Multiple scattering of light in cold atoms : from light localisation to plasma physics

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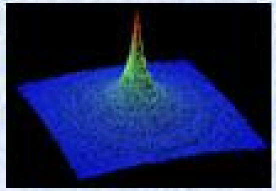
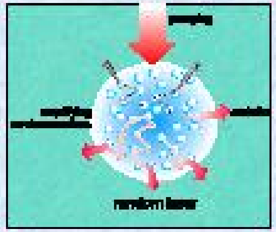
1) Multiple scattering :

- **Light Localization**



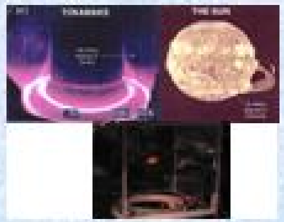
- **(Random) Atom Laser**

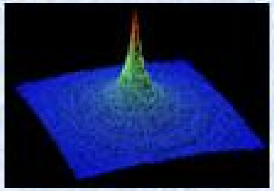


- **Lévy Flight**

2) Mechanical effects :

- **Plasma physics**





1) Multiple scattering :

- **Light Localization**
- (Random) Atom Laser
- Lévy Flight

2) Mechanical effects :

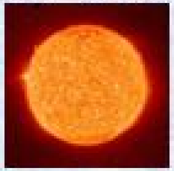
- Plasma physics

Wave propagation in disordered media :

< 1958 : on average : interferences washed out : random walk / diffusion

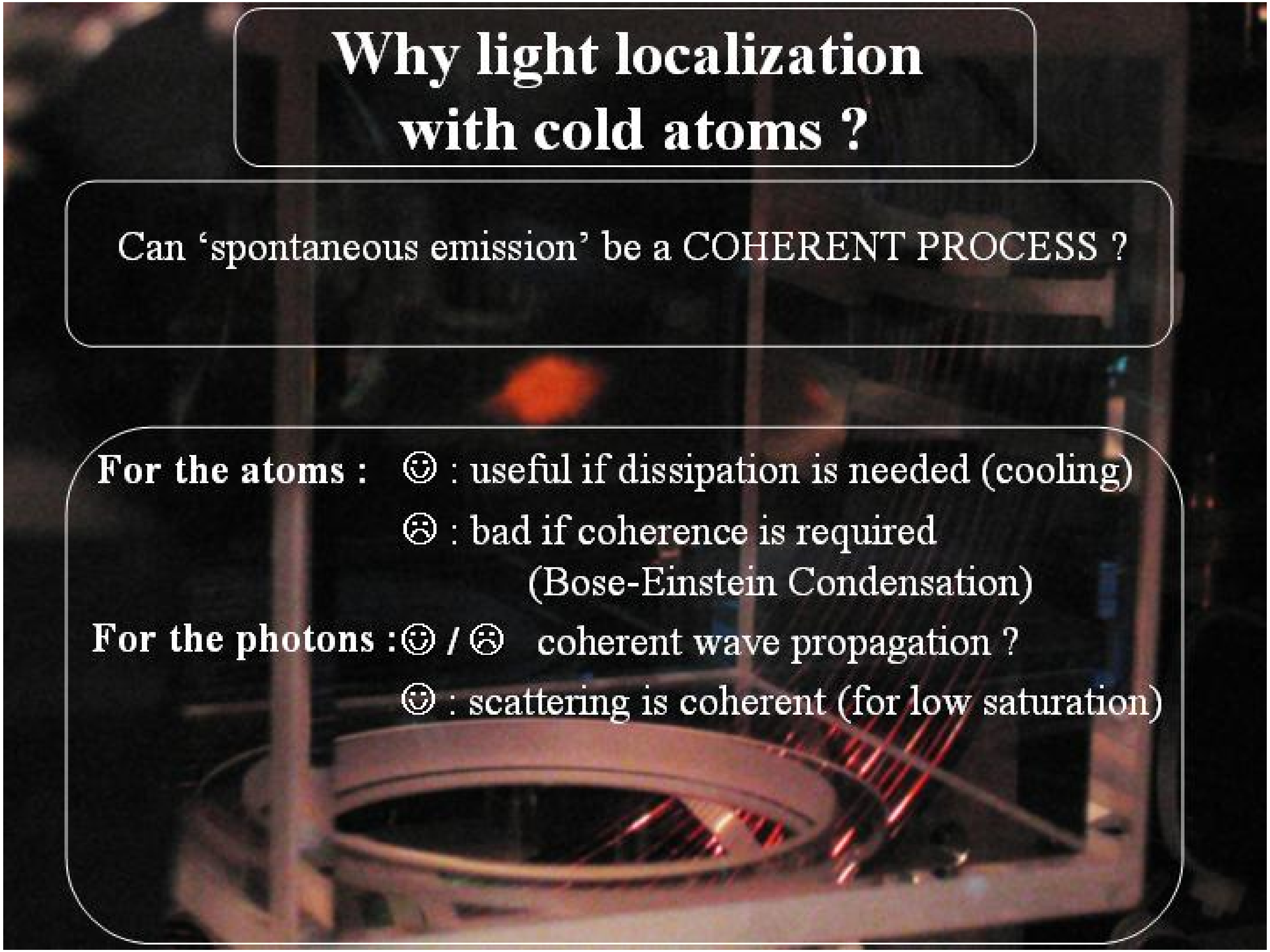
Light : radiation trapping in stars

Electrons : metal (Drude model)



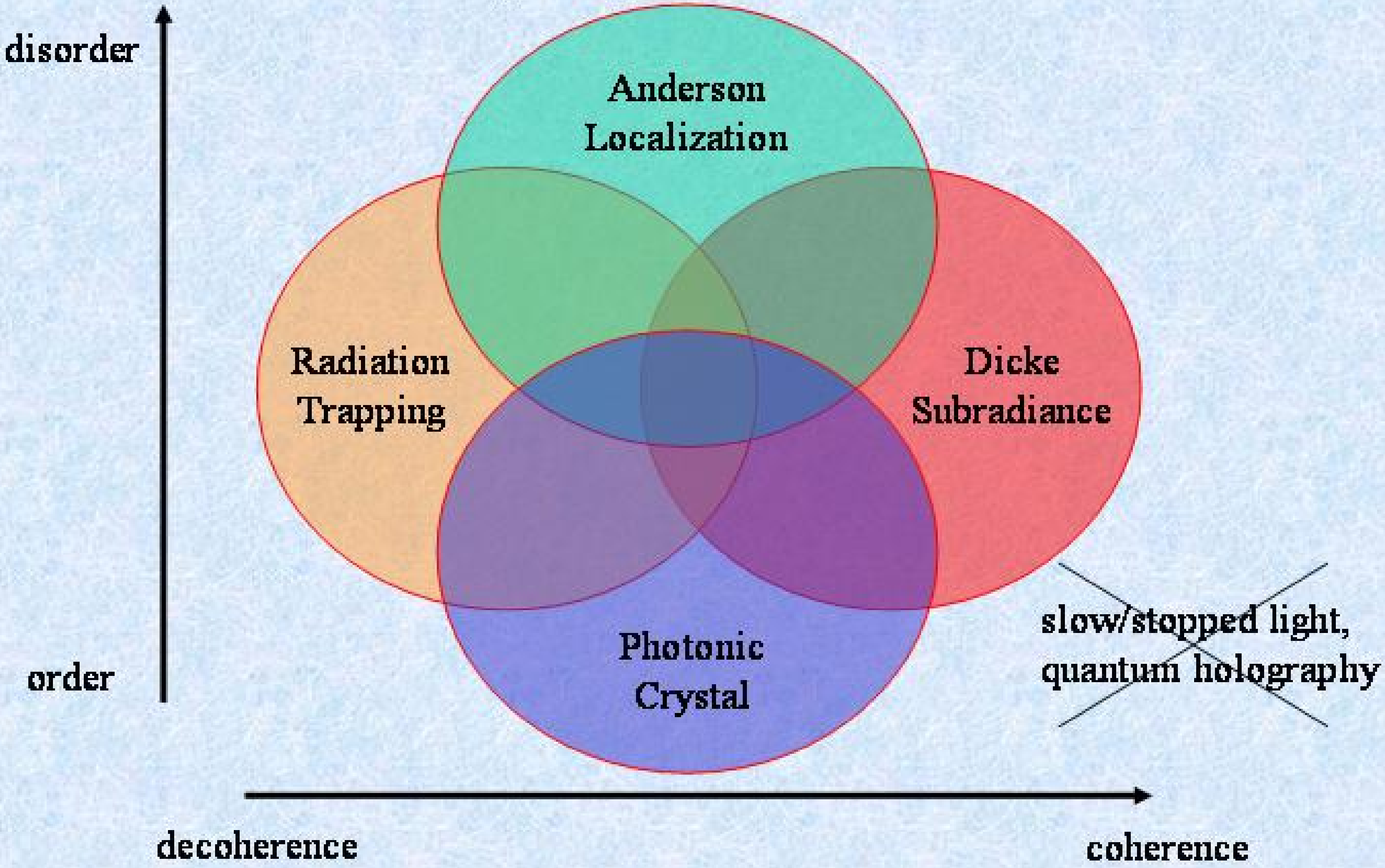
1958 : P.W. Anderson : vanishing diffusion for strong disorder !

- **Solid State Physics :**
  Metal-Insulator Transitions for electrons
- **Light Scattering :**
  Photonic Crystals, Colloidal Systems, White Paint
- **Bose-Einstein Condensate :**
  Matter Waves in Disordered Potential
- **Atomic physics :**
  Radiation Trapping, Dicke States


Why light localization
with cold atoms ?
Can ‘spontaneous emission’ be a COHERENT PROCESS ?
For the atoms : ☺ : useful if dissipation is needed (cooling)
☹ : bad if coherence is required
(Bose-Einstein Condensation)
For the photons : ☺ / ☹ coherent wave propagation ?
☺ : scattering is coherent (for low saturation)

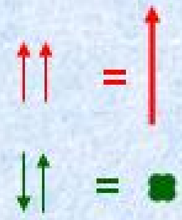
Atomic Physics and Quantum Multiple Scattering :

How to trap a photon with N atoms ?



