Coherent Light Scattering from Optically Dense Cold Atomic Gases

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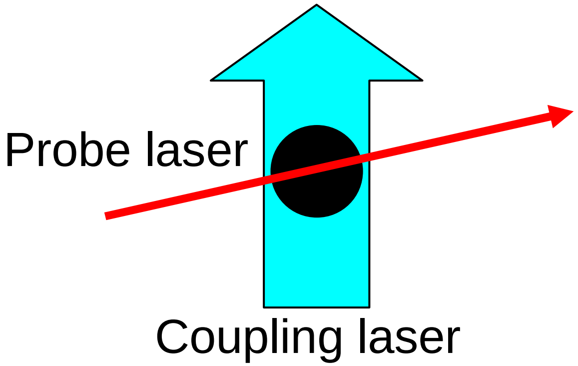
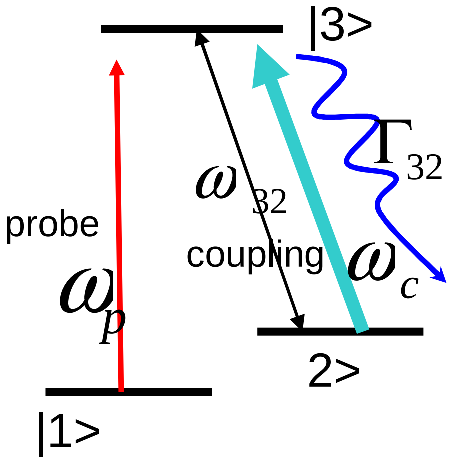
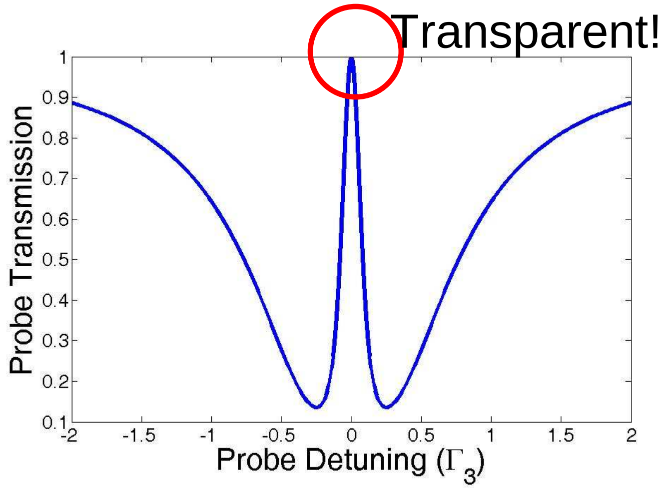
Institute of Atomic & Molecular Sciences, Academia Sinica

IAMS

Research Project: Nonlinear Optics and Quantum Memory based on Electromagnetically Induced Transparency (EIT)







$$\left| dark \right\rangle = \cos\theta \left| 1 \right\rangle - \sin\theta \left| 2 \right\rangle$$

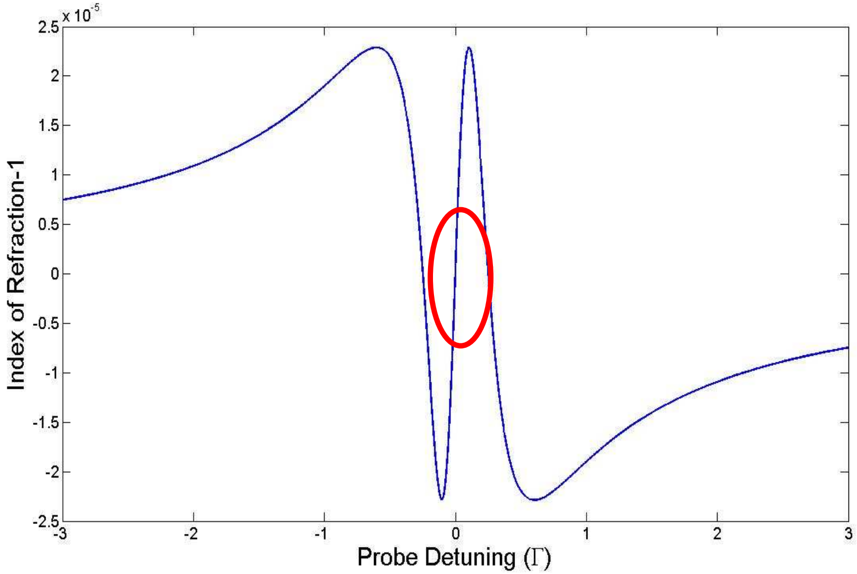
Diagonalize the Hamiltonian $H=H_A+H_{AC}+H_{AP}$

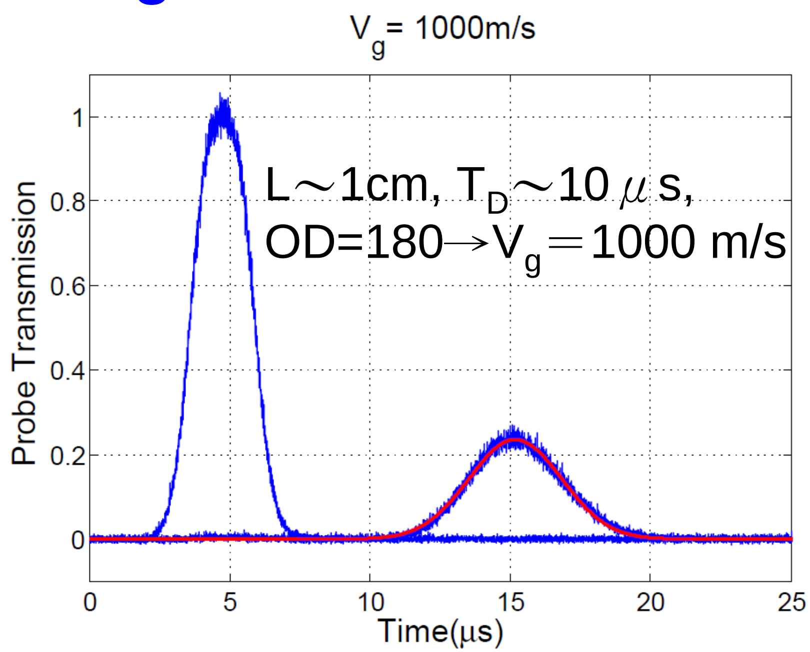
$$\tan\theta = \frac{\Omega_p}{\Omega_c}$$

$$\left\langle 3 \right| \vec{d} \bullet \vec{E} \left| dark \right\rangle = 0$$

For a review, see Rev. Mod. Phys. 77, 633,2005

EIT & Slow Light





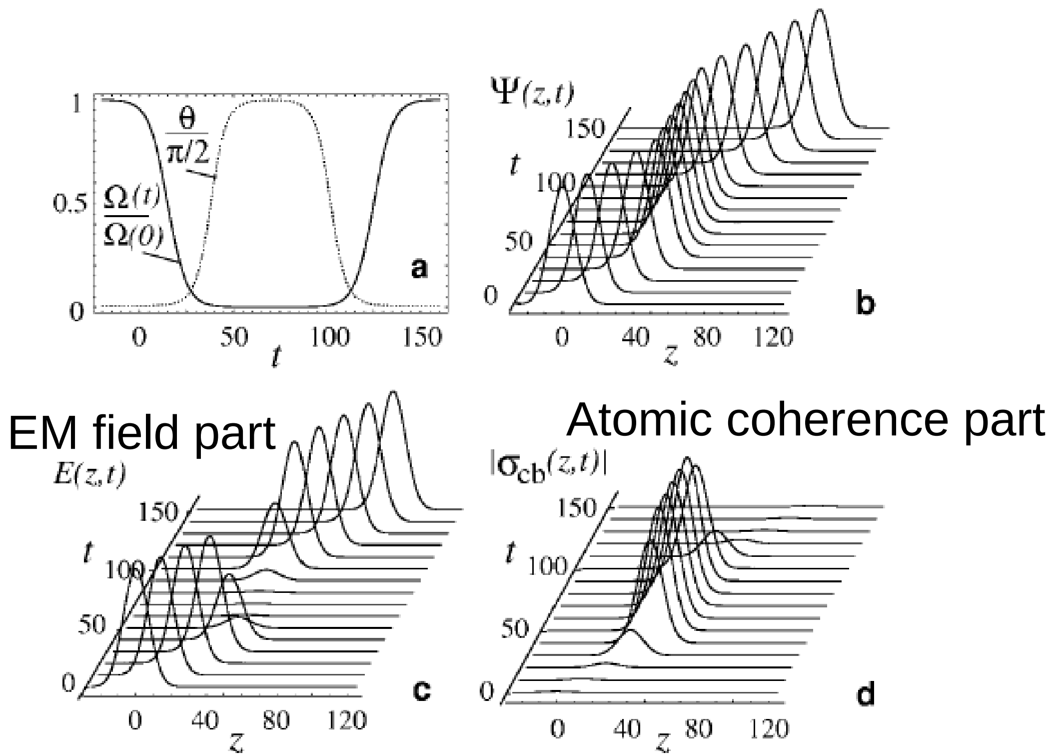
$$\omega_p(k_p) = ck_p / n(\omega_p)$$

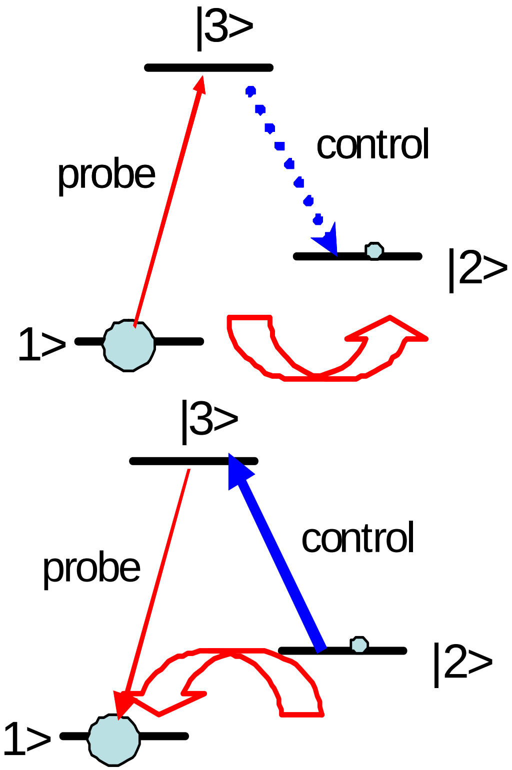
$$v_g = \frac{d\omega_p}{dk_p}\Big|_{\delta_p=0} = \frac{1}{dk_p \big/ d\omega_p \big|_{\delta_p=0}} = \frac{c}{n + \omega_p (dn/d\omega_p)\big|_{\delta_p=0}} \equiv \frac{c}{n+n_g}$$

$$T_D = L\left(\frac{1}{v_g} - \frac{1}{c}\right) = \frac{n_g L}{c} = (n\sigma L)\frac{\Gamma}{\Omega_c^2 + \gamma\Gamma_{31}} \approx OD\frac{\Gamma}{\Omega_c^2}$$

Large optical depth (OD) and small ground-state decoherence rate γ are two crucial factors in all EIT-based applications !

Slow Light, Dark-State Polariton, Quantum Memory





$$\Psi(z,t) = \cos\theta\, E_p(z,t) - \sin\theta \sqrt{N}\rho_{21}(z,t)e^{i\Delta kz}$$

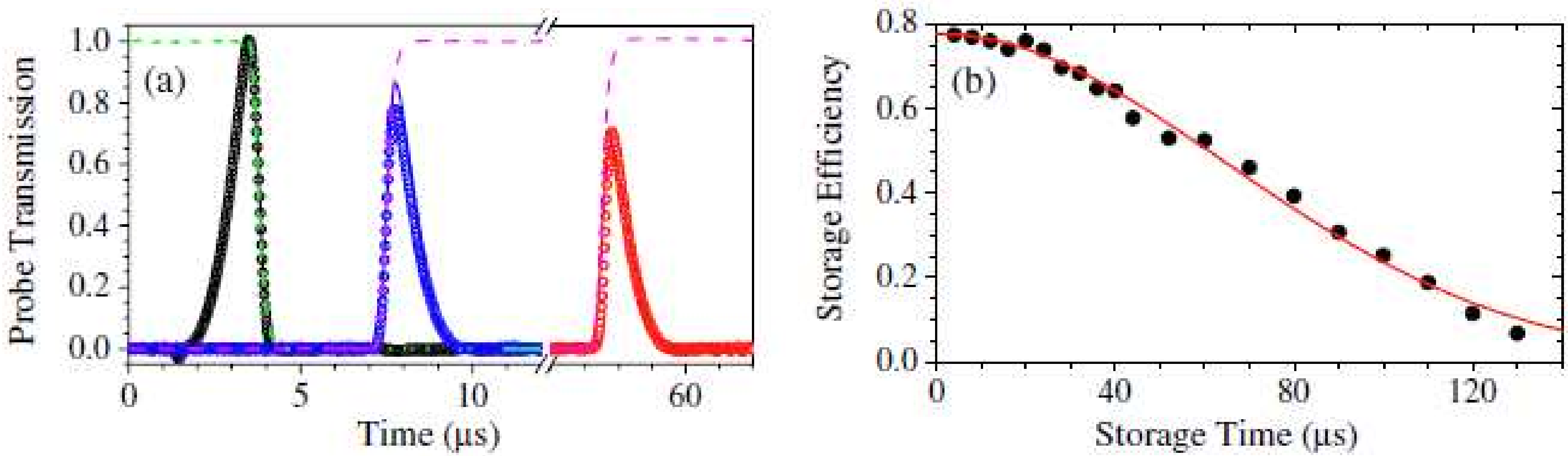
$$\tan\theta = N\frac{3\lambda^2}{2\pi}c\frac{\Gamma_{31}}{\Omega_c^2}; \Delta k = k_c - k_p$$

$$[\frac{\partial}{\partial t} + c\cos^2\theta\frac{\partial}{\partial z}]\Psi(z,t) = 0; v_g = c\cos^2\theta$$

Lukin&Fleischhauer, PRL 84,5094,2000

Storage of Light & Quantum Memory

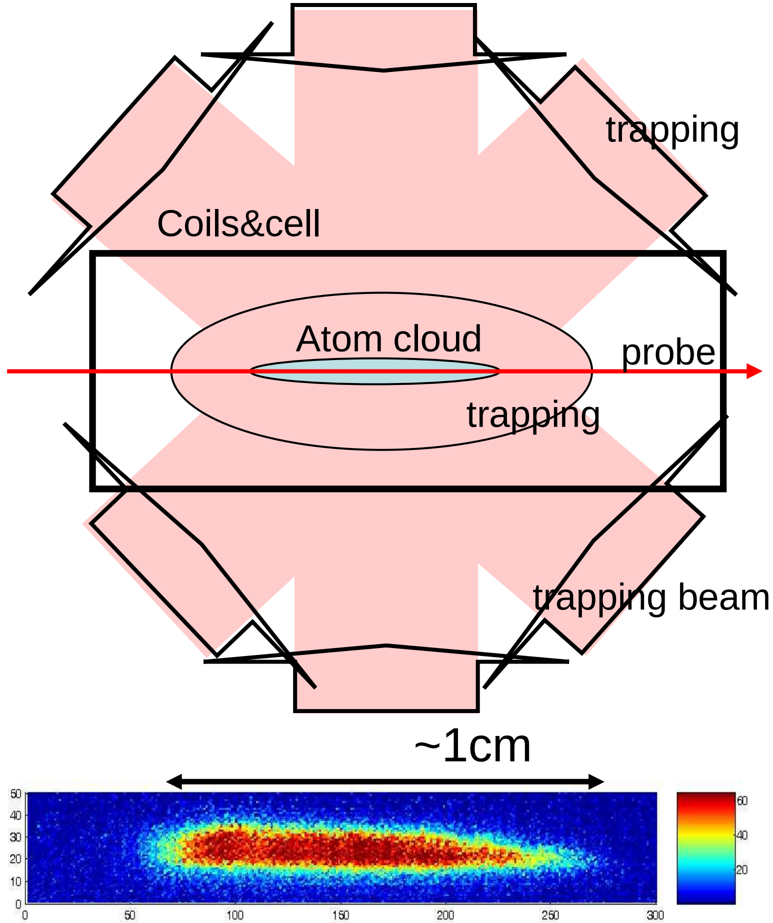
- Quantum memory to store quantum state of light which is important in long distance quantum communication.
- Storage time ~ 16 sec (cold atoms in optical lattice), or even 1 minute (solid crystal) have been achieved recently by other groups.
- Storage efficiency ~78% in EIT-based memory has been achieved by Prof. Yu's group in NTHU and us.



