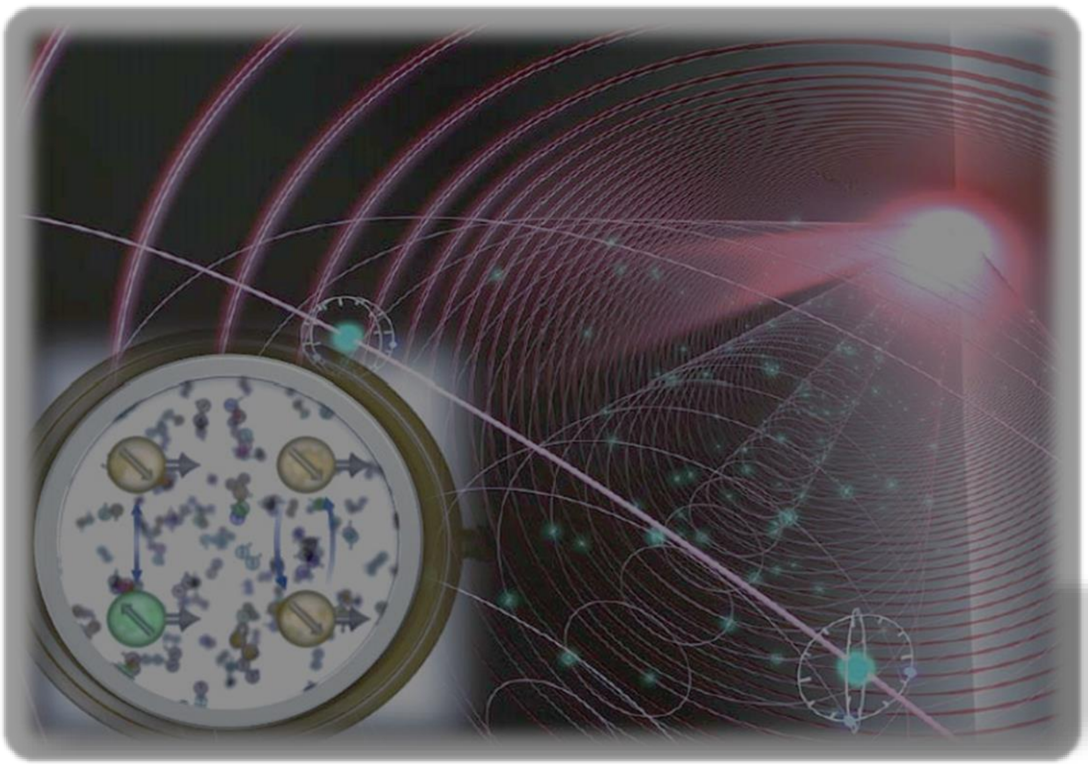
Quantum magnetism at temperature regimes above quantum degeneracy

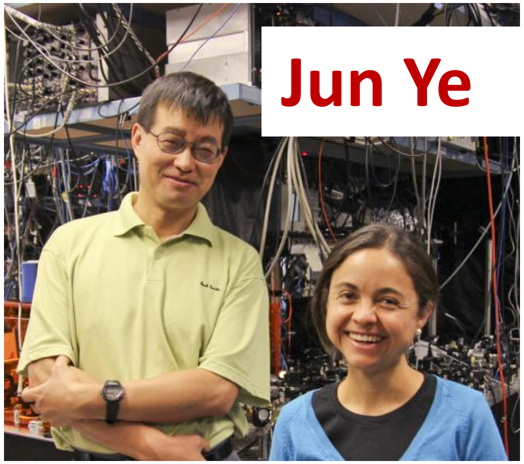
Ana Maria Rey

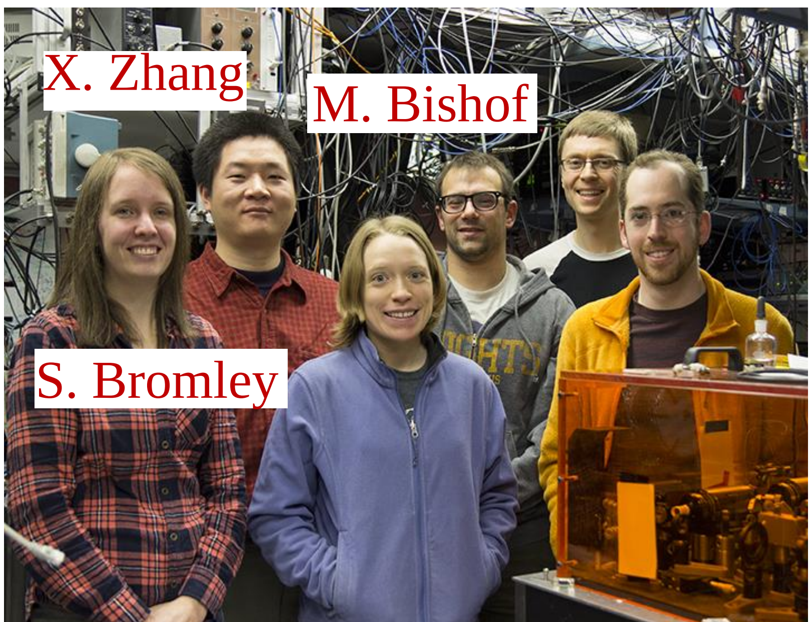


JILA NIST CU

INT International Conference, Frontiers in Quantum Simulation with Cold Atoms, March 30 – April 2, 2015

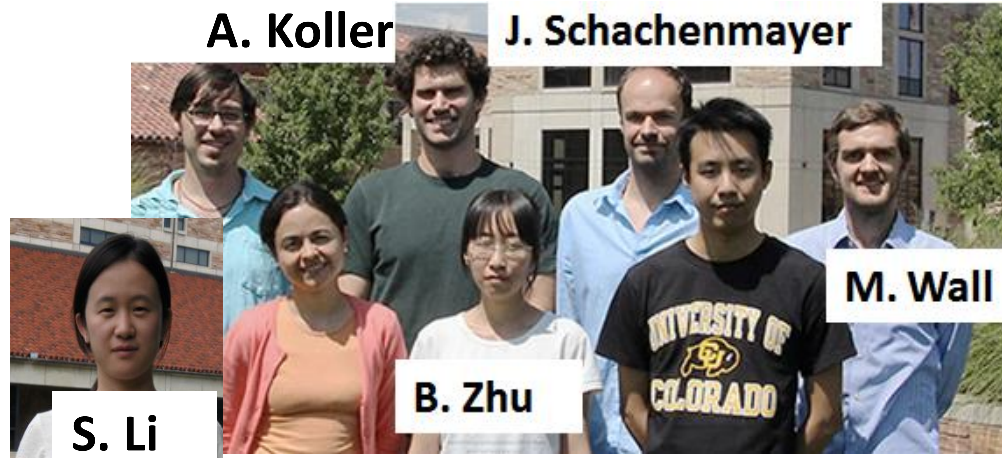
The JILA Sr team:





M. Martin (Caltech)

Theory:



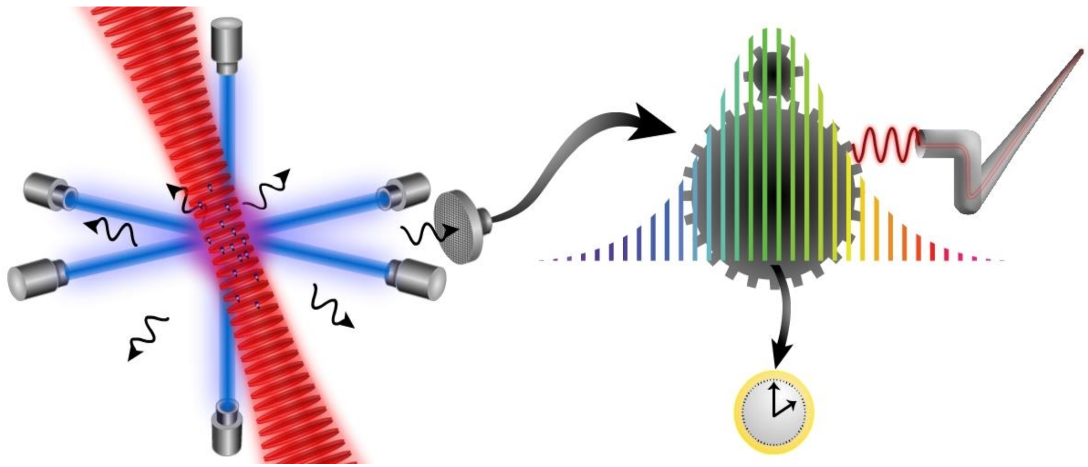
N. Cooper

A. Gorshkov, P. Julienne, C. Kraus, P. Zoller

Alkaline-earth (like) atoms: Best time keepers

Unique atomic properties

Atomic clock experiments



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

Alkaline earth clocks –super coherence

Metastable states

$^3P_0$ (e)

ν_0=5x10^{14} Hz

$^1S_0$ (g)

Linewidth $\Delta\nu_0$~ mHz

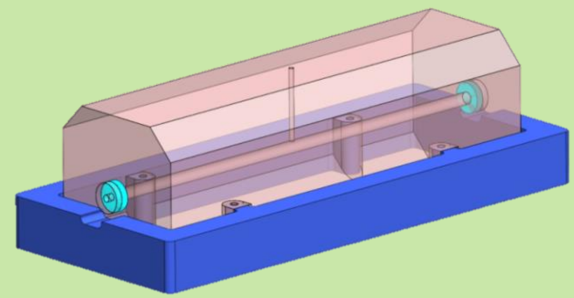
lifetime ~ 10^2 sec

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:

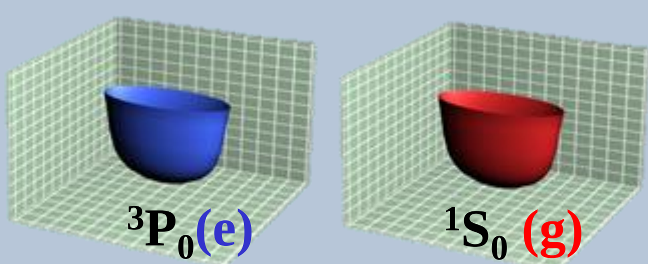
Q>10^{15}, seconds coherence time



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

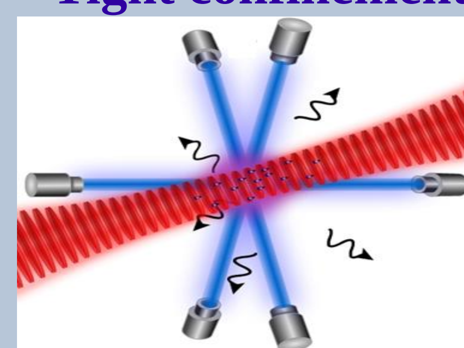
Same trapping potential for both states

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



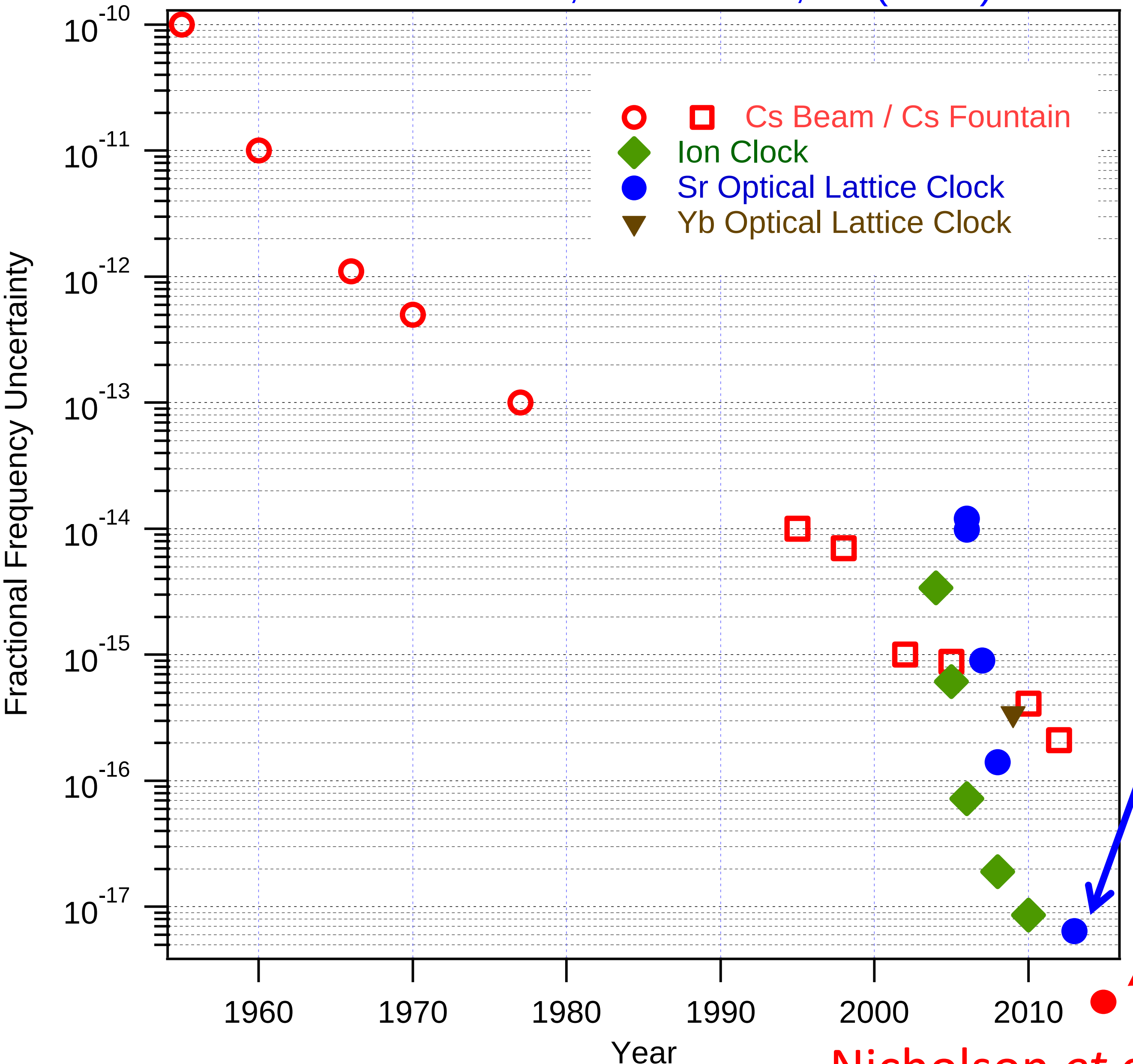
No Doppler
No recoil
No stark shifts

Tight confinement



A new frontier for clock stability & accuracy

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



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

Achieving this 100x faster than other clocks

Now:
2.1×10^{-18}

Nicholson *et al.*,arXiv:1412.8261

Many body physics with clocks ?

