Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Thursday, July 5, 9:00 AM – Trapped ion quantum sensing

Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Quantum simulation ⇔ Analog quantum simulation

Ion trap quantum simulation references (incomplete):

review – R. Blatt and C.F. Roos, Nature Physics 8, 277 (2012); J. Bollinger et al.,
https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=912704; C. Monroe, ..,
http://iontrap.umd.edu/wp-content/uploads/2014/10/VarennaLecture2013.pdf

Penning trap – Bohnet, .., Science 352, 1297 (2016); Gärttner, .., Nat. Phys., 13, 781 (2016)

linear rf trap - K. Kim, New J. Physics 13, 105003 (2011); P. Richerme, .., Nature 511, 198 (2014); P. Jurcevic, .., Nature 511, 202 (2014); PJ. Smith, .., Nature Physics 12, 907 (2016); Jurcevic, .., Phys. Rev. Lett. 119, 080501 (2017); J. Zhang, .., Nature 543, 217 (2017); J. Zhang, .., Nature 551, 601 (2017).

Why quantum simulation?

- The 1st quantum revolution (Bohr, Heisenberg,…) $\Longrightarrow$ understand single particle Q.M. produced the transistor, laser, …
- Many problems require much more than single particle treatments
  - quantum many-body systems, “More is different”
  - highly entangled states
  - phases of quantum matter
- quantum complexity ingredients:

qubits (spin-1/2)

$$|\uparrow\rangle \equiv |1\rangle \text{ and } |\downarrow\rangle \equiv |0\rangle$$

+superposition

$$\alpha|\uparrow\rangle + \beta|\downarrow\rangle \qquad (|\uparrow_1\rangle + |\downarrow_1\rangle)\otimes(|\uparrow_2\rangle + |\downarrow_2\rangle)\cdots$$

N qubits, 2^N states

+entanglement

$$|\uparrow_1\rangle|\uparrow_2\rangle + |\downarrow_1\rangle|\downarrow_2\rangle$$

$\Longrightarrow$ quantum many problems can be “exponentially” difficult

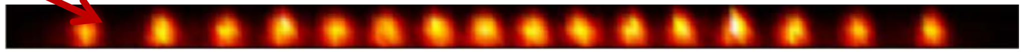
Motivation – understand quantum many-body physics

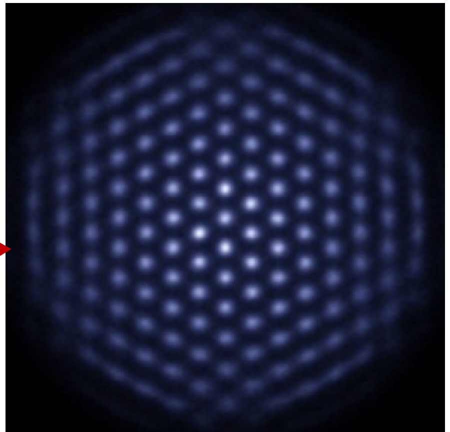
How are we to understand quantum many-body systems?

- quantum computation (if and when a Q. computer exists)
- develop novel approximate theoretical methods
- quantum simulation

- Feynman (1982) – use well controlled quantum system to emulate another system or model that is not understood

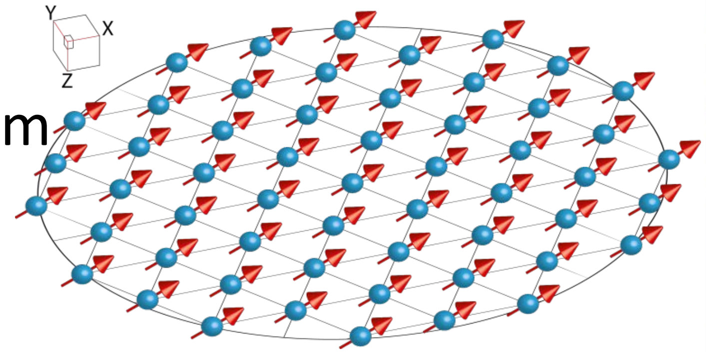
- platforms being used for quantum simulation:
  - neutral atoms and molecules in optical lattices
  - superconducting circuits
  - photons
  - trapped ions
  - •
  - •

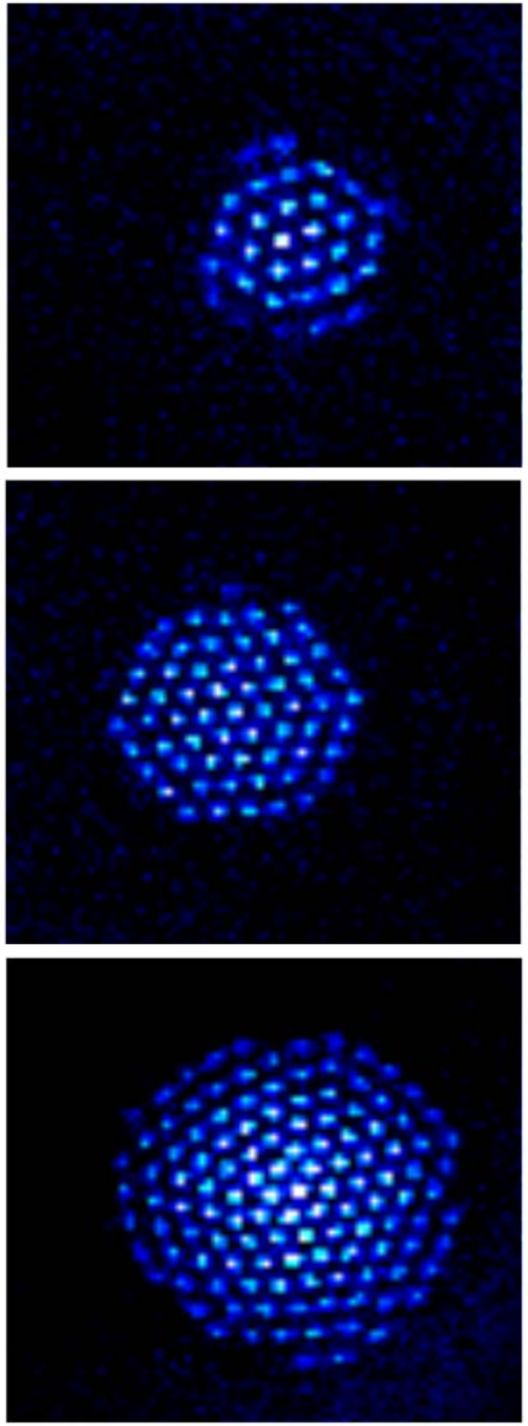




Quantum Simulation in a Penning trap

- trapped ion crystals – good for simulating quantum magnetic interactions
  (Ch Wunderlich et al., 2003; Porras & Cirac, 2004)

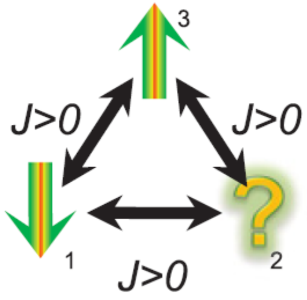




- exquisite quantum simulations with ion strings (N<20) in linear rf traps (Blatt group, Monroe group, …)

$$H_{\text{trans. Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z + B_\perp \sum_i \sigma_i^x$$

- Penning trap – platform for quantum simulation with large 2D (N> 200) ion crystals
  - triangular lattice and antiferromagnetic interaction $(J_{i,j} > 0) \Longrightarrow$ frustration

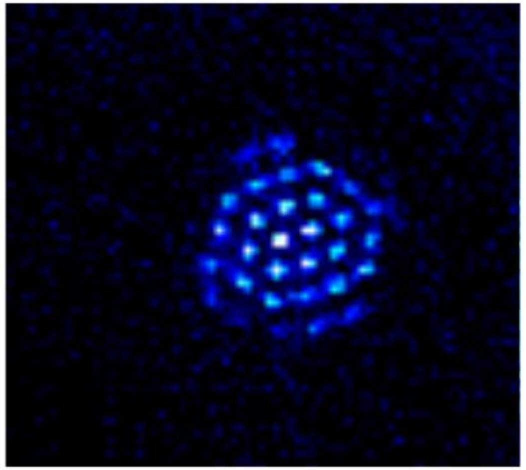


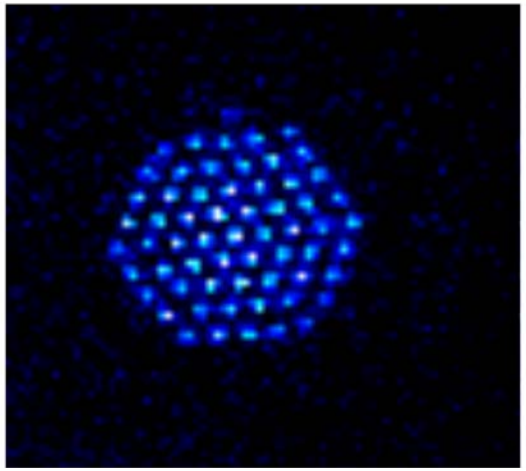
Quantum Simulation in a Penning trap

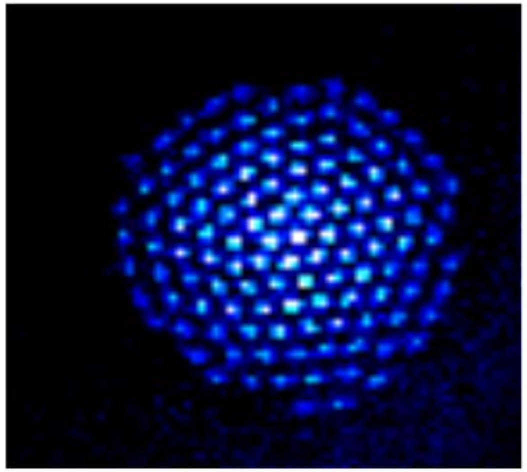
$$H_{\text{trans. Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z + B_\perp \sum_i \sigma_i^x$$

- Iconic model of quantum magnetism; calculation of ground states and dynamics very hard for frustrated systems
  - quantum phase transitions
  - quantum annealing protocols
  - many-body localization
  - spin-liquid behavior??

- benchmark quantum dynamics and entanglement
  - Bohnet et al., Science 2016, arXiv:1512.03756
  - Gaerttner et al., arXix:1608.08938







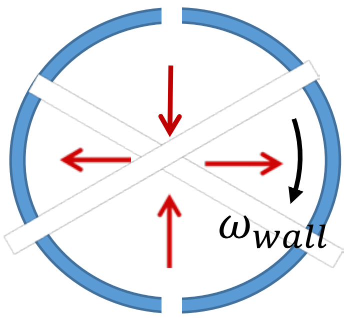
Trapped ion quantum simulation

1. Quantum simulation with 2d ion arrays in a Penning trap

2. Quantum simulation with 1d ion crystals in linear rf traps

1. Quantum simulation with 2d ion arrays in a Penning trap

- ion crystals in Penning traps

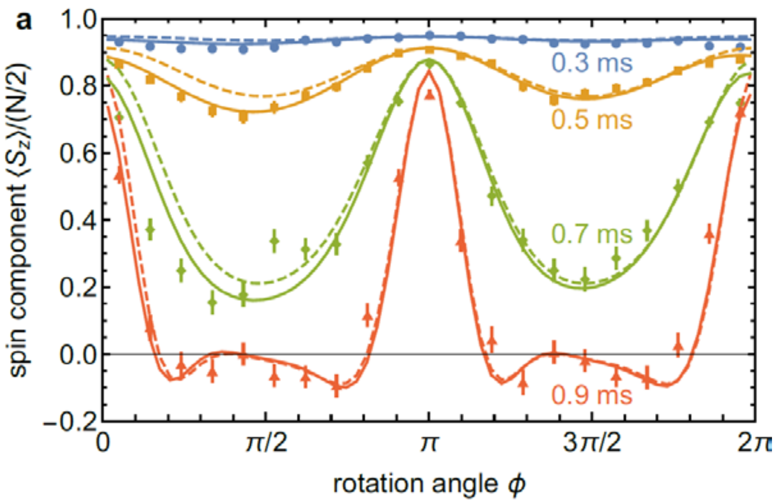


- - high magnetic field qubit
  - modes

- engineering tunable Ising dynamics

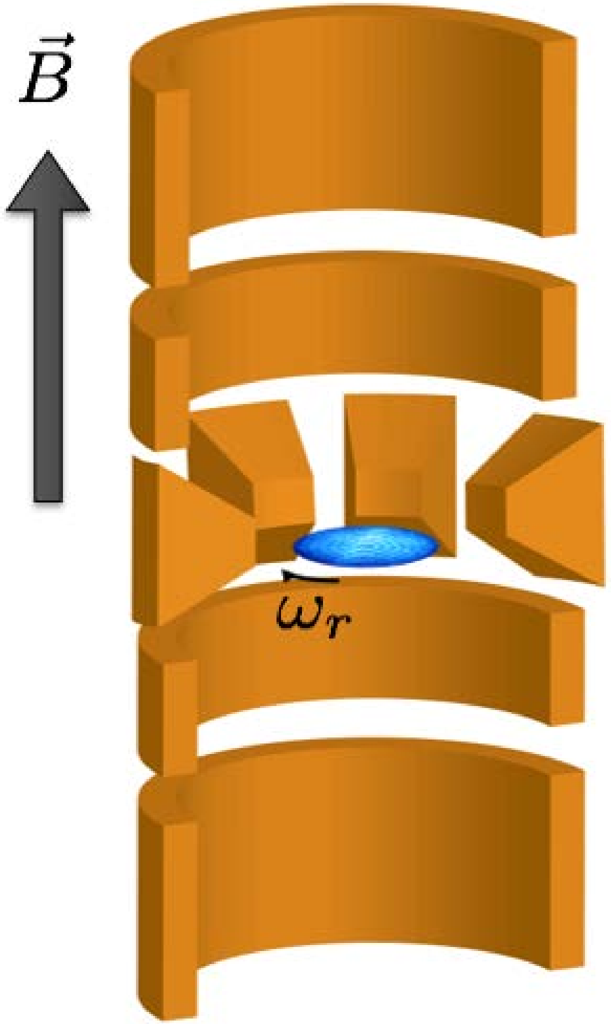
$$H_{Ising} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

- benchmark quantum dynamics, entanglement
  - -spin squeezing
  - - out-of-time correlations (OTOC)



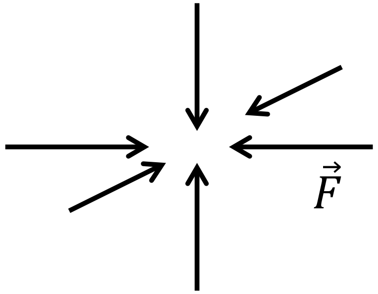
Penning traps

Confinement through static electric and magnetic fields



g-factors, atomic phys.	–	U of Wash., Mainz, Harvard, Imperial College, NIST, ..
mass spectroscopy	–	U of Wash., Harvard, ISOLDE/CERN, …
ICR mass spectroscopy	–	everywhere
cluster studies	–	Mainz/Griefswald
non-neutral plasmas	–	UCSD, Berkeley, Princeton, NIST, ..
anti-matter	–	UCSD, Harvard, CERN, Swansea, …
quantum information/simulation	–	NIST, Imperial College, Sydney, ….

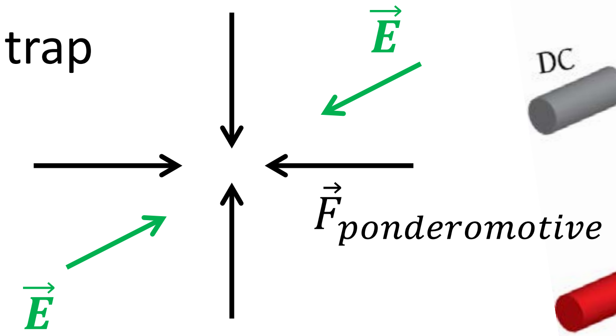
linear rf trap vs Penning trap

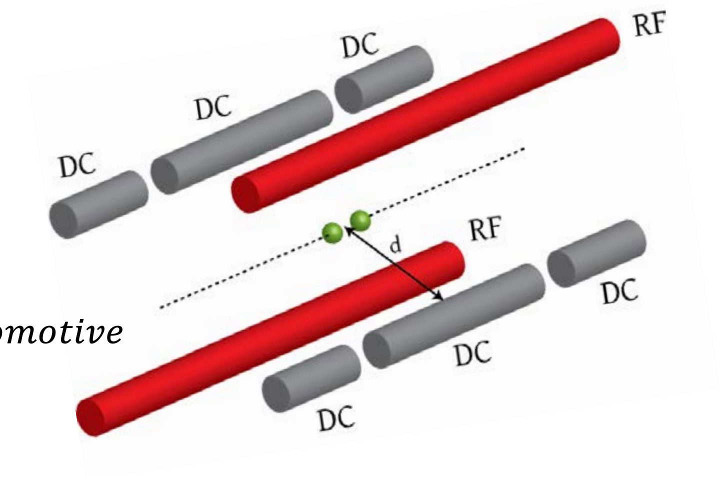


ideal ion trap

desire $\vec{\nabla} \cdot \vec{F} \neq 0$

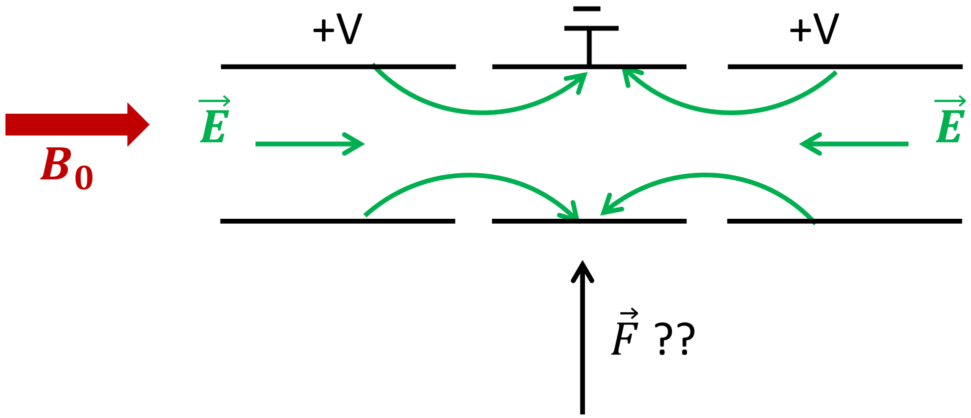
linear rf trap





confinement ↔ conservation of energy

Penning trap



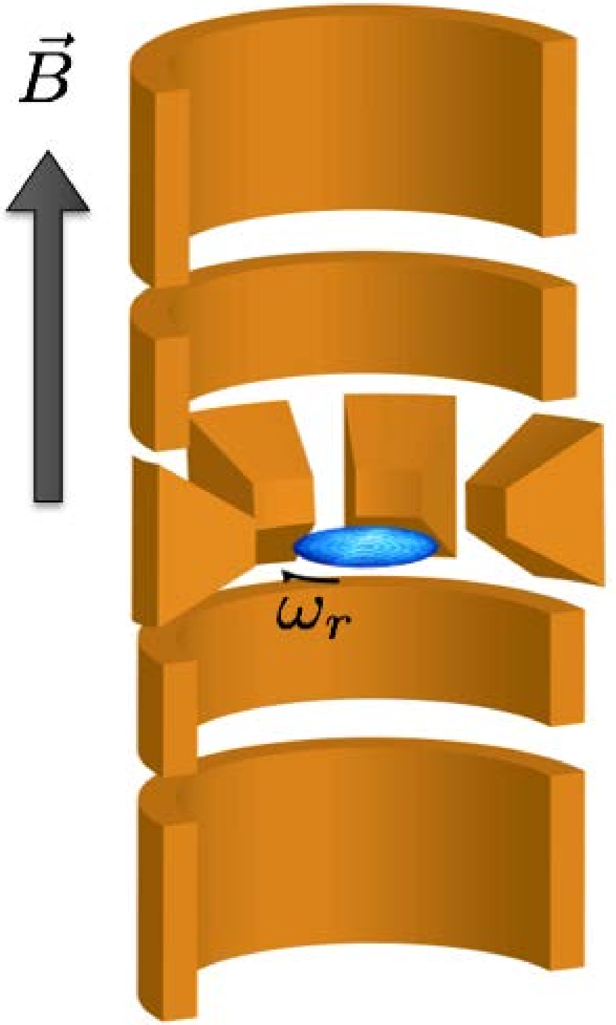
axial confinement ↔ conservation of energy

radial confinement ↔ conservation of angular momentum

Dubin and O'Neil, RMP 71 (1999)

