Lecture II: Precision quantum metrology

Jun Ye
JILA, NIST & Univ. of Colorado
http://jila.colorado.edu/YeLabs

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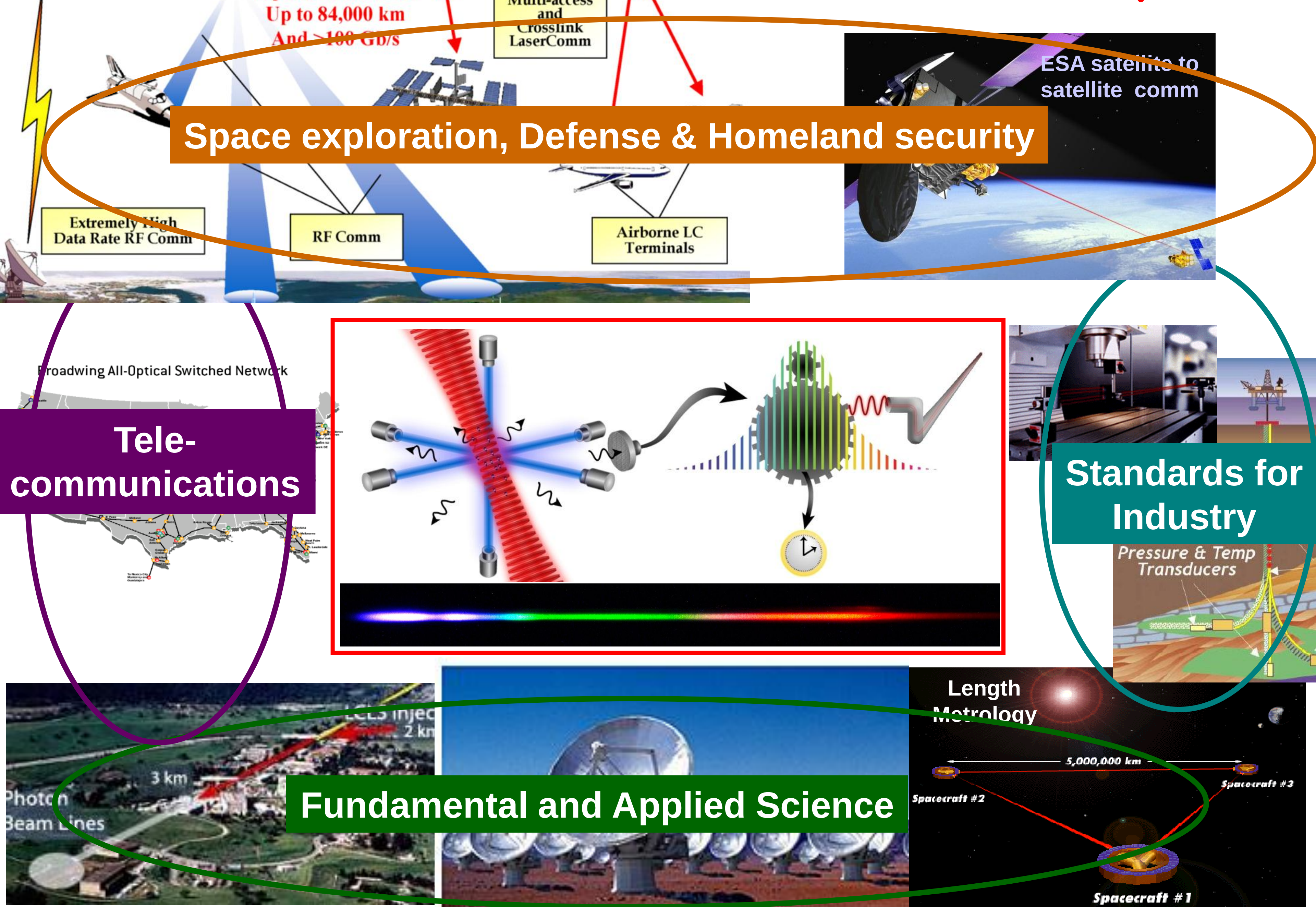
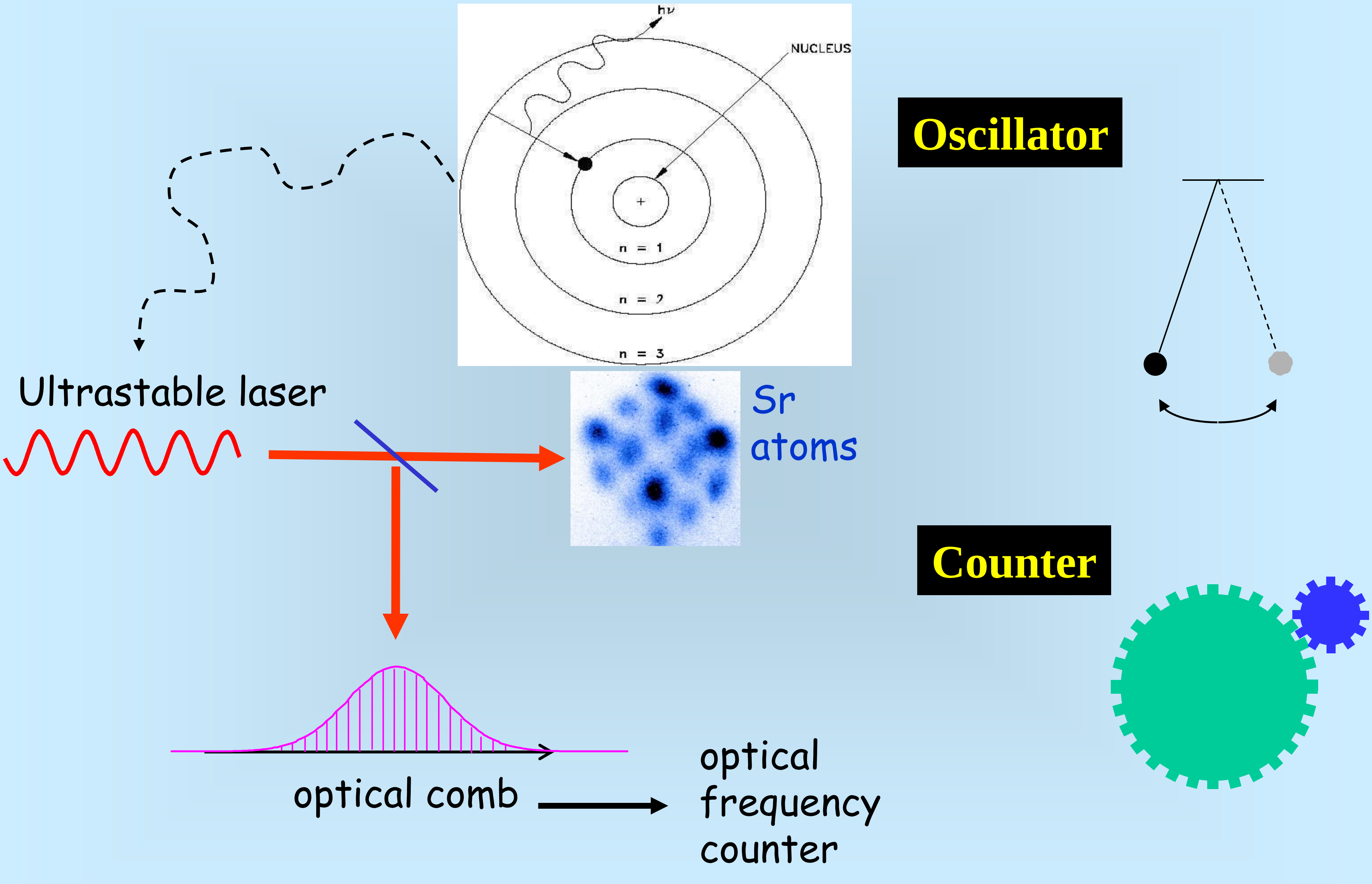
$ Funding $

**NIST, NSF,
AFOSR, DARPA
DOE, ONR**

Clocks are everywhere



Optical atomic clocks



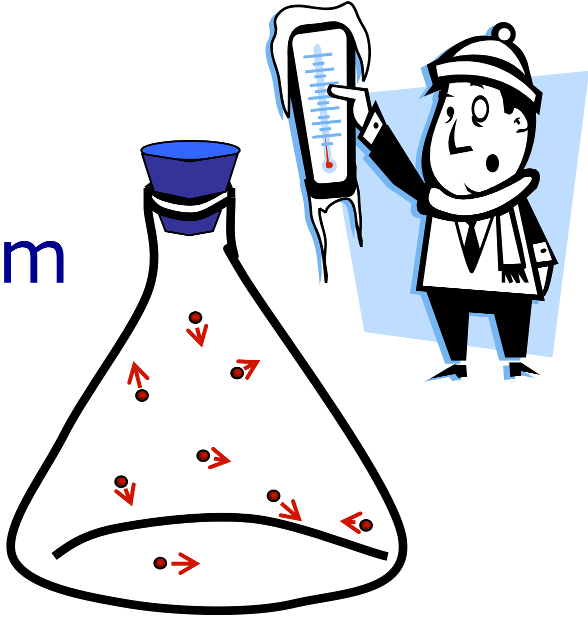
Ultracold Matter

Precise control of a quantum system

The most precise measurements, e.g., clocks

Quantum information

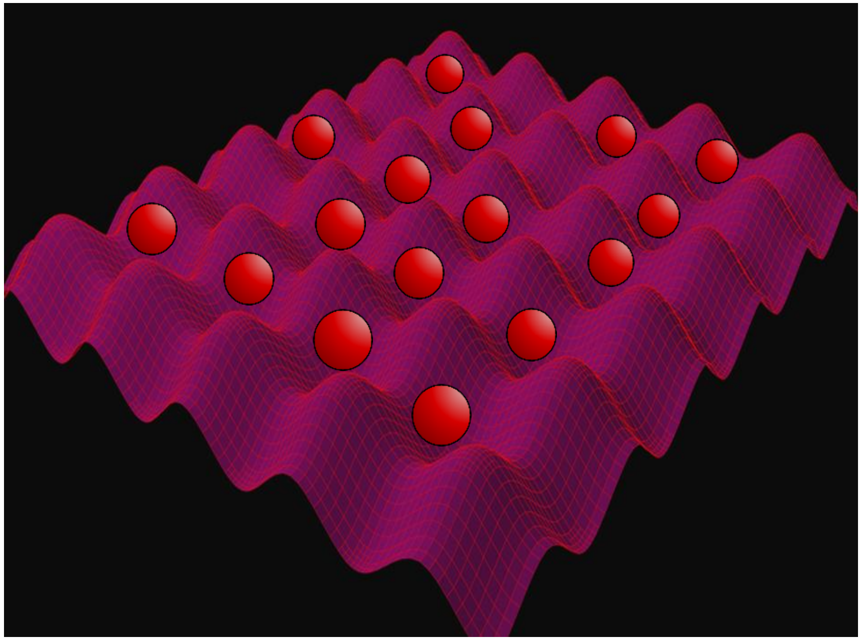
Quantum sensors



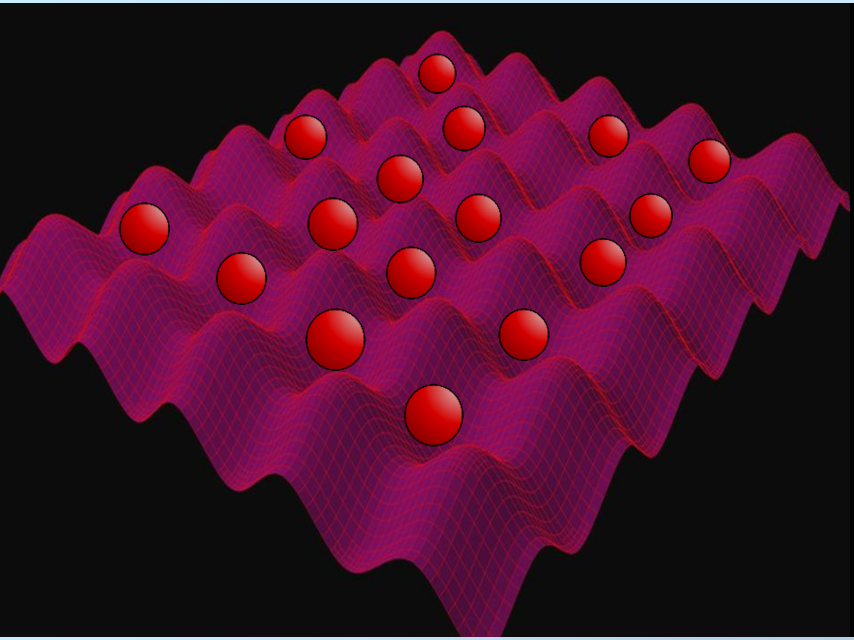
Control: A tool for understanding complexity

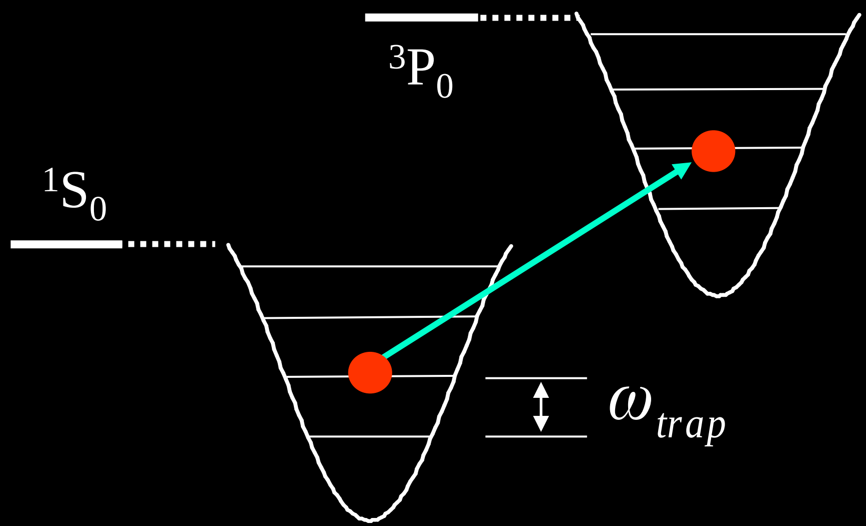
Strongly correlated many-body quantum systems

- Superfluidity & Superconductivity
- Quantum magnetism
- (Fully-)Quantum chemistry



Quantum metrology in optical lattice





- Atomic confinement << λ ($e^{ikx} \sim 1$, $k = 2\pi/\lambda_{probe}$)
- Trap potential identical for $^1S_0$ and $^3P_0$

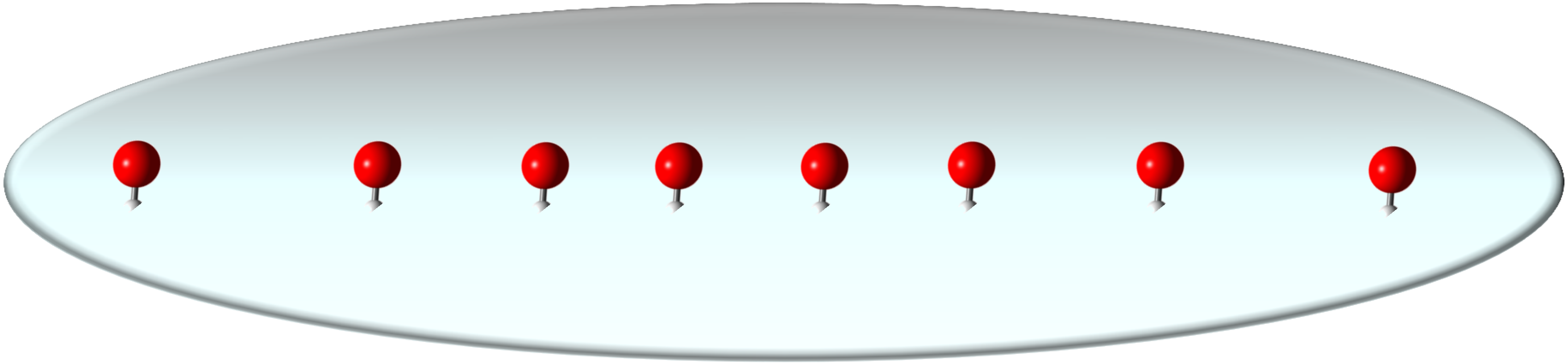
- Precision improvement by $N^{1/2}$

$$\frac{\delta\omega(\tau)}{\omega_0} = \frac{1}{Q} \times \frac{1}{\sqrt{N}} \times \sqrt{\frac{T_c}{\tau}}$$

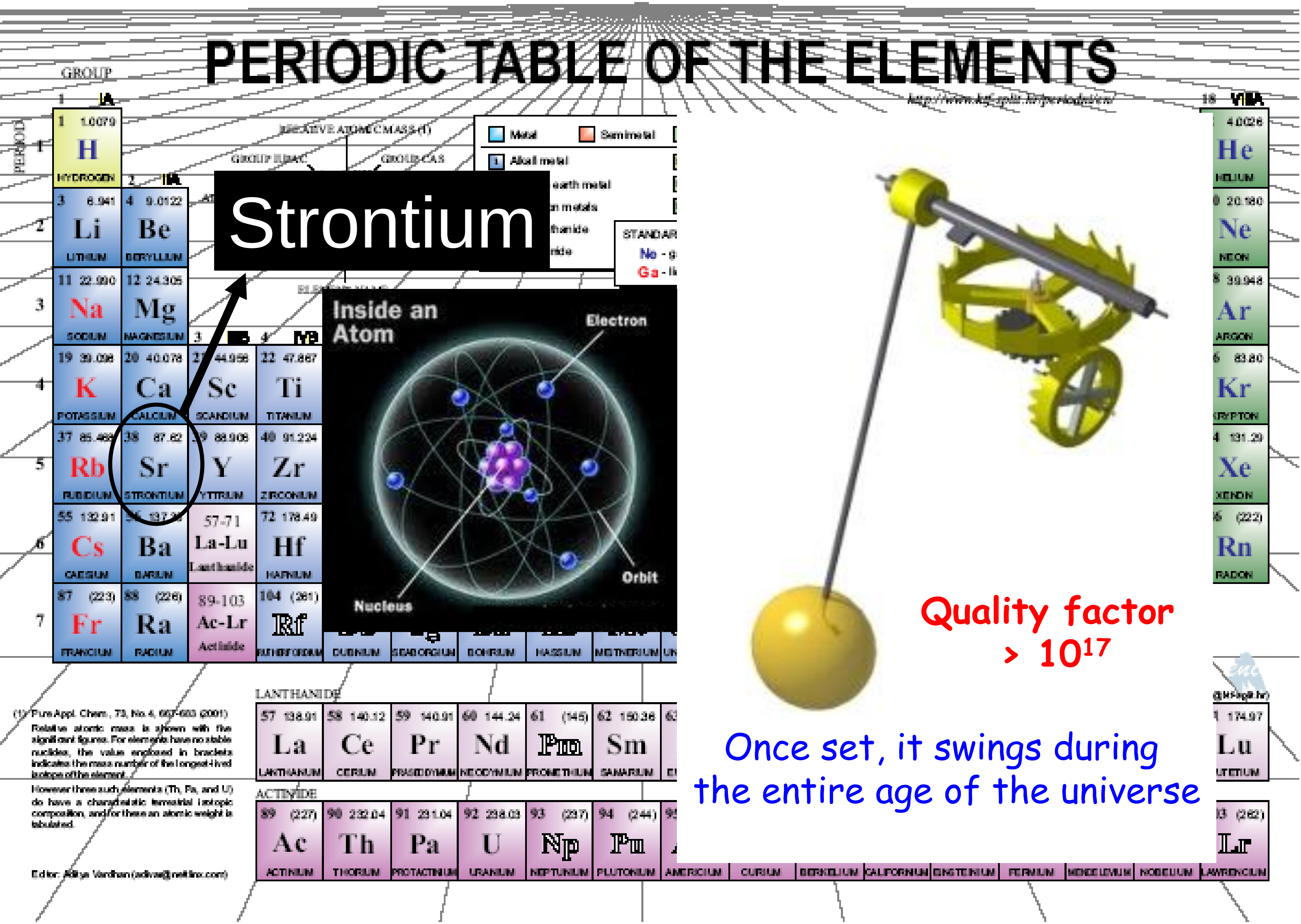
- Long coherence time; Zero Doppler shift, Zero recoil shift

- No light shift from the trap; but, Interaction effects? Accuracy?

