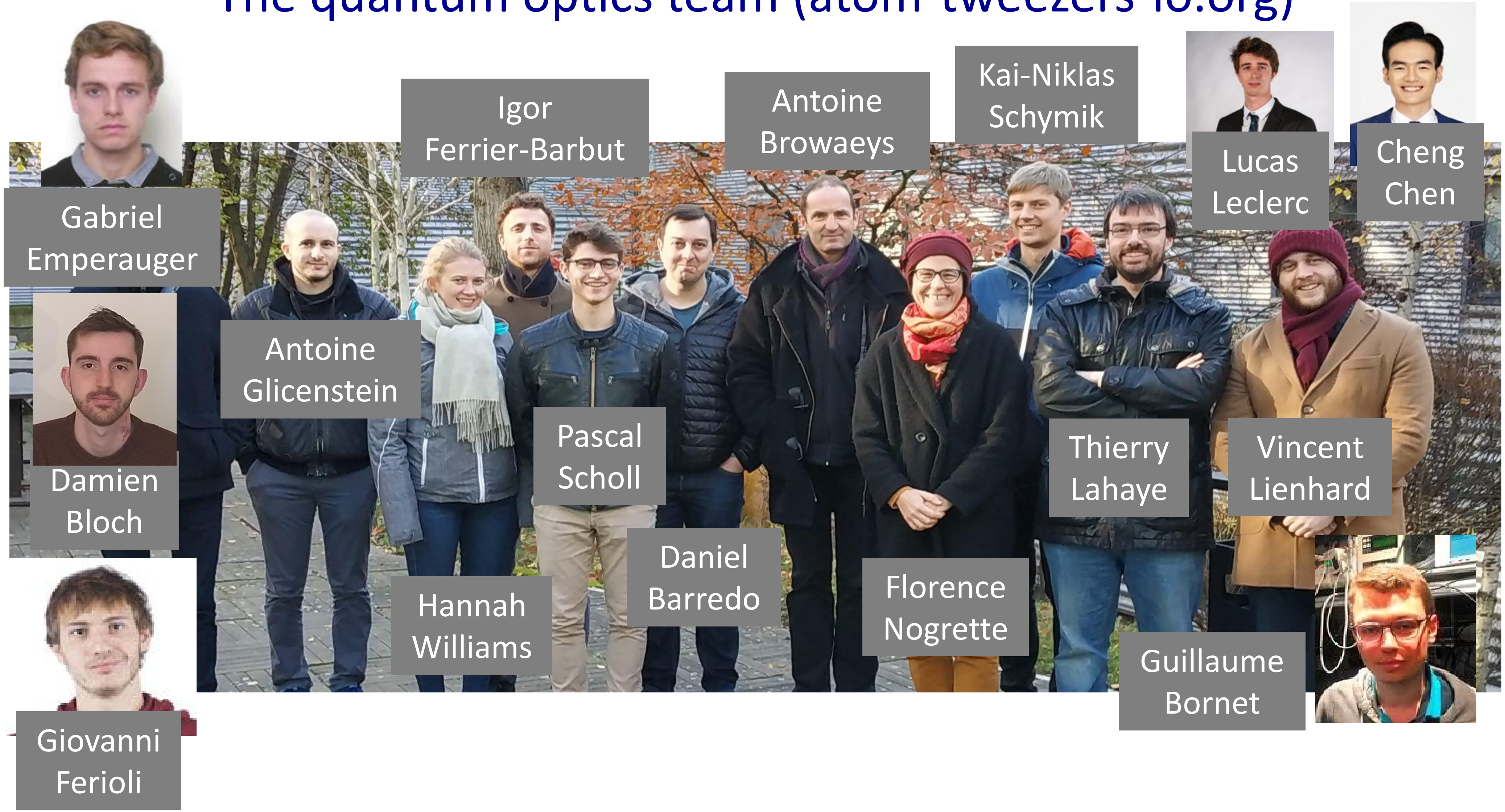
Observation of a superradiant phase transition in free space

Ferioli Giovanni

23-06-22, SPICE workshop
Ingelheim

The quantum optics team (atom-tweezers-io.org)



Collaborators F. Robicheaux & Tyler Sutherland

DGA SIRTEQ îledeFrance erc European Research Council Established by the European Commission PASQuanS

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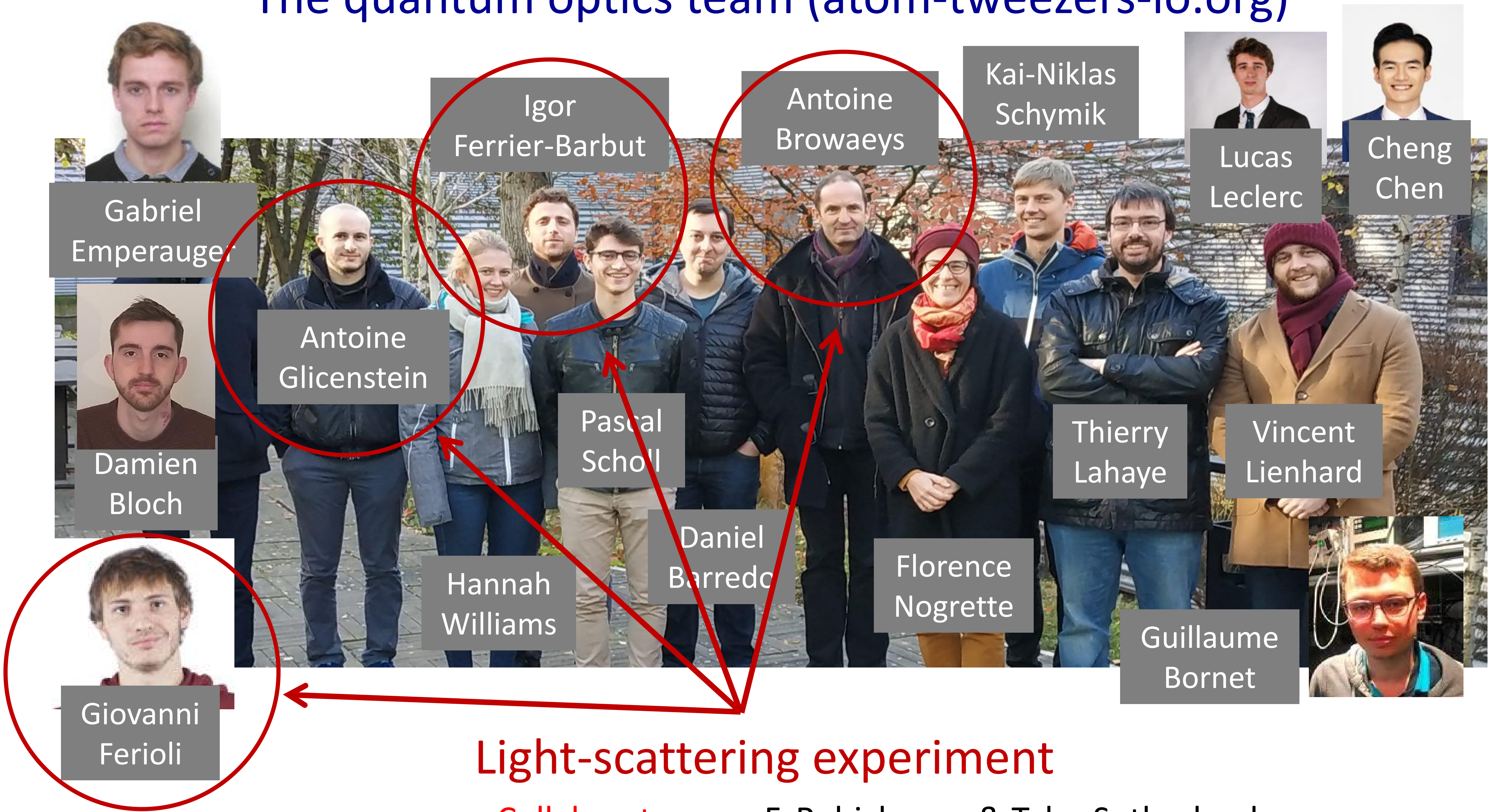

Light-scattering experiment

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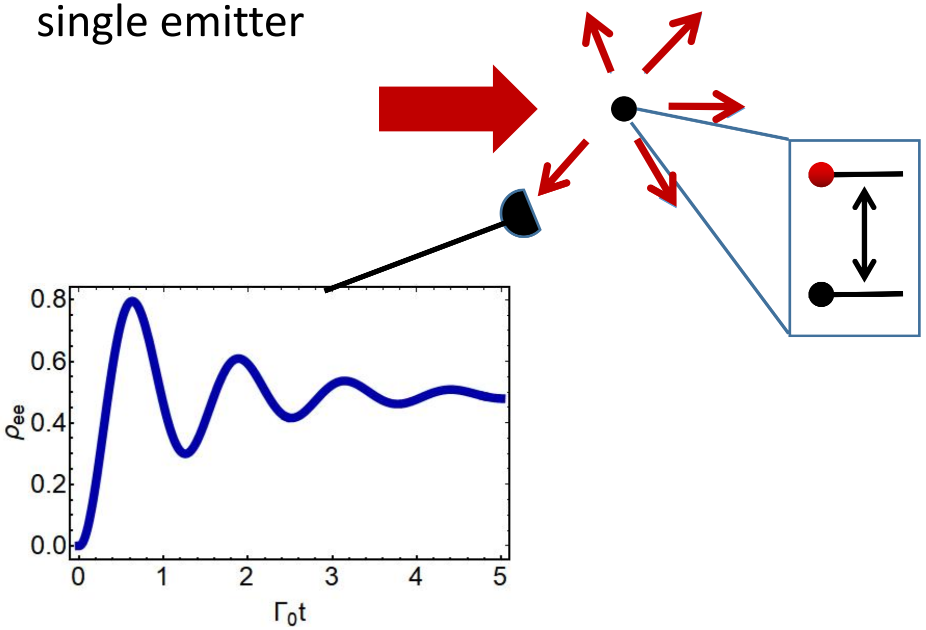
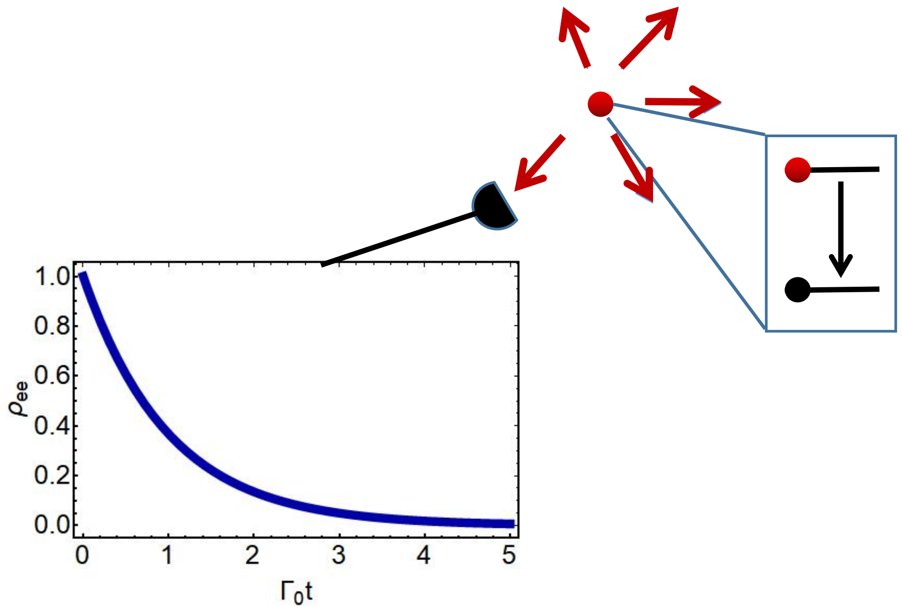
light + atoms: a many-body system

single emitter





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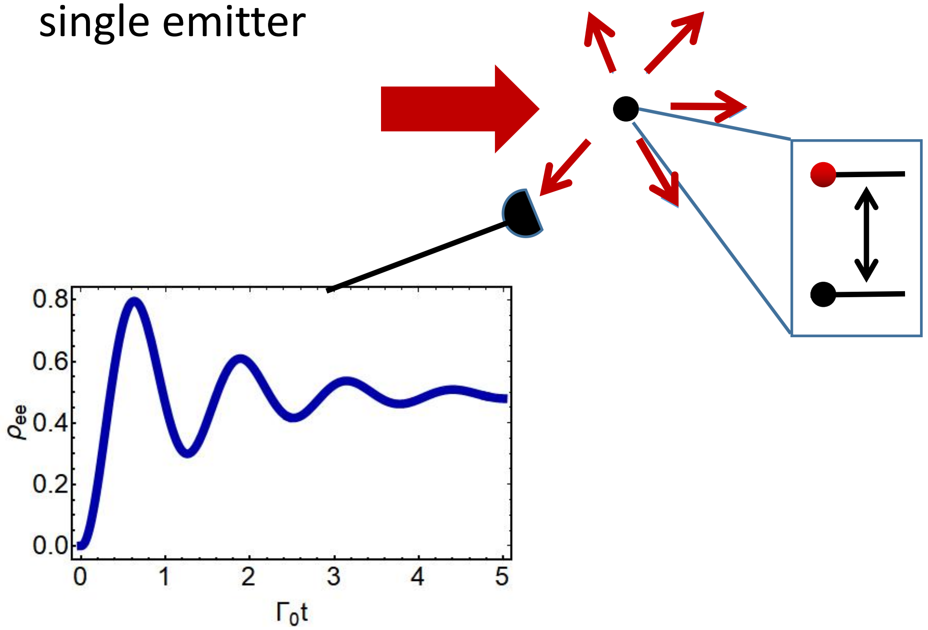
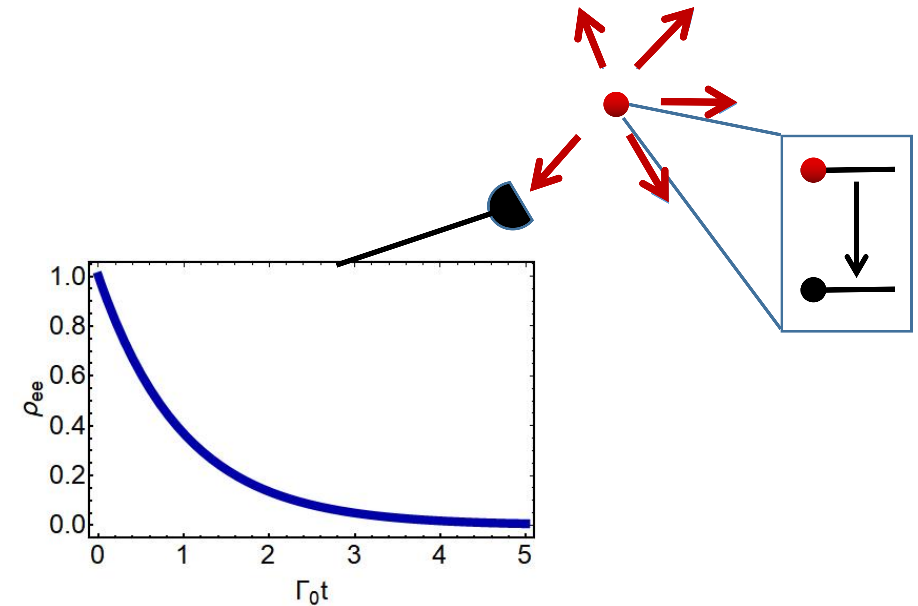




many emitters: much more complex system!!

