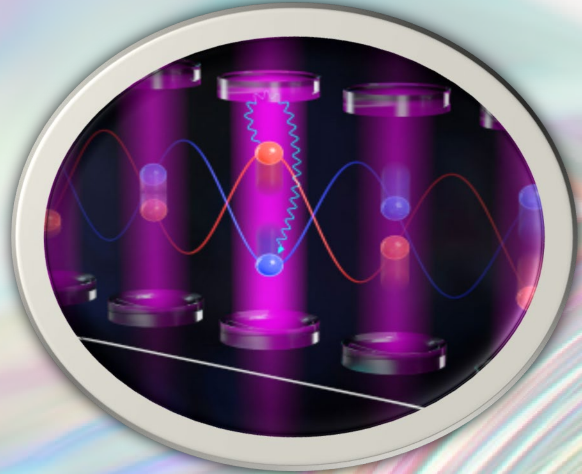
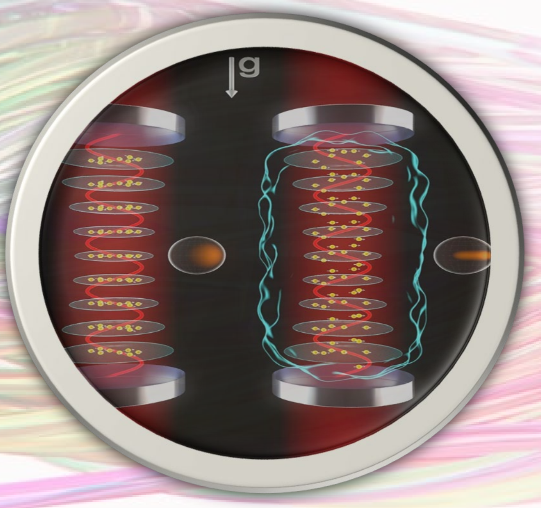
More than two can dance: Twisting, double-twisting & binding in an optical cavity

Ana Maria Rey



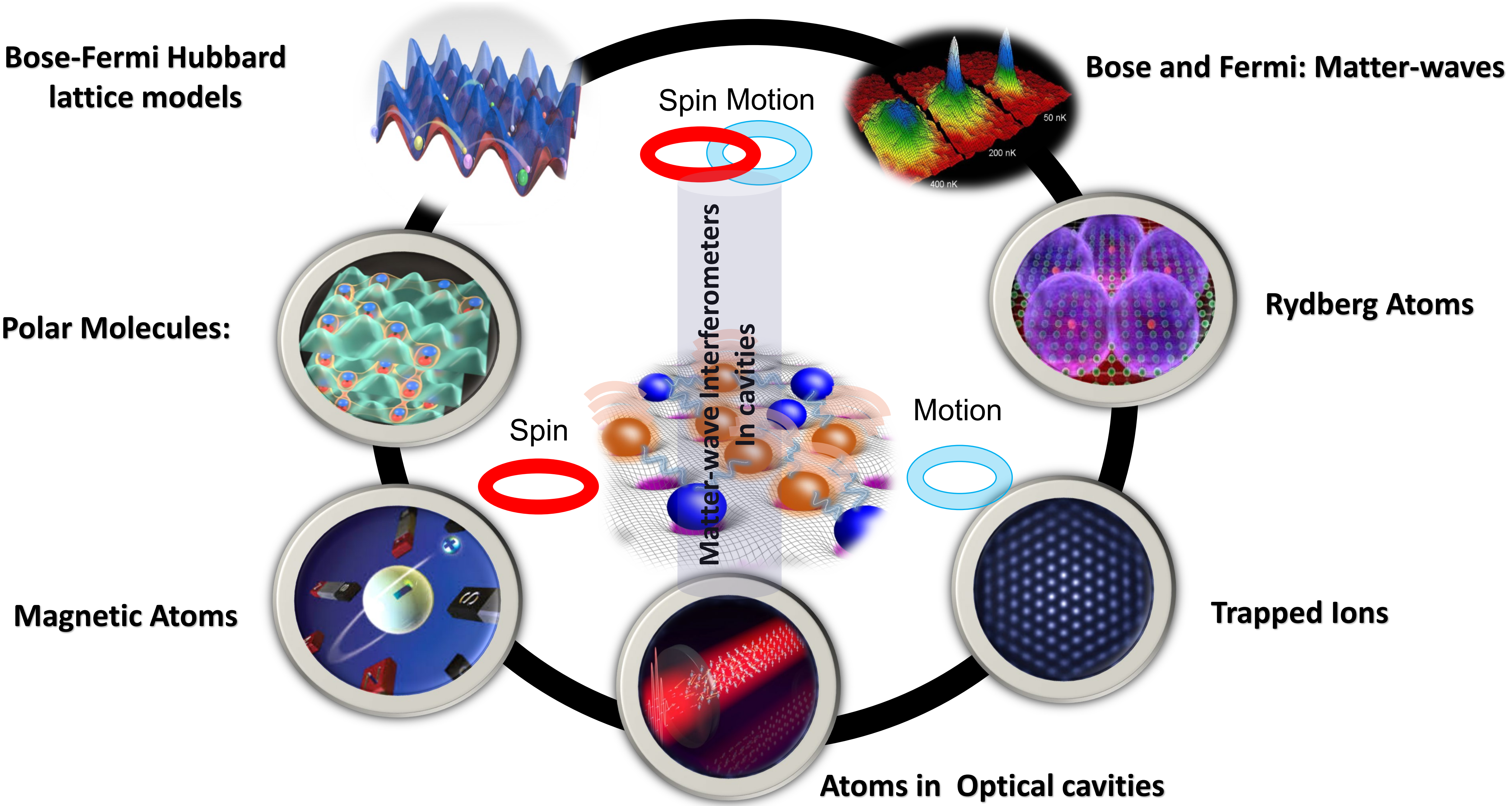


Long-Range Interactions and Dynamics in Complex Quantum Systems, July 25th (2025)

JILA NIST CU

Controllable Long-range Interacting Systems

Controllable Interacting Systems



Theory:

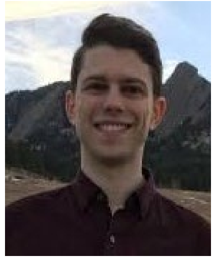
D. Barberena

R. Lewis-Swan

A. Piñeiro

B. Sundar

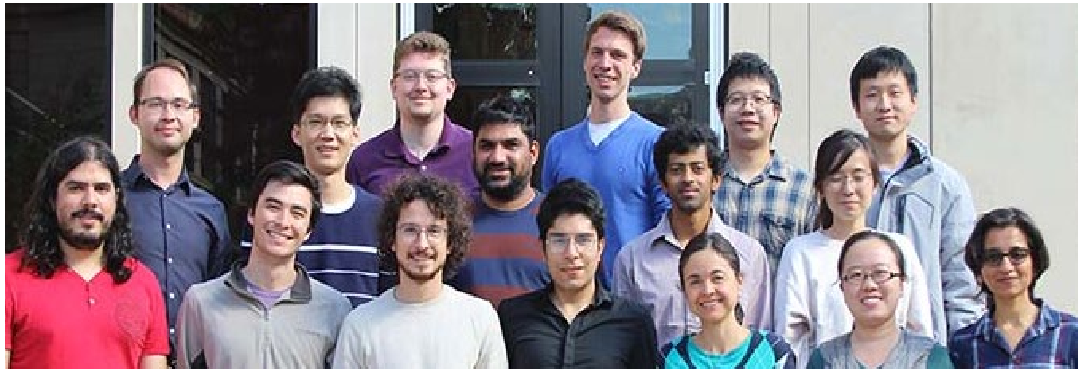
E. Chaparro



J. Young

A. Shankar

B. Zhu



J Bollinger, Klaus MØlmer, M. Holland, R. Fazio

Experiment:

Z. Niu

E. Yilun

D. Young

C. Maruko

E. Bohr

M. Norcia,
V. M. Schäfer

J. Ye

Hamiltonian Engineering

Binding and Twisting

- Cavity-mediated momentum-exchange interaction
  Luo, Zhang, Koh, Wilson, Chu, Holland, Rey, Thompson, *Science 384 ,551 (2024*)

- Solitons in arbitrary dimensions stabilized by photon-mediated interactions
  Zhang, Chu, Luo, Thompson,· Rey, arXiv:2504.1707

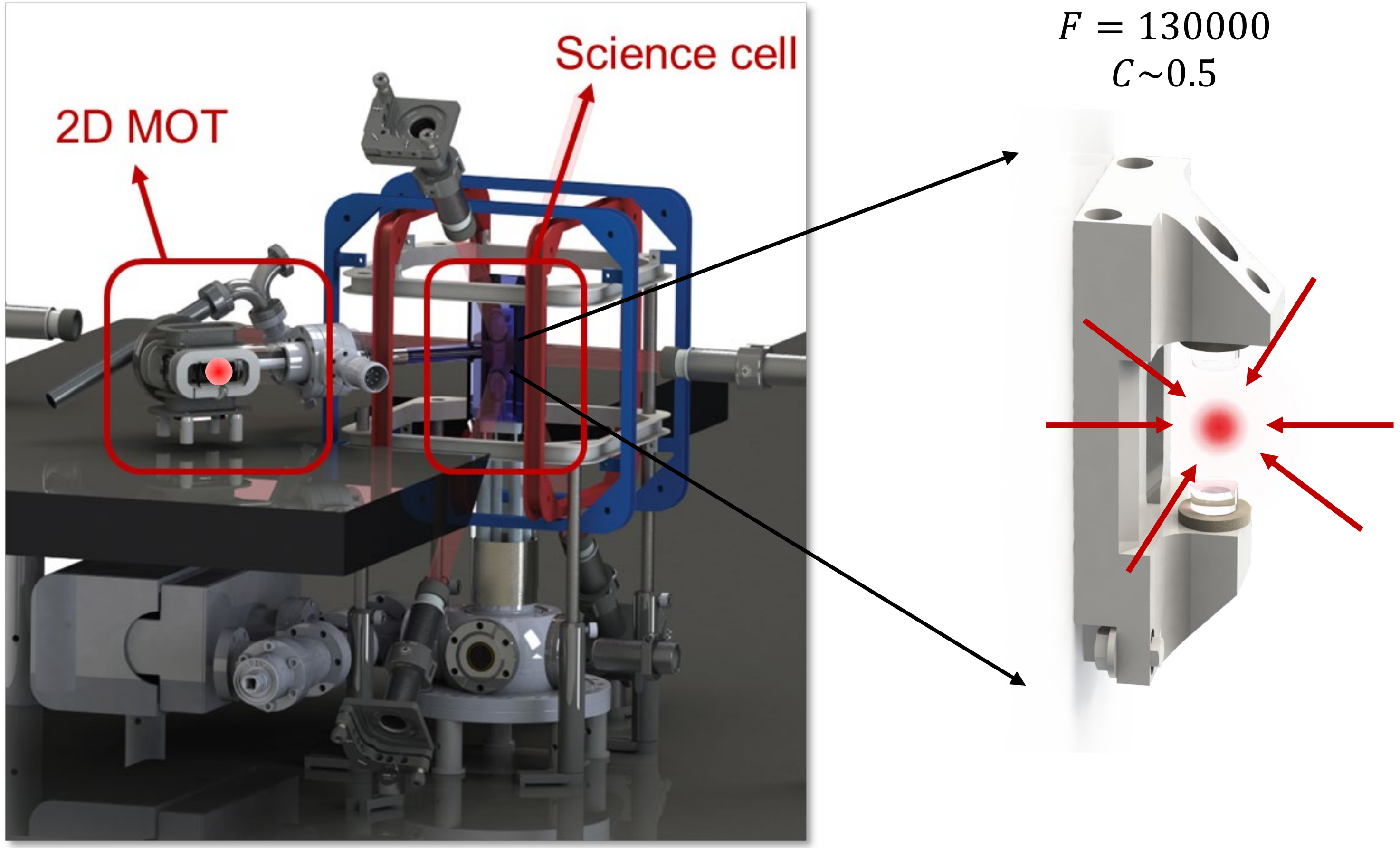
Double the Twisting

- XYZ Hamiltonian engineering of momentum states
  Luo*, Zhang*, Chu, Maruko, Rey, Thompson, Nature Physics, 916 (2025)

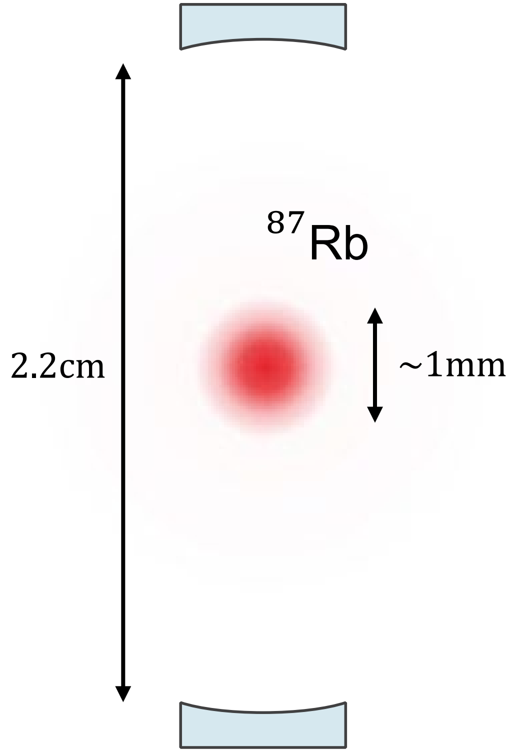
Many - Buddies

- Observation of three and four-body interactions between momentum states mediated by a high-finesse cavity
  Luo*, Zhang*, Chu, Maruko, Rey, Thompson, arXiv:2410.12132, In press Science