An interacting many-body quantum system



$U \sim 1\ \text{Hz} \sim 50 \times 10^{-12}\ \text{K}$


PERIODIC TABLE OF THE ELEMENTS
Strontium
Inside an Atom
Electron
Orbit
Nucleus
Quality factor
> 10^17
Once set, it swings during
the entire age of the universe

Alkaline Earth versus Alkali

Alkali | **Alkaline Earth**

All-Optical Cooling to Ultra-Low Temperatures

Alkali:
Polarization Gradient
Stimulated Raman
VSCPT
Limited to Low Densities

Alkaline Earth:
High Density
Intercombination line sub-recoil
Sideband Cooling in Dipole Traps
Low Transfer Efficiency

Cold / Ultra-Cold Collisions

Alkali:
High Collision Rates
Feshbach Resonances
Hyperfine structure

Alkaline Earth:
Quantitative Studies
Diverse polar molecules
Low Collision Rates

BEC / FDG

Alkali:
Ground-State Magnetic Traps
Tunable Interactions
Only two Fermions: ^{40}K, ^{6}Li

Alkaline Earth:
Diversity of Bose, Fermi Isotopes
Optical Feshbach resonance
Structure Free Ground State

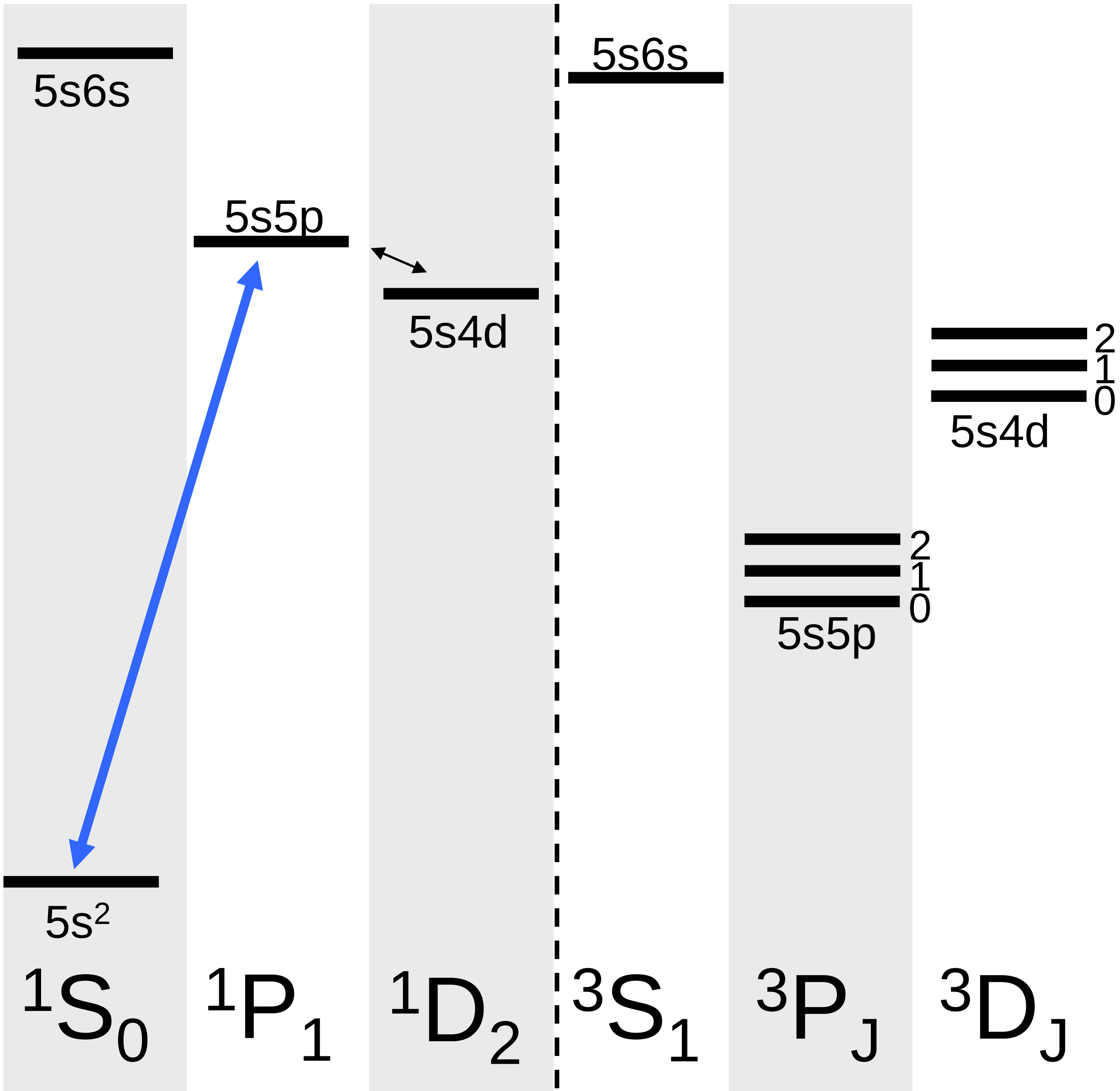
Time / Frequency Metrology

Alkali:
Microwave Clocks
Small Optical Line Q

Alkaline Earth:
High Optical Line Q
Second-Stage Cooling Required

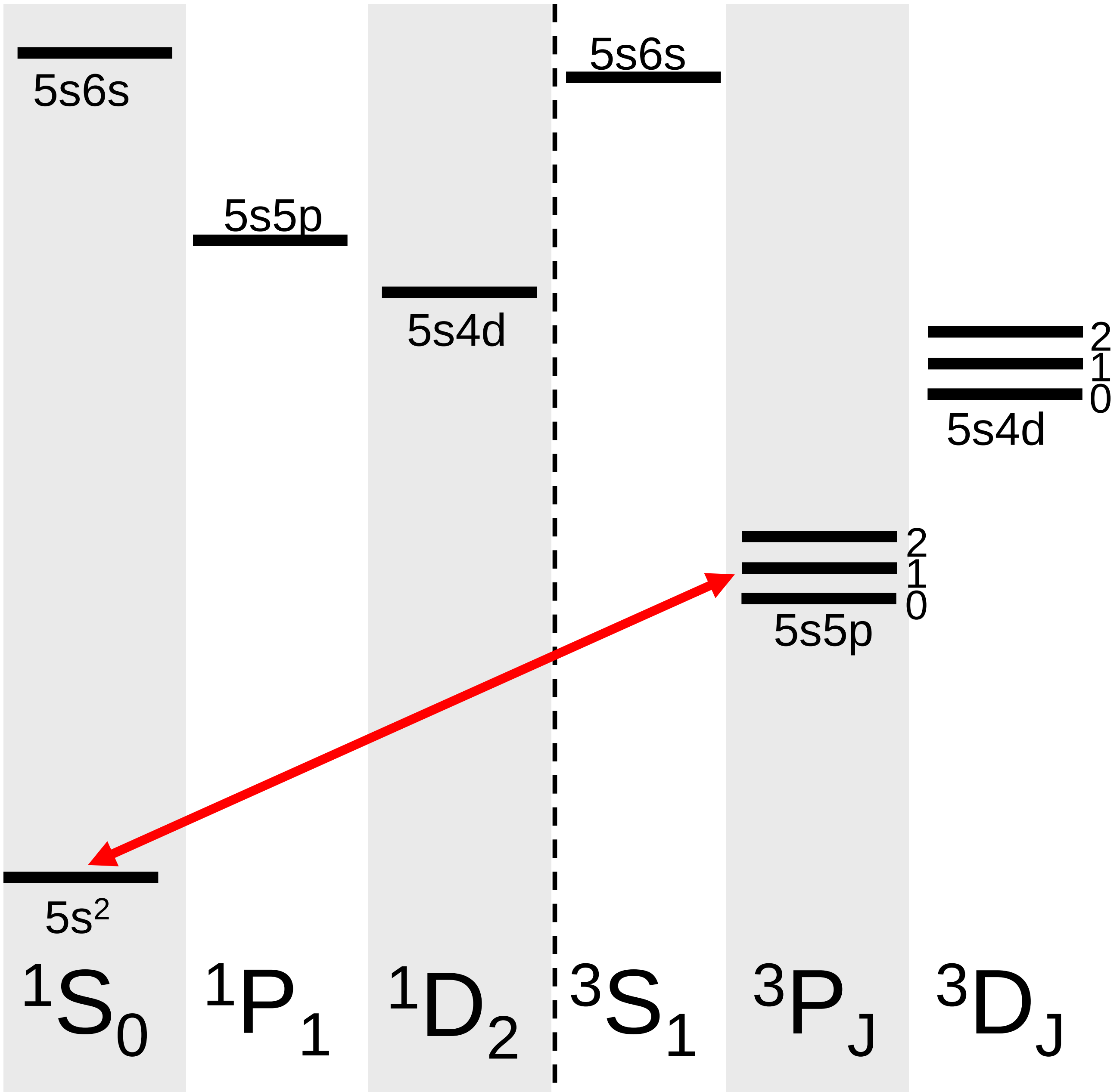
Strontium: first stage cooling

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

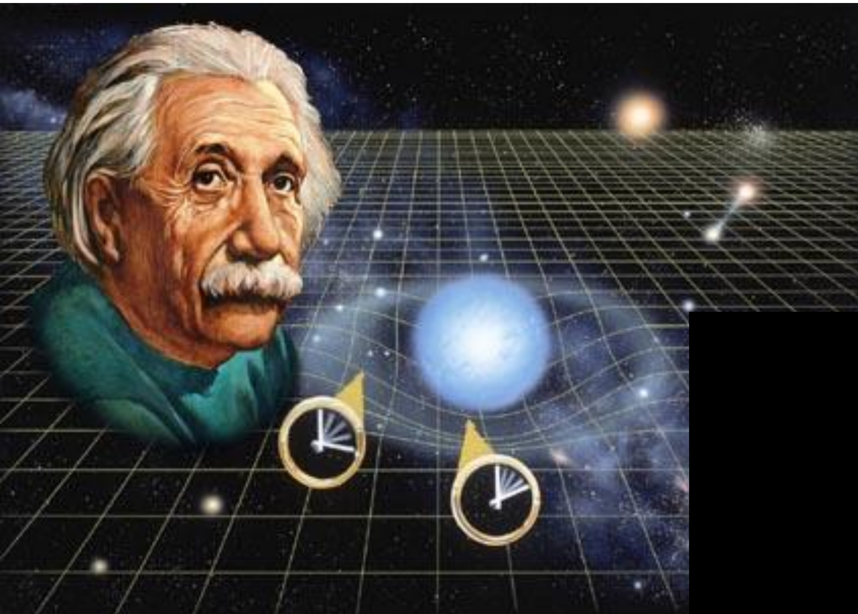


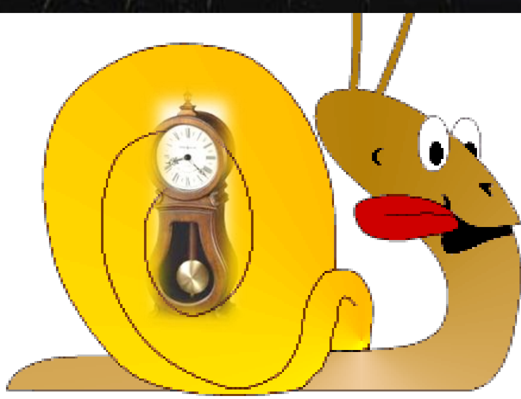
Strontium: Narrow Line Laser Cooling

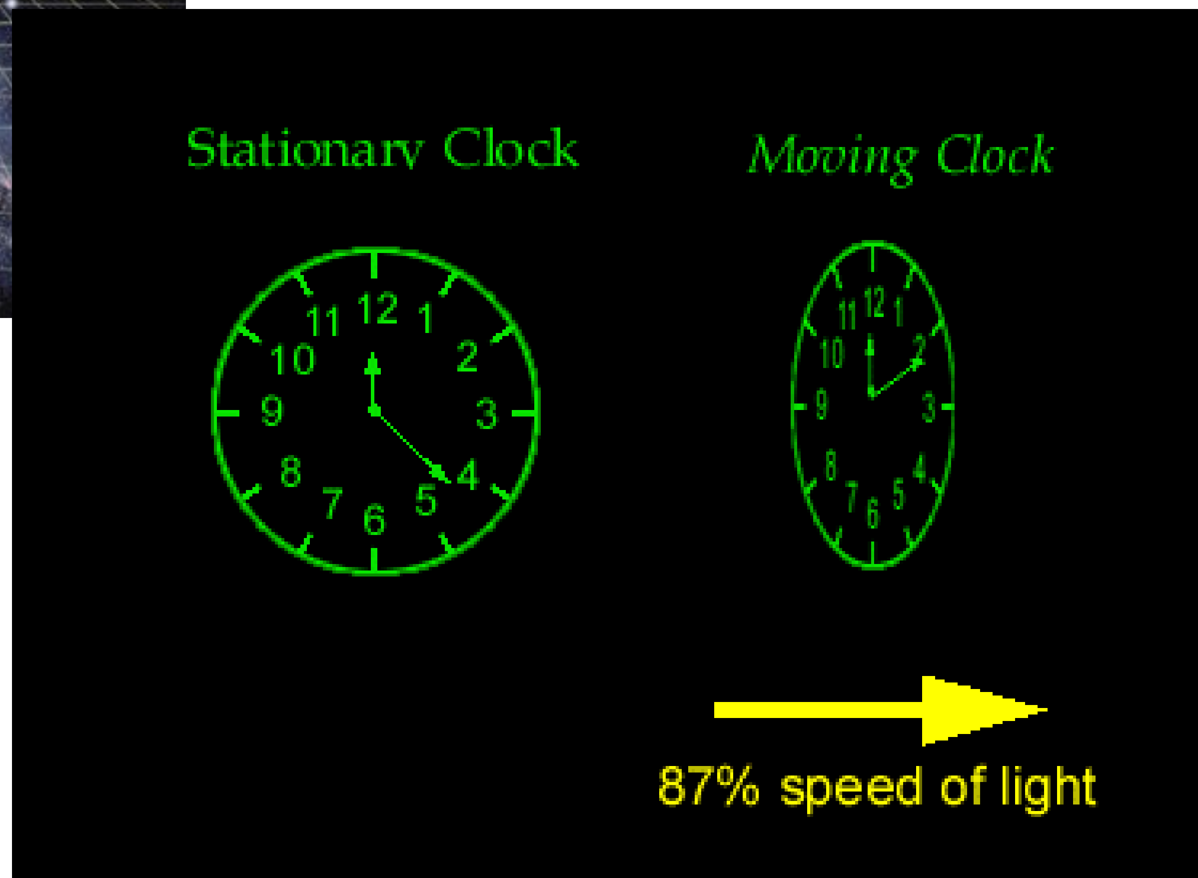
- smaller dipole moment
- closed transition
- J=0 to J=1
- diode laser accessible



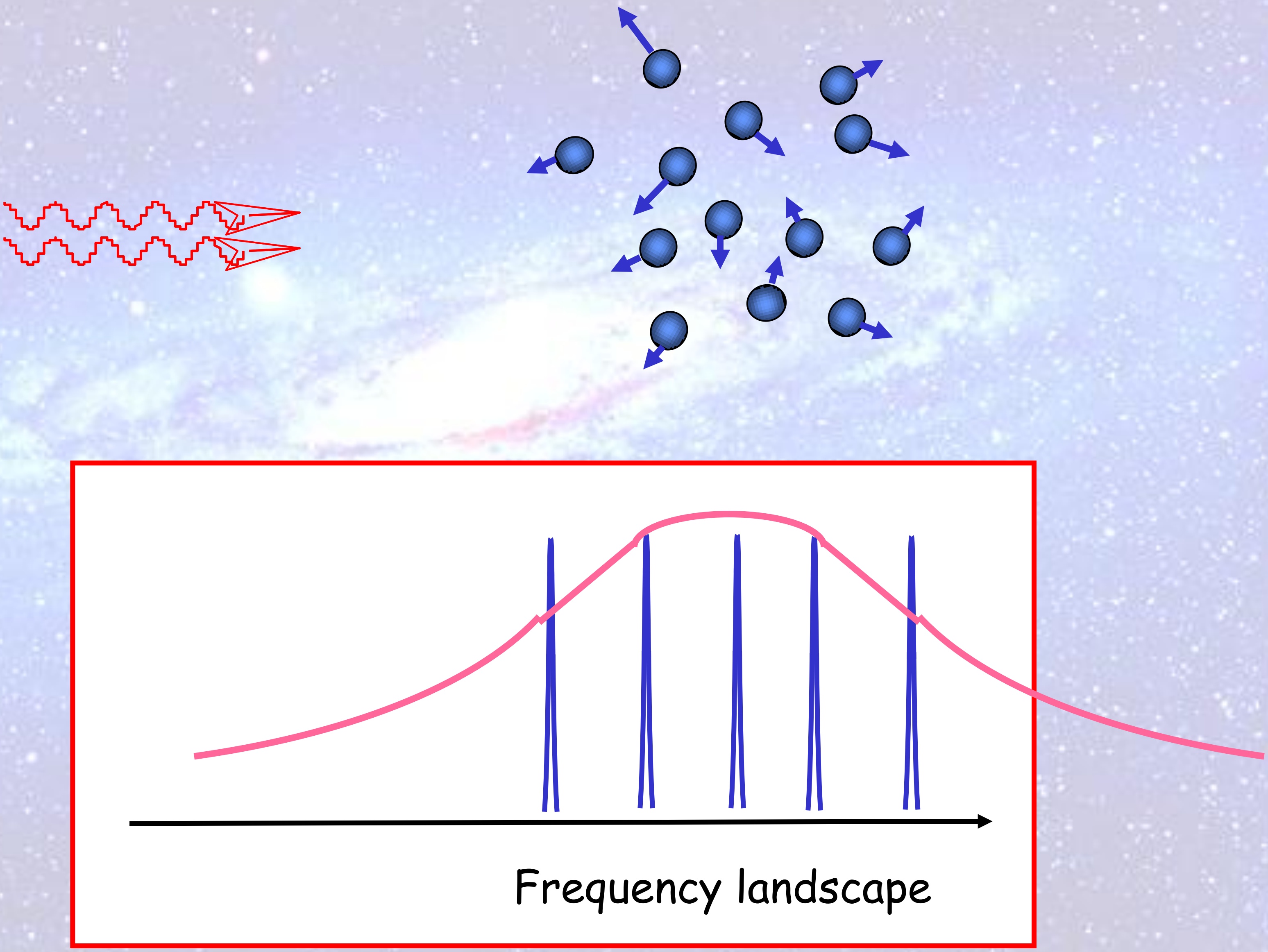
"Bad" things about motion –
Short observations; Relativity (Doppler) shifts



