Superradiant dynamics in dilute cold atomic clouds

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ABSTRACT:

We study experimentally and numerically the superradiant dynamics of a dilute cold atomic clouds driven by a weak laser beam (linear-optics regime). Linear-optics superradiance has already been observed in our team and our goal now is to show, numerically and experimentally, a non-intuitive feature, which is that the superradiant decay rate can be made larger by smoothing the laser switch-off. In other words, the collective atomic decay rate is a non-monotonous function of the switch-off duration of the driving laser: the maximum decay rate is not obtained for the fastest laser switch-off. This study led us to a better understanding on what is the physical nature of superradiance in the linear-optics regime.

[1] R. H. Dicke, Phys. Rev. **93**, 99 (1954).

[2] M. O. Scully, A. A. Svidzinsky, Science **325**, 1510 (2009).

[3] M. O. Araújo, I. Kresic, R. Kaiser, W. Guerin, Phys. Rev. Lett. **117**, 073002 (2016).

[4] A. D. Kuraptsev, I. M. Sokolov, M. D. Havey, Phys. Rev. A **96**, 023830 (3017).

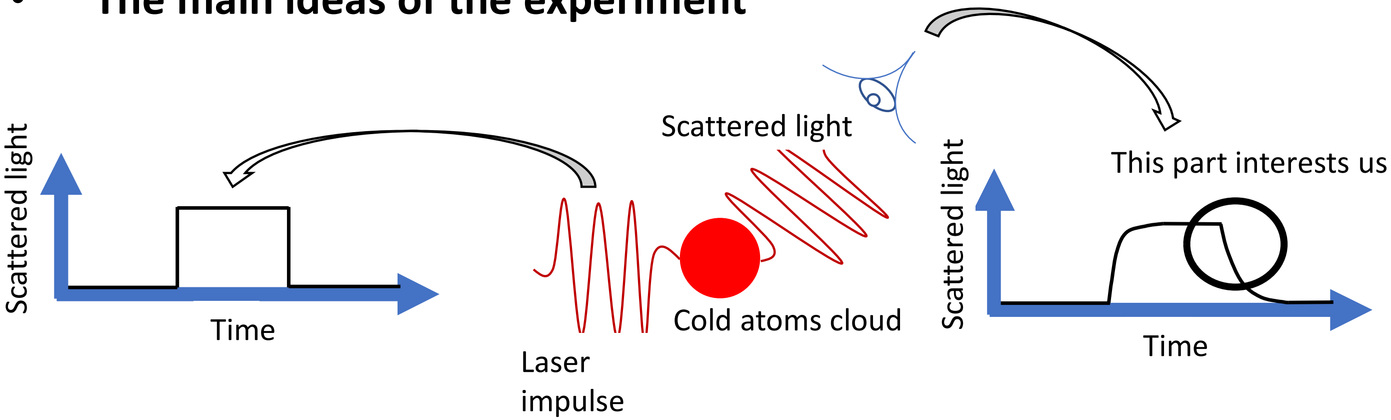
[5] P. Weiss, A. Cipris, R. Kaiser, I. M. Sokolov, W. Guerin, Phys. Rev. A **103**, 023702 (2021).

INPHYNI

SUPERRADIANCE:

Superradiance generally refers to the accelerated radiation rate of a collection of excited atoms due to the collective interaction of the sample with light and the vacuum reservoir [1]. However superradiance is still observable in the linear-optics regime, when there is only one quantum of excitation shared among the atoms [2,3]. How can we understand superradiance in this case?
Recent studies showed that we could describe superradiance with an "optical" model called linear-dispersion theory [4,5]. In this model, based on a single scattering event embedded in an effective medium, we can interpret superradiance as a dispersion effect associated with the scattering and propagation through the sample.

