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

2583-5

Workshop on Coherent Phenomena in Disordered Optical Systems

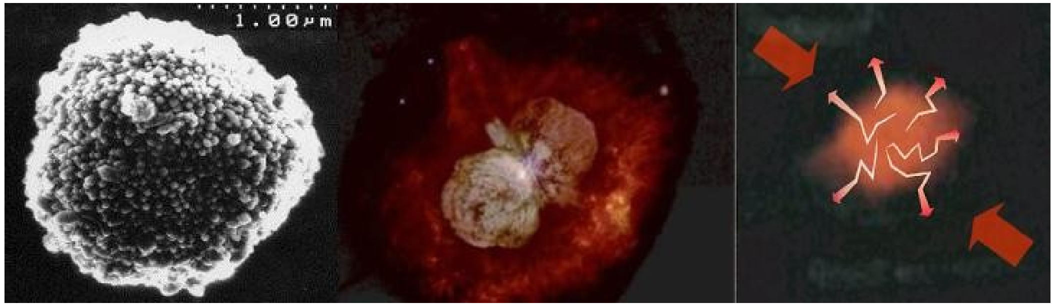
26 - 30 May 2014

A Cold-Random Laser: From Atomic to Astrophysics

Robin KAISER
INLN, Nice
France

Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it
ICTP is governed by UNESCO, IAEA, and Italy, and it is a UNESCO Category 1 Institute

A Cold-atom Random Laser: From Atomic to Astrophysics



Robin KAISER
INLN, Nice, France

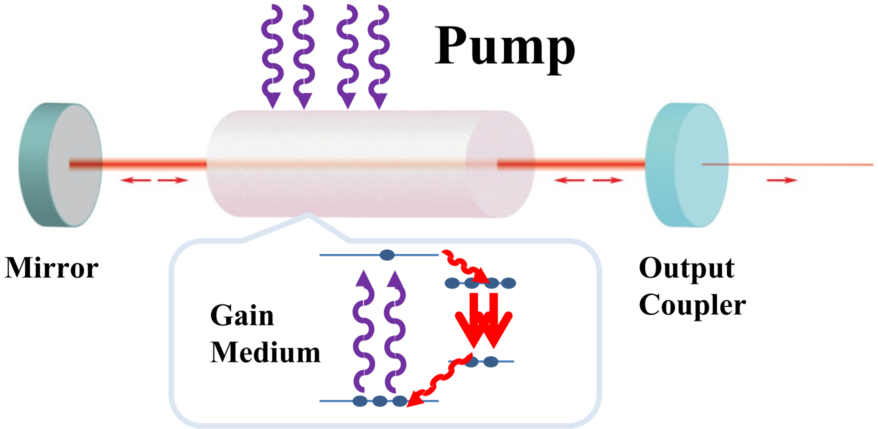
Q. Baudouin, N. Mercadier, V. Guarrera, W. Guerin
Collaborations : R. Carminati, S. Skipetrov

Workshop on Coherent Phenomena in Disordered Optical Systems, Trieste , 26 - 30 May 2014

1. **Introduction**
2. **Cold Atoms**
   - Multiple scattering
   - Gain
3. **Random lasing with cold atoms**
   - Predictions
   - Experiments
   - Model
4. **Outlook**

1. **Introduction**
2. **Cold Atoms**
   - Multiple scattering
   - Gain
3. **Random lasing with cold atoms**
   - Predictions
   - Experiments
   - Model
4. **Outlook**

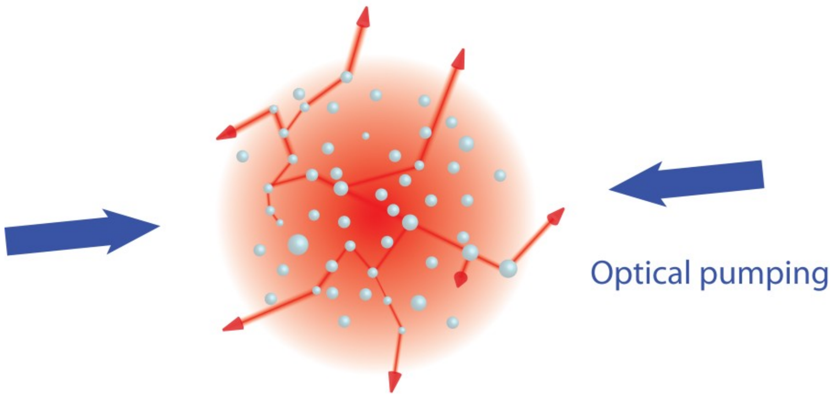
- Cavity Laser



Ingredients:

- Gain Medium
- Cavity
  → Feedback & Mode Selection

- Random Laser



- Gain Medium
- **Multiple scattering**

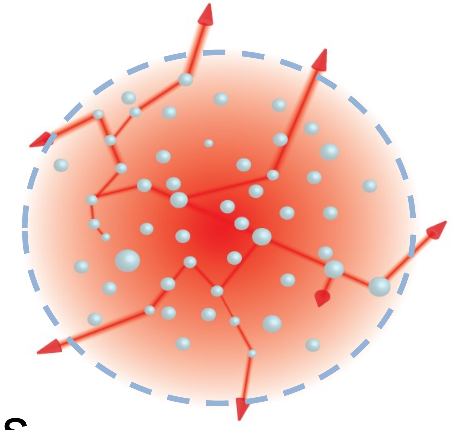
*V.S. Letokhov, Sov. Phys. JETP **26**, 835-840 (1968)*

1939–2009

Pioneer in Laser physics : Basov
(Nobel prize 1964, with C. Townes , Prokhorov)

Main ingredient for a random laser :

Gain in volume (ℓ_g) vs **Losses** at surface (via diffusion : ℓ_{sc})



⇒ **Critical volume / mass : photonic bomb**

1) Diffusion equation with gain + boundary conditions

$$\frac{1}{c}\frac{\partial \Phi_\omega(\mathbf{r},t)}{\partial t} = D\Delta\Phi_\omega(\mathbf{r},t) + Q_\omega(\mathbf{r},t)N_0\Phi_\omega(\mathbf{r},t)$$

2) Unfolded path longer than gain length

$N \ell_{sc} > \ell_g$

$N \propto b^2 = (L/\ell_{sc})^2$

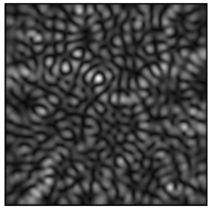
$L^2 / \ell_{sc} > \ell_g$

$L > \sqrt{\ell_{sc}\ell_g}$

Theory of random lasers :

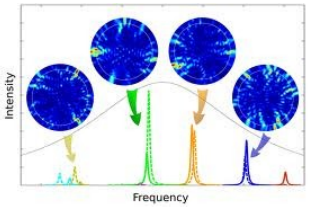
interface between
laser theory and **multiple scattering** and **waves in random media (localisation)**

- Role of interferences (modes of passive system)



C. Vanneste P. Sebbah, H. Cao, PRL **98,** 143902 (2007)

- Mode coupling in multimode laser (Petermann factor)

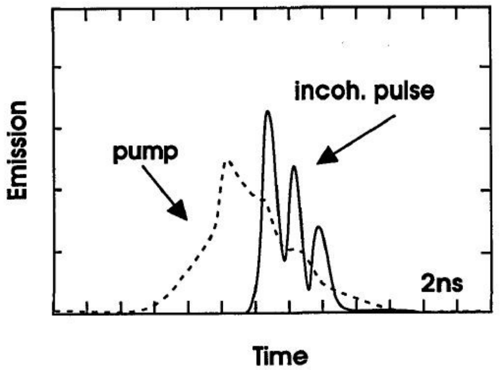


H. E. Tureci, Li Ge, S. Rotter, and A. D. Stone, Science **320**, 643 (2008).

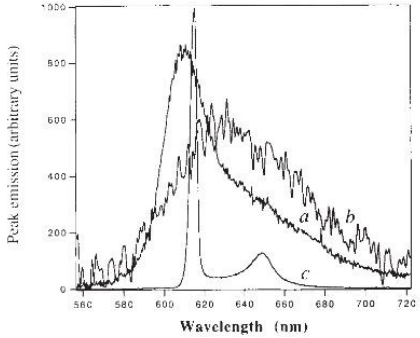
+ Spectral narrowing, photon statistics, role of ASE, superradiance, …

Pionneering experiments by

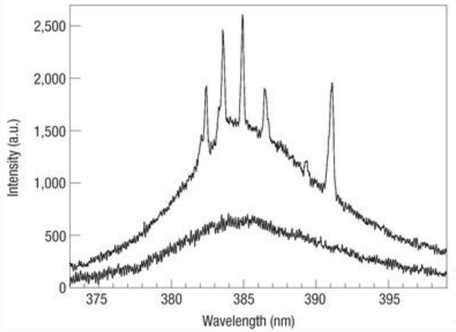
A. Migus et al. : laser crystal into a powder
J. Opt. Soc. Am. **B10,** 2358 (1993)

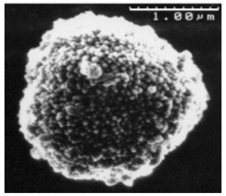


N. Lawandy et al. : suspended TiO_2 laser dye
Nature **368,** 436 (1994)



H. Cao et al. : ZnO powder
PRL, **82**, 2278 (1999)





REVIEW ARTICLE

The physics and applications of random lasers

DIEDERIK S. WIERSMA

nature physics | VOL 4 | MAY 2008 | www.nature.com/naturephysics 359

© 2008 Nature Publishing Group

Random LASERS

Development, Features and Applications

Hui Cao

24 Optics & Photonics News ■ January 2005
1047-6938/05/01/0024/6-$0015.00 © Optical Society of America

REVIEW ARTICLES | FOCUS

PUBLISHED ONLINE: 27 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.29

nature photonics

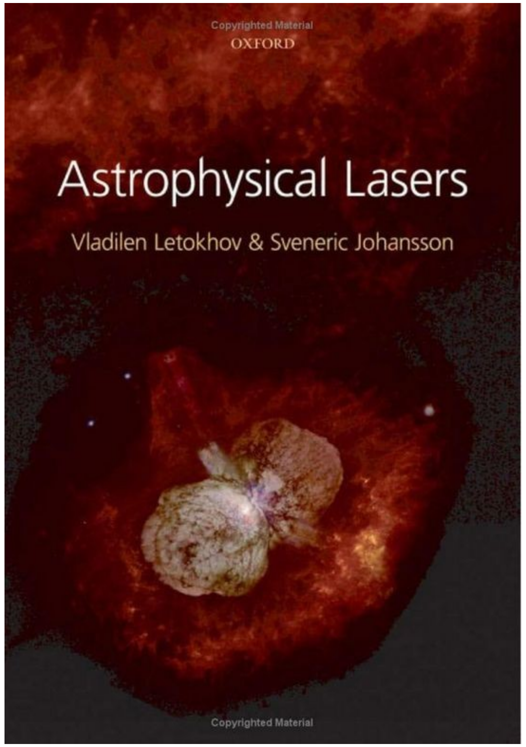
Disordered photonics

Diederik S. Wiersma

Random lasing :
Pioneering idea by V. Letokhov in 1966/1967

Stimulated Radio Emission of the interstellar Medium,
JETP 4, 321 (1966)
Light generation by a scattering medium with a negative resonant absorption,
JETP 26, 835 (1968)

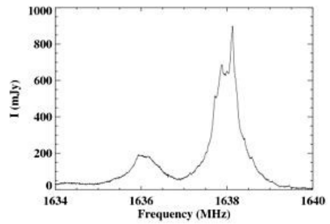
1939–2009



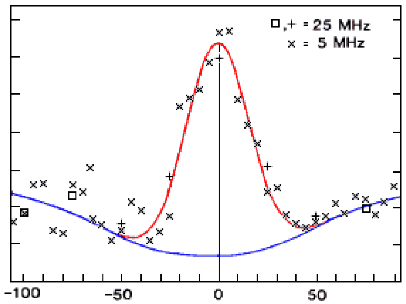
Letokhov, V. S. & Johansson S. *Astrophysical Lasers* (Oxford University Press, 2009).

