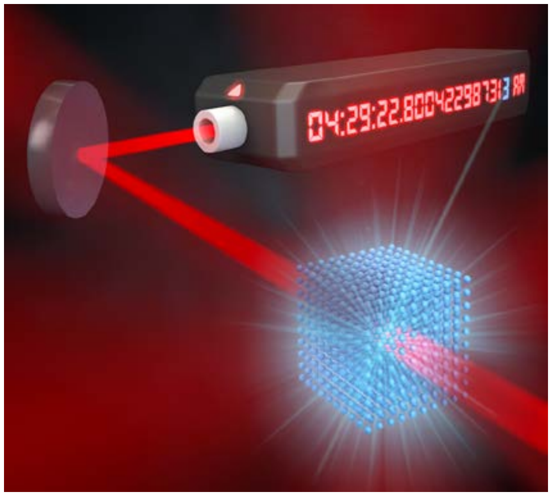
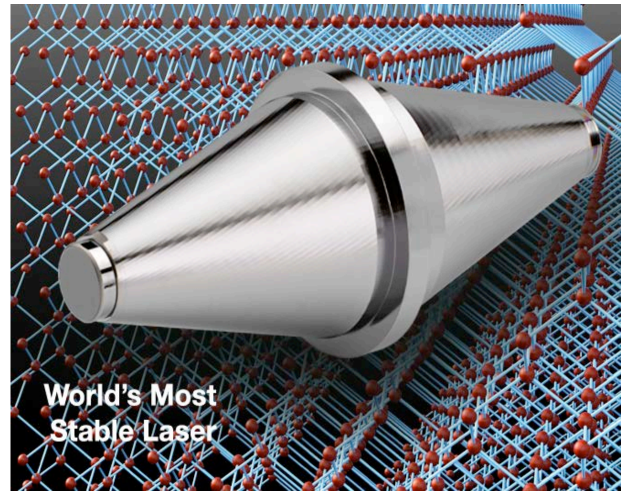
Measurement at the quantum frontier

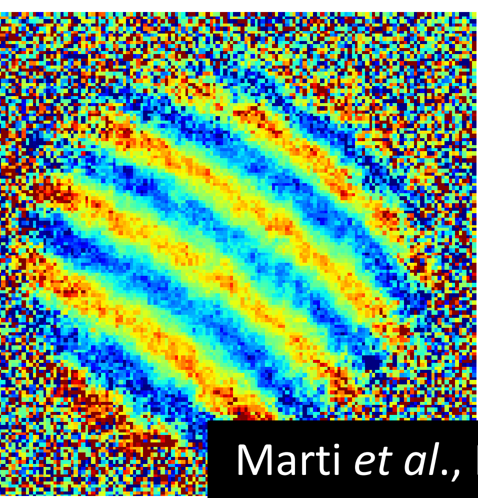
J. Ye

Boulder Summer School, July 24, 2018



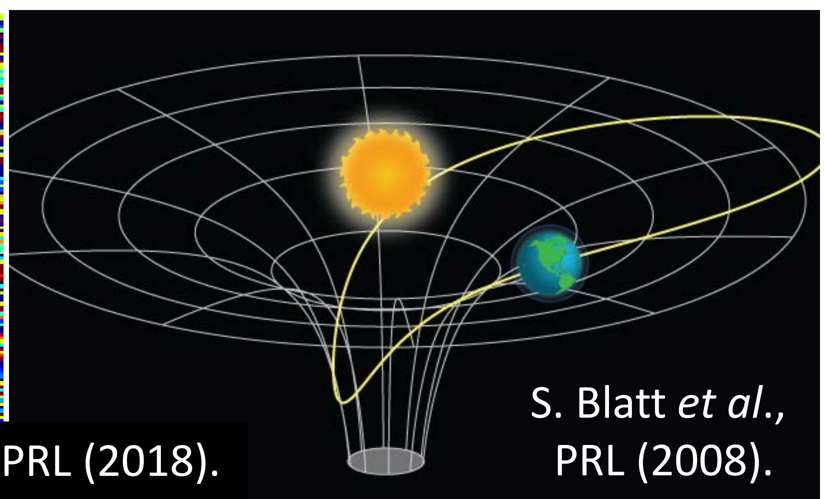


Quantum sensing



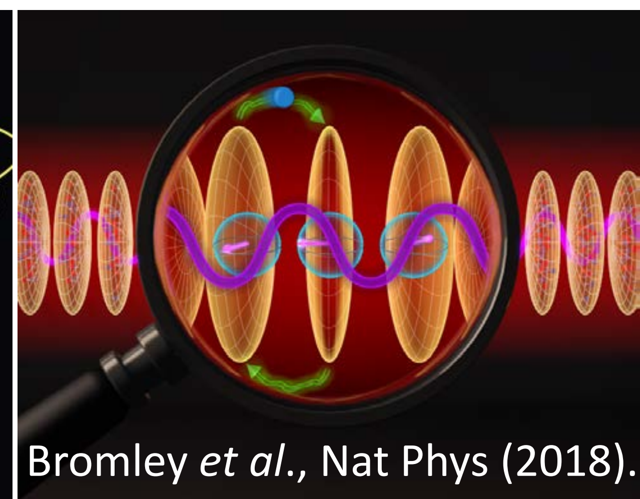
Marti *et al.*, PRL (2018).

Table-top search for new physics



S. Blatt *et al.*, PRL (2008).

Many-body dynamics



Bromley *et al.*, Nat Phys (2018).

Lecture outlines

Lecture I

- Simple atomic physics
- Basic quantum physics
- Basic laser science

→ The ingredients for control & measurement of quantum coherence

Lecture II

- Atomic interactions
- Spin Hamiltonians
- Emergence of complexity from simple ingredients

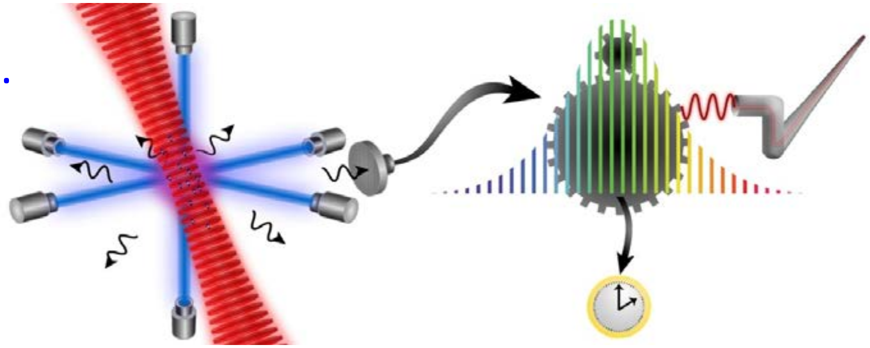
→ A new frontier: quantum metrology & many-body physics

Atomic/Molecular Ultracold Matter

Precise control of quantum systems

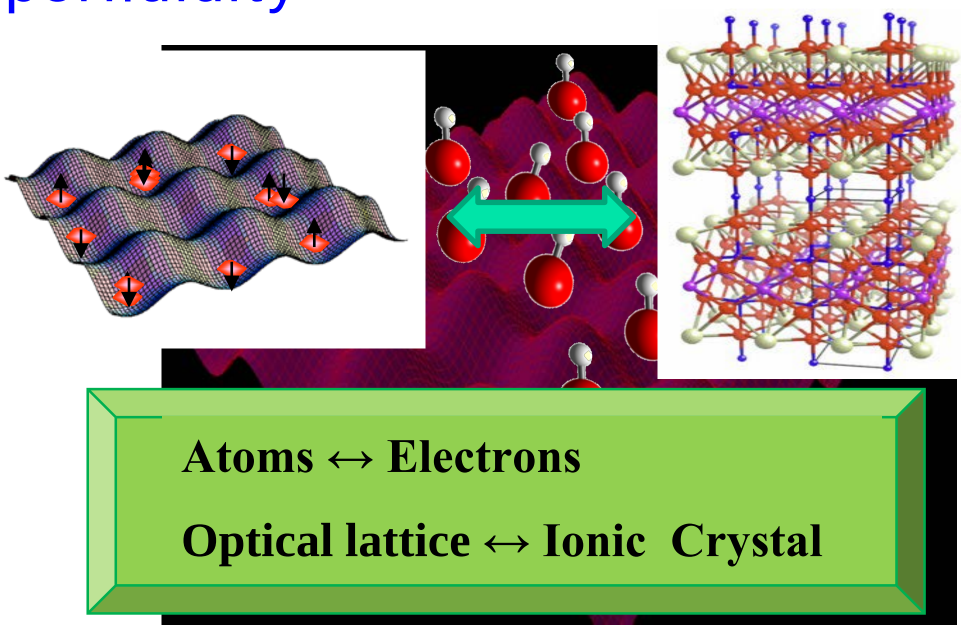
- Clocks, quantum information, sensors

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



Understanding complexities & strong correlations

- Superconductivity & Superfluidity
- Quantum magnetism
- Quantum chemistry



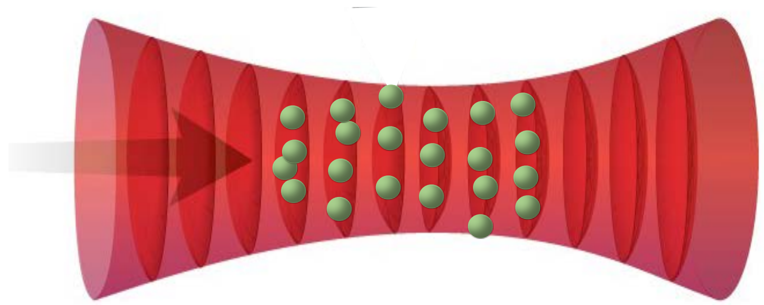
Universality & scaling

- Contact vs. long-range
- Drive vs. interaction

Precision metrology meets many-body physics

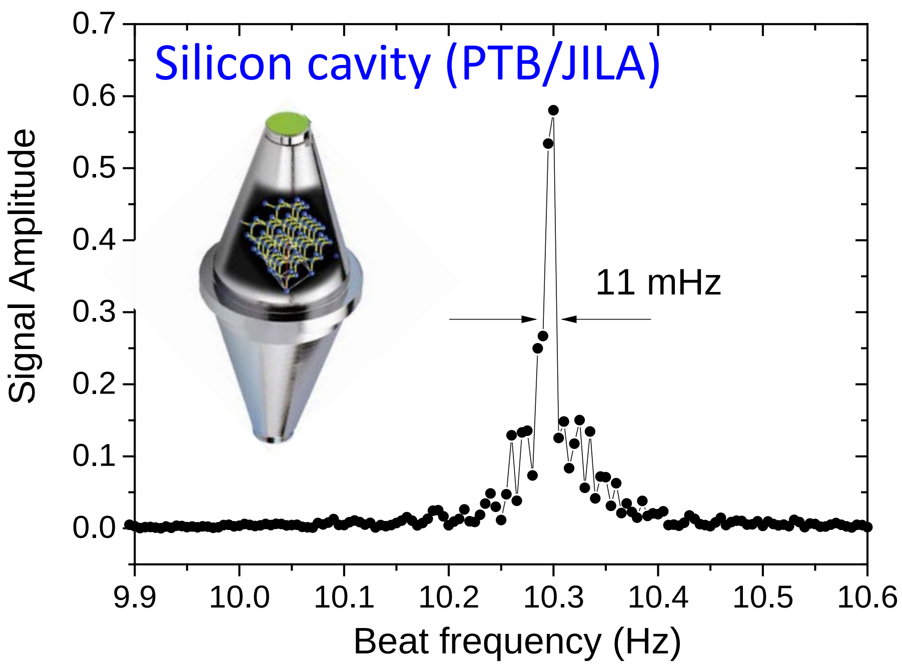
Martin *et al*., Science **341**, 632 (2013).

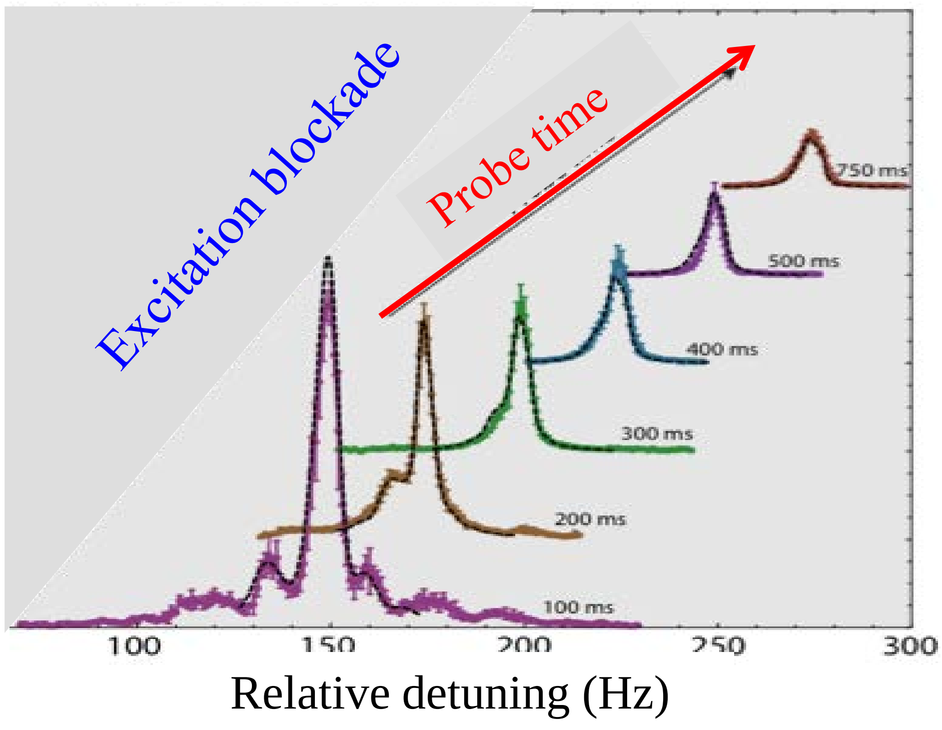
A new generation of stable lasers



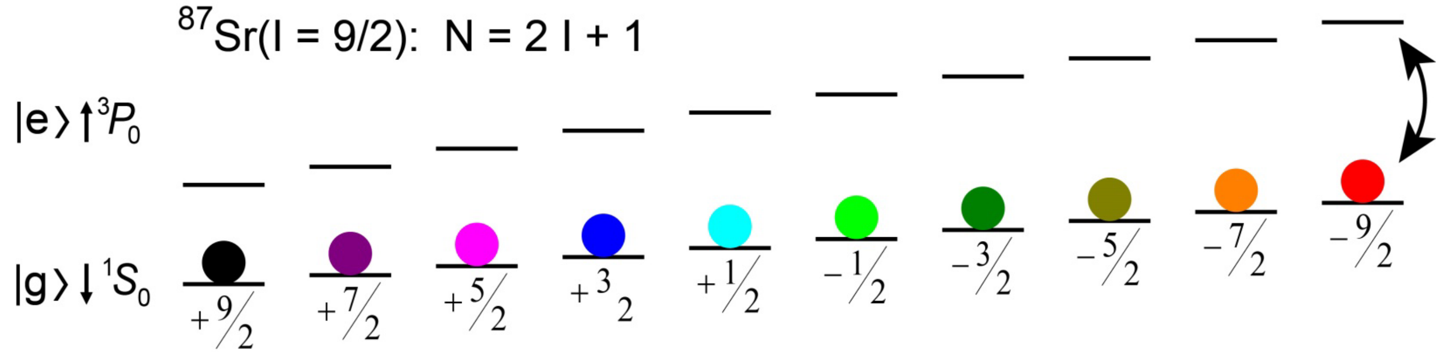
1D Lattice

0.01 Hz per laser

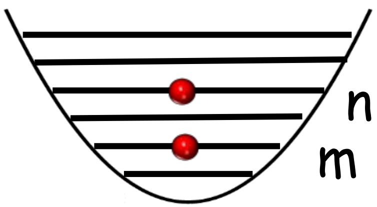




3 degrees of freedom: electronic, nuclear, spatial



hyperfine coupling $I \cdot J = 0.$



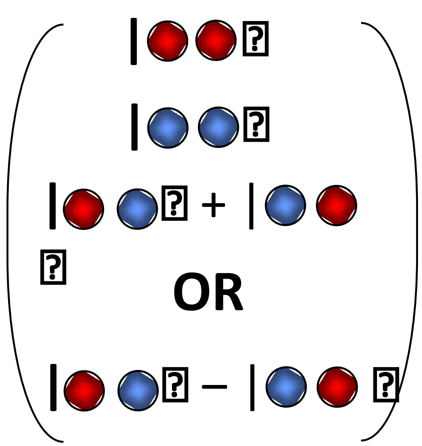
$|n\ m\rangle + |m\ n\rangle$

Spatially Symmetric

$|n\ m\rangle - |m$

Spatially Anti-Symmetric

nuclear ⊗ electronic ⊗ motional



⊗

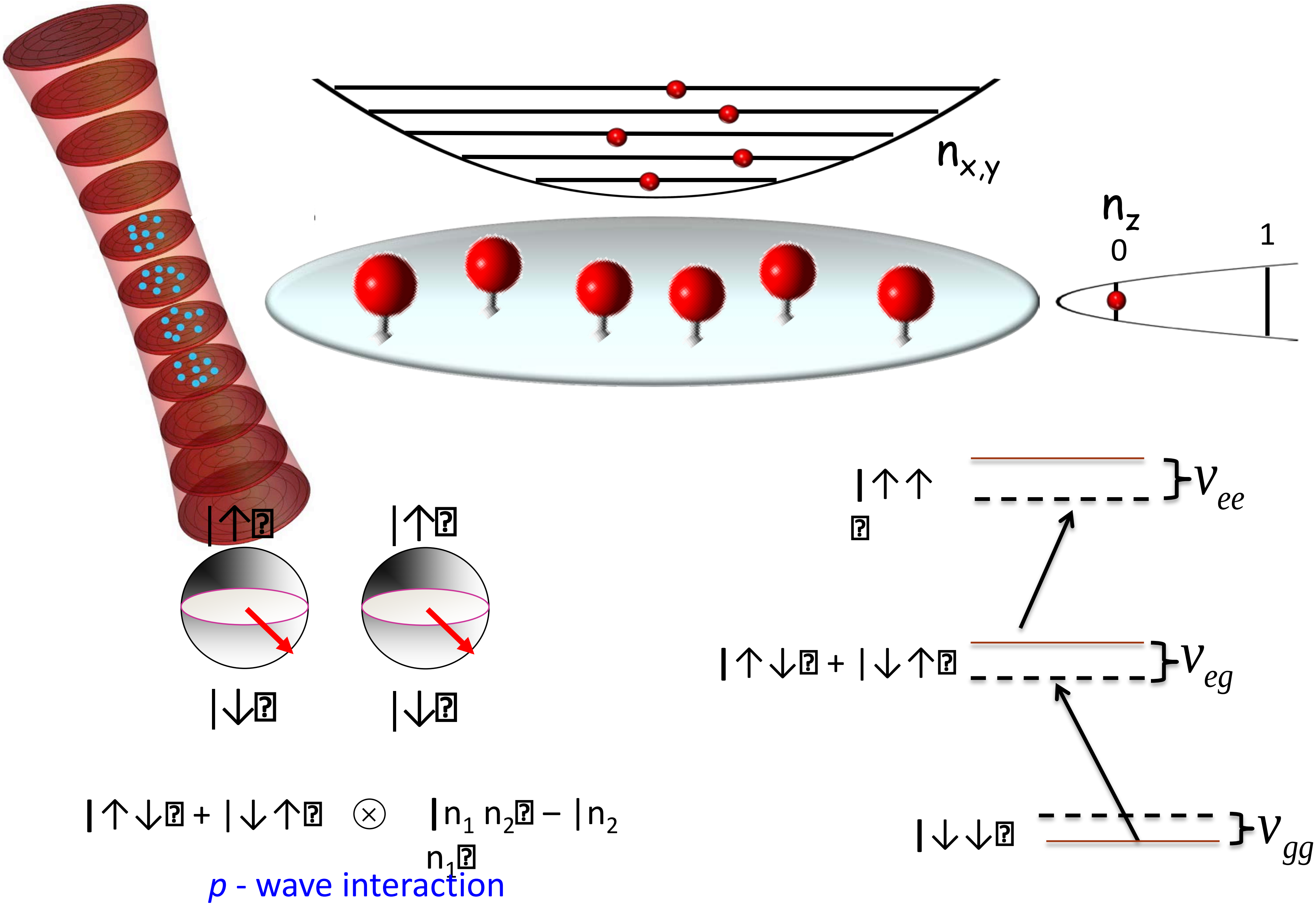
$|\uparrow\uparrow\rangle$
$|\downarrow\downarrow\rangle$
$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$
OR
$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

⊗

$|n\ m\rangle + |m\ n\rangle$
OR
$|n\ m\rangle - |m\ n\rangle$

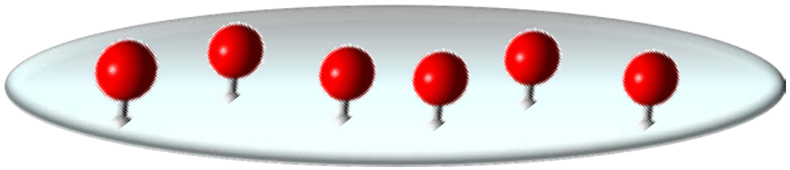
= "–"

