Superradiance on the milihertz linewidth strontium clock transition

2016-11-07

QFLL Journal club

James K. thompson

- Ph.D @ MIT, with D. E. Pritchard
  - Precision measurement with Ion trap
- Post doc with V. Vuletic
  - Atomic quantum memory
  - Entangled photon source
- Current interest
  - Superradiant laser
  - Entangled spin-squeezed states

A superradiant laser

- A laser working in superradiant regime
- Theoretical suggestion
  - D. meiser and M.J. Holland, "Steady-state superradiance with alkaline-earth-metal atoms" PRA 2010
- Experimental realization
  - Raman superradiant laser with Rb-87 atoms
    - J. G. Bohnet et al, "A steady-state superradiant laser with less than one intracavity photon" Nature 2012
  - Superradiance of Sr-87 atoms

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICAL SCIENCE

Superradiance on the millihertz linewidth strontium clock transition

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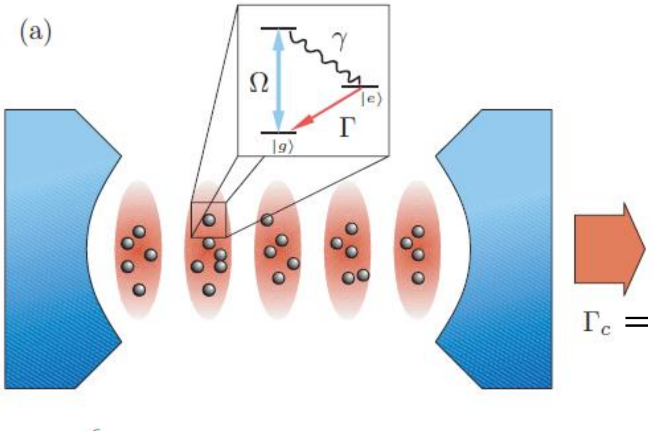
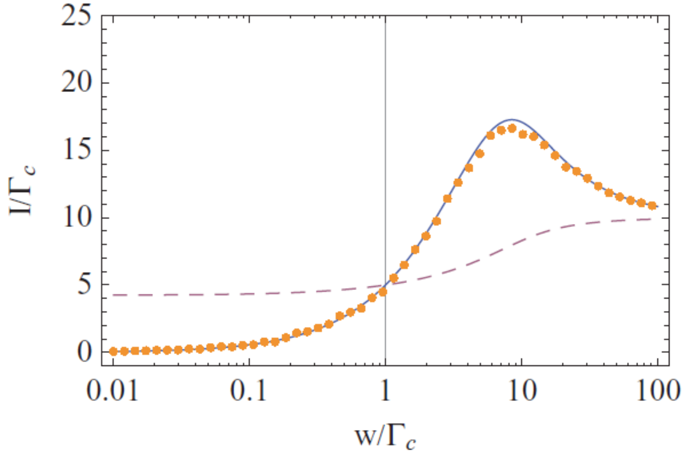
Steady-state superradiance (theory)

D. meiser and M.J. Holland, PRA 81, 033847 (2010)



$\Gamma_c = \dfrac{g^2}{\kappa}$



$$\frac{d\hat{\rho}}{dt} = -\frac{\Gamma_c}{2}(\hat{J}_+\hat{J}_-\hat{\rho} + \hat{\rho}\hat{J}_+\hat{J}_- - 2\hat{J}_-\hat{\rho}\hat{J}_+)$$