Astrophysics and (random) lasing

Space « masers »: H.Weaver, et al., *Nature*, **208**, 29-31 (1965):
higher accuracy for red shift measurements

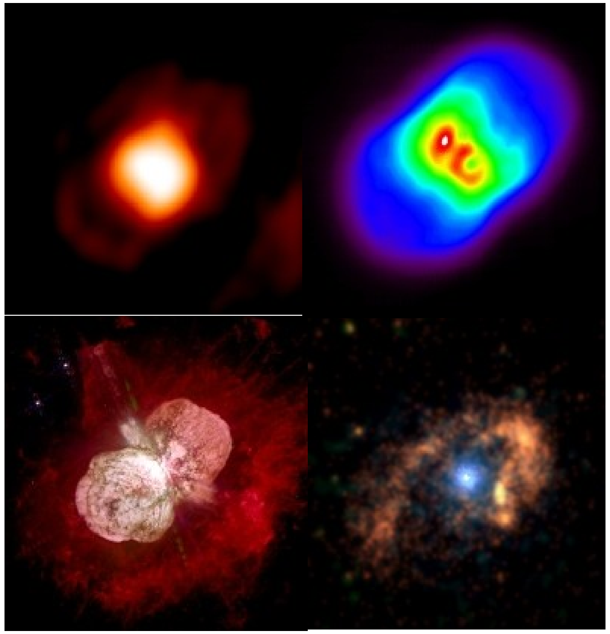


Space « lasers »: M. Mumma, et al., Science, **212**, 45(1981)
atmospheres of Mars and Venus (CO2 lines)
(measure wind speed on Mars)

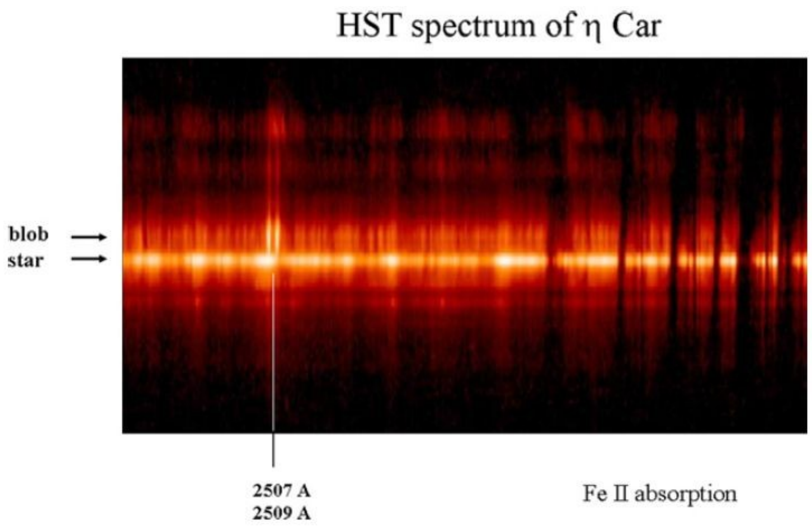


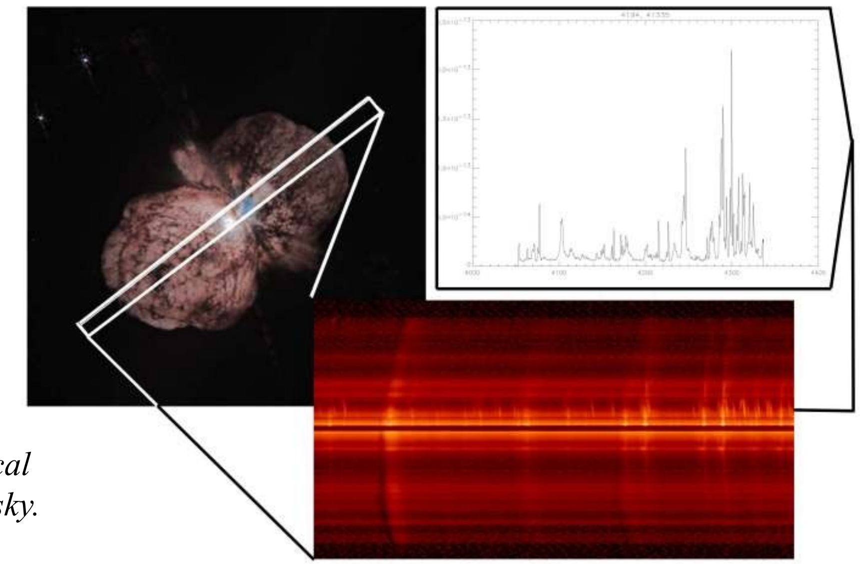
Eta Carinae

one of the most massive
and luminous stars known



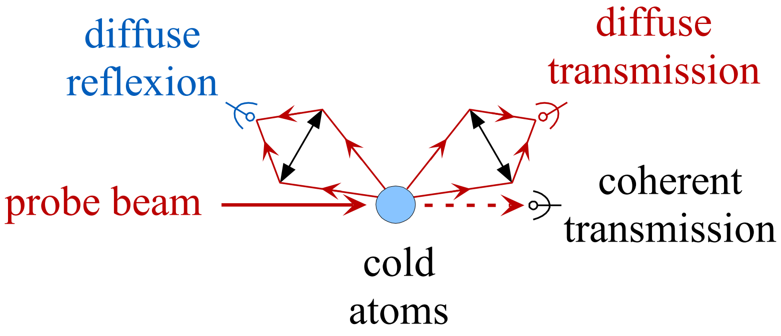
Eta Carinae in different wavelength regions: radio, infrared, optical and X-ray. The X-ray image covers a ~3 times larger area on the sky. Credits: ATCA (S.White); CTIO (E.Polomski); HST (NASA/J.Morse/K.Davidson); Chandra (NASA/CXC/SAO).



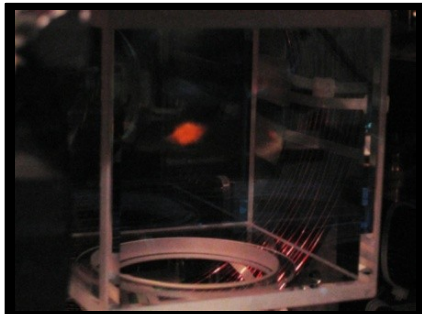


1. Introduction
2. **Cold Atoms**
    - Multiple scattering
    - Gain
3. Random lasing with cold atoms
    - Predictions
    - Experiments
    - Model
4. Outlook

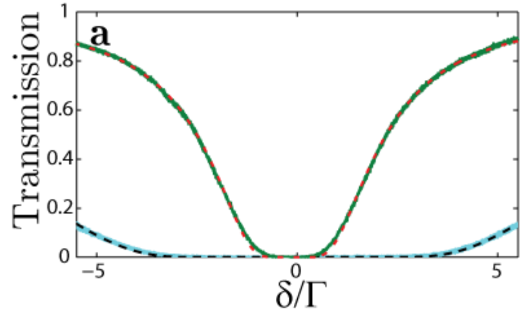
Multiple Scattering of Light by Cold Atoms



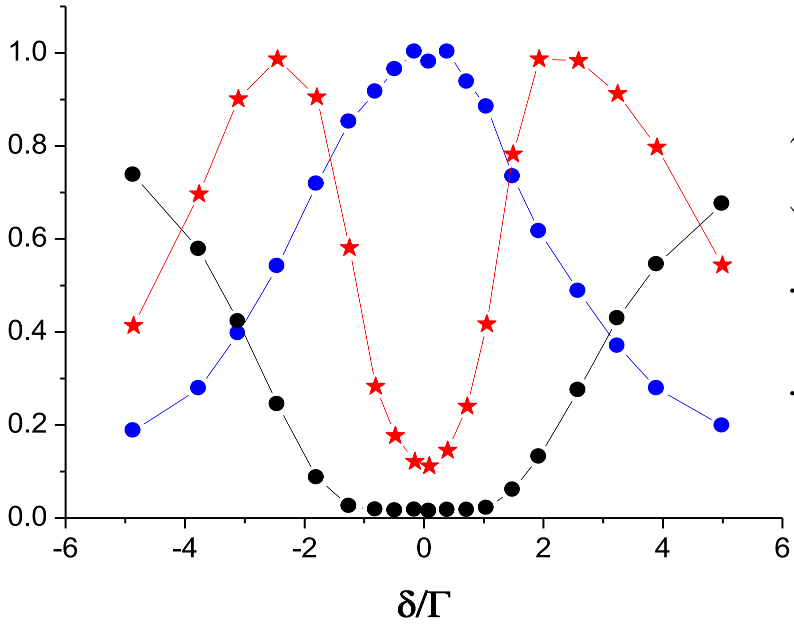
$$T = e^{-b} = e^{-\sigma n L} = e^{-L/\ell_{sc}}$$

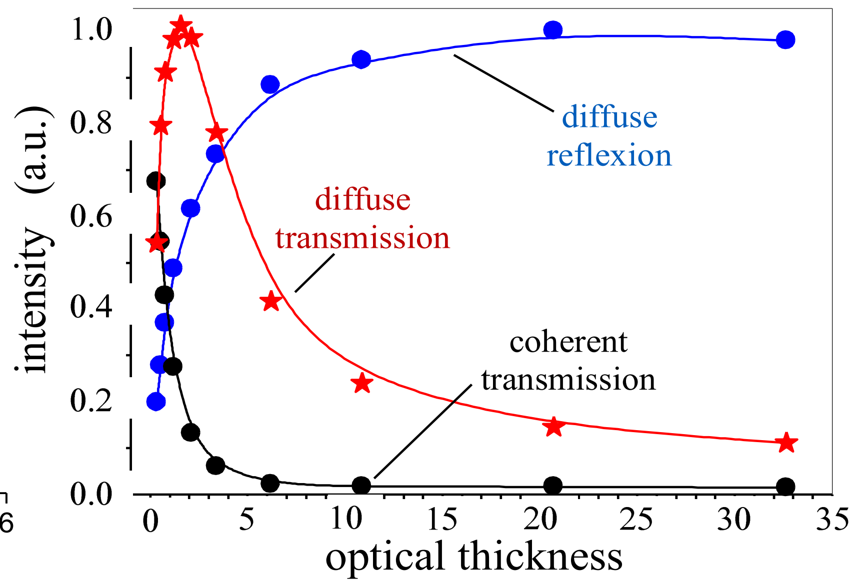


MOT parameters :
Atom number : $N_{at} \sim 10^{10}$
Optical thickness $b_0 = 300$
Density ~ 5 10^{10} at/cc

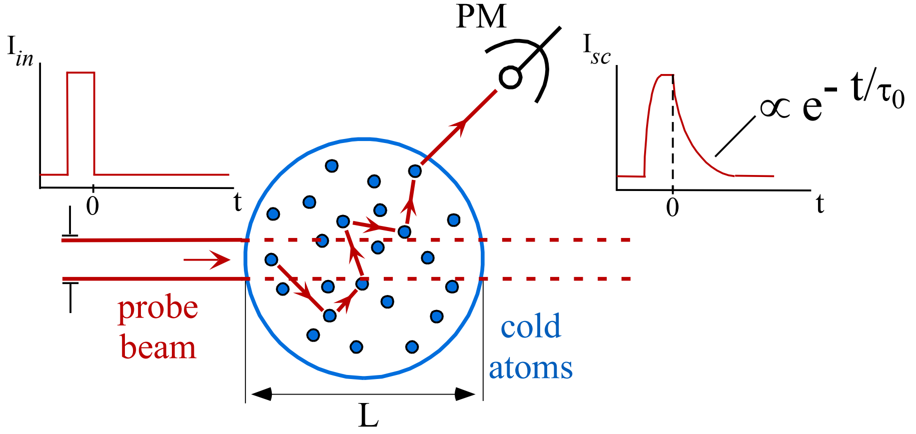


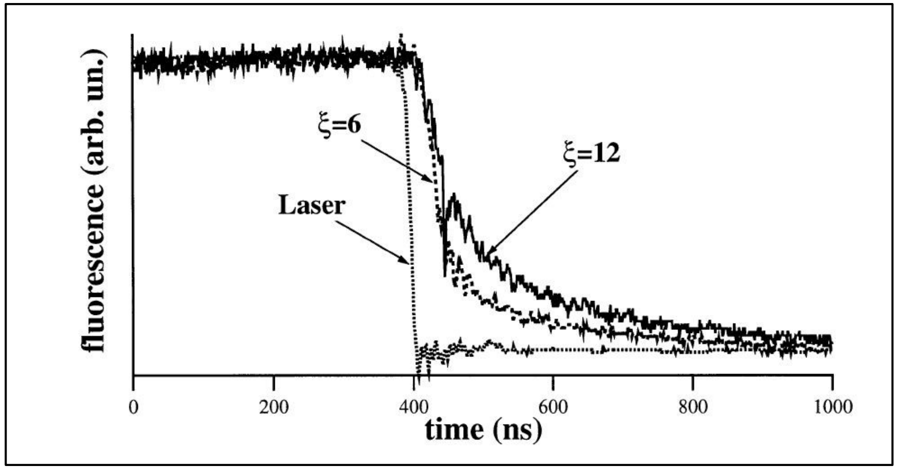
$b_0 = 300$



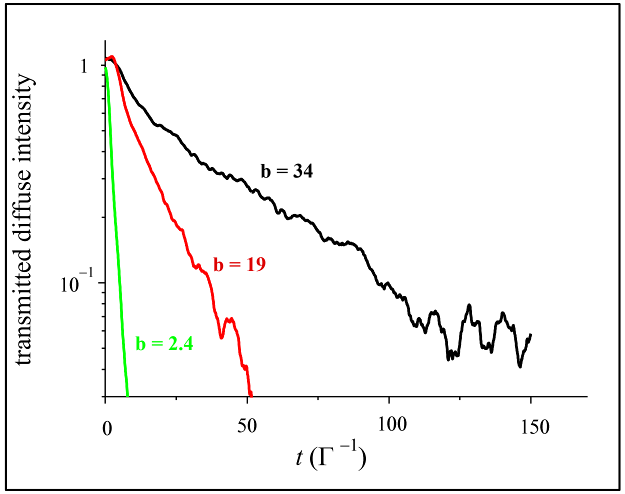


Time dependent experiments





A. Fioretti et al., Opt. Comm. **149**, 415 (1998)



G. Labeyrie et al., PRL, **91**, 223904 (2003)

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

transport mean-free path

transport time

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

transport velocity

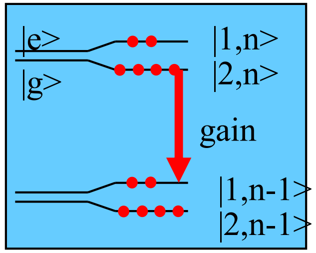
$v_{tr} \approx 3 \cdot 10^{-5}\, c$

Gain with Cold Atoms:

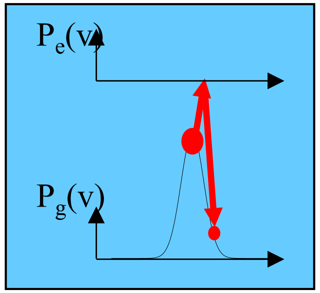
- **Pump probe spectroscopy with cold atoms**

G. Grynberg, C. Robilliard, Phys. Rep. **355**, 335 (2001)

- **Mollow gain** (used in 'lasing without inversion')
  ⇒ internal degree of freedom of 2 level system
  ⇒ excited/ground state population inversion : $\pi_e > \pi_g$
  ⇒ requires high pump intensities

