Simulation of XXZ Spin Models using Sideband Transitions in Trapped Bosonic Gases

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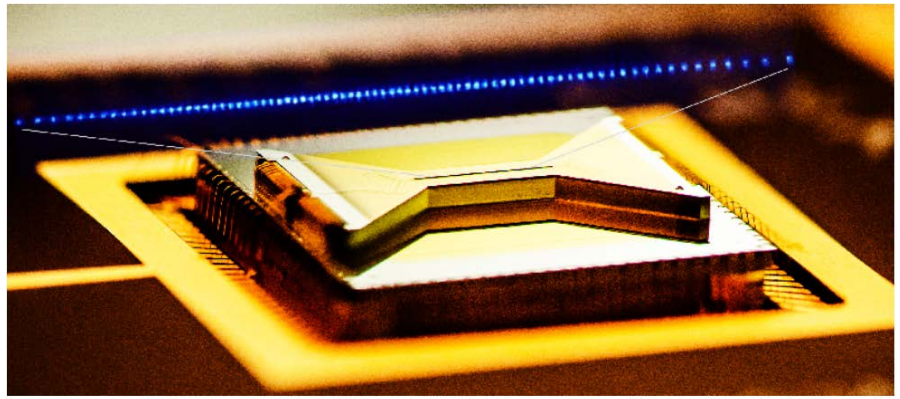
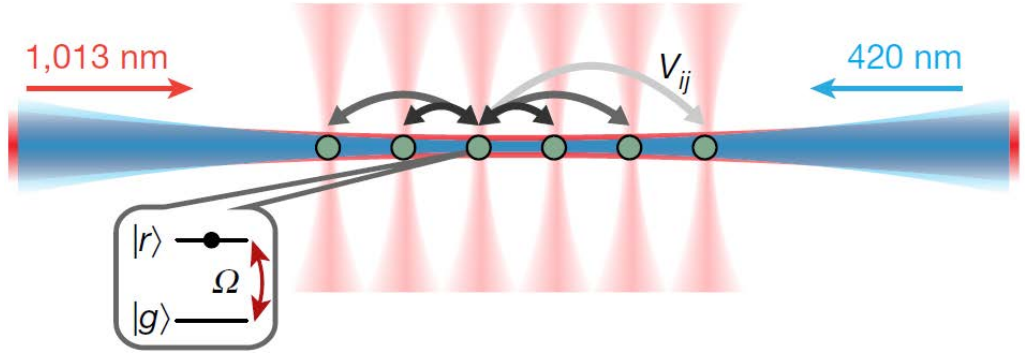
DAMOP, June 4th, 2020

Simulation of long-range spin models

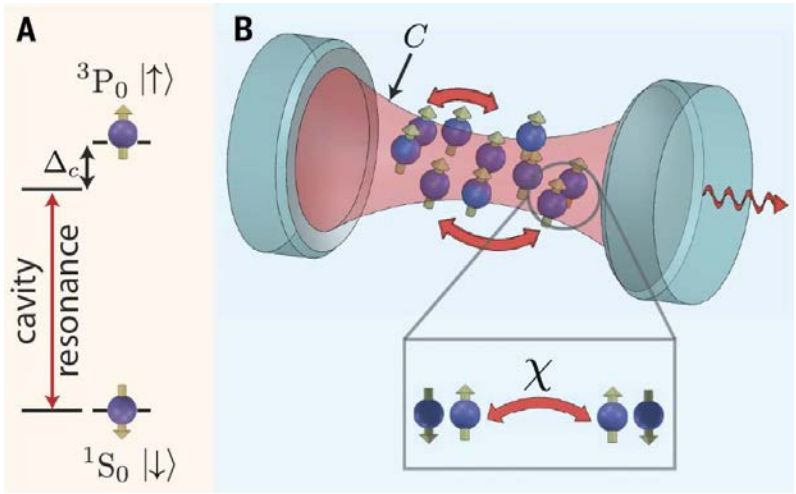
- Trapped ions — Nature 551, 601 (2017)



- Rydberg atoms — Nature 551, 579 (2017)

