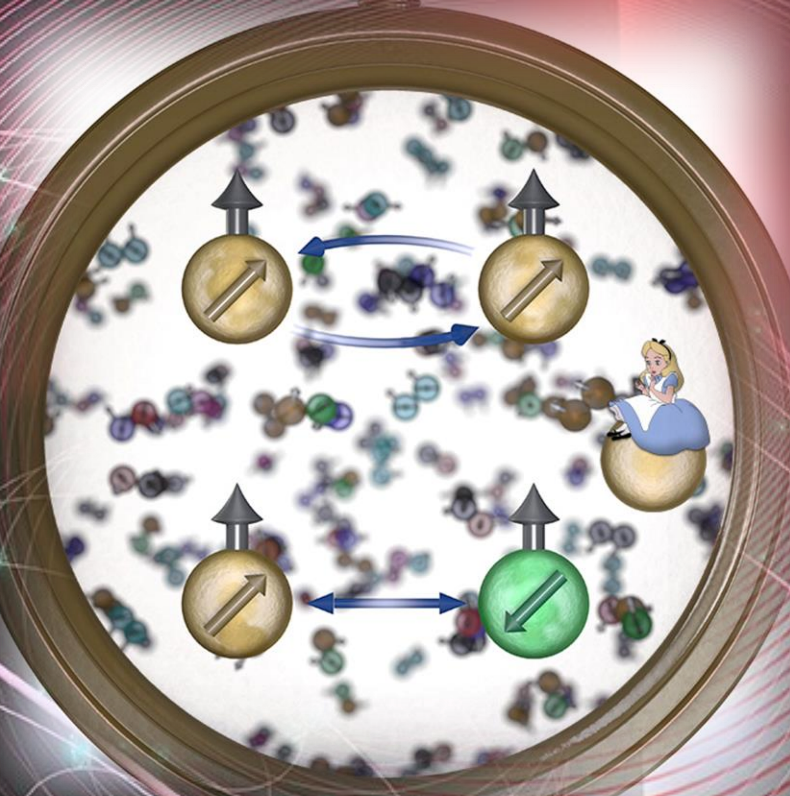
Optical lattice clock & Spin-orbit coupled fermions

Jun Ye
JILA, NIST & Univ. of Colorado

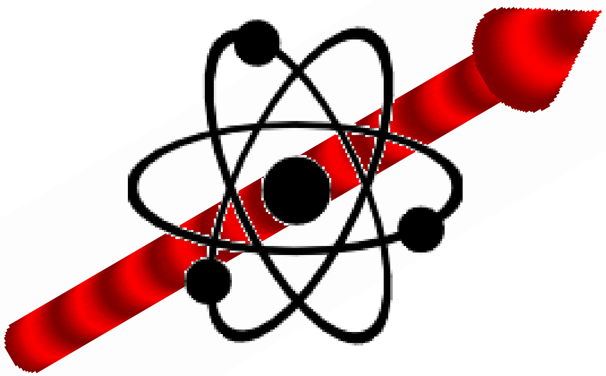


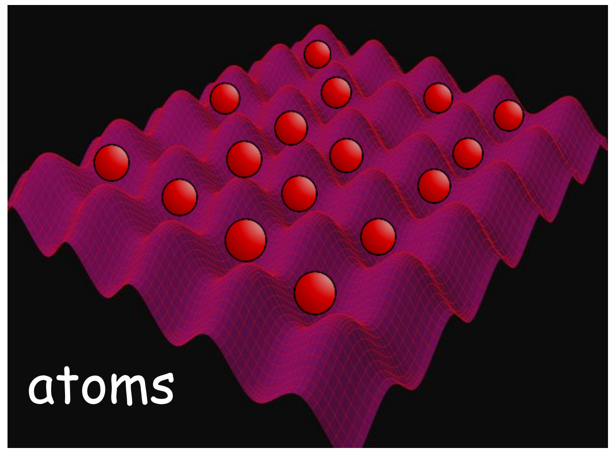
Synthetic Quantum Matter
KITP, Nov. 28, 2016

Scientific vision for clock research

Understand emerging quantum many-body systems

with “clock” precision and control

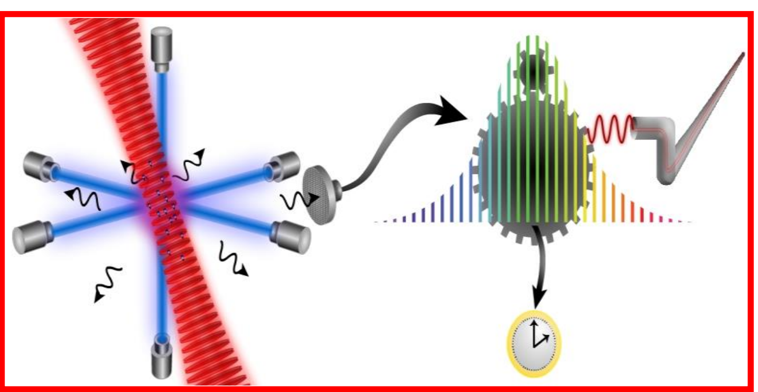




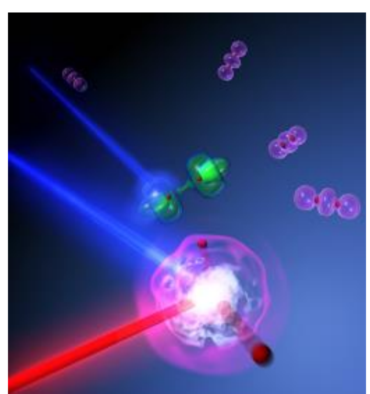
Is there a limit for clock? Or new opportunity for fundamental physics ?

AMO physics - CM, high energy, astrophysics

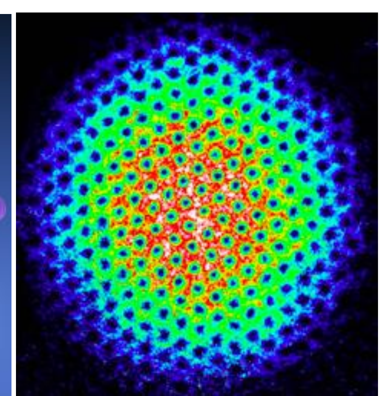
Ultraprecise



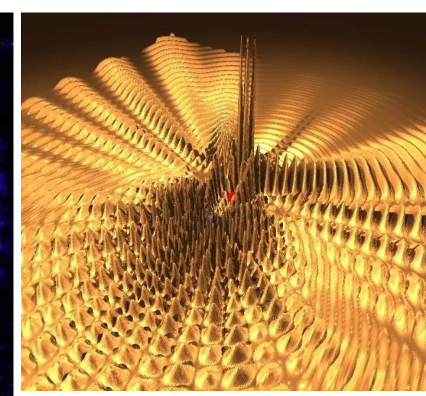
Ultrafast



Ultracold

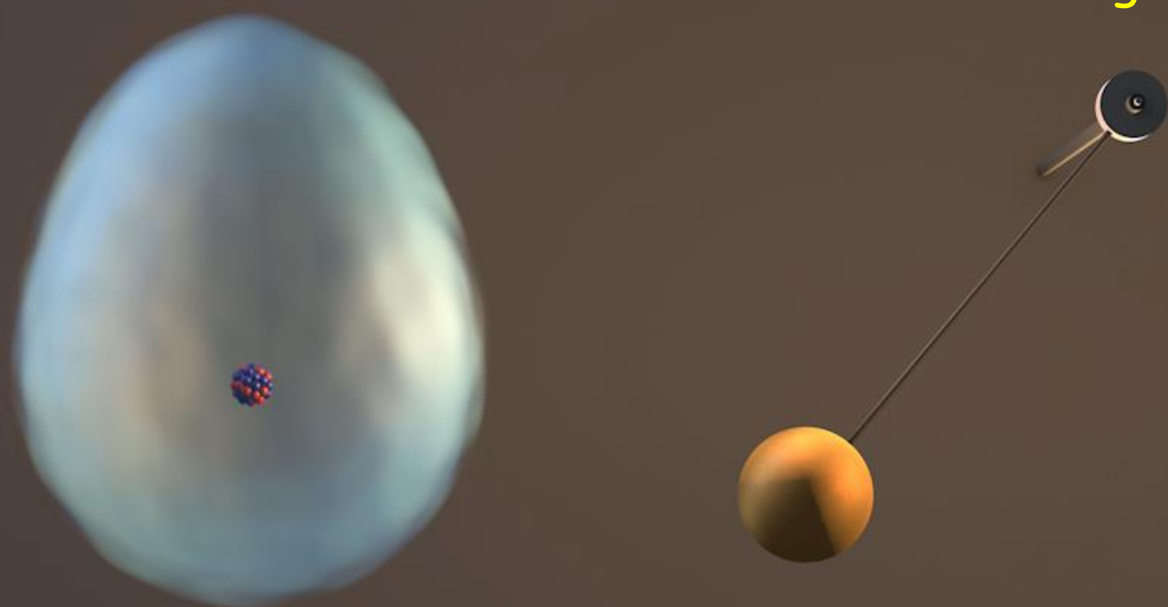


Theory



Nature's high Q oscillator

Once set, it swings during
the entire age of the universe

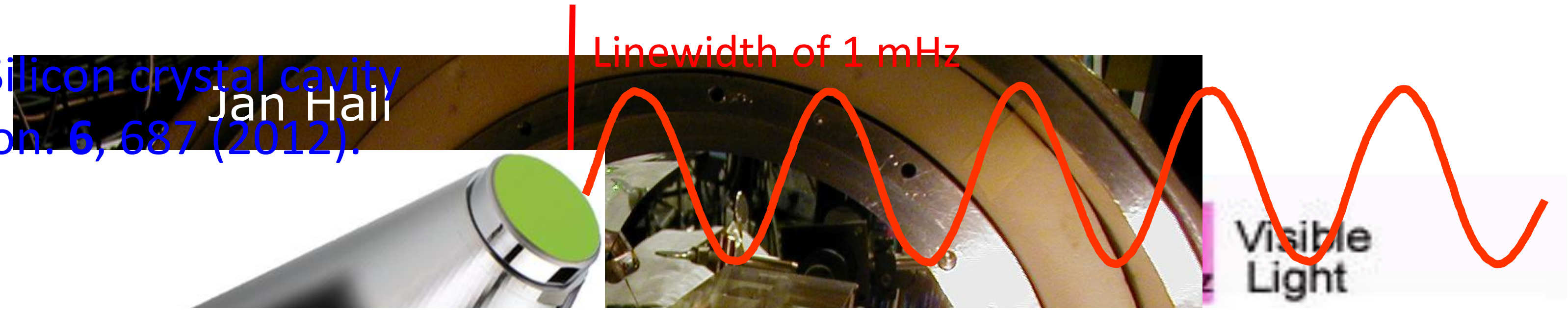


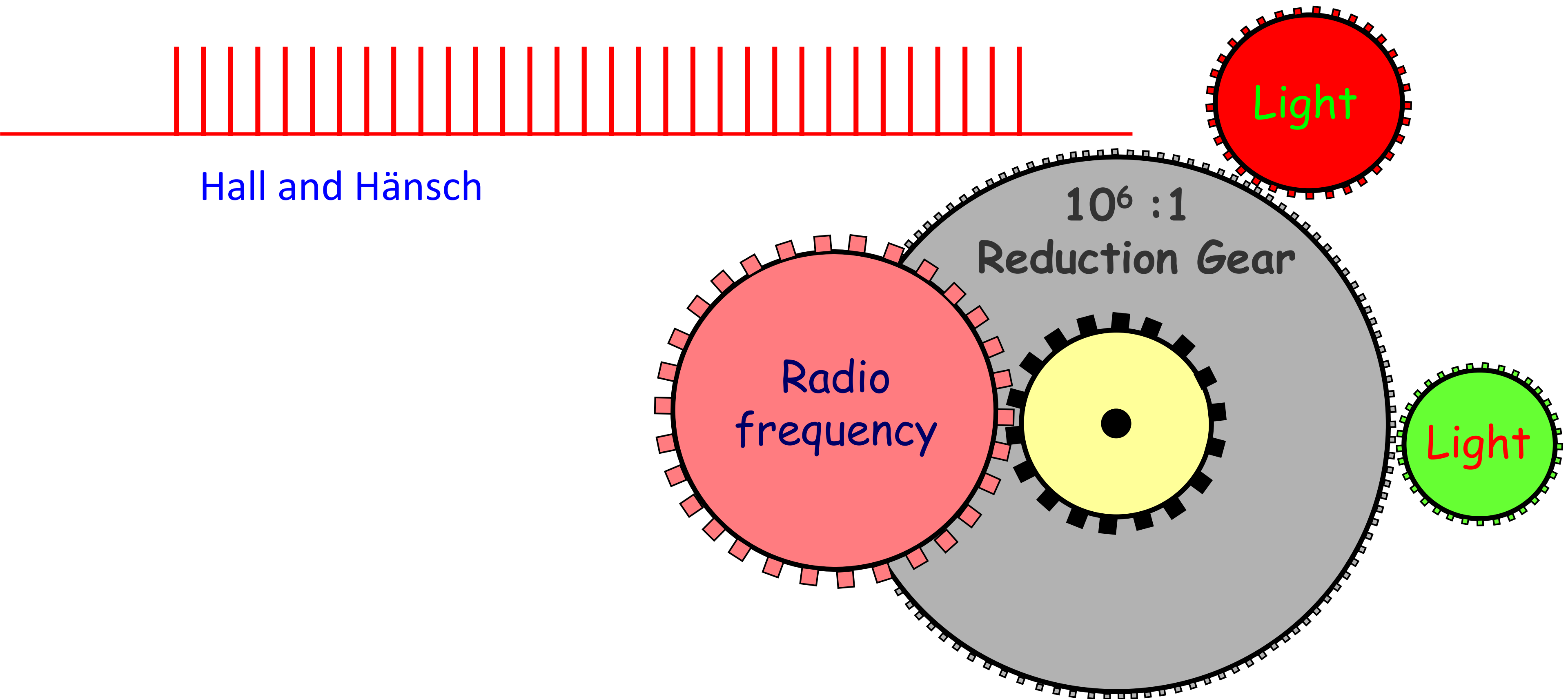
Quality factor > 10^{17}

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

Control of light –
the electromagnetic spectrum

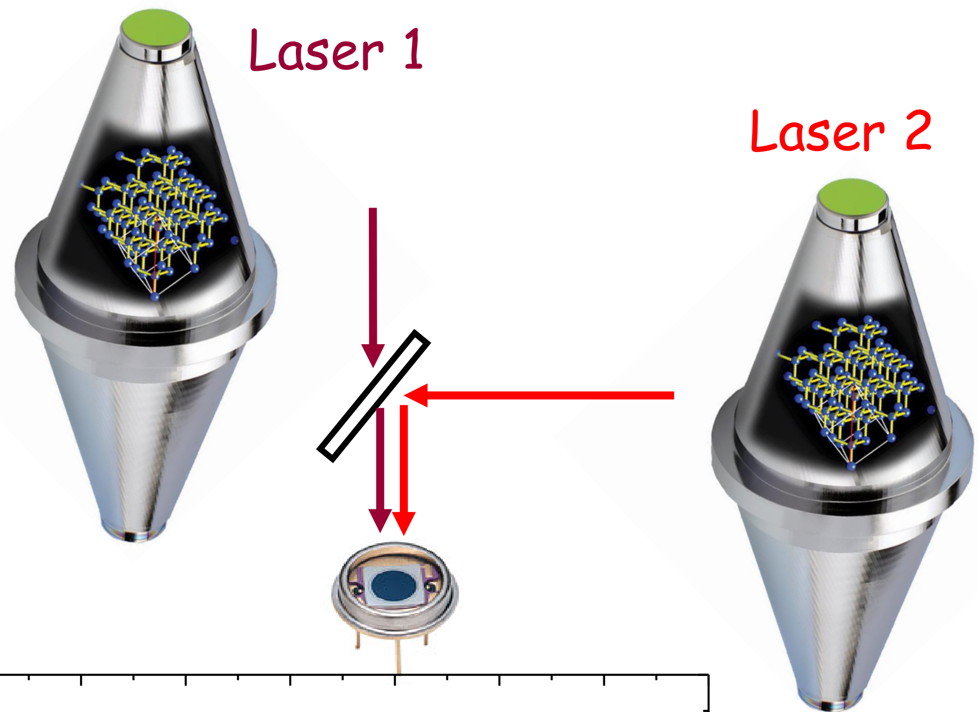
PTB – JILA: Silicon crystal cavity
Nature Photon. **6**, 687 (2012).

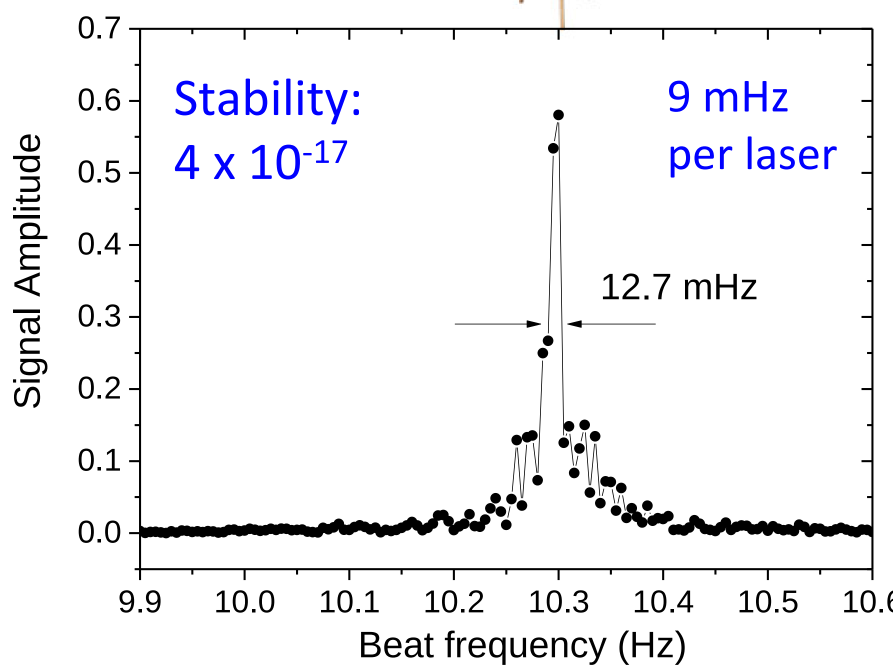




Measurement of coherence > 20 s

Beating of two sound waves (10^3 Hz)

