Title: Optical lattice clocks with bosonic/fermionic Sr and with the other atomic elements

Date: Jul 17, 2008 02:00 PM

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Abstract: To date, optical clocks based on singly trapped ions1) and ultracold neutral atoms trapped in the Stark-shift-free optical lattices2) are regarded as promising candidates for future atomic clocks. So far â€œoptical lattice clocksâ€• have been evaluated with uncertainty of 1Ã—10-15 (ref. 3)) limited by that of Cs atomic clocks. Frequency comparison between highly-stable and accurate optical lattice clocks is, therefore, crucial for their further evaluation. Looking toward fractional uncertainties of 10-16 and below, collisional frequency shift, Black body radiation (BBR) shift, and hyperpolarizability effects, all of which depend on interrogated atomic elements and experimental configurations, are becoming major concerns. In this talk, we discuss optimal lattice geometries in view of the quantum statistics and related spins of interrogated atoms. This leads to two promising configurations for the lattice clock: One-dimensional (1D) lattice loaded with spin-polarized fermions4) and 3D lattice loaded with bosons. We present frequency comparison of these two optical lattice clocks using fermionic 87Sr and bosonic 88Sr. Such lattice clock comparison will offer an important step to ascertain the clocksâ€™ uncertainty beyond the Cs limit of 1Ã—10-15. As for the latter two issues, the BBR and the lattice laser related uncertainties, we discuss prospects for a cryogenic clock, a â€œblue-detunedâ€• magic wavelength, and a Hg based optical lattice clock5). References: 1) T. Rosenband et al., Science 319 (2008) 1808. 2) H. Katori, M. Takamoto, V. G. Pal\'chikov and V. D. Ovsiannikov, Phys. Rev. Lett. 91 (2003) 173005. 3) S. Blatt et al., Phys. Rev. Lett. 100 (2008) 140801. 4) M. Takamoto et al., J. Phys. Soc. Jpn. 75 (2006) 104302

n search of variation of fundamental couplings and mass scales,
erimeter Institute, July 14 - 18, 2008

Optical lattice clocks with bosonic/fermionic Sr and with the other atomic elements

Department of Applied Physics, The University of Tokyo,
CREST, Japan Science and Technology Agency,

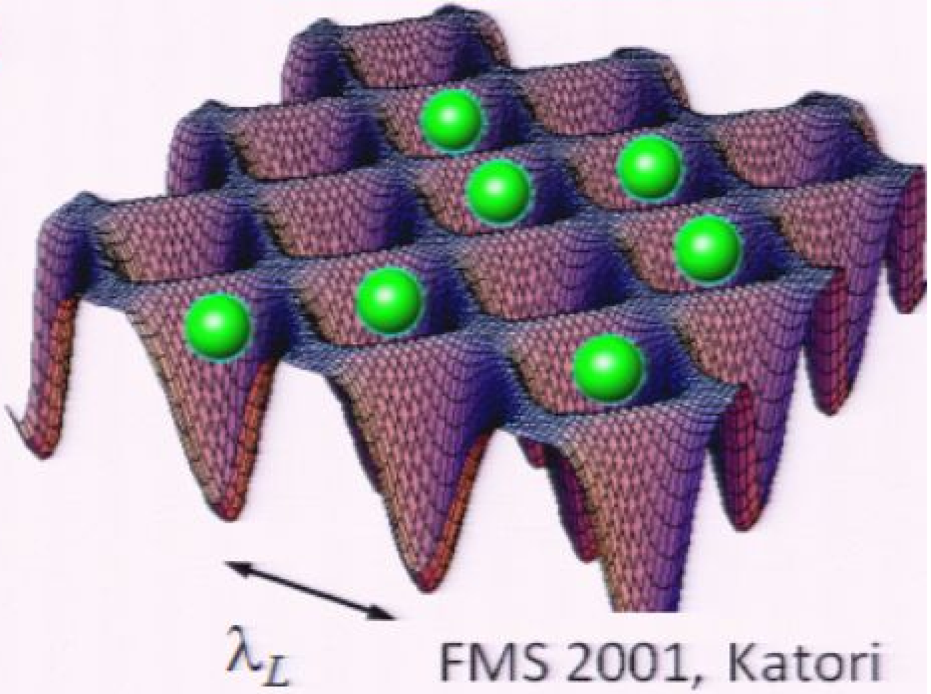
Hidetoshi Katori

Outline: strategies to achieve beyond 10^{-17}

- Introduction: 2001-2007
- **Designing ultimate optical lattice clocks**
  - Quantum statistics & lattice geometries
  - Bosonic 3D/ Fermionic 1D lattice clock
- Remaining issues
  - Collision shift: Coherence in excitation of fermionic system
  - Higher order light shift: Blue-detuned magic wavelength
  - Blackbody shift: Cryogenic lattice clock 10mHz@77K
  - Minimally destructive state measurement
  - Long distance frequency dissemination
- New atomic elements
  - Optical clocks frequency comparison
  - Test of constancy of constant; Hg & Yb vs Sr
- Summary

Our approach (2001-): Designing novel atom traps for atomic clock

◎ Light-shift-free optical lattice that confines **millions of neutral atoms** in separate micro-traps (LDR)



FMS 2001, Katori Nature 2005

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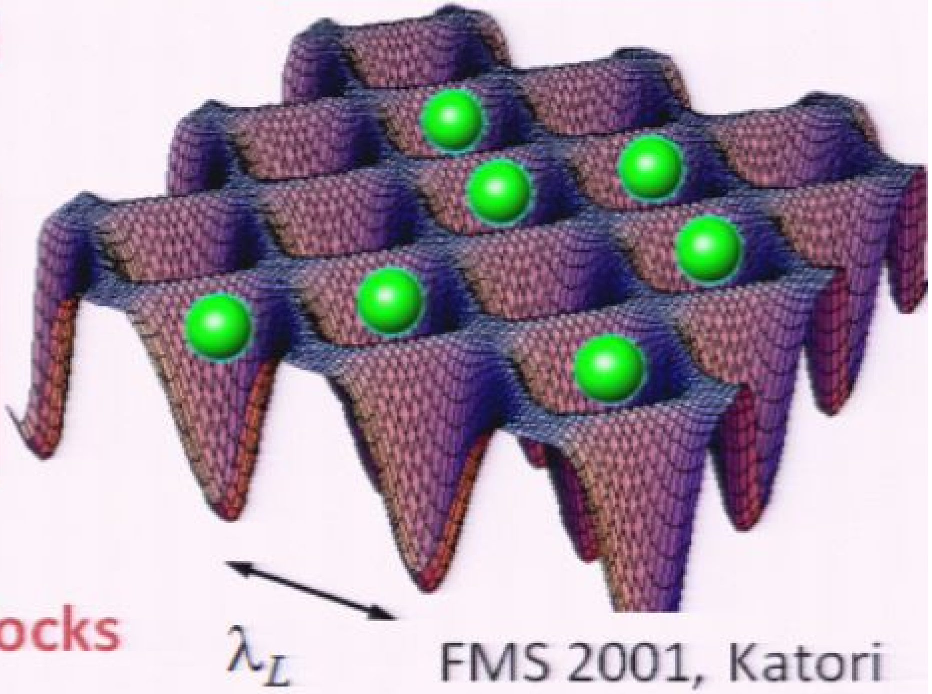
"Optical Lattice Clock" allows

- No collision shifts
- No Doppler shifts
- Long interaction time

Similar to Paul trap

- ***N* atoms: $S/N \sim N^{1/2}$**,

therefore simulates **millions of ion-clocks** operated in parallel.



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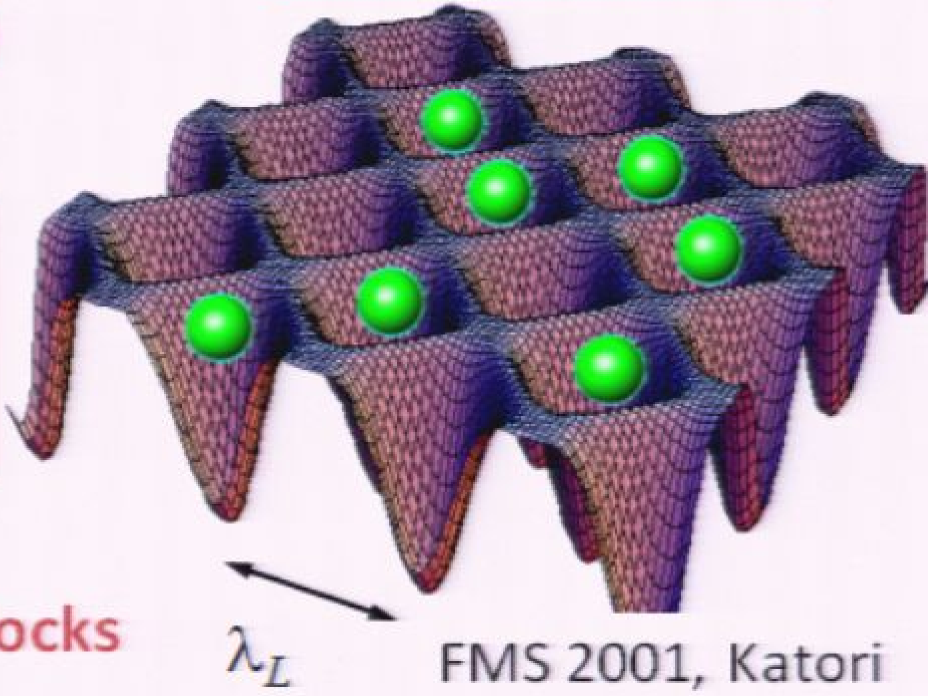

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- No collision shifts
- No Doppler shifts
- Long interaction time

Similar to Paul trap

- ***N* atoms: *S*/*N* ~ $N^{1/2}$**,

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---

he success of this approach is not obvious: Atom/Ion frequency standards ave been studied solely in "perturbation free environment".

◎Challenge: Does well-designed perturbation help precision measurements? How far can we control perturbation?

Elimination of light field perturbation in optical dipole traps (1999)

$$\nu_{\text{atom}} = (E_e - E_g)$$

Katori, Ido, & Gonokami, *J. Phys. Soc. Jpn*. **68**, 2479 (1999)

FORT for Rb C-QED experiment: J. McKeever et al., *Phys. Rev. Lett.* **90**, 133602 (2003)

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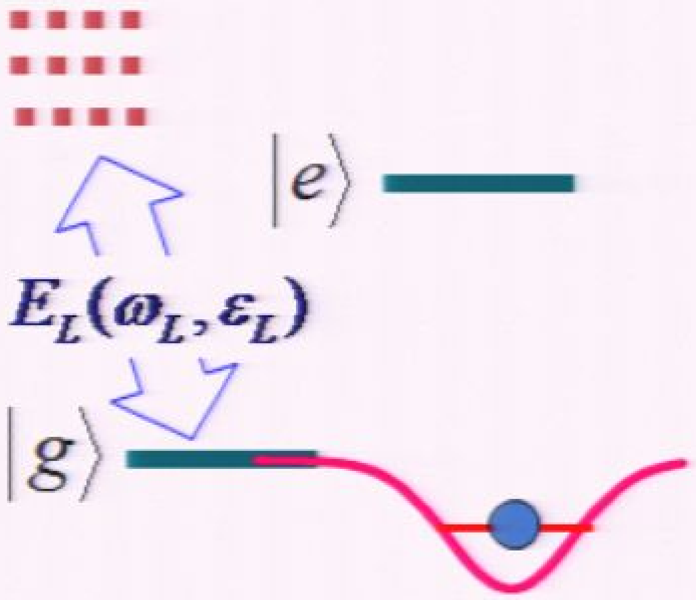

$$E'_g = E_g - \frac{1}{2}\alpha_g(\omega_L, \varepsilon_L)\left|E_L(r)\right|^2$$

$$\nu_{\mathrm{atom}} = (E_e - E_g)$$

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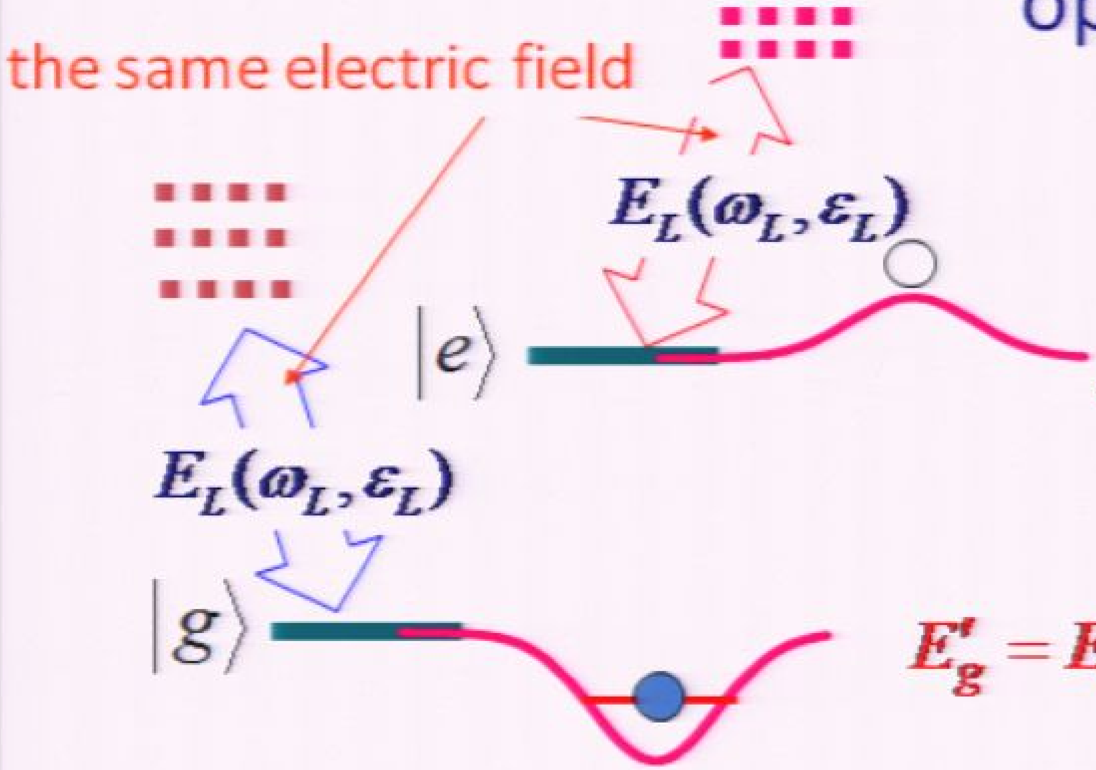

$$E'_e = E_e - \frac{1}{2}\alpha_e(\omega_L,\varepsilon_L)|E_L(r)|^2$$

$$E'_g = E_g - \frac{1}{2}\alpha_g(\omega_L,\varepsilon_L)|E_L(r)|^2$$

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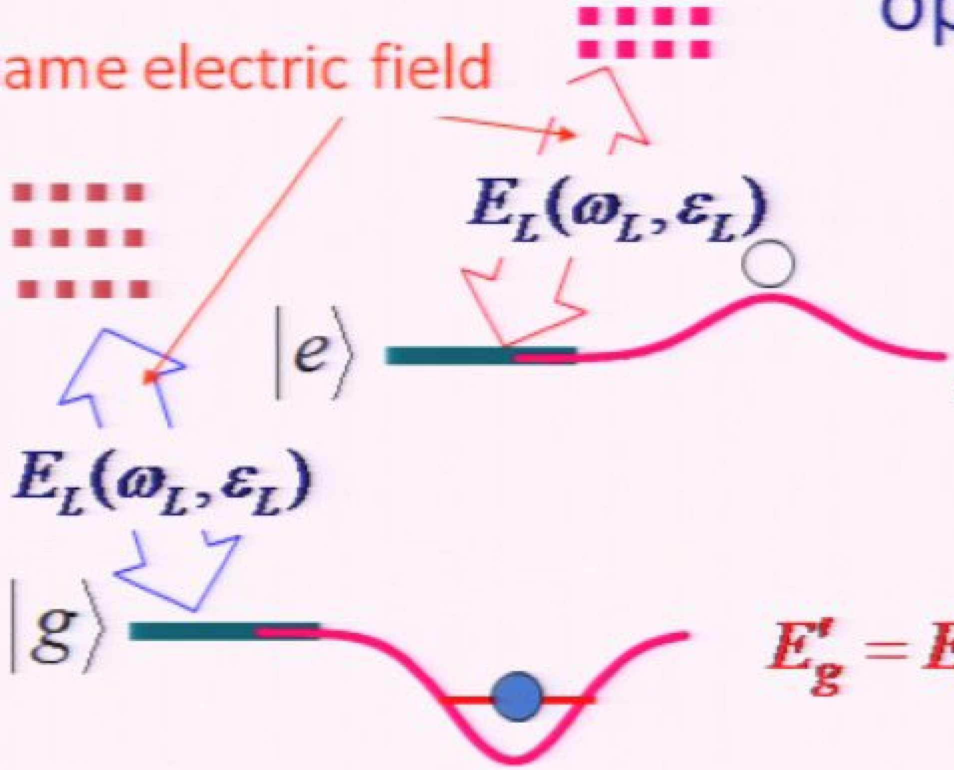
Katori, Ido, & Gonokami, *J. Phys. Soc. Jpn*. **68**, 2479 (1999)

Elimination of light field perturbation in optical dipole traps (1999)

the same electric field



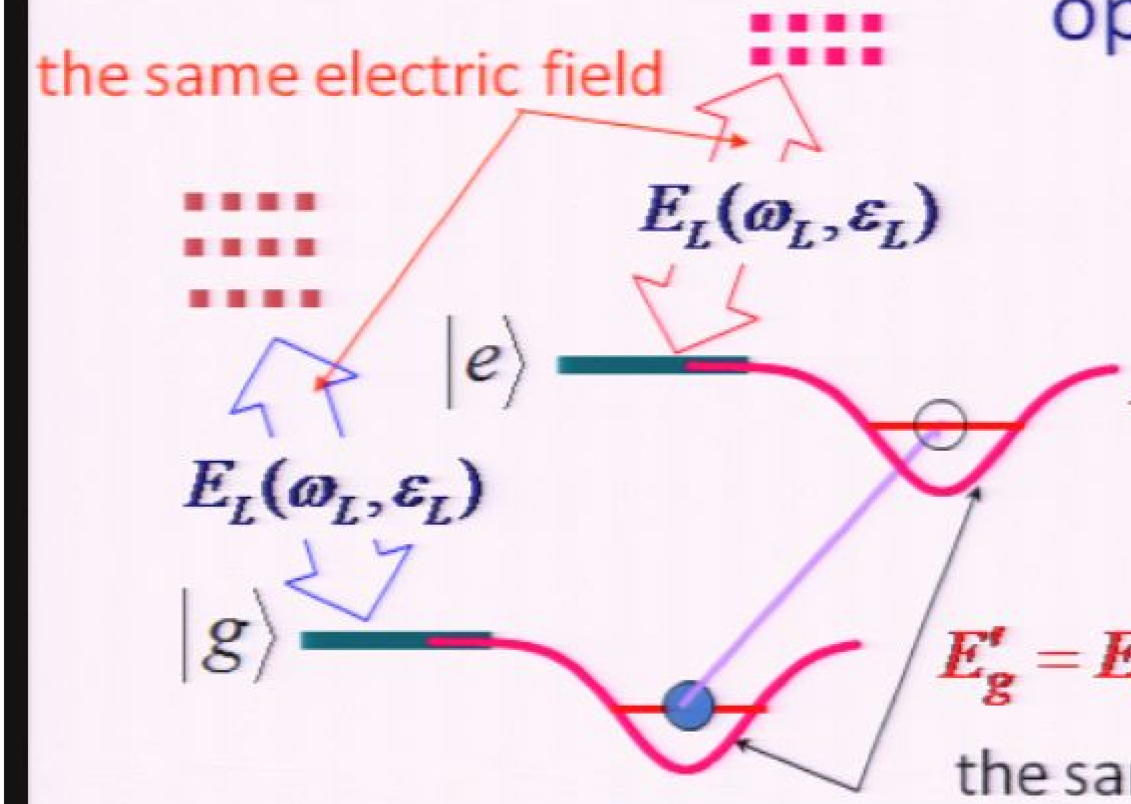
$$E_e' = E_e - \frac{1}{2}\alpha_e(\omega_L,\varepsilon_L)\left|E_L(r)\right|^2$$

$$E_g' = E_g - \frac{1}{2}\alpha_g(\omega_L,\varepsilon_L)\left|E_L(r)\right|^2$$

$$\nu_{\text{atom}} = (E_e - E_g) - \boxed{\frac{\{\alpha_e(\omega_L,\varepsilon_L) - \alpha_g(\omega_L,\varepsilon_L)\}}{2}\left|E_L(\omega_L,\varepsilon_L)\right|^2} + O(E^4$$

Katori, Ido, & Gonokami, *J. Phys. Soc. Jpn.* **68**, 2479 (1999)

Elimination of light field perturbation in optical dipole traps (1999)



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Light field perturbation can be eliminated, if the "Differential polarizability" is ZERO

Katori, Ido, & Gonokami, *J. Phys. Soc. Jpn*. **68**, 2479 (1999)

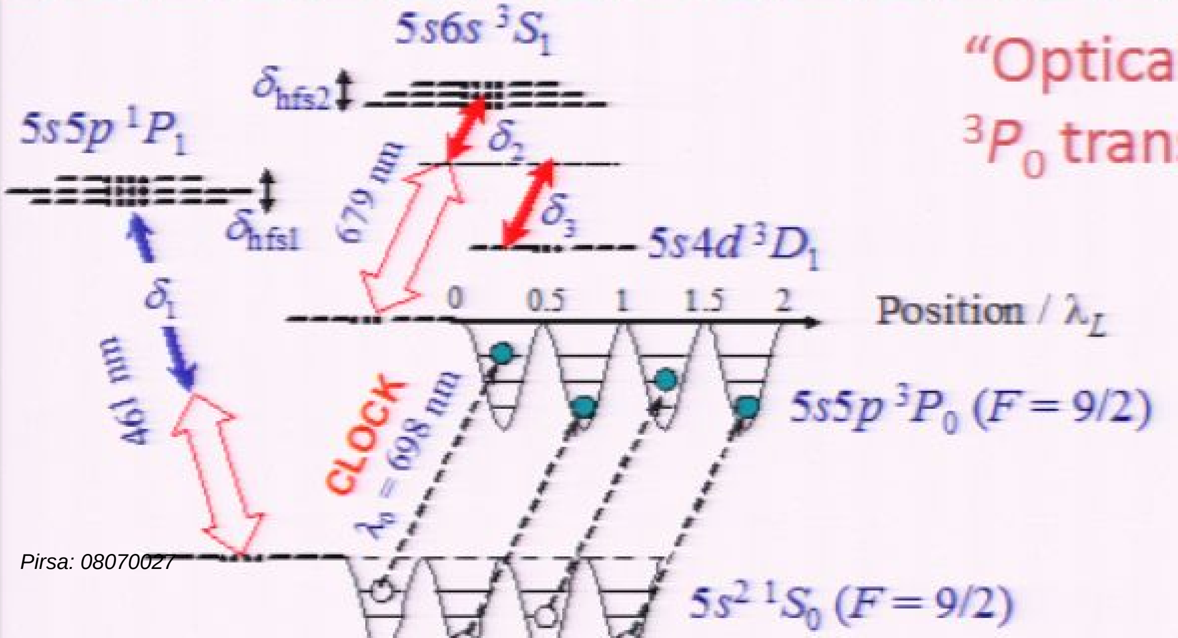
FORT for Rb C-QED experiment: J. McKeever et al., *Phys. Rev. Lett.* **90**, 133602 (2003)

Important! requirement as a CLOCK

A protocol to set differential polarizability to zero:

$\boxed{\Delta\alpha = \alpha_e(\omega_L, \varepsilon_L) - \alpha_g(\omega_L, \varepsilon_L) = 0}$ should be shared

1) Light **polarization** is difficult to define/measure, but its **frequency/wavelength** can be defined far more precisely.
2) Light polarization couples to the angular momentum *J*
3) Use of (nearly) scalar state ***J*=0**: $\Delta\alpha(\omega_L) = 0$
4) ***J*=0→*J*=0** transition is strictly forbidden: mixing necessary



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

H. Katori, *FSM* (Scotland,2001)

✓Give finite transition moment;
— hf mixing $\gamma_{^3P_0} \sim (160\ \mathrm{s})^{-1}$
— B-field mixing

A. V. Taichenachev *et al.*, *PRL.* 96, 083001 (2006).

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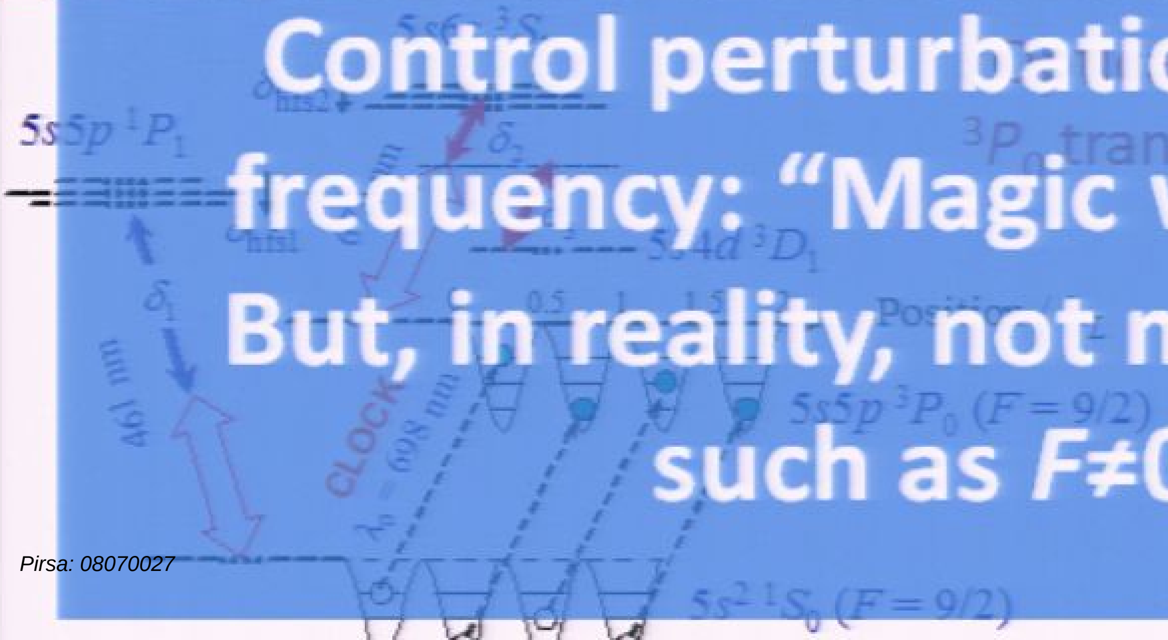
Essence of Lattice Clock Idea:

—Good control over perturbation —

Make more accurate (18digit) clock using less accurate clock (10digit)

Control perturbation solely by frequency: "Magic wavelength"

But, in reality, not necessary so, such as *F*≠0, …



…at the $^1S_0$-$^3P_0$ transition of ^{87}Sr (*I*=9/2)

…(Scotland,2001)

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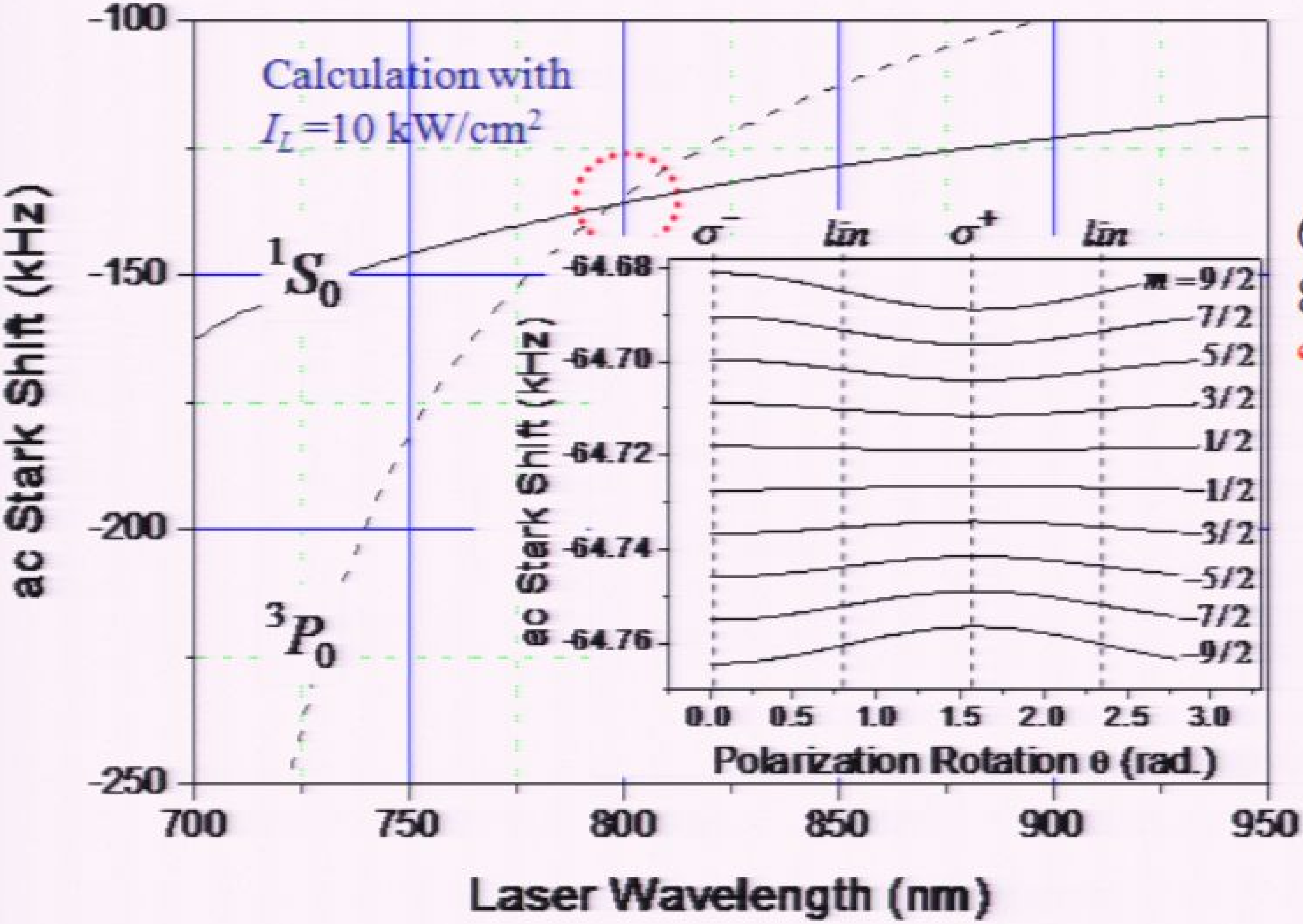
Light Shift cancellation on the $^1S_0(F=9/2)$-$^3P_0(F=9/2)$ transition



Frequency dependence

$$\frac{d\nu_{ac}}{d\omega_L} \approx 10^{-9}$$

6 dig→15 dig

813.428 nm (exp.)

“magic” wavelength

Polarization Dependence: Vector light shift ($F \neq 0$)

$$\frac{d\nu_{ac}}{d\theta_L} = 0.83 \text{ mHz/mra}$$

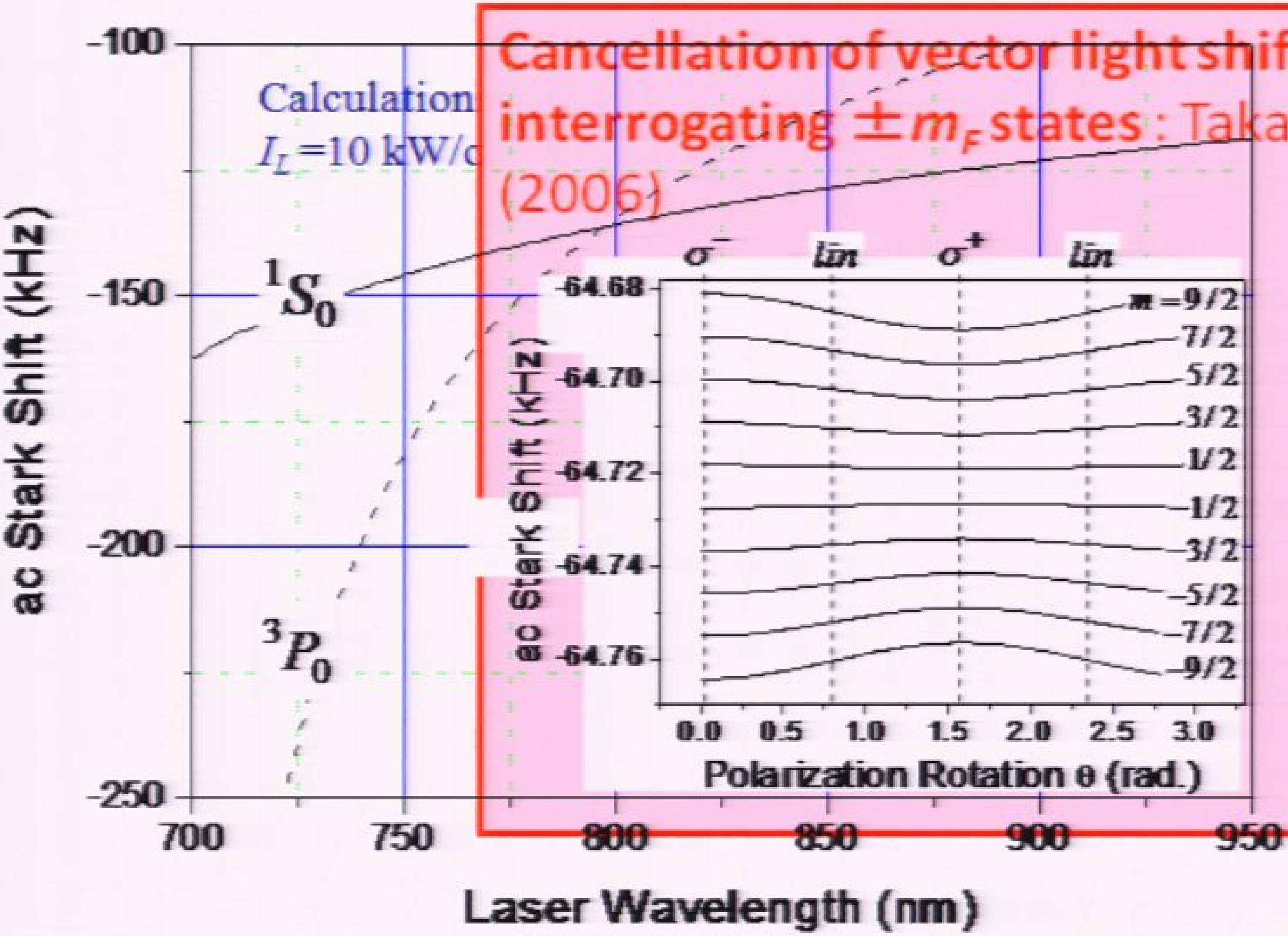
4th order light shift

10^{-3} Hz/(10 kW/cm

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

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

Cancellation of vector light shift by alternately interrogating $\pm m_F$ states : Takamoto et al. JPSJ (2006)



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4th order light shift

10^{-3} Hz/(10 kW/cm

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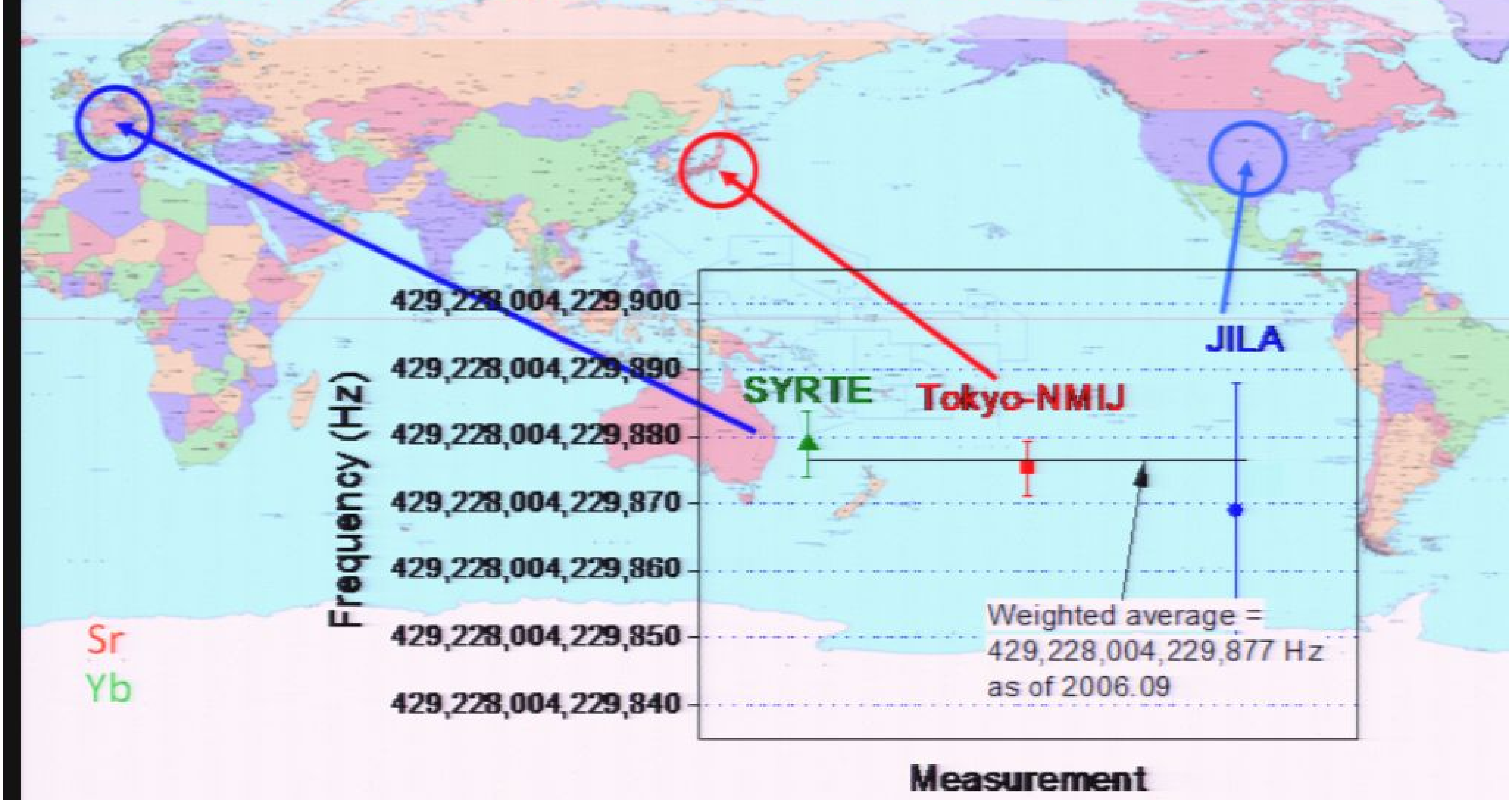
Realization of Sr lattice clocks in the world and adoption as “the secondary representation as a second” in 2006.10



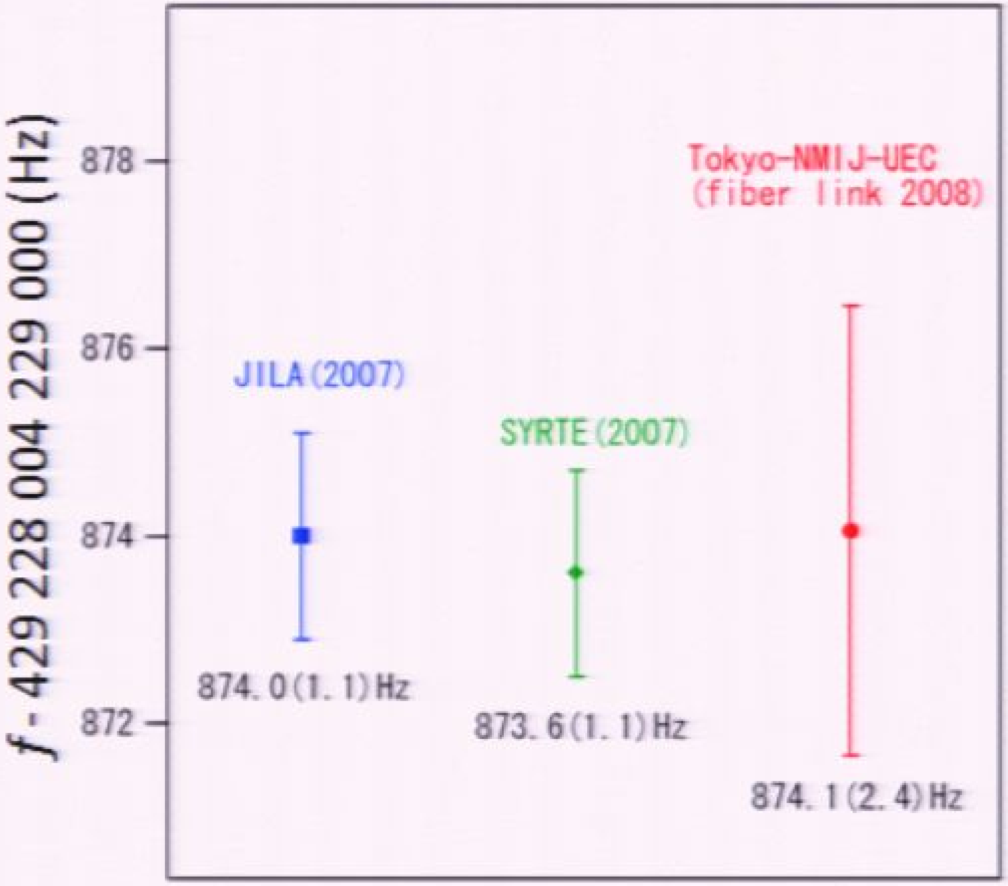
Weighted average = 429,228,004,229,877 Hz as of 2006.09

JILA: Ludlow, et al., PRL 96, 033003 (2006)

Tokyo-NMIJ: Takamoto, et al., J. Phys. Soc. Jpn. 75, 104302 (2006).

