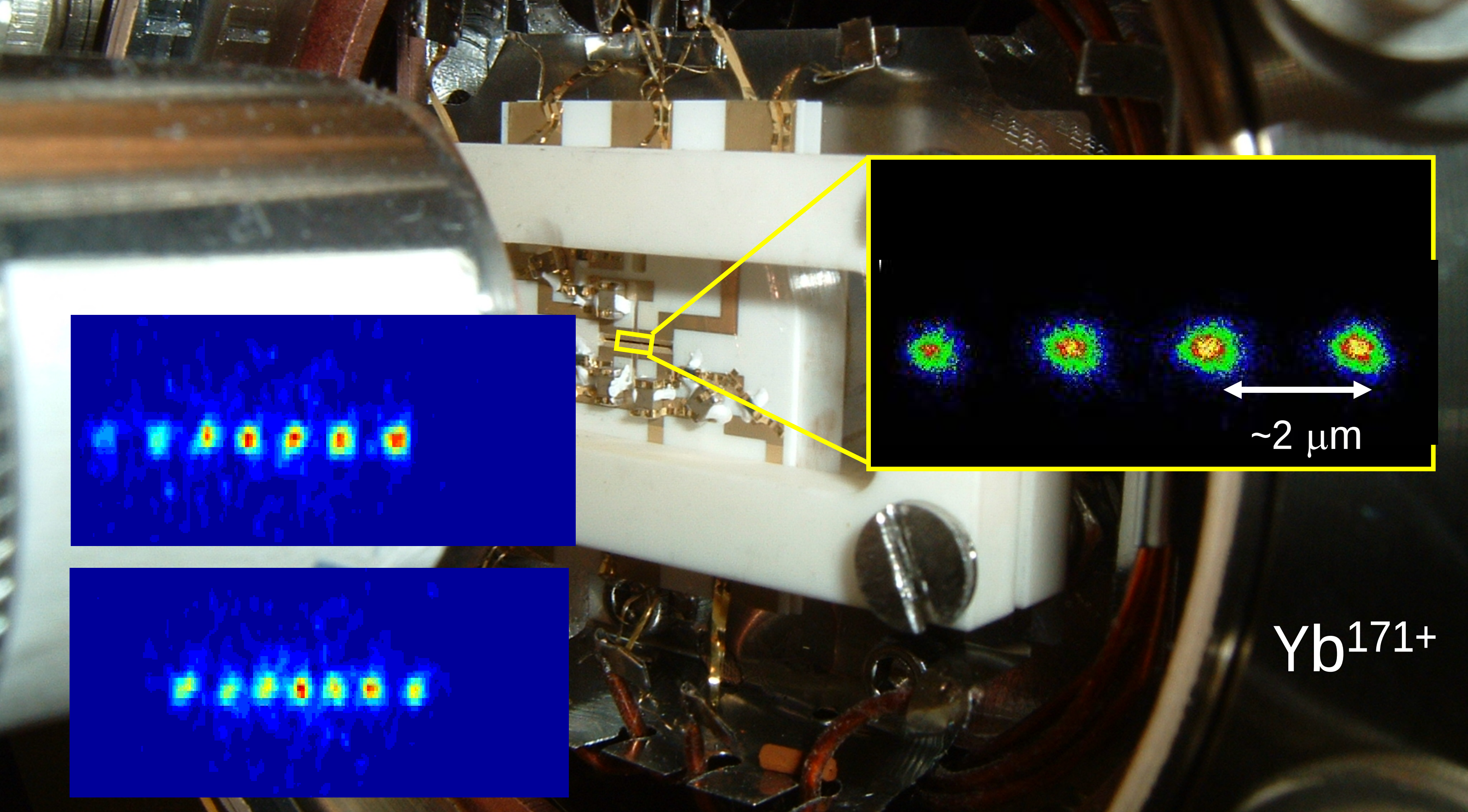
Can adiabatic fast passage be used in ion trap quantum simulators?

Jim Freericks (Georgetown),

Linear Paul ion trap platform

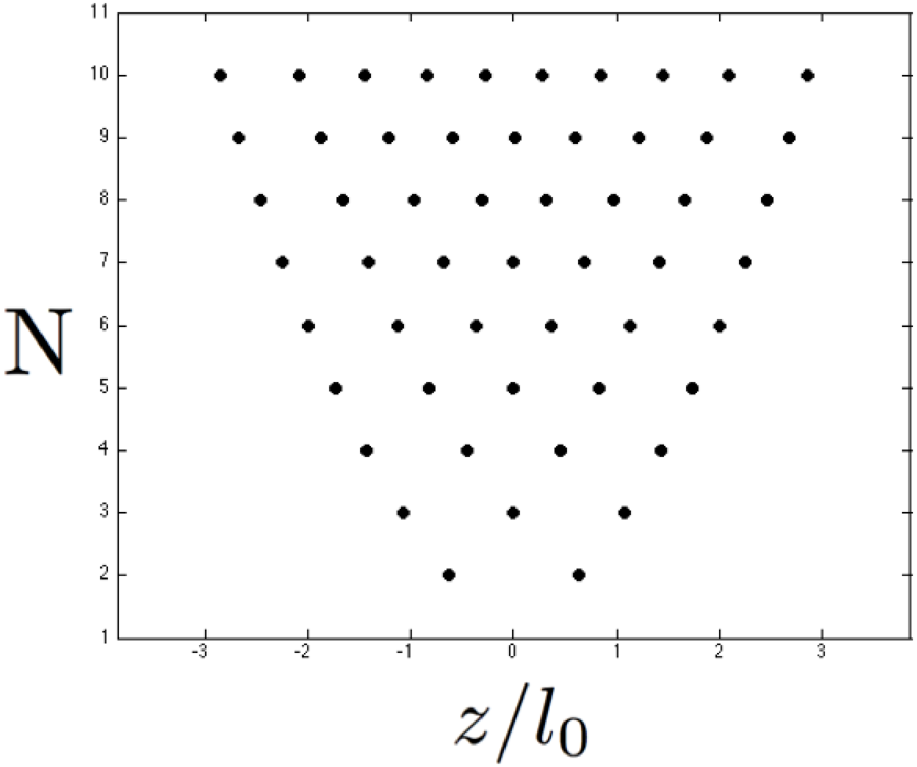
Cold ions in linear Paul trap (Monroe group, UMD and JQI)