JILA Cavity QED Rb System



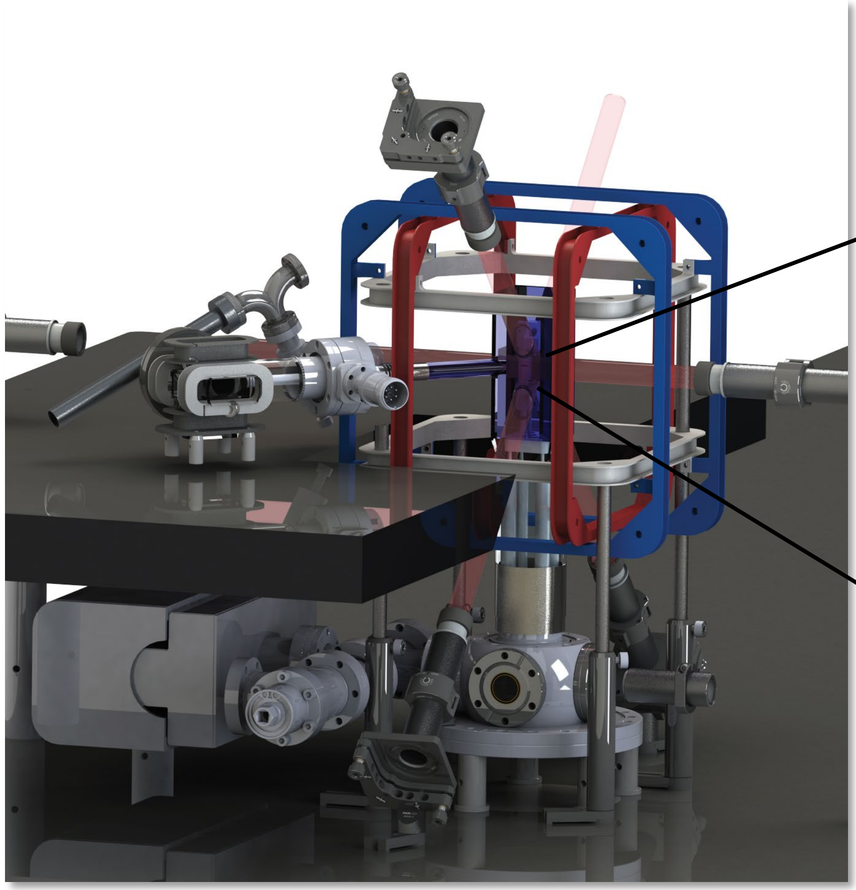
$FSR = 6.79$ GHz
$\kappa = 52$ kHz



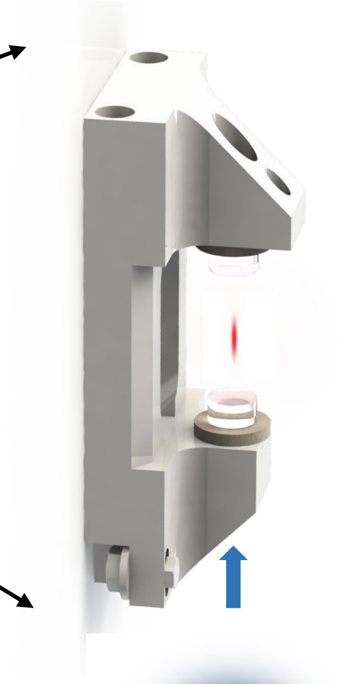
Vertical high-finesse cavity

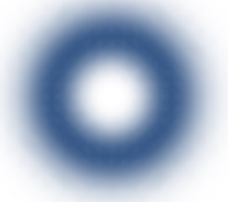
Atoms Doppler Cooled to few μK

JILA Cavity QED Rb System

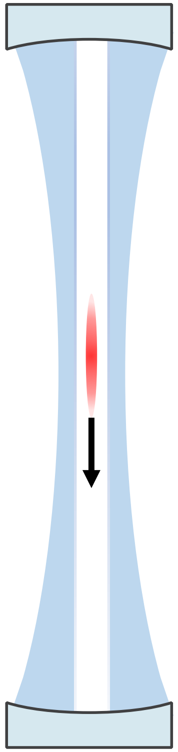


$F = 130000$
$C \sim 0.5$



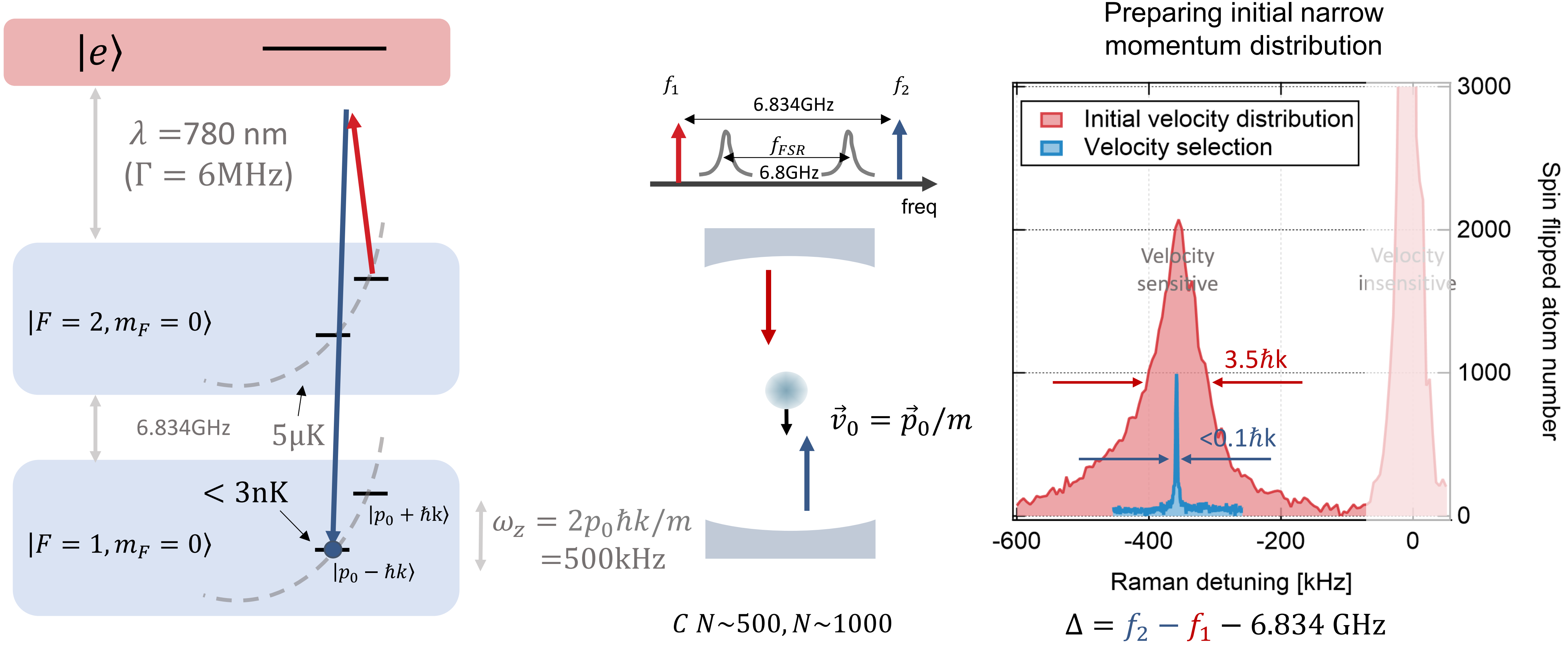


Repulsive



760nm dipole trap
(exciting multiple FSR)

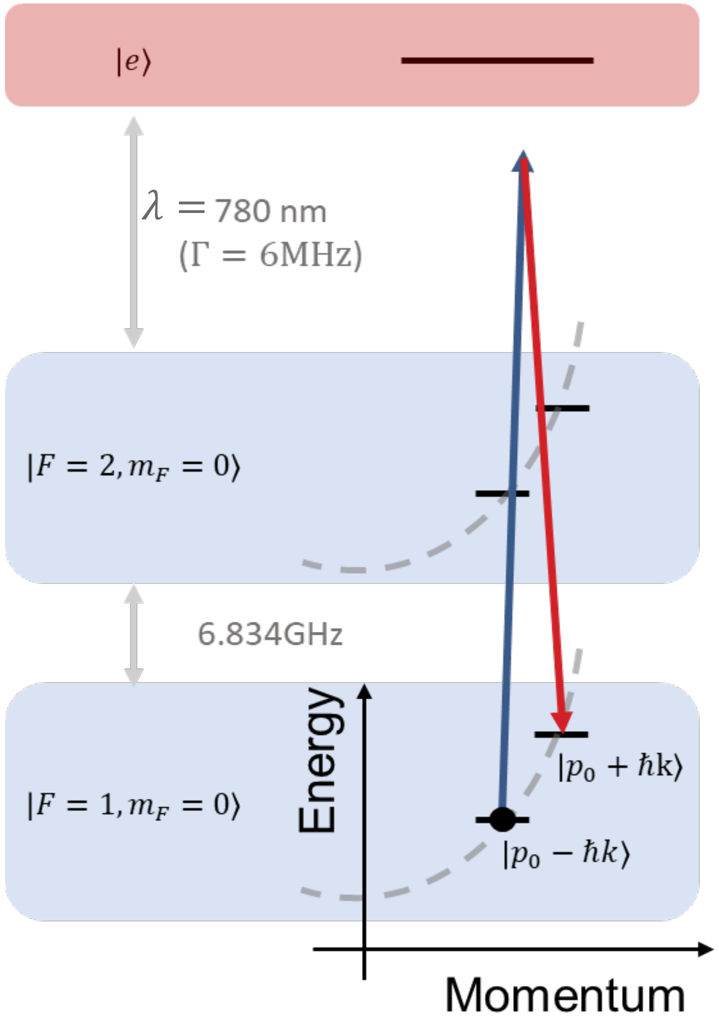
Velocity Selection: Narrow momentum distribution



$\Delta = f_2 - f_1 - 6.834\ \text{GHz}$

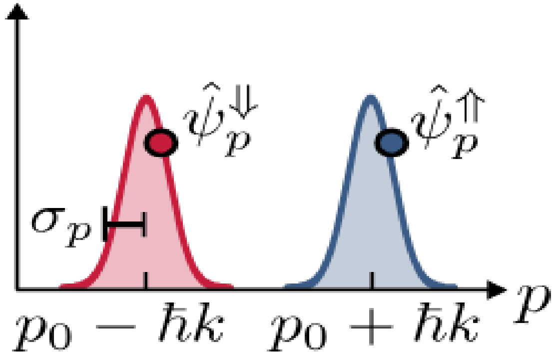
Bragg- Interferometer: Only momentum states

Luo, Zhang, …, Rey, Thompson, *Science 384 (6695), 551 (2024)*



$\omega_z = 2p_0\hbar k/m$
$=500\mathrm{kHz}$

Momentum distribution



$$\sigma_p \sim 0.1\hbar k \ll 2\hbar k$$

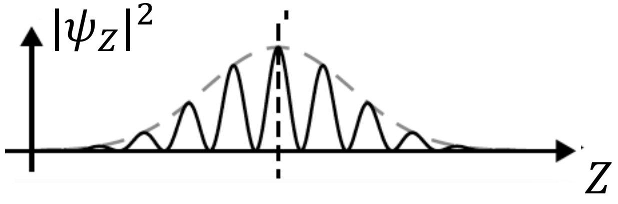
$$p \in [-\hbar k, \hbar k]$$

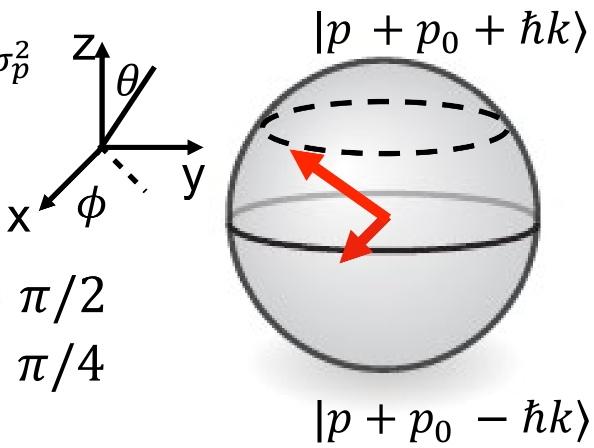
$$|\psi(p)\rangle = \sin(\frac{\theta}{2})\,|p + p_0 + \hbar k\rangle + \cos\,(\frac{\theta}{2})\,e^{i\phi}|p + p_0 + \hbar k\rangle$$

Density grating

$$|\psi_Z|^2 = [1 + \sin\theta\cos(2kZ - \phi)]\,e^{-Z^2\sigma_p^2}$$

$\theta = \pi/2$
$\theta = \pi/4$

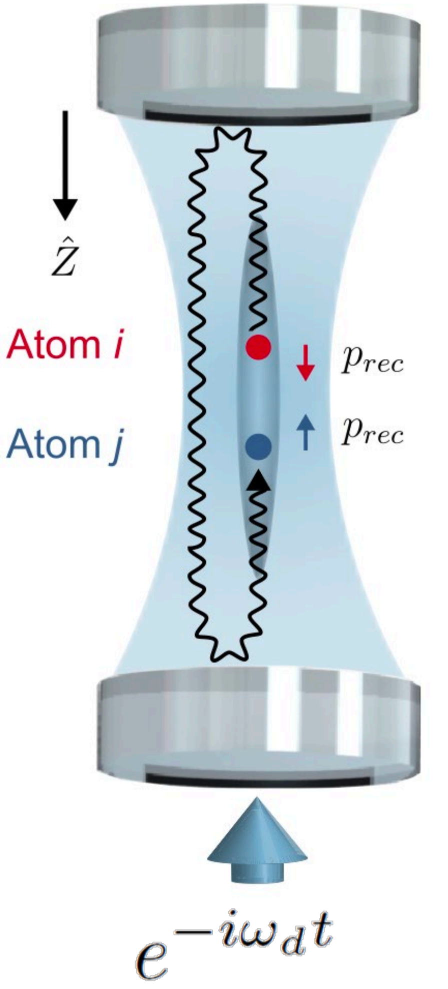




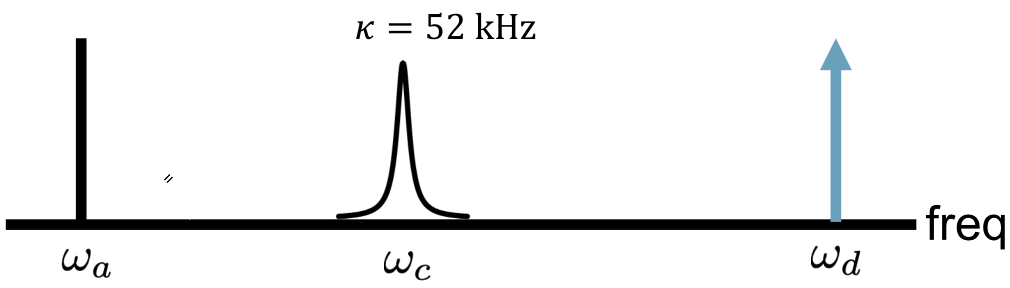
$\theta = \pi/2$
$\theta = \pi/4$

Shankar *et al* *QS&T.* **4** 045010 (2019)
Wilson *et a, PRA* **106**, 043711 (2022)

Atom/Light Hamiltonian



$$\hat{H}_{\text{lab}} = \hat{H}_{\text{atom}} + \hat{H}_{\text{light}} + \hat{H}_{\text{int}}$$



$$\hat{H}_{\text{light}} = \hbar\left(\eta\hat{a}^\dagger e^{-i\omega_d t} + \eta^*\hat{a}e^{i\omega_d t}\right) + \hbar\omega_c\hat{a}^\dagger\hat{a}$$

$$\hat{H}^e_{\text{atom}} = \hbar\omega_a \int \hat{\psi}^\dagger_e(Z)\hat{\psi}_e(Z)\,dZ$$

$$\hat{H}^g_{\text{atom}} = \int \hat{\psi}^\dagger_g(Z)\frac{\hat{p}^2}{2m}\hat{\psi}_g(Z)\,dZ$$

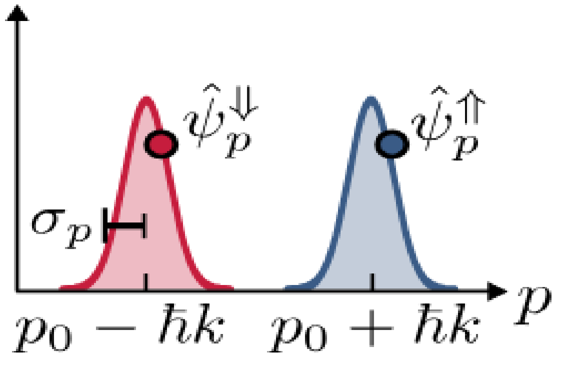
Kinetic energy

$$\omega_z = \frac{2kp_0}{m}$$

$$\hat{S}_\alpha = \sum \hat{s}_\alpha(p)$$

$$\hat{H}^g_{\text{atom}} = \omega_z\hat{s}_z + \frac{2\hbar k}{m}\sum_p p\hat{s}_z(p) + \sum_p \frac{p^2}{2m}\hat{I}$$

Doppler dephasing $\vec{v}_{rec}$

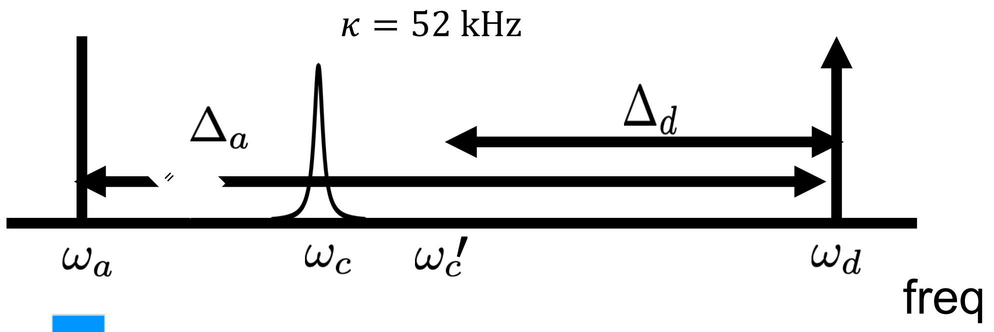


Atom-Light Interaction

Tavis-Cuming Interaction

$$\hat{H}_{\text{int}} = \hbar g_0 \int \cos(kZ) \left[\hat{a}\hat{\psi}_e^\dagger(Z)\hat{\psi}_g(Z) + \hat{a}^\dagger\hat{\psi}_g^\dagger(Z)\hat{\psi}_e(Z) \right] dZ$$

$$\Delta_a = \omega_a - \omega_d \sim 500 \text{ MHz} \qquad \Delta_a \gg \sqrt{N_{\text{ph}}}\, g_o$$



