Correlations d'une source laser superradiante Continue

COCO

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Z. Zhang (First-TF), Y. Pargoire, C. Serna, B. Pasquiou, B. Laburthe-Tolra

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J. Huckans

Bloomsburg commonwealth university

AG First-TF, 1st October 2026

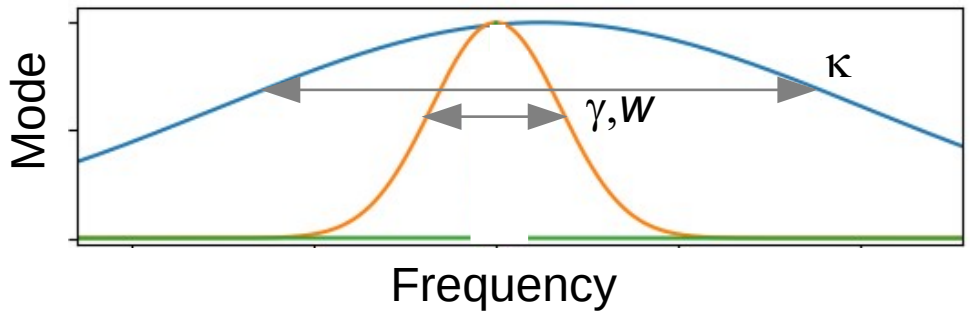
Domaine de Recherche et d'Innovation Majeur

The superradiant laser : an optical frequency reference

A laser in the “bad cavity” limit

Cavity linewidth broader than gain medium linewidth (all broadenings included)
→ **radiation frequency robust to cavity length fluctuations**

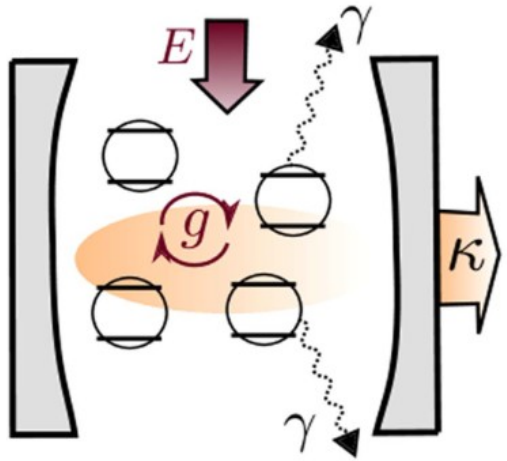
Meiser, Holland, PRL 102, 163601 (2009); JB Chen 2009, Chinese Science Bulletin 54, 348 (2009)



Gain medium = (cold) atoms with a population inversion on an optical “clock” line
→ **radiation frequency self-stabilized on the clock transition frequency**

Furthermore,
with γ *: natural width of the transition*
and Γ_c *: single-atom emission rate to the cavity mode,* << γ
radiation linewidth tends to Γ_c << γ

(“weak coupling regime”, C = Γ_c / γ *< 1)*

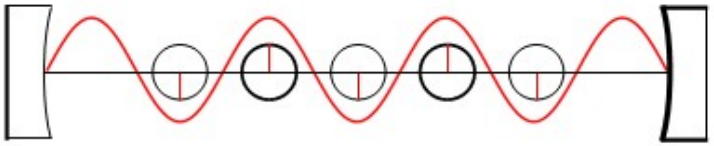


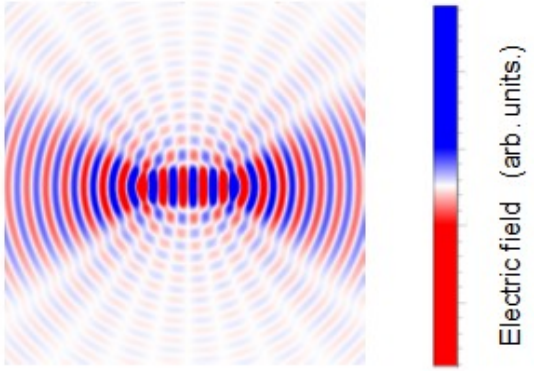
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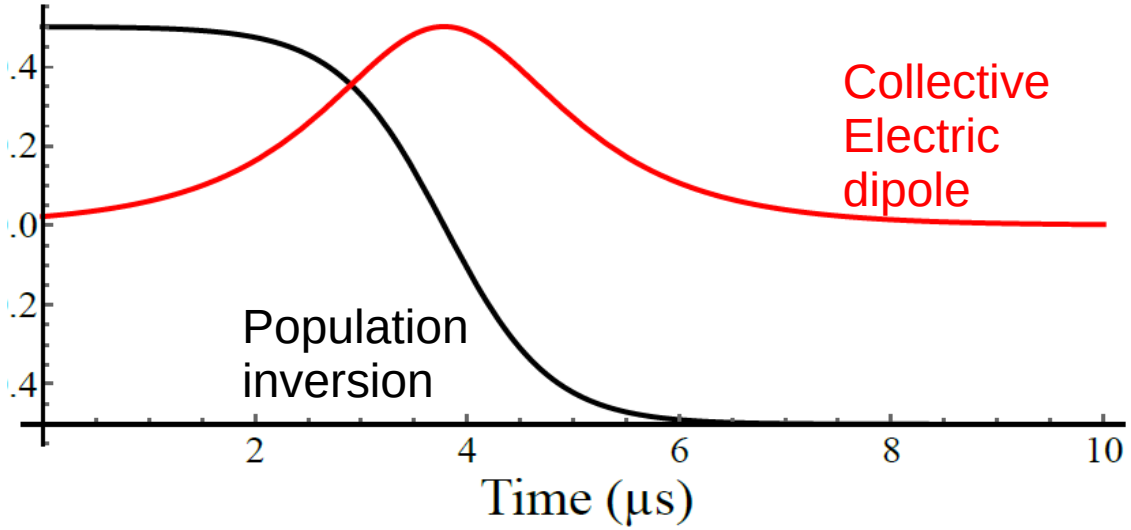
Why is it called “superradiant” ?

In a bad cavity optical laser, each atom (an oscillating electric dipole) tends to **adjust its phase such that its radiation interferes constructively with the other atoms’**, towards the cavity mode.





The same phenomenon explains the better known “superradiant pulses” (from dense samples typically)

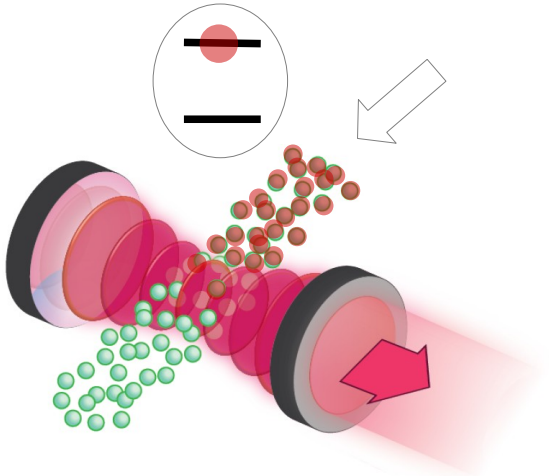


In contrast to most literature on superradiance (*one de-excitation pulse*), in superradiant lasers energy should be reinjected to sustain the emission, ideally ***continuously***.

Conference announcement: first realisation of CW regime, 2026, F. Schreck’s team

The CoCo project

Reinjecting pre-excited atoms



Atomic beam “rugged superradiant laser” proposal:
Liu et al, PRL 125, 253602 (2020)

Requires resilience of superradiance to atomic motion (Doppler shifts, transit)

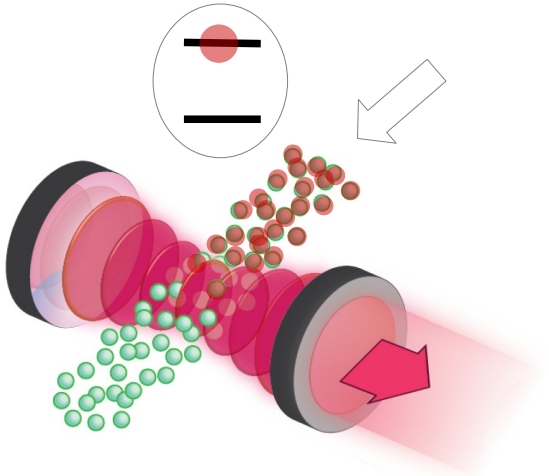
→ easier when the line is not too weak,
such as the **Sr intercombination line (7 kHz)**

CoCo objectives:
- prepare the population inversion
- demonstrate **CW** superradiant lasing
→ probing the role of correlations (photon-photon, atom-atom, …)
→ probing emission regimes

Two superradiant laser prototypes in France: Marion Delehaye (Femto-st) and ours.
Collaboration started with first-tf funding SureCo, continues to develop.

