Coherent superflash effect in cold atoms: Revealing forward scattering field in optically thick medium

David Wilkowski

School of Physical and Mathematical Science (NTU, Singapore)
Center for Quantum Technologies (NUS, Singapore)
Institut NonLineaire de Nice (UNS, France)
UMI Merlion-MajuLab (France/Singapore) NEW

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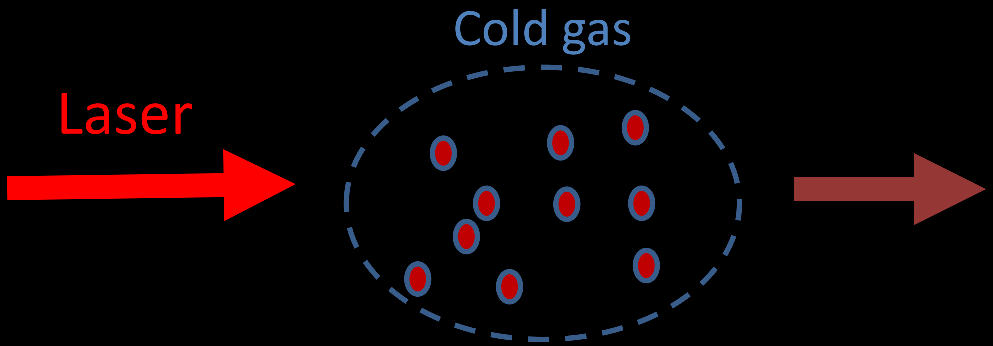
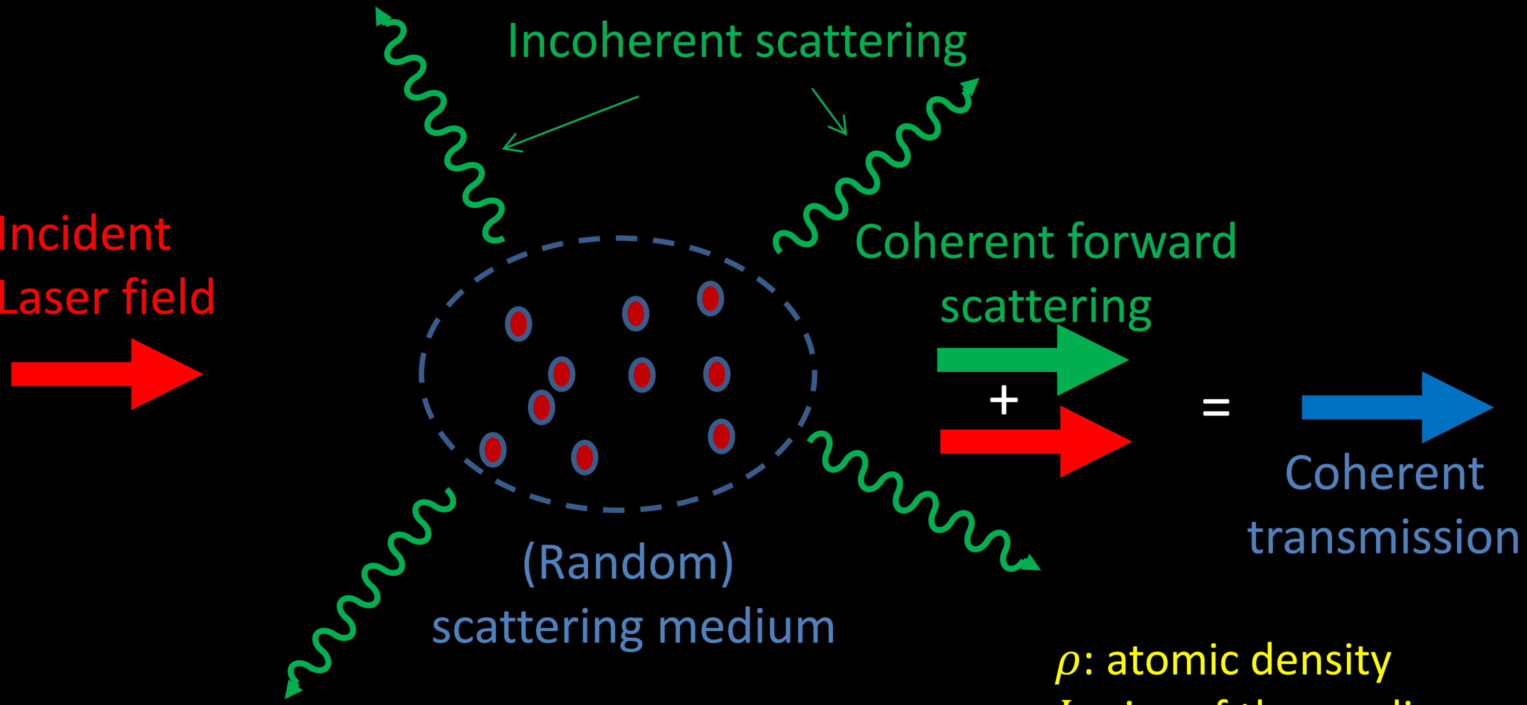
Outline of the talk



