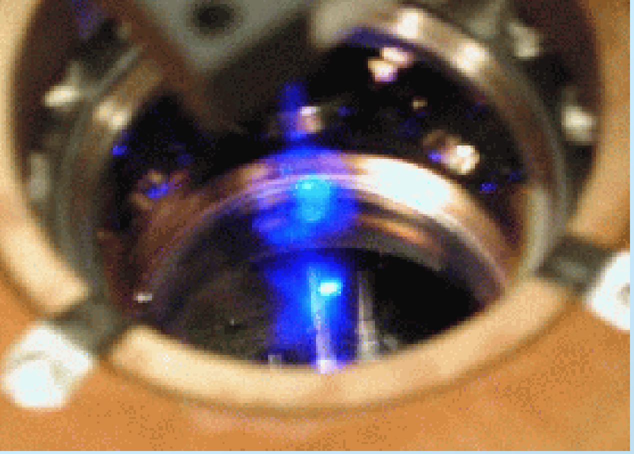


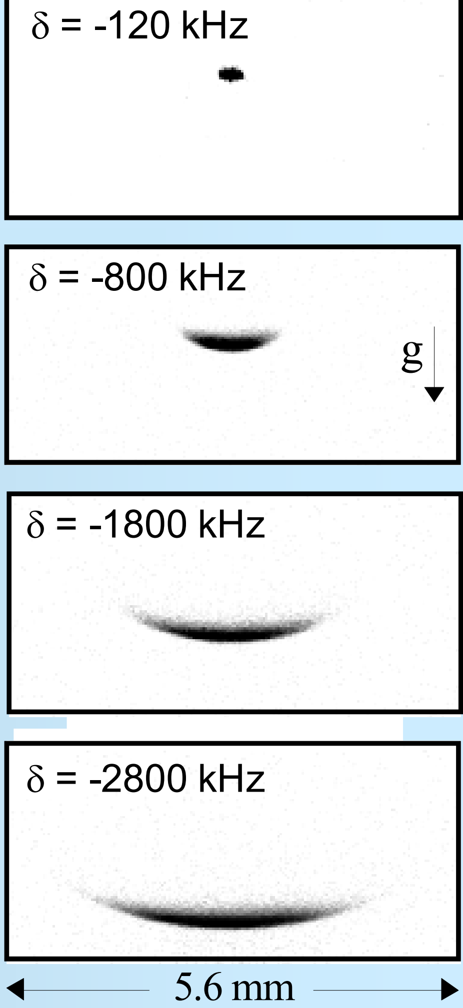
Sr optical lattice

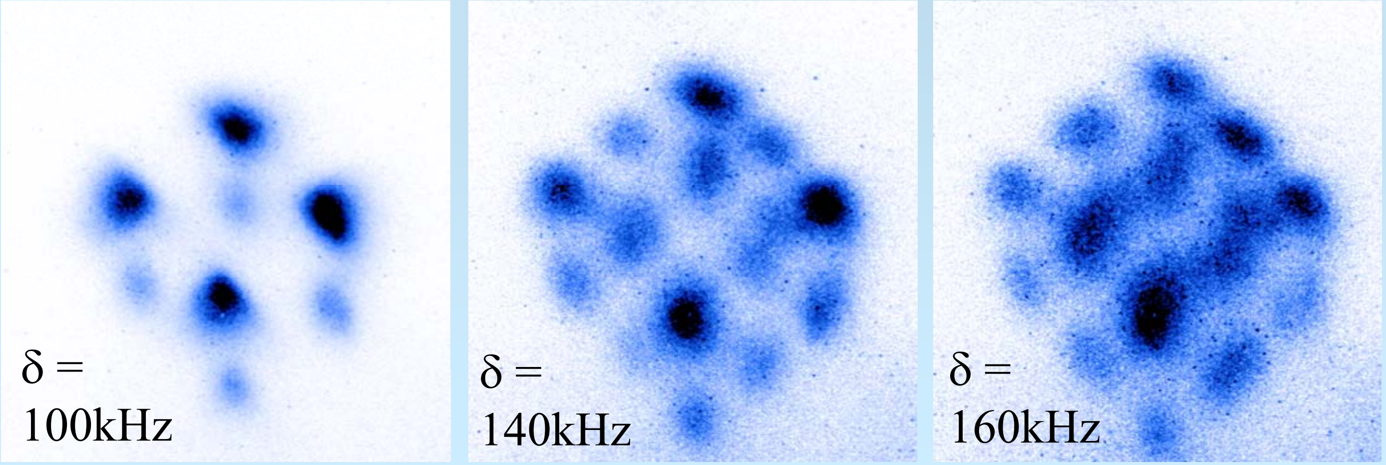
J. Ye

JILA, NIST and University of Colorado

http://jilawww.colorado.edu/YeLabs

Michigan Quantum Summer School
Ann Arbor, June 16, 2008



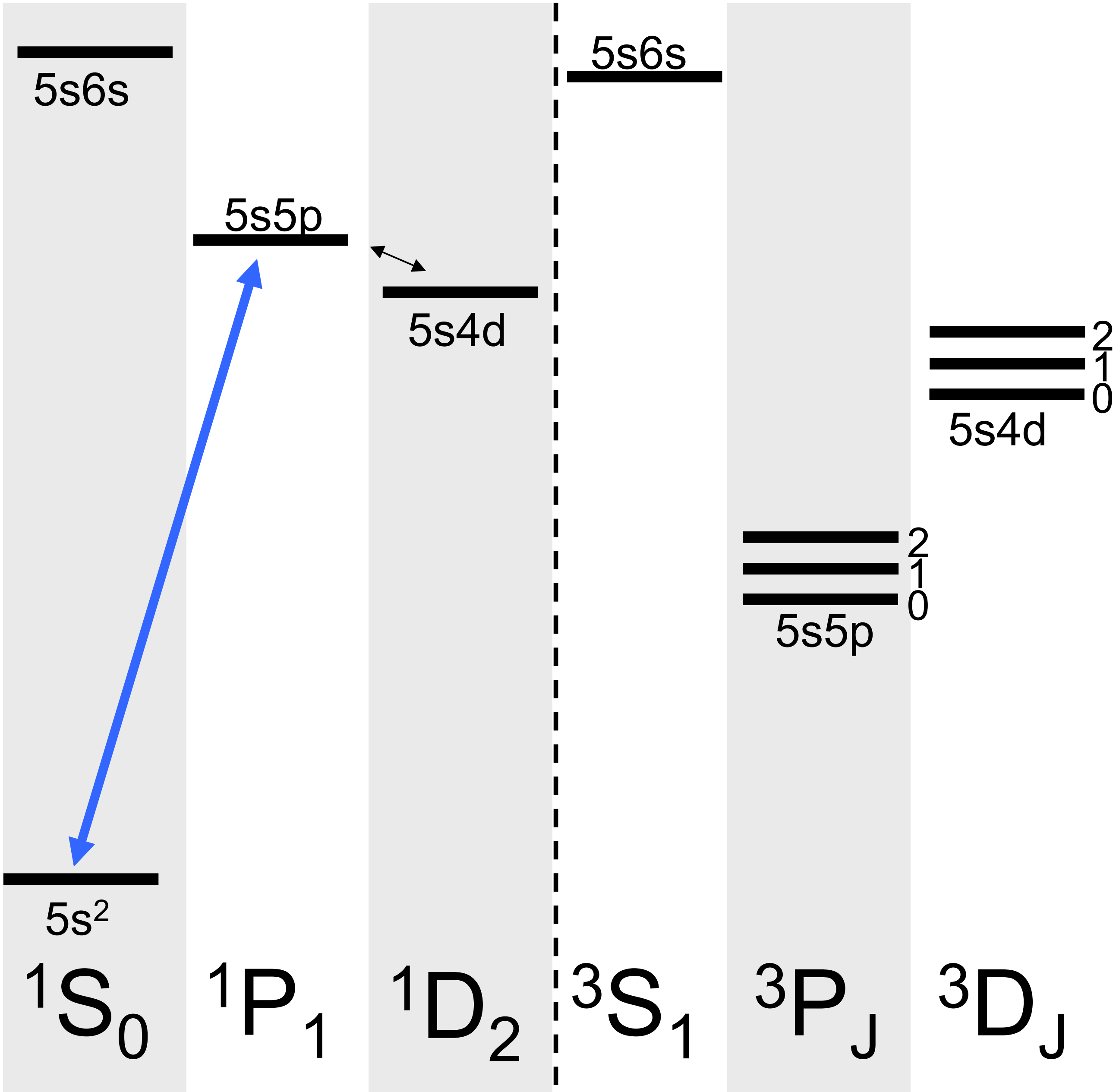


Alkaline Earth versus Alkali

Alkali	Alkaline Earth
All-Optical Cooling to Ultra-Low Temperatures	
Polarization Gradient	High Density
Stimulated Raman	Intercombination line sub-recoil
VSCPT	Sideband Cooling in Dipole Traps
Limited to Low Densities	Low Transfer Efficiency
Cold / Ultra-Cold Collisions	
High Collision Rates	Quantitative Studies
Feshbach Resonances	
Hyperfine structure	Low Collision Rates
BEC / FDG	
Ground-State Magnetic Traps	Diversity of Bose, Fermi Isotopes
Tunable Interactions	Optical Feshbach resonance
Only two Fermions: ^{40}K, ^{6}Li	Structure Free Ground State
Time / Frequency Metrology	
Microwave Clocks	High Optical Line Q
Small Optical Line Q	Second-Stage Cooling Required

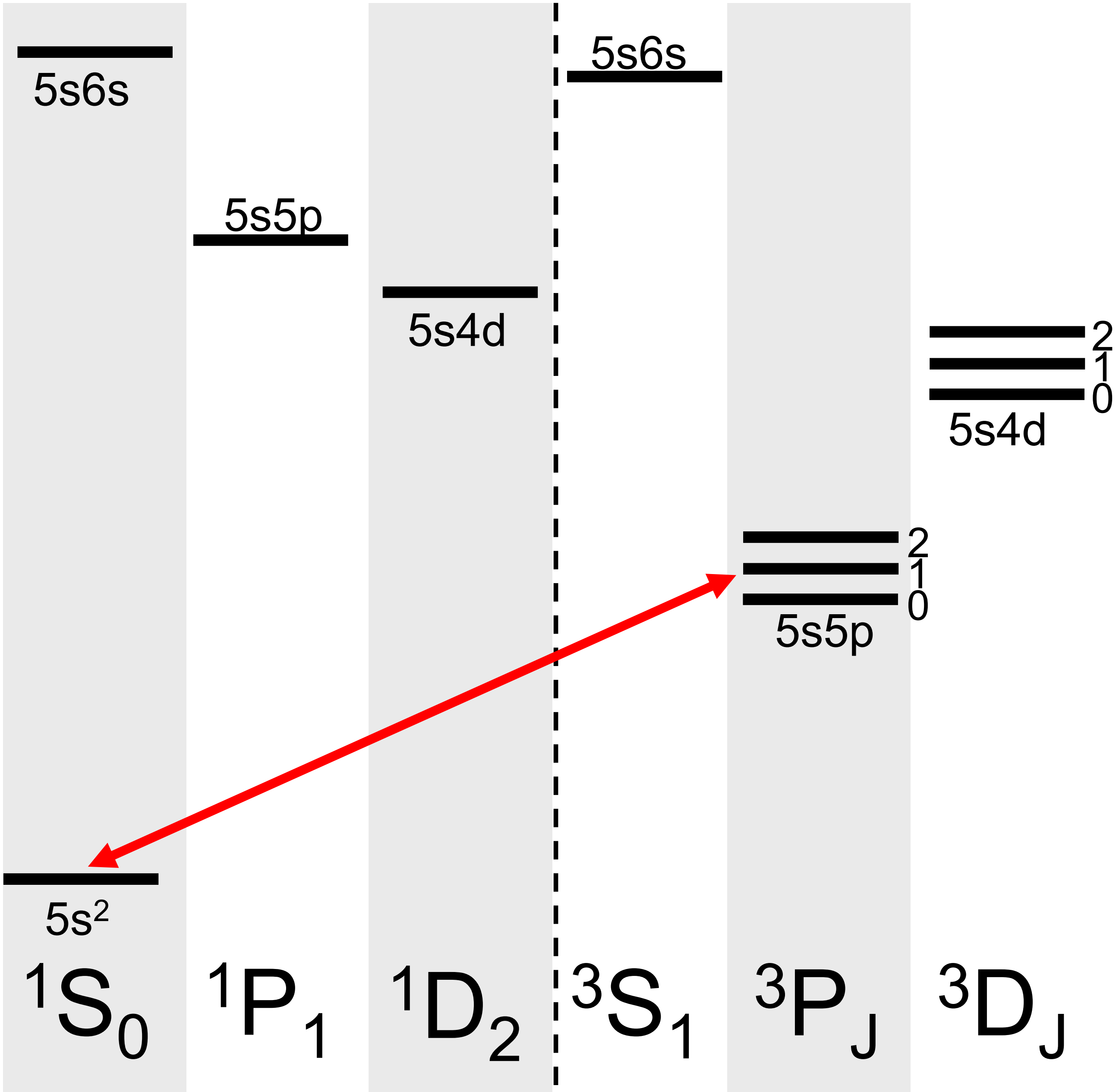
Strontium: Pre-cooling

- large dipole moment
- mostly closed transition
- J=0 to J=1
- diode laser with frequency doubling



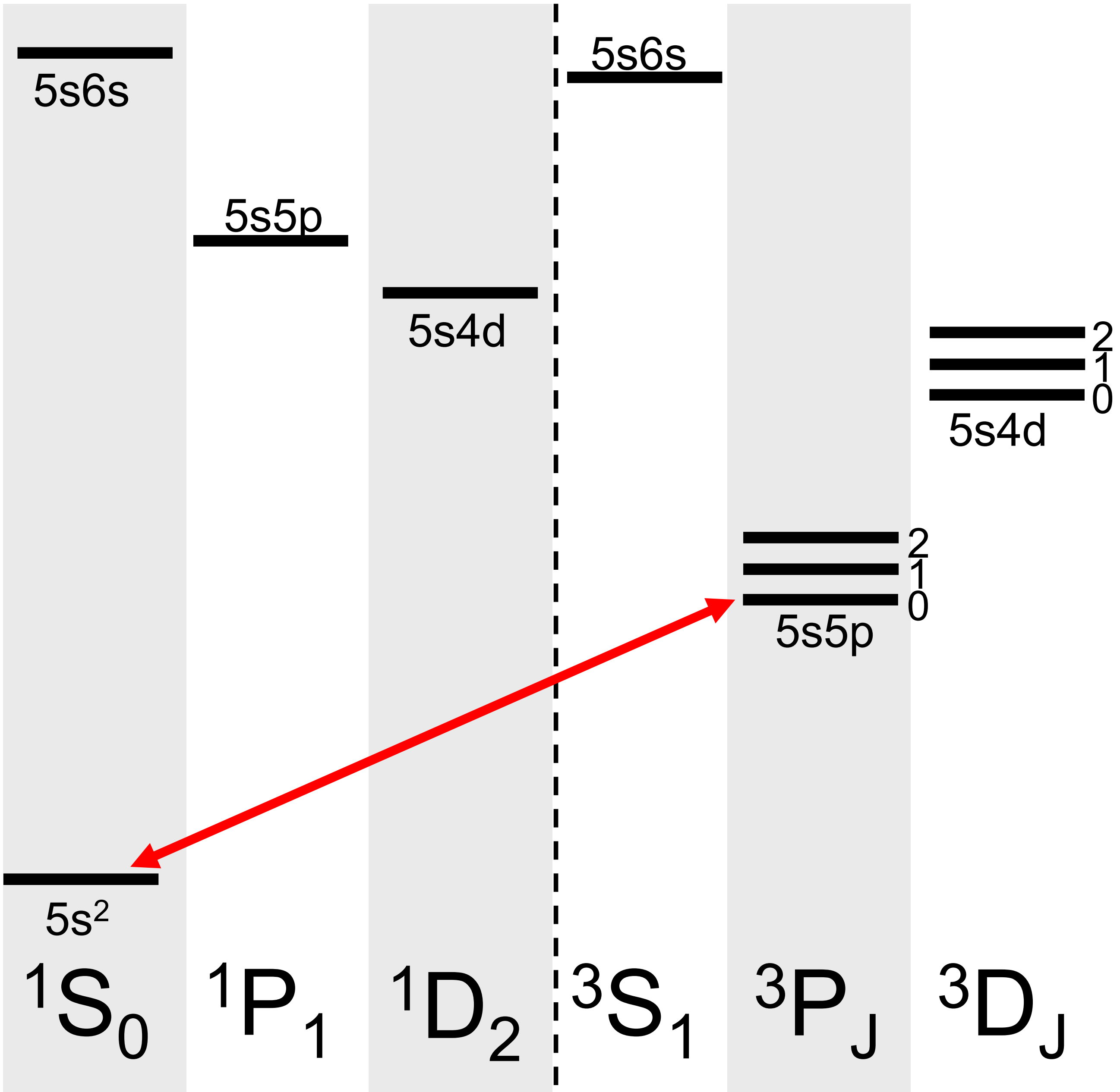
Strontium: Narrow Line Laser Cooling

- smaller dipole moment
- closed transition
- J=0 to J=1
- diode laser accessible