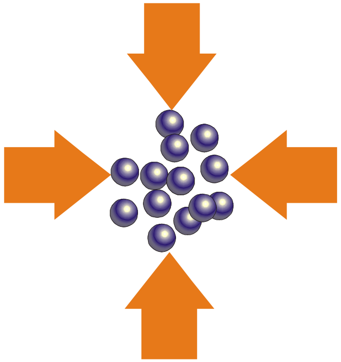




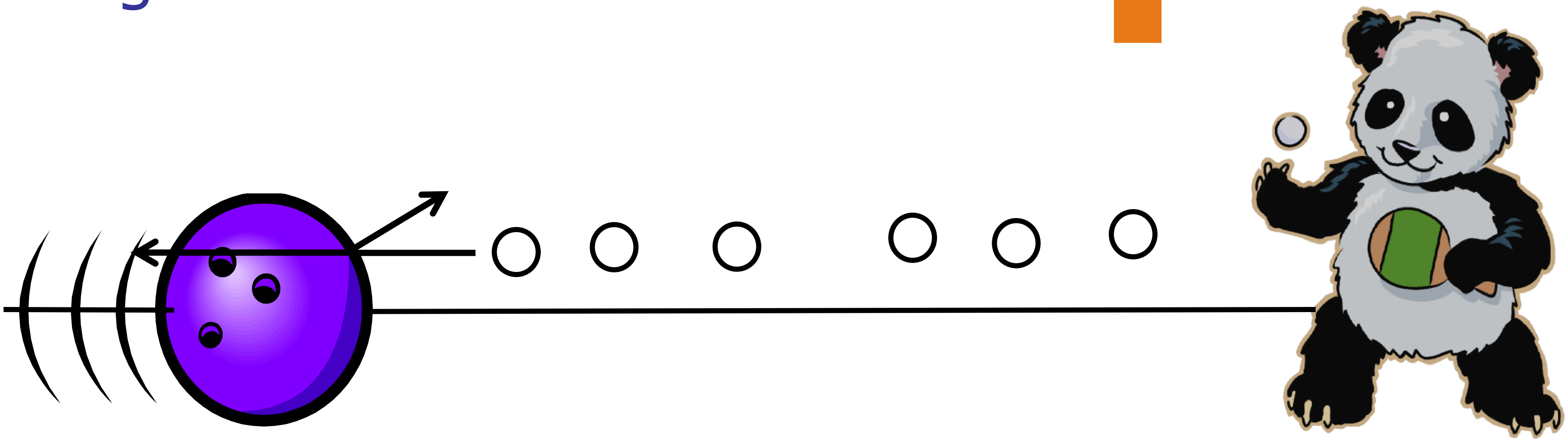
The Doppler Problem



Cooling atoms using lasers

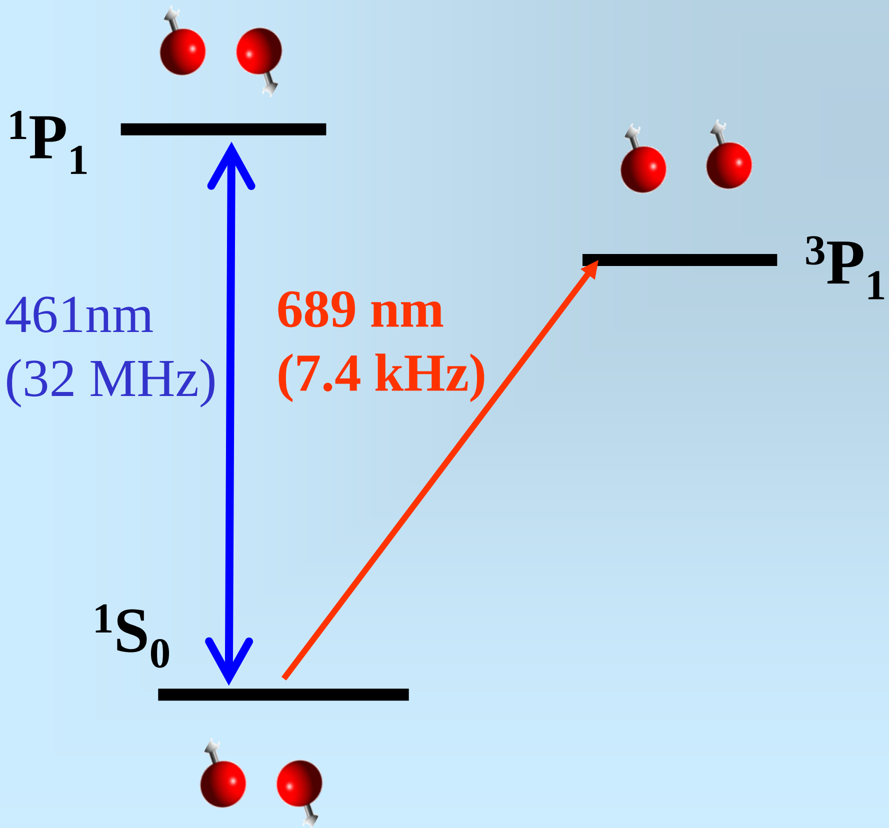


Always pushing atoms
against their motions

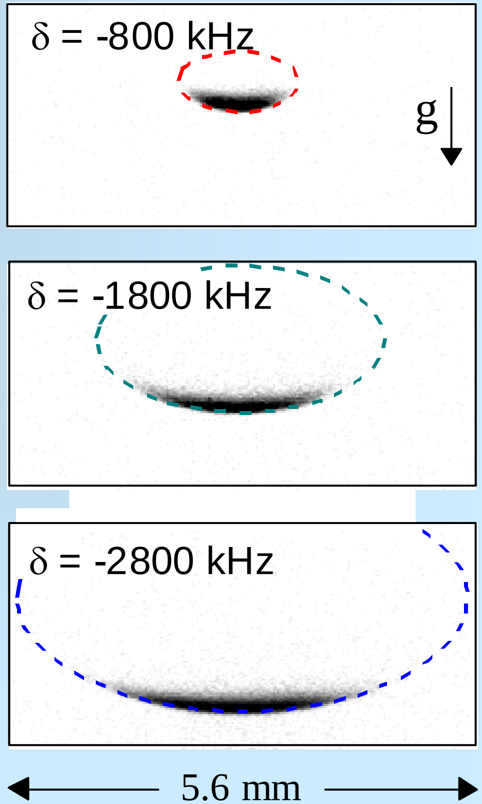


Stop the moving atom

1 billionth (10^{-9}) of room temperature

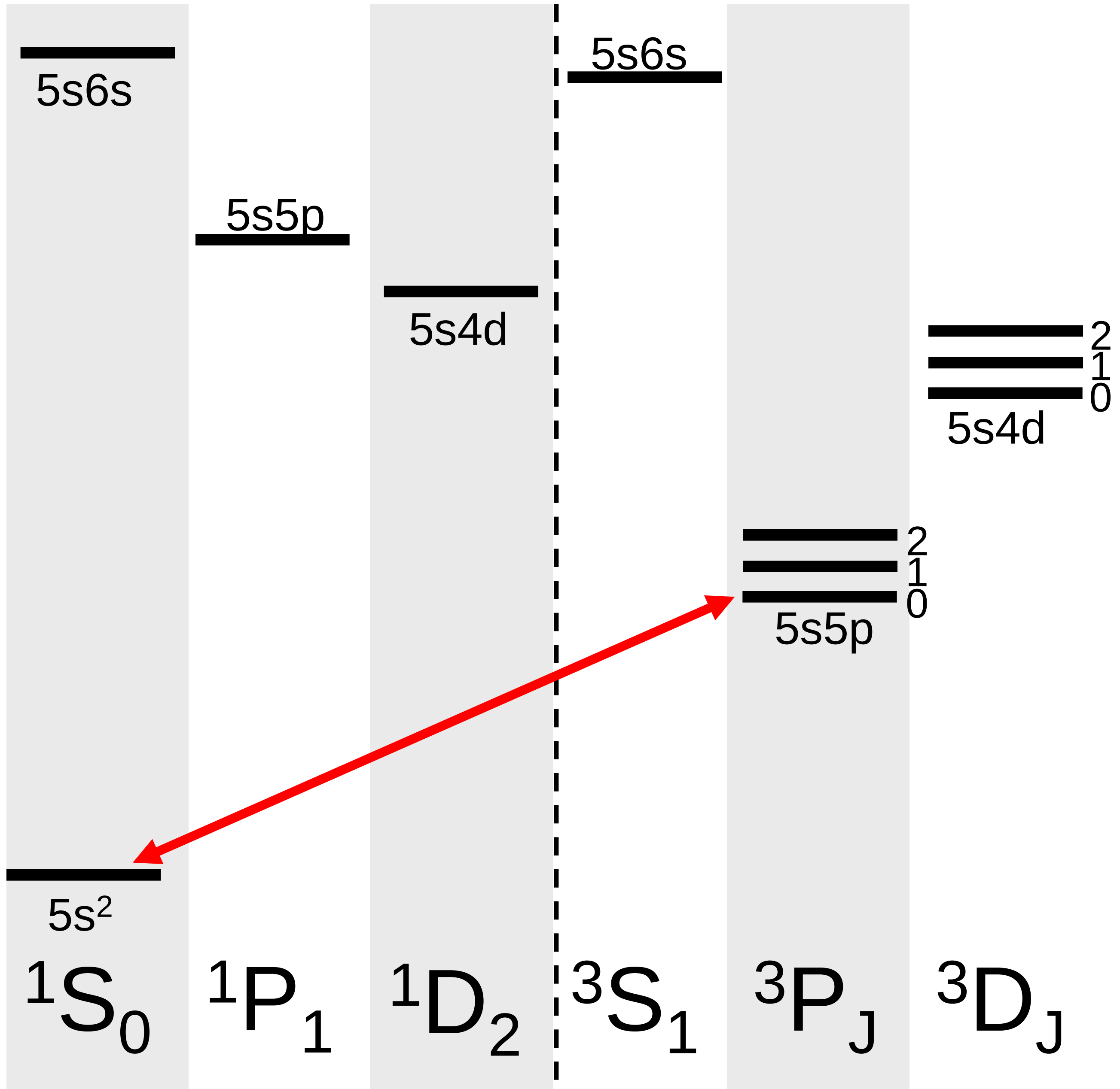


T ~ 0.5 photon recoil
~ 220 nK



Strontium: Clock Transition

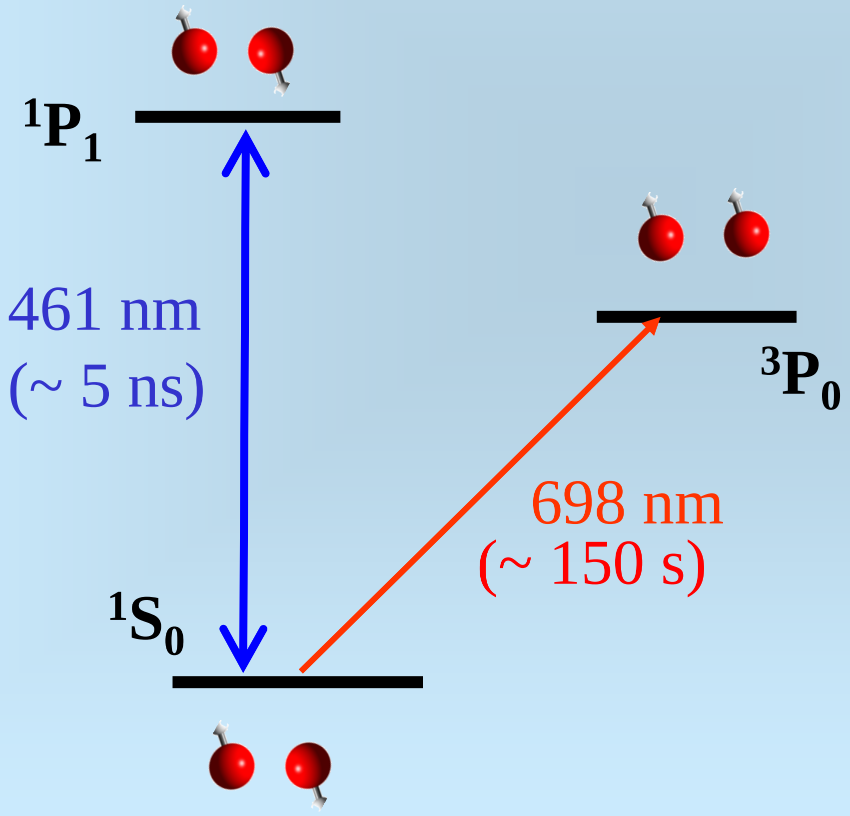
- HFI provides $^1S_0$-$^3P_0$ clock (~ 1mHz)
- field insensitive states
- diode laser
- accessible Stark-free confinement wavelength
- clock states J=0



Alkaline earth - A tale of Twin Electrons

JILA, Tokyo, Paris, NIST, PTB, Florence, NICT, NPL, NIM, NRC

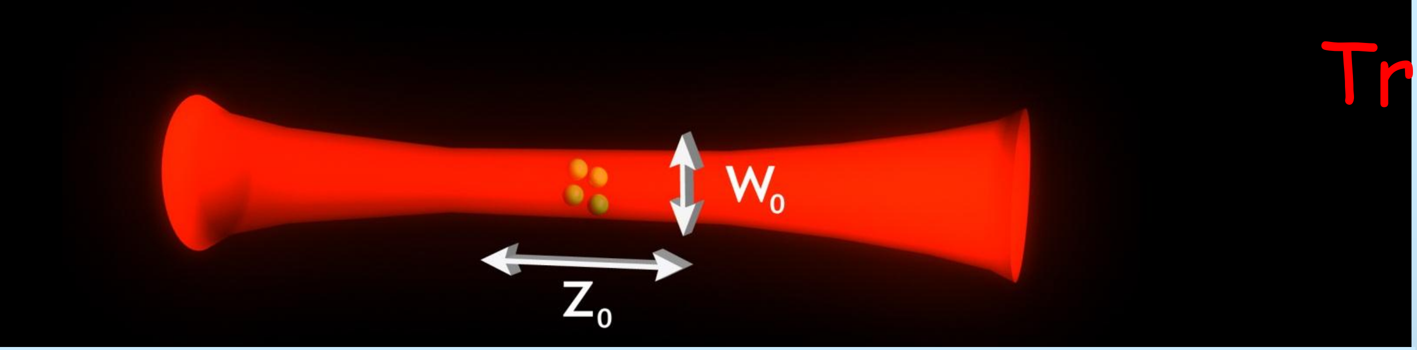
Science 314, 1430 (2006).
PRL 98, 083002 (2007).
Science 319, 1805 (2008).



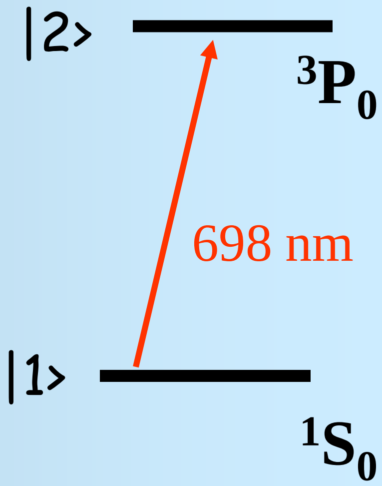
Metastable state
quality factor

$Q > 10^{17}$

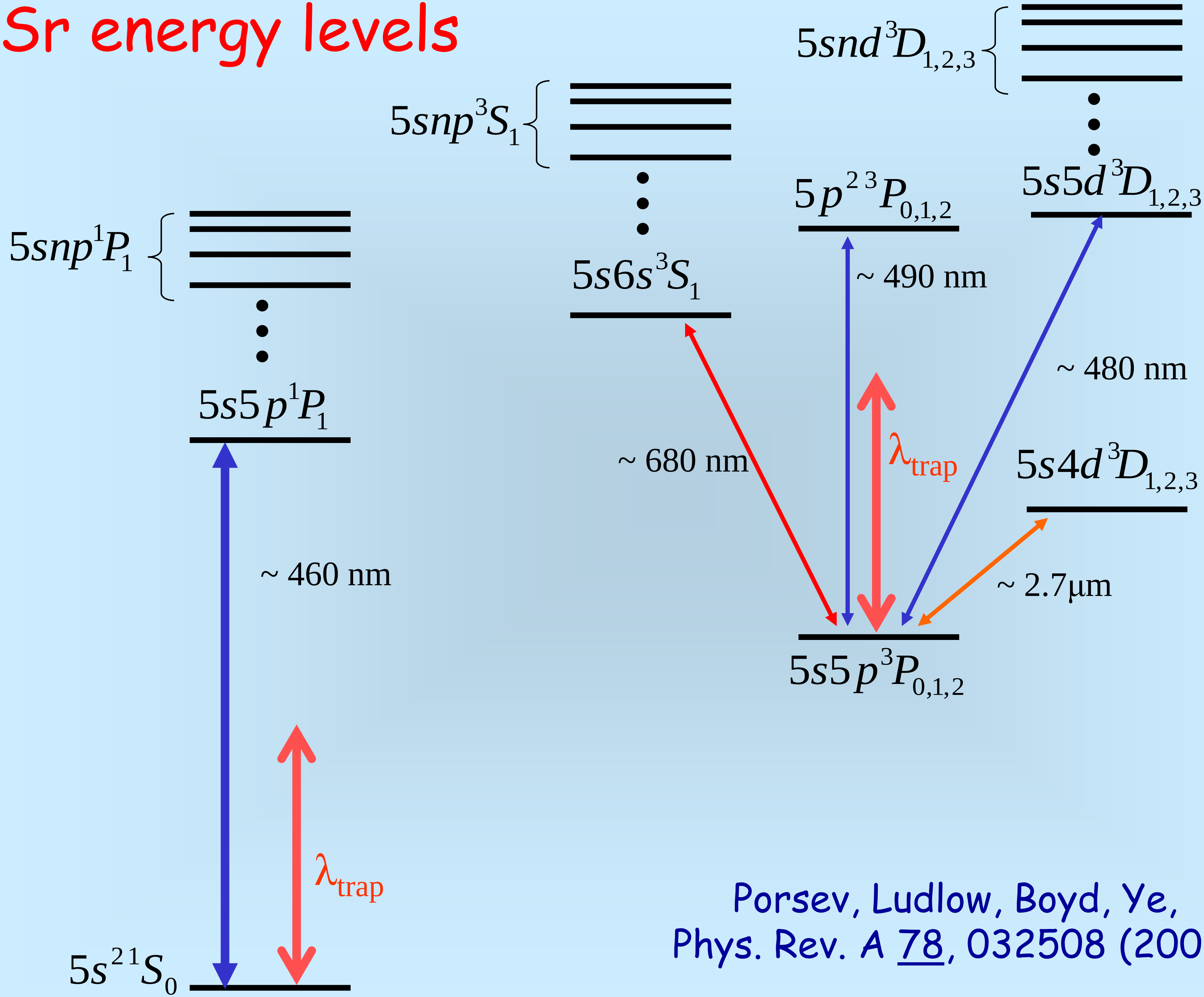
Trapping atom with light



Ye, Kimble, & Katori,
Science **320**, 1734 (2008).