$\rho \sim \exp[-(H - \omega_r P_\theta)/(k_B T)]$

Penning trap: many particle confinement with static fields



$^9Be^+$, B_0 = 4.5 T

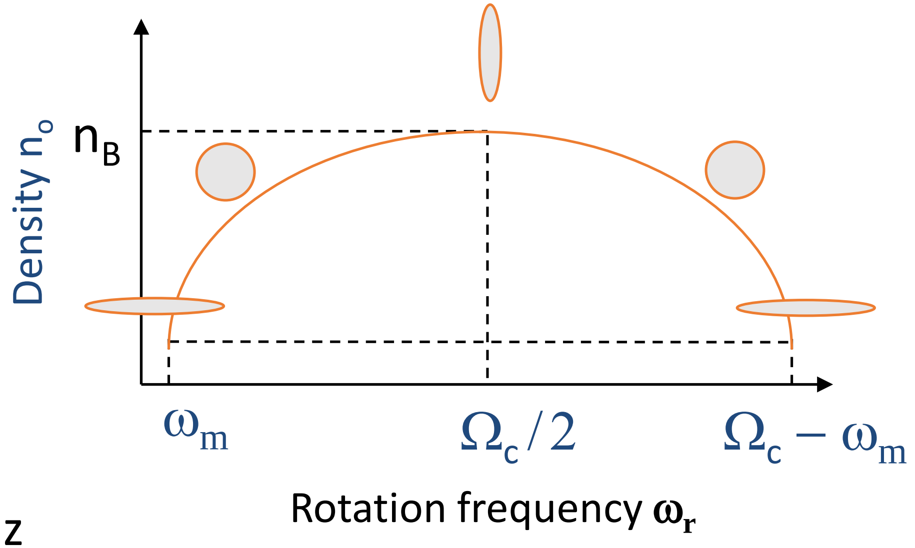
$\frac{\Omega_c}{2\pi} \sim$ 7.6 MHz, $\frac{\omega_z}{2\pi} \sim$ 1.6 MHz, $\frac{\omega_m}{2\pi} \sim$ 160 kHz

- radial confinement due to rotation – ion plasma rotates $v_\theta = \omega_r r$ due to ***ExB*** fields

Lorentz force from rotation is directed radially inward

$$\varphi_{trap}(r,z) \approx \frac{1}{2} m\omega_z^2 \left(z^2 - \frac{r^2}{2} \right) \quad \overset{\text{rotating frame}}{\Rightarrow}$$

$$\varphi_{rot}(r,z) = \frac{1}{2} m\omega_z^2 \left(z^2 + \left(\frac{\omega_r (\Omega_c - \omega_r)}{\omega_z^2} - \frac{1}{2} \right) r^2 \right)$$

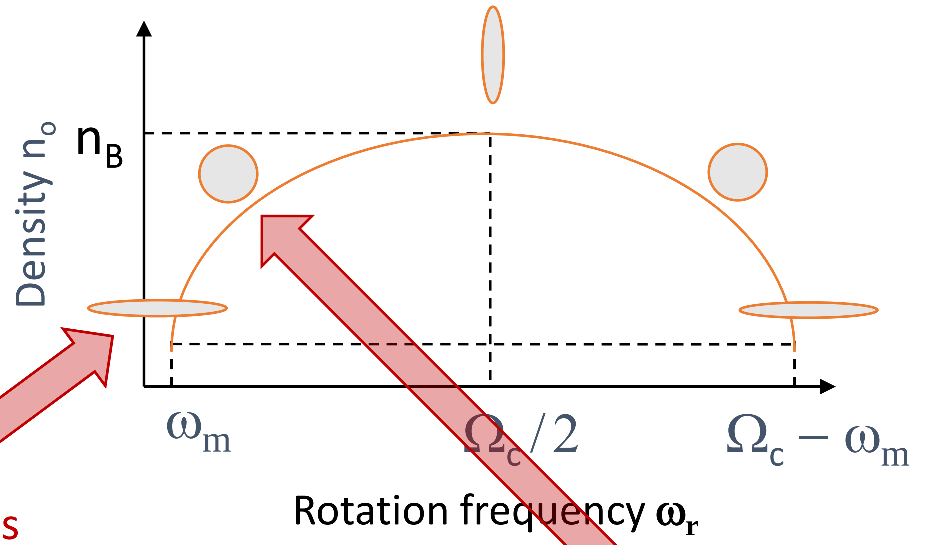


Ion crystals form as a result of minimizing Coulomb potential energy

T→ 0.4 mK (Doppler laser cooling) ⇒ $q^2/a_{WS} \gg k_B T, 2a_{WS} \sim$ ion spacing

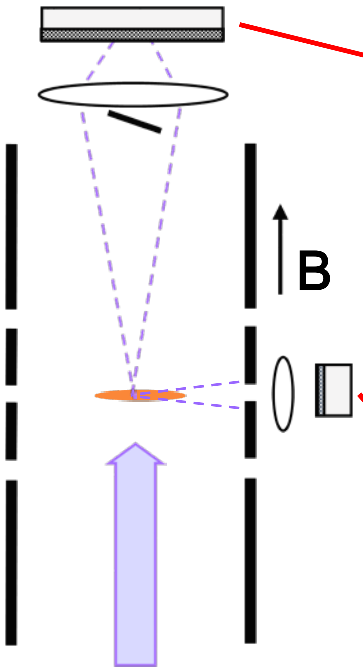
type of crystal depends on crystal size and shape

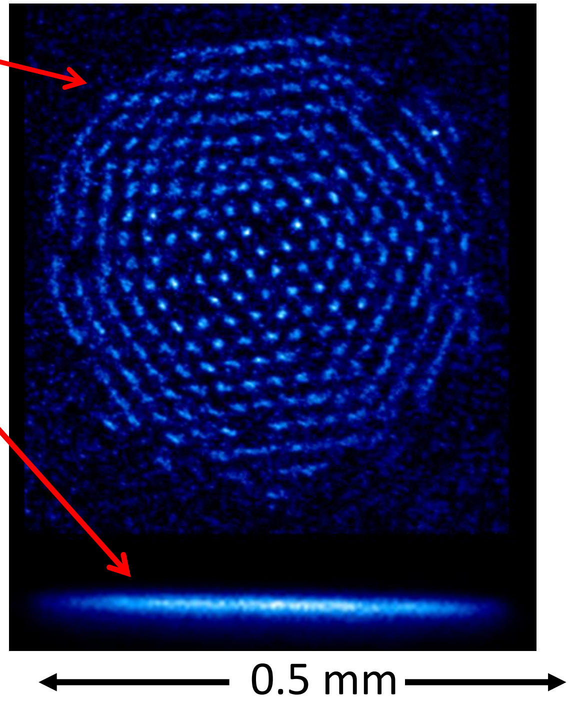
Mitchell et.al., Science (1998)



single planes

bcc crystals with N>100 k

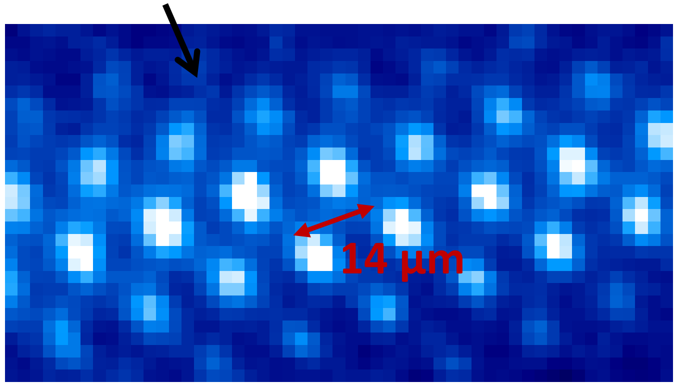




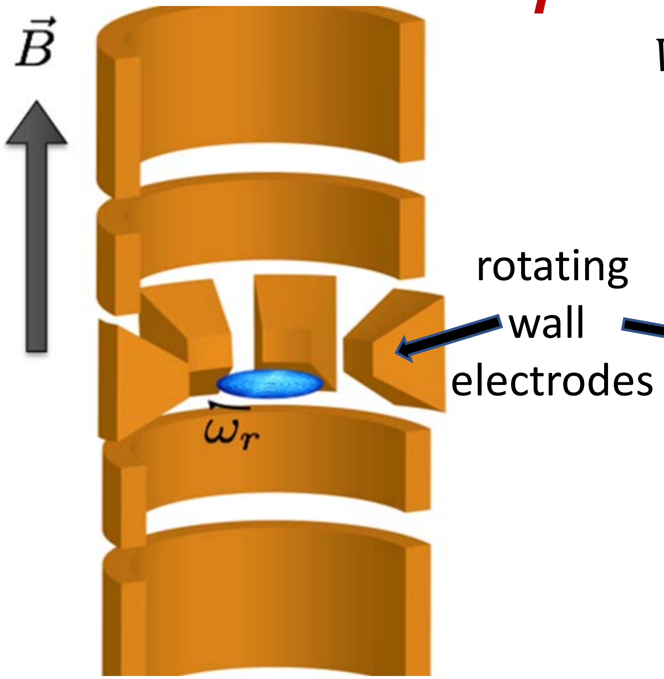
observed with:

Bragg scattering

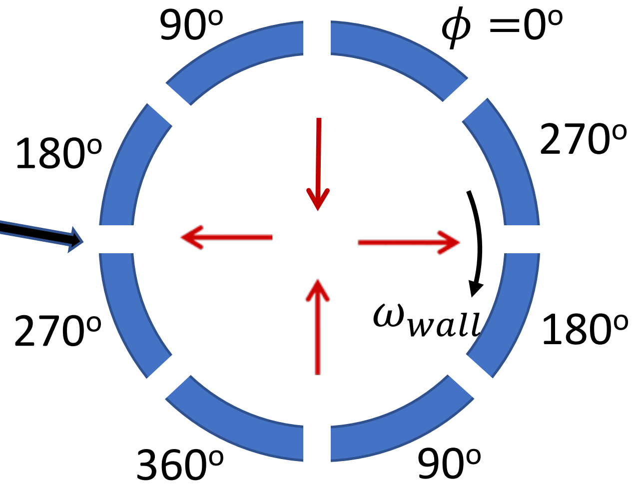
ion fluorescence imaging



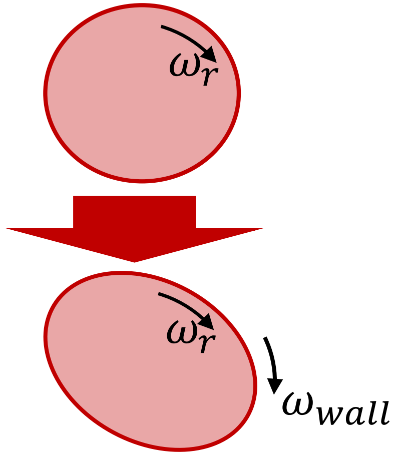
Precise ω_r control with a rotating electric field



$V_{sector} = V_{Wall}\, sin(\omega_{drive} t + \phi)$



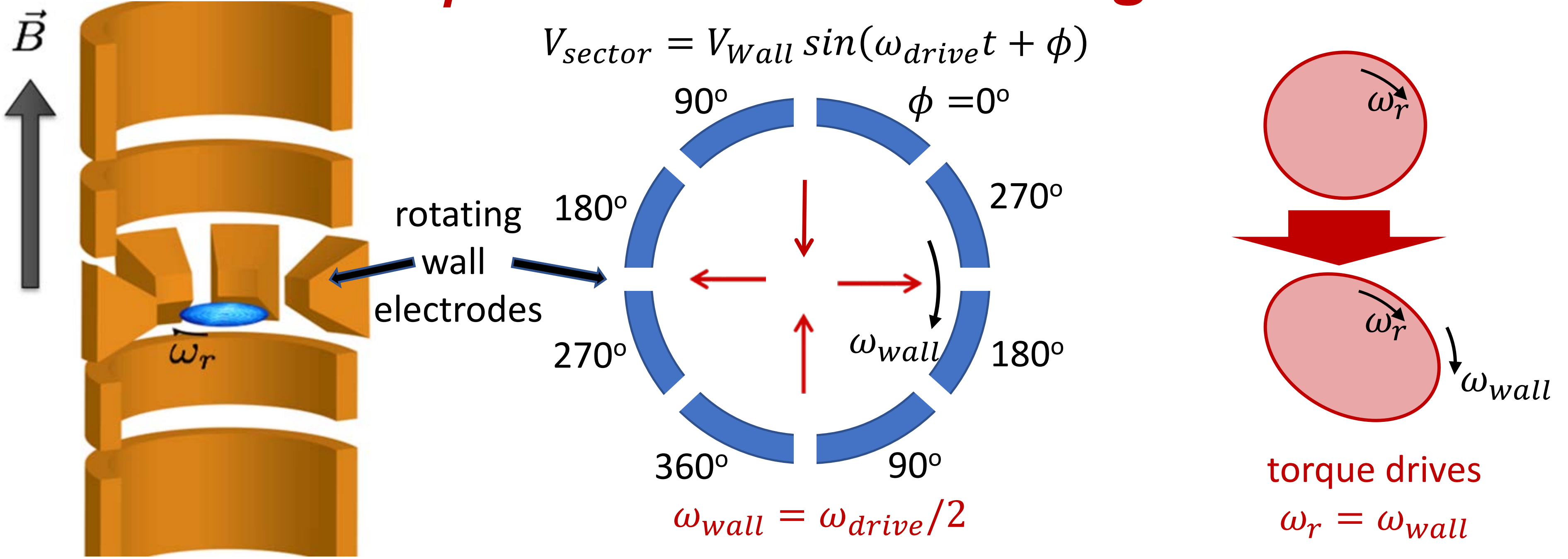
$\omega_{wall} = \omega_{drive}/2$

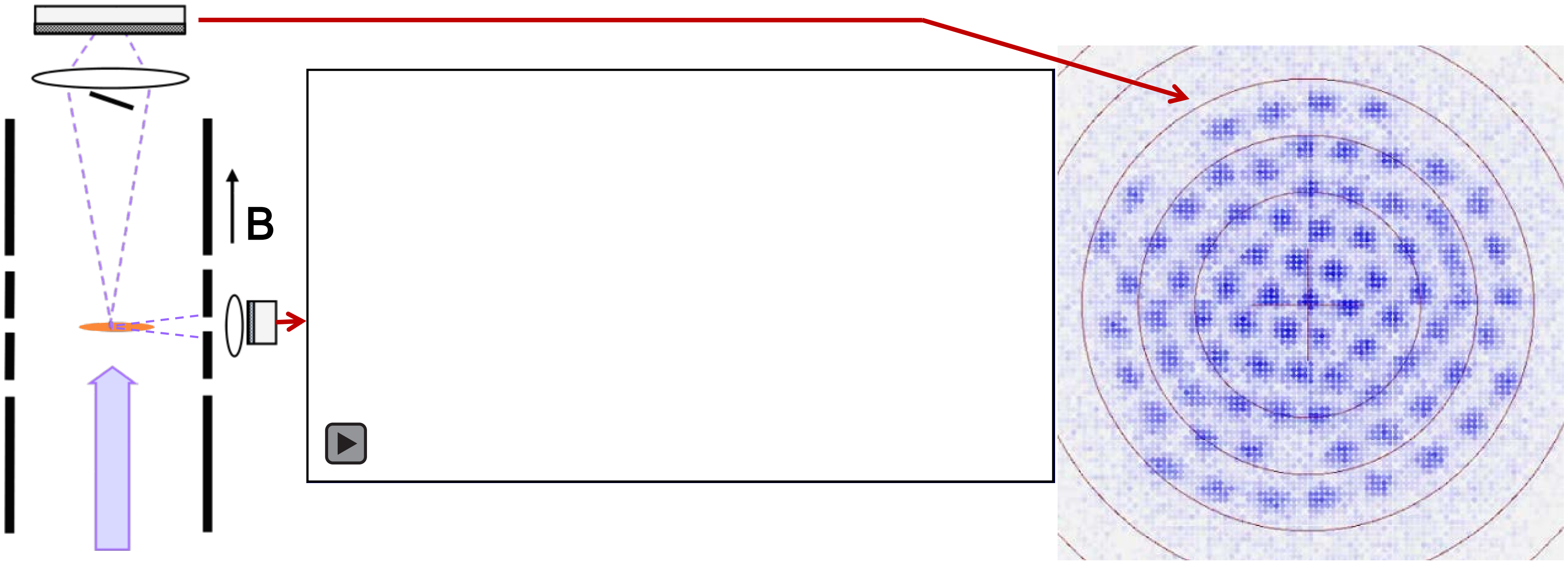


torque drives
$\omega_r = \omega_{wall}$

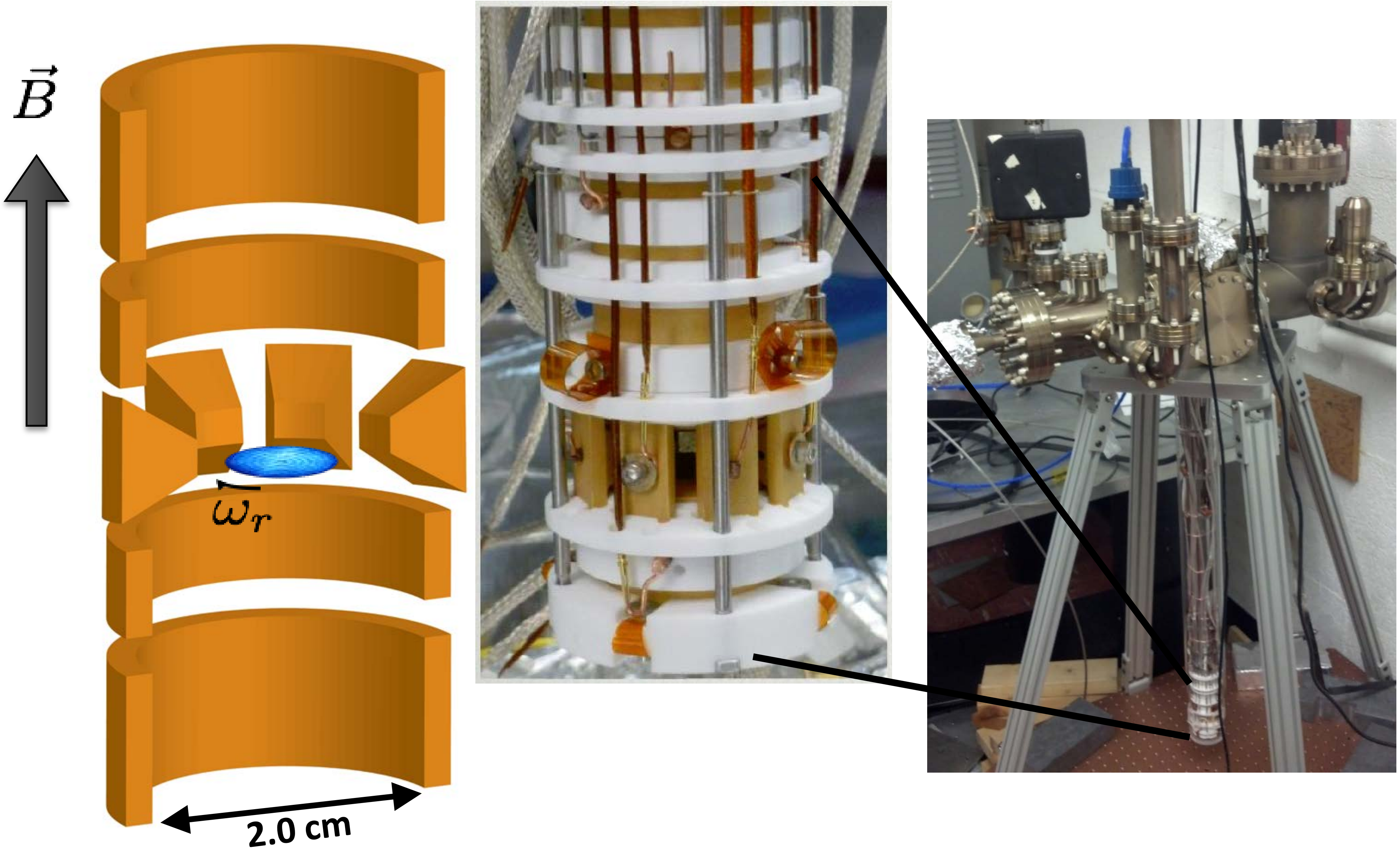
rotating wall potential simulation

Precise ω_r control with a rotating electric field





NIST Penning trap



$^9Be^+$, $B_0 = 4.5$ T, $\frac{\Omega_c}{2\pi} \sim 7.6$ MHz, $\frac{\omega_z}{2\pi} \sim 1.6$ MHz, $\frac{\omega_m}{2\pi} \sim 160$ kHz