Elimination of the excited state

Rotating frame of the pump

$$\Delta_d = \omega_d - \omega_c - \frac{N g_0^2}{2\Delta_a}$$

Detuning between pump field and dressed cavity resonance

$$\hat{H}_{\text{light}} = -\hbar\Delta_d \hat{a}^\dagger\hat{a} + \hbar\left(\eta\hat{a}^\dagger + \eta^*\hat{a}\right)$$

$$H_{a-c} = G\ \hat{a}^\dagger\hat{a} \int dZ [\underbrace{\hat{\psi}_g(Z)^\dagger e^{i2kZ}\hat{\psi}_g(Z)}_{\hat{S}_+} + \underbrace{\hat{\psi}_g(Z)^\dagger e^{-i2kZ}\hat{\psi}_g(Z)}_{\hat{S}_-}] = G\ \hat{a}^\dagger\hat{a}\,(\hat{S}_- + \hat{S}_+) = 2G\ \hat{a}^\dagger\hat{a}\hat{S}_x$$

$$G = \frac{\hbar g_o^2}{4\Delta_a}$$

Effective Atom-Atom Interaction

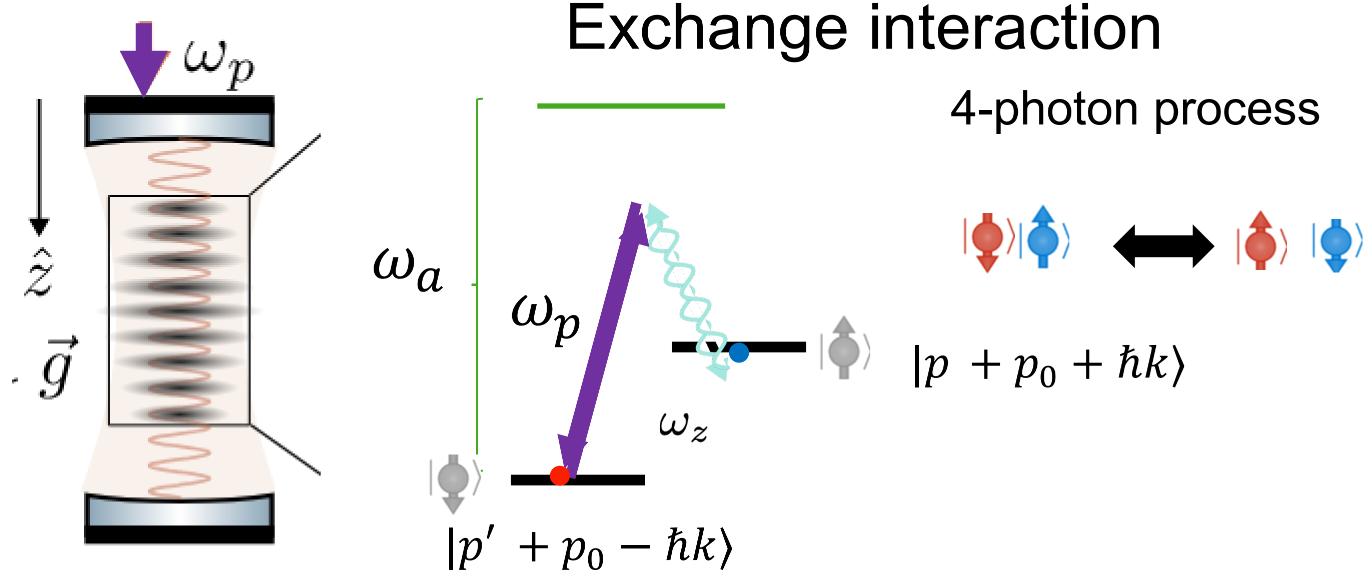
After adiabatic elimination of the cavity mode ($G\alpha_o^2\sqrt{N} \ll \Delta_d \pm \omega_z$)

$$\hat{a} = \alpha_0 + \hat{b}, \qquad \alpha_0 = \frac{\eta}{\Delta_d + i\kappa/2} \qquad \hat{b}^\dagger\,\hat{b} \ll 1$$

$$\hat{H}_{\text{coll}} \approx \chi\left(\hat{S}_- e^{-i\omega_z t} + \hat{S}_+ e^{i\omega_z t}\right)\left(\hat{S}_- e^{-i\omega_z t} + \hat{S}_+ e^{i\omega_z t}\right) \qquad \chi N \sim 5\text{kHz}$$

$$\sim \chi\left(\hat{S}_-\hat{S}_+ + \hat{S}_-\hat{S}_+\right)$$

Exchange interaction



Richerme, …, Monroe, *Nature*, 511, 198-201 (2014)
Jurcevic, …, Roos, *Nature*, 511, 202-205 (2014)
Franke, …, Rey, Roos, *Nature* 621, 740-745 (2023)

Twisting and Binding in the Cavity

$$H_{gg} = H_{sp} + H_{coll}$$

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

Many-body gap protection

One-axis twisting

Doppler dephasing

$$H_{sp} = 2\frac{\hbar k}{m}\sum_p p\hat{s}_z(p)$$

$\vec{v}_{rec}$

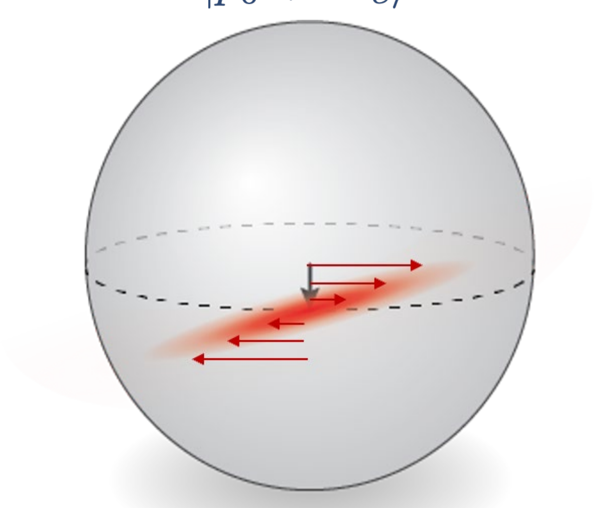
One Axis Twisting shift of Brag Interferometer

OAT → Invesrion dependent phase shift

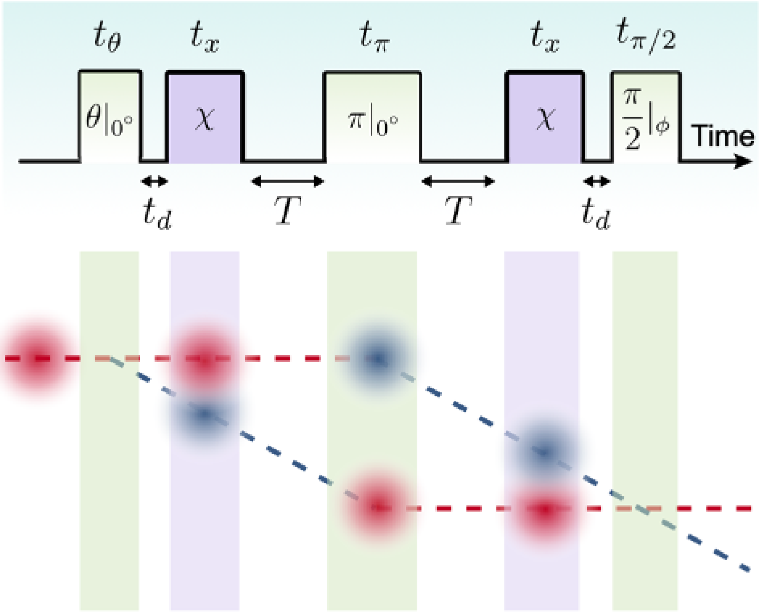
$$\hat{H}_{\mathrm{OAT}} \approx -\chi(\hat{S}_z\hat{S}_z) \approx -2\chi\langle\hat{S}_z\rangle\hat{S}_z$$

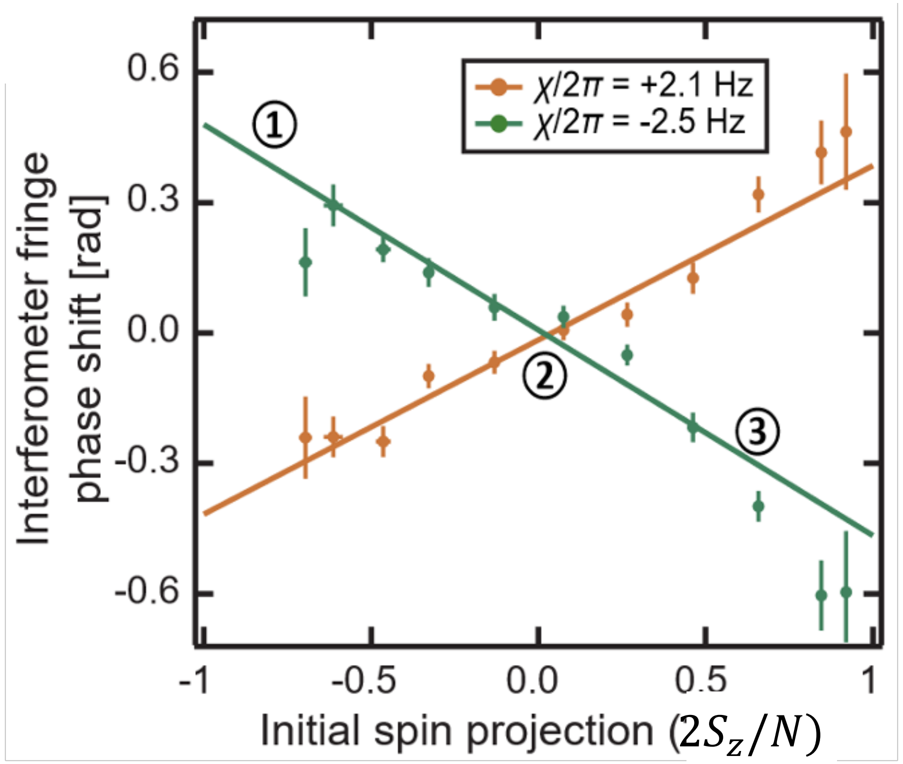
$$\rightarrow \Delta\phi = -2\chi\langle\hat{S}_z\rangle t$$

Kitagawa, Ueda PRA 47, 5138 (1993)
Wineland *et al* PRA 50, 67 (1994)
Sorensen *et al* Nature 409, 63 (2001)
Pezze *et al* RMP 90, 035005 (2018)
...



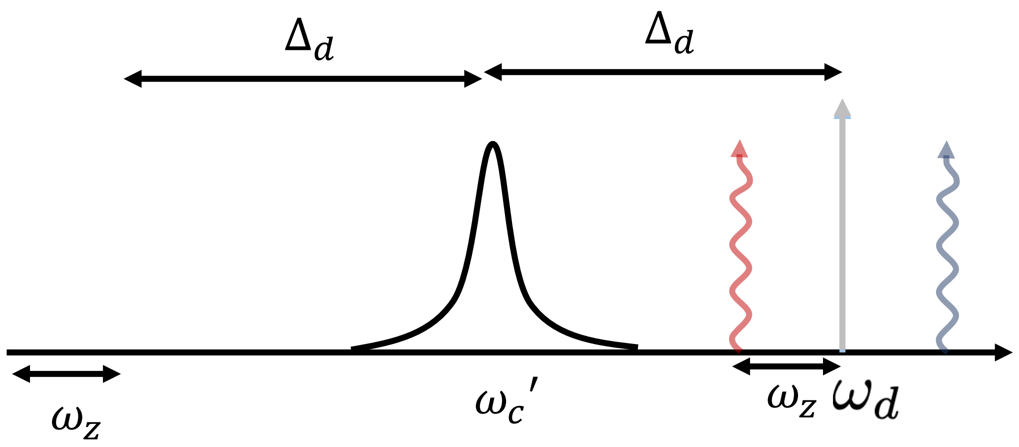
Interferometer





Luo, Zhang, …, Holland, Rey, Thompson, Science **384**, 551 (2024)

Changing χ: Scanning pump tone through resonance

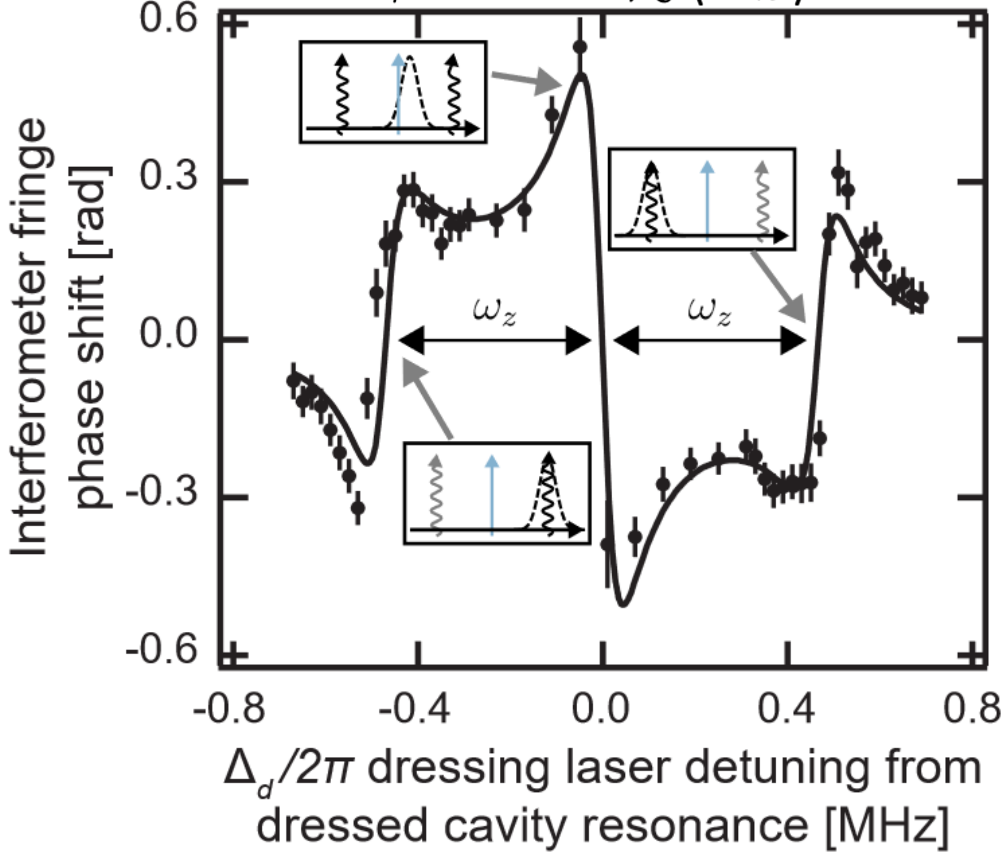


$$\chi \propto \frac{|\eta|^2}{{\Delta_d}^2 + \frac{\kappa^2}{4}} \left(\frac{\Delta_d + \omega_z}{(\Delta_d + \omega_z)^2 + \frac{\kappa^2}{4}} + \frac{\Delta_d - \omega_z}{(\Delta_d - \omega_z)^2 + \frac{\kappa^2}{4}} \right)$$

Carrier

Sidebands

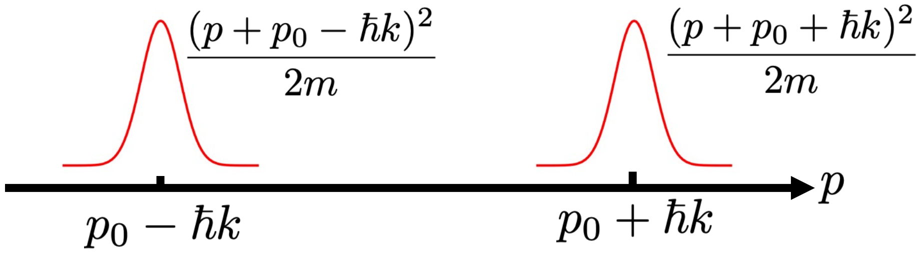
$$\Delta\phi = -2\chi\langle \hat{S}_z \rangle t$$



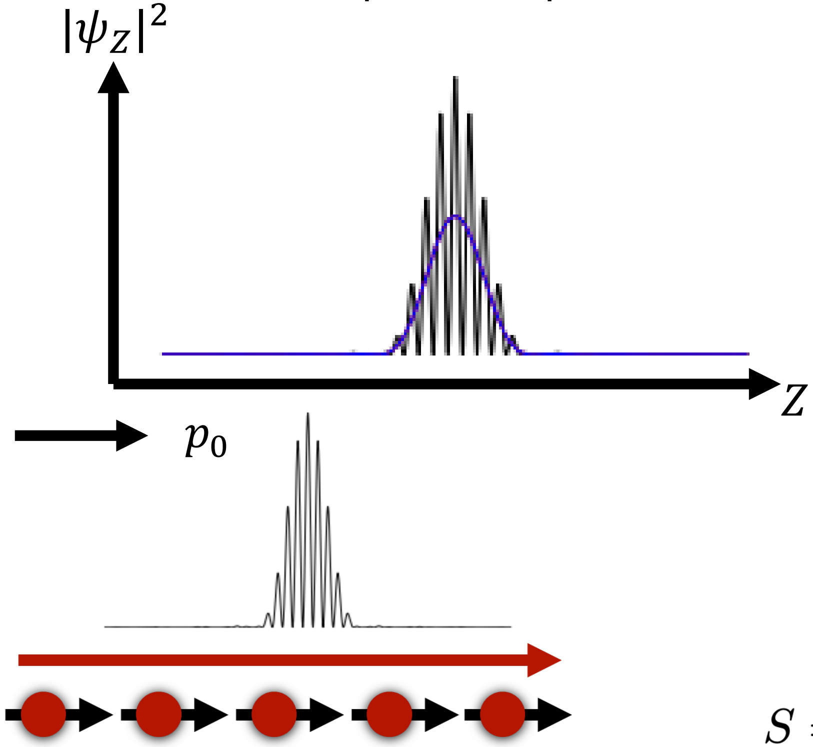
at fixed inversion

Non-Interacting Atoms

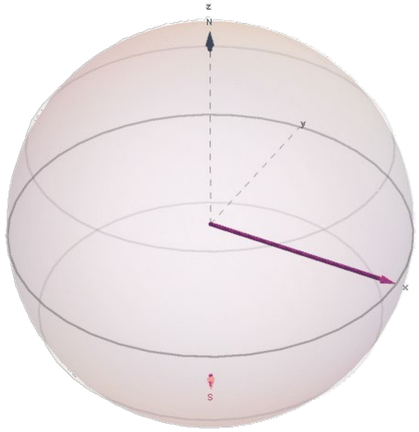
$$H_{\rm sp} = 2\frac{\hbar k}{m}\sum_p p\hat{s}_z(p)dp$$