SYRTE: Targat, et al., PRL 97, 130801 (2006).

Recent frequency measurements ("07-08)



JILA (2007): M. Boyd, et al., Phys. Rev. Lett. 98, 083002 (2007)

SYRTE (2007): X. Baillard, et al., Eur. Phys. J. D, DOI: 10.1140/epjd/e2007-00330-3

Tokyo (2008): in preparation

Excellent agreement of Sr optical lattice clocks in Boulder/Paris/Tokyo **6×10^{-16} !**

Up to 15 digits accuracy, atomic interactions did not appear, but surely they will.
This talk gives

Designing ultimate optical lattice clocks,

which minimize
atomic interactions (collisional shift)
light shift perturbations (polarization dependent light shift or "vector light shift")
In view of "Lattice Geometry" & "Quantum Statistics"

Note:
Fermions have half integer spin ($F \neq 0$) → sensitive to $\boldsymbol{\varepsilon}_L$
Bosons (may) have zero spin (J=0)→ insensitive to $\boldsymbol{\varepsilon}_L$

Collisional frequency shifts

— Differential mean field energy on the clock transition —

mean field energy: $g^{(2)} \frac{4\pi\hbar^2}{m} an$

$g^{(2)}$: two-particle correlation function at zero distance

a : s - wave scattering length

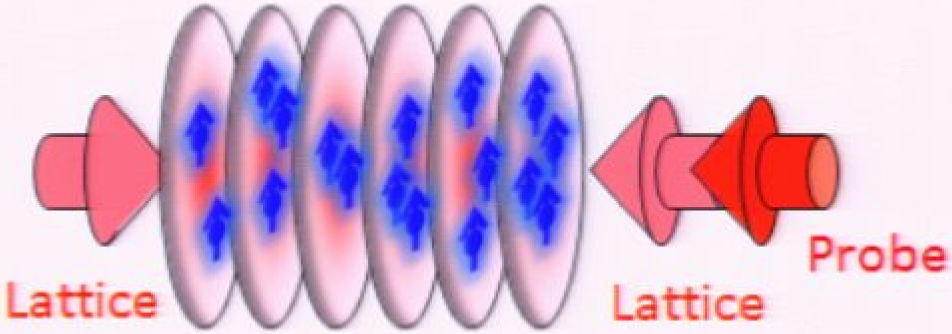
n : atom density

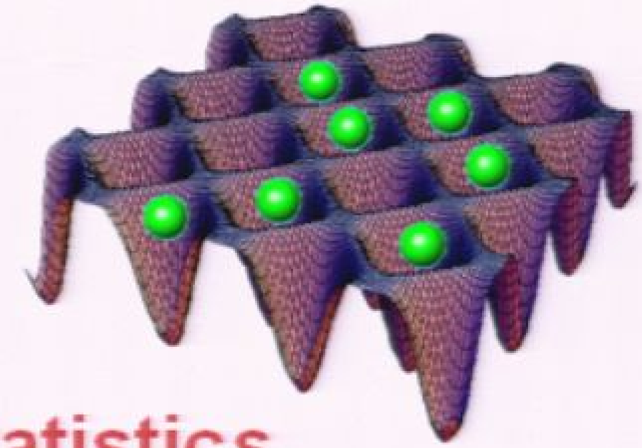
1) identical bosons: $1 \text{ (BEC)} \leq g^{(2)} \leq 2 \text{ (thermal)}$

2) distinguishable particles: $g^{(2)}=1$

3) identical fermions: $g^{(2)} = 0$ (Pauli principle)

Collision shift suppression:
Proposal for Cs clock: K. Gibble, and B. J. Verhaar, Phys. Rev. A **52**, 3370 (1995).
Demonstration in RF: S. Gupta *et al., Science* ***300***, 1723 (2003).





Quantum statistics

Atoms in a site

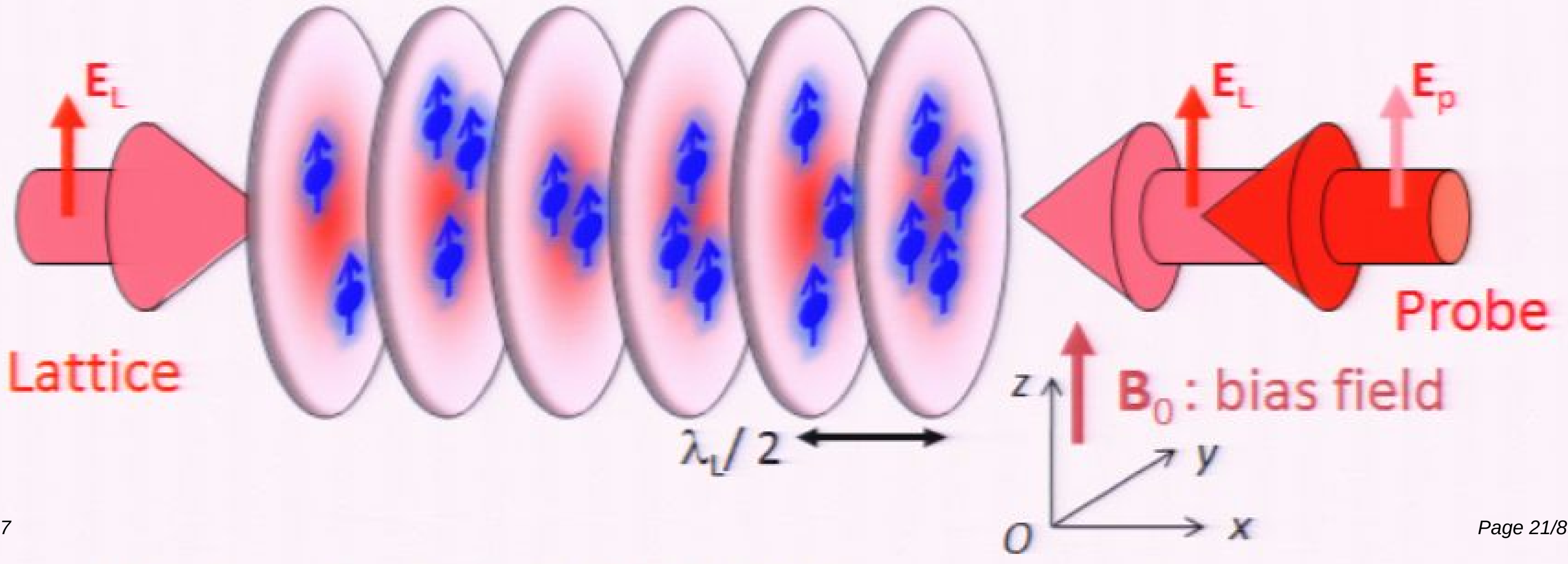
Lattice geometry

	Fermion ($F \neq 0$)	Boson ($J=0$)
1D (2D)	◎**Pauli blocking** (Spatially uniform polarization)	× Cold collsions $1 \le g^{(2)} \le 2$
3D	△vector shifts? (Local elliptical polarization)	◎Mott insulator state ◎**Better S/N ?** (Larger # of atoms)

Single occupancy lattice

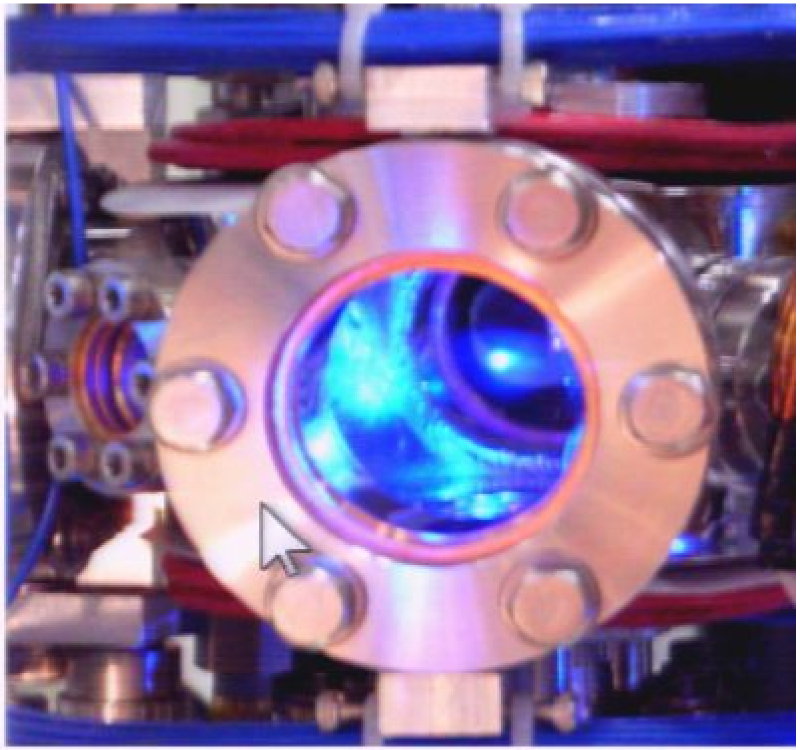
(1)1D Lattice clock with spin-polarized Fermions

- Tens of polarized-atoms in a pan-cake lattice-potential
  - Lamb-Dicke confinement for probe laser
- Pauli principle: “identical fermions cannot collide”
  - Coherent optical excitation of atom ensemble in the Lamb-Dicke regime
  - much more difficult than that in MW! (MIT-group in 2003)
- Cancellation of Zeeman shift & vector light-shift
  - Alternative interrogation of atoms in both stretched state $\pm m_F$



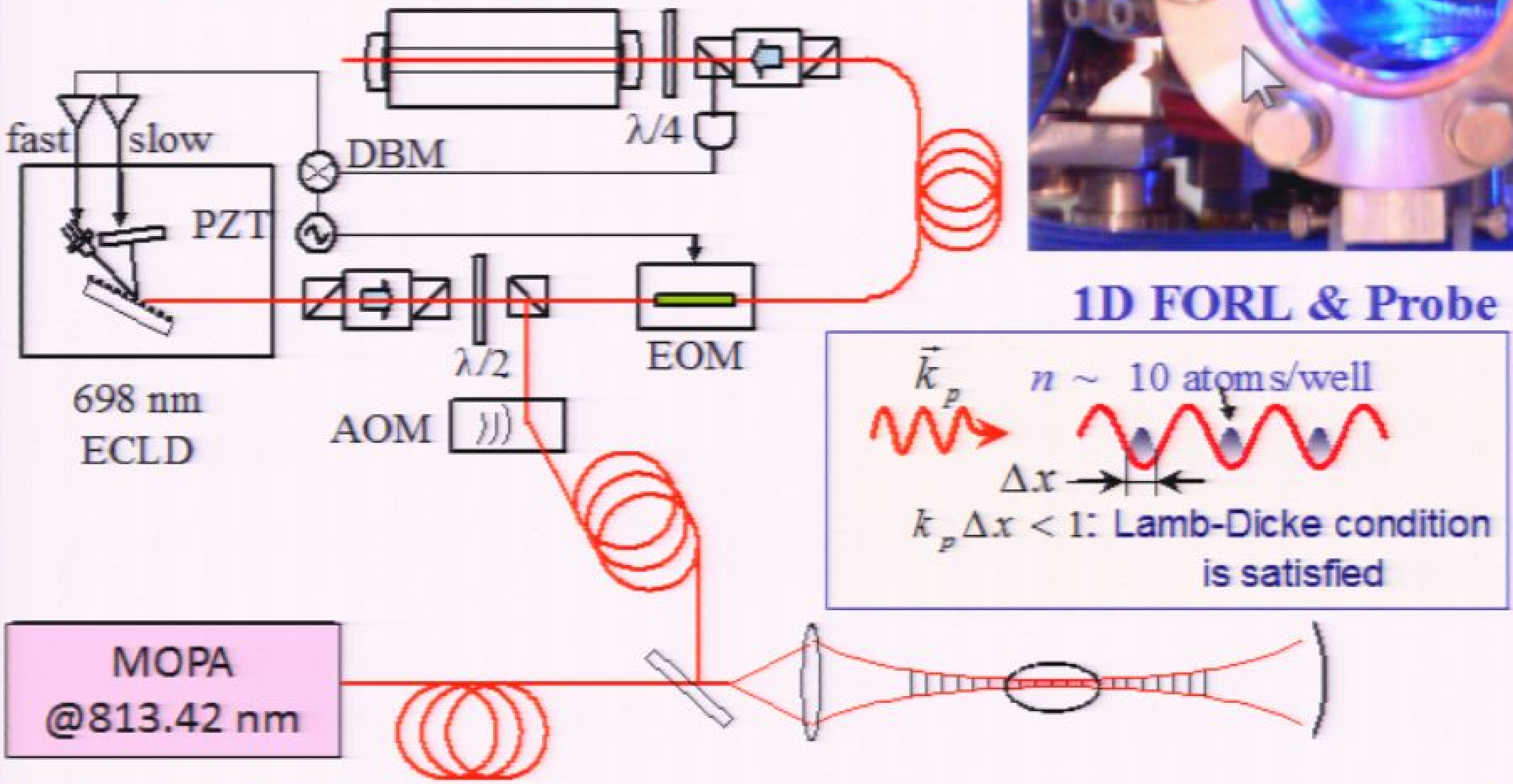
akamoto, et al., J. Phys. Soc. Jpn. 75, 104302 (2006)

Experiment



Laser linewidth < 10 Hz

ULE cavity:
drift rate 0.13 Hz/s



1D FORL & Probe

$n \sim$ 10 atoms/well

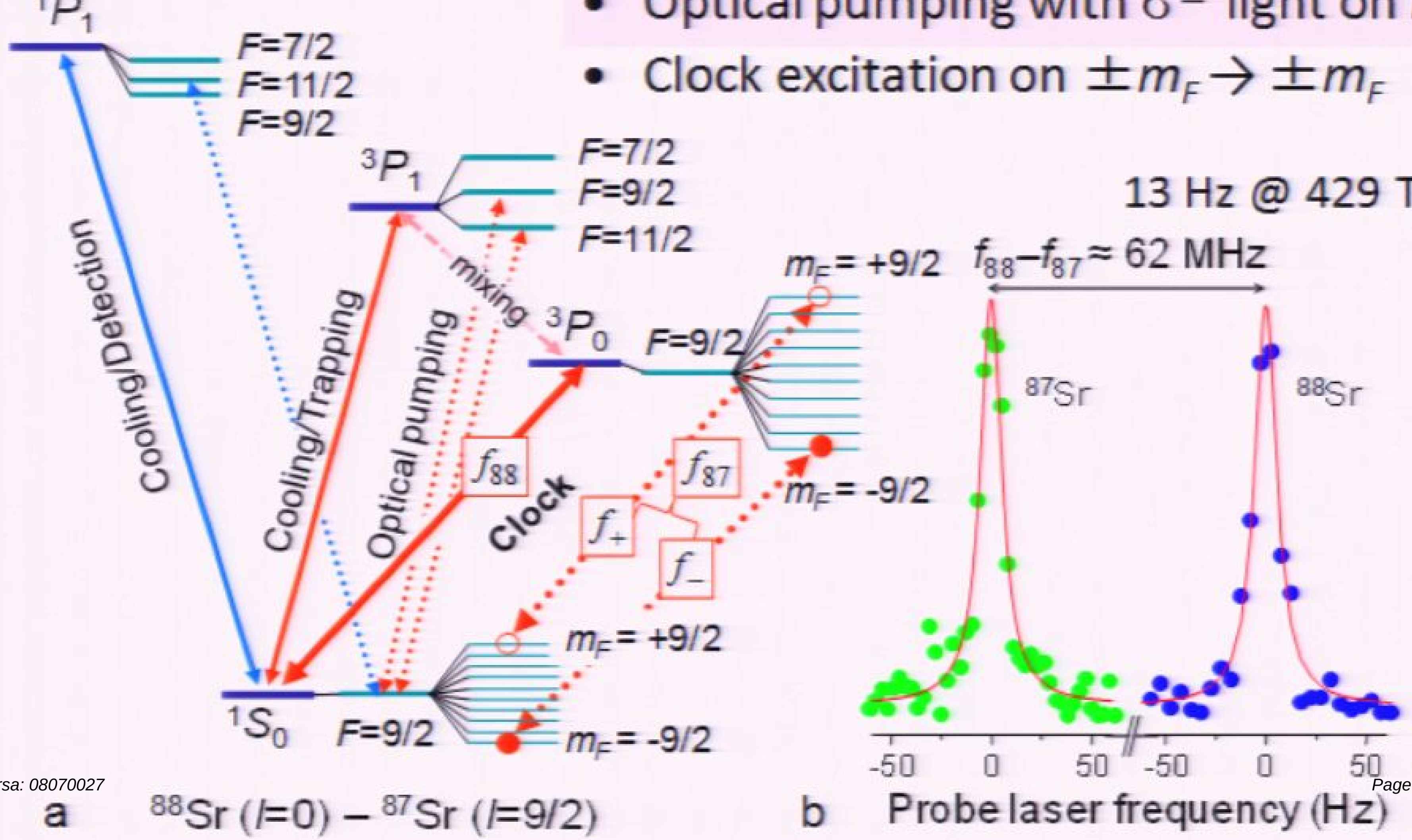
$k_p \Delta x < 1$: Lamb-Dicke condition is satisfied

DMOT scheme: Mukaiyama *et al.*, Phys. Rev. Lett. **90**, 113002 (2003)

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

Energy levels for ^{88}Sr(I=0) & ^{87}Sr(I=9/2)

- 1st and 2nd stage laser cooling
- Loading into 1D lattice
- Optical pumping with $\sigma^{\pm}$ light on $F \rightarrow F$
- Clock excitation on $\pm m_F \rightarrow \pm m_F$



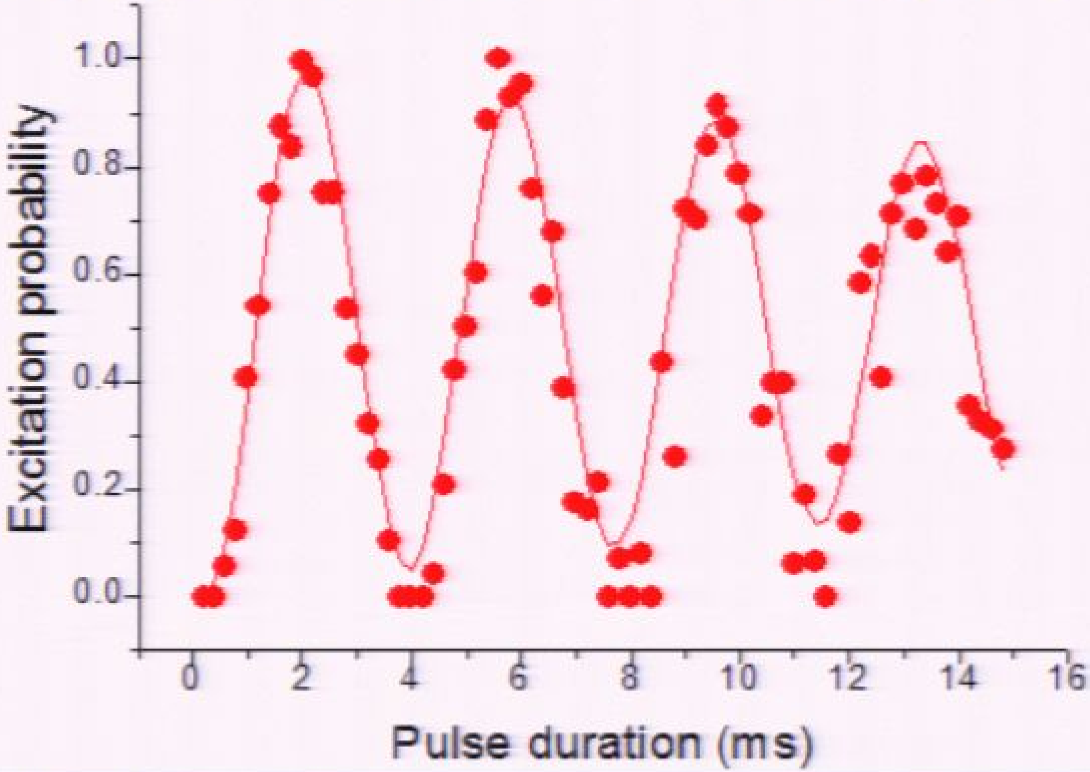
a ^{88}Sr (I=0) – ^{87}Sr (I=9/2)

b Probe laser frequency (Hz)

Rabi oscillation:

Indication of exciting fermionic system in phase

Preservation of fermionic identity: Pauli blocking of collisions



Nearly 100% coherent excitation will suppress collisions, if p-wave tunneling does not come in.

Imperfections:

- Spatial inhomogeneity of probe intensity/Rabi oscillation
- Finite Lamb-Dicke parameter; $\eta \sim 0.34$
- Spatial over wrap of lattice and probe laser (radial vibrational states)

$$\Omega_{n,n} = \Omega_0 \prod |\langle n_j| \exp(\mathrm{i}k_j j)|n_j\rangle|,$$

Cancellation of Zeeman & vector light shift

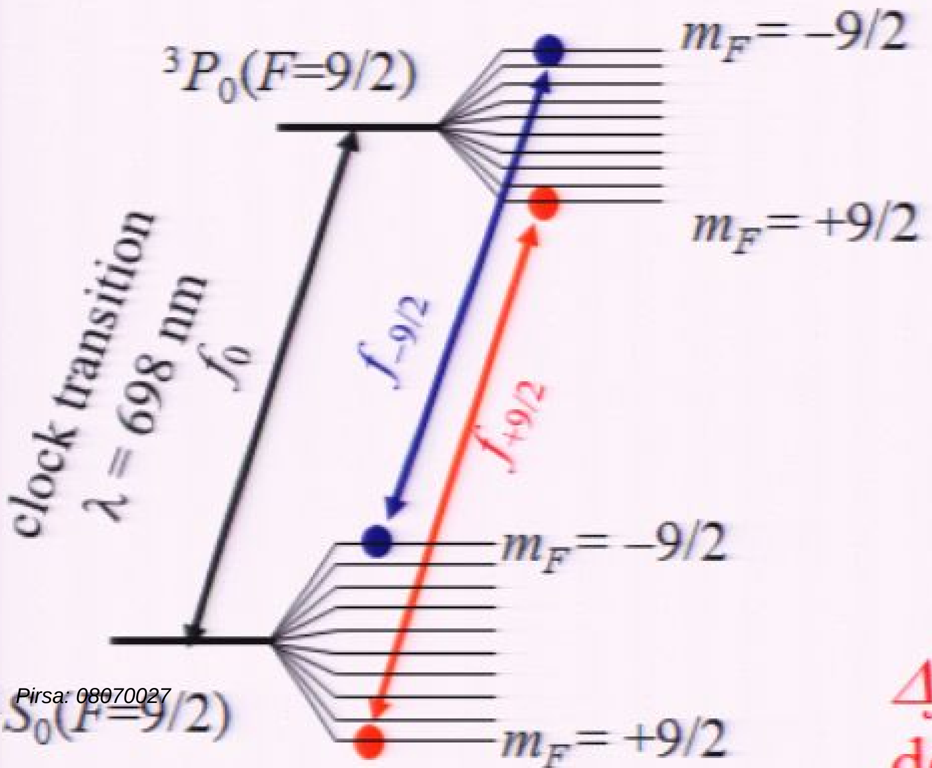
1) Static B_0 applied to define quantization axis in spin polarization
2) Effective B-field, δB_{vec} due to ellipticity of the lattice laser

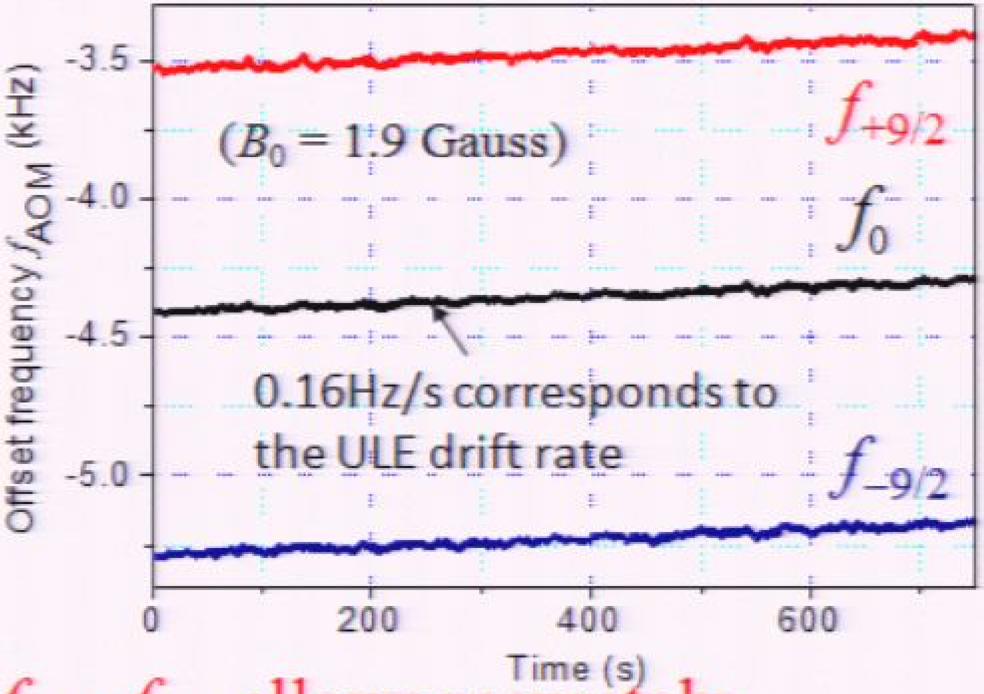
$$\delta f_m \propto m B_{\mathrm{eff}} \quad (B_{\mathrm{eff}} = B_0 + \delta B_{\mathrm{vec}})$$ ← Linear shift

$$f_0 = \frac{f_{+9/2} + f_{-9/2}}{2}$$

Virtual "spin-0" atom simulated!

Takamoto, et al., J. Phys. Soc. Jpn. 75, 104302 (2006).





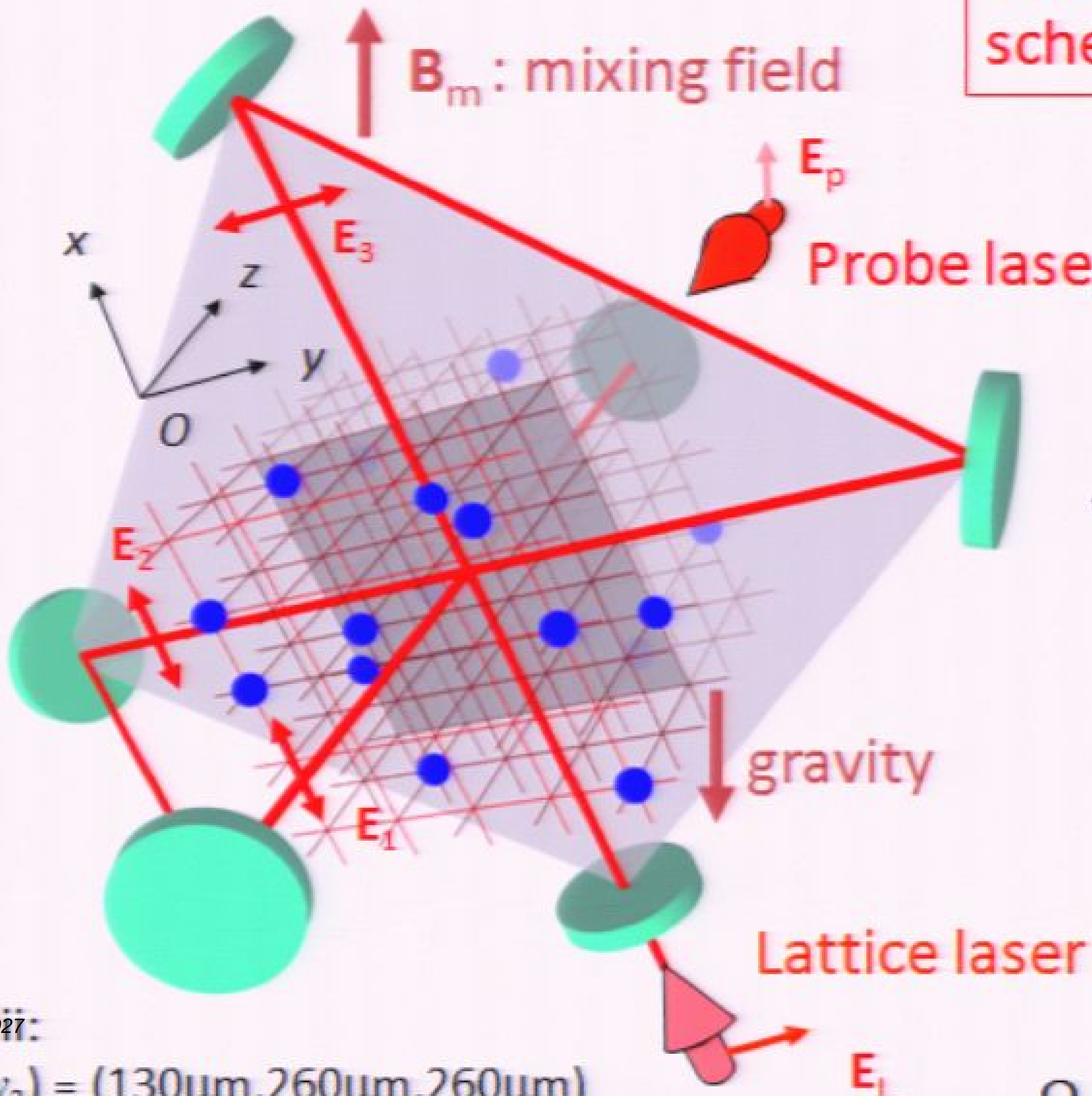
0.16Hz/s corresponds to the ULE drift rate

$\Delta f = f_{+9/2} - f_{-9/2}$ allows accurately determining the 2nd order Zeeman shifts

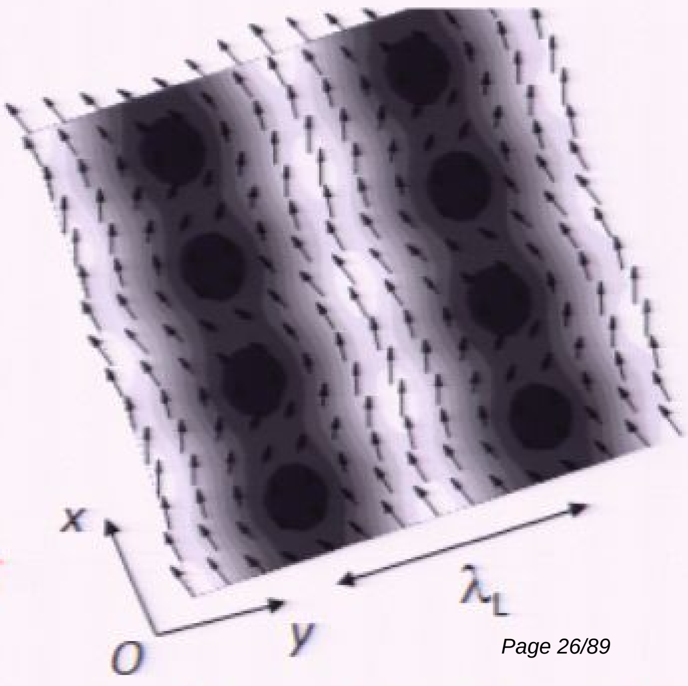
3D lattice clock

- Single-occupancy trap: free from collision shift
- Spatial rotation of light polarization/local elliptical polarization

Vector-shift cancellation scheme for *F*≠0 is inapplicable



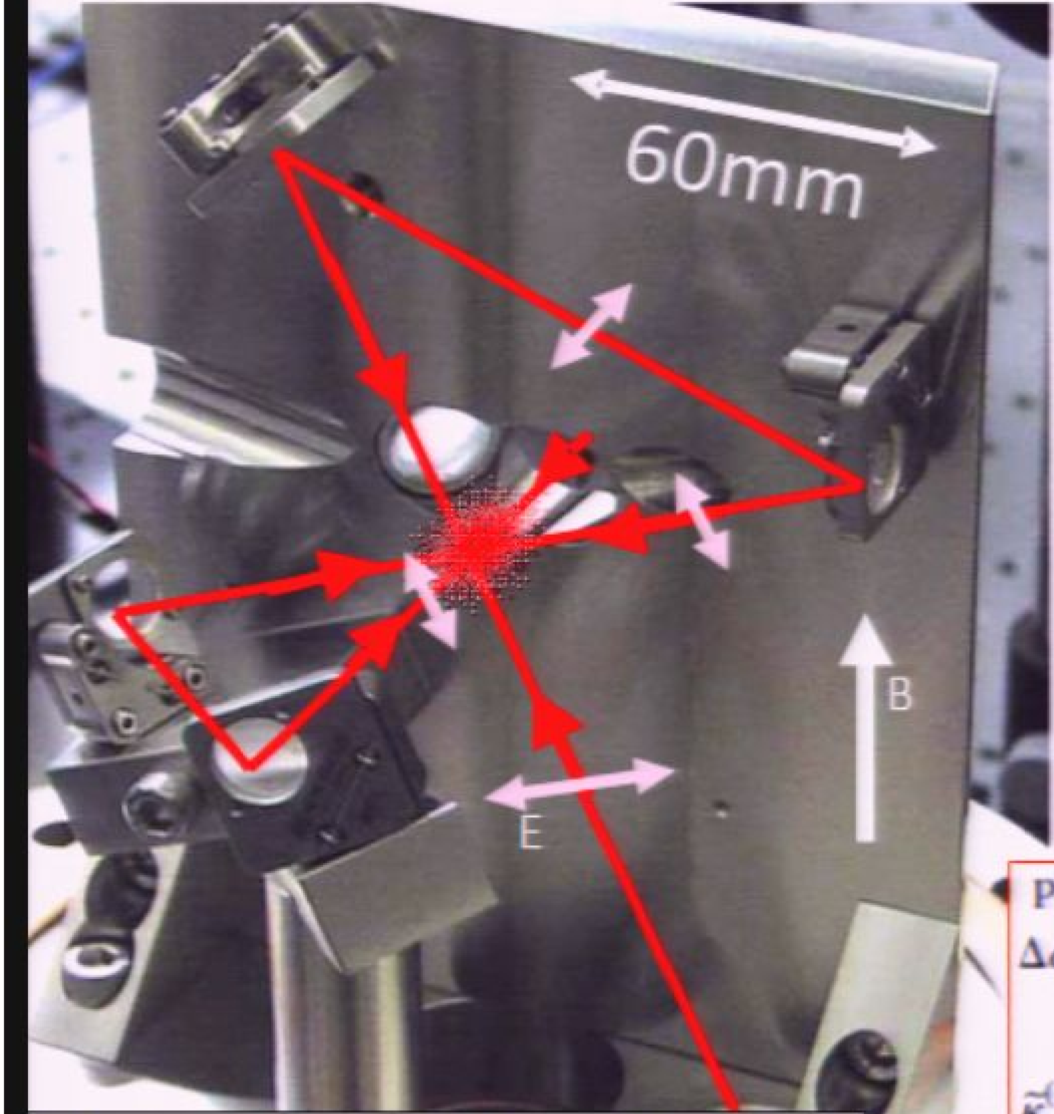
E-field vector



/e² radii:

