Observation of a Dynamical Phase Transition in a Quantum Simulator of Lipkin-Meshkov-Glick Model using Bosonic Gases

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Dynamical phase transition (DPT) in LMG model

Equilibrium Phase Transition: a non-analytic dependence on system parameters in equilibrium order parameters

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Dynamical Phase Transition (DPT): a non-analytic dependence on system parameters in time-averaged order parameters of quench dynamics

Another definition: Phys. Rev. Lett. 120, 130601 (2018)

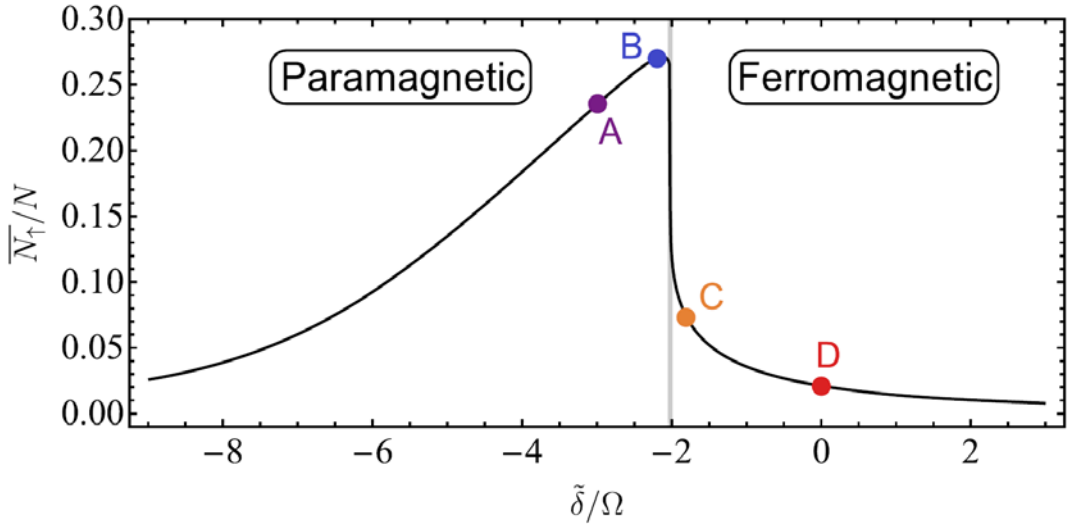
Lipkin-Meshkov-Glick (LMG) Model:

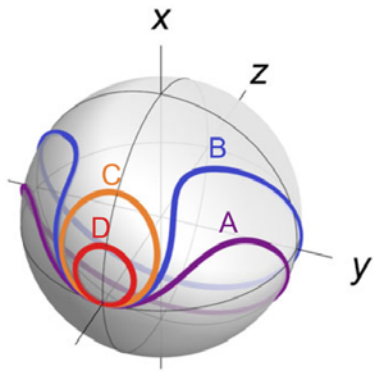
$$H_{\mathrm{LMG}} = \chi S^z S^z + \Omega S^x - \tilde{\delta} S^z$$

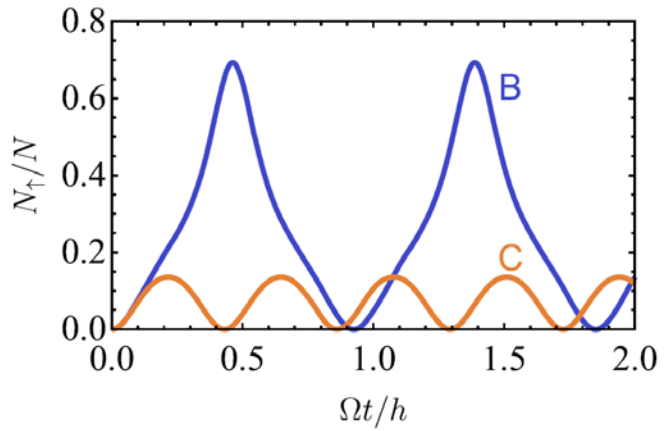
Initialize all spins in $|\downarrow\rangle$ state | Sudden quench to detuning $\tilde{\delta}$ | Evolution under H_{LMG} | Measure longtime average of excitation fraction $\overline{N_\uparrow}/N$