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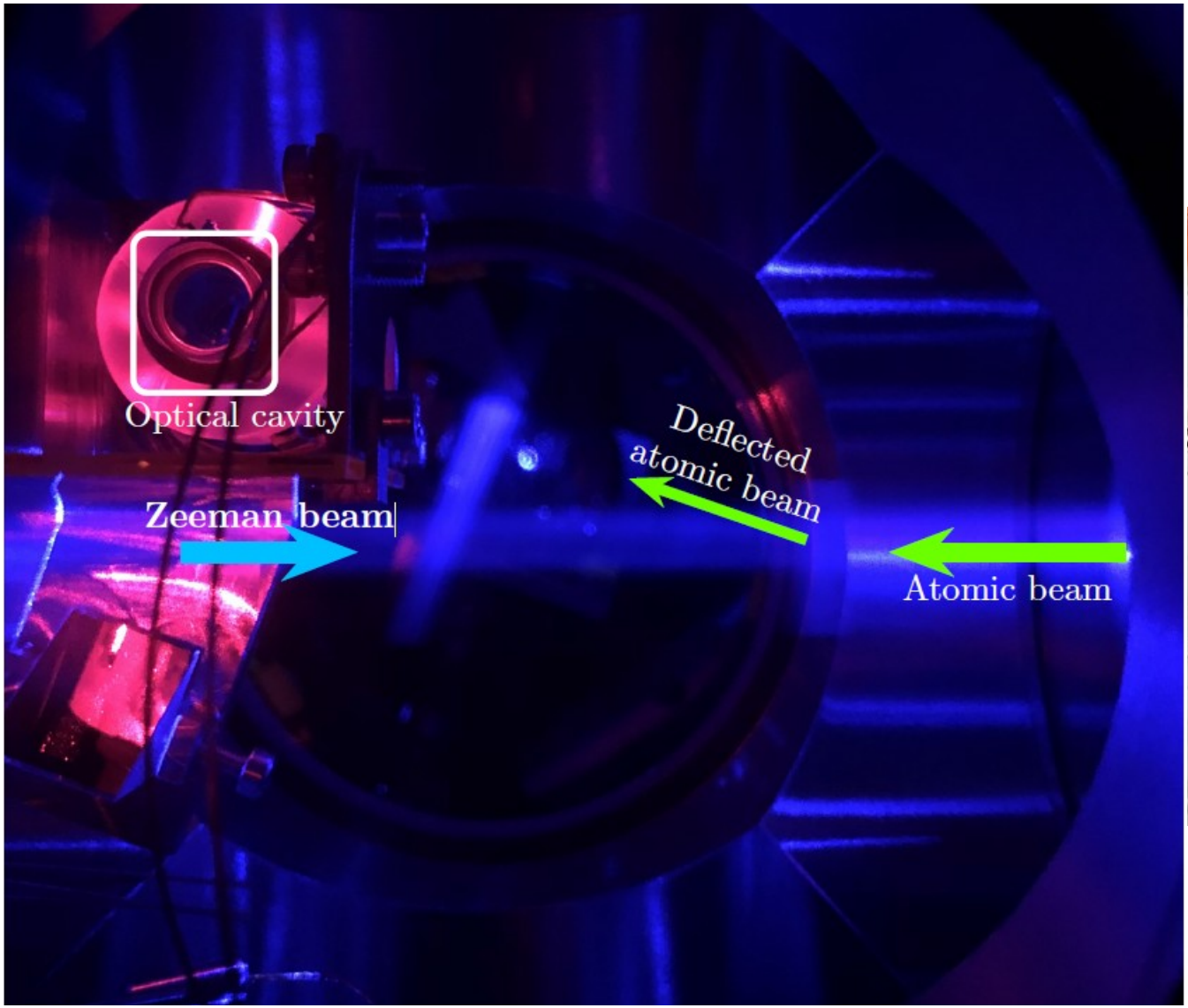
(2) probing the role of correlations (photon-photon, atom-atom, …)

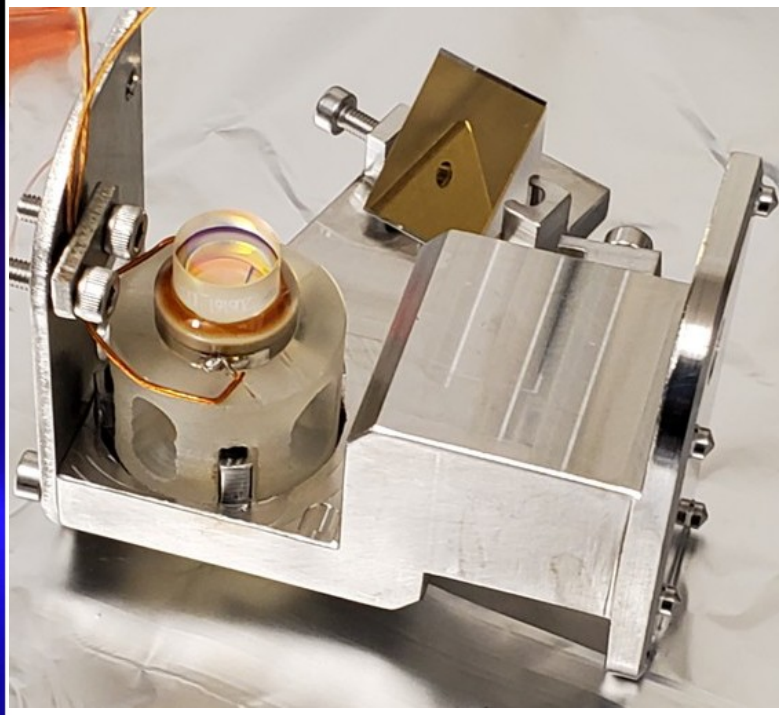
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(1) Continuous excitation demonstration

Strontium 88 superradiant laser on the 7 kHz wide intercombination line $^1S_0 \rightarrow {}^3P_1$