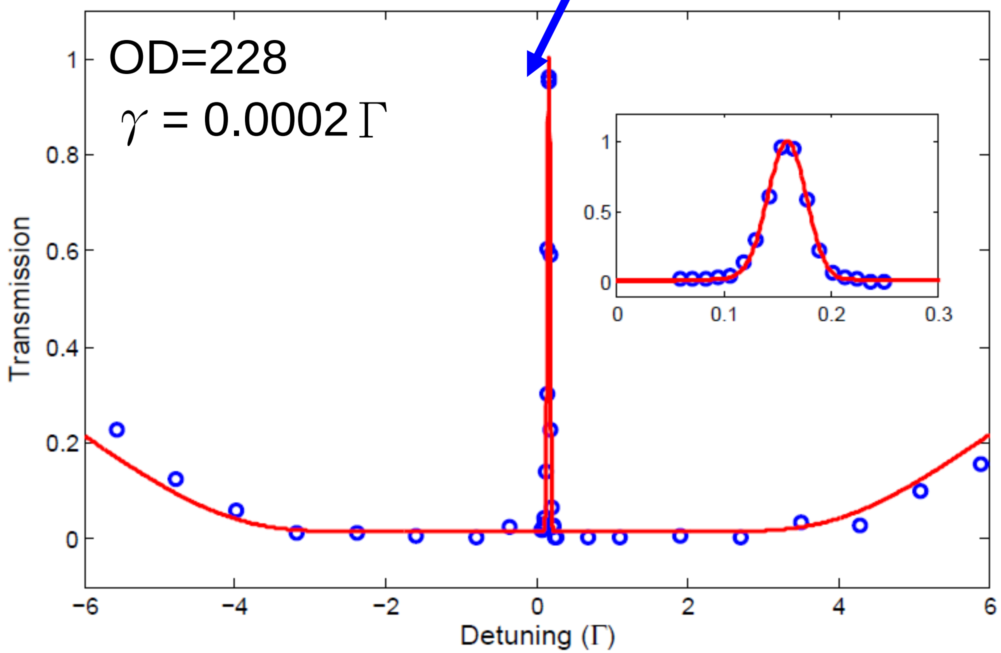
Yi-Hsin Chen et.al. Phys. Rev. Lett. 110, 083601(2013)

Dark & Compressed Two-dimensional MOT

- Large-OD cold atomic samples are routinely obtained by a combination of techniques including two-dimensional MOT, dark and compressed MOT and optical pumping.



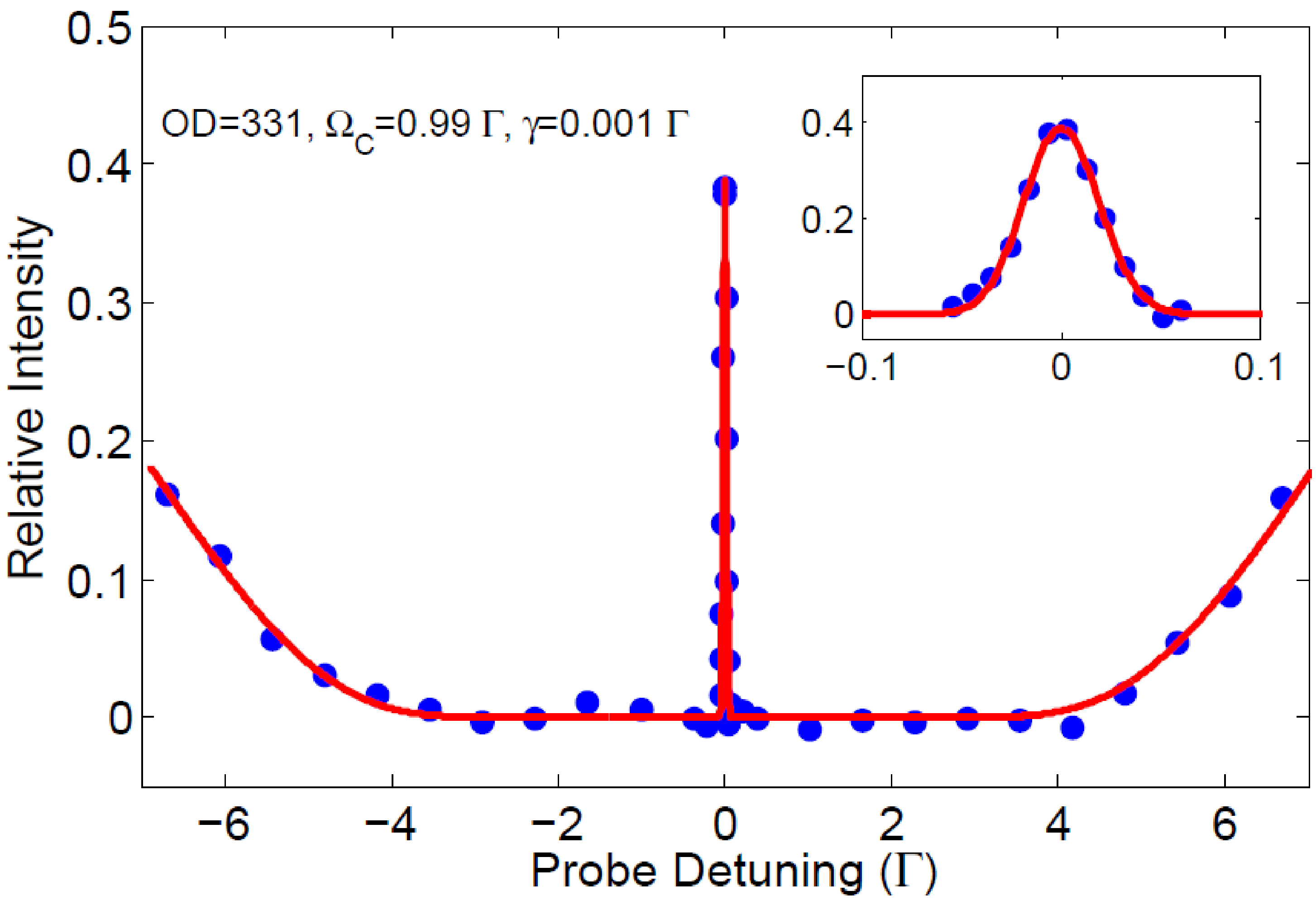
$T = e^{-228} \approx 10^{-99} \Rightarrow 0.95$ due to EIT !



W.W. Lin, H. C. Chou, P. P. Dwivedi, Y. C. Chen, I. A. Yu, Opt. Exp. 16, 3753(2008)

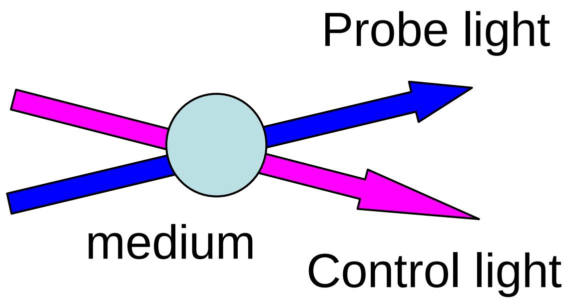
A Recent Improvements on the System

August 5, 2013, OD>300, for Cs D_2 F=3→ F'=4 transition

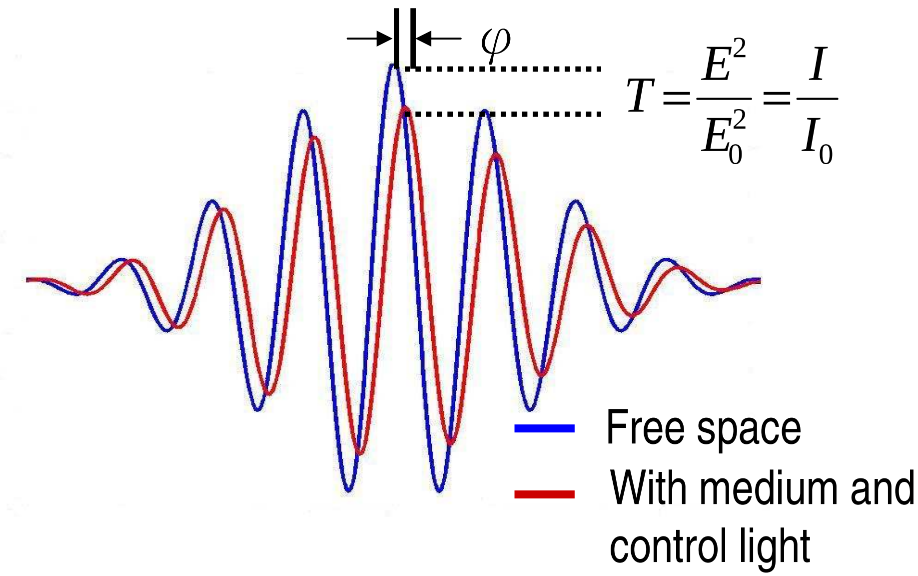


Nonlinear Interaction between Photons

- Controlling light by light is through the cross-Kerr effect.



Manipulation of photon by photon via matter (atoms…etc)

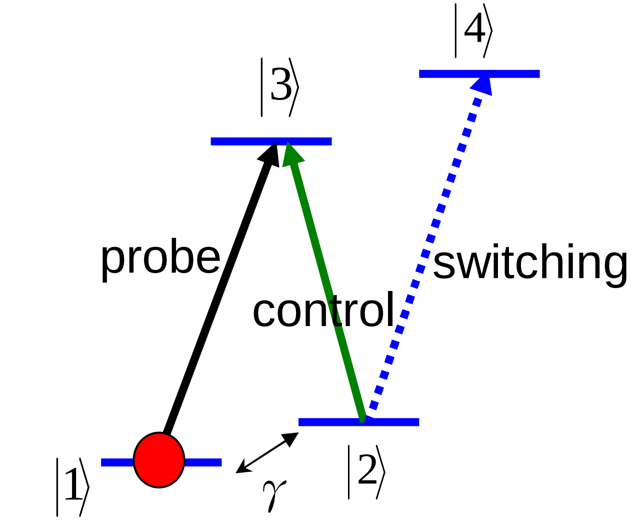


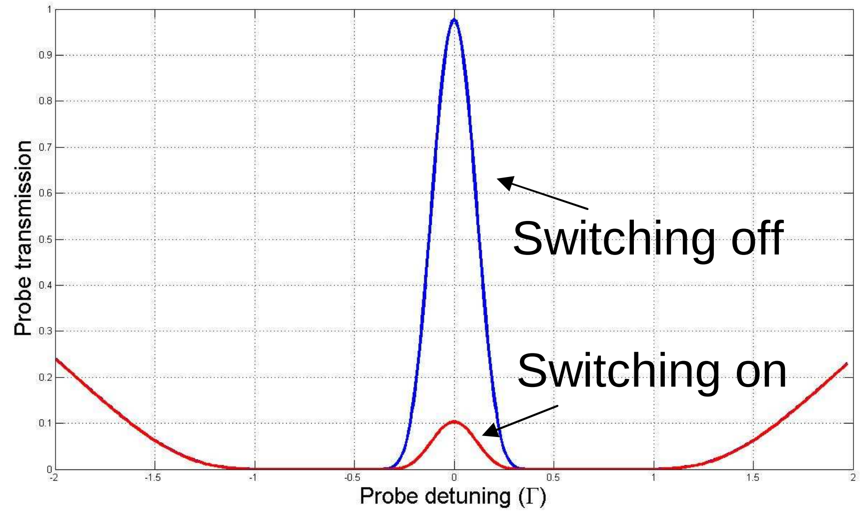
φ : **Cross-phase modulation** (XPM), controlling the **phase** of light by light, $\propto \mathrm{Re}[\chi^{(3,cross-Kerr)}]$

T : **All-optical switching** (AOS), controlling the **intensity** of light by light $\propto \mathrm{Im}[\chi^{(3,cross-Kerr)}]$

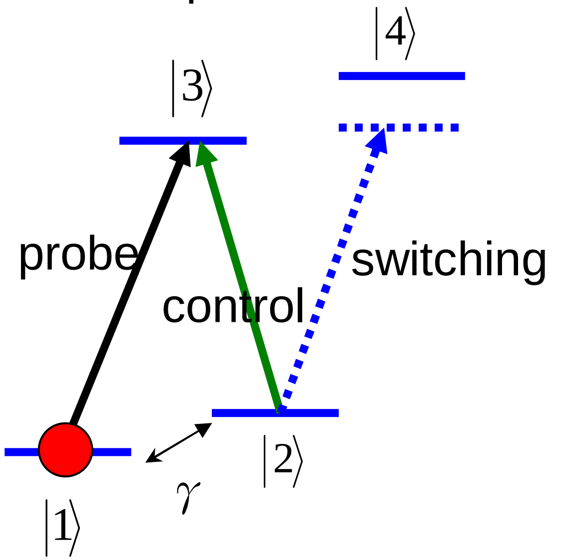
EIT-based Controlling Light by Light : N-type Scheme

