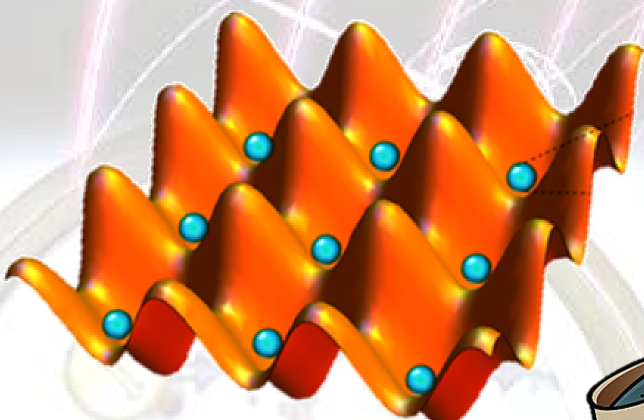
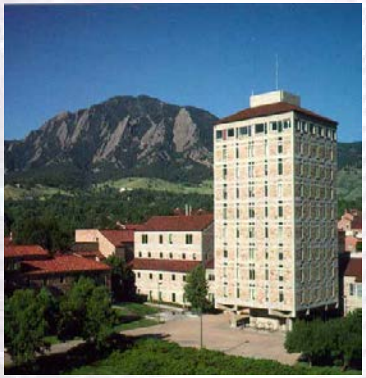
Exploring many-body physics with ultra-cold quantum matter

Ana Maria Rey

JILA
NIST CU





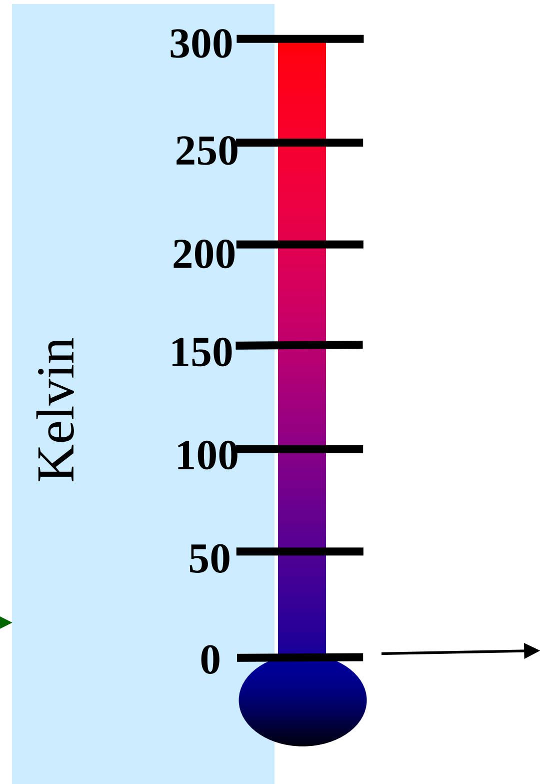
QIP Tutorials

Boulder, Colorado, January 12th, 2019

Ultra-cold atoms

Room temperature

Velocity~ 300 m/s



He condensation T=4K

Velocity~ 90 m/s

10^{4-6} atoms

T = 10-100 nK

Density: 10^{11-13} cm^{-3}

Velocity~ cm/s

Chu, Cohen-Tannoudji, Phillips:
Laser cooling: microK

Cornell, Ketterle, Wieman:
100 nanoK: Bose Einstein Condensation

1997

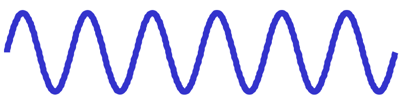
2001

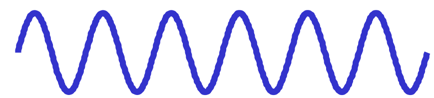
Optical lattices

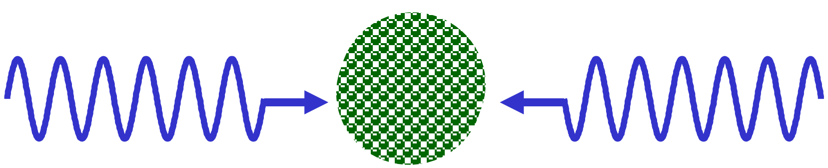
Artificial crystals of light

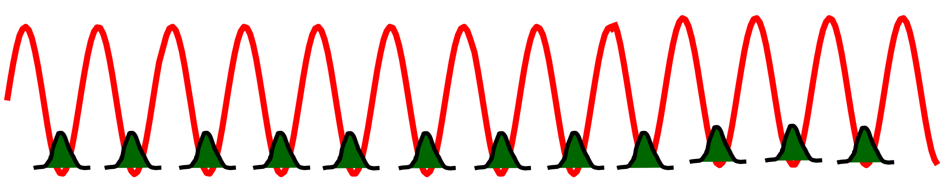
When atoms are illuminated by laser beams they feel a force which depends on the laser intensity.

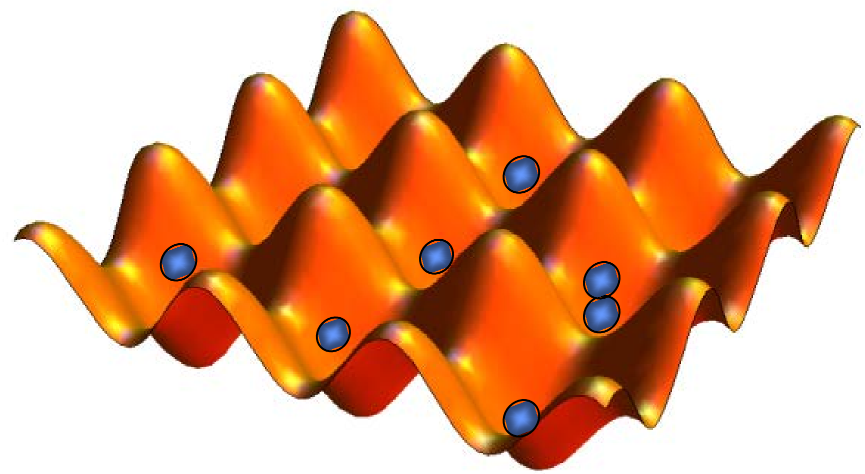
Two counter-propagating beams form a standing wave



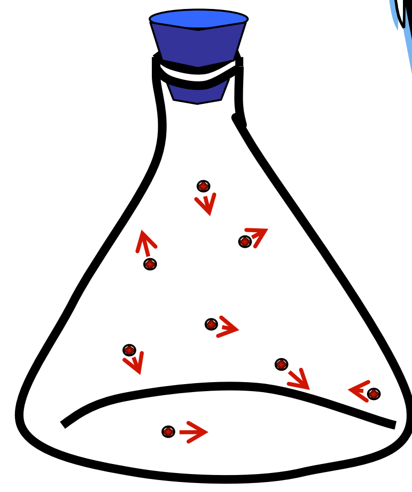


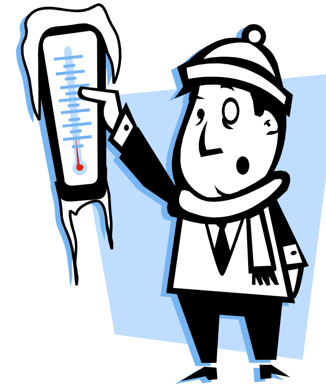






What can we do with ultra-cold atoms?





A tool for understanding complex many-body quantum systems

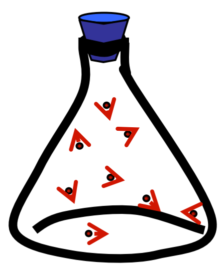
Scientific Vision

GOAL: Harnessing many-body quantum systems and using them for applications ranging from quantum information to metrology.

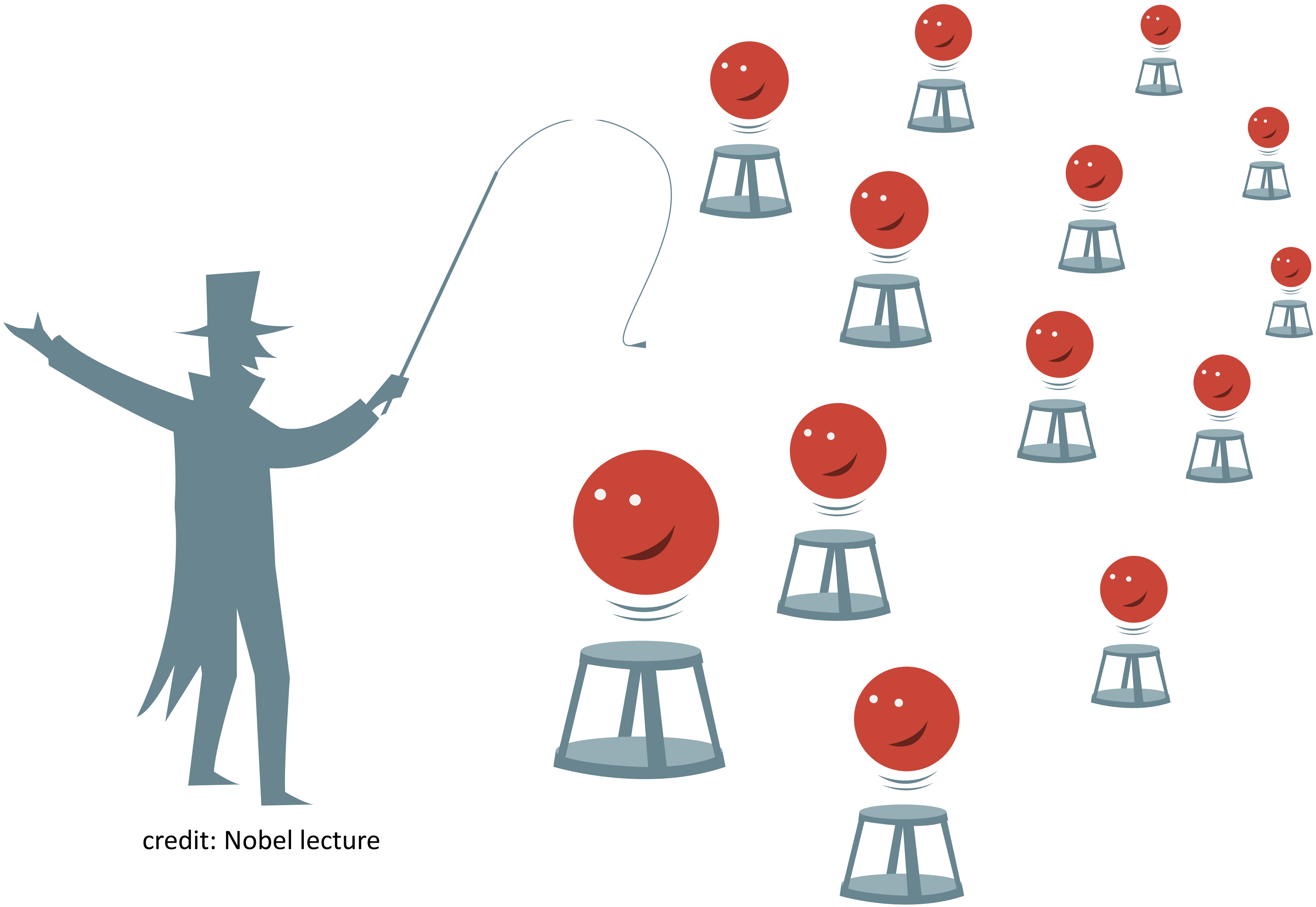
How do complex behaviors emerge from simple constituents and their interactions?

- Well-understood microscopics
- Tunable interactions
- Access to quantum dynamics

AMO

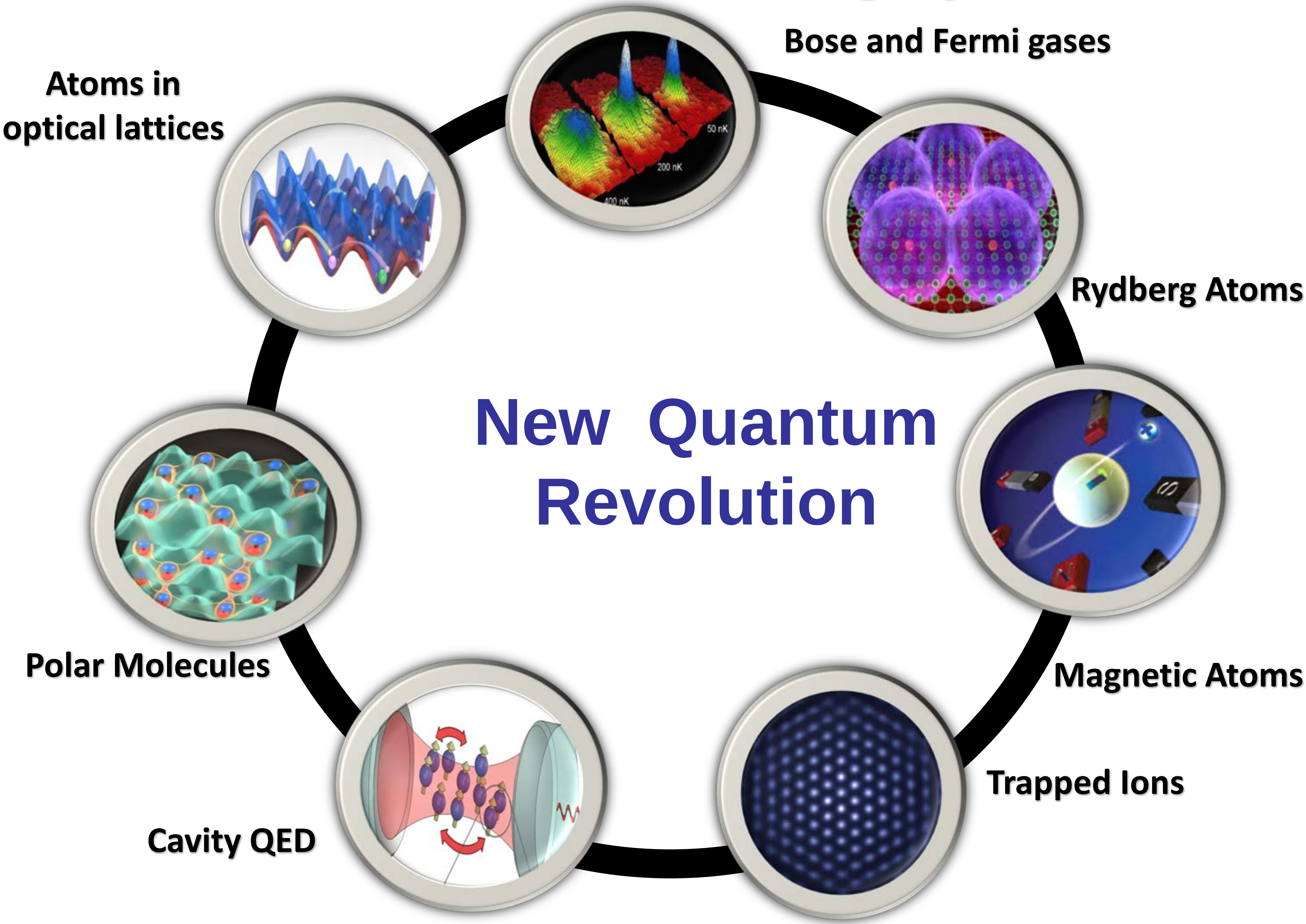


Nearly Complete Control of Independent particles



credit: Nobel lecture

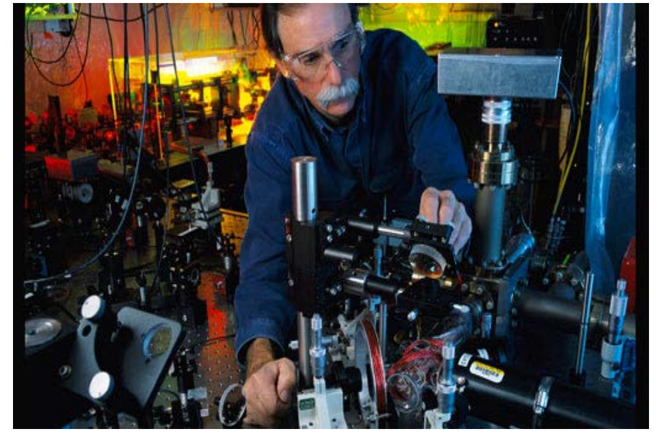
Controllable Interacting Systems



Nobel Prize 2012

Serge Haroche: Photons

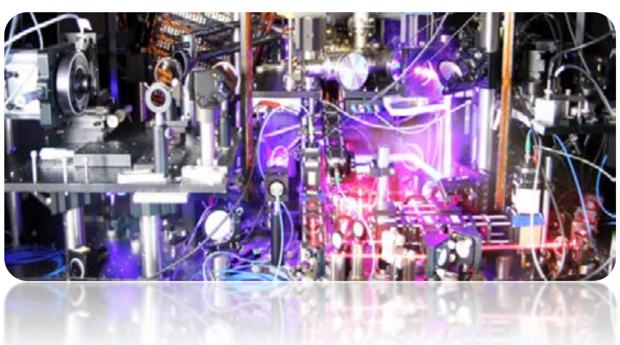
David J. Wineland: Ions



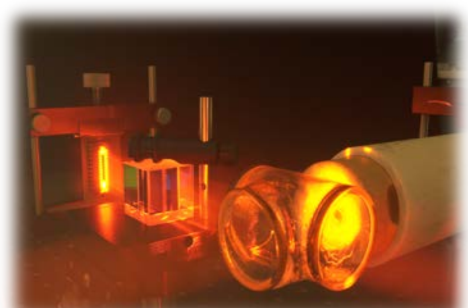
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

NEXT? State-of-the-art sensors

Atomic Clocks

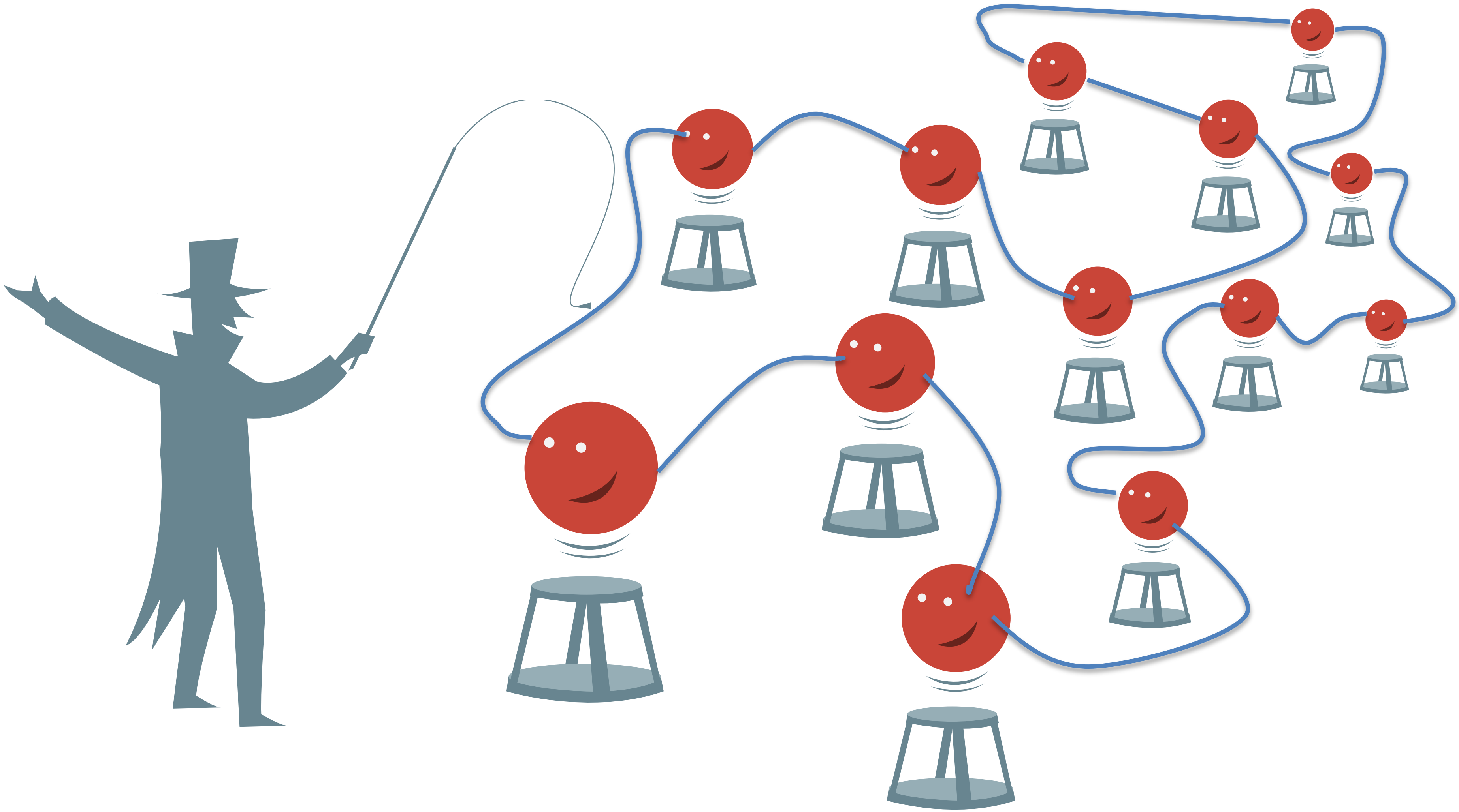


Magnetometers

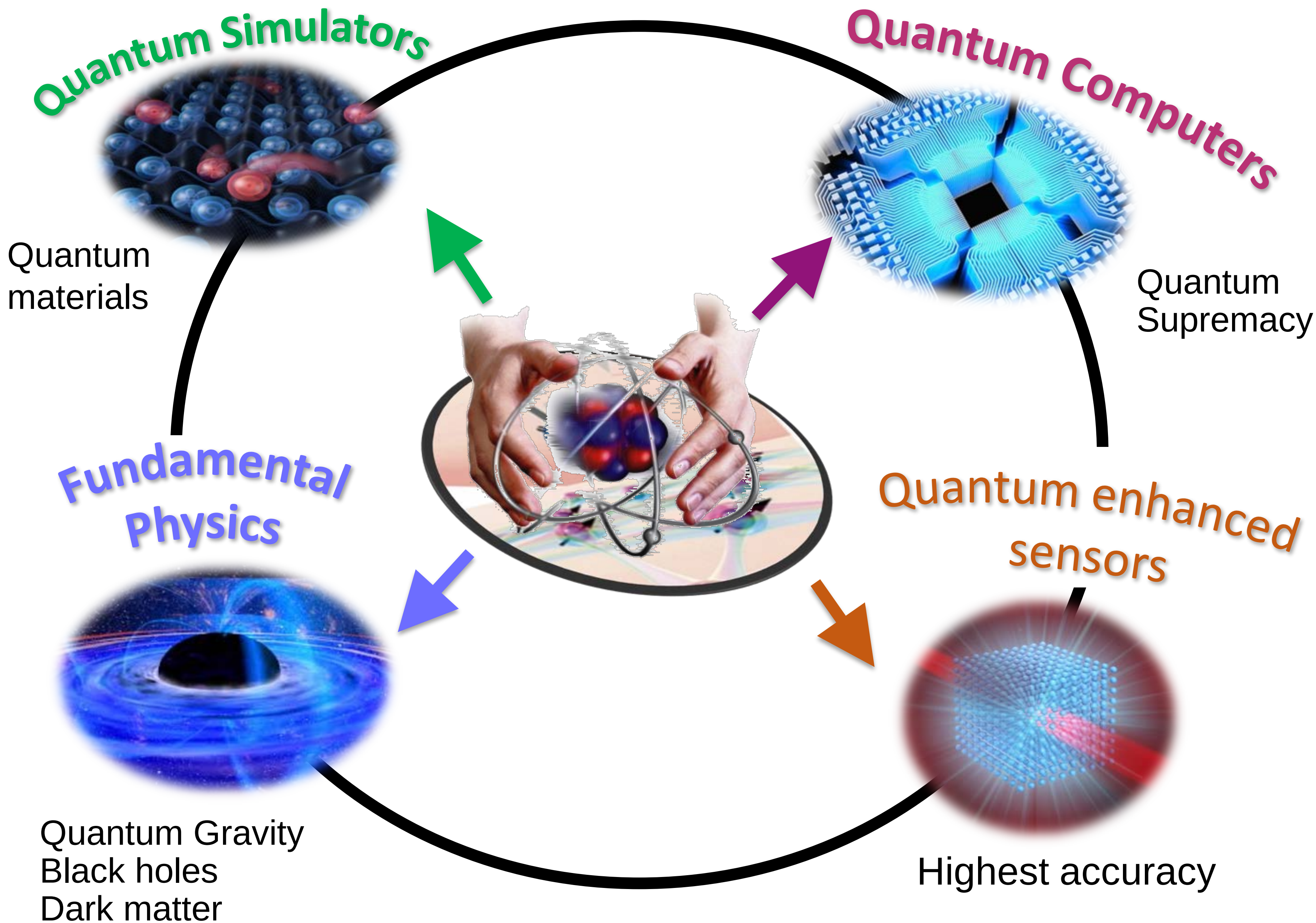


Interferometers

Control of correlated Many-body Quantum Systems



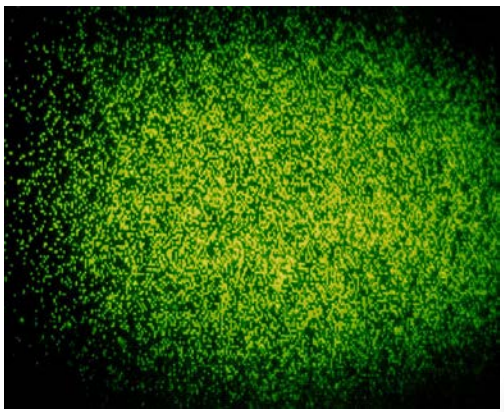
Control of correlated Many-body Quantum Systems

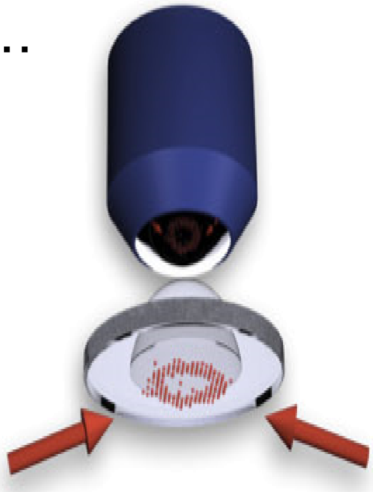


Individual Atom Control of Many-body systems

Quantum gas microscopes

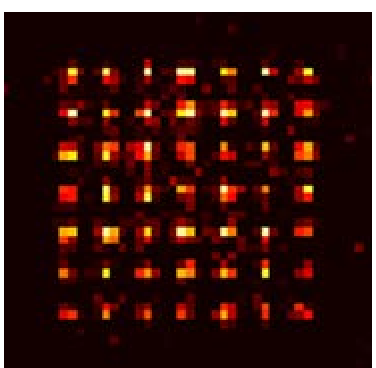
Harvard, MIT, Princeton, Munich, Toronto, Glasgow, …