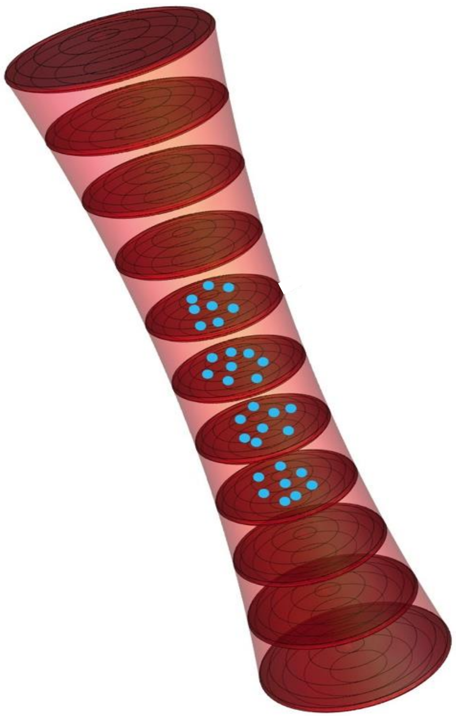


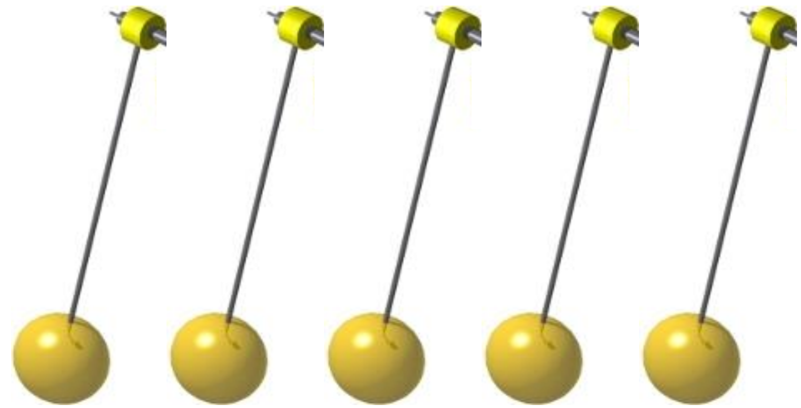


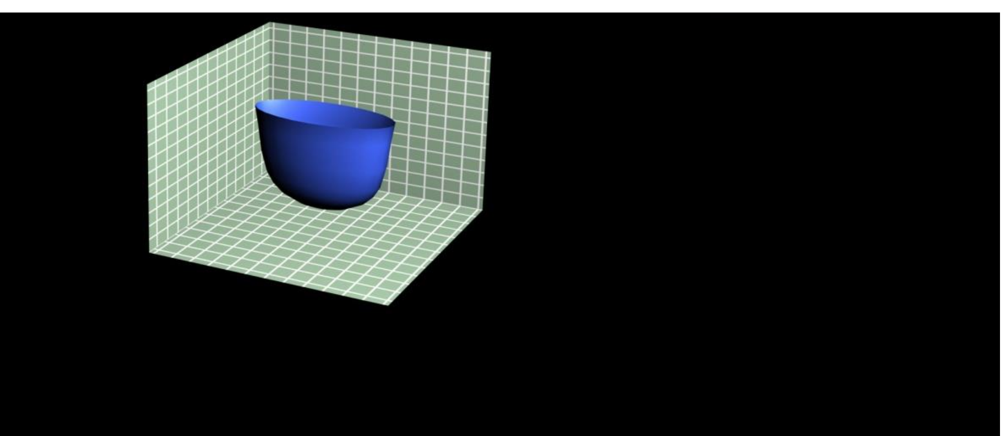
PTB – JILA
2016

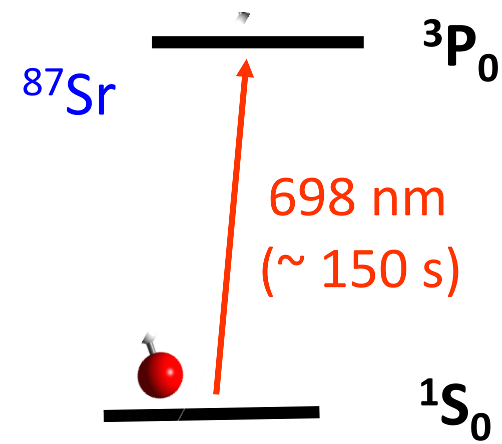
Holding atoms in a magic light bowl

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

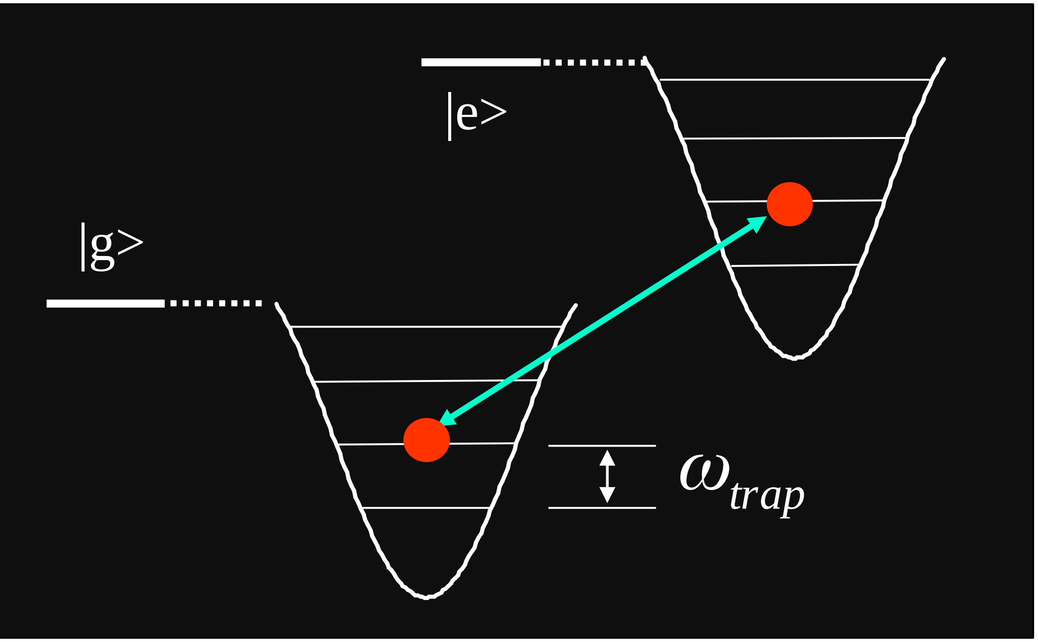


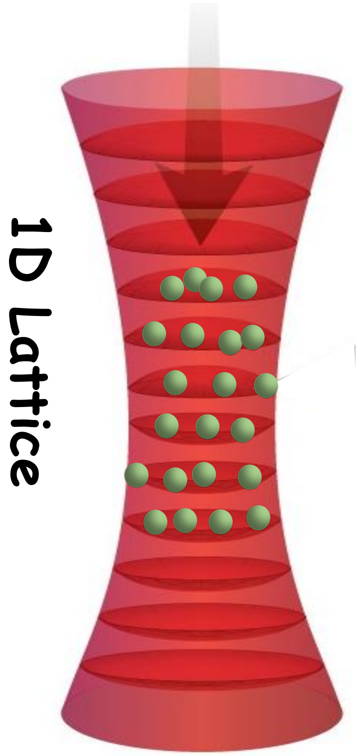


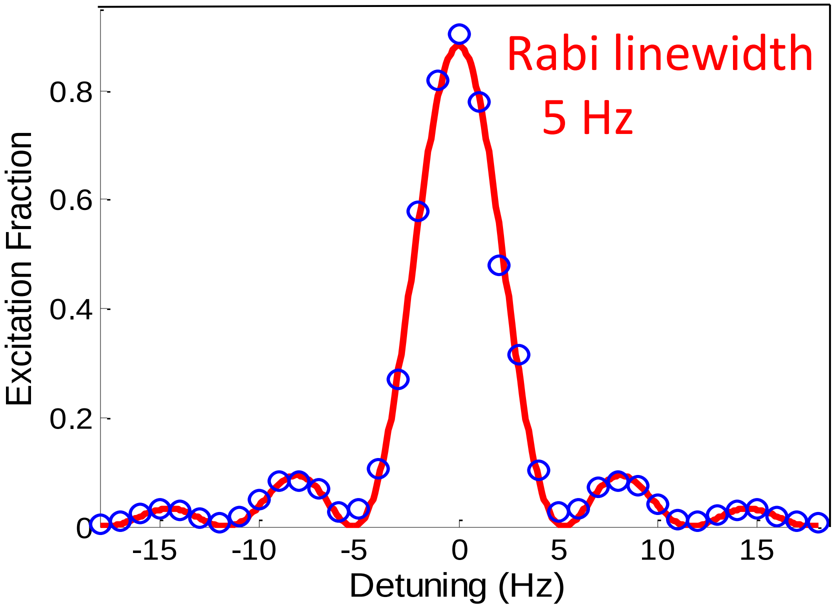




Precision metrology in optical lattice



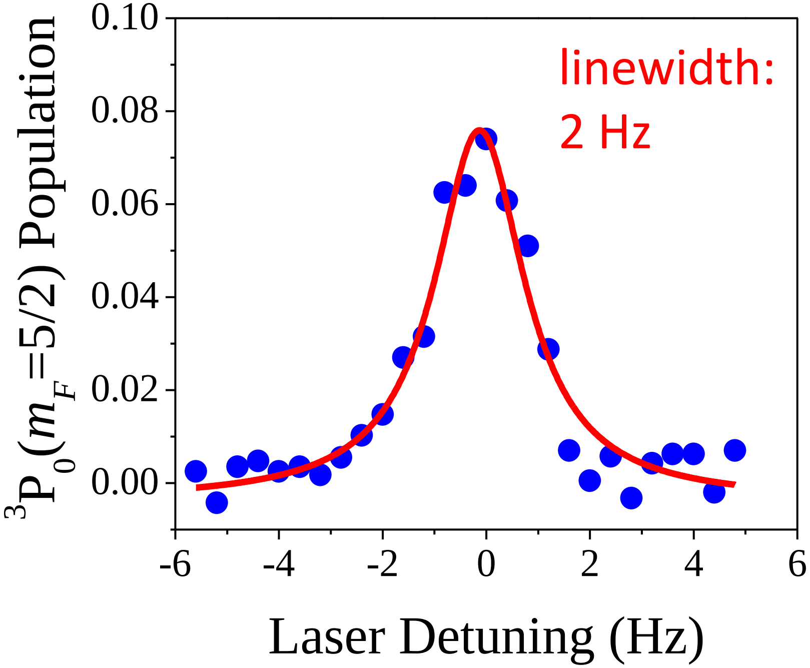




- Precision improvement by $N^{1/2}$
- Doppler & Recoil shifts = 0
- Atomic interaction effects?

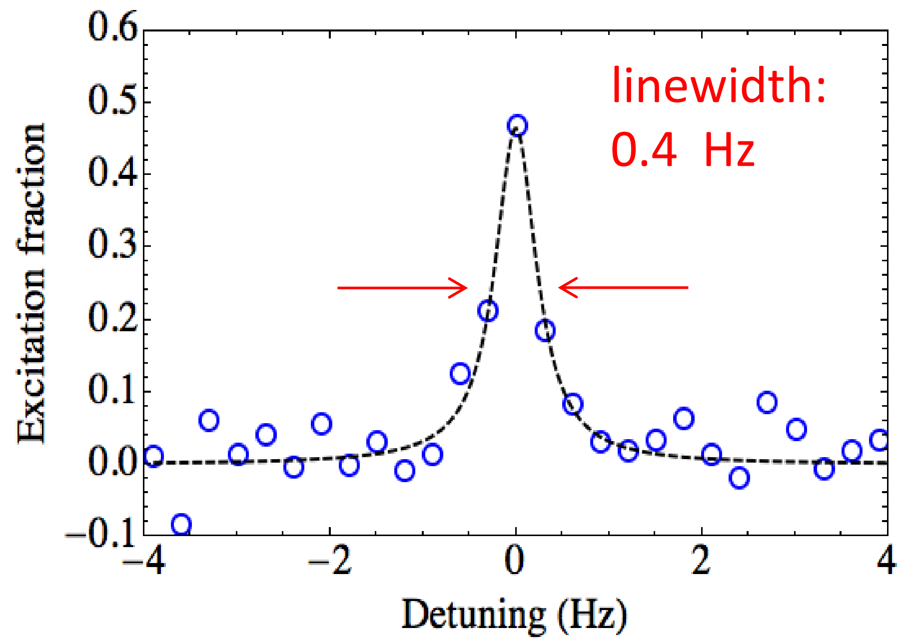
Coherent spectroscopy Q > 1 x 10^{15}

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



2016: Sr linewidth ~0.08 Hz
(Fermi gas 3D lattice)

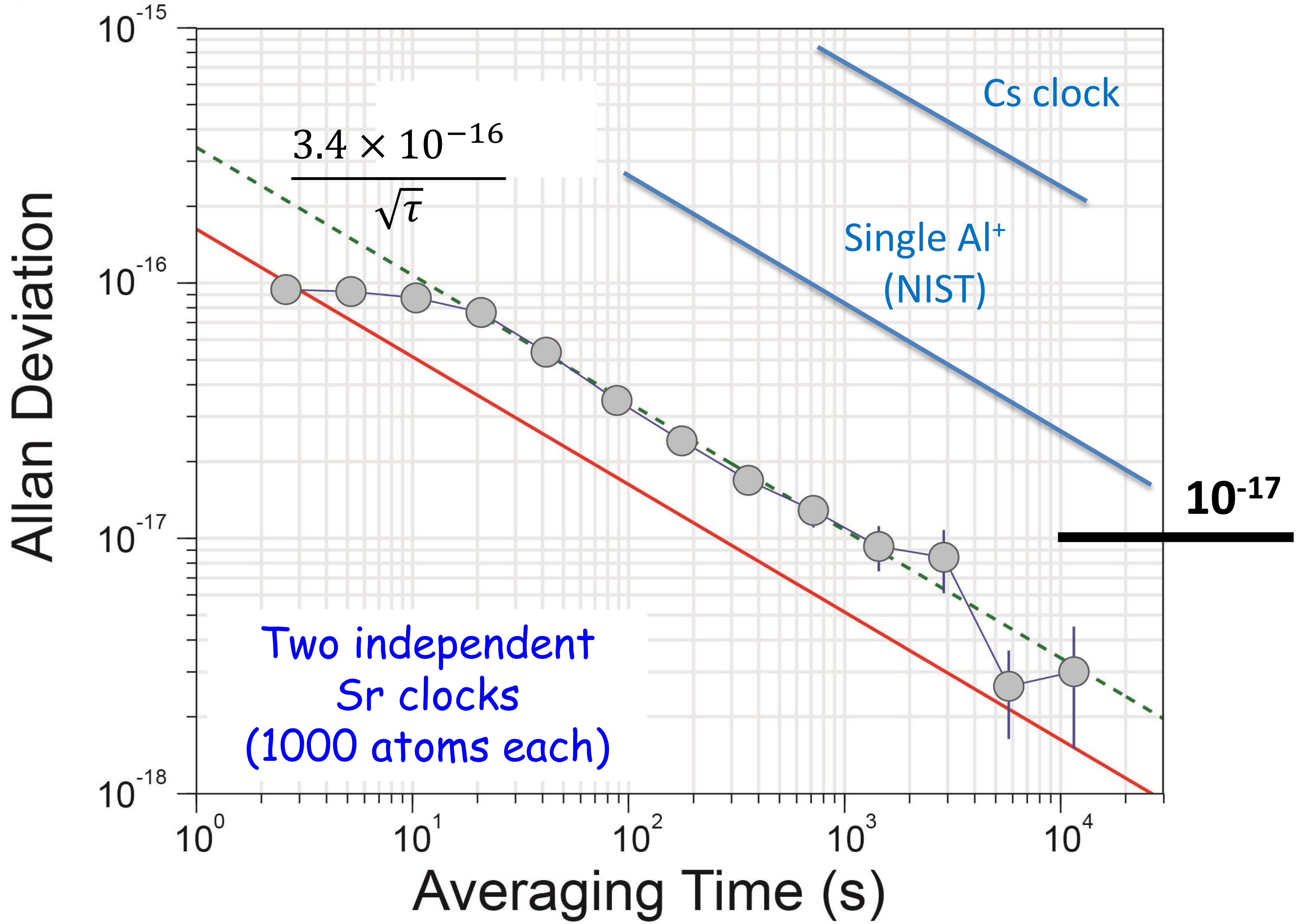
Martin *et al.*, Science **341**, 632 (2013).



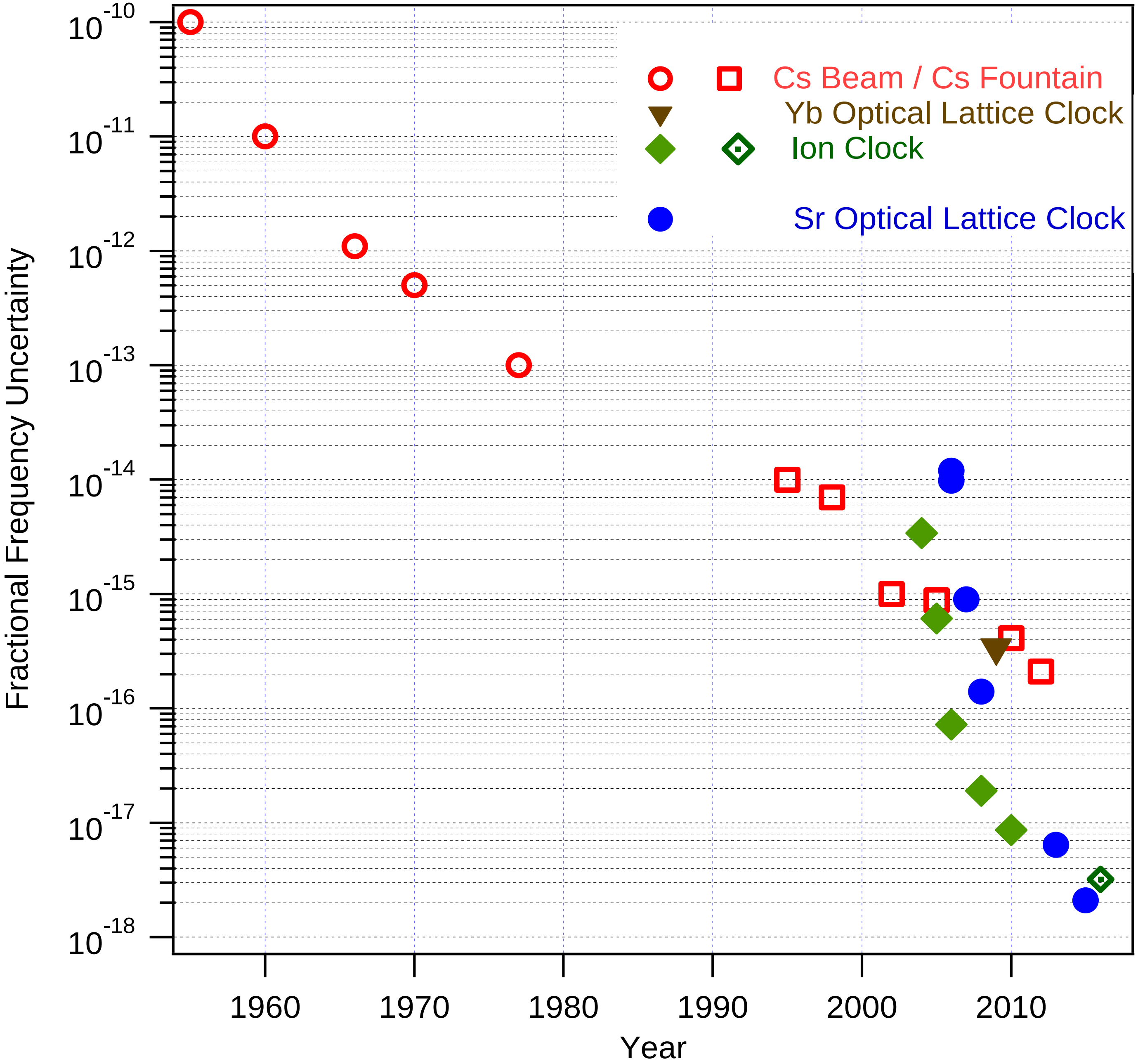
Lattice clock – pushing the clock stability

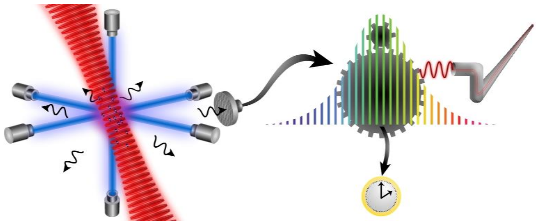
Nicholson *et al.*, PRL **109**, 230801 (2012); Bloom *et al.*, Nature 2014.

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



A new frontier for clock stability & accuracy





JILA Sr Clock II :

lowest uncertainty in atomic clocks: 2.1×10^{-18}

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

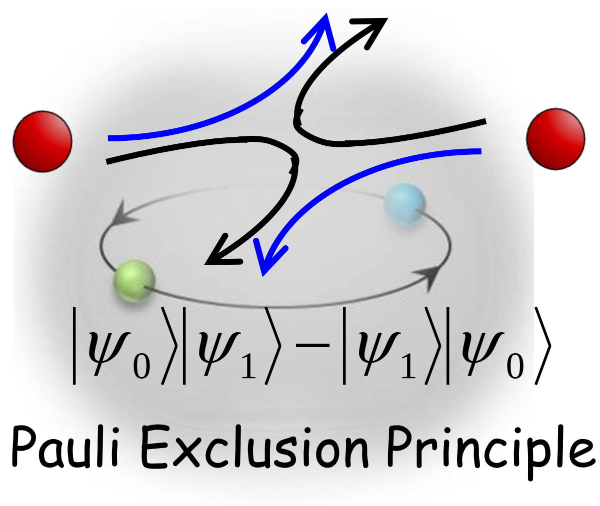
Nicholson *et al.*, Nature Comm. **6** (2015).

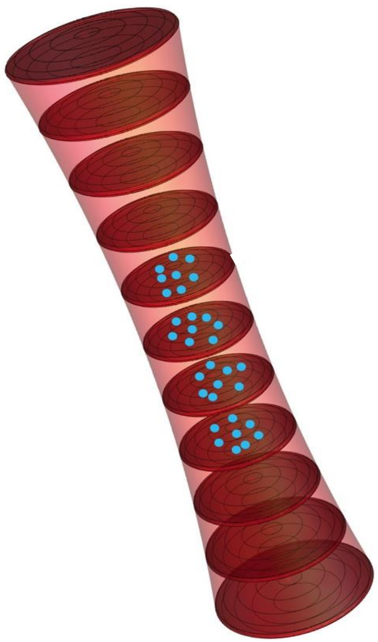
Huntemann *et al.*, PRL **116**, 063001 (2016).