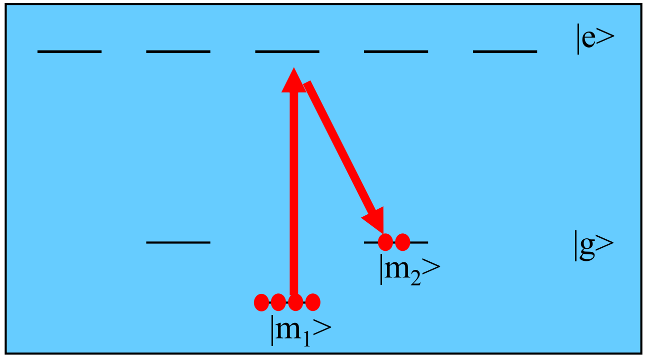


- **Recoil induced resonances / Rayleigh gain**
  (used in 'Collective Atomic Recoil Laser')
  ⇒ external degree of freedom (motion)
  ⇒ population inversion : $\pi(v+dv)>\pi(v)$ (free moving atoms)
  ⇒ vibrational levels of ground population inversion : $\pi_n > \pi_{n'}$
  (atoms bound in lattice)
  ⇒ requires ultracold atoms



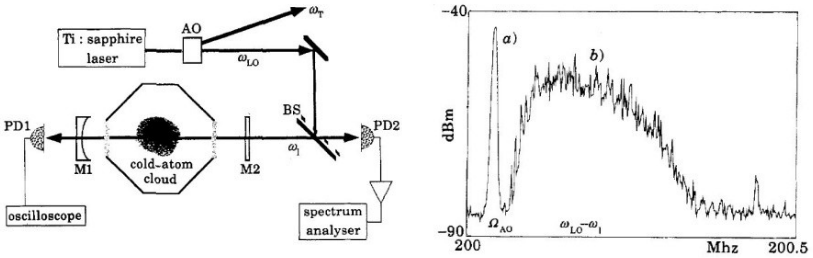
- **Raman gain**
  ⇒ internal degree of freedom of multilevel system
  ⇒ population inversion : $\pi_{g1} > \pi_{g2}$
  ⇒ large in cold atoms

- **Four Wave Mixing**



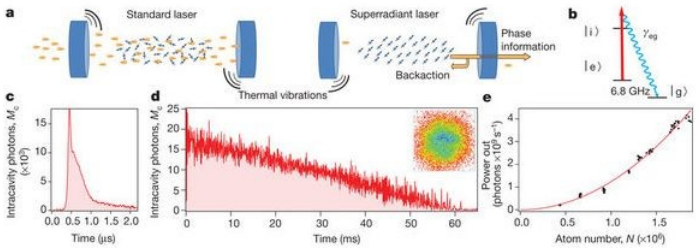
Lasing with Cold Atoms:

- Raman Lasers with Cold Atoms



L. Hilico, C. Fabre, E. Giacobino, EPL, **18**, 685 (1992)

Figure 1: **A steady-state superradiant laser.**

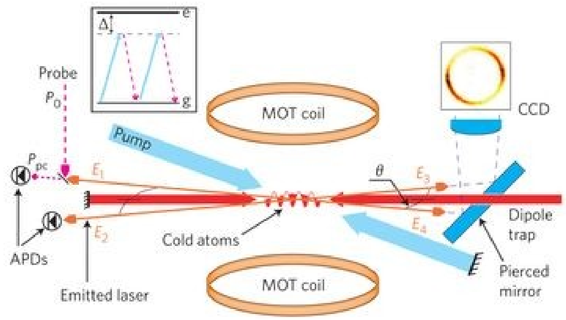


a, Left: in a standard, good-cavity laser far above threshold, many photons (yellow) circulate inside the cavity, extracting energy from the largely incoherent atomic gain medium (blue). Thermal vibrations of the mirror surfaces modulat...

J. Bohnet, *et al*., Nature **484**, 78 (2012).

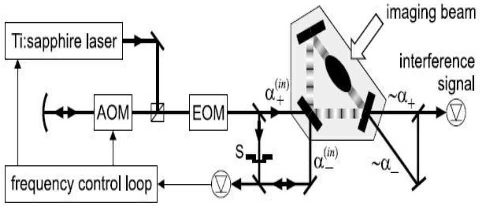
- Four wave mixing gain + DFB laser

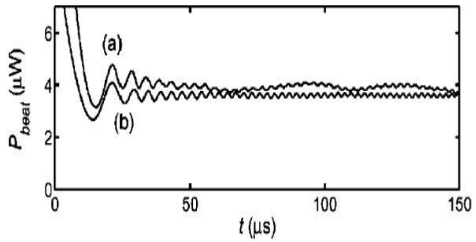
A. Schilke, C. Zimmermann, Ph. Courteille, W. Guerin,
B. Nature Photon. **6**, 101 (2011).



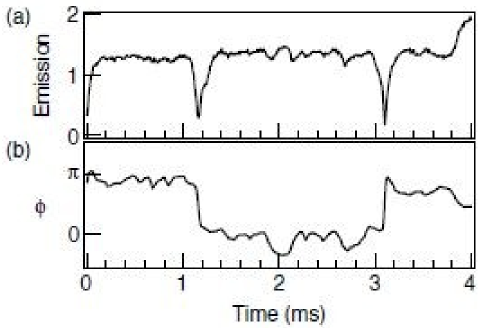
Lasing with Cold Atoms:

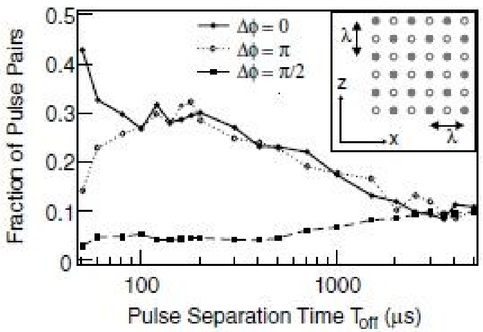
- « Recoil Induced Resonance » Lasers with Cold Atoms



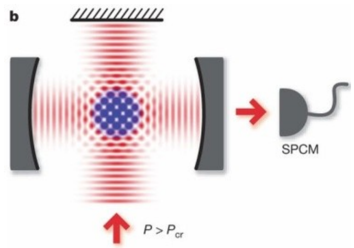


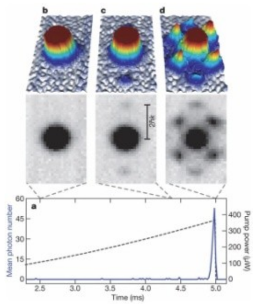
S. Slama, et al., PRL, **91**, 183601 (2003)





A. Black, et al., PRL, **91**, 203001 (2003)





K.Baumann, et al. Nature **464**, 1301 (2010)

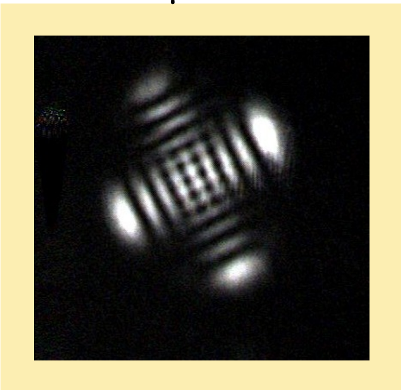
Lasing with Cold Atoms: INLN experiments

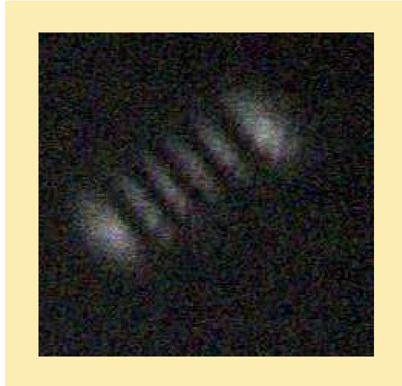
Raman Laser 2 μW

Mollow Laser 30 μW

Raman Laser 2 μW

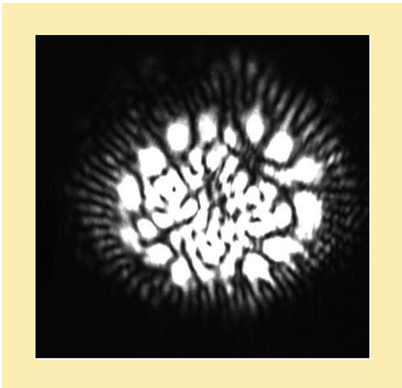
One Pump Beam

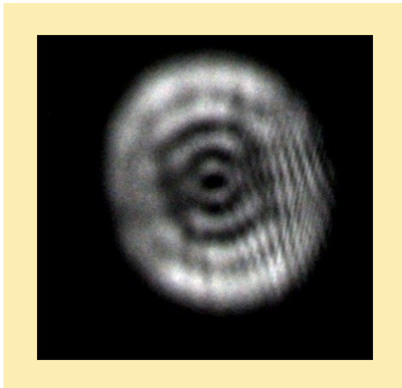


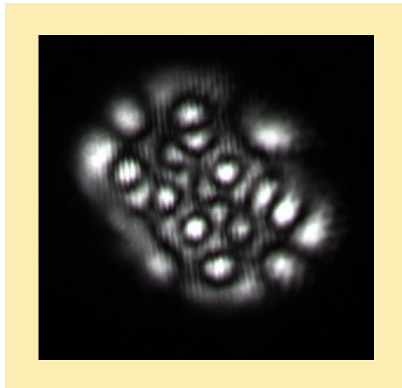


-4Γ ω_{at} $+4\Gamma$ Pump Detuning

Two Pump Beams







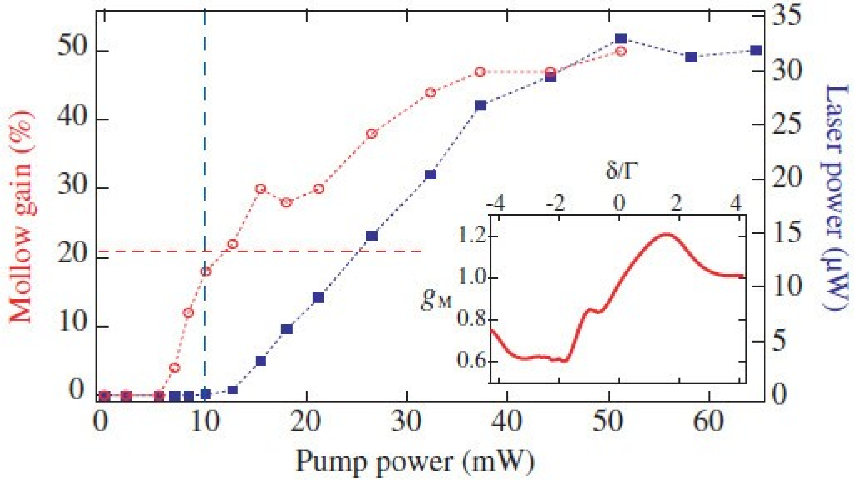
FWM Laser 300 μW

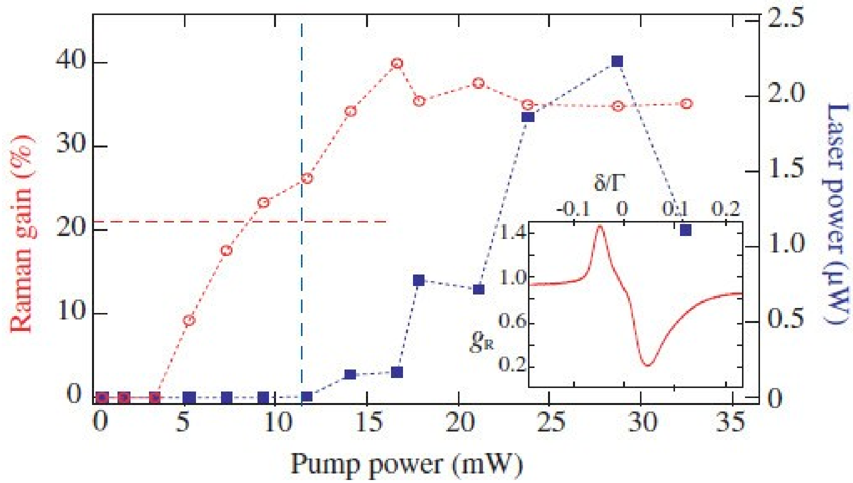
Mollow Laser 30 μW

… Laser 300 μW

W. Guerin, et al. PRL,**101**,093002 (2008)

Lasing with Cold Atoms: threshold condition : gain=loss





W. Guerin, et al. PRL,**101**,093002 (2008)

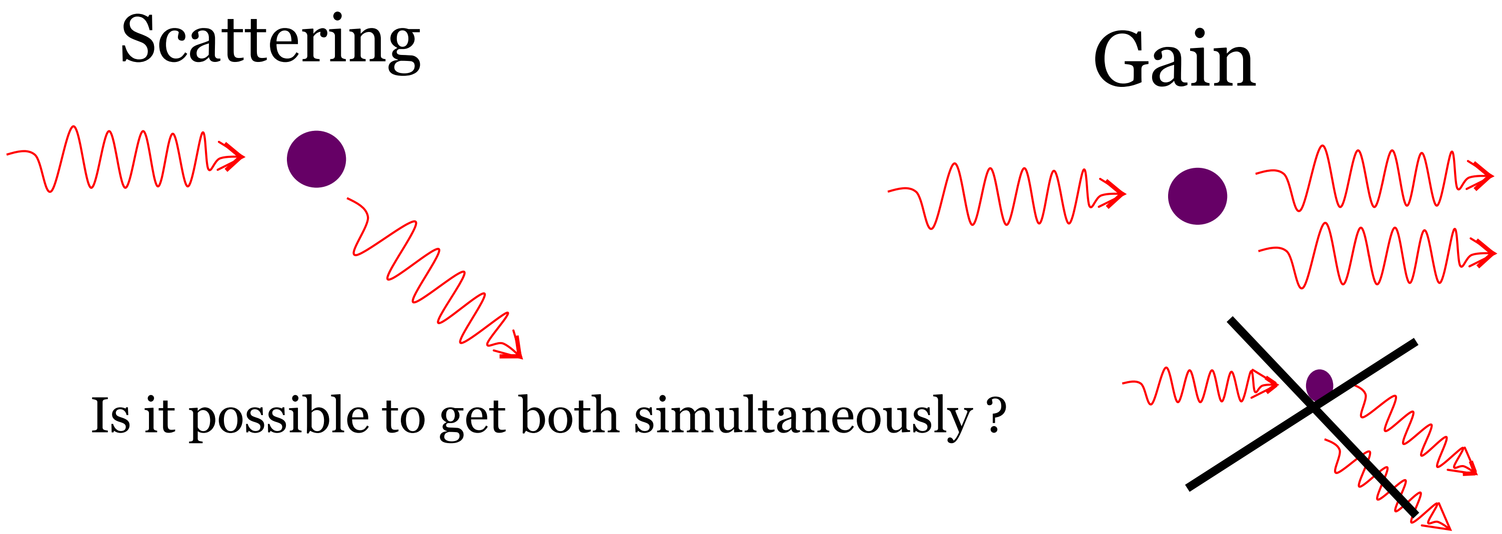
1. Introduction
2. Cold Atoms
   - Multiple scattering
   - Gain
3. **Random lasing with cold atoms**
   - Predictions
   - Experiments
   - Model
4. Outlook

- **Multiple Scattering of Light by Cold Atoms** ✓

- **Lasing with Cold Atoms:** ✓

How to combine these ingredients ?

