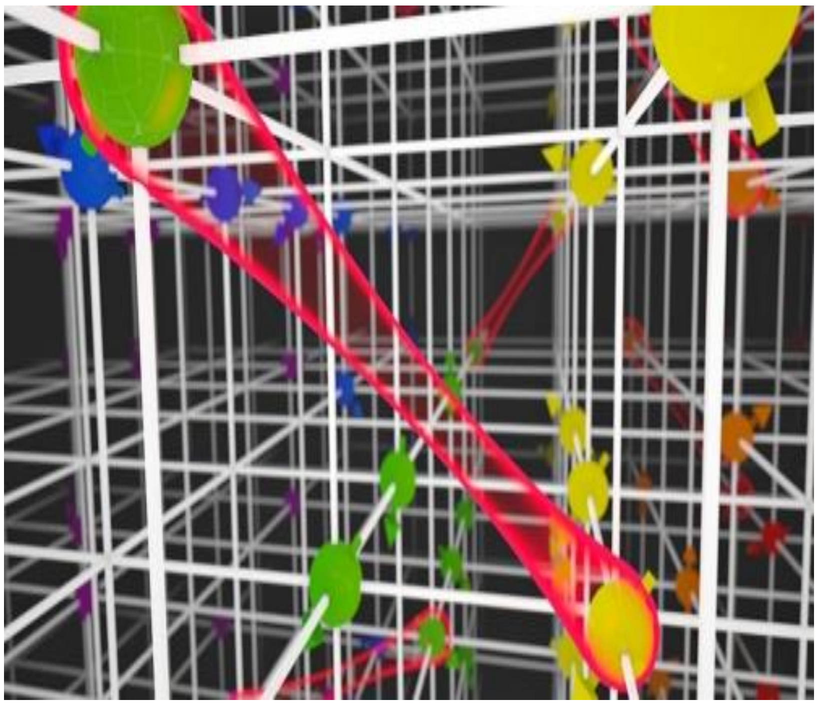
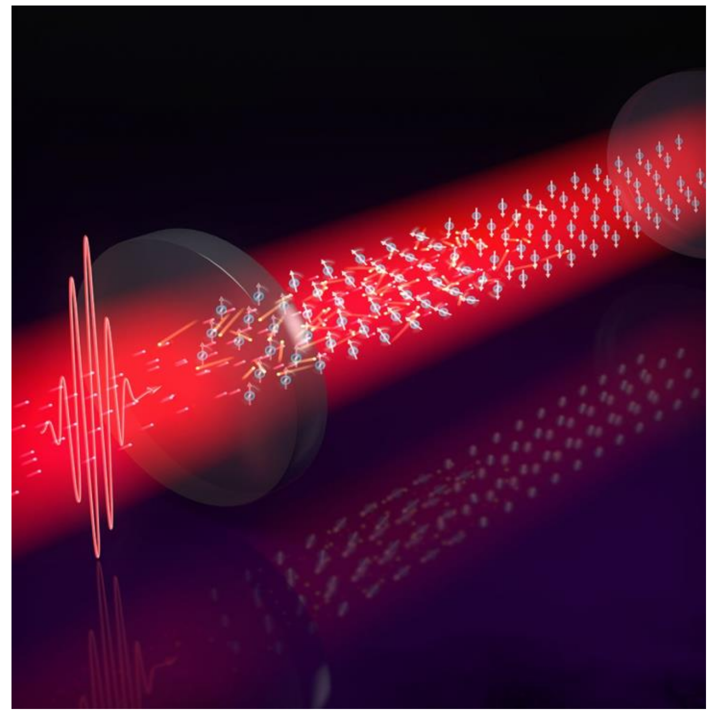
Dynamical Phase Transitions In Cold Atomic Gases

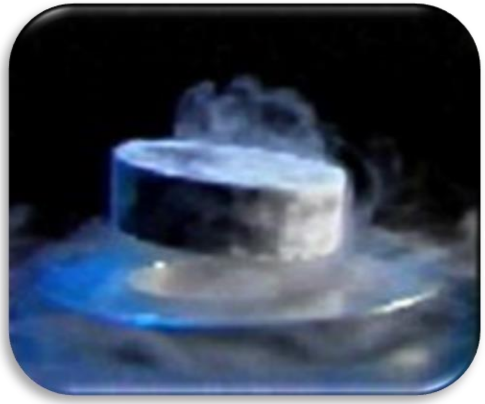
Ana Maria Rey

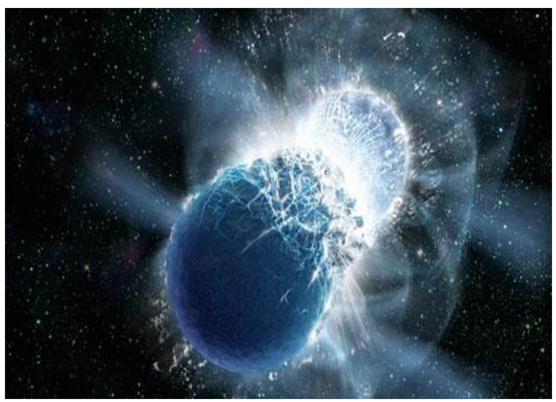




Quantum Science Seminar, July 30th (2020)

Many body systems are fascinating and useful

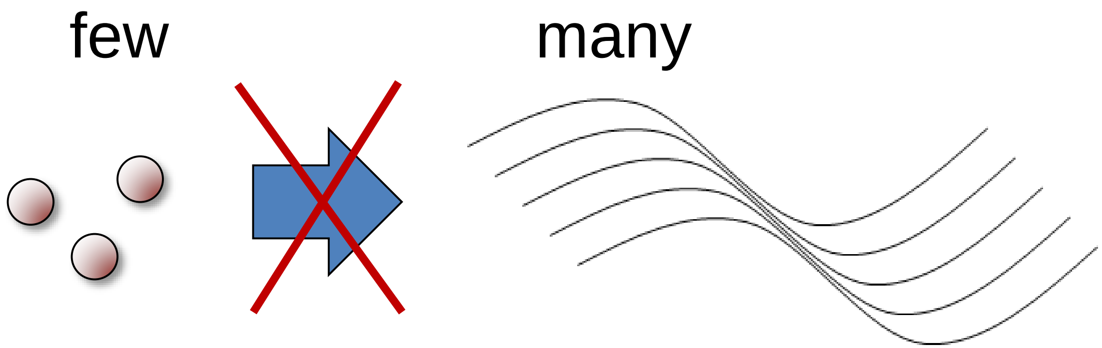






And typically Out-of-Equilibrium

… But They Are Extremely Complex

P. W. Anderson: "The behavior of a piece of matter is NOT just a sum of the behavior of its constituent particles"   Nobel 1977



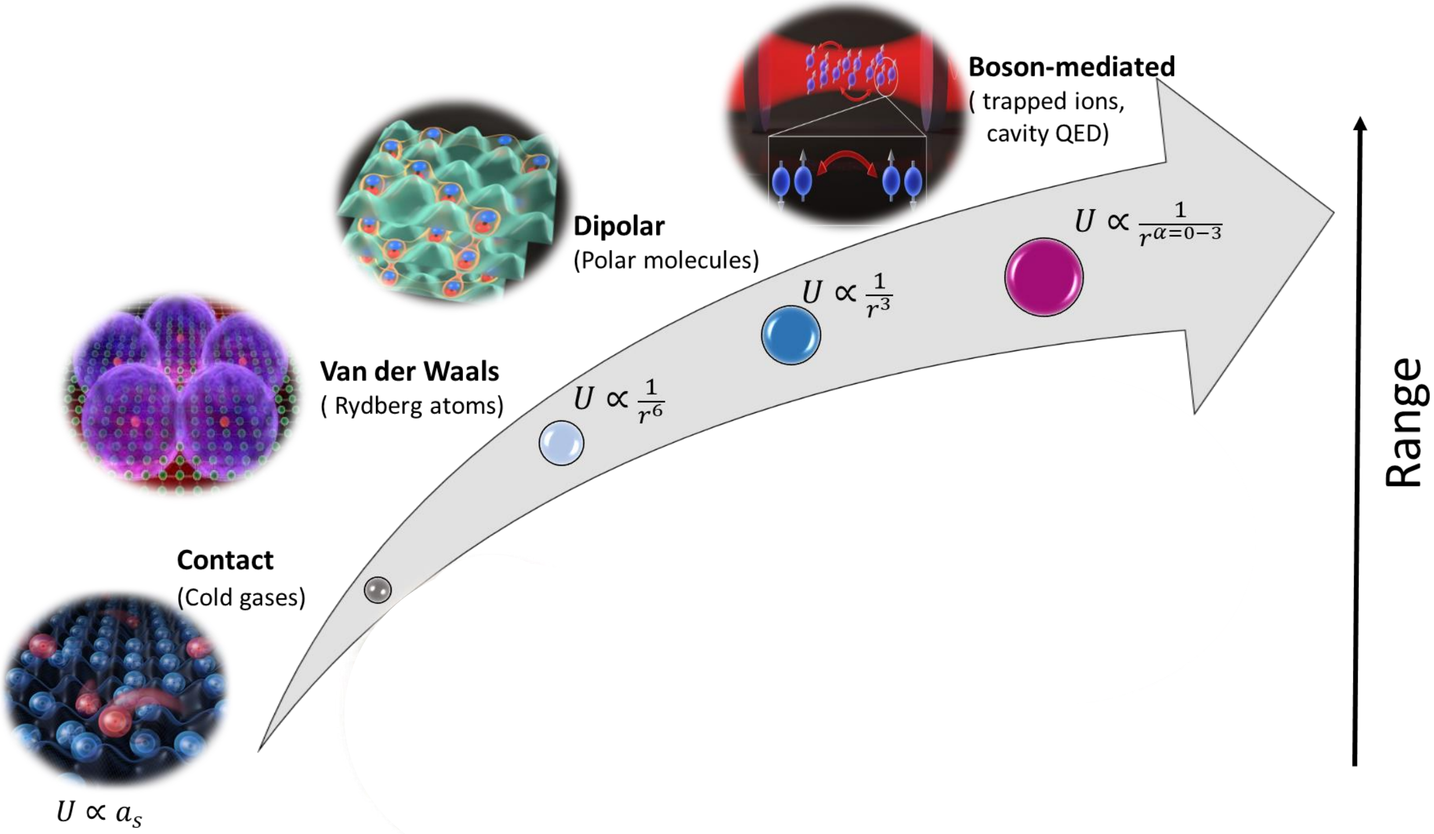
Specially out-of-equilibrium

- Can be strongly correlated and entangled
- Lack a simple description in terms of statistical mechanics
- Feature new types of exotic behaviors prohibited to exist at equilibrium conditions
- Can we understand them?

Scientific Vision

GOAL: Harnessing many-body quantum AMO systems and using them for applications ranging from quantum information to metrology.

- Well-understood microscopics
- Tunable interactions
- Access to quantum dynamics



Scientific Vision

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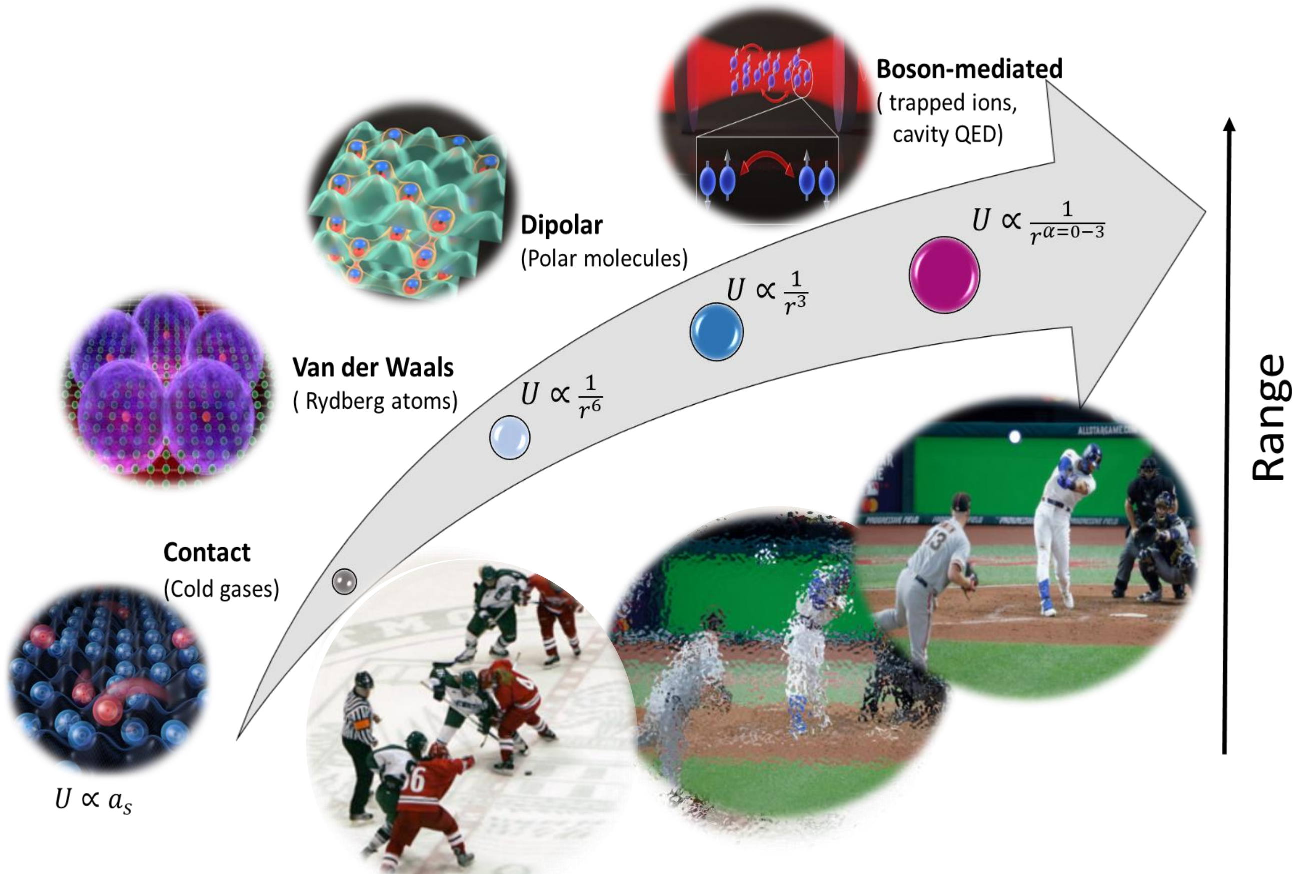
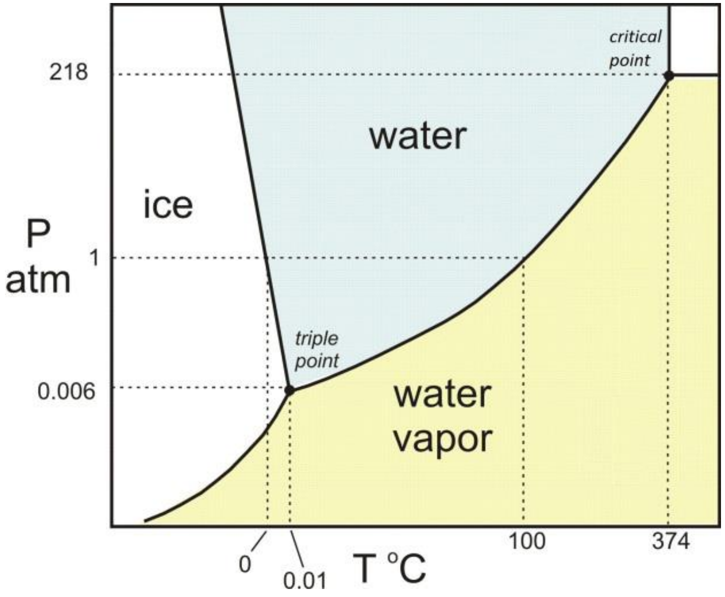


Equilibrium Phase Transitions

Phase Transition: Abrupt (non-analytic) change of behavior as a result of the change of system's parameters, such as temperature (classical), or others control parameter (quantum @ T=0).

Typically describe by an **order parameter**:
Quantity that changes non-analytically at the transition point.



Equilibrium:

- ❑ Minimization of Free energy**.**
- ❑ Slow change of system parameters.

Order Parameter: Density

Non-Equilibrium Phase Transitions

Very General: Include open and closed systems:

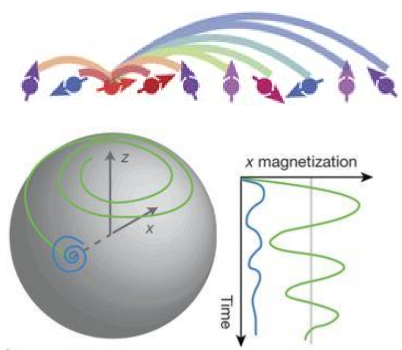
Here: Dynamical Phase Transitions (Closed systems, Unitary Dynamics)

A time averaged order parameter distinguishes two distinct dynamical phases and features a non-analytic behavior at the critical point.