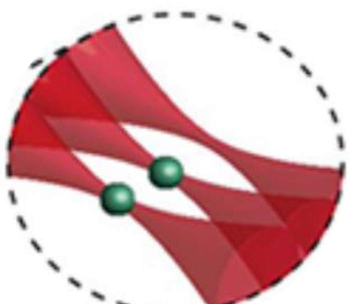




Optical Tweezer Arrays

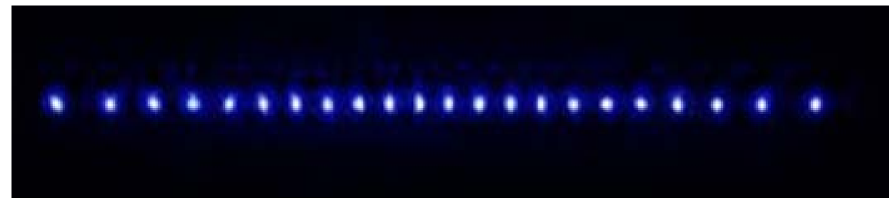
Harvard/MIT, JILA, France,





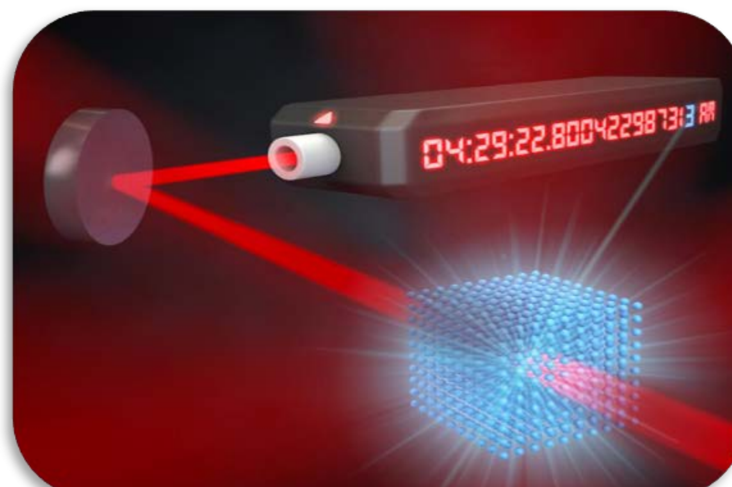
Ion traps

JQI, NIST, Innsbruck…



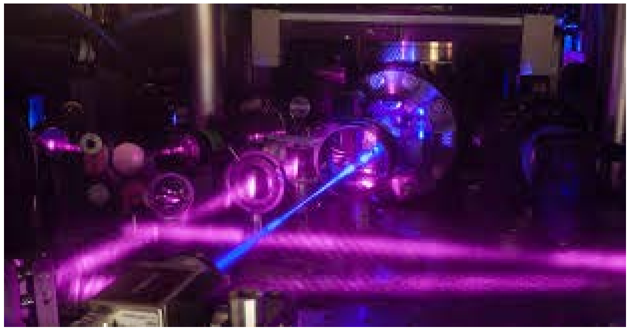
Optical Lattice Clocks

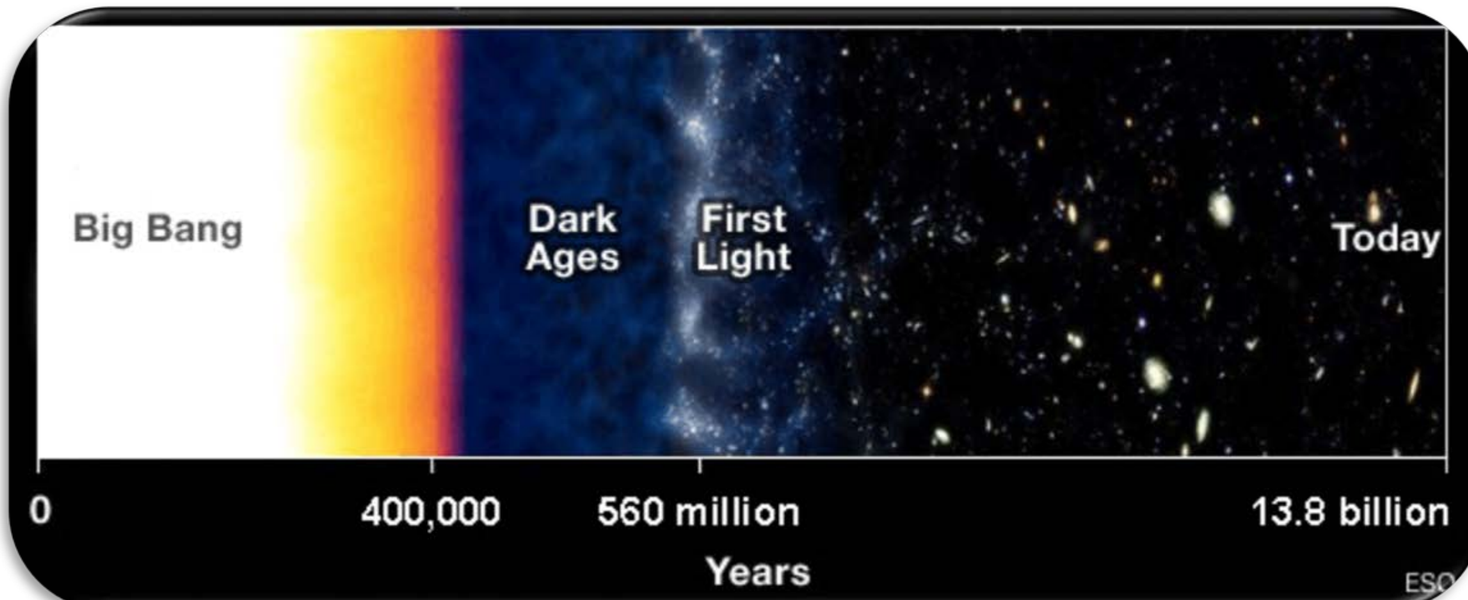
JILA, NIST



Ultra Precise

Neither gain nor lose one second in some 15 billion years—roughly the age of the universe.

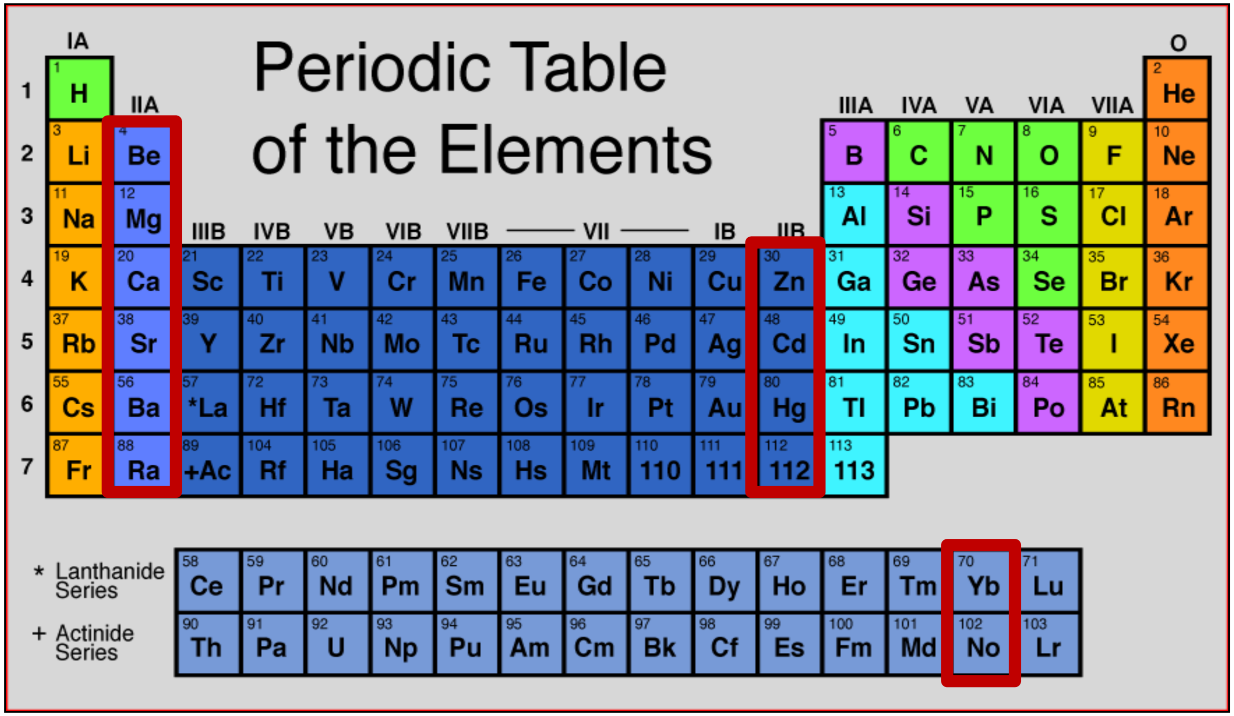


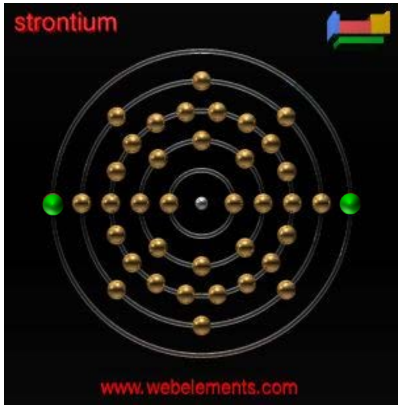


0.000 000 000 000 000 002

Alkaline Earth (-like) Atoms: AEA

A TALE OF TWIN ELECTRONS

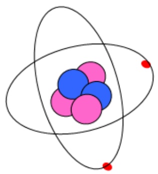




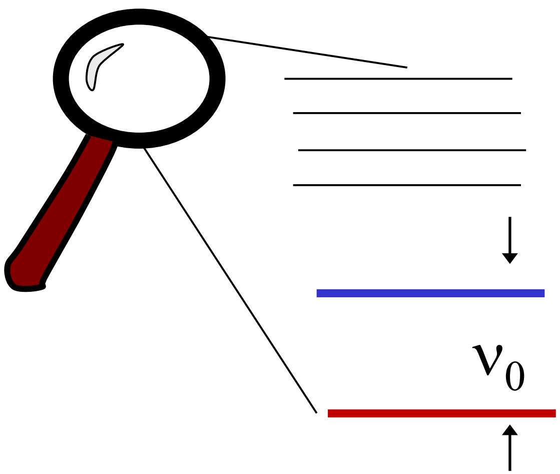
Fermionic isotopes have nuclear spin I > 0.

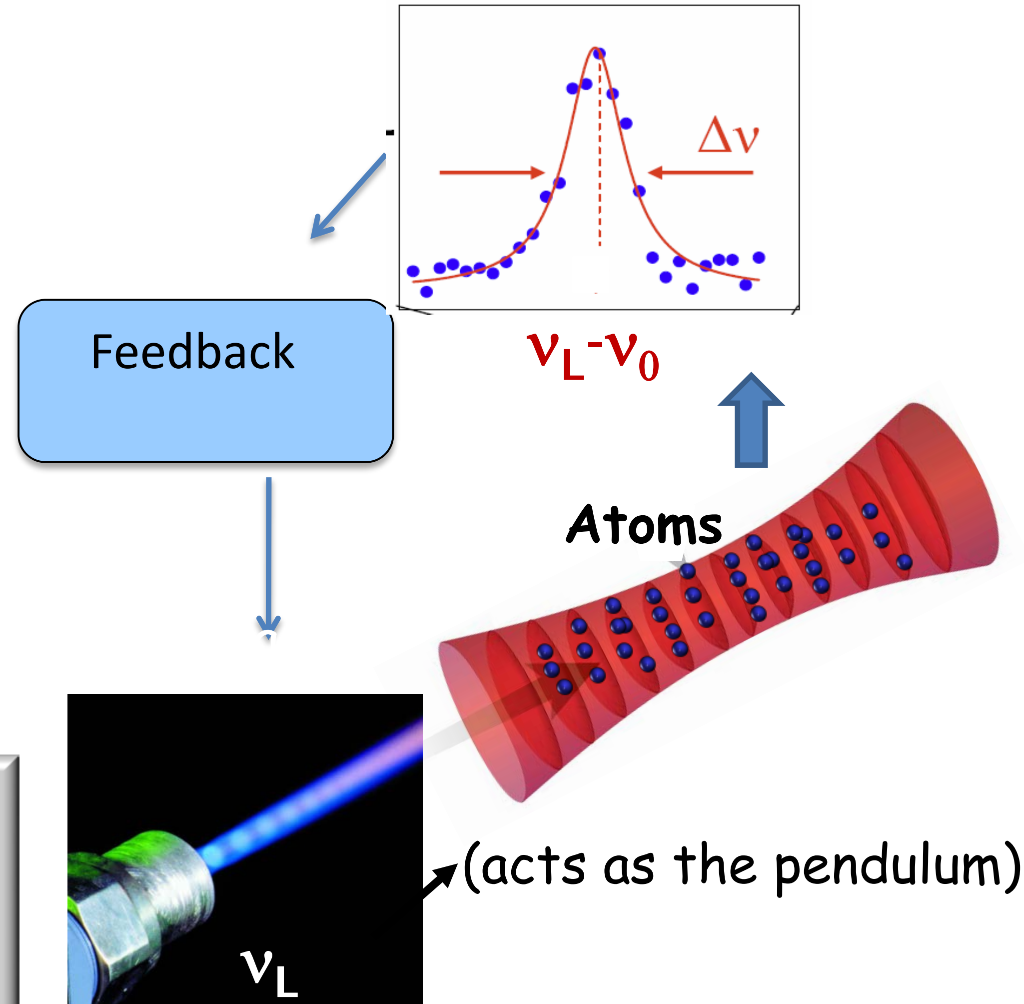
Atomic clock

Quantization of energy levels in an atom: unrivaled definition of the second



atom



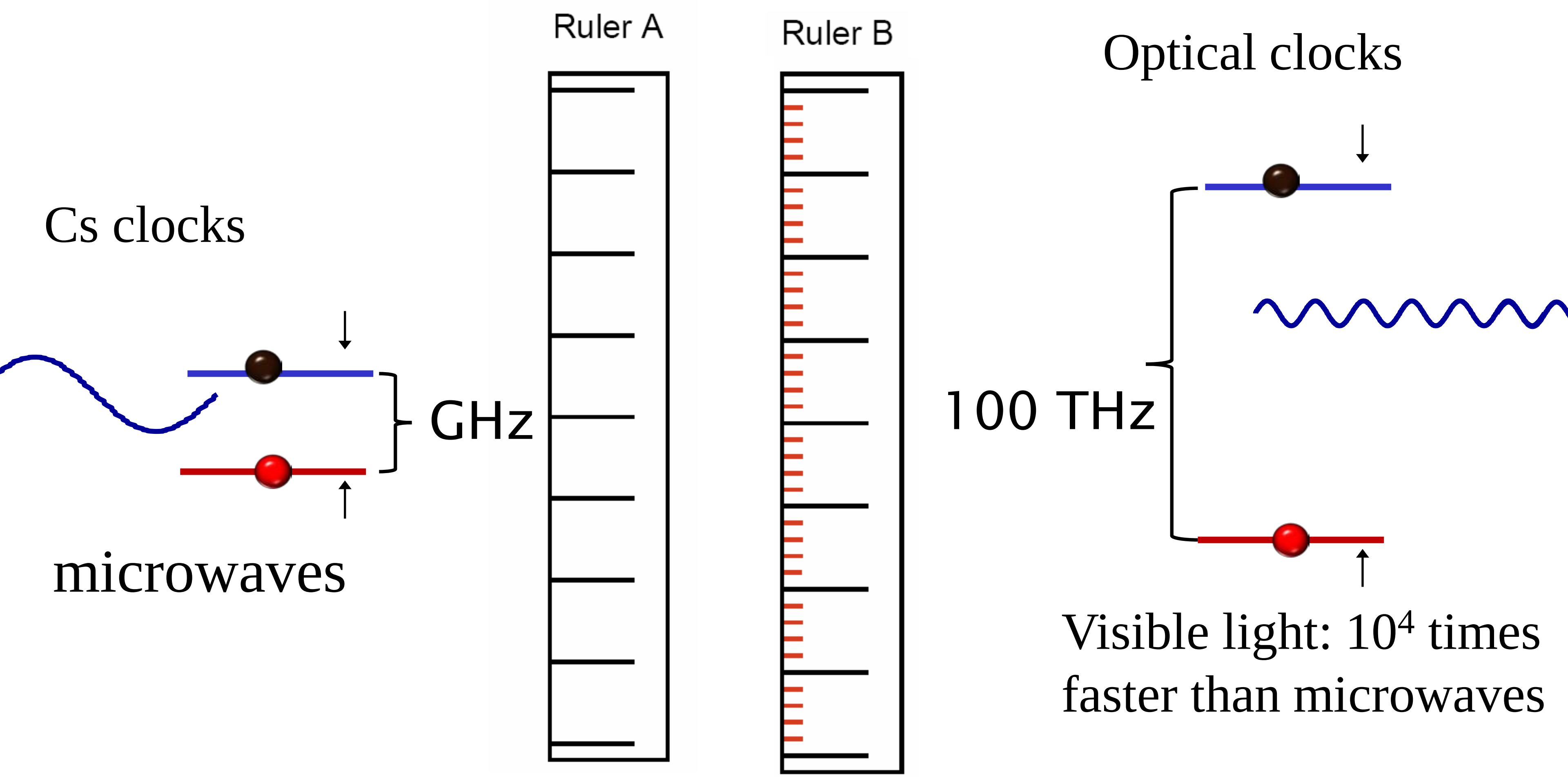


"Since 1967 the definition of the second is based on the splitting of two levels of the cesium (Cs) 133 atom"

However the precision of the Cs clock is currently not the best in the world

Optical clocks: even better

Which one them is more precise?

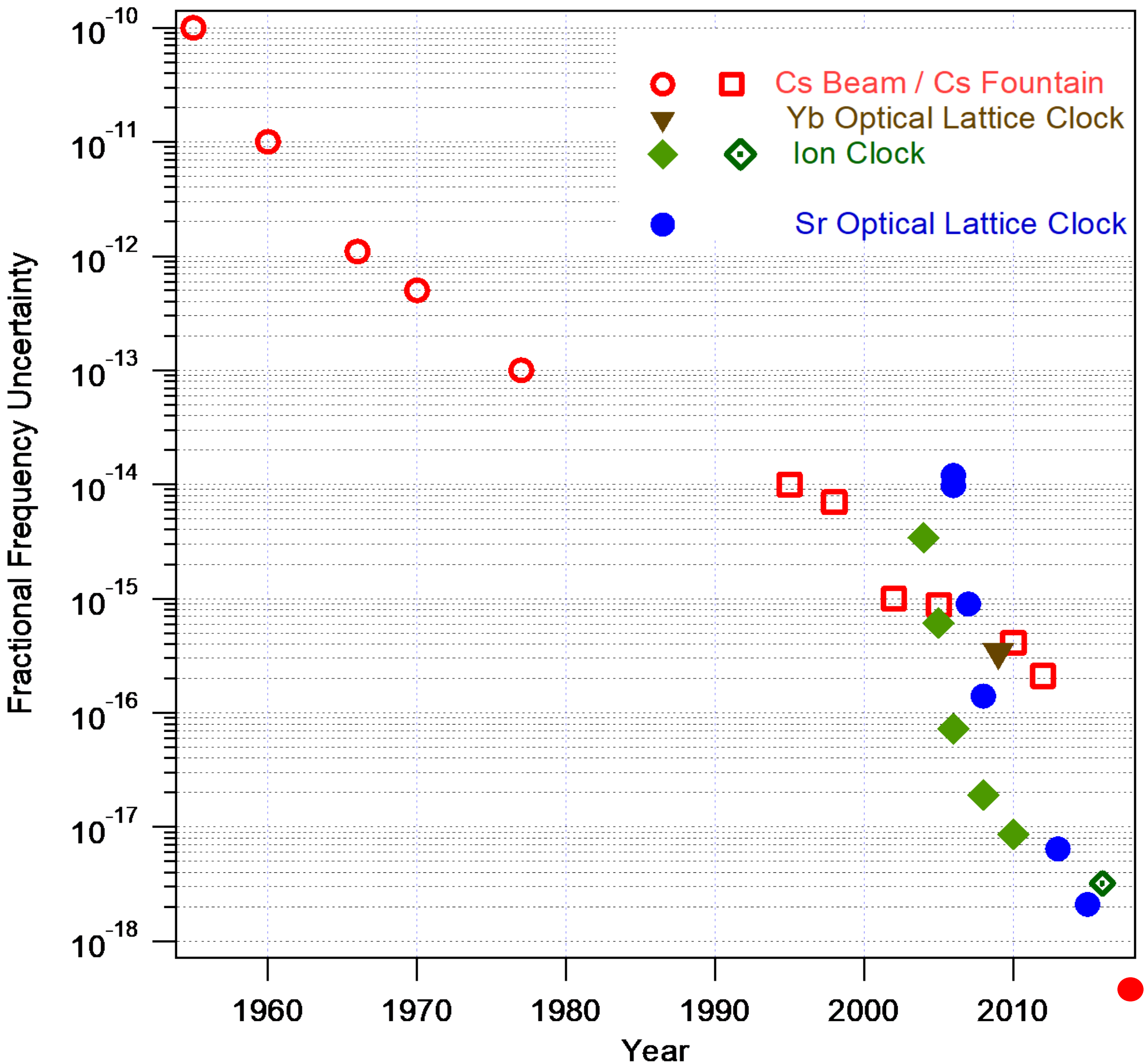


More ticks higher resolution The same holds for clocks

Optical clocks have faster ticks and thus are more precise

A new frontier for clock stability & accuracy

Bloom *et al*., Nature **506**, 71 (2014). Nicholson et al, Nat. Com., 6, 6896(2015)



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

Achieving this 100x faster than other clocks

Now: 2.1×10^{-18}

Alkaline earth clocks -super coherence

Metastable states

$^3P_0$ (e)

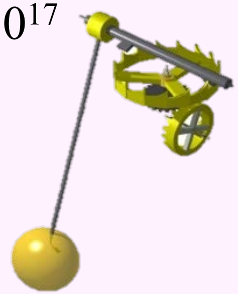
Linewidth $\Delta\nu_0 \sim$ mHz

$\nu_0 = 5\mathrm{x}10^{14}$ Hz

lifetime ~ 10^2 sec

$^1S_0$ (g)

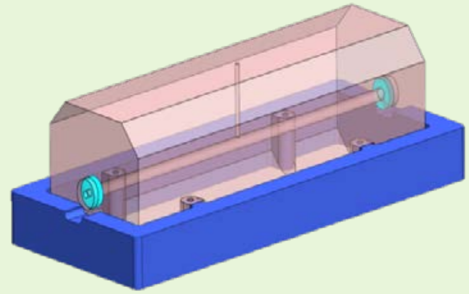
Quality factor: $Q = \nu_0 / \Delta\nu_0 > 10^{17}$

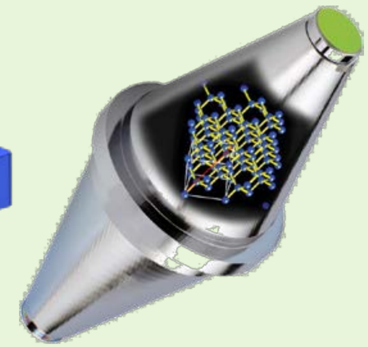


Once set, it swings during the entire age of the universe

JILA state-of-the-art laser:

$Q > 10^{15}$, seconds coherence time

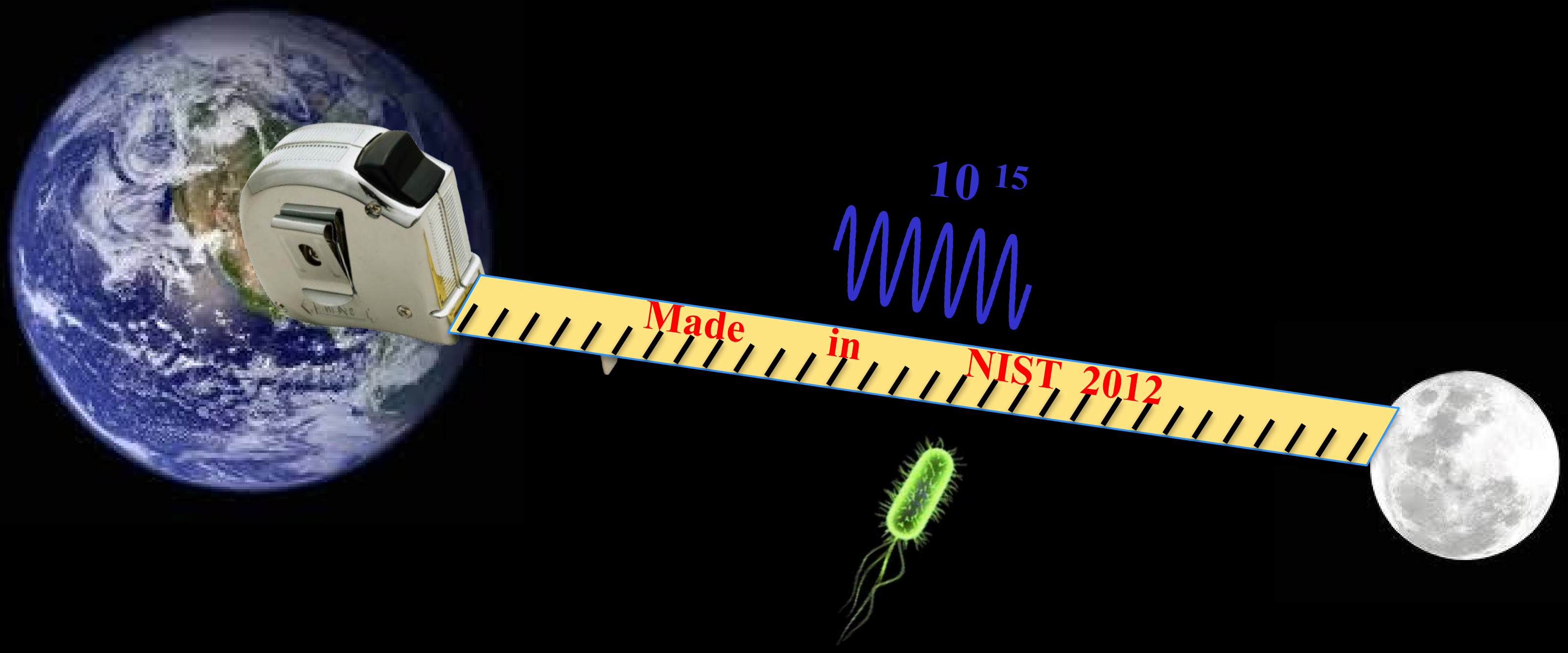




Nicholson *et al*, PRL **109** 230801 (2012)

G.D. Cole *et al* Optica 3, 647 (2016)