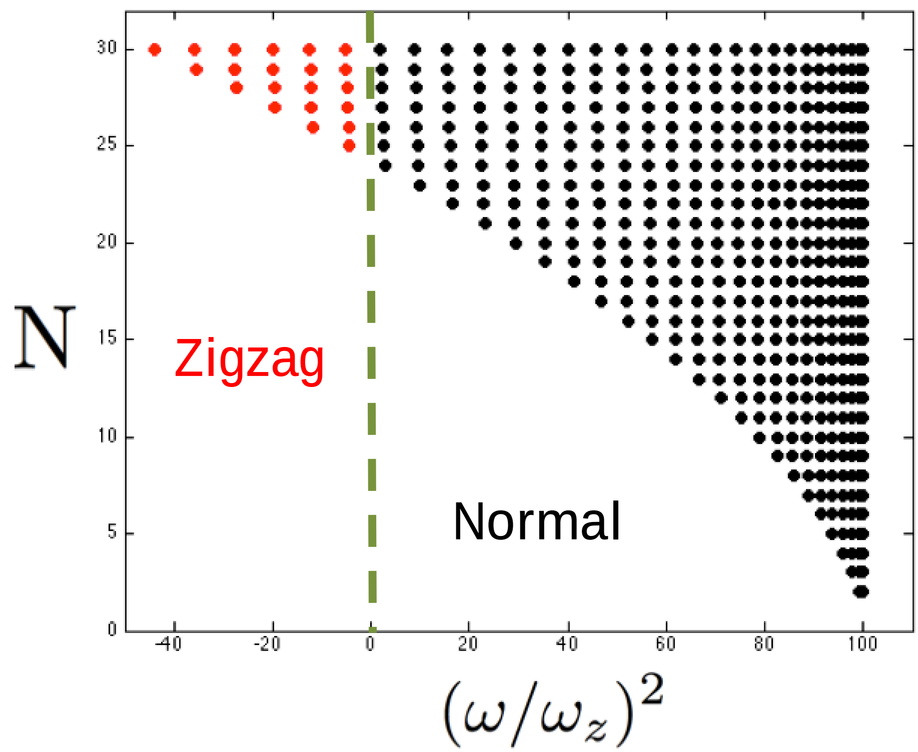


From: R. Blatt, Univ. Innsbruck

Equilibrium positions and phonons

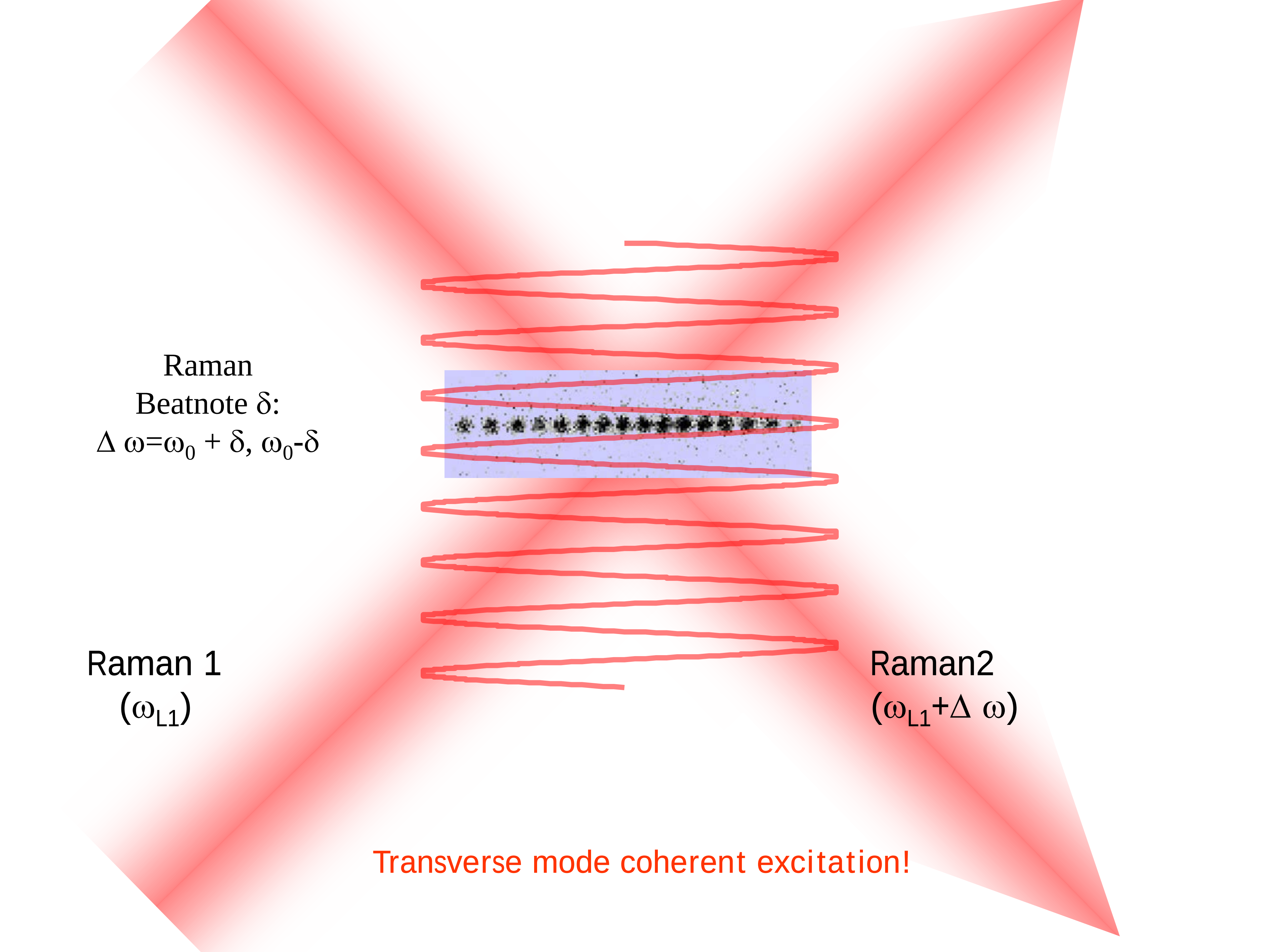
Equilibrium positions Paul trap





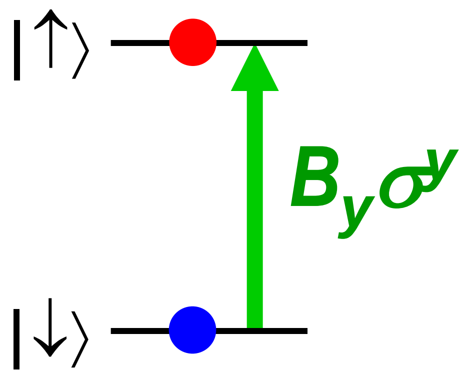
James, Appl. Phys. B (1998).

Spin-phonon coupling by spin-dependent optical dipole force

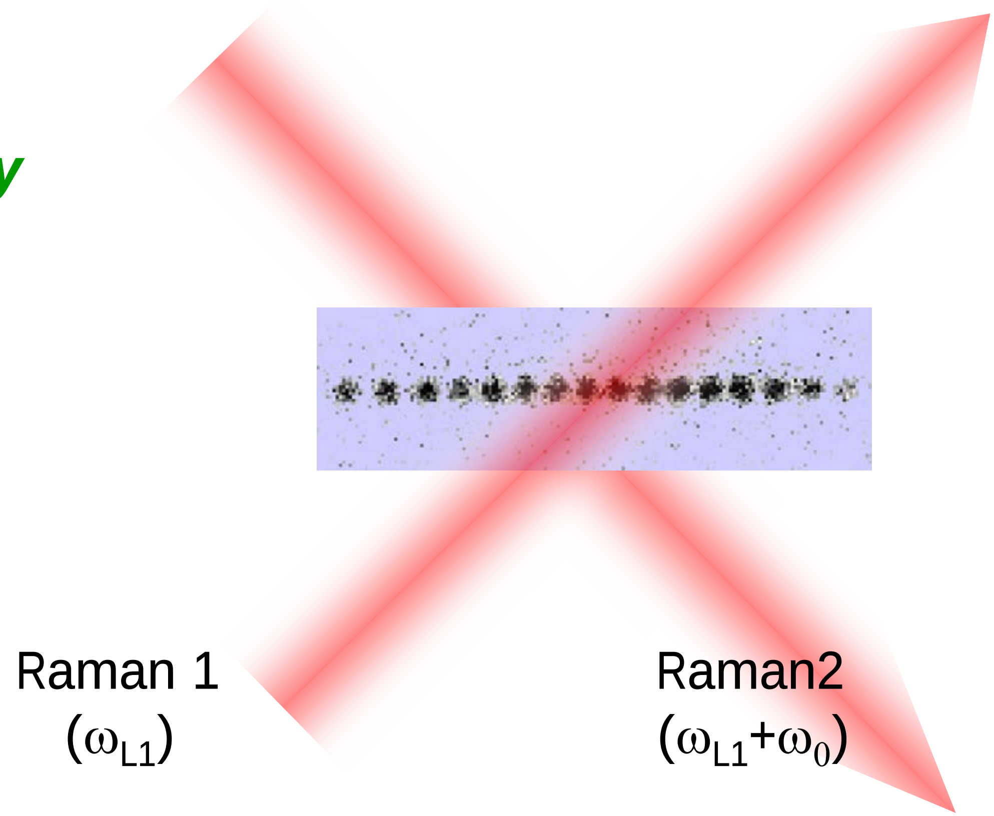

Raman
Beatnote δ:
Δ ω=ω0 + δ, ω0-δ
Raman 1
(ωL1)
Raman2
(ωL1+Δ ω)
Transverse mode coherent excitation!

Effective magnetic fields

$$H_B = B_y \sigma^y$$



$\delta=0$(Static)



$\Delta\ \omega=\omega_0$

Generating the effective spin-spin Hamiltonian by adiabatically eliminating the phonons

Spin-dependent force Hamiltonian

$$H(t) = H_{ph} + H_{laser-ion}(t) + H_B(t)$$

$$H_{ph} = \sum_{\nu\alpha} \hbar\omega_\nu^\alpha (a_{\nu\alpha}^* a_{\nu\alpha} + \frac{1}{2}) \qquad H_B(t) = \sum_i B(t) \bullet \sigma_i$$

$$H_{l-i}(t) = -\hbar \sum_i \Omega_i \Delta k \bullet \sum_{\nu\alpha} \frac{\sqrt{2M\omega_\nu^\alpha}}{\sqrt{\hbar}} e_\alpha b_i^{\nu\alpha} (a_{\nu\alpha}^* + a_{\nu\alpha}) \sigma_i^x \sin(\mu t)$$

Integrate out the phonons by “completing the square”

Effective Spin Hamiltonian

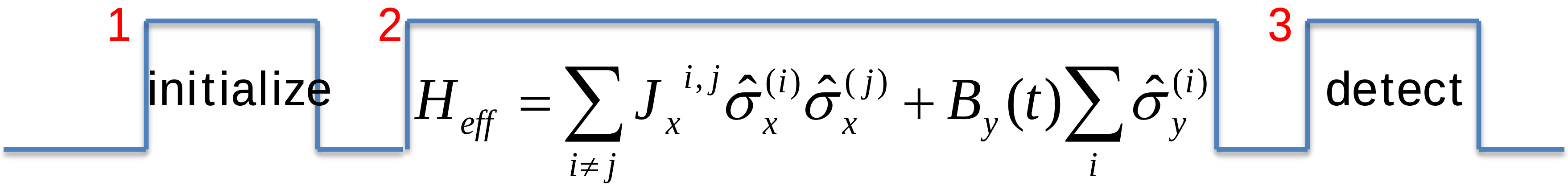
$$U_{spin}(t) = T_t \exp[-i\int_0^t dt'\{\sum_{ij} J_{ij}(t')\sigma_i^x \sigma_j^x + B(t') \bullet \sum_i \sigma_i \}]$$

$$J_{ij}(t) = \frac{\hbar^2}{4M}\sum_\nu \frac{\Omega_i \Omega_j (\Delta k_x)^2 b_i^{x\nu} b_j^{x\nu}}{\mu^2 - \omega_\nu^{x2}}[1-\cos(2\mu t) - 2\frac{\mu}{\omega_\nu^x}\sin(\omega_\nu^x t)\sin(\mu t)]$$

Note: spin-spin couplings are functions of t which can be thought of as generating a static Hamiltonian, plus additional time-dependent phases that enter the evolution operator.

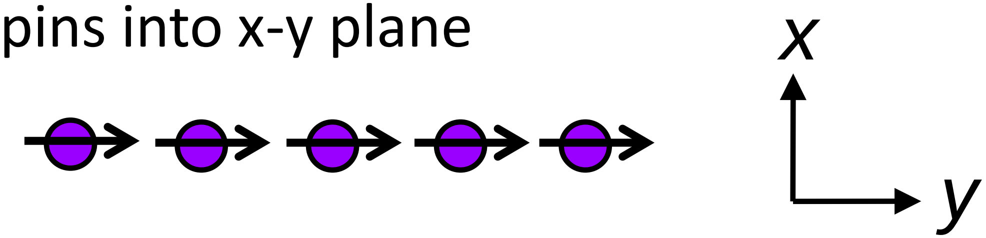
Paul trap simulations

Route to observing frustration: Adiabatic protocol

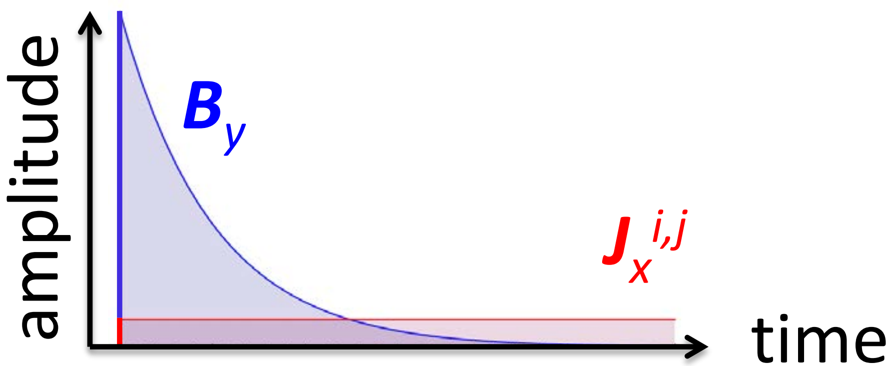


$$H_{eff} = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B_y(t) \sum_i \hat{\sigma}_y^{(i)}$$

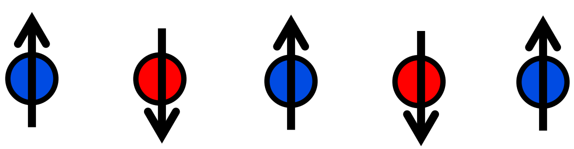
Step 1: Polarize all spins into x-y plane



