Clock & quantum matter

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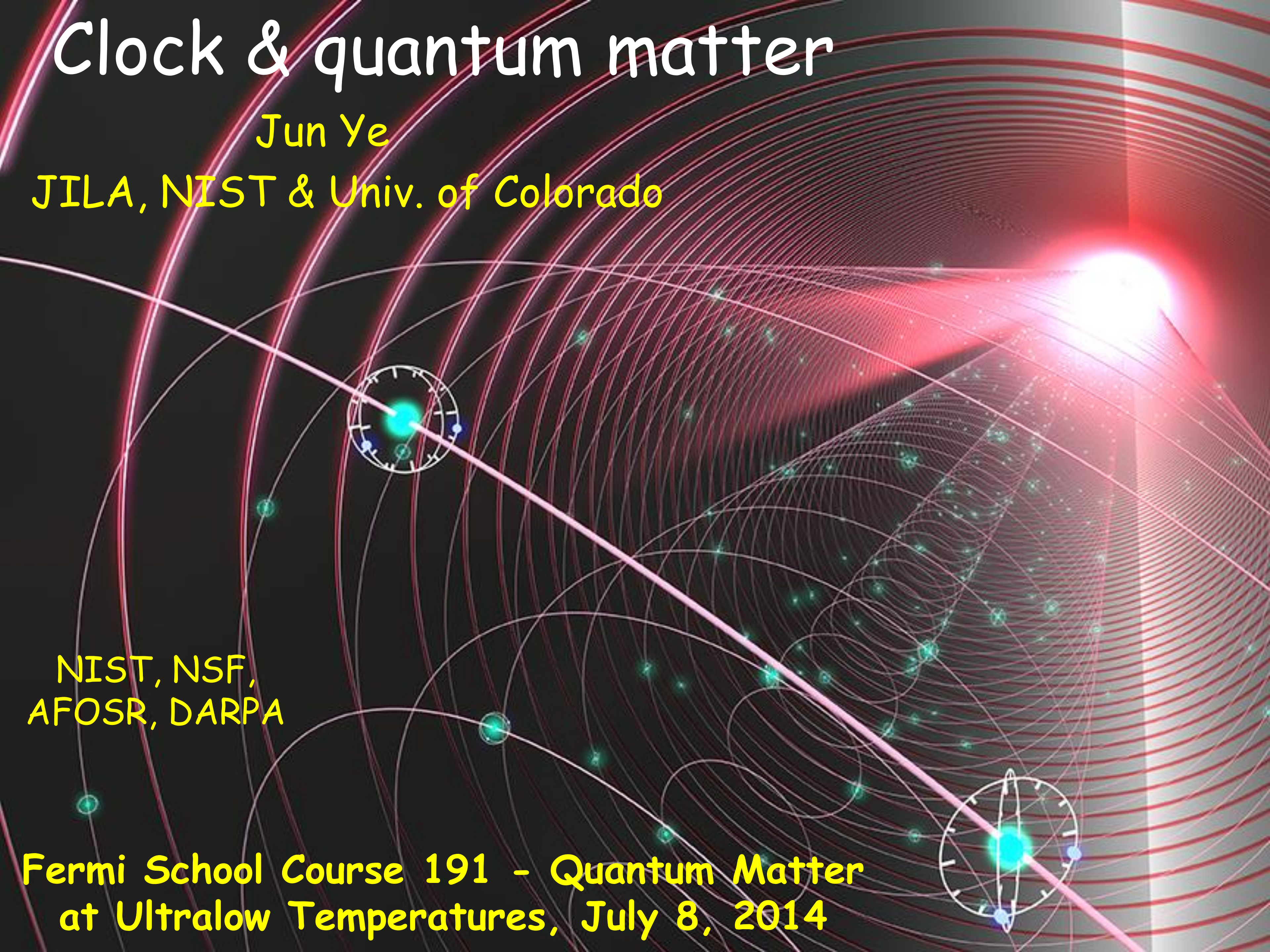
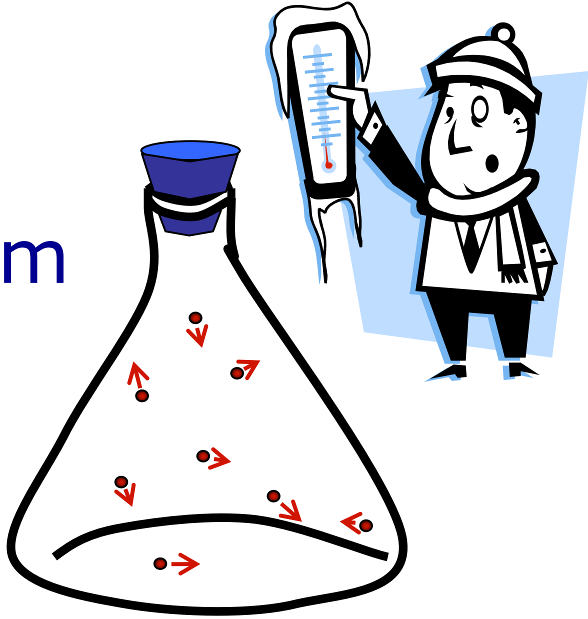
JILA, NIST & Univ. of Colorado



NIST, NSF,
AFOSR, DARPA

Fermi School Course 191 - Quantum Matter at Ultralow Temperatures, July 8, 2014

Ultracold Matter



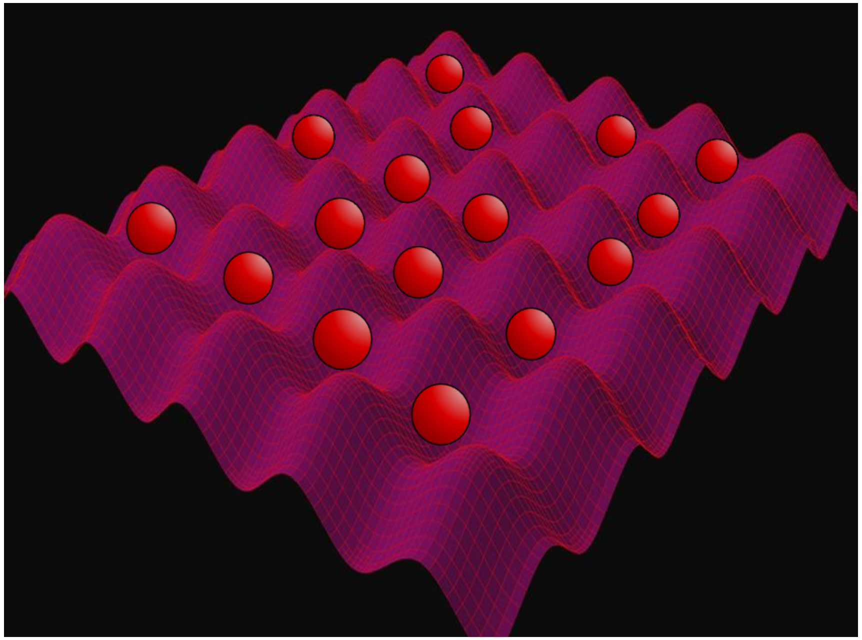
Precise control of a quantum system

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
- Quantum chemistry

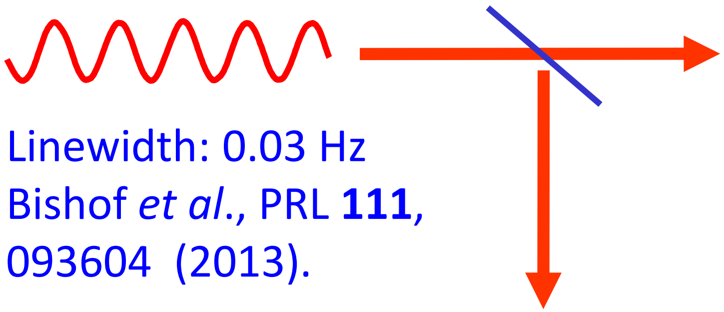
Optical Atomic Clock

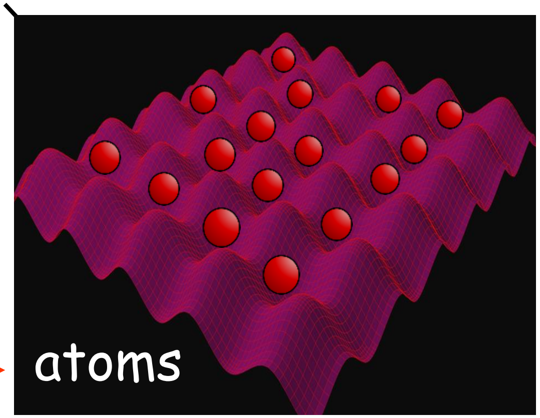
Boyd *et al.*,
Science **314**, 1430 (2006).

Oscillator

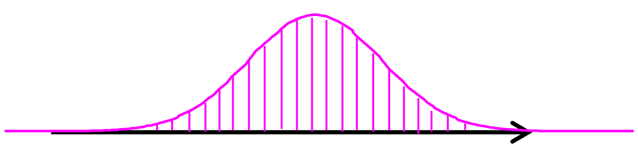
Quality factor
>10^{17}

Ultrastable laser

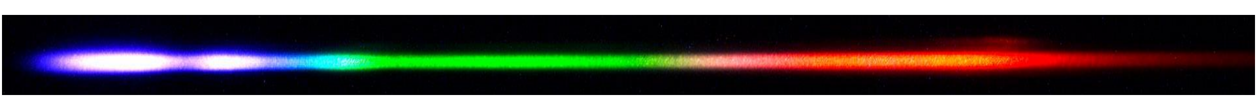




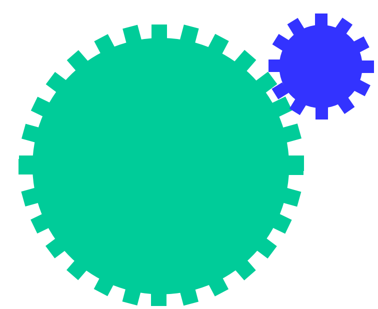
Linewidth: 0.03 Hz
Bishof *et al.*, PRL **111**, 093604 (2013).



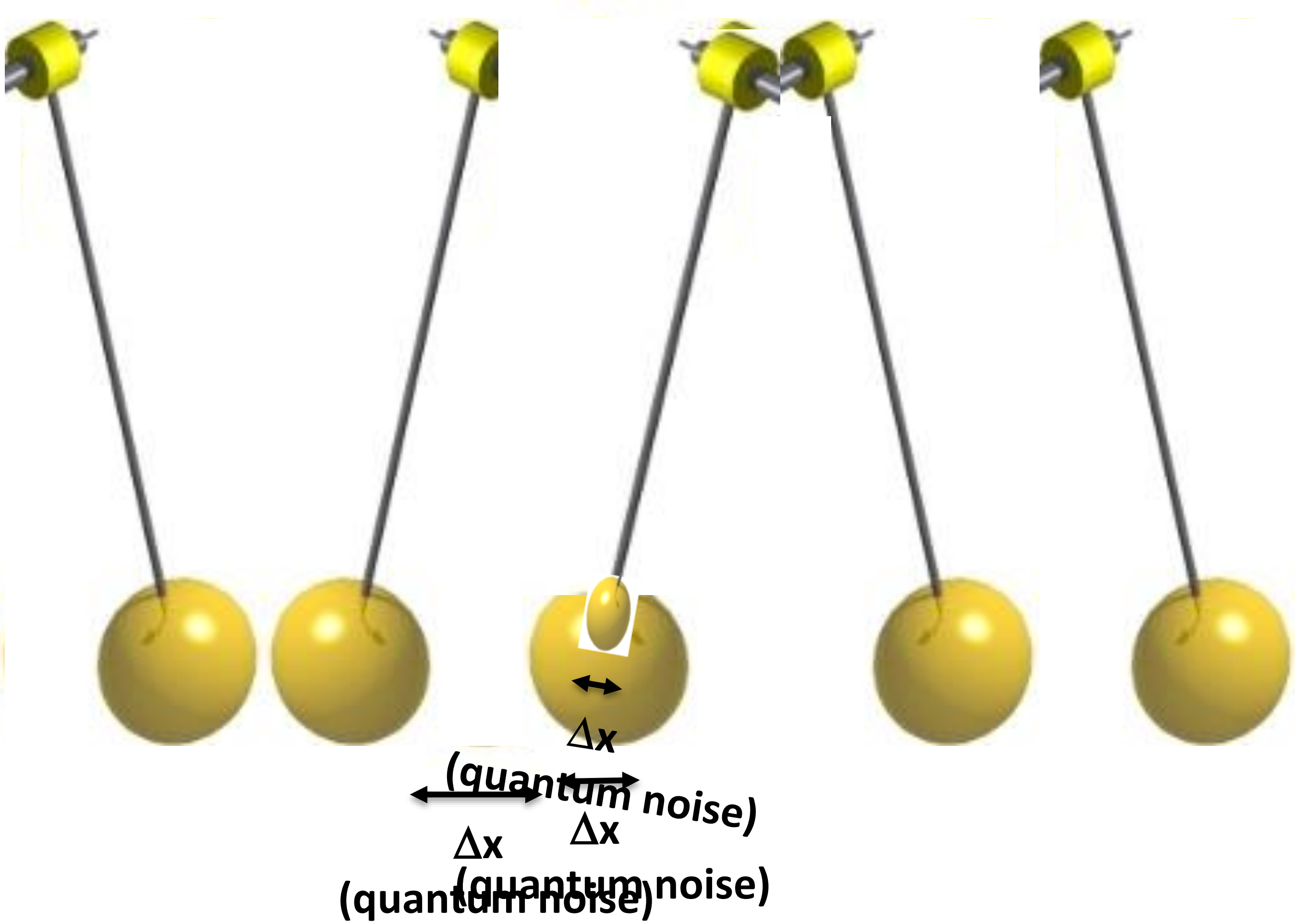
optical frequency comb → counter



Counter



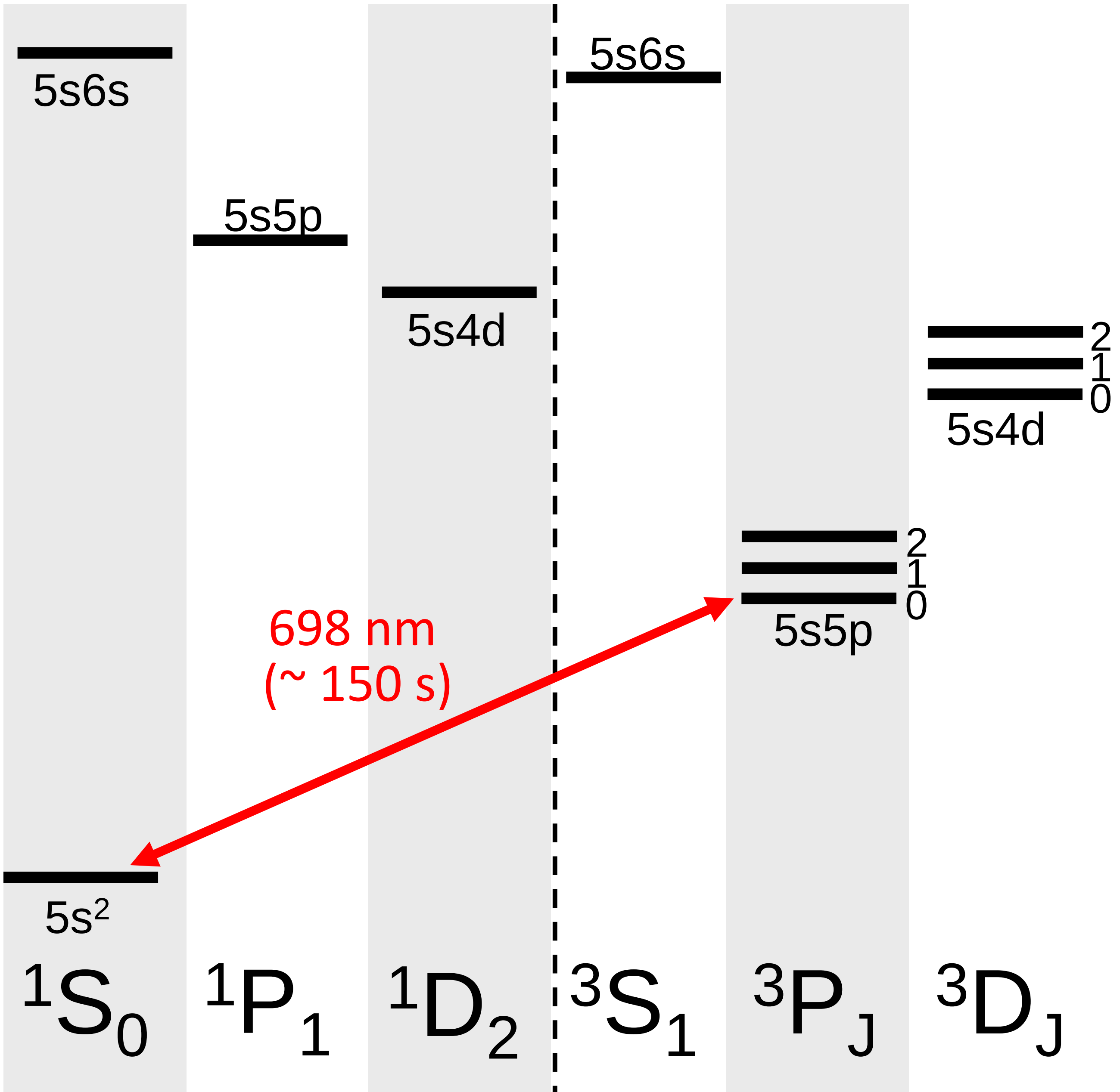
Quantum Clock



- Precise quantum state engineering → fundamental quantum noise
- Many parallel quantum systems → increased precision
- Understanding interactions
- Quantum entanglement / correlations → beyond standard quantum noise

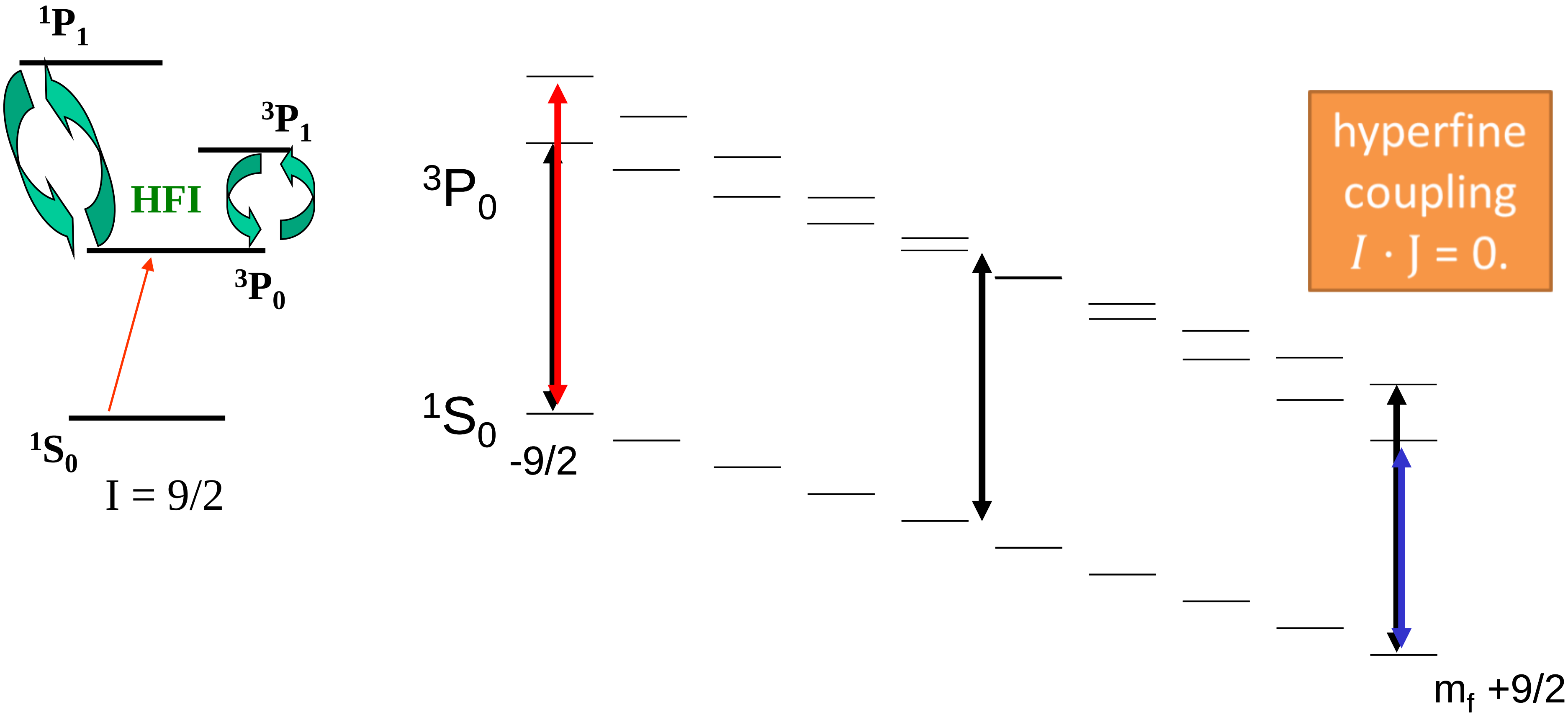
Strontium: Clock Transition

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



Differential Landé *g*-factor

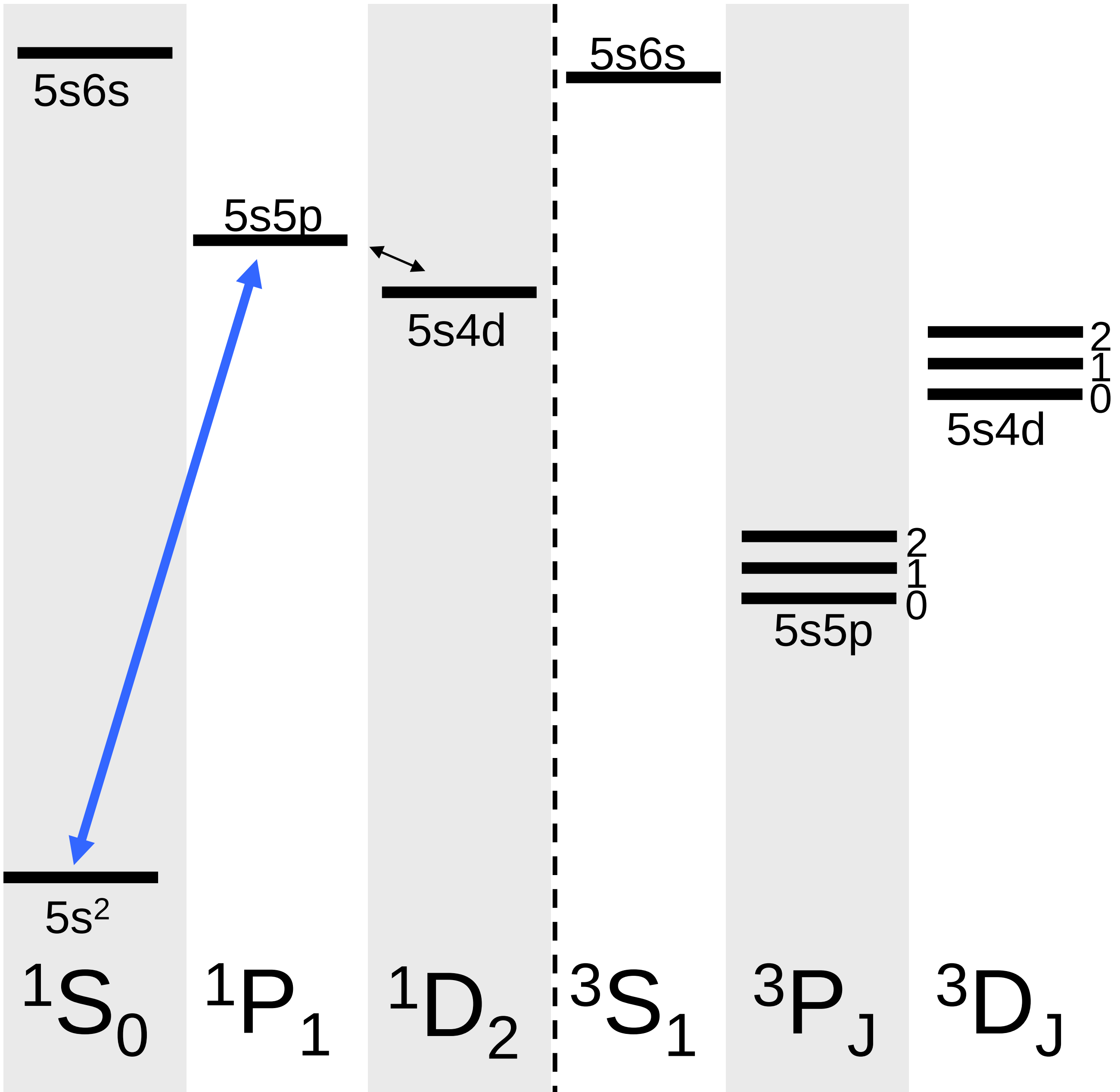
$$|^3P_0' \rangle = |^3P_0\rangle + c_1|^1P_1\rangle + c_2|^3P_1\rangle$$