JILA LASER



Alkaline earth clocks –super coherence

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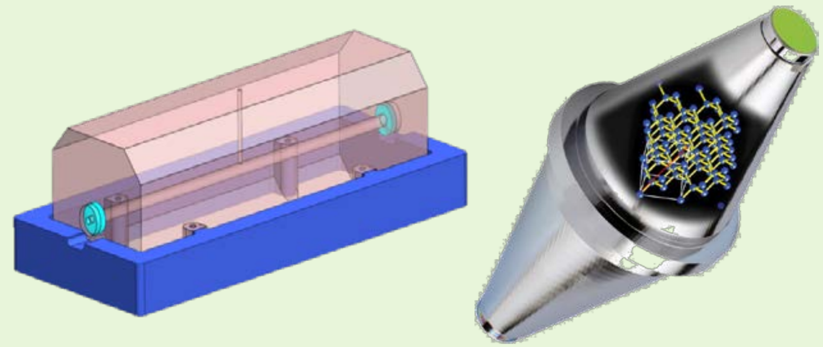
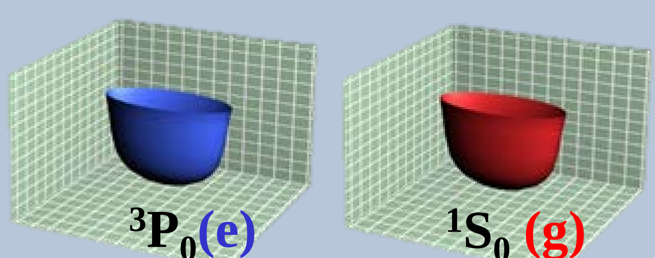


Nicholson *et al*, PRL **109** 230801 (2012)
G.D. Cole *et al* Optica 3, 647 (2016)

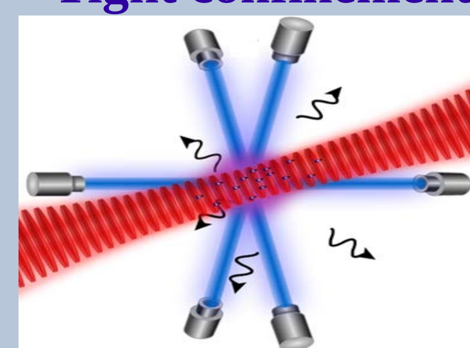
Same trapping potential for both states

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

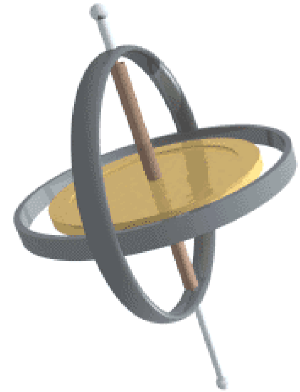


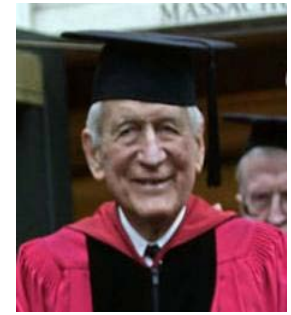
No Doppler
No recoil
No stark shifts

Tight confinement



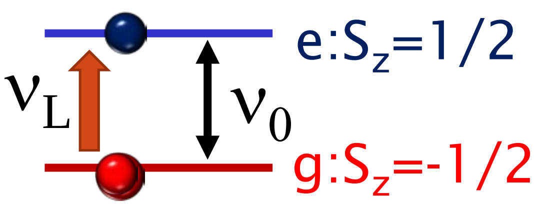
Ramsey Spectroscopy





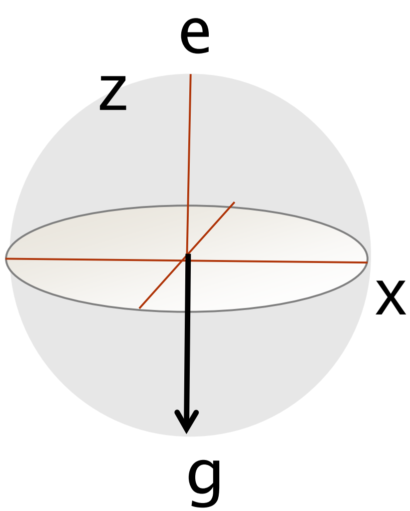
N. Ramsey. Nobel prize 1989

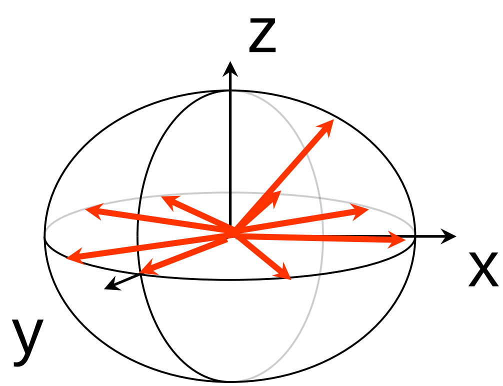
Spin S=1/2

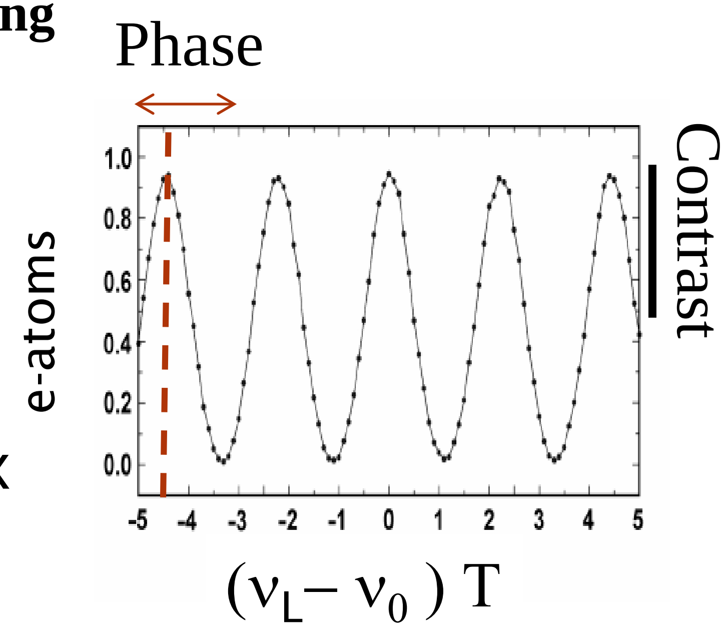


$B=\delta\,\hat{z}$

$\delta = 2\pi(\nu_L - \nu_0)$: **Detuning**

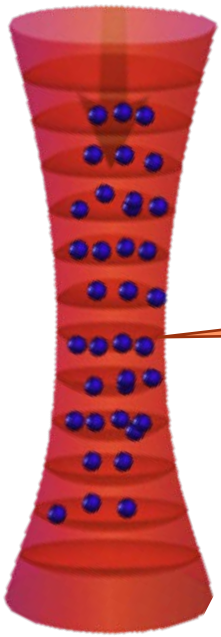


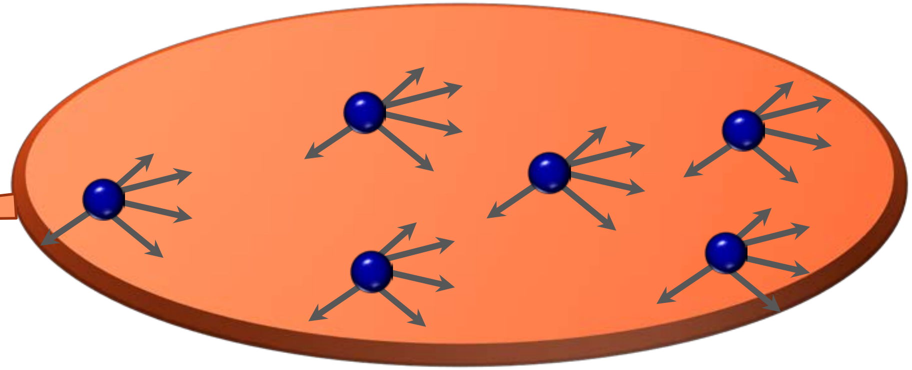




What happens in the real experiment with many atoms?

1D lattice clock: T~μK



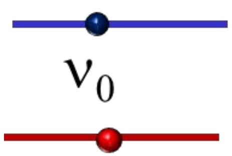


No interactions

Large collective spin:
Better signal to noise

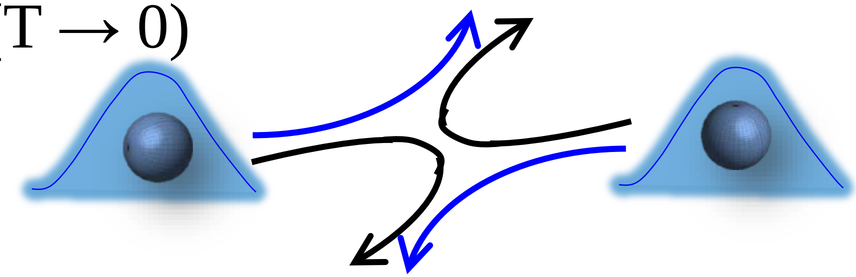
$$S = N/2$$

All the spins
precess collectively

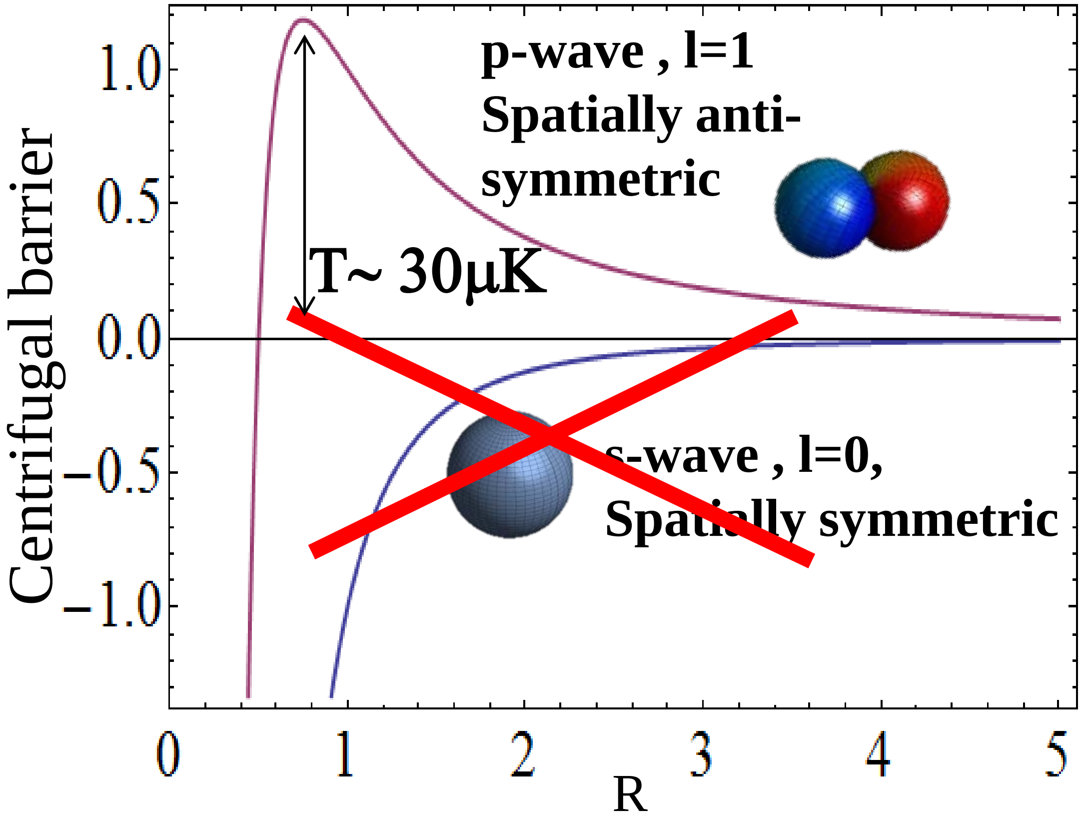


Scattering in quantum mechanics

(1) Particles behave like waves (T → 0)



(2) Angular momentum is quantized: Ultra cold atoms collide via the lowest partial waves

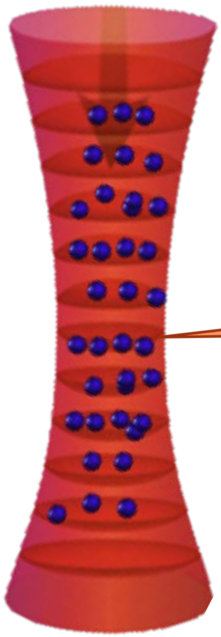


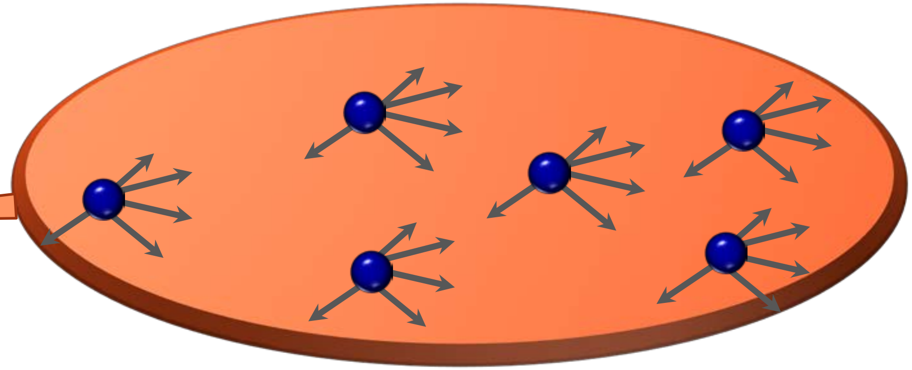
(3) Quantum statistics matter

Pauli Exclusion principle

Identical fermions ⇨ anti-symmetric spatial wave function ⇨ *p*-wave

1D lattice clock: T~μK





No interactions

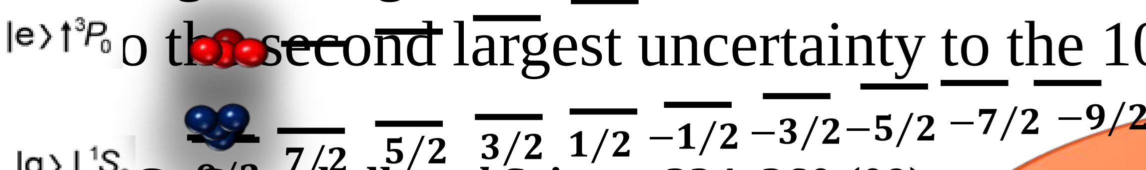
Large collective spin:
Better signal to noise

$S = N/2$

All the spins
precess collectively

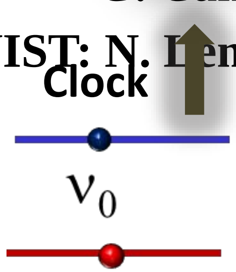
Interactions:

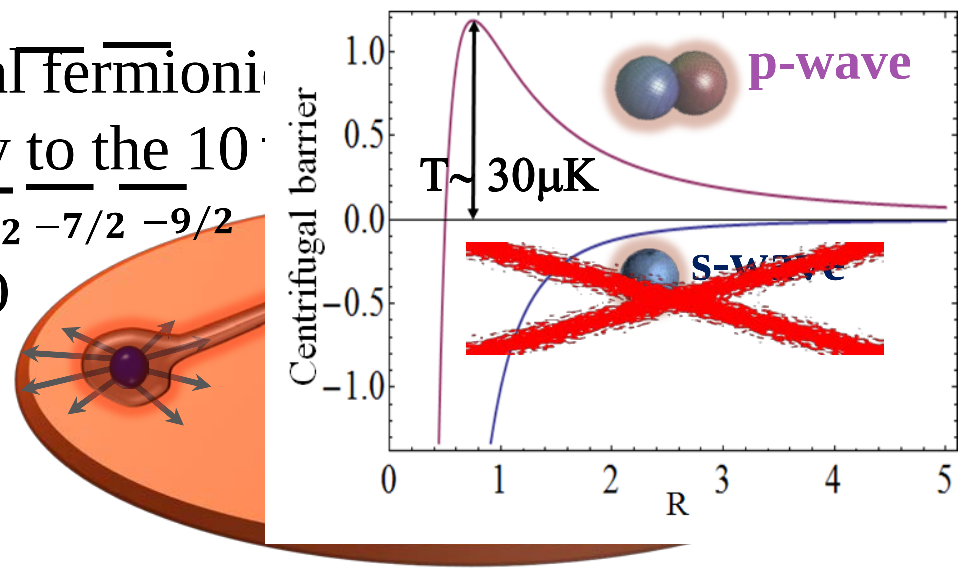
- Degrade signal: even in identical fermioni
  o the second largest uncertainty to the 10



G. Campbell *et al* Science 324, 360 (09)

NIST: N. Lemke *et al* PRL 103,063001 (09)





Many body physics with clocks ?

Atomic Clock

Many-body Physics

Exquisite Control

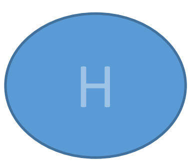
Ultra-precise

Long probing times

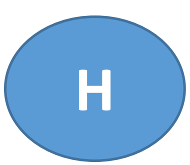
Quantum Magnetism,

Many-body physics

Short probing time



Long probing time

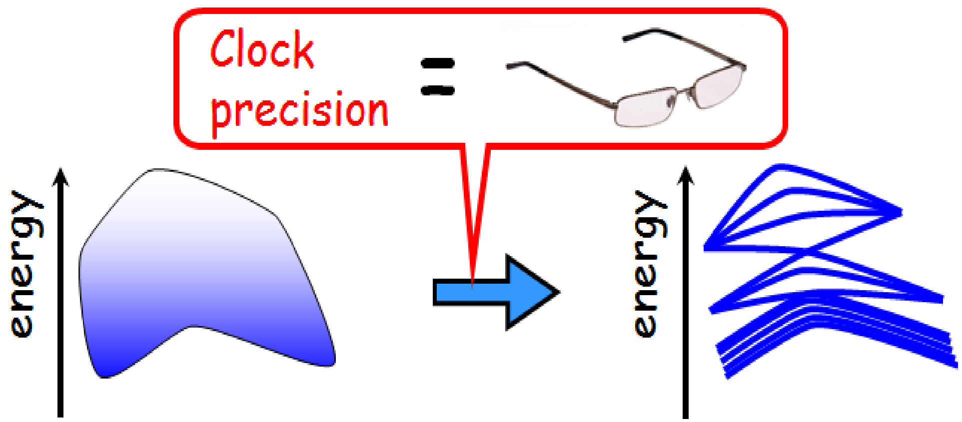


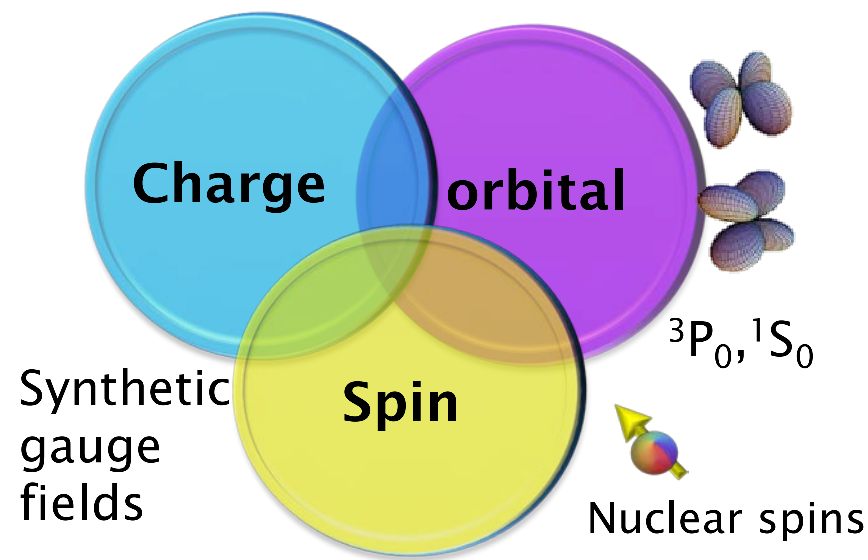
Many body physics with clocks ?

Optical AEA Clock

Many-body Physics

Strongly correlated materials





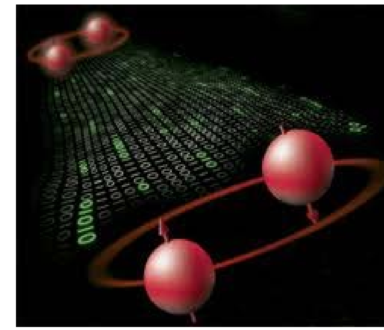
Richard Feynman

"Simulating Physics with computers" *IJTP, 21,467 1982*

The Nobel Prize in Physics 1965

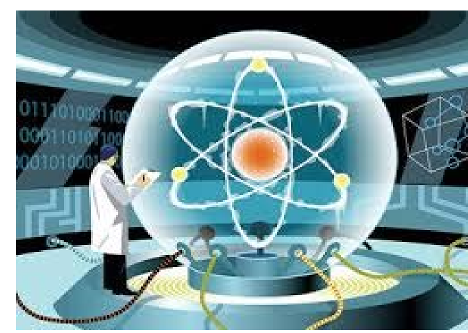
Digital: Quantum Computer

A machine that can perform computations using quantum mechanical elements.

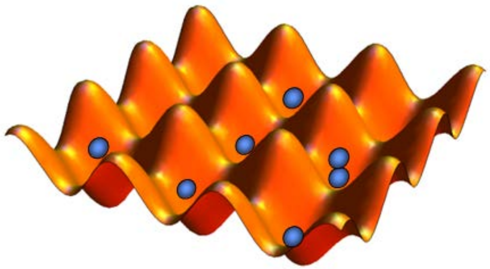


Analog: Quantum Simulation

Use a controllable quantum system to simulate another quantum system



The Ultra-cold atom Simulator



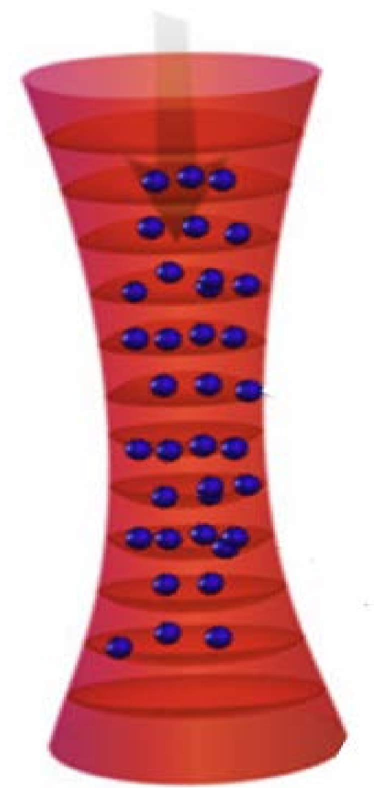
Atoms ↔ Electrons

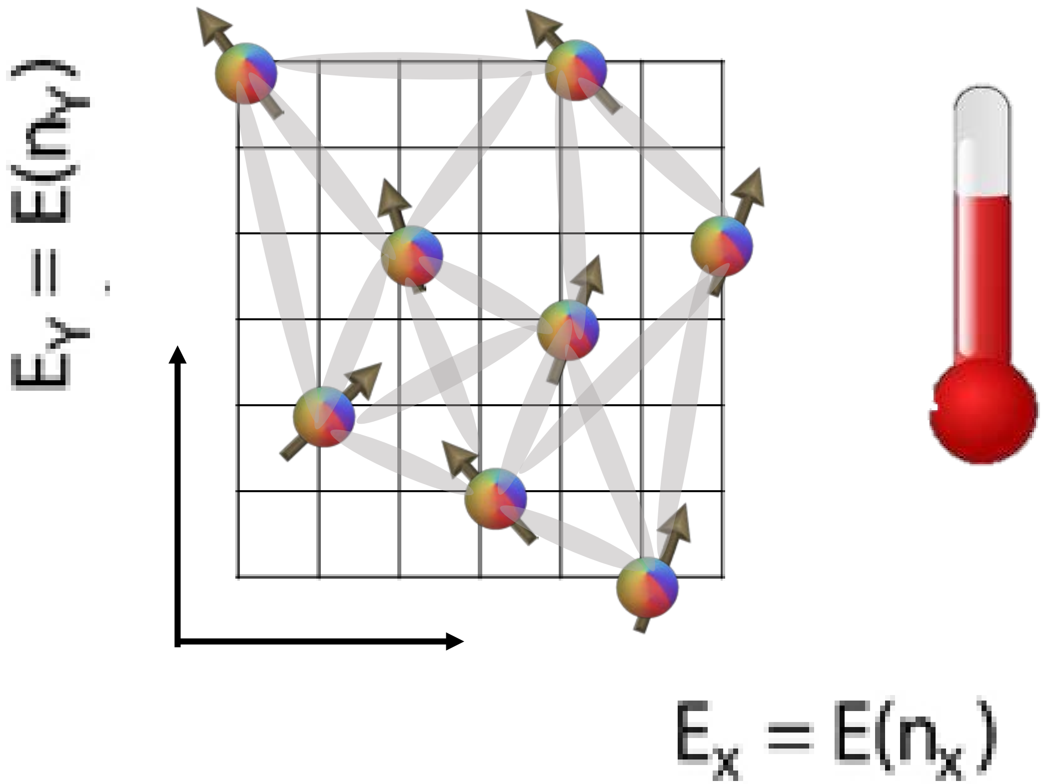
Optical lattice ↔ Solid Crystal

AMO	CM
• Fully controllable, no defects, no vibrations	• Very complex condensed matter environment
• Lattice spacing micrometers	• Lattice spacing Angstroms
• Atoms mass ~ 10-100 amu	• Electron mass 1/1900 amu
• Low-Temperature : 0.01 nK	• Low –Temperature : T~ 1 K

