# Photonic properties of 1D-ordered cold atoms

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*Institut de Physique de Nice (INPHYNI)*

*Université Côte d'Azur & CNRS*

https://inphyni.univ-cotedazur.eu/sites/cold-atoms

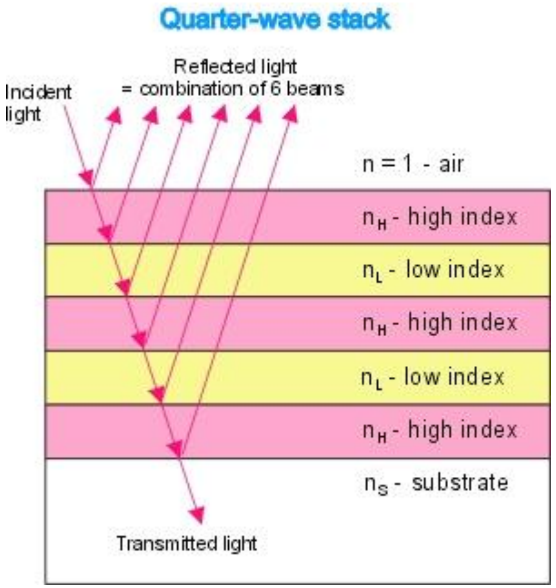
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

# Optics in periodic media: an old subject

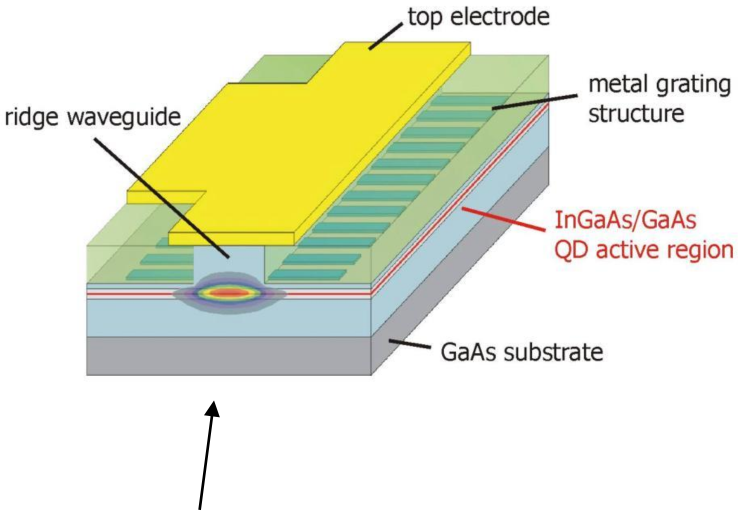
Rayleigh:

"On the maintenance of vibrations by forces of double frequency, and on the propagation of waves through a medium endowed with a periodic structure", *Philosophical Magazine* **24**, 145 (1887).

"On the reflection of light from a regularly stratified medium", *Proc. Royal Society of London* **93**, 565 (1917).




→ Bragg mirrors




**Active medium** + periodic modulation: distributed feedback laser (DFB)

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

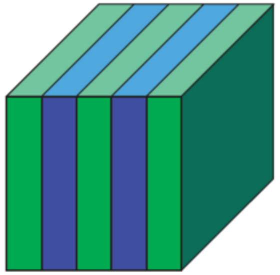
# Optics in periodic media: photonic crystals

VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

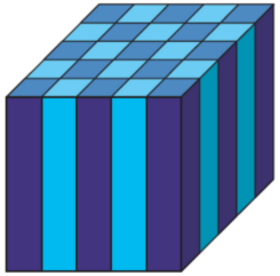
**Inhibited Spontaneous Emission in Solid-State Physics and Electronics**

Eli Yablonovitch
*Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701*
(Received 23 December 1986)

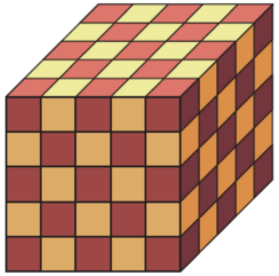
1-D



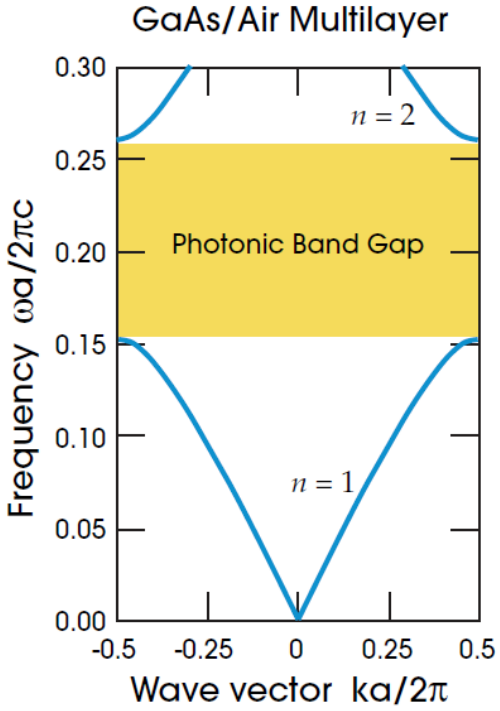
2-D



3-D



→ Birth of a new field: photonic crystals / nanophotonics




<u>Theory for wave propagation in a periodic potential:</u>

→ Bloch theorem

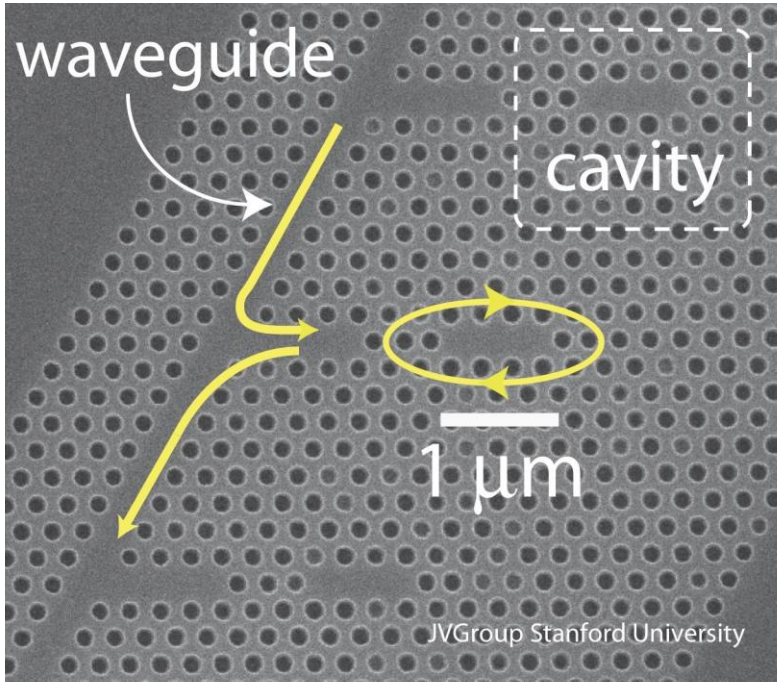
→ Band structure / dispersion relations

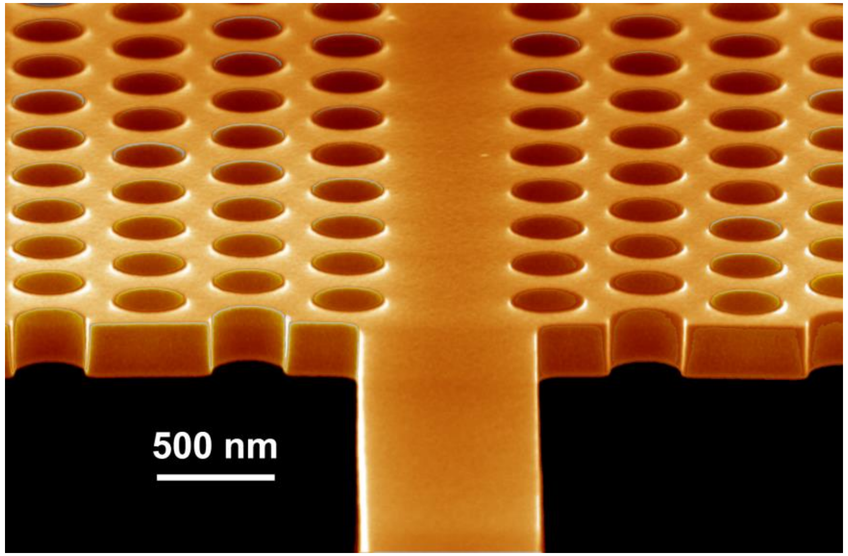
→ Avoided crossing between bands

→ Band gaps

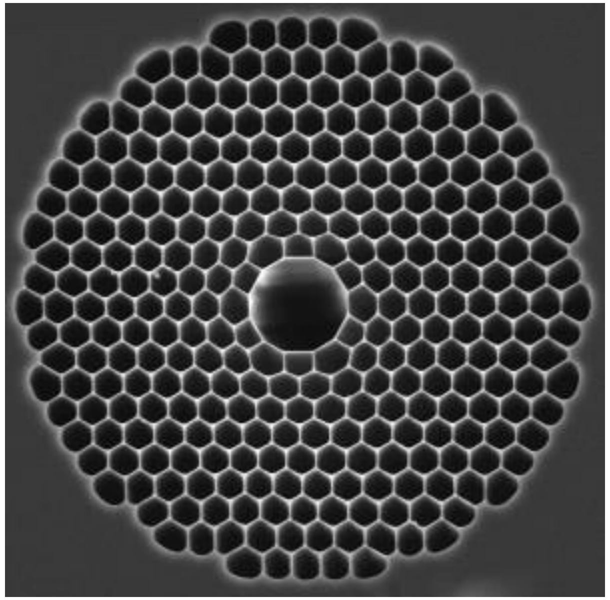
# Optics in periodic media: 2D photonic crystals

Planar waveguides and cavities



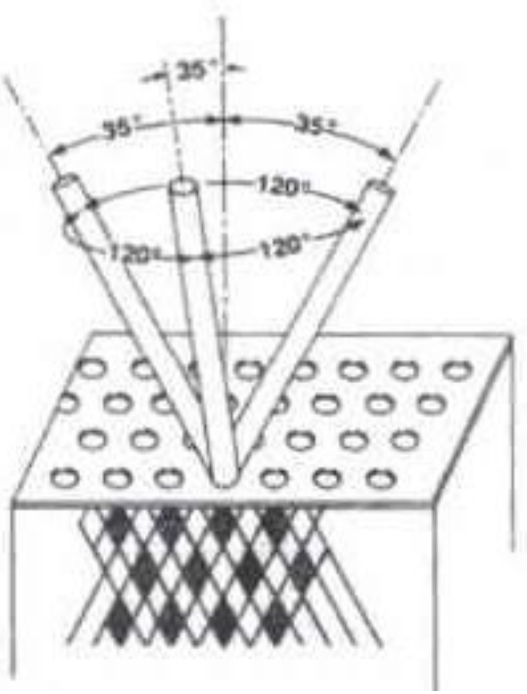




Photonic crystal fibers

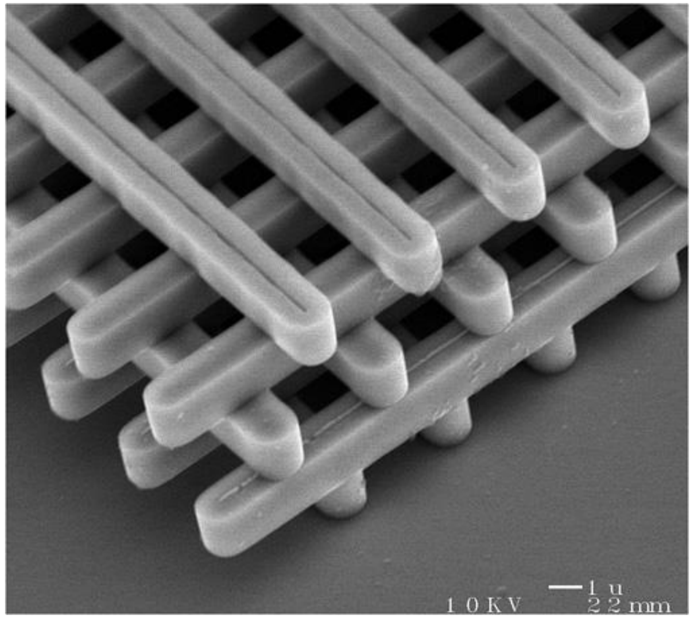


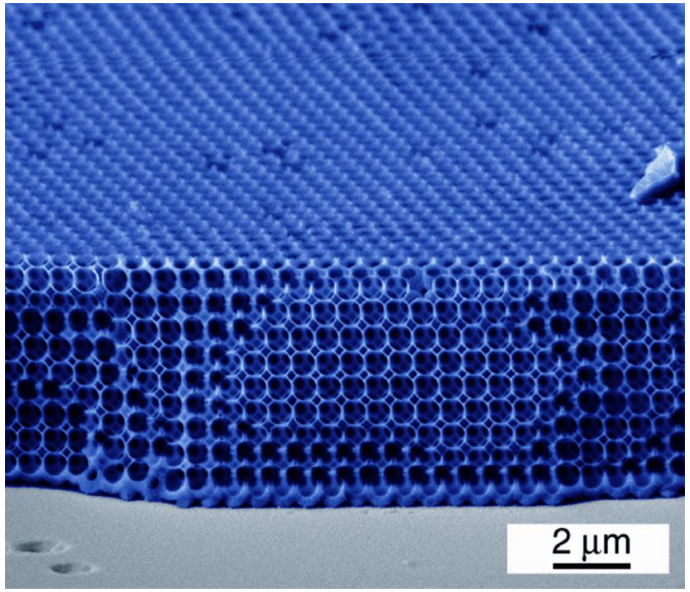
# Optics in periodic media: 3D photonic crystals

