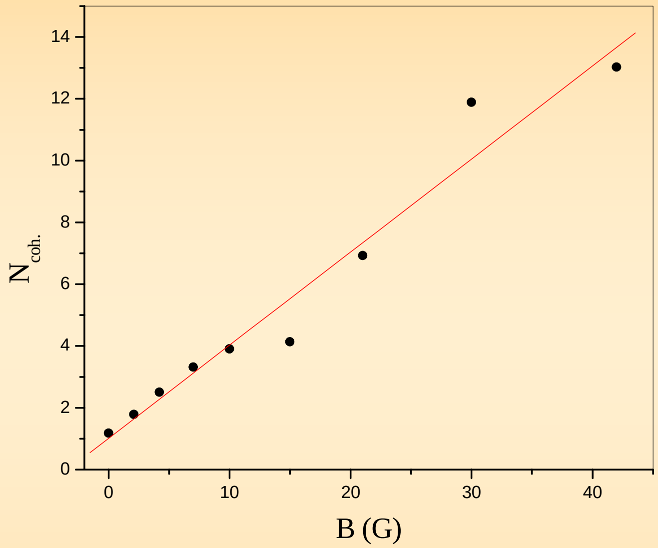


Phys. Rev. Lett. **93**, 143906 (2004)

Restoring Coherence Length with Magnetic Fields

$\mu B \gg \Gamma$ effective 2 level system





Coherence length :

☹ **REDUCED by internal structure (3-4’)**

☺ **RESTORED by magnetic field**

Weak Localization

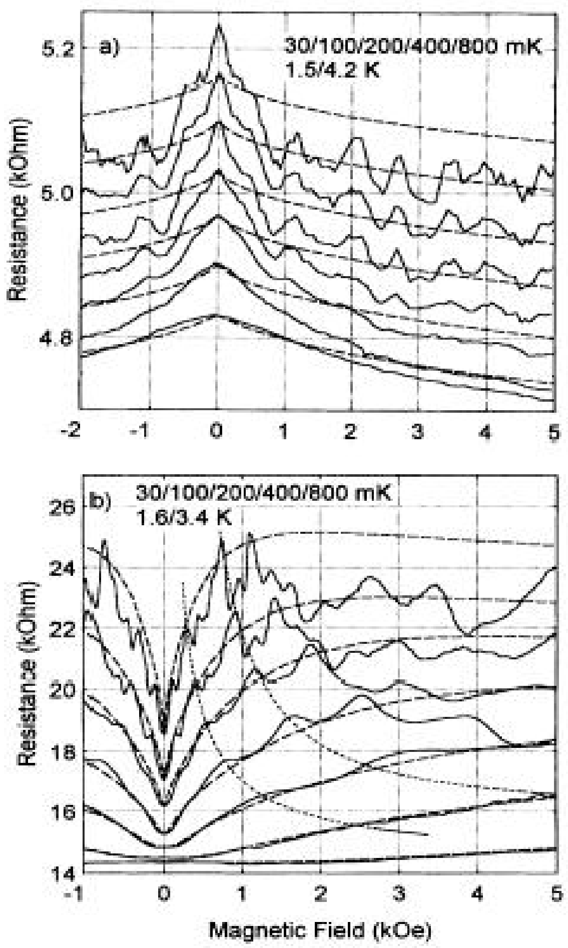


FIG. 2. Resistance changes as a function of the magnetic field for the wires of n^+-Cd$_{1-x}$Mn$_x$Te with $x = 0$ (a) and $x = 1\%$ (b) at various temperatures between 30 mK and 4.2 K (traces for the lowest temperatures are shifted upward). Dashed lines represent magnetoresistance calculated in the framework of 3D weak-localization theory [4,14]. Dotted lines are guides for the eye, and visualize a strong temperature dependence of the resistance features in Cd$_{0.99}$Mn$_{0.01}$Te (b).

negative
magneto-resistance

increased
weak localization :

magnetic impurities
+ magnetic field

from Phys. Rev. Lett. **75**, 3170 (1995)

Time Resolved Experiments :

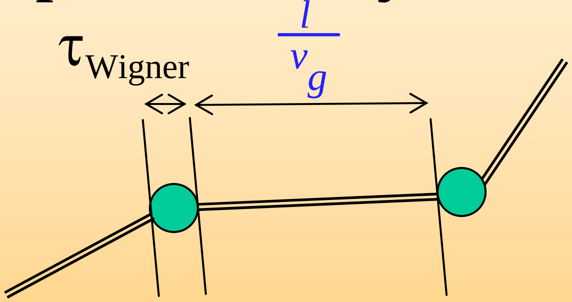
- Phase velocity : $c = \frac{c_0}{n}$ propagation of phase for a monochromatic wave

$c > 0$ $c \lessgtr c_0$

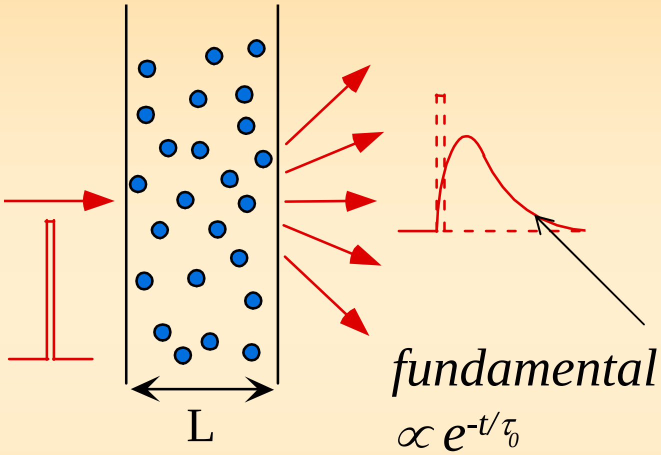
- Group velocity : $v_g = \frac{\partial\omega}{\partial k}$ propagation of transmitted gaussian pulse with slowly varying envelope