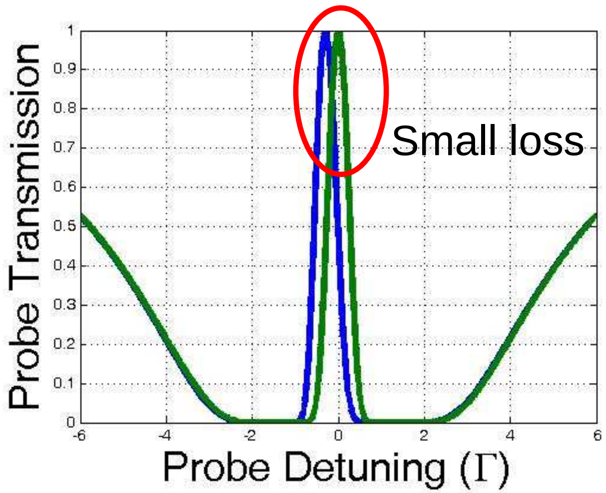
All-optical switching

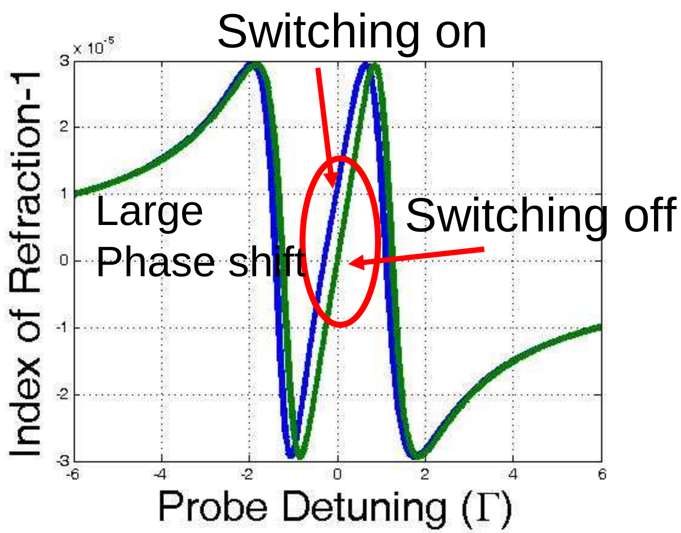




cross-phase modulation







Schmidt & Imamoglu Opt. Lett. 21,1936,1996

A summary of previous works

- Cross-phase modulation with double slow light

  Bor-Wen Shiau et.al. Phys. Rev. Lett. 106, 193006(2011).

- Enhanced all-optical switching with double slow light

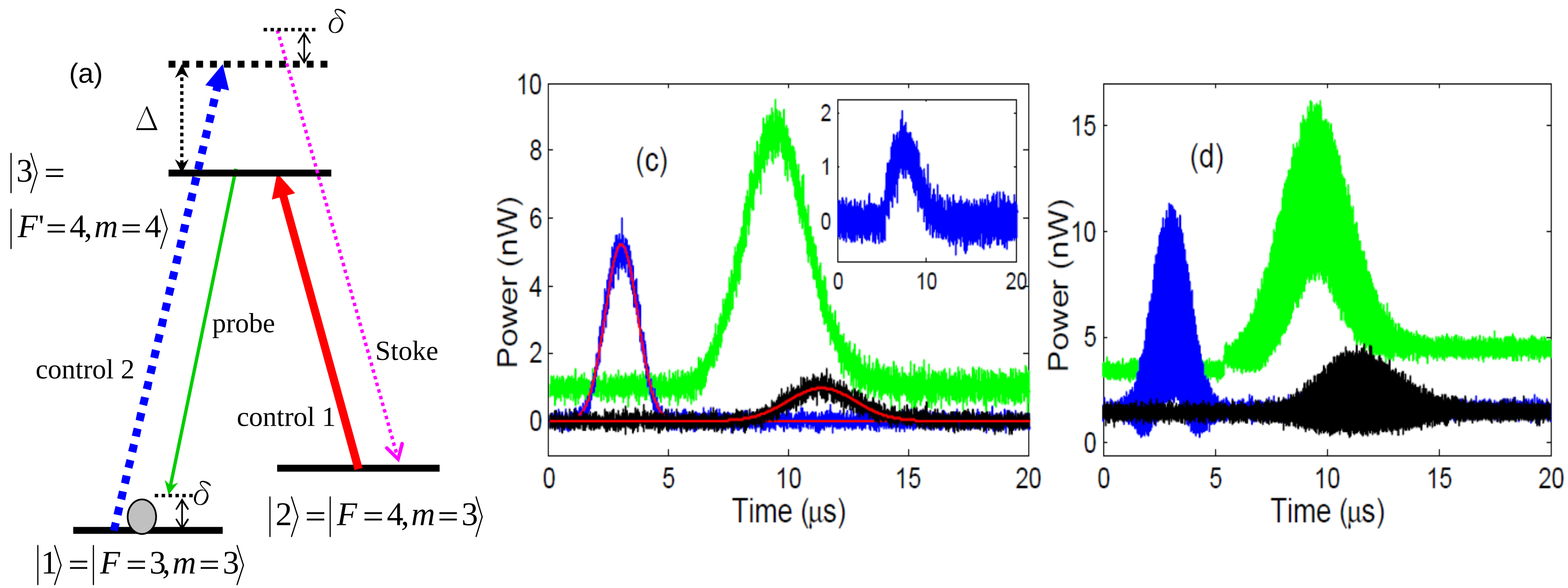
  Chi-Ching Lin et.al. Phys. Rev. A 86, 063836(2012)

- Enhanced all-optical switching with two stopped light pulses

  Yi-Hsin Chen et. al. Phys. Rev. Lett. 108, 173603(2012).

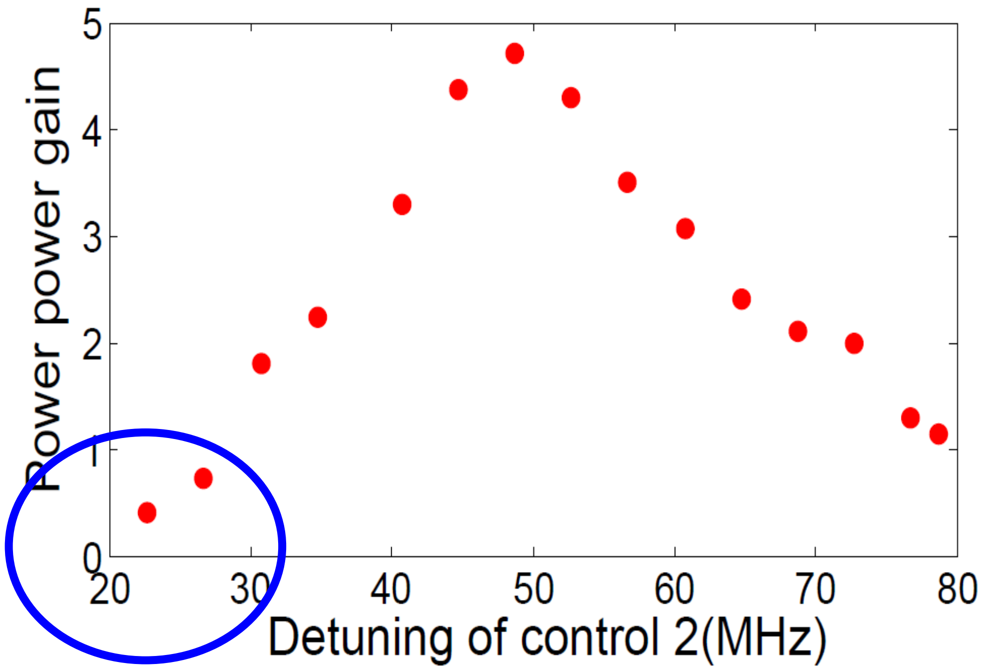
A recent work:
Amplified Slow & Stored Light by Four-Wave Mixing

- A maximum energy gain of 17 at an OD of 230 is obtained with a pump laser intensity of 2 mW/cm^2, 1000 times weaker compared to hot vapor experiments.
- Observed significant quantum noise due to finite excited-state population even for a classical pulse in optically dense media. It supports the theoretical work by M. Fleischhauer's (PRA 2013).



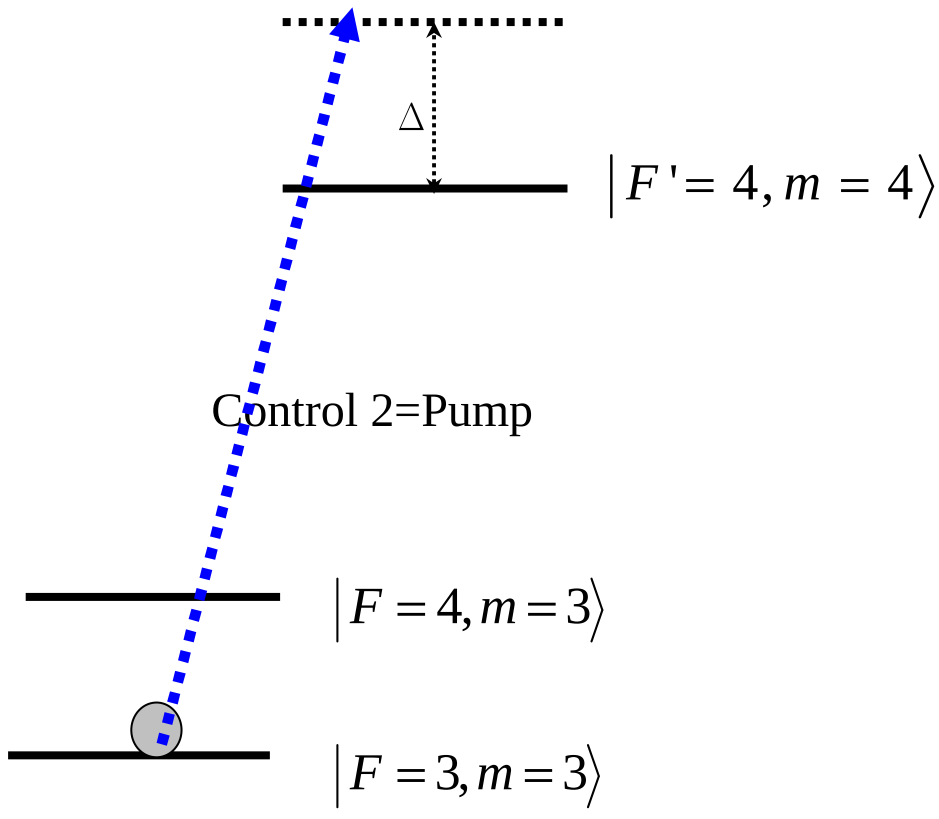
Y. F. Hsiao, C. C. Lin, & YCC, In preparation.

Where the story begin !

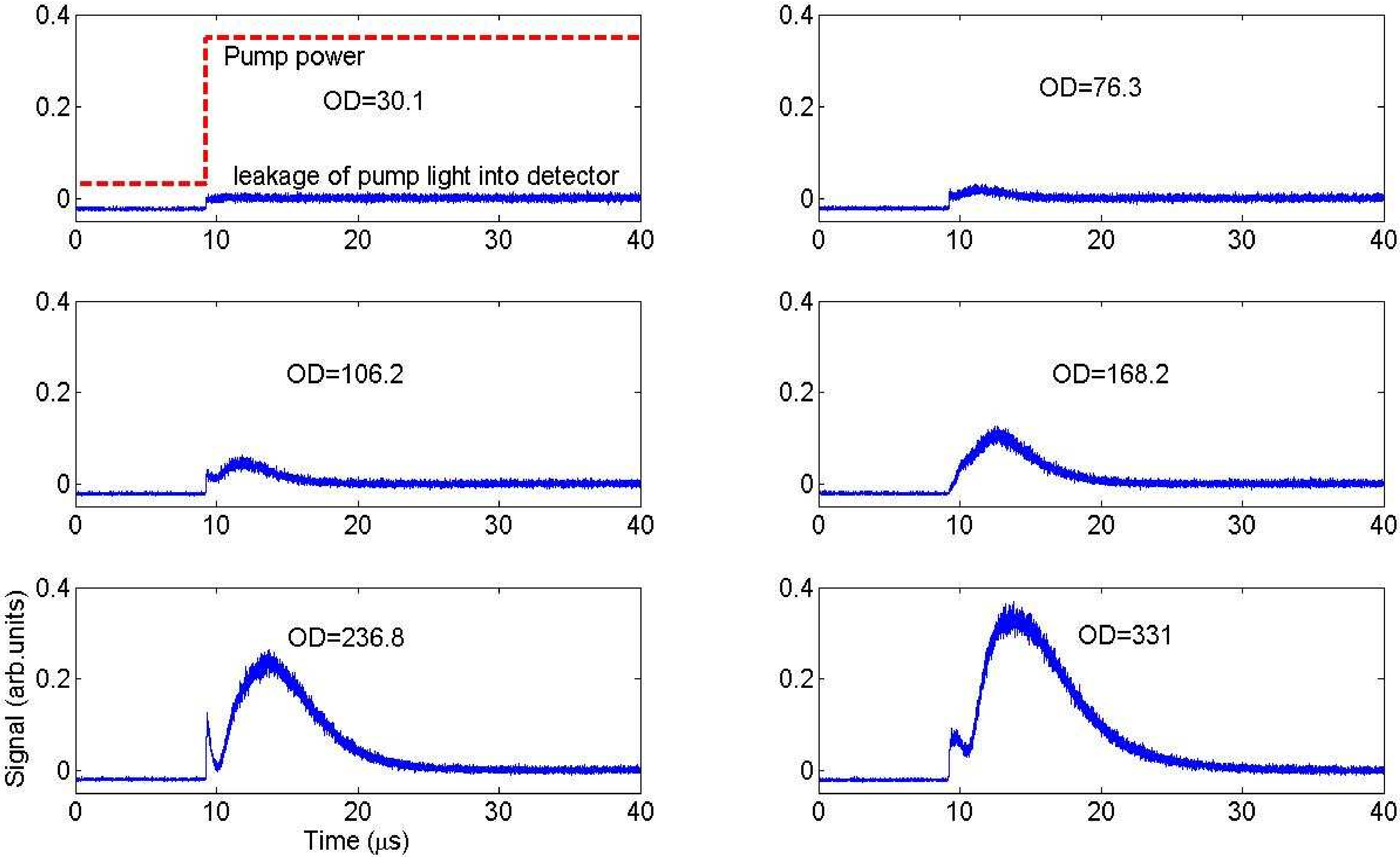


• Found interesting signal even when the control 1 and probe are both off in four-wave mixing experiment at high optical depths!