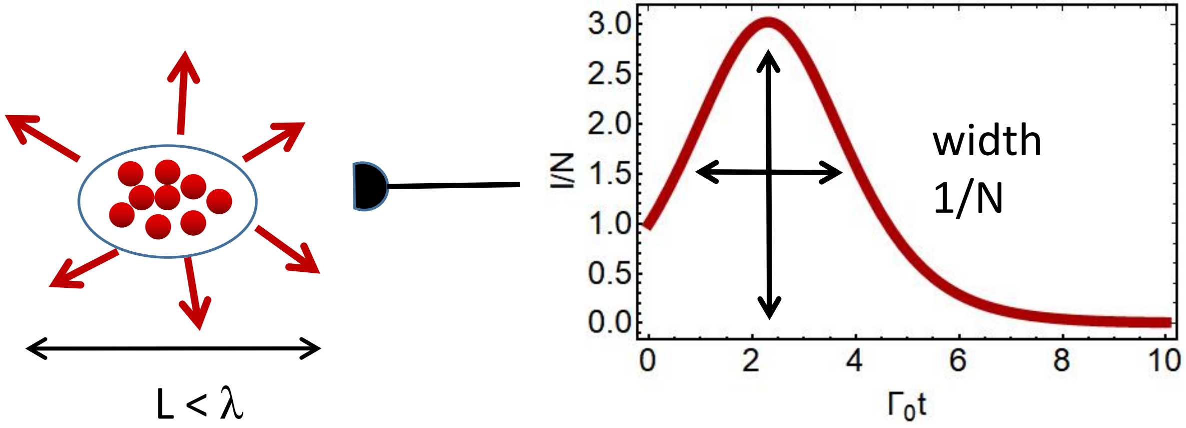
first example by Dicke in 1954:

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

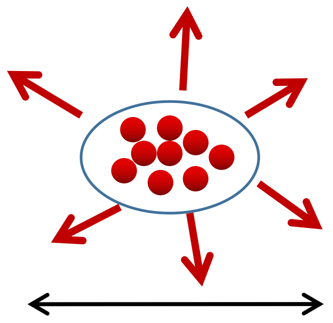
R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received August 25, 1953)

peak scales as N



Dicke's superradiance

What is the main idea? use the proper basis: symmetric states!!

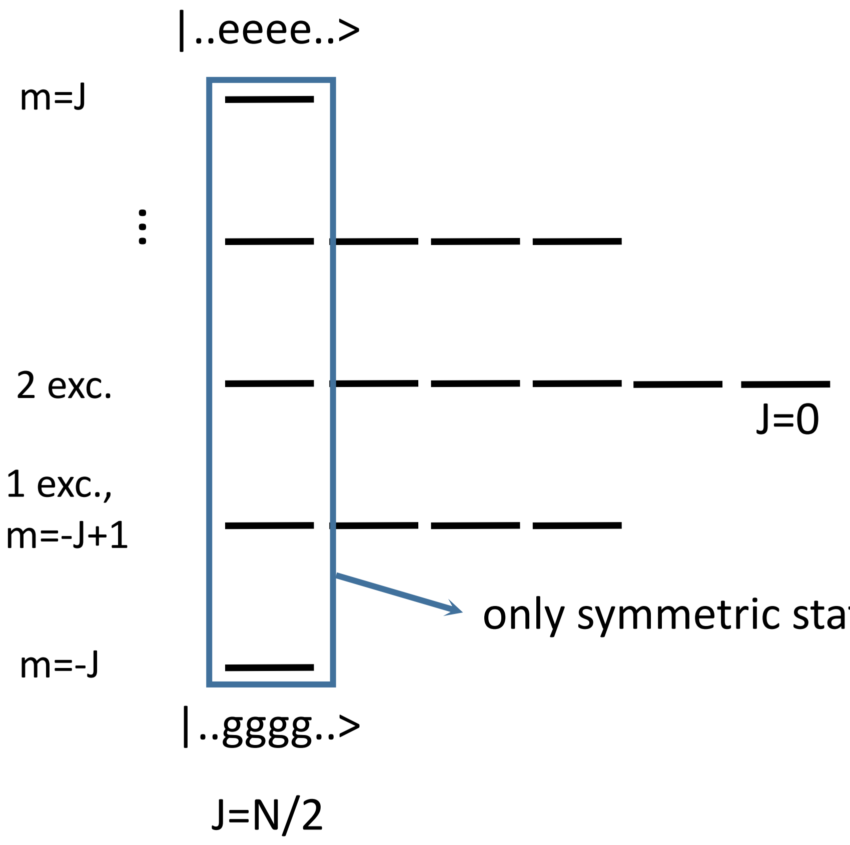


Collective dipole operator

$$H = -\sum_{i}^{Nat} d_i E(r_i) = -E \sum_{i}^{Nat} d_i = -ED$$

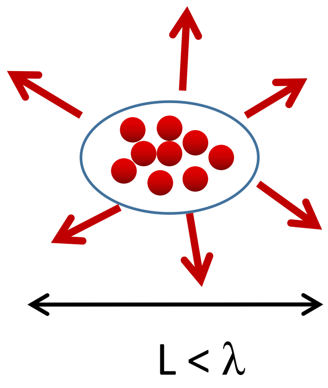
Even classicaly the hamiltonian is symmetric w.r.t. particle exchange

Dicke's superradiance



only symmetric states, equivalent to spin system lJ,m> , J=N/2 and m=-J,...,J

What is the main idea? use the proper basis: symmetric states!!



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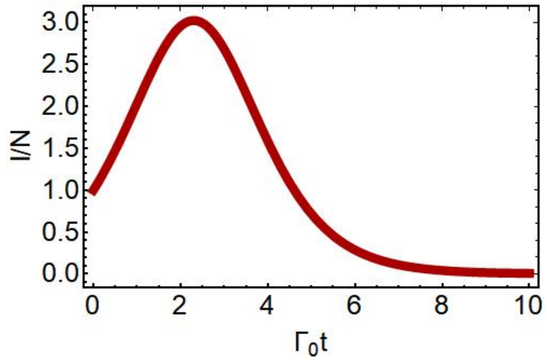
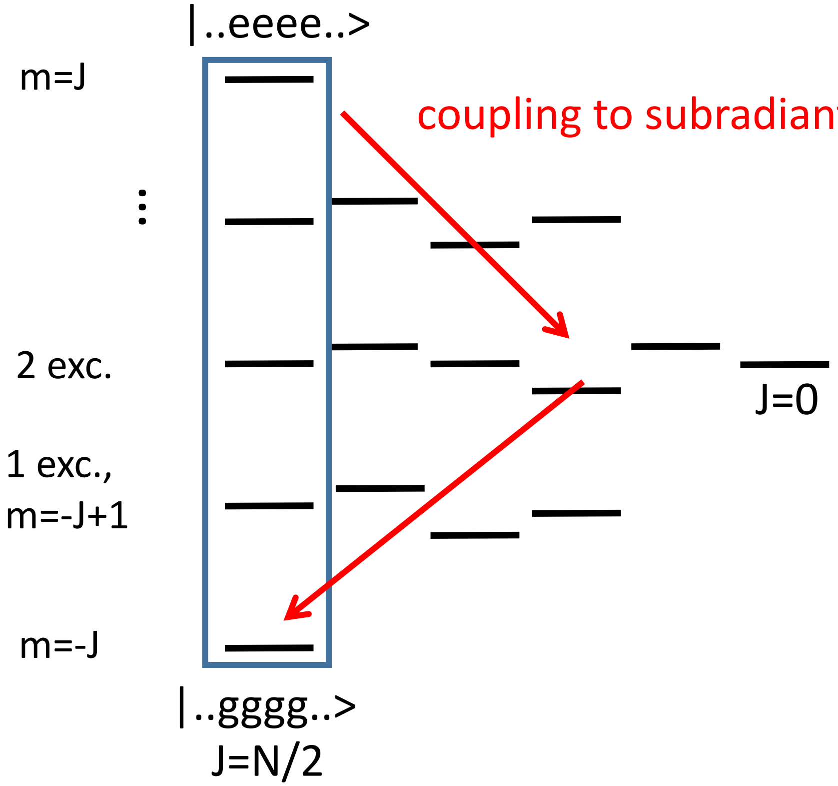
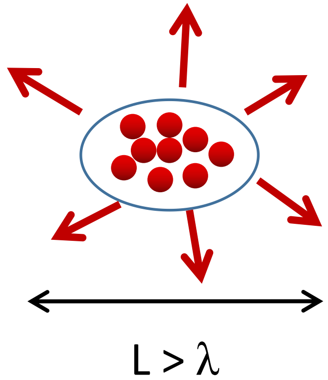


I $\sim N^2$

Dicke's superradiance, Is it the full story??



1-



Finite size effects

2- $$V_{dd} = \sum_{i,j}^{N} \Omega_{i,j}\sigma_i^{+}\sigma_j^{-}$$

(light induced) dipole-dipole interaction

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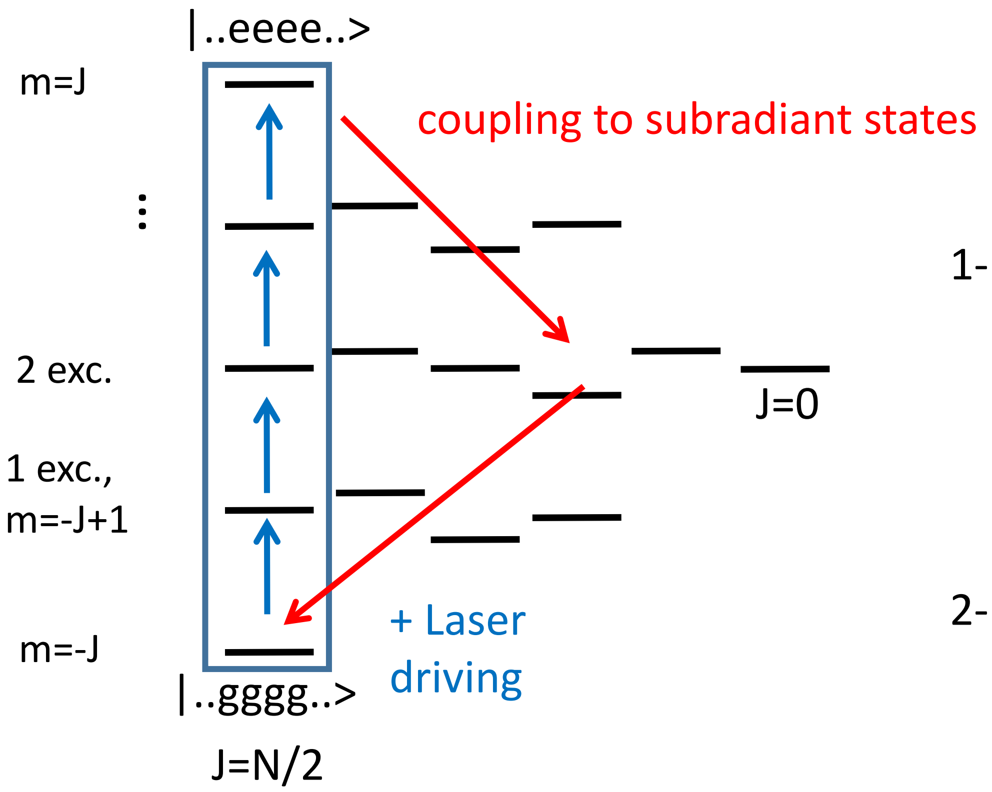
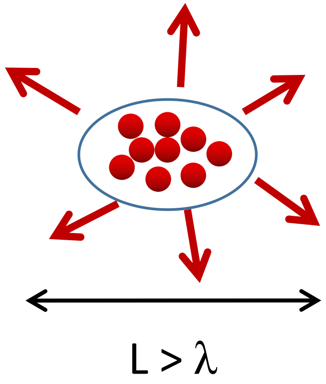


1- 

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3- **What is the effect of an external driving??**

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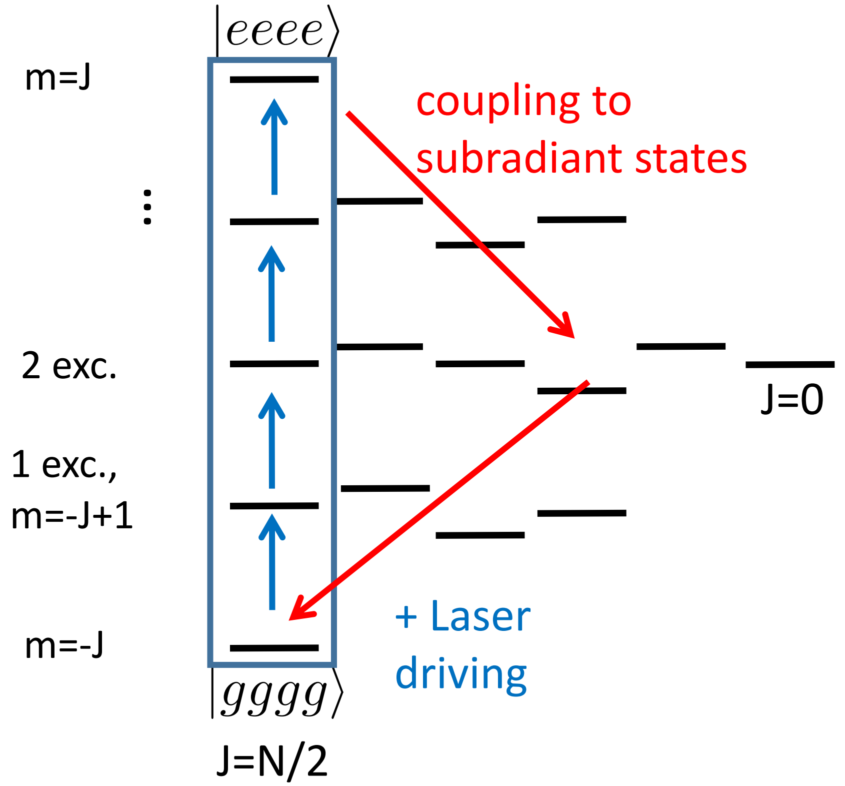
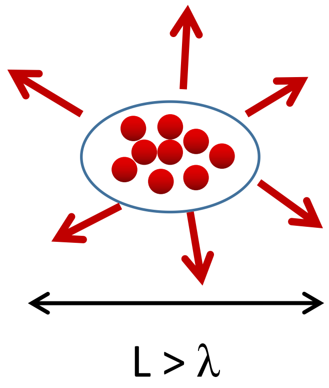