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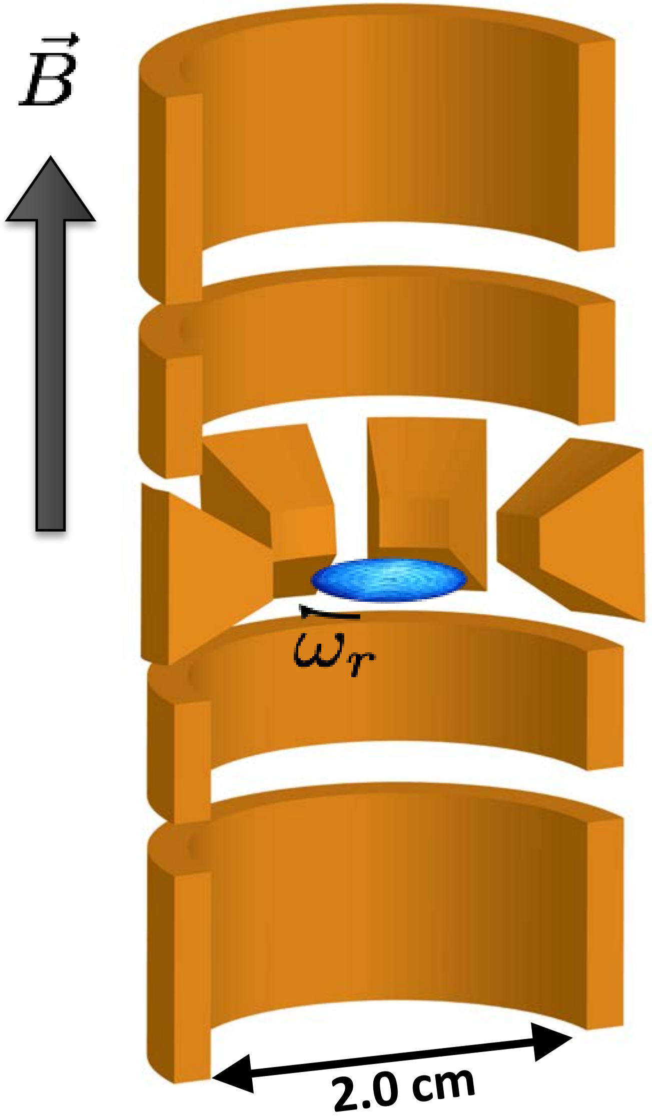
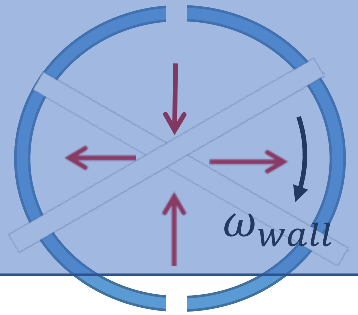


4.5 Tesla superconducting solenoid

1. Quantum simulation with 2d ion arrays in a Penning trap

- ion crystals in Penning traps

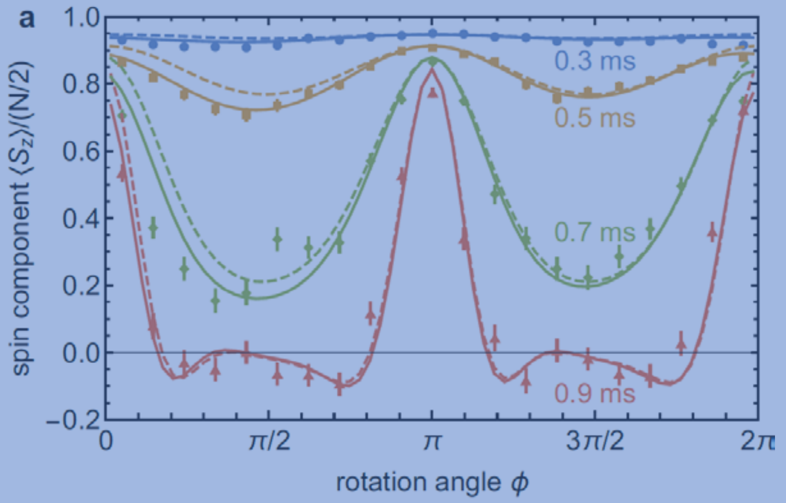


- - high magnetic field qubit
  - modes

- engineering tunable Ising dynamics

$$H_{Ising} = \frac{1}{N} \sum_{i<j} J_{i,j} \sigma_i^z \sigma_j^z$$

- benchmark quantum dynamics, entanglement
  - -spin squeezing
  - - out-of-time correlations (OTOC)