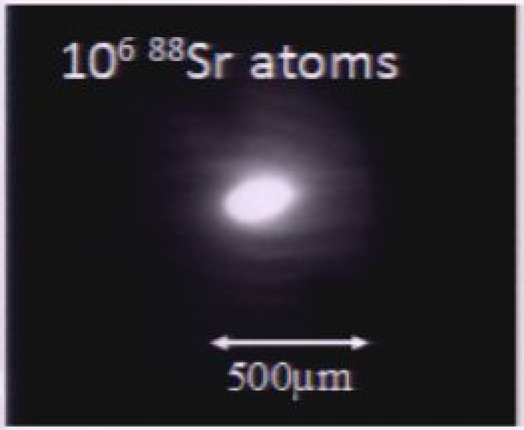
$w_1,w_2,w_3) = (130\mu m,260\mu m,260\mu m)$

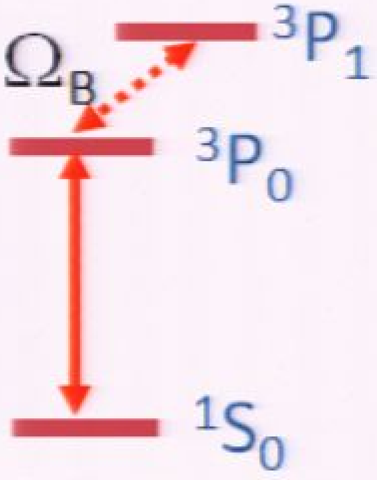
(2) 3D optical lattice clock with Bosonic ^{88}Sr



olume: 520µm × 520µm × 260µm
attice density: $7 \times 10^{12}/\mathrm{cm}^3$
of lattice sites: 6×10^7
ower enhancement: 17

$^1S_0$-$^3P_0$ transition moment is induced by applied B-field, instead of nuclear spin (^{87}Sr):
Taichenachev et al., PRL 2006



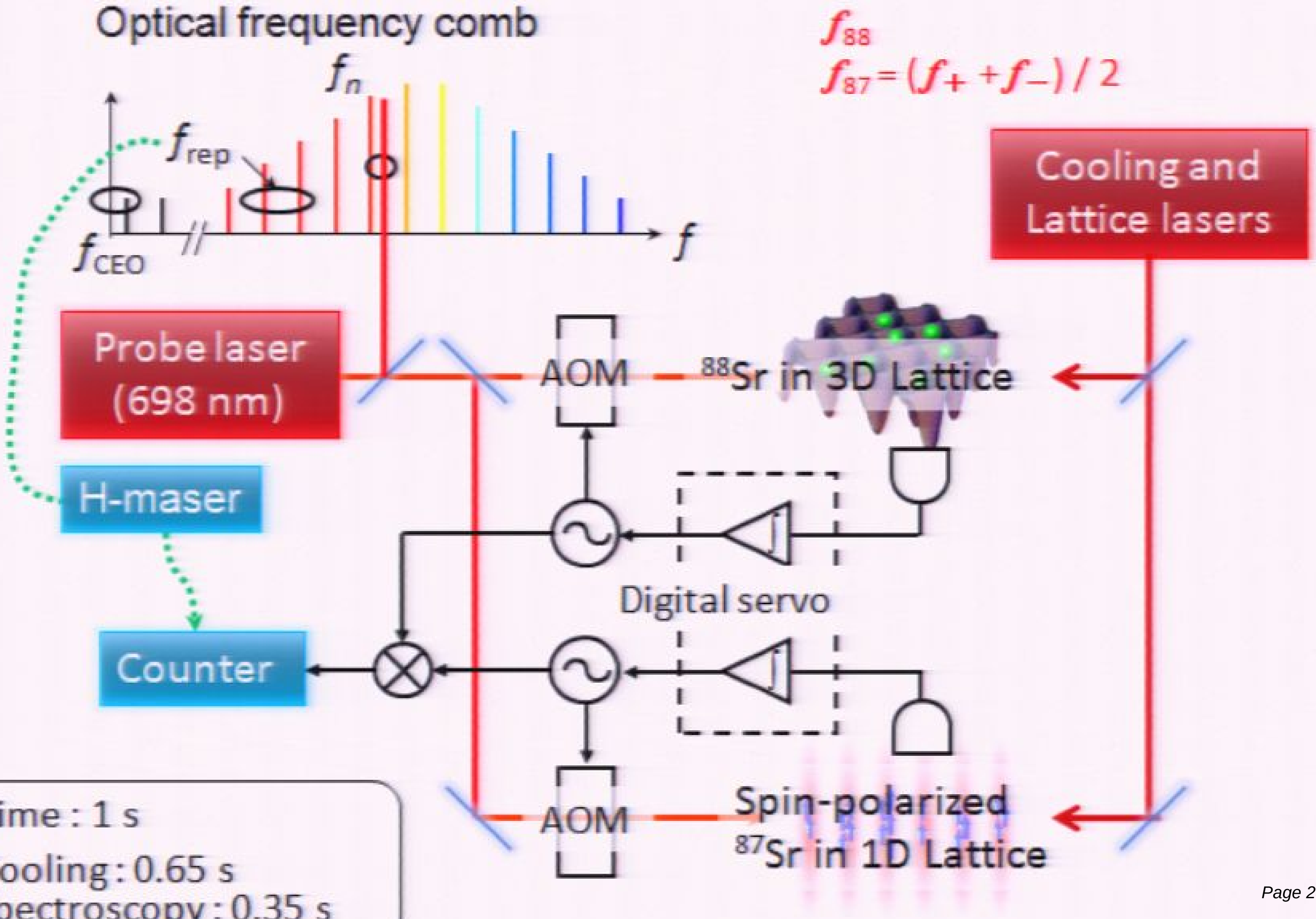


PHYSICAL REVIEW A **76**, 023806 (2007)

$$\Delta\omega \equiv \Delta\omega_e - \Delta\omega_g$$
$$= \{\tilde{\kappa}^{(0)}(\omega) + \tilde{\kappa}^{(1)}(\omega,\mathbf{e},\mathbf{b})B + \tilde{\kappa}^{(2)}(\omega,\mathbf{e},\mathbf{b})B^2 + \cdots\}|E|^2.$$
$$\tilde{\kappa}^{(1)}(\omega,\mathbf{e},\mathbf{b}) = \tilde{\xi}(\omega)\sin(2\varepsilon)(\mathbf{n}_e \cdot \mathbf{b})$$

All E-vectors on the B-plane to minimize E-B coupling

Frequency comparison between optical lattice clocks with "**non-interacting**" bosons and fermions

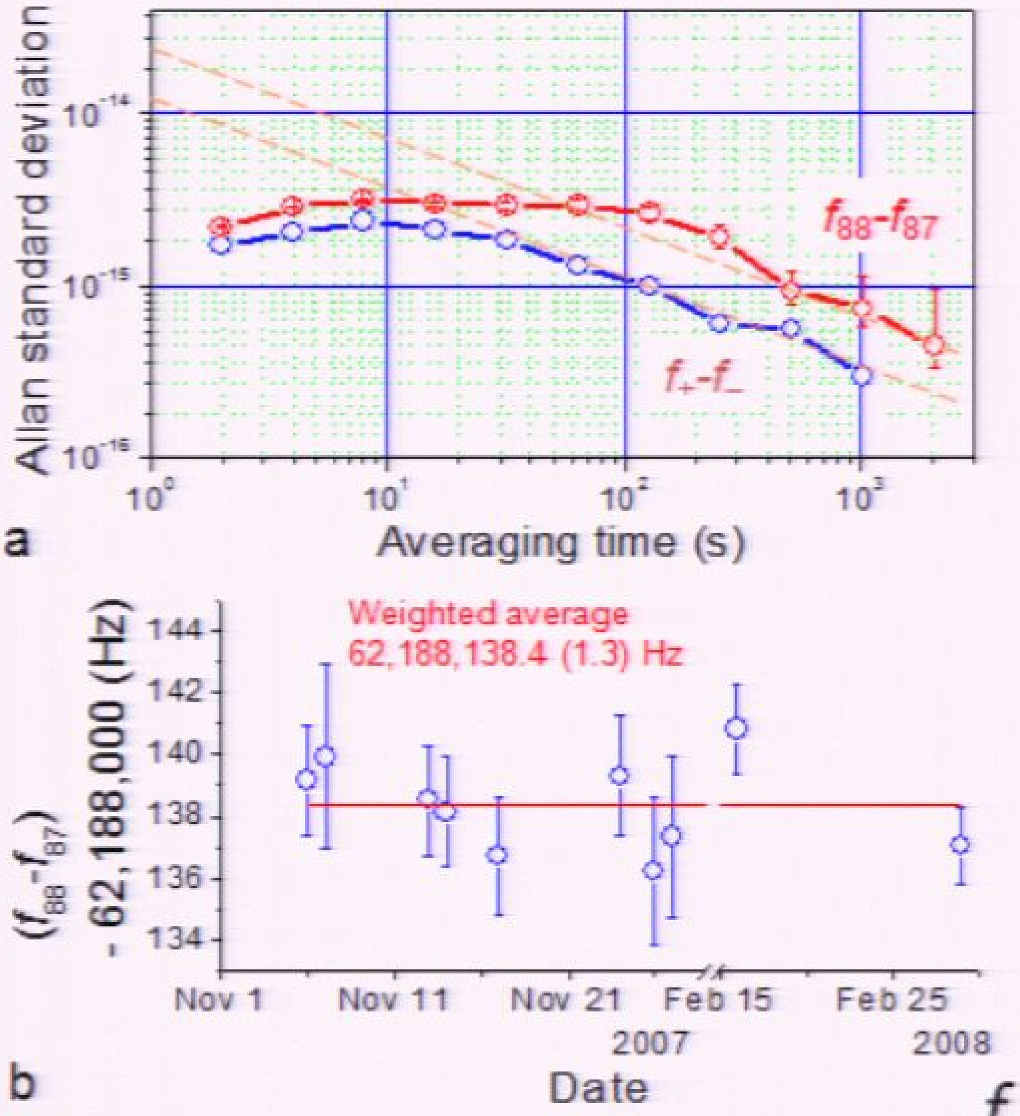


f_{88}

$f_{87} = (f_+ + f_-)/2$

Cyclic time : 1 s
- Cooling : 0.65 s
- Spectroscopy : 0.35 s

Allan deviation and isotope shift of ^{87}Sr/^{88}Sr clocks



f_{88}

$f_{87} = (f_+ + f_-)/2$

Ref: 62,188,134.4 (32) Hz with 1D lattice
X. Baillard et.al, Opt. Lett. 32,1812 (2007)

$$f_{88} - f_{87} = 62{,}188{,}138.4(1.3)\ \text{Hz}$$

$$f_{88}/f_{87} = 1.000000144883693(3$$

Akatsuka, M. Takamoto, & H.K. submitted

Uncertainty budgets for ^{87}Sr and ^{88}Sr optical lattice clocks

	^{87}Sr	^{88}Sr
Contributor	Correction (Uncertainty) (Hz)	Correction (Uncertainty) (Hz)
Lattice scalar light shift §	-0.22 (0.33)	-0.23 (1.09)
Lattice vector light shift	0 (0.01)	0 (0.014)*
Lattice 4th-order light shift §	-0.017 (0.015)	-0.12 (0.10)
Probe light shift	0.03 (0.001)	7.48 (0.36)
Blackbody shift ¶	2.4 (0.2)	2.4 (0.2)
2nd-rder Zeeman shift	0.772 (0.01)	128.61 (0.31)
Collision shift	0.4 (0.3)	-0.034 (0.3)
Systematic total	3.37 (0.49)	138.11 (1.25)
Isotope shift f_{88}-f_{87}	62,188,138.4 (1.3) Hz	

$f_m(^{88}\mathrm{Sr}) - f_m(^{87}\mathrm{Sr}$
$= -100(100)$ MH

$7(6)\ \mu\mathrm{H}/E_r^2$

T = 301(5) K

Larger correction
For bosonic clock

Collision shift appears?

Even though spin-polarized sample is prepared, excitation process is not necessarily in phase! S-P collisions may exist

Connection to variation of constants?

- Naïve idea:
  - Isotope shift can be measured far more accurately for two bosonic isotopes as perturbations cancels out
  - Isotope shift ~ Mass shift
  - Reduced mass: $\mu = \dfrac{m(AM)}{(AM)+m}$; $\left[\begin{array}{c} m : \text{mass of electron} \\ AM : \text{mass of nucleus} \end{array}\right]$
  - Isotope shift:

$$\Delta_{88-86} = \frac{m(M_{88} - M_{86})}{M_{88}(M_{86} + m)} \nu_{88}$$

^{88}Sr-^{86}Sr dual clock

$$\approx 2.6 \times 10^{-4} \frac{m}{M} \cdot 0.43 \times 10^{15} \text{ (Hz)}$$

$$\approx \frac{m}{M} \times 10^{11} \text{(Hz)} \sim 10^{8} \text{(Hz)} \quad M \approx m_p \approx m_n$$

$$\frac{\delta(M/m)}{M/m} = -\frac{\delta\Delta_{88-86}}{\Delta_{88-86}} \approx \frac{10^{-3}\text{(Hz)}}{10^{8}\text{(Hz)}} = 10^{-11}$$

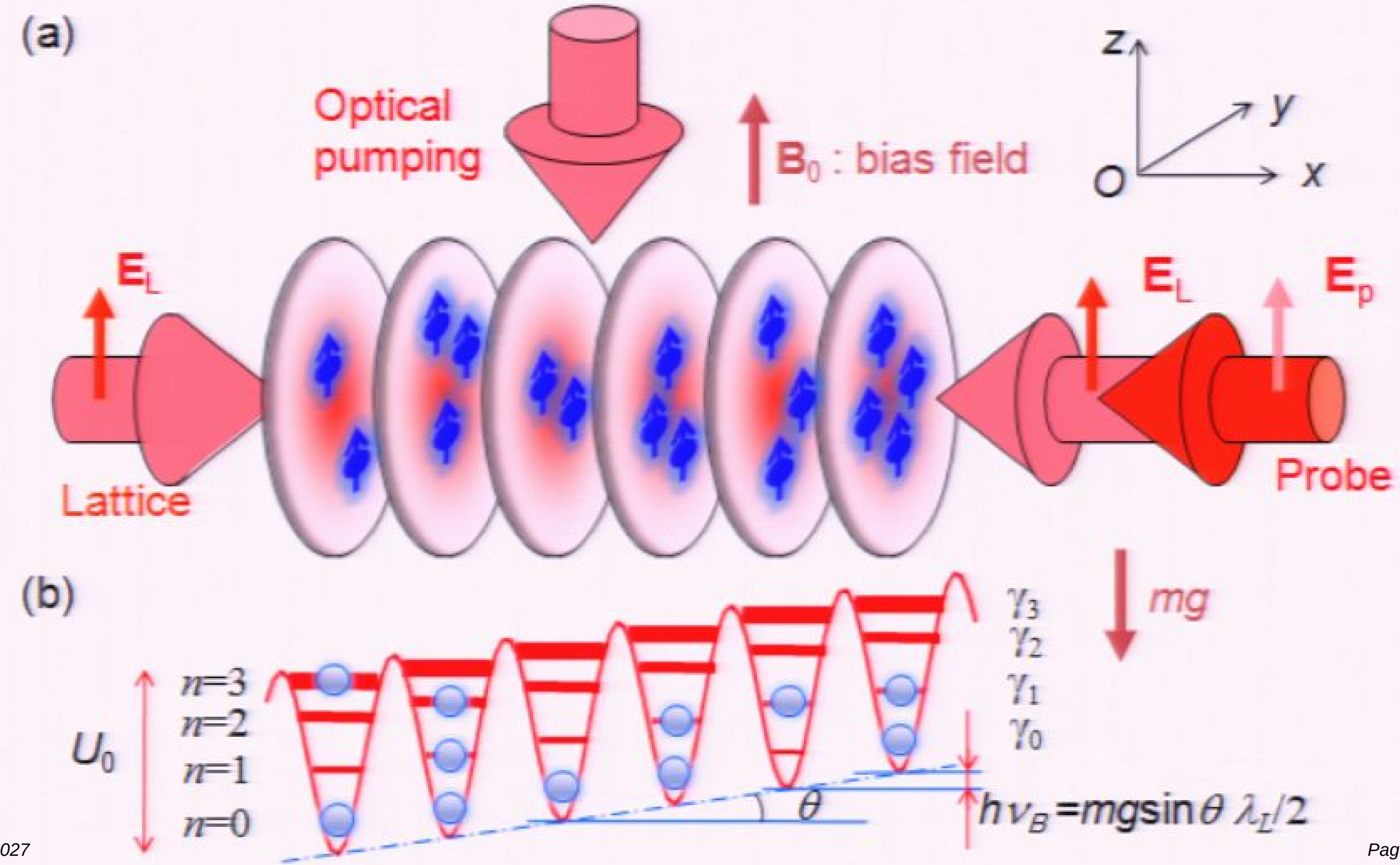
May be not very attractive

Remaining problems/Future investigation

- Pauli blocking of collision shift
  - Coherence in excitation of fermionic system
  - Tunneling bandwidth/vibrational states
- Higher order light shift
  - Blue-detuned magic wavelength, trap at antinodes
- Blackbody shift
  - Cryogenic lattice clock (in progress) 10mHz@77K
- Remote frequency measurement
  - Optical fiber link between Tsukuba-Tokyo
- Explore new atomic elements
  - May solve above problems
  - Optical clocks frequency comparison
  - Test constancy of constant; Hg vs Sr

(1) Coherence and Rabi Oscillations of Spin-Polarized Fermions in an Optical Lattice:

— What prevent us from coherent excitation? —

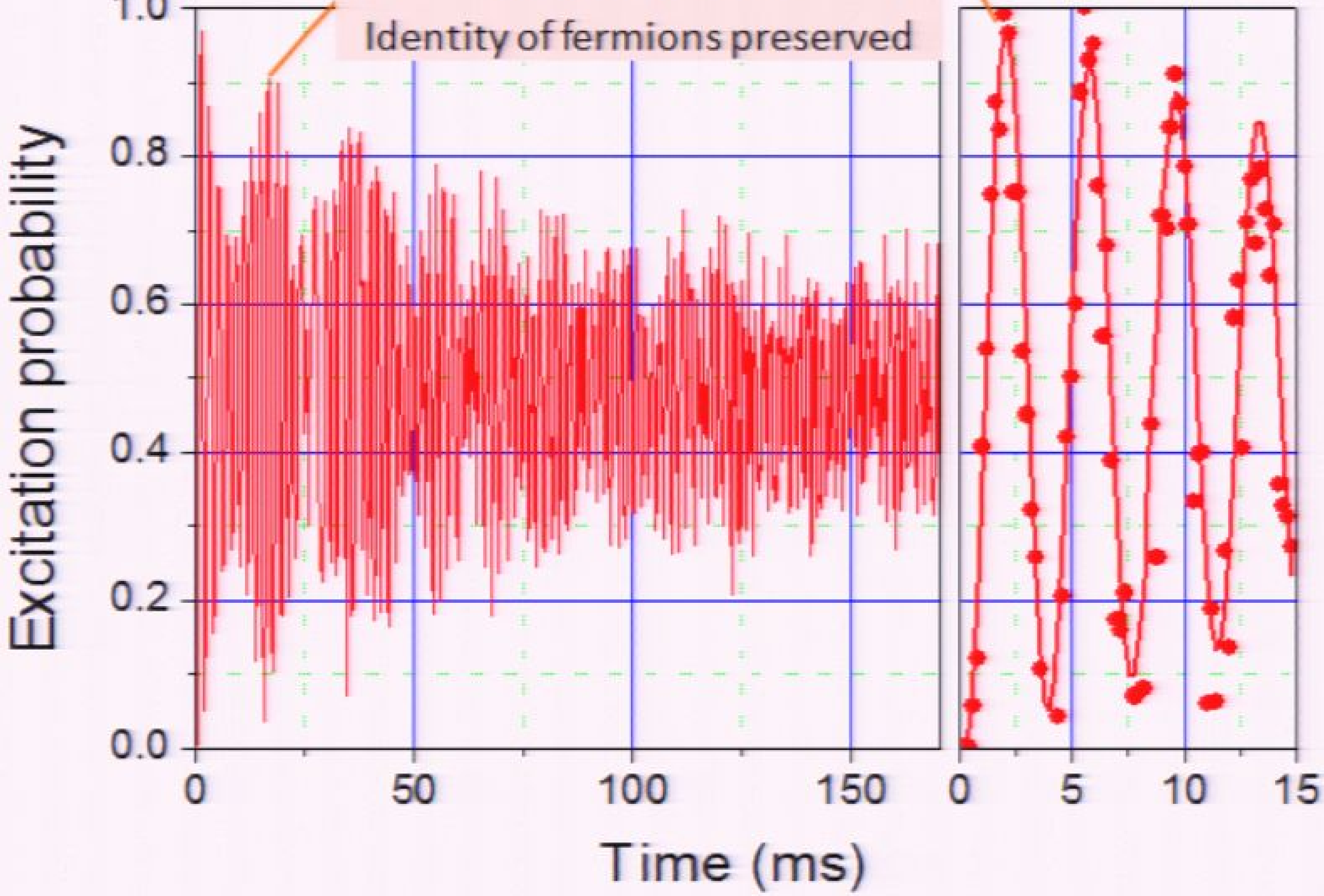


Rabi oscillations as a probe for vibrational state occupation and tunneling

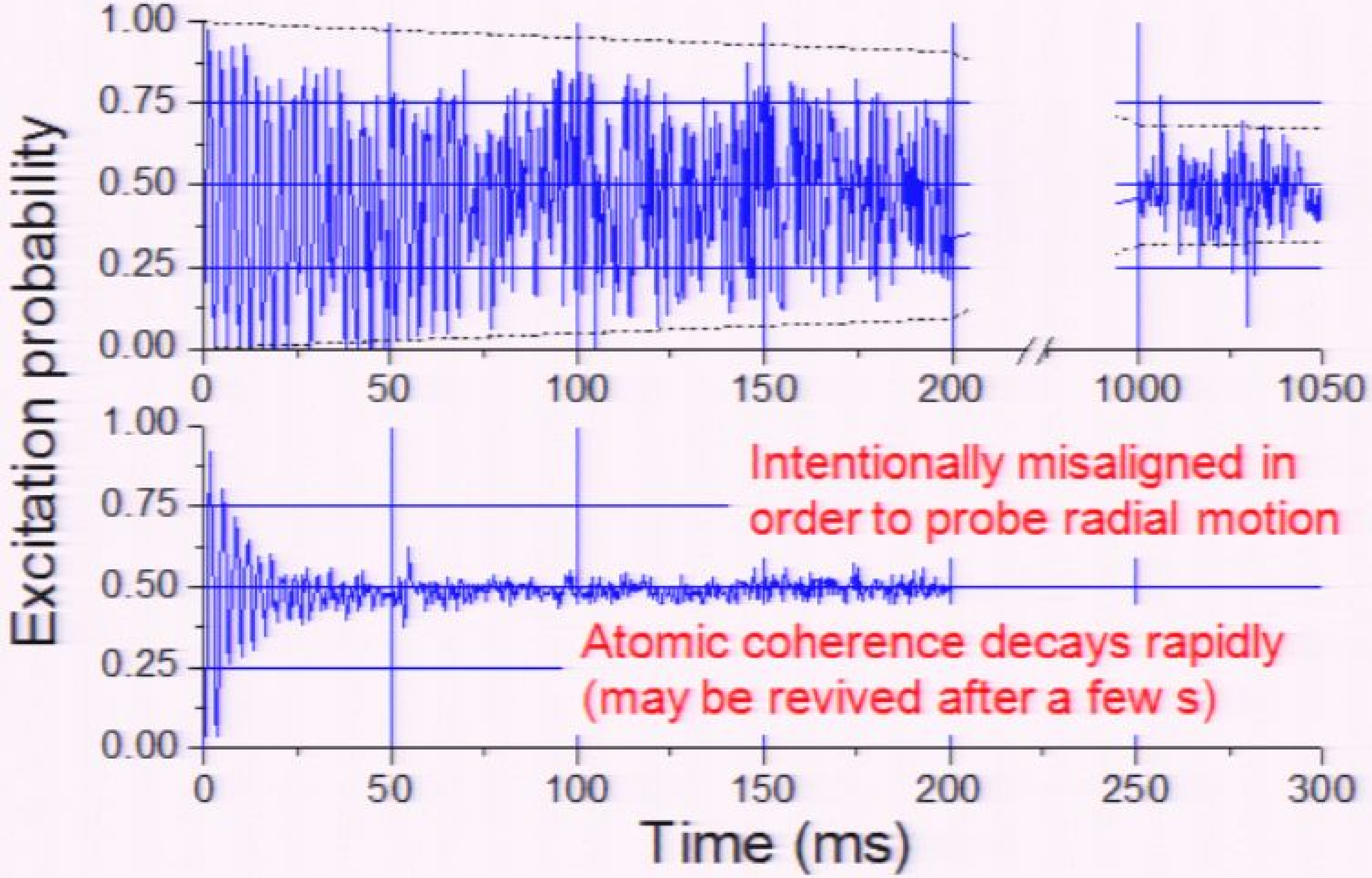
$$\Omega_{n,n} = \Omega_0 \prod_{j=x,y,z} |\langle n_j|\exp(ik_j j)|n_j\rangle|,$$

Collapses and Revivals
Interference of n=0&n=1 component

Excitation>99%:
Identity of fermions preserved



Long lived population oscillation over 1s; Even longer than laser coherence time



Intentionally misaligned in order to probe radial motion

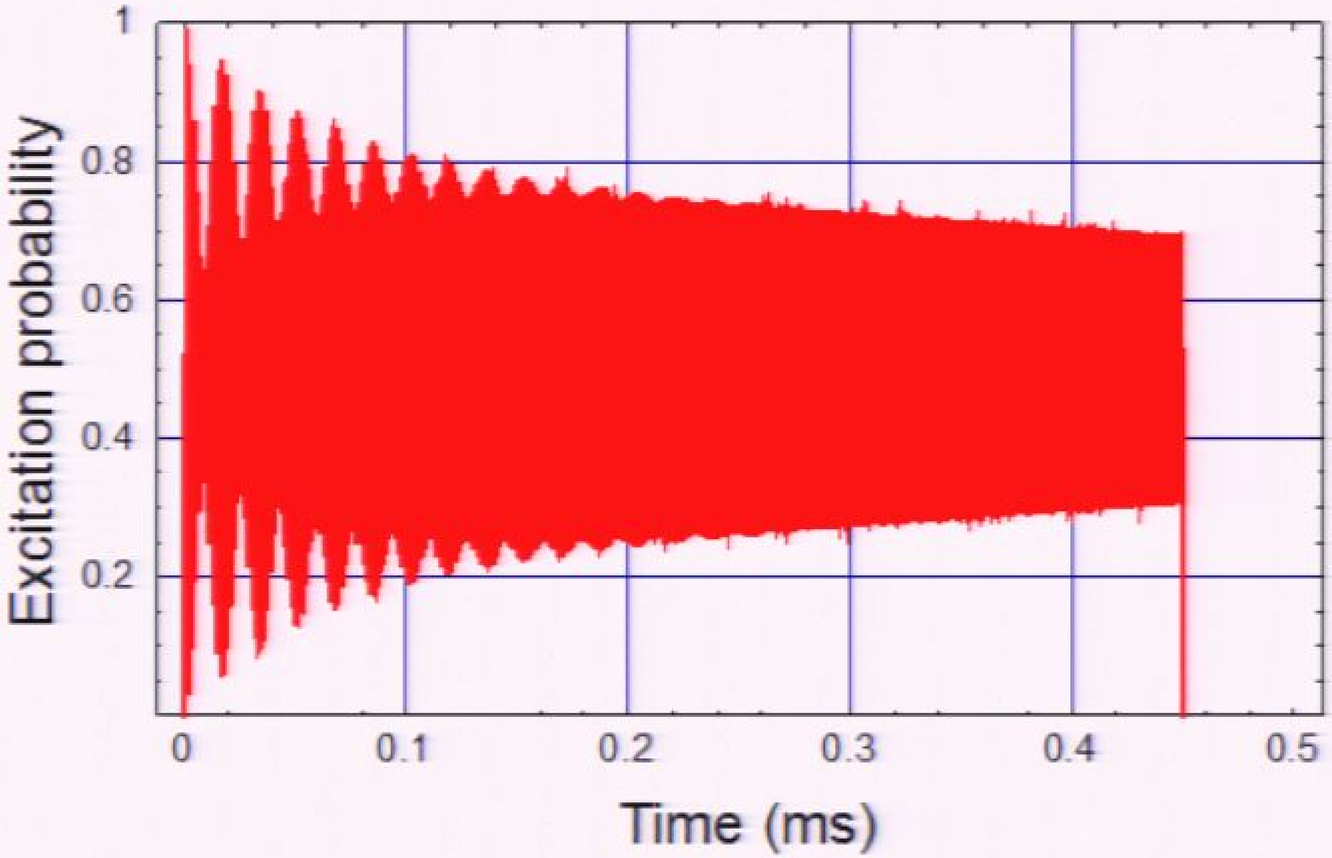
Atomic coherence decays rapidly (may be revived after a few s)

Very long atomic coherence limited residual gas collisions & lattice photon scattering: Presently~1 s (Future 10 s)

Pauli blocking collision will be feasible!

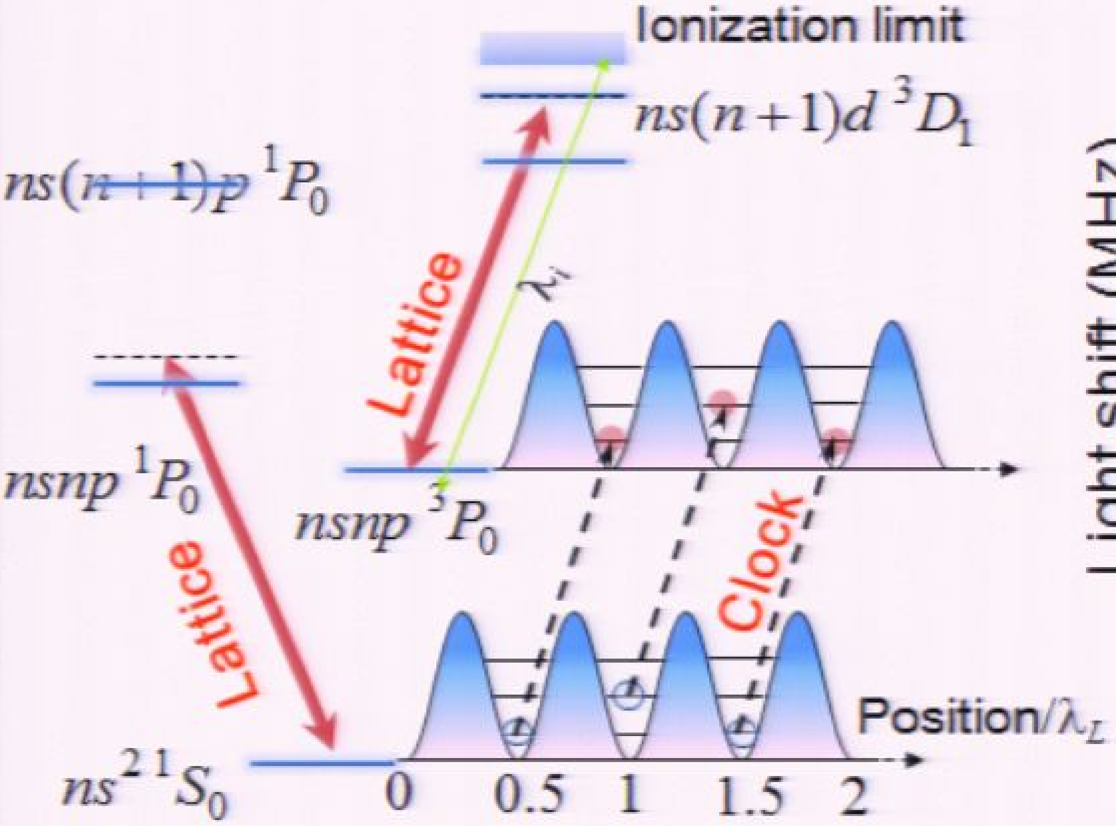
Simulation with optical Bloch equation

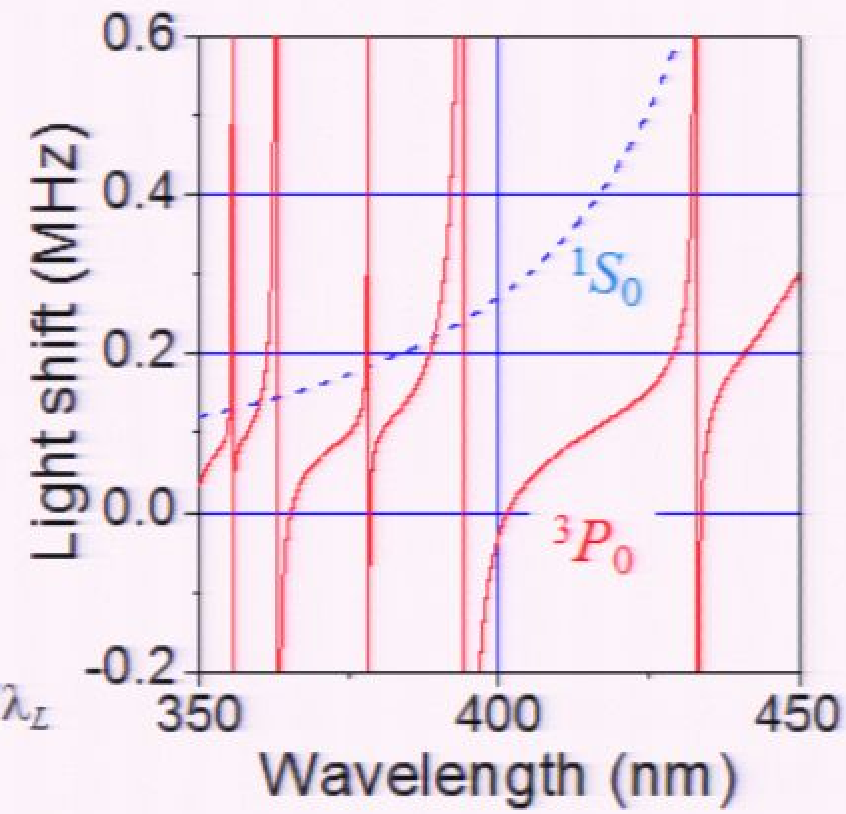
- Laser coherence limited atomic coherence
- Spread in *n* states causes collapses/revivals
- Tunneling bandwidth as Doppler shifts
- Suppression of tunneling by Wannier-Stark effects



(2) A magic wavelength for "blue-detuned" lattice

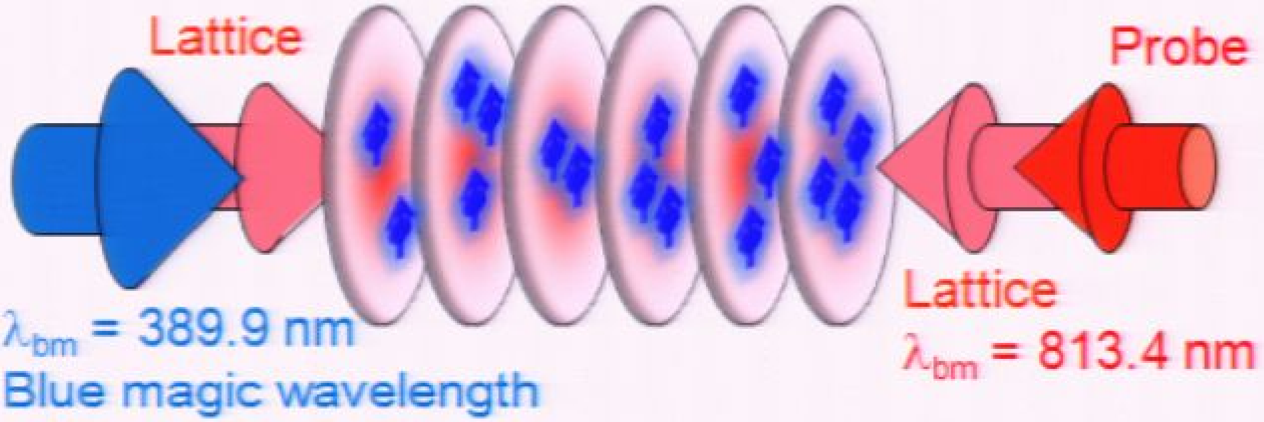
— confine Sr-atoms at the intensity minima as Paul trap —