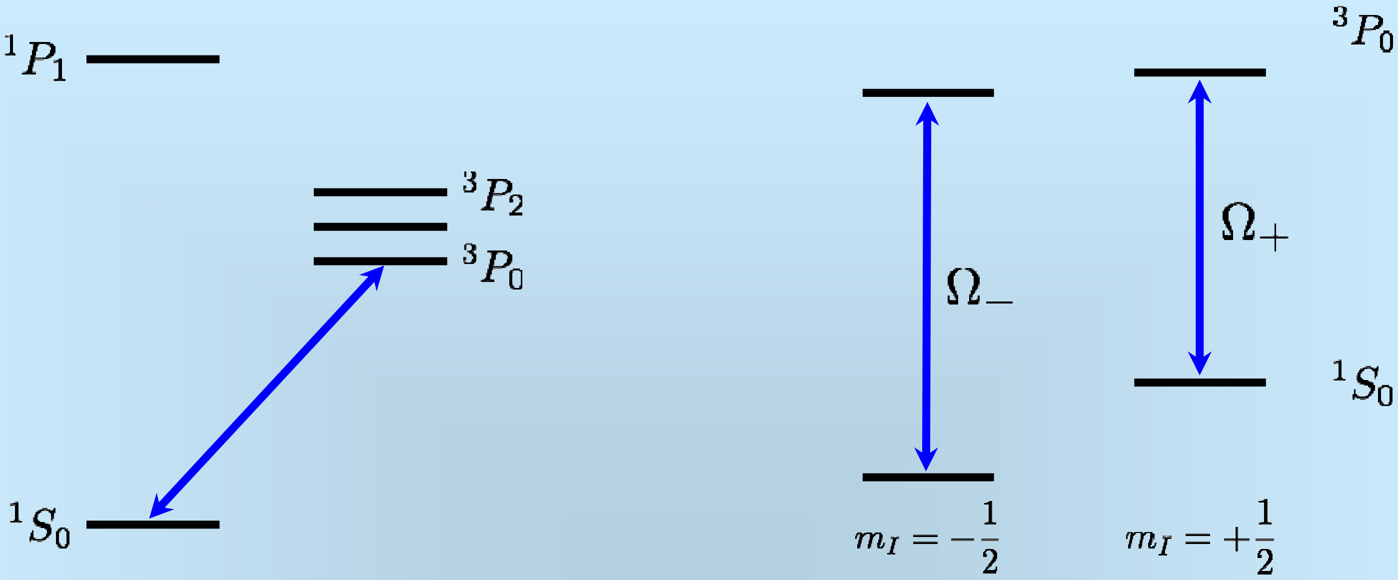


Strontium: Clock Transition

- HFI provides $^1S_0$-$^3P_0$ clock (~ 1mHz)
- field insensitive states
- diode laser
- accessible Stark-free confinement wavelength
- clock states J=0



Quantum Simulations with Alkaline Earth



New Features:

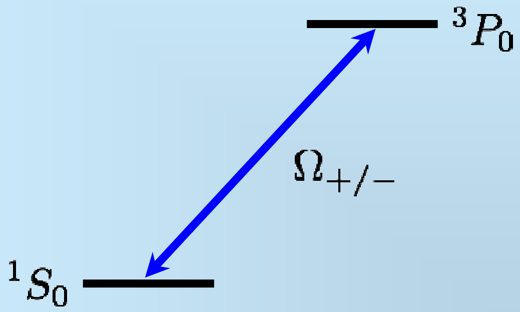
- Metastable optical states
- Clock transition – spectral resolution
- Nuclear spin decouples from the electronic state

Implementation:

- Nuclear spin states for quantum information storage
- Electronic state for:
  - Creation of state-dependent lattices
  - Access to control and readout

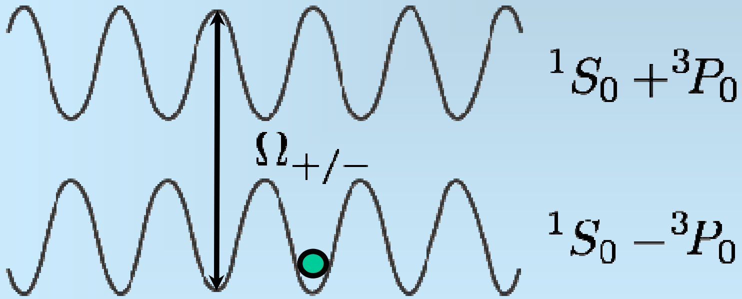
- Many ideas originally invented for Alkali atoms freed from technical problems
- New possibilites

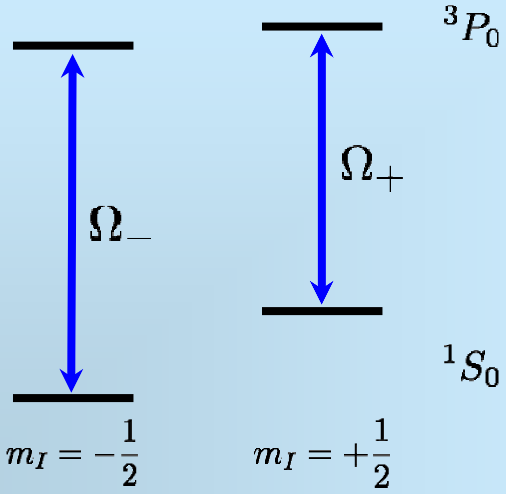
State-dependent lattices



Dressed Potentials:

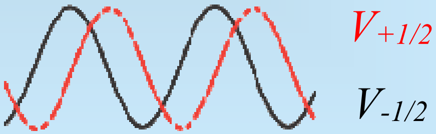
- Resonant coupling on clock transition
- Use a standing wave
  (oscillating Rabi frequency)
- AC-Stark split states:





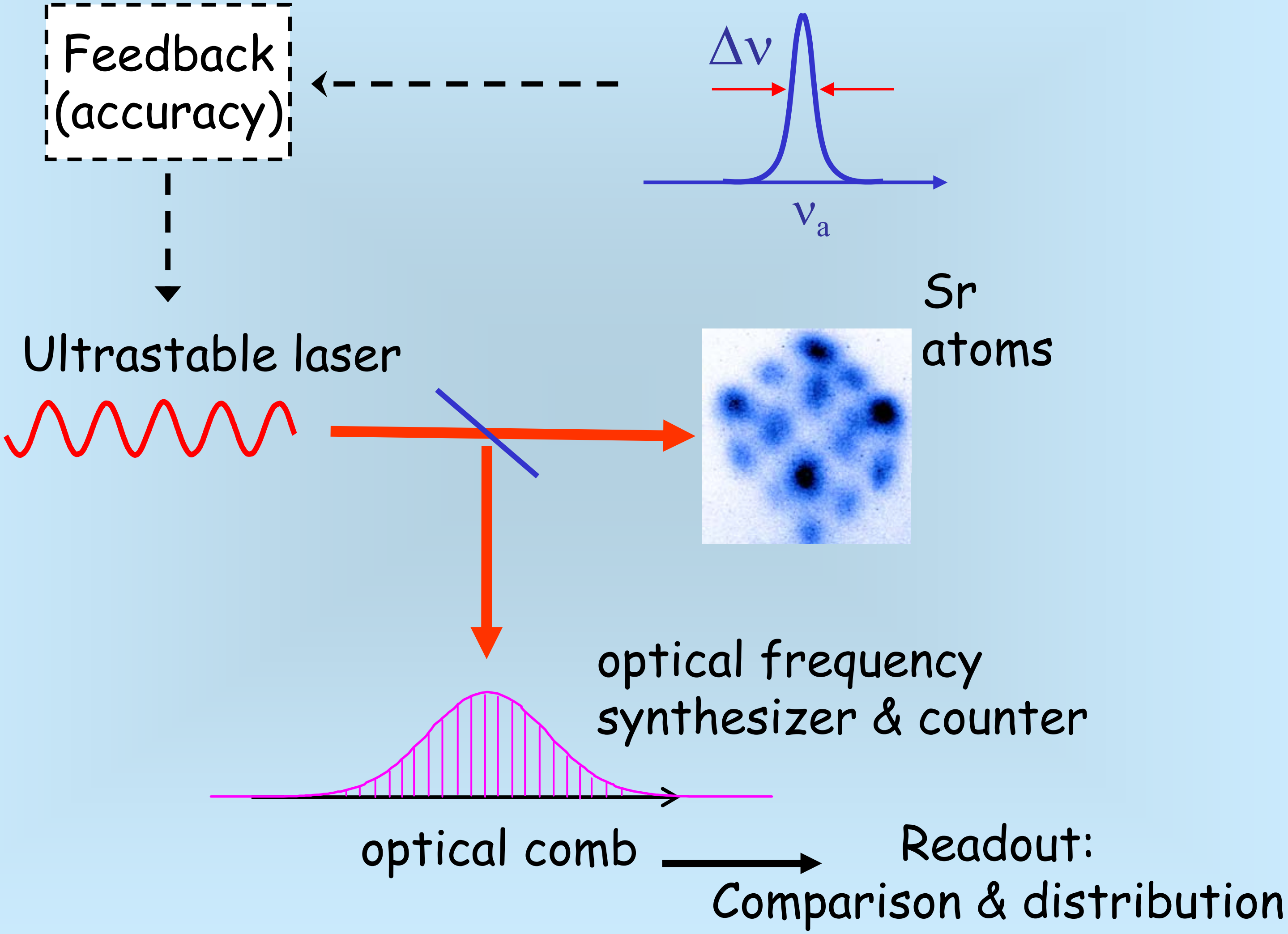
Spin-dependent lattices:

- Differential Zeeman shift
- Frequency-addressed resonant coupling
- Separately controllable lattices for two nuclear spins



Andrew Daley and Peter Zoller

Optical atomic clocks



Feedback
(accuracy)

Ultrastable laser

Sr
atoms

optical frequency
synthesizer & counter

optical comb

Readout:
Comparison & distribution

Control of matter

Long - term quantum coherence:

Clean separation between internal & external degrees of freedom

Both in well defined quantum states

Cool Alkaline Earth - Strontium

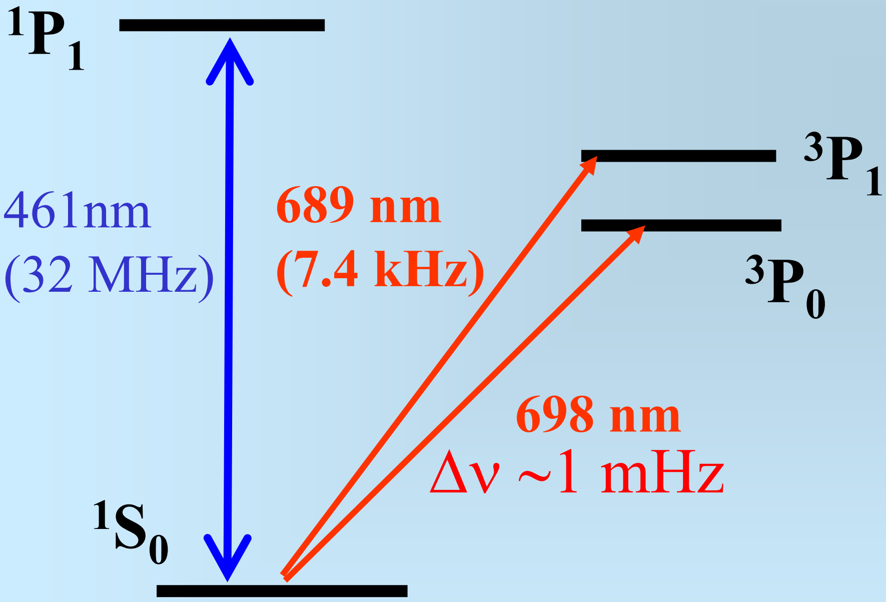
JILA, SYRTE, Tokyo, LENS, PTB, NPL, NRC, NIM

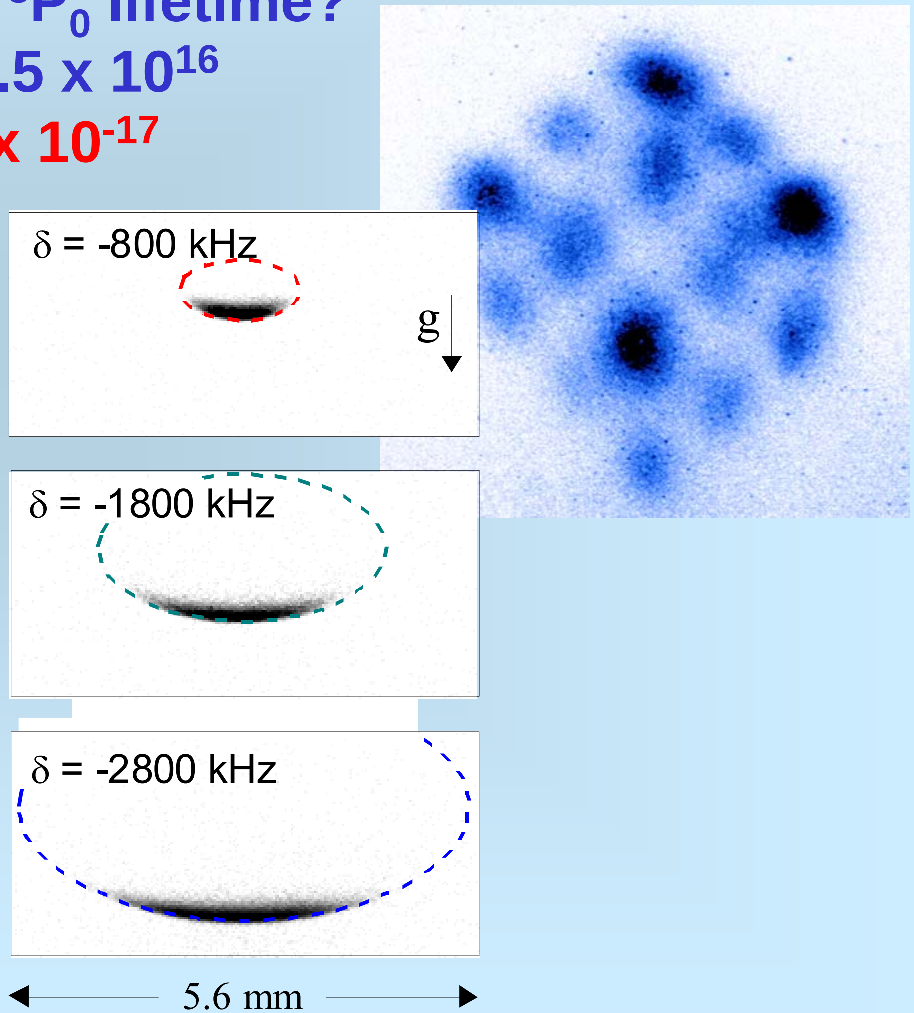
T ~ 0.5 photon recoil
~ 220 nK

How many cycles are there in the $^3P_0$ lifetime?

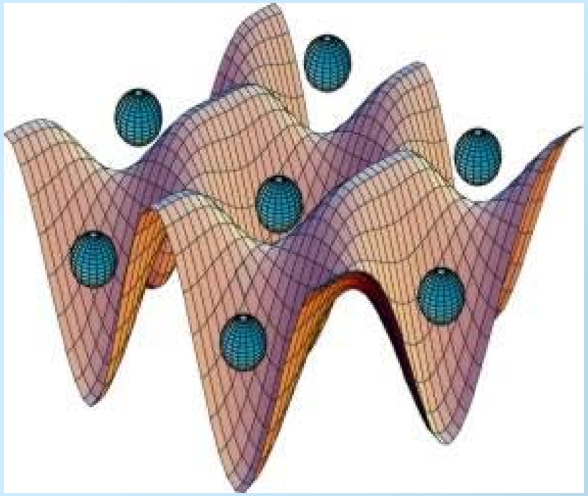
$(4.3 \times 10^{14}$ Hz$) \times (150$ s$) = 6.5 \times 10^{16}$

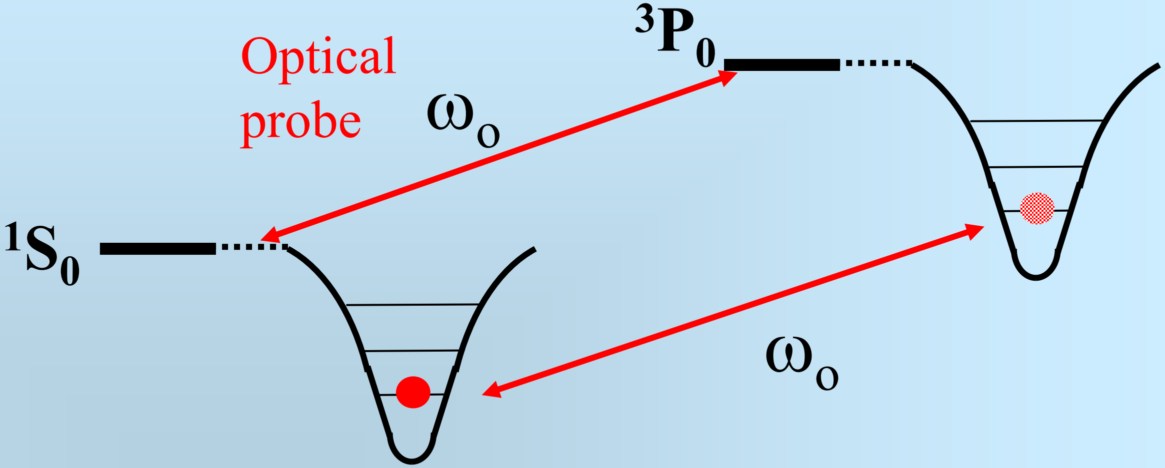
or, in fractional terms: 1.5×10^{-17}





Quantum metrology in optical lattice





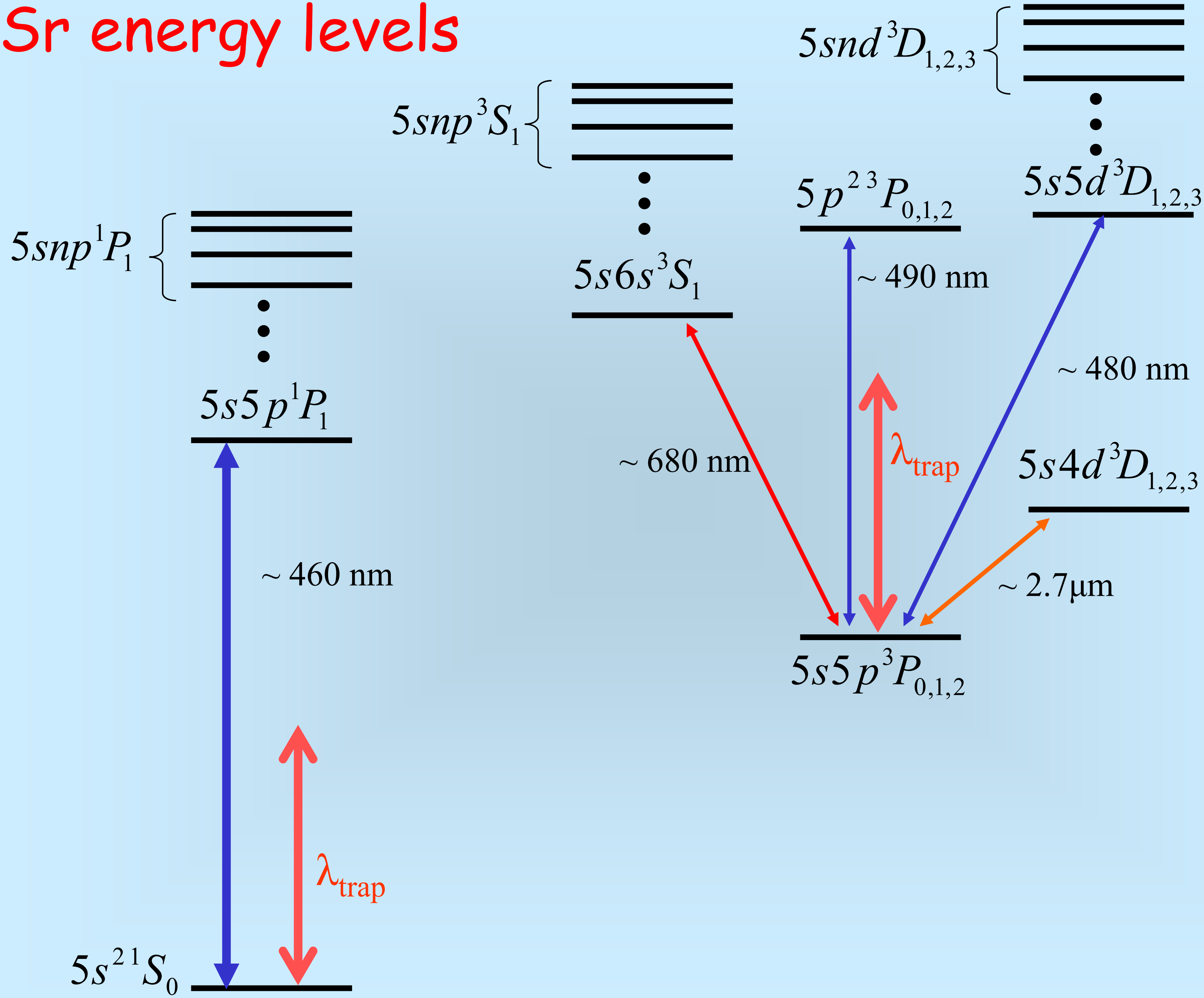
- **Atomic confinement $\ll \lambda$ ($e^{ikx} \sim 1$, $k = 2\pi/\lambda_{probe}$)**

- **Trap potential identical for $^1S_0$ and $^3P_0$**

Ye, Kimble, Katori, Science (June 27, 2008).