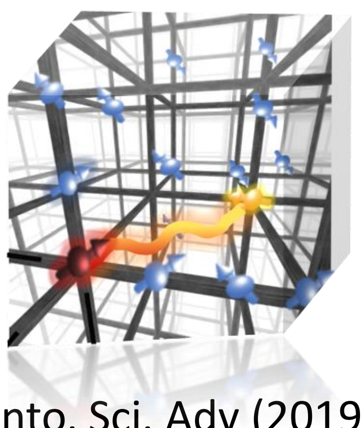
- ❑ Dynamical: Not found by minimization of free energy
- ❑ New symmetries
- ❑ Robust generation of useful entangled states

53 ions

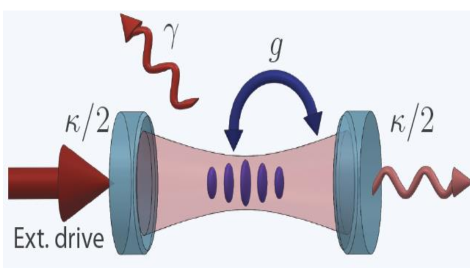
Many-body: Several thousands to million



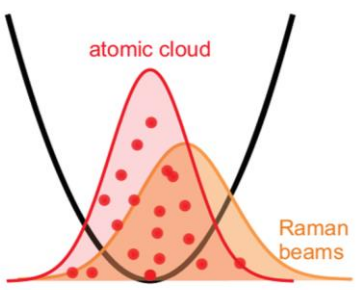
JQI, Nature(2018)



Toronto, Sci. Adv (2019)



JILA, Nature (2020)



Hannover, Arxiv(2020

Other Definitions: Innsbruck, PRL(2017) & Hamburg, Nat. Phys (2018)

M. Heyl, EPLA (2019)

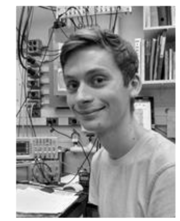
Theory

The Toronto team:

Joseph Thywissen

S. Smale

B. Olsen



K. Jackson

S Trotzky

The JILA Sr teams:

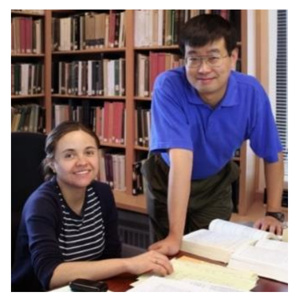
James Thompson

M. Norcia

J. Cline

J. Silva

D. Young



Jun Ye

Jan Arlt

Carsten Klempt

DARPA

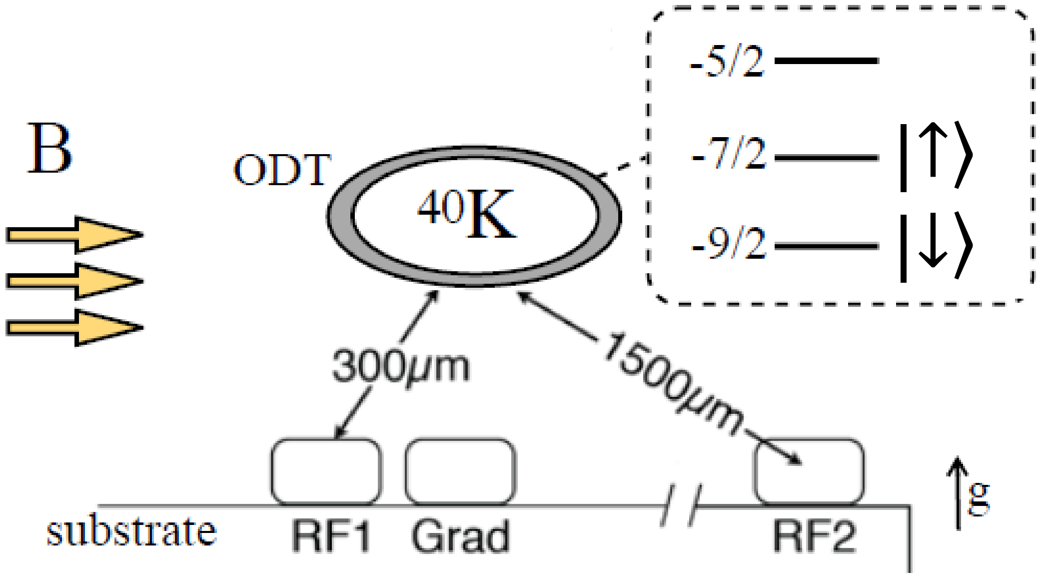
NSF

Toronto Experiment

S. Smale *et al* Science Advances 5, eaax1568 (2019)

3D Trapped Quantum degenerate ^{40}K, T/T_F~0.3-0.5, N~ $3x10^4$

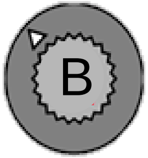
Use lowest two hyperfine states

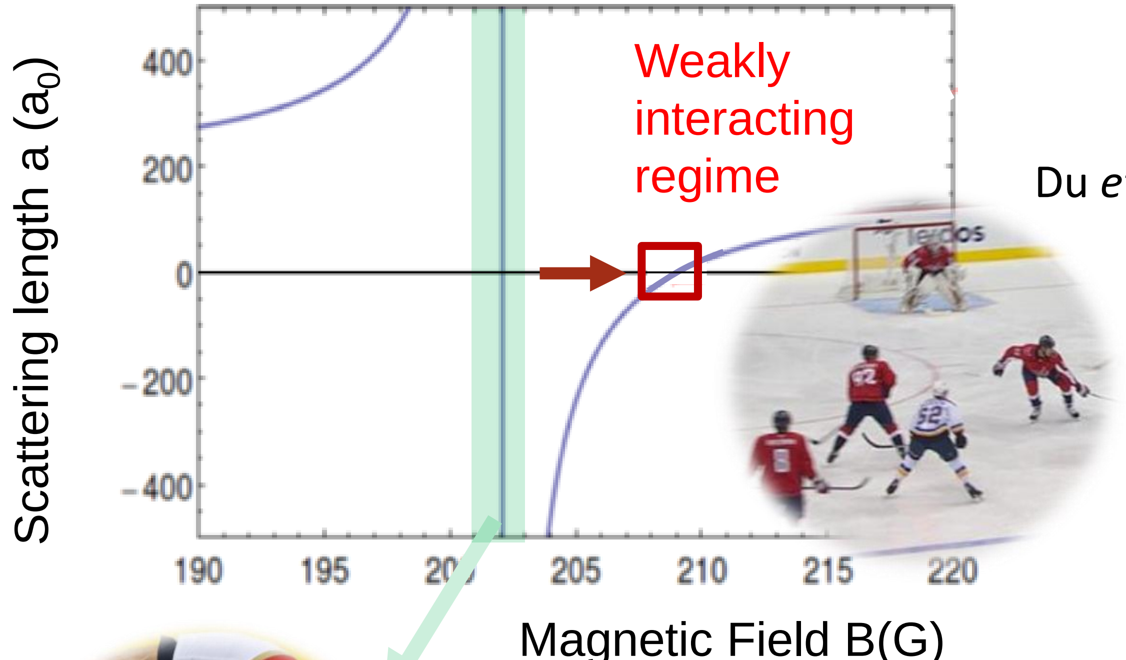


Proximal wires give strong RF (for spin flips, gradient control)

Control of Interactions via Feshbach Resonance

- Strength of Contact of Interactions: set by a single parameter, scattering length
- In some atoms can be controllably varied via magnetic fields



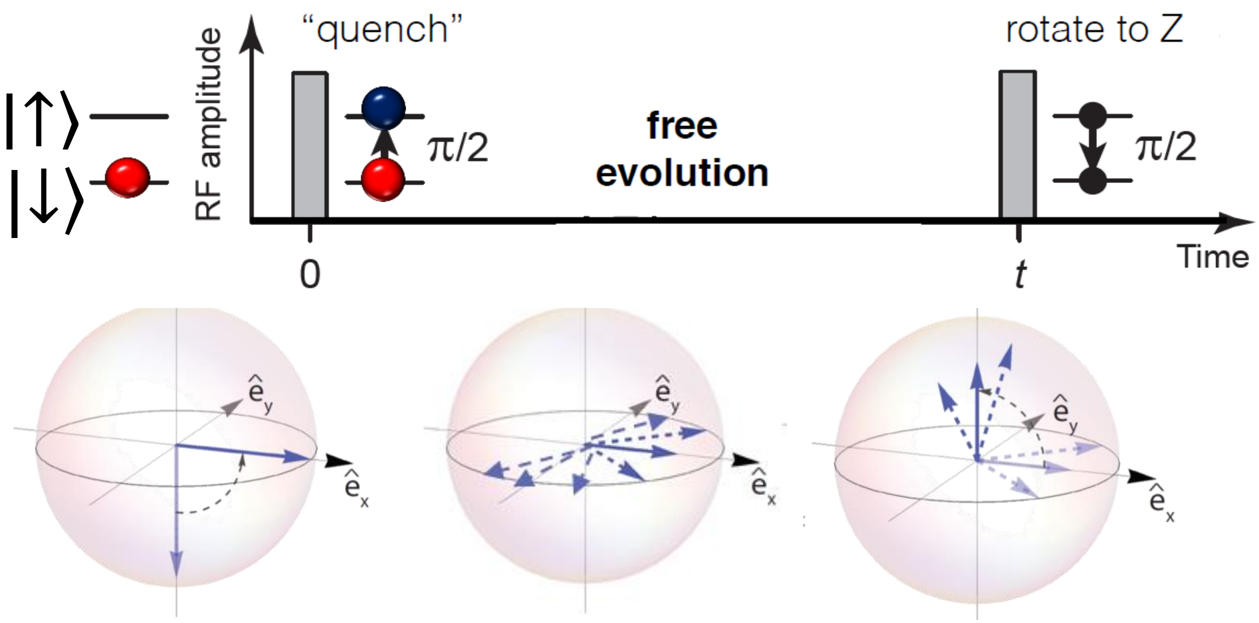


Du *et al* PRL (2008)

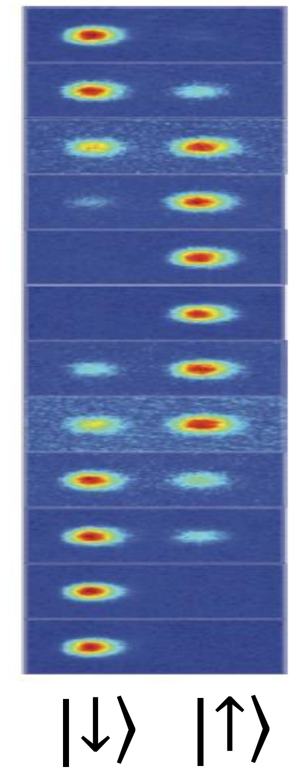
Strongly Interacting Regime:
Hydrodynamics Behavior
Connection to High Tc, Quark-Gluon plasma…

Observables

Total magnetization of ensemble



Stern-Gerlach



Directly observed:

total *transverse* magnetisation

$$\mathcal{C} = \sqrt{\left\langle \hat{S}^{x}(t)\right\rangle^{2} + \left\langle \hat{S}^{y}(t)\right\rangle^{2}}$$

$$\hat{S}^{x,y,z} = \sum_{i=1}^{N} s_i^{x,y,z}$$

but initial:

$$\left\langle \hat{S}^{z}(0)\right\rangle = 0$$

& constant

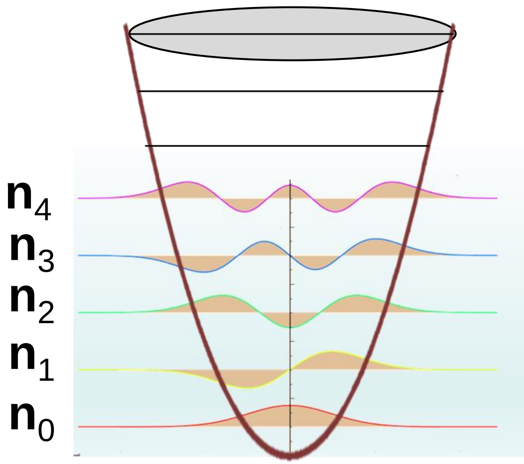
so can interpret it as:

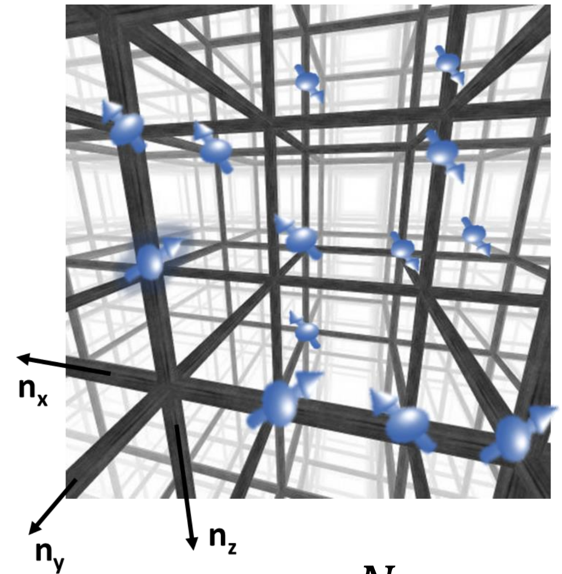
$$\mathcal{S} = \sqrt{\left\langle \hat{\vec{S}}(t)\right\rangle \cdot \left\langle \hat{\vec{S}}(t)\right\rangle}$$

Total magnetization

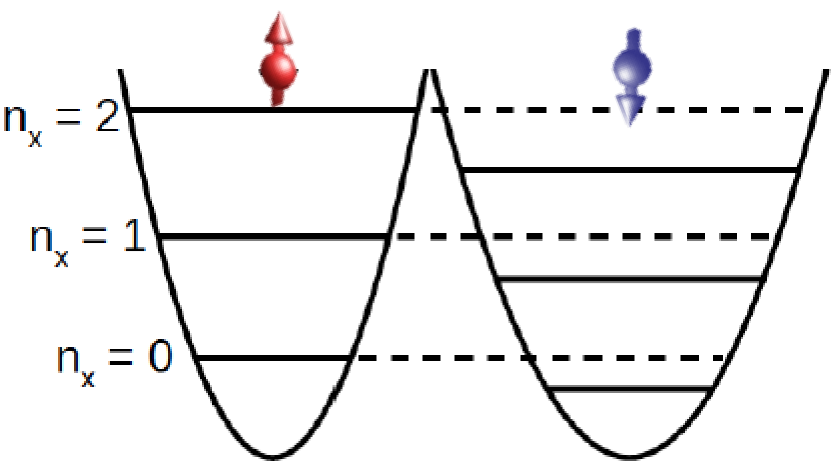
Non-Interacting Atoms

Non-interacting 3D harmonic oscillator modes





Spin-dependent energy shifts



$$\boldsymbol{\omega}_{\uparrow\downarrow} = \boldsymbol{\omega} \mp \Delta\boldsymbol{\omega}$$

$$\hat{H}_0 = E + \sum_{i=1}^{N} h_i \, s_i^z$$

$$h_i = 2\Delta\boldsymbol{\omega} \cdot \boldsymbol{n}_i$$

Control in the lab:

1. Curvature in (real) B
2. Vector light shift

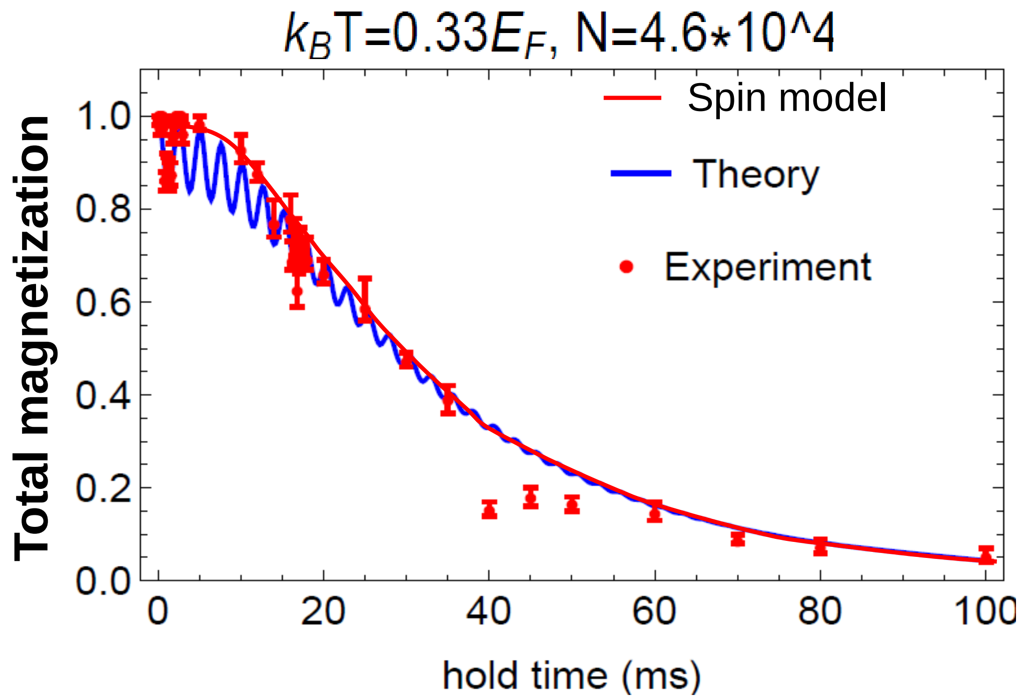
Non-Interacting Atoms

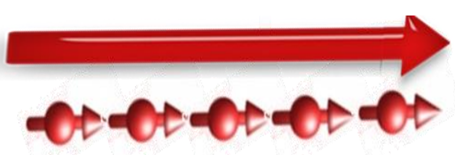
Dephasing: loss of phase coherence

$$\hat{H}_0 = \sum_i h_i \, s_i^z$$

$$h_i = 2\Delta\boldsymbol{\omega} \cdot \boldsymbol{n}_i$$

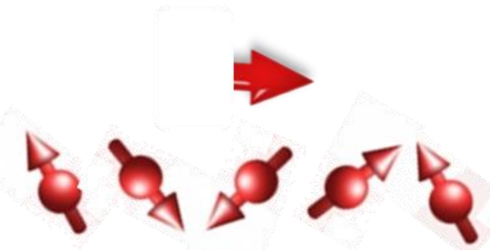
$$\hat{S}^{x,y,z} = \sum_{i=1}^{N} s_i^{x,y,z}$$

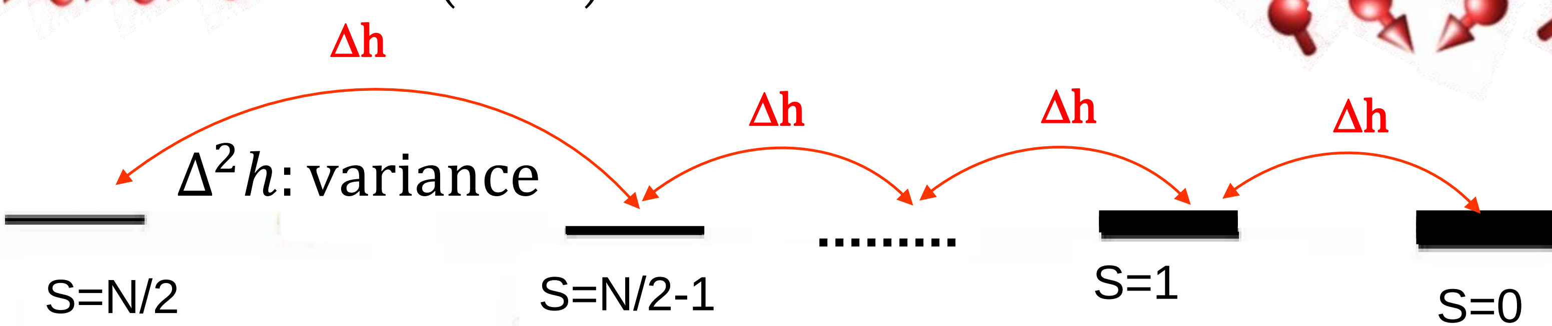




H_0 does not conserve S

$$\left(\vec{\hat{S}} \cdot \vec{\hat{S}}\right) |S, M\rangle = \mathbf{S}(\mathbf{S}+\mathbf{1}) \, |S, M\rangle$$



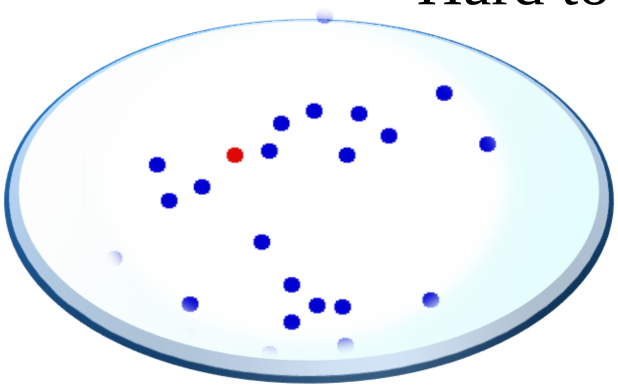


Weakly Interacting gas

Idea: Model the atoms as quantum magnets- frozen in energy space

Position

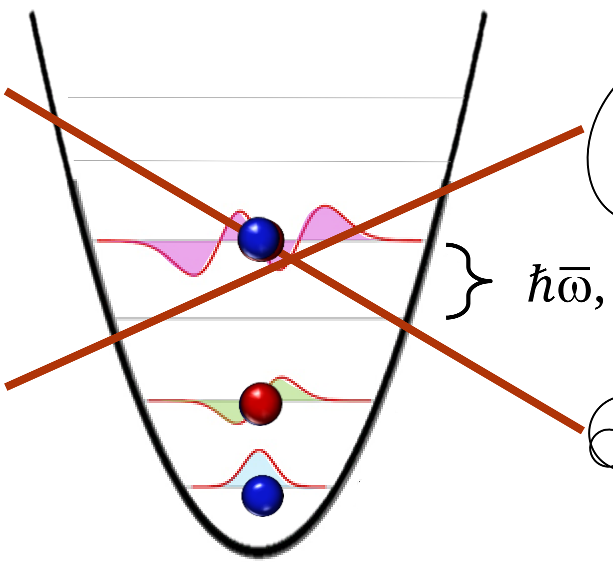
Hard to model

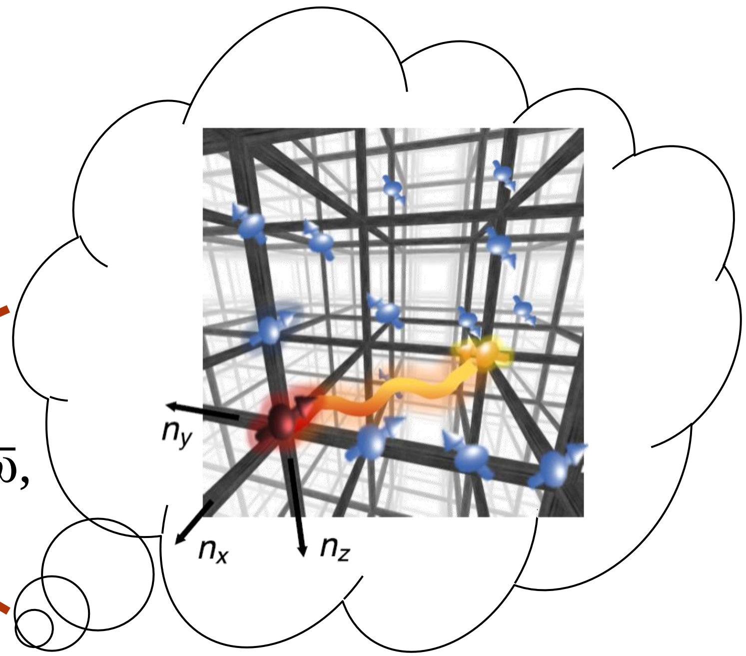


Weak interactions simplify physics

Frozen motional levels

Delocalized modes: Long range interactions





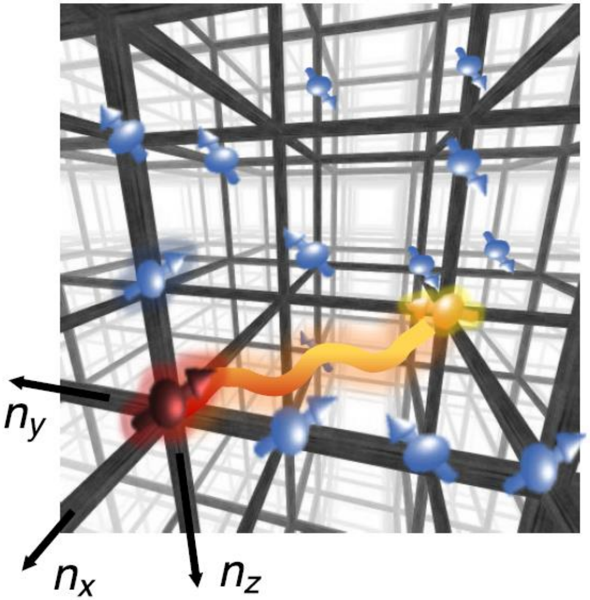
Energy lattice: Spin model

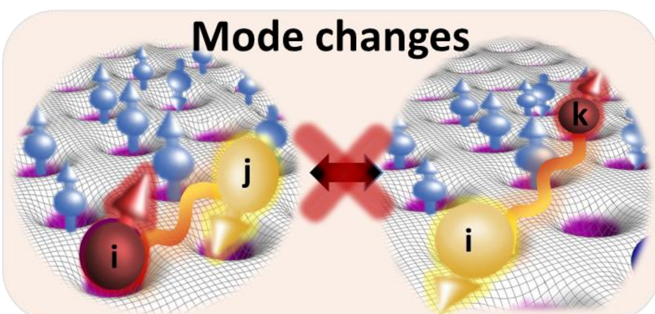
Atomic Clocks: M. Martin *et al* ,Science **341**, 632 (2013)
X. Zhang *et al*, Science **345**, 1467 (2014)

Weakly Interacting gas

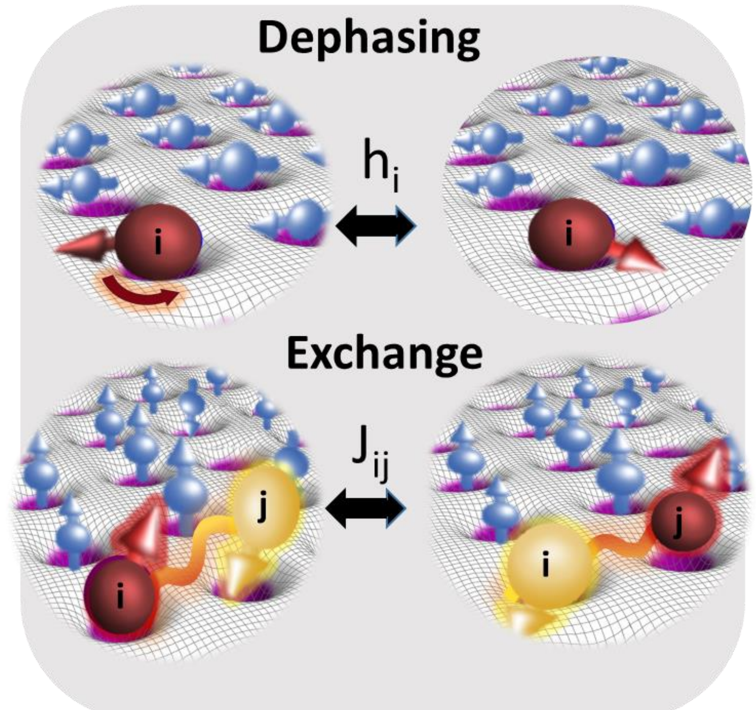
Spin model approximation: Frozen motional levels

Spin lattice model





$$\hat{H} = -\sum_{i>j} J_{ij}(a)\,\vec{\hat{s}}_i \cdot \vec{\hat{s}}_j + \sum_i h_i\,\hat{s}_i^z$$



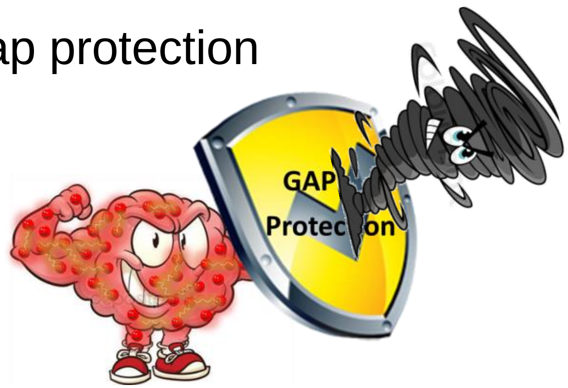
a: scattering length

$$J_{ij} \propto a \int d^3\boldsymbol{r}\,(\phi^2_{\uparrow n_i}(\boldsymbol{r})\,\phi^2_{\downarrow n_j}(\boldsymbol{r}))$$

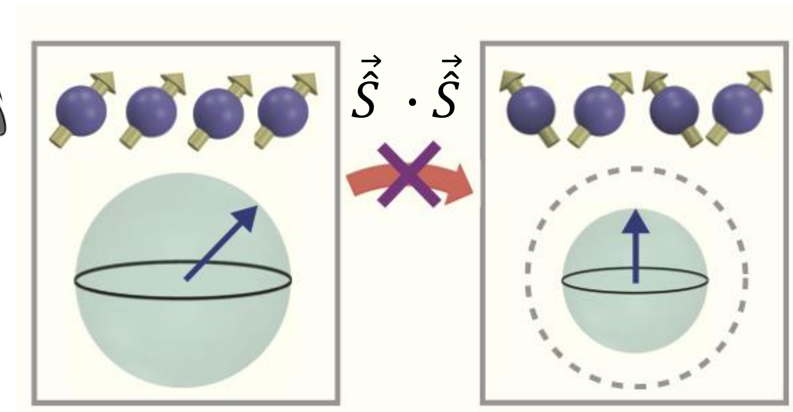
Weakly Interacting gas

$$\hat{H} = -\sum_{i>j} J_{ij}\, \vec{\hat{s}}_i \cdot \vec{\hat{s}}_j + \hat{H}_0$$

Gap protection



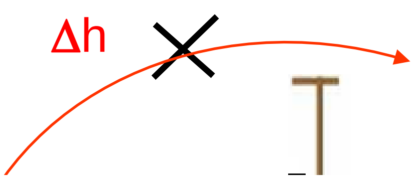
Stabilizes alignment



Exchange energy change from

$S = N/2 \rightarrow S = N/2 - 1$

Collective gap



PHYSICAL REVIEW A **77**, 052305 (2008)

s

Many-body protected entanglement generation in interacting spin systems

A. M. Rey,[1] L. Jiang,[2] M. Fleischhauer,[3] E. Demler,[2] and M. D. Lukin[1,2]

Mean-Field Picture

$$\hat{H}_{MF} = \sum_i \hat{\vec{s}}_i \cdot \vec{\boldsymbol{B}}_i^{\mathrm{ef}}(t) \qquad \vec{\boldsymbol{B}}_i^{\mathrm{ef}} = h_i \hat{z} - 2\sum_j^N J_{ij} \left\langle \hat{\vec{s}}_j(t) \right\rangle$$

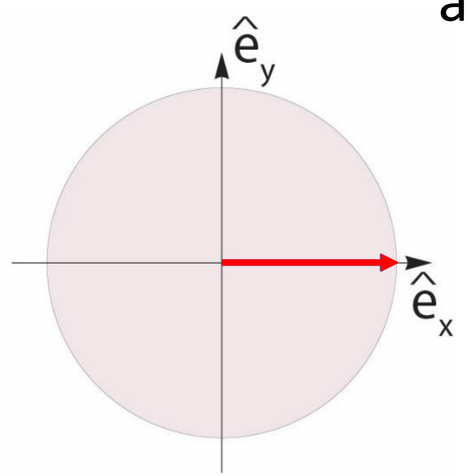
Semi-classical picture:

Identical spin-rotation effect (ISRE)
C. Lhuillier, F. Laloe, *J. Phys.-Paris* **43**, 225 (1982).