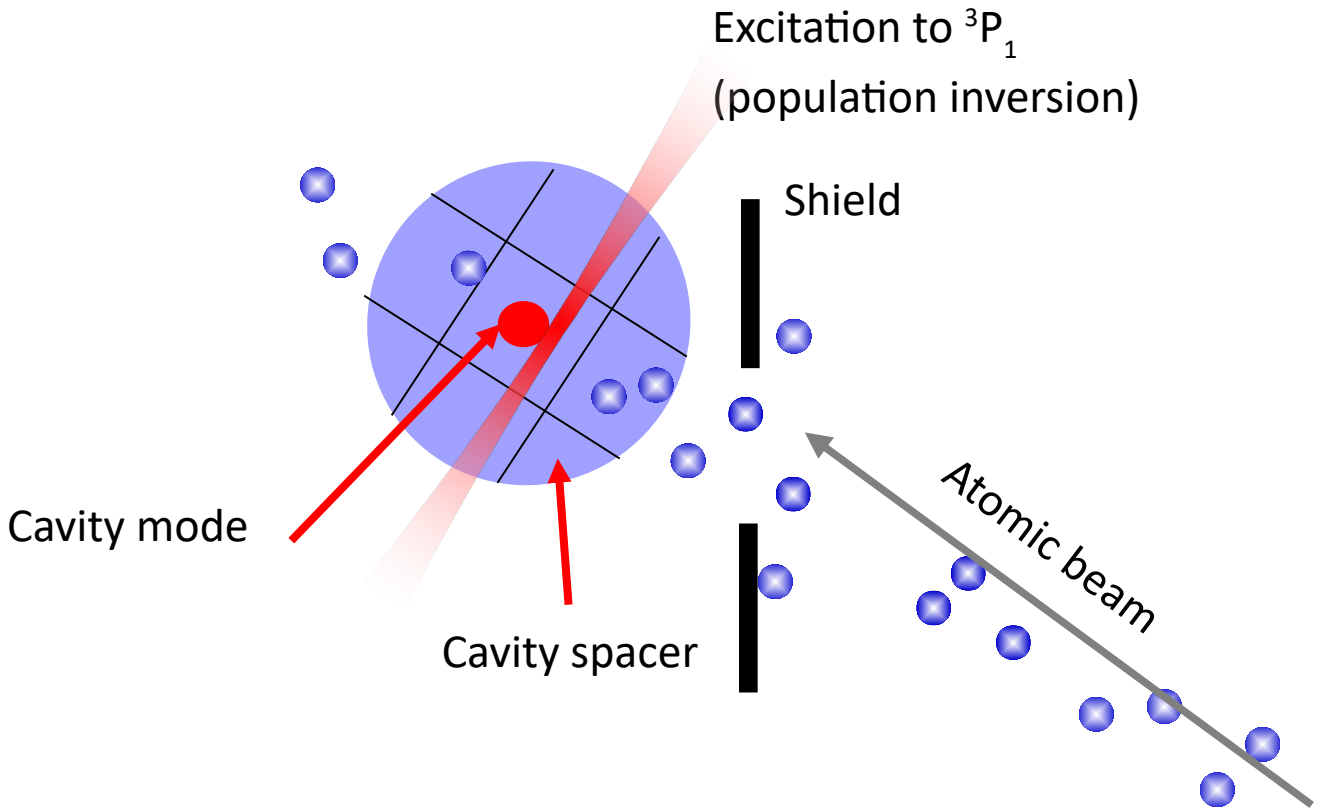




Experimental platform funded by FIRST-TF SureCo project, ANR, Sirteq

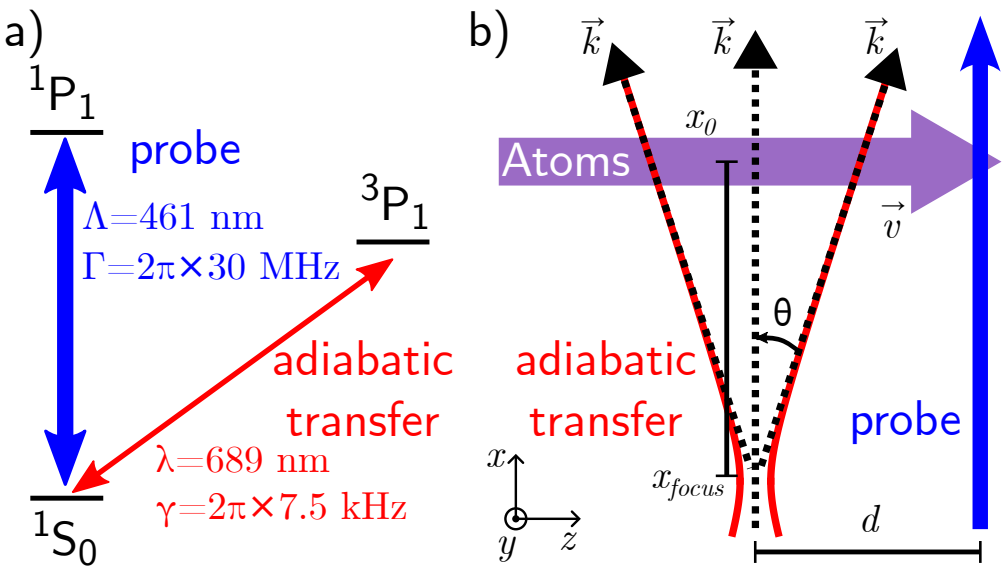
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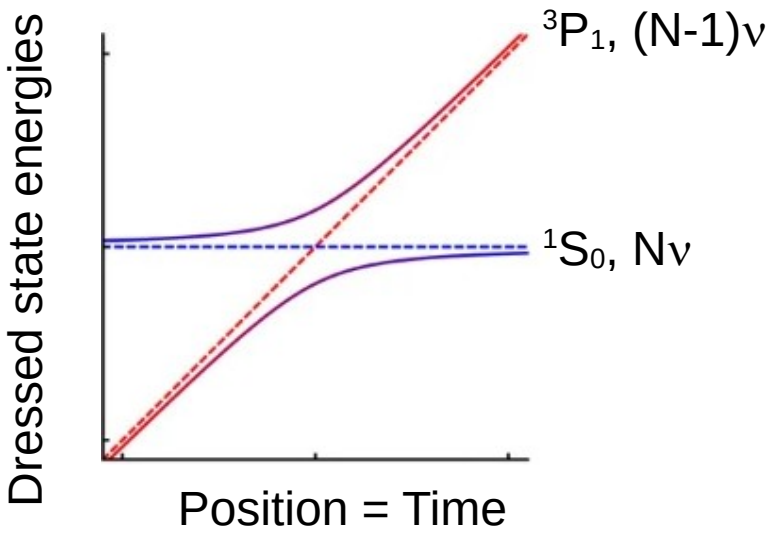
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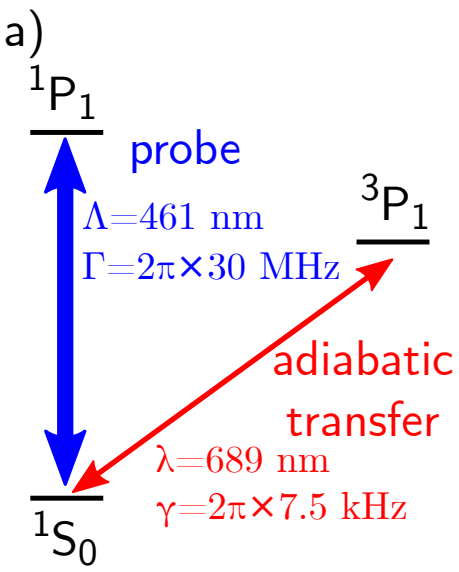
As in V. Lorent et al, Opt. Commun. 64, 41–44 (1987)

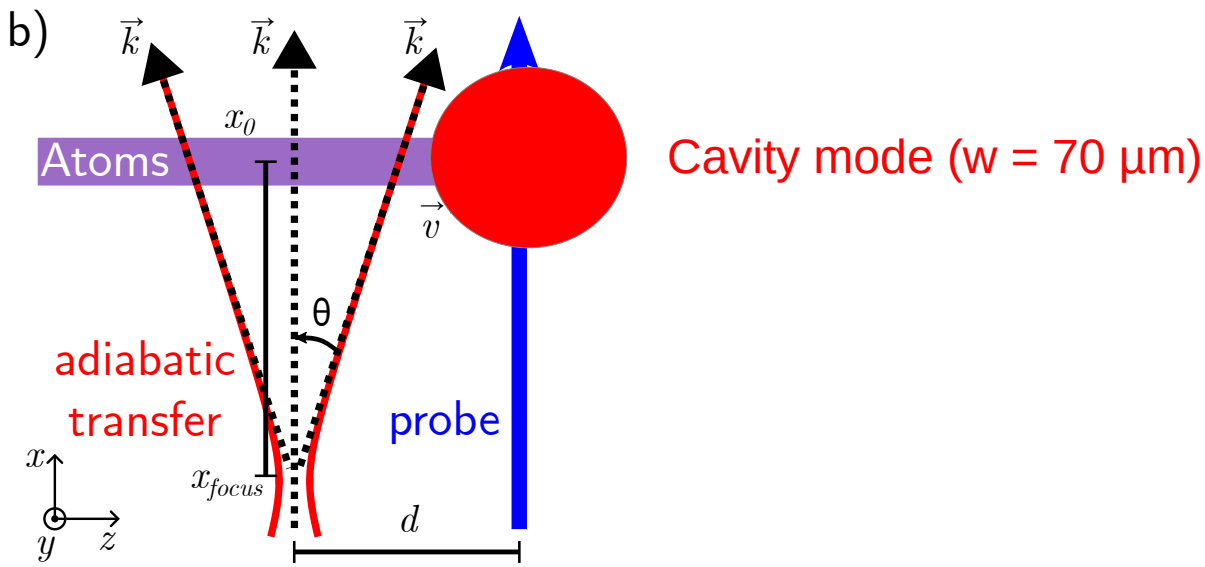




(1) Continuous excitation demonstration

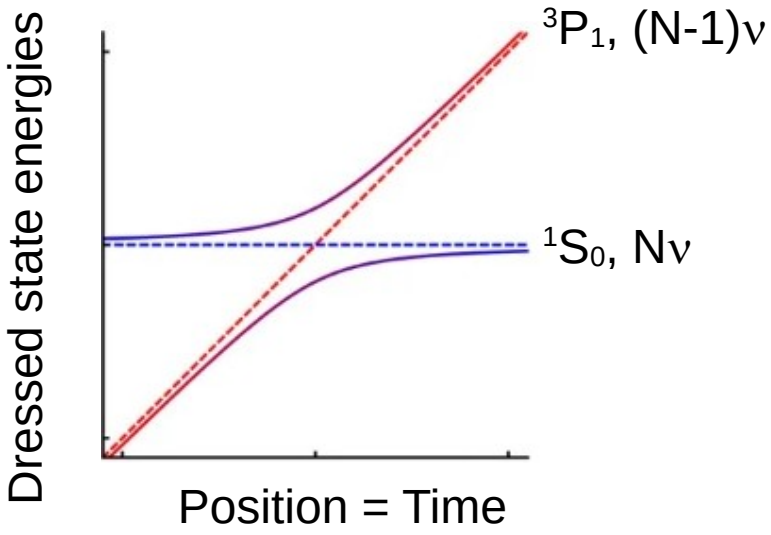
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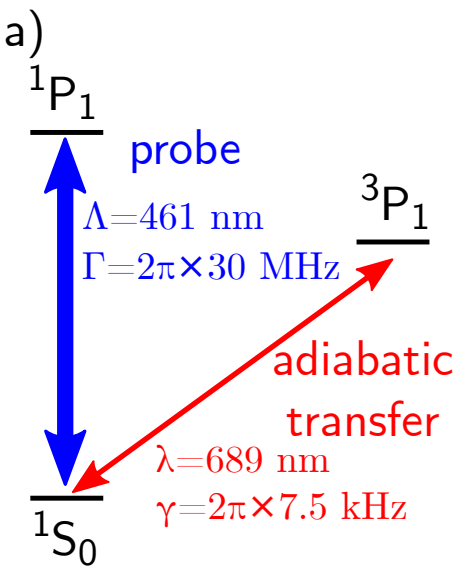
Cavity mode (w = 70 µm)