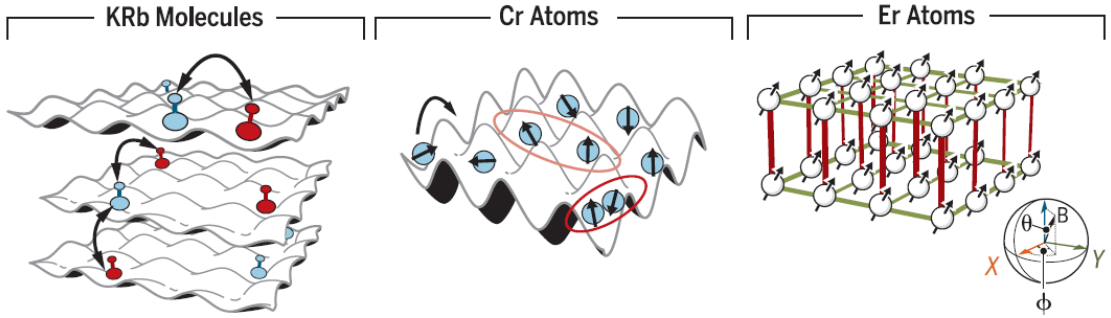


- Cavity QED — Science 361, 259 (2018)



- Polar molecules & magnetic atoms

Science 357, 1002 (2017)



Spin models in trapped atomic gases

Previous Literature:

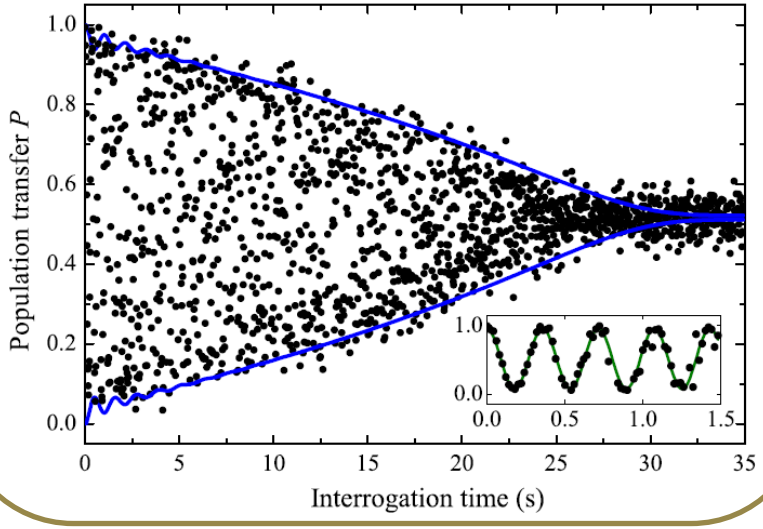
- Emulation of long-range spin model via purely contact interaction using carrier transition
- Many-body gap protection in isotropic Heisenberg models

This Research:

- The role of motional sidebands: adding anisotropy to Heisenberg models
- Applications in quantum simulation and metrology since coherence time is not affected by the sideband protocol

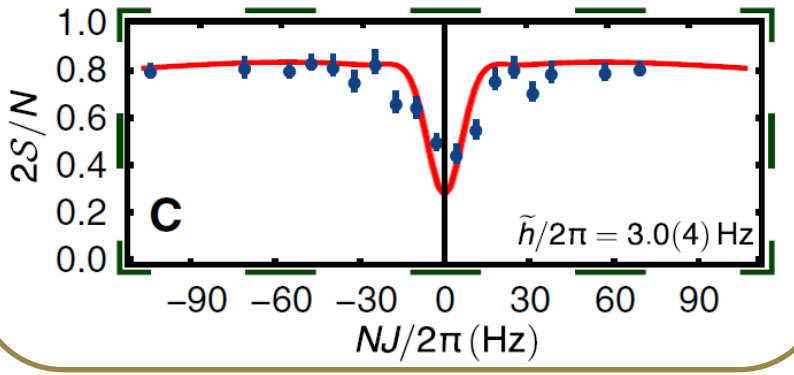
- Bosonic system

Phys. Rev. Lett. 106, 240801 (2011)