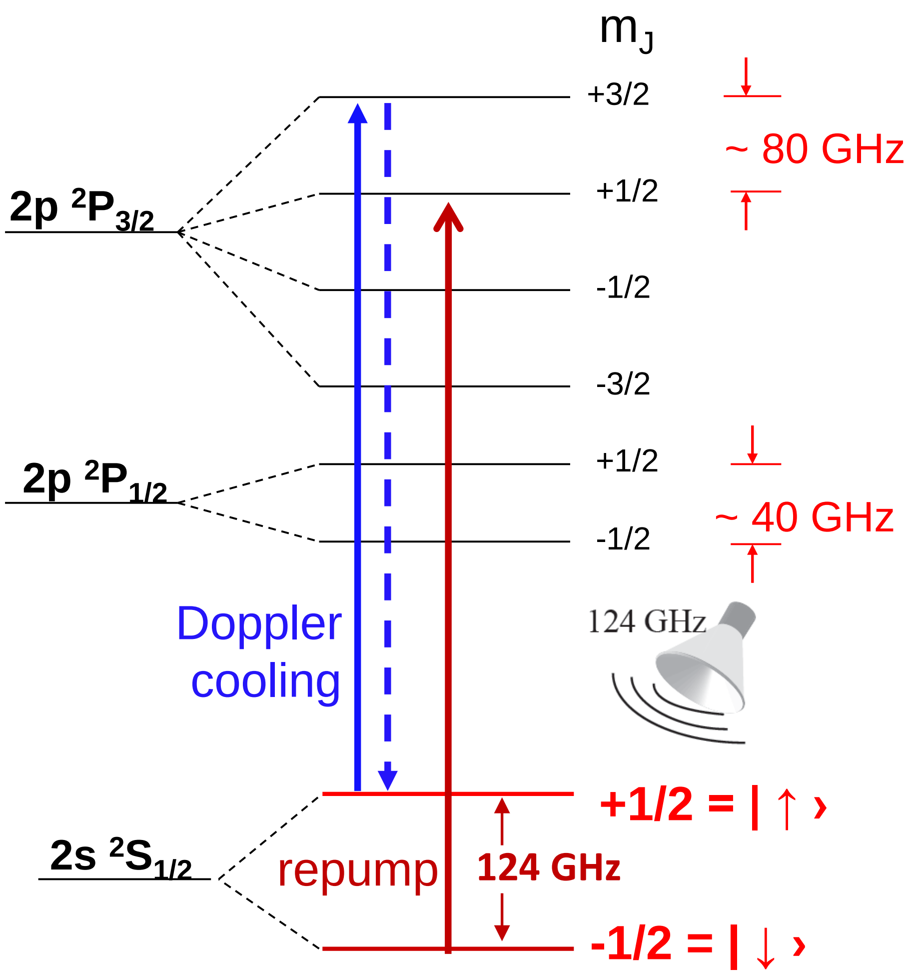


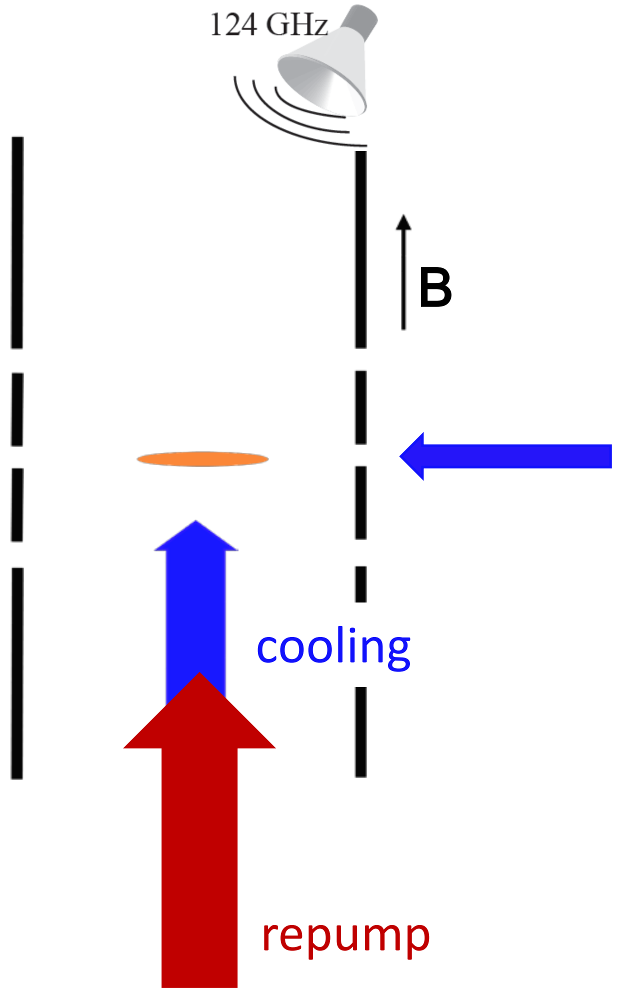
Be^+ high magnetic field qubit

$^9Be^+$, B ~ 4.5 T, $\omega_o/2\pi$ ~124.1 GHz

$$H_{\mu W} = \sum_i B_\perp \hat{\sigma}_i^x ,$$

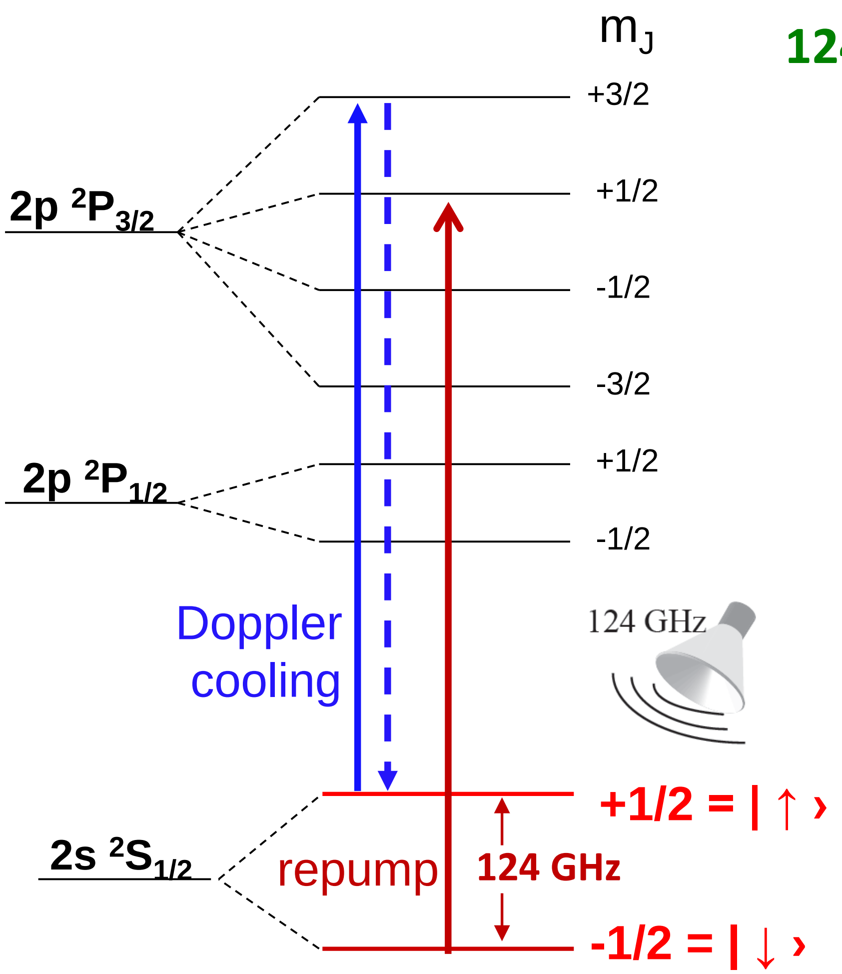
$$B_\perp > 10 - 15\,\text{kHz}$$



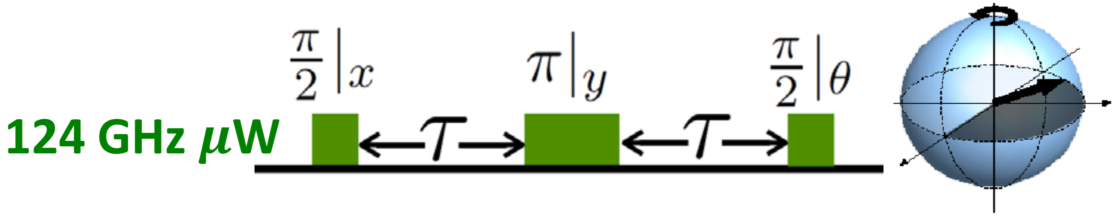


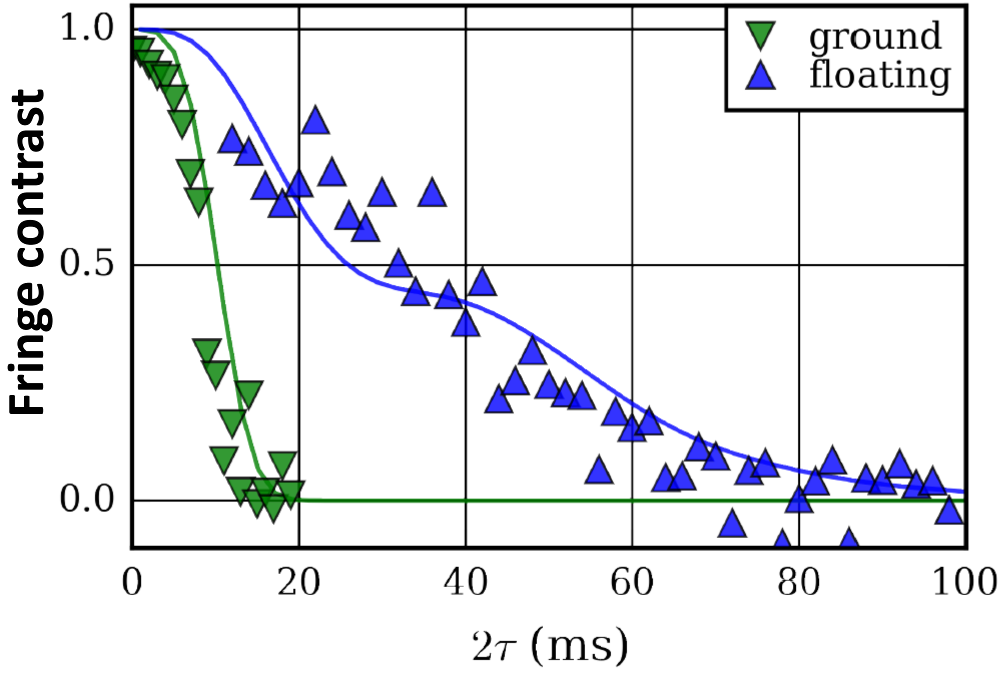
Be+ high magnetic field qubit

$^9Be^+$, B ~ 4.5 T, ω_o /2π ~124.1 GHz



T2 coherence

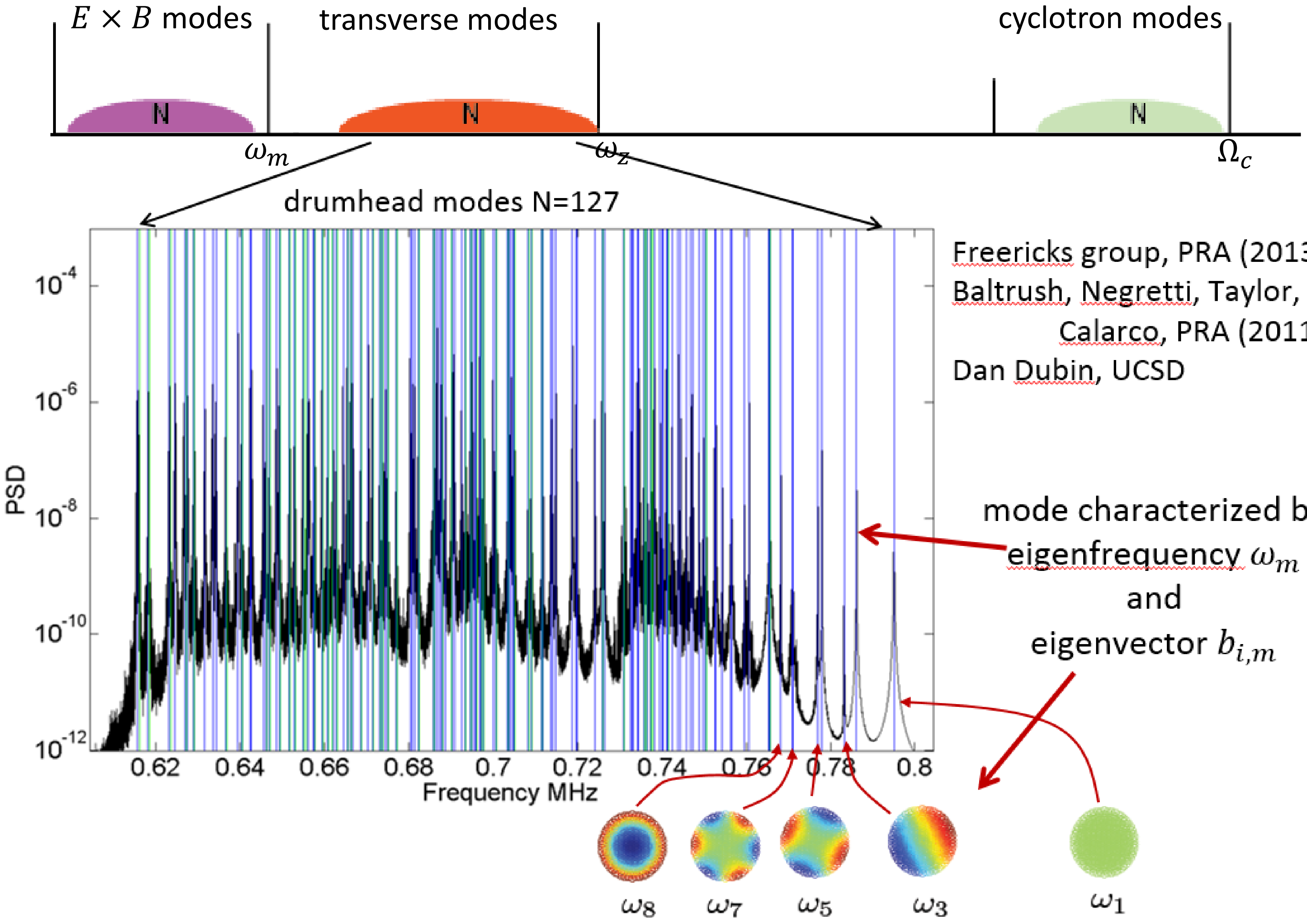




Spin-echo precession time →

Britton et al., PRA (2016)
arXiv_1512.00801

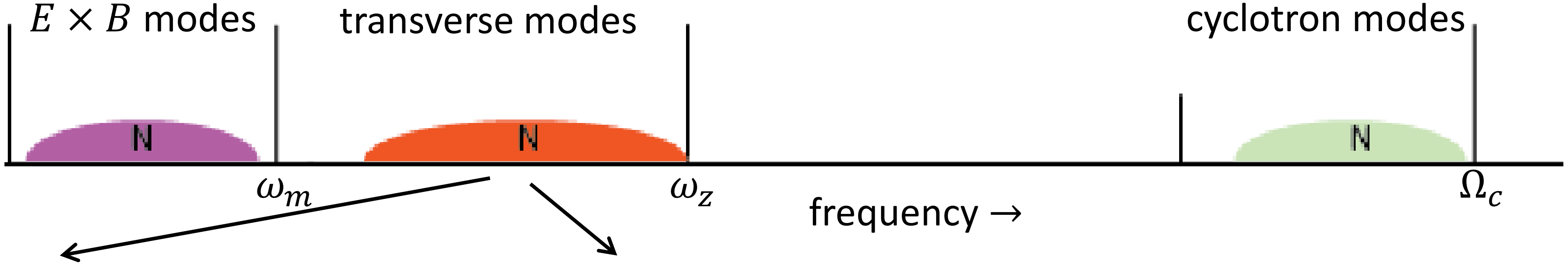
Transverse (drumhead) modes

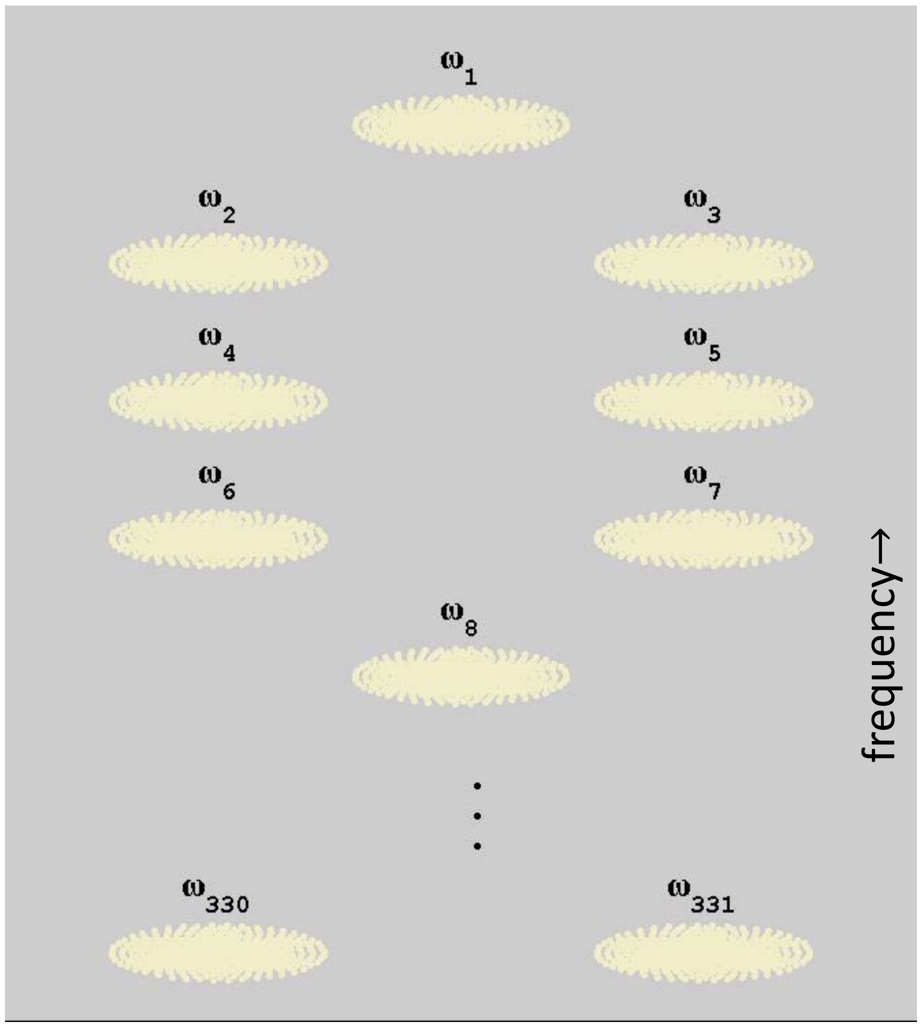


Freericks group, PRA (2013)
Baltrush, Negretti, Taylor, Calarco, PRA (2011)
Dan Dubin, UCSD

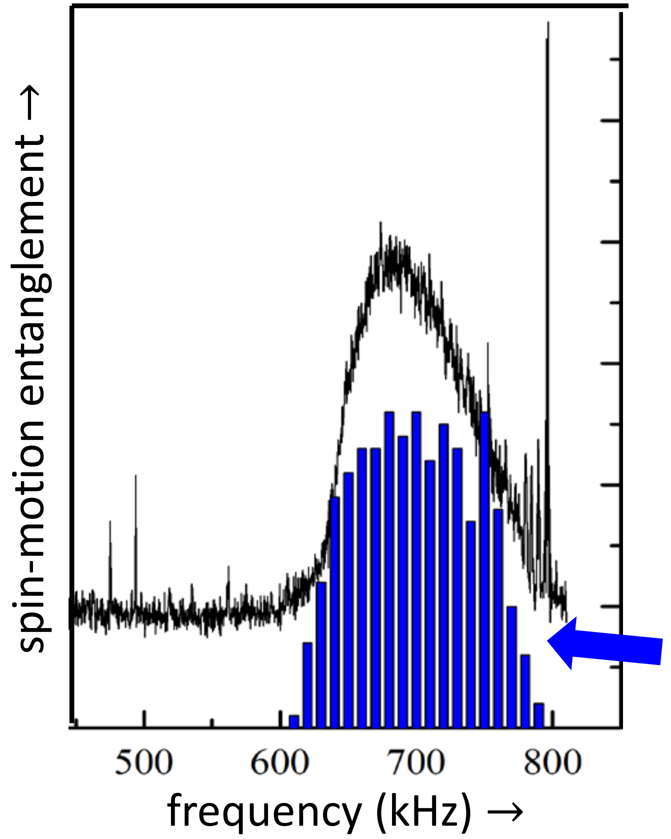
mode characterized by eigenfrequency ω_m
and
eigenvector $b_{i,m}$

Transverse (drumhead) modes





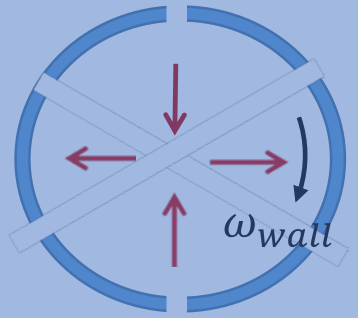
Sawyer, et al., PRL 108, (2012)
Sawyer, et al., PRA 89, (2014)



theory histogram of drumhead modes

1. Quantum simulation with 2d ion arrays in a Penning trap

- ion crystals in Penning traps



- - high magnetic field qubit
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- engineering tunable Ising dynamics

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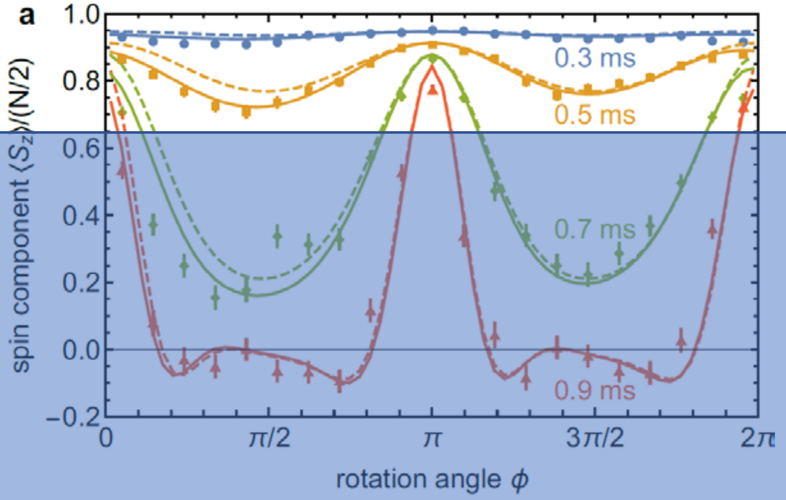
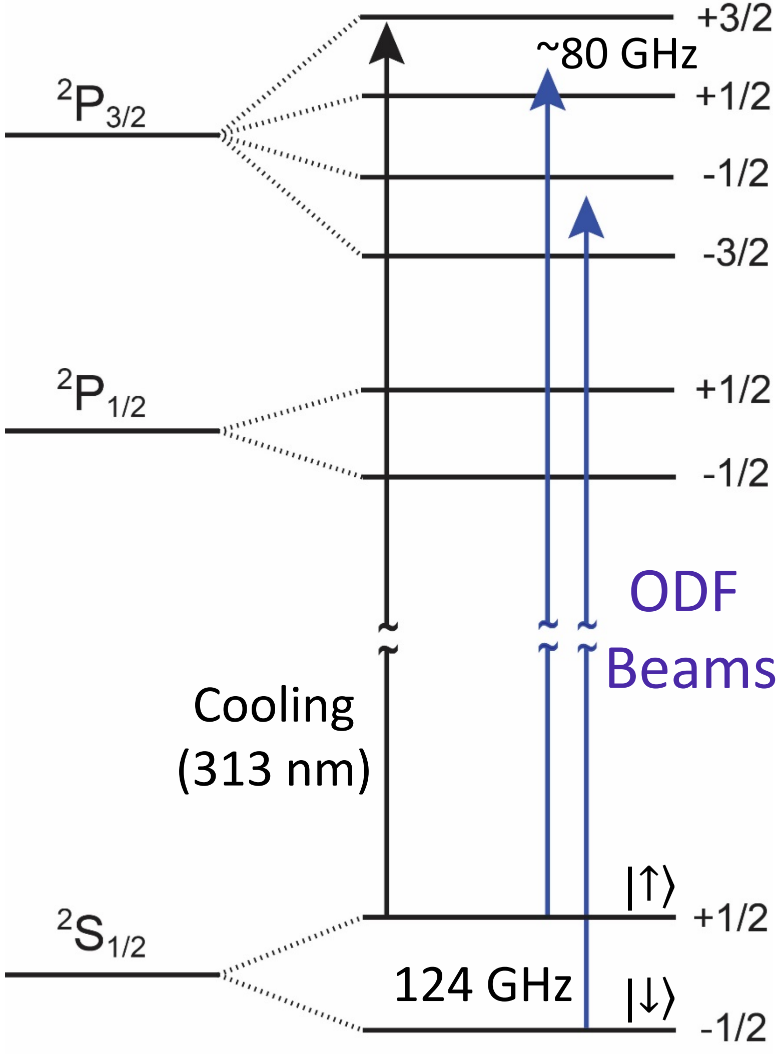
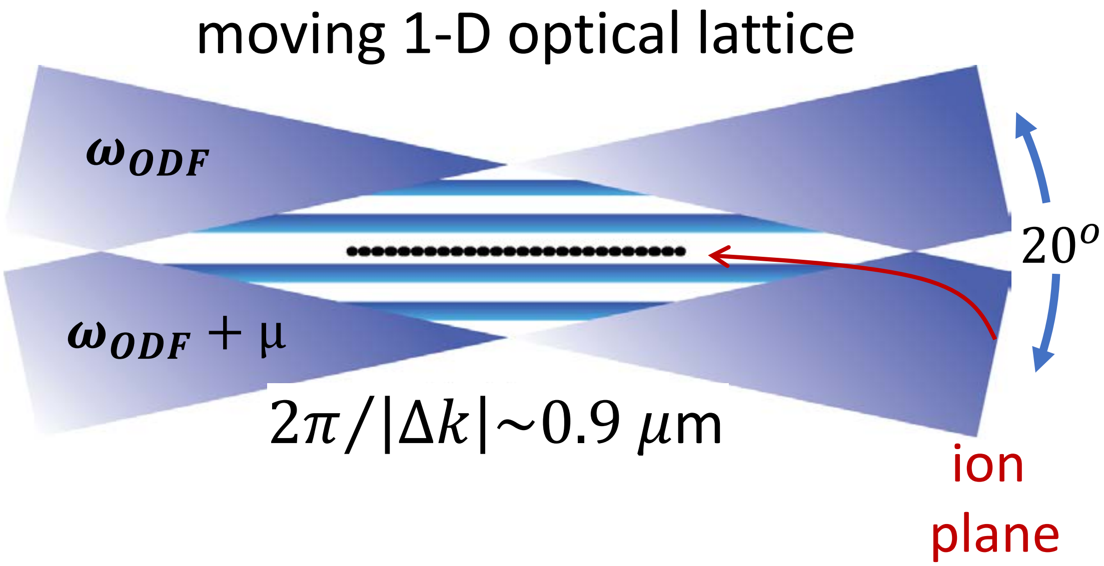


- benchmark quantum dynamics, entanglement
  - -spin squeezing
  - - out-of-time correlations (OTOC)

Engineering quantum magnetic couplings with spin-dependent forces





- $F_\uparrow(t) = -F_\downarrow(t)$
  $F_\uparrow(t) = F_0 \cos(\mu t)$
- alignment of 1D lattice and ion plane

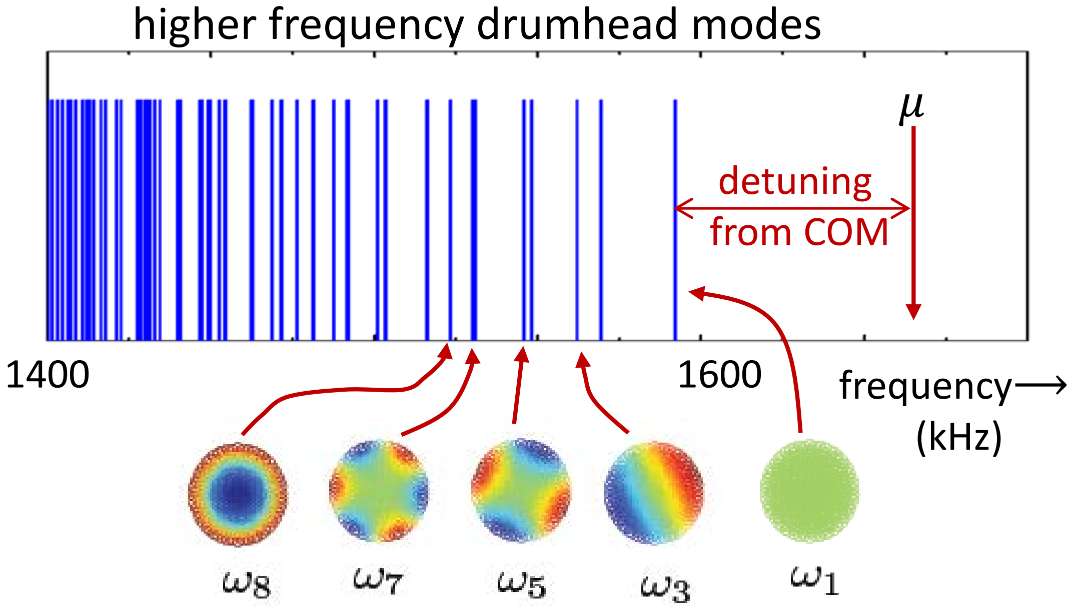
Leibfried et al., Nature **422**, (2003) - Sorensen and Molmer, PRL (1999) quantum gates through spin-dependent forces with small numbers of ion in rf traps

Engineering quantum magnetic couplings

$$\hat{H}_{ODF}(t) = -F_0 \cos(\mu t) \sum_{j=1}^{N} \hat{z}_j \cdot \hat{\sigma}_j^z =$$

$$\hat{z}_j = \sum_{m=1}^{N} b_{jm} \sqrt{\frac{\hbar}{2M\omega_m}} \left(\hat{a}_m^\dagger e^{i\omega_m t} + \hat{a}_m e^{-i\omega_m t} \right)$$