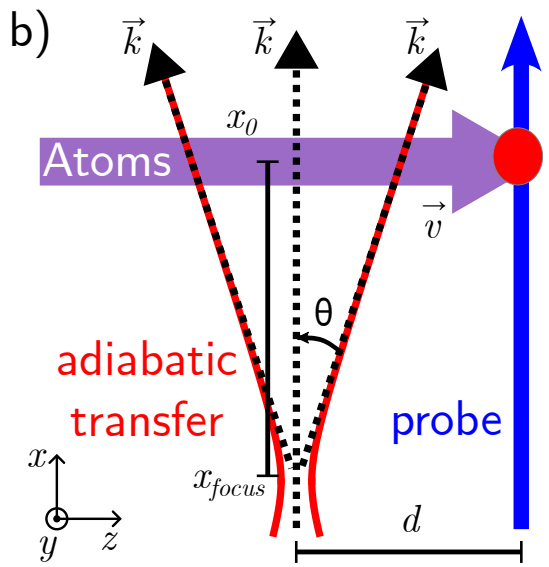
N.A. 0.044
Waist crossed: 100 µm



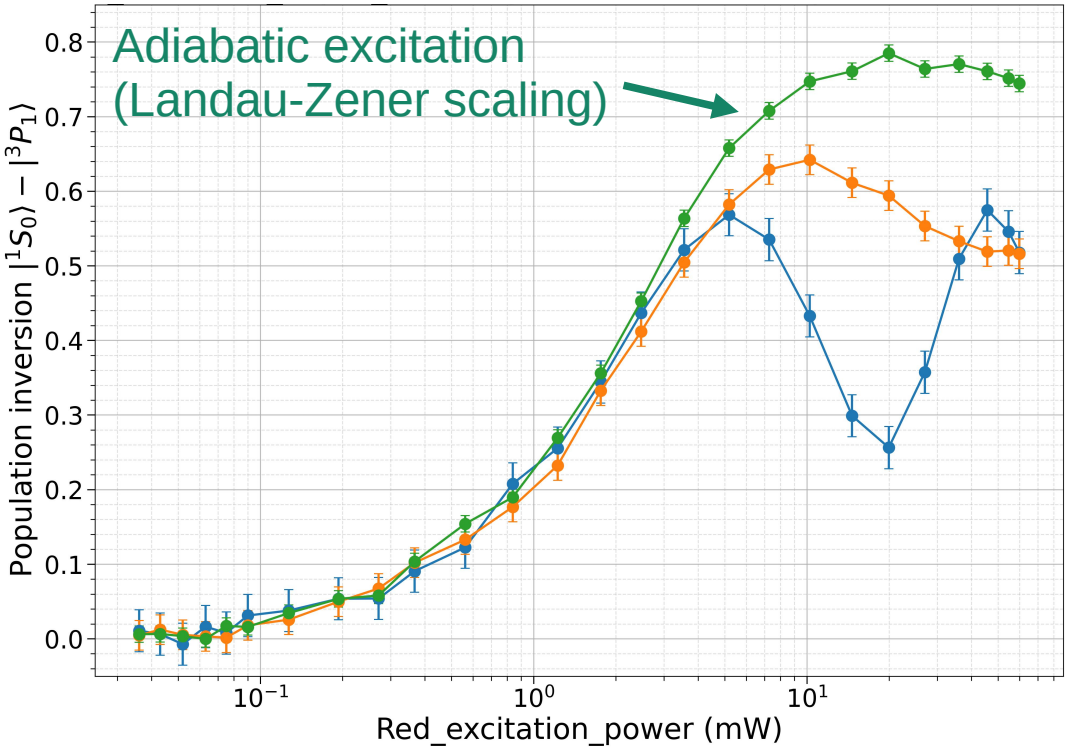
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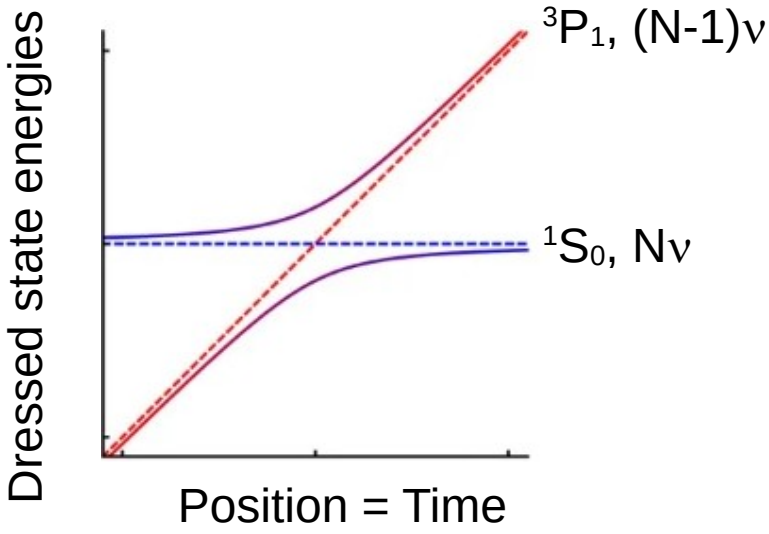
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N.A. 0.044
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About 80% excitation to $^3P_1$, robust to MHz Doppler shifts.

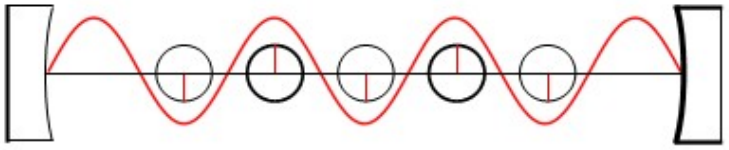
Now:

- generating new data with better π-transition selection.
- concentrating the flux on a lower Doppler spread range along the cavity (narrow-line laser cooling)

(2) Studying the correlations of the SR laser

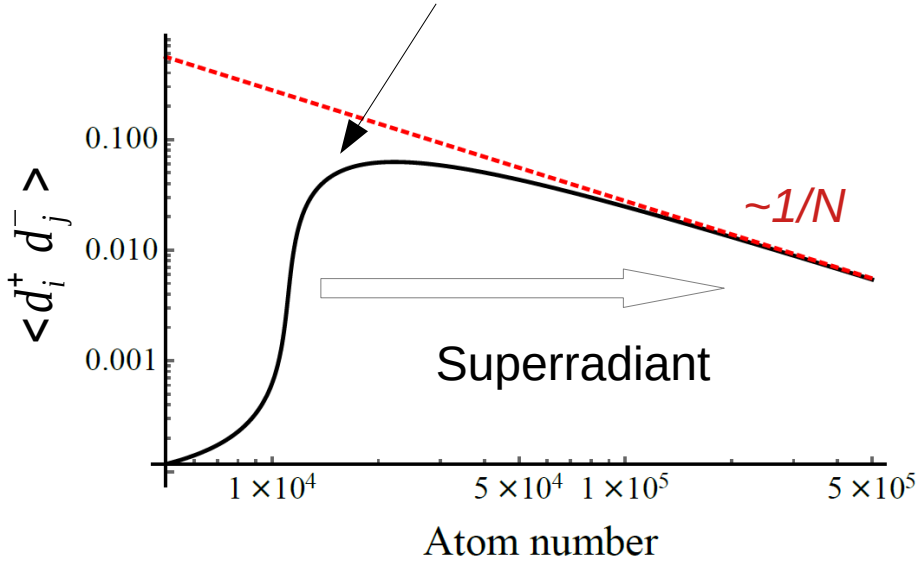
Theoretical result prior to the CoCo project:
Laburthe-Tolra et al., Scipost Physics Core 6, 015 (2023)

Atomic correlations suddenly enhance the collective dipole
→ power surge, phase rigidity



Collective electric dipole:

$$\langle D_x^2 + D_y^2 \rangle = \frac{N}{2} + N(N-1) \; < d_i^+ \; d_j^- >$$



Power and linewidth are related to correlations between atoms;
and atom-atom correlations spike around the threshold.