Ferioli, et Al., PRX 2021
Ferioli, et Al. PRL 2021
Glicenstein, et Al., Optics Letter 2022

1-



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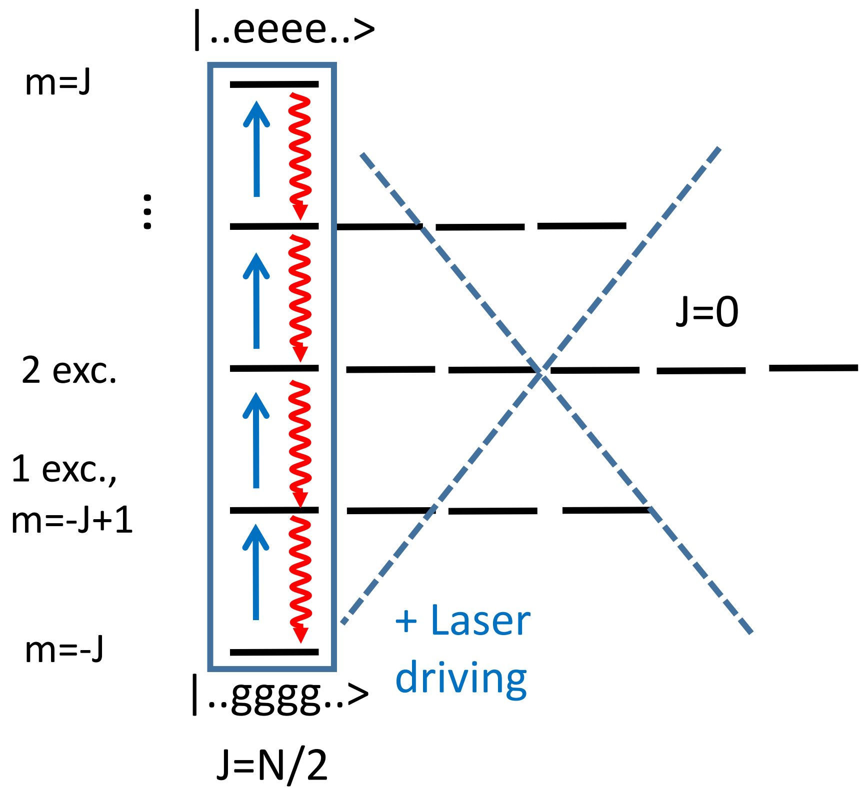
This talk

3- **What is the effect of an external driving??**

Ferioli et al. , in preparation

Driven Dicke model:

D. Walls J. Phys. B 1980



~~1- Finite size effects~~

~~2- (light induced) dipole-dipole interaction~~

3- **What is the effect of an external driving??**

$$H = \Omega_D(S^+ + S^-)$$

Narducci PRA 1978
Walls, Agarwal…
Carmichael

$$\frac{d\rho}{dt} = -i\Omega_D[S^+ + S^-, \rho] + \frac{\Gamma}{2}(2S^-\rho S^+ - S^+S^-\rho - \rho S^+S^-)$$

1. Solve dynamics and steady-state up to 50 atoms

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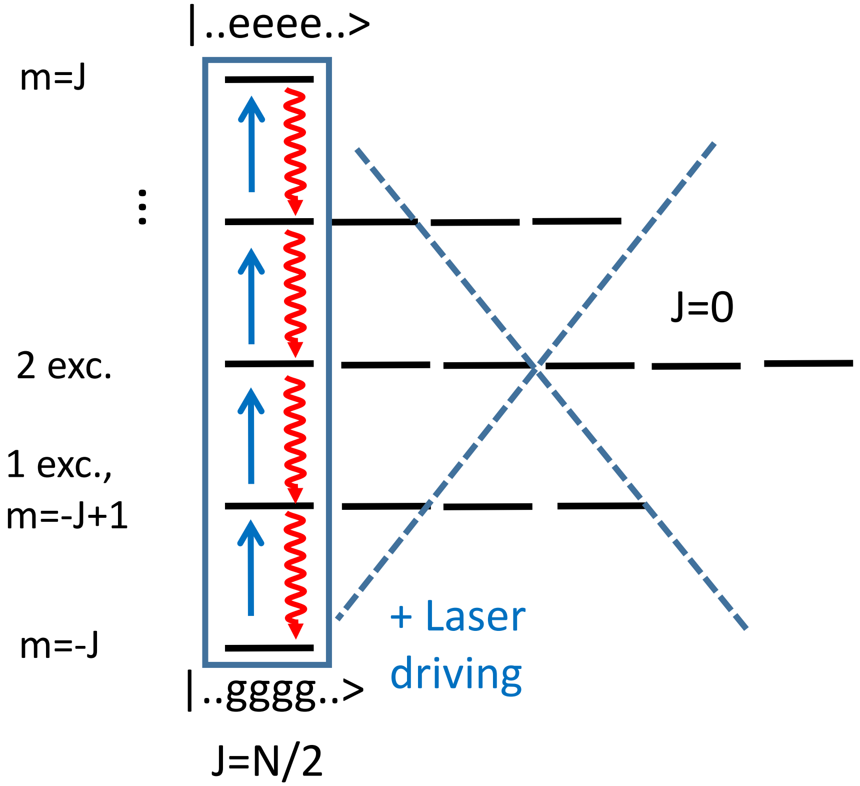

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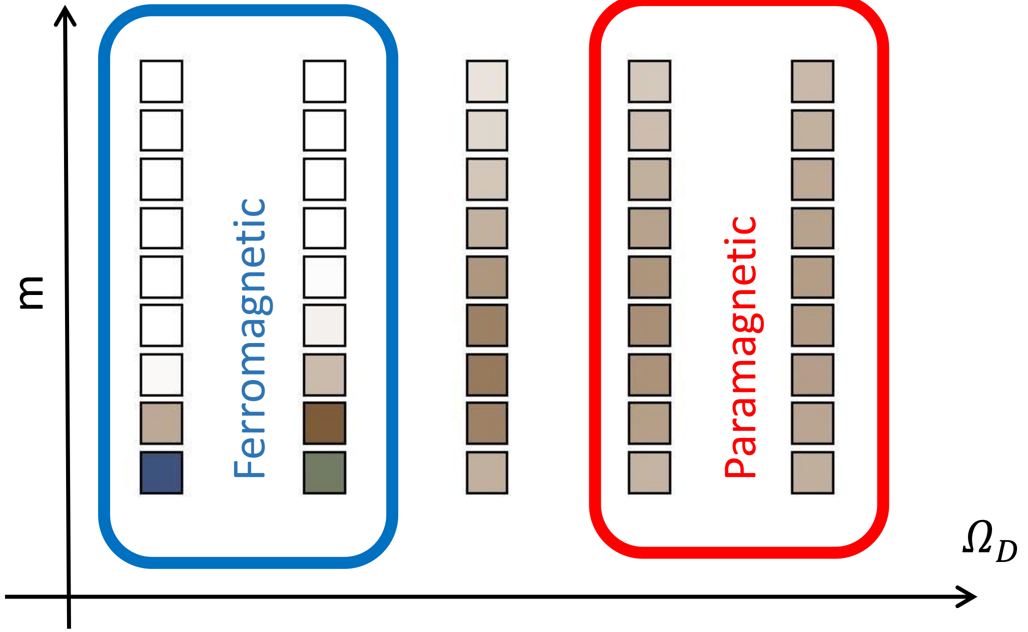
N=8



1. Solve dynamics and steady-state up to 50 atoms

2. **Existance of two (non-equilibrium) phases**

Experimental platform - close to Dicke's regime

More details in:
Glicenstein, PRA 2021, PRL 2020

1- N = 2000 atoms, T = 200 μK

2- Dense cloud: n ~ 10^{14} at/cm^3

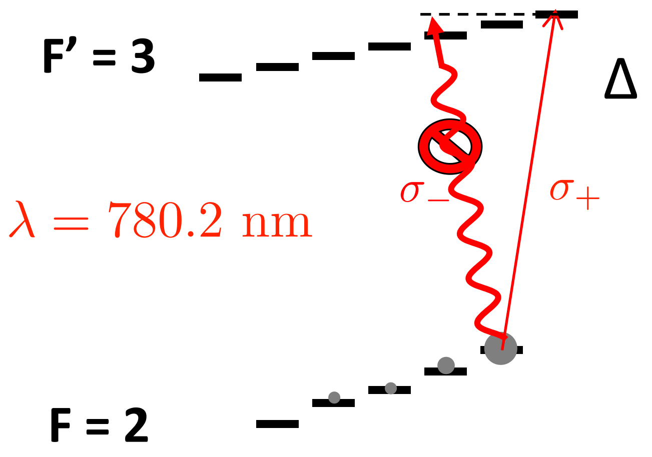
3- Volume ~λ^3, Close to Dicke limit

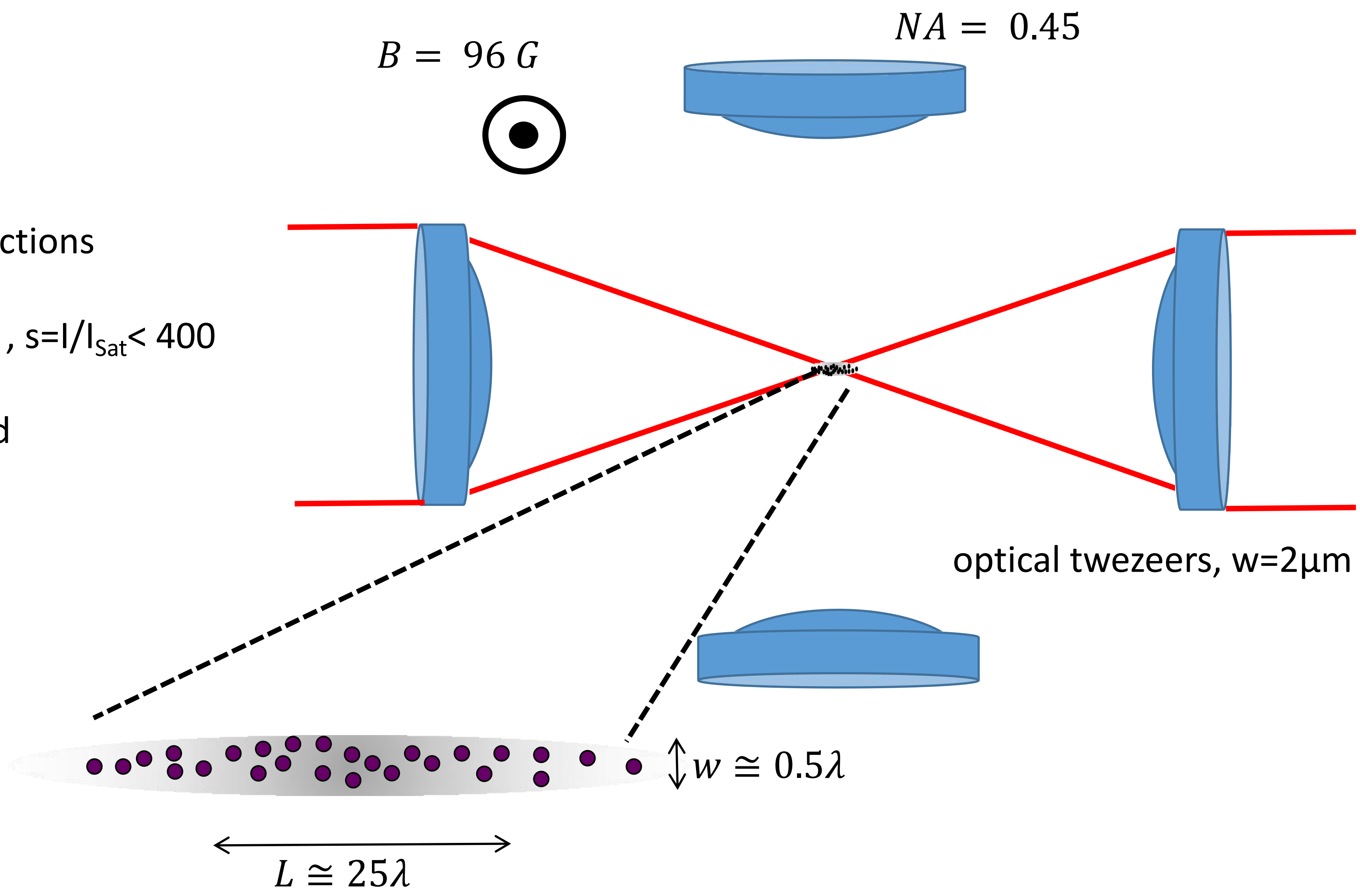
4- Repetition rate > 2Hz

5-Detecting (and manipulating) in two directions

6- Driving: resonant light linearly polarized , $s=I/I_{Sat}< 400$

7- clean 2 level system, large magnetic field





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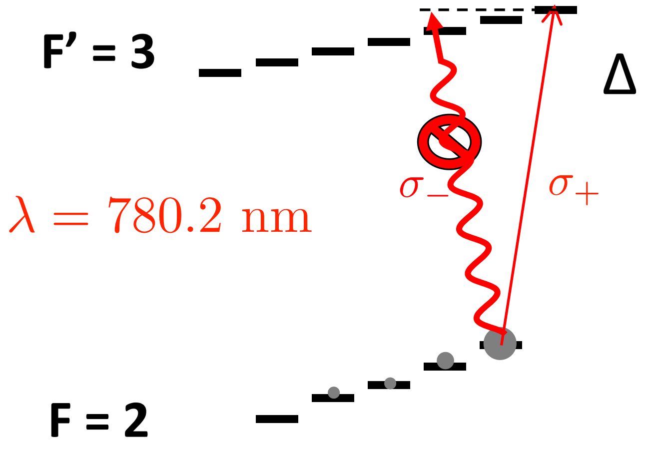

