2010/12/16　量子エレクトロニクス研究会

冷却原子系におけるディッケ超放射の物理と応用
Dicke superradiance in a gas of ultracold atoms

東京大学大学院総合文化研究科
鳥井寿夫
The Univ. of Tokyo, Komaba
Yoshio Torii

Outline

- Dicke superradianec in a ultracold atomic gas
  - Brief review of Dicke superradiance
  - Holographic storage of light pulses in a BEC
  - possible applications
- Precise intensity correlation measurement of light from a optical mollasses

Previous works

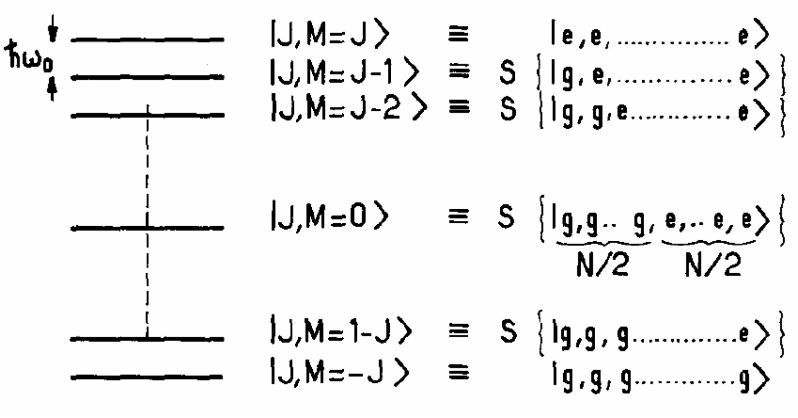
Current work

- Creation of Rb-Sr (Li-Sr) polar molecules for searching an electron EDM

Kuga Torii lab(2008)

N-atom spontaneous emission

N-atom system ⇔ N spin-1/2 system with the total spin J = N/2 (assumption: *Indiscernability* of the atoms with respect to photon emission)



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

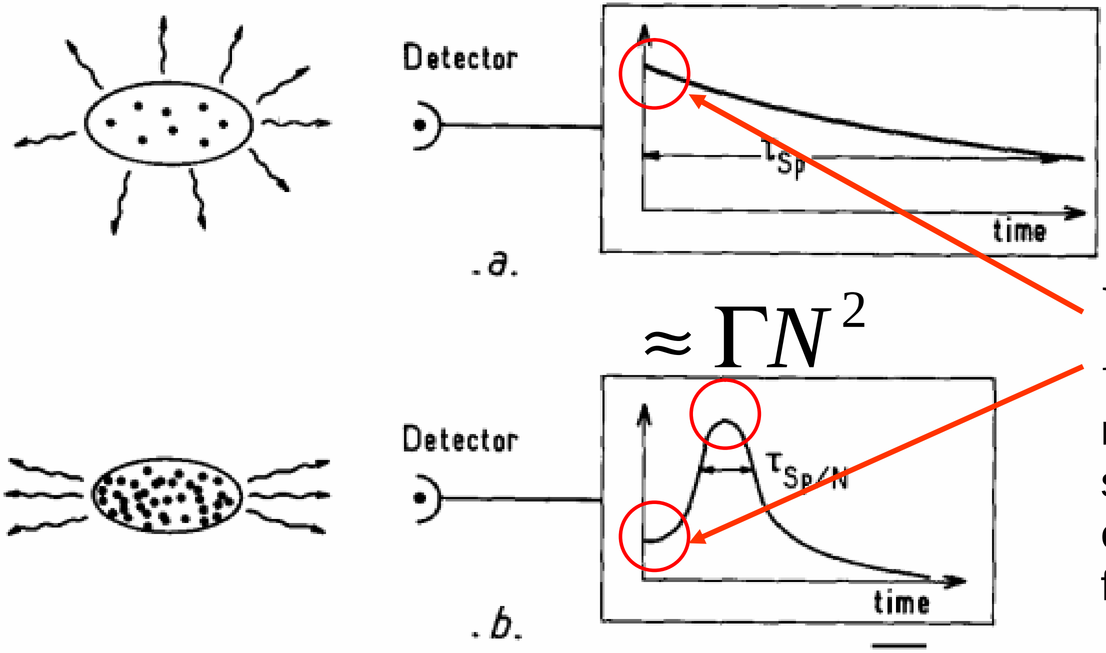
Spontaneous emission rate of the N-atom system:

$$\begin{aligned}\Gamma_N &= \Gamma\langle J,M\,|\,J_+J_-\,|\,J,M\rangle \\ &= \Gamma(J+M)(J-M+1) \\ &= \Gamma N_e(N_g+1)\end{aligned}$$

↑

Enhancement by the number of photons already emitted

Comparison between ordinary and superradiant emission



$\approx \Gamma N^2$

ΓN

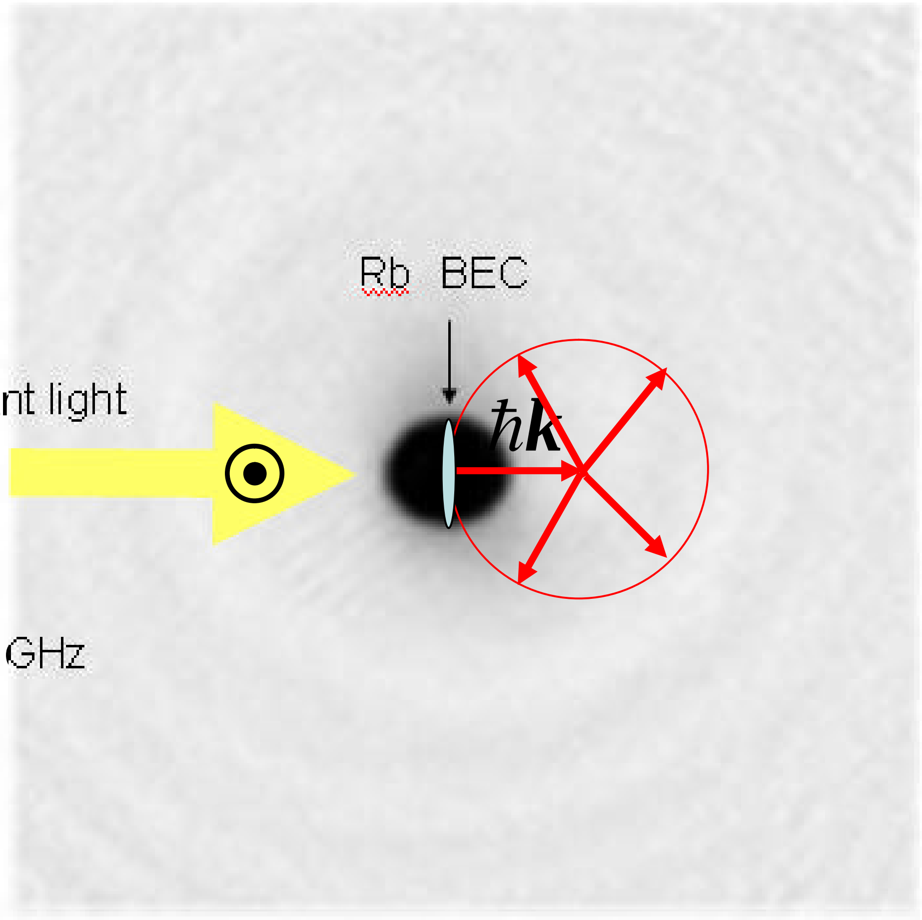
normal spontaneous emission at first

Fig. 1. Comparison between the general characteristics of ordinary fluorescence and superradiance experiments. (a) Ordinary spontaneous emission is essentially isotropic with an exponentially decaying intensity (time constant τ_{sp}). (b) Superradiance is anisotropic with an emission occurring in a short burst of duration $\sim\tau_{sp}/N$.

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

Rayleigh scattering in a Rb BEC

Off-resonant light



63 mW/cm^2

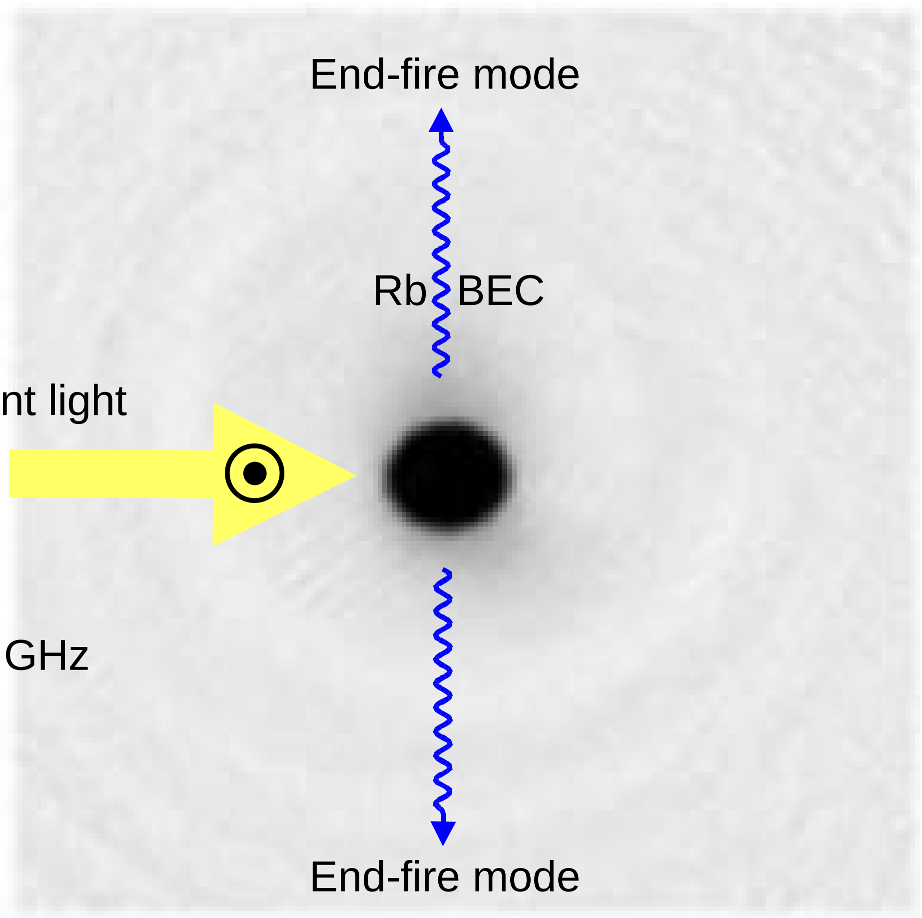
detuning: -4.4 GHz

Pulse duration:
25 µs-3200 µs

30 ms TOF

D. Schneble, Y.T., M. Boyd, E. W. Streed, D. E. Pritchard, and W. Ketterle, Science **300**, 475 (2003)

Rayleigh scattering in a Rb BEC



End-fire mode

Rb BEC

Off-resonant light

End-fire mode

63 mW/cm^2

detuning: -4.4 GHz

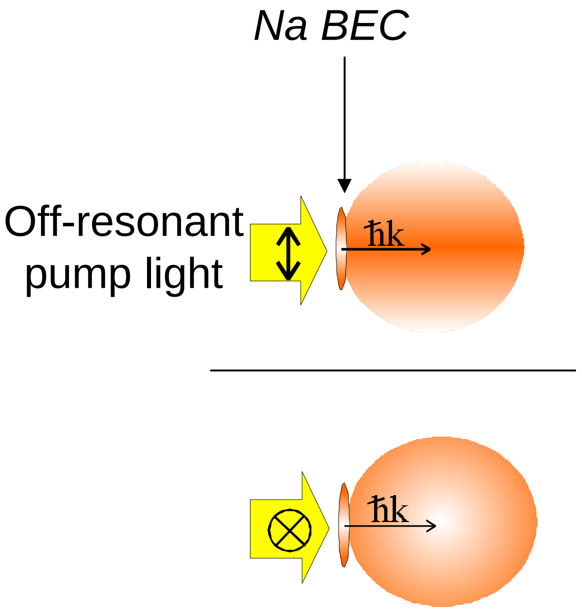
Pulse duration:
25 µs-3200 µs

30 ms TOF

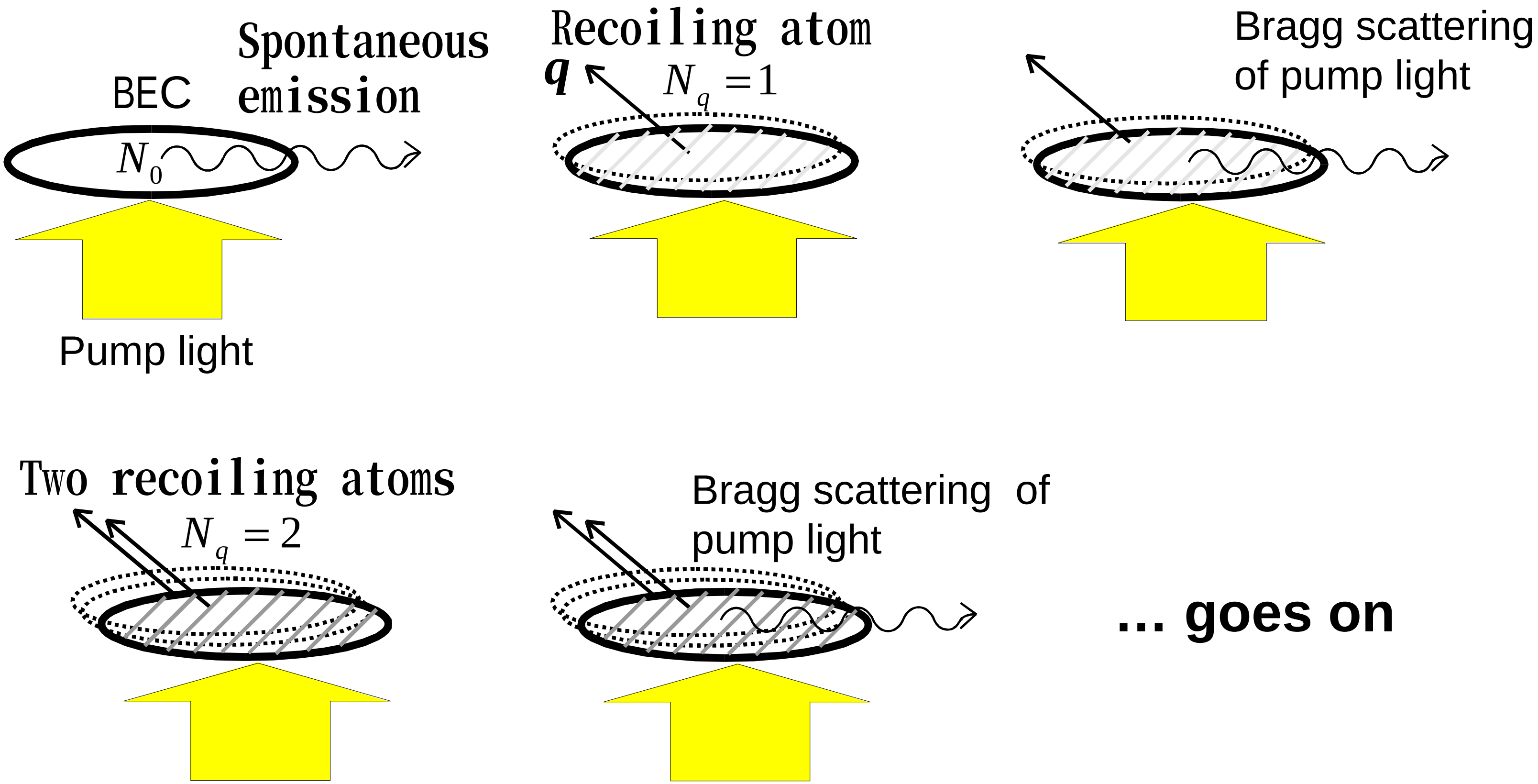
D. Schneble, Y.T., M. Boyd, E. W. Streed, D. E. Pritchard, and W. Ketterle, Science **300**, 475 (2003)

Superradiant Rayleigh scattering from a Bose-Einstein condensate

S. Inouye, et. al., Science **285**, 571 (1999)



Semiclassical interpretation of superradiance



BEC

N_0

Spontaneous emission

Pump light

Recoiling atom

$\boldsymbol{q}$

$N_q = 1$

Bragg scattering of pump light

Two recoiling atoms

$N_q = 2$

Bragg scattering of pump light

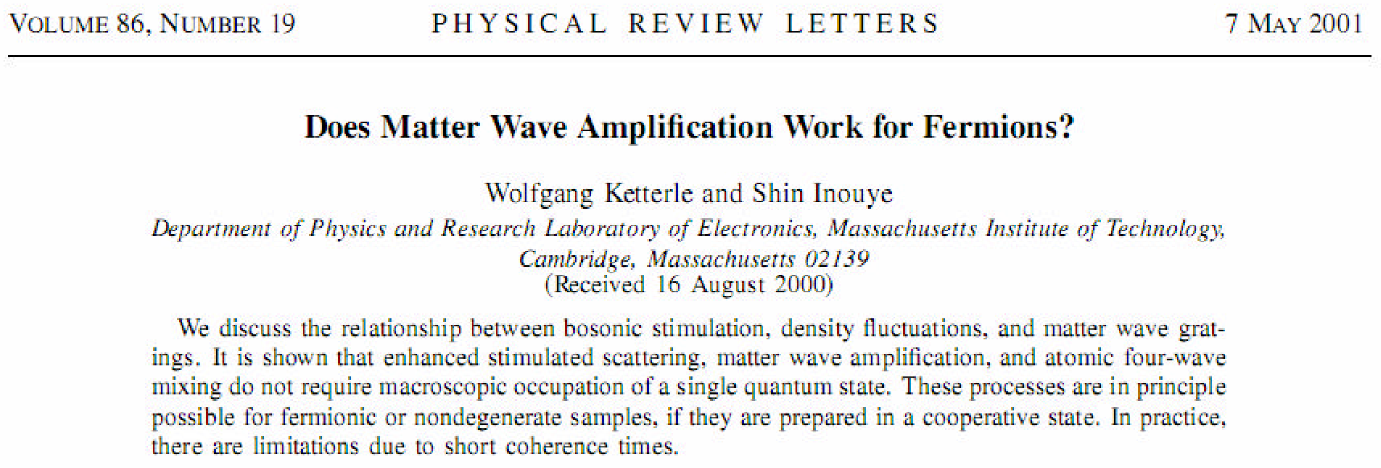
… goes on

The rate of light scattering is enhanced by the number of recoiling atoms

$$\dot{N}_q \propto N_0 N_q$$

Amplification of matter-wave

Superradiance happens for Fermions, therefore for thermal atoms also



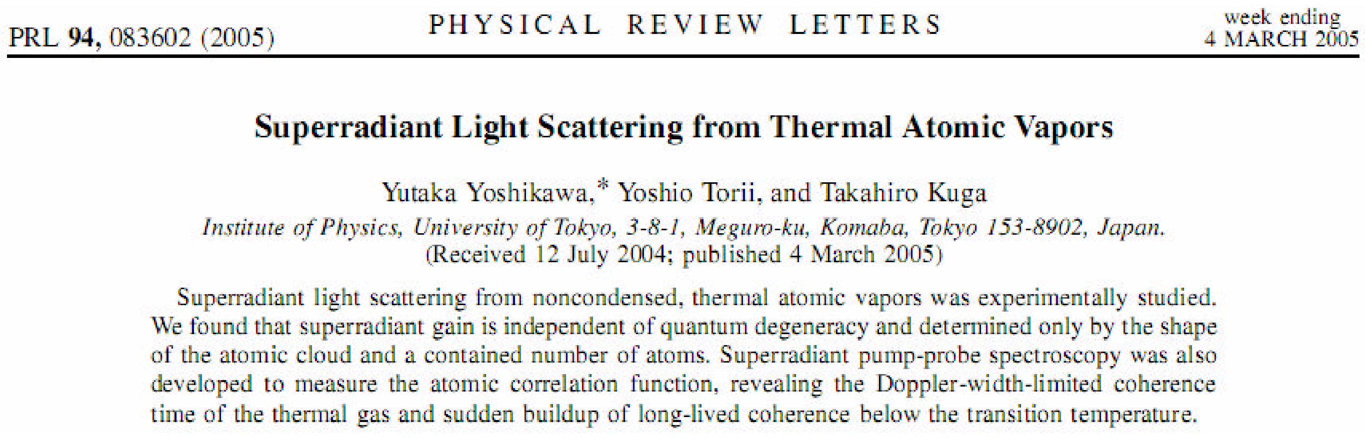
VOLUME 86, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 2001

Does Matter Wave Amplification Work for Fermions?

