Quantum simulation and sensing with large trapped-ion crystals

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NIST-Boulder
Ion storage group

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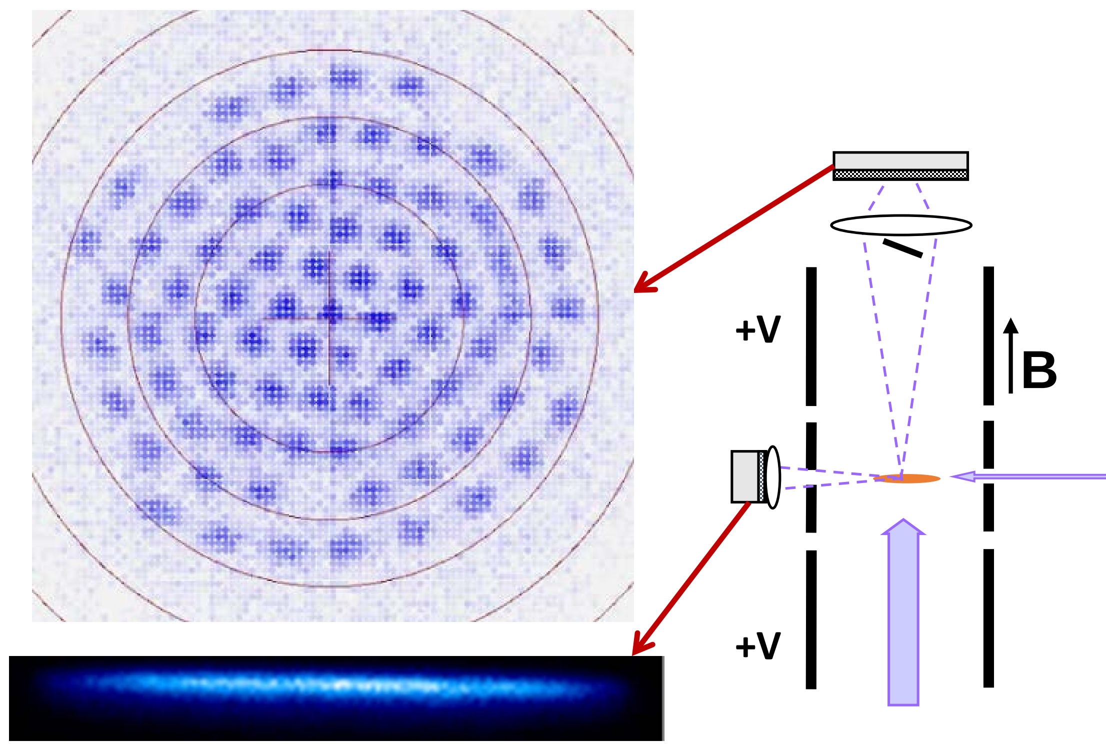
theory –Rey group (JILA/NIST)
Holland group (JILA/NIST)
Freericks group (Georgetown)
Michael Foss-Feig (Honeywell)
Dan Dubin (UCSD)

- Dicke model $\delta a^{\dagger}a + \frac{2g}{\sqrt{N}}(a + a^{\dagger})S_z + B_{\perp}S_x$
- measure quantum spin dynamics through squeezing and MQC protocol
- motional amplitude sensing



National Institute of Standards and Technology

NSF

NIST ion storage group (2019)

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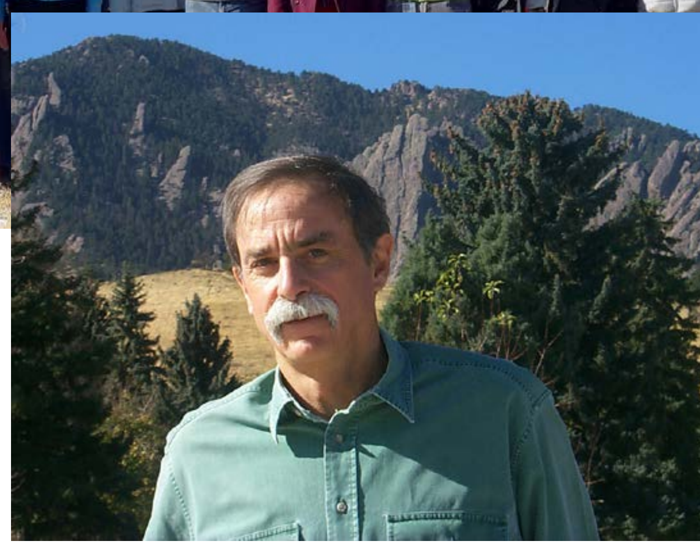
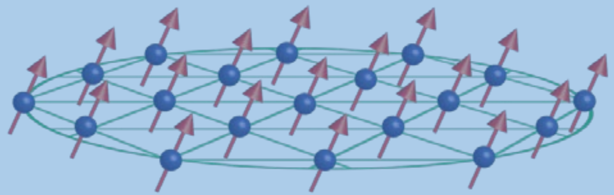