A time dependent effective magnetic field generated by other atoms which favors alignment

Non Interacting

Large enough Interactions

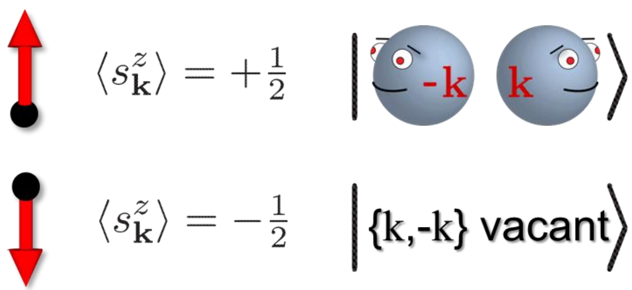


Self-rephasing with increasing interaction

Rb atoms magnetically trapped on a chip: C. Deutsch *et al* PRL (2010).
C. Solaro *et al* PRL (2016)

Simulating a BCS Superconductor

$$H \sim \sum_k \epsilon_k \hat{s}_k^z + \frac{J}{2}\sum_{kq} \hat{s}_k^+ \, \hat{s}_q^- = \sum_k \epsilon_k \hat{s}_k^z + J\hat{S}^+ \cdot \hat{S}^-$$



$$\Delta \equiv \frac{J}{2}\langle \hat{S}^- \rangle$$ Order parameter or gap function

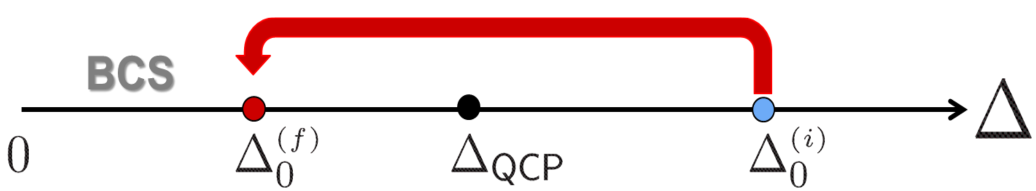
$$|\langle \hat{S}^- \rangle| = \sqrt{\langle \hat{S}^x(t) \rangle^2 + \langle \hat{S}^y(t) \rangle^2}$$

- **Integrable (Richardson-Gaudin model)**

<u>Method</u>: Self-consistent non-equilibrium mean field theory

- Exact solution to nonlinear classical spin dynamics via integrability,
- Lax construction: Frequency spectrum ruling dynamics V. Gurarie, M. Foster

Quenches in superconductors



Gap dynamics

VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Collective Rabi Oscillations and Solitons in a Time-Dependent BCS Pairing Problem

R. A. Barankov,[1] L. S. Levitov,[1] and B. Z. Spivak[2]
[1]*Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, Massachusetts 02139, USA*
[2]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*

PRL 96, ... ending ...NE 2006

REPORTS

SUPERCONDUCTIVITY

Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor

Ryusuke Matsunaga,[1]* Naoto Tsuji,[1] Hiroyuki Fujita,[1] Arata Sugioka,[1] Kazumasa Makise,[2] Yoshinori Uzawa,[3]† Hirotaka Terai,[2] Zhen Wang,[2]‡ Hideo Aoki,[1,4] Ryo Shimano[1,5]*

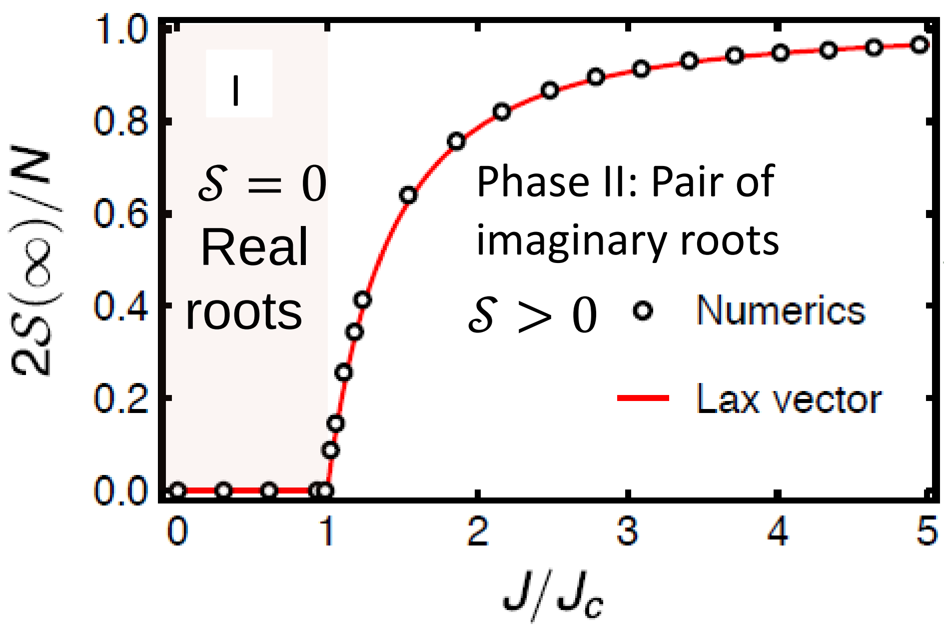
- Hard in real materials.
- Need of ultra-fast pulses
- Small quenches

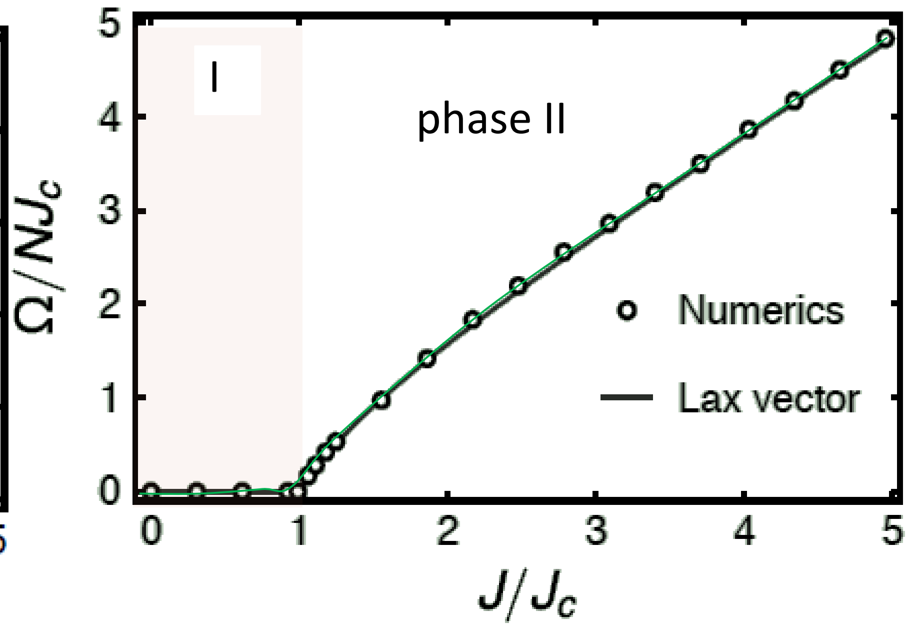
Dynamical Phase Transition (All-To-All)

$$\hat{H} \approx -\bar{J}\,\vec{\hat{S}} \cdot \vec{\hat{S}} + \sum_i h_i\, s_i^z \qquad \bar{J} \propto a/\sqrt{N}$$

Gap Frequency: Ω

$$\Omega = 2J\mathcal{S}(\infty)$$



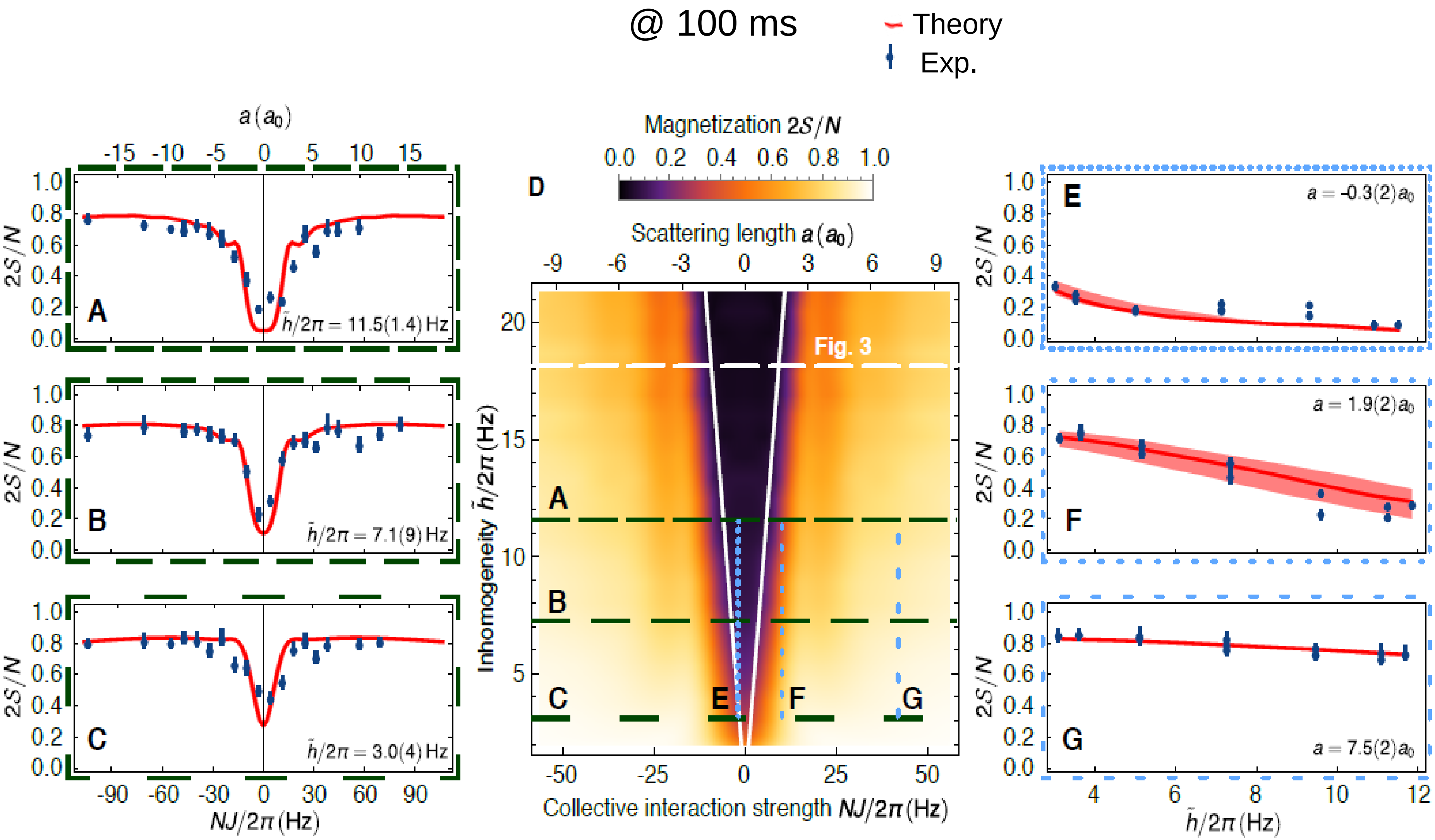


Finite steady state magnetization $J > J_c$

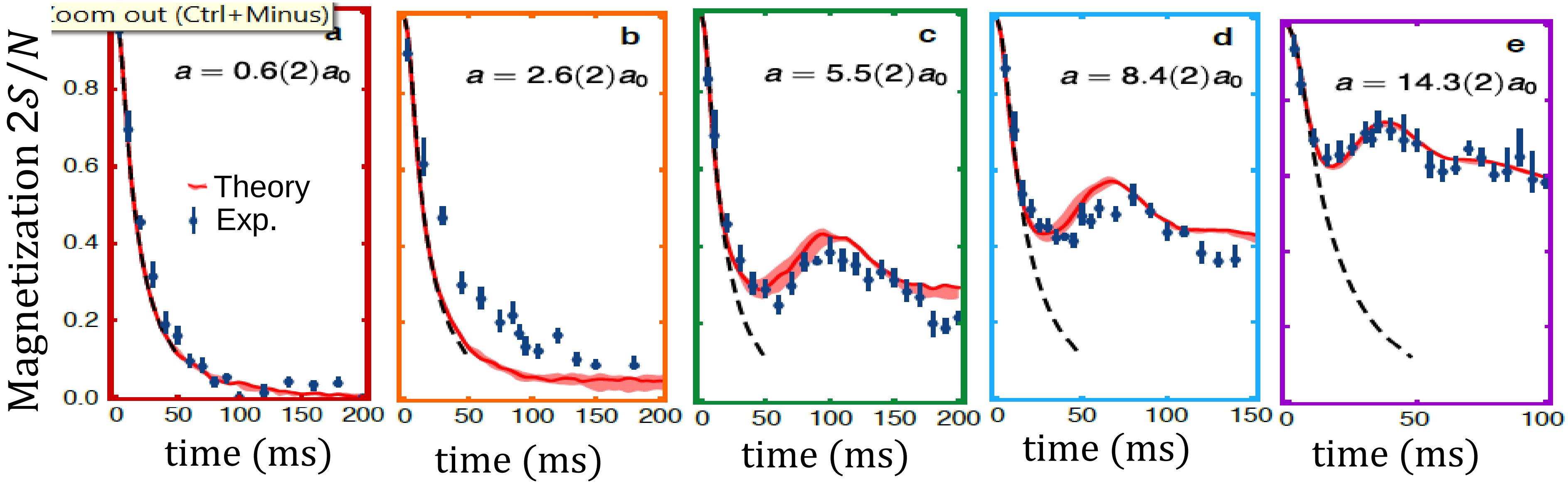
$$\mathcal{S}(\infty) = \frac{N}{2}\frac{\pi\, J_c}{2\, J}\cot\left(\frac{\pi J_c}{2\, J}\right) \qquad NJ_c = \frac{2\sqrt{3}\,(\Delta h)}{\pi}$$

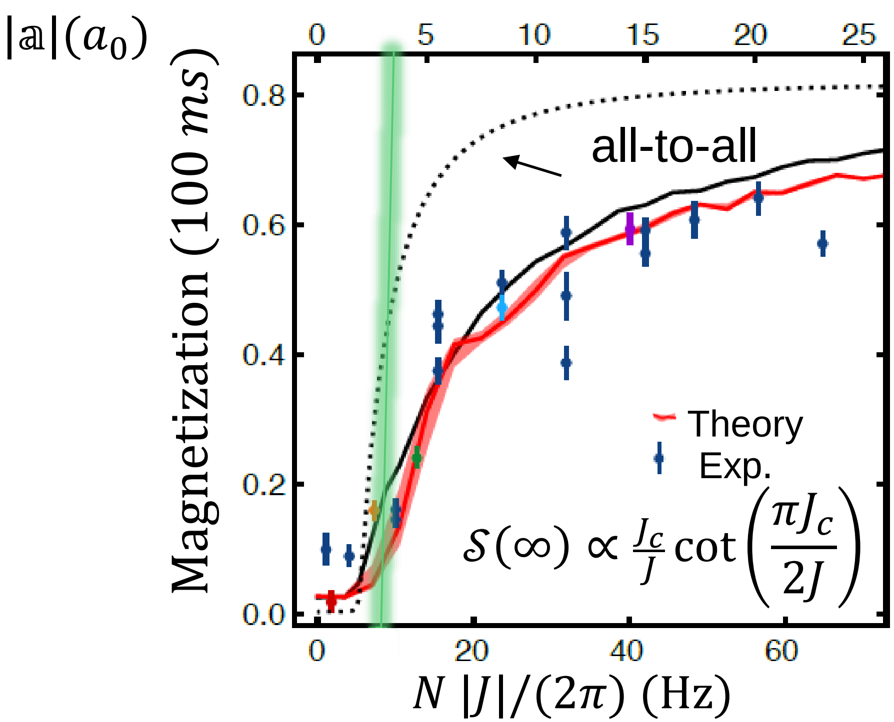
For 1D Exact

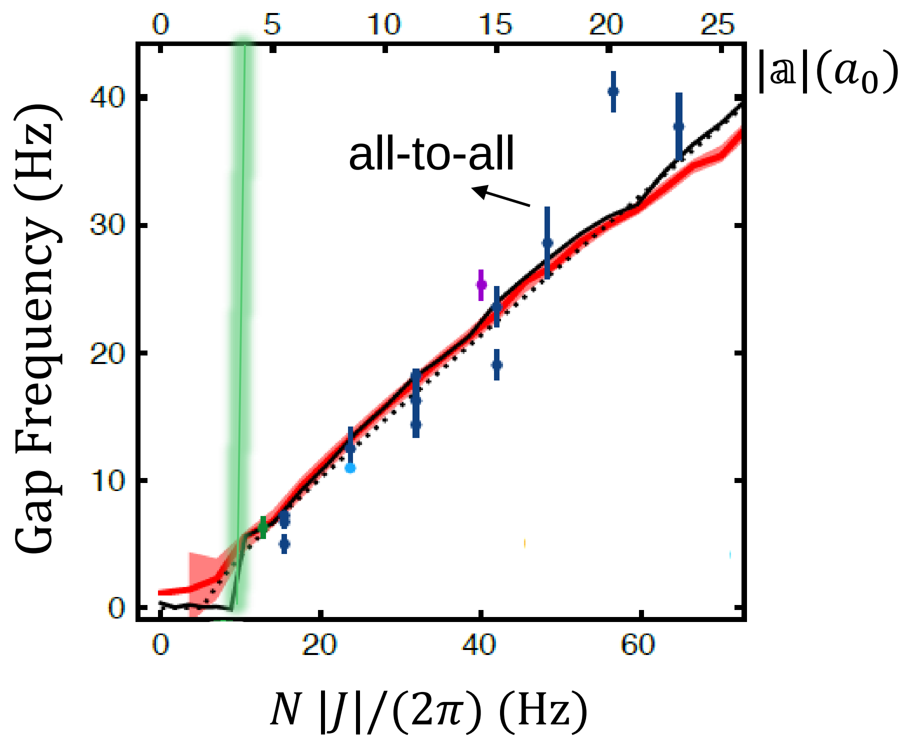
Dynamical Phase Transition - Observation