Cooperative decay into cavity mode

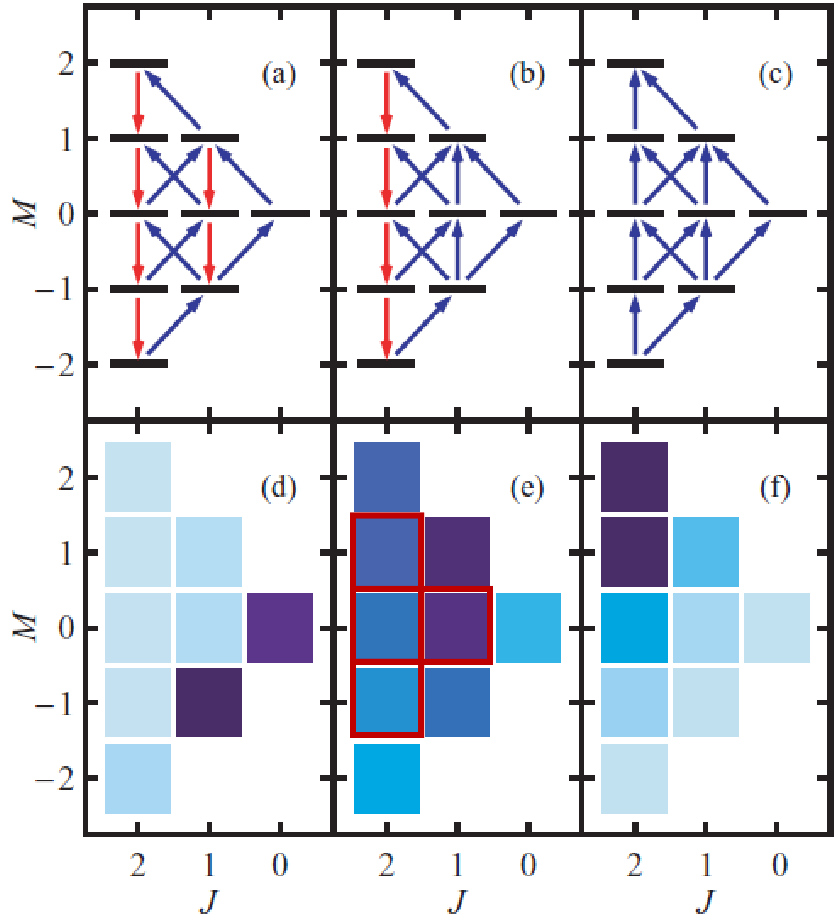
$$-\frac{w}{2}\sum_{j=1}^{N}(\hat{\sigma}_-^{(j)}\hat{\sigma}_+^{(j)}\hat{\rho} + \hat{\rho}\hat{\sigma}_-^{(j)}\hat{\sigma}_+^{(j)} - 2\hat{\sigma}_+^{(j)}\hat{\rho}\hat{\sigma}_k{-}^{(j)}).$$

Incoherent pumping of individual atoms

- Bad cavity regime
- Intermediate pumping regime $\Gamma_c < w < N\Gamma_c$
- *NC* >> 1 (collective decay dominant)
- $w \sim N\Gamma_c$ (atom repumping is fast enough)

Steady-state superradiance (theory)