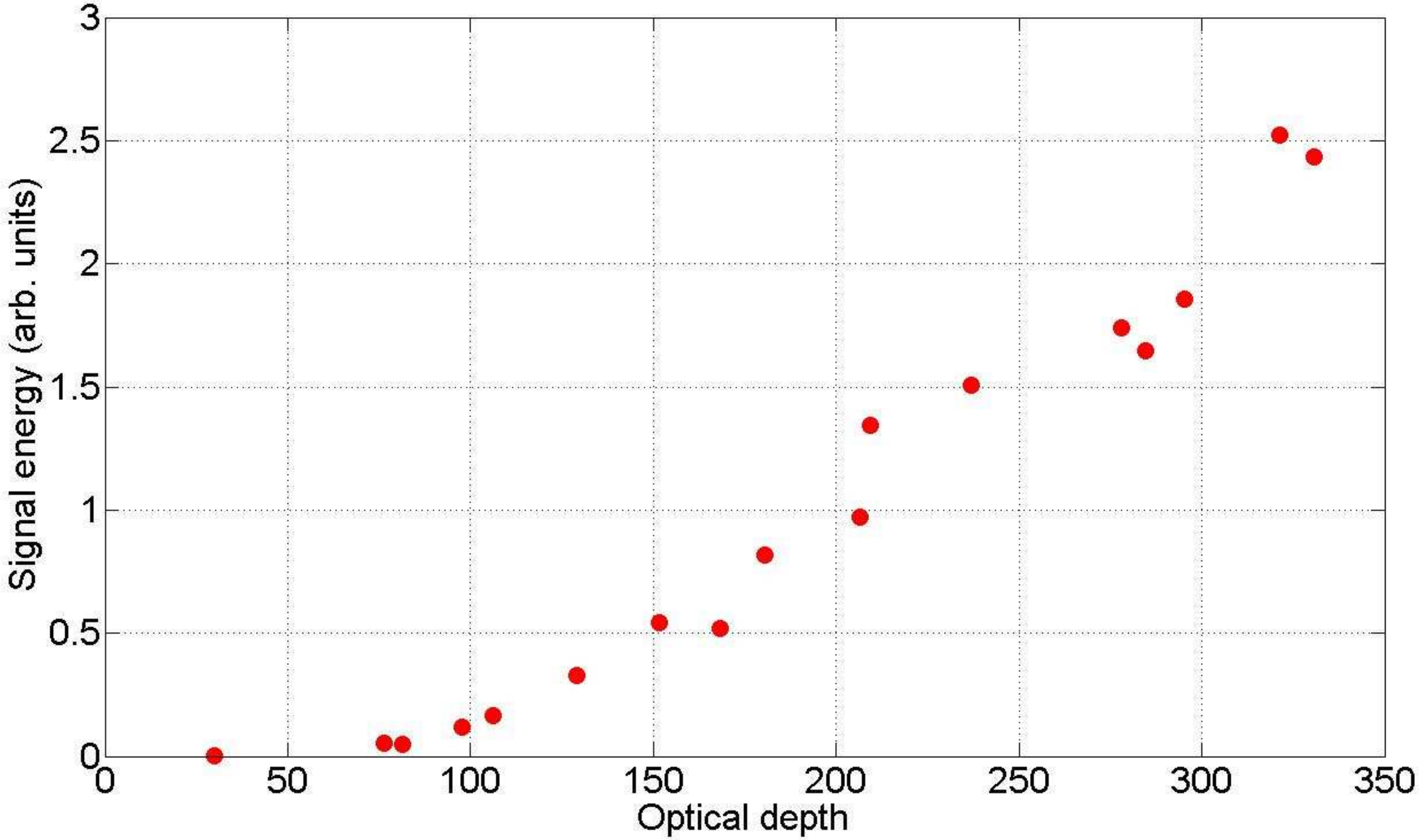
Back to the Most Simple Case



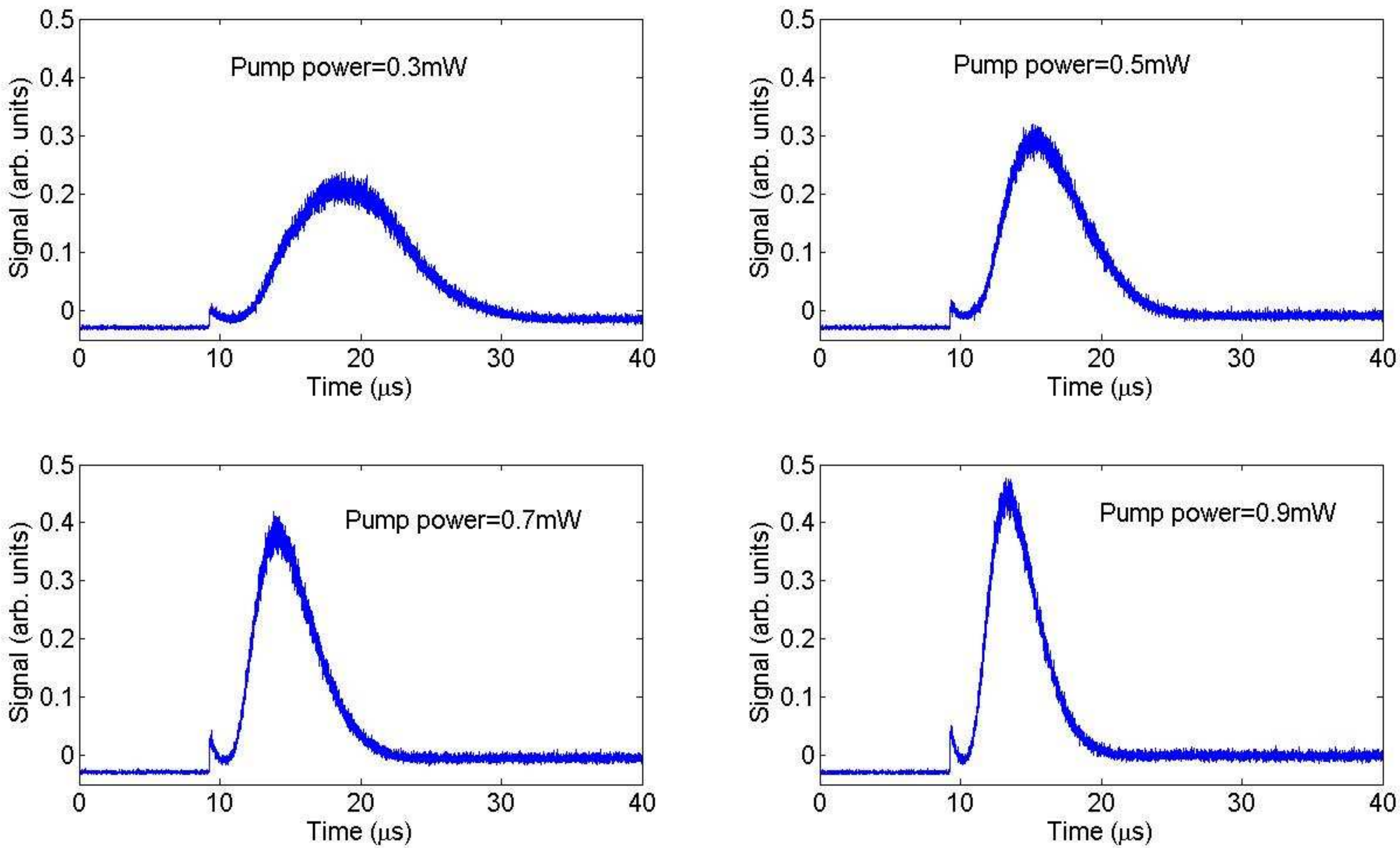
Signal versus OD



Threshold Behavior !



Signal versus Pump Power

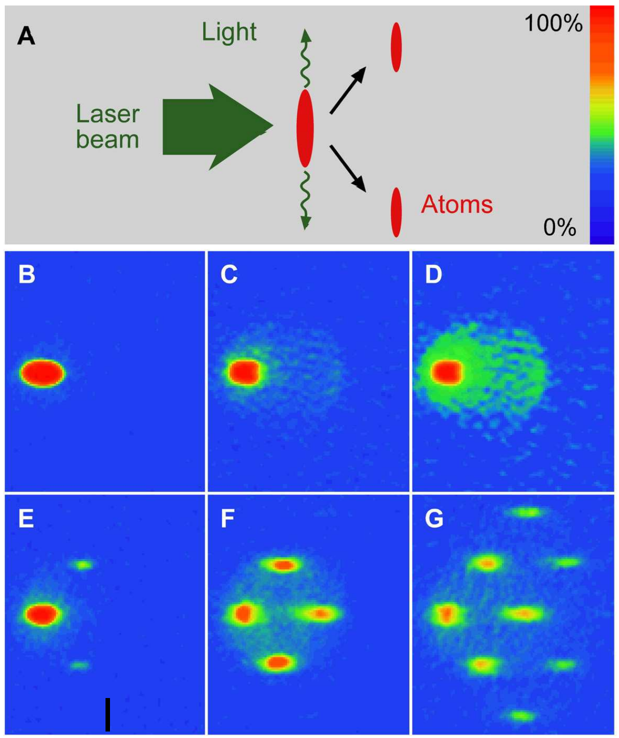


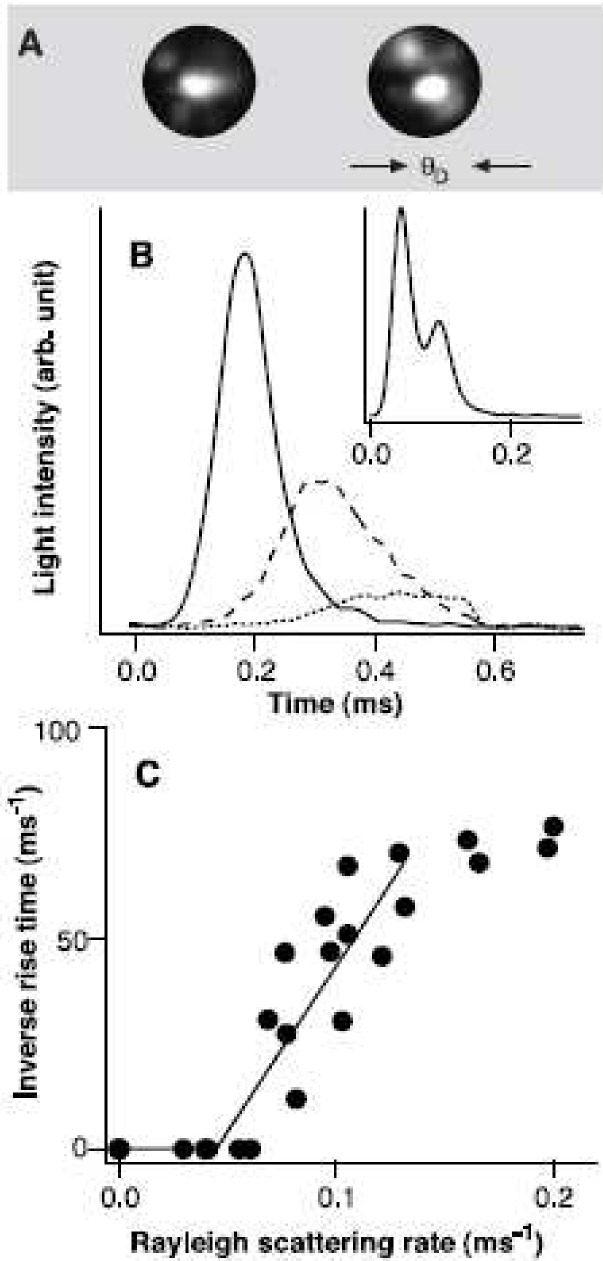
Superradiance ?

Science 285,571(1999)

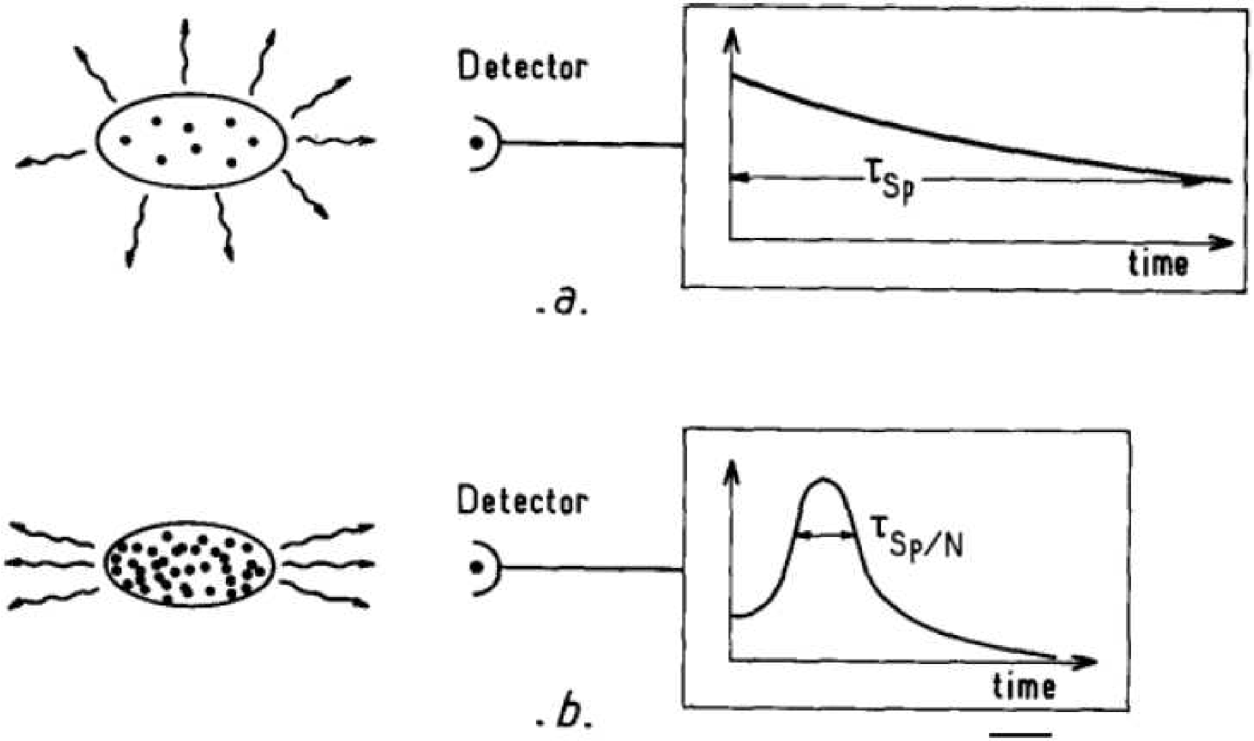
Superradiant Rayleigh Scattering from a Bose-Einstein Condensate

S. Inouye,* A. P. Chikkatur, D. M. Stamper-Kurn, J. Stenger, D. E. Pritchard, W. Ketterle





Dicke Superradiance

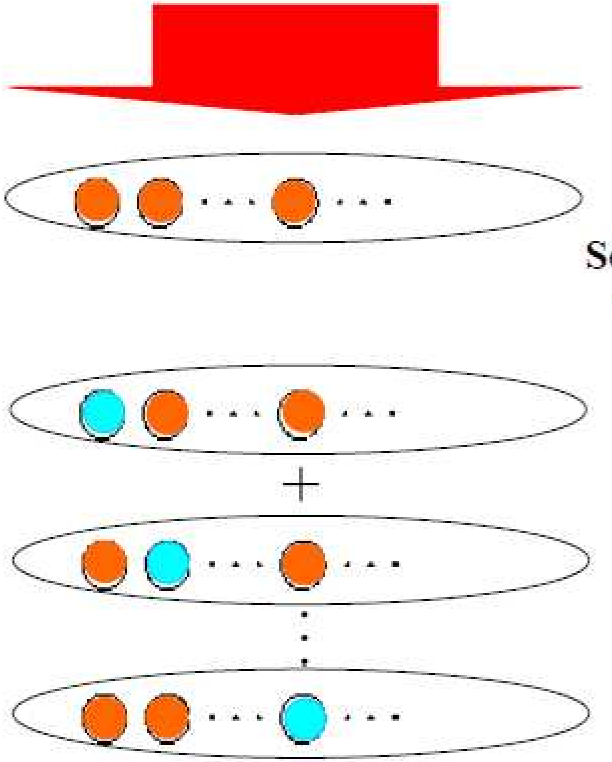


M. Gross, and S. Haroche, Phys. Rep. **93**, 301-396 (1982).

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

Dicke’s original idea: Collective spin operator

Assumption: the atomic ensemble couples to the electromagnetic field in an *indiscernible* way.



