Workshop on Ultracold Fermi Gases,
Levico, 4-6 March 2004

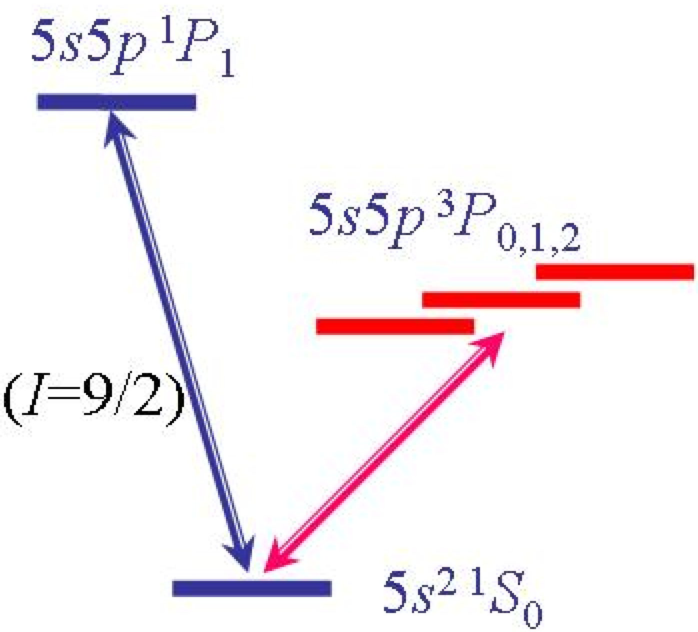
Ultracold Fermions: Application to Ultrastable Optical Clock

Engineering Research Institute, the University of Tokyo and PRESTO, JST

Hidetoshi Katori

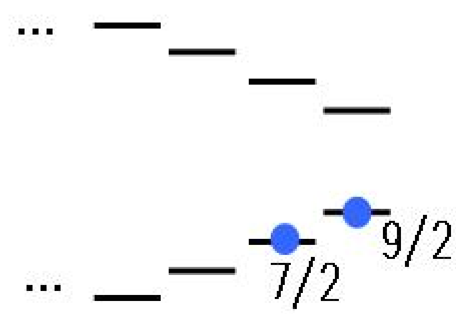
Ultracold fermionic alkaline-earth (like) atoms

^{87}Sr (Tokyo, JILA,…)
^{171,173}Yb (Kyoto,…)



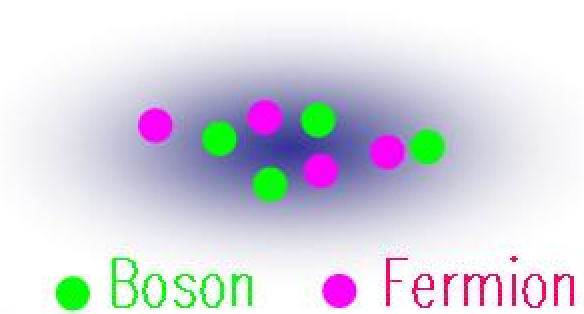
- Two valence electrons
  - No electronic spins in the ground state (I=9/2)
  - Optical dipole trap
- Narrow optical transitions available
  - **Narrow-line laser cooling near T_F**
- Long-lived metastable states, $^3P_0$ & $^3P_2$
  - hyperfine-mixed lifetime ~ 100s
  - MOT or MT in the $^3P_2$ state; 2 degenerate samples possible
  - **Optical clock on the $^1S_0$-$^3P_0$ transition & collision suppression**

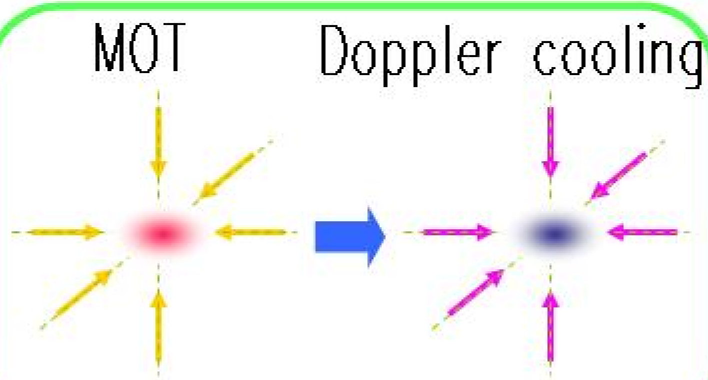
Production of Ultracold Fermions



Evaporative Cooling
s-wave scattering between nonidentical fermions

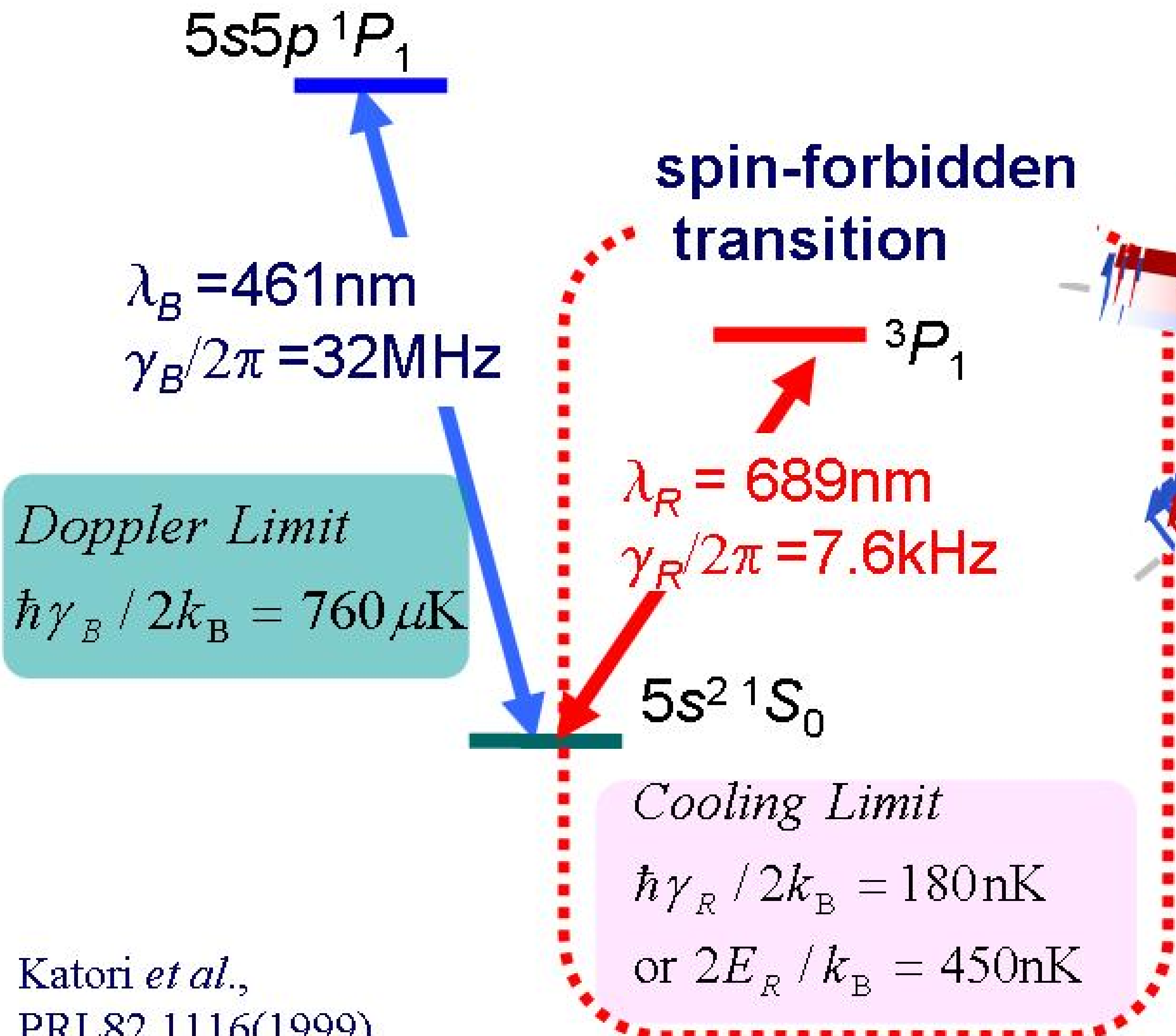
Sympathetic Cooling
of two isotopes (bosons and fermions)