D. meiser and M.J. Holland, PRA 81, 033847 (2010)

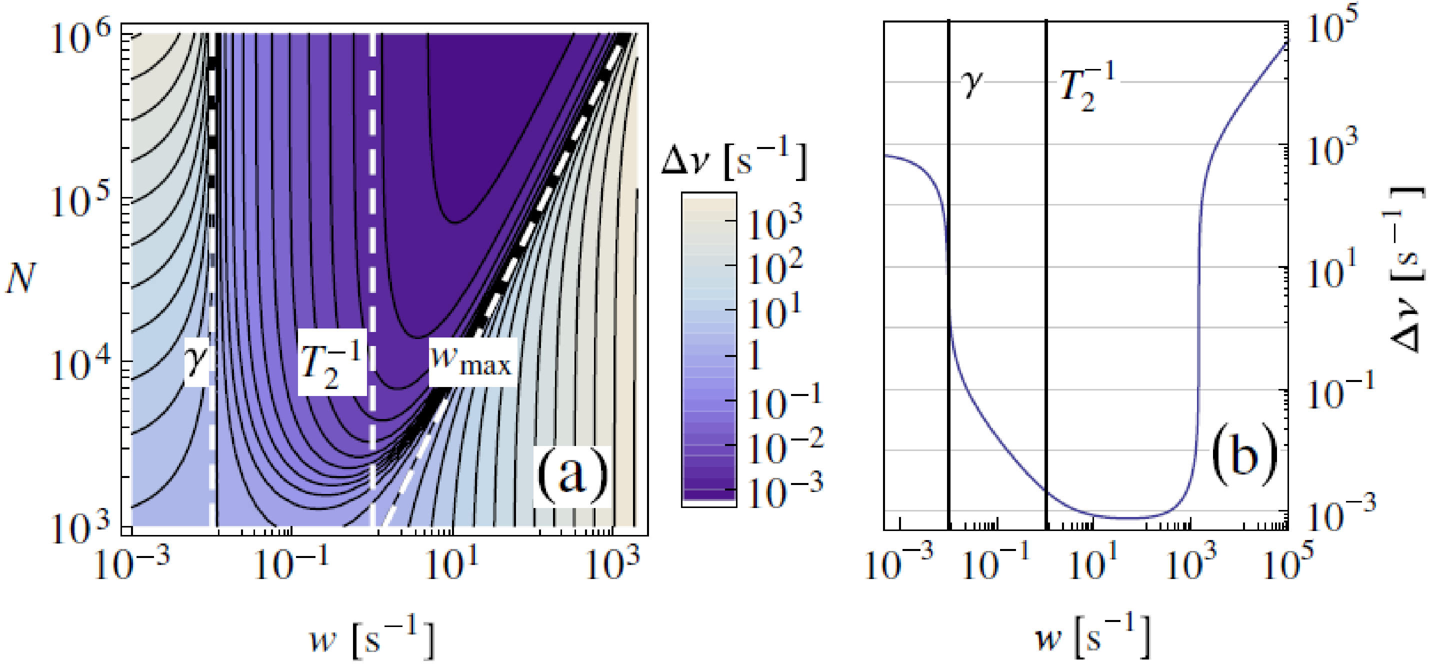


weak pumping ← w → strong pumping

- Intermediate pumping
  - J≠0 & M=0 states populated
  - superradiant decay process survives.
- Weak pumping
  - Subradiant states populated
- Strong pumping
  - Fully excited

Steady-state superradiance (theory)

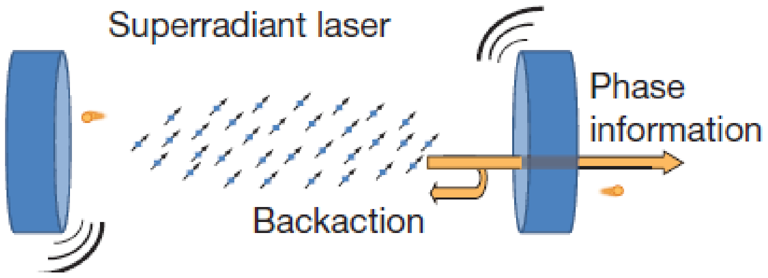
D. meiser et al, PRL 102, 163601 (2009)