- N quantum absorbers improve precision by $N^{1/2}$
- No ac Stark shift from the trap; Collision shift minimized
- Long observation time; Zero Doppler shift, Zero recoil shift

Sr energy levels



$5snd\,^3D_{1,2,3}$

$5snp\,^3S_1$

$5p^2\,^3P_{0,1,2}$

$5s5d\,^3D_{1,2,3}$

$5snp\,^1P_1$

$5s6s\,^3S_1$

~ 490 nm

~ 480 nm

λ_{trap}

$5s5p\,^1P_1$

~ 680 nm

$5s4d\,^3D_{1,2,3}$

~ 460 nm

~ 2.7µm

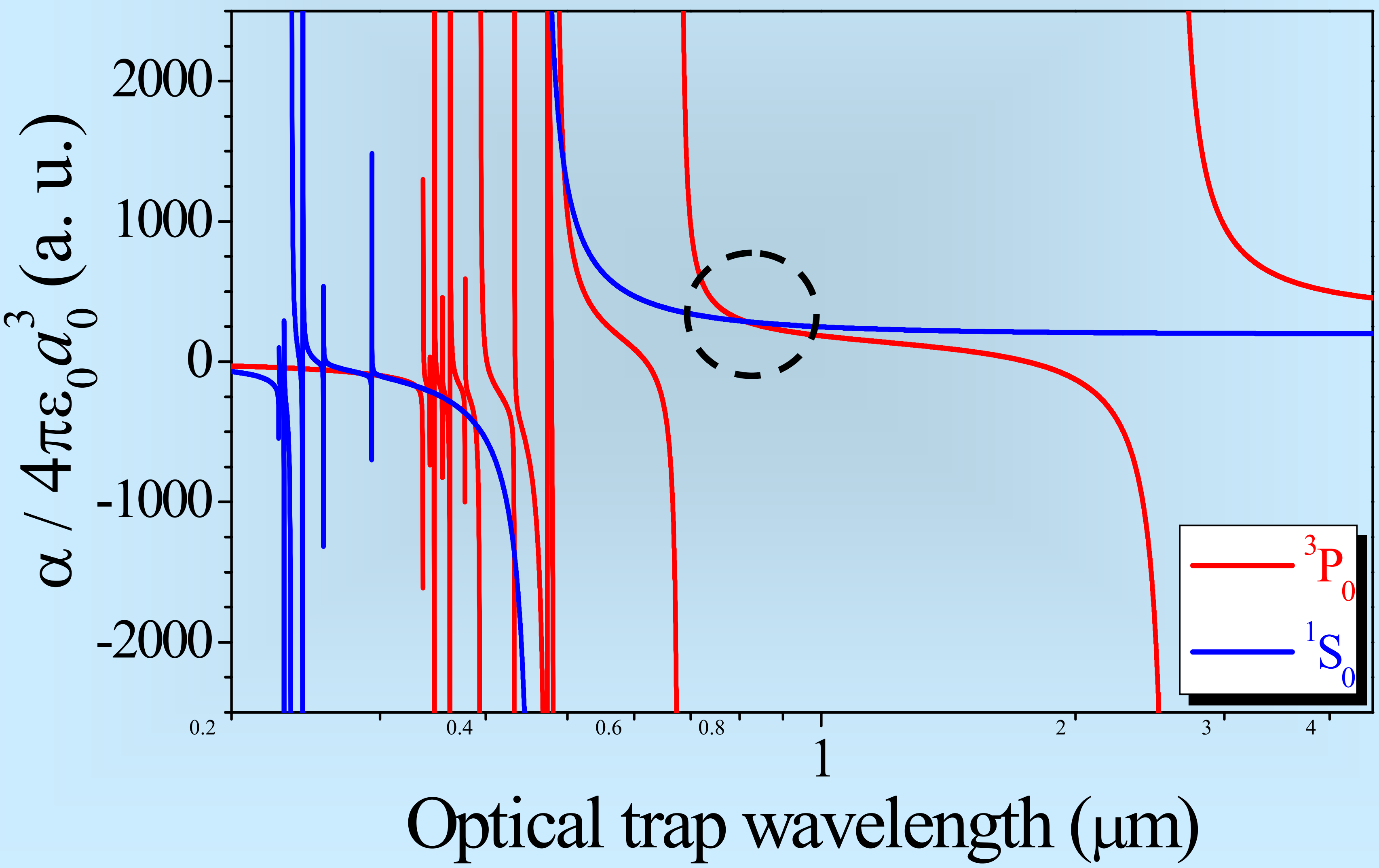
$5s5p\,^3P_{0,1,2}$

λ_{trap}

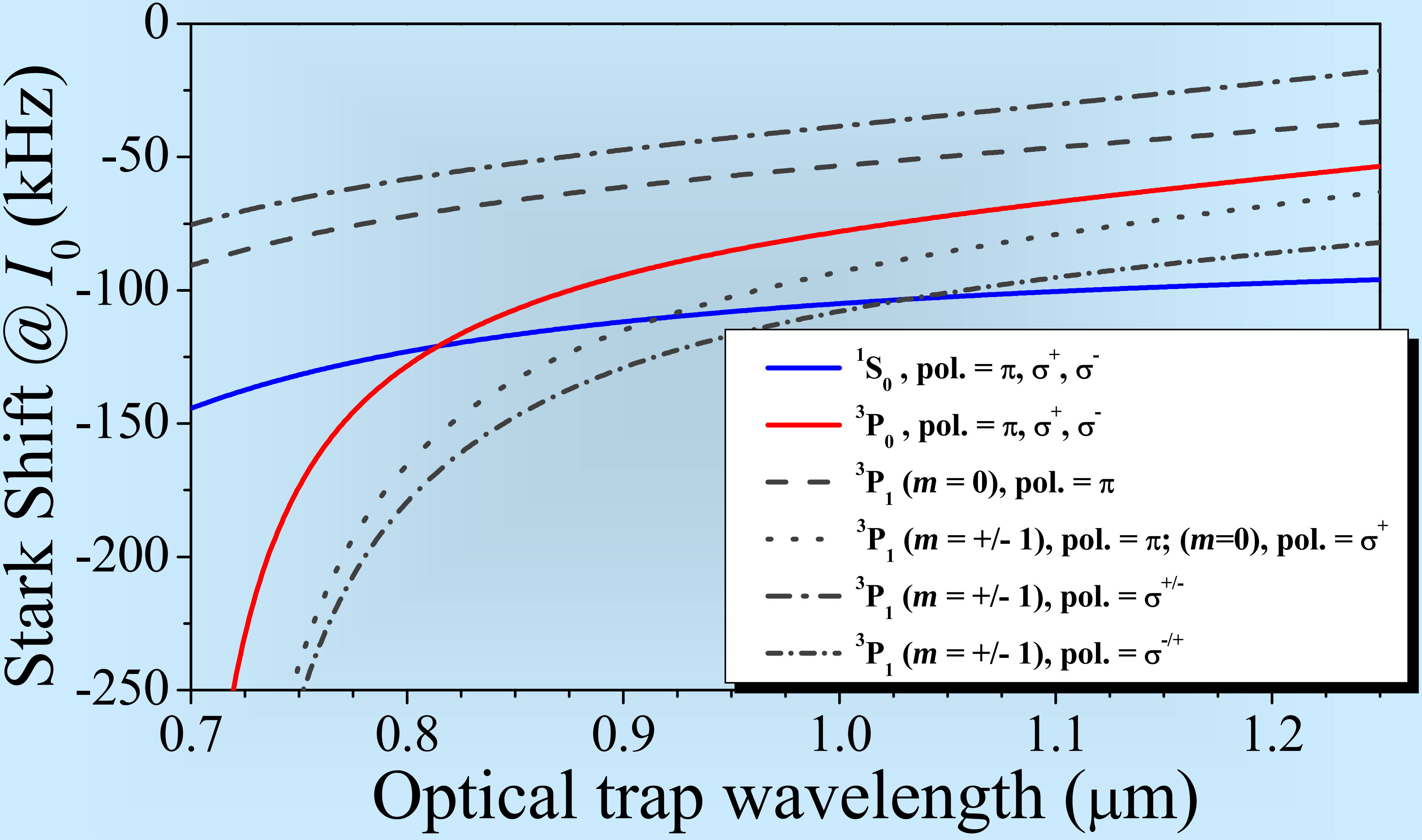
$5s^2\,^1S_0$

Crossing of polarizabilities

Ye, Kimble, & Katori, Science, June 27, 2008.



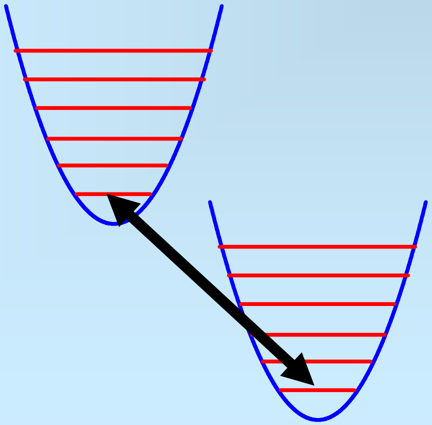
It's a mess if J ∓ 0



Important Regimes for Spectroscopy

$\omega_{trap} >> \Gamma$ well-resolved sideband

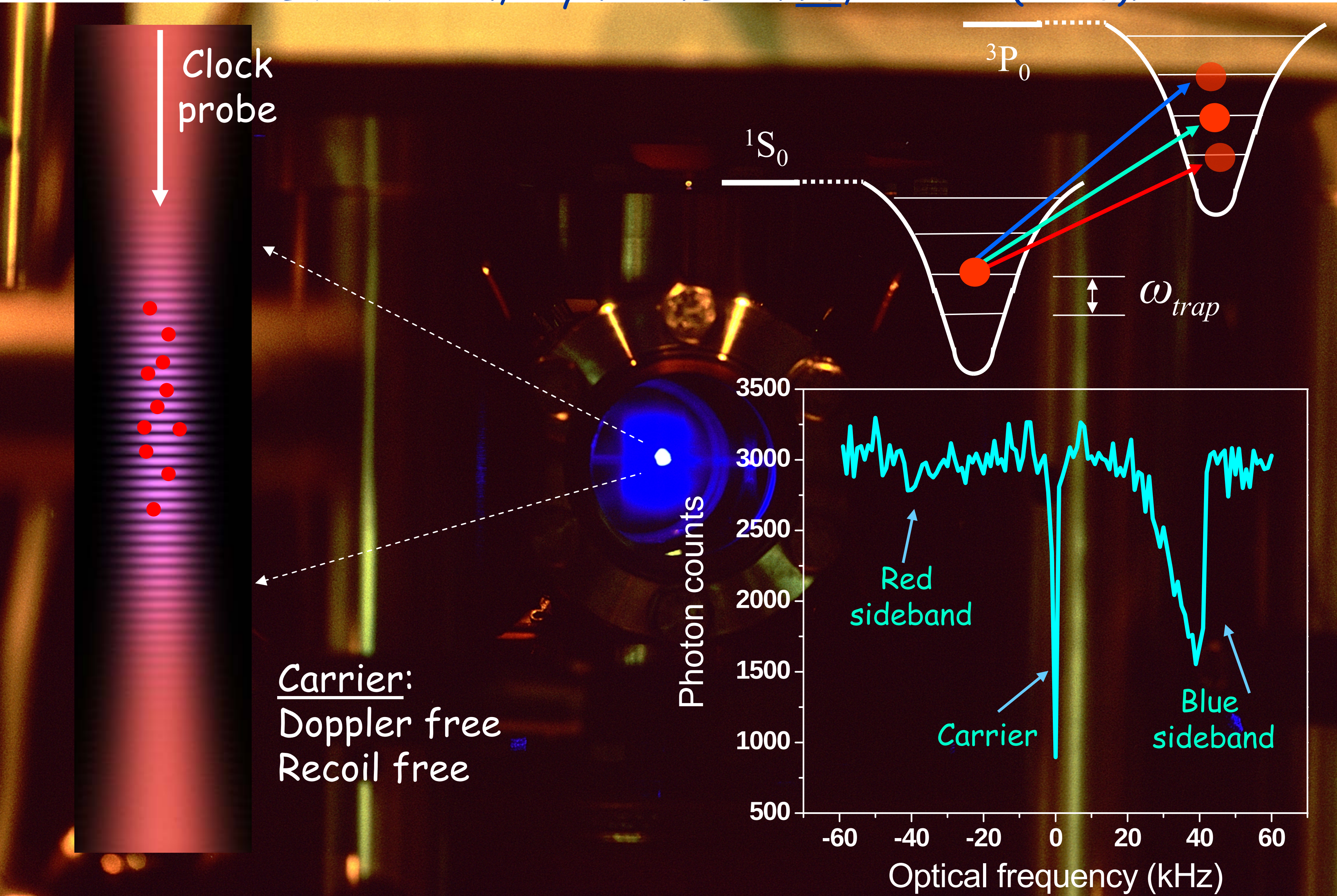
Lamb-Dicke $\omega_{trap} >> \omega_{recoil}$



uniform confinement

Spectroscopy at the magic wavelength

Ludlow et al., Phys. Rev. Lett. 96, 033003 (2006).