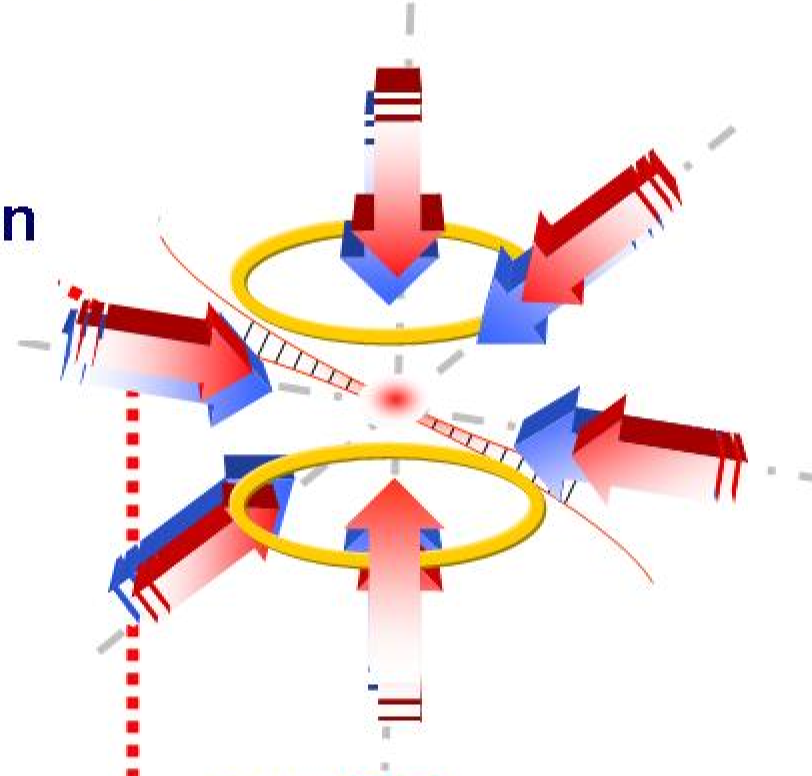




Narrowline Doppler cooling
in the optical lattice

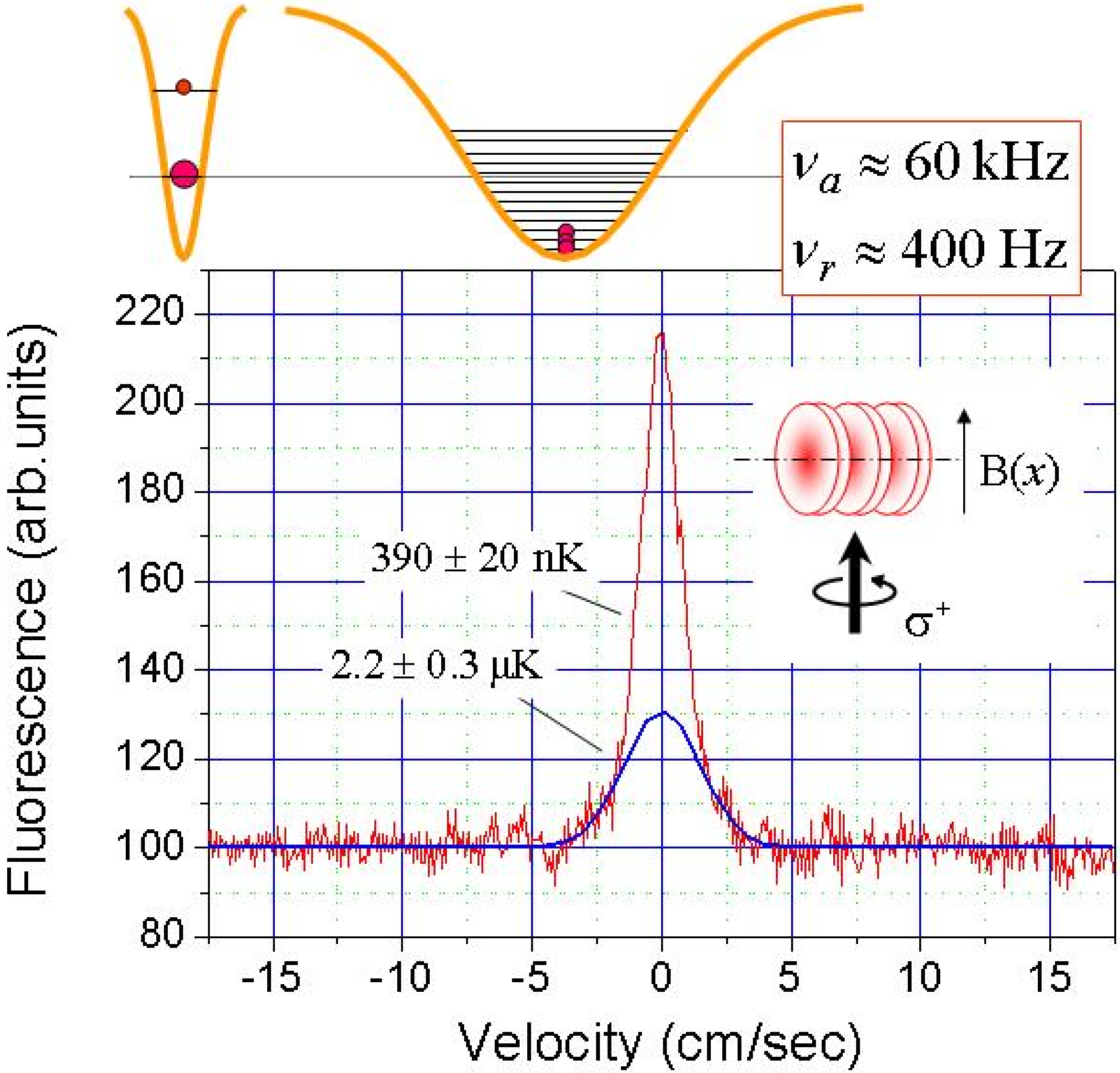
Optical access to near degeneracy on the narrow intercombination transition

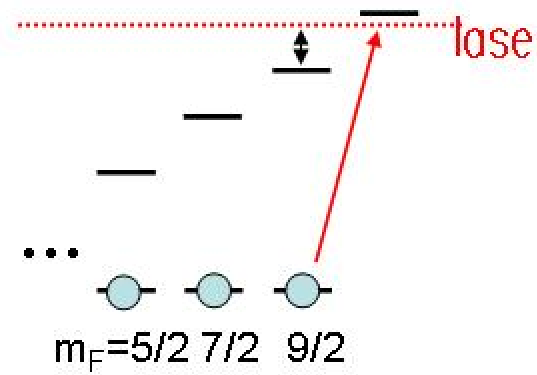




Katori *et al.*,
PRL82,1116(1999)

Doppler cooling and spin-polarization in the 1D optical lattice





$N_0 \approx 1 \times 10^2$ / site

$N_{n_z=0} \approx 80\,\%$

$N_{m=9/2} \approx 80\,\%$

$$T_F = (h\nu_r / k_B)\sqrt{2N^*}$$

$$\approx 0.2\,\mu\mathrm{K}$$

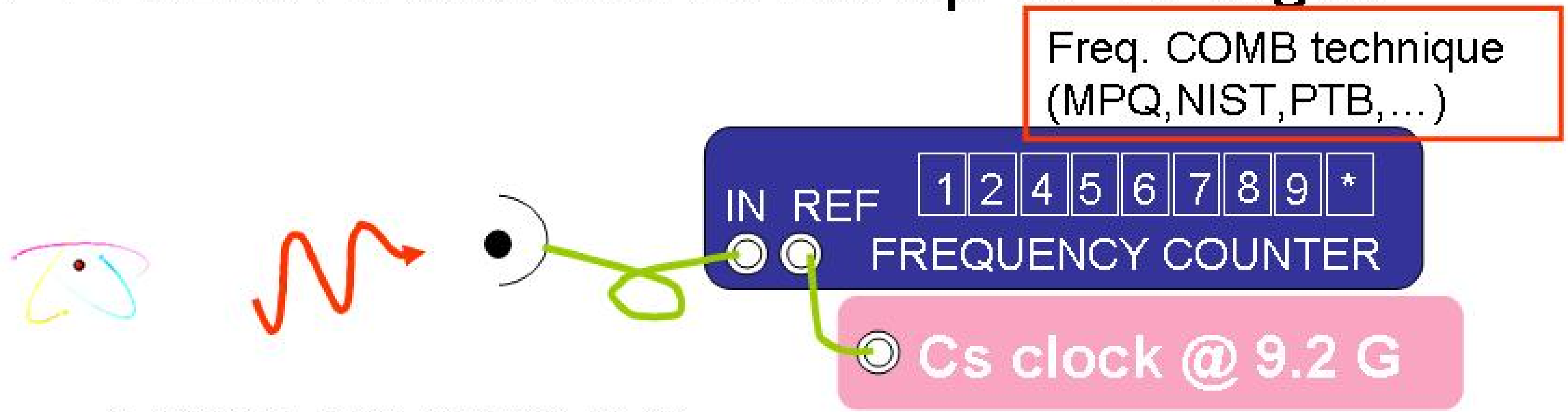
$$T / T_F \approx 2$$

Mukaiyama, *et al.*, PRL 90, 113002 (2003).

Outline: Optical Clock with Fermions

- Introduction
  - Status & limit of present atom spectroscopy
  - Collisional frequency shift
- Optical lattice clock
  - Motivation and idea
  - Light shift cancellation
- Experimental demonstration
- Summary & prospects

Atom Clocks & Atom spectroscopy
- Precision measurements up to 15 digits -



$$f_{H(1S-2S)} = 2\,466\,061\,413\,187\,103(46)\ \mathrm{Hz}$$
$$f_{Hg} = 1\,064\,721\,609\,899\,143(10)\ \mathrm{Hz}$$
$$f_{Ca} = 455\,986\,240\,494\,158(26)\ \mathrm{Hz}$$

Accuracy limited by the definition of SI-second or the accuracy of Cs clock

$$\dot{f}_{Ca} / f_{Ca} \le 8\times10^{-14} / yr. \quad \dot{f}_{Hg} / f_{Hg} \le 30\times10^{-14} / yr.$$

The physics expected beyond 15 digits

- Precise determination of fundamental constants
- Detection of variation of fundamental constants
- …

Improving stability of an atom clock

Allan deviation: a measure for the clock stability

$$\frac{\Delta \nu}{\nu_0} \approx \frac{\delta \nu}{\nu_0} \frac{1}{\sqrt{N \times M}} \left(= \frac{1\text{Hz}}{10^{10}\text{Hz}} \frac{1}{\sqrt{10^6 / \text{s} \times 10^4 \text{s}}} \right)$$

$\frac{\delta \nu}{\nu_0}$ → Q^{-1}

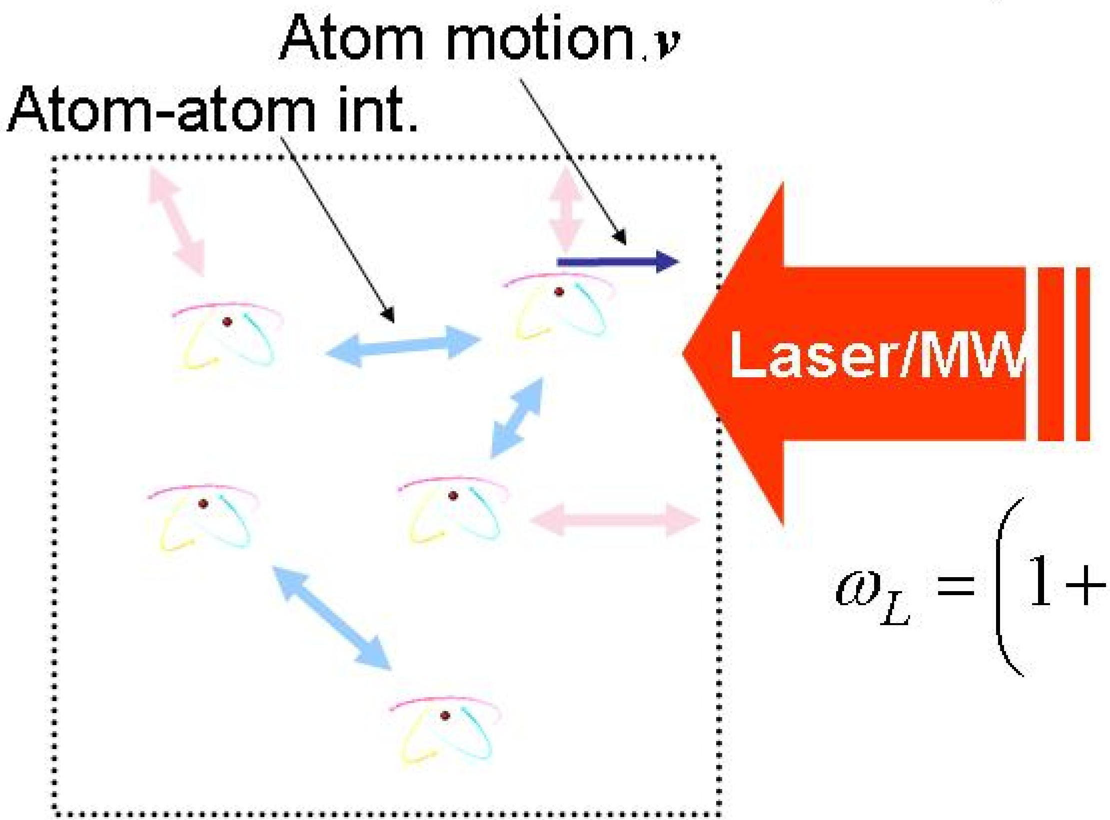
$N \times M$ → Total number of measurements

10^{10} Hz: Microwave

10^{15} Hz: OPTICAL

5 digits of improvement is expected for optical clock

Spectroscopic accuracy



1st order Doppler shift

Zeeman, BBR shift

$$\omega_L = \left(1 + \frac{v}{c}\right)(\omega_0 + \delta_{\text{col}} + \delta_{\text{EM}} + \ldots)$$

Collision shift

Cold collision frequency shift is difficult to handle.