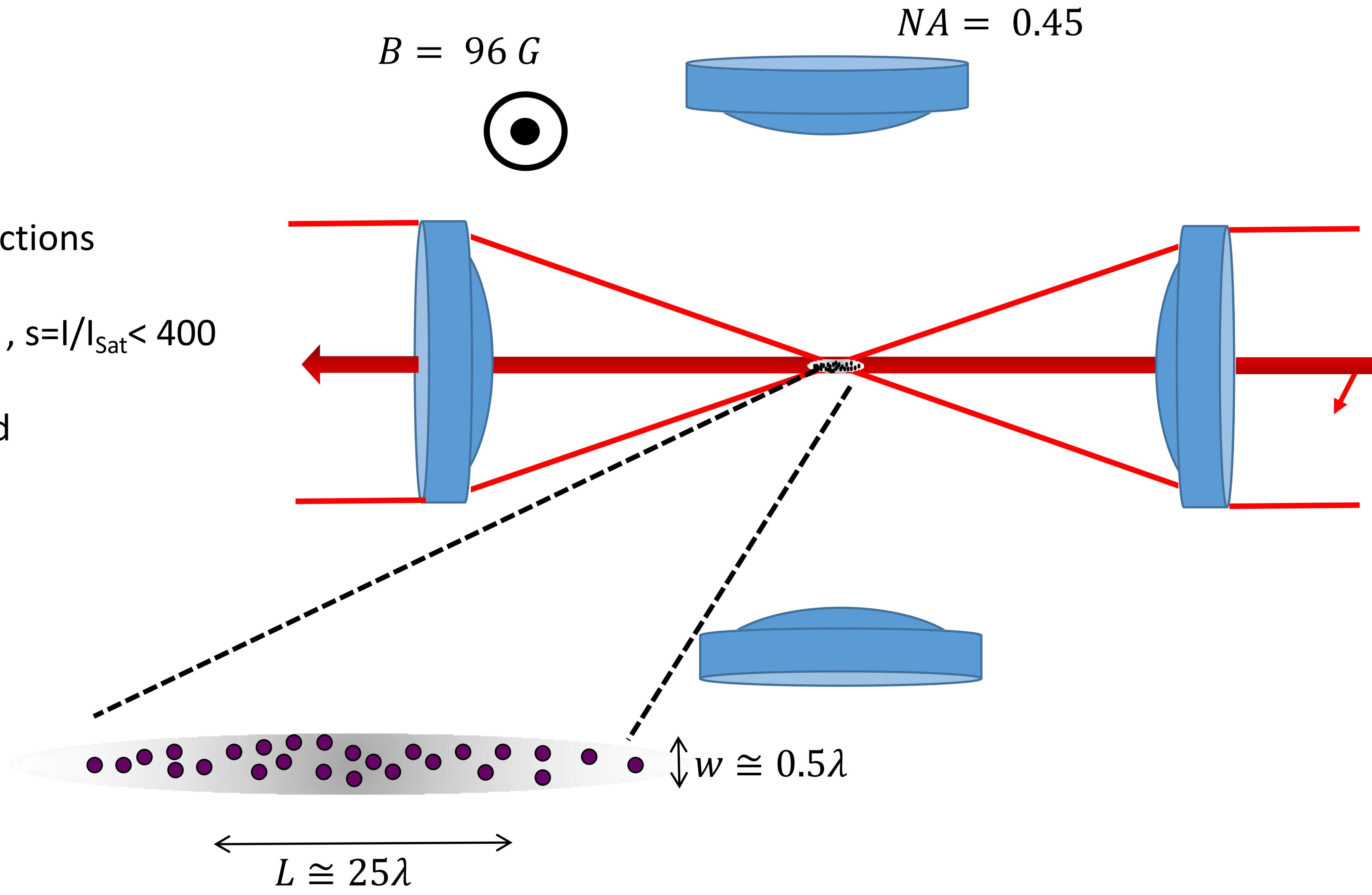

Experimental platform - close to Dicke's regime

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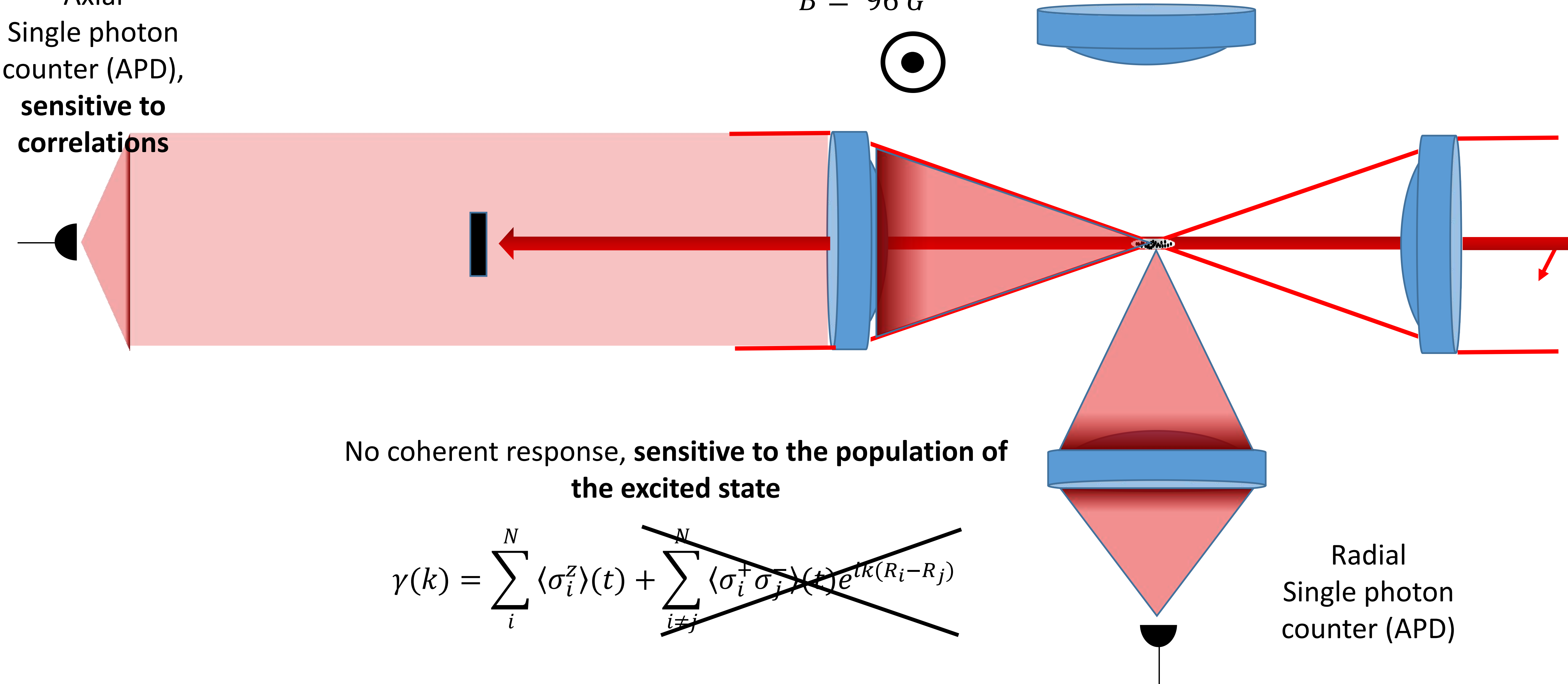
$$\gamma(k) = \sum_{i}^{N} \langle \sigma_i^z \rangle(t) + \sum_{i \neq j}^{N} \langle \sigma_i^+ \sigma_j^- \rangle(t) e^{ik(R_i - R_j)}$$

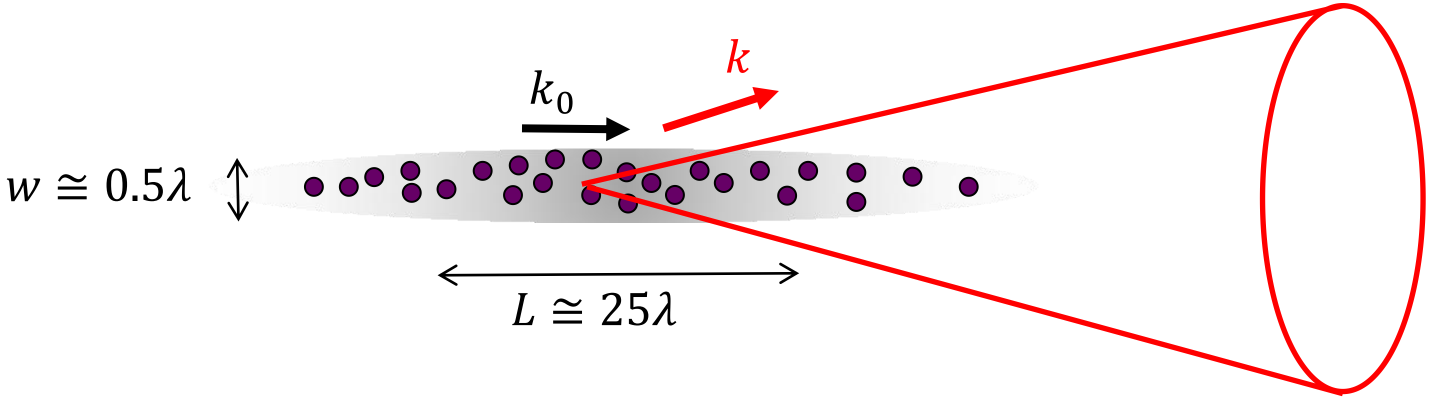


No coherent response, **sensitive to the population of the excited state**

$$\gamma(k) = \sum_{i}^{N} \langle \sigma_i^z \rangle(t) + \cancel{\sum_{i \neq j}^{N} \langle \sigma_i^+ \sigma_j^- \rangle(t) e^{ik(R_i - R_j)}}$$

Experimental platform - close to Dicke's regime

θ_D = diffraction angle $\frac{\lambda}{w}$



$$E_{Sc}(k) = \sum_{m}^{N} E_0 e^{i(k-k_0)R_m}$$

Power radiated in the diffraction mode

$$P_N = \vartheta_D N {E_0}^2 + {E_0}^2 \int dk \sum_{m \neq n}^{N} e^{i(k-k_0)(R_m - R_n)}$$

$$= \vartheta_D N {E_0}^2 + {E_0}^2 N^2 \int dk \frac{1}{N^2} \sum_{m \neq n}^{N} e^{i(k-k_0)(R_m - R_n)}$$

Structure factor

Effective number of atoms emitting in the diffraction mode:

$$\tilde{N} = \frac{P_N}{N {E_0}^2} \cong N\mu$$

μ is the (integral of the) structure factor, in our case is about **0.004(2)**

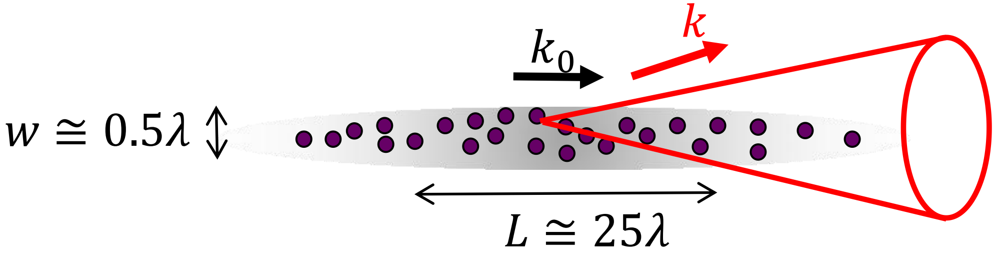
Power radiated by N independent atoms

Allen and Eberly, 1987
Gross and Haroche, 1982
NE Rehler, JH Eberly PRA 1971

As a cQED system..... but in free space

$$\widetilde{N} = \frac{P_N}{\vartheta_D N {E_0}^2} \cong N\mu$$

effective atom number depends on the cloud geometry



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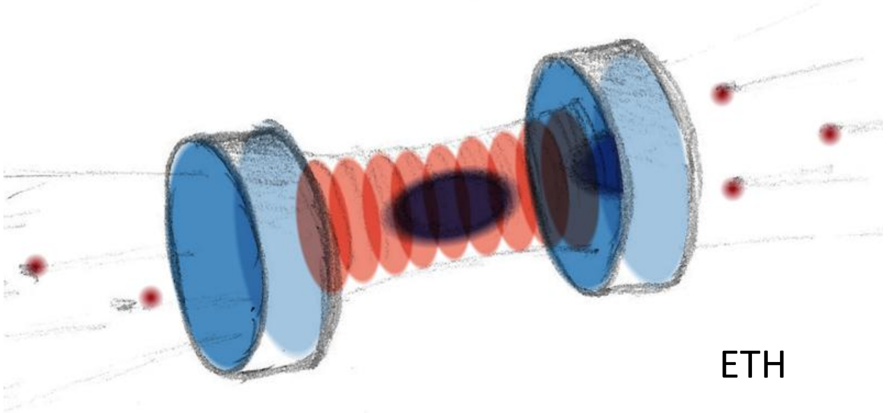
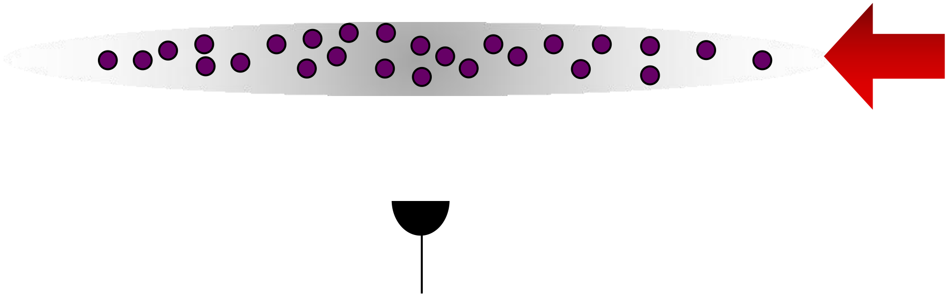


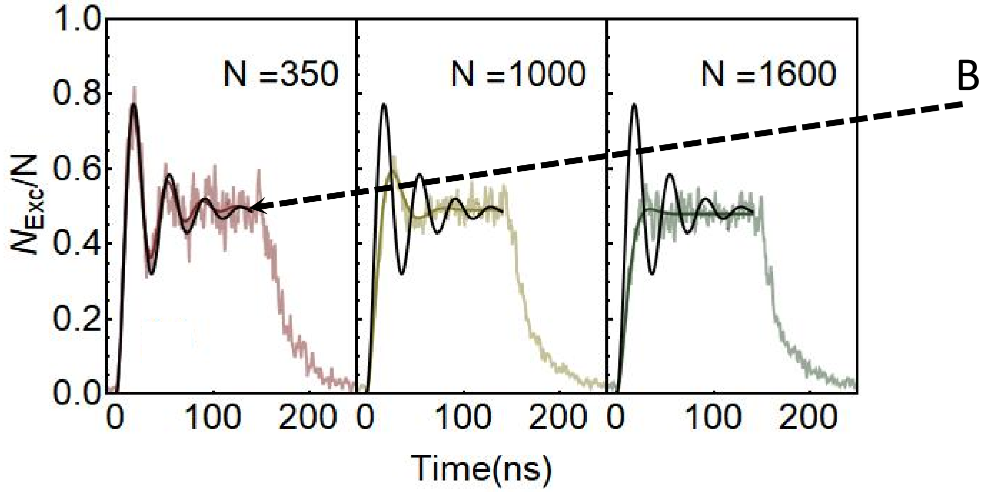
Take-home message: a cQED system.... but in free space!!

our cloud is a system of $\widetilde{N}$ atoms coupled to a single radiation mode, as in a cavity (but without it)