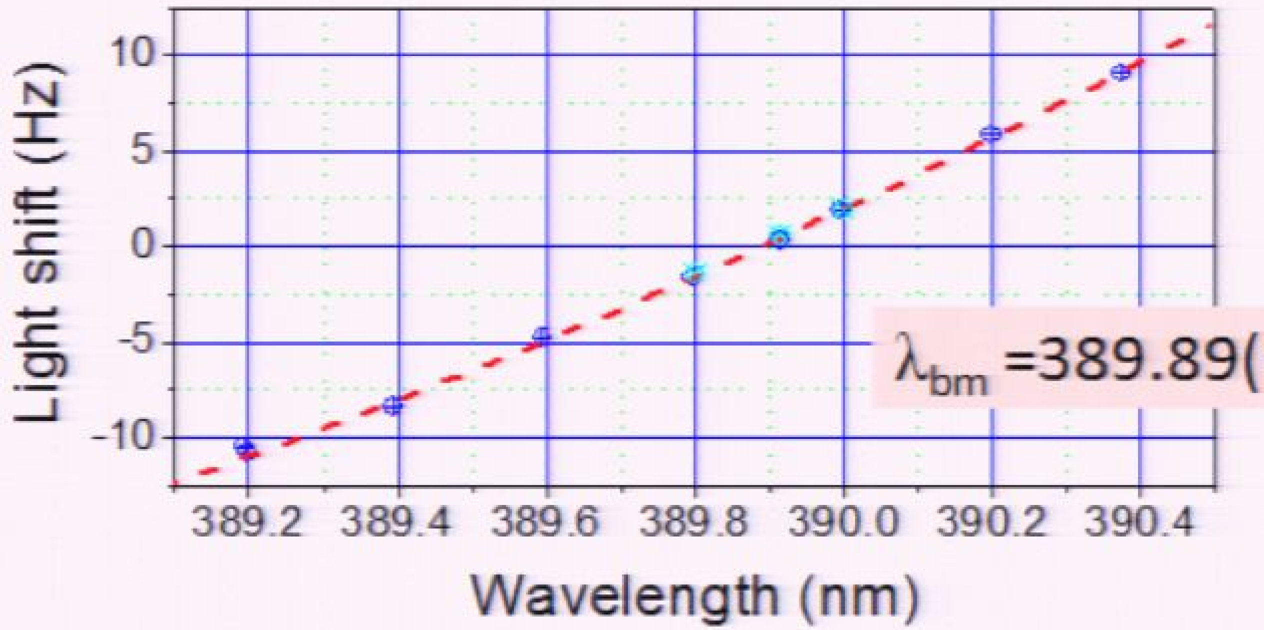
- Atoms see about 10% of maximum light intensity, or $1\,\mathrm{kW/cm^2}$
  - Reduced higher order effects $\sim I^2$
- Optical lattice with 390-nm-light
  - Better confinement; smaller Lamb-Dicke parameter
  - Influence of two photon ionization / hyperpolarizability?
  - Closer atomic separation (195 nm) → RDDI with 3 mm, useful in QIP

Experimental determination of the blue magic wavelength



λ_{bm} = 389.9 nm
Blue magic wavelength

λ_{bm} = 813.4 nm



λ_{bm} =389.89(1) nm

$T=10\mu K$; 0.1× 10 kW/cm2, $\nu<10^{-2}/$

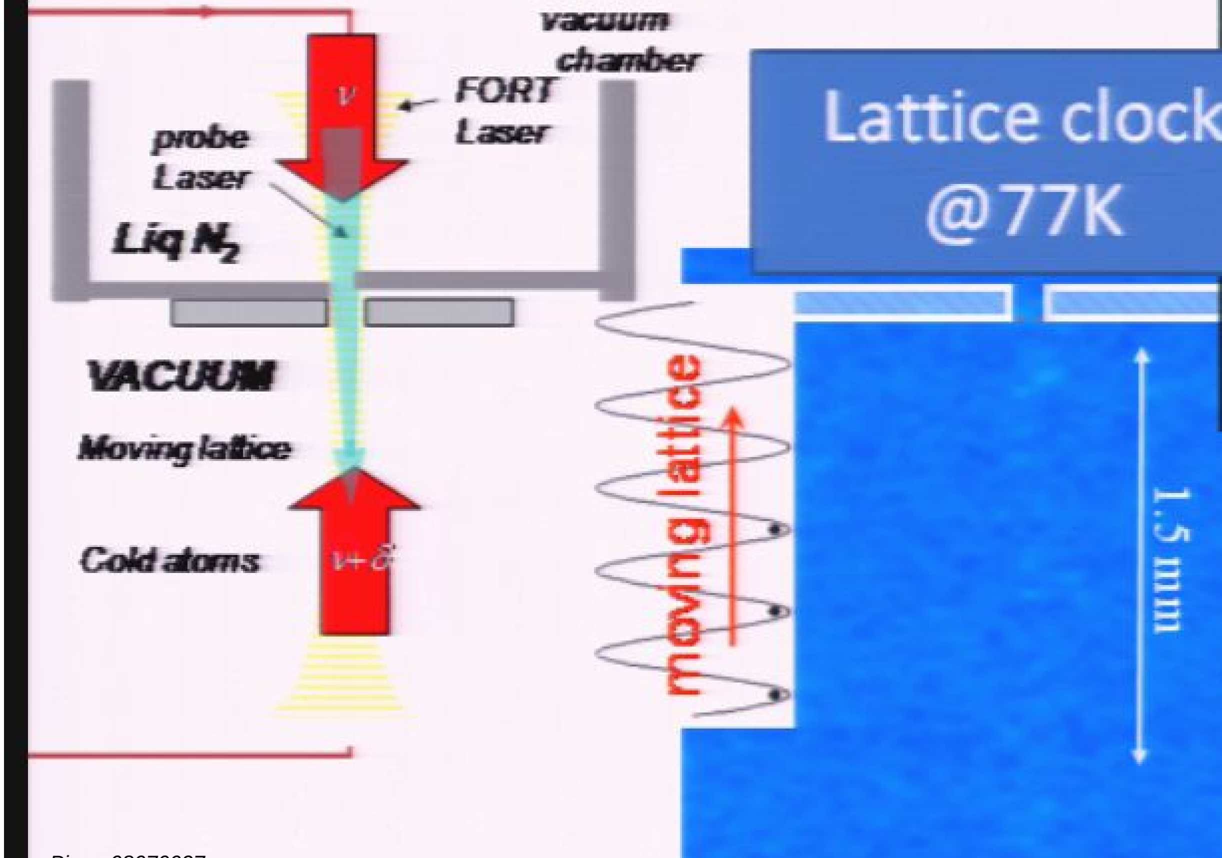
Cryogenic lattice clock

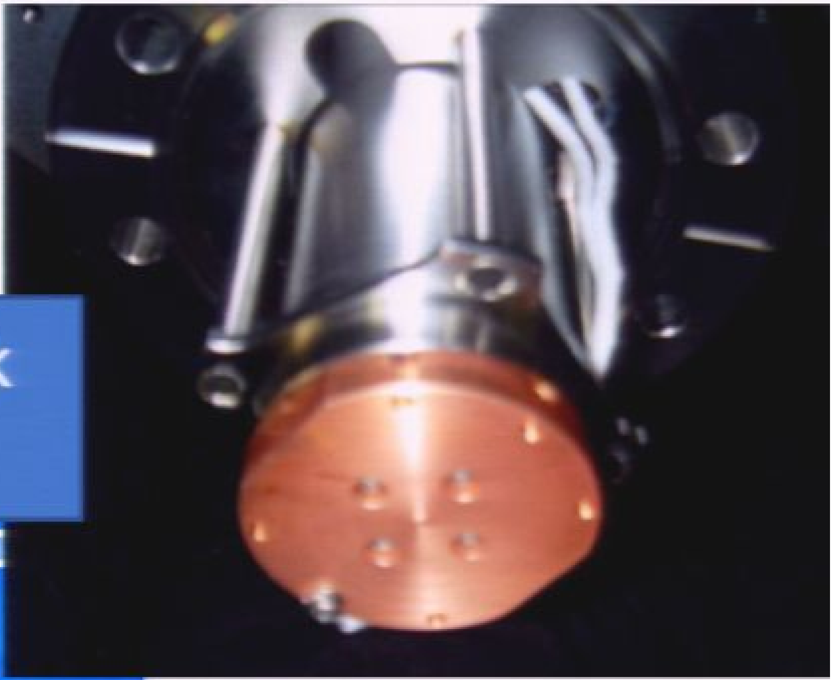
Black body shift rapidly decreases as temperature:

ν_{Sr}= 2.4 Hz x(T/300 K)^4

~ 10 mHz @ 77K

Lattice clock @77K





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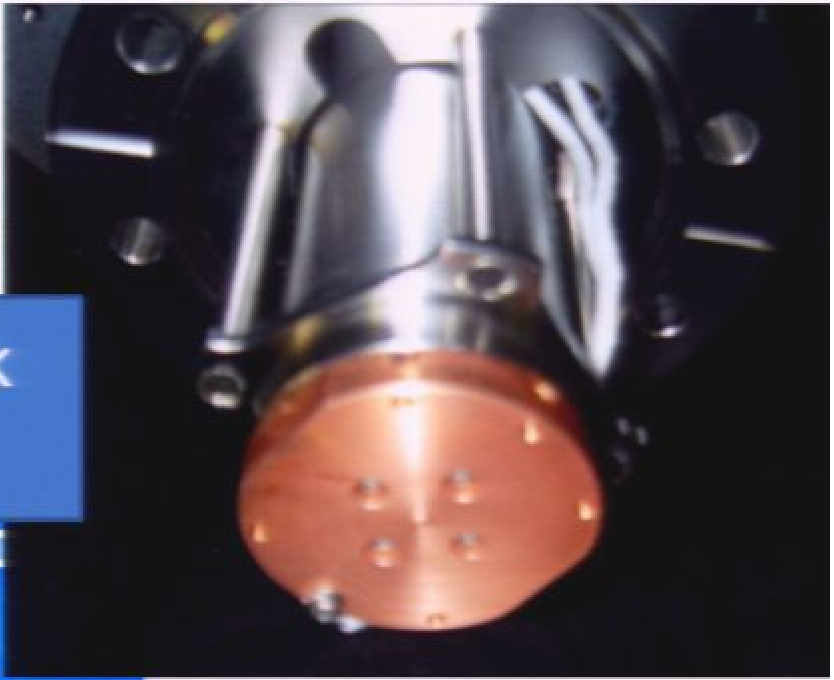

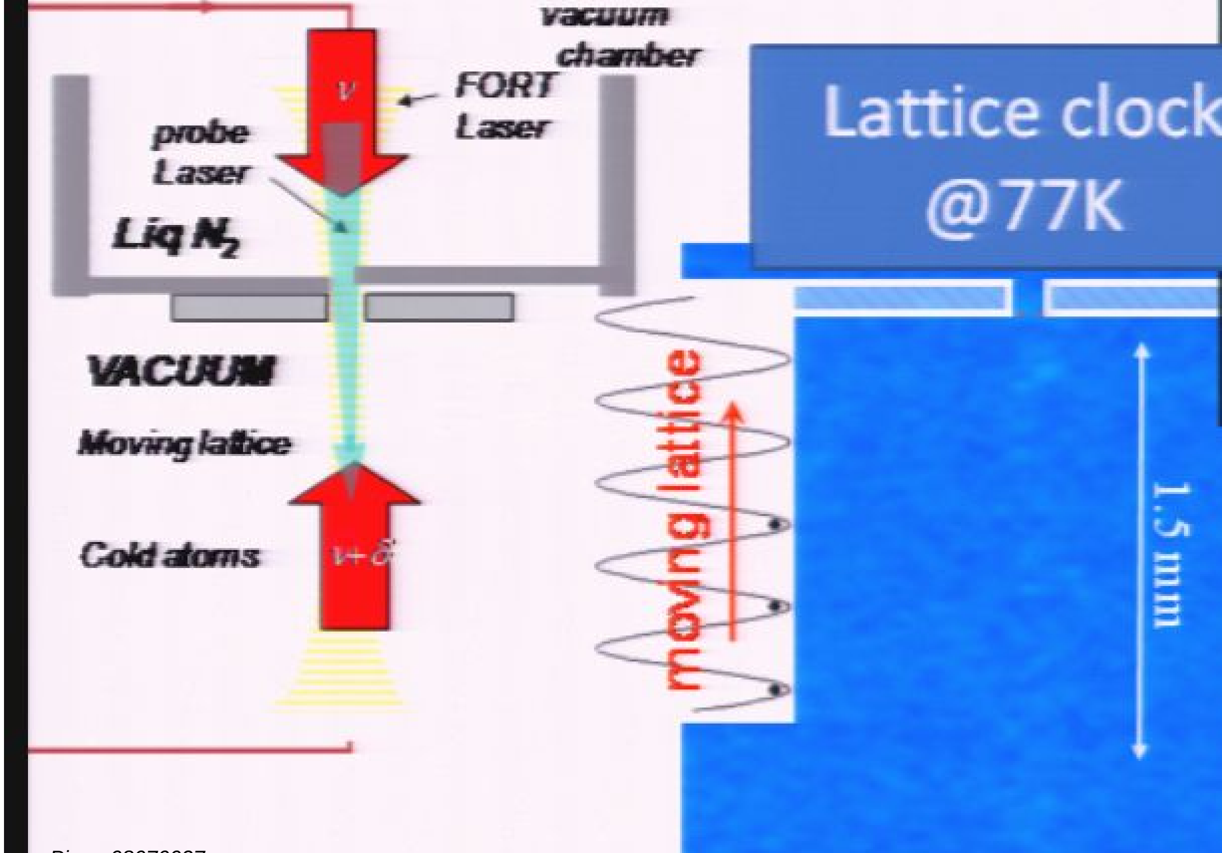

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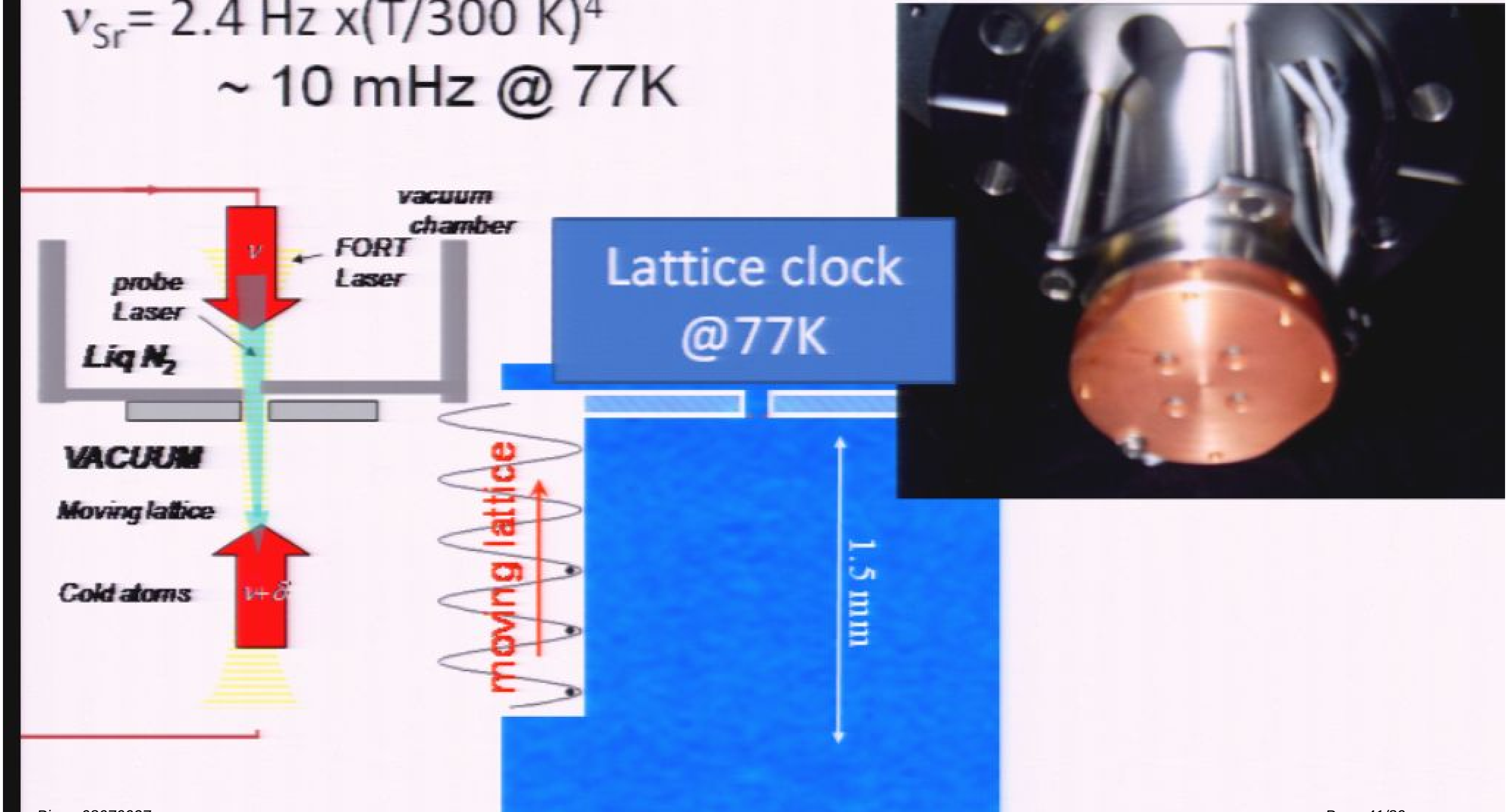

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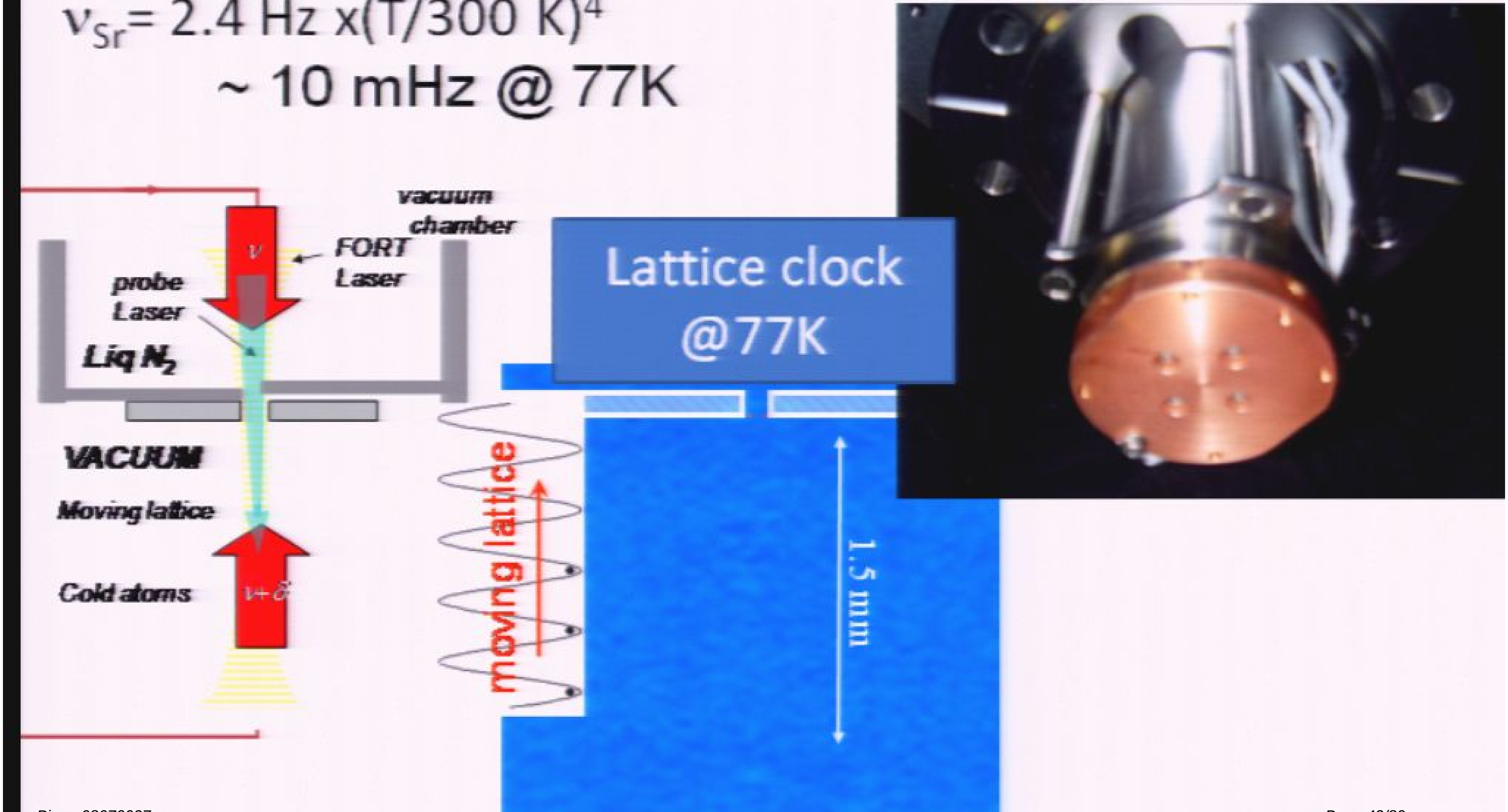

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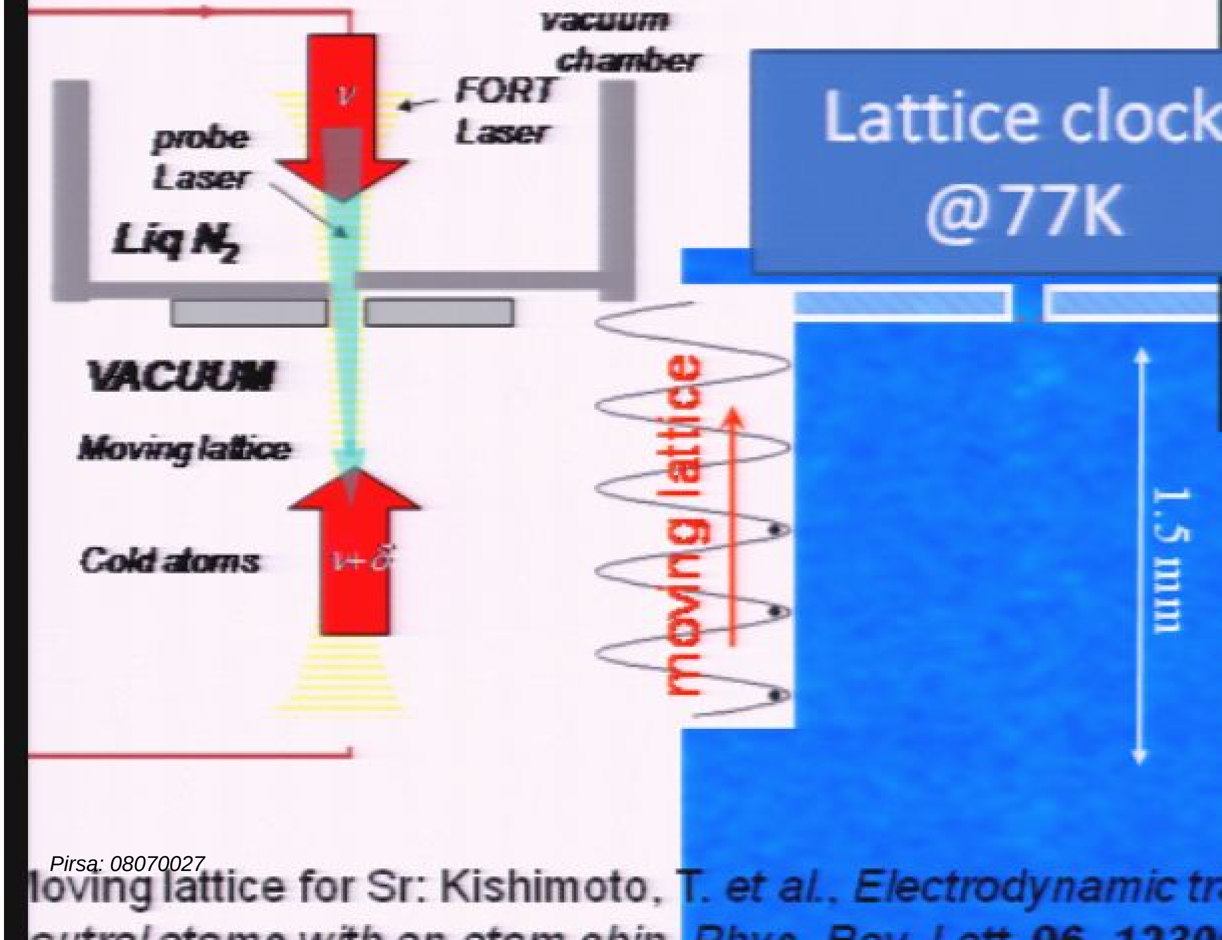

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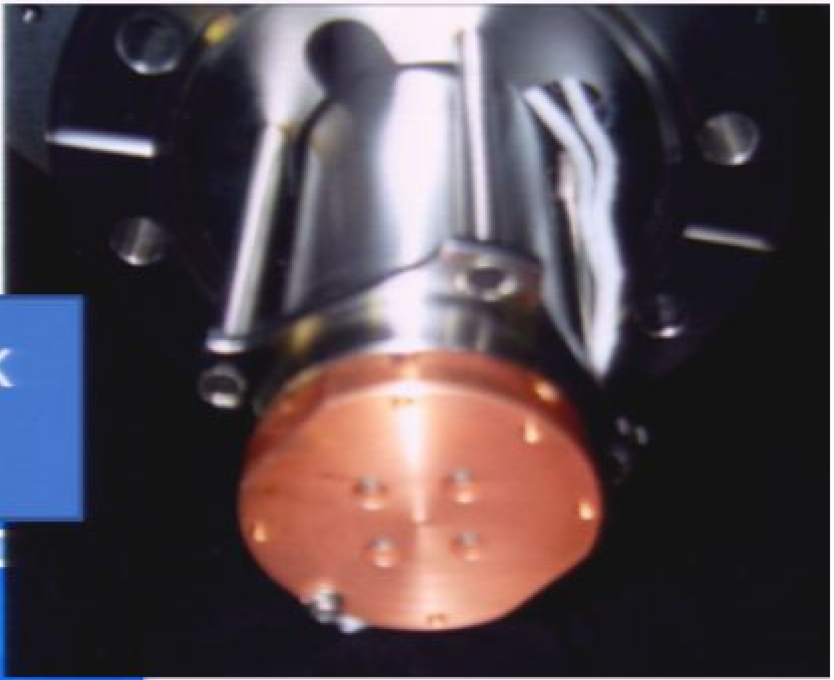

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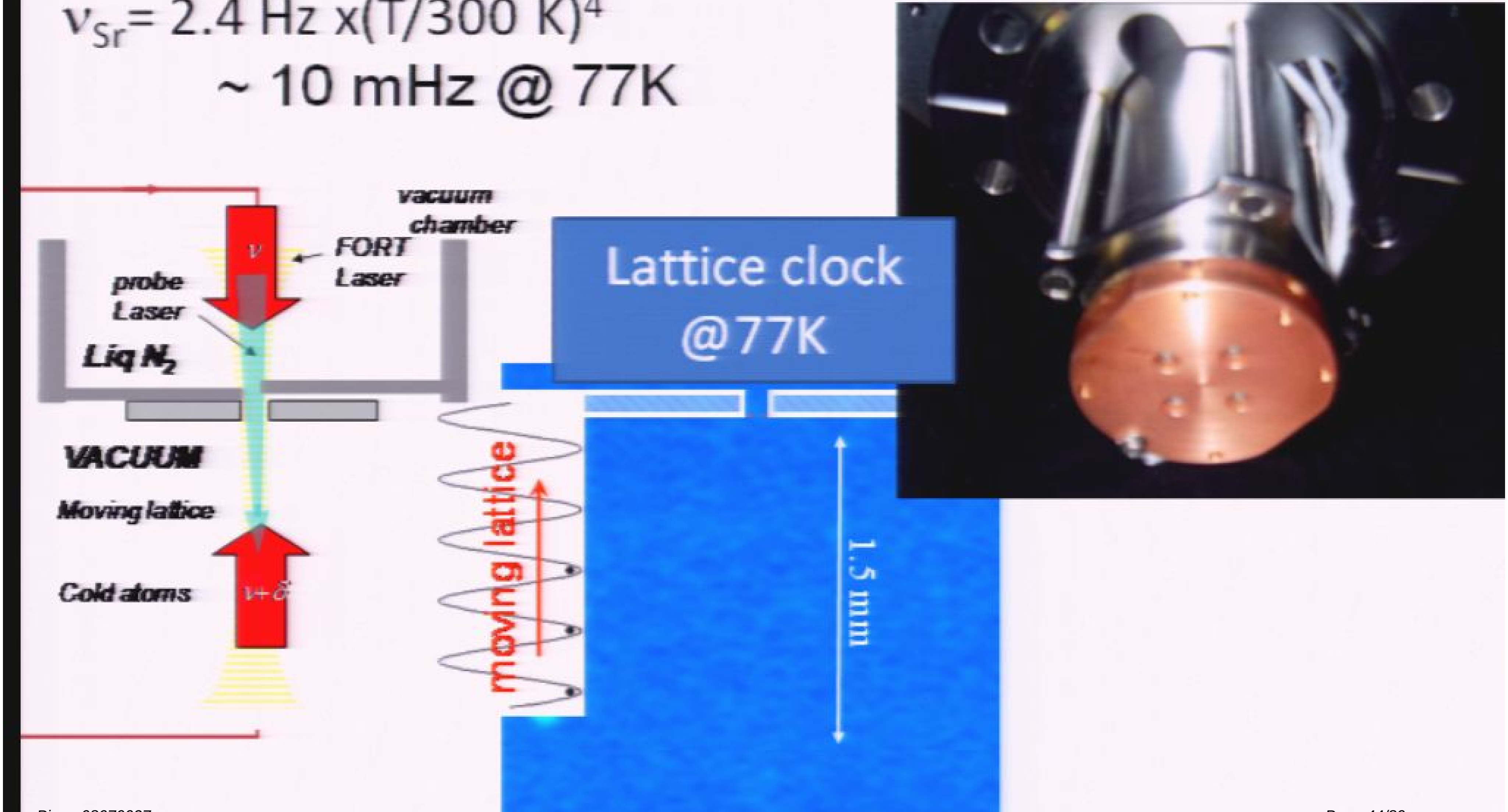

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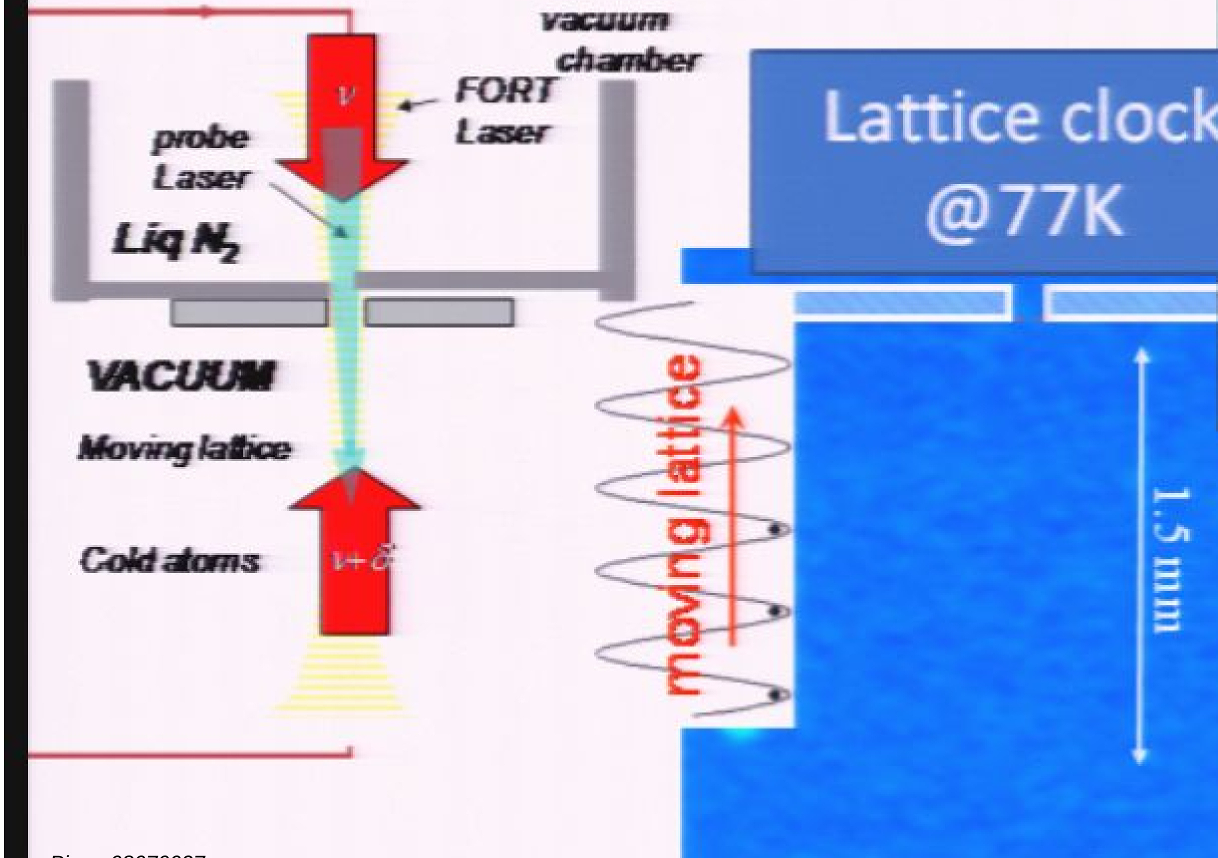

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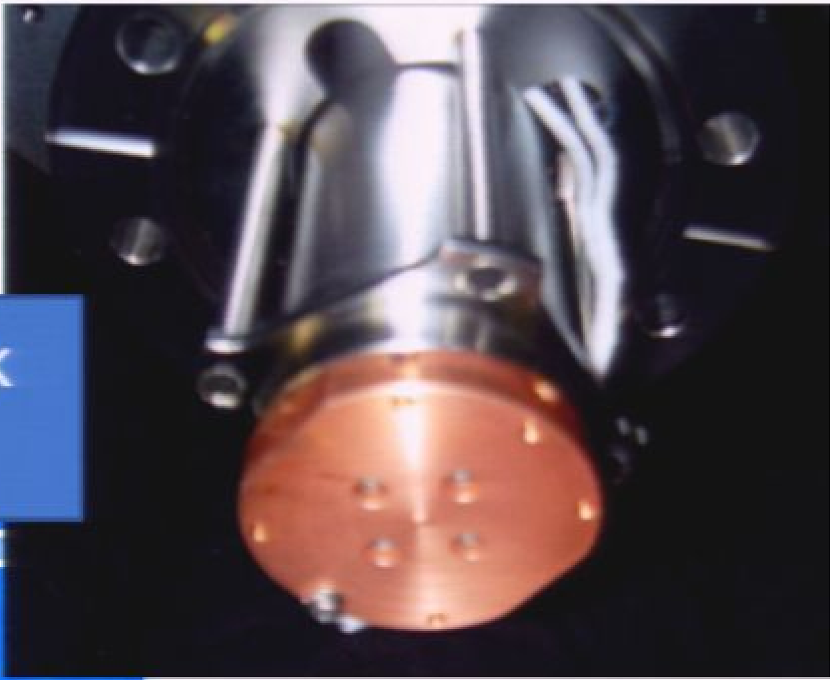

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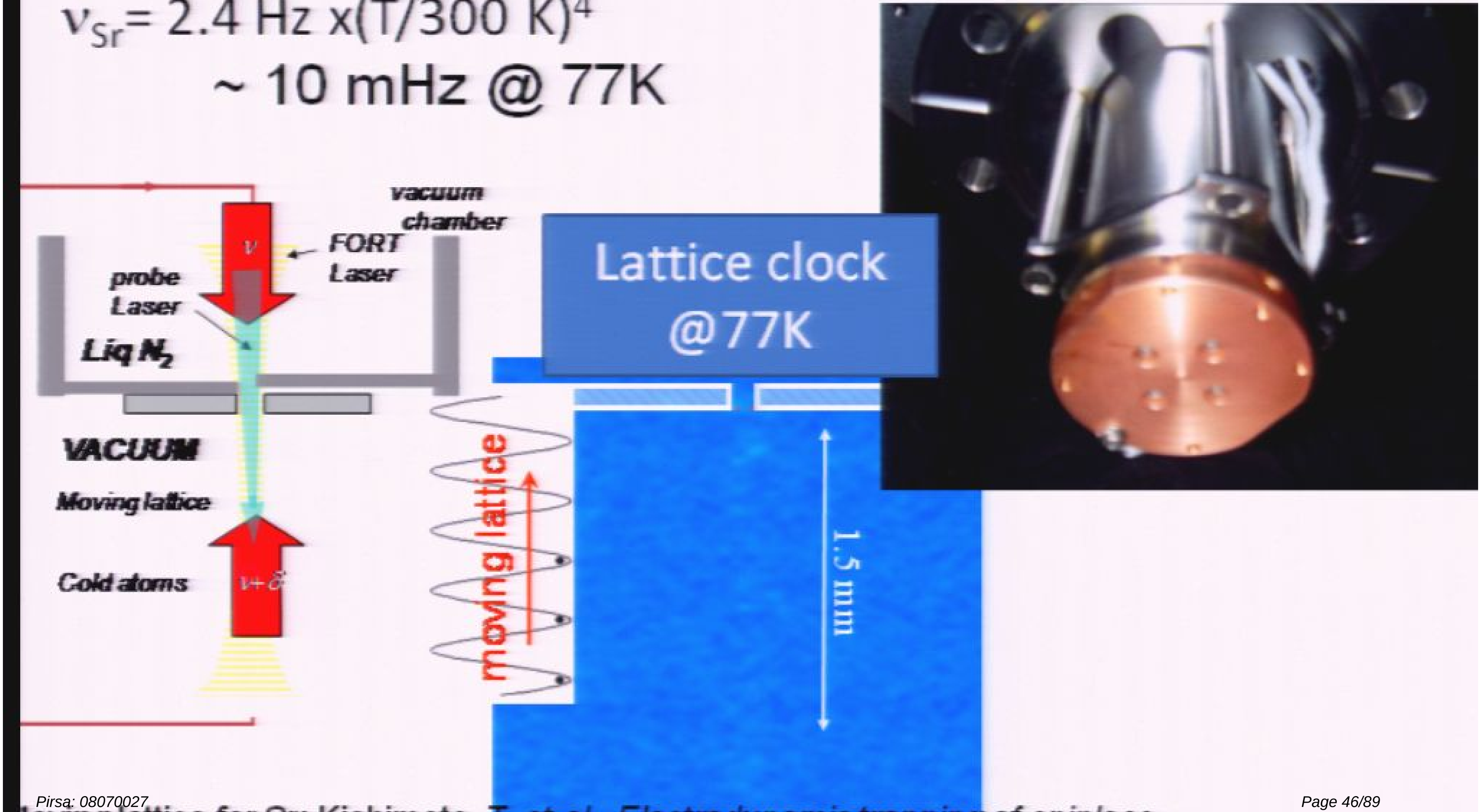