Dynamical Phase Transition - Observation



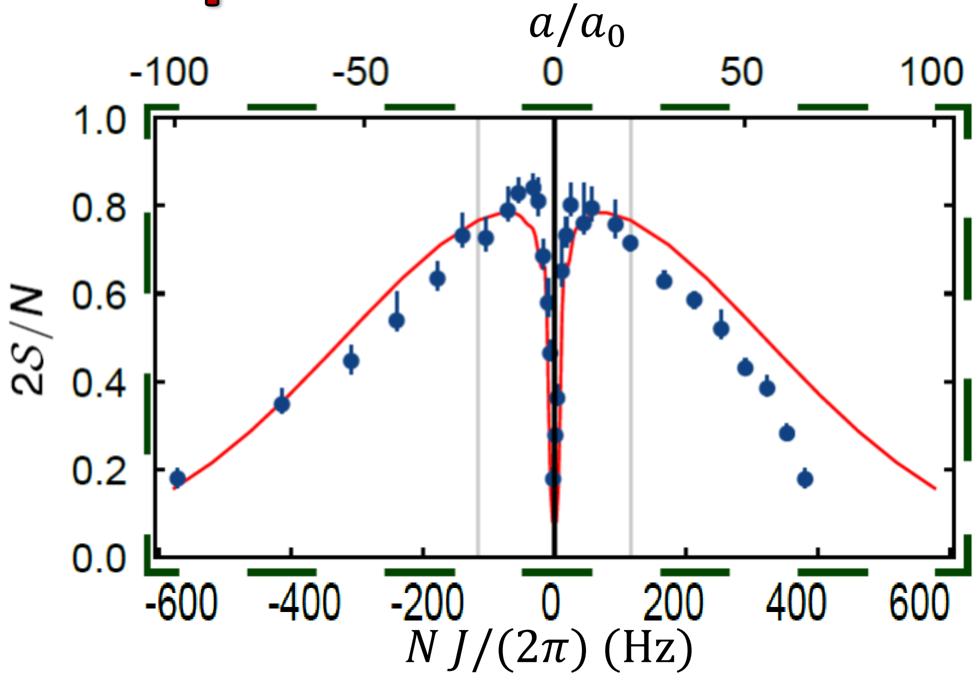




Validity of the spin model

$$\mathcal{S}(t) \rightarrow \mathcal{S}(t)e^{-\Gamma(a)t}$$

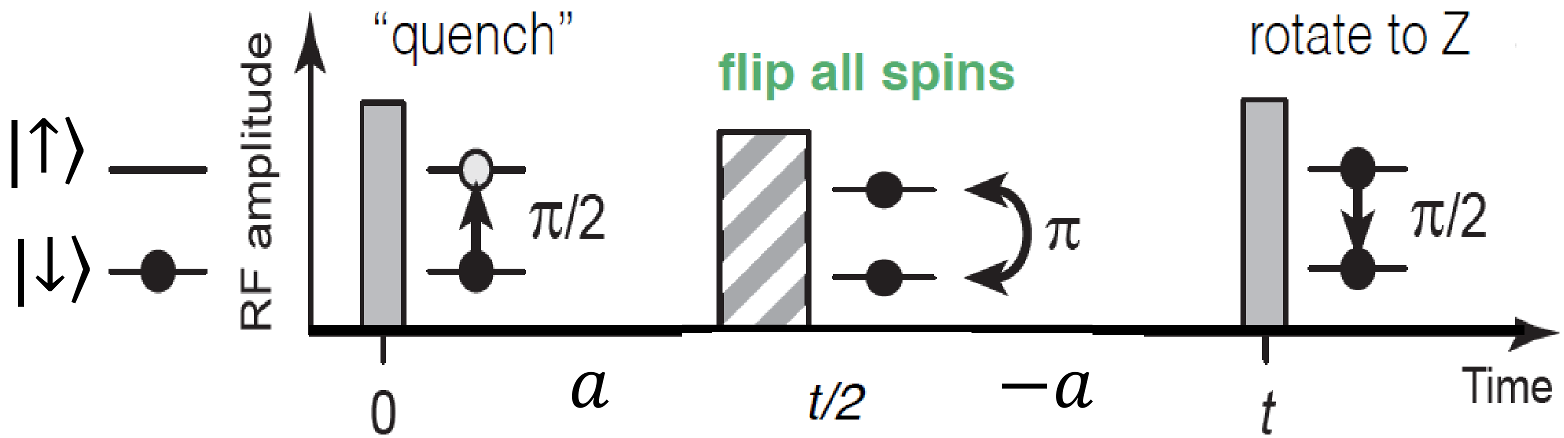
$$\Gamma(a) = \Gamma_0 + \gamma\left(\frac{a}{a_0}\right)^2$$



Validity of the spin model

Idea: Use many body echo

If we can time reverse the spin model then we should not see dynamics



$$\hat{H} = -\sum_{i>j} J_{ij}\, \vec{\hat{s}}_i \cdot \vec{\hat{s}}_j + \sum_i h_i\, \hat{s}_i^z$$

$$\hat{H}\psi \rightarrow -\hat{H}\psi$$

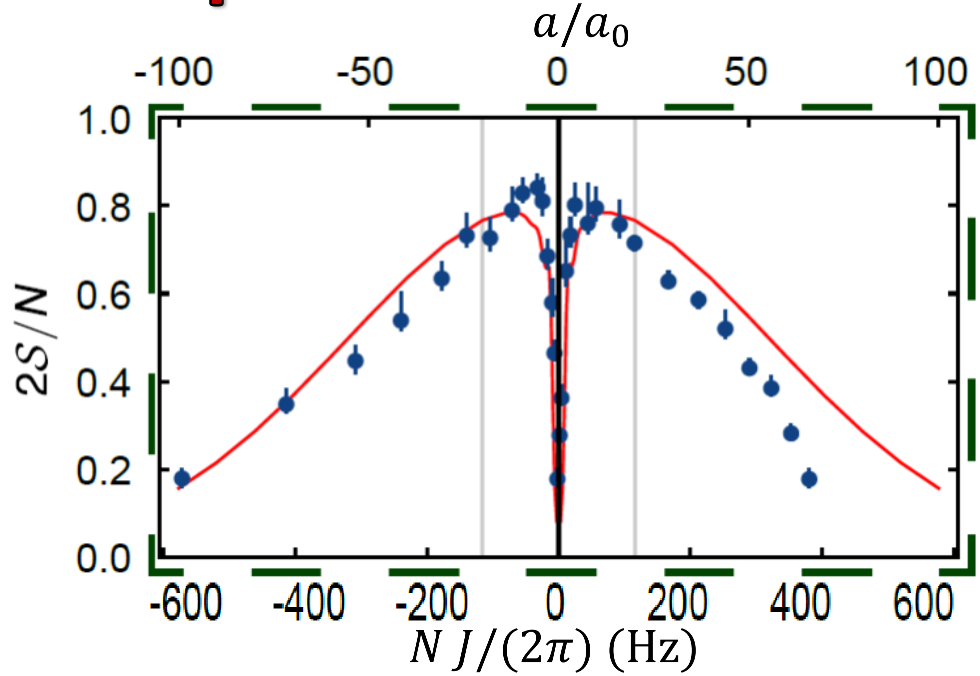
..as if $t \rightarrow -t$

Validity of the spin model

No time reversal

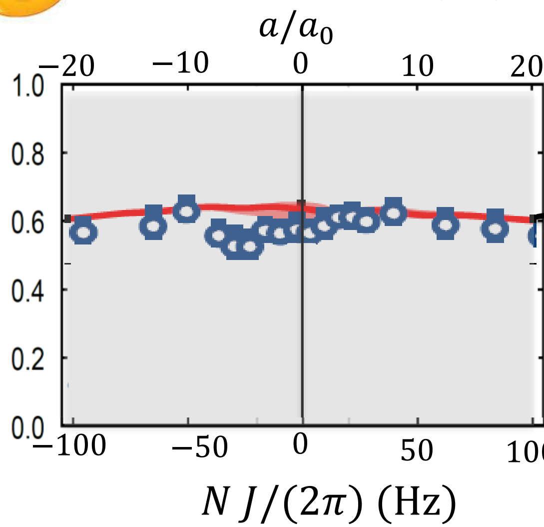
$$\mathcal{S}(t) \rightarrow \mathcal{S}(t)e^{-\Gamma(a)t}$$

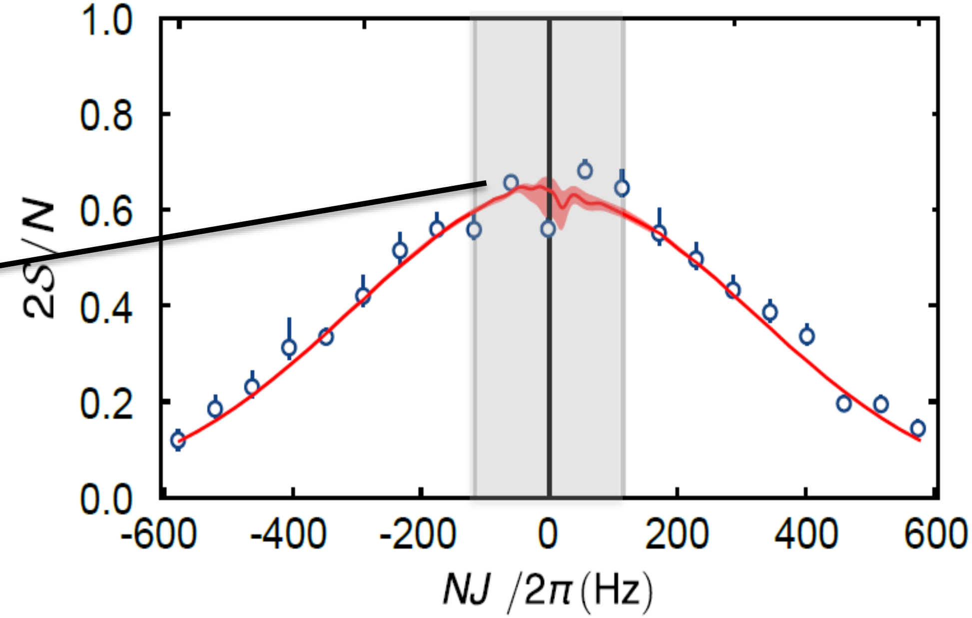
$$\Gamma(a) = \Gamma_0 + \gamma\left(\frac{a}{a_0}\right)^2$$



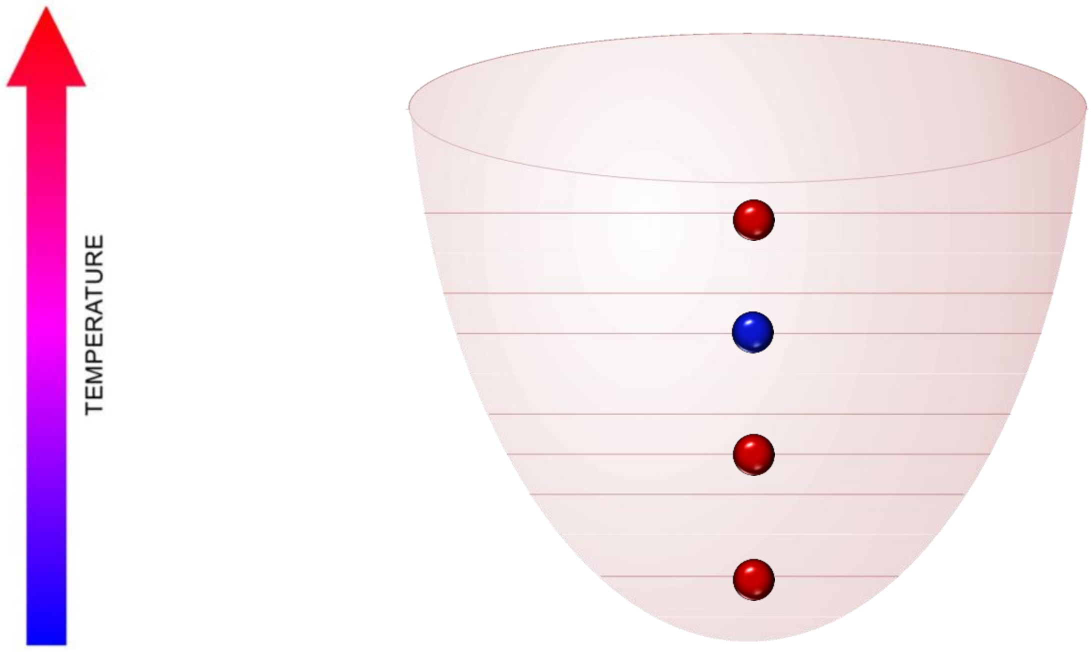
Time reversal

$$\Gamma(a) = \tilde{\Gamma}_0 + \gamma\left(\frac{a}{a_0}\right)^2$$





Thermal Bosons and Fermions Alike



Doubly occupied modes energetically suppressed $T \gg T_c$

Thermal bosons can also be described by a spin model in the collisionless regime: trapping frequency $\gg$ interaction

Bosonic Spin Model

A. Chu, J. Will, J. Arlt, C. Klempt, and A. M. Rey, arXiv:2004.01282

- [87]Rb atomic gases $|\downarrow\rangle \equiv |F=1, m_F=0\rangle$ $|\uparrow\rangle \equiv |F=2, m_F=0\rangle$

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

$$J_{ij} = \frac{4\pi\hbar^2}{m}V_{ij}^{\rm ex}a_{\uparrow\downarrow}$$

$a_{\sigma\sigma'}$: scattering lengths

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

$$B_i = \frac{4\pi\hbar^2}{m}\sum_j\left(V_{ij}^{\Uparrow\Uparrow}a_{\uparrow\uparrow} - V_{ij}^{\Downarrow\Downarrow}a_{\downarrow\downarrow}\right) + h_i$$

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

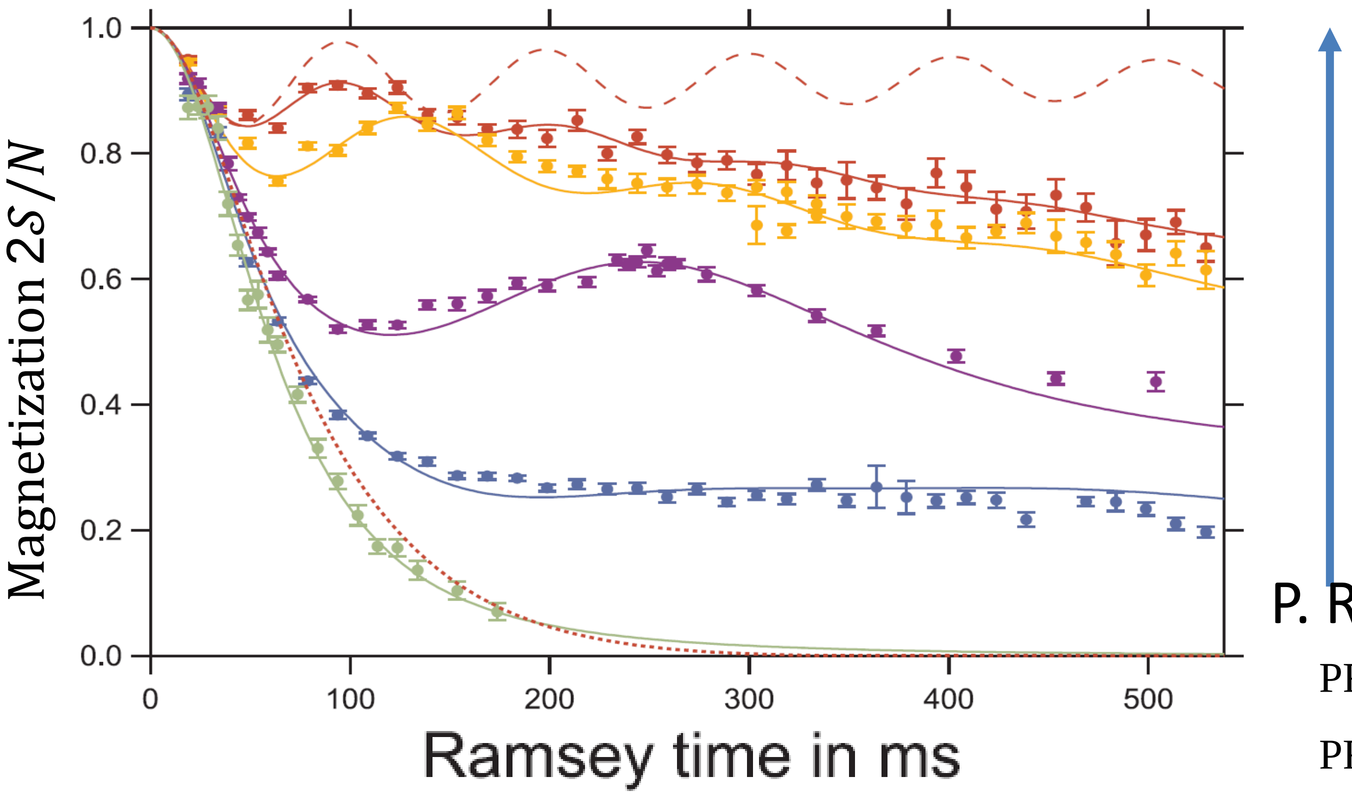
^{87}Rb Experiment: Similar DPT

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

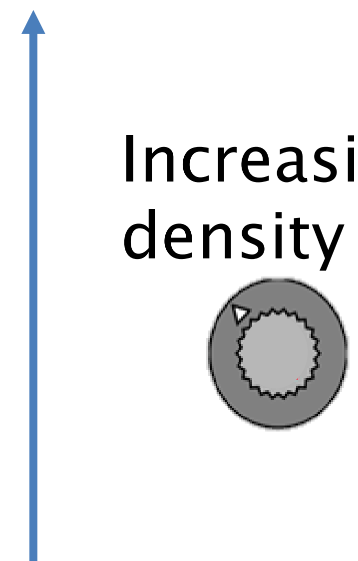
$$\phi_i^{\Uparrow}(\mathbf{R}) = \phi_i^{\Downarrow}(\mathbf{R})$$

