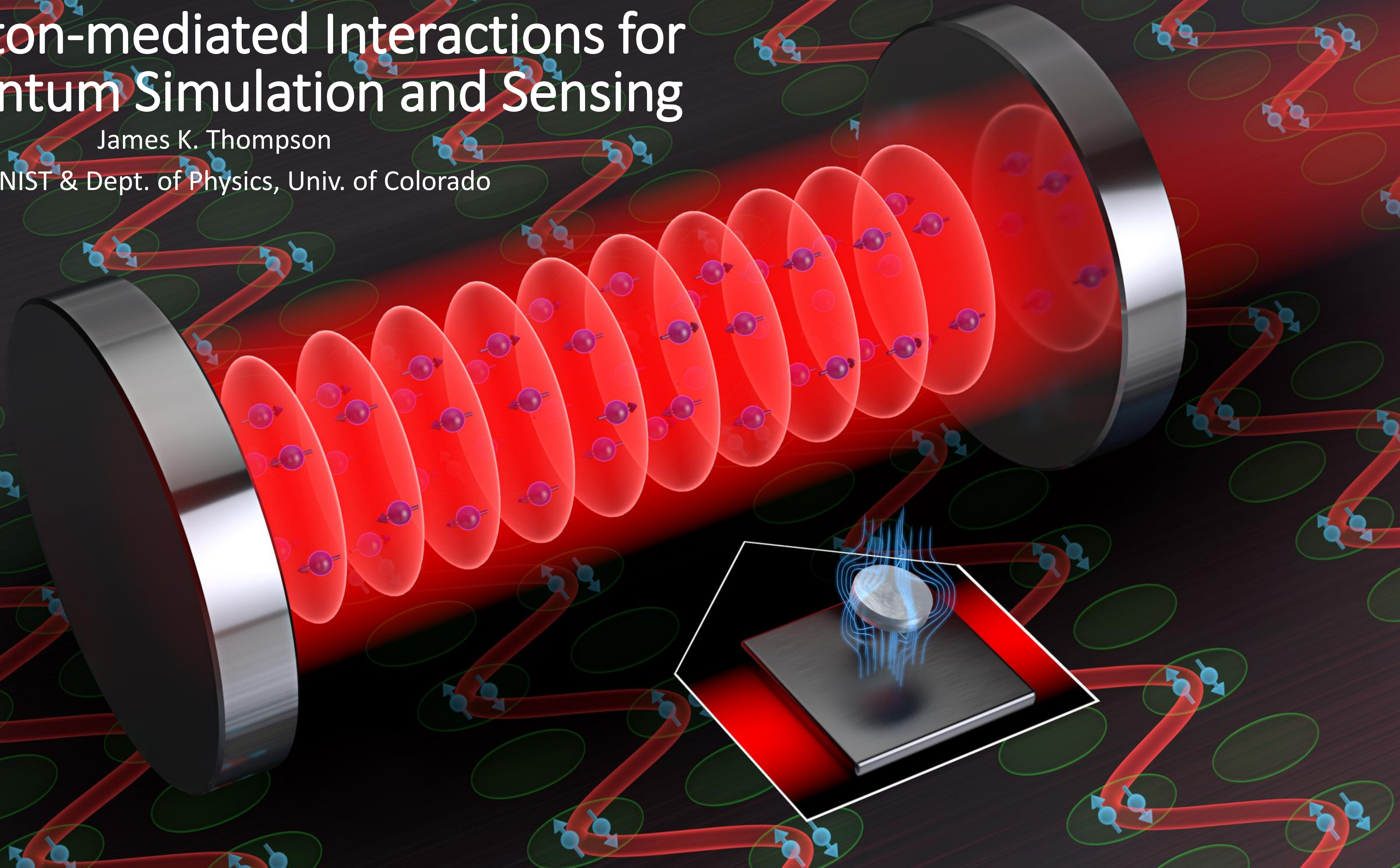
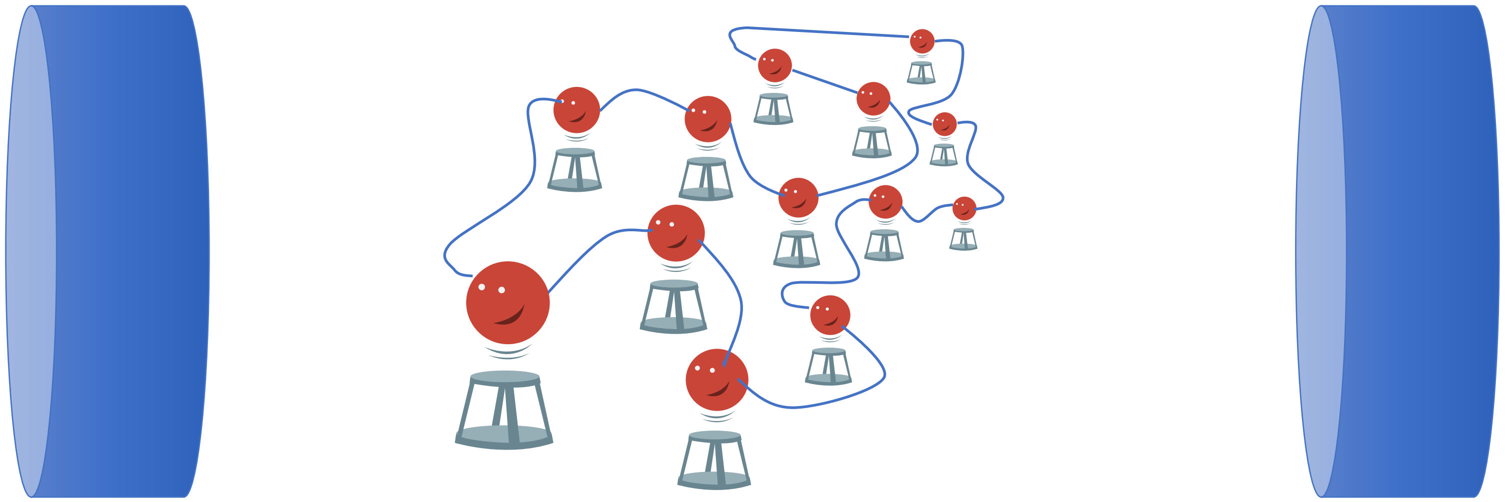
Photon-mediated Interactions for Quantum Simulation and Sensing

James K. Thompson

JILA, NIST & Dept. of Physics, Univ. of Colorado



Correlations and Entanglement Facilitated by Optical Cavity



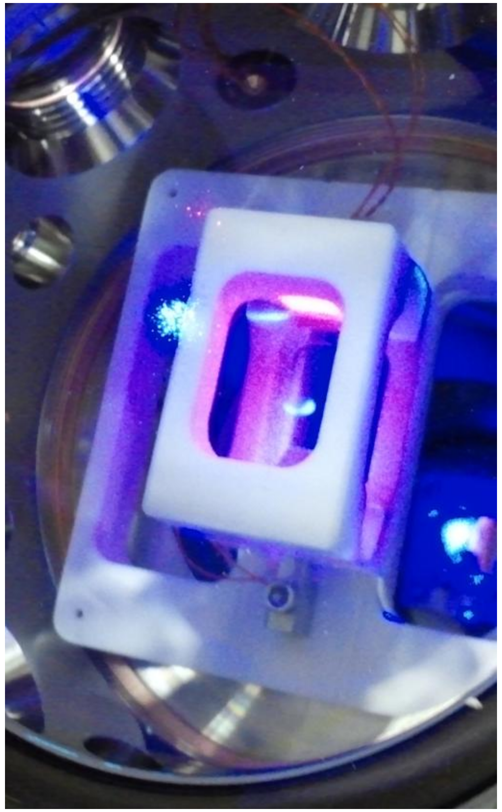
Explore fundamental science of quantum sensing and simulation

Use *All* of Quantum Mechanics:

Unitary Dynamics, Quantum Measurement, Dissipation

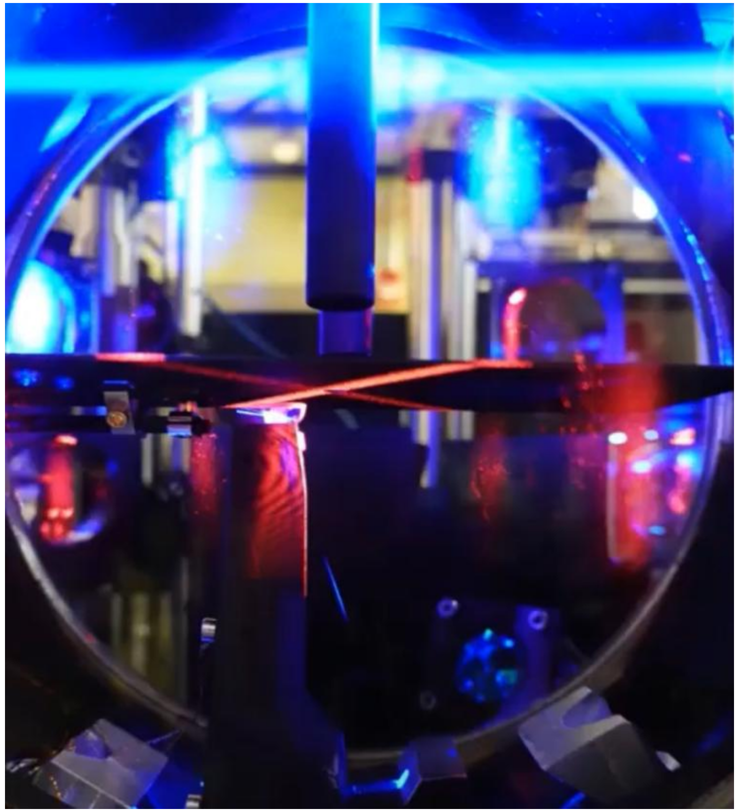
Correlations and Entanglement Facilitated by Optical Cavity

Strontium



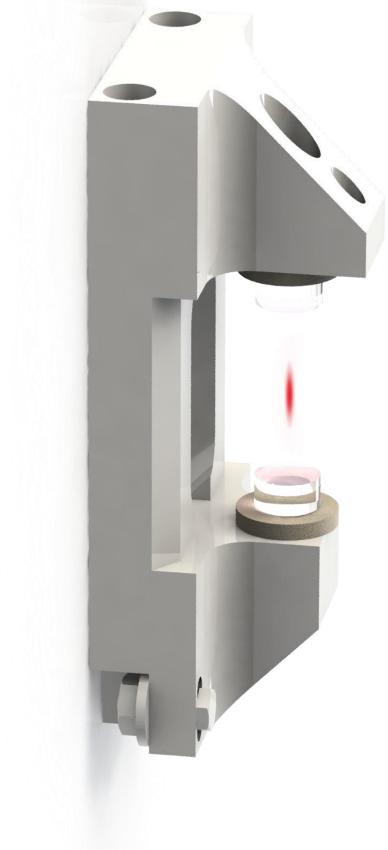
Quantum Simulation

Strontium Ring Cavity



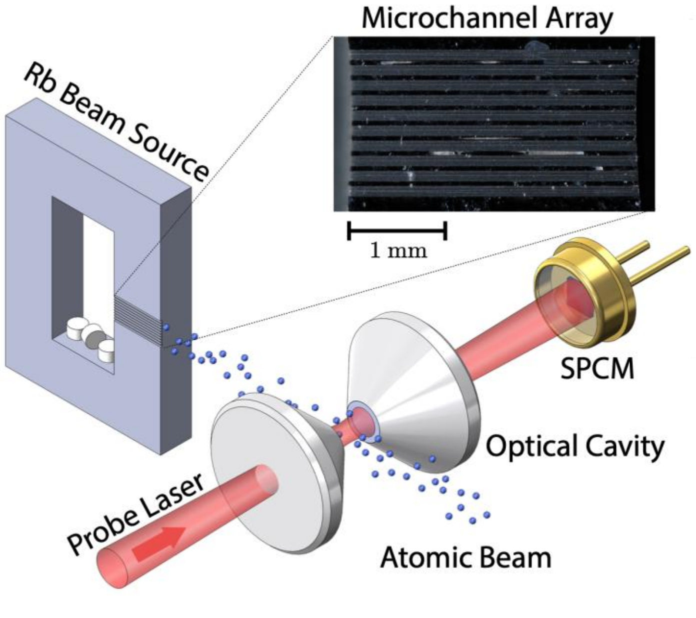
Continuous Superradiance

Rubidium



Matterwave Interferometry

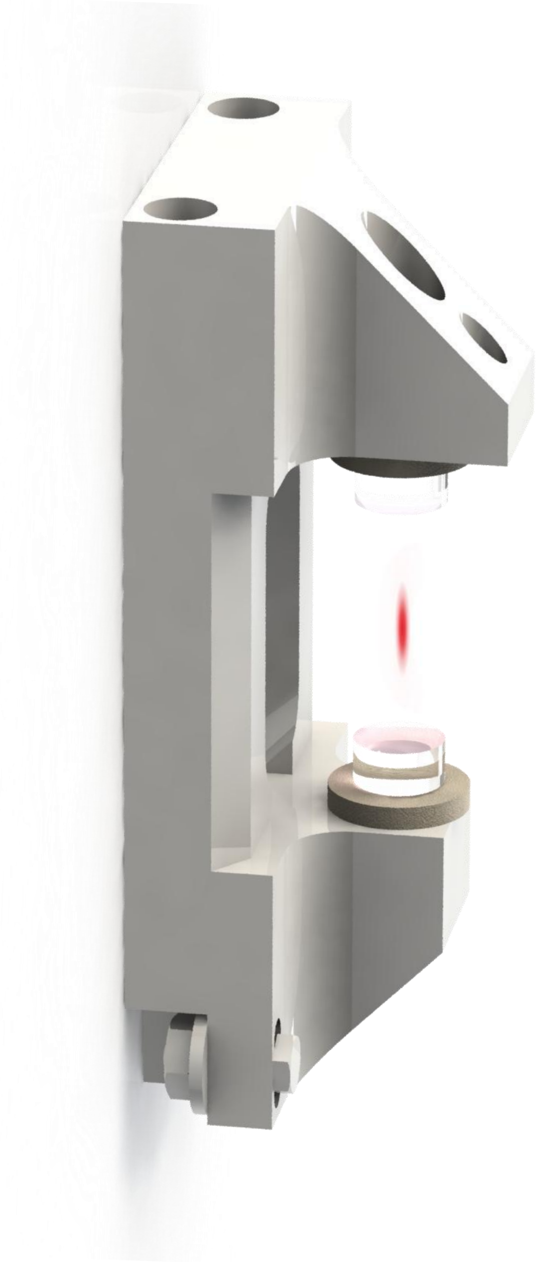
Rubidium Thermal Beam



Larsen, Hensley,...Kitching, Thompson
Science Adv. 12 eaec3179 (2026)

Non-classical light

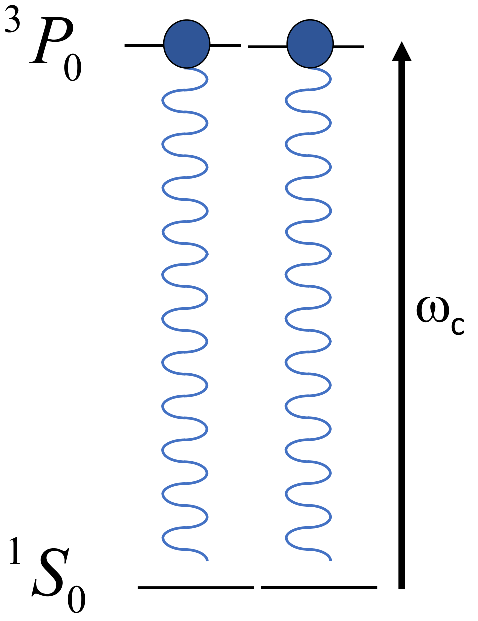
Topics for Today



- **From Superradiance to Exchange Interactions**
- Expanded Palette of Interactions: XYZ, 3- & 4-body
- Quantum Sensing: entanglement for matterwave interferometers and clocks
- Quantum Simulation: dynamical phases in BCS-BEC crossover

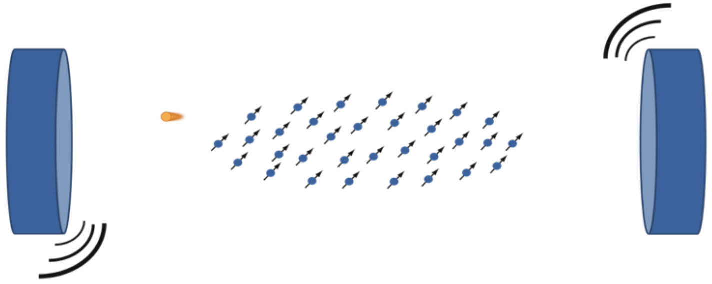
Cavity on Resonant with Atoms: Superradiance

Strontium Clock Transition
1 mHz or 118(3) sec



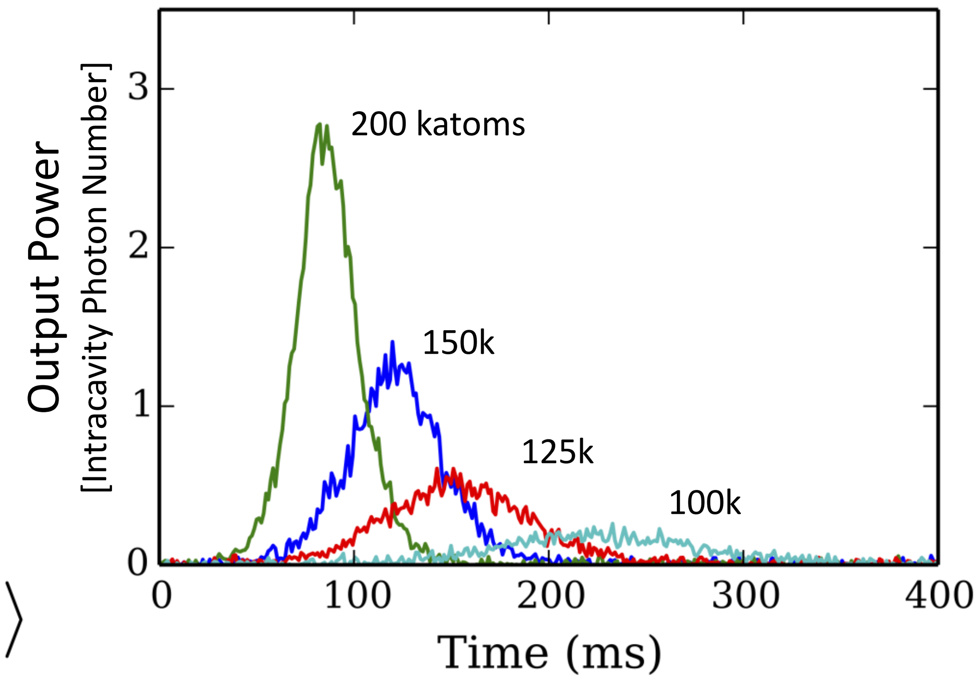
Which atom decayed?
Cannot tell!

$$|\psi\rangle \propto |eg\rangle + |ge\rangle$$



photon
emitted

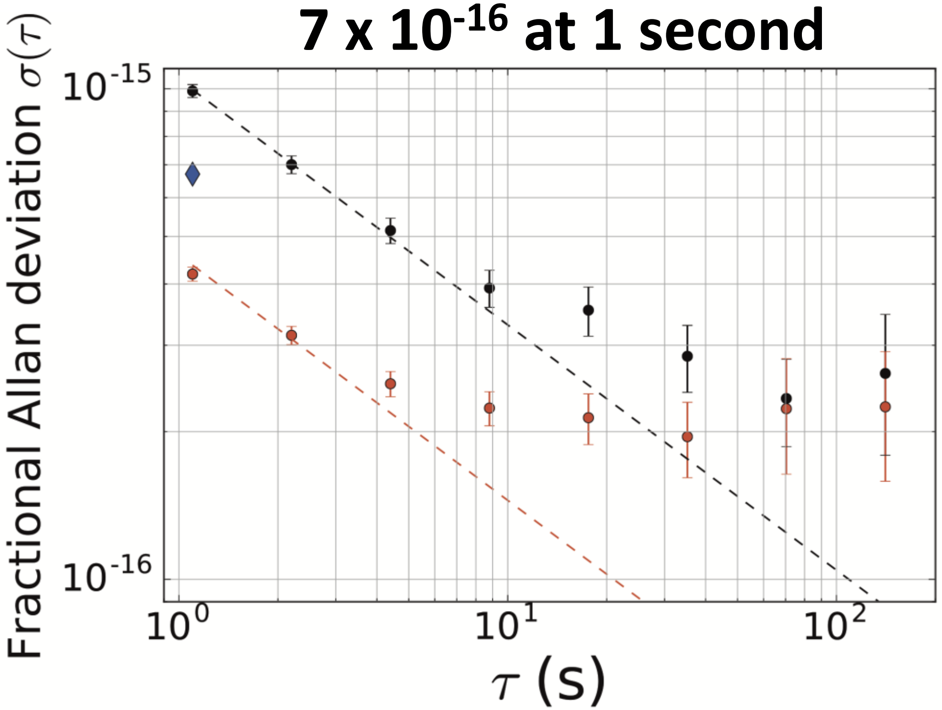
Spontaneous laser pulses



500,000 x less sensitive to cavity frequency noise

Norcia,…Ye, Thompson *PRX* **8**, 021036 (2018)

7 x 10^{-16} at 1 second



Most precise active atomic clock

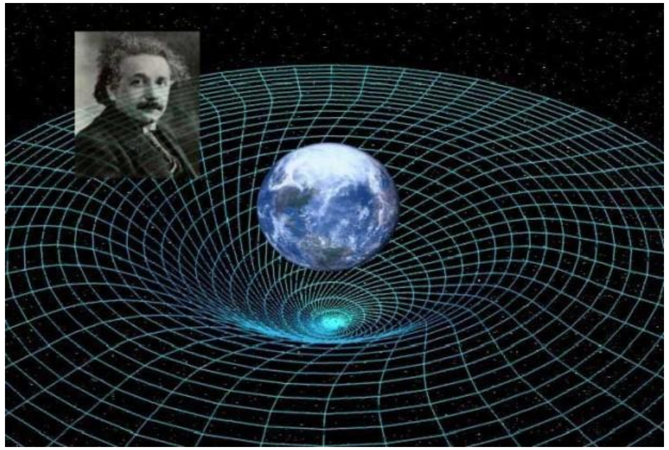
Meiser, Ye, Carlson, Holland, *PRL* 102, 163601 (2009)
Jingbaio Chen, *Chinese Sci. Bull.* 54, 348 (2009)
Bohnet,…Holland, Thompson, *Nature* (2012)
Norcia, Thompson *PRX* (2016)
Norcia,…Thompson, *Science Adv.*(2016)

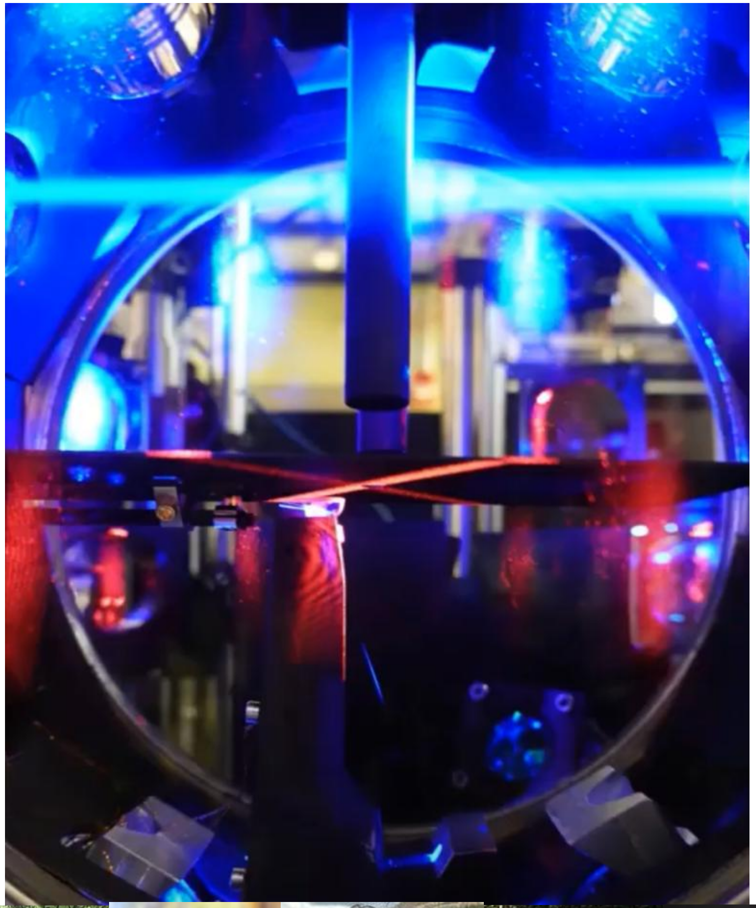
Laske,…Hemmerich *PRL* 123 103601 (2019)
Schäffer,…Thomsen *PRA* 101 013819 (2020)
Kristensen, Bohr,…Zelevinsky, Thomsen, Müller *PRL* 130, 223402 (2023)

Pulsed → Continuous Superradiant Lasing

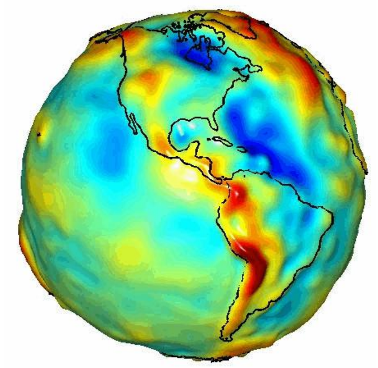
Goal: $\Delta f/f \sim 10^{-18}$ at one second

Resolve 1 cm in 1 sec

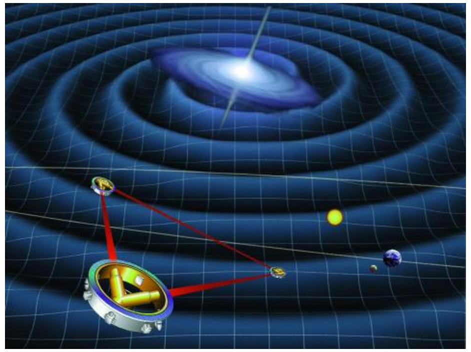




Geodesy



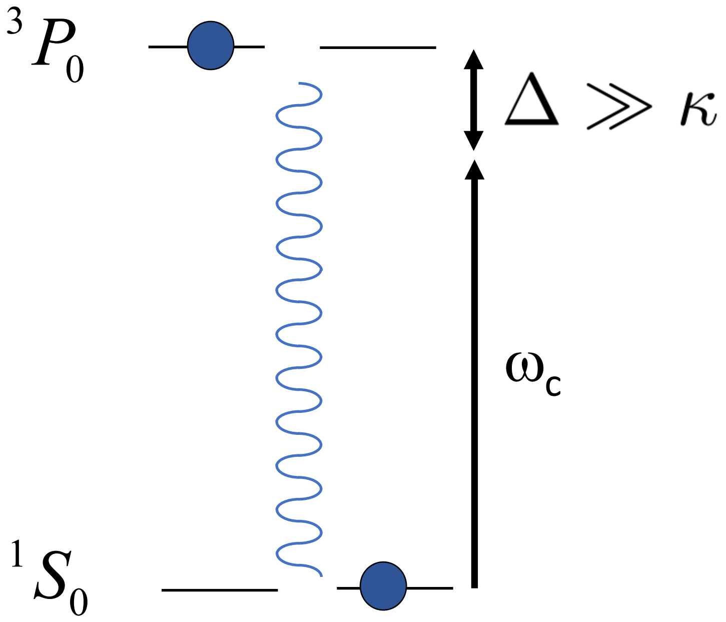
Gravitational Waves

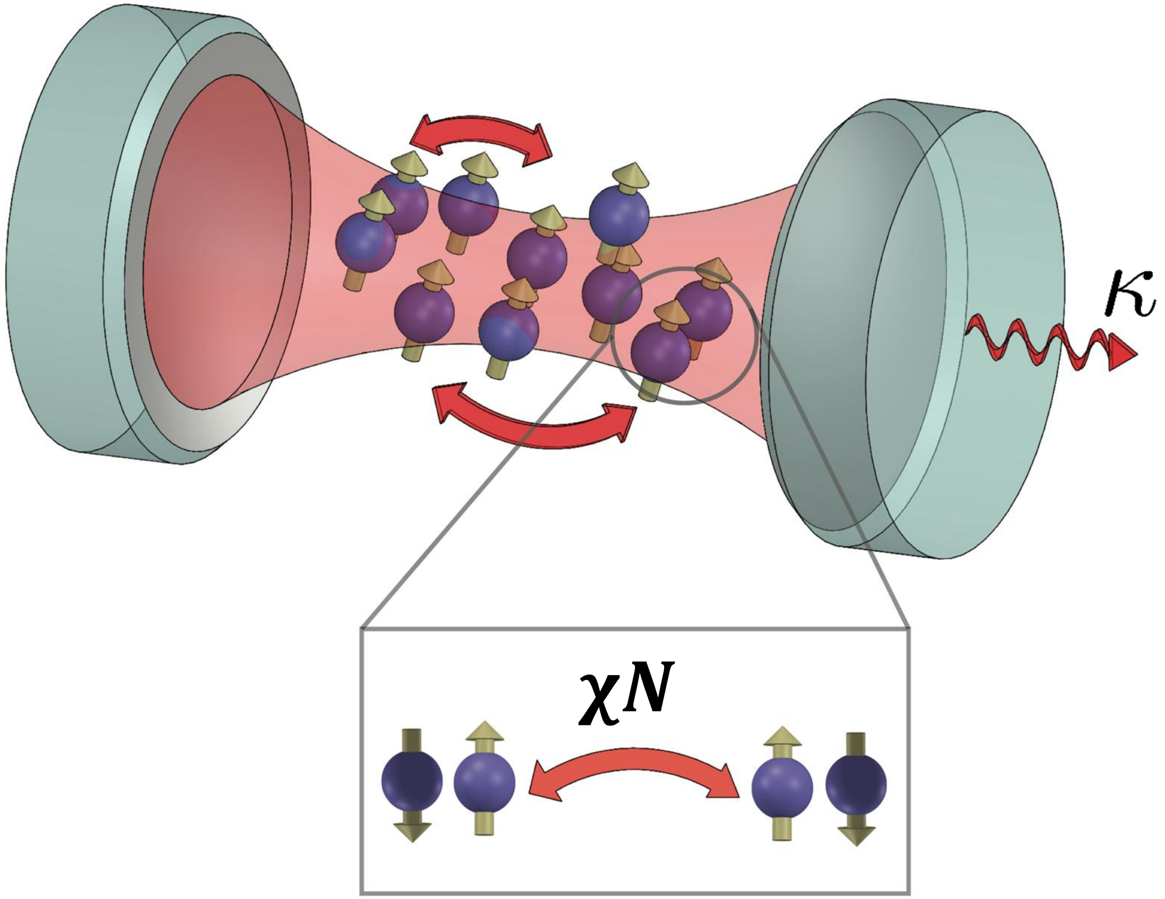


Dark Matter

Cline, Schäfer, Niu, Young, Yoon, Thompson *PRL* (2025)
Schäfer, Niu, Cline,…Ritsch, Thompson, *Nature Physics* (2025)

Detune the Cavity: Spin-Exchange Interactions

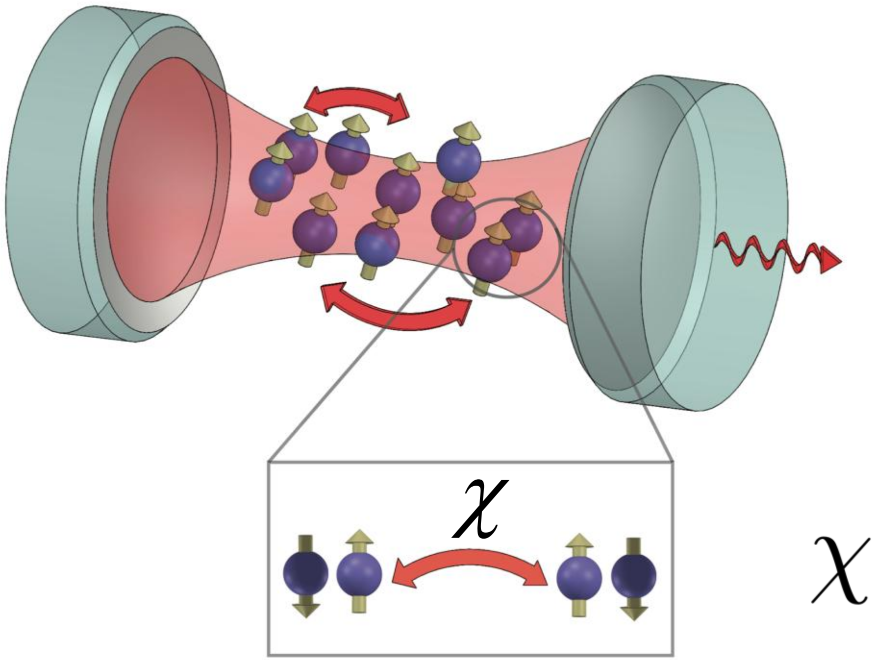


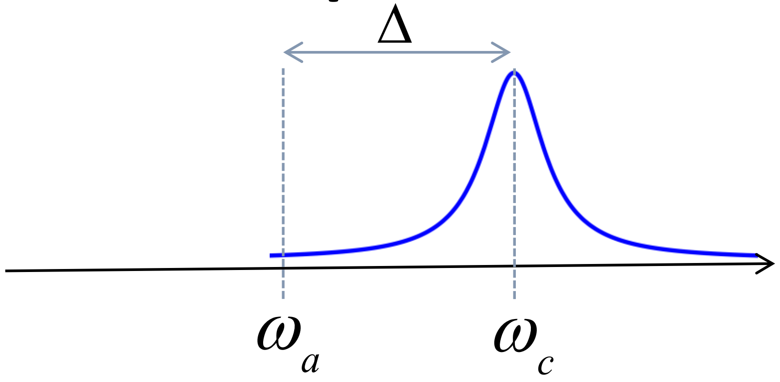


$$\hat{H} = \chi \hat{S}_+ \hat{S}_- = \chi \sum_{k,k'}^{N} \hat{\sigma}_+^k \hat{\sigma}_-^{k'}$$