Impossible to specify the emitter of photon.

Symmetric collective spin (raising) operator

$$\hat{S}^{+} = \frac{1}{\sqrt{N_a}} \sum_{i=1}^{N_a} \hat{S}_i^{+}$$

$$\hat{S}^{+}|0_a\rangle = \frac{1}{\sqrt{N_a}} \sum_{i=1}^{N_a} |g\rangle_1 |g\rangle_2 \cdots |s\rangle_i \cdots |g\rangle_{N_a}$$

The excited state of the many-atom state is a symmetric superposition of the tensor product of the single spin state: An *entangled state*.

Regard N_a atoms as ½-spin system expressed by the ***collective angular momentum*** state $|s,m>$

Angular momentum state

$$|s,s\rangle \equiv |s\rangle_1|s\rangle_2\cdots|s\rangle_i\cdots|s\rangle_{N_a}$$

$$\vdots$$

$$|s,m\rangle \equiv \frac{1}{(s+m)!}\binom{N_a}{s+m}^{-\frac{1}{2}}\left(N_a^{\frac{s-m}{2}}(\hat{S}^+)^{s+m}\right)|0_a\rangle$$

$$\vdots$$

$$|s,-s+1\rangle = \frac{1}{\sqrt{N_s}}\sum_{i=1}^{N_a}|g\rangle_1|g\rangle_2\cdots|s\rangle_i\cdots|g\rangle_{N_a}$$

$$|s,-s\rangle \equiv |g\rangle_1|g\rangle_2\cdots|g\rangle_i\cdots|g\rangle_{N_a} = |0_a\rangle$$

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

$s = \frac{N_a}{2}$: total spin

$m = \frac{N_s - N_g}{2}$: magnetic quantum number

Squared matrix element for the transition

$$|s,m-1\rangle \rightarrow |s,m\rangle$$

$$\langle s,m|N_a\hat{S}^+\hat{S}^-|s,m\rangle = (s+m)(s-m+1)$$

$$= N_s(N_g+1)$$

$$(N_a = N_s = \tfrac{N_a}{2}) \quad = \frac{N_a}{2}\left(\frac{N_a}{2}+1\right)$$

$$\approx N_a^2$$

One model of Superradiance

Collective enhancement

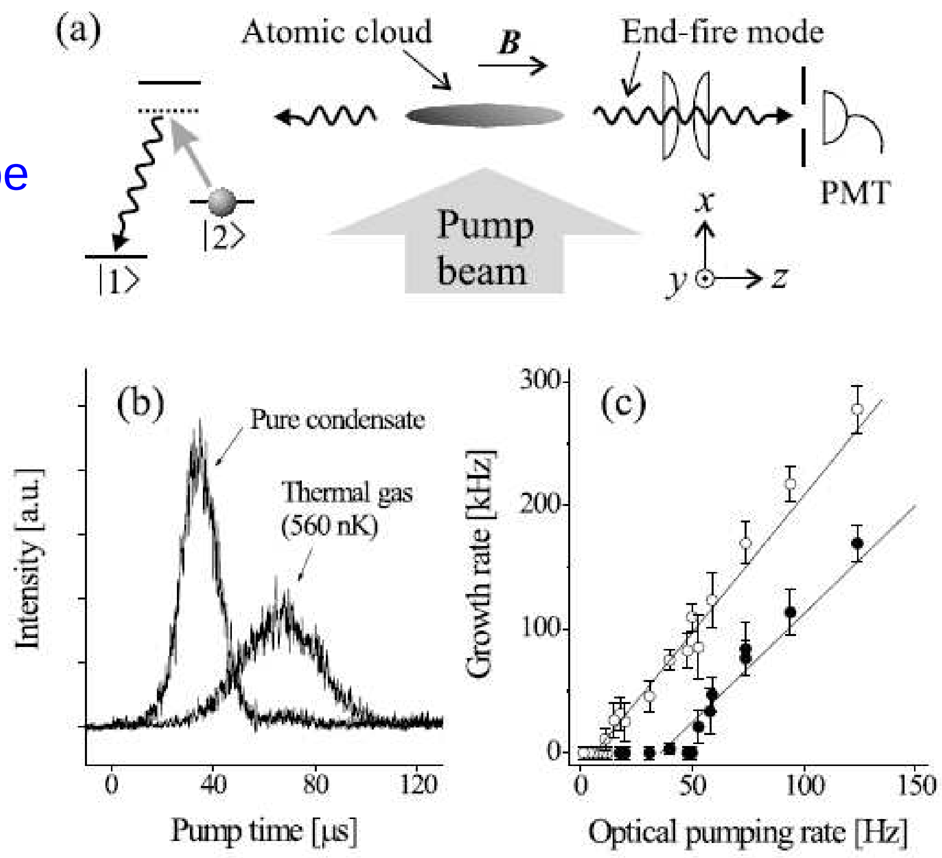
Cooperativy is crucial not quantum degenracy !

PRL 94, 083602 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Superradiant Light Scattering from Thermal Atomic Vapors

Yutaka Yoshikawa,* Yoshio Torii, and Takahiro Kuga
Institute of Physics, University of Tokyo, 3-8-1, Meguro-ku, Komaba, Tokyo 153-8902, Japan.
(Received 12 July 2004; published 4 March 2005)

Raman type



Cavity-assisted Superradiance

PRL 98, 053603 (2007) PHYSICAL REVIEW LETTERS week ending 2 FEBRUARY 2007

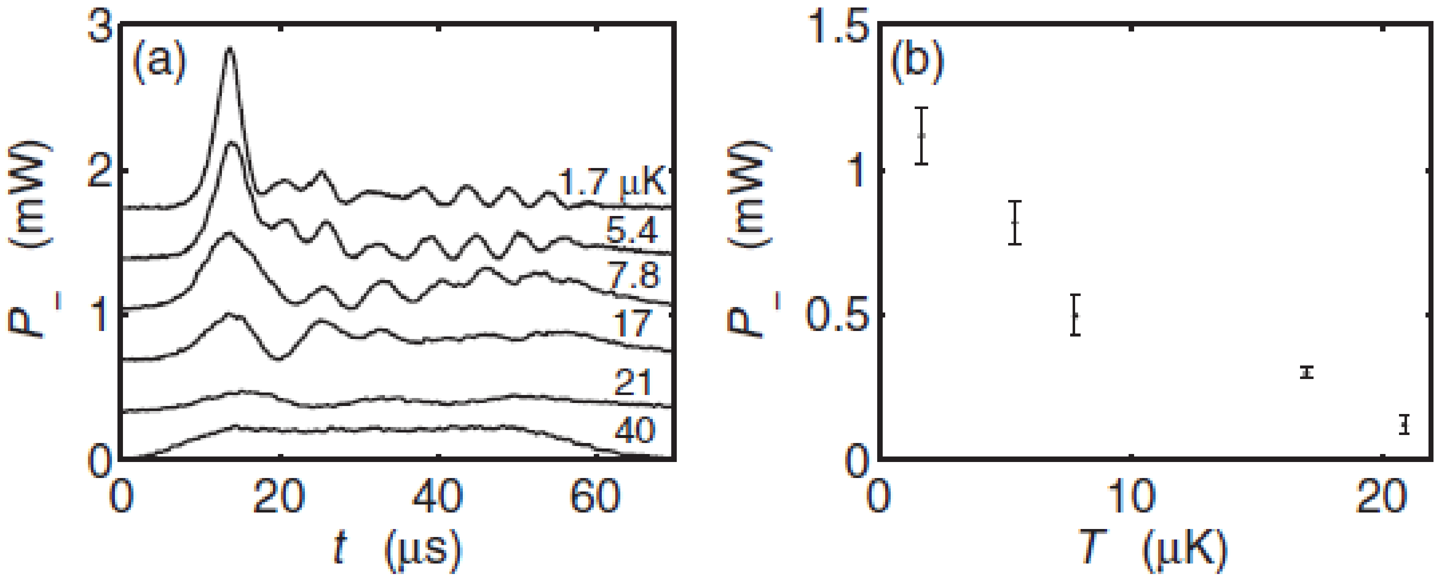
Superradiant Rayleigh Scattering and Collective Atomic Recoil Lasing in a Ring Cavity

S. Slama, S. Bux, G. Krenz, C. Zimmermann, and Ph. W. Courteille

Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany

(Received 25 October 2006; published 1 February 2007)

Collective interaction of light with an atomic gas can give rise to superradiant instabilities. We experimentally study the sudden buildup of a reverse light field in a laser-driven high-finesse ring cavity filled with ultracold thermal or Bose-Einstein condensed atoms. While superradiant Rayleigh scattering from atomic clouds is normally observed only at very low temperatures (i.e., well below 1 μK), the presence of the ring cavity enhances cooperativity and allows for superradiance with thermal clouds as hot as several 10 μK. A characterization of the superradiance at various temperatures and cooperativity parameters allows us to link it to the collective atomic recoil laser.



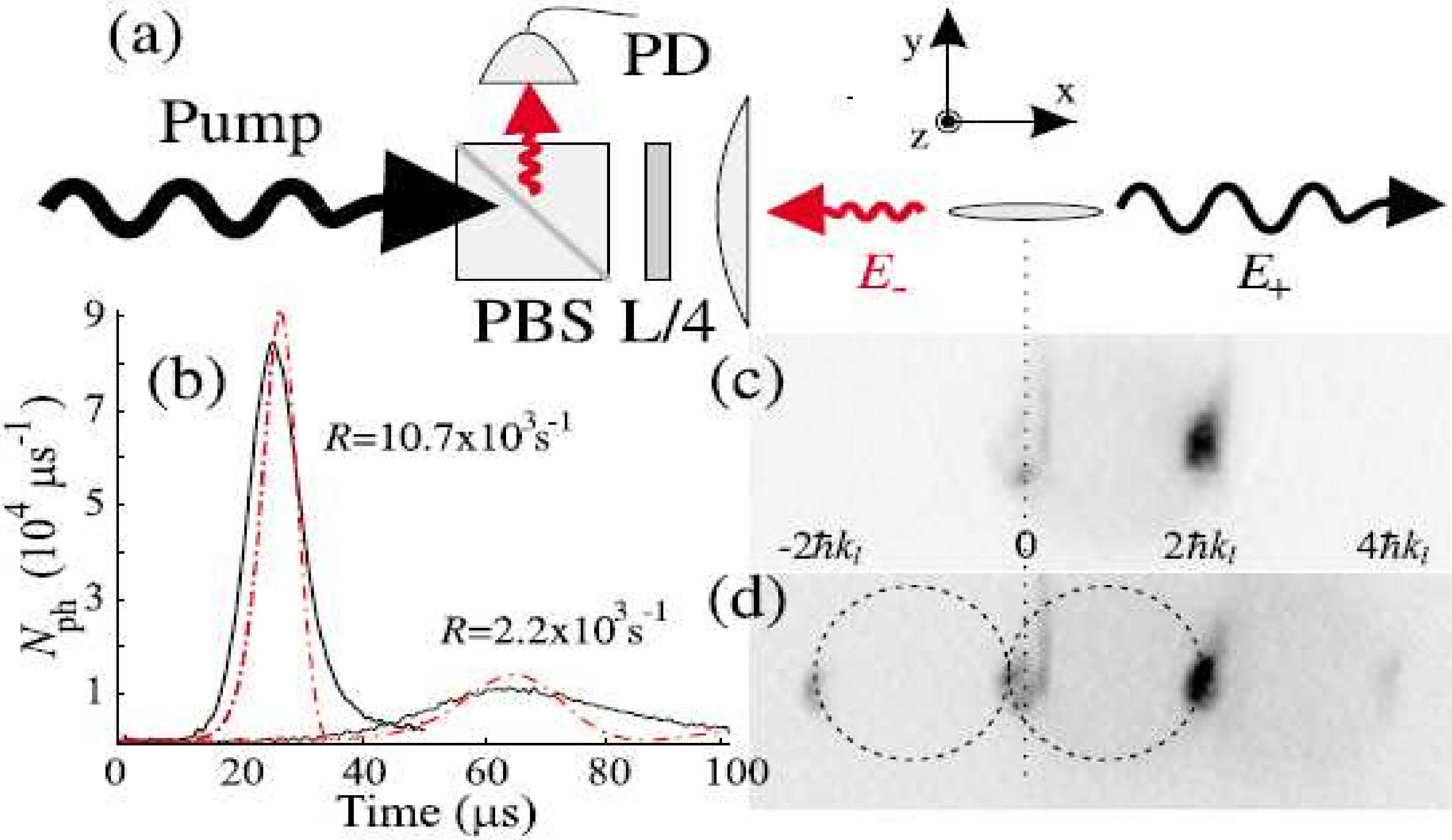
It is well-known that high optical depth is corresponding the effect of an optical cavity.