~ 10^{-14} for Cs fountain clock

- ✓ Difficulty in determining accurate atom density
- ✓ Controlling the cold collision shift (F. Pereira Dos Santos *et al.* 2002)
- ✓ Use of fermionic atoms (Gibble&Verhaar 1995, Gupta *et al.* 2003)

Cold collision shifts in spectroscopy

Trade off:
Better stability ~ Larger # of atoms
~ Larger atom density
~ Larger collisional shifts

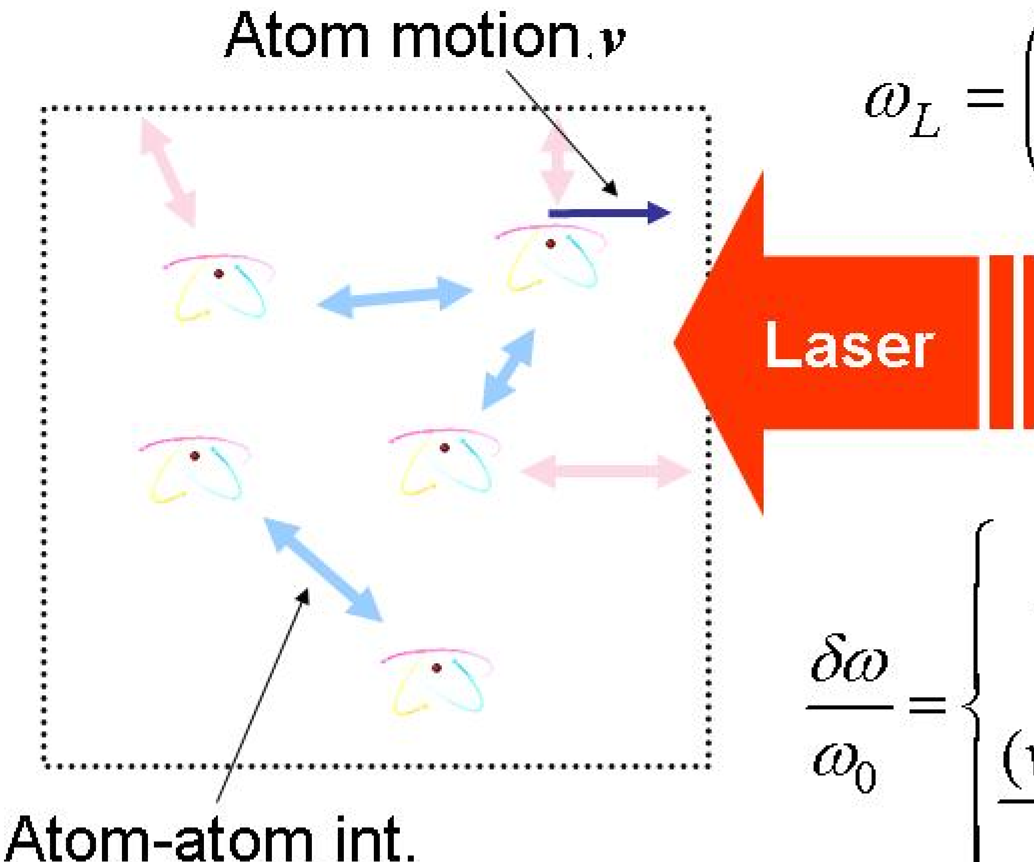
Measured or expected collision shifts

- Cesium(MW) : 10^{-14}~ 10^{-15} (sub mHz level)
- Rubidium(MW) : -4 Hz @10^{13}cm^{-3} (Harber et al.)
- Calcium(OPTICAL) : <10Hz (PTB/NIST)

. Collision shifts can be suppressed for polarized fermions

Clock shift (5 kHz) suppression factor of 30 has been demonstrated on RF transition. (Gupta *et al*. 2003)

Spectroscopic accuracy: Advantage of using optical transition



$$\omega_L = \left(1 + \frac{v}{c}\right)(\omega_0 + \underbrace{\delta_{\mathrm{col}} + \delta_{\mathrm{EM}} + \ldots}_{\Delta})$$

$$n = 10^{11}\,\mathrm{cm}^{-3},\ a = 100 a_0$$

$$\Rightarrow \delta_{col} = \frac{2\hbar}{m} n a \sim 0.6\,\mathrm{Hz} \quad \left(\Delta\nu/\nu \sim 10^{-15}\right)$$

$$\frac{\delta\omega}{\omega_0} = \begin{cases} \dfrac{\Delta}{\omega_0} \\ \dfrac{(v/c)\cancel{\omega_0}}{\cancel{\omega_0}} \end{cases}$$

5 digits improvement in optical regime

Reduction of the Doppler shift is crucial in the realization of optical clock

"Optical Lattice Clock"

- Suppression of Doppler shift by tight confinement
  - Single ion in LDR
  - Ensemble of neutral atoms in free space
  - How to share advantages
- Spectroscopy of strontium atoms in LDR ($^1S_0$-$^3P_1$)
  - Stark-free optical lattice
  - Removal of 1st order Doppler & recoil shift
- Optical Lattice Clock on the $^1S_0$-$^3P_0$ transition
  - Polarization insensitive light-shifts in $J = 0 - J = 0$
  - Spectroscopy of ^{87}Sr in an optical lattice
  - Suppression of collision shifts

Better optical clocks in the future?

Single-Ion clock

Hg^+(NIST), Yb^+(NPL,PTB)
Sr^+(NPL,NRC), In^+(MPQ)…

In RF trap,

Long interaction time
Lamb-Dicke regime
No collision shifts
x Quantum projection noise

Neutral-atom clock

Ca (PTB,NIST),
Mg (Hannover), Sr,…

In freely falling,

x Limited interaction time
x Residual Doppler shifts
x Collision shift …
Good signal to noise ratio

Share the advantages of both schemes

N fermionic quantum absorbers
trapped in the Lamb-Dicke regime
"Optical Lattice Clock"

Advantage of increasing quantum absorbers

e.g. in order to attain 10^{-18} stability

$$\frac{\Delta\nu}{\nu_0} \approx \frac{\delta\nu}{\nu_0}\frac{1}{\sqrt{N \times M}}$$

$$= \frac{1\text{Hz}}{10^{15}\text{Hz}}\frac{1}{\sqrt{1/\text{s} \times 10^6\text{s}}} = \frac{1\text{Hz}}{10^{15}\text{Hz}}\frac{1}{\sqrt{10^6/\text{s} \times 1\text{s}}}$$

Observe single ion for 10 days

Observe millions of atoms for 1 s.

---

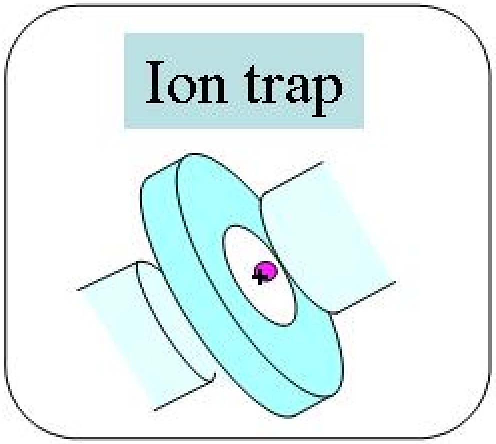
cf. gravitational shift: $\delta\nu / \nu \approx gl / c^2 \approx 10^{-18}$ for $l = 1\,\text{cm}$

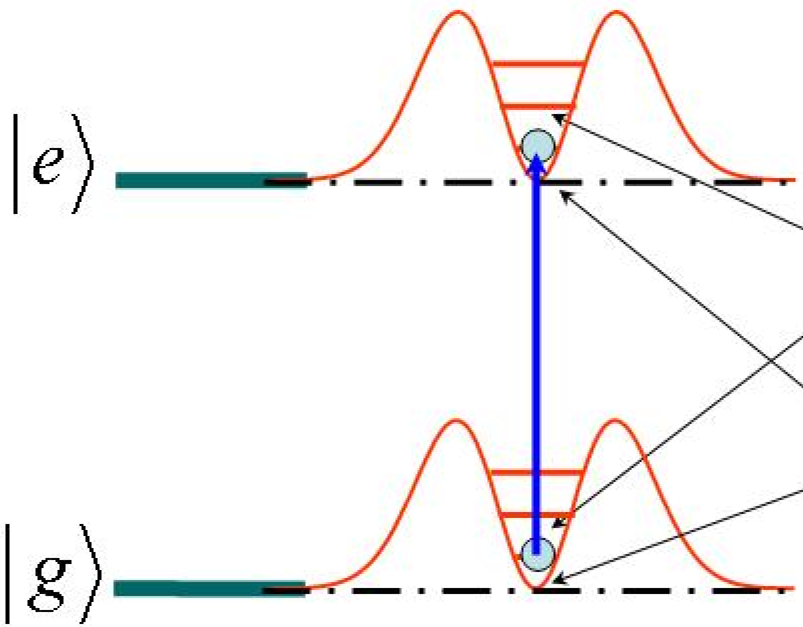
Simulate "ion-trap" like confinement in neutral atoms

Charged particle--- Lorentz force

<u>RF quadrupole trap</u>

- Confinement (nearly) independent of trapped electronic states





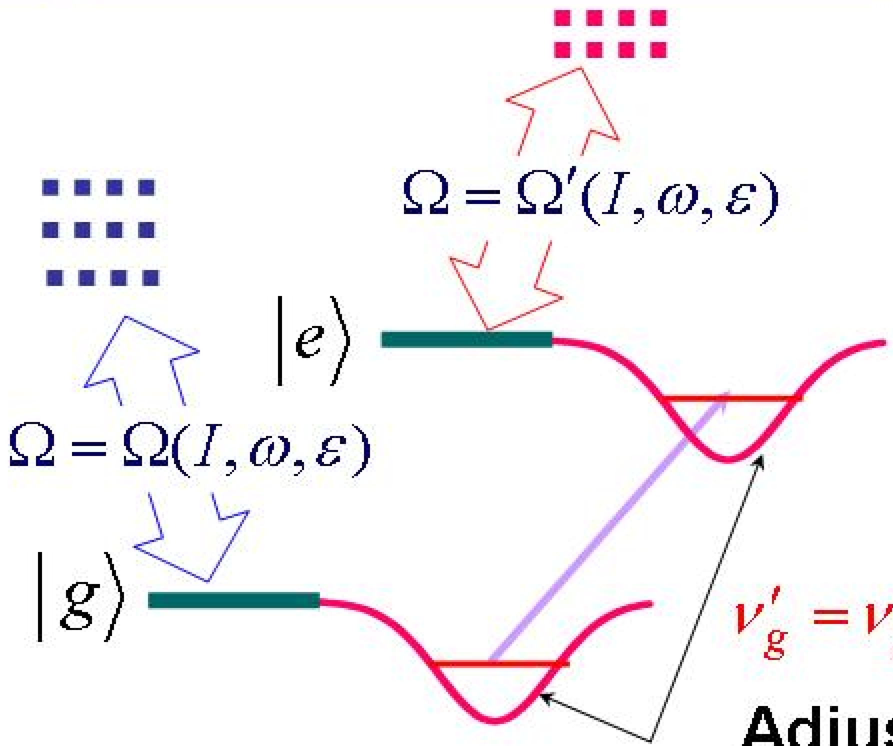
Degenerate trap frequency

- Stark shift cancellation

Trapped at nearly zero of the electric field

- Higher order light shift for red detuned trap

Light shift cancellation



$$\nu'_e = \nu_e - \frac{1}{2h}\alpha_e(\omega_L, \varepsilon_L)\left|E(r)\right|^2$$

$$\nu'_g = \nu_g - \frac{1}{2h}\alpha_g(\omega_L, \varepsilon_L)\left|E(r)\right|^2$$

Adjustment required!