Yablonovite



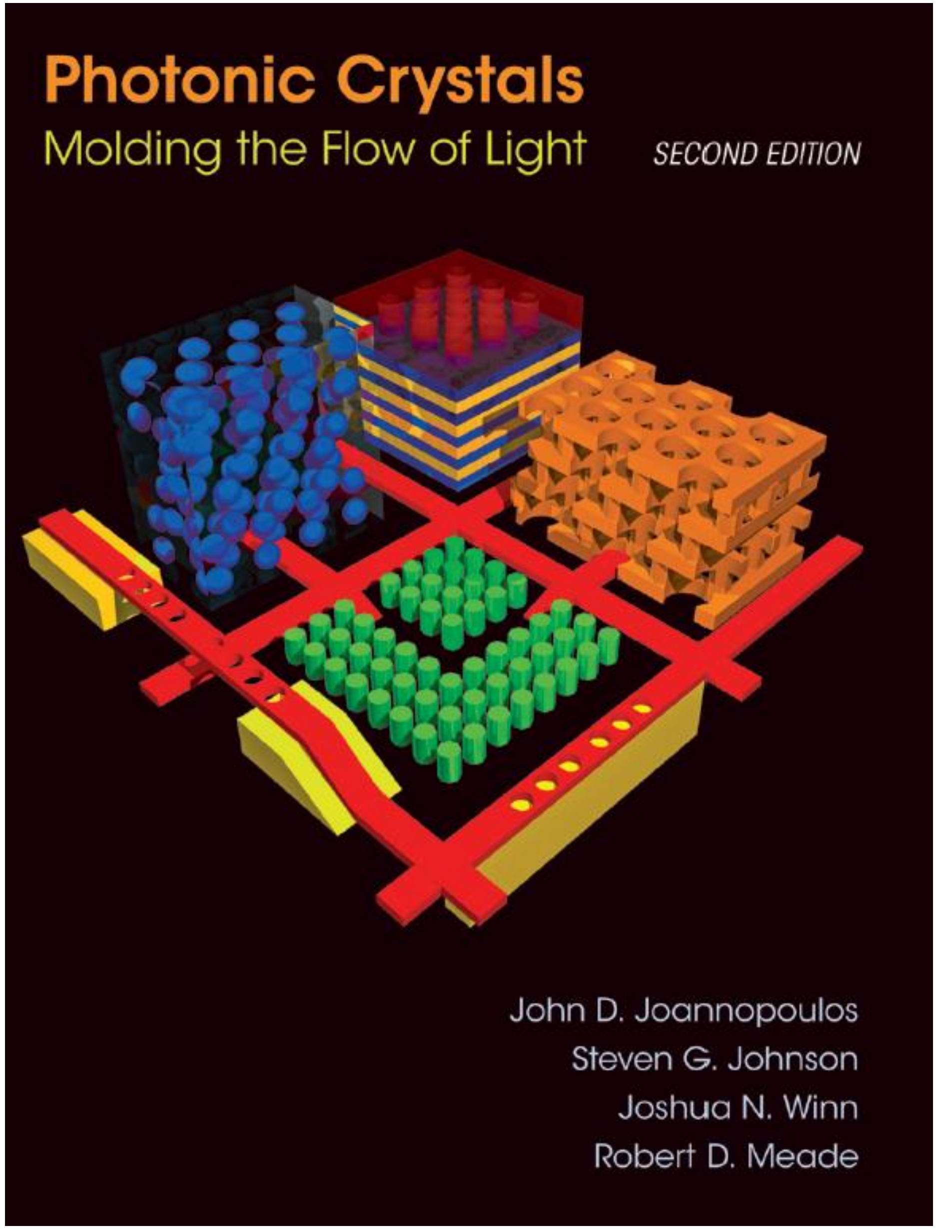

Woodpile



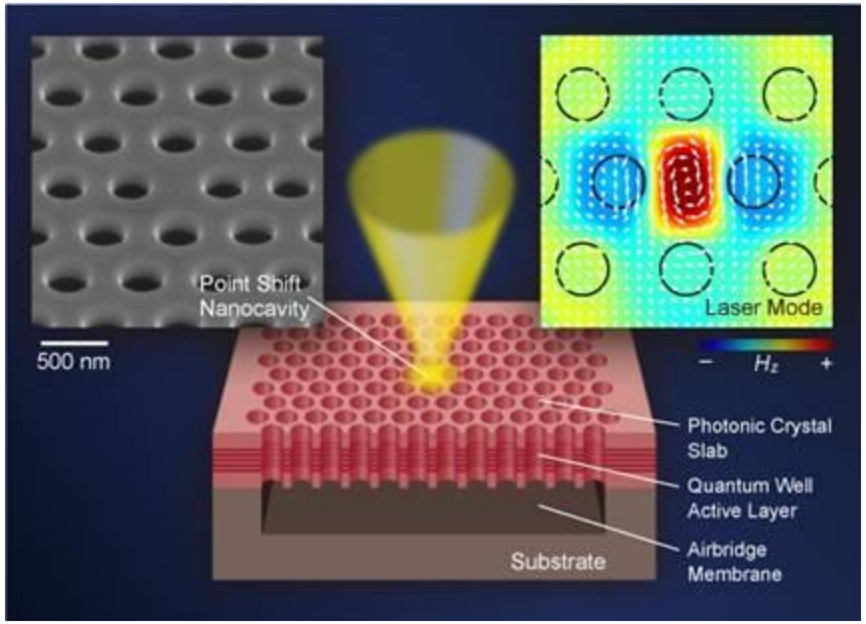

Inverse opal

# Optics in periodic media: a major topic




**Active medium** + photonic crystal

→ "Photonic crystal lasers" / "nanolasers"

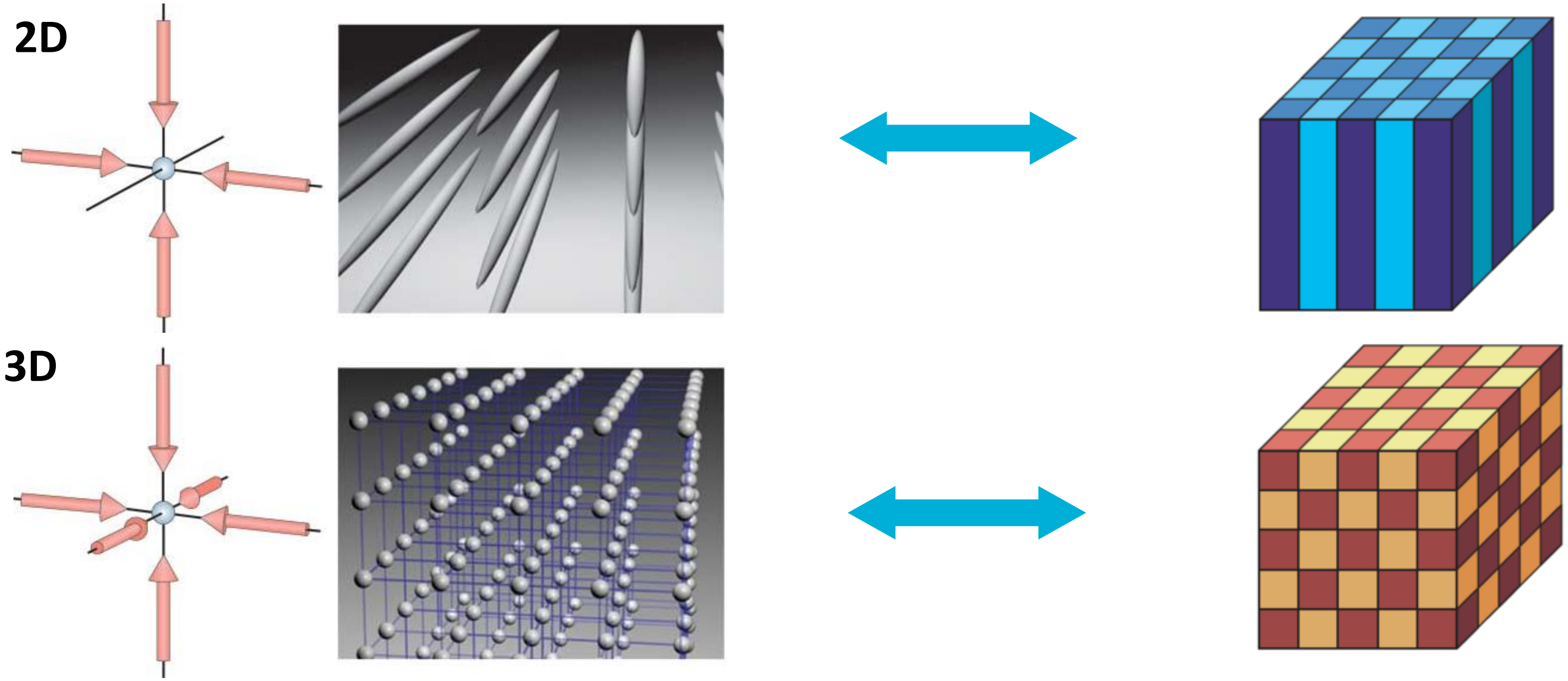


# Optics in periodic media: with cold atoms!

**Why ? Atoms are different !**

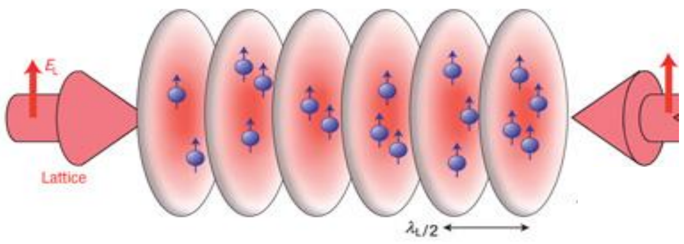
- Very narrow spectral features (≈MHz), highly dispersive → tunability, new effects ?
- Versatile, very nonlinear → new possibilities, new effects ?

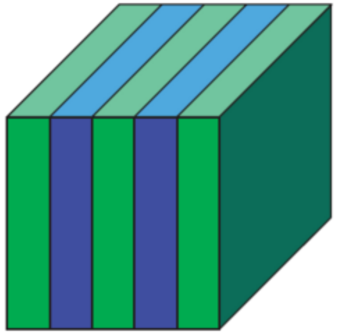
Optical lattices / Photonic crystals



# Photonic band gaps in 1D optical lattices

**1D**




PHYSICAL REVIEW A VOLUME 52, NUMBER 2 AUGUST 1995


**Photonic band gaps in optical lattices**


I. H. Deutsch, R. J. C. Spreeuw,* S. L. Rolston, and W. D. Phillips

*National Institute of Standards and Technology, PHYS A167, Gaithersburg, Maryland 20899*

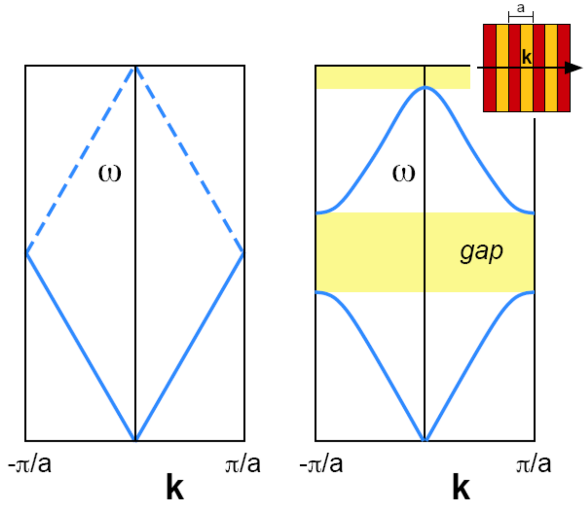


(Received 31 August 1994; revised manuscript received 5 December 1994)


→ **Theoretical prediction** with quasiresonant 1D lattices (red or blue-detuned)

No experimental observation !