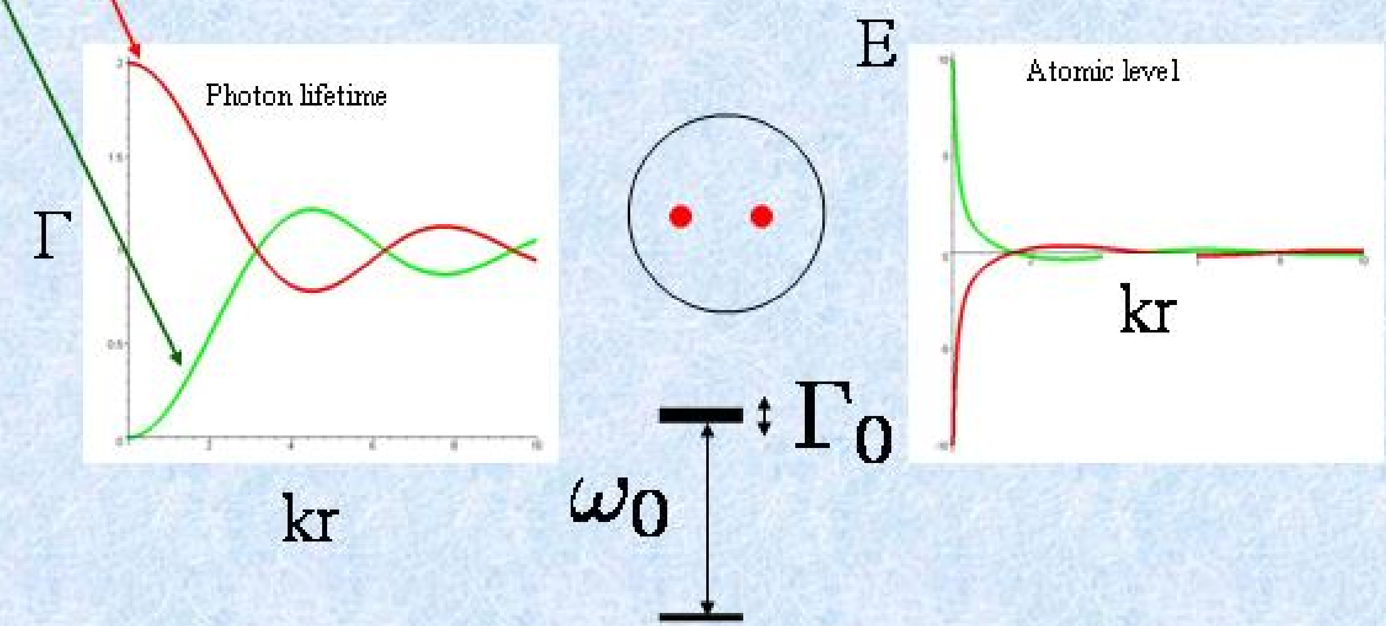
How to trap 1 photon with 2 atoms ?

1954 : Dicke



Superradiance = symetric state (±easy to observe)

Subradiance = antisymetric states (difficult to observed)

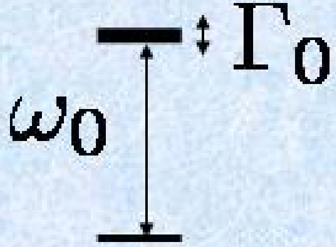


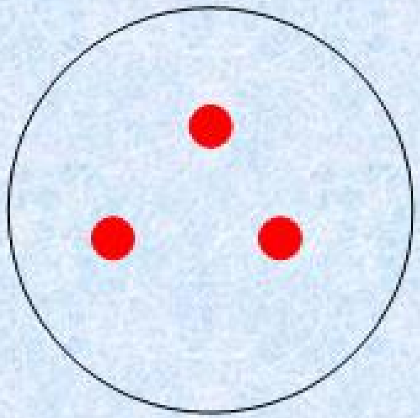
Can one bind 3 atoms with 1 photon?

or

Can one bind 1 photon with 3 atoms ?

$$\mathrm{H}_e = \left(\hbar\omega_0 - i\frac{\hbar\Gamma_0}{2}\right) S_z + \frac{\hbar\Gamma_0}{2} \sum_{i\neq j} V_{ij} S_i^+ S_j^-$$



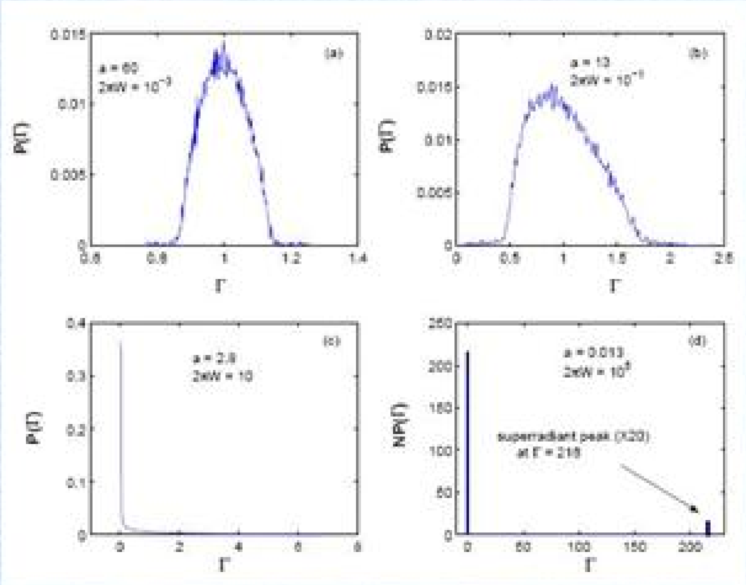


possibility of Effimov type bound states ?

Photon Escape Rates from effective Hamiltonian

$$\mathrm{H}_e = \left(\hbar\omega_0 - i\frac{\hbar\Gamma_0}{2}\right) S_z + \frac{\hbar\Gamma_0}{2}\sum_{i\neq j} V_{ij} S_i^+ S_j^-$$

$$\Gamma_{ij} \equiv \langle \gamma_{ij} \rangle = \frac{\sin x_{ij}}{x_{ij}}$$

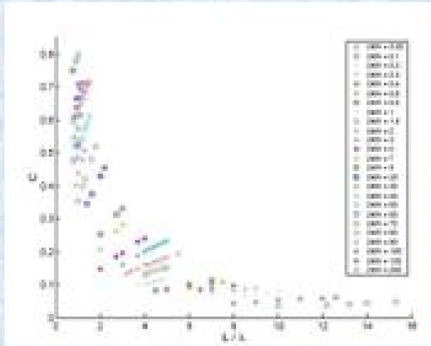


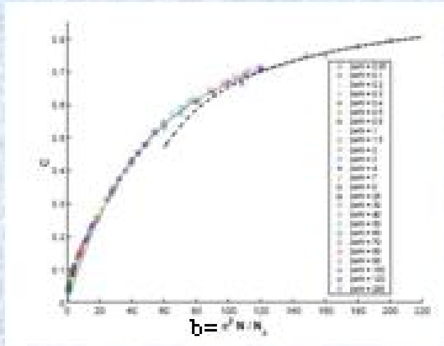
size : a = L/λ

disorder parameter W=1/kl

scaling parameter C

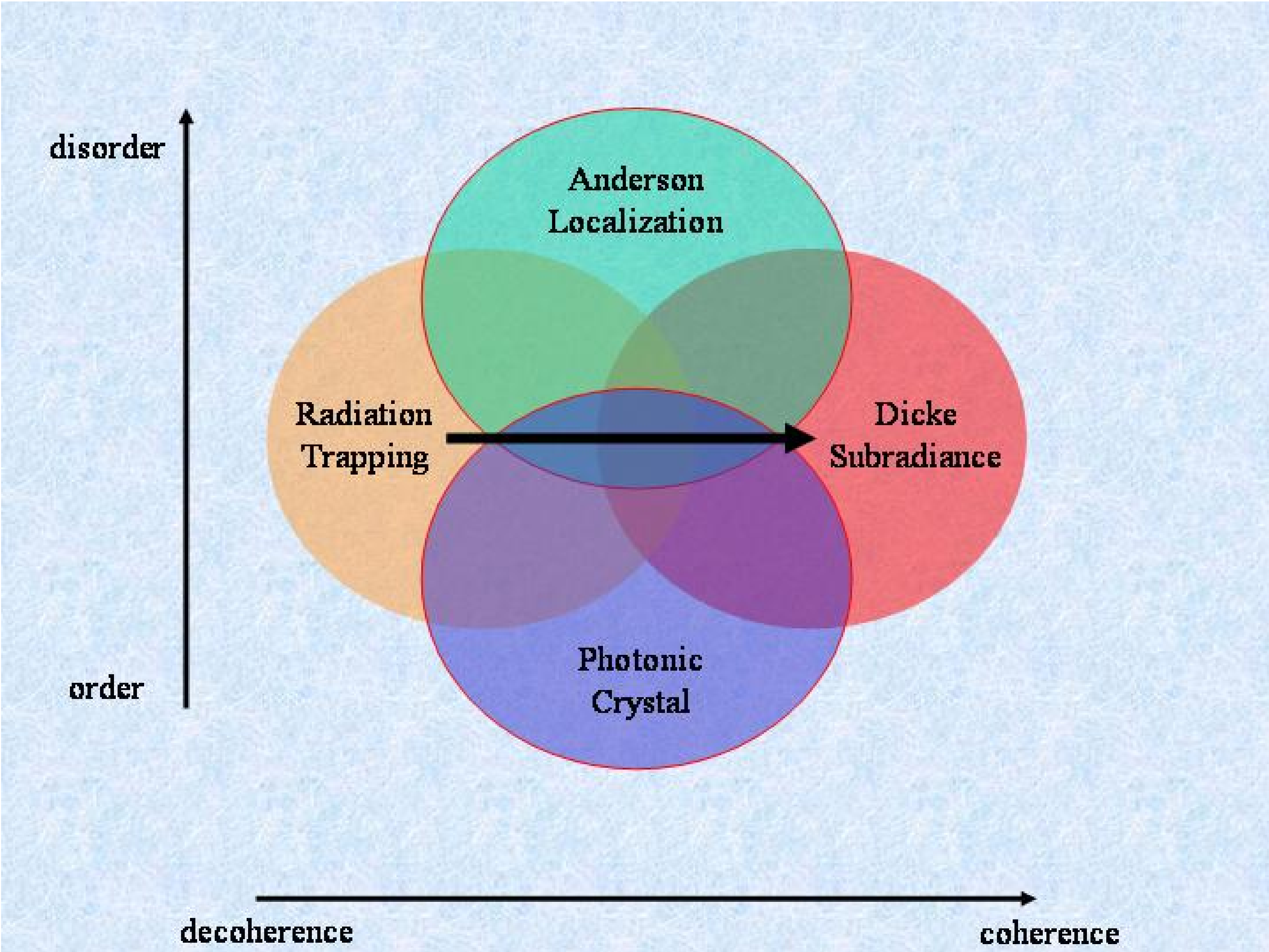
$$\mathrm{C(a,W)} = 1\text{-}2 \int_1^{\infty} d\Gamma P(\Gamma)$$





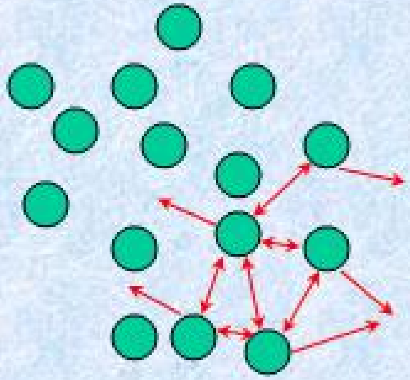
no phase transition observed with P(Γ)