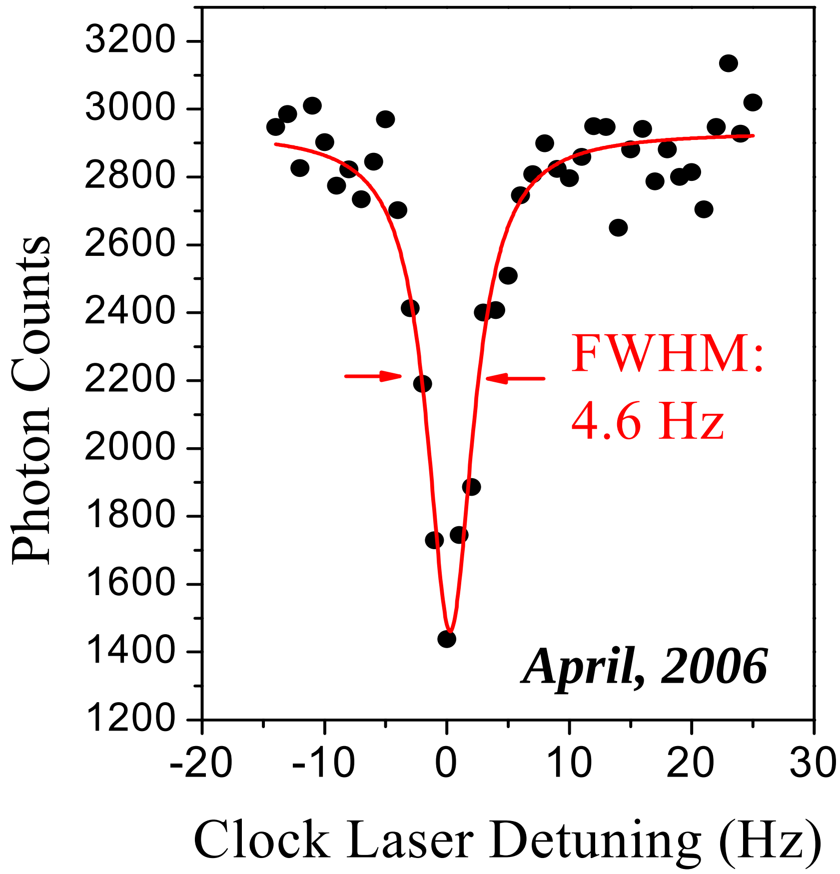
Clock probe

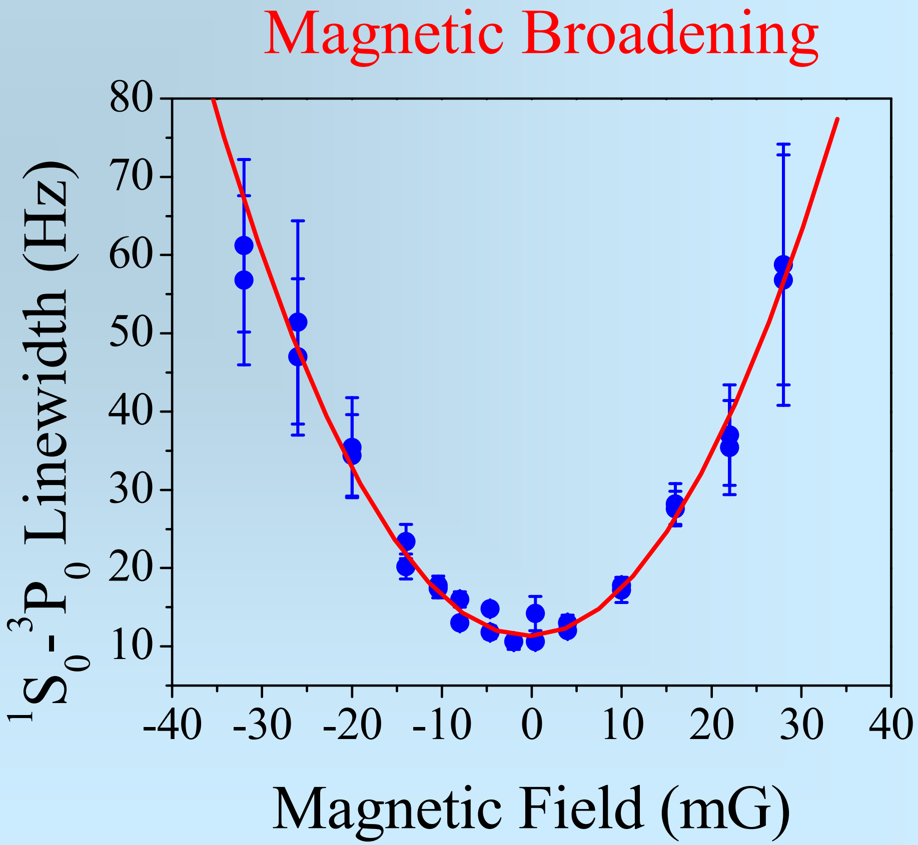
Carrier:
Doppler free
Recoil free

Zoom into the carrier of ^{87}Sr $^1S_0 - {}^3P_0$

- *Single trace without averaging*

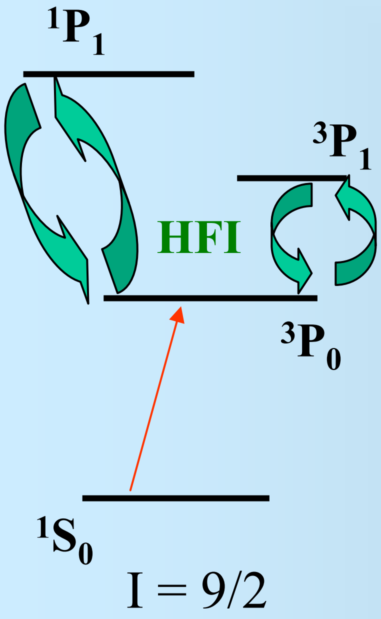
***Q* ~ 1 x 10^{14}**





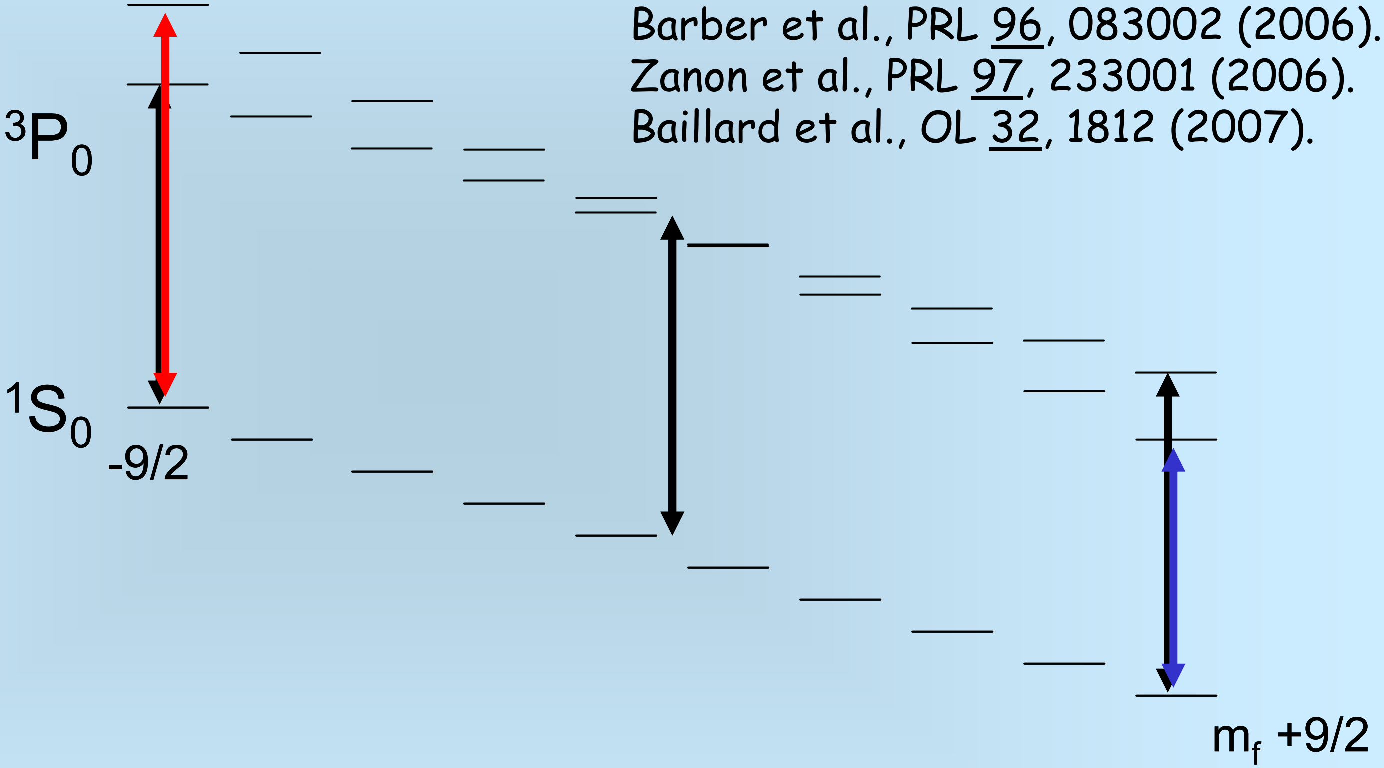
Differential *g*-factor & Tensor polarizability

$$|{}^3P_0'\rangle = |{}^3P_0\rangle + c_1|{}^1P_1\rangle + c_2|{}^3P_1\rangle$$



Proposals & work based on Bosons:

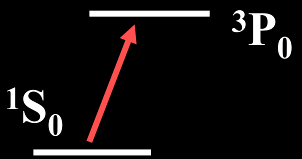
Santra et al., PRL 94, 173002 (2005).
Hong et al., PRL 94, 050801 (2005).
Barber et al., PRL 96, 083002 (2006).
Zanon et al., PRL 97, 233001 (2006).
Baillard et al., OL 32, 1812 (2007).



- $^3P_0$ *g*-factor different from $^1S_0$ due to hyperfine
- m_F – dependent vector & tensor AC shifts from the lattice trap
- All can be determined with high-resolution measurement

Optical Measurement of Nuclear *g*-factor

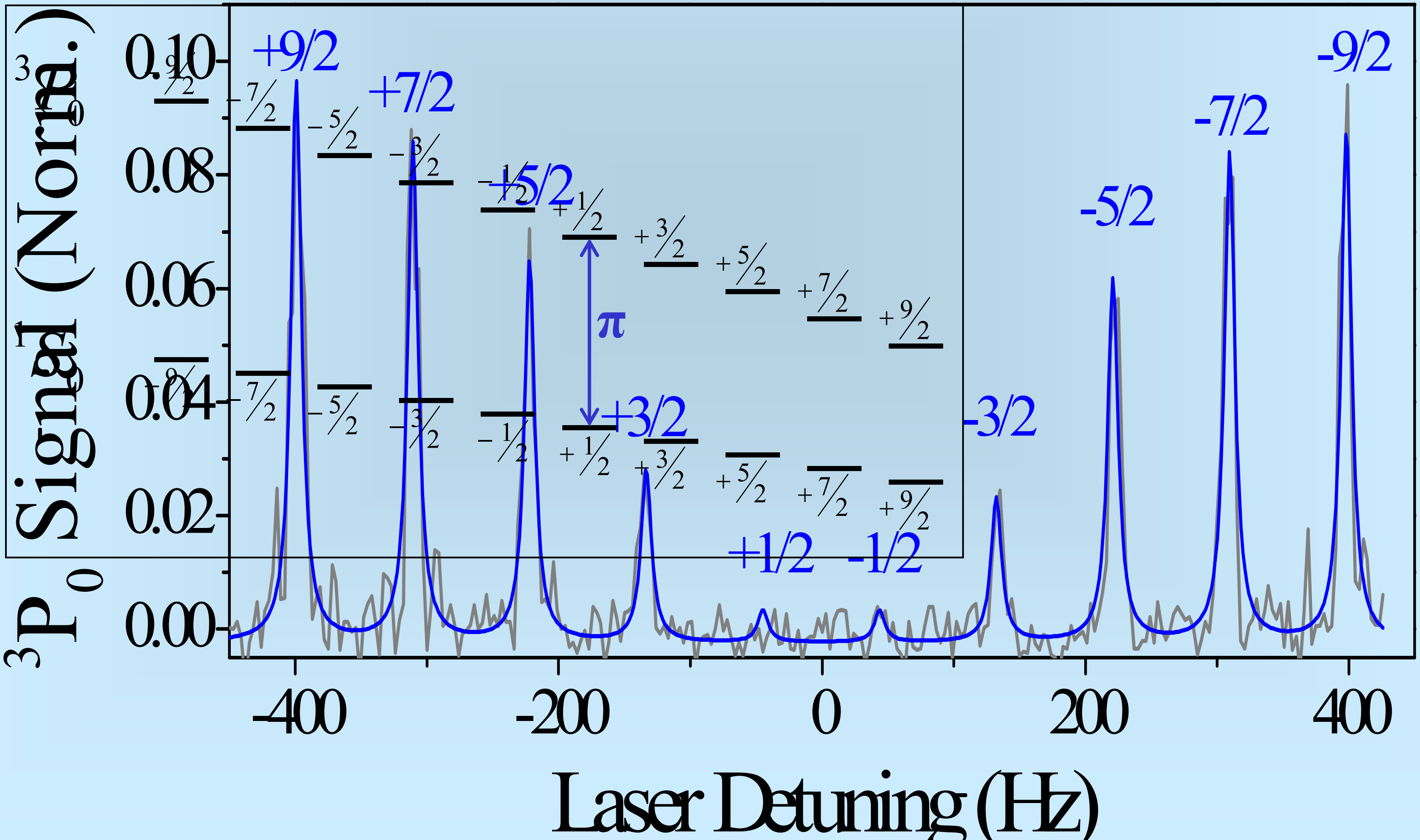
Boyd, Zelevinsky, Ludlow, Foreman, Blatt, Ido, & Ye, Science 314, 1430 (2006).



No net electronic angular momentum

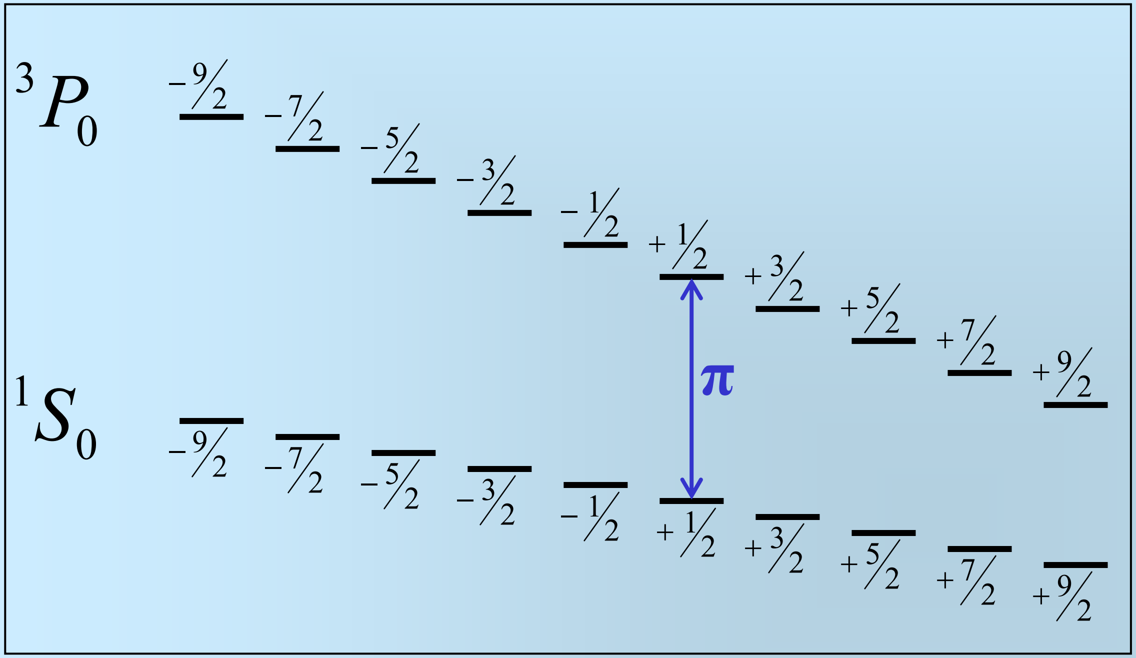
Δg = -108.4(4) Hz/(G m_F)

$^3P_0$ lifetime 140(40) s



Scalar, vector, tensor polarizabilities

Boyd *et al.*, Phys. Rev. A 76, 022510 (2007).



Hyperpolarizability
~ $(I_{trap})^2$: <1E-17
P. Lemonde, SYRTE

$\Delta\alpha$: differential polarizability

ξ: polarization ellipticity

$$\nu_{\pi_{mF}} = \nu_0$$

Clock frequency

$$-\Delta g \; m_F \; \mu_0 \; B$$

1st order Zeeman

$$-\left(\Delta\alpha^S - \Delta\alpha^T F(F+1)\right) I_{trap}$$

Scalar + Tensor polarizability

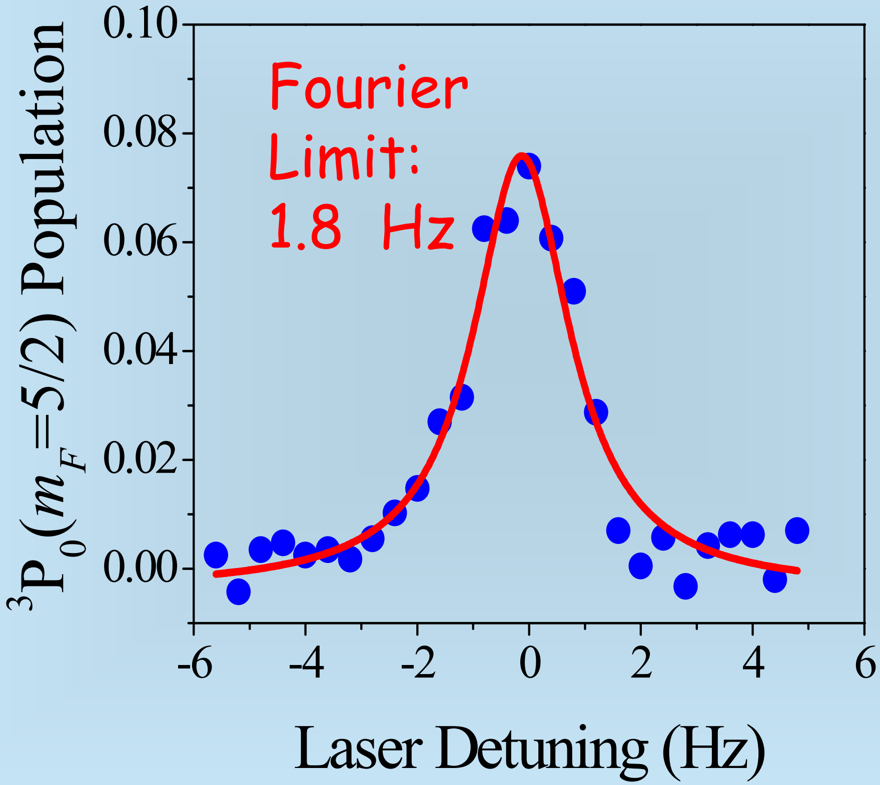
$$-\left(\Delta\alpha^V \xi \, m_F + \Delta\alpha^T 3m_F^2\right) I_{trap}$$

Vector + Tensor polarizability

Coherent spectroscopy Q ~ 2.5 x 10^{14}

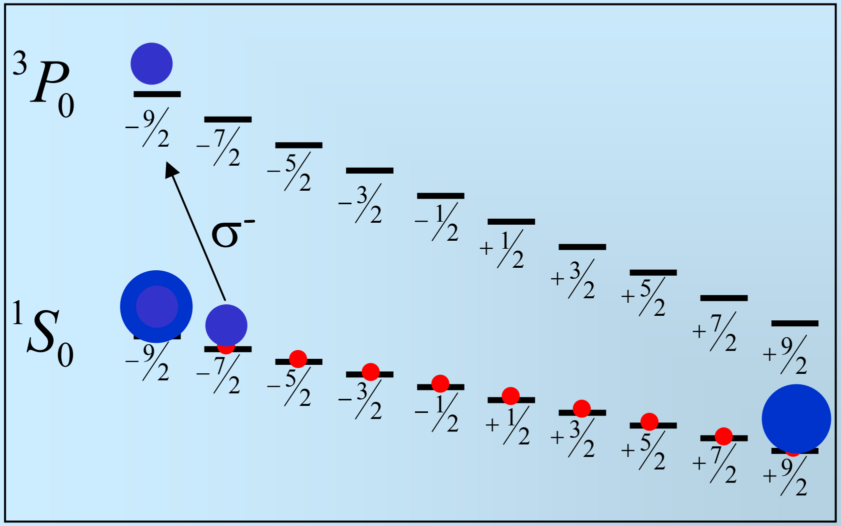
Boyd, Zelevinsky, Ludlow, Foreman, Blatt, Ido, Ye, Science 314, 1430 (2006).