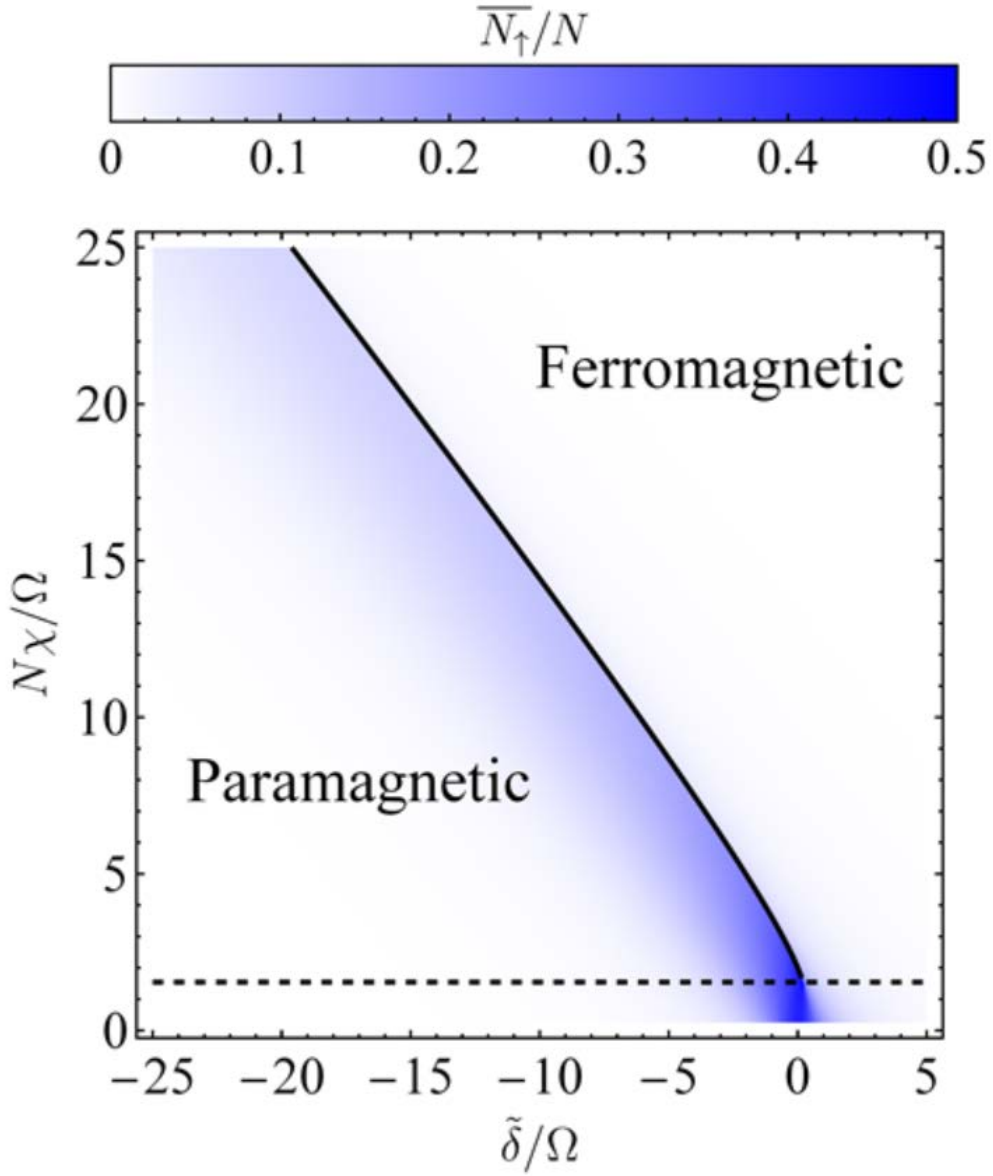
Dynamical phase transition (DPT) in LMG model

