The laser which came from the cold

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The work presented in this talk...

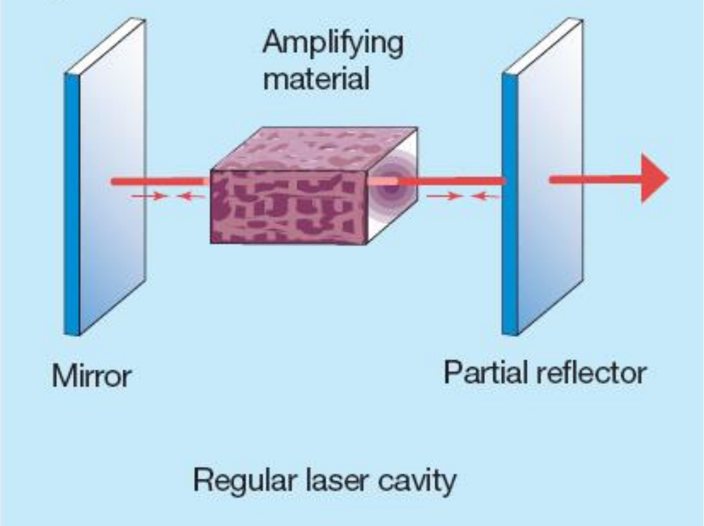
...has been done: @ INLN (post-doc, 2007 – 2009)
@ Tübingen University, Germany (post-doc, 2010 – 2012)
@ INLN (CR CNRS, since end 2012)

Most of it is contained in the following PhD thesis:
- Frank Michaud, Nice, 2008
- Nicolas Mercadier, Nice, 2010
- Alexander Schilke, Tübingen, 2013
- Quentin Baudouin, Nice, 2013

The work at INLN has been supervised by **Robin Kaiser**

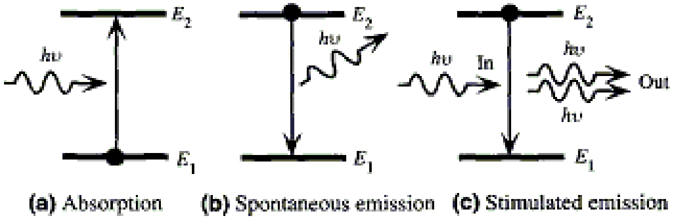
More information at: http://www.inln.cnrs.fr/activites/themesrecherche/atomes-froids

What is a laser ?



Two ingredients for a **standard laser** :

1) An amplifying material
   (Gain based on stimulated emission)



2) An optical cavity

Roles of the optical cavity:

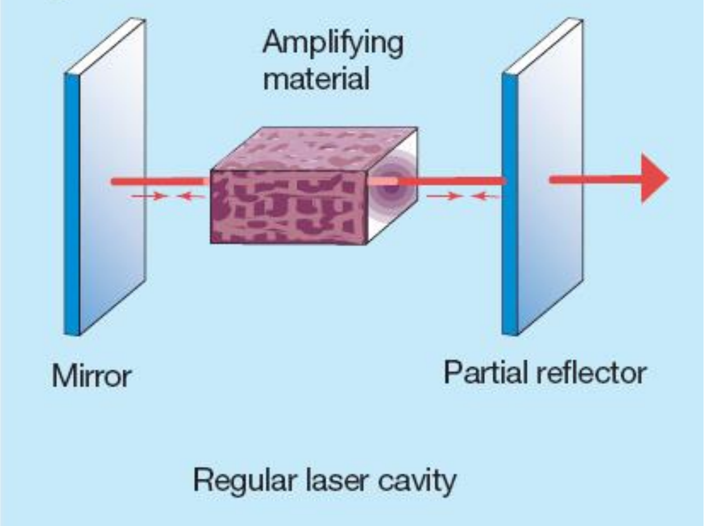
- To provide feedback

→ Chain reaction: intensity grows until gain saturation

- Fabry-Perot interferometer

→ Mode selection: spatial and temporal coherence properties

What is a laser ?



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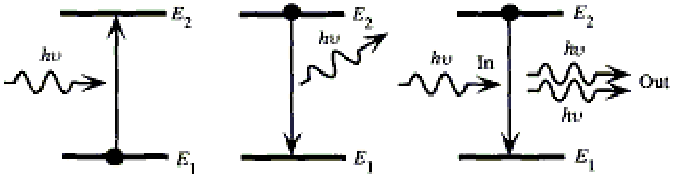


(a) Absorption (b) Spontaneous emission (c) Stimulated emission

2) ~~An optical cavity~~

Roles of ~~the optical cavity~~:

- To provide feedback

→ Chain reaction: intensity grows until gain saturation

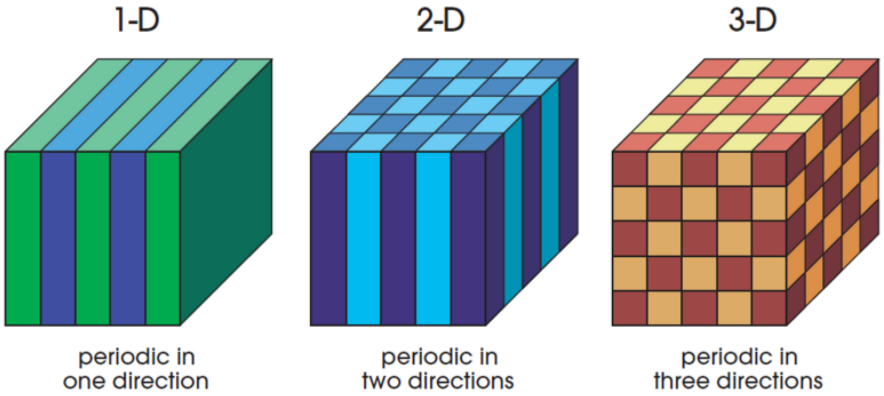
~~- Fabry-Perot interferometer~~

~~→ Mode selection: spatial and temporal coherence properties~~

?

Trapping light without mirrors (1)

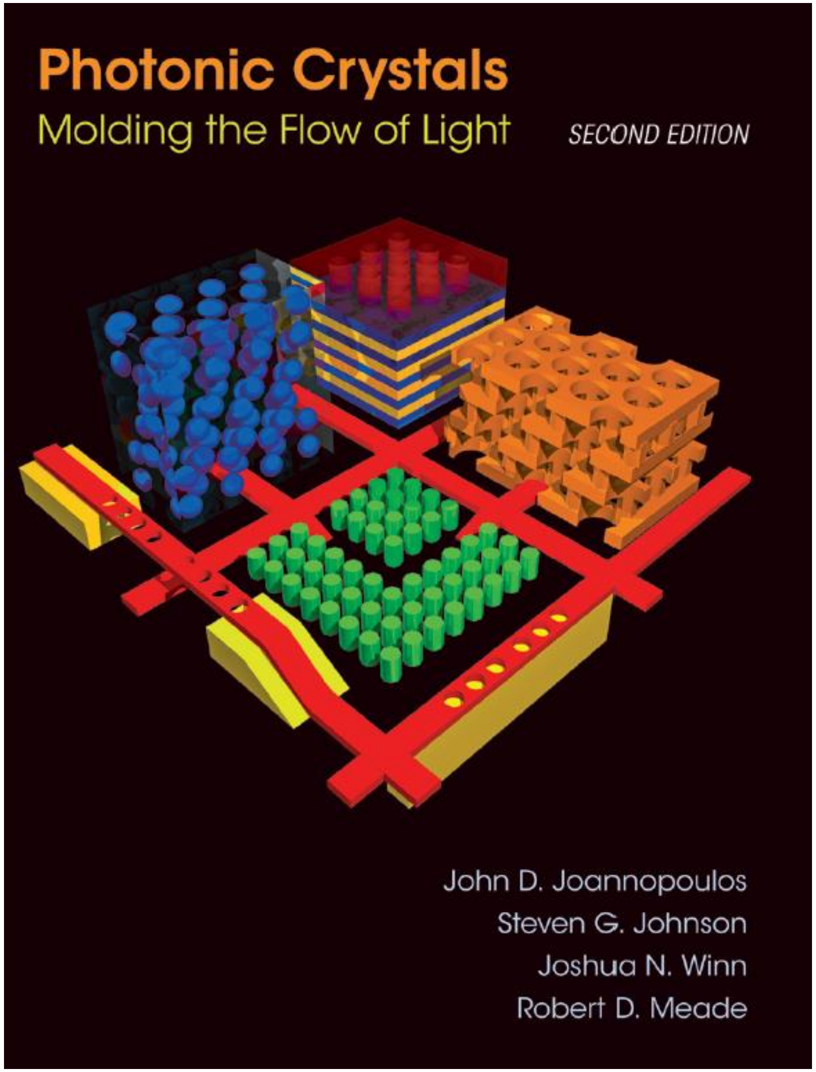
First possibility: use a **periodic medium**



Photonic crystals can confine light in 1D, 2D or 3D.

Can be combined with light emitters (e.g. quantum dots) or amplifiers.

→ "photonic crystal lasers" / "nanolasers"

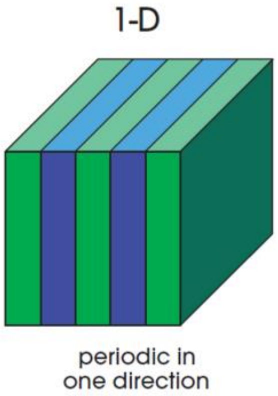


Photonic Crystals
Molding the Flow of Light
SECOND EDITION

John D. Joannopoulos
Steven G. Johnson
Joshua N. Winn
Robert D. Meade

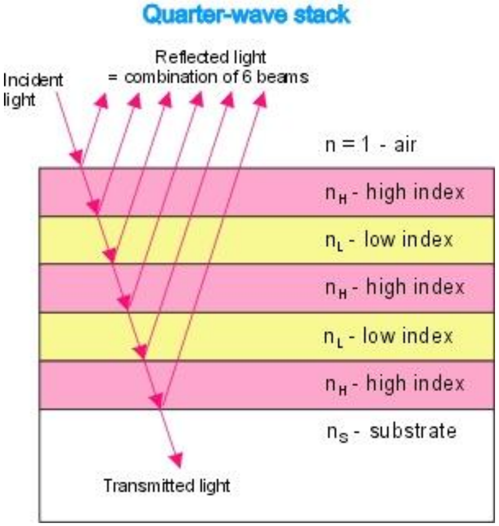
Trapping light without mirrors (1)

First possibility: use a **periodic medium** (1D case)



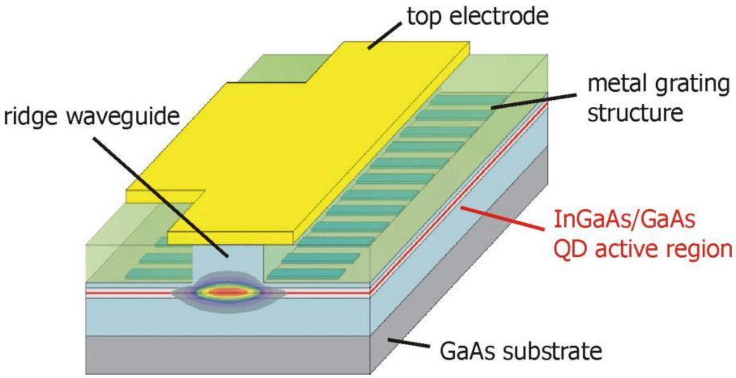
Light propagation is a 1D periodic medium is known since Rayleigh.

→ Bragg mirrors



Active medium (gain) + 1D modulation: known since the 70s…

→ “distributed feedback laser” (DFB).