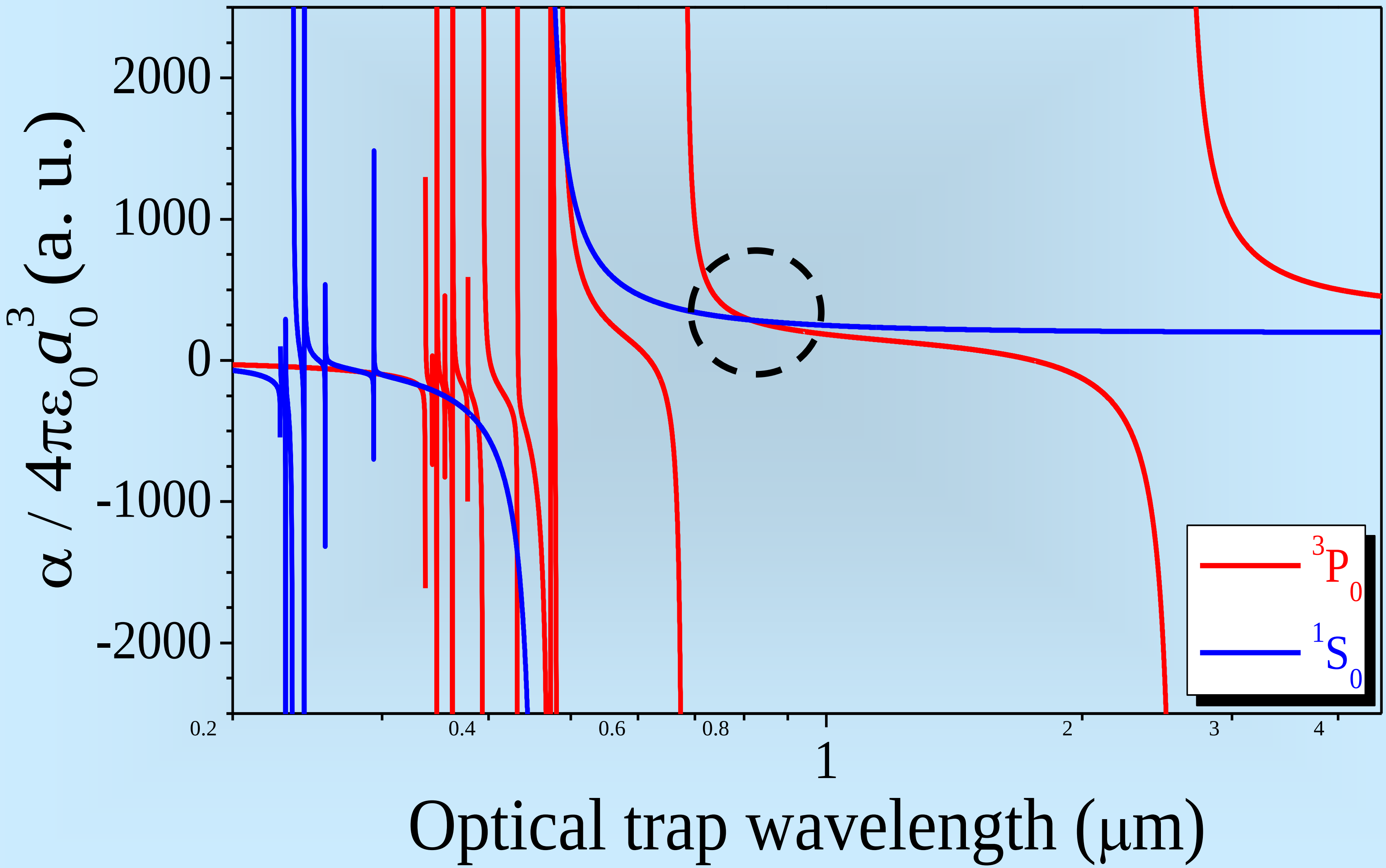


Sr energy levels

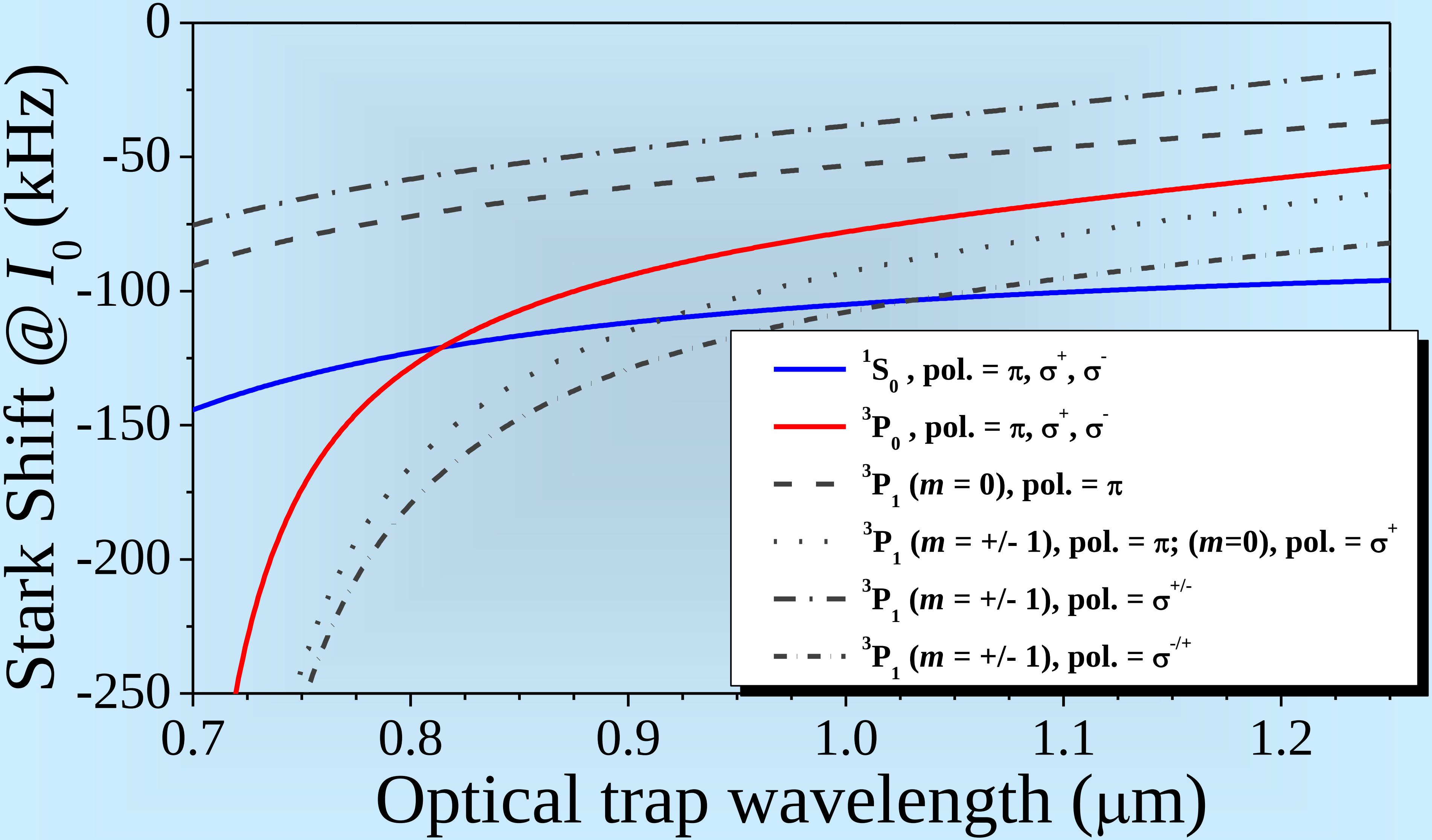


Porsev, Ludlow, Boyd, Ye,
Phys. Rev. A 78, 032508 (2008).

Crossing of polarizabilities



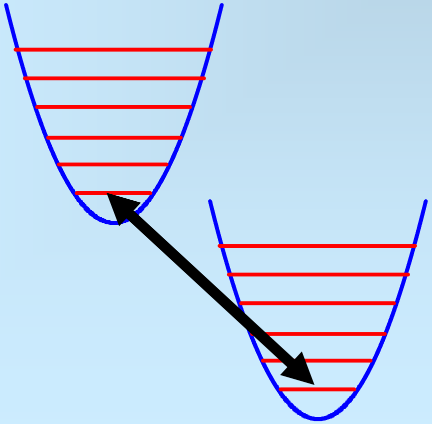
It's a mess if J ≠ 0



Important Regimes for Spectroscopy

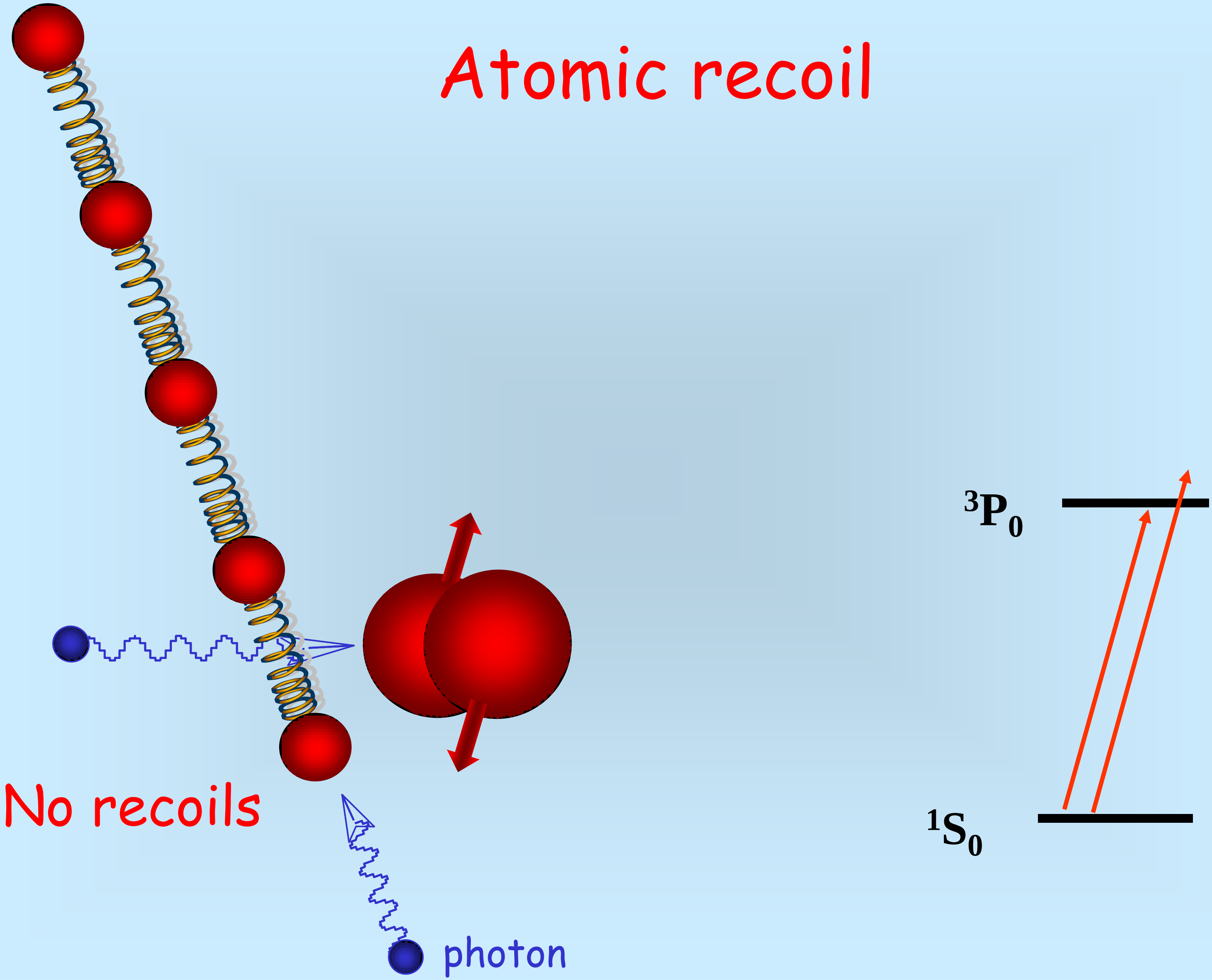
$$\omega_{trap} >> \Gamma$$ well-resolved sideband

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



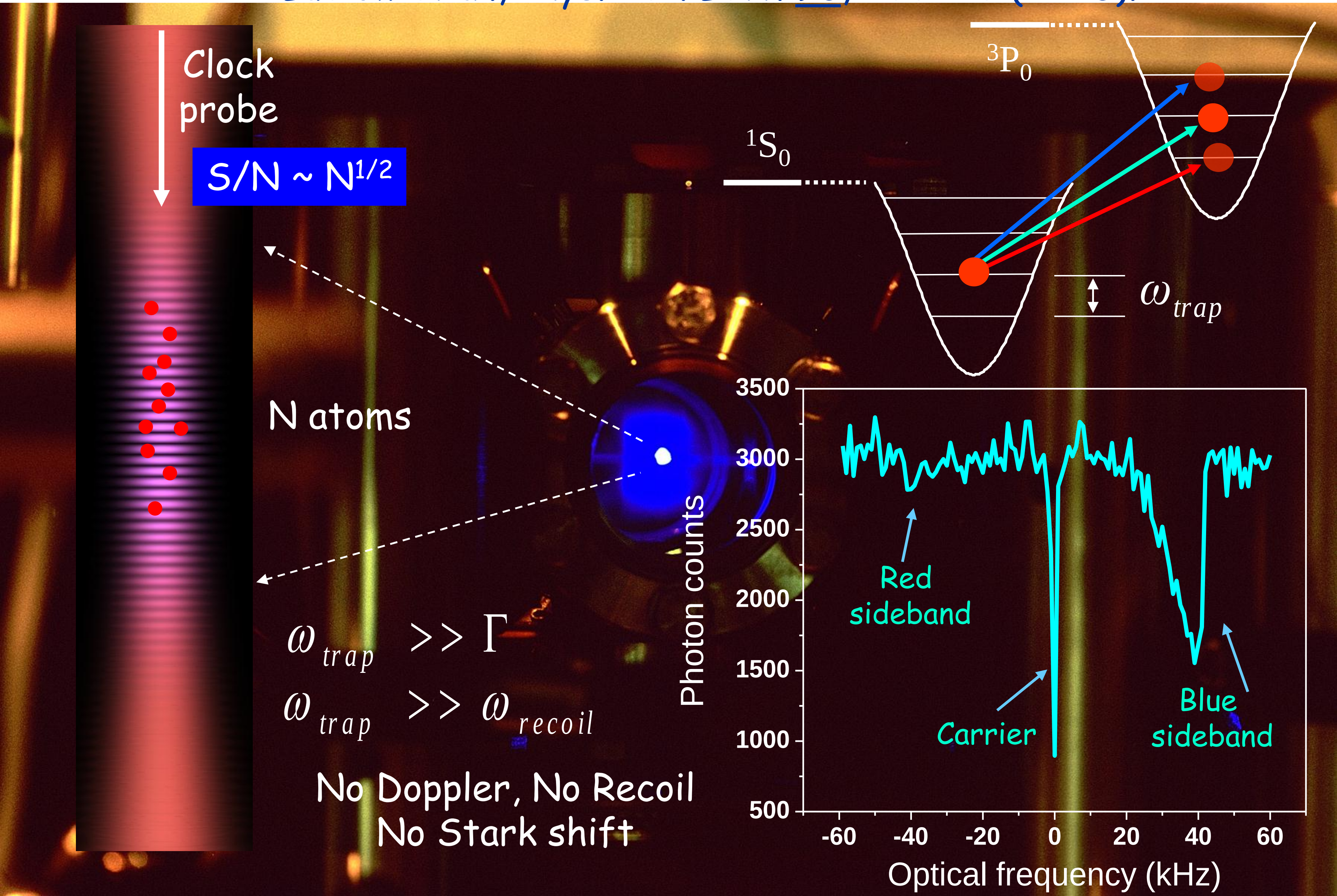
uniform confinement

Atomic recoil

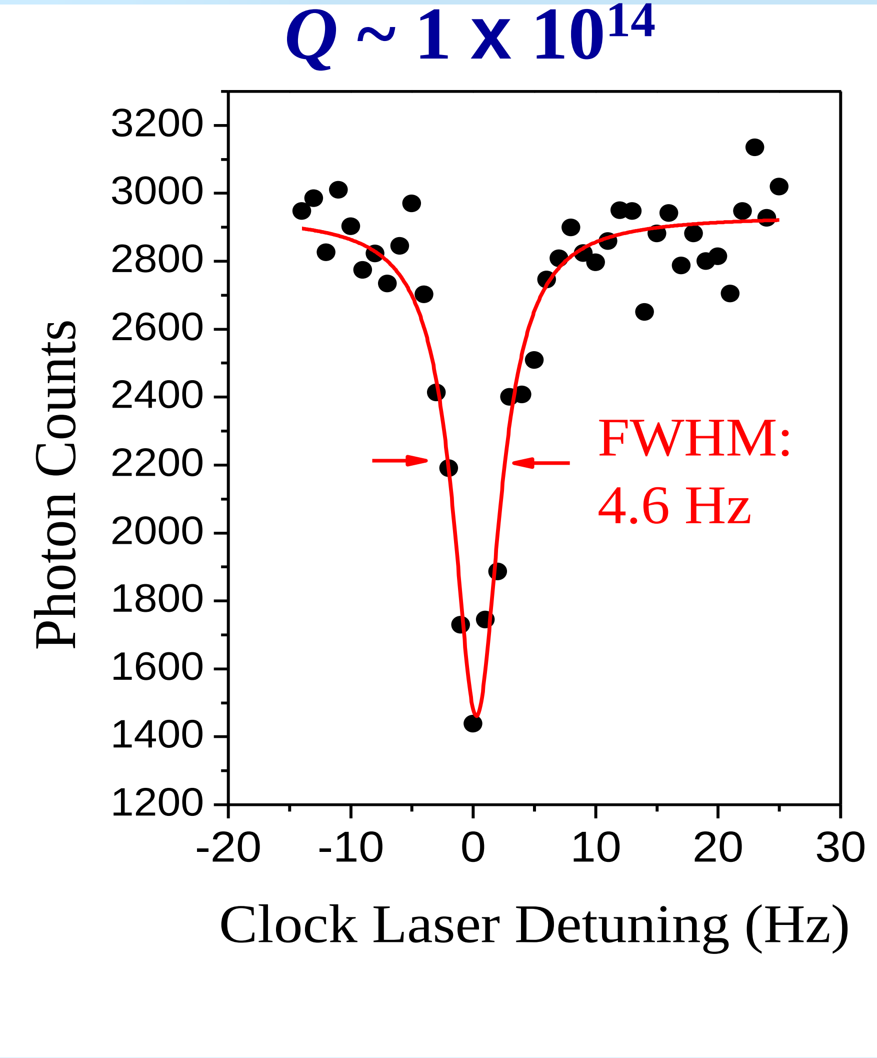


Spectroscopy at the magic wavelength

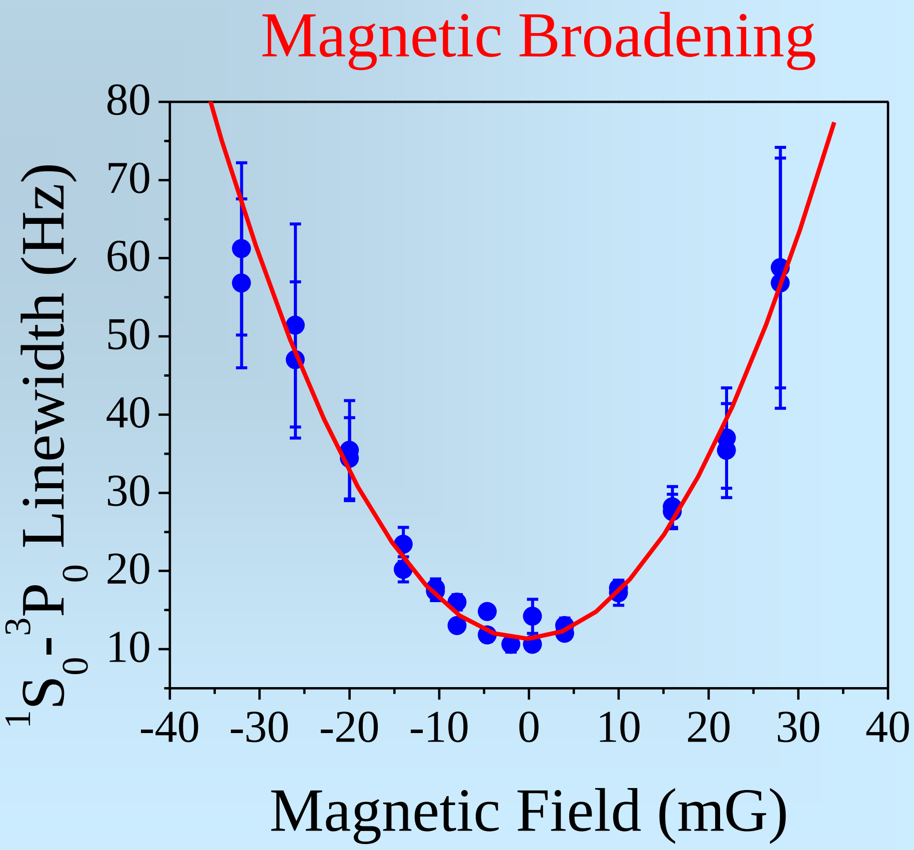
Ludlow et al., Phys. Rev. Lett. 96, 033003 (2006).