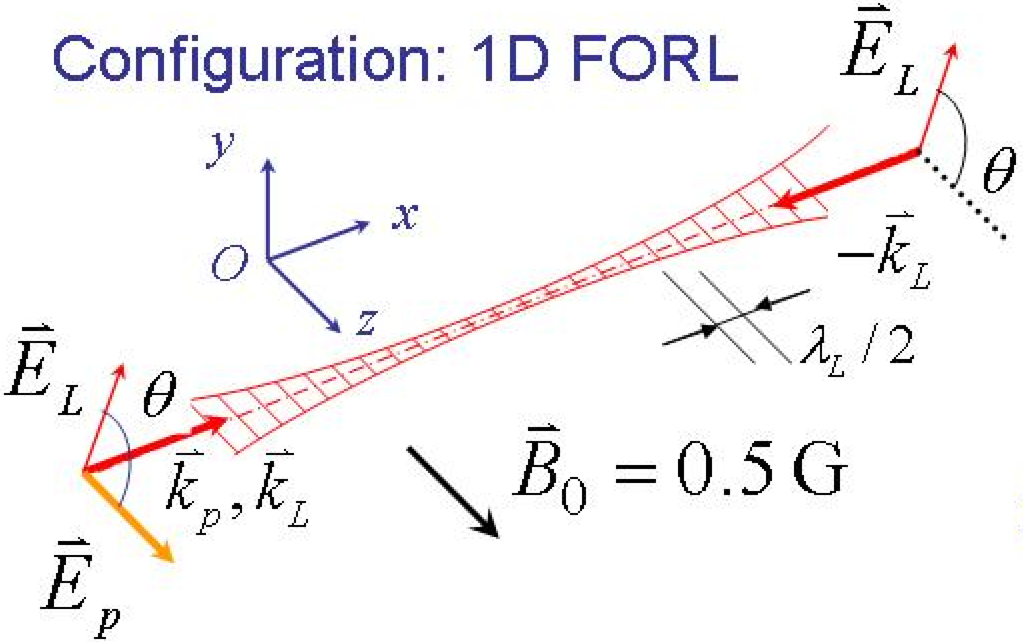
$$\nu_{abs} = (\nu_e - \nu_g) \qquad + O(E^4)$$

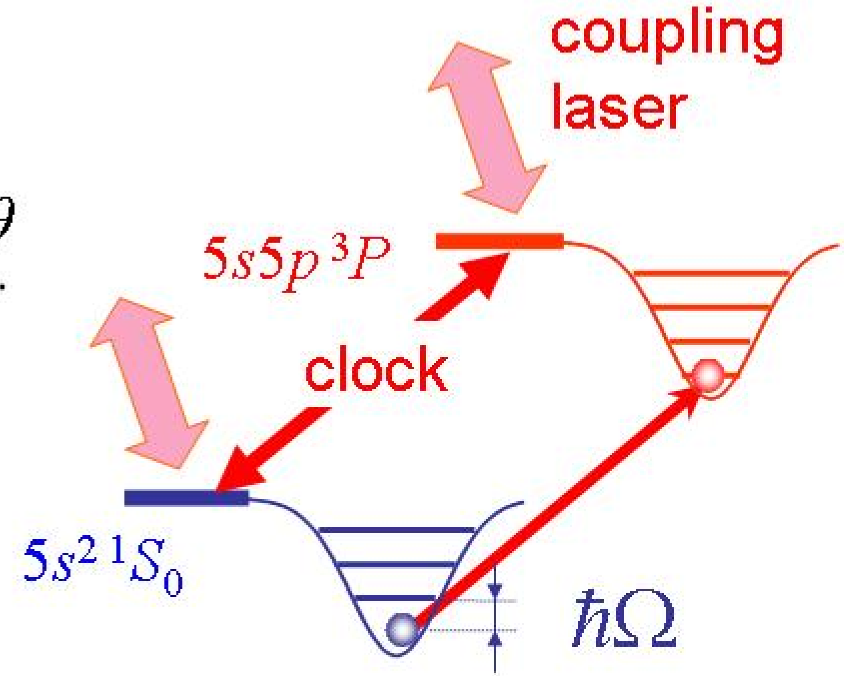
Intensity fluctuation can be cancelled out at magic wavelength

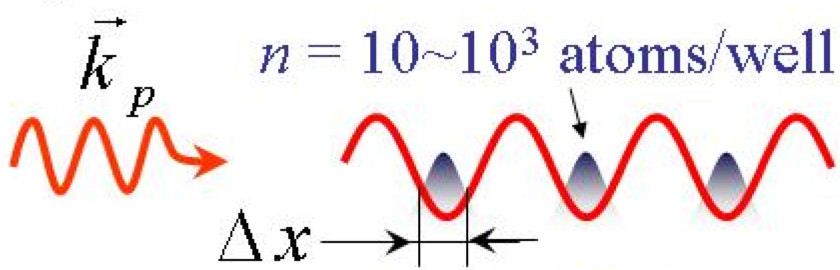
Light shifts for $^1S_0$ & $^3P_1$ states of Sr: Katori *et al.*, *J. Phys. Soc. Jpn.* **68**, 2479 (1999)
FORT for Rb C-QED experiment: Kimble group (2003)

Experiment: Spectroscopy of tightly confined atoms
- removal of Doppler & recoil shifts -