Quantum magnetism

in an optical lattice clock at micro K

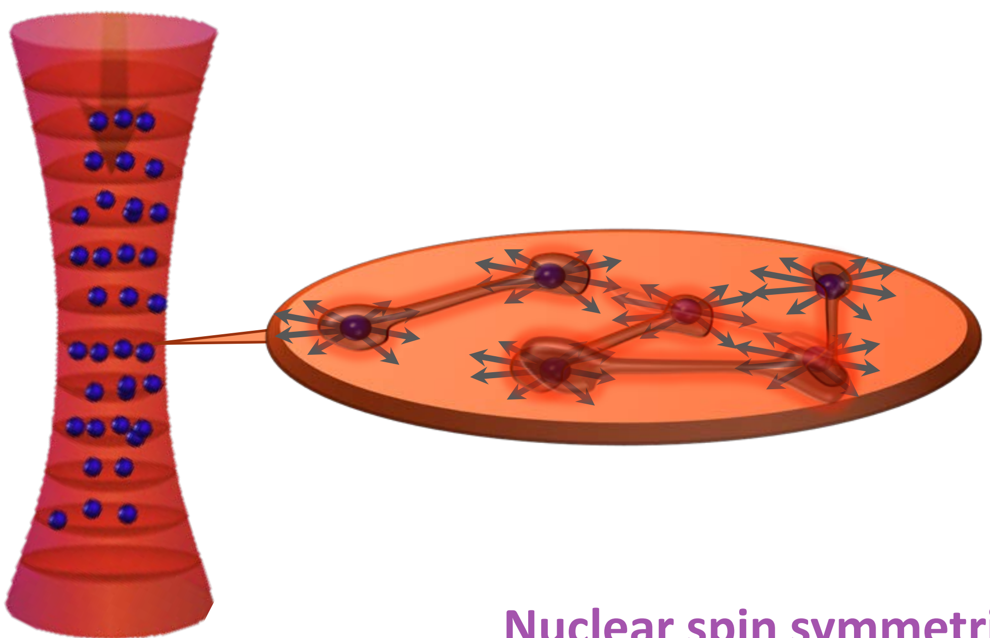


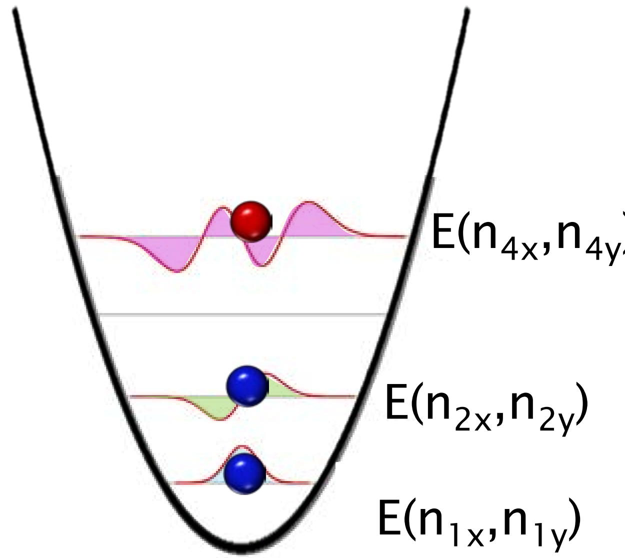


M. Martin *et al*, Science 341, 632 (2013)

N. Lemke *et al*, PRL 107, 103902 (2011)

P-wave Interactions

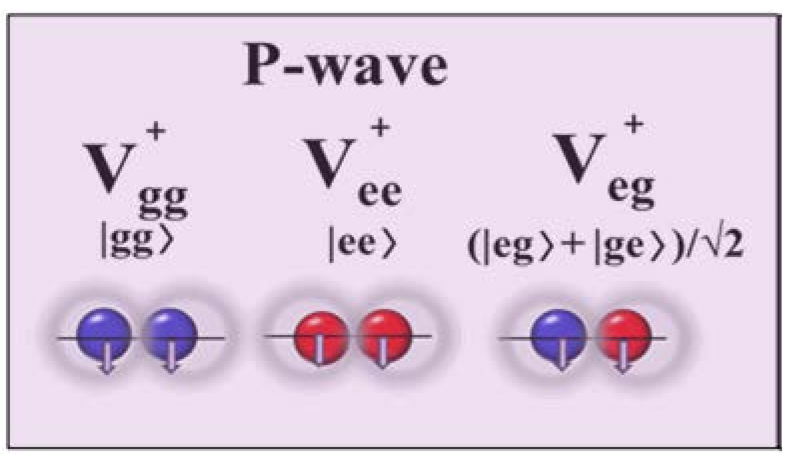




Nuclear spin symmetric fermions

$^3P_0$ (e)

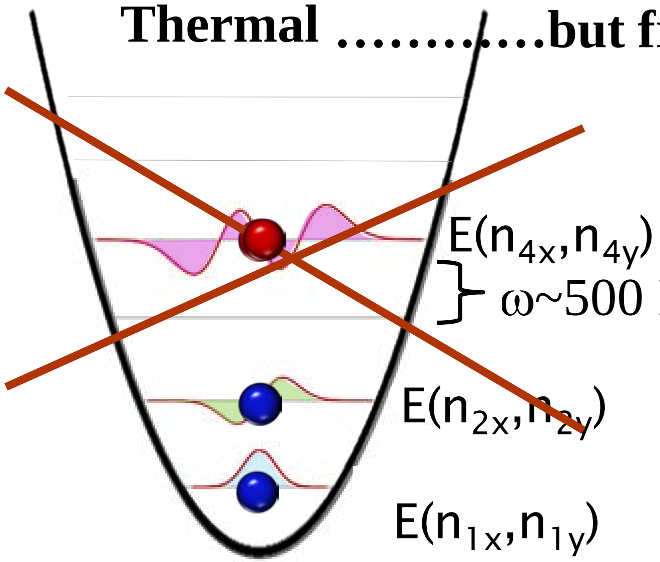
$^1S_0$ (g)



1D lattice clock: A large spin simulator

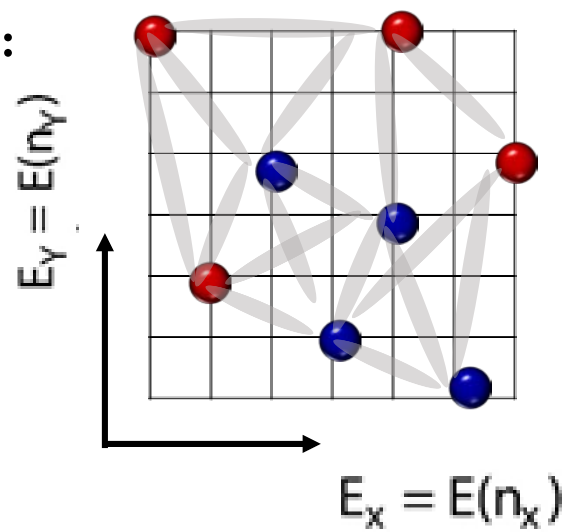
$^3P_0$ (e) $^1S_0$ (g) **Interaction Energy~ 1 Hz** **Weak interactions simplify physics**

Thermal ……….….but frozen motional levels



Delocalized modes: Long range interactions

Energy lattice:



Collective spin model

$$H = -\delta S^z + \chi (S^z)^2 + C\mathcal{N} S^z$$

δ:Detuning

$$S^\alpha = \sum_{n=1}^{\mathcal{N}} S_n^\alpha$$

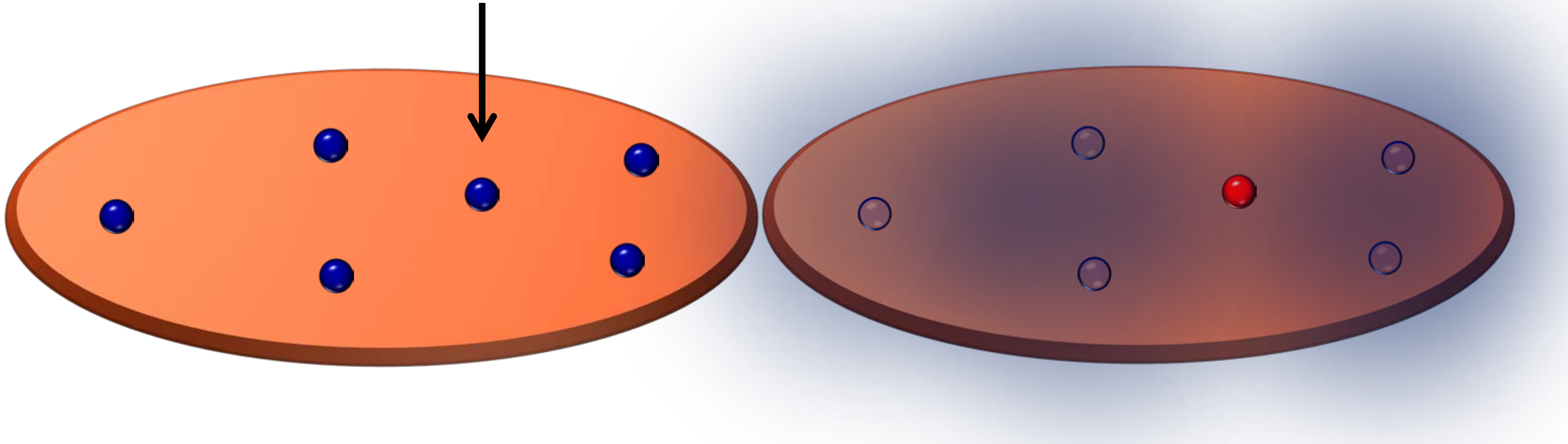
$\mathcal{N}$ atoms

χ and C: P-wave Interaction parameters

$$C = (V_{ee} - V_{gg})/2$$

$$\chi = (V_{ee} - 2V_{eg} + V_{gg})/2$$

Mean Field: Phase shift



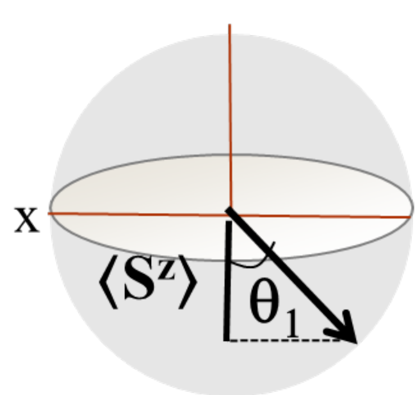
Treat other surrounding atoms as an average

$$-\delta\, S^z + \chi (S^z)^2 \;\rightarrow -\delta\, S^z + 2\chi\, S^z \langle S^z \rangle$$

$$\delta \rightarrow \delta - 2\chi \langle S^z \rangle$$

Density shift

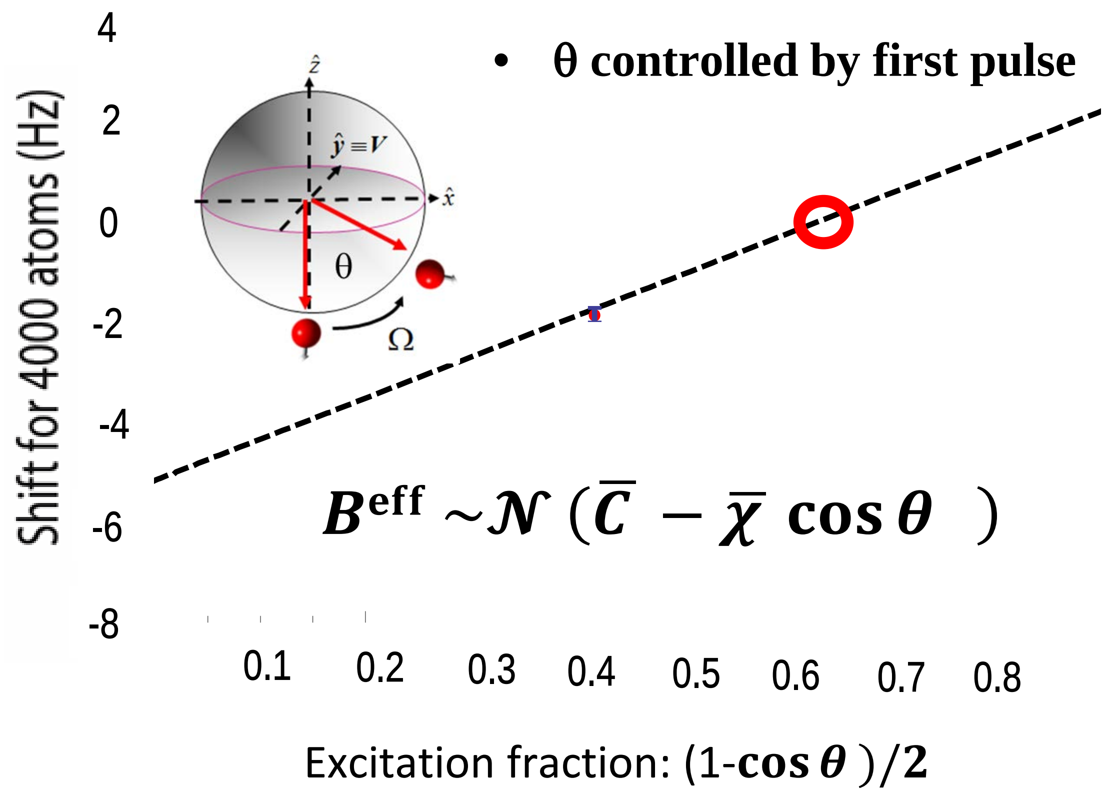
Spin precesses with a modified rate with depends on atom number



θ_1 controlled by first pulse area

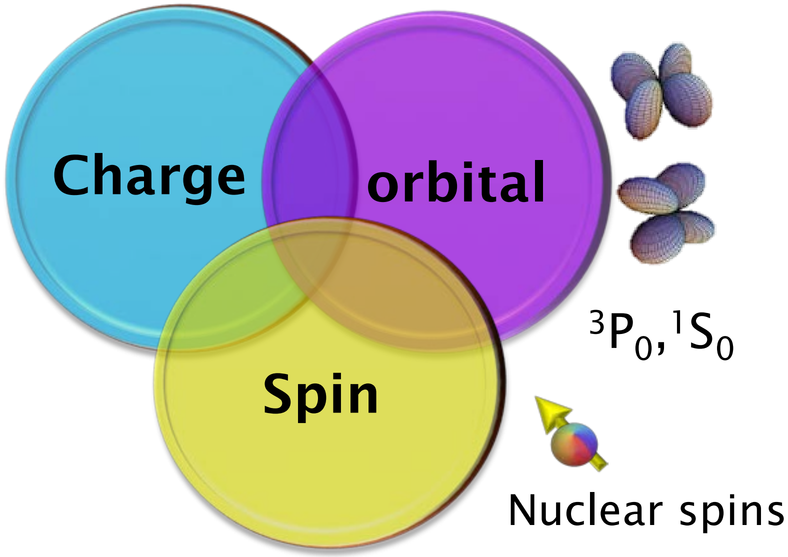
P-wave interactions: 1D lattice clock

Theory vs experiment



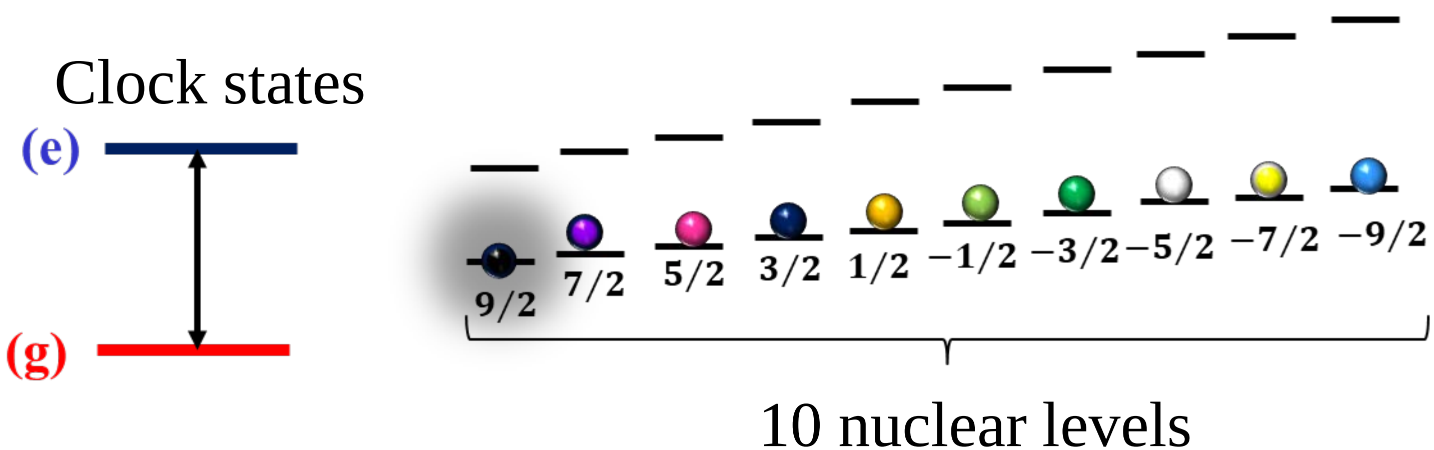
- **Determine p-wave interaction parameters**
  Ludlow *et al*, Phys. Rev. A 84, 052724 (2011)
- **Operate sweet spot: no density shift**
  Lemke *et al* *PRL* 107, 103902 (2011)

Direct observation of SU(N) symmetry

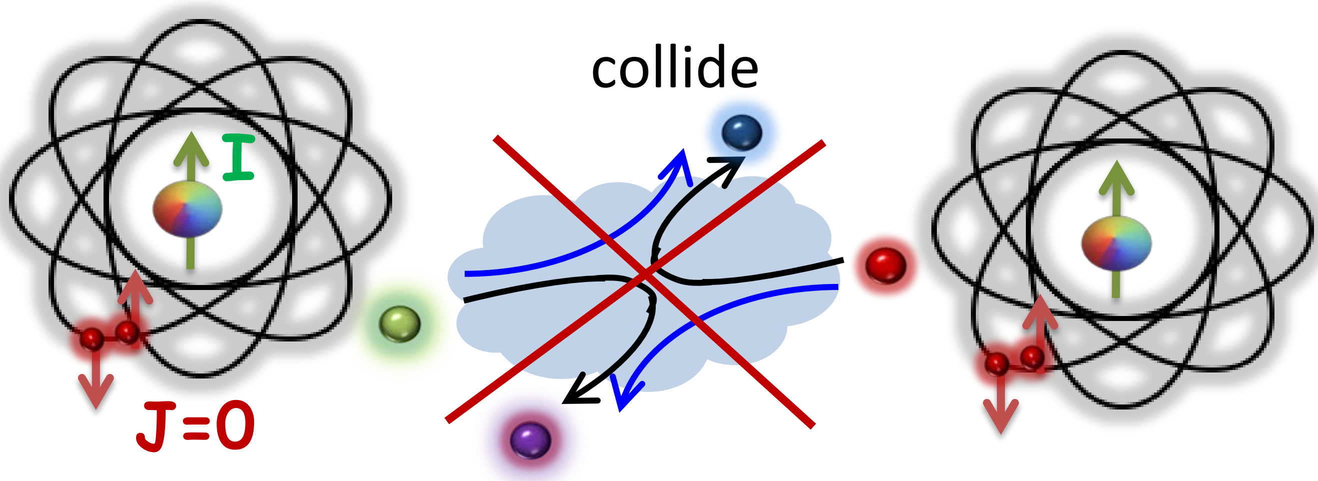


JILA: Science, 345,1467 (2014)

See also: Munich (Nature Physics, 2014) Florence (PRL, 2014) groups

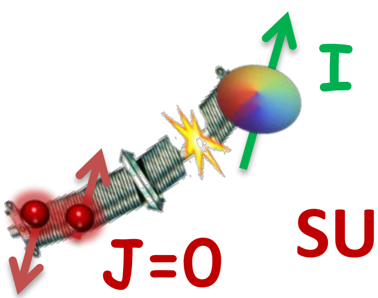


Alkaline-earth Collisions



hyperfine coupling
$I \cdot J = 0.$

Nuclear spin and electron spin decoupled



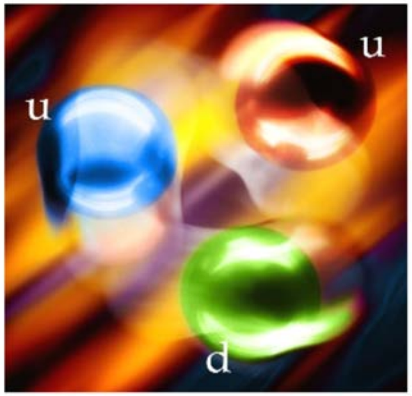
Up to N=2I+1=10

SU(N=2I+1) symmetry: I independent collisions

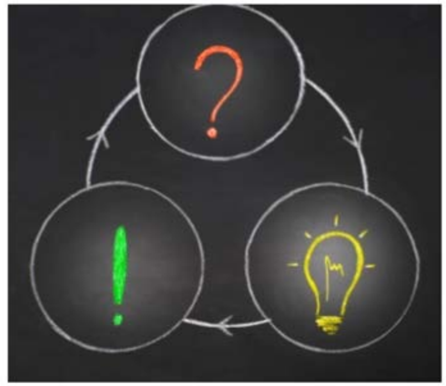
No spin changing collisions.

A.Gorshkov,…,AMR, Nature P.(2010) && M. Cazalilla *et al* NJP (2010)

SU(N) symmetry: remarkable consequences in a quantum system



Fundamental: Quarks: SU(3) symmetry



Easier calculations: 1/N expansion

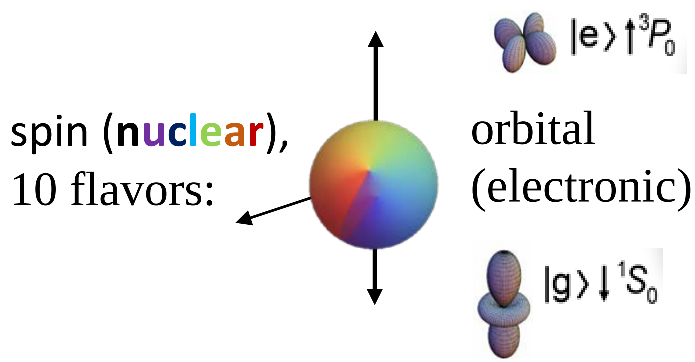
Error-free quantum computer

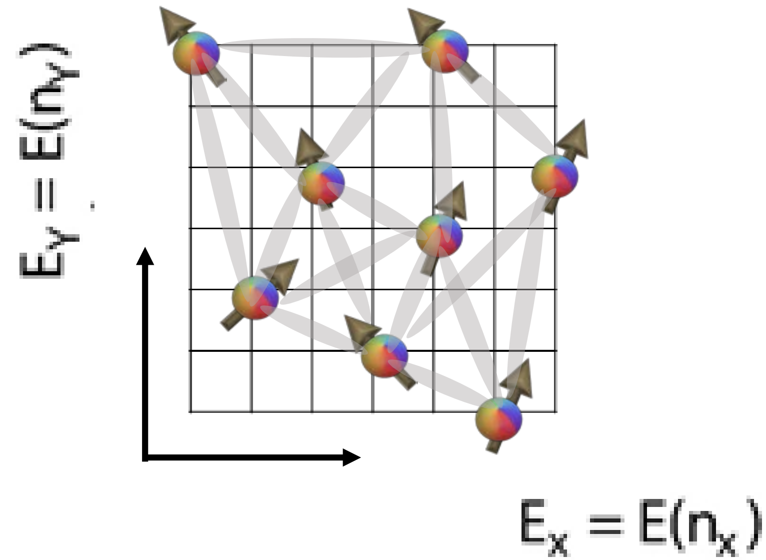
New states of matter

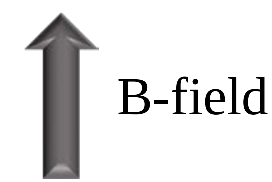
Chiral spin liquids: disordered even at T=0. Brother of fractional quantum Hall, anyon excitations.

M Hermele, V Gurarie, AMR, PRL 103 135301 (2009).

SU(N) orbital magnetism



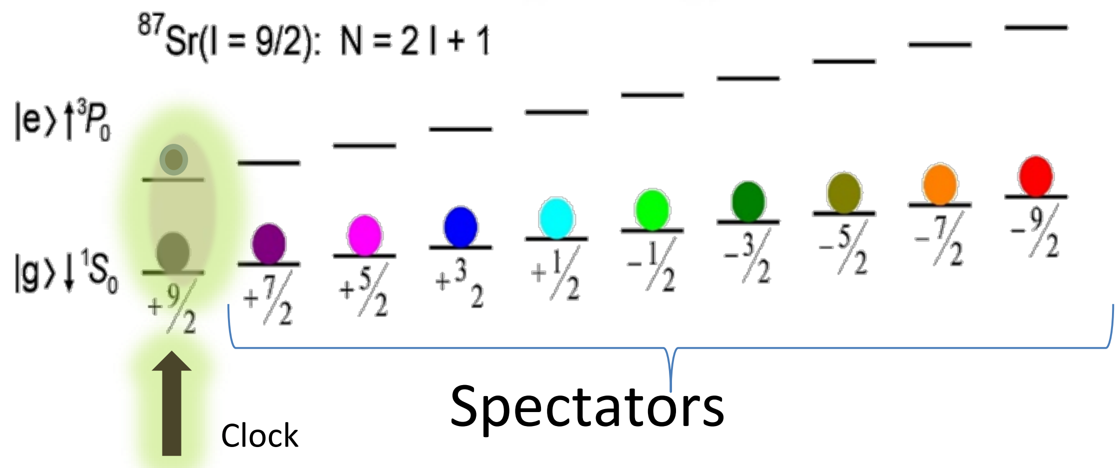




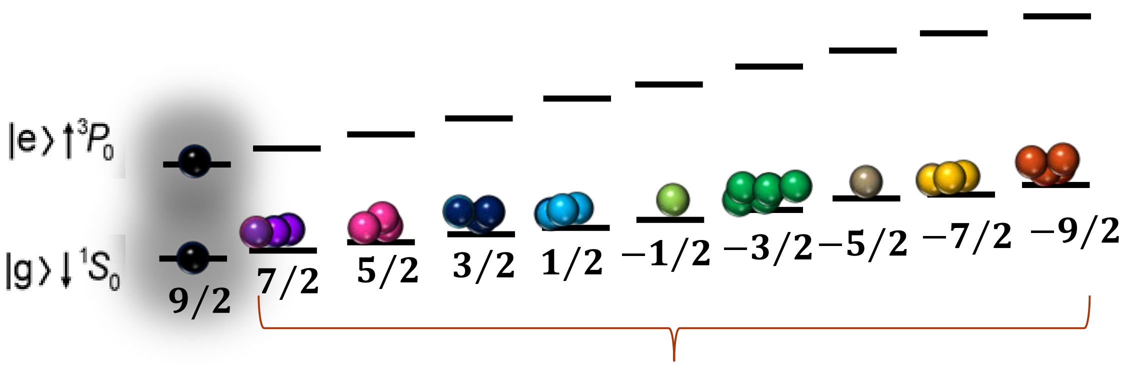
Atoms trapped in array of disk-shaped pancake

Ultra-stable clock laser

Statistical mixture



Density shifts and SU(N) symmetry



$\mathcal{N}_I$
Interrogated

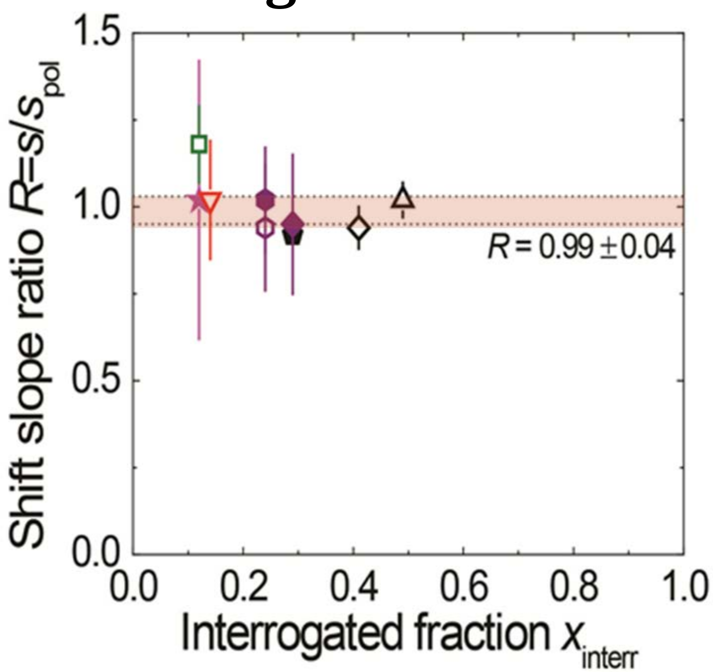
$\mathcal{N}_S$ **: Spectators**

- SU(N): density shift only depends on the total number of spectators not on its distribution