Wave packet separation

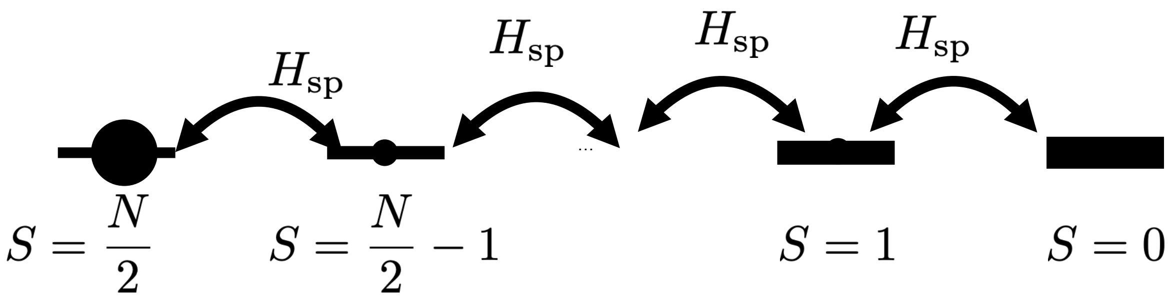


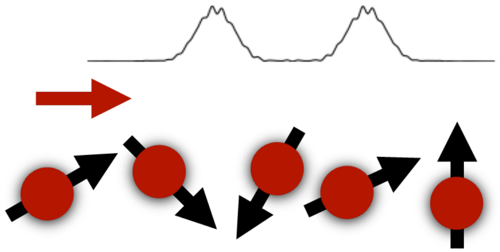
Shrink of Bloch vector length



$H_{\rm sp}$ doesn't conserve S

$$\hat{S}^2|S, S_z\rangle = S(S+1)|S, S_z\rangle$$



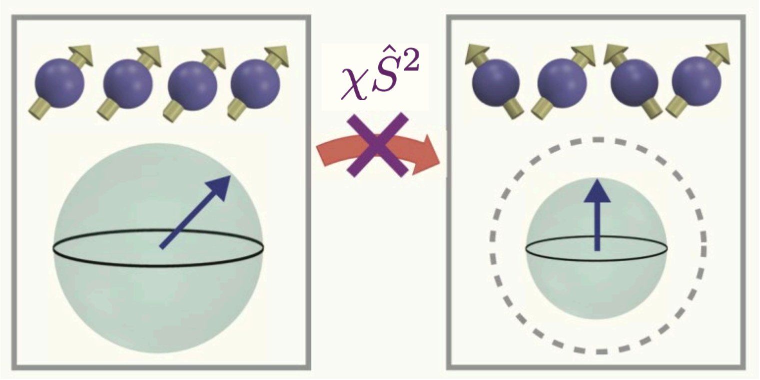


Many-body gap protection

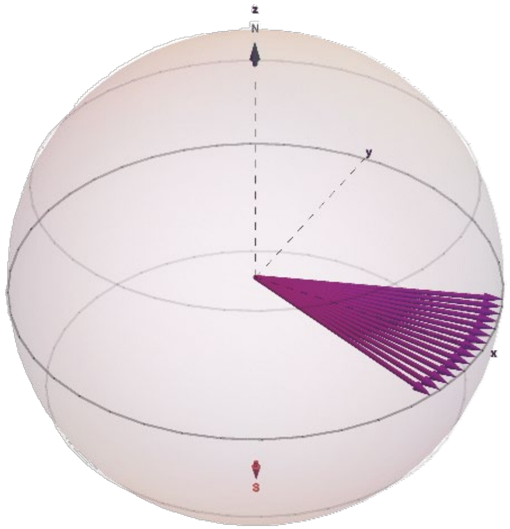
$$\hat{H}_{\text{coll}} \approx \chi\left(\hat{\boldsymbol{S}} \cdot \hat{\boldsymbol{S}} - \hat{S}_z^2\right)$$

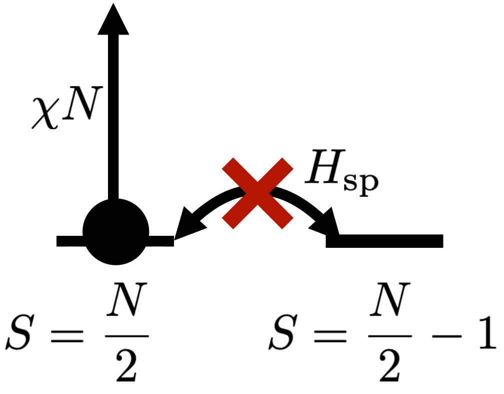
$$H_{\text{sp}} = 2\frac{\hbar k}{m}\sum_p p\,\hat{s}_z(p)$$

Binding wave packets together!



Locking spin together





Rey, …, Lukin, Phys. Rev. A **77**, 052305 (2008)
Norcia, …, Rey, Thompson, *Science* **361** 259 (2018)
Smale, He …, Rey, Thywissen *Sci. Adv* (2019)
Davis,…Schleier-Smith PRL125, 060402 (2020)
Franke, …, Rey, Roos, *Nature* 621, 740-745 (2023)

Binding wave-packets

Experiment sees momentum exchange interaction slows down dephasing!!.

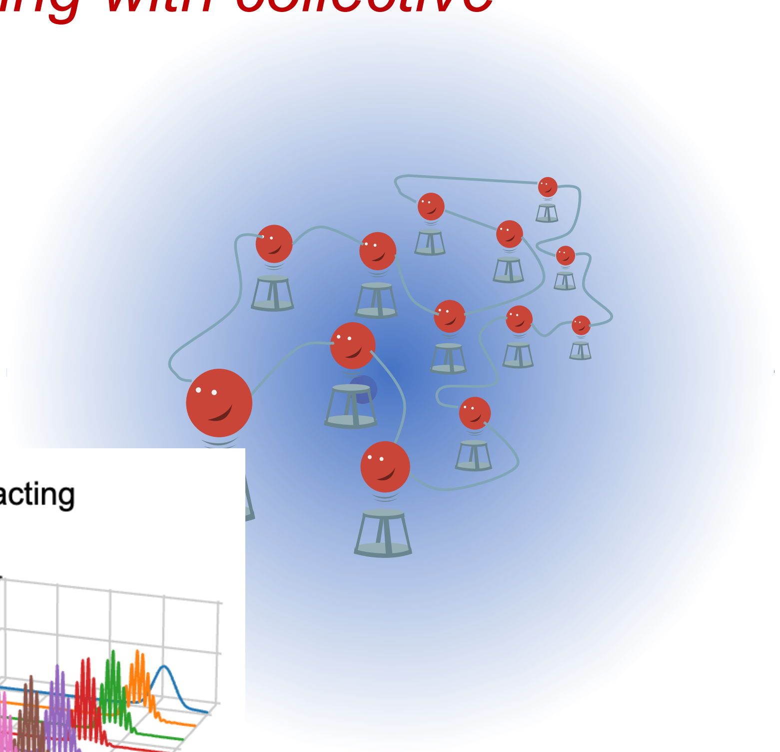
Ideal experiment: No-binding

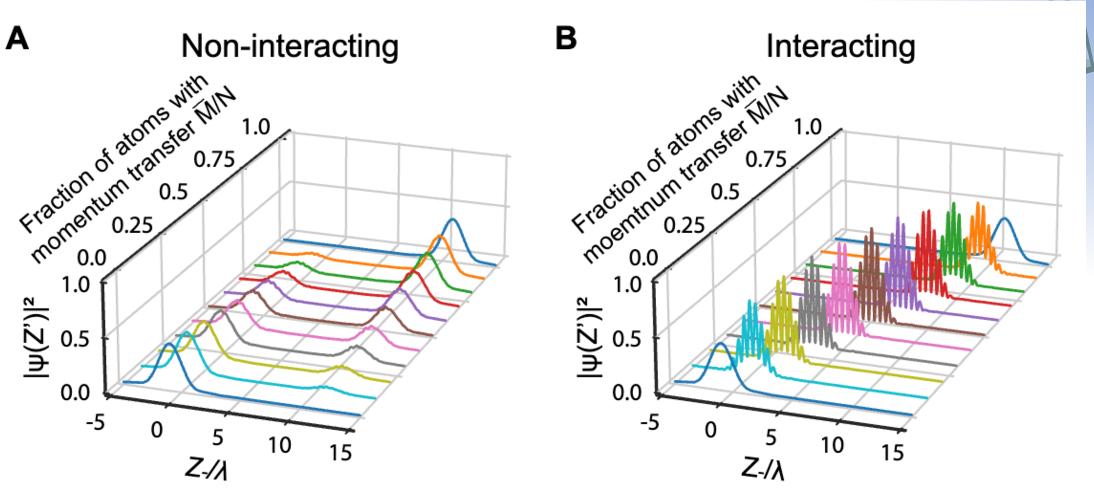
$$\vec{v}_{rec} = \hbar k/m$$

Ideal experiment: Binding

$\vec{v}_{rec}/N$

Suppressing Doppler dephasing with collective recoil!
A la Mossbauer!
A la Lamb-Dicke





Cavity QED implementation of BCS model

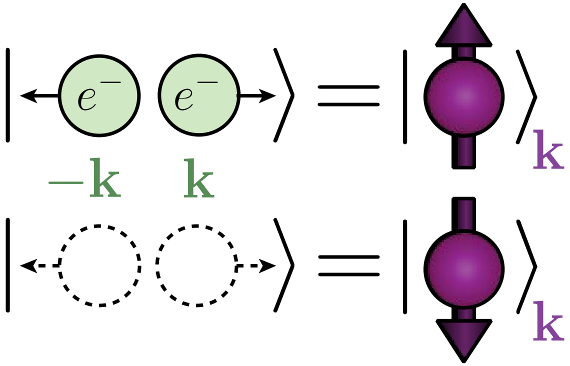
BCS model

$$\hat{H} = \sum_{\mathbf{k},\sigma} \varepsilon_{\mathbf{k}} \hat{c}^{\dagger}_{\mathbf{k},\sigma} \hat{c}_{\mathbf{k},\sigma} - \chi \sum_{\mathbf{k},\mathbf{k}'} \hat{c}^{\dagger}_{\mathbf{k},\uparrow} \hat{c}^{\dagger}_{-\mathbf{k},\downarrow} \hat{c}_{\mathbf{k}',\uparrow} \hat{c}_{-\mathbf{k}',\downarrow}$$

Kinetic energy of electrons

Scattering of Cooper pairs

Anderson pseudospin mapping



$$\Delta_{\mathrm{BCS}} \equiv \frac{\chi}{2} \langle \hat{S}_{-} \rangle$$

Cavity QED implementation

$$\hat{H} = \sum_{\mathbf{k}} \varepsilon_{\mathbf{k}} \hat{S}^{z}_{\mathbf{k}} - \chi \sum_{\mathbf{k},\mathbf{k}'} \hat{S}^{+}_{\mathbf{k}} \hat{S}^{-}_{\mathbf{k}'}$$

Doppler dephasing

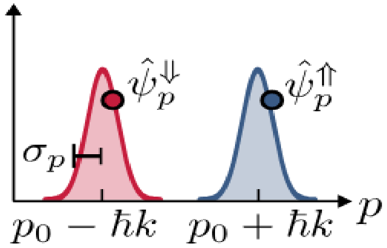
Spin-exchanged interactions

Lewis-Swan, …, Thompson, Rey, PRL **126** (17), 173601 (2021)
Young, Chu, …, Rey, Thompson *Nature* **625**, 679-684 (2024)

Many-body gap protection with momentum spins

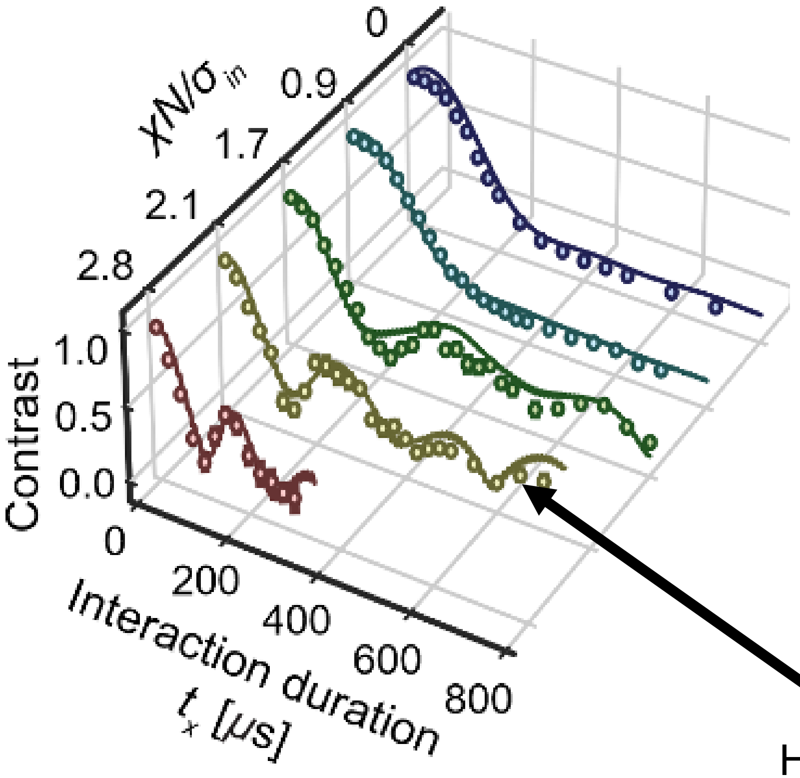
Luo, Zhang, …, Rey, Thompson, *Science 384 (6695), 551 (2024)*

$$H_{\rm sp} = 2\frac{\hbar k}{m}\sum_p p\hat{s}_z(p)$$ **Kinetic energy of electrons**

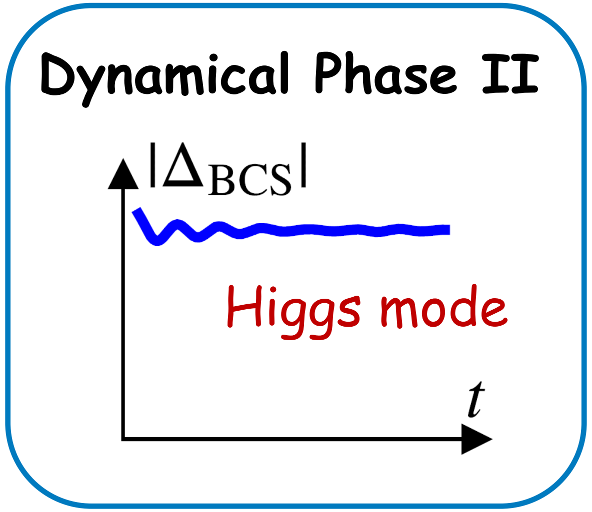


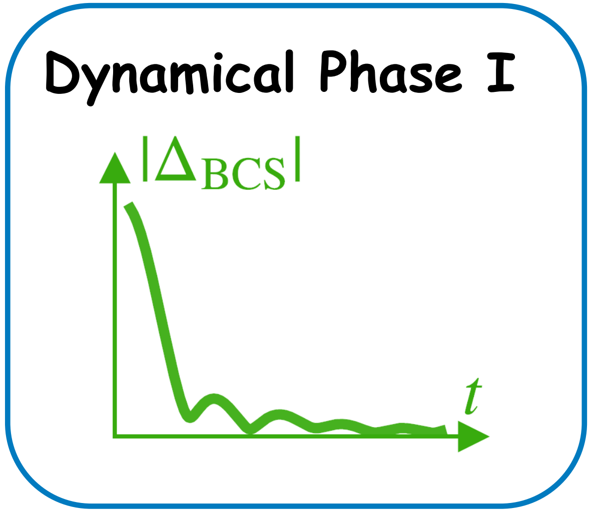
Protection against contrast loss

$$\hat{H}_{\rm coll} \approx \chi\left(\hat{\boldsymbol{S}}\cdot\hat{\boldsymbol{S}} - \hat{S}_Z^2\right)$$ **Interaction Energy**

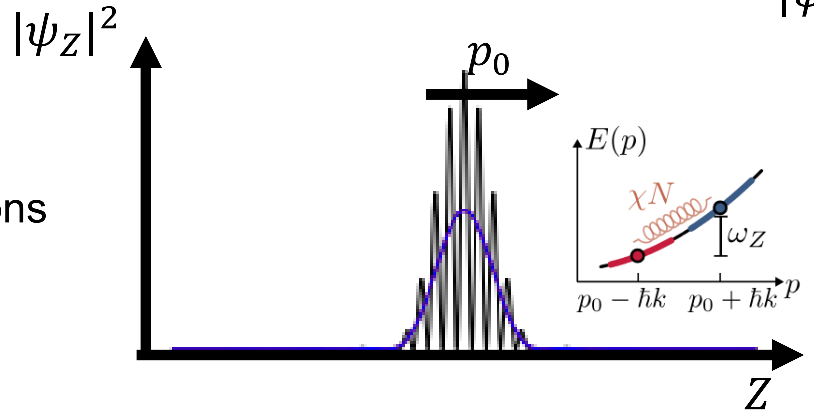


Higgs oscillations

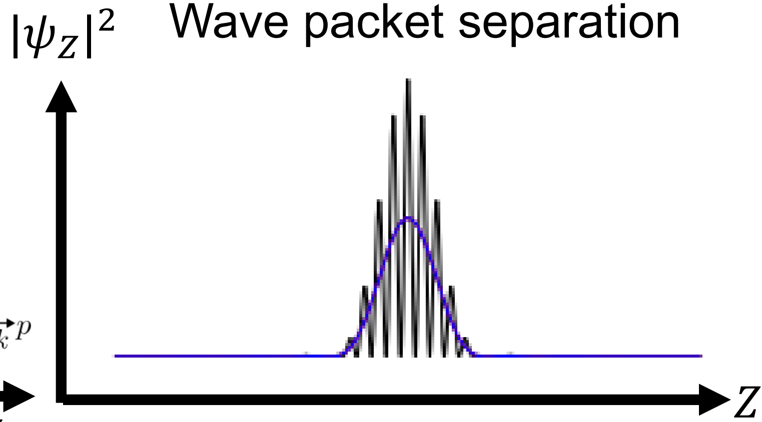




Binding wave packets together!