Ultracold fermions: say NO to collisional shifts

Theory: Ana Maria Rey

But … …

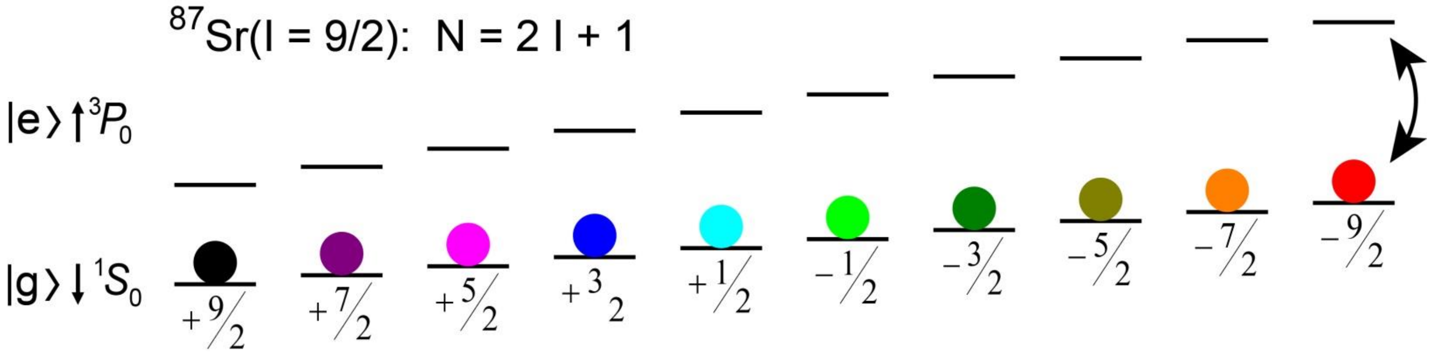




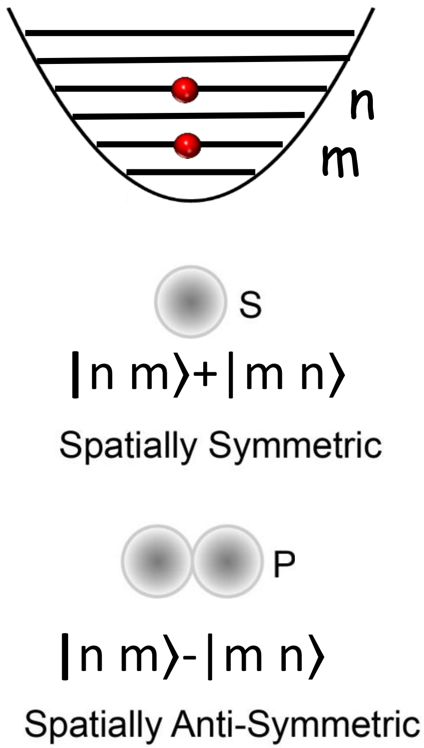
^{87}Sr, at precision ~10^{-15}, zero shift: PRL **98**, 083002 (2007).
First appearance, ~10^{-16}: Science **324**, 360 (2009).
Reduced shift, ~ 10^{-17}: Science **331**, 1043 (2011).
< 10^{-18}: PRL **109**, 230801 (2012).

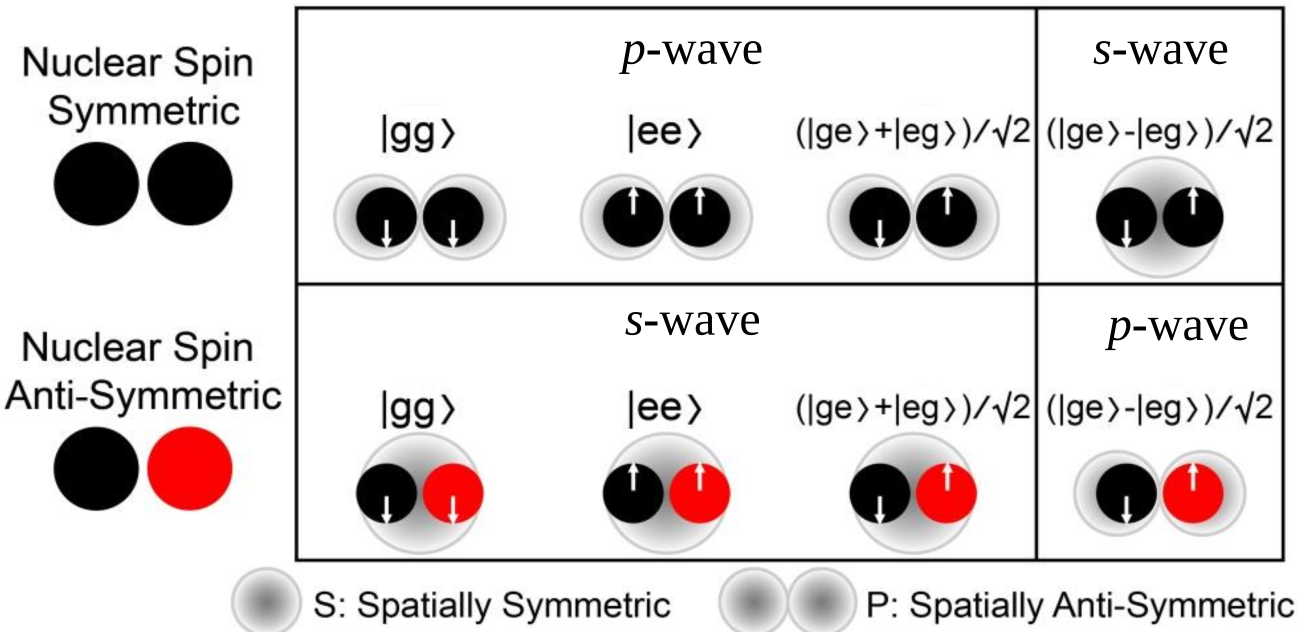
See related work of Yb clock by Ludlow *et al*.

3 degrees of freedom: electronic, nuclear, spatial



hyperfine coupling $I \cdot J = 0.$

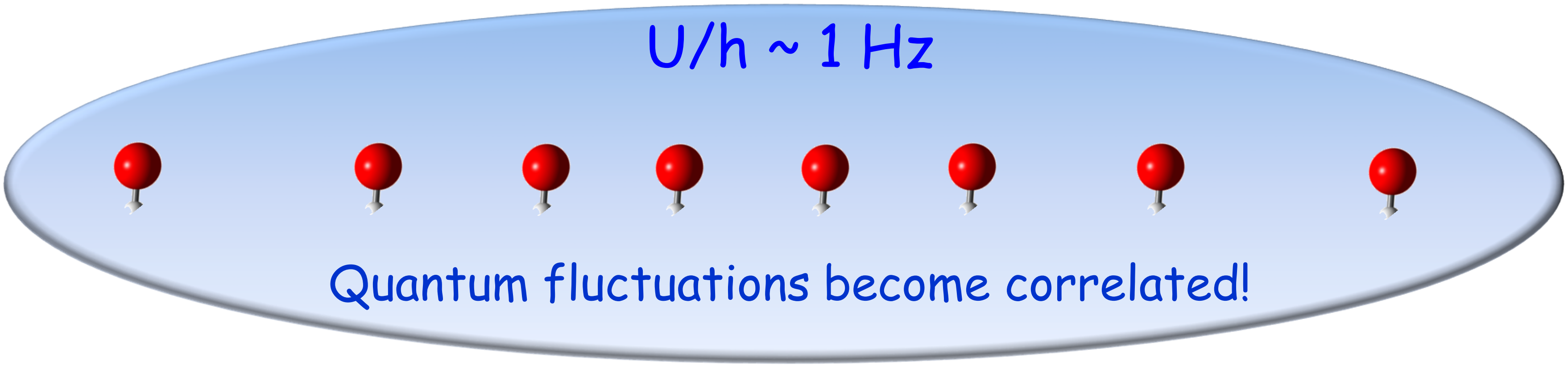


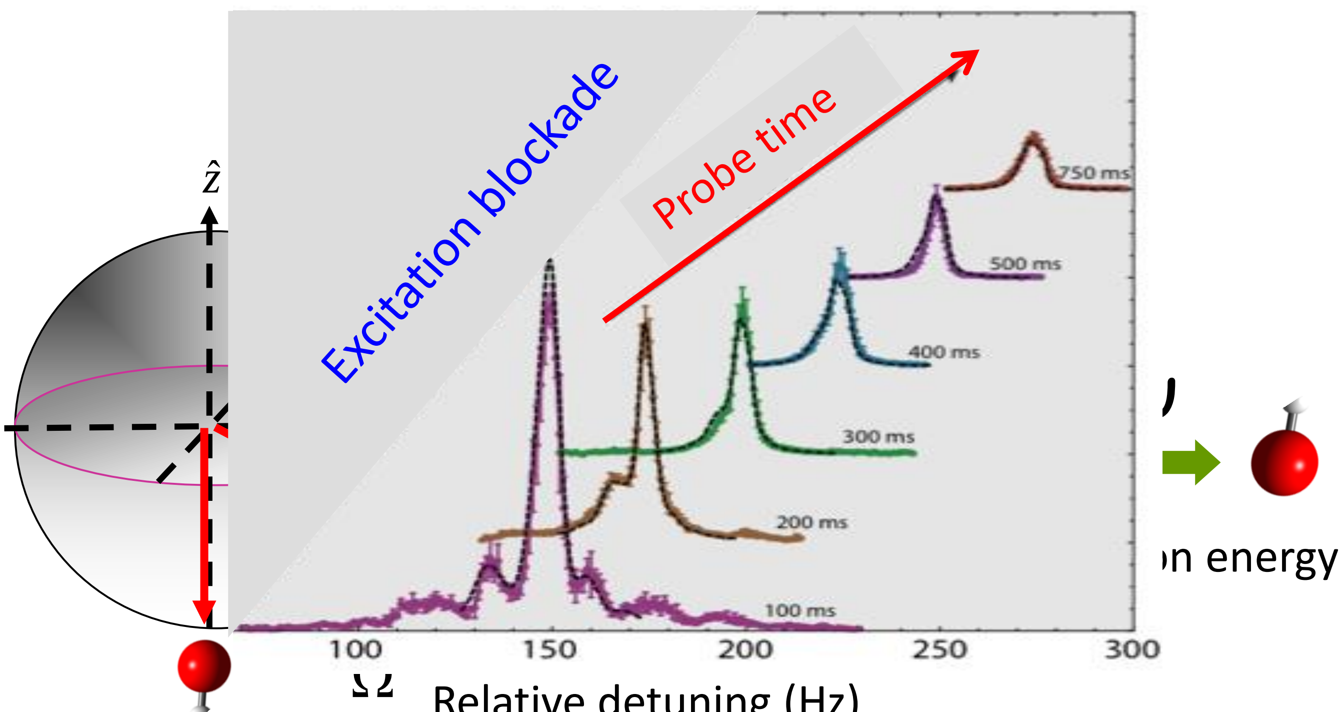


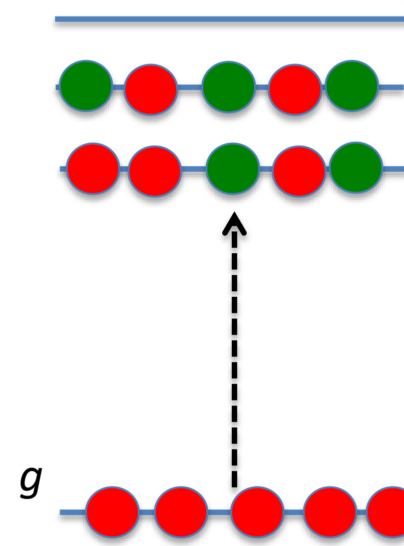
Gorshkov *et al.*, Nature Phys. **6**, 289 (2010).

Clock probe of many-body spin dynamics

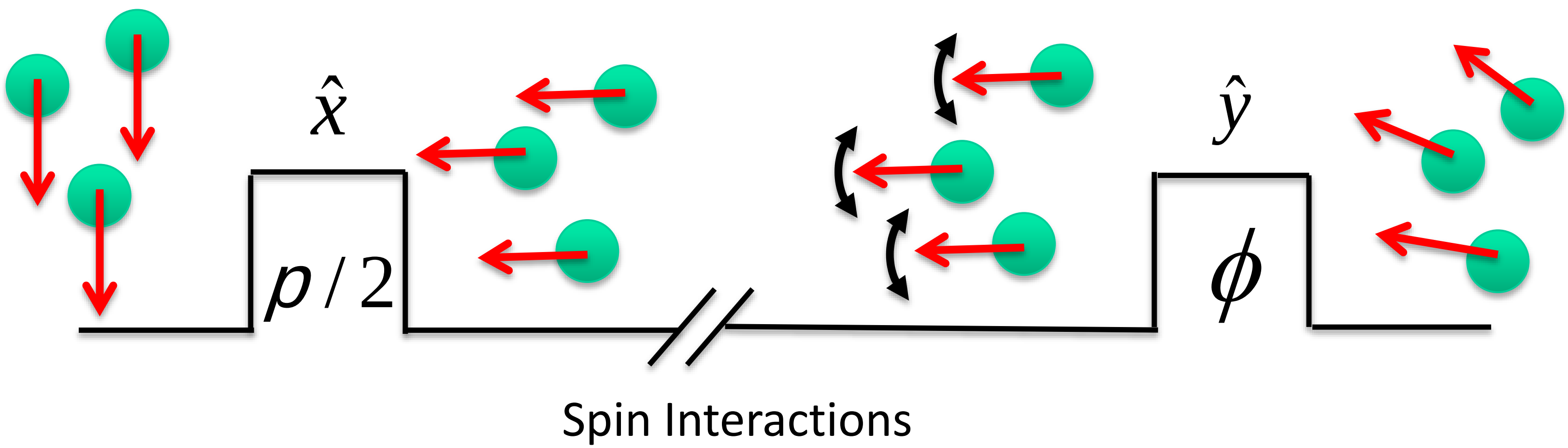
Martin *et al.*, Science **341**, 632 (2013).

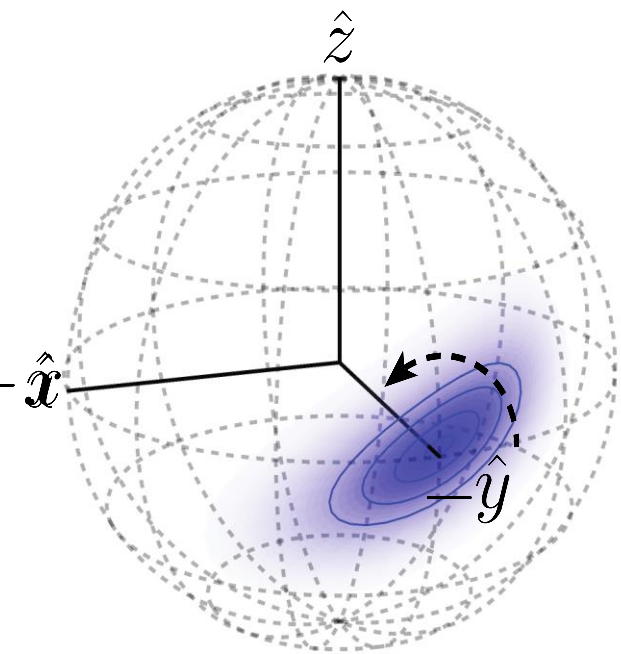


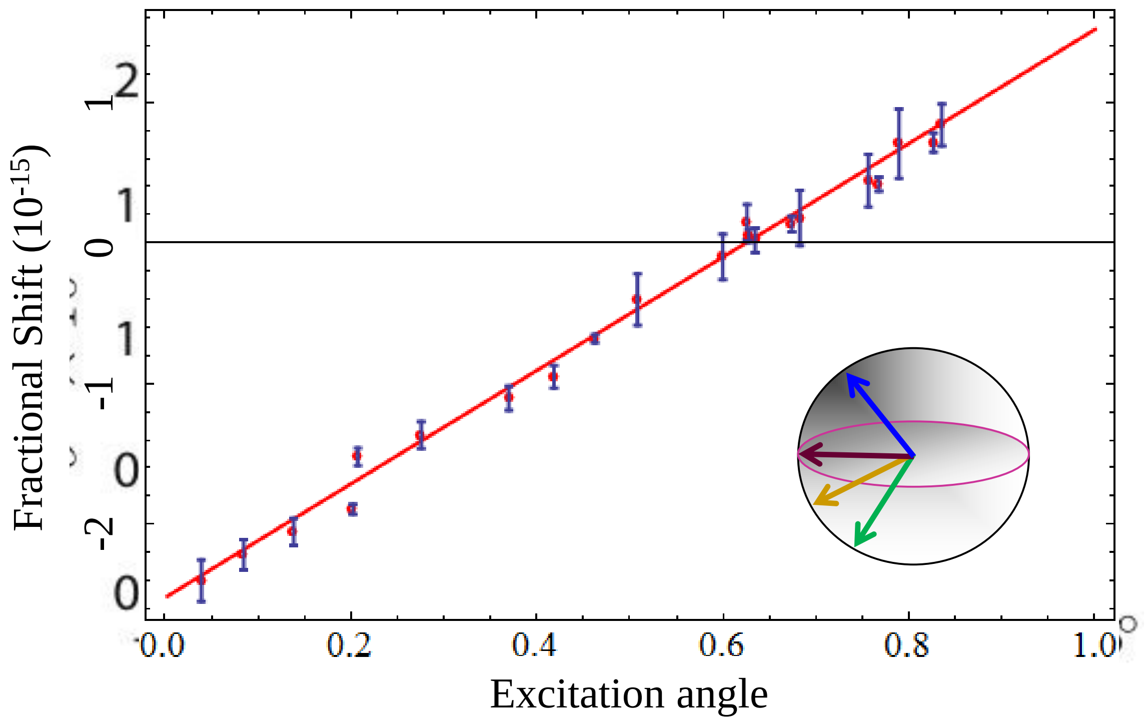




Ramsey spectroscopy for spin correlations

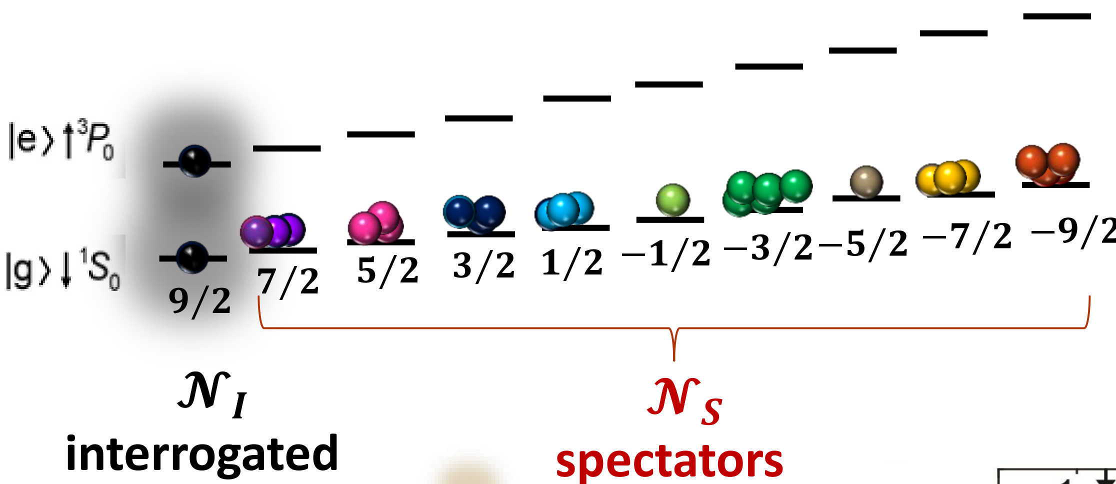




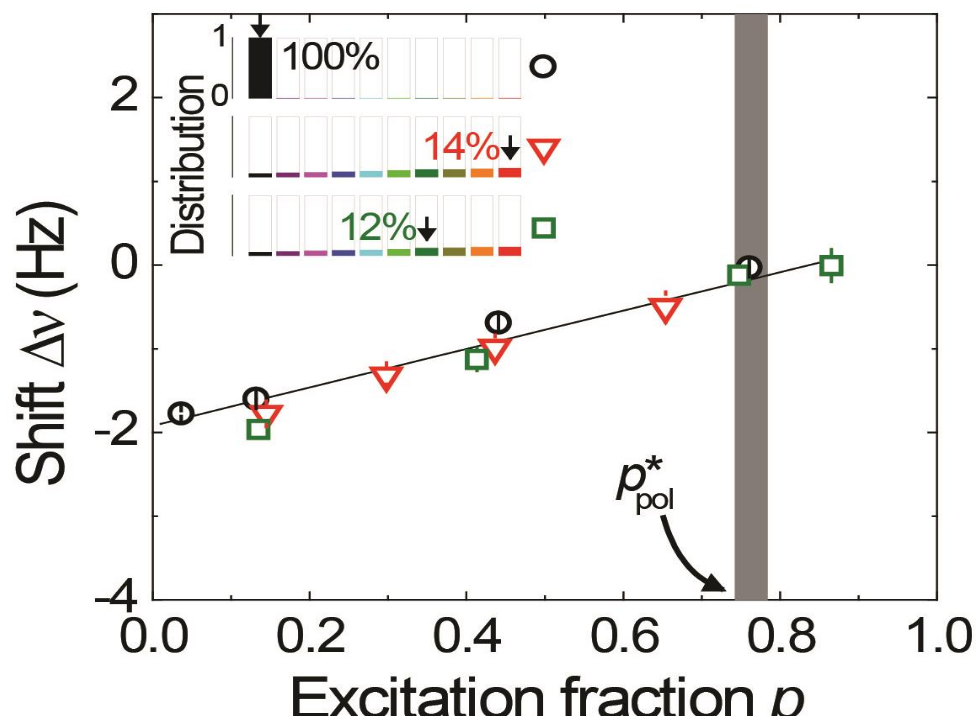


Density shifts & SU(N) symmetry

Zhang *et al*., Science **345**, 1467 (2014). Fallani, Inguscio (2014); Fölling, Bloch (2014)