Step 2: Ramp from high to low field

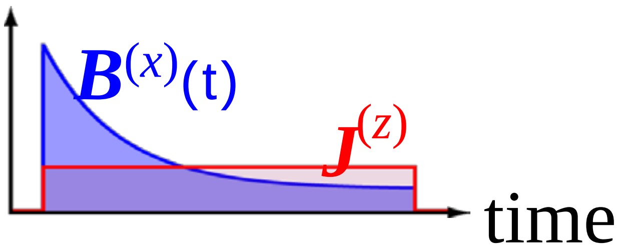


Step 3: Measure all spins along *x*

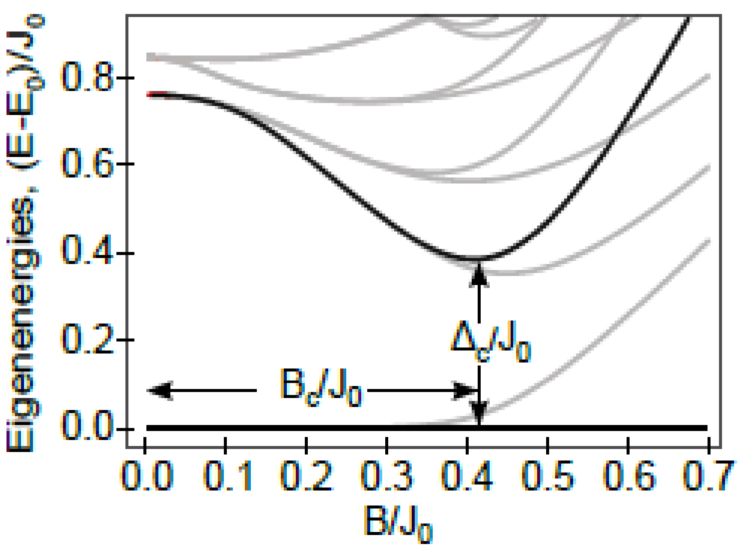


R. Islam, CS, W. C. Campbell, S. Korenblit, J. Smith, A. Lee, E. E. Edwards, C.-C. J. Wang, J. K. Freericks, and C. Monroe, Science **340**, 583 (2013)

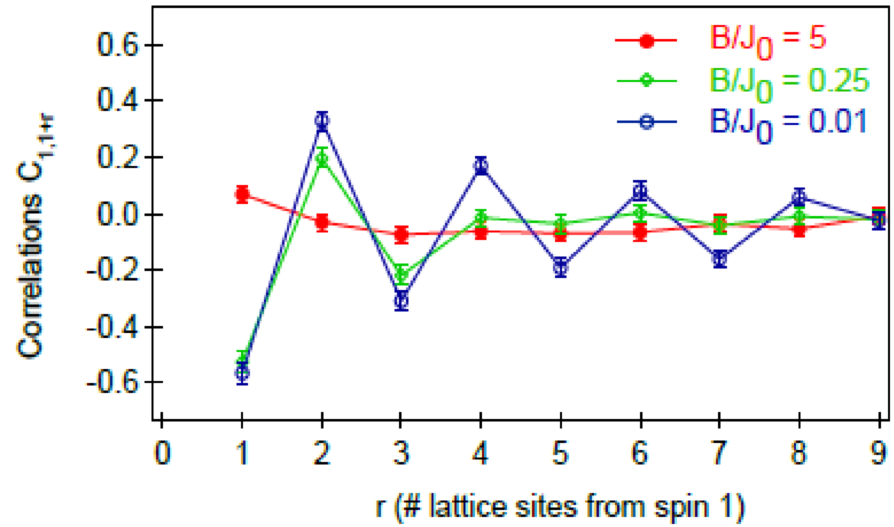
Results



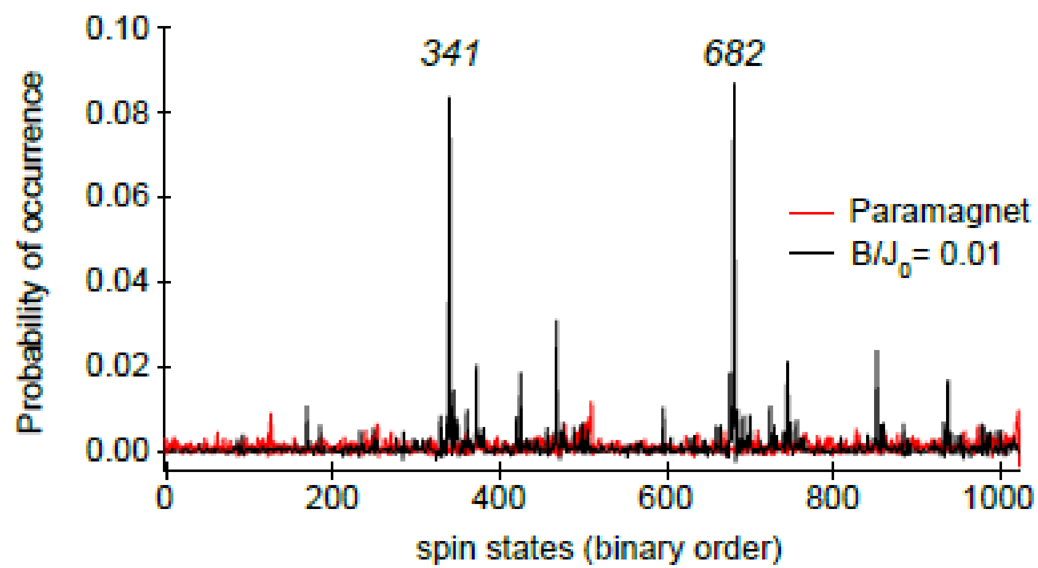
$B^{(x)}(t)$
$J^{(z)}$
time



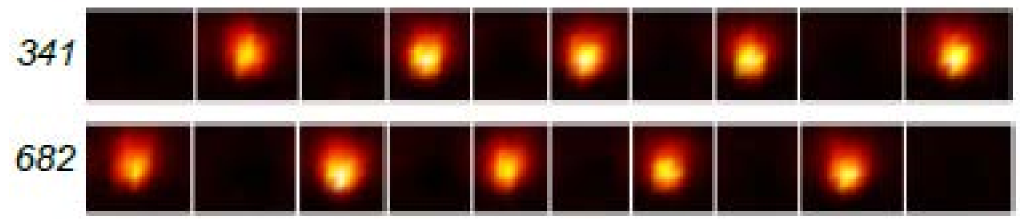
Eigenenergies, $(E-E_0)/J_0$
0.0
0.2
0.4
0.6
0.8
Δ_c/J_0
B_c/J_0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
B/J_0



Correlations $C_{1,1+r}$
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
$B/J_0 = 5$
$B/J_0 = 0.25$
$B/J_0 = 0.01$
0 1 2 3 4 5 6 7 8 9
r (# lattice sites from spin 1)



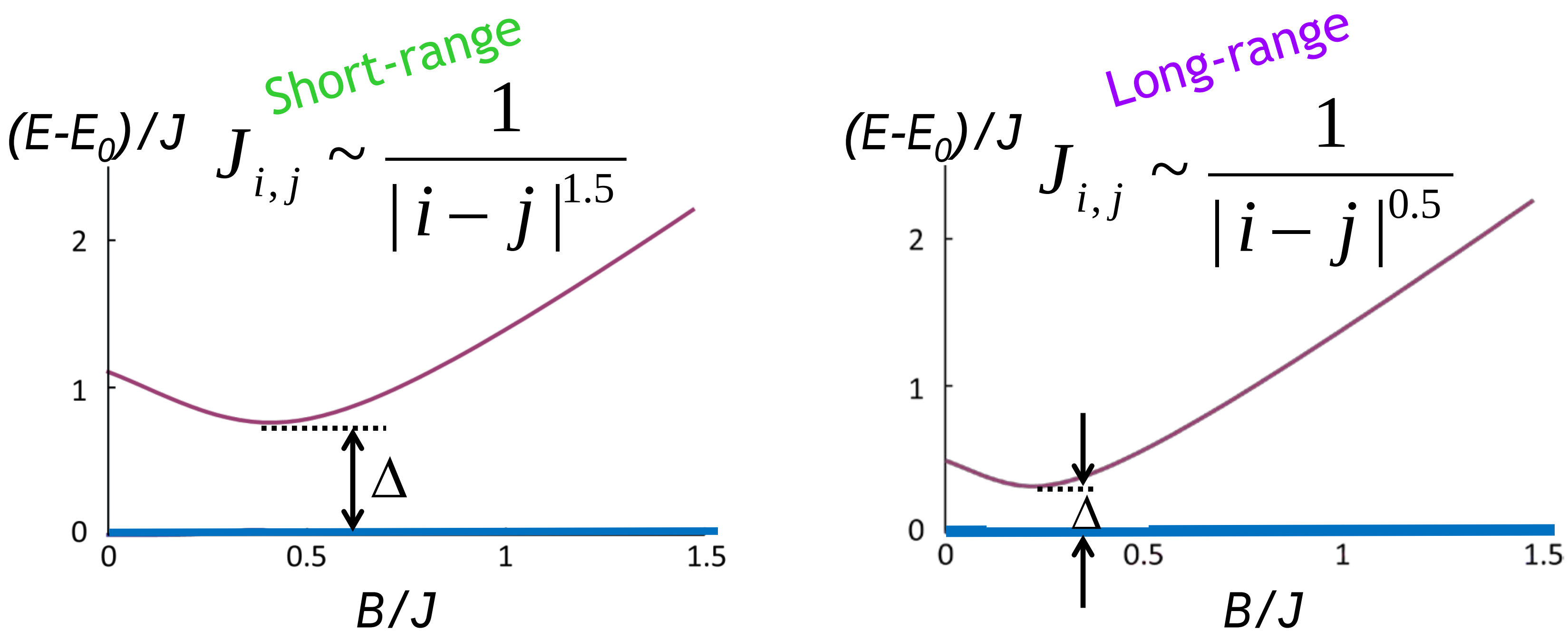
Probability of occurrence
0.10
0.08
0.06
0.04
0.02
0.00
341
682
Paramagnet
$B/J_0 = 0.01$
0 200 400 600 800 1000
spin states (binary order)



341
682

Route to observing frustration: Energy gaps

Energy gaps between ground and excited states are smaller for long-range interactions which lead to more frustration



Ramping the Hamiltonian *non-adiabatically* probes frustration

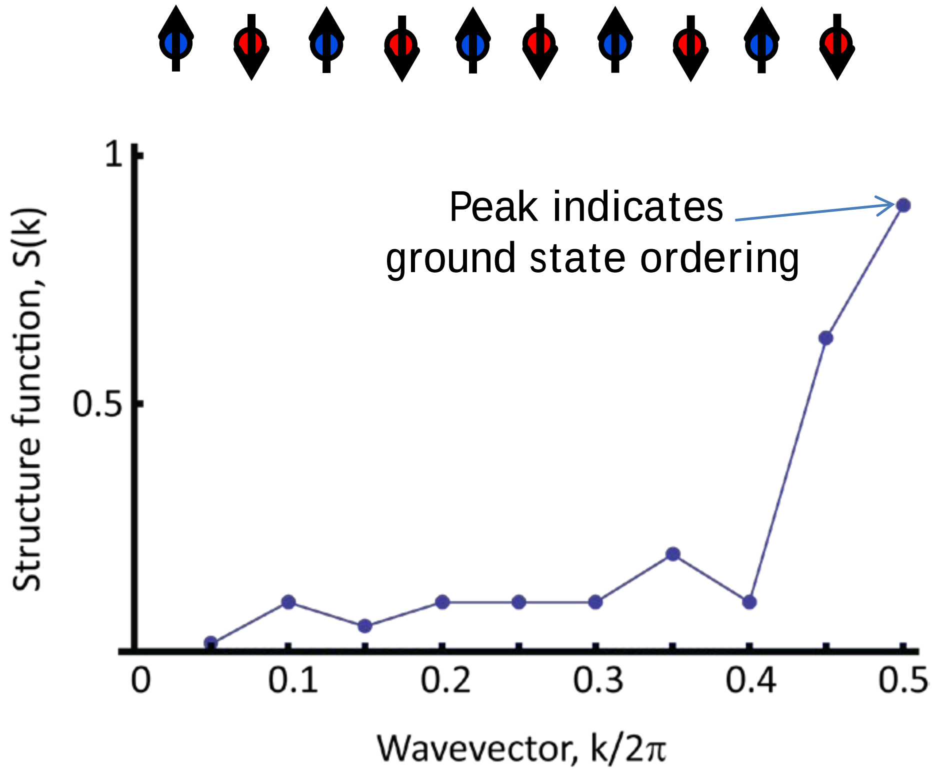
R. Islam, CS, W. C. Campbell, S. Korenblit, J. Smith, A. Lee, E. E. Edwards, C.-C. J. Wang, J. K. Freericks, and C. Monroe, Science **340**, 583 (2013)