cold atoms on resonance : $v_g < 0$ $|v_g| << 0$

- Transport velocity : propagation of scattered wave energy $0 < v_{tr} < c_0$



Time Resolved Experiments : Radiation Trapping



fundamental (Holstein) mode

$\propto e^{-t/\tau_0}$

diffusion theory

$$D = \frac{1}{3}\,\frac{l_{tr}^{2}}{\tau_{tr}}$$

transport mean-free path

transport time

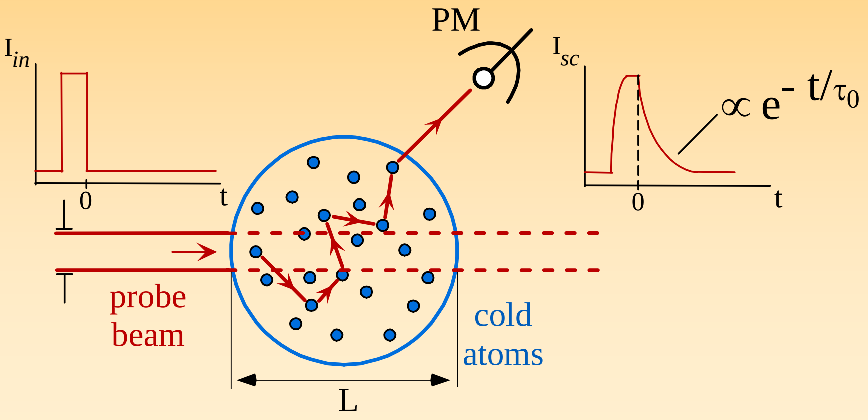
$$= \frac{1}{3}\, l_{tr}\, v_{tr}$$

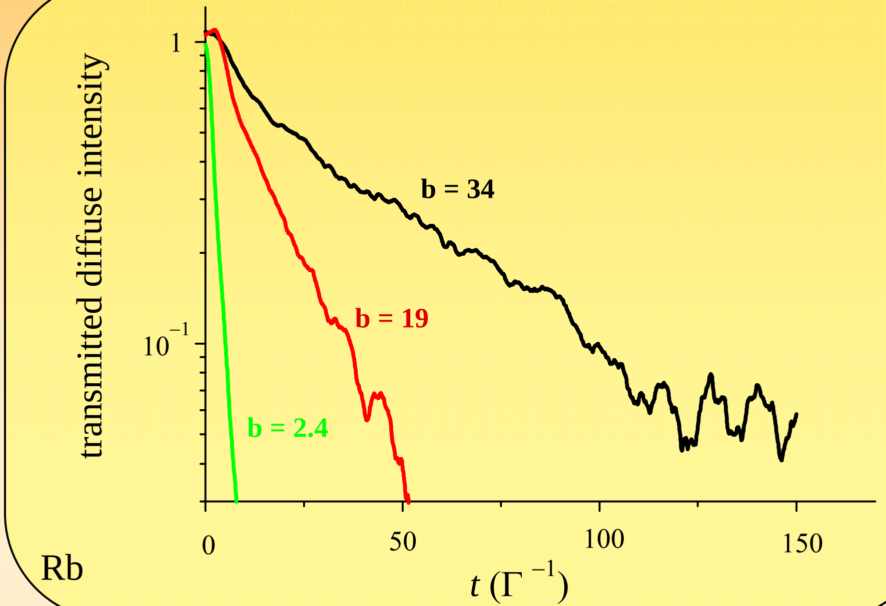
transport velocity

$$\tau_0 \approx \frac{L^2}{\pi^2 D} = \frac{3}{\pi^2}\, b^2\, \tau_{tr}$$

$b = \frac{L}{l}$ optical thickness

Slow Diffusion of Light





$$\tau_0 \approx \frac{L^2}{\pi^2 D} \Rightarrow \boxed{D \approx 0.66 m^2/s}$$

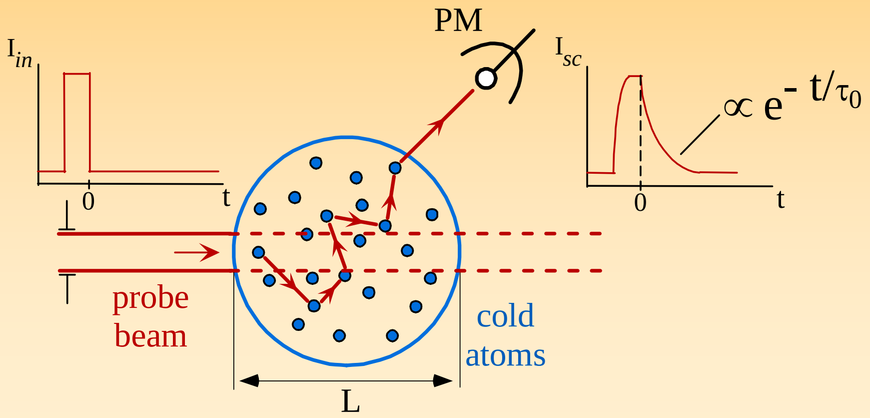
NO interference effect !

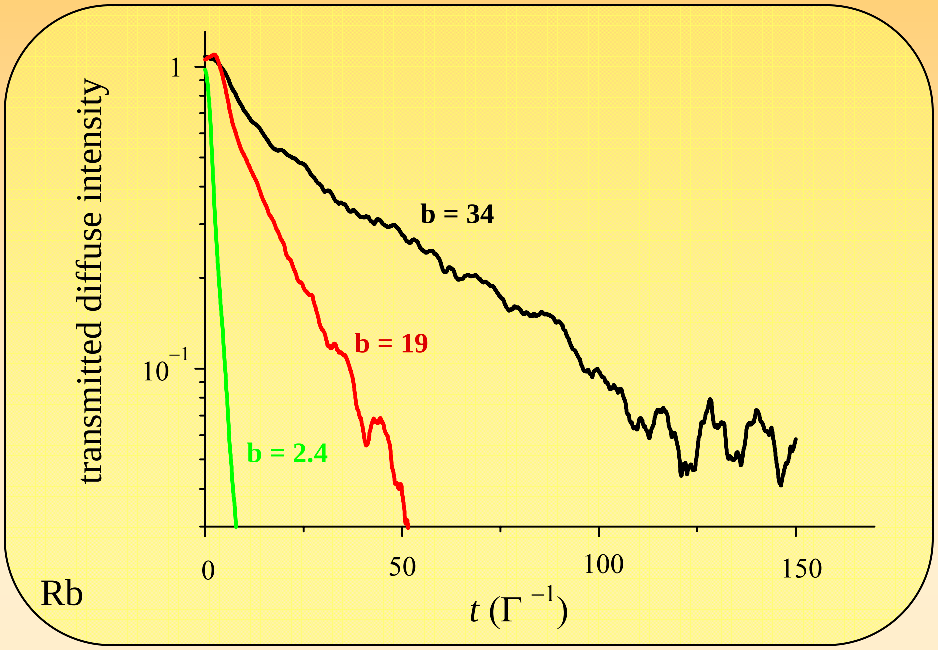
≠ Localization

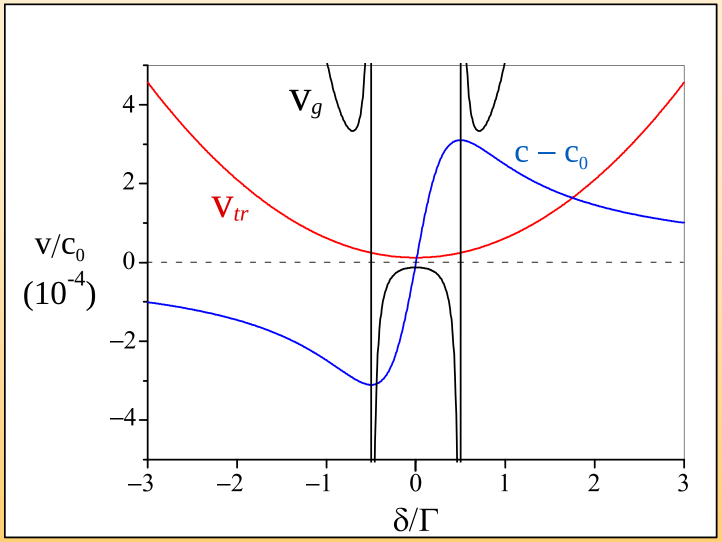
for b=34 : $\tau_0 \approx 52\ \tau_{nat}$ L=4mm

Phys. Rev. Lett. **91**, 223904 (2003)

Slow transport of Light







$b = 34$:

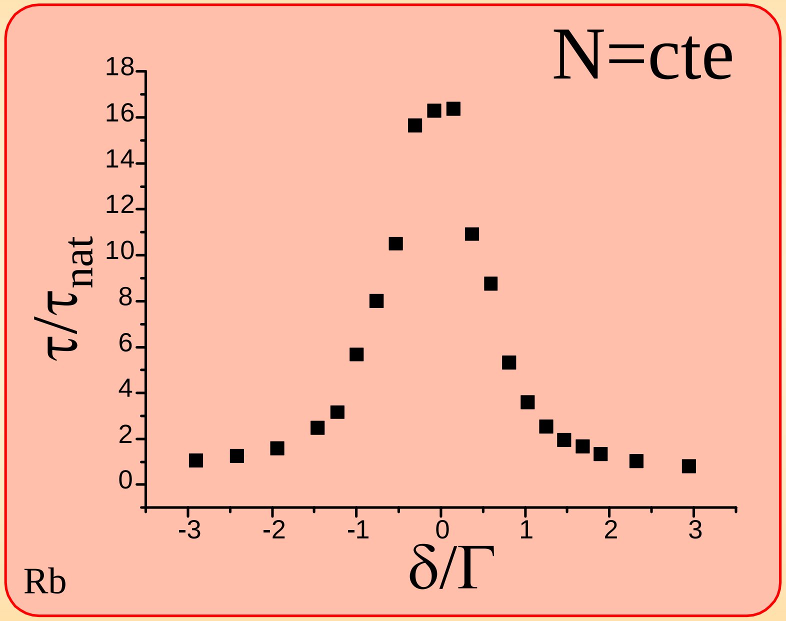
$\delta = 0$

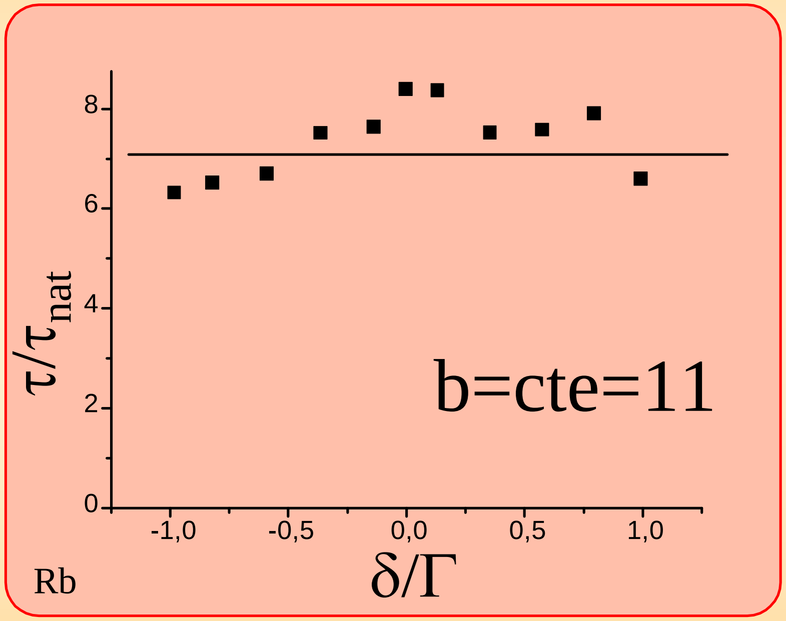
$$\frac{v_{tr}}{c_0} = \frac{\ell_{tr}}{\tau_{tr}} \approx 3 \cdot 10^{-5}$$

Phys. Rev. Lett. **91**, 223904 (2003)

Transport time for light in cold atoms

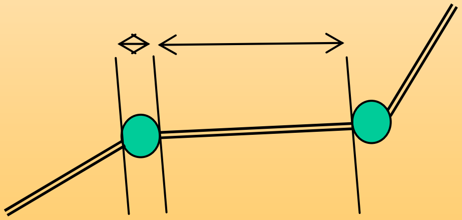
$$\tau_0 \approx \frac{L^2}{\pi^2 D} = \frac{3}{\pi^2} b^2 \tau_{tr}$$





Transport Time :
Independent of δ

$$\tau_{tr} \approx \tau_{Wigner}(\delta) + \frac{\ell(\delta)}{v_{gr}(\delta)}$$

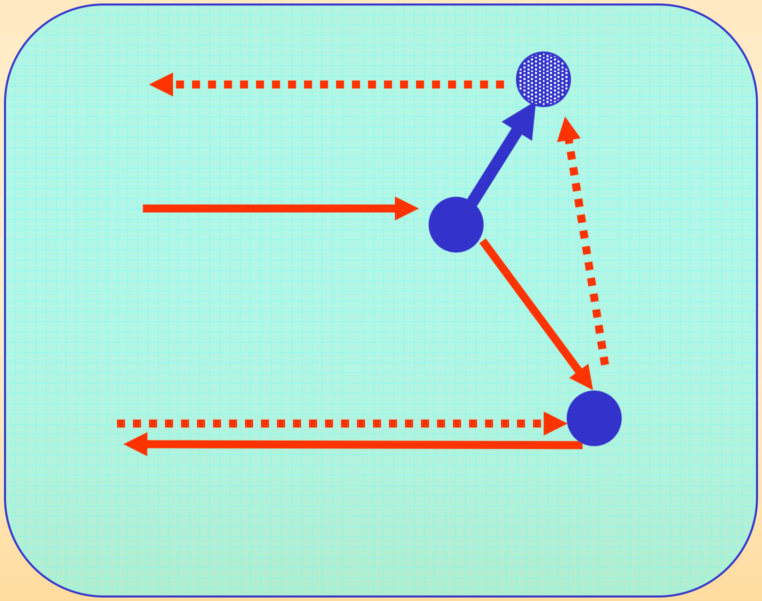


Phys. Rev. Lett. **91**, 223904 (2003)

Dynamical Breakdown of CBS

scatterer should not move faster than light

A.A.Golubenstev, Sov. JETP **59**, 26 (1984)



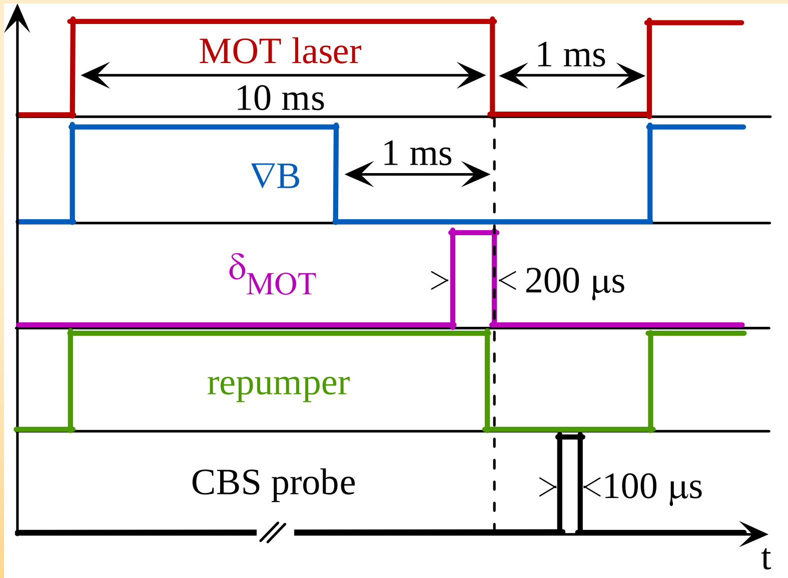
'fast' atomic dynamics
vs
'slow' light transport