Norcia,…Rey, Thompson, *Science* **361**, 6399, 259 (2018)
Davis,,…Schleier-Smith *PRL* **122**, 010405 (2019)
Muniz,…Rey, Thompson *Nature* **580** 602-607 (2020)
Periwal,…Schleier-Smith *Nature* **600**, 630-635 (2021)
Luo,…Holland, Rey, Thompson *Science* **384** 551 (2024)

Spin Exchange versus Superradiance





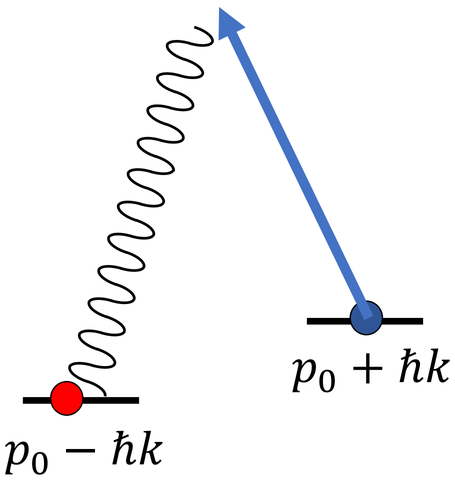
$$\Gamma_c = \underbrace{\frac{4g^2}{\kappa}}_{C\gamma} \frac{1}{1+(2\Delta/\kappa)^2}$$

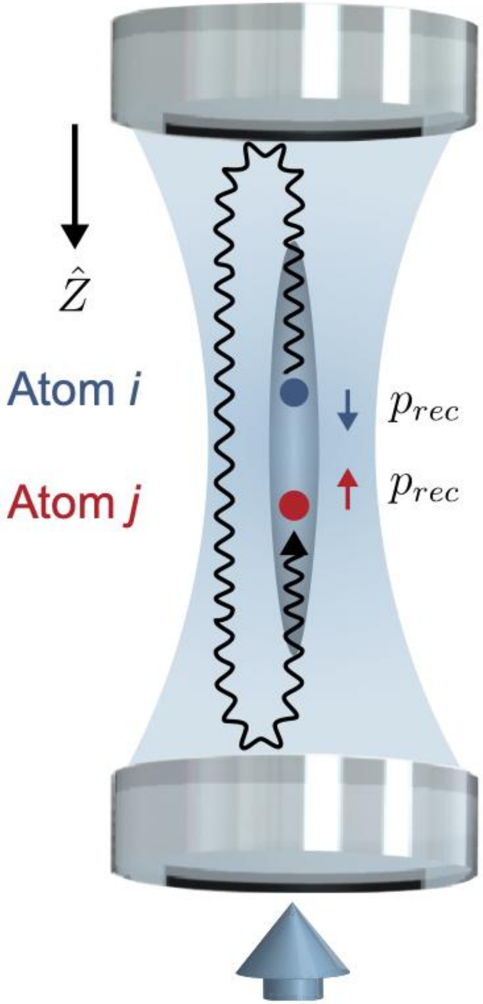
$$\chi = \underbrace{\frac{4g^2}{\kappa}}_{C\gamma} \frac{\Delta/\kappa}{1+(2\Delta/\kappa)^2}$$

$$\frac{\text{Unitary Dynamics}}{\text{Collective Dissipation}} = \frac{\chi}{\Gamma_c} = \frac{\Delta}{\kappa}$$

Momentum-Exchange Interaction

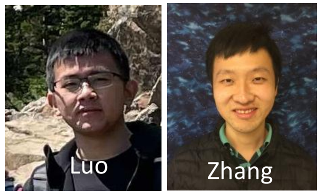
4-photon Process



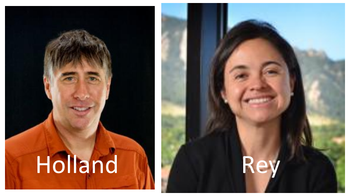


Exchange Interaction

$$\hat{H}_{ex} = \chi \sum_{i,j}^{N} \hat{\sigma}_j^+ \hat{\sigma}_i^- = \chi \hat{J}_+ \hat{J}_-$$

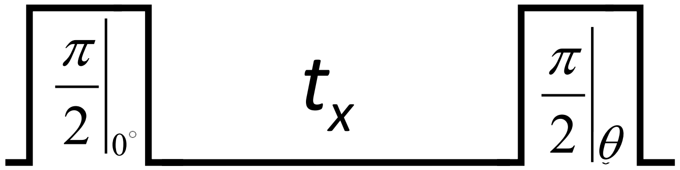


<u>Momentum</u>: Chengyi Luo, Zhang, Koh, Wilson, Chu, Holland, Rey, Thompson *Science* 384 551 (2024)
Wilson, Jäger, Reilly, Shankar, Chiofalo, Holland, *PRA* 106, 043711 (2022)
Shankar, Salvi, Chiofalo, Poli, Holland, *Qu. S&T.* 4 045010 (2019)

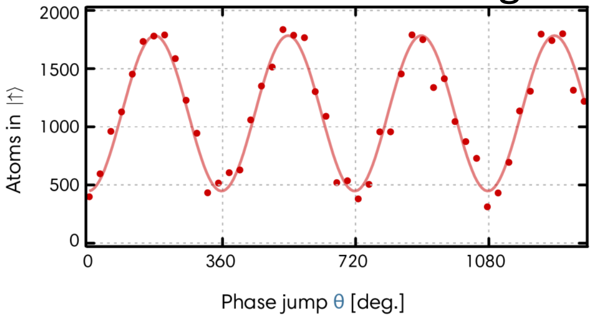


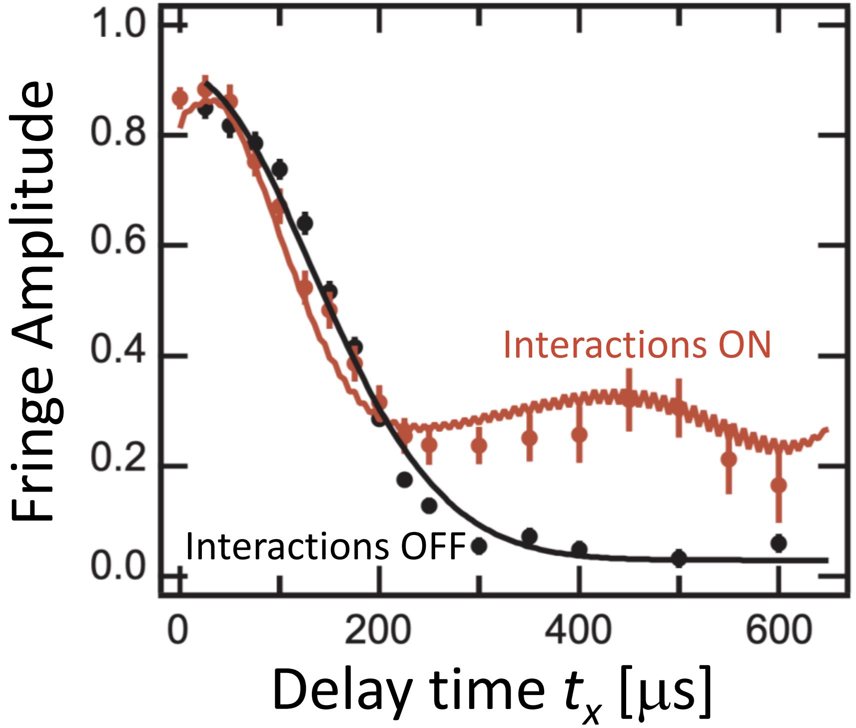
Binding Wave Packets Together

$$H_{ex} \approx \chi \hat{J}_+ \hat{J}_- \approx \chi \left(J^2 - J_z^2 \right)$$

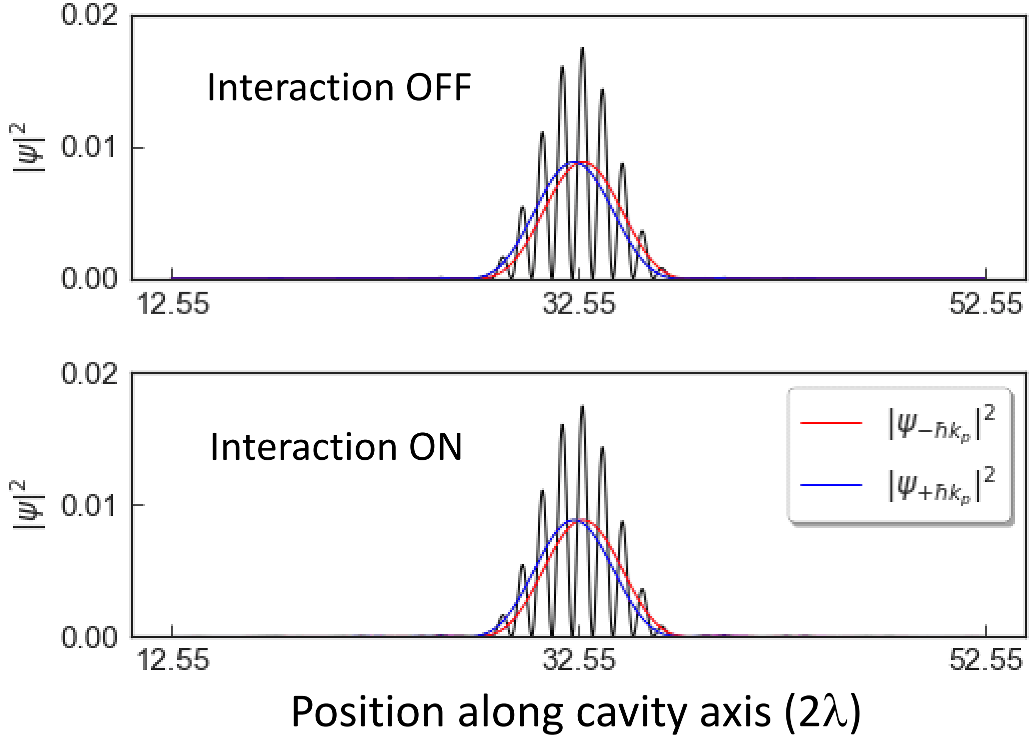


Interferometer Fringe





Simulation of $|\psi(Z, t)|^2$



Collective Recoil *Gedanken*

No Interactions

Single Photon

1 atom at

$$v = \frac{\hbar k}{m}$$

Momentum Exchange Interactions

Single Photon

N atoms at

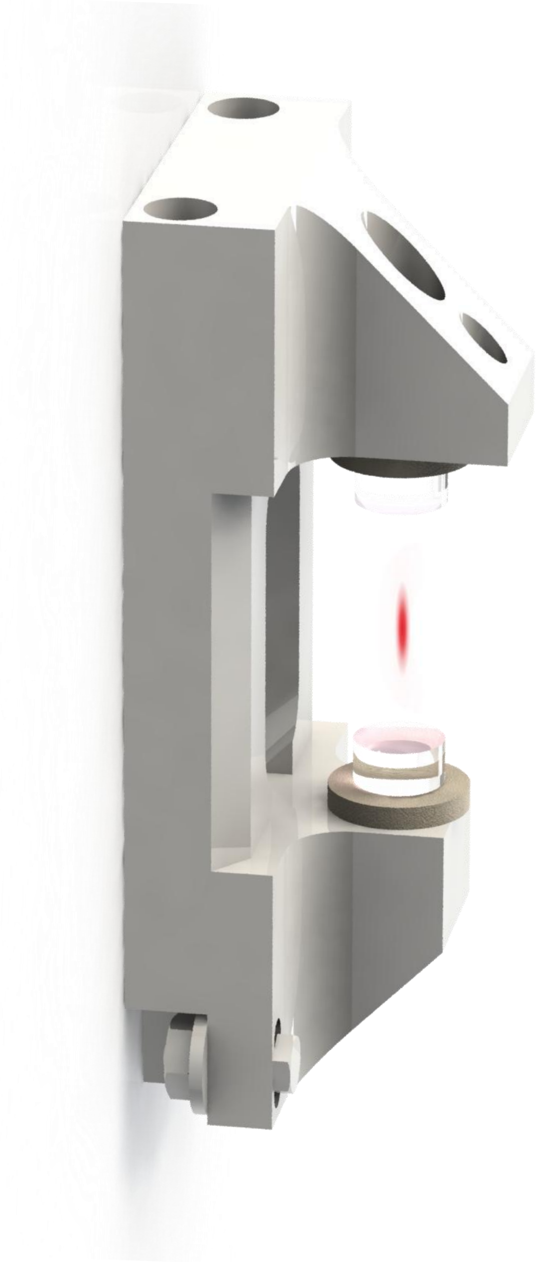
$$v = \frac{\hbar k}{N\,m}$$

The atoms collectively recoil as a single object and Doppler dephasing is suppressed.
Similar to Mossbauer or Lamb-Dicke spectroscopy.

Observe on narrow strontium transition: Niu, Schäfer, Zhang… Rey, Thompson, *PRL* (2025)

Next: both collective recoil & solitons: Zhang, Chu, Luo, Thompson, Rey *PRL* (2025)

Topics for Today



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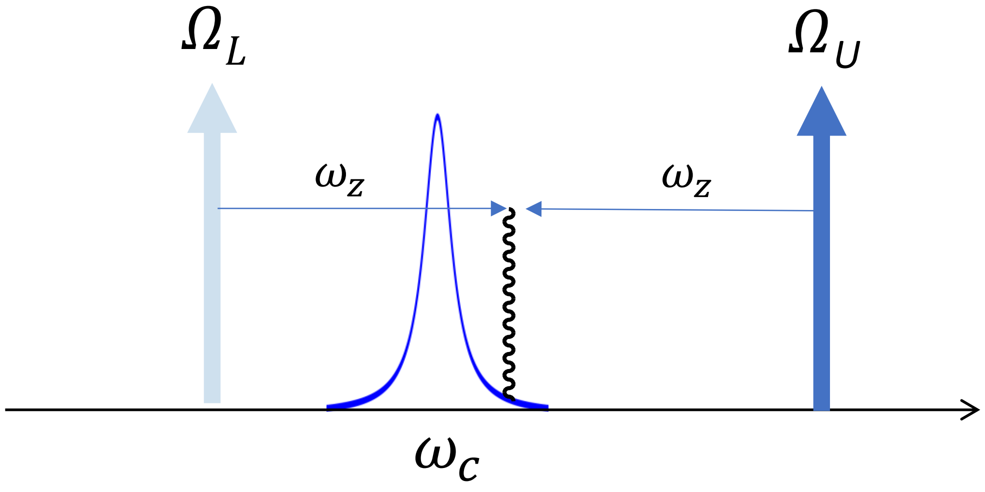
- **Expanded Palette of Interactions: XYZ, 3- & 4-body**
- Quantum Sensing: entanglement for matterwave interferometers and clocks
- Quantum Simulation: dynamical phases in BCS-BEC crossover

Engineering General Hamiltonians: XYZ

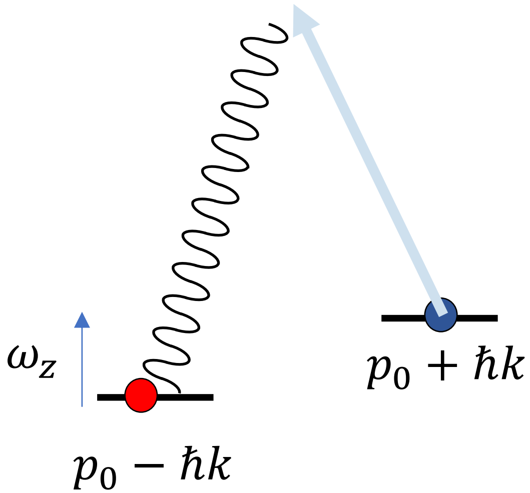
Luo, Zhang, Chu, Maruko, Rey, Thompson *Nature Physics* (2025)



$$\boxed{\hat{H} = \alpha J_x^2 + \beta J_y^2 + \gamma J_z^2}$$

4-photon processes that conserve energy

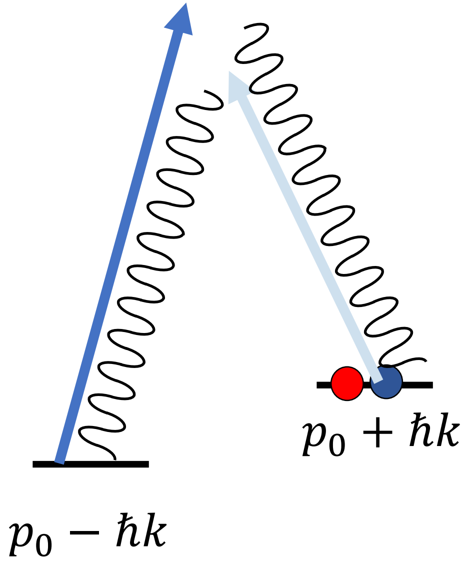
Momentum exchange



$$H_{ex} = \chi_e J_+ J_-$$

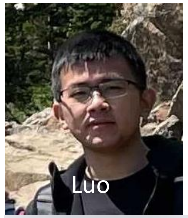
$$\propto (\Omega_U^2 g^2 + \Omega_L^2 g^2)$$

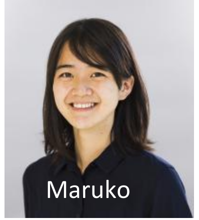
Momentum pair lowering/raising

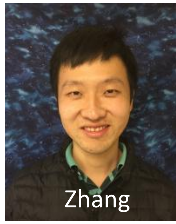


$$H_p = \chi_p (J_+^2 + J_-^2)$$

$$\propto \Omega_U \Omega_L g^2$$



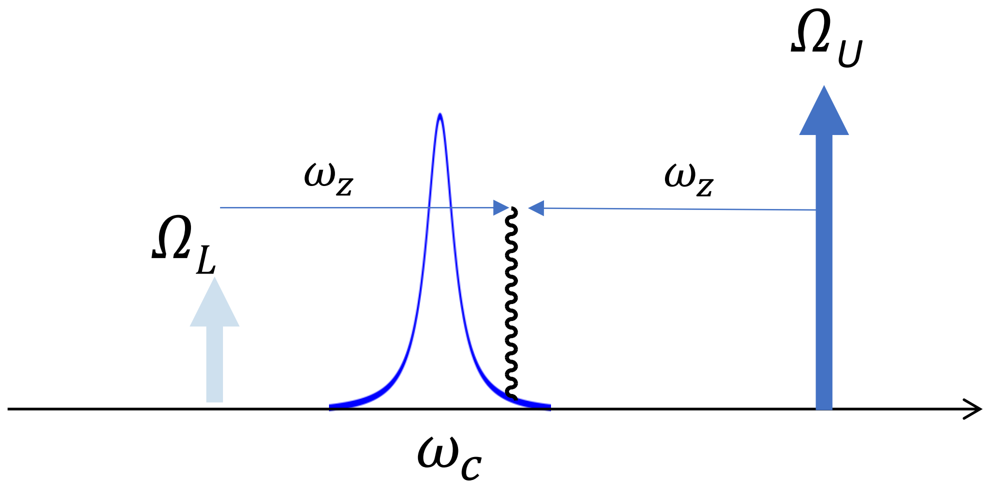


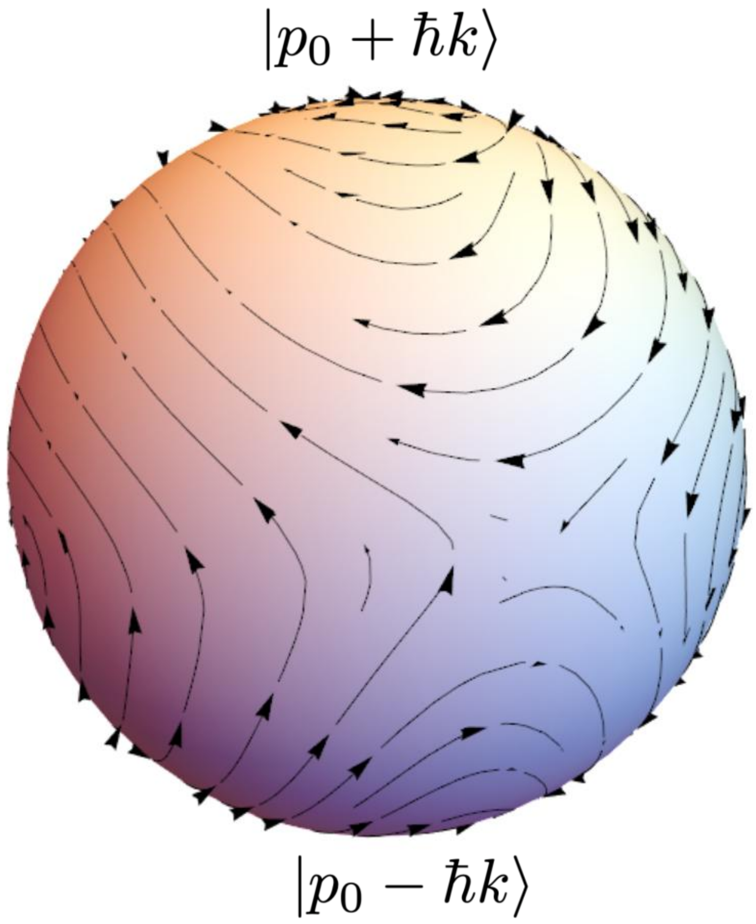


XYZ: Creation of Two-axis Counter Twisting

$$H = \chi(J_x^2 - J_z^2) + \chi J^2$$

at $\Omega_L^2 / \Omega_U^2 \sim 0.06$:





$$H_{ex} = \chi_e J_+ J_-$$

$$\propto (\Omega_U^2 g^2 + \Omega_L^2 g^2)$$

$$H_p = \chi_p (J_+^2 + J_-^2)$$

$$\propto \Omega_U \Omega_L g^2$$

Theory proposal with four applied tones:
Borregaard,…Schleier-Smith, Sørensen *NJP* 19 093021 (2017)

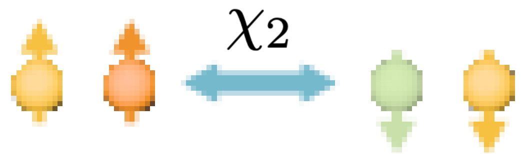
Luo, Zhang, Chu, Maruko, Rey, Thompson *Nature Phys.* (2025)

Beyond 2-Body Interactions: 3 & 4 Body Interactions

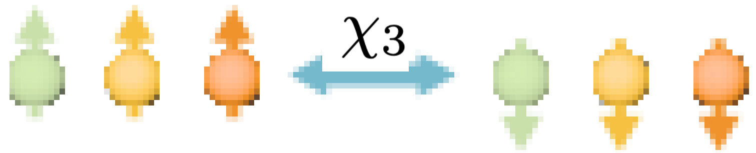
Luo, Zhang, Maruko, Chu, Rey, Thompson *Science* (2025)

Everything in cavity-QED ensemble systems has been two-body interactions:

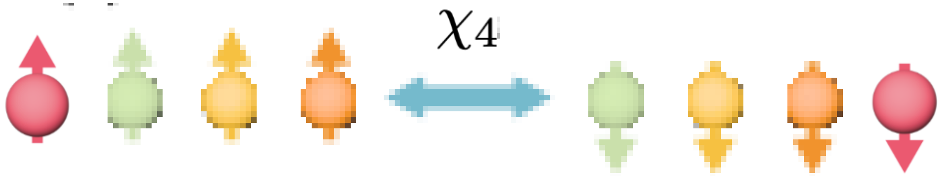
$$\boxed{N\chi_2} \quad \hat{H}_2 = \chi_2\left(\hat{J}_+^2 + \hat{J}_-^2\right) = \chi_2 \sum_{ij}^{N} \left(\hat{\sigma}_i^+\hat{\sigma}_j^+ + \hat{\sigma}_i^-\hat{\sigma}_j^-\right)$$



$$\boxed{N^2\chi_3} \quad \hat{H}_3 = \chi_3\left(\hat{J}_+^3 + \hat{J}_-^3\right) = \chi_3 \sum_{ijk}^{N} \left(\hat{\sigma}_i^+\hat{\sigma}_j^+\hat{\sigma}_k^+ + \hat{\sigma}_i^-\hat{\sigma}_j^-\hat{\sigma}_k^-\right)$$

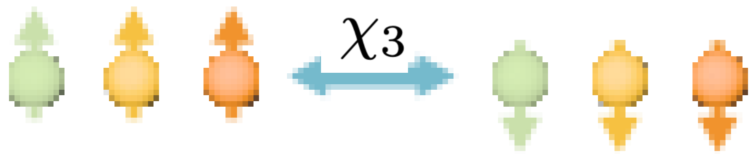


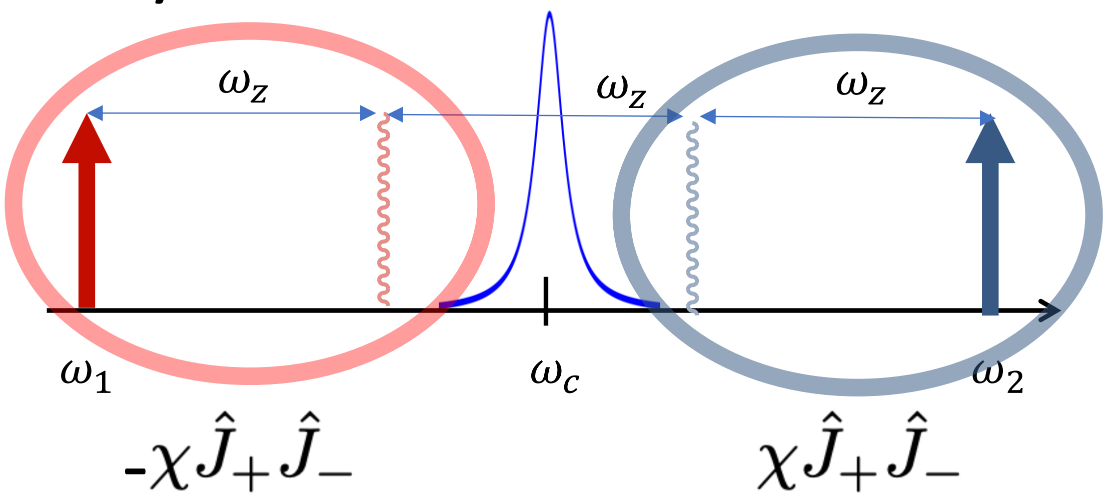
$$\boxed{N^3\chi_4} \quad \hat{H}_4 = \chi_4\left(\hat{J}_+^4 + \hat{J}_-^4\right) = \chi_4 \sum_{ijkl}^{N} \left(\hat{\sigma}_i^+\hat{\sigma}_j^+\hat{\sigma}_k^+\hat{\sigma}_l^+ + \hat{\sigma}_i^-\hat{\sigma}_j^-\hat{\sigma}_k^-\hat{\sigma}_l^-\right)$$

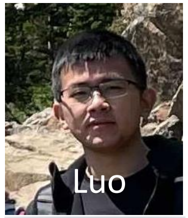


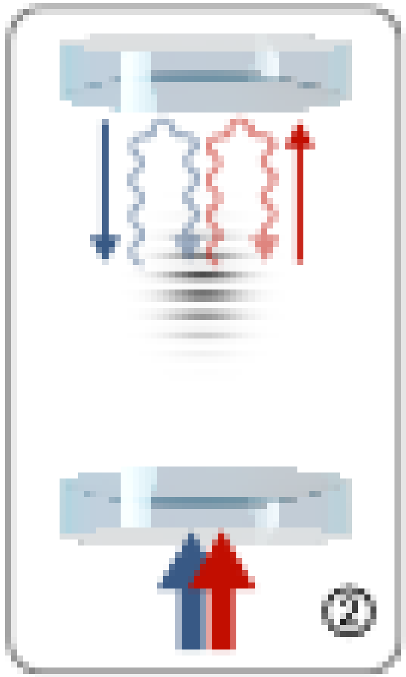
Generating 3-Body Interactions

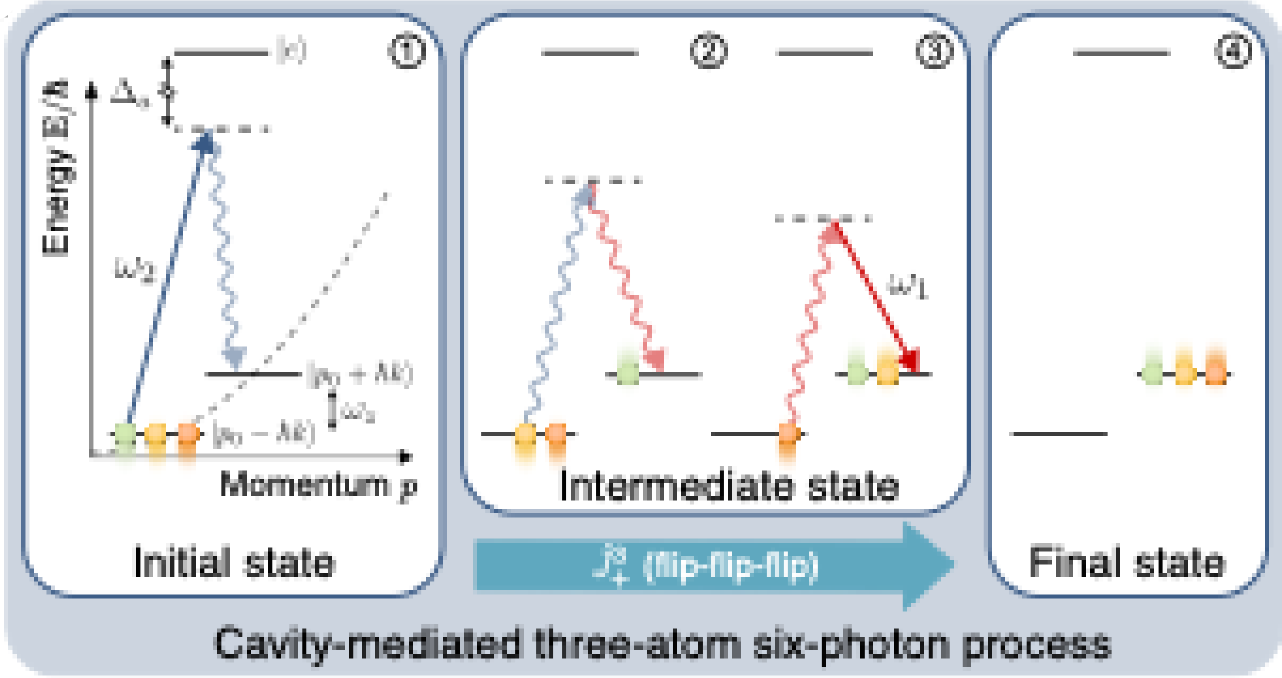
$$\hat{H}_3 = \chi_3 \left(\hat{J}_+^3 + \hat{J}_-^3\right)$$





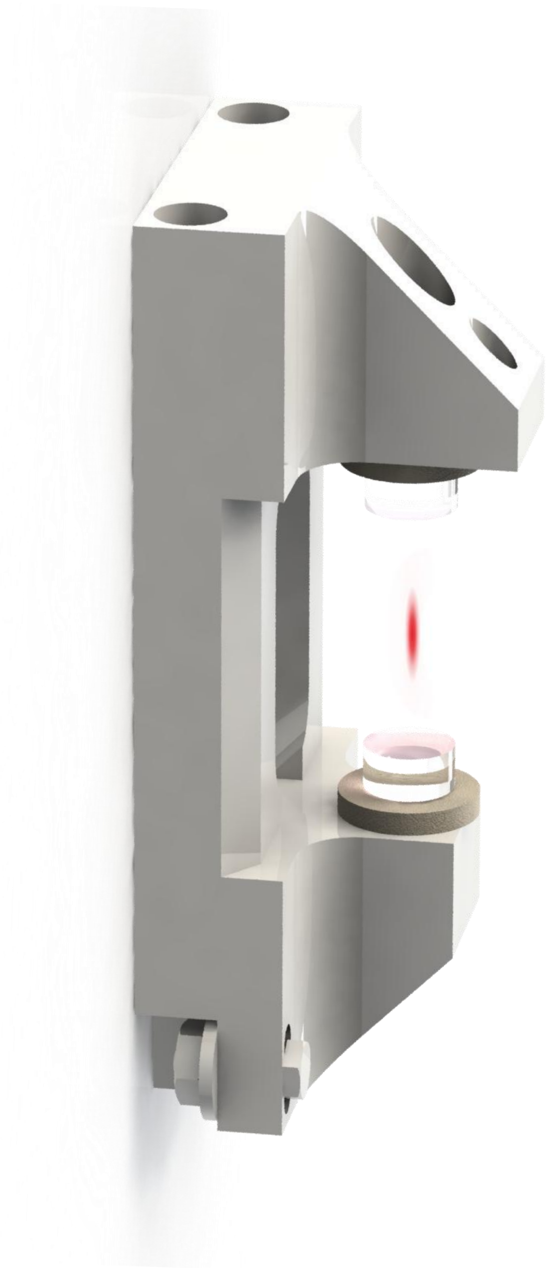






Luo, Zhang, Maruko, Bohr, Chu, Rey, Thompson *Science* 390 925 (2025)