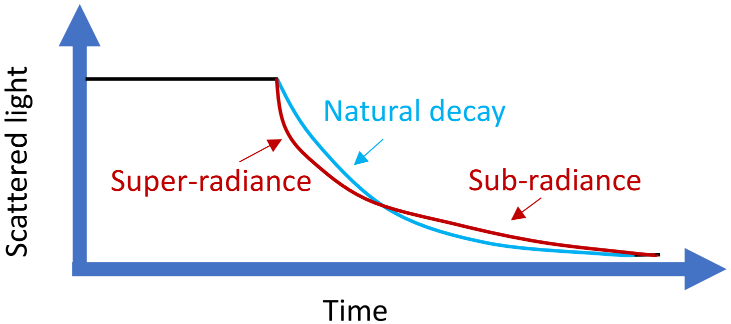
- **The main ideas of the experiment**



Hypothesis

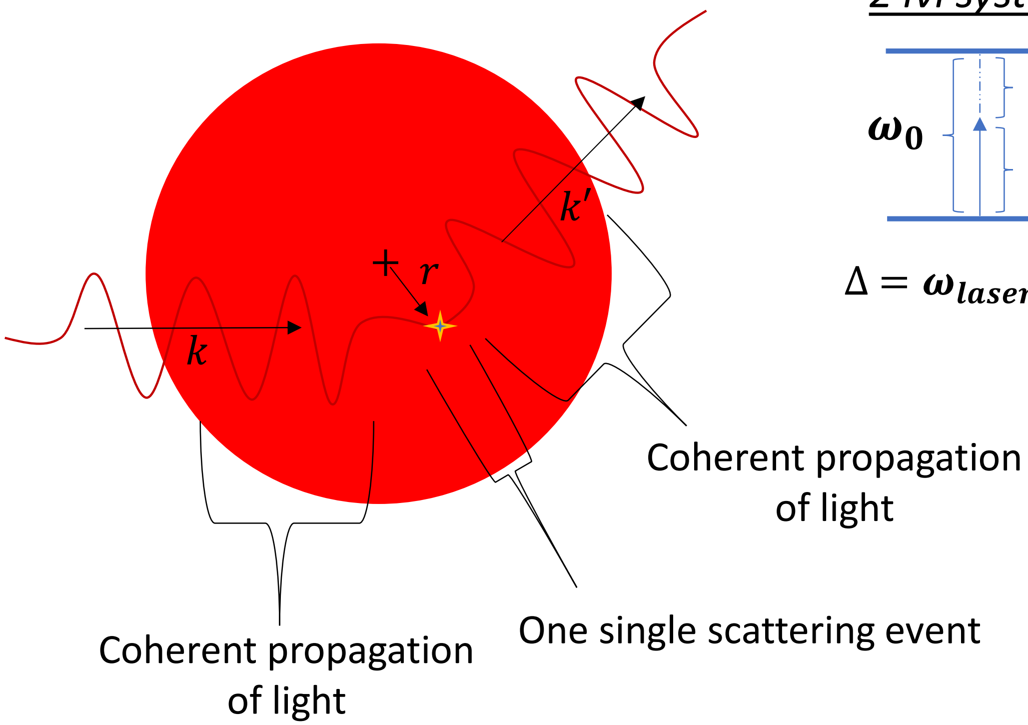
- ***Linear-optics regime***
  → *small laser amplitude*
  → *small saturation parameter*
- ***Observation at 45°***
  → *off axis from the probe laser beam*
- ***Extended and dilute system***
  → *wavelength ≪ interatomic distances & cloud radius*

- **Difference between one and many atoms**

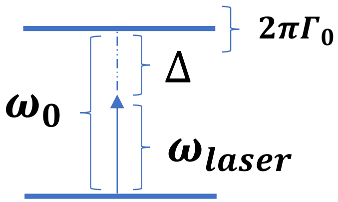


- **Why is it different ?**
- **What is the nature of the effect ?**
- **How to amplified or disamplified super-radiance ?**