Wolfgang Ketterle and Shin Inouye
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

(Received 16 August 2000)

We discuss the relationship between bosonic stimulation, density fluctuations, and matter wave gratings. It is shown that enhanced stimulated scattering, matter wave amplification, and atomic four-wave mixing do not require macroscopic occupation of a single quantum state. These processes are in principle possible for fermionic or nondegenerate samples, if they are prepared in a cooperative state. In practice, there are limitations due to short coherence times.



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

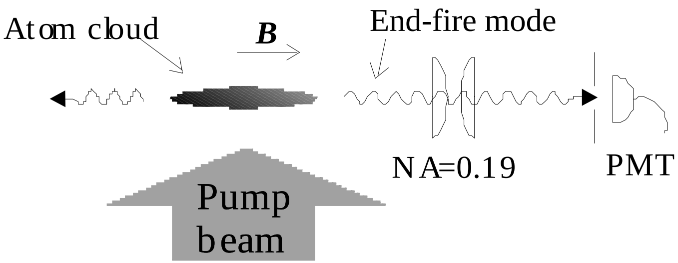
Superradiant Light Scattering from Thermal Atomic Vapors

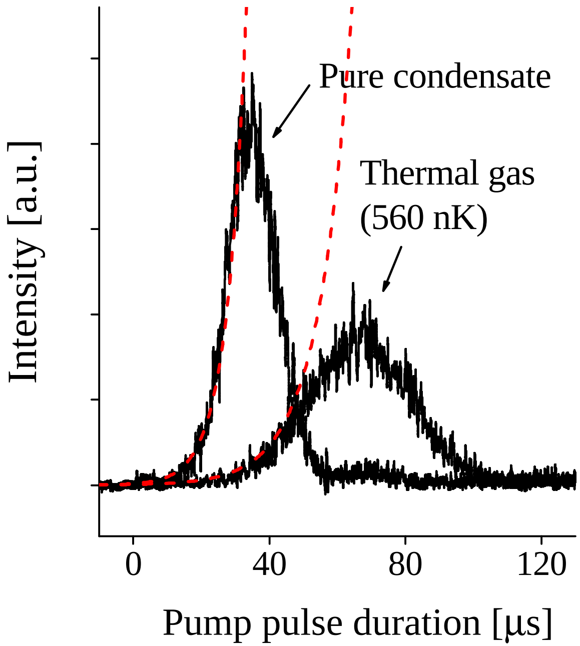
Yutaka Yoshikawa,* Yoshio Torii, and Takahiro Kuga
Institute of Physics, University of Tokyo, 3-8-1, Meguro-ku, Komaba, Tokyo 153-8902, Japan.

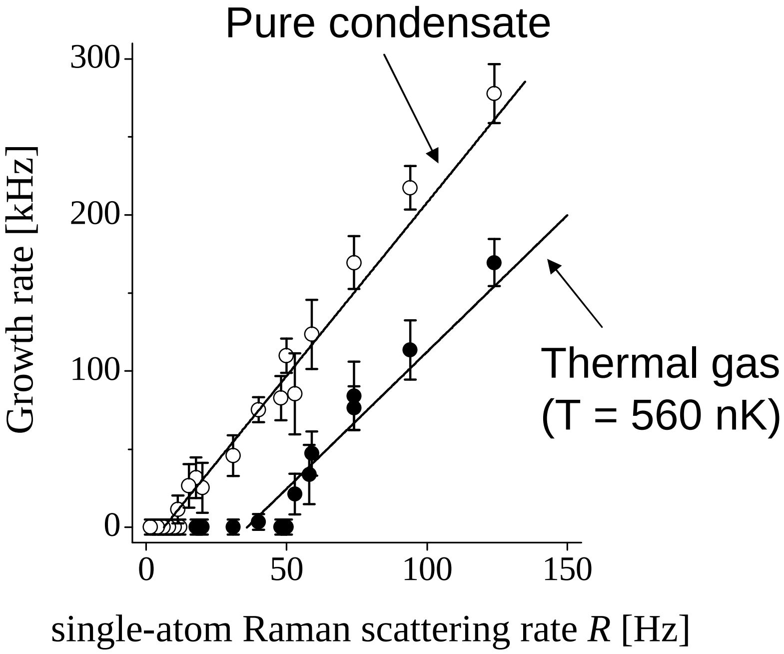
(Received 12 July 2004; published 4 March 2005)

Superradiant light scattering from noncondensed, thermal atomic vapors was experimentally studied. We found that superradiant gain is independent of quantum degeneracy and determined only by the shape of the atomic cloud and a contained number of atoms. Superradiant pump-probe spectroscopy was also developed to measure the atomic correlation function, revealing the Doppler-width-limited coherence time of the thermal gas and sudden buildup of long-lived coherence below the transition temperature.

Superradiance in a Thermal gas

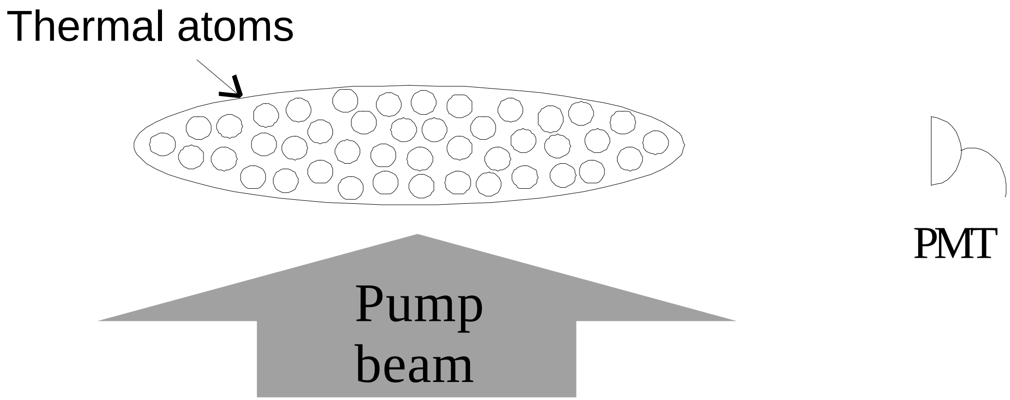


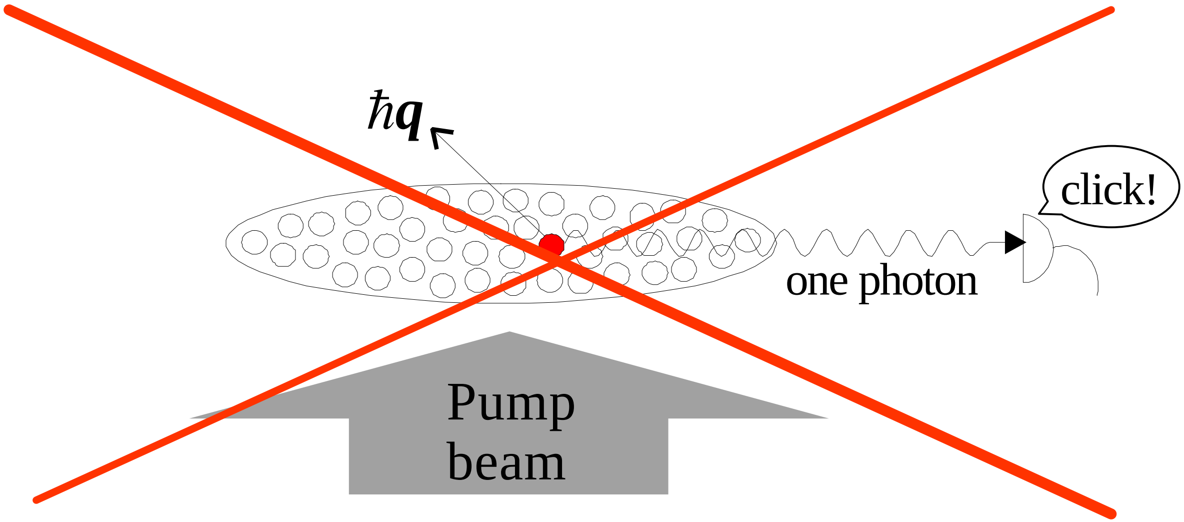




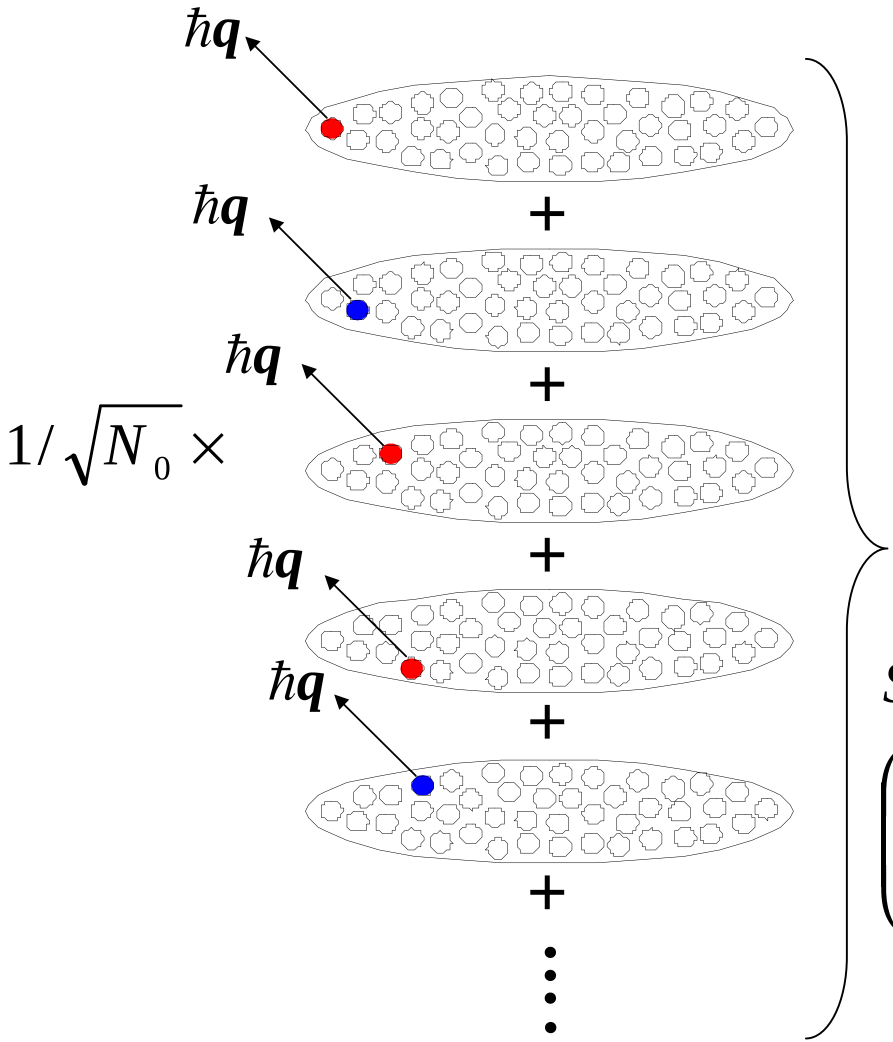
Y. Yoshikawa, Y. T. and T. Kuga, PRL **94** 083602 (2005)

Where is the grating?

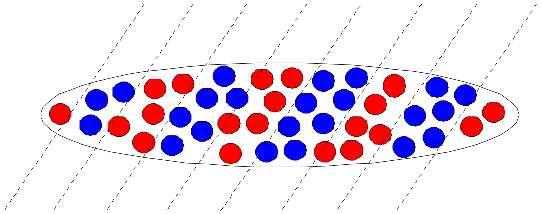




The origin of the grating
(Collective mode excitation)



One atom is excited to the collective atomic mode defined by S^+

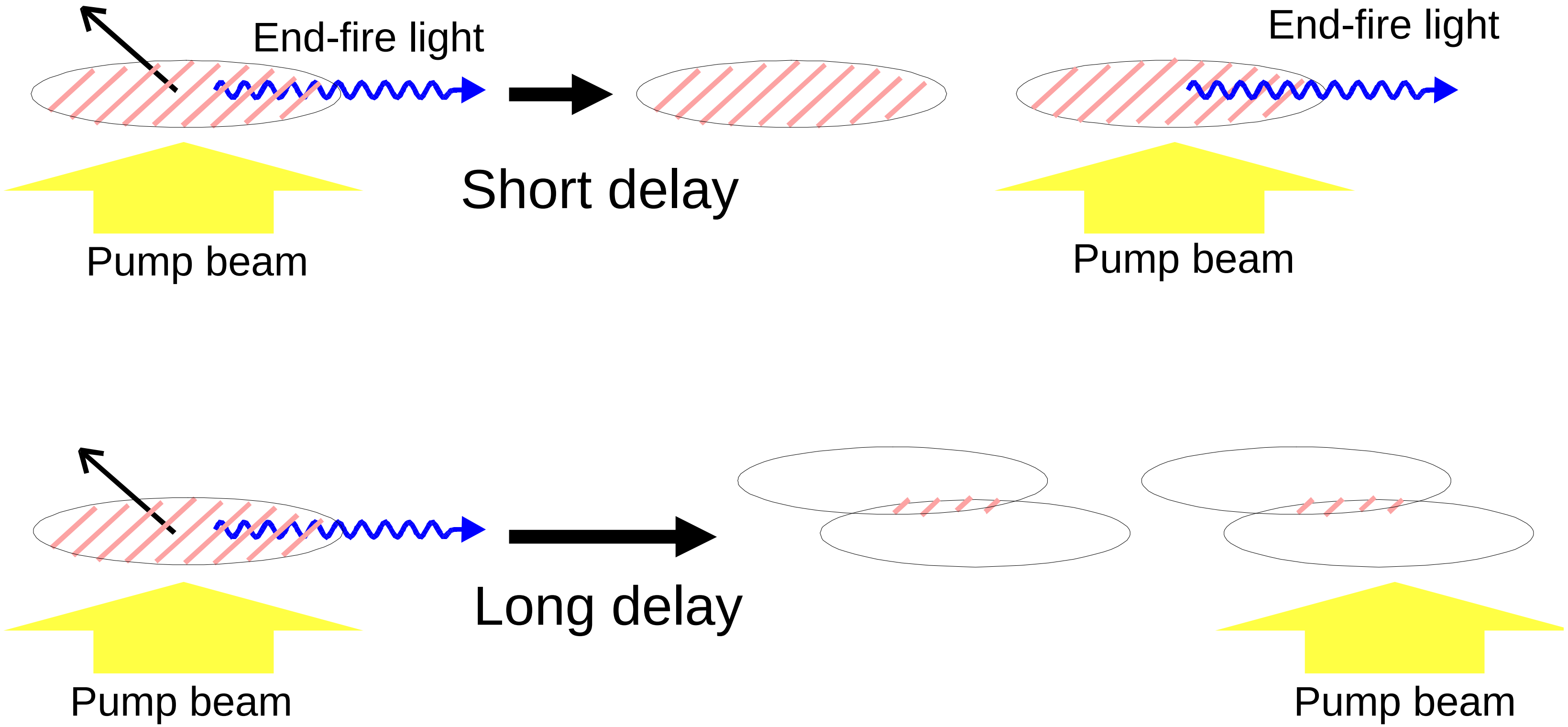


$$S^+ | J, M = -J > = | J, M = -J + 1 >$$

$$\left(S^+ \equiv \frac{1}{\sqrt{N_0}} \sum_{i=1}^{N_0} e^{i\boldsymbol{q}\cdot\boldsymbol{r}_i} | \hbar q >_i < 0 | \right)$$

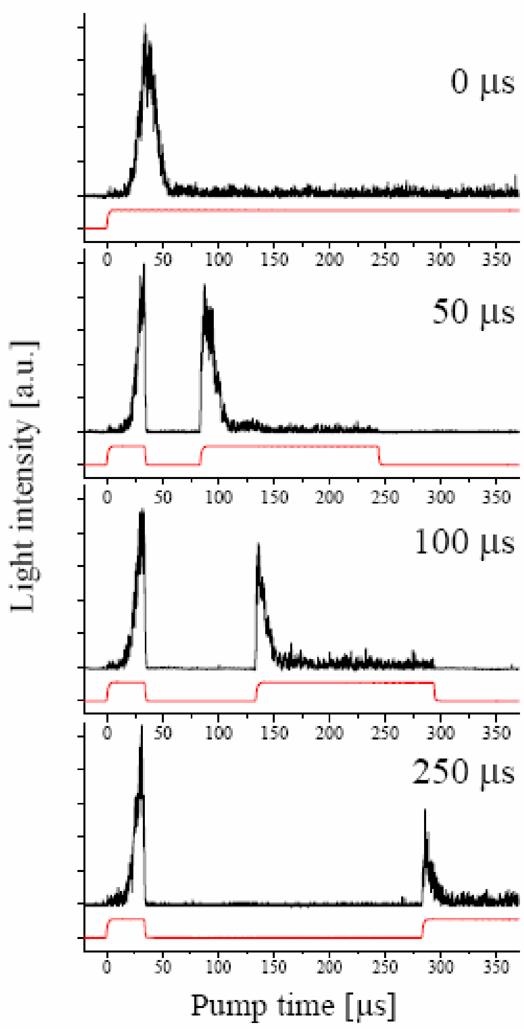
Phase factor depending on the position

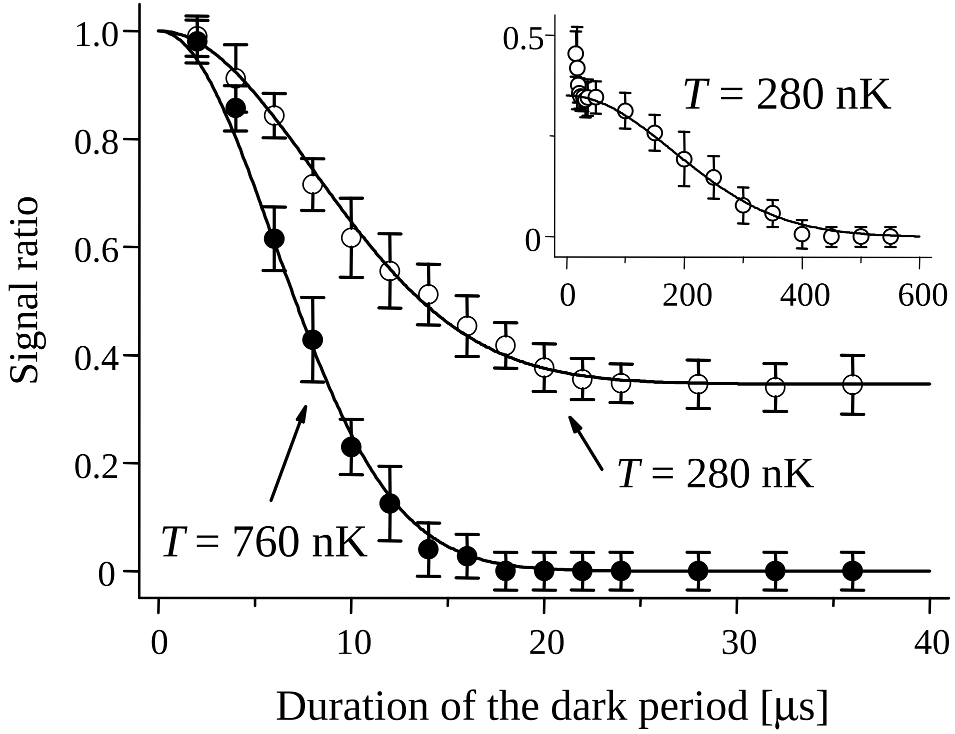
How long does the grating survive?