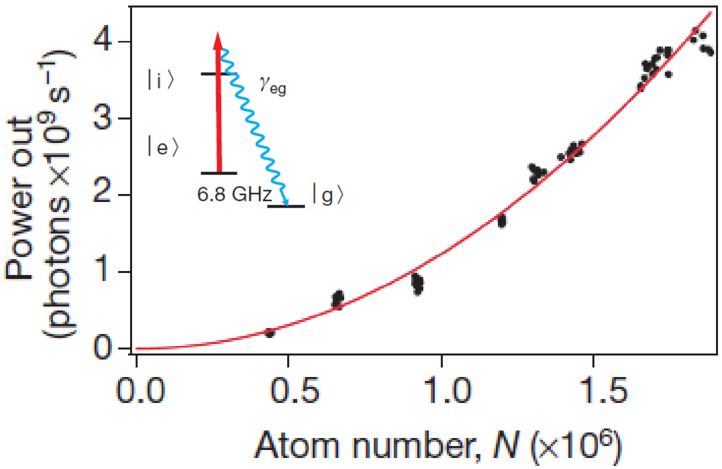


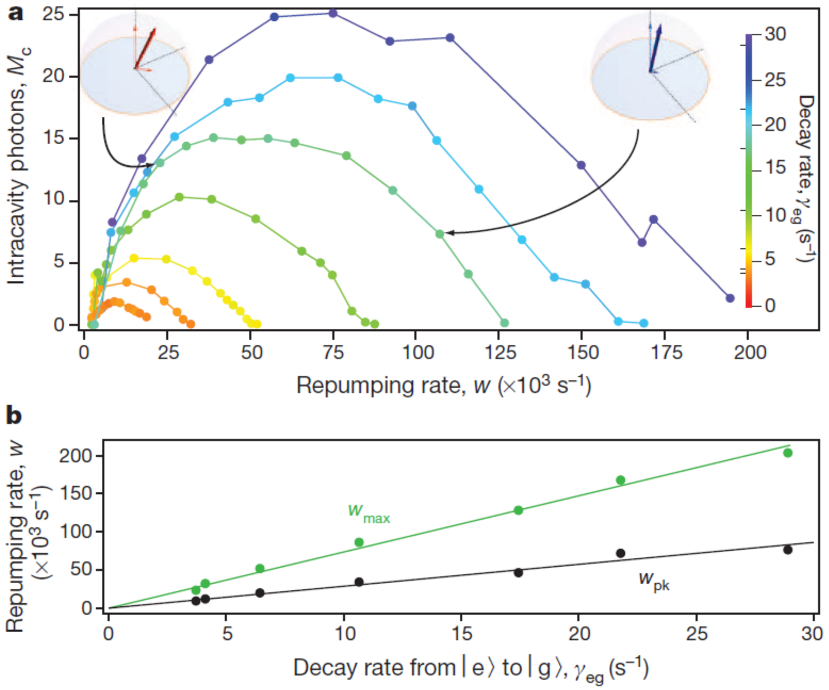
- Minimum laser linewidth $\Delta\nu = C\gamma$
- Less frequency pulling $P \approx \frac{2\gamma}{\kappa} \ll 1$

Raman superradiant laser (former exp.)