- Fermionic system

Sci. Adv. 5, eaax1568 (2019)



Experimental setup

- ^{87}Rb atomic gases

$$|\downarrow\rangle \equiv |F = 1, m_F = 0\rangle$$
$$|\uparrow\rangle \equiv |F = 2, m_F = 0\rangle$$

- Drive motional sidebands via Raman beams
- Gas temperature:

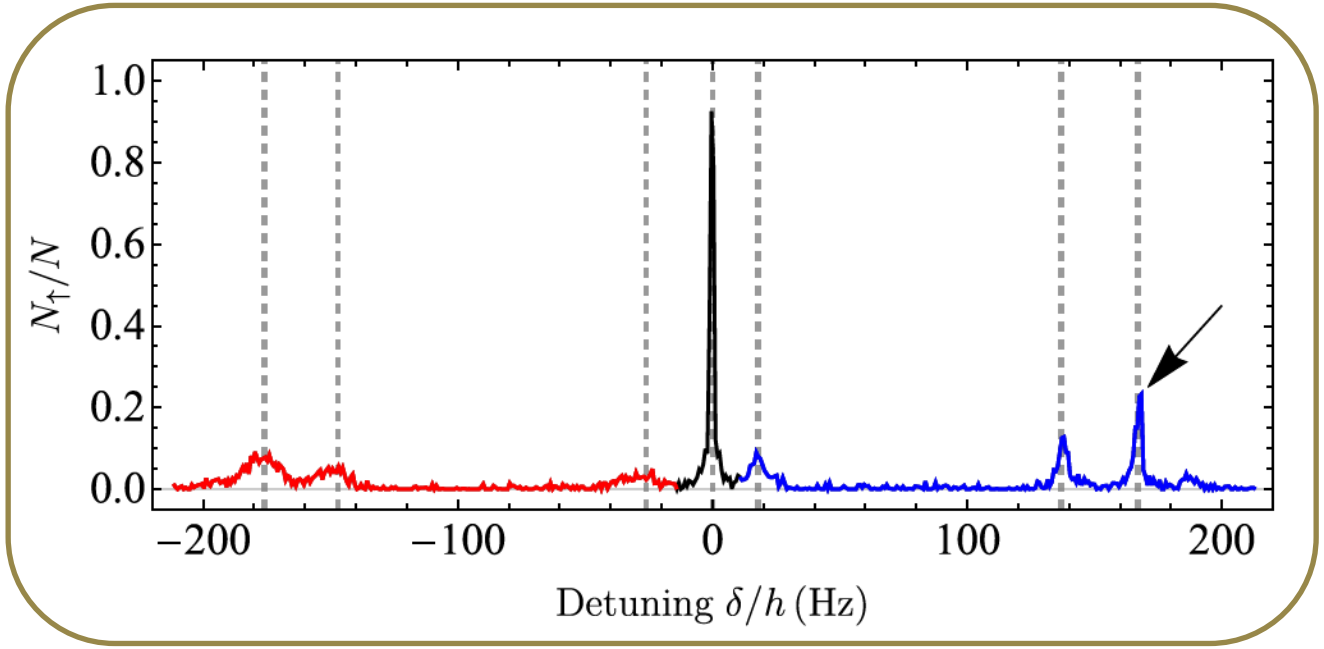
  375(25)nK

- Trapping frequency:

  143Hz, 21.5Hz, 171Hz

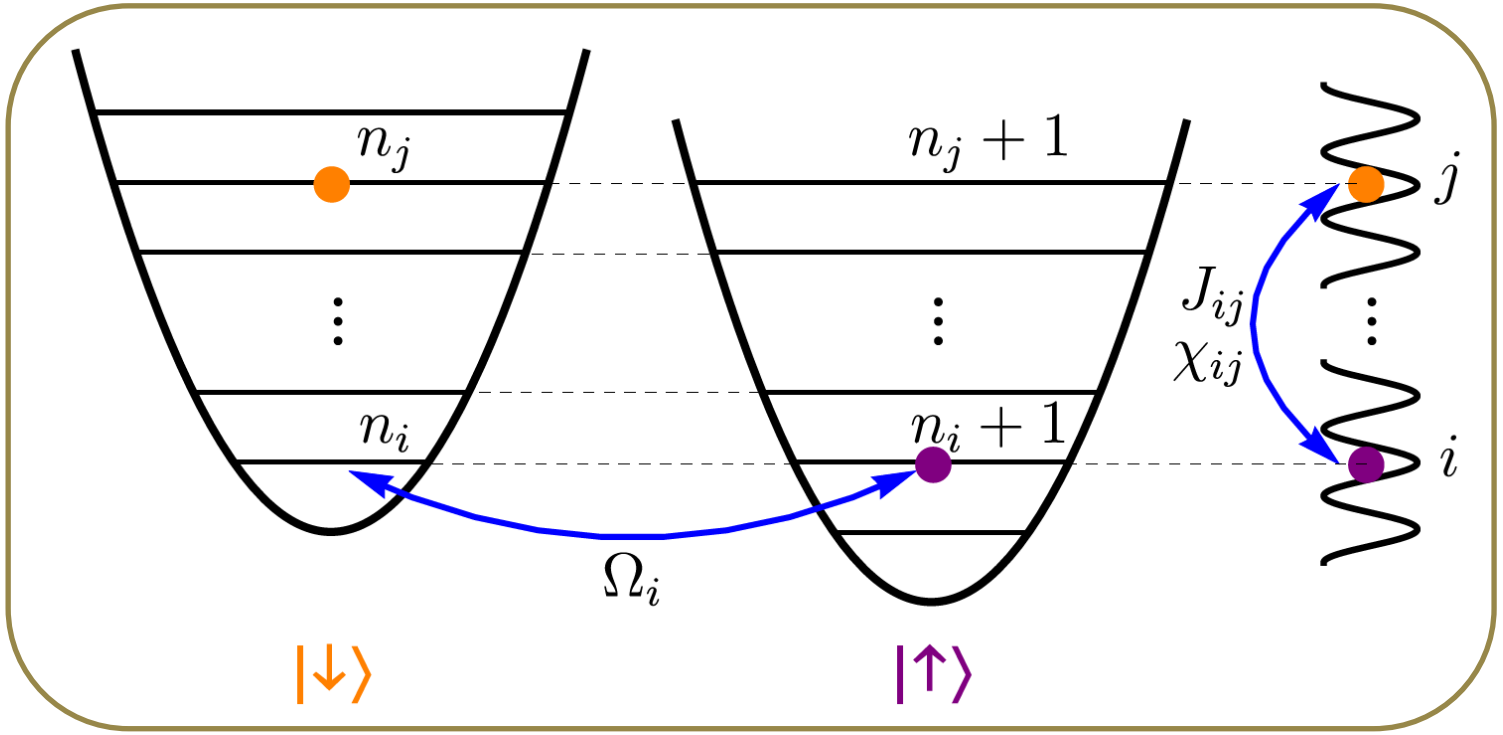
- Atom density:

$$0.46 \text{ to } 4.8 \times 10^{12}\text{cm}^{-3}$$



Collisionless regime: trapping frequency ≫ interaction

Harmonic trap as mode-space lattice



- Blue sideband transition

$$|\Uparrow_i\rangle = |\uparrow; n_i^X, n_i^Y, n_i^Z + 1\rangle$$

$$|\Downarrow_i\rangle = |\downarrow; n_i^X, n_i^Y, n_i^Z\rangle$$

- Similar definitions can apply to carrier and red sideband transitions

$$H_{\text{int}} = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ij} \chi_{ij} S_i^z S_j^z + \sum_i B_i S_i^z$$