Topics for Today



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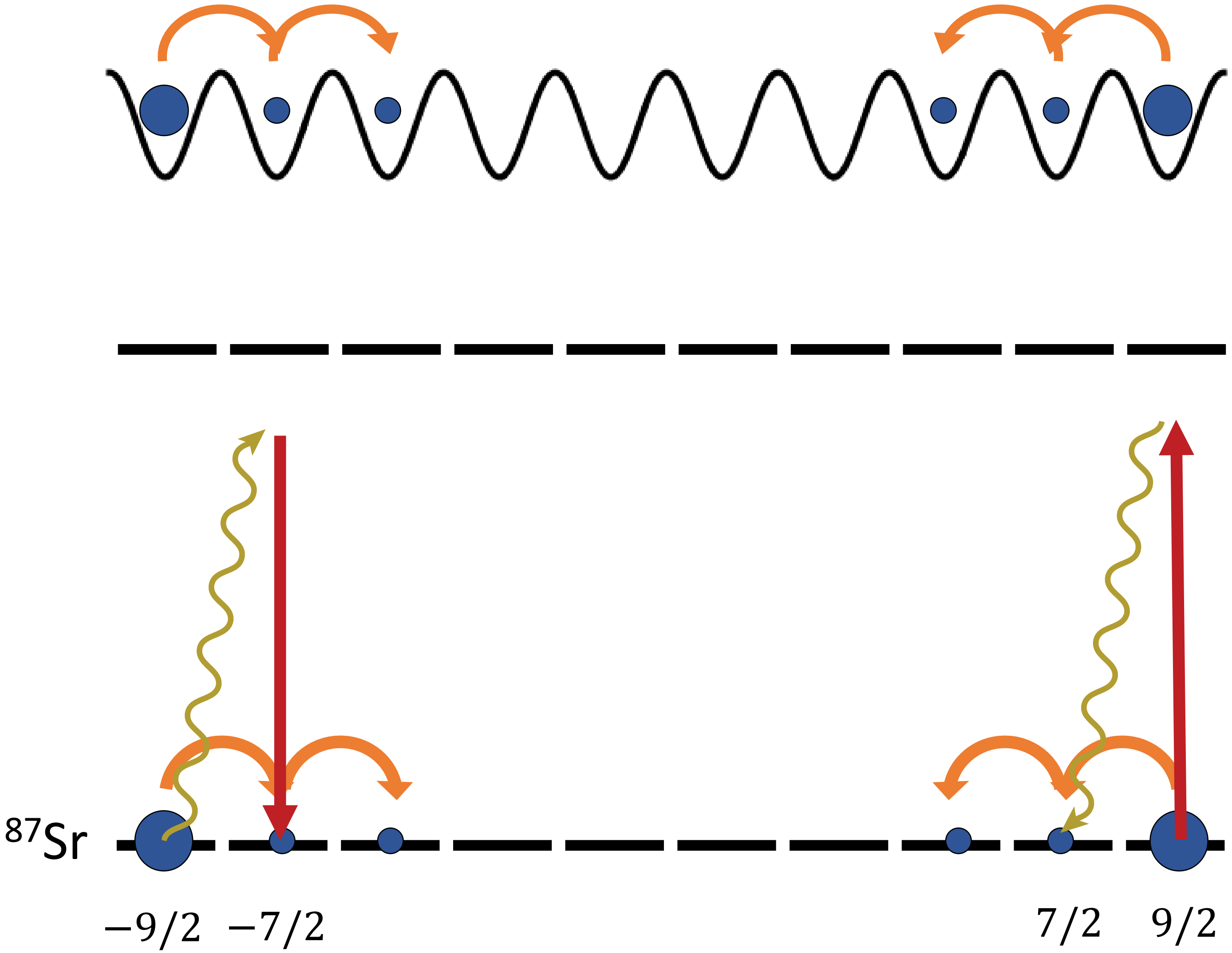
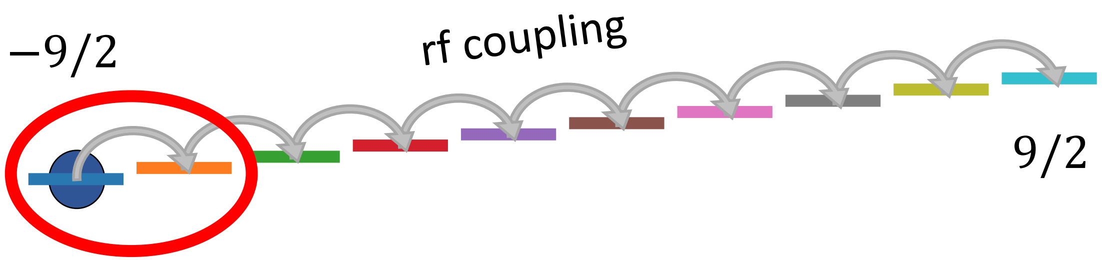
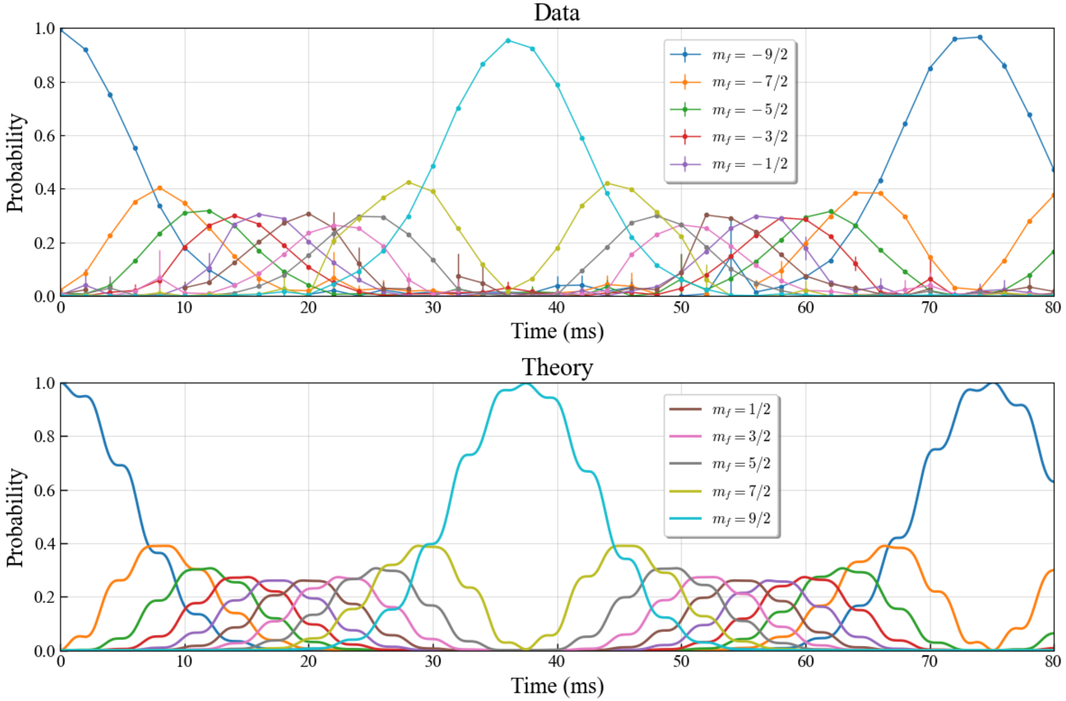
Correlated Hopping in Large Synthetic Dimension



Resolve All 10 Ground Nuclear States



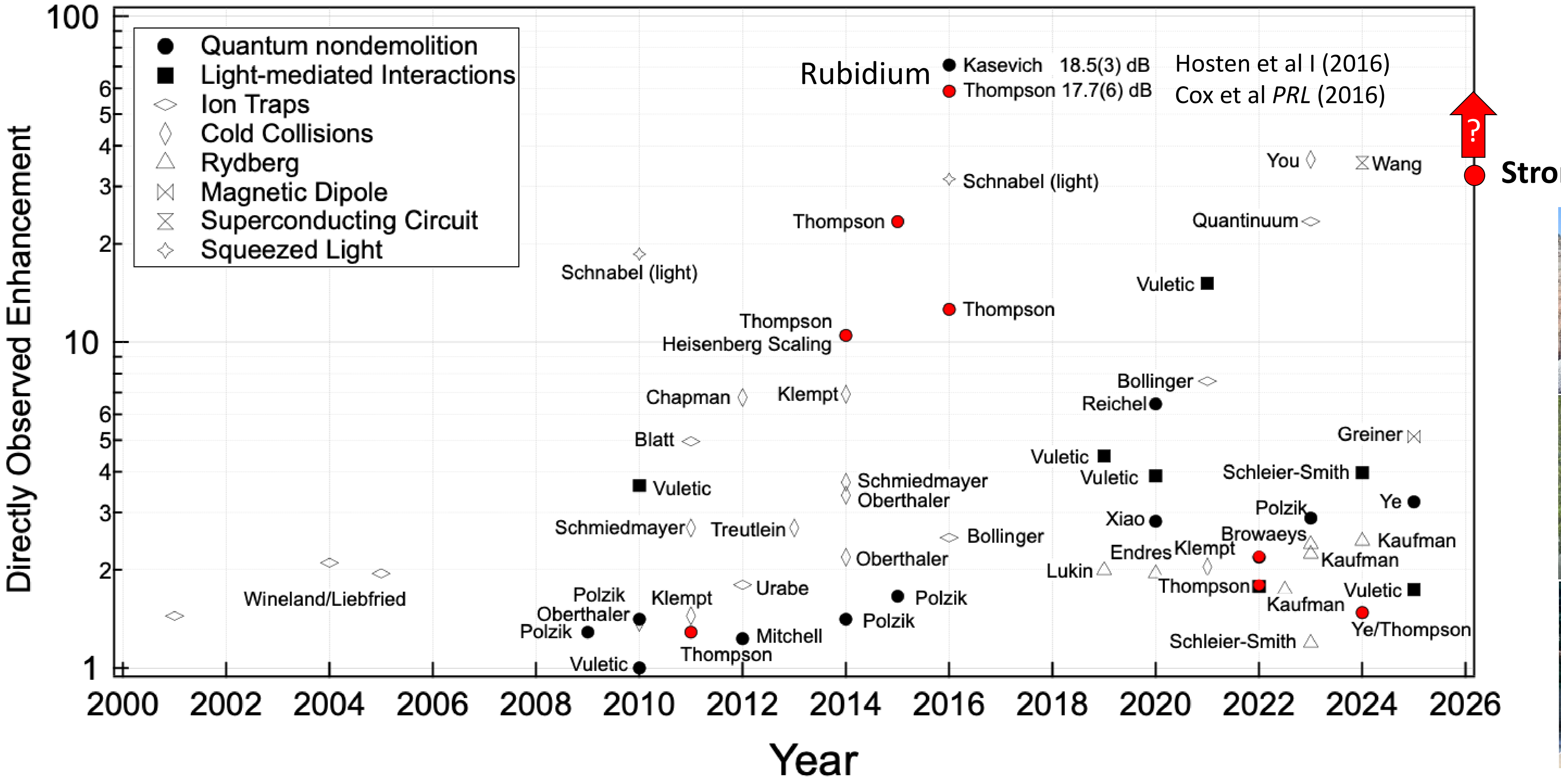
Imprecision 20 dB below Projection Noise Level



Chu, Orioli, Barberena, Thompson, Rey, *PRR* 5 (2), L022034 (2023)

Spin 1: Davis…**Schleier-Smith**, *PRL* 122, 010405 (2019), Finger… **Esslinger** *PRL* 132, 093402 (2024)

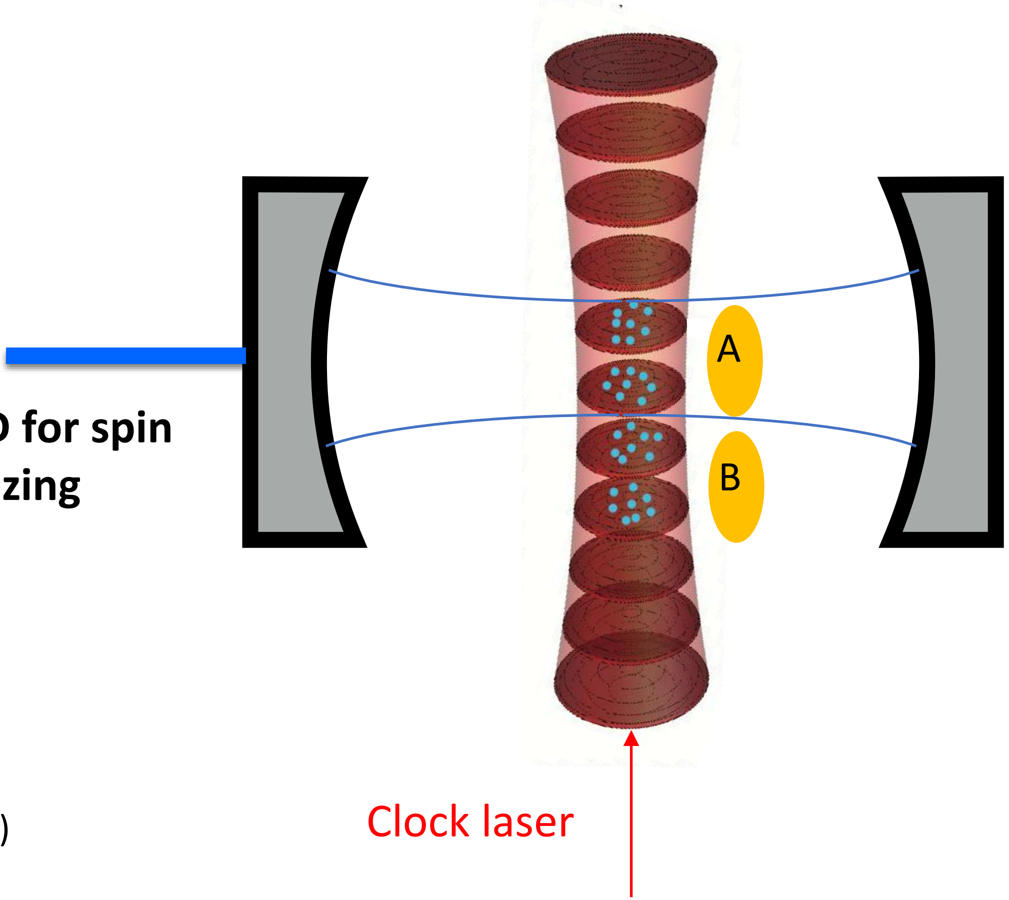
Entanglement Enhancements Beyond SQL



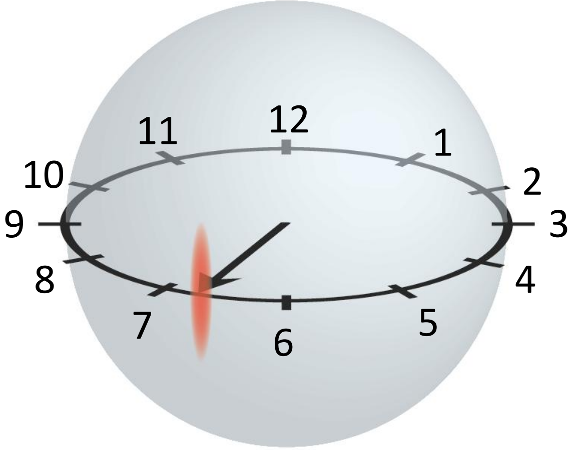
QND Spin squeezing in a state-of-the-art Sr optical clock at 10^{-17}

Norcia, Thompson *PRA* (2016)
Robinson, Tso, Miklos, Thompson, Ye, *Nature Physics* (2024)

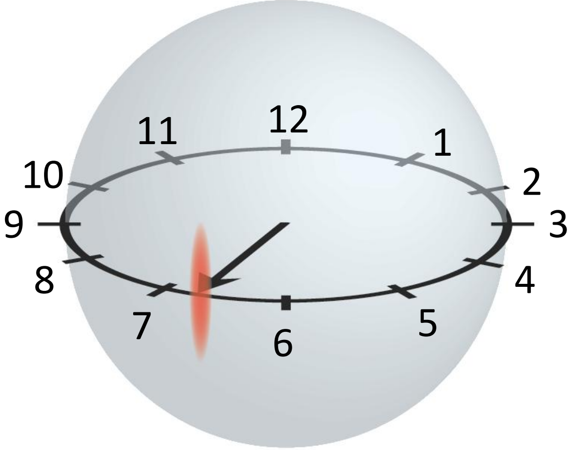
Cavity QED for spin squeezing



Clock A



Clock B

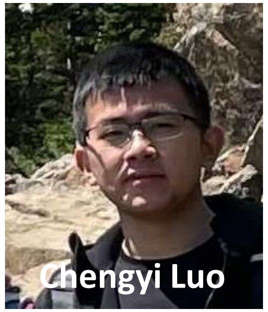


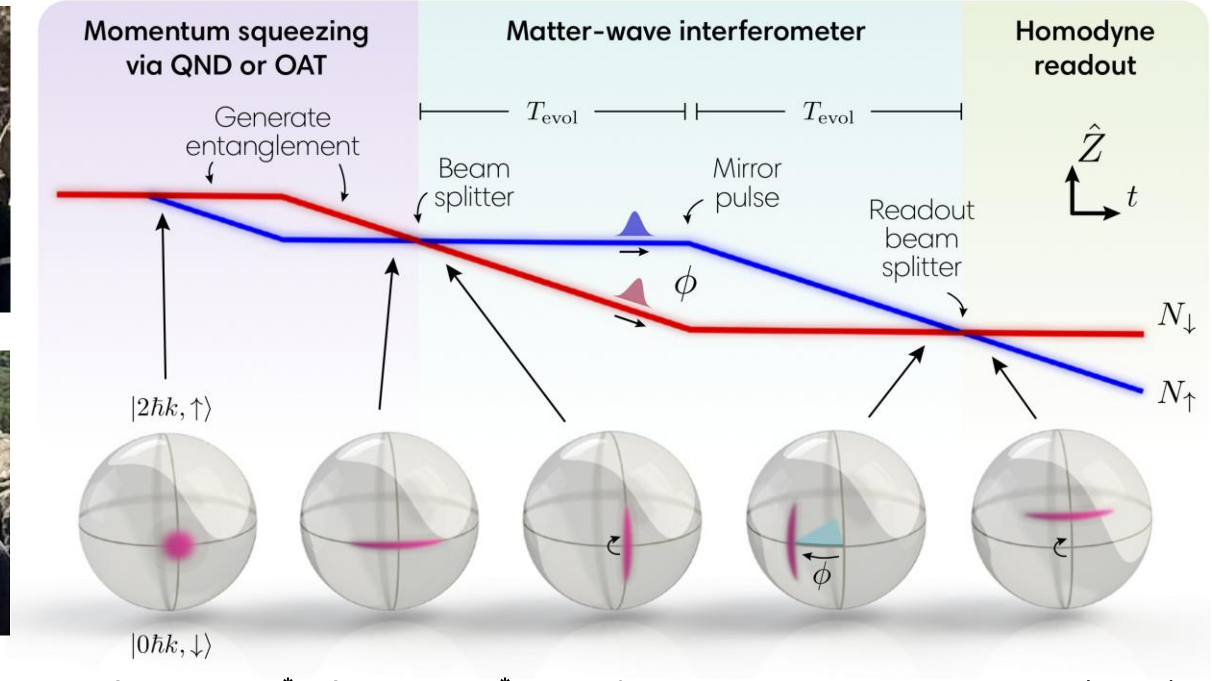
Poster Tuesday!
Yang, Miklos, Tso, Kraus, Hur, Ye *PRL* (2025)

Lieb-Mattis states for robust entangled differential phase sensing
Kaubruegger, Padilla, Shankar, …, Gorshkov, Molmer, Thompson, Rey, *PRX* 16, 021052 (2026)

Resource for Entanglement-Enhanced Matterwave Interferometer

Rubidium Matterwave Interferometer

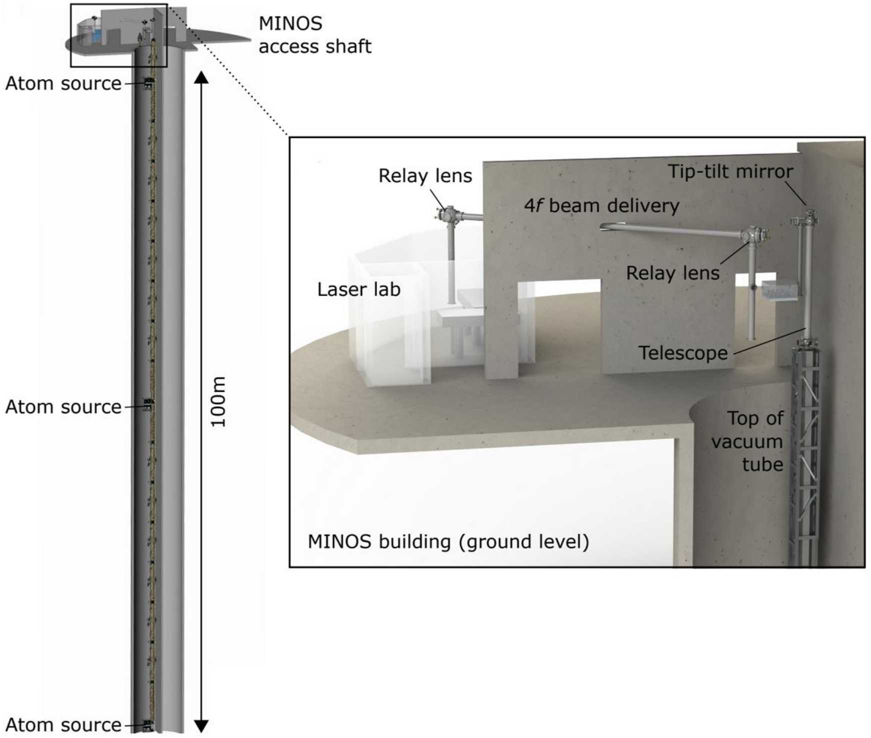




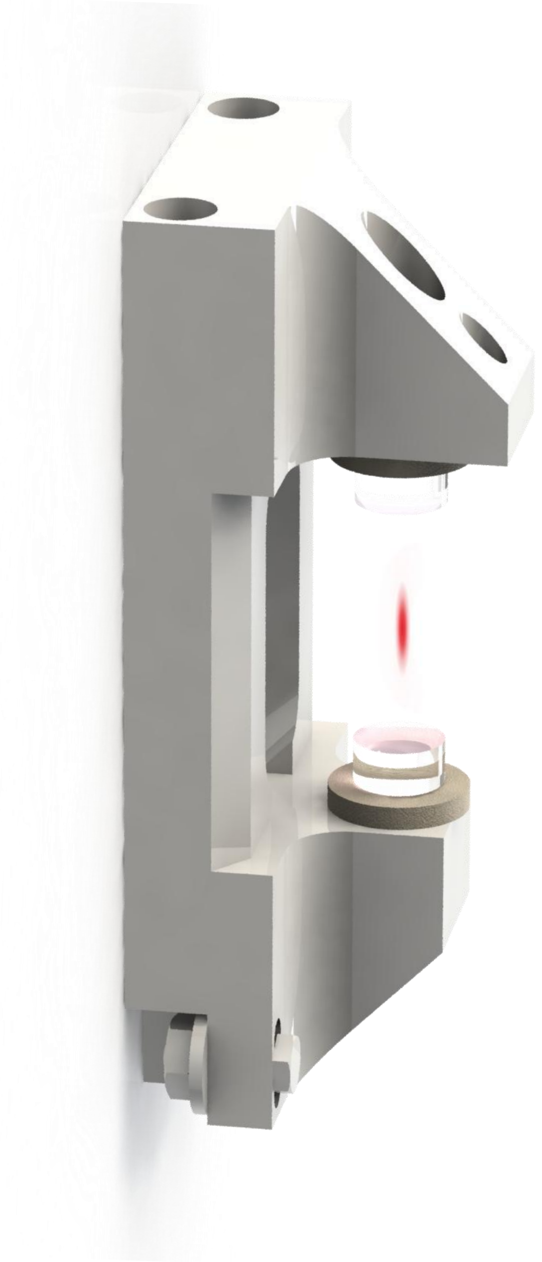
Graham Greve*, Chengyi Luo*, Wu, Thompson *Nature* **610** 472-477 (2022)
Cassens, Meyer-Hoppe, Rasel, Klempt PRX **5** 011029 (2025)

Next Generation: Strontium

MAGIS-100, ZAIGA, AION



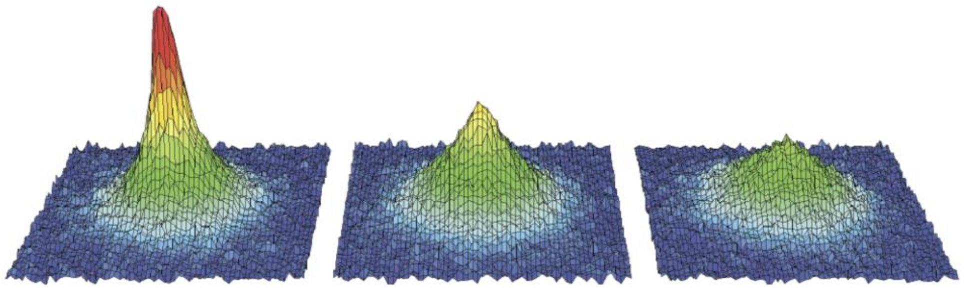
Topics for Today



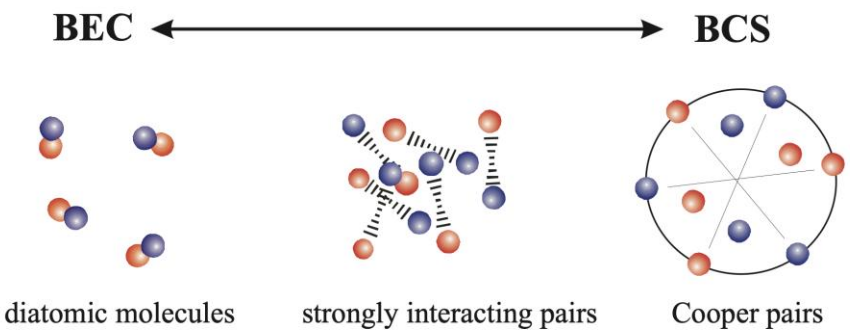
- From Superradiance to Exchange Interactions
- Expanded Palette of Interactions: XYZ, 3- & 4-body
- Quantum Sensing: entanglement for matterwave interferometers and clocks
- **Quantum Simulation: dynamical phases in BCS-BEC crossover**

Superconductivity and Superfluids: nano to Mega Kelvin

~nK

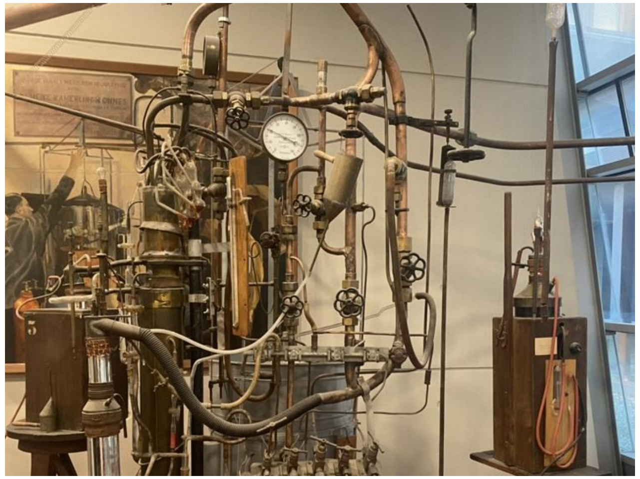


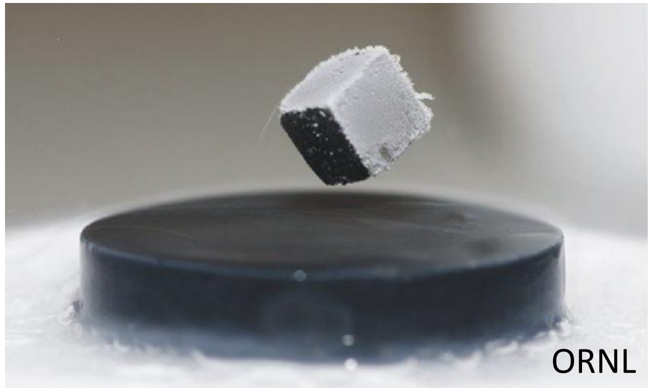
Regal, Greiner, Jin PRL 92 040403 (2004)



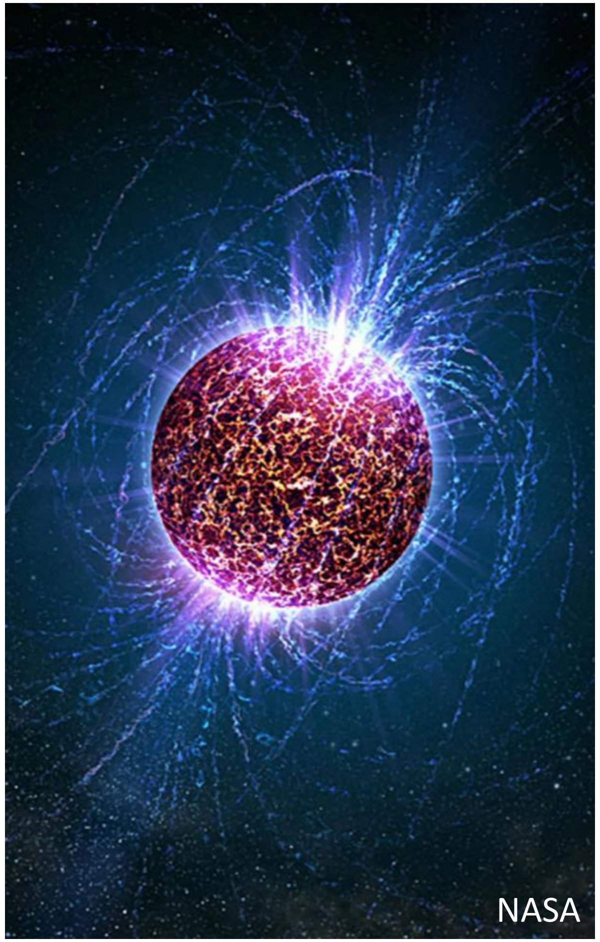
~K

Kamerlingh Onnes
Lorentz Center, Leiden





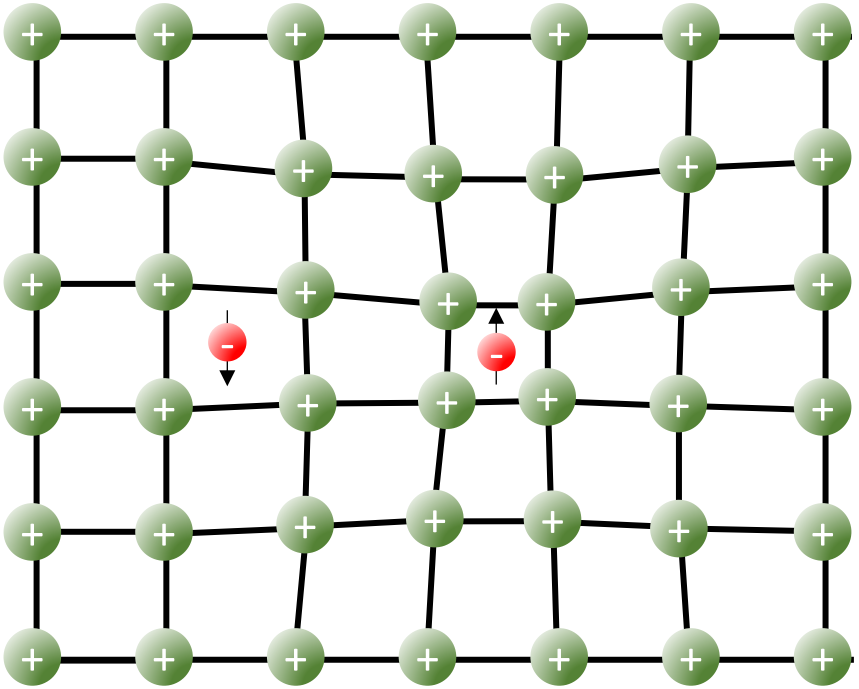
~MK



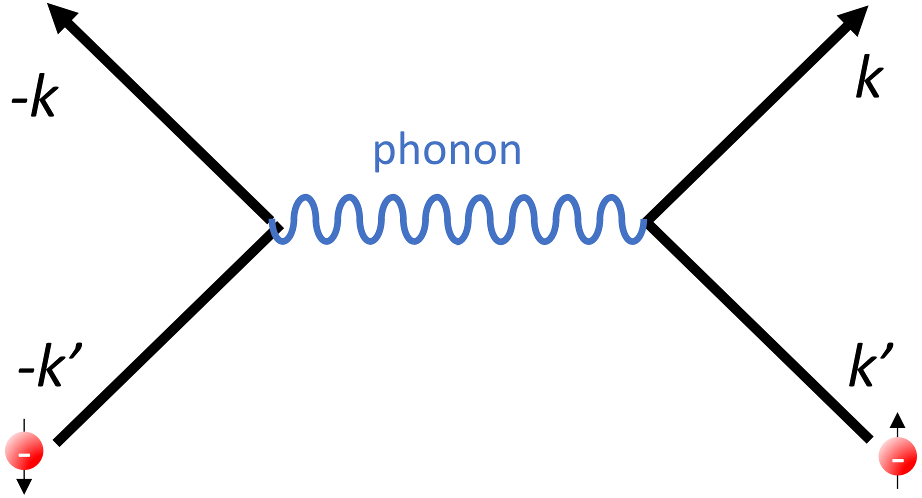
BCS: Electrons Attract Each Other

Bardeen, Cooper, Schrieffer, Phys. Rev. **106** (1) 162–164 (1957)