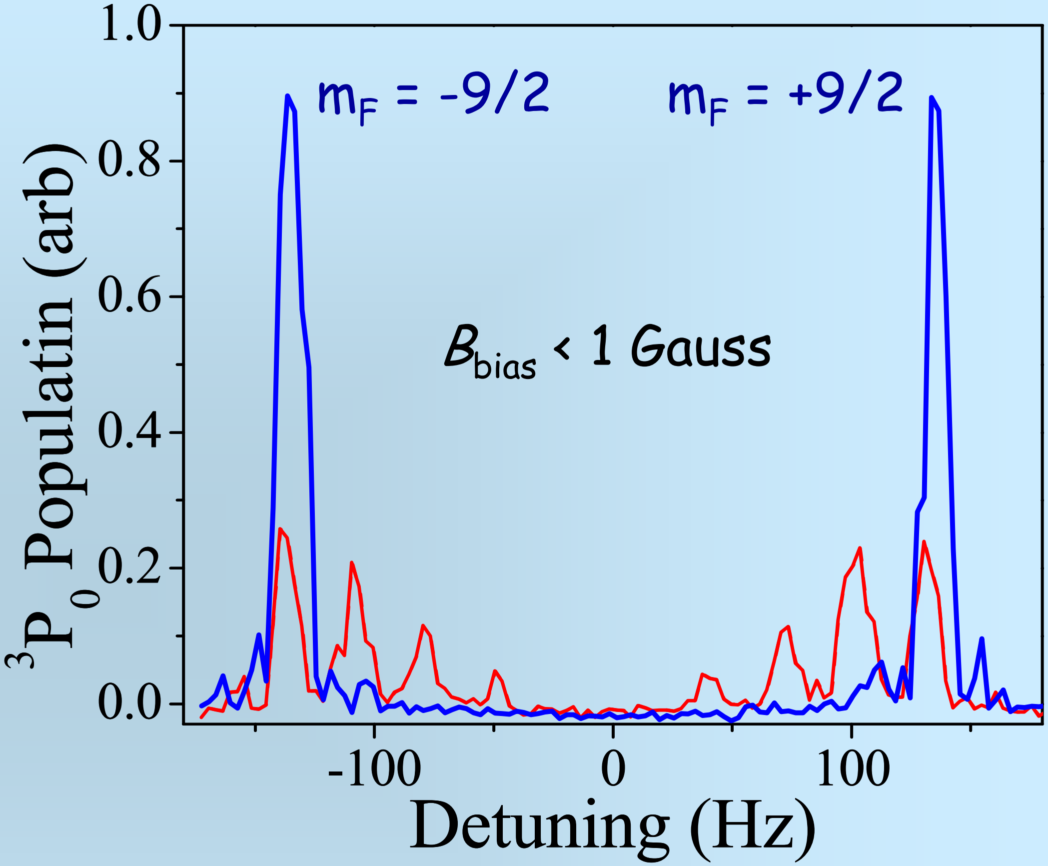
Boyd, Ludlow, Blatt, Foreman, Ido, Zelevinsky, Ye, PRL 98, 083002 (2007).



- **Instability ~ 2 x $10^{-15}/\sqrt{\tau}$**
- **Inaccuracy ~ 1 x 10^{-16}**

Optical manipulation of nuclear spins



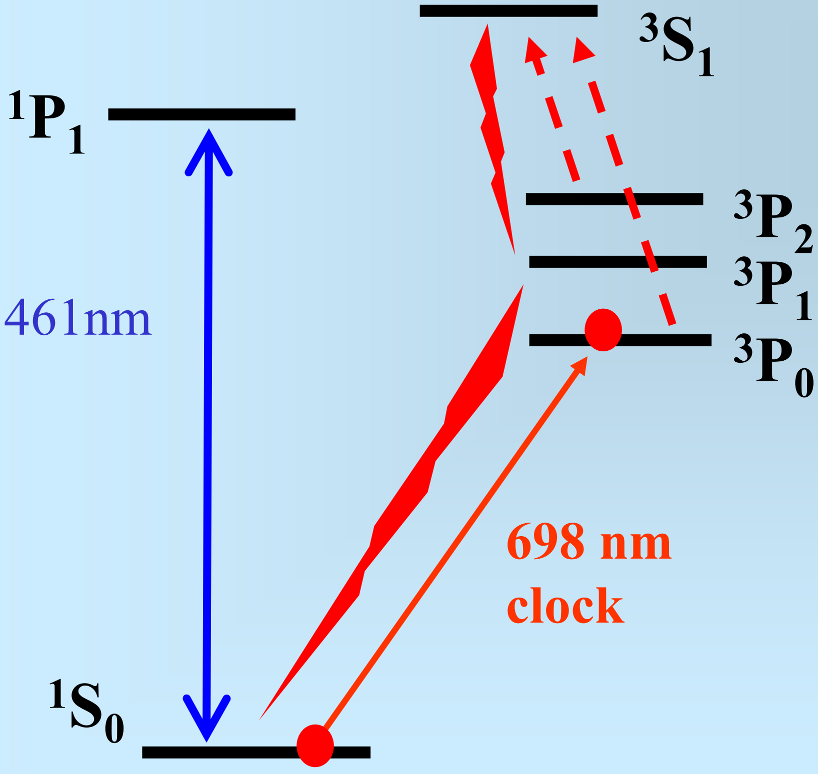


- Optically addressed, long coherence time
- Nuclear spin entanglement via electronic dipolar interactions
- Control electronic interaction via nuclear spins
- Cooling of atoms without nuclear spin decoherence (Deutsch)
- Individually addressable via a magnetic gradient field

Clock operation – Atom Lock & Normalization

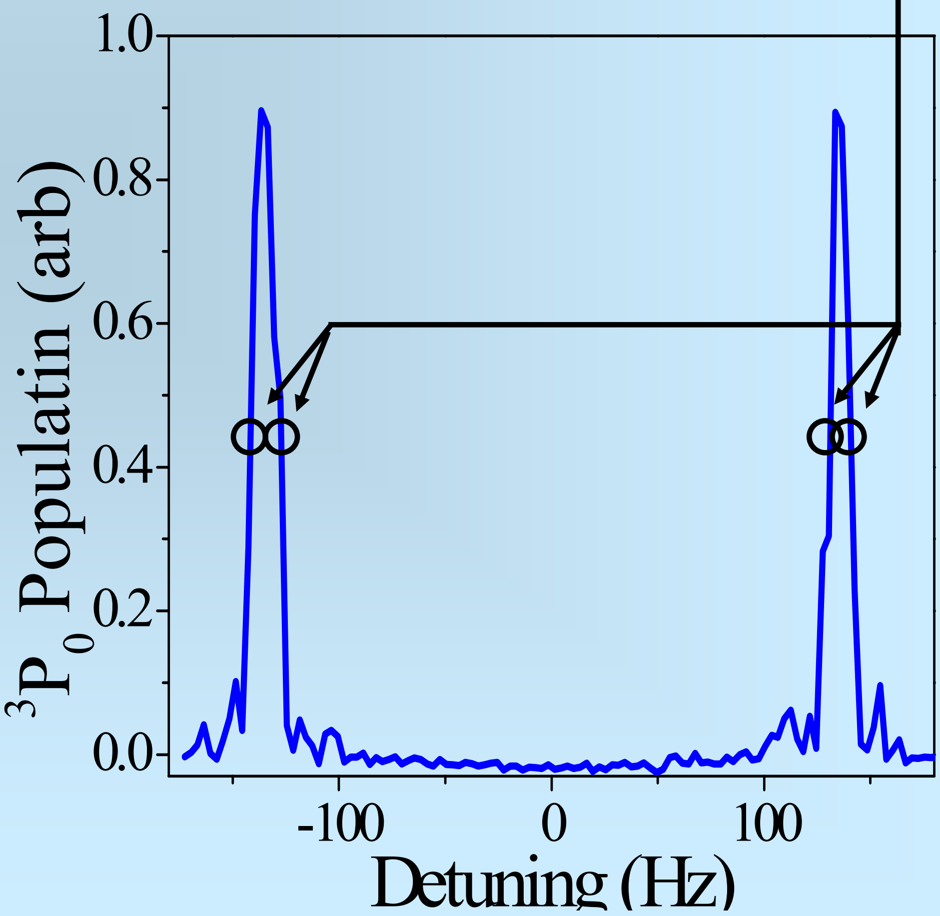
Normalization

Reduction of atom number fluctuations

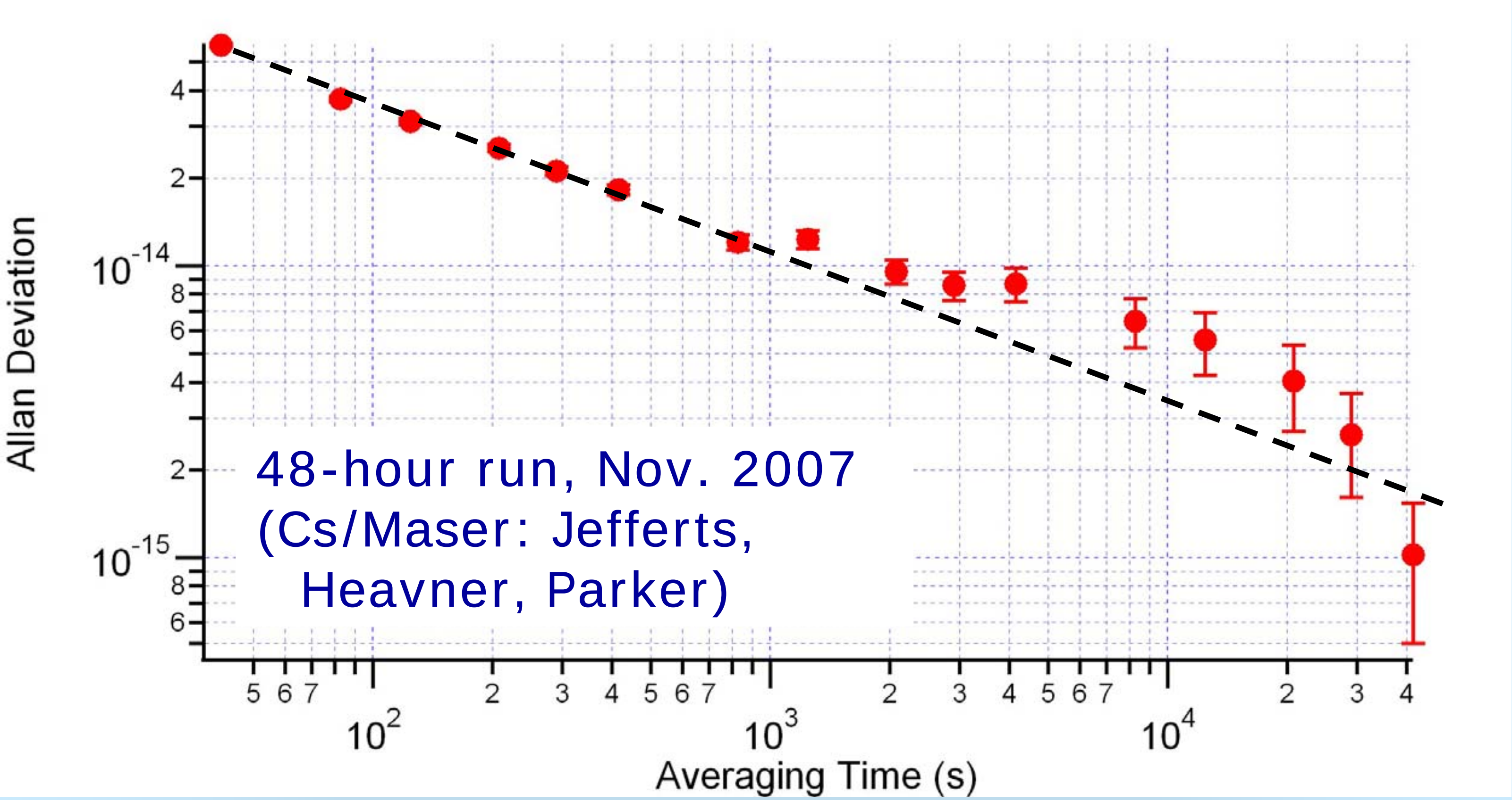


Lock to Atoms

Signal integration from both spin-polarized peaks



Clock comparison: Sr lattice / Cs-fountain

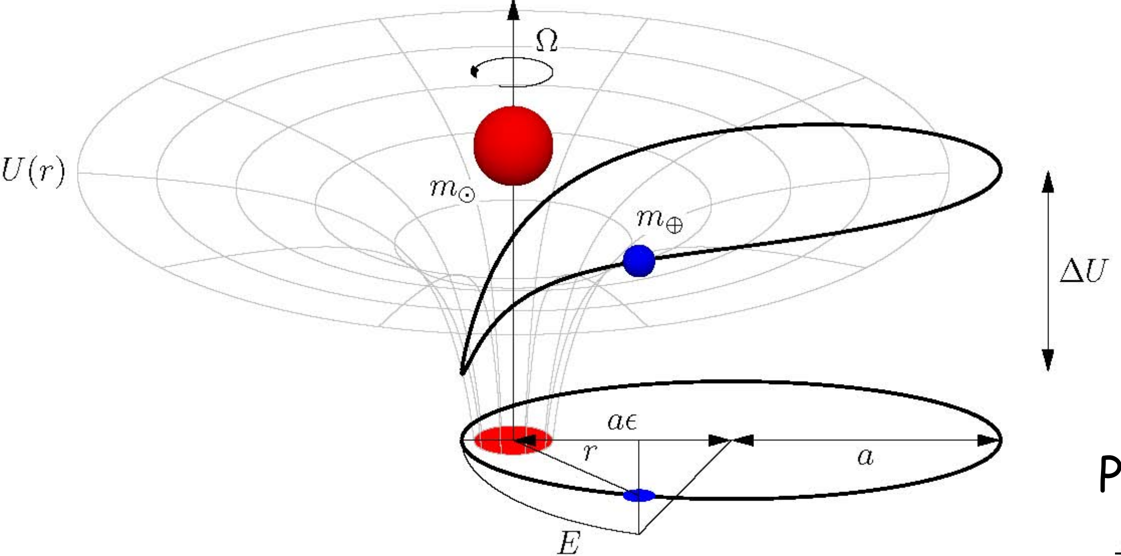


48-hour run, Nov. 2007
(Cs/Maser: Jefferts,
Heavner, Parker)

Absolute freq. measurement: ±0.4 Hz (8.5×10^{-16})

(limited by Cs/H-maser)

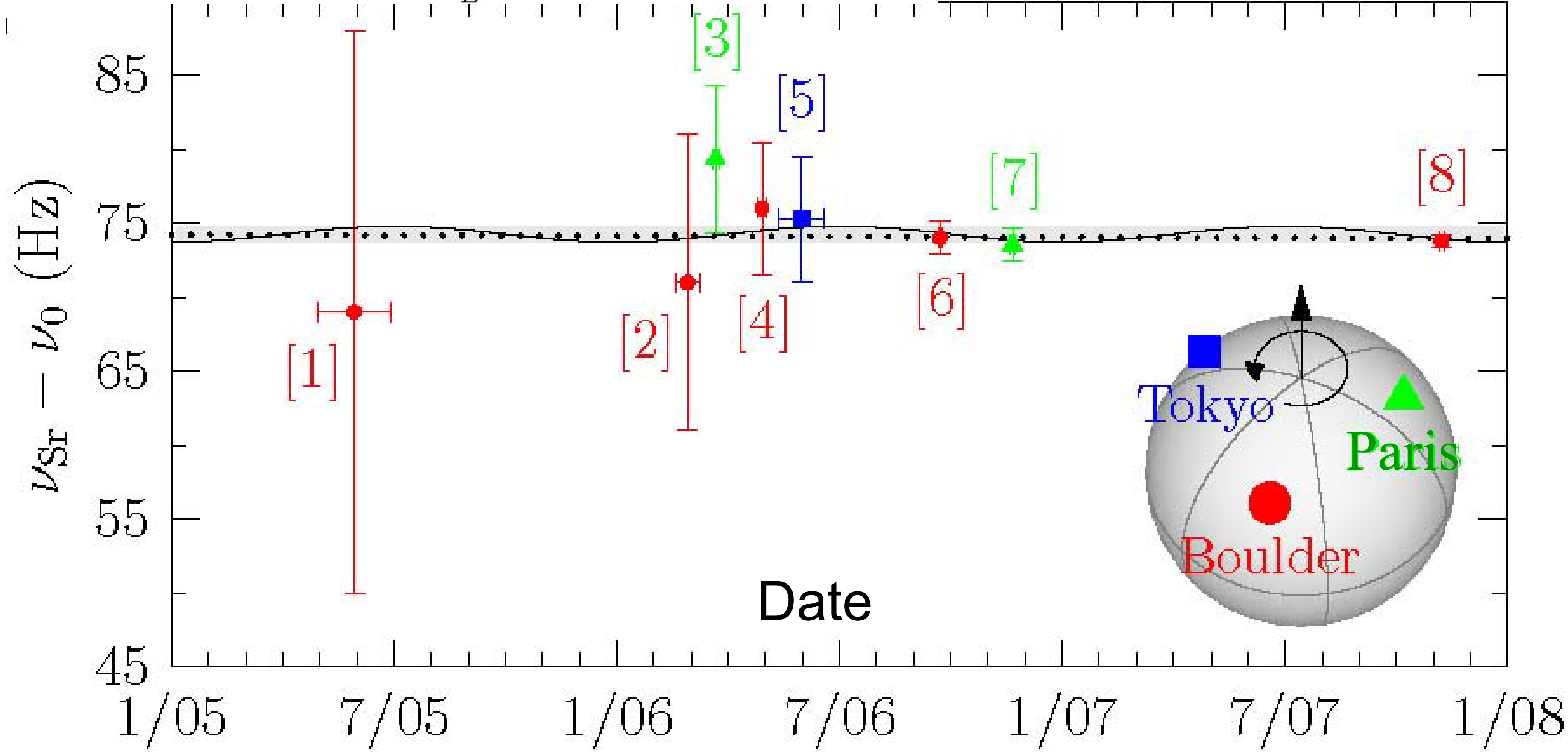
Need better clocks



Annual variations?