→ **Could we get experimental information on photon-photon correlations ?**

(2) Studying the correlations of the SR laser

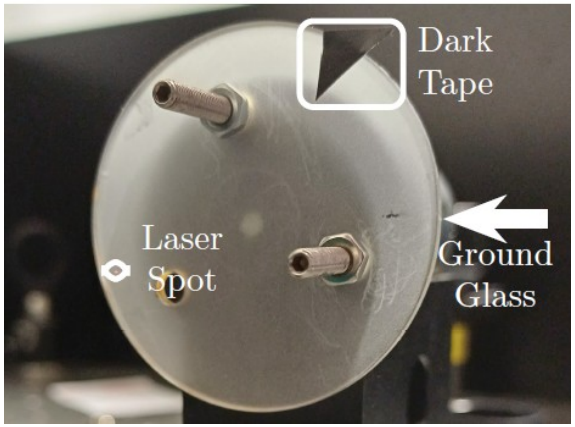
→ Built and characterized a g^2 measurement capability (**C. Serna internship**, with supervision by **Z. Zhang**)

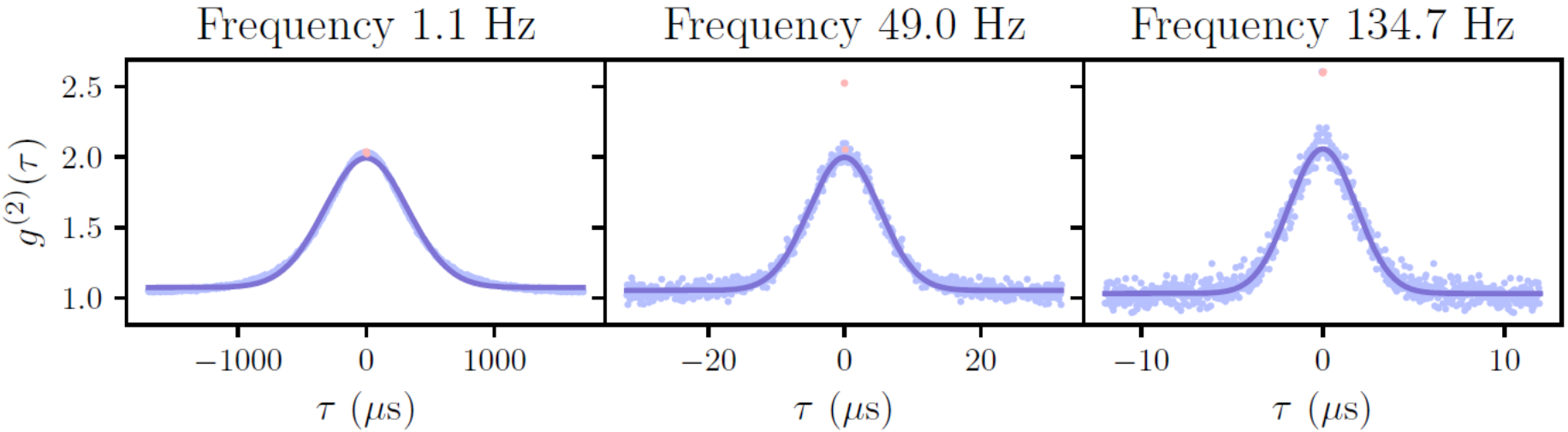
$$g^{(2)}(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle^2}$$

Detection: one fiber-coupled single photon counting module. An FPGA module records click intervals and forwards to a computer for g^2 extraction.

Benchmark on pseudo-thermal light: engineered a fluctuating speckle from a laser, coupled locally to a fiber.

W. Martienssen and E. Spiller, Am. J. Phys. 32, 919 (1964)

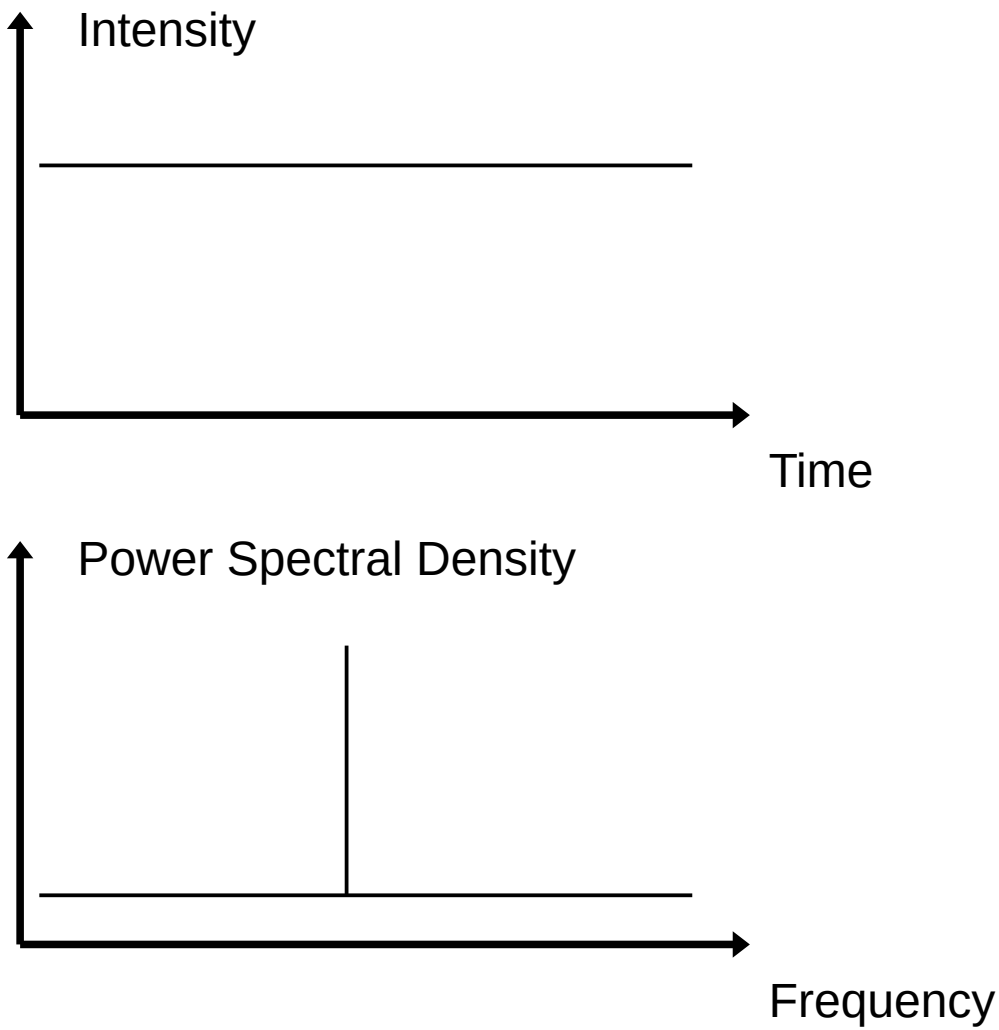




Experimental benchmarks with flux and timescales relevant to SR laser study

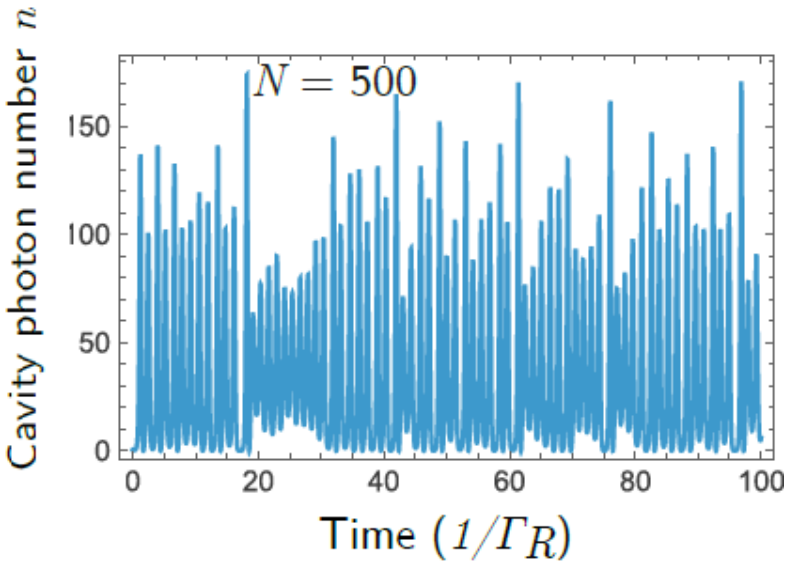
(3) Stability regimes of the SR laser

The optical reference we want to see:



(3) Stability regimes of the SR laser

Laburthe-Tolra, RDSV, and Pasquiou, arXiv:2606.21675 :
Instabilities of the continuous superradiant laser (theory)



$$N \quad > \quad \frac{\kappa^2(8\Gamma_R + \kappa)}{4g^2(\kappa - 4\Gamma_R)} \equiv N_c^*$$

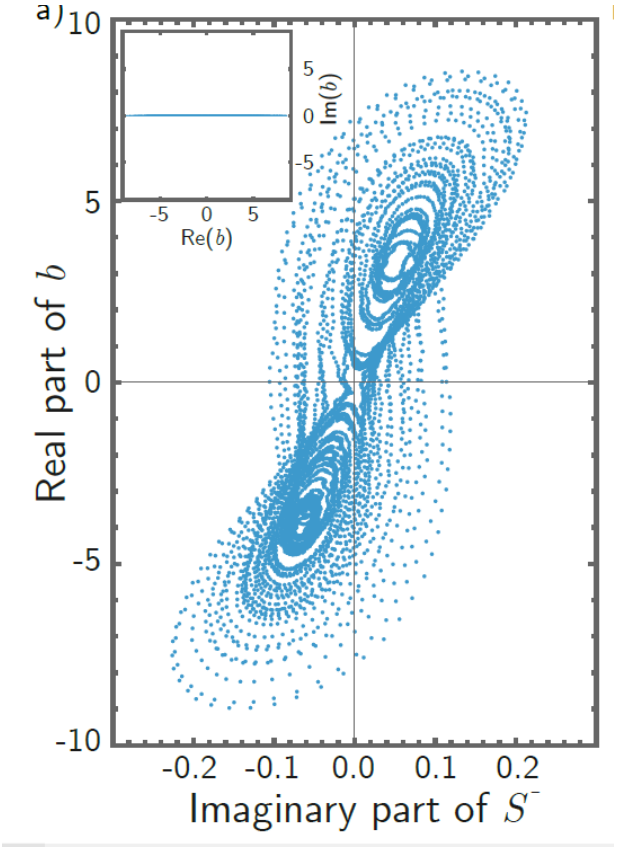
($\kappa > 4\,\Gamma_R$)

g: atom-light coupling
κ: photon leakage rate
Γ_R: 1/transit time

Chaotic behaviour, *even without including (quantum) fluctuations*

(3) Stability regimes of the SR laser

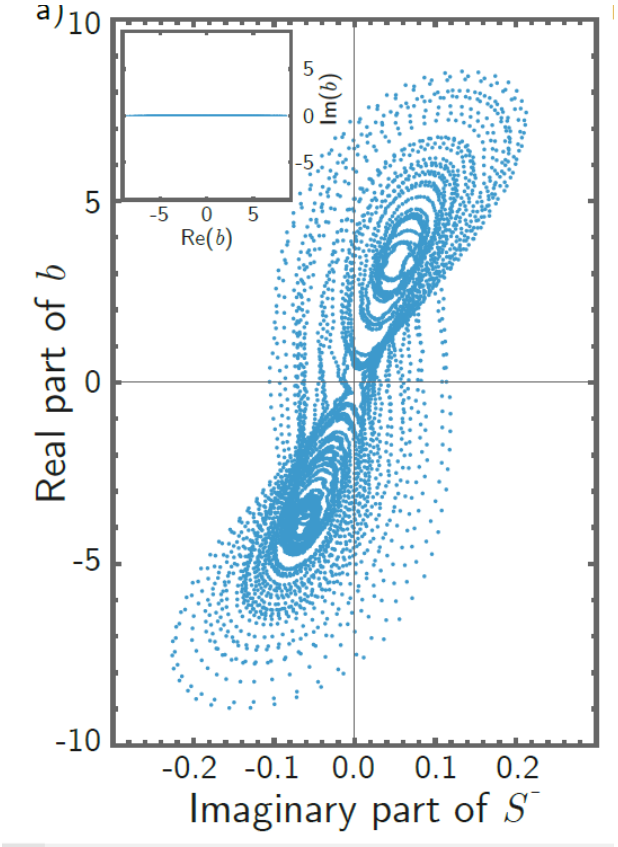
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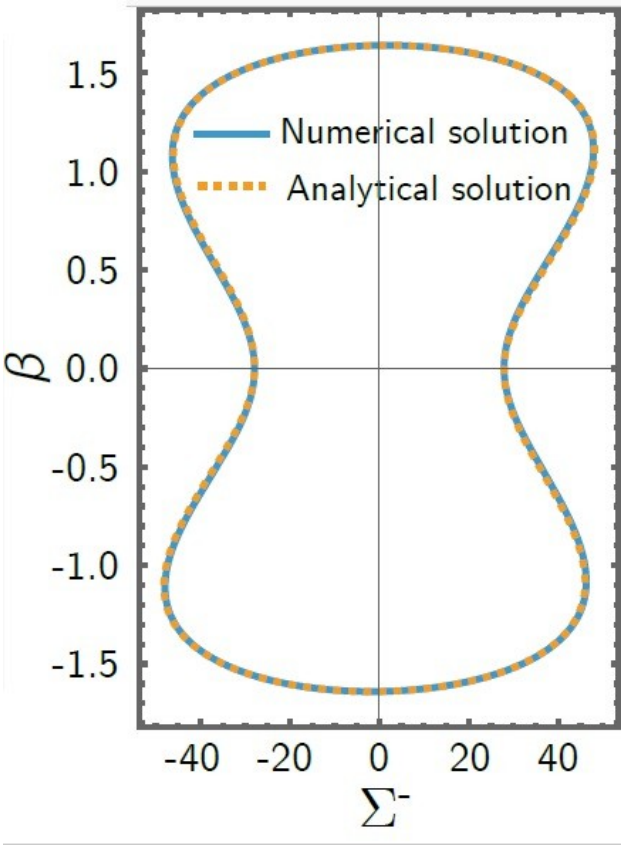
Dynamics simulation,
without any fluctuation term
(“mean field”)

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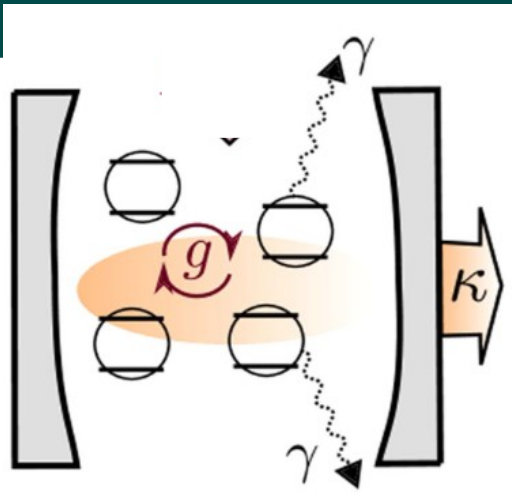


Turns into regular self-pulsing behaviour at large atom number.

Phase flip rate → $\sqrt{N/N_c}\,\Gamma_R$

(3) Stability regimes of the SR laser

Generic laser equations : <u>three</u> coupled variables



Cavity optical field $$i\frac{db}{dt} = gS^- - \frac{i}{2}\kappa b$$

Gain medium polarisation (collective electric dipole) $$i\frac{dS^-}{dt} = -2gbS^z - i\frac{\Gamma_1}{2}S^-$$

Population inversion $$i\frac{dS^z}{dt} = gbS^+ - gb^\dagger S^- - i\Gamma_2(S^z - Nd_0),$$

Good cavity laser: typically assumes gain medium's polarization damps fastest:
→ "adiabatically eliminates" S- variable. Non-chaotic coupled equations.

Bad cavity laser: typically assumes cavity field damps fastest:
→ "adiabatically eliminates" b variable. Non-chaotic coupled equations.