Long-range XXZ models in mode-space lattice

$$H_{\text{int}} = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ij} \chi_{ij} S_i^z S_j^z + \sum_i B_i S_i^z$$

$$J_{ij} = \frac{4\pi\hbar^2 a_{\uparrow\downarrow} V_{ij}^{\text{ex}}}{m} \qquad \chi_{ij} = \frac{4\pi\hbar^2 (V_{ij}^{\Uparrow\Uparrow} a_{\uparrow\uparrow} + V_{ij}^{\Downarrow\Downarrow} a_{\downarrow\downarrow} - V_{ij}^{\Uparrow\Downarrow} a_{\uparrow\downarrow} - V_{ij}^{\text{ex}} a_{\uparrow\downarrow})}{m}$$

$$V_{ij}^{\text{ex}} = \int \mathrm{d}^3\mathbf{R} \phi_i^{\Uparrow}(\mathbf{R}) \phi_i^{\Downarrow}(\mathbf{R}) \phi_j^{\Uparrow}(\mathbf{R}) \phi_j^{\Downarrow}(\mathbf{R}) \qquad V_{ij}^{\sigma\sigma'} = \int \mathrm{d}^3\mathbf{R} [\phi_i^{\sigma}(\mathbf{R})]^2 [\phi_j^{\sigma'}(\mathbf{R})]^2$$

- Carrier transition → $\phi_i^{\Uparrow}(\mathbf{R}) = \phi_i^{\Downarrow}(\mathbf{R})$ → XXX models
- Sideband transition → $\phi_i^{\Uparrow}(\mathbf{R}) \neq \phi_i^{\Downarrow}(\mathbf{R})$ → XXZ models

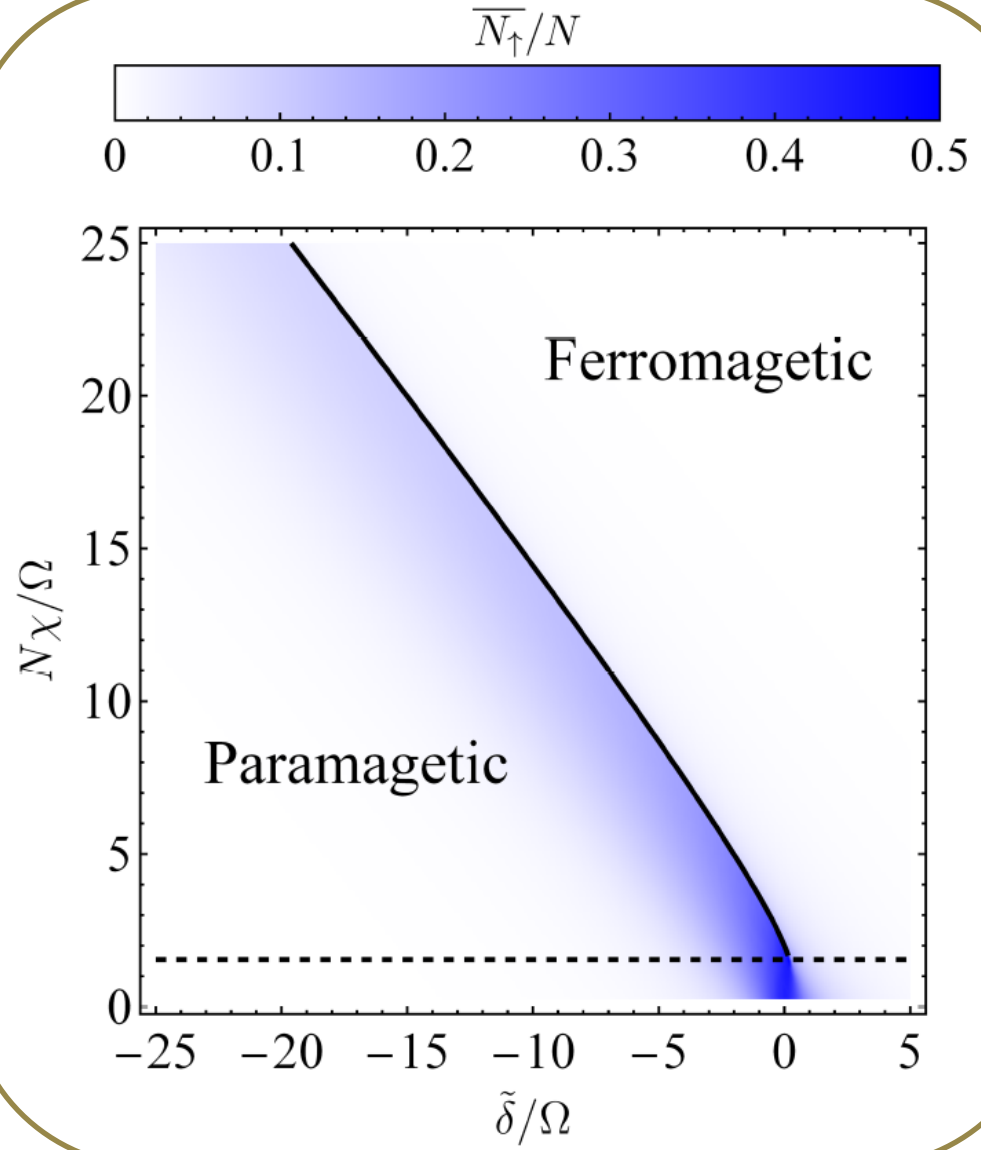
Dynamical phase transition (DPT) in LMG model