Atomic Clock

Many-body Physics

Exquisite Control

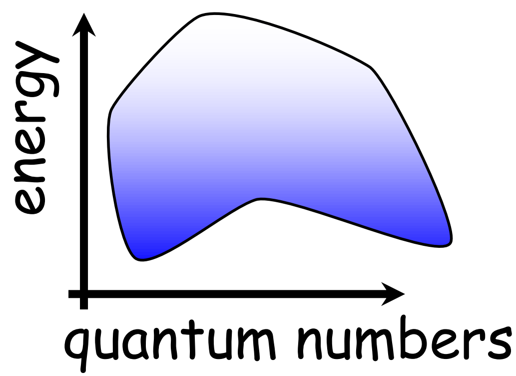
Ultra-precise

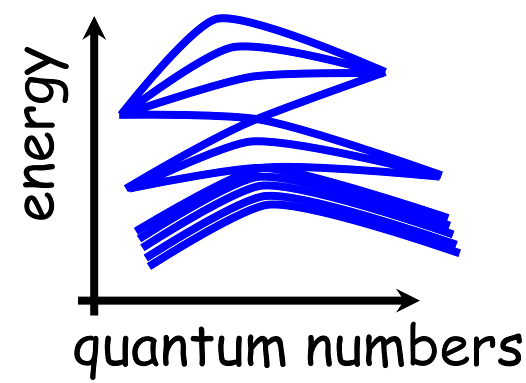
Long probing times

Quantum Magnetism,

many-body physics

Clock precision = 





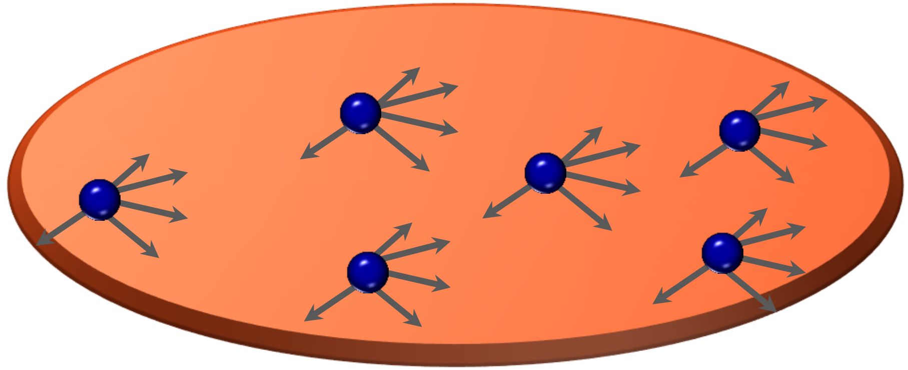
1D lattice clock: T~μK

$S = N/2$

Large collective spin: Good better signal to noise

No interactions

All the spins precess collectively

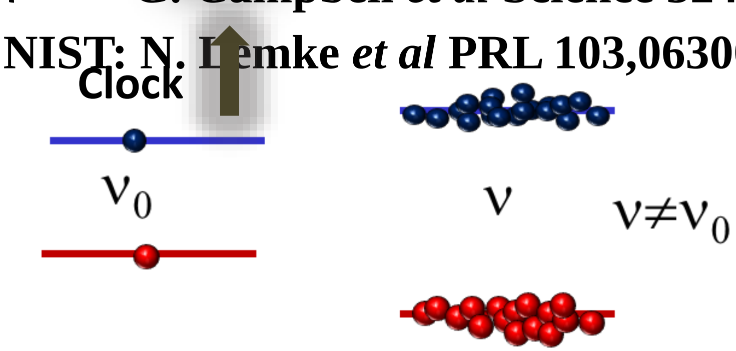


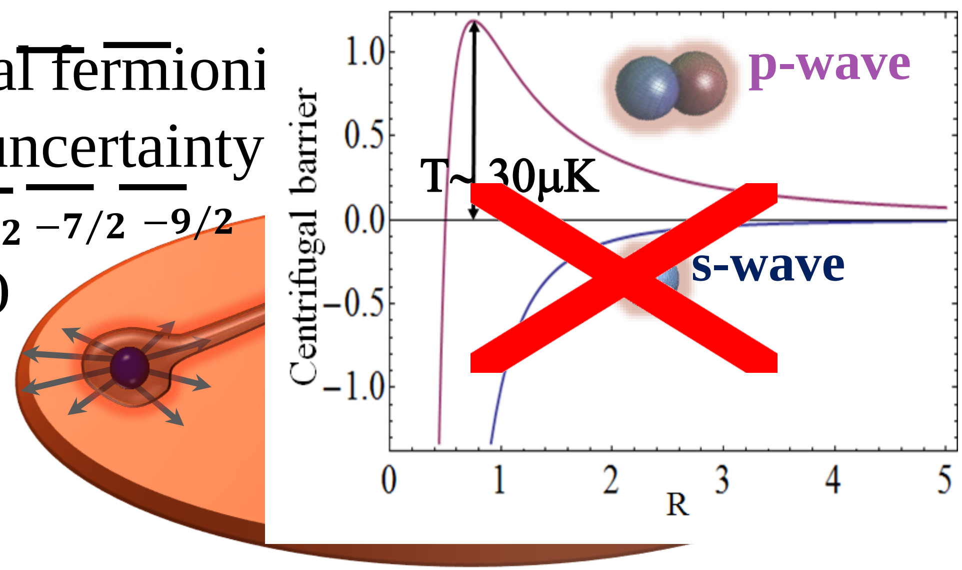
Interactions:

- Degrade signal: even in identical fermioni gave rise to the second largest uncertainty error budget

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

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





Exploring many-body physics with Sr clocks

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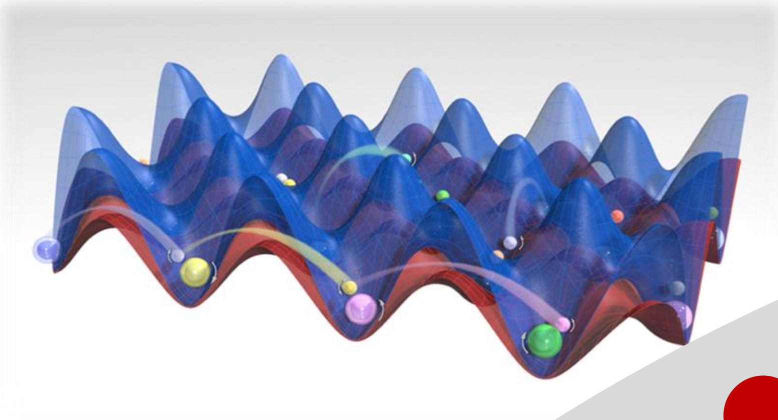


?

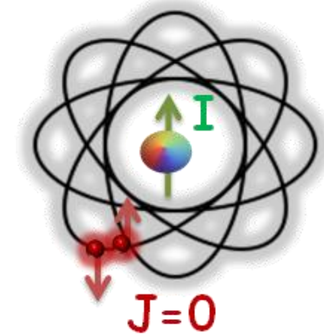
Observation of SU(N) symmetry and characterization of scattering parameters: Science, 345,1467 (2014).

Confirmation of Elastic/Inelastic p-wave interactions: many-body spin system in an optical lattice clock: Science 341, 632 (2013) & 331, 1043 (2011).

Theoretical prediction: SU(N) symmetry & chiral spin liquid phases: Nature Physics (2010) , PRL (2009).

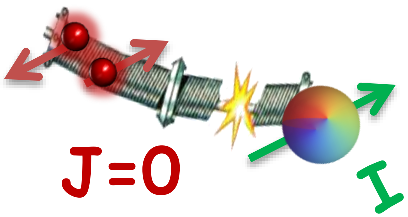
Observation of frequency dependent density shifts in polarized fermionic clocks: Science 324,360(2009).

SU(N) interactions



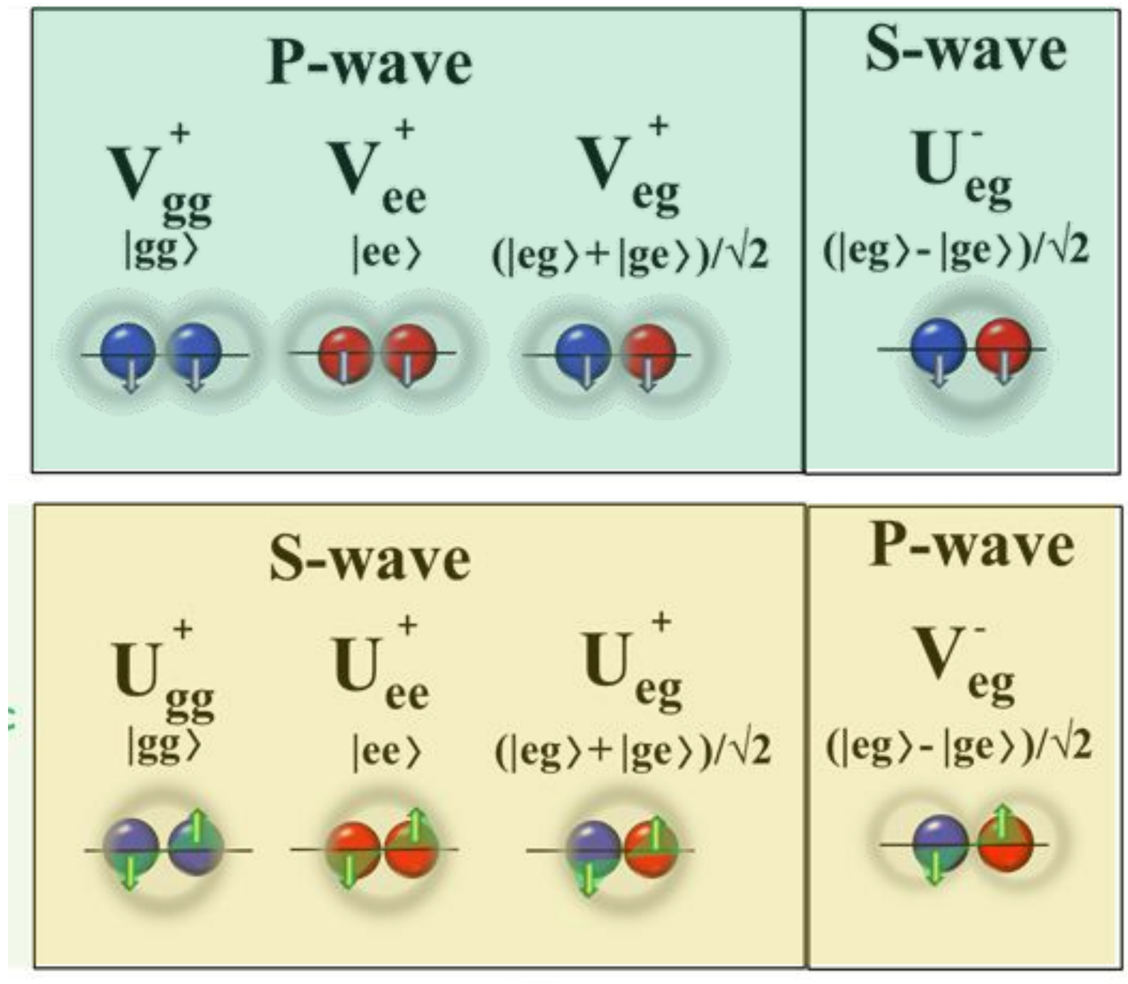
SU(N=2I+1) symmetry: I independent scattering parameters

$$V^{\pm}_{\alpha\beta} \sim \left(b^{\pm}_{\alpha\beta}\right)^3 \quad U^{\mp}_{\alpha\beta} \sim a^{\mp}_{\alpha\beta}$$



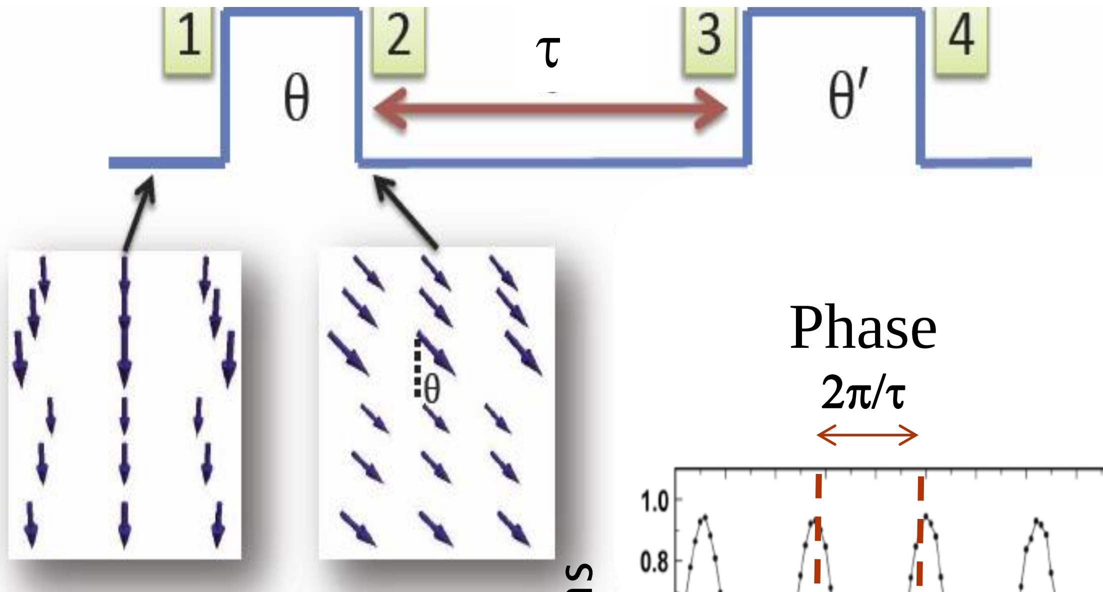
Nuclear spin symmetric

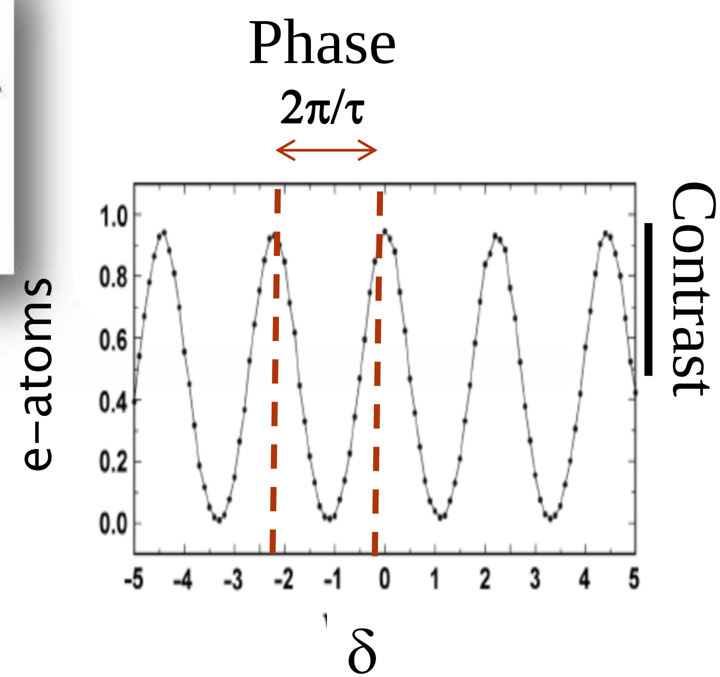
Nuclear spin Anti-symmetric



Ramsey Spectroscopy

1. Initially $|\downarrow\downarrow\downarrow\rangle$
2. Rotate spins by θ
3. Wait time τ
4. Read θ’ component





Ramsey fringe: $A(\tau)\cos[(\delta+B^{\mathrm{eff}})\,\tau]$

Contrast **Phase**

Spin precesses with a modified rate which depends on atom number: $\mathcal{N}$.