Problem : the scatterers and amplifiers are **the same atoms** !



Is it possible to get both simultaneously ?

Pumping, necessary to get gain, reduces drastically the scattering cross-section ☹

Letokhov **diffusive** model

$$L > 2\pi\sqrt{\frac{\ell_{sc}\ell_g}{3}}$$

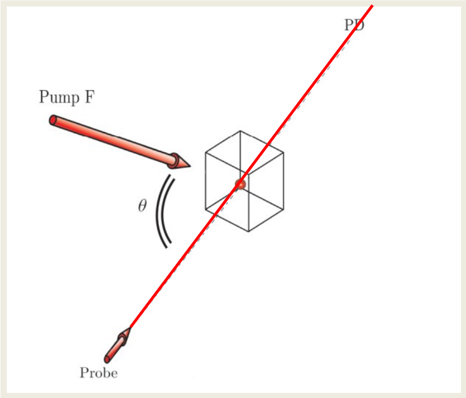
(sphere geometry)

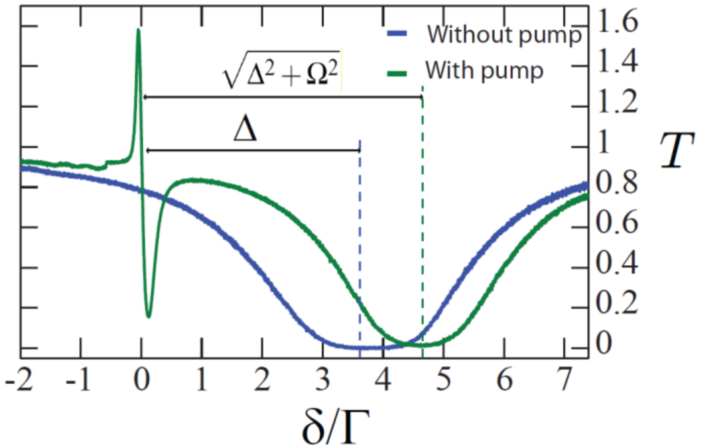
ℓ_g = linear gain length

ℓ_{sc} = mean free path $\ell_{sc} = \frac{1}{n\,\sigma_{sc}}$

Transmission experiments: $T = e^{-L/\ell_{ex}}$

with the extinction length $\frac{1}{\ell_{ex}} = \frac{1}{\ell_{sc}} - \frac{1}{\ell_g}$





The atomic polarizability

$$\sigma_{ex} = k\,\mathrm{Im}(\alpha) = \sigma_0\,\mathrm{Im}(\tilde{\alpha})$$

$$\sigma_{sc} = \frac{k^4}{6\pi}|\alpha|^2 = \sigma_0|\tilde{\alpha}|^2$$

$$\sigma_0 = \frac{3\lambda^2}{2\pi} = \frac{6\pi}{k^2}$$ = on-resonance atomic cross-section

$$\alpha = \frac{\sigma_0}{k}|\tilde{\alpha}|$$ = polarizability (with ~ : dimensionless)

$$L > 2\pi\sqrt{\frac{\ell_{sc}\ell_g}{3}}$$

$$\frac{1}{\ell_{ex}} = \frac{1}{\ell_{sc}} - \frac{1}{\ell_g}$$

On-resonance optical depth : $b_0 = n\sigma_0 L$

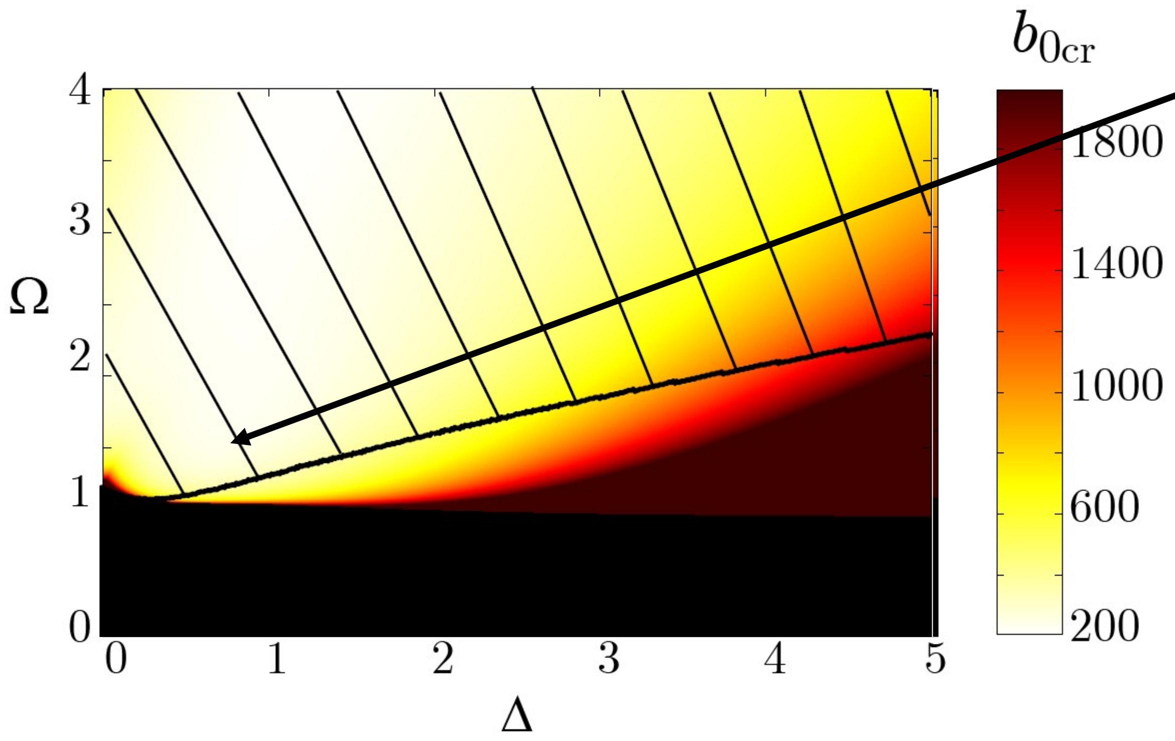
$$b_0 > \frac{2\pi}{\sqrt{3|\tilde{\alpha}|^2\left(|\tilde{\alpha}|^2 - \mathrm{Im}(\tilde{\alpha})\right)}}$$

α depends on :
- Gain scheme
- Rabi frequency Ω of the pump
- atom-pump detuning Δ
- detuning δ from the pump

Example : Mollow gain

$$\tilde{\alpha}(\Omega,\Delta,\delta) = -\frac{1}{2}\frac{1+4\Delta^2}{1+4\Delta^2+2\Omega^2}\times\frac{(\delta+i)(\delta-\Delta+i/2)-\Omega^2\delta/(2\Delta-i)}{(\delta+i)(\delta-\Delta+i/2)(\delta+\Delta+i/2)-\Omega^2(\delta+i/2)}$$

with Ω, Δ, δ in unit of Γ.



The best :

$b_{0cr} \approx 200.$

Hard, but it's reached in some cold-atoms experiments.

1) A threshold exists !

2) within reach ☺

3) signature ?

L.S. Froufe-Perez & al, PRL. **102**, 173903 (2009)

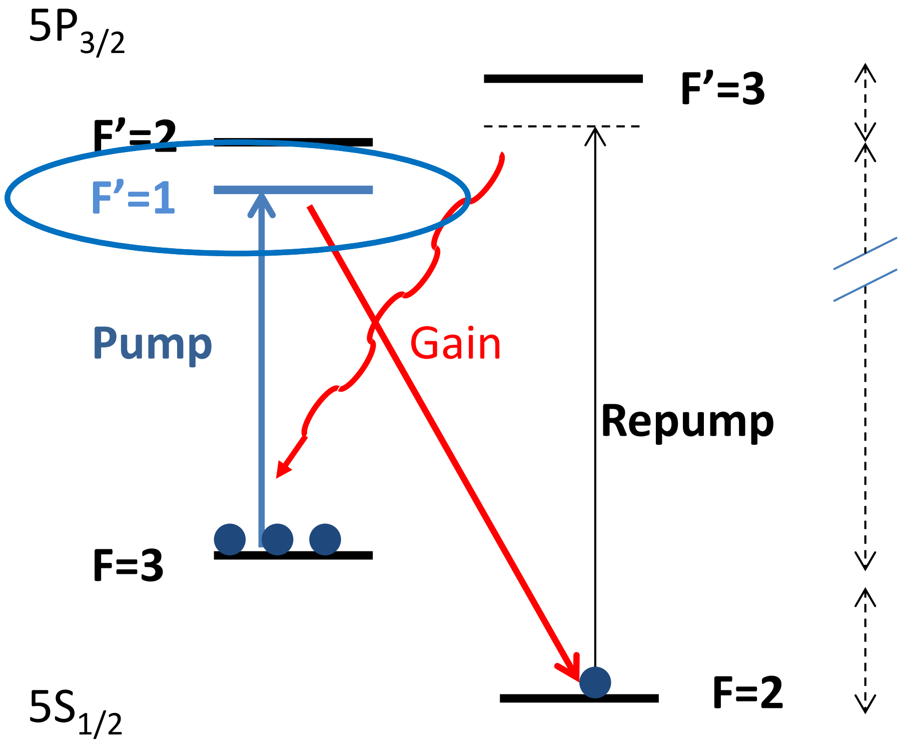
Best choice of gain scheme ?

Gain mechanism	Evaluation method	b_{0cr}	Validity of the diffusion approx.	Other problem	Ref.
Mollow gain	Analytical α	~ 200	✗	Pump penetration ☹	[1]
NDFWM	Exp. & Num.	∞	✓	Inelastic scattering ☹	
Raman gain (Zeeman)	Exp.	~ 200	✗	Detection ☹	[2]
Raman gain (Hyperfine)	Num.	~ 90	✗		

N. Mercadier: PhD 2011
Diffusion résonante de la lumière: laser aléatoire à atomes et vols de Lévy des photons

[1] Phys. Rev. Lett. **102**, 173903 (2009).
[2] Opt. Express **17**, 11236 (2009).