J. Bohnet et al, Nature 484, 78 (2012)

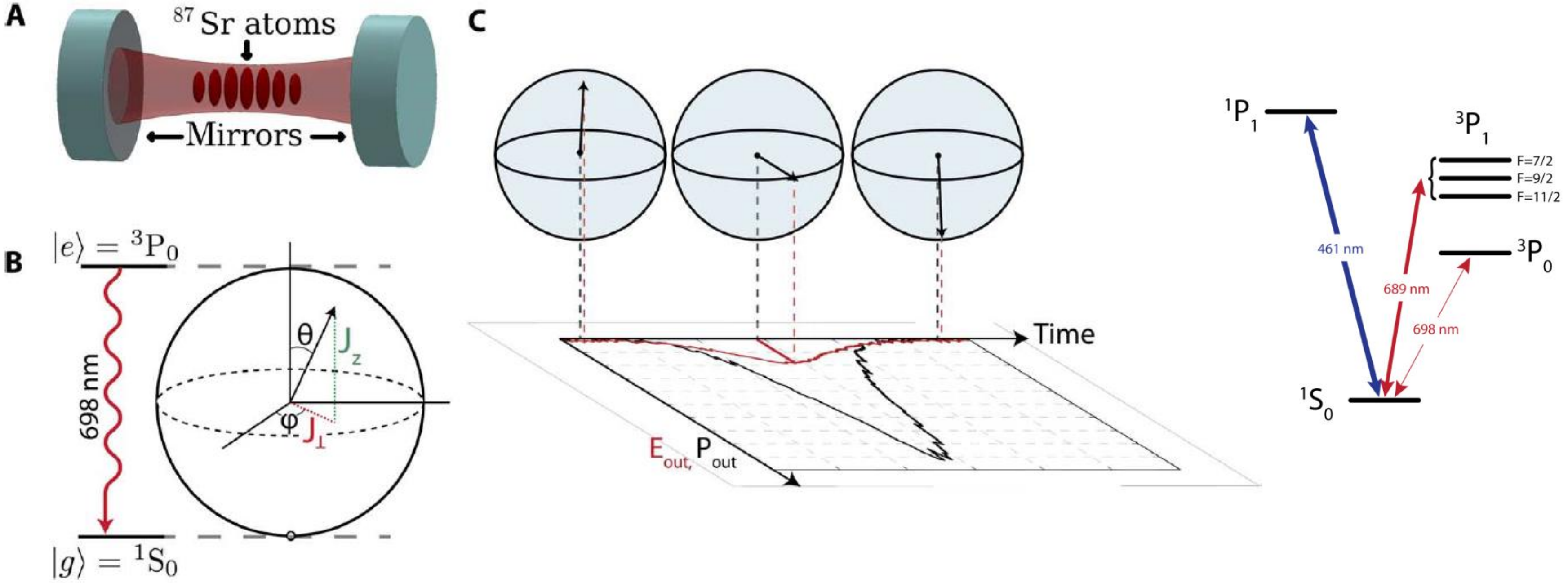






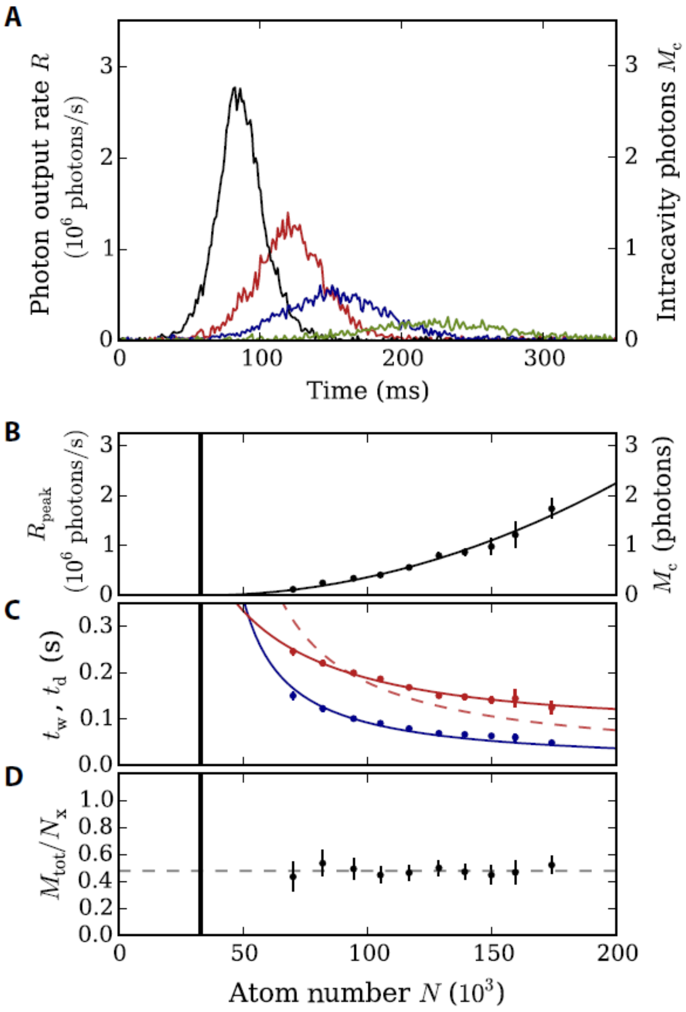
- Rb-87 atoms. Raman lasing process.
- N^2 emission, superradiance quenching due to strong repumping, narrow linewidth of 350Hz