Electron-induced lattice distortions mediate interactions



Phonons mediate interactions



Effective interaction after eliminating phonon modes

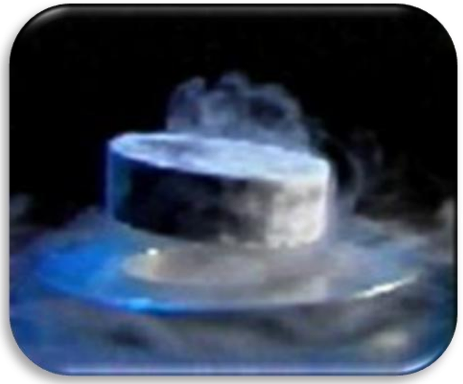
$$-\chi\, \hat{c}^\dagger_{k,\uparrow}\hat{c}^\dagger_{-k,\downarrow}\hat{c}_{k',\uparrow}\hat{c}_{-k',\downarrow}$$

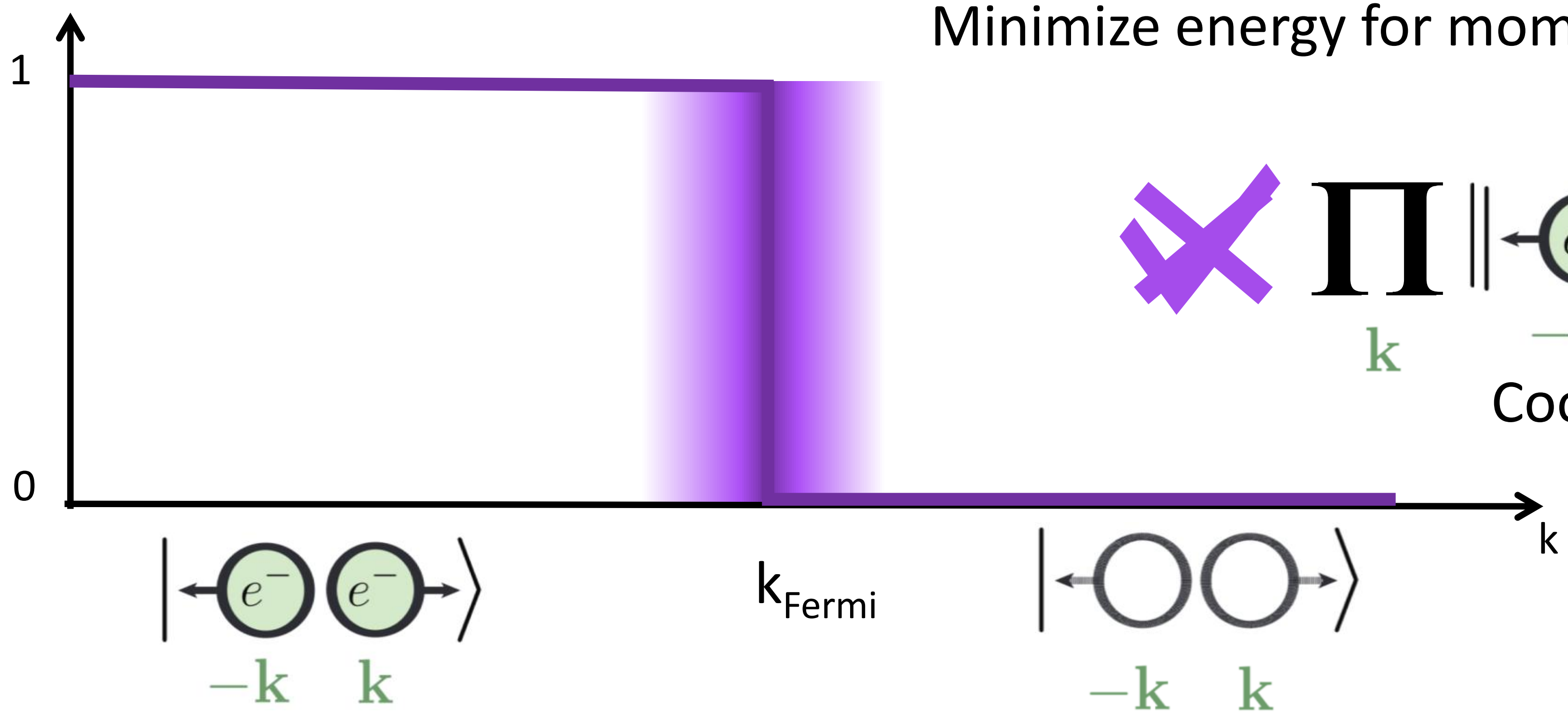
Model Bardeen-Cooper-Schrieffer Hamiltonian

$$\hat{H} = \sum_{k,\sigma} \epsilon_k \hat{c}^\dagger_{k,\sigma} \hat{c}_{k,\sigma} \; - \chi \sum_{k,k'} \hat{c}^\dagger_{k,\uparrow} \hat{c}^\dagger_{-k,\downarrow} \hat{c}_{k',\uparrow} \hat{c}_{-k',\downarrow}$$

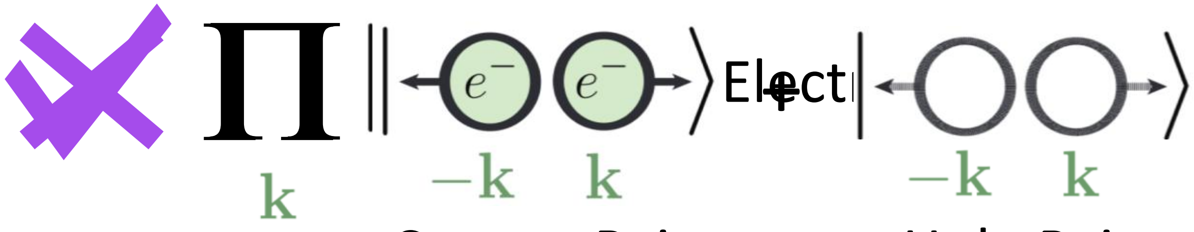
Single-Particle Dispersion

Attractive Interactions via lattice phonons





Minimize energy for momentum states *k* near Fermi-level



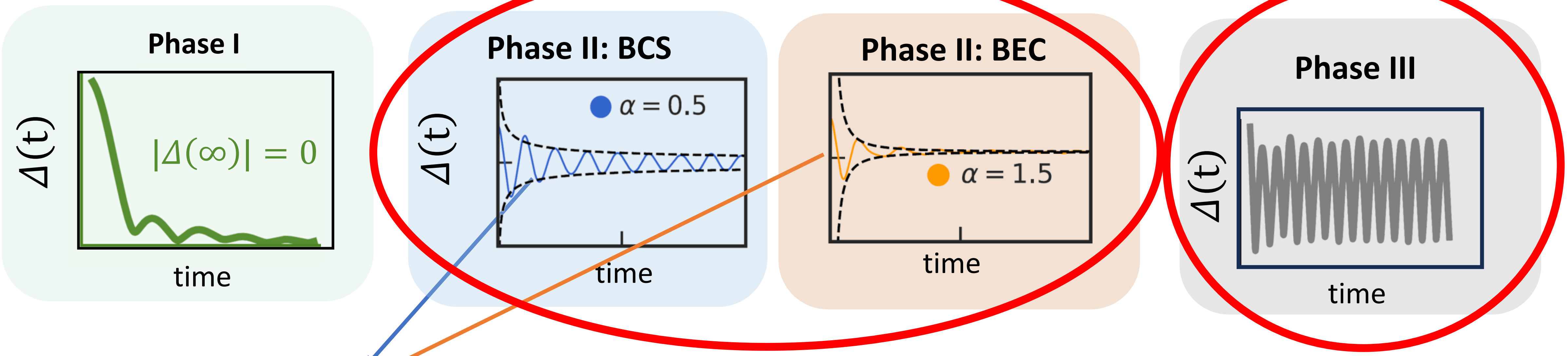
Dynamical Phases of s-wave BCS Model

$$\hat{H} = \sum_{k,\sigma} \epsilon_k \hat{c}^\dagger_{k,\sigma}\hat{c}_{k,\sigma} - \chi \sum_{k,k'} \hat{c}^\dagger_{k,\uparrow}\hat{c}^\dagger_{-k,\downarrow}\hat{c}_{k',\uparrow}\hat{c}_{-k',\downarrow}$$

Quench interaction strength of χ → Pairing amplitude Δ behavior

Predictions: Foster, Gurarie, Yuzbashyan,Levitov…

Three Dynamical Phases



Higgs Oscillations

$$|\Delta(t)| = \Delta_\infty + At^{-\alpha}\cos(\omega_{\mathrm{H}} t + \phi),$$

"Time crystal"

$$\Delta(t \to \infty) = \Delta_\infty e^{-2it\mu_\infty}$$

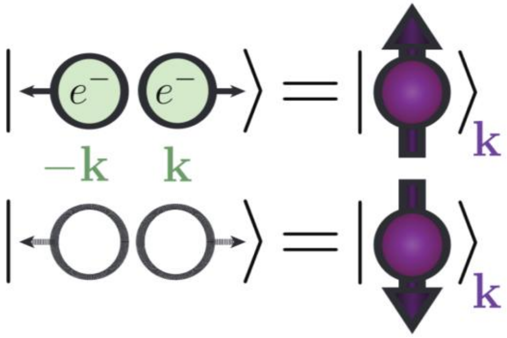
V. Gurarie, Phys. Rev. Lett. 103, 075301 (2009)

Experiment Status in 2024

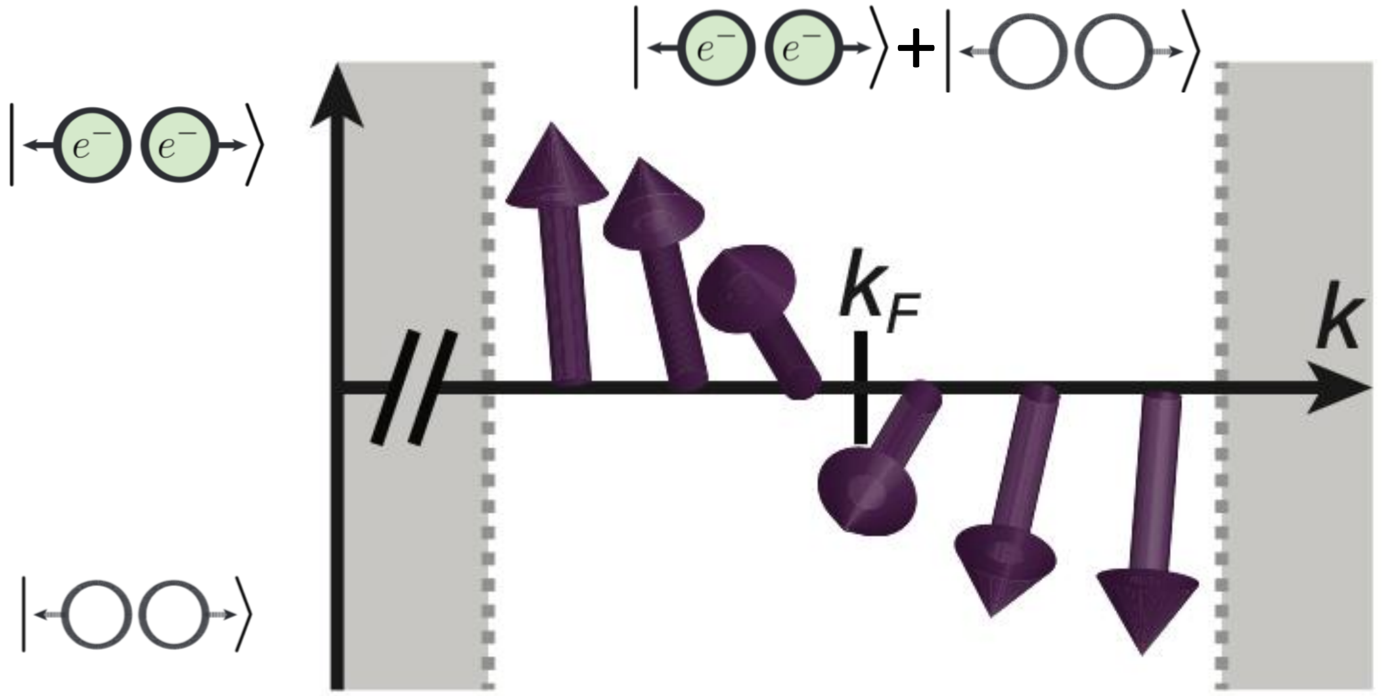
Signatures of dynamical phases	Experimental Status	References
Dynamical phase transition between distinct nonequilibrium regimes	✓ Observed in a quantum-simulator platform	Smale…Rey, Thywissen, *Sci. Adv.* **5**, eaax1568 (2019)
Higgs oscillations in superconductors	✓ Observed	Matsunaga et al., *PRL* **111**, 057002 (2013)
Higgs oscillations in ultracold Fermi gases	✓ Observed	Behrle et al., *Nat. Phys.* **14**, 781 (2018); Dyke…Vale *PRL* **132**, 223402 (2024)
Higgs-like modes in unconventional superconductors	✓ Observed	Méasson et al., *PRB* **89**, 060503 (2014); Matsunaga et al., *PRL* **113**, 247002 (2014)
Finite pairing gap after excitation	✓ Observed	Matsunaga et al., *PRL* **109**, 187002 (2012)
Universal $t^{-1/2}$ Phase-II decay	✗ Not established	—
Phase-III persistent oscillations	✗ Not observed	—

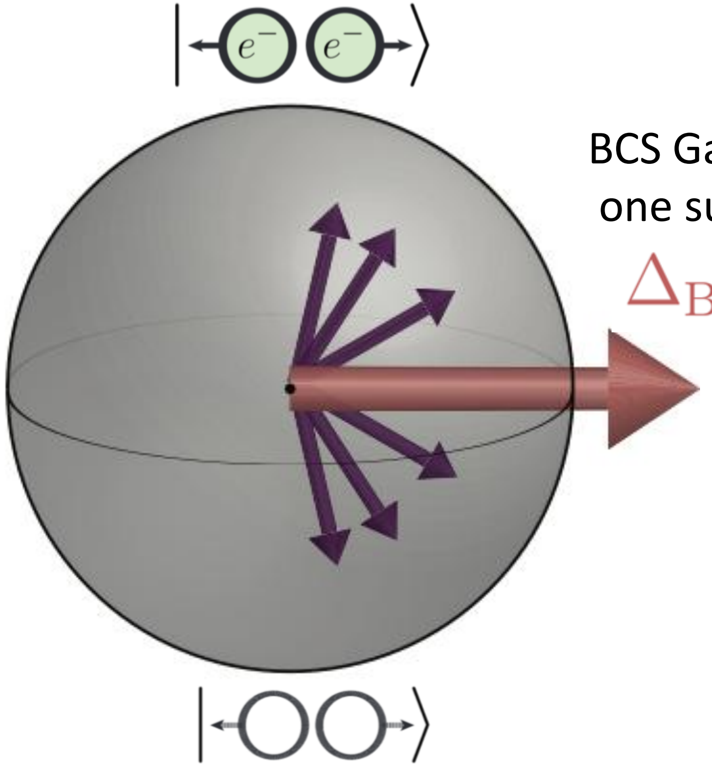
BCS Hamiltonian: Anderson Pseudo-Spin Mapping

P.W. Anderson *Phys. Rev.* **112** 6 (1958)



$$\hat{H} = -\chi \sum_{k,k'} \underbrace{\hat{c}^{\dagger}_{k,\uparrow}\hat{c}^{\dagger}_{-k,\downarrow}}_{\hat{S}^{+}_{k}} \underbrace{\hat{c}_{k',\uparrow}\hat{c}_{-k',\downarrow}}_{\hat{S}^{-}_{k'}} + \sum_{k,\sigma} \epsilon_k \underbrace{\hat{c}^{\dagger}_{k,\sigma}\hat{c}_{k,\sigma}}_{\hat{S}^{z}_{k}}$$



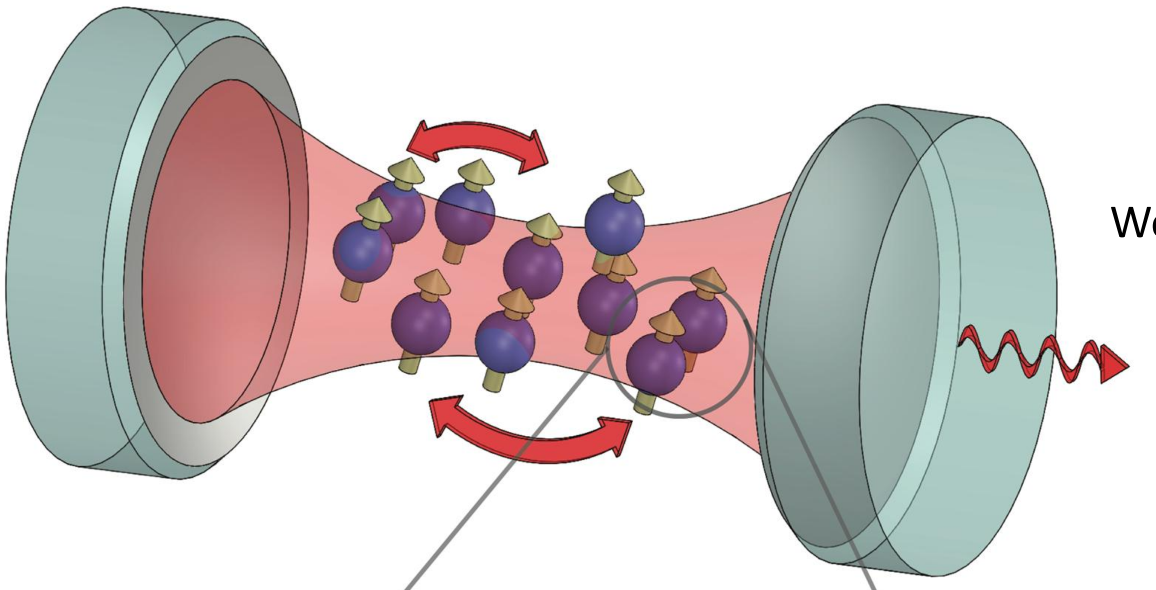


BCS Gap: energy to break one superposition state

$$\Delta_{\mathrm{BCS}} = \chi \langle \hat{S}^{-} \rangle$$

Lewis-Swan…Thompson, Rey *PRL* **126** 173601 (2021)
Young, Chu…Rey, Thompson *Science* (2024)

Measuring the BCS gap/pairing amplitude



Weak light field leaking from cavity

$$\langle \hat{a}(t) \rangle \propto \chi \langle \hat{S}_- \rangle \propto \Delta_{BCS}(t)$$

VOLUME 90, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 13 JUNE 2003

Measurement of Positive and Negative Scattering Lengths in a Fermi Gas of Atoms

C. A. Regal and D. S. Jin*

Radio-Frequency Spectroscopy of Ultracold Fermions

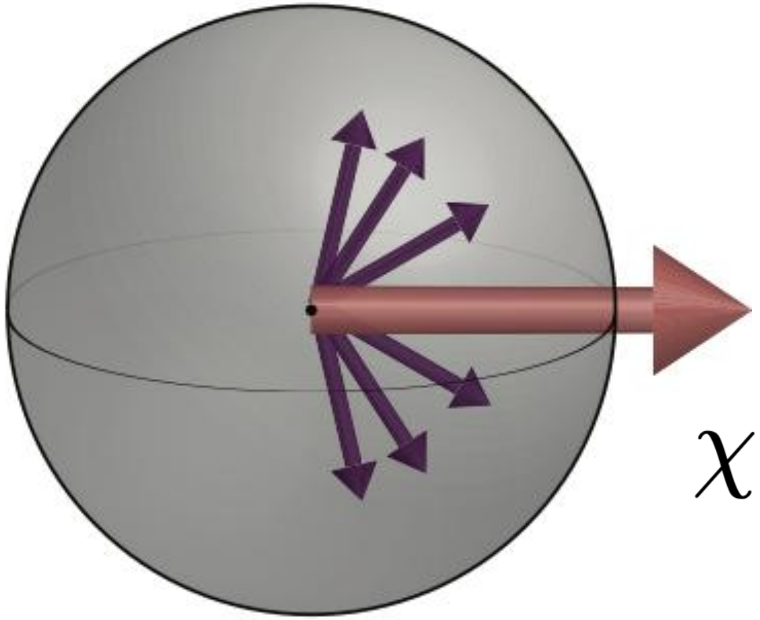
S. Gupta,[1*] Z. Hadzibabic,[1] M. W. Zwierlein,[1] C. A. Stan,[1] K. Dieckmann,[1] C. H. Schunck,[1] E. G. M. van Kempen,[2] B. J. Verhaar,[2] W. Ketterle[1]

SCIENCE VOL 300 13 JUNE 2003

Observation of the Pairing Gap in a Strongly Interacting Fermi Gas

C. Chin,[1] M. Bartenstein,[1] A. Altmeyer,[1] S. Riedl,[1] S. Jochim,[1] J. Hecker Denschlag,[1] R. Grimm[1,2*]

SCIENCE VOL 305 20 AUGUST 2004



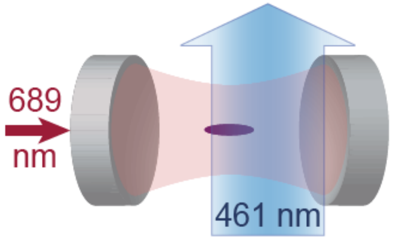
$$\chi \langle \hat{S}_- \rangle$$

Observation of Quenches 1 to 2 & 2 to 3

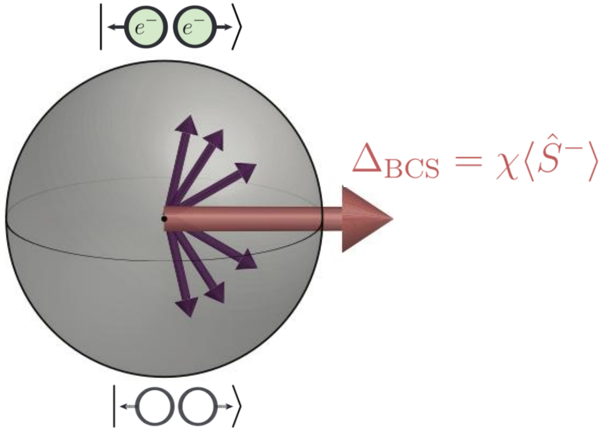
$$\hat{H} = -\chi \hat{S}^+ \hat{S}^- + \sum_k E(k)\, \hat{S}^z_k$$

Change χN by varying N

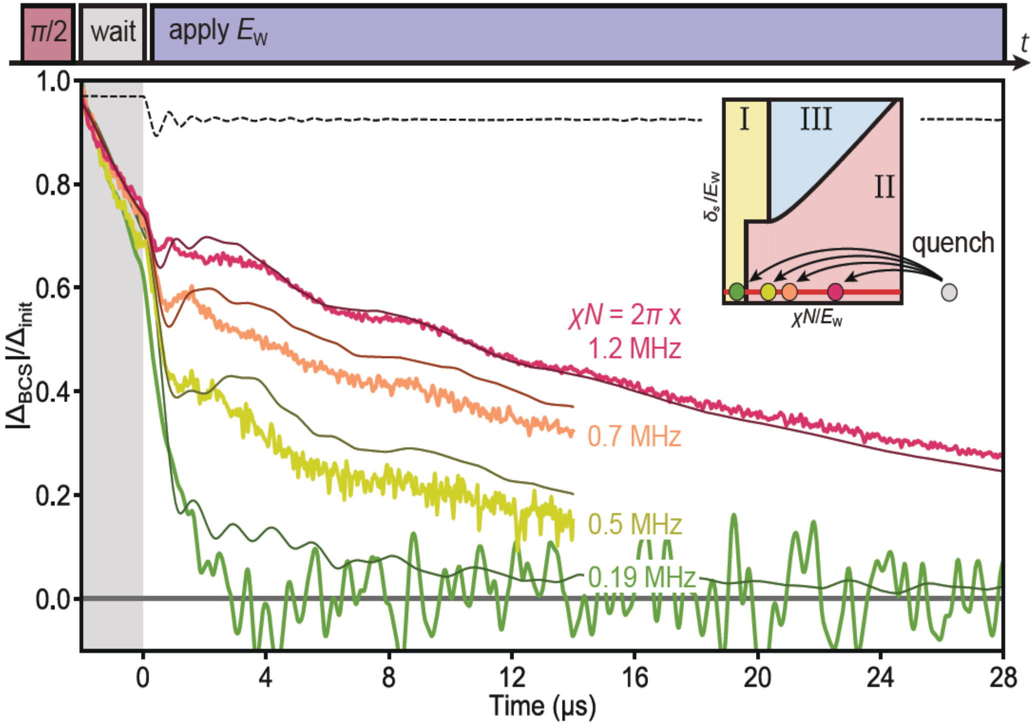
Programmable inhomogeneous light shifts



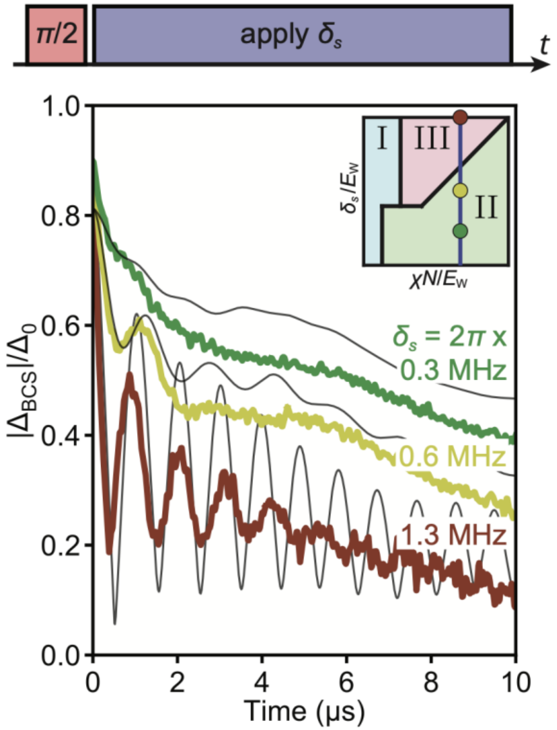
Heterodyne detect light from cavity to measure Δ(t)



Phase I to Phase II

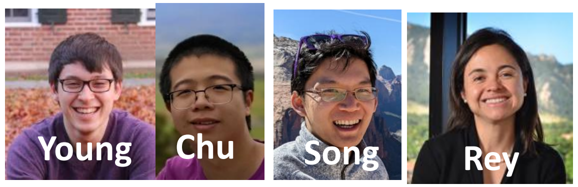


Phase II to Phase III

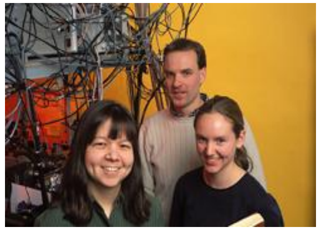


Deutsch...Reichel, **Rosenbusch** , Phys. Rev. Lett. **105**, 020401 (2010)
Spin self-rephasing efffect
Smale...Rey, **Thywissen**, *Sci. Adv.* 5: eaax1568 (2019)
Davis...**Schleier-Smith** *PRL*. 125, 060402 (2020)
Luo, Zhang...Holland, Rey, Thompson *Science* 384 551 (2024)
Niu,... Rey, Thompson, *PRL* (2025)

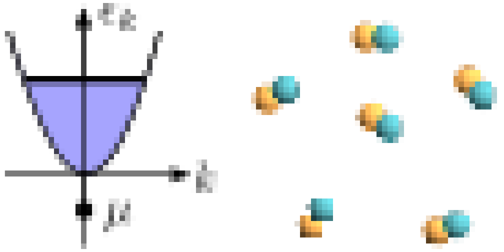
Young,,...Rey, Thompson, *Nature* 625, 679 (2024)
Young,...Rey, Thompson *PRL* (2025)

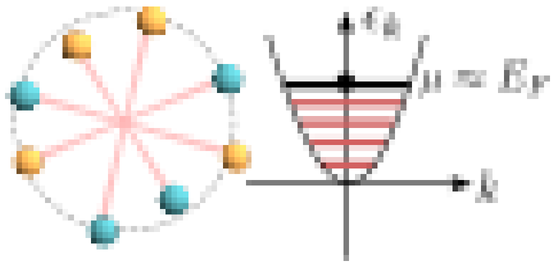


BEC-BCS Crossover in Anderson Spin-Textures

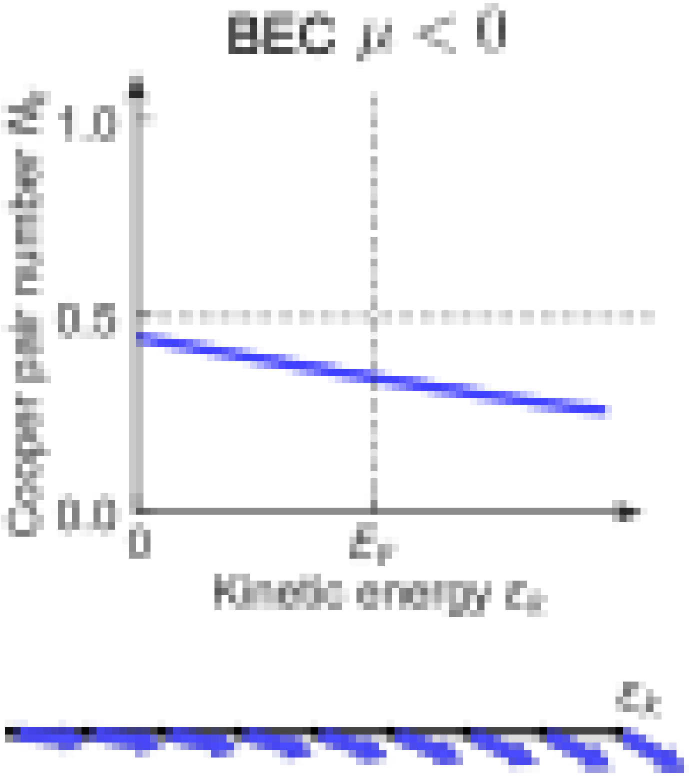


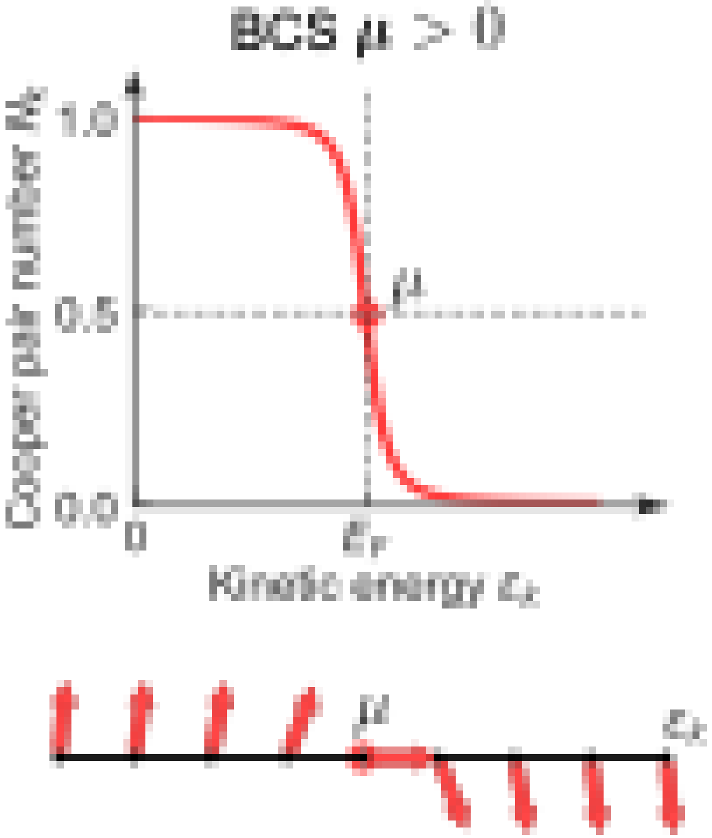
Regal, Greiner, Jin
Phys. Today (2004)

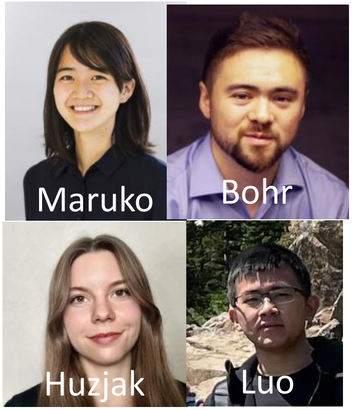




Increasing interaction strength via Feshbach resonance

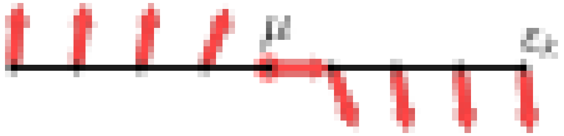






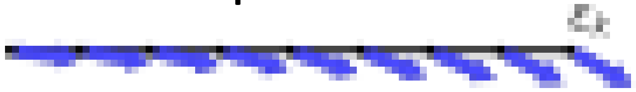
Damping of Higgs Oscillations from BCS to BEC