Our choice for gain : Hyperfin Raman Gain



Rubidium 85

gain ☺ : $b_{0,cr} = 90$

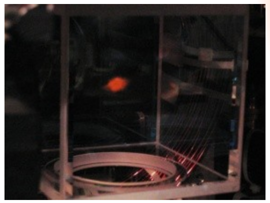
scattering ☹

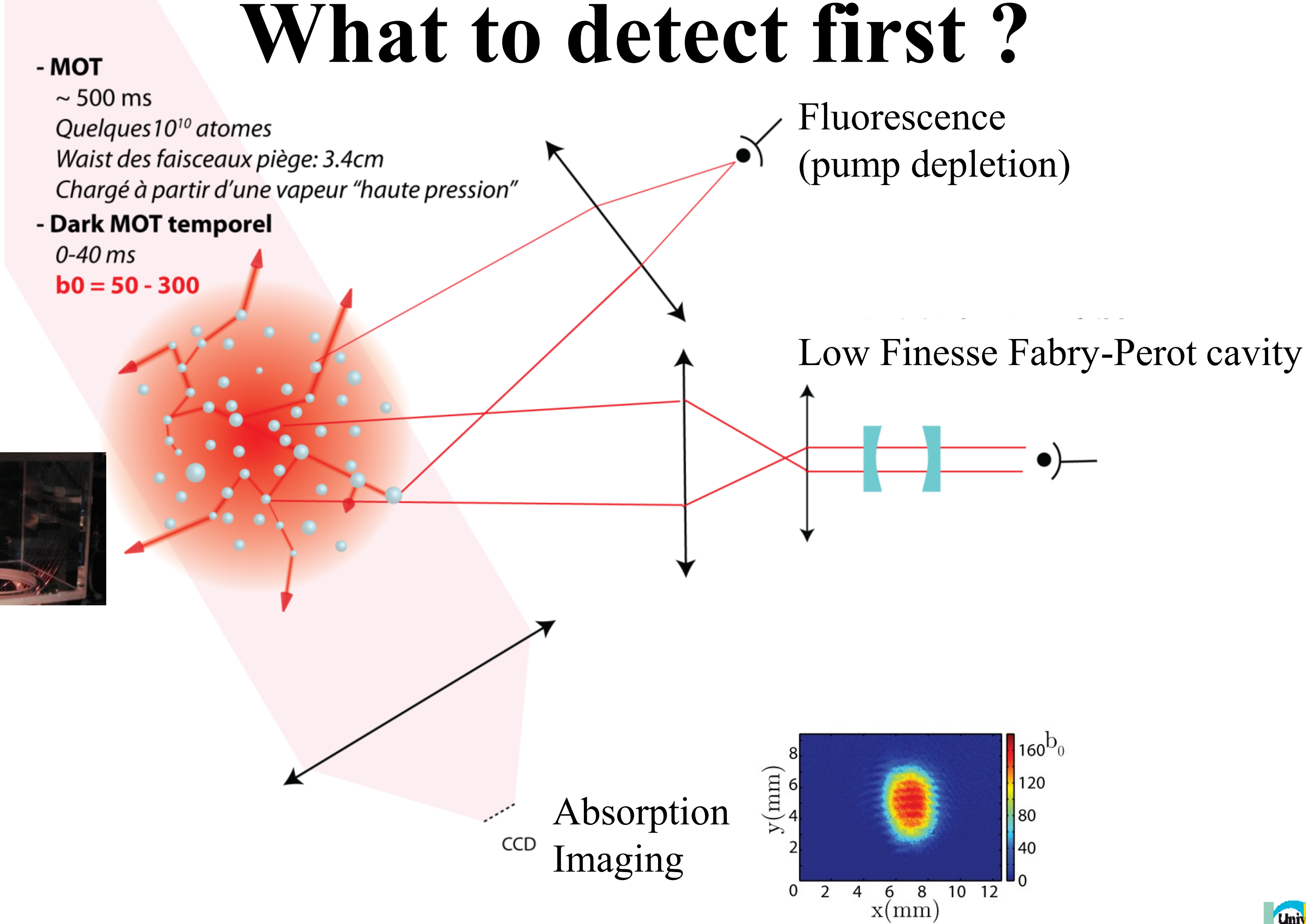
Added scattering

F=2 – F'=1 : scattering ☺

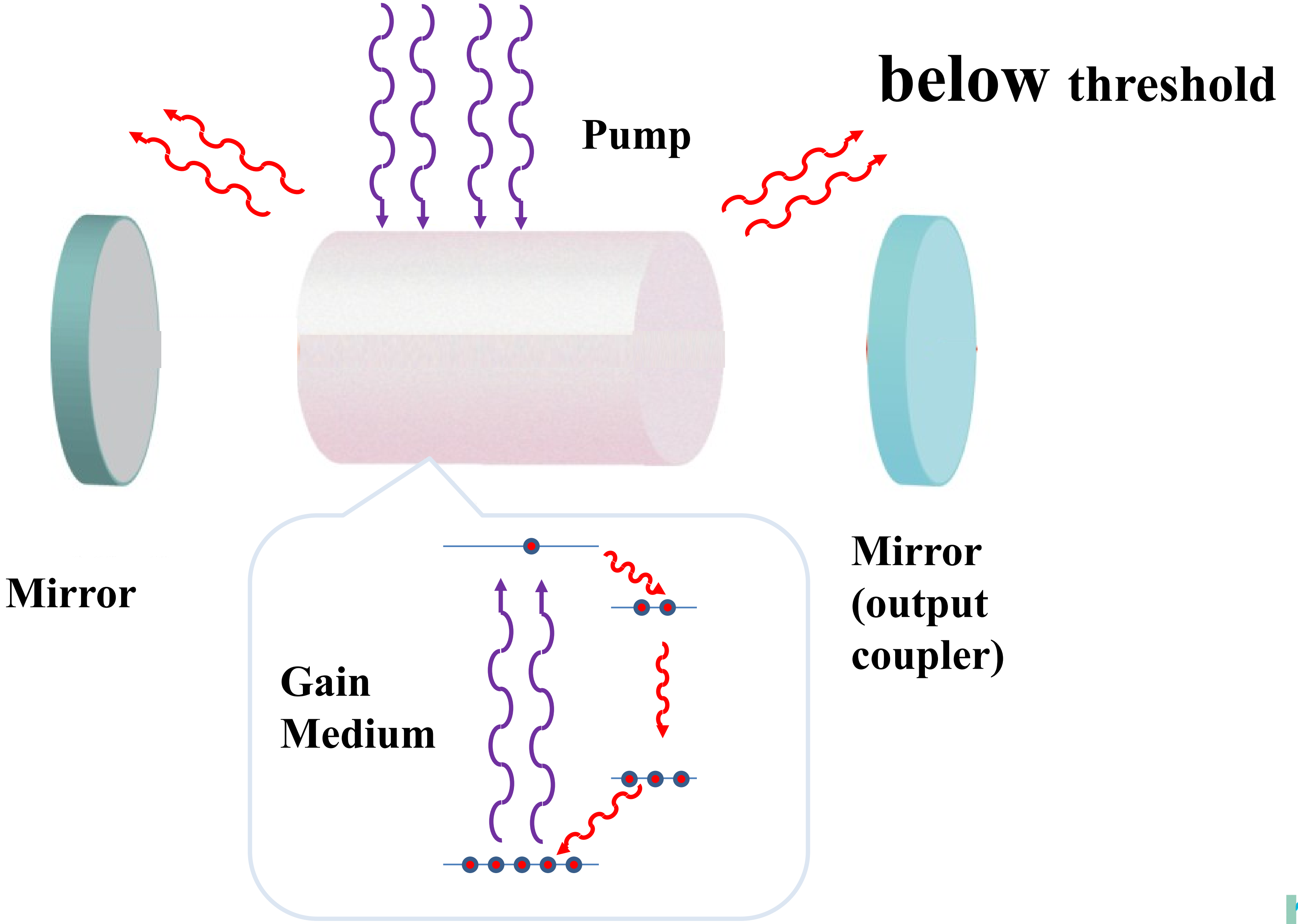
$b_{0,cr}$=30 !

The Experimental Setup : What to detect first ?