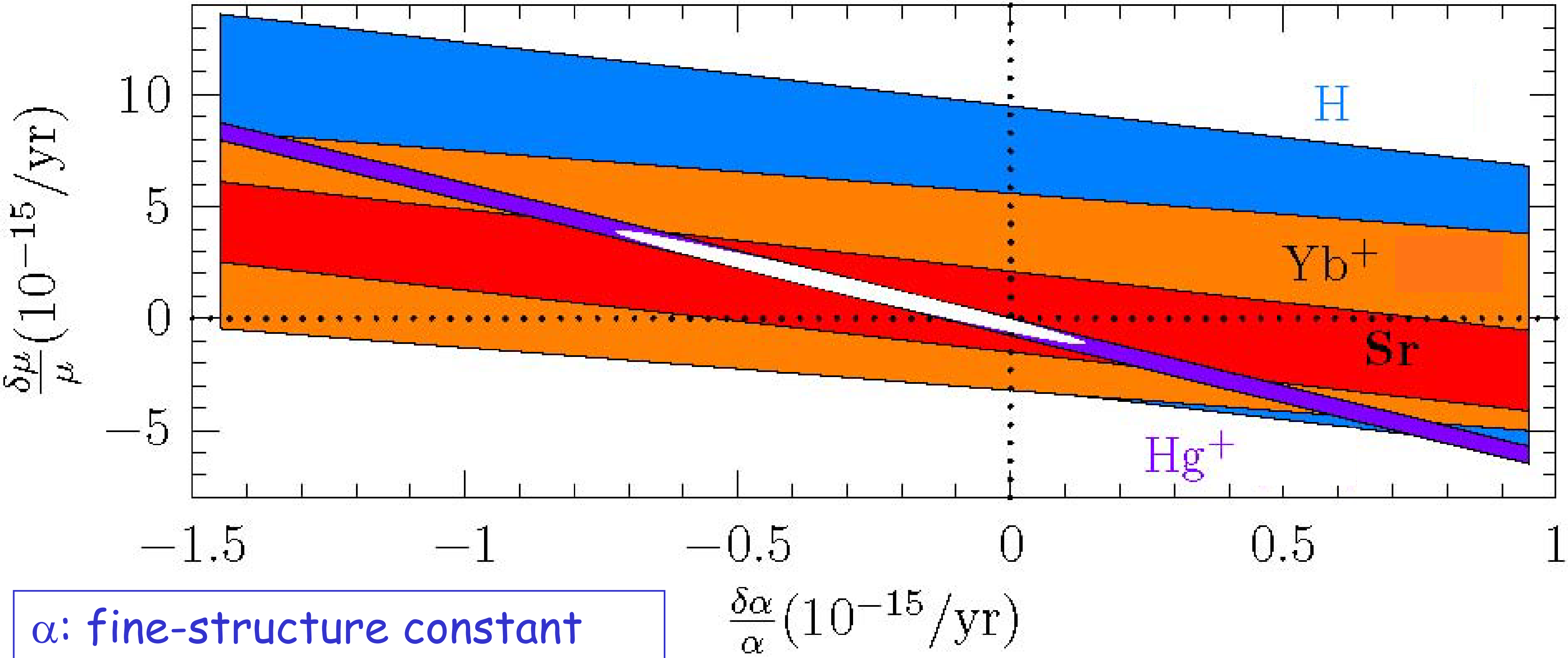
Fundamental constants & gravitational potential

S. Blatt *et al.*,
Phys. Rev. Lett. 100, 140801 (2008).



Constraints on possible time-dependent variations of fundamental constants

Sr frequency drift < 4.6 × 10^{-16}/year

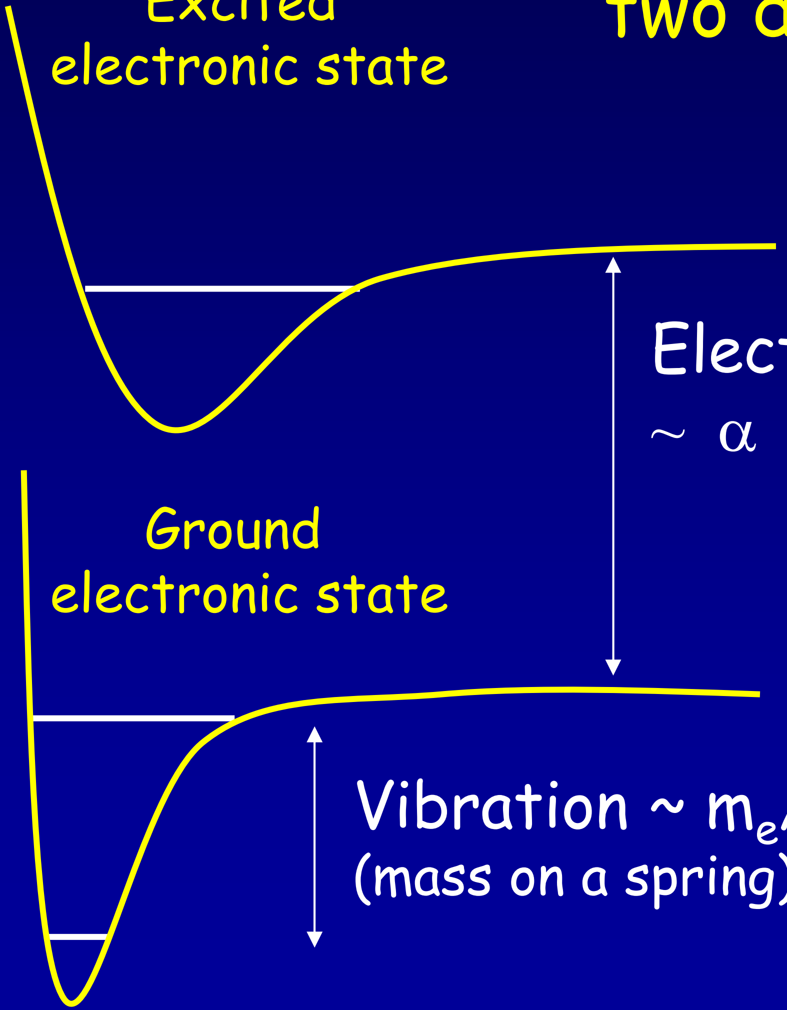


α: fine-structure constant
μ: electron/proton mass ratio

Hg^+ - Cs: T. Fortier *et al.*, Phys. Rev. Lett. <u>98</u>, 070801 (2007).
Yb^+ - Cs: E. Peik *et al.*, Phys. Rev. Lett. <u>93</u>, 170801 (2004).
H – Cs: M. Fischer *et al.*, Phys. Rev. Lett. <u>92</u>, 230802 (2004).

Ultracold molecules: Test fundamental principles

One system, two different fundamental forces!



Excited electronic state

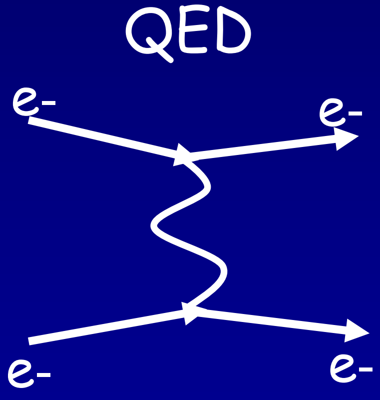
Ground electronic state

Electronic

$\sim \alpha$

Vibration $\sim m_e/m_p$

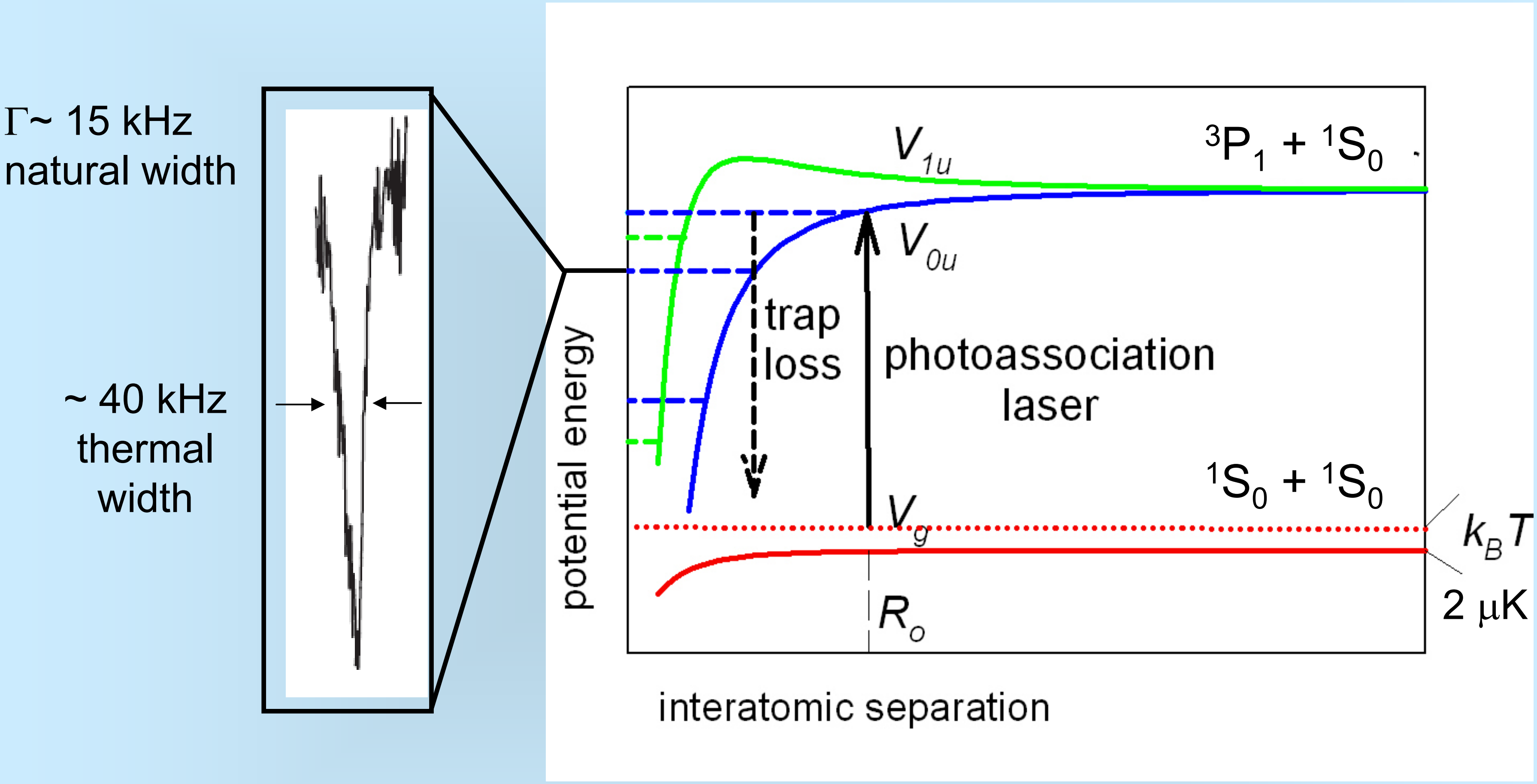
(mass on a spring)



QED

Strong interactions

Strontium optical Feshbach resonance

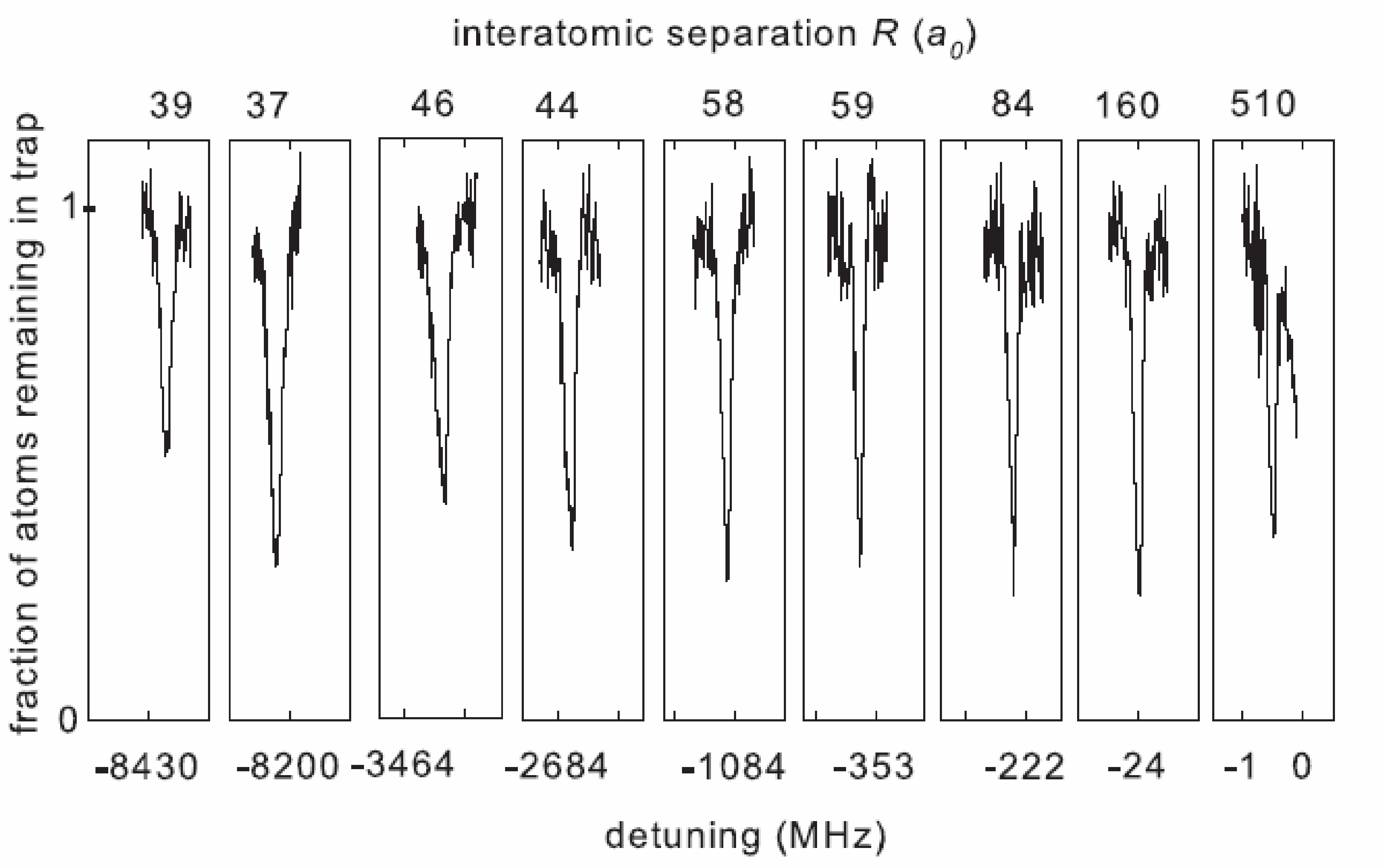


- Narrow line
- Structureless ground state in ^{88}Sr

Near threshold Photoassociation

Zelevinsky *et al.*, PRL 96, 203201 (2006).

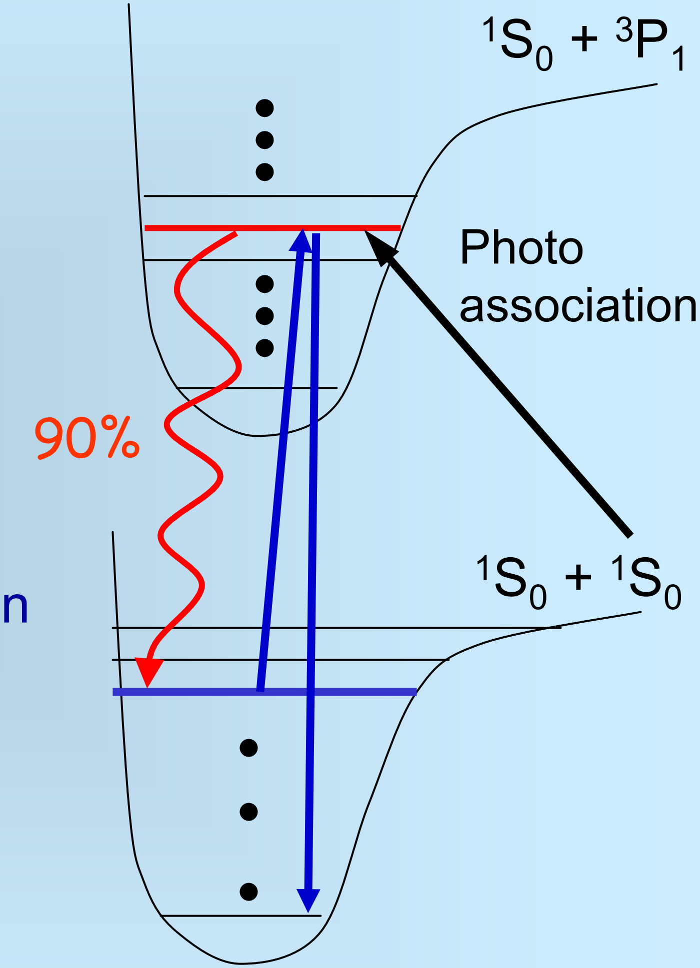
10^{-5} agreement between experiment and theory



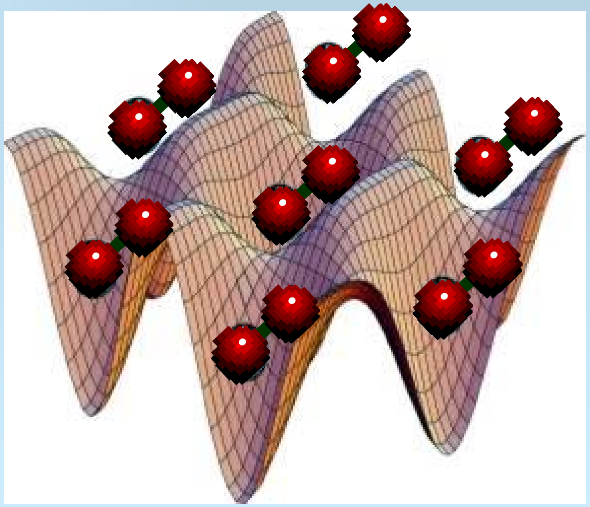
Nine least bound states measured

Ultracold Sr_2 Molecules in Lattice

- Ground and excited state potentials similar – favorable decay to electronic ground state
- Structureless ground state