# Is the 1D case interesting?




Bloch-Floquet theorem in 1D: every lossless, infinite, periodic system has a band gap.

(index modulation small → gap narrow, but always there)

→ PBG in 1D: trivial

**But we're experimentalists !**

We **don't** have:

- an infinite medium
- a lossless medium
- a perfectly periodic medium

→ Necessary size ? depends on the index contrast

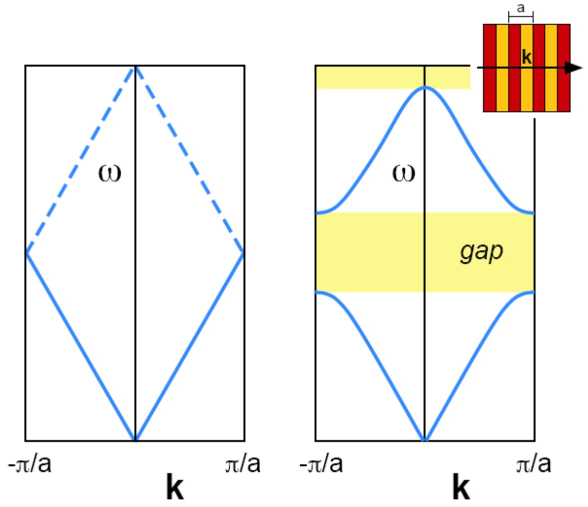
Atomic vapors: $\rho \approx 10^{11}$-$10^{12}$ cm$^{-3}$

$$n - 1 \propto \rho \mathrm{Re}(\alpha)$$

→ $n - 1 \approx 10^{-4}$-$10^{-3}$

→ we need several $10^3$ layers !

# Is the 1D case interesting?

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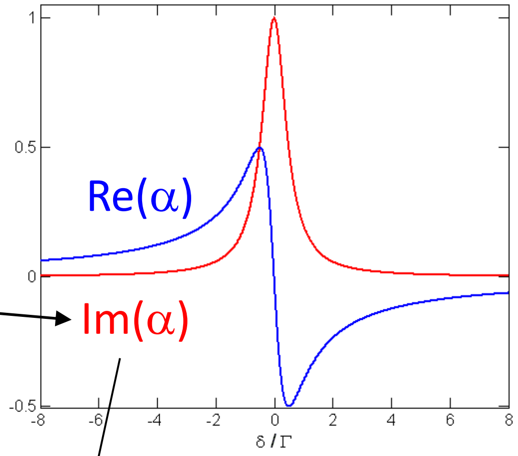
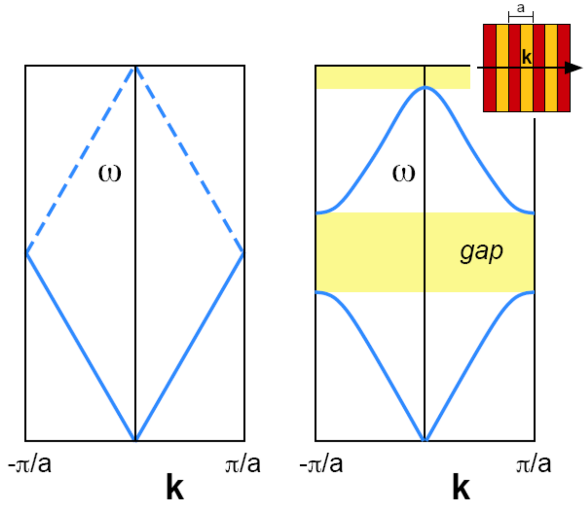



$T = e^{-\rho \mathrm{Im}(\alpha) kL}$

→ must be small !

# Is the 1D case interesting?

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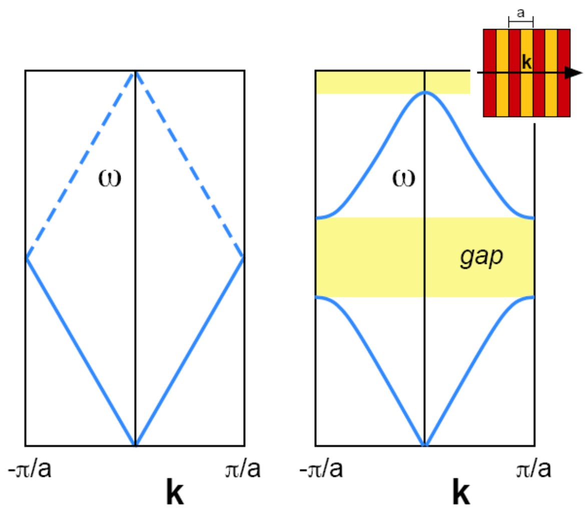
The atomic distribution along the lattice is inhomogeneous

# Is the 1D case interesting?

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**But we're experimentalists!**

We **don't** have:

- an infinite medium
- a lossless medium
- a perfectly periodic medium

→ What is the best we can achieve?

→ And what can we do with such a system?

# Outline

Experiments done at Tübingen (Germany) between 2010 and 2012

1) Photonic band gaps with two-level atoms

2) Photonic band gaps with EIT

3) Temporal dynamical effects

On-going experiments at Nice

# Outline

Experiments done at Tübingen (Germany) between 2010 and 2012

**1) Photonic band gaps with two-level atoms**

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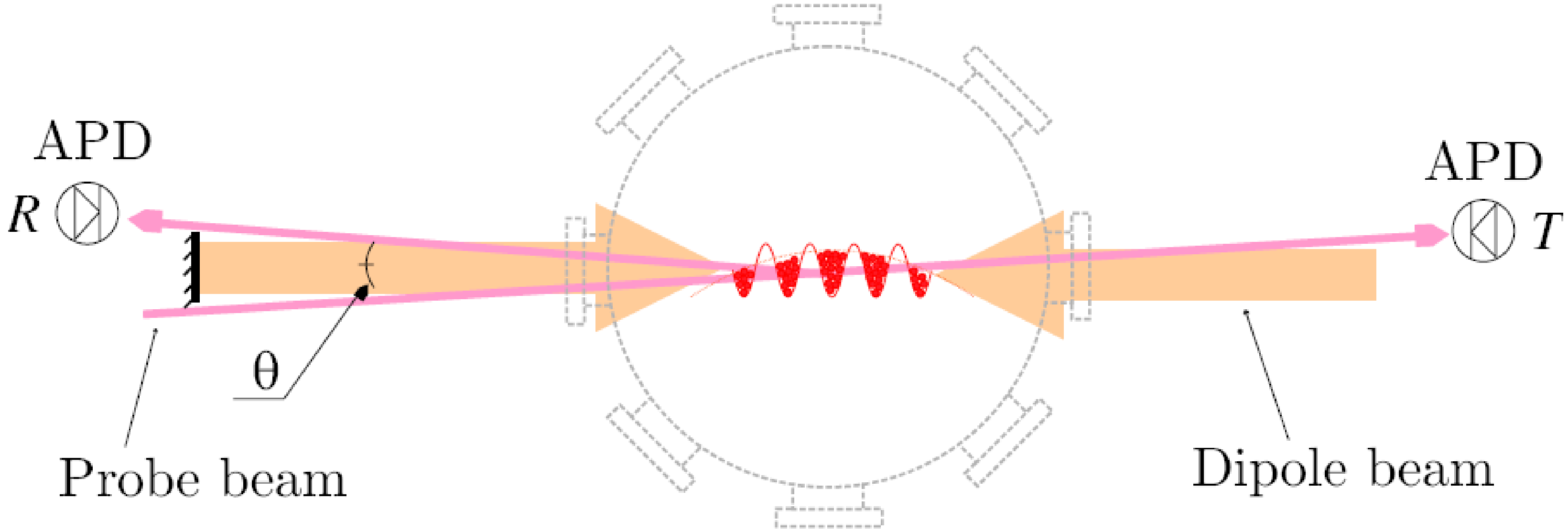
# Experimental setup