In the latter case, when N> Nc* , the approximation becomes invalid
→ **<u>three</u>** <u>non-linearly coupled parameters,</u> **<u>allowing for chaos</u>**

H. Haken, Analogy between higher instabilities in fluids and lasers, Physics Letters A 53, 77–78, (1975)

<u>Numbers:</u> Nc = 11 Nc on our apparatus, within reach for experimental study.*
Luckily, Nc >> Nc for a machine designed to maximise metrological figures of merit.*

Conclusion

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J. Huckans, Commonwealth university

(1) On-the-fly excitation in an atomic beam, with MHz Doppler shifts, demonstrated.
Cleaner π transition transfer ongoing.
P*ublication in preparation*

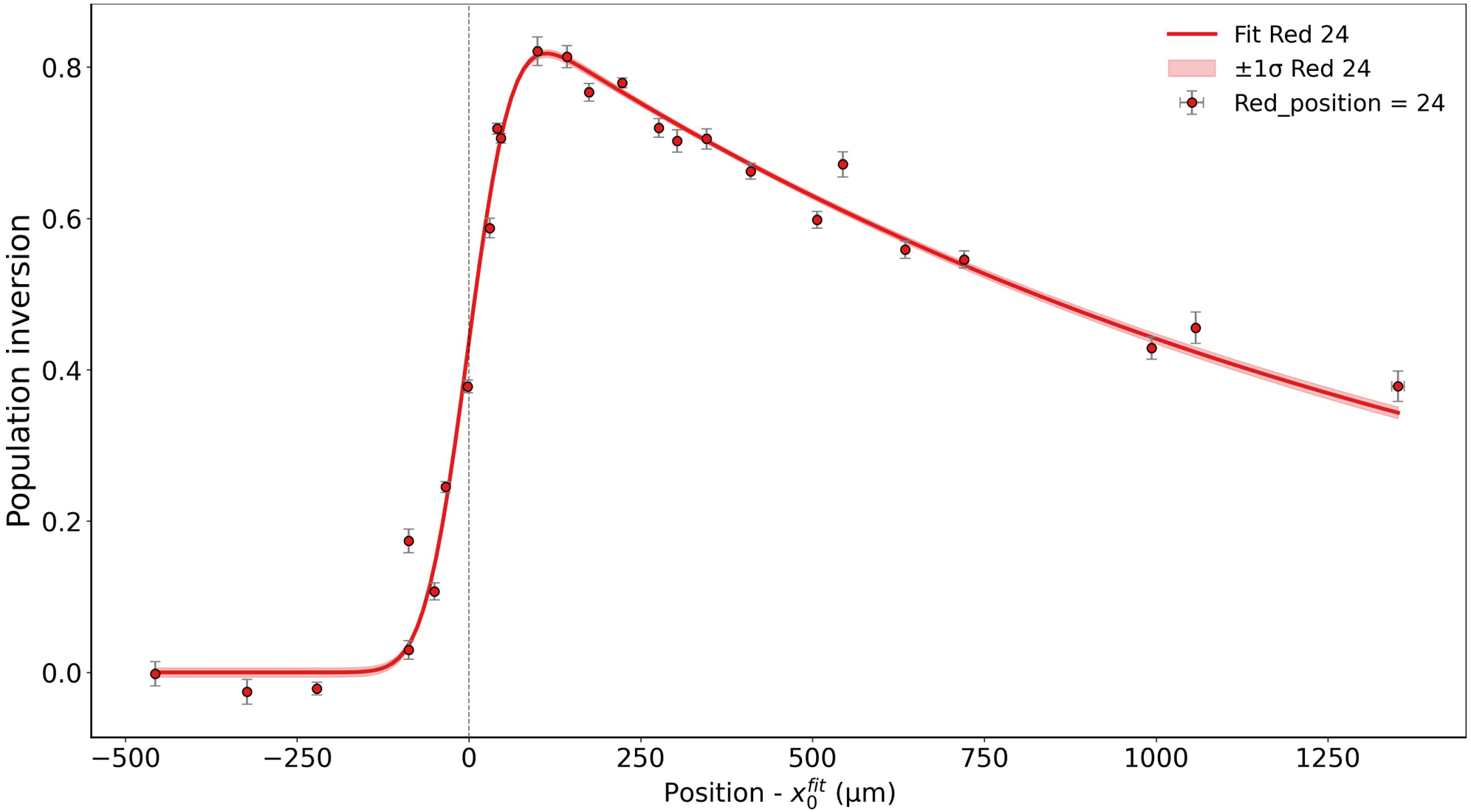
- Cavity spectroscopy detects the state preparation.
Now perfecting the atomic beam directionality to progress towards superradiance

(2) Towards correlation measurements: a photon-g^2 extraction capability implemented and characterized

(3) Stability regimes:
(re-)discovery of the Lorenz-Haken model, predicting chaos and self-pulsing
Laburthe-Tolra et al, arXiv:2606.21675
Consequences for optical references with N approaching Nc ?*

A promising collaboration dynamics triggered within France (M. Delehaye, J. Lodewyck) and at european scale (F. Schreck, G. Kazakov, ...)

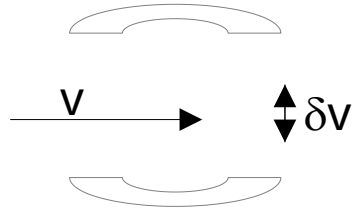
Allowable travel distance

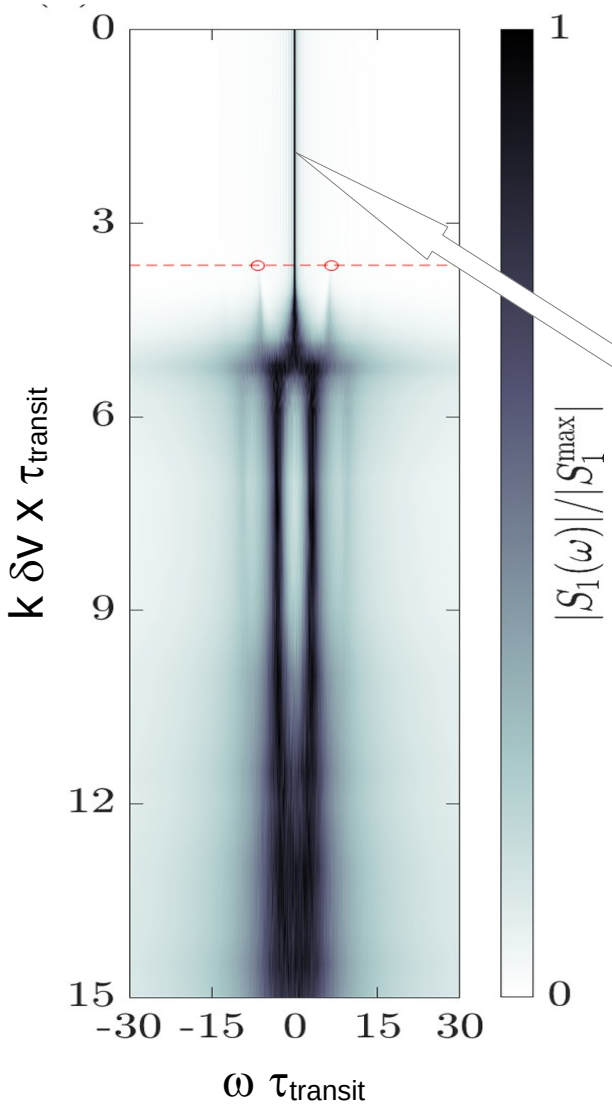


Excitation decay 1/e lengthscale 820 μm (velocity 60 m/s)