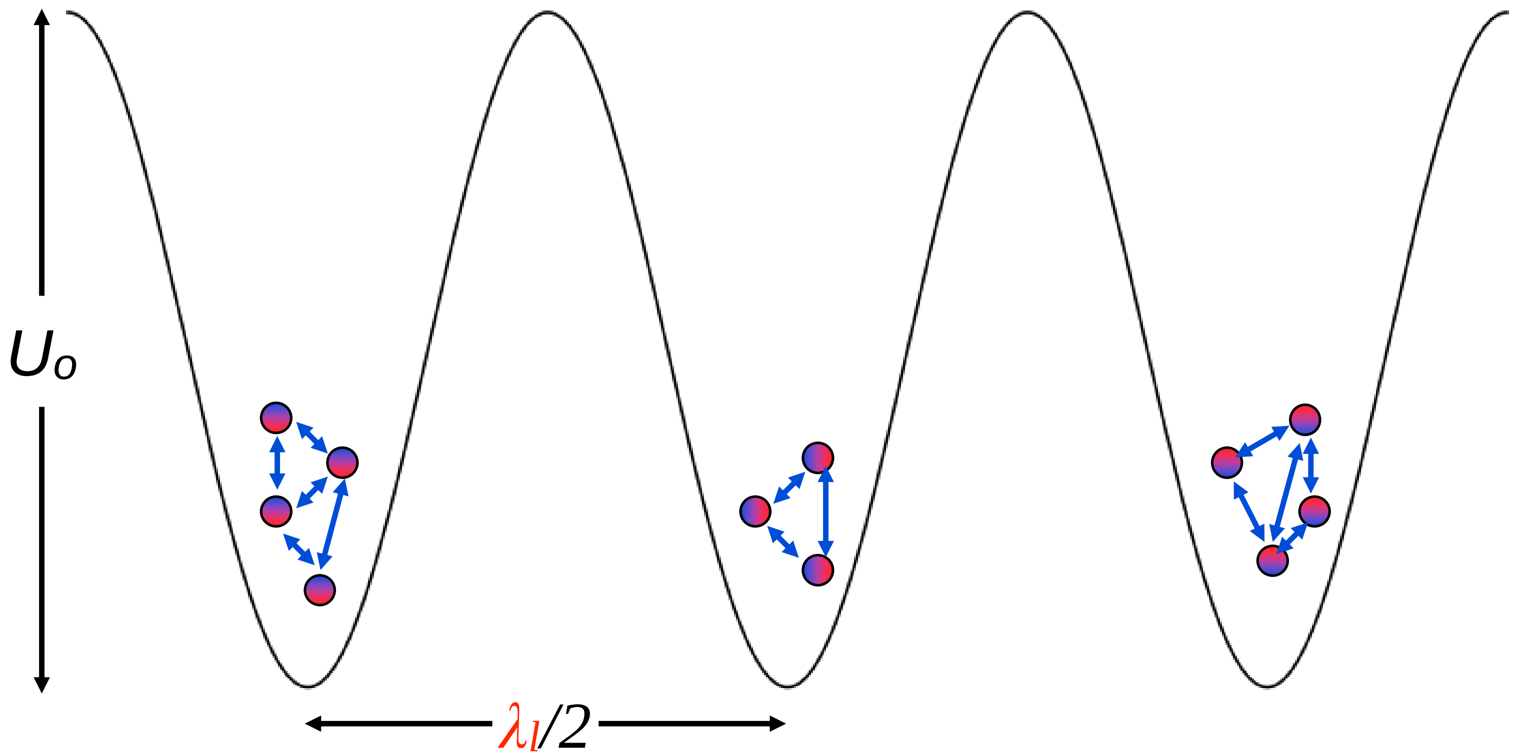


SU(N): shift depends only on $\mathcal{N}_S$, not distributions



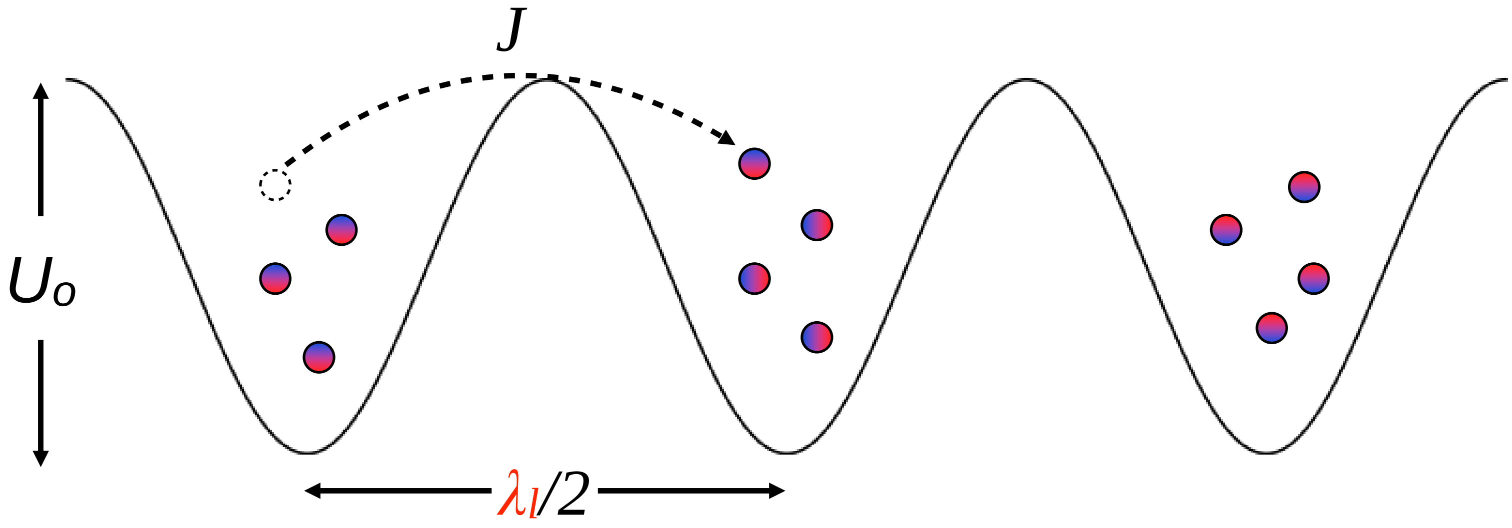
So far, single site interactions

- Identical fermions, *p-wave* collision dominates
- Multiple nuclear spins, *s*- and *p*-waves under SU(N)



$U_o >> E_R$:   Tunneling negligible

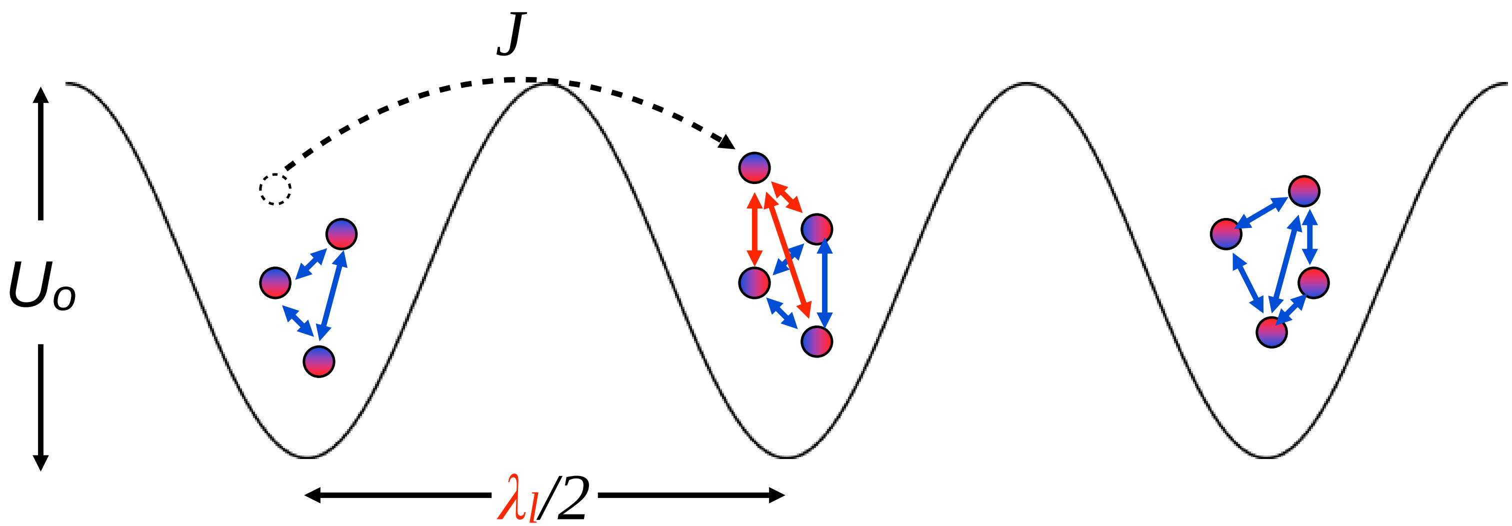
Setting atoms free



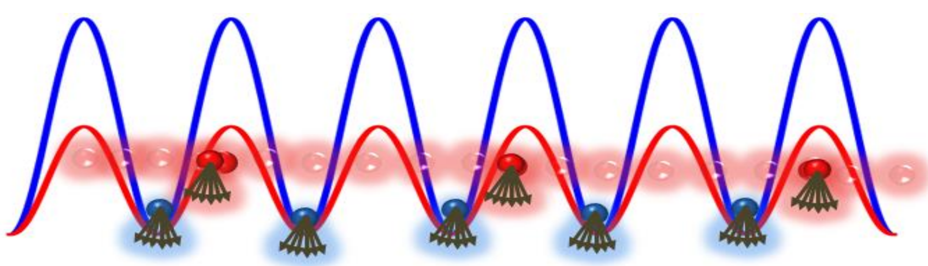
$U_o \sim E_R$:   Tunneling at rate J

A new regime for interactions

Tunneled atoms distinguishable, *s*-wave collisions allowed.

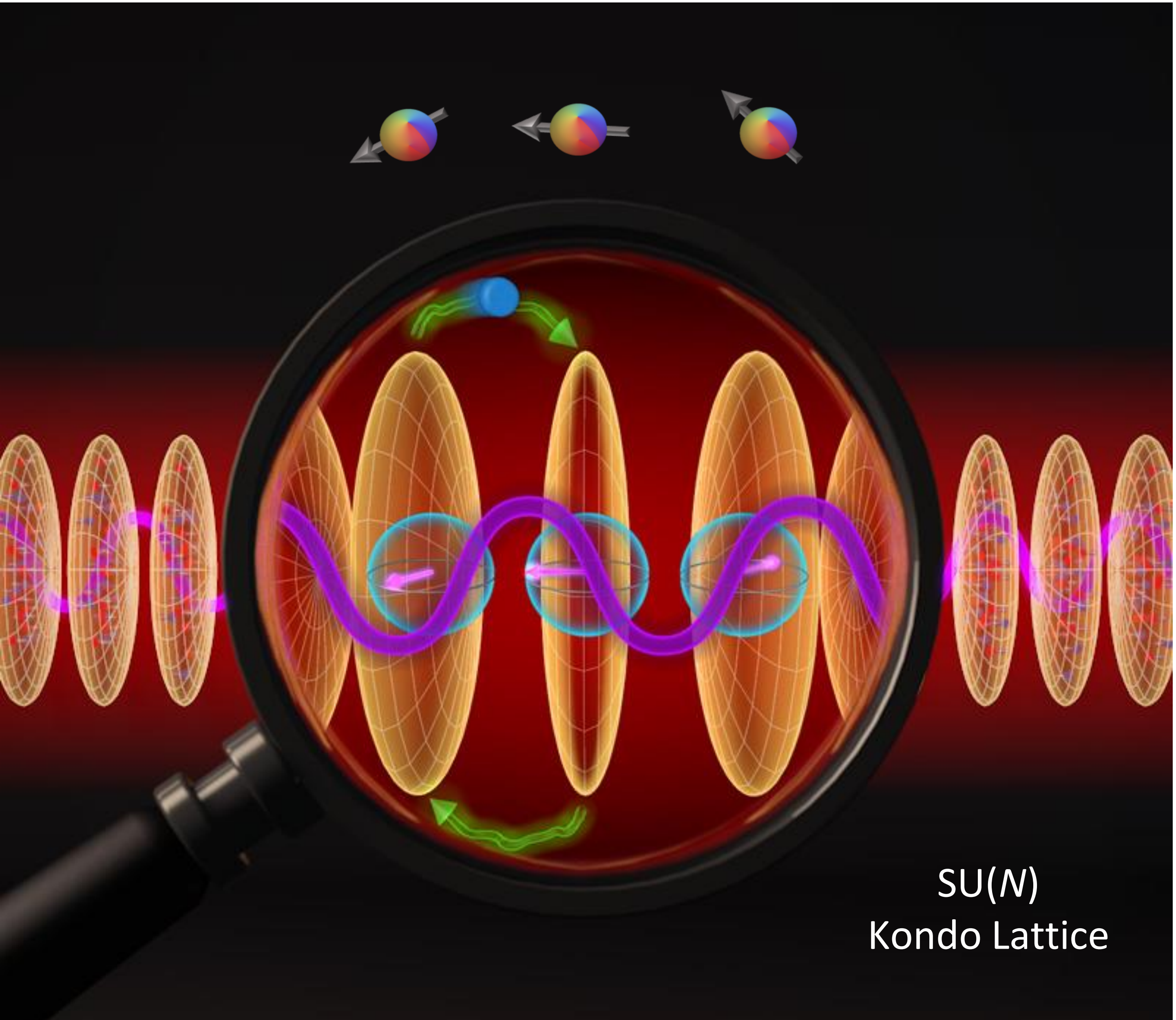


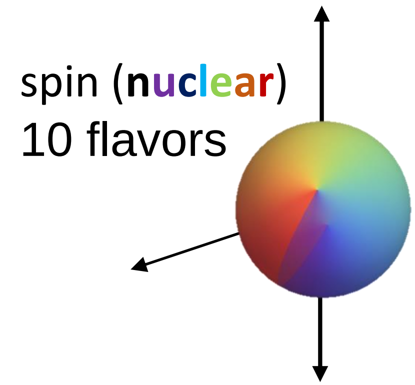
SU(*N*)
Kondo Lattice



Exploring SU(*N*) & spin-orbital coupling

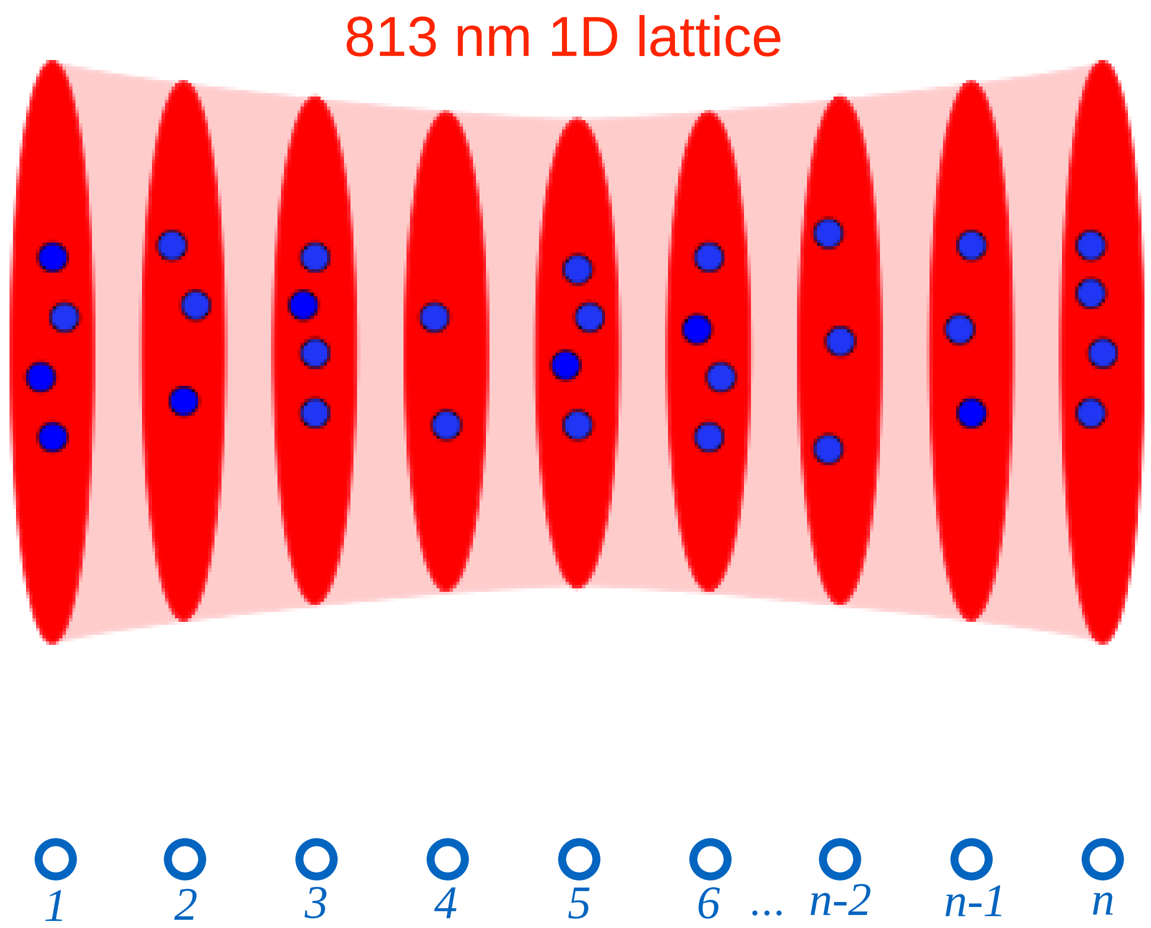
Wall *et al.*, PRL **116**, 035301 (2016); Kolkowitz *et al.*, Nature, in press (2016).