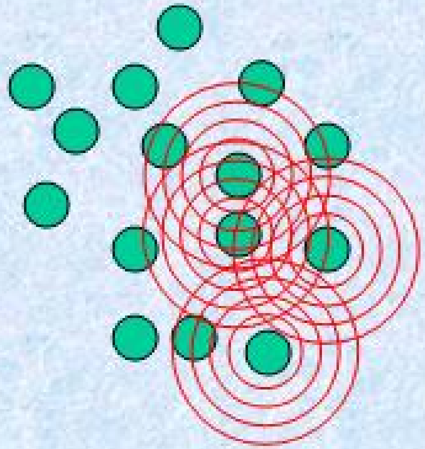
E. Akkermans, A. Gero, R. Kaiser, Phys. Rev. Lett, **101**, 103602 (2008)



disorder
order
Anderson Localization
Radiation Trapping
Dicke Subradiance
Photonic Crystal
decoherence
coherence

Photons ... ... are waves





Random walk :

Diffusion coefficient

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

$\ell = 1/n\,\sigma$

Interference correction to Diffusion coefficient

$D \approx D_0\,[1 - 1/(k\,\ell)^2]$

Strong Localization (D=0) :

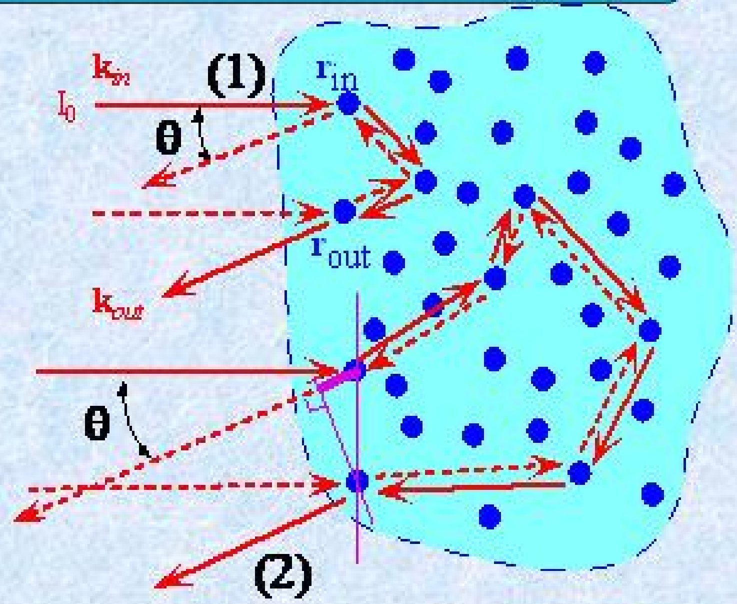
Ioffe-Regel criterium : $k\,\ell \approx 1$

(near field scattering $\ell \approx \lambda$)

$n \approx 10^{14}$ at/cc

Weak Localization => Coherent Backscattering

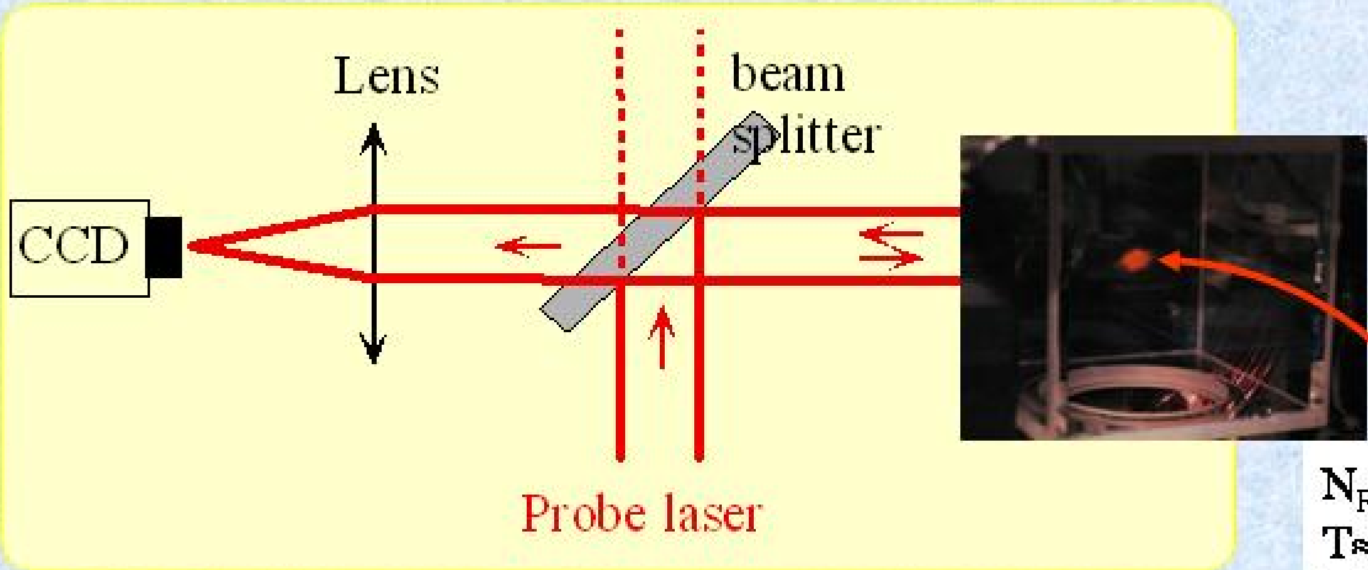
- **uncorrelated** paths add incoherently
- **correlated** (i.e. reciprocal) paths add coherently



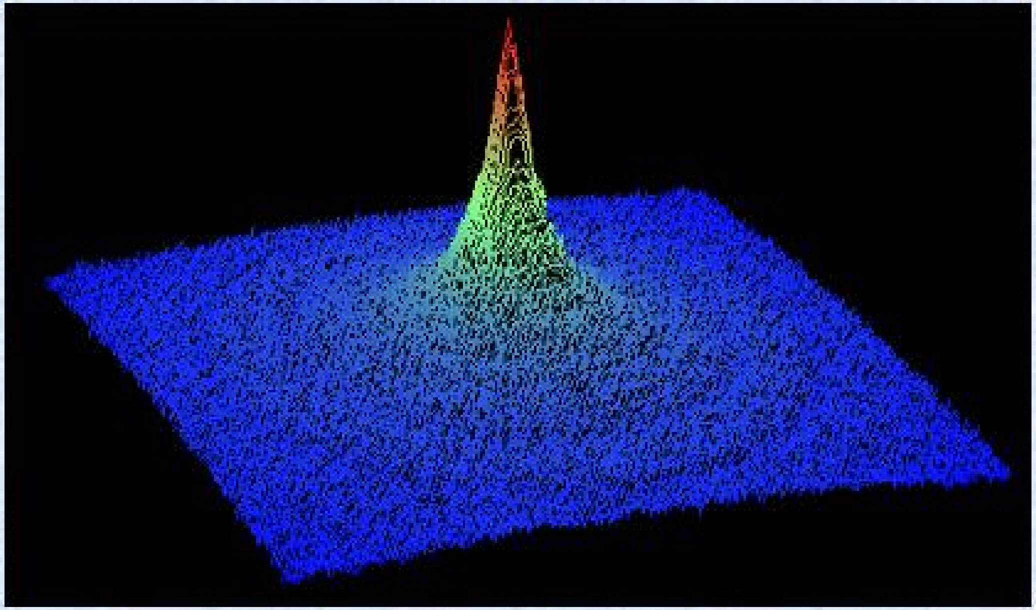
$\Delta\varphi = (k_{in} + k_{out}).(r_{in} - r_{out})$ $\theta = 0 \Rightarrow \Delta\varphi = 0$ for any path

Coherent Backscattering $\frac{\langle I(0) \rangle}{\langle I(\theta) \rangle} = 2$

multiple self-aligned Sagnac interferometer



$N_{Rb} \approx 10^{10}$
$T \approx 100 \mu K$
$kl \approx 1000$

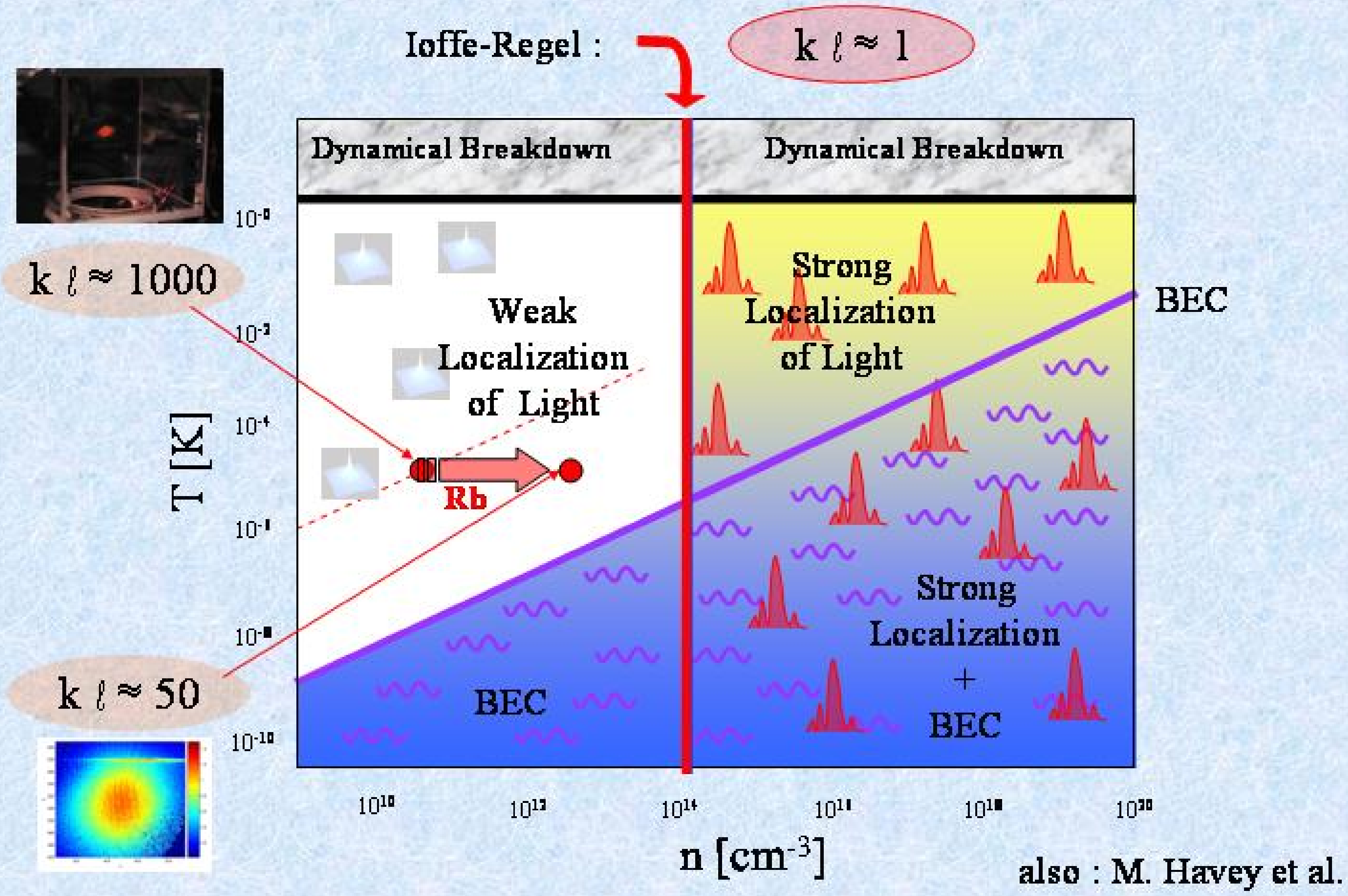


Coherence after resonant scattering with atoms !