$$B^{\mathrm{eff}} = \mathcal{N}\,(\bar{C} - \cos\theta\;\;\bar{\chi})$$

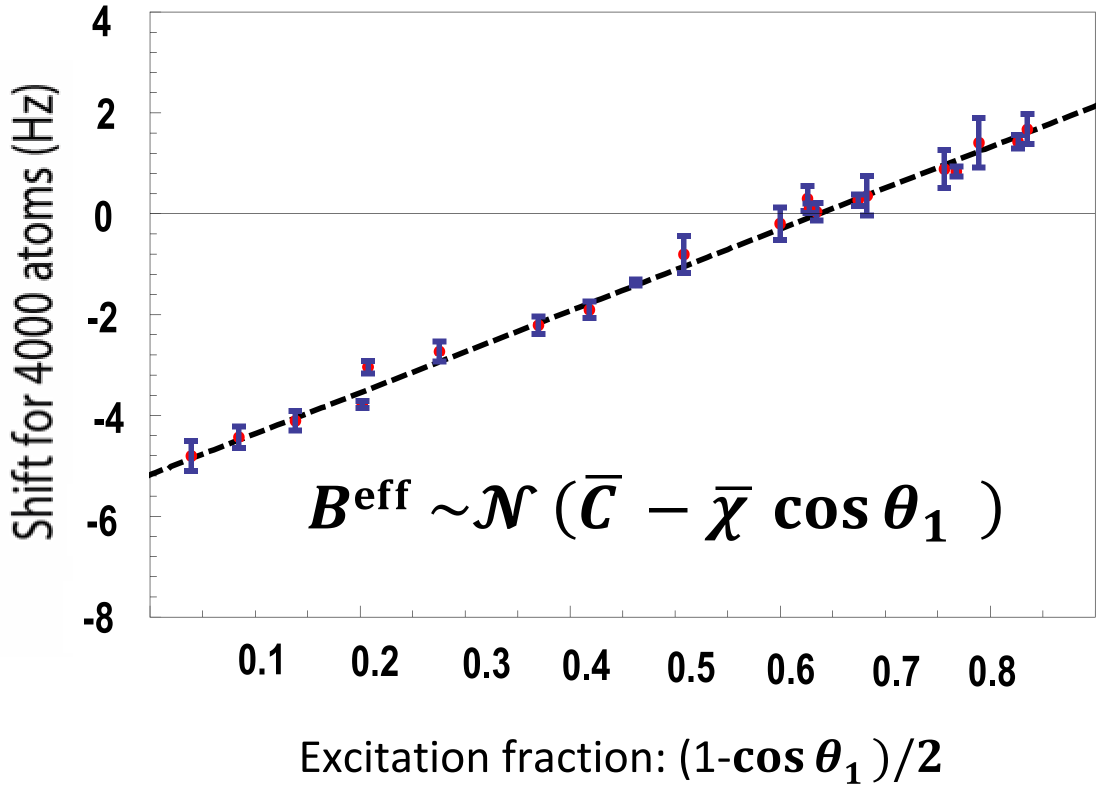
χ and C: P-wave Interaction parameters

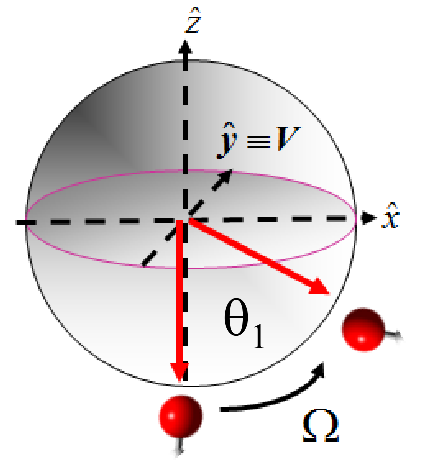
$$C = (V_{ee} - V_{gg})/2$$

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

P-wave interactions: 1D lattice clock

Theory vs experiment





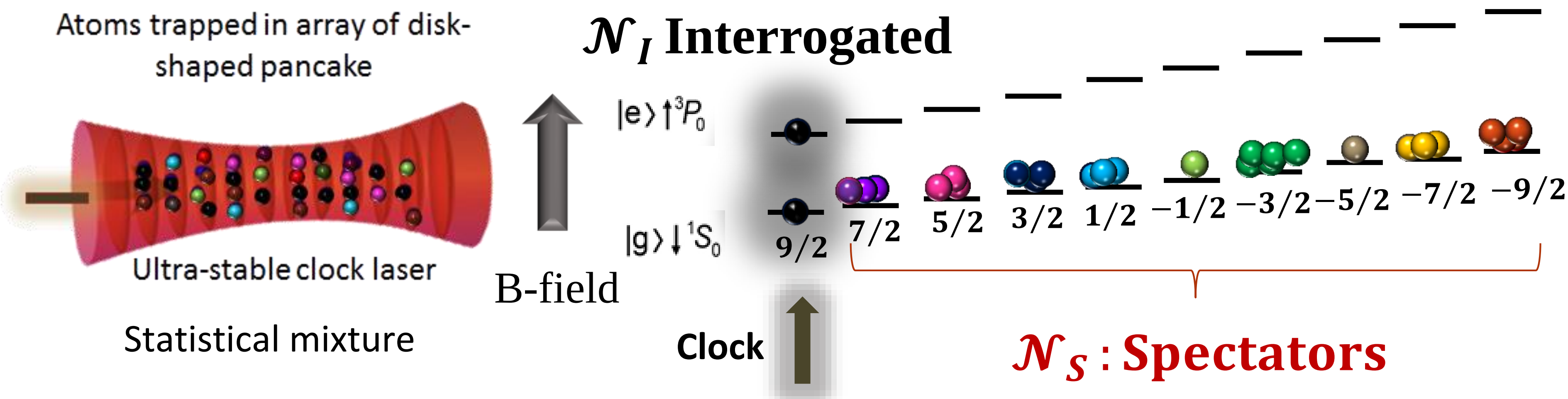
θ_1 controlled by first pulse

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

Ludlow *et al*, Phys. Rev. A 84, 052724 (2011)

N. Lemke,…AMR, C. Oates 107, 103902 (2011)

SU(N) orbital magnetism: large B



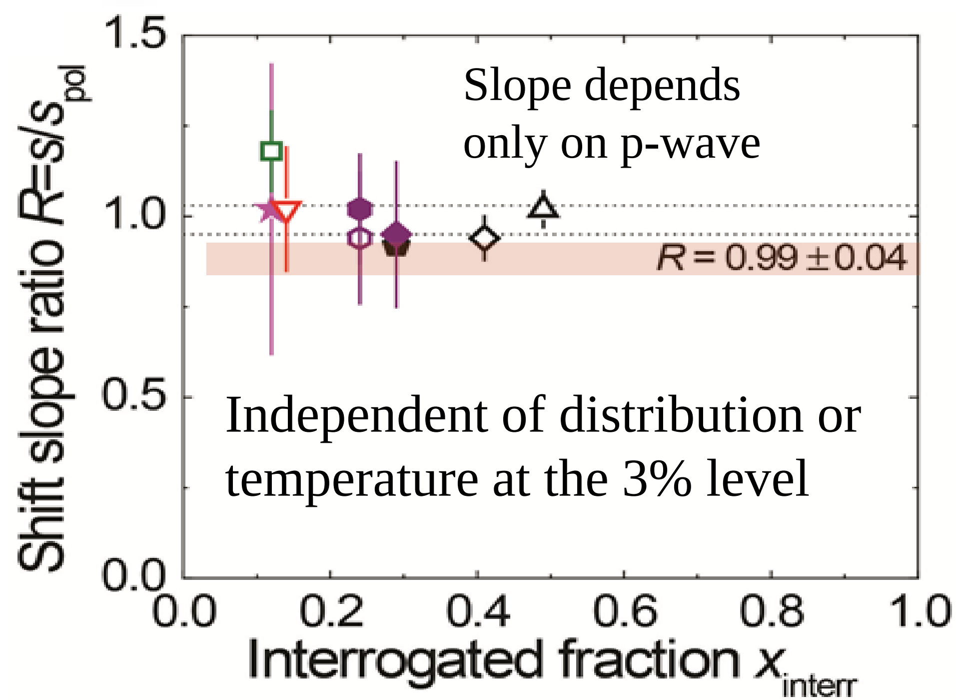
- SU(N): density shift only depends on the total number of spectators not on its distribution

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

Spectators density shift

$$\Delta\nu^S = \bar{\Lambda}\mathcal{N}_S$$

Both *s* and *p*-wave contributions



Determination of scattering parameters

Use: Relation between p and s-wave through Van-der-Waals coefficient

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

Exploring many-body physics with Sr clocks

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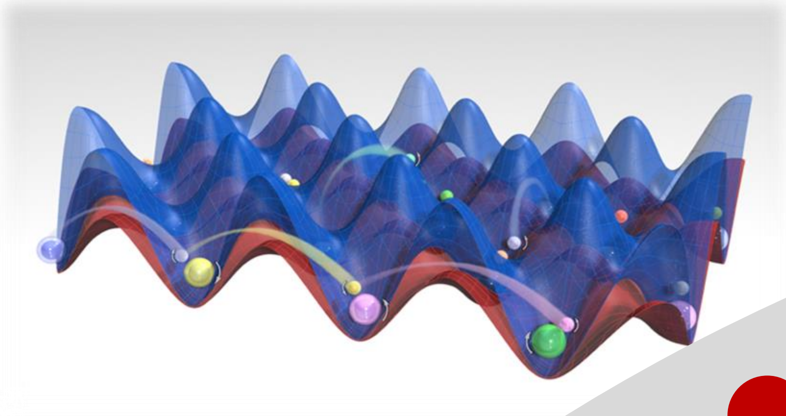


● ?

Topological pumping & transport.

Engineering & controlling spin-orbit coupling.

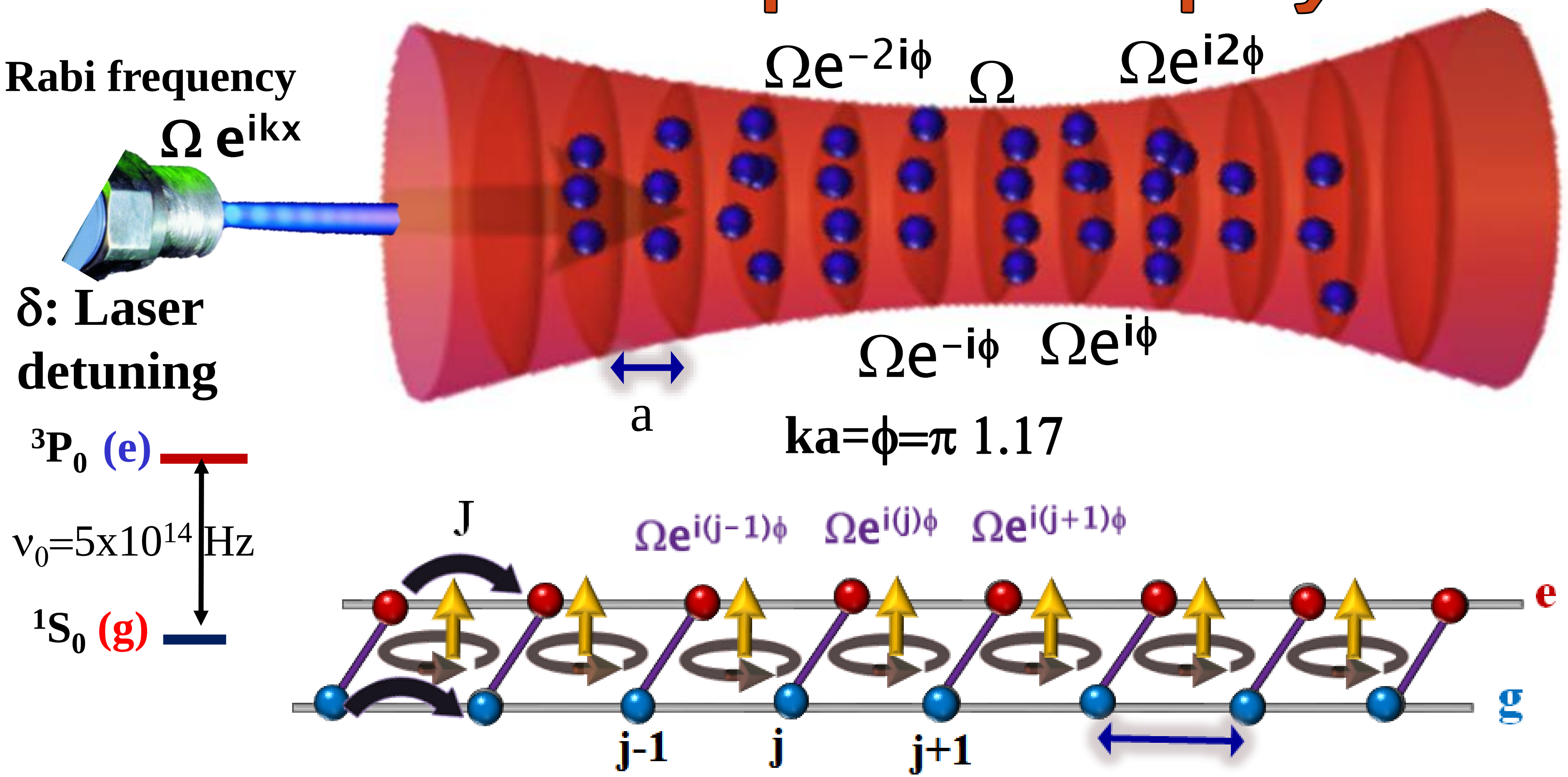
Observation of SU(N) symmetry and characterization of scattering parameters: Science, 345,1467 (2014).

Confirmation of Elastic/Inelastic p-wave interactions: many-body spin system in an optical lattice clock: Science 341, 632 (2013) & 331, 1043 (2011).

Theoretical prediction: SU(N) symmetry & chiral spin liquid phases: Nature Physics (2010) , PRL (2009).