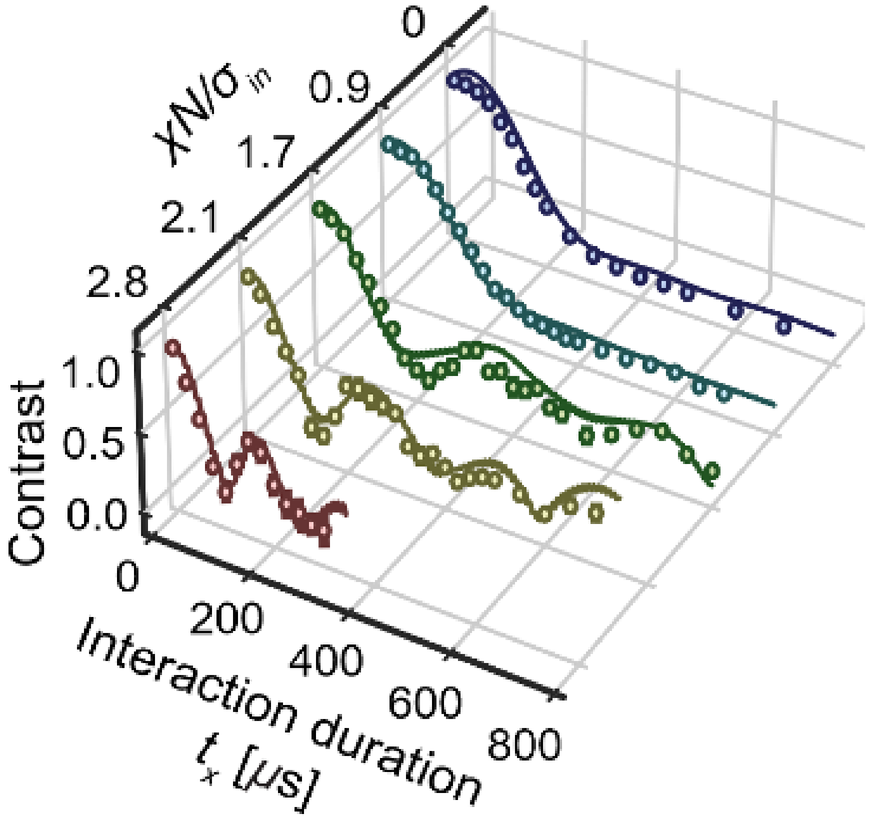
Wave packet separation



Also fermionic gases at unitarity, C. Vale, PRL 132, 223402 (2024)

Many-body gap protection

Protection against contrast loss in Rb Bragg matter-wave interferometer



From Binding to soliton Formation

Can exchange interaction prevent the wave packet broadening?

H. Zhang, A. Chu, C. Luo, J. K. Thompson, A. M. Rey, arXiv:2504.1707

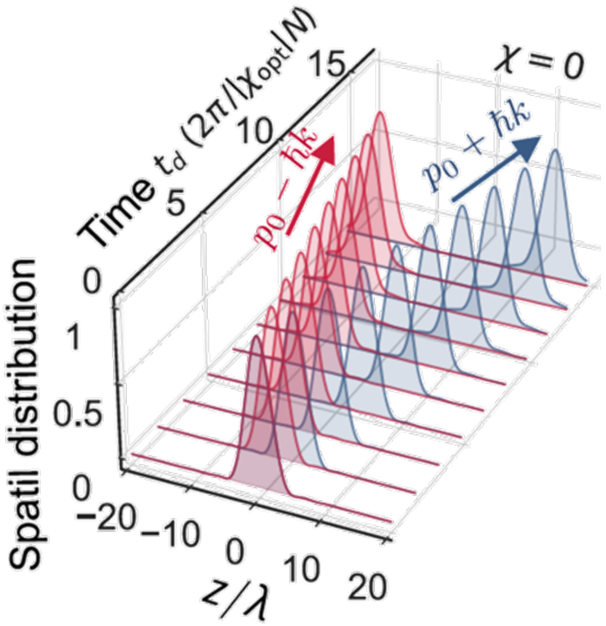
- Solitons in matter waves: 1D (stable, Salomon and Hulet’s groups (2002))
  2D (Townes solitons), 3D (instable, Cornell-Wieman group (2001))

  2D Purdue : Phys. Rev. Lett. 127, 023604 (2021), use of a Feshbach resonance with 133Cs

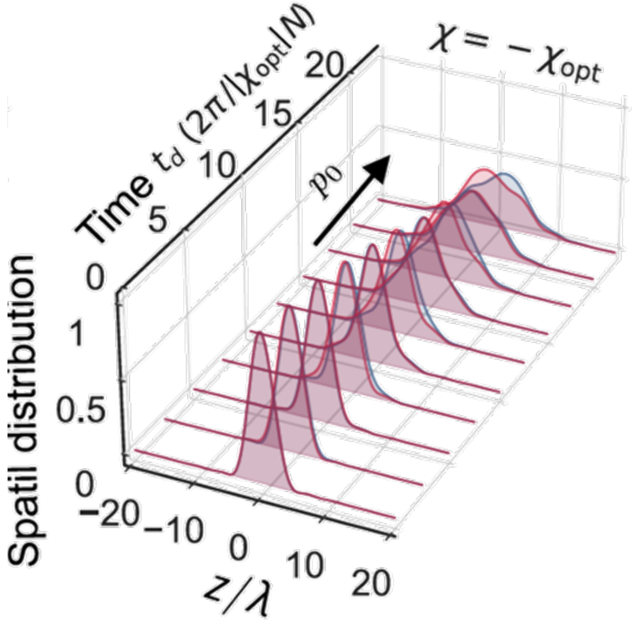
  2D Paris :   Phys. Rev. Lett. 127, 023603 (2021), use of a two-component gas with 87Rb

- Soliton in thermal gas (no BEC necessary) and arbitrary dimension;
- New opportunities for dispersion engineerir

1D Case

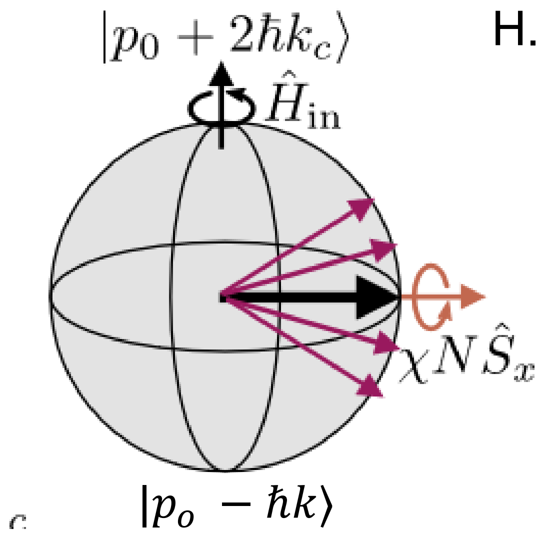


Binding with dispersion



From Binding to soliton Formation

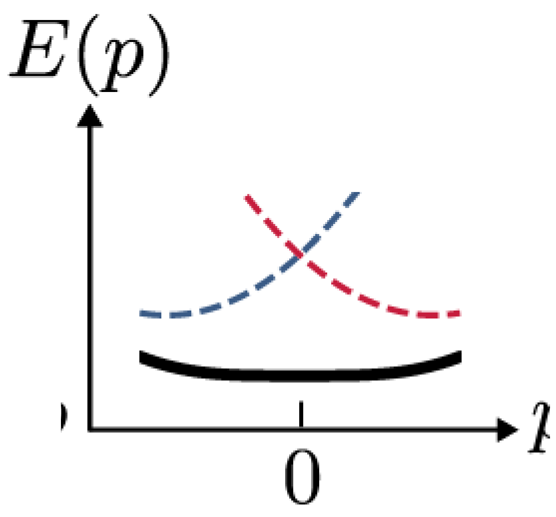
H. Zhang, A. Chu, C. Luo, J. K. Thompson, A. M. Rey, arXiv:2504.1707

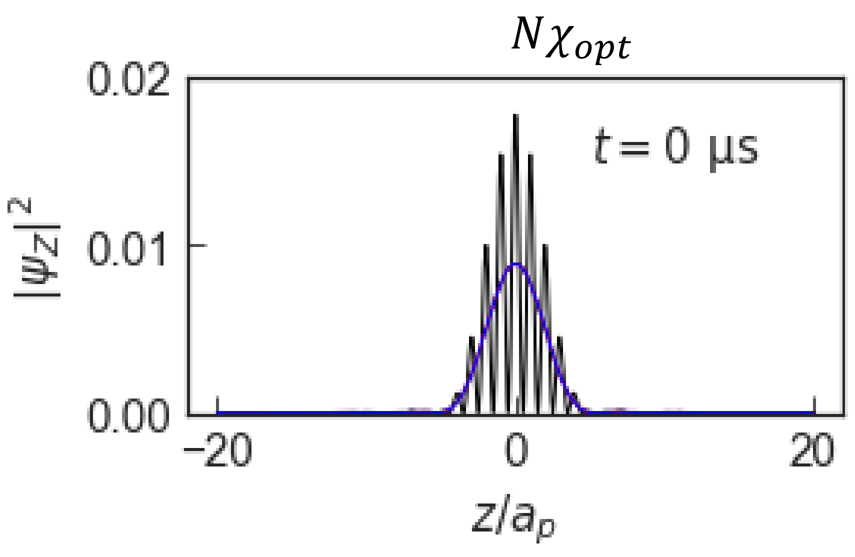


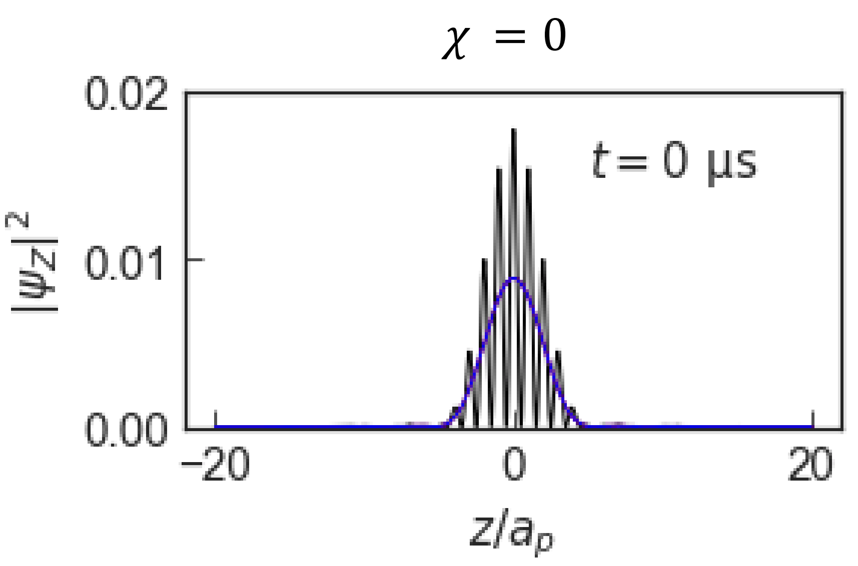
$$\hat{H}_{ex} = \chi(\hat{S}_x^2 + \hat{S}_y^2) \approx 2\chi(\langle\hat{S}_x\rangle\hat{S}_x + \cancel{\langle\hat{S}_y\rangle}\hat{S}_y) \approx N\chi\hat{S}_x$$

$$\hat{H}_{kin} = \sum_p \frac{p^2}{2m}\hat{I} + \frac{2\hbar k}{m}\sum_p p\hat{s}_z(p) \qquad E_p = \sqrt{|N\chi|^2 + 4E_R^2 p^2} + \frac{p^2}{2m}$$

$$E_p \approx N\chi + \left(1 + \frac{4E_R^2}{N\chi}\right)\frac{p^2}{2m} \qquad N\chi_{opt} = -4E_R^2 \qquad m^* \to \infty$$

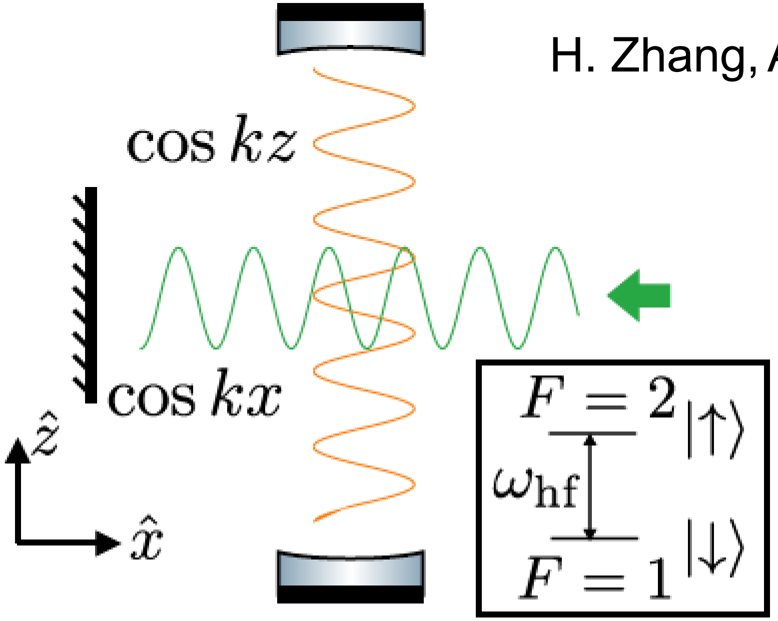






From 1D to 2D

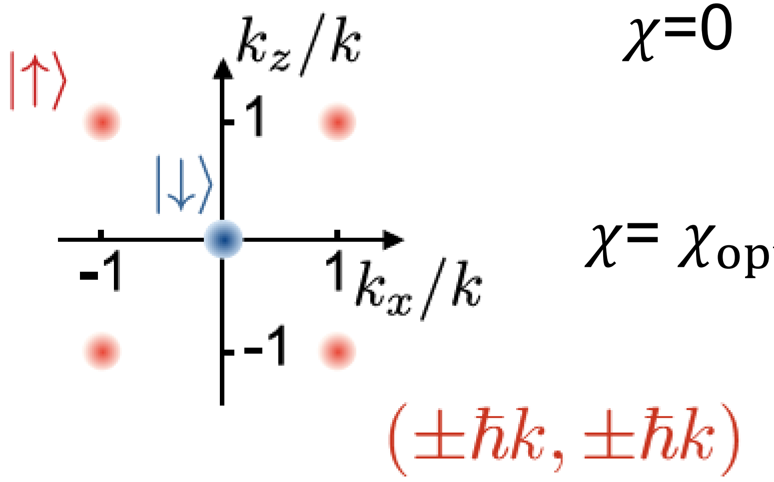
H. Zhang, A. Chu, C. Luo, J. K. Thompson, A. M. Rey, arXiv:2504.1707