N drumhead eigenvalues ω_m and eigenvector $\vec{b}_m$



$$\hat{U}_{ODF} = \hat{U}_{SP}(t) \cdot \hat{U}_{SS}(t)$$

Produces spin-phonon coupling

- useful metrology tool
- source of decoherence

dominant for large $|\mu - \omega_m|$

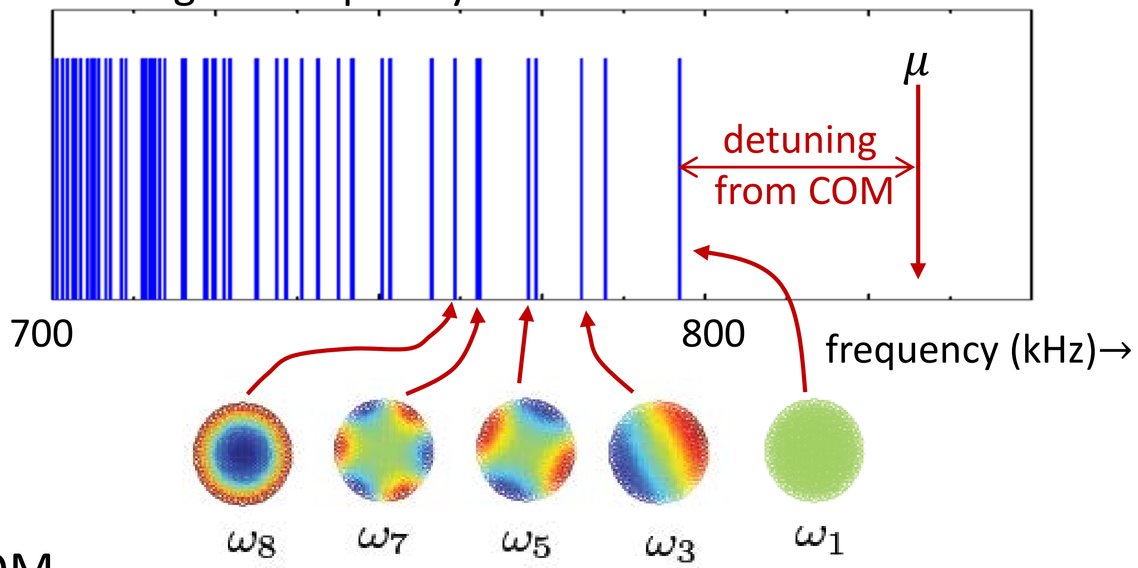
$$\hat{U}_{SS}(t) = \exp\left[-i \frac{1}{N} \sum_{i<j} J_{i,j} \sigma_i^z \sigma_j^z \right]$$

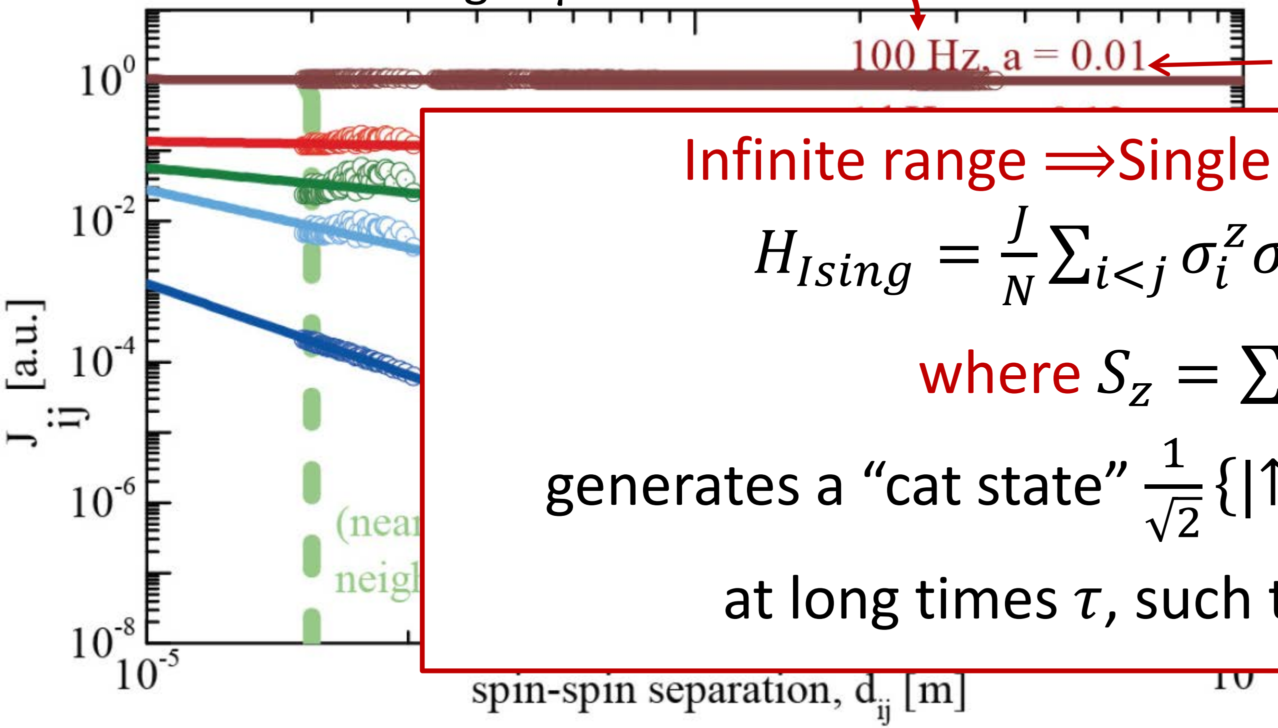
$$J_{i,j} \approx \frac{F_0^2 N}{2\hbar M} \sum_m \frac{b_{im} b_{jm}}{\mu^2 - \omega_m^2}$$

Ising coupling coefficients determined by transverse modes

$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z,$$

$$J_{i,j} = \frac{F_0^2 N}{\hbar\cdot 2M}\sum_{m=1}^{N}\frac{b_{i,m}b_{j,m}}{\mu^2-\omega_m^2}$$





Infinite range ⟹Single axis twisting

$$H_{Ising} = \frac{J}{N}\sum_{i<j}\sigma_i^z\sigma_j^z = \frac{2J}{N}S_z^2$$

where $S_z = \sum_i \frac{\sigma_i^z}{2}$

generates a “cat state” $\frac{1}{\sqrt{2}}\{|\uparrow\uparrow\uparrow\cdots\uparrow\rangle + |\downarrow\downarrow\downarrow\cdots\downarrow\rangle\}$

at long times τ, such that $\frac{2J}{N}\tau = \frac{\pi}{2}$

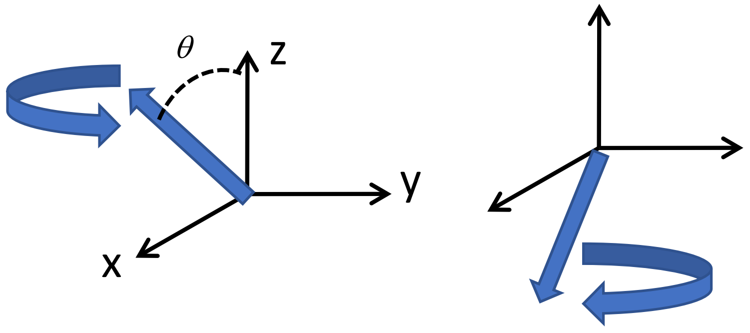
Mean field dynamics: Simple spin precession

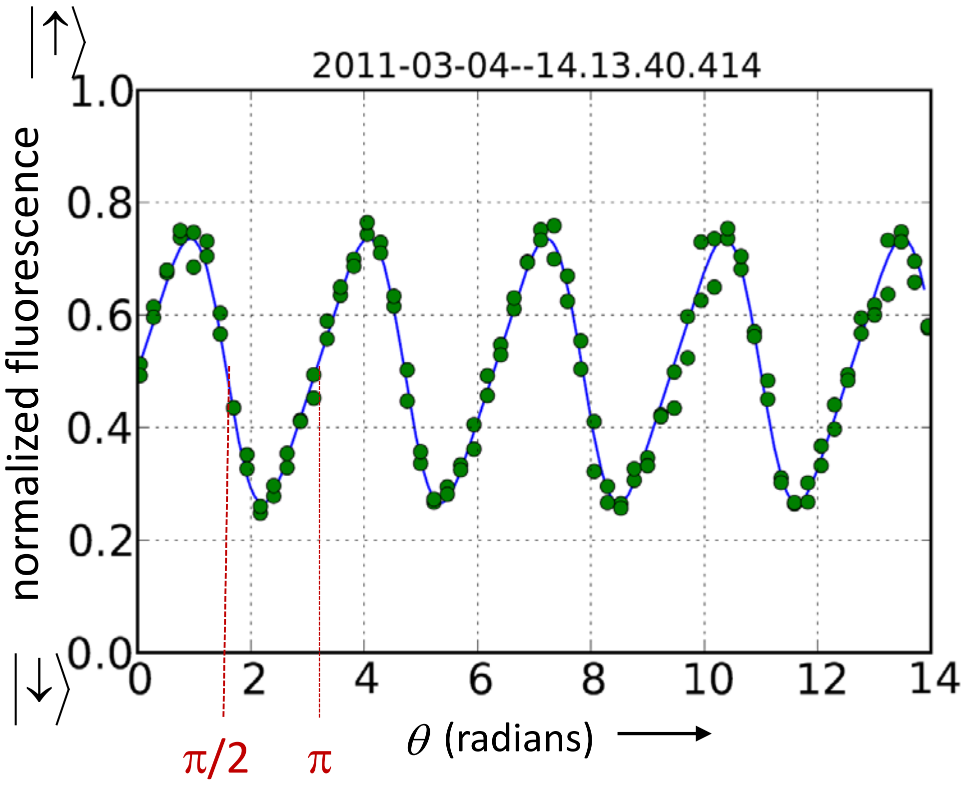
$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

mean field limit

$$H_{\text{Ising}}^{MF} = \sum_j \overline{B}_j\,\sigma_j^z/2,$$

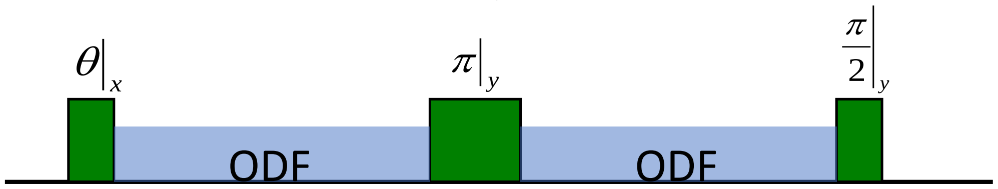
$$\overline{B}_j = \frac{2}{N}\sum_{i,i\neq j} J_{i,j}\langle\sigma_i^z\rangle = \frac{2}{N}\left(\sum_{i,i\neq j} J_{i,j}\right)\cos(\theta)$$





Measure $\overline{J} \equiv \frac{1}{N^2}\sum_{i\neq j} J_{i,j}$ with spin-echo

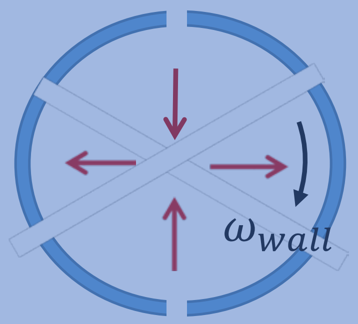
$$\overline{J}\Big/(\hbar 2\pi) \approx 2-4\ \text{kHz}$$



prepare $|\uparrow\rangle$ detect $|\uparrow\rangle$

1. Quantum simulation with 2d ion arrays in a Penning trap

- ion crystals in Penning traps

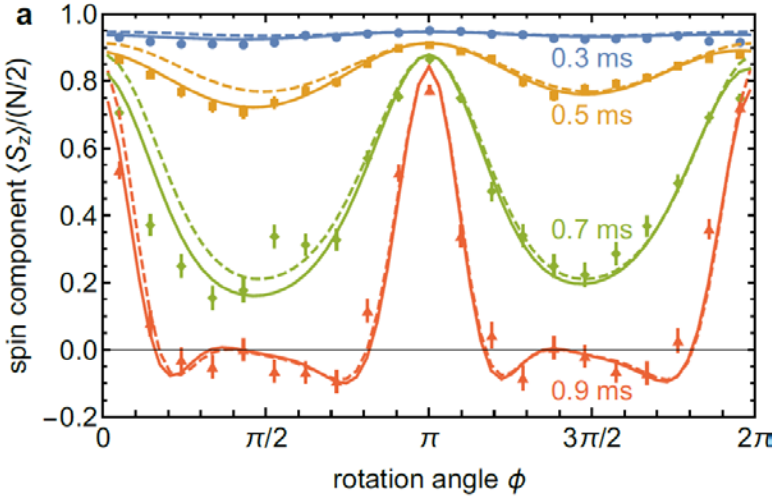


- - high magnetic field qubit
  - modes

- engineering tunable Ising dynamics

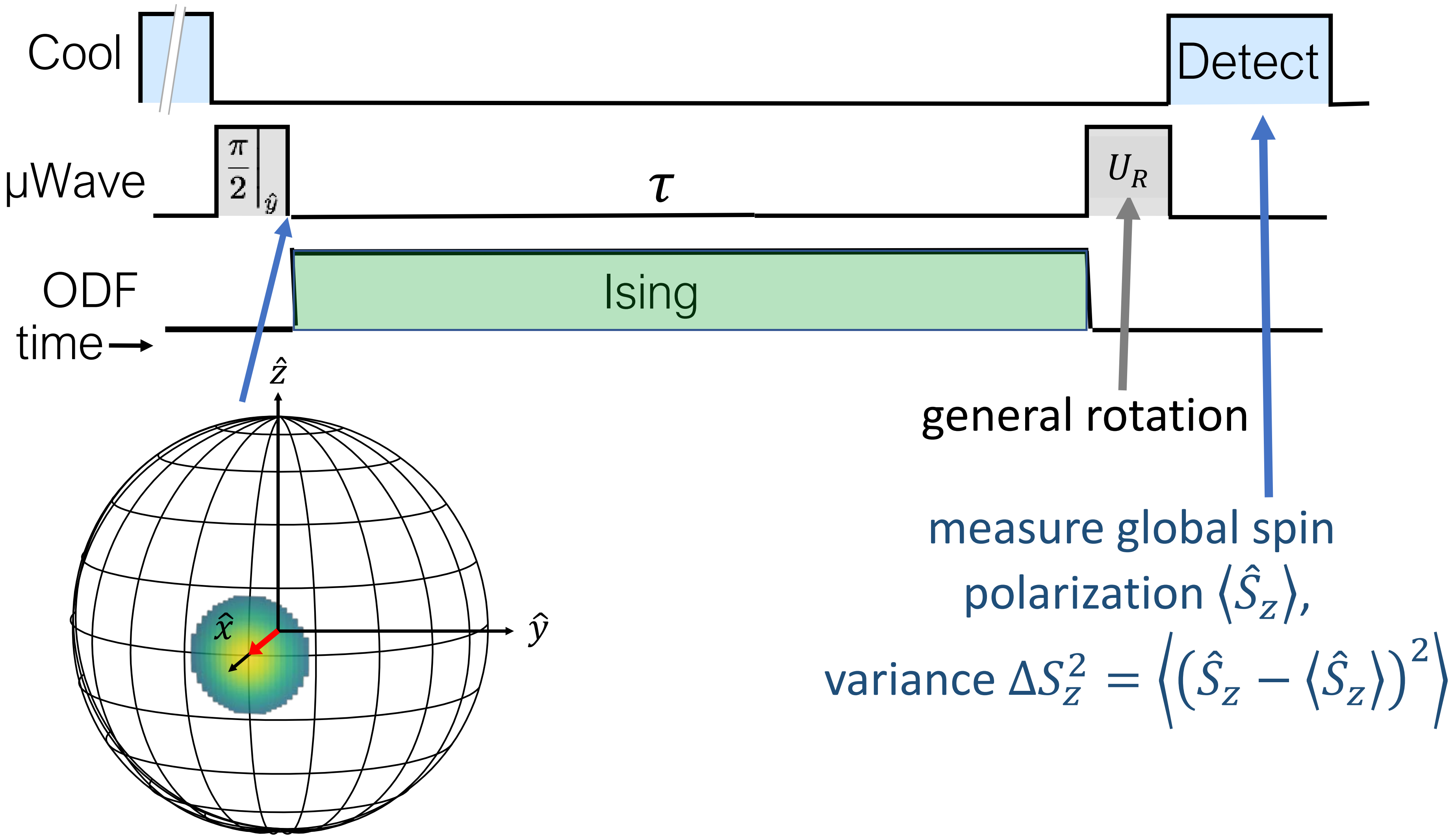
$$H_{Ising} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

- benchmark quantum dynamics, entanglement
  - -spin squeezing
  - - out-of-time correlations (OTOC)



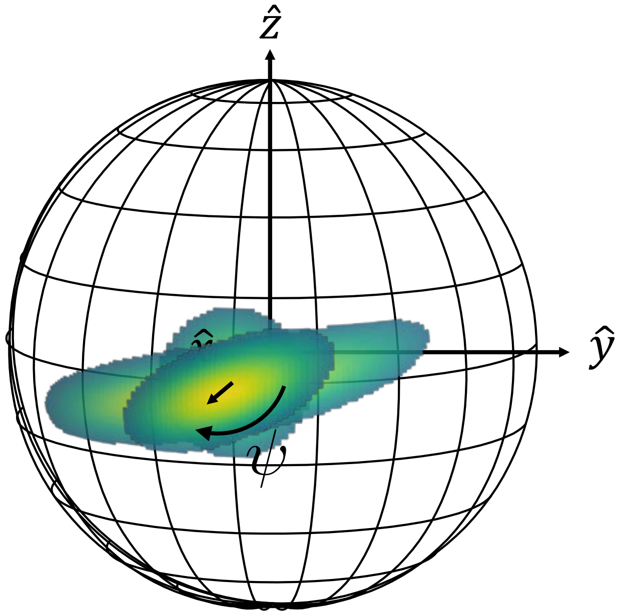
Benchmarking quantum dynamics

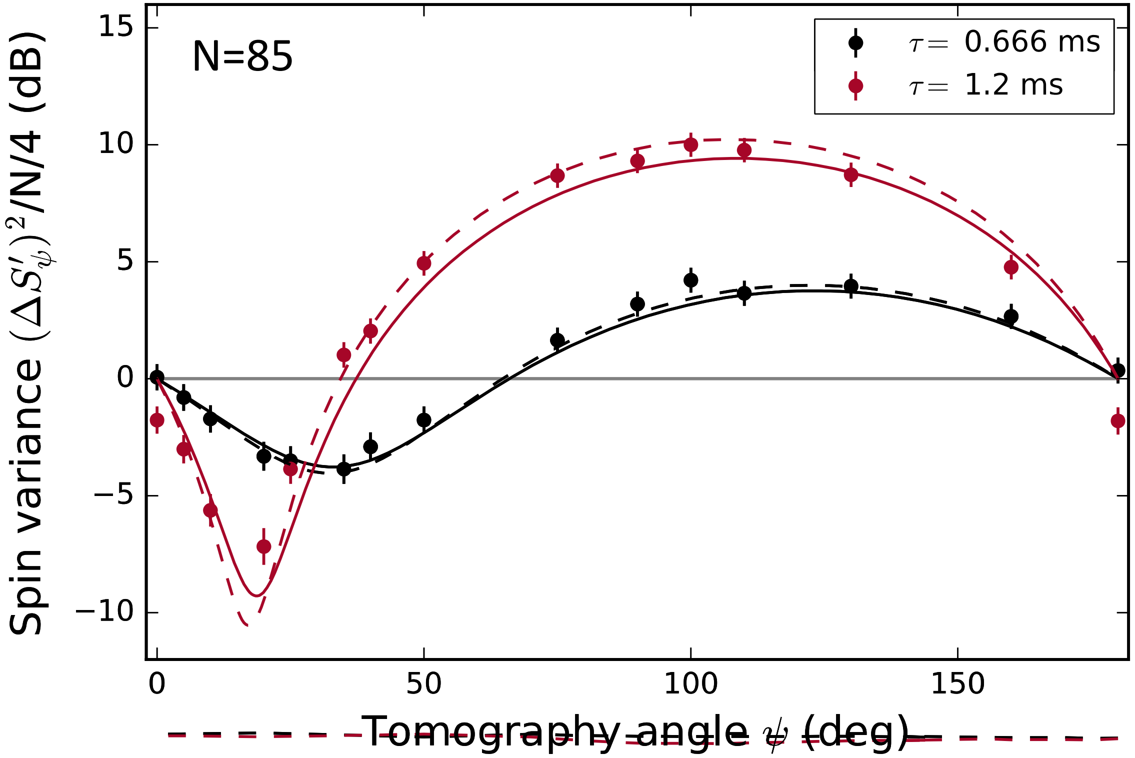
- employ infinite range interactions $H_{Ising} \approx \frac{2J}{N} S_z^2, S_z \equiv \sum_i \sigma_i^z /2$
- prepare eigenstate of $H_\perp = \sum_i B_\perp \hat{\sigma}_i^x$, turn on H_{Ising}