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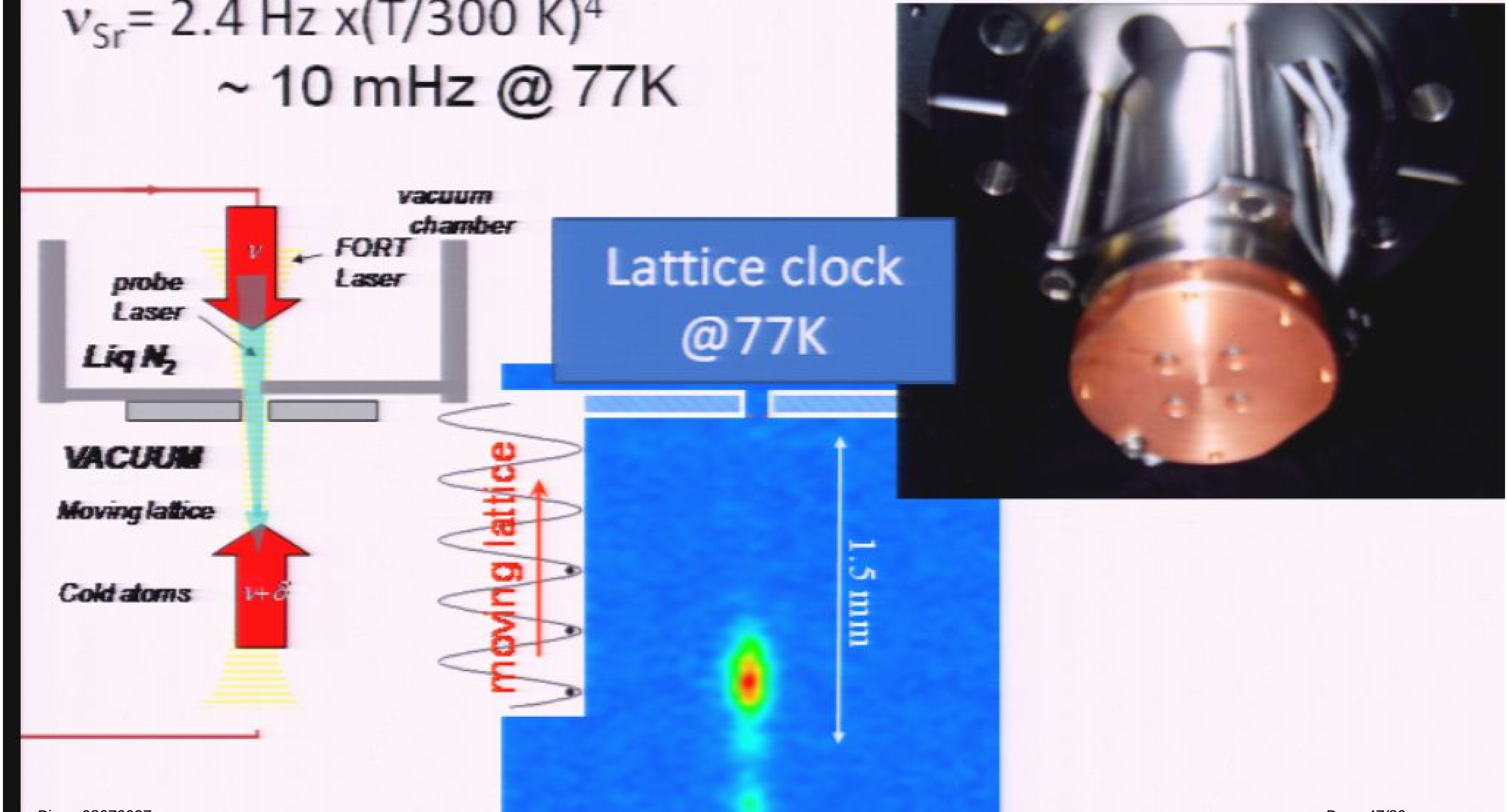

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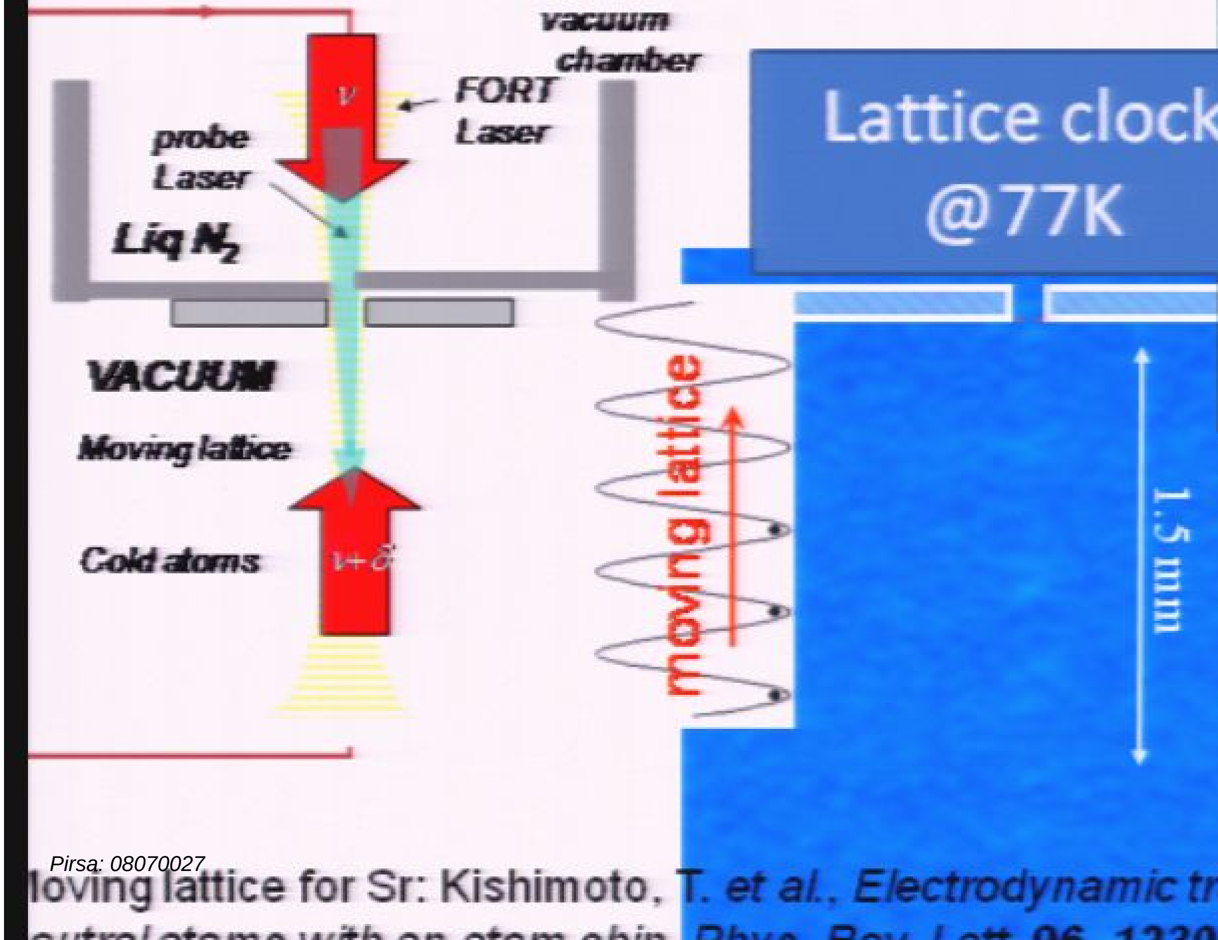

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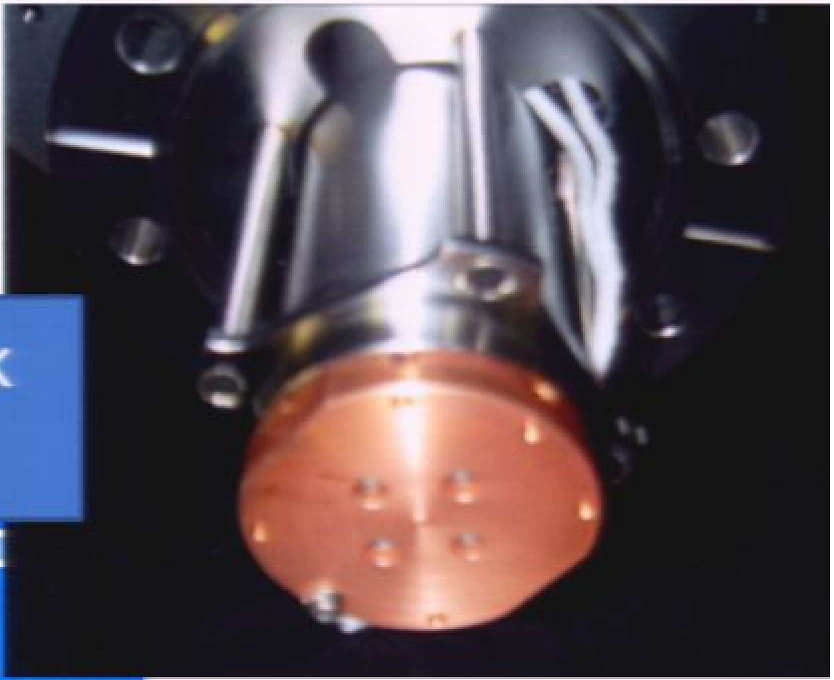

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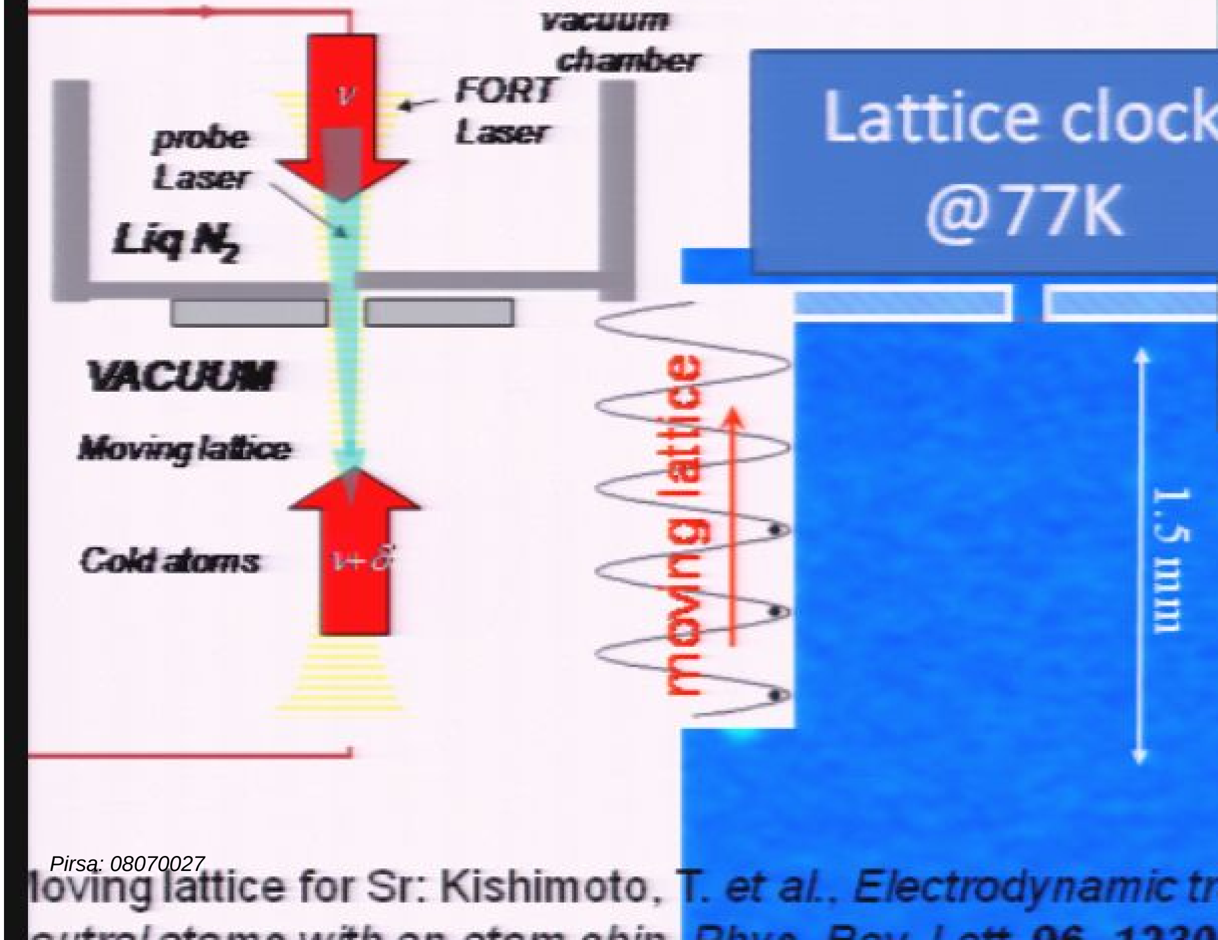

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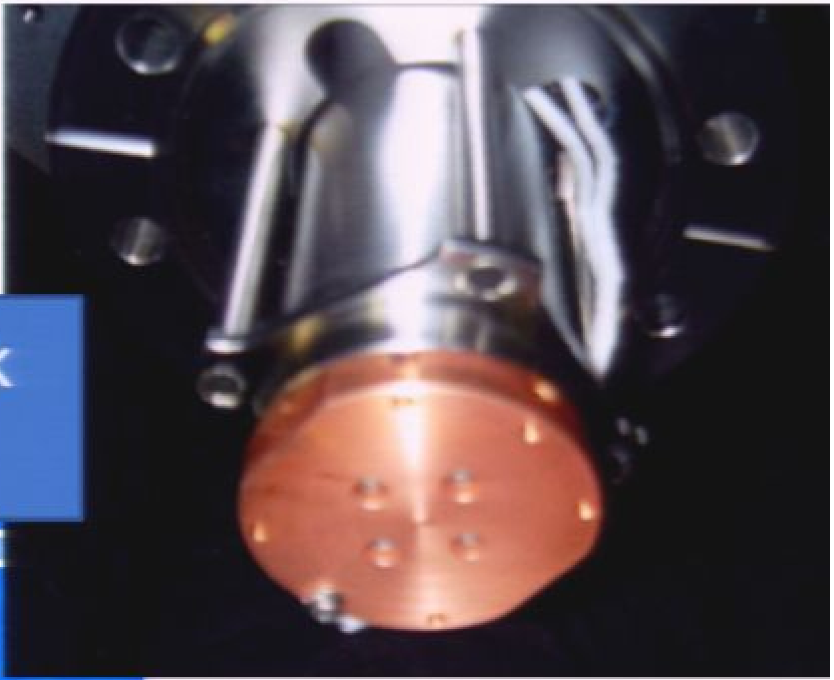

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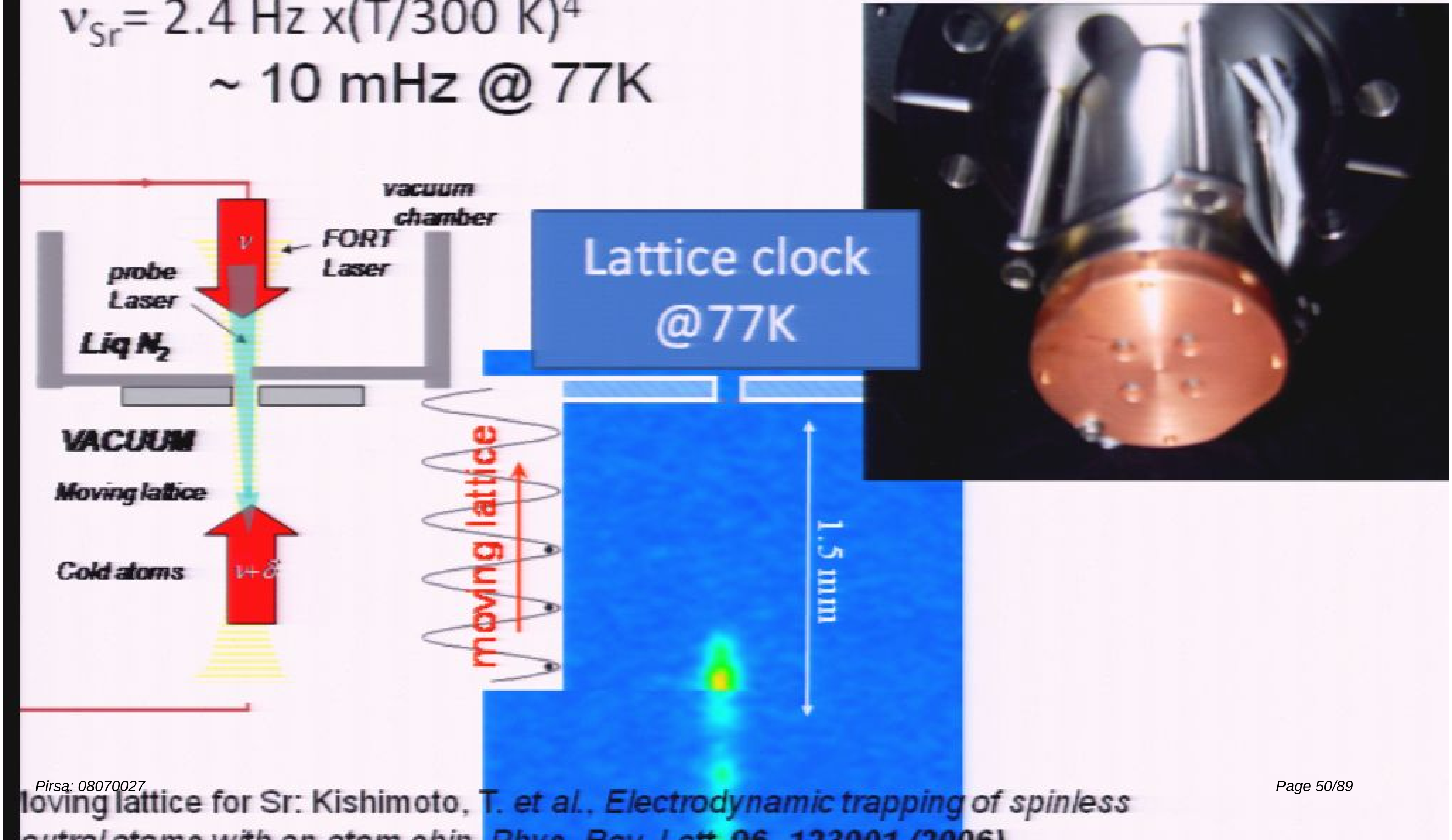

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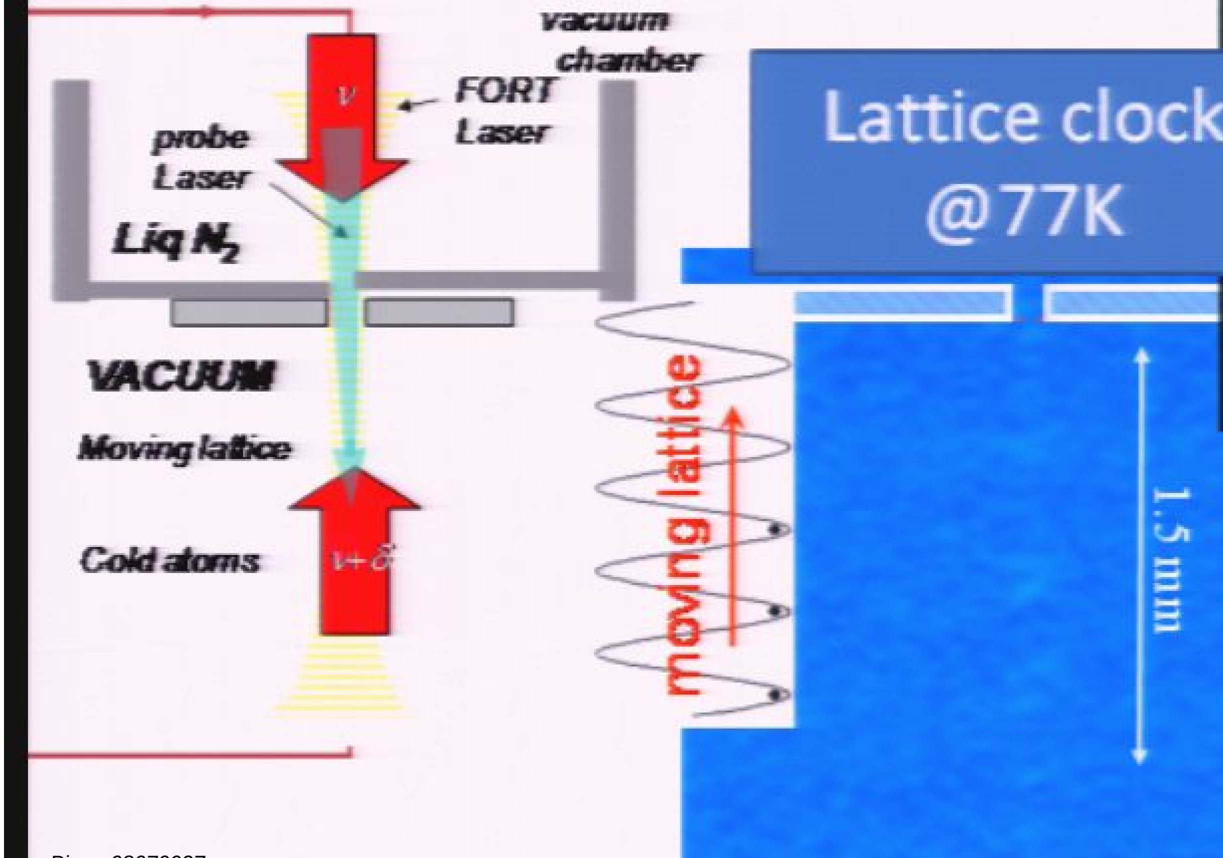

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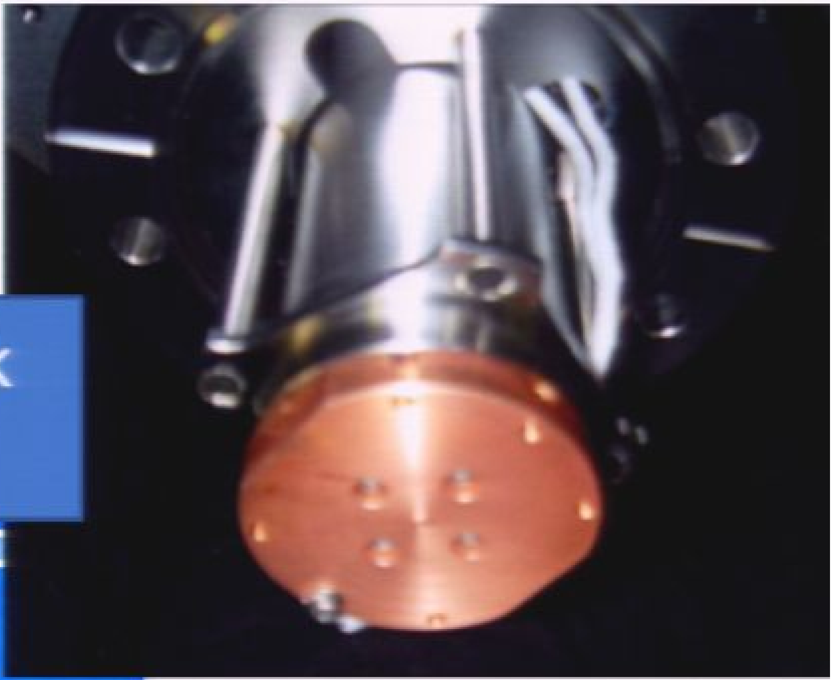

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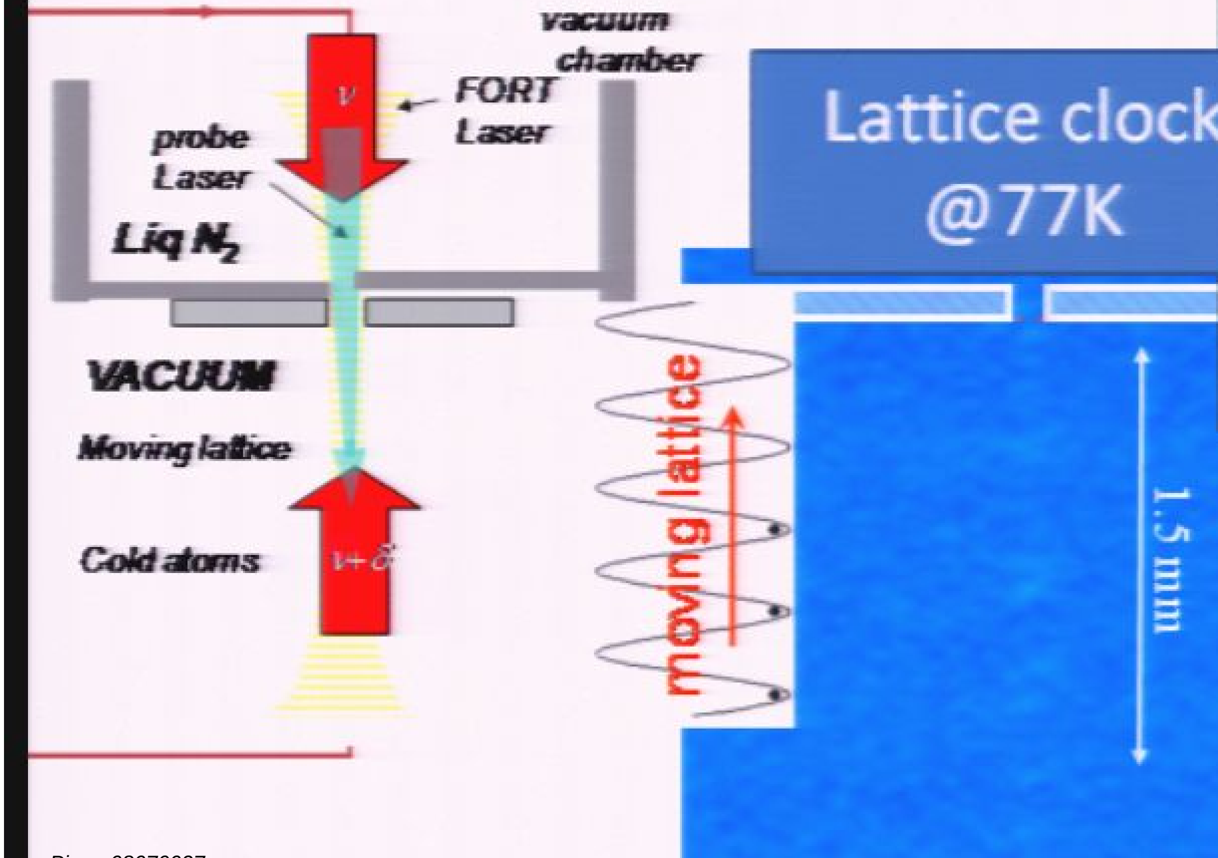

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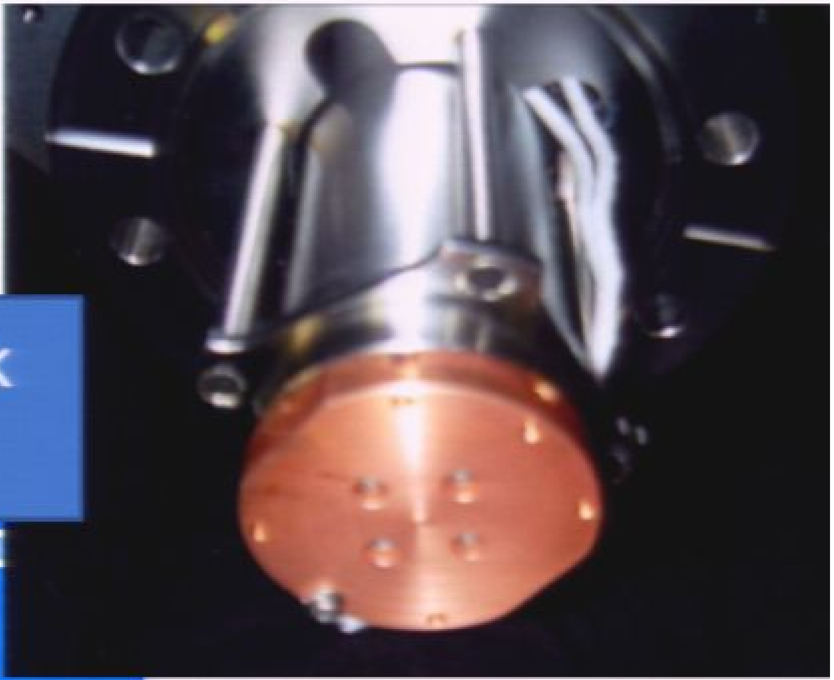

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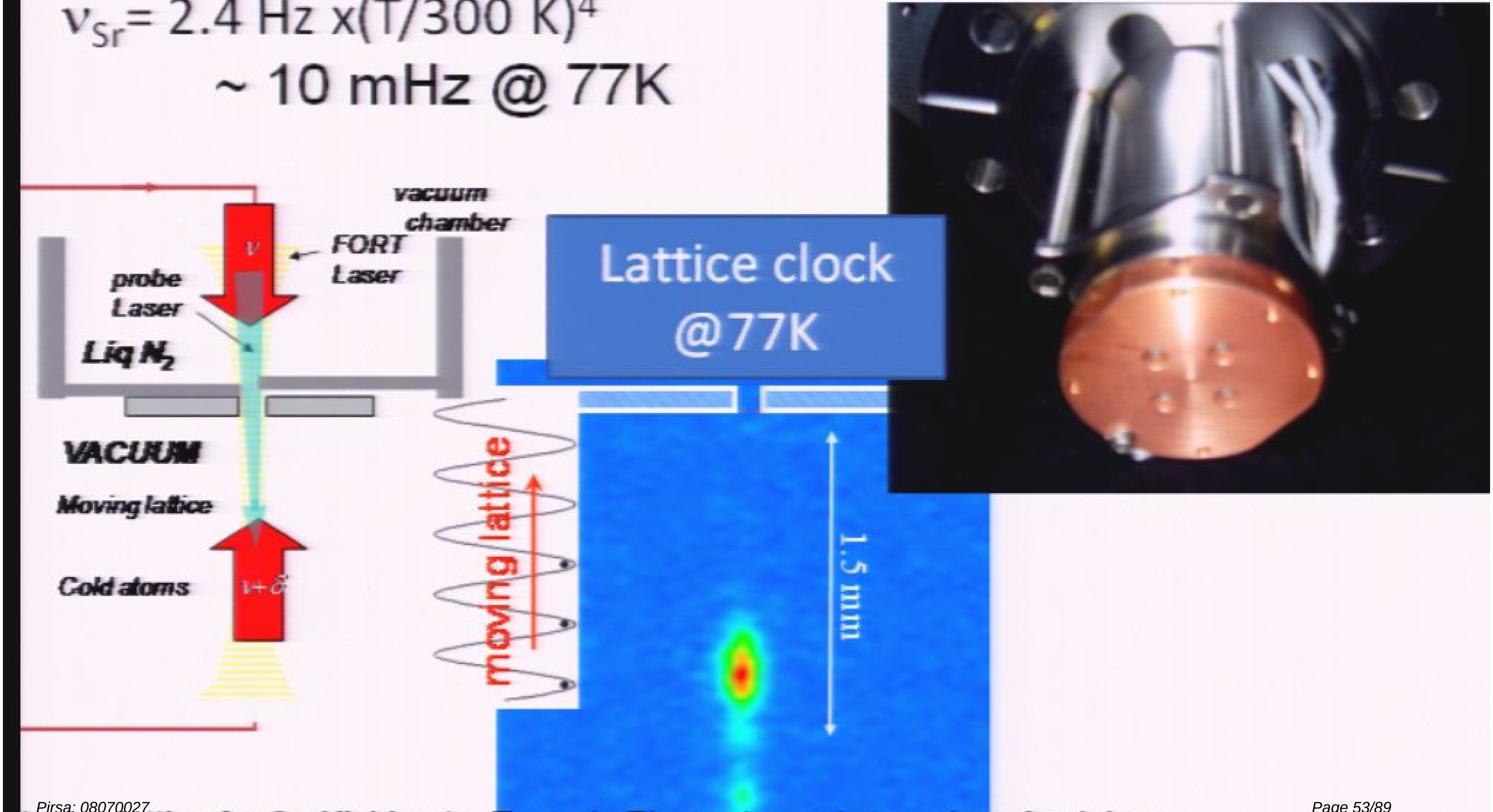

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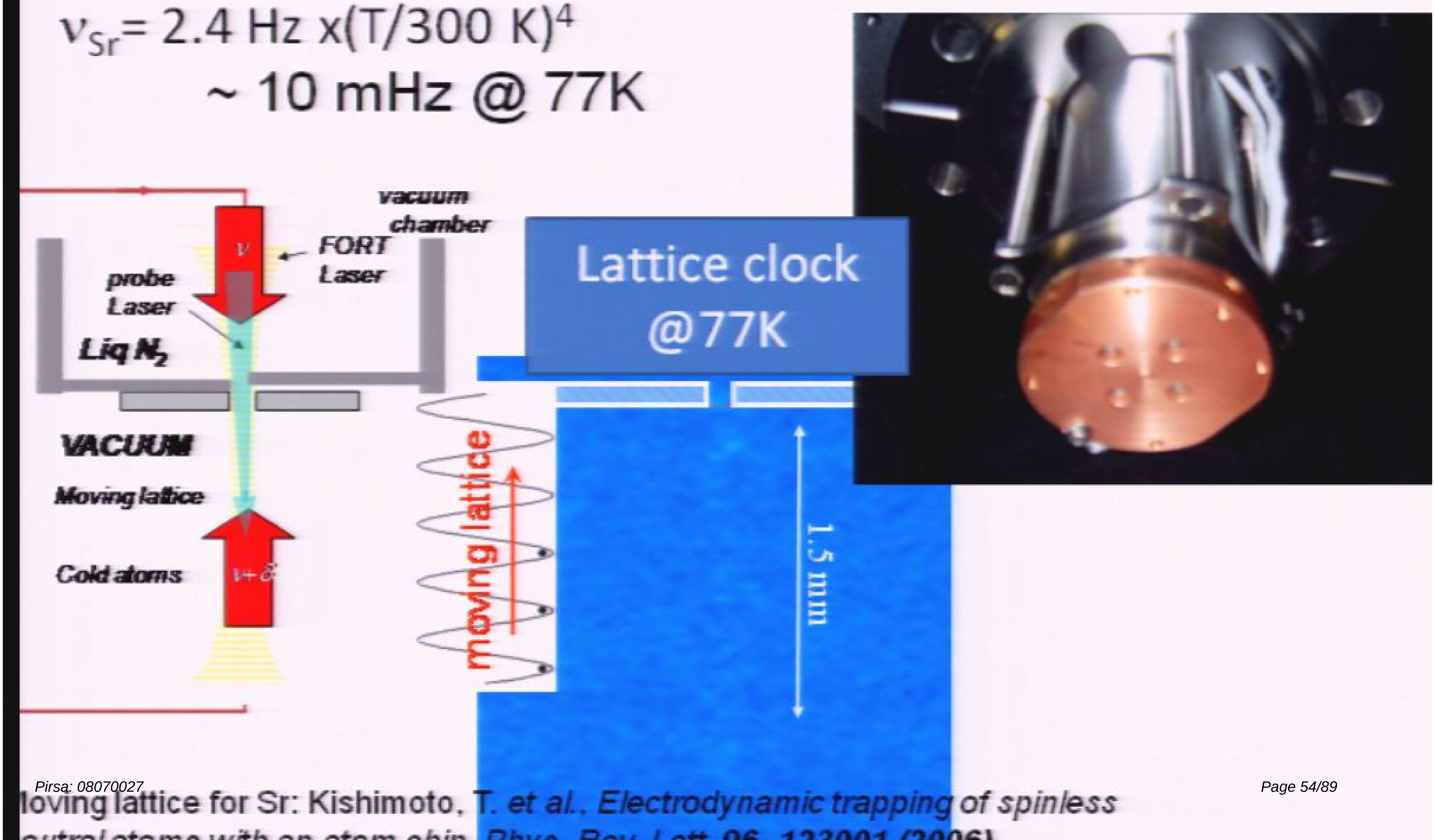