Frustration of Magnetic Order

Structure function

$$\boxed{S(k) = \frac{1}{N}\left|\sum_{|i-j|} G(i,j)e^{-ik|i-j|}\right|}$$

$$G(i,j) = \langle \sigma_x{}^i \sigma_x{}^j \rangle - \langle \sigma_x{}^i \rangle \langle \sigma_x{}^j \rangle$$



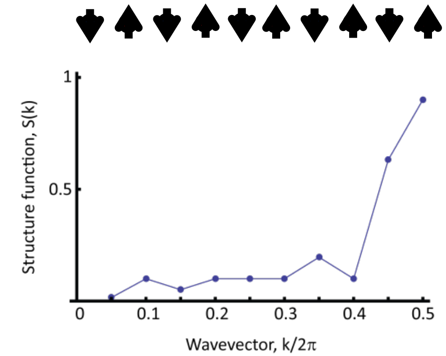
R. Islam, CS, W. C. Campbell, S. Korenblit, J. Smith, A. Lee, E. E. Edwards, C.-C. J. Wang, J. K. Freericks,and C. Monroe, Science **340**, 583 (2013)

Frustration of Magnetic Order

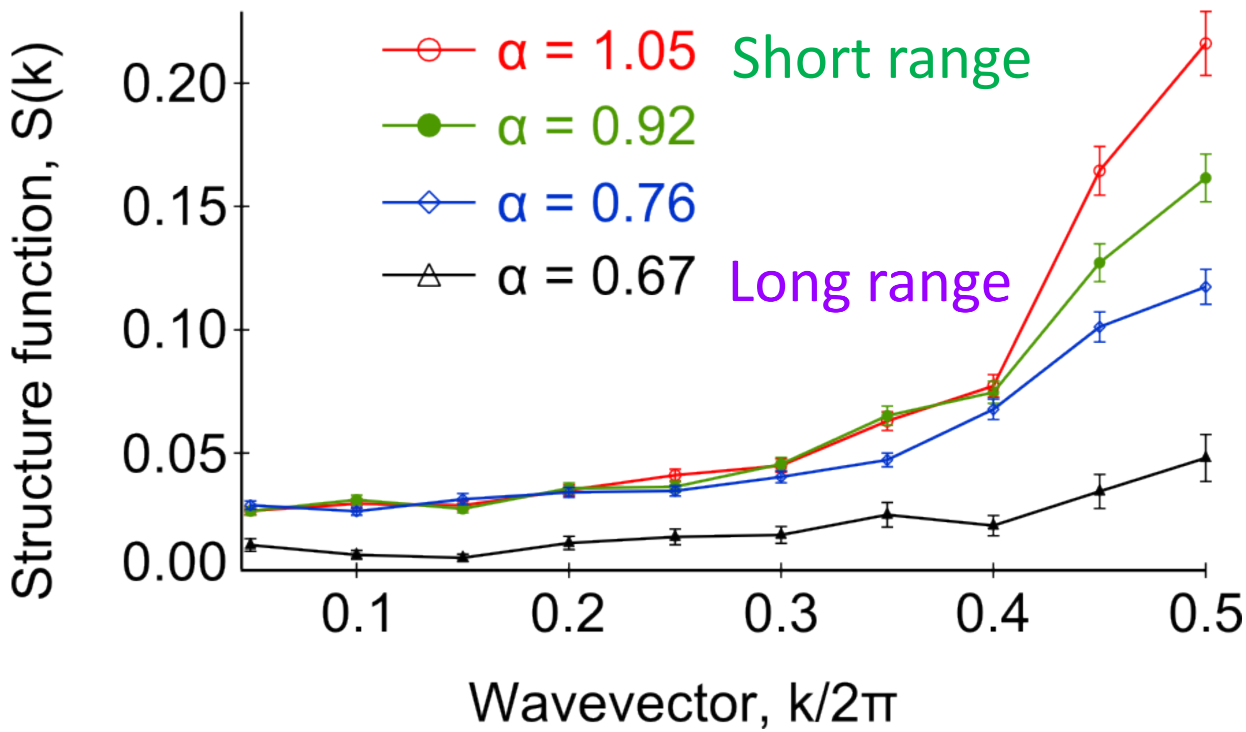
Structure function

$$\boxed{S(k) = \frac{1}{N}\left|\sum_{|i-j|} G(i,j)e^{-ik|i-j|}\right|}$$

$$J_{i,j} \approx \frac{J_0}{|i-j|^{\alpha}}$$



B/J=0.01



Increasing frustration

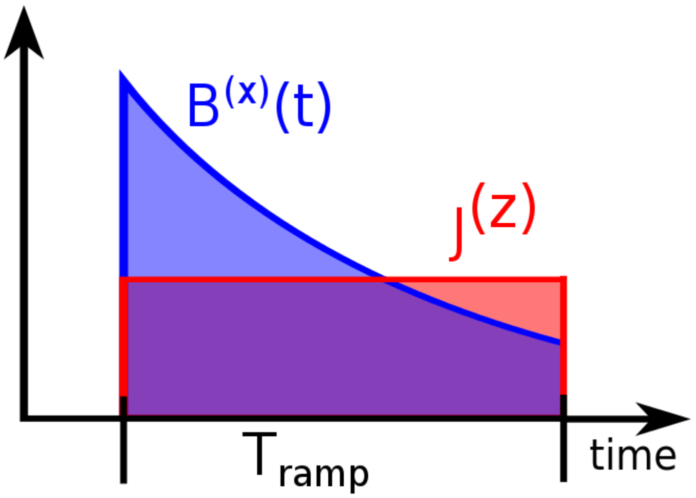
R. Islam, CS, W. C. Campbell, S. Korenblit, J. Smith, A. Lee, E. E. Edwards, C.-C. J. Wang, J. K. Freericks, and C. Monroe, Science **340**, 583 (2013)

Spectroscopy of excitations

Once diabatic excitations have occurred, then they cause oscillations in observables at frequencies given by the excitation energies of the states that were excited, relative to the ground state

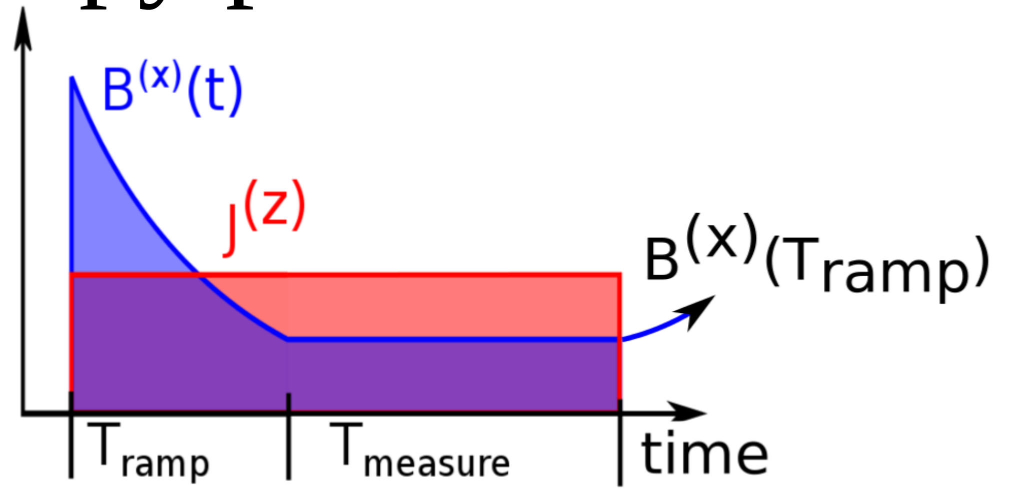
Spectroscopy protocol

- Evolve diabatically, creating excitations



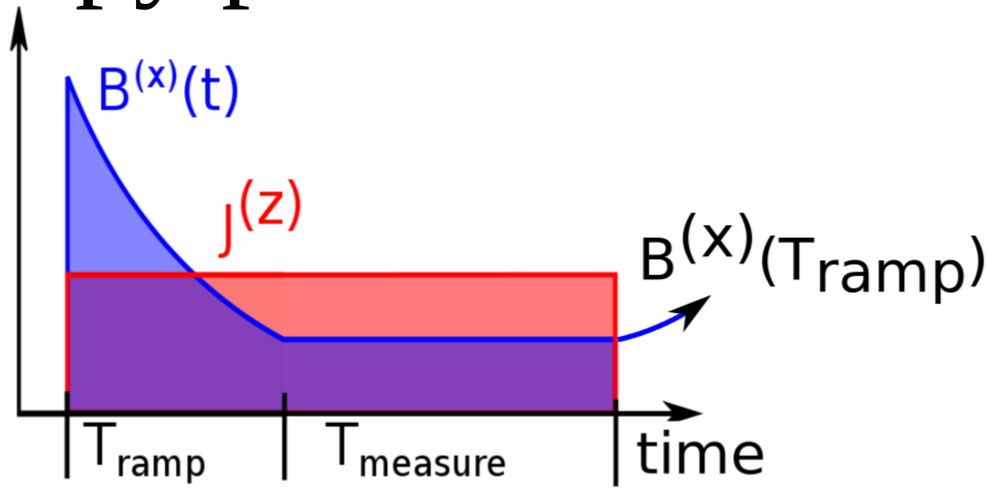
Spectroscopy protocol

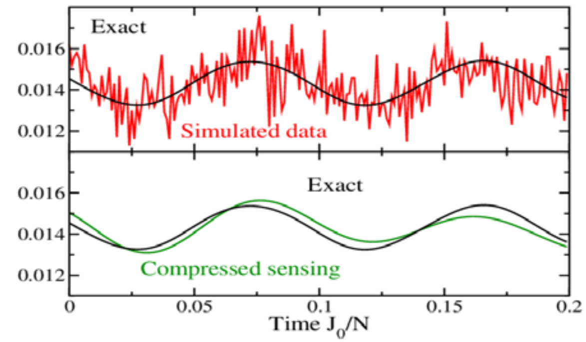
- Evolve diabatically, creating excitations
- Fix magnetic field at a constant value after the excitations have been made