Benchmarking quantum dynamics

Bohnet *et al.*, *Science* 352, 1297 (2016)

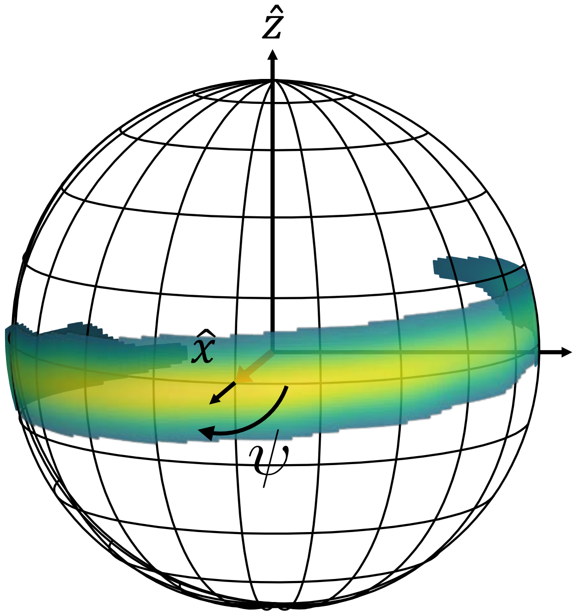


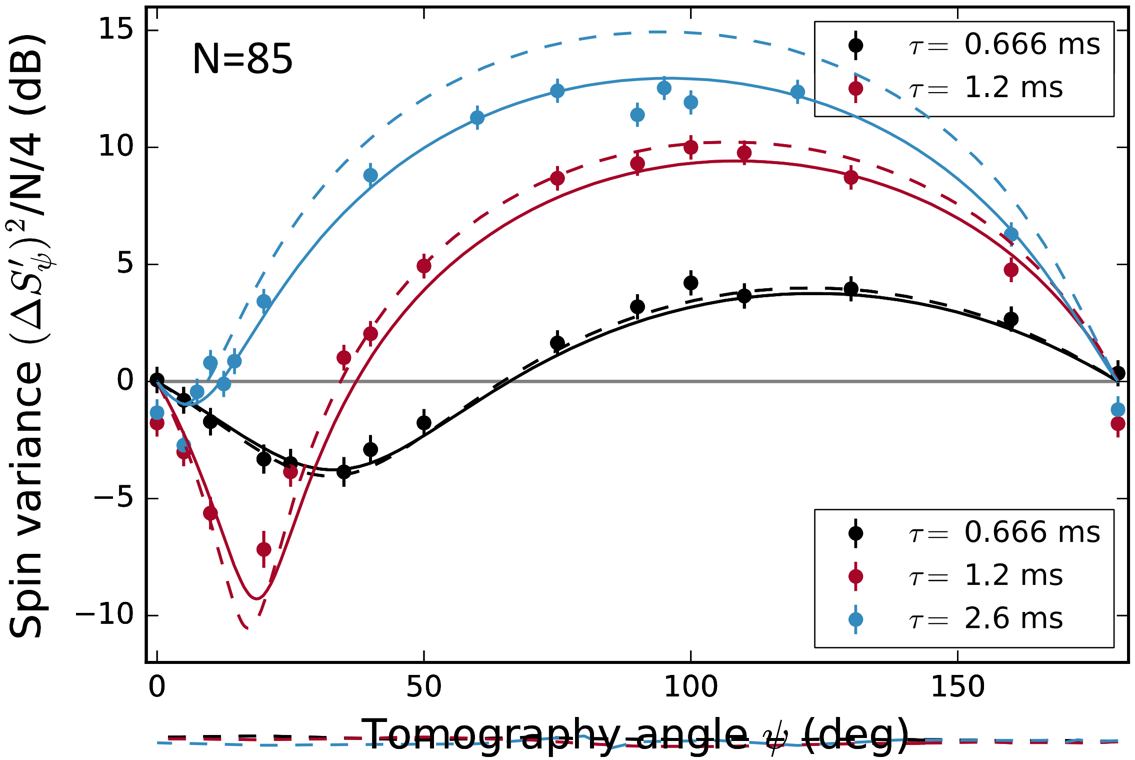


- Measurements of Ramsey squeezing parameter $\Rightarrow$ prove entanglement for $25 < N < 220$
- Largest inferred squeezing: -6.0 dB

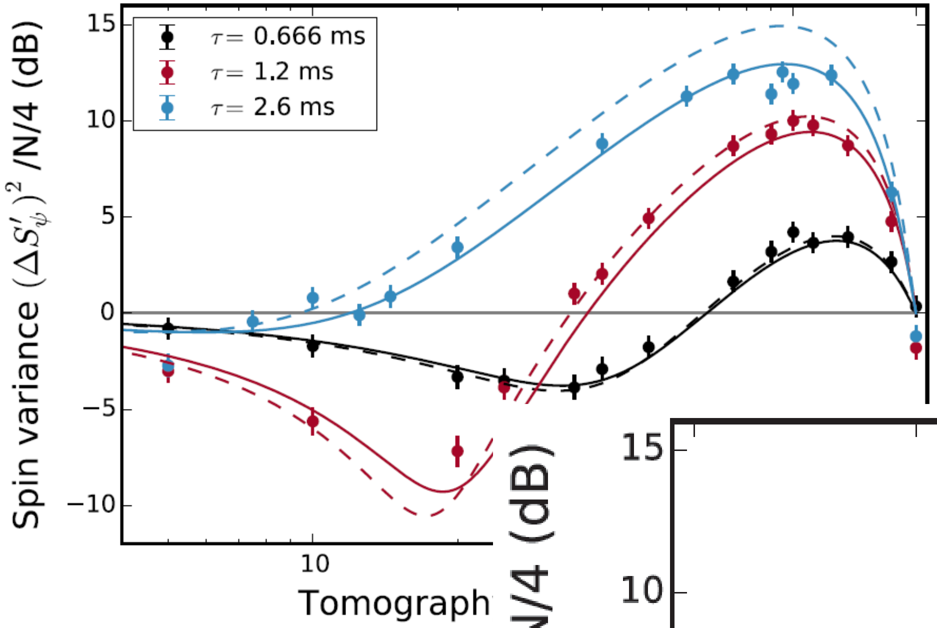
Benchmarking quantum dynamics

Bohnet *et al.*, *Science* 352, 1297 (2016)



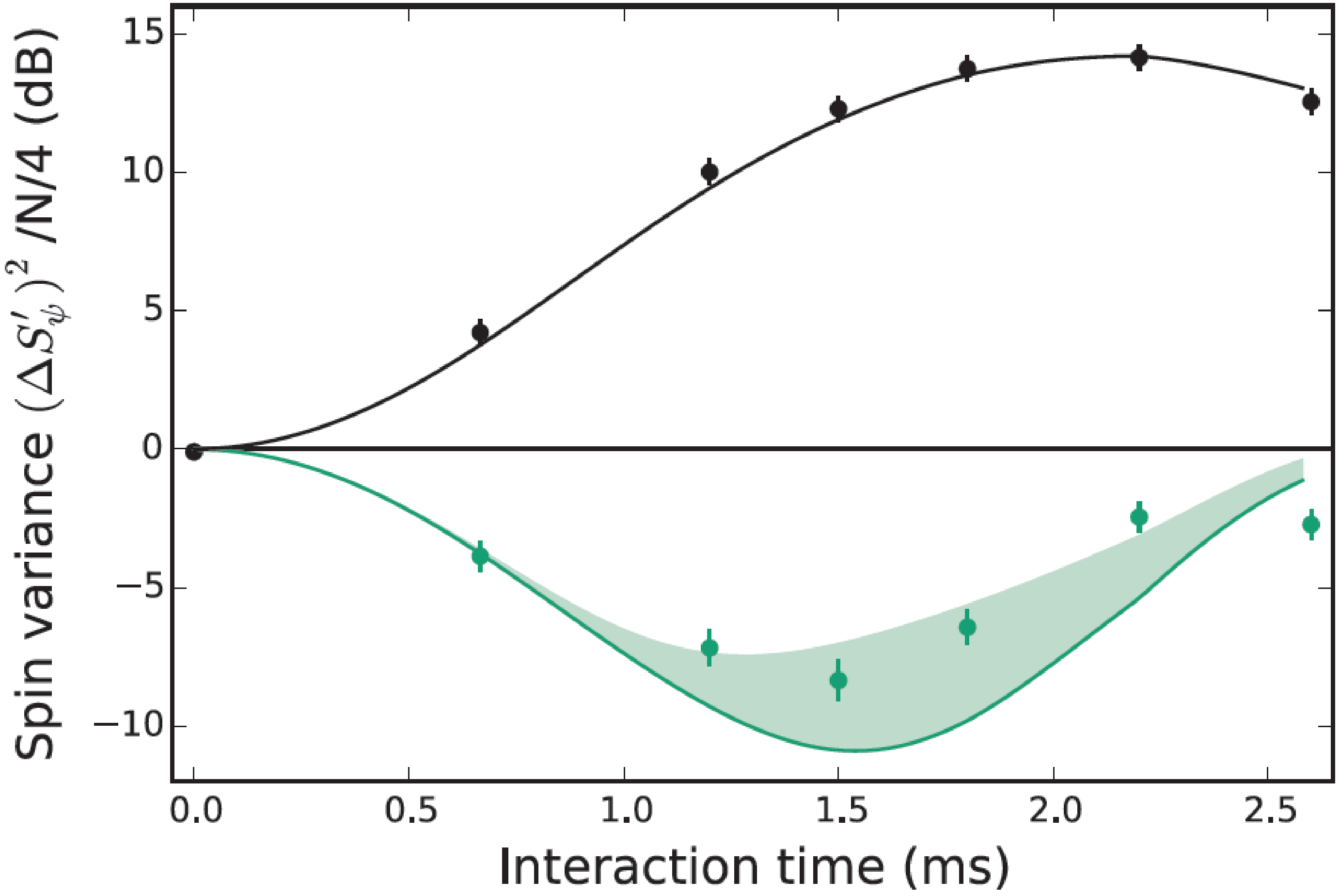


Benchmarking quantum dynamics



N = 86

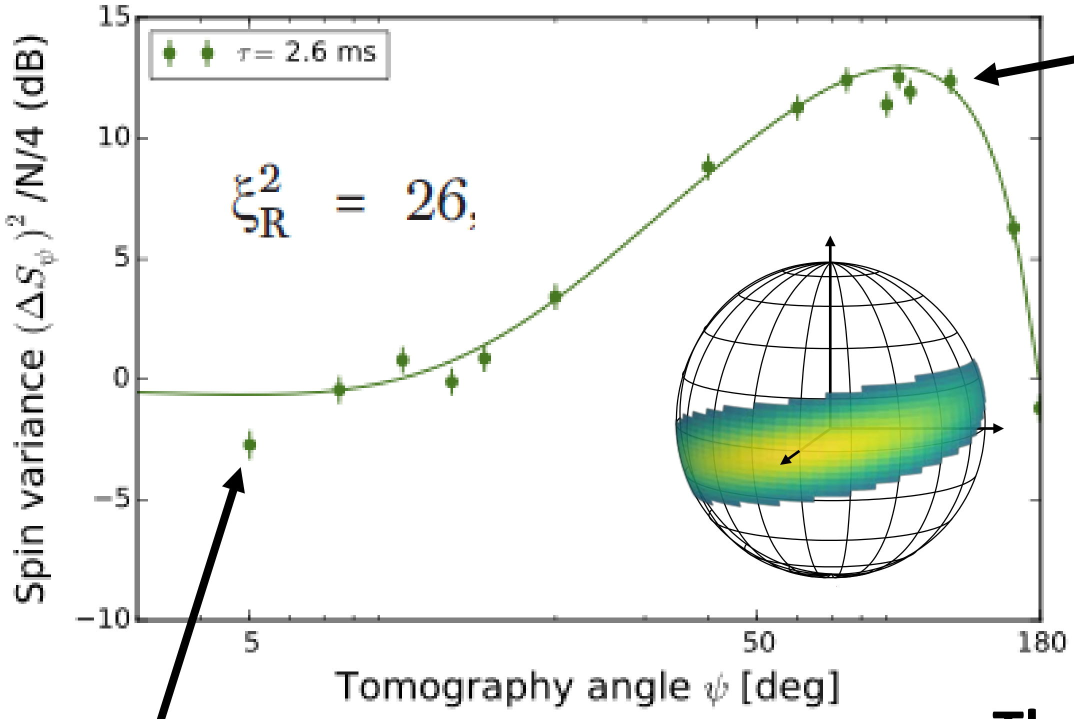
Time dependence of squeezed and anti-squeezed variance

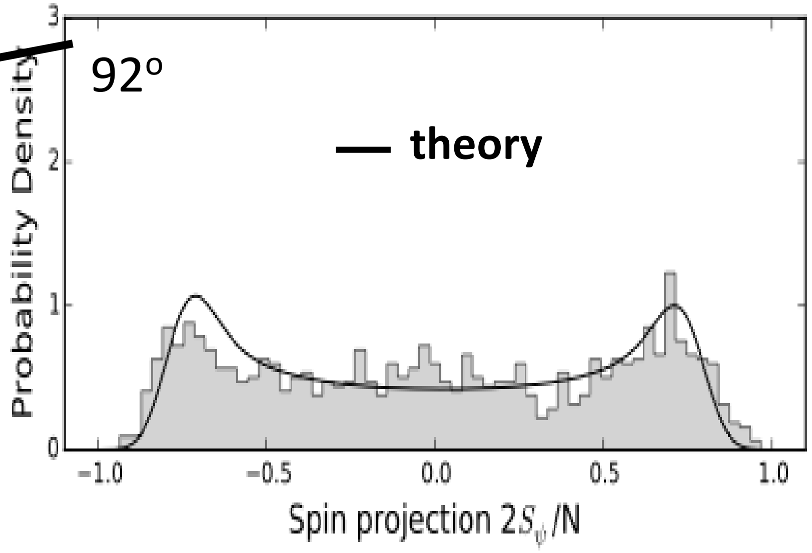


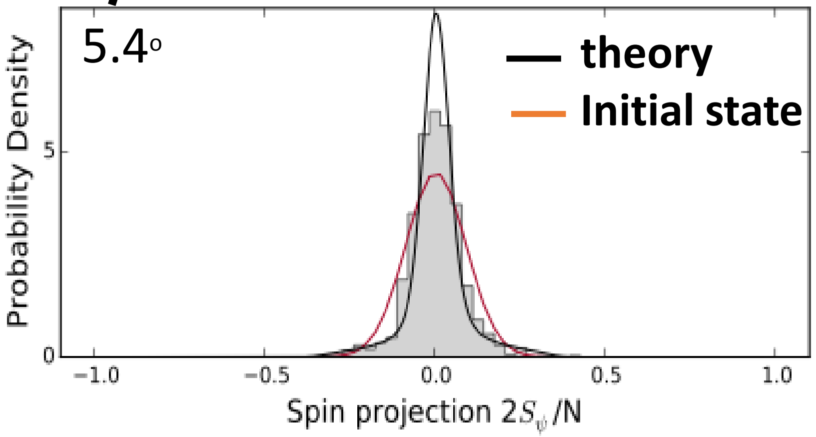
Bohnet *et al.*, Science352 (2016)

Over-squeezed states: benchmark via full counting statistics

N=127 $\pm$ 4







Theory: need to compute N-point correlations:

$$\langle \sigma_1^+ \sigma_2^+ \sigma_3^+ \cdots \sigma_n^+ \sigma_{n+1}^- \cdots \sigma_N^- \rangle$$

M. Wall (Rey group)

Out-of-time-order correlation functions

$$F(t) \equiv \langle\psi|W(t)^\dagger V^\dagger W(t)V|\psi\rangle \text{ where } \mathrm{W(t)} = \mathrm{e}^{iHt}W(0)e^{-iHt},$$

$$[V, W(0)] = 0$$

$$Re[F(t)] = 1 - \langle|[W(t), V]|^2\rangle/2$$

⇒ **measures failure of initially commuting operators to commute at later times**

⇒ **quantifies spread or scrambling of quantum information across a system's degrees of freedom**

Swingle et al., arXiv:1602.06271; Shenker et al., arXiv:1306.0622; Kitaev (2014)

Difficult to measure ⟺ possible with time-reversal of dynamics

time reversal is possible in many quantum simulators!