Our architecture for an atomic-beam SR laser

Tunable transit time and Doppler shift distribution



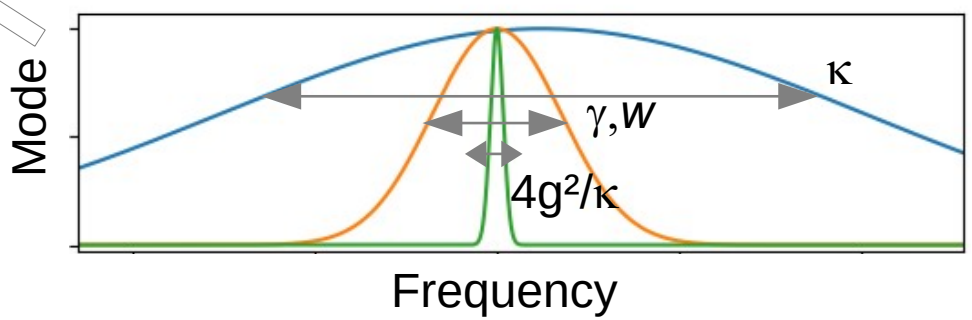


Theory / S. Jäger et al,
Phys. Rev. A, vol. 104,
page 033711, 2021

For Doppler spread k δv = 200 kHz,
with 2 10^9 atoms /s through mode,

our experiment at beam velocity 50 m/s

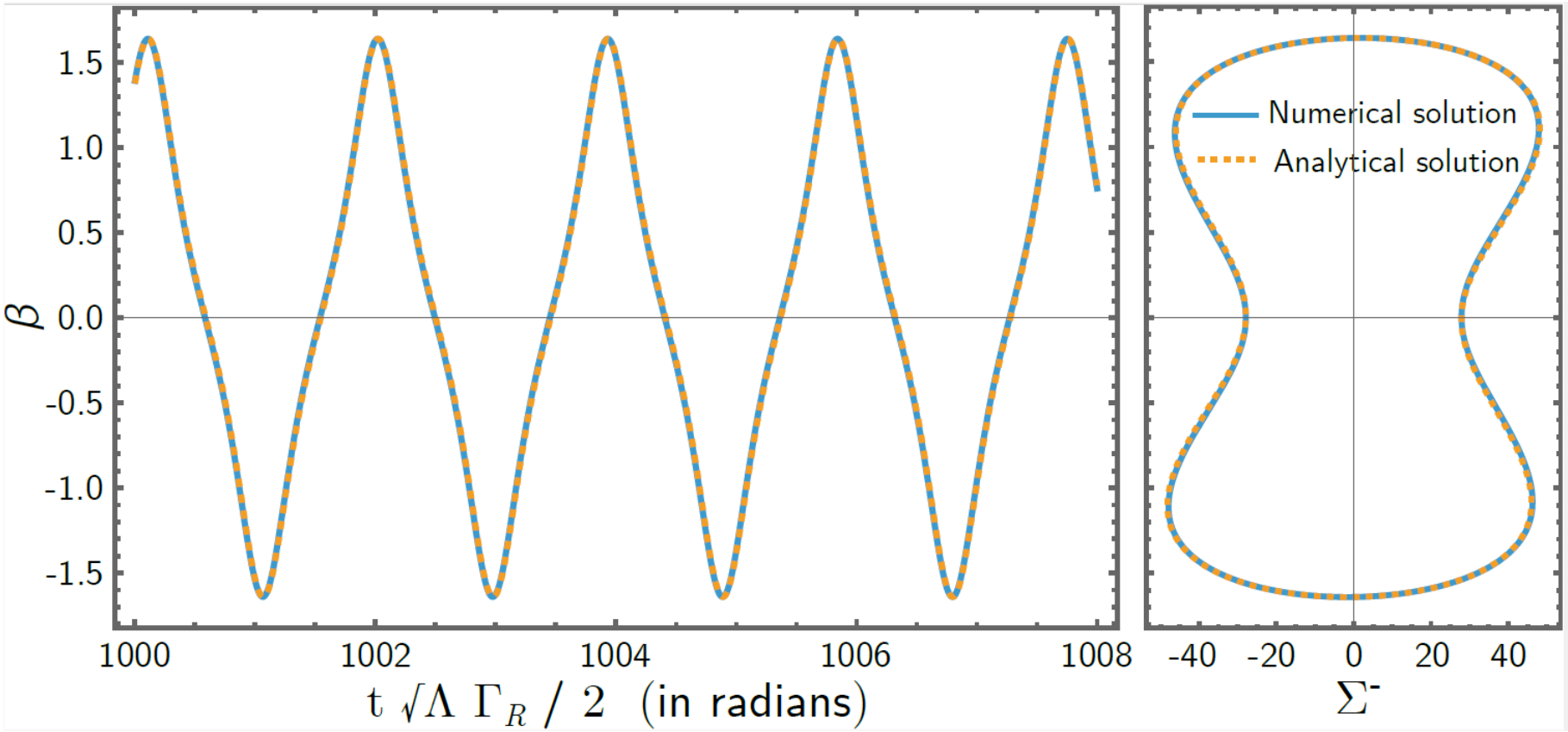
Linewidth ~ $4g^2/\kappa$ << γ



For us, w ~ 100 kHz,
γ = 7 kHz
$4g^2/\kappa$ ~700 Hz

Stability regimes of the SR laser

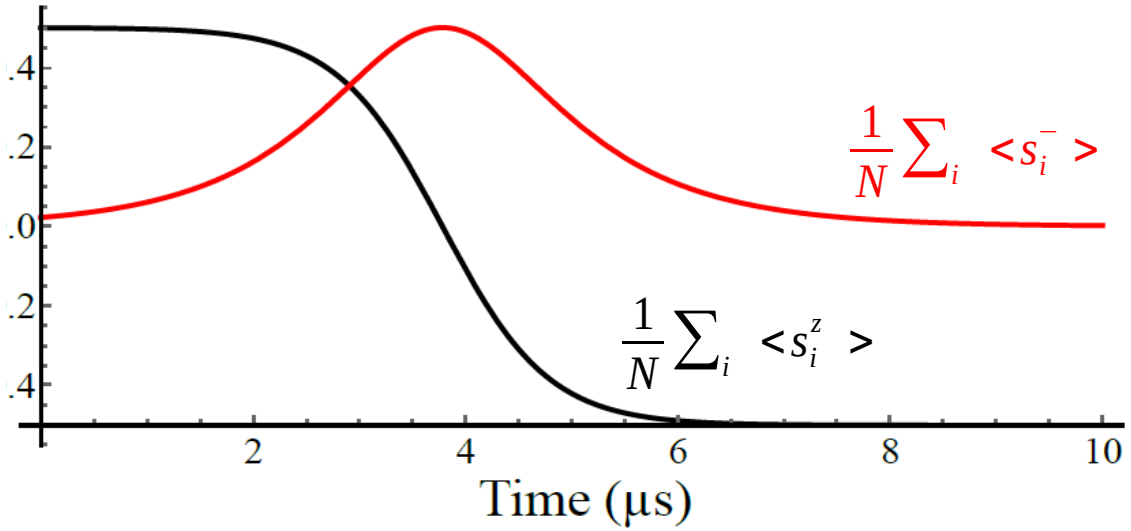
arXiv:2606.21675 : Instabilities of the continuous superradiant laser



Turns into regular self-pulsing behaviour at large atom number

Static situation

Laburthe-Tolra et al, Scipost Physics Core 6, 015



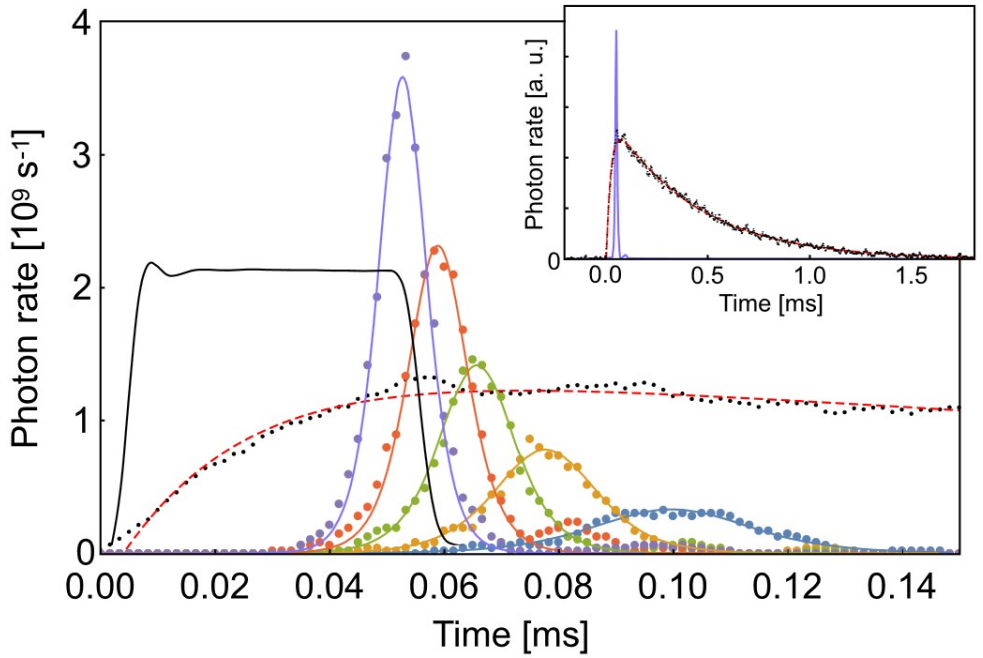
Superradiant pulse if

$$(N_e - N_g)\frac{g^2}{\kappa\gamma} > \frac{1}{4}$$

Also expressed as

$$(N_e - N_g)C > \frac{1}{4}$$

Pulse duration < 1/γ



Laske et al, PRL 123, 103601 (2019)

Our architecture

Strontium 88 superradiant laser on the 7 kHz wide intercombination line $^1S_0 \rightarrow {}^3P_1$