Observation of frequency dependent density shifts in polarized fermionic clocks: Science 324,360(2009).

1D lattice clock: A quantum simulator of spin-orbit physics



A. Celi *et al* PRL 112, 043001 (2014)[a]

Synthetic Gauge Fields in Synthetic Dimensions

A flux ladder: Minimal instance of Hofstadter model

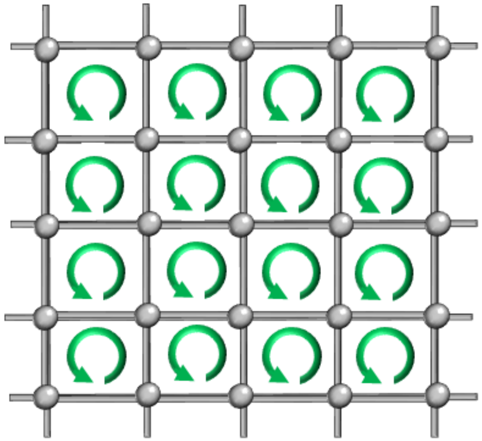
D. Hügel& B. Paredes PRA 89,023619(2014)

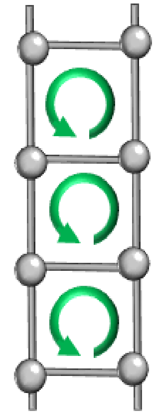
Hofstadter model:

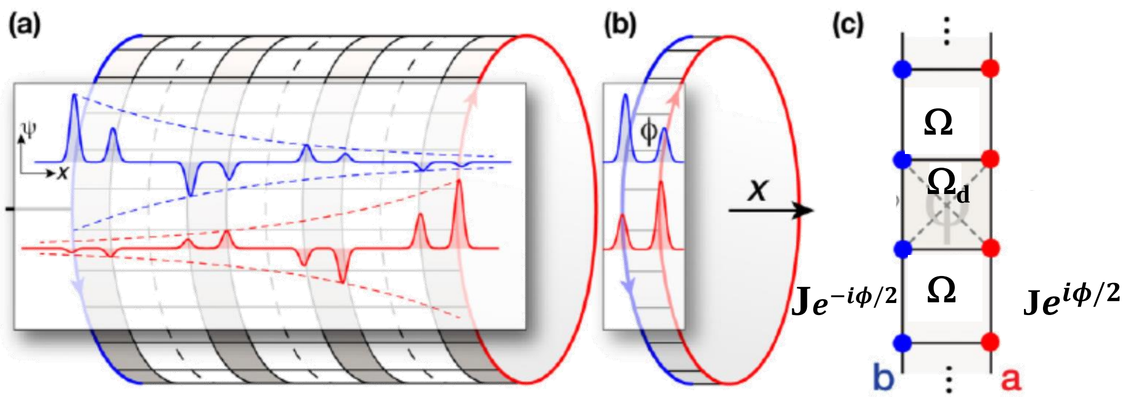
Lattice integer quantum Hall
Topologically non-trivial bands,
chiral edge states

Eigenstates of 2-leg ladder with rational flux 2π/3 are edge states of 2D model!

Away from this flux: adiabatically connected chiral states.





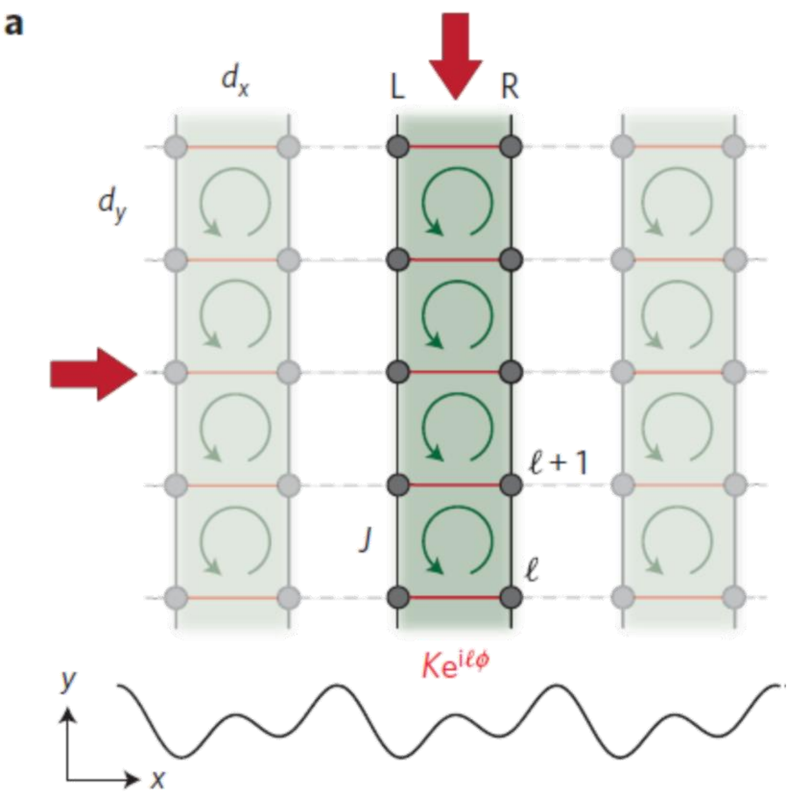


Non-trivial topology

$$\Omega_d > \Omega_d^{crit}$$

Bosonic Implementation

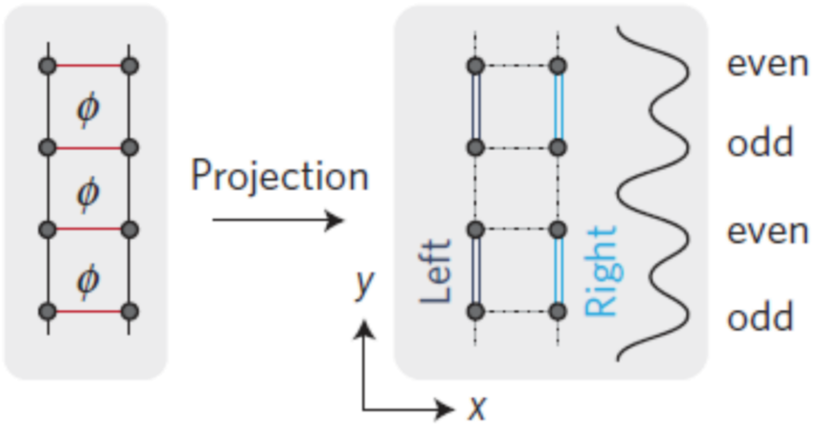
I. Bloch: Nature physics 10,(2014)



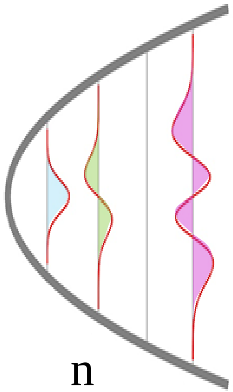
- Array of coupled doubled wells in a synthetic gauge-field: $\phi=\pi/2$
- Bose-Einstein condensate of Rb atoms~10-50 nK
- Probing tools:

Time of flight

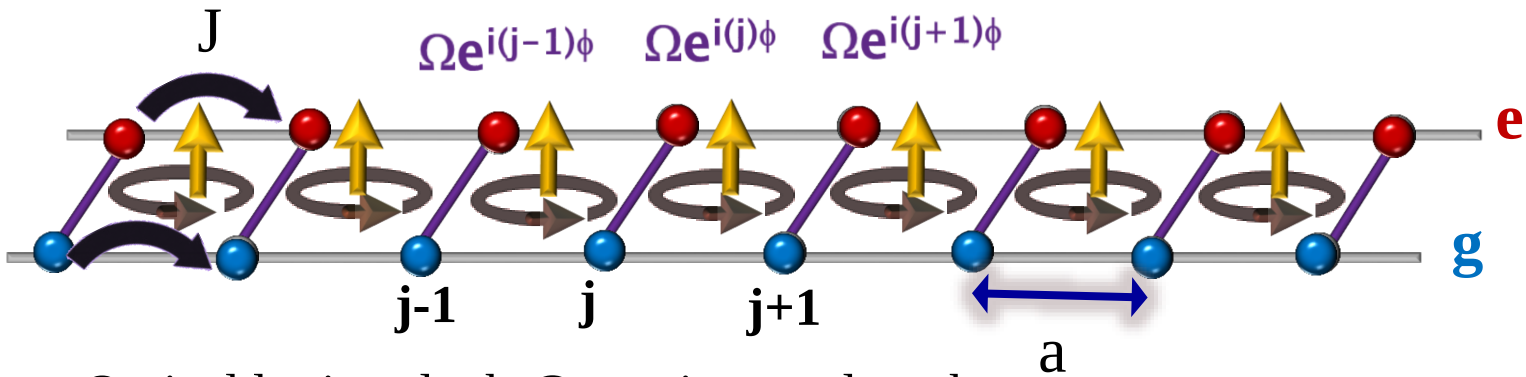
Projection to isolate double-wells



Flux clock ladder

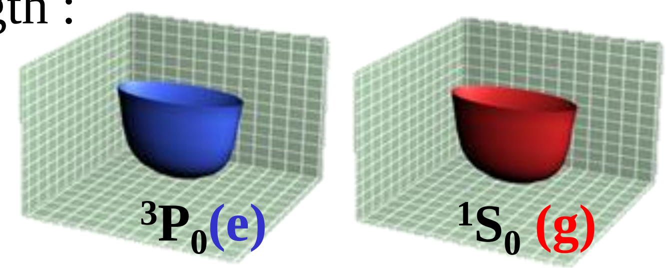


Thermal transverse modes

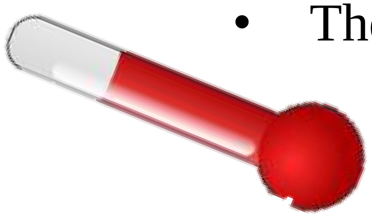


- Optical lattice clock @ magic wavelength :

  ka=ϕ=π 1.17



$$V(r) = [V_0 + V_{lat}\ cos^2(z\pi/a)]e^{-2r^2/w_0^2}$$



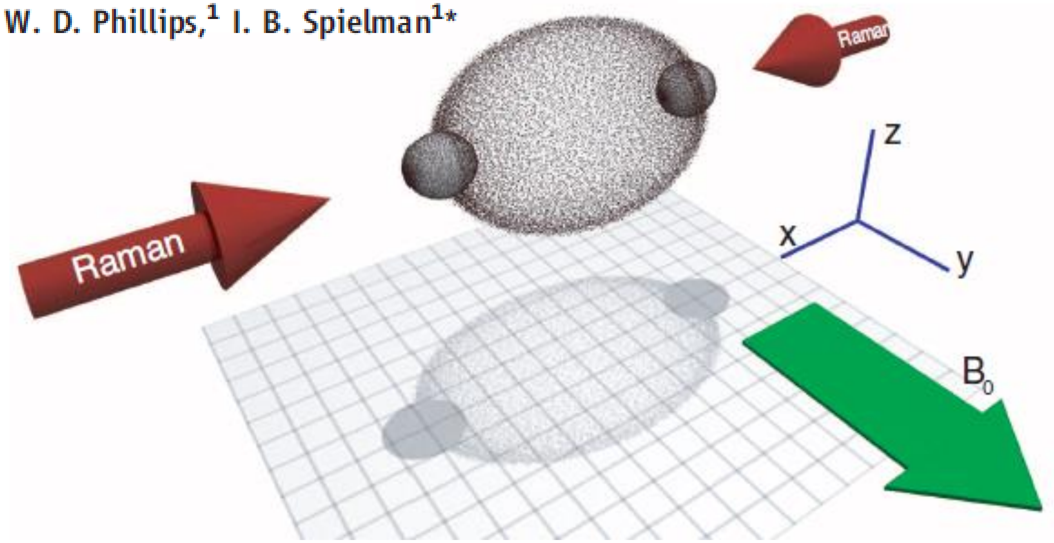
- Thermal fermions @ T~1-5 μK :
  - Thermal axial modes
  - lowest band but J«T: Infinite temperature
- Axial and radial directions coupled: Gaussian potential
- Current probing tools: Rabi and Ramsey spectroscopy

Exquisite clock sensitivity

Spin-orbit coupling can modify collisions

Synthetic Partial Waves in Ultracold Atomic Collisions

R. A. Williams,[1] L. J. LeBlanc,[1] K. Jiménez-García,[1,2] M. C. Beeler,[1] A. R. Perry,[1] W. D. Phillips,[1] I. B. Spielman[1]*



Science, ***335*** *314(2012):*

Collisions of two optically dressed BEC lead to effective higher partial wave scattering

Identical spin coupled fermions can collide via effective p-wave

- Majorana modes:

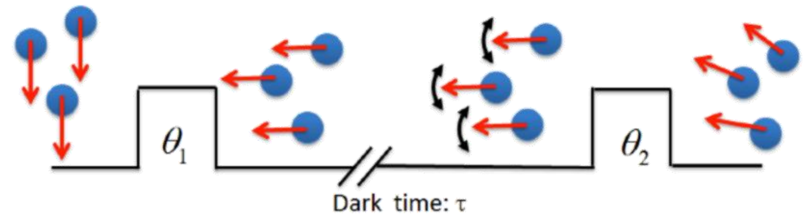
C. Zhang, et al, PRL, 101, 160401 (2008).