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

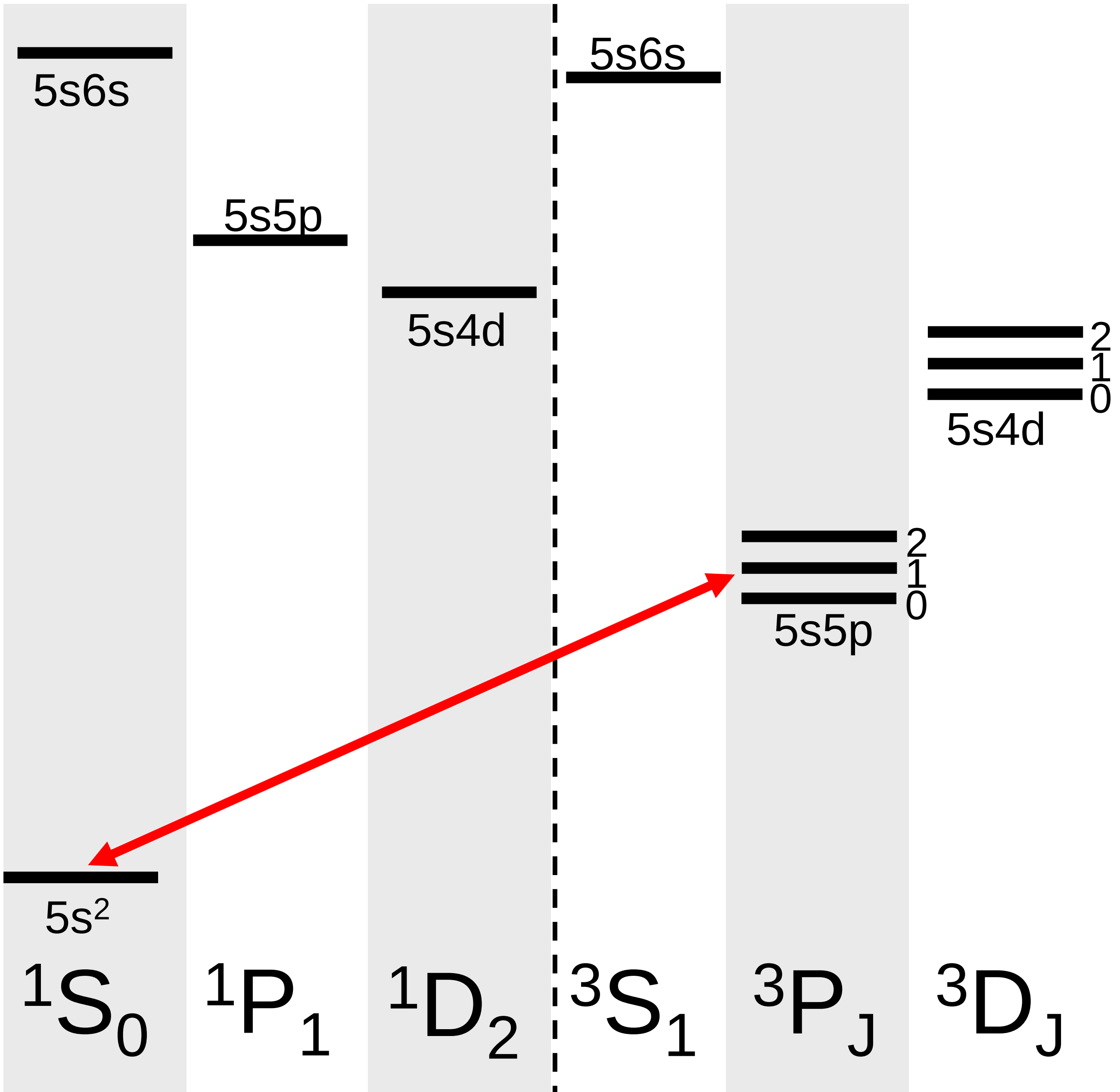
Strontium: first stage cooling

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



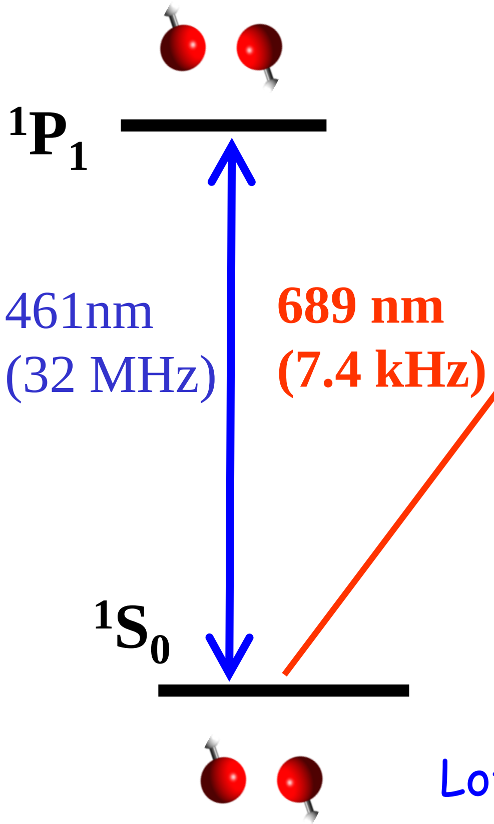
Strontium: Narrow Line Laser Cooling

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

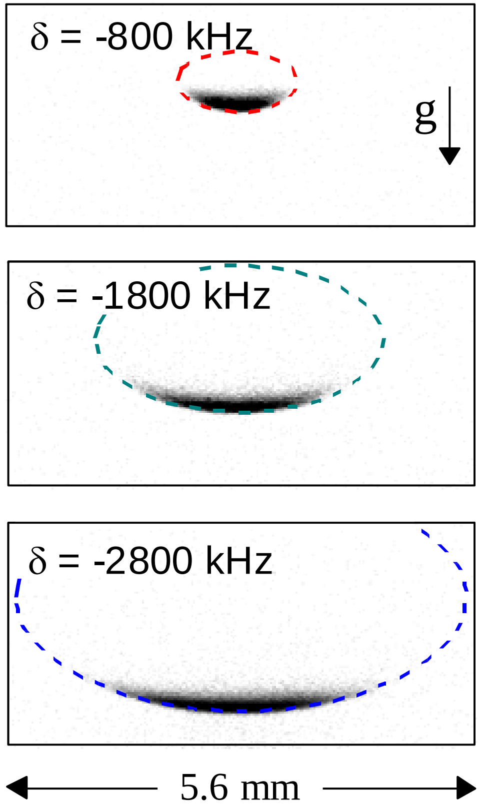


Stop the moving atom

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



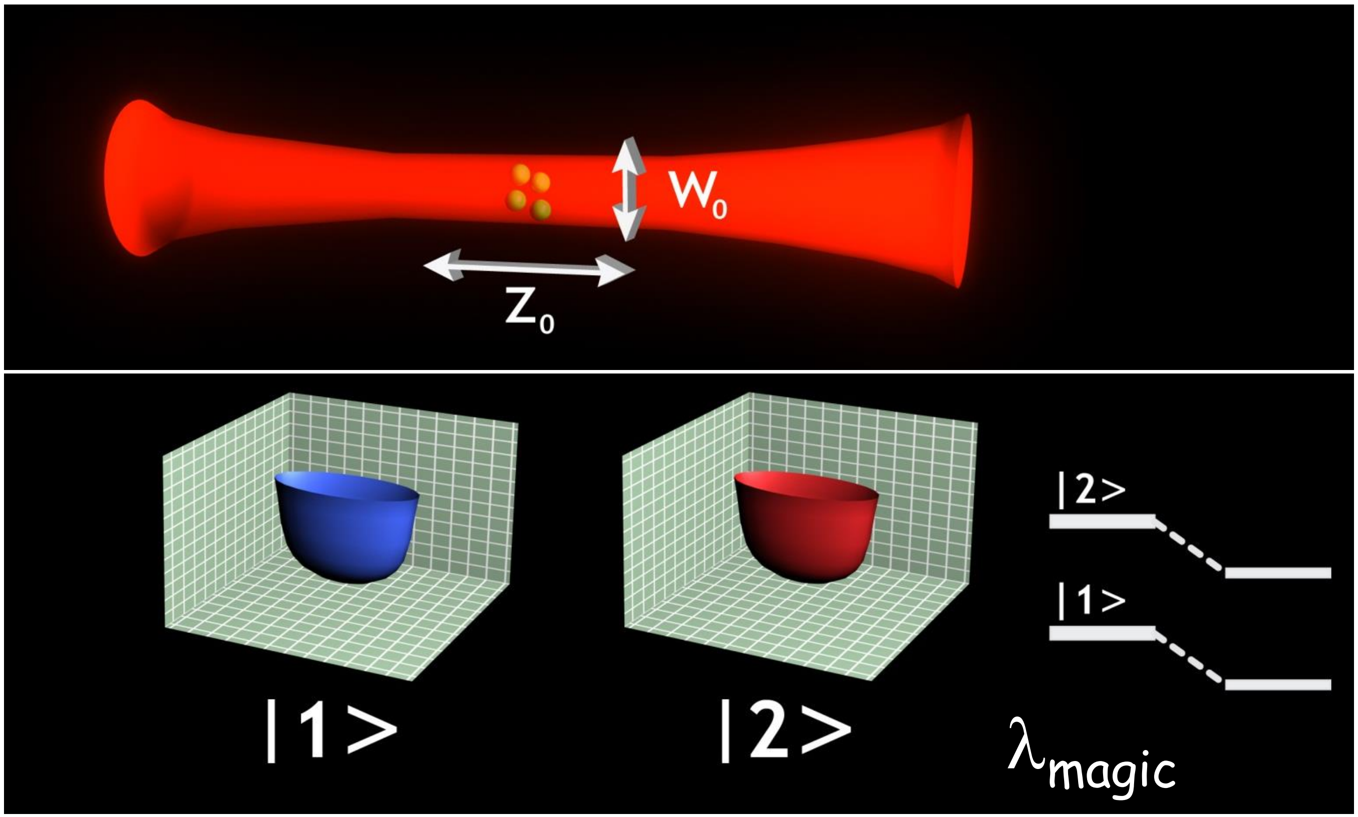
T ~ 0.5 photon recoil
~ 220 nK

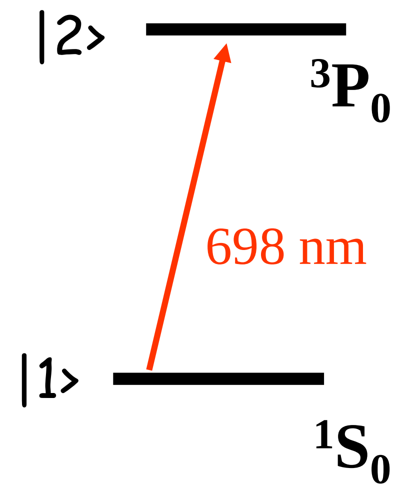


Loftus *et al.*, PRL **93**, 073003 (2004).

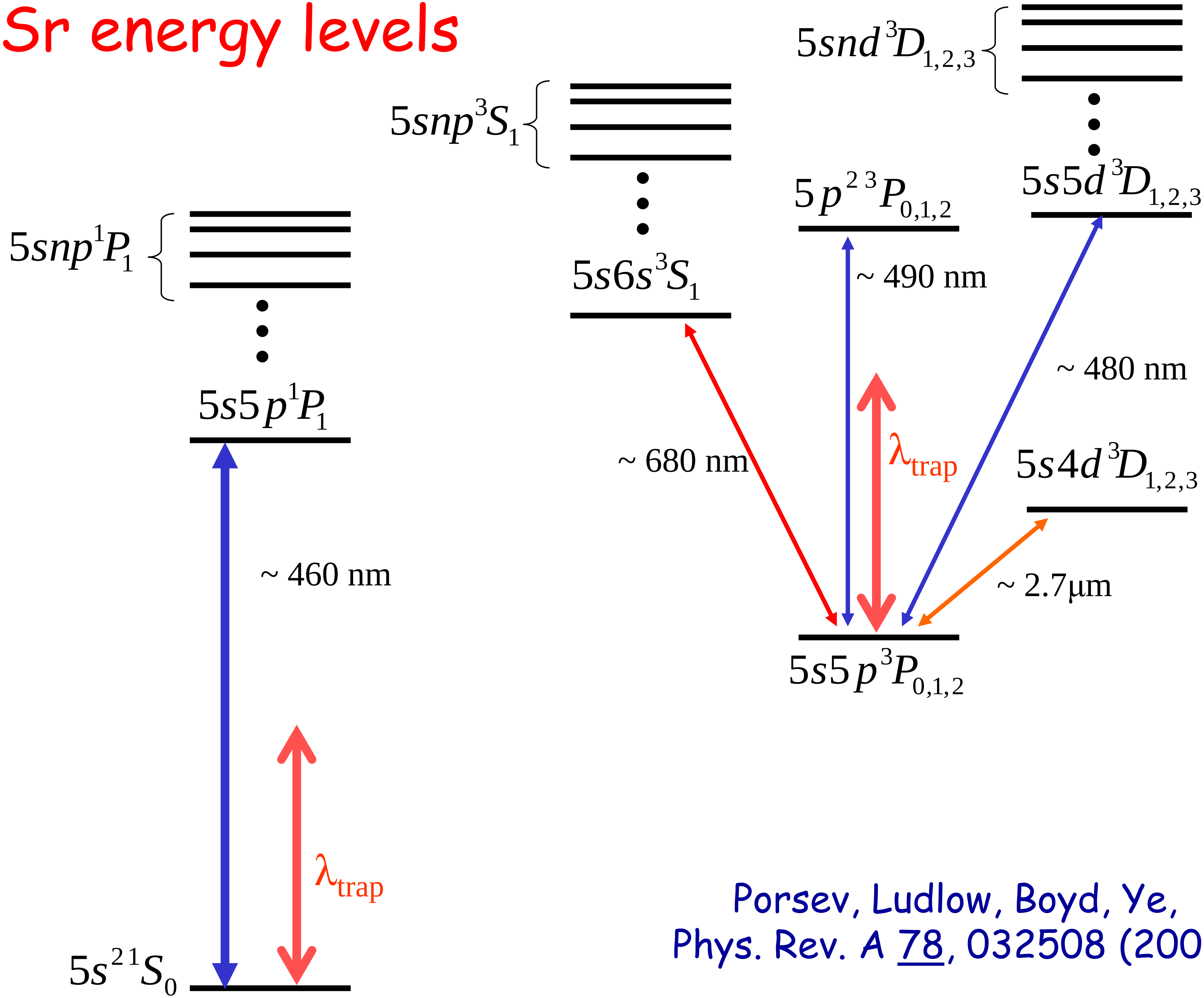
Optical dipole trap at "magic" wavelength

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



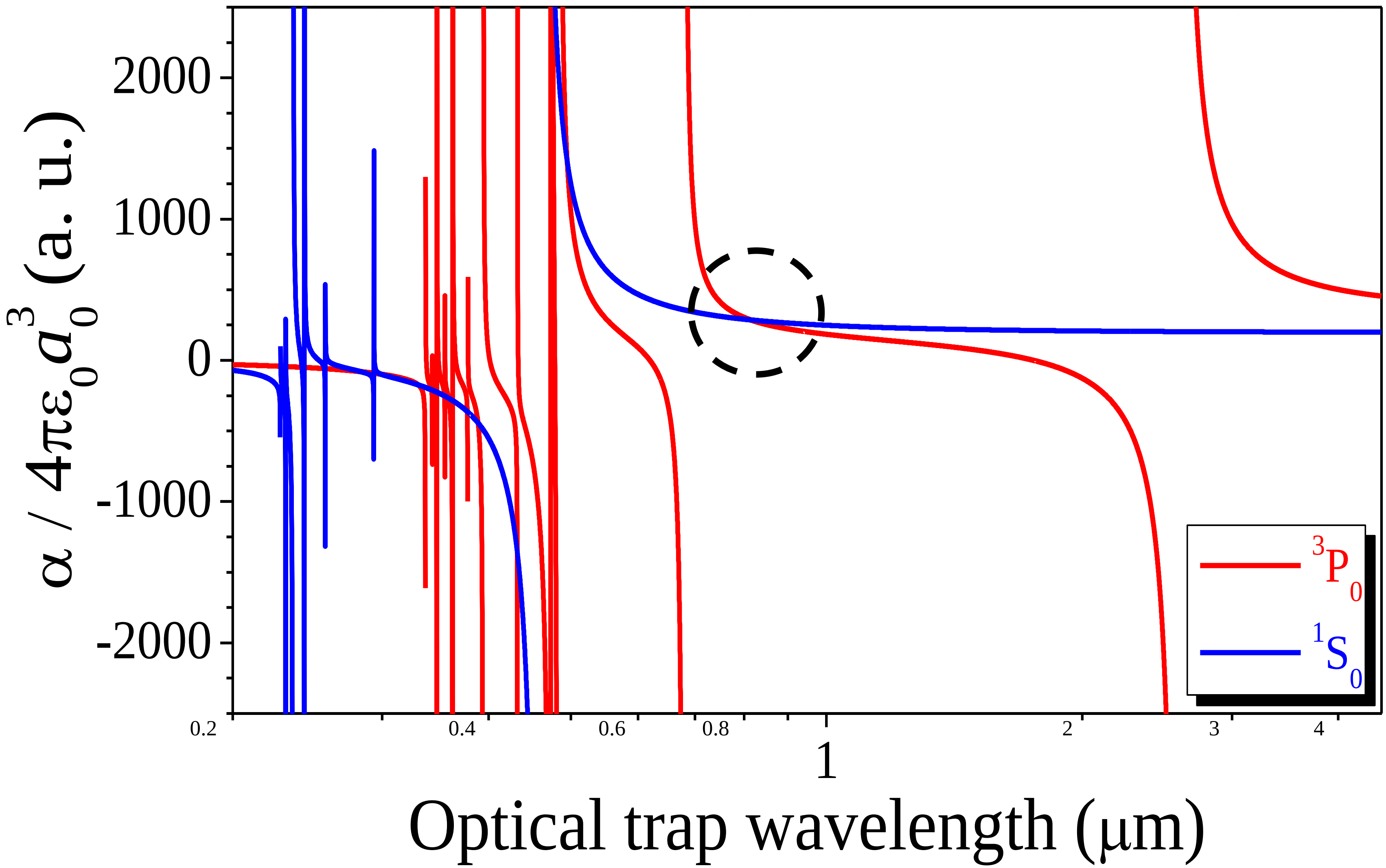


Sr energy levels

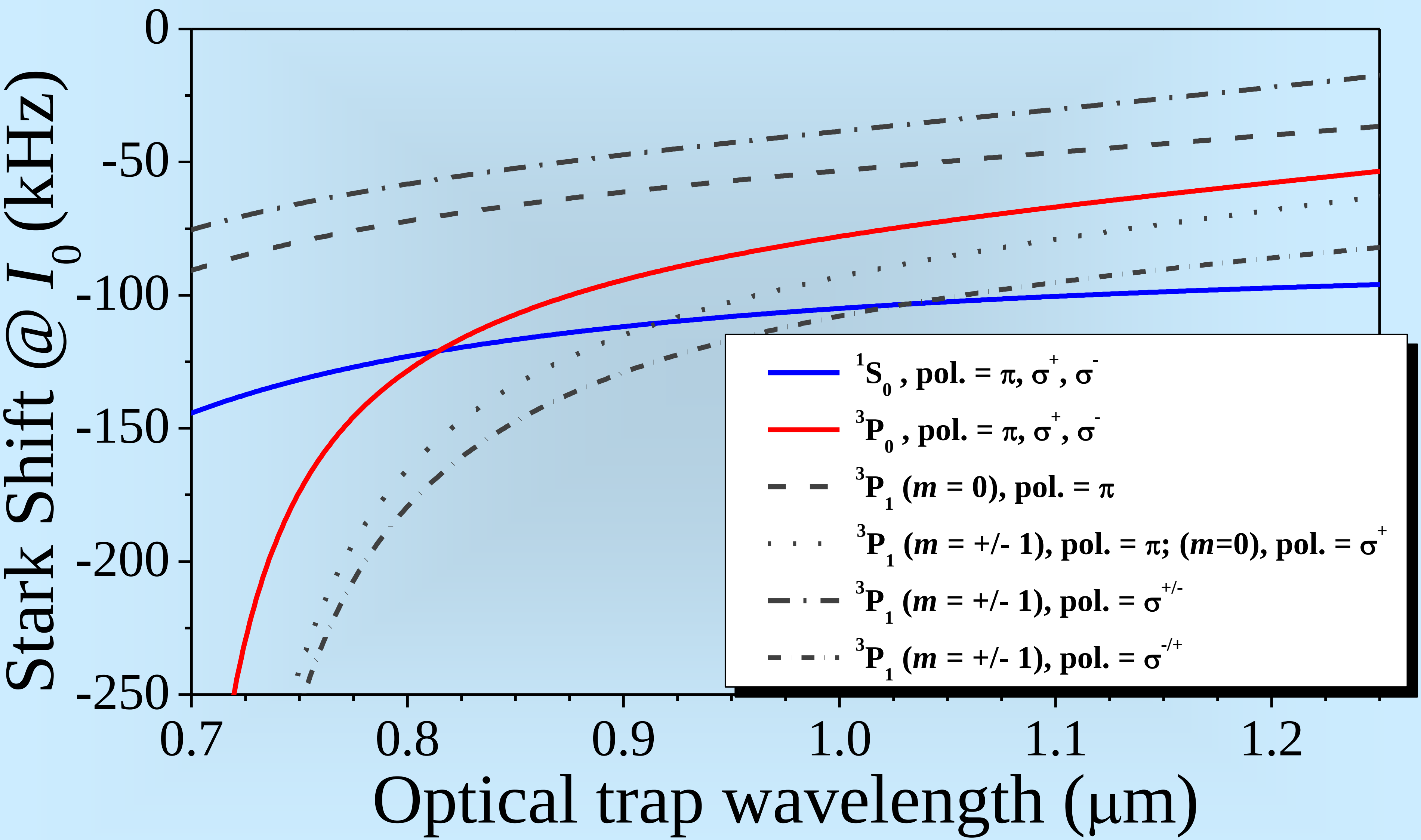


Porsev, Ludlow, Boyd, Ye,
Phys. Rev. A 78, 032508 (2008).