`Kogelnik & Shank, Appl. Phys. Lett. **18**, 152 (1971).`

Trapping light without mirrors (2)

Second possibility: use a **diffusive (disordered) medium**

Many scatterers at random positions

→ Multiple scattering

→ “Radiation trapping”

Trapping light without mirrors (2)

Second possibility: use a **diffusive (disordered) medium**

Many scatterers at random positions

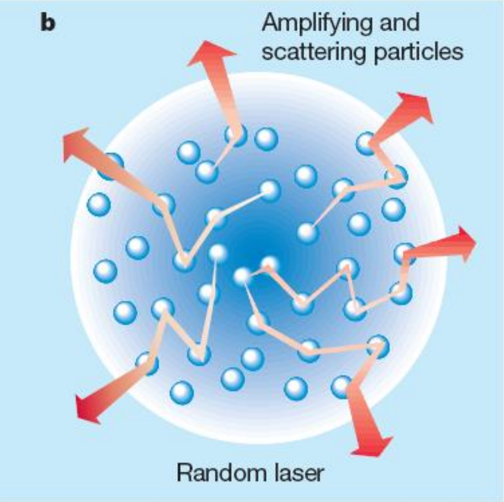
→ Multiple scattering

→ "Radiation trapping"

Multiple scattering + gain: "**Random laser**"

→ Emission in all directions

→ Mode and coherence properties: complicated !

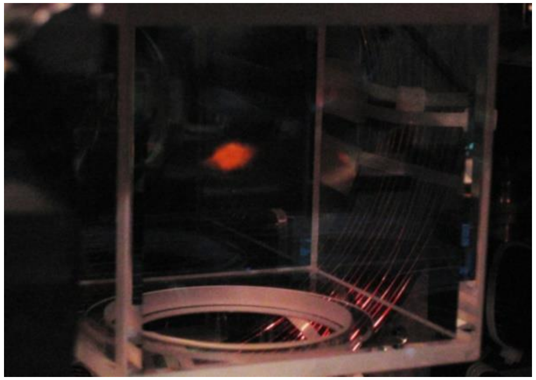


Initial proposal in 1968 !

First realized in 1995, extensively studied since the 2000s

Letokhov, Sov. Phys. JETP **26**, 835 (1968).
Wiersma, Nature Phys. **4**, 359 (2008).

Mirrorless lasers with cold atoms ?



We use atomic vapors, laser-cooled to T ~ 20-150 µK.

→ Almost no Doppler broadening

→ **Very sharp resonance** (width 6 MHz ↔ 0.000012 nm ↔ 25 neV ↔ 0.0002 cm^{-1})

For near-resonant light, a cold-atom vapor is an optical medium with some properties many orders of magnitude different than usual (standard dielectric media):

- Highly diffusive: very opaque without absorption
- Highly dispersive
- Highly nonlinear (a few mW)
- Very sensitive to external fields → highly versatile

$$\boxed{\sigma = \frac{3\lambda^2}{2\pi}\frac{1}{1+4\delta^2/\Gamma^2}}$$

Outline

☑ Introduction

☐ Standard lasing with cold atoms

☐ DFB lasing with cold atoms

☐ Random lasing with cold atoms

☐ Concluding remarks

Basic tool: the magneto-optical trap

Rubidium 85

λ = 780 nm

$\Gamma/2\pi$ = 6 MHz

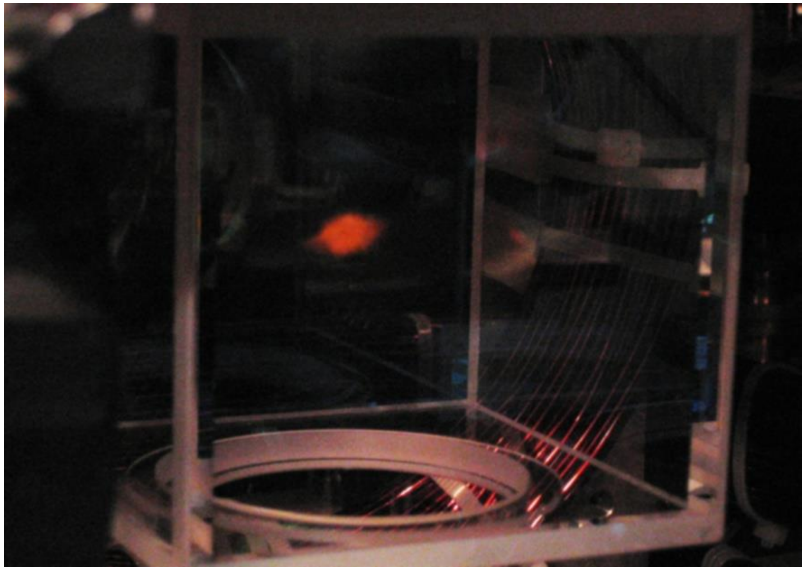
MOT parameters:

N ~ 10^8-10^{10} atoms

T ~ 20-150 µK

L ~ 1-2 mm

ρ ~ 10^{11} at/cm^3



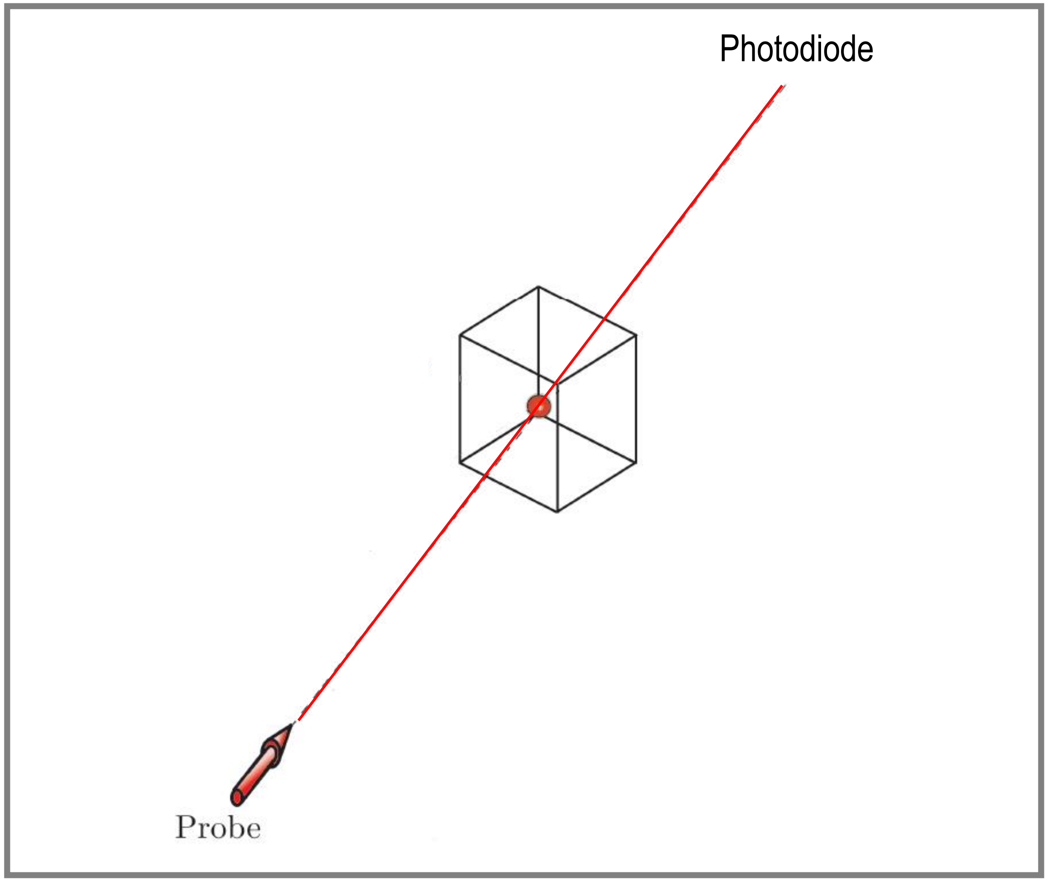
$$T = e^{-b} = e^{-\sigma\rho L} = e^{-L/\ell_{\mathrm{sc}}}$$