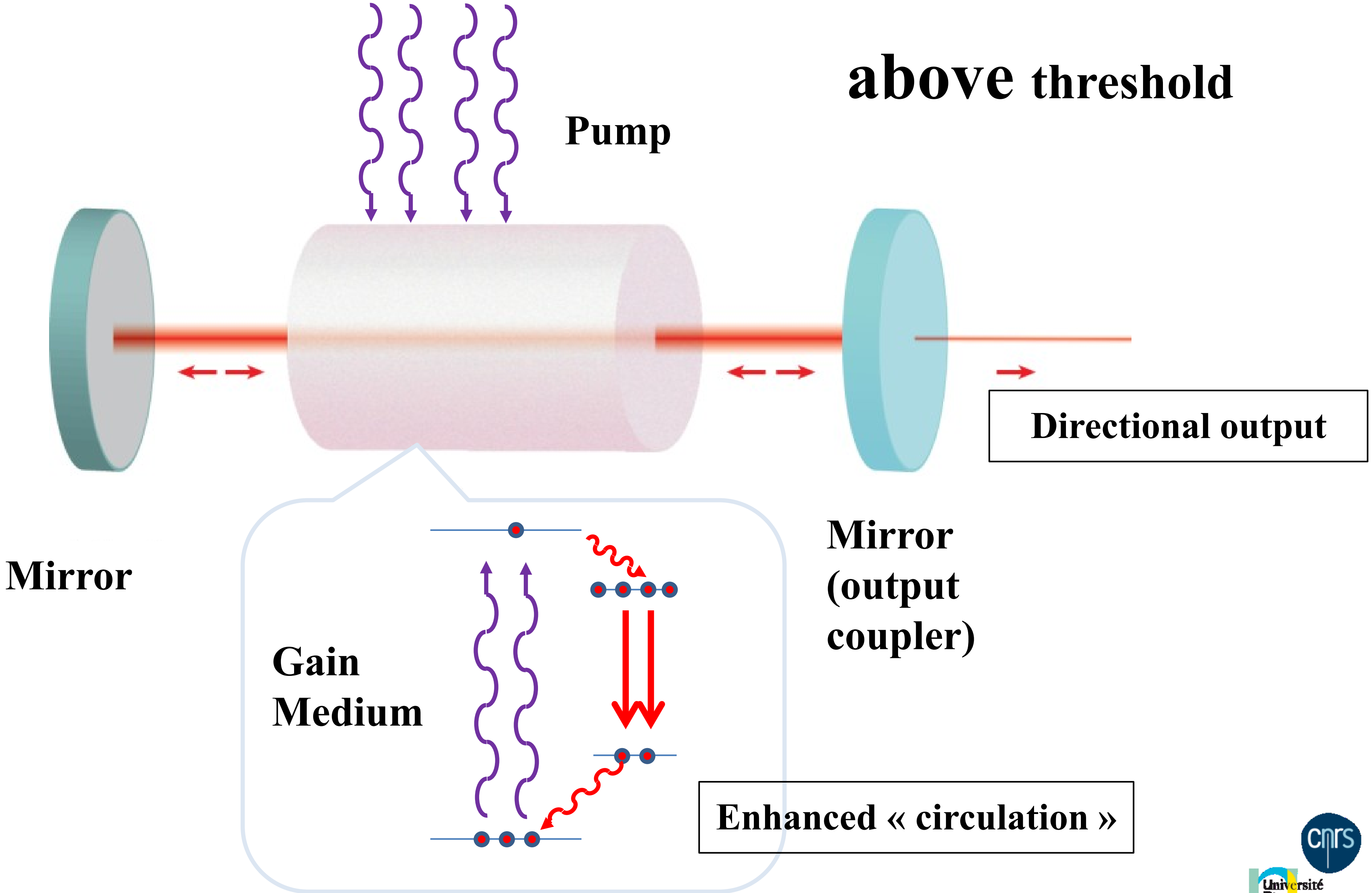




A simple laser model

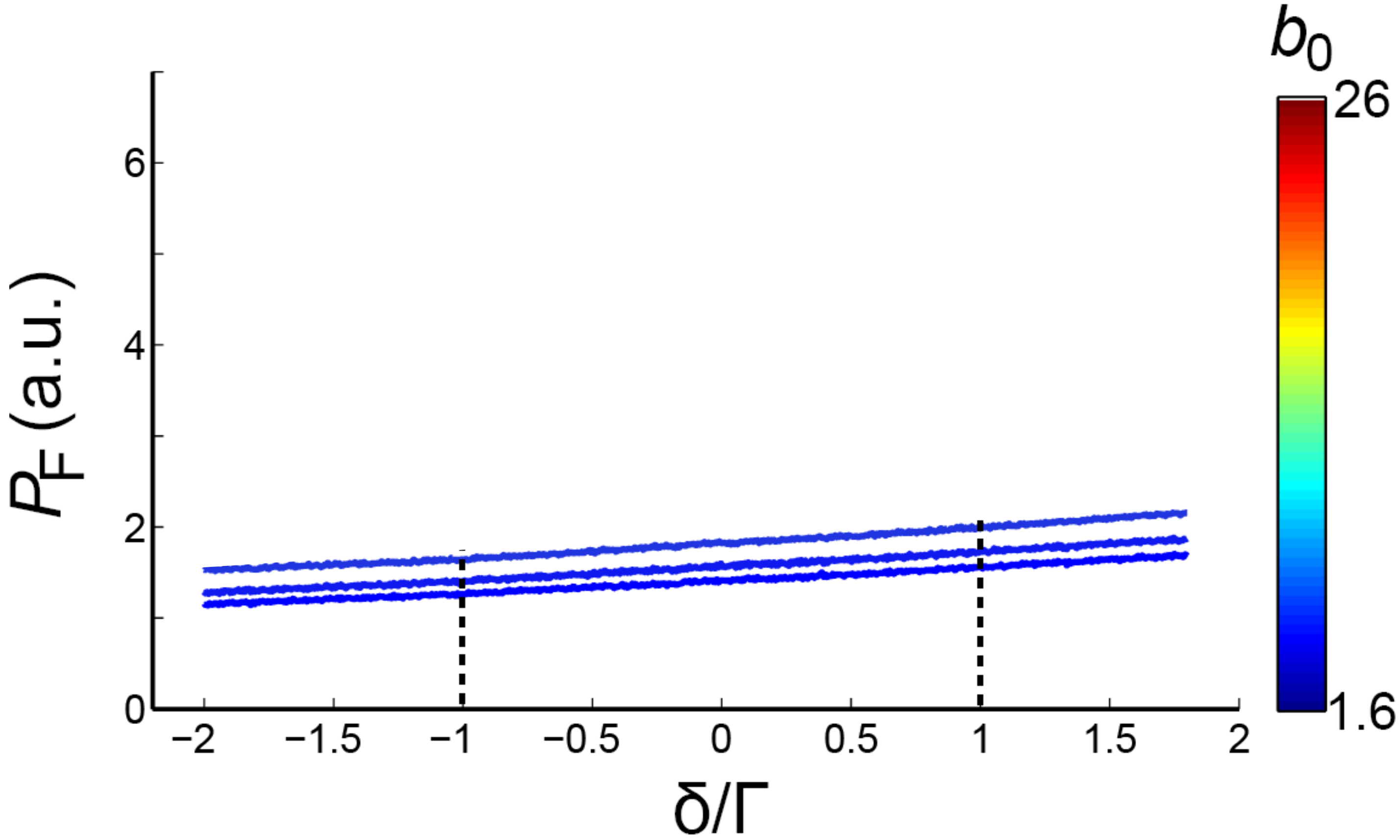


A simple laser model



Total Fluorescence

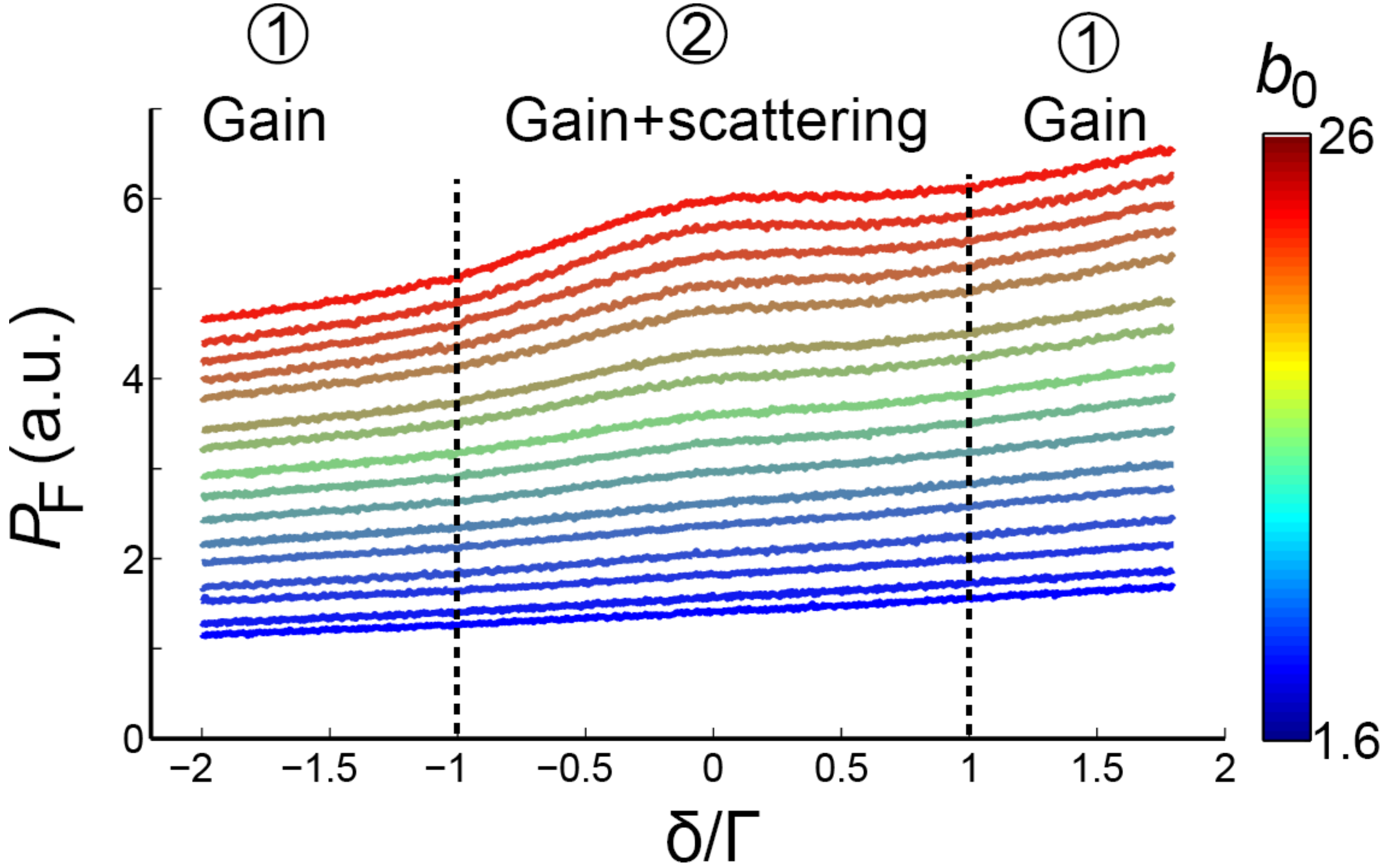
- **No increase due to redirection of emitted photons** (as in cavity laser)
- N=c^{te} ! vary compression = change b_0 @ c^{te} N



F=3 ⟶ F'=1

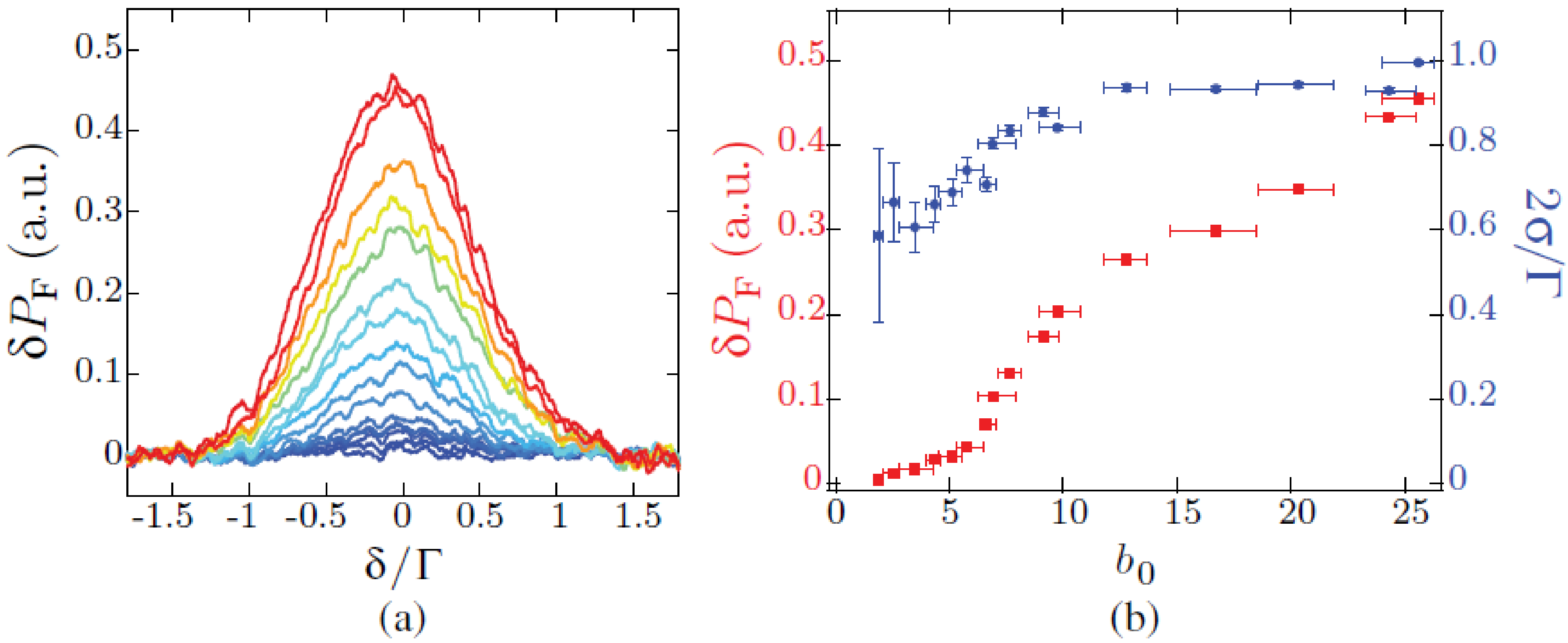
Total Fluorescence

- No increase due to redirection of emitted photons (as in cavity laser)
- N=c^{te} ! vary compression = change b_0 @ c^{te} N



Additional Fluorescence at RL condition

subtract the “ASE” background : extracted gaussian peak



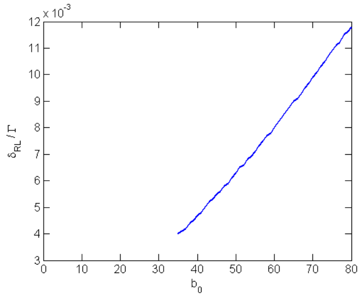
Microscopic modelling for cold atom random lasing

1) Input parameters : pump and repump lasers $\{\Omega_{Raman}, \Delta_{Raman}, \Omega_{pump}, \Delta_{pump}\}$
system « size » b_0

2) Ω_{RL} , Δ_{RL} => density matrix / optical Bloch equations (4 level, 3 lasers)
=> σ_{sc} , σ_{ext}, σ_g
=> 4+1 model : σ_{sc}+ scattering $\sigma_{2\text{-}1'}$

3) Compute (**Δ_{RL} free parameter)**

$$2\pi \sqrt{(\sigma_0^2 / 3\sigma_g\sigma_{sc})} = b_{0,Letokhov}$$



4) If $b_{0,exp} > b_{0,Letokhov}$: our experiment must have more scattering
increase Ω_{RL}

5) $b_{0,exp} = b_{0,Letokhov}$: we know Ω_{RL} (**including saturation**, which sets losses = gain)

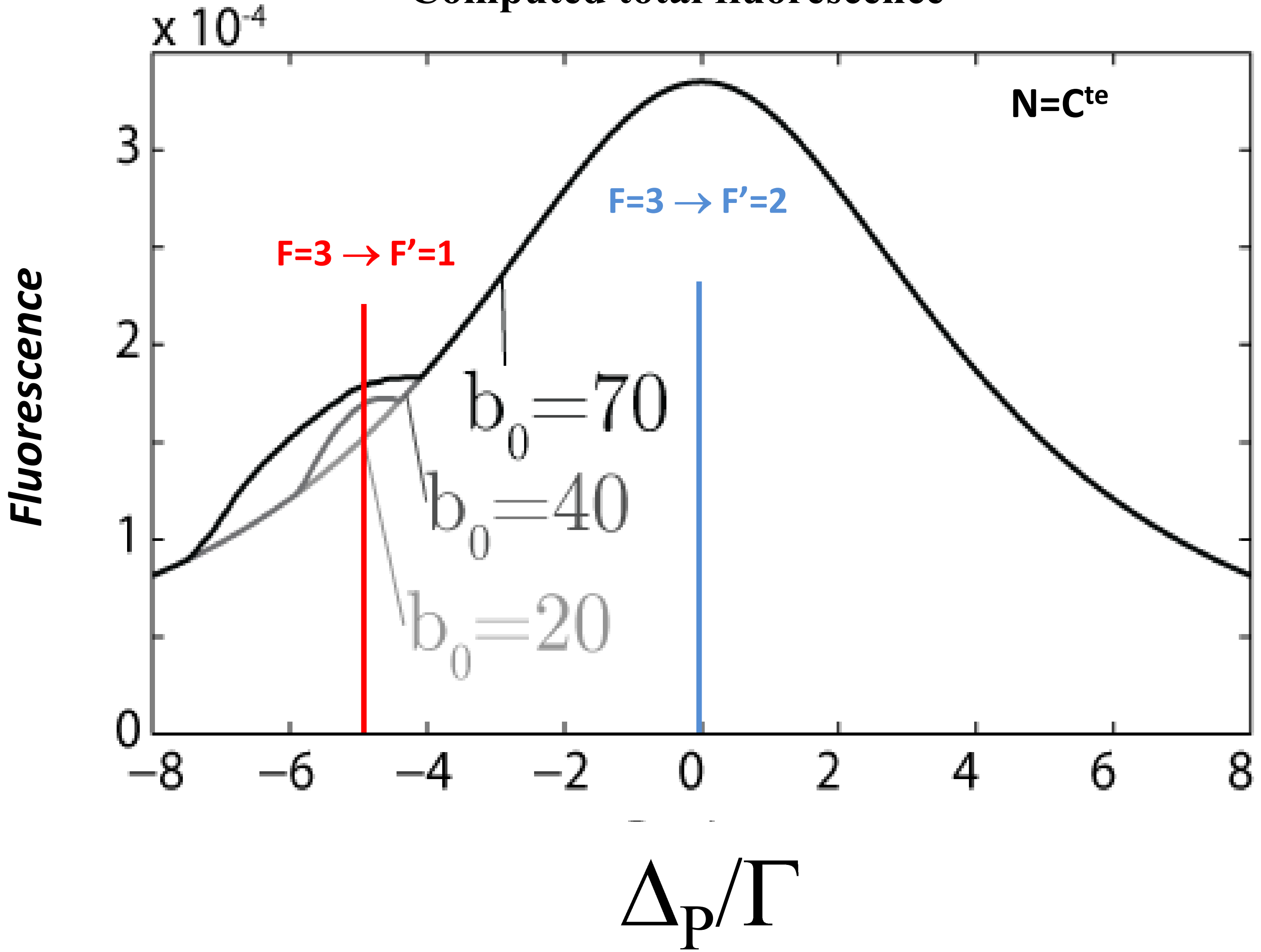
6) Compute pump and repump extinction = total fluorescence ☺

7) ☹ misses Raman hyperfin gain below threshold

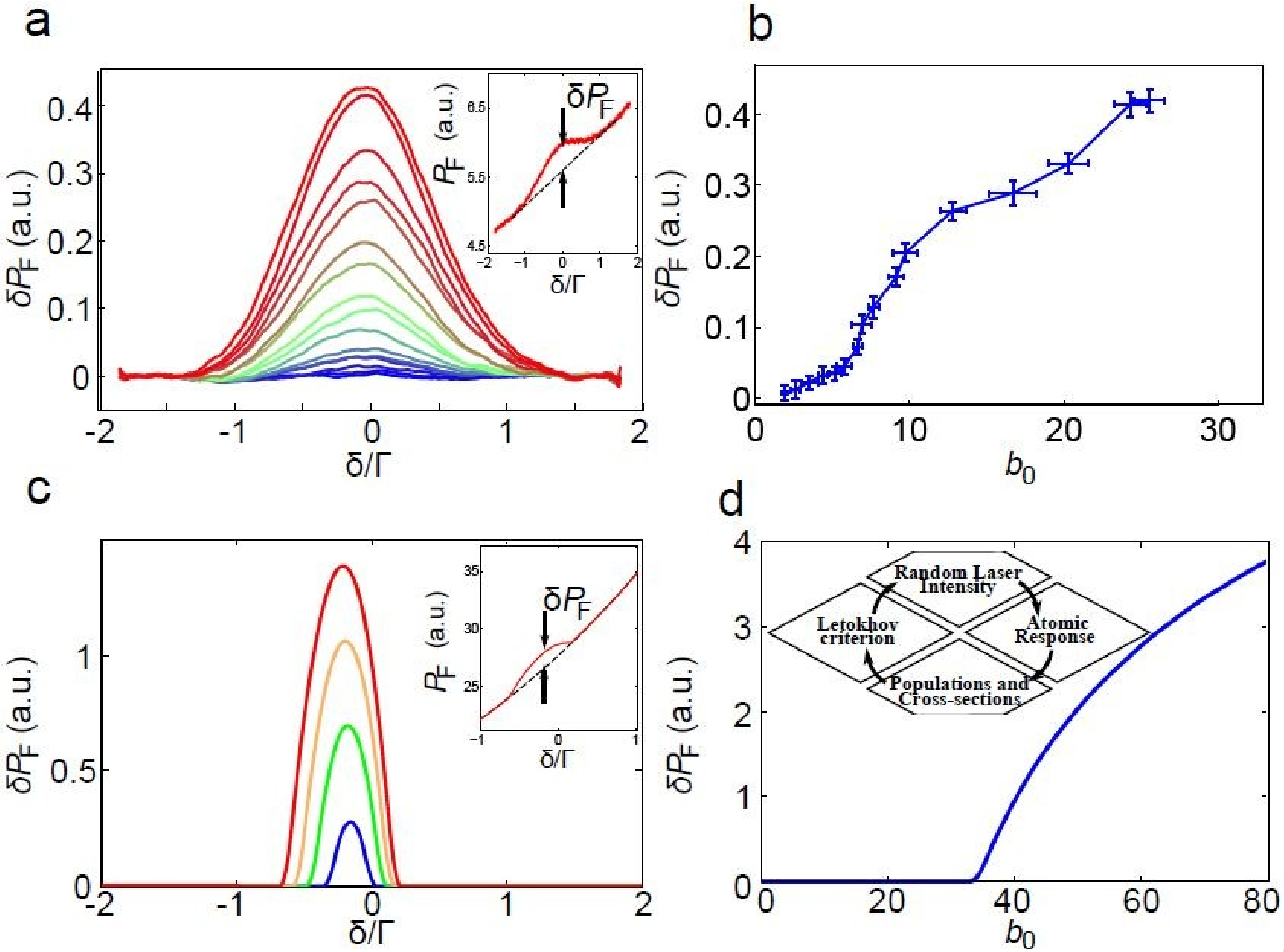
Microscopic modelling for cold atom random lasing