Spectroscopy protocol

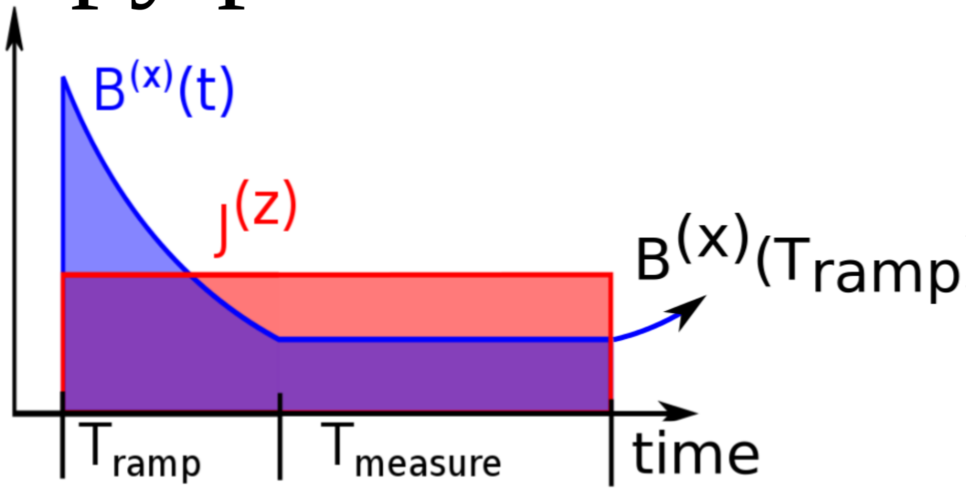
- Evolve diabatically, creating excitations
- Fix magnetic field at a constant value after the excitations have been made
- Measure a low-noise observable (like the probability to be in a specific product state.)

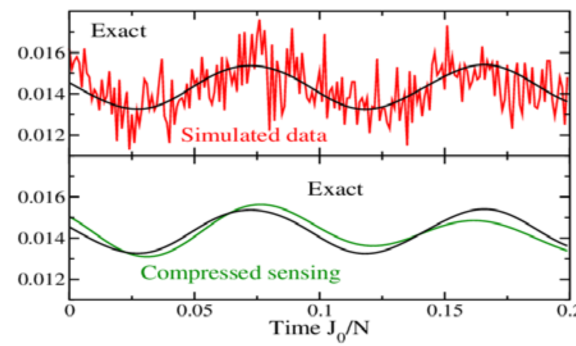


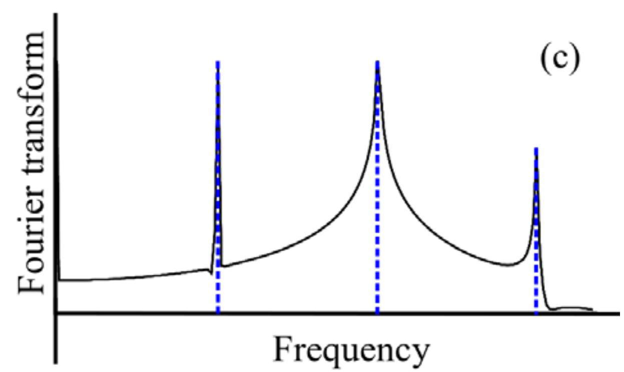


Spectroscopy protocol

- Evolve diabatically, creating excitations
- Fix magnetic field at a constant value after the excitations have been made
- Measure a low-noise observable
- Signal process the oscillations as a function of time to determine the energy difference

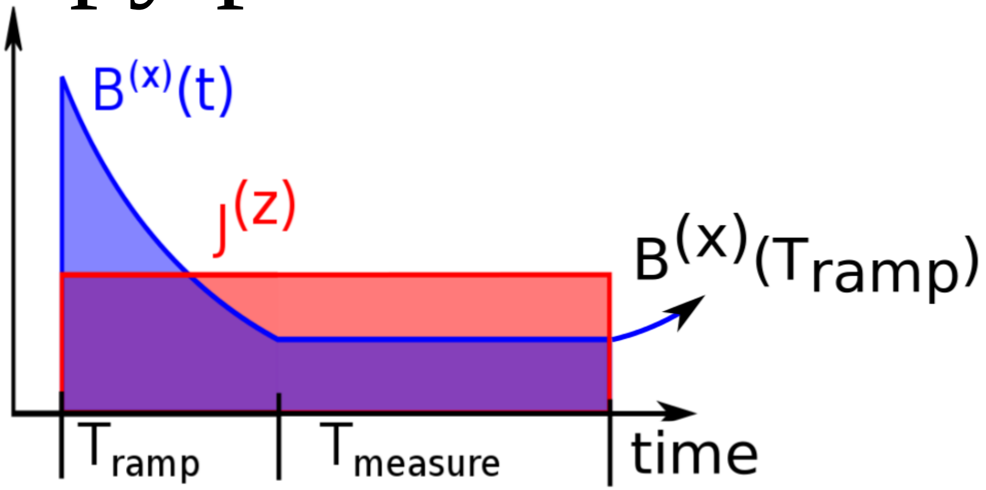


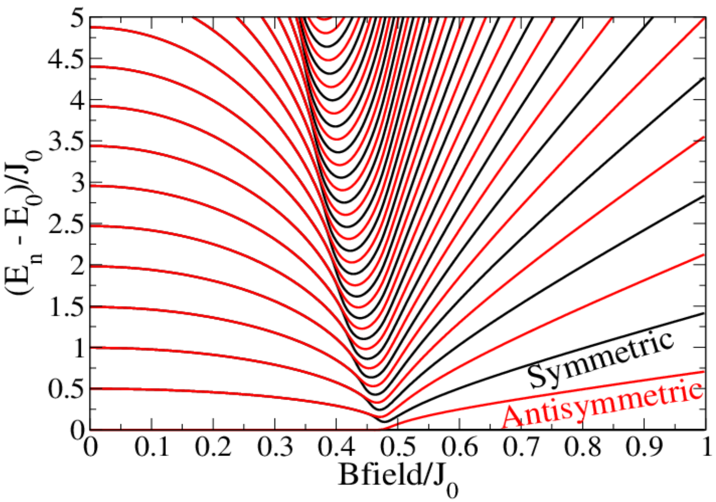




Spectroscopy protocol

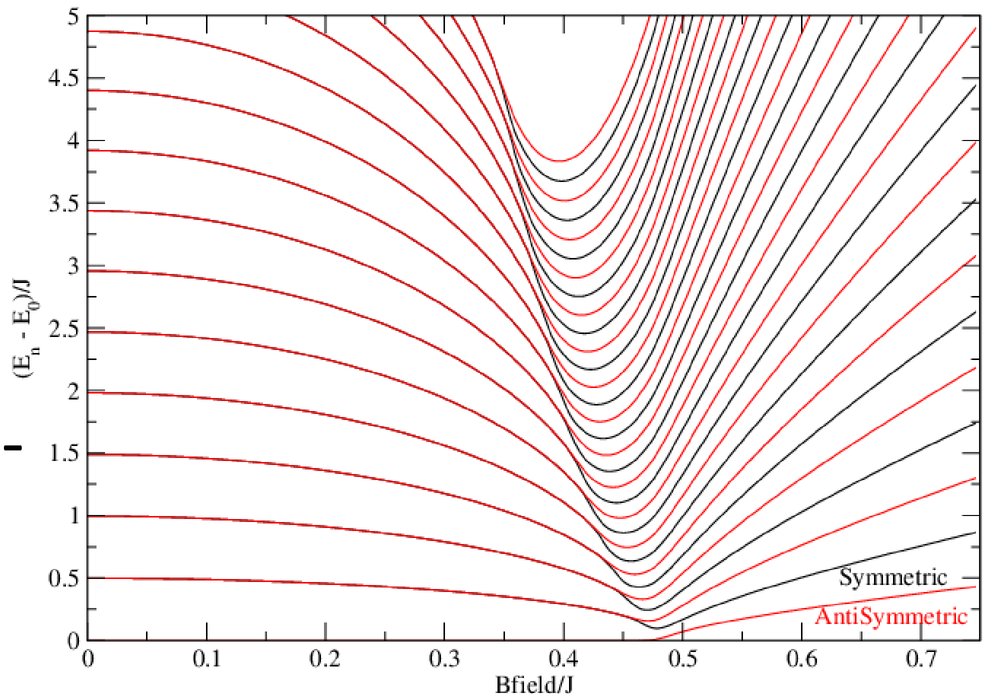
- Evolve diabatically, creating excitations
- Fix magnetic field at a constant value after the excitations have been made
- Measure a low-noise observable
- Signal process the oscillations as a function of time to determine the energy difference
- Repeat to map spectra for different B fields