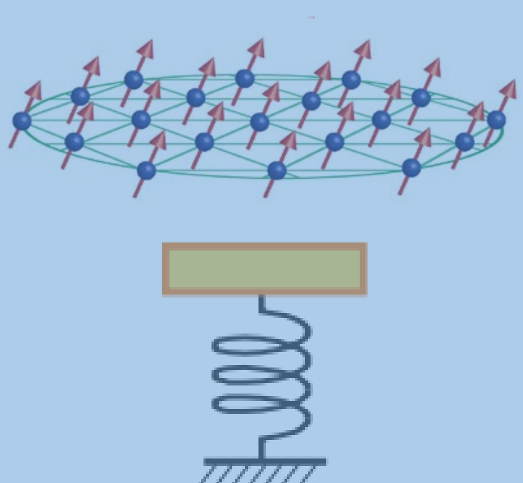
Outline:

- Penning trap features
  - high field qubit, modes, ground-state cooling
- Quantum simulation - engineering Ising interactions with spin-dependent forces

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

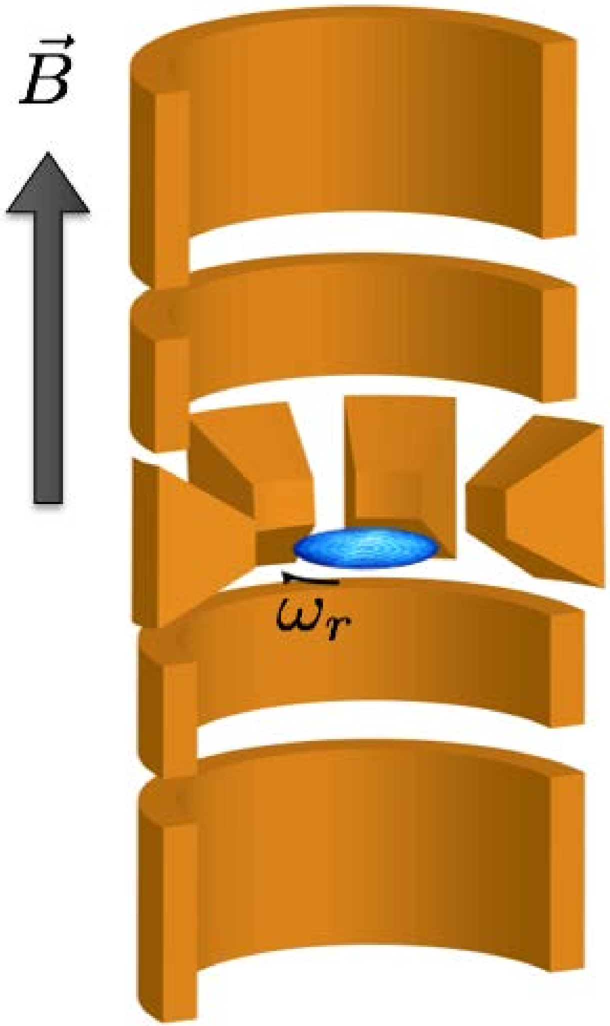


  - benchmark quantum dynamics through spin-squeezing and multi-quantum coherence protocol (Loschmidt echo)
- Stronger interactions – parametrically drive the phonons



- Sensing small COM (center-of-mass) motion
  - spin-dependent forces

Penning trap: many particle confinement with static fields



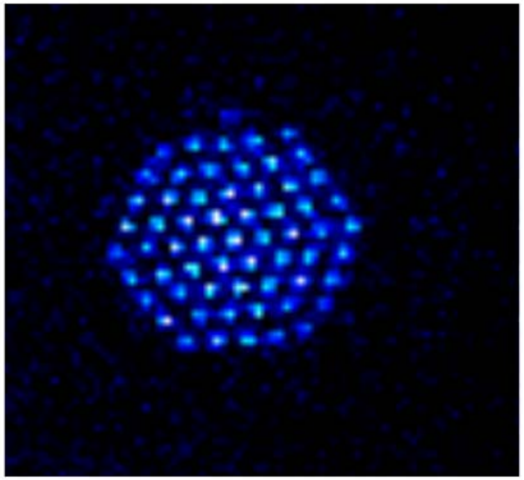
$^9Be^+$, B=4.5 T: $\frac{\Omega_c}{2\pi} \sim 7.6$ MHz, $\frac{\omega_z}{2\pi} \sim 1.6$ MHz, $\omega_m \sim 160$ kHz