Storage (coherent) time of the grating is limited by the size of the wavepacket

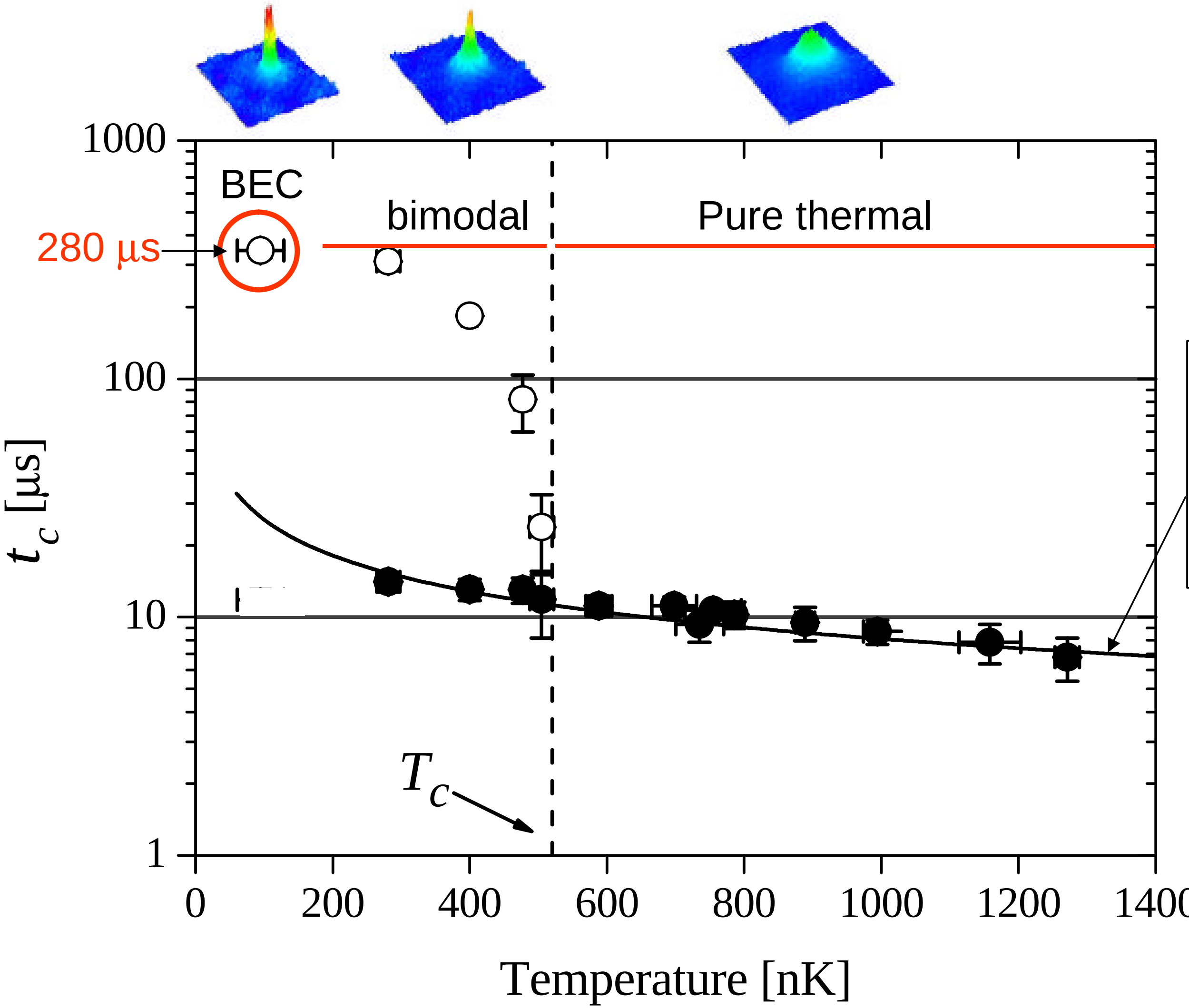
Storage (coherence) time measurement





Y. Yoshikawa, Y. T. and T. Kuga, PRL **94** 083602 (2005)

Storage time vs. temperature



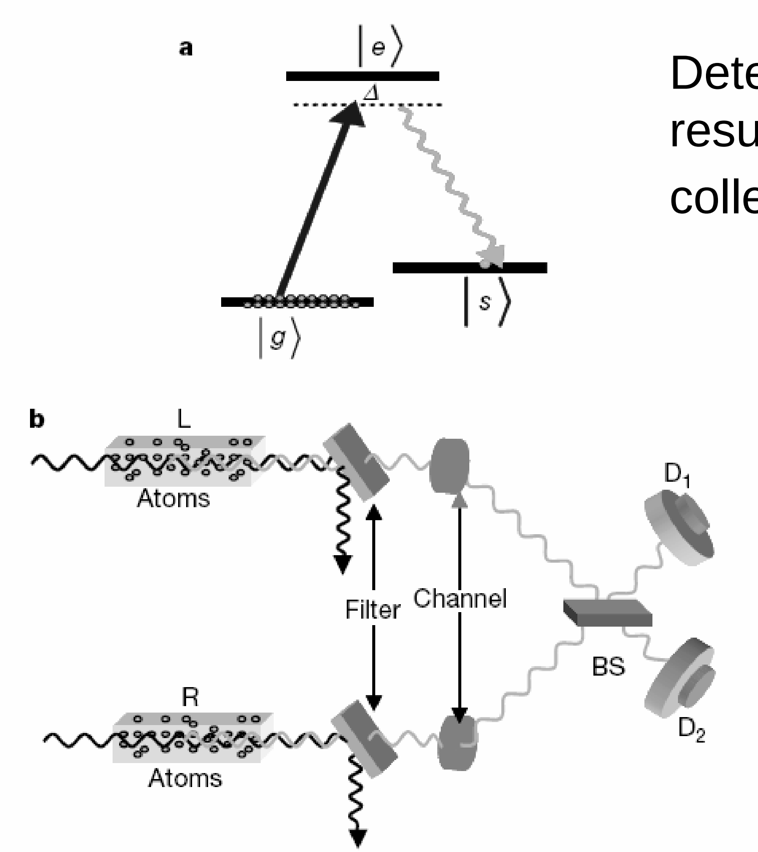
$$t_{\mathrm{c}} = \frac{1}{2k\bar{v}} = \frac{l}{4p}\sqrt{\frac{m}{k_{\mathrm{B}}T}}$$

An application of Dicke superradiance:
Storage of light pulses in a Bose-Einstein condensate

Y. Yoshikawa, et al., Phy. Rev. Lett. **99**, 220407 (2007)

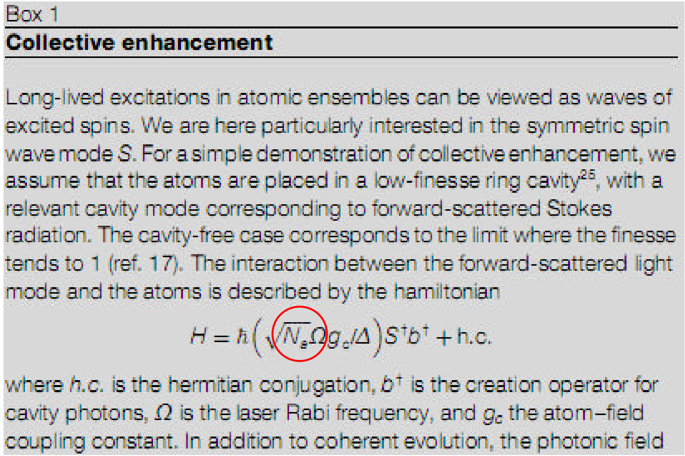
Y. Yoshikawa, et al., Phys. Rev. **A 79**, 025601 (2009)

Motivation: DLCZ protocol (long distance quantum network)



Detection of a forward-scattered photon results in the excitation of the symmetric collective mode defined by

$$S^+ \equiv \frac{1}{\sqrt{N}}\sum_{i=1}^{N} | s >_i < g |$$



Box 1

Collective enhancement

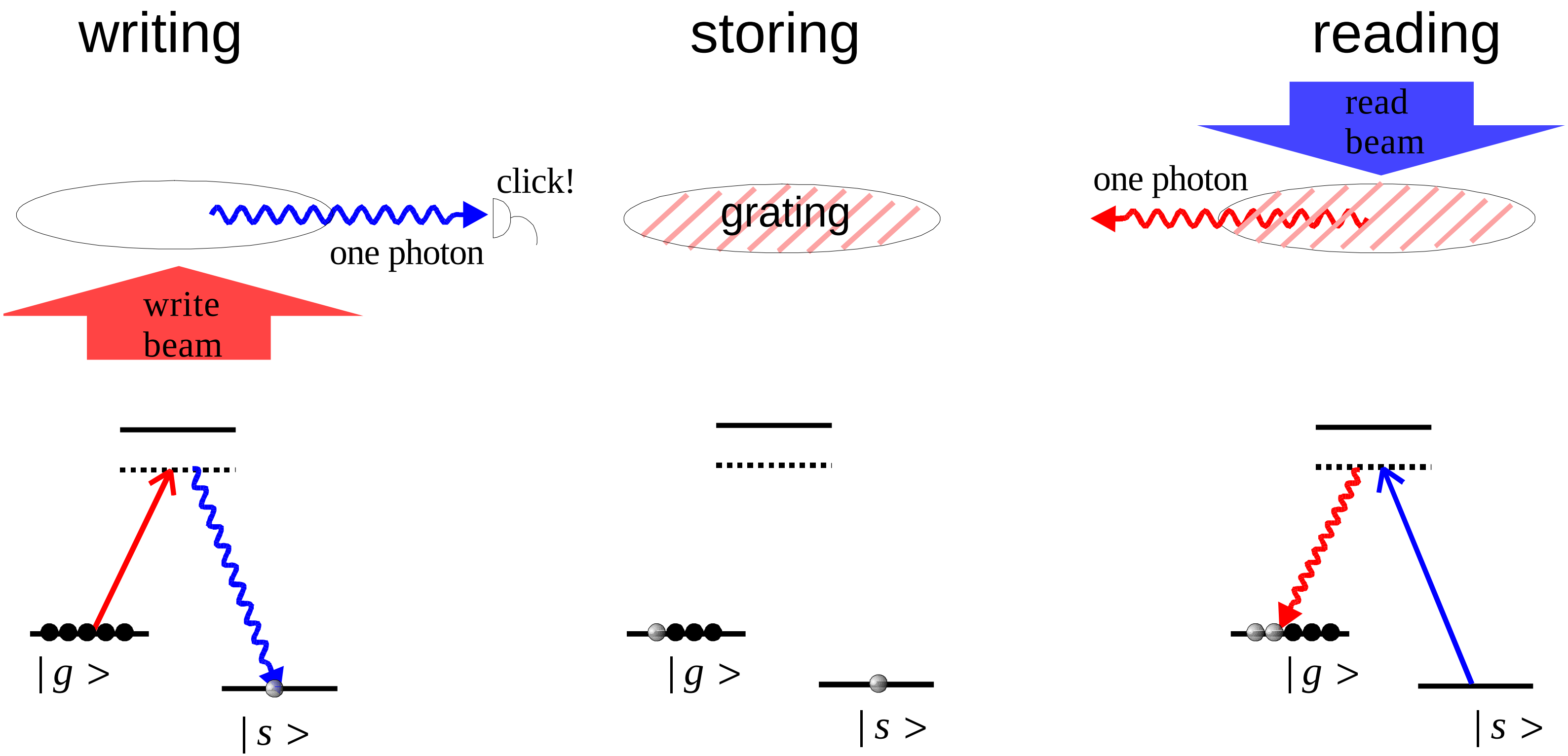
Long-lived excitations in atomic ensembles can be viewed as waves of excited spins. We are here particularly interested in the symmetric spin wave mode *S*. For a simple demonstration of collective enhancement, we assume that the atoms are placed in a low-finesse ring cavity[25], with a relevant cavity mode corresponding to forward-scattered Stokes radiation. The cavity-free case corresponds to the limit where the finesse tends to 1 (ref. 17). The interaction between the forward-scattered light mode and the atoms is described by the hamiltonian

$$H = \hbar\left(\sqrt{N_a}\,\Omega g_c/\Delta\right)S^\dagger b^\dagger + \text{h.c.}$$

where *h.c.* is the hermitian conjugation, $b^\dagger$ is the creation operator for cavity photons, Ω is the laser Rabi frequency, and g_c the atom–field coupling constant. In addition to coherent evolution, the photonic field

L.-M. Duan, M. D. Lukin, J. I. Cirac,and P. Zoller, Nature. **414**, 413 (2001)

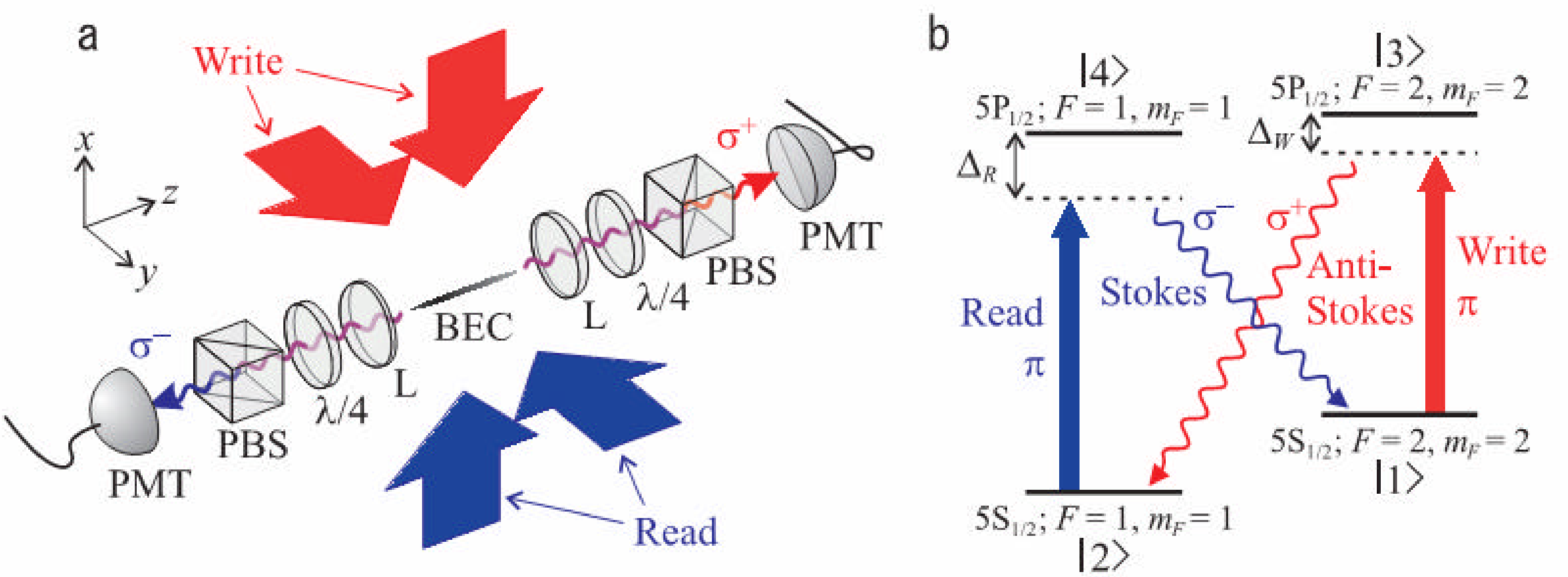
Writing, storing, and reading of a single photon


writing

storing

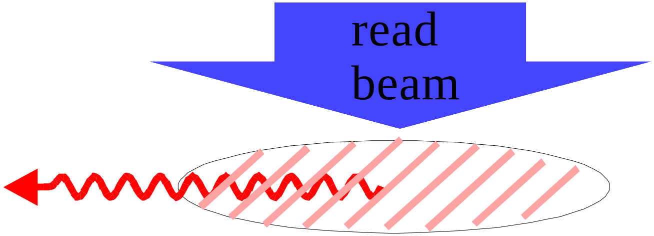
reading

Multiple storage and retrieval of light pulses in a BEC



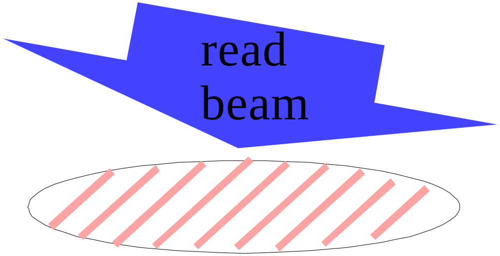
Selective retrieval of phonons (Phase-matching condition)