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

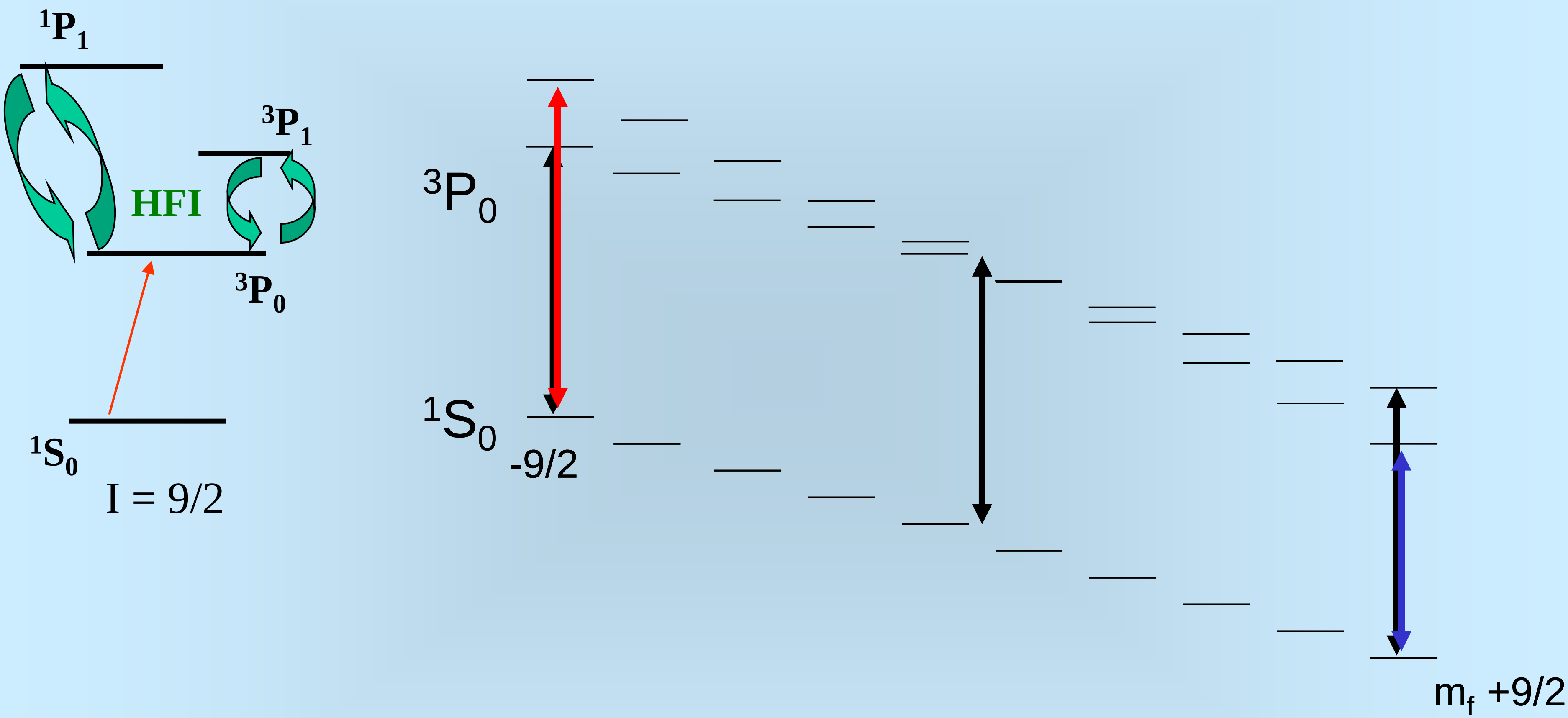


- Single trace without averaging



Differential Landé *g*-factor

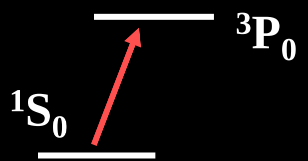
$$|^3P_0^{'} > = |^3P_0 > + c_1|^1P_1 > + c_2|^3P_1 >$$



- $^3P_0$ g-factor different from $^1S_0$ due to hyperfine
- Zeeman-shift; vector & tensor light shifts
- All are determined with high-resolution measurement

Optical Measurement of Nuclear *g*-factor

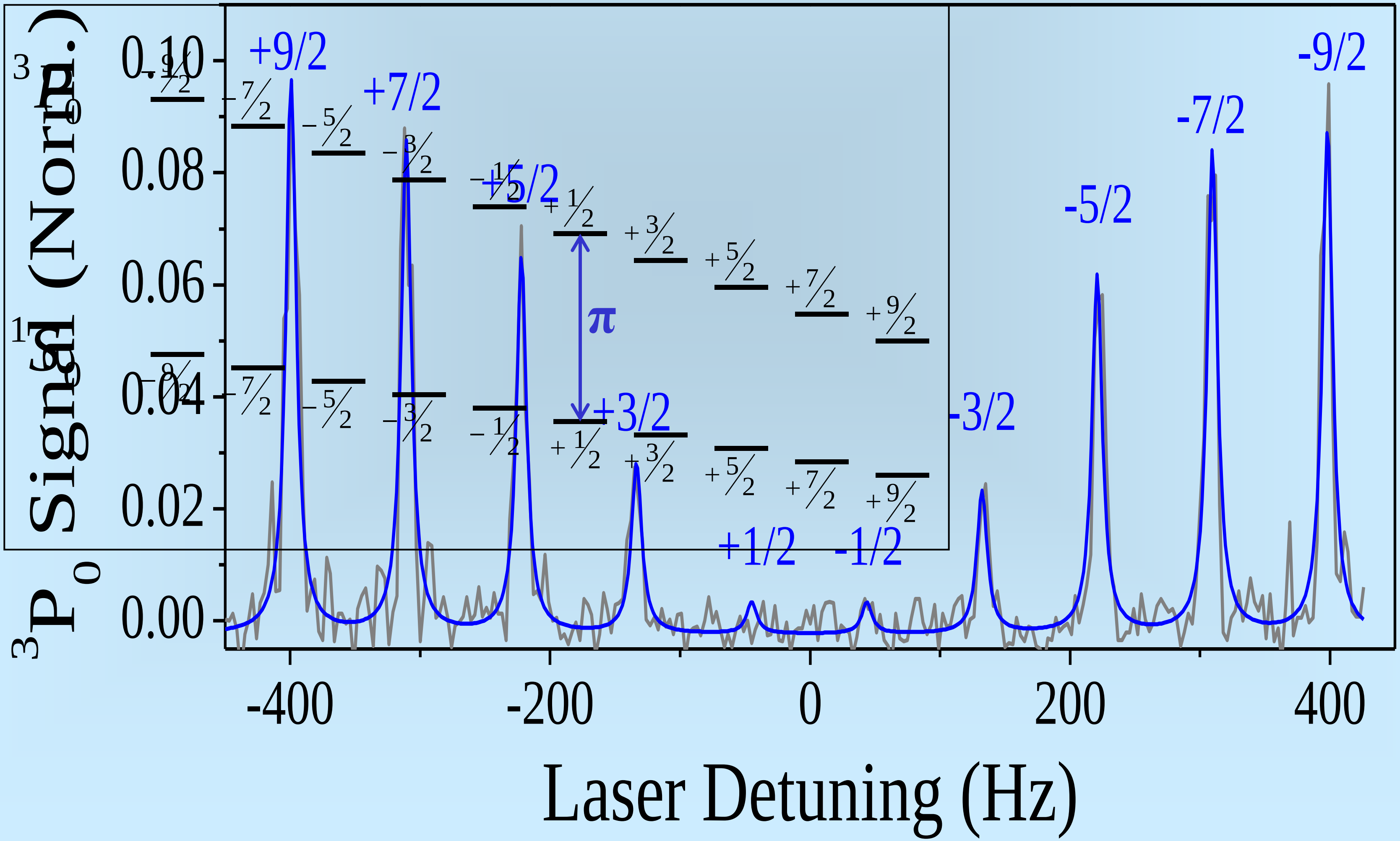
Boyd, Zelevinsky, Ludlow, Foreman, Blatt, Ido, & Ye, Science 314, 1430 (2006).



No net electronic angular momentum

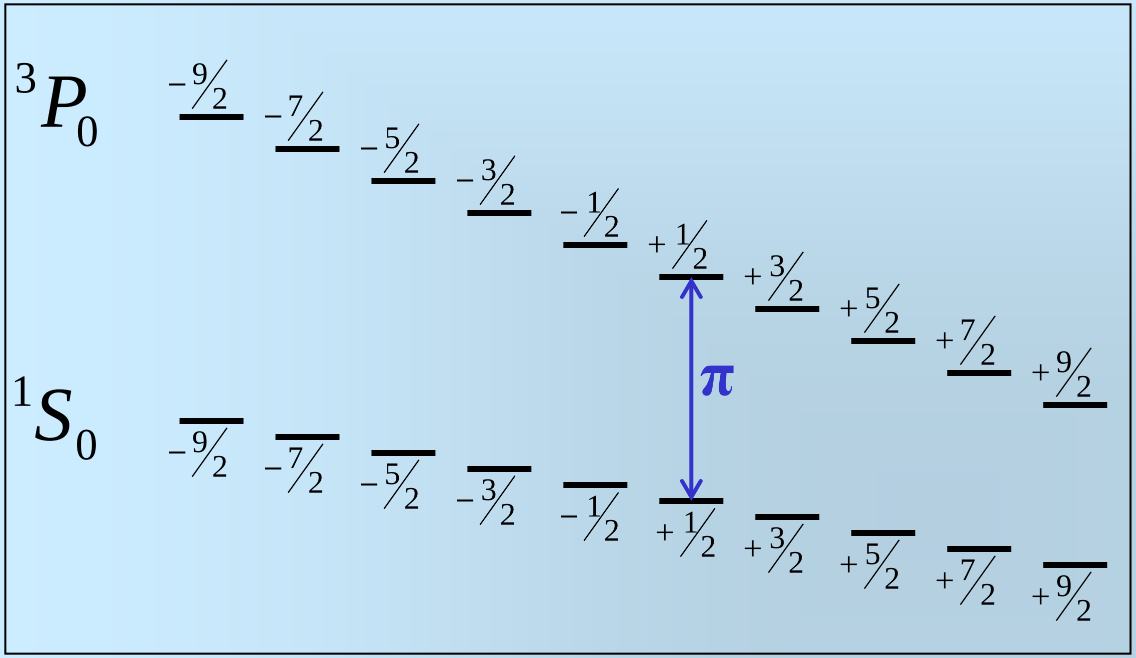
Δg = -108.4(4) Hz/(G m_F)

$^3P_0$ lifetime 140(40) s



Scalar, vector, tensor polarizabilities

Boyd *et al.*, PRA 76, 022510 (2007). Westergaard et al. PRL 106, 210801 (2011).



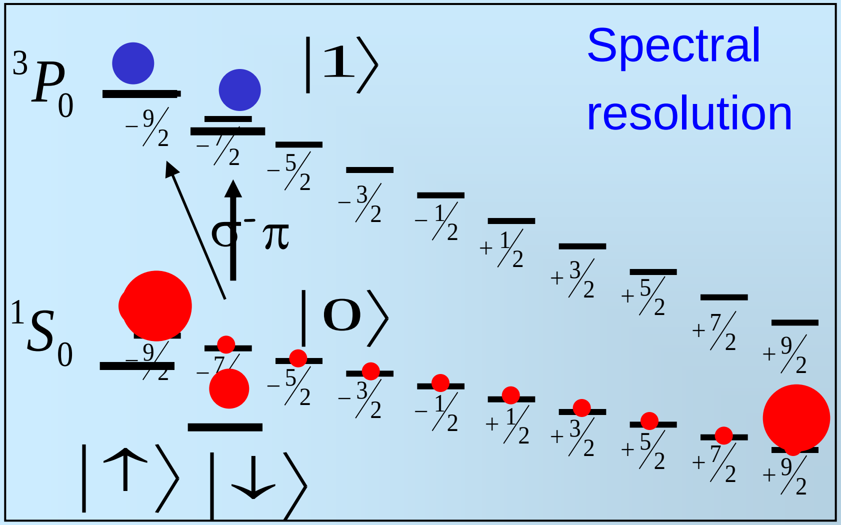
Hyperpolarizability
~ $(I_{trap})^2$: <1E-17
P. Lemonde, SYRTE

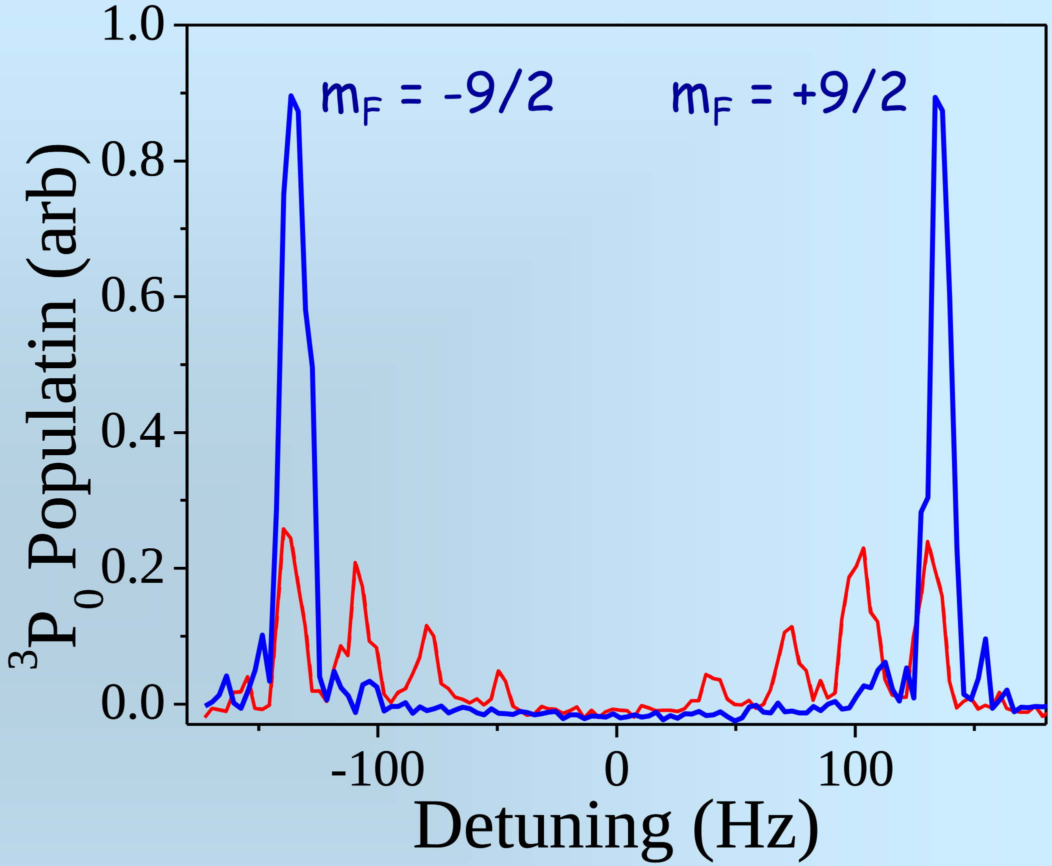
$\Delta\alpha$: differential polarizability

ξ: polarization ellipticity

$$
\begin{aligned}
\nu_{\pi_{mF}} = \; & \nu_0 && \text{Clock frequency} \\
& -\Delta g \; m_F \; \mu_0 \; B && \text{1st order Zeeman} \\
& -\left(\Delta\alpha^S - \Delta\alpha^T F(F+1)\right) I_{trap} && \text{Scalar + Tensor polarizability} \\
& -\left(\Delta\alpha^V \xi \, m_F + \Delta\alpha^T \, 3m_F^2\right) I_{trap} && \text{Vector + Tensor polarizability}
\end{aligned}
$$

Coherent optical manipulation of nuclear spins





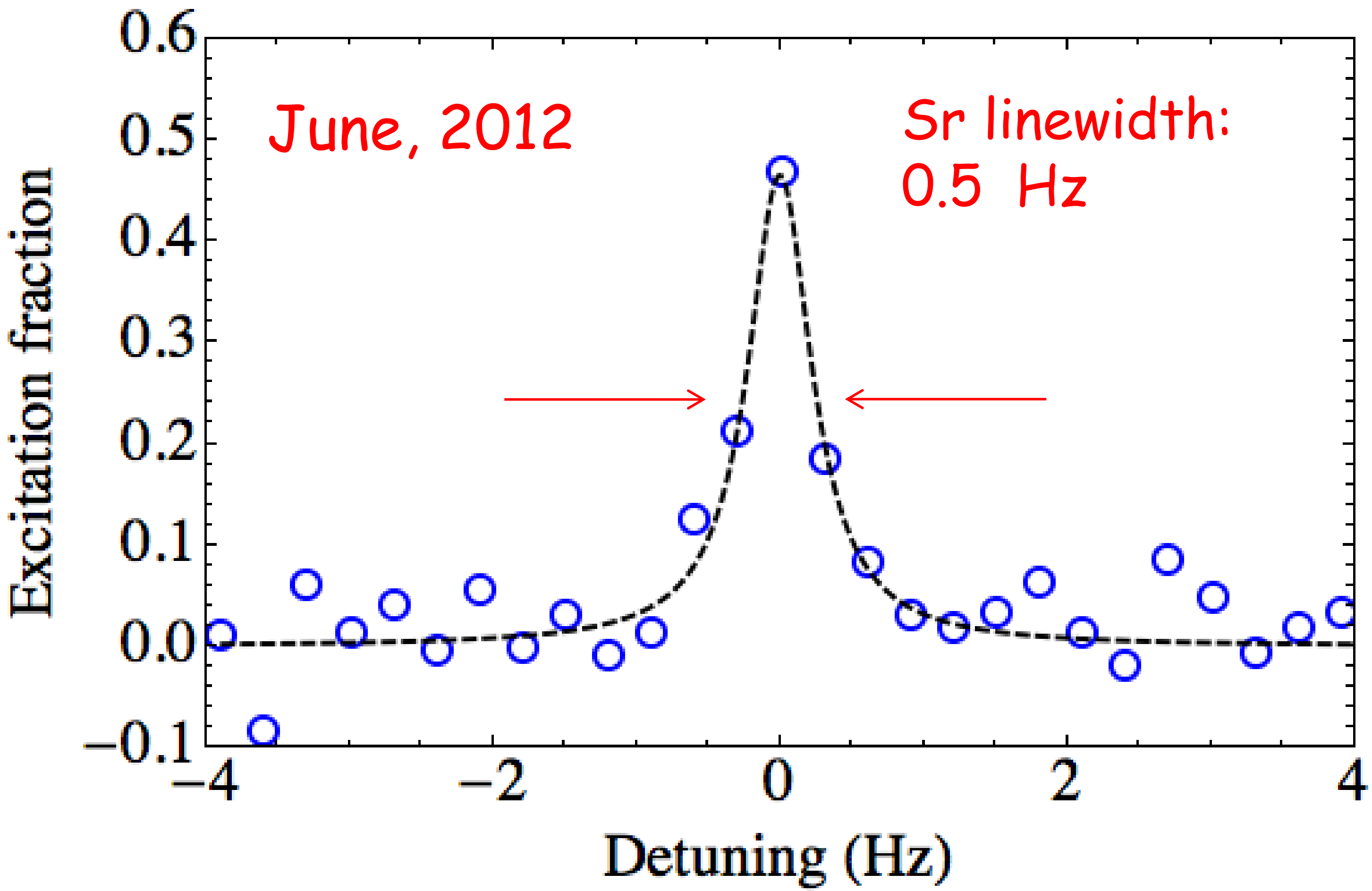
Quantum computing
Quantum register
Quantum simulations

- Two stable spin systems, separately manipulated or entangled.
- Nuclear spins for information storage & accessed via electronic qubits.
- Electronic states for state-dependent lattice & control.
- SU(*N*) symmetry; spin – orbital coupling dynamics.

Deutsch *et al.*, PRL **98** (2007); PRL **99**, (2007). Daley *et al.*, PRL **101** (2008).
Gorshkov *et al.*, PRL. **102** (2009); Nature Phys. **6**, 289 (2010).

Coherent spectroscopy Q ~ 1 x 10^{15}

Boyd *et al.*, Science 314, 1430 (2006); PRL 98, 083002 (2007).



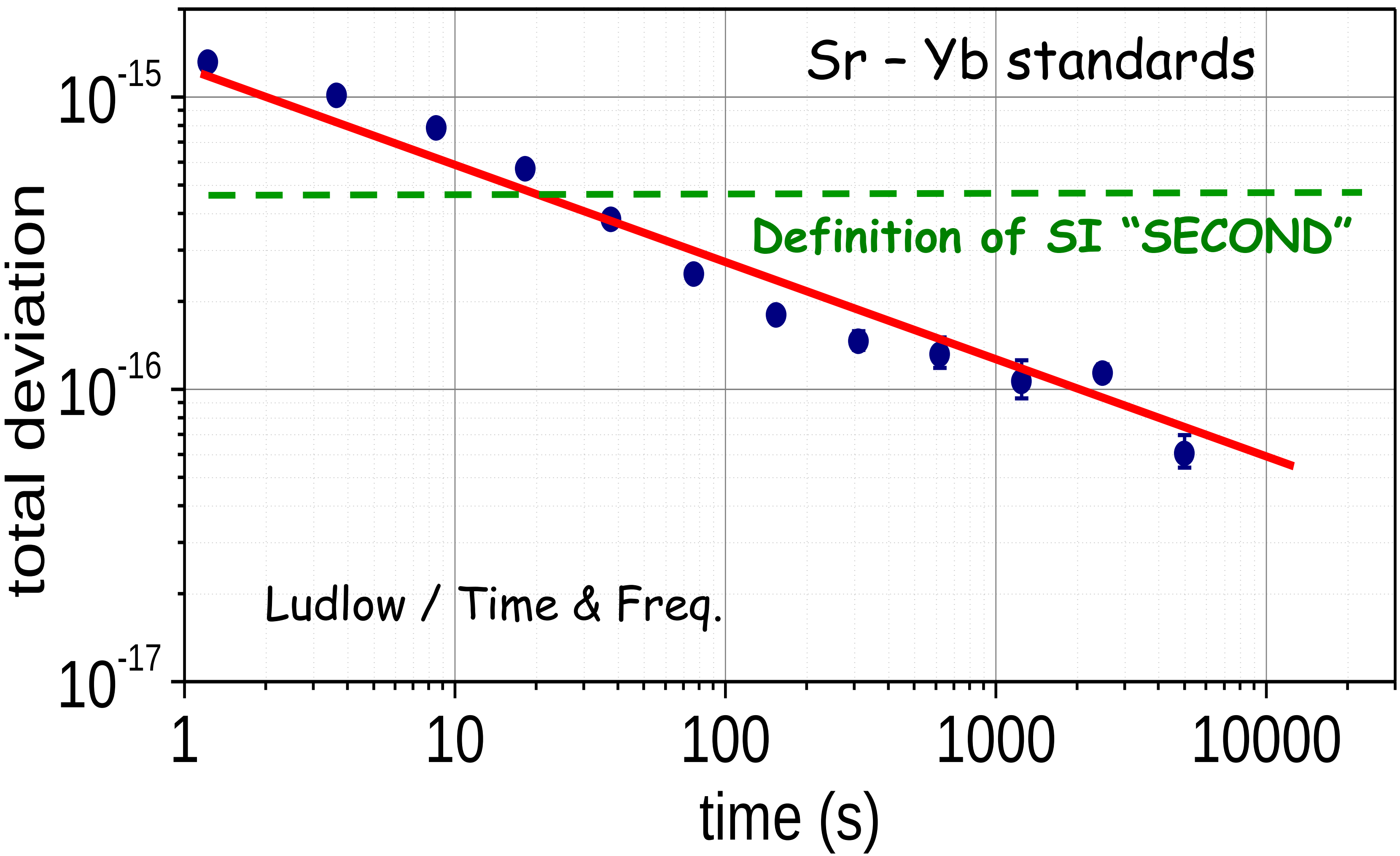
Instability ~ 2 x $10^{-16}/\sqrt{\tau}$

Near the quantum projection noise

JILA Sr atomic clock

Science **314**, 1430 (2006); Science **319**, 1805 (2008); Science **320**, 1734 (2008); Science **324**, 360 (2009); Science **331**, 1043 (2011).