L. Jiang et al., PRL. 106, 220402 (2011)

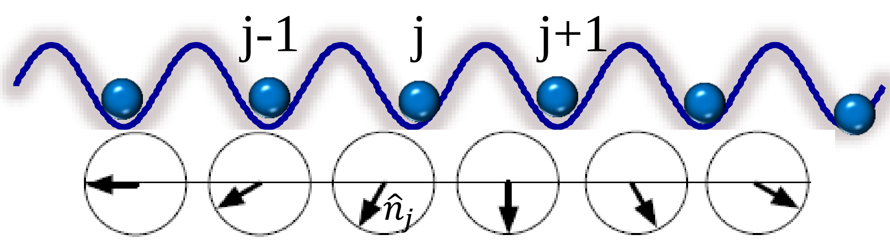
- Fractional Hall phases

M. Lewenstein Nat. Com. 4, 2046 (2013)

Ramsey spectroscopy



Simple picture:



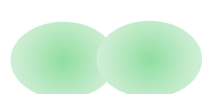
$$\mathrm{H} = \frac{\Omega}{2} \sum_j \hat{n}_j \cdot \overrightarrow{\sigma_j} \qquad \hat{n}_j = \{\cos(j\phi), \sin(j\phi), 0\}$$

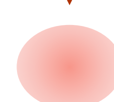
$|g\rangle_j \; |g\rangle_{j+1}$ ➡

$$\left[\left[\cos\left(\frac{\Omega t}{2}\right)|g\rangle_j + i e^{i\phi j} \sin\left(\frac{\Omega t}{2}\right)|e\rangle_j\right]\left[\cos\left(\frac{\Omega t}{2}\right)|g\rangle_{j+1} + i e^{i\phi(j+1)} \sin\left(\frac{\Omega t}{2}\right)|e\rangle_{j+1}\right]$$

$$A|\mathbf{triplets}\rangle + B \sin(\phi/2)|\mathbf{singlet}\rangle$$

➡





Tunneling:

preserves spin

p-wave interactions

s-wave interactions

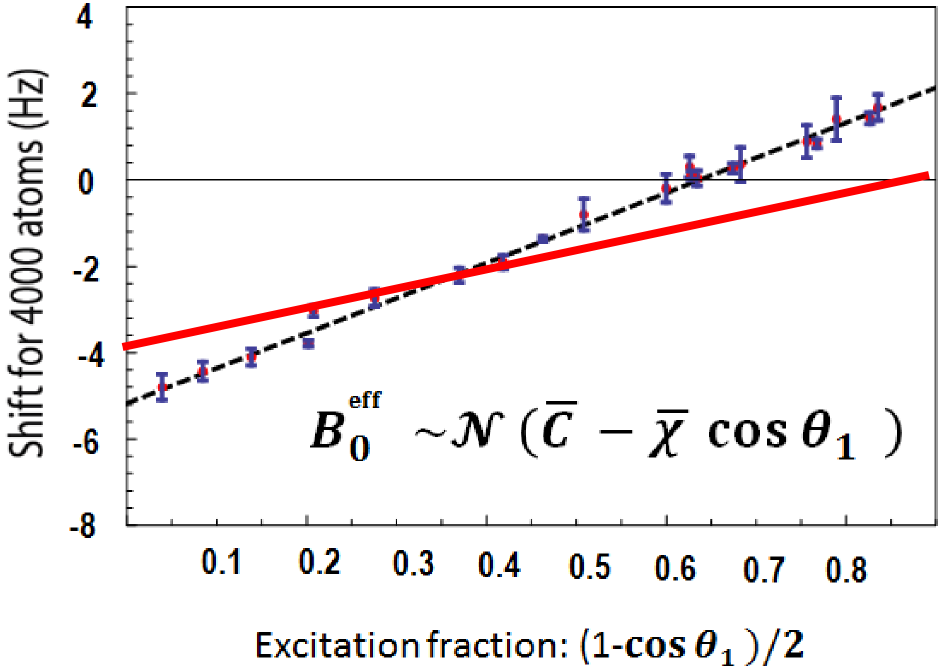
1D lattice clock:

Observations: spin-orbit induced density shift proportional to s-wave interactions in polarized fermions

$$B^{\text{eff}} = B_0^{\text{eff}} - \mathcal{N}\,(J\tau)^2\bar{\xi}\,\cos\theta_1\,\sin^2\left(\frac{\phi}{2}\right)$$

Theory vs experiment: No tunneling

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



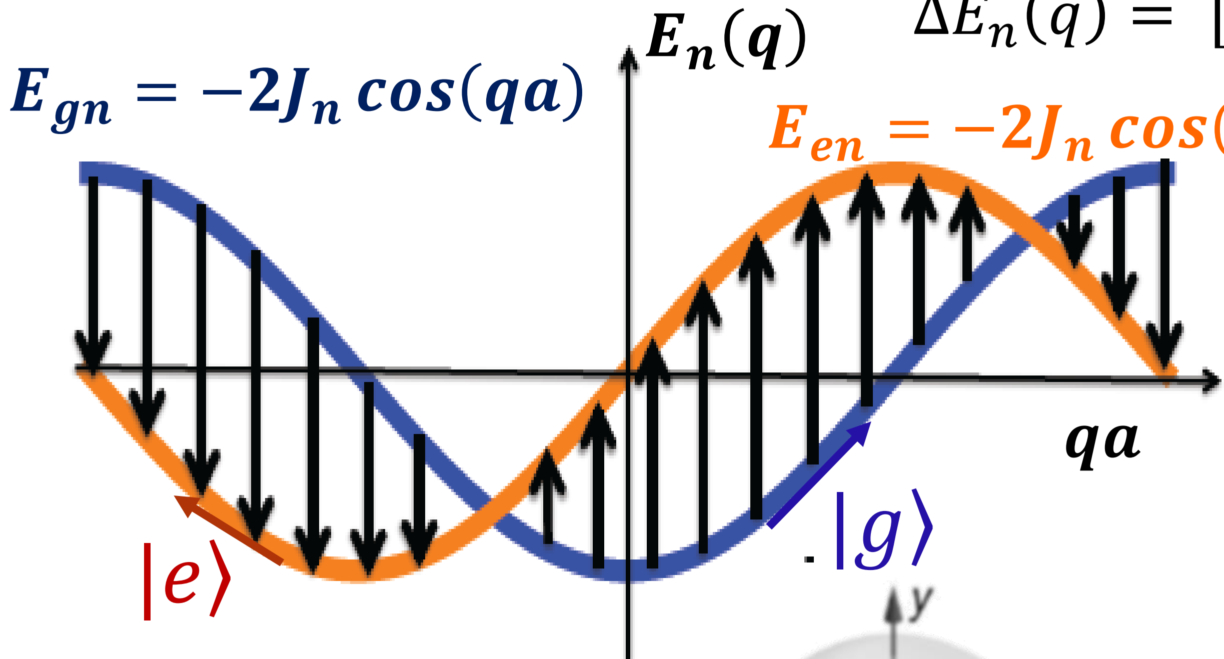
$\bar{\xi}$: s-wave contribution: U_{eg}^{+}

$$\xi = \left(V_{eg}^{-} - U_{eg}^{+}\right)/6$$

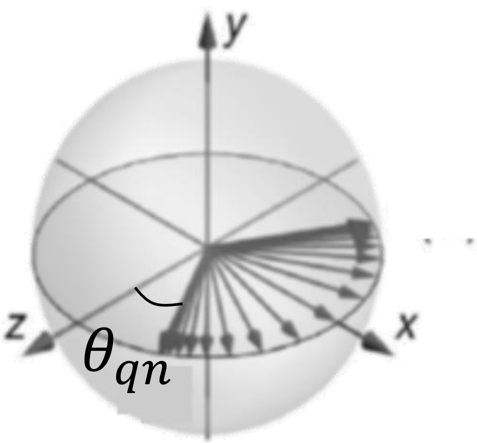
Rabi Case

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

$$\Delta E_n(q) = [E_{en} - E_{gn}]/2$$



n: harmonic oscillator



$$|\psi_{qn}^{-}\rangle = \begin{pmatrix} \cos(\theta_{qn}/2) \\ \sin(\theta_{qn}/2) \end{pmatrix}$$

$$\tan\theta_{qn} = \frac{\Omega_n(q),}{\Delta E_n(q) - \delta}$$

Non-zero chirality;

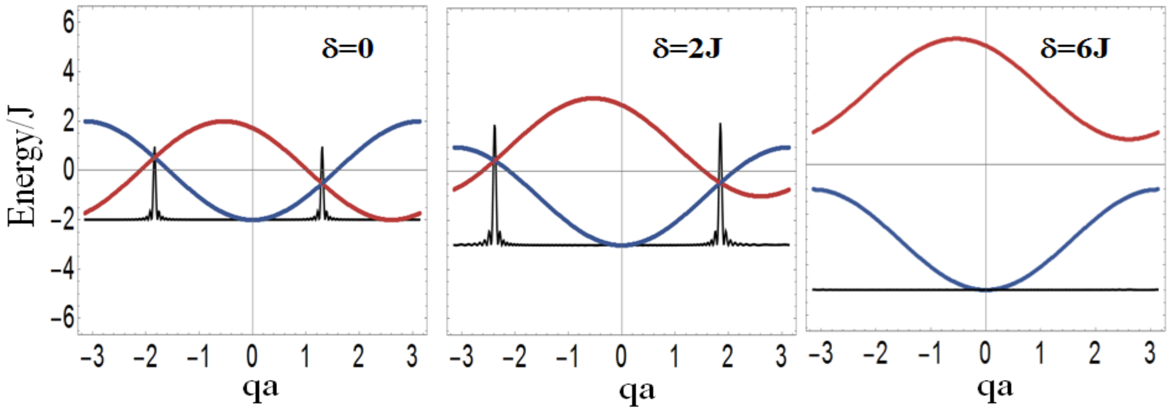
$$C = qa\langle\hat{\sigma}_z\rangle$$

chiral current

$$J_C = \left\langle \hat{\sigma}_z \frac{\partial H_q}{\partial q} \right\rangle$$

Rabi spectroscopy

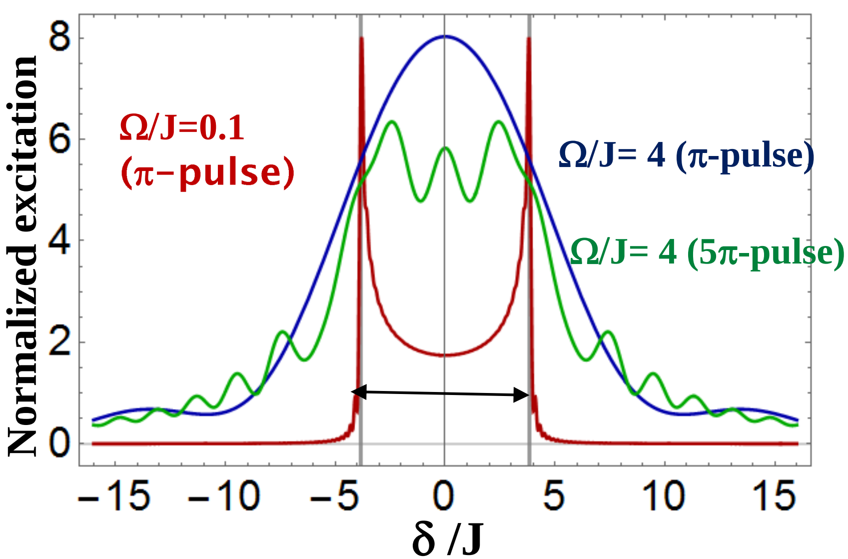
Information about ϕ and J for Ω<J



Thermal Rabi shape

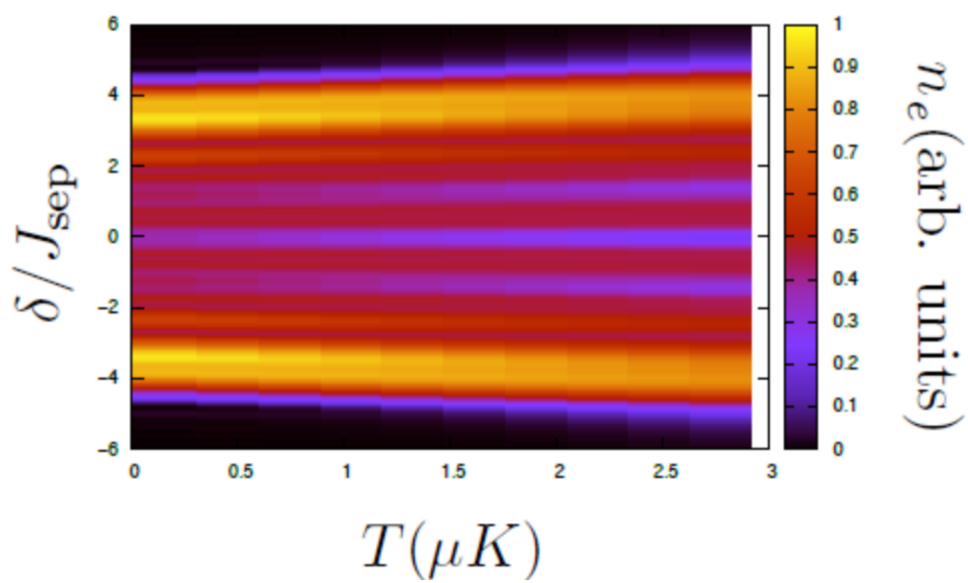
$$V(r) = [V_0 + V_{lat}\ \cos^2(z\pi/a)]e^{-2r^2/w_0^2}$$

Ideal separable



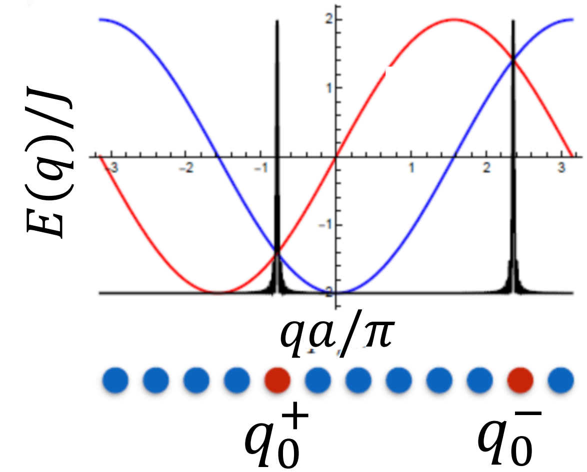
width = 8*J*Sin[*ϕ*/2]

$h\nu_{transverse}$ ~900 Hz



Can we determine the band chirality spectroscopically?