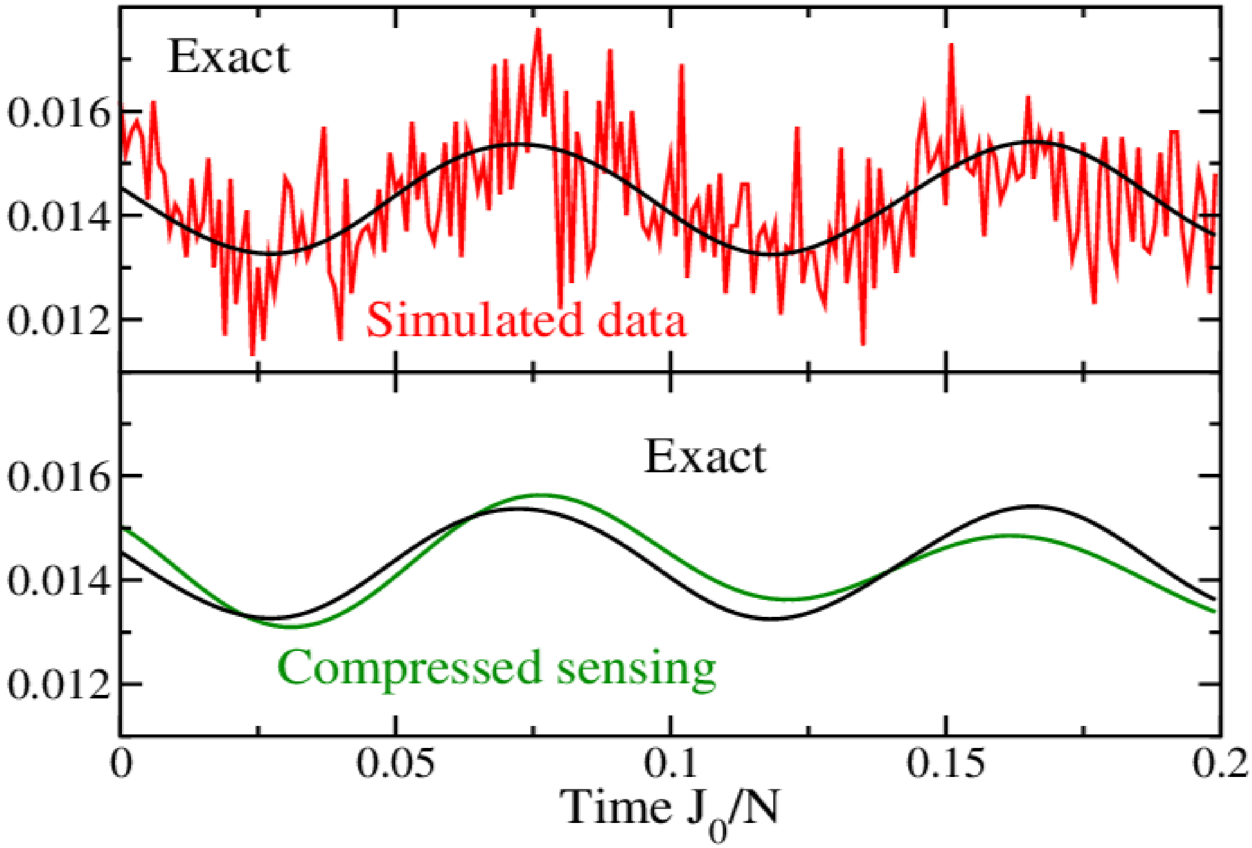


Test Case: Infinite-range transverse field Ising model

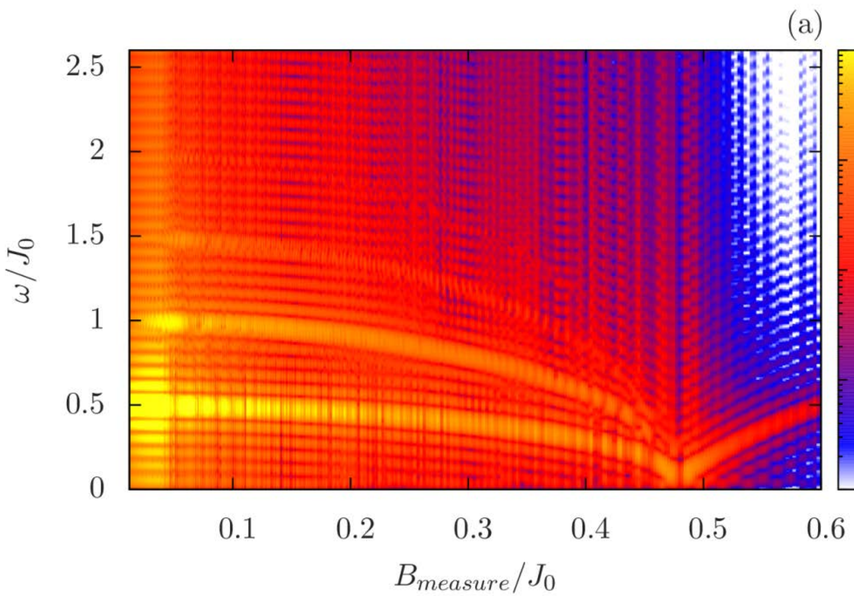
- Total spin S^2 is a good quantum number, so Hilbert space shrinks from 2^N down to N+1 for a ferromagnetic system
- Eigenstates have a spin-reflection parity (even/odd against spin flips of all spins)
- We work with N=400

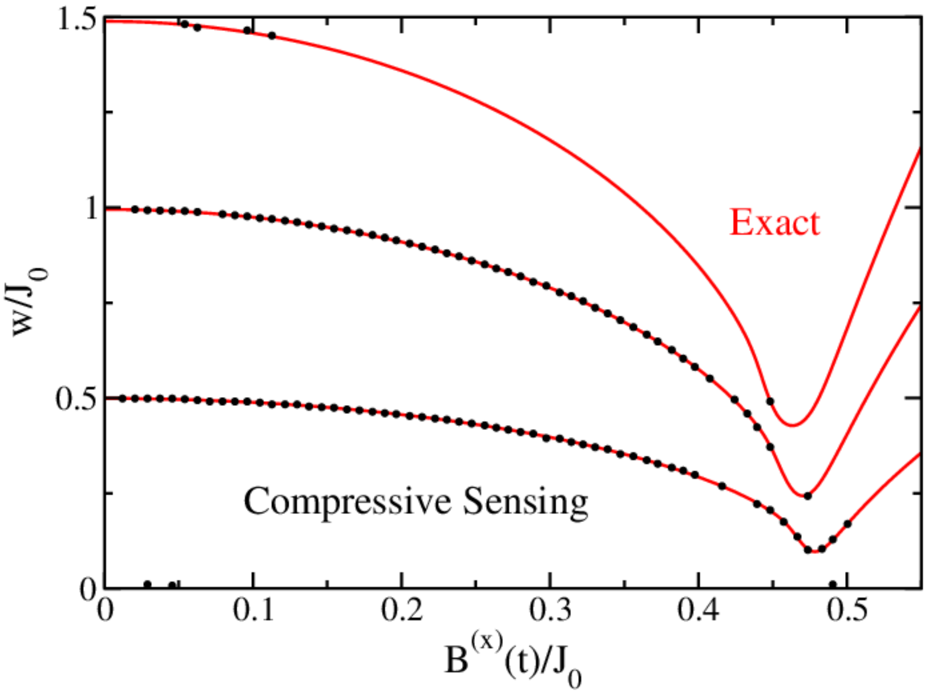


Extracting energy differences from time traces



Energy spectra





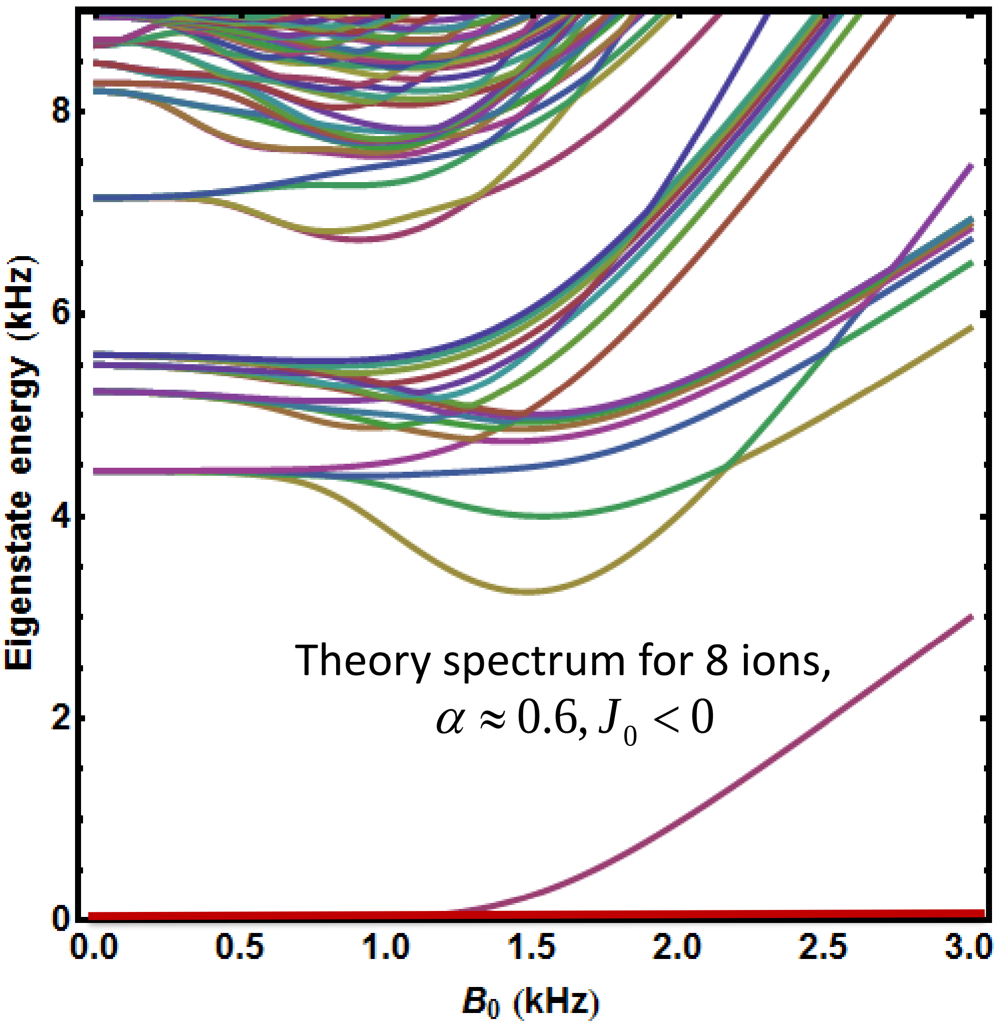
Regular Fourier transform

Compressive sensing

Alternative spectroscopy method via modulation spectroscopy in the Monroe lab

Many-body Rabi spectroscopy

$$H = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe} \sin(2\pi f t)\right) \sum_i \hat{\sigma}_y^{(i)}$$



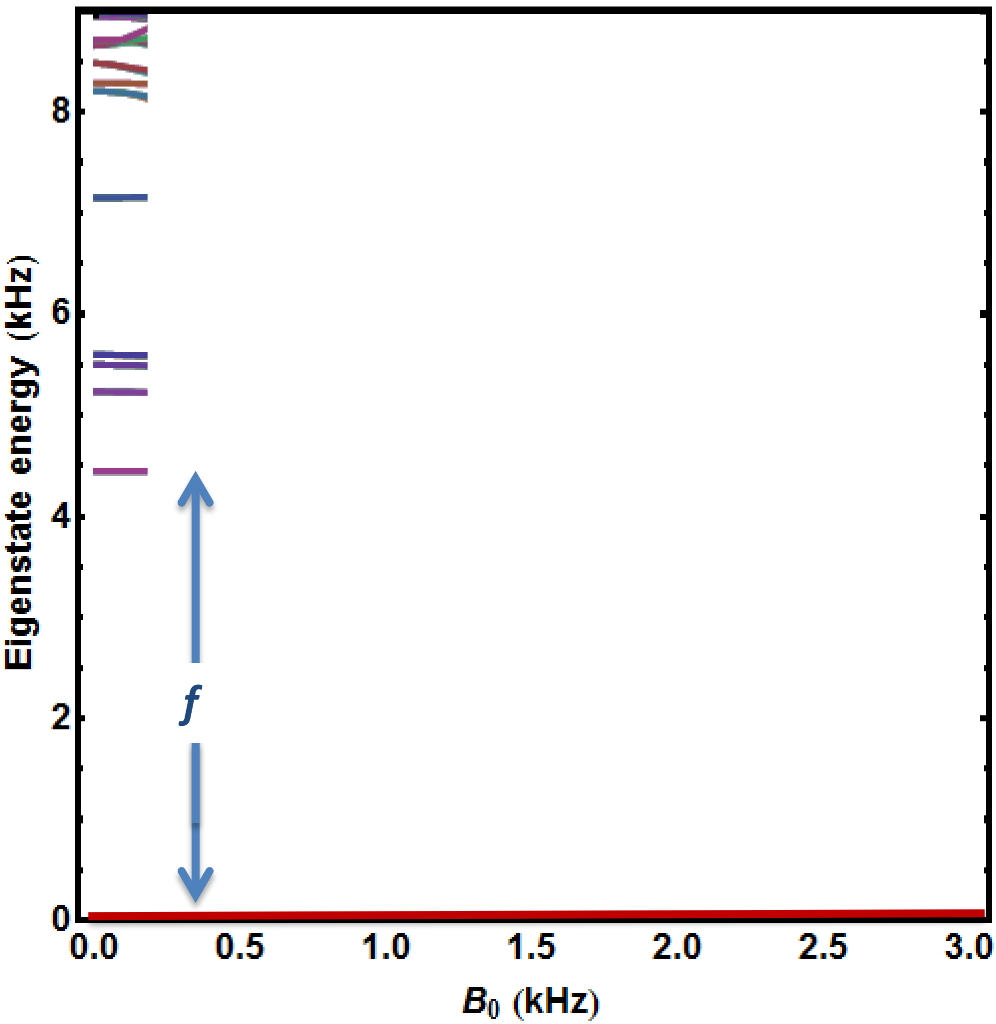
B_{probe} drives transitions if:

- $\left\langle a \left| \sum_i \hat{\sigma}_y^{(i)} \right| b \right\rangle \neq 0$
- Probe freq. matches energy splitting, $f \approx |E_a - E_b|$

C. Senko, J. Smith, P. Richerme,
A. Lee, and C. Monroe, in preparation

Many-body Rabi spectroscopy

$$H = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe} \sin(2\pi f t)\right) \sum_i \hat{\sigma}_y^{(i)}$$



E.g., at low field,

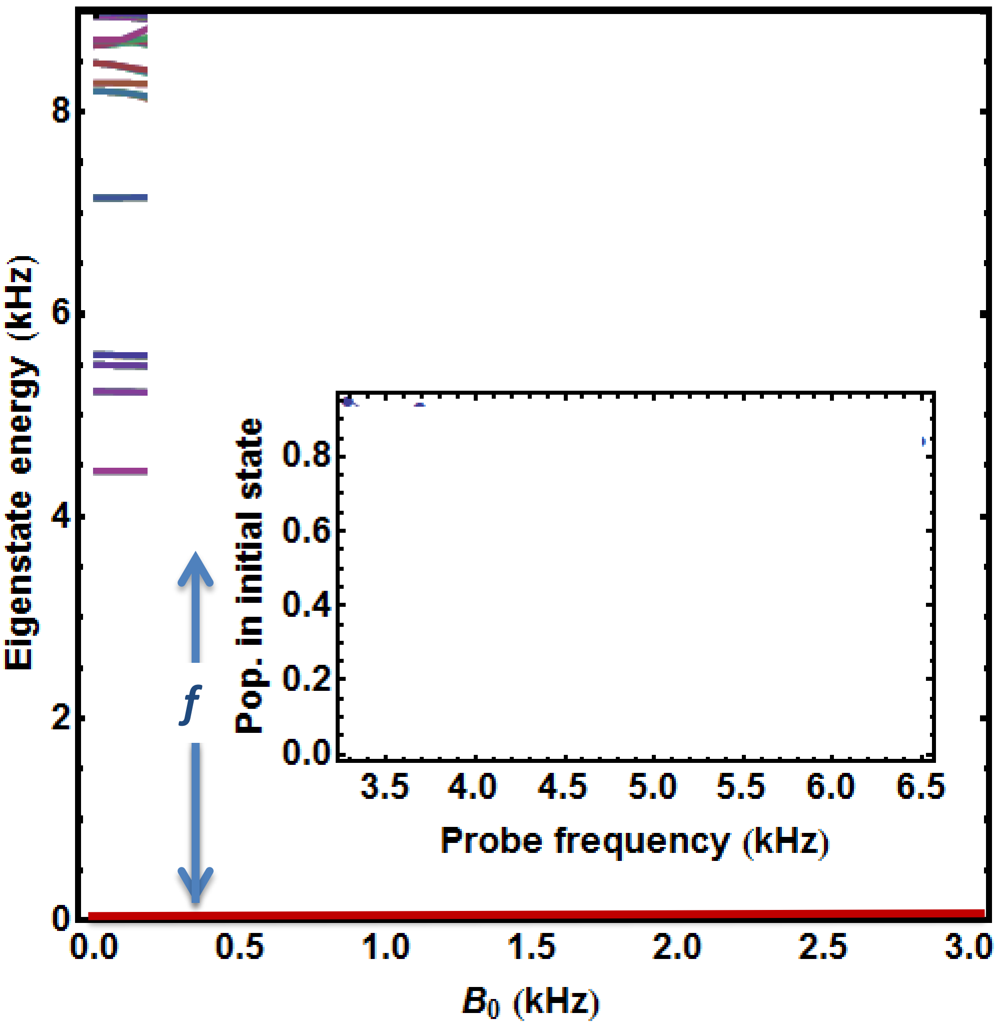
B_{probe} drives transitions if:

- States differ by exactly one spin flip along x
- Probe freq. matches energy splitting, $f \approx |E_a - E_b|$

C. Senko, J. Smith, P. Richerme, A. Lee, and C. Monroe, in preparation

Many-body Rabi spectroscopy

$$H = \sum_{i\neq j} J_x^{i,j}\hat{\sigma}_x^{(i)}\hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe}\sin(2\pi f t)\right)\sum_i \hat{\sigma}_y^{(i)}$$



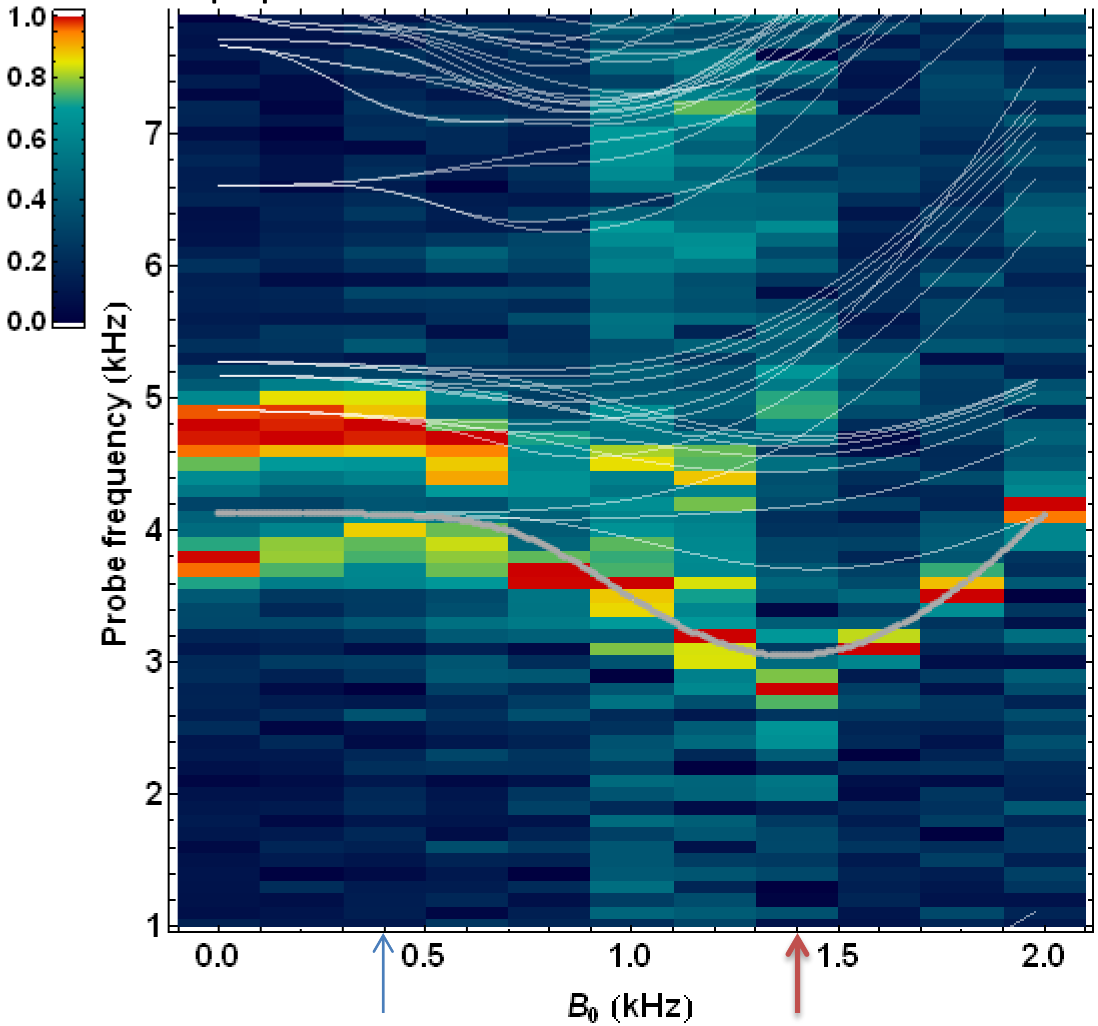
Protocol:

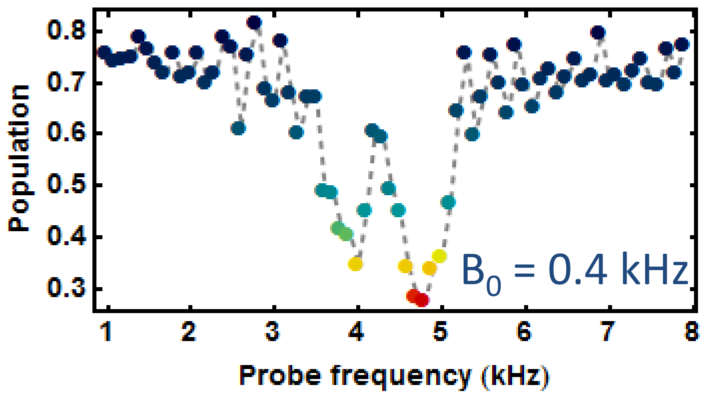
- Prepare eigenstate
  - Often, $\left|\downarrow\downarrow\downarrow\downarrow\cdots\right\rangle_x$
- Apply probe field for fixed time (3 ms)
- Scan probe frequency and observe transitions

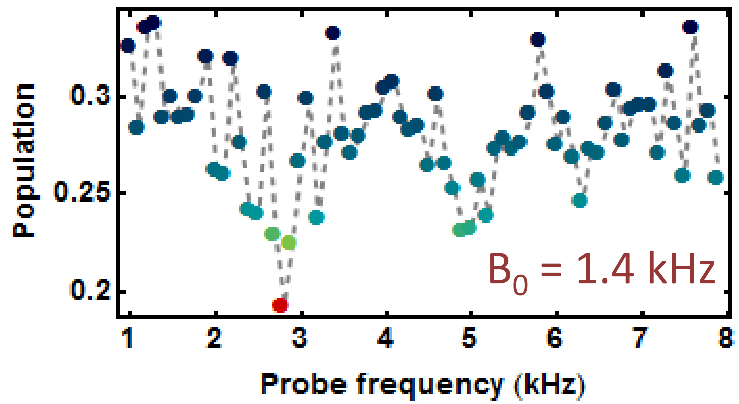
C. Senko, J. Smith, P. Richerme,
A. Lee, and C. Monroe, in preparation