Interactions between Fermions



1D lattice clock: spin model

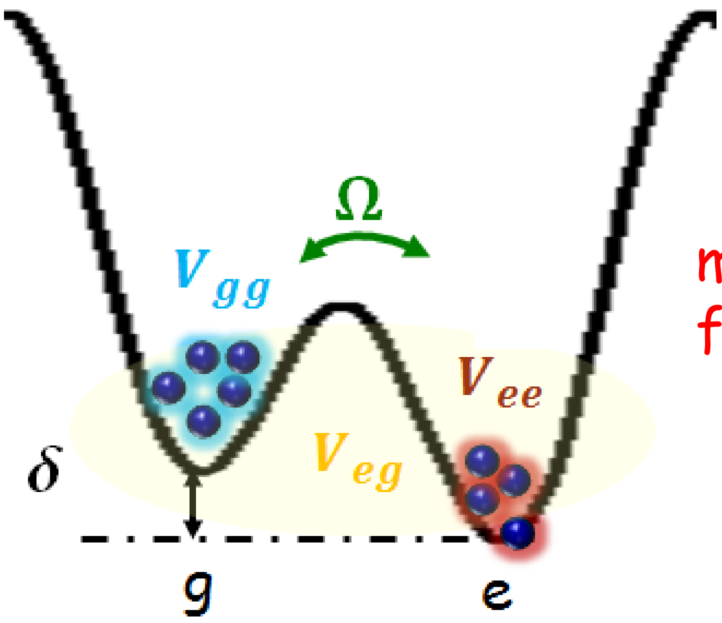
Collective-spin $S = N/2$



$$\hat{H}/\hbar = -\delta S^z - \Omega S^x + \chi\,(S^z)^2 + C\,(N-1)\,S^z$$

$$C = \frac{v_{ee} - v_{gg}}{2}$$

$$\chi = \frac{v_{ee} + v_{gg} - 2v_{eg}}{2}$$



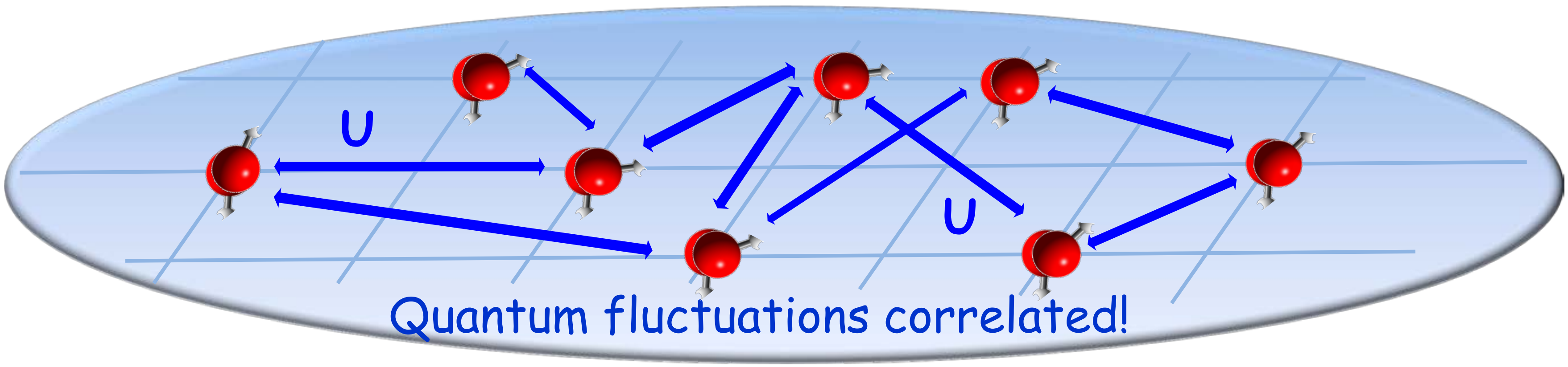
mapping interacting fermions to bosons

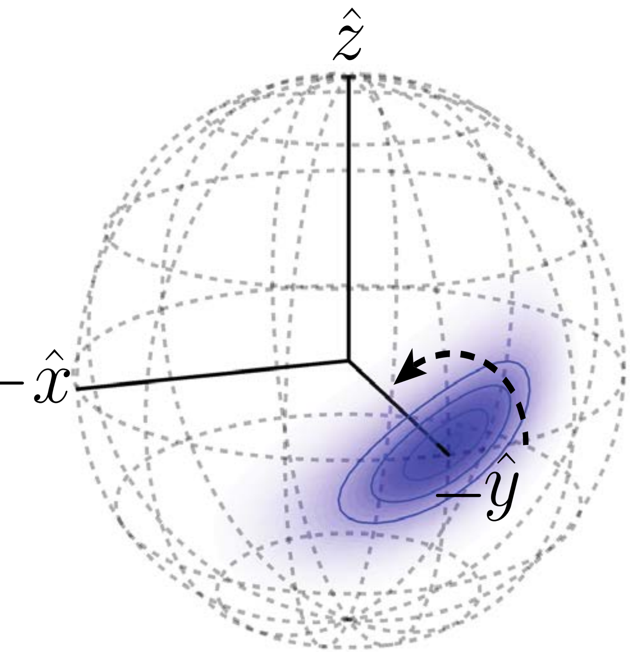
Two-component BEC:
Sorensen, Moller, Cirac, Zoller, Lewenstein, …

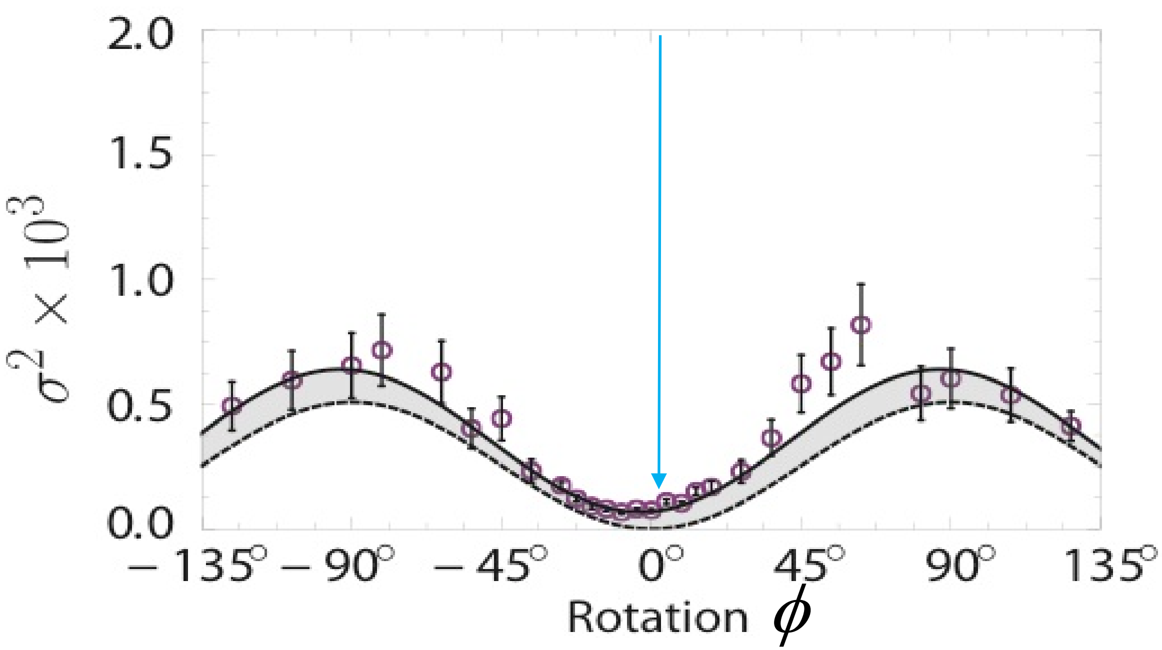
Clock probes many-body spin dynamics

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

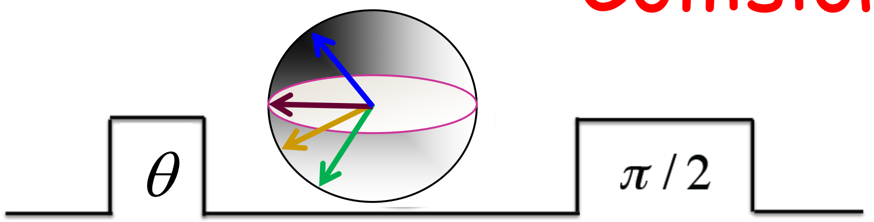
$$\hat{H}/\hbar = \chi\left(S^z\right)^2 + C\left(N-1\right)S^z$$

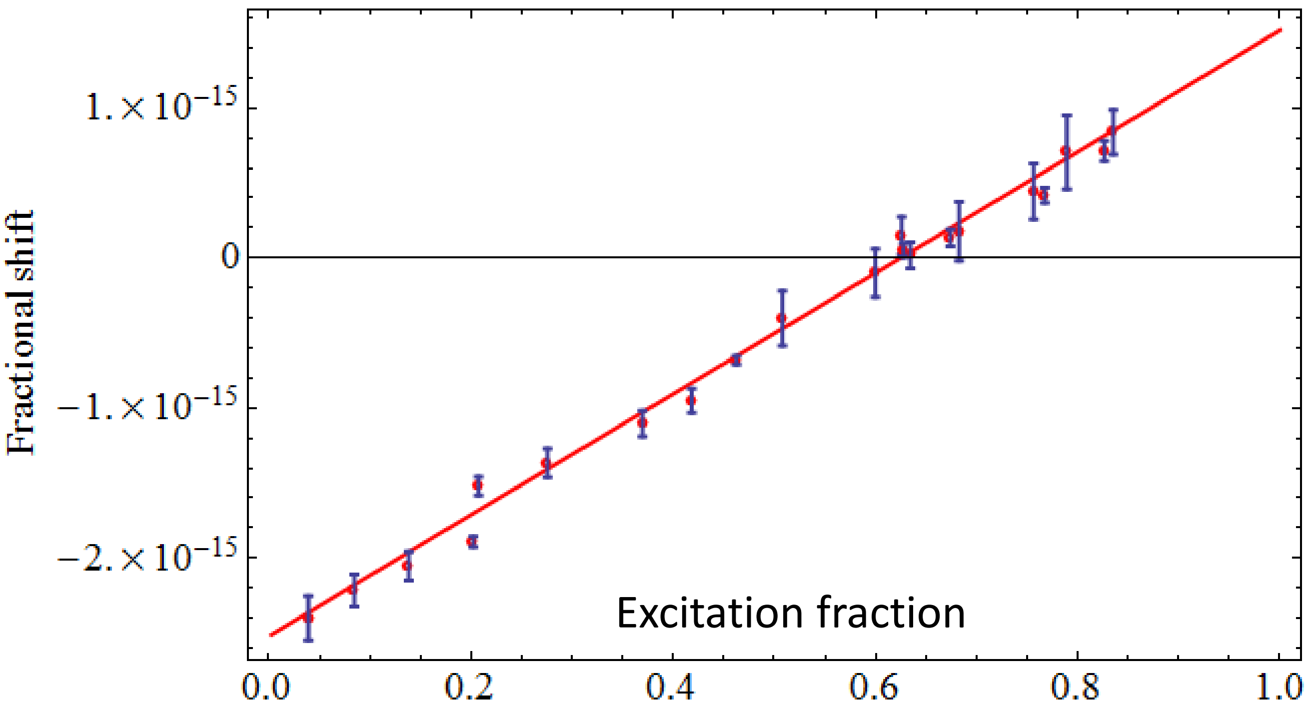






Collisional frequency shift





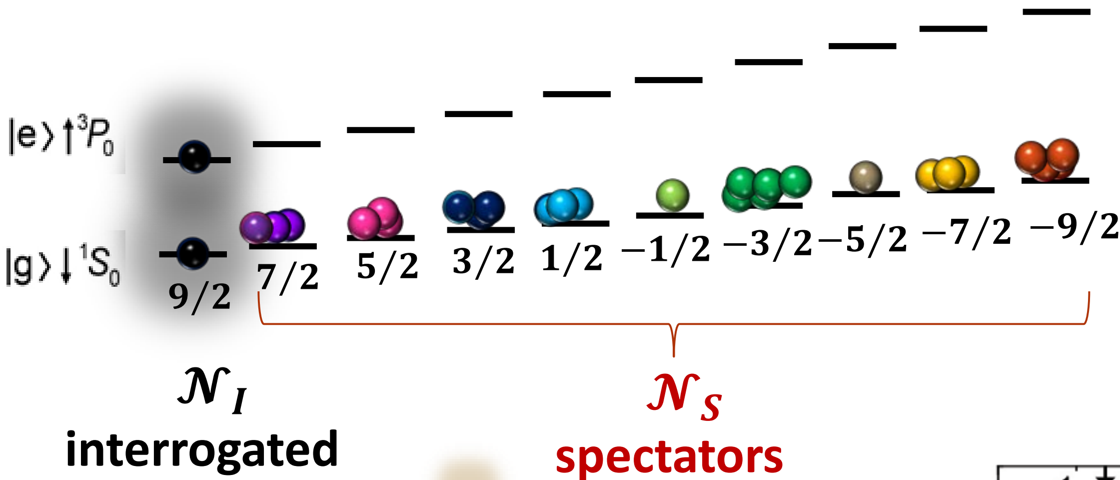
$$\frac{V_{ee}-V_{gg}}{V_{eg}-V_{gg}} = 0.4$$

Collisional shift has a linear dependence on $S_z = \cos(\theta)$.

$$\Delta\nu = H / S_z \sim \underbrace{\frac{V_{ee}-V_{gg}}{2}}_{C} + \cos(\theta)\underbrace{\left[\frac{2V_{eg}-V_{ee}-V_{gg}}{2}\right]}_{\chi}$$

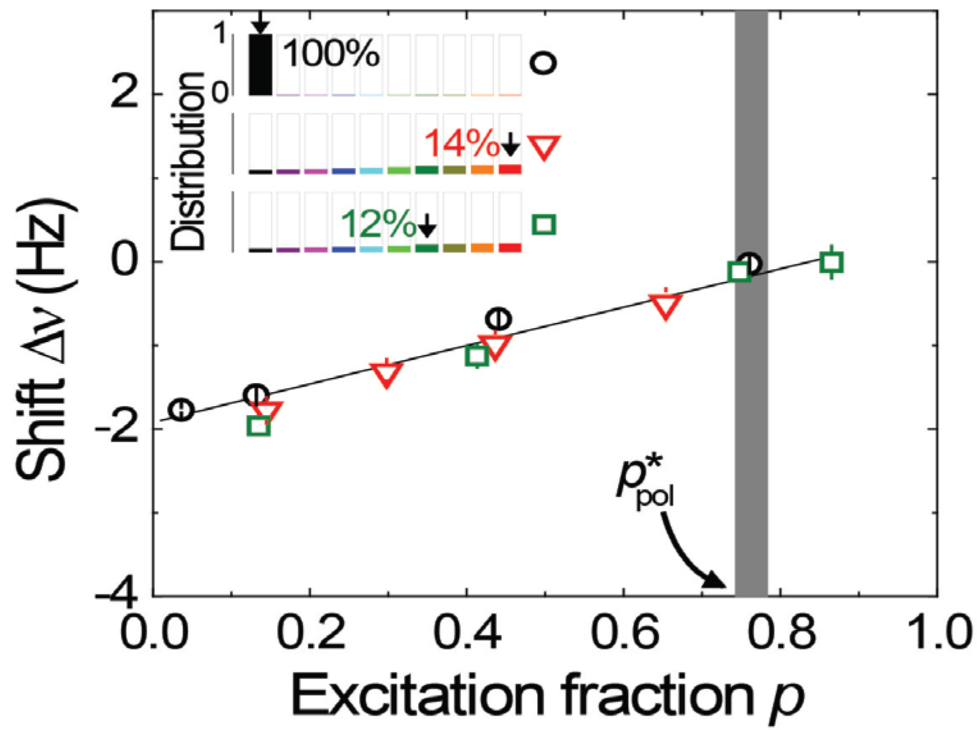
Density shifts & SU(N) symmetry

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



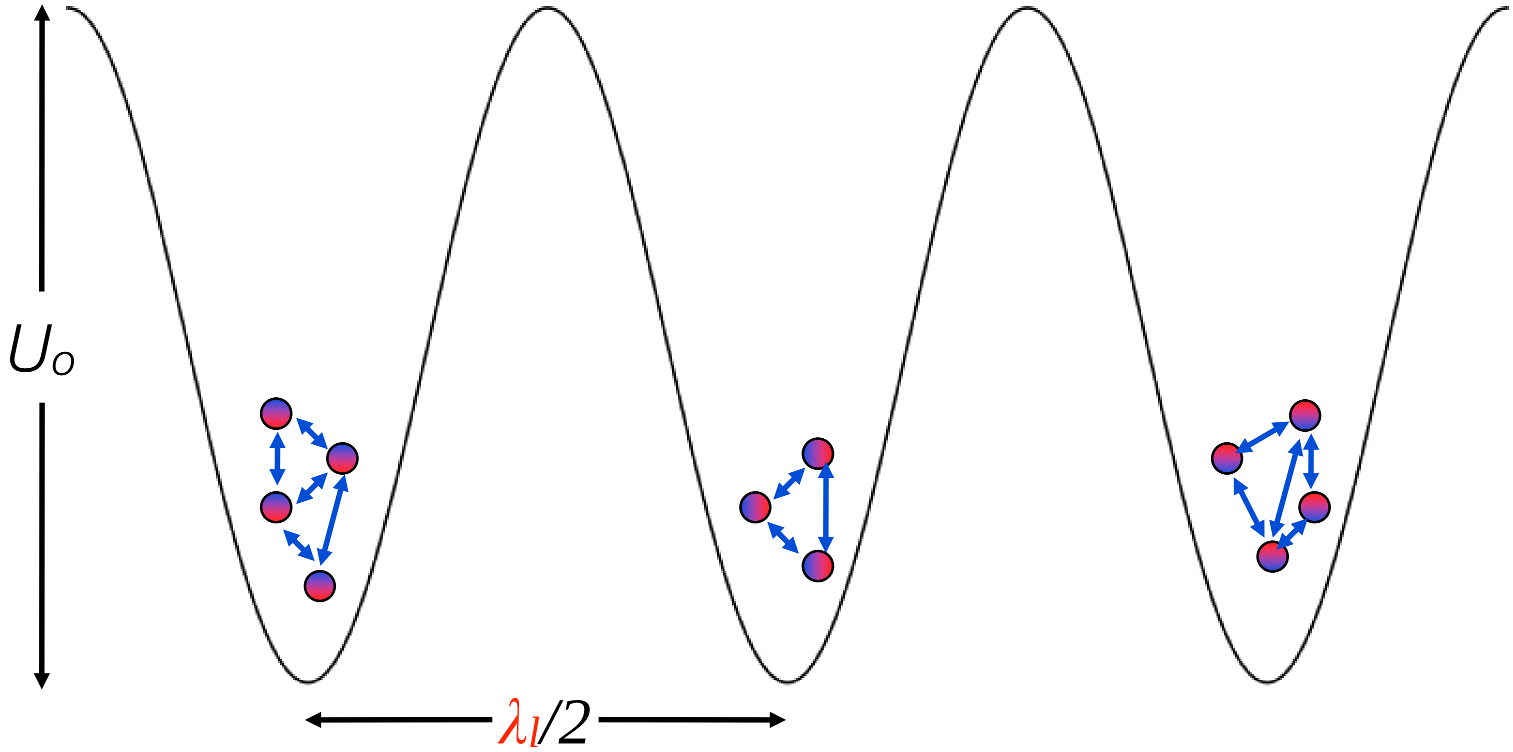
hyperfine coupling $I \cdot J = 0$.

lepends only on
ributions



So far, interactions in a single pancake

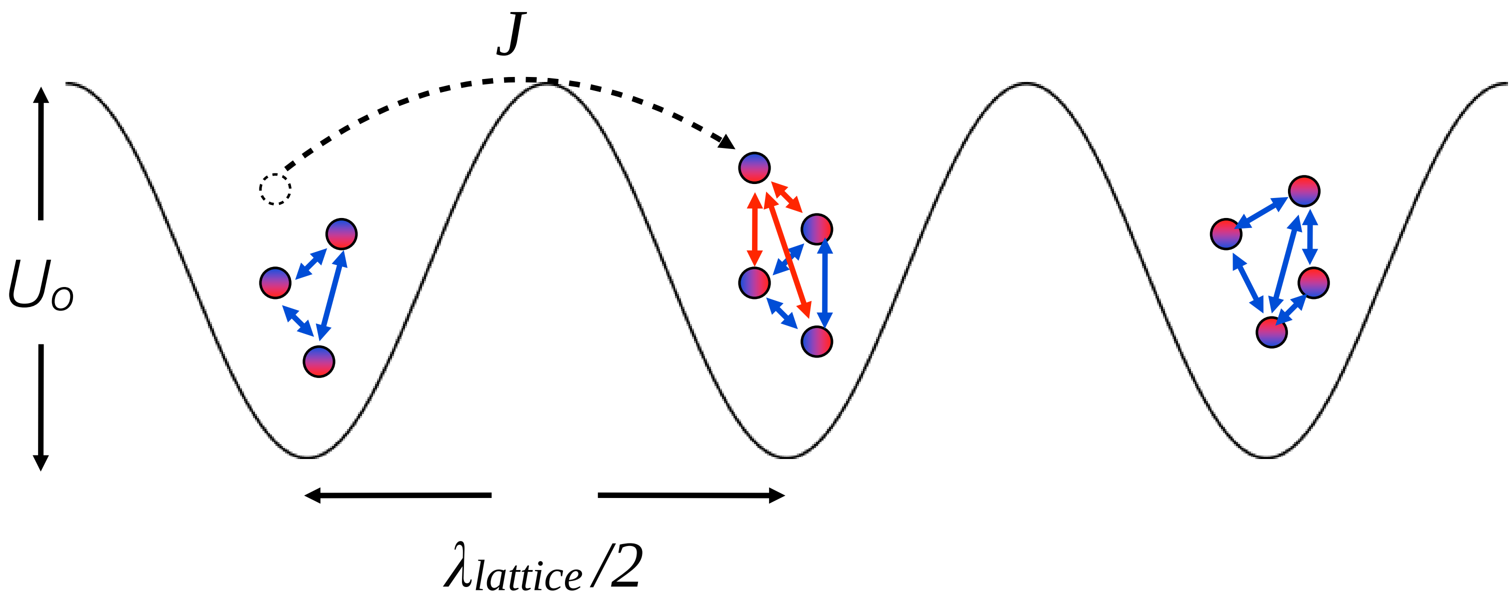
- Identical fermions, *p-wave* dominates
- Multiple nuclear spins, *s*- and *p*-waves under SU(*N*)