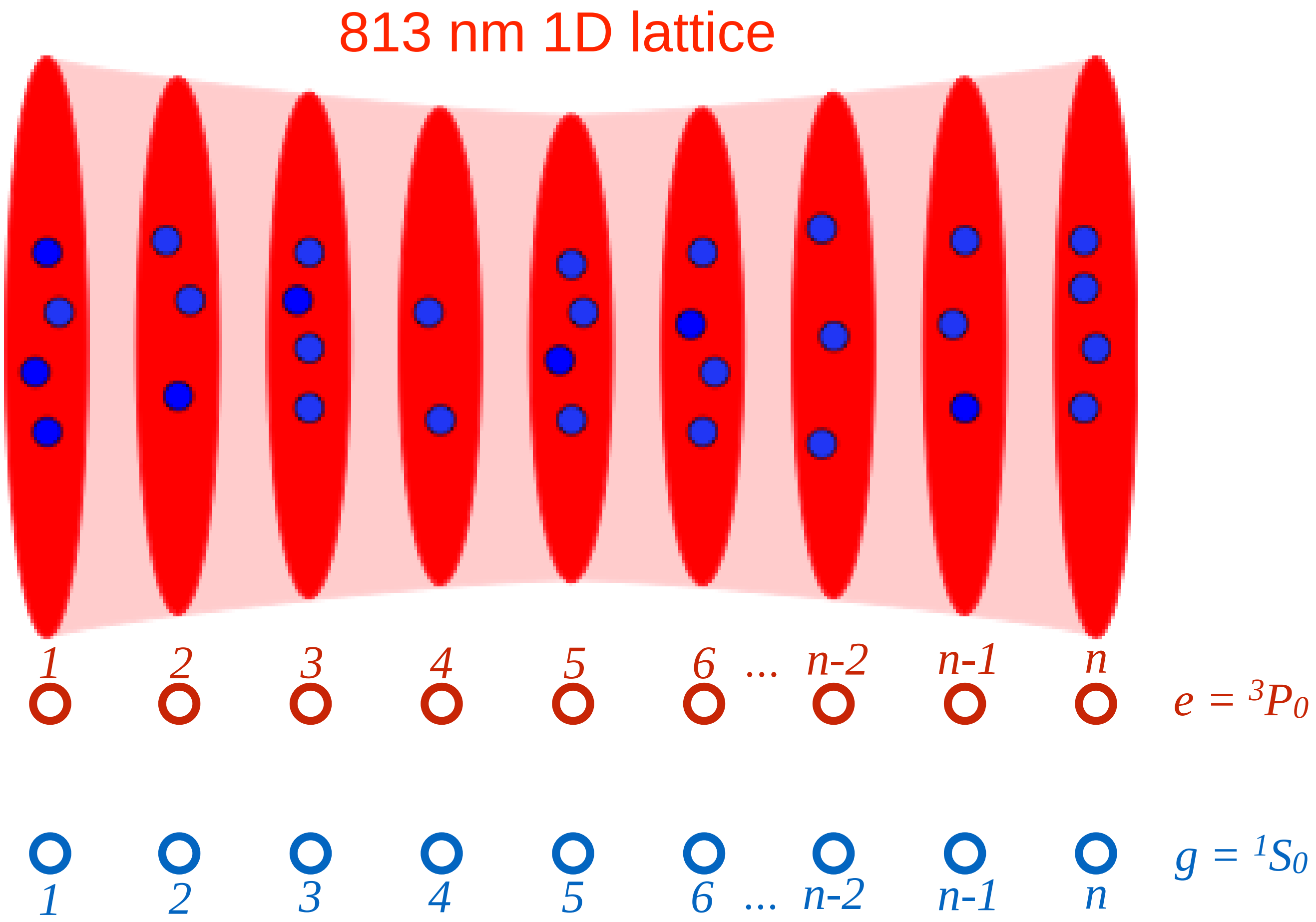


Related work in Yb:
Inguscio/Fallani,
arXiv:1609.04800

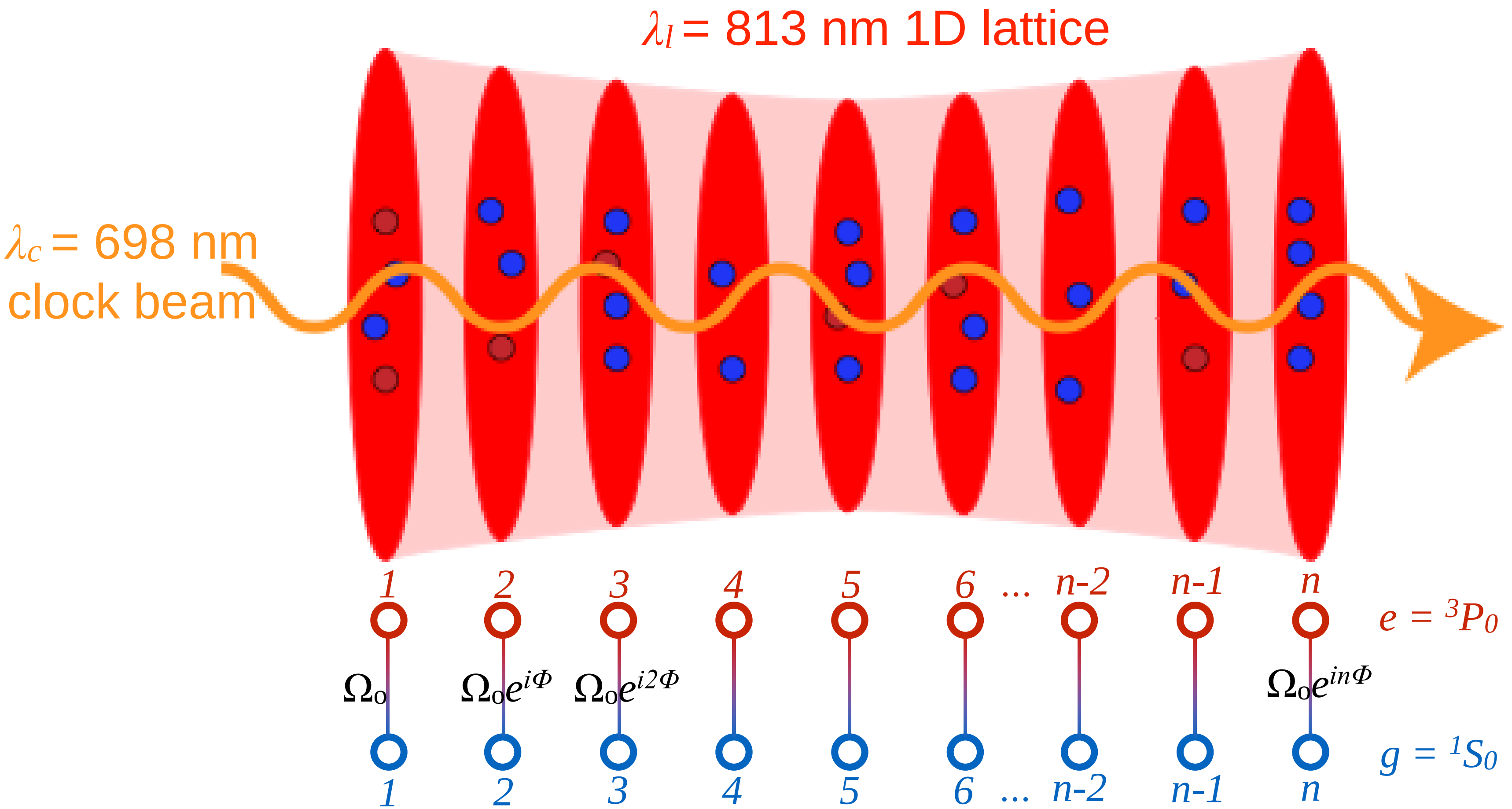
Synthetic magnetic field in the clock



Synthetic magnetic field in the clock

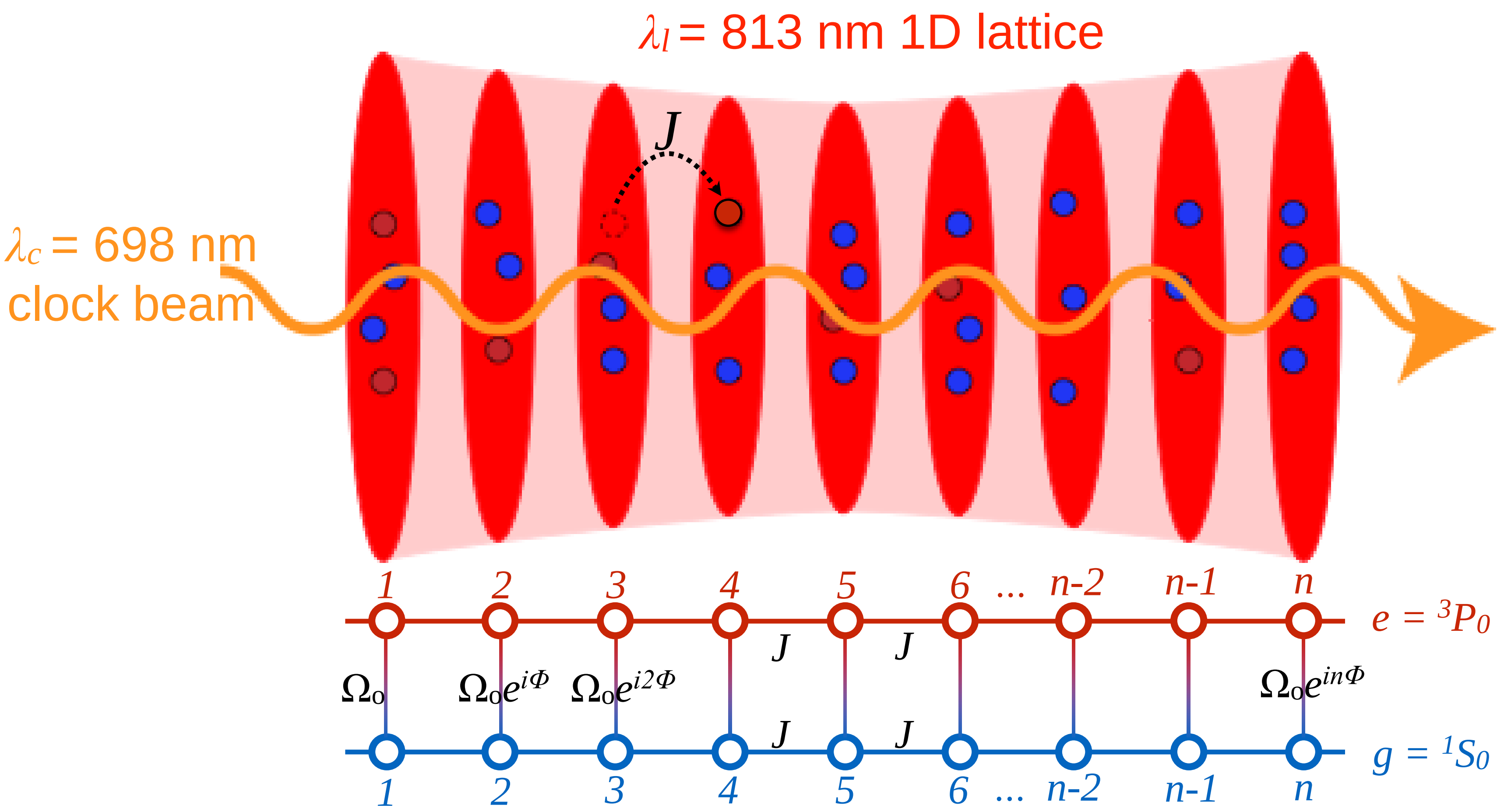


Synthetic magnetic field in the clock



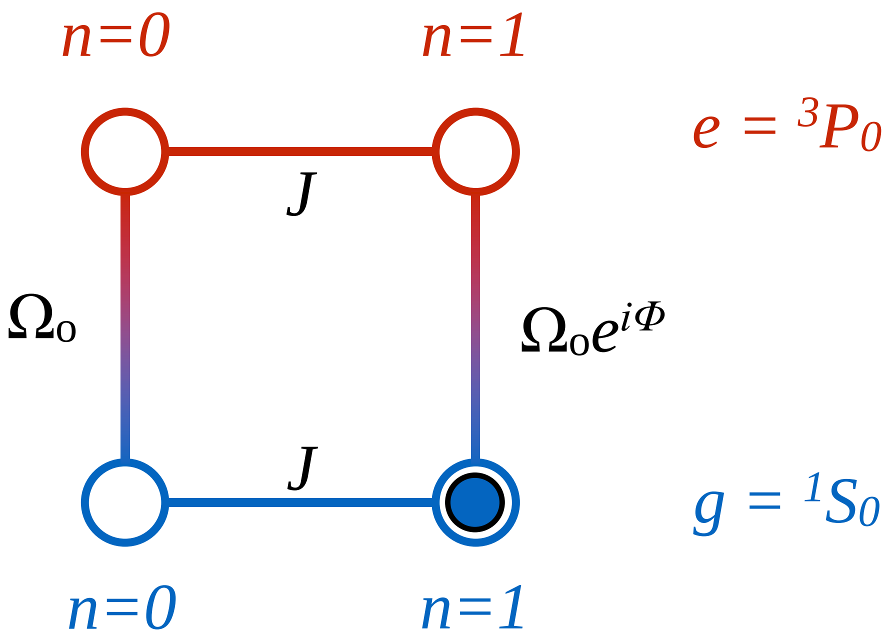
$$\Phi = \pi \lambda_l / \lambda_c$$

Synthetic magnetic field in the clock



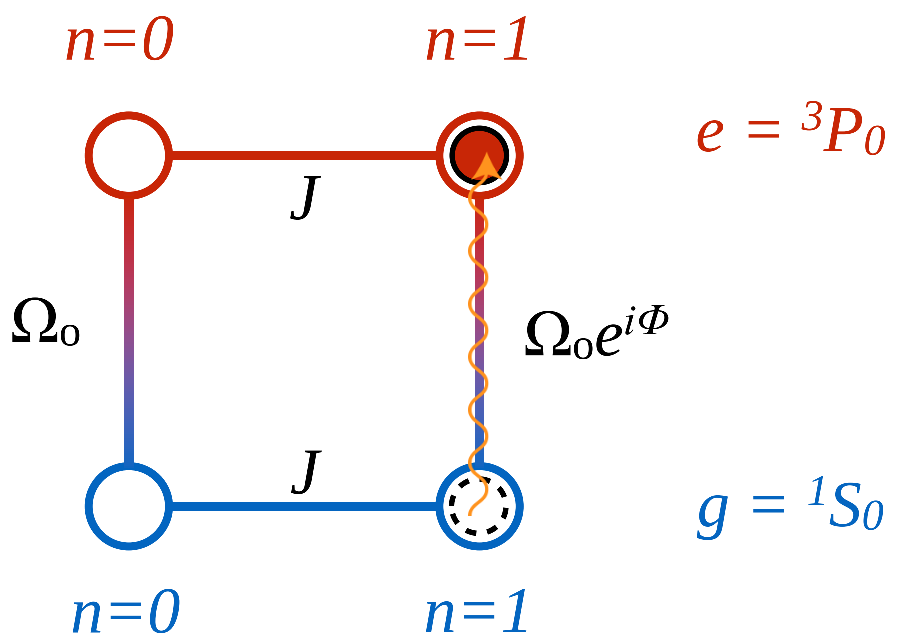
$\Phi = \pi\lambda_l/\lambda_c$ Tunneling rate J

Synthetic magnetic field in the clock



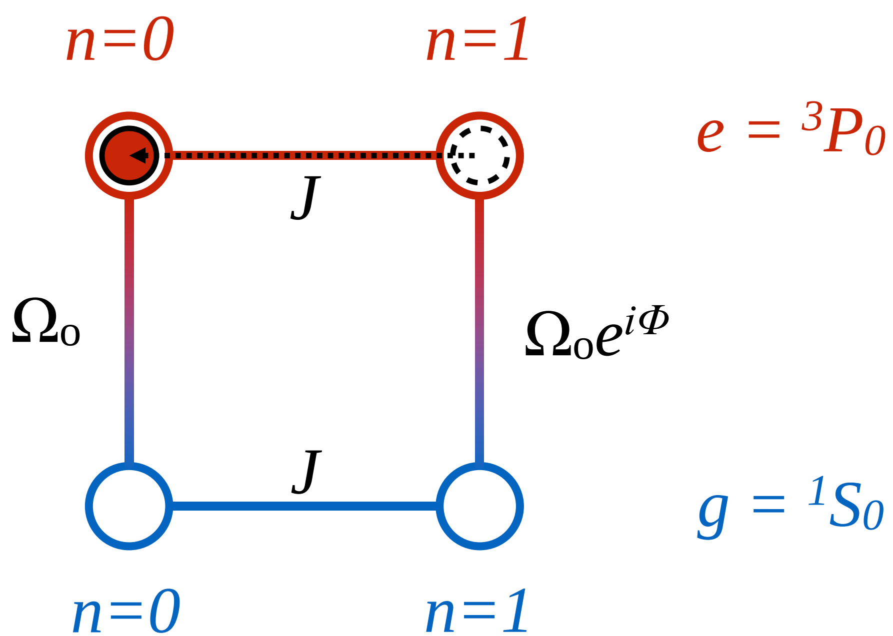
$$\psi_o = |1, g\rangle$$

Synthetic magnetic field in the clock



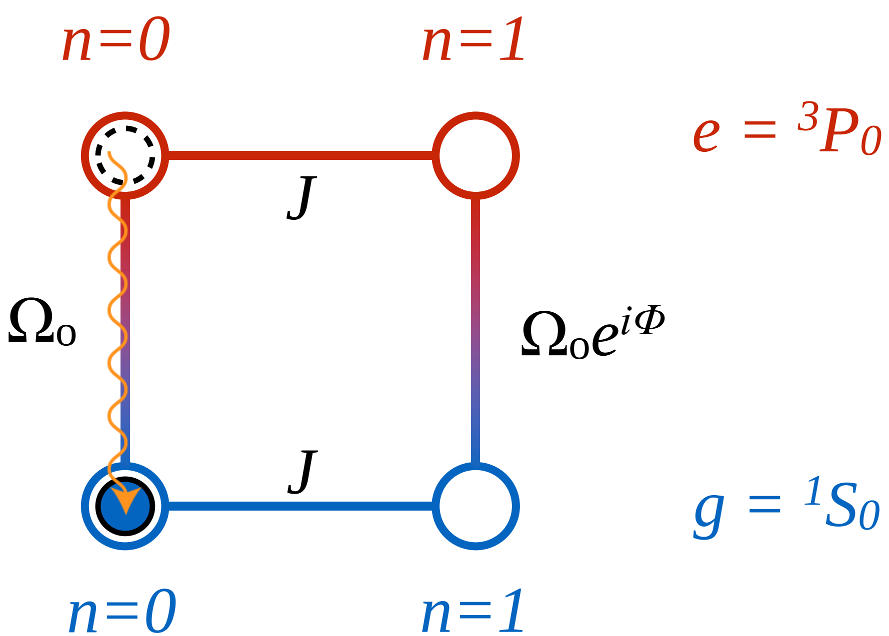
$$\psi_1 = e^{i\phi}\left|1,e\right\rangle$$

Synthetic magnetic field in the clock



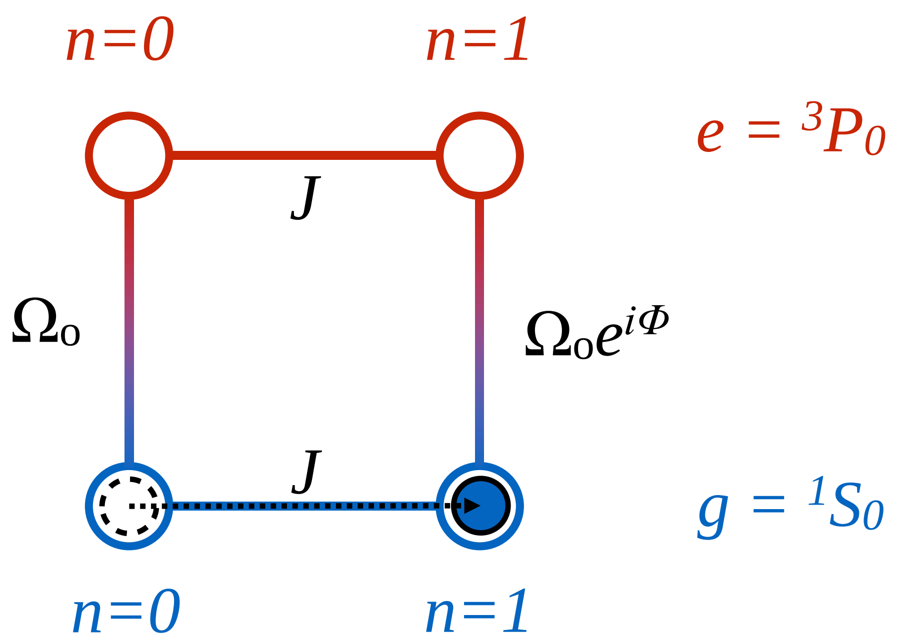
$$\psi_2 = e^{i\phi}\left|0,e\right\rangle$$

Synthetic magnetic field in the clock



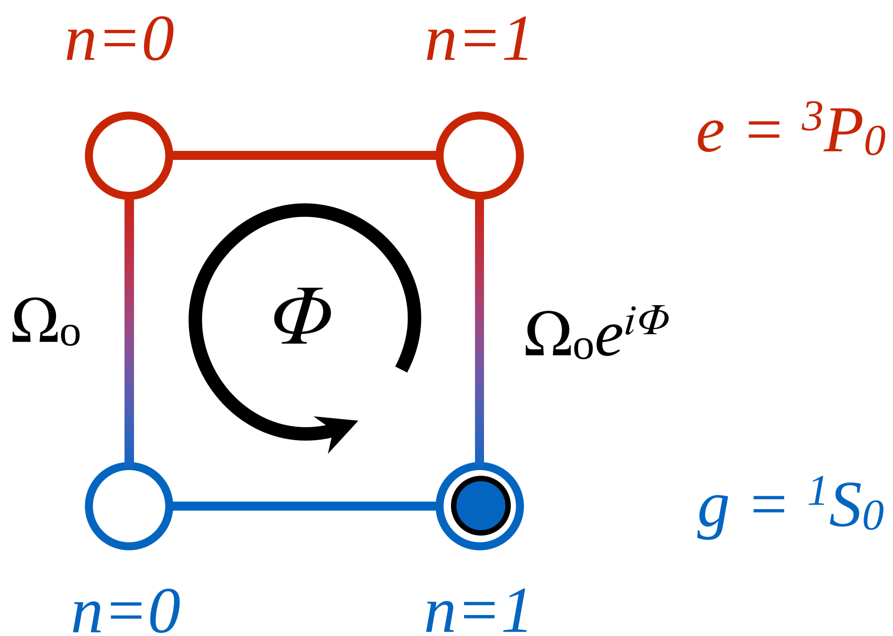
$$\psi_3 = e^{i\phi}\left|0,g\right\rangle$$