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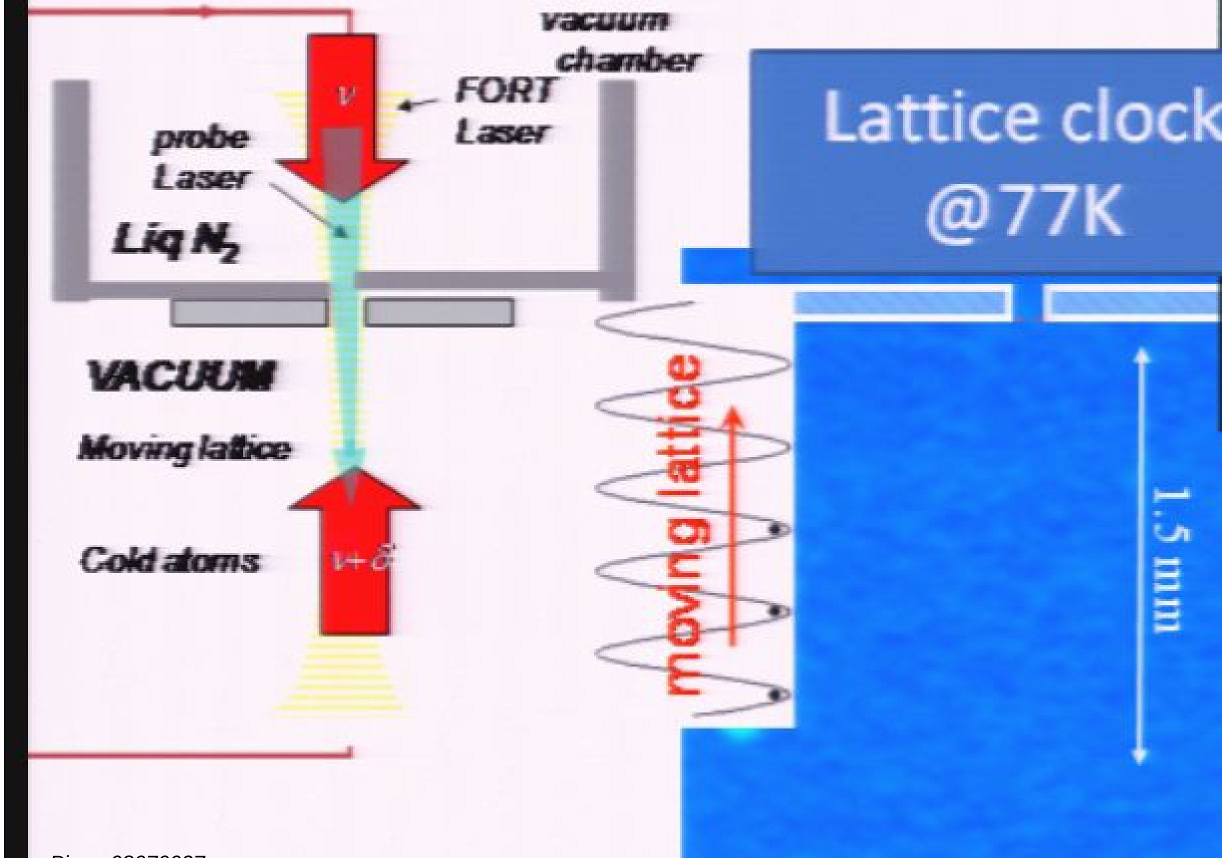

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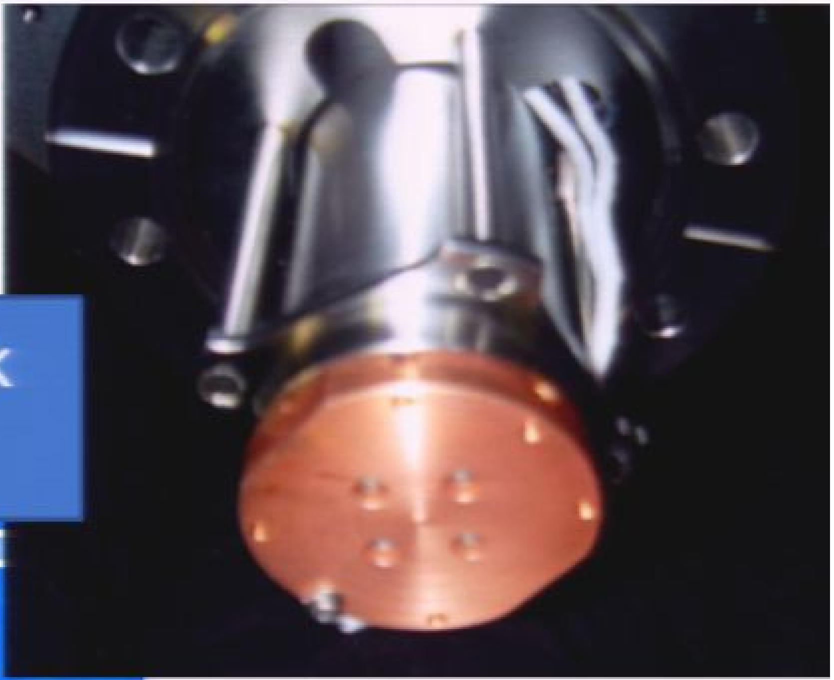

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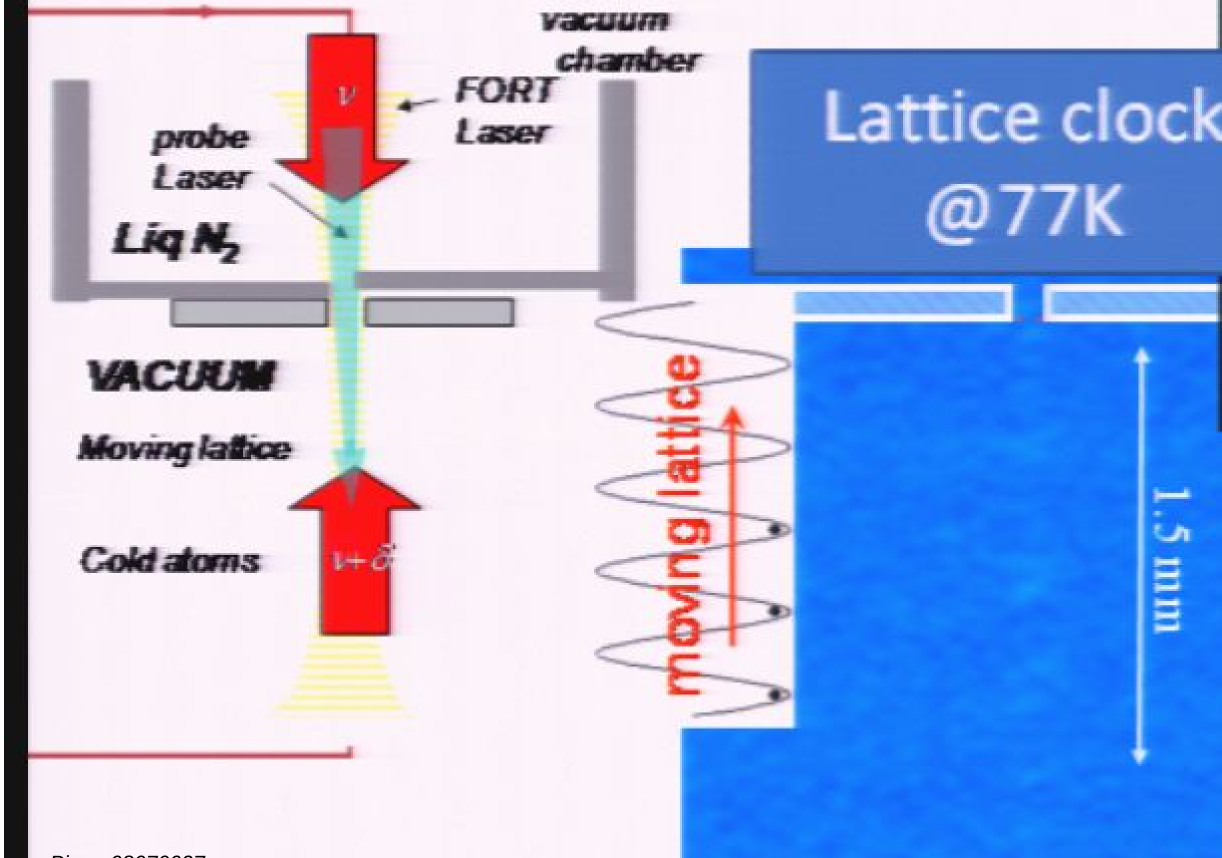

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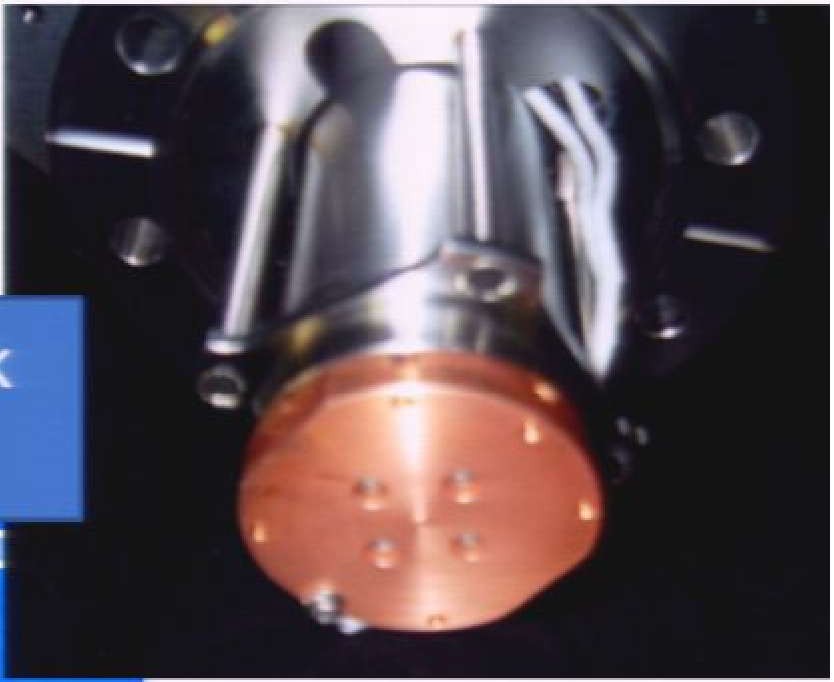

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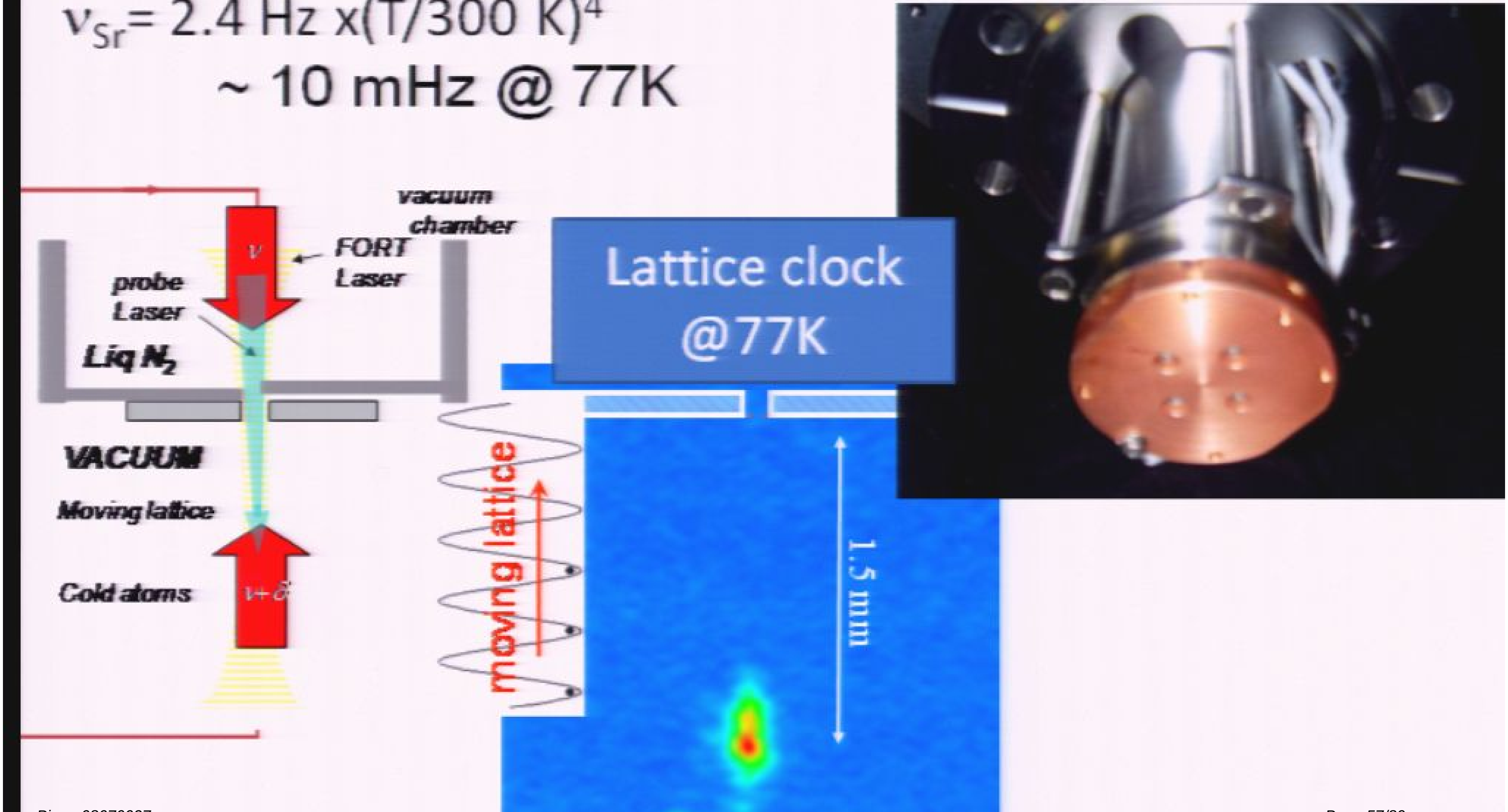

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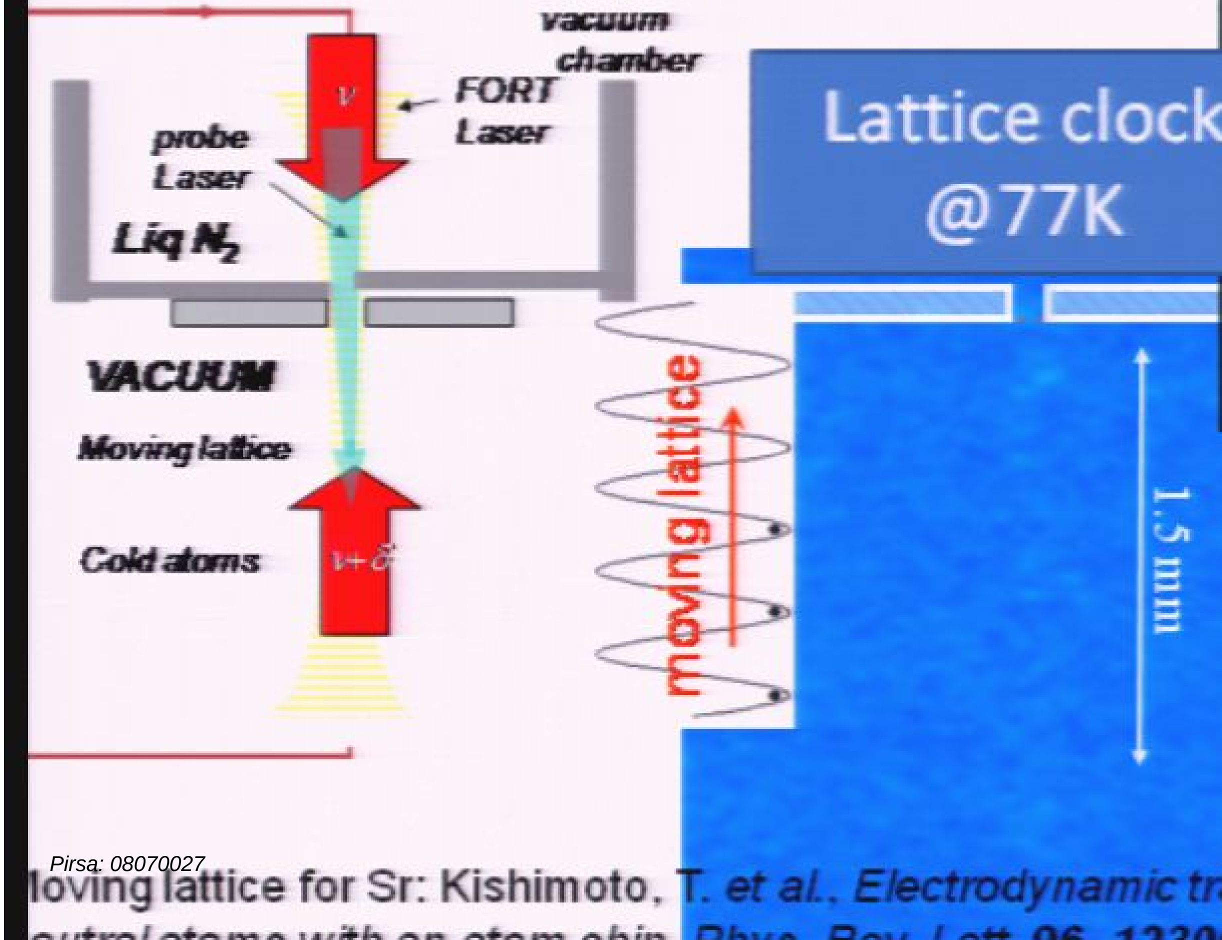

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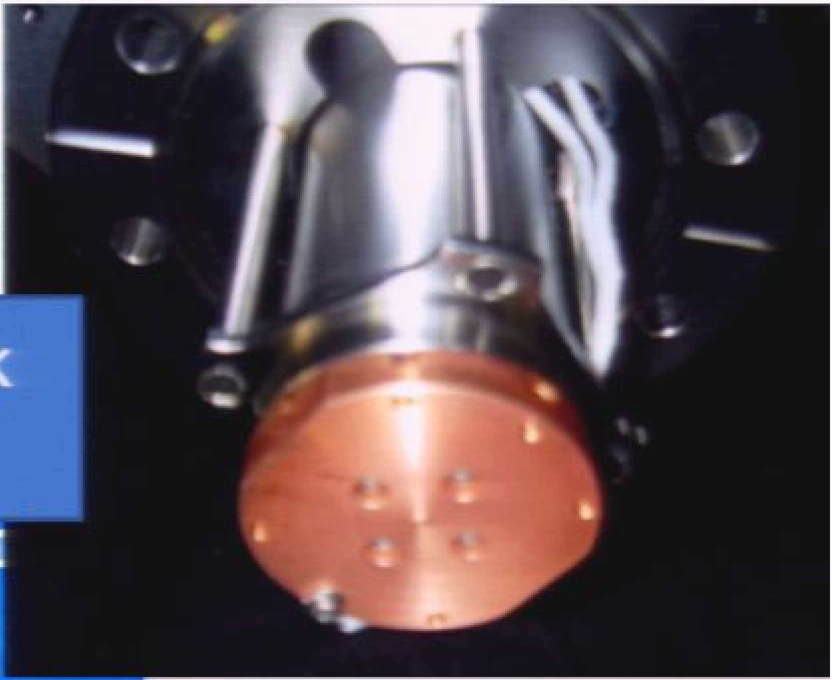

*Moving lattice for Sr: Kishimoto, T. *et al.*, *Electrodynamic trapping of spinless neutral atoms with an atom chip*, Phys. Rev. Lett. 96, 123001 (2006)*

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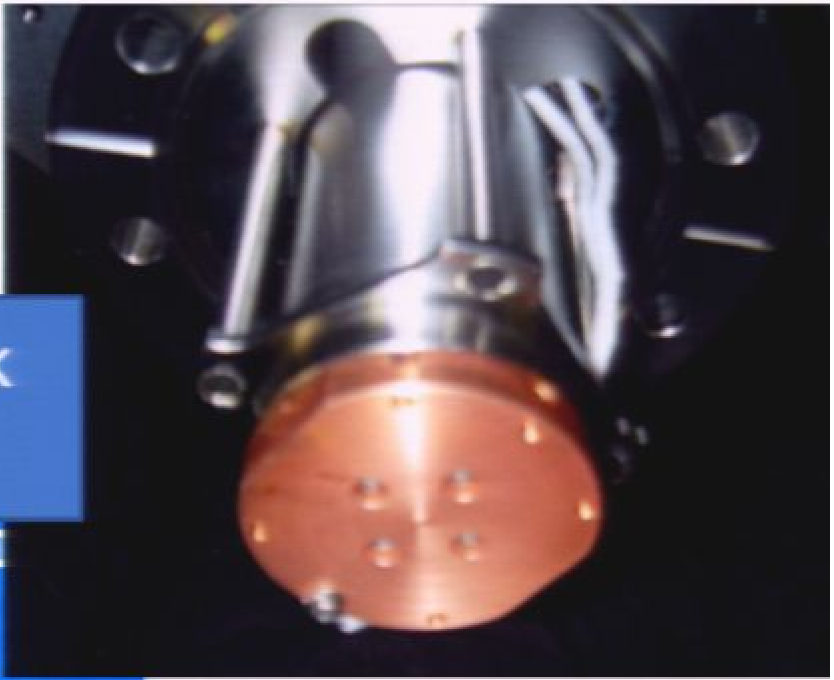

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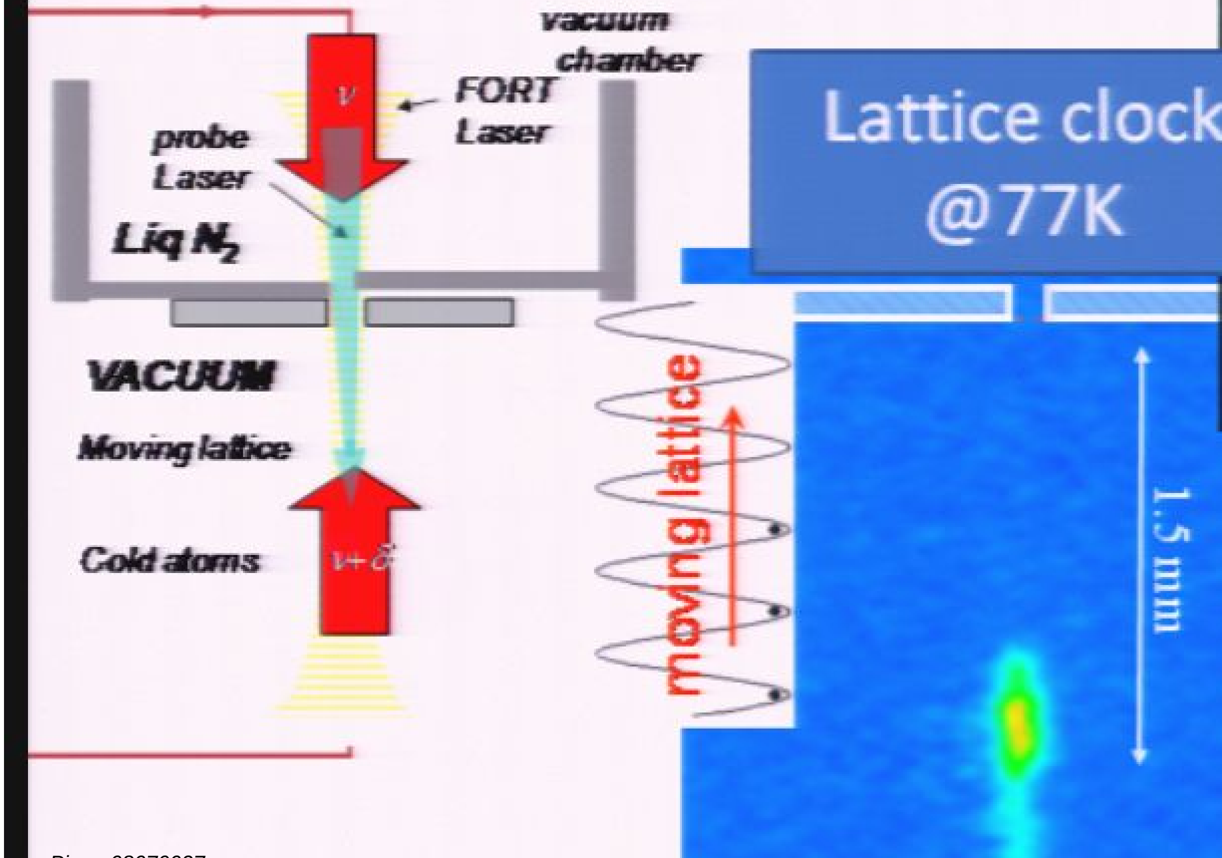

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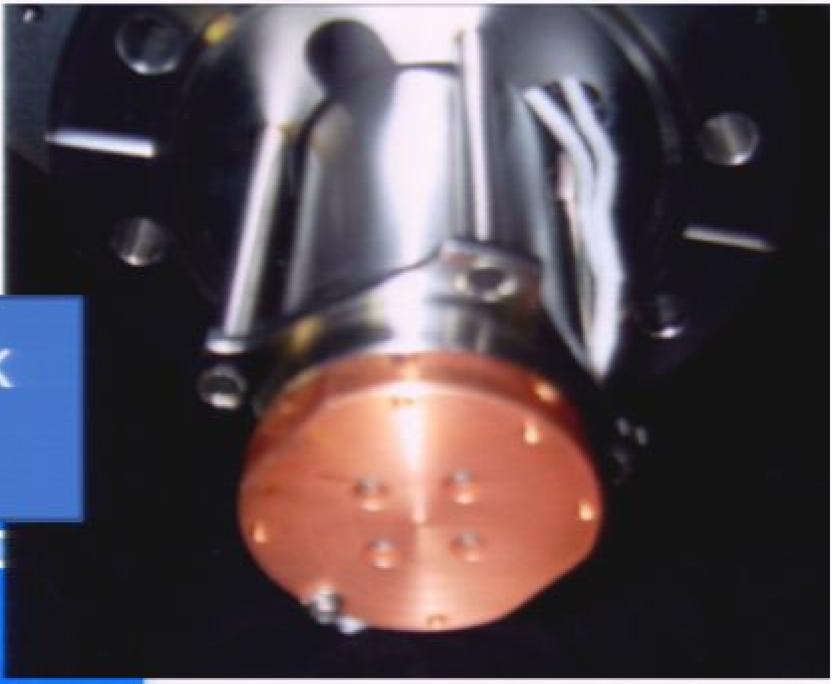
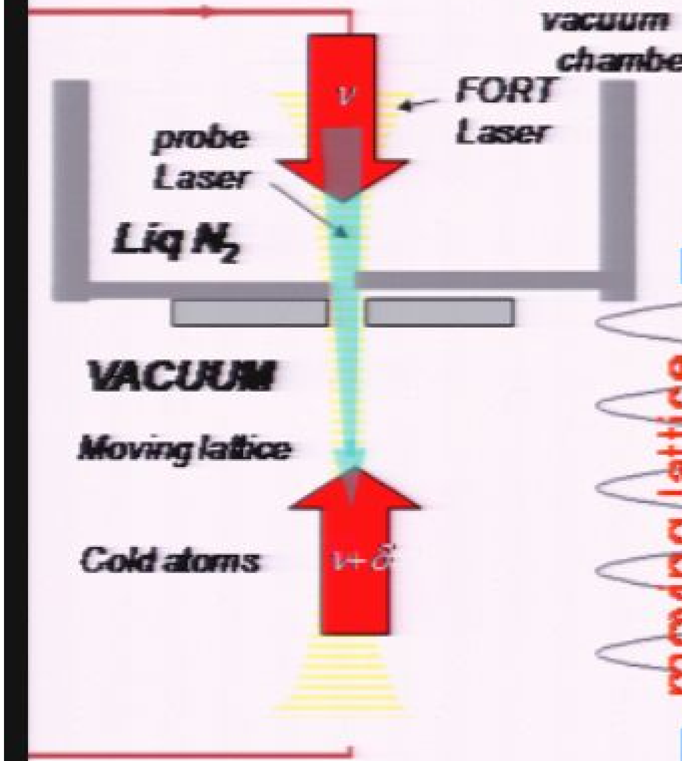
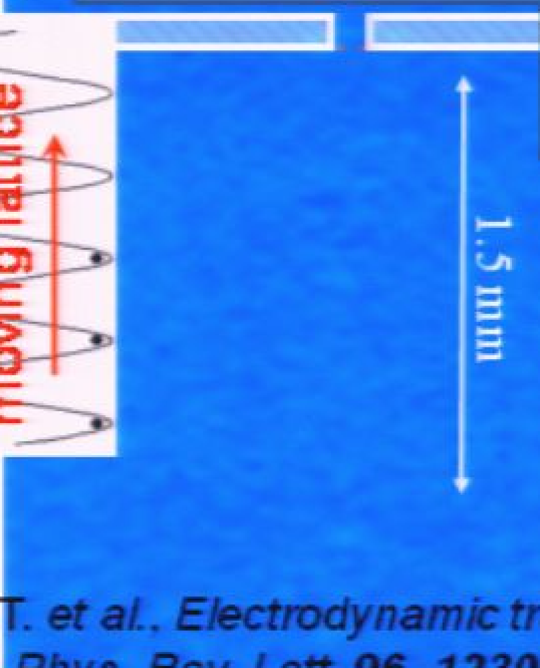




Lattice clock @77K



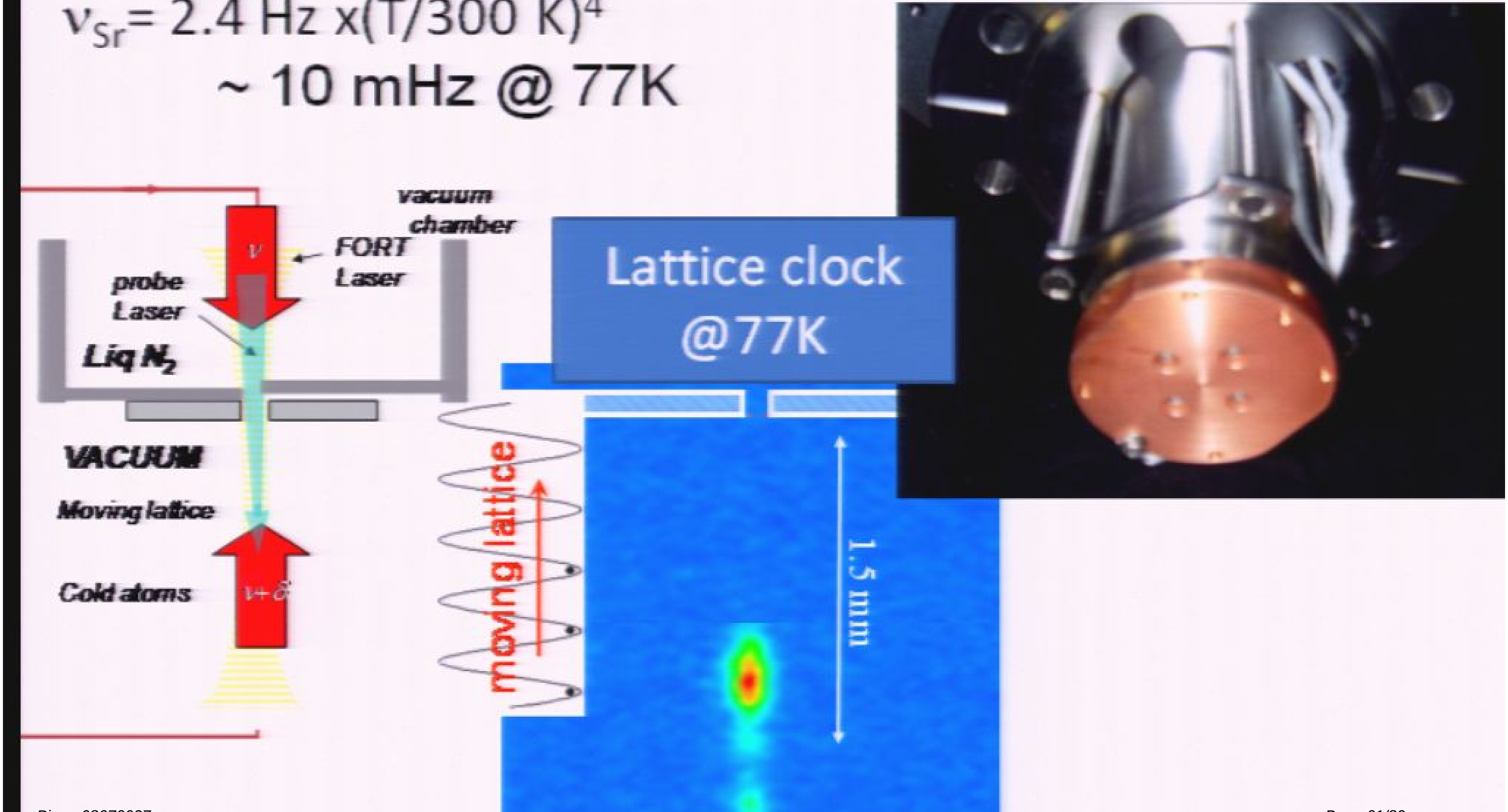
loving lattice for Sr: Kishimoto, T. *et al., Electrodynamic trapping of spinless* eutral atoms with an atom chip, *Phys. Rev. Lett.* 96, 123001 (2006)

Cryogenic lattice clock

Black body shift rapidly decreases as temperature:

$\nu_{Sr} = 2.4\ \mathrm{Hz} \times (T/300\ \mathrm{K})^4$

$\sim 10\ \mathrm{mHz}\ @\ 77\mathrm{K}$



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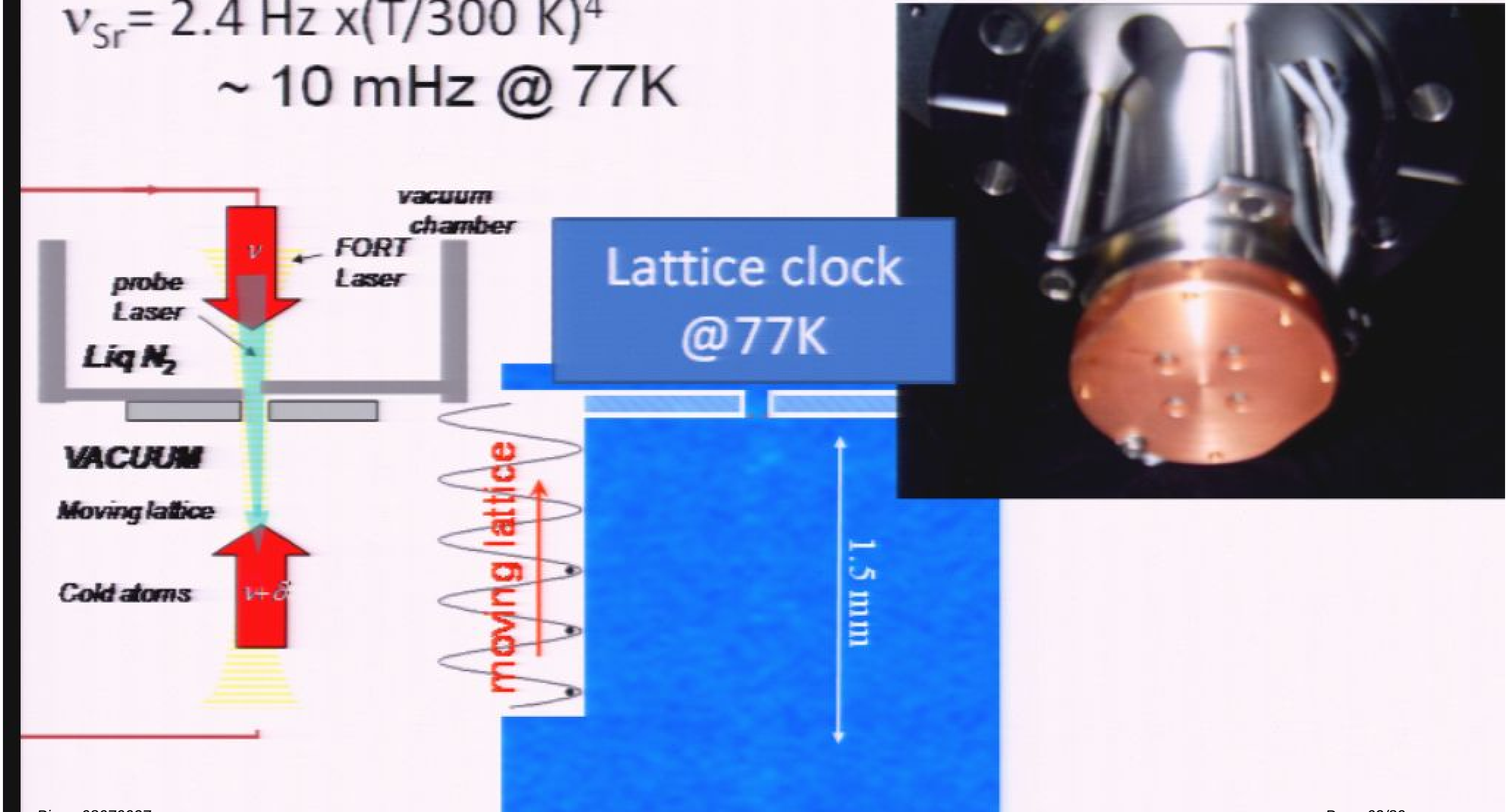