Measuring a critical gap

$$H = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe} \sin(2\pi f t)\right) \sum_i \hat{\sigma}_y^{(i)}$$







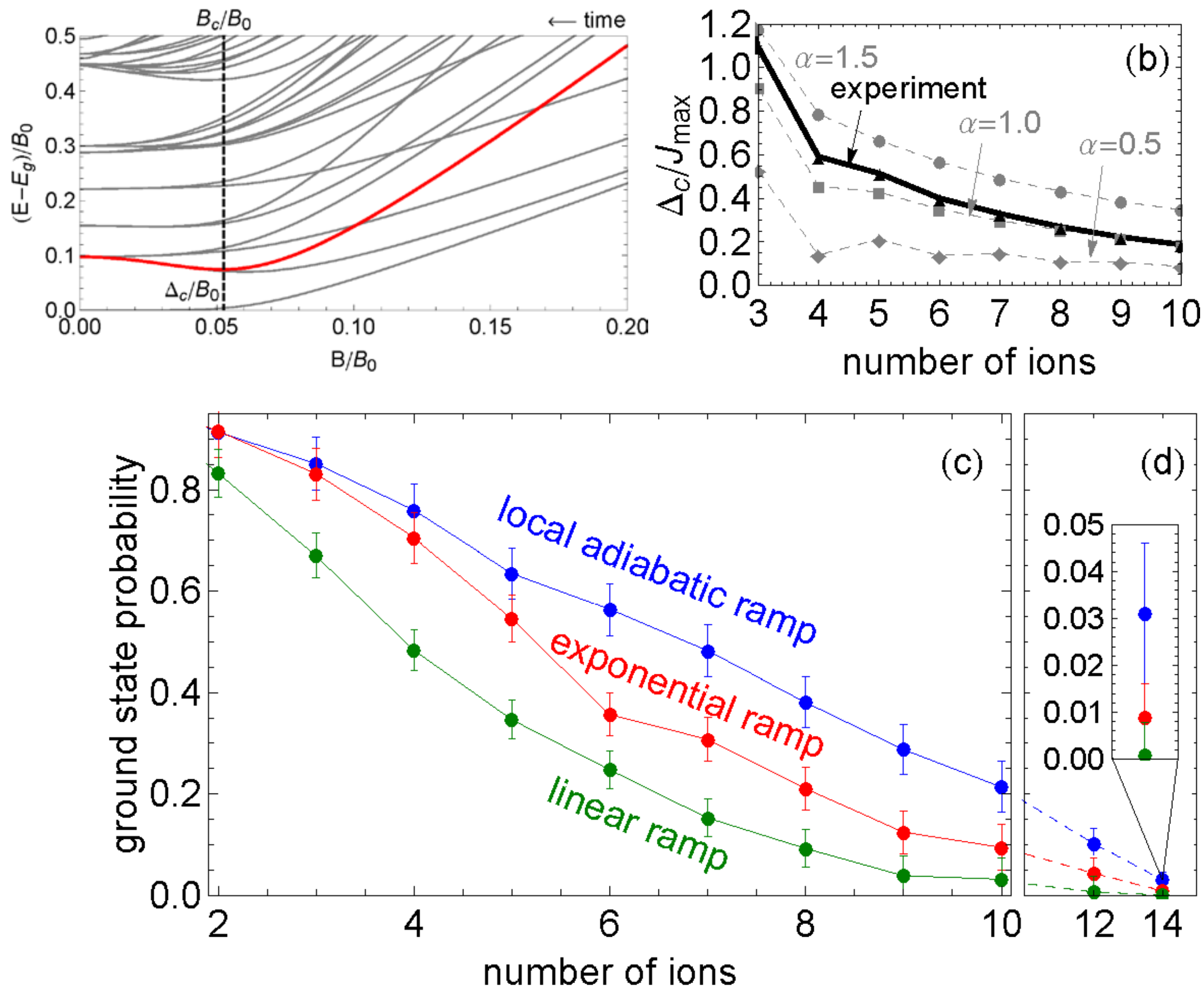
C. Senko, J. Smith, P. Richerme,
A. Lee, and C. Monroe, in preparation

Shortcuts to adiabaticity

Local adiabatic ramp

For a local adiabatic ramp, we keep the diabaticity parameter γ constant to determine the time-dependent field

$$\gamma = \left| \frac{\Delta^2(B)}{\dot{B}(t)} \right|$$



P. Richerme, C. Senko, J. Smith, A. Lee, S. Korenblit, and C. Monroe, Phys. Rev. A 88, 012334 (2013).

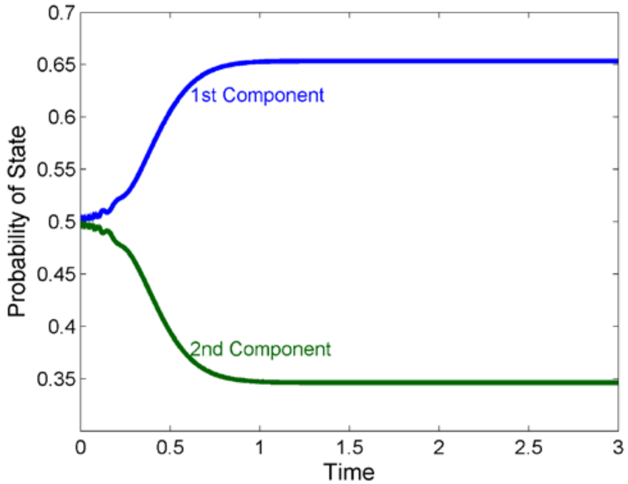
Adding counter diabatic terms

Del Campo et al. showed how to determine the operators for a nearest neighbor Ising model, but we are investigating long-range Ising models, so we construct the counter diabatic terms for small numbers of ions.

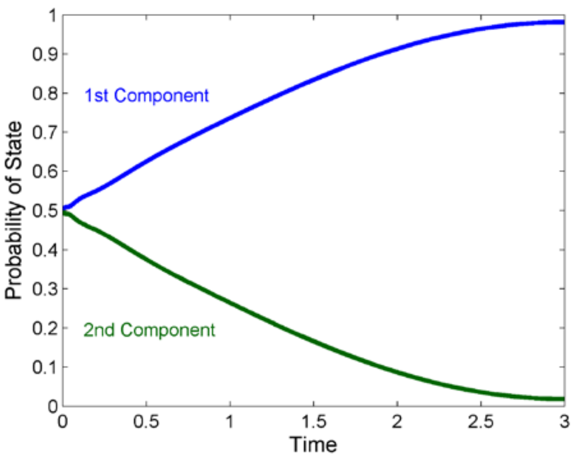
First, one should note symmetries of the Hamiltonian. There is a spatial reflection symmetry about the center, and there is a spin-reflection symmetry where x->-x, y->y, and z->-z. States can be classified as even or odd with respect to each parity operator.

N=2

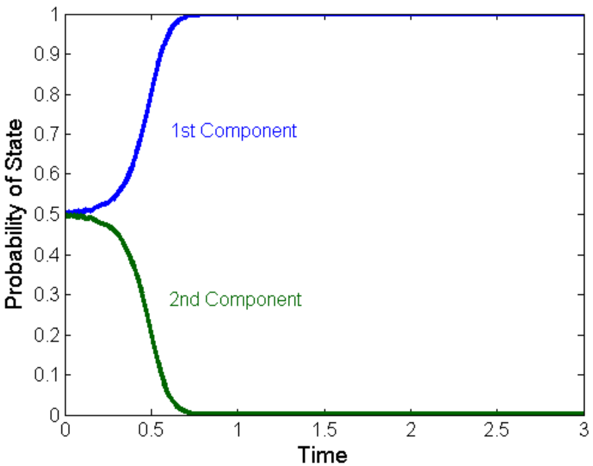
$$H'(t) = -\frac{\dot{B}(t)}{2+8B^2(t)}\left(\sigma_1^z\sigma_2^x + \sigma_1^x\sigma_2^z\right)$$



exponential ramp



optimal ramp

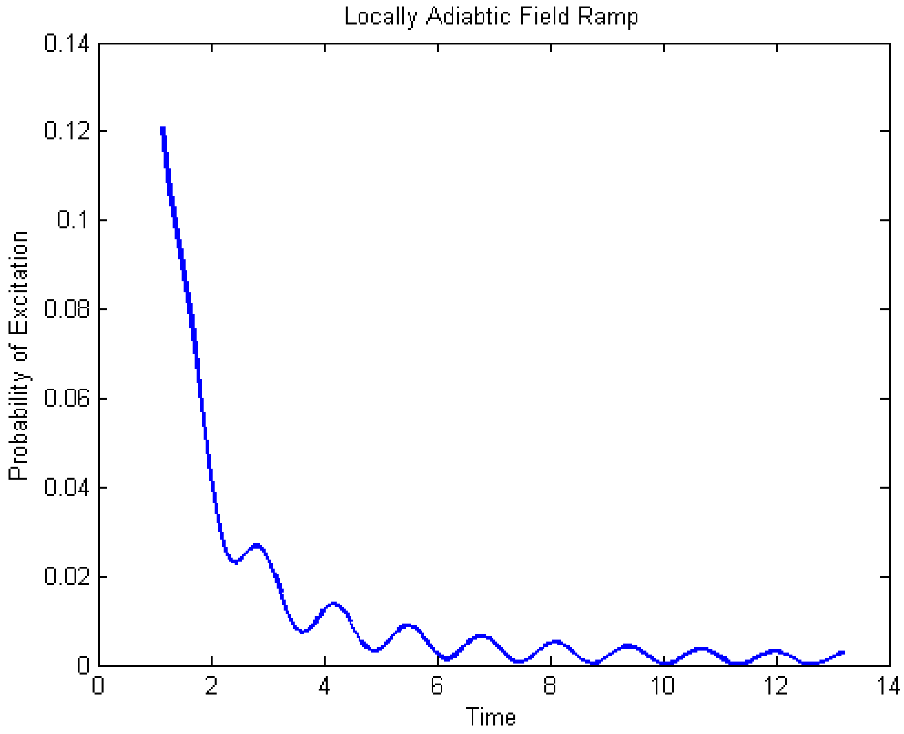


fast adiabatic

Experimental implementation

Working with an optimized B(t) is the easiest thing to do experimentally.

Otherwise, one needs to find approximate operators for counter diabatic terms that are experimentally viable.



Using weak fast passage is likely to get to a higher final state probability.

People who did the hard work

Joseph Wang
Los Alamos

Bryce Yoshimura
Georgetown

Wes Cambell
UCLA

Nick Johnson
Alabama and Georgetown

Monroe group,
Maryland and JQI