$$H_{\mathrm{LMG}} = \chi S^z S^z + \Omega S^x - \tilde{\delta} S^z$$

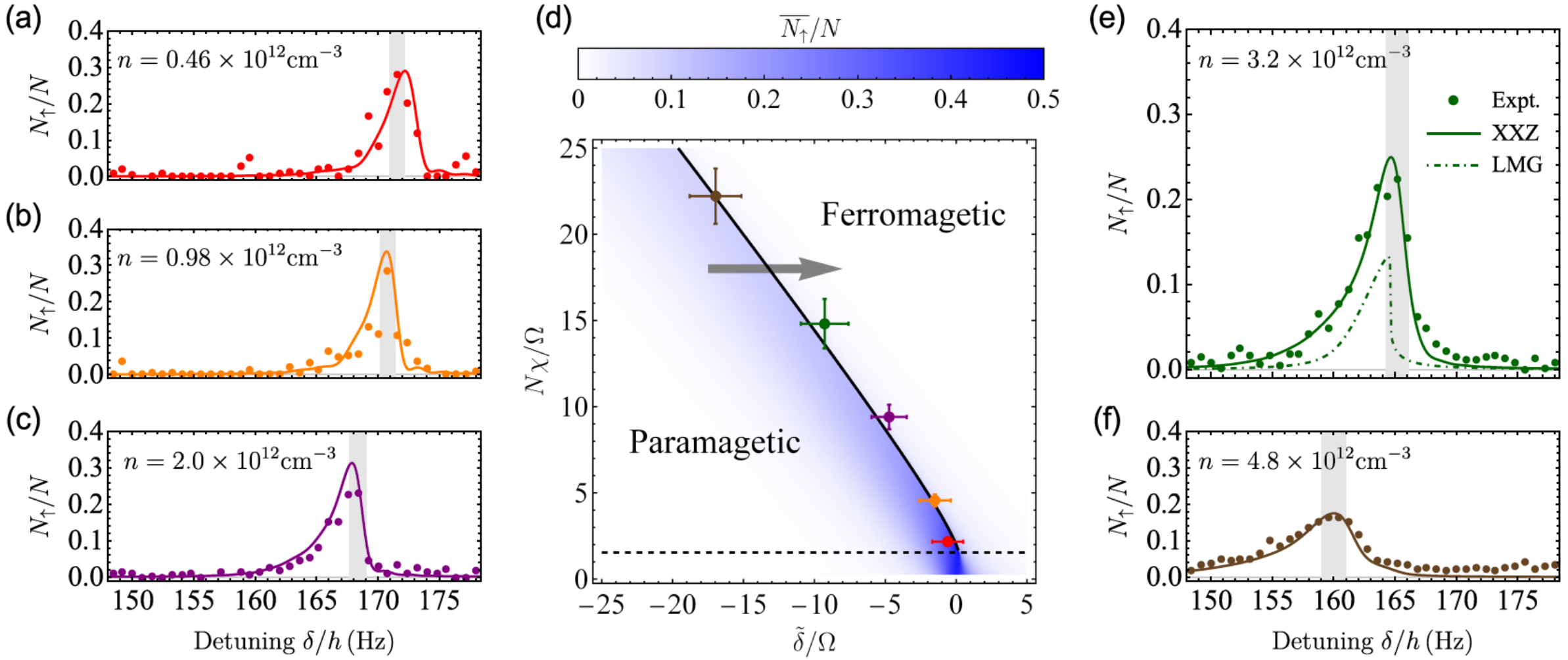
- Initialization: all spins in $|\downarrow\rangle$ state
- Order parameter: Long-time average of excitation fraction

$$\overline{N_\uparrow}/N = \lim_{T\to\infty} \frac{1}{T} \int_0^T N_\uparrow(t)/N$$