Input parameters : pump and repump lasers $\{\Omega_P, \Delta_P, \Omega_{rep}, \Delta_{rep}\}$, system « size » b_0

Computed total fluorescence



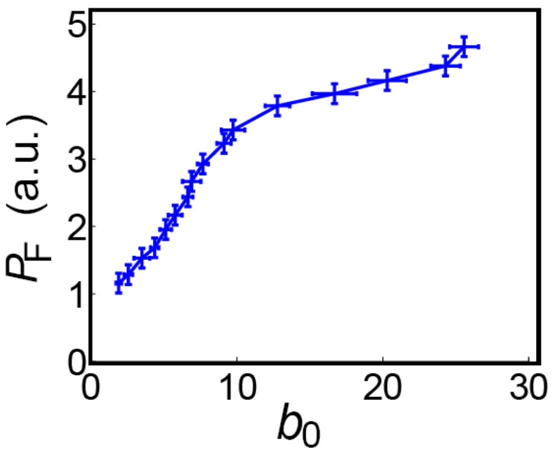
Microscopic modelling for cold atom random lasing

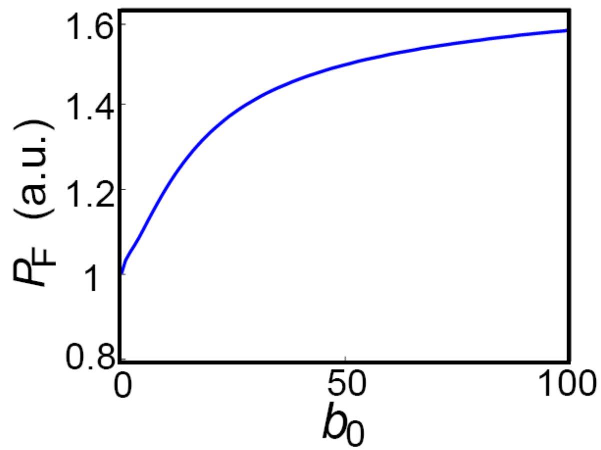


Microscopic modelling for cold atom amplified spontaneous emission

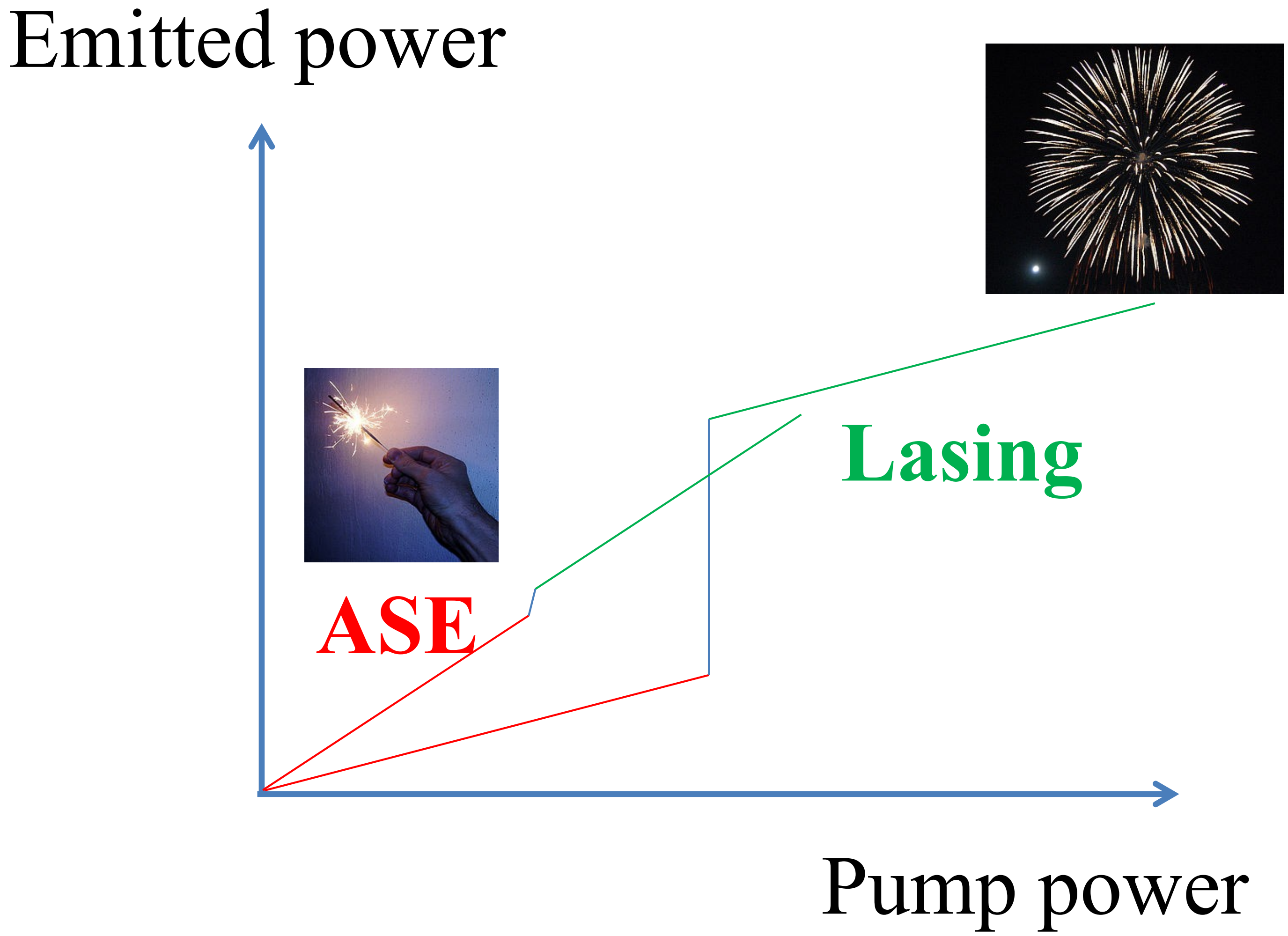
Optical Bloch equations (no scattering) :
Start with Ω_{RL}=0
Source term corresponding to spontaneous Raman scattering
Compute intensity at the center of the cloud (emission from all atoms towards center)
Scan detuning of emitted light for maximum emission
Includes gain saturation

Amplified Spontaneous Emission



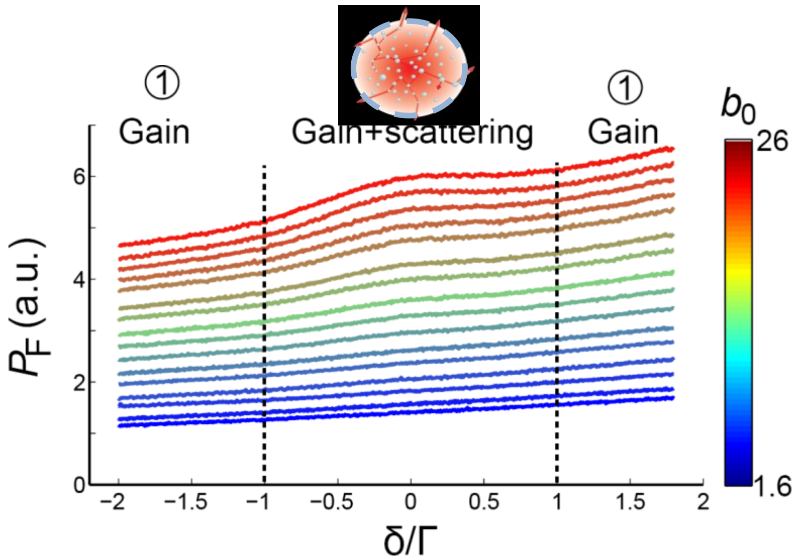


ASE and gain saturation



Conclusion:

- Combination of scattering and gain observed in cold atoms
- Microscopic Model in qualitative agreement
- Dilute gaz quasi cw random laser

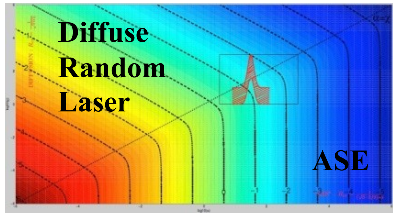


A cold-atom random laser
Q. Baudouin, N. Mercadier, V. Guarrera, W. Guerin, R. K.
[Nature Physics, 05 May 2013]()

1. Introduction
2. Cold Atoms
   - Multiple scattering
   - Gain
3. Random lasing with cold atoms
   - Predictions
   - Experiments
   - Model
4. **Outlook**

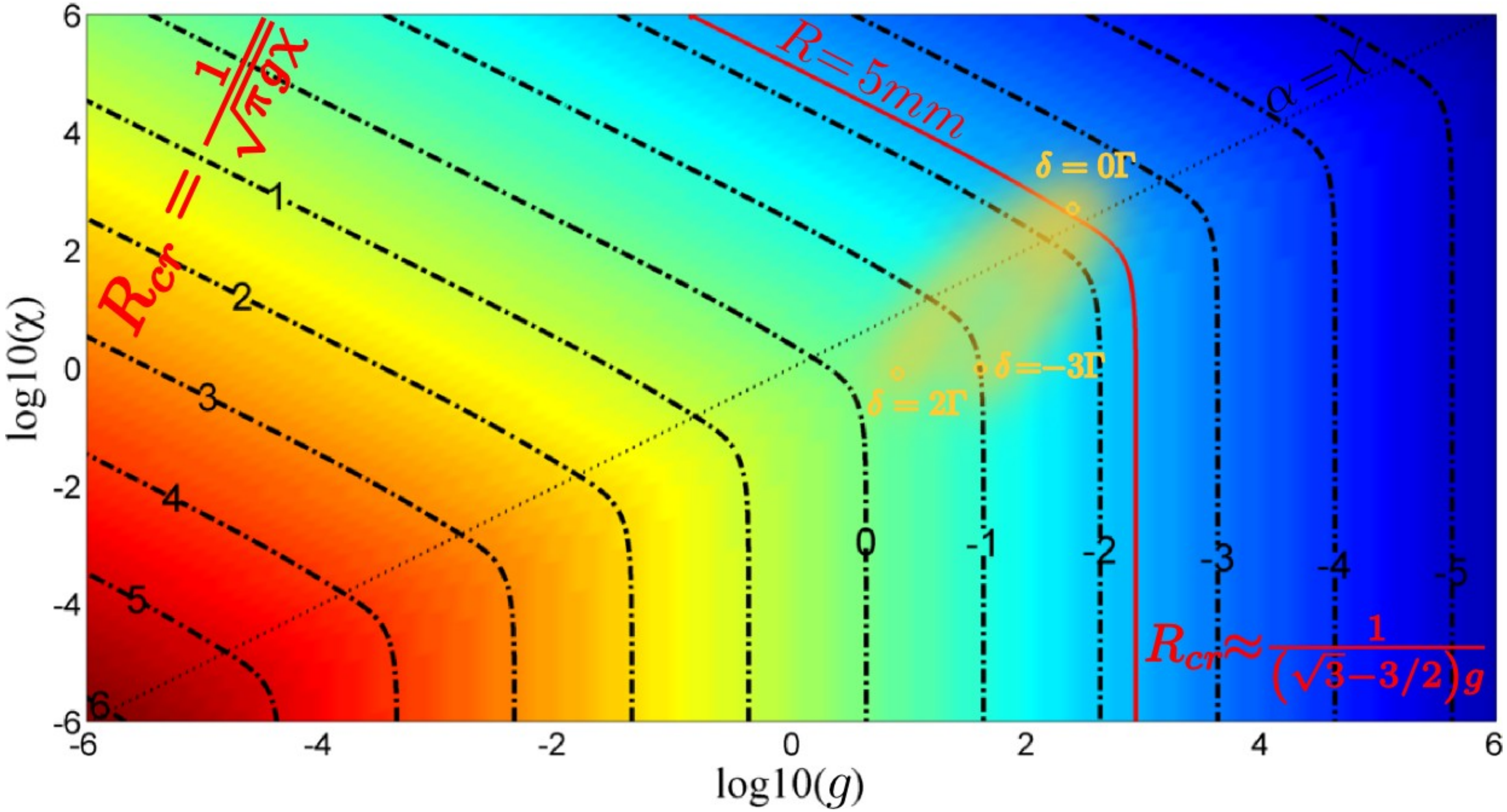
What to do next :