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

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



Increasing density



P. Rosenbusch group

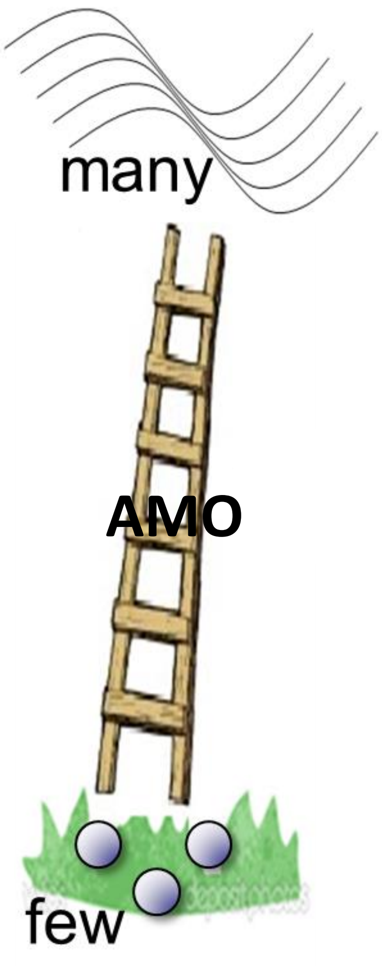
PRL 105, 020401 (2010)

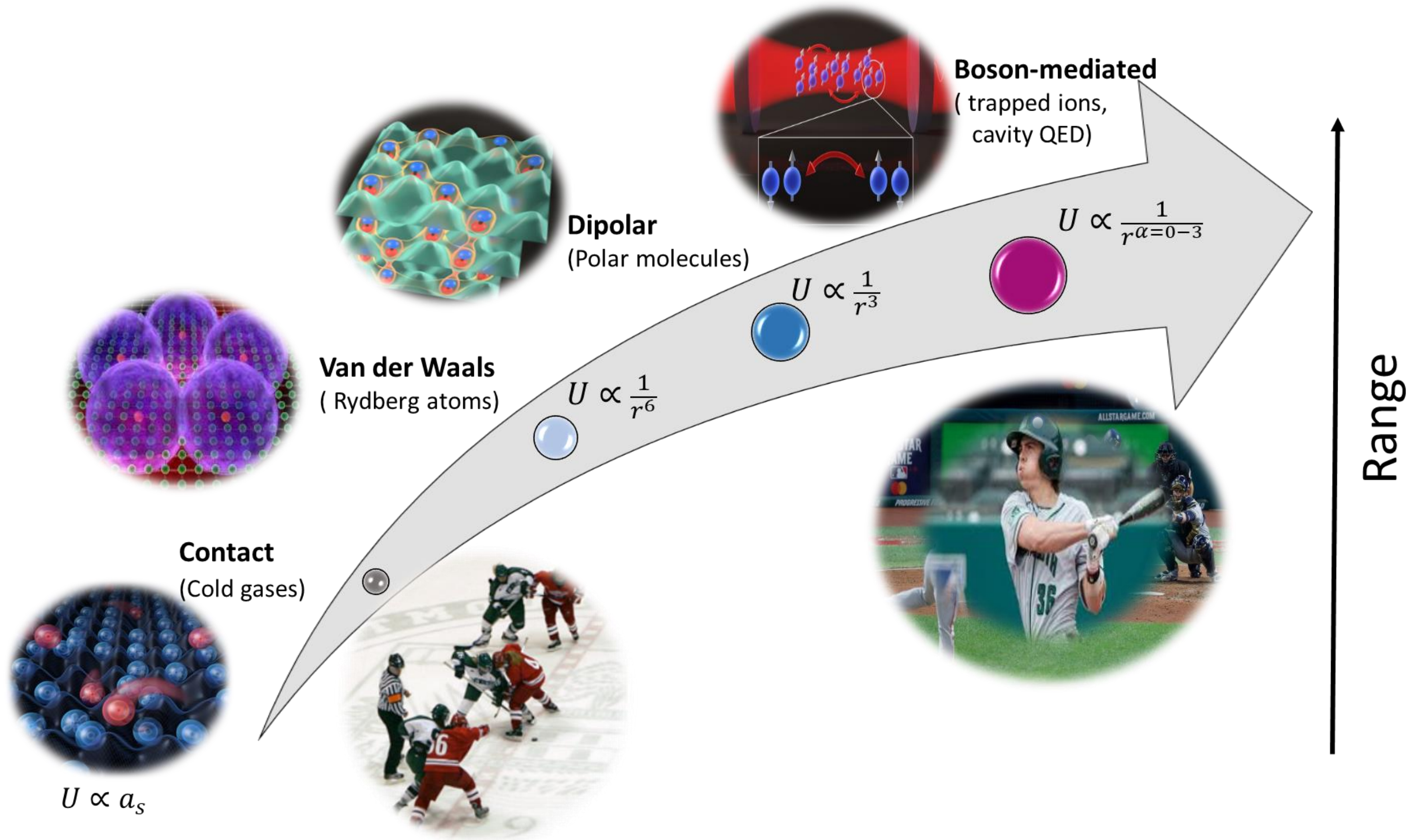
PRL 106, 240801 (2011)

Scientific Vision

GOAL: Harnessing many-body quantum systems and using them for applications ranging from quantum information to metrology.

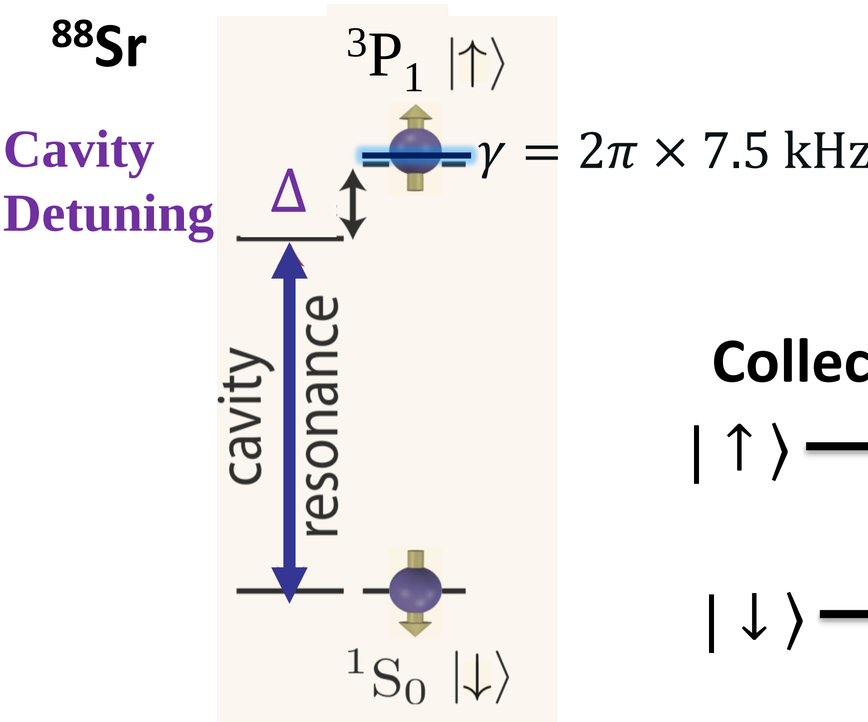
- Well-understood microscopics
- Tunable interactions
- Access to quantum dynamics

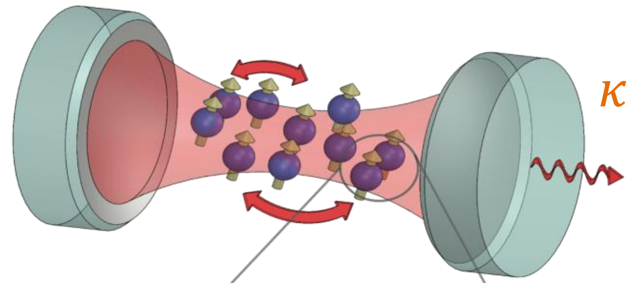




Sr : New regime in Cavity QED

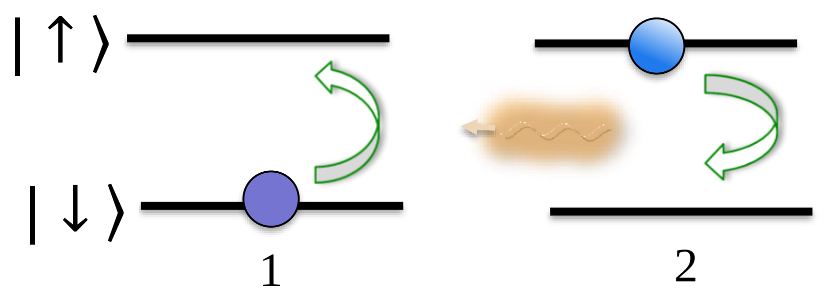
J. A. Muniz *et al*, A. M. Rey and J.K. Thompson Nature 580, 602 (2020)





$\kappa = 2\pi \times 160\ kHz$
Cavity Decay

Collective light mediated interactions



Unitary Dynamics

$\Delta \gg \kappa$

$$\hat{J}^{x,y,z} = \frac{1}{2}\sum_i \hat{\sigma}_i^{x,y,z}$$

Collective spin

Elastic

$$\hat{H} = \chi \hat{J}^+ \hat{J}^-$$

$$\chi \propto \frac{g^2}{\Delta}$$

Dissipative

$$\mathcal{L}_{spin} = \sqrt{\Gamma}\hat{J}^-$$

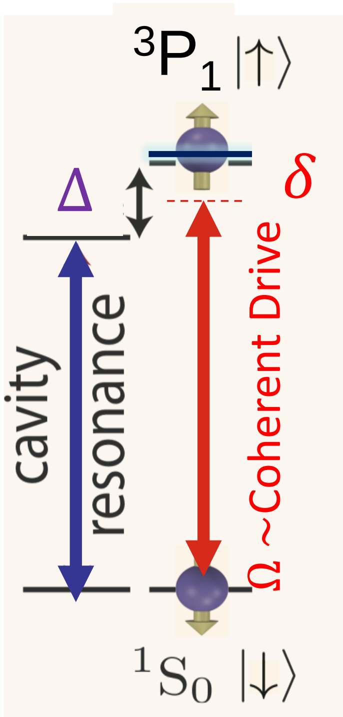
$$\frac{\Gamma}{\chi} \propto \frac{\kappa}{\Delta}$$

Dynamical Phase Transition (DPT)

J.A. Muniz,… , A M. Rey, J.K. Thompson, Nature 580, 602 (2020)

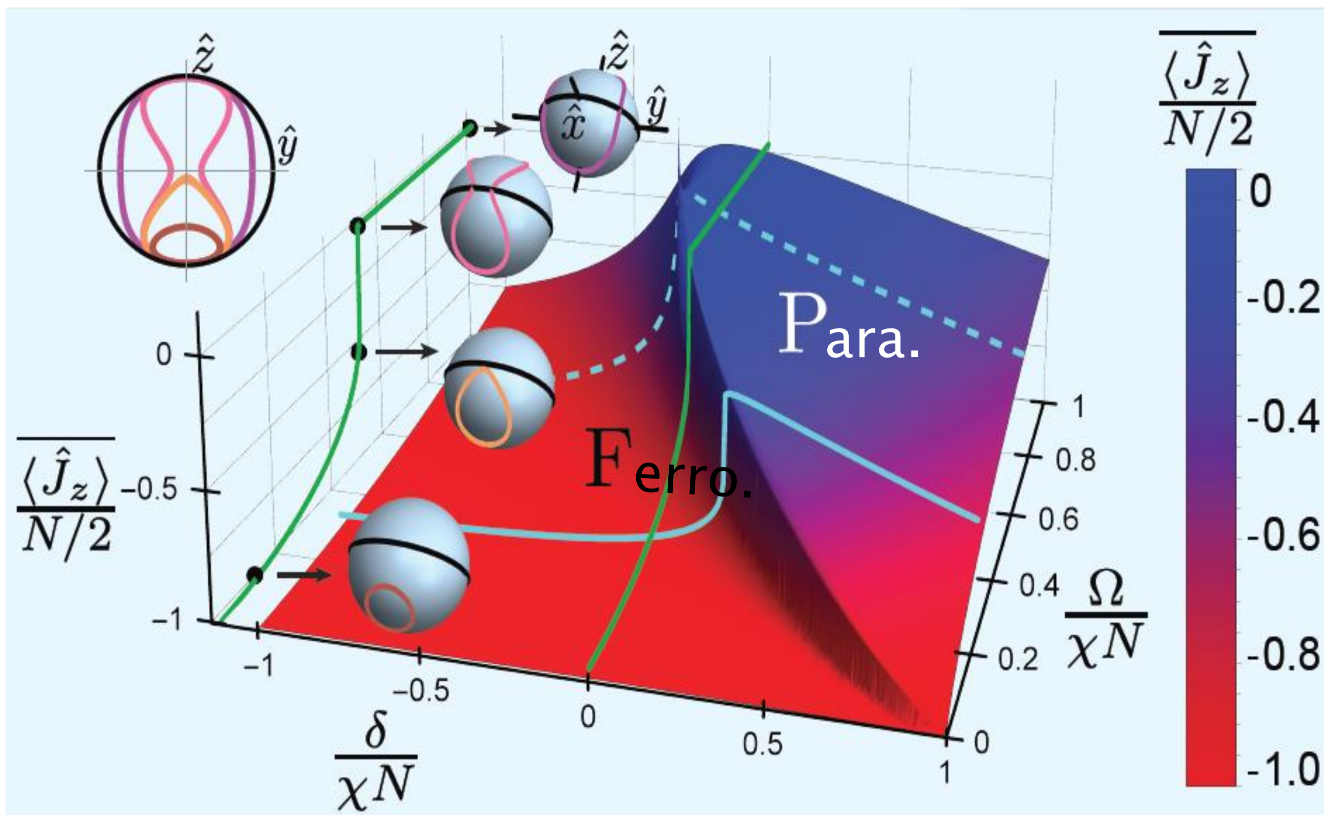
$$\hat{H} = -\chi \hat{J}^{+}\hat{J}^{-} + \Omega\,\hat{J}_x + \delta\,\hat{J}_z$$