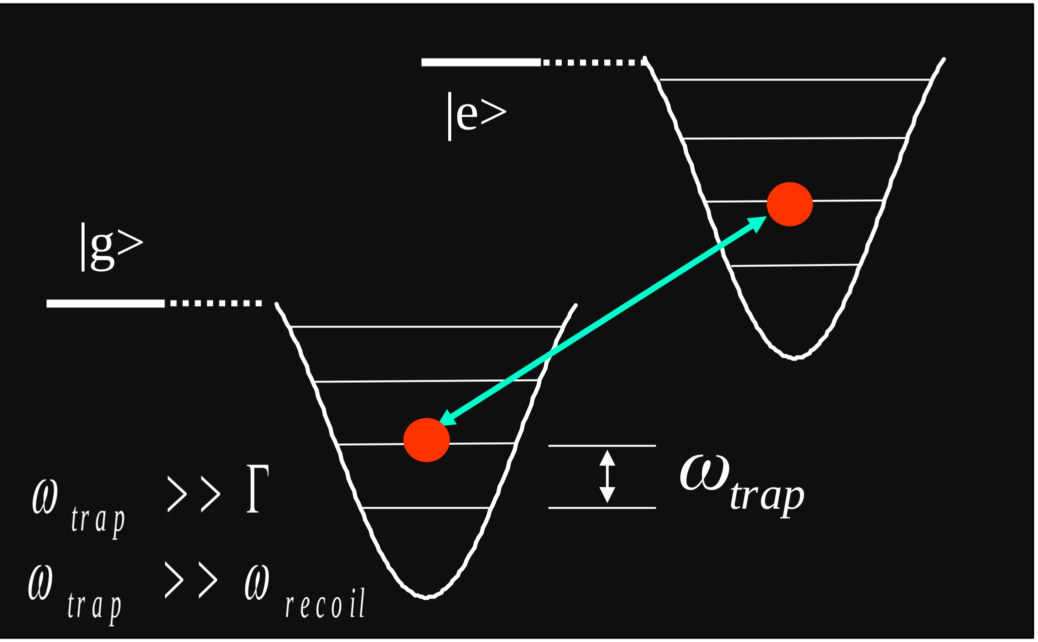
Crossing of polarizabilities

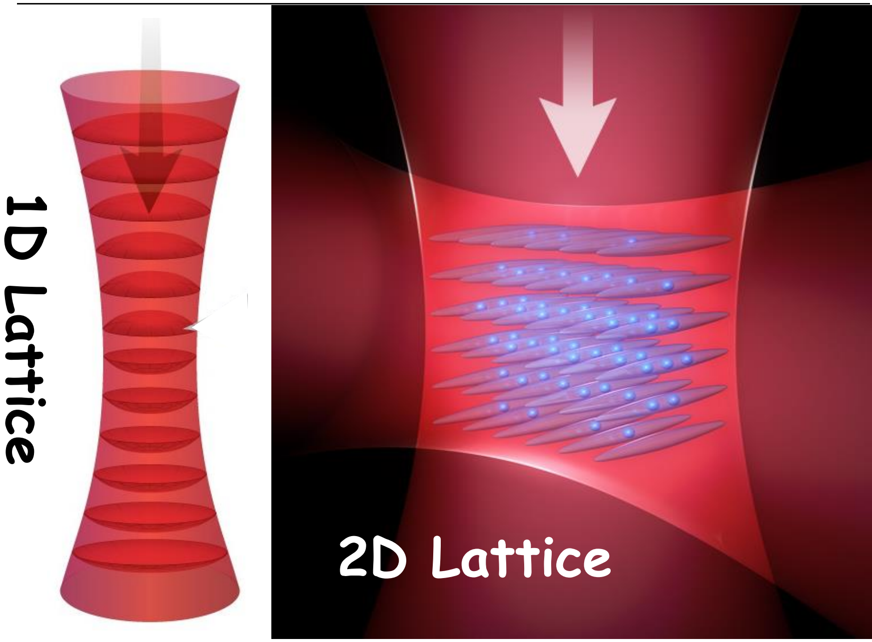


It's a mess if J ≠ 0



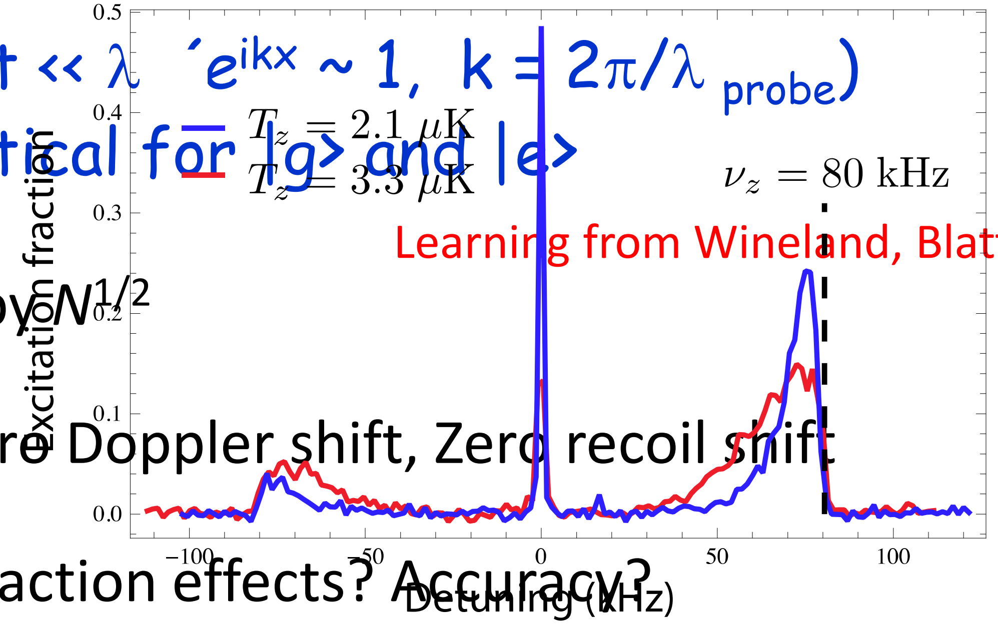
Quantum metrology in optical lattice



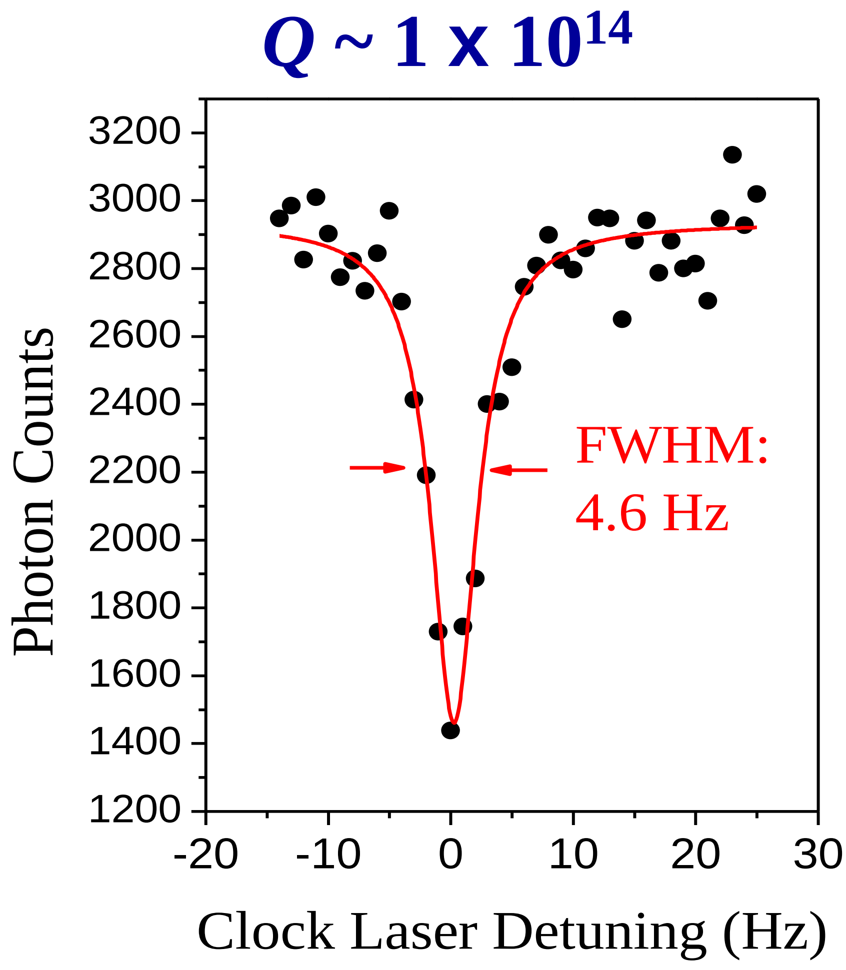


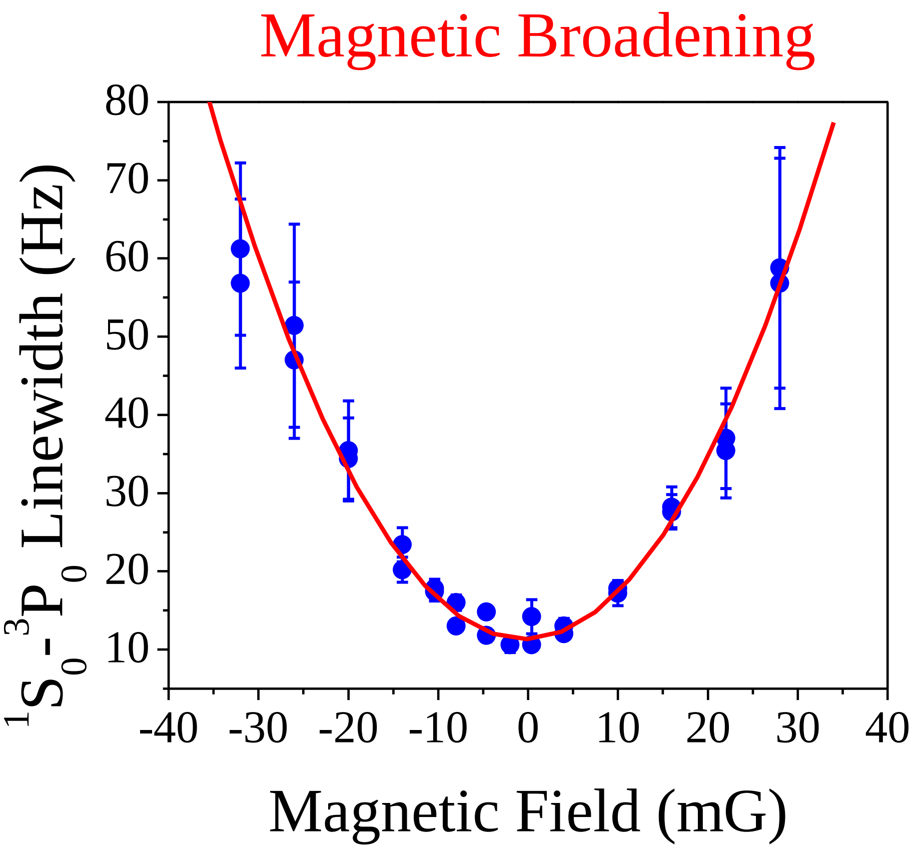
- Atomic confinement << λ ´e^{ikx} ~ 1, k = 2π/λ $_{probe}$)
- Trap potential identical for |g> and |e>

- Precision improvement by $N^{1/2}$
- Long coherence time; Zero Doppler shift, Zero recoil shift
- No Stark shift; but, Interaction effects? Accuracy?



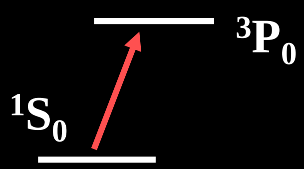
Zoom into the carrier of ^{87}Sr $^1S_0$ - $^3P_0$





Measurement of nuclear *g*-factor

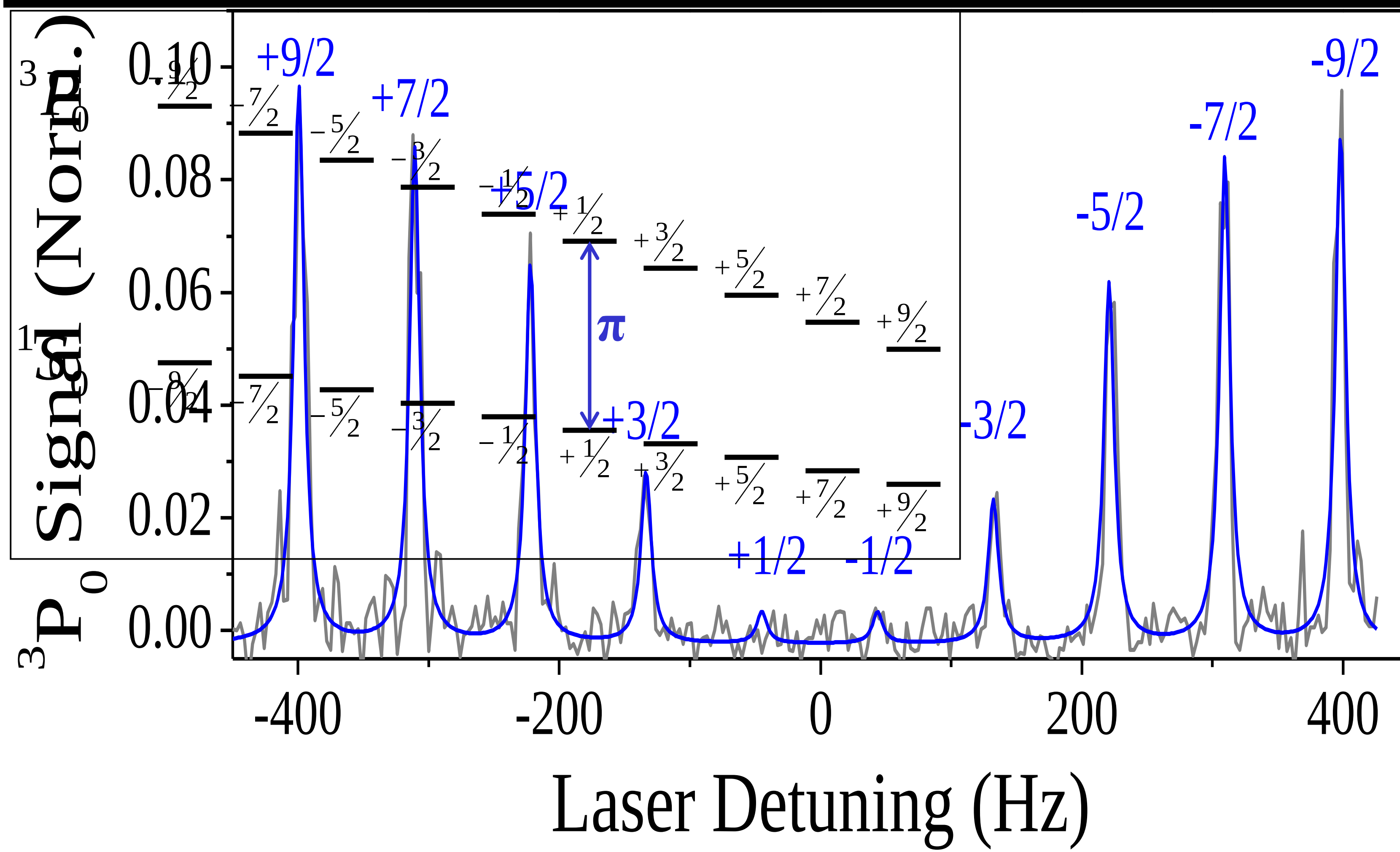
Boyd, Zelevinsky, Ludlow, Foreman, Blatt, Ido, & Ye, Science 314, 1430 (2006).



J = 0

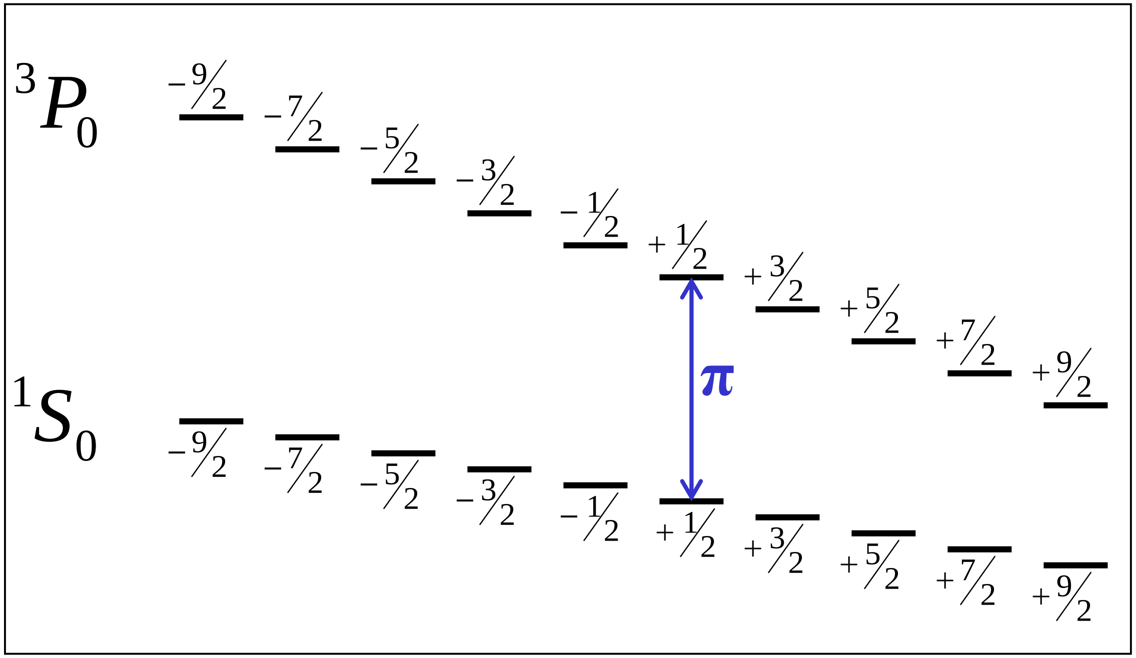
Δg = -108.4(4) Hz/(G m_F)

$^3P_0$ lifetime 140(40) s



Scalar, vector, tensor polarizabilities

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



$\Delta\alpha$: differential polarizability

ξ: polarization ellipticity

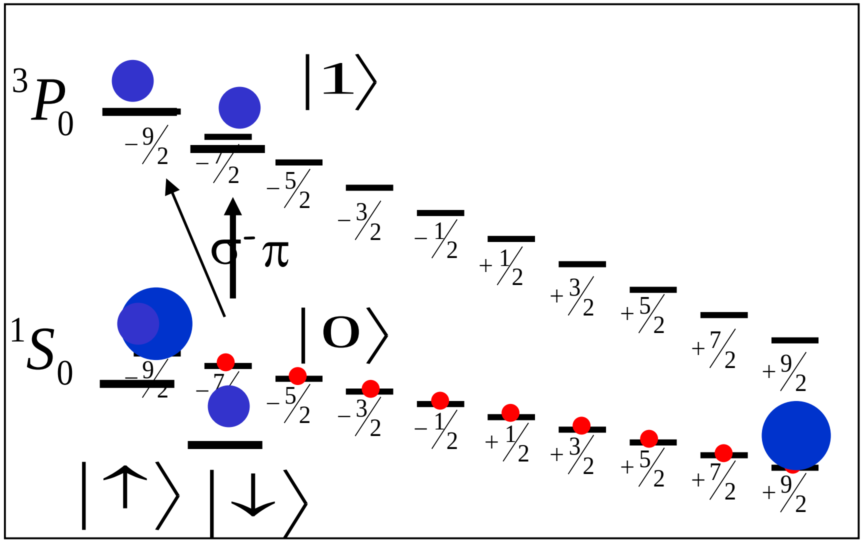
$$\nu_{\pi_{mF}} = \nu_0$$ Clock frequency