Macroscopic description: ***The linear dispersion model***



2 lvl system



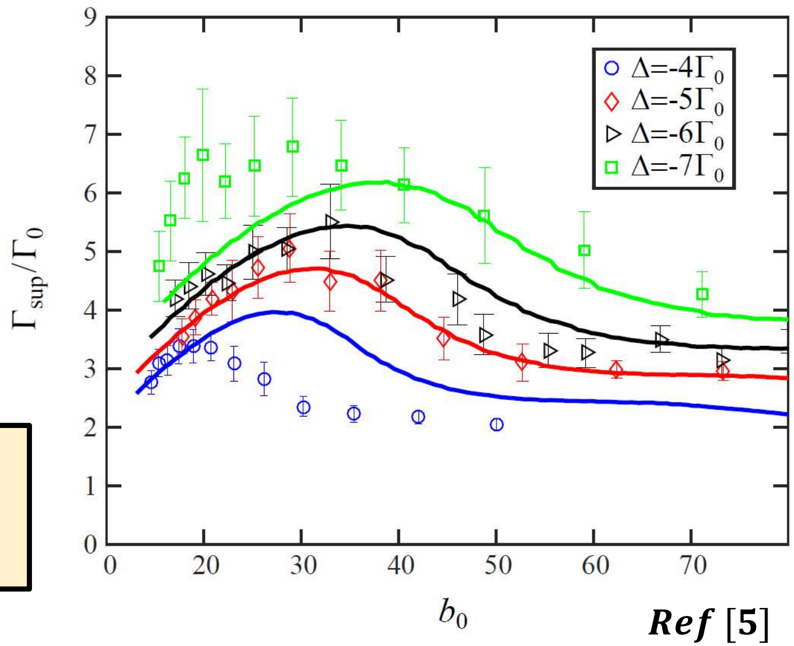
$$\Delta = \omega_{laser} - \omega_0$$

- **Resonant optical thickness b_0**

$$b(\Delta) = \frac{b_0}{1 + 4\Delta^2/{\Gamma_0}^2}$$

- **Polarisability**

$$\alpha(\Delta) = \frac{6\pi}{k_0^3} \times \frac{-2\Delta/\Gamma_0 + i}{1 + 4\Delta^2/\Gamma_0}$$



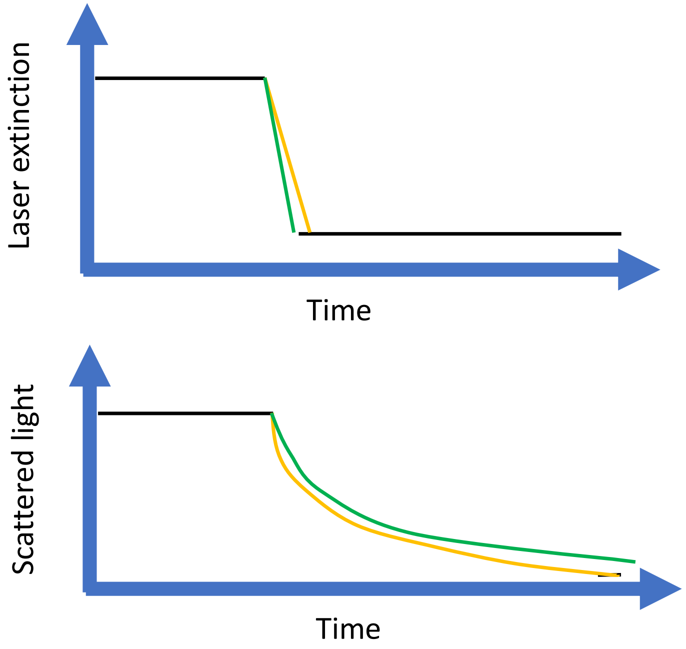
Ref [5]