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





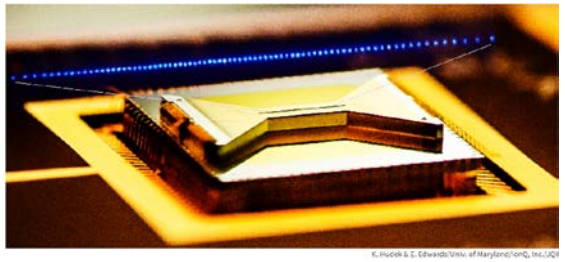




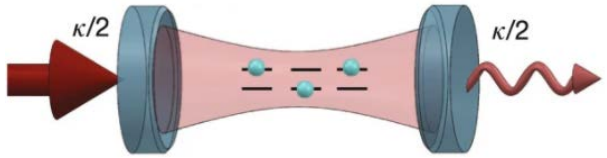
Quantum simulation of LMG model

- Simulation of LMG model with intrinsic long-range interaction

  - Trapped ions

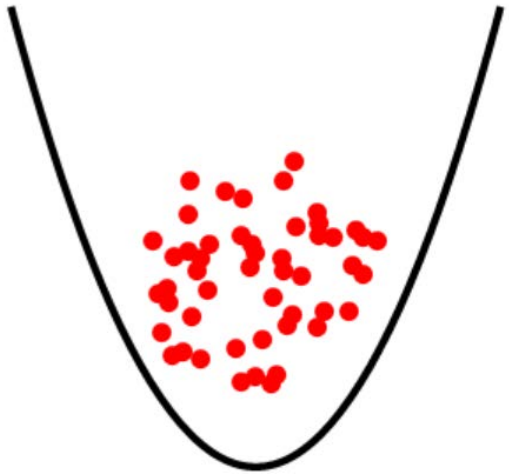


  - Cavity QED

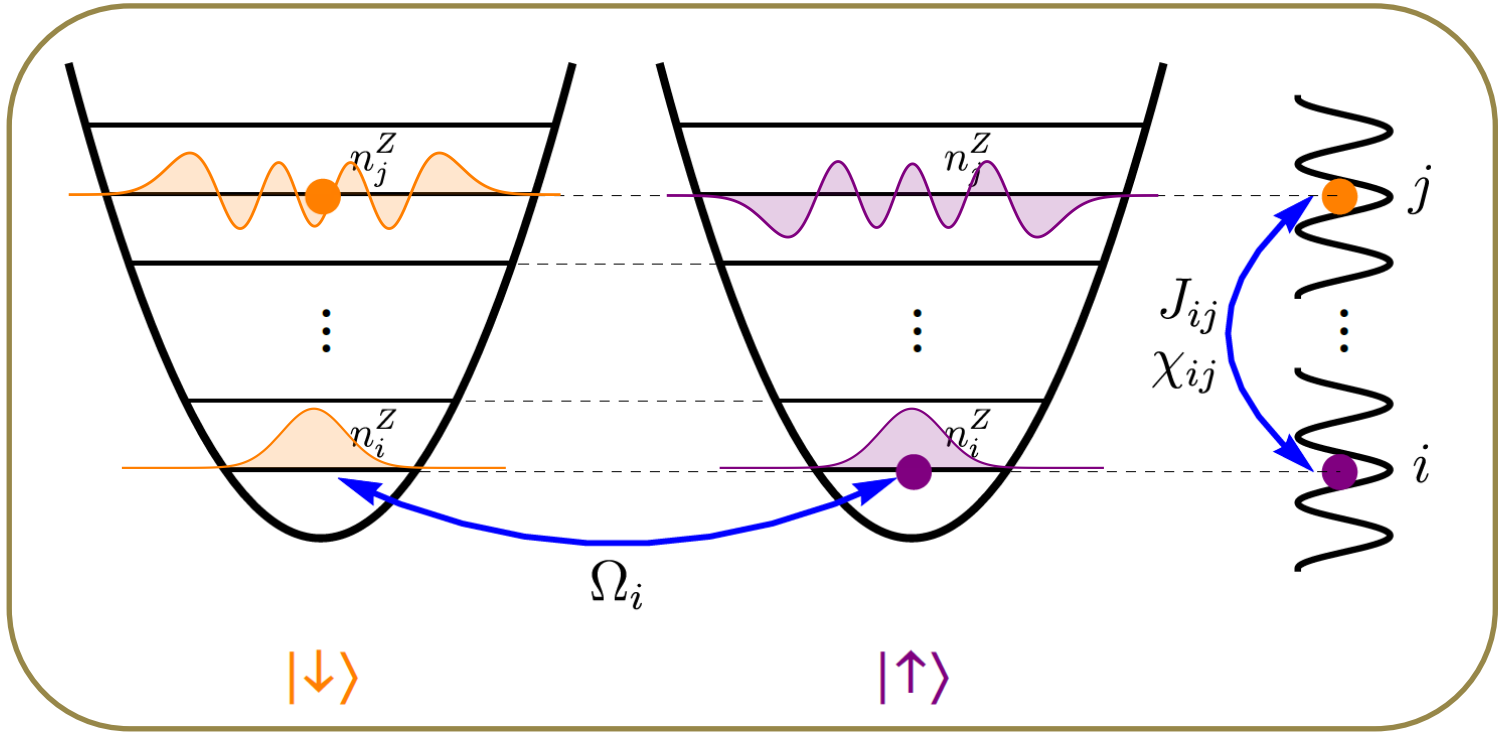


Nature 551, 601 (2017)
Nature 580, 602 (2020)

- What about the quantum systems feature intrinsic contact interaction such as trapped bosonic gases?