BCS Spin Texture



$$\theta_0 = 0$$

BEC Spin Texture

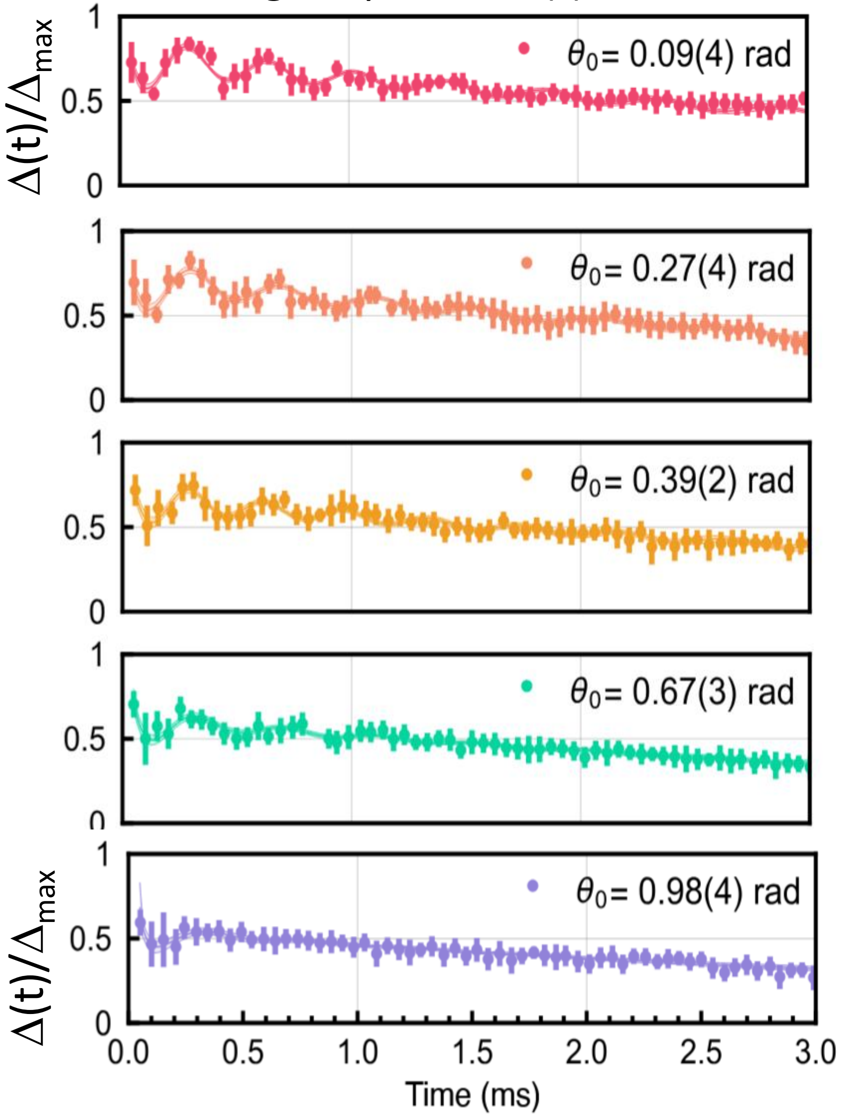


$$\theta_0 > 0$$

Poster Thursday!

manuscript
in preparation

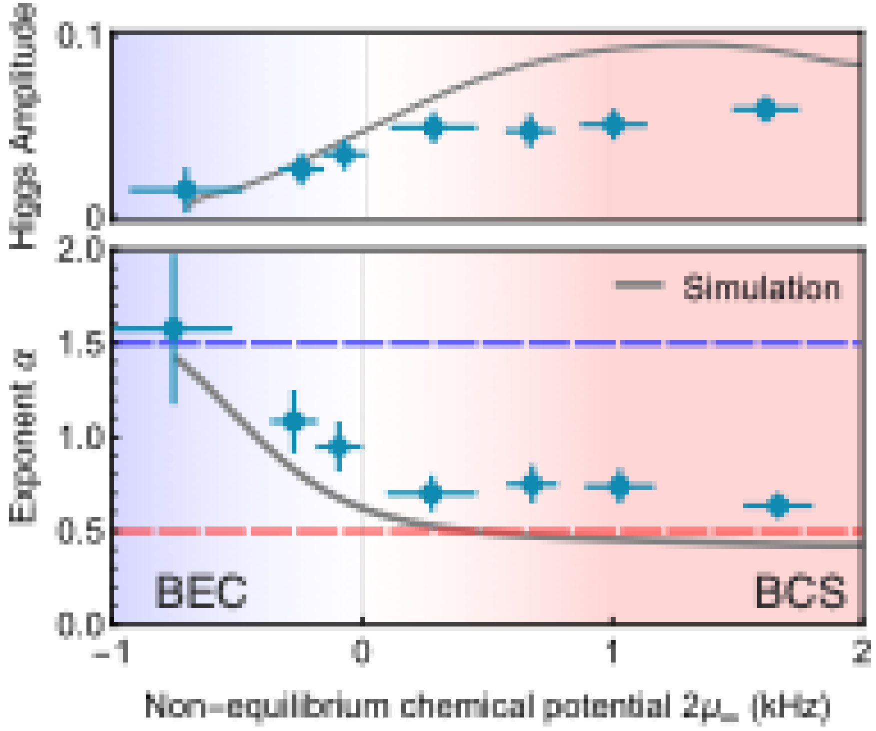
Paring Amplitude Δ(t) vs time



Future: Dynamics of topological states p + ip, d + id

Chu…Thompson, Rey, arXiv:2512.17889

$$|\Delta(t)| = \Delta_\infty + At^{-\alpha}\cos(\omega_{\mathrm{H}}t + \phi),$$

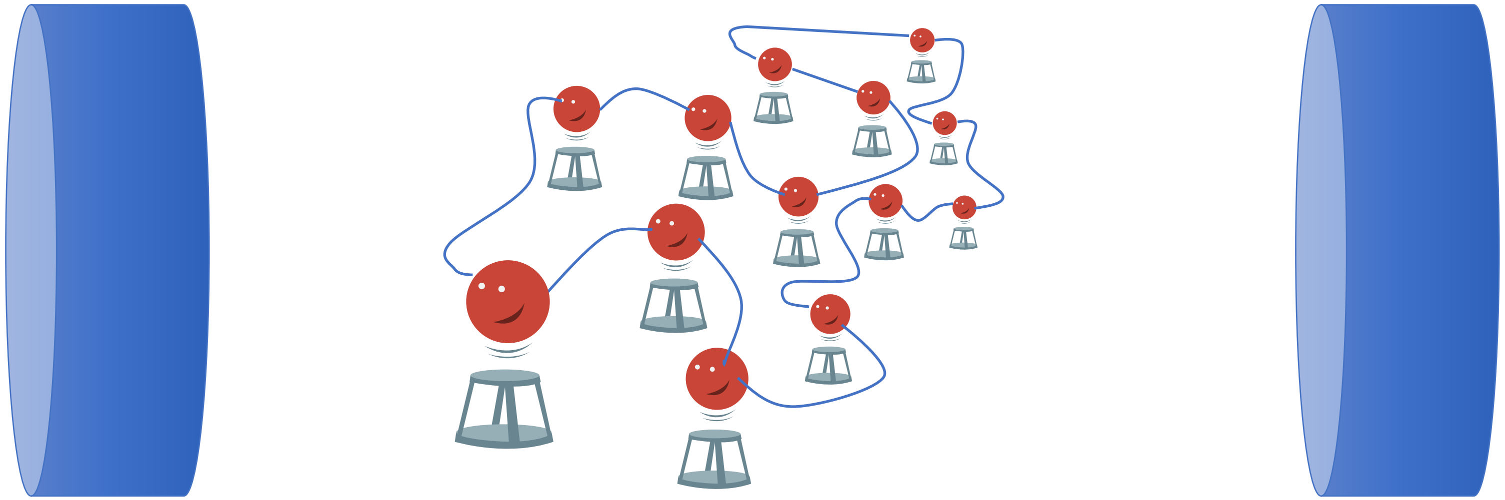


BCS: α_{exp} = 0.65(8)

α_{thy} = 0.50

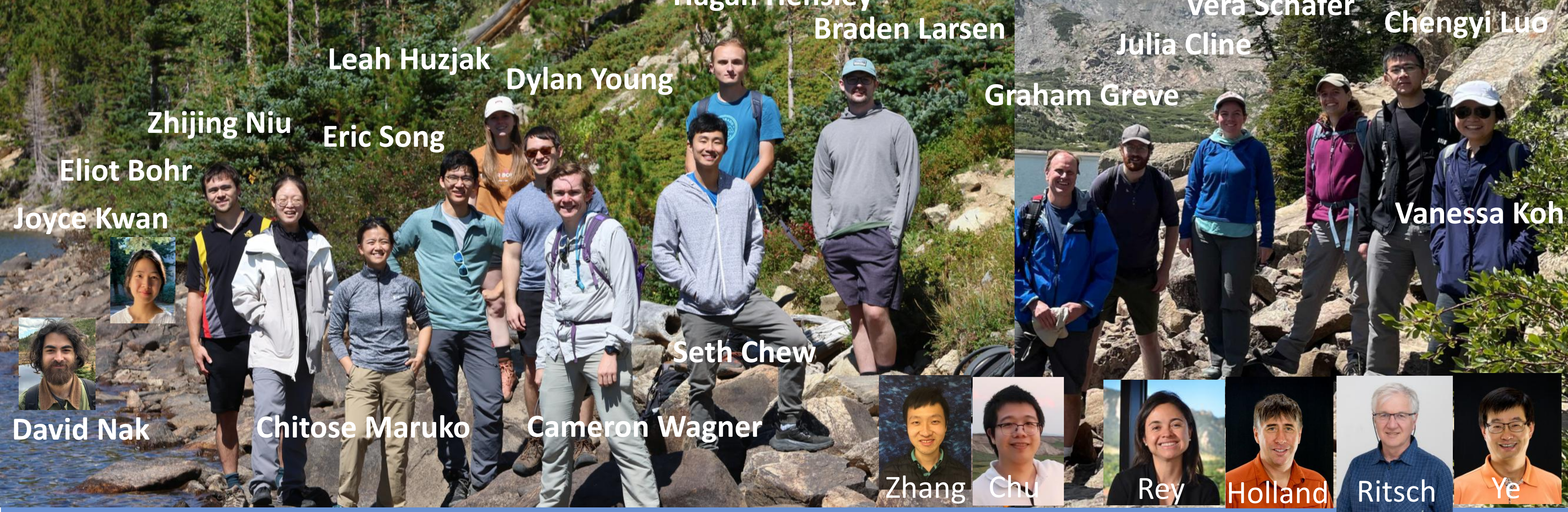
Gurarie *PRL* 103, 075301 (2009)

Correlations and Entanglement Facilitated by Optical Cavity



Explore fundamental science of quantum sensing and simulation

Thanks to the Team!



<u>Former Group Members:</u>

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John Kitching

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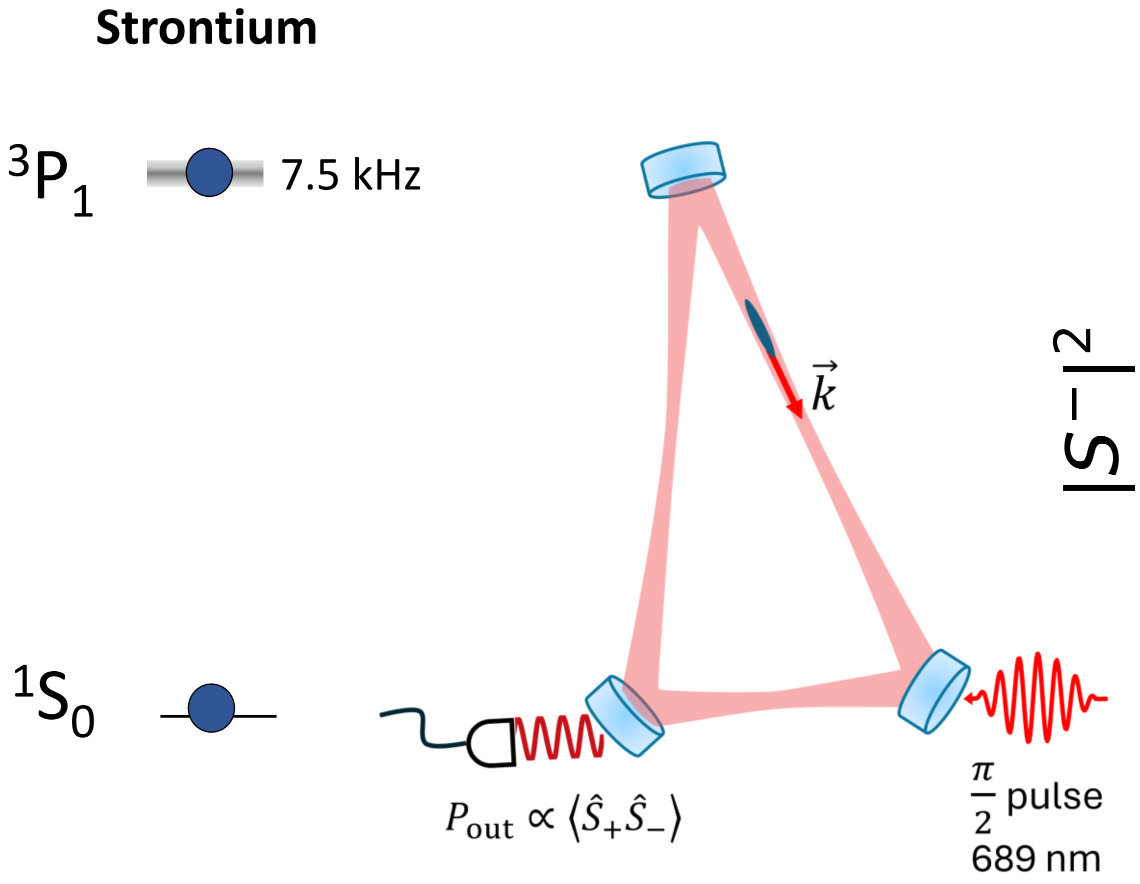
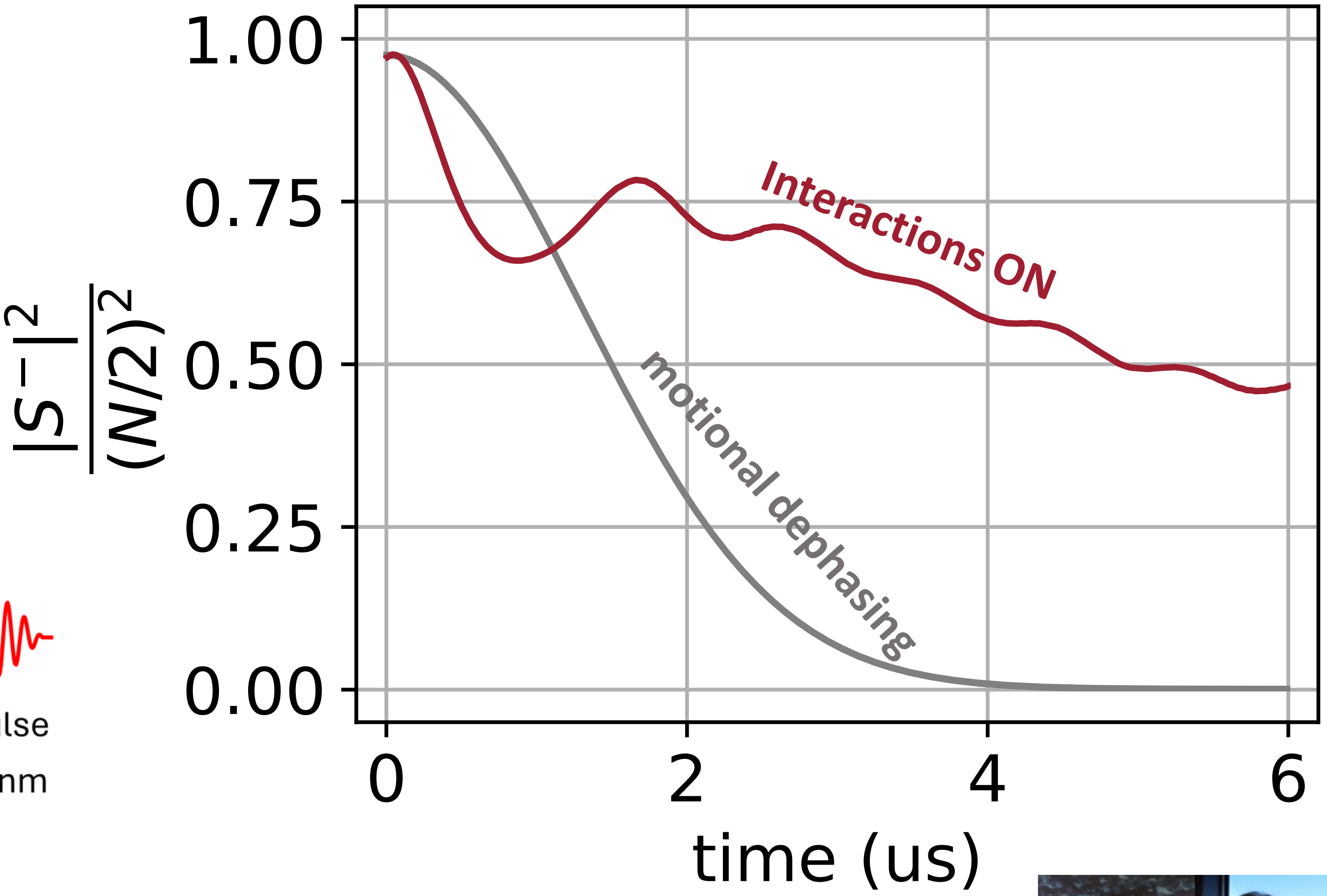
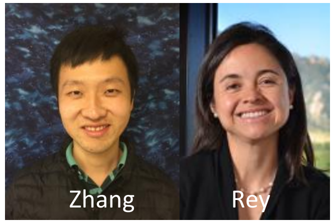
NSF PFC
NSF QSense
DOE QSA
DARPA/ARO
NIST
Lockheed
Heising-Simons

Suppress Motional Dephasing on an Optical Clock Transition?





Niu, Schäfer, Zhang… Rey, Thompson, *PRL* (2025)



Two-axis Counter Twisting Dynamics–a Magical Unicorn

PHYSICAL REVIEW A VOLUME 47, NUMBER 6 JUNE 1993

Squeezed spin states

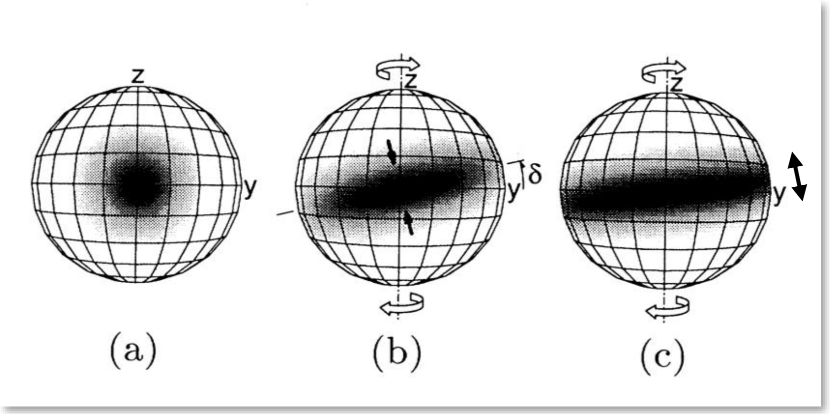
Masahiro Kitagawa and Masahito Ueda

Nippon Telegraph and Telephone Corporation Basic Research Laboratories, Musashino, Tokyo 180, Japan

(Received 12 February 1991; revised manuscript received 3 December 1992)

The basic concept of *squeezed spin states* is established and the principles for their generation are discussed. Two proposed mechanisms, referred to as *one-axis twisting* and *two-axis countertwisting*, are shown to reduce the standard quantum noise $S/2$ of the coherent S-spin state down to $\frac{1}{2}(S/3)^{1/3}$ and $\frac{1}{2}$, respectively. Implementations of spin squeezing in interferometers are also discussed.

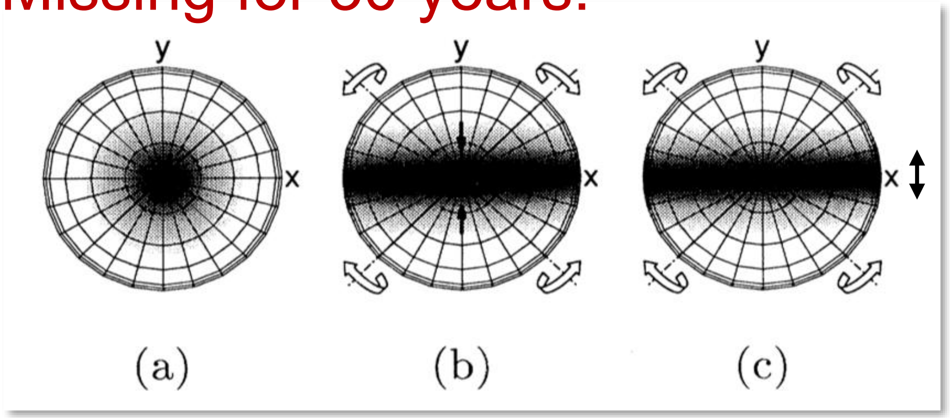
42.50.Dv, 03.65.Bz



$\frac{1}{N^{\frac{2}{3}}}$

One-axis twisting $\hat{H} = \hbar\chi \hat{J}_z^2$

Missing for 30 years!



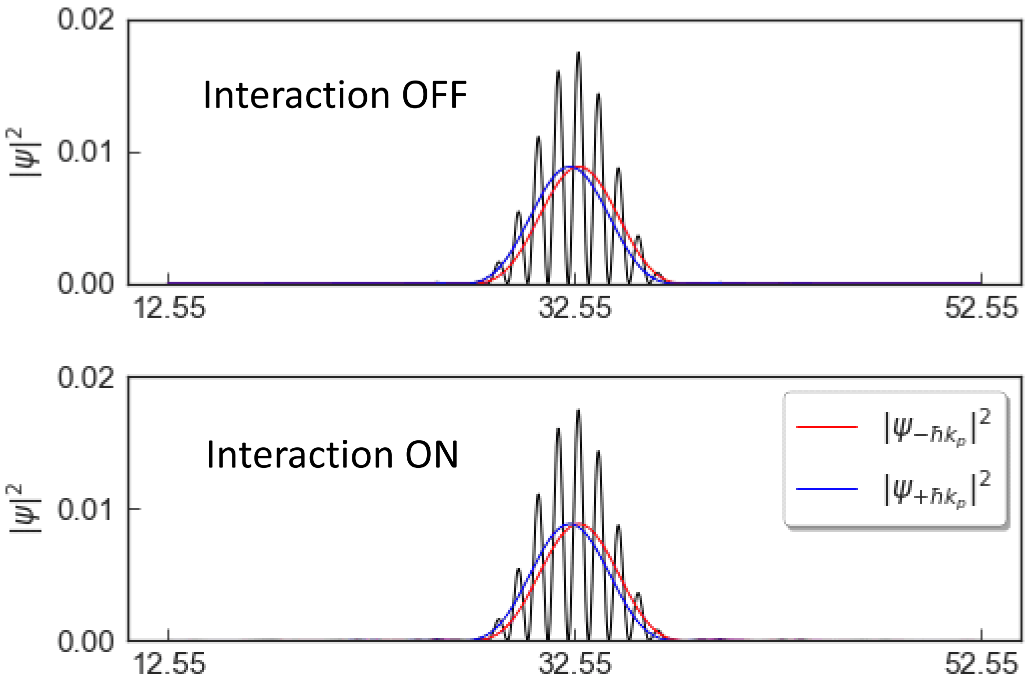
$\frac{1}{N}$

Two-axis twisting $\hat{H} = \hbar\chi(\hat{J}_+^2 + \hat{J}_-^2)$

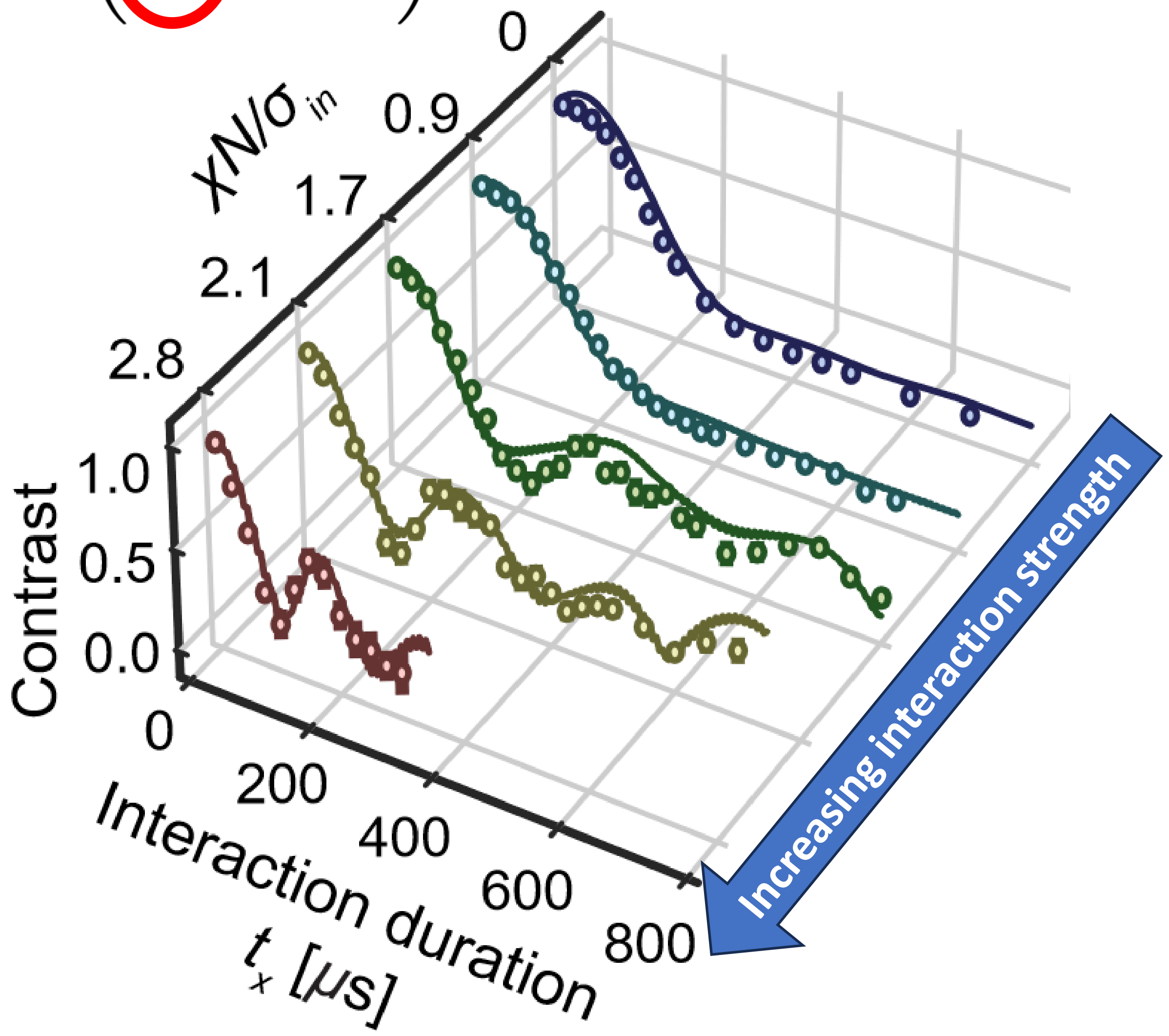
Binding wave packets together with a "spring" χN

$$\hat{H} = \chi \hat{J}_+ \hat{J}_- \approx \chi \left(\hat{J}^2 - \hat{J}_z^2 \right)$$

Simulation of $|\psi(Z, t)|^2$

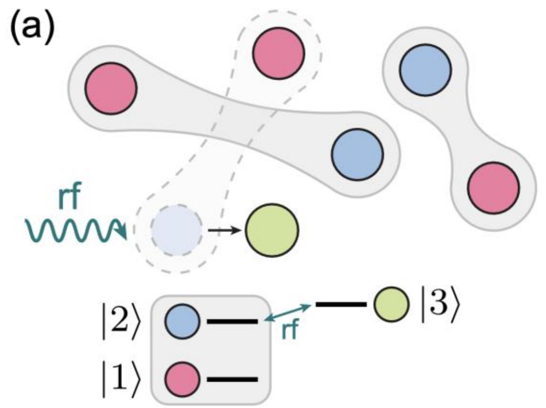


Position along cavity axis (2λ)

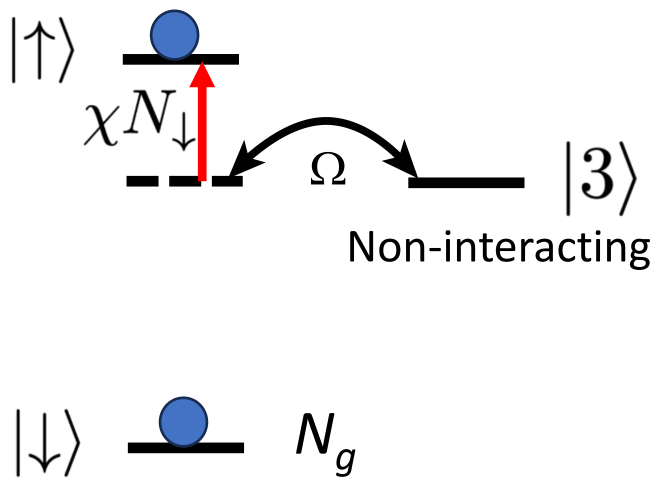


Distinguishing BCS Gap from the “Spectral Gap”

Degenerate gases:
Zoller, Jin, Ketterle, Grimm, etc.