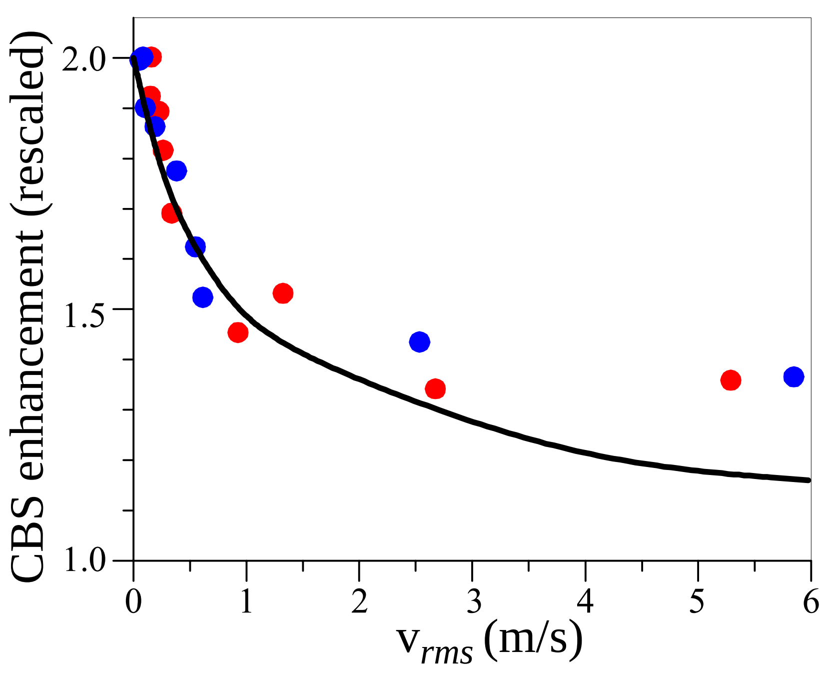
$$\mathbf{v}\,\tau_{\mathbf{tr}} \ll \lambda$$

at resonance : $\mathbf{kv} \ll \Gamma$

Experimental Observation of Dynamical Breakdown

heating by intense near-resonant optical molasse



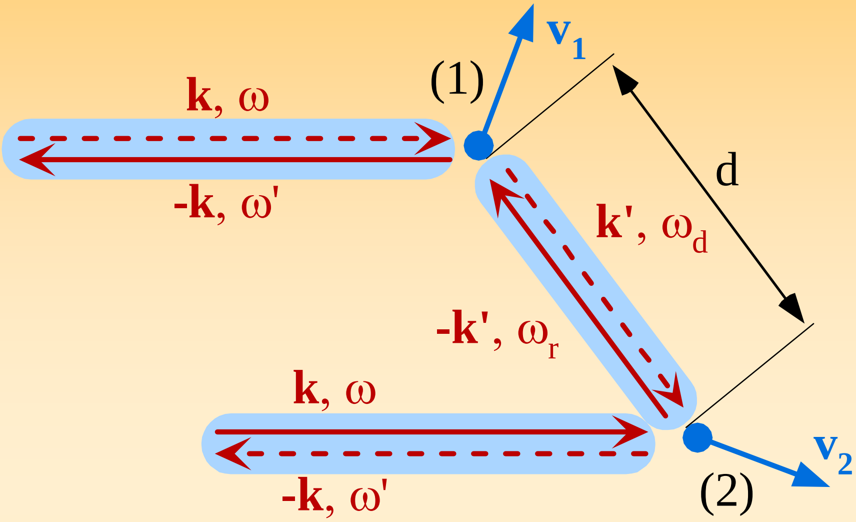


Dynamical breakdown of CBS

Doppler effect

$\Rightarrow$

$\neq$ frequencies



<u>2 contributions</u> :

- scattering :
  - attenuation : $\sqrt{\sigma} = \dfrac{1}{[1+4(\delta/\Gamma)^2]^{1/2}}$
  - phase shift : $\varphi = \arctan(\Gamma/2\delta)$

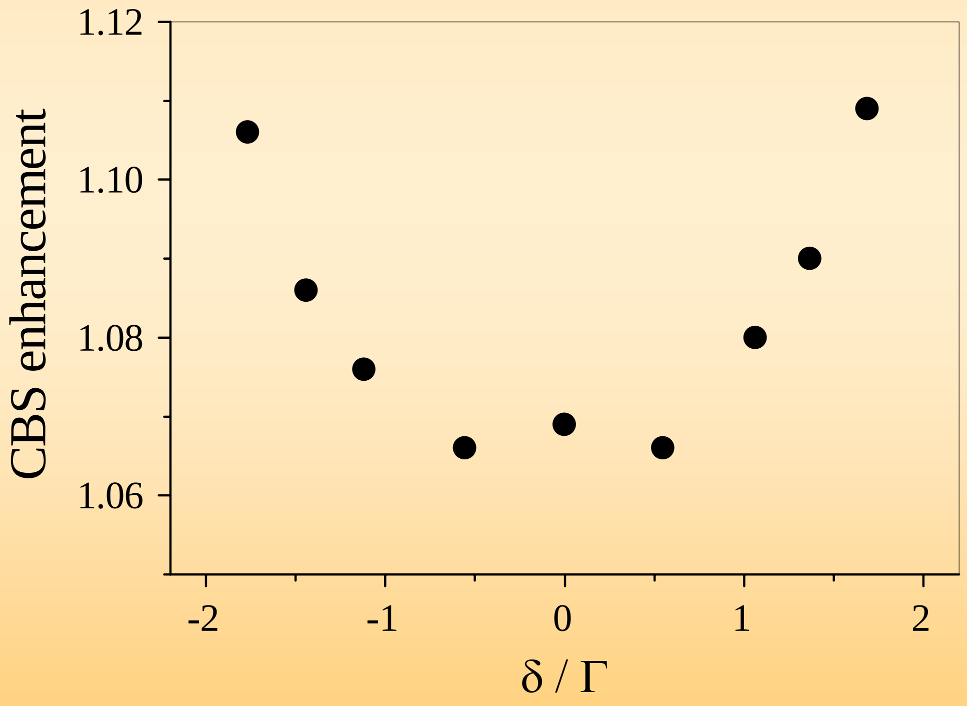
- propagation in effective medium :

$n = 1 + N\alpha/2$
  - attenuation : $e^{-d/2\ell}$
  - phase shift : $\varphi = 2\pi.n.d / \lambda_0$

Dynamical Breakdown of CBS

large detuning : $\delta >> kv$

$\Rightarrow$ partial restoration of interference contrast

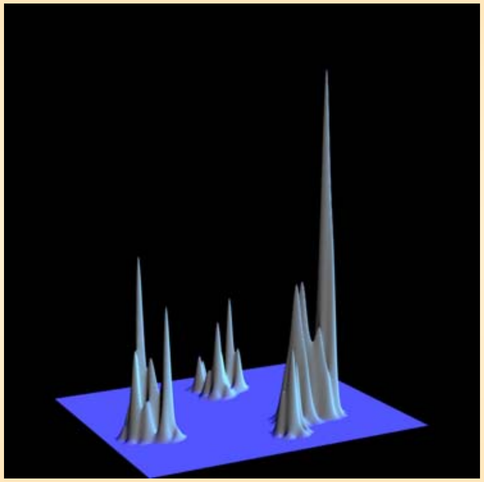


$\Rightarrow$ room temperature CBS possible?