Phase-matched read beam



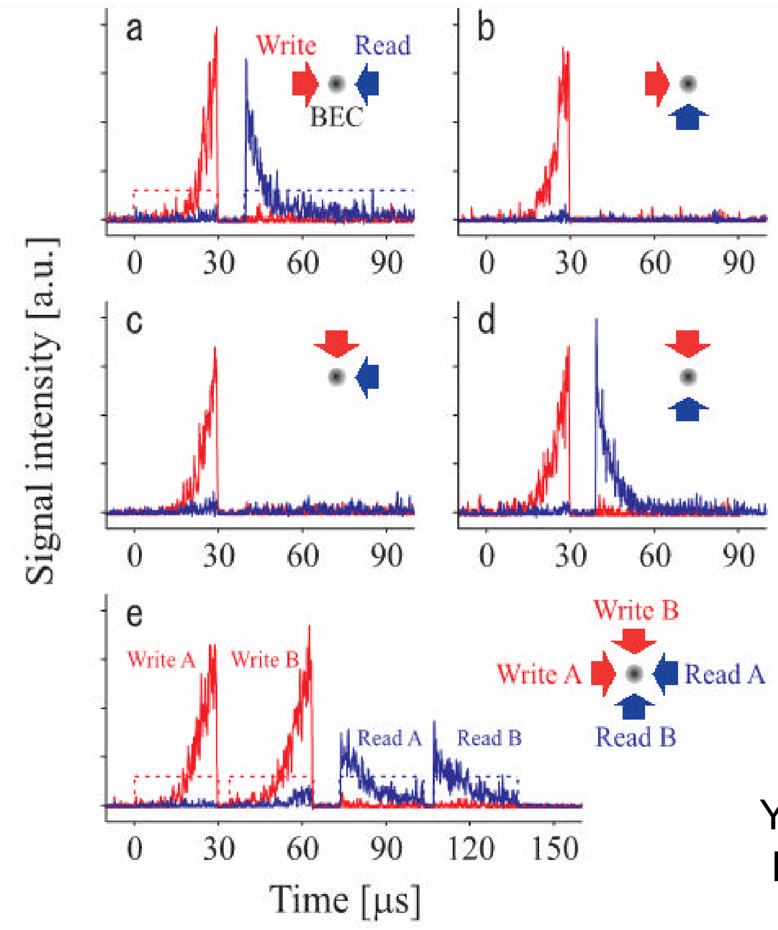
The read beam is diffracted
(successful retrieval)

Phase-mismatched read beam



The read beam just passes
through

Multiple storage and retrieval of light pulses in a BEC



Possible applications

- Arbitrary-number photon generator
- Multiple quantum memory
- Quantum atom optics

Y. Yoshikawa, K. Nakayama, Y. T. and T. Kuga,
Phys. Rev. Lett. **99**, 220407 (2007).

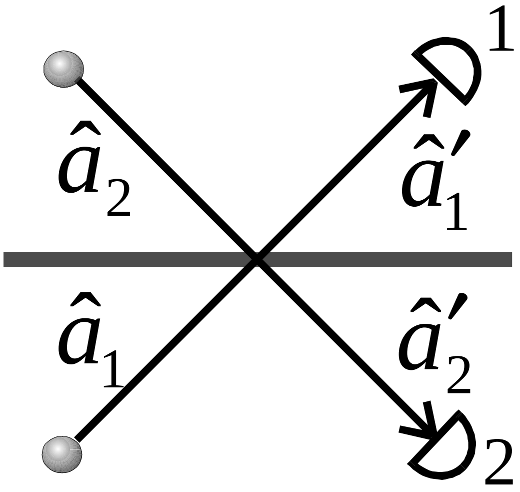
Mandel’s two-photon interference

Input state

$$\hat{a}_1^+ \hat{a}_2^+ \,|\, 0, 0 >$$

Beam splitter operation

$$\begin{pmatrix} \hat{a}'_1 \\ \hat{a}'_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix}$$



Output state

$$\frac{1}{2}\left(\hat{a}_1'^+ + \hat{a}_2'^+\right)\left(\hat{a}_1'^+ - \hat{a}_2'^+\right) |\, 0, 0 >$$

Bunching

$$= \frac{1}{2}\left(\left(\hat{a}_1'^+\right)^2 + \left(\hat{a}_2'^+\right)^2\right) |\, 0, 0 > = \boxed{\frac{1}{\sqrt{2}}\left(|\, 2, 0 > + \,|\, 0, 2 >\right)}$$

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)

A fourth-order interference technique has been used to measure the time intervals between two photons, and by implication the length of the photon wave packet, produced in the process of parametric down-conversion. The width of the time-interval distribution, which is largely determined by an interference filter, is found to be about 100 fs, with an accuracy that could, in principle, be less than 1 fs.

PACS numbers: 42.50.Bs, 42.65.Re

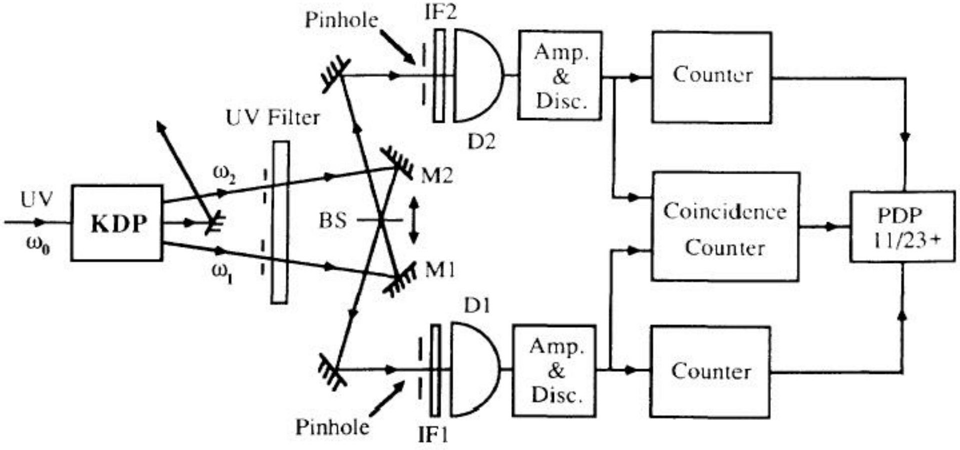


FIG. 1. Outline of the experimental setup.

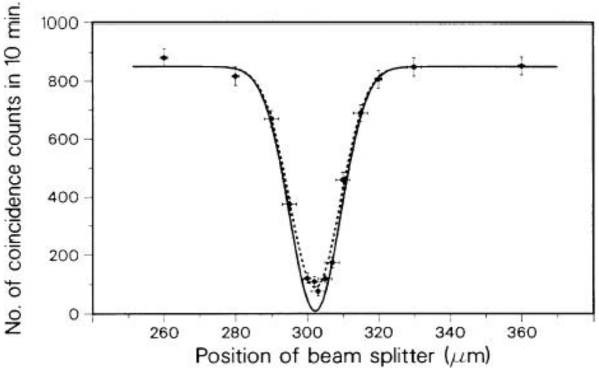
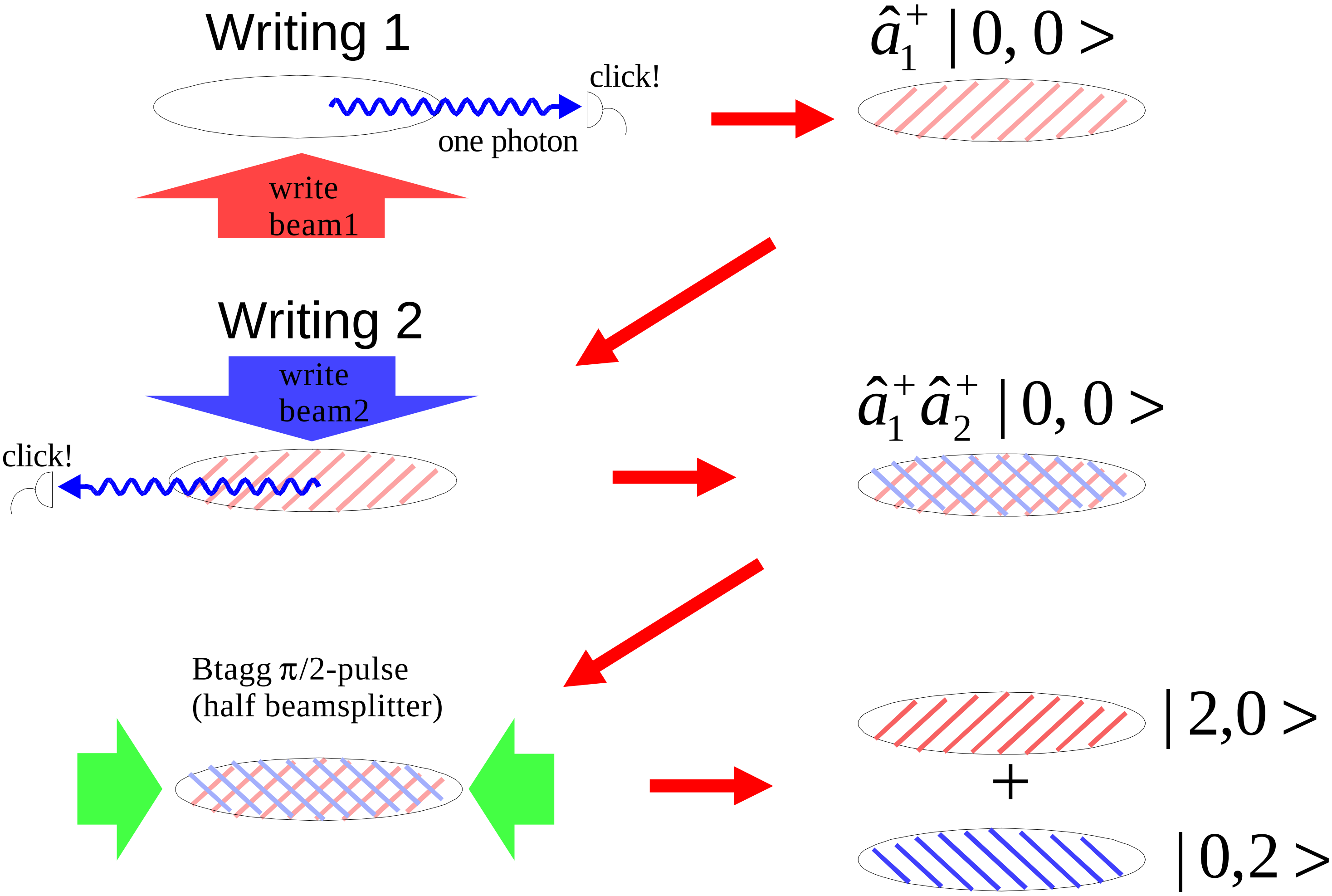


FIG. 2. The measured number of coincidences as a function of beam-splitter displacement $c\,\delta\tau$, superimposed on the solid theoretical curve derived from Eq. (11) with $R/T=0.95$, $\Delta\omega=3\times10^{13}$ rad s^{-1}. For the dashed curve the factor $2RT/(R^2+T^2)$ in Eq. (11) was multiplied by 0.9. The vertical error bars correspond to one standard deviation, whereas horizontal error bars are based on estimates of the measurement accuracy.

Two-*atom* interference



Writing 1

click!

one photon

write beam1

$\hat{a}_1^+ \,|\, 0,\, 0 >$

Writing 2

write beam2

click!

$\hat{a}_1^+ \hat{a}_2^+ \,|\, 0,\, 0 >$

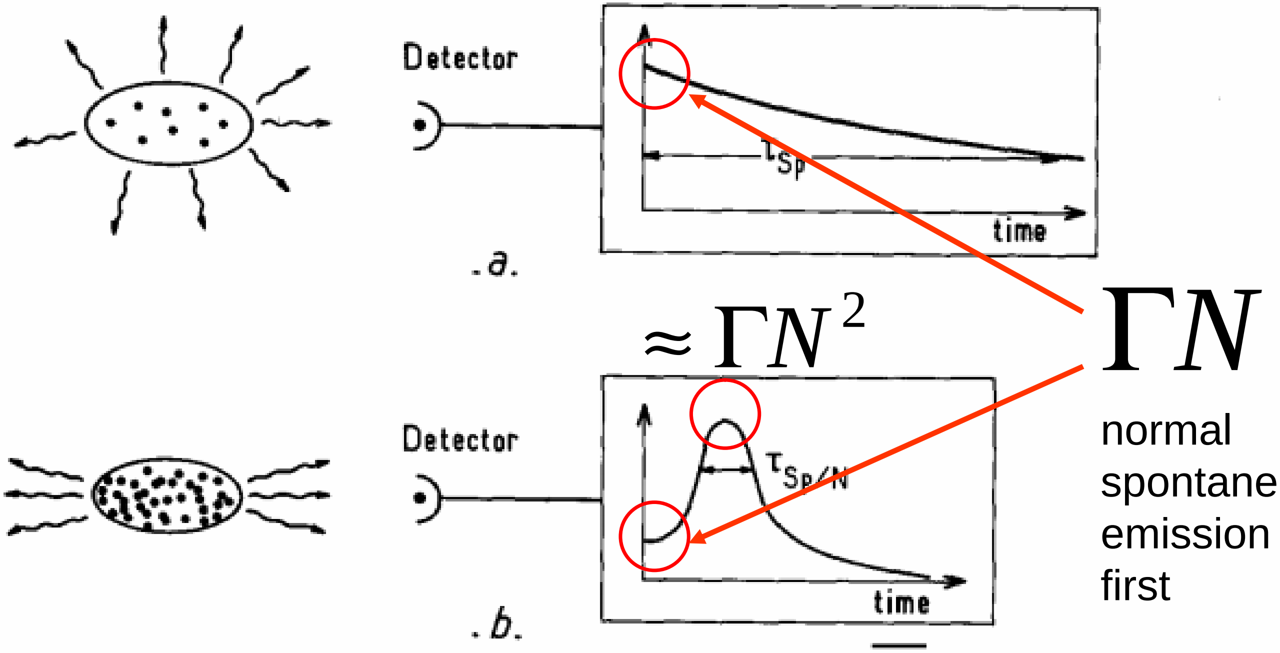
Btagg π/2-pulse
(half beamsplitter)

$|\, 2,0 >$

$+$

$|\, 0,2 >$

Comparison between ordinary and superradiant emission



$$\approx \Gamma N^2$$

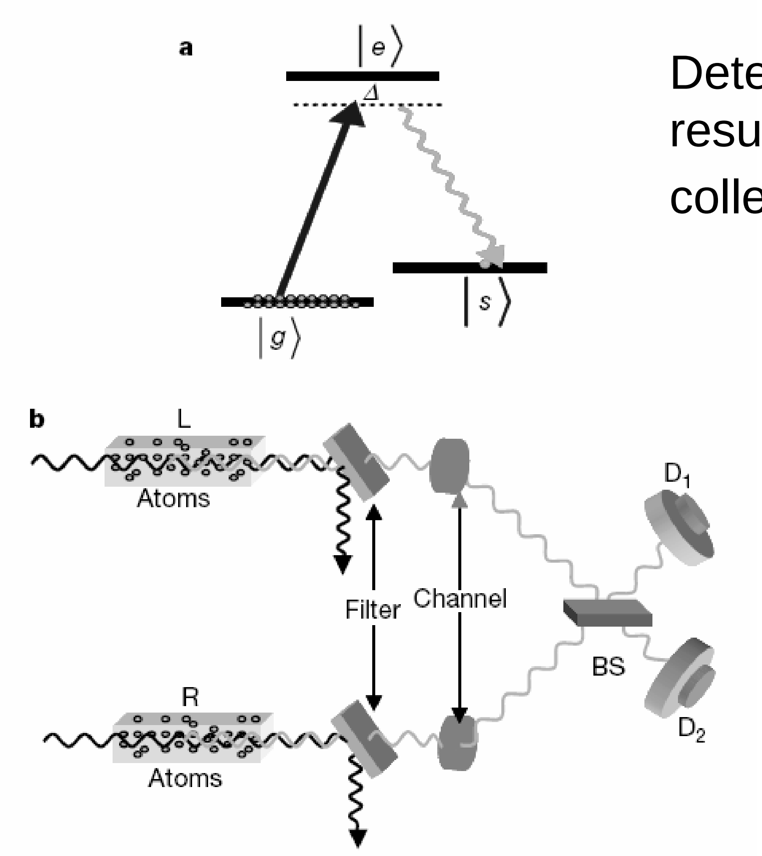
$$\Gamma N$$

normal spontaneous emission at first

Fig. 1. Comparison between the general characteristics of ordinary fluorescence and superradiance experiments. (a) Ordinary spontaneous emission is essentially isotropic with an exponentially decaying intensity (time constant τ_{sp}). (b) Superradiance is anisotropic with an emission occurring in a short burst of duration $\sim\tau_{sp}/N$.