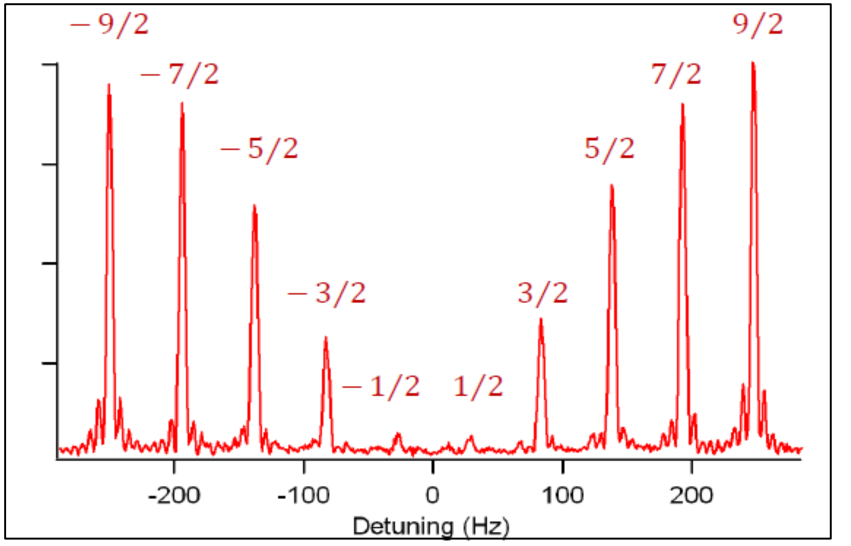
$$- \Delta g \; m_F \; \mu_0 \; B$$ 1st order Zeeman

$$- (\Delta\alpha^S - \Delta\alpha^T F(F+1)) I_{trap}$$ Scalar + Tensor polarizability

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

Quantum information with Sr Atoms





New Features:

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

Implementation:

- Nuclear spin states for qubit storage (low sensitivity to external fluctuations)
- Electronic state for:
  - Creation of state-dependent lattices
  - Access to qubits (control & readout)
- Spin-dependent lattices for quantum simulation

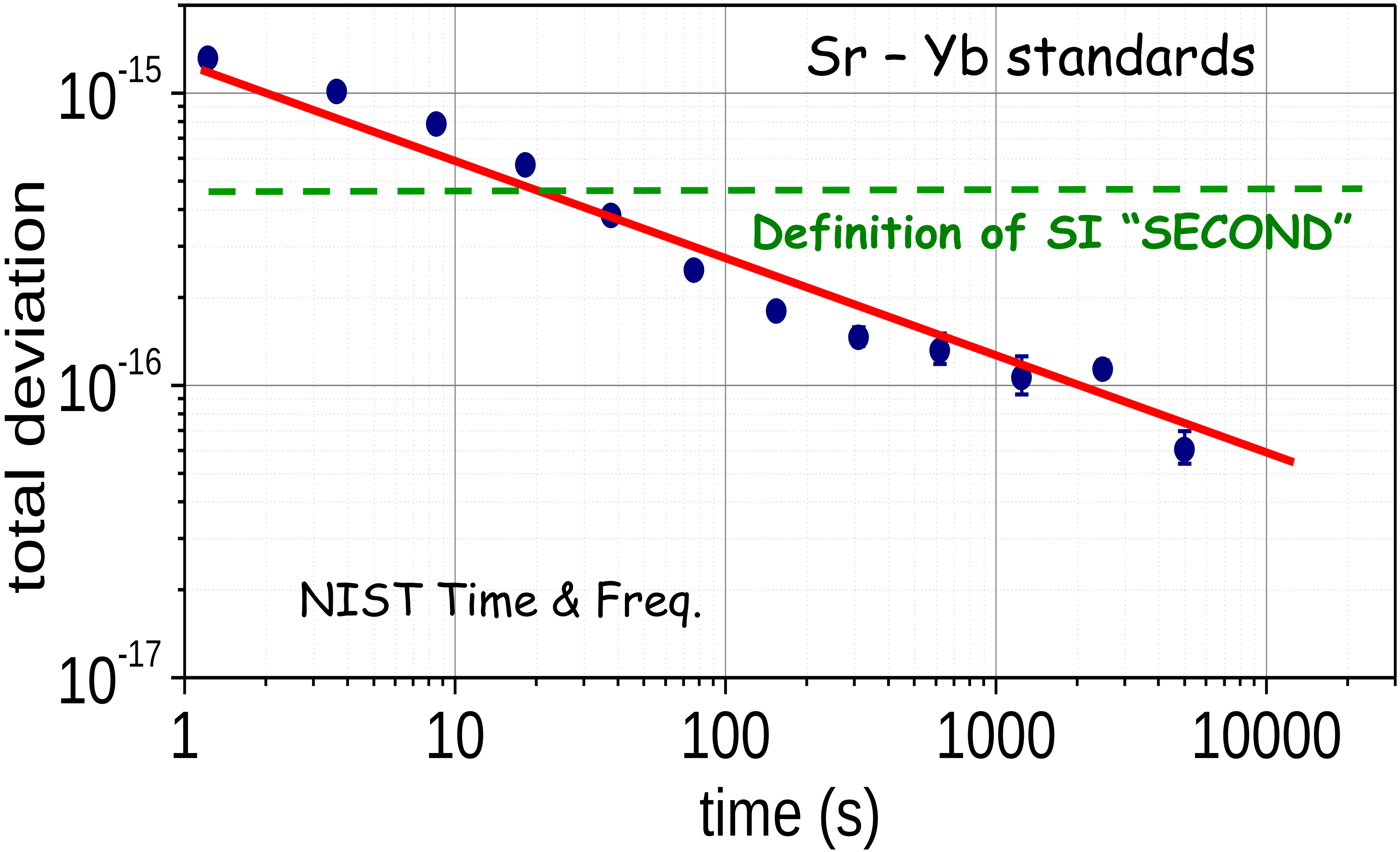
Deutsch *et al.*, PRL **98** (2007); PRL **99**, (2007). Daley *et al.*, PRL **101** (2008). Gorshkov *et al.*, PRL. **102** (2009); Nature Phys. **6**, 289 (2010).

Sr optical atomic clock

Ludlow *et al.*, Science **319**, 1805 (2008). (10^{-16})

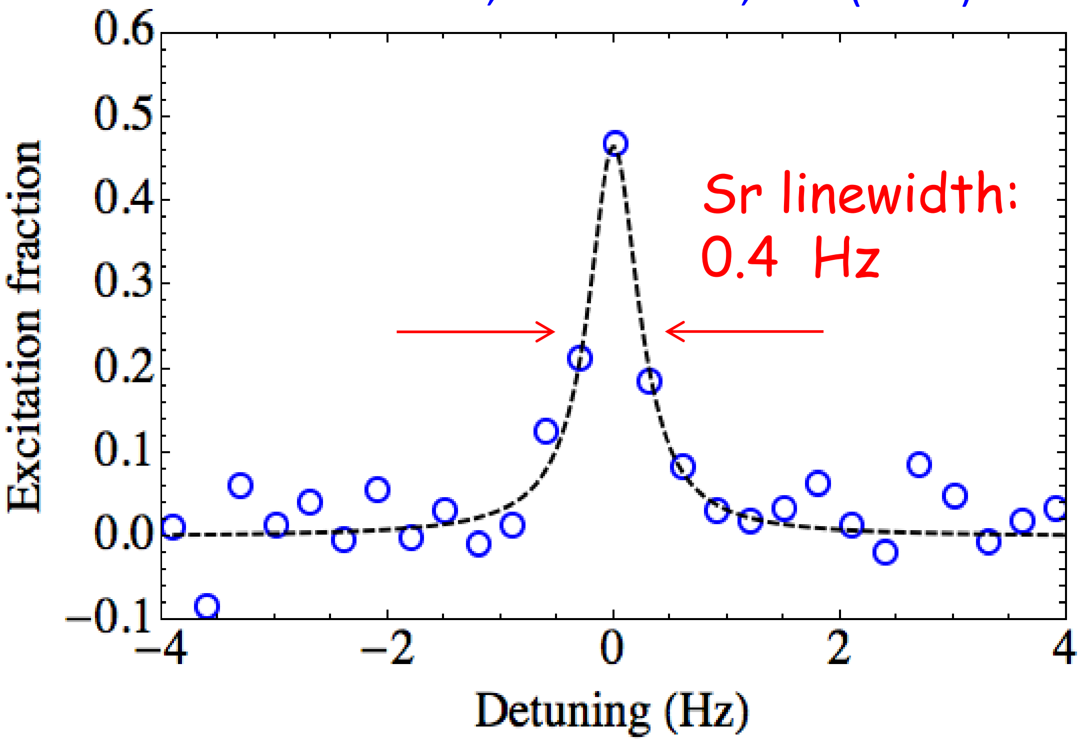
JILA, SYRTE, Tokyo, PTB, Florence, INRIM, NICT, NPL, NIM, NRC

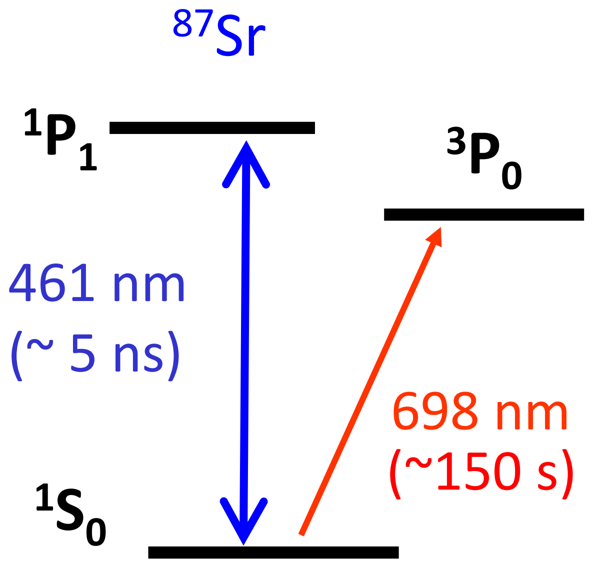
Falke *et al.*, Metrologia **48**, 399 (2011). Le Targat *et al.*, Nat. Comm. **4**, 2109 (2013).

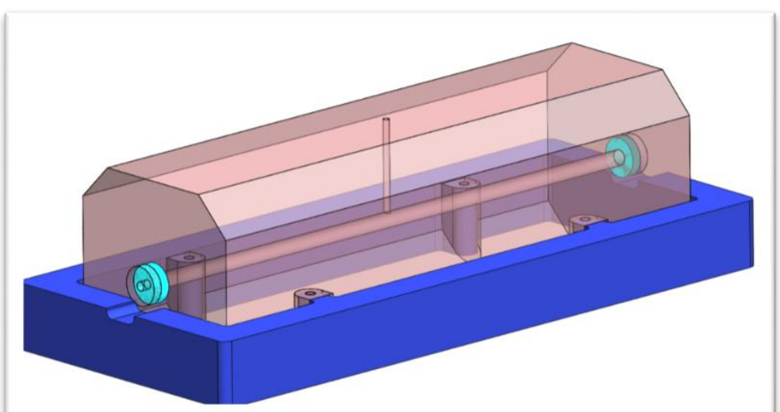


Coherent spectroscopy Q ~ 1 x 10^{15}

Martin *et al.*, Science **341**, 632 (2013).







JILA 40 cm ULE cavity:

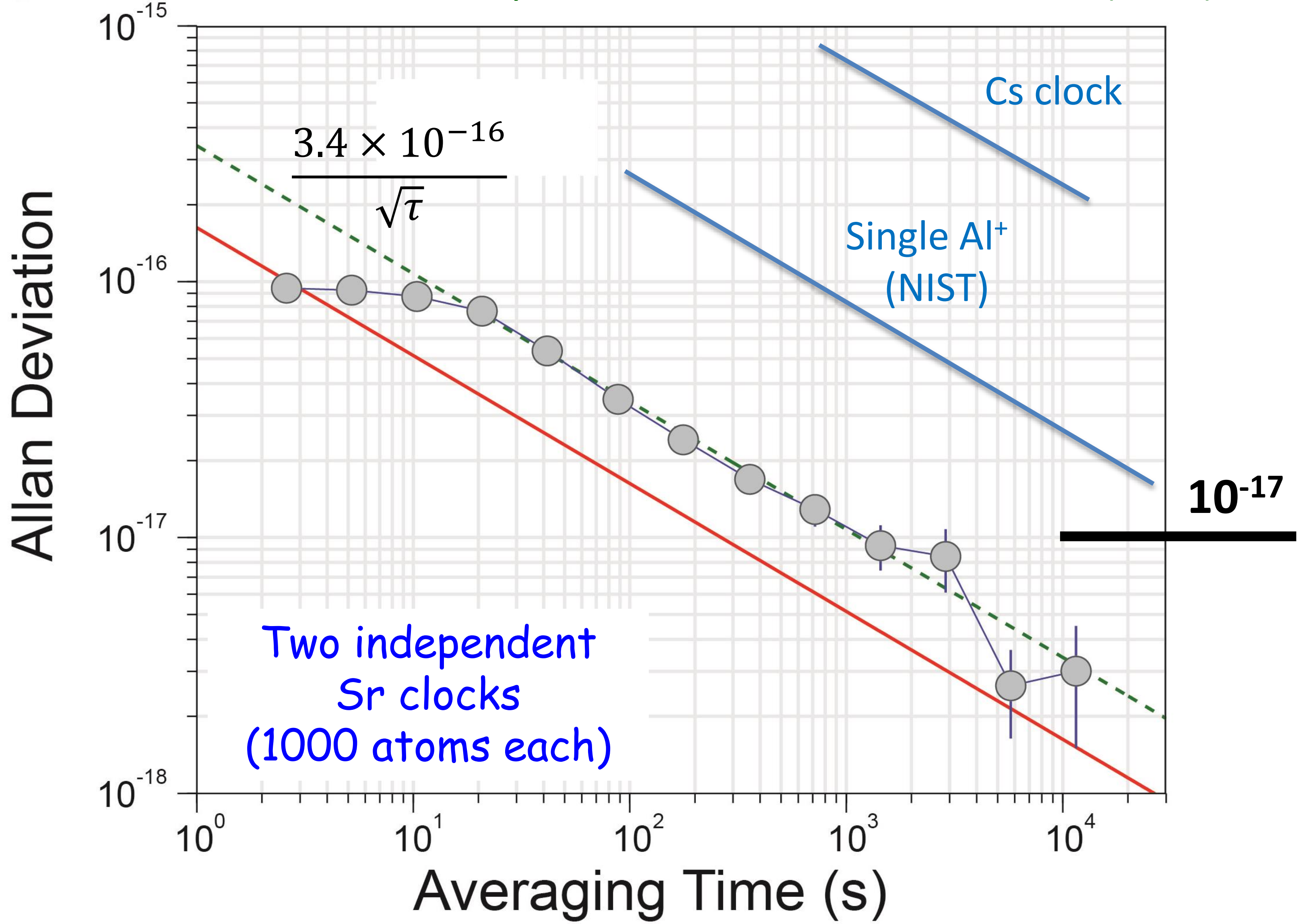
Linewidth: 0.026 Hz

Bishof *et al.*, PRL **111**, 093604 (2013).

Sr clock – pushing the clock stability

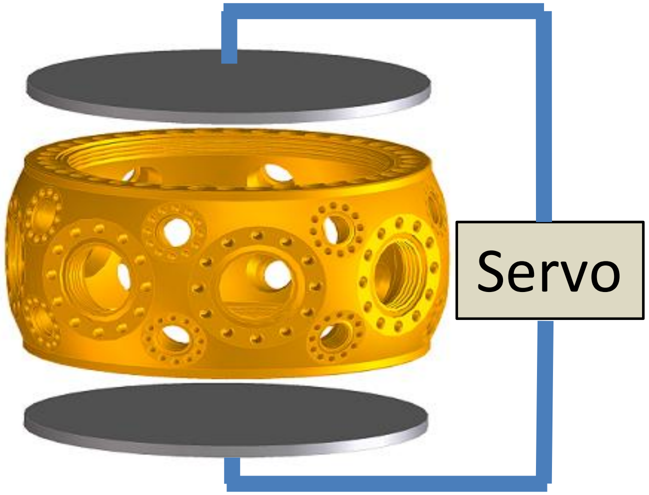
Nicholson *et al.*, PRL **109**, 230801 (2012).

Yb clock: Hinkley, Ludlow *et al.*, Science **341**,1215 (2013)

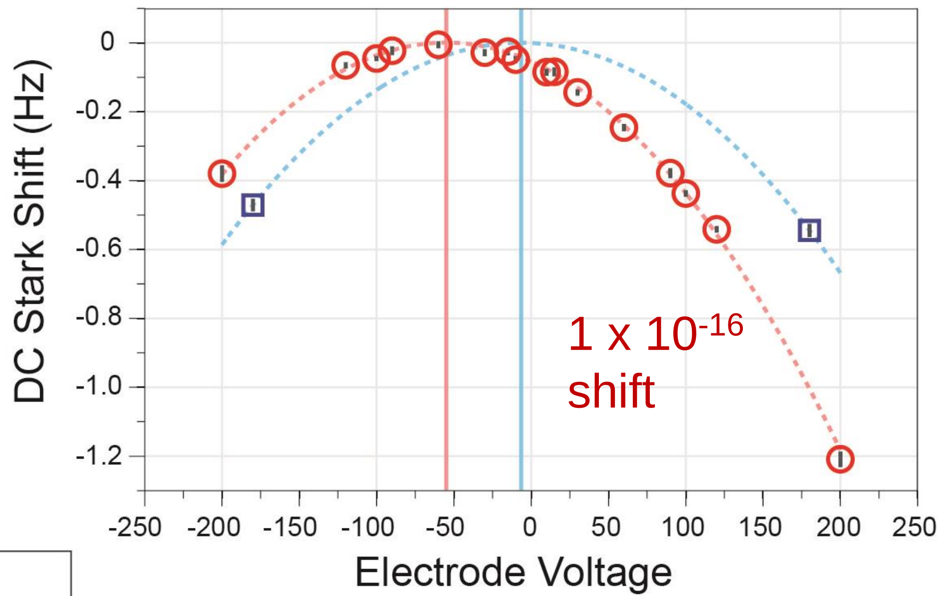


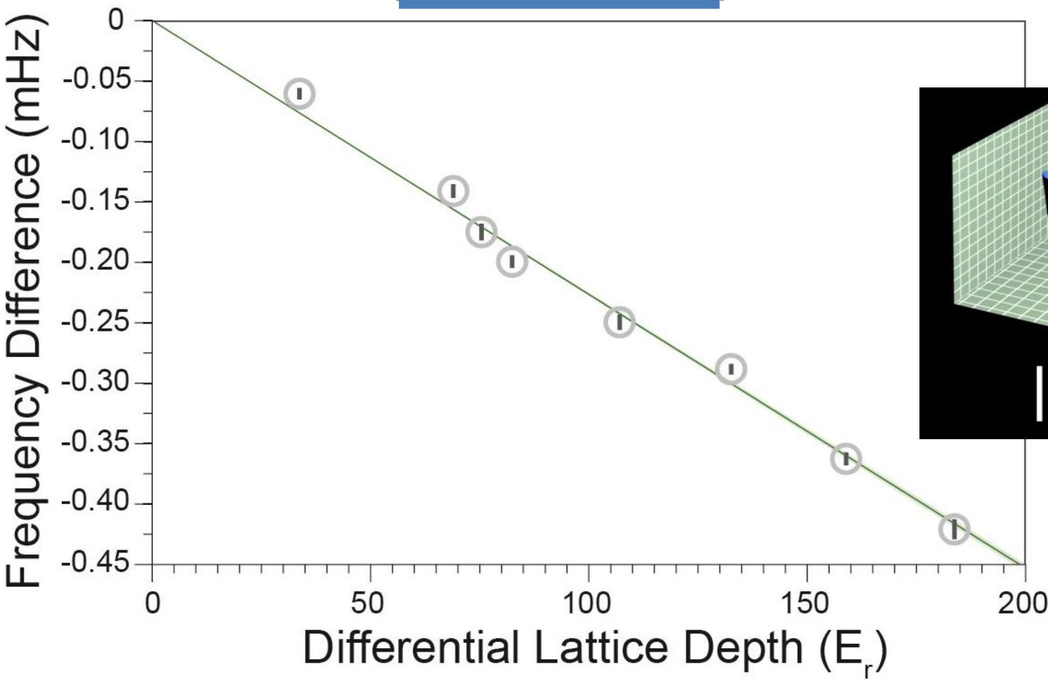
Sr clock – pushing the clock accuracy

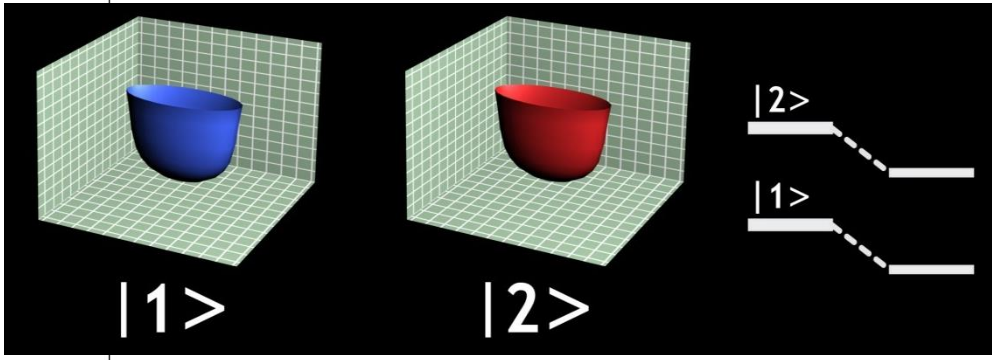
- Active cancellation
- 1×10^{-19} in 1000 s