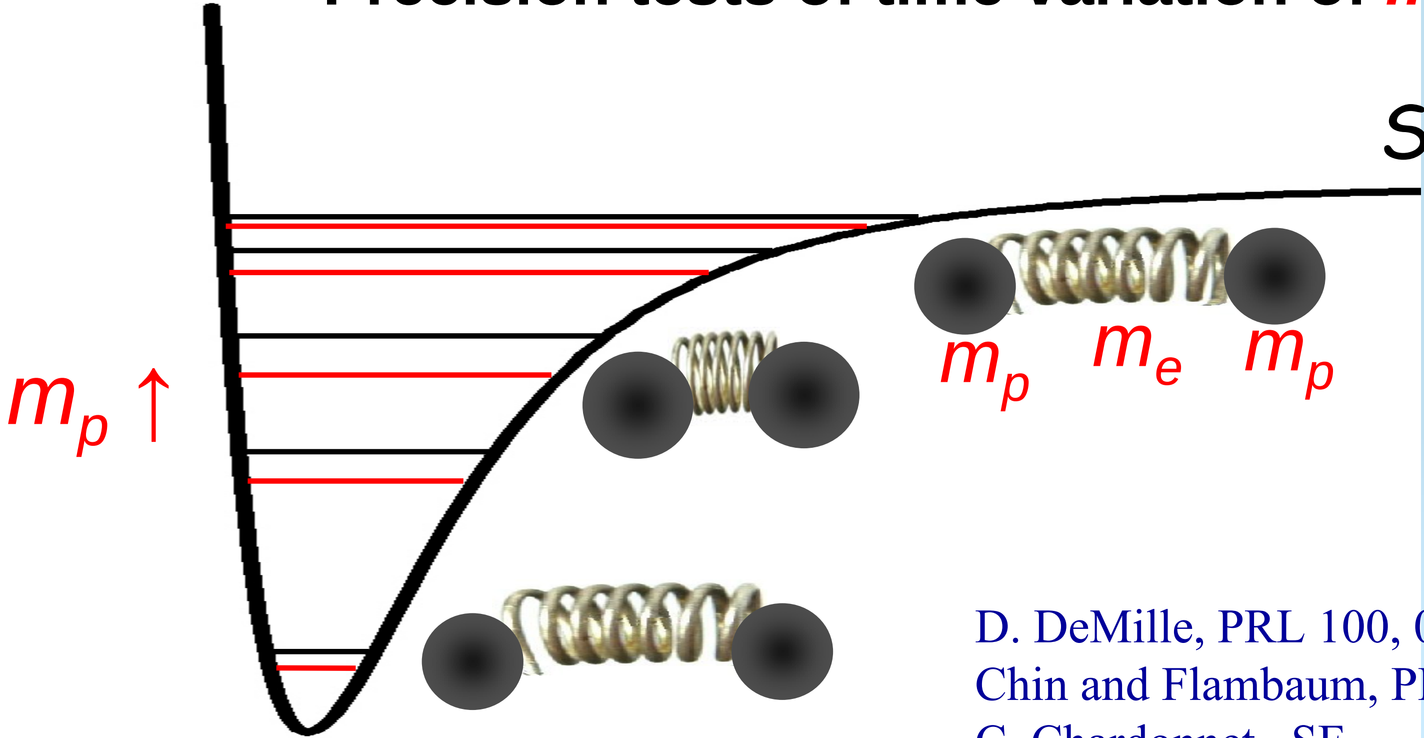
Raman transition for ground state production



Molecular Clock – Sensitivity to Mass Ratio

Zelevinsky, Kotochigova, Ye, Phys. Rev. Lett. 100, 043201 (2008).

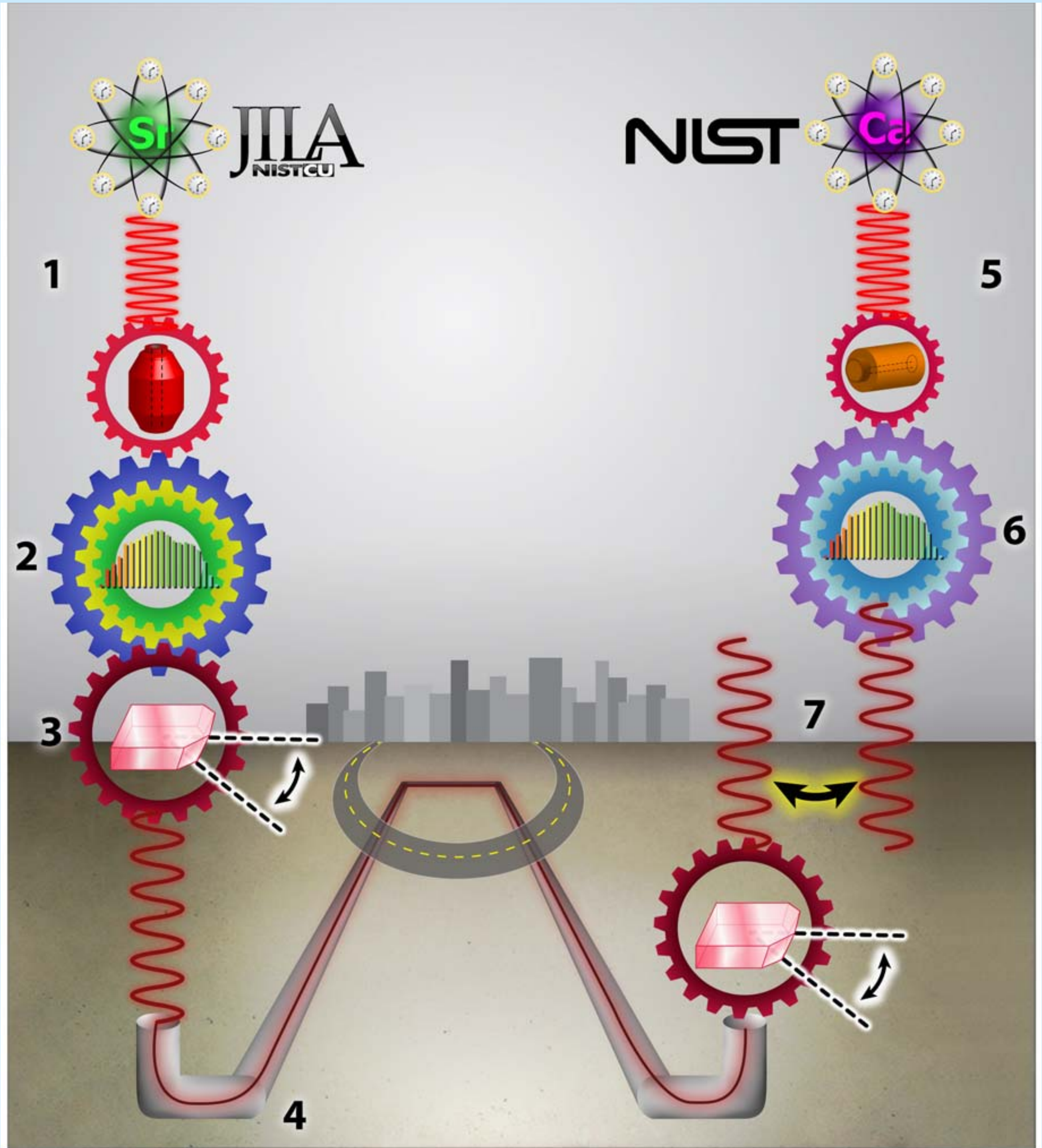
- Molecular potentials depend on electron mass, m_e
- Kinetic energy depends on proton mass, m_p
- Vibrational spacings depend on m_p / m_e
- **Precision tests of time variation of m_p / m_e?**



Sr$_2$ in lattice

D. DeMille, PRL 100, 043202 (2008).
Chin and Flambaum, PRL 96, 230801 (2006).
C. Chardonnet, SF$_6$

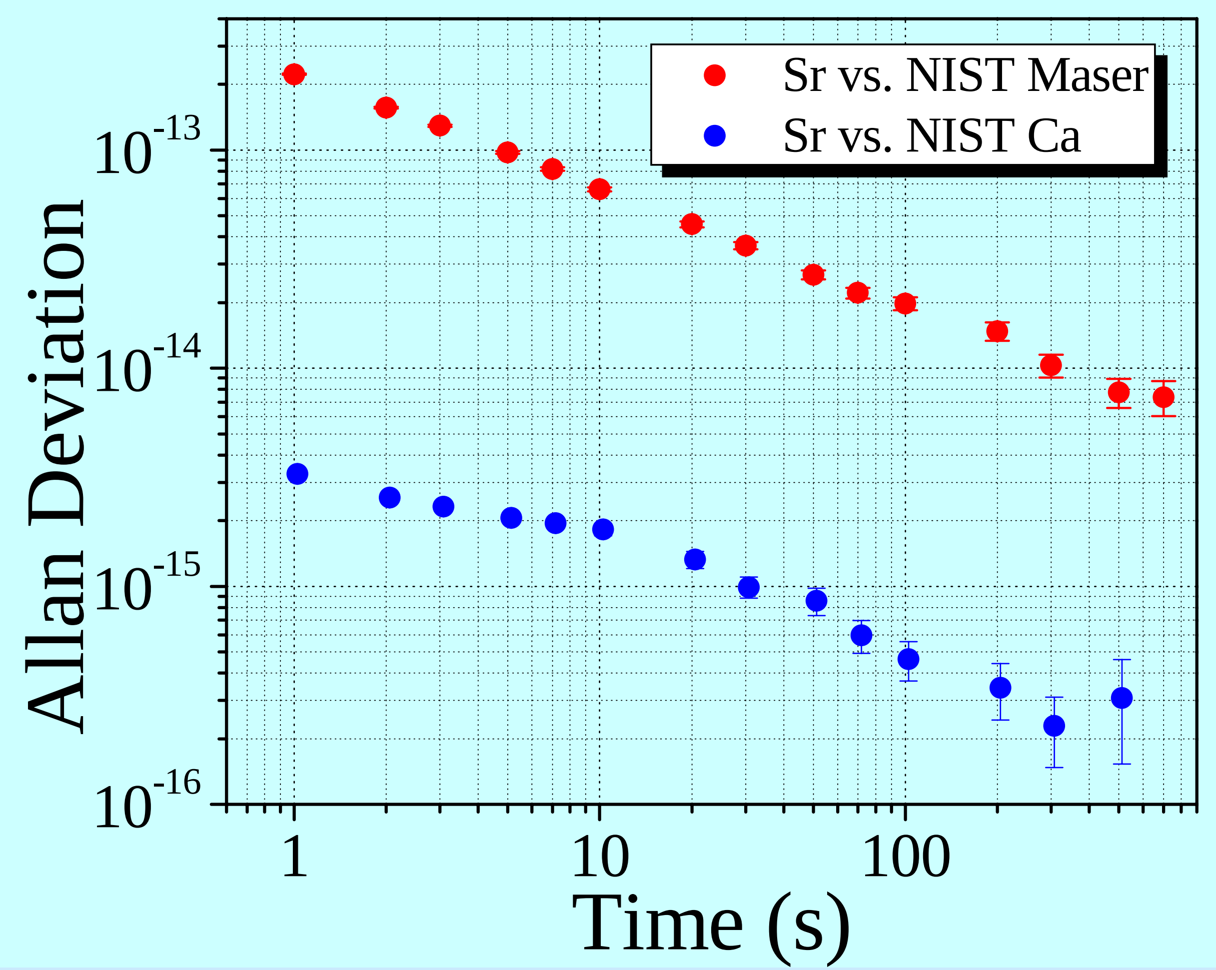
Optical clock comparison – Sr vs. Ca



Ludlow et al. (JILA);

Fortier et al. (NIST)

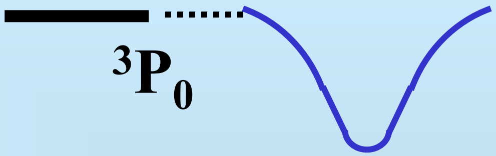
Optical clock comparison – Sr vs. Ca



Ludlow et al.
(JILA);

Fortier et al.
(NIST)

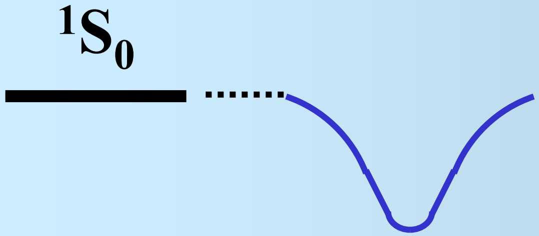
Magic wavelength trap

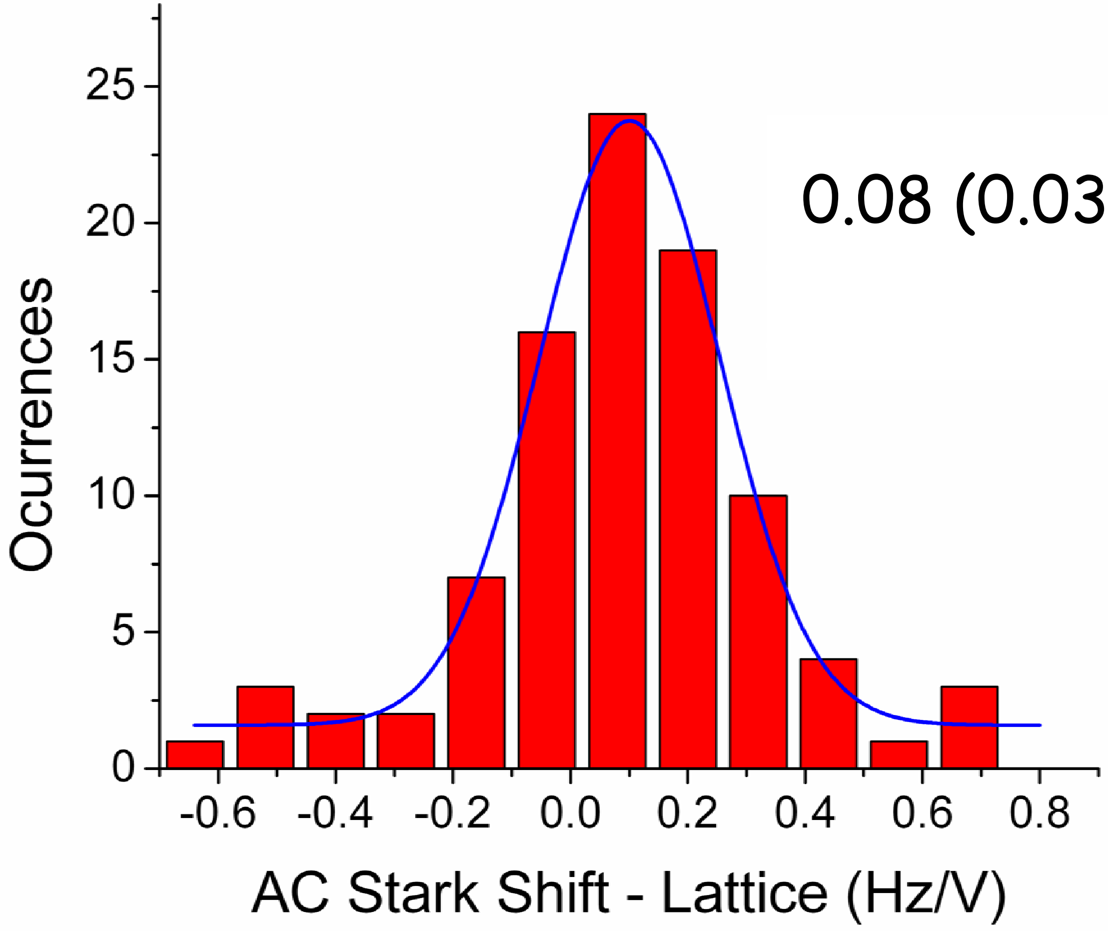


Caltech: Ye, Vernooy, Kimble, PRL 83, 4987 (1999).

Tokyo: Katori *et al.*, JPSJ 68, 2429 (1999).

Ye, Kimble, & Katori, Science, June 27, 2008.

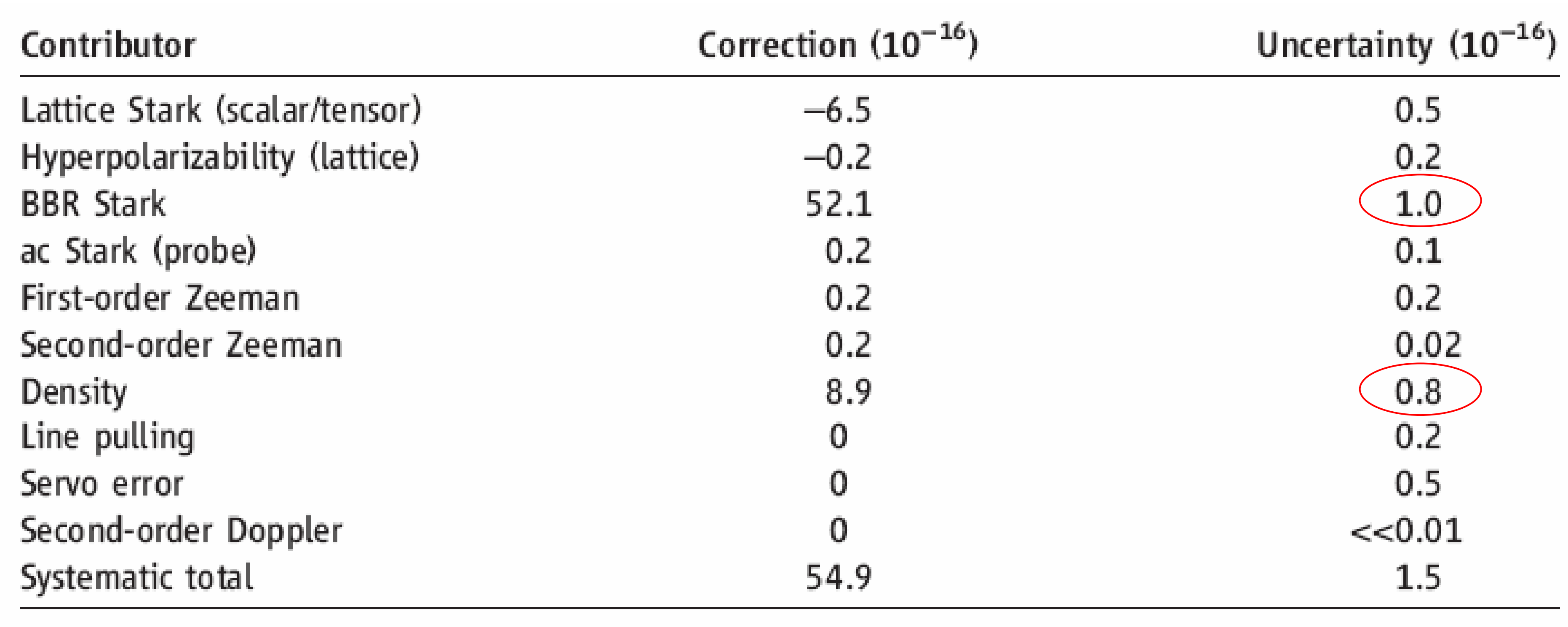




0.08 (0.03) Hz

Atomic Systematics

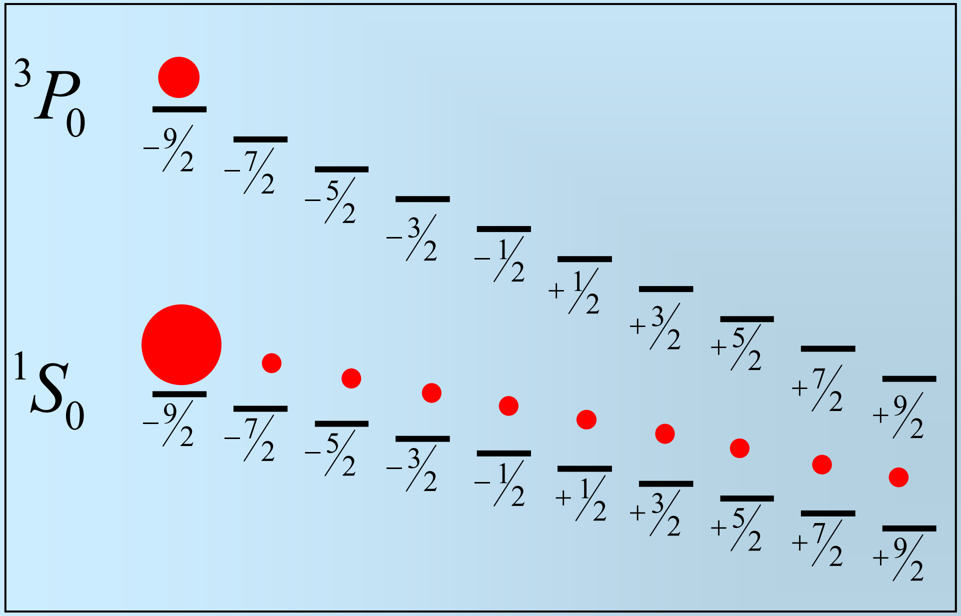
A. Ludlow et al., Science 319, 1805 (2008).