1. Add a drive perpendicular to the cavity
2. Velocity select atoms at $\boldsymbol{p_0} = \{0,0\}$
3. Use an additional hyperfine level to generate a finite $\omega_z = \omega_{hf}$

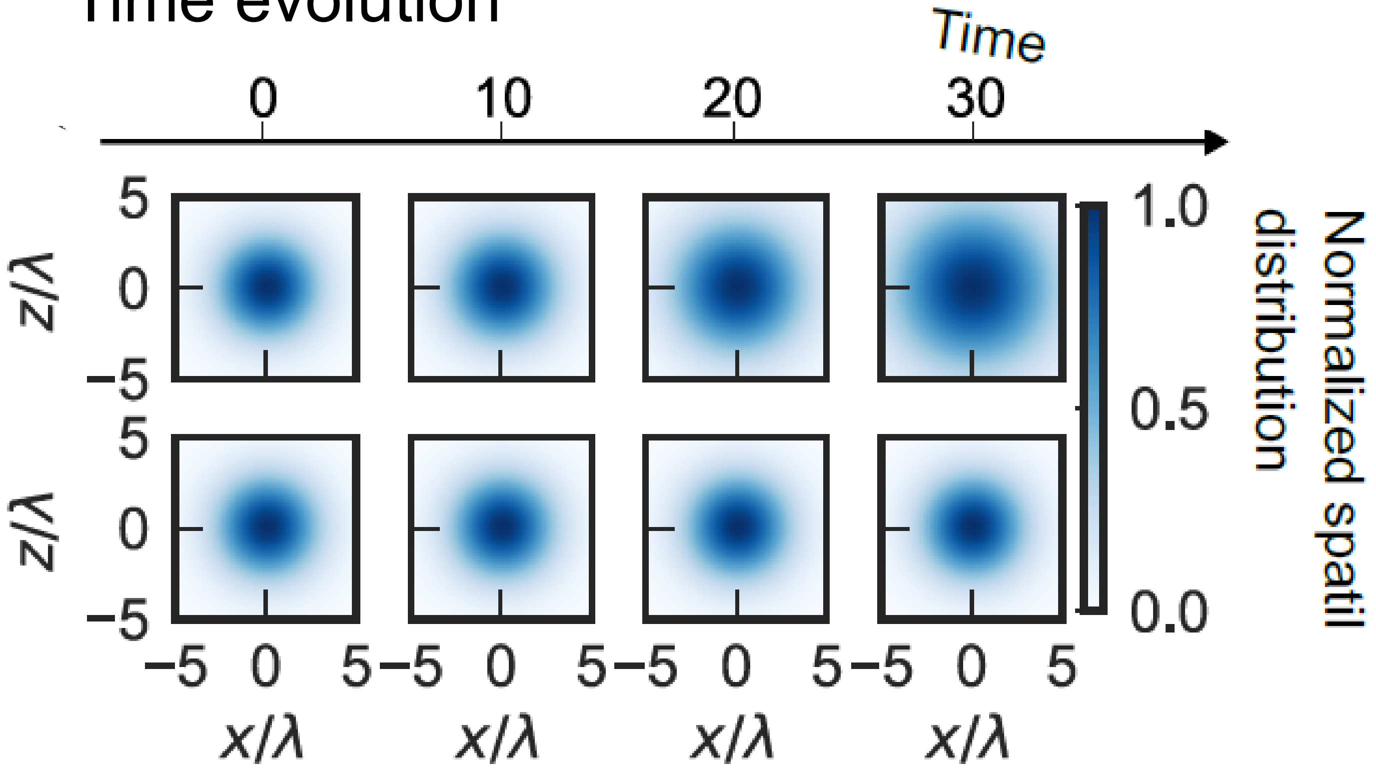
Time evolution

Momentum distribution



χ=0

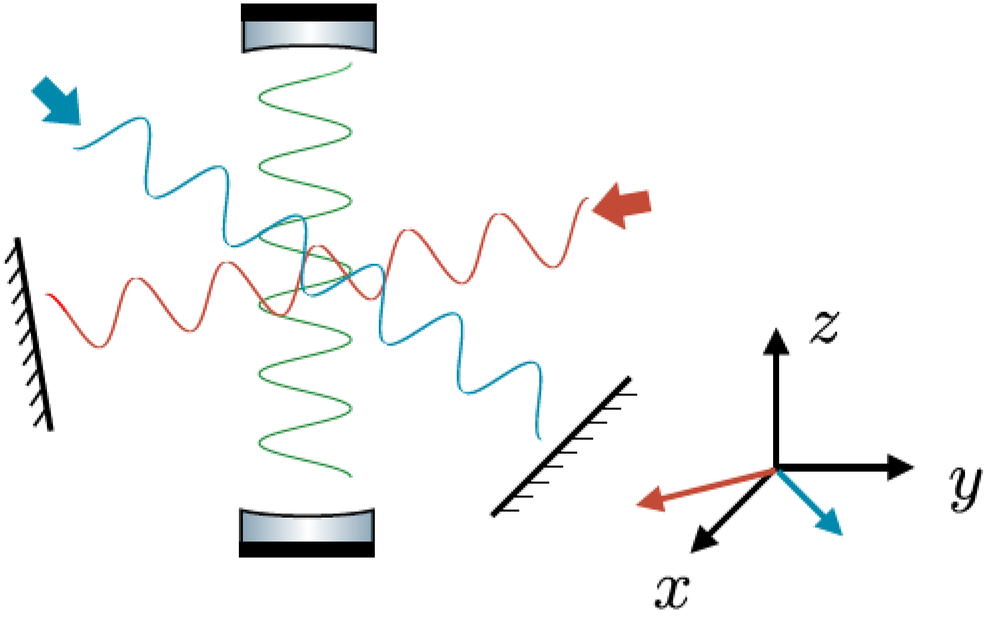
$\chi = \chi_{\rm opt}$

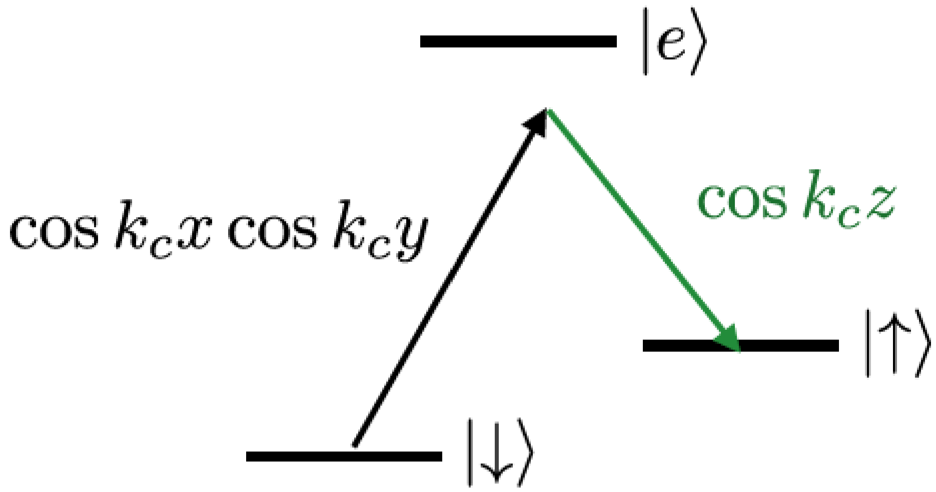


From 2D to 3D Solitons

H. Zhang, A. Chu, C. Luo, J. K. Thompson, A. M. Rey, arXiv:2504.1707

Add another perpendicular drive





No dispersion in all directions!!

Two-Axis- Counter-Twisting (TACT)

Squeezed spin states

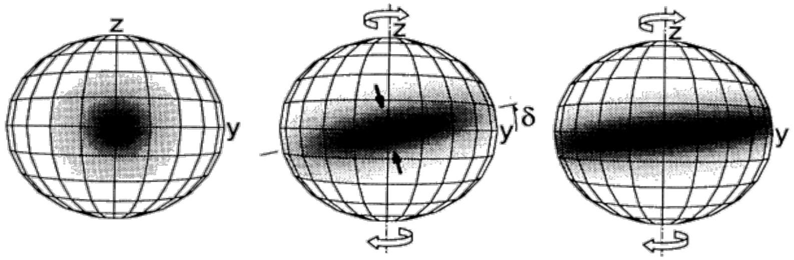
Masahiro Kitagawa and Masahito Ueda

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

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

Missing for 30 years!

One-axis twisting $H_{\mathrm{OAT}}/\hbar = \chi \hat{S}_z^2$

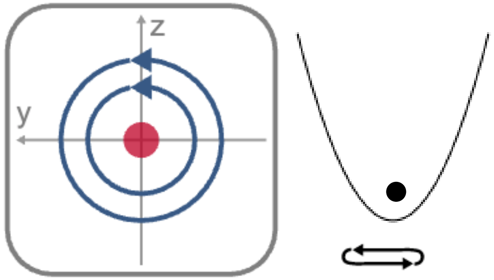


$\widehat{H}_{OAT} \sim B_{\mathrm{ef}}\,\hat{S}^z \quad B_{\mathrm{ef}} = 2\chi\langle \hat{S}^z \rangle$

$$\xi = min\frac{\sqrt{N}\langle \Delta\, \hat{S}^{\psi} \rangle}{|\langle \vec{S} \rangle|} \qquad \xi^2 \sim \frac{1}{N^{2/3}}$$

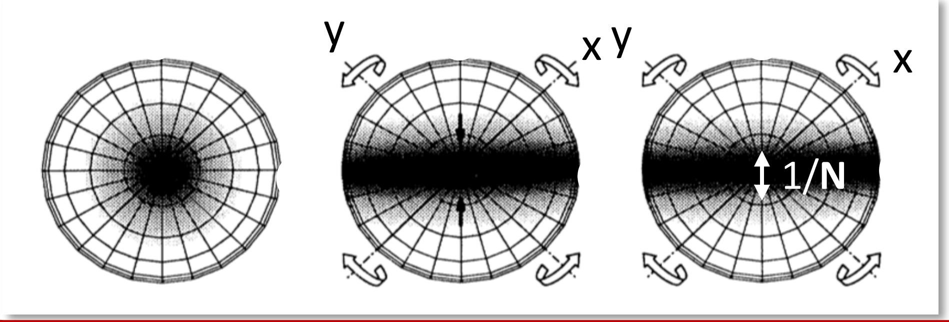
- Entanglement witness, $\xi^2 < 1$
- Enhanced sensitivity

Stable point



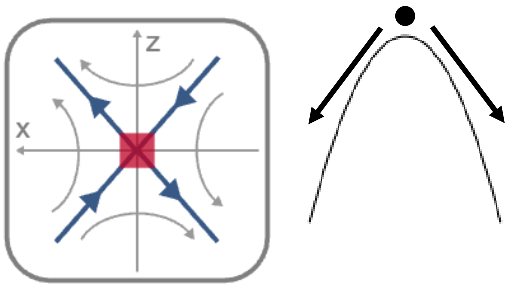
Slow

Two-Axis twisting $\widehat{H}_{\mathrm{TAT}}/\hbar = \chi(\hat{S}_x^2 - \hat{S}_y^2)$



$$\xi^2 \sim \frac{1}{N}$$

Saddle point



Exponentially fast!!

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

Ions: Wineland, Monore, Leibfried, Bollinger, Roos, Blatt
Cavities: Vuletić, Kasevich, Thompson, Schleier-Smith, Reichel
Collisions: Oberthaler, Treutlein, Klempt, Schmeidmayer, Chapman, You
Rydberg: Kaufman, Schleier-Smith, Broeways

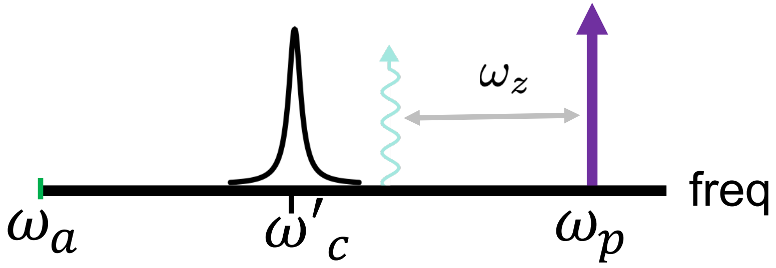
Luo*, Zhang*, Rey, Thompson, Nat Phys 21, 916(2025)
Miller, …, Lukin, Ye, Nature 633, 332 (2024)

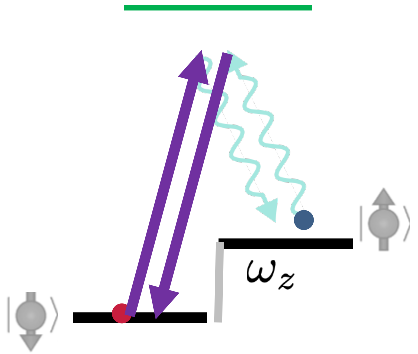
Hamiltonian Engineering with two pumps

Luo*, Zhang*, Chu, …, Rey, Thompson, Nat. Phys. **21**, 916 (2025)

Exchange interaction

$$H_{\mathrm{ex}} = \chi_e \hat{S}_- \hat{S}_+$$





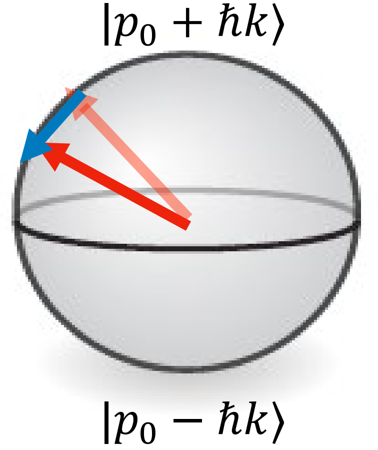
XYZ Hamiltonian Engineering

Luo*, Zhang*, Chu, …, Rey, Thompson, Nat. Phys. **21**, 916 (2025)

General Hamiltonian

$$H_{XYZ} = \chi_e \overbrace{\hat{S}_+\hat{S}_-}^{(\hat{S}^2 - \hat{S}_z^2)} + \chi_{\text{pair}}(\overbrace{\hat{S}_+^2 + \hat{S}_-^2}^{(\hat{S}_x^2 - \hat{S}_y^2)}) \quad = \chi_x \hat{S}_x^2 + \chi_y \hat{S}_y^2 + \chi_z \hat{S}_z^2$$

Probe the collective dynamics

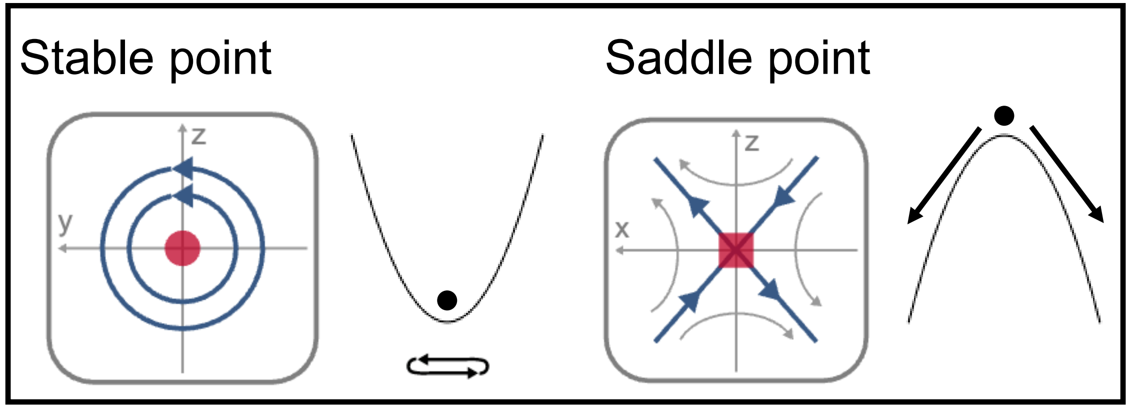


Probe the global flow line on the Bloch Sphere

1. Prepare an arbitrary spin coherent state with $\langle \hat{S}_{x,y,z} \rangle$
2. Evolve the system under H_{XYZ} for a short time Δt

$$e^{-iH_{XYZ}\Delta t} \sim 1 - i\, H_{XYZ}\Delta \mathrm{t}$$

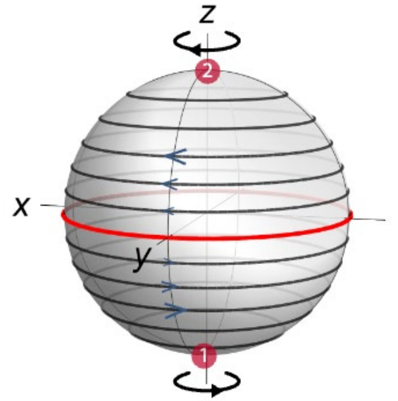
3. Measure the changes in the spin observables $\Delta\langle \hat{S}_{x,y,z} \rangle$
4. Measure the changes with different initial states and obtain the flow line