Harmonic trap as mode-space lattice



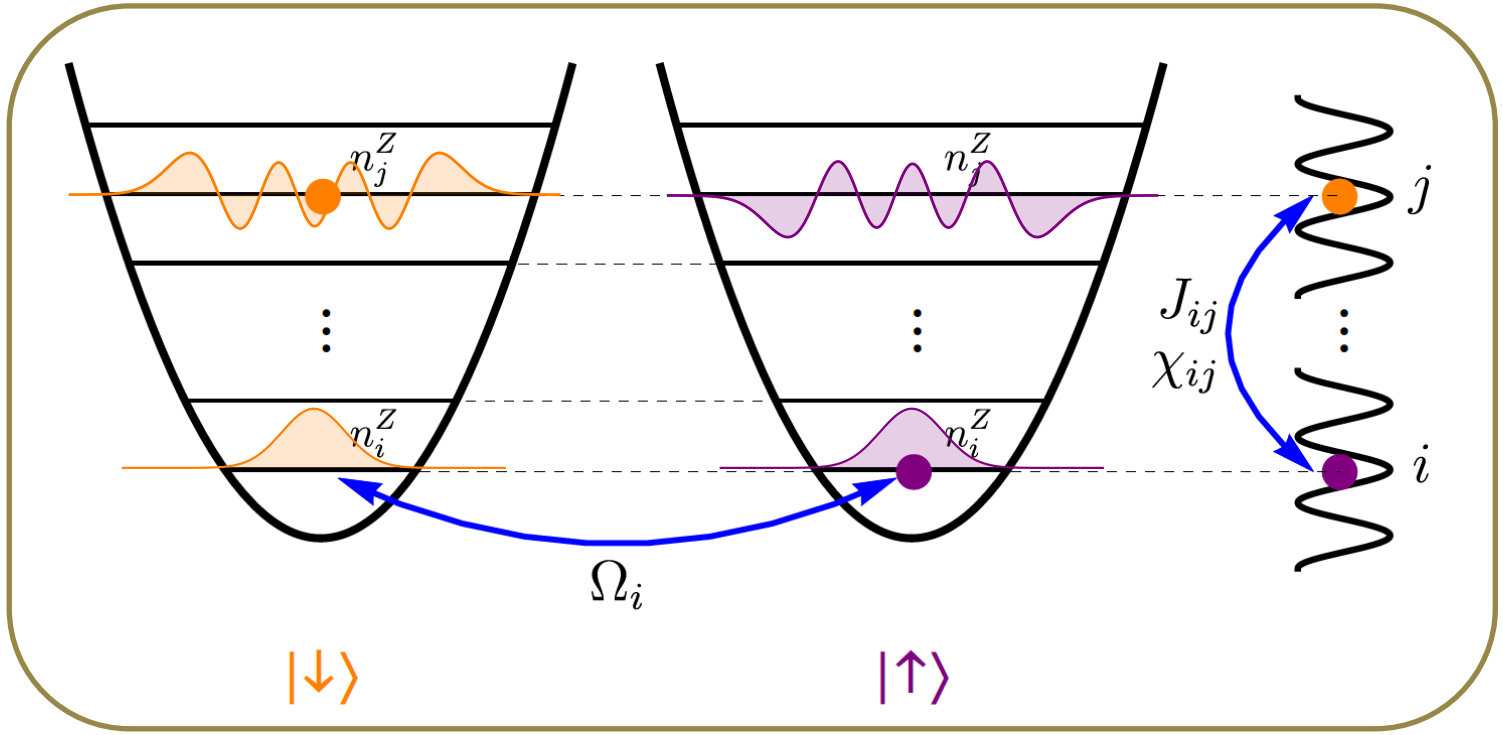
Collisionless regime: trapping frequency ≫ interaction

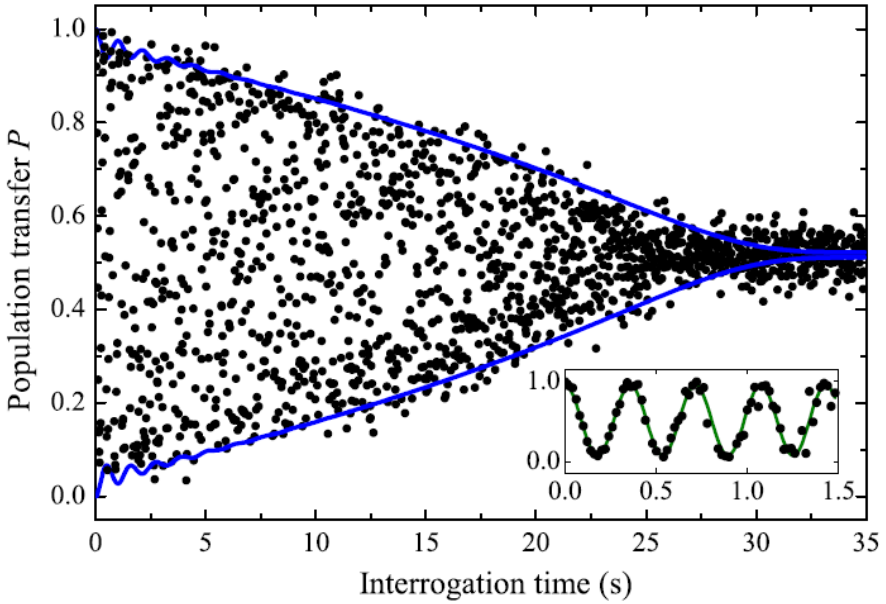
Frozen atoms in 3D lattice in mode space

Contact interaction of bosonic atoms

$$H_{\text{int}} = \sum_{\sigma\sigma'=\uparrow,\downarrow} \frac{U_{\sigma\sigma'}}{2} \int d^3\mathbf{R}\psi_\sigma^\dagger(\mathbf{R})\psi_{\sigma'}^\dagger(\mathbf{R})\psi_{\sigma'}(\mathbf{R})\psi_\sigma(\mathbf{R})$$