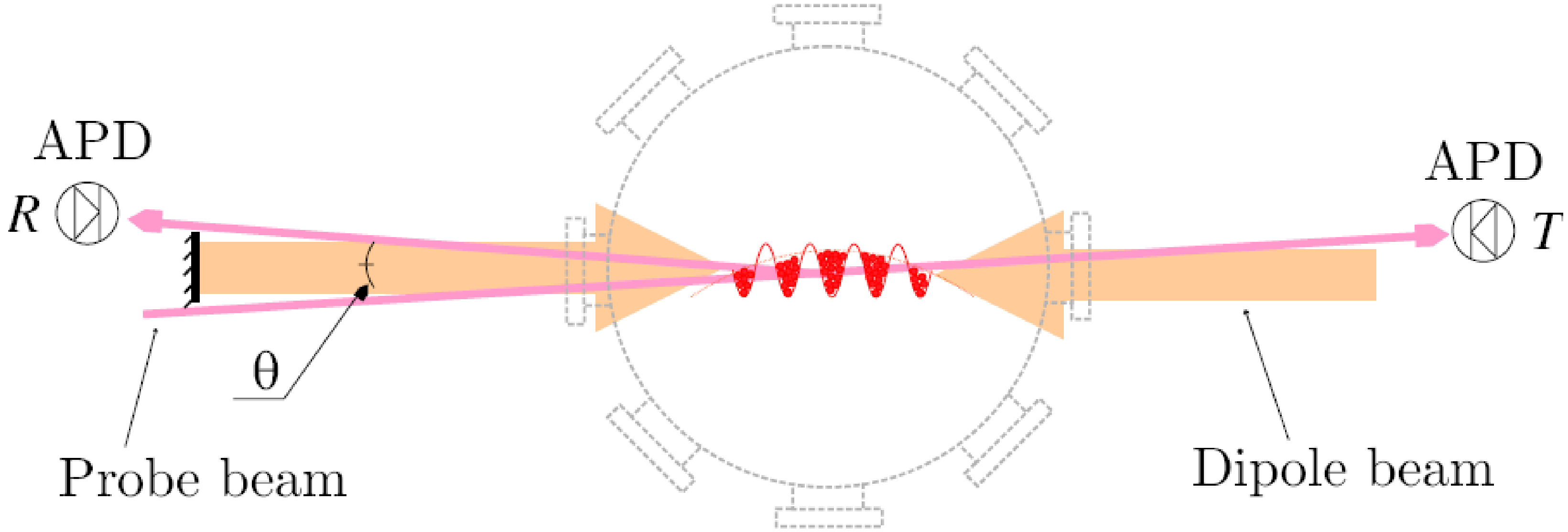

**Atoms**: laser-cooled $^{87}$Rb, $\lambda_0$ = 780.24 nm.

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

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

**Measurements**: transmission $T$ and reflection $R$ spectra.

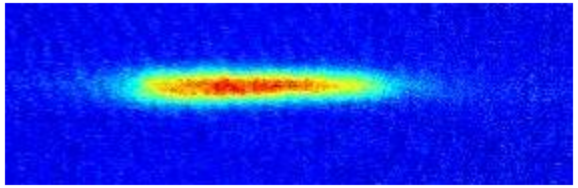
# Experimental setup




**Atom sample:**

$N$ = 5×10$^7$

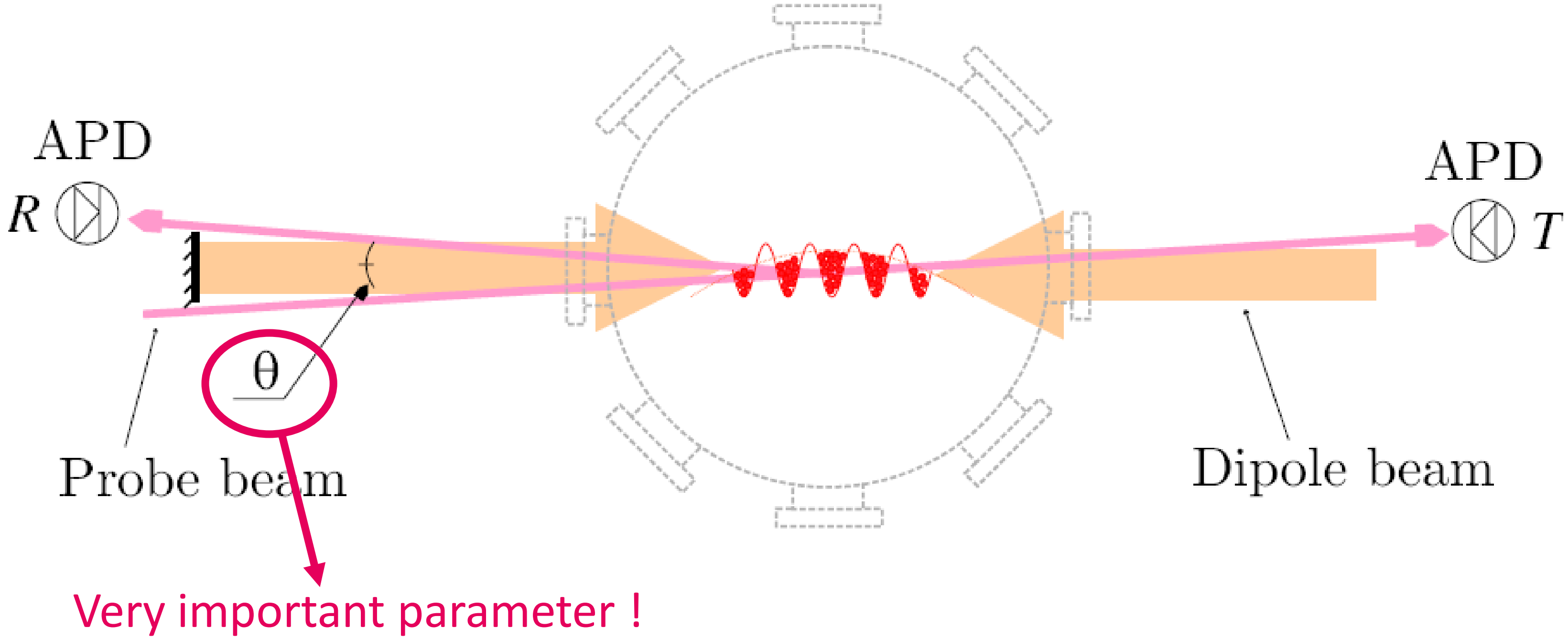
$T$ ≈ 100 µK



↕ ≈ 200 µm

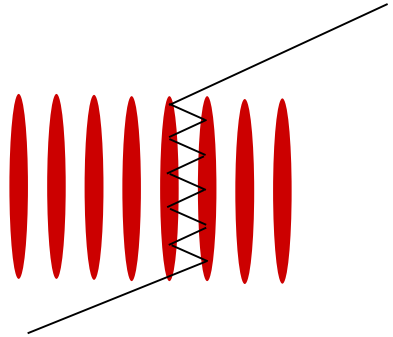
$L$ ≈ 3 mm → 7700 atomic layers

# Experimental setup



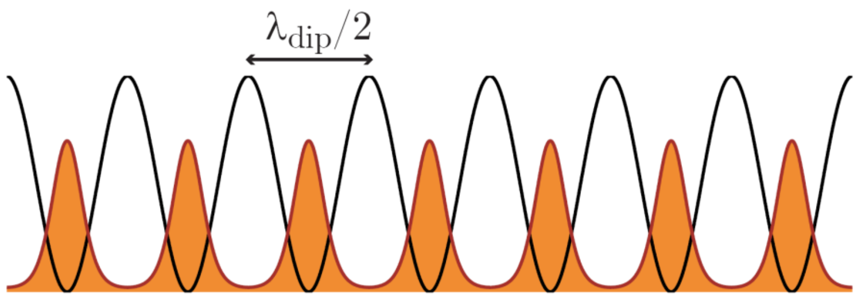

θ ≈ 0 : lattice too close to resonance & difficult detection.

θ too large : limited interaction length, or equivalently, limited number of reflections.



→ Good trade-off: θ ≈ 2°

# Bragg condition




- Lattice periodicity: $\lambda_{dip}/2$ → $K_{lat} = 4\pi/\lambda_{dip}$
- Bragg condition: $2\, n(\delta)\, k_0 \cos(\theta) = K_{lat}$

  → $\lambda_{dip} \cos(\theta) = \lambda_0/n(\delta)$

$\delta$: probe – atom detuning

$n$: average refractive index

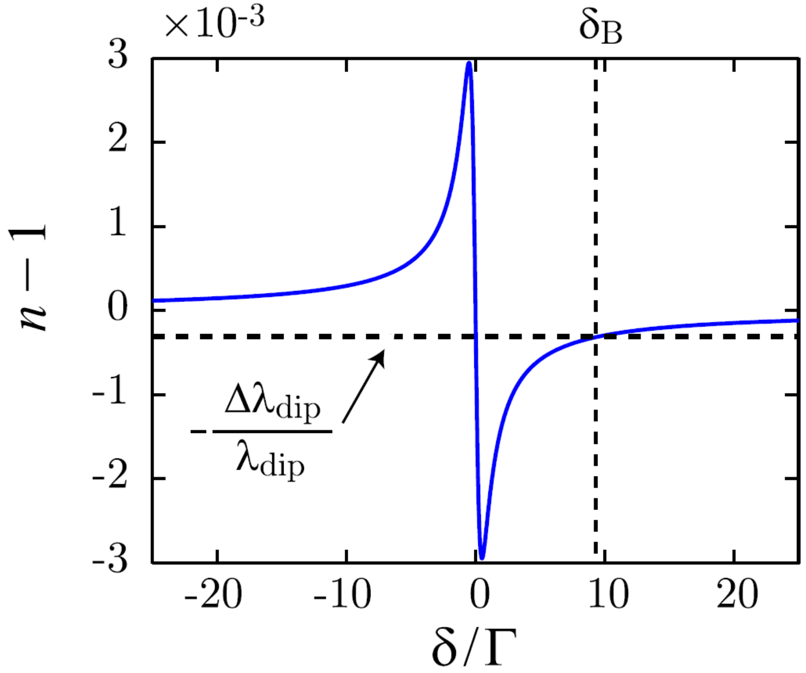
- We keep constant $\theta$ and tune $\lambda_{dip}$ around $\lambda_{dip0} = \lambda_0/\cos(\theta)$ ("geometric Bragg condition")

  → $\lambda_{dip0}$ = 780.7 nm with $\theta$ = 2°.

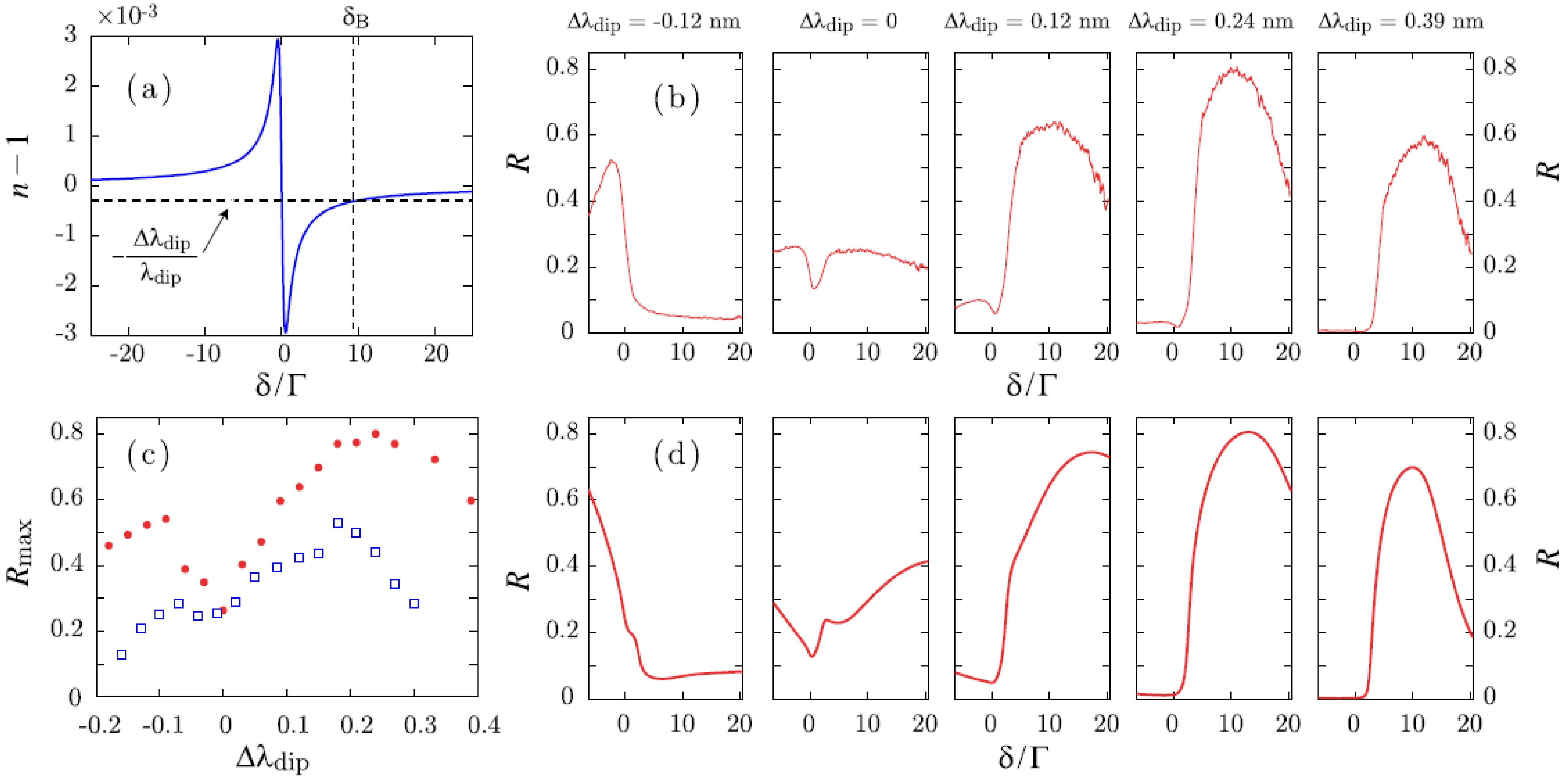
- Let's define $\Delta\lambda_{dip} = \lambda_{dip} - \lambda_{dip0}$

$$n(\delta) - 1 = -\frac{\Delta\lambda_{dip}}{\lambda_{dip}}$$

$$n - 1 \propto \rho \mathrm{Re}(\alpha)$$



# Reflection spectra vs $\lambda_{dip}$



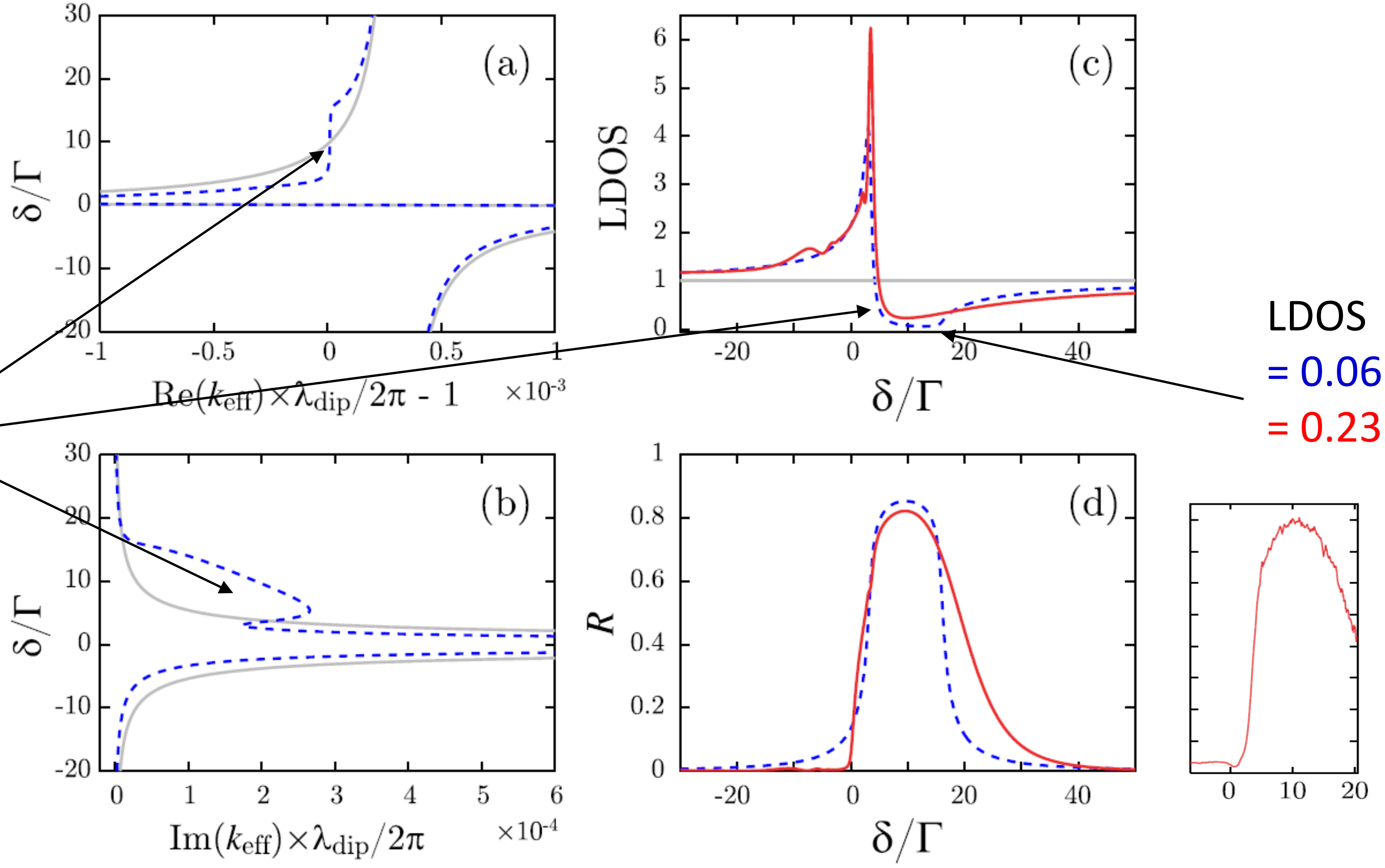

$N$ = 6×10$^7$ atoms

$N$ = 2×10$^7$ atoms

Maximum obtained reflectivity: 80 %

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

# Dispersion relations and local DOS




Band gap

LDOS
= 0.06
= 0.23

disordered medium
infinite lattice
finite distribution

1D model based on transfer matrices, $\Delta\lambda_{dip}$ = 0.24 nm.