Synthetic magnetic field in the clock



$$\psi_f = e^{i\phi}|1,g\rangle$$

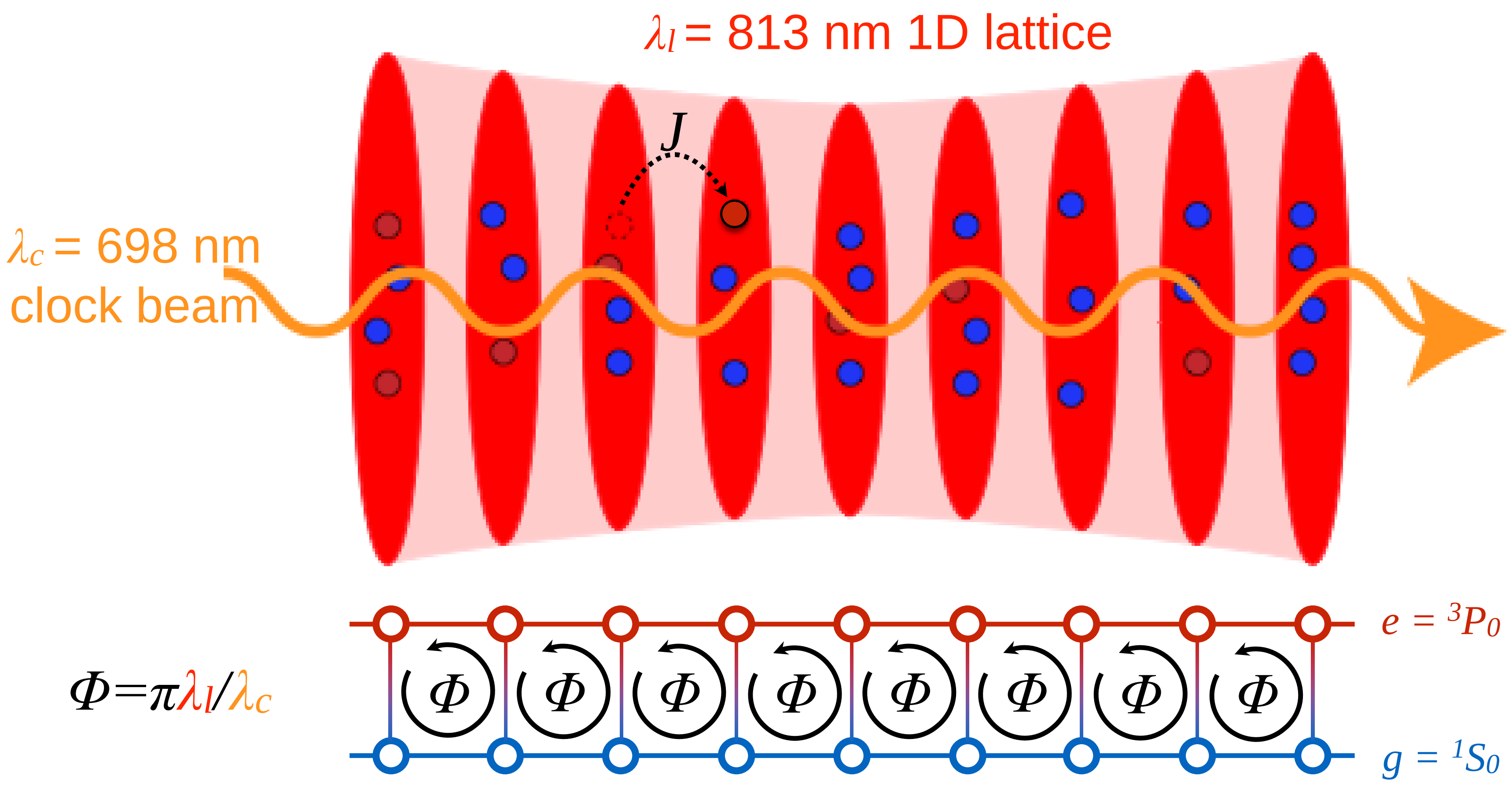
Synthetic magnetic field in the clock



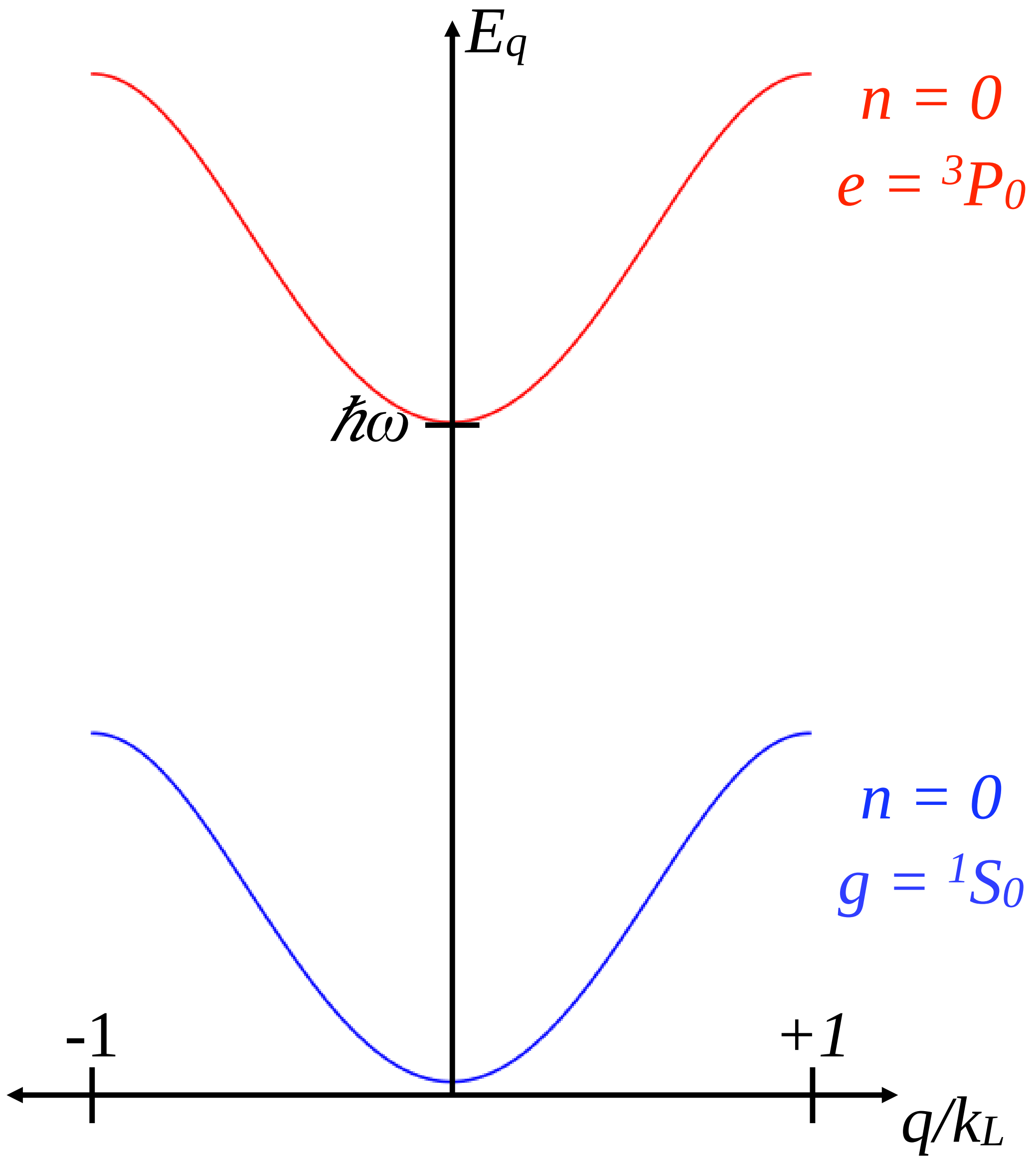
$$\psi_f = e^{i\phi}\psi_o$$

Synthetic magnetic field in the clock

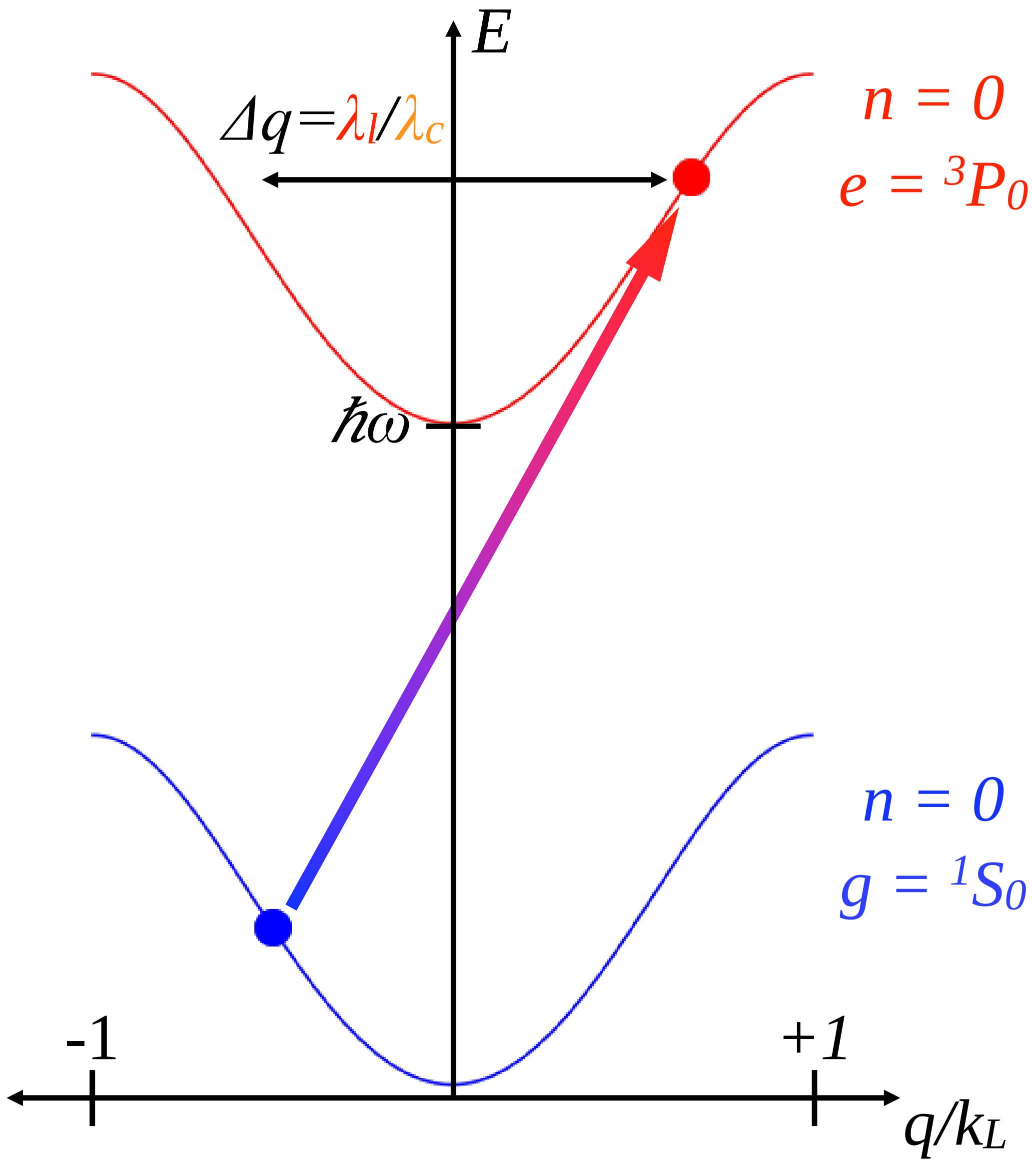
- Charged fermion in a synthetic magnetic field
- Clock transition for spectroscopy
- Many-body interaction under spin-orbit coupling



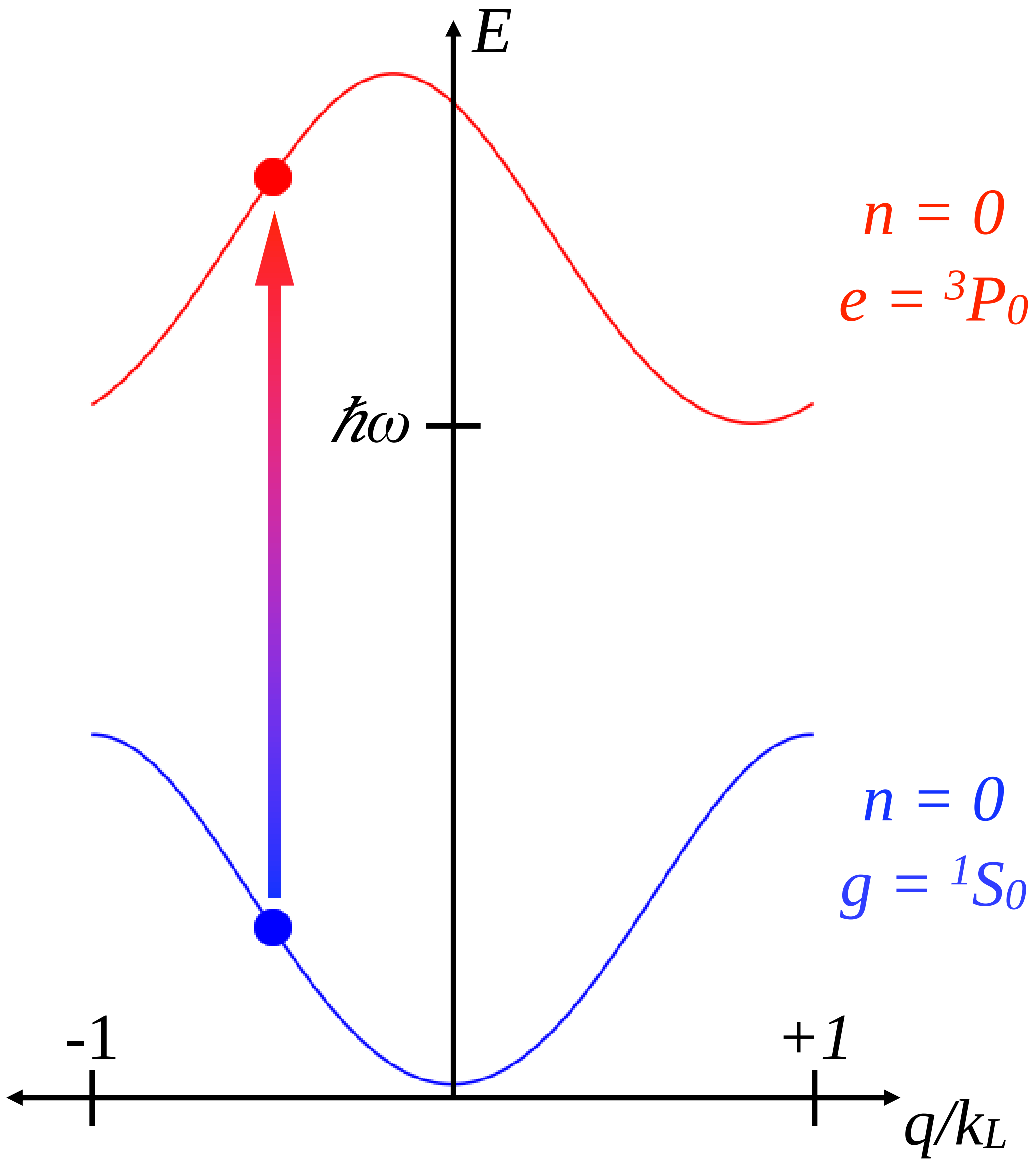
Spin-orbit coupled band structure



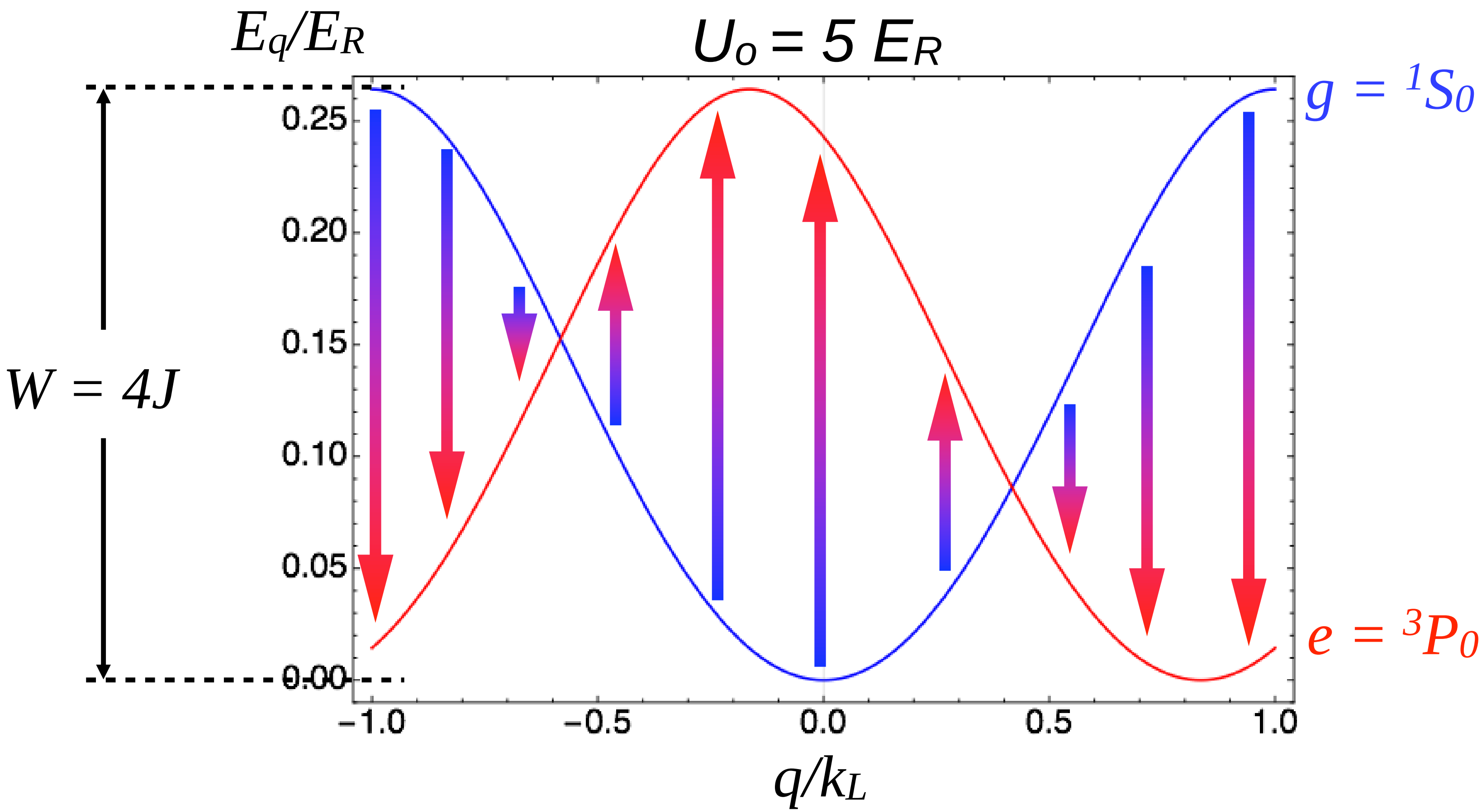
Spin-orbit coupled band structure



Spin-orbit coupled band structure

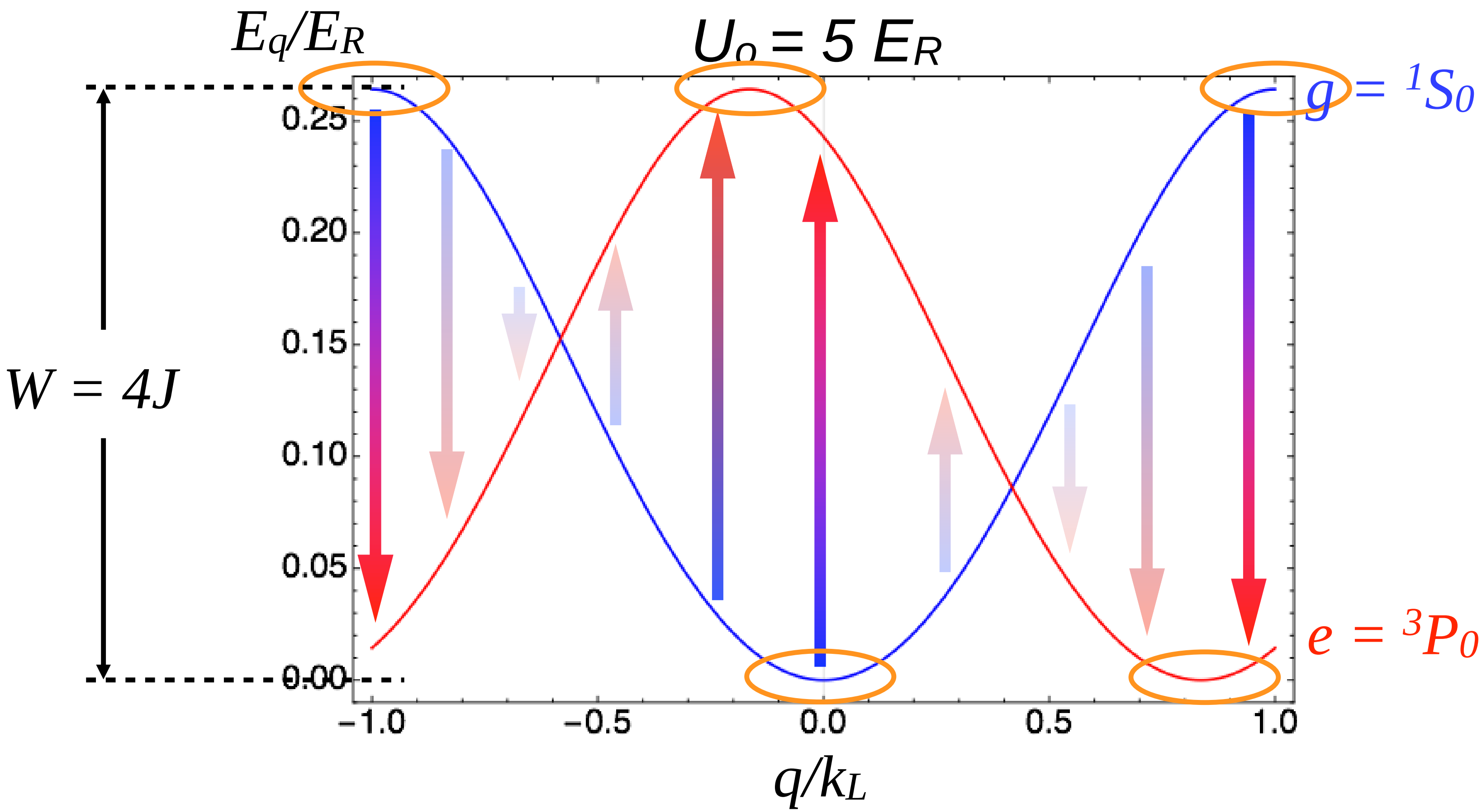


Spin-orbit coupled band structure



Varying detuning at different quasi-momenta
→ broadening of the transition.