Long-range spin model: carrier transition





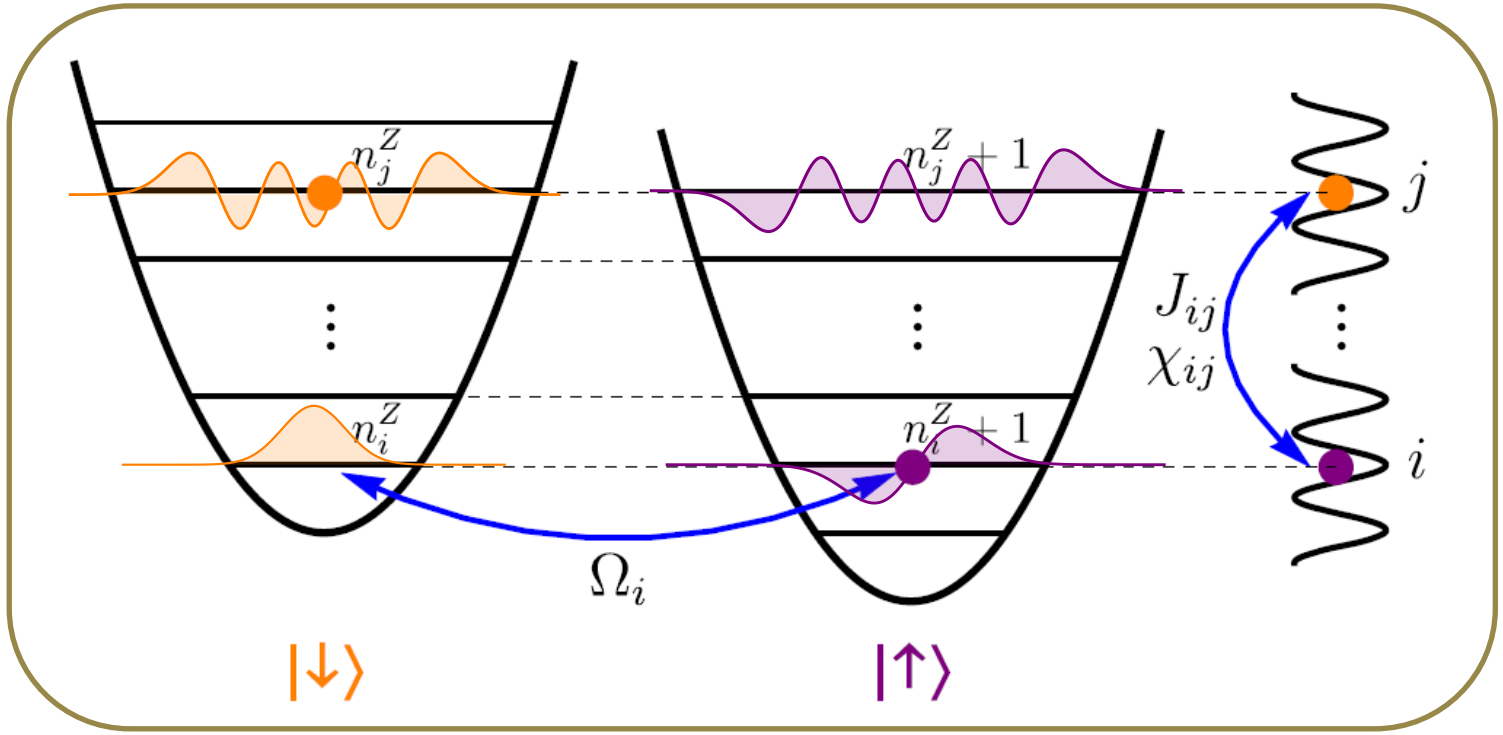
Phys. Rev. Lett. 106, 240801 (2011)

Carrier transition

$$\phi_i^{\Uparrow}(\mathbf{R}) = \phi_i^{\Downarrow}(\mathbf{R})$$

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

Long-range spin model: sideband transition



- Blue sideband transition

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

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

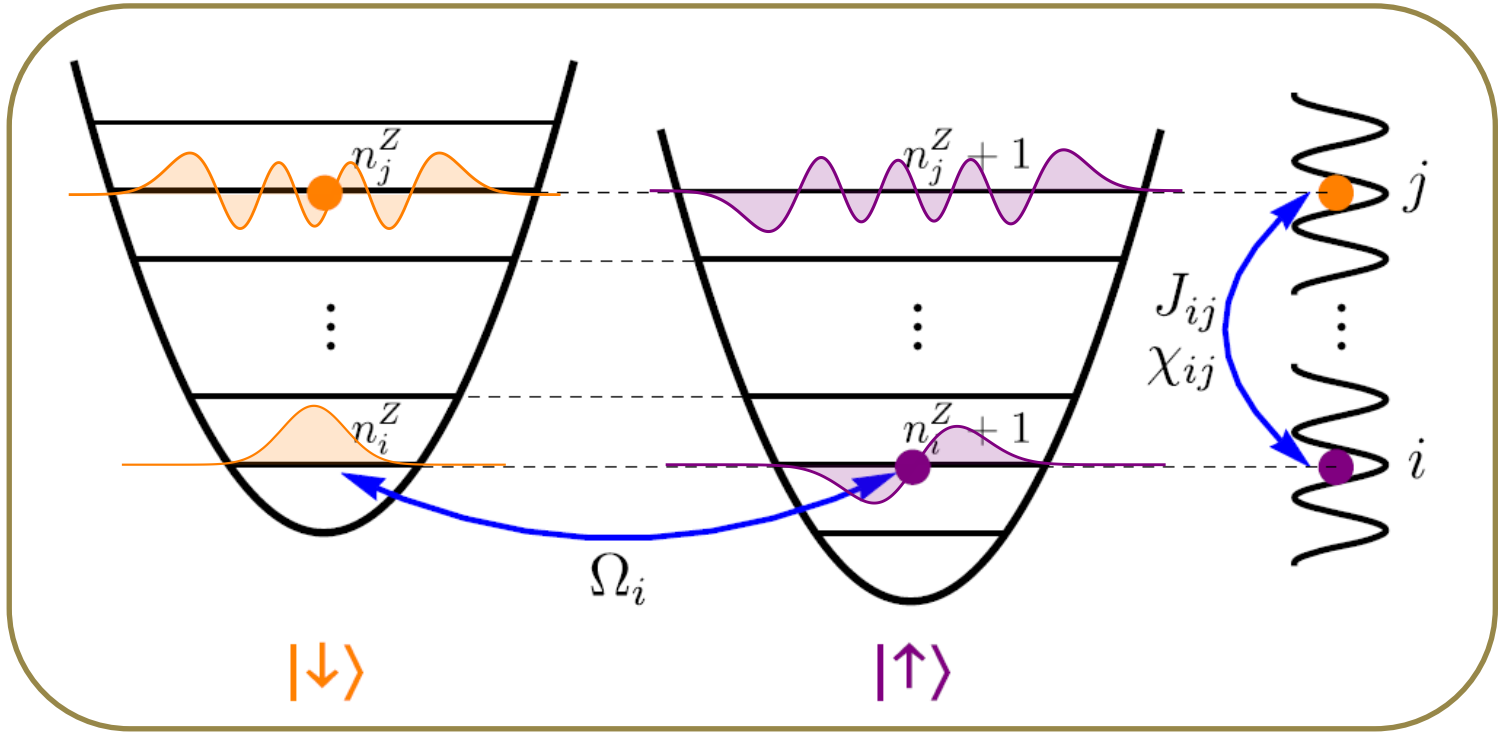
- Add anisotropy to Heisenberg models by tuning overlap integrals of wave function