^{88}Sr



Lipkin-Meshkov-Glick model

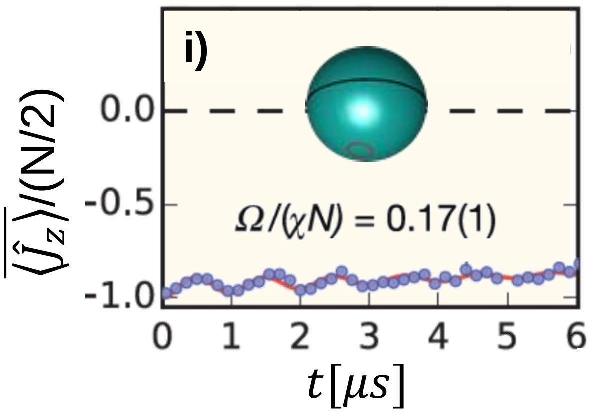
Order Parameter: Time averaged magnetization $\overline{\langle \hat{J}_z \rangle}$

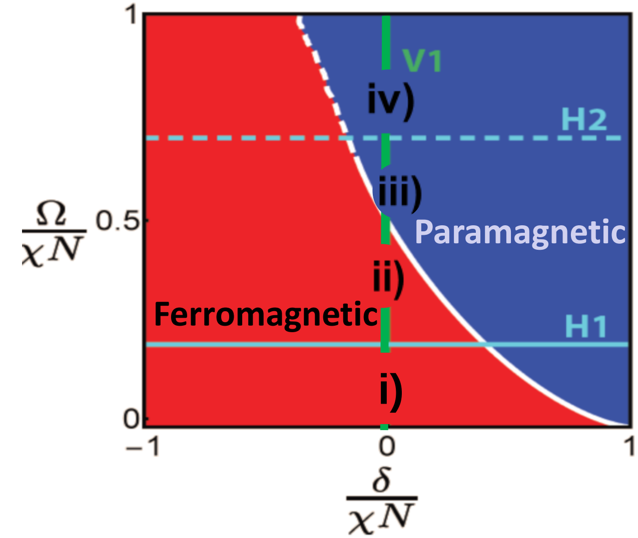


Experimental Observation of DPT: δ=0

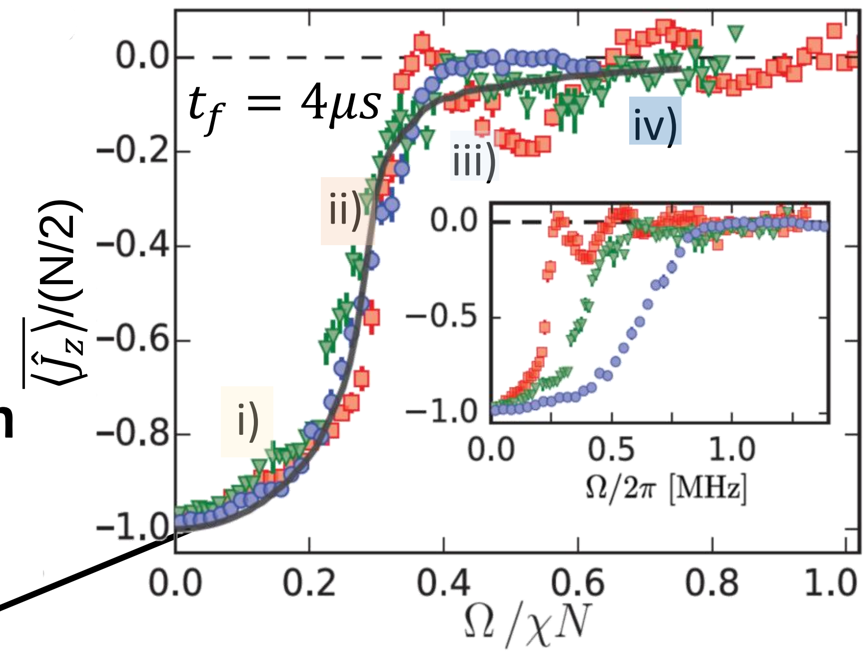
Order Parameter: time averaged magnetization $\overline{\langle \hat{J}_z \rangle}$

Experiment — Theory





N = (935; 620; 320) x 10^3

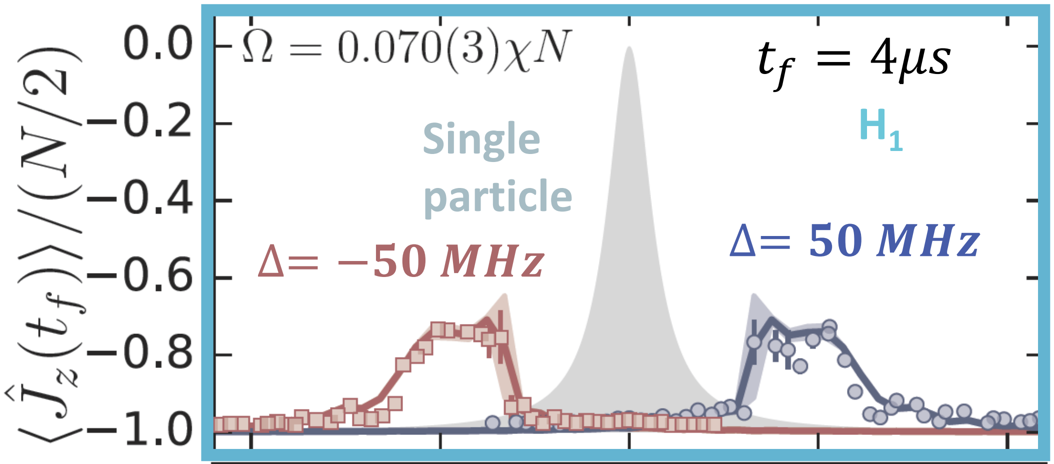


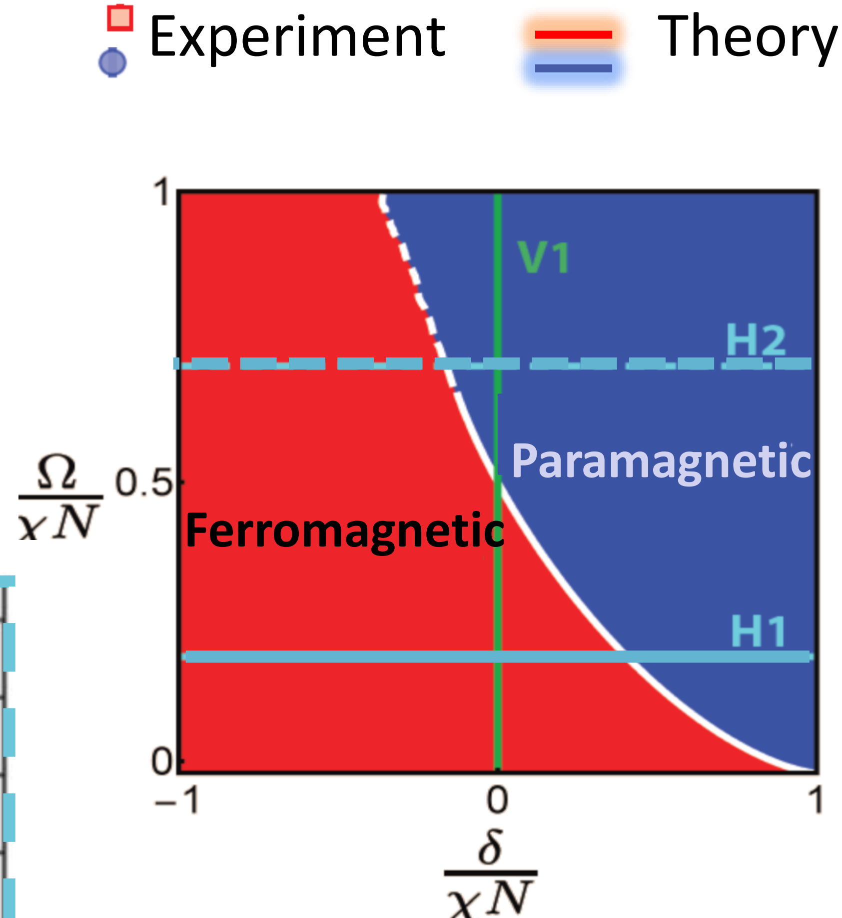
- ❑ Theory reproduces experiment when accounting for inhomogeneities
- ❑ N scaling

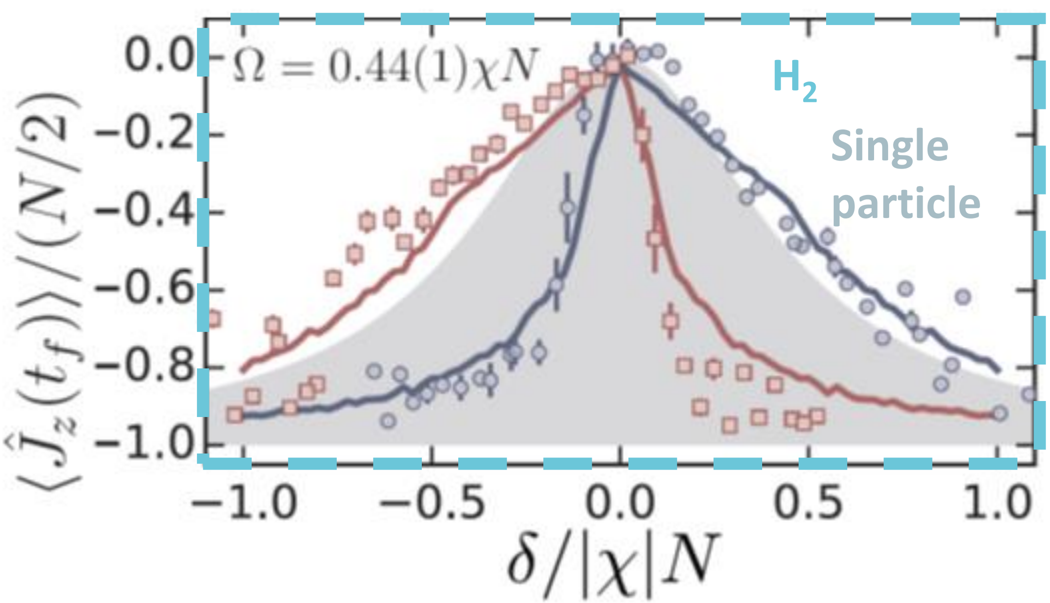
Theoretical calculation

Experimental Observation of NEPT: δ≠0

- ❑ Competition of interactions and longitudinal field







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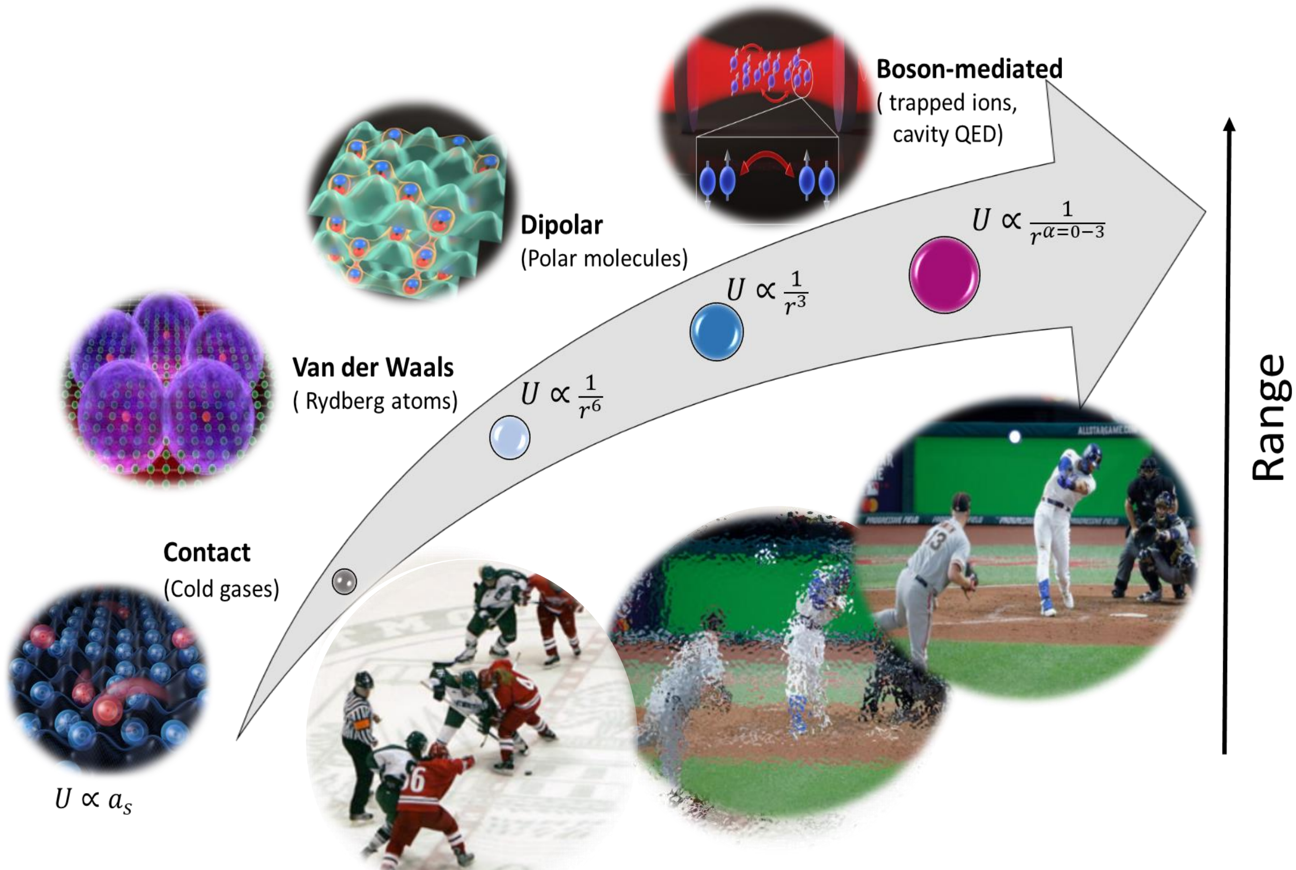

Bosonic Spin Model

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

Can we make χ_{ij} non-zero

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

?

^{87}Rb Experimental Set-up

A. Chu, J. Will, J. Arlt, C. Klempt, and A. M. Rey, arXiv:2004.01282

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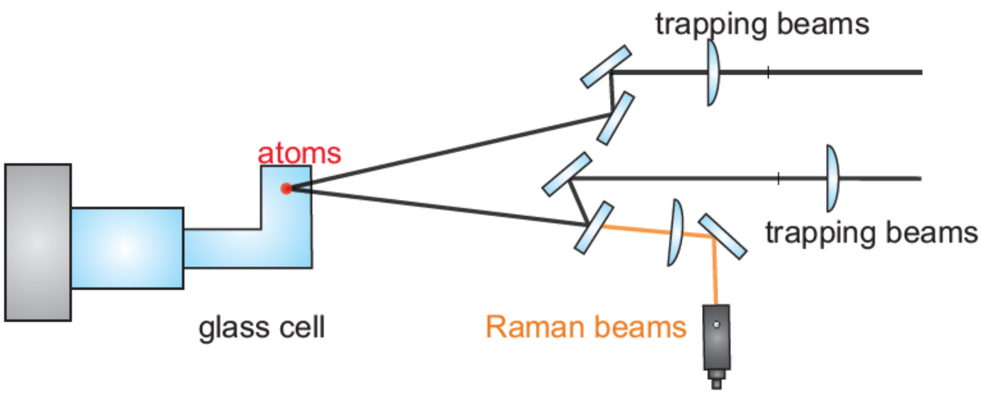
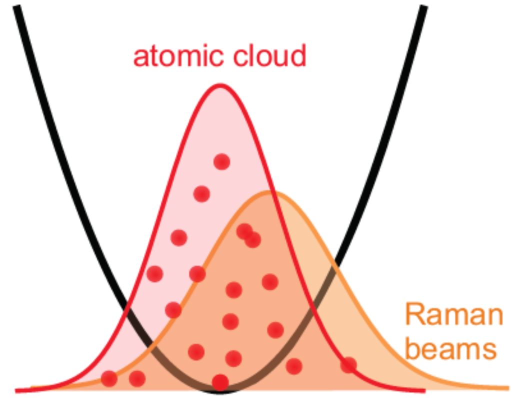
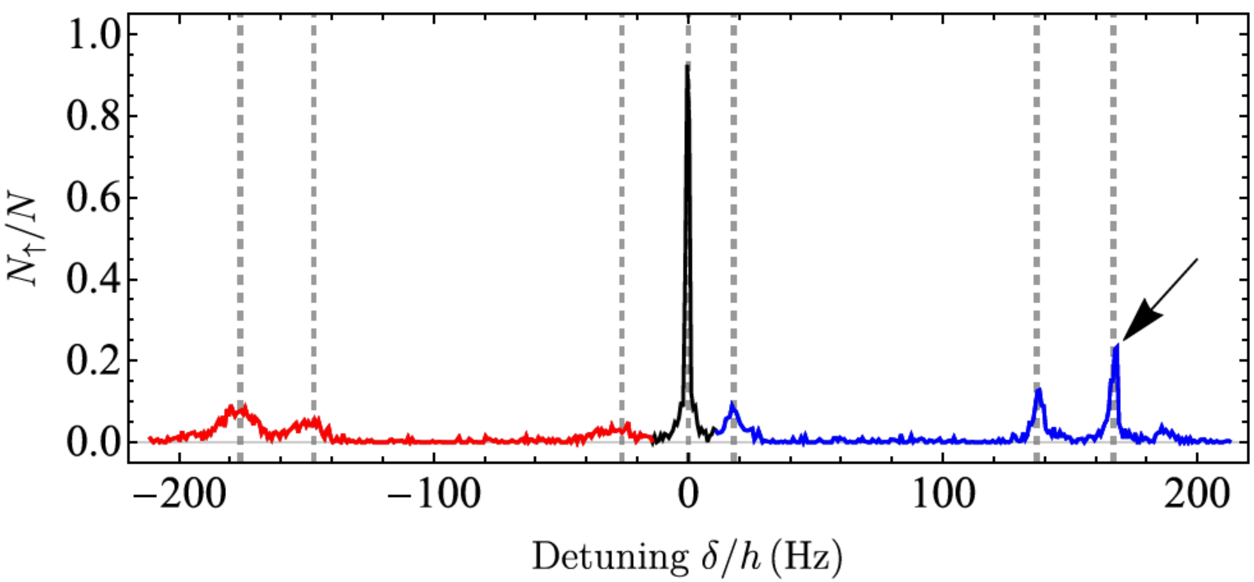
Main Idea: Use a sideband