- Phase diagram: Detuning and interaction vary with a fixed Rabi frequency



Experimental probe of DPT with inhomogeneity



Theoretical prediction of spin squeezing

- Ramsey spin squeezing parameter

$$\xi^2 = \min_\theta N(\Delta S_\theta^\perp)^2/|\langle \mathbf{S}\rangle|^2$$

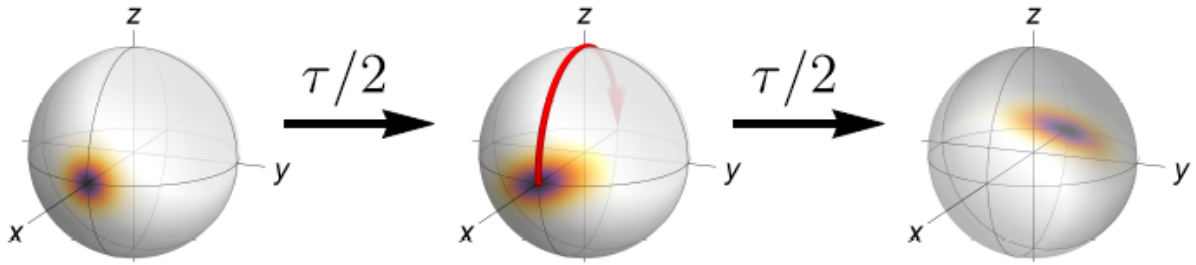
- Discrete truncated Wigner approximation (DTWA)

  Phys. Rev. X 5, 011022 (2015)

- 6dB squeezing for N=1000 atoms, limited by the inhomogeneities in Ising couplings

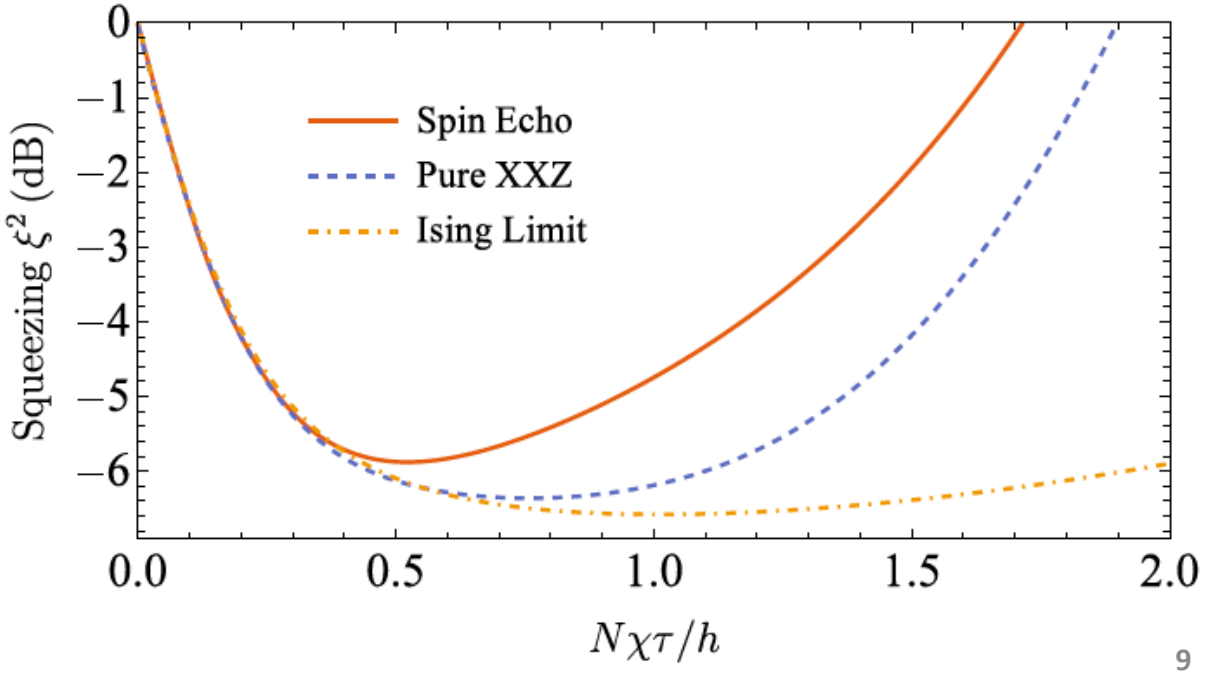
- This sideband protocol can apply to a wide range of systems