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

Interrogated atoms p-wave shift

Spectators generate a density shift



Confirmed SU (N) symmetry in the clock at the 3% level

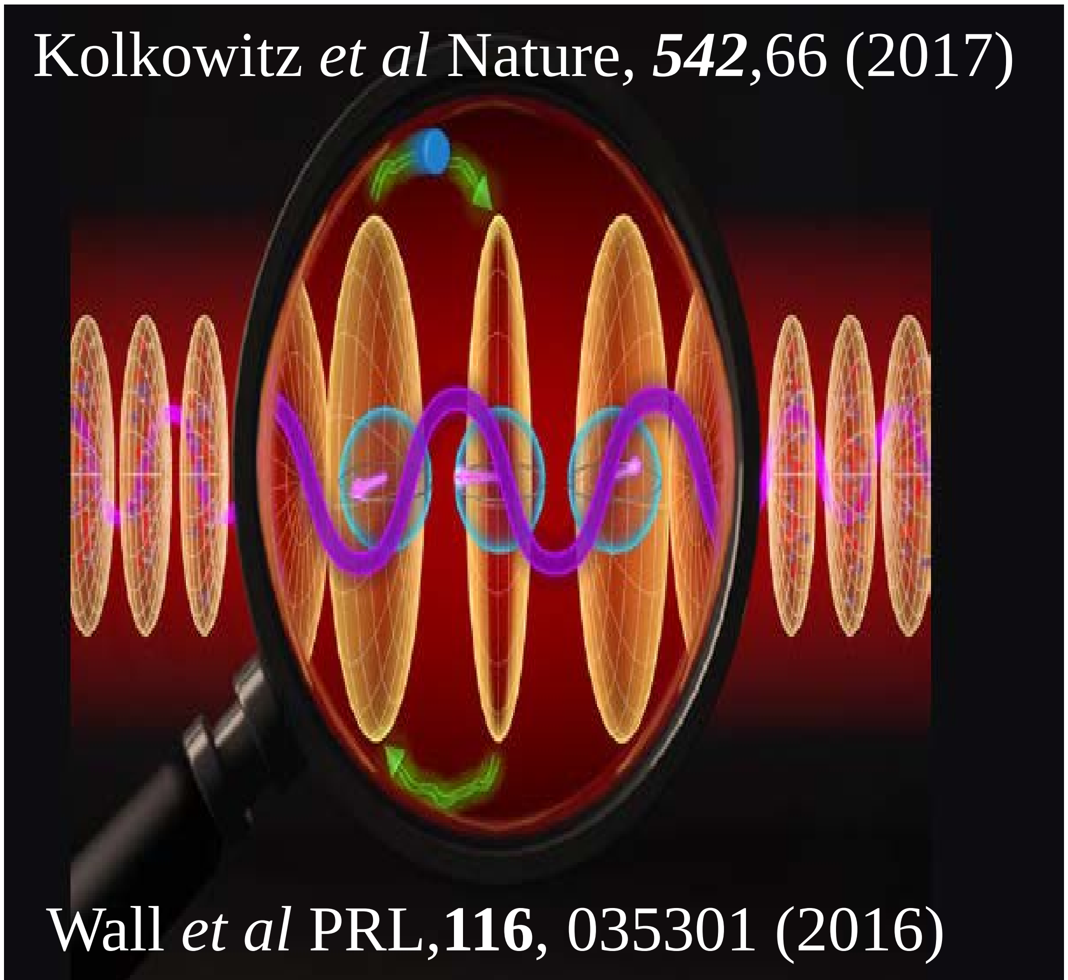
Science (2014) , 345,1467

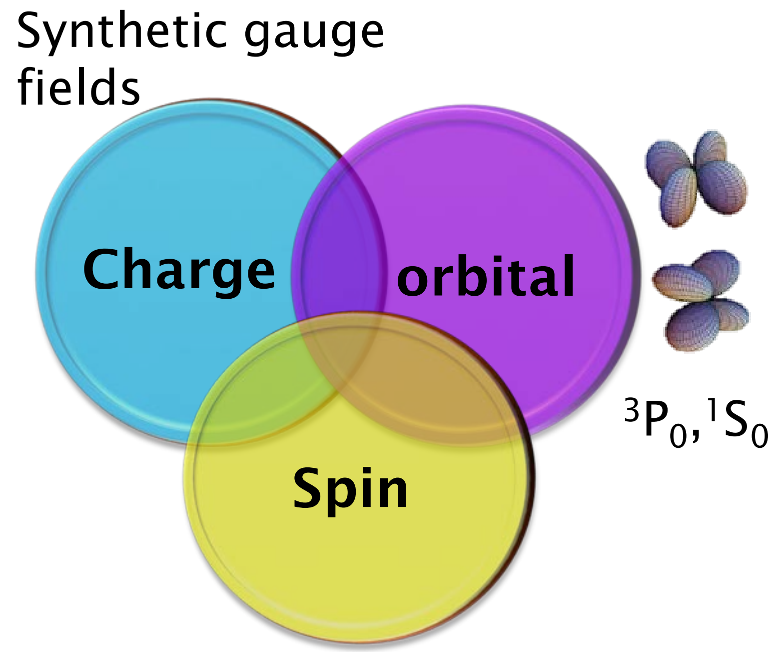
www.idigitaltimes.com/big-bang-theory-season-8-premiere-spoilers-will-sheldons-spin-symmetry-theory-paper-pass-peer-review

Getting Started

According to scientists working on the big bang theory it all began with Sheldon's participation in a JILA research team hoping to confirm via direct observation the spin symmetry theory in quantum physics. Sheldon, used to working in the theoretical realm, found his colleagues alienating, like Penny in Seasons 1 through 3 of "The Big Bang Theory." However, under the tutelage of Ana Maria Rey and Jun Ye, Sheldon has learned how best to unify the two fields, resulting in their remarkable new findings.

1D lattice clock:
Synthetic fields/spin-orbit physics





Ultra-cold Atoms Implementation

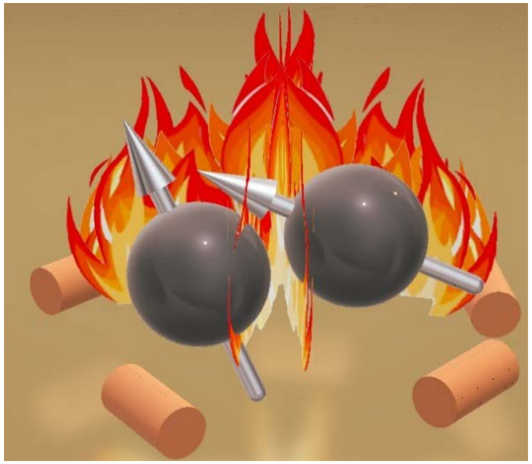
Generated by laser beams

Advantage: Fully Controllable

Issues: Heating from spontaneous emission

Important Steps (before 2017):

Rb: JQI(Spielman), China(J. Pan), Washington St (Engels), Munich(Bloch), Purdue (Engels), **Harvard (Greiner): pair of particles**
Na: MIT (Ketterle)
K: China (Zhang)
Li: MIT (Zwierlein)
Dy: Stanford (Lev)
Yb: Lens (Fallani)



No interplay observed with interactions in a many-body lattice system

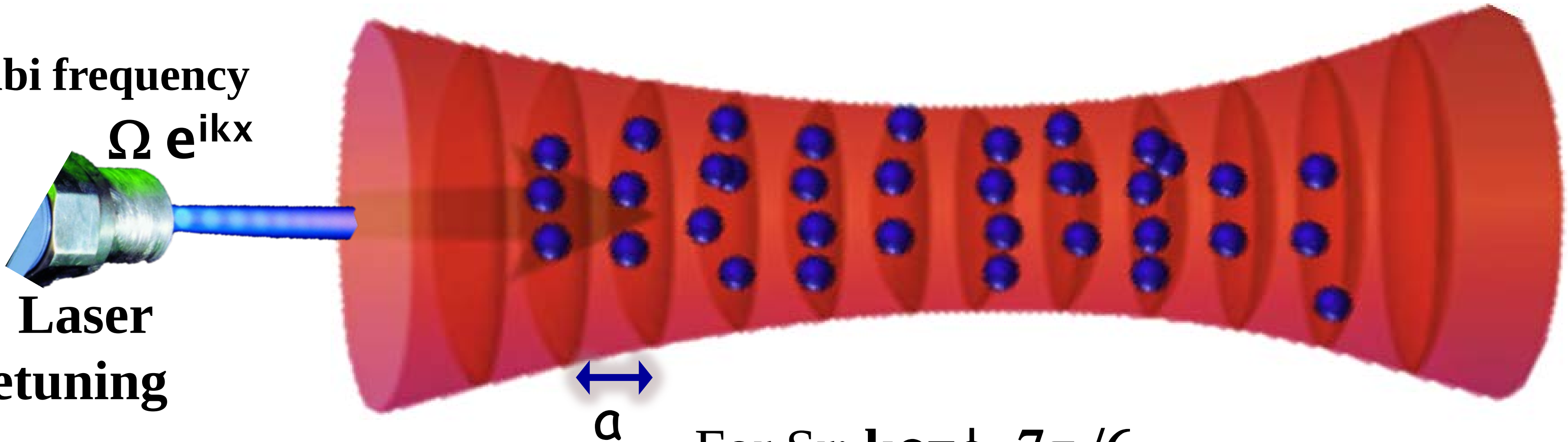
Optical lattice clocks: New opportunities

SOC Coupled Fermions in a Clock

Rabi frequency

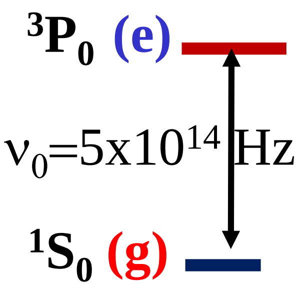
$\Omega\ e^{ikx}$

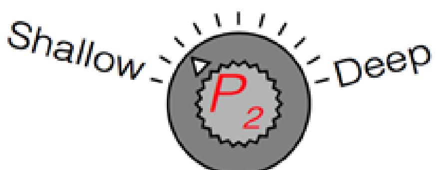
δ: Laser detuning

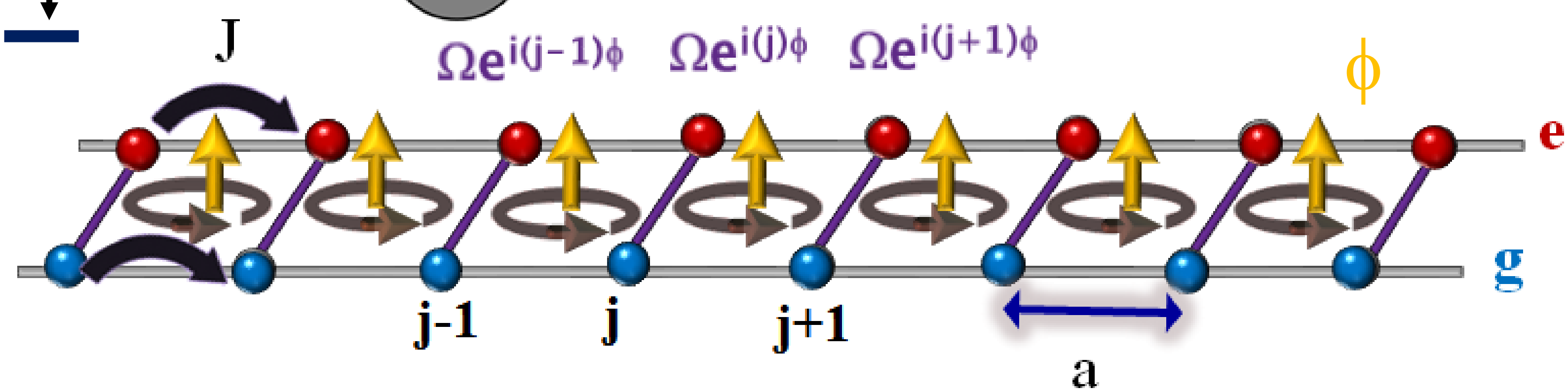


For Sr: $\mathbf{ka}=\phi=7\pi/6$

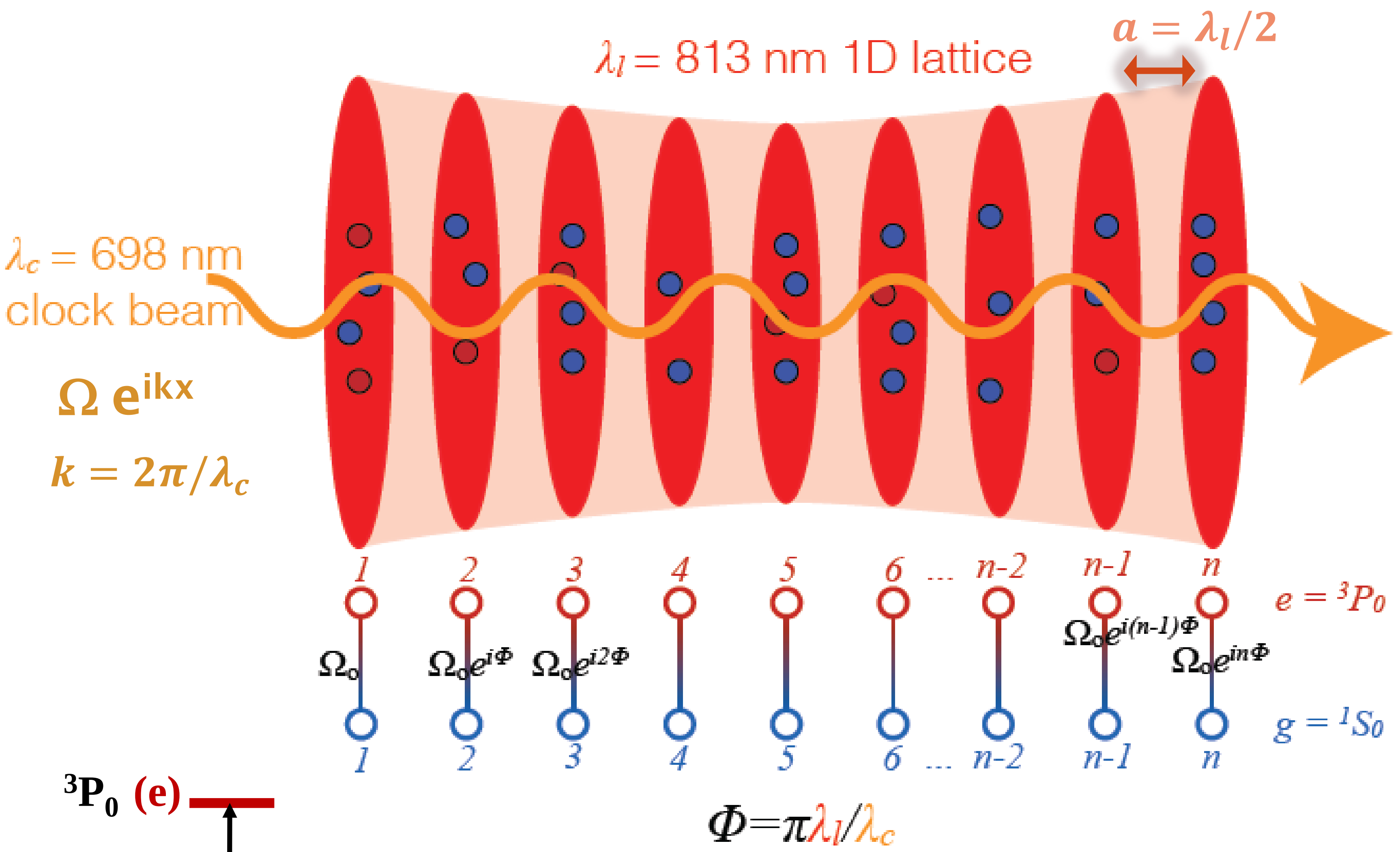
Allow tunneling to feel the phase

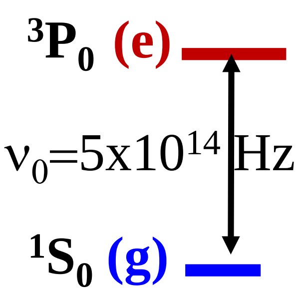






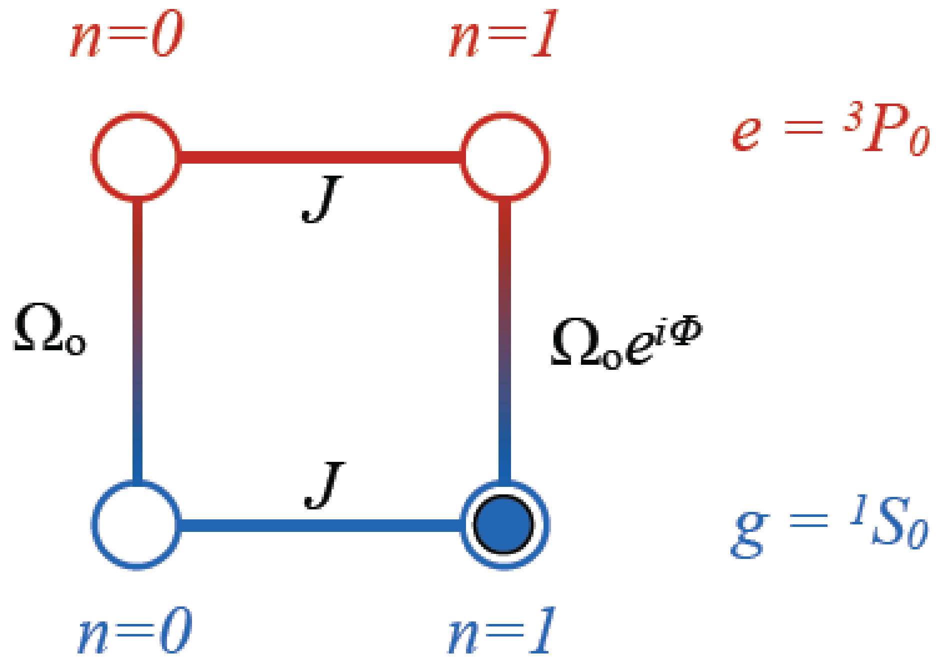
Generating a synthetic magnetic field in our clock:





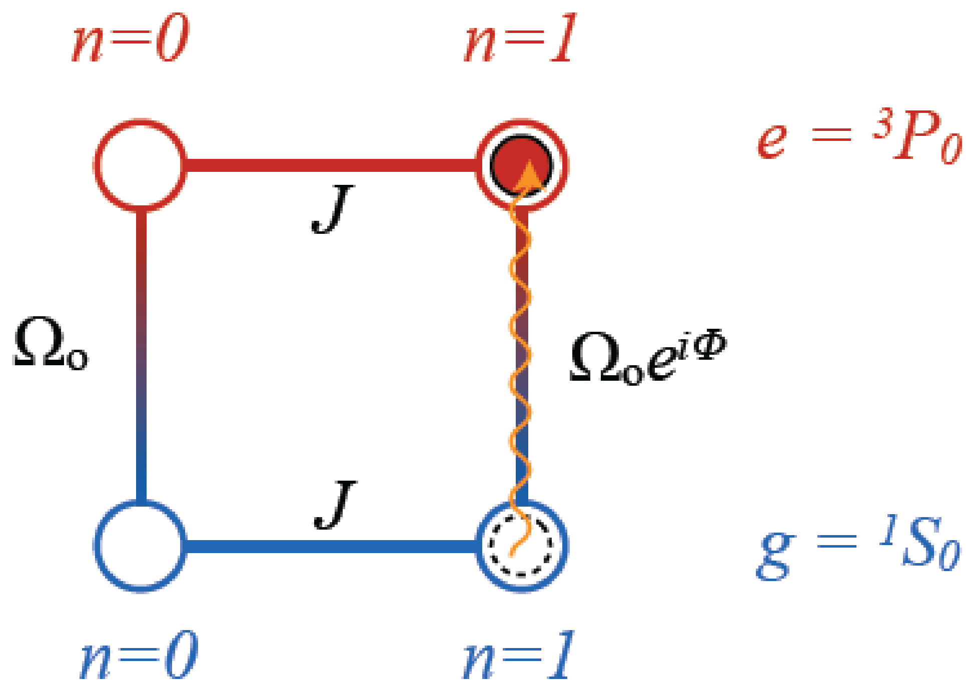
For Sr: $ka = \Phi = 7\pi/6$

Generating a synthetic magnetic field in our clock:



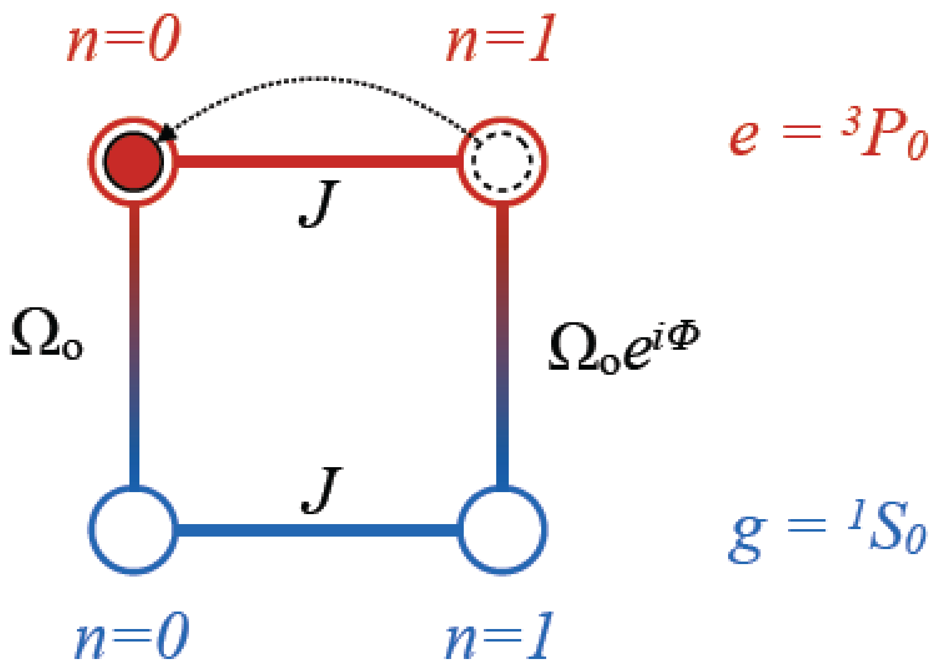
$$\psi_o = |1, g\rangle$$

Generating a synthetic magnetic field in our clock:



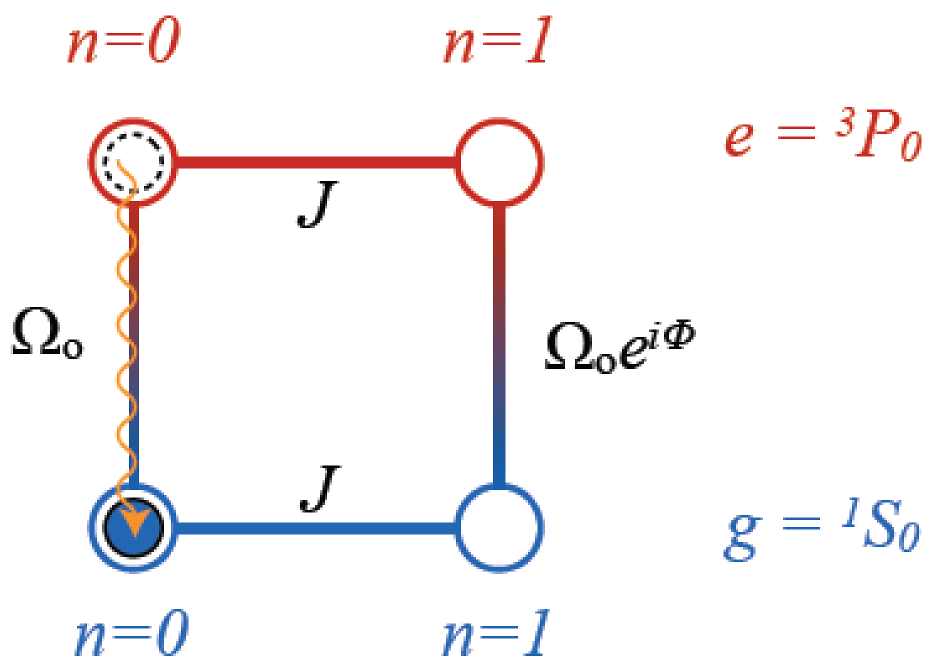
$$\psi_1 = e^{i\Phi}\left|1,e\right\rangle$$

Generating a synthetic magnetic field in our clock:



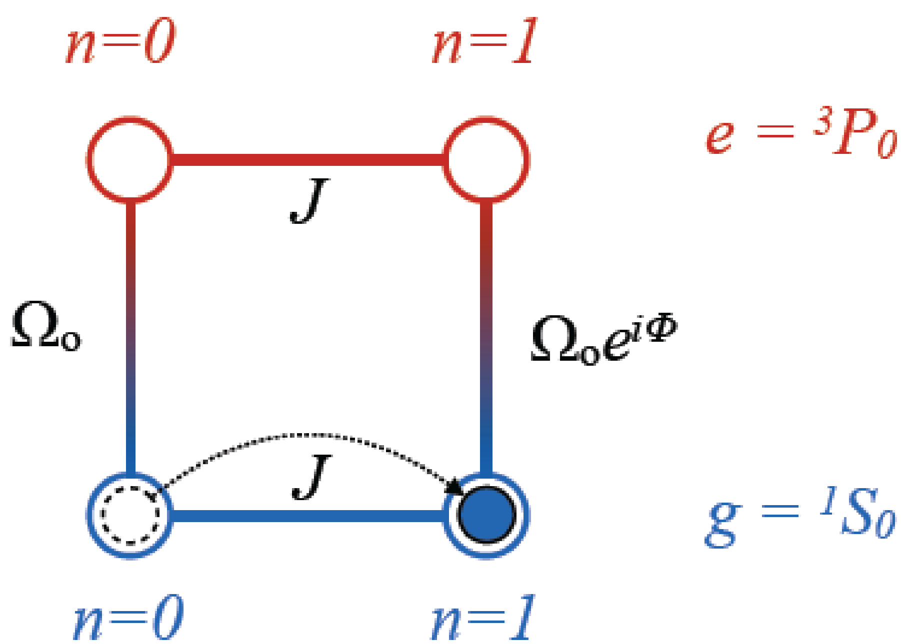
$$\psi_2 = e^{i\Phi}|0,e\rangle$$

Generating a synthetic magnetic field in our clock:



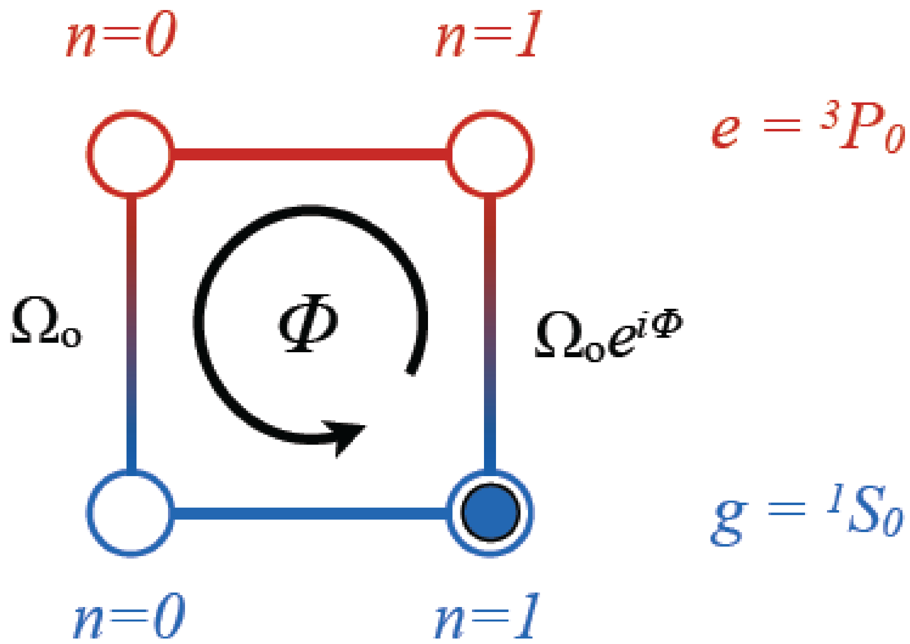
$$\psi_3 = e^{i\Phi}|0,g\rangle$$

Generating a synthetic magnetic field in our clock:



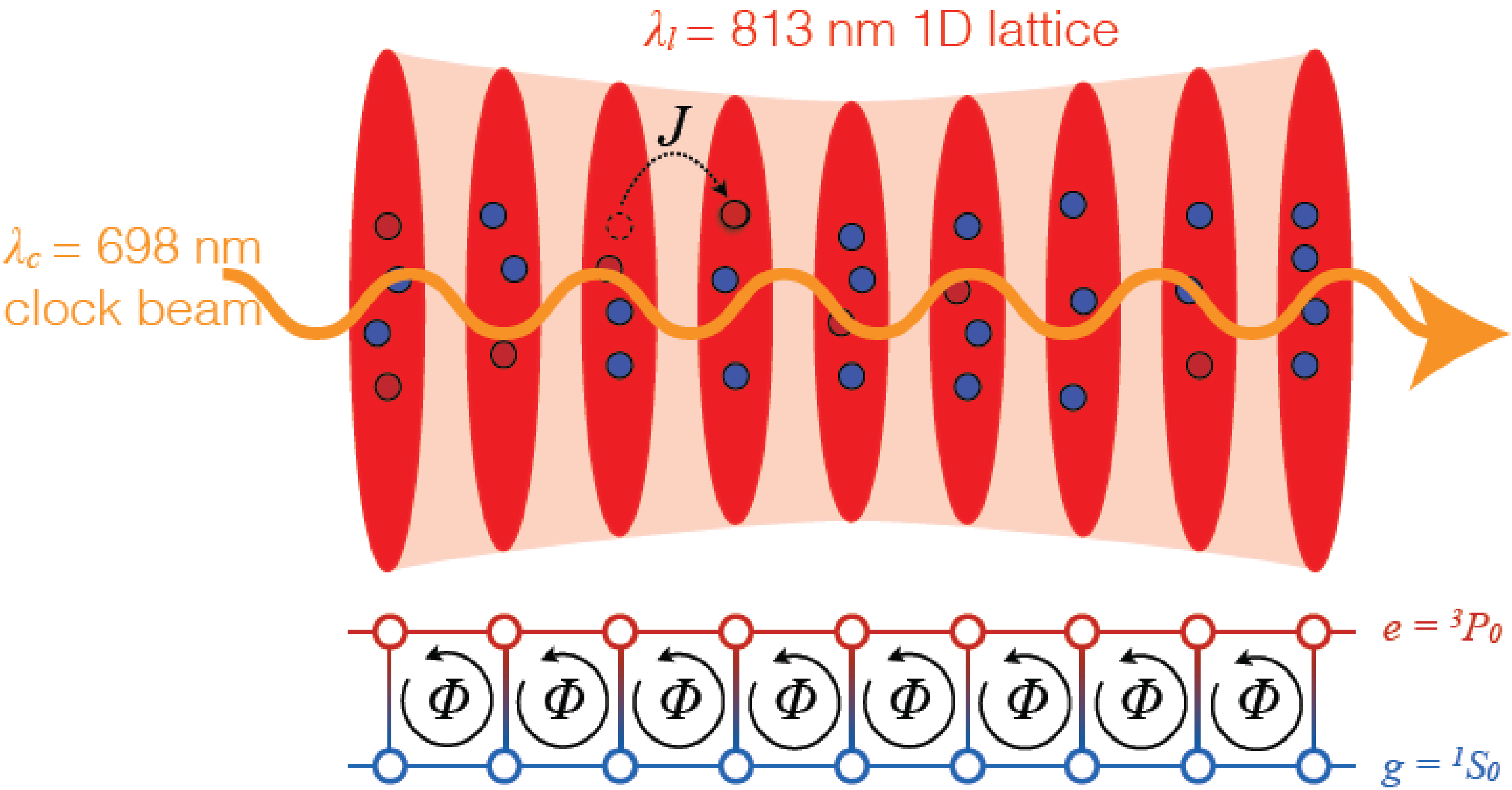
$$\psi_f = e^{i\Phi}\left|1, g\right\rangle$$

Generating a synthetic magnetic field in our clock:



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

Generating a synthetic magnetic field in our clock:



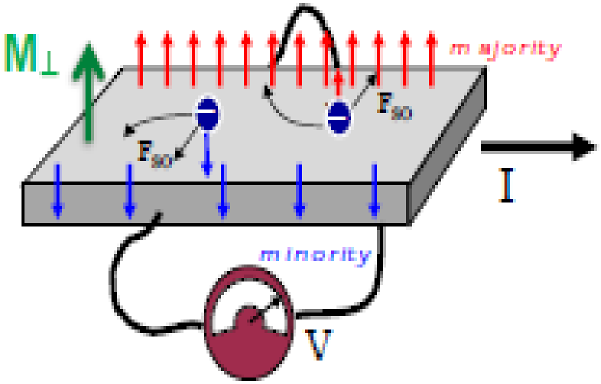
$$\Phi = \pi\lambda_l/\lambda_c$$

Two-leg flux ladder: atoms feel effective Lorentz force

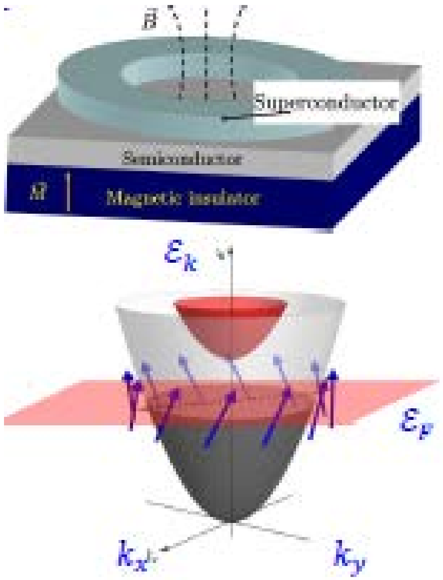
Spin-orbit coupling: Fundamental in Nature

Coupling between electron motion and its spin: relativistic effect

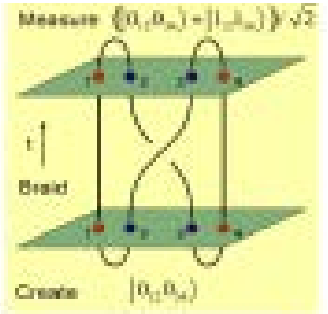
Spintronic devises

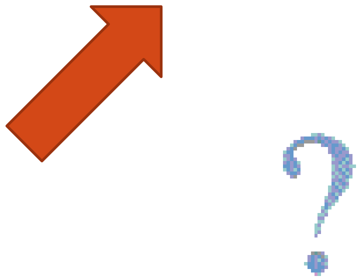


Topological superconductors



Quantum Information



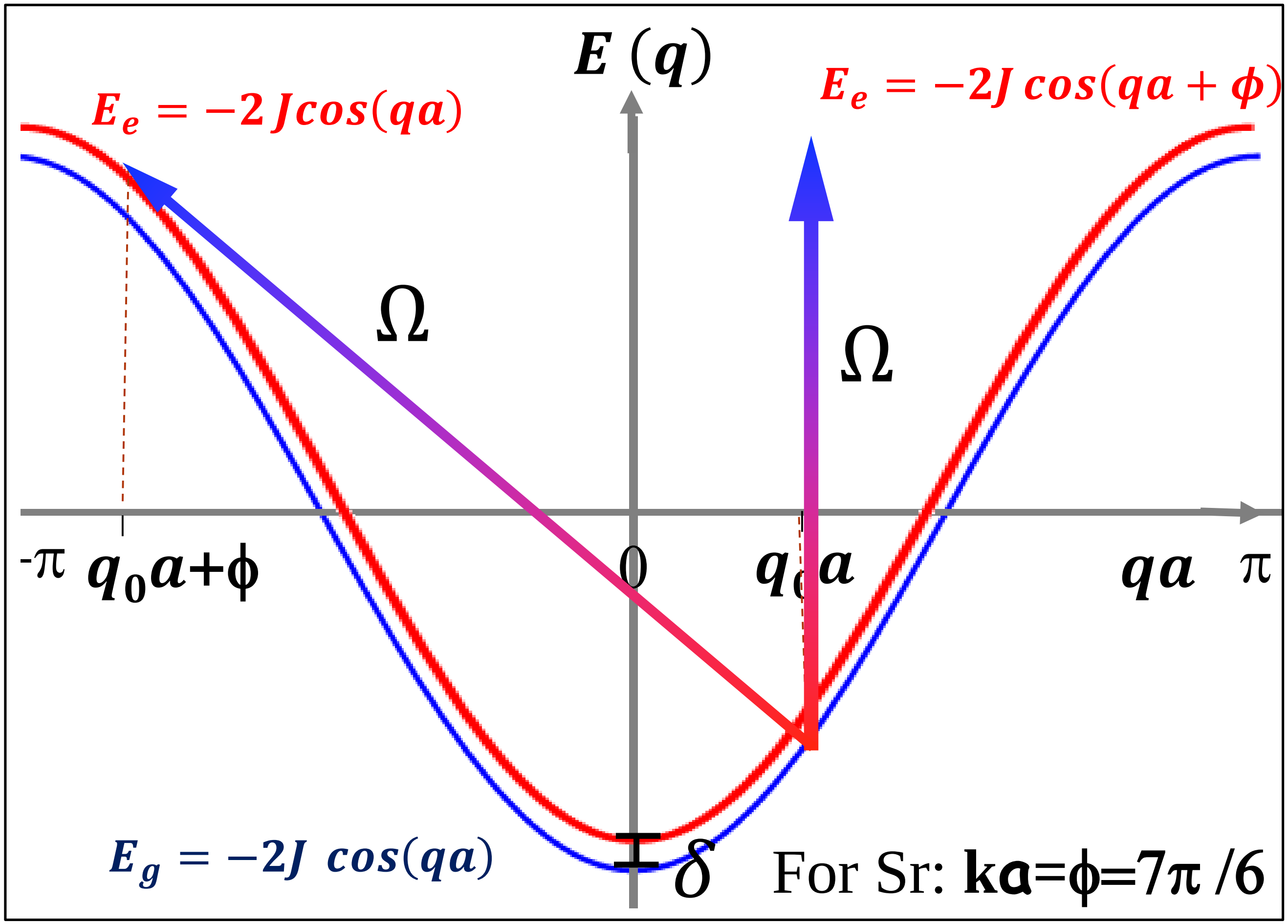


Topological Insulators

Spin-orbit coupling

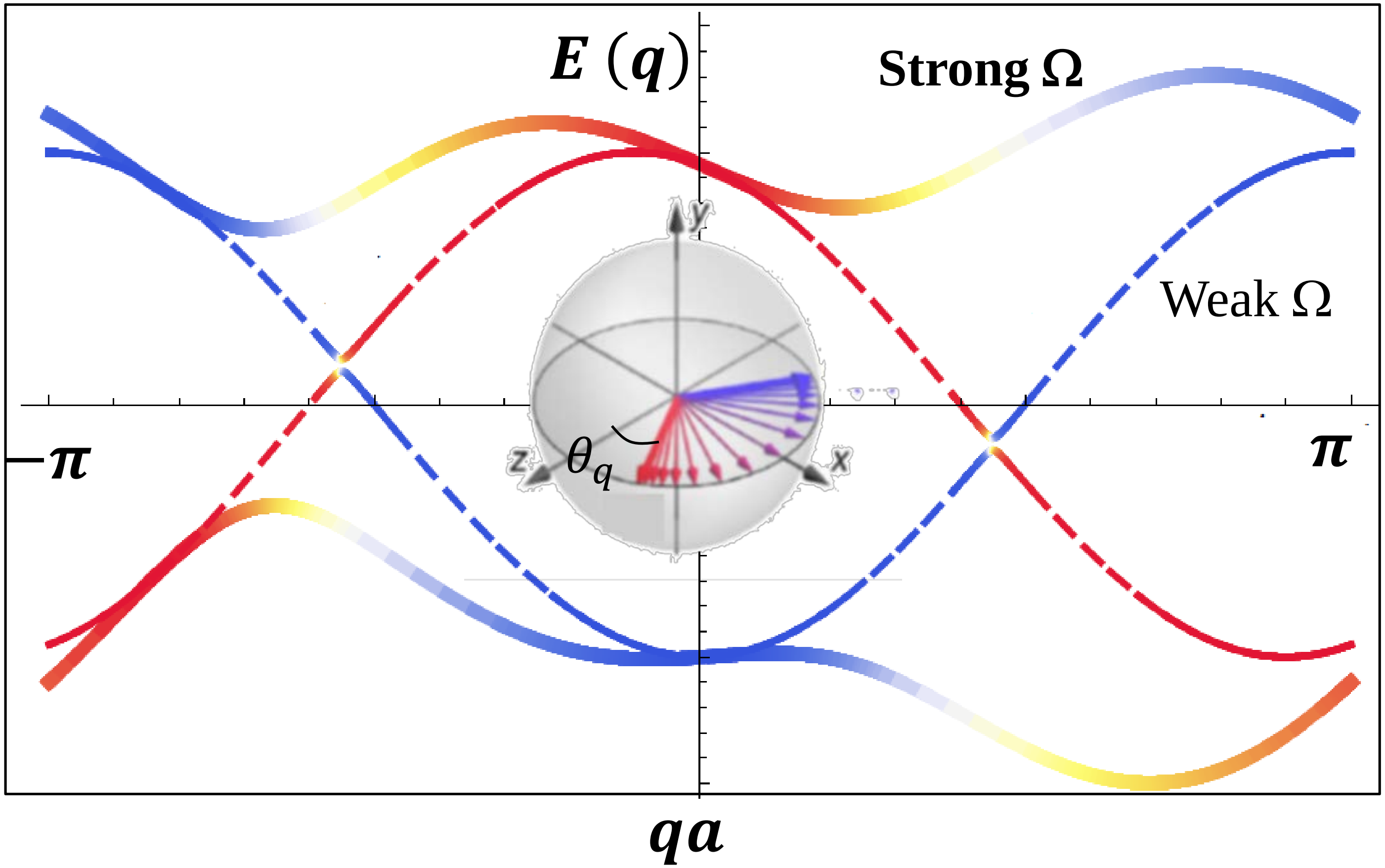
$$H_{qv} = \vec{B}_{eff}(q) \cdot \hat{\vec{\sigma}} \qquad \vec{B}_{eff}(q) = \frac{1}{2}\{\Omega, 0, \Delta E(q) - \delta\}$$

$$\Delta E(q) = [E_e - E_g]/2$$



Spin-Orbit Coupling

$H_{qv} = \overrightarrow{B}_{eff}(q) \cdot \hat{\vec{\sigma}}$ $\qquad \overrightarrow{B}_{eff}(q) = \frac{1}{2}\{\Omega, 0, \Delta E(q) - \delta\}$



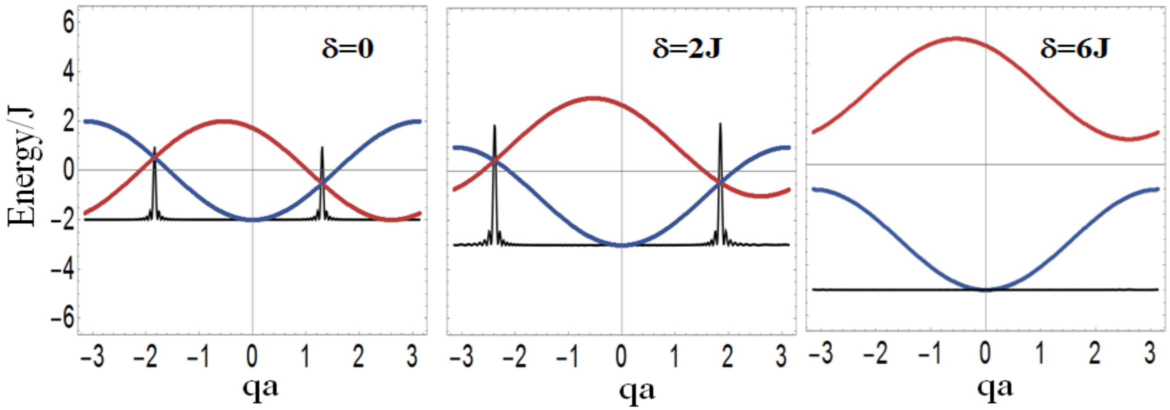
$\tan\theta_q = \dfrac{\Omega}{\Delta E(q) - \delta}$

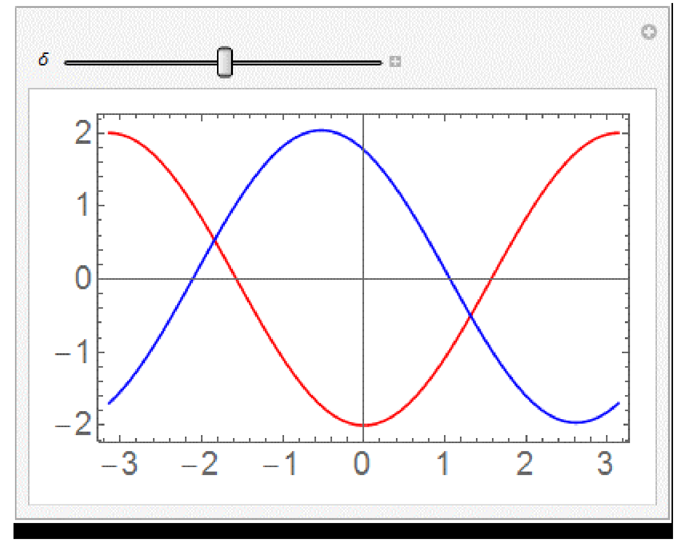
Spin-motion locking: spin points at an angle θ_q that depends on q

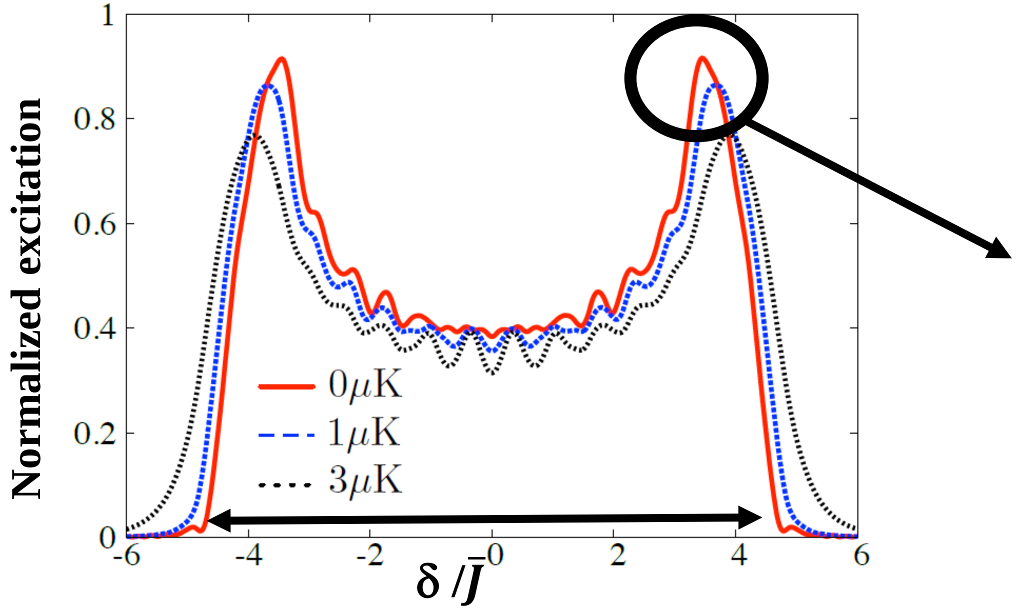
Chirality

Rabi spectroscopy

Information about ϕand J for Ω<J







width 2Δ= $8\bar{J}$Sin[$\phi/2$]

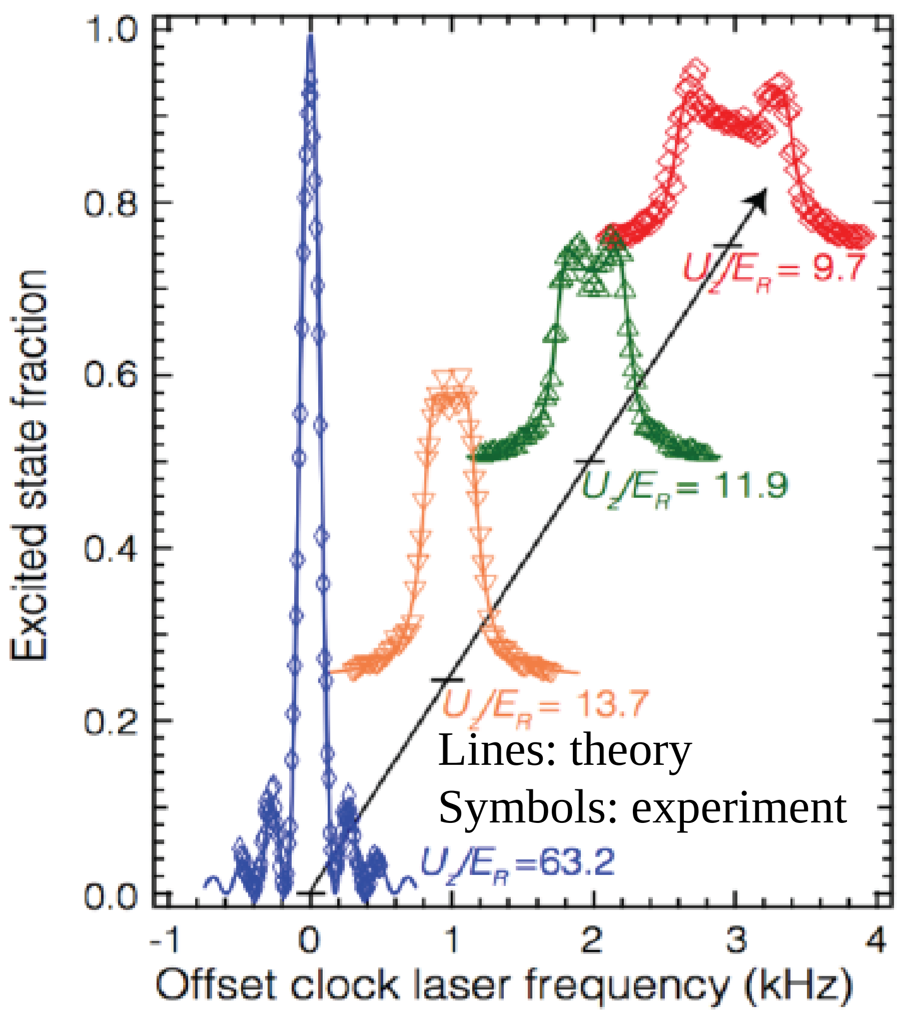
van Hove singularities:

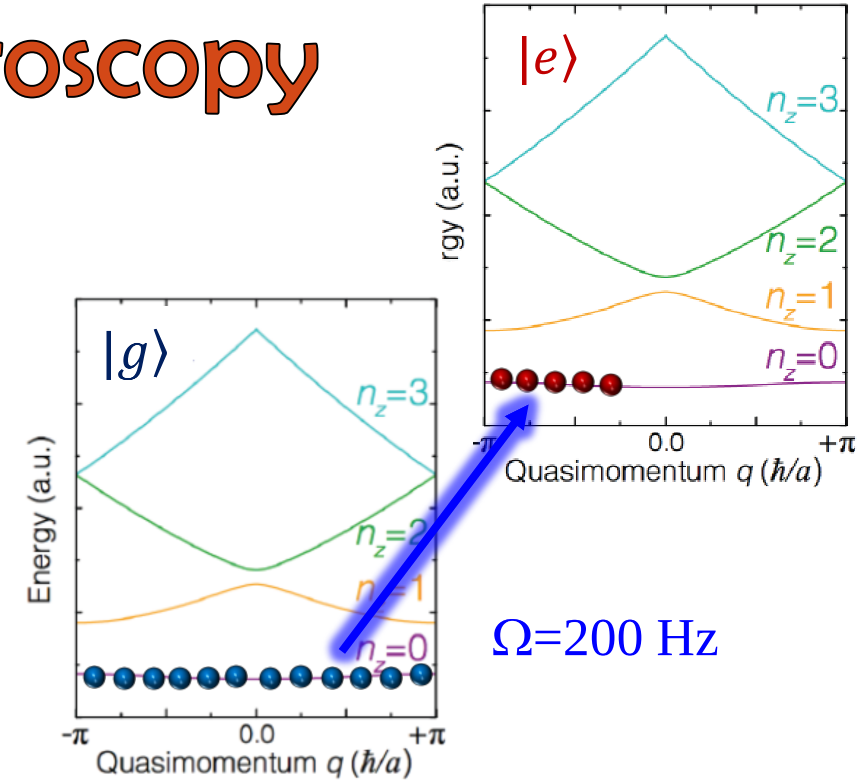
Density of states diverges

Wall *et al* PRL**116**, 035301 (2016).