Superradinace of Sr atoms in cavity



- ^{87}Sr atoms (Group II) : $^1S_0$ to $^3P_0$ - 698nm (1mHz linewidth)
  - 2.5 * 10^5 atoms Loaded on optical lattice (magic wavelength of 813nm)
  - Cavity finense 2.4 × 10^4 , $\kappa = 2\pi \times 160$kHz
  - Single atom cooperativity = 0.33, $g = 2\pi \times 3.7$Hz @ max. coupling
- Adiabatic transfer (sideband pump beam freq swept 200khz in 20ms)
  - Pumping efficiency = 75%
  - Kick ground state atoms by heating beam (461nm)

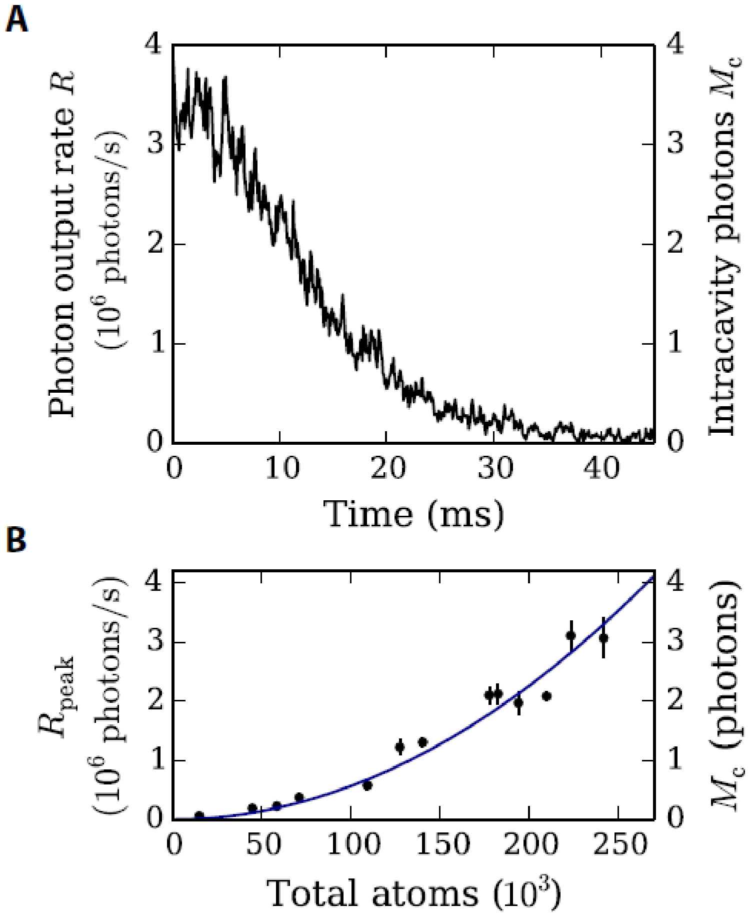
Superradinace of Sr atoms in cavity



- Superradiance pulse
- Varing atom number
  - B. $R_{\mathrm{peak}} = \frac{1}{4\xi} N_x^2 C\gamma,$ $N_x = N - N_t$, $N_t = 3.3 \times 10^4$
  - C. pulse delay $t_d \approx \frac{2(\ln N + \gamma_e)}{N_x C\gamma}$