DC Stark effect - patch charges





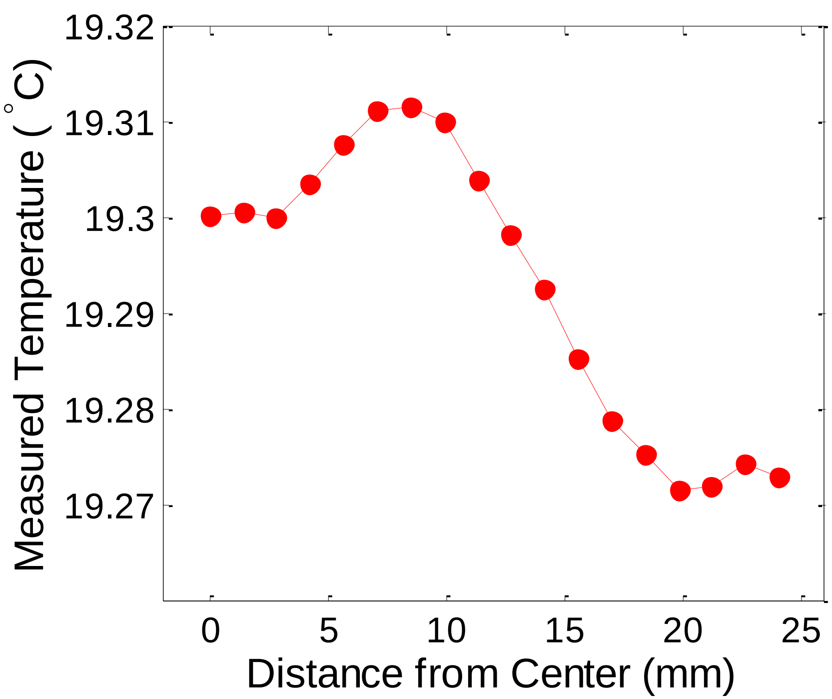


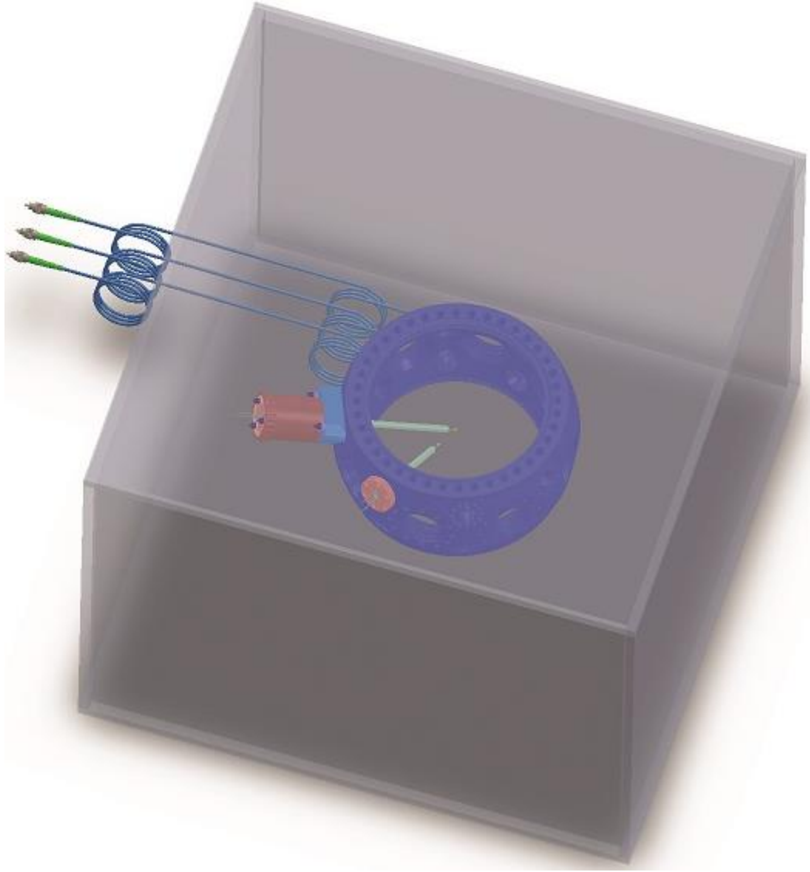
AC Stark effect (lattice):
the two "bowls" are the same
to 3.7×10^{-18}

Sr clock – pushing the clock accuracy

Middelmann *et al.*, IEEE Trans. Instrum. Meas. **60**, 2550 (2011);
Middelmann *et al.*, PRL **109**, 263004 (2012). Safronova *et al.*, PRA **87**, 012509 (2013).

- Movable and fixed thermometers
- Silicon diode sensors
  - 26.7 mK uncertainty
- Platinum sensors
  - 10 mK uncertainty (NIST calibration)





- Thermal shield blocks stray radiation
- T variation = 0.1 K
- Small thermal gradients

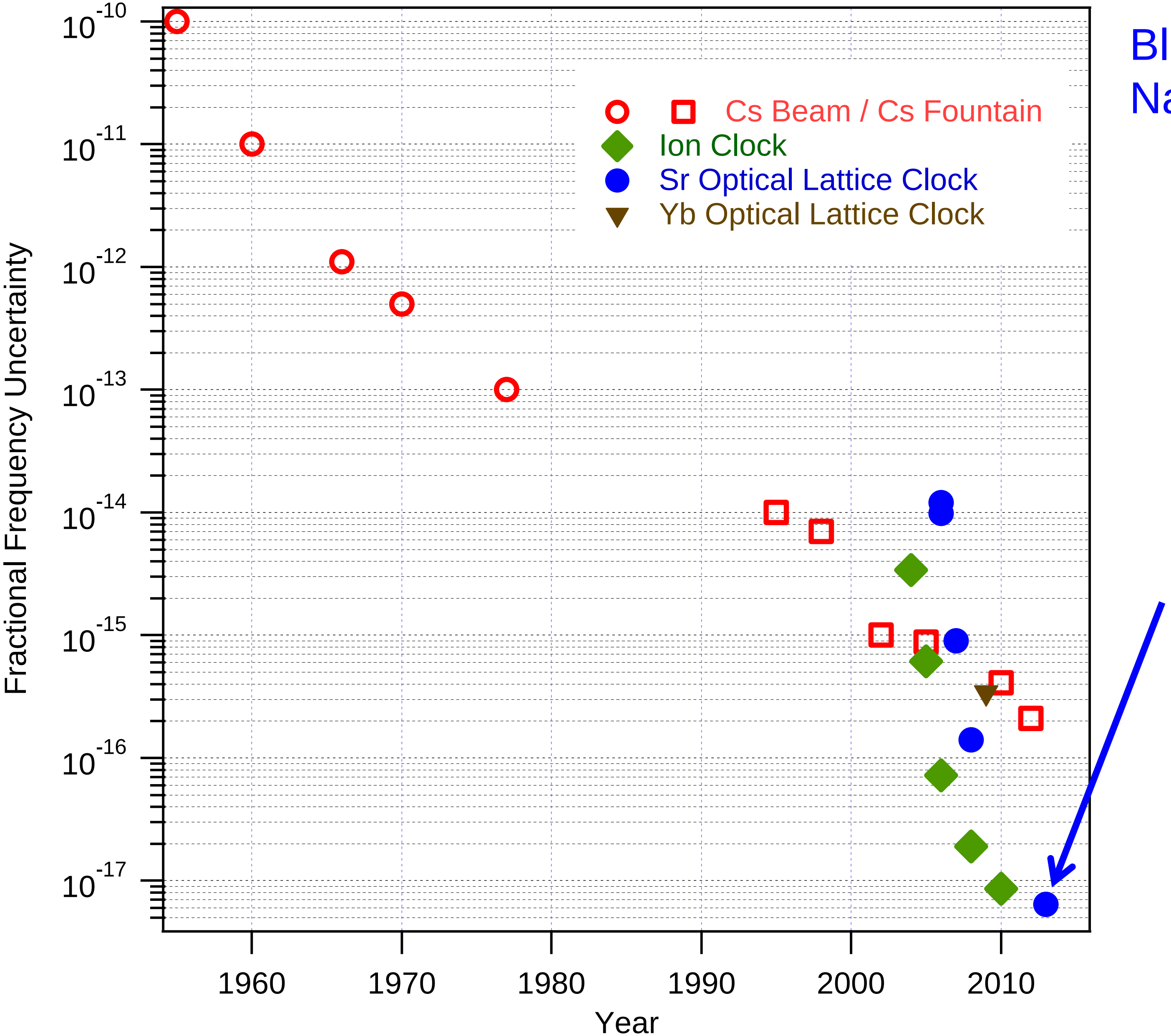
Sr clock - Table of uncertainties

Shifts and Uncertainties in Fractional Frequency Units $\times 10^{-18}$

Sources for Shift	Δ_{SrI}	σ_{SrI}	Δ_{SrII}	σ_{SrII}
BBR Static	-4832	45	-4962.9	1.8
BBR Dynamic	-332	6	-346	3.7
Density Shift	-84	12	-4.7	0.6
Lattice Stark	-279	11	-461.5	3.7
Probe Beam AC Stark	2	5	0.8	1.3
1^{st} Order Zeeman	0	<0.1	-0.2	1.1
2^{nd} Order Zeeman	-175	1	-144.5	1.2
Residual Lattice Vector Shift	0	<0.2	0	<0.2
Line Pulling & Tunneling	0	<0.1	0	<0.1
DC Stark	-4	4	-3.5	2
Background Gas Collisions	0.07	0.07	0.63	0.63
AOM Phase Chirp	-7	20	-1	1
2^{nd} Order Doppler	0	<0.1	0	<0.1
Servo Error	1	4	0.4	0.6
Totals	-5710	53	-5922.5	6.4

Frequency comparison of SrI & SrII clocks at 24 x 10^{-18}

Sr clock – a new frontier for stability & accuracy



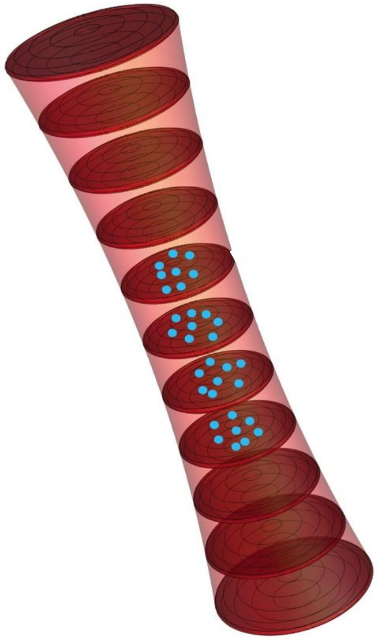
Bloom *et al.*, Nature **506**, 71 (2014).

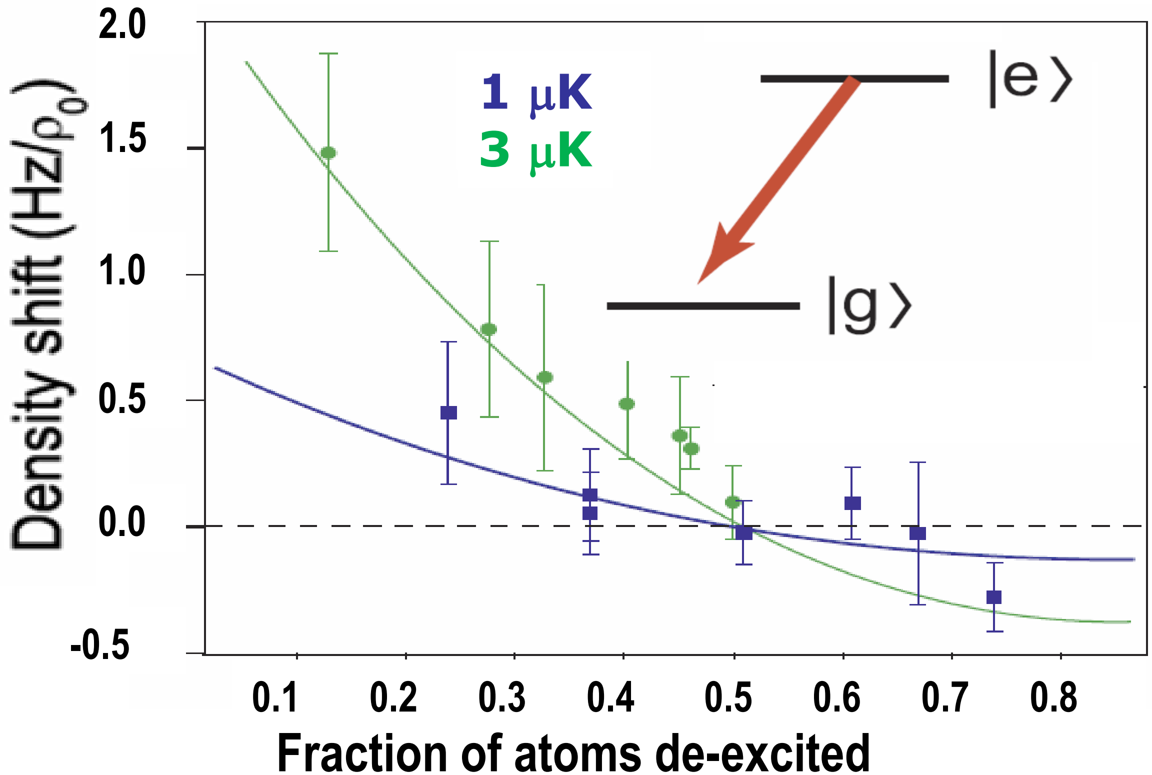
Sr: lowest uncertainty in all atomic clocks: 6.4 x 10^{-18}

Achieving this much faster than previous records

Collisional shift with ultracold fermions

But, first appearance, ~10^{-16} : Campbell *et al*, Science **324**, 360 (2009).





^{87}Sr, at precision ~10^{-15}, zero shift: PRL **98**, 083002 (2007).

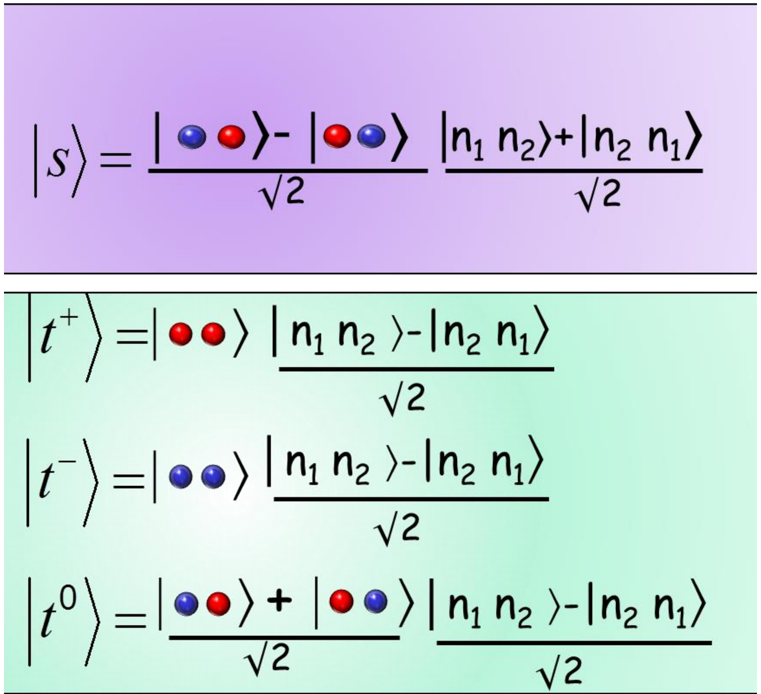
Reduced shift: (10^{-17}) Science **331**, 1043 (2011).

(< 10^{-18}) PRL **109**, 230801 (2012).

Ana Maria Rey

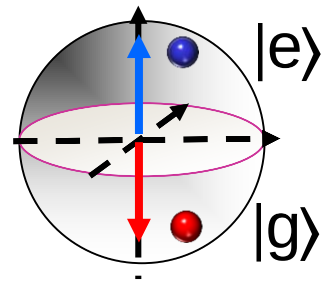
See also related work of Yb clock by Ludlow *et al*.

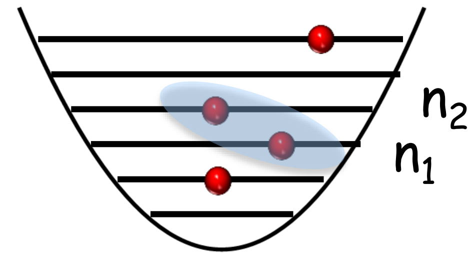
Lattice clock: fermionic spin interactions



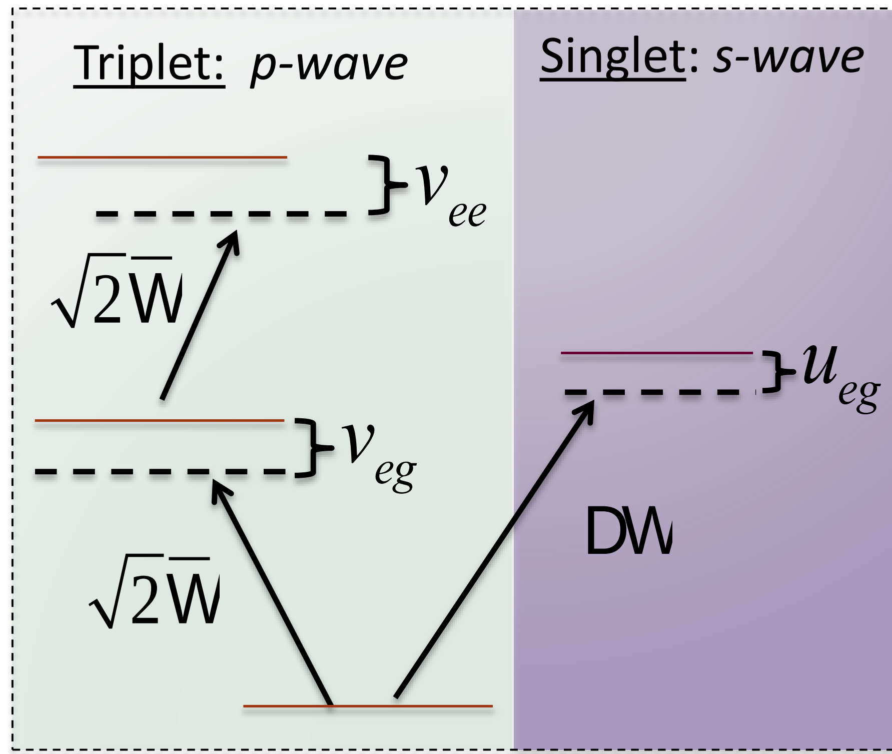
Singlet

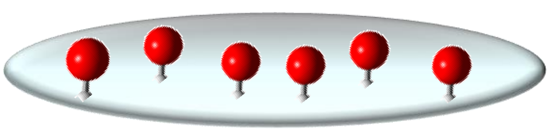
Triplet





Rey *et al.*, Annals Phys. **340**, 311 (2014).





With *N* atoms:

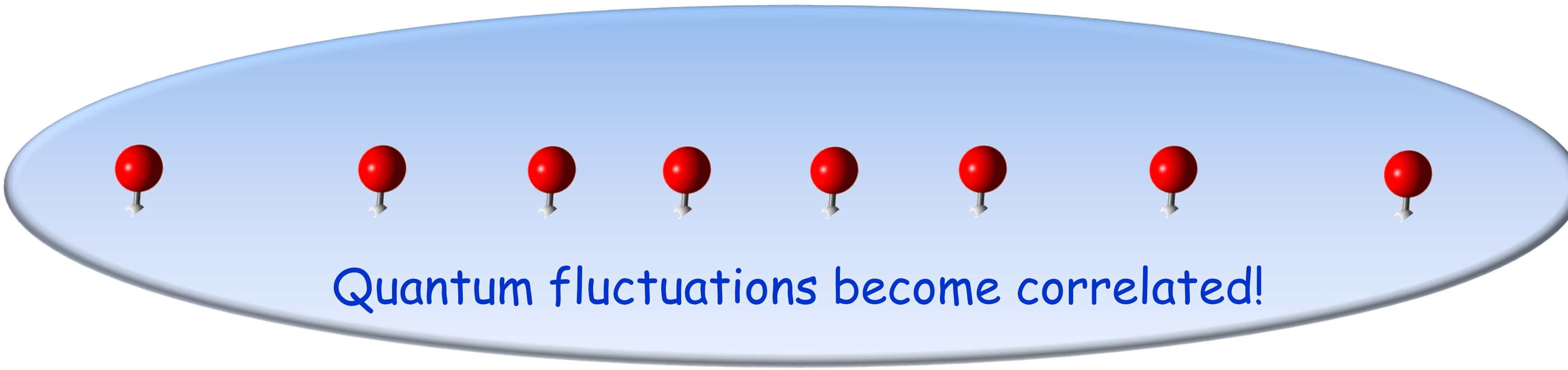
- *s*-wave suppressed (contributing as sideband)
- *p*-wave dominant (interacting fermions act like bosons)

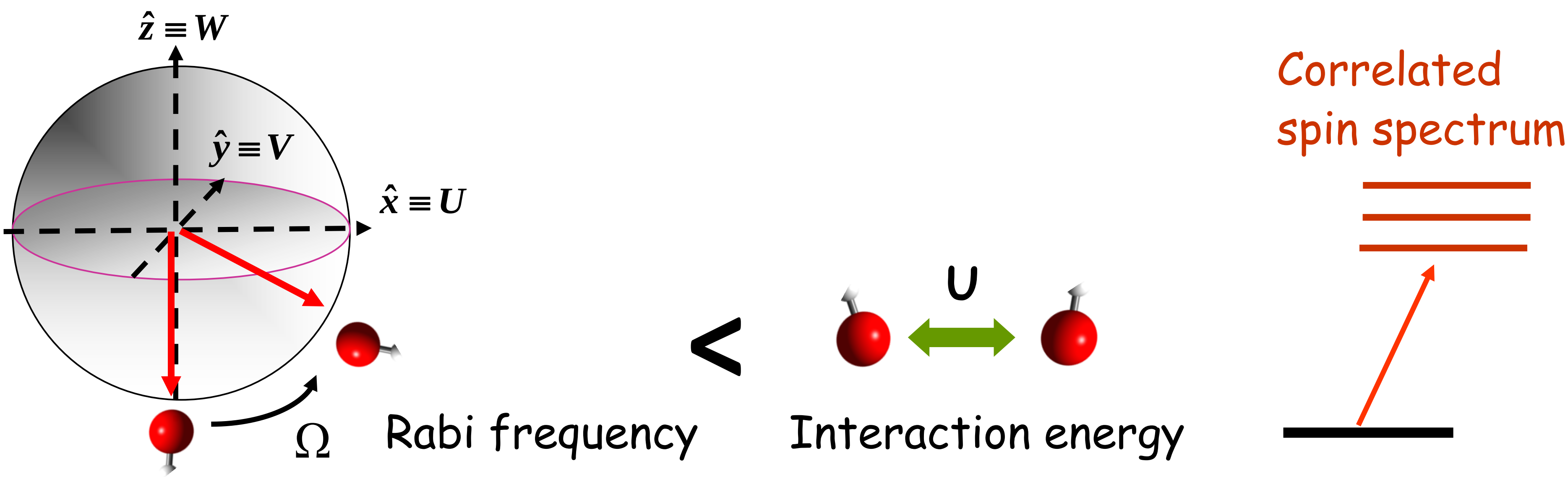
Yb: PRL **103**, 063001 (2009).