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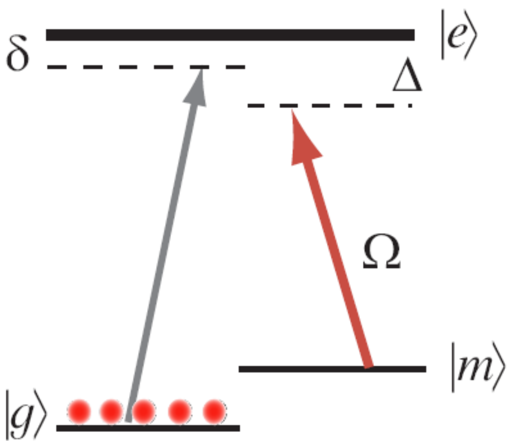
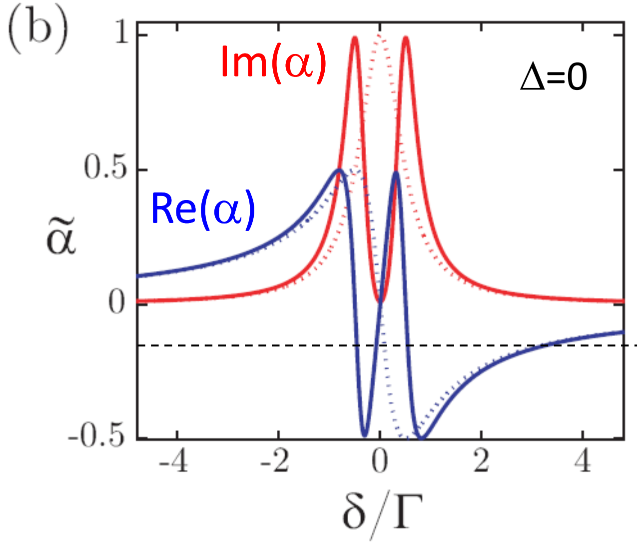
# Q: Can the PBG be improved by using EIT?




$$\alpha = \frac{2|d_{ge}|^2}{\varepsilon_0 \hbar \Gamma} \times \frac{-\Gamma}{2\delta + i\Gamma - \Omega^2/[2(\delta - \Delta + i\gamma)]}$$

$-\frac{\Delta\lambda_{\text{dip}}}{\lambda_{\text{dip}}}$

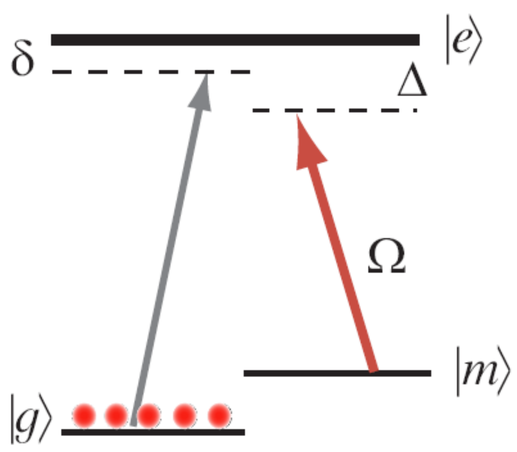
EIT: Im(α) vanishes → **transparency window**

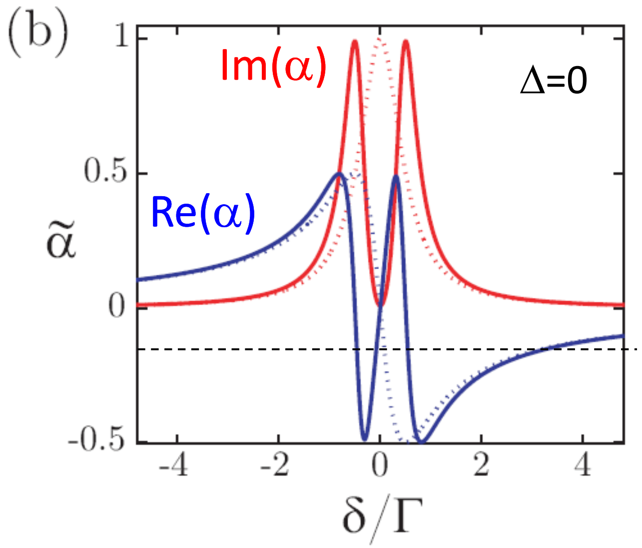
But: where Im(α) = 0, Re(α) = 0 → *n* = 1

And also: same Im(α) @ Bragg

A: Unfortunately not ☹

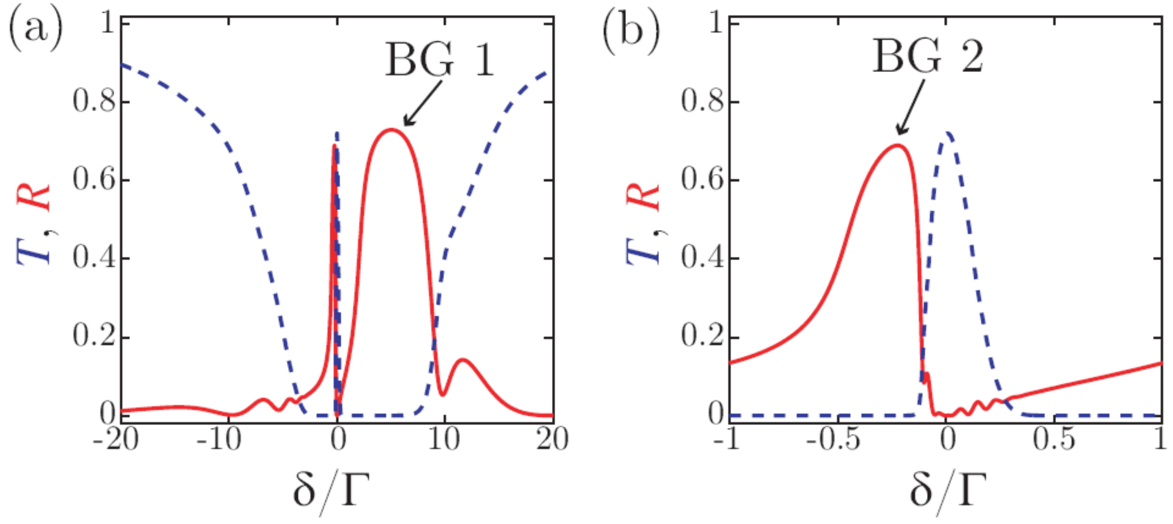
# A new, electromagnetically-induced photonic band gap




$$-\frac{\Delta\lambda_{\rm dip}}{\lambda_{\rm dip}}$$

$$\alpha = \frac{2|d_{ge}|^2}{\varepsilon_0 \hbar \Gamma} \times \frac{-\Gamma}{2\delta + i\Gamma - \Omega^2/[2(\delta - \Delta + i\gamma)]}$$

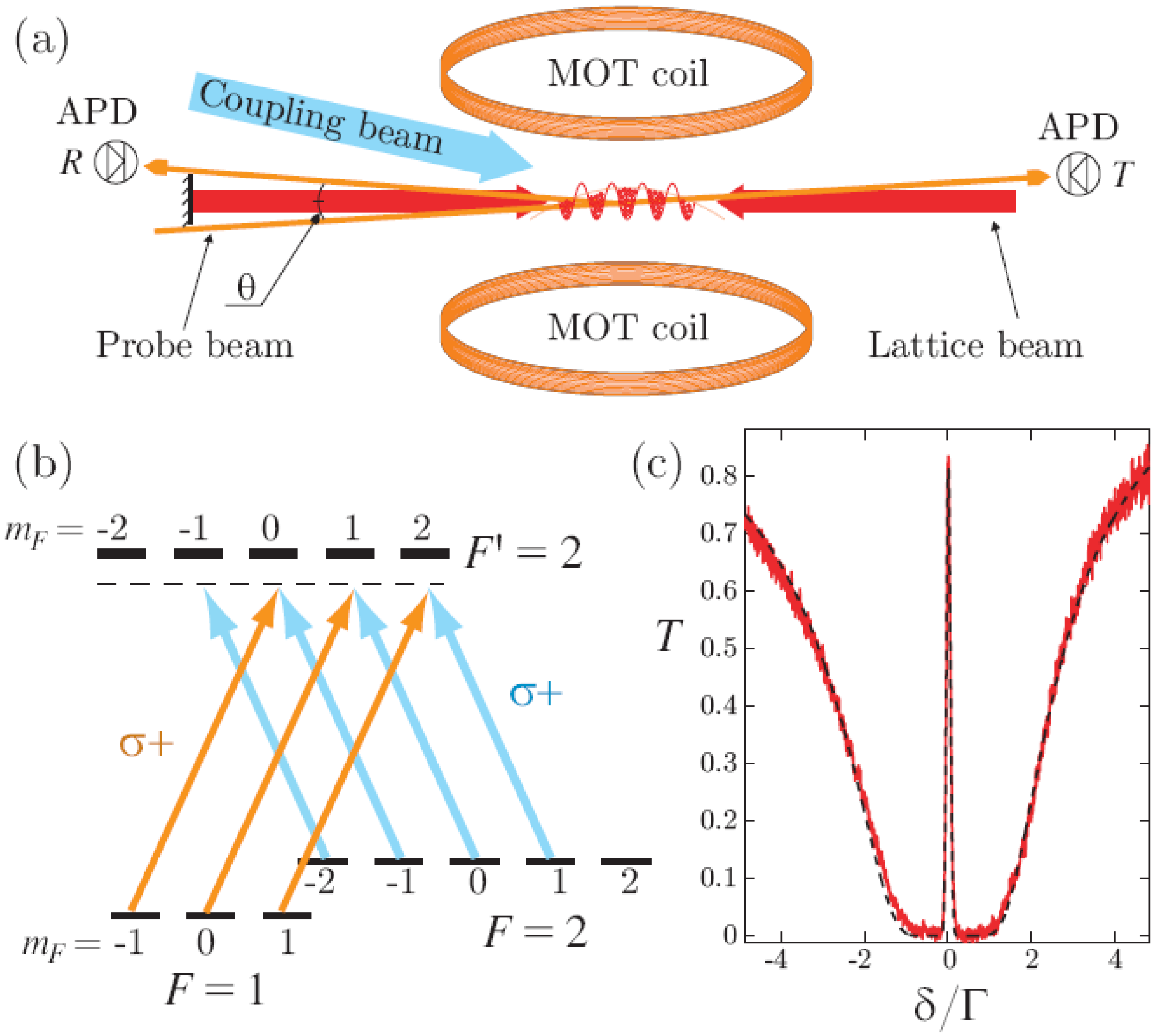



Very narrow and controllable !