End-pump Configuration

PHYSICAL REVIEW A **78**, 051403(R) (2008)

Rayleigh superradiance and dynamic Bragg gratings in an end-pumped Bose-Einstein condensate

A. Hilliard,* F. Kaminski, R. le Targat, C. Olausson, E. S. Polzik, and J. H. Müller
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen Ø, Denmark
(Received 14 July 2008; published 18 November 2008)



Theoretical Analysis

PRL **104,** 050402 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Electromagnetic Wave Dynamics in Matter-Wave Superradiant Scattering

L. Deng,[1,2] M. G. Payne,[1] and E. W. Hagley[1]

[1]*Physics Laboratory, National Institute of Standards & Technology, Gaithersburg, Maryland 20899, USA*

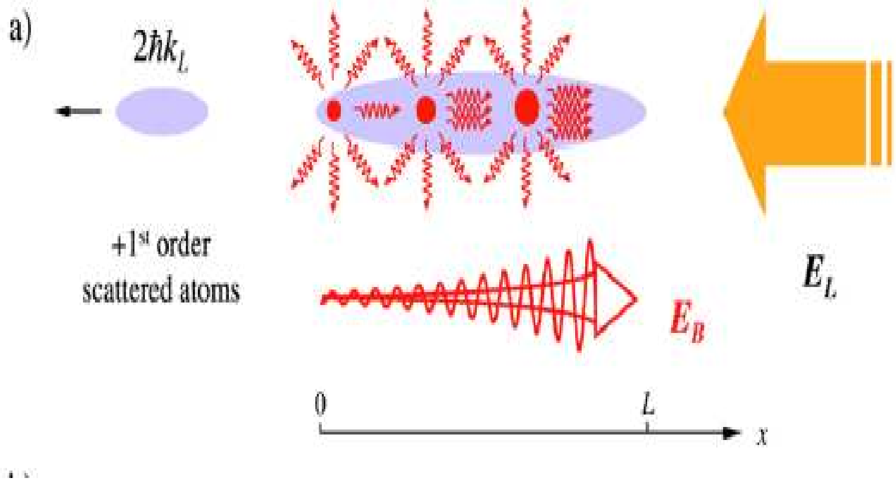
[2]*Center for Cold Atom Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Science, Wuhan 430071, China*

(Received 27 September 2009; published 2 February 2010)

We present a small-signal wave propagation theory on matter-wave superradiant scattering. We show, in a longitudinally excited condensate, that the backward-propagating, superradiantly generated optical field propagates with ultraslow group velocity and that the small-signal gain profile has a Bragg resonance. We further show a unidirectional suppression of optical superradiant scattering, and explain why matter-wave superradiance can occur only when the pump laser is red detuned. This is the first analytical theory on field propagation in matter-wave superradiance that can explain all matter-wave superradiance experiments to date that used a single-frequency, long-pulse, red-detu

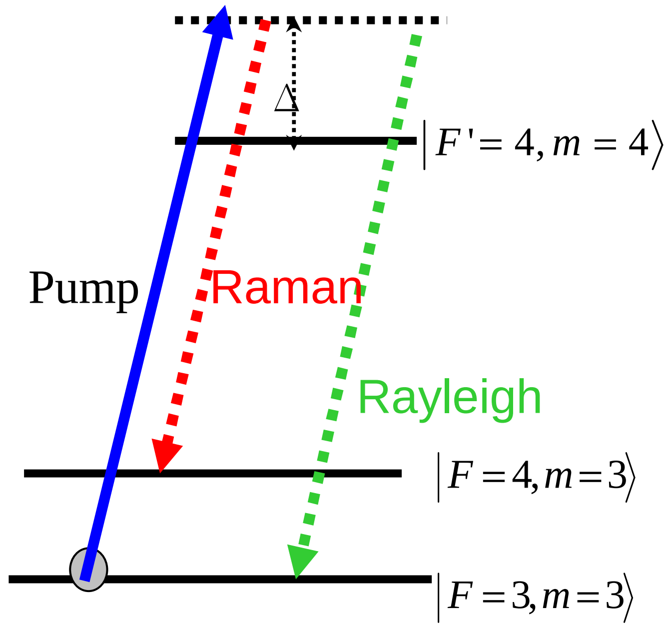
Unifortunately!

momentum and moving to the left [Fig. 2(a)]. Processes involving absorption of a laser photon and subsequent emission of a photon in the direction of the pump laser transfer negligible momentum to the condensate and will not be considered here.



Identify its Polarization

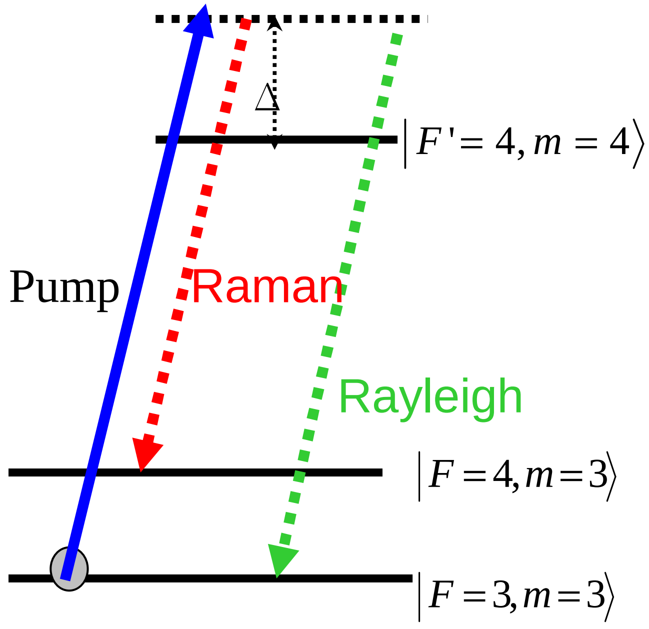
- Polarization the same as the pump beam.

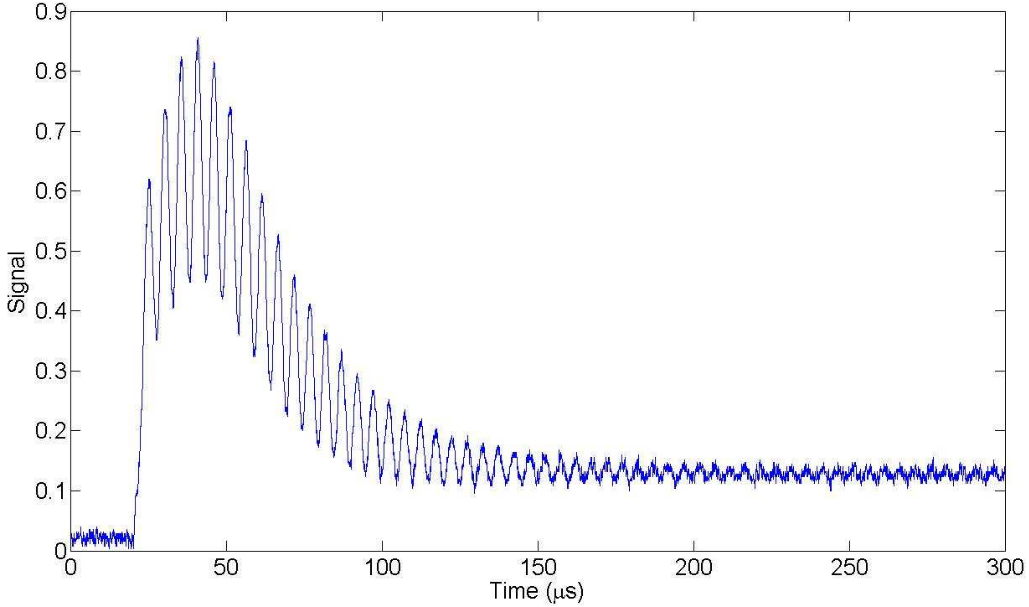


Identify its Frequency : Raman or Rayleigh?

- Prepare a beam near resonance with either F=4 →F'=4 or F=3→ F'=4 transition and beat with the signal.
- No beat signal is found with reference near resonant with F=4→ F'=4 transition.
- Beating with a beam ~ pump frequency

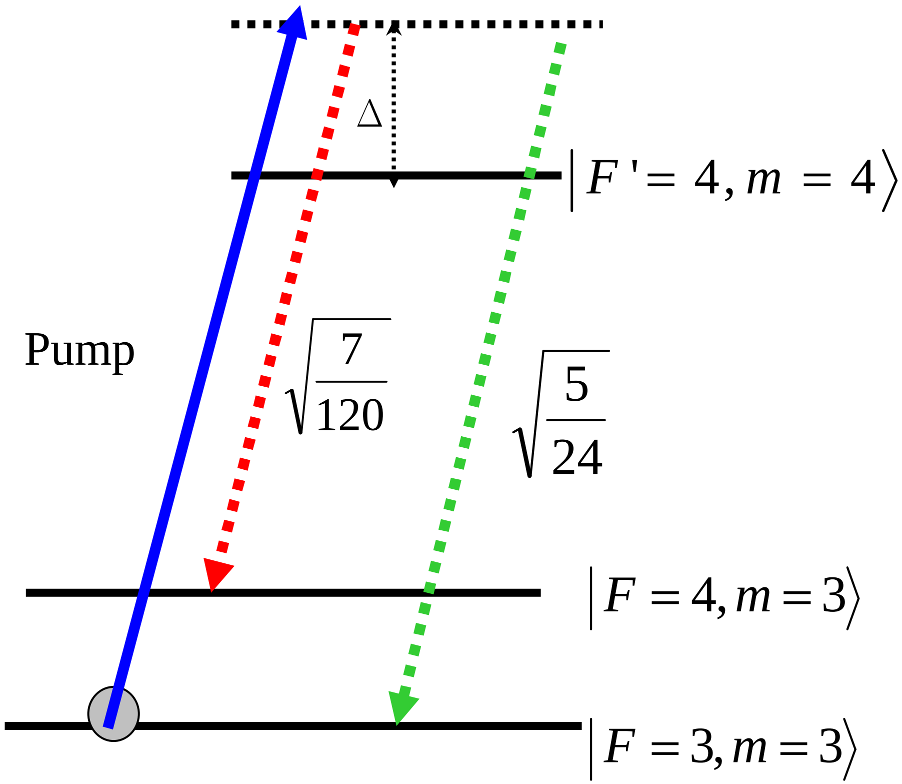
Should be Rayleigh type!.





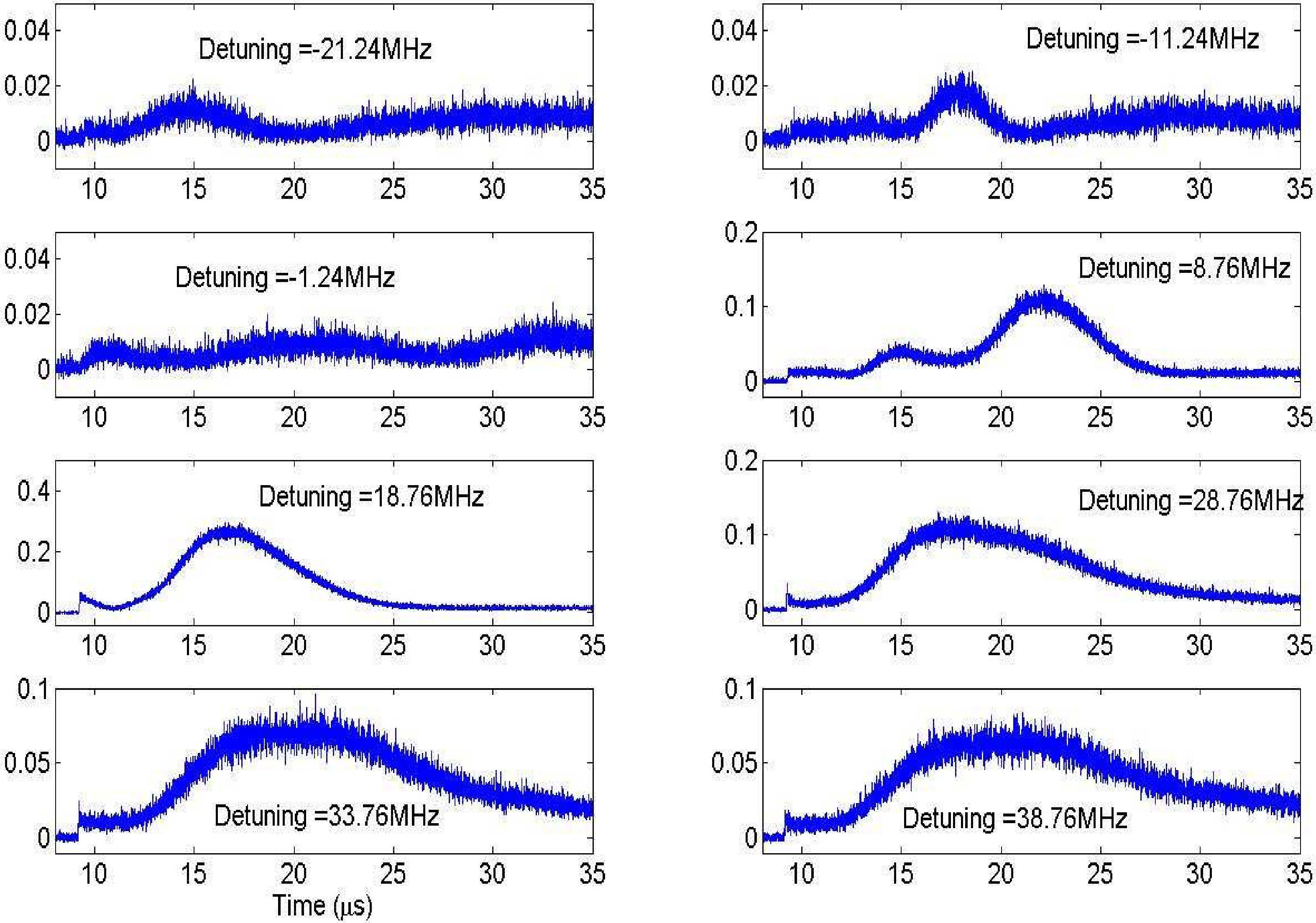
- f_{ref}-f_{pump}=200 kHz
- f_{signal}-f_{ref}=193.53(0.68) kHz

Transition dipole moment : Clebsch-Gordon coefficient



- If the superradiance exists, it favors Rayleigh scattering.