- Coherent transmission in the stationary regime
  - Beer-Lambert law and **forward scattering field**
  - How to measure the forward scattering field?
  - Maximum intensity using energy conservation argument
- Transient regime
  - Forward scattering and coherent (super)flash of light
  - Phase and intensity measurement
  - Dicke superradiance and coherent (super)flash?
- Conclusion

Incoherent and coherent scattering



Incident
Laser field

Incoherent scattering

Coherent forward
scattering

+

=

Coherent
transmission

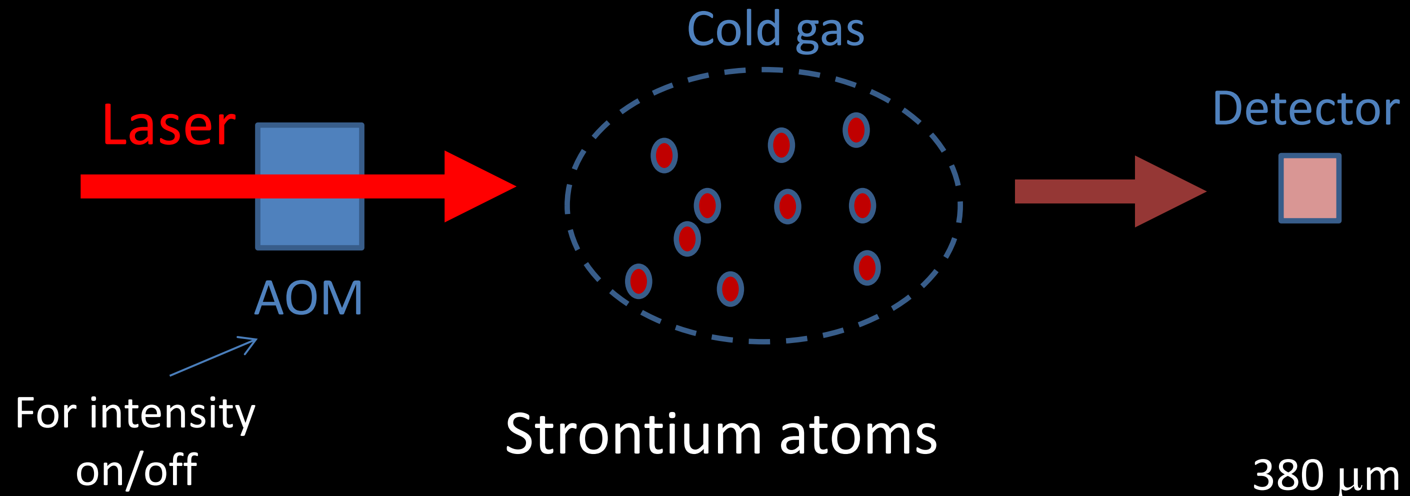
(Random)
scattering medium

ρ: atomic density
L: size of the medium
σ: scattering cross-section

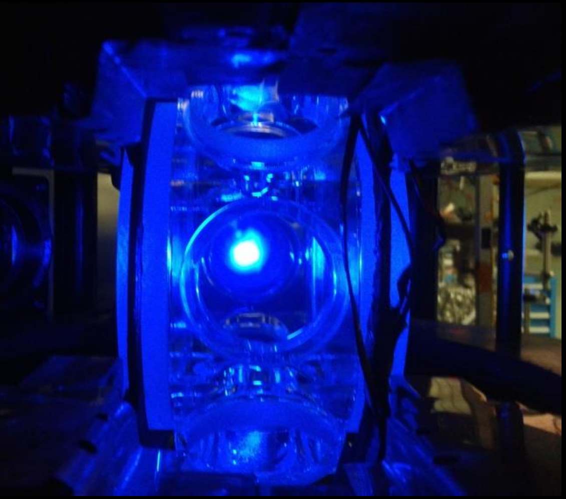
Coherent transmission: $I_t = I_0 \exp(-b)$ (Beer-Lambert law)

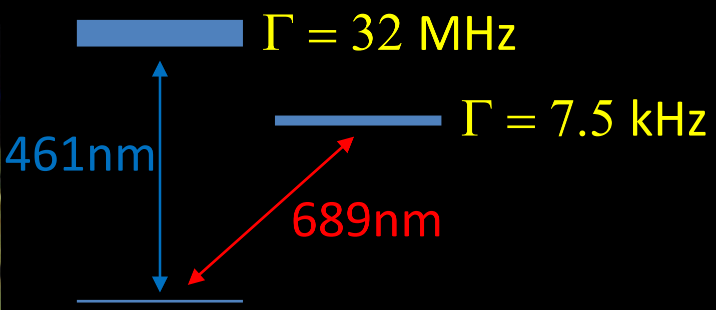
$b = \rho\sigma L$ is the optical thickness