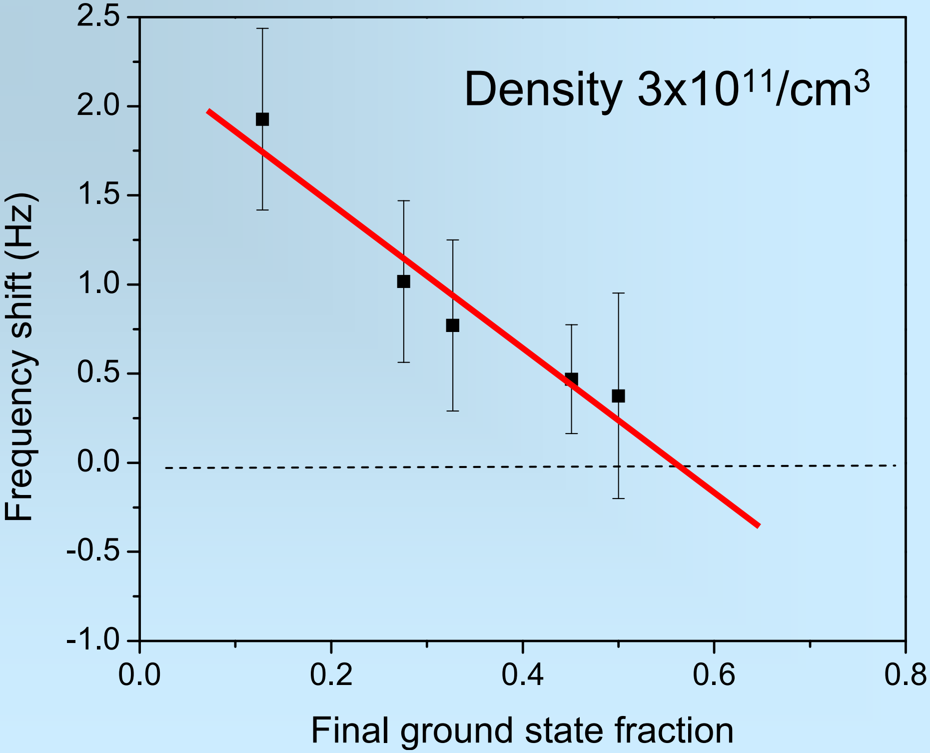
Contributor	Correction (10^{-16})	Uncertainty (10^{-16})
Lattice Stark (scalar/tensor)	–6.5	0.5
Hyperpolarizability (lattice)	–0.2	0.2
BBR Stark	52.1	1.0
ac Stark (probe)	0.2	0.1
First-order Zeeman	0.2	0.2
Second-order Zeeman	0.2	0.02
Density	8.9	0.8
Line pulling	0	0.2
Servo error	0	0.5
Second-order Doppler	0	<<0.01
Systematic total	54.9	1.5

Reading out atomic interactions via clock shifts

A. Ludlow et al., Science 319, 1805 (2008)

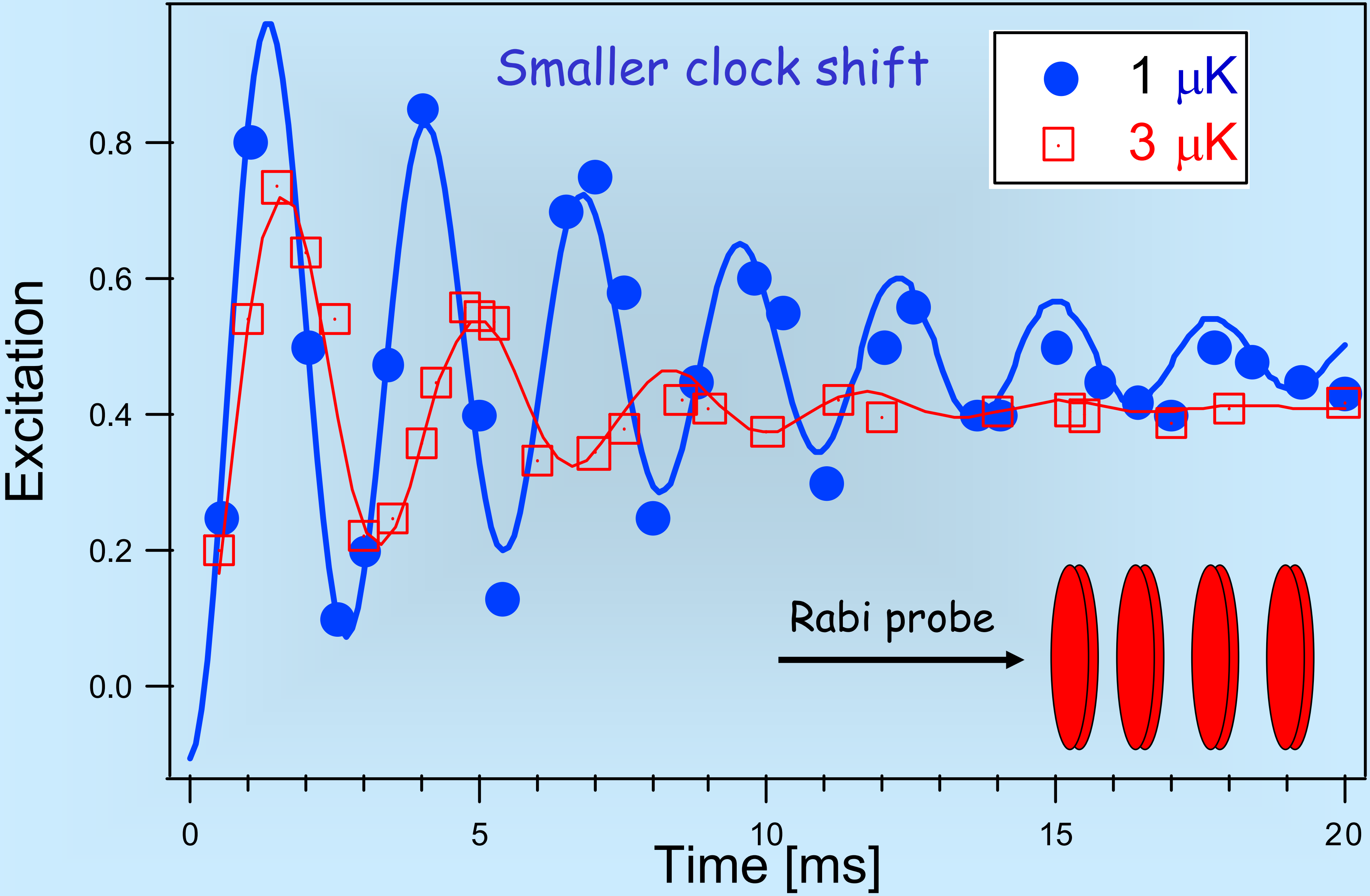


< 1×10^{-16} uncertainty



Decoherence inhomogeneity inside lattice

G. K. Campbell et al.



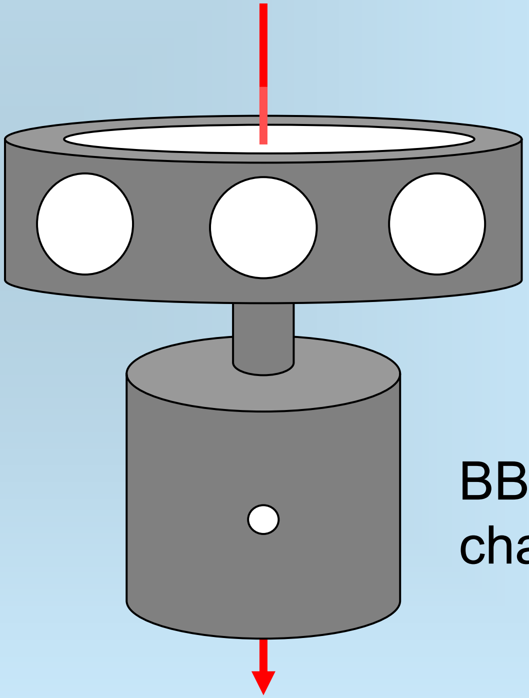
Blackbody Radiation Shift

current uncertainty: 1x10^{-16}

$$\delta E \approx -\frac{2}{15}(\alpha\pi)^3 T^4 \alpha_d(0)[1+\eta]$$

<u>Static Polarizability Measurements</u>

- DC Electric Field
- Dynamic Polarizability
- Long λ Stark measurement
- BBR controlled measurement

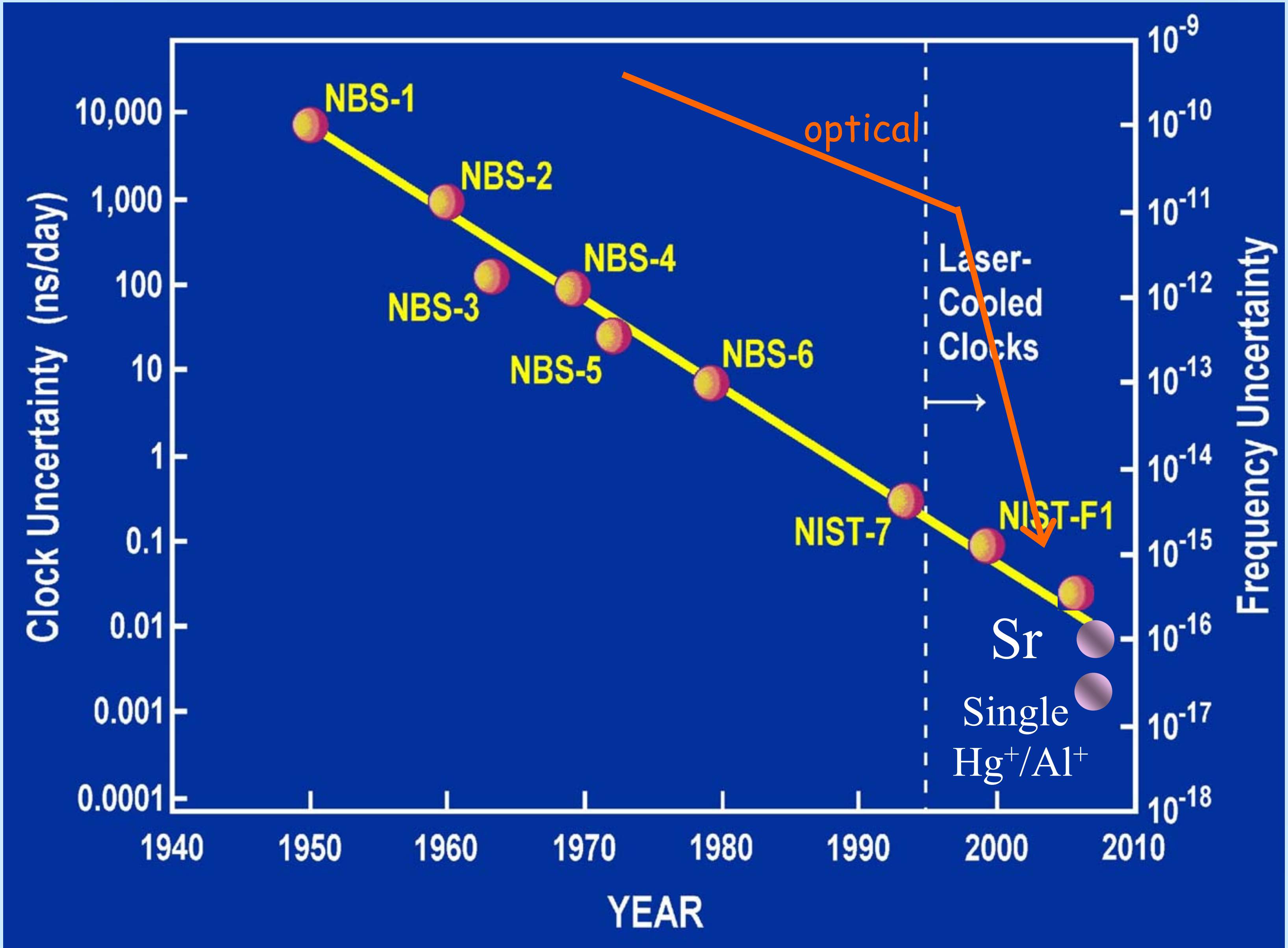


trapping and cooling

BBR chamber

Accurate atomic clocks

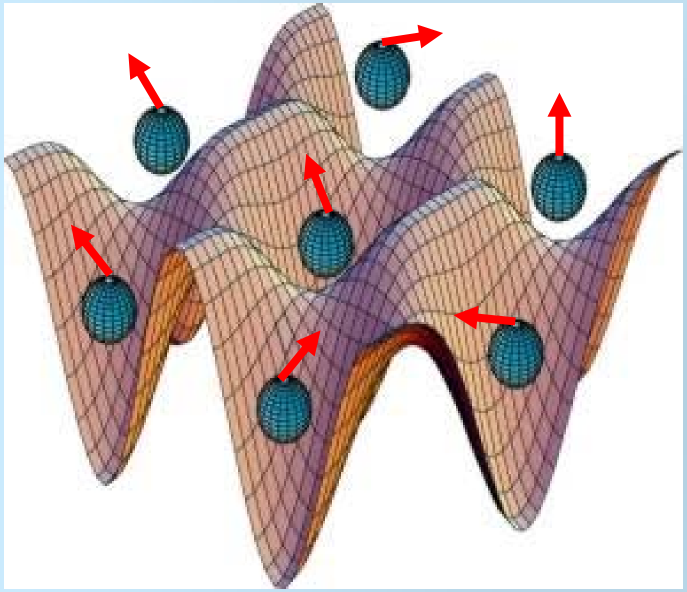
Ludlow *et al.*, Science 319, 1805 (2008).
Rosenband *et al.*, Science 319, 1808 (2008).



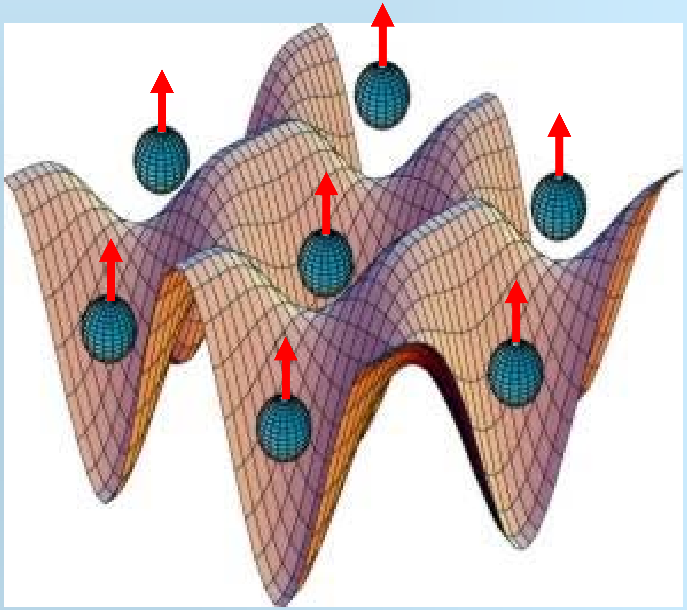
What is the noise?

Quantum projection measurement

Wineland et al., 1993; Polzik et al., 1998; Jessen et al., 2006



$$\frac{1}{\sqrt{N}}$$



$$\frac{1}{N}$$

Spin squeezing via measurement of lattice
– in collaboration with D. Meiser & M. Holland

Special thanks

Ultracold Sr

M. Boyd
A. Ludlow
S. Blatt
G. Campbell
M. Martin

T. Zelevinsky (Columbia)
T. Zanon (Univ. Paris 13)
T. Ido (Tokyo)
T. Loftus (U. Washington)
J. Thomsen (Copenhagen)

M. Holland, C. Greene (JILA)
J. Bergquist, S. Diddams, T. Fortier, C. Oates, T. Parker, S. Jefferts (NIST)
P. Julienne (NIST), S. Porsev (Petersburg), E. Arimondo (Pisa), P. Zoller