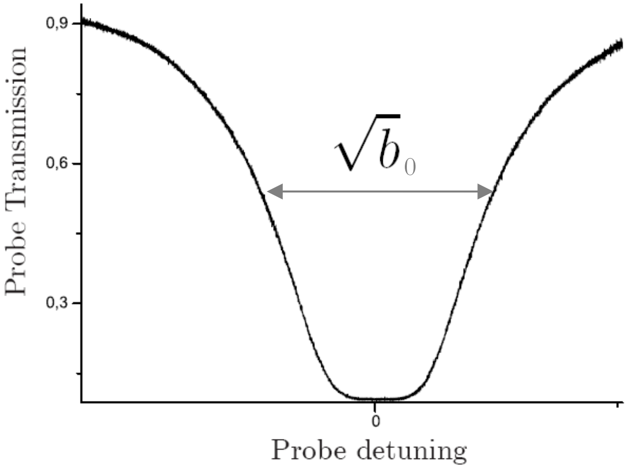
Typically, on resonance, b_0 = 20 – 100

With some efforts: up to b_0 ~ 250

Gain with cold atoms

Spectroscopy in transmission

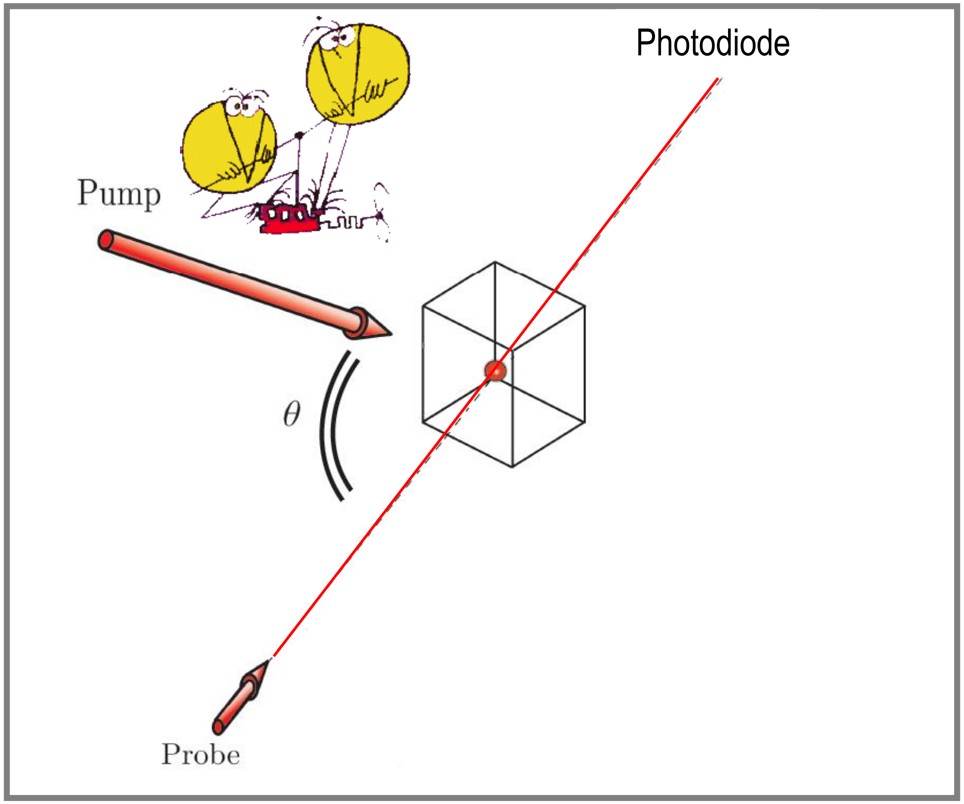


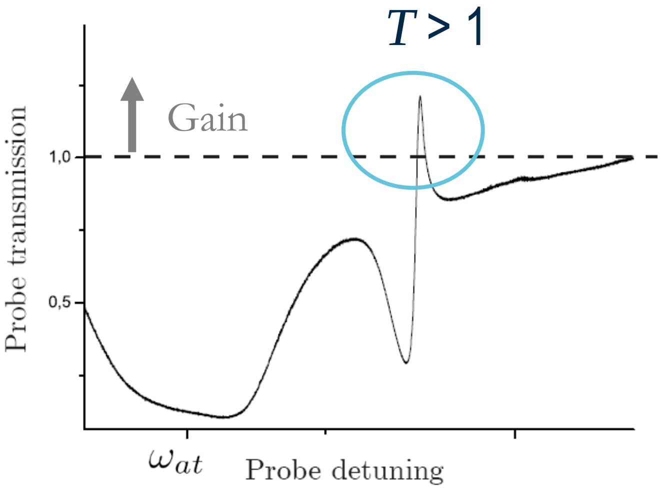


b_0 : on-resonance optical thickness

Gain with cold atoms

Pump-probe spectroscopy

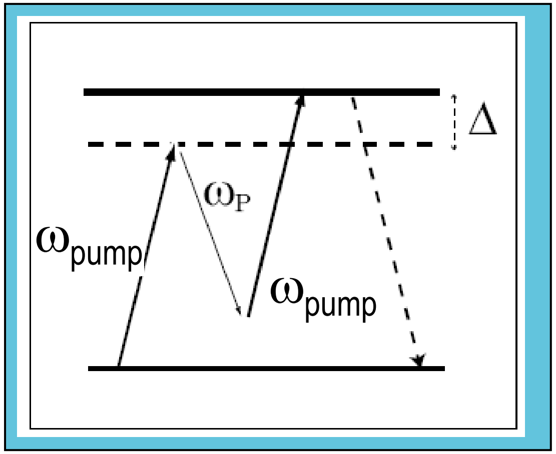


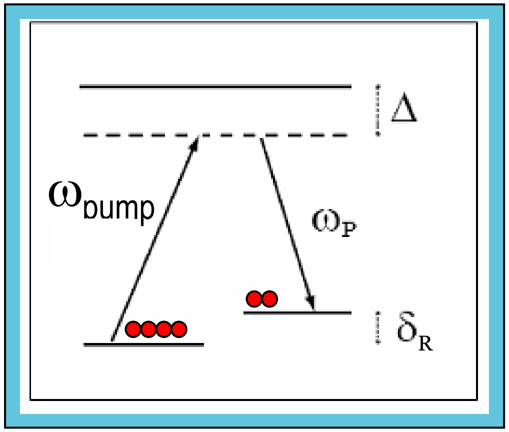


Several gain mechanisms

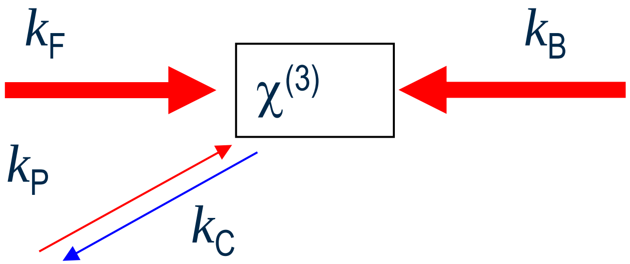
- **Mollow gain.** Two-level atoms + one pump: 3-photon transition (population inversion in the dressed-state basis)

`Mollow, Phys. Rev. A 5, 2217 (1972).`



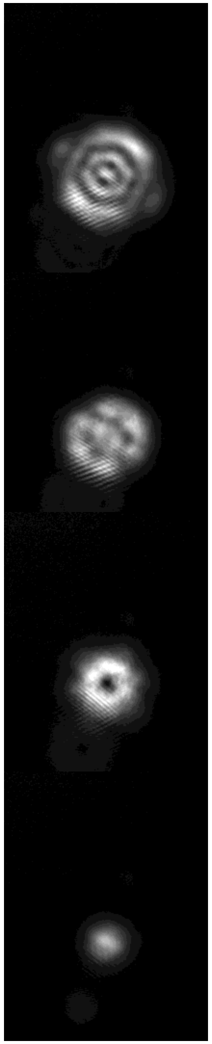


- **Raman gain.** Three-level atoms + one pump: 2-photon Raman transition (population inversion between the two ground states – hyperfine or Zeeman levels)



- **Degenerate four-wave mixing**. Parametric gain using the nonlinear atomic susceptibility (needs two pumps)

Standard lasing with cold atoms



Laser radiation ≈ 300 µW

Cold atoms inside !

- Mollow laser for small pump detuning.
- (Zeeman) Raman laser for larger pump detuning, single pump.
- DFWM laser for larger pump detuning and two pumps.

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

Outline

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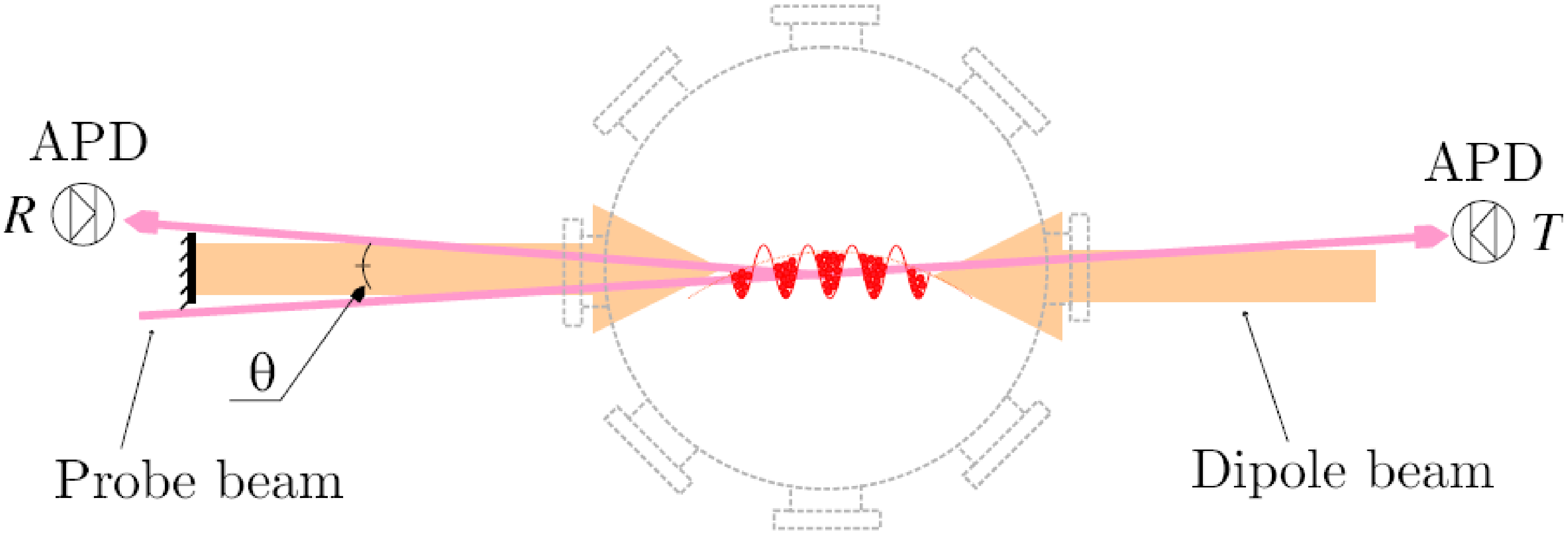
Atoms trapped in a 1D lattice



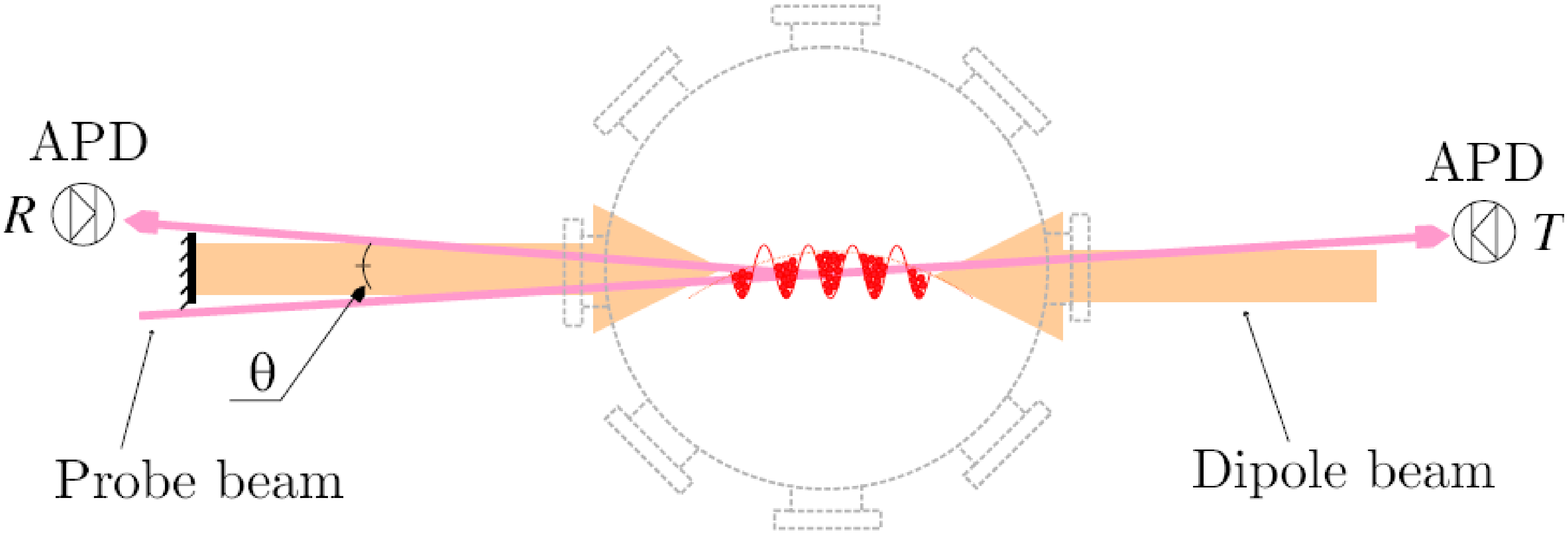
Atoms: laser-cooled ^{87}Rb, λ_0 = 780.24 nm.

Lattice beam: tunable Ti-Sa laser, 1W, waist 200 μm, wavelength $\lambda_{lat} > \lambda_0$.

Detection tools: probe beam and avalanche photodiodes (APD).

Measurements: transmission T and reflection R spectra.

Atoms trapped in a 1D lattice



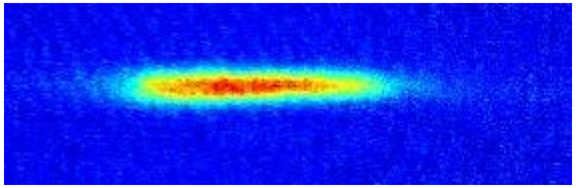
Atomic sample:

$N = 5\times10^{7}$

$T \sim 100\ \mu\text{K}$

$\rho \sim 10^{11}\text{-}10^{12}\ \text{cm}^{-3}$

→ $n - 1 \sim 10^{-4}\text{-}10^{-3}$

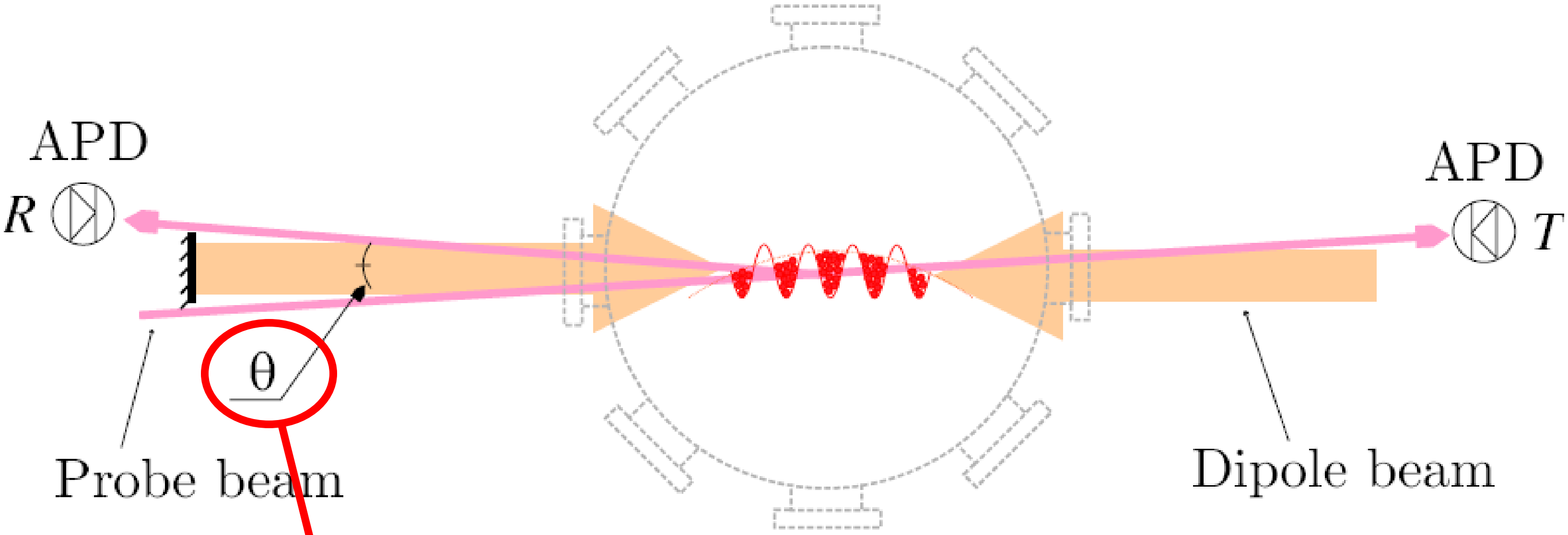


↕ ~ 200 µm

↔

$L \sim 3$ mm → 7700 atomic layers

Atoms trapped in a 1D lattice



Very important parameter !