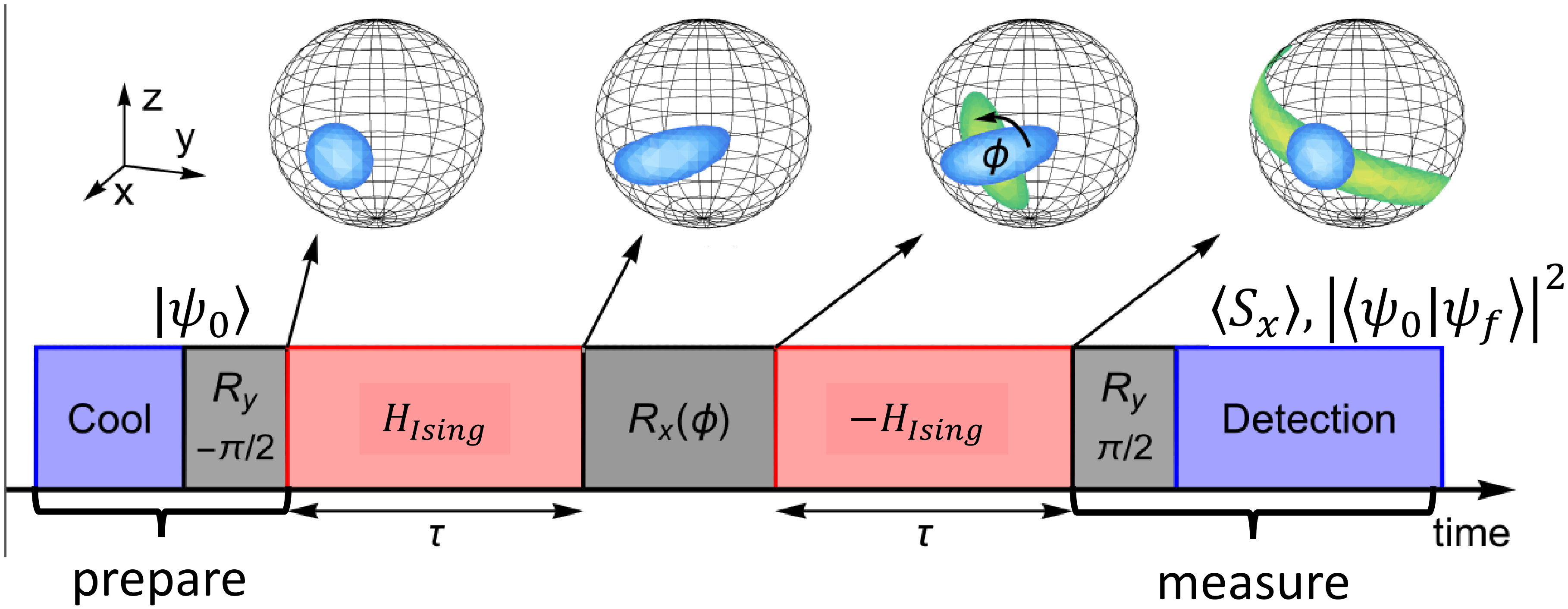
Time reversal of the Ising dynamics

$$H_{Ising} = \frac{J}{N}\sum_{i<j} \hat{\sigma}_i^z \hat{\sigma}_j^z, \ \frac{J}{N} \cong \frac{F_0^2}{\hbar 4 m \omega_z} \cdot \frac{1}{\mu - \omega_z}$$

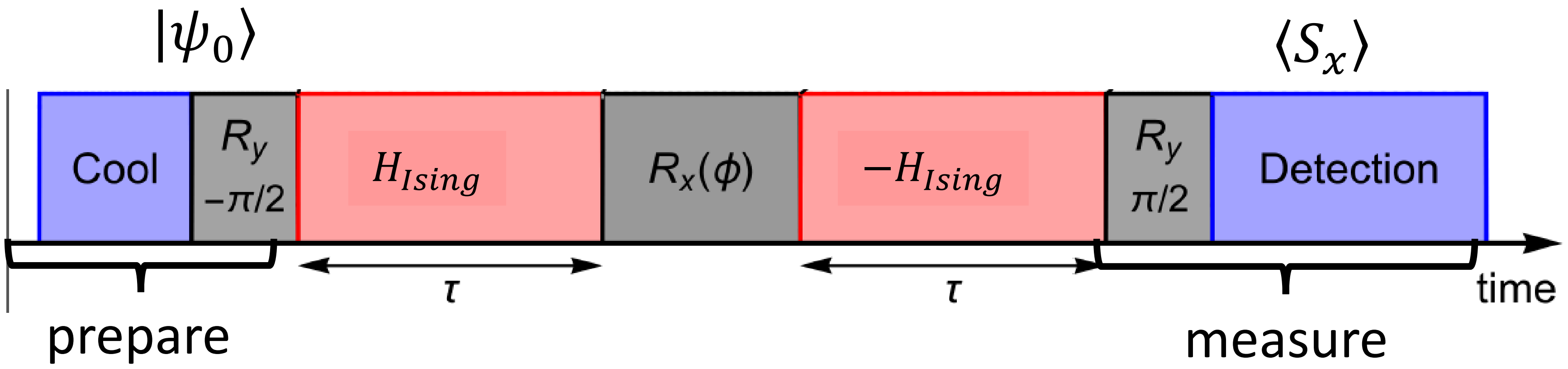
Change $\mu = \omega_z + \delta$ (antiferromagnetic)
to $\mu = \omega_z - \delta$ (ferromagnetic)

Multiple quantum coherence protocol

- Probe higher-order coherences and correlations (Pines group, 1985)



Multiple quantum coherence protocol



$$\langle S_x \rangle = \langle \Psi_0 | \, e^{iH_{Ising}\tau} \, e^{i\phi S_x} \, e^{-iH_{Ising}\tau} S_x \, e^{iH_{Ising}\tau} \, e^{-i\phi S_x} \, e^{-iH_{Ising}\tau} | \Psi_0 \rangle$$

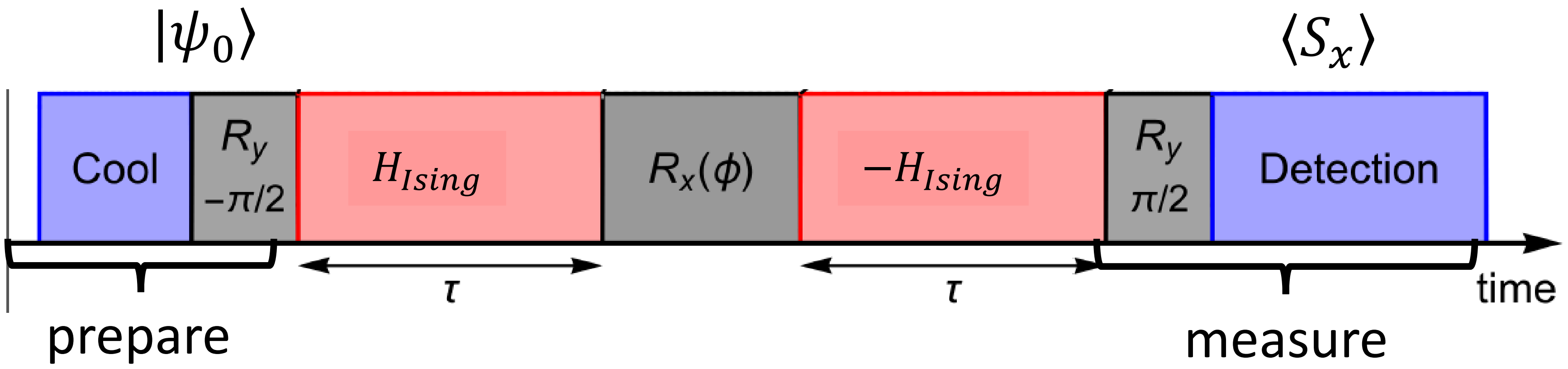
$$= \frac{2}{N} \langle \Psi_0 | \, \underbrace{e^{iH_{Ising}\tau} \, W^\dagger \, e^{-iH_{Ising}\tau}}_{W^\dagger(t)} \underbrace{V^\dagger}_{V^\dagger(0)} \, \underbrace{e^{iH_{Ising}\tau} \, W \, e^{-iH_{Ising}\tau}}_{W(t)} \underbrace{V}_{V(0)} | \Psi_0 \rangle$$

Out-of-time-order correlation (OTOC) function

⇒ **quantifies spread or scrambling of quantum information across a system's degrees of freedom**

Swingle et al., arXiv:1602.06271; Shenker et al., arXiv:1306.0622; Kitaev (2014)

Multiple quantum coherence protocol

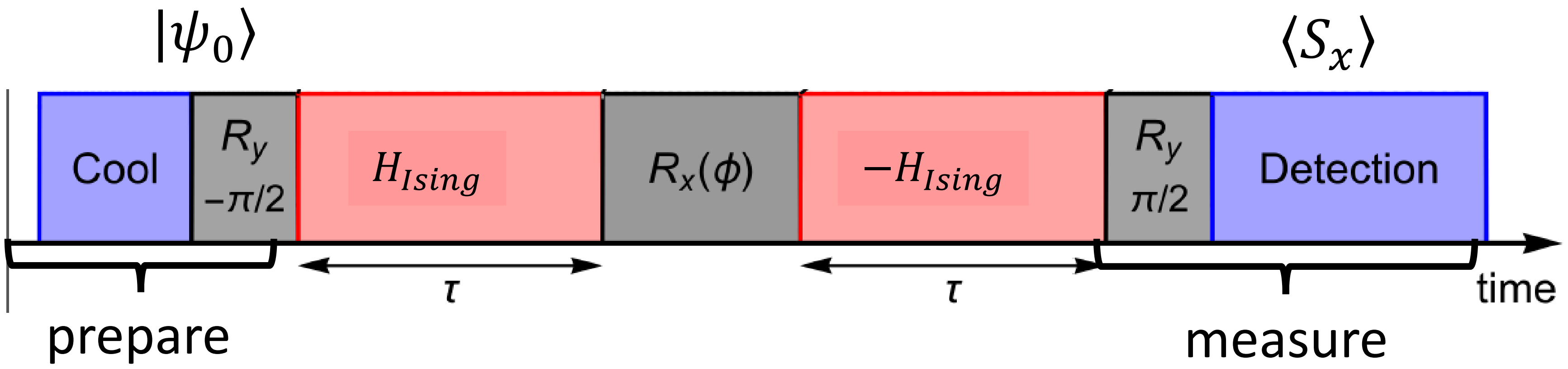


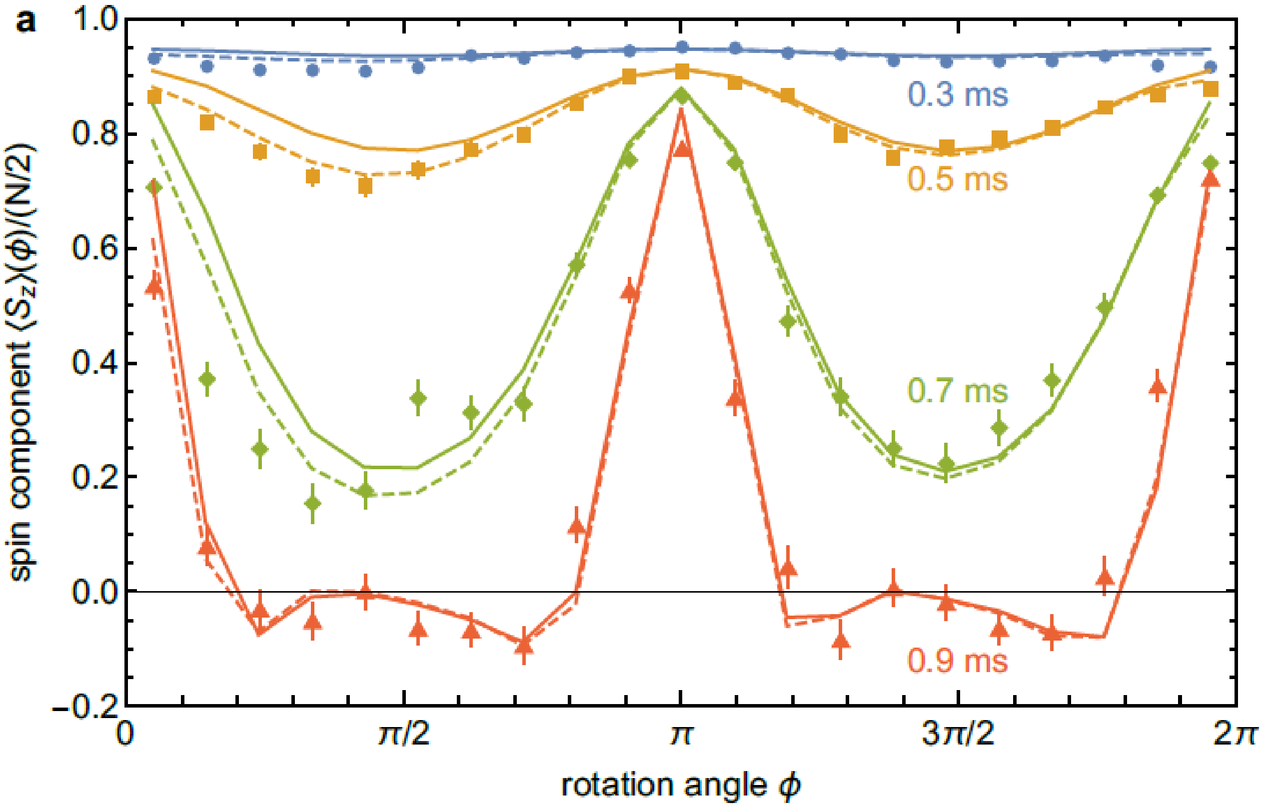
$$\langle S_x\rangle = \langle \Psi_0|\, e^{iH_{Ising}\tau}\, e^{i\phi S_x}\, e^{-iH_{Ising}\tau} S_x\, e^{iH_{Ising}\tau}\, e^{-i\phi S_x}\, \underbrace{e^{-iH_{Ising}\tau}|\Psi_0\rangle}_{\equiv |\Psi\rangle}$$

$$= \sum_m \langle \Psi|C_m|\Psi\rangle\, e^{i\phi m} \qquad C_m = \sum \underbrace{\sigma_1^z \sigma_4^y \ldots \sigma_k^z}_{\text{At least m terms}}$$

m^{th} order Fourier coefficient $\langle \Psi|C_m|\Psi\rangle$ indicates
$|\Psi\rangle$ has correlations of at least order m

MQC protocol – $\langle S_x \rangle$ measurement





$$H_{Ising} = J/N \sum_{i<j} \sigma_i^z \sigma_j^z$$

$$J \lesssim 5kHz$$

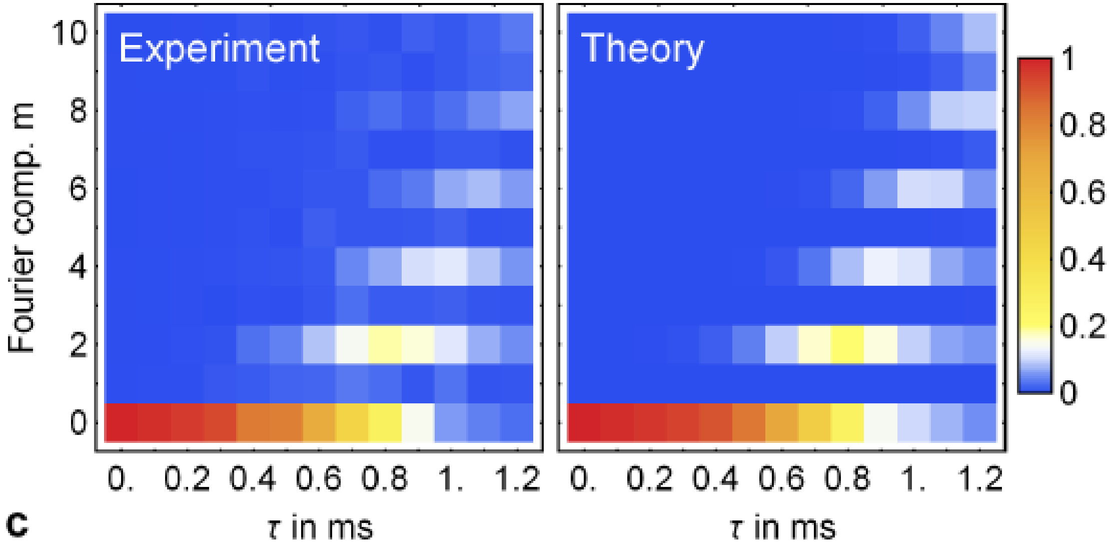
$$N = 111$$

$$\Gamma = 93Hz$$

[Gärttner, Bohnet et al. Nature Physics 2017]

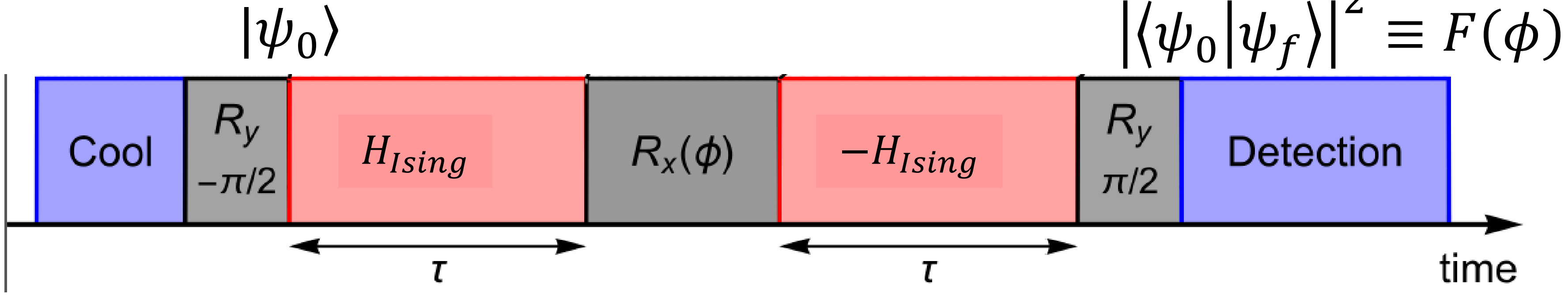
Fourier transform of magnetization

[Gärttner, Bohnet et al. Nature Physics 2017]

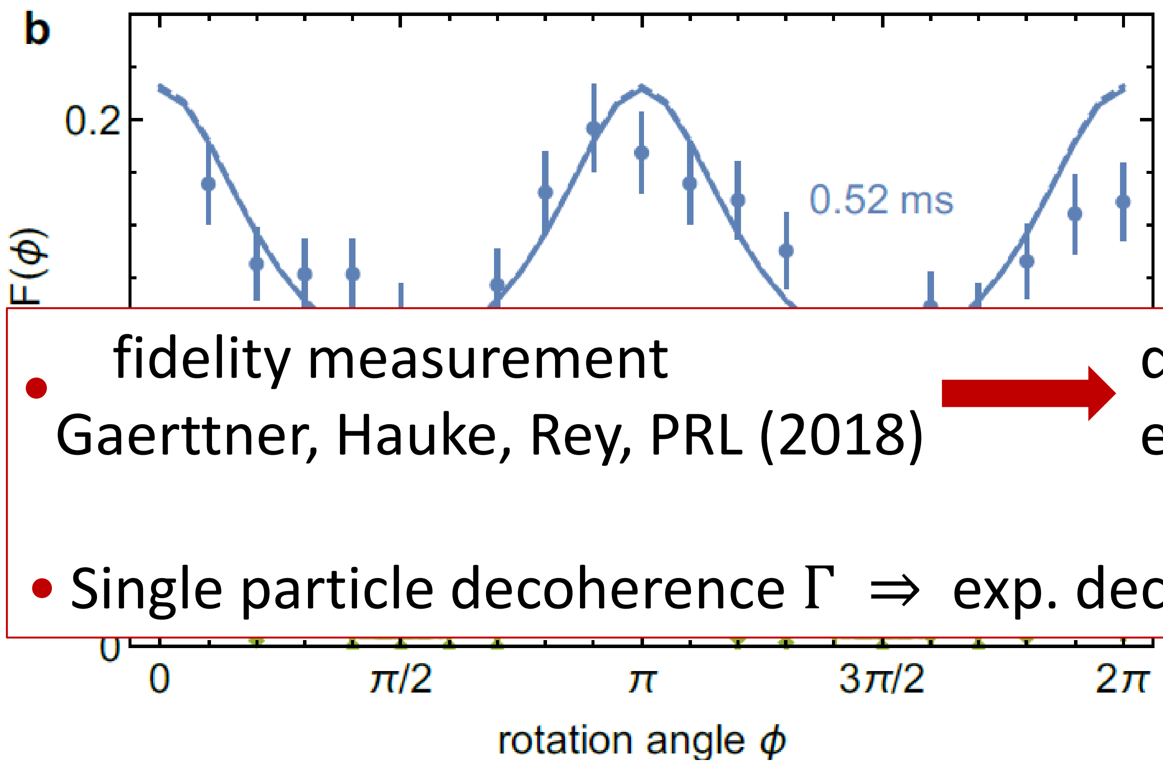


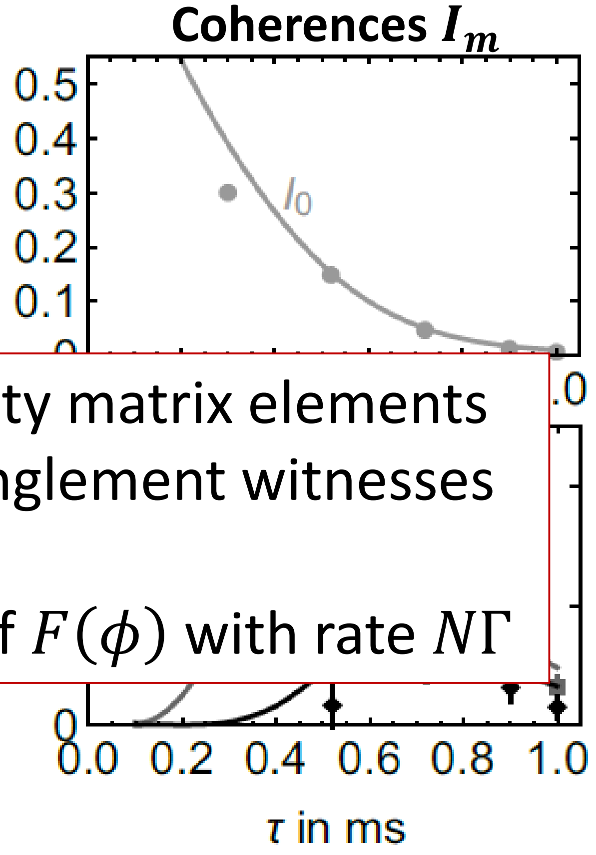
- Measure build-up of 8-body correlations
- Only global spin measurement
- Illustrates how OTOCs measure spread of quantum information

MQC protocol – $|\langle\psi_0|\psi_f\rangle|^2$ fidelity measurement



- Measure $|\langle\psi|\downarrow\cdots\downarrow\rangle|^2$ through photon count histograms





- fidelity measurement → density matrix elements
  Gaerttner, Hauke, Rey, PRL (2018) → entanglement witnesses

- Single particle decoherence Γ $\Rightarrow$ exp. decay of $F(\phi)$ with rate $N\Gamma$

Trapped ion quantum simulation

2. Quantum simulation with 1d ion crystals in linear rf traps

- nice examples of non-equilibrium quantum simulations

- propagation of correlations in 1d crystals with long range interactions

  "Non-local propagation of correlations in quantum systems with long-range interactions," P. Richerme, ..C. Monroe, Nature 511, 198 (2014).