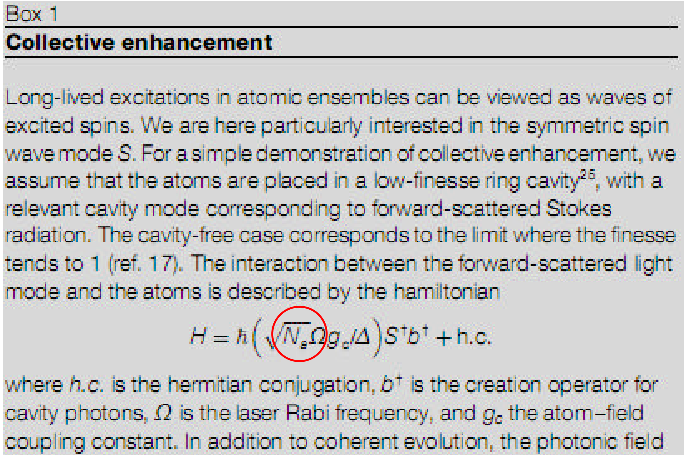
From M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982)

Motivation: DLCZ protocol (long distance quantum network)



Detection of a forward-scattered photon results in the excitation of the symmetric collective mode defined by

$$S^{+} \equiv \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |s>_i < g|$$



Box 1

Collective enhancement

Long-lived excitations in atomic ensembles can be viewed as waves of excited spins. We are here particularly interested in the symmetric spin wave mode *S*. For a simple demonstration of collective enhancement, we assume that the atoms are placed in a low-finesse ring cavity[25], with a relevant cavity mode corresponding to forward-scattered Stokes radiation. The cavity-free case corresponds to the limit where the finesse tends to 1 (ref. 17). The interaction between the forward-scattered light mode and the atoms is described by the hamiltonian

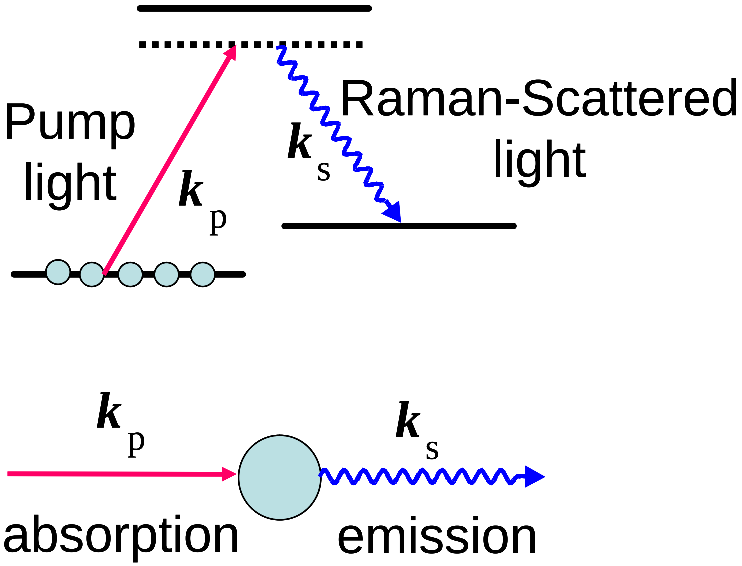
$$H = \hbar\left(\sqrt{N_a}\,\Omega g_c/\Delta\right) S^{\dagger} b^{\dagger} + \text{h.c.}$$

where *h.c.* is the hermitian conjugation, $b^{\dagger}$ is the creation operator for cavity photons, Ω is the laser Rabi frequency, and g_c the atom–field coupling constant. In addition to coherent evolution, the photonic field

L.-M. Duan, M. D. Lukin, J. I. Cirac,and P. Zoller, Nature. **414**, 413 (2001)

Forward Raman scattering and (seeded) two photon emission

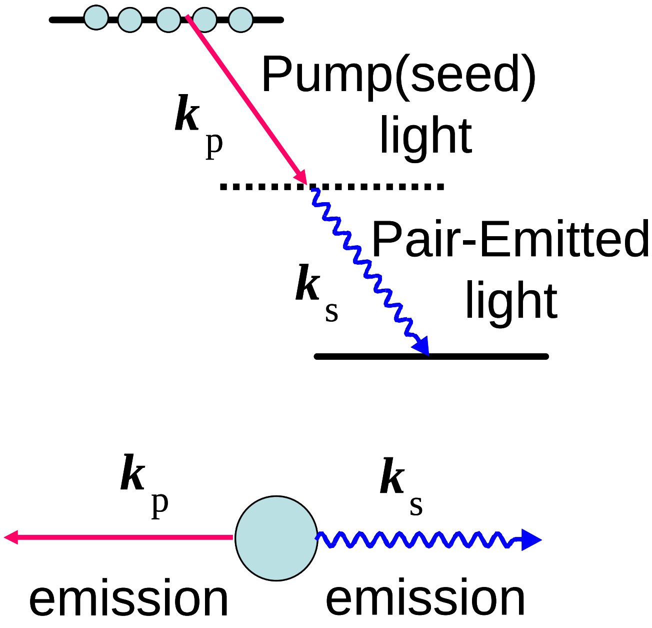
(a)



$$e^{-i\boldsymbol{k}_\mathrm{p}\cdot\boldsymbol{r}} \cdot e^{+i\boldsymbol{k}_\mathrm{s}\cdot\boldsymbol{r}} = \enclose{circle}{1}$$

Position independent
→collective enhancement

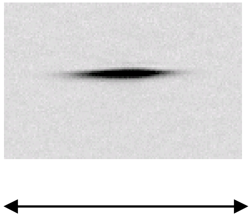
(b)



$$e^{+i\boldsymbol{k}_\mathrm{p}\cdot\boldsymbol{r}} \cdot e^{+i\boldsymbol{k}_\mathrm{s}\cdot\boldsymbol{r}} = \enclose{circle}{1}$$

Position independent
→collective enhancement

Mode pattern of superradiant pulse



500 μm

Rb^{87}, $|F=2, m_F=2>$

Number of BEC : 8×10^5

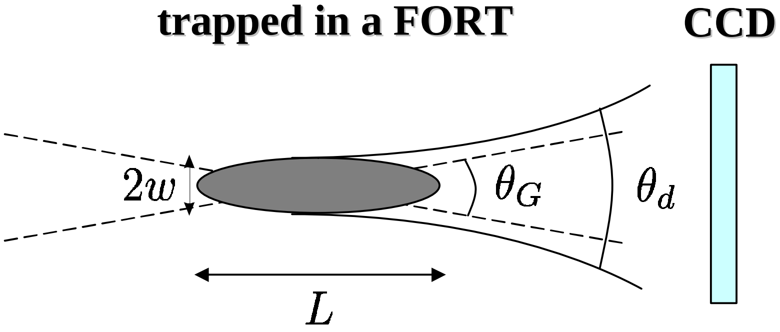
Lifetime : ~1.5 s

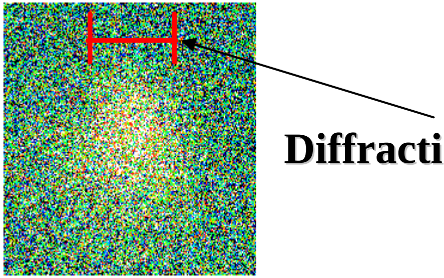
$2\omega = 12$ μm

$L = 145$ μm

$F \sim 0.9$

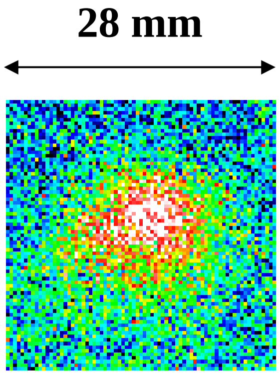
Superradiant emission of BEC trapped in a FORT



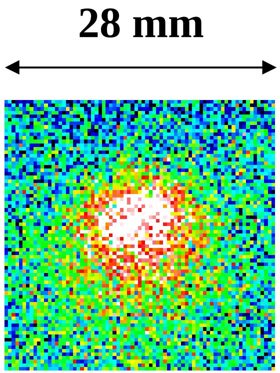


Diffraction angle

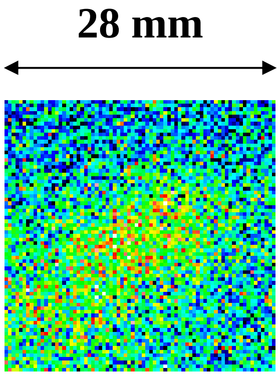
(Regrettably) changing Mode pattern



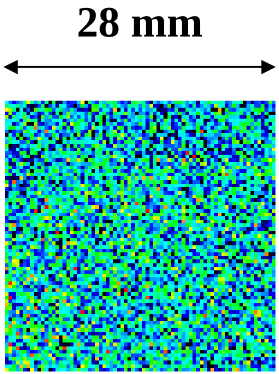
Spont. Raman Rate ~260 Hz



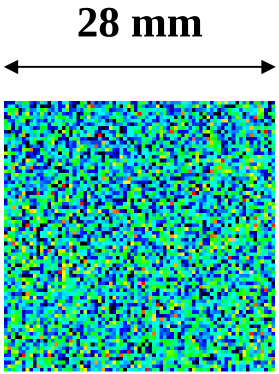
Spont. Raman Rate ~52 Hz



Spont. Raman Rate ~26 Hz

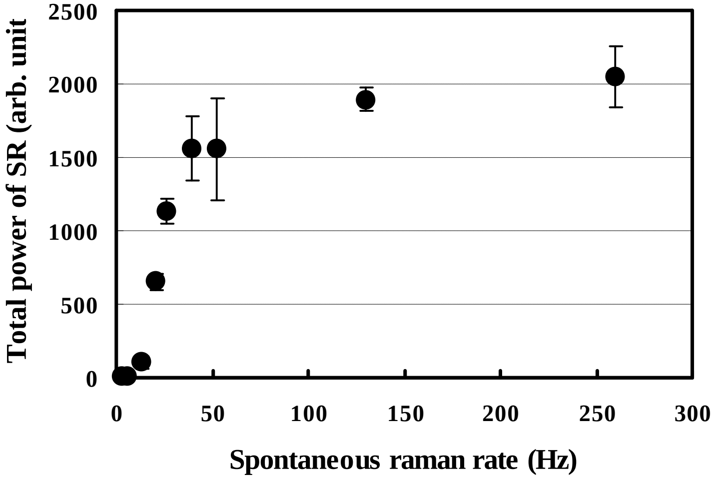


Spont. Raman Rate ~13 Hz



Spont. Raman Rate ~2.6 Hz

Exposure time
~ 500 ms
Pumping time
20 µs ~ 500 ms

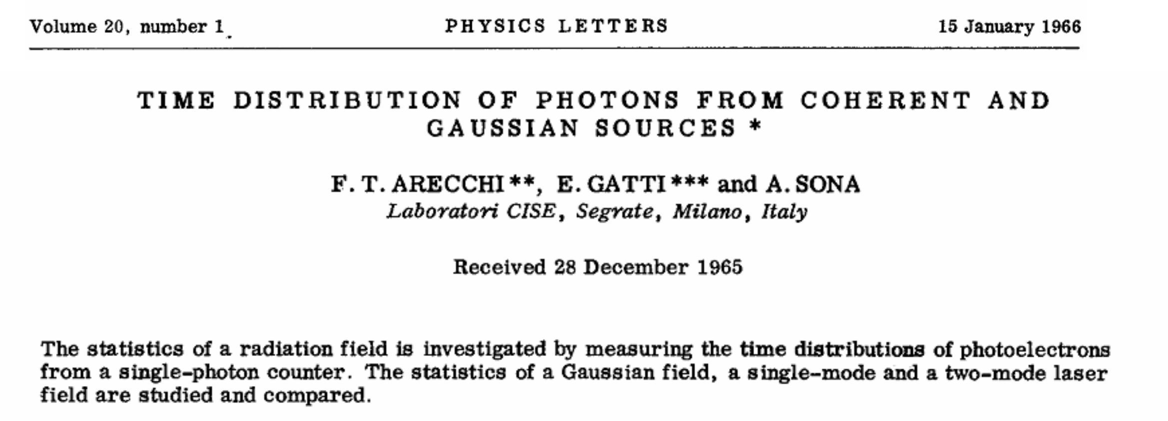


Precise intensity correlation measurement for atomic resonance fluorescence from optical molasses

Nakayana, et. al, Optics Express,
18, 6604 (2010)

物理学温故知新（by久我先生）の一つ

Second-order correlation function



Volume 20, number 1 PHYSICS LETTERS 15 January 1966

TIME DISTRIBUTION OF PHOTONS FROM COHERENT AND GAUSSIAN SOURCES *

F. T. ARECCHI **, E. GATTI *** and A. SONA
Laboratori CISE, Segrate, Milano, Italy

Received 28 December 1965

The statistics of a radiation field is investigated by measuring the time distributions of photoelectrons from a single-photon counter. The statistics of a Gaussian field, a single-mode and a two-mode laser field are studied and compared.

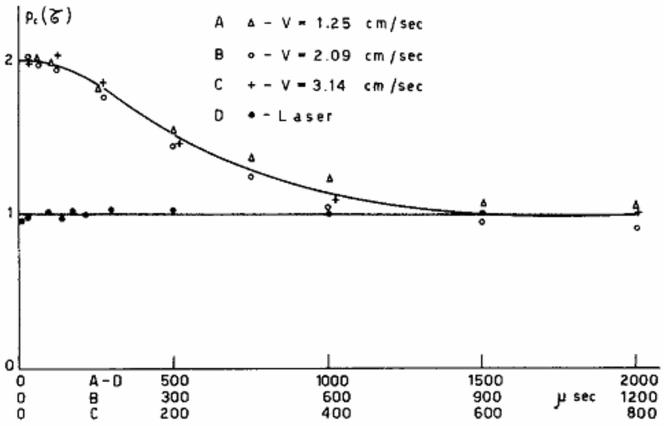


Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

Second-order correlation function

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

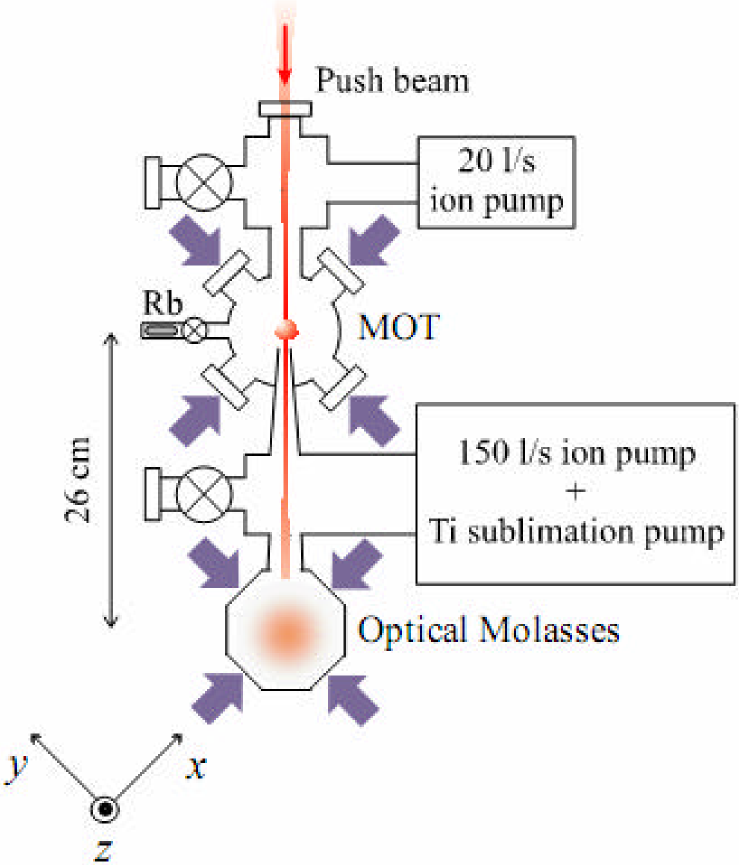
For thermal (chaotic) light

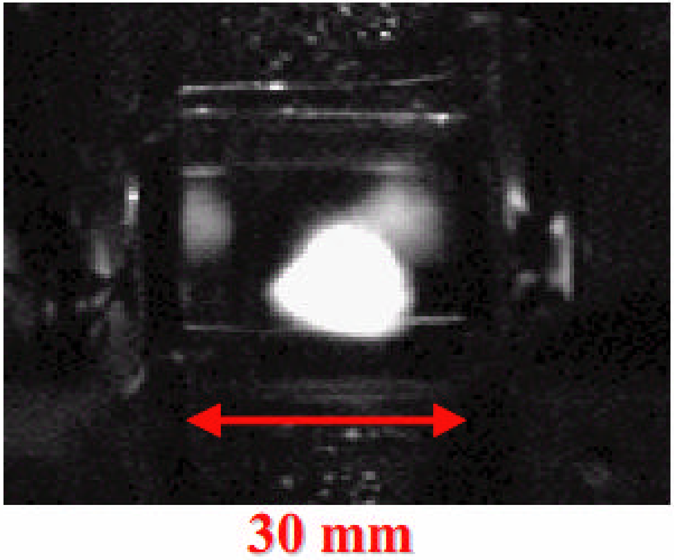
$$g^{(2)}(t) = 1 + \left|g^{(1)}(t)\right|^2$$

For coherent light

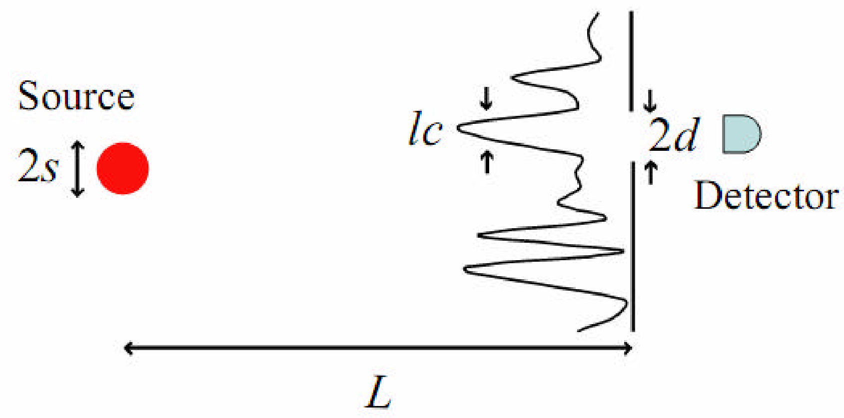
$$g^{(2)}(t) = 1$$

Light source: continuous optical molasses of Rb atoms





Criteria for spatially-coherent detection



Typical size of the speckle

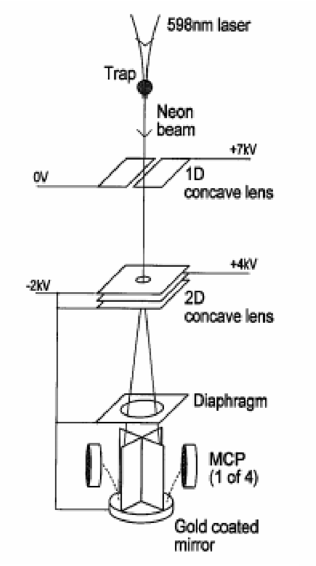
$$l_c \approx \frac{l L}{s}$$

For spatially-coherent detection of intensity fluctuation

$$d < l_c = \frac{l}{q}$$

q : Apparent angle of the source from the detector

Atomic intensity correlation (Hanbury-Brown Twiss) experiment



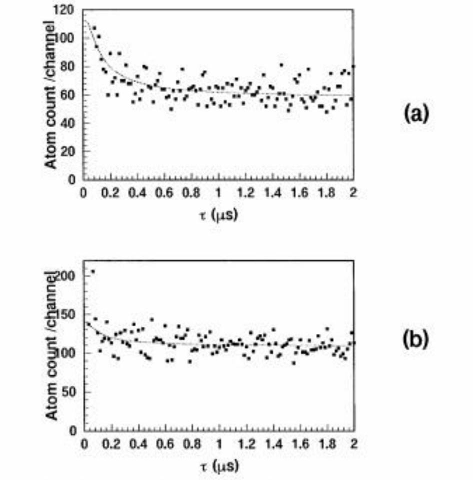


FIG. 2. The second order correlation spectrum: (a) with a coherent atomic beam, in which the beam with the diameter of 0.3 mm at the defocuser was expanded to cover the gold-coated mirror of 12 mm in diameter, and (b) with an incoherent beam, in which the beam of 2.3 mm in diameter hit the mirror without deflection.