$\sin q_0^{\pm} = \delta/(4J\sin(\phi/2))$



1. Selectively apply a π pulse for $q_0^{\pm}$

Use detuning and small Ω

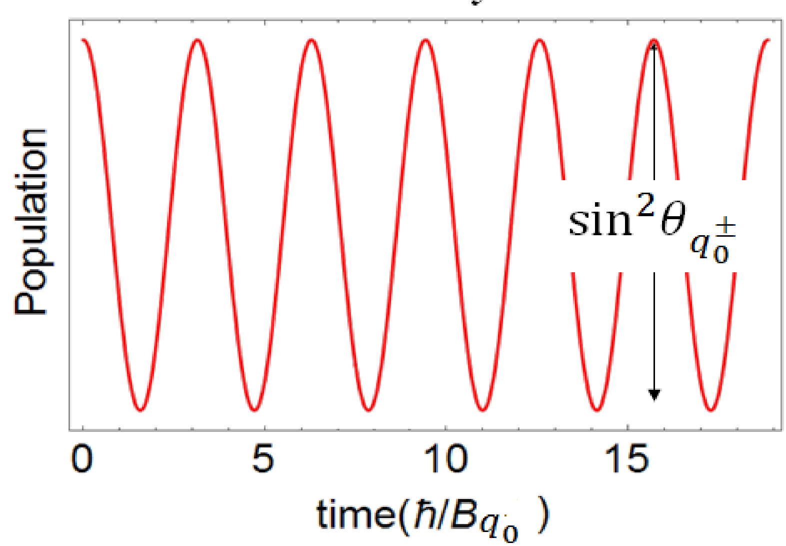
2. Quench Ω to desired value and let the system Rabi oscillate under $H_q = \vec{B}_q \cdot \hat{\vec{\sigma}}$

$$\langle\sigma_z\rangle_{q_0} = cos^2(\theta_{q_0}) - \cos(2t|\vec{B}_{q_0}|)sin^2(\theta_{q_0})$$

$$\langle\sigma_z\rangle_q = -(cos^2(\theta_q) - \cos(2t|\vec{B}_q|)sin^2(\theta_q))$$

3. Repeat 2 but without 1

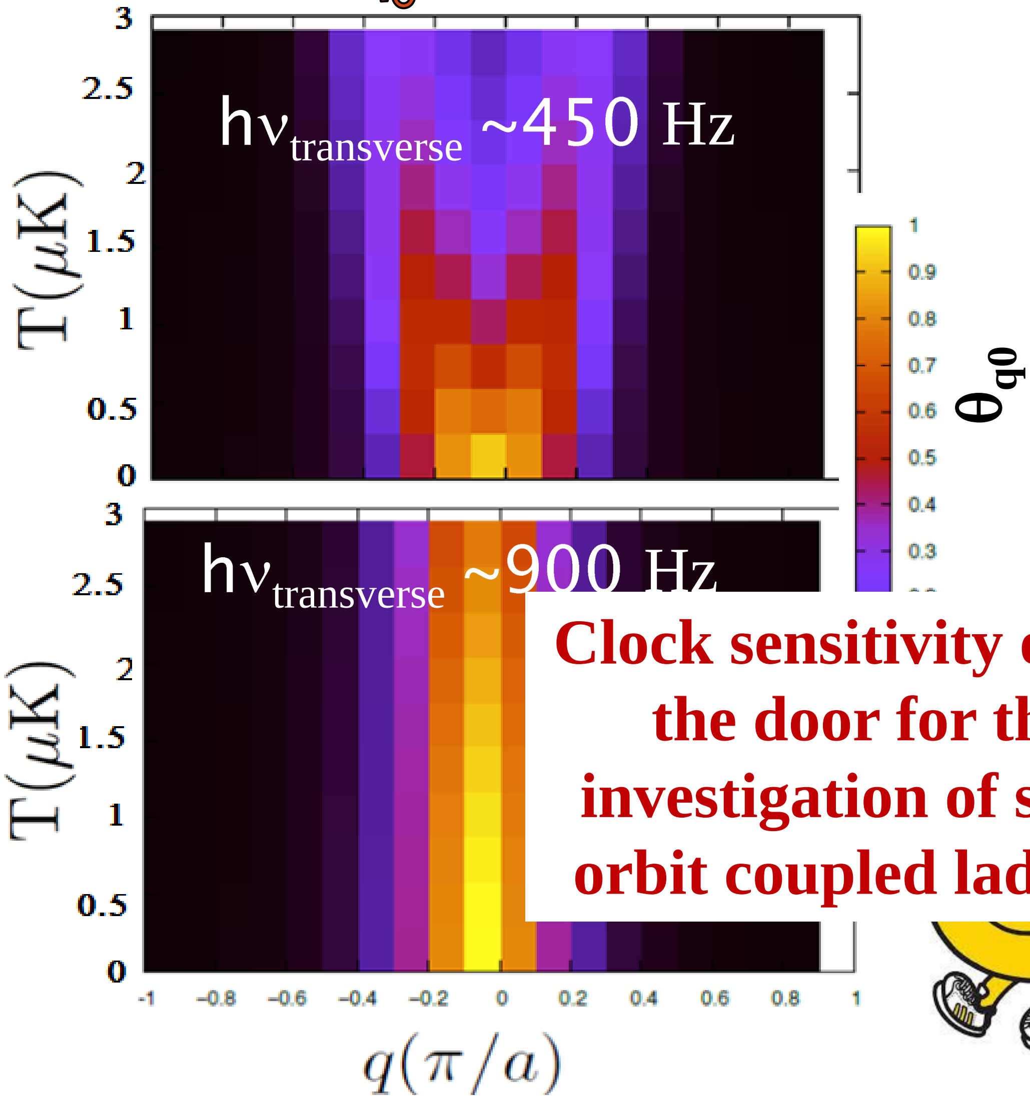
$$\langle\sigma_z\rangle_q = -(cos^2(\theta_q) - \cos(2t|\vec{B}_q|))sin^2(\theta_{nq}$$



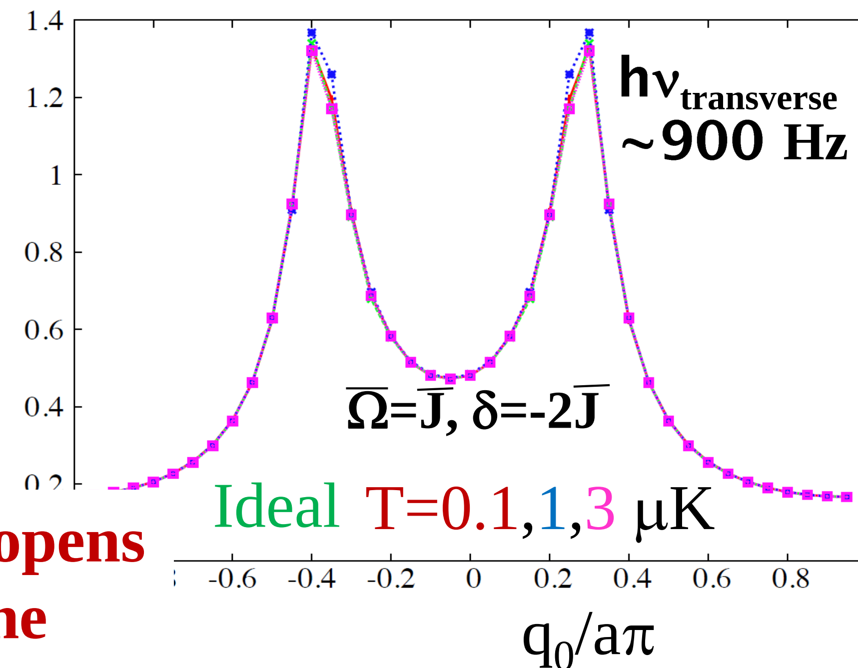
How about with real conditions?

Issue: For a given δ, the selected $q_0^{\pm}$ depends on J. In reality J depends on transverse mode n

q_0 selection



How well can we extract θ_{q0} ?



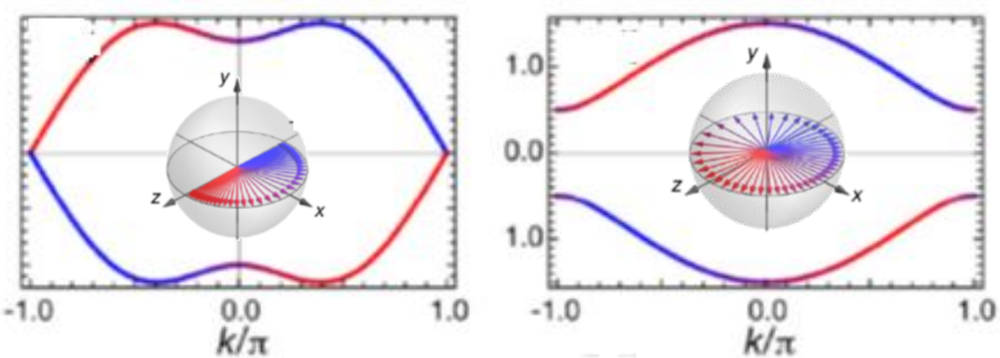
Clock sensitivity opens the door for the investigation of spin-orbit coupled ladders

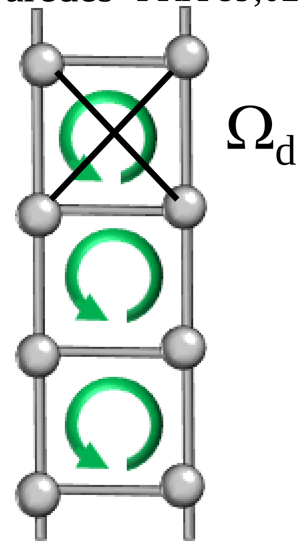
Outlook

❑ Non-trivial topological bands

D. Hügel& B. Paredes PRA 89,023619(2014)

$$\widetilde{H}_q = H_q + \Omega_d \cos(qa)\hat{\sigma}_x \qquad H_q = \vec{\widetilde{B}}^{\,\mathrm{eff}} \cdot \vec{\hat{\sigma}}$$





Closing the gap: effective magnetic field vanishes at some q

$\widetilde{B}_z^{\mathrm{eff}}=0$ by controlling δ

$$|\uparrow\rangle = a|e,0\rangle + |e,1\rangle\sqrt{1-a^2}$$

$\widetilde{B}_x^{\mathrm{eff}}=0$ by dressing e with higher bands

$$|\downarrow\rangle = |g,0\rangle$$

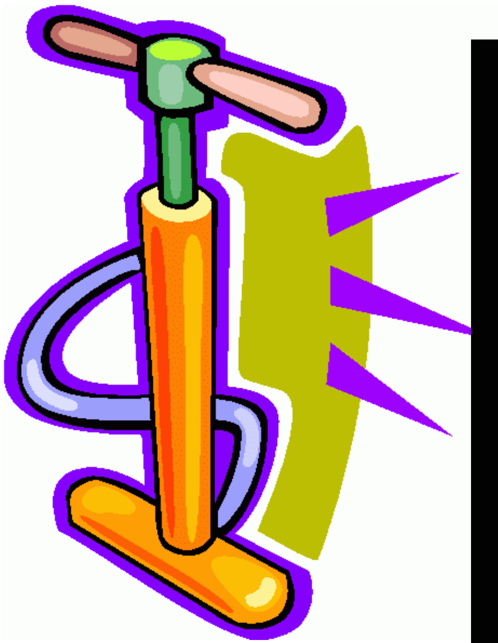
❑ Including p-wave interactions

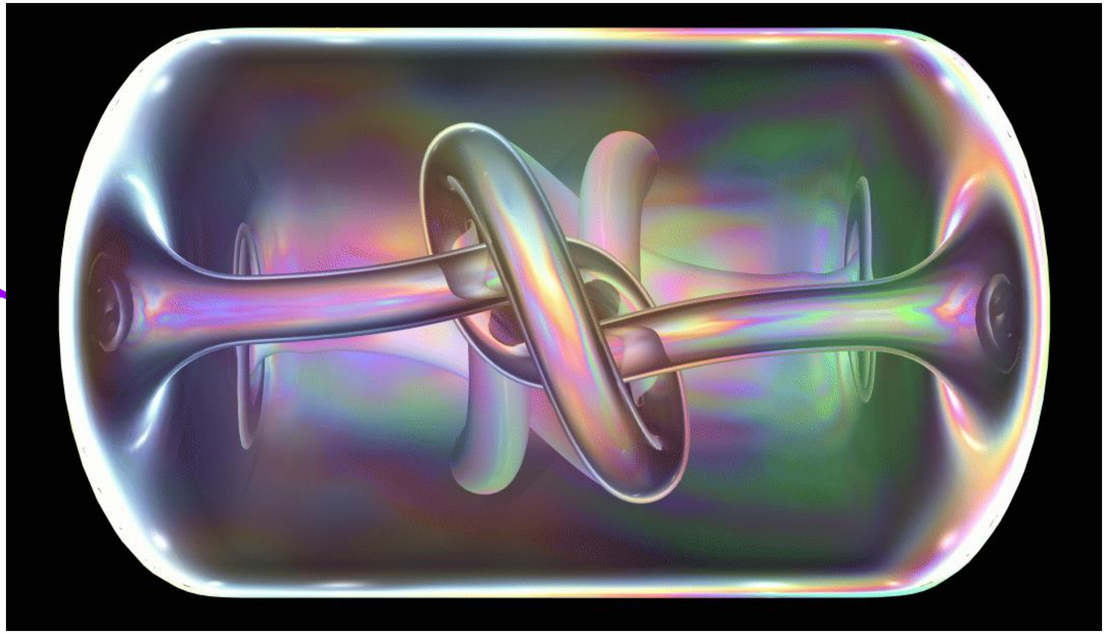
$$H_p \approx E_R V_{n_z} \sum_{q,q',k,\sigma\sigma'} \left(\frac{b_{\sigma\sigma'}}{a}\right)^3 (\cos q \cos q' \cos k)\, \hat{c}^\dagger_{\sigma,q'+k}\hat{c}^\dagger_{\sigma',q-k}\hat{c}_{\sigma',q}\hat{c}_{\sigma,q'}$$

↓

Mean-field $: \cos(qa)\hat{\sigma}_x \sum_{q'} B_{qq'}\langle\hat{\sigma}_x\rangle$

Topological Pumping and Transport





Use synthetic direction in a more versatile way

N. R. Cooper, A. M. Rey: arXiv:1503.05498

L. Wang, M. Troyer, and X. Dai, PRL. 111,026802 (2013).

F. Mei *et al.,* PRA 90, 063638 (2014).

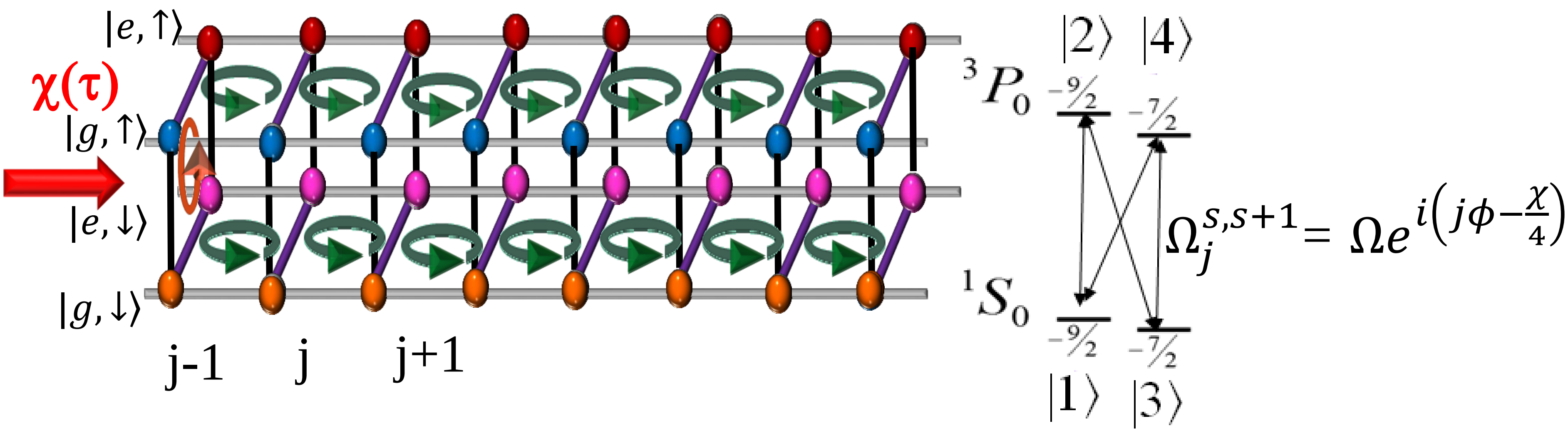
R. Wei and E. J. Mueller, arXiv:1502.04208.