- $\lambda_{lat} > \lambda_0$ to trap the atoms, and the lattice period is $\lambda_{lat}/2$

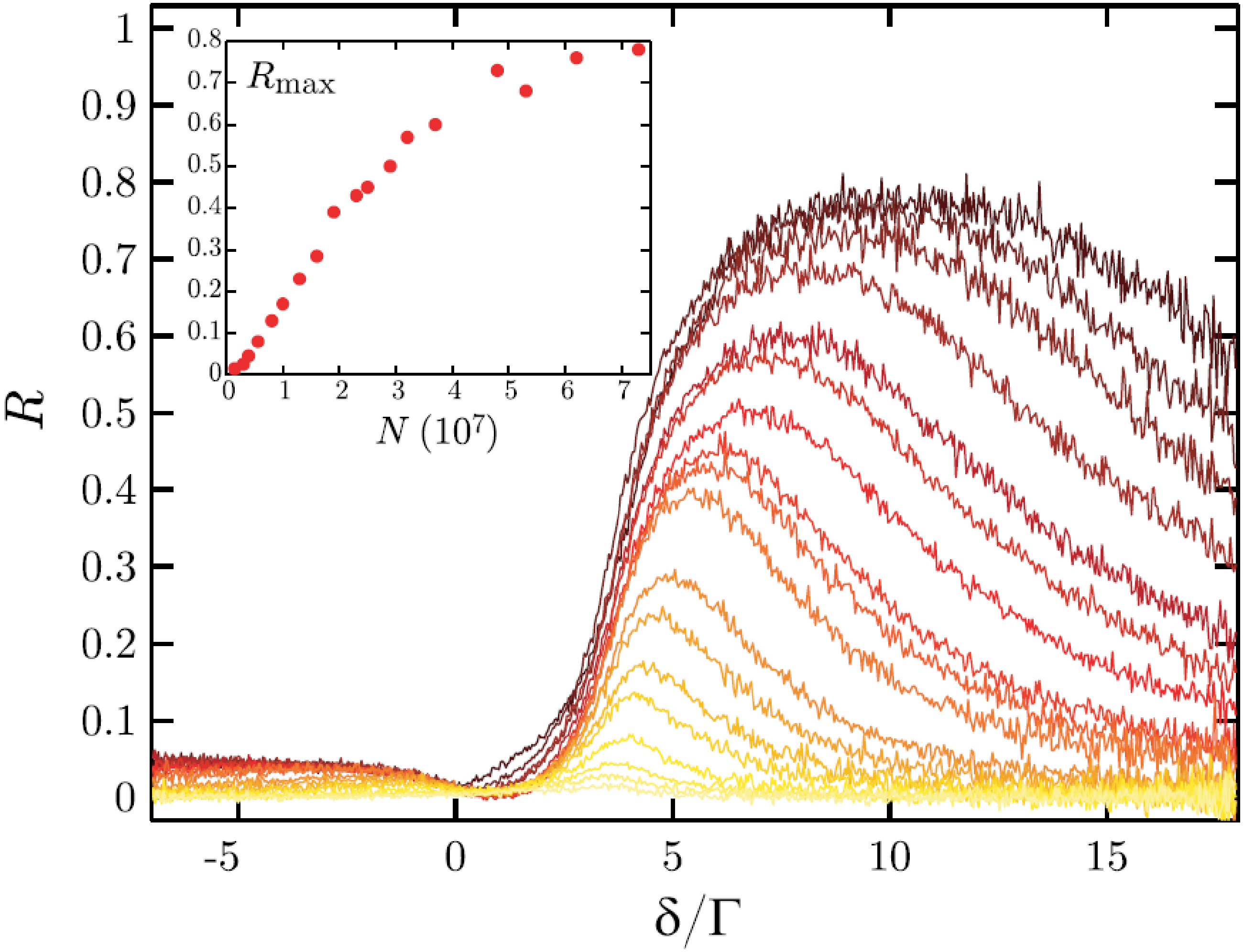
- the refractive index n is nonnegligible only around $\lambda \sim \lambda_0$

→ The Bragg condition can only be fulfilled with an angle such that $\lambda_{lat} \sim \lambda_0/\cos(\theta)$

If θ too large : bad overlap between the probe beam and the atomic cloud.

Efficient Bragg reflection

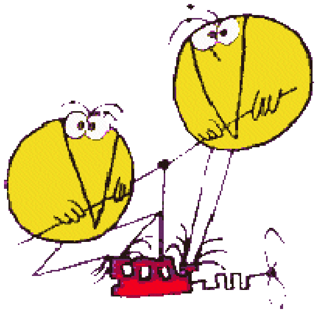
Bragg reflection spectra for increasing atom number (or density ρ), at the optimum λ_{lat}.



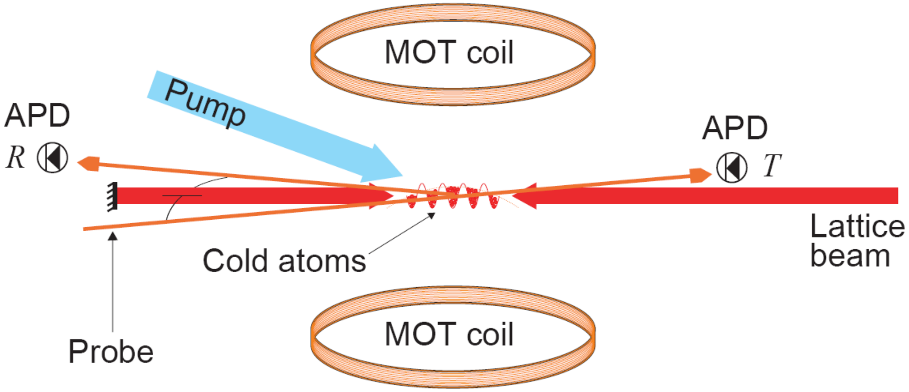
→ 80% reflection

Schilke *et al.*, Phys. Rev. Lett. **106**, 223903 (2011).

Adding gain... with four-wave mixing

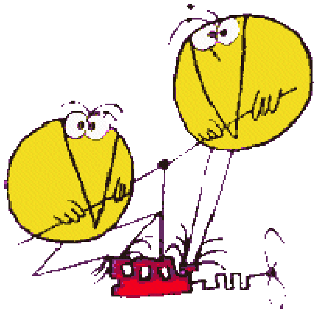


We have to **pump** !



Several gain mechanisms are possible with cold atoms (see previous part!).

Adding gain... with four-wave mixing



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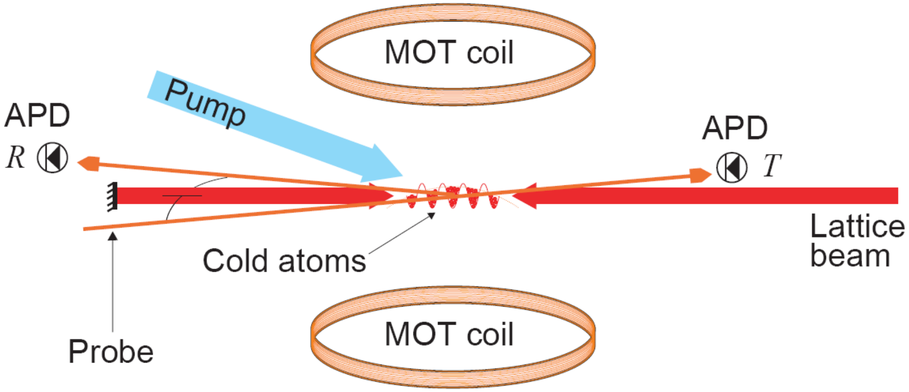
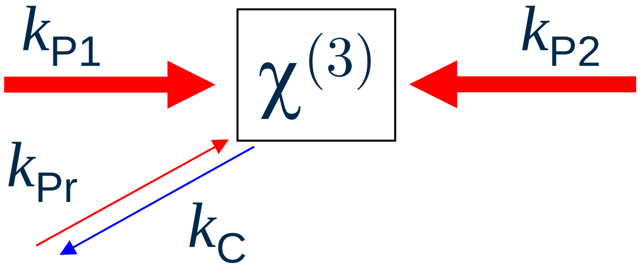


Several gain mechanisms are possible with cold atoms (see previous part!).

One possibility: **four-wave mixing**



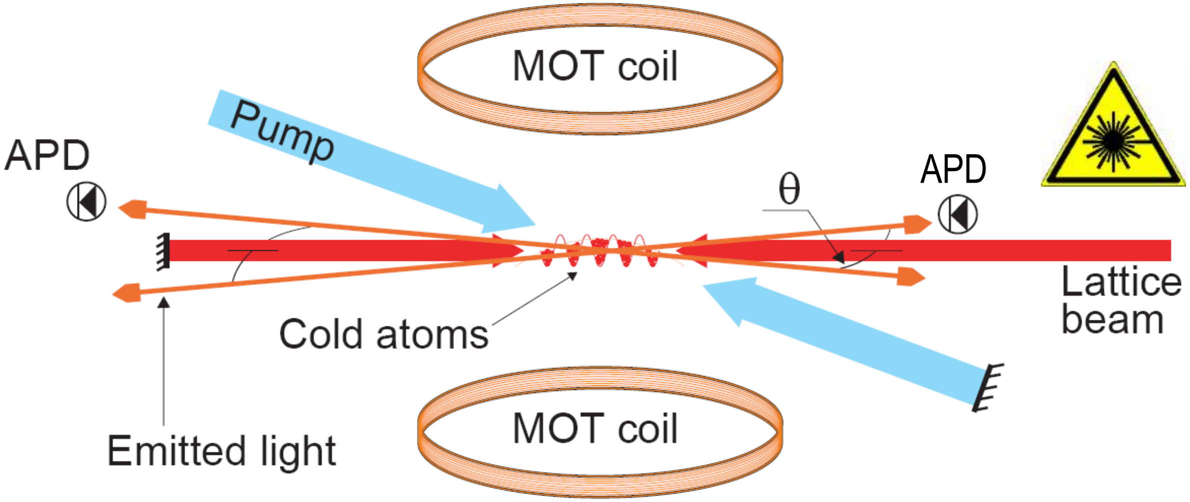
Phase-conjugation mechanism

→ **“backward gain”**

Degenerate FWM:

$$\omega_{P1} = \omega_{P2} = \omega_{Pr} = \omega_C$$

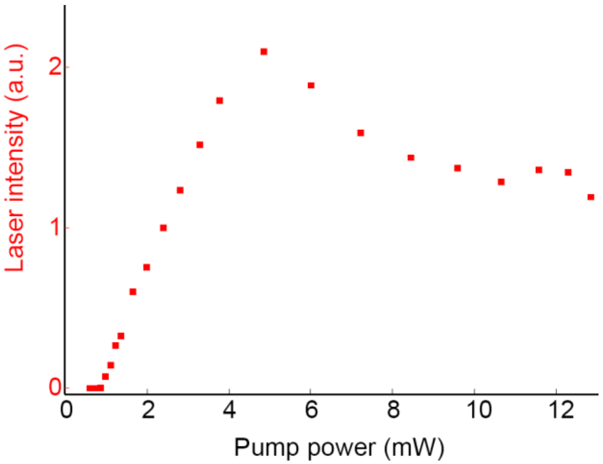
Adding gain... produces a laser !