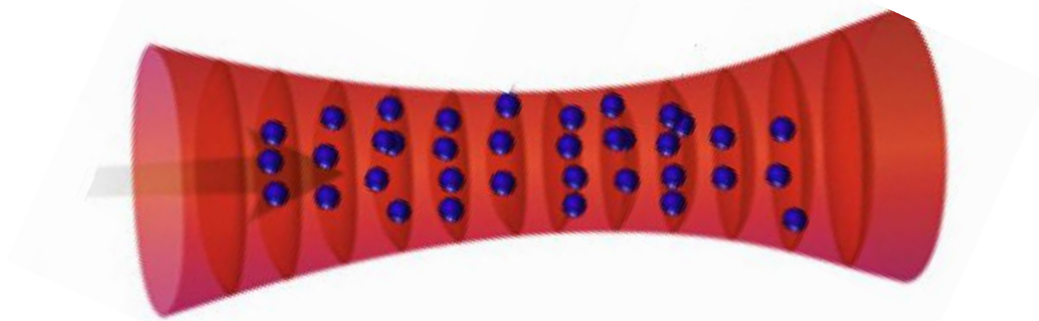
10, 000, 000, 000, 000, 000 ± 1 (10^{-16})



Collision is a big deal for Sr Systematics

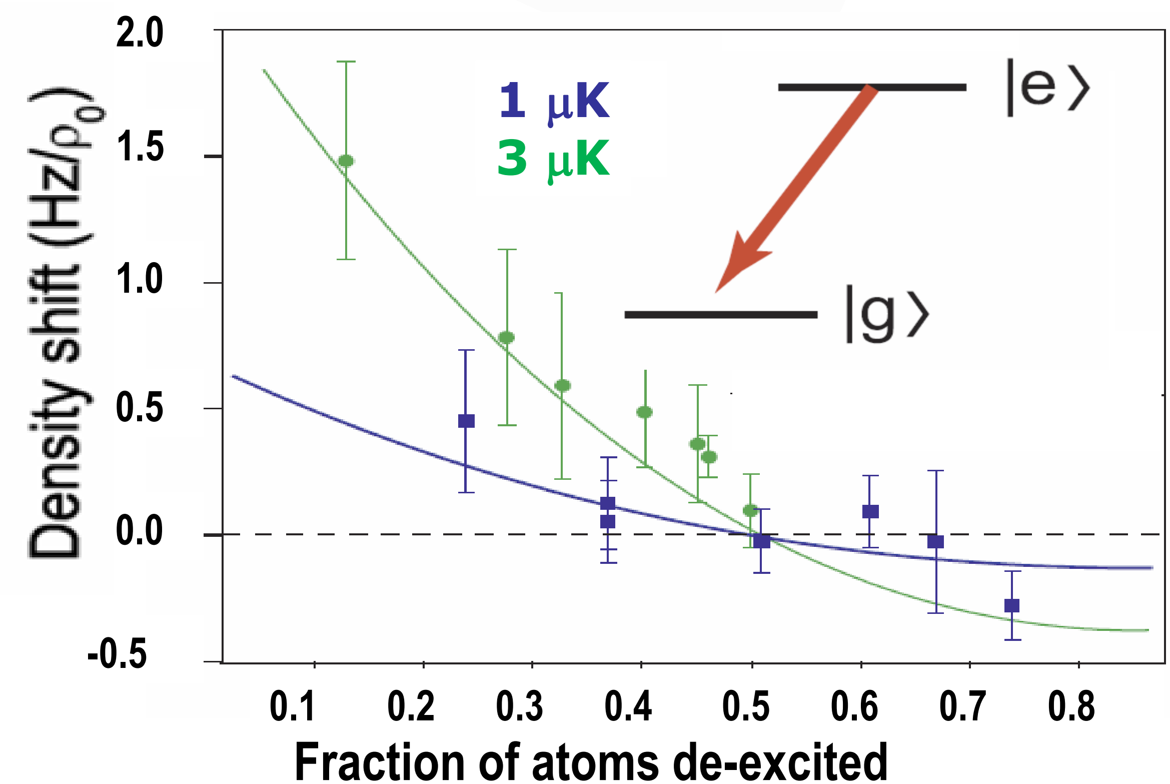
Contributor	Correction (10^{-16})	Uncertainty (10^{-16})
Lattice Stark (scalar/tensor)	−6.5	0.5
Hyperpolarizability (lattice)	−0.2	0.2
BBR Stark	52.1	1.0
ac Stark (probe)	0.2	0.1
First-order Zeeman	0.2	0.2
Second-order Zeeman	0.2	0.02
Density	8.9	0.8
Line pulling	0	0.2
Servo error	0	0.5
Second-order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

1D lattice



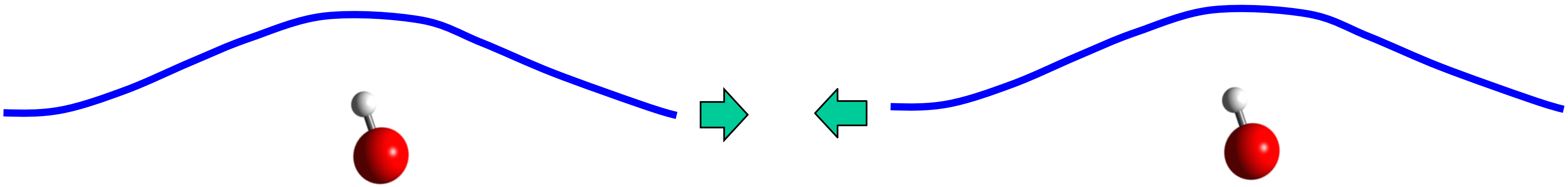
Measurement of frequency shift (10^{-16}) for spin-polarized fermions

G. Campbell *et al*, Science **324**, 360 (2009).

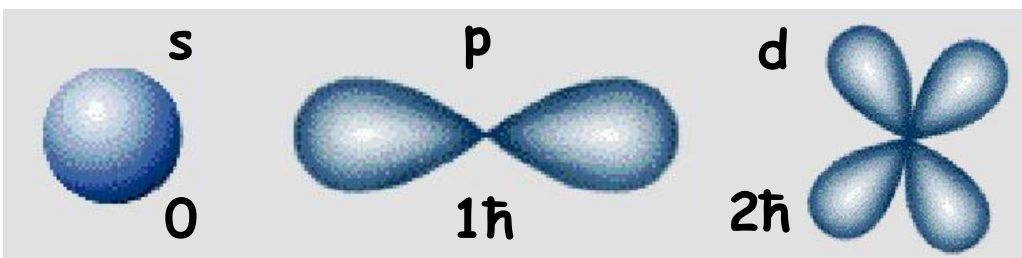


Interactions between identical Fermions

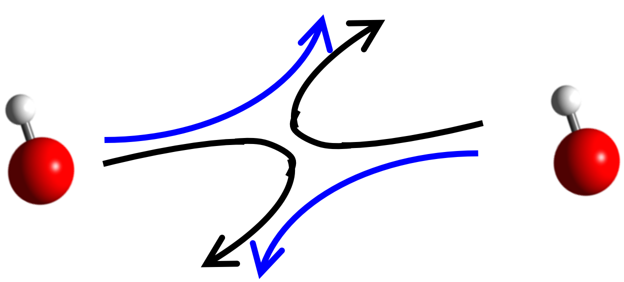
(1) Particles behave like waves (T -> 0)



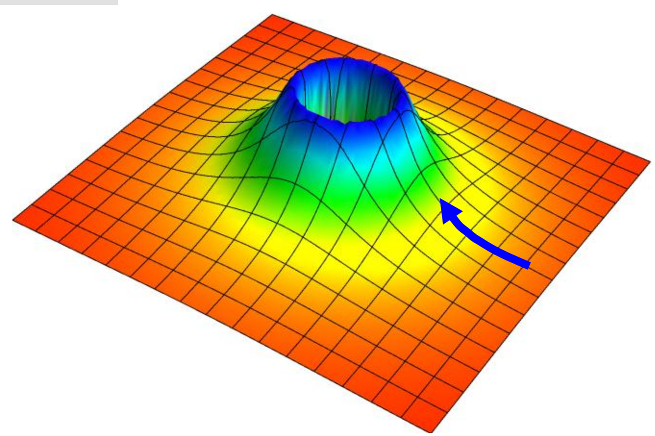
(2) Angular momentum is quantized



(3) Quantum statistics matter

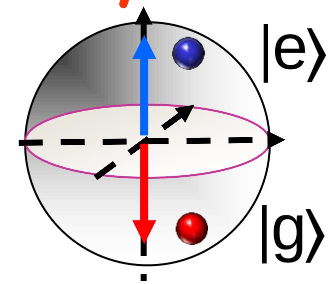


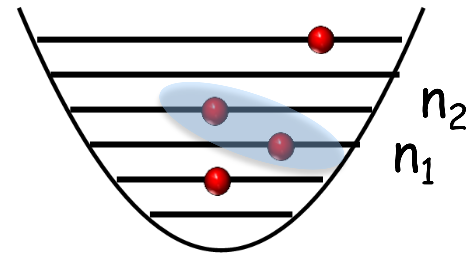
$$|\psi_0\rangle|\psi_1\rangle - |\psi_1\rangle|\psi_0\rangle$$



Fermions ⇨ *L* = 1, *p*-wave collisions

Lattice clock: an interacting quantum system





Singlet State

Interaction

$U \propto a_{eg}^{-}$

$$|s\rangle = \frac{|{\color{blue}\bullet}{\color{red}\bullet}\rangle - |{\color{red}\bullet}{\color{blue}\bullet}\rangle}{\sqrt{2}} \frac{|n_1\, n_2\rangle + |n_2\, n_1\rangle}{\sqrt{2}}$$

Triplet States

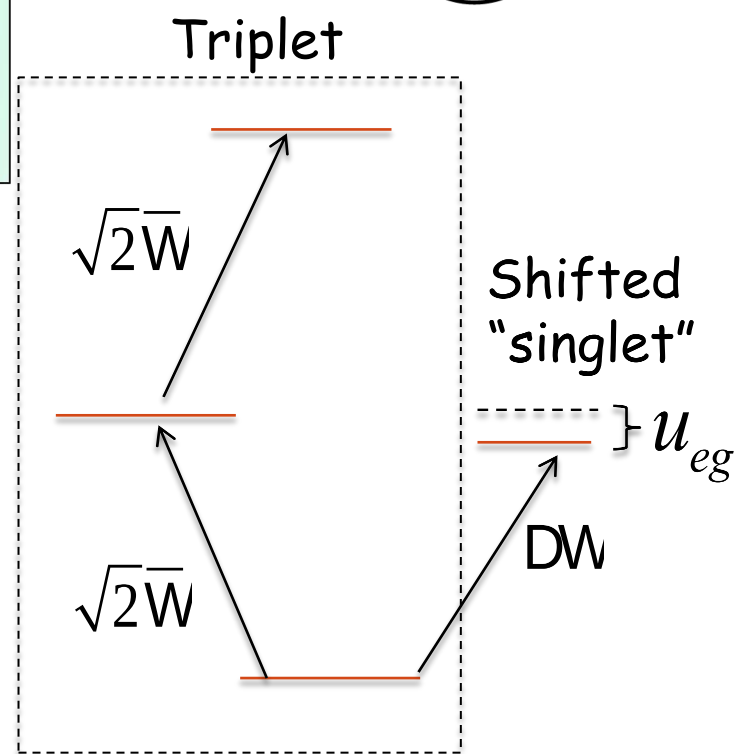
No s-wave collisions

$U = 0$

$$|t^{+}\rangle = |{\color{red}\bullet}{\color{red}\bullet}\rangle \frac{|n_1\, n_2\rangle - |n_2\, n_1\rangle}{\sqrt{2}}$$

$$|t^{-}\rangle = |{\color{blue}\bullet}{\color{blue}\bullet}\rangle \frac{|n_1\, n_2\rangle - |n_2\, n_1\rangle}{\sqrt{2}}$$

$$|t^{0}\rangle = \frac{|{\color{blue}\bullet}{\color{red}\bullet}\rangle + |{\color{red}\bullet}{\color{blue}\bullet}\rangle}{\sqrt{2}} \frac{|n_1\, n_2\rangle - |n_2\, n_1\rangle}{\sqrt{2}}$$



Singlet state → *s*-wave interaction shift.

Triplet states can also have *p*-wave interactions.

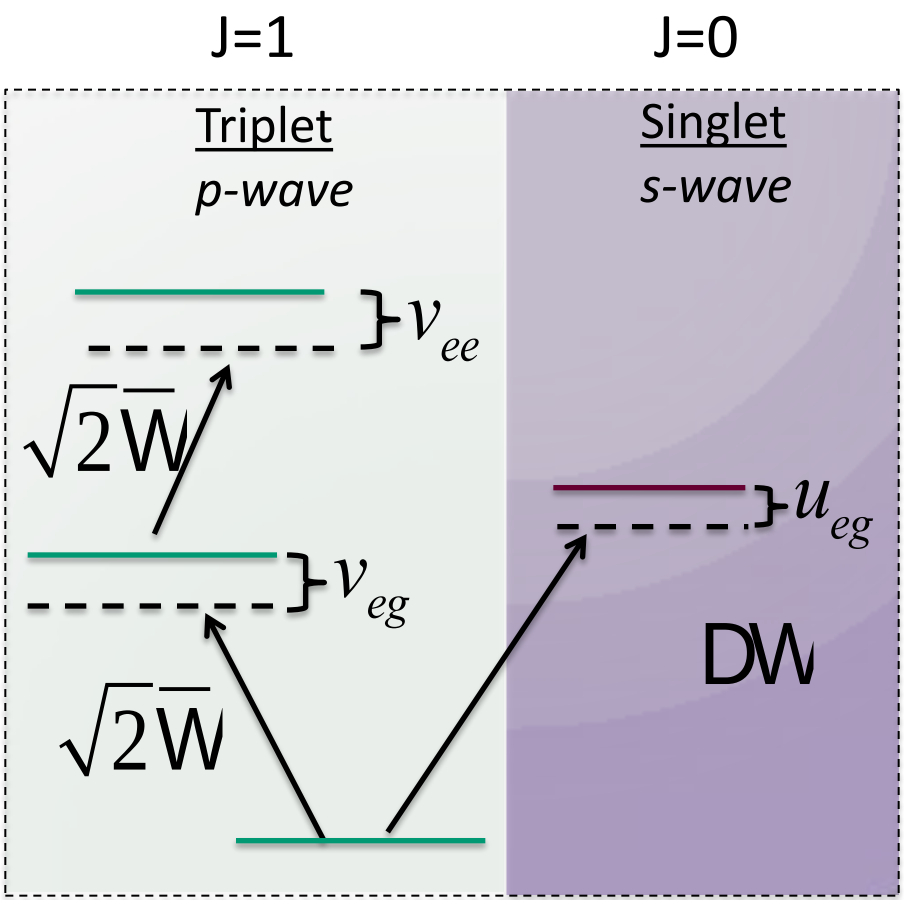
Rey *et al* PRL (2009), Gibble PRL (2009),
Yu & Pethick, PRL (2010).

Swallows et al., Science **331**, 1043 (2011).

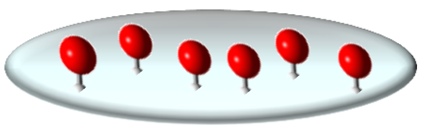
p-wave interactions

Two-particle:

Lemke *et al.* PRL **107** (2011);
Bishof *et al.* PRA **84**, 052716 (2011).

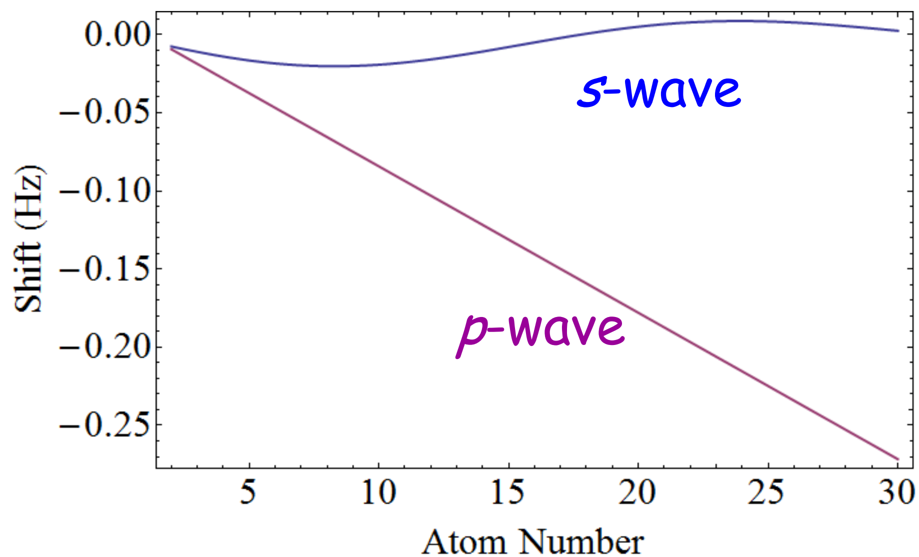


Many-particle: J=N/2

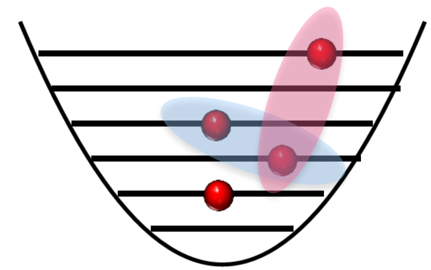


In a strongly interacting system:

- *s*-wave suppressed (contributing as sidebands)
- *p*-wave dominant (acting on the carrier)



Spin model
(Ana Maria Rey *et al.*)



Pseudo-spin $S = N/2$

$$\hat{H}/\hbar = -\delta S^z - \Omega S^x + \frac{J^\perp}{2}\vec{S}\cdot\vec{S} + \chi\left(S^z\right)^2 + C\left(N-1\right)S^z$$

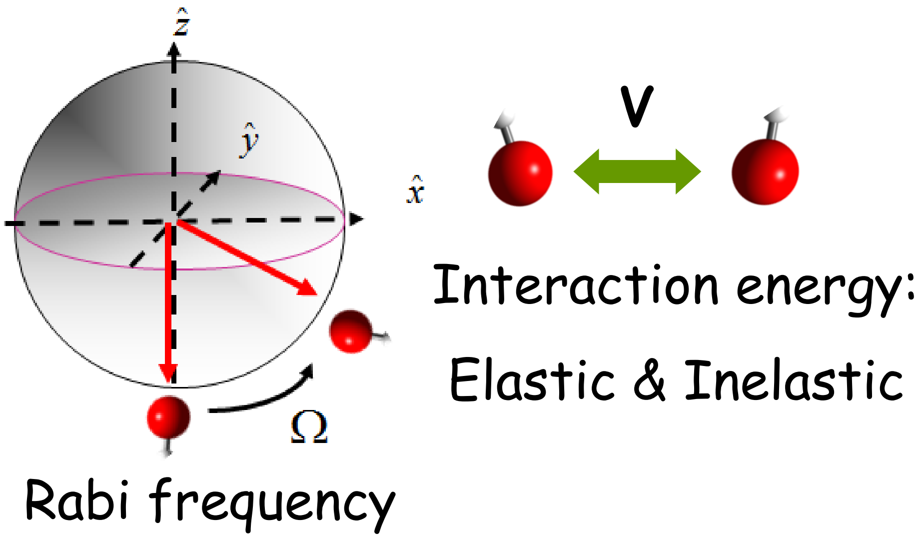
$$C = (V_{ee} - V_{gg})/2$$
$$\chi = (V_{ee} + V_{gg} - 2V_{eg})/2$$
$$J^\perp = V_{eg} - U_{eg}$$

δ and Ω: laser detuning and Rabi freq.