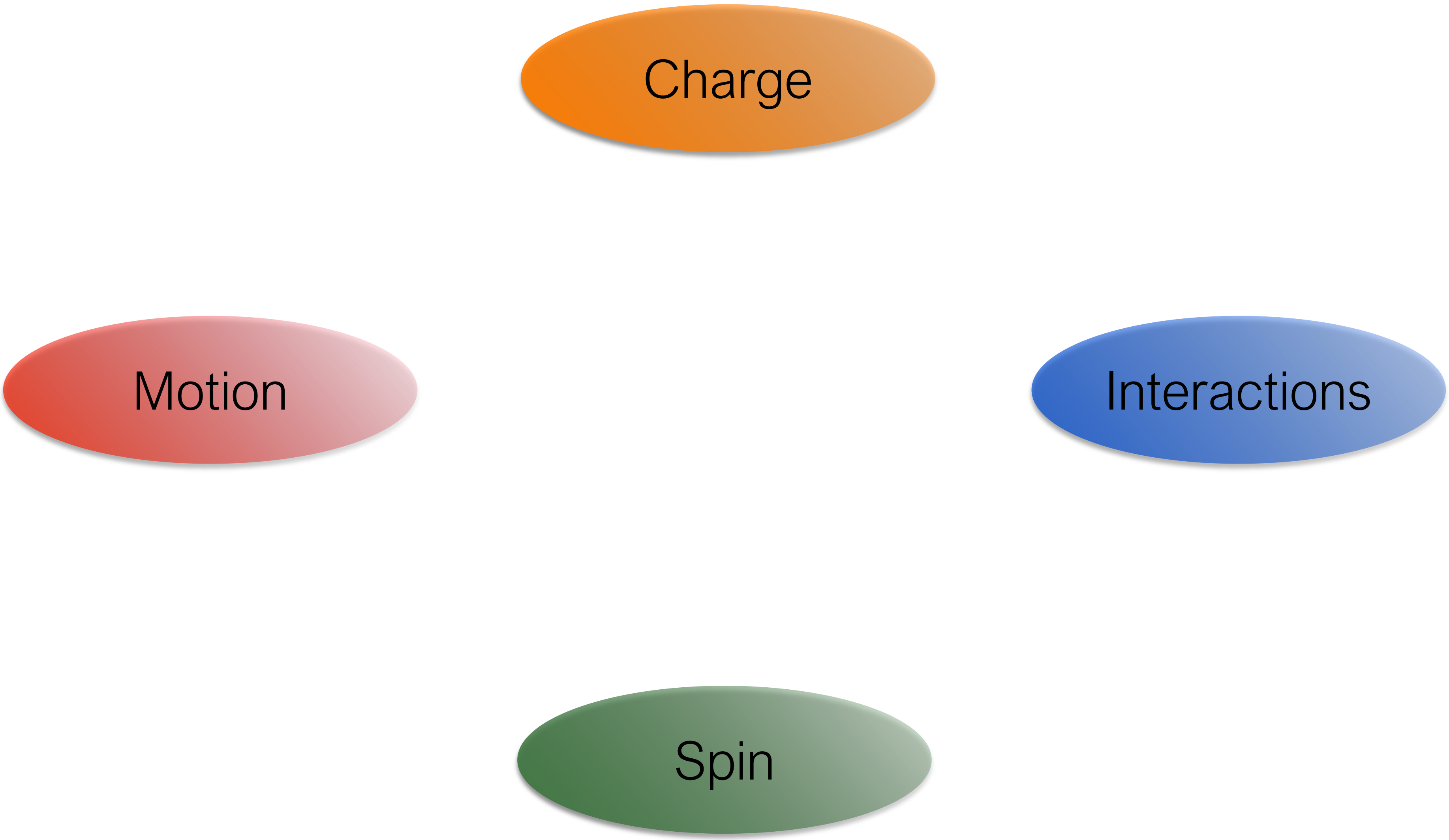
$U_o >> E_R$: Tunneling negligible

A new regime for interactions

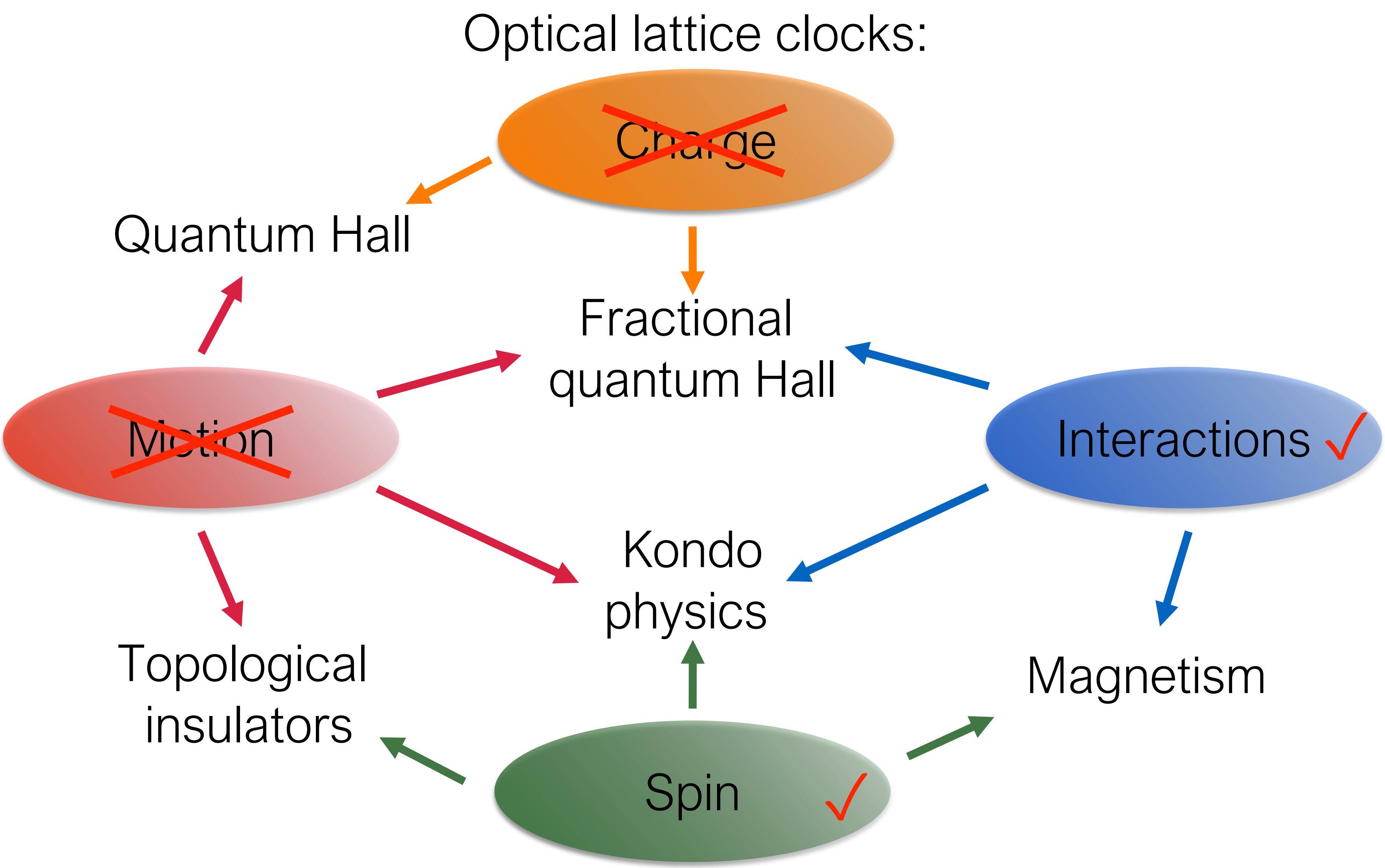
… when tunneling is allowed.



Quantum simulation wishlist

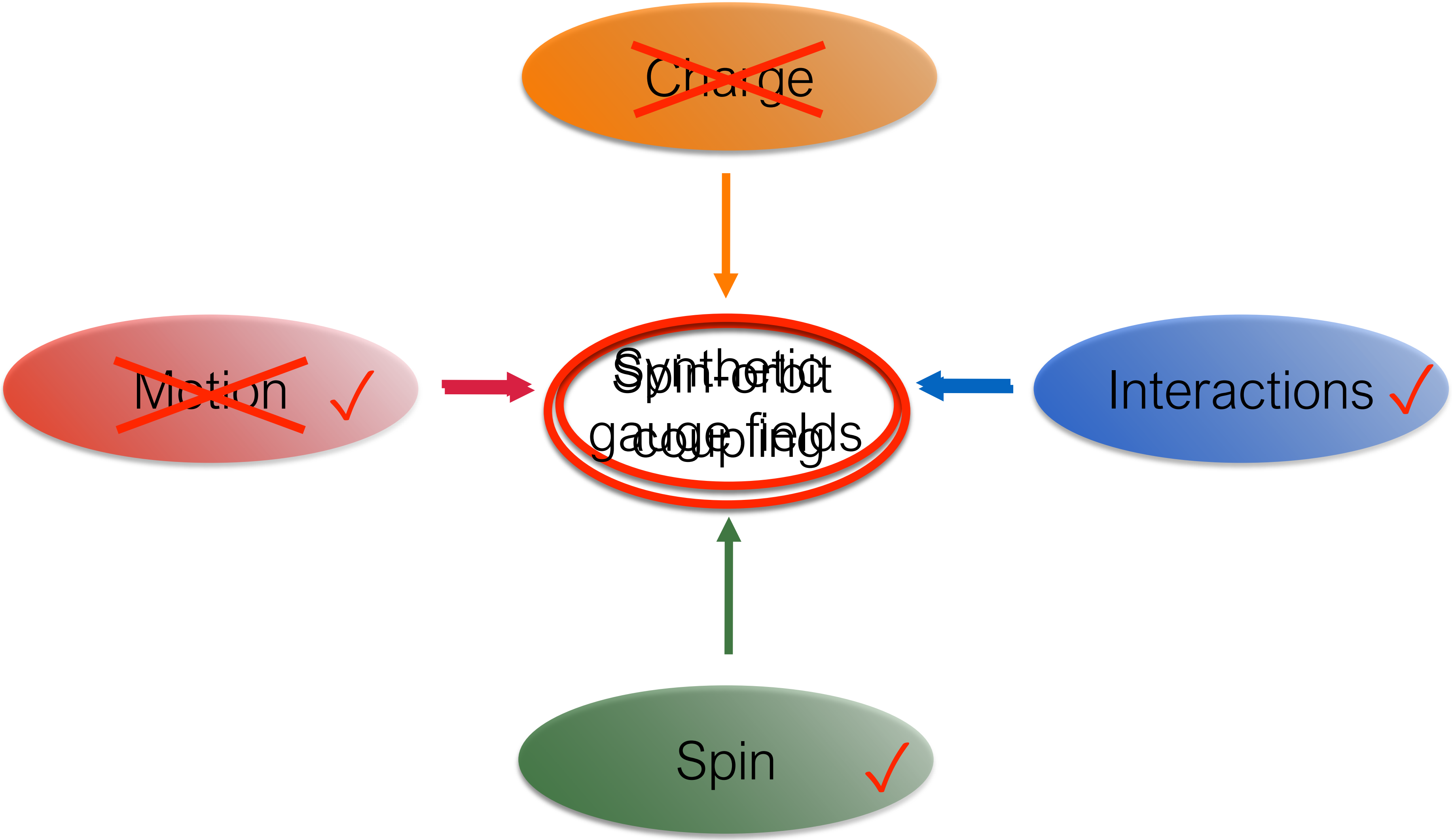


Quantum simulation wishlist



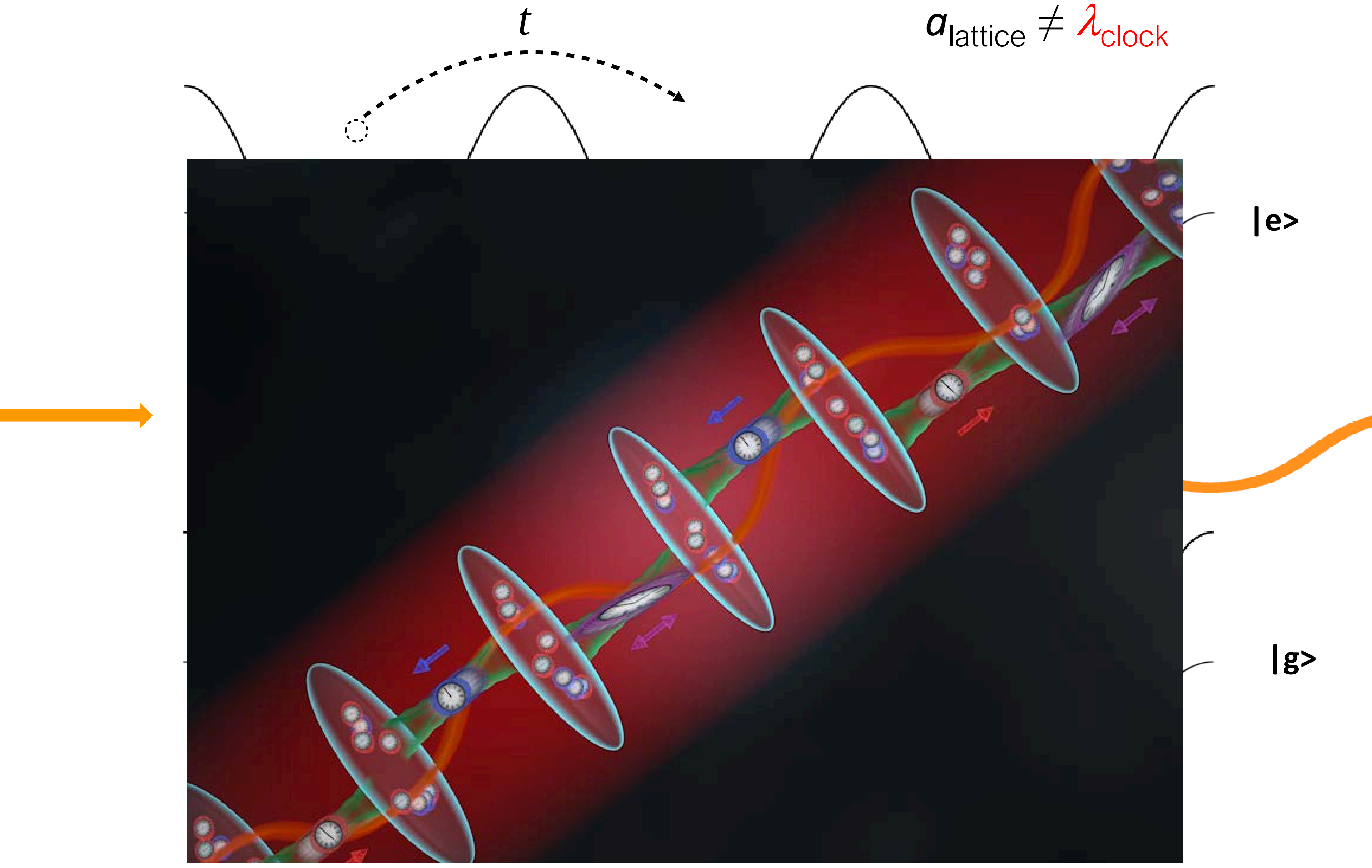
Quantum simulation wishlist

Optical lattice clocks:

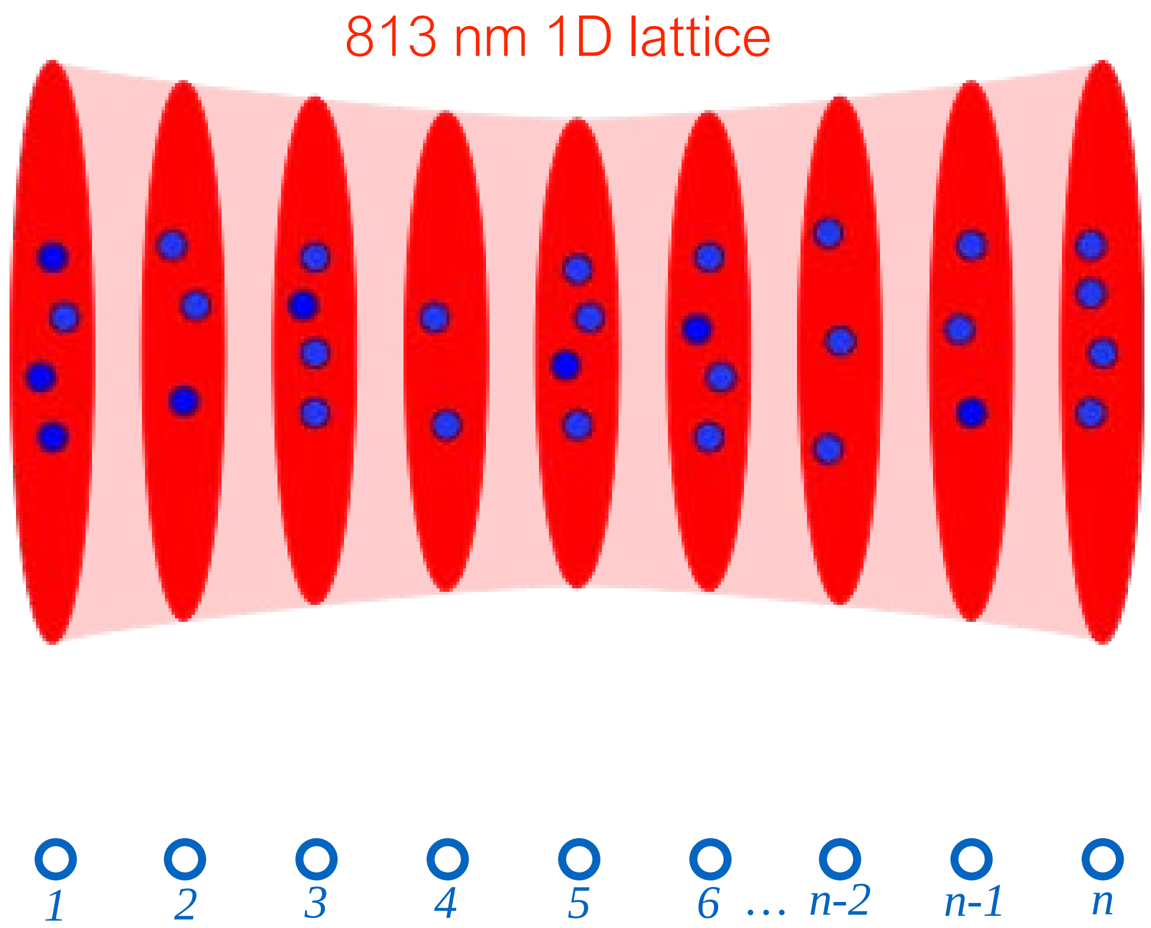


Spin-orbit coupled fermion interactions

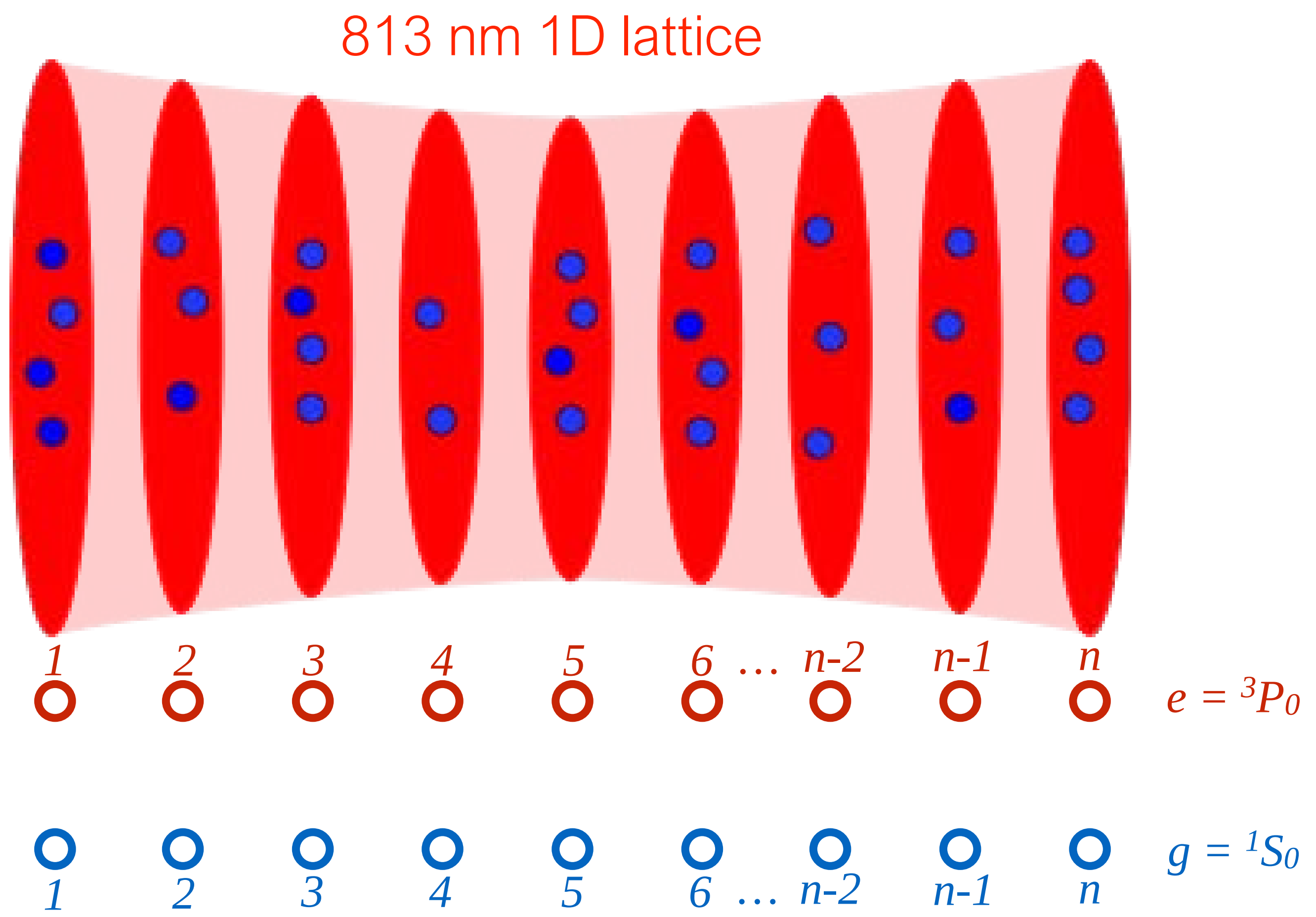
Kolkowitz *et al.*, Nature **542**, 66 (2017); Bromley *et al.*, Nature Phys. (2018).