Detuning Dependence

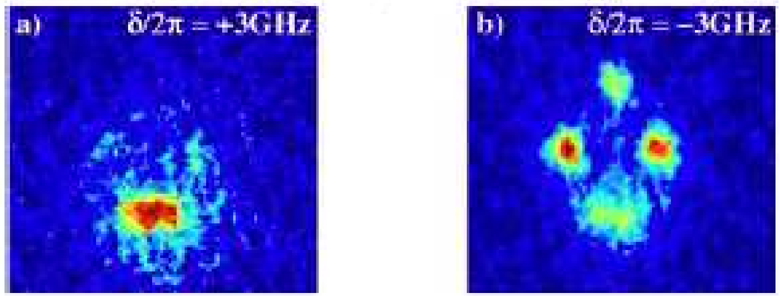


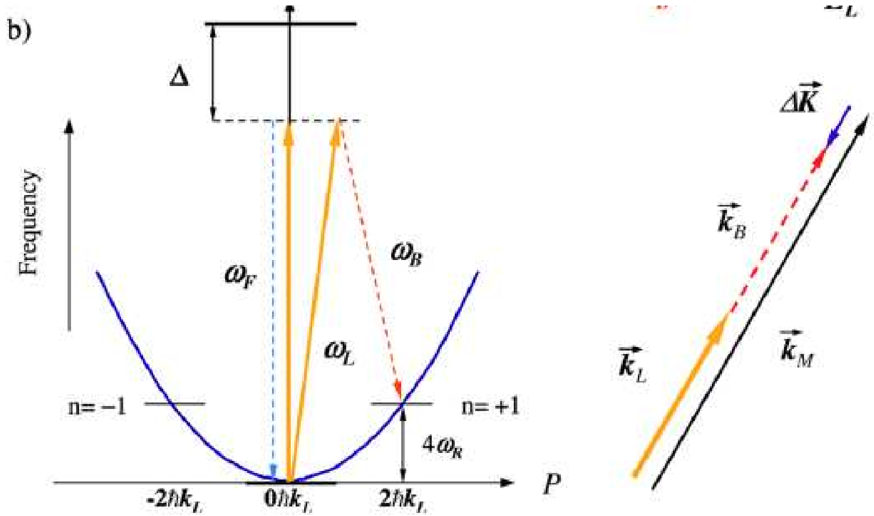
PRL 105, 220404 (2010) PHYSICAL REVIEW LETTERS week ending 26 NOVEMBER 2010

Observation of a Red-Blue Detuning Asymmetry in Matter-Wave Superradiance

L. Deng,[1] E. W. Hagley,[1] Qiang Cao,[2] Xiaorui Wang,[2] Xinyu Luo,[2] Ruquan Wang,[2] M. G. Payne,[1] Fan Yang,[3] Xiaoji Zhou,[3] Xuzong Chen,[3] and Mingsheng Zhan[4,5]

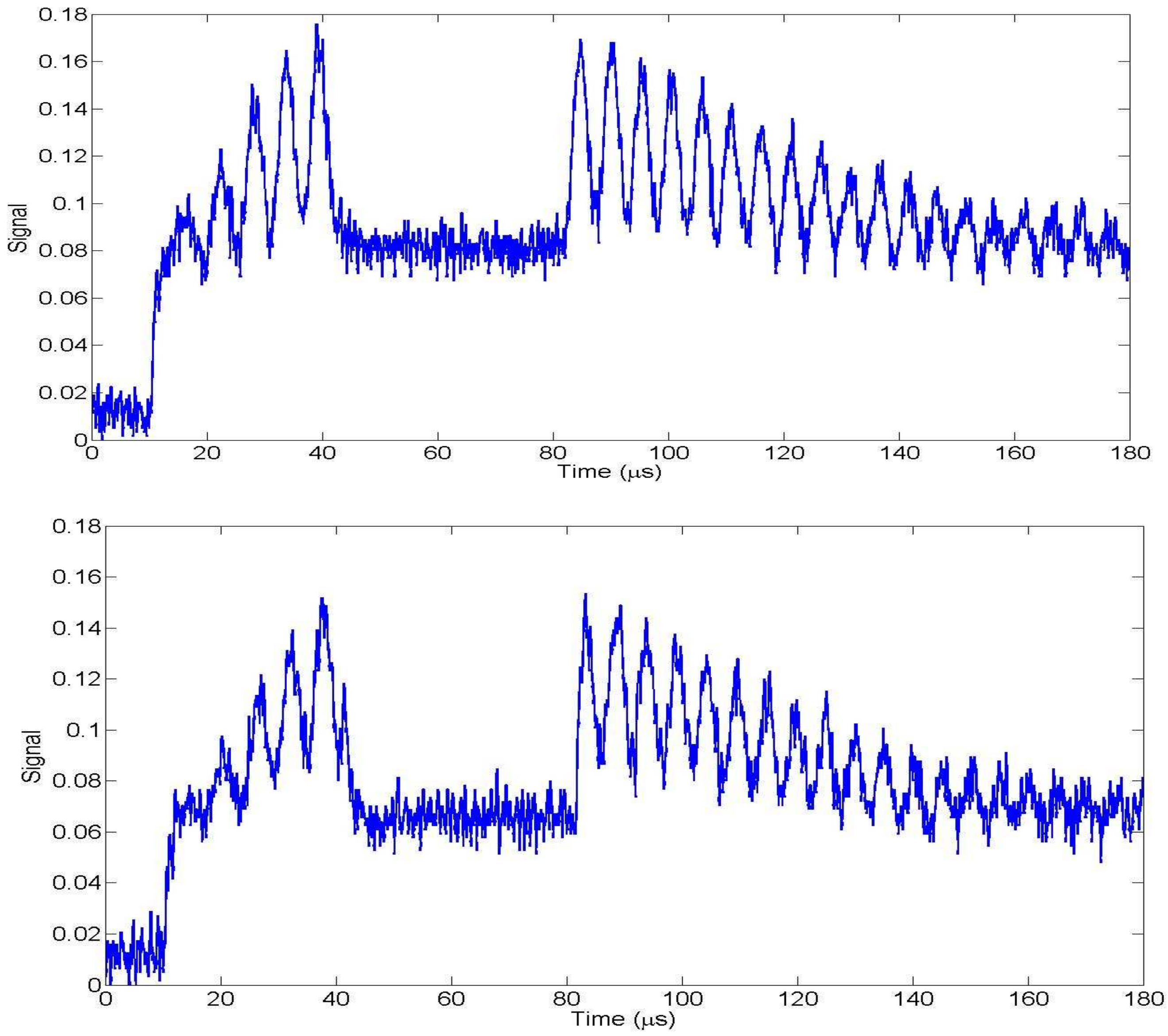
We report the first experimental observation of strong suppression of matter-wave superradiance using blue-detuned pump light and demonstrate a pump-laser detuning asymmetry in the collective atomic recoil motion. In contrast to all previous theoretical frameworks, which predict that the process should be symmetric with respect to the sign of the detuning of the pump laser from the one-photon resonance, we find that for condensates the symmetry is broken. With high condensate densities and red-detuned pump light the distinctive multiorder, matter-wave scattering pattern is clearly visible, whereas with blue-detuned pump light superradiance is strongly suppressed. However, in the limit of a dilute atomic gas symmetry is restored.





- Energy and momentum conservation condition of light and matter and condensate energy dispersion relation explain this asymmetry!

Storage and Preserve Phase Coherence ?



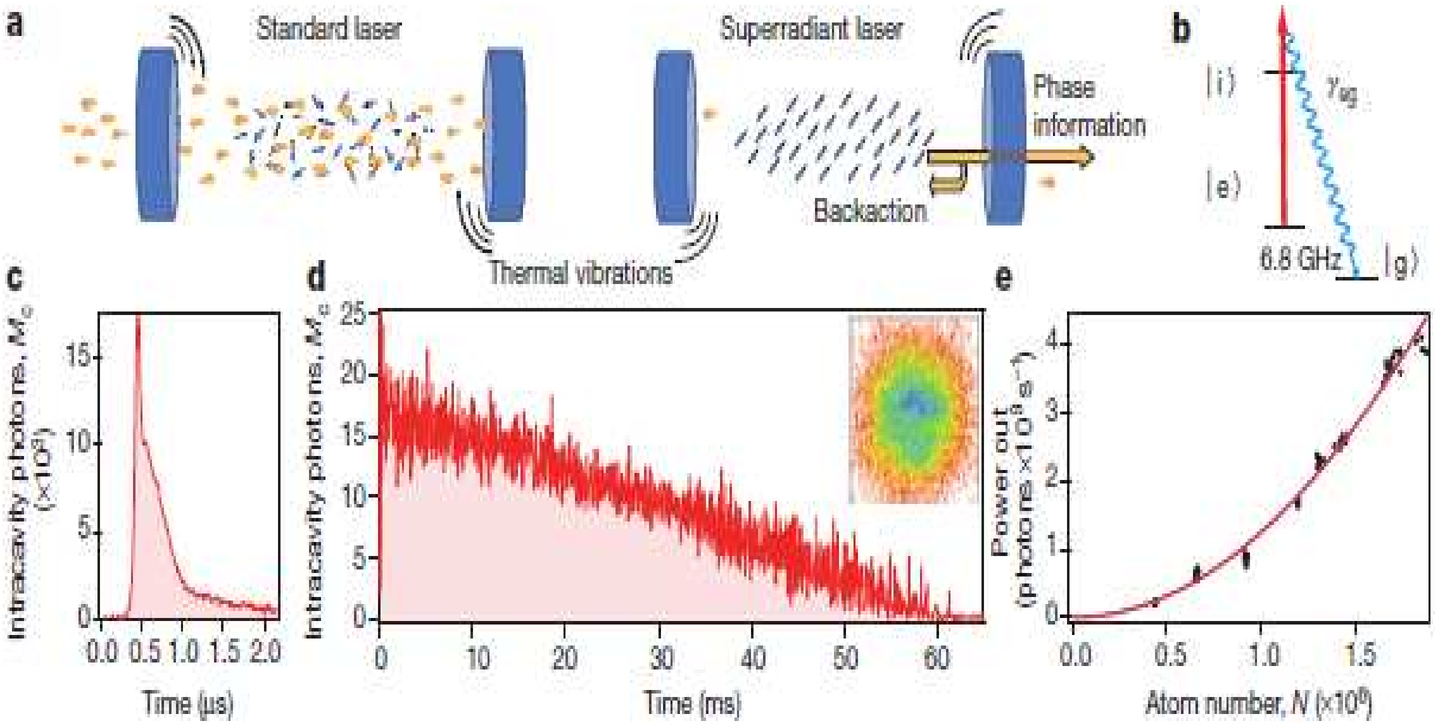
A Recent Experiment on Superradiant Laser

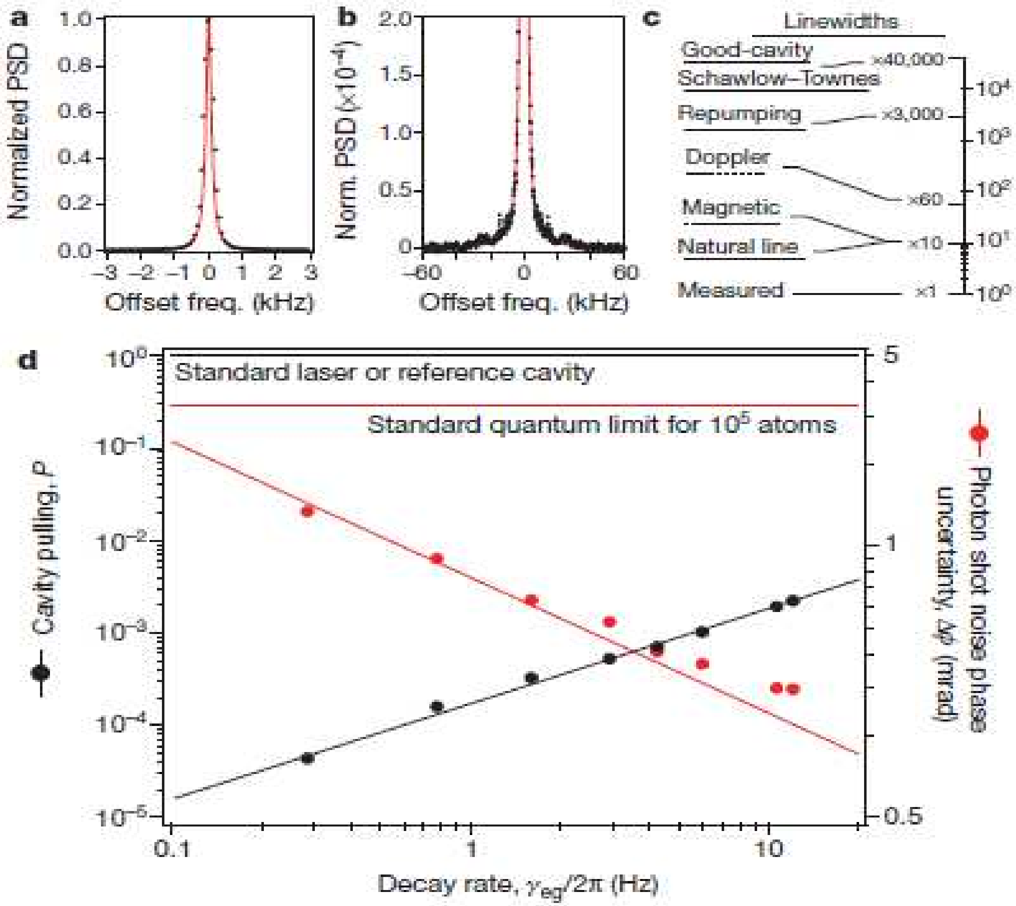
LETTER

doi:10.1038/nature10920

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

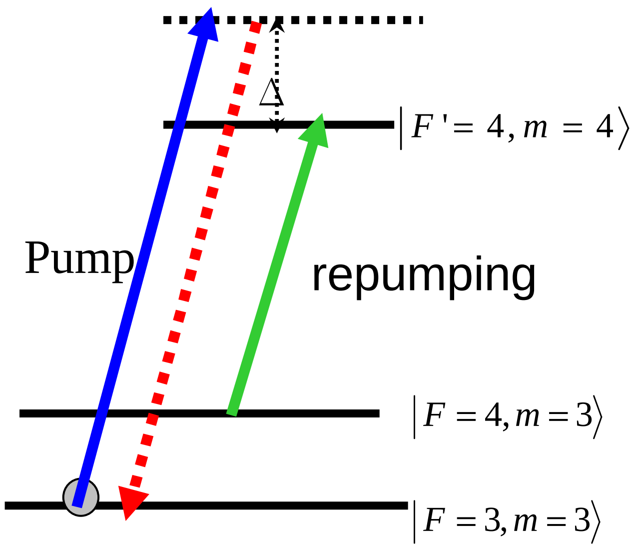
Justin G. Bohnet[1], Zilong Chen[1], Joshua M. Weiner[1], Dominic Meiser[1]†, Murray J. Holland[1] & James K. Thompson[1]



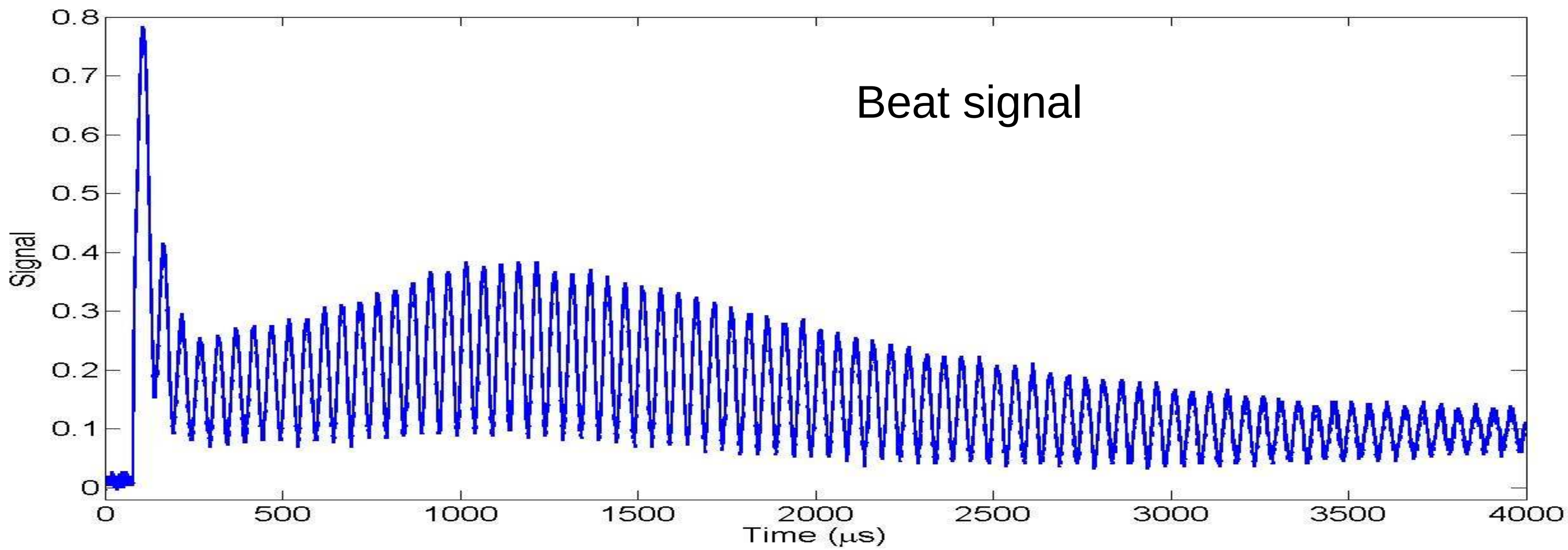


- Operate in the bad-cavity limit (atomic decay rate <<cavity decay rate), reduce cavity pulling effect and thus effect of cavity thermal or vibration noise.
- Prospect of mHz-linewidth laser for optical clock experiment!