See also: Petrosyan, Phys. Rev. A **76**, 053823 (2007)

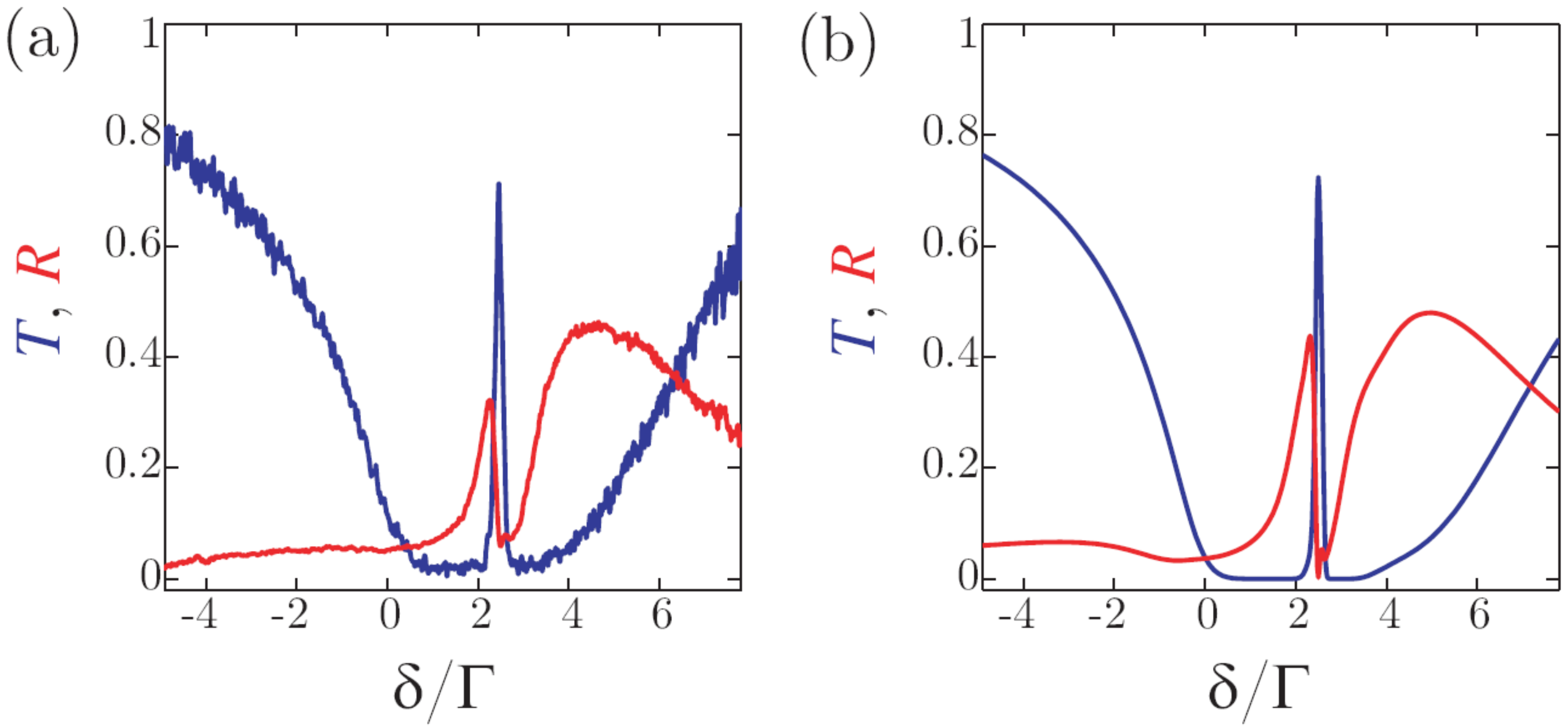
# PBG with EIT: experiment

- New laser phase-locked to the probe beam
- Different addressed transitions



# PBG with EIT: experiment

Experiment Theory




+ characterization as a function of the coupling-beam parameters...

A. Schilke *et al.*, Phys. Rev. A **86**, 023809 (2012)

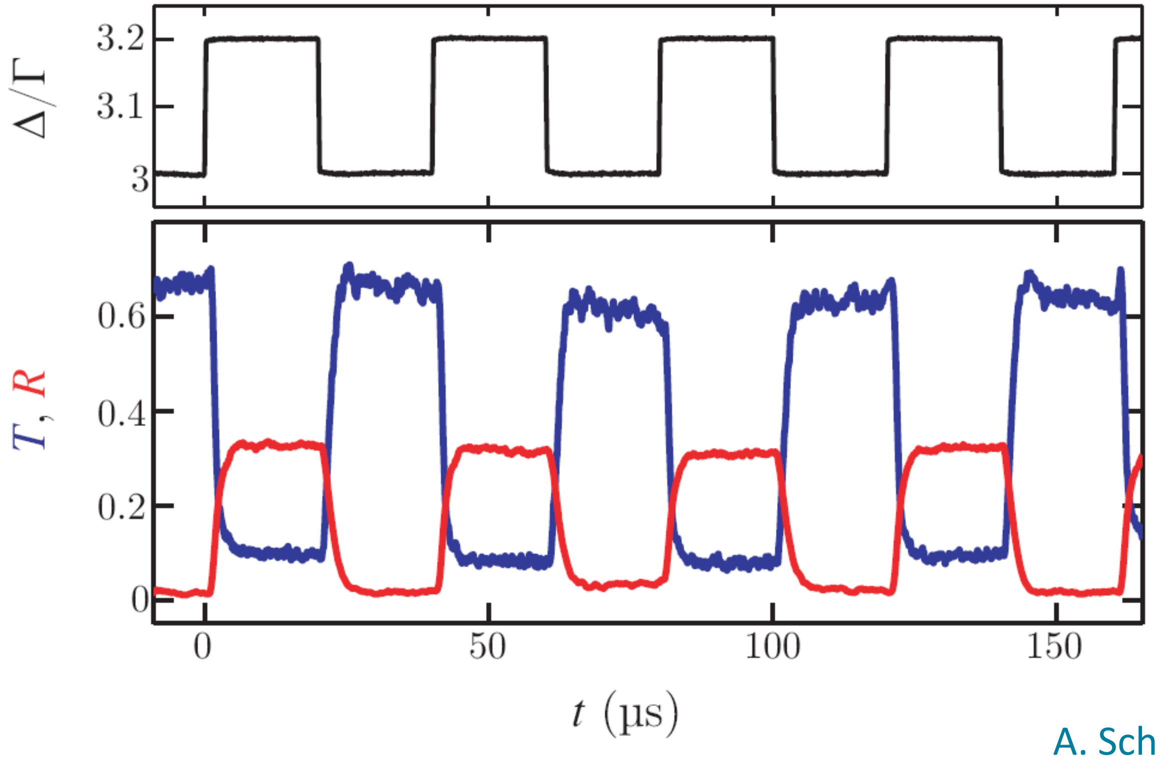
# Possible application: all-optical switching

Probe @ $\delta = 3\,\Gamma$

Coupling beam switched between $\Delta = 3$ and $\Delta = 3.2\,\Gamma$

→ Transmission / Reflection

→ two-port all-optical switch




A. Schilke *et al.*, Phys. Rev. A **86**, 023809 (2012)

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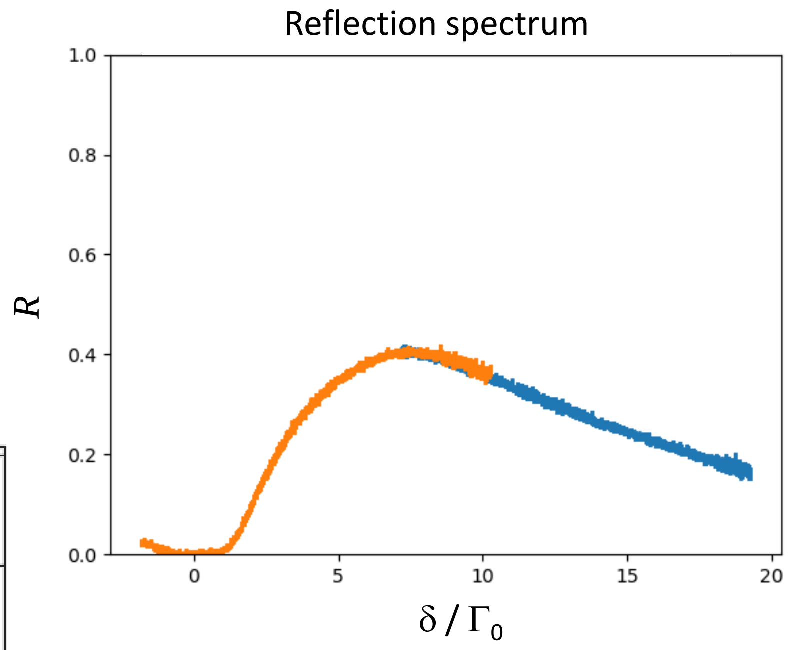
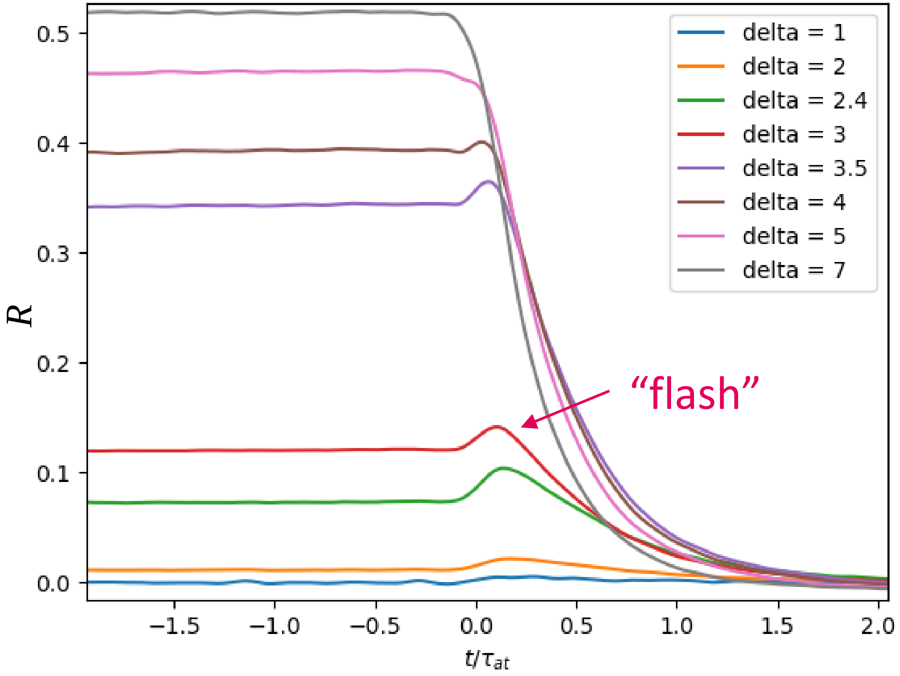
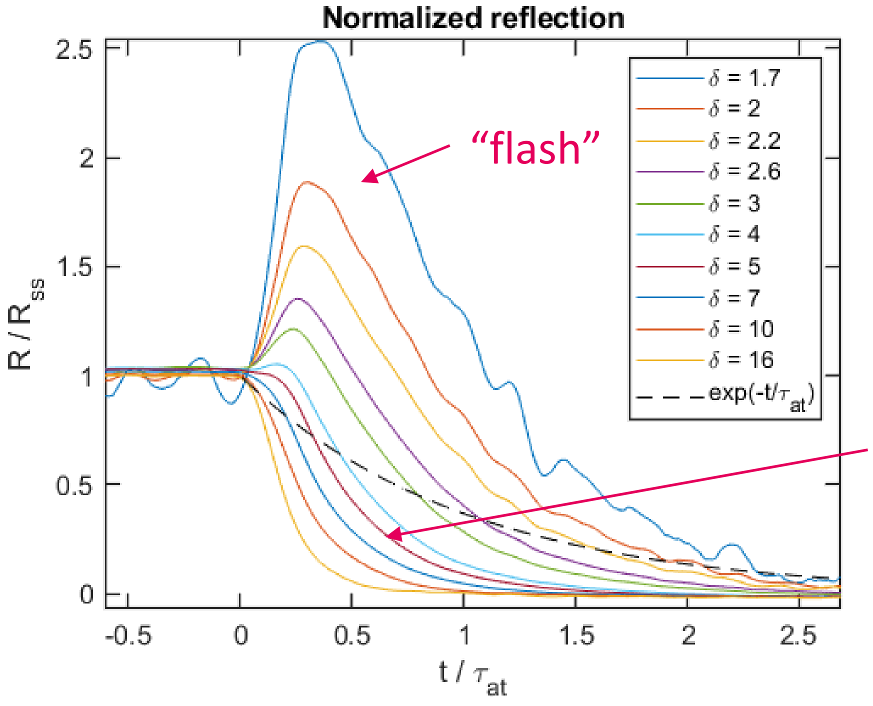
# Optical transients in the reflection

- We switch on and off the incident probe beam with a duration $\tau_{laser} \approx 1$ ns << $\tau_{at} = 26$ ns
- High bandwidth detectors
- Temporal response of the Bragg reflection