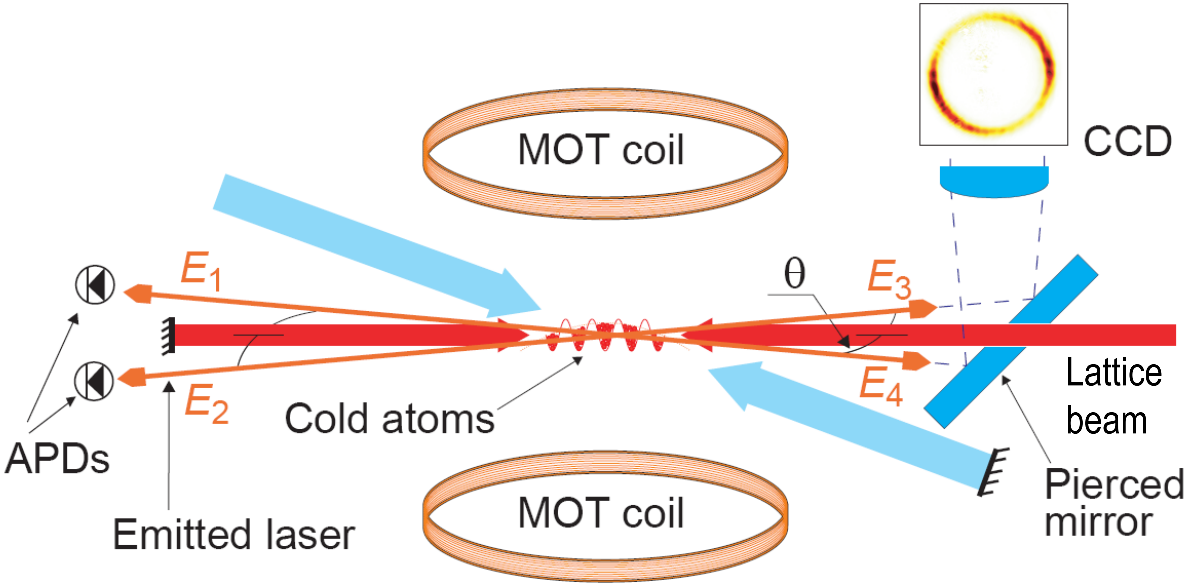
→ Huge signals on our R and T photodiodes **even without probe beam !**

→ Threshold with the pump power

→ Laser

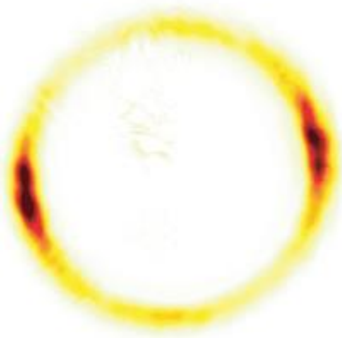


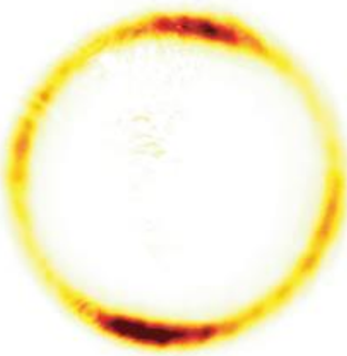
Beam profile



→ **Cone-shaped emission**

Distributed feedback


λ_{dip} = 780.55 nm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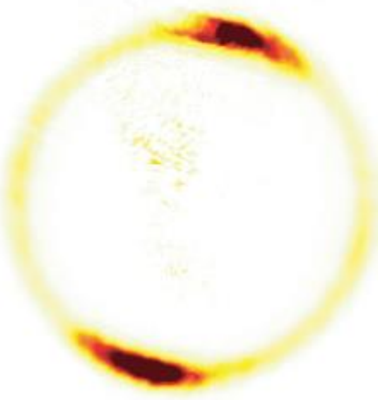
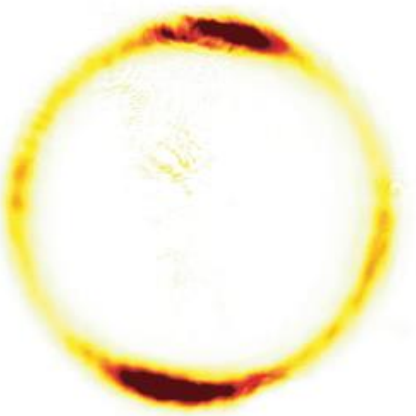
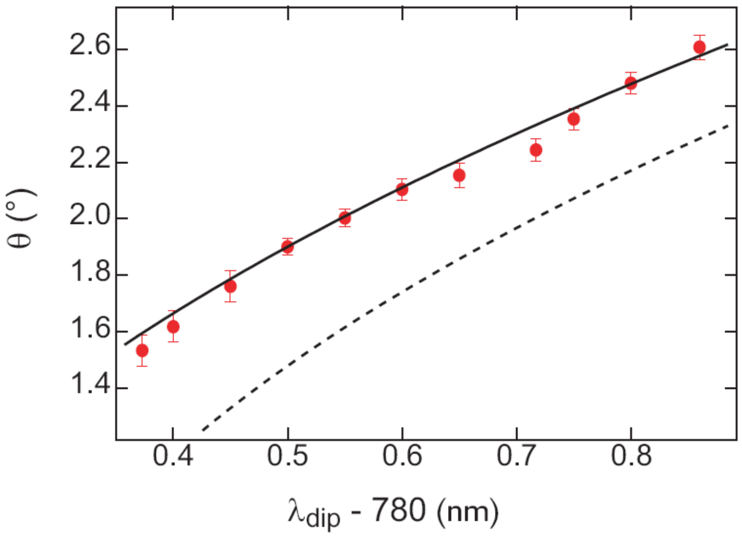

λ_{dip} = 780.75 nm


λ_{dip} = 780.80 nm



Well explained by the **Bragg condition**:

$$\lambda_{\mathrm{dip}} \cos(\theta) = \lambda_0 / \bar{n}$$

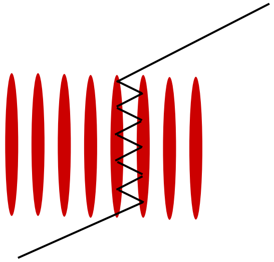
$$\bar{n} - 1 = (2.2 \pm 0.5) \times 10^{-4}$$

Schilke *et al.*, Nature Photon. **6**, 101 (2012).

Complete feedback: Bragg + FWM

$\theta \neq 0$ → the Bragg feedback alone is **unstable** (walk-off)

Why is it working ?



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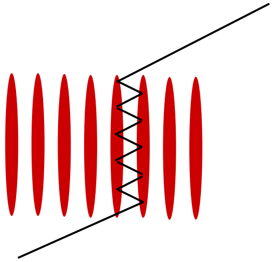
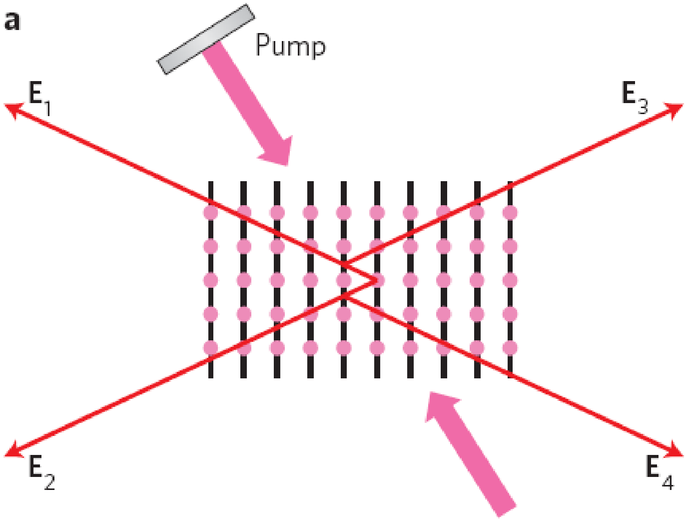
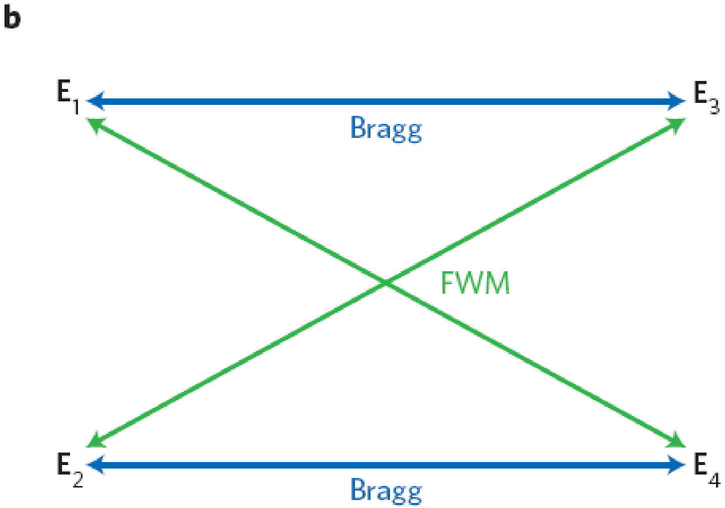


FWM is a **phase-conjugation** process (backward gain)





→ creates a feedback loop without walk-off

(No observed DFB laser with Raman gain !)

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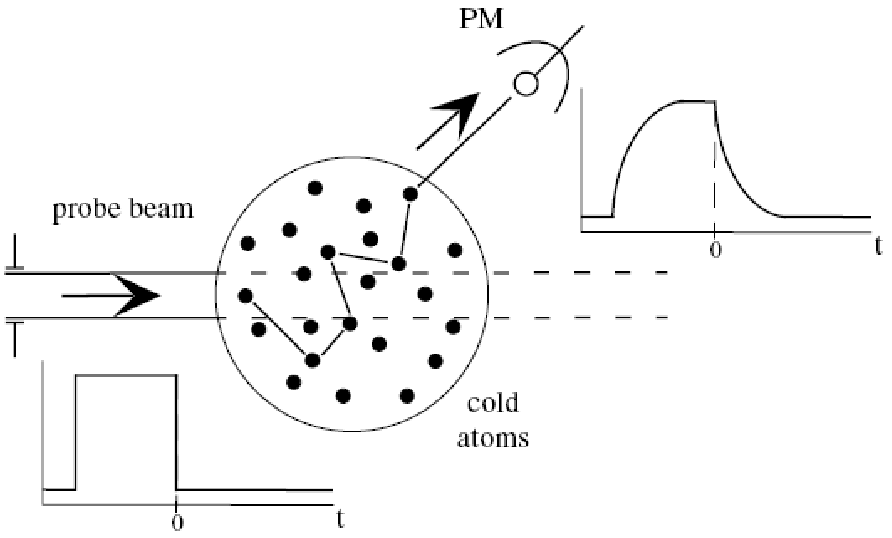
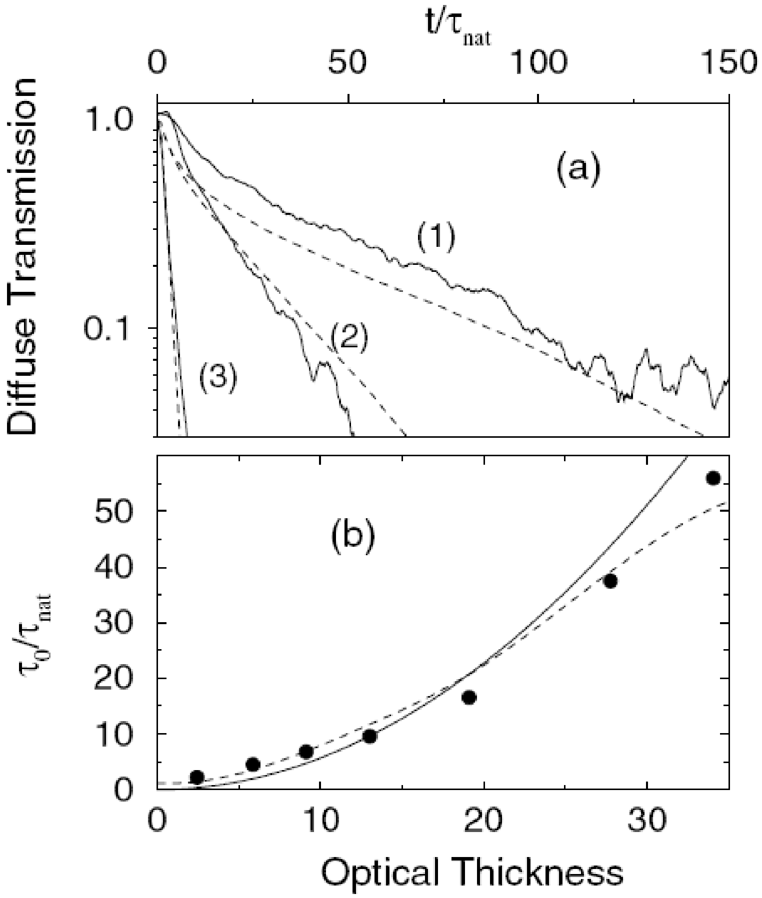
Radiation trapping in cold atoms



$$v_E \simeq 3.1 \times 10^{-5} c$$

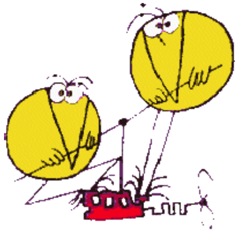


Labeyrie *et al.*, Phys. Rev. Lett. **91**, 223904 (2003).