Dynamics of the excited state population

Preliminary results



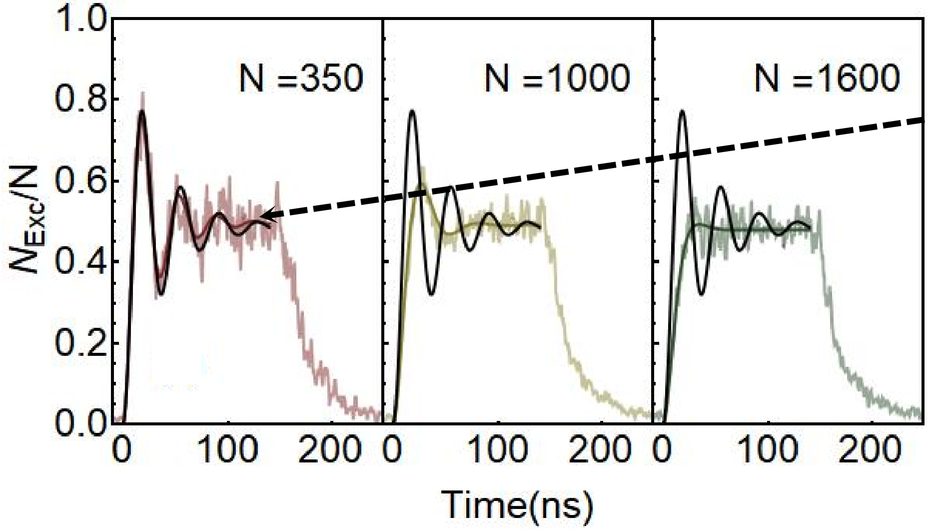


Black: Optical Bloch Equation,
single atom response

(a) fixed driving strength
s = 35

Dynamics of the excited state population

Preliminary results



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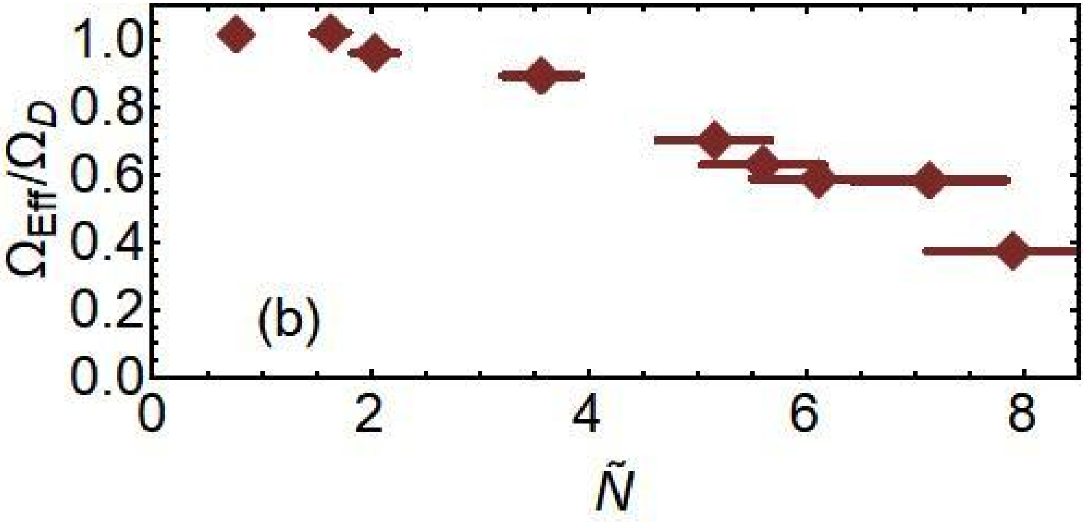
Reduction of Rabi frequency increasing N



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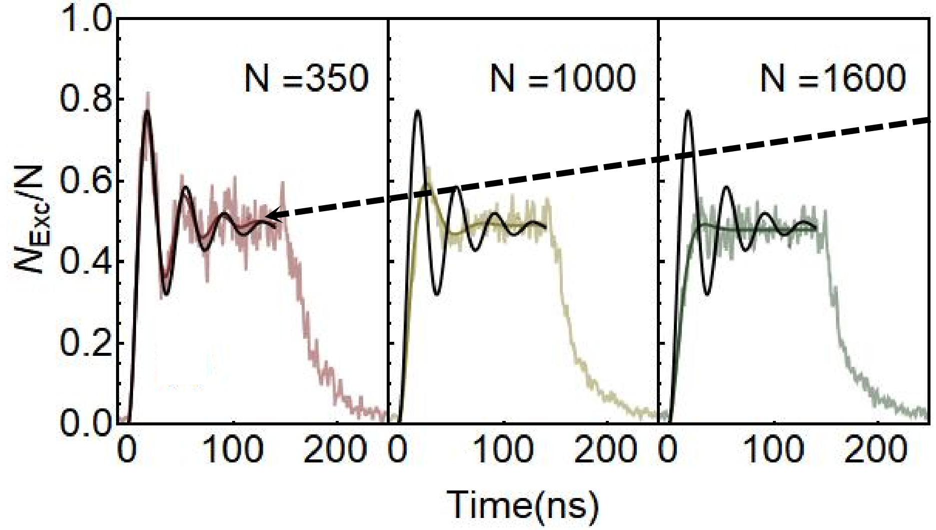

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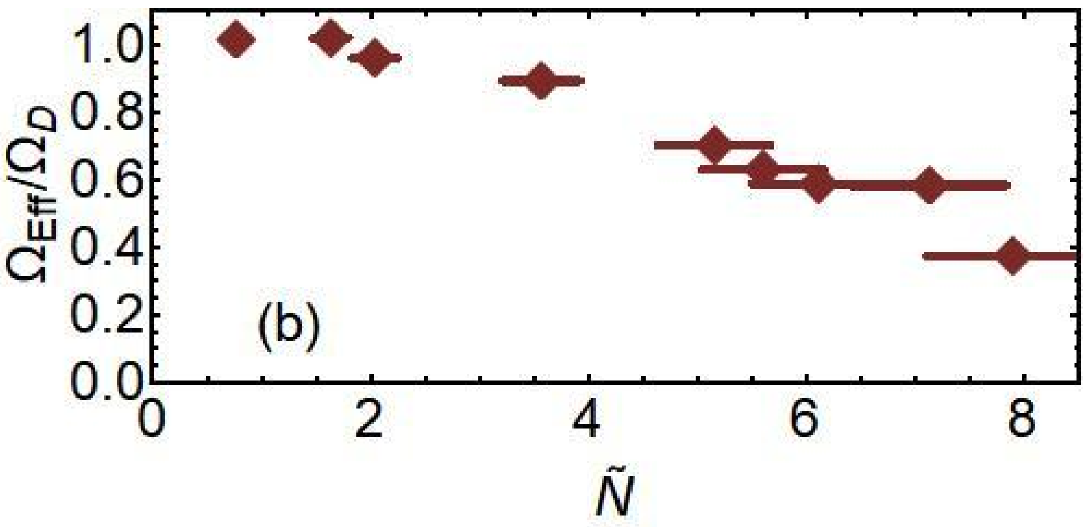

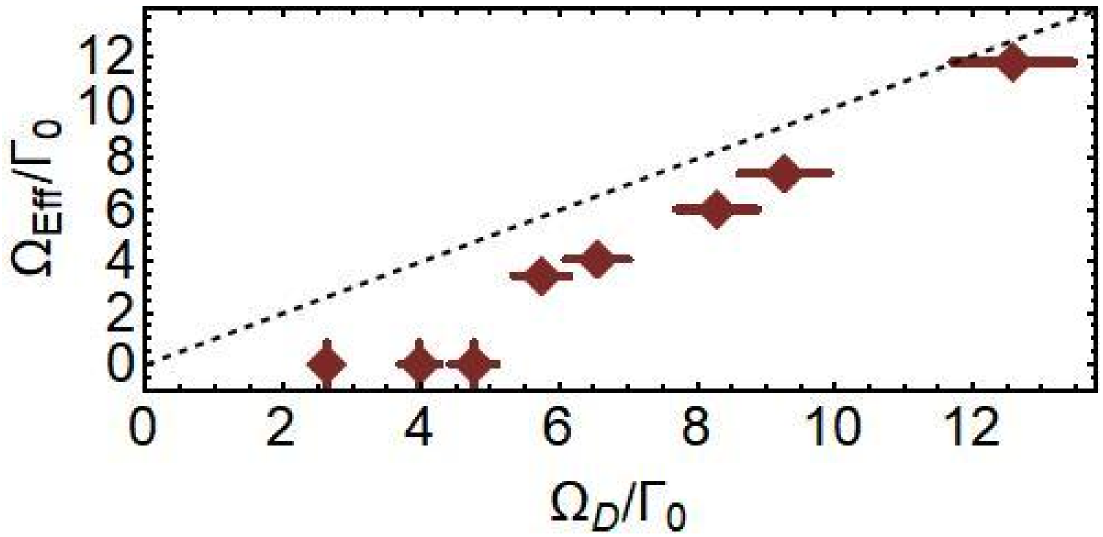

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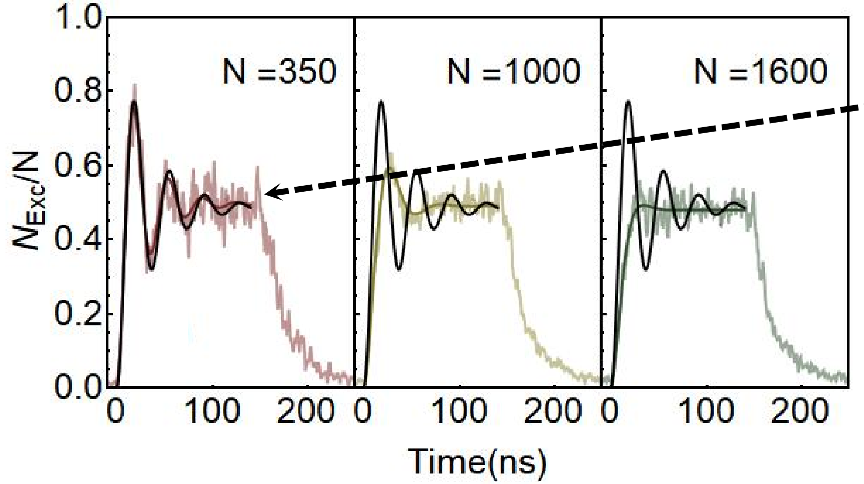
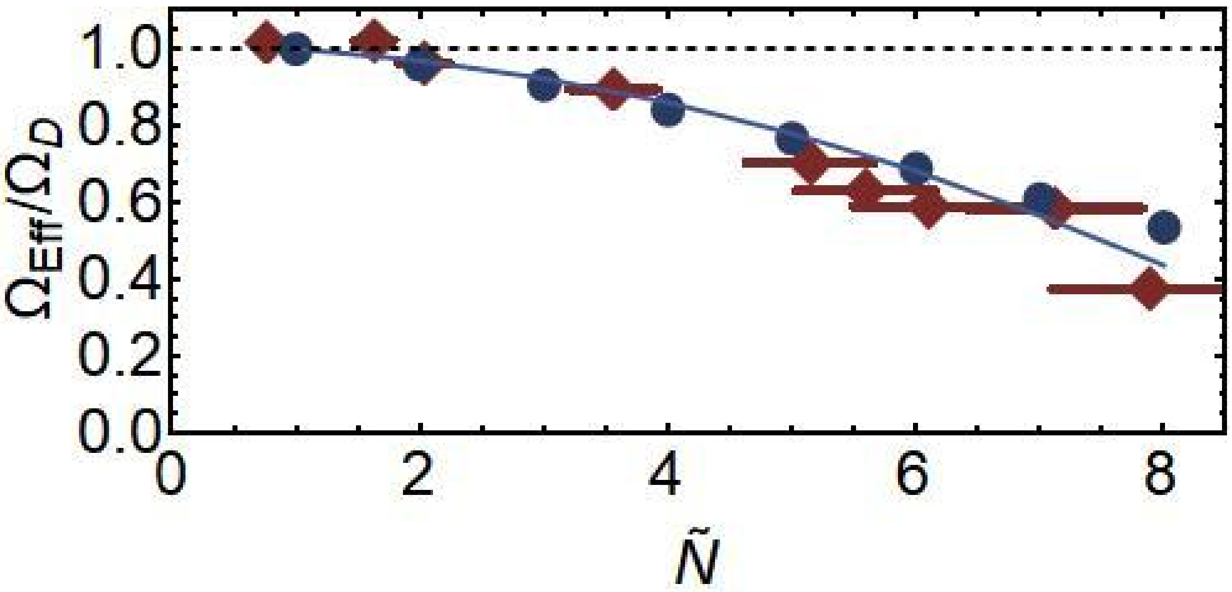
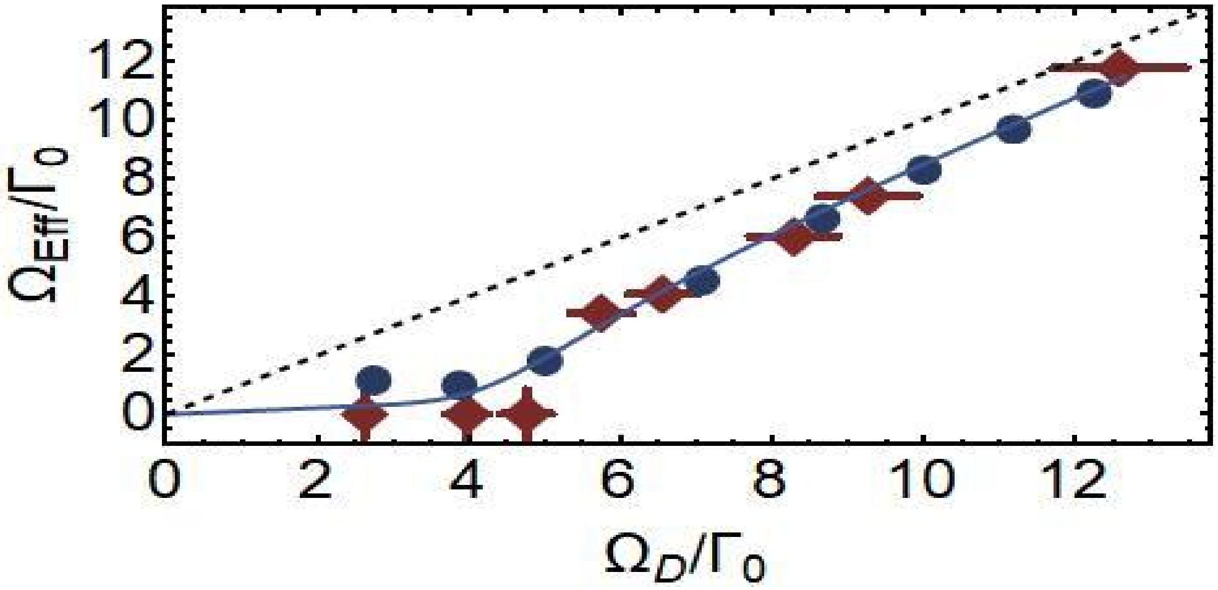