Muñoz-Arias, Deutsch, Poggi PRX Quantum **4**, 020314 (2023)

XYZ Hamiltonian Engineering

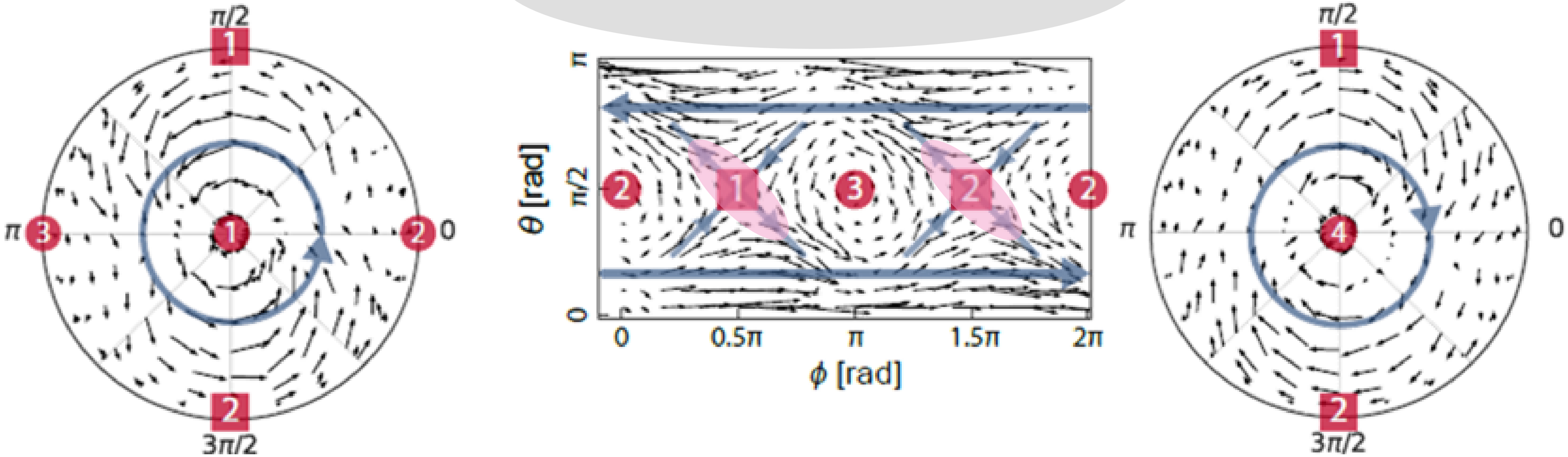
0 ≈ 0.17 1 $|\alpha_2/\alpha_1|$



$\chi_{\text{pair}} = 0$

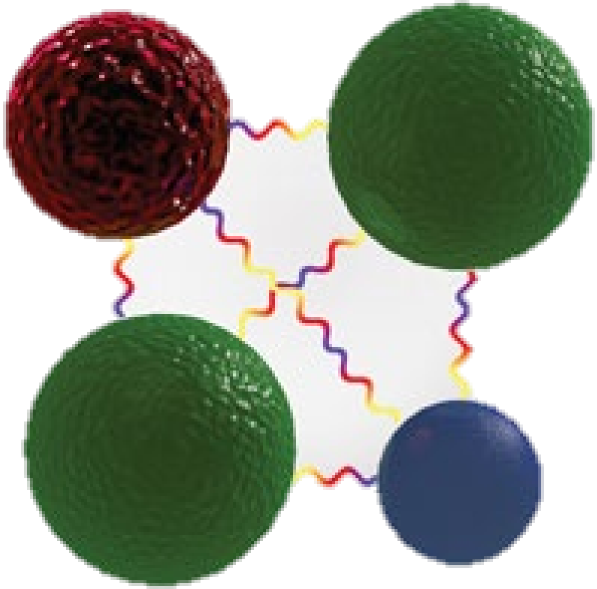
$\chi_e(\hat{S}^2 - \hat{S}_z^2)$

Data!!



Luo*, Zhang*, Chu, …, Rey, Thompson, Nat. Phys. **21**, 916 (2025)

Multi-body Interactions



Not natural in our systems. Need to be engineered !!

Multi-body Interactions

Fundamental for

- ❑ Quantum Information: error correction

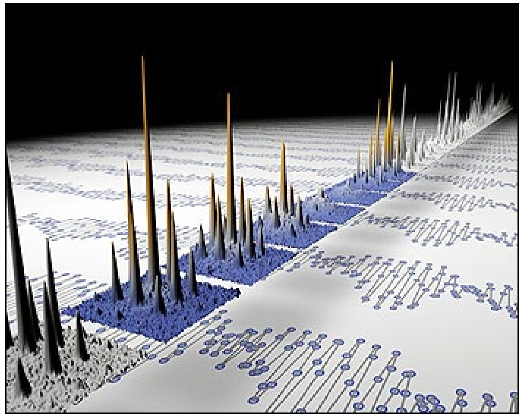
  S. Girvin *et al* review: arXiv:2407.10381….

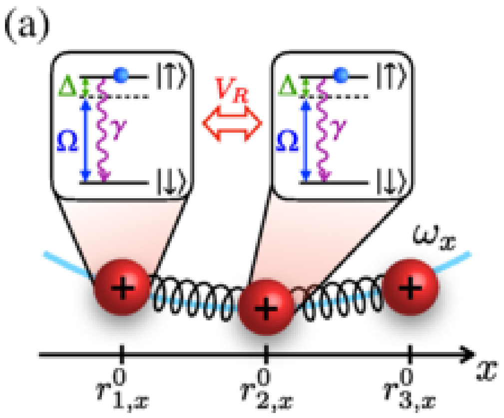
- ❑ Quantum information: qubits vs qudits

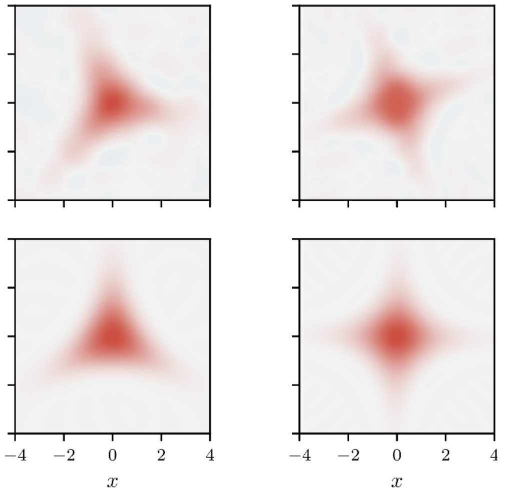
  O. Katz *et al* Nature Physics 19 1452 (2024), PRX Quantum 4, 030311(2023), PRL 129,063603 (2023)
  O. Bazavan et al arXiv:2403.05471 (2024) …..

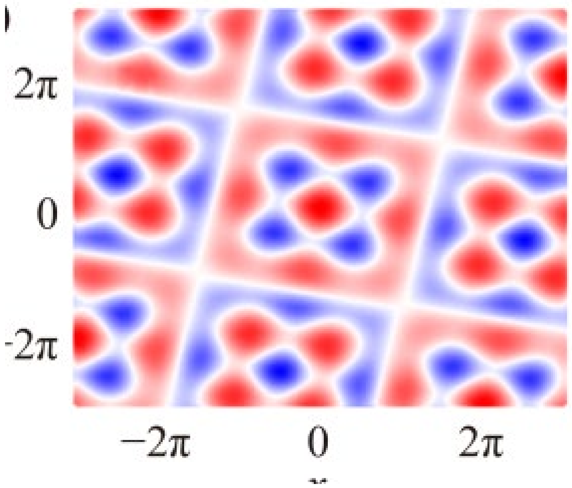
- ❑ Quantum Simulation:

  A. Daley et al PRL 102, 040402 2009; S. Will et al Nature 465, 197 (2010); A. Goban *et al* Nature 563, 369 (2018), F. M. Gambetta *et al* PRL 125, 133602 (2020)…







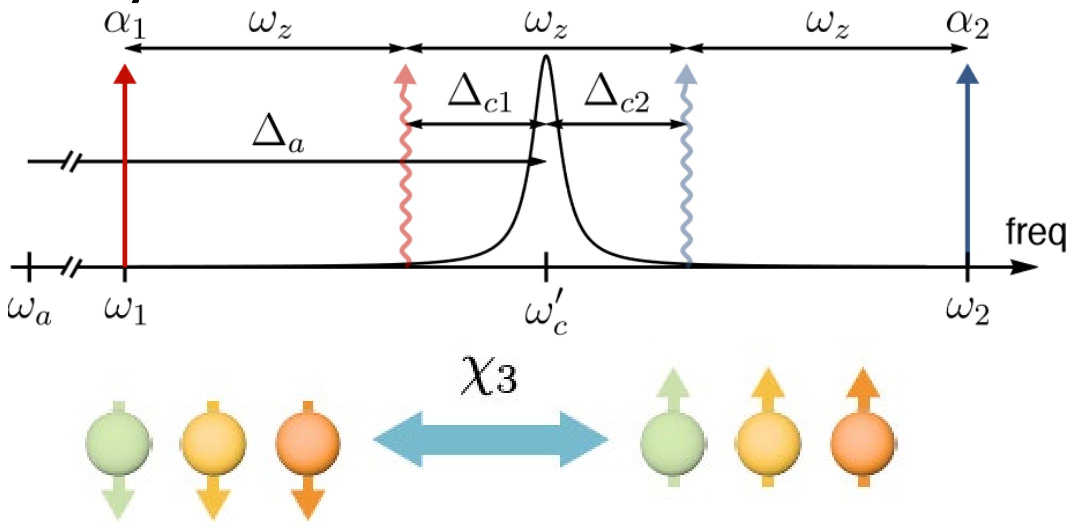


N>2–body Interactions in our Cavity

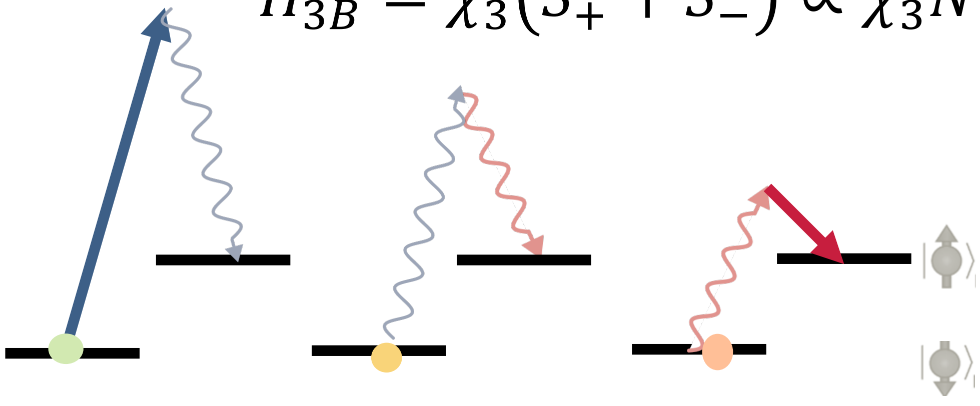
Realization of three and four-body interactions between momentum states in a cavity through optical dressing

C. Luo, H.g Zhang, …Rey, Thompson, arXiv.2410.12132, Science, In press

Three –body



$$H_{3B} = \chi_3\left(\hat{S}_+^3 + \hat{S}_-^3\right) \propto \chi_3 N^3$$

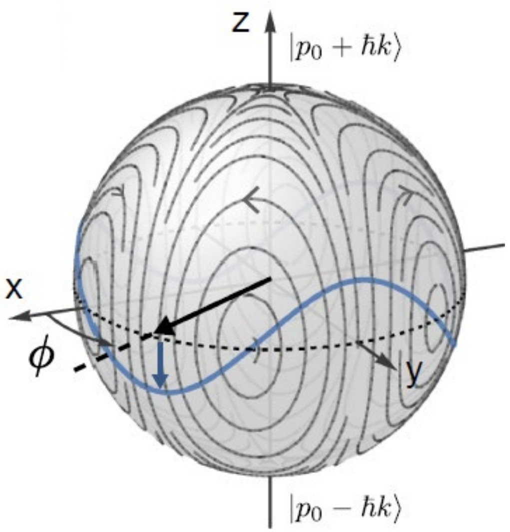


- Cancellation of two-body by construction
- Balance superradiance

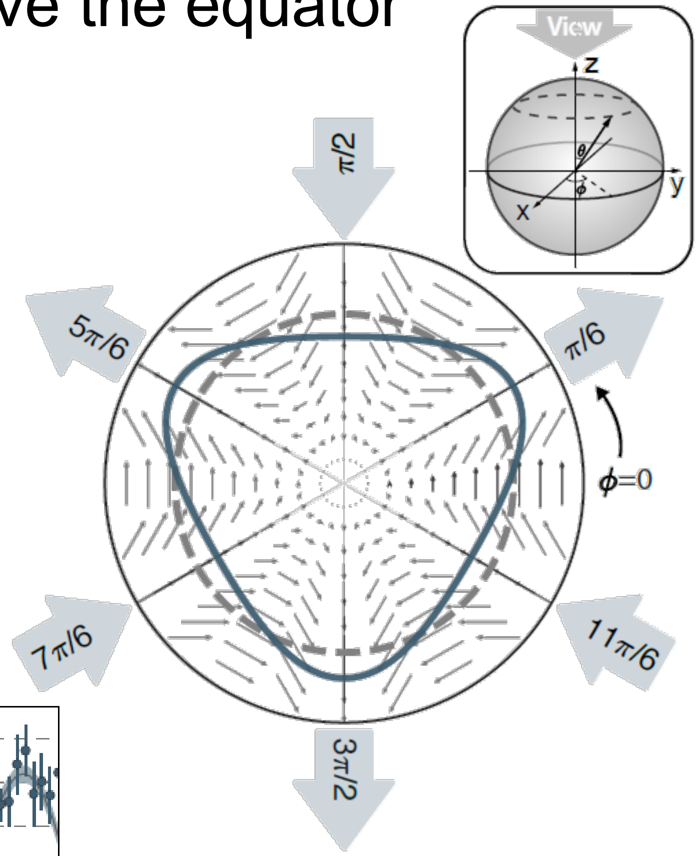
$$L_+ = \sqrt{\Gamma}\hat{S}_+ \quad L_- = \sqrt{\Gamma}\hat{S}_-$$

Three –body Interactions in our Cavity

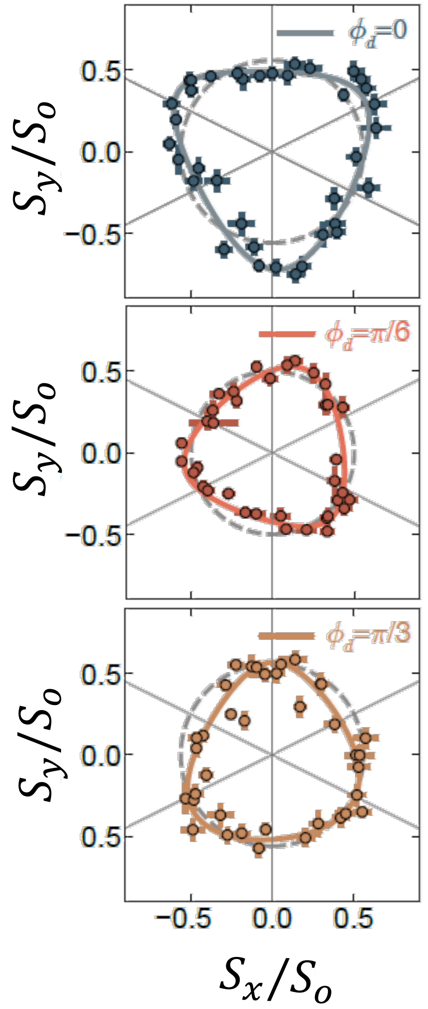
At the equator



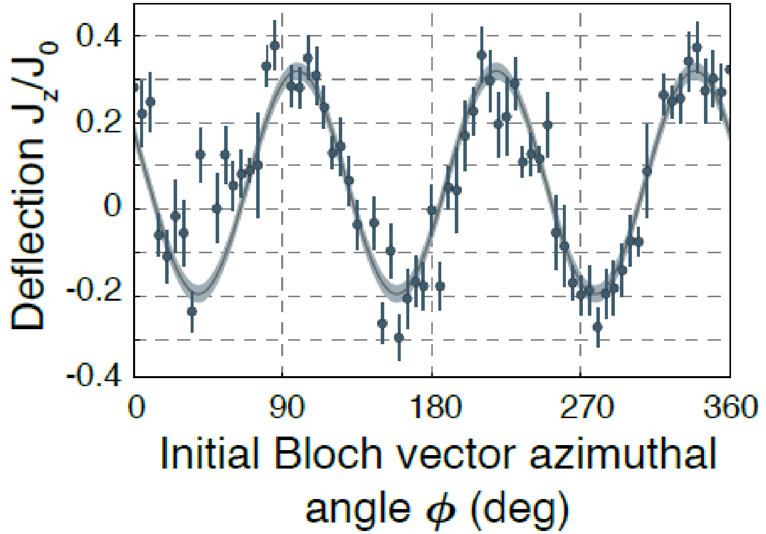
Above the equator



Mean-field dynamics
viewed from the north pole



Data



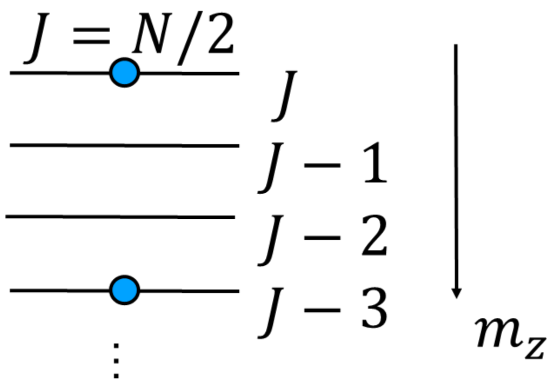
$$H_{3B} = \chi_3\left(e^{i3\phi}\hat{S}_+^3 + e^{-i3\phi}\hat{S}_-^3\right)$$