(a)



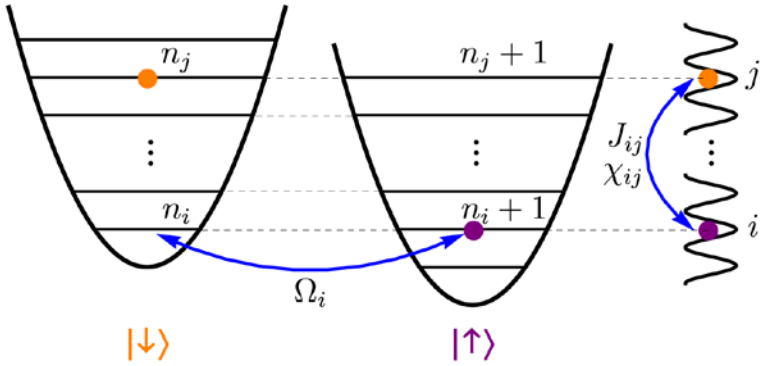
$$H_{\text{int}} = \sum_{ij} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ij} \chi_{ij} S_i^z S_j^z + \sum_i B_i S_i^z$$

(b)

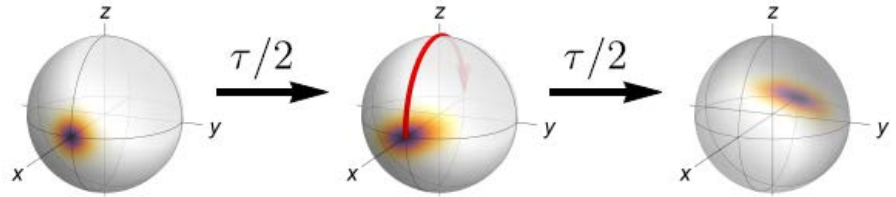


Conclusion

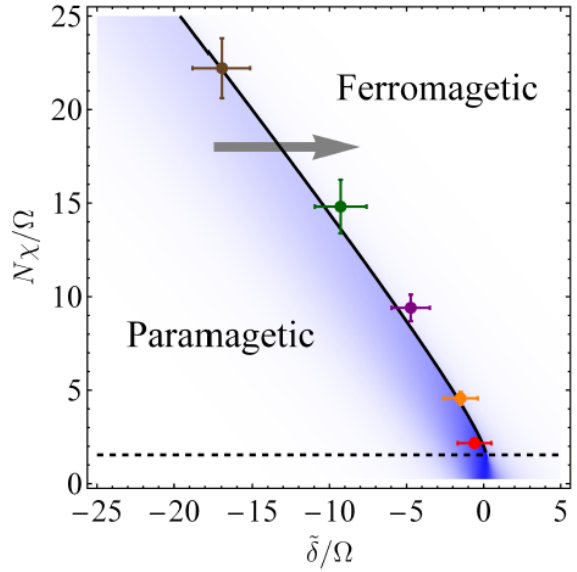
- Simulate long-range XXZ model via motional sidebands



- Potential of motional sidebands in spin squeezing generation



- Experimental demonstration via a probe of DPT



Thank you for your attention!

Anjun Chu, Johannes Will, Jan Arlt, Carsten Klempt, and Ana Maria Rey, arXiv:2004.01282