Combining gain and scattering ?

The scatterers and the amplifiers are **the same atoms** !

Pumping

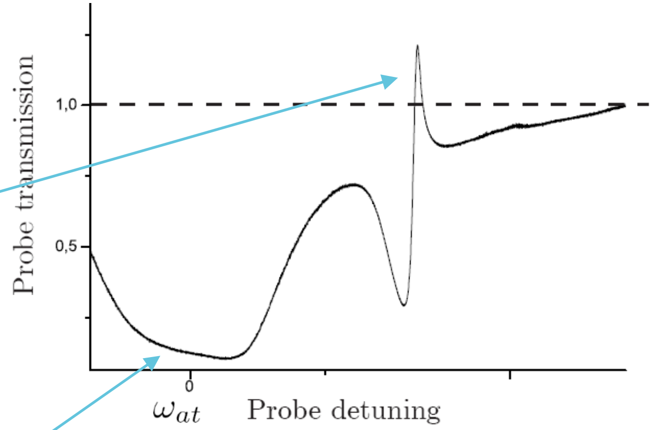


Gain ☺

Saturation ☹

→ elastic scattering ➘

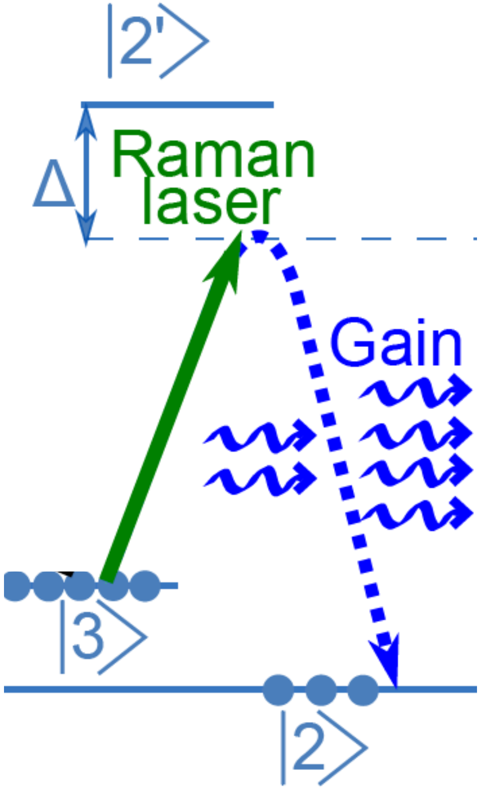
→ inelastic scattering ➚



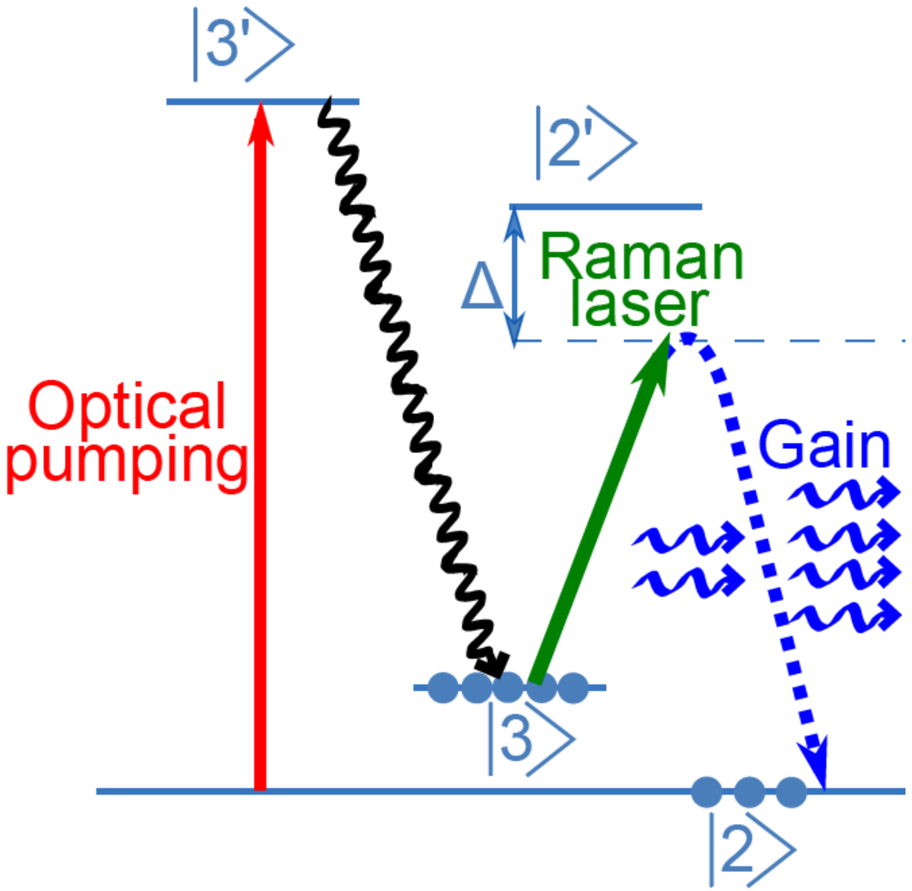
Gain and scattering do not occur at the same frequency !!! ☹ ☹ ☹

Is it possible to get enough scattering and gain *simultaneously* ?

Raman gain between hyperfine levels

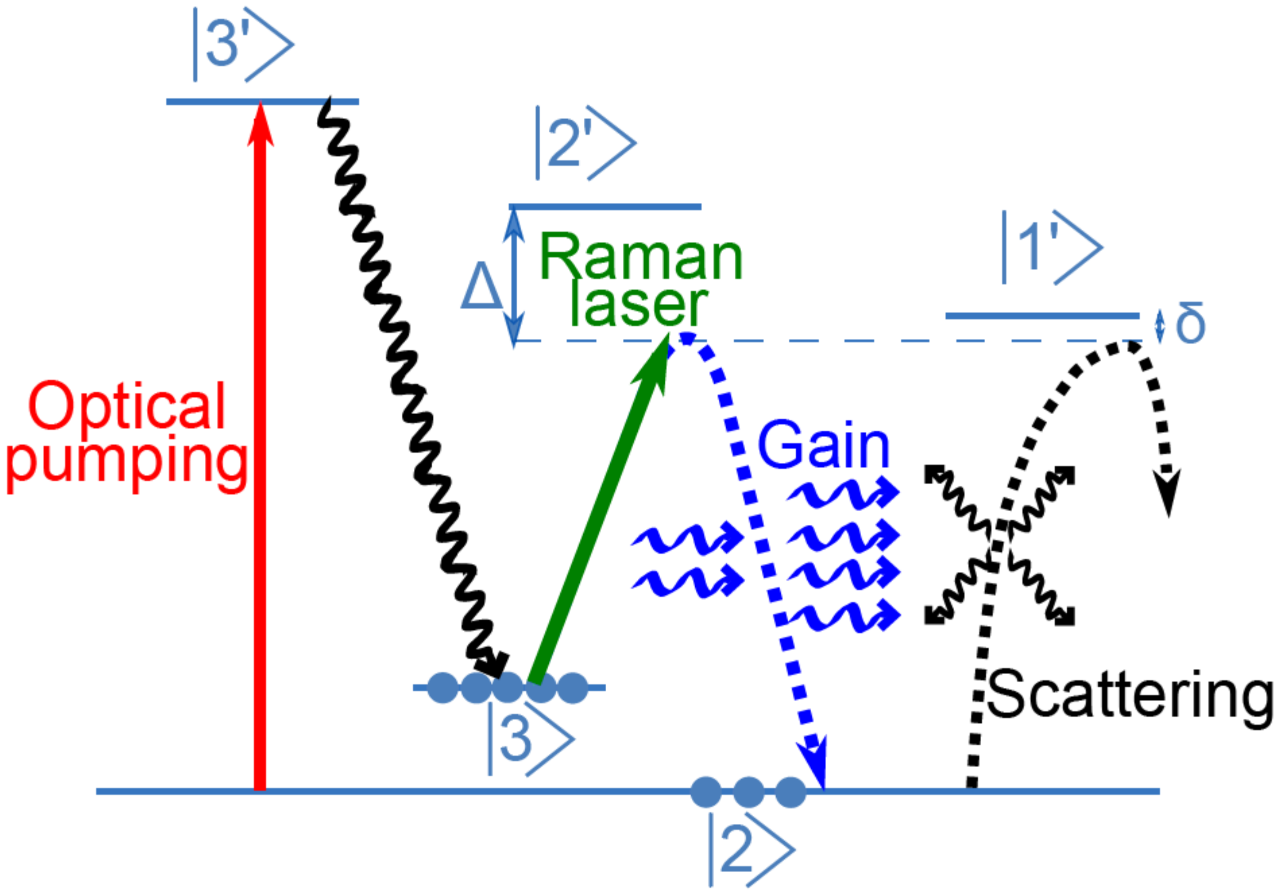


Raman gain between hyperfine levels



Raman gain between hyperfine levels

with additional scattering



Experiment

- The random laser emission:
  - is not spatially separated from elastic scattering from the external lasers
  - is very hard to spectrally separate