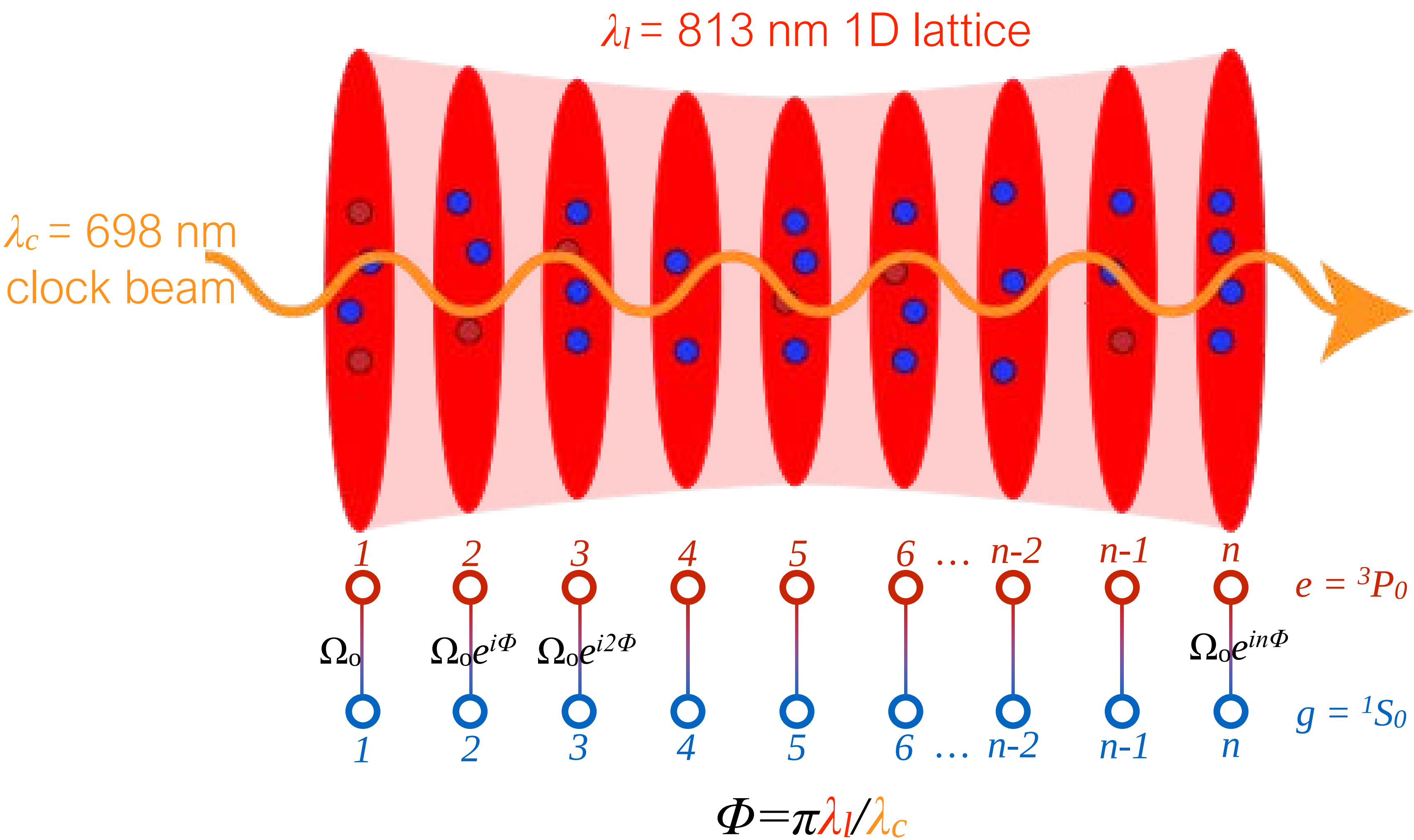
Synthetic magnetic field in the clock



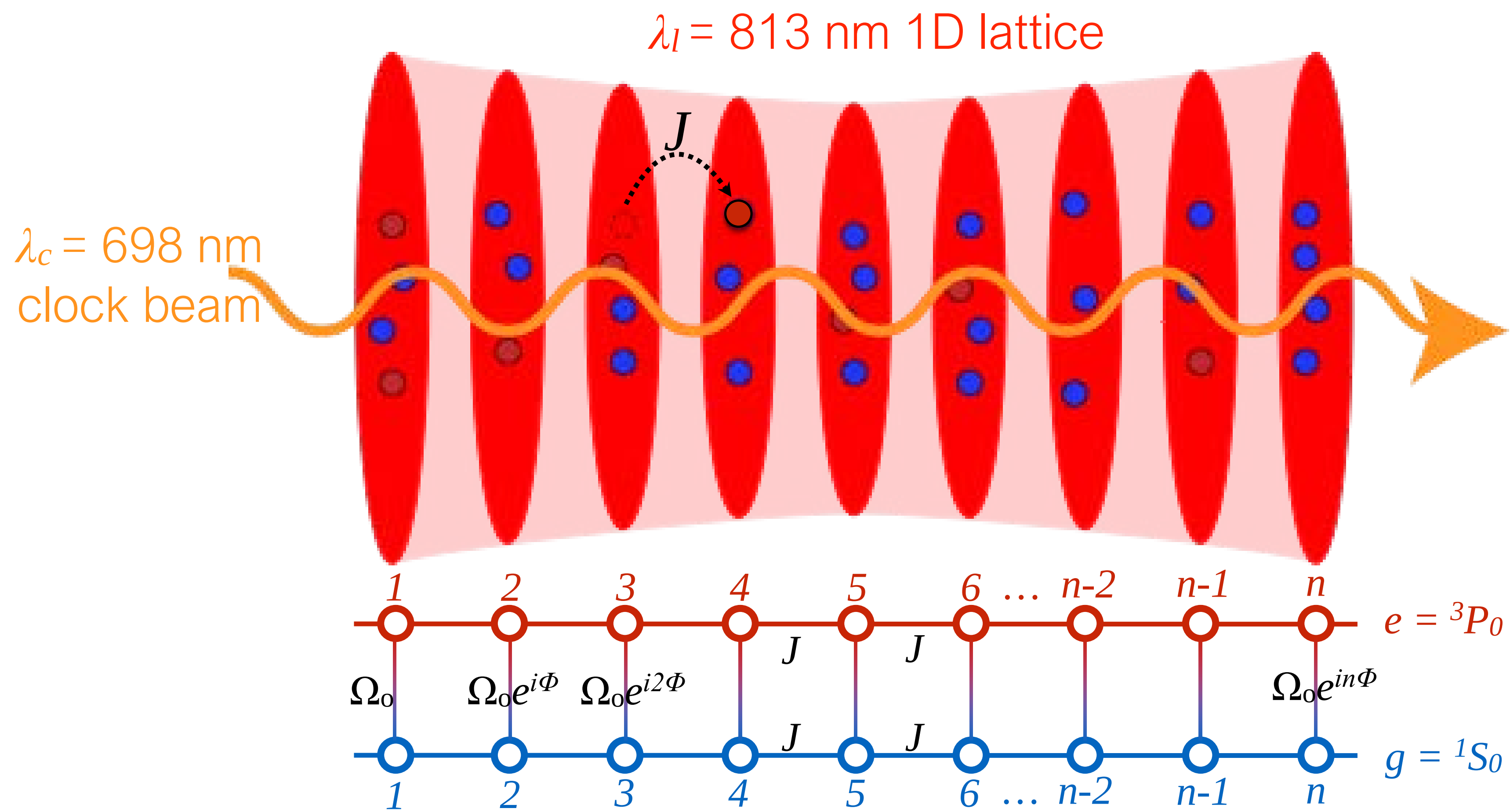
Synthetic magnetic field in the clock



Synthetic magnetic field in the clock

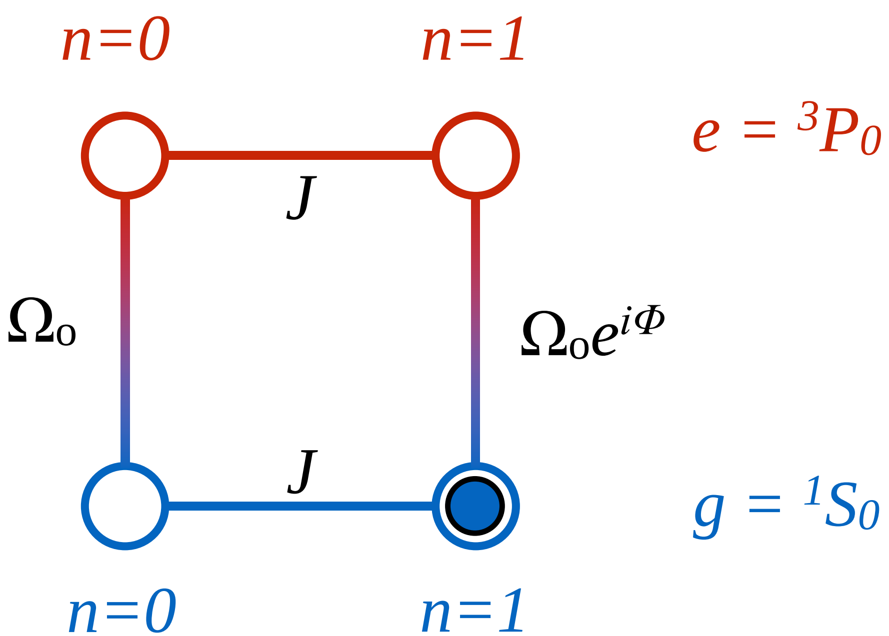


Synthetic magnetic field in the clock



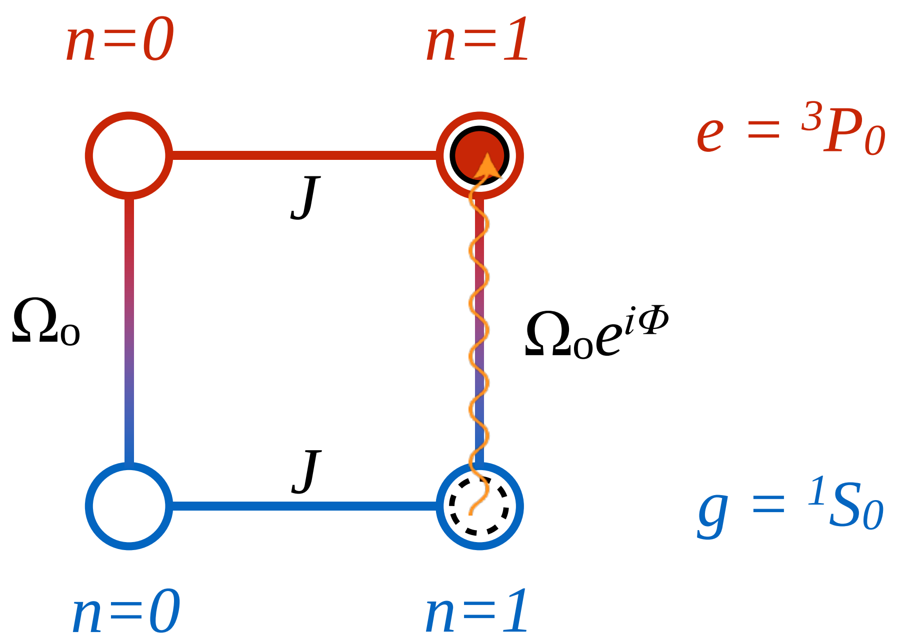
$\Phi = \pi \lambda_l / \lambda_c$ Tunneling rate J

Synthetic magnetic field in the clock



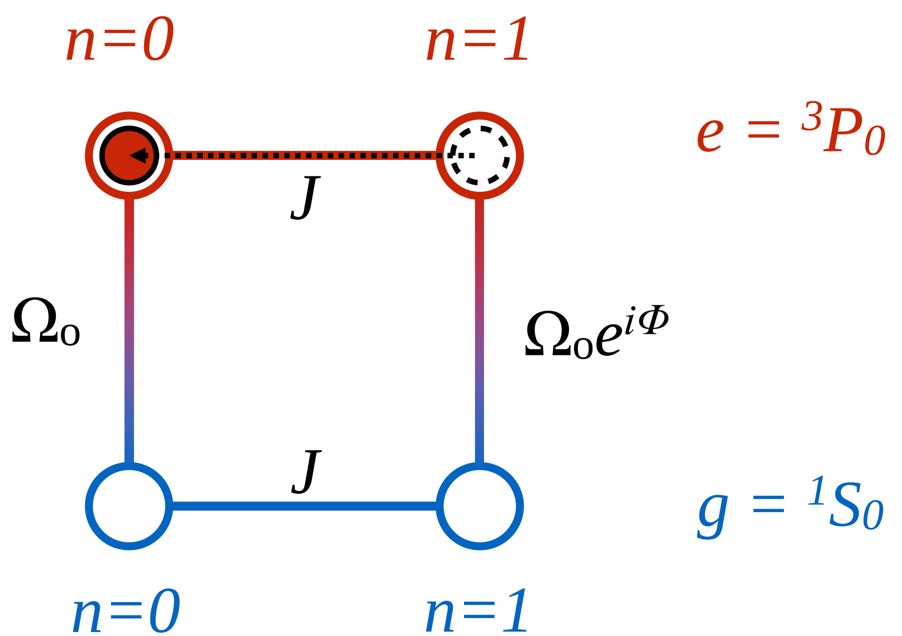
$$\psi_o = |1, g\rangle$$

Synthetic magnetic field in the clock



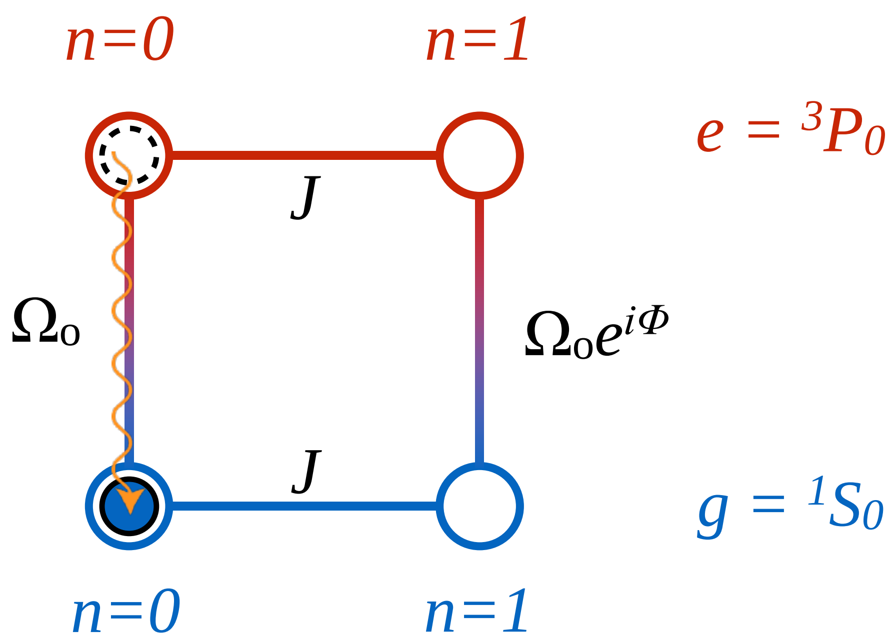
$$\psi_1 = e^{i\phi} |1, e\rangle$$

Synthetic magnetic field in the clock



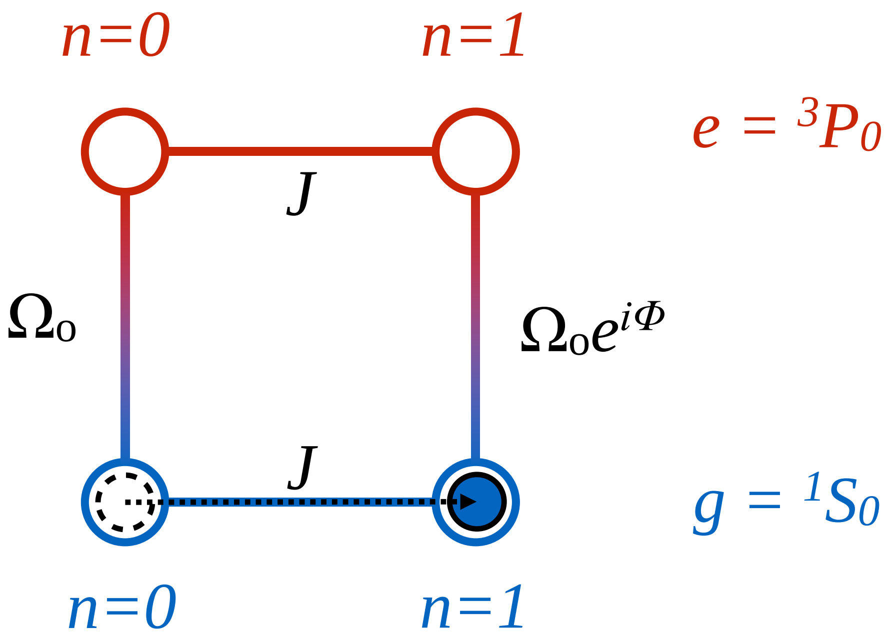
$$\psi_2 = e^{i\phi} |0, e\rangle$$

Synthetic magnetic field in the clock



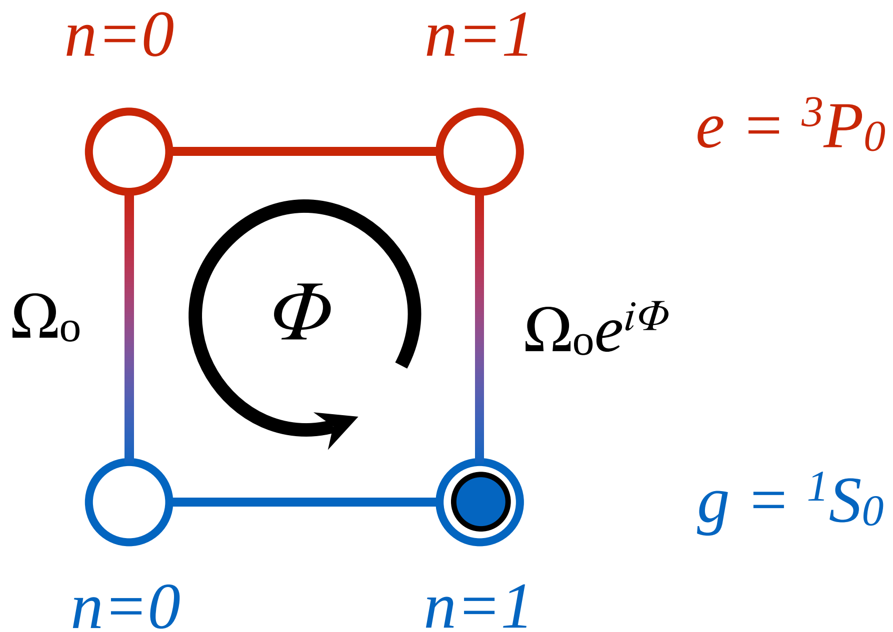
$$\psi_3 = e^{i\phi}\left|0,g\right\rangle$$