cone width: $\frac{1}{kl}$

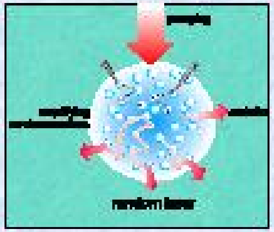
Phys. Rev. Lett. **83**, 5266 (1999)

Towards strong localization of light



1) **Multiple scattering :**

- Light Localization
- **(Random) Atom Laser**

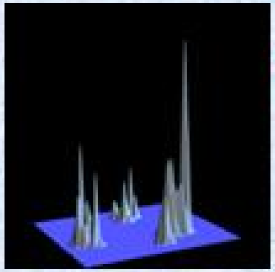


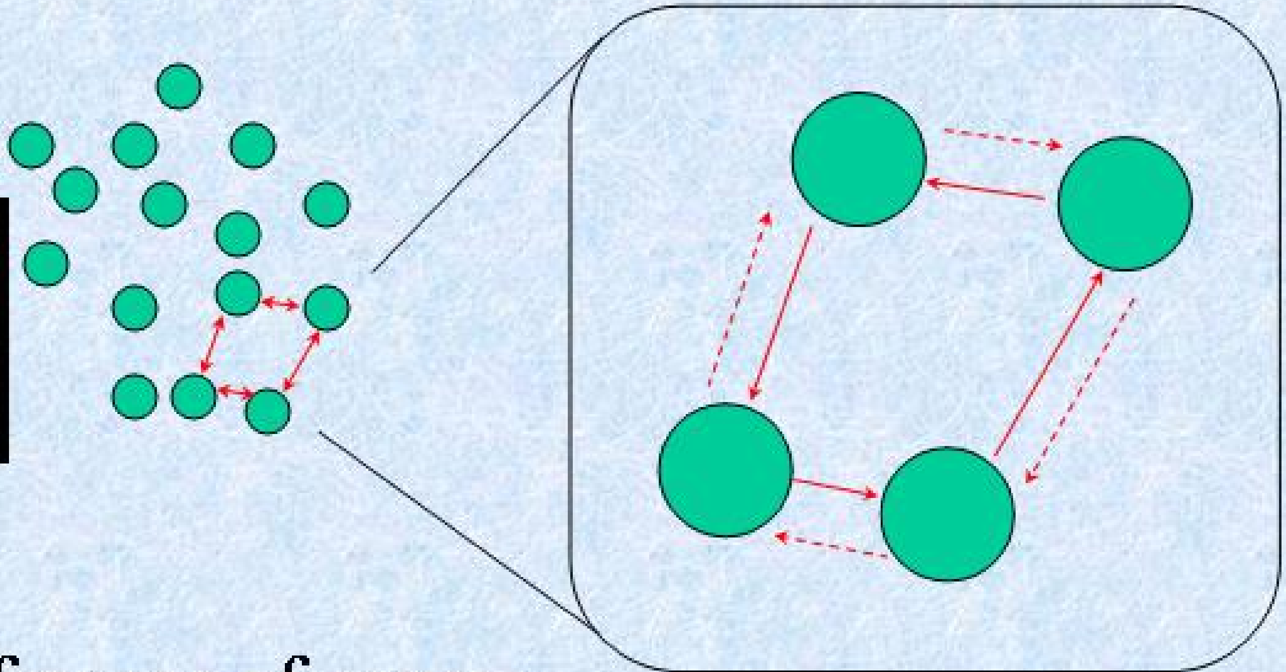
- Lévy Flight

2) Mechanical effects :

- Plasma physics

Strong Localization of light : $k\,\ell \approx 1$

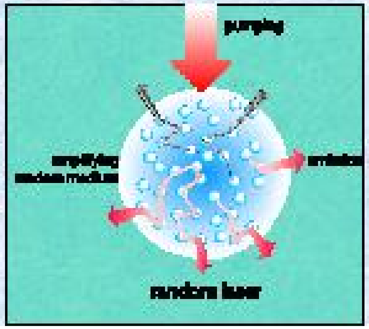




- Interference of waves propagating along closed loops?

- 'random cavities' : 'precursor' modes ?

  $\Rightarrow$ random laser



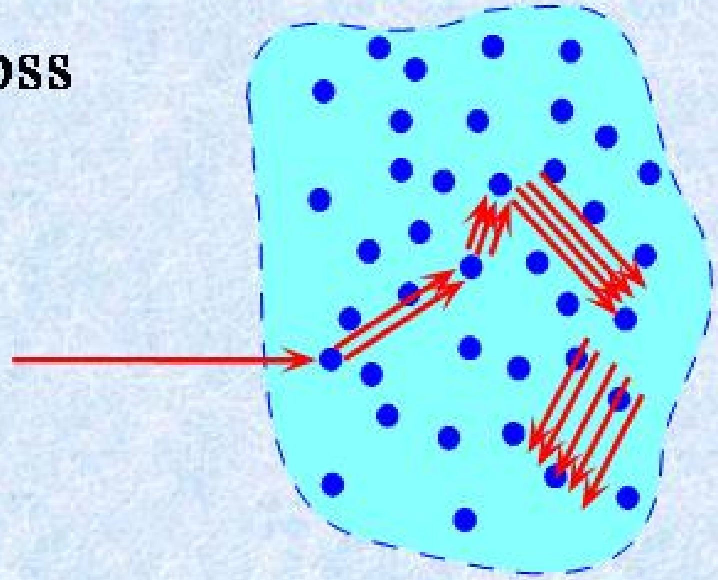
Incoherent Random Laser 'Photonic Bomb'

Diffuse regime : $k\ell >> 1$

- (unfolded path length) * gain > loss
- Volume Gain vs Surface Loss

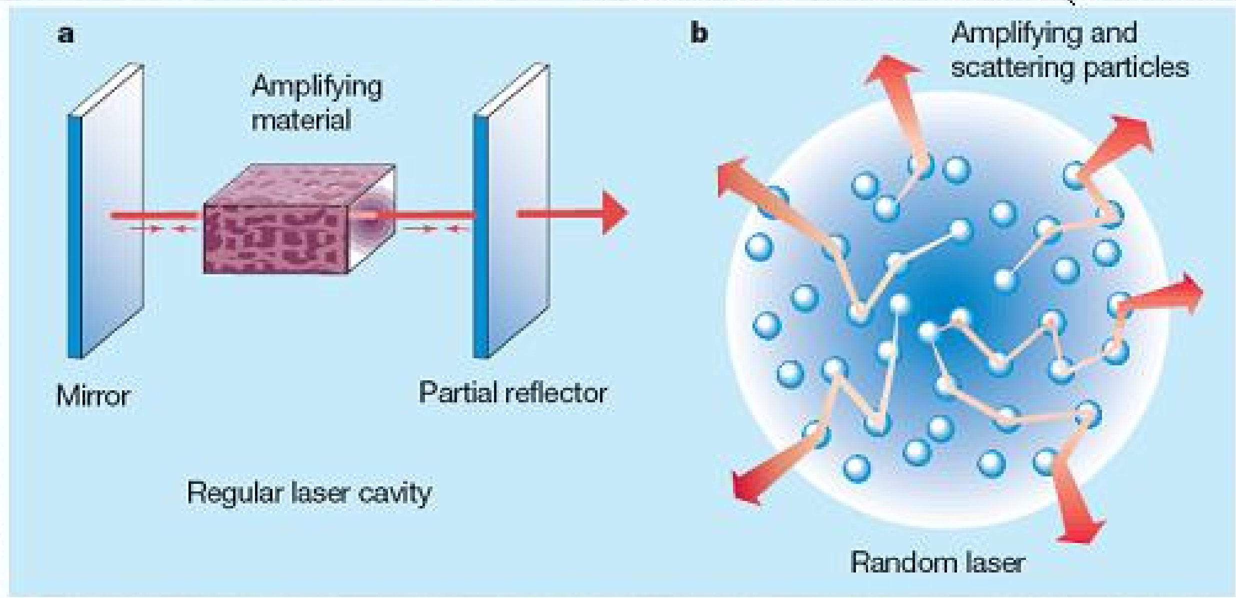
$\Rightarrow$ critical mass/volume

$$L > 2\pi\sqrt{\frac{l_g l_{sc}}{3}}$$



Random laser : Laser whose feedback is provided by multiple scattering in the gain medium itself.

The « Photonic Bomb » (Lethokov, 1967)

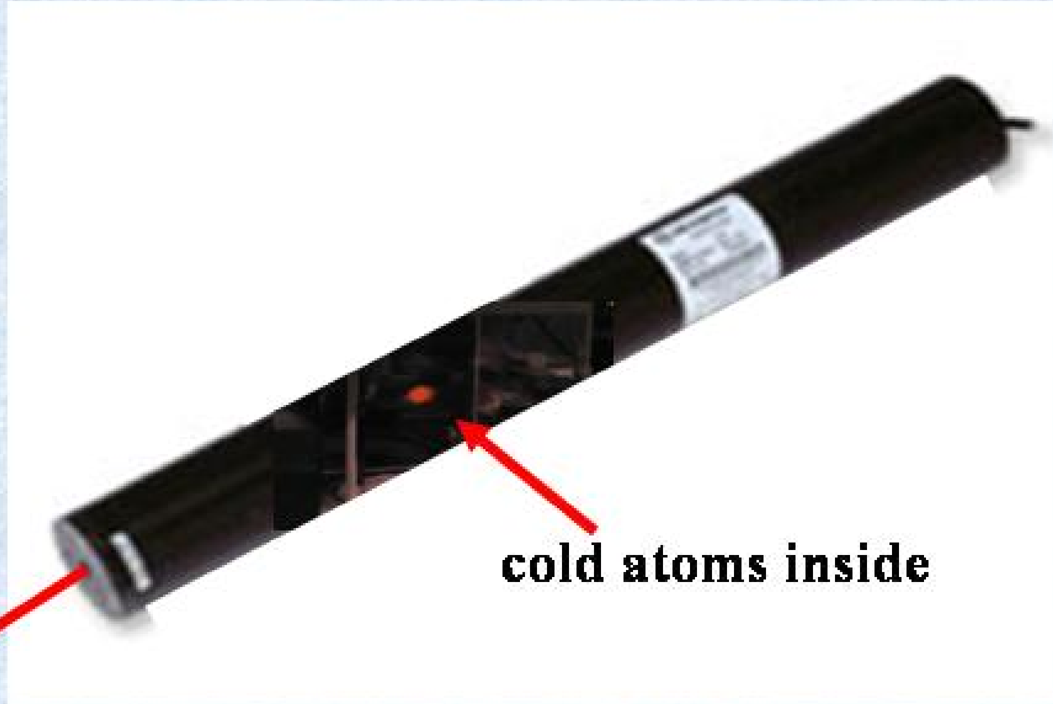


Threshold : Gain = Losses
Gain is provided by the amplifying medium, losses come from the cavity.