Inelastic light scattering

In localized regime ⇒

large build-up factors expected

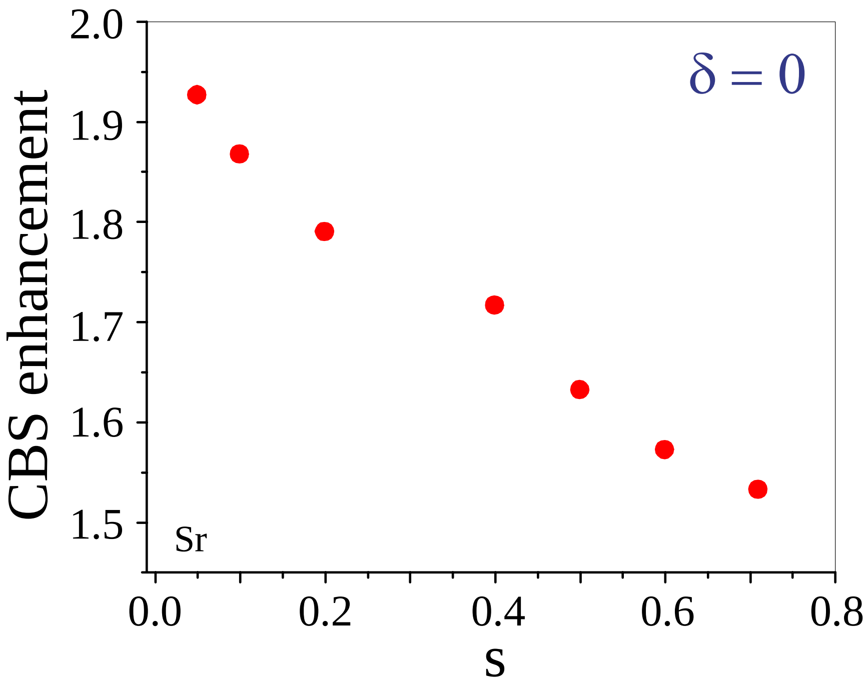


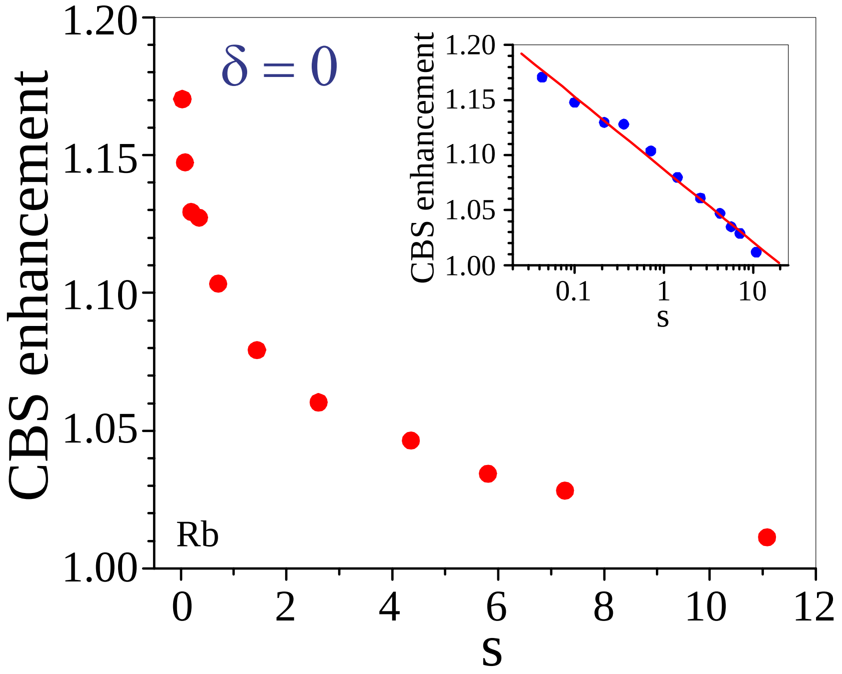
⇒ saturation of atomic transition

⇒ inelastic scattering : phase coherence ?

Influence of larger saturation on CBS

inelastic scattering : Mollow triplet ...





Phys. Rev. E 70, 036602 (2004).

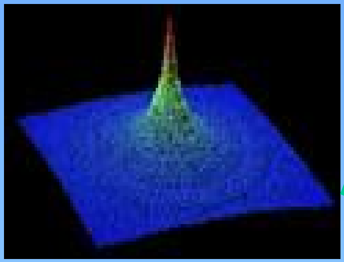
Inelastic scattering effects similar to Doppler induced frequency redistribution

Some questions concerning matter wave scattering by light potential

Light scattering		Matter wave scattering
Polarization of light	↔	Internal structure of atoms
Internal structure of atoms	↔	Polarization of light
Electric field : $\partial_t^2 E$	↔	Matter wave : $\partial_t \Psi$
Resonant point scatterers	↔	Continuous potential
Classical fields / bosons	↔	Bosons / Fermions

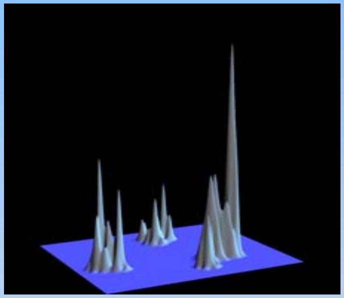
Perspectives

Light scattering



Coherent light transport beyond CBS

- ⇒ (quantum) statistics
- ⇒ fluctuations, correlations
- ⇒ Sagnac interferometer ($v_{tr}/c=10^{-5}$)
- ⇒ random laser (+ gain)

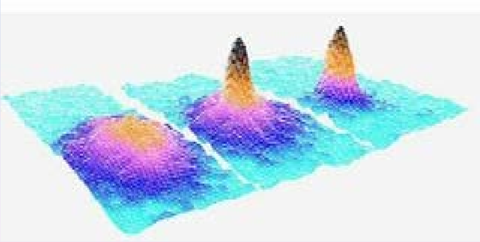


Strong Localization : $n\lambda^3 \approx 1$

- ⇒ dynamical analysis, spectroscopy
- ⇒ cold collisions & super-/subradiance
- ⇒ dipole blockade?

Matter wave scattering

Rb : BEC
Sr : ‘red’ MOT

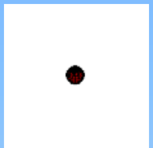


CBS with matter waves
Strong Localization

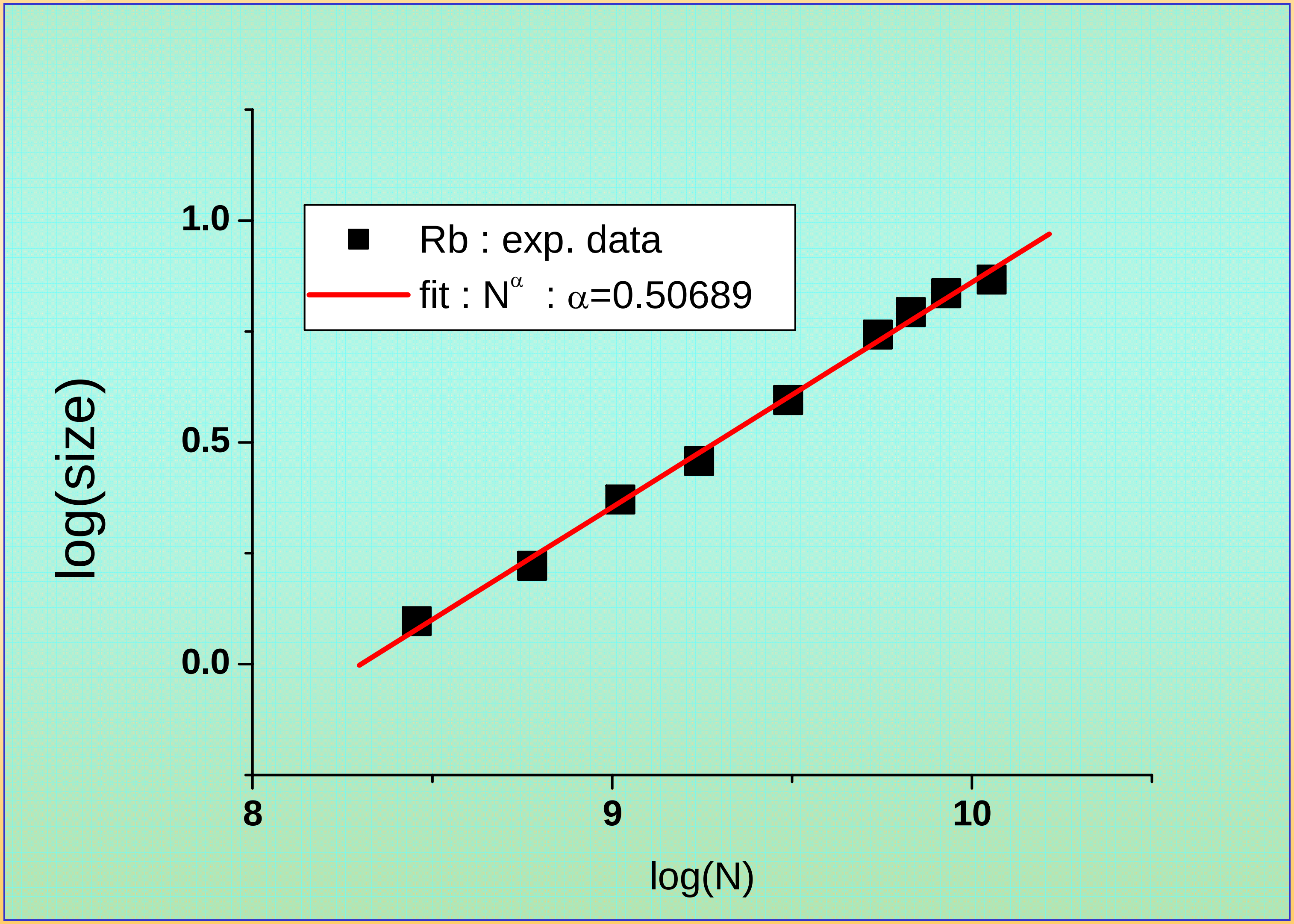
Current Status of our experiments :