^{87}Rb Experimental Set-up

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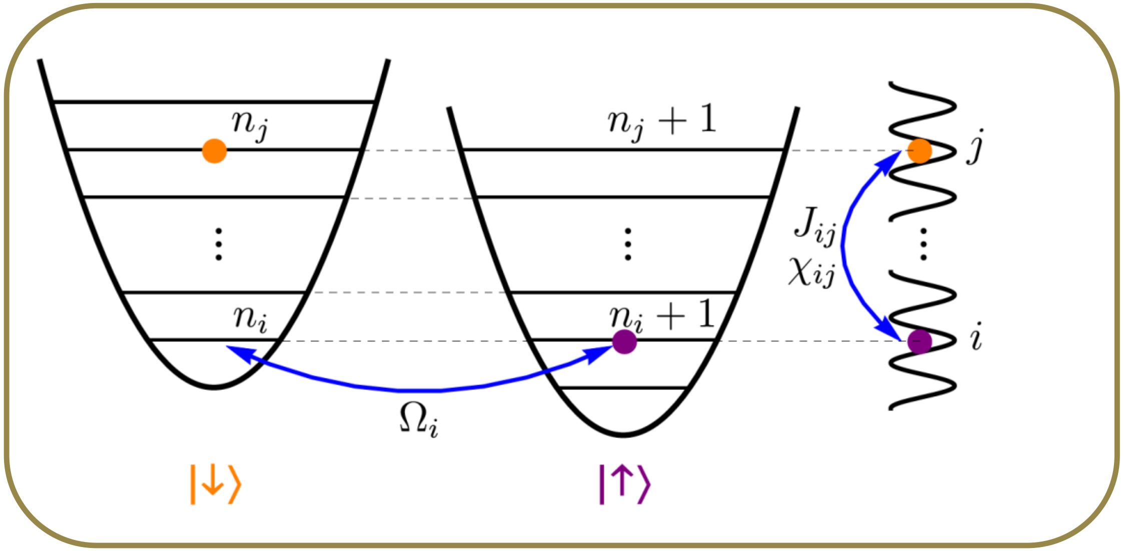


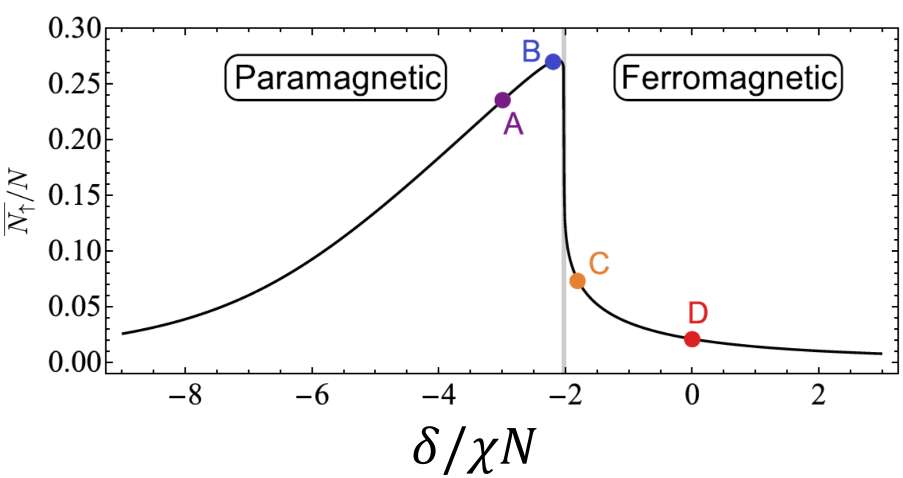
- Blue sideband transition

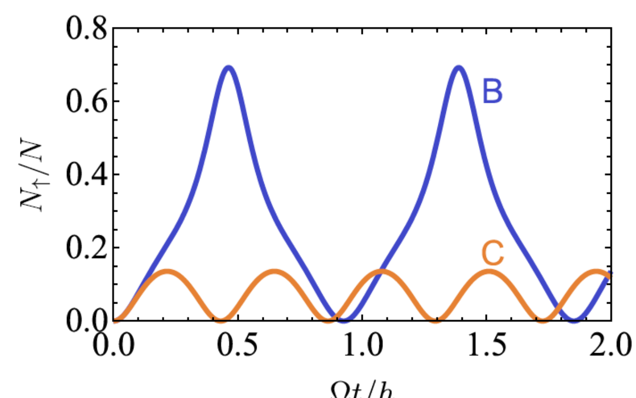
$$|\Uparrow_i\rangle = |\uparrow; n_i^X, n_i^Y, n_i^Z + 1\rangle$$
$$|\Downarrow_i\rangle = |\downarrow; n_i^X, n_i^Y, n_i^Z\rangle$$

Coherent Raman drive

Lipkin-Meshkov-Glick model: Like in the cavity

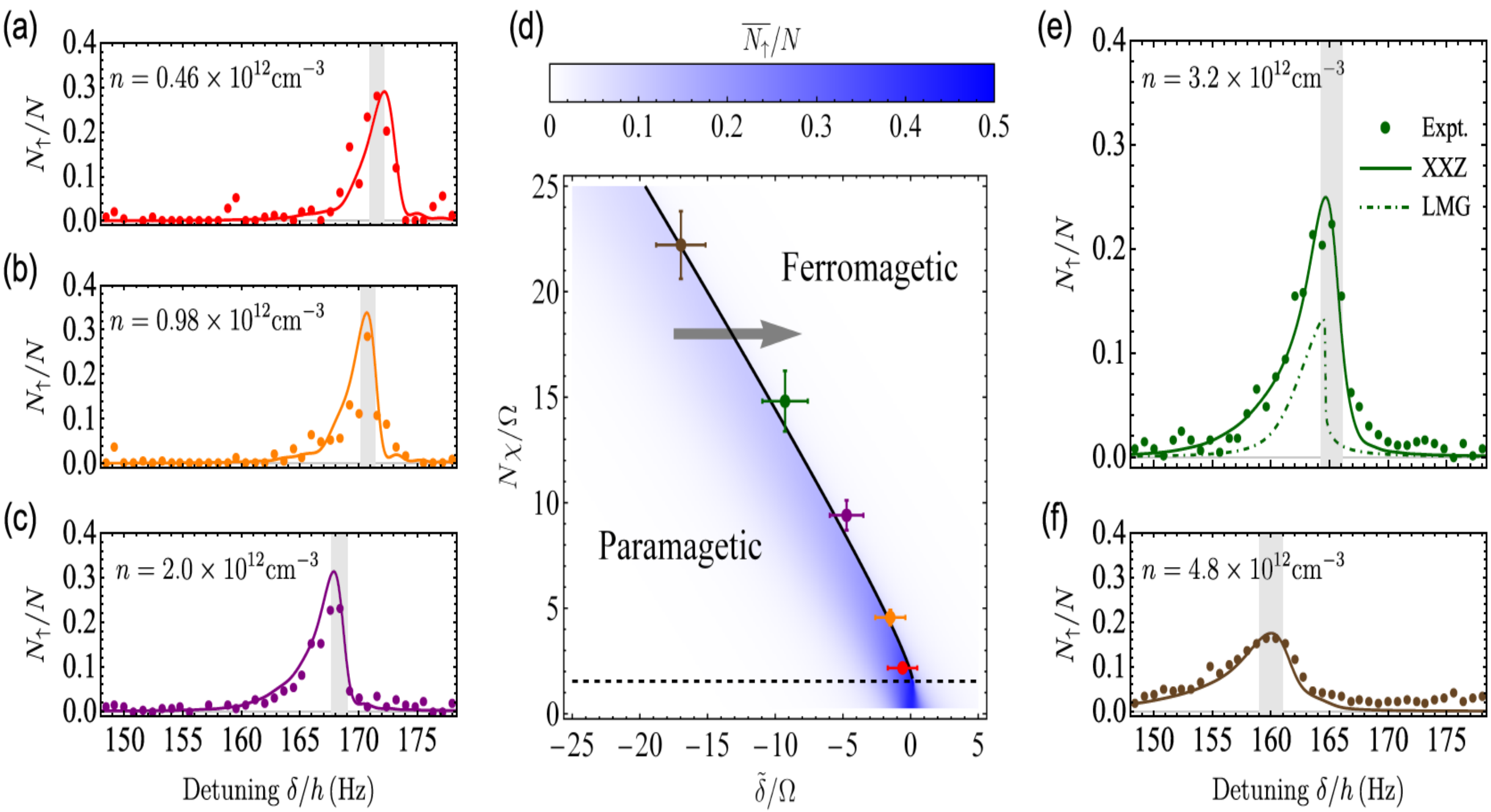
$$\hat{H} = -\bar{J}\vec{S}\cdot\vec{S} + \chi(\hat{S}^z)^2 + \Omega\ \hat{S}_x + \delta\ S_z$$



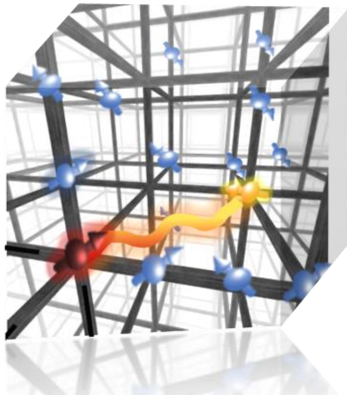


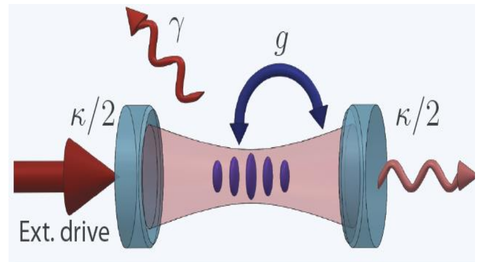
^{87}Rb Experimental DPT

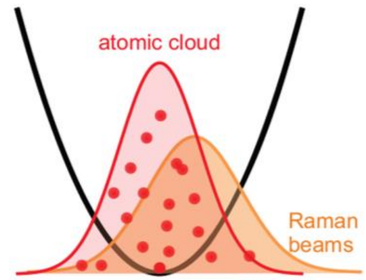
A. Chu, J. Will, J. Arlt, C. Klempt, and A. M. Rey, arXiv:2004.01282



Dynamical Phase Transitions







Toronto, Sci. Adv (2019)   JILA, Nature (2020)

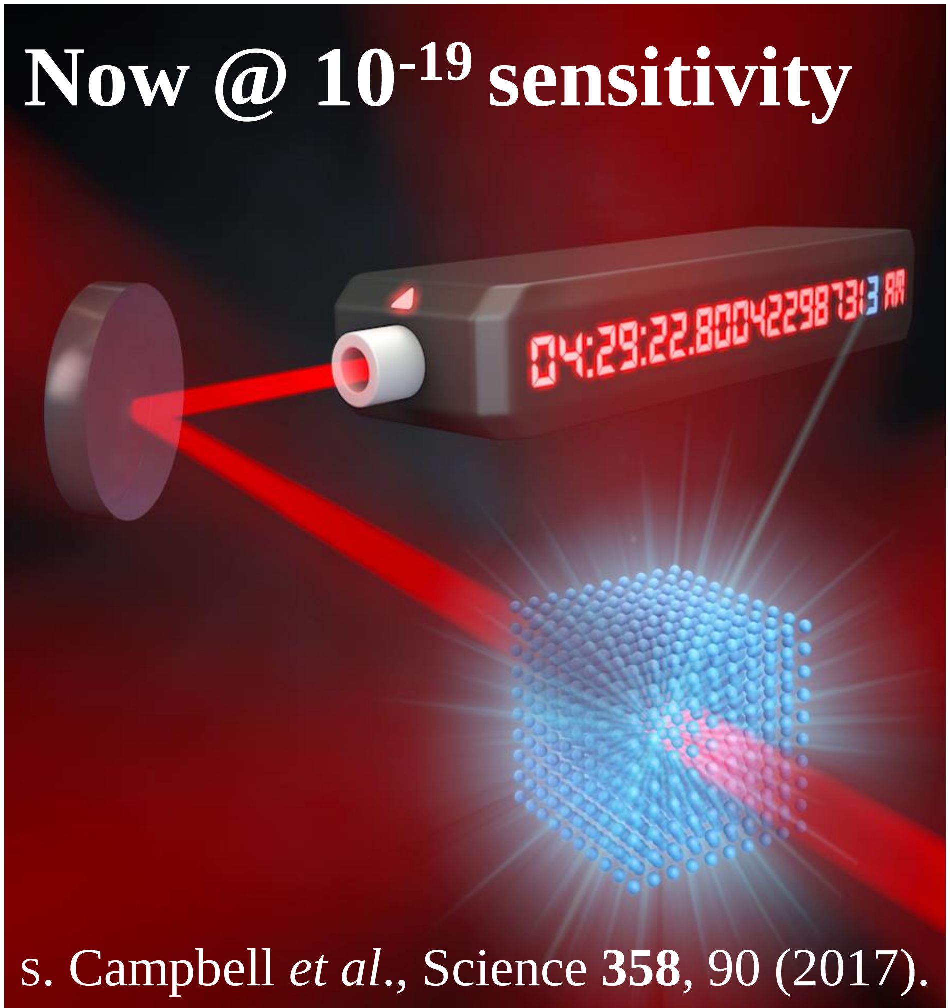
- ❑ Dynamical: Not found by minimization of free energy ✓
- ❑ New symmetries ✓
- ❑ Robust generation of useful entangled states ?

So far everything has admitted a mean field description

Time evolution restricted to relatively short times

New generation of atomic clocks: 3D ultra-cold fermionic lattice clock

Scaling up the Sr quantum clock: 3D lattice



s. Campbell *et al*., Science **358**, 90 (2017).

- High accuracy at highest density
- All degrees of freedom at the quantum level

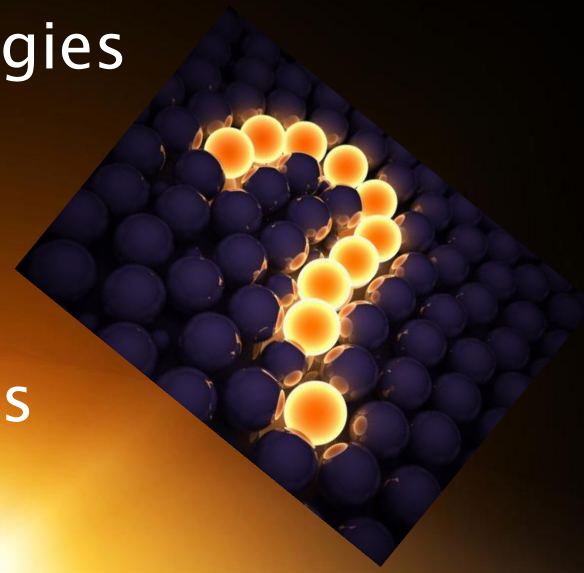
N~ 10^4 atoms below 80 nK,
T/T_F ~ 0.1

- **Now 12s quantum coherence (Record for quantum coherence in 3D lattices).**

Quantum Physics with Ultra-Cold Atoms

Only the beginning: Bright vista ahead

Quantum technologies



Quantum computers

Quantum simulators

Synthetic materials

Thank YOU!