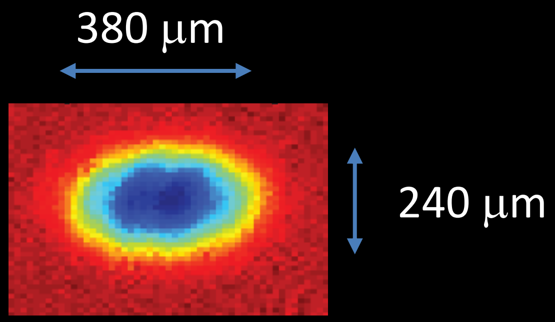
Coherent transmission set up



Strontium atoms







Atoms number: $3\ 10^{8}$
Density: ~10^{12} atoms/cm^{3}
Temperature: 3 µK
Optical thickness: 19

How to measure the forward scattering intensity?

Our starting point is: $E_t = E_0 + E_s$

At $t = 0$, we abruptly switch the incident field off

(Free induction decay ($b \ll 1$): First introduced in NMR [E. Hahn, Phys. Rev. **77**, 297 (1950)])

We get: $E_t(t = 0^+) = \cancel{E_0} + E_s$

Thus: $I_s = I_t(t = 0^+)$

The switching time is challenging since it should be <u>much</u> faster than medium response time (two-level atom: Γ^{-1})

For this purpose we use the "very slow" intercombination line of atomic strontium Γ^{-1} = 21 μs

Forward scattering field maximum intensity?

Our starting point: $E_t = E_0 + E_s$

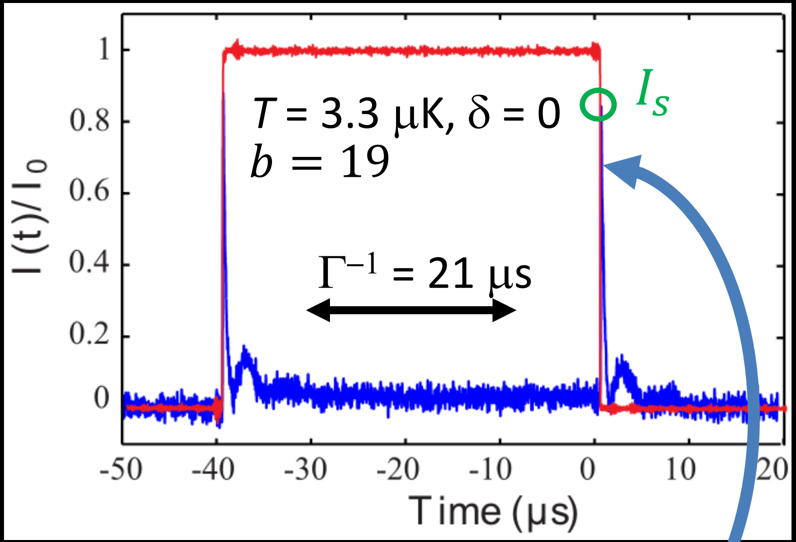
The energy conservation law imposes:

$I_t \leq I_0$, then $I_s \leq 4I_0$

However, since the scattering field is built upon the incident field, we might believe that $I_s \leq I_0$

- True for $\mathrm{b} \gg 1$:

$I_t = I_0 \exp(-b) \simeq 0$ and $I_s \simeq I_0$



$I_s \leq I_0$ -> Coherent Flash of Light

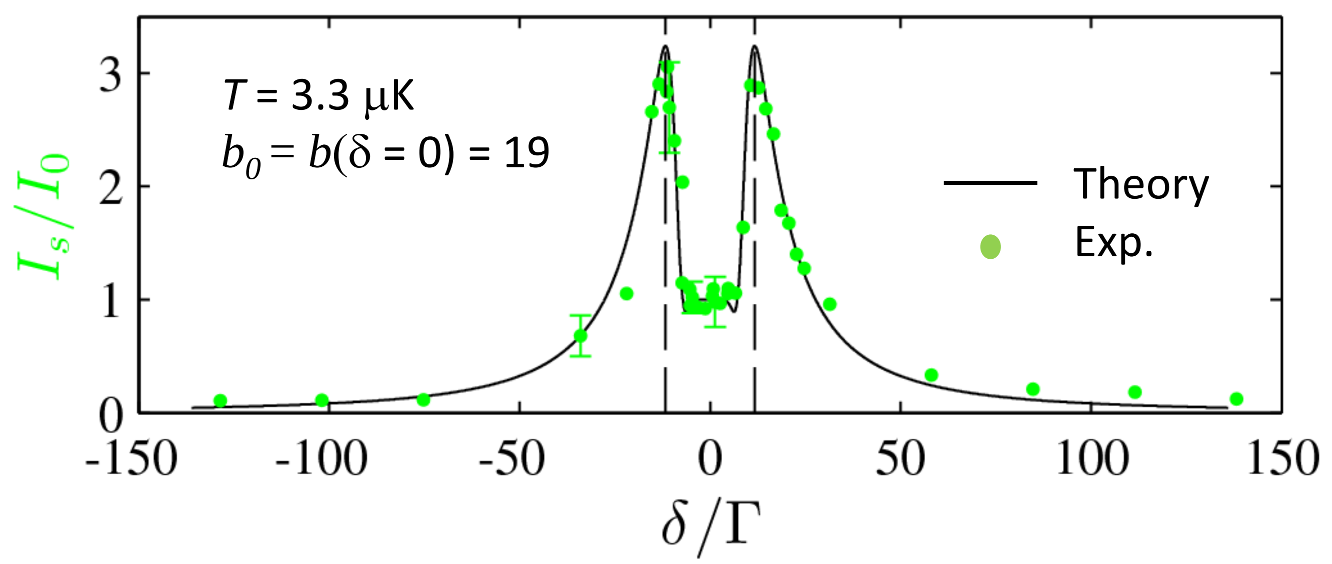
[M. Chalony et *al*, *Phys. Rev. A*, **84,** 011401 (2011)]