Configuration: 1D FORL





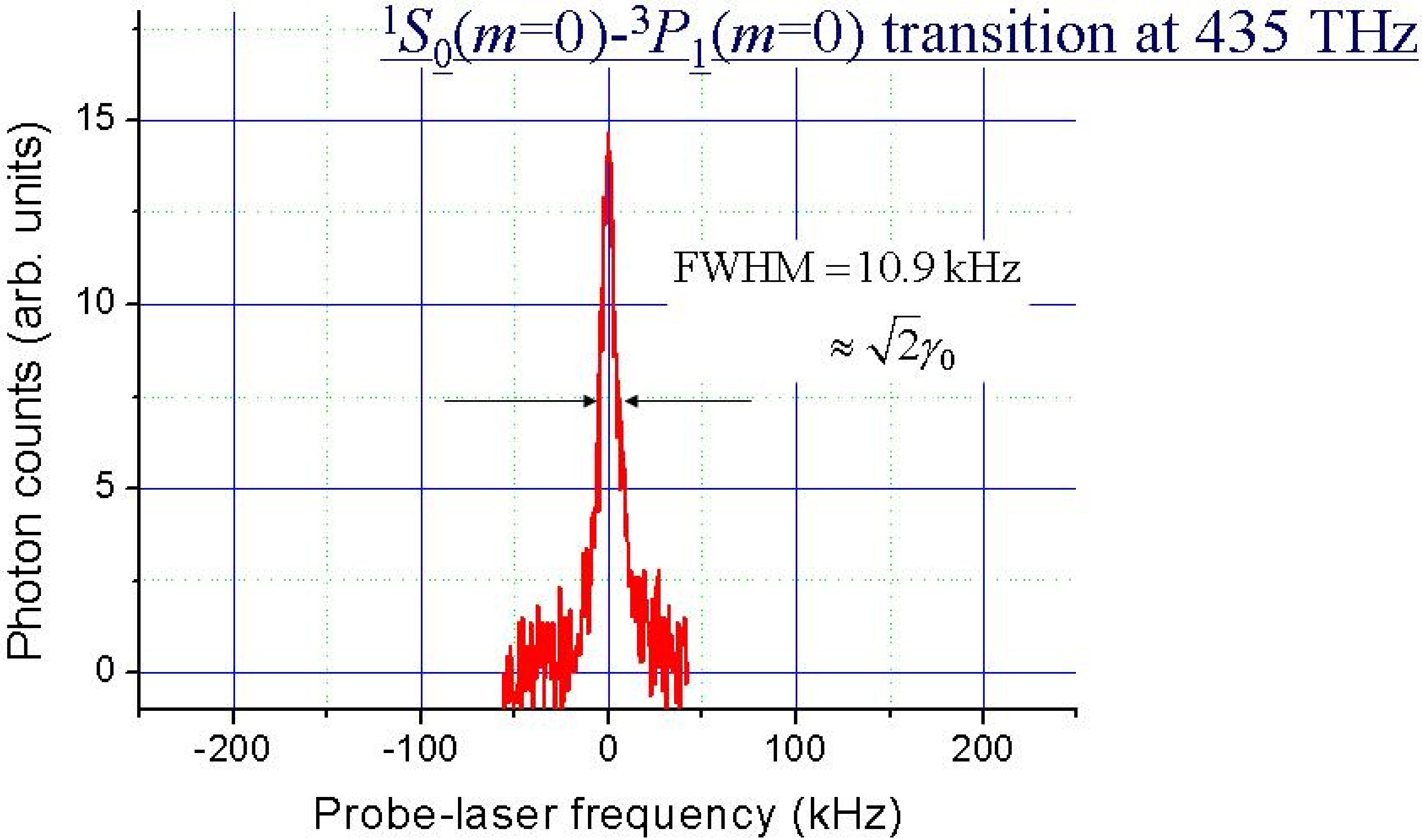


$k_p \Delta x < 1$: Lamb-Dicke condition is satisfied

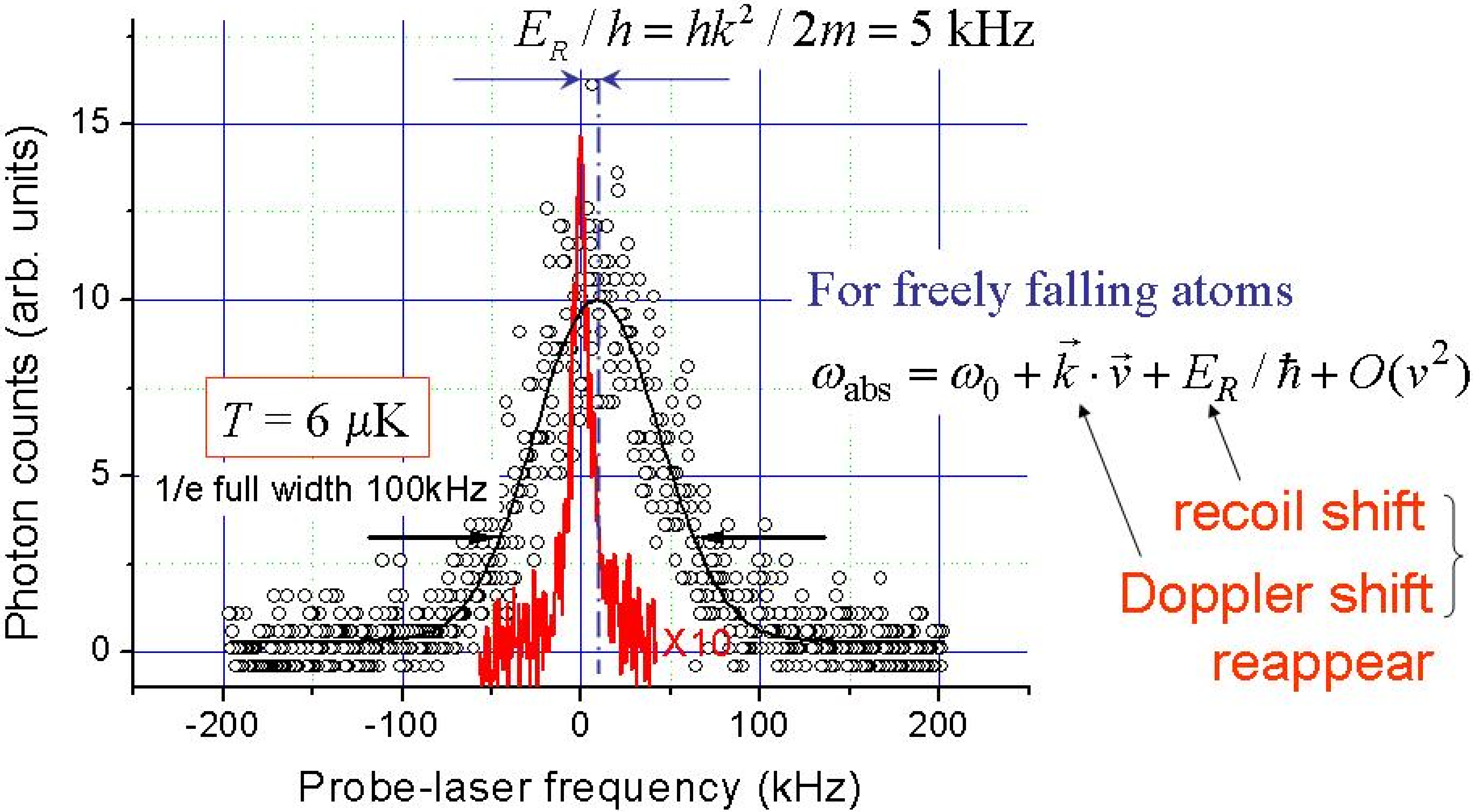
Suppression of motional sidebands

$$\langle n' | \exp(ikr) | n \rangle \approx \langle n' | n \rangle = \delta_{n'n}$$

Suppression of Doppler & photon-recoil shift in the Lamb-Dicke regime



Suppression of Doppler & photon-recoil shift in the Lamb-Dicke regime



T. Ido and H. Katori, *Phys.Rev. Lett.* **91**, 053001(2003)

Toward perfect control over light shifts

$$\hbar\nu = \hbar\nu_0 - \Delta\alpha(\omega_L, \xcancel{\hat{\varepsilon}_L})|E|^2/2! - \Delta\gamma(\omega_L, \hat{\varepsilon}_L)|E|^4/4! - \cdots$$

$$\begin{cases} \Delta\alpha(\omega_L, \xcancel{\hat{\varepsilon}_L}) = \alpha_e(\omega_L, \xcancel{\hat{\varepsilon}_L}) - \alpha_g(\omega_L, \xcancel{\hat{\varepsilon}_L}) \rightarrow 0 \\ \Delta\gamma(\omega_L, \hat{\varepsilon}_L) = \gamma_e(\omega_L, \hat{\varepsilon}_L) - \gamma_g(\omega_L, \hat{\varepsilon}_L) \end{cases}$$

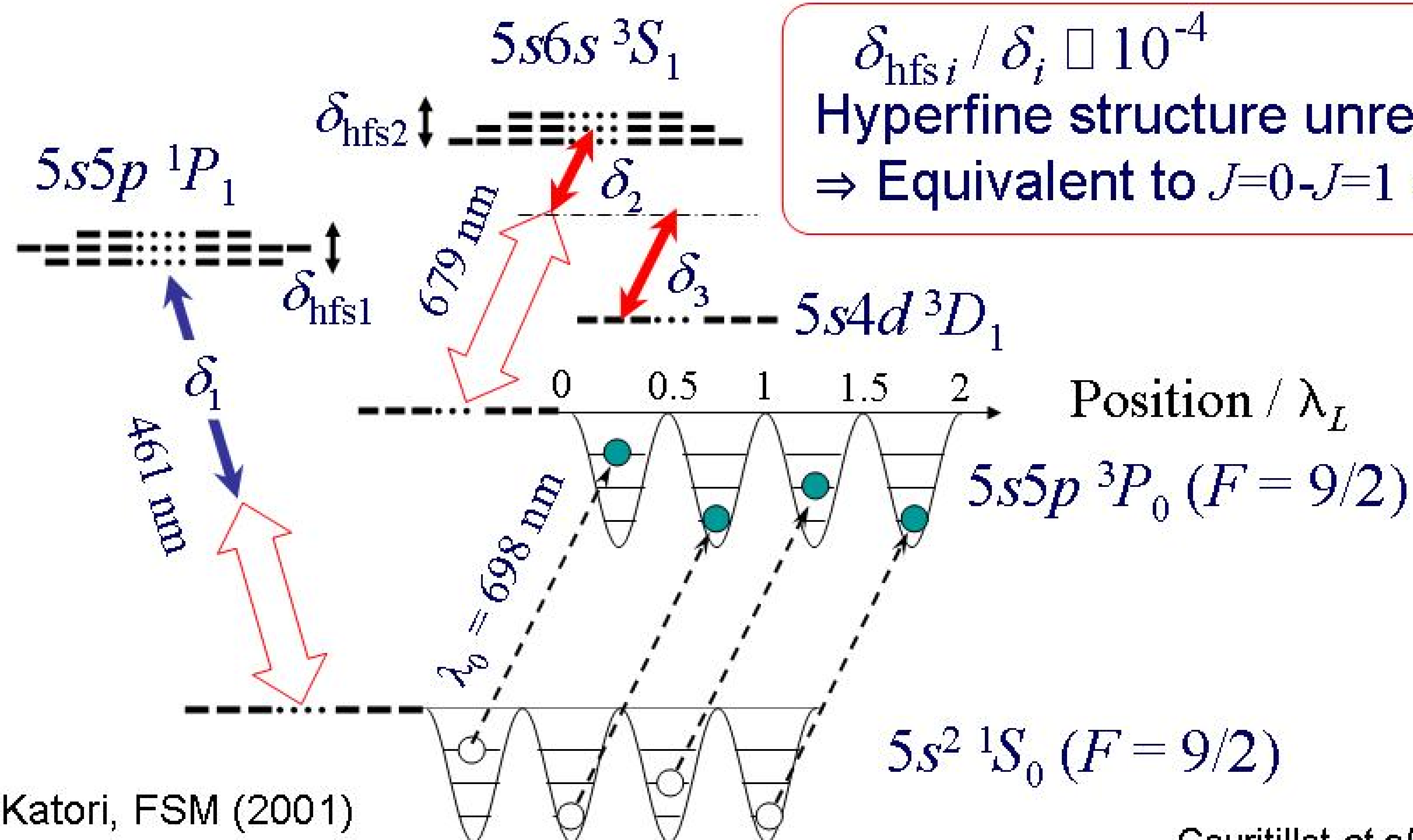
- Polarization insensitive light shifts
  - Use of isotropic coupling with $J = 0$ state
  - Tensor shift due to hyperfine splitting
- Higher order light shifts
  - Contribution of 4th order shifts
  - approx. 1 mHz for 10 kW/cm^2 (5×10^{-18})

V. G. Pal'chikov *et al.*, J. Opt. B5, S131 (2003).

Design for the "Optical Lattice Clock" on ${}^1S_0$-${}^3P_0$ transition of ^{87}Sr (I=9/2)

Hyperfine mixing: $\tau_{{}^3P_0} = A \times \tau_{{}^3P_1} + B \times \tau_{{}^1P_1} + \cdots \sim 160\,\mathrm{s}$

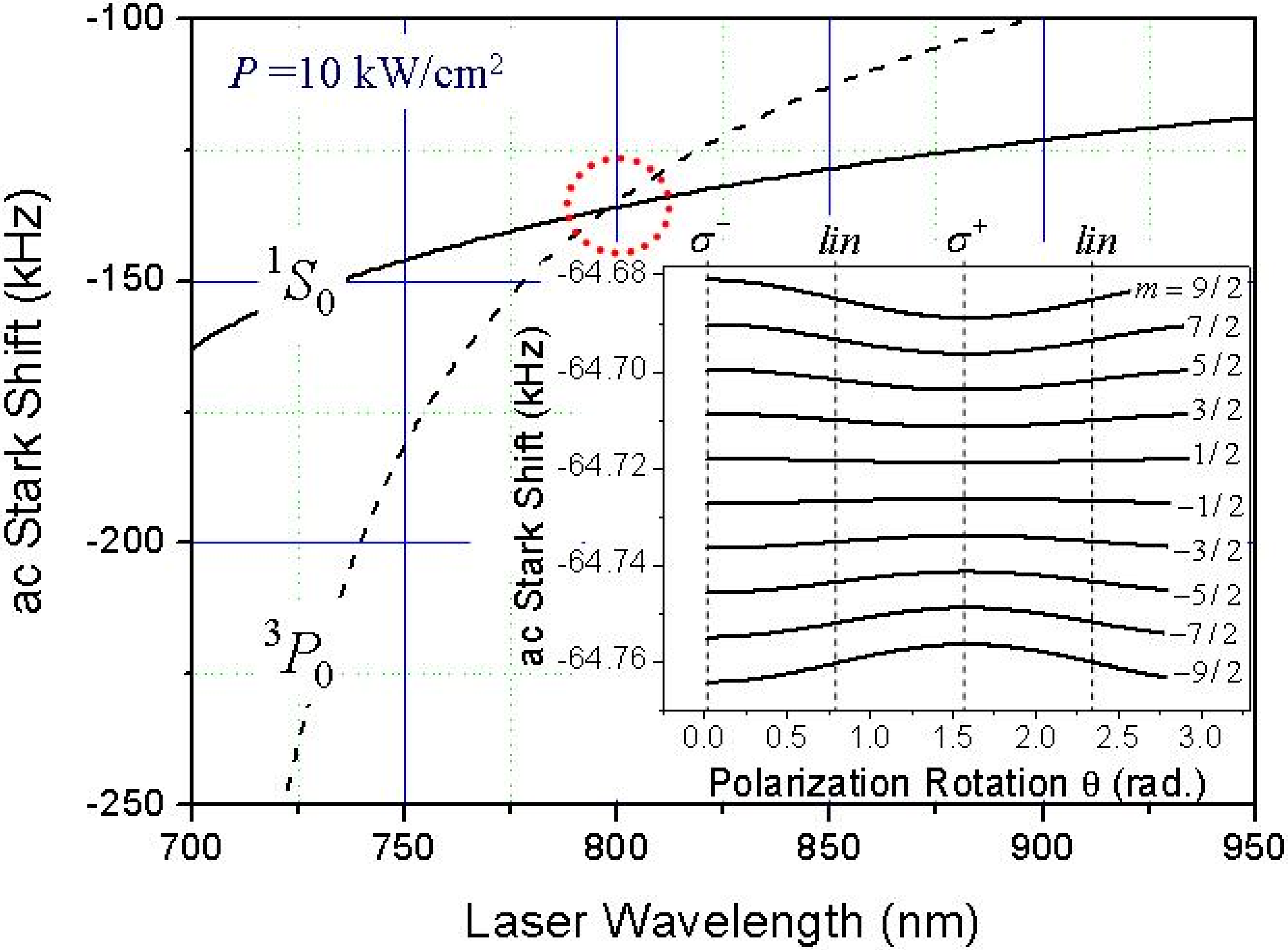
$\delta_{\mathrm{hfs}\,i} / \delta_i \sim 10^{-4}$
Hyperfine structure unresolved
⇒ Equivalent to J=0-J=1 coupling