  "Quasiparticle engineering and entanglement propagation in a quantum many-body system" P. Jurcevic, .., R. Blatt, C. F. Roos Nature 511, 202 (2014),

- dynamical phase transitions

  "Direct observation of dynamical quantum phase transitions in an interacting many-body system", P. Jurcevic, .., R. Blatt, C. F. Roos, Phys. Rev. Lett. 119, 080501 (2017).

  "Observation of a Many-Body Dynamical Phase Transition in a 53-Qubit Quantum Simulator," J. Zhang, .., C. Monroe, Nature 551, 601 (2017).

- non-equilibrium phases

  "Observation of a Discrete Time Crystal," J. Zhang, P.W. Hess, A. Kyprianidis, P. Becker, Lee, J. Smith, G. Pagano, I.-D. Potirniche, A.C. Potter, A. Vishwanath, N.Y. Yao, C. Monroe, Nature 543, 217 (2017)

Observation of a discrete time crystal – Monroe group

Crystals in space are an example of the breaking of spatial translation symmetry

Could there be states of matter that break translation symmetry in time? (Wilczek, PRL 2012)

Forbidden for ground states and thermal equilibrium! (Bruno PRL (2013); Watanabe & Oshikawa PRL (2015))

What about non-equilibrium systems?
Yes for periodically driven Floquet systems ↔ possess a discrete time translation symmetry
↔ broken through a subharmonic response
↔ called a Discrete Time Crystal (DTC)

Properties of a Discrete Time Crystal:

1. Subharmonic oscillation stabilized by many-body interactions
2. Robust against perturbations (rigidity)
3. Infinite autocorrelation time

Observation of a discrete time crystal – Monroe group

10 $^{171}Yb^+$ ions in a linear rf trap
– 12.6 GHz hyperfine qubit

Floquet Hamiltonian:

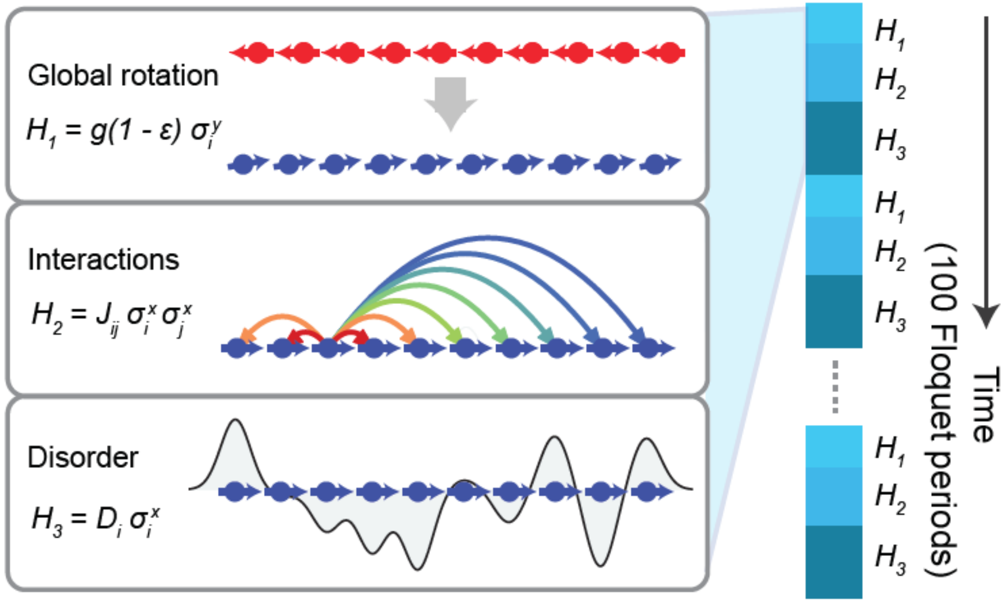
$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i \sigma_i^x & \text{time } t_3. \end{cases}$$

Optically driven Raman transitions; approx. π-pulse

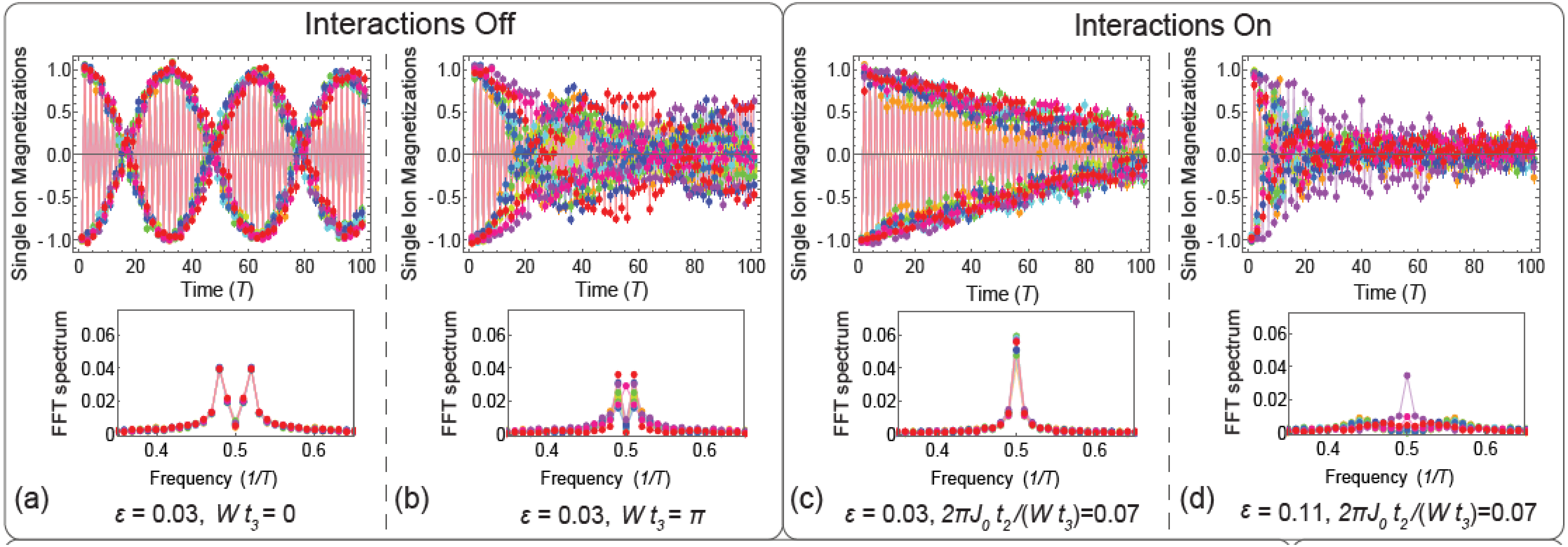
Globally applied MS interaction

Programmable disorder from individual AC Stark shifts

Overall period
$T = t_1 + t_2 + t_3$ repeated



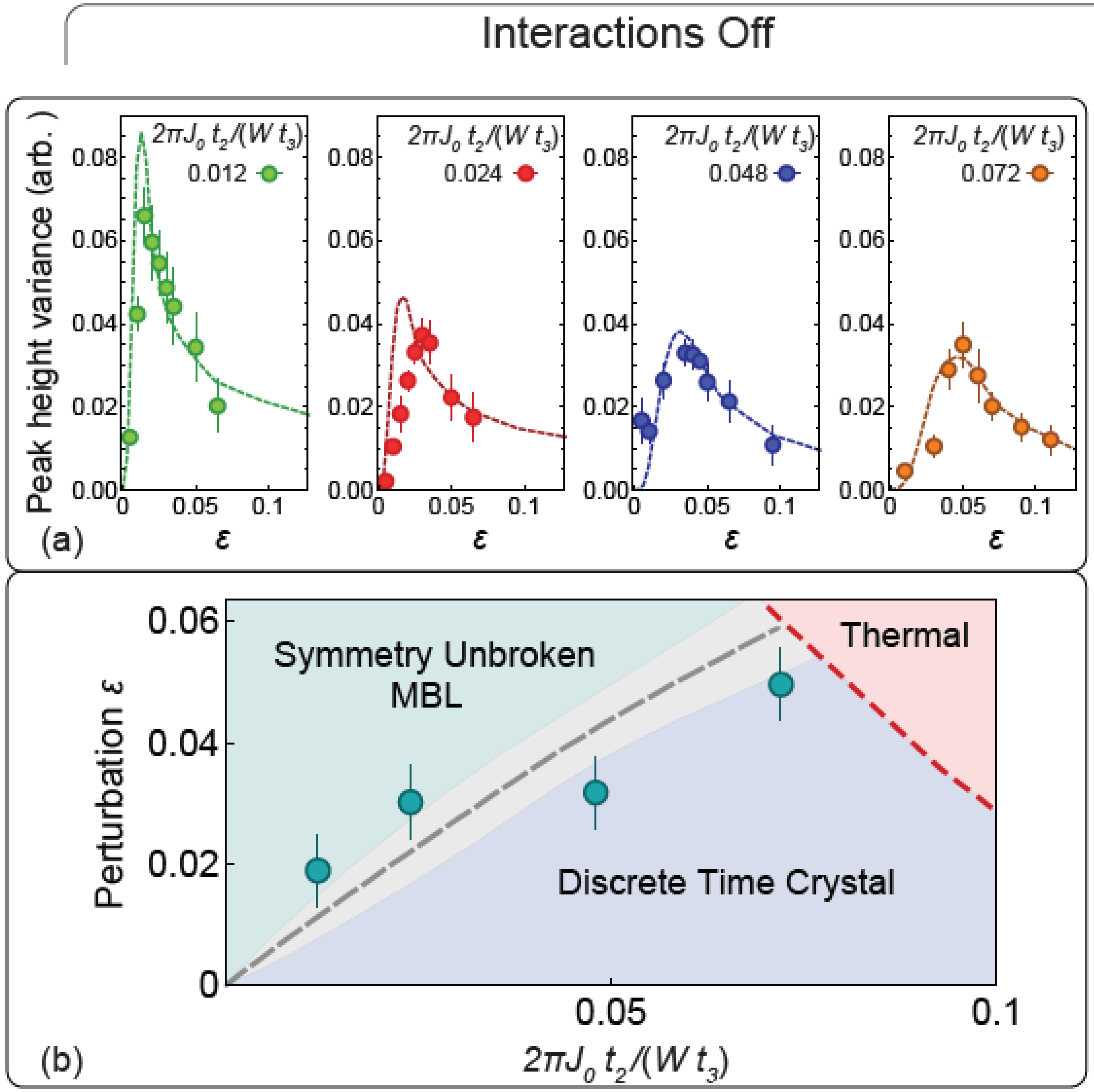
Observation of a discrete time crystal – Monroe group

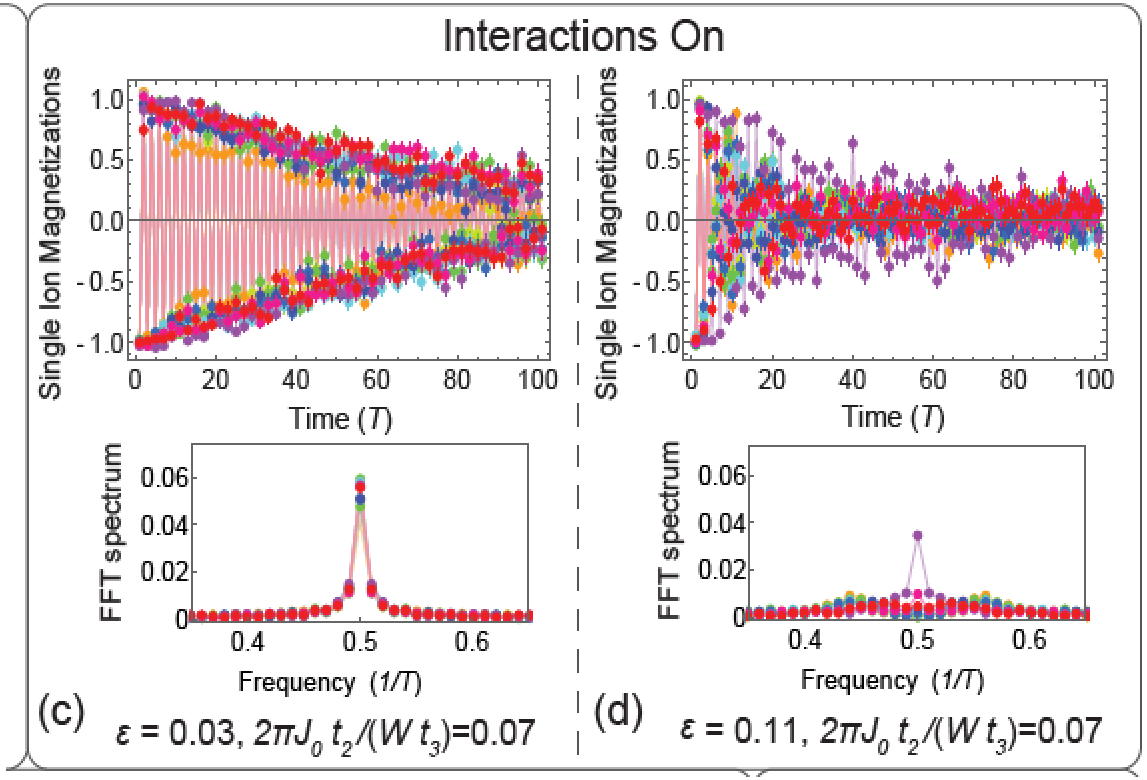


$$T = t_1 + t_2 + t_3$$

$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x \sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i \sigma_i^x & \text{time } t_3. \end{cases}$$

Observation of a discrete time crystal – Monroe group



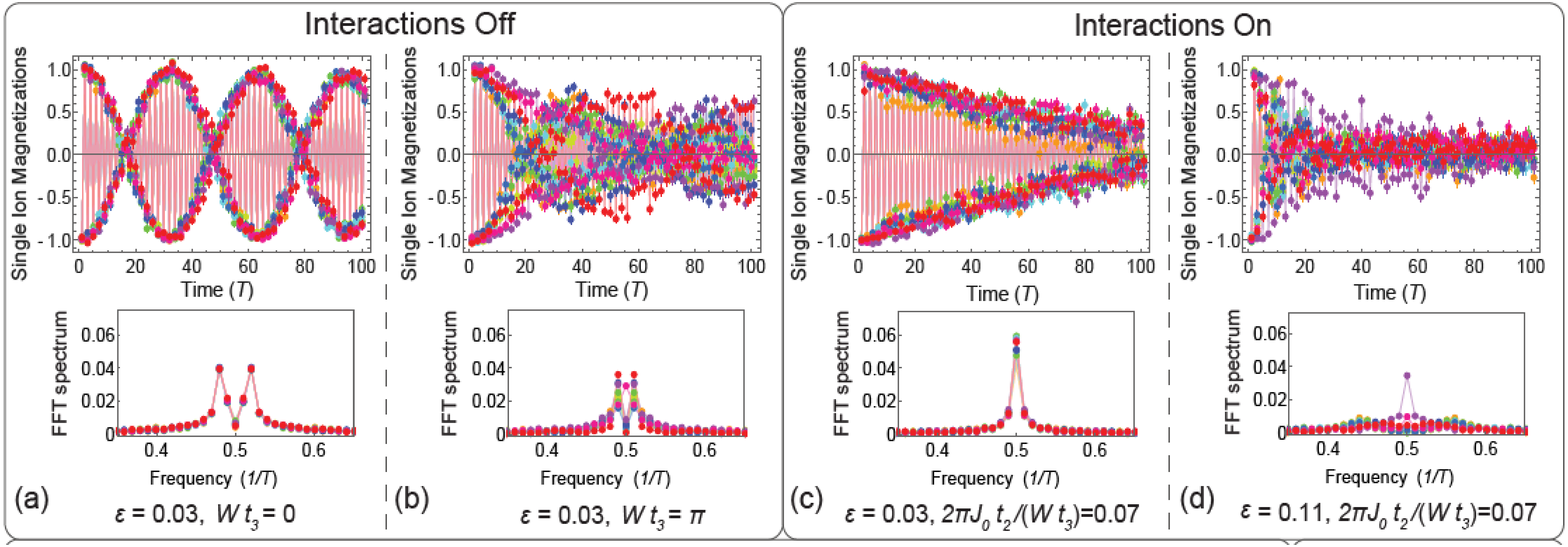


$(H_3 = \sum_i D_i \sigma_i^z$ time t_3.

Discrete Time Crystal broken for large disorder ϵ

→ determines phase boundary of DTC

Observation of a discrete time crystal – Monroe group



Properties of a Discrete Time Crystal:

1. Subharmonic oscillation stabilized by many-body interactions ✓
2. Robust against perturbations (rigidity) ✓
3. Infinite autocorrelation time ?

Desirable to increase the number of qubits !

Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Thursday, July 5, 9:00 AM – Trapped ion quantum sensing