Synthetic magnetic field in the clock



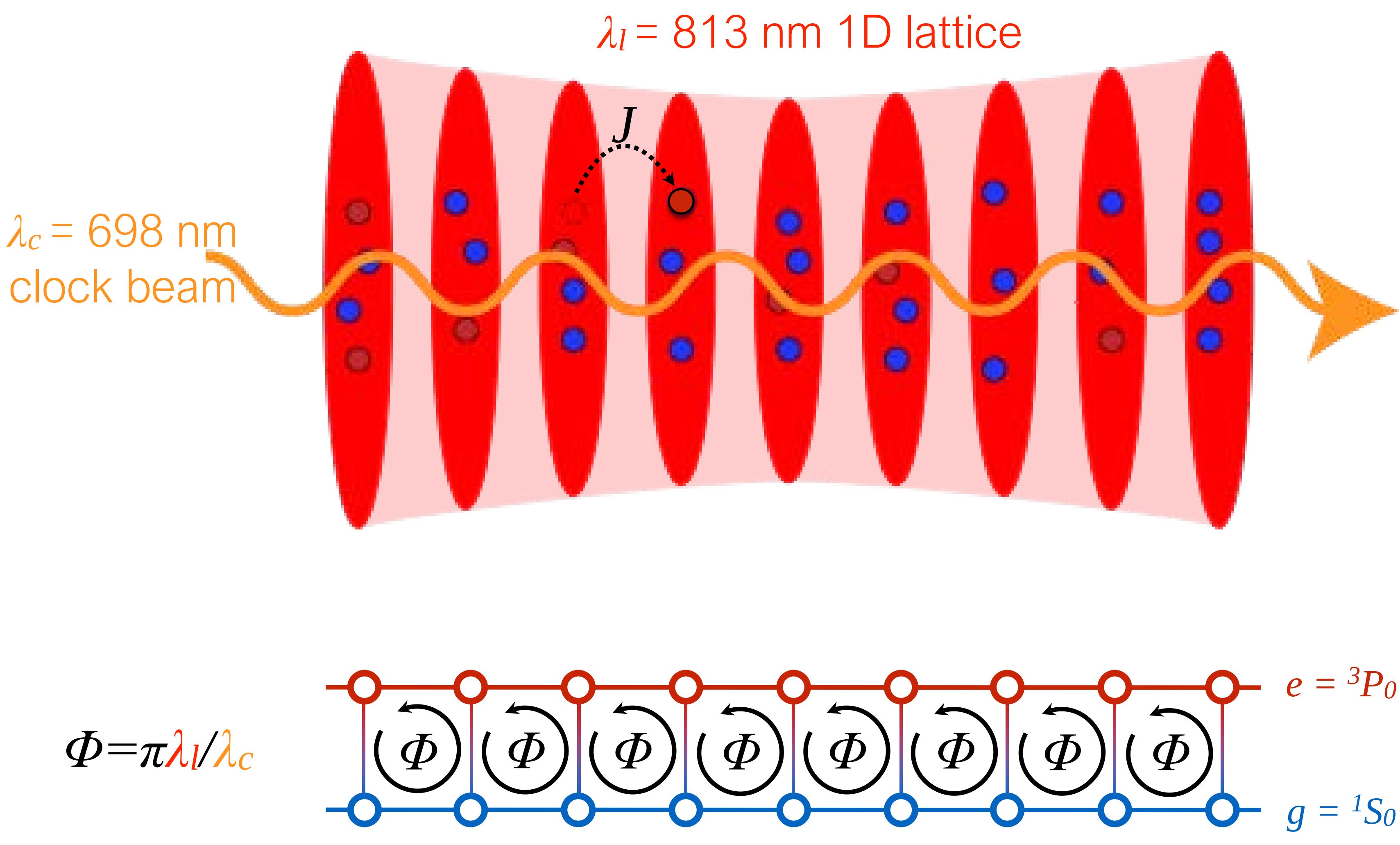
$$\psi_f = e^{i\phi}\left|1,g\right\rangle$$

Synthetic magnetic field in the clock

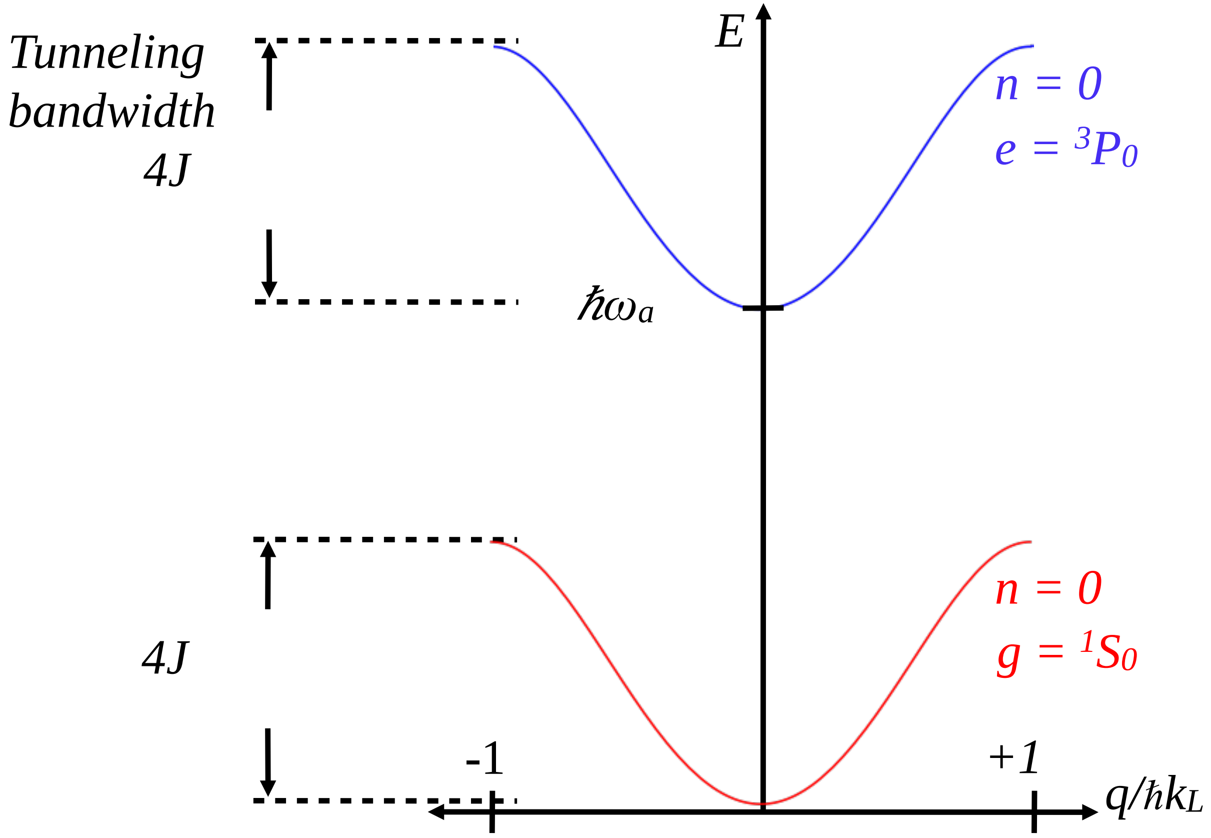


$$\psi_f = e^{i\phi}\psi_o$$

Synthetic magnetic field in the clock

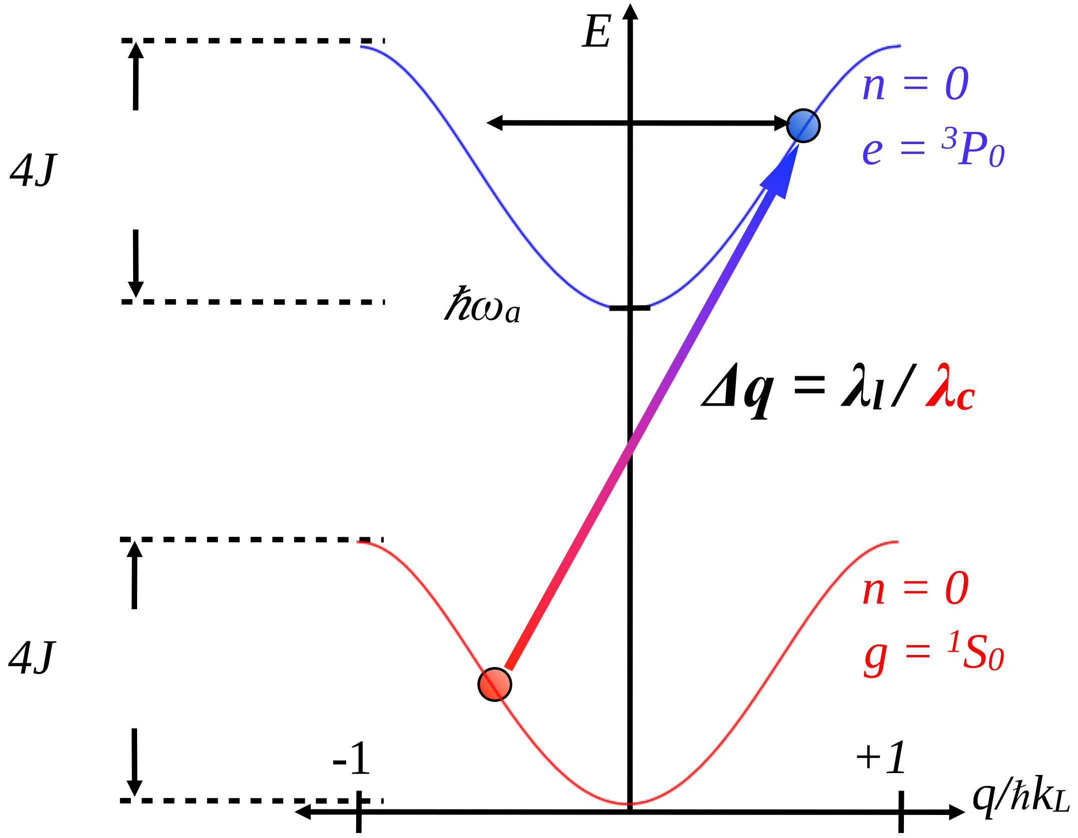


Spin-orbit coupling



Spin-orbit coupling

Kolkowitz *et al.*, Nature **542**, 66 (2017).

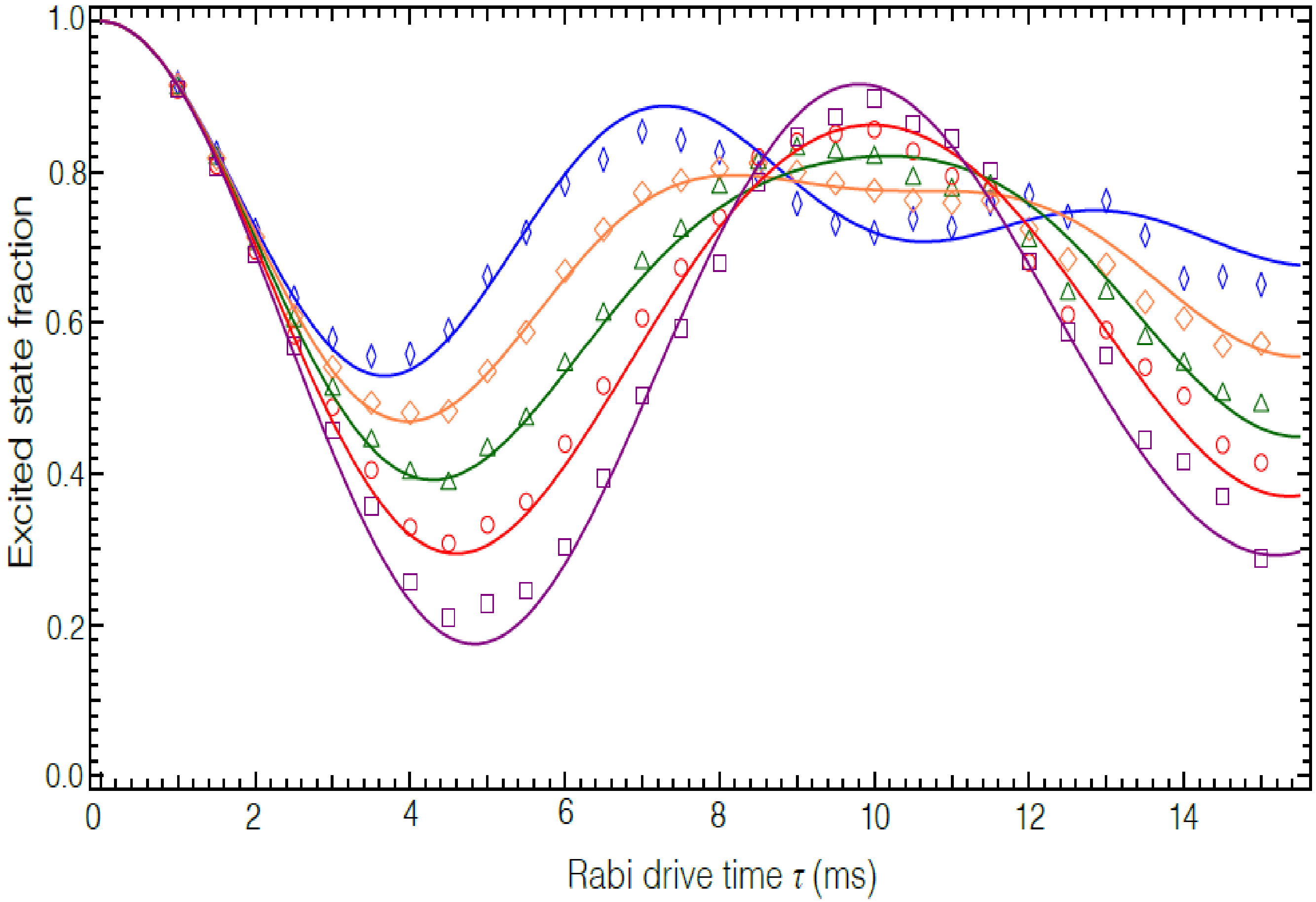


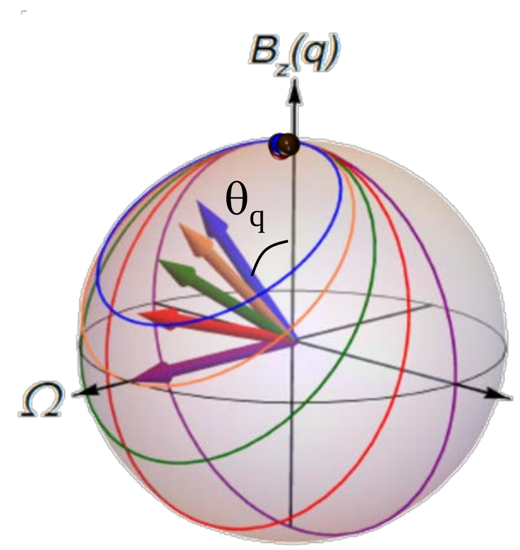
Spin-orbit coupling

Kolkowitz *et al.*, Nature **542**, 66 (2017).

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

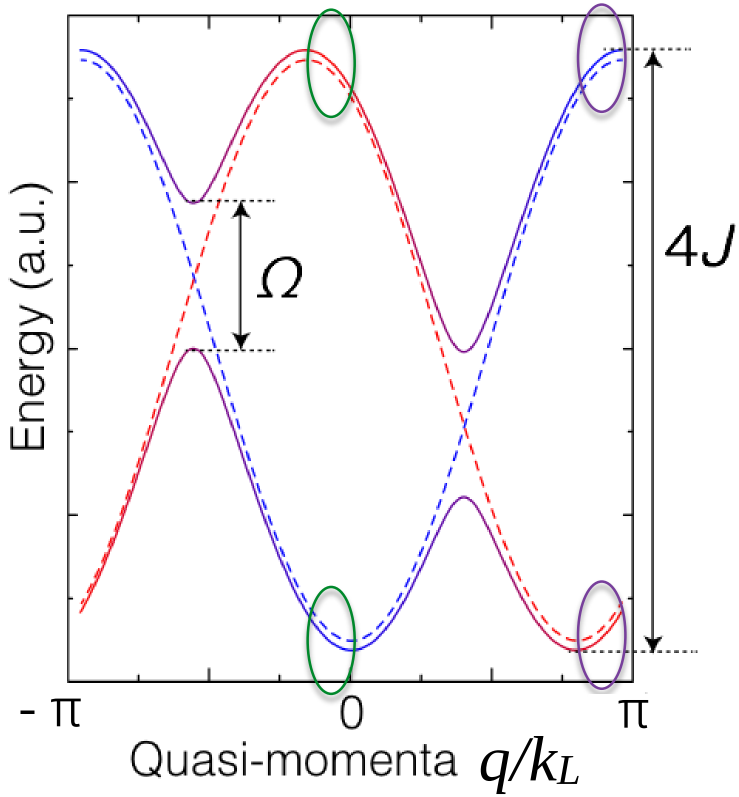
$$\Delta E(q) = -J\,[\cos(\pi q/k_L + \Phi) - \cos(\pi q/k_L)]$$