**Preliminary data**

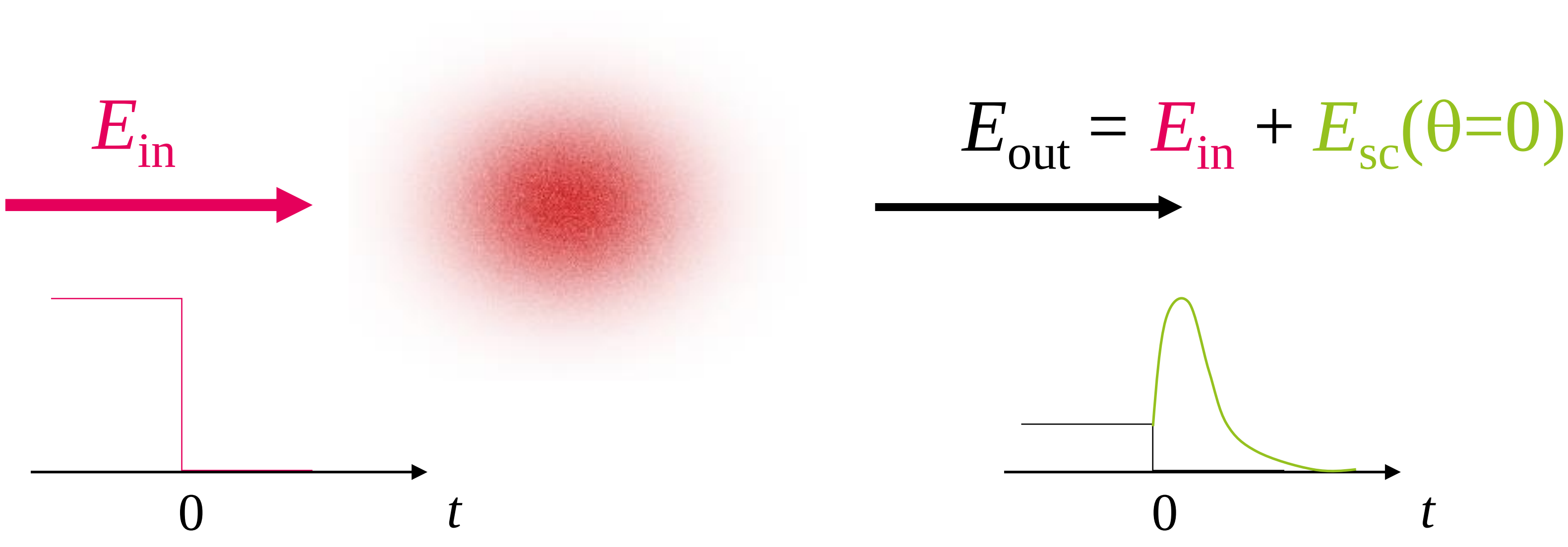



Superradiant decay

# A flash in the reflection?

The “flash” effect in transmission in a disordered medium:



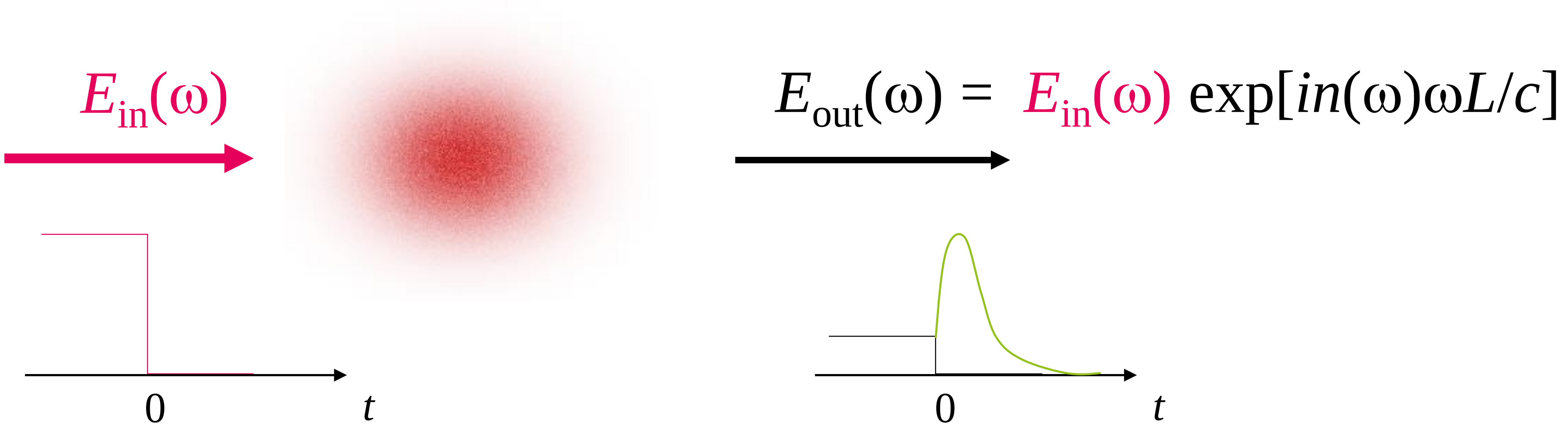

Extensively studied by the group of D. Wilkowski (Singapore)

Chalony *et al.*, PRA 84, 011401(R) (2011)
Kwong *et al.*, PRL 113, 223601 (2014)
Kwong *et al.*, PRL 115, 223601 (2015)

In the Bragg reflection, there is only a scattered field, no incident field. But still a flash !?

# A flash in the reflection?

To simulate the flash effect: go to Fourier space

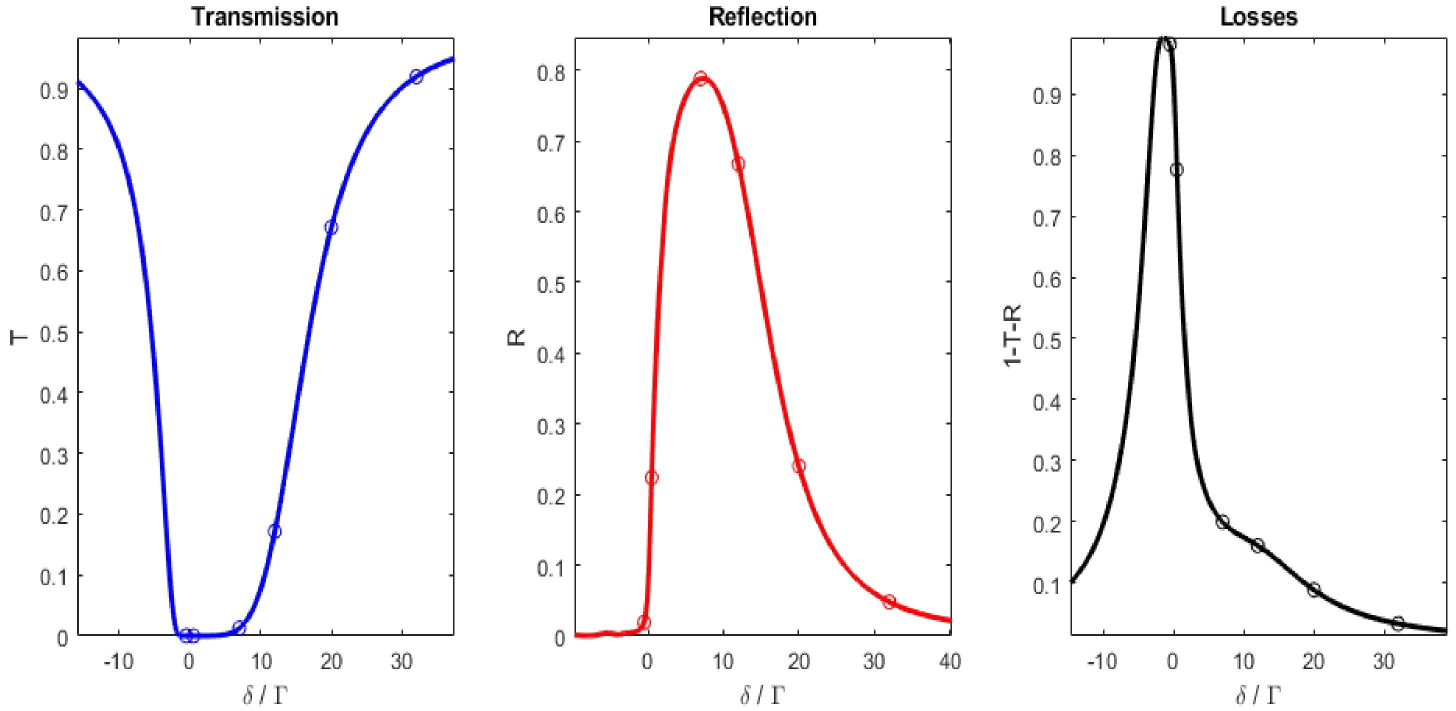



For the Bragg reflected field: the same with the transfer matrix formalism to compute $E_t$ and $E_r$

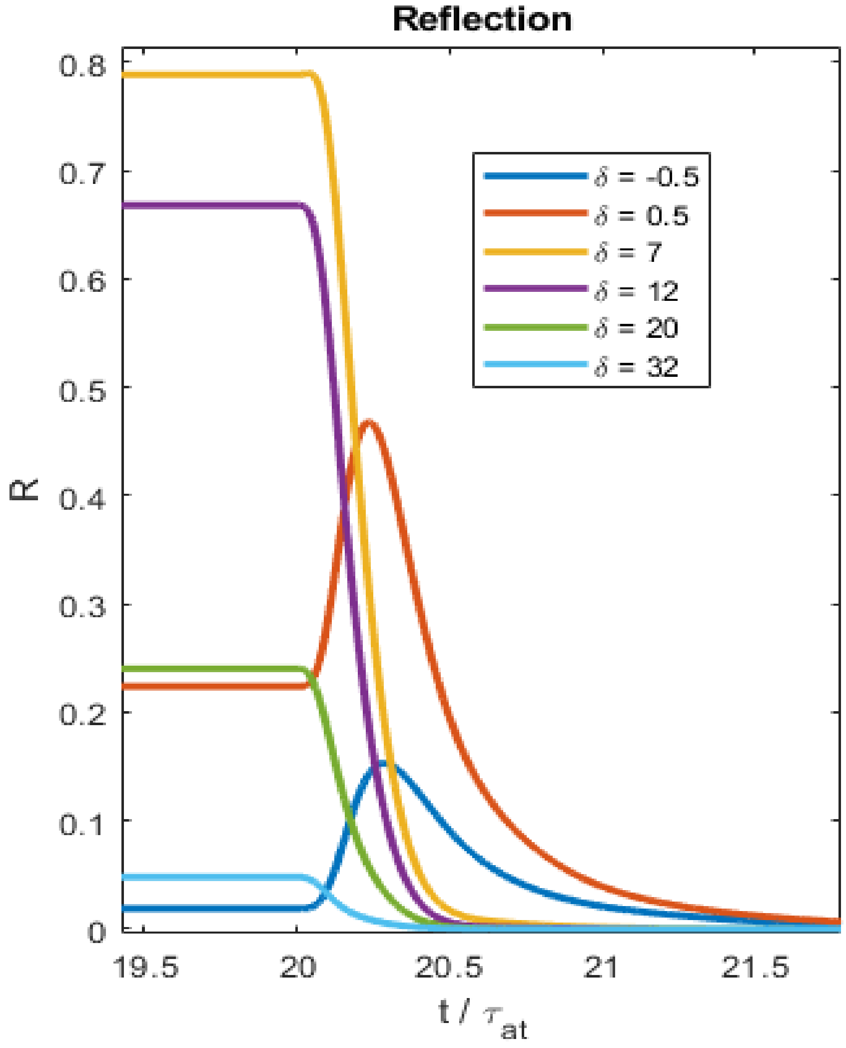
→ Transmitted and reflected intensities as a function of time

# Flash in the reflection: simulation and interpretation

**Spectra**




**Temporal dynamics at the switch-off**




→ Flash effect observed on the near-resonance side of the reflection spectrum.