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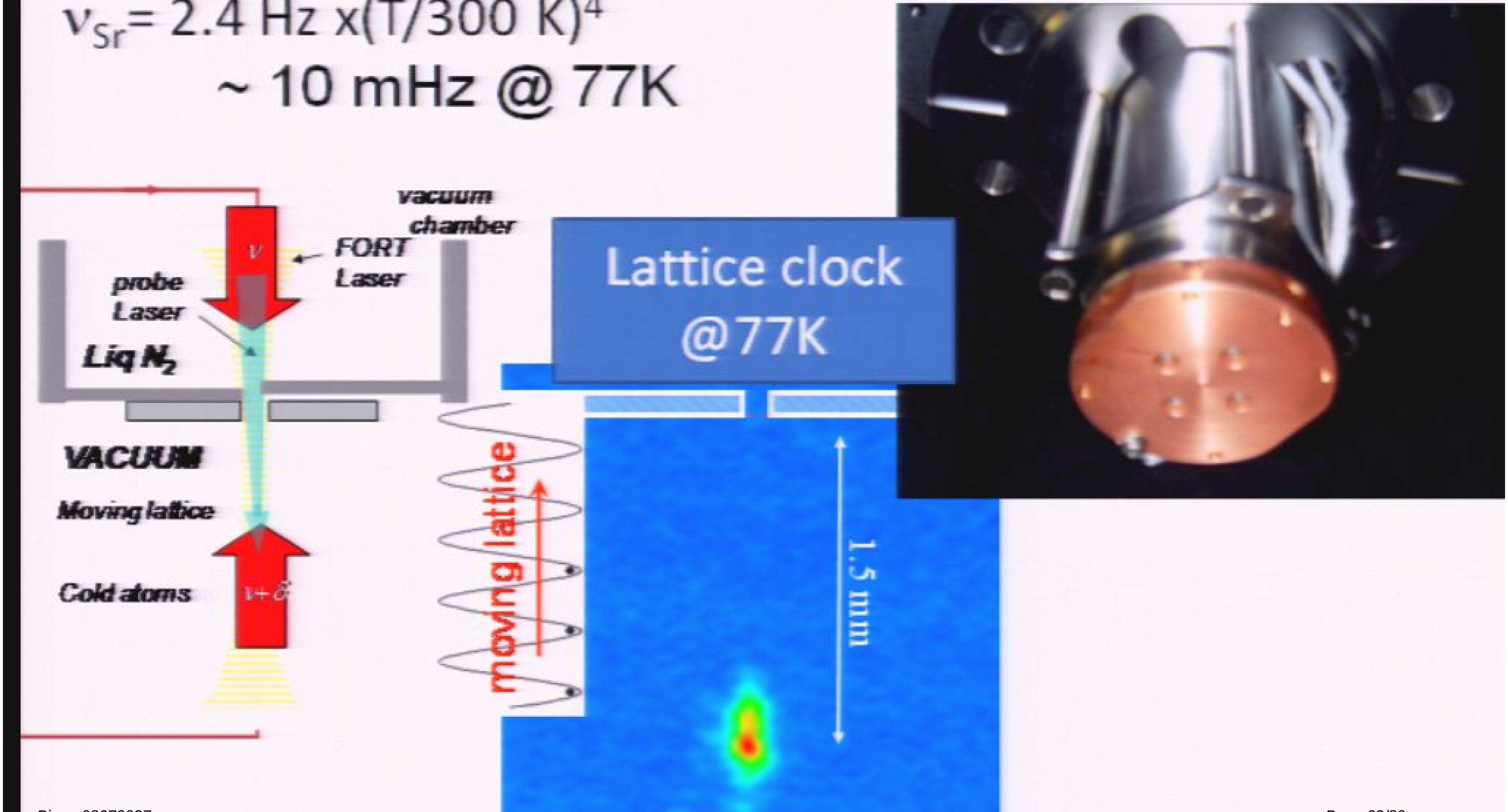

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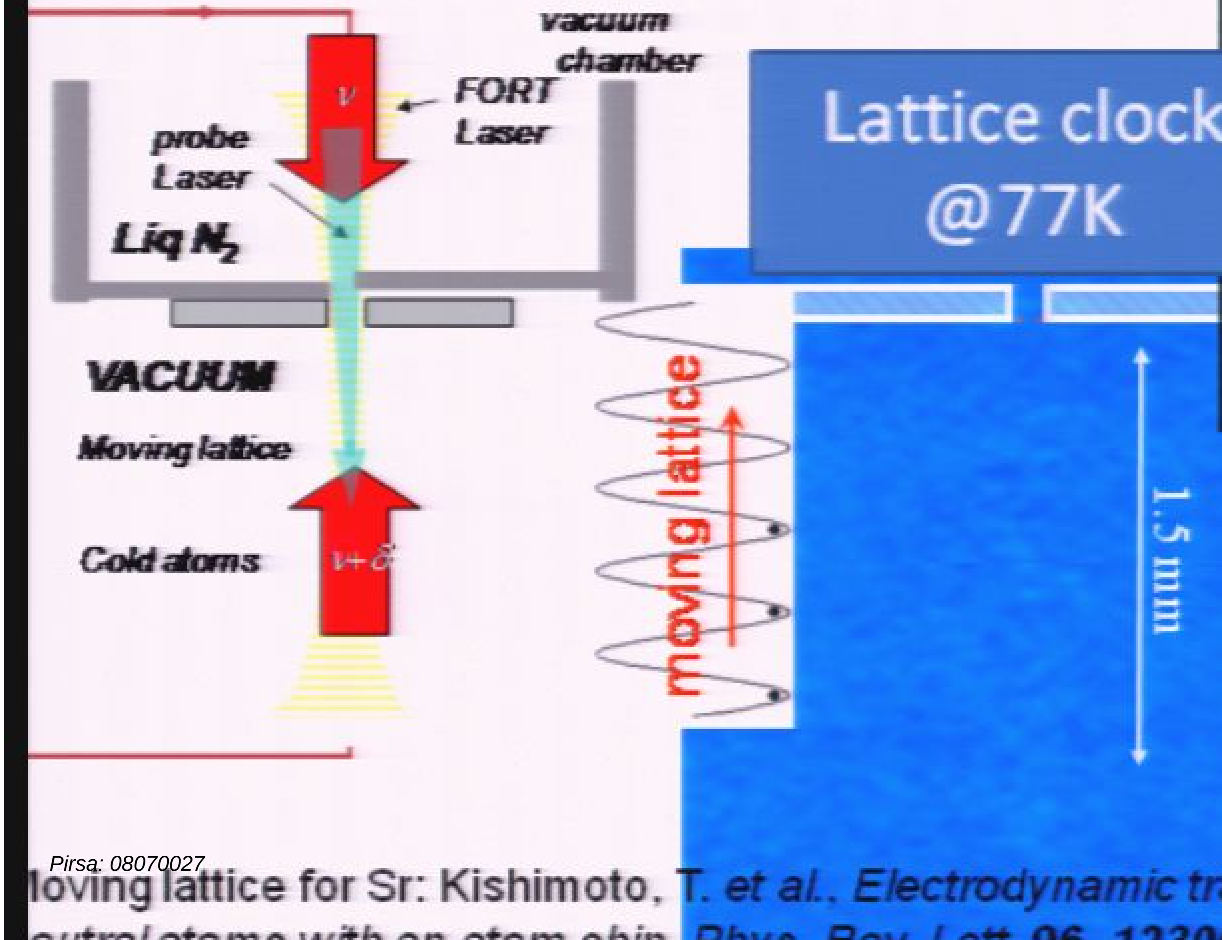
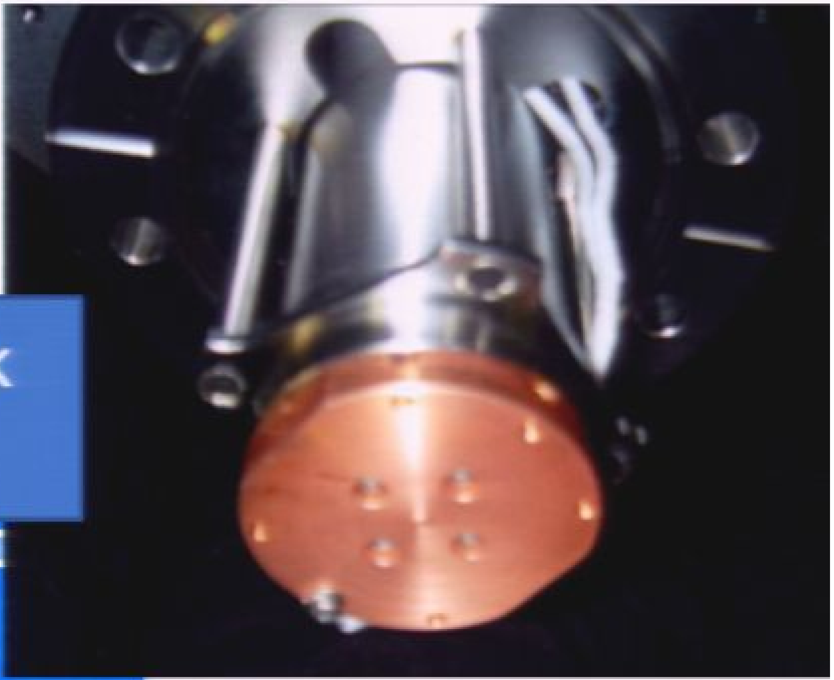


Lattice clock @77K



loving lattice for Sr: Kishimoto, T. *et al., Electrodynamic trapping of spinless*
eutral atoms with an atom chip, *Phys. Rev. Lett.* 96, 123001 (2006)

Remote frequency measurement with optical fiber link

Background

1) Precision frequency measurement

★MW signal transfer, SYRTE-LPL, 43 km fiber, CO_2/OsO_4 frequency measurement
C. Daussy et al., Phy. Rev. Lett. 94, 203904 (2005).

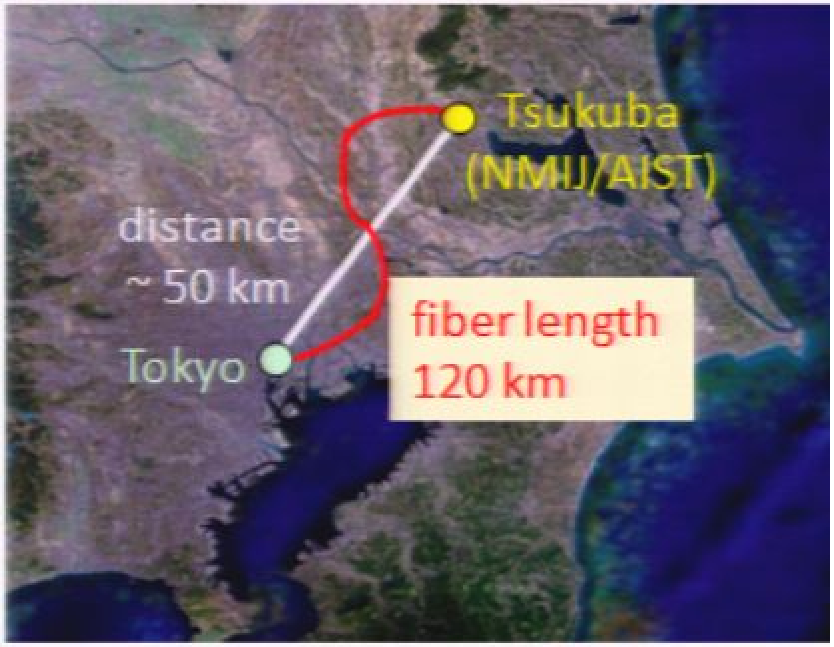
★MW/Optical signal transfer, JILA-NIST, 4 km fiber, Sr lattice clock frequency measurement
M. M. Boyd *et al., Phys. Rev. Lett.* 98, 083002 (2007).
A. D. Ludlow *et al., Science* 319, 1805 (2008).

2) Fiber link noise test

★Optical signal transfer, NIST, 251 km fiber, stability 6×10^{-19}@ 100 s
N.R. Newbury et al., Opt. Lett. 32, 3056 (2007).

★Optical signal transfer, ILS/UEC, 25 km fiber, fiber length within 1 μm, for ALMA project
M. Musha et al., App.. Phys. B 82, 555 (2006).

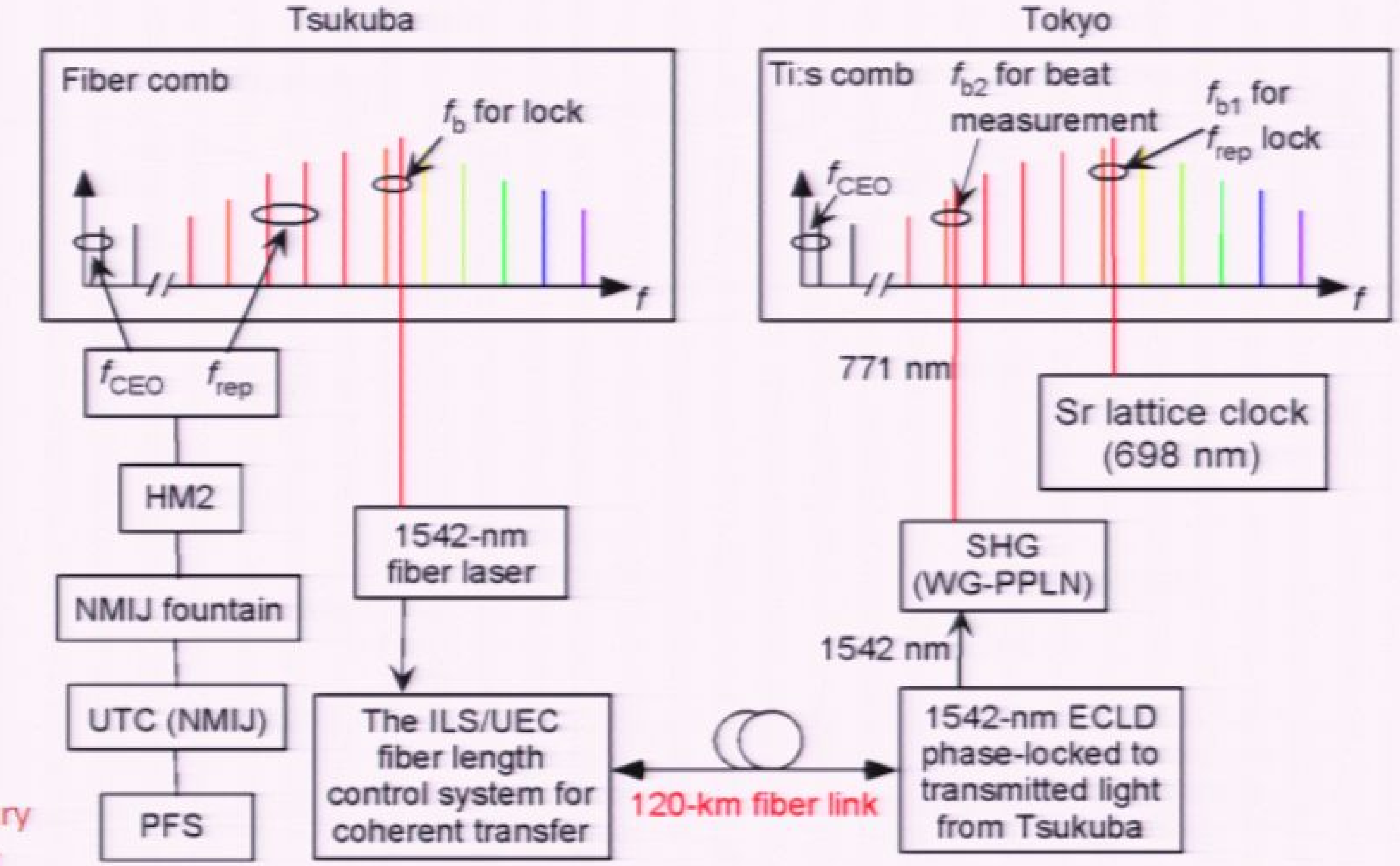
Fiber link in the present experiment



100 km fiber from JGN, NICT, Japan
+
20 km local fiber at Tsukuba and Tokyo

Total loss – 52 dB
Optical frequency transfer @ 1.5 μm

Schematic diagram of experimental setup



Tsukuba

Fiber comb

f_b for lock

f

f_{CEO} f_{rep}

HM2

NMIJ fountain

UTC (NMIJ)

PFS

1542-nm fiber laser

The ILS/UEC fiber length control system for coherent transfer

120-km fiber link

Tokyo

Ti:s comb

f_{b2} for beat measurement

f_{b1} for f_{rep} lock

f_{CEO}

f

771 nm

Sr lattice clock (698 nm)

SHG (WG-PPLN)

1542 nm

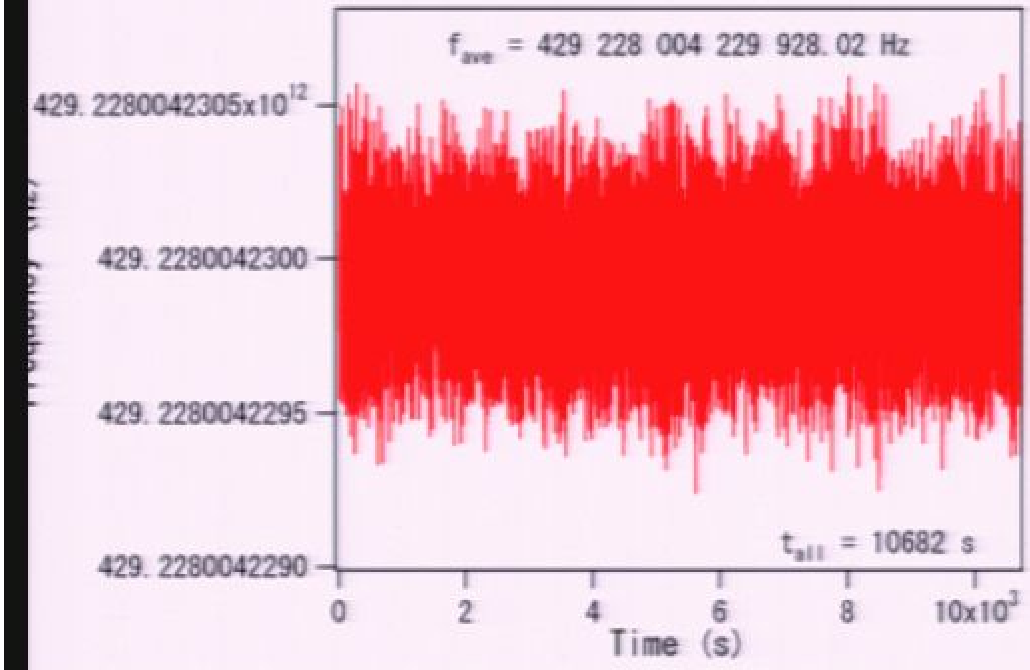
1542-nm ECLD phase-locked to transmitted light from Tsukuba

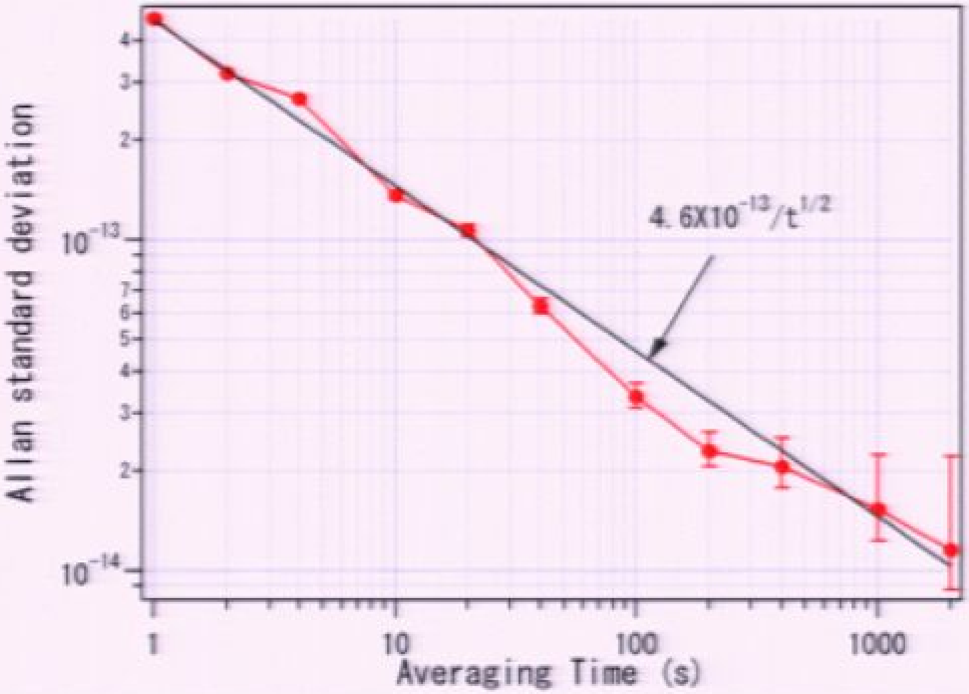
PFS: Primary Frequency Standards in Circular T (BIPM)

★ The ILS/UEC fiber length control system:
M. Musha et al., App.. Phys. B 82, 555 (2006).
M. Musha et al., to be published

Fiber link stability: $8\text{x}10^{-16}$ @ 1 s.

Measured frequency and stability





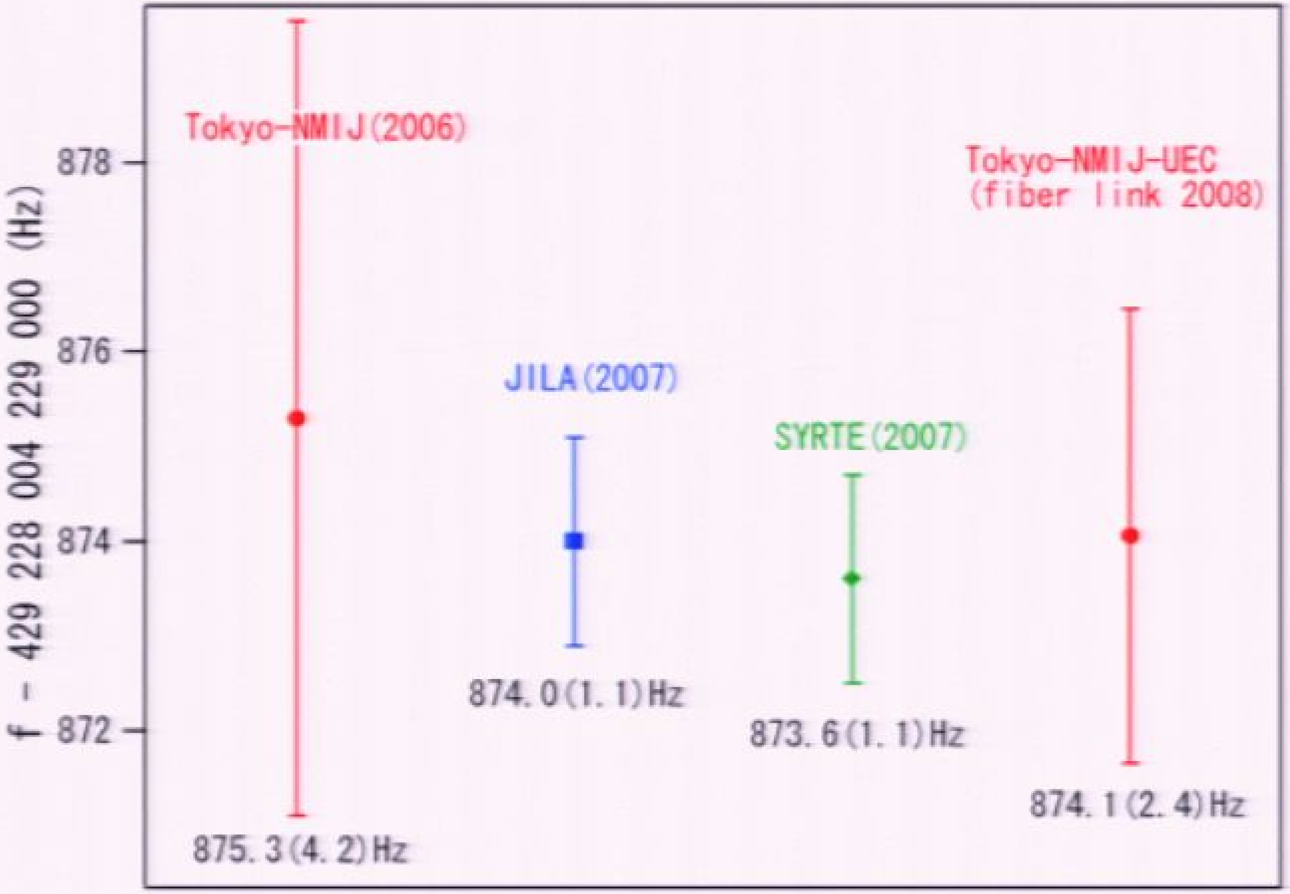
Frequency of Sr lattice clock at Tokyo measured based on the H-maser (HM2) at Tsukuba using the 120-km fiber link.

Total measurement time 10682 s (3 hours). March 17, 2008.

Stability of 4.6×10^{-13} @ 1 s was limited by the short term stability of HM2.

Frequency uncertainty limited by the stability @ 10682 s is 4.5×10^{-15}.

Absolute frequency of Sr lattice clock



Frequency difference between our present and previous measurements is –1.2 Hz. We found a wrong value for the altitude of the lab in Tokyo, which led to a frequency difference of – 0.4 Hz (10 m height difference).

The agreement between our present value and the JILA and SYRTE values is $6x10^{-16}$.

Tokyo-NMIJ (2006): J. Phys. Soc. Jpn. 75, 104302 (2006).
JILA (2007): Phys. Rev. Lett. 98, 083002 (2007)
SYRTE (2007): Eur. Phys. J. D, DOI: 10.1140/epjd/e2007-00330-3

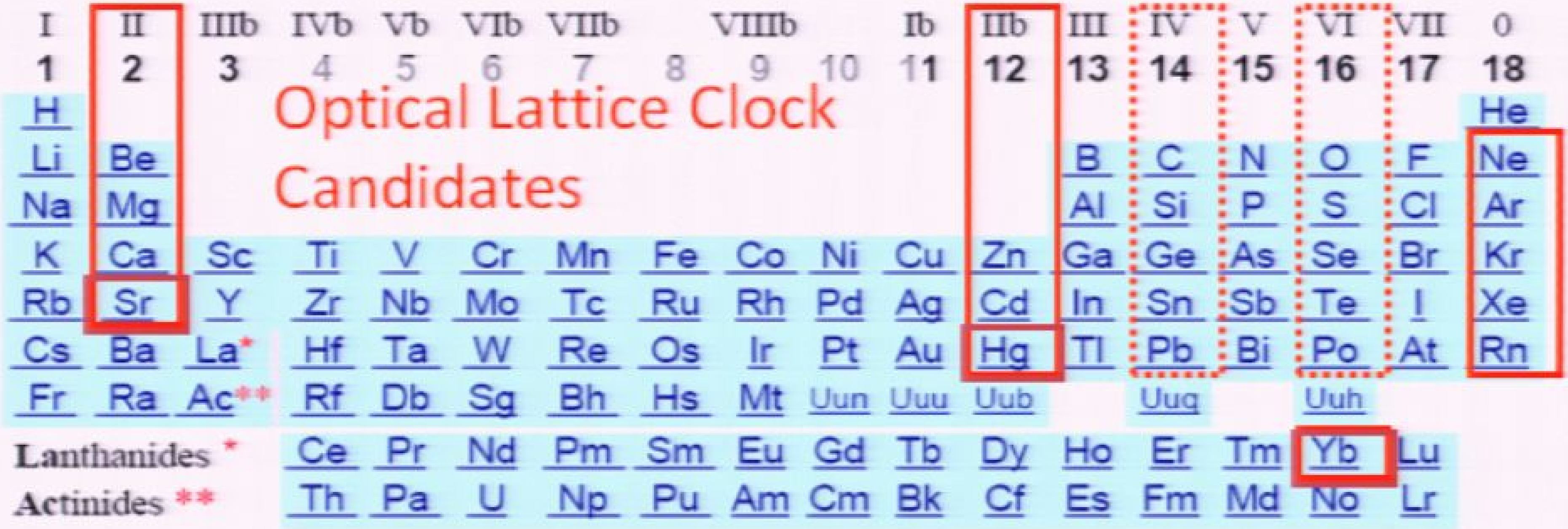
Corrections and uncertainties

	Frequency (Hz)		Uncertainty (Hz)	Uncertainty (relative)
Measured frequency	928.02		1.9	4.5E-15
	Correction (Hz)	Correction (relative)	Uncertainty (Hz)	Uncertainty (relative)
y(HM2)-y(NMIJ_F1)	-54.90	-1.279E-13	1.15	2.7E-15
y(NMIJ_F1)-y(PFS)	-1.50	-3.5E-15	0.69	1.6E-15
BBR	2.4		0.2	
2nd order Zeeman shift	0.772		0.01	
Gravitational shift	-0.9		0.09	
Collision shift	0.4		0.3	
Lattice scalar light shift	-0.22		0.33	
Lattice 4th order light shif	-0.017		0.015	
Probe laser light shift	0.03		0.001	
Corrected frequency	874.06		2.4	5.6E-15

Link between HM2 & NMIJ-F1: March 17, 2008
Link between NMIJ-F1 and PFS: March14-18, 2008

SI is no longer the reference @Univ. Tokyo!

"The frequency ratio of two clocks contains physics"



Optical Lattice Clock Candidates

	I	II	IIIb	IVb	Vb	VIb	VIIb		VIIIb		Ib	IIb	III	IV	V	VI	VII	0
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	H																	He
	Li	Be											B	C	N	O	F	Ne
	Na	Mg											Al	Si	P	S	Cl	Ar
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	Fr	Ra	Ac**	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq		Uuh		
Lanthanides *				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
Actinides **				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Exploring the constancy of physical constant, such as $\alpha = e^2/hc$, at the limit:

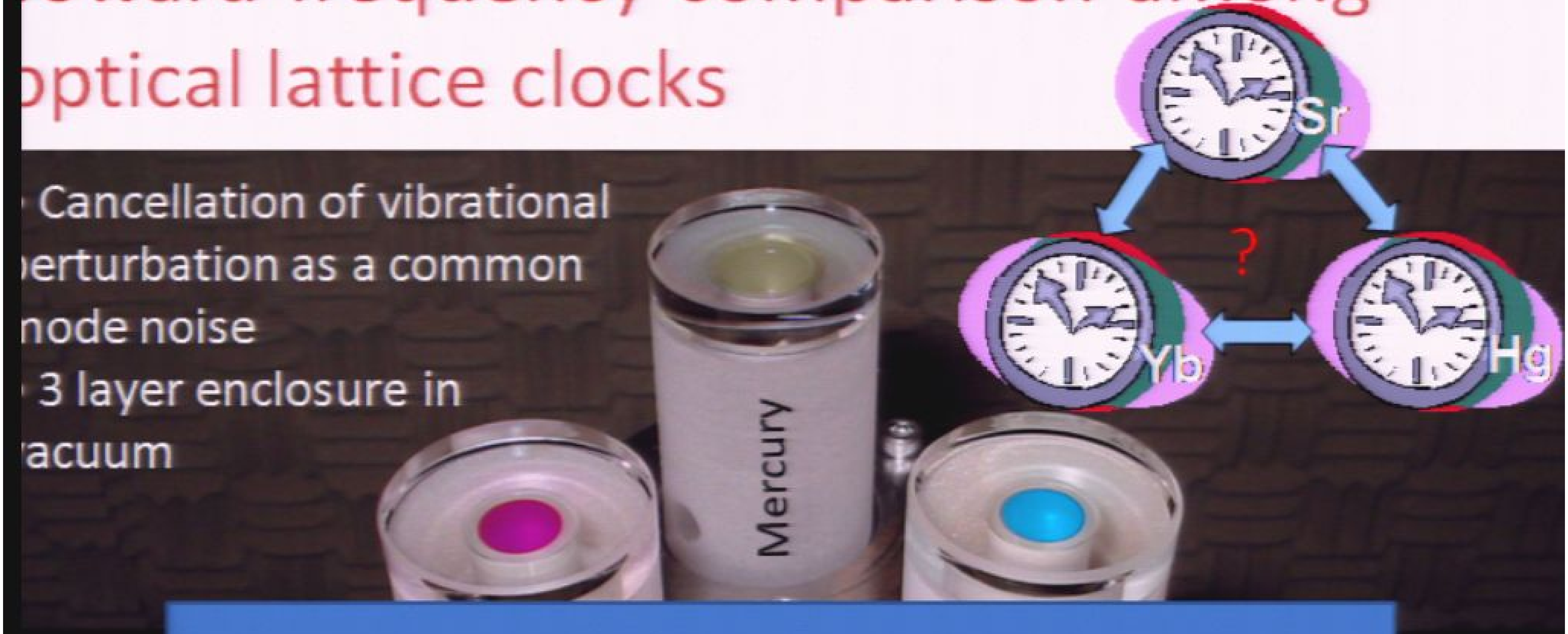
- Atomic transition frequency depends on α;
- Relativistic correction $\sim\alpha^2 Z^2$; larger for heavier atoms
- Cancellation of gravitational perturbation as a common mode noise (experimental)

Toward frequency comparison among optical lattice clocks

- Cancellation of vibrational perturbation as a common mode noise
- 3 layer enclosure in vacuum

aser stabilization to 3 ULEs
r(698nm),Yb(578nm), &
Hg(1063nm/4)

Toward frequency comparison among optical lattice clocks



- Cancellation of vibrational perturbation as a common mode noise
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Atoms	Sr	Yb	Hg
Clock transition	698 nm	578 nm	266 nm
Magic wavelength	813.4 nm	759.6 nm	358 nm
Frequency change	6.2×10^{-19}	3.1×10^{-18}	0.8×10^{-17}

E. J. Angstmann, V. A. Dzuba, and V. V. Flambaum, Phys. Rev. A 70 014102 (2004)

$\Delta\alpha/\alpha=10^{-17}$

aser sta
r(698nr
Ig(1063

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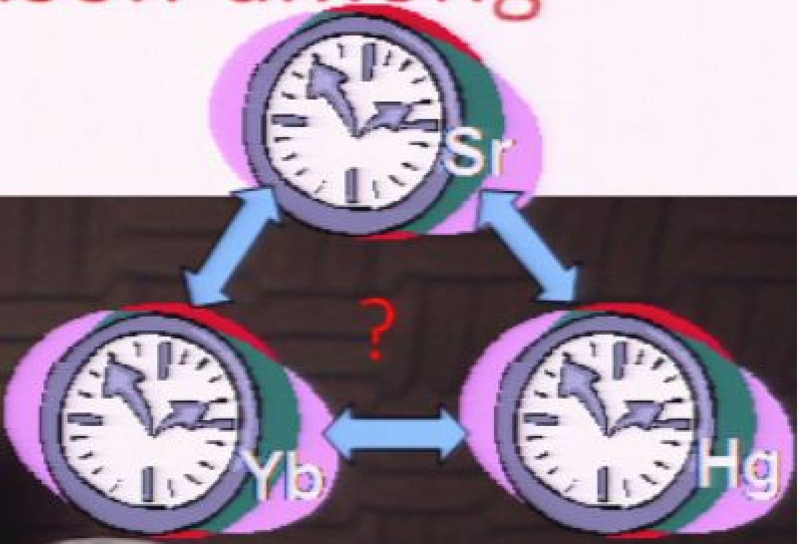

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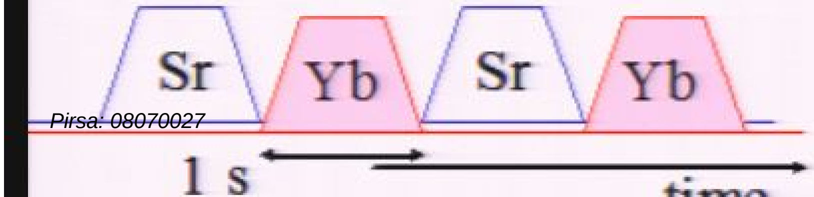
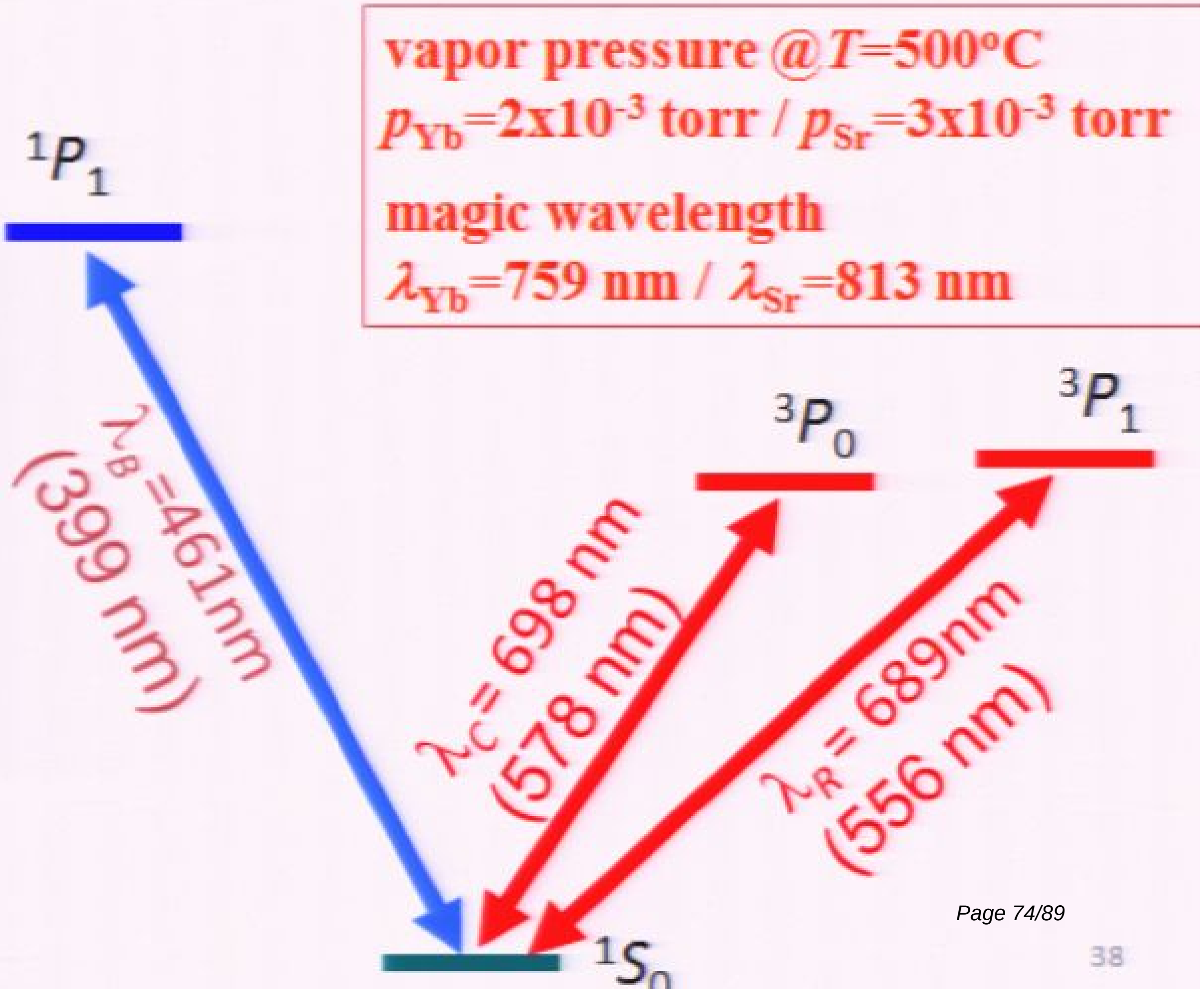
Dual optical lattice clock: Sr/Yb