Sideband transition

$$\phi_i^{\Uparrow}(\mathbf{R}) \neq \phi_i^{\Downarrow}(\mathbf{R})$$

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

Long-range spin model: sideband transition



Collective interaction in mode-space

+

Raman laser drive for blue sideband

Collective limit
(Dicke manifold)

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

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:

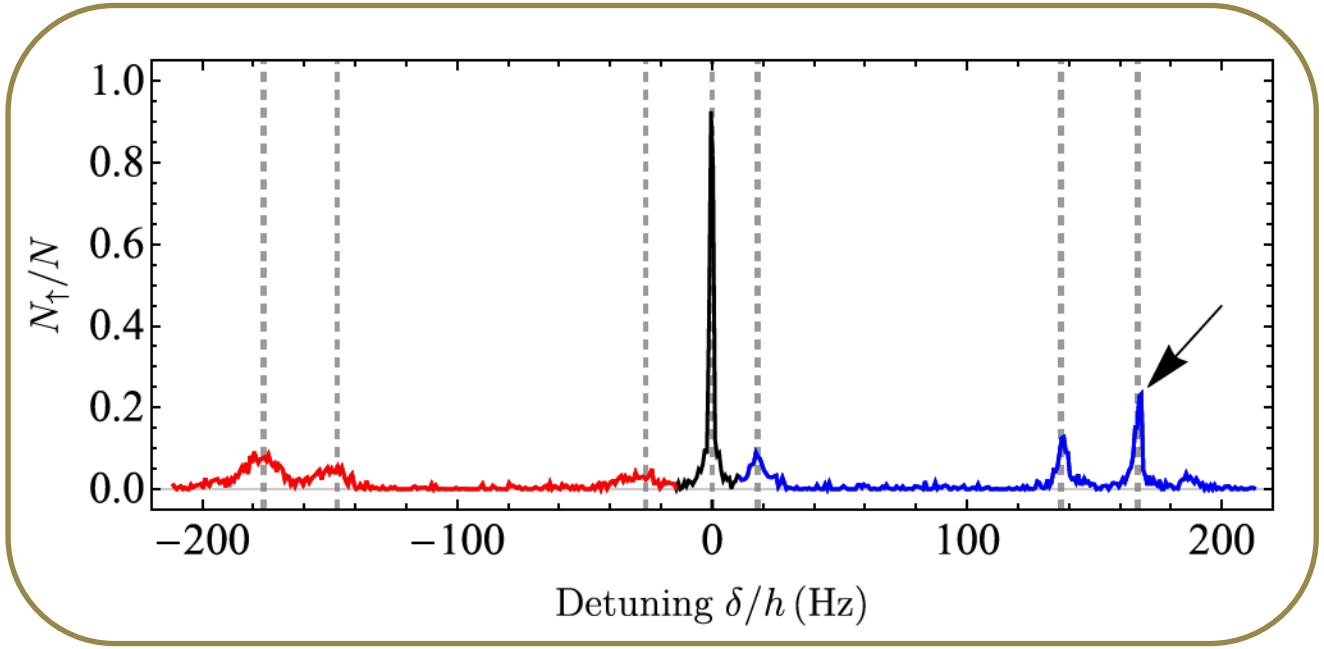
  375(25)nK

- Trapping frequency:

  143Hz, 21.5Hz, 171Hz

- Atom density:

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

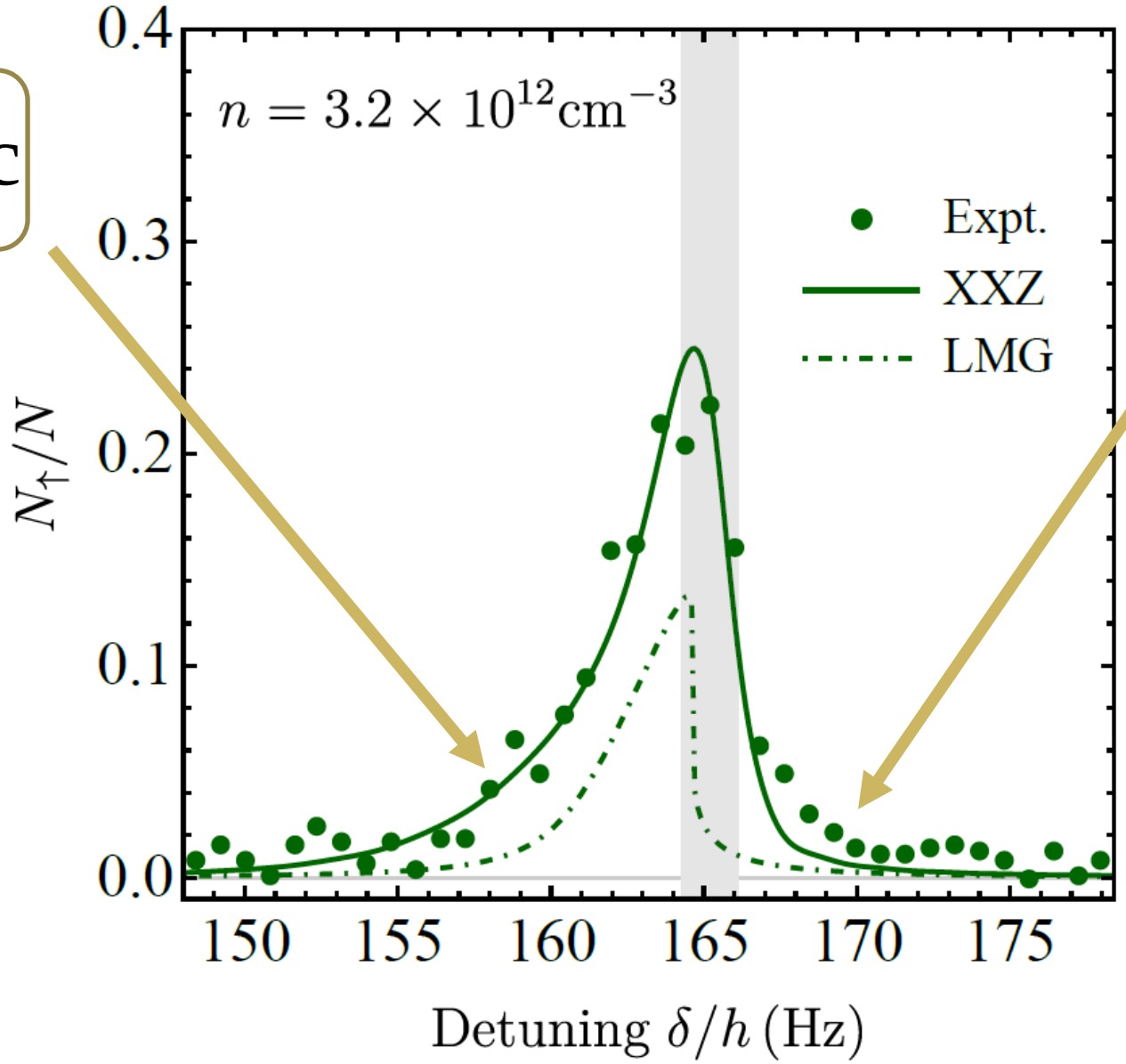


Collisionless regime: trapping frequency ≫ interaction

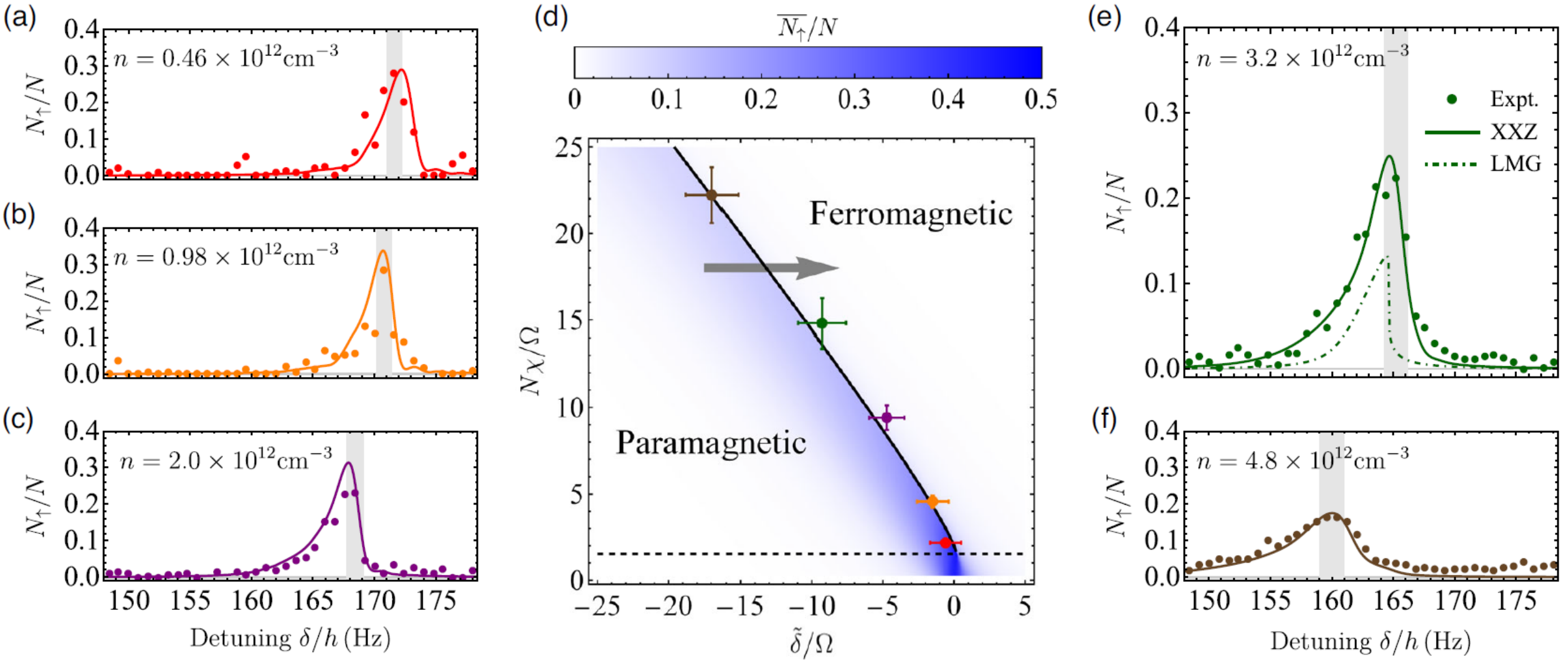
Experimental probe of DPT with inhomogeneity

Paramagnetic

Ferromagnetic

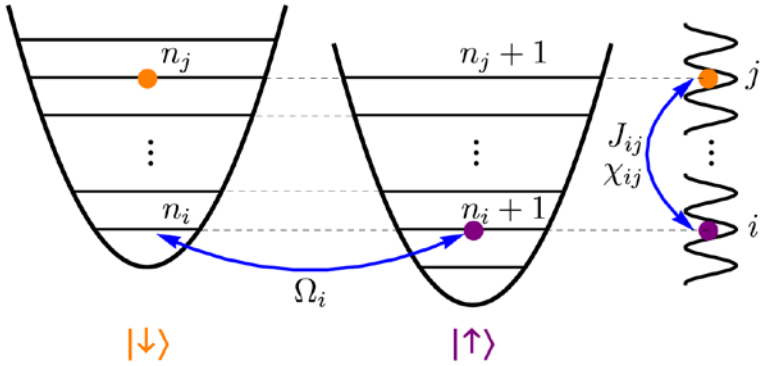


Experimental probe of DPT with inhomogeneity

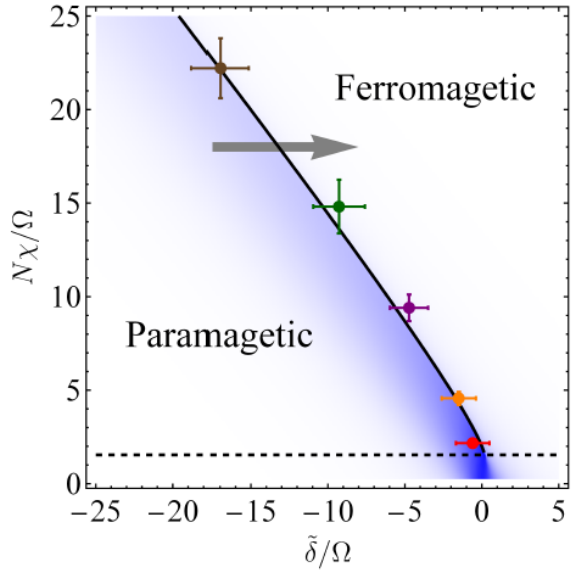


Thank you for your attention!

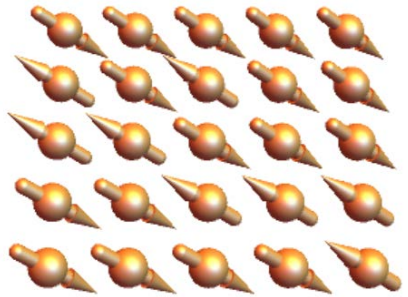
- Simulation of long-range XXZ model via motional sidebands

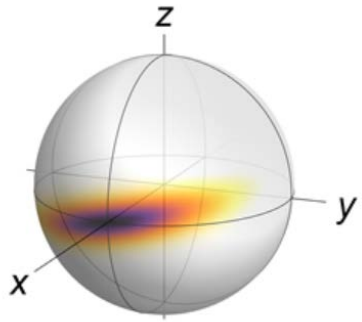


- Observation of dynamical phase transition in LMG model



- New possibilities in quantum simulation and metrology





A. Chu, J. Will, J. Arlt, C. Klempt, and A. M. Rey, Simulation of XXZ Spin Models Using Sideband Transitions in Trapped Bosonic Gases, Phys. Rev. Lett. 125, 240504 (2020)