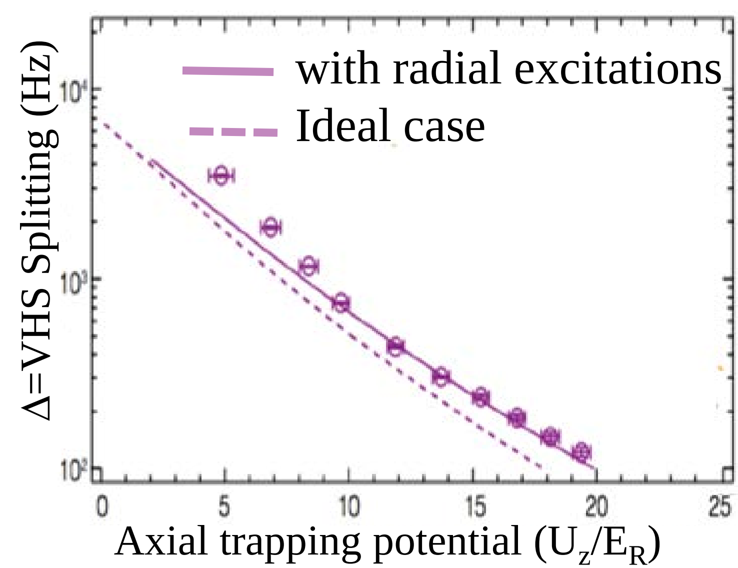
Rabi spectroscopy

Lowest band

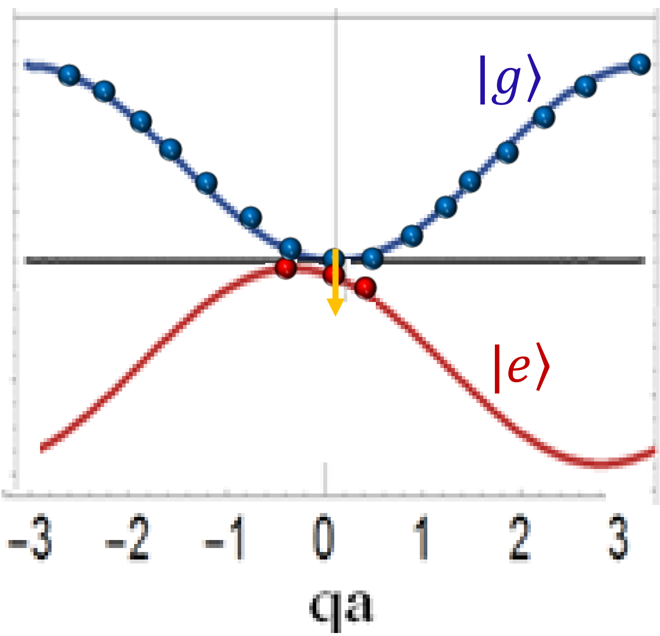


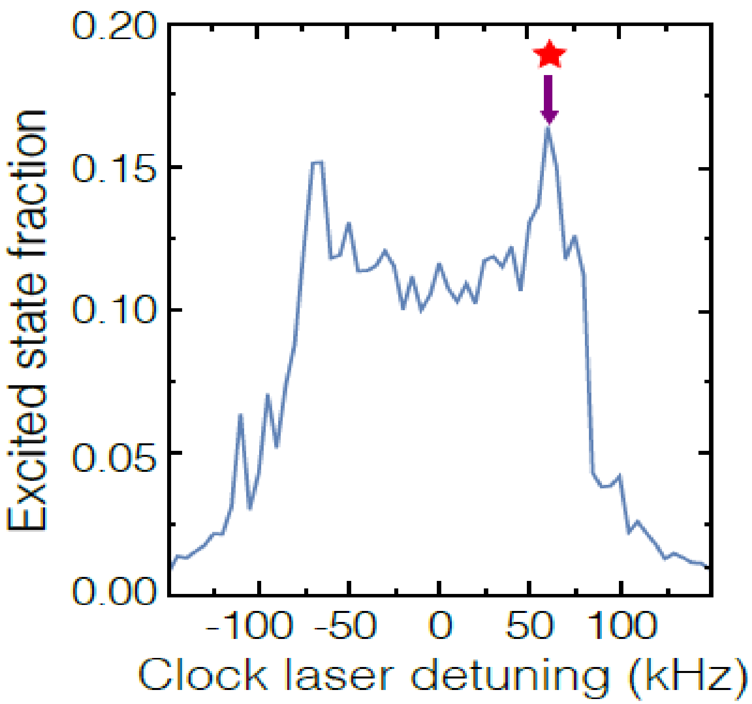


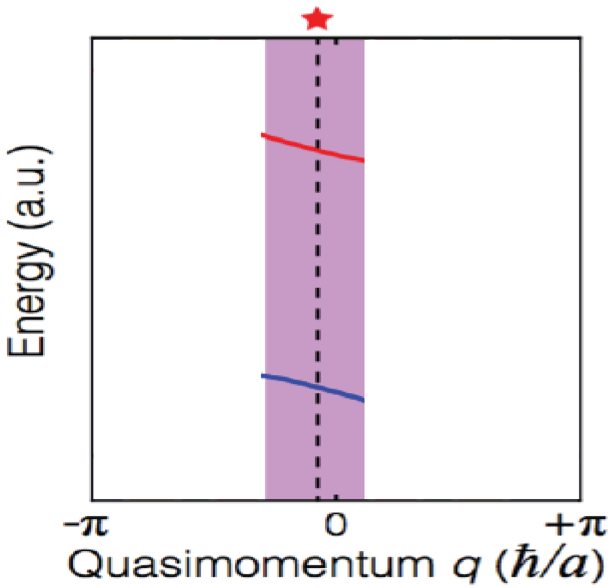
Ω=200 Hz



Momentum resolved spectroscopy



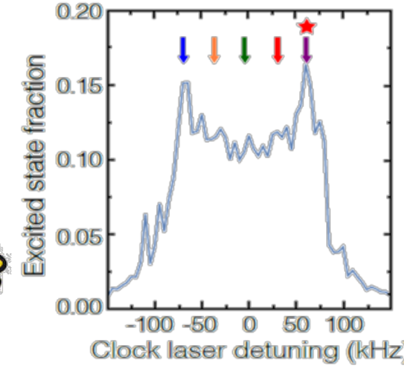




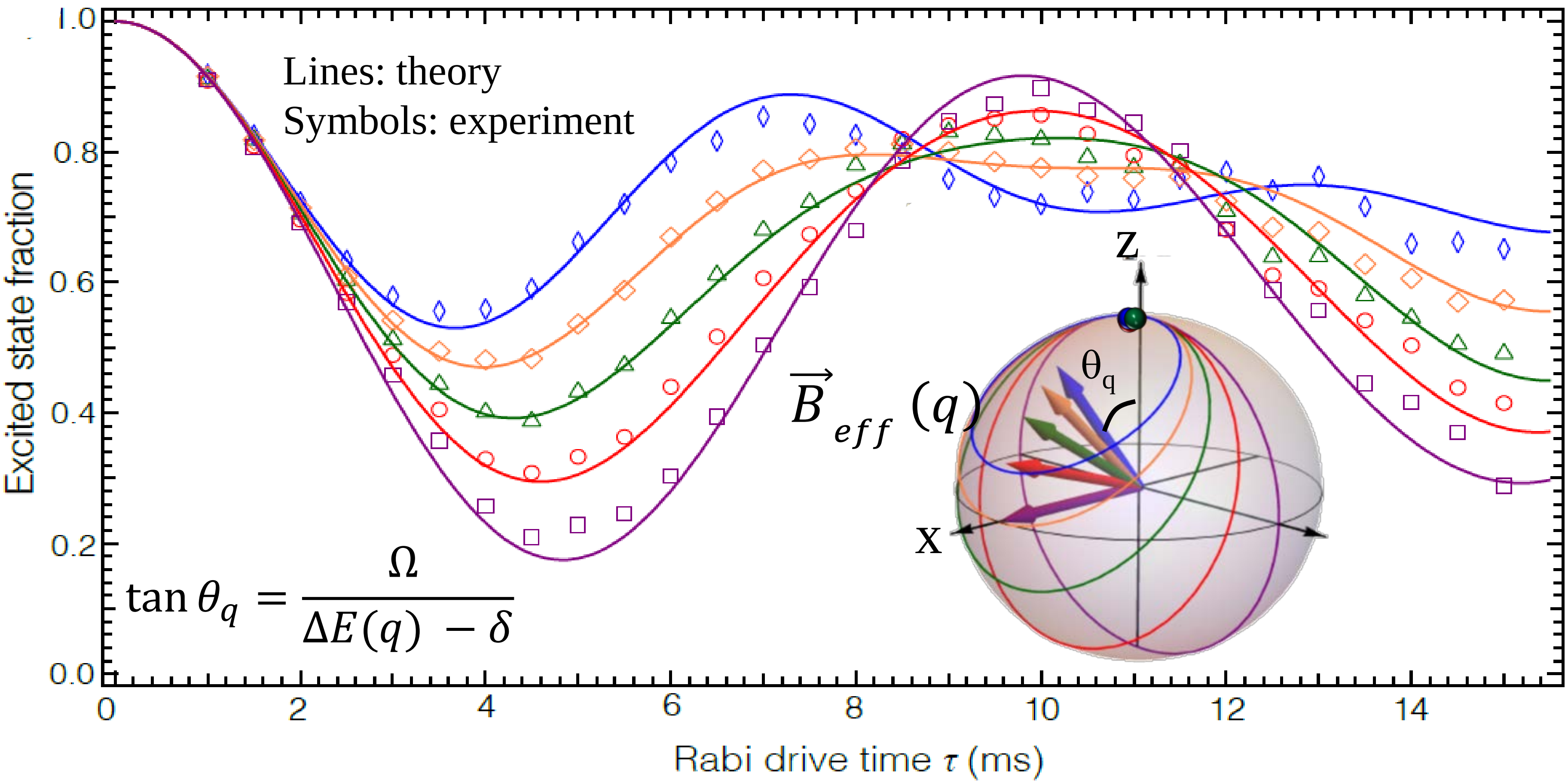
- Momentum selection: π pulse g-e Ω=10 Hz
- Clear up pulse: Remaining atoms in e
- Rabi oscillations under a stronger Rabi pulse Ω =100 Hz at δ★

Can we measure chirality, θ_q?

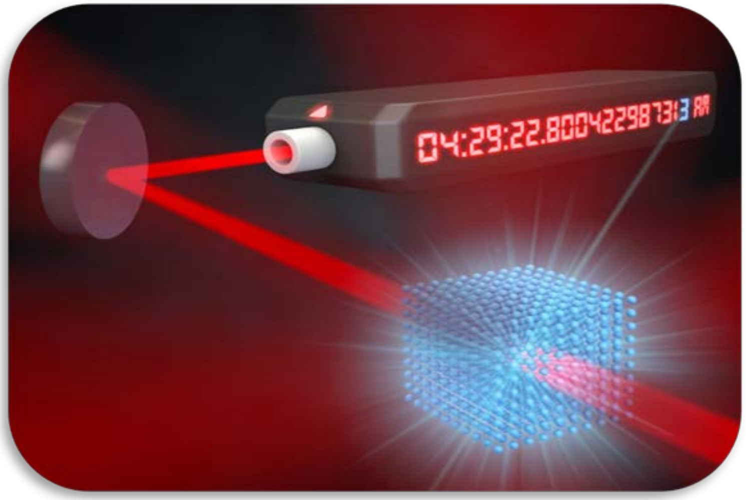
Using momentum resolve Rabi oscillations we can extract θ_q



Clock sensitivity opens the door for the investigation of SOC

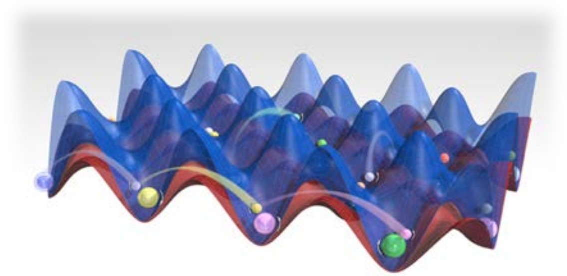


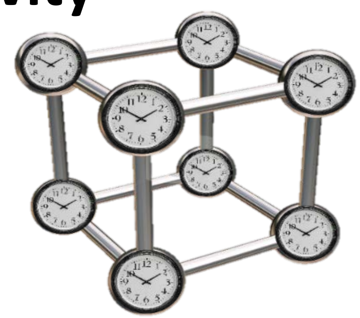
Quantum degenete Sr 3D lattice clock



~ 10^4 atoms below 80 nK, T/T_F ~ 0.1 for each nuclear spin component

Science, *358*(6359)2017   Now @ 10^{-19} sensitivity



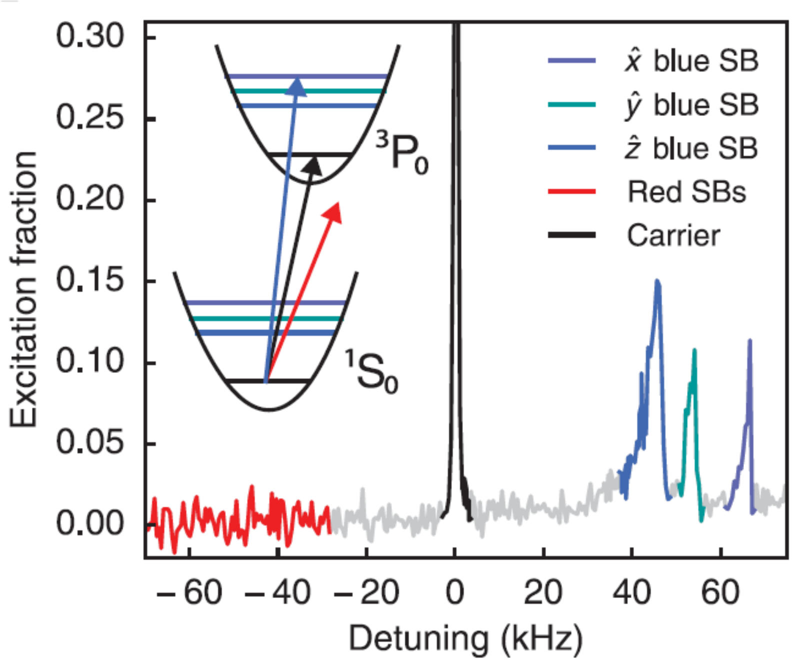


- For many-body physics
  - Single-site control & manipulation
  - SU(N) two orbital magnetism
  - Large scale entanglement

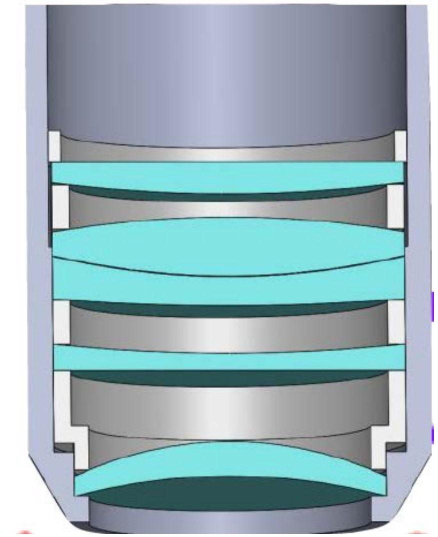
- For metrology
  - High accuracy at highest density
  - All degrees of freedom at quantum level
  - Quantum enhanced sensing

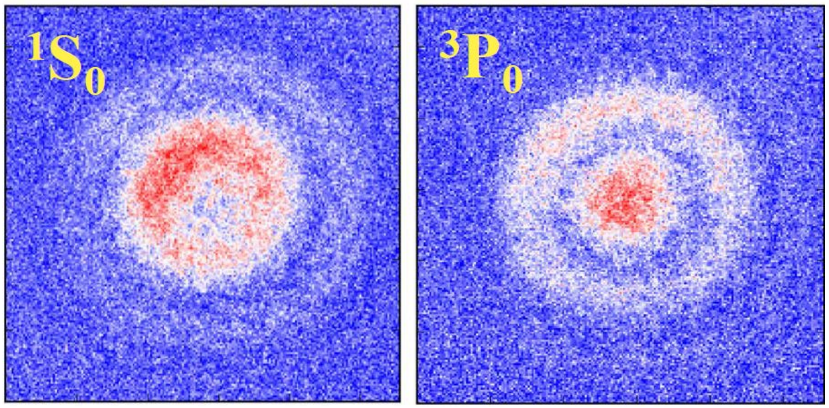
Combine the best probing tools

Energy resolution



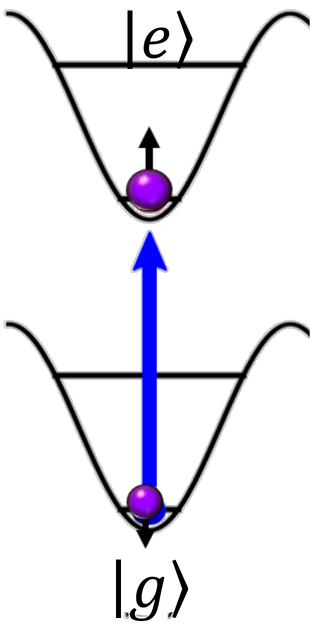
Spatial resolution

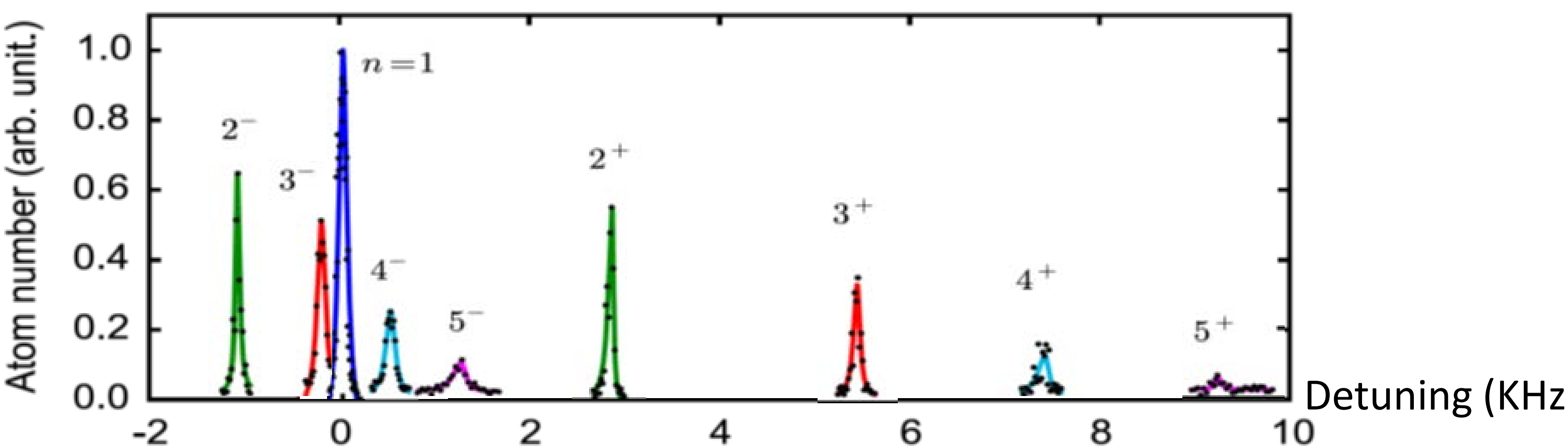




Sr 3D optical lattice clock

- **Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock: Nature (2018)**





Sr 3D optical lattice clock

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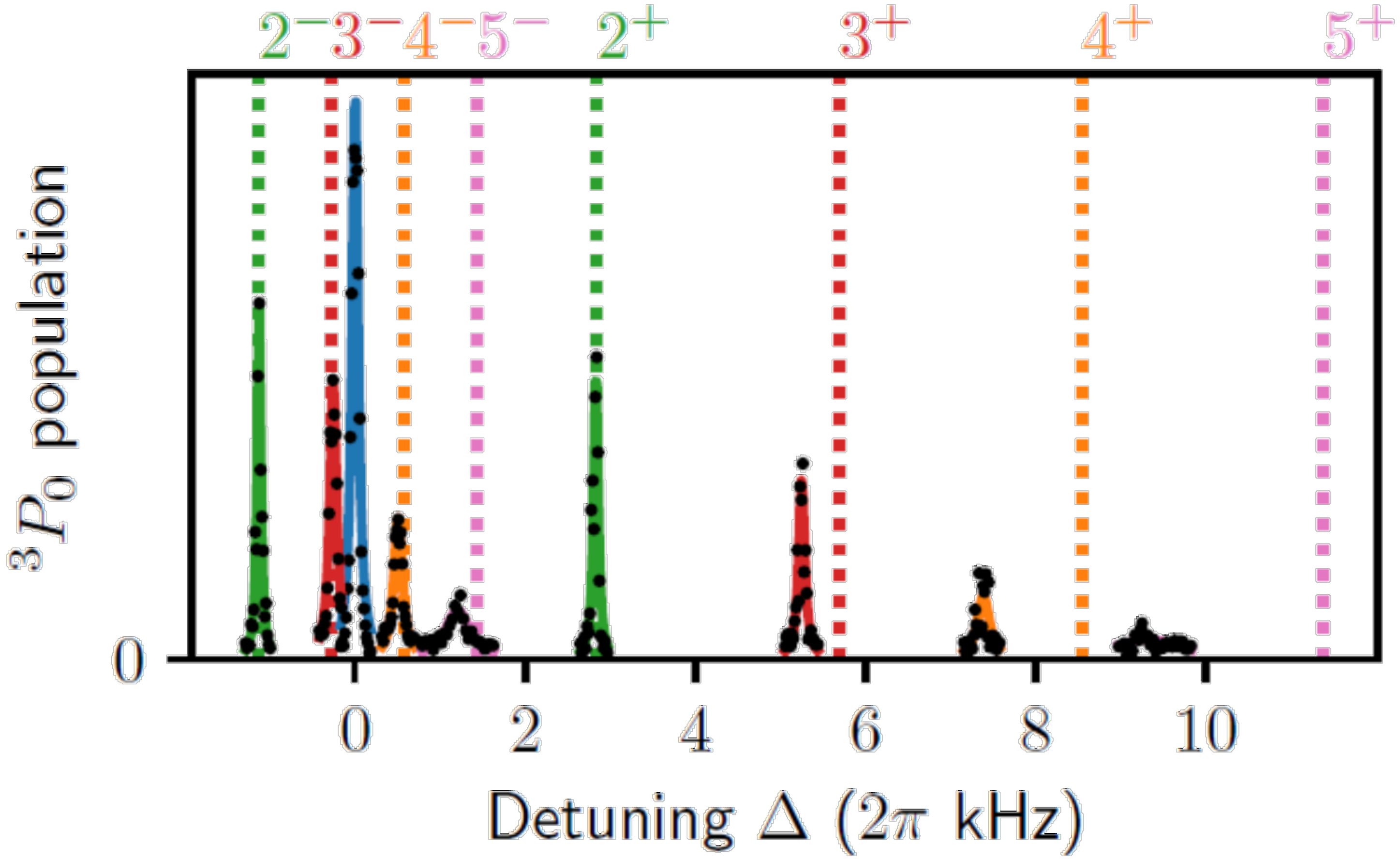


Dashed lines = two-body theory

Number of pairs

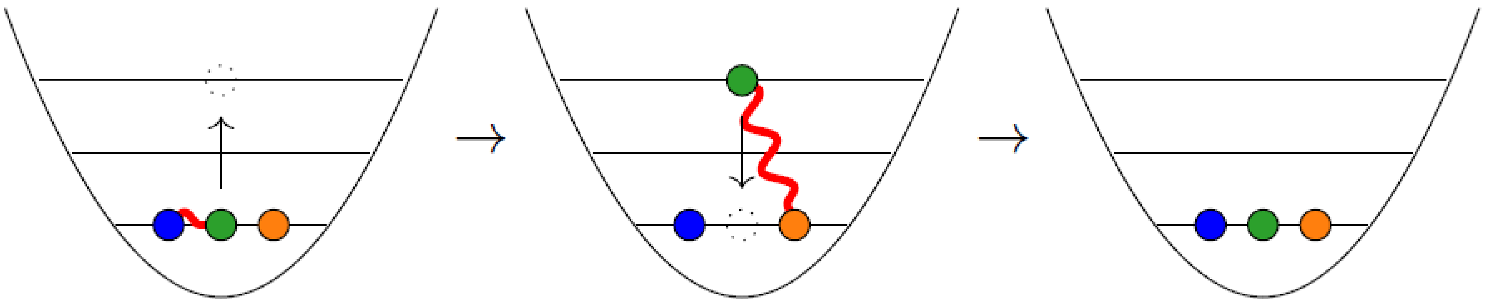
$$H^{2-body} = \frac{U_{gg}}{2}\hat{n}_g(\hat{n}_g - 1)$$

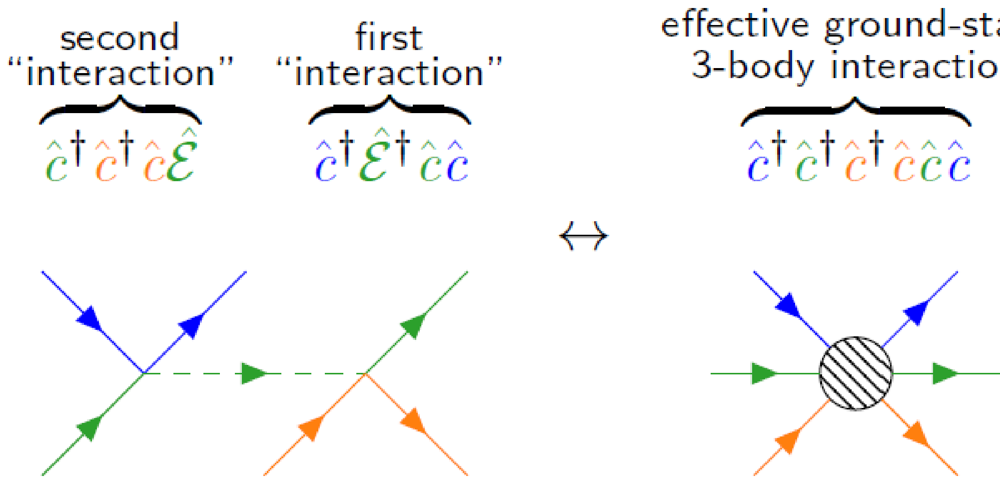
Sr 3D optical lattice clock

- **Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock: Nature (2018)**

Second order processes

Color = nuclear spin



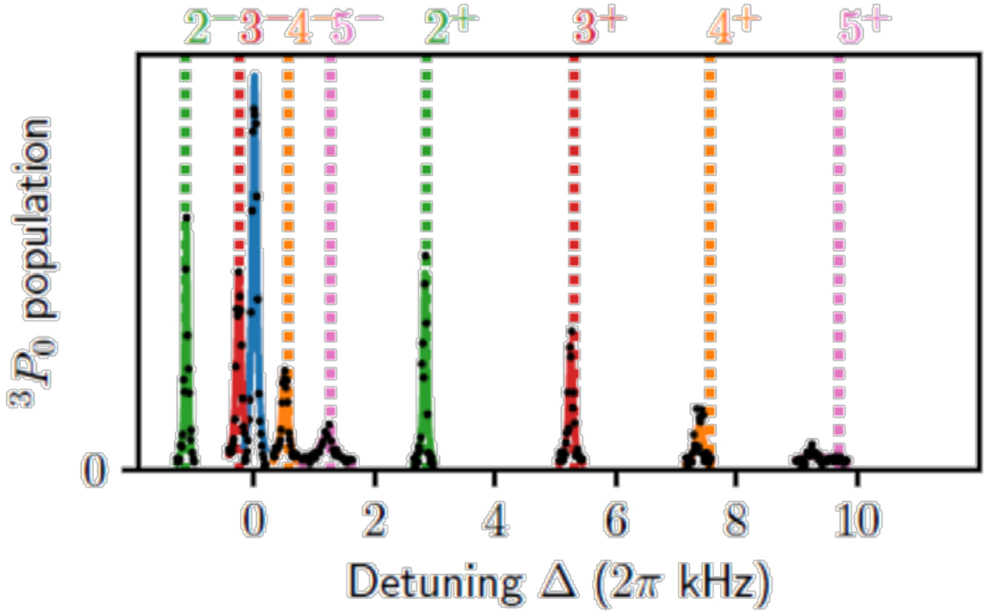


$$\hat{c}^\dagger \hat{c}^\dagger \hat{c} \hat{\mathcal{E}} \quad \hat{c}^\dagger \hat{\mathcal{E}}^\dagger \hat{c} \hat{c} \quad \leftrightarrow \quad \hat{c}^\dagger \hat{c}^\dagger \hat{c}^\dagger \hat{c} \hat{c} \hat{c}$$

$$H^{3-body} : \frac{\tilde{U}_{ggg}}{6} \hat{n}_g (\hat{n}_g - 1)(\hat{n}_g - 2)$$

