LETTER

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A steady-state superradiant laser with less than one intracavity photon

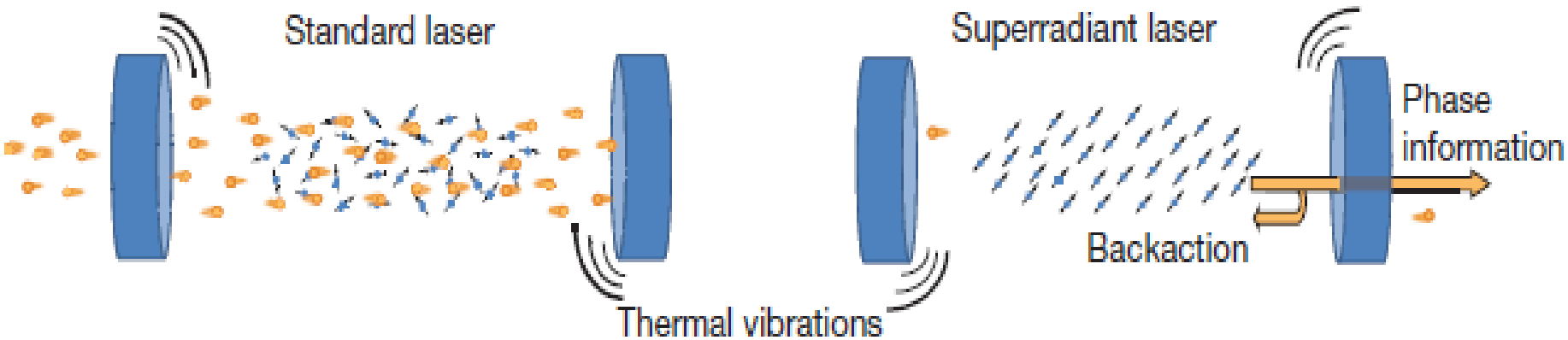
Justin G. Bohnet[1], Zilong Chen[1], Joshua M. Weiner[1], Dominic Meiser[1]†, Murray J. Holland[1] & James K. Thompson[1]

operate deep in the 'bad-cavity', or superradiant, regime, where the bare atomic linewidth is much less than the cavity linewidth. Here we demonstrate a Raman superradiant laser source in which spontaneous synchronization of more than one million rubidium-87 atomic dipoles is continuously sustained by less than 0.2 photons on average inside the optical cavity. By operating at low intracavity photon number, we demonstrate isolation of the collective atomic dipole from the environment by a factor of more than ten thousand, as characterized by cavity frequency pulling measurements. The emitted light has a frequency linewidth, measured relative to the Raman dressing laser, that is less than that of single-particle decoherence linewidths and more than ten thousand times less than the quantum linewidth limit typically applied to 'good-cavity' optical lasers[10], for which the cavity linewidth is much less than the atomic linewidth. These results demonstrate several key predictions for future superradiant lasers, which could be used to improve the stability of passive atomic clocks[3] and which may lead to new searches for physics beyond the standard model[11,12].

Superradiance

The weak intracavity photon field acts mainly as a communication bus to drive spontaneous synchronization of the atomic dipoles and to extract information about the phase stored in the collective atomic dipole. The synchronized atomic dipoles radiate at an increased rate, a phenomenon known as superradiance or superfluorescence.

Theory



good-cavity laser

many photons

incoherent atom

bad-cavity laser

Continuous stimulated emission
Less than one photon in cavity

Collective atomic dipole stores the coherence

Schawlow-Townes full-width at half-maximum

calculated the fundamental (quantum) limit for the linewidth of a laser

$$\Delta f_{\mathrm{ST}} = \frac{1}{4\pi}\frac{hf}{P_{\mathrm{out}}}\left(\frac{2\gamma_{\perp}\kappa}{2\gamma_{\perp}+\kappa}\right)^{2}$$