Black: Optical Bloch Equation,
single atom response

(a) fixed driving strength
s = 35

Driven-Dicke results, (almost) No adjustable parameter
First experimental realization!





$$\frac{d\rho}{dt} = -i\Omega_D[S^+ + S^-, \rho] + \frac{\Gamma}{2}(2S^-\rho S^+ - S^+S^-\rho - \rho S^+S^-)$$

Dynamics of the excited state population

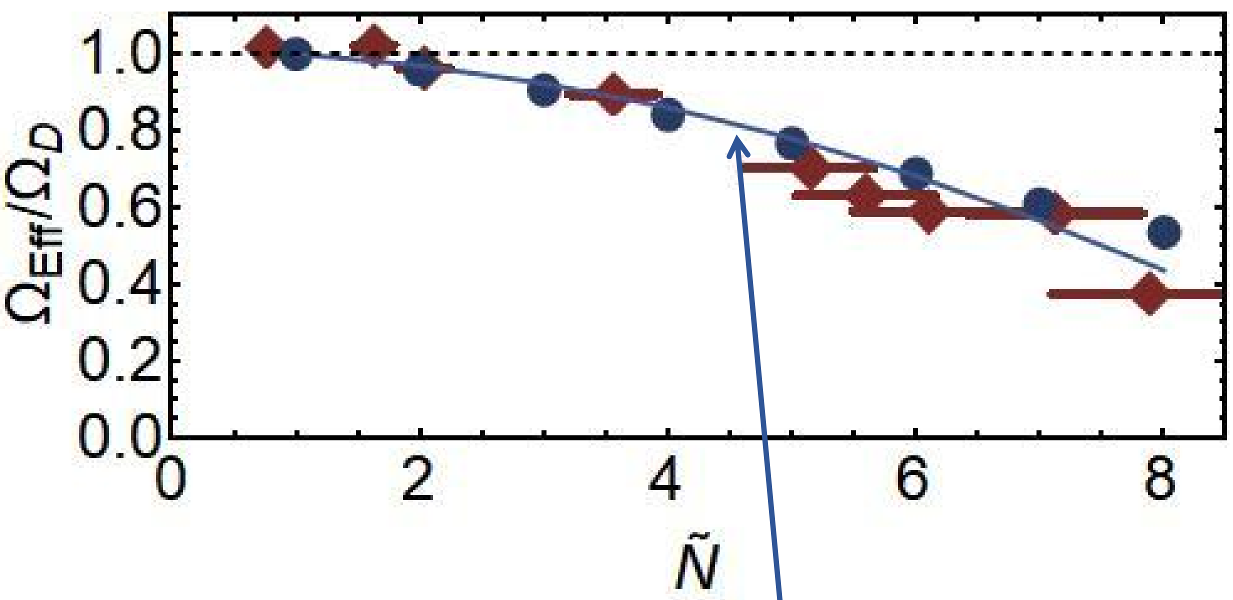
Preliminary results

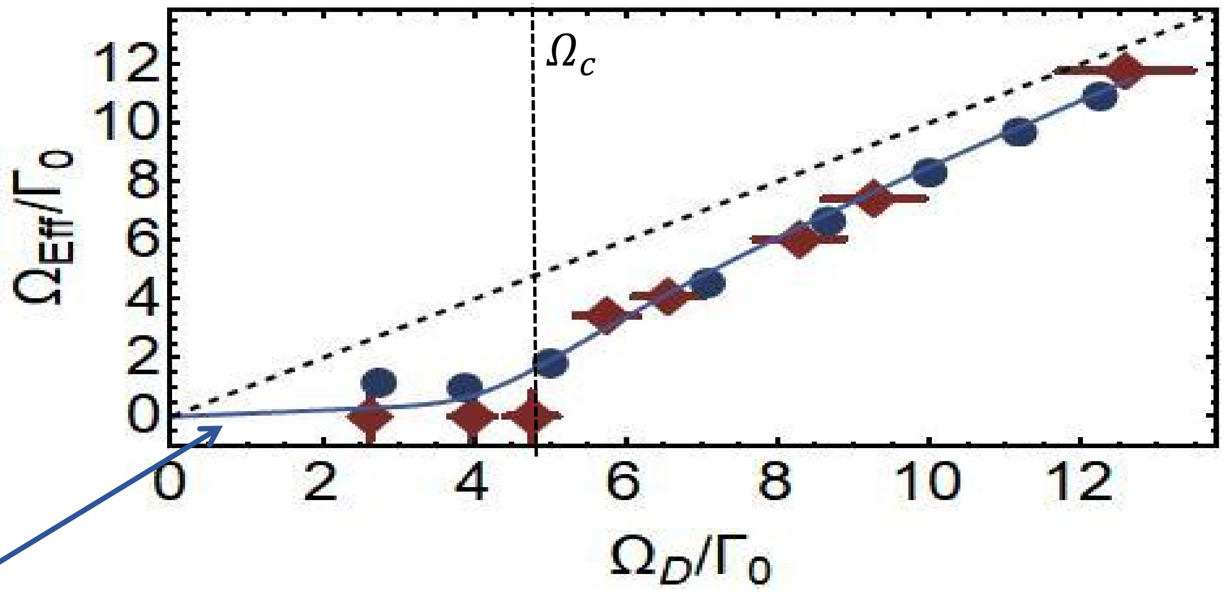
Origin: collective screening effect

$$\Omega_{Eff} = \Omega_D + 2\pi/hE_S = \Omega_D - i\Gamma_0\langle S^-\rangle < \Omega_D$$

Field radiated by the other atoms

max collective dipole: $\langle S^-\rangle = - iN/2 \longrightarrow \Omega_D > \Omega_c = \Gamma_0 N/2$





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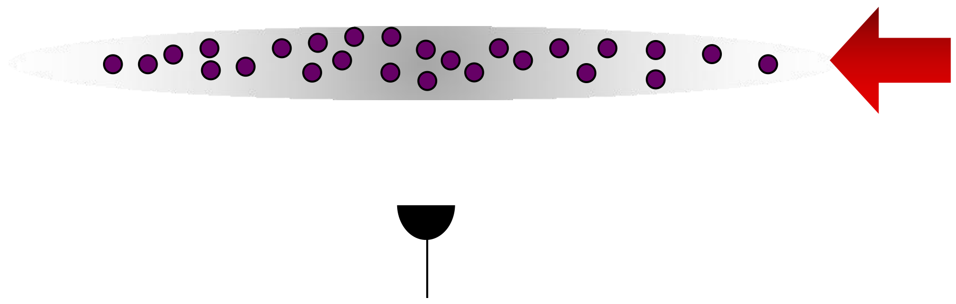
Steady-State properties

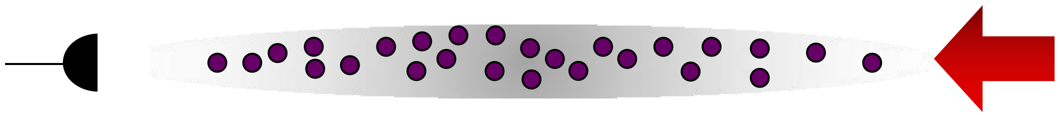
Preliminary results

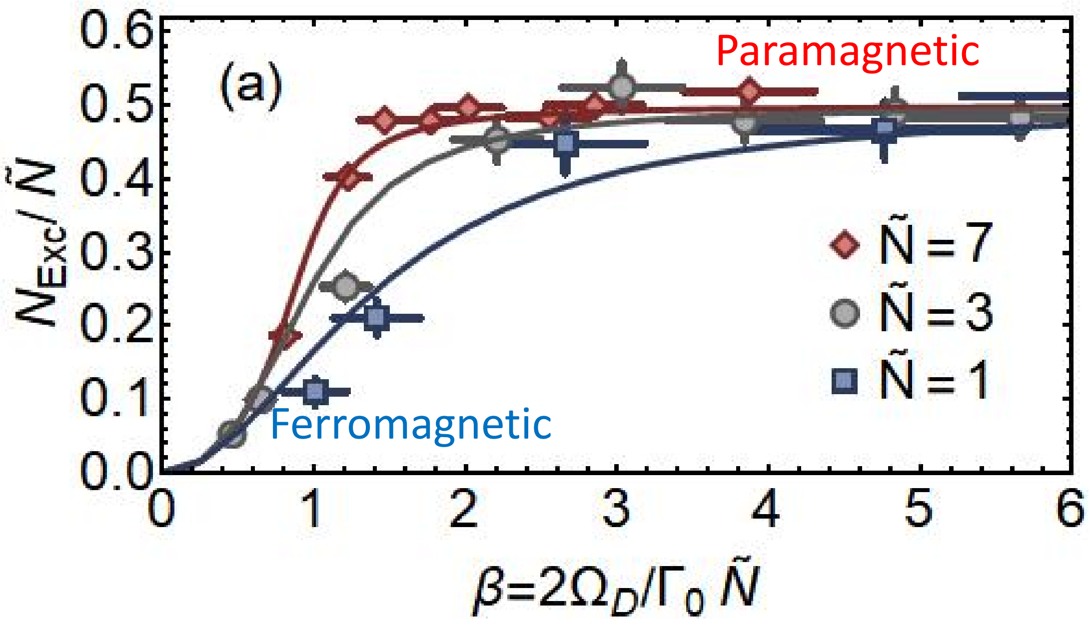
Natural "scale" : $\beta = \frac{2}{\Gamma \widetilde{N}} \Omega_D$ driving