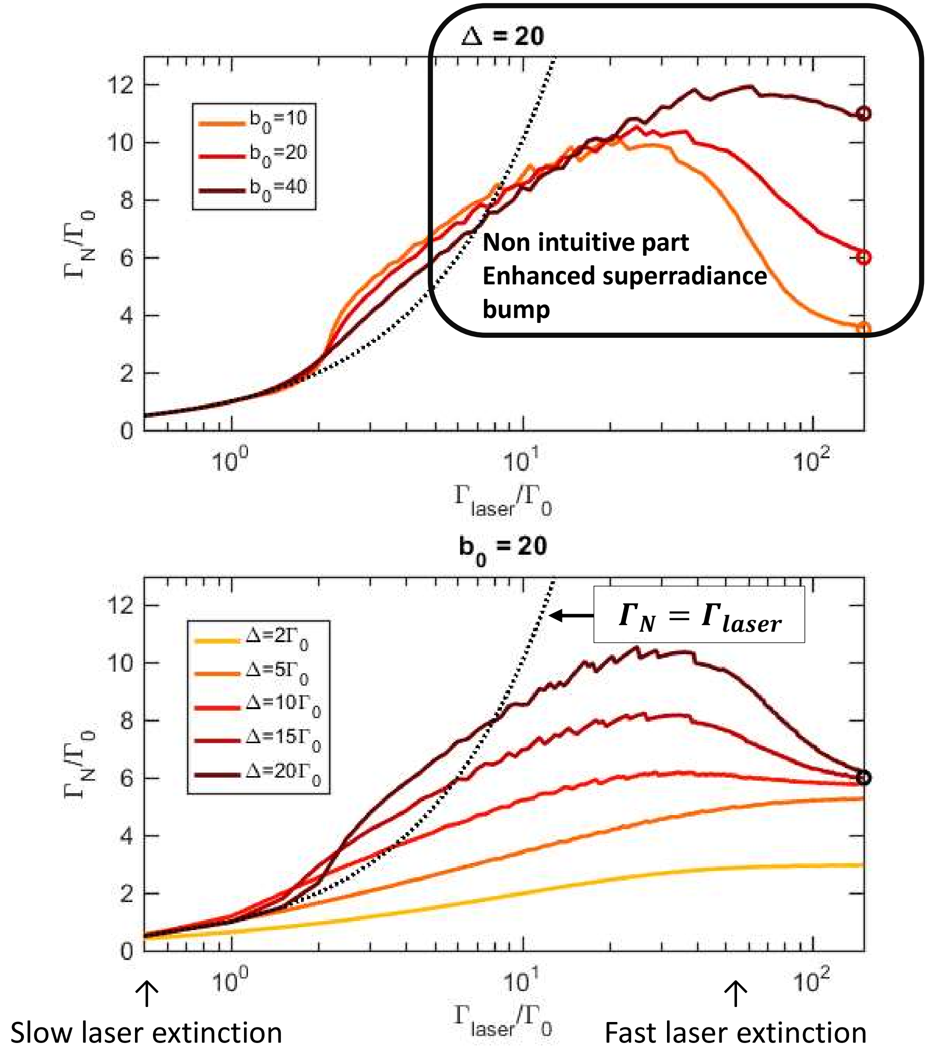
$$I_{k'}(t) \propto \int d^3\rho(r) \left| \int_{-\infty}^{\infty} d\omega E_0(\omega) e^{-i\omega t} e^{i\frac{b_0(r,k')}{2}\alpha(\omega)} \alpha(\omega) e^{i\frac{b_0(r,k)}{2}\alpha(\omega)} \right|^2$$

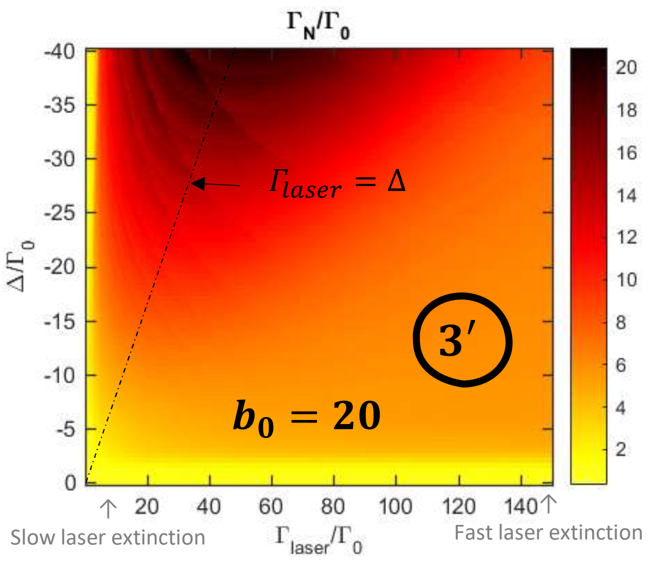
What do we want to do ?