P_{OUT} **: power exiting the cavity**

f **: oscillation frequency**

h **: Planck's constant**

k **: cavity power decay rate**

Schawlow-Townes full-width at half-maximum

$$\Delta f_{\mathrm{ST}} = \frac{1}{4\pi}\frac{hf}{P_{\mathrm{out}}}\left(\frac{2\gamma_{\perp}\kappa}{2\gamma_{\perp}+\kappa}\right)^{2}$$

$$\gamma_{\perp} = \gamma_{\mathrm{eg}}/2 + 1/T_2$$

The transverse decoherence rate of the lasing optical transition

r_{eg} **: rate of decay from the excited state to the ground state**

$1/T_2$ **: additional atomic dephasing mechanism**

Frequency pulling coefficient

Cavity frequency, atomic frequency is not identical system average frequency is,

$$f = (2\gamma_\perp f_{\mathrm{cav}} + \kappa f_{\mathrm{atomic}})/(2\gamma_\perp + \kappa).$$

The cavity frequency changes the oscillation frequency from the atomic transition frequency by an amount

$$P \equiv \mathrm{d}f/\mathrm{d}f_{\mathrm{cav}} = 2\gamma_\perp/(2\gamma_\perp + \kappa).$$

Theory

Good-cavity $(2\gamma_\perp \gg \kappa)$:

$$\Delta f_{GST} = \frac{k}{4\pi M_c}$$

$$P \approx 1$$

Bad-cavity $(2\gamma_\perp \ll \kappa)$

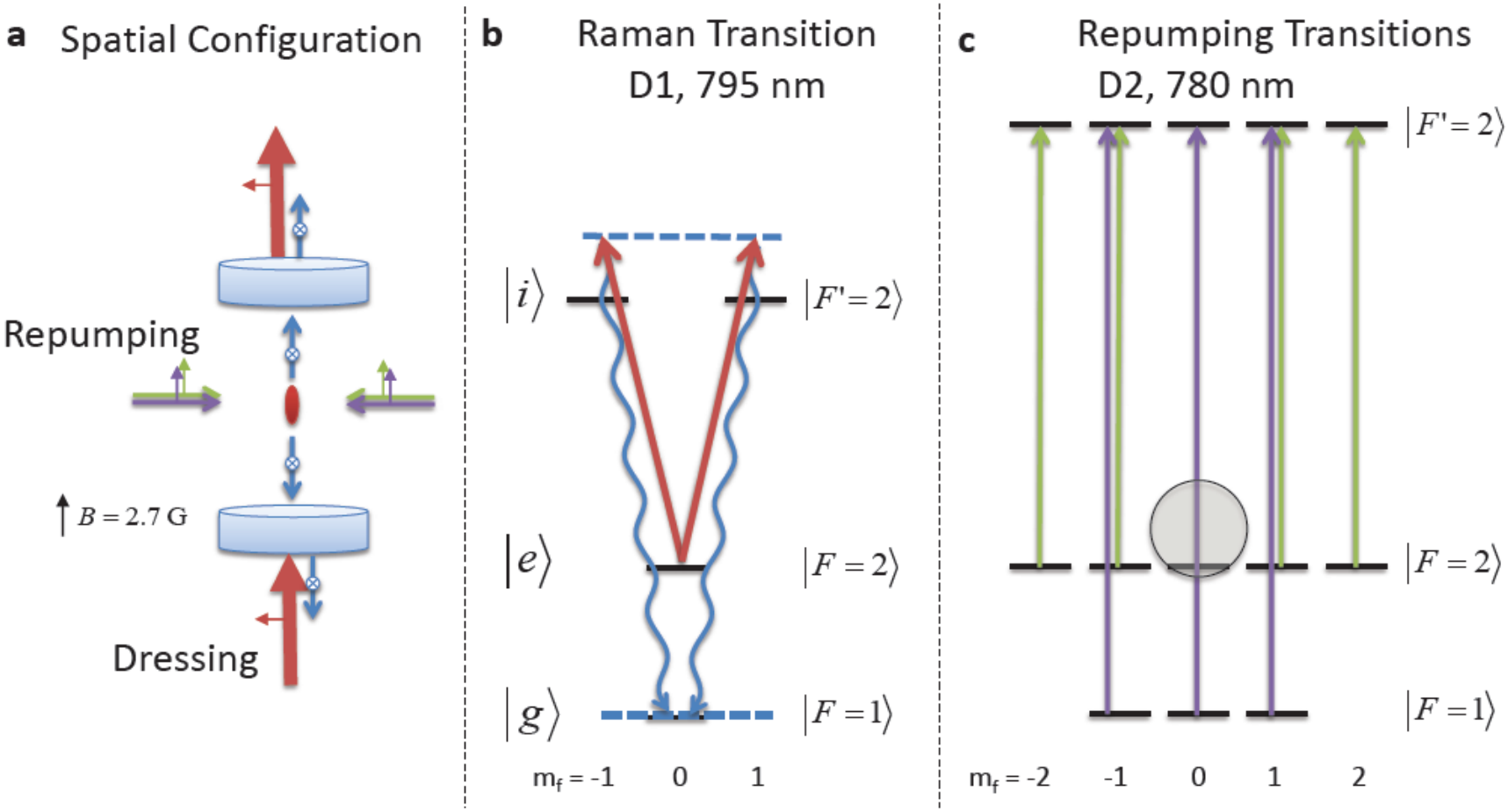
$$\Delta f_{GST} = \frac{(r_\perp)^2}{\pi k M_c}$$