Katori, FSM (2001)

Couritillot *et al. PRA* (2003)

Light Shift cancellation on the $^1S_0(F=9/2)$-$^3P_0(F=9/2)$ transition



Frequency dependence

$\lambda_L = 797$ nm

$$\frac{d(\Delta\nu_{ac})}{d\omega_L} \approx -1\,\frac{\text{Hz}}{\text{GHz}}$$

Polarization dependence

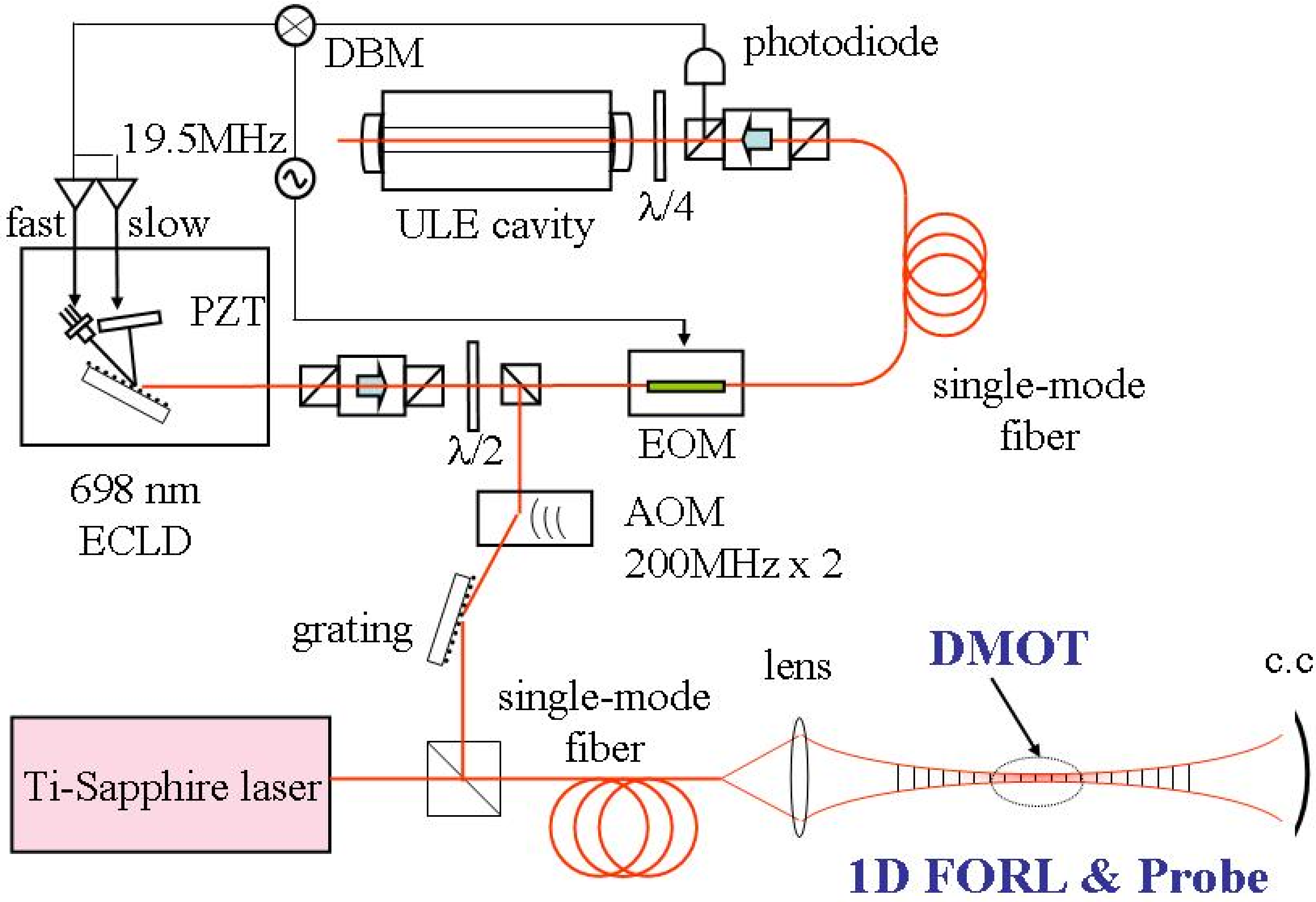
$$\frac{d\nu_{ac}}{d\theta_L} = 0.83\ \text{Hz/rad}$$

$$m_F = \pm 1/2 \rightarrow \pm 1/2$$

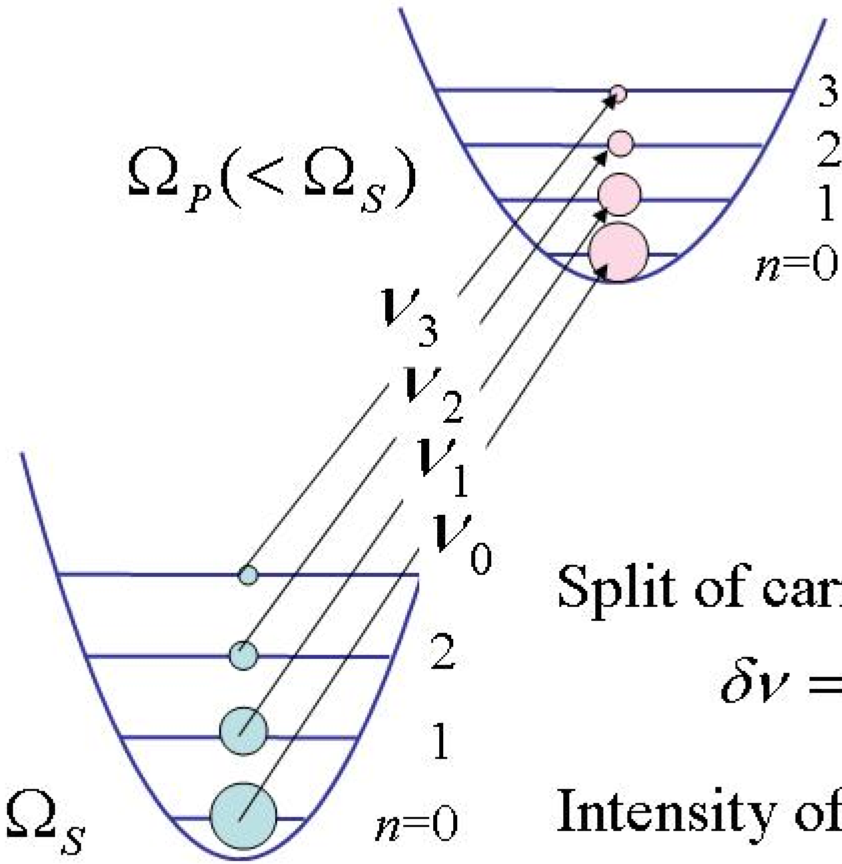
linear pol.

Katori, Takamoto, Pal'chikov & Ovisannikov, *Phys. Rev. Lett.* **91**,173005(2003)

Experimental setup



Inhomogeneous broadening of carrier spectrum for non-degenerate lattice



light shift difference

$$\hbar \nu_n = \hbar \omega_0 + \overbrace{(u_P - u_S)}$$

$$+ (n + \frac{1}{2}) \hbar \underbrace{(\Omega_P - \Omega_S)}$$

vibrational energy difference

$$(\Omega_i \approx k \sqrt{-2u_i / m})$$

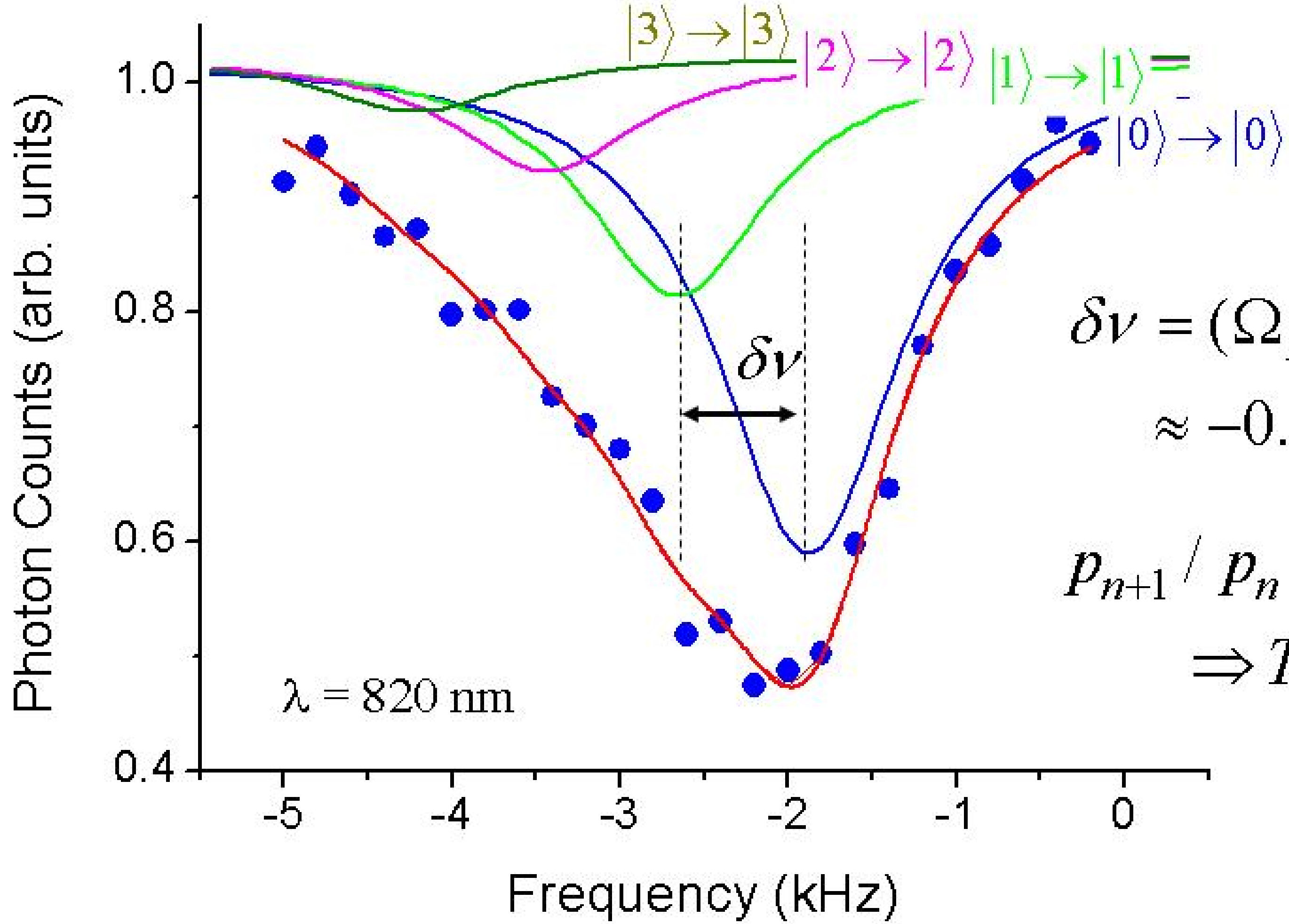
Split of carrier component:

$$\delta \nu = \nu_n - \nu_{n-1} = \Omega_P - \Omega_S$$

Intensity of ν_n proportional to Boltzmann factor:

$$p_{n+1} / p_n = \exp(-\hbar \Omega_S / k_B T)$$

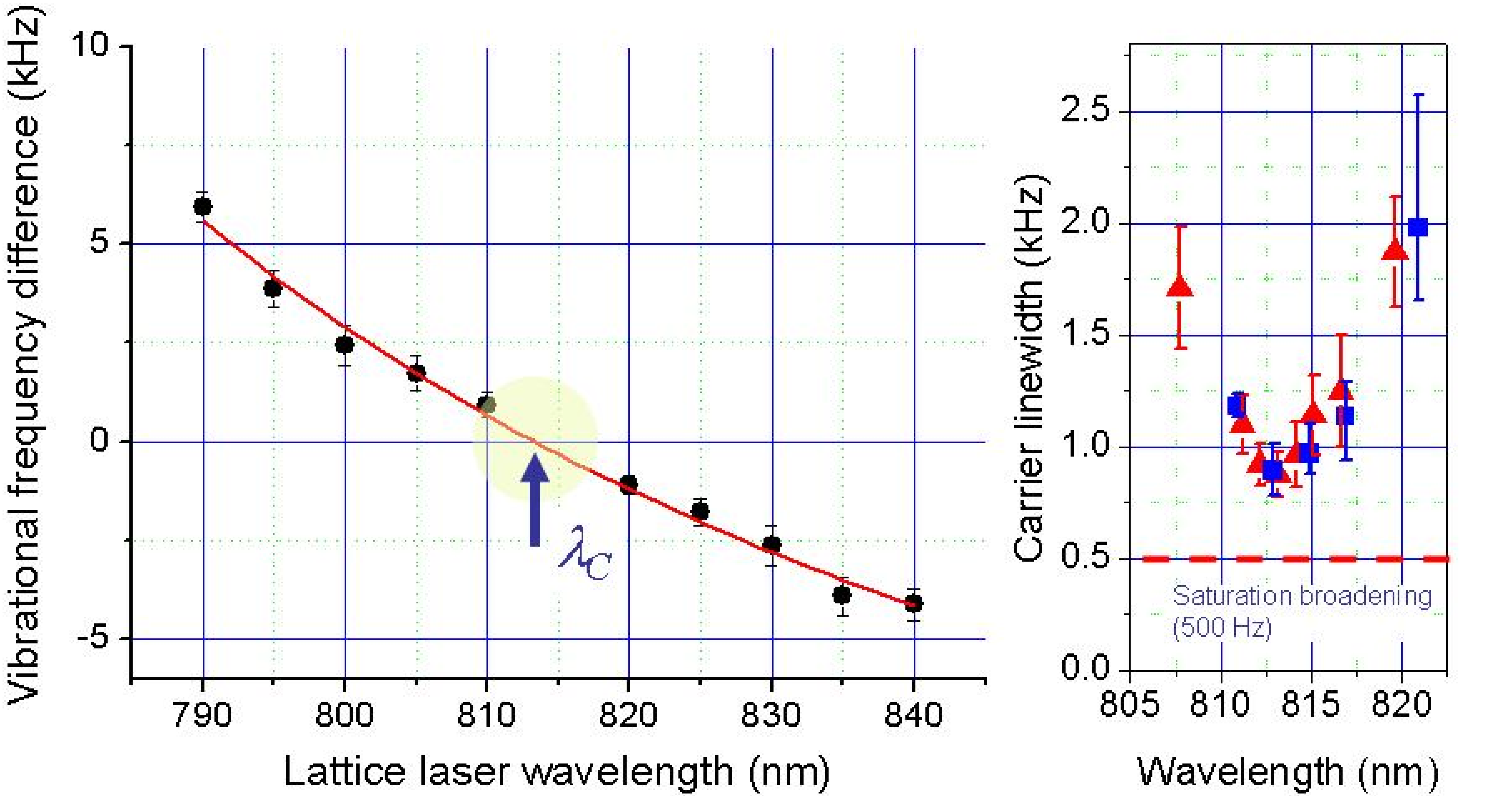
Inhomogeneous broadening of carrier spectrum $(\lambda_L \neq \lambda_C)$



$$\delta\nu = (\Omega_P - \Omega_S)/2\pi$$
$$\approx -0.77 \text{ kHz}$$

$$p_{n+1}/p_n \approx 0.49$$
$$\Rightarrow T = 4\mu\text{K}$$

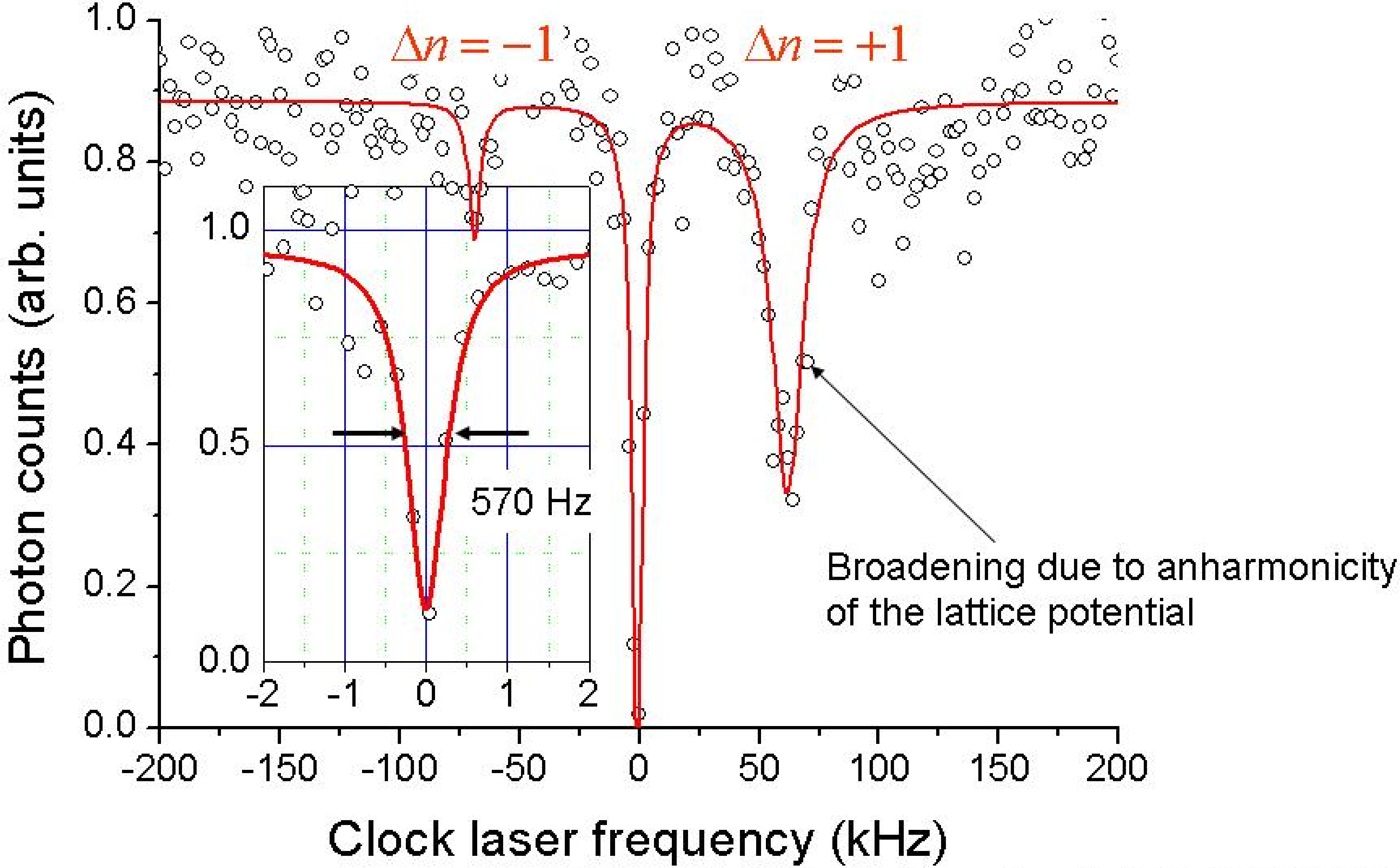
Determination of the degenerate wavelength



Cancellation wavelength: λ_C = **813.5(9) nm** (exper.)

cf. λ_C = **797 nm** (theory); **2%** difference

Spectroscopy of the $^1S_0$ (F=9/2)-$^3P_0$ (F=9/2) transition in an optical lattice at λ_L~λ_C



Takamoto & Katori, *Phys. Rev. Lett.* **91**, 223001(2003)

Summary of Uncertainties

- Optical lattice potential
  - Lattice frequency: $\mathrm{d}(\Delta\nu_{ac})/\mathrm{d}\omega_L = -1\,\mathrm{Hz/GHz}\ (\rightarrow 1\,\mathrm{mHz})$
  - Lattice polarization: $\mathrm{d}\nu_{ac}/\mathrm{d}\theta_L = 0.83\,\mathrm{Hz/rad}\ (\rightarrow 1\,\mathrm{mHz})$
  - Higher order light shifts $\delta\nu_{ac} \approx 1\,\mathrm{mHz}\ @\ I = 10\,\mathrm{kW/cm^2}$
    - Contribution of two photon resonance?
- Blackbody shifts/quenching

  $\nu_B \approx -2.4\,\mathrm{Hz}\ @\ T = 293\,\mathrm{K}\ (\Delta\nu_B \approx 10\,\mathrm{mHz}\ @\ \Delta T < 0.5\,\mathrm{K})$
  - ^3P - ^3D transition at **2.6 μm**
  - Lifetime reduction to **100 s @ T = 300 K**
- Collisional frequency shifts: $\nu_C \approx 0$
  - Collision suppression by 3D optical lattice
  - Statistical suppression