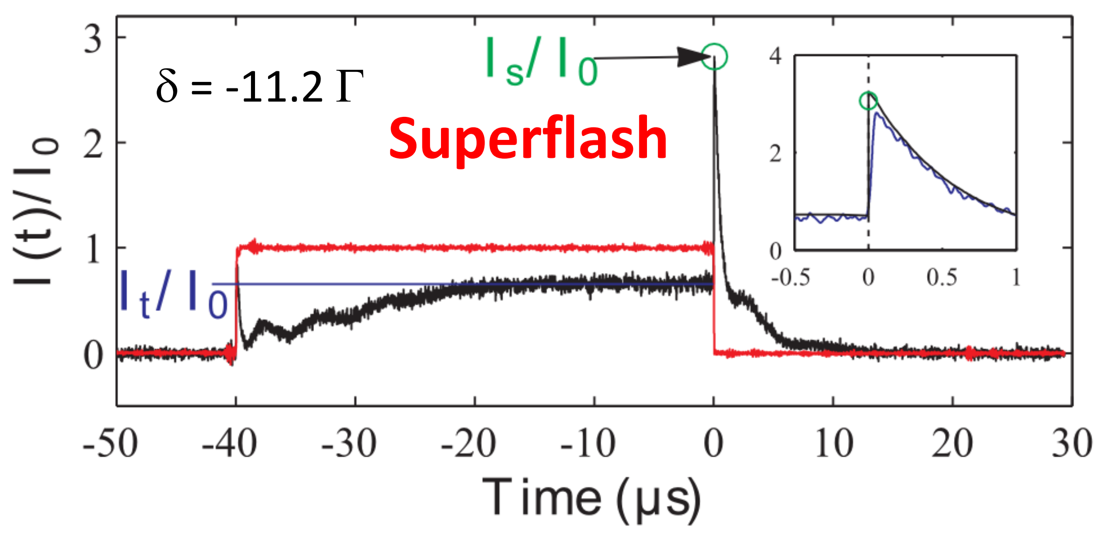
If $I_s > I_0$ we get a coherent superflash