Spin-orbit coupled band structure

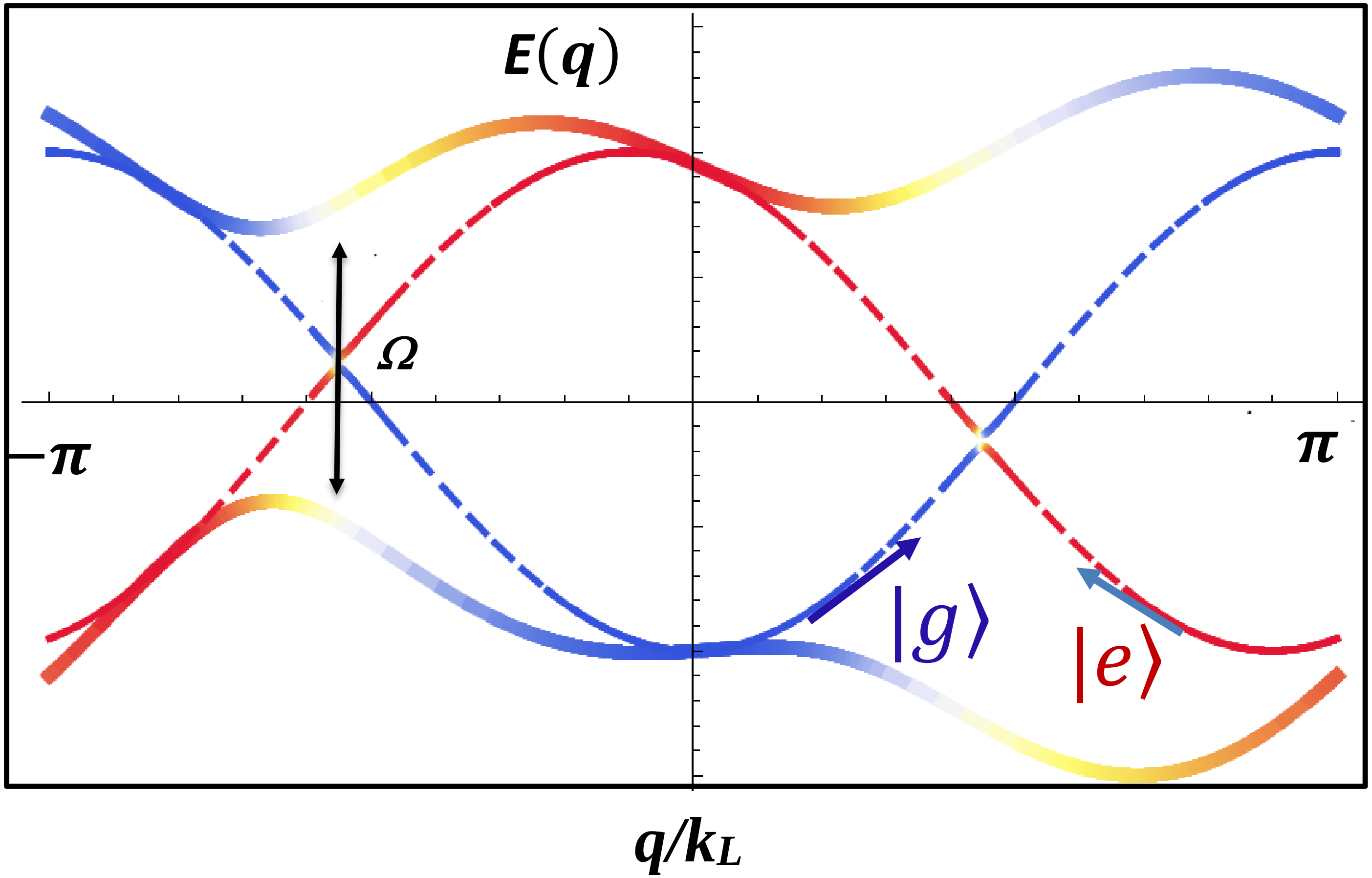


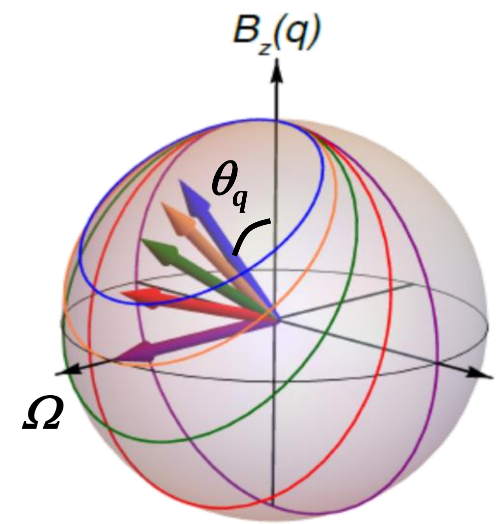
Density of states diverge at $dE/dk = 0$:
van Hove singularities

Probe spin-orbit coupled band structure

$$H_q = -\,\Omega S^x \; - \; (\Delta E(q) + \delta) S^z \quad = \; \vec{B}_{eff}\,(q,\delta) \cdot \hat{\vec{S}}$$

$$\Delta E(q) = -J\,[cos(\pi q/k_L + \Phi) - cos(\pi q/k_L)]$$

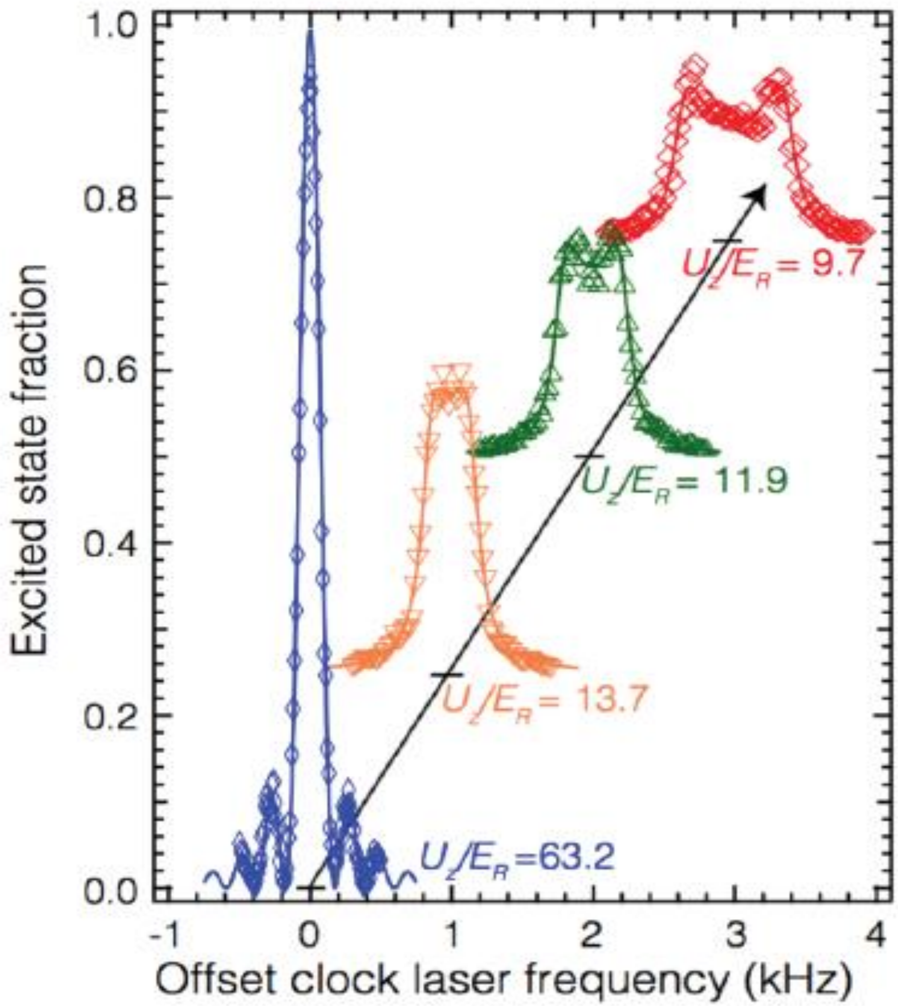


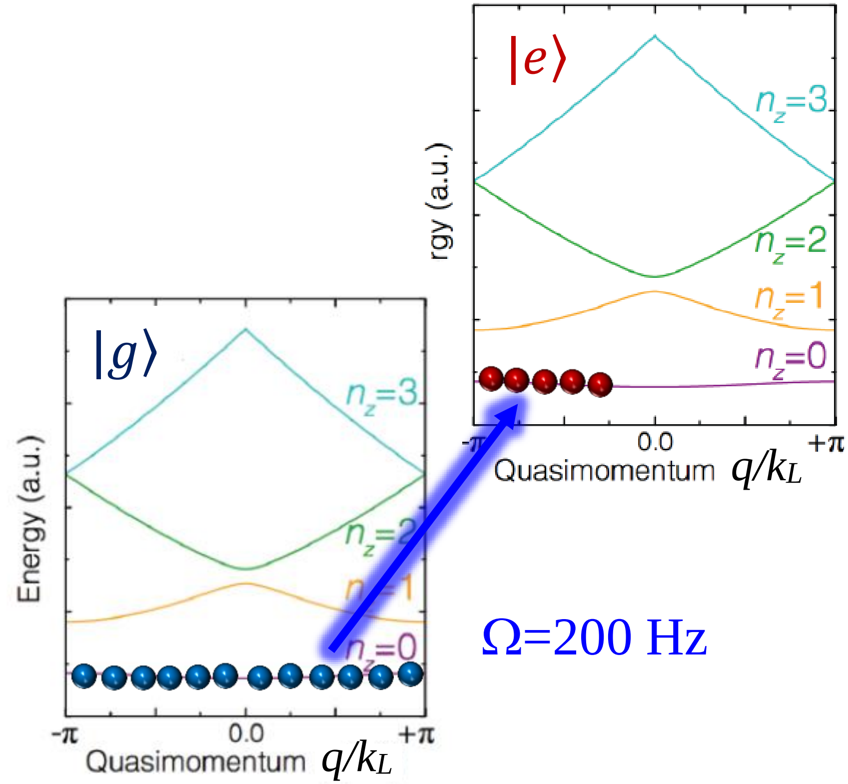


Spin-motion locking: non-zero chirality determined by θ_q

Rabi spectroscopy

Lowest band





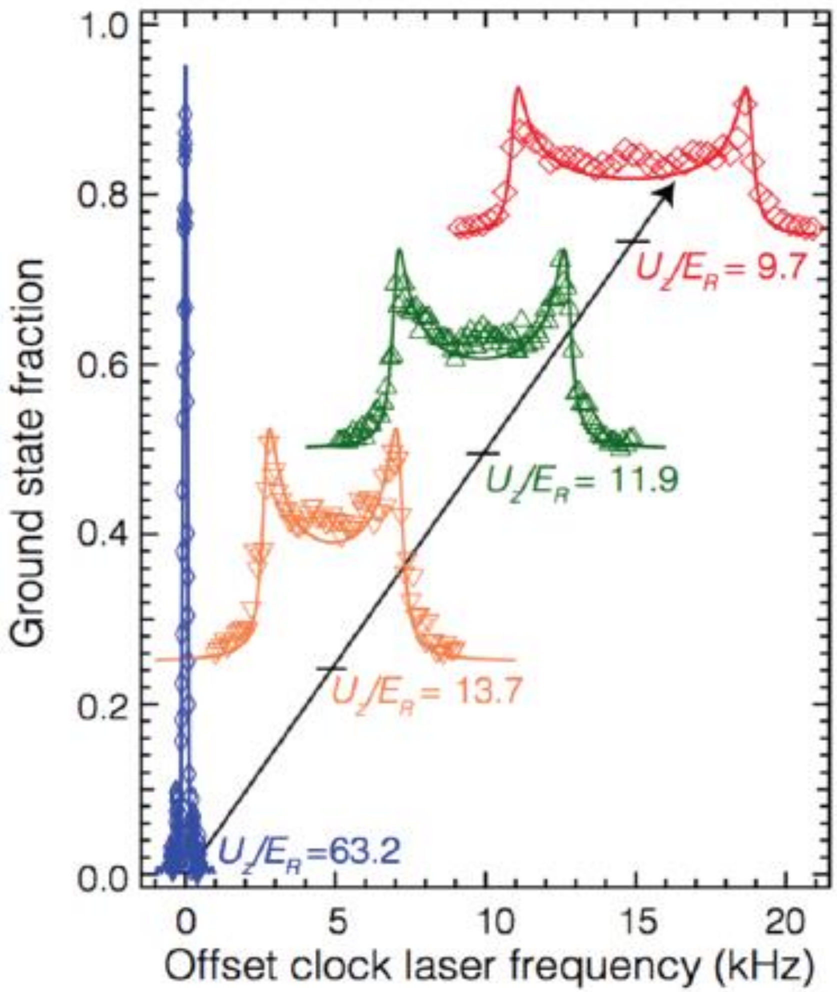
Ω=200 Hz

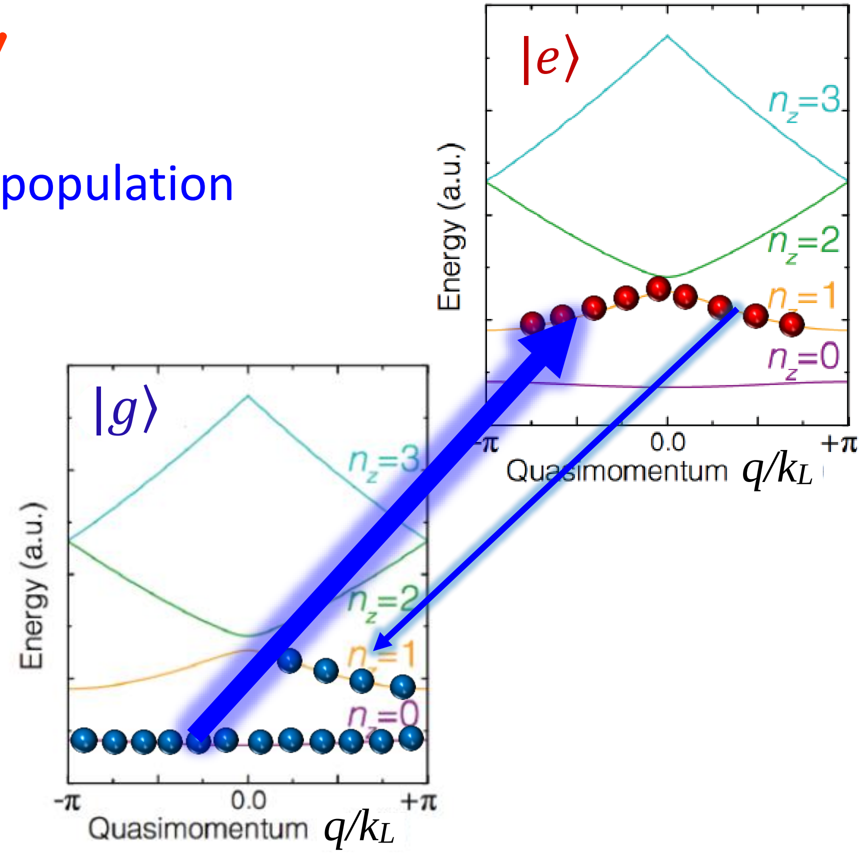
Lines: theory
Symbols: experiment

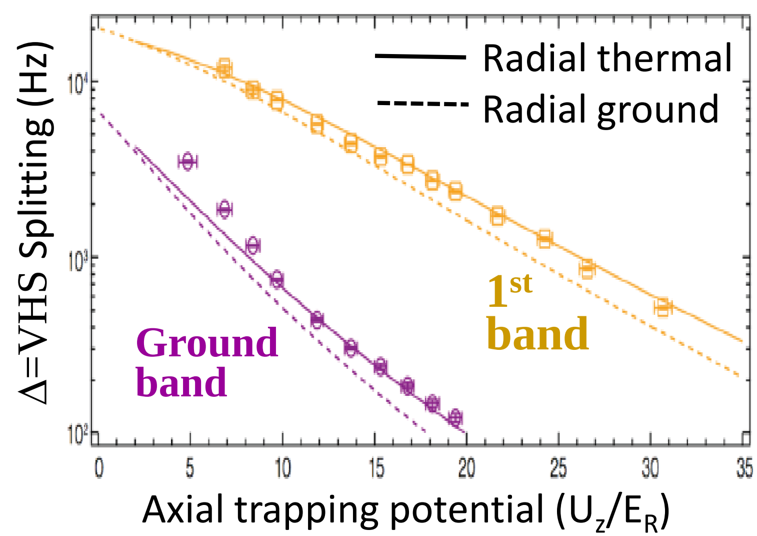
Rabi spectroscopy

- ✓ Spectroscopic control of excited band population
- ✓ No band relaxation for ~ 1 s

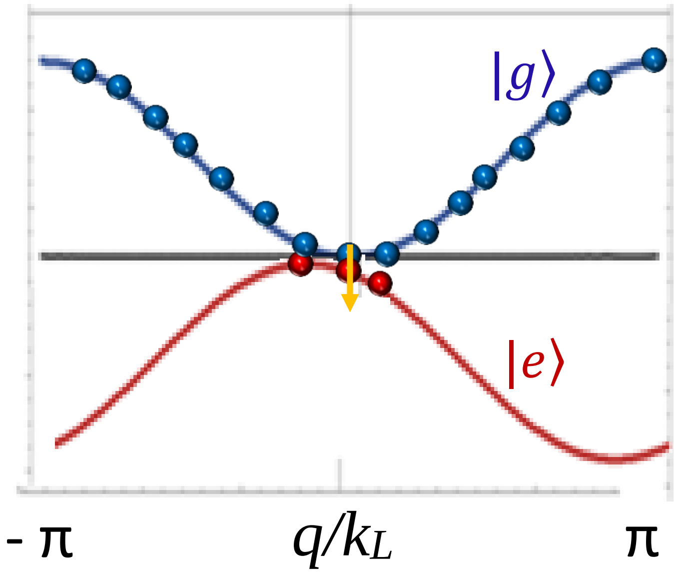
First Excited band

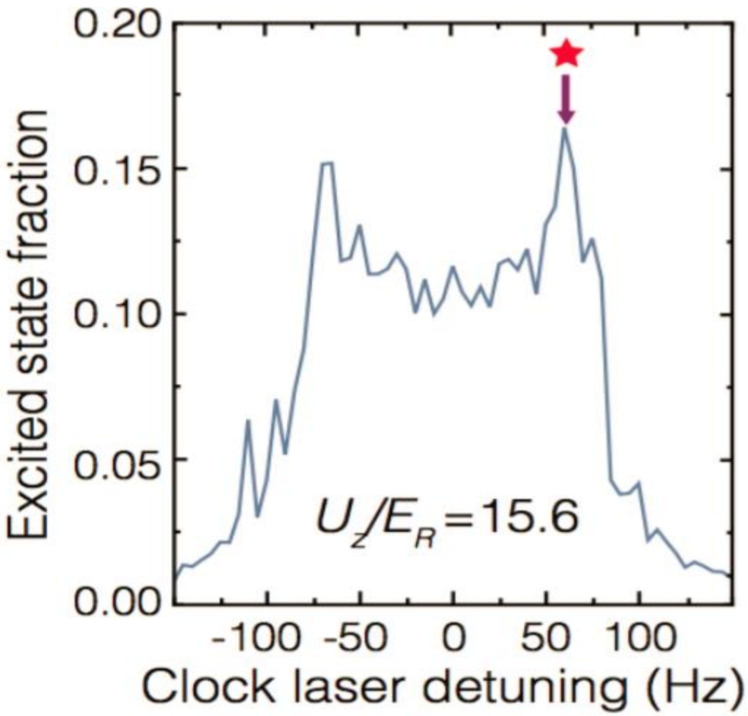


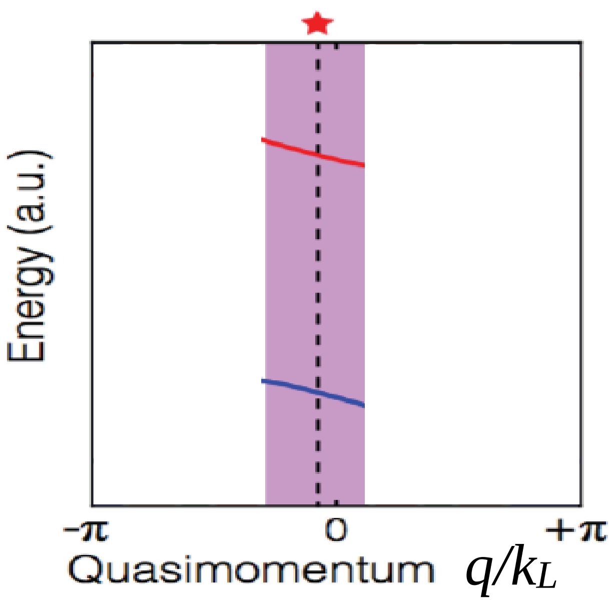




Momentum-resolved spectroscopy





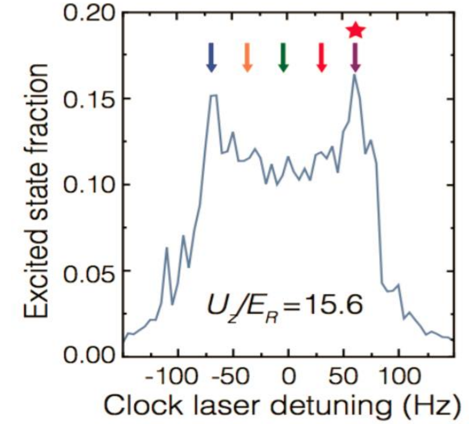


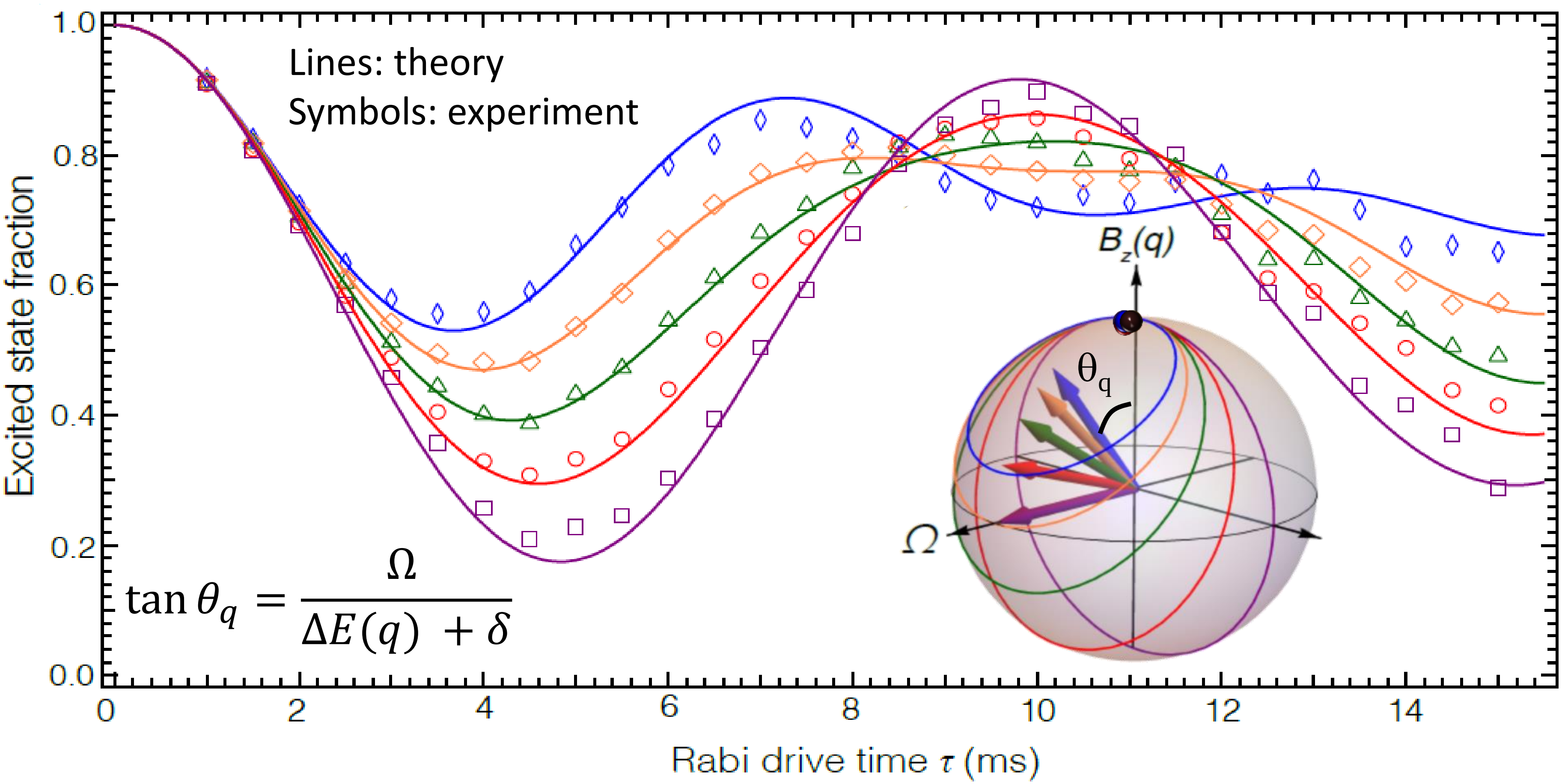
- Momentum selection: π pulse (g → e), Ω = 10 Hz
- Cleaning pulse: Remove all atoms in g
- Rabi oscillations with Ω =100 Hz at $\delta =$ ★