Repumping ON: Quasi-continuous operation



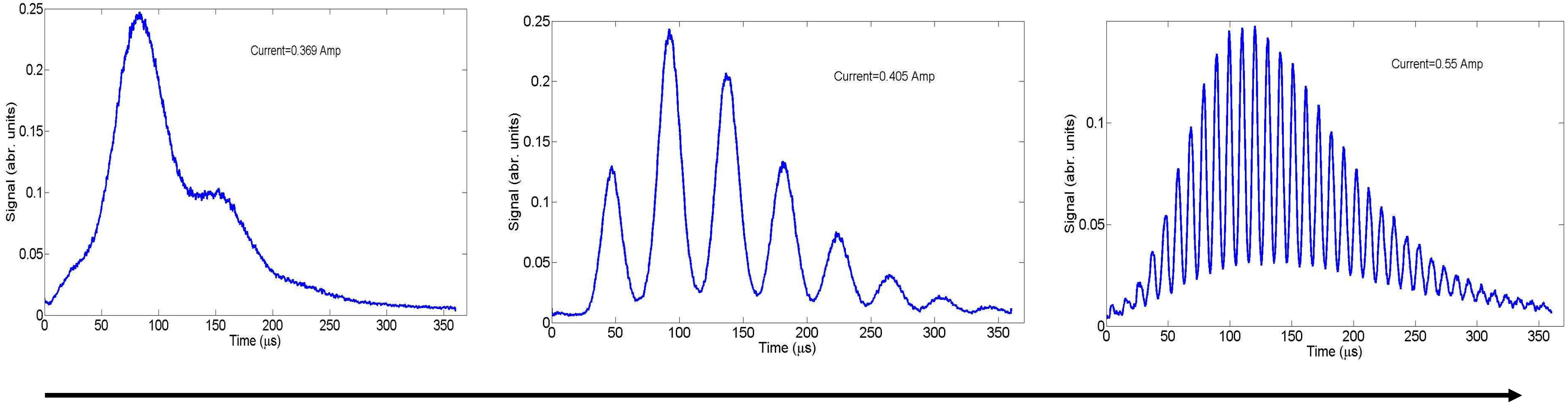
- Add repumping to prevent population loss due to optical pumping effect to F=4 ground tate
.
- The signal last quasi-continuously, limited by the fly-away time of atom when MOT is off.



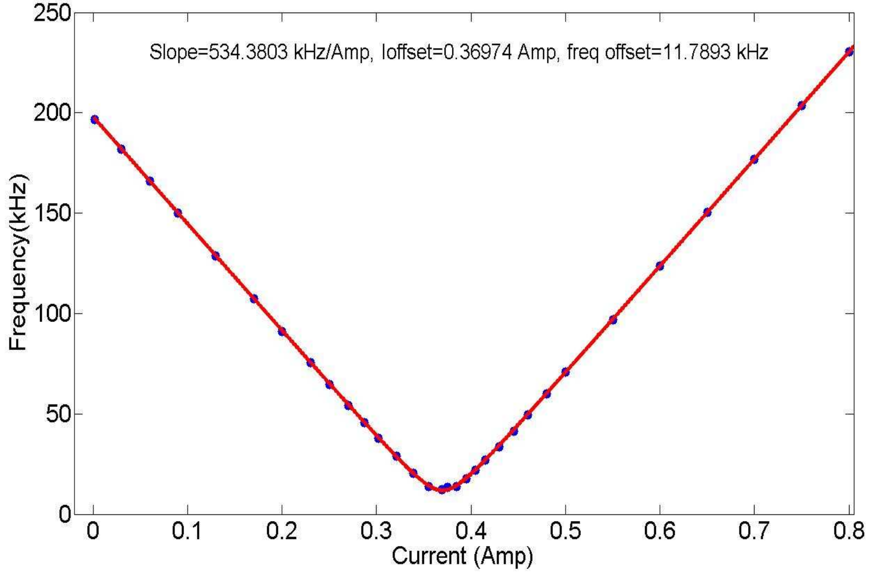
Effect of Magnetic Field

- Optical pumping to the rightmost Zeeman state prepared a magnetization, transverse magnetic field cause a Larmor procession.
- The superposition of Zeeman states cause a modulation on the transition rate due to different Clebsch-Gordon coefficients.
- A simple (one beam) and quick (single shot) way to determine the magnetic field !

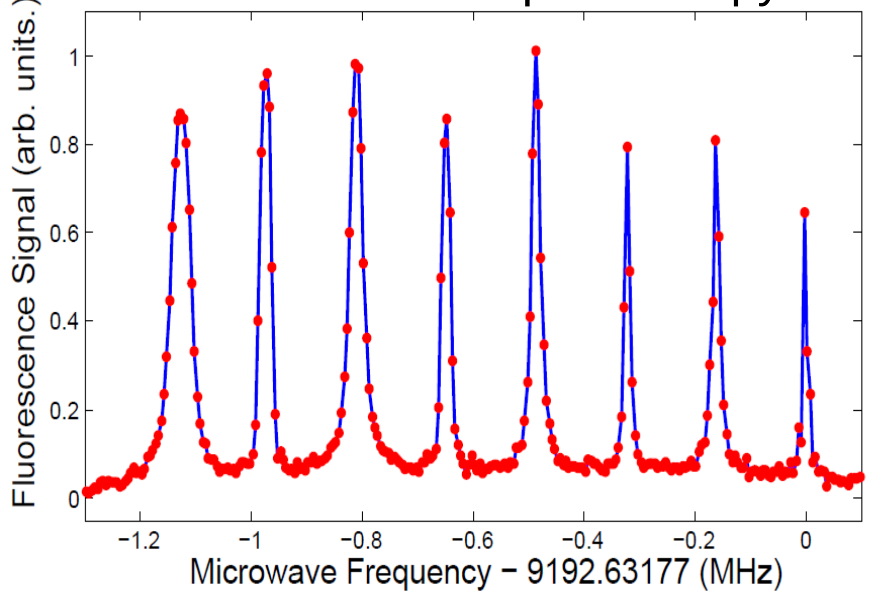
(No beating reference beam present, just power data)



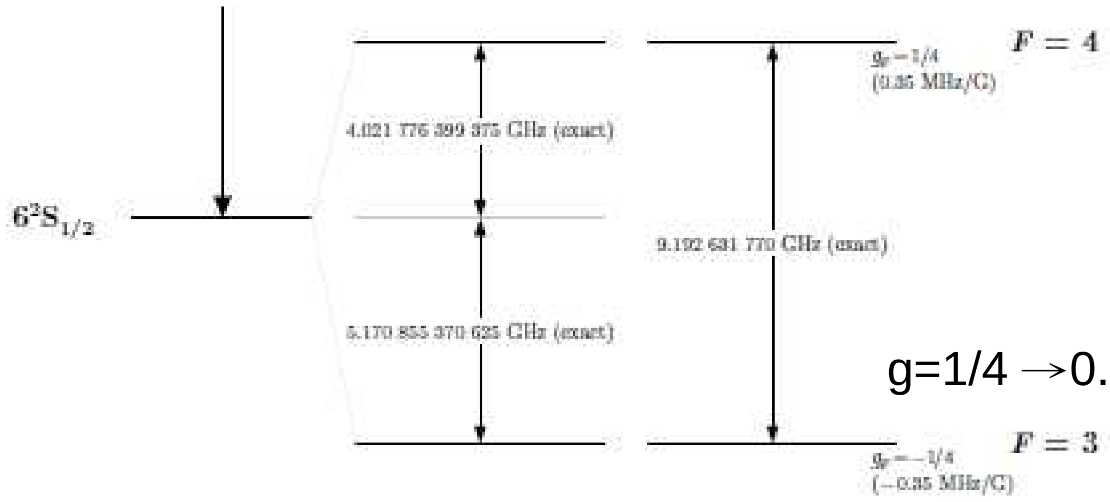
Increasing the applied magnetic field in the transverse direction



Previous microwave-spectroscopy data



- Compare to previous microwave spectroscopy calibration of coil current and magnetic field, we infer 0.3497MHz/Gauss.
- However, this method is much simple and fast!



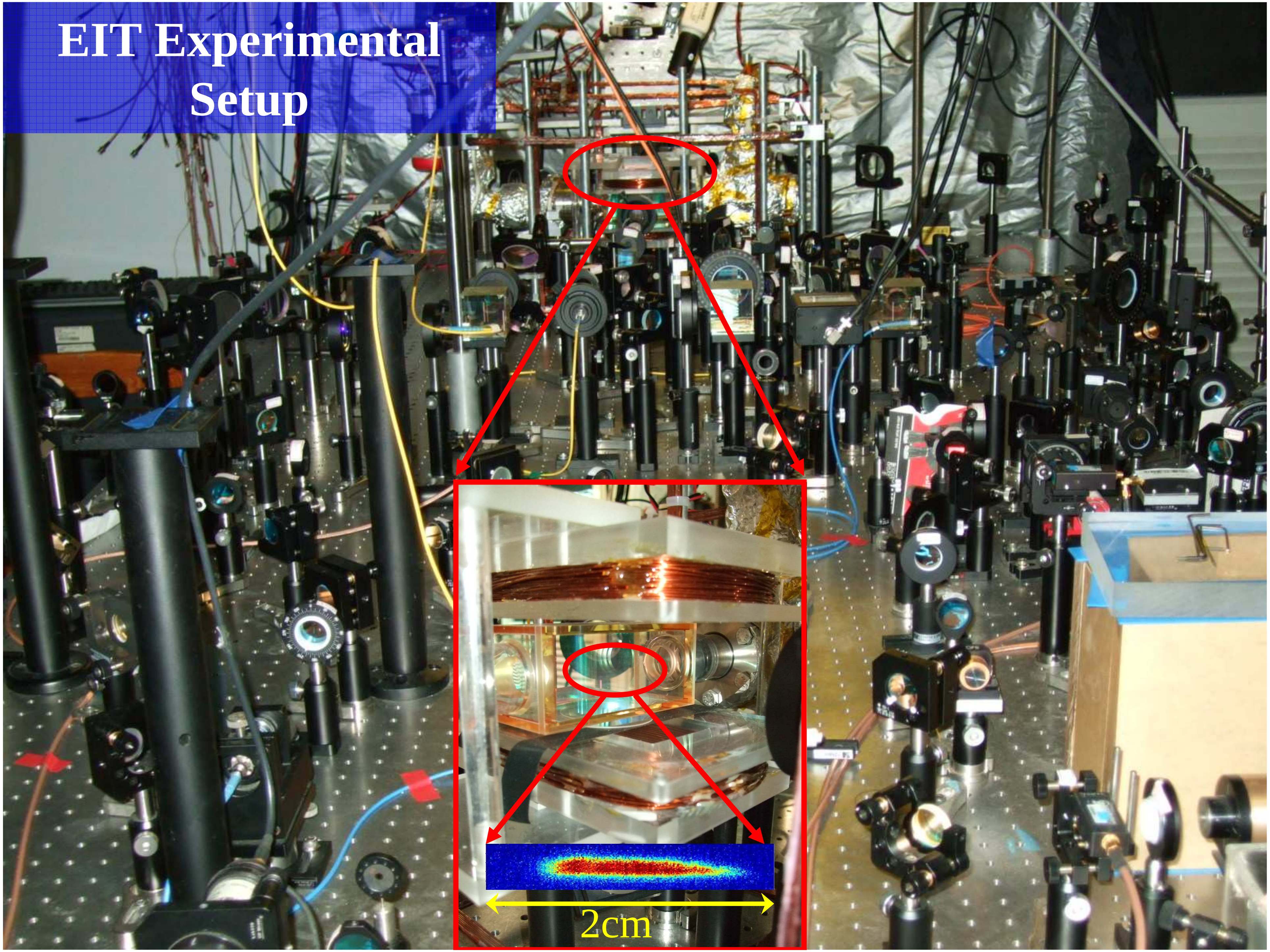
g=1/4 →0.3499MHz/Gauss

Open Question

- Is what we observed just some combinations of lensing or diffraction effect due to large optical depth ? It seems unlikely!
  1. Only with the good alignment for the probe beam in FWM experiment, will we see this signal when blocked the control 1 and probe beams. This signal is a well collimated beam ~0.1 deg and approximately in the probe beam path for FWM experiment !
  2. It can be stored and retrieved when turn off and back on the pump beam. The pulse shape looks like discontinued.
  3. Its frequency is a few kHz different from that of pump beam!

- Need different energy level configuration e.g. the Raman superradiance scheme or different geometry arrangement to check this.
- Need theoretical input and help!

EIT Experimental Setup



- Graduate student and Postdoc position available !
- Working on

1. Molecular cooling
2. Single-photon Nonlinear optics with ultracold atoms

- Contact chenyc@pub.iams.sinica.edu.tw