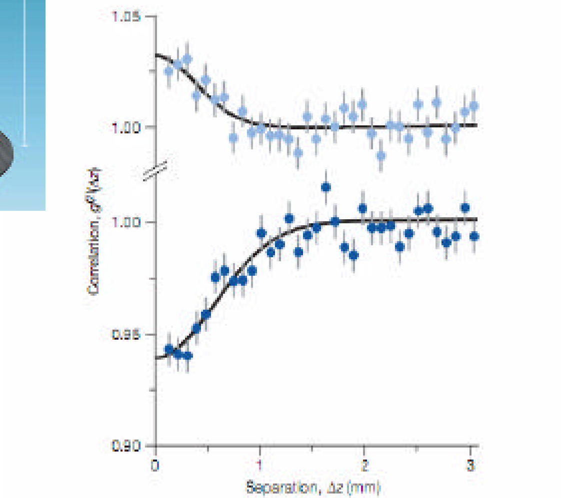
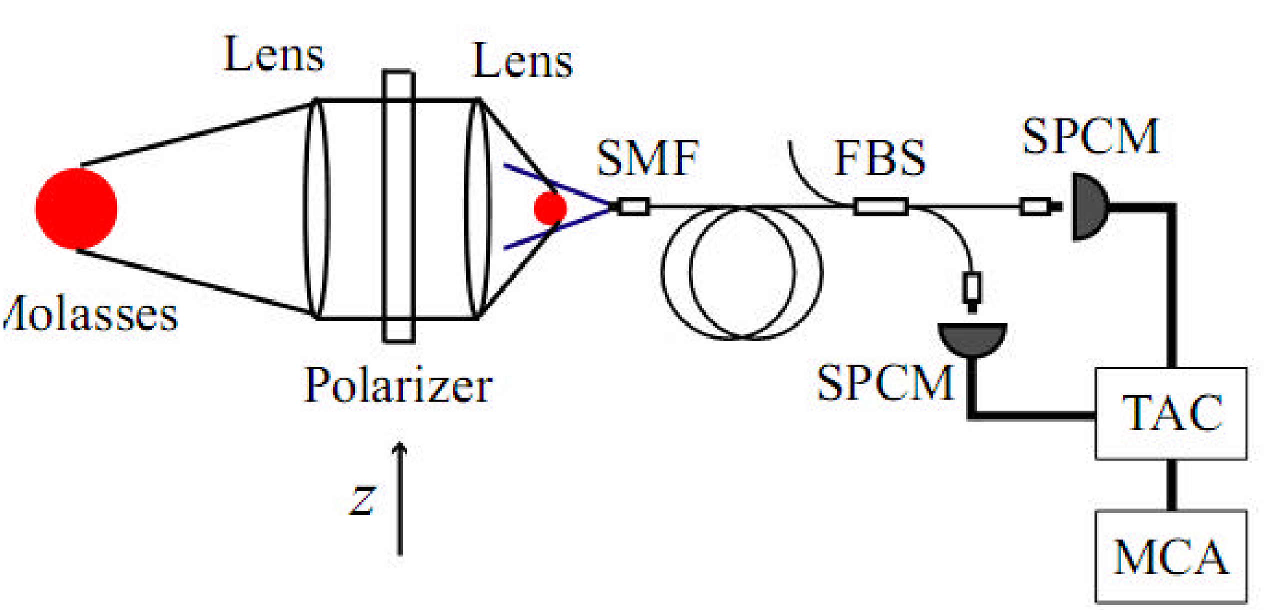


Figure 2 | Normalized correlation functions for ^{4}He* (bosons) in the upper plot, and ^{3}He* (fermions) in the lower plot. Both functions are measured at

M. Yasuda and F. Shimizu,
Phys. Rev. Lett.,**77**, 3090 (1996)

T. Jeltes, et. al, Nature, **445**, 402
(2007)

Setup for Intensity correlation measurement



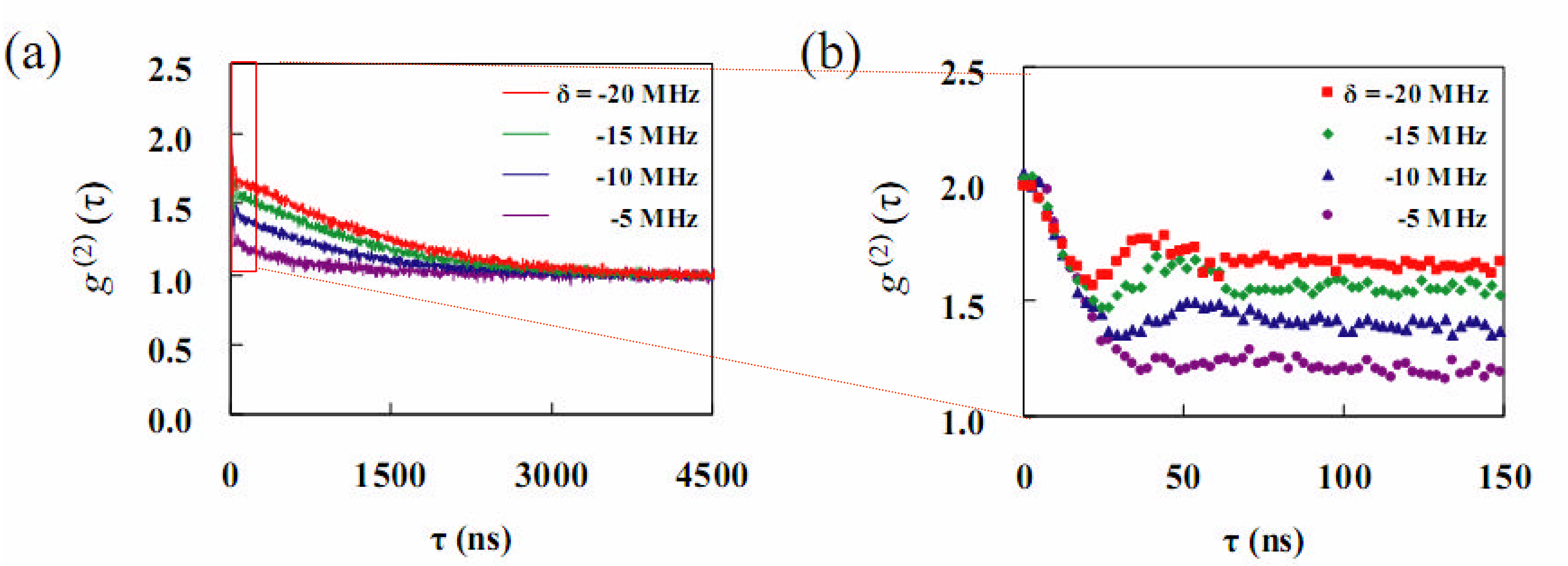
Acceptance angle of the single mode fiber

$$q \approx \mathrm{NA} = \frac{2l}{pd} \rightarrow d \approx \frac{l}{q}$$

Fiber core diameter

Spatially-coherent detection condition is automatically satisfied!

Measured $g^{(2)}(\tau)$ of molasses fluorescence



Spectra of resonance fluorescence

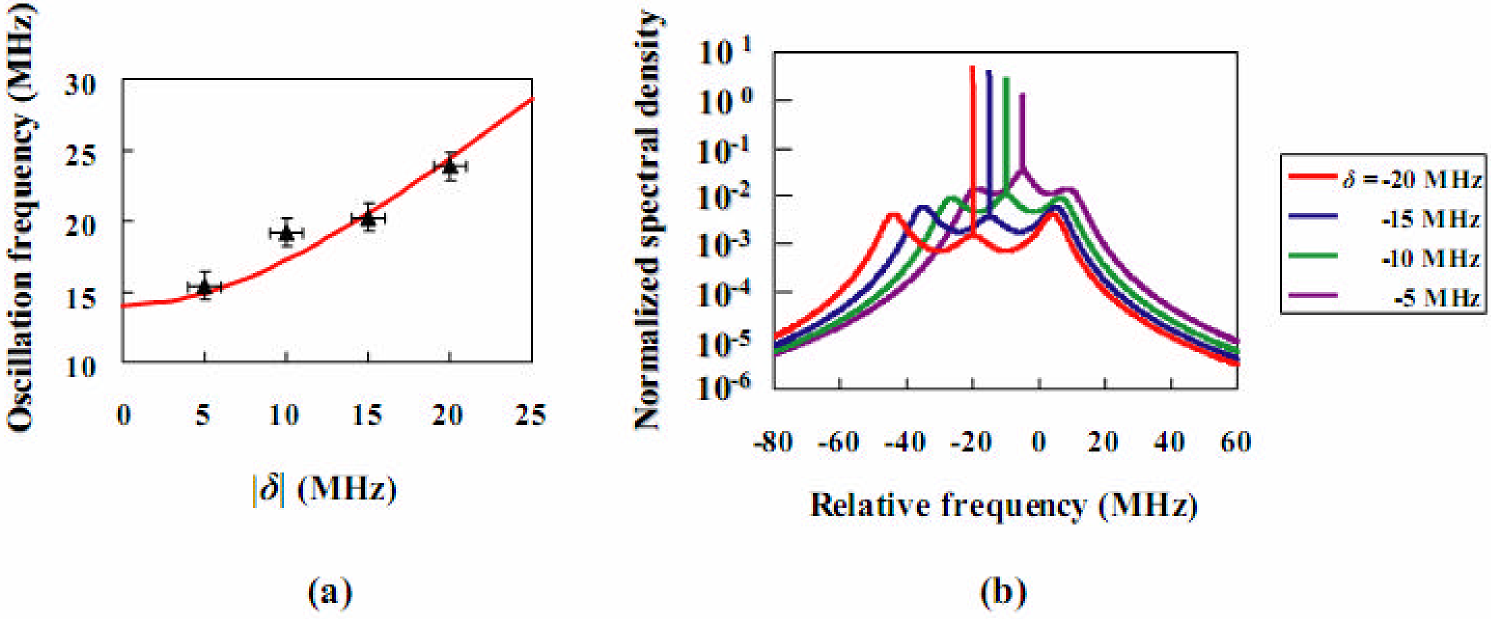
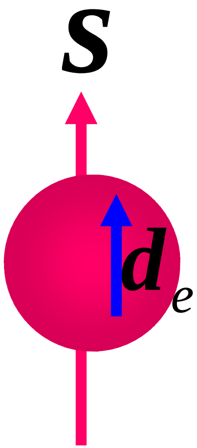


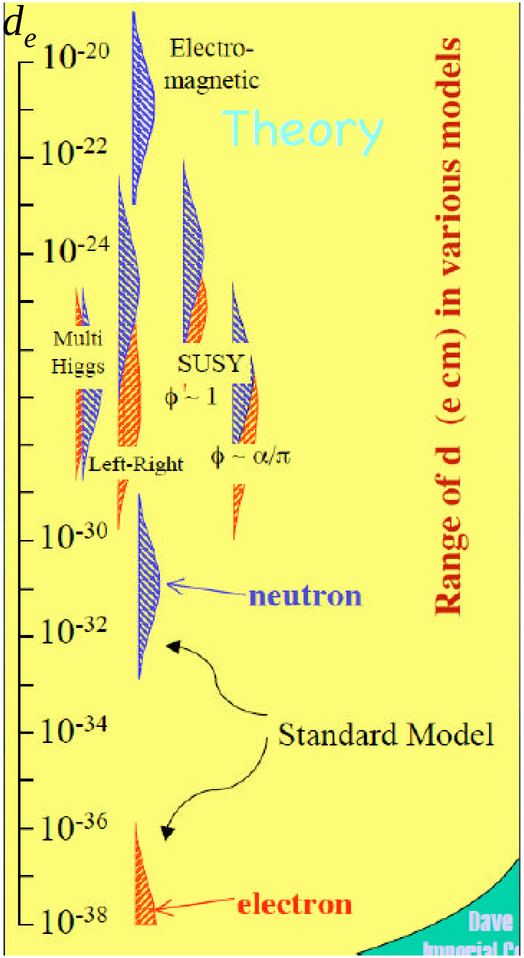
Fig. 5. (a) Oscillation frequency in $g^{(2)}(\tau)$. Triangles are experimental points, and red solid line is the effective Rabi frequency $\Omega_{\mathrm{eff}}(\delta)$. (b) Theoretical curve of the spectral density of the fluorescence for several detuning parameters versus the relative frequency.

Search for electron eternal dipole moment (EDM) using Rb-Sr 、Li-Sr polar molecules

東京大学大学院総合文化研究科
青木貴稔、大坪望、梅沢孝太郎、山中優輝、生駒大輔、鳥井寿夫

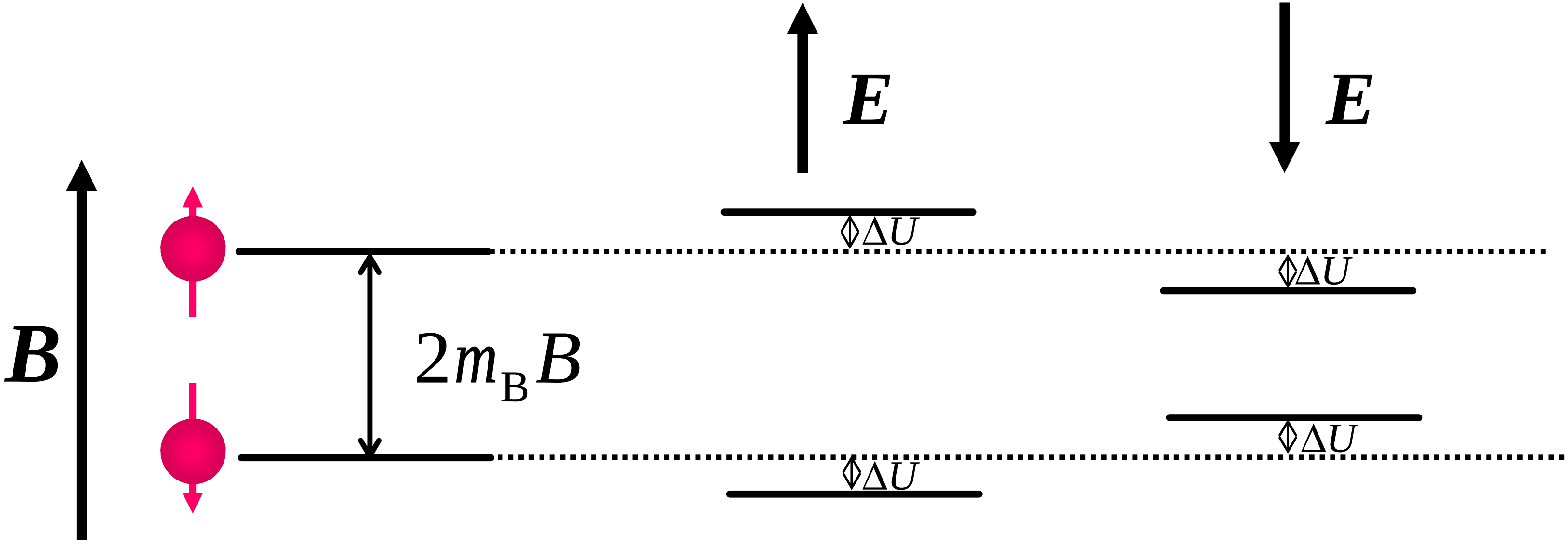
Electron EDM: A test for the theory beyond the Standard Model





e-EDM: eternal electric dipole moment (aliened to the electron spin)

Principle of e-EDM measurement



Interaction betweeen e-EDM (d_e) and the electric field

$$H = -\mathbf{d}_e \cdot \boldsymbol{E}$$

Frequency shift due to the E field

$$d = \frac{4\Delta U}{\hbar} = \frac{4d_e E}{\hbar}$$

Search for e-EDM with atoms

$$\Delta U = -\boldsymbol{d}_{\text{atom}} \cdot \boldsymbol{E} = -R\boldsymbol{d}_e \cdot \boldsymbol{E}$$

R: enhancement factor $\propto Z^3$

114 for Cs (Z=)

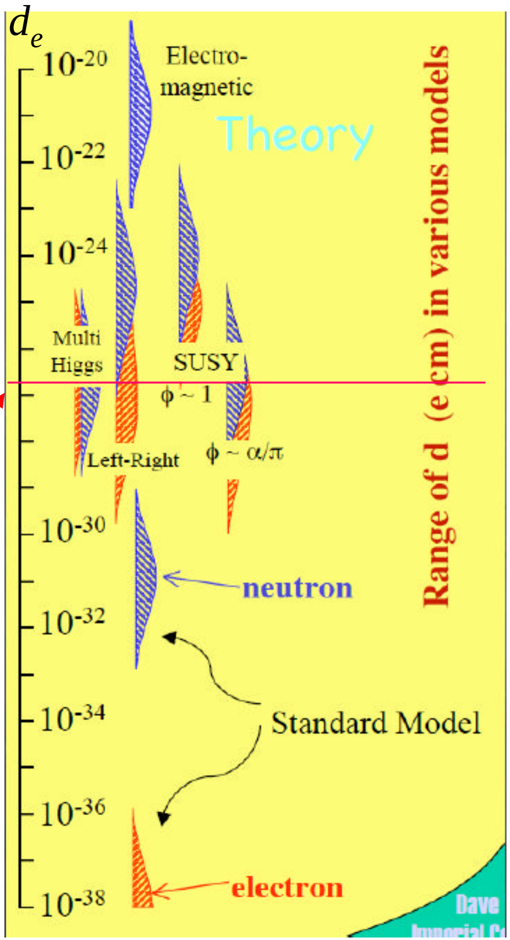
585 for Tl (Z=)

1150 for Fr (Z=87)