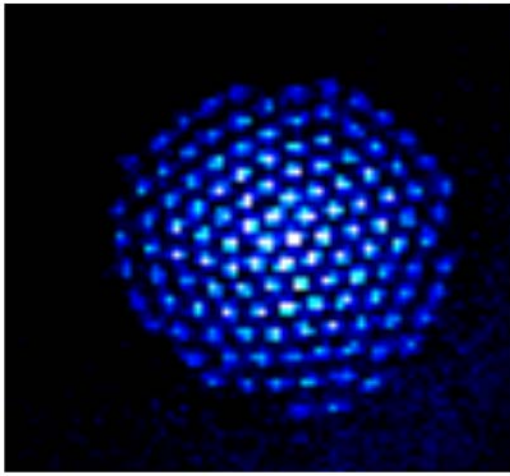
- axial confinement from electrostatic trapping potential

$$\phi_{trap} \approx \frac{1}{2} m\omega_z^2 \left(z^2 - \frac{r^2}{2} \right)$$

- radial confinement due to Lorentz force from crystal rotation ω_r

- ω_r controlled by rotating potential



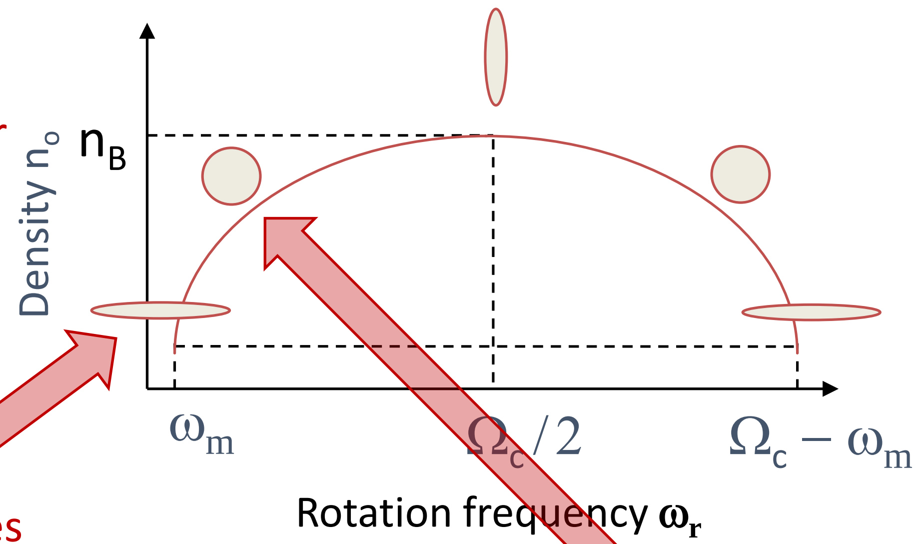


Ion crystals form as a result of minimizing Coulomb potential energy

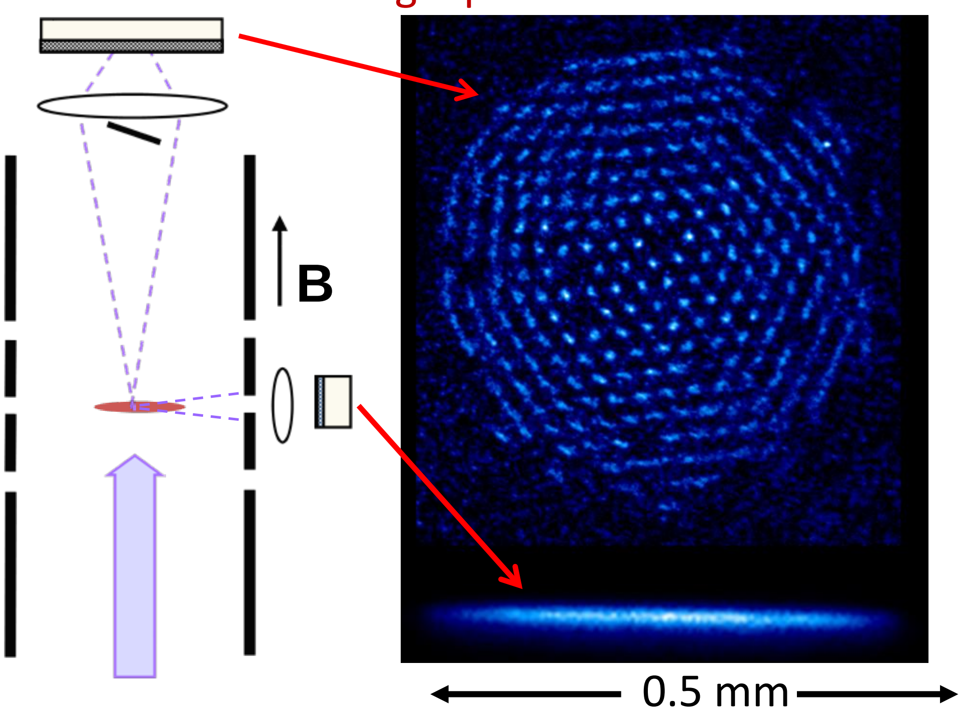
T→ 0.4 mK (Doppler laser cooling) ⇒ $q^2/a_{WS} \gg k_B T$, $2a_{WS} \sim$ ion spacing

type of crystal, nearest neighbor ion spacing depend on ω_r

Mitchell et.al., Science (1998)