Momentum-resolved Rabi oscillation

chiral angle θ_q

Clock sensitivity opens the door for investigation of spin-orbit coupled ladders

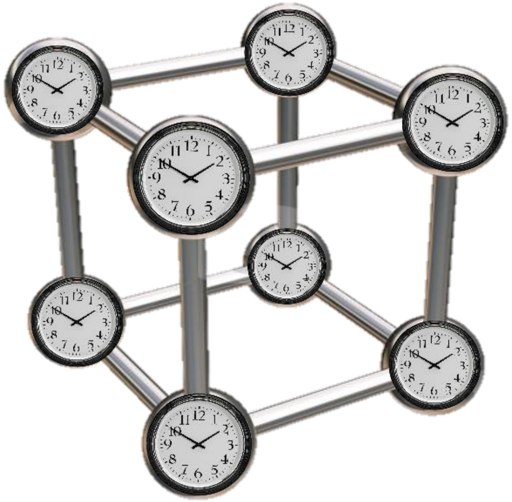




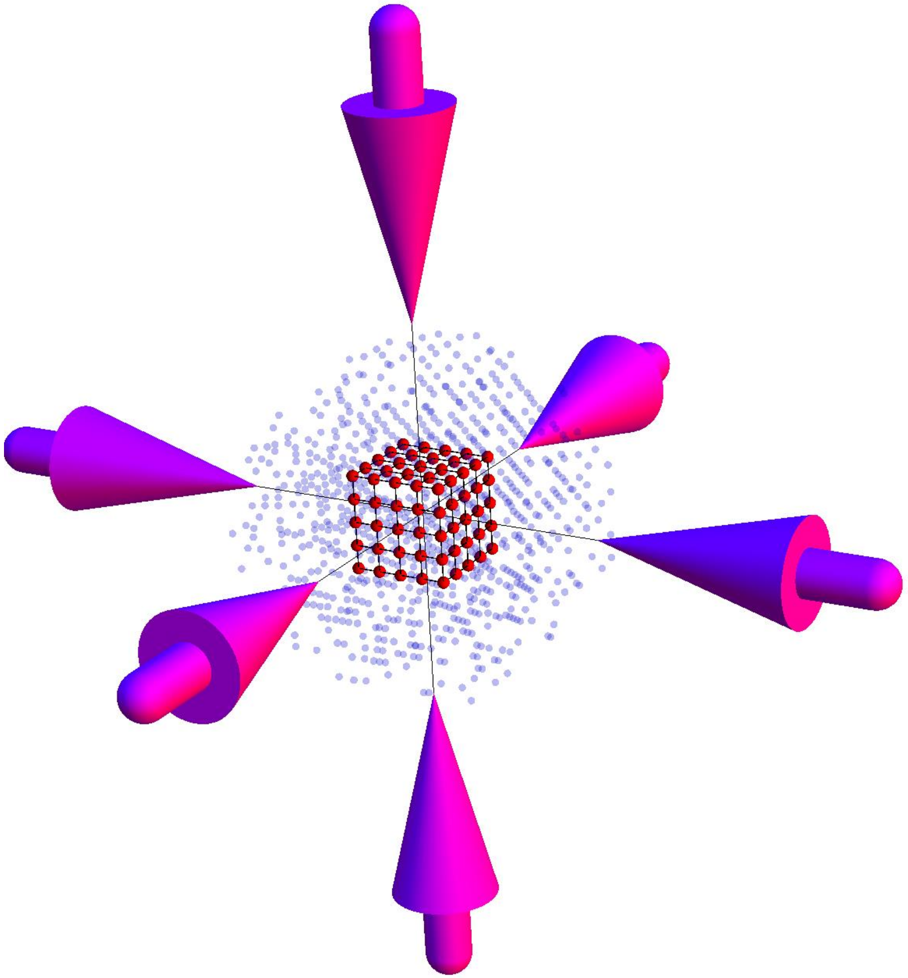
$$\tan\theta_q = \frac{\Omega}{\Delta E(q) + \delta}$$

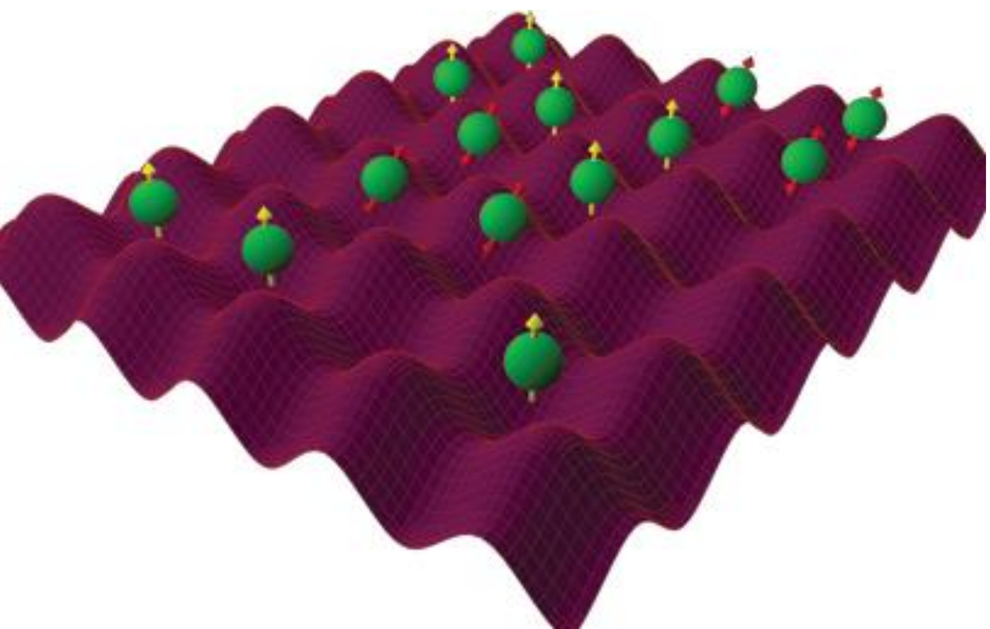
3D Fermi Band Insulator Clock

Scaling up the Sr quantum clock: 1 million atoms, 160 s



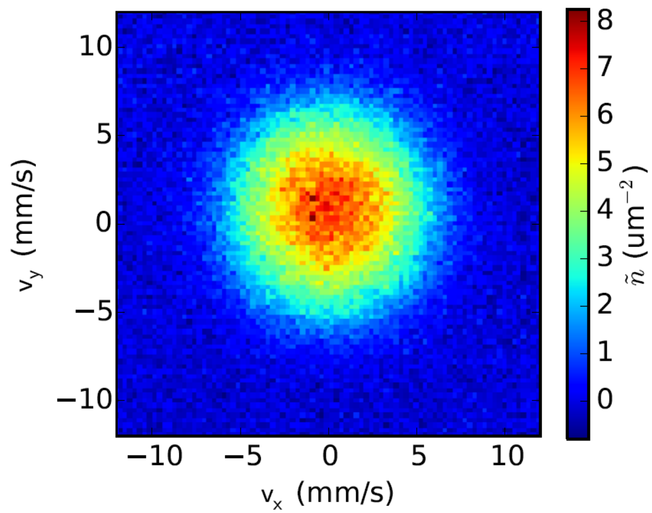
1 atom per site ← Pauli
Exclusion Principle or energy gap

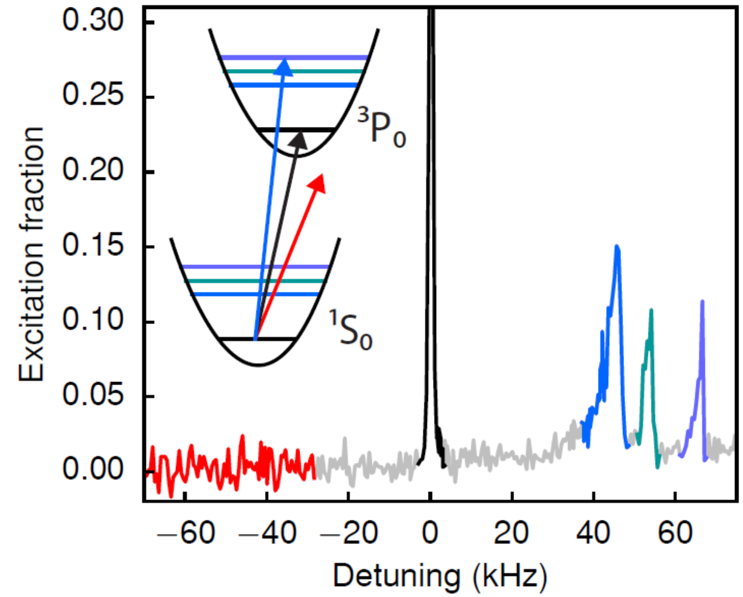


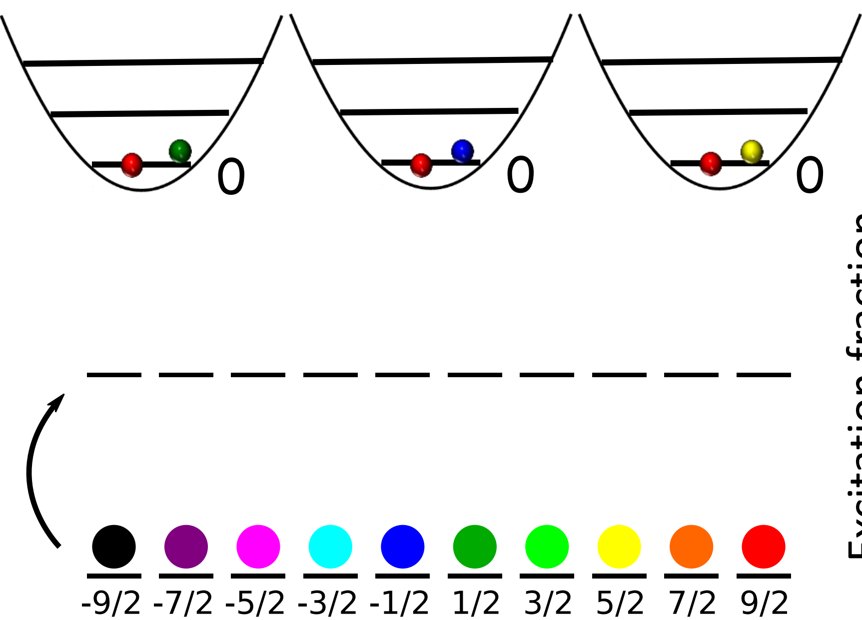


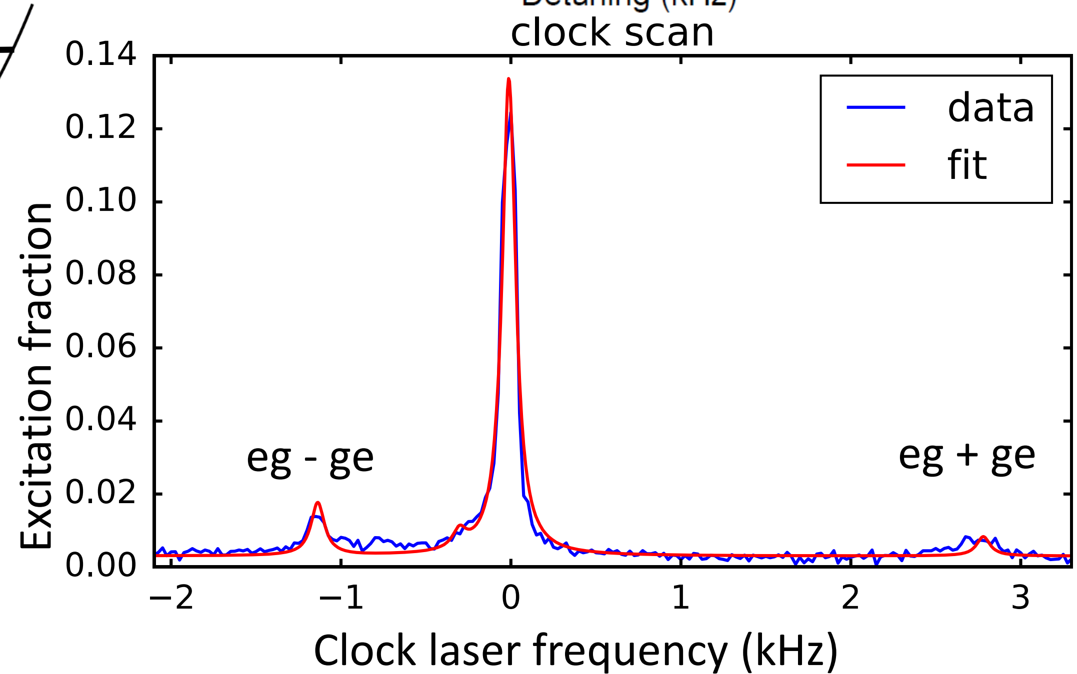
A Fermi Band Insulator Clock

4×10^4 ^{87}Sr atoms; 40 nK; 2 nuclear spin states, each $T/T_F = 0.08$

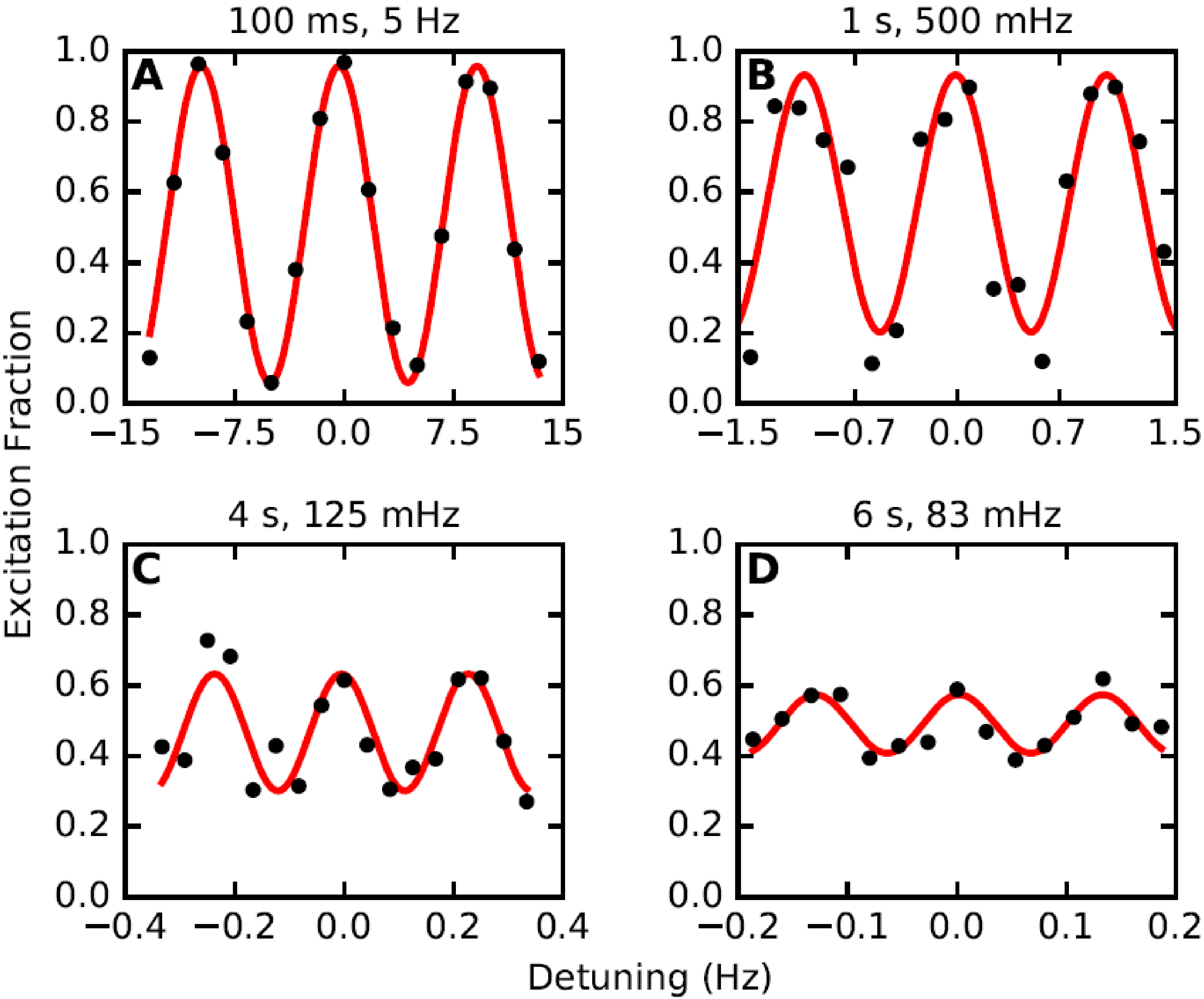








Record long atom-light coherence

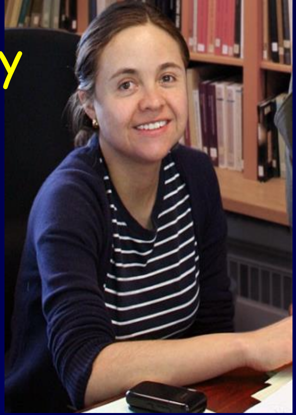


Ramsey fringe width 0.08 Hz

Q ~5.4 x 10^{15}

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

A. M. Rey



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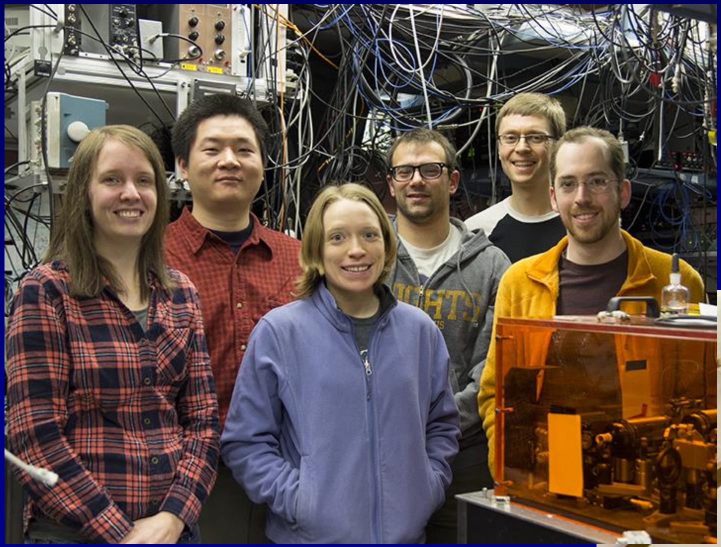

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