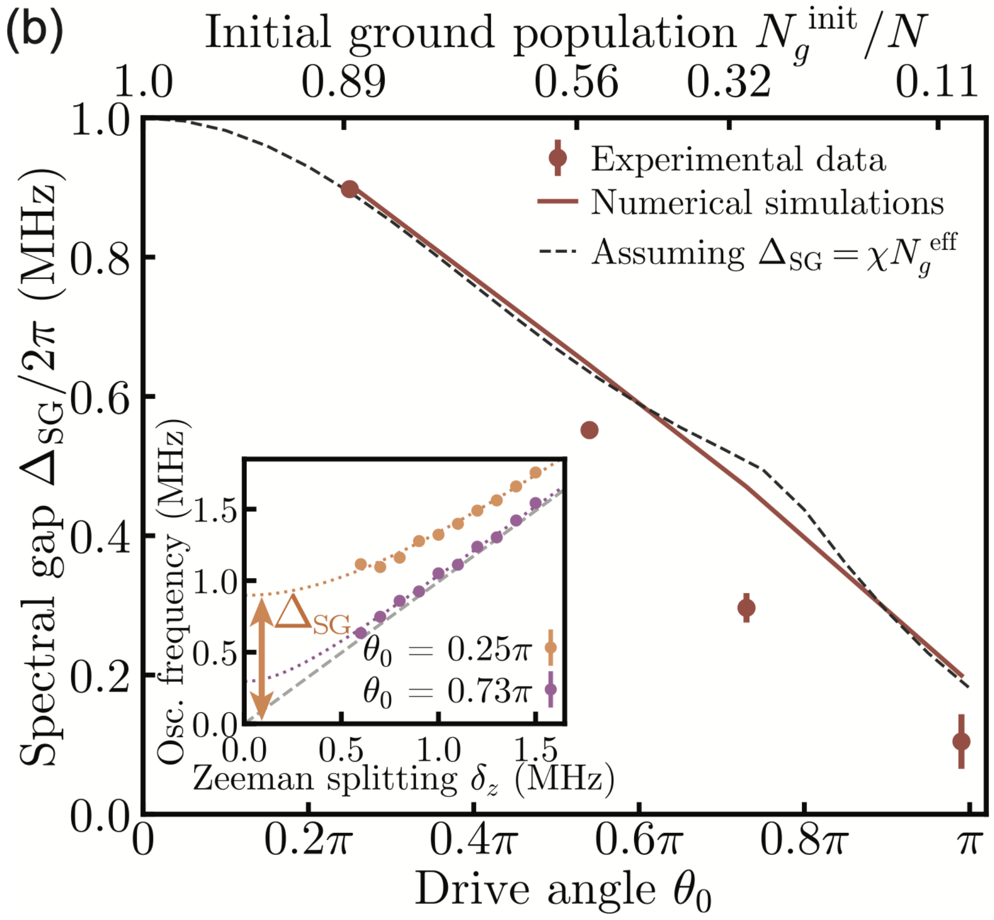
$\chi N = 2\pi \times 1$ MHz fixed, scan Ω



Actually 2 different energy scales:

BCS Gap: χN

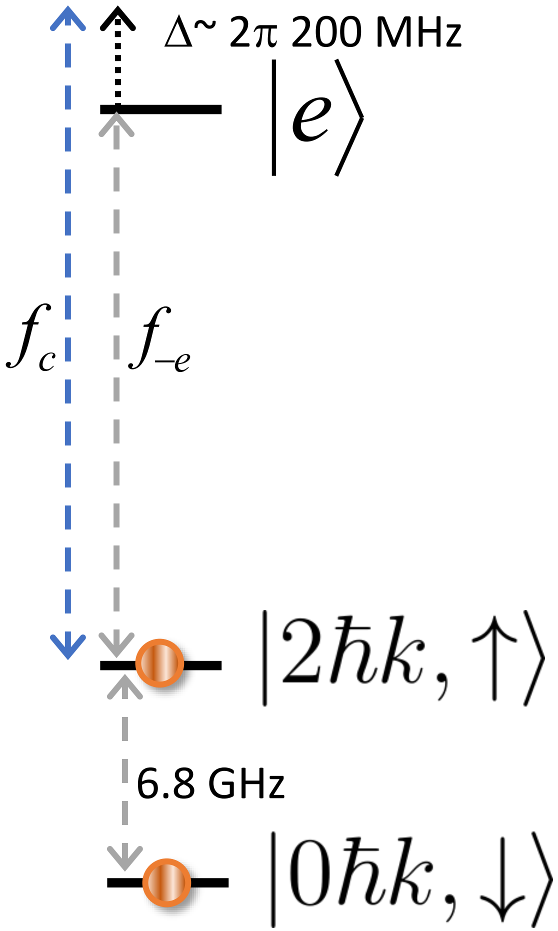
Spectral Gap: χN_g

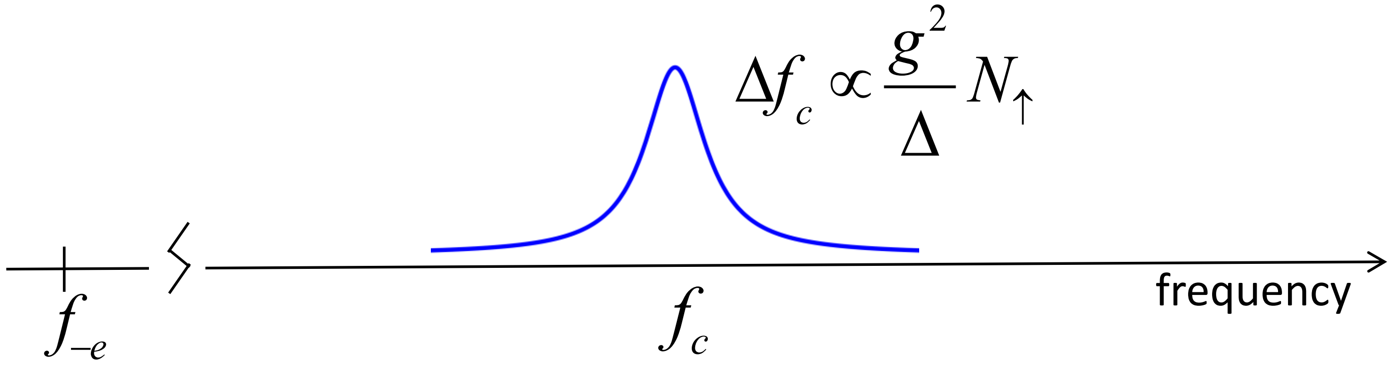


Toward Squeezing: State-Dependent Cavity Frequency Shifts

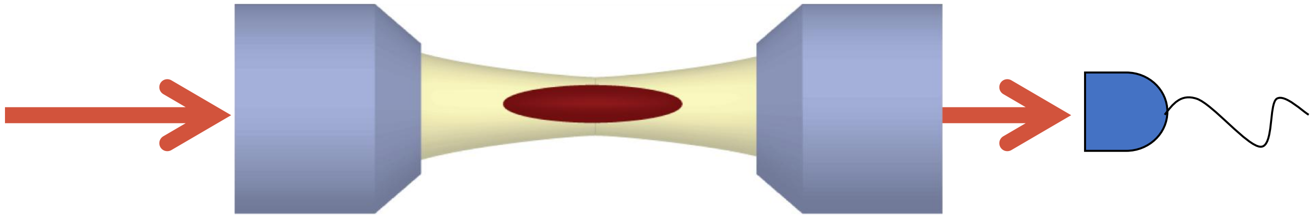
Thy for experimentalists: Chen, Bohnet, Weiner, Cox, Thompson PRA **89** 043837 (2014)

$$\hat{H}_{QND} = \chi_{QND} \hat{N}_{\uparrow} \hat{c}^{\dagger} \hat{c}$$





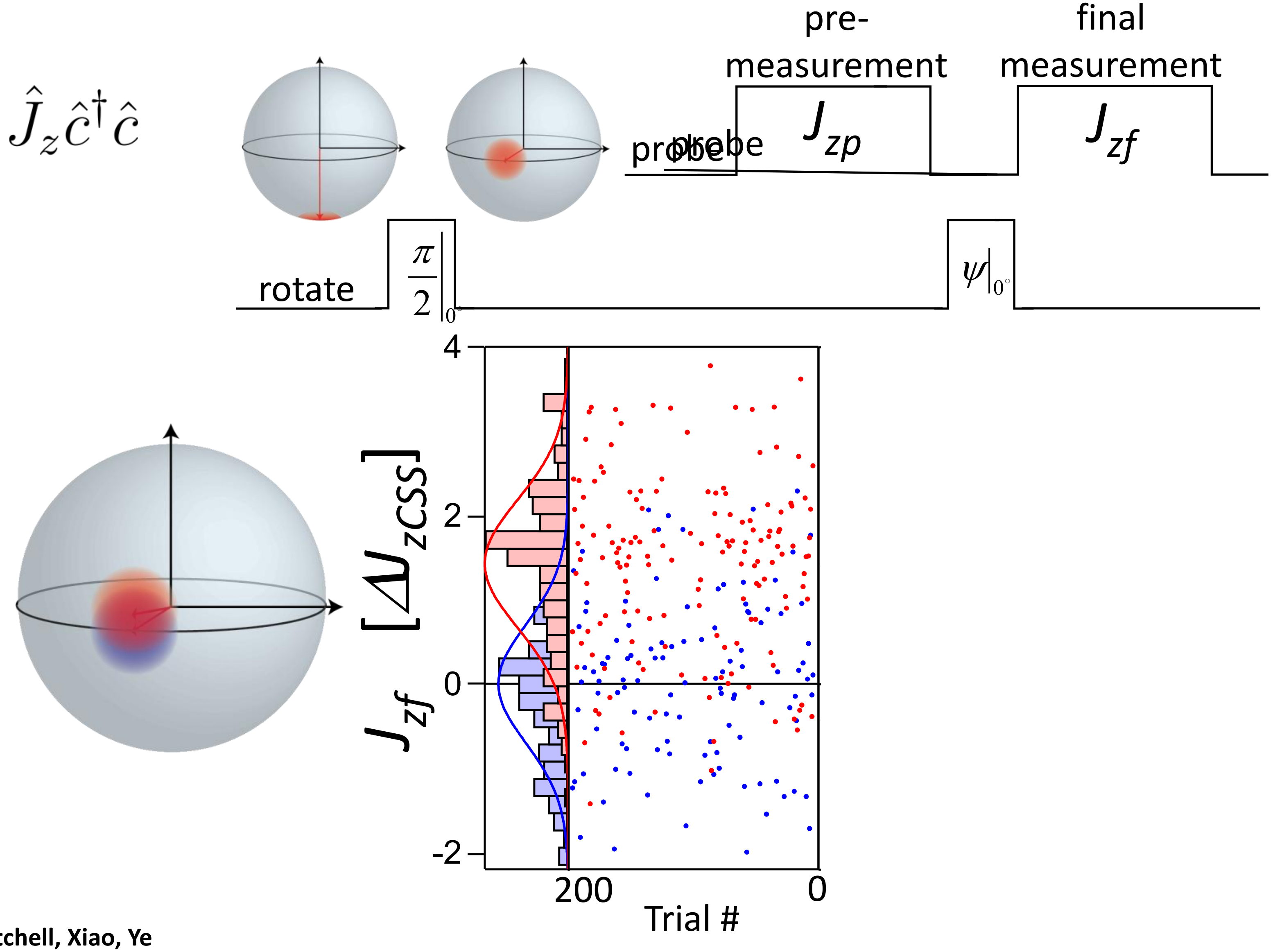
Atoms in up act like pieces of glass that shift the cavity resonance frequency



Measuring the shift of the cavity frequency does not reveal *which* atoms are in up.

QND: Measure the Quantum Noise and Subtract It Out

$$\hat{H}_{QND} = \chi_{QND} \hat{J}_z \hat{c}^\dagger \hat{c}$$



See also: Vuletic, Kasevich, Polzik, Mitchell, Xiao, Ye

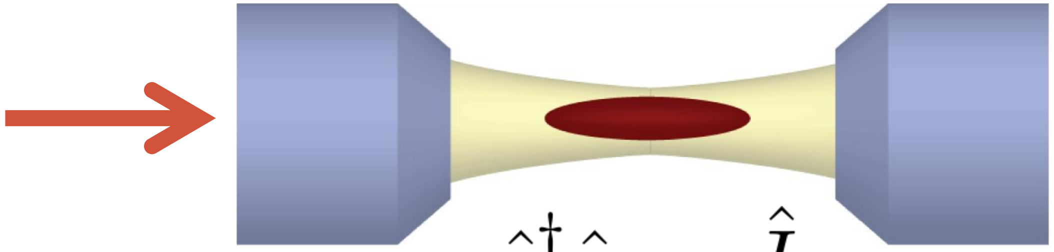
Kevin Cox, Greve, Weiner, Thompson, *PRL* **116**, 093602 (2016)

Justin Bohnet, Cox, Norcia, Weiner, Chen, Thompson, *Nature Photonics* **8** (9) 731 (2014)

Zilong Chen, Bohnet, Sankar, Dai, Thompson *PRL* **106** 133601 (2011)

Spin-Spin Dynamical Momentum Squeezing

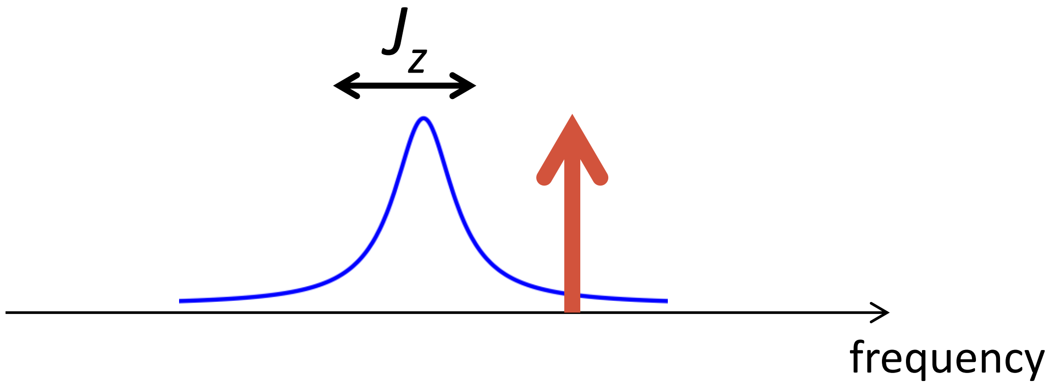
Leroux, Schleier-Smith, Vuletic *PRL* 104 073602 (2010)

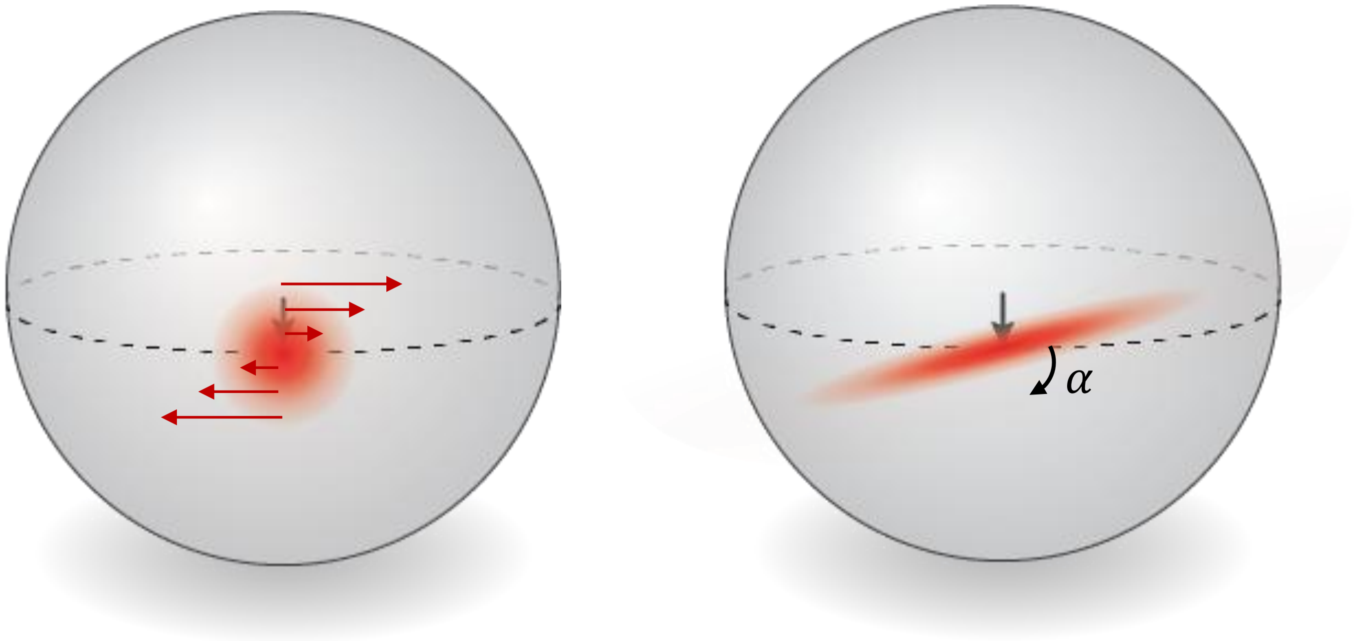


$$\hat{c}^\dagger\hat{c} \propto \hat{J}_z$$

$$\hat{H}_{QND} = \left(\chi_{QND}\hat{c}^\dagger\hat{c}\right)\hat{J}_z$$

$$\hat{H}_{OAT} = \chi_{OAT}\hat{J}_z^2$$

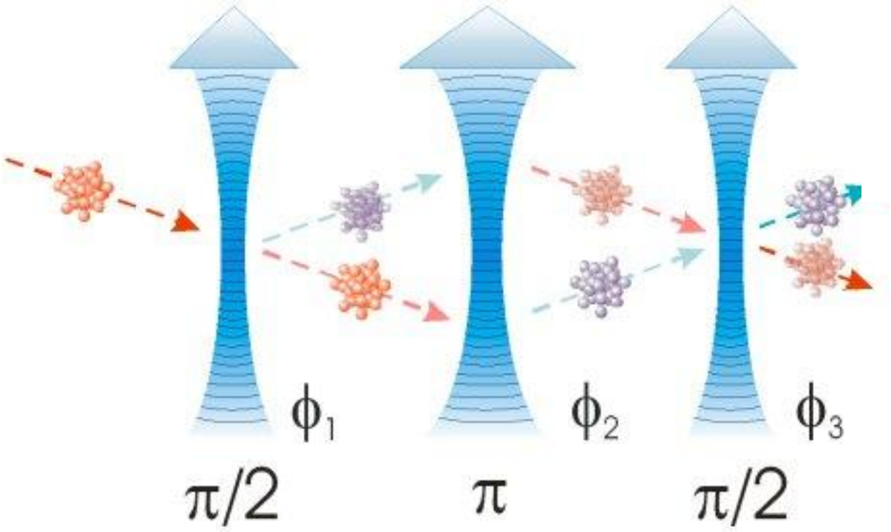




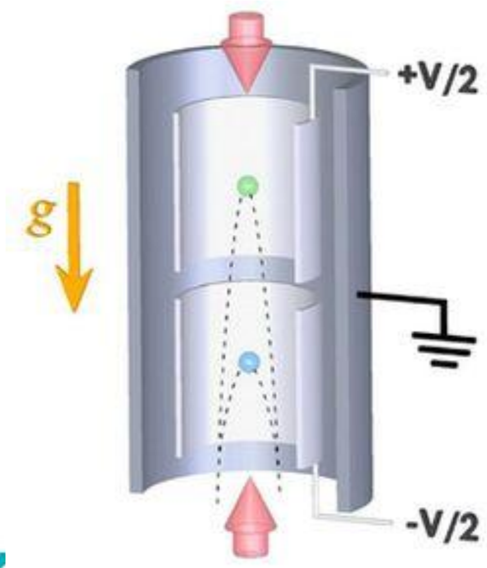
Light-Pulse Matter wave Interferometers

Use pulses of light to spatially split the atomic wave function

Kasevich & Chu *PRL* **67** 181 (1991)



Credit: Peters and Kasevich groups

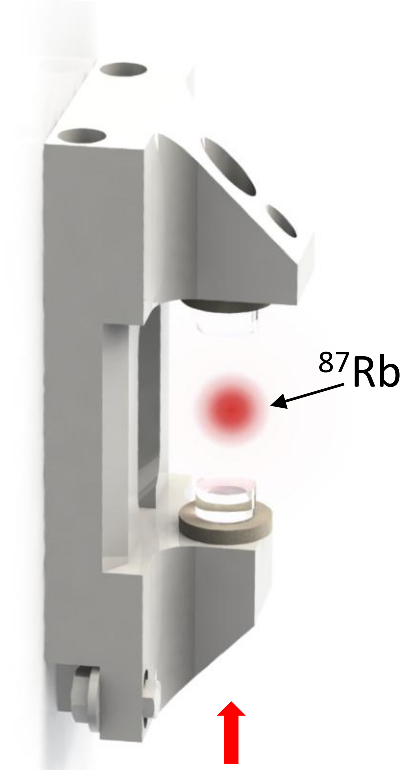


Navigation
Gyroscopes
Accelerometers
Gravimetry
Fine-structure constant
Test QED: g-factor at $\sim 10^{-12}$
Test Atomic Charge Neutrality
Dark matter, Dark energy
Geodesy, resource exploration

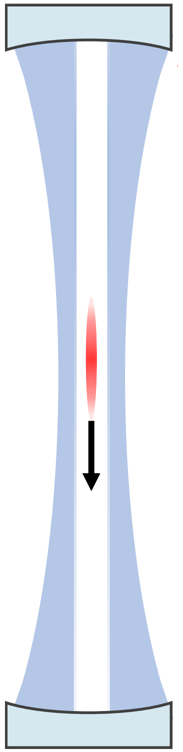
Einstein's Equivalence Principle
Gravitational constant G
Gravitational wave detection

Graham, Hogan, Kasevich, Rajendran *PRL* **110** 171102 (2013)
Chaibi,…Landragin, Bouyer *PRD* **93** 21101 (2016)
Quantum Memory: Norcia, Cline, Thompson *PRA* 96 042118 (2017)

Rb Matter wave Interferometer



Bragg/Raman,
Probe, Pump



Repulsive dipole trap

Atoms free fall along cavity axis

guided by repulsive dipole trap

11 dB Directly observed squeezing as atoms fall along axis
Cox, Greve, Wu, Thompson, *Phys. Rev. A* **94**, 061601(R) (2016)

Experimental Parameters:

$F = 130{,}000$

$C \sim 0.5$

$\kappa \sim 2\pi \times 52$ kHz

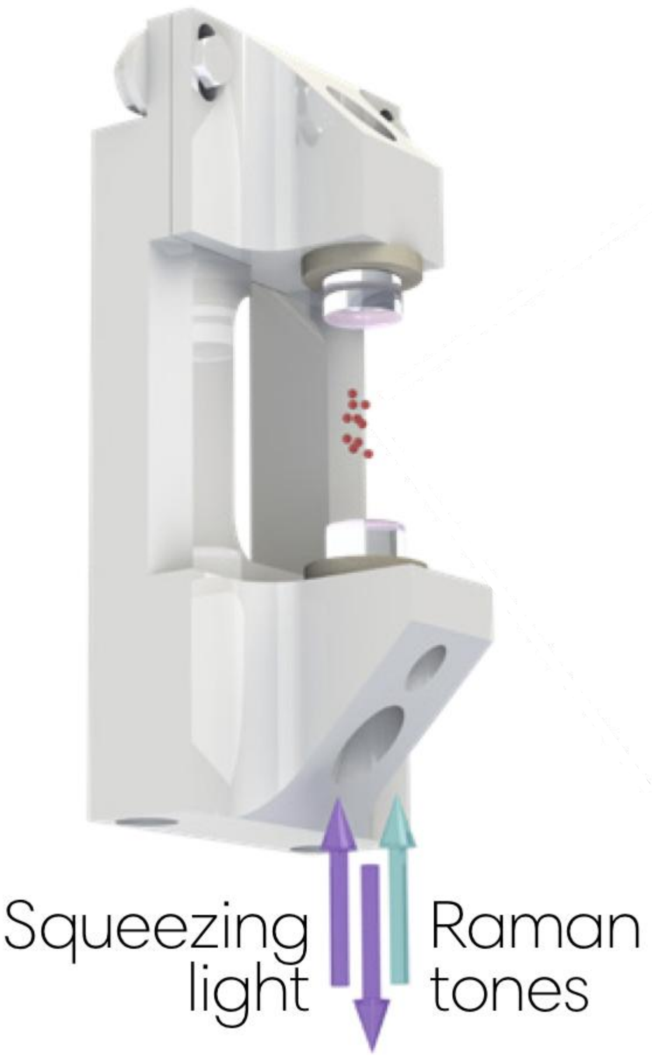
$N \sim 500 - 1000$ atoms

$FSR \sim 6.800$ GHz

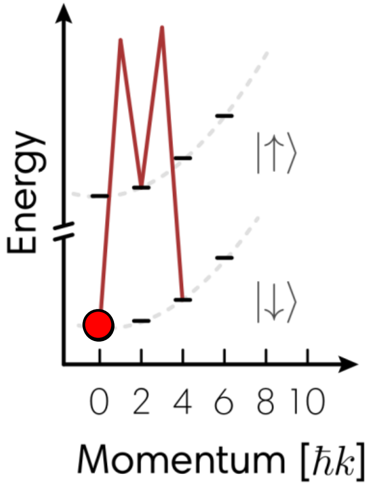
Cavity detuning from atomic transition

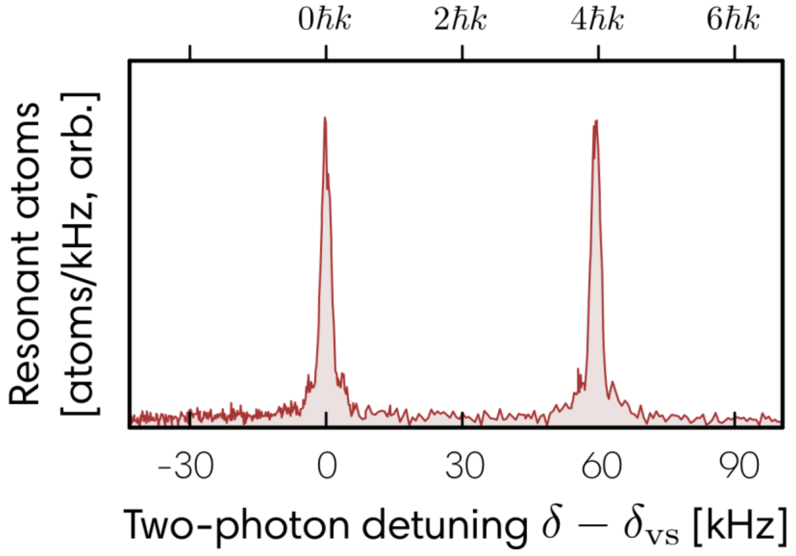
$\Delta\omega_a \sim 2\pi \times 500$ MHz

Coherent Control of Momentum States

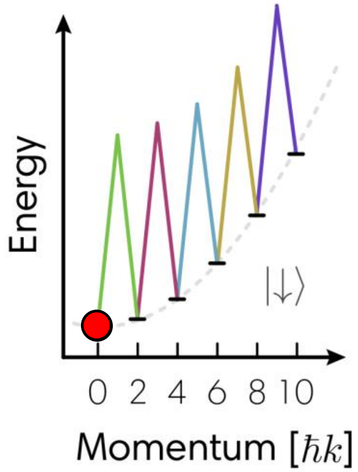


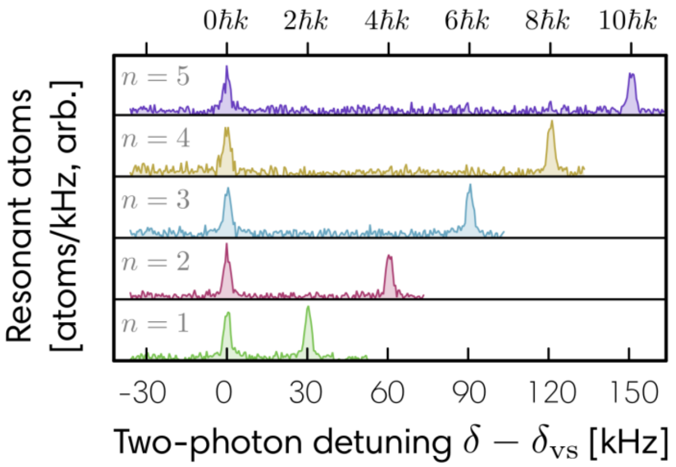
Raman Momentum Transfer



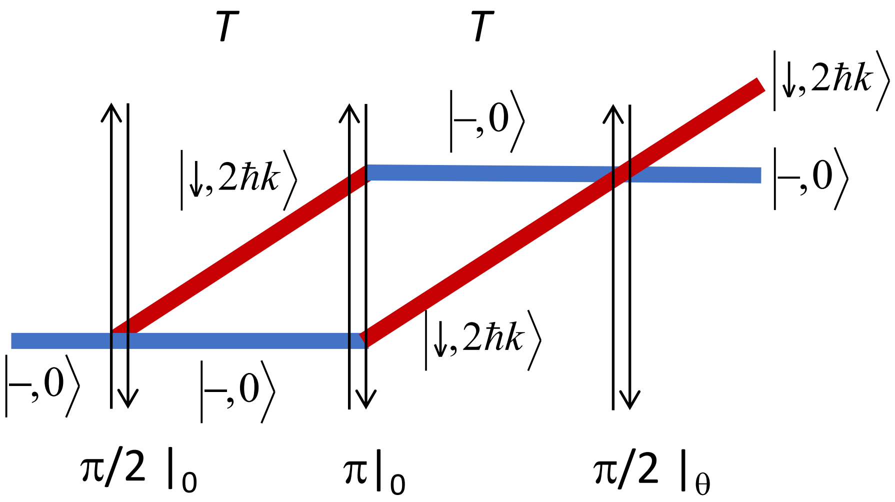


Bragg Large Momentum Transfer

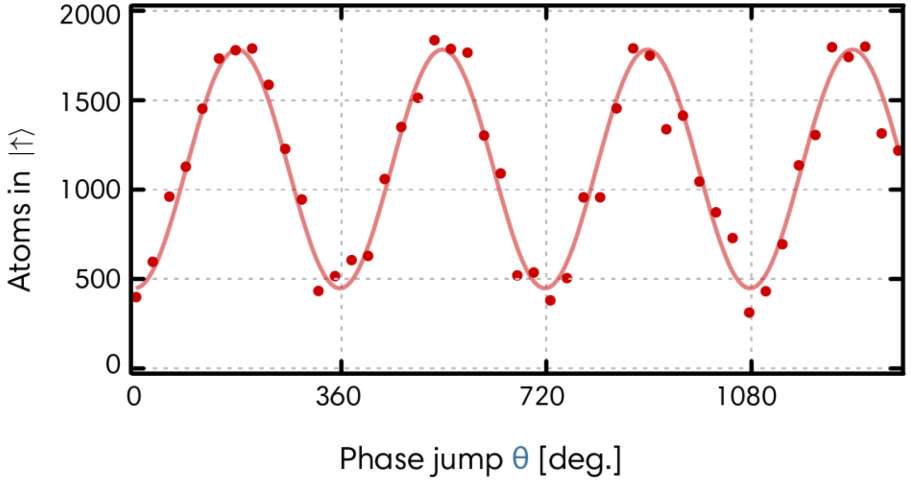


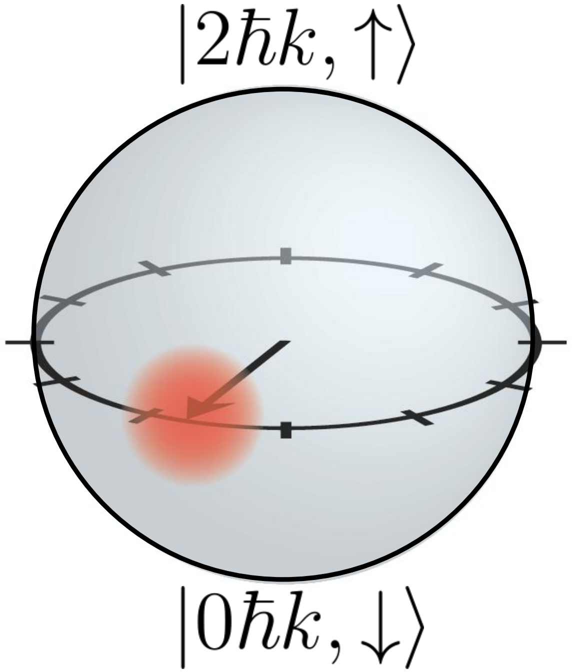


Intracavity Guided Matter-wave Interferometer

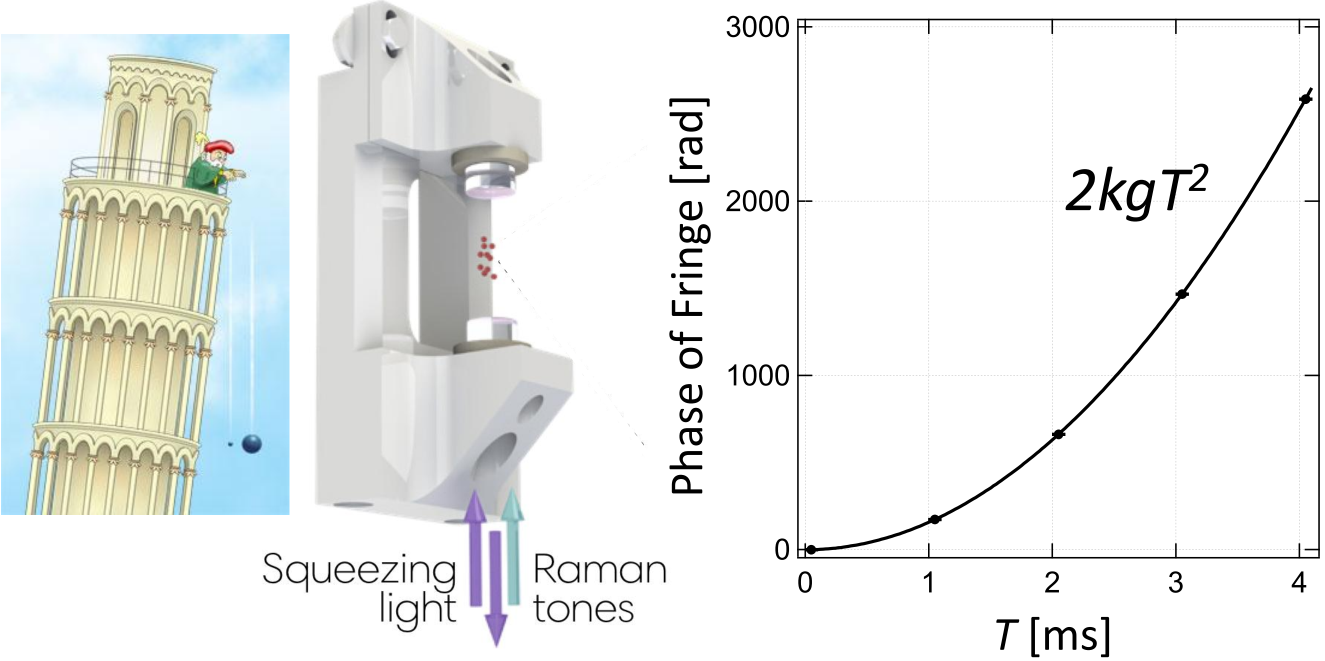


Matter wave Interferometer Fringe





Inertial Sensing of Free Fall

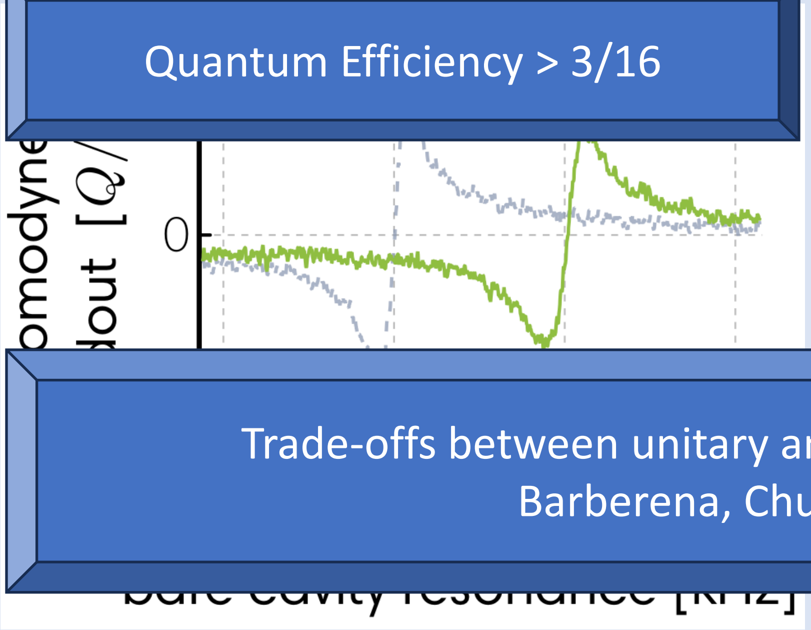


Generating Matterwave Squeezed States

Quantum Nondemolition Measurements

$$\hat{H}_{QND} = \chi_{QND} \hat{J}_z \hat{c}^\dagger \hat{c}$$

Quantum Efficiency > 3/16

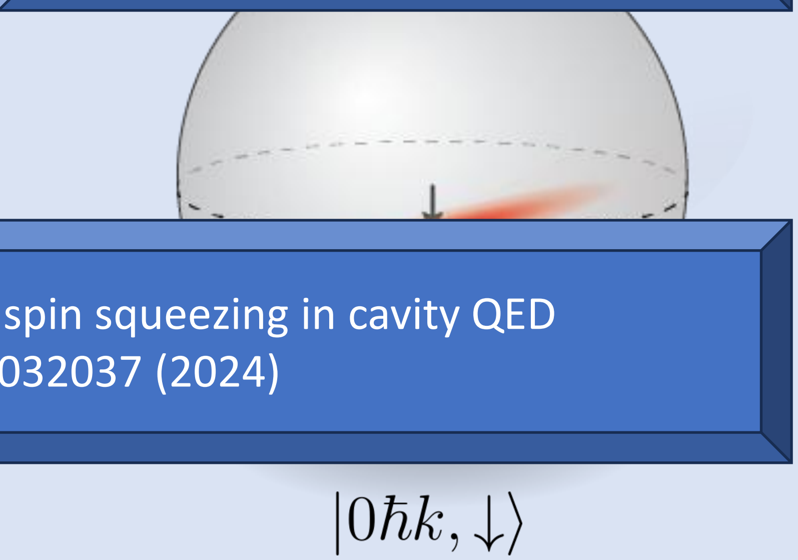


3.4 ± 1 dB squeezing

One-axis Twisting

$$\hat{H}_{OAT} = \chi_{OAT} \hat{J}_z^2$$

Quantum Efficiency < 3/16

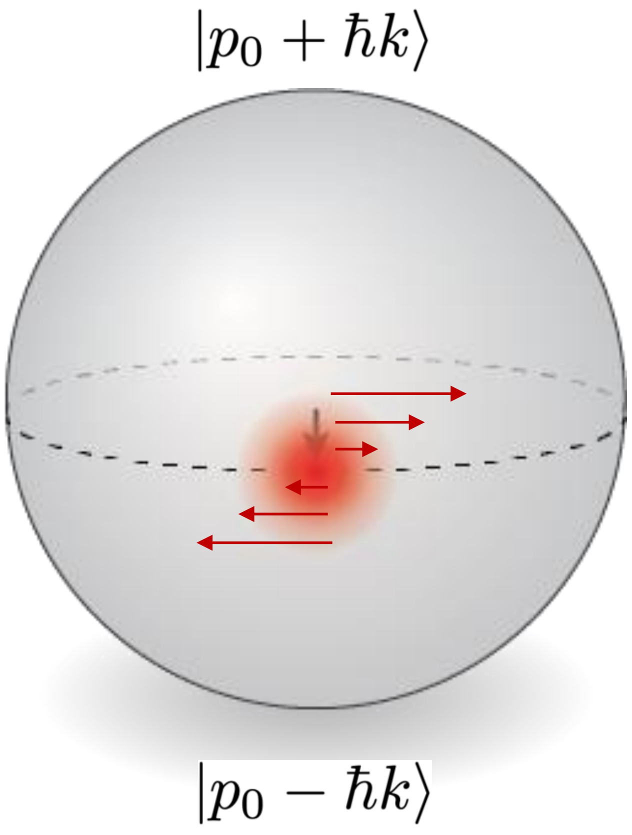


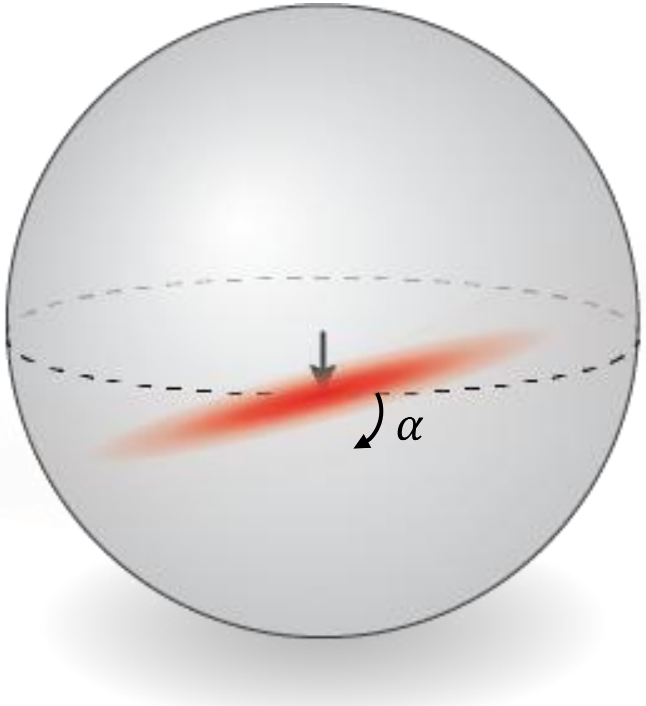
2.5±0.6 dB squeezing

Trade-offs between unitary and measurement induced spin squeezing in cavity QED
Barberena, Chu, Thompson, Rey *PRR* 6, L032037 (2024)