Probe many-body quantum spin dynamics at clock precision

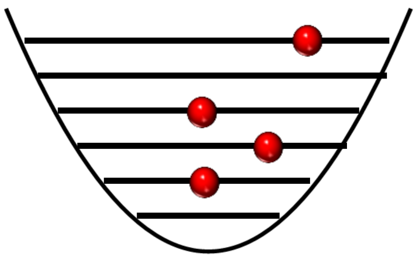
Martin *et al.*, Science **341**, 632 (2013).

U/h ~ 1 Hz





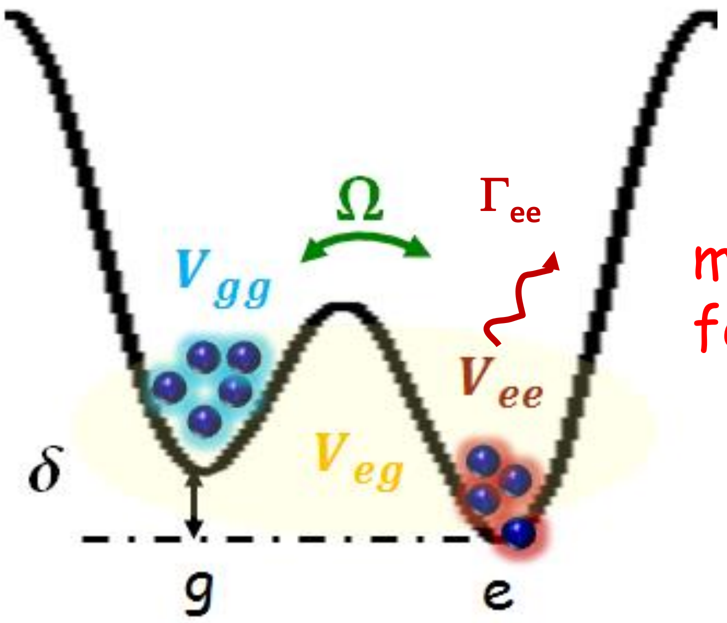
Spin model
(Ana Maria Rey *et al.*)



Collective-spin $S = N/2$

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

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

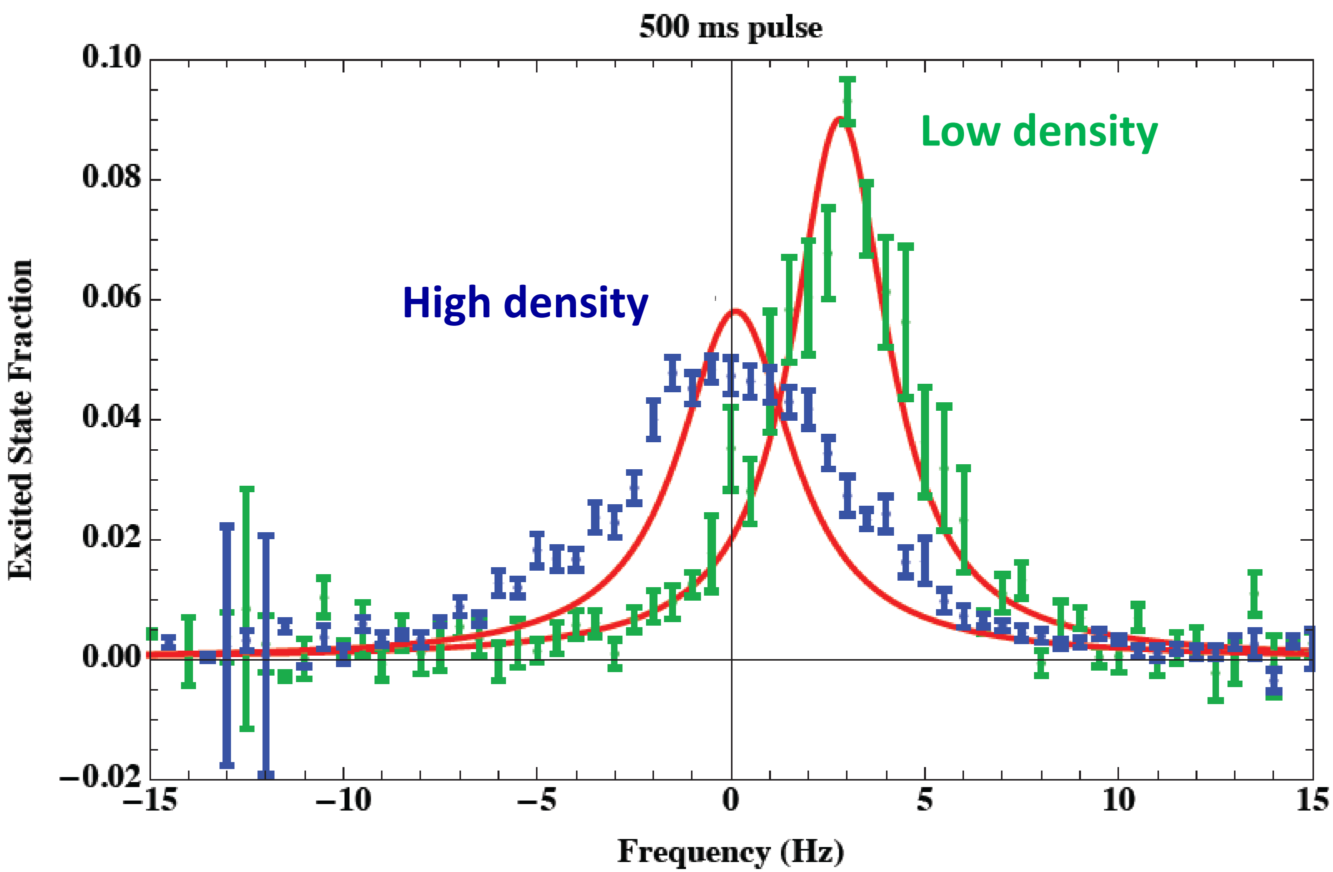


mapping interacting fermions to bosons

Two-component BEC:
Sorensen, Moller, Cirac, Zoller, Lewenstein, …

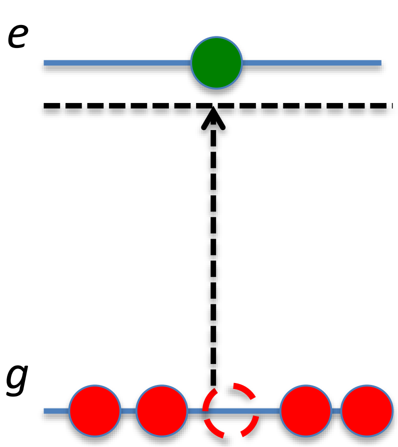
Linear response regime
(Rabi spectroscopy)

2 uK sample temperature

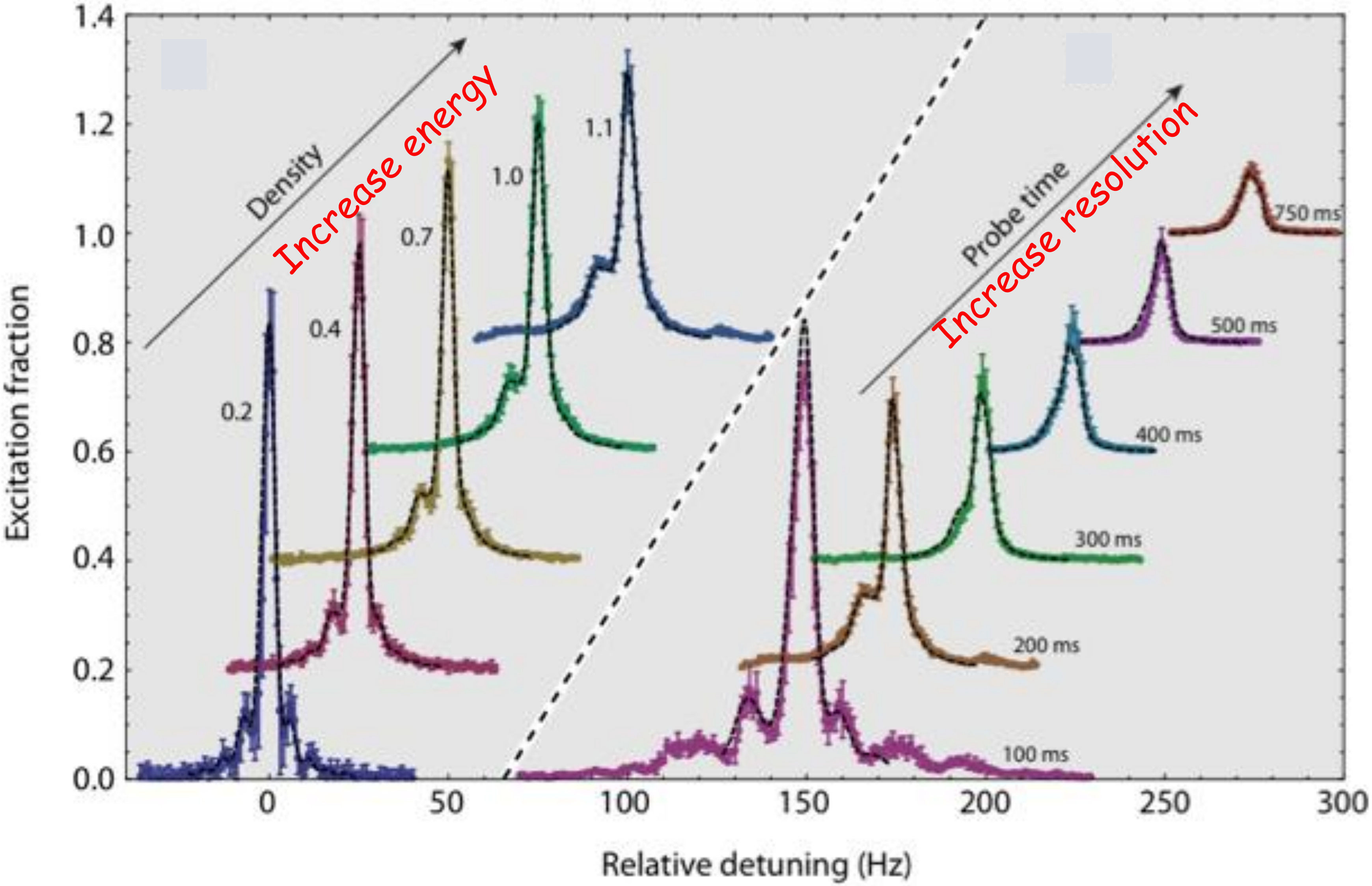


Experiences shift

$$\Delta E \propto V_{eg}(N-1)$$



Rabi spectroscopy with strong interactions

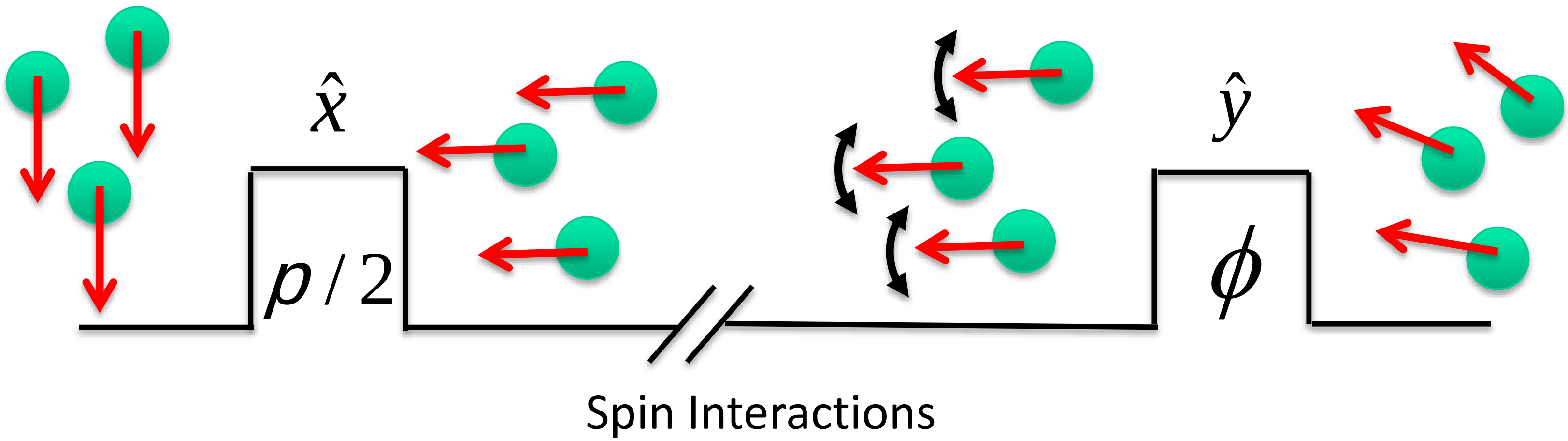


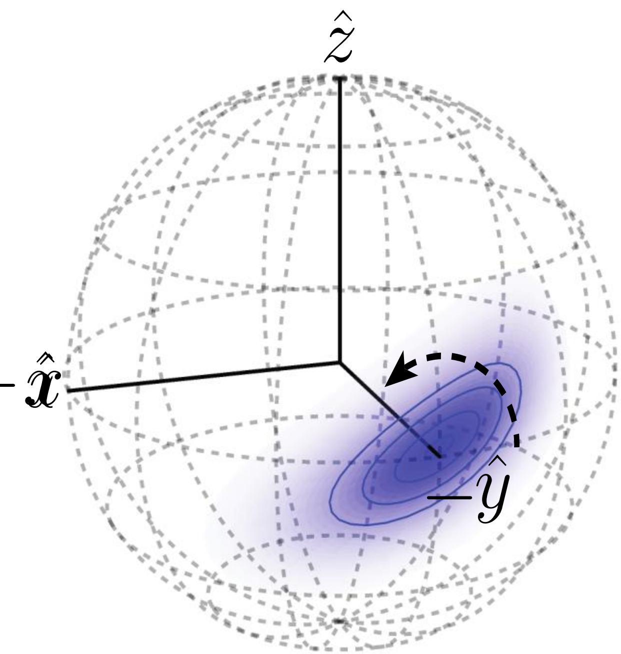
Structure due to interactions:

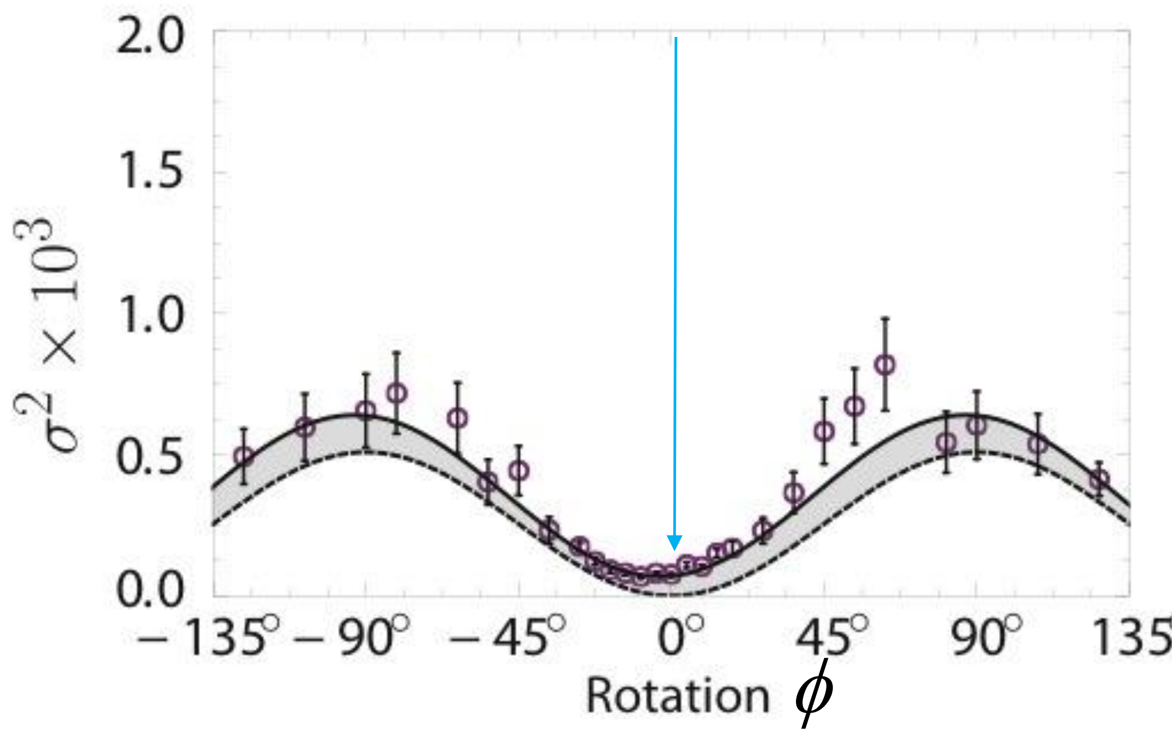
excitation blockade at increasing U or decreasing Ω.

Ramsey spectroscopy for spin correlations

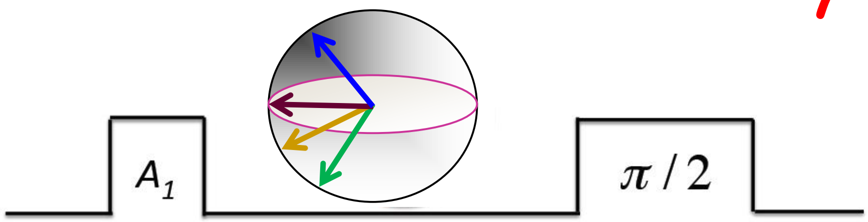
$$\hat{H}/\hbar = \chi\left(S^z\right)^2 + C\left(N-1\right)S^z$$

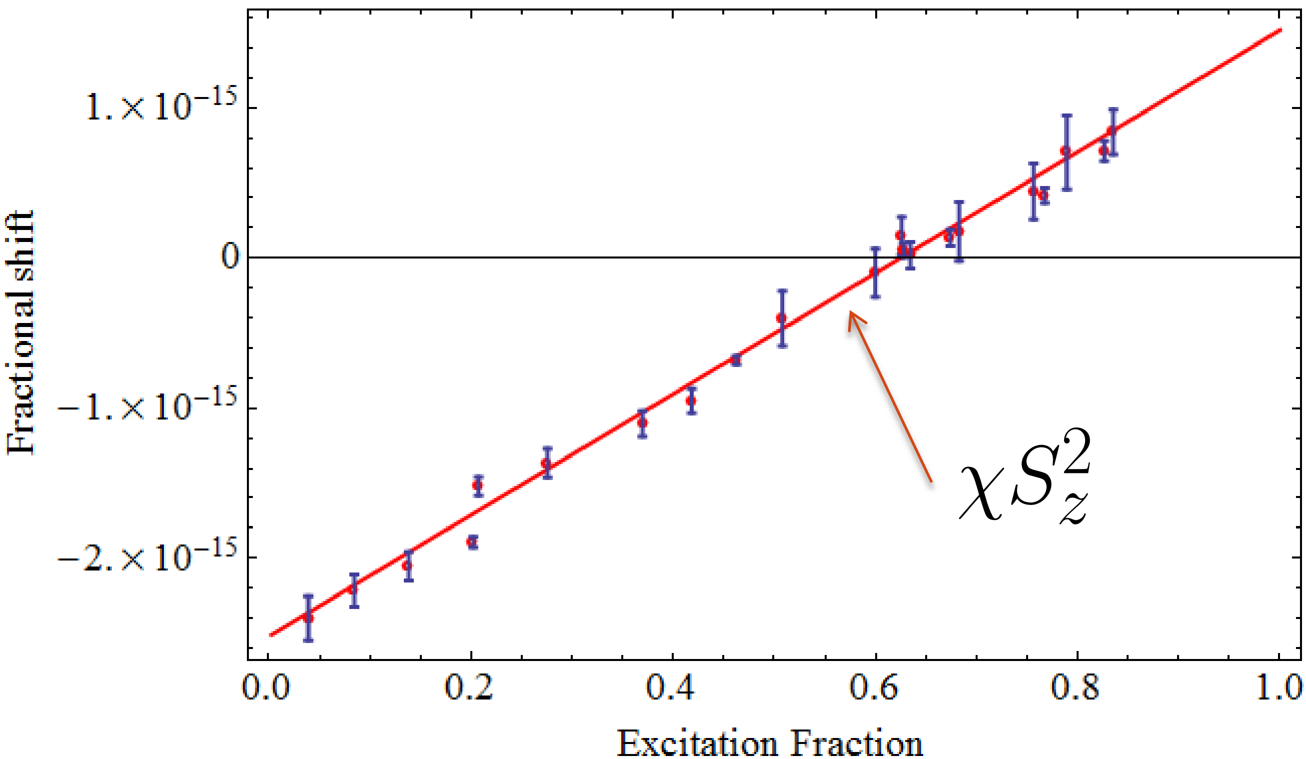






Density shift in Ramsey





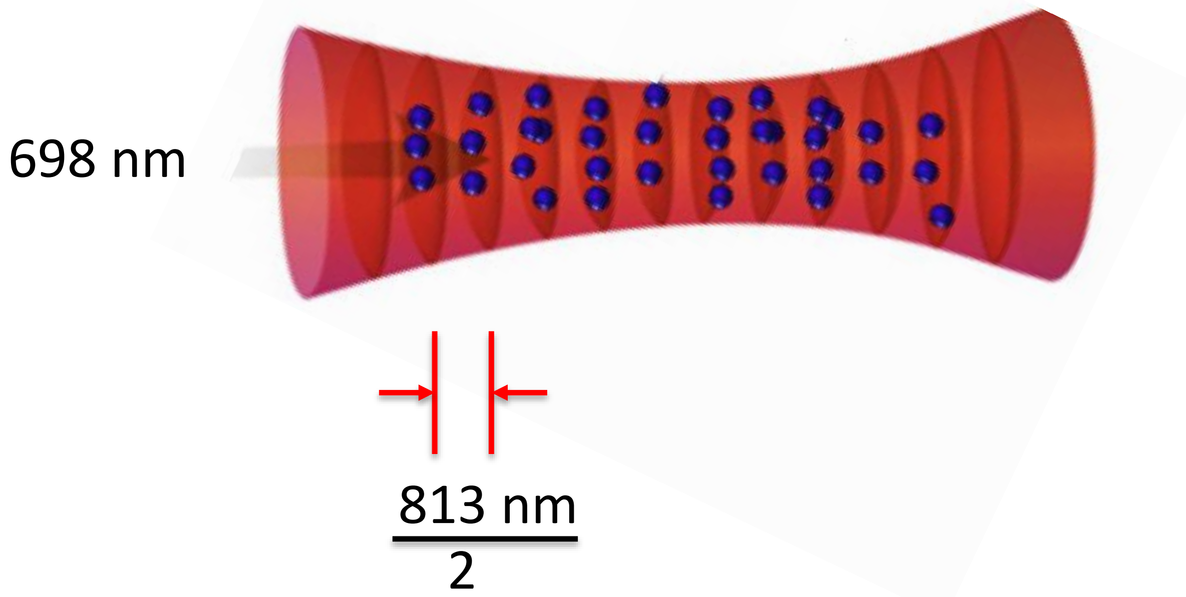
$$\frac{V_{ee} - V_{gg}}{V_{eg} - V_{gg}} = 0.4$$

Collisional shift has a linear dependence on the tipping angle.