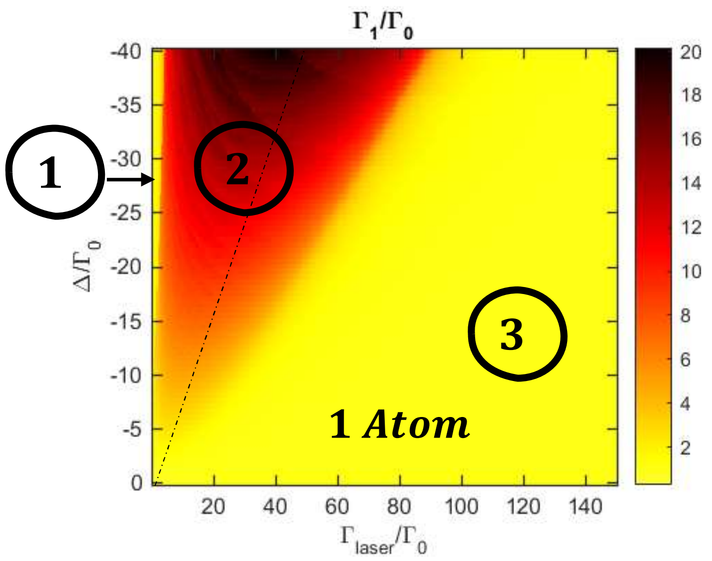
- *Testing the model and show experimentaly a non intuitive prediction of it*

↳ ***Increasing super-radiance by decreasing the sharpness of the laser extinction***









$$I_{k'}(t) \propto \int d^3\rho(r) \left| \int_{-\infty}^{\infty} d\omega E_0(\omega) e^{-i\omega t} \alpha(\omega) \right|^2$$

$$I_{k'}(t) \propto \int d^3\rho(r) \left| \int_{-\infty}^{\infty} d\omega E_0(\omega) e^{-i\omega t} e^{i\frac{b_0(r,k')}{2}\alpha(\omega)} \alpha(\omega) e^{i\frac{b_0(r,k)}{2}\alpha(\omega)} \right|^2$$

$$\alpha = \frac{6\pi}{k^3} \times \frac{-2\Delta/\Gamma_0 + i}{1 + 4\Delta^2/\Gamma_0}$$

$$\Delta = \omega - \omega_0$$

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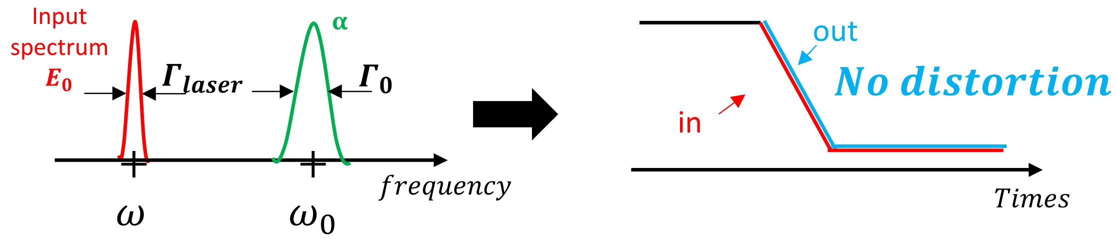
1 $\Gamma_{laser} \to 0$ Slow limit



2 $\Gamma_{laser} \sim \Delta$

Intermediate regime: the output follow the input until the limit $\Gamma_{laser} \sim \Delta$

➡ ***Fast decay***

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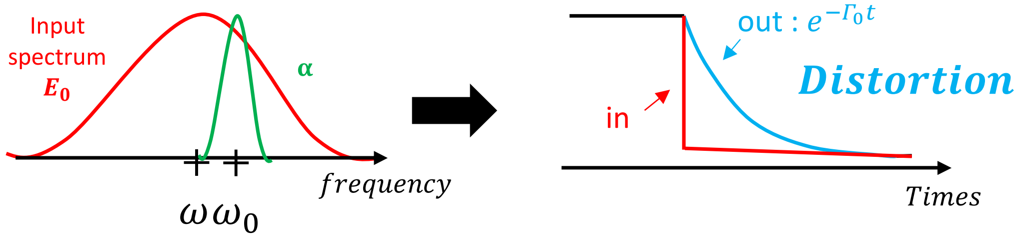
3 $\Gamma_{laser} \gg \Delta$