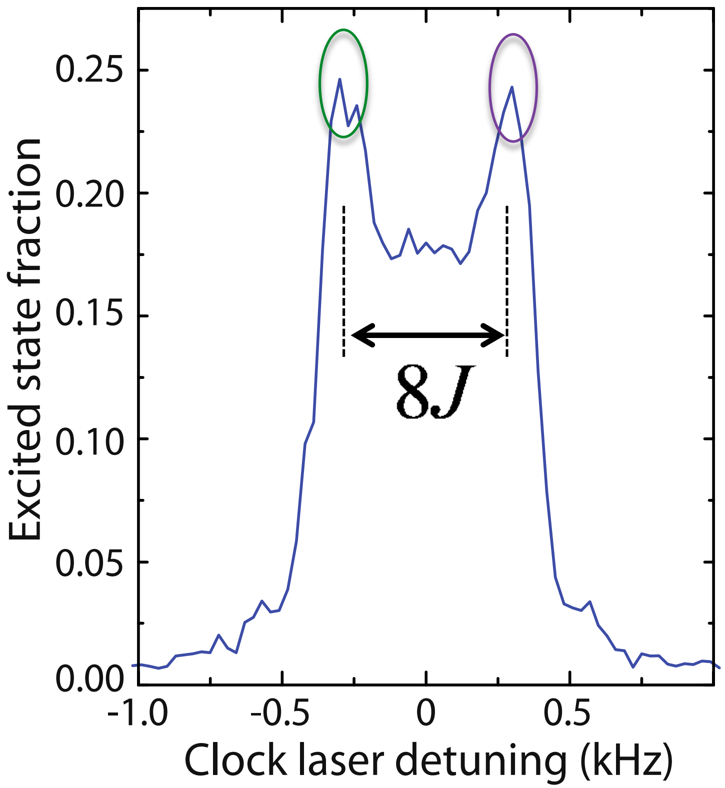




Spin-motion locking: $\vec{B}(q_i) \cdot \vec{s}_i$

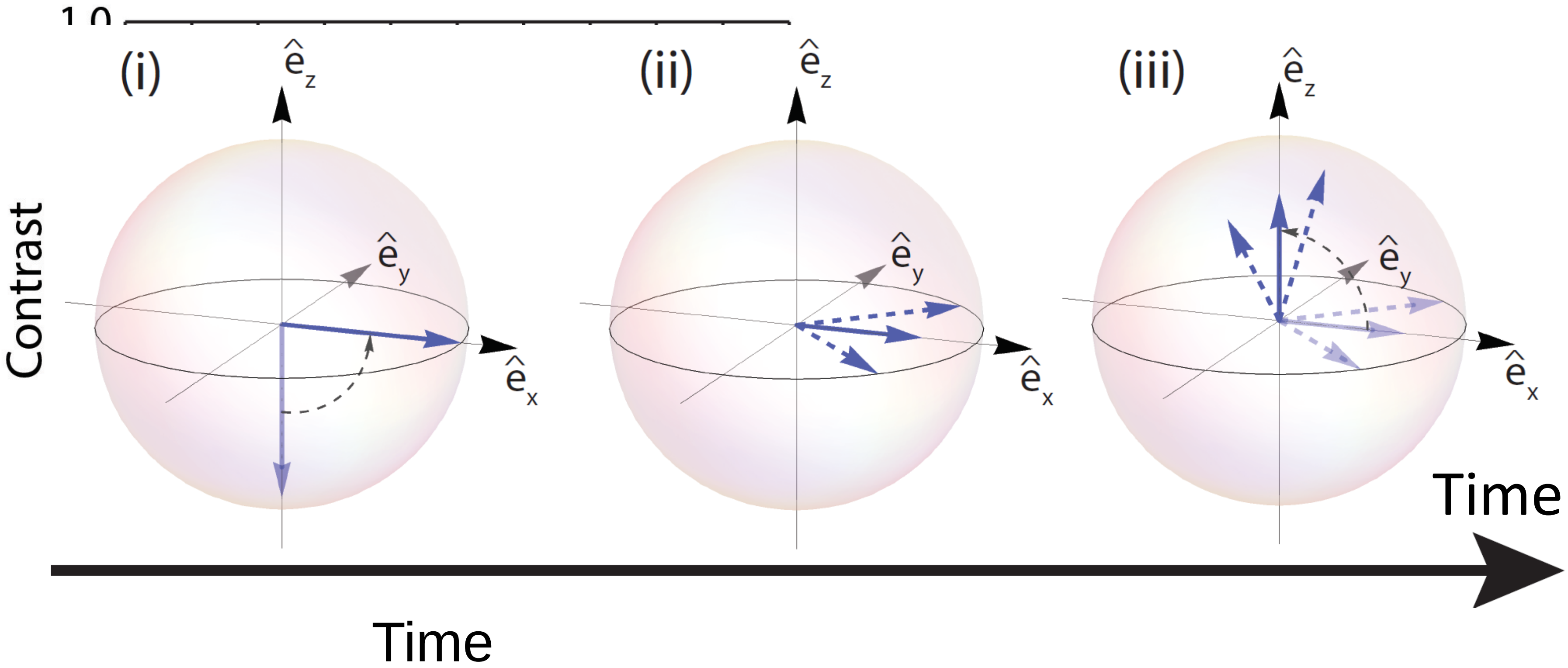
Spin-orbit coupled band structure





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

Interacting fermions under SOC



$$\hat{H}/\hbar = \vec{B}(q_i) \cdot \vec{s}_i$$

$$+ \chi (S^z)^2 + C(N-1) S^z$$

$$+ \xi \vec{S} \cdot \vec{S}$$

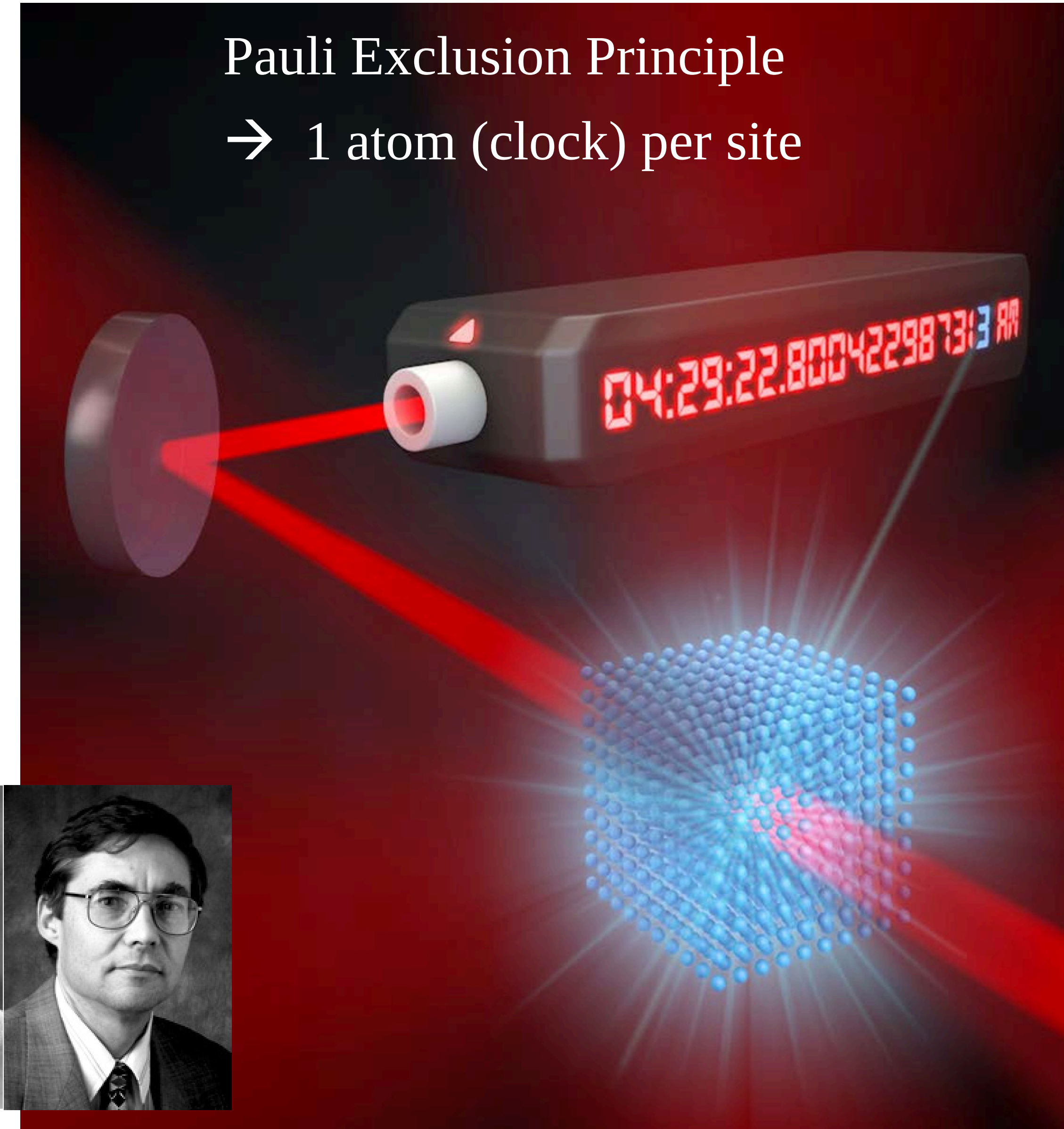
3D Fermi Insulator Clock

Scaling up the Sr quantum clock:

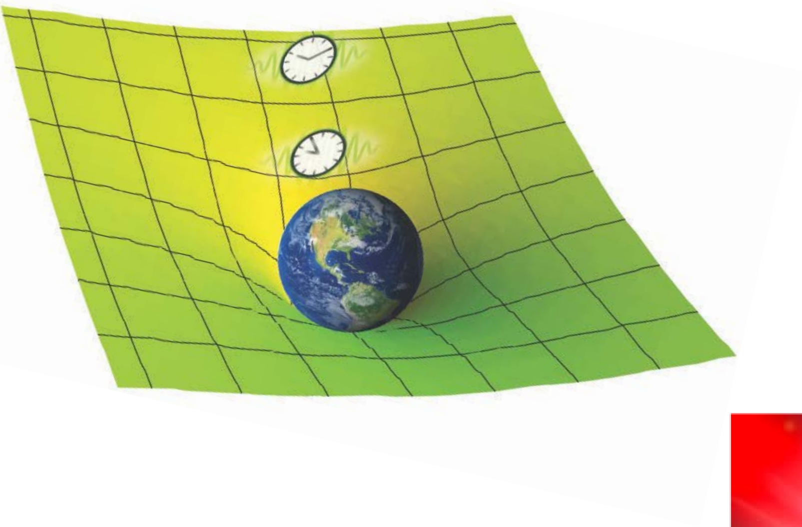
1 million atoms
(100 x 100 x 100 cells)

Coherence 160 s

Precision 3 x 10^{-20} $Hz^{-1/2}$

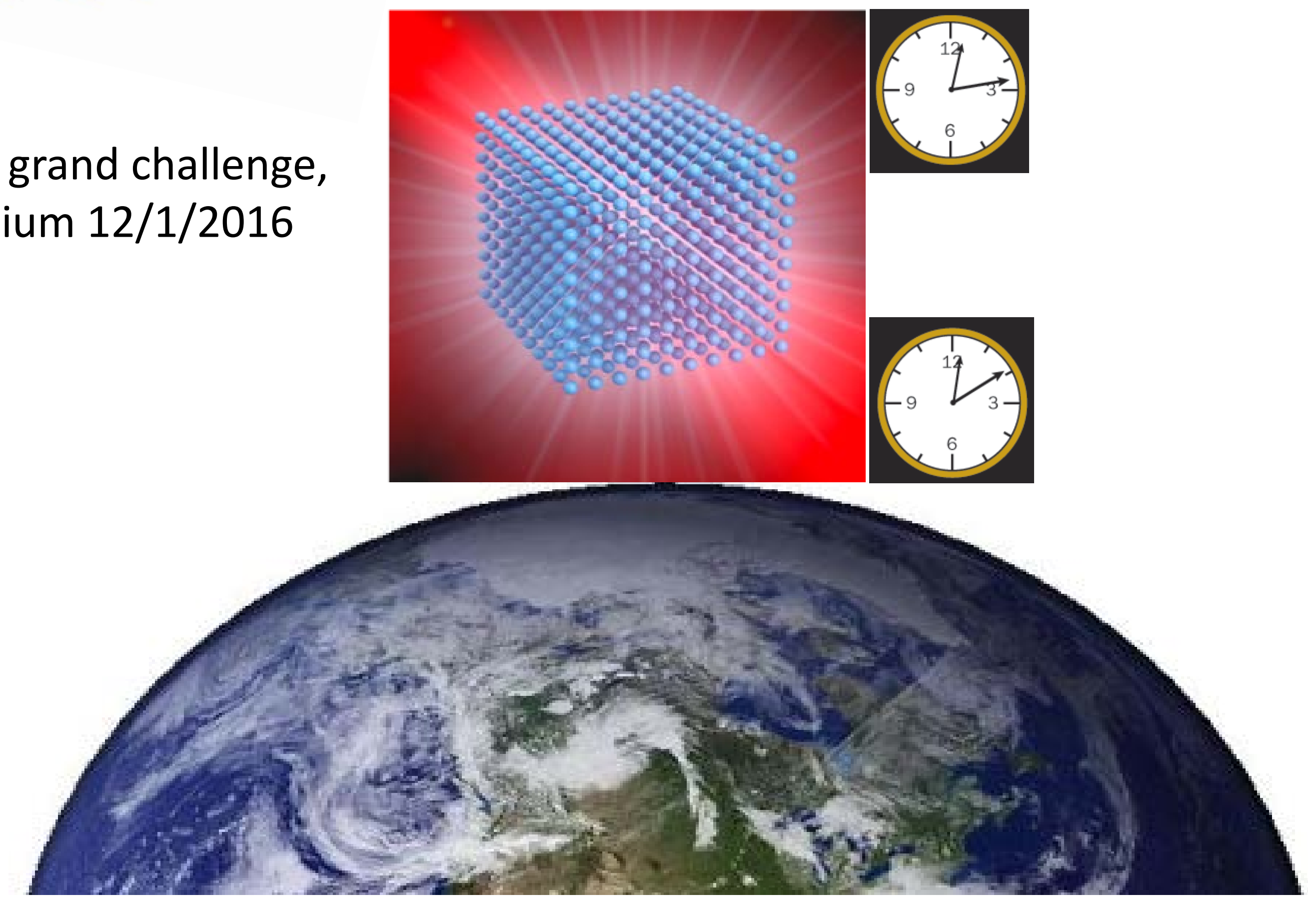


Gravitational potential & gravity at once ?



Extreme spatial resolution & precision

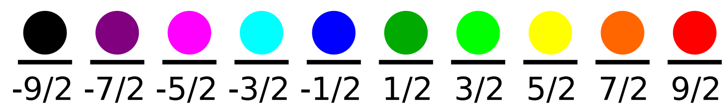
Jean Dalibard's grand challenge,
Kastler Symposium 12/1/2016



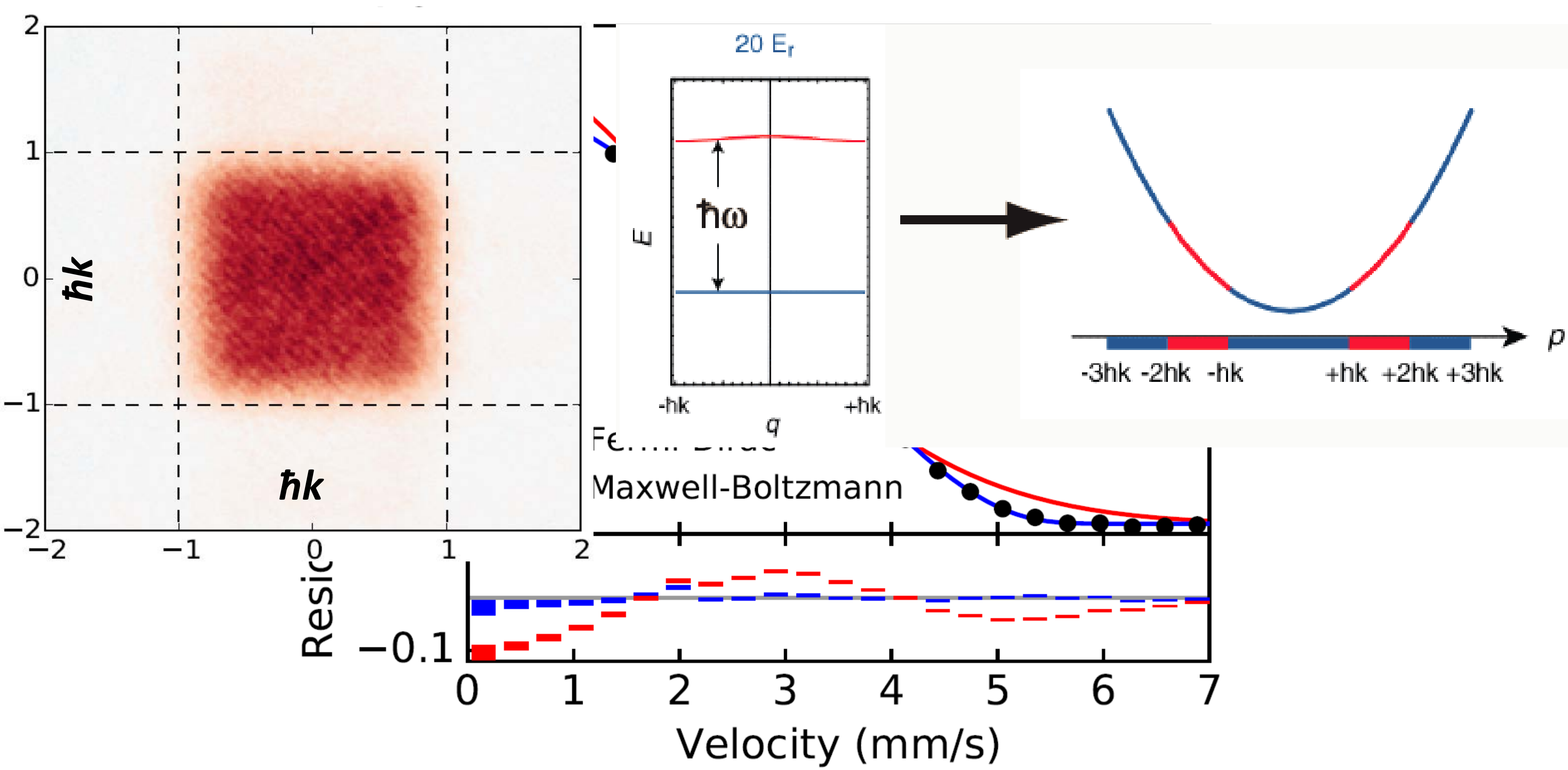
Deeply Fermi degenerate

63,000 ^{87}Sr atoms (6,300 per nuclear spin state); 8.1 nK

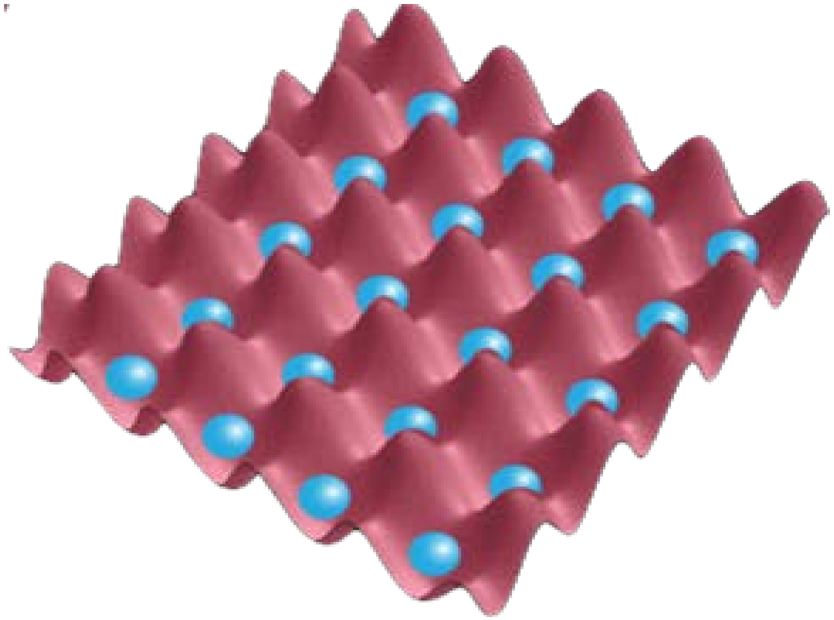
$T/T_F = 0.05$

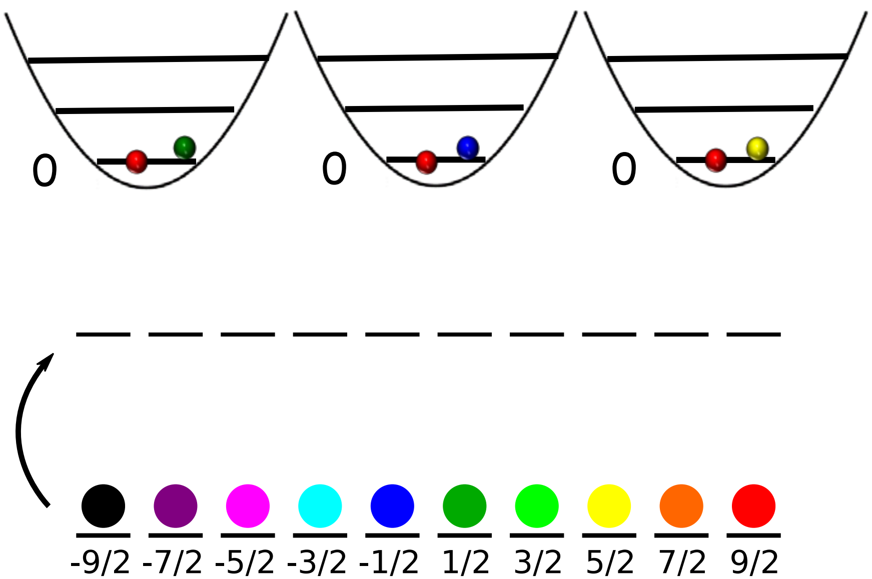


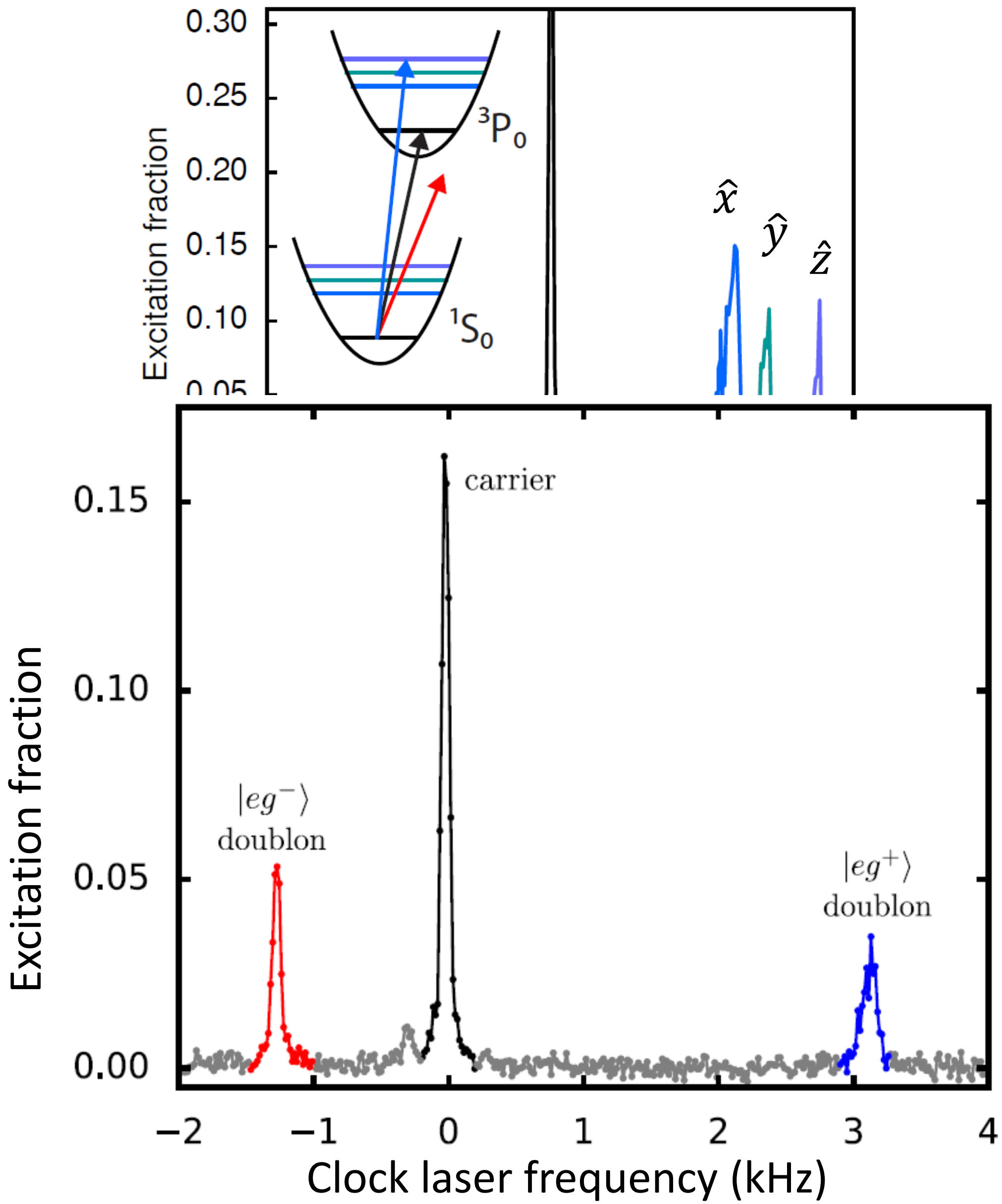
SU(*N*) → *same scattering length for all spin states*