Forward scattering field intensity

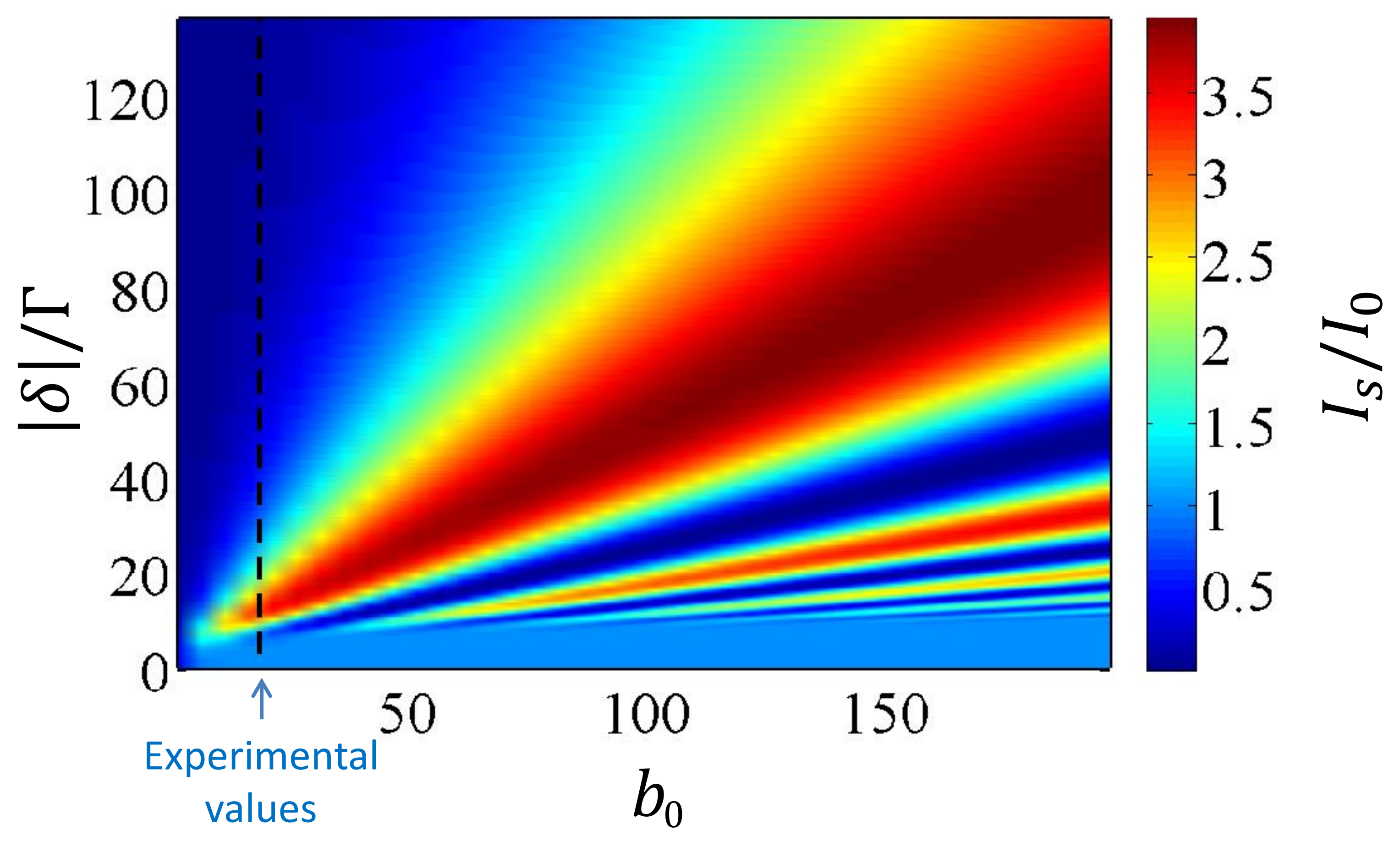
We observe:

- $I_s > I_0$, but $I_s < 4I_0$
- We get a superflash
- Max $I_s \simeq 3.2$
  at $|\delta| \simeq 11\,\Gamma$