The cold-atom random laser : Amplifiers and scatterers are the same atoms. Gain and losses are not independent.

Recent reviews:
H. Cao, Waves Random Media **13**, 1 (2003).
H. Cao, J. Phys. A **38**, 10497 (2005).
D. Wiersma, Nature Physics **4**, 359 (2008).

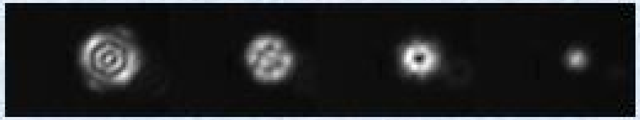
Cavity + Cold Atoms with Gain :

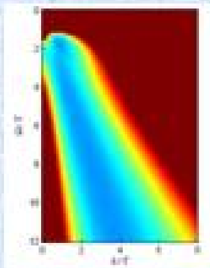


Laser Radiation ≈ 300μW

W. Guerin, F. Michaud, R. Kaiser, Phys. Rev. Lett,101,093002 (2008)

Cold Atoms for Random Optical Laser
(CAROL)

Lasing at and close to resonance : ✓ ☺ 

Threshold prediction ✓ ☺ 

⇒ increase optical thickness to 300 : ☹ but 

Signature of random laser with cold atoms ? ? ?

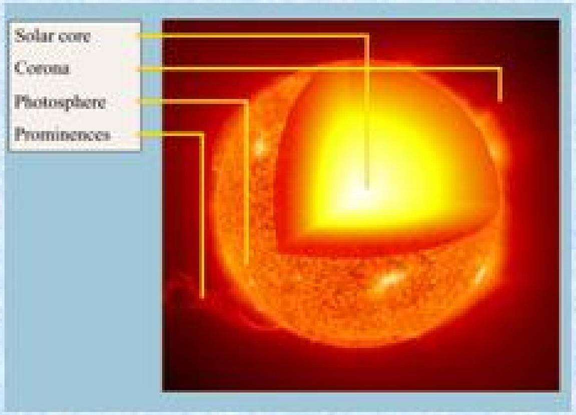
1) Multiple scattering :

- Light Localization
- (Random) Atom Laser
- Lévy Flight

2) Mechanical effects :

- Plasma physics

Atomic physics :
radiation trapping

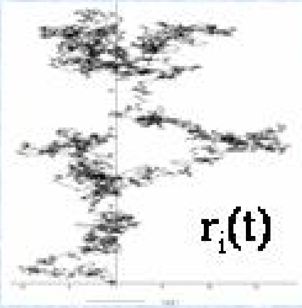


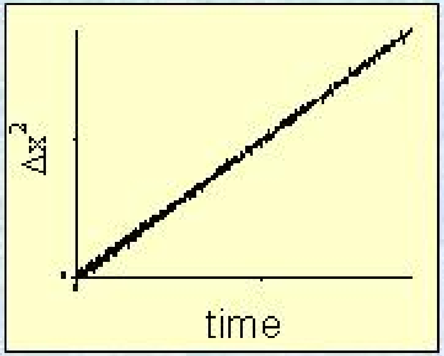
1947 : Holstein

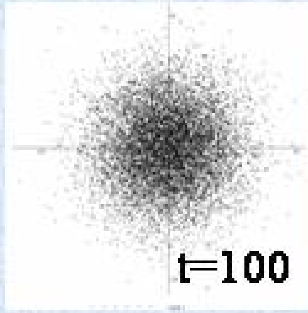
Random walk of photons
Radiation trapping in atomic vapours
Inelastic scattering (Levy flights)

Mean Free Path -- Diffusion

Normal Diffusion : $\Delta x^2 = \frac{1}{2} D t$ $\quad \mathrm{D} \propto \frac{l^2}{\tau}$







Ok, if l and D exist : $l = \frac{\int dx\, x P(x)}{\int dx P(x)}$ $\quad D = \frac{\int dx\, x^2 P(x)}{\int dx P(x)}$

$$\mathrm{P(x)} \propto exp(-x/l_0) \Rightarrow l = \langle x \rangle = l_0$$

$$\mathrm{D} \propto \frac{l_0^2}{\tau}$$

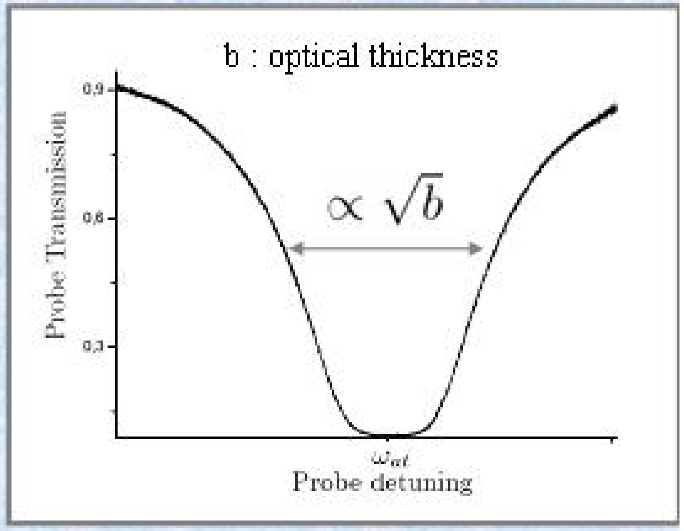
$$P(x) \propto \frac{1}{x^{\alpha}}$$

non stationnary	'ballistic'	'super-diffusive'	normal diffusion
$\int P = \infty$	$l = \infty$	$D = \infty$	$D < \infty$

1 2 3 α

Atomic Phsyics

Cold Atoms : no Doppler broadening
no pressure broadening



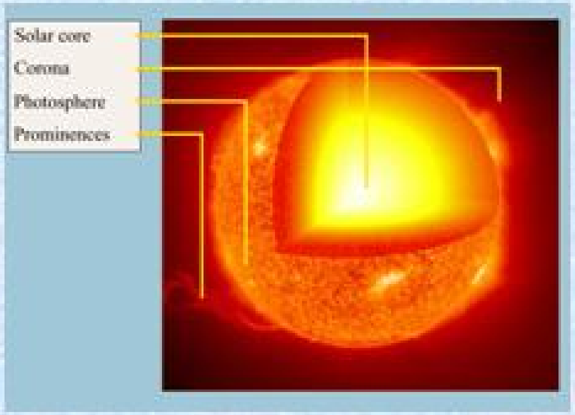
$$P(x,\omega) \propto e^{-n\sigma(\omega)x}$$

Hot Atoms ⇒ Doppler broadening
⇒ Frequency redistribution

$$P(x) \propto \int d\omega f(\omega) e^{-n\sigma(\omega)x}$$

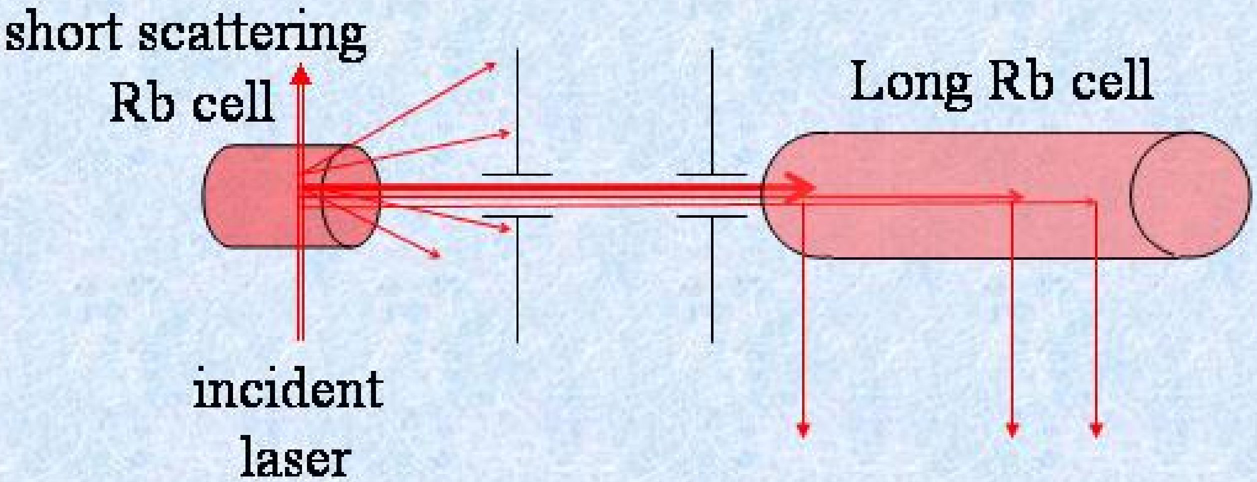
$$f(\omega) \propto e^{-\omega^2} \Rightarrow P(x) \propto \frac{1}{x^2\sqrt{\ln x}}$$

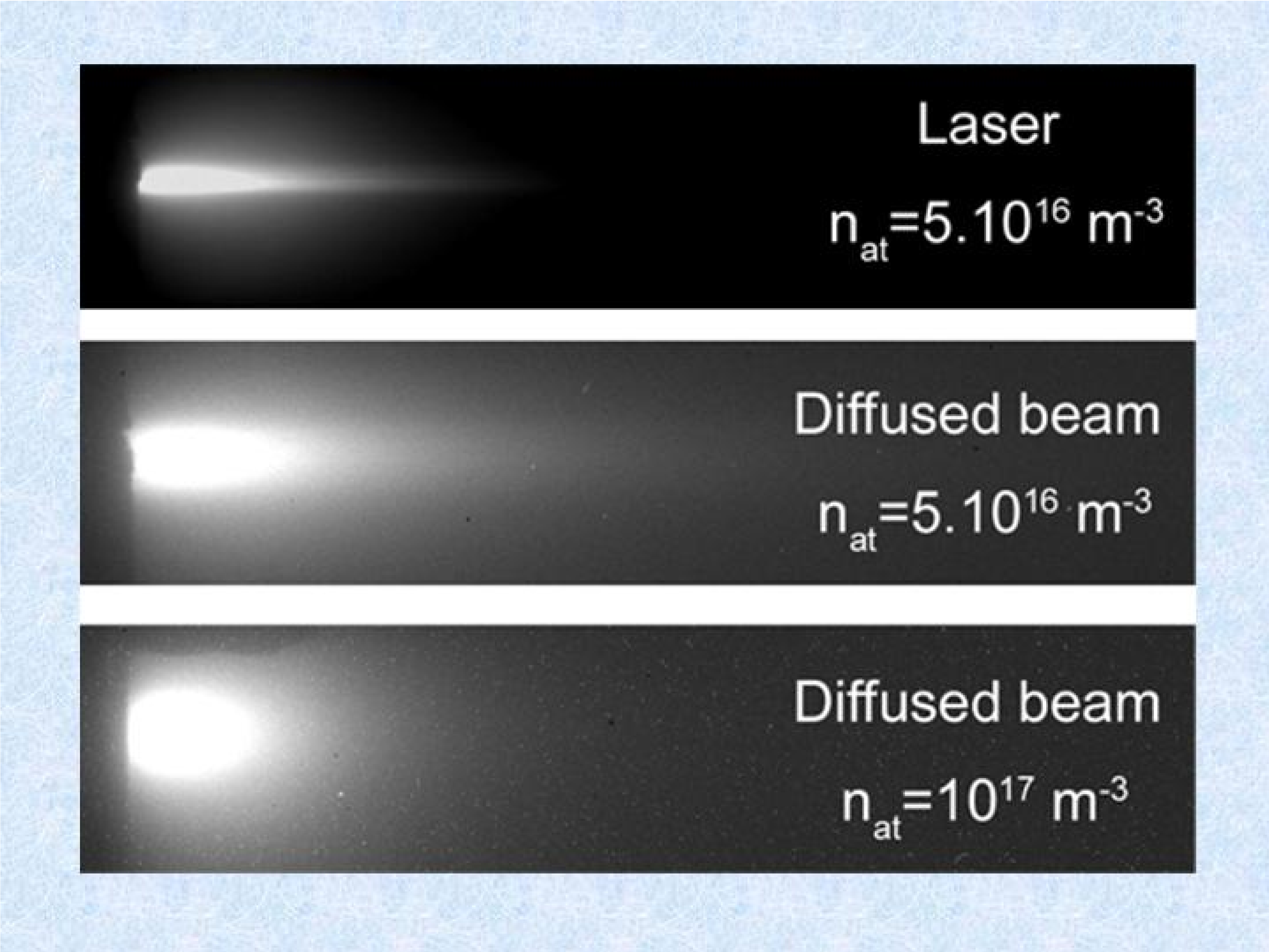
How to measure P(x) ?