Rb :

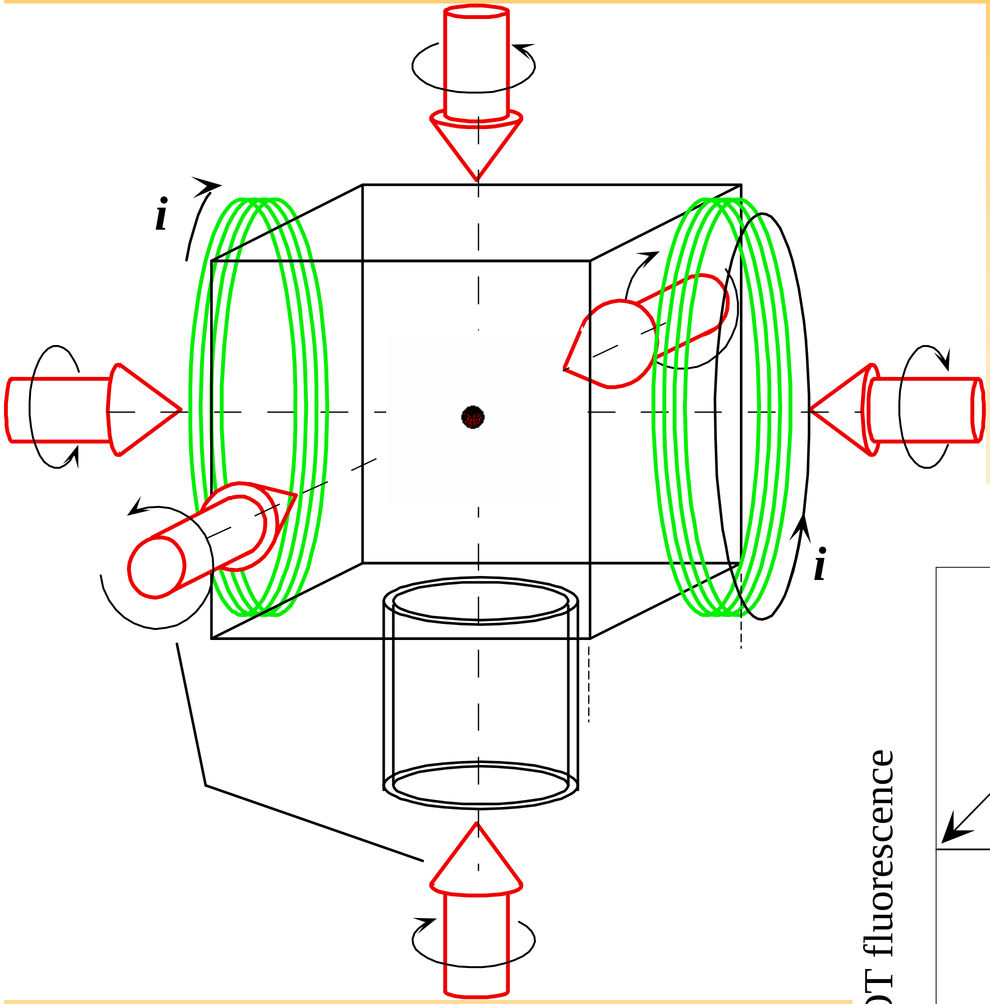
- ⇒ new scaling law : $L \propto \& N$: ✓
- ⇒ compression : $n\lambda_{opt}^3 \approx 1$
- ⇒ random laser (add pump) : 4 wave mixing : ✓
- ⇒ plasma physics (mechanical effects) : ✓



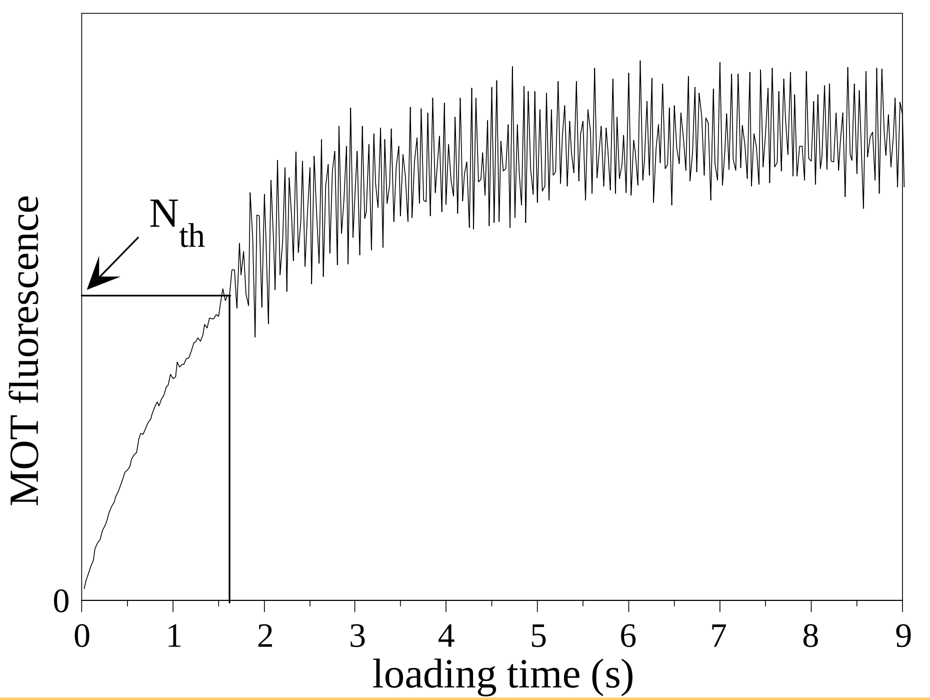
MOT size with many cold Atoms ⇒ compression...