One-Axis Twist Shift of Bragg Interferometer

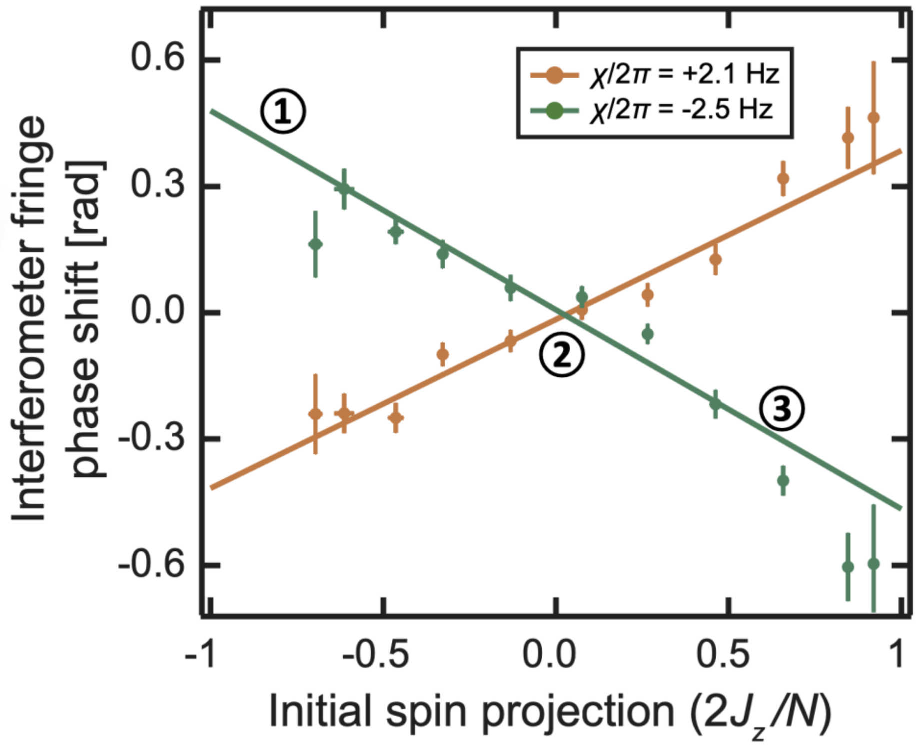
$$H_{ex} \approx \chi \hat{J}_+ \hat{J}_- \approx \chi \left(J^2 - J_z^2 \right)$$





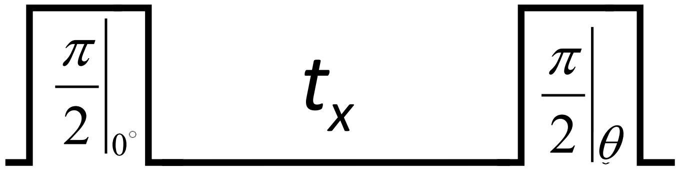
Improving laser technology to observe squeezing

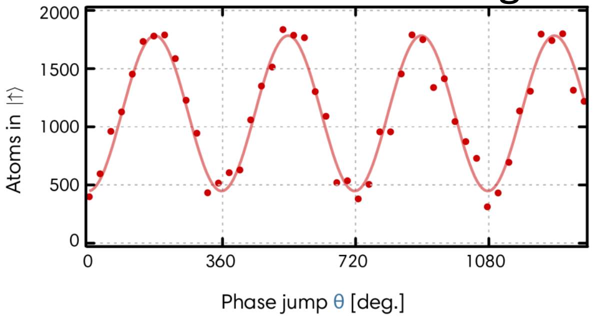
See at mean field:
Phase shift ~ J_z

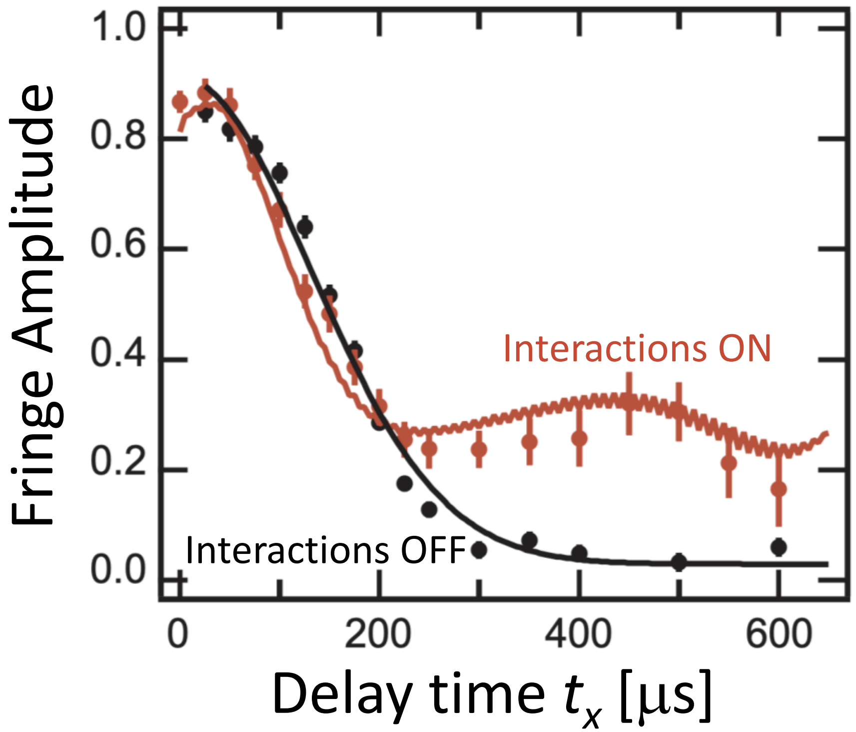


Binding Wave Packets Together

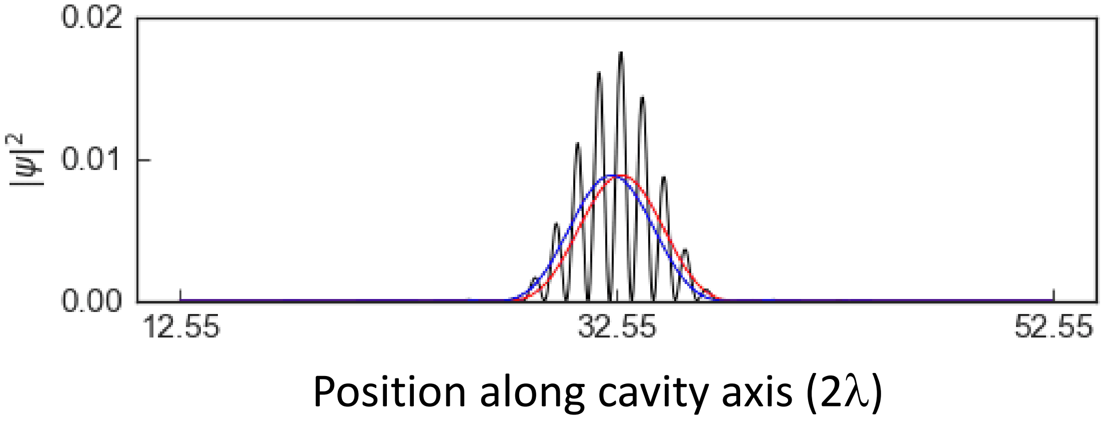
$$H_{ex} \approx \chi \hat{J}_+ \hat{J}_- \approx \chi\left(J^2 - J_z^2\right)$$







Simulation of $|\psi(Z, t)|^2$

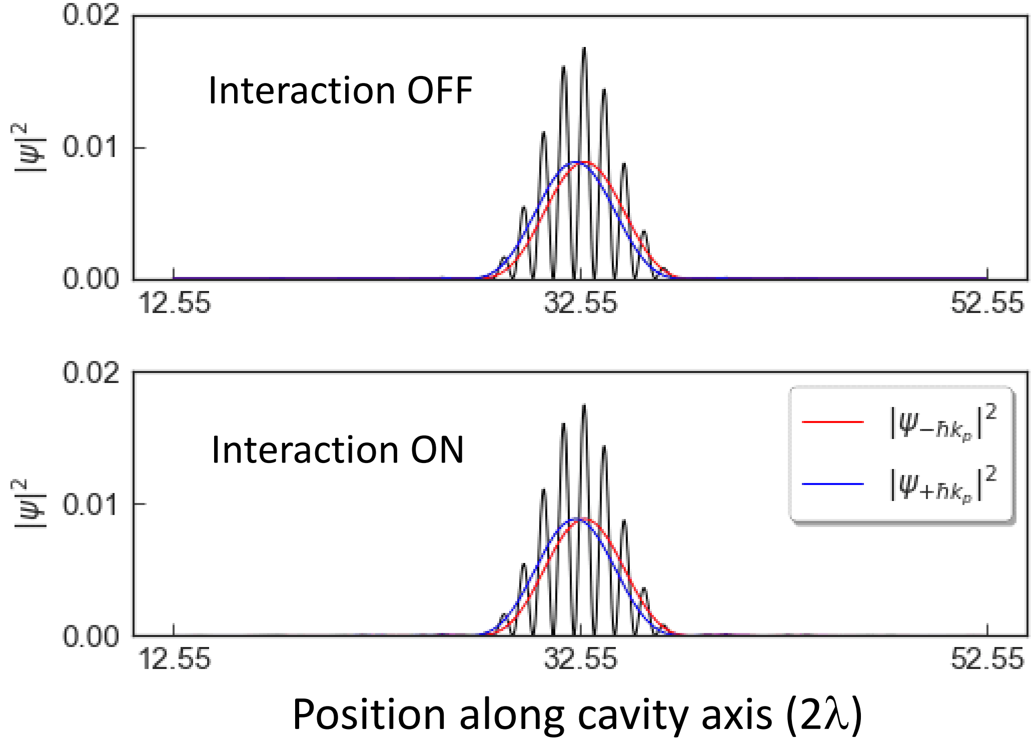


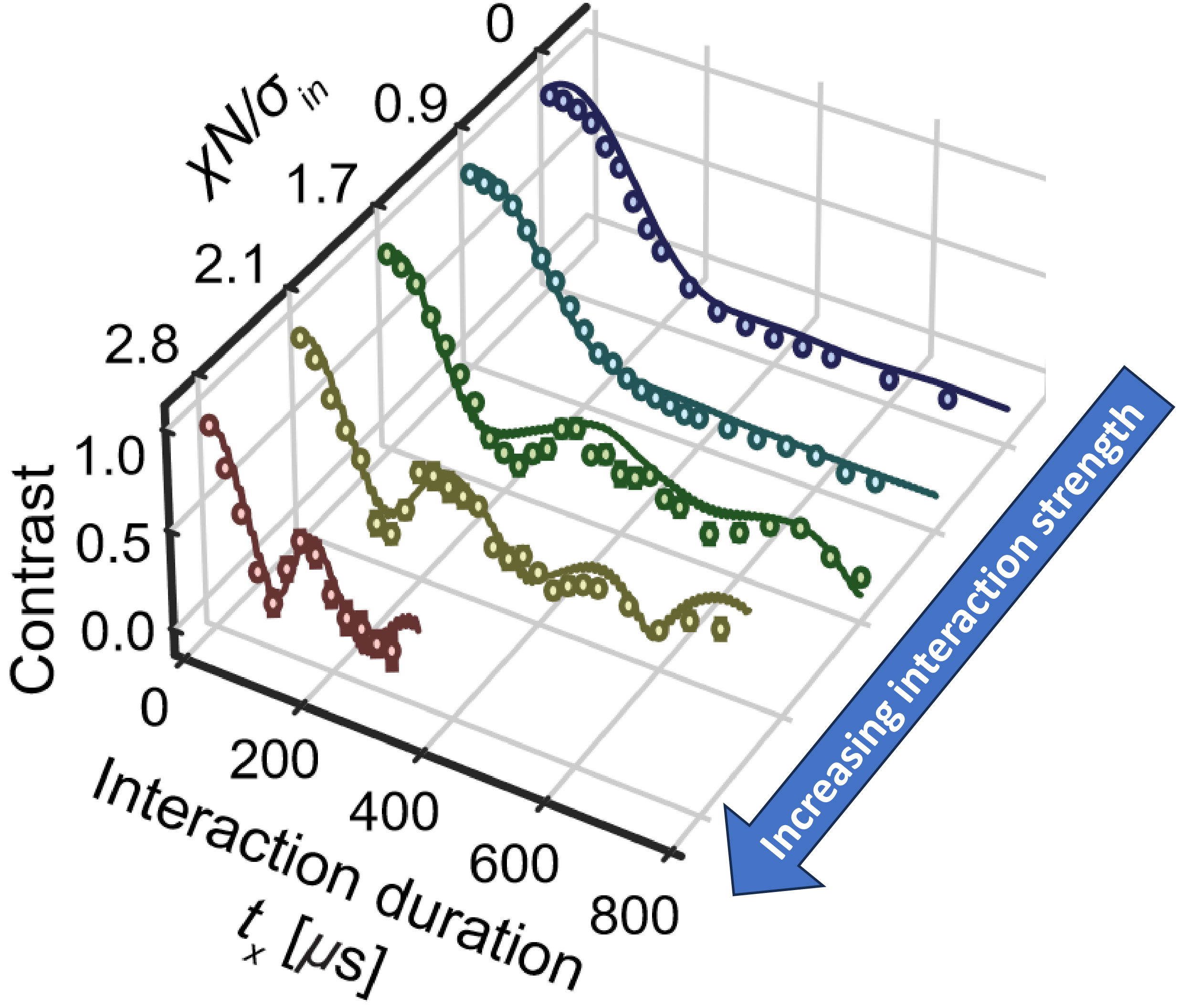
Coherence time extended → wave packets not separating!

Binding wave packets together with a “spring” χN

$$H_{eff} \approx \chi(J^2 - J_z^2)$$

Simulation of $|\psi(Z, t)|^2$

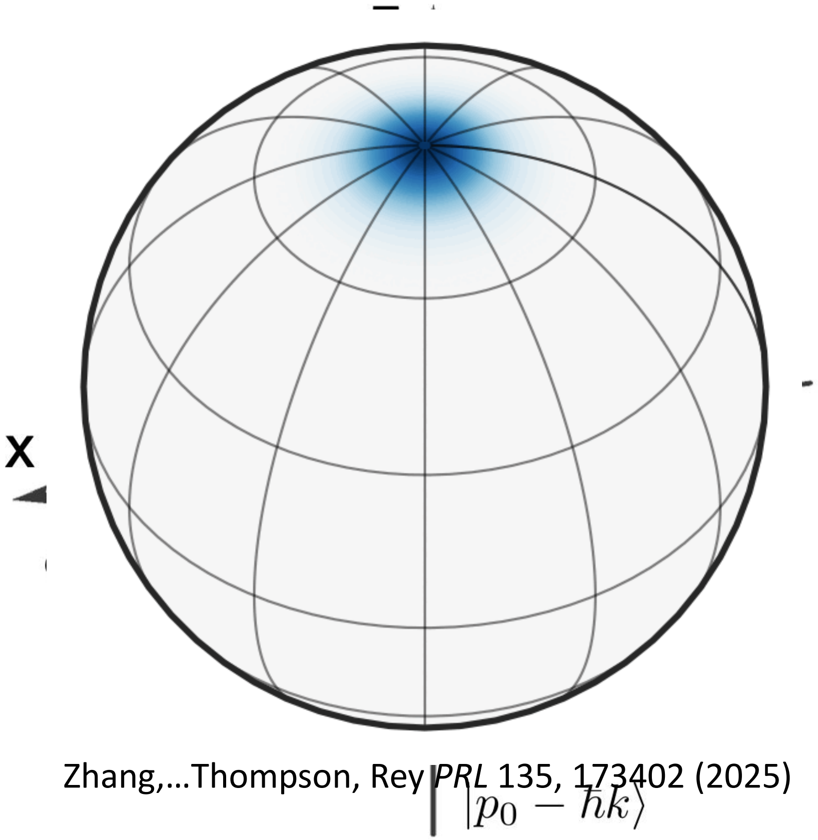




3-Body Interaction Dynamics

Mean field equations of motion

$$\dot{J}_z = -3i\chi_3(J_+^3 - J_-^3)$$
$$\dot{J}_+ = -6i\chi_3 J_z J_-^2$$

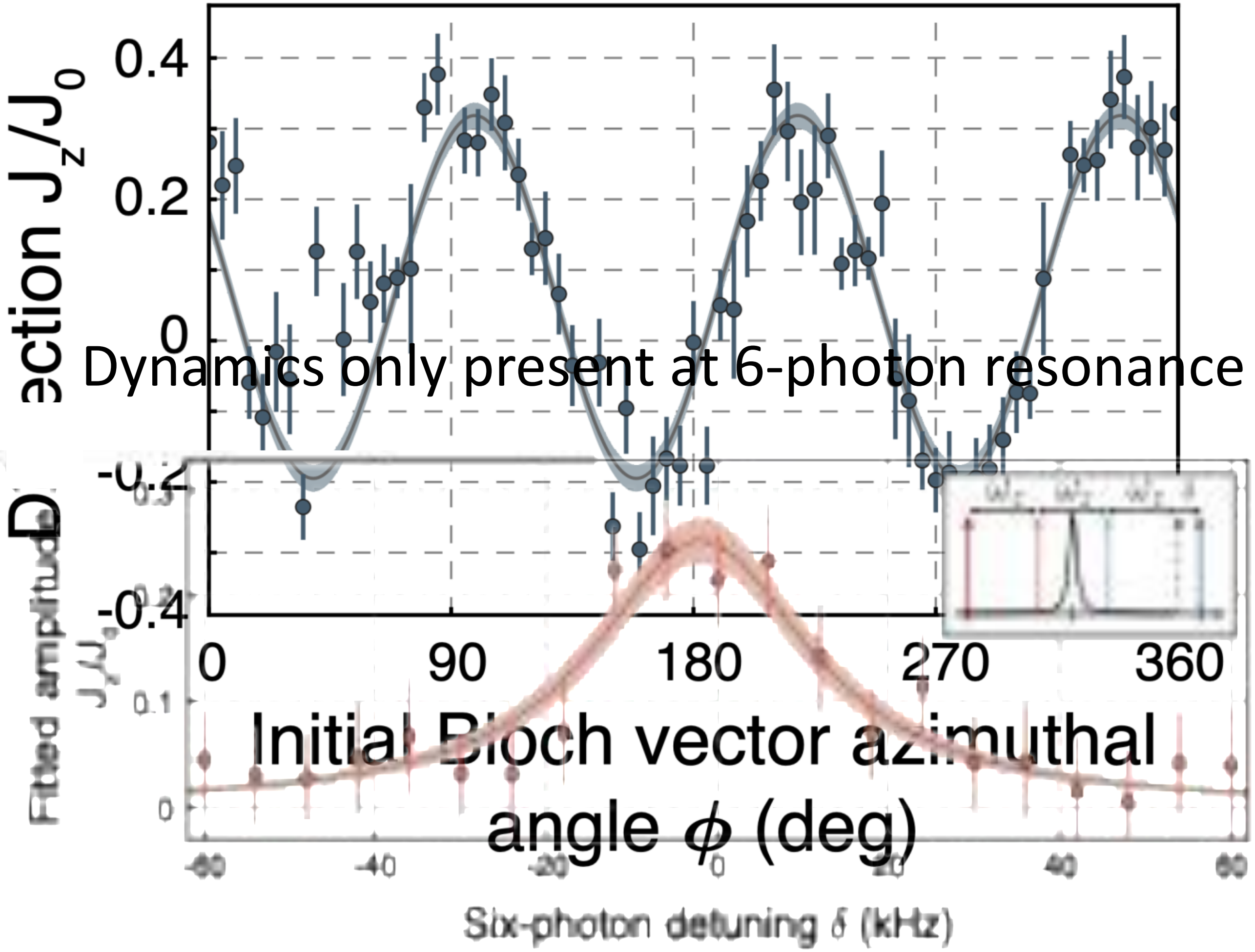


Zhang,…Thompson, Rey *PRL* 135, 173402 (2025)

8 Fixed Points: 6 stable at equator
2 Trifurcation points at N & S poles

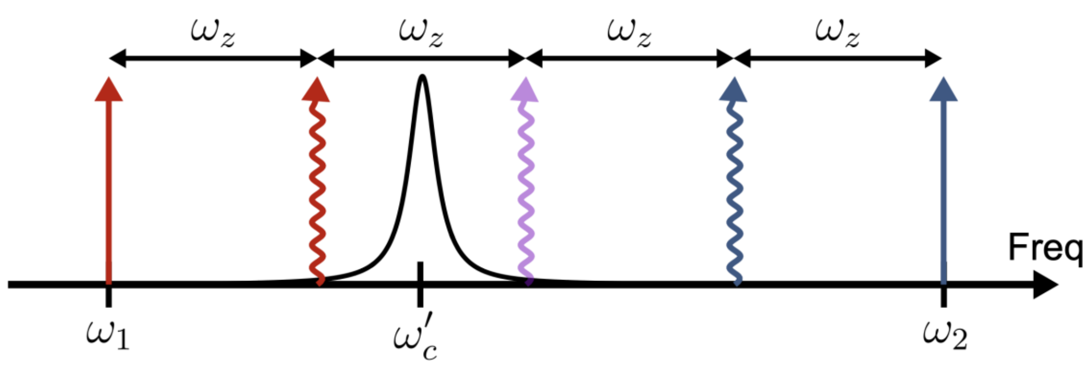
Observed dynamics of the
6 stable fixed points along the equator

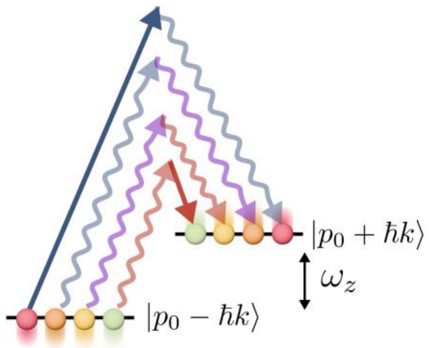
Dynamics only present at 6-photon resonance

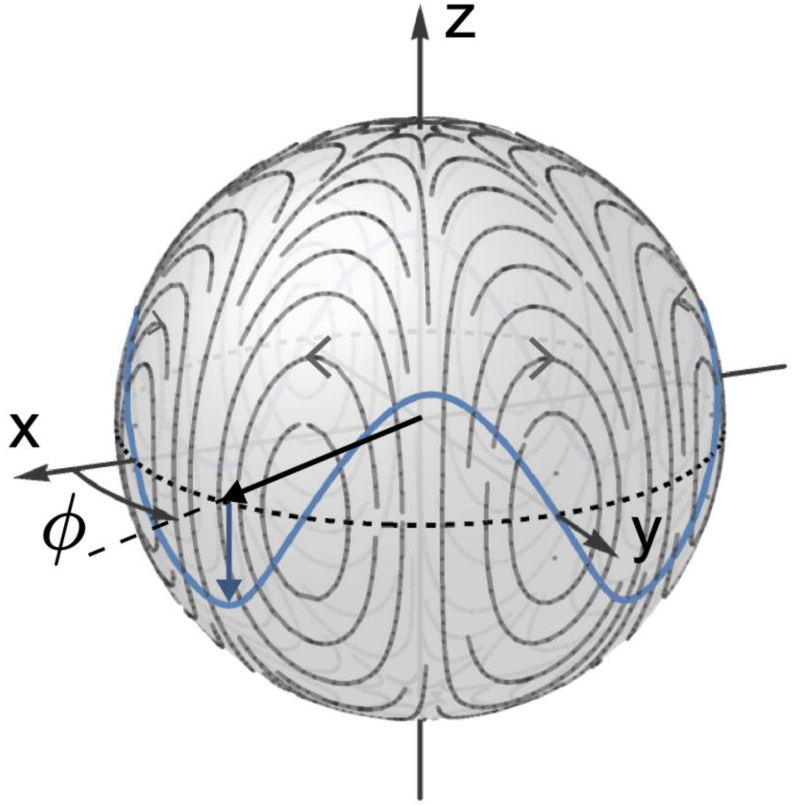


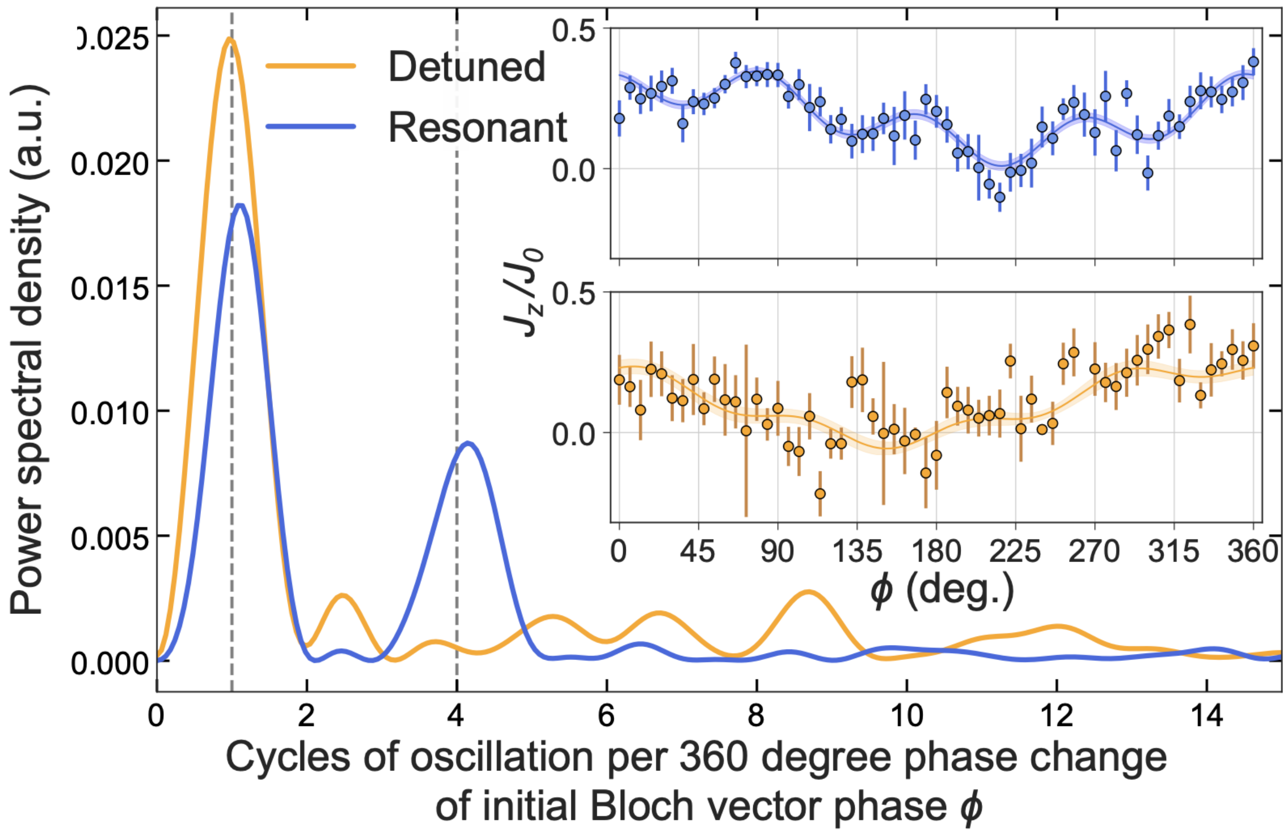
4-body Interaction: 4 atoms / 8 photons

$$\hat{H}_4 = \chi\left(\hat{J}_+^4 + \hat{J}_-^4\right)$$



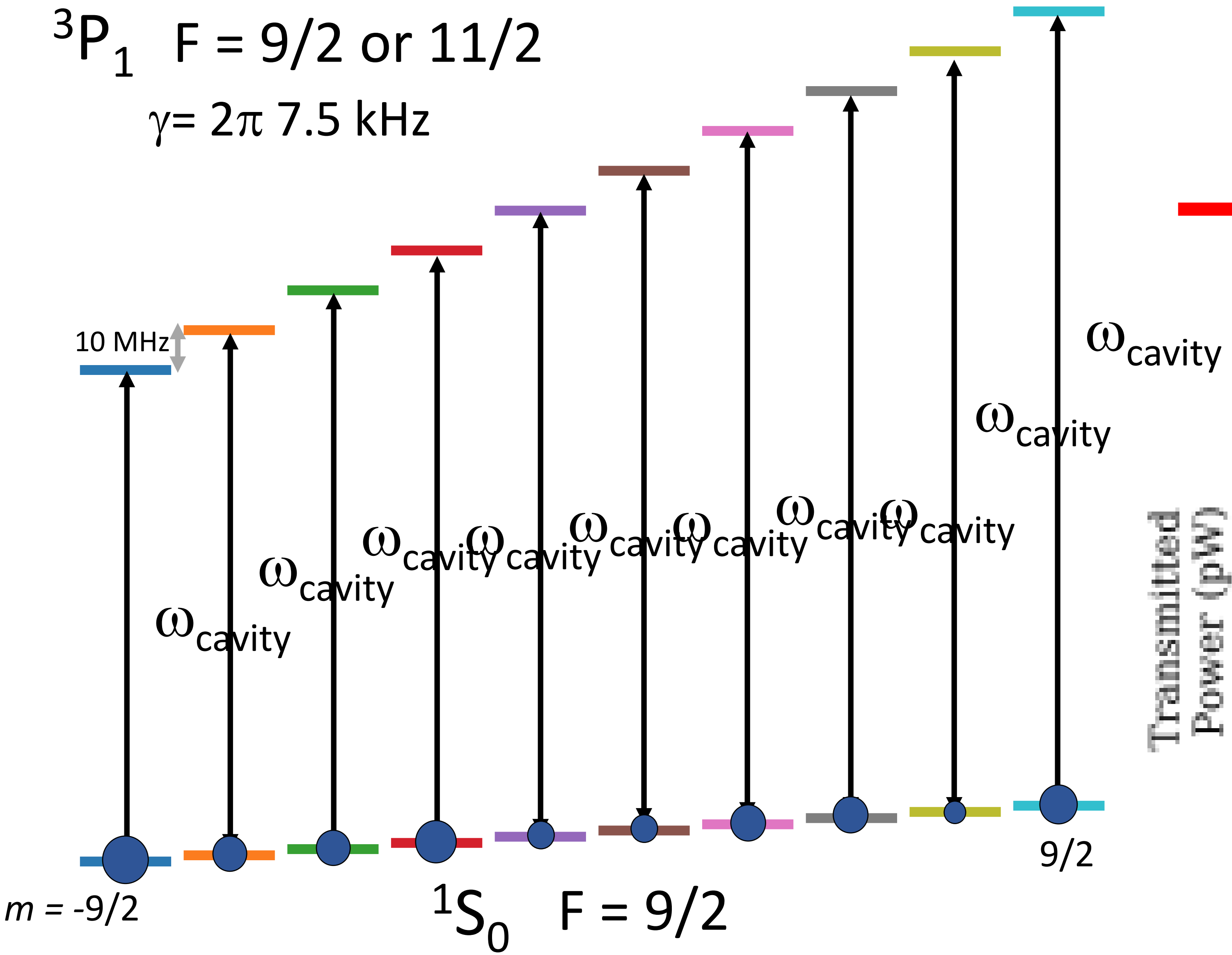


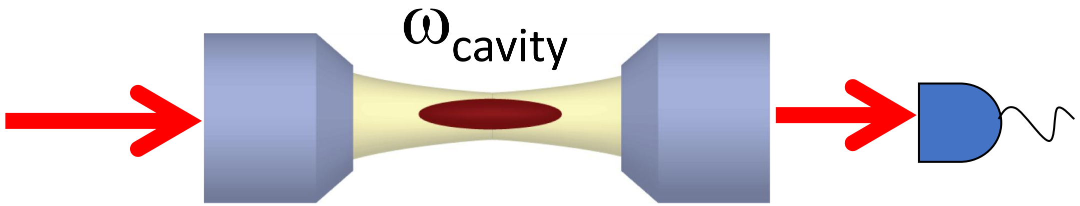


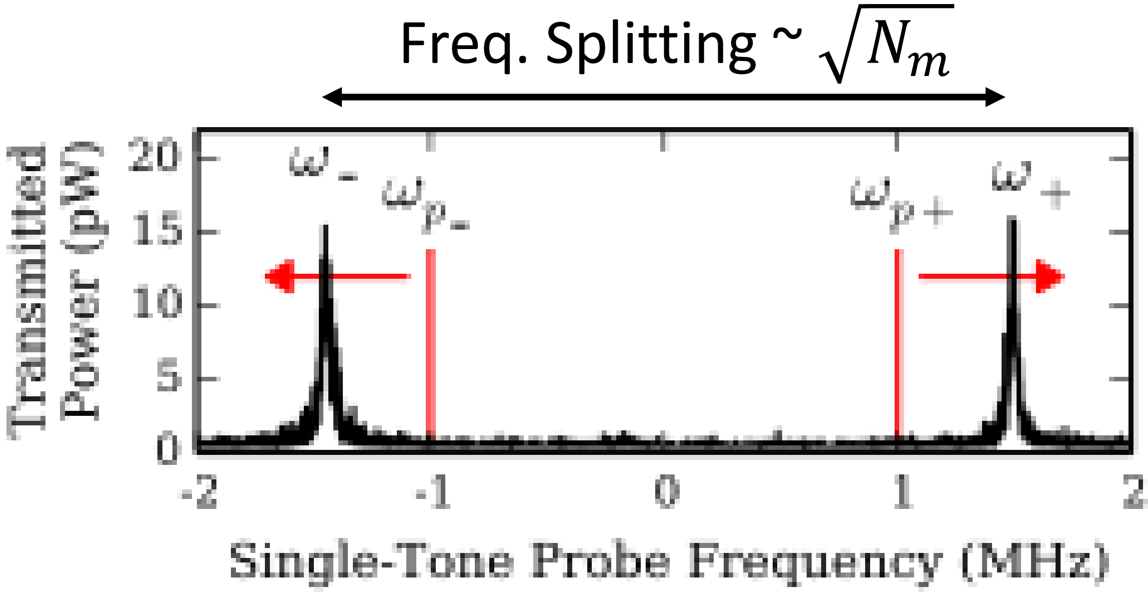


10 Fixed Points: 8 stable at equator
2 Quadrafurcation™ points at N & S poles

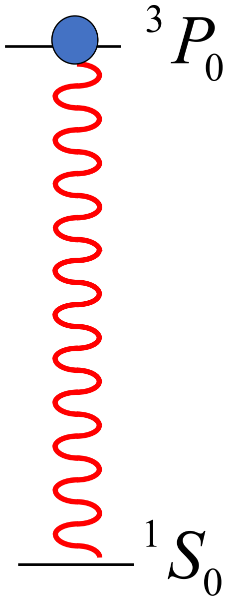
Challenge: Resolving 10 Nuclear Spin States in Single Shot