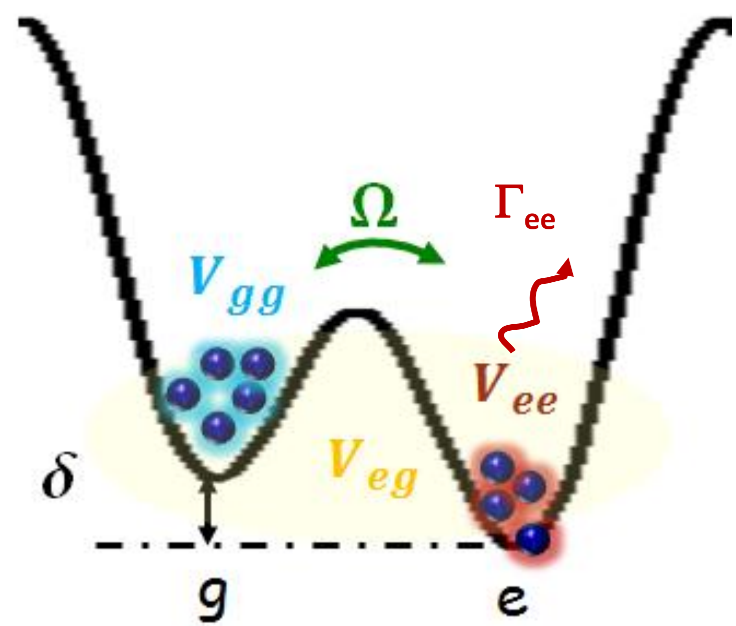
Micheli, A., Jaksch, D., Cirac, J., & Zoller, P. (2003). Physical Review A, **67**(1) (2003)

Mapping interacting Fermions to Bosons

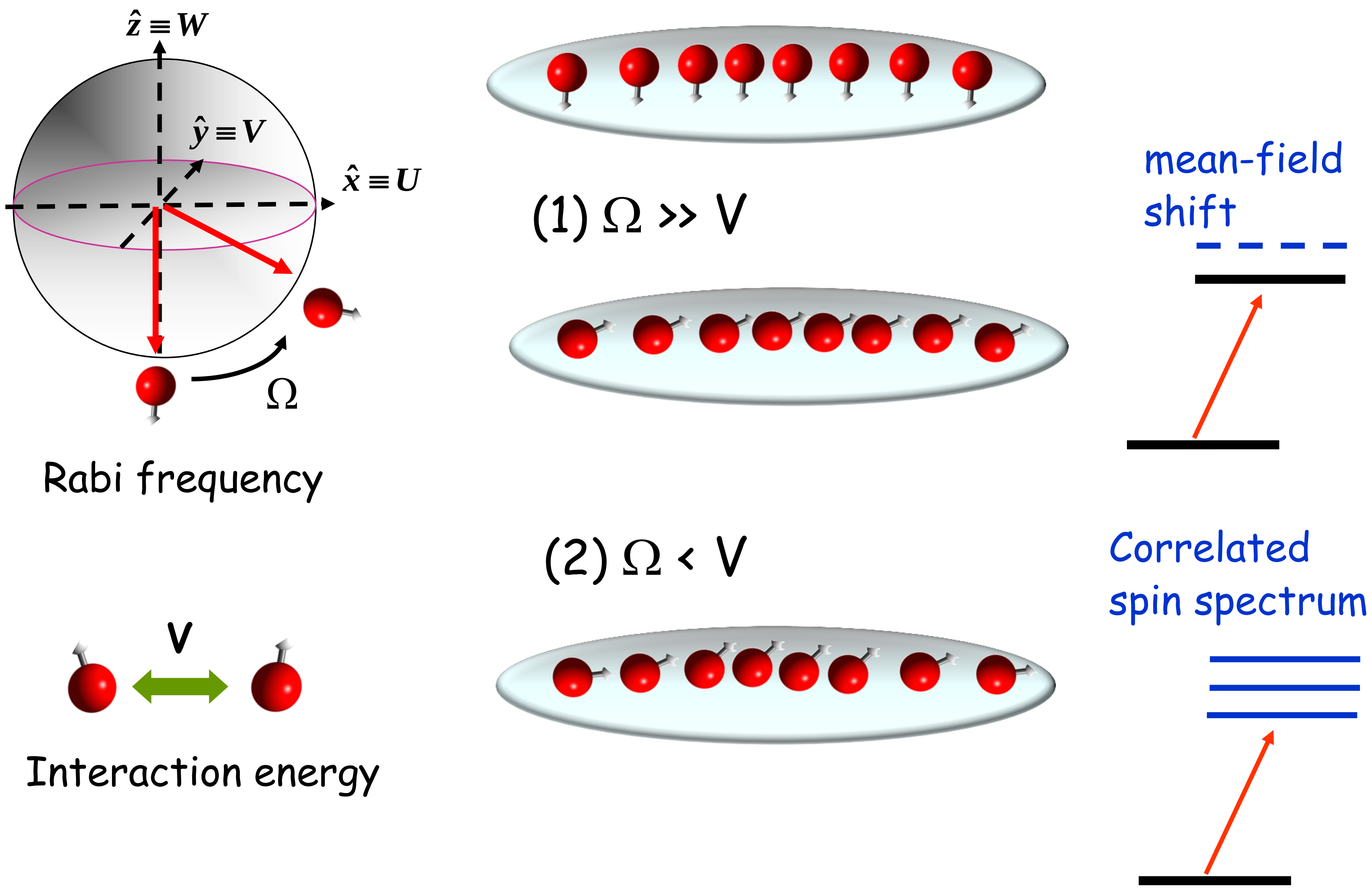
Competition between Ω and V



mapping to bosons
GPE (mean field + loss)

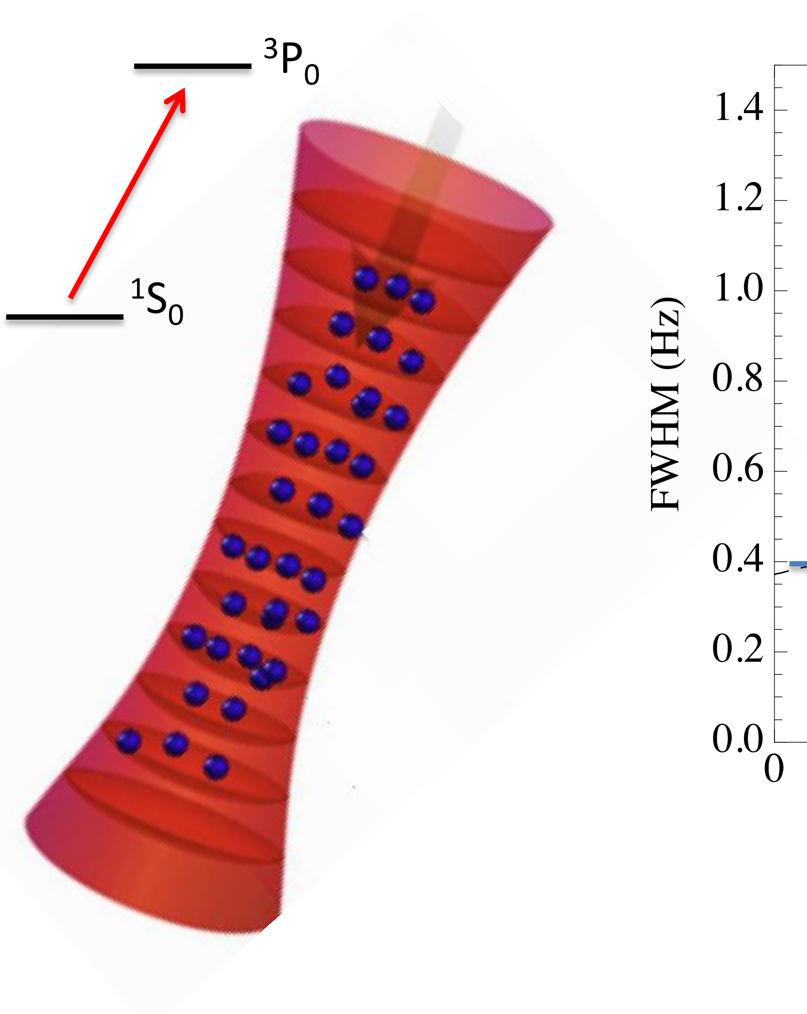


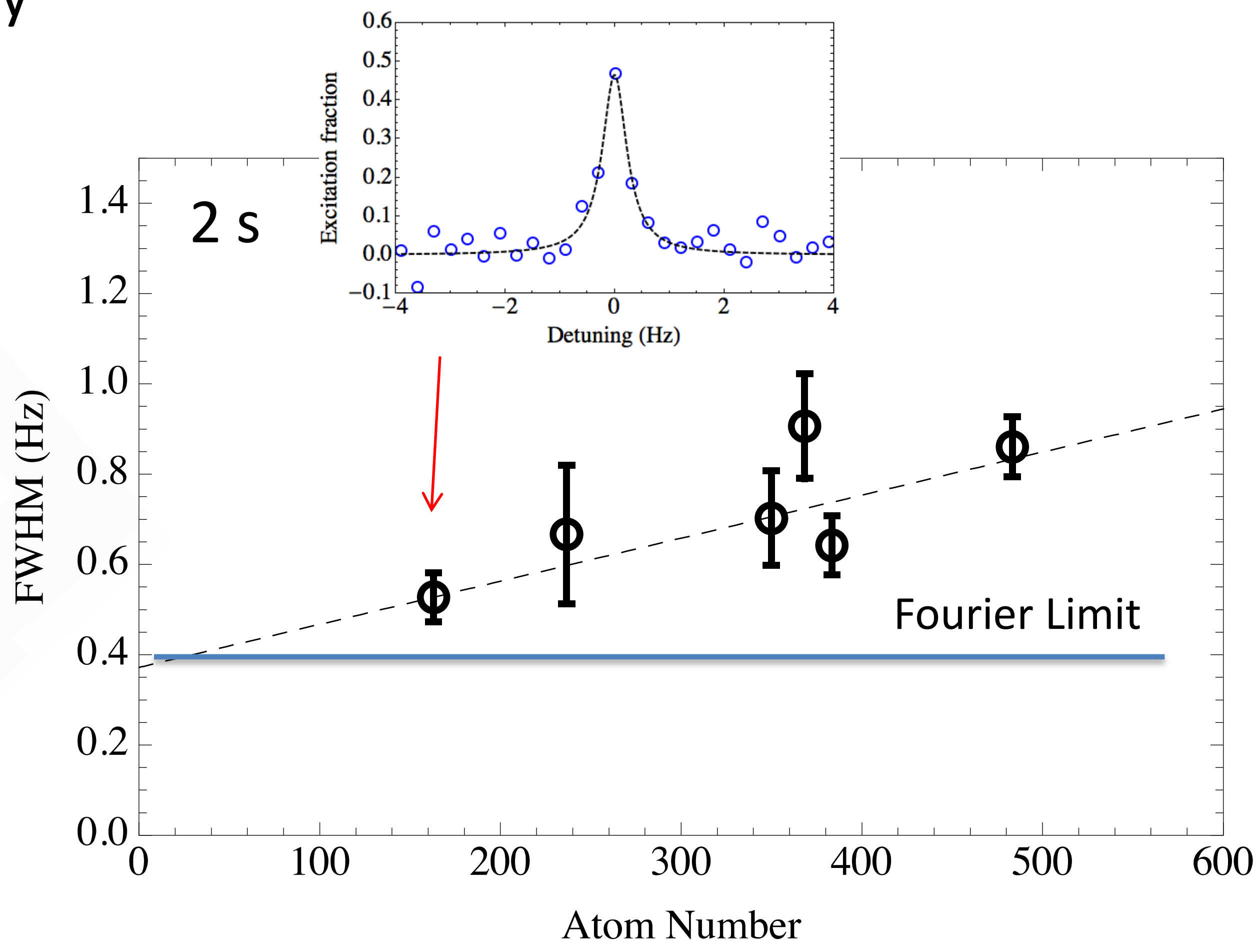
Competition between Ω and V



2-s optical/atomic coherence

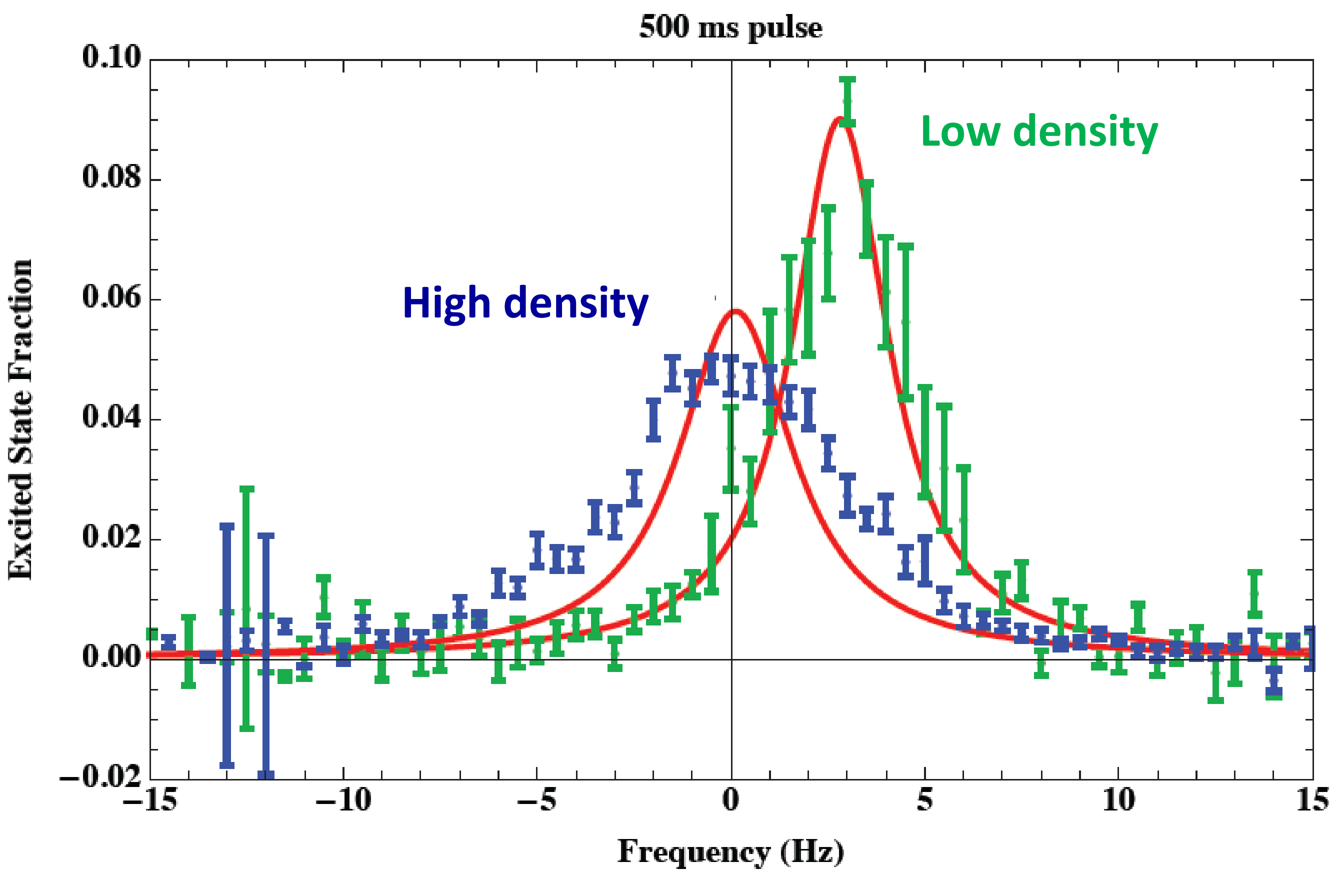
1D lattice spectroscopy





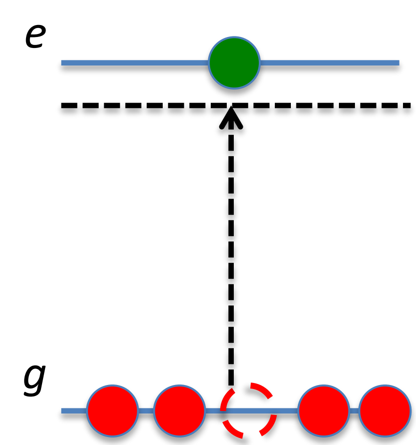
Linear response regime
(Rabi spectroscopy)

2 uK sample temperature

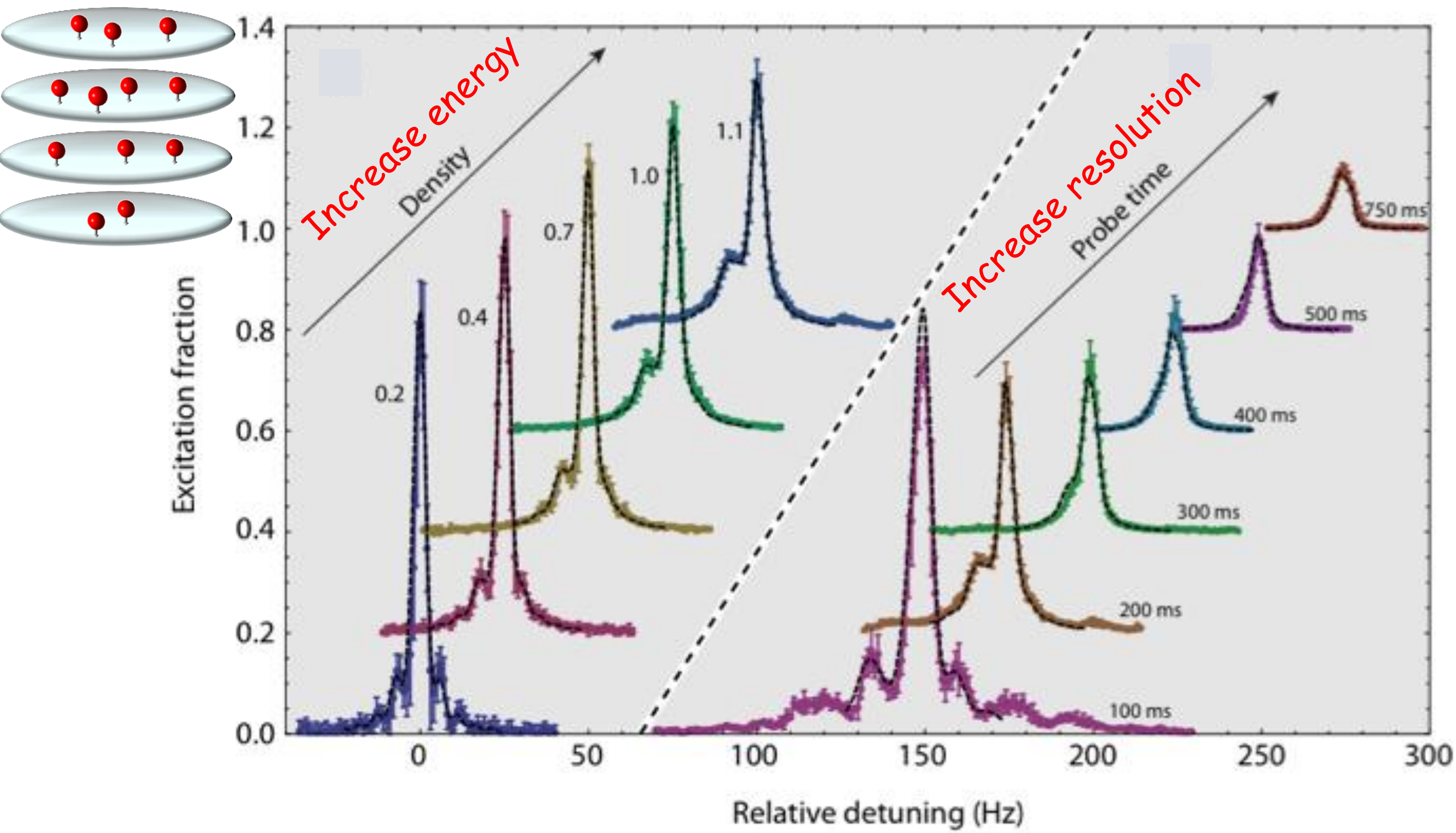


Experiences shift

$$DE \propto v_{eg} \frac{(N - 1)}{V}$$



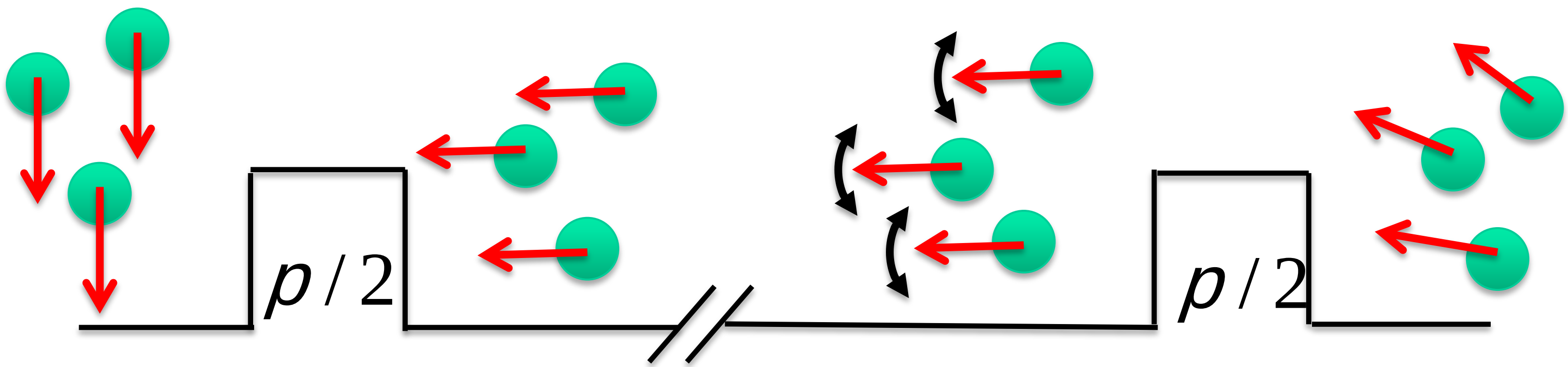
Rabi spectroscopy with strong interactions