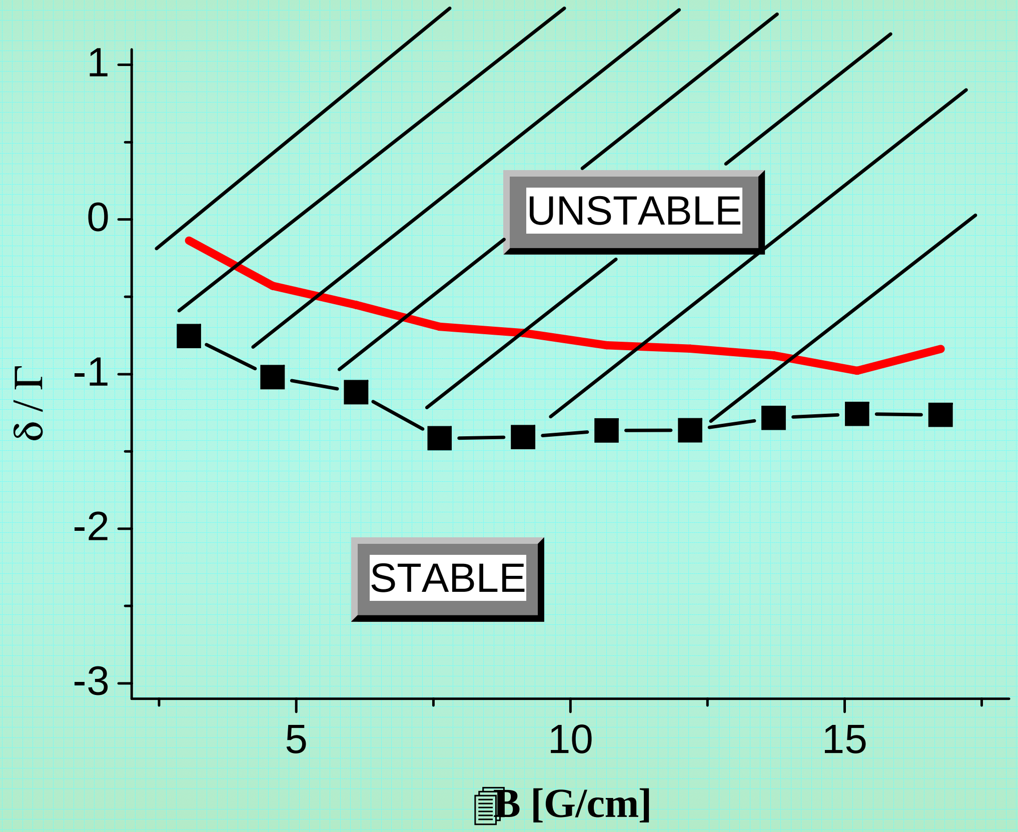
Self Sustained Oscillation of MOT size



MOT Loading



Instability : phase diagram



Current Status of our experiments :

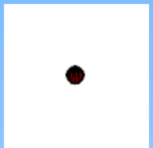
Rb :

⇒ new scaling law : $L \propto$ 🙰 N : ✓

⇒ compression : $n\lambda_{opt}^3 \approx 1$

⇒ random laser (add pump) : 4 wave mixing : ✓

⇒ plasma physics (mechanical effects) : ✓



Sr :

⇒ extra heating on blue MOT : ✓

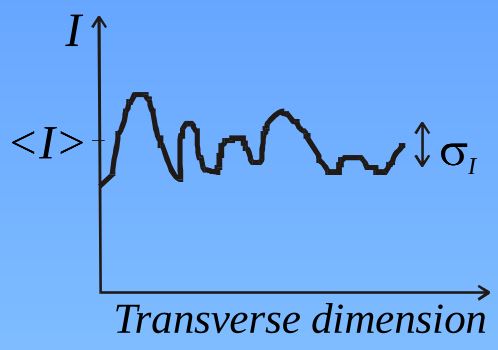
⇒ Red Mot (50% transfer efficiency) : ✓

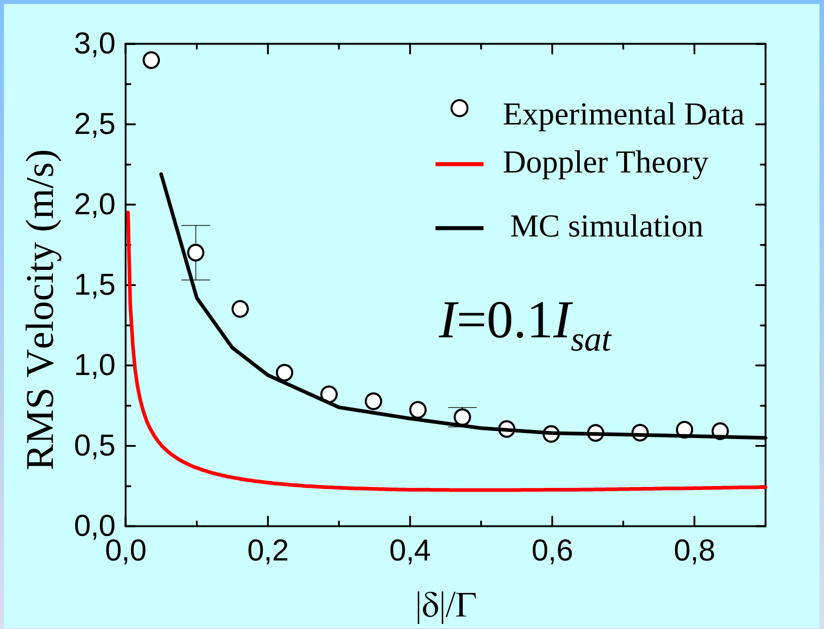
⇒ $T=1\mu K$: ($n\lambda_{DB}^3 \approx 10^{-4}$) ✓

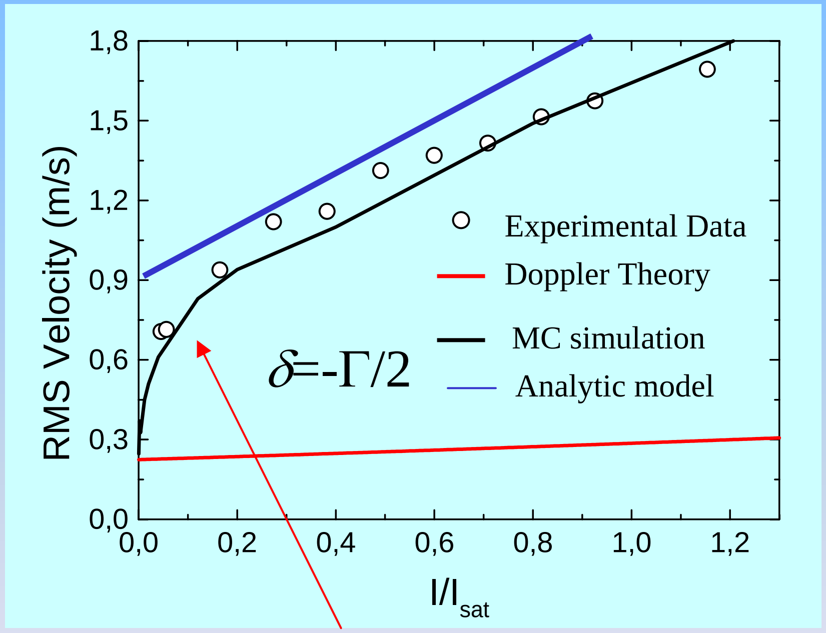
⇒ more cooling and more atoms : $n\lambda_{opt}^3 \approx 1$