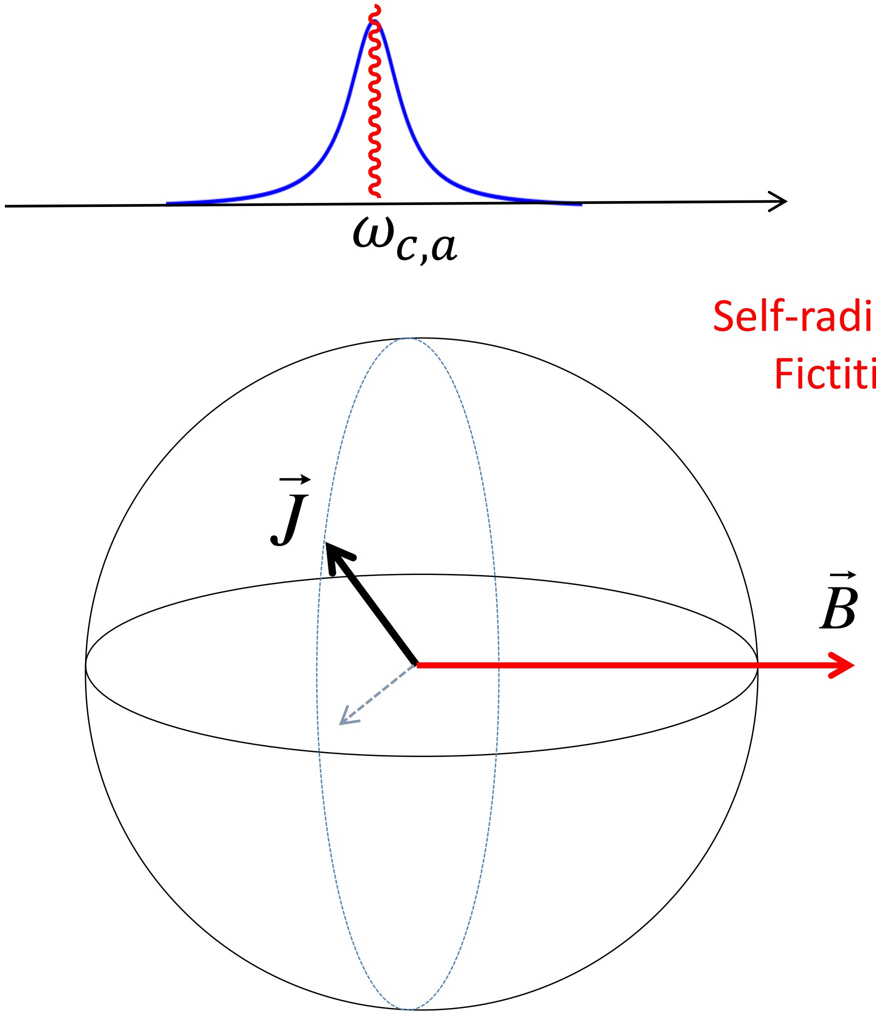




Detuning the Cavity Rotates the Rotation Axis

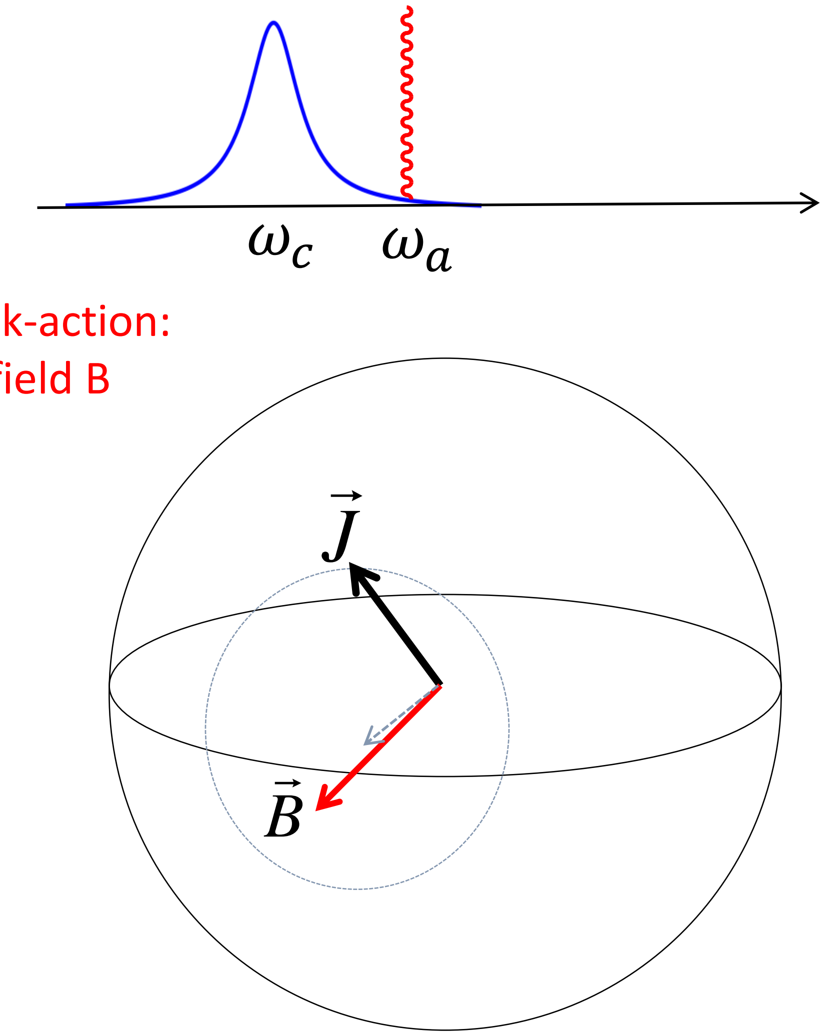


Resonant: Superradiance



Self-radiated field's back-action:
Fictitious magnetic field B

Non-resonant: Hamiltonian



Emergence of Spin Exchange Interactions

Norcia,.., Rey, JKT, *Science* **361**, 6399, 259 (2018)
Davis,,…Schleier-Smith *PRL* **122**, 010405 (2019)

Classical Dipole-Field Interaction Hamiltonian

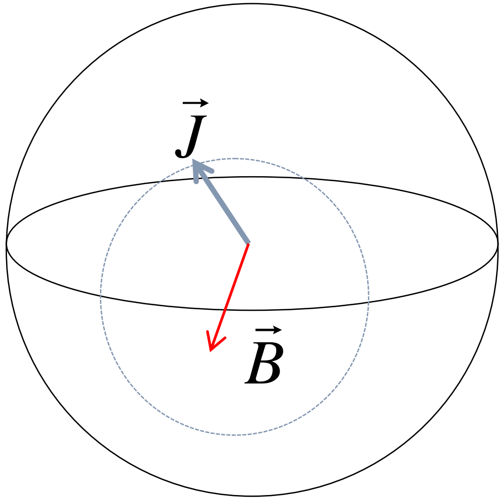
$$H \propto \vec{J} \cdot \vec{B}$$

$$\vec{B} \propto J_x \hat{x} + J_y \hat{y}$$

$$H \propto J_x^2 + J_y^2$$

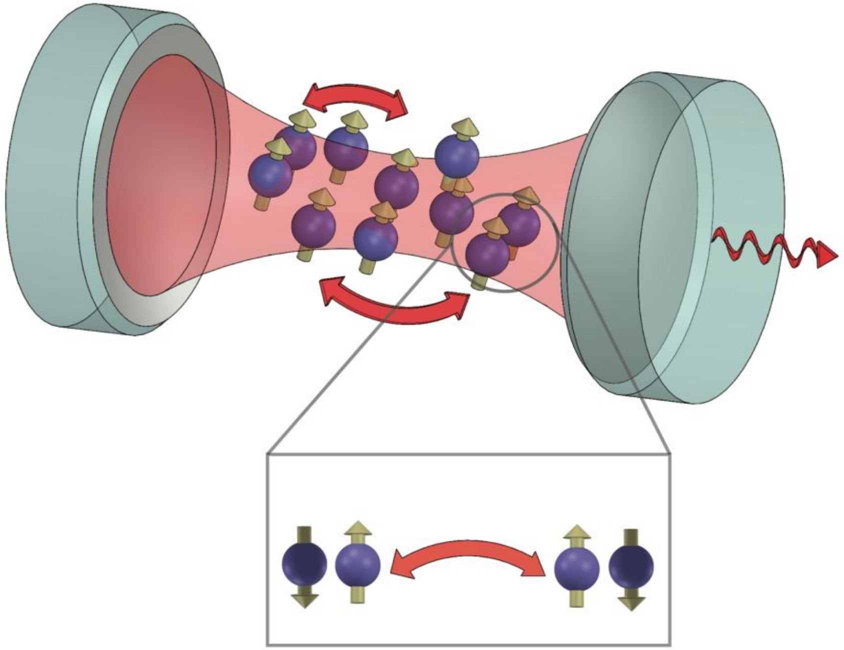
$$J_{\pm} = J_x \pm i J_y$$

$$H \propto J_+ J_-$$

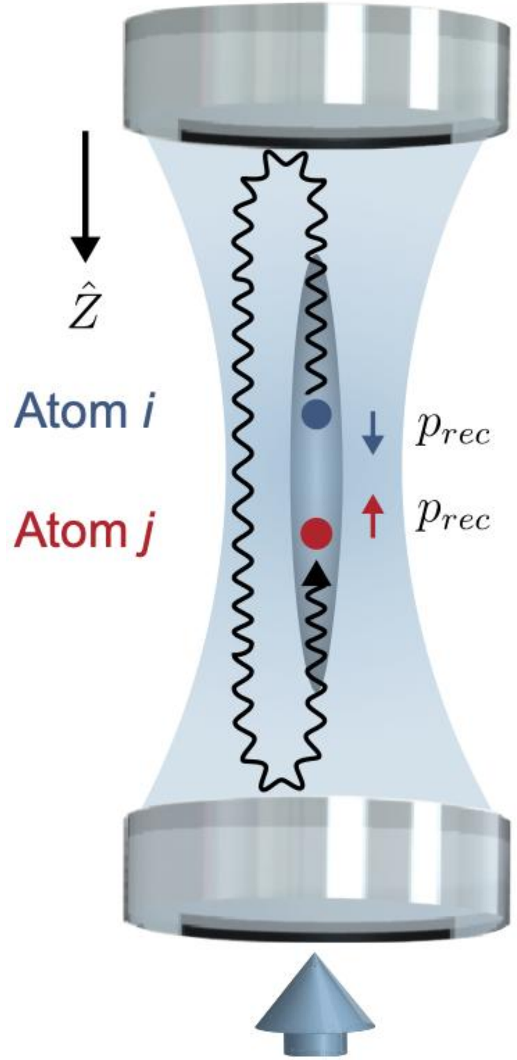


Quantum Hamiltonian—"just add hats"

$$\hat{H} = \chi \hat{J}_+ \hat{J}_- = \tfrac{1}{4} \chi \sum_{i,j}^{N} \hat{\sigma}_i^+ \hat{\sigma}_j^-$$



Collective Scattering from Moving Bragg Mirror



Initial Bragg Pulse: superposition

$$|p_0 - \hbar k\rangle \rightarrow \frac{1}{\sqrt{2}}(|p_0 - \hbar k\rangle + |p_0 + \hbar k\rangle) = \cos k\left(Z - \frac{p_0}{m}t\right)$$

Moving atomic density grating

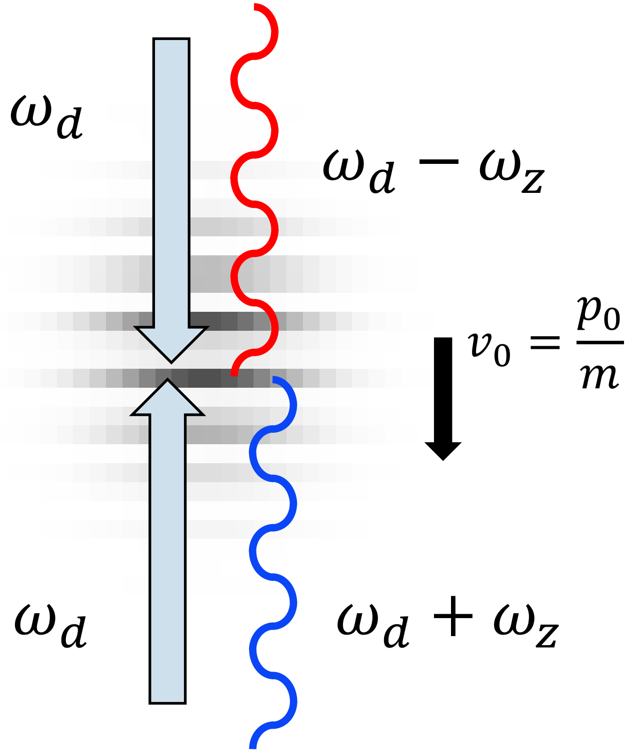
$$\mathrm{P(Z)} = \cos^2 k\left(Z - \frac{p_0}{m}t\right) \rightarrow n(Z)$$ index of refraction $n_1 \sim 10^{-8}$

<u>Collective</u>

back scattered fields coherently add!

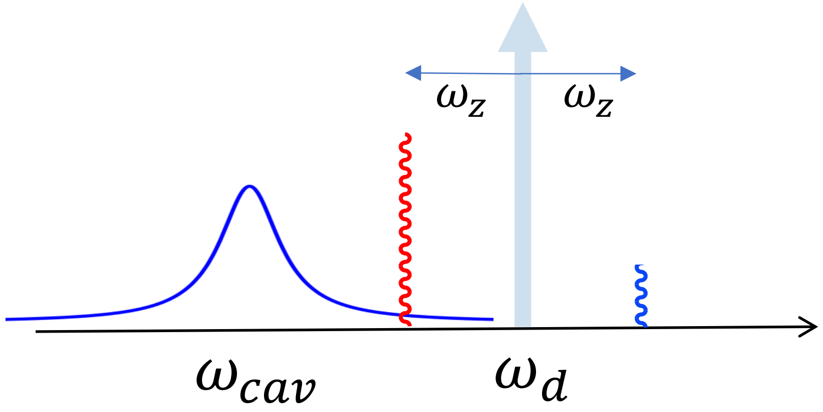
$E = N E_1$

Power ~ E^2 ~ N^2



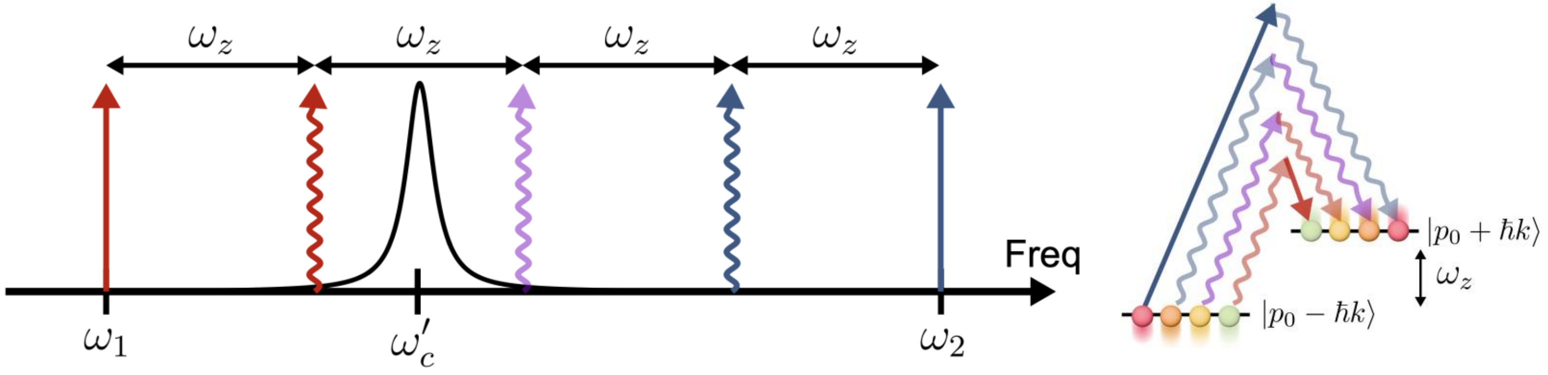
Doppler shift after bouncing off of a moving mirror

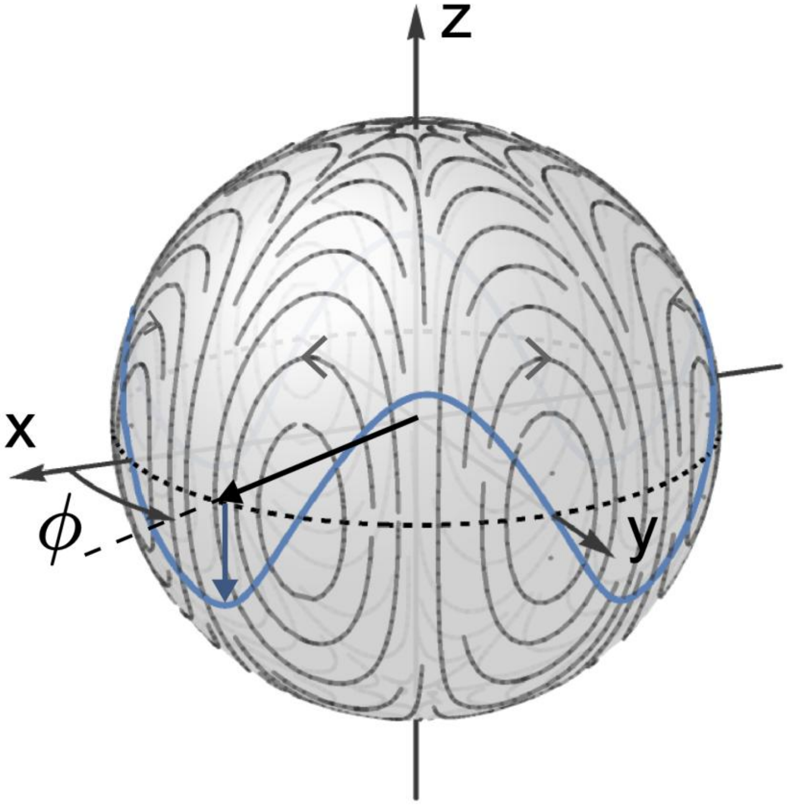
$$\omega_z = 2kv_0$$

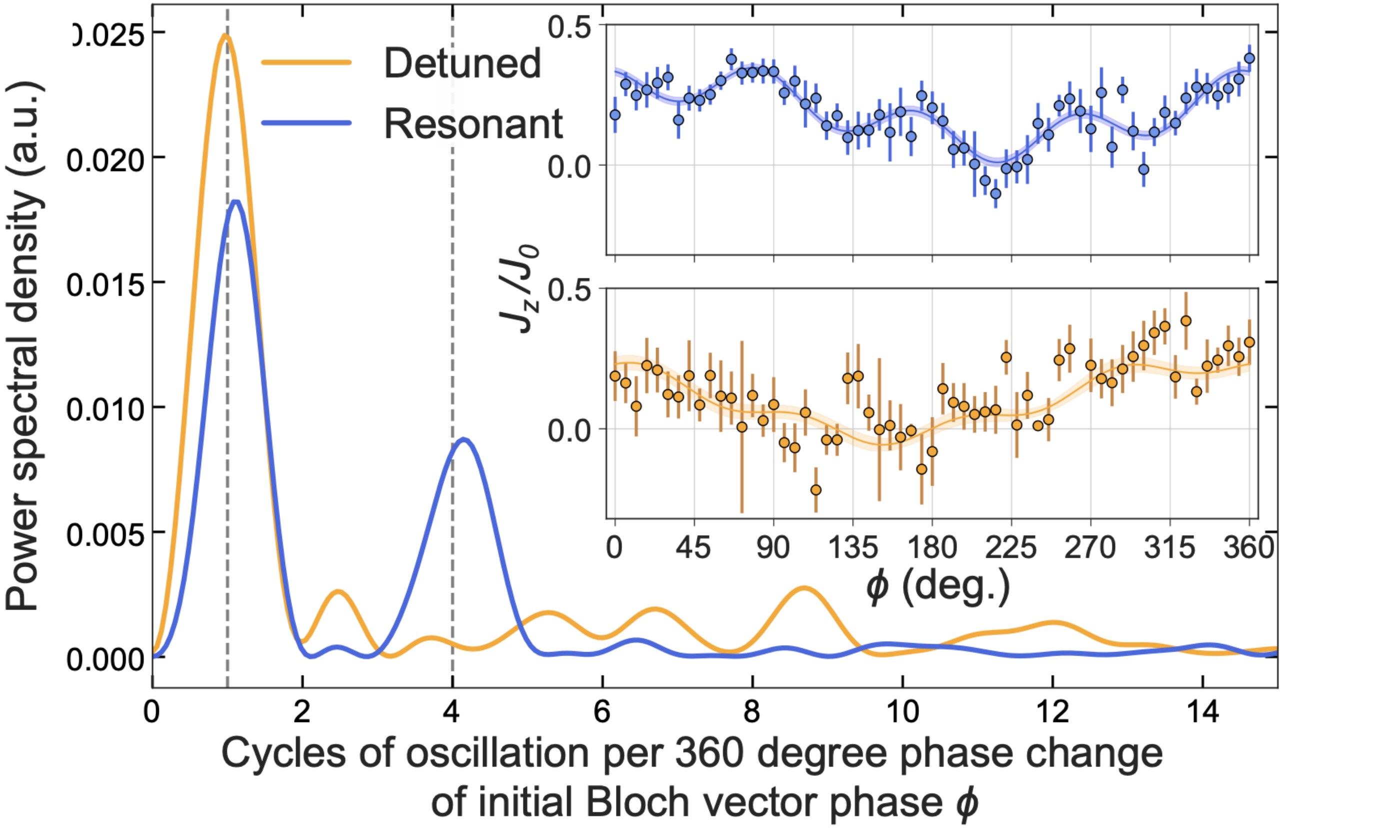


4-body Interaction: 4 atoms / 8 photons

$$\hat{H}_4 = \chi\left(\hat{J}_+^4 + \hat{J}_-^4\right)$$





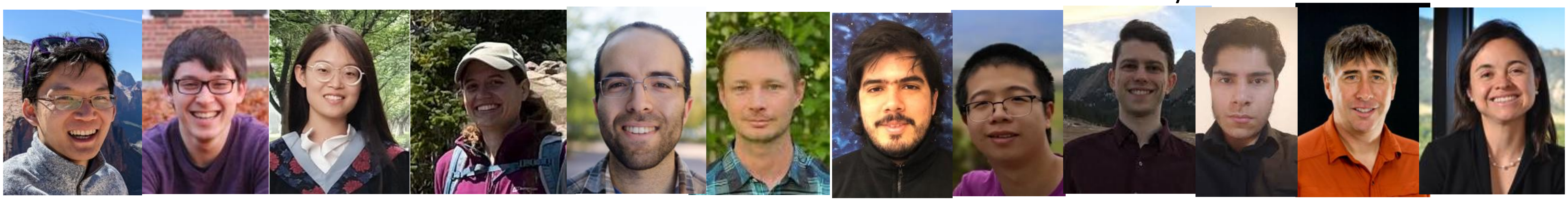


10 Fixed Points: 8 stable at equator
2 Quadrafurcation™ points at N & S poles

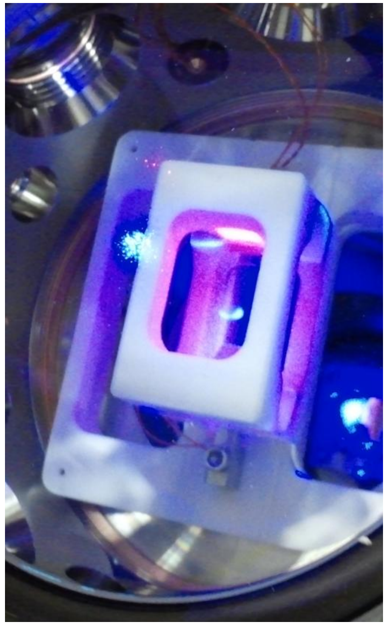
Topics for Today

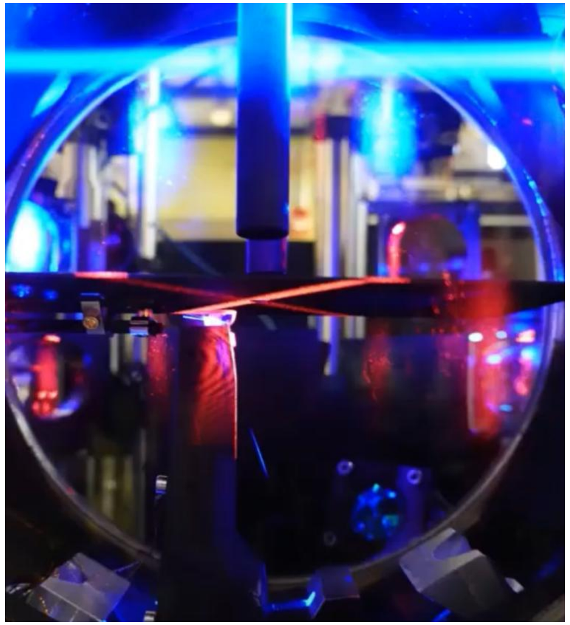
Sr Experiments

Theory



Eric Song | Dylan Young | Zhijing Niu | Vera Schäfer | Juan Muniz | Matt Norcia | Diego Barberena | Anjun Chu | Jeremy Young | Edwin Chaparro | Murray Holland | Ana Maria Rey



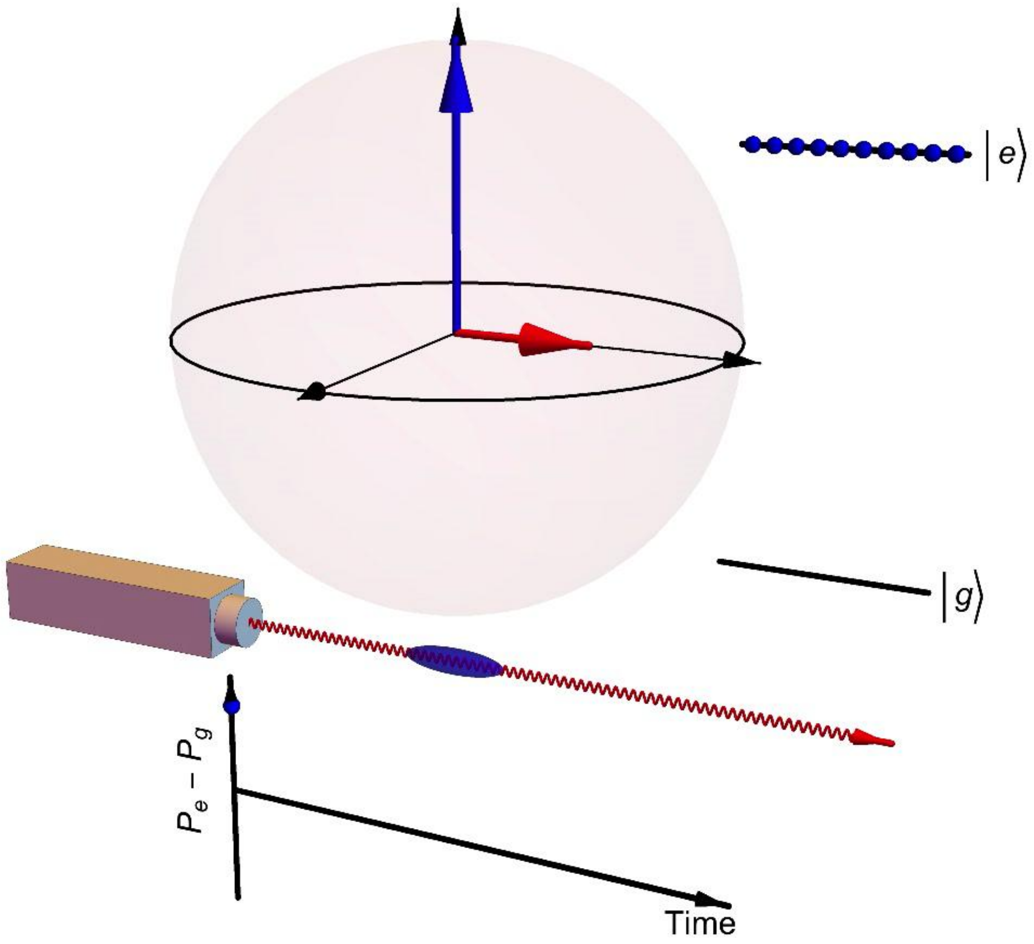


- Superradiance
- Lasing between momentum states
- Dissipative phase transition
- Dark laser
- Berry phases for one-axis twisting

Start Simple! Rabi Flopping

Applied field described as
fictitious magnetic field B

$$H \propto \vec{J} \cdot \vec{B}$$



Superradiance: A self-driven ½ Rabi flop

Field radiated into cavity
by atomic dipoles described by
fictitious magnetic field B:

$$H \propto \vec{J} \cdot \vec{B}$$

$$\vec{B} \propto J_y \hat{x} + J_x \hat{y}$$