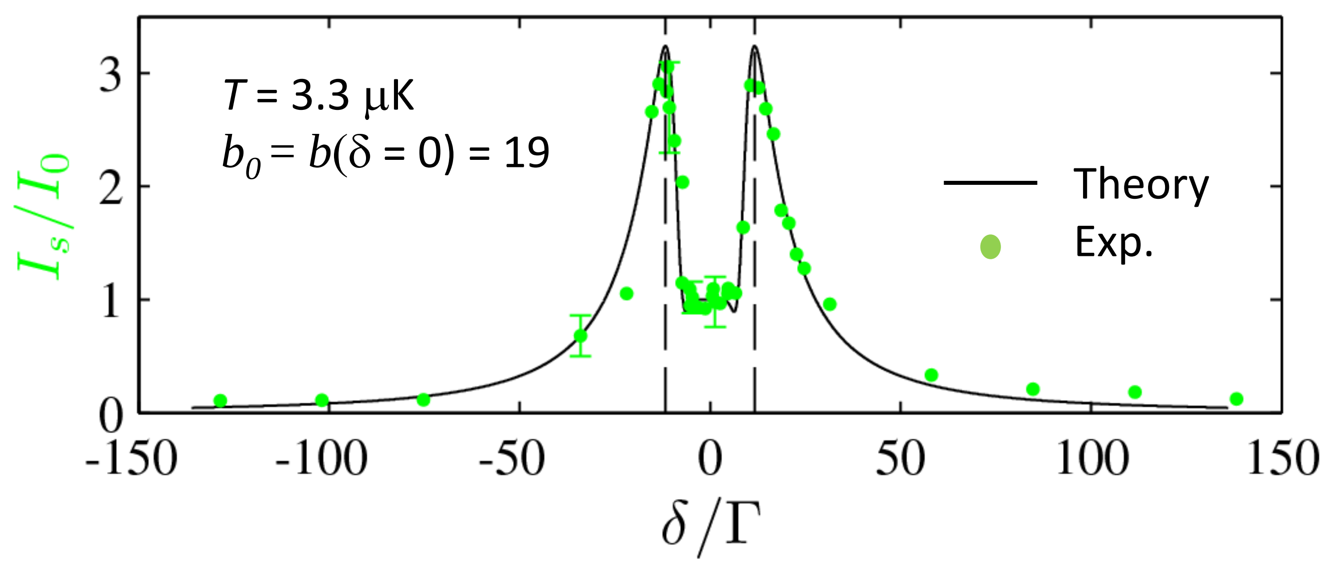


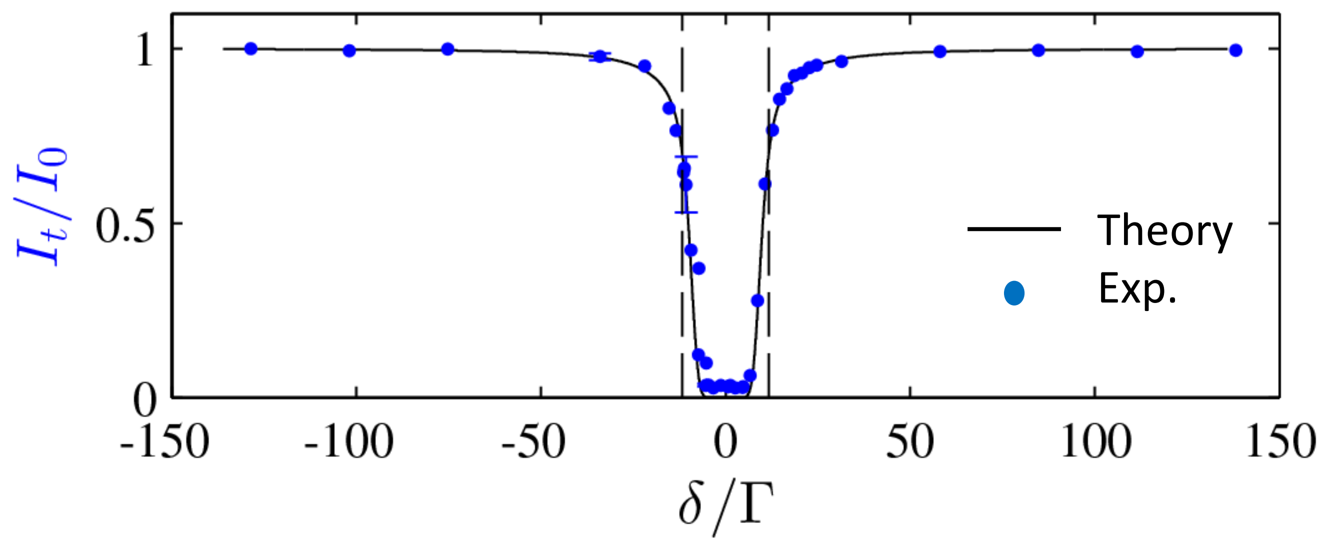
Superflash peak intensity: theory predictions



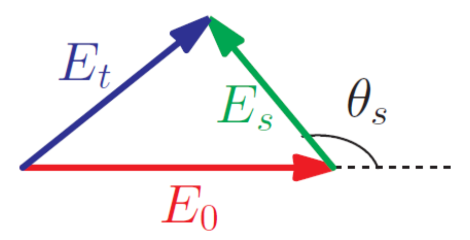
$b_0 \gg 1$ and $\delta \gg \Gamma$ we expect $I_s = 4I_0$, with $I_t = I_0$