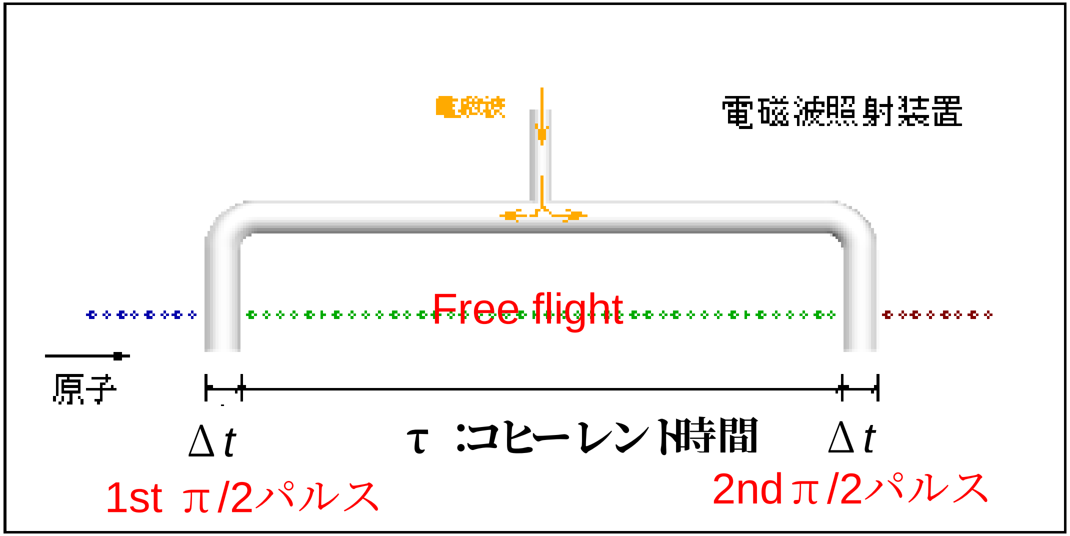
Experiment using Tl atoms

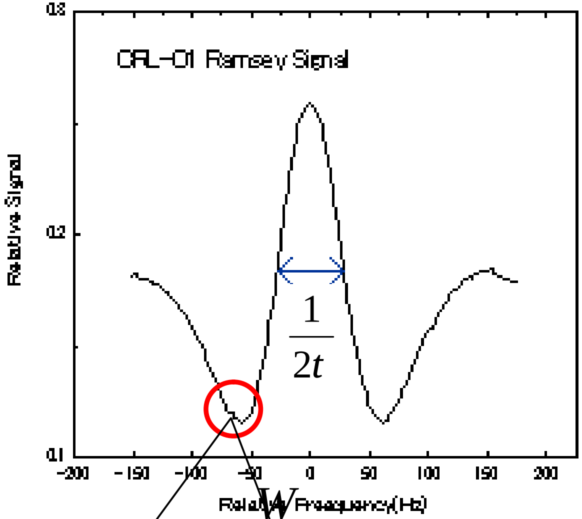
$d_e < 1.6\text{x}10^{-27}$ e cm

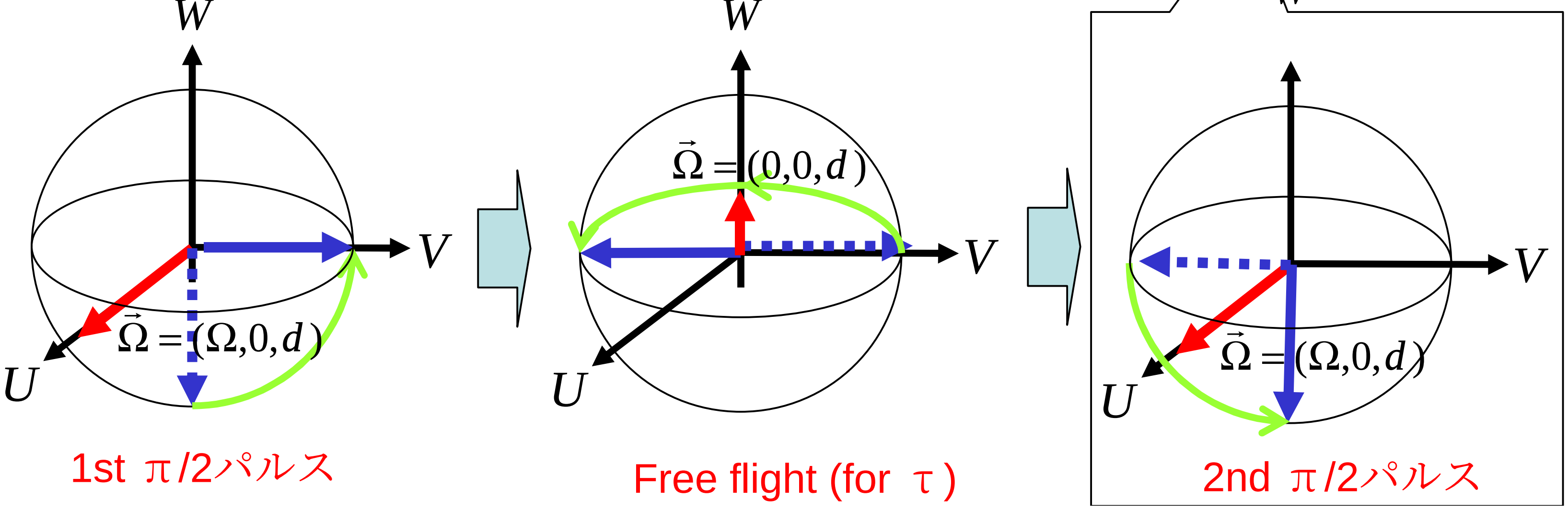
Commins, Ross, DeMille, Regan



ラムゼー共鳴法





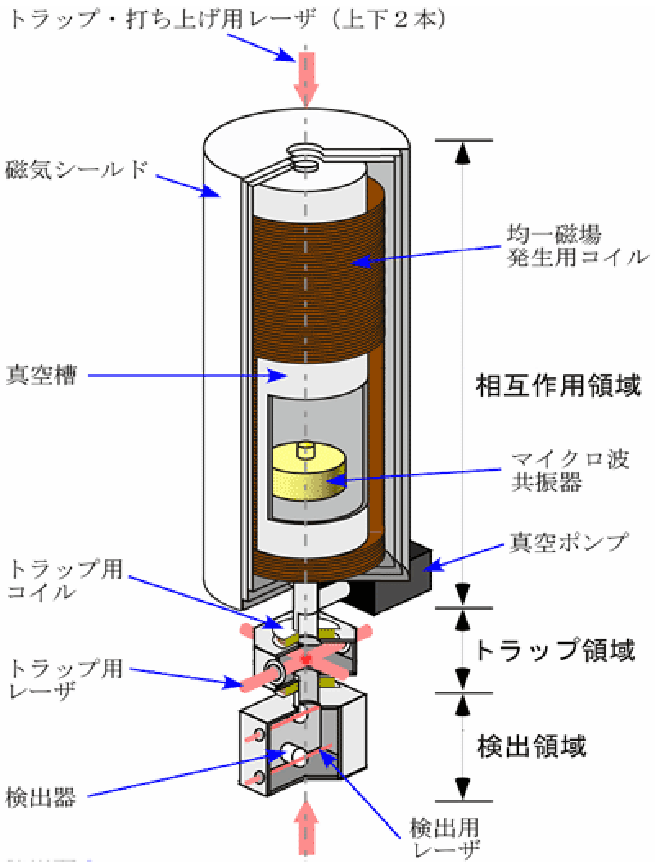


1st π/2パルス

Free flight (for τ)

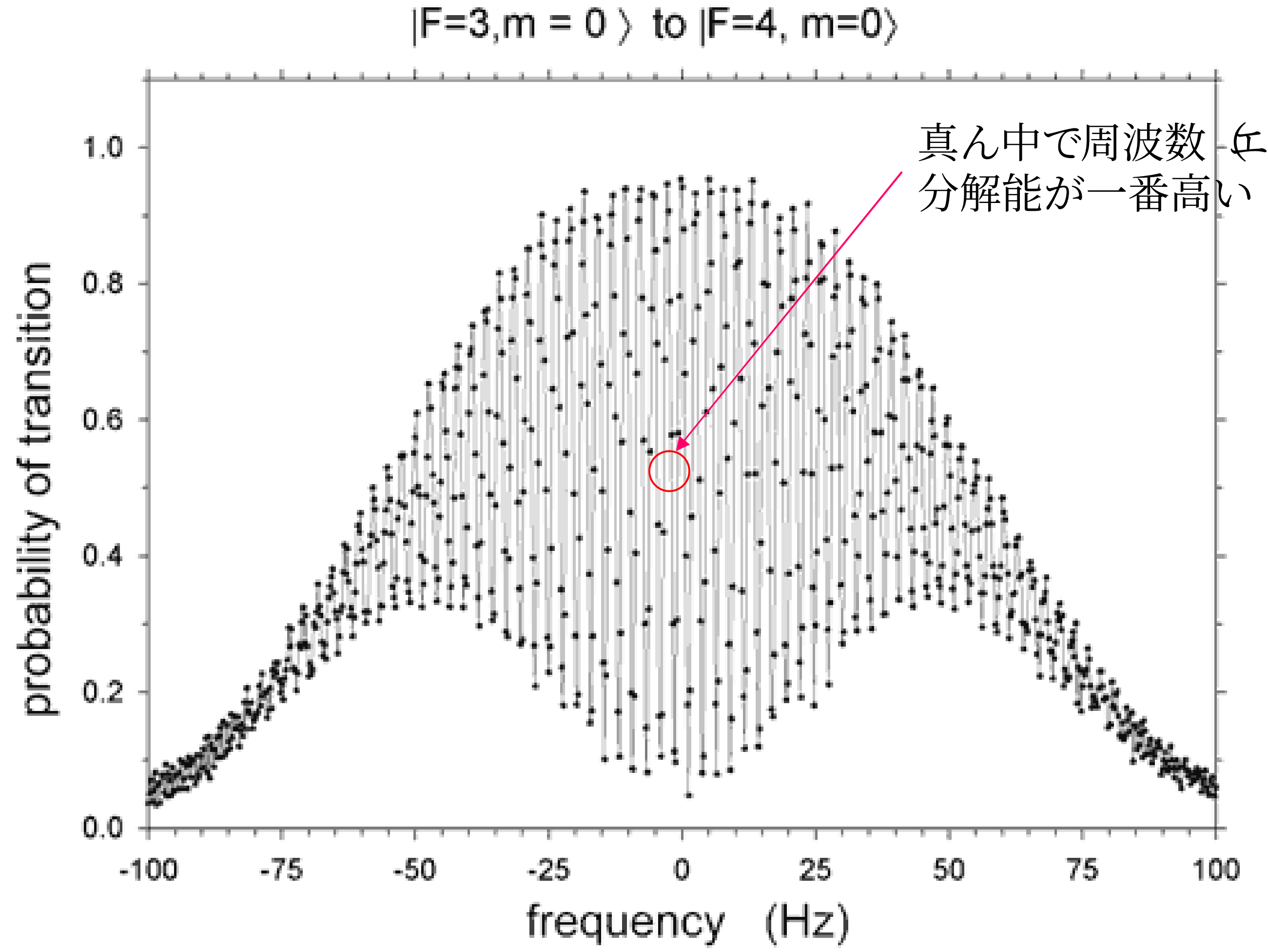
2nd π/2パルス

Cs fountain atom clock



http://www.aist.go.jp/aist_j/press_release/pr2003/pr20030609/pr20030609.html

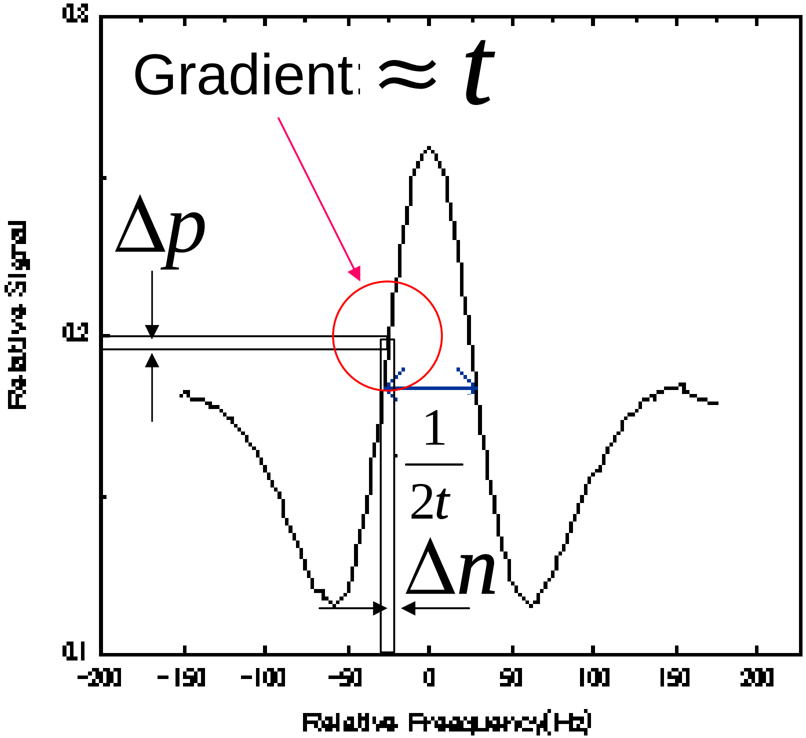
Ramsay fringe of atomic fountain



真ん中で周波数（エネルギー）
分解能が一番高い

http://physics.nist.gov/TechAct.Archive/TechAct.98/Div847/div847h.html

Frequency uncertainty (projection noise) of Ramsay interferometer



In case of using a trapped atoms (molecule)

N	# of atoms in a trap
t	Time for a Single measurement
T	Total (integrated) observation time

# of all measured atoms

Uncertainty of probability

$$\Delta p \approx 1/\sqrt{N \cdot \frac{T}{t}} \rightarrow \Delta n = \frac{\Delta p}{t} = \frac{1}{\sqrt{NTt}}$$

極性分子における有効電場（内部電場）

現在の実験技術限界
E ～ 100 kV/cm → 極性分子内の内部電場
E ～ 1～100 GV/cm

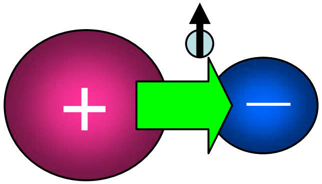
電場が
1000～1000000倍に向上する

スピンの角度変化

$$q \propto \Delta U\, t = -\boxed{d_e}\, \boxed{E_{eff}}\, \boxed{t}$$

eEDM

paramagnetic molecule



Unpaired electron

diamagnetic
atom
(Alkali-earth
atom)

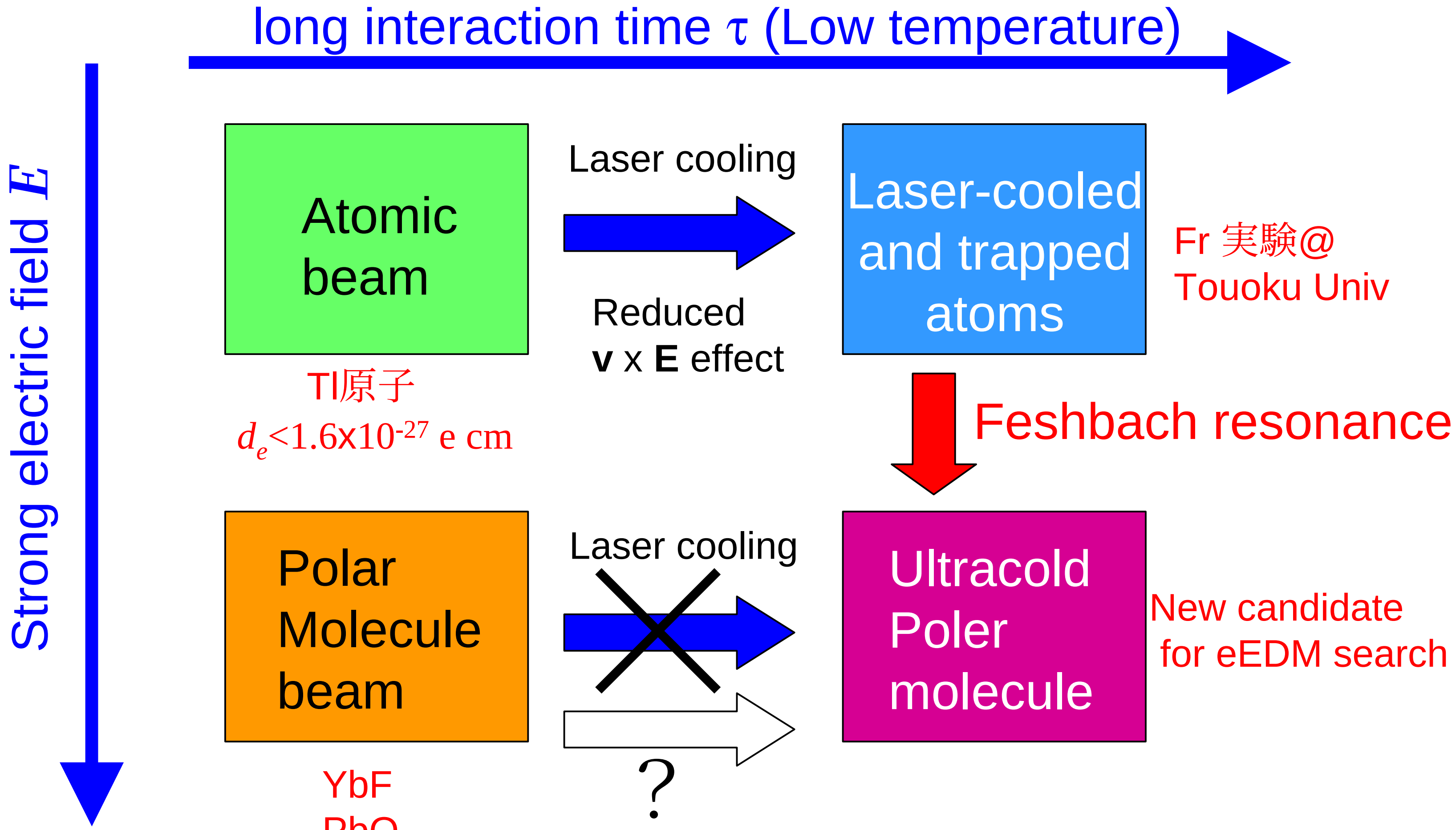
paramagnetic
Atom
(Alkali atom)

Internal electric field
1～100 GV/cm

$$dd_e = \frac{\hbar}{|P|\, E_{eff}\sqrt{t\ N\ T}}$$

P：偏極率
E_{eff}：内部電場×R
t：相互作用時間
N：一回の測定の分子数
T：積算時間

Route to improve e-EDM sensitivity



long interaction time τ (Low temperature)

Strong electric field *E*

Atomic beam

Tl原子

d_e<1.6x10^{-27} e cm

Laser cooling

Reduced

v x **E** effect

Laser-cooled and trapped atoms

Fr 実験@

Touoku Univ

Feshbach resonance

Polar Molecule beam

YbF

PbO

Laser cooling

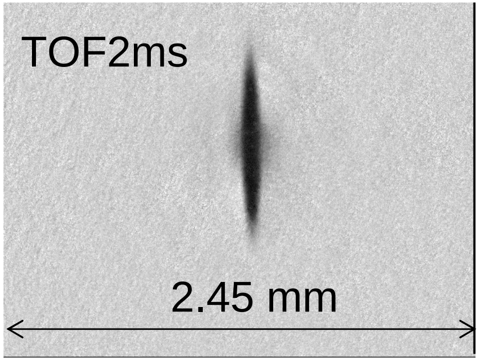
?