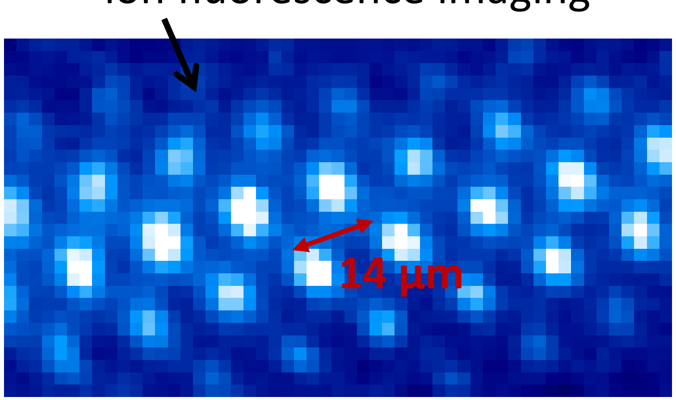


single planes

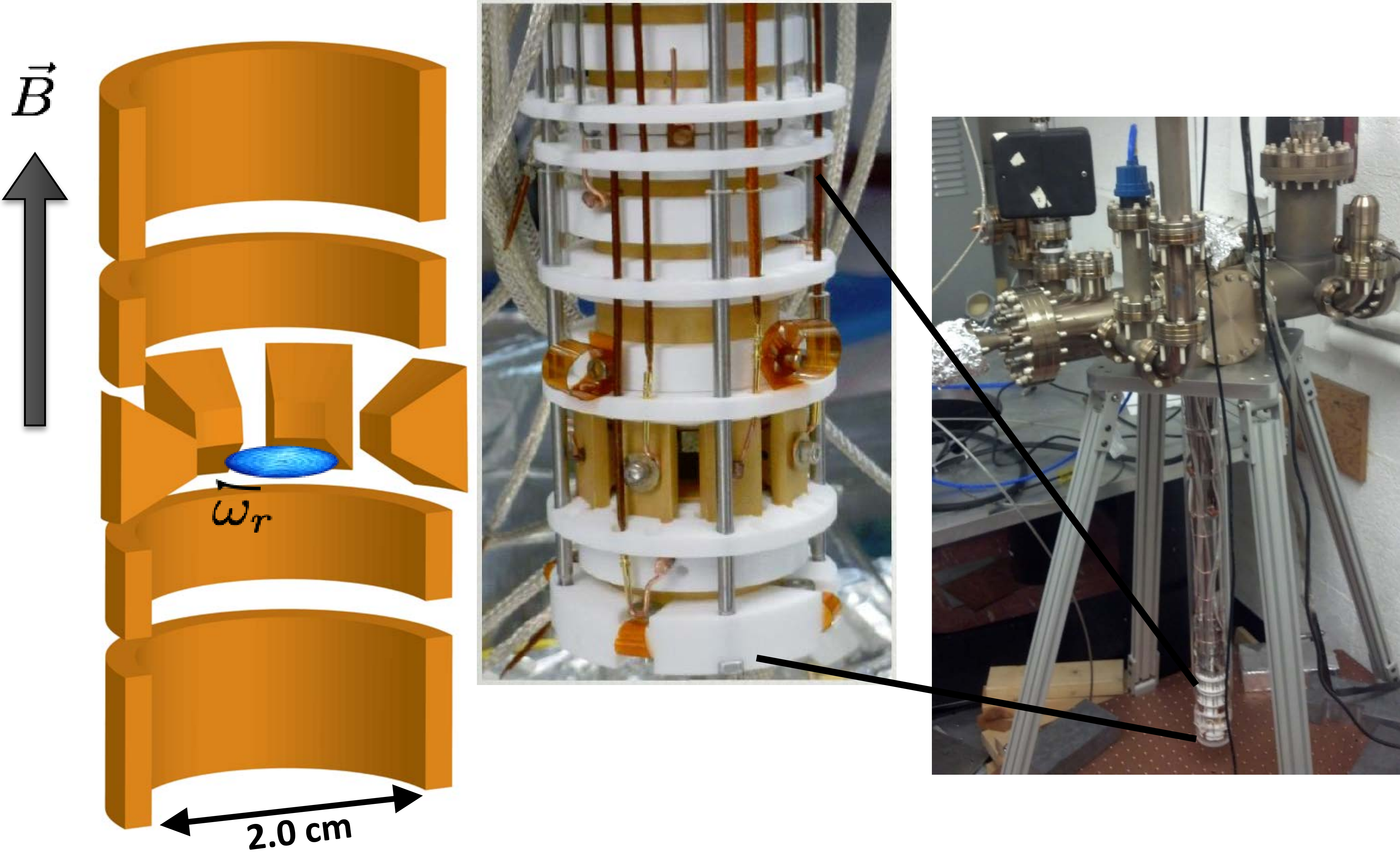


bcc crystals with N>100 k

observed with:
- Bragg scattering;