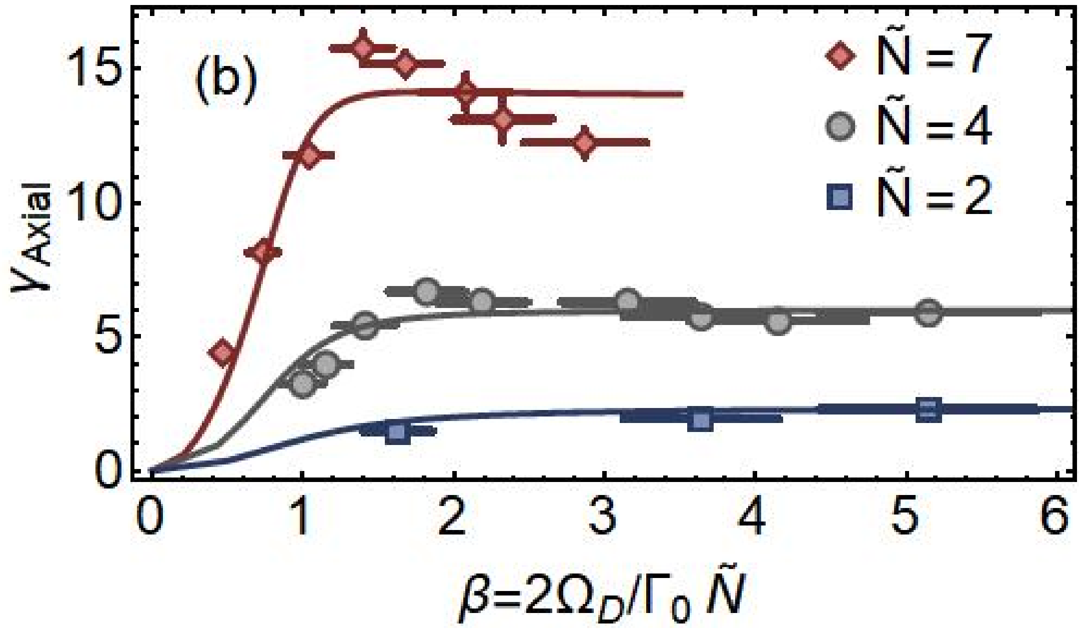
Excitations hosted in the atoms



Photons emitted in the superradiant mode



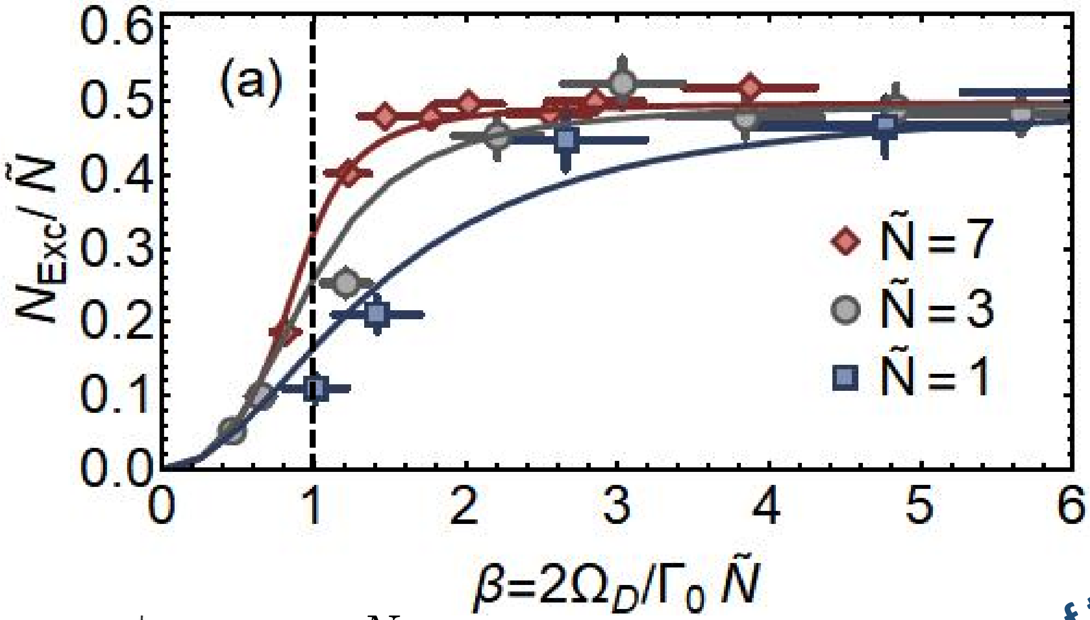




Steady-State properties

Preliminary results

Atomic part



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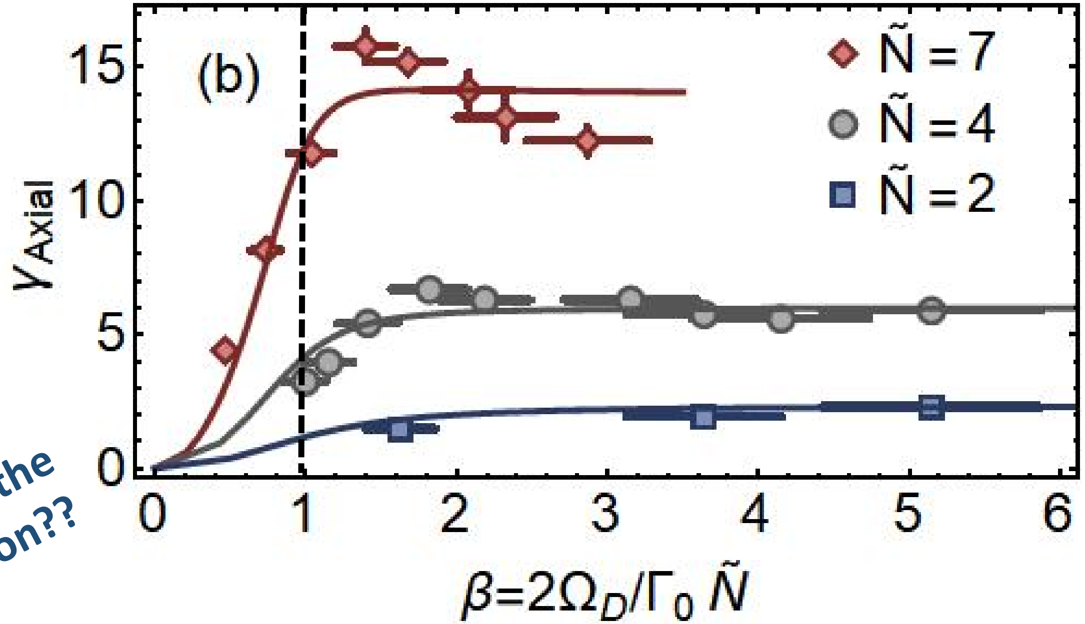
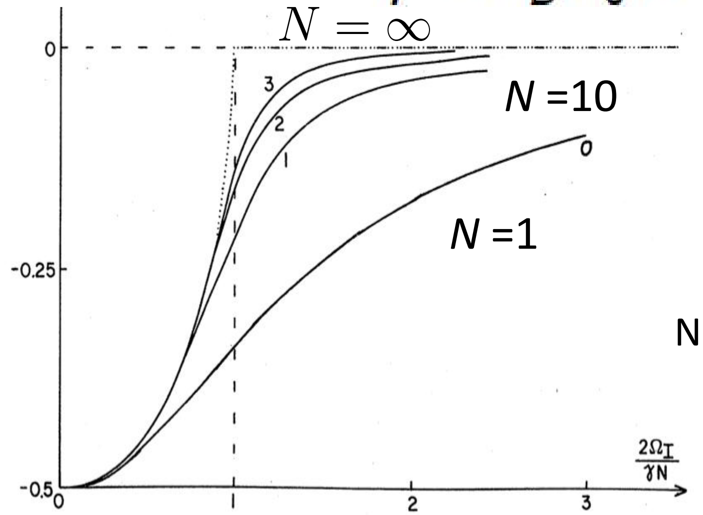
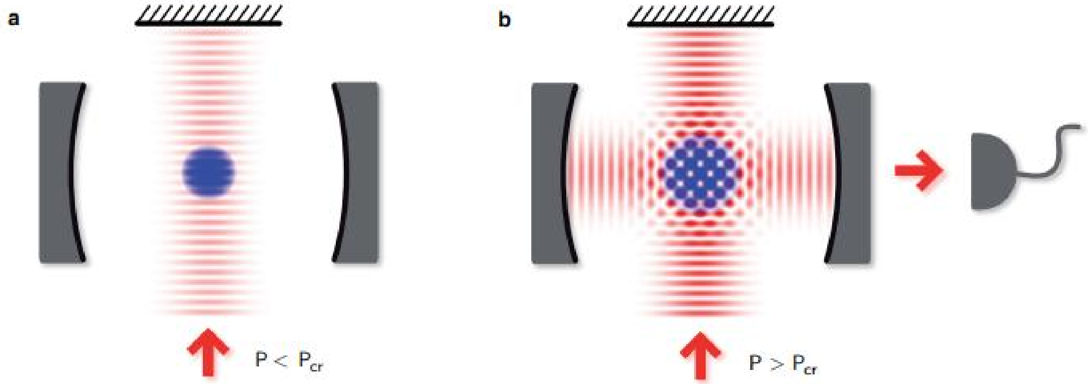


Observation of the onset of the superradiant phase transition??



Narducci, PRA 1978

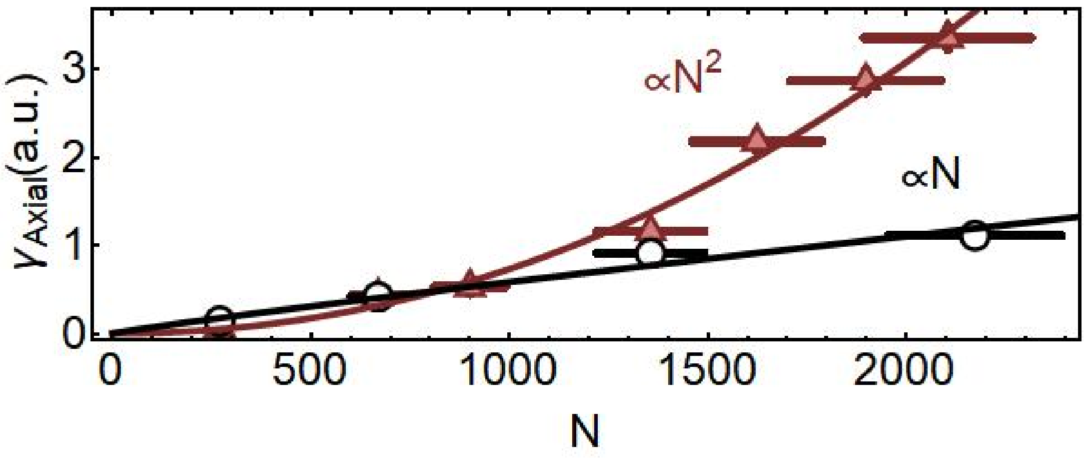


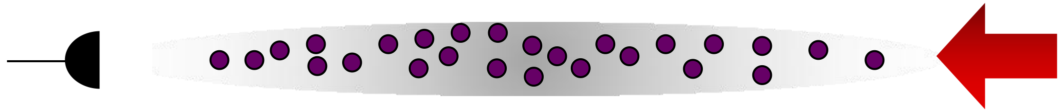
Esslingher team, Nature 2012

Superradiant Phase-Transition in steady-state

Preliminary results

Can we really observe two different phases?





Crossing-over to a superradiant phase driven by the strength of the pump

Superradiant Phase-Transition in steady-state

Preliminary results

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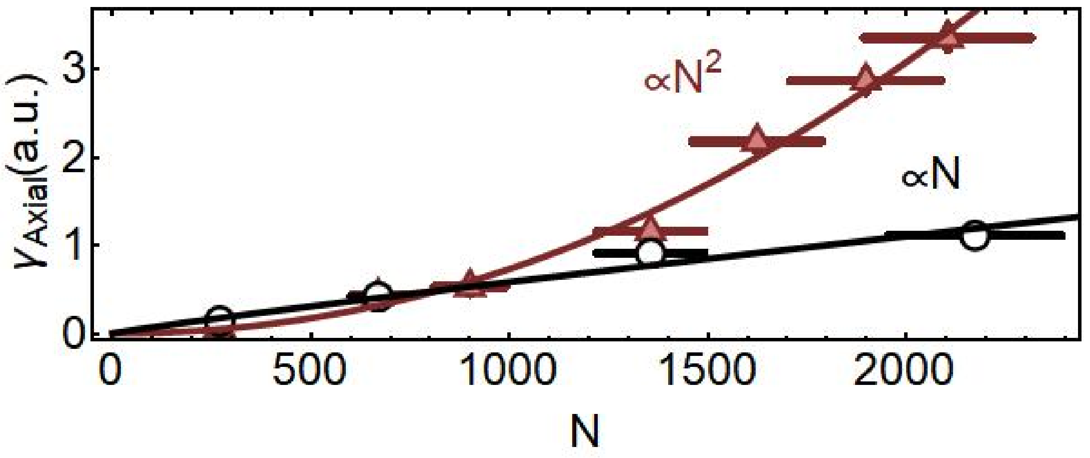
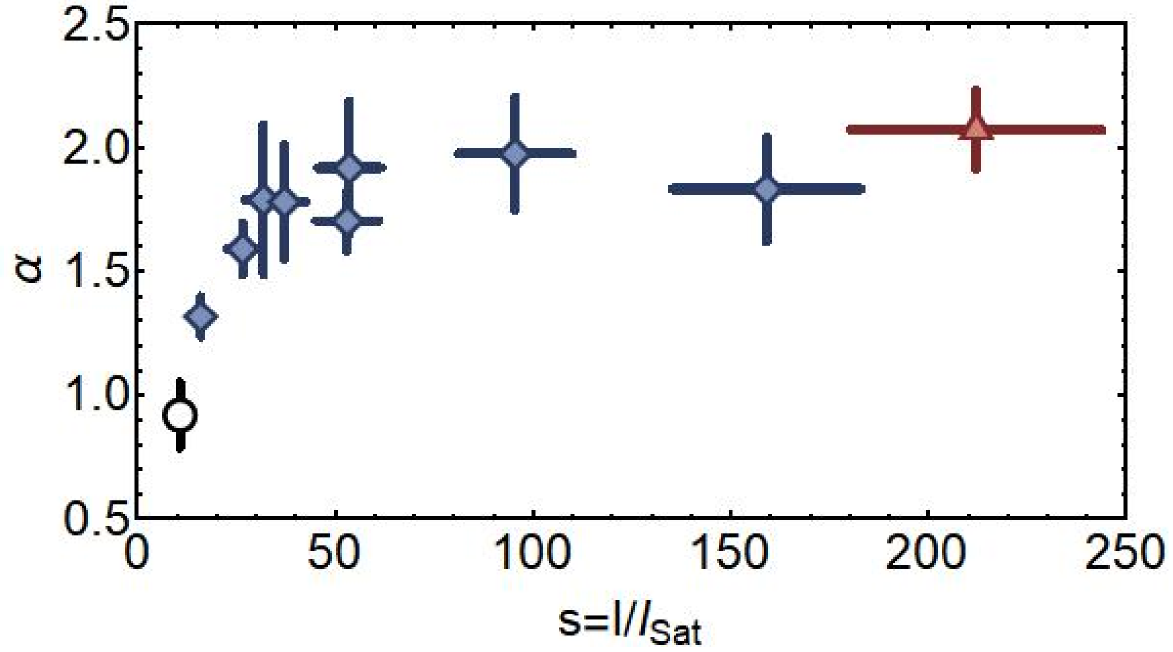
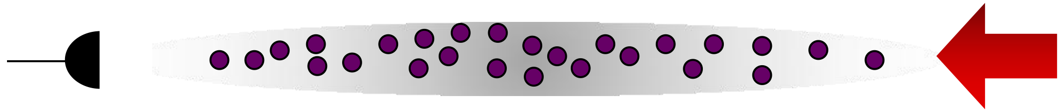




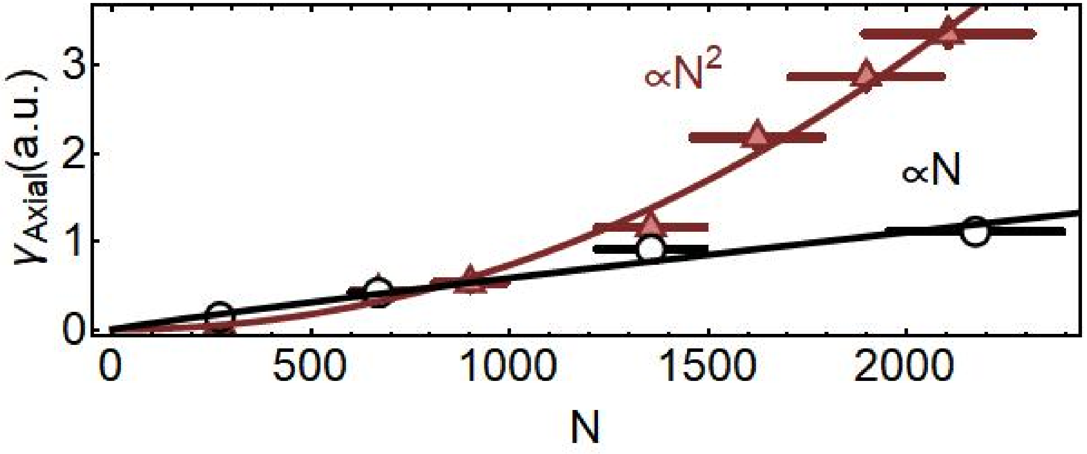


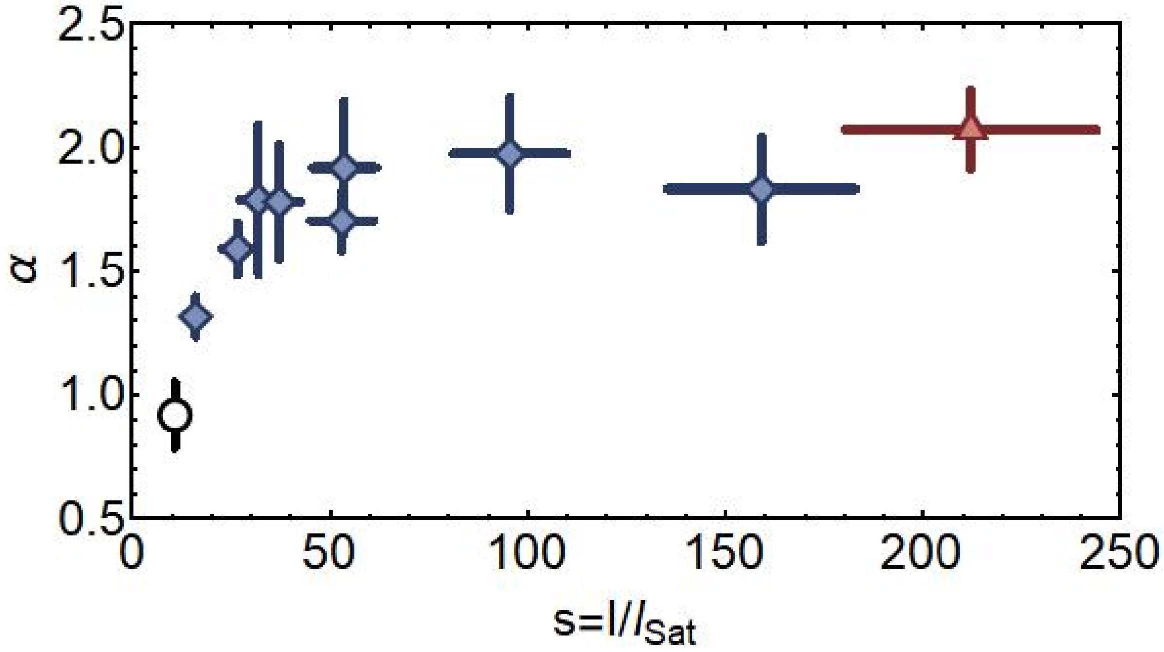
Crossing-over to a superradiant phase driven by the strength of the pump

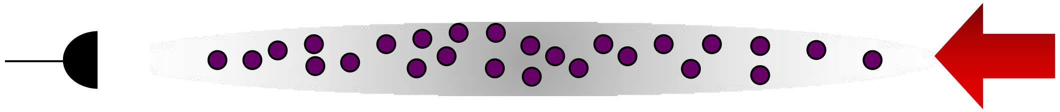
Superradiant Phase-Transition in steady-state

Preliminary results

Can we really observe two different phases?