Topological Pumps:

Transfer charge/particles in a quantized fashion: closely related to the quantized Hall transport in the quantum Hall effect.

1D system: Transport quantized according to a Chern number C, defined over [D. J. Thouless(1983)]:

- ❑ 1D Brillouin zone (1D lattice) +
- ❑ Time-dependent periodic parameter in a cycle (synthetic dimension)



Also with Raman: M. Mancini et al., arXiv:1502.02495, B. K. Stuhl et al., arXiv:1502.02496.

Local dressed states: No tuneling

$$H_{\Omega,j} \approx \sum_s \Omega_j |s\rangle\langle s+1| + \Omega_j^* |s+1\rangle\langle s| \qquad \Omega_j = -\Omega e^{i\left(j\phi - \frac{\chi(\tau)}{4}\right)}$$

$$E_j = -2\,\Omega \cos\left(\frac{\chi(\tau)}{4} - j\phi + k_s\right)$$

$$|k_s\rangle = \frac{1}{2}\sum_s e^{isk_s}\,|s\rangle$$

$$k_s = \{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\}$$

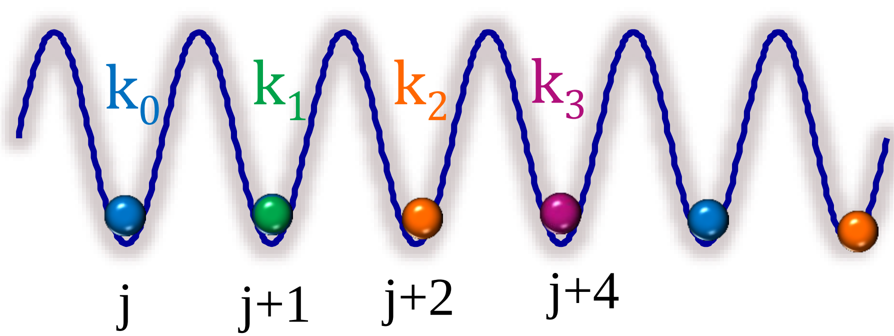
Preparation ground state

1. Initially |s=0,s=0,…⟩

2. Slowly increase Ω and decrease δ

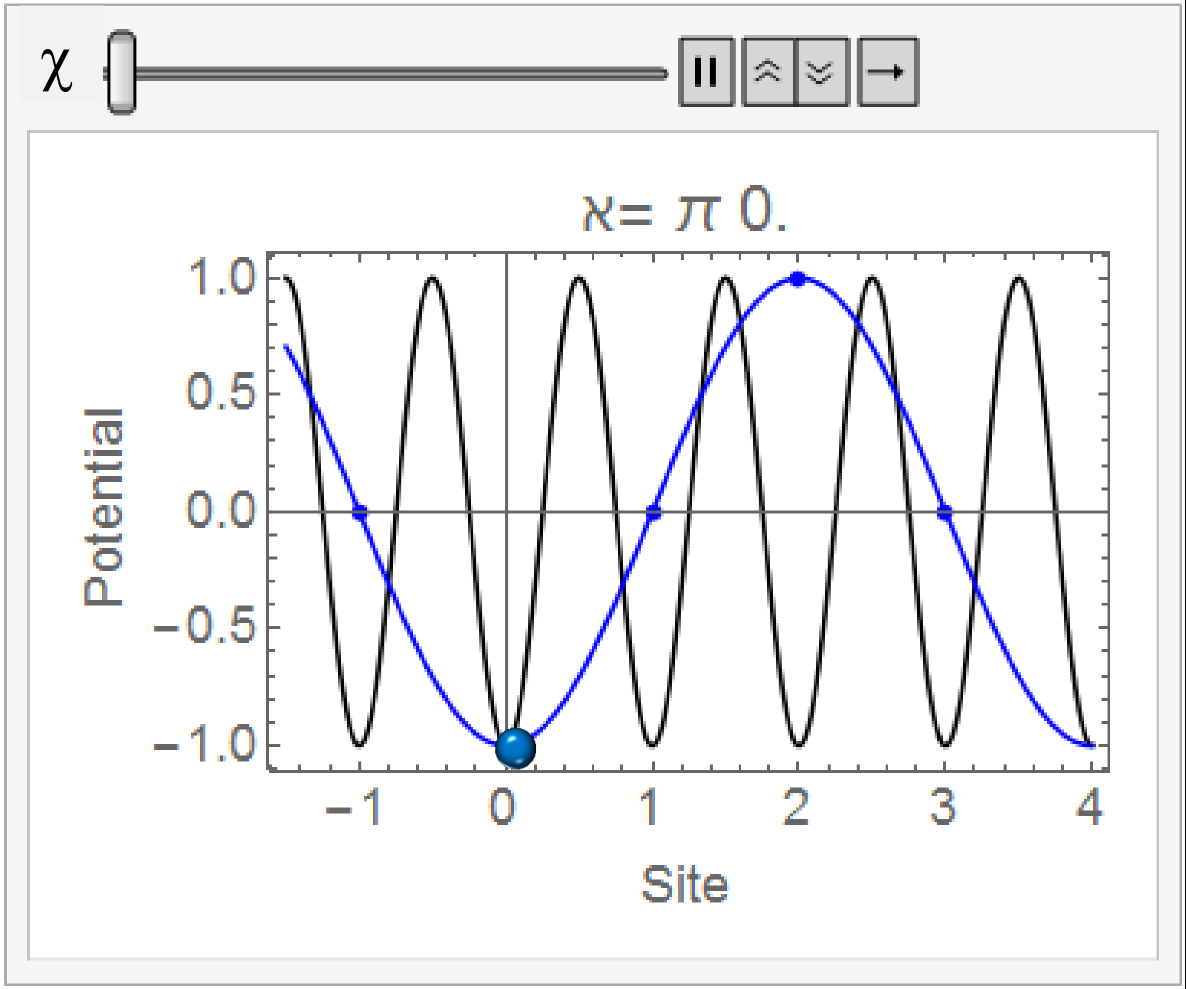
$$H_\delta \approx \delta \sum_s s|s\rangle\langle s|$$

For example: ϕ=π/2



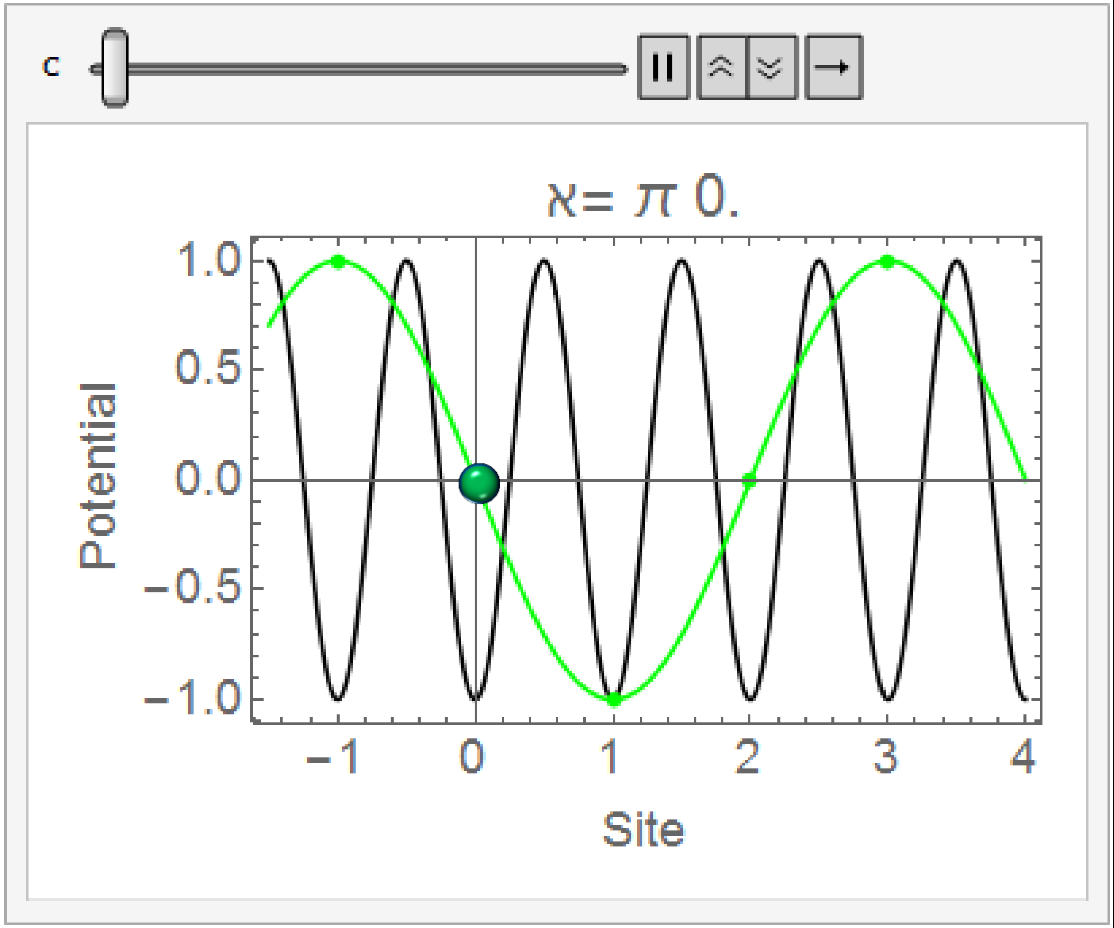
The ground state has alternating dressed states

Quantized adiabatic transport



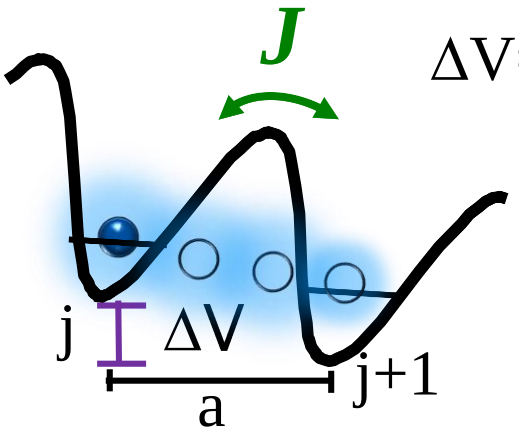
- At τ=0 a k_s=0 particle is at j=0 and χ=0
- Turn on tunneling: J
- Particle frozen because next site is off resonance.
- Adiabatically increase χ. Slowly than J/h
- At $\chi=\pi$ tunneling resonance appears
- Particle is adiabatically pumped to j=1 at $\chi=2\pi$

Spin dependent adiabatic transport



- At $\tau=0$ a $k_s=\pi/2$ particle is at $j=0$ and $\chi=0$
- Transport will be in the other direction when varying χ

Force sensing



ΔV= Fa

At χ=π $H=\begin{pmatrix} -\Delta V/2 & -J \\ -J & -\Delta V/2 \end{pmatrix}$

$$|\psi\rangle_+ = \left[[\cos\left(\frac{\Theta}{2}\right)|k_s=0\rangle_j + \sin\left(\frac{\Theta}{2}\right)|k_s=0\rangle_{j+1}\right]$$

$$\sin^2\left(\frac{\Theta}{2}\right) \sim \frac{1}{2}\left(1-\frac{\Delta V}{2J}+\cdots\right)$$

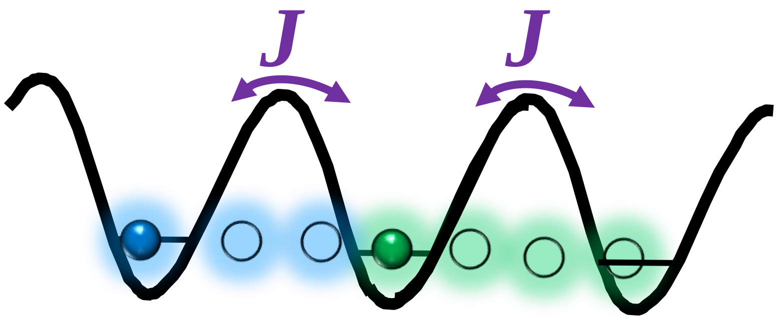
Protocol:

1. Suddenly turn off J=0
2. Reverse χ to 0
3. $|k_s=0\rangle_{j+1}$ is now excited state
4. Slowly turn off Ω and on δ
5. Measure s≠1 population

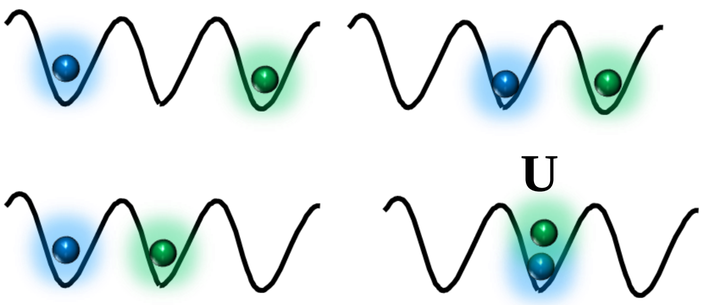
Population of $|k_s=0\rangle_{j+1}$ proportional to ΔV

How to measure interactions

For the case U≪J,Ω



At $\chi=\pi$
State ~ equal superposition of



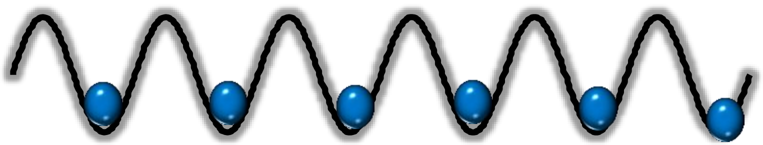
- Turn off J will lead to Ramsey oscillations with frequency U measureable spectroscopically
- In a double well superlattice the same procedure to measure ΔV can be applied to measure U
- If the interactions are not SU(4) $k_s \neq 0, \pi/2$ will be populated

For the case U≫J,Ω Transport will be blocked

Topology: J~Ω ??