- Combining ASE + random lasing model
  compare coherent vs incoherent models



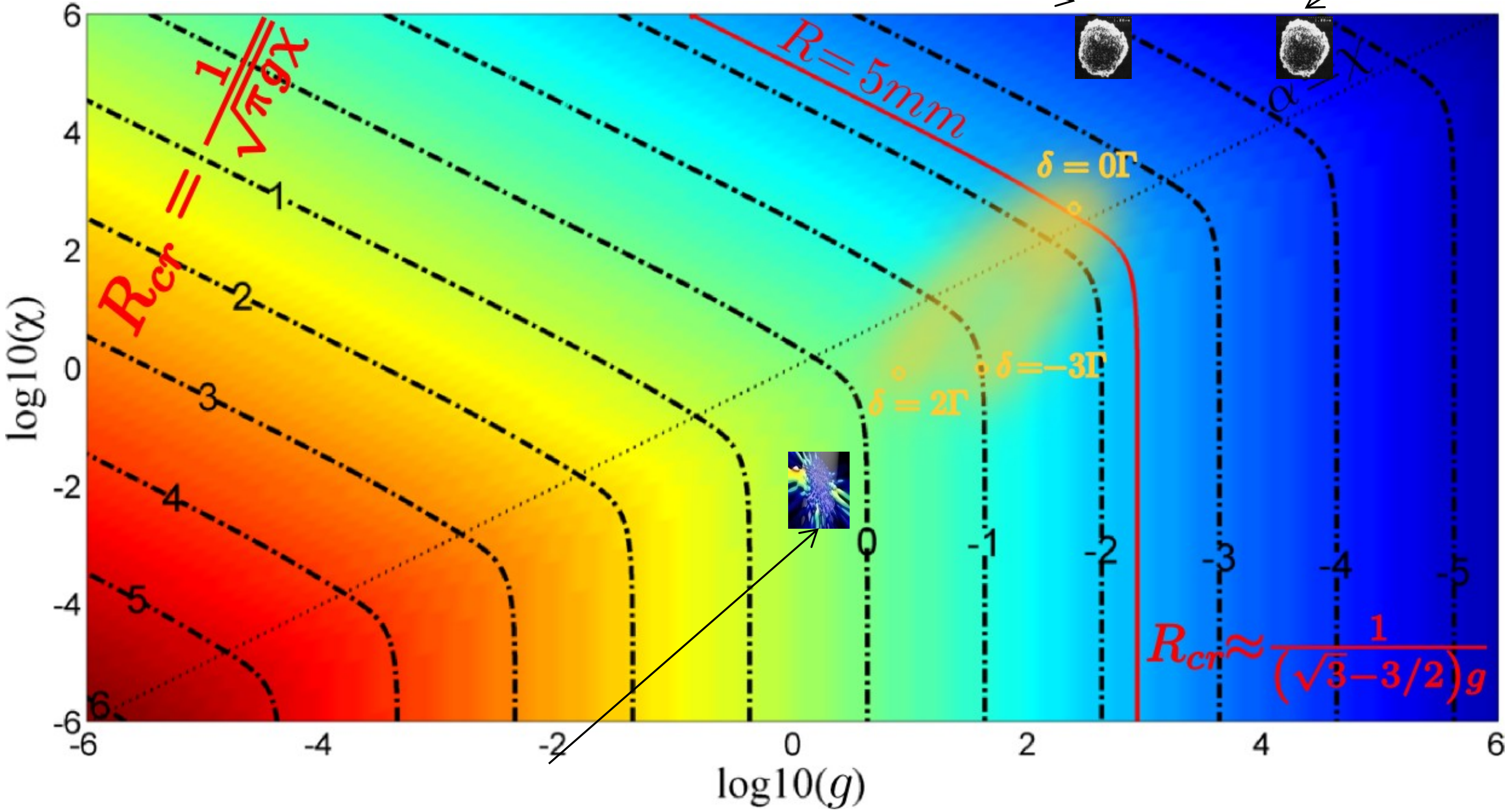
Generalised Letokhov threshold

Model decomposition of radiative transfer equation



Generalised Letokhov threshold

Experiments by H. Cao (PRL, **82**, 2278, 1999) and A. Lagendijk (PRL, **98**, 143901, 2007)



Theory by D. Stone (Science, **320**, 643, 2008.)

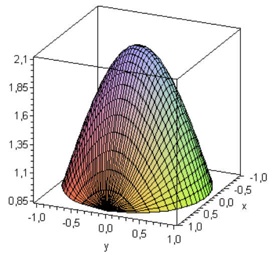
Courtesy S. Rotter

Numerical experiment in non diffusive regim

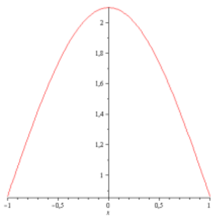
Douglas Stone group

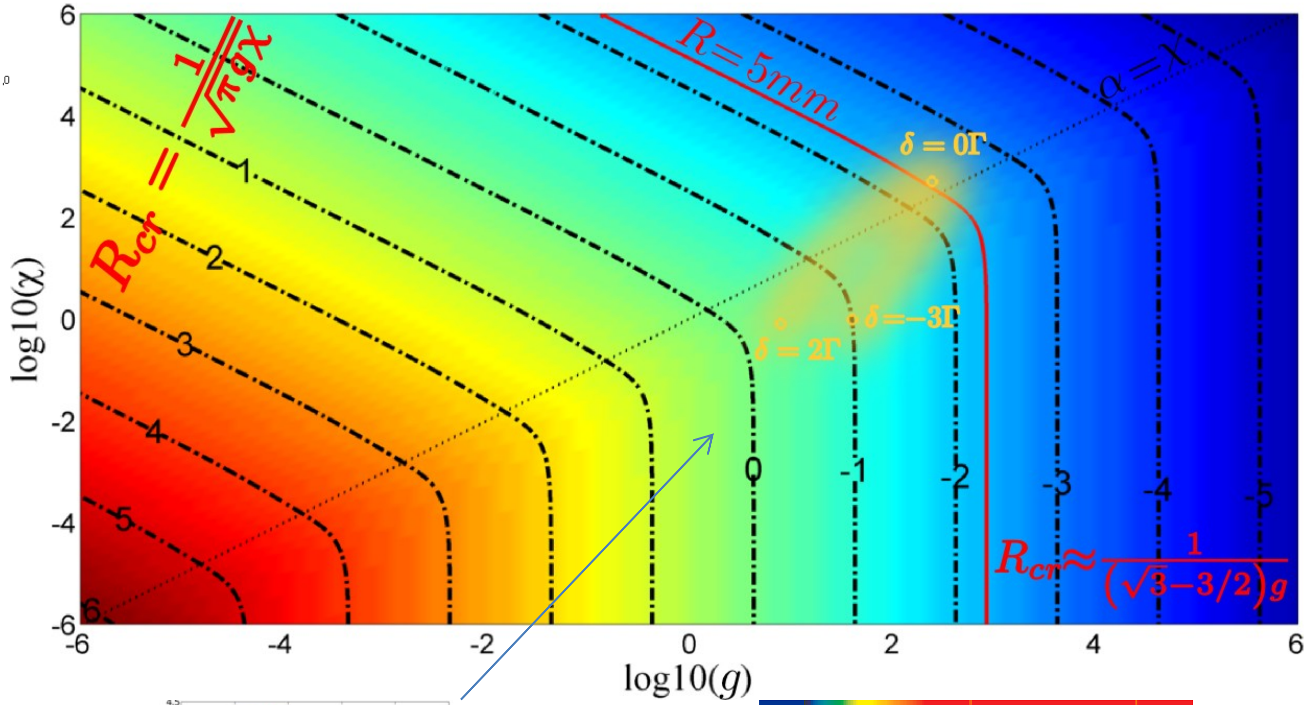
For $\alpha = 4$, $\chi = 0{,}01$ they find $R_{cr} = 1$ | With our non diffusive criterion: $R_{cr} = \frac{1}{(\sqrt{3}-3/2)\alpha}$ we find $R_{cr} = 1{,}08$ and the good shape of mode

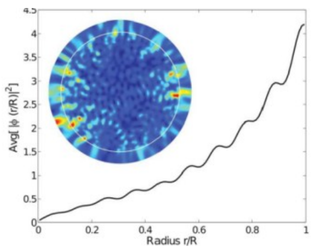
Shape of Lasing modes

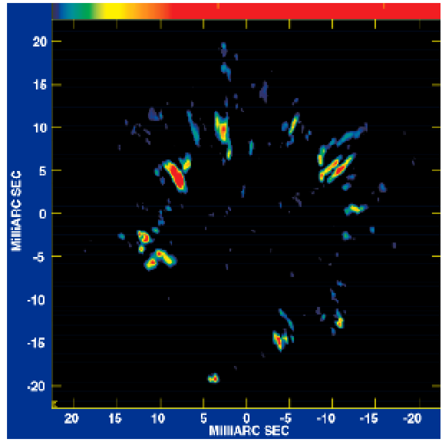


Diffuse Random Laser



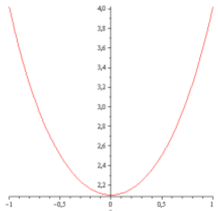


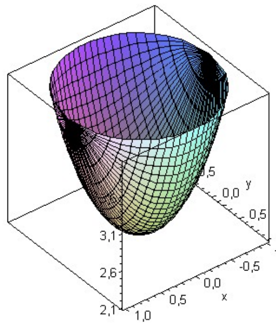




43 GHz (SiO) maser in TX-cam star

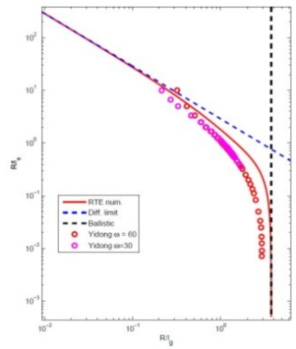
ASE



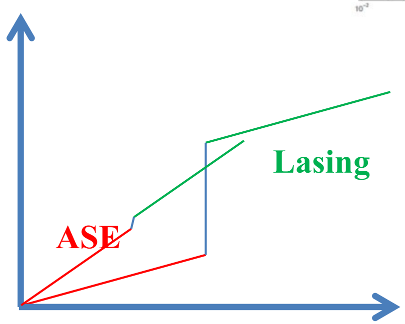


A&A, **432**, 531, 2005

What to do next :

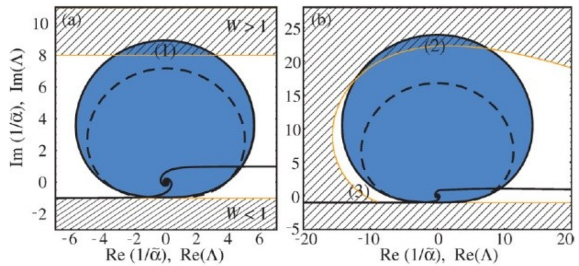


- Compare coherent vs incoherent models (S. Rotter, Y. Chong)



- Increase « Photonic Bomb » threshold behaviour

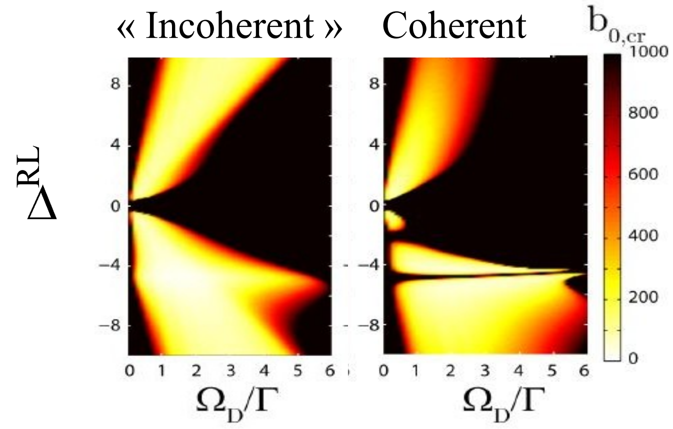
- Light Coherence : Cooperativity effects (above and below threshold)
  A.Goetschy, S.Skipetrov,
  EPL, 96, 34005 (2011)



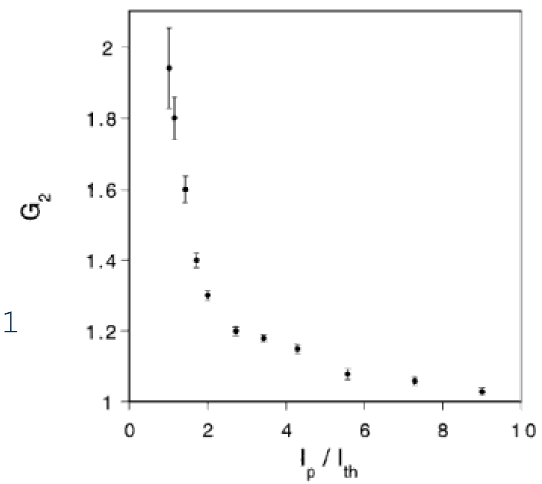
- Zeeman structure & polarisation (D. Kupriyanov et al.)

More to do :

- Atomic Coherence effects (connection to EIT in multiple scattering)



- **Spectral width and Photon Statistics : $g^2(\tau)$**



Cao *et al.*, PRL 2001

- Test different gain schemes (astrophysical schemes)
- Time dependent experiments (switch on, pulsing)
- Atom motion (negative radiation pressure?)

From Cold Atoms to Astrophysics

- Gain and scattering : Mars, Venus, Jupiter,
  Eta Carinae, Wolf-Rayet WC stars

Table 1
Maser/laser action in space

Microwaves	Molecules	OH, 18.5 cm	Weaver et al. (1965)
	>100 molecular species	H_2O, 1.35 cm	Cheung et al. (1969)
			Townes (1997)
Submillimeters	Atom	H^{**}	Strelnitskii et al. (1996)
IR	Molecule (Mars, Venus)	CO_2, 10 μm	Johnson et al. (1976)
			Mumma et al. (1981)
Optical waves	Ion, atom	$Fe^{+} \simeq 1$ μm	Johansson and Letokhov (2002)
	η Carinae, gas condensations	OI, 8446 Å	Johansson and Letokhov (2005a–c)

S. Johansson ,V. Letokhov, New Astronomy Reviews, **51**, 443 (2007)


Thank you for your attention