A Fermi Gas Mott Insulator Clock

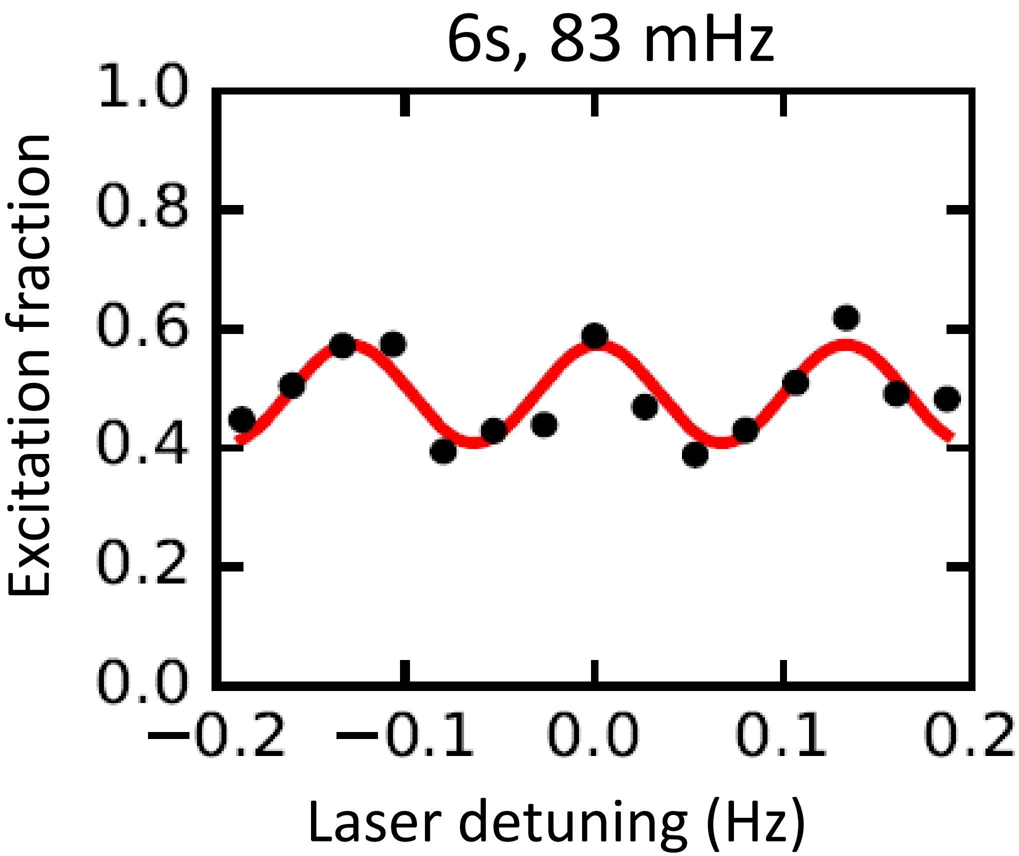






Long atom-light coherence

S. Campbell *et al.*, Science **358**, 90 (2017).

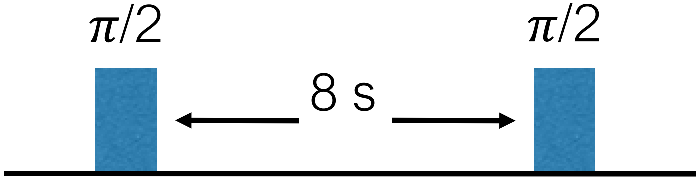


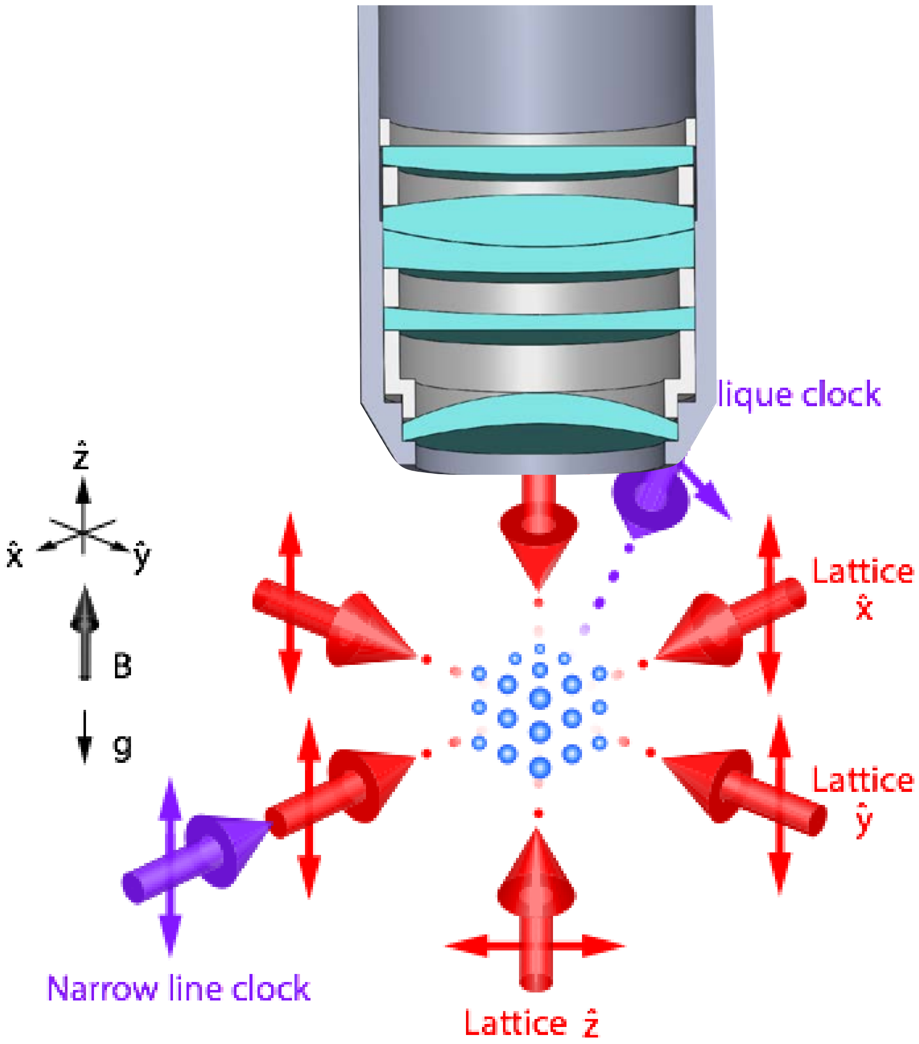
Atom-Light coherence: 10 s

Quality factor: 8×10^{15}

Spatial + Spectral resolution

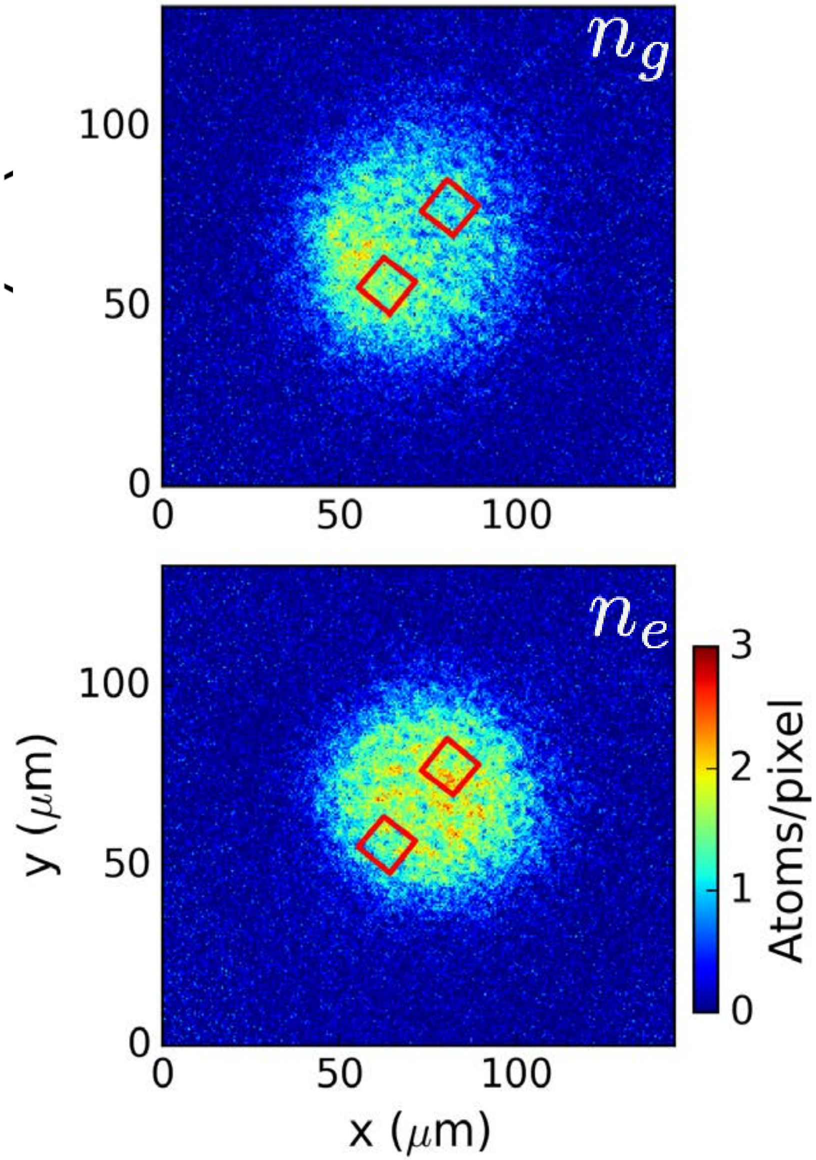
Marti *et al.*, Phys Rev Lett **120**, 103201 (2018).

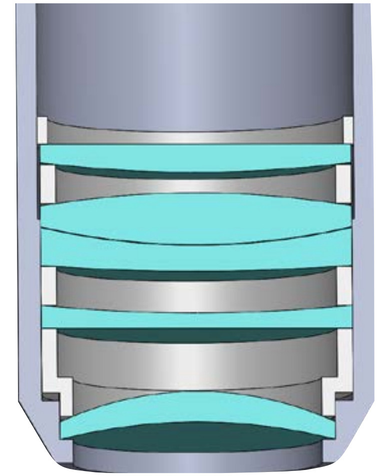




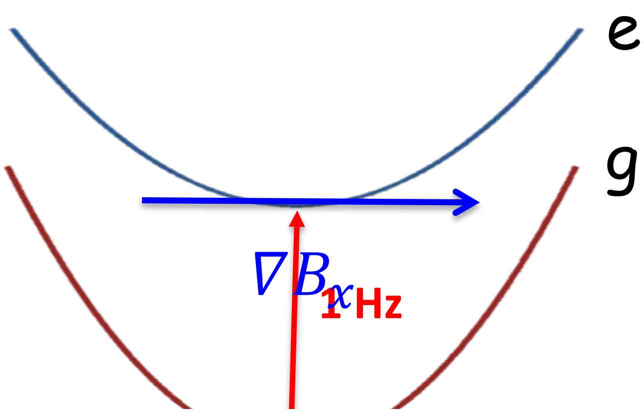
Spatial + Spectral resolution

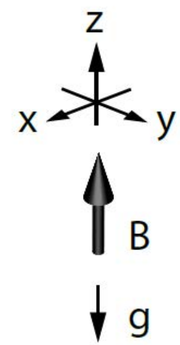
Marti *et al*., Phys Rev Lett **120**, 103201 (2018).

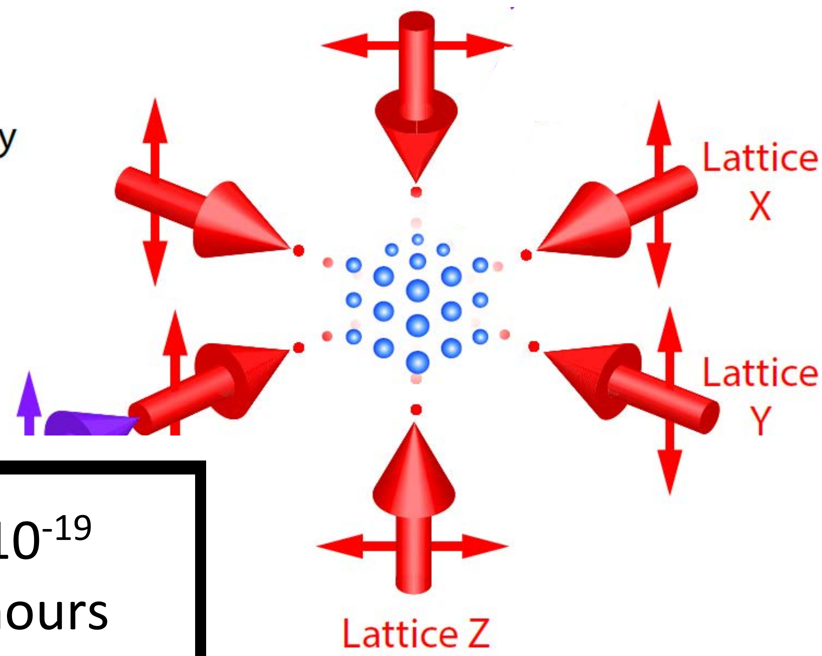


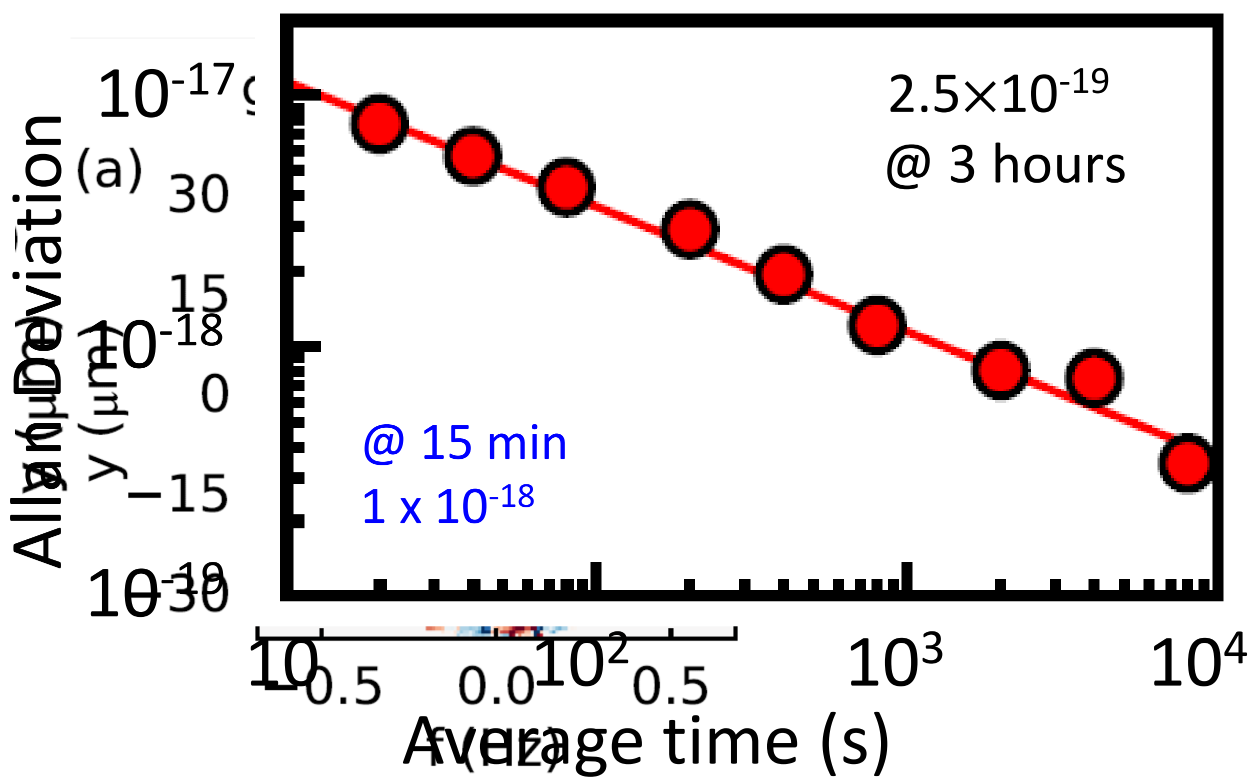


Snap shots of optical phase evolutions

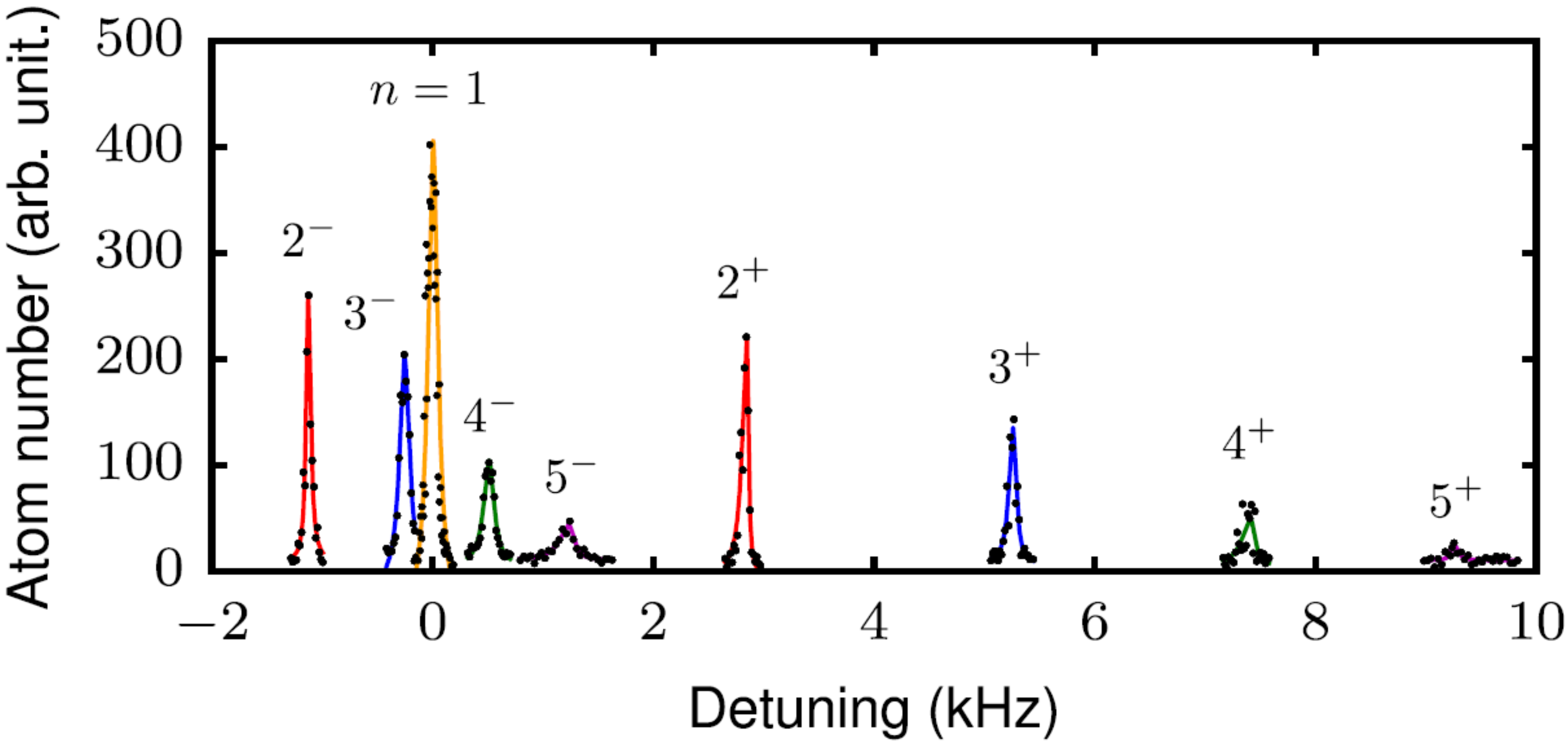


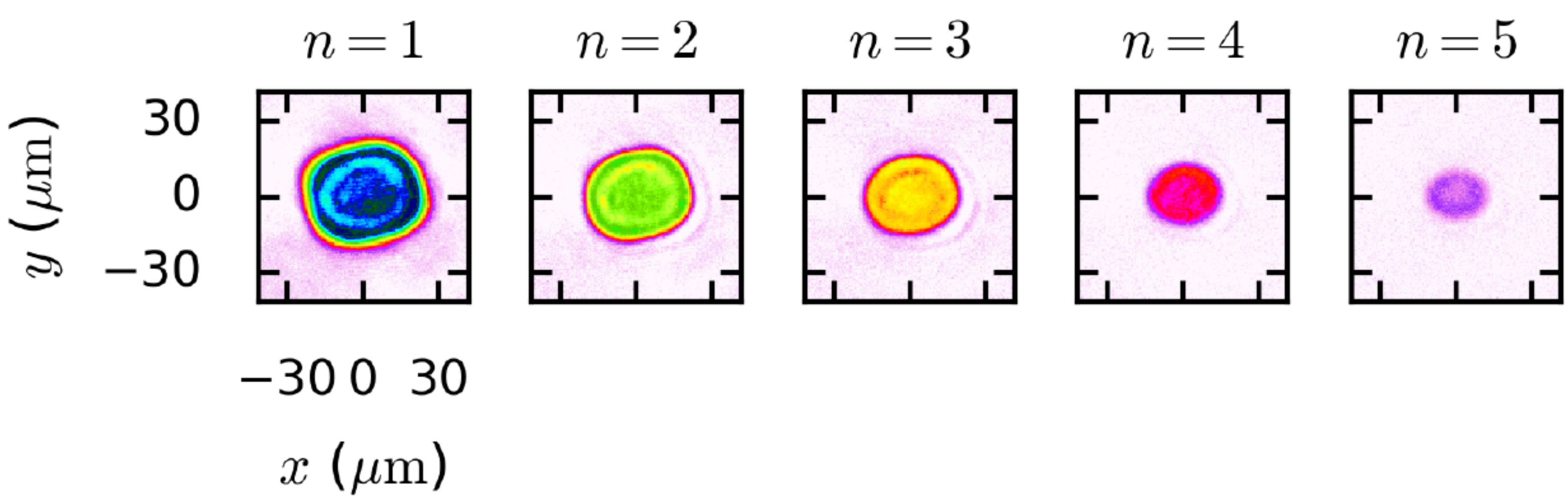






Emergence of multi-atom interactions

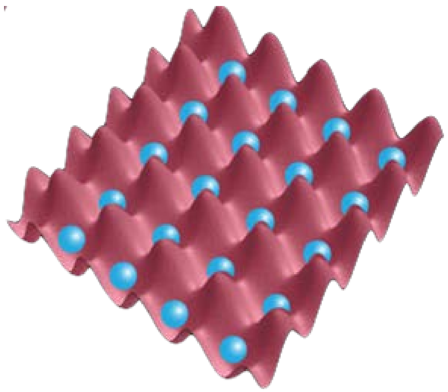


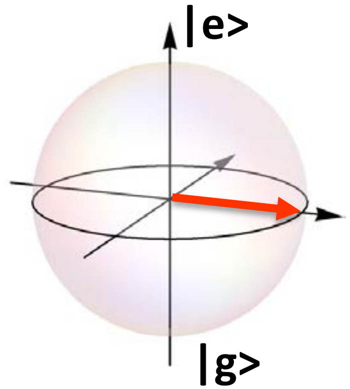


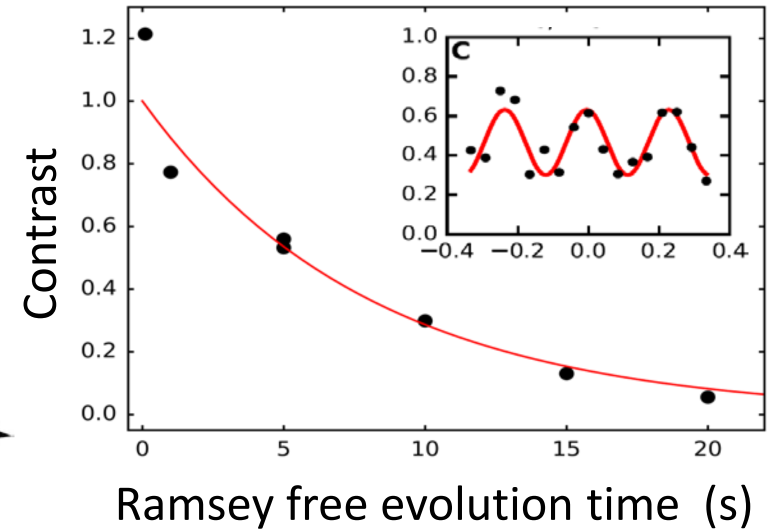
So, let's go for the 160 s coherence time ?