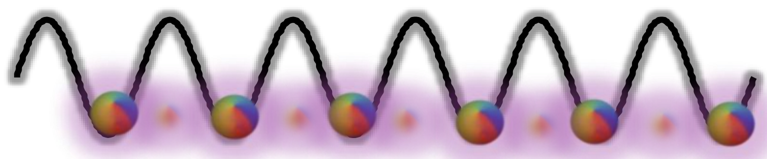
- Bloch waves of Harper Eq. with $\phi=2\pi p/q$ characterize by: $\{k_x, k_s+\chi/4\}$
- Topological bands with $C \neq 0$: Chern Number when k_x vary $(-\pi/q, \pi/q)$ and χ from $(0, 2\pi)$
- For an insulating state C: # particles than move under adiabatic: $\chi = 0 \rightarrow 2\pi$
- One filled band , p/q=1/4 → $C = 1$

Preparation:



Band Insulator at $\Omega=0$

$\Omega>0$ at $\chi \neq \pi$

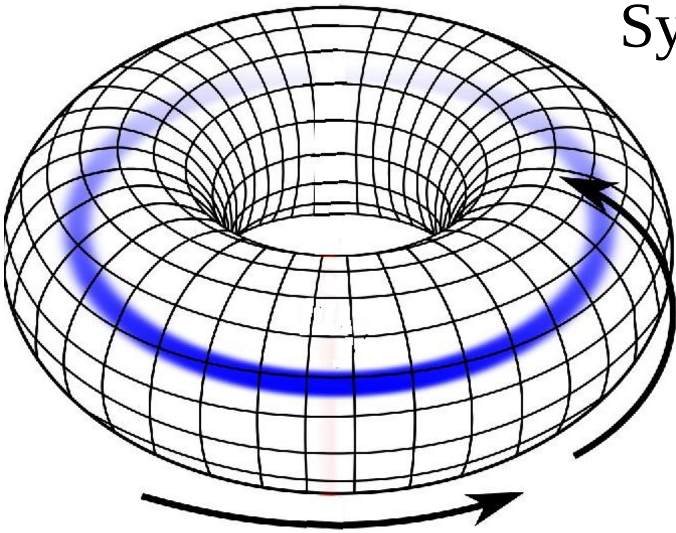


Non-trivial topological insulator

How can be adiabatically connected??

Ok, since 1D k_s is discrete

Topological Transport



Force: F_x

Synthetic current

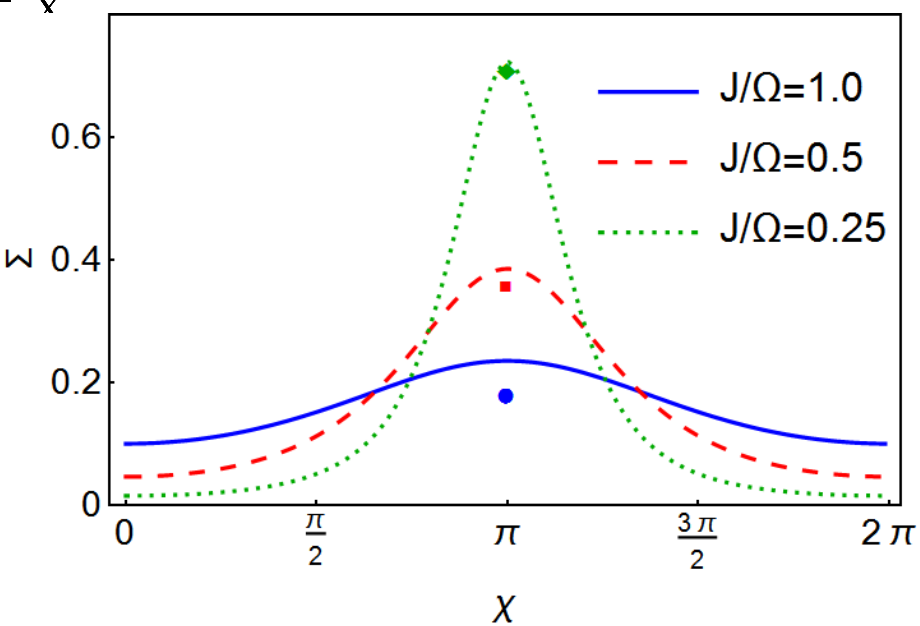
$$\langle I \rangle_s = \left\langle \frac{\partial H_\Omega}{\partial \chi} \right\rangle = -N a F_x \Sigma \quad \int_0^{2\pi} \Sigma d\chi = \mathcal{C}$$

quantized

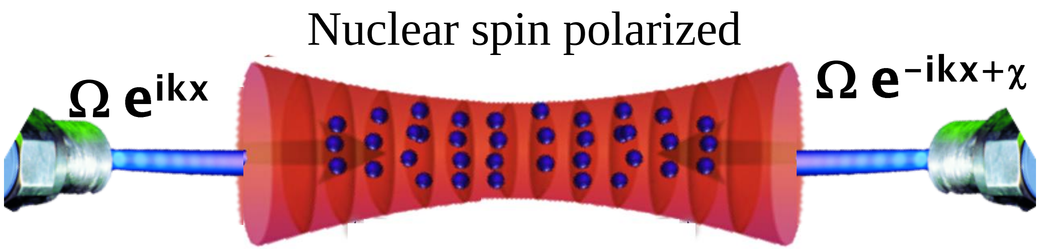
Σ: Average Berry curvature

Local picture: $\langle I \rangle_s = -\, aN \, \dfrac{\Omega \Delta V}{4\sqrt{2}J}$

$$\Longrightarrow \Sigma = \frac{\Omega}{4\sqrt{2}J}$$

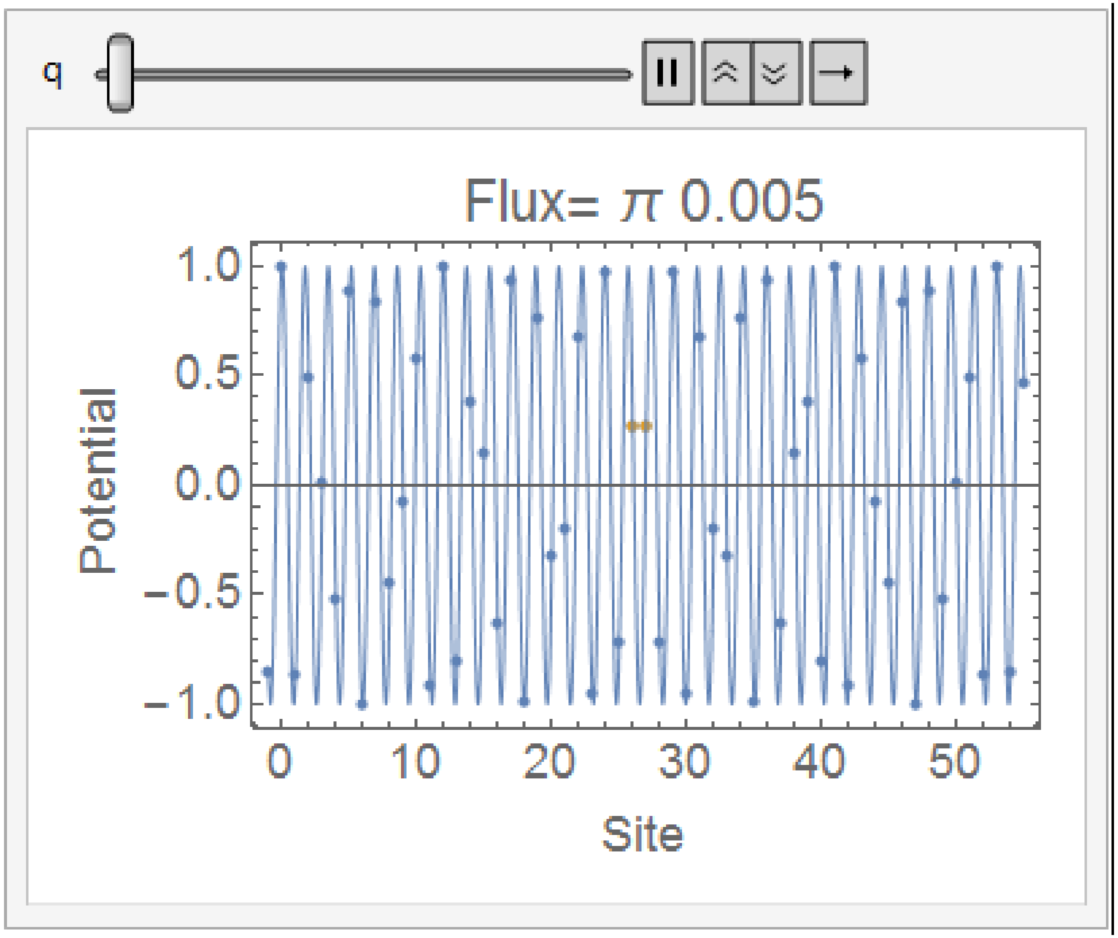


Simpler Implementation for Sr clock



Two levels

$$|k_s = 0, \pi\rangle = \frac{|g\rangle \pm |e\rangle}{\sqrt{2}}$$



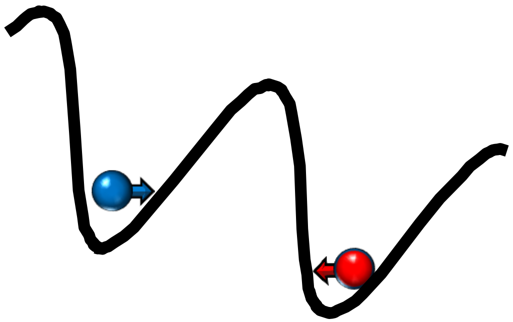
$$H_{\Omega,j} = 2\Omega\cos(\chi - j\phi)\hat{\sigma}_x$$

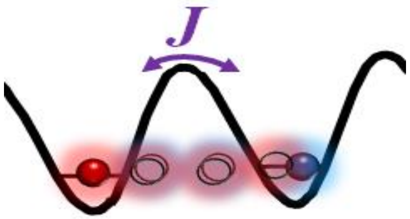
$$\phi \approx \frac{117}{100}\pi$$

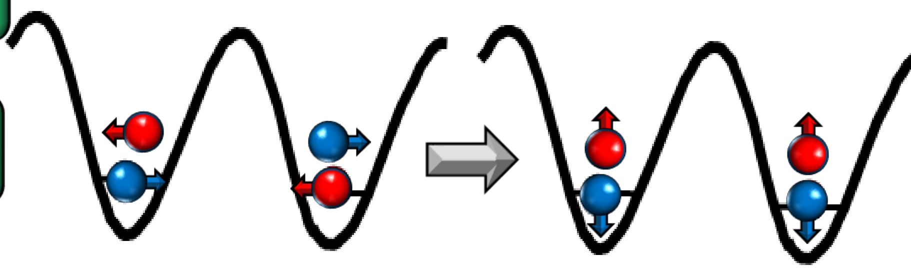
Transport in the clock

Protocol:

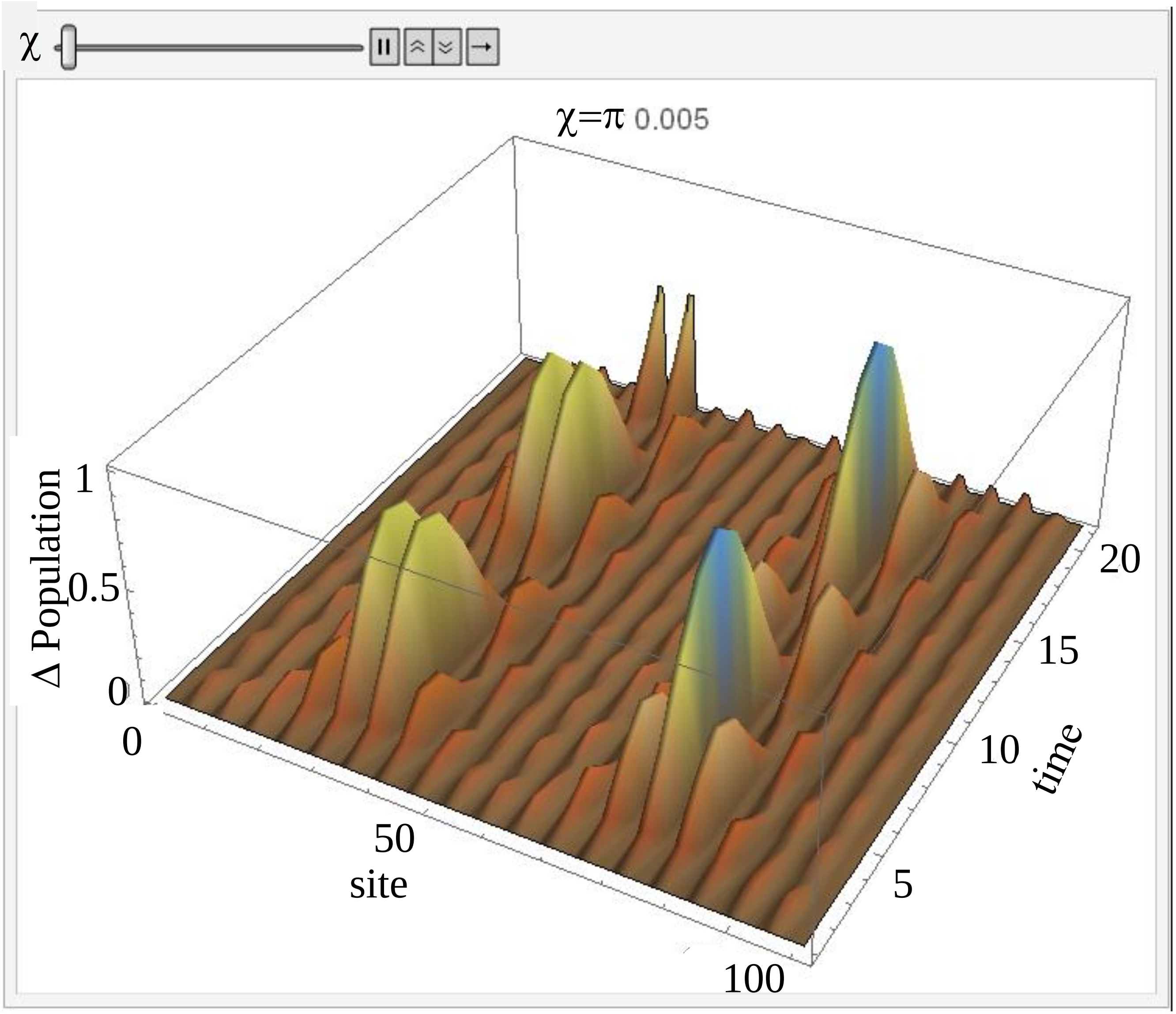
1. Prepare local dressed levels J=0
2. Adjust χ and turn on J fast
3. Wait for tunneling
4. Ramp up lattice and vary χ
5. Solwly turn off Ω and on δ
6. Measure e







Measuring transport in the clock



- Should be spatially solvable with a B-field gradient

Outlook

- Clock sensitivity can allow for probing spin orbital physics and quantum magnetism at μK temperature.

- Spin-orbit experiment under preparation in the JILA clock

- Many-body localization in the clock?

$$H_{\Omega,j} = 2\Omega\cos(\chi - j\phi)\hat{\sigma}_x \qquad \phi \approx \frac{117}{100}\pi$$

- Synthetic gauge fields + SU(N): route for a stabilize chiral spin liquid ?

arXiv:1501.04086,Synthetic gauge fields stabilize a chiral spin liquid phase, G. Chen, K.R.A. Hazzard, A.M. Rey & M. Hermele

Thanks for your attention