In Stars … ☹

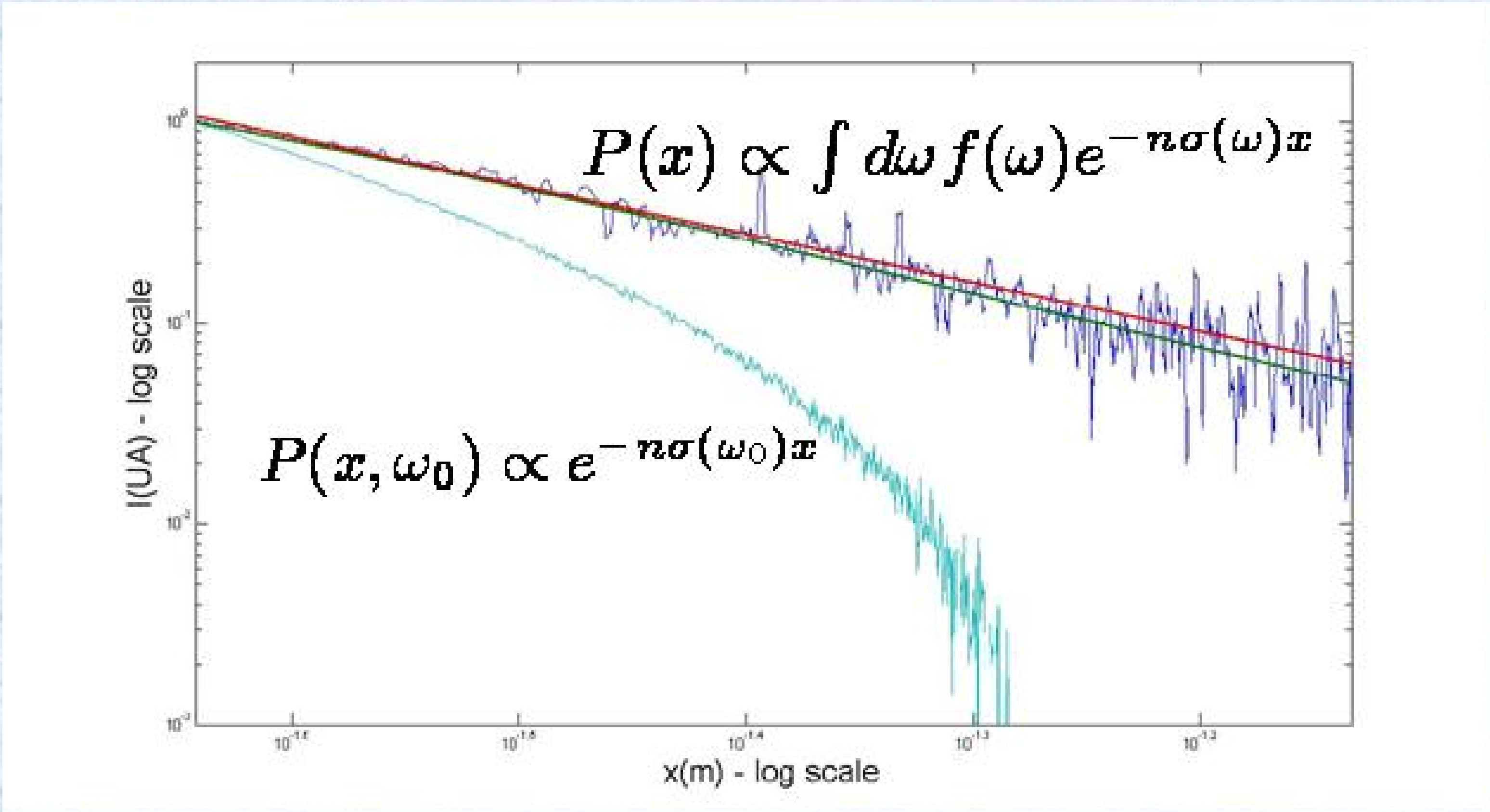
In the lab ☺



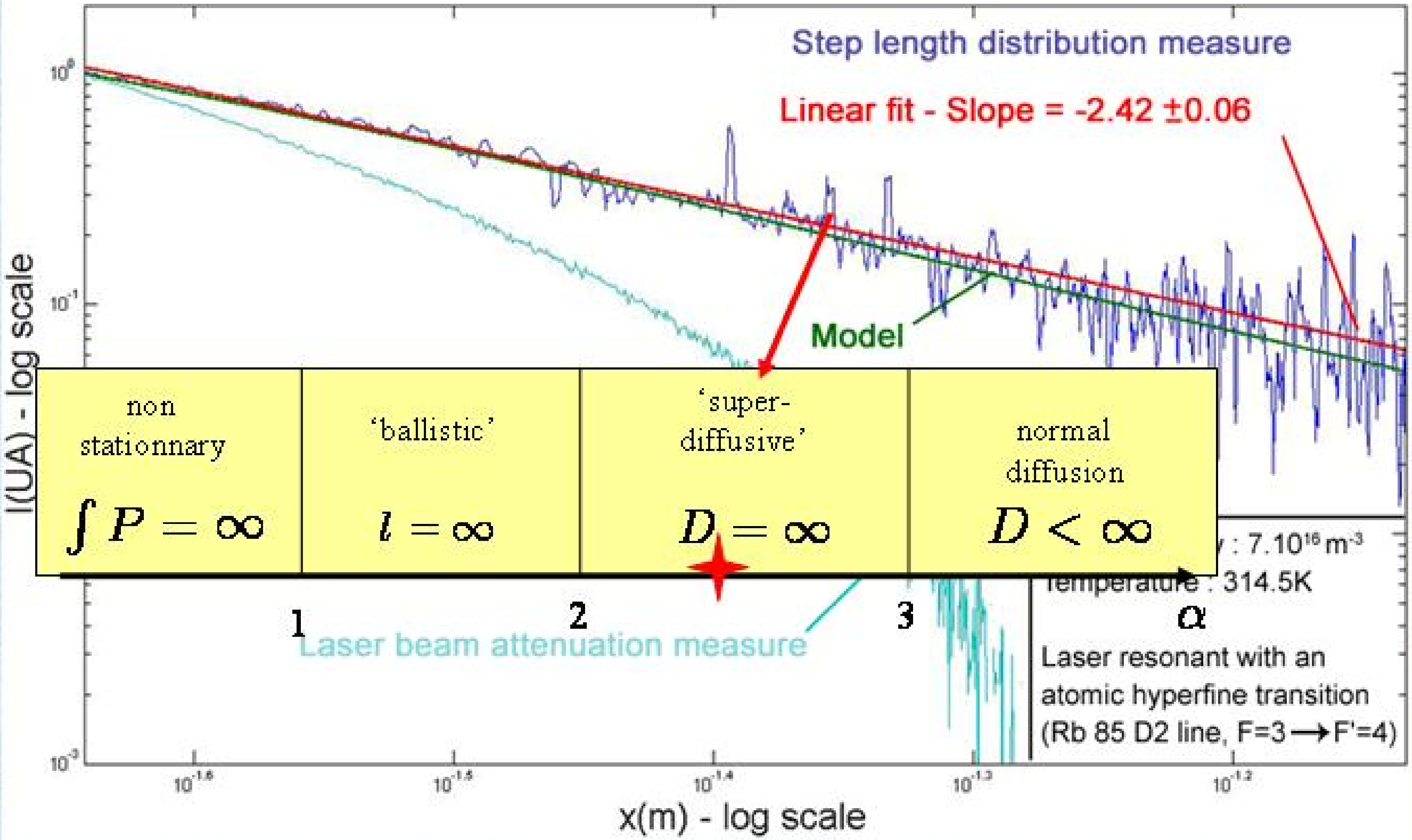


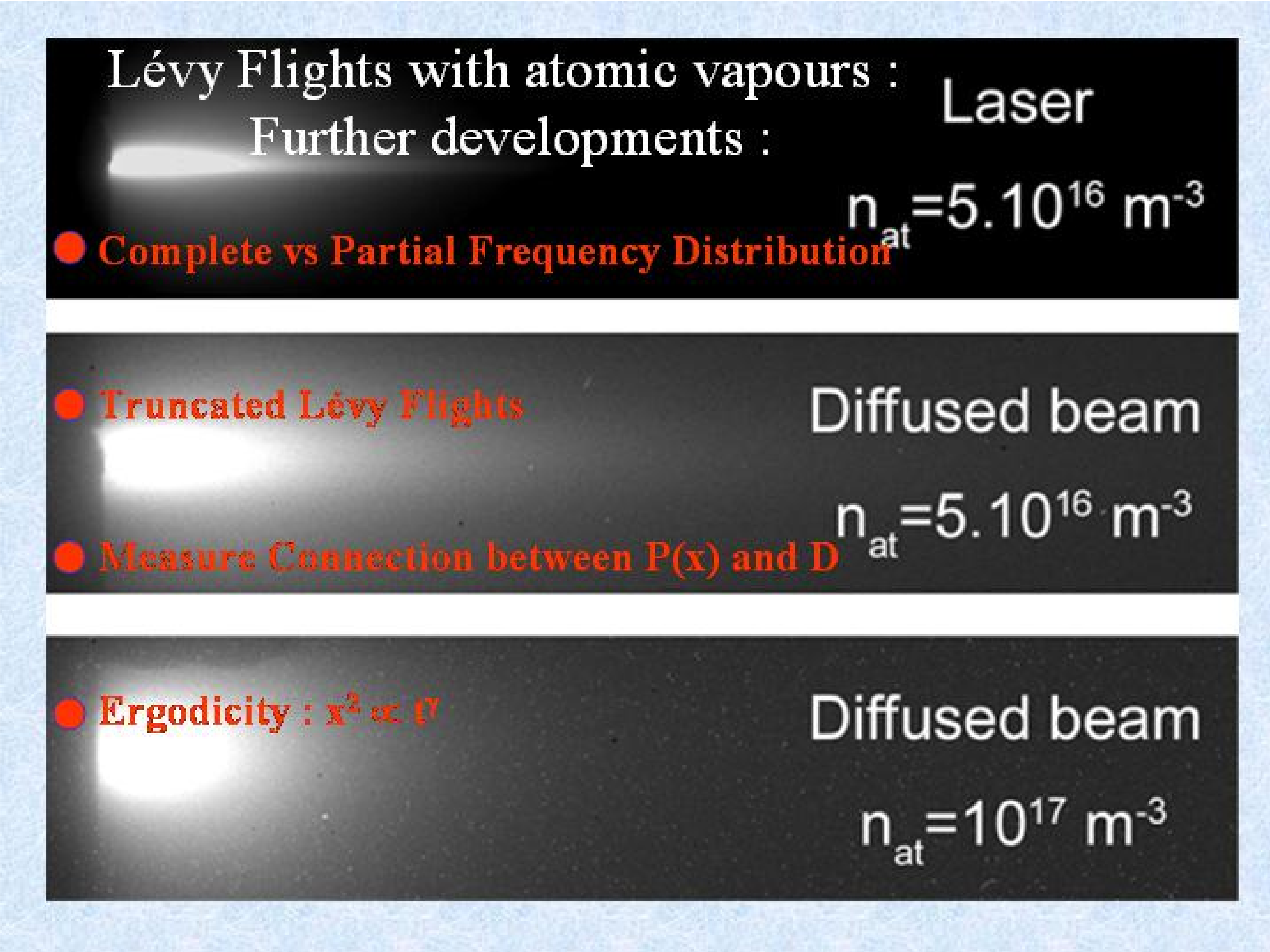
Laser
n_{at}=5.10^{16} m^{-3}
Diffused beam
n_{at}=5.10^{16} m^{-3}
Diffused beam
n_{at}=10^{17} m^{-3}


Laser
n_{at}=5.10^{16} m^{-3}
Diffused beam
n_{at}=5.10^{16} m^{-3}


$P(x) \propto \int d\omega\, f(\omega) e^{-n\sigma(\omega)x}$
$P(x,\omega_0) \propto e^{-n\sigma(\omega_0)x}$
I(UA) - log scale
x(m) - log scale

Step length distribution



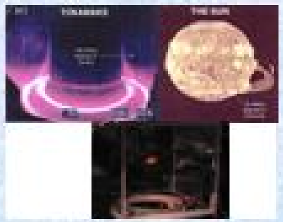

Lévy Flights with atomic vapours :
Further developments :
Laser
$n_{at}=5.10^{16}\ m^{-3}$
Complete vs Partial Frequency Distribution
Truncated Lévy Flights
Diffused beam
$n_{at}=5.10^{16}\ m^{-3}$
Measure Connection between P(x) and D
Ergodicity : $x^2 \propto t^\gamma$