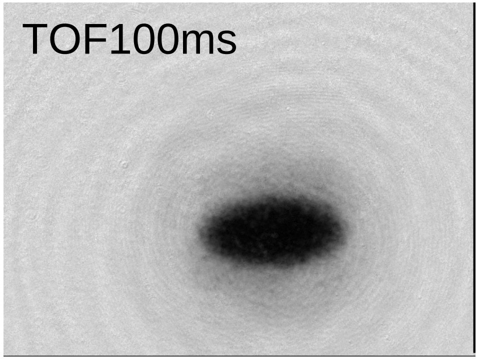
Ultracold Poler molecule

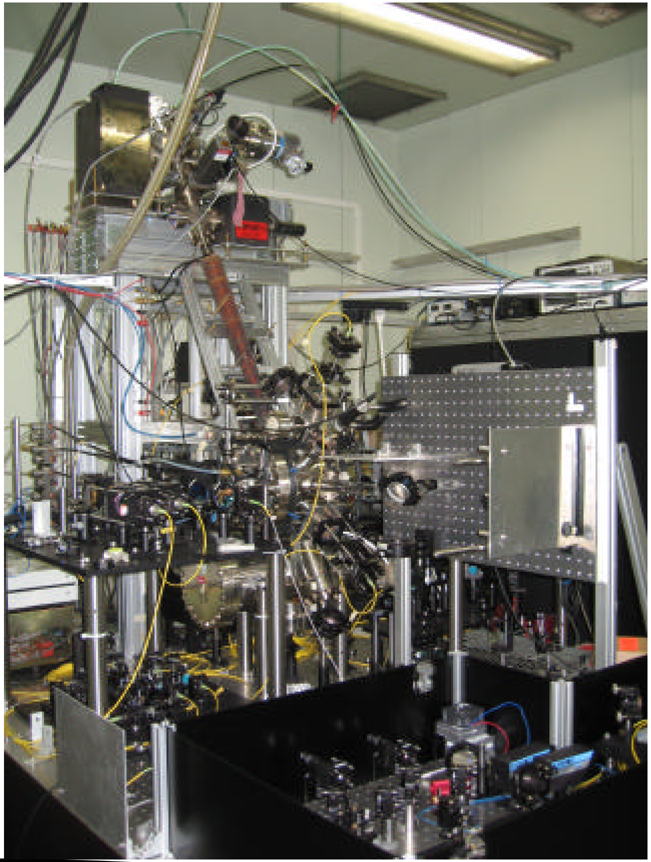
New candidate

for eEDM search

Rb BEC machine @Komaba





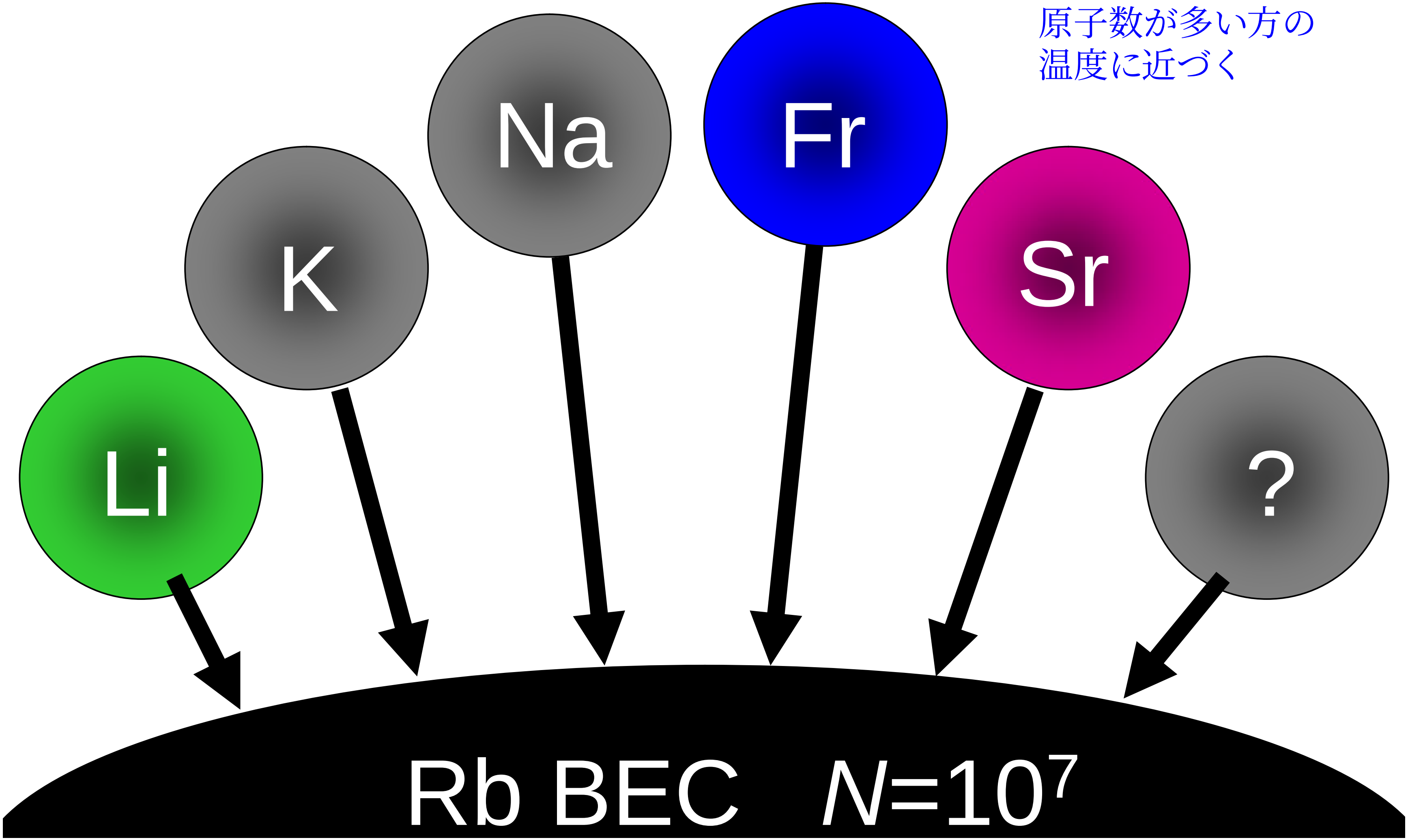


Rb BEC $N=10^7$

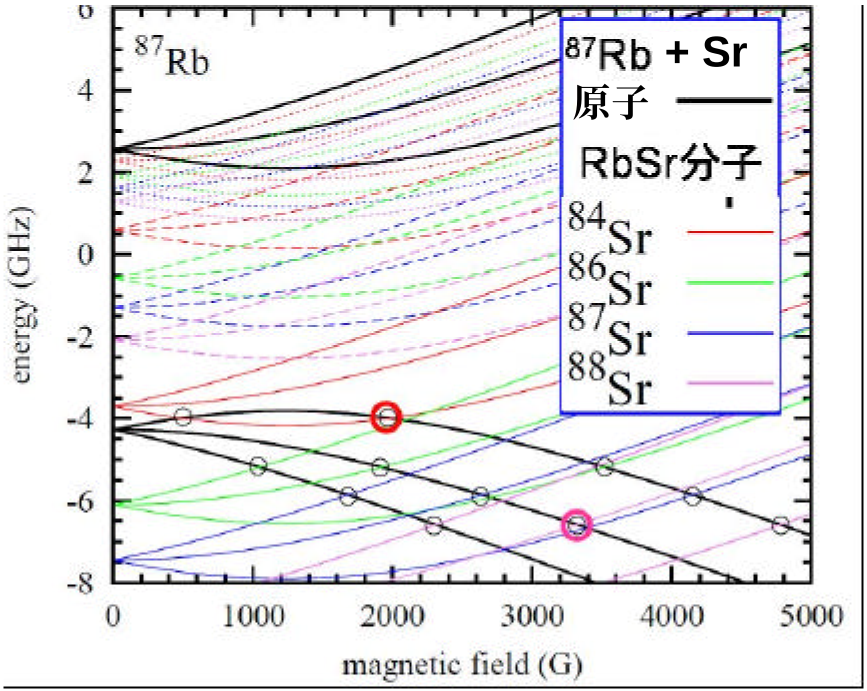
Rb BEC as a coolant for other atoms

到達温度 $$T_f = \frac{N_1 T_1 + N_2 T_2}{N_1 + N_2}$$

原子数が多い方の
温度に近づく



Rb-Sr Feshbach resonance (prediction)



arXiv: 1006.3006 15 Jun. 2010

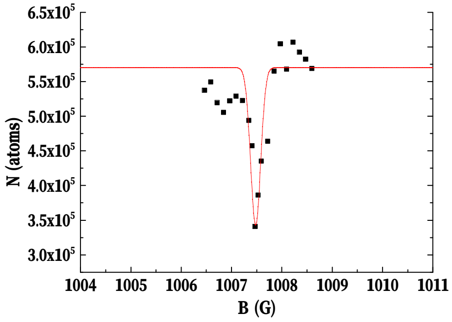
特に幅が広いフェッシュバッハ共鳴

	B_{res}	ΔB	M_F
^{87}Rb^{84}Sr	1959 G	122 mG	-1
^{87}Rb^{88}Sr	3280 G	101 mG	0
	4716 G	153 mG	+1

鳥井研　実験

^{87}Rbで1007G　幅200 mGの
フェッシュバッハ共鳴を観測

2009年日本物理学会　27aZF-9



研究背景　　異なる原子種の混合系と異核分子

異核分子

電気双極子モーメントを持つ

•アルカリ原子-アルカリ原子

K-Rb, Li-Na, Li-Rb, Li-K, Rb-Cs, Li-Csなど

分子の振動基底状態　S=0　電子スピン無し

•アルカリ原子-2電子系原子（アルカリ土類、希土類など）

Rb-Yb, Li-Yb

Rb-Sr

分子の振動基底状態

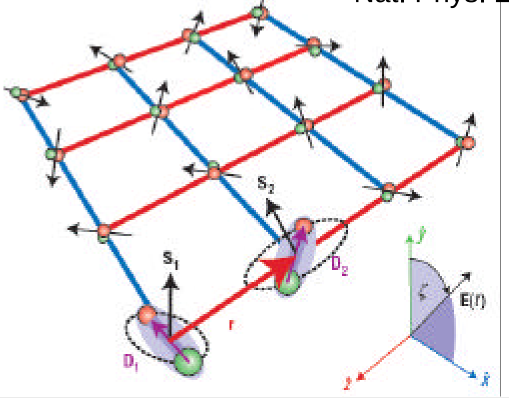
S=1/2　電子スピンを持つ

•新しいフェッシュバッハ共鳴
•新たな量子シミュレーション
•電子EDM探索など精密測定

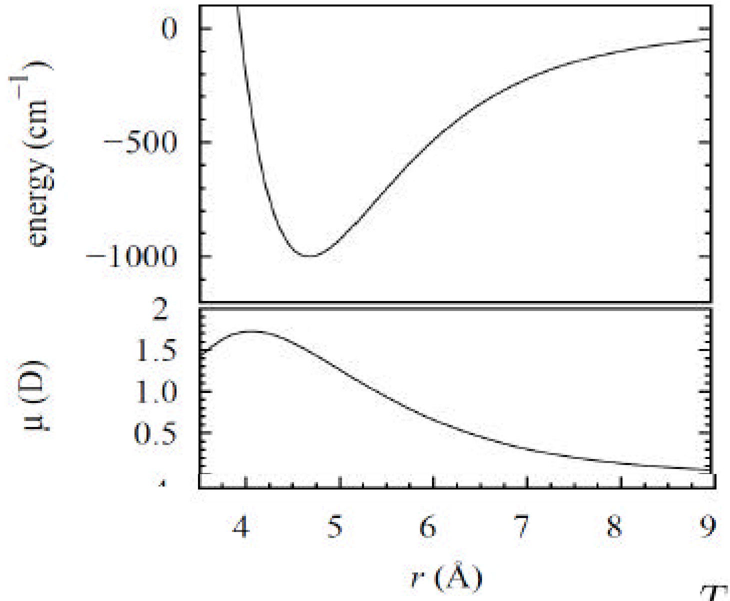
新たな量子シミュレーション

Lattice Spin models

Nat. Phys. 2, 341 (2006)



Rb-Sr 極性分子の電気双極子モーメント



arXiv: 1006.3006 15 Jun. 2010

異核分子の振動基底状態における
電気双極子モーメント

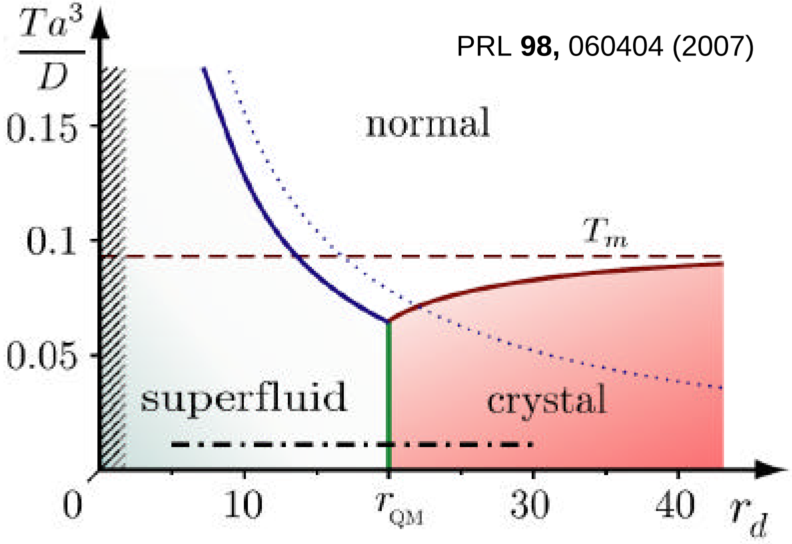
RbK (JILA) m = 0.57 D

RbSr m = 1.36 D

極性分子の新たな量子相の理論

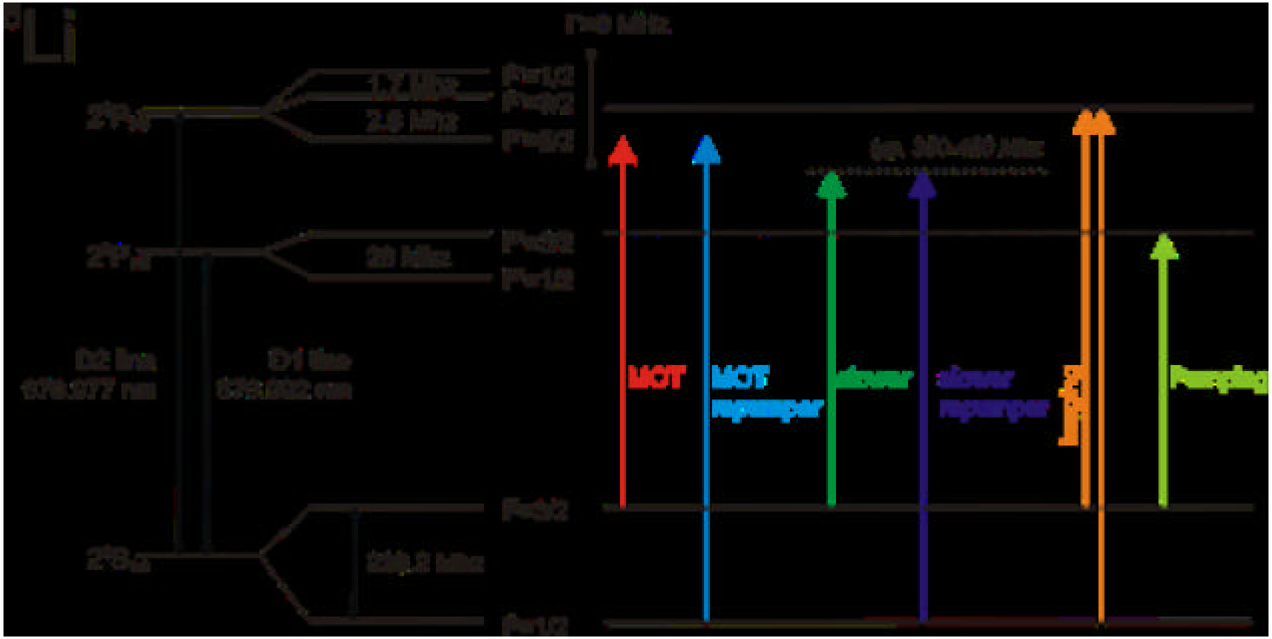
電気双極子-双極子相互作用
による結晶化

$D \propto m^2$ が大きいほど
新しい量子相を探索できる

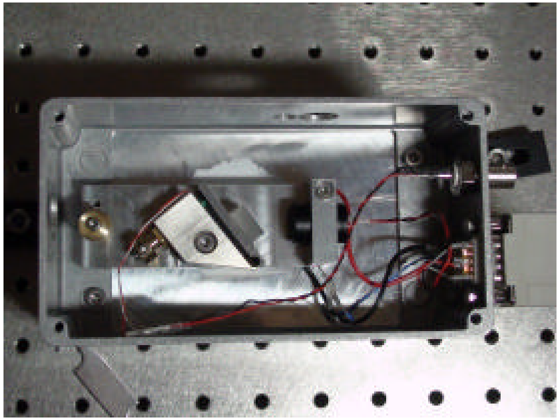


PRL **98,** 060404 (2007)

Li原子のエネルギー準位とレーザー冷却用遷移

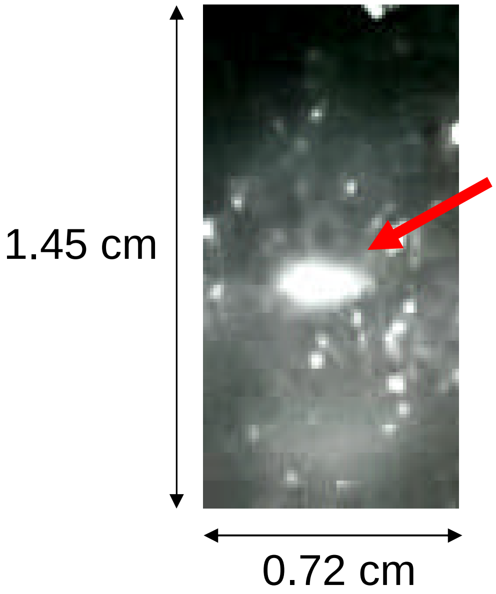


Li原子のレーザー冷却のためのECLD作製



671nmで発振@70℃

Sr MOT was achieved(2010.9)



Sr MOT !!!

個数 10^7 個

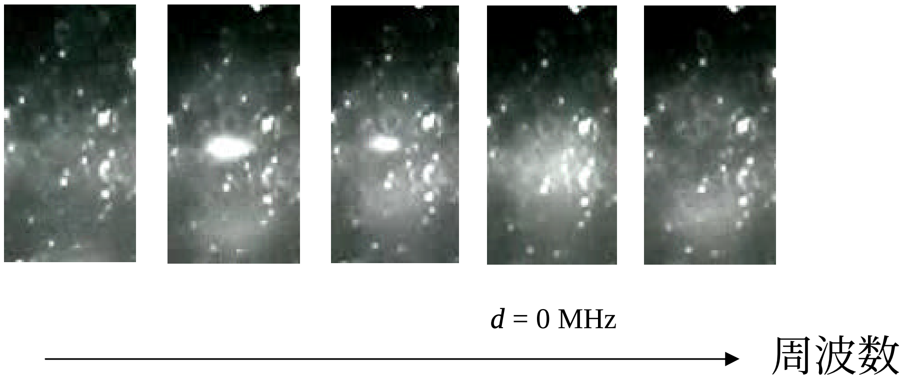
461 nm

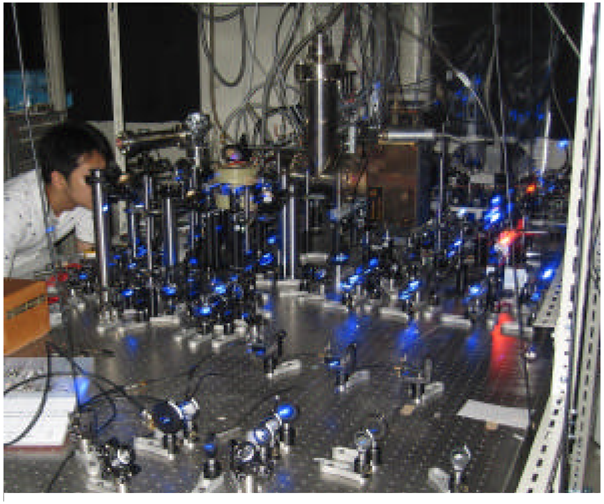
- Slowing 光 3 mW
  離調 -630 MHz

- MOT 光 直径 5 mm
  上下 4 mW, 左右 8mW
  離調 -40 MHz

MOT 磁場 157 G/cm (50 A)

Sr Oven 412℃





Summary

- Rb BEC machine ($N_c \sim 10^7$) under operation
- Sr (blue) MOT ($N \sim 10^7$), ready for red MOT
- Li light source (ECLD+TA) almost ready

In 2011
Conbine Rb machine
with Sr, Li mixed oven
and slower