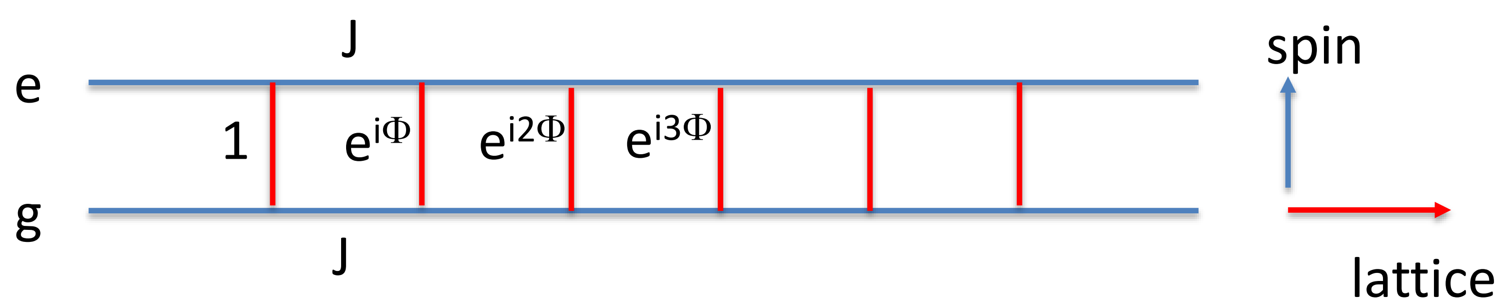
CS_z $\qquad$ χS_z^2

$$\Delta \upsilon \sim \frac{V_{ee} - V_{gg}}{2} + \cos(\bar{\Omega} t)\left[\frac{2V_{eg} - V_{ee} - V_{gg}}{2}\right]$$

Turning *p*-wave to *s*-wave interactions

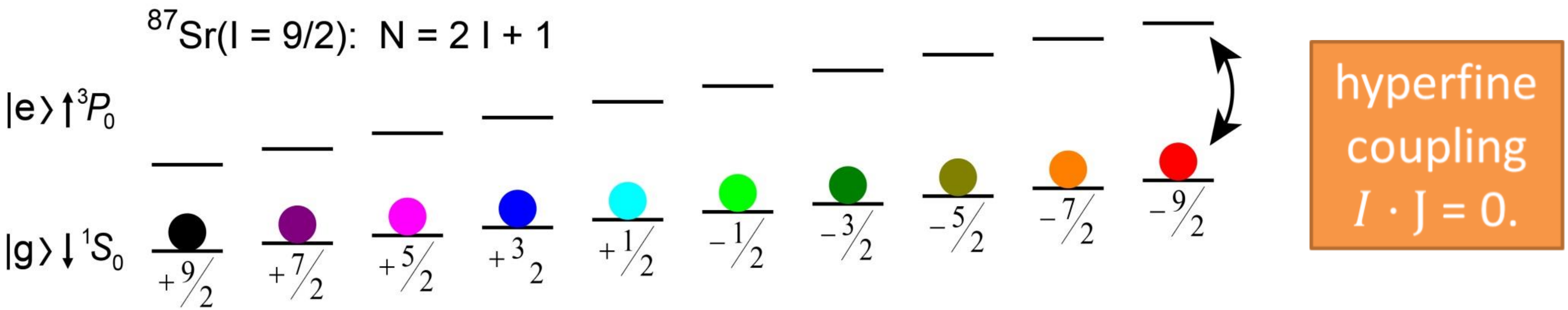


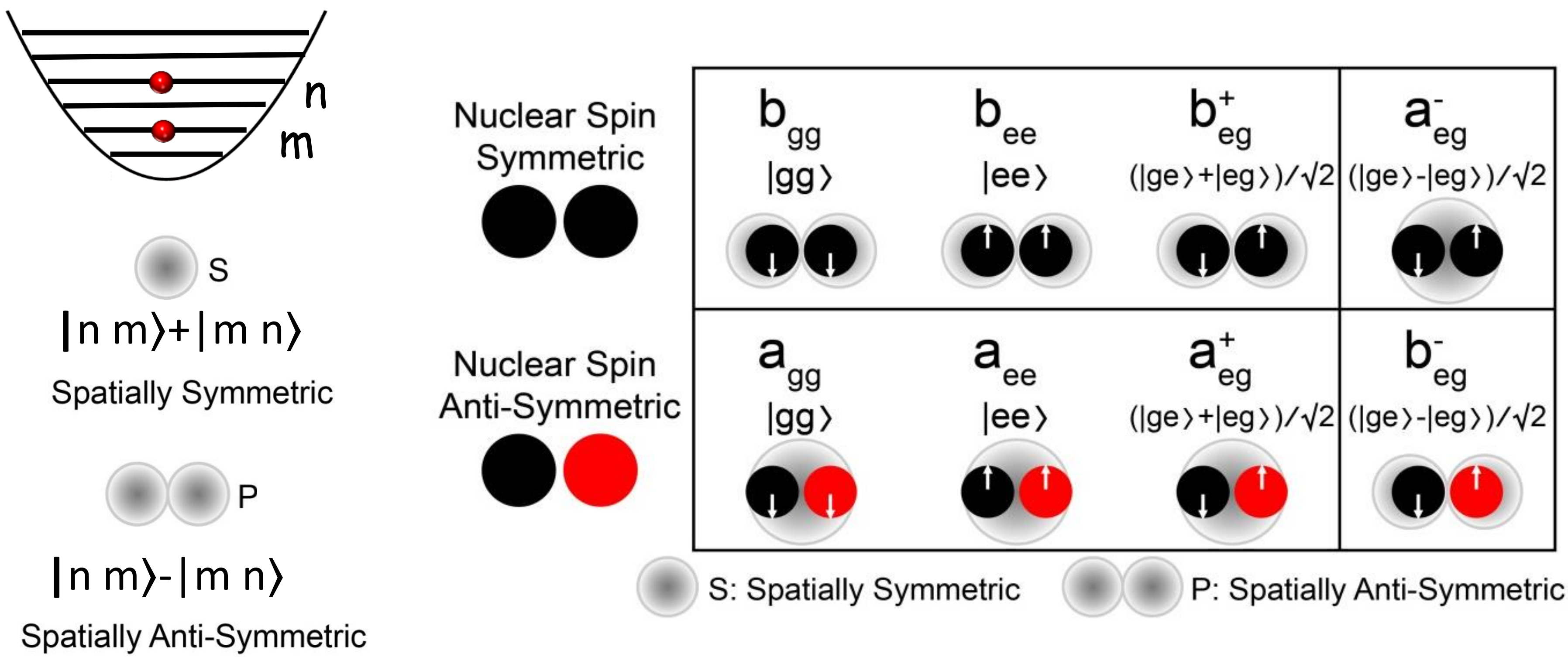
$$\Phi = ka = 2\pi/698 \times 813/2 = 1.16\,\pi$$



Lewenstein, Dalibard, Spielman, ...

3 degrees of freedom: electronic, nuclear, spatial

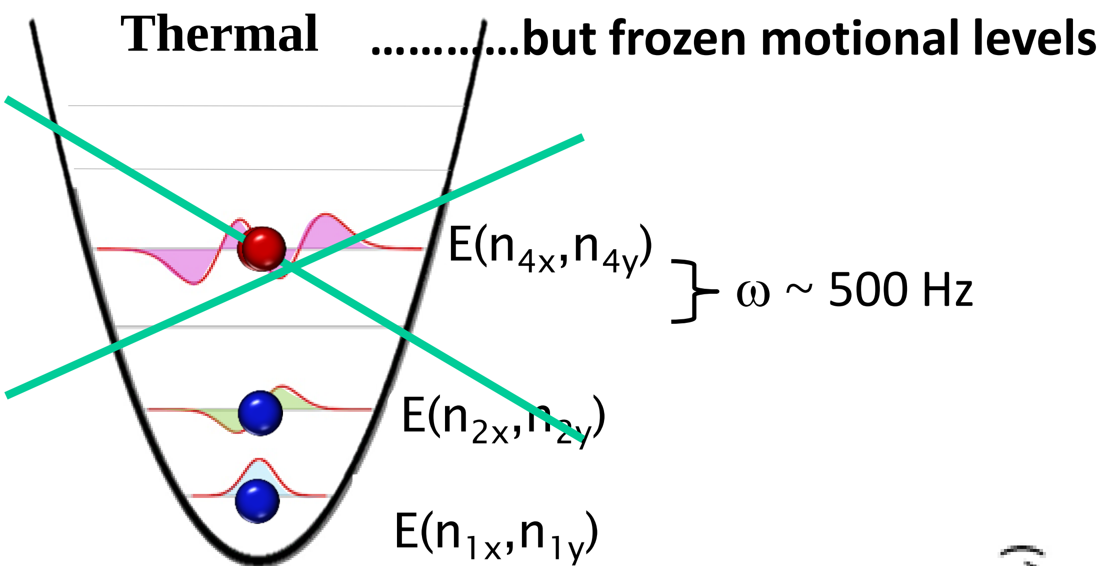


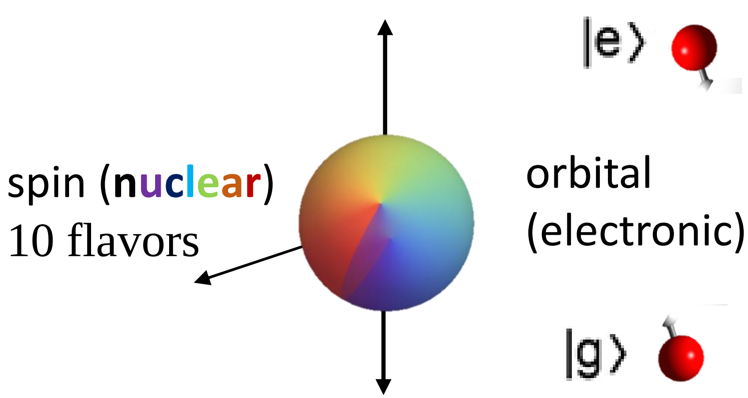


Gorshkov *et al.*, Nature Phys. **6**, 289 (2010).

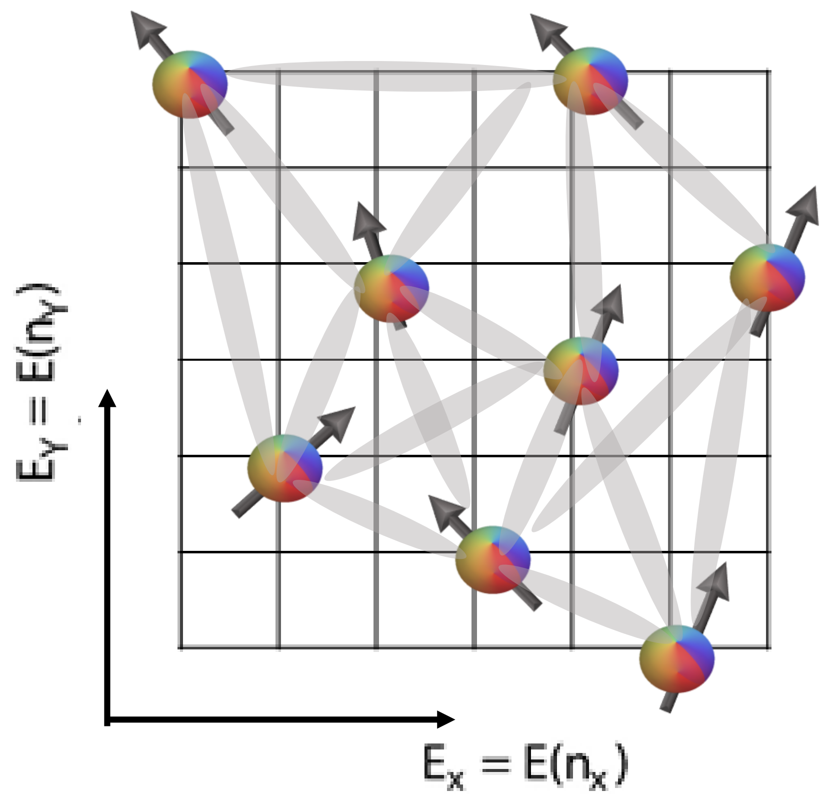
1D lattice clock: spin model at high temperatures (μK)

Interaction Energy ~ 1 Hz



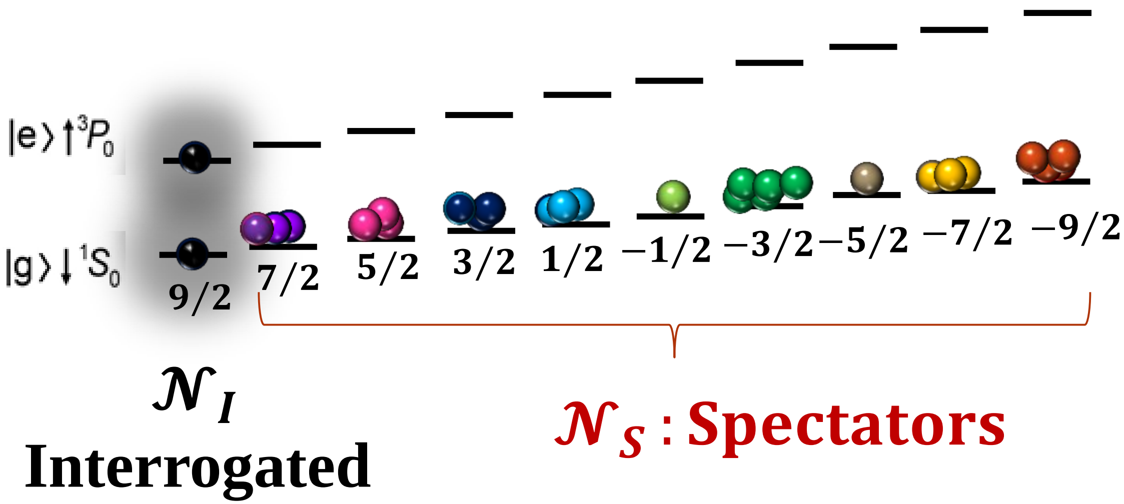


Energy lattice: delocalized modes – long range interactions

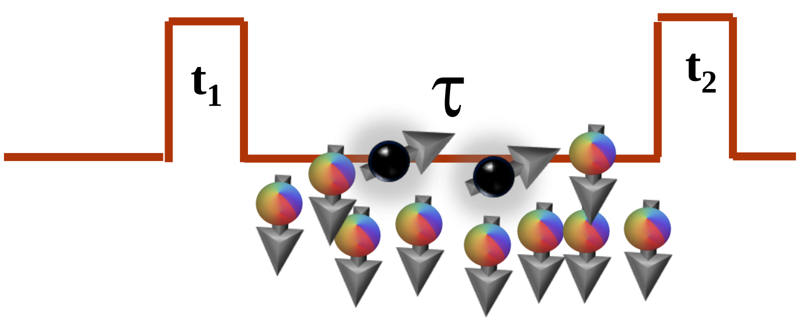


Density shifts & SU(N) symmetry

X. Zhang, *et al.*, arXiv:1403.2964 (2014); Science, to be published



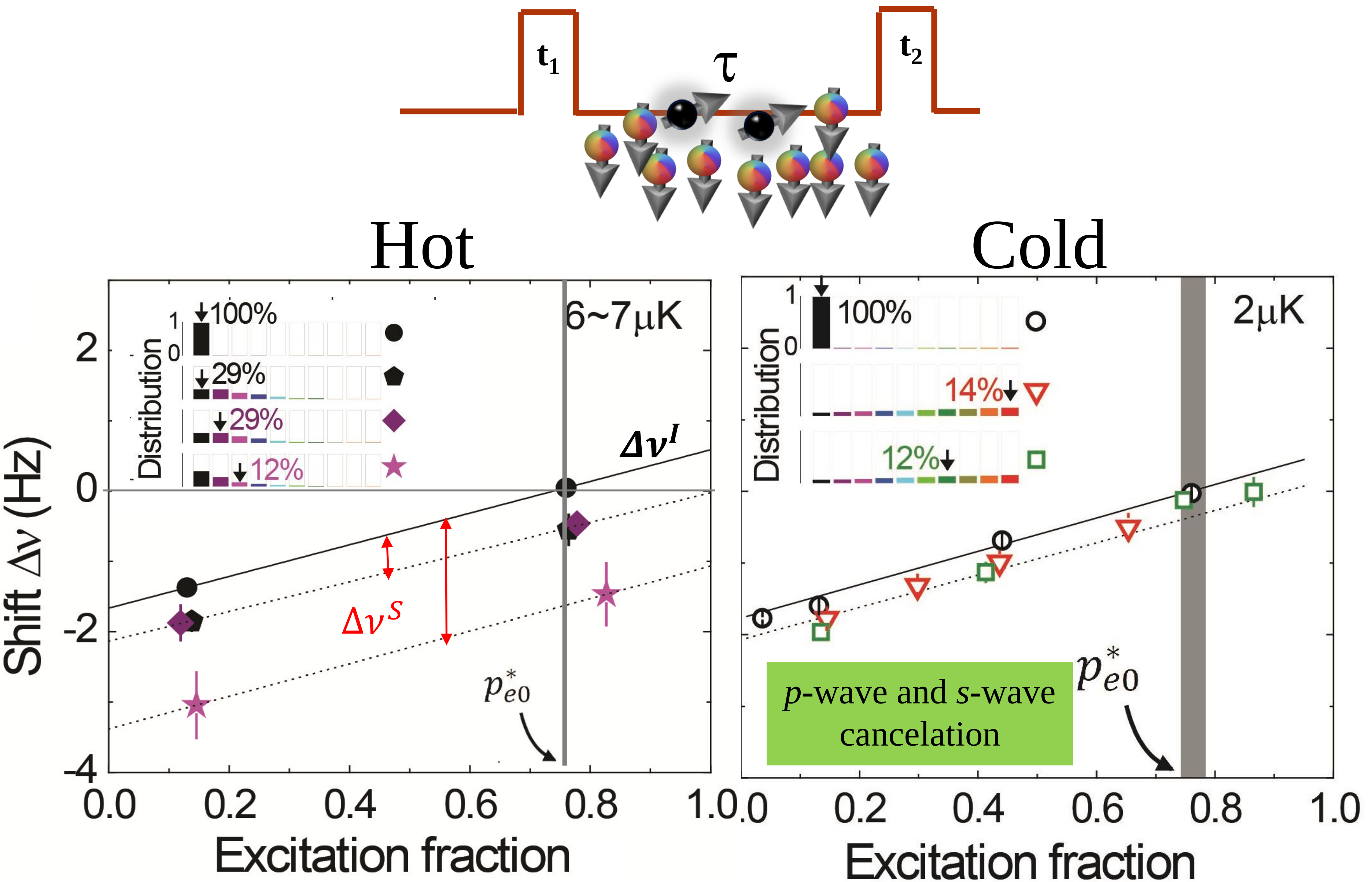
SU(N): shift depends only on $\mathcal{N}_S$, not distributions



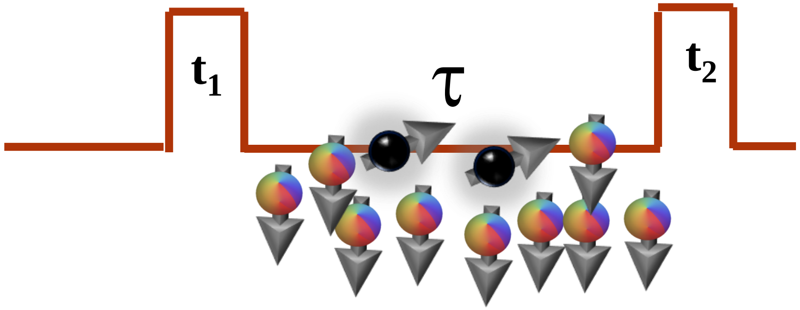
$$\Delta\nu = \Delta\nu^I + \Delta\nu^S$$