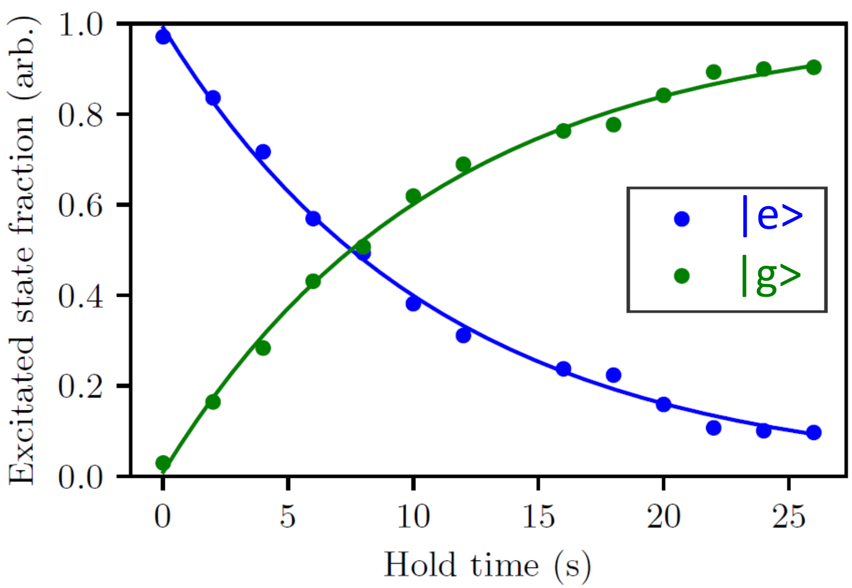
We must reduce the lattice intensity !

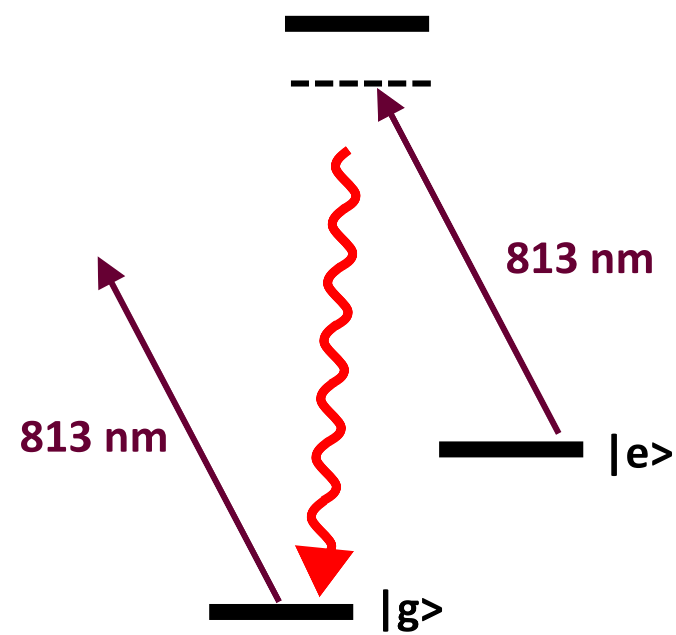
For |g> atoms, lattice lifetime is >100 s



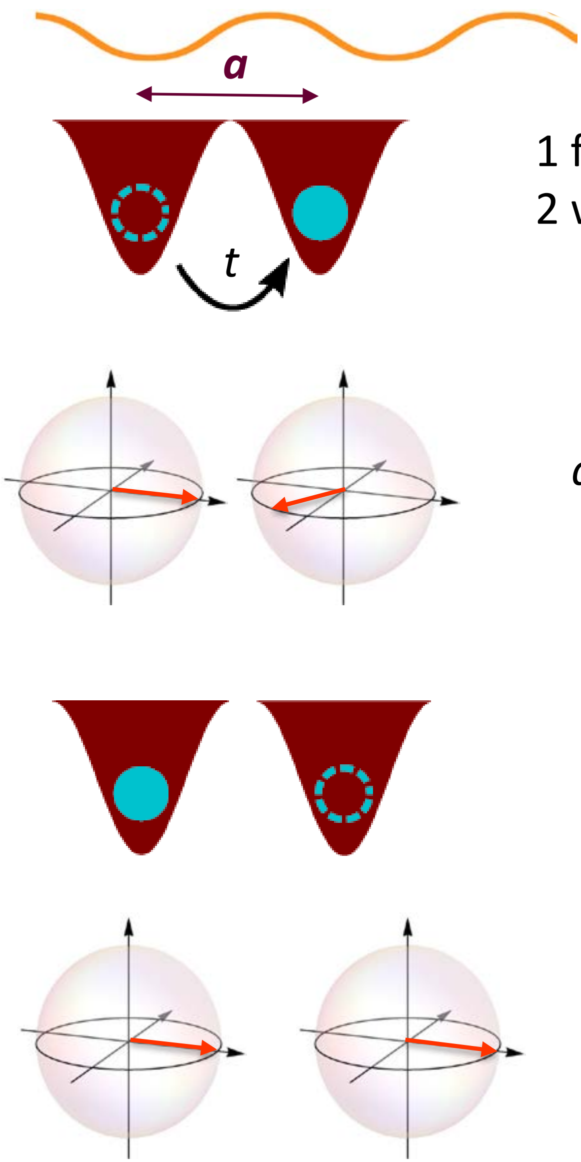








A Fermi band/Mott insulator clock



λ_{clock}

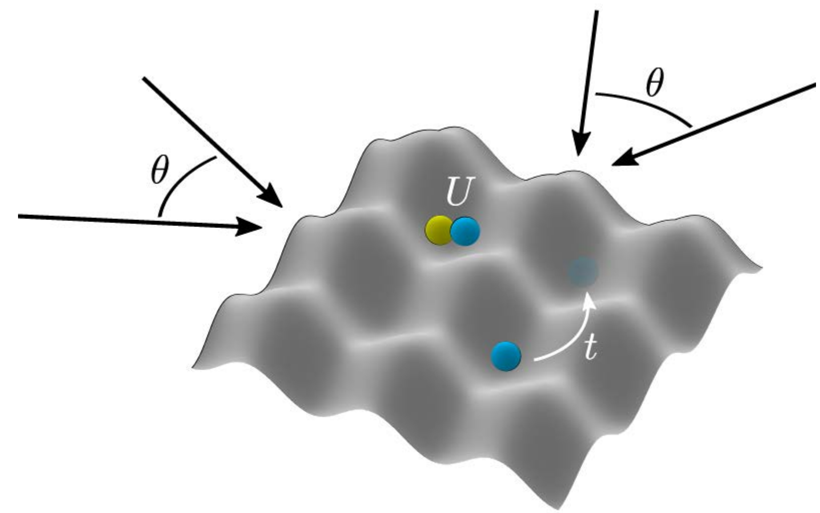
1 fermion
2 wells

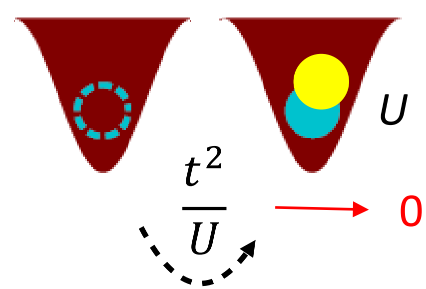
$a \neq \lambda_{clock}$

$a = \lambda_{clock}$

$e^{ika} = 1$

Lattice spacing = 813 nm / 2sin(θ/2)





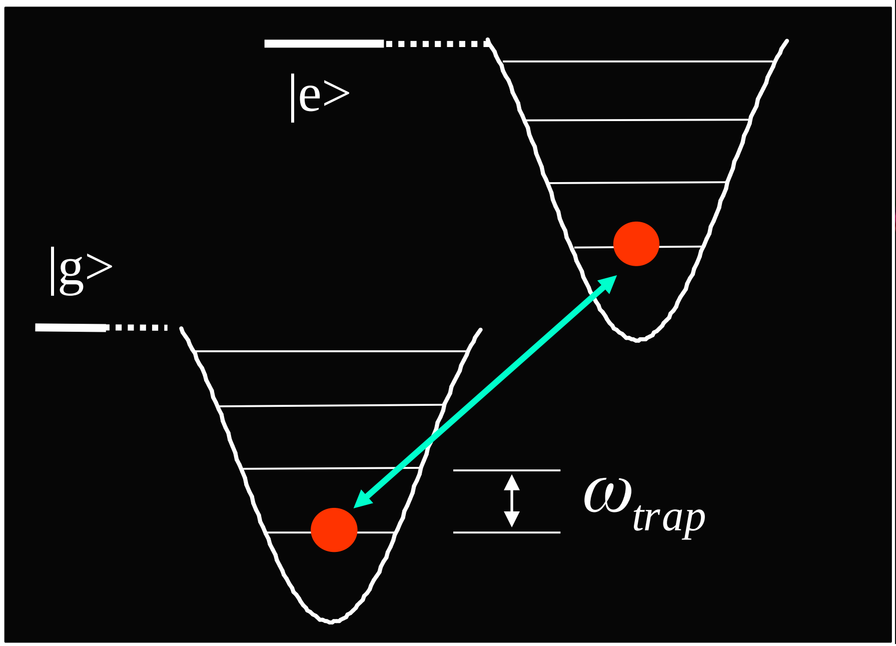
2 fermions
2 wells

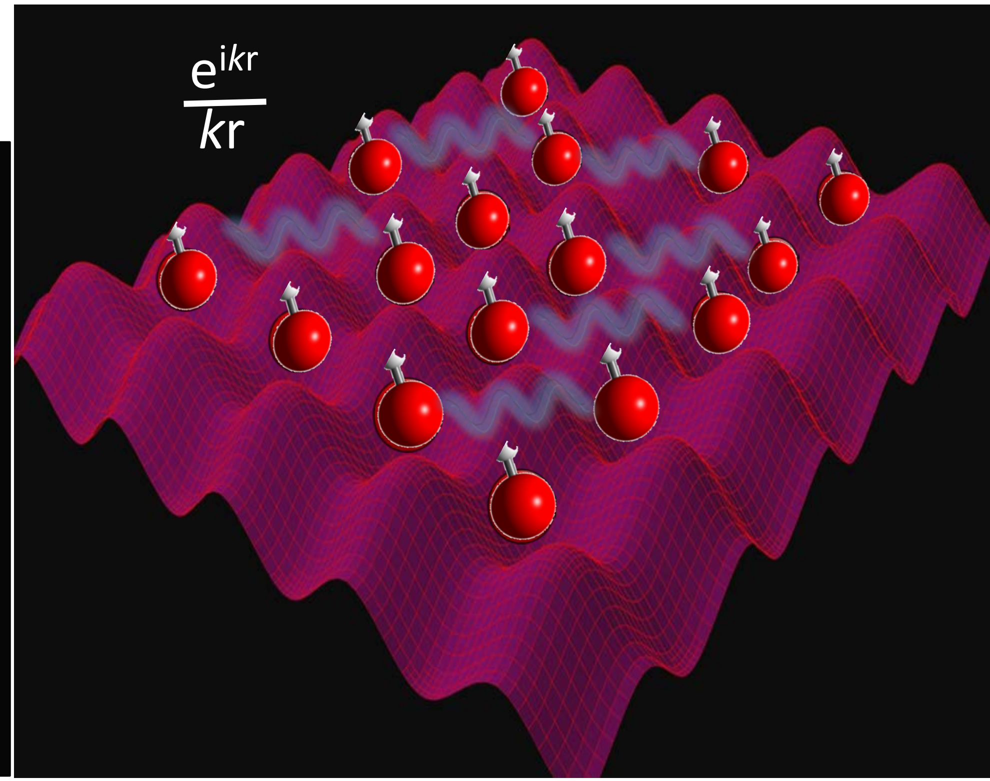
Kolkowitz *et al.*, Nature **542**, 66 (2017); Bromley *et al.*, Nature Phys. (2018).

Sr clock: the next systematic uncertainty – collective dipoles

Chang, Ye, Lukin, Phys. Rev. A **69**, 023810 (2004).

≤ 1 mHz effect for a unity filled lattice (10^{-19})

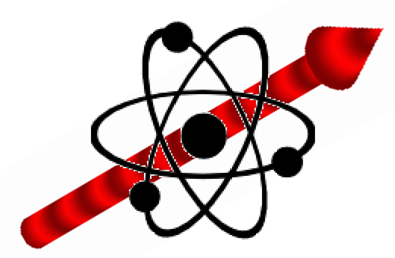


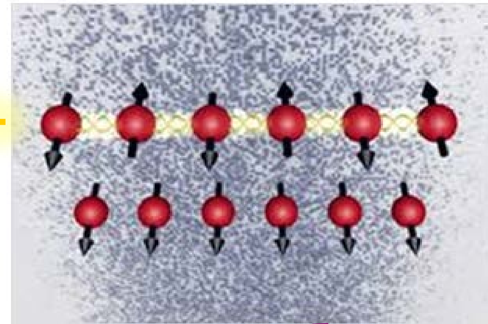


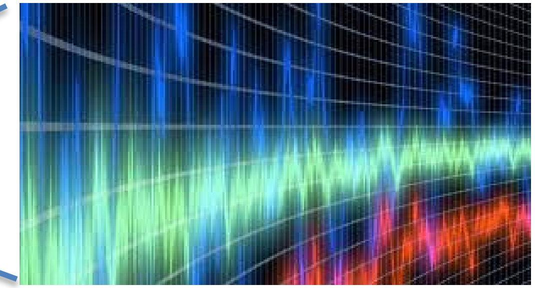
- Collective dipolar couplings ($^1S_0 - {}^3P_1$: Bromley *et al.*, Nature Comm., 2016)
- Real part: clock shift; Imaginary part: line broadening, super-radiance

Quantum Measurement Frontier

Optical atomic clock



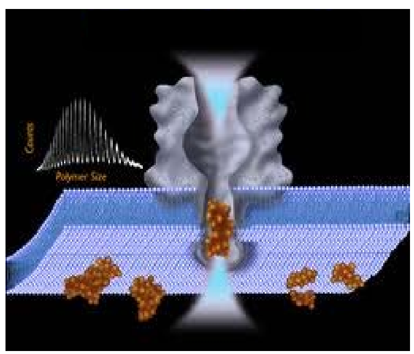


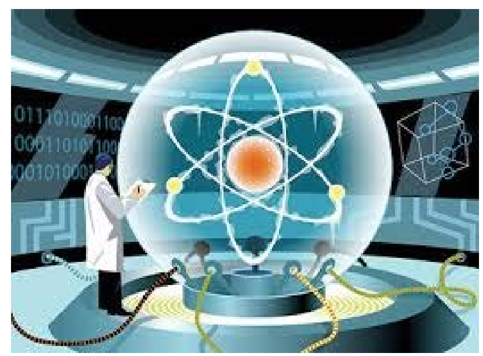


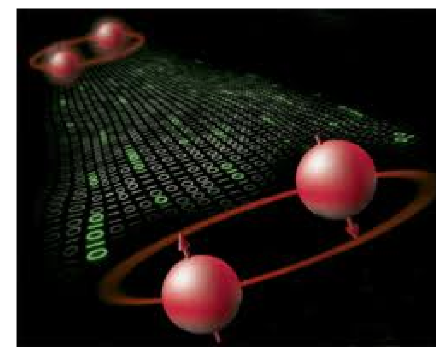
Advanced materials

Quantum information

Advanced metrology







Room-Temp. superconductor

↓

Loss-less electric grid

Protein folding

↓

Drug design

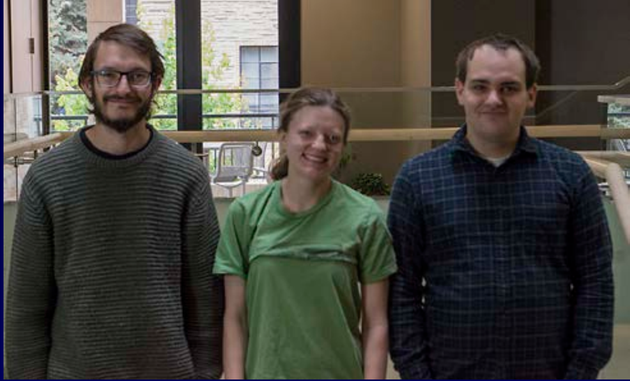
Entangled-states

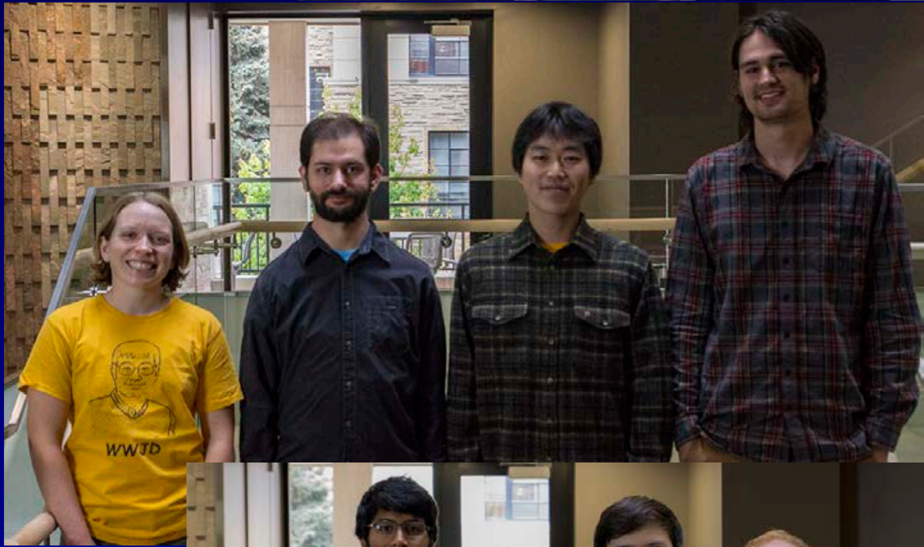
Quantum Simulators

Quantum Cryptography

Sr optical clock
– advancing state-of-the-art

S. Bromley
T. Bothwell
S. Kolkowitz
J. Robinson
L. Sonderhouse
E. Oelker
S. Campbell
R. Hutson
G. E. Marti
A. Goban





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G. Campbell (JQI, NIST)
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M. Boyd (AO Sense)
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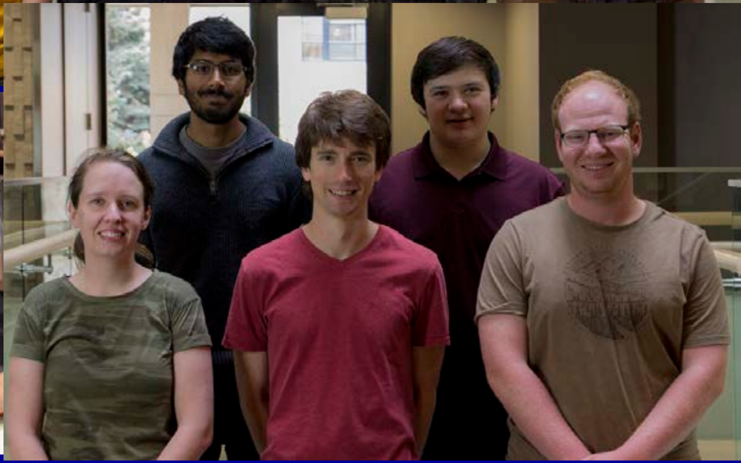
S. Foreman (U. San Fran)
X. Huang (WIPM)
T. Ido (Tokyo NICT), X. Xu (ECNU)
T. Loftus (AO Sense)

A. M. Rey



NIST, PTB, M. Holland, P. Julienne, M. Lukin, M. Safronova, R. Walsworth, S. Yelin, P. Zoller …