Forward scattering field reconstruction





From I_0, I_s and I_t
We can get E_s



Forward scattering field reconstruction

"Normal" flash: $I_s < I_0$

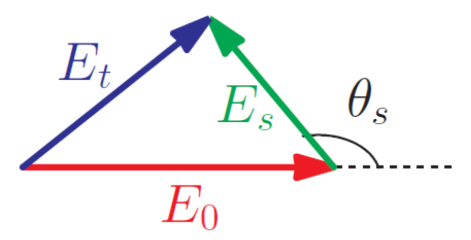
Superflash: $I_s > I_0$

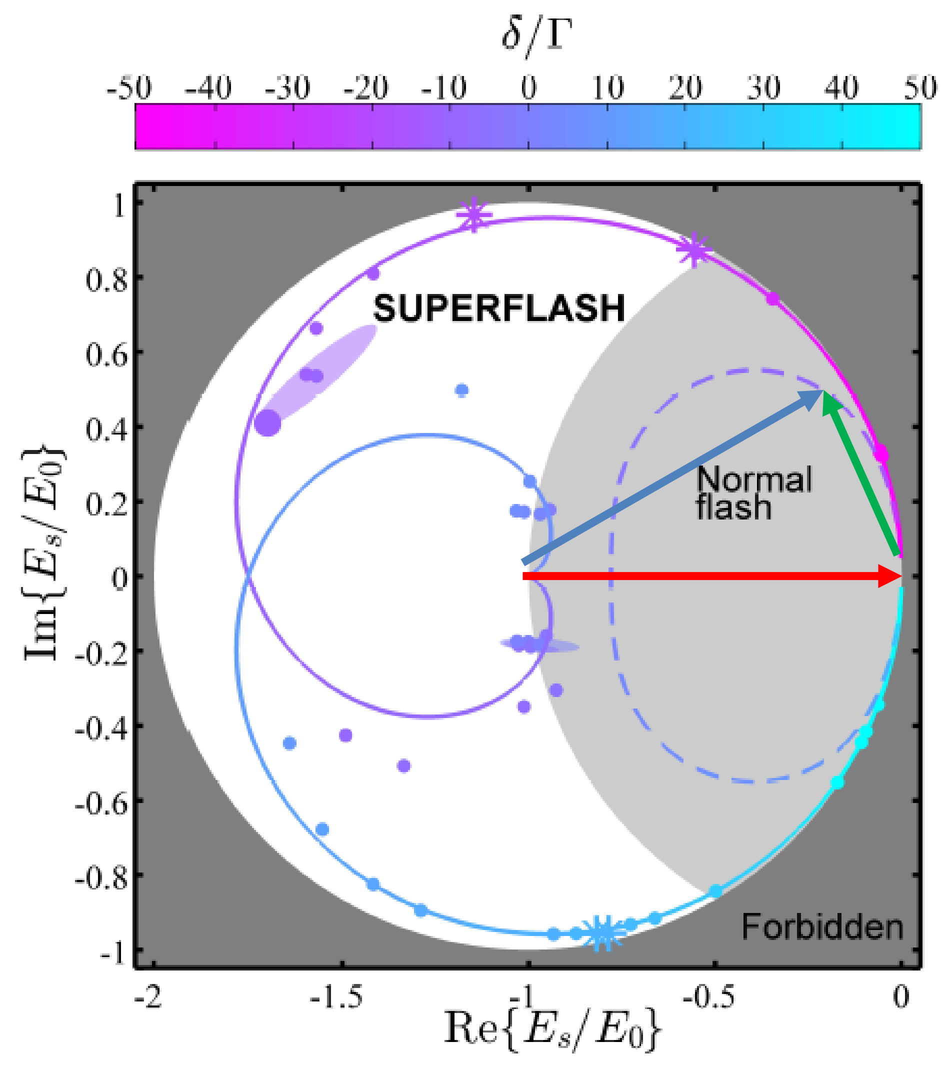
- - - - $b_0 = 3$

— $b_0 = 19$

● Data points (reconstruction method)

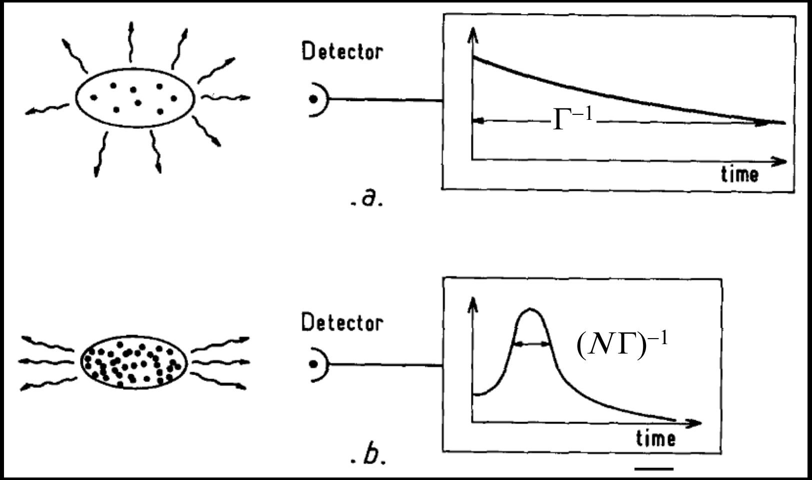
✳ Data points (phase rotation method)





Coherent (super)flash and Dicke superradiance ?

- Dicke has considered an ensemble of excited state atoms. From this initial preparation, a macroscopic polarization is built during spontaneous emission leading to the so-called Dicke superradiance (DS) [RH Dicke. *Phys. Rev.* **93,** 99 (1954)]
- One experimental signature of DS is the short emission of radiators ensemble



From: M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982)

- In the coherent superflash experiment, the macroscopic polarization of the medium comes from the laser excitation. The 2 phenomena (Coherent flash and DS) lead to the same cooperative emission, with the same decay time $(b_0\Gamma)^{-1}$
  [R Friedberg and SR Hartmann, Phys. Rev. *A* **13**, 495 (1976)]

Flash decay time

We calculate the initial decay time of the (super)flash:

$$\tau = \frac{dI(0^+)}{dt}\frac{1}{I(0^+)} = \frac{2}{\Gamma b_0(0)}\frac{1+\exp(-b)-2\exp(-b/2)\cos(\theta_t)}{1-\exp(-b/2)\cos(\theta_t)}$$

[M. Chalony, R. Pierrat, D. Delande, and D. Wilkowski, *Phys. Rev. A*, **84,** 011401 (2011)]

$$\tau\Gamma \underset{\delta\to 0}{=} \frac{2}{b_0(0)} \quad \text{and} \quad \tau\Gamma \underset{\delta\to\infty}{=} \frac{4}{b_0(0)}$$

Same decay than the Dicke superradiance

Where:

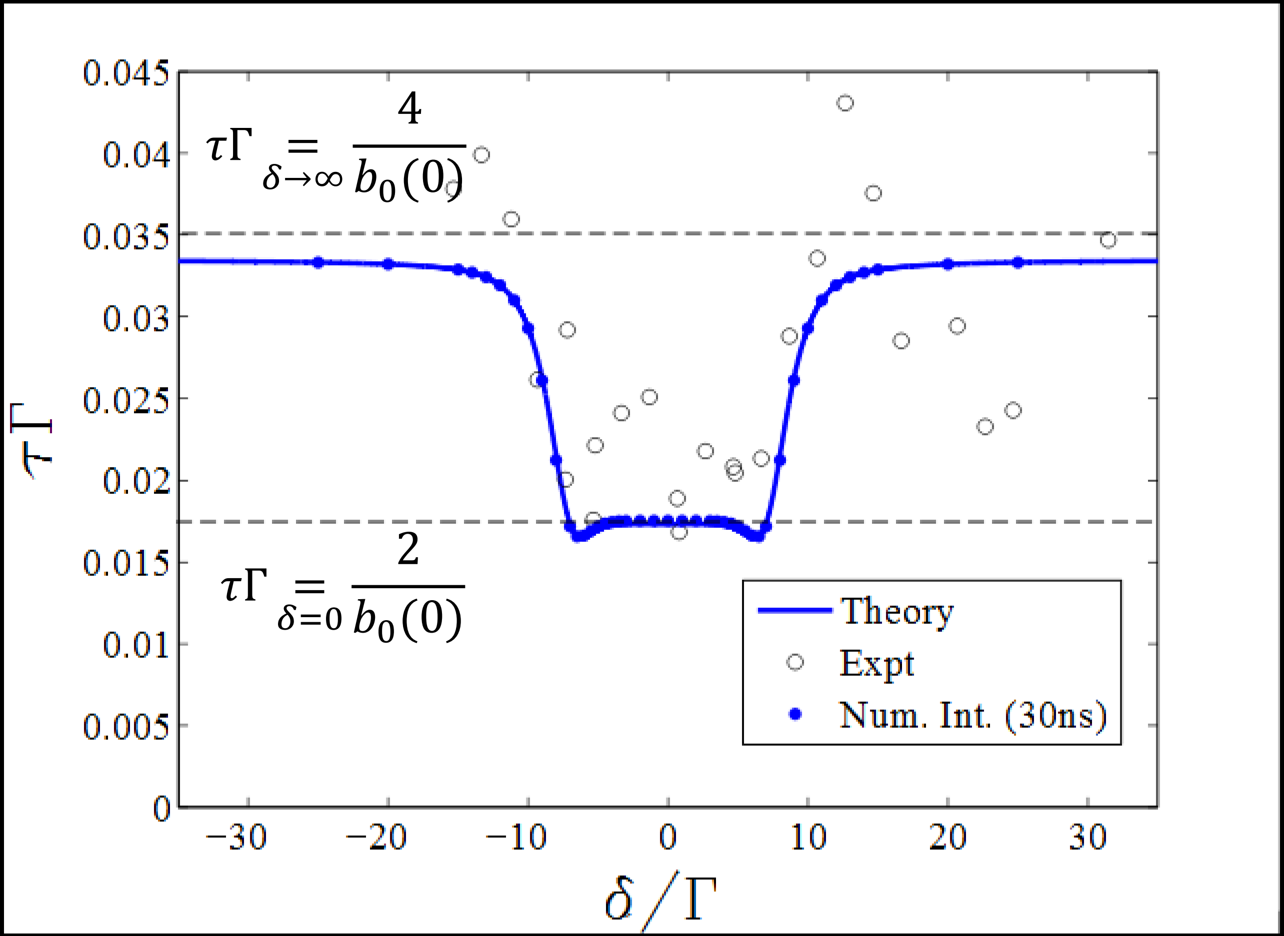
$b_0(0)$ is the optical thickness at resonance and at zero temperature

b is the optical thickness at the laser frequency at the sample temperature

θ_t is the phase of the transmitted field E_t

(Super)flash decay time

$$\tau = \frac{dI(0^+)}{dt}\frac{1}{I(0^+)}$$



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Summary

We measure the forward scattering field E_s of an optically thick medium. It is a cooperative emission in the forward direction.

E_s is measured by switching the incident field off:

$$E_s = E_t(t = 0^+)$$

We find that due to phase rotation of the field at $\delta \gg \Gamma$ and $b_0 \gg 1$, one has $I_s > I_0$, leading to a coherent superflash of light

The value of I_s is bounds to $4I_0$, limited only by the energy conservation law.

The flash decay time seems in agreement with superradiance emission decay time (work in progress).

People

Chang Chi kwong (PhD)

Tao Yang (Post-Doc)

Kanhaiya Pandey (post-doc)

Romain Pierrat
(IL, ESPCI, Paris)

Mukhtar Musawwadah (RA)

Mysore Pramod (RA)

Frederic Leroux (PhD)

Dominique Delande
(LKB, ENS/UPMC, Paris)

For further details see: C.C. Kwong et *a.l.* arXiv:1405.5413

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