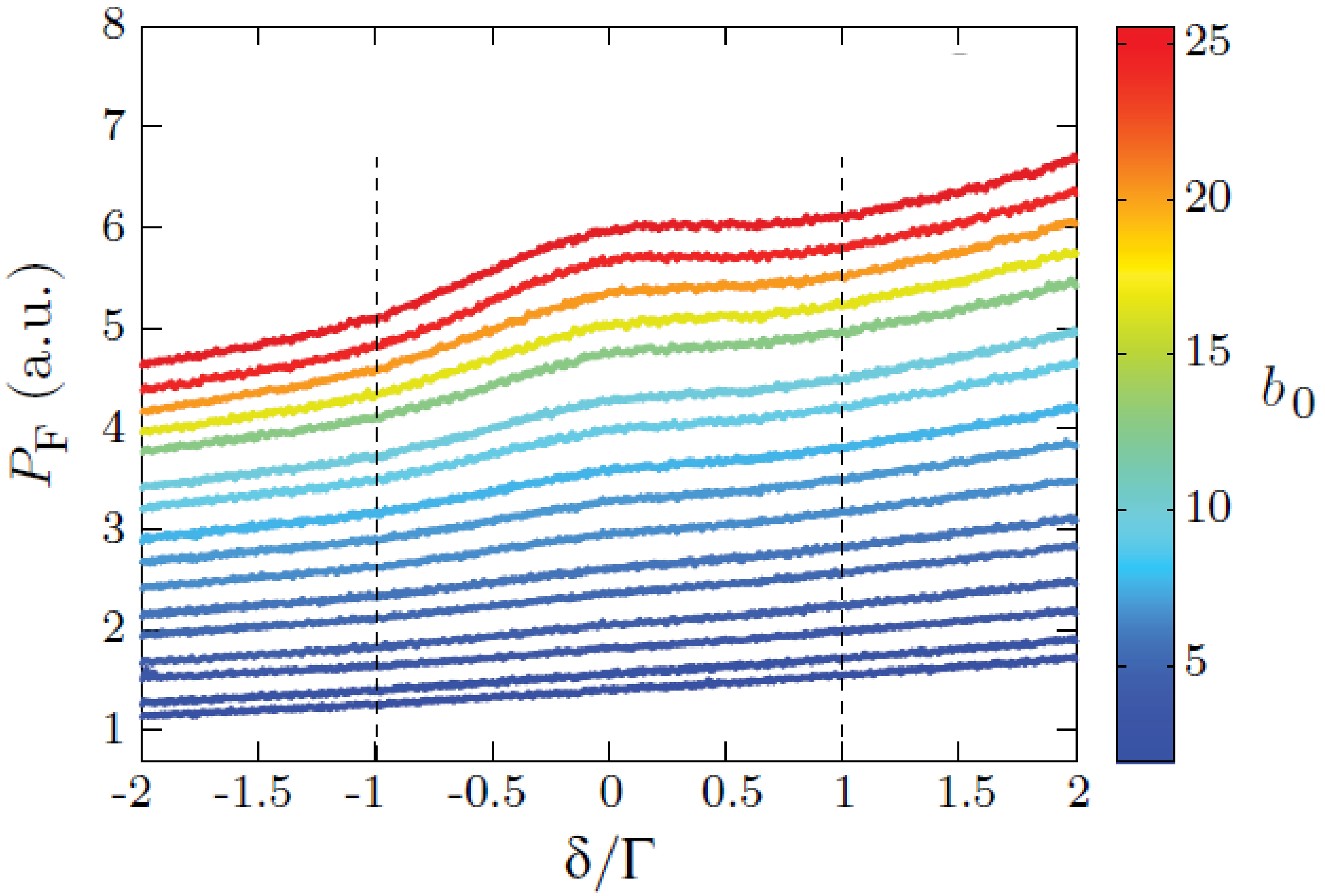
→ **We look at the total fluorescence** (= pump depletion)

- We change b_0 (defines the threshold) with a **constant atom number**.

→ changes are only due to collective effects

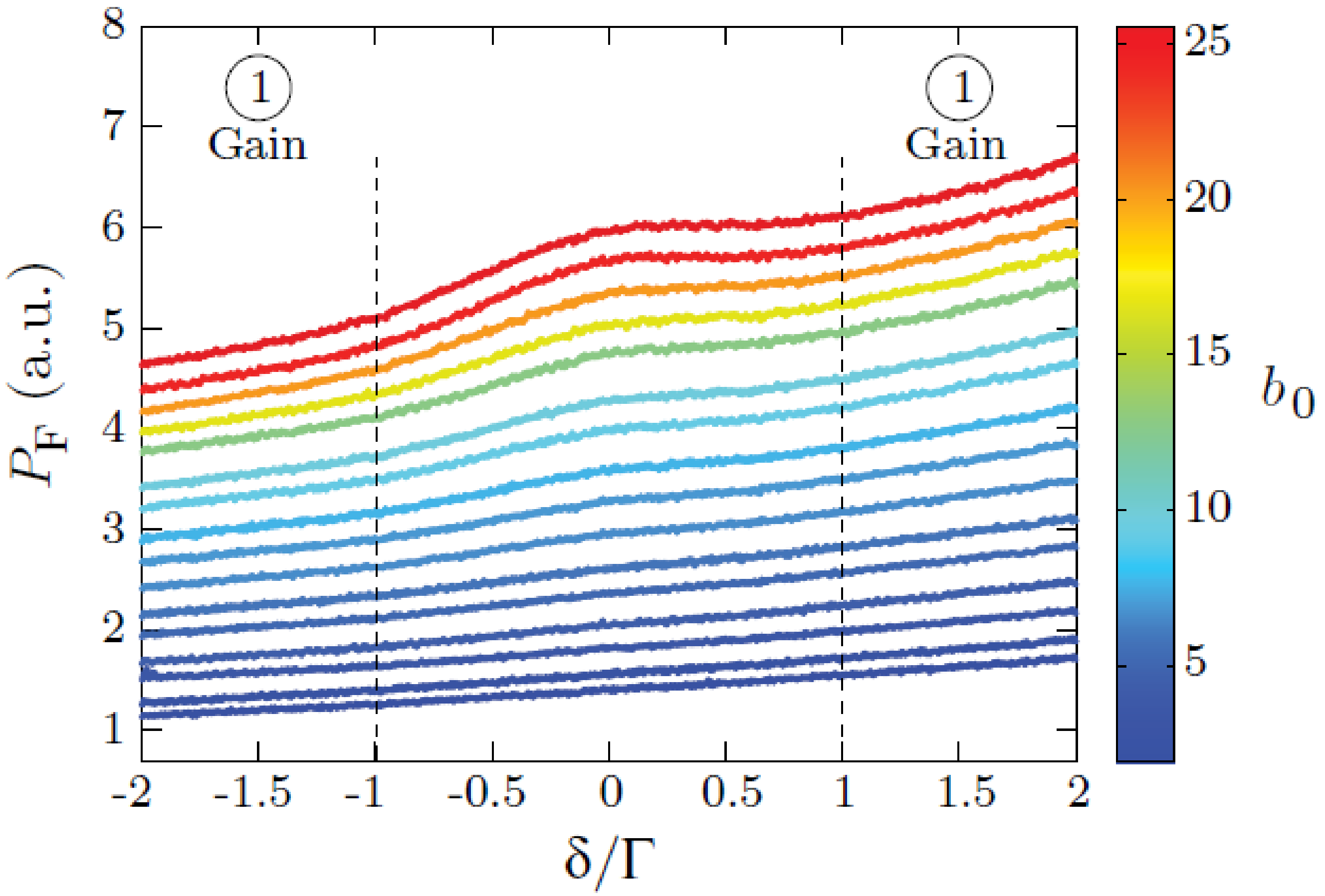
- We sweep slowly (steady-state) the Raman laser (no probe) around the frequency where Raman gain is on resonance with the |2> → |1'> transition.

Observations



Observations

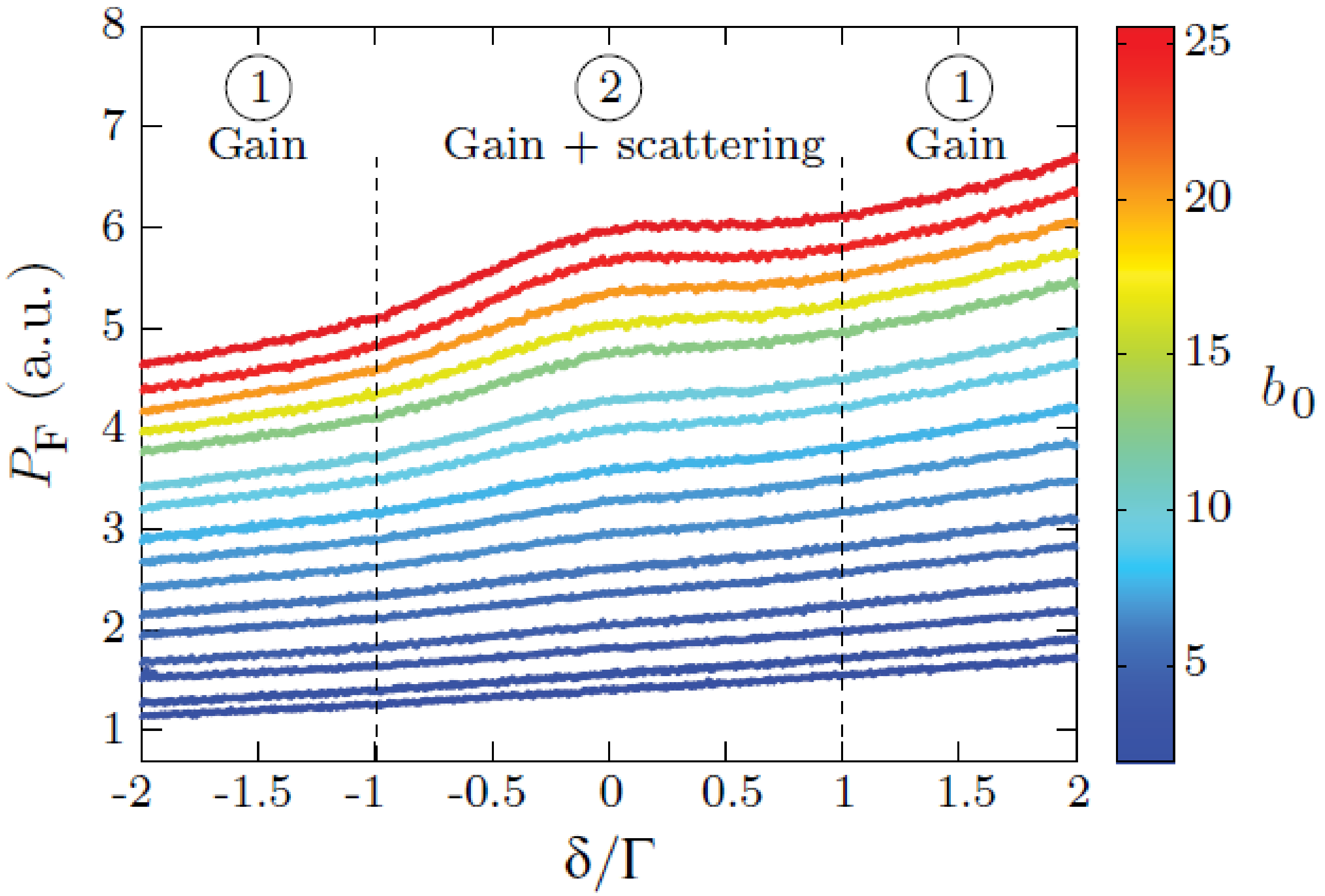
1- Overall increase of fluorescence → Amplified spontaneous emission



Observations

1- Overall increase of fluorescence → Amplified spontaneous emission

2- Increase of fluorescence around $\delta = 0$ → combined effect of gain and multiple scattering

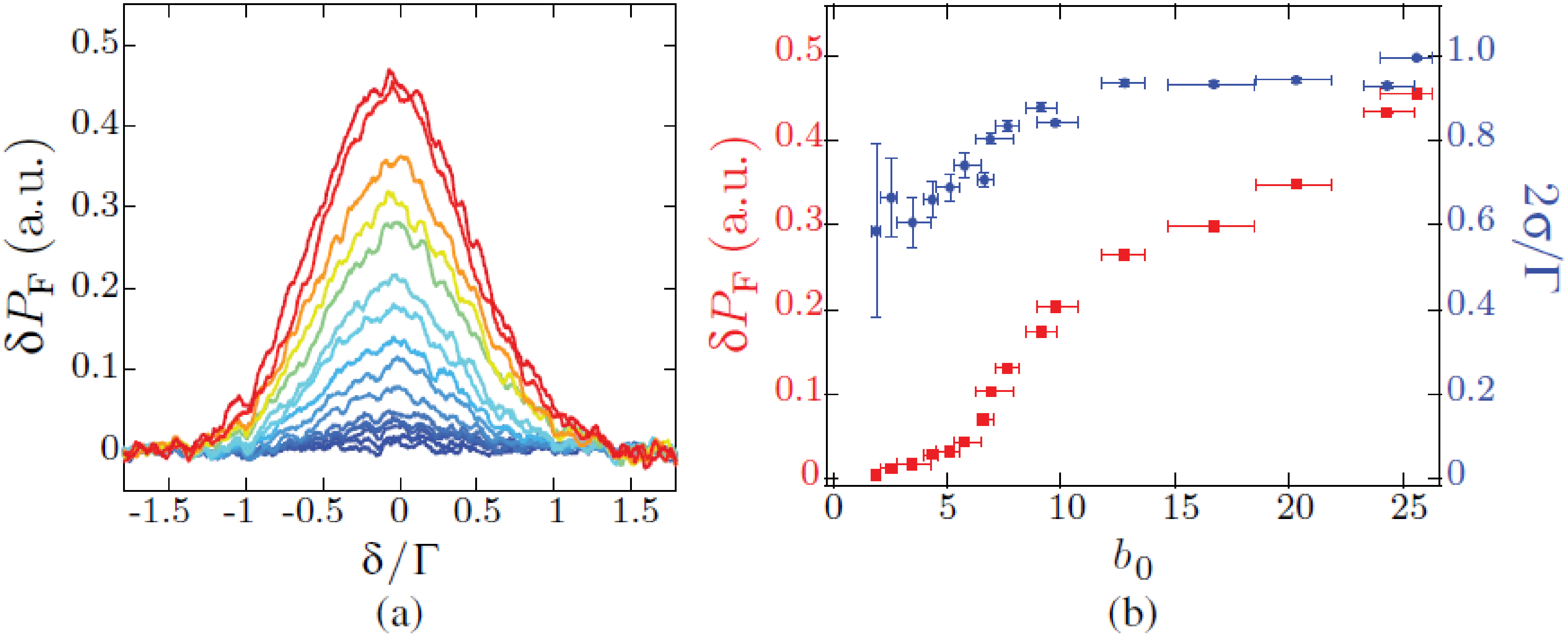


Signature of random lasing

Fit of the wings → we can subtract the "ASE" background

→ More visible bump (Gaussian shape)

→ The amplitude has a **threshold with b_0**



Baudouin *et al.*, Nature Phys. **9**, 357 (2013).