Sr 3D optical lattice clock

- **Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock: Nature (2018)**



Multi-body theory (third order)

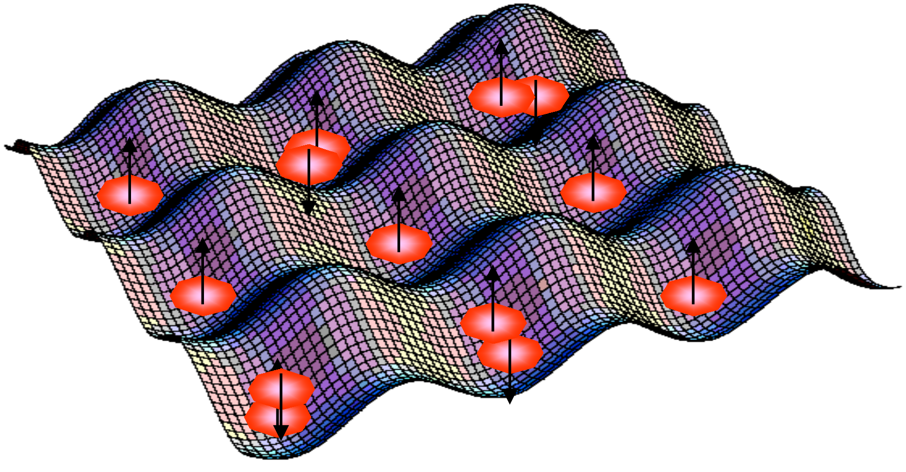
Next: Two orbital SU(N) Hubbard model by allowing tunneling

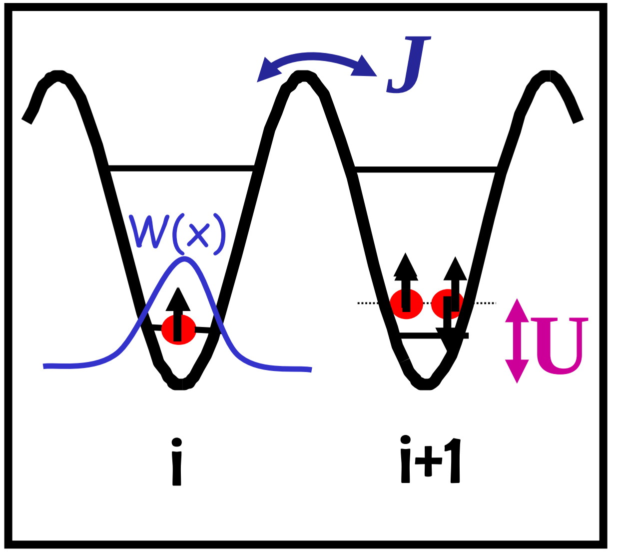
Hubbard Hamiltonian

The Hubbard model is a minimal model for interacting fermions in a lattice. It was invented to study magnetism in strongly correlated systems.

$$H = \sum_{i\sigma} -J\,(\hat{c}_{i,\sigma}^{\dagger}\,\hat{c}_{i+1,\sigma} + \text{h.c.}) + \sum_i U\,\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + \Omega \sum_i i^2 \hat{n}_i$$

Hopping Energy *Interaction Energy* *Parabolic potential*



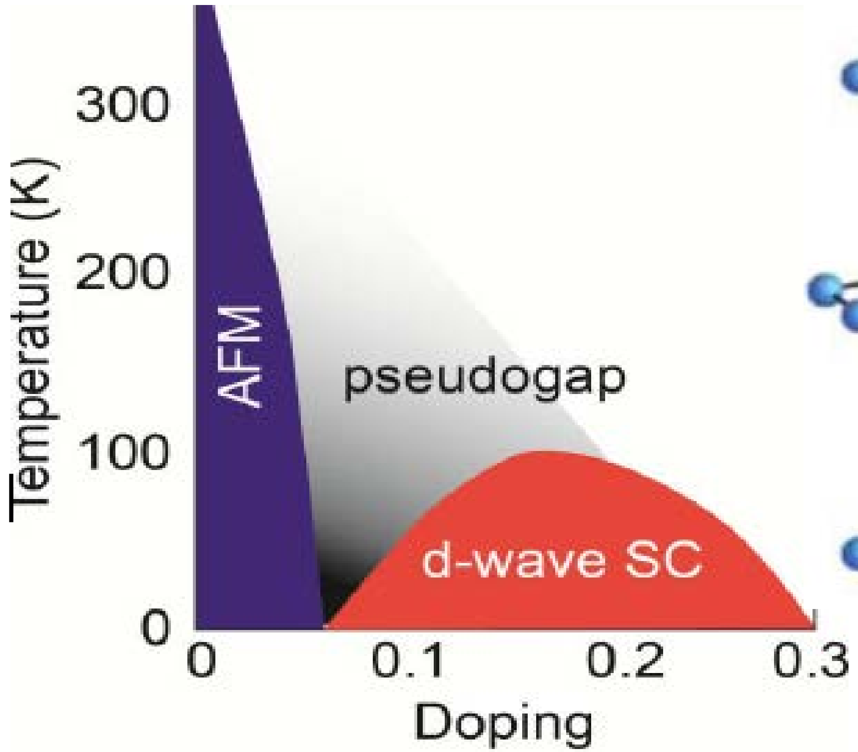


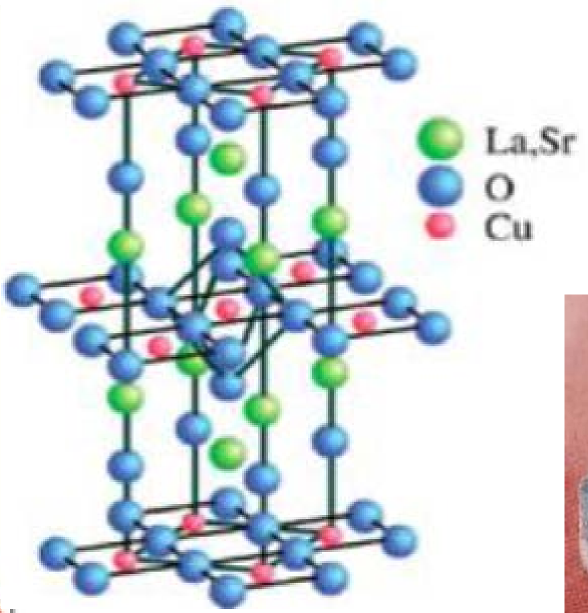
A Mott insulator made of fermions first observed 2008: at ETH (Esslinger group) and Mainz (Bloch group). Many groups now

Hubbard Model is very complex

Its phase diagram in 2 and 3 dimensions remains unknown

Possible phase diagram





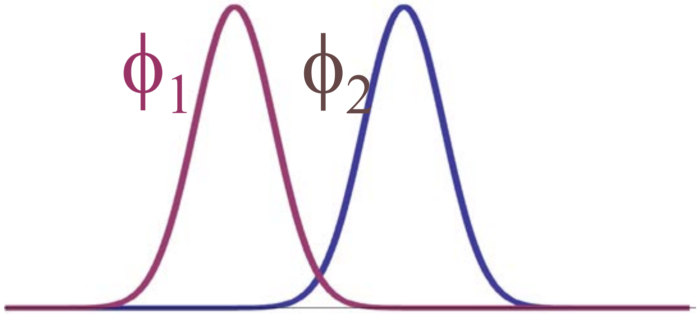
Use to model cuprate superconductors: High Temperature superconductivity

Can cold atoms help to identify the phase diagram ?

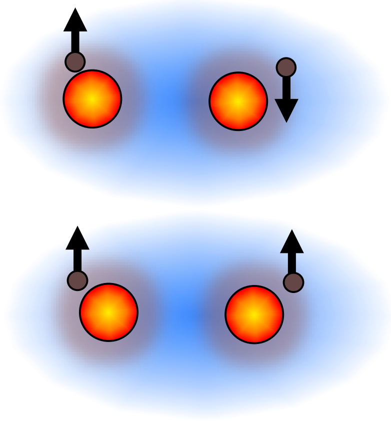
Super-Exchange Interactions

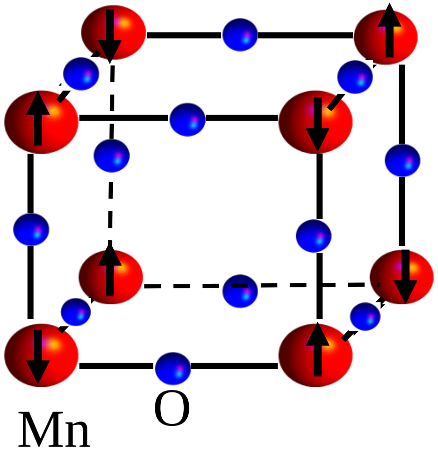
- Spin order can arise even though the wave function overlap is practically zero.

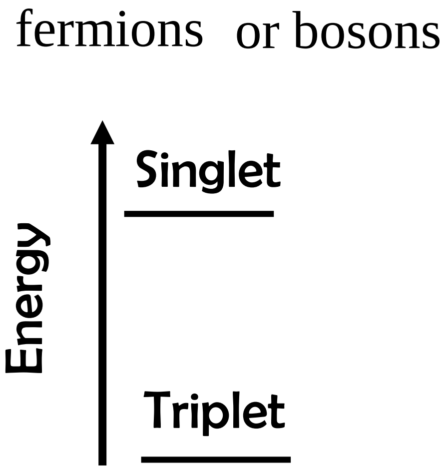
Super- Exchange ⟷ Virtual processes



E.g. Two electrons in a hydrogen molecule, MnO





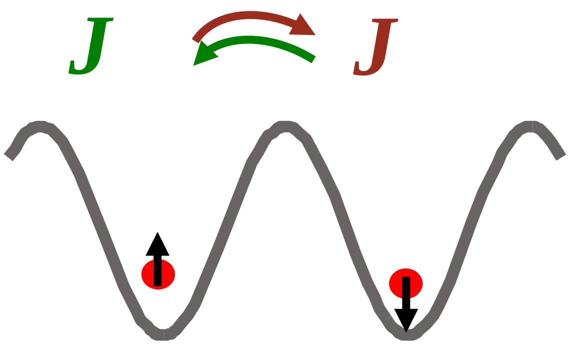


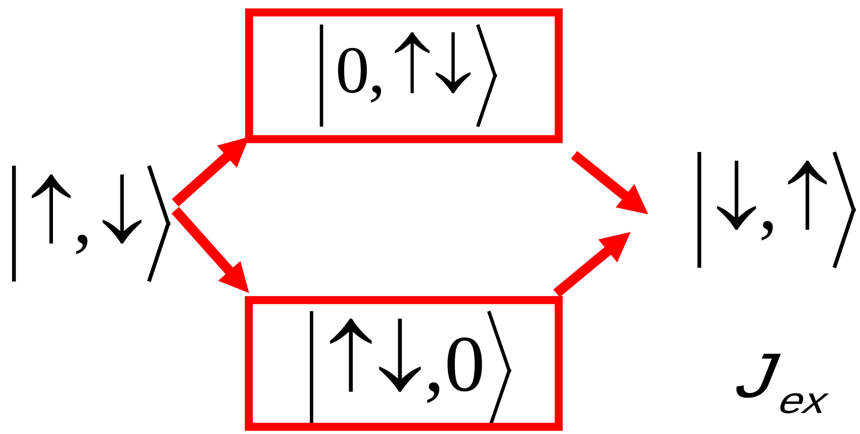
P.W. Anderson, Phys. Rev. **79**, 350 (1950)

Super-exchange in optical lattices

Consider a double well with two atoms

- ✓ At zero order in J , the ground state is Mot insulator with one atom per site and all spin configurations are degenerated
- ✓ J lifts the degeneracy: An effective Hamiltonian can be derived using second order perturbation theory via virtual particle hole excitations





$$J_{ex} = \frac{2J^2}{U}$$

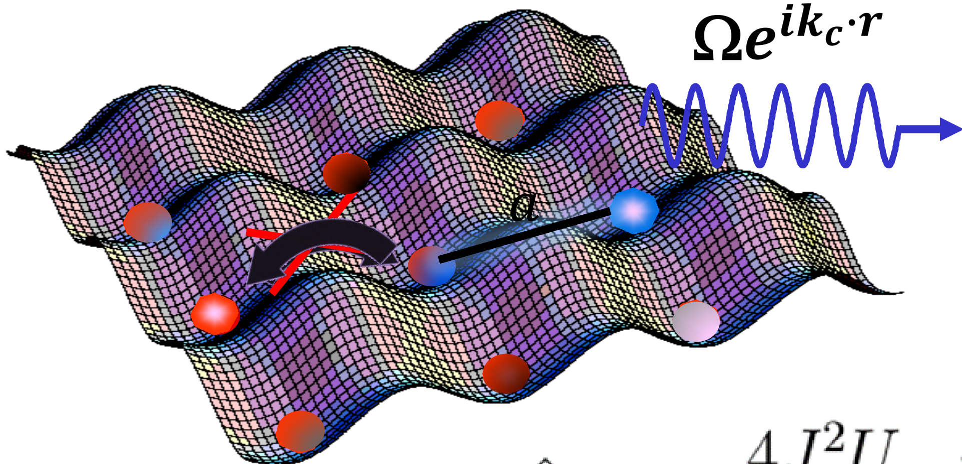
$|m\rangle$: Virtual particle-hole excitations

$$\hat{H}_{eff} = -\sum_m \frac{\hat{K}|m\rangle\langle m|\hat{K}}{E_m}$$

$$H_{eff} = \mp 2J_{ex} \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j$$

- Bosons , + Fermions

Combining Super-exchange & SOC



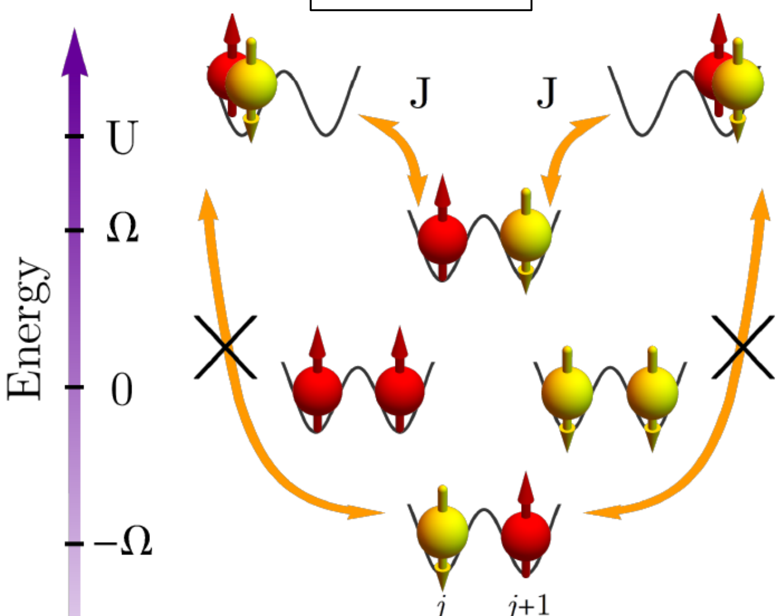
$$k_c a = (\pi, \pi)$$

$$\downarrow$$

$$\Omega \sum_j (-1)^j \hat{\sigma}_z$$

$$\hat{H}_{\rm se} \approx \frac{4J^2U}{\Omega^2 - U^2} \sum_{\langle j,k \rangle} \hat{S}^z_j \hat{S}^z_k + \mathcal{O}\left(\frac{J^2}{U}\right)$$

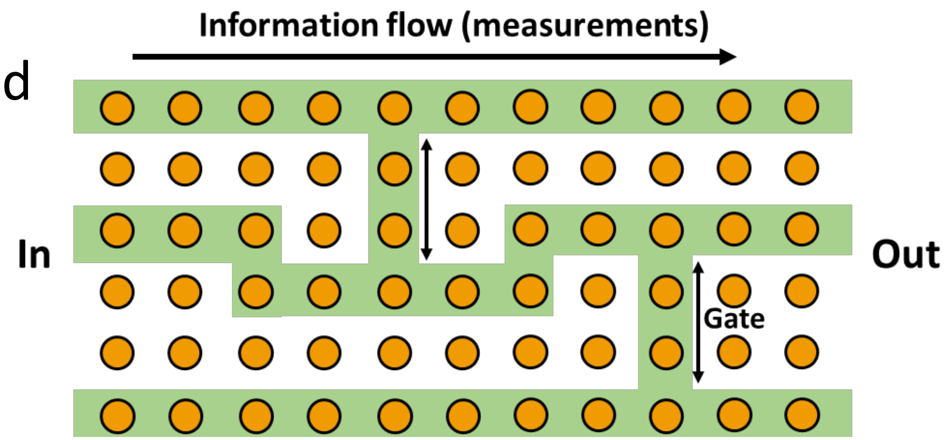
Our Case



Ising interactions: Useful for cluster state generation

Cluster states

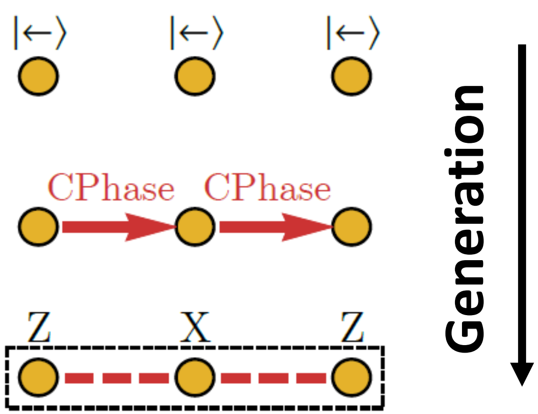
- Highly entangled many-qubit resource state



- Can do one-way measurement-based quantum computation: D≥2
- Generate with Ising interaction:

$$|\psi(0)\rangle = |\leftarrow, \leftarrow, \leftarrow, \cdots\rangle$$

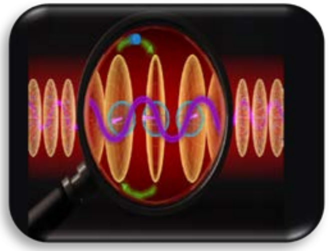
$$|\psi\rangle_{\rm c} = \prod_{\langle j,k\rangle} \exp\left[-i\left(\hat{S}_j^z \hat{S}_k^z + \frac{1}{2}\hat{S}_j^z + \frac{1}{2}\hat{S}_k^z\right)\pi\right]|\psi(0)\rangle$$

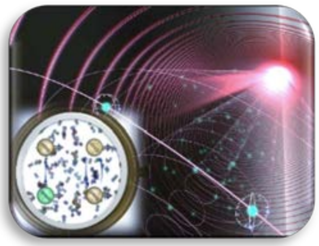


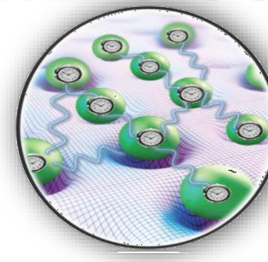
- state quality: stabilizer correlations

$$\langle {\rm ZXZ}\rangle_j = 2^{2D+1}\langle \hat{S}_j^x \prod_{\langle j,k\rangle} \hat{S}_k^z\rangle = 1$$

Exploring quantum physics with clocks





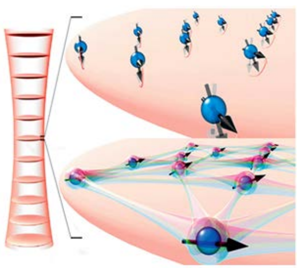


?

3D quantum degenerate clock (2017)

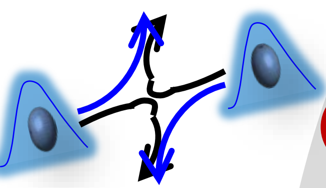
Clock simulates synthetic magnetic fields: (2017)

JILA Best atomic clock (2015).

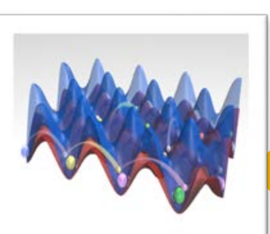


Clock measures SU(N) symmetry (2014)

Clock as a simple quantum simulator: (2013)



Unraveled the mysterious collisions seen in the clock: (2011).

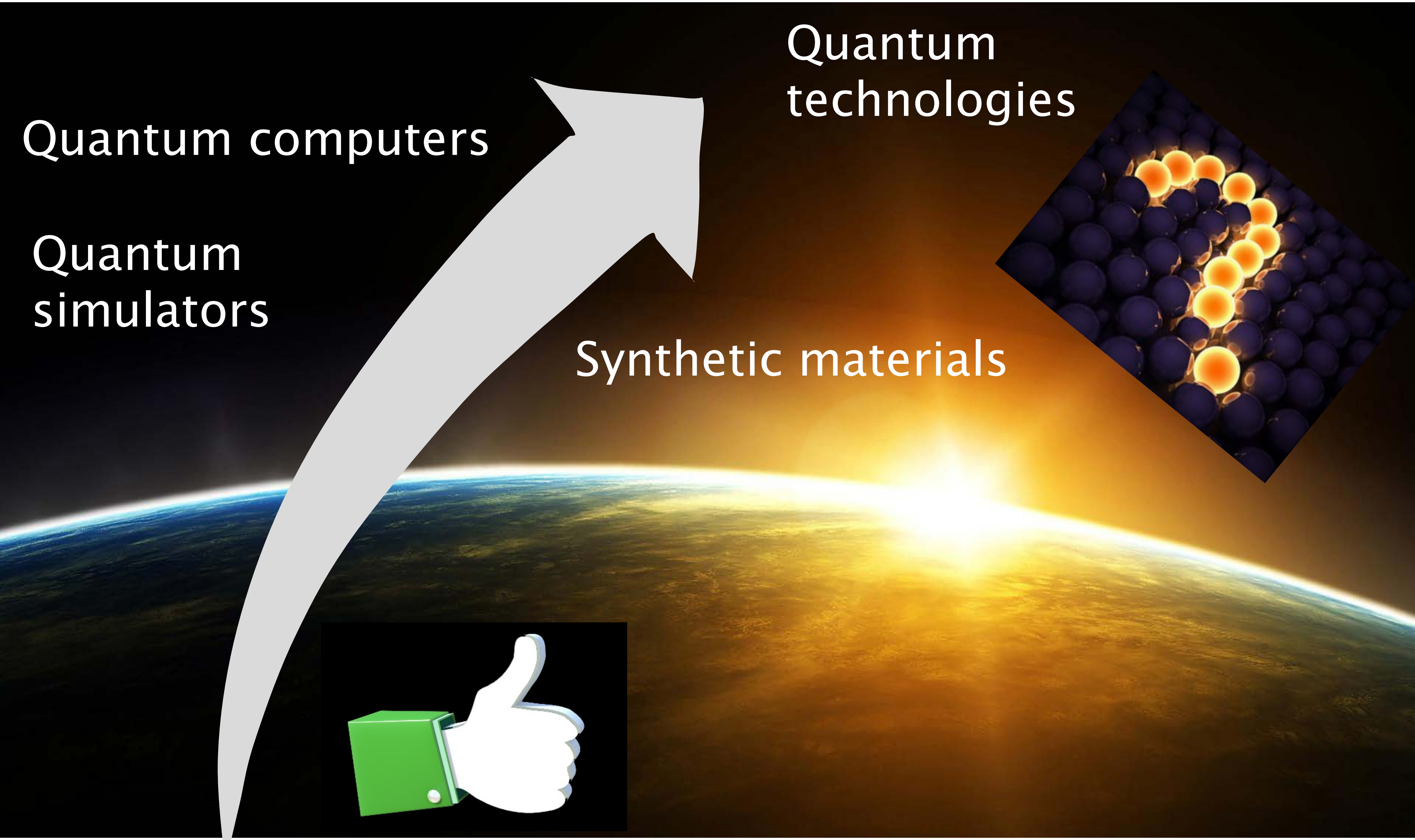


Theoretical proposal: Alkaline earth atoms exhibit exotic magnetism (2010)

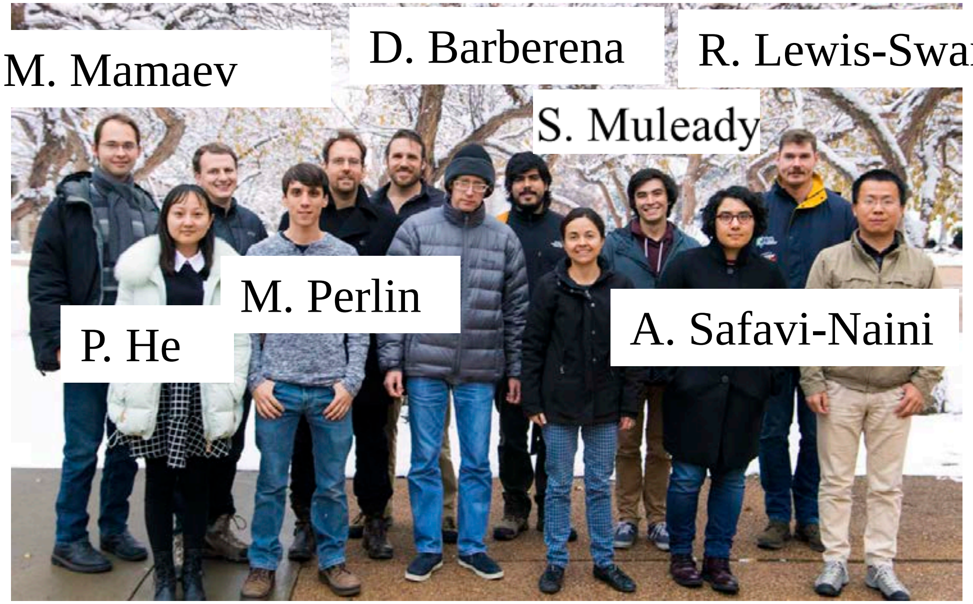
JILA y NIST clocks see atomic collisions (2009).

Quantum Physics with Atomic Clocks

Only the beginning: Bright vista ahead

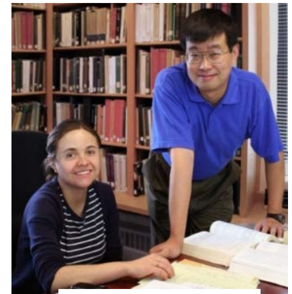


Theory:



M. Wall, A. Gorshkov,V. Gurarie, M. Hermele, M. Safronova, P. Julienne

The JILA Sr team:



Jun Ye