Unitary time evolution under $H=\chi_3\,(S_+^{\,3}+S_-^{\,3})$

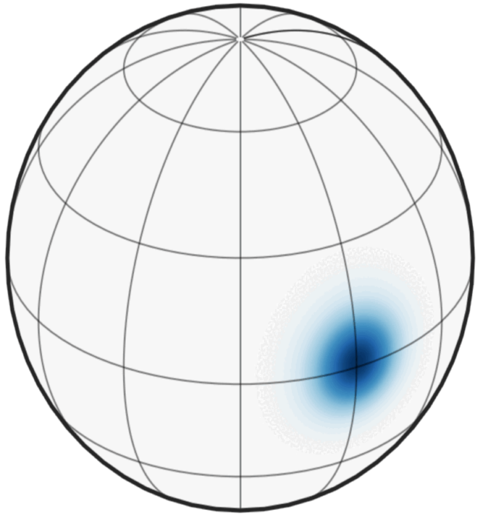
- Start with $|\uparrow,\cdots,\uparrow\rangle$ — the fixed point for mean-field dynamics

$$|\psi_t\rangle = \sum_m c_{J-3m}(t)|J, m_z = J-3m\rangle, J = N/2$$

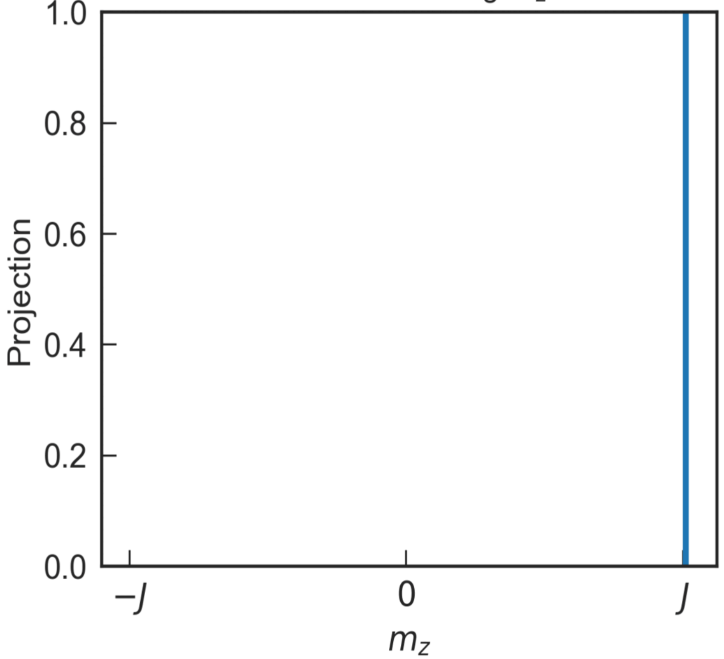
Dicke ladder



Spin Wigner Function



Distribution along m_z



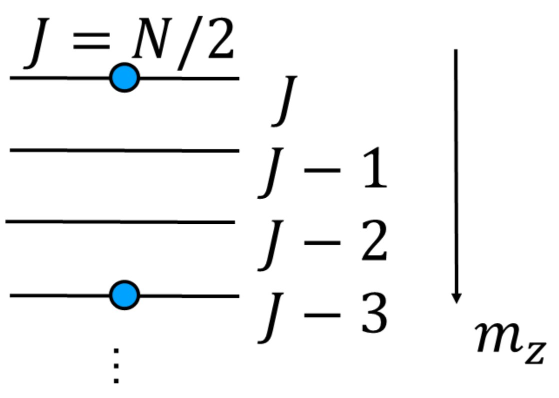
Unitary time evolution under $H=\chi_3\,(S_+^{\,3}+S_-^{\,3})$

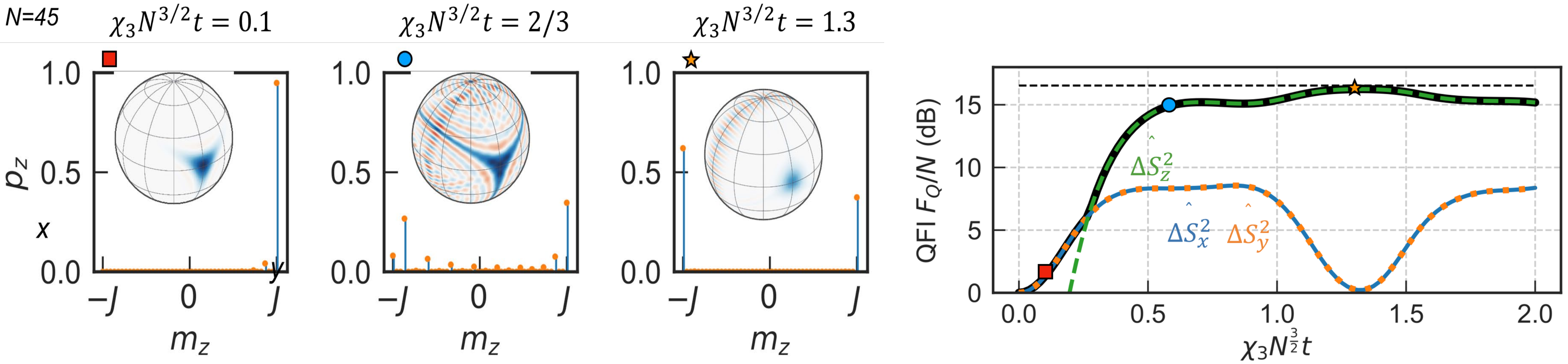
- Start with $|\uparrow,\cdots,\uparrow\rangle$ — the fixed point for mean-field dynamics

$$|\psi_t\rangle = \sum_m c_{J-3m}(t)|J, m_z = J-3m\rangle, J = N/2$$

- Vanishing spin-squeezing parameters
- GHZ state generation for $N = 6n + 3$ atoms at $\chi_3 N^{3/2} t = 1.3$

Dicke ladder

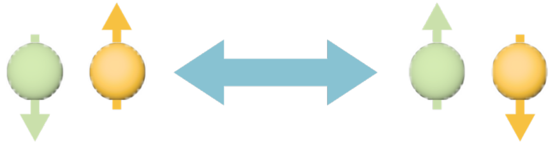




Note that a final rotation along the x-axis is performed to visualize the GHZ state.

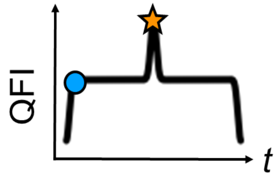
Comparing relevant timescales

Exchange interaction



$$H_{\rm ex} = \chi_{\rm ex}\hat{S}_+\hat{S}_- = \chi_{\rm ex}(\hat{S}^2 - \hat{S}_z^2)$$

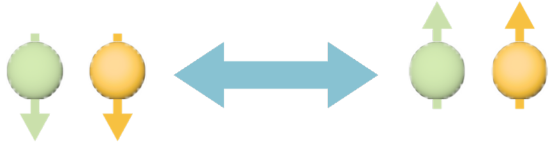
Luo, Zhang et al., Science **384** (6695), 551-556 (2024)



$\chi_{\rm ex} t_{\rm plat,ex} = 1/\sqrt{N}$

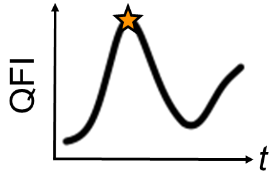
$\chi_{\rm ex} t_{\rm GHZ,ex} = \pi/2$

Two-axis twisting



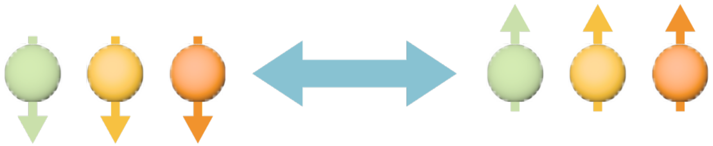
$$H_2 = \chi_2(\hat{S}_+^2 + \hat{S}_-^2)$$

Luo, Zhang et al., *Nature Physics*, **1** (2025)



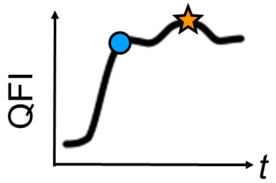
$\chi_2 t_{\rm peak,2} \approx \ln 4N/2N$

Three-body interactions



$$H_3 = \chi_3(\hat{S}_+^3 + \hat{S}_-^3)$$

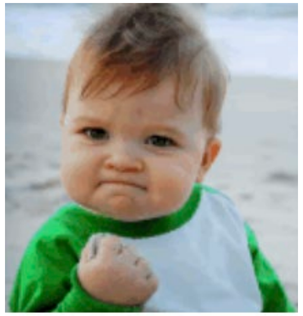
Luo, Zhang et al., arXiv:2410.12132 (2024)



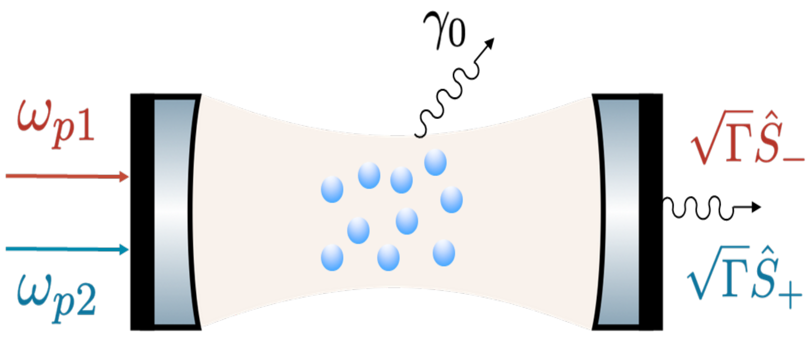
$\chi_3 t_{\rm peak,3} \approx 0.66/N^{3/2}$

$\chi_3 t_{\rm GHZ,3} \approx 1.3/N^{3/2}$

$$\frac{\sqrt{N}\chi_3}{\chi_{2,\rm ex}} \sim \frac{\sqrt{N}\mathcal{G}}{\Delta_c} \equiv \eta \ll 1 \longrightarrow$$ Requirement to eliminate cavity photons



$$\frac{t_{\rm GHZ,ex}}{t_{\rm GHZ,3}} \sim N\eta \qquad \frac{t_{\rm plat,ex}}{t_{\rm peak,3}} \sim \sqrt{N}\eta \qquad \frac{t_{\rm peak,2}}{t_{\rm peak,3}} \sim \eta \ln N$$



Realistic dissipative dynamics

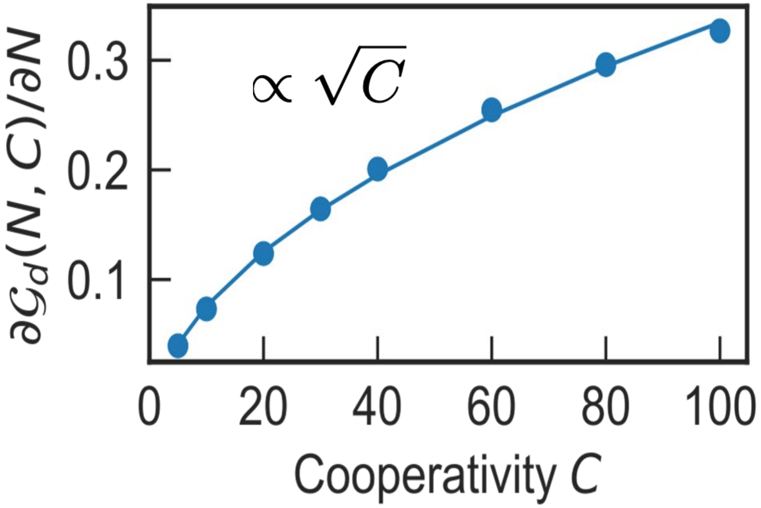
$$L_+ = \sqrt{\Gamma}\hat{S}_+ \quad L_- = \sqrt{\Gamma}\hat{S}_- \quad L_{\mathrm{sp,i}} = \sqrt{\gamma_0}\hat{s}_{i,-}$$

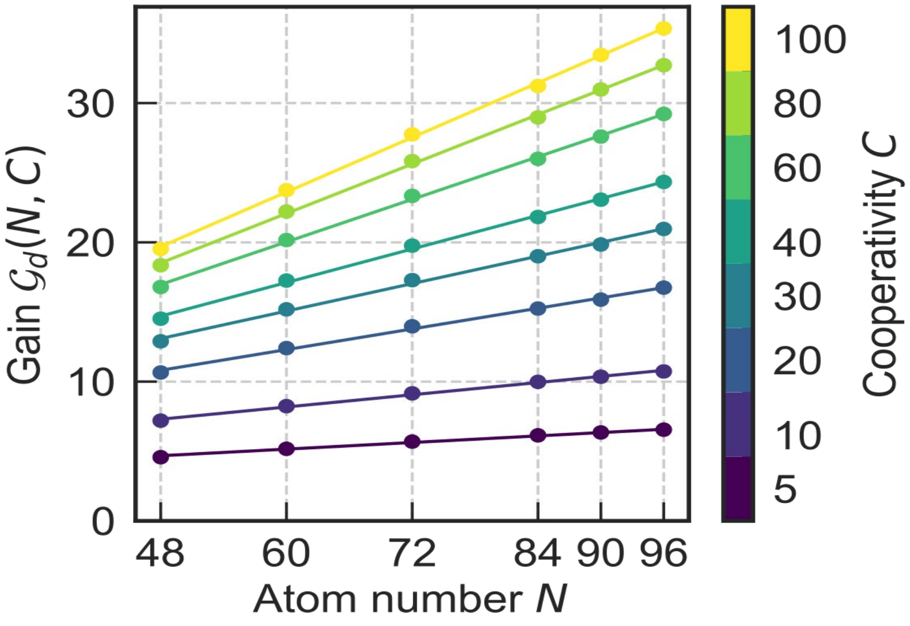
- Typically, spin flips lead to $\sqrt{NC}$ scaling

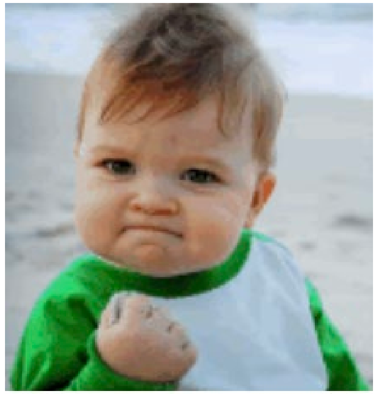
- With balanced superradiance, no collective enhancement!

$$\langle\dot{\hat{S}}_x\rangle = \cdots - \Gamma\langle\hat{S}_x\rangle \quad \langle\dot{\hat{S}}_y\rangle = \cdots - \Gamma\langle\hat{S}_y\rangle \quad \langle\dot{\hat{S}}_z\rangle = \cdots - 2\Gamma\langle\hat{S}_z\rangle$$

- Here, we obtain a new scaling $N\sqrt{C}$ for the metrological gains!







Leroux et al, PRL 104, 073602 (2010)
Davis et al. PRL 116, 053601 (2016)
Borregaard. et al.,NJP 19, 093021 (2017)
Chu et al., PRL 127, 210401 (2021)
Colombo et al, Nat. Phys.18, 925 (2022)

Only the beginning: Great vista ahead!!

Ultracold atoms in an optical cavity

Thank YOU!!

Use All of Quantum Mechanics:

- Unitary Dynamics, Quantum Measurement, Dissipation
- Entanglement and correlations