Diffused beam
$n_{at}=10^{17}\ m^{-3}$

1) Multiple scattering :

- Light Localization
- (Random) Atom Laser
- Lévy Flight

2) Mechanical effects :

- Plasma physics



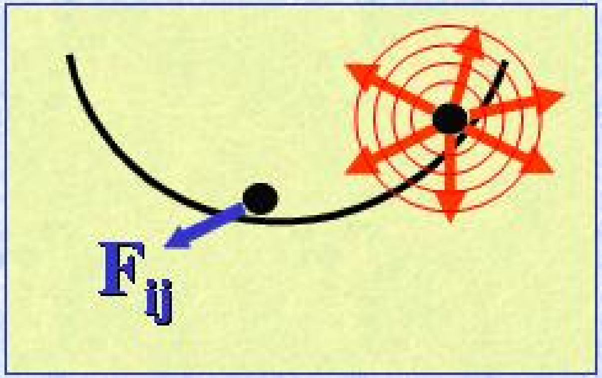
Mechanical Effects of Multiple Scattering of light

$F_i = \underbrace{- \kappa x_i - \gamma v_i}_{\text{Magneto-Optical Trap}} + \mathbf{F_{ij}}$

$\mathbf{I_{ij} \propto P_{diff} / r_{ij}^2}$

Coulomb type force

$$F_{ij} = \frac{q_{eff}^2}{4\pi\varepsilon_0 r^2}$$



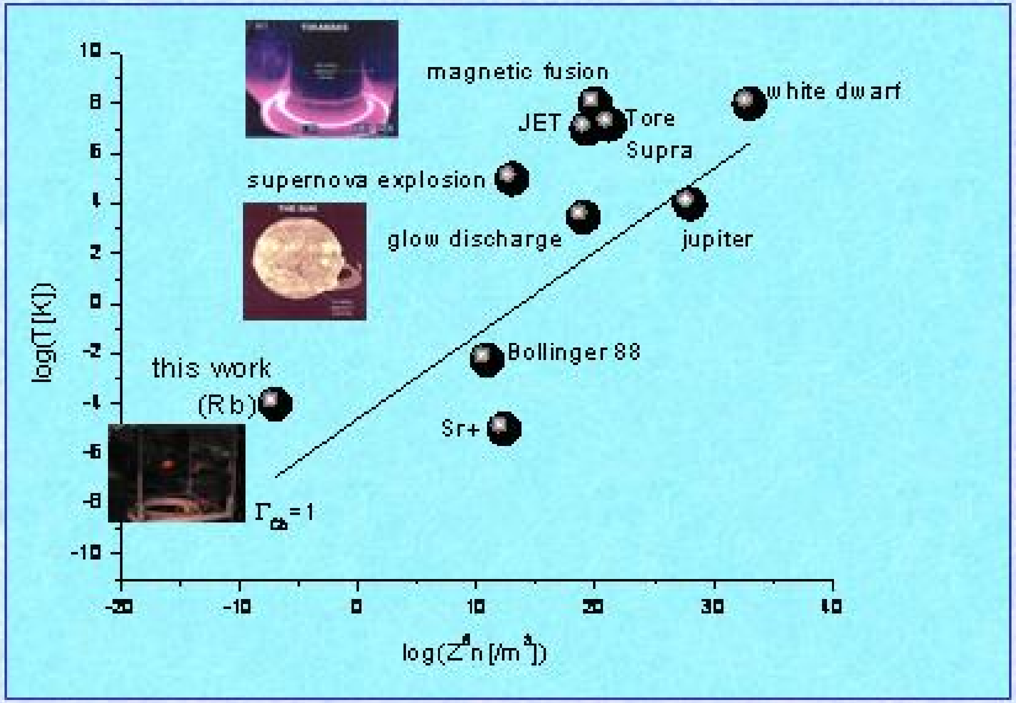
Plasma Physics with Neutral Cold Atoms

Coulomb type force

$$F_{ij} = \frac{q_{eff}^2}{4\pi\varepsilon_0 r^2}$$

effective charge

$$q_{eff} = \sqrt{\varepsilon_0 \frac{\hbar k \Gamma}{2} \frac{I_{inc}}{I_{sat}} \frac{\sigma_0}{\left(1+\frac{4\delta^2}{\Gamma^2}\right)^2}} \approx 10^{-4}\, q_e$$