Outline

- ☑ Introduction
- ☑ Standard lasing with cold atoms
- ☑ DFB lasing with cold atoms
- ☑ Random lasing with cold atoms
- ☐ Concluding remarks

Concluding remarks

Two experiments

- The DFB laser, based on **order** (made in Germany)
- The random laser, based on **disorder** (made in Nice)

Which one was the *simplest* ?

Concluding remarks

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The DFB laser !

It took 6 months, the RL 4 years !

Concluding remarks

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Which one was the *simplest* ? The DFB laser ! It took 6 months, the RL 4 years !

Because **it's only 1D**... → easy to have many layers
→ directional emission easy to detect

We might investigate the 3D case in the future...

Concluding remarks

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Because **it's only 1D**... → easy to have many layers
→ directional emission easy to detect

We might investigate the 3D case in the future...

The random laser experiment is far from being finished, we want:

- more data;
- different (more spectacular) signatures. Some spectral or coherence properties ?

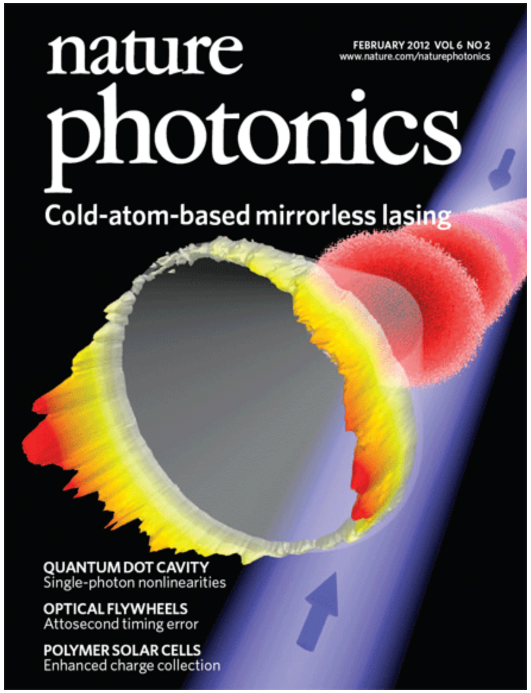
→ PhD thesis of Samir Vartabi Kashani, INLN, on-going.

Concluding remarks

We made the first **mirrorless lasers based on cold atoms**

The whole laser is only made of a few millions atoms in a very dilute gas phase.

→ The *lightest* laser ever ! M ~ 10 fg.



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Cold-atom-based mirrorless lasing

QUANTUM DOT CAVITY
Single-photon nonlinearities

OPTICAL FLYWHEELS
Attosecond timing error

POLYMER SOLAR CELLS
Enhanced charge collection

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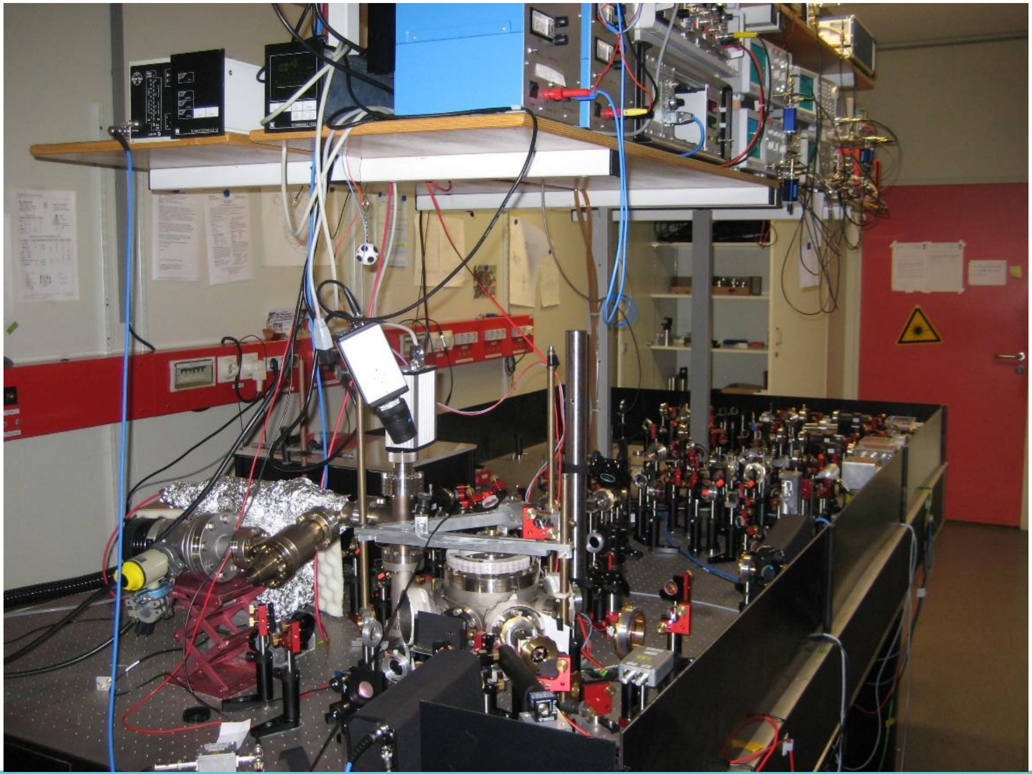

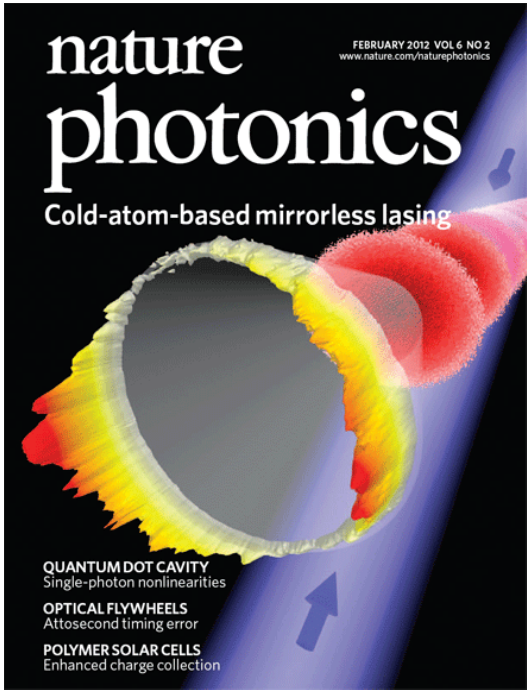

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We made the first **mirrorless lasers with cold atoms**

The whole laser is only made of a few millions atoms in a very dilute gas phase.

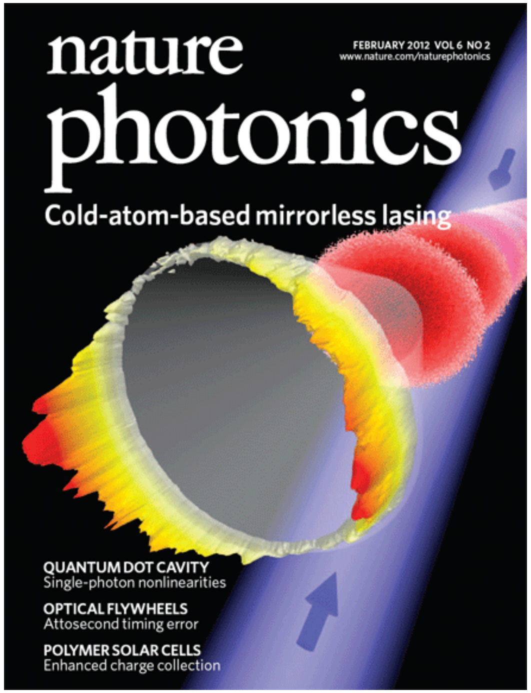
→ The *lightest* laser ever ! M ~ 10 fg.

But...

There is a big, complex, and expensive machinery behind it...

And: no new λ, low power

→ limited practical interest ☹



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So, what is it interesting for ?

Interest of the DFB laser experiment

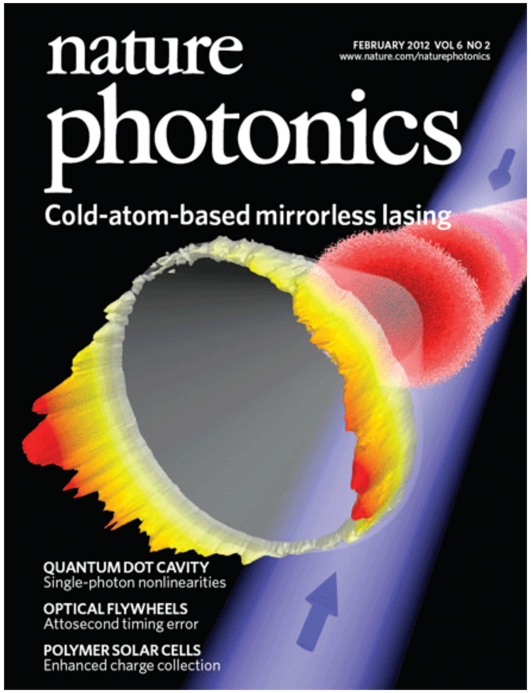
DFB lasers are well known and their physics understood.

But this one has a **cone-shaped emission**. This is **new !**

Why ?

- Because of the ***sharp resonance***: in standard DFB laser, the emission wavelength adapts itself to the lattice periodicity, because the gain bandwidth is large.

- Because of the ***high nonlinearity and versatility*** of cold atoms: just retroreflecting the pumping beam makes a new gain mechanism appear (FWM), which makes the feedback with angle stable.



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→ Very good illustration that applying known physics in a new system allows discoveries

Interest of the random laser experiment

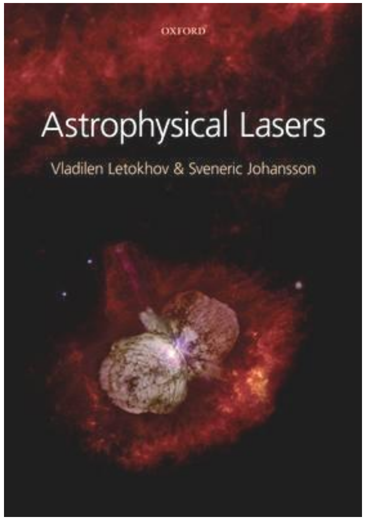
Our random laser is not very convenient: hard to produce, hard to characterize…

But it has unique features:

- It's truly 3D (homogeneous pumping) thanks to the sharp resonance.
- The scatterers are all identical (monodisperse sample), and perfectly known, without absorption.
- The average over the position configuration is done.

→ Possible to develop *ab initio* models without any free parameters.

→ Perfect test-bed for theoreticians (on-going collaborations)



OXFORD

Astrophysical Lasers

Vladilen Letokhov & Sveneric Johansson

Also: the first RL based on atomic vapors. Extension to hot atoms ?

→ Would be closer to astrophysical systems (natural RL in space ?)

Thanks

Thank you for your attention