$\delta\nu \le 10\,\mathrm{mHz}$

$\dfrac{\delta\nu}{\nu} \le 2\times 10^{-17}$

Quantum suppression of collisional shifts

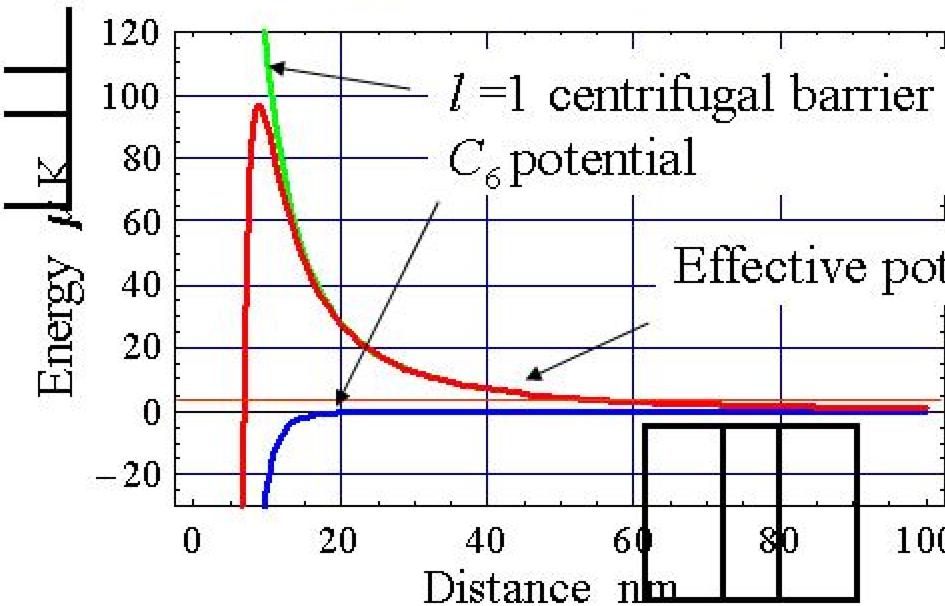
^{87}Sr: Fermionic particle

If the samples are prepared

- in the same magnetic substate m_F
- at sufficiently low temperature
- and coherently excited,

Statistical suppression of the collisional shifts can be expected.

See, Disappearance of collision shifts in RF: S. Gupta, *et al.*, Science 300, 1723 (2003).



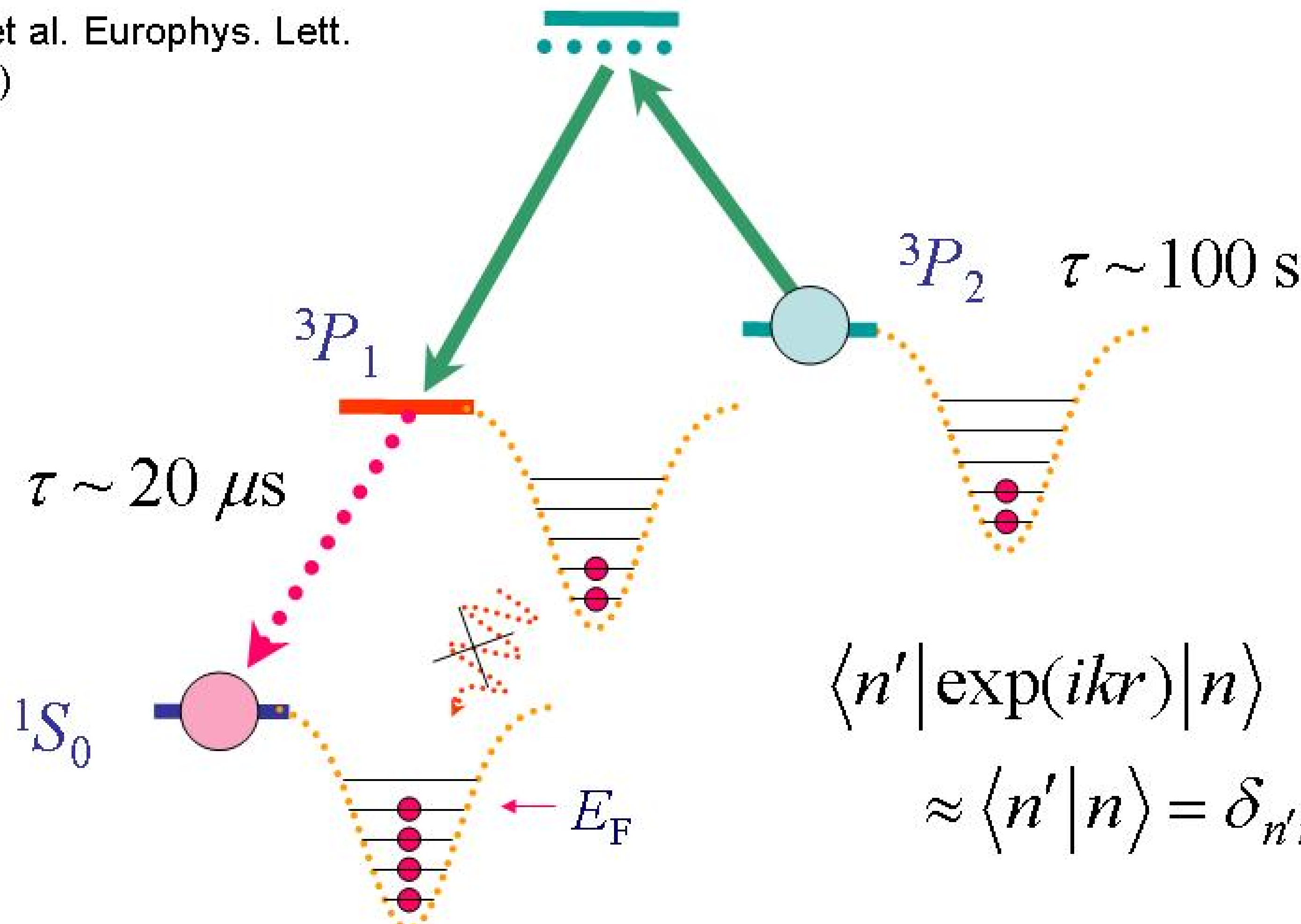
$$U_{eff}(r) = \frac{l(l+1)\hbar^2}{2\mu r^2} - \frac{C_6}{r^6}$$

$E_{in} \sim k_B \times$ (a few μK)

Res.Dip-Dip. potential $U = a\hbar\gamma/(r/\lambda\!\!\!^{-})^3$ with $\gamma/2\pi$=1 mHz can not support bound states for $60\,\mathrm{nm} < d < \lambda\!\!\!^{-}$

Independently prepared degenerate fermions in the long-lived metastable states: Control of radiative modes by Pauli blocking effect

T. Busch, et al. Europhys. Lett. 44,1 (1998)



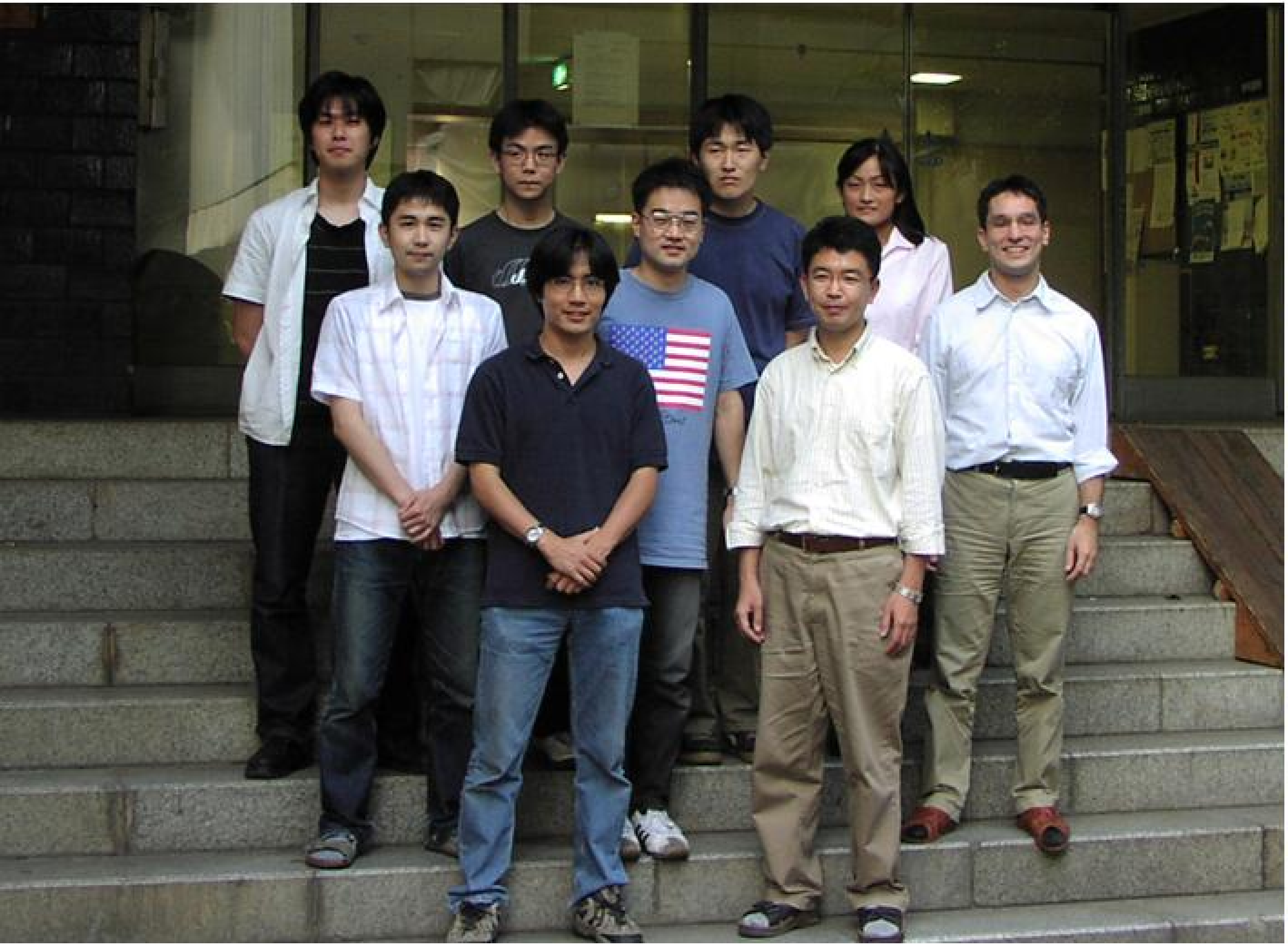
$$\langle n' | \exp(ikr) | n \rangle \approx \langle n' | n \rangle = \delta_{n'n}$$

Summary & Prospects

- Laser cooling of alkaline-earth Fermions.
- Well-designed perturbation help precision measurements: 10^{-17}~10^{-18} accuracy & stability@1s
- Use of quantum statistical properties in precision measurement.

- Comparison of Sr/Yb lattice clock in search for α variation

The group at the University of Tokyo



Masao Takamoto
Masami Yasuda
Tetsuo Kishimoto
Hidekazu Hachisu
Jun Fujiki
Tomoya Akatuka
Kotaro Okamura

Hidetoshi Katori

Former collaborator
Taro Eichler
(ERATO)
Tetsuya Ido
Takashi Mukaiyama
Li Ying
Makoto Gonokami