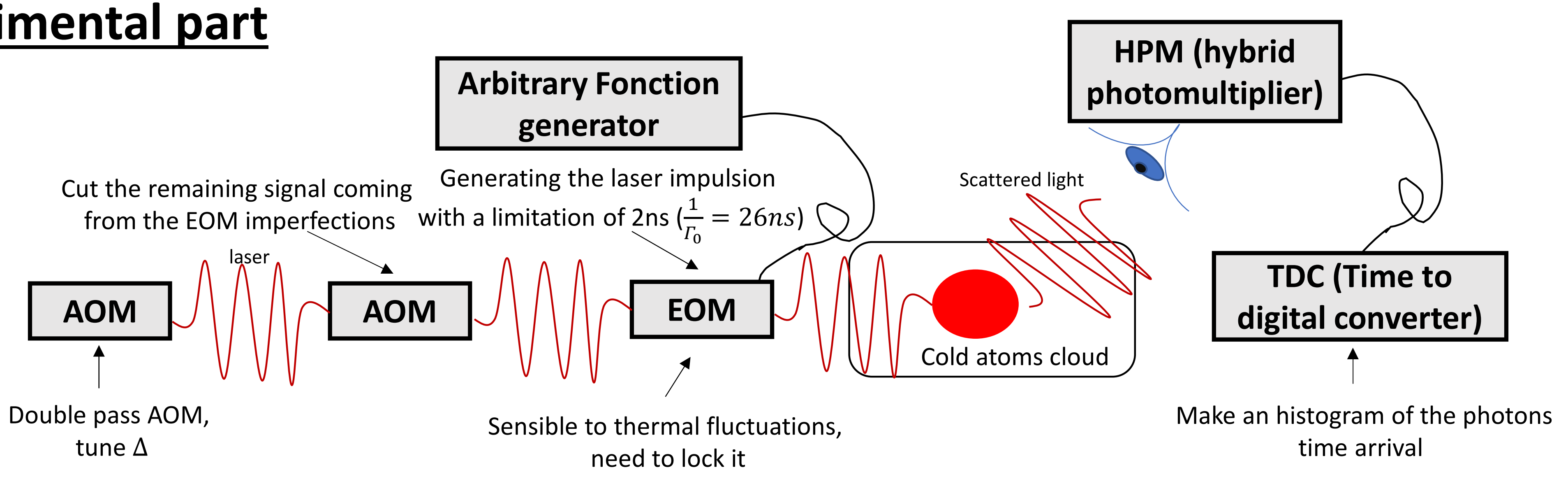
3′ $\Gamma_{laser} \gg \Delta$

The many atoms are filtering the resonant light ⇒ It attenuates the distortion effect coming from α

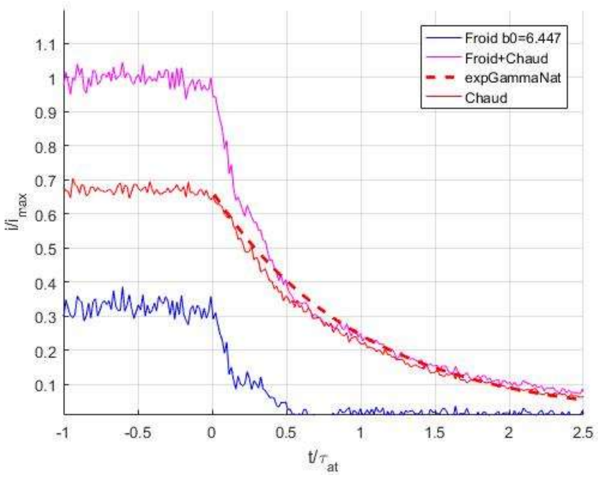
➡ The output will follow more or less the input again (at early time)

⇒ ***Small distortion / Superradiance***

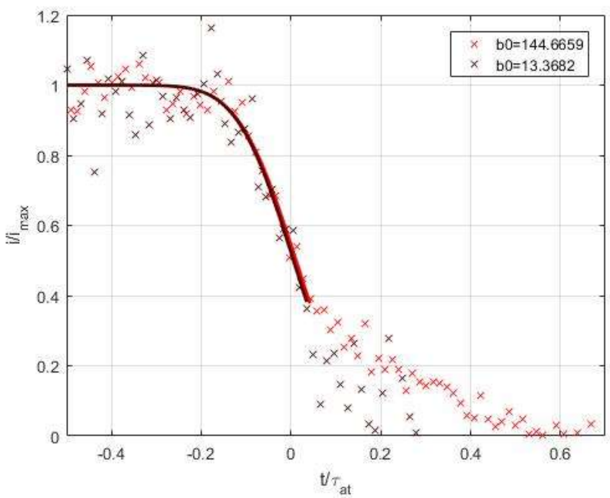
Experimental part



Subtraction of the hot vapor signal



Fitted cold signal



Provisional result

(More data are currently being acquired)