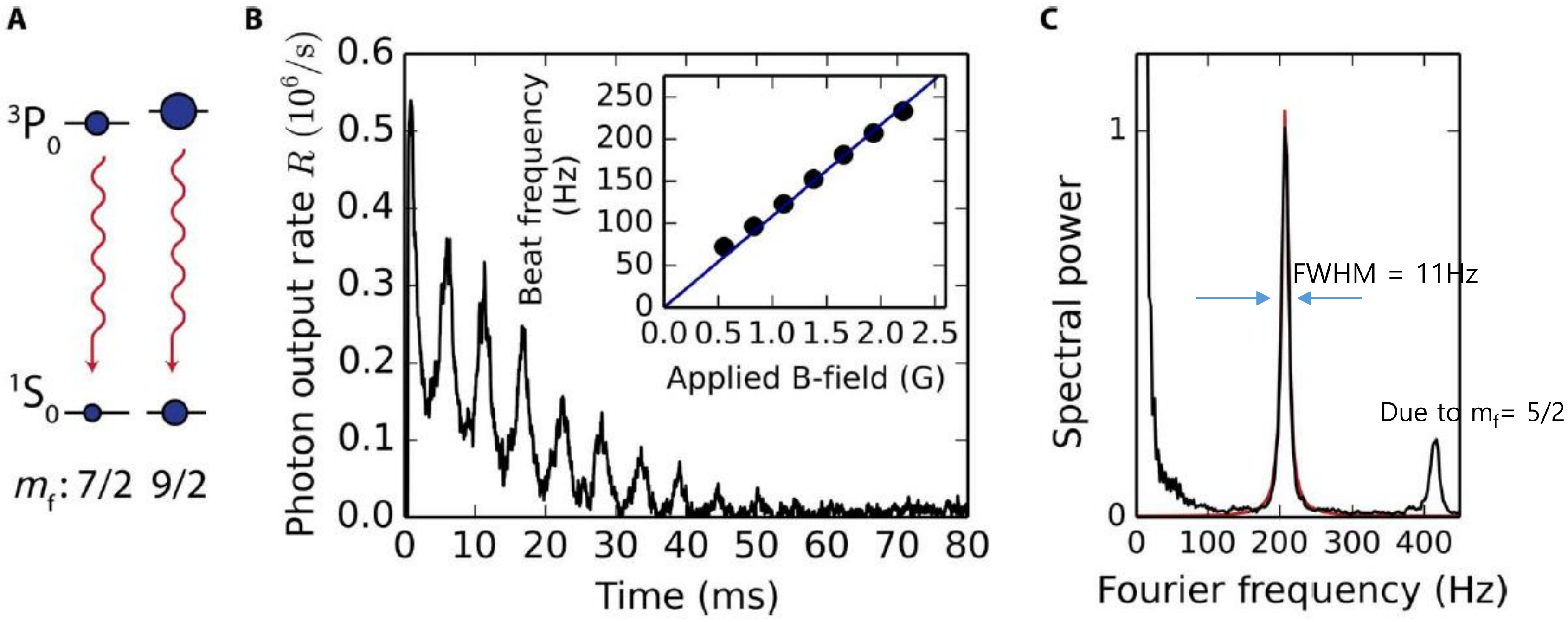
    pulse width $t_w \approx 7.05/(N_x C\gamma)$
  - D. integrated photon number M_{tot} = atom number participated with superradiance

Seeding atomic coherence



- Adiabatic transfer in superposition state.
- Pump field couple to cavity mode → phase coherence conserved.
- No threshold or delay time

Two-color superradiance



FWHM = 11Hz

Due to m_f= 5/2

- Initial preparation ; both populated in m_f=7/2 and 9/2
- Beating of two color emission.

Comparison of two exp.

Raman superradiant laser with Rb-87

Nature 2012

- Raman lasing
  - No clock transition (too fast decay rate) → need controllable transition
  - Easy to make incoherent continuous repumping
  - Raman control laser limit the final linewidth of superradinat laser

Superradiance with Sr-87

Science 2016

- Two-level superradinace
  - Using clock transition (appropriate decay rate)
  - Hard to establish incoherent continuous pumping → why CW operation is yet demonstrated, but they will find the way…
  - Better linewidth (?) than former exp. ~ 350(25)Hz
- Seeding coherence
  - It will not work in cw way.