⇒ cold collision (blue MOT) ✓

Atom moving across laser profile: additional fluctuations ⇒ heating (correlation time vs friction)







$\tau_c=\tau_v$

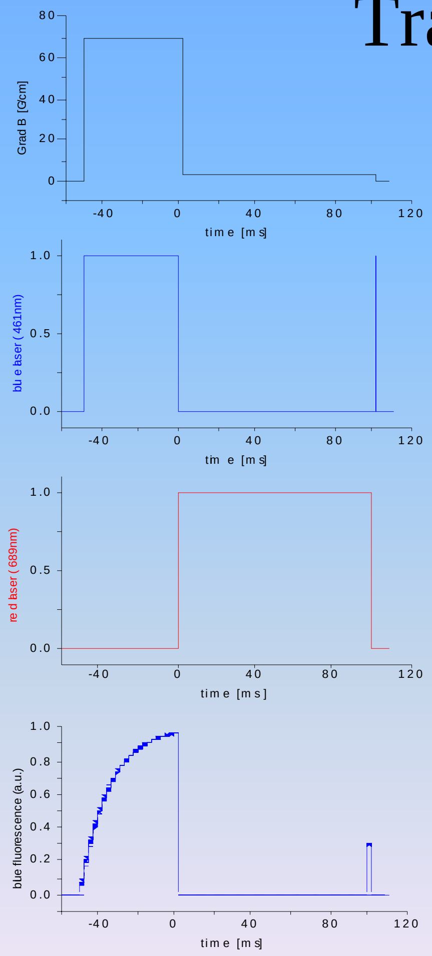
$\sigma_I/\langle I\rangle=0.18$ and $L_c=100$ μm, $v_\perp=1$m/s ⟷ $\tau_c=100$ μs

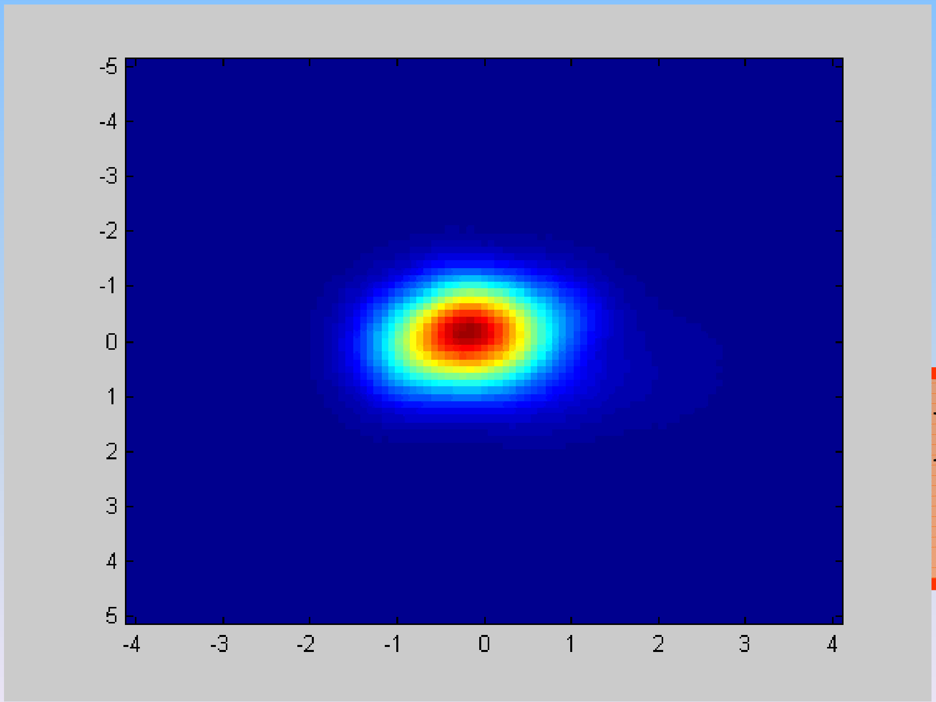
Broadband Transfer to Red MOT

Transfer Limitation :

atoms moving out of the laser

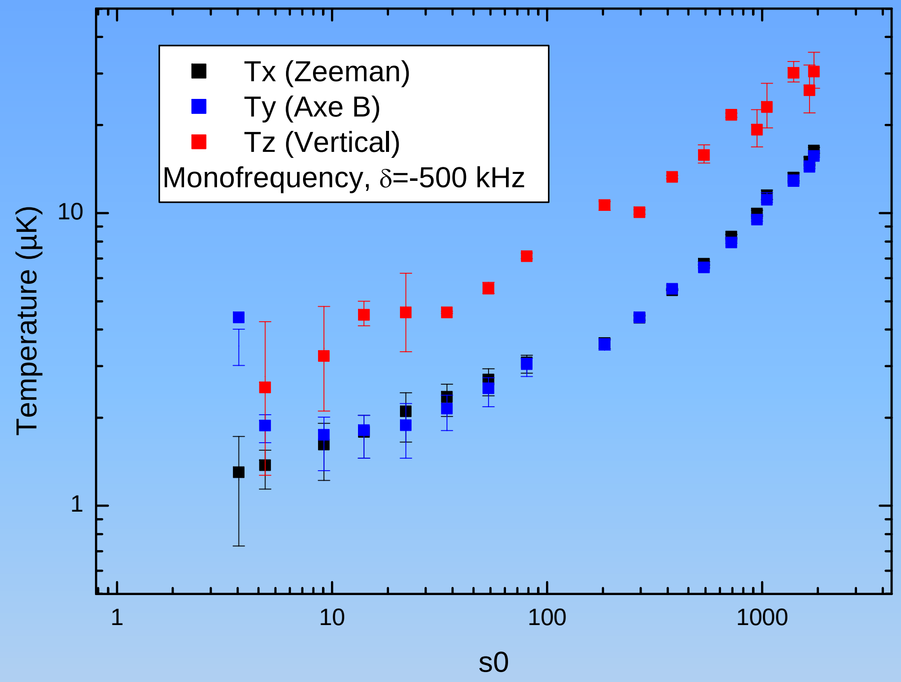
atoms moving out of resonance





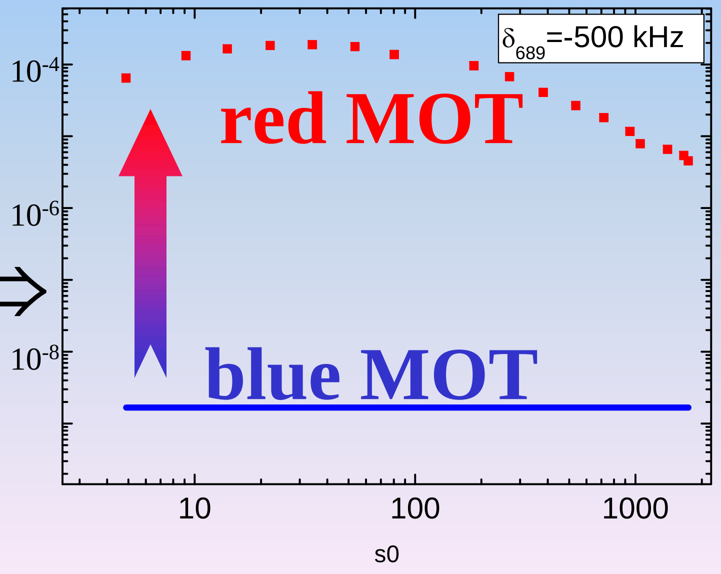
Max transfer :
50% !

Sr : Red MOT



⇐ temperature

phase space density ⇒



Towards strong localization of light