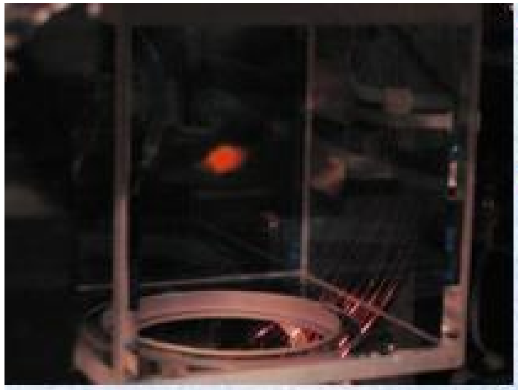
$\Downarrow$

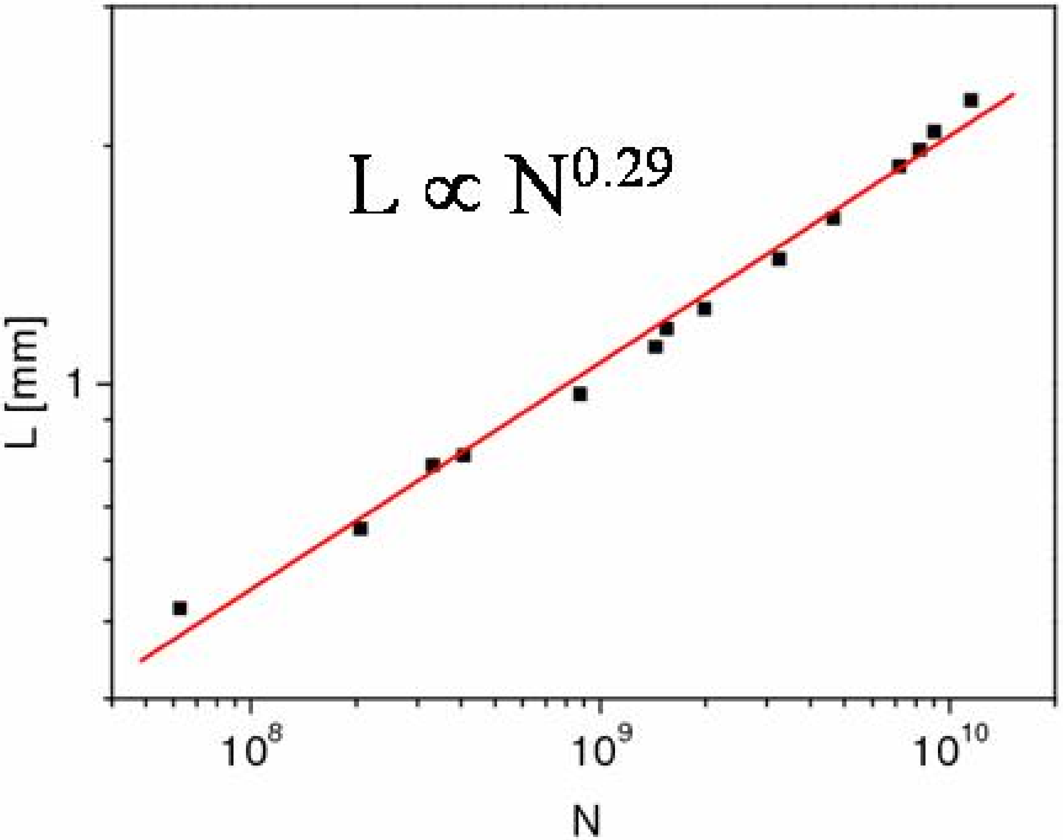
plasma frequency ≈100 Hz

Debye length ≈100μm

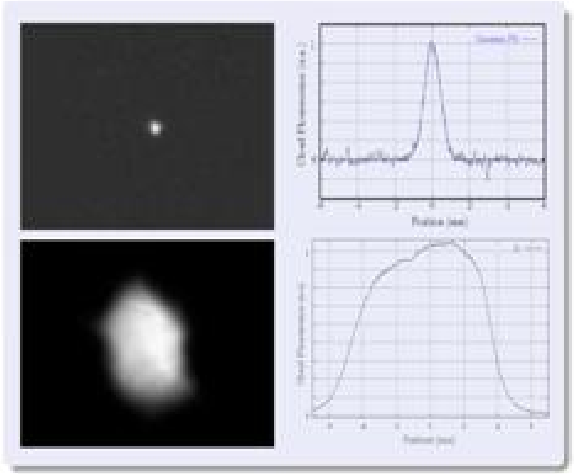
Γ_{cb} ≈0.1

MOT size

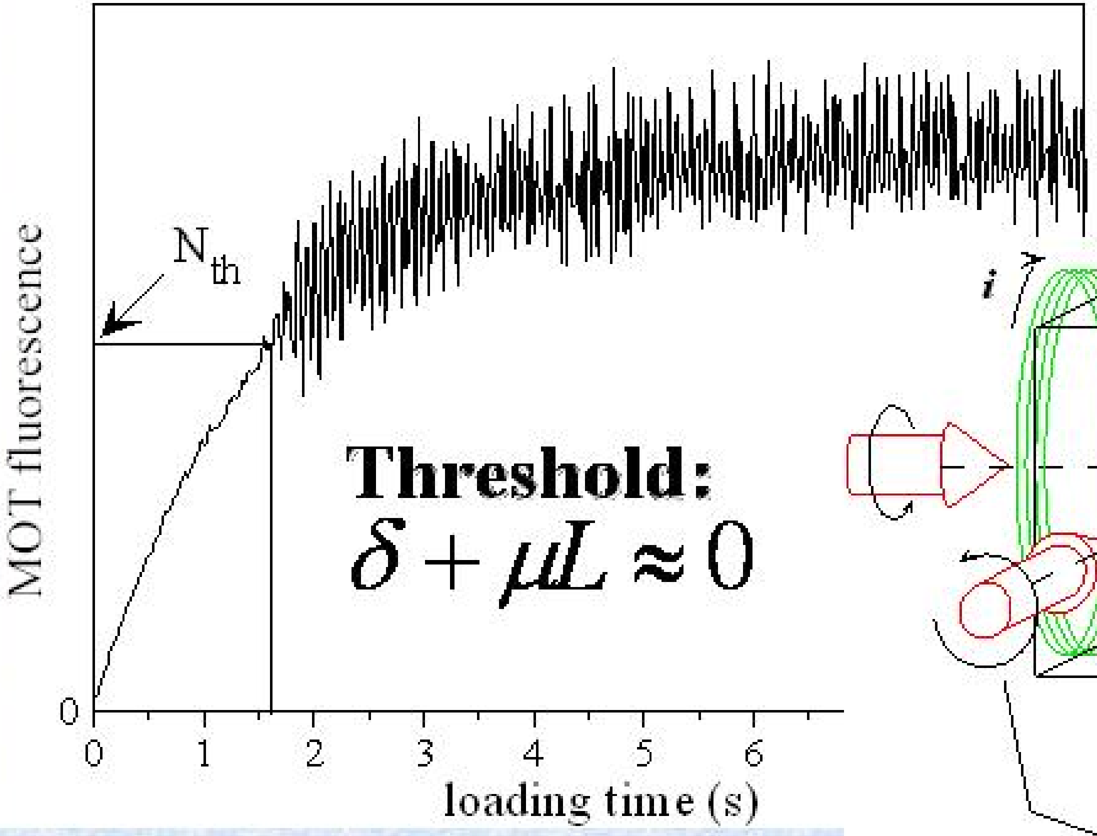




Experimental Images:

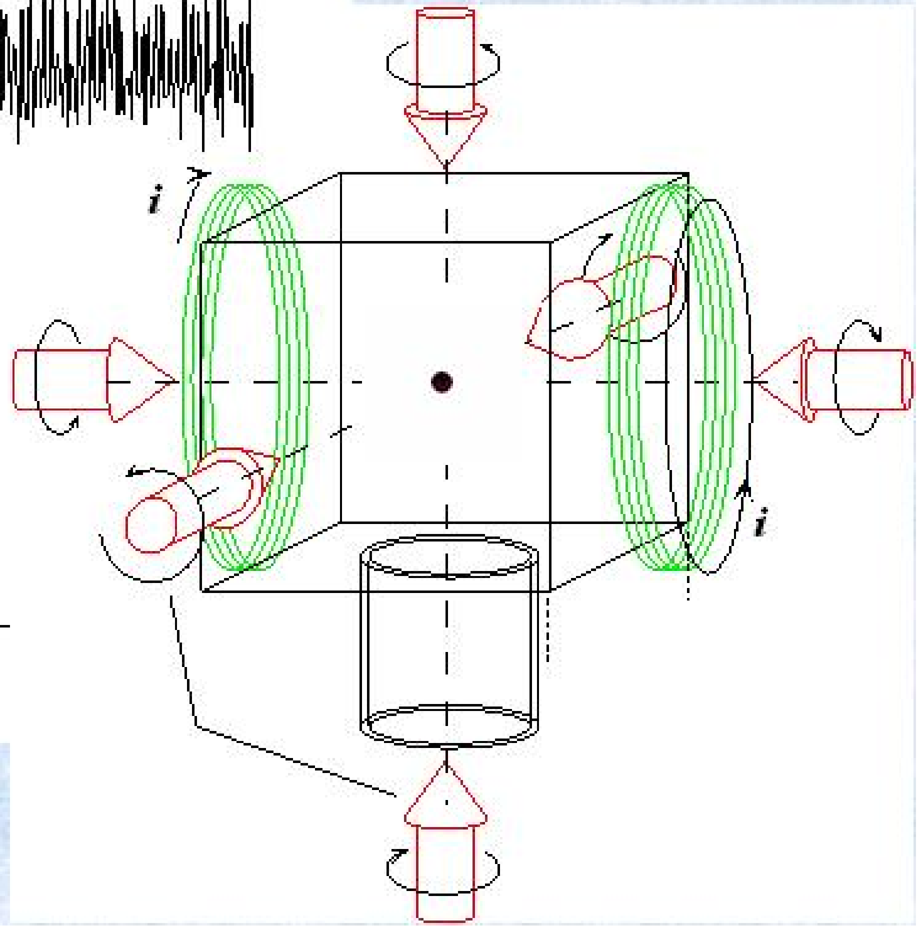


Self Sustained Oscillation of MOT



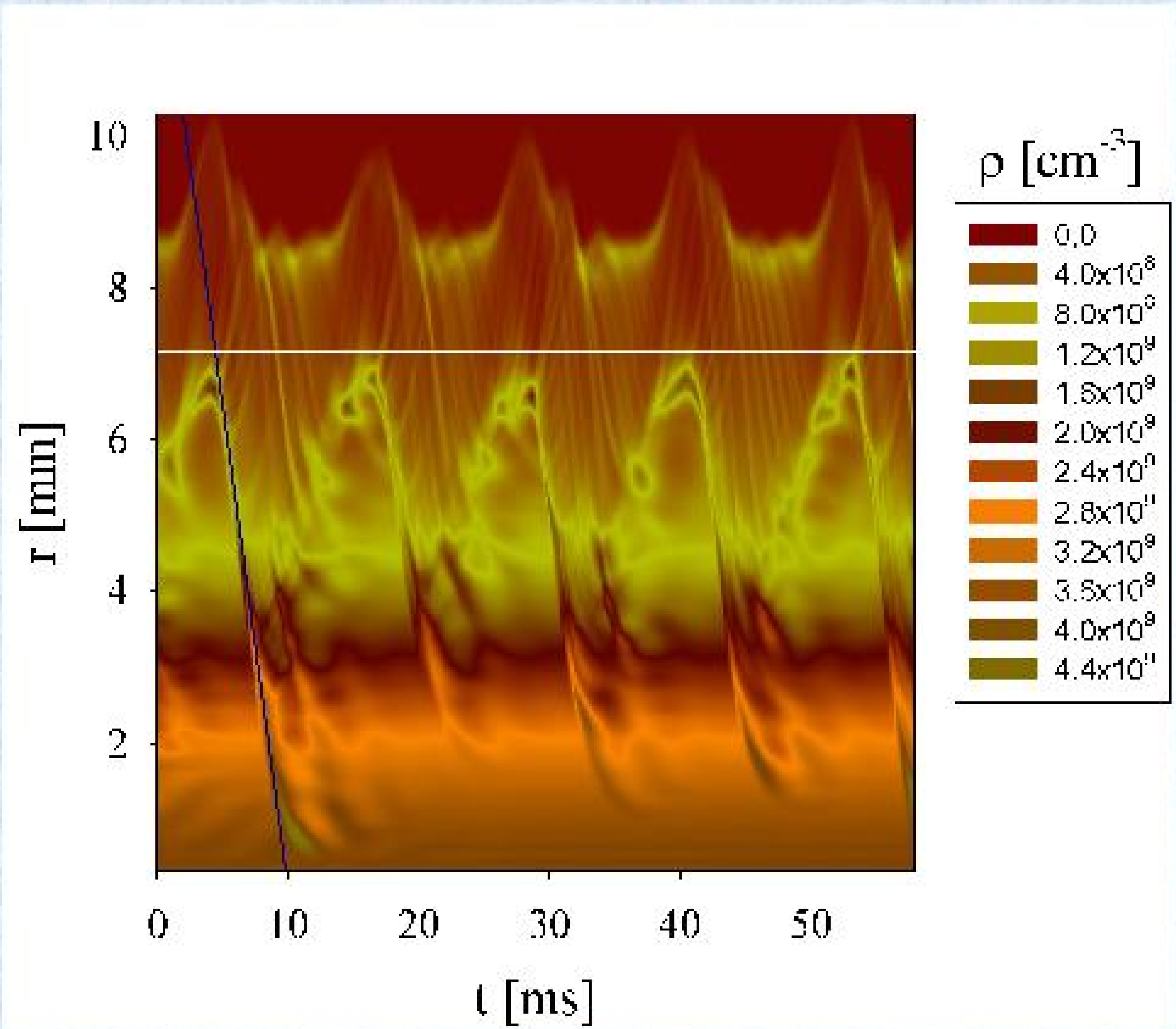
Threshold:

$$\delta + \mu L \approx 0$$



Phys. Rev. Lett. **96**, 023003 (2006)

complex spatio-temporel evolution : Turbulence with cold atoms?



PRA 74, 023409 (2006).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