$$P \ll 1$$

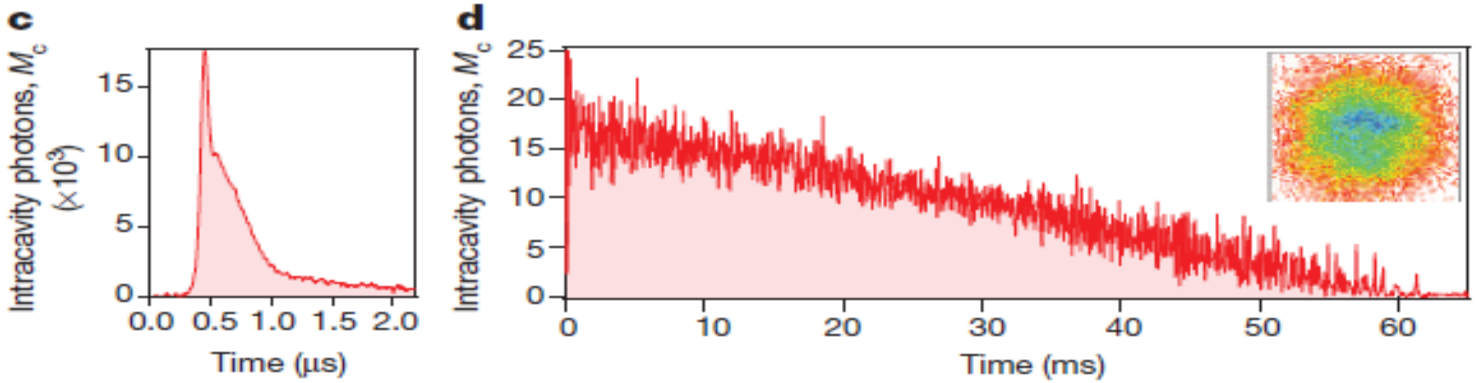
Bad cavity $P \ll 1$

Drastically, reducing the impact of noise in the cavity frequency

Experiment


a
Spatial Configuration
Repumping
$B = 2.7$ G
Dressing
b
Raman Transition
D1, 795 nm
$|i\rangle$
$|F' = 2\rangle$
$|e\rangle$
$|F = 2\rangle$
$|g\rangle$
$|F = 1\rangle$
$m_f = -1$ 0 1
c
Repumping Transitions
D2, 780 nm
$|F' = 2\rangle$
$|F = 2\rangle$
$|F = 1\rangle$
$m_f = -2$ -1 0 1 2

Experiment



c. With no repumping light a single superradiant pulse is emitted

d. With optical repumping back to e state, we observe quasi-continuous emission limited by atom loss.
The atoms emit into a single spatial mode of the cavity (TEM00) imaged on a charge-coupled device