- ion fluorescence imaging



NIST Penning trap



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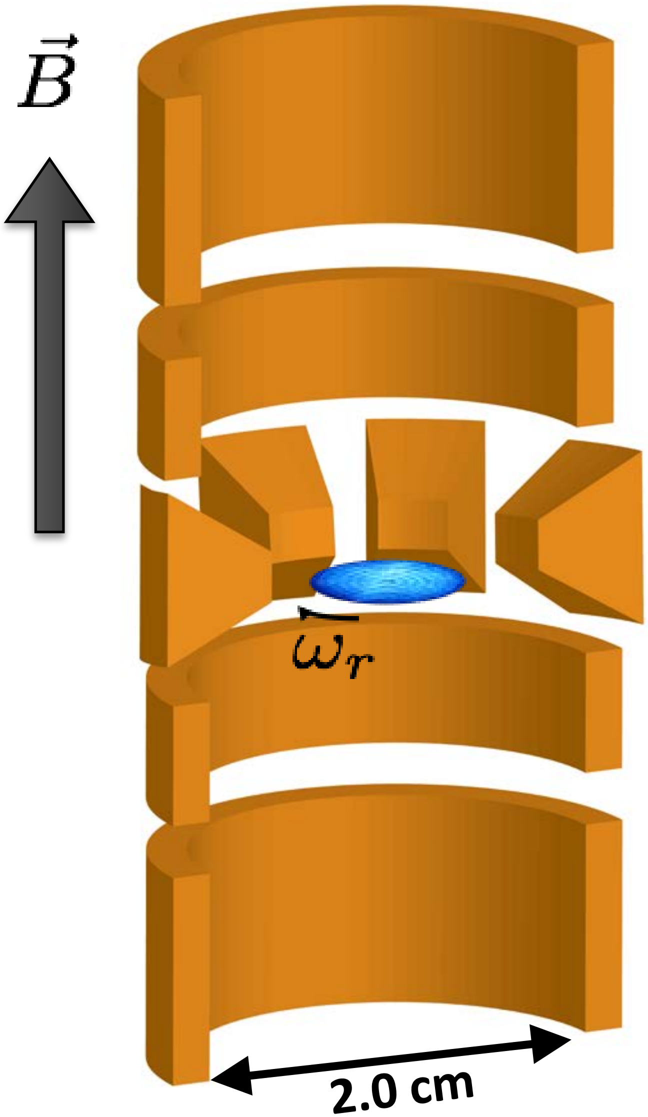