- Treat **gravitational perturbation as a common mode noise**
- Good compatibility of optics & vapor pressure
- Optical-optical frequency comparison; test of α variation



vapor pressure @ T=500°C
p_{Yb}=2x10^{-3} torr / p_{Sr}=3x10^{-3} torr

magic wavelength
λ_{Yb}=759 nm / λ_{Sr}=813 nm

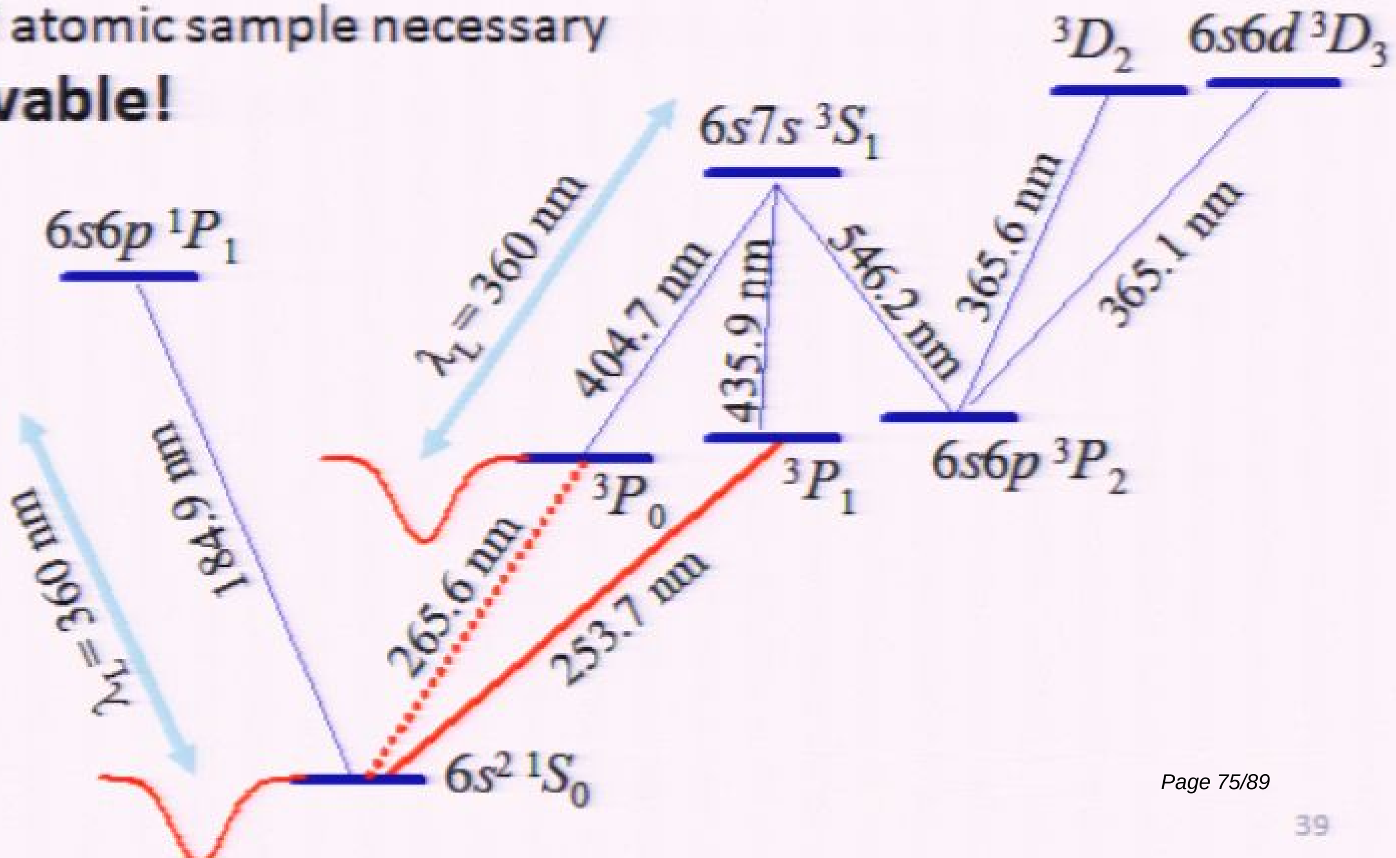


Optical lattice clock with mercury

H. Hachisu *et al., Phys. Rev. Lett.* **100**, 053001 (2008)

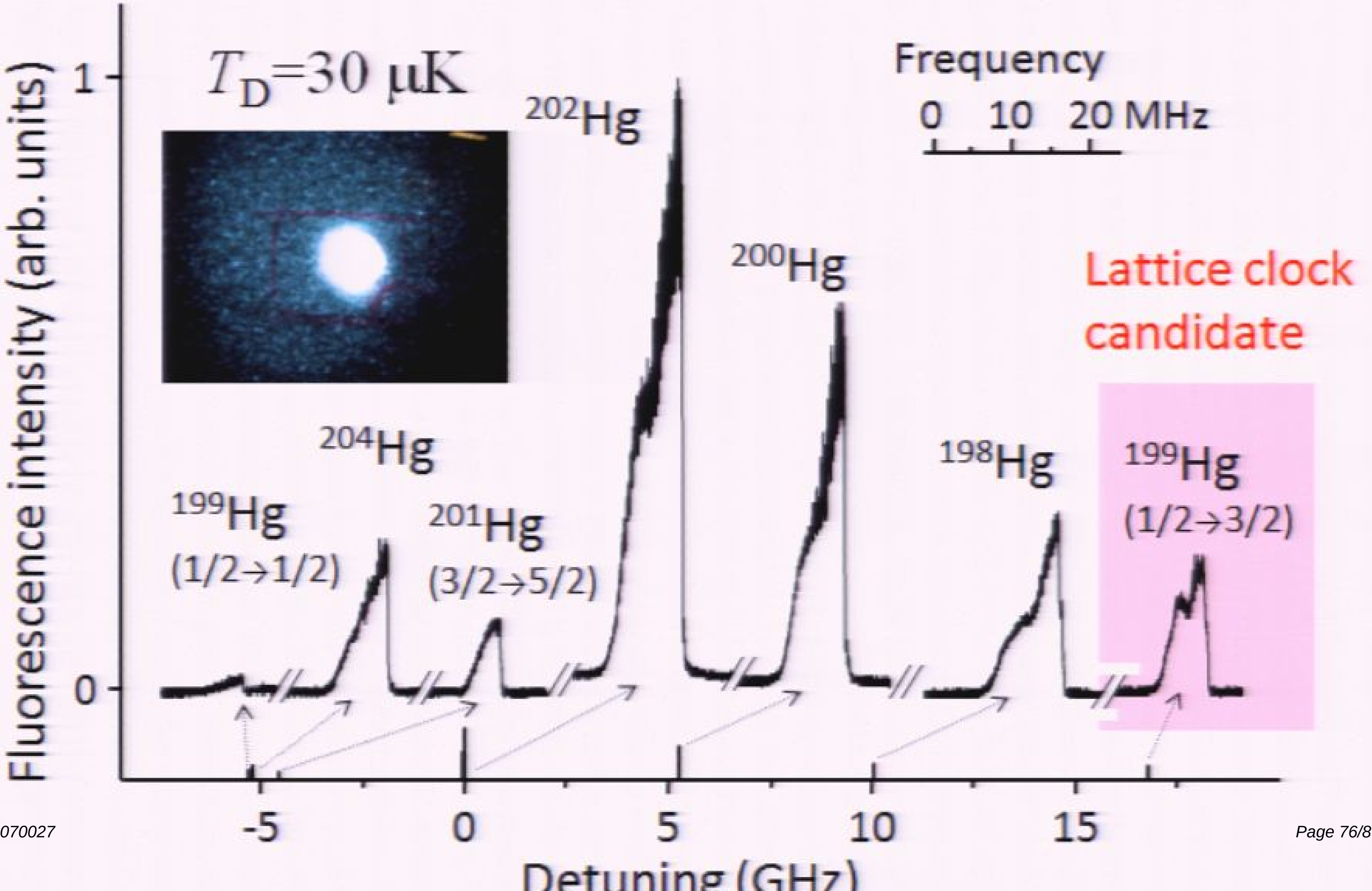
1) **Heaviest** lattice clock candidate
   - ✓ Large α dependence: $\Delta\nu/\nu = 0.8 \times 10^{-16}$ for $\Delta\alpha/\alpha = 10^{-16}$
2) **Very small BBR** shift: -0.18Hz@300K << Sr,Yb
3) Hyperpolarizability effects: $\delta\nu \sim 0.3$mHz
4) Require high laser intensity for lattice : ~ 2 kHz/(kW/cm^2)
   - ✓ Moderately cold atomic sample necessary

10^{-19} accuracy achievable!



Magneto-optical trapping of Hg isotopes

—Highest-Z non-radioactive atom trapped so far —



The group

Univ. of Tokyo/CREST

H. K.

M. Takamoto(RA:Sr-1D)

H. Hachisu

(JST/PD: Hg, atom chip)

T. Akatsuka (JST/Sr-3D)

R. Higashi (D3:Yb)

K. Hamada (M2: chip)

K. Miyagishi（M2:Hg)

Y. Nakagawa (M1:Yb-Sr)

K. Nakahana（M1:Sr)

Funding: SCOPE(03-08), PRESTO, CREST

Postdoc position available, contact

katori@amo.t.u-tokyo.ac.jp

Collaborators

—Theory:

V. G. Pal'chikov, V. D. Ovsiannikov

A. Derevianko, S. G. Porsev,

—Frequency link, Cs fountain clock:

AIST/NMIJ: F. L. Hong, M. Imae, Y. Fujii, H. Inaba, S. Yanagimachi, A. Takamizawa, T. Ikegam

UEC: M. Musha, K. Nakagawa

Summary

- Excellent agreement of Sr clocks in JILA/SYRTE/Tokyo:6 × 10^{-16}
- Lattice clocks with non-interacting atoms
  - geometry for reduced uncertainty
  - Spin-polarized fermions in 1D/Bosons in 3D
  - Clock comparison at 5 × 10^{-16} @2,000 s achieved f_{88}/f_{87}=1.000000144883693(3)
- Remaining issues and future investigation
  - Rabi oscillation in the clock transition
    - Laser limited atomic coherence/Pauli blocking
  - Blue magic wavelength: simulates "Paul trap"
  - Frequency comparison between different atoms
    - Sr/Yb/Hg clocks as a probe for α variation

Dual optical lattice clock: Sr/Yb

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- Good compatibility of optics & vapor pressure
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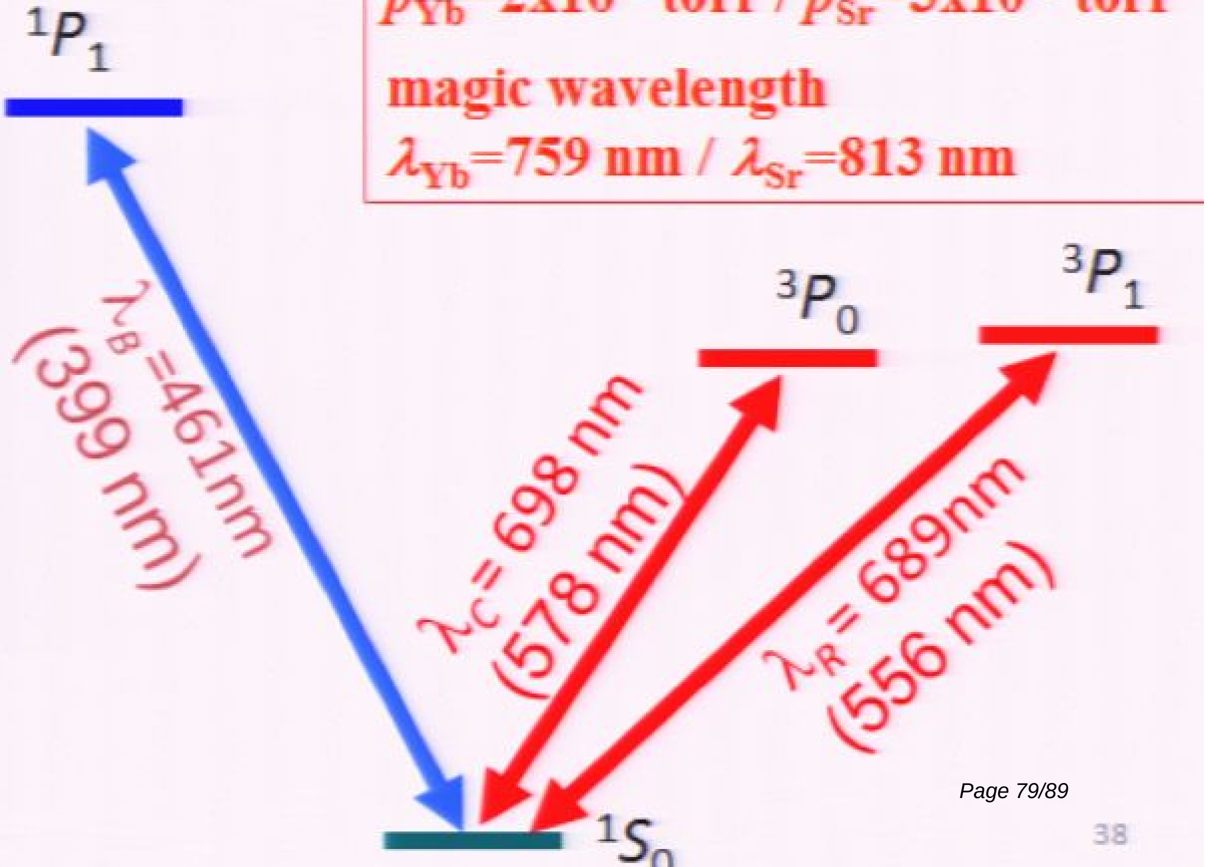

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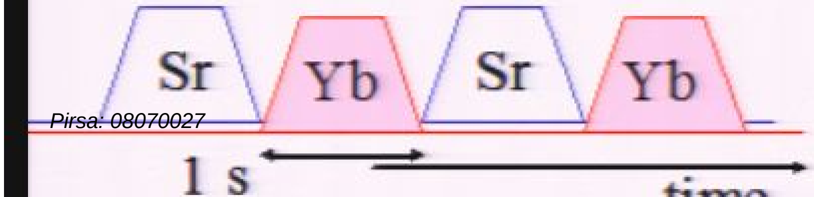

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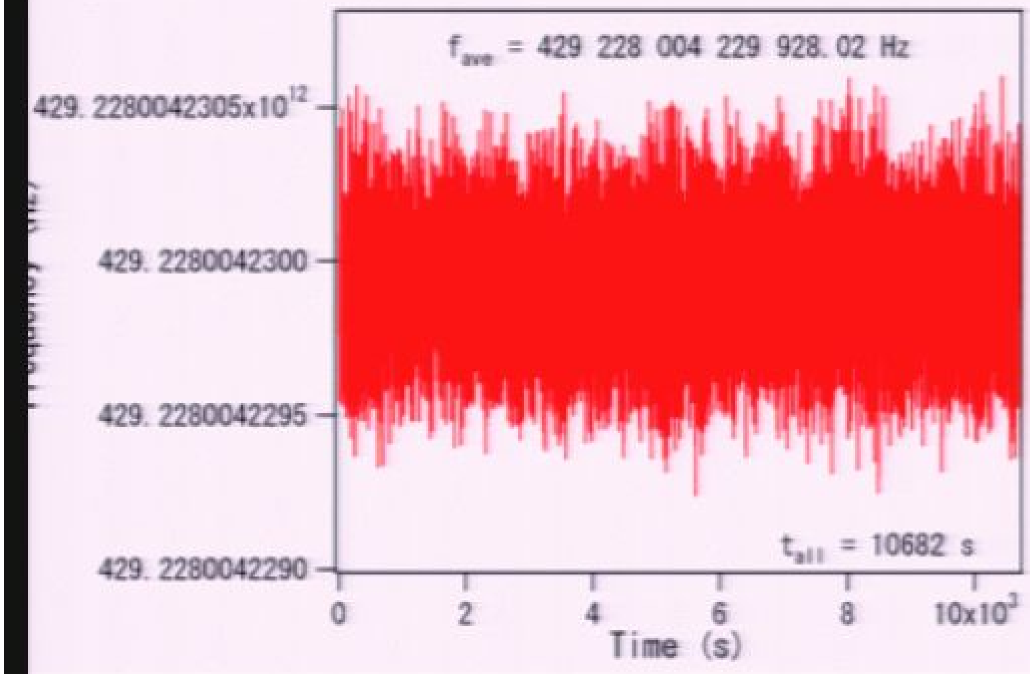

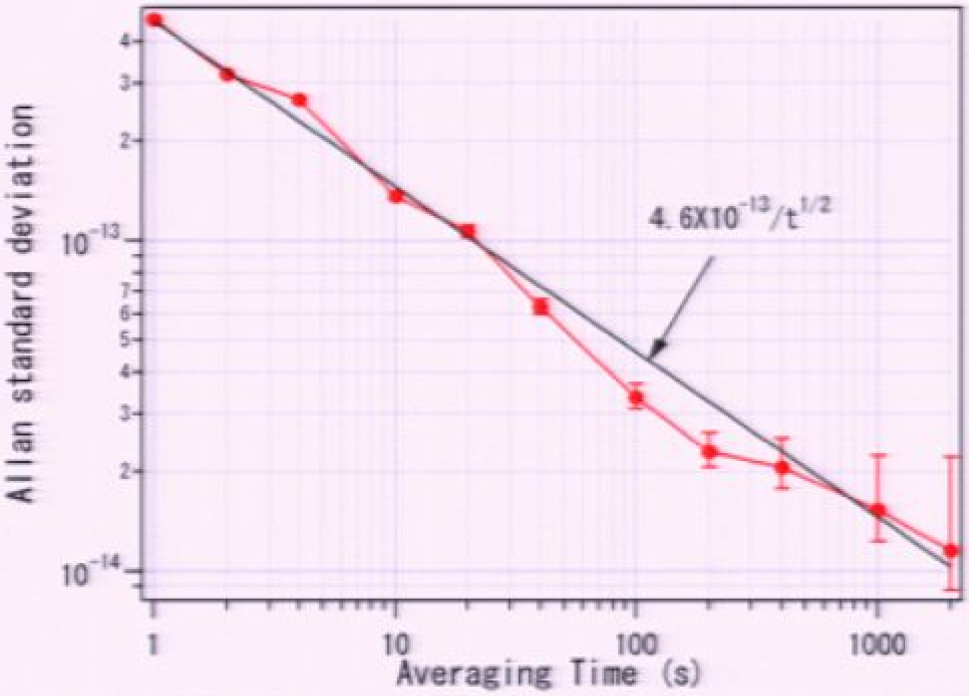

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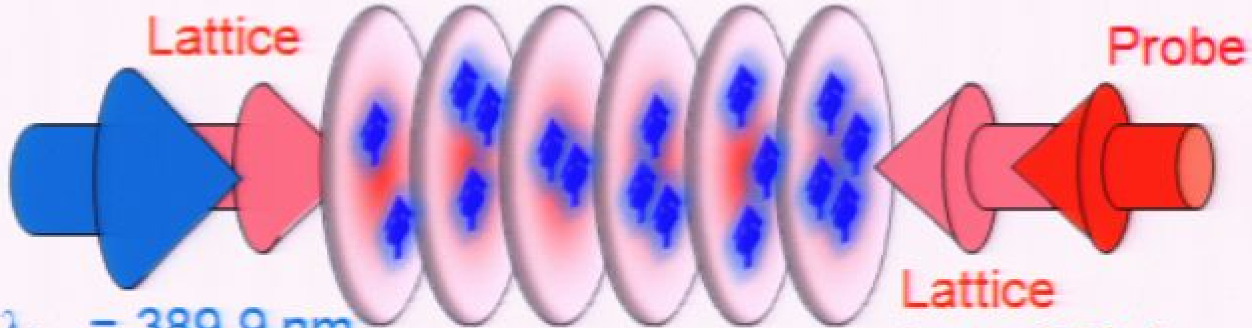
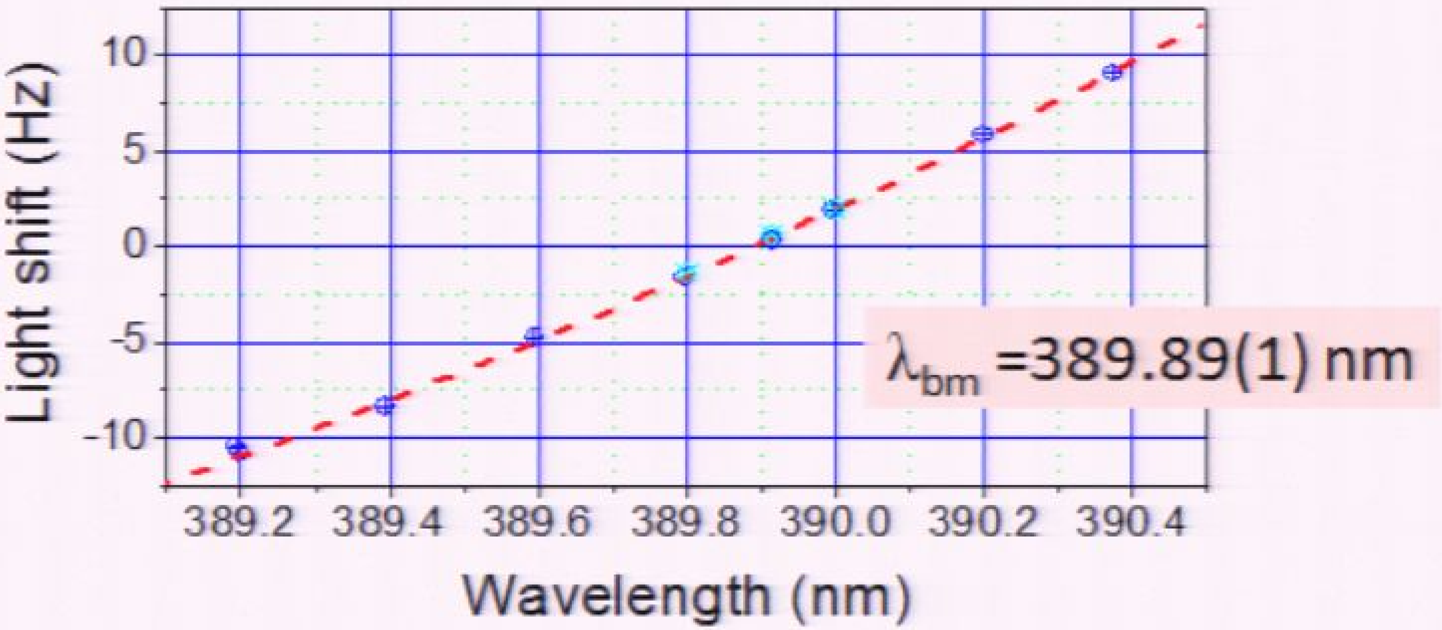
Experimental determination of the blue magic wavelength



λ_{bm} = 389.9 nm
Blue magic wavelength

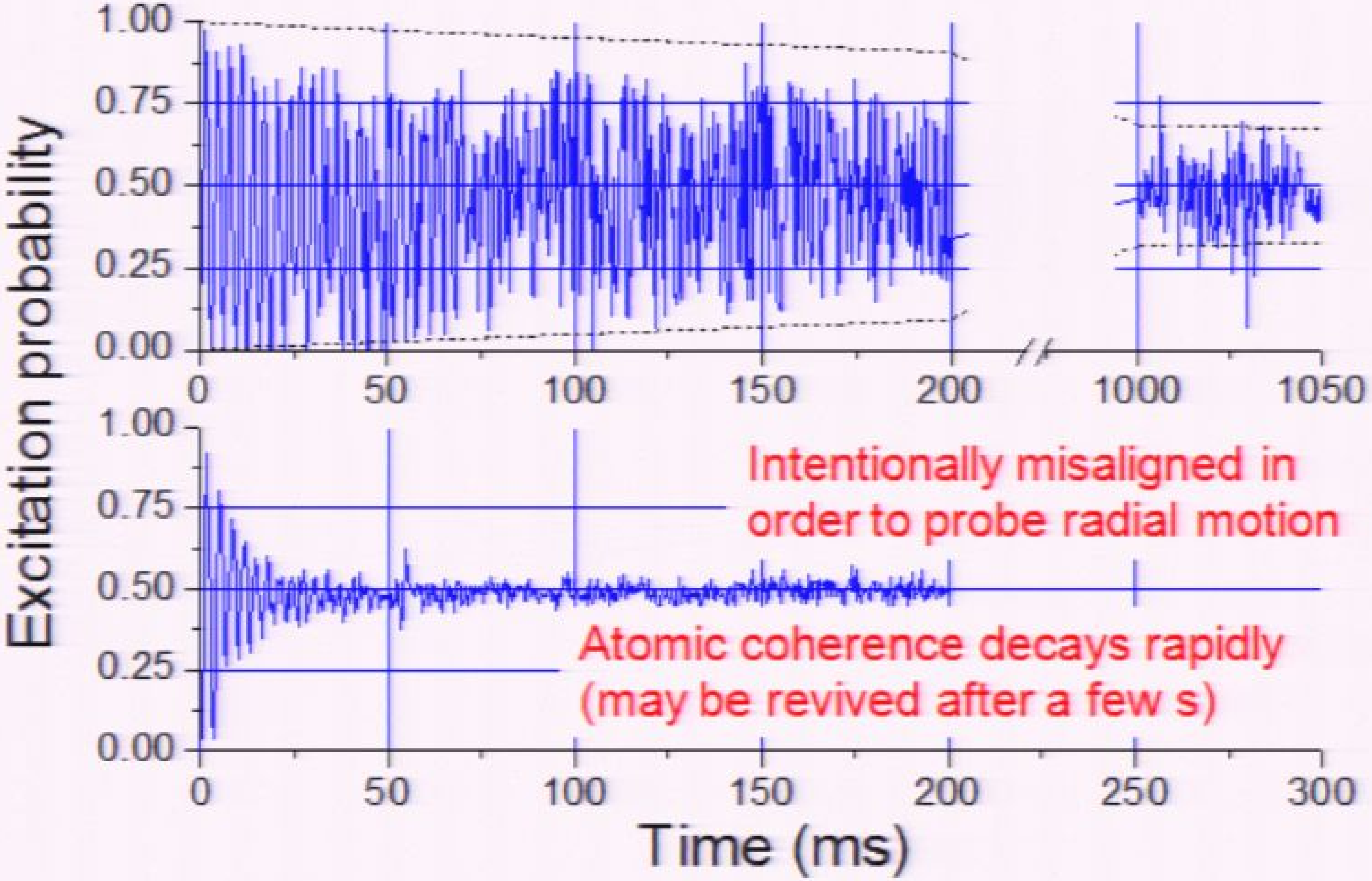
Lattice
λ_{bm} = 813.4 nm



λ_{bm} =389.89(1) nm

$T=10\mu K$: 0.1×10 kW/cm2 $\gamma<10^{-2}/$

Long lived population oscillation over 1s;
Even longer than laser coherence time



Intentionally misaligned in order to probe radial motion

Atomic coherence decays rapidly (may be revived after a few s)

Very long atomic coherence limited residual gas collisions & lattice photon scattering: Presently~1 s (Future 10 s)

Pauli blocking collision will be feasible!

Uncertainty budgets for ^{87}Sr and ^{88}Sr optical lattice clocks

	^{87}Sr	^{88}Sr
Contributor	Correction (Uncertainty) (Hz)	Correction (Uncertainty) (Hz)
Lattice scalar light shift §	-0.22 (0.33)	-0.23 (1.09)
Lattice vector light shift	0 (0.01)	0 (0.014)*
Lattice 4th-order light shift §	-0.017 (0.015)	-0.12 (0.10)
Probe light shift	0.03 (0.001)	7.48 (0.36)
Blackbody shift¶	2.4 (0.2)	2.4 (0.2)
2nd-rder Zeeman shift	0.772 (0.01)	128.61 (0.31)
Collision shift	0.4 (0.3)	-0.034 (0.3)
Systematic total	3.37 (0.49)	138.11 (1.25)
Isotope shift f_{88}-f_{87}	62,188,138.4 (1.3) Hz	

$f_m(^{88}\mathrm{Sr}) - f_m(^{87}\mathrm{Sr})$
$= -100(100)$ MH

$7(6)\ \mu H/E_r^2$

T = 301(5) K

Larger corrections
For bosonic clock

Collision shift appears?

Even though spin-polarized sample is prepared, excitation process is not necessarily in phase! S-P collisions may exist

Cryogenic lattice clock

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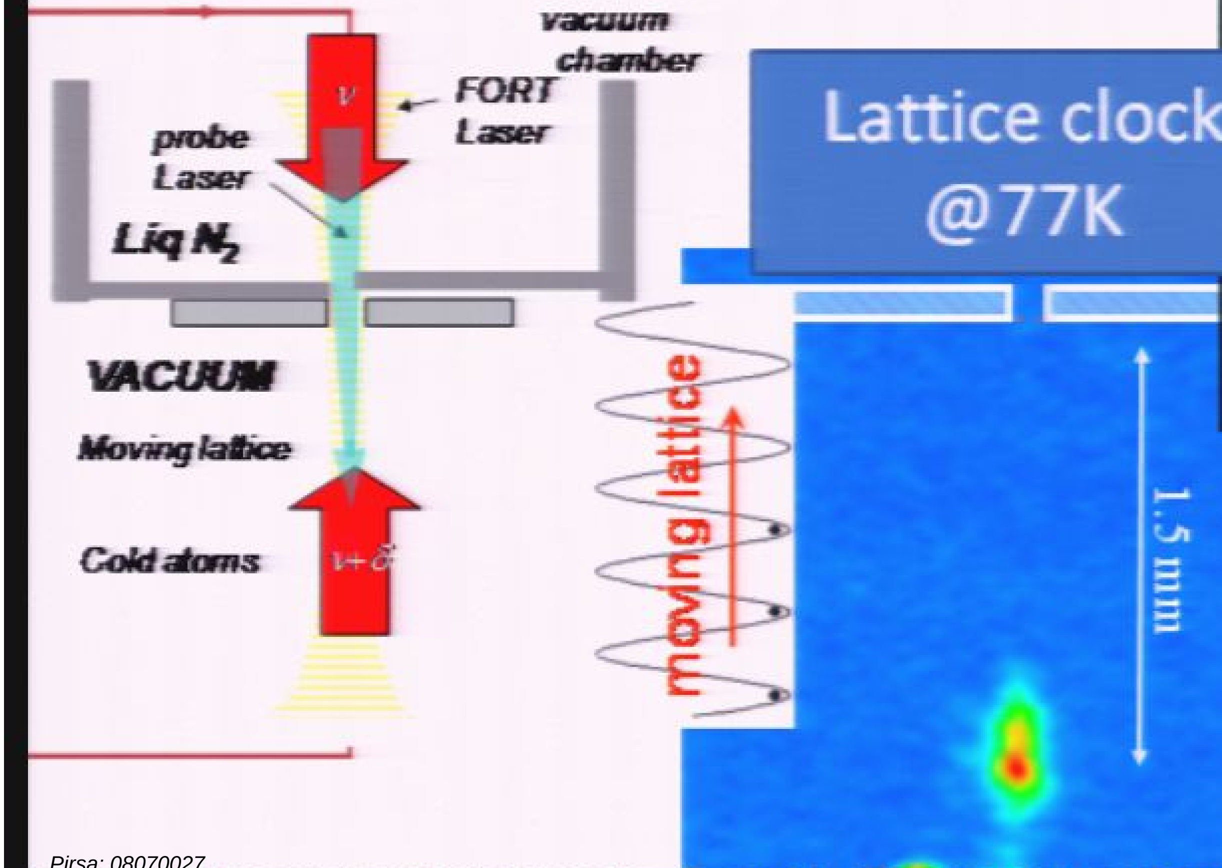
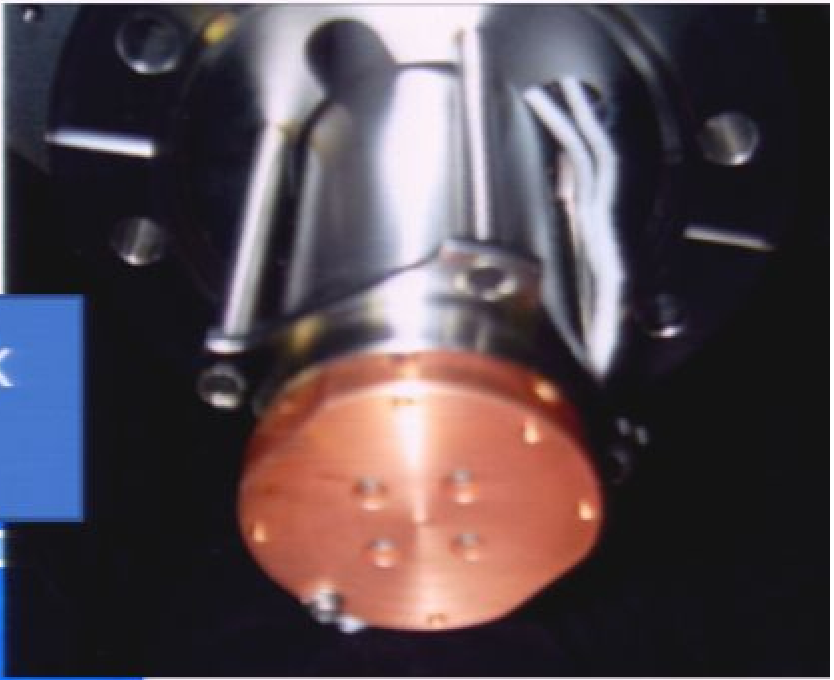
$\sim 10\ \text{mHz} @ 77\text{K}$





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Moving lattice for Sr: Kishimoto, T. *et al.*, *Electrodynamic trapping of spinless neutral atoms with an atom chip*, Phys. Rev. Lett. 96, 123001 (2006)

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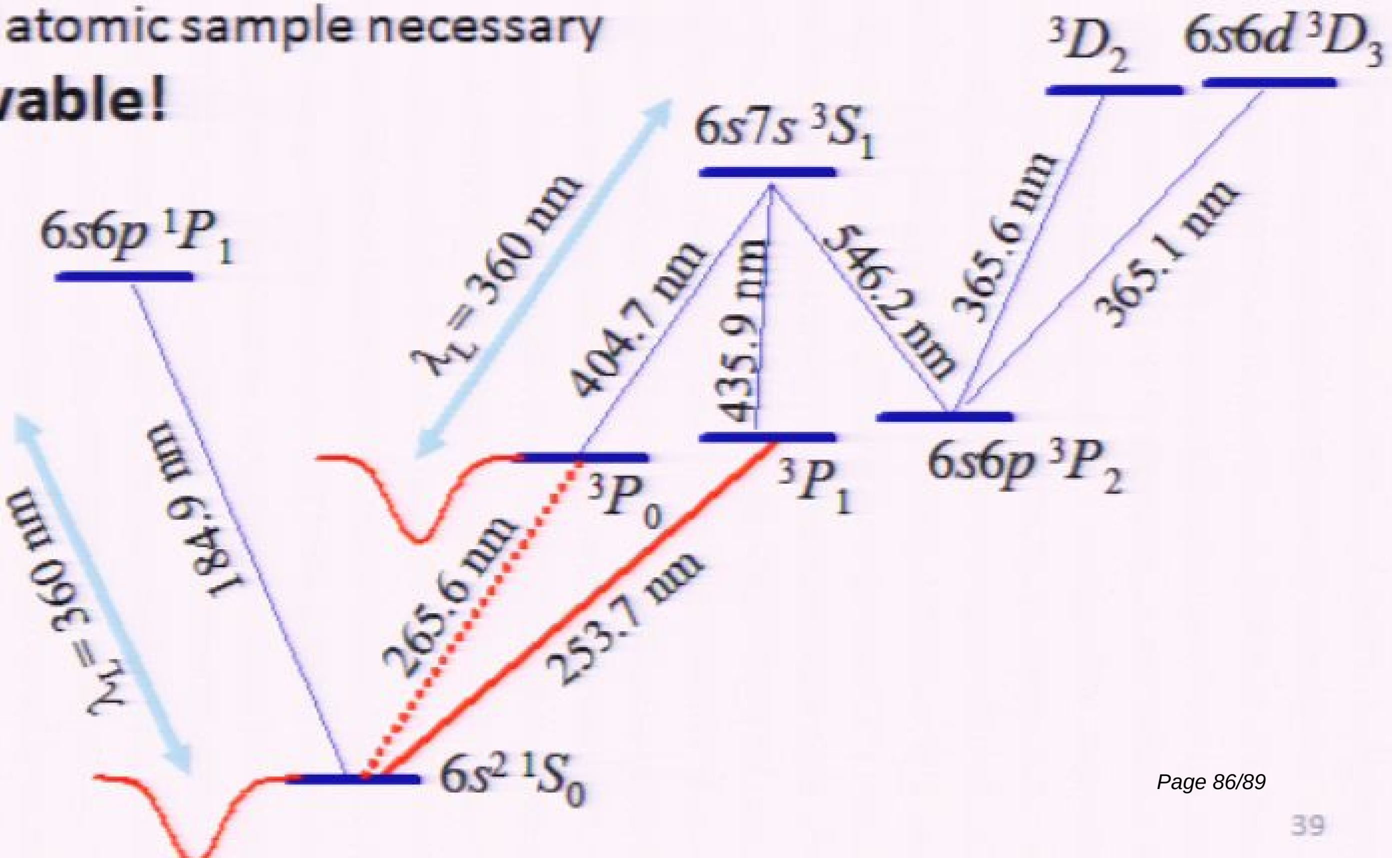

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1