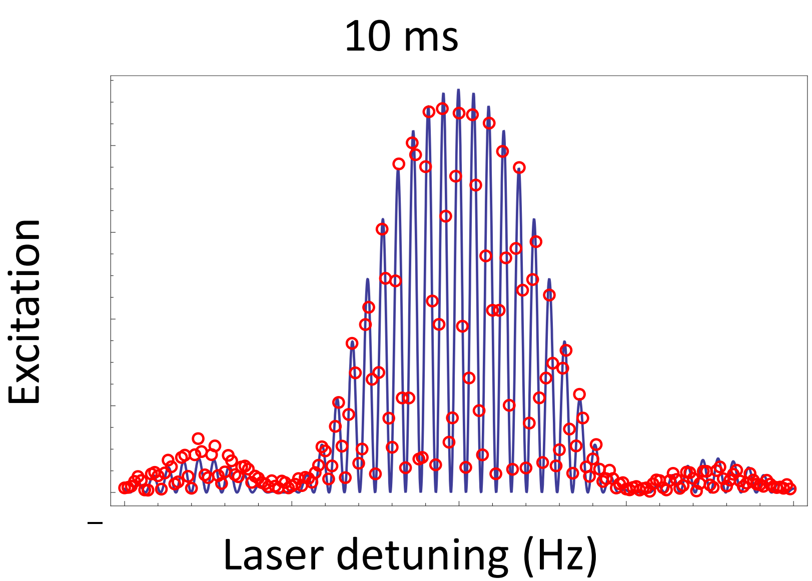
Structure due to interactions (both elastic & inelastic).
– excitation blockade at increasing density or probe time.

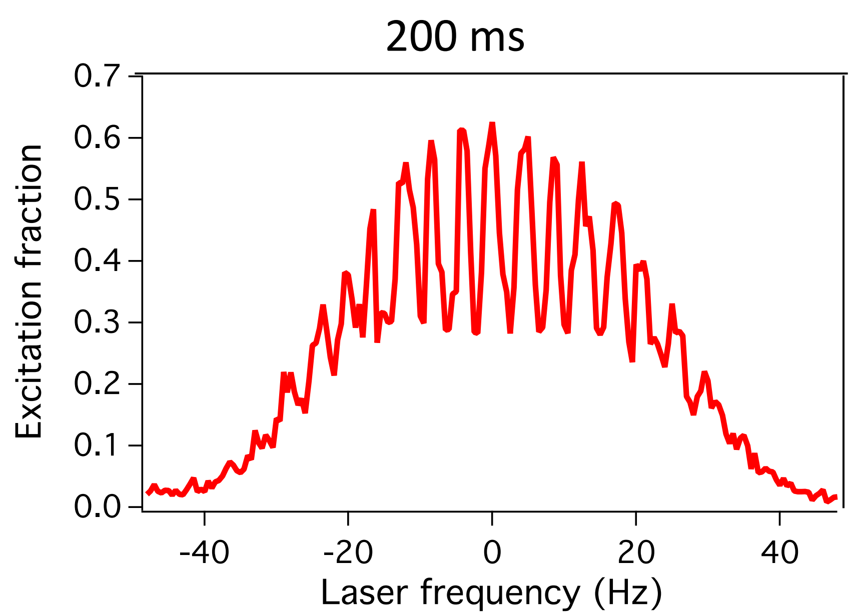
Ramsey spectroscopy under interactions

$$\hat{H}/\hbar = \chi\left(S^z\right)^2 + C\left(N-1\right)S^z$$

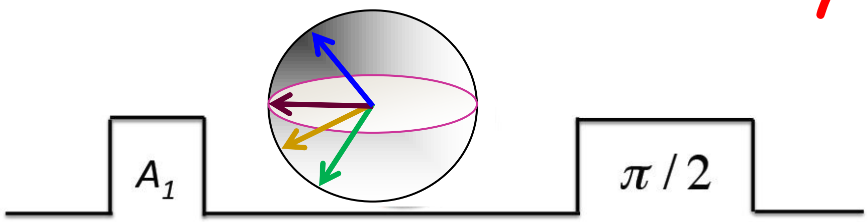


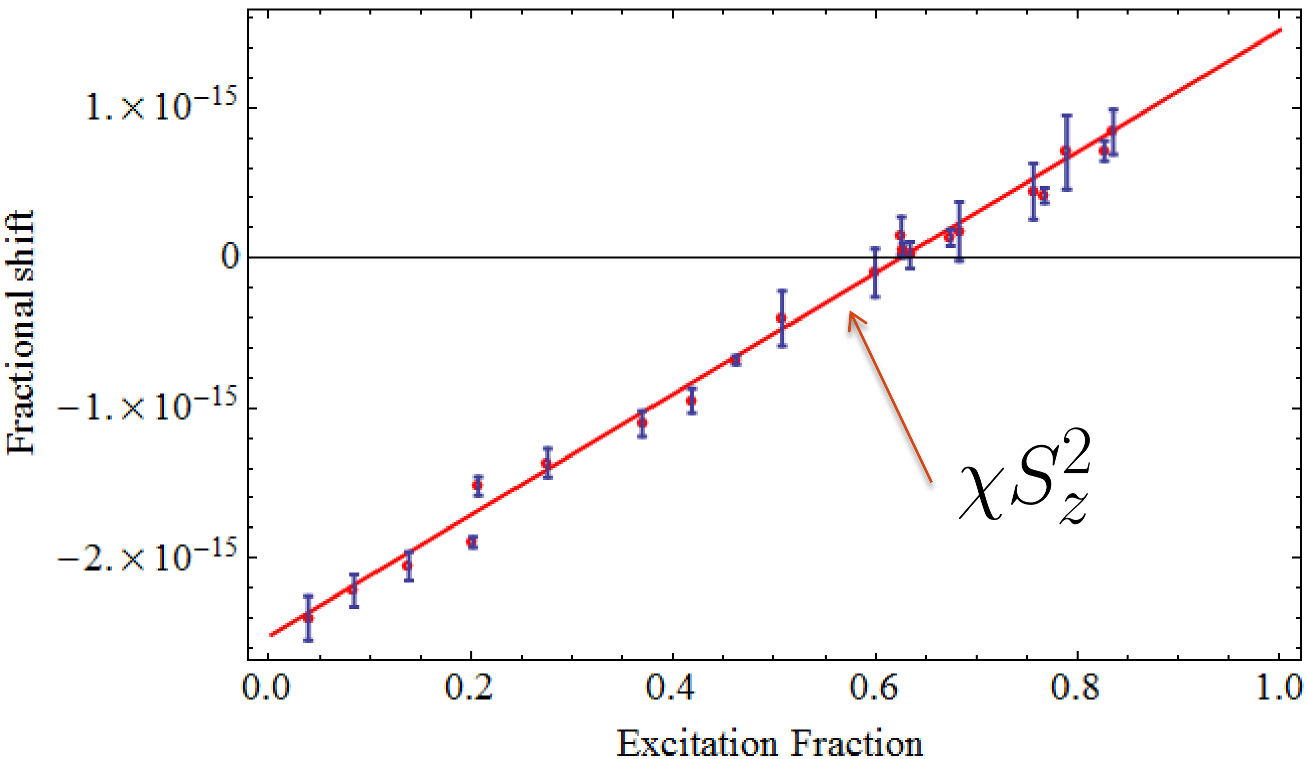
Interaction dominates over optical dephasing





Density shift in Ramsey





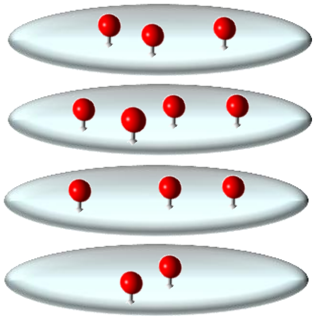
$$\frac{V_{ee}-V_{gg}}{V_{eg}-V_{gg}} = 0.4$$

Collisional shift has a linear dependence on the tipping angle.

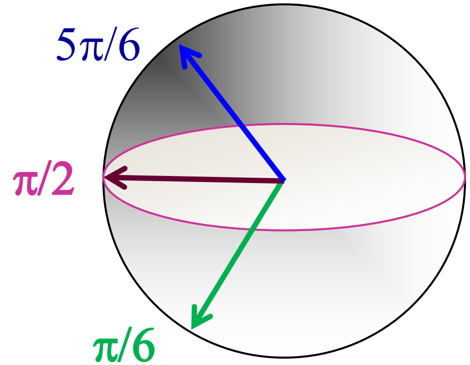
$$2\pi\Delta\upsilon \sim \underbrace{\frac{V_{ee}-V_{gg}}{2}}_{CS_z} + \cos(\bar{\Omega}t)\underbrace{\left[\frac{2V_{eg}-V_{ee}-V_{gg}}{2}\right]}_{\chi S_z^2}$$

Beyond mean field

Interaction & Poissonian distribution → Ramsey fringe decay

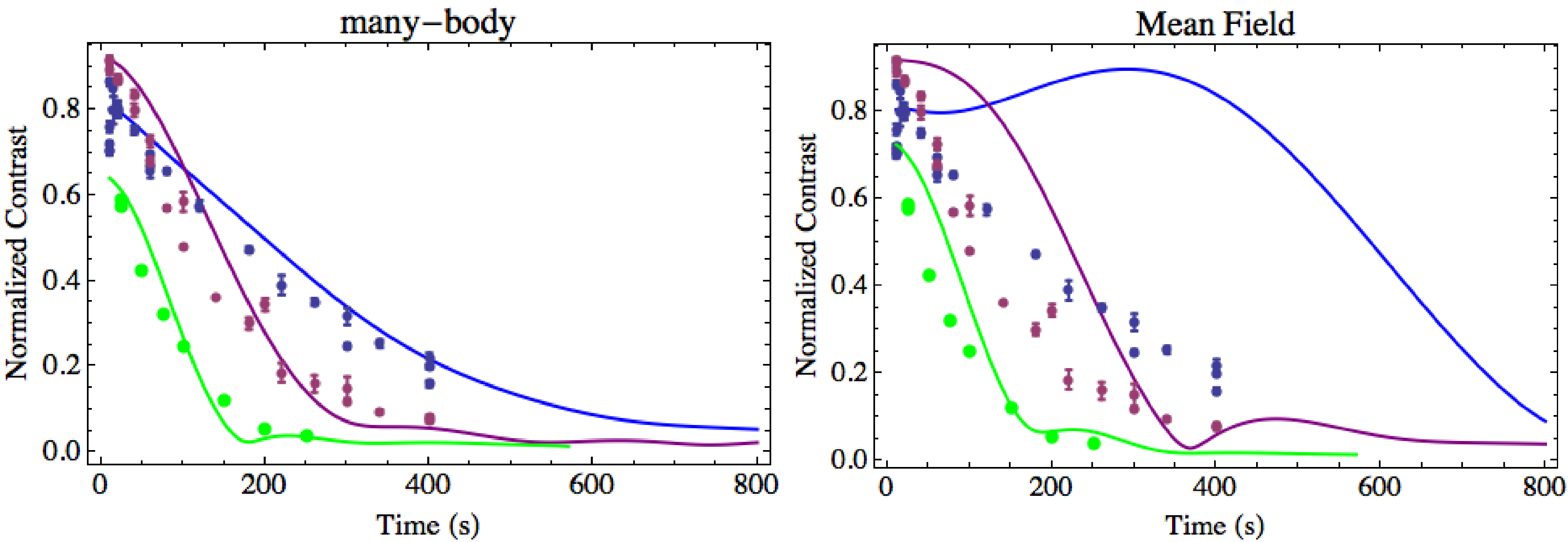


$$N_e = \sum_N N_e^N \, P(N)$$



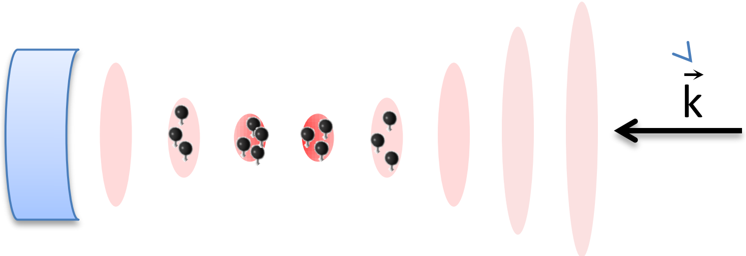
Tipping angle dependence

Ramsey fringe decay vs. the spin tipping angle

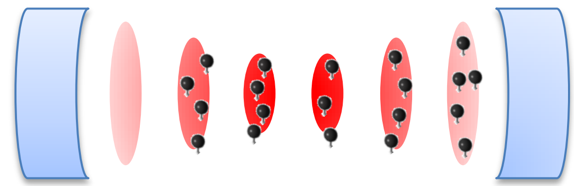


Cavity-Enhanced Lattice System

Retroreflected Lattice:

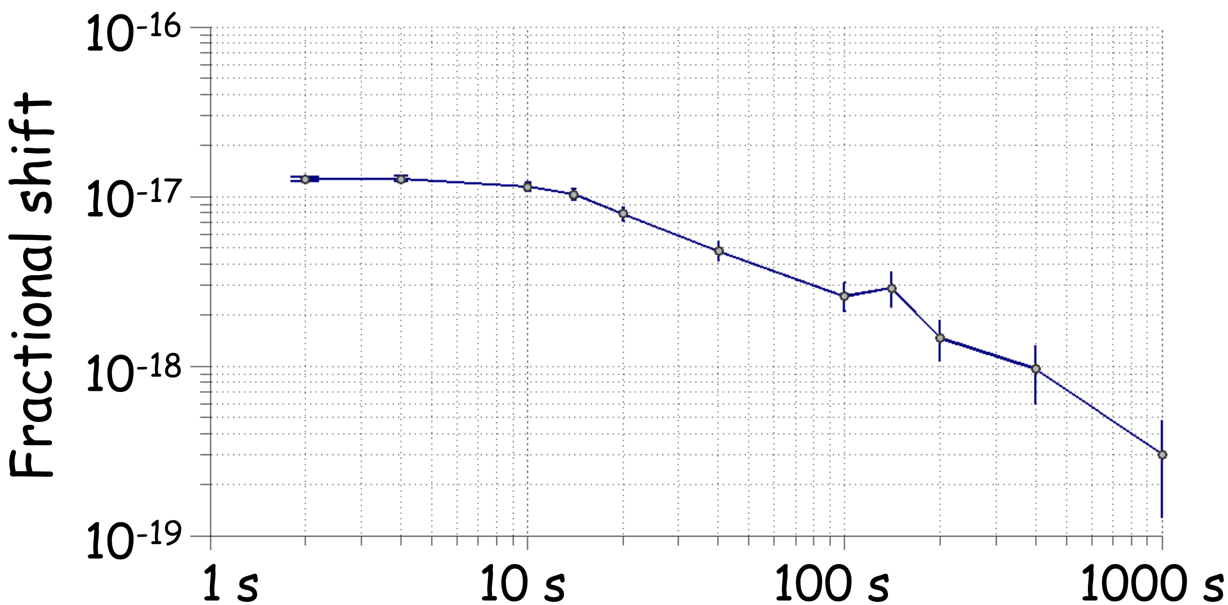


Cavity Lattice:



	ν_{axial}	ν_{radial}	N
Retro-Refl.	80 kHz	450 Hz	10^3
Cavity	90 kHz	100 Hz	10^5

Pierre Lemonde
SYRTE



Density shift: 10^{-17}
Uncertainty: 5×10^{-19}

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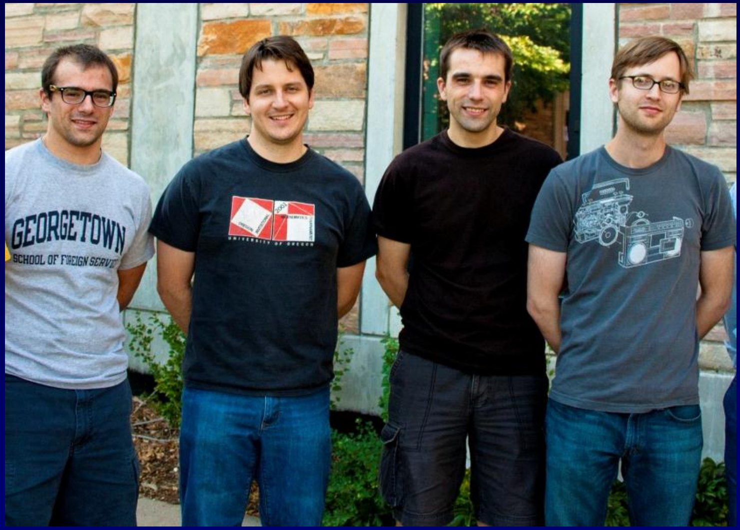

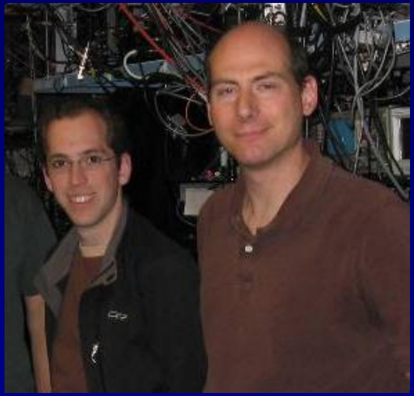

M. Swallows (JPL/Caltech)
S. Blatt (Harvard)
A. Ludlow (NIST)
Y. Lin (NIM, Beijing)
G. Campbell (U. Maryland)
M. Boyd (AO Sense)
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S. Foreman (Stanford U.)
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T. Ido (Tokyo NICT)
T. Loftus (AO Sense)
X. Xu (ECNU)

Ana M. Rey
(theory)