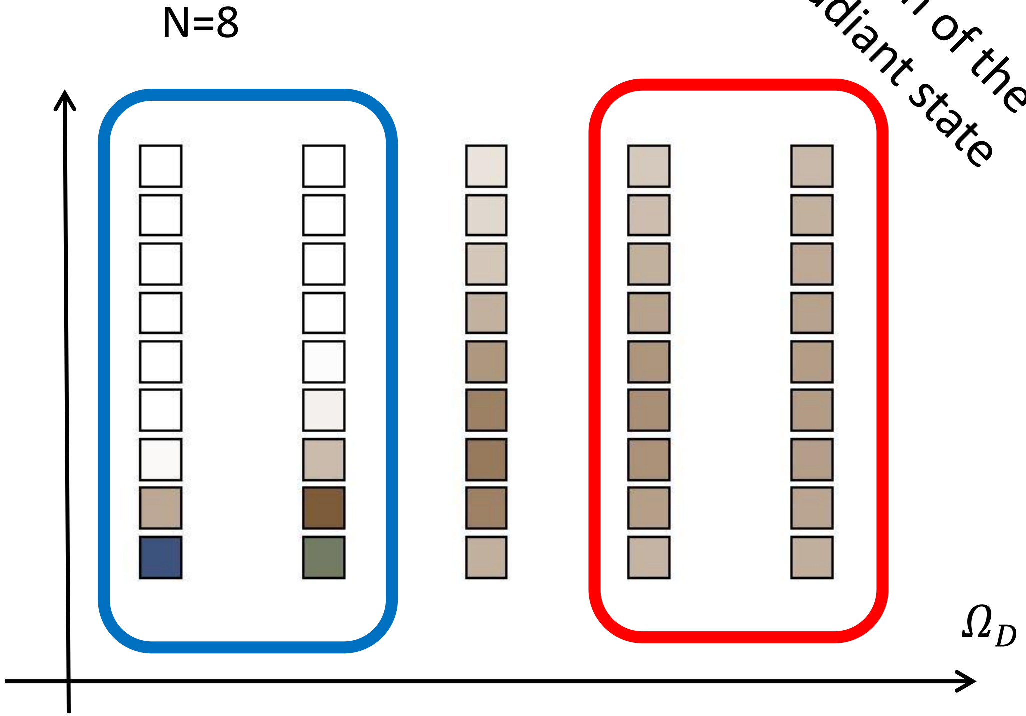






Crossing-over to a superradiant phase driven by the strength of the pump

macroscopic occupation of the most superradiant state

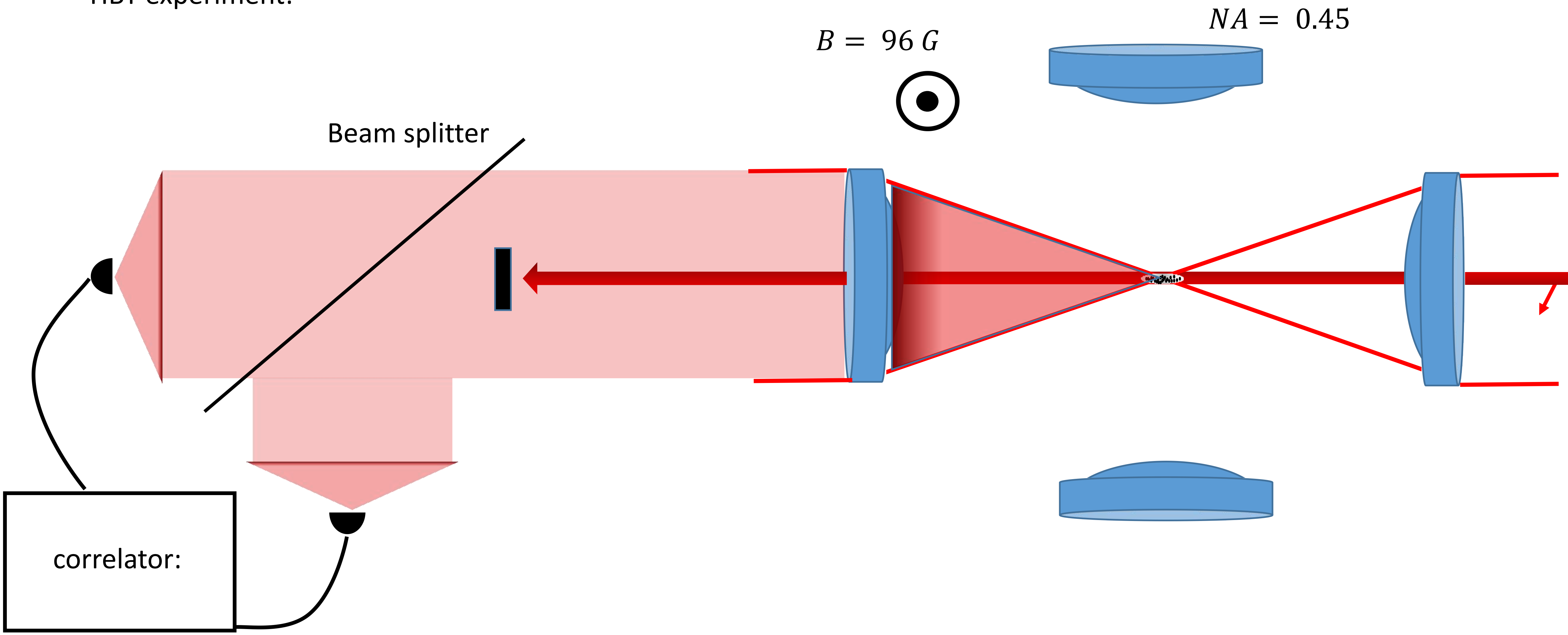


Intensity correlation

Preliminary results

Superradiance is originated by correlations, are they present also in the light emitted?

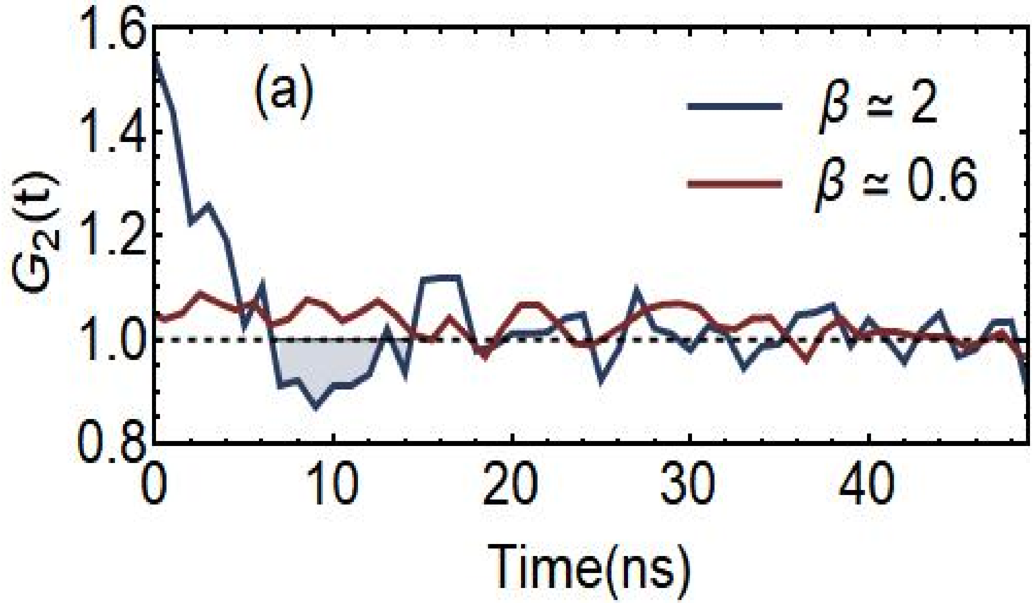
HBT experiment:

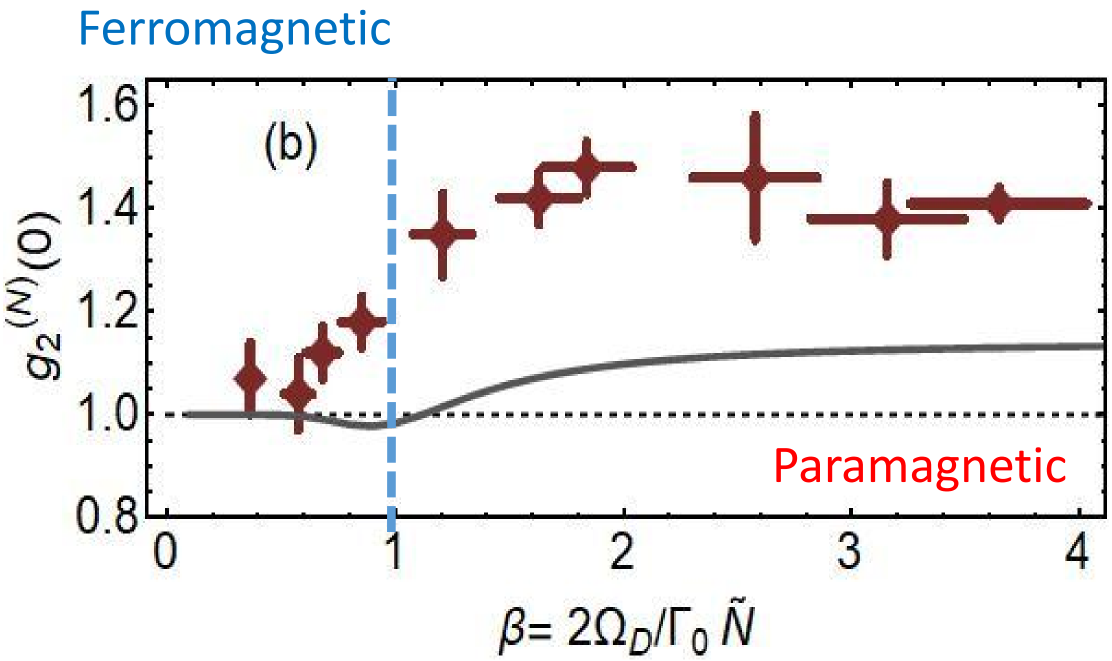


Intensity correlation

Preliminary results

Superradiance is originated by correlations, are they present also in the light emitted?

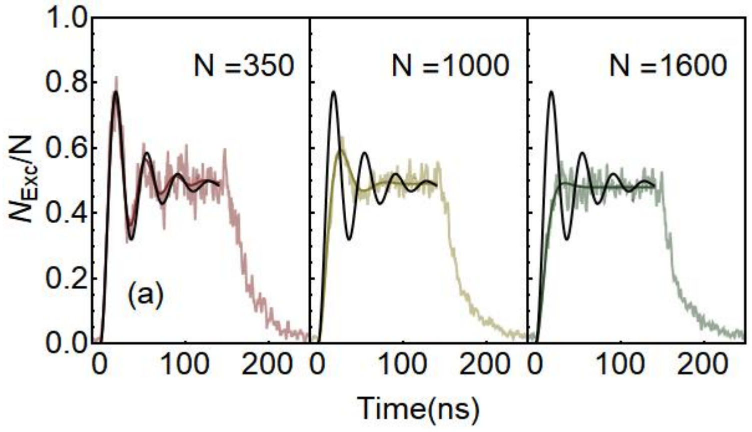




Violation of Siegert relation: correlated system

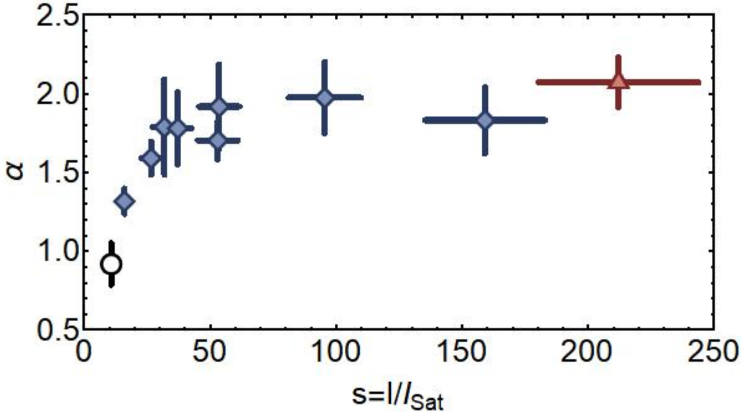
Two phases possess also different photon statistic

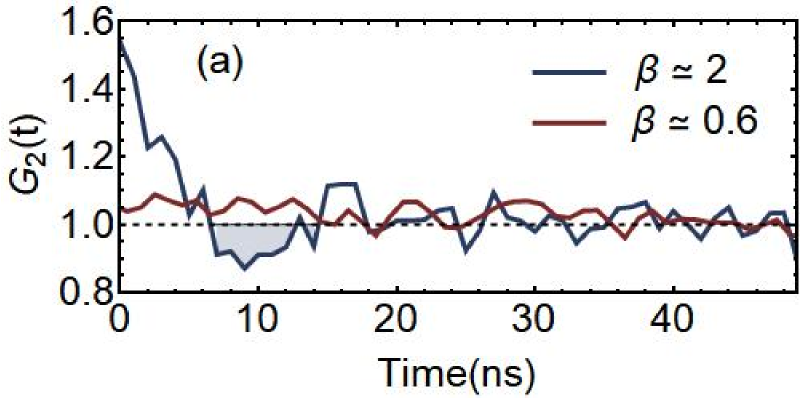
Conclusions



(1) first experimental observation of Driven-Dicke model in free space and observation of the collective screening effect

(2) observation of crossing over to a superradint phase driven by the pump strength (as in cQED)





(3) Correleted system (beyond mean field)

Ferioli, et Al., in preparation

Outlooks

(1) Is there a miscroscopic theoretical justification of the model?

(2) is our system a superradiant laser?

Ferioli, et Al., in preparation

Thanks for the attention!!

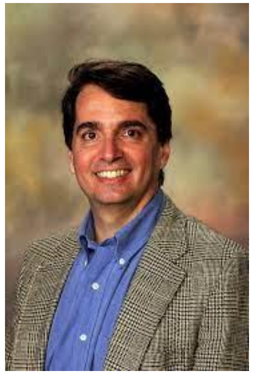
Antoine Glicenstein

Igor Ferrier-Barbut

Antoine Browaeys

Collaborators

F. Robicheaux & Tyler Sutherland



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