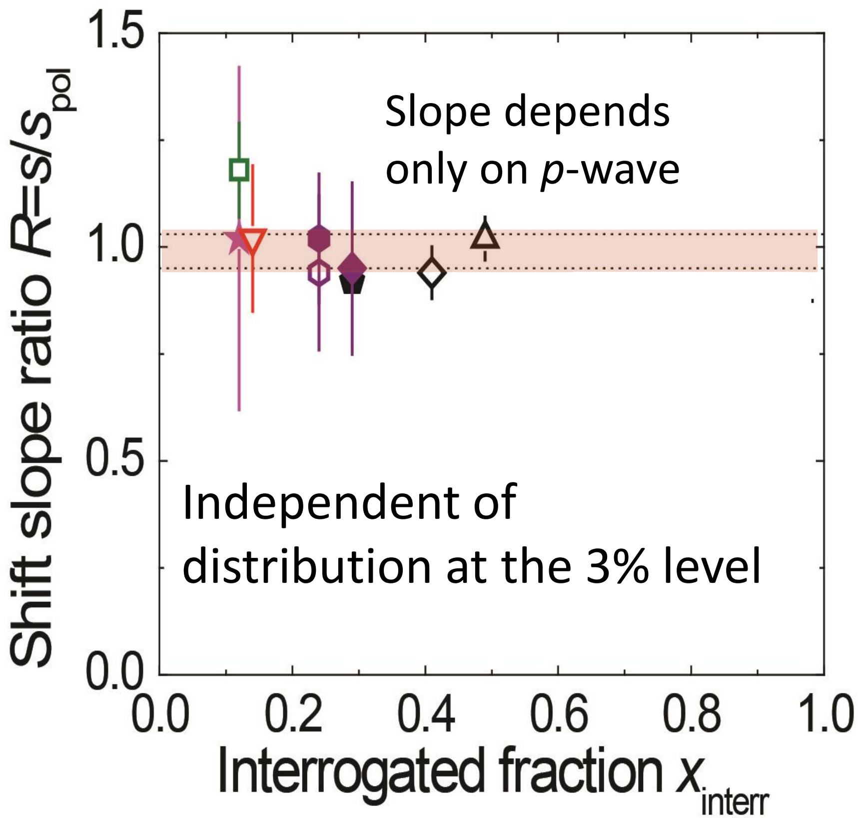
***p*-wave**   ***s*- & *p*- wave**

Density shifts & SU(N) symmetry

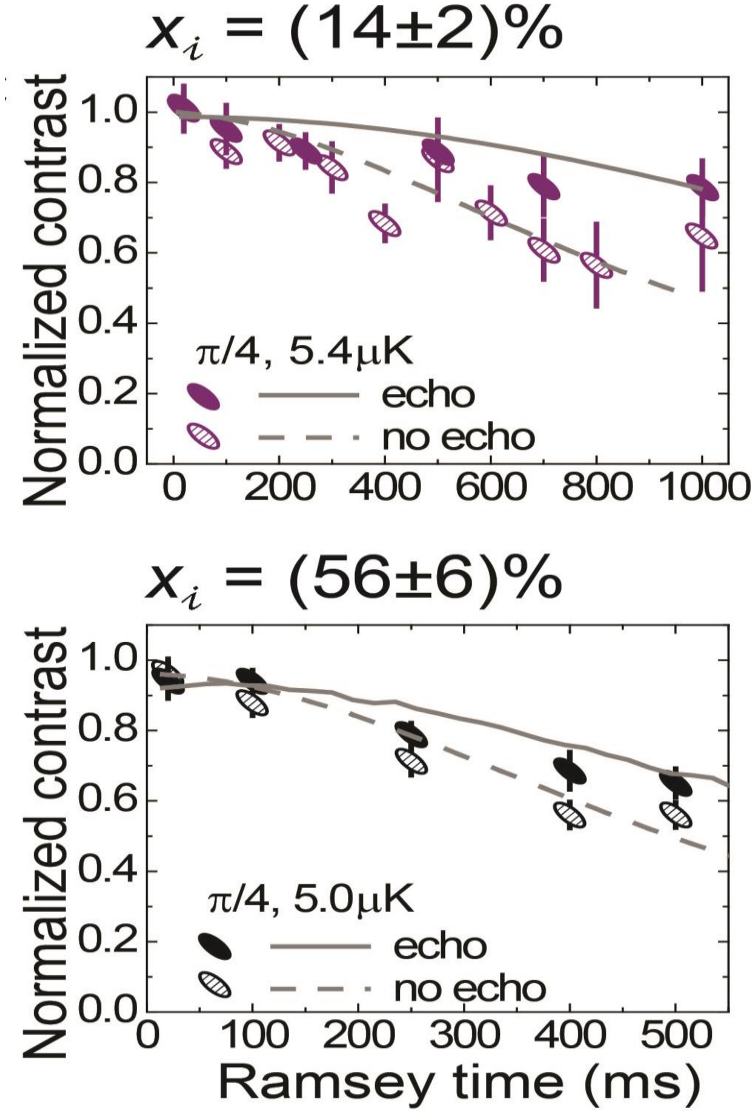


Density shifts & SU(N) symmetry





Dynamics

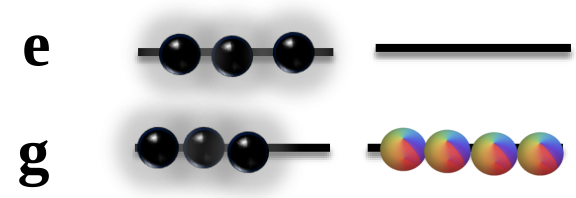


Interaction parameters

X. Zhang, *et al.*, arXiv:1403.2964 (2014).

Channel	*S*-wave(a_o)	*P*-wave(a_o)	Determination
gg	**96.2(1)**	**74(2)**	**[S-wave] Two-photon photo-associative** **[P-wave] Analytic relation**
eg⁺	**169(8)**	**-169(23)**	**[S-wave] Analytic relation** **[P-wave] Density shift in a polarized sample**
eg⁻	**68(22)**	-42^{+103}_{-22}	**[S-wave] Density shift in a spin mixture at different T** **[P-wave] Analytic relation**
***ee* (elastic)**	**176(11)**	**-119(18)**	**[S-wave] Analytic relation** **[P-wave] Density shift in a polarized sample**
***ee* (inelastic)**	$\tilde{a}_{ee} =$ **46(19)**	$\tilde{b}_{ee} =$ **125(15)**	**Two-body loss measurement**

Spin exchange at B=0 for Yb



Bloch group: arXiv:1403.4761
Spin exchange

Inguscio group: arXiv:1406.6642
Coherent exchange oscillations

Spin-orbit Hamiltonian with alkaline-earths

$$H = -\sum_{<i,j>,\alpha} J_\alpha \left(c^\dagger_{i,\alpha\sigma} c_{j,\alpha\sigma} + c^\dagger_{j,\alpha\sigma} c_{i,\alpha\sigma}\right) + \sum_{\alpha i} U_{\alpha\alpha} \hat{n}_{i,\alpha\uparrow} \hat{n}_{i,\alpha\downarrow} + V \sum_i \hat{n}_{i,g} \hat{n}_{i,e} + J_{ex} \sum_{i,\alpha,\sigma,\sigma'} c^\dagger_{i,g\sigma} c^\dagger_{i,e\sigma'} c_{i,g\sigma'} c_{i,e\sigma}$$

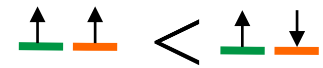
$V = (U_{eg}^{+} + U_{eg}^{-})/2$

Direct

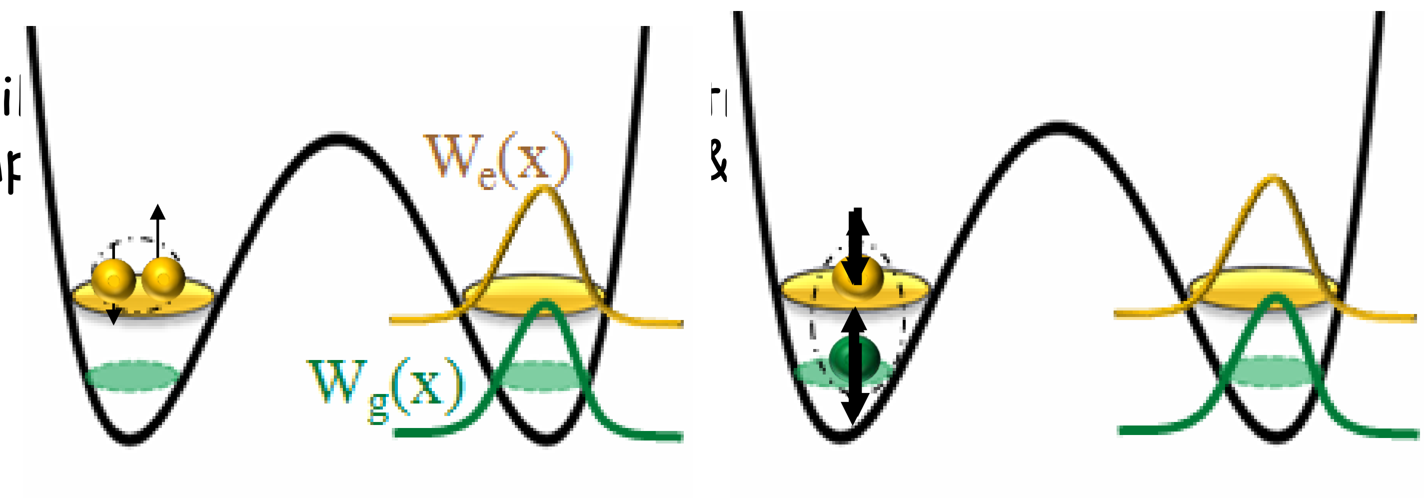
$J_{ex} = (U_{eg}^{+} - U_{eg}^{-})/2$

Exchange interaction
Hunds Rule coupling

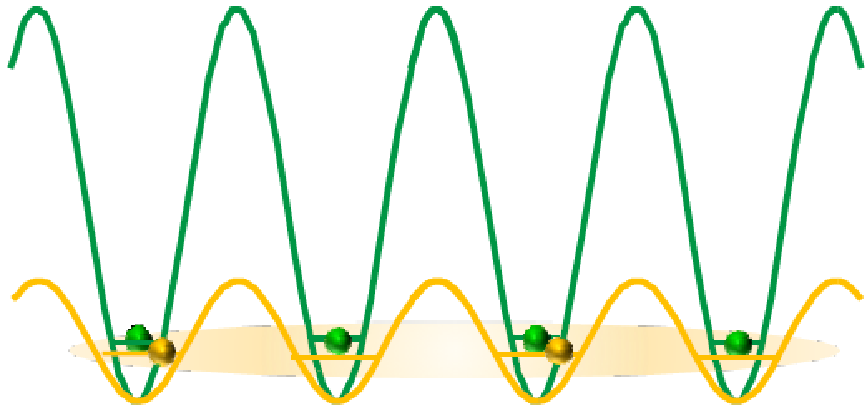
e.g: Energies



- The Hamil
- High temp



Kondo lattice model with alkaline-earths

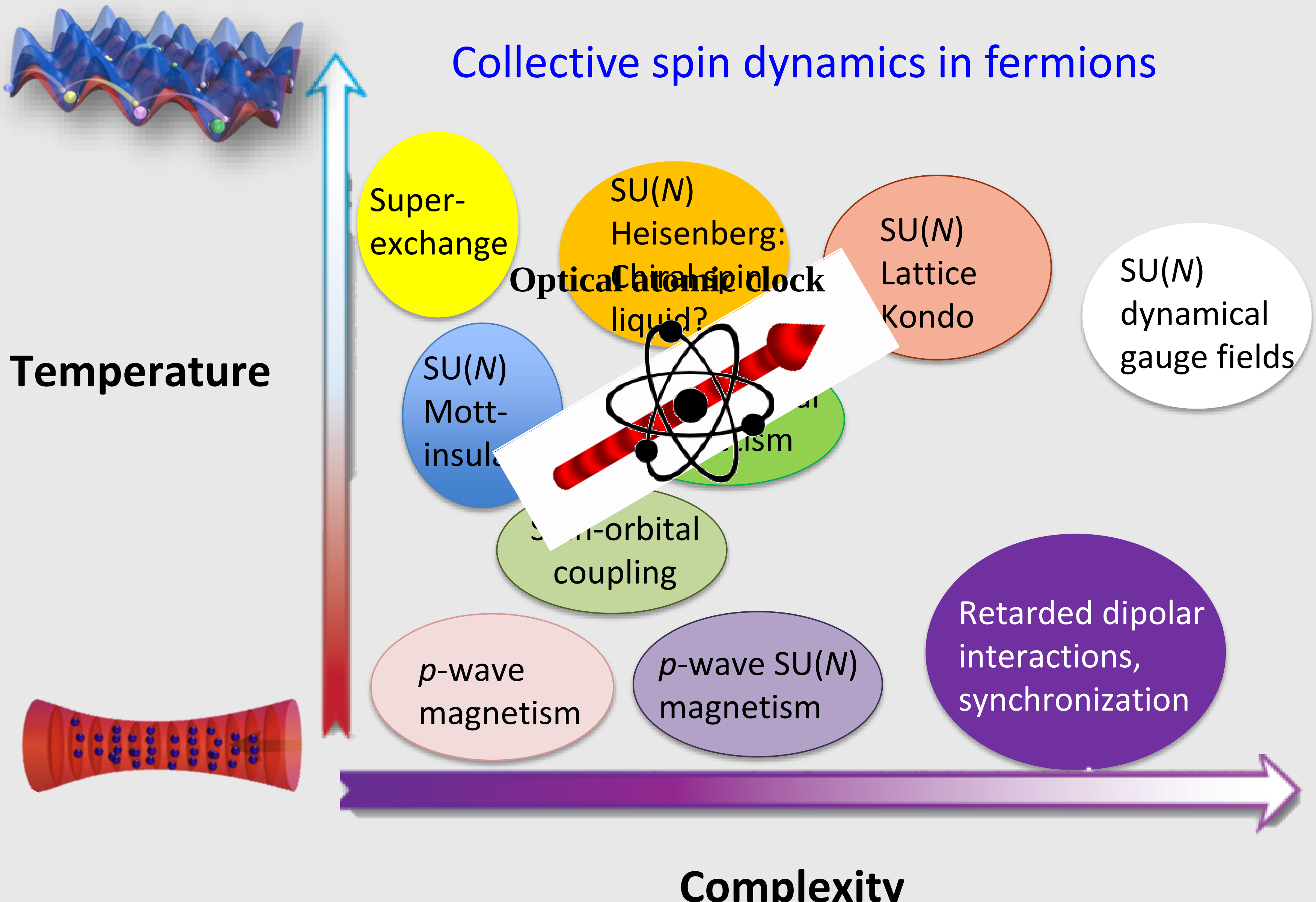


- A deep lattice for ***g*** atoms → Mott insulator for localized spins
- A shallow lattice for few ***e*** atoms → conduction "electrons"
- Tune U_{eg} singlet & triplet interactions for
  a large exchange coupling between ***e*** and ***g*** atoms
- Explore transport properties by tilting the optical lattice

Future explorations are rich

Quantum magnetism under high temperatures

Collective spin dynamics in fermions

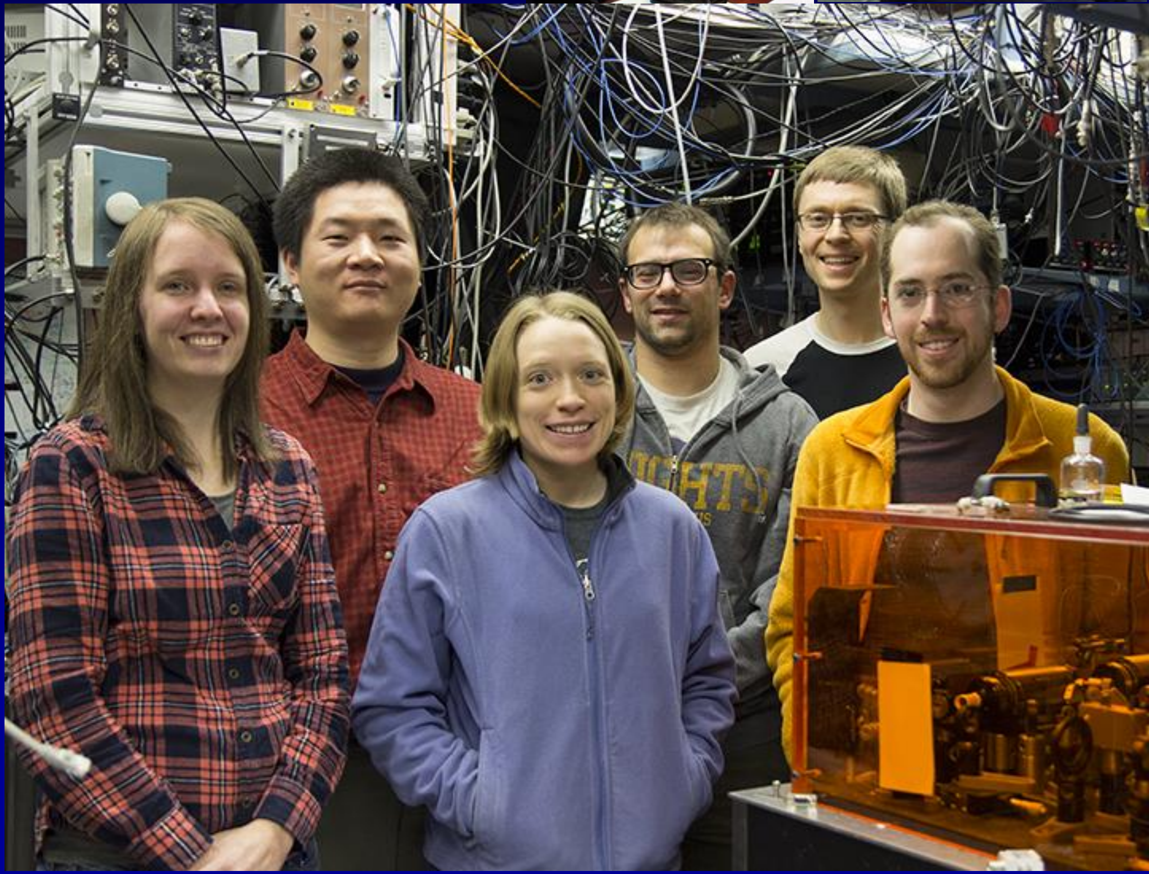


Sr optical clock (10^{-18}) – advancing state-of-the-art

B. Bloom
T. Nicholson
S. Campbell
M. Bishof
X. Zhang
S. Bromley
W. Zhang

Ana Maria Rey

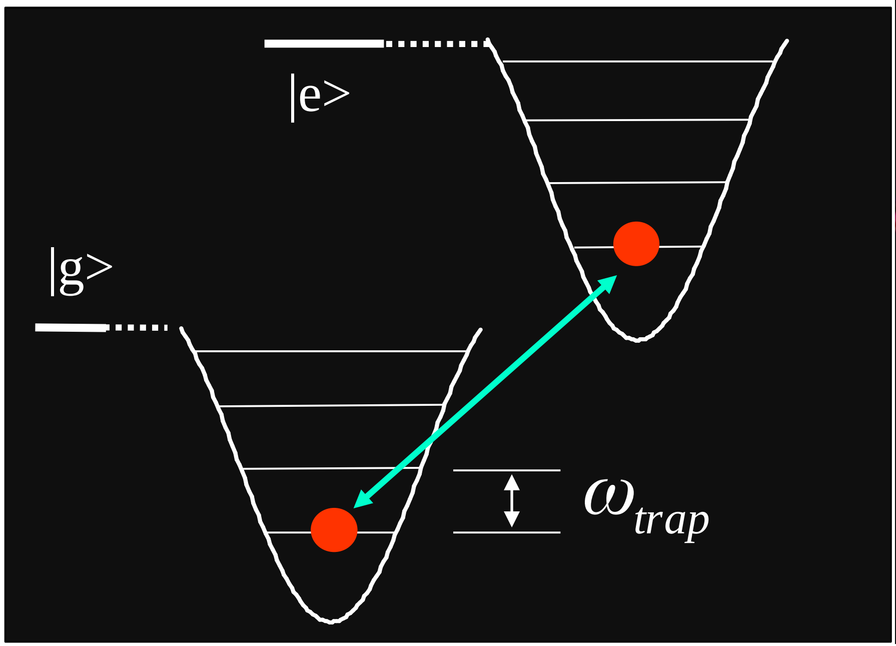
M. Martin (Caltech)
J. Williams (JPL)
M. Swallows (AO Sense)
S. Blatt (Harvard)
A. Ludlow (NIST)
Y. Lin (NIM, Beijing)
G. Campbell (JQI, NIST)
M. Boyd (AO Sense)
J. Thomsen (U. Copenhagen)
T. Zelevinsky (Columbia U.)
T. Zanon (Univ. Paris 13)
S. Foreman (U. San Fran)
X. Huang (WIPM)
T. Ido (Tokyo NICT)
T. Loftus (AO Sense)

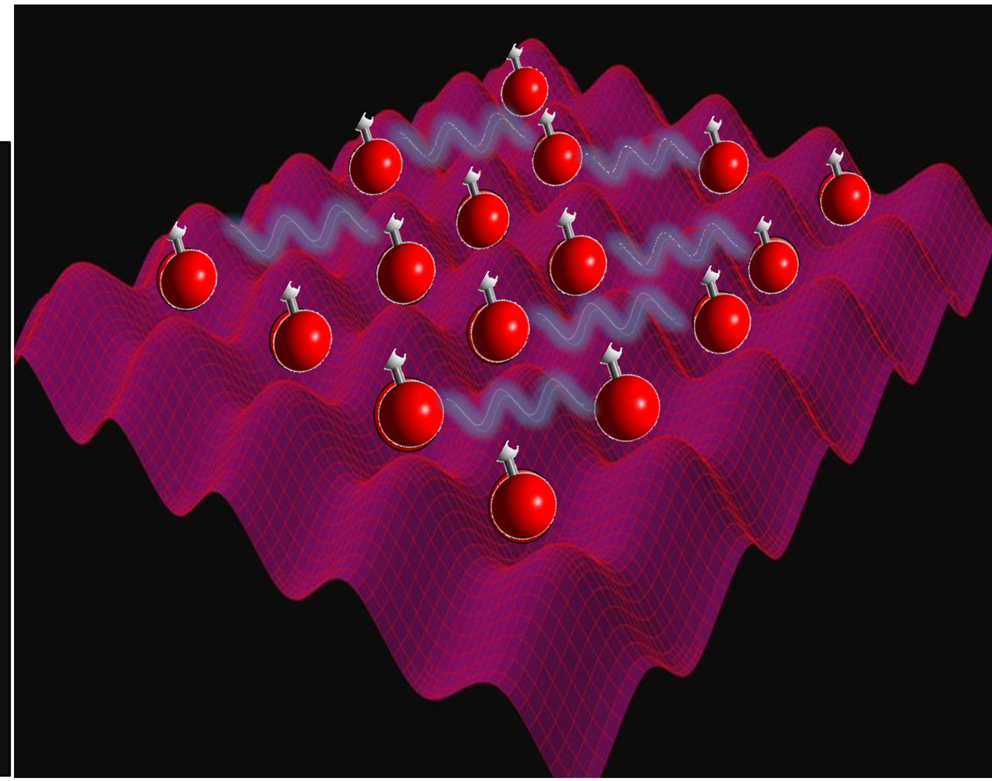


M. Holland, M. Lukin, P. Zoller, P. Julienne, …
NIST Time & Frequency Colleagues

Dipolar collective coupling (retardation, super/sub-radiance) in 3D optical lattice

1 – 10 mHz effect for a unity filled lattice
(10^{-17} – 10^{-18})





- How to control / tune them ?
- How to use them for entanglement, squeezing, correlations ?
- How to explore many-body complex behavior ?