→ Qualitatively like the experiment ☺

→ Interpretation: temporal or spectral picture

# Superradiant decay of the reflection

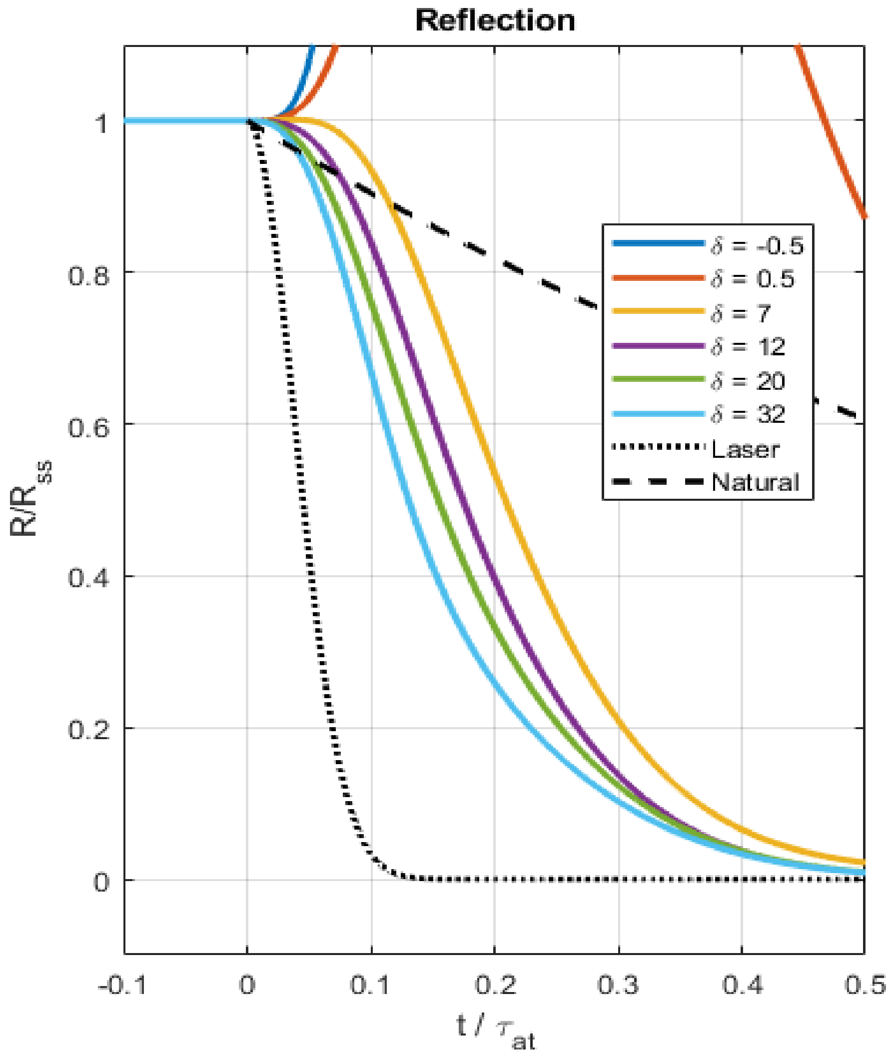
Superradiant decay, in the linear optics regime, has been observed in a:

- In the scattered light (off-axis, disordered medium): our group — Araújo *et al.*, PRL **117**, 073002 (2016)
- The forward lobe (Timed-Dicke state, constructive interference in the forward direction): Havey — Roof *et al.*, PRL **117**, 073003 (2016)
- In the coherent flash (in transmission): Wilkowski — Kwong *et al.*, PRL **115**, 223601 (2015)
- In Raman quantum memories: Felinto, LeBlanc,…
- In microscopic ensembles (dense clouds, 1D chain, nanofibers, etc…): Kimble, Rolston, Browaeys, Rauchenbeutel, etc…

Here, scattering by a macroscopic ensemble in a specific (Bragg) direction with constructive interference.

# Superradiant decay of the reflection

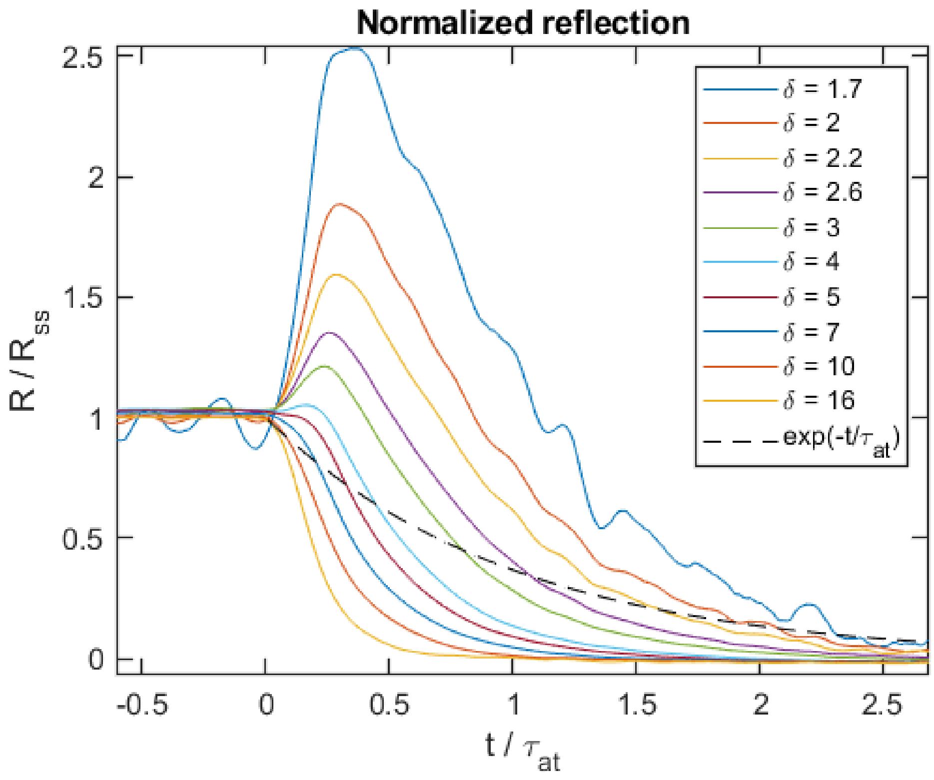
Same simulations as previously:




→ Clearly superradiant

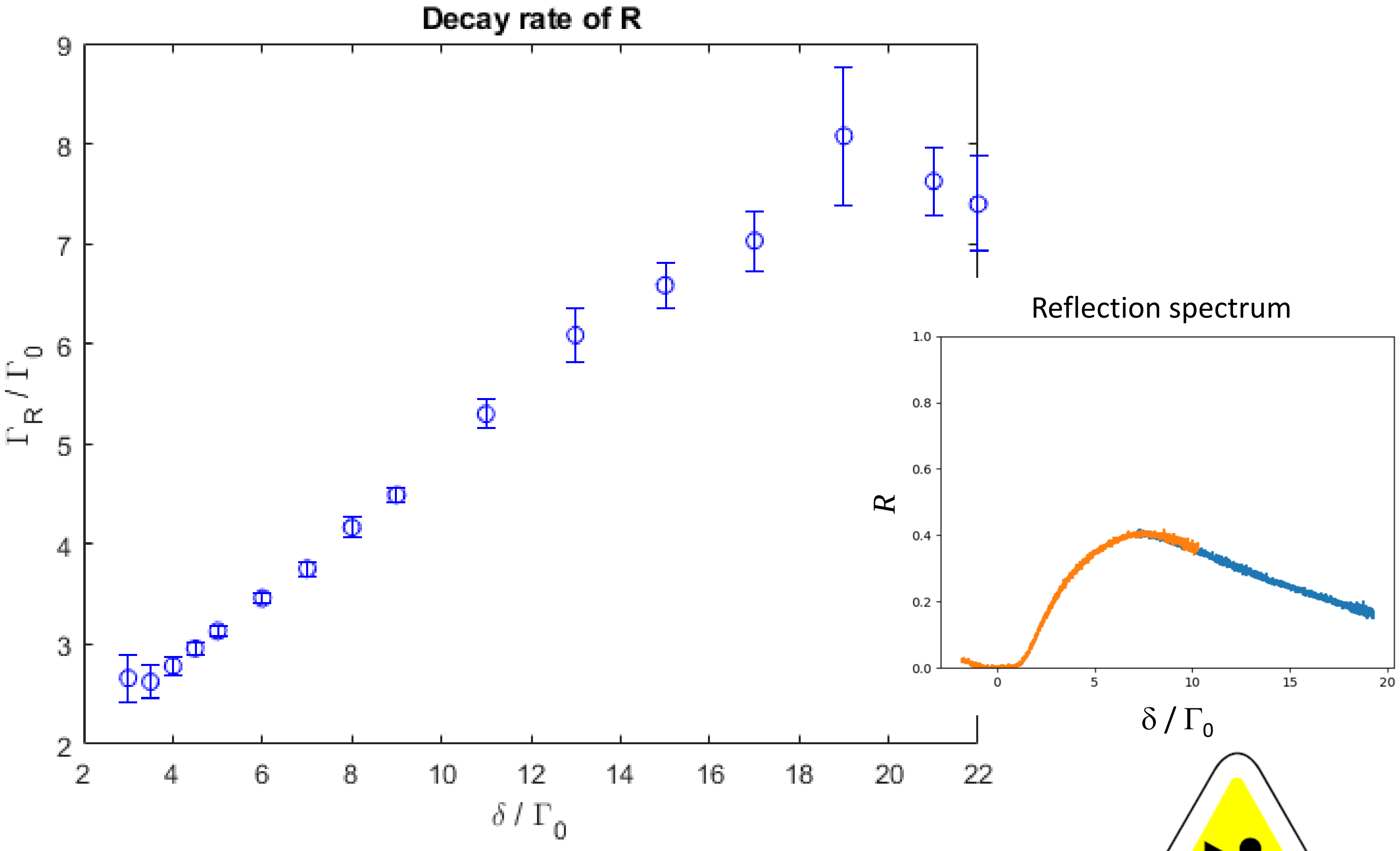
→ Decay rate increases with the detuning

→ Qualitatively like the experiment ☺

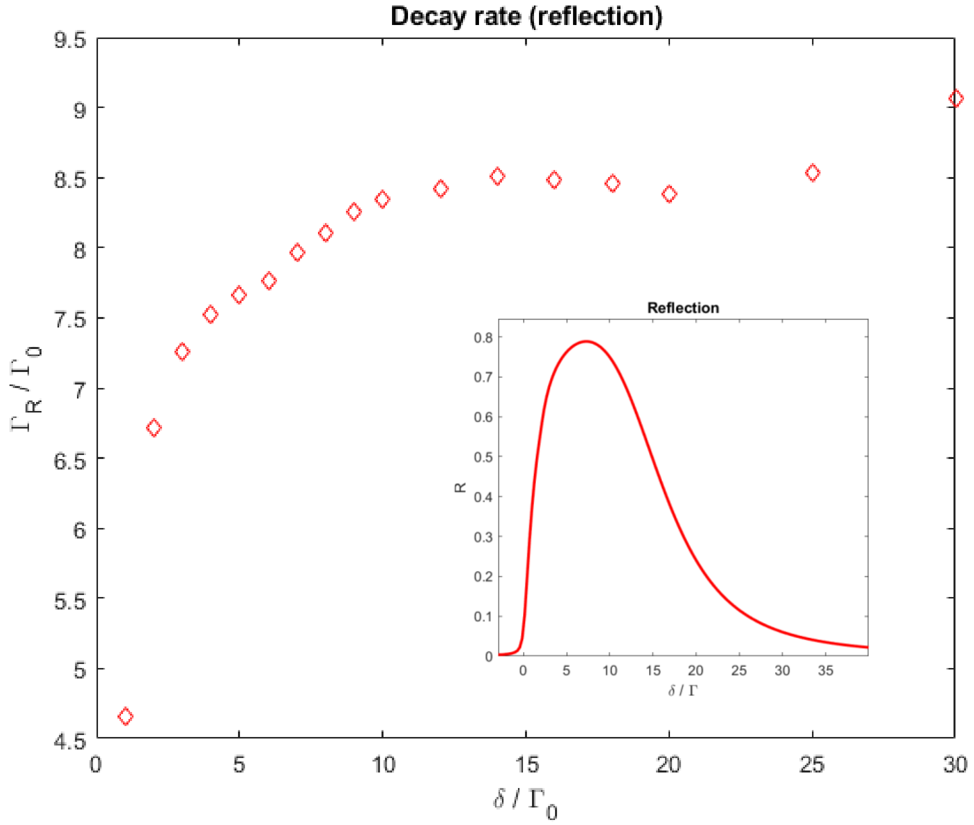



# Superradiant decay of the reflection

## Preliminary data




## Preliminary simulations



# Summary

- Steady-state properties:
  - Bragg reflection > 80% possible ☺
  - Discussion on the intrinsic limitations (scattering losses)

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

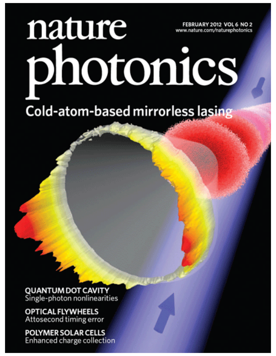
- Bragg + EIT: A new band gap
  - Not better (at best, same amount of losses) ☹
  - Narrower and externally controllable ☺ → two-port all-optical switch

Schilke *et al.*, Phys. Rev. A **86**, 023809 (2012)

- Bragg + FWM: Distributed feedback laser (mirrorless laser)

Not discussed today

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




- Bragg + temporal dynamics:
  - A nonintuitive flash effect
  - Superradiant decay

Asselie *et al.*, in preparation

# Future

<u>Rich system:</u>

- Spontaneous emission of excited atoms inside the lattice?
- Pulse propagation, slow light?
- EIT-quantum memory with two output ports?
- Nonlinear effects: quantum correlations?
- A controllable, nonlinear, lossless beam splitter?
- Applications?

New ideas and collaborations welcome!

Strong analogies with 1D chains of atoms → Bragg reflection with a 1D chain near a nanofiber

Corzo *et al.*, PRL **117**, 133603 (2016)
Olmos *et al.*, PRA **104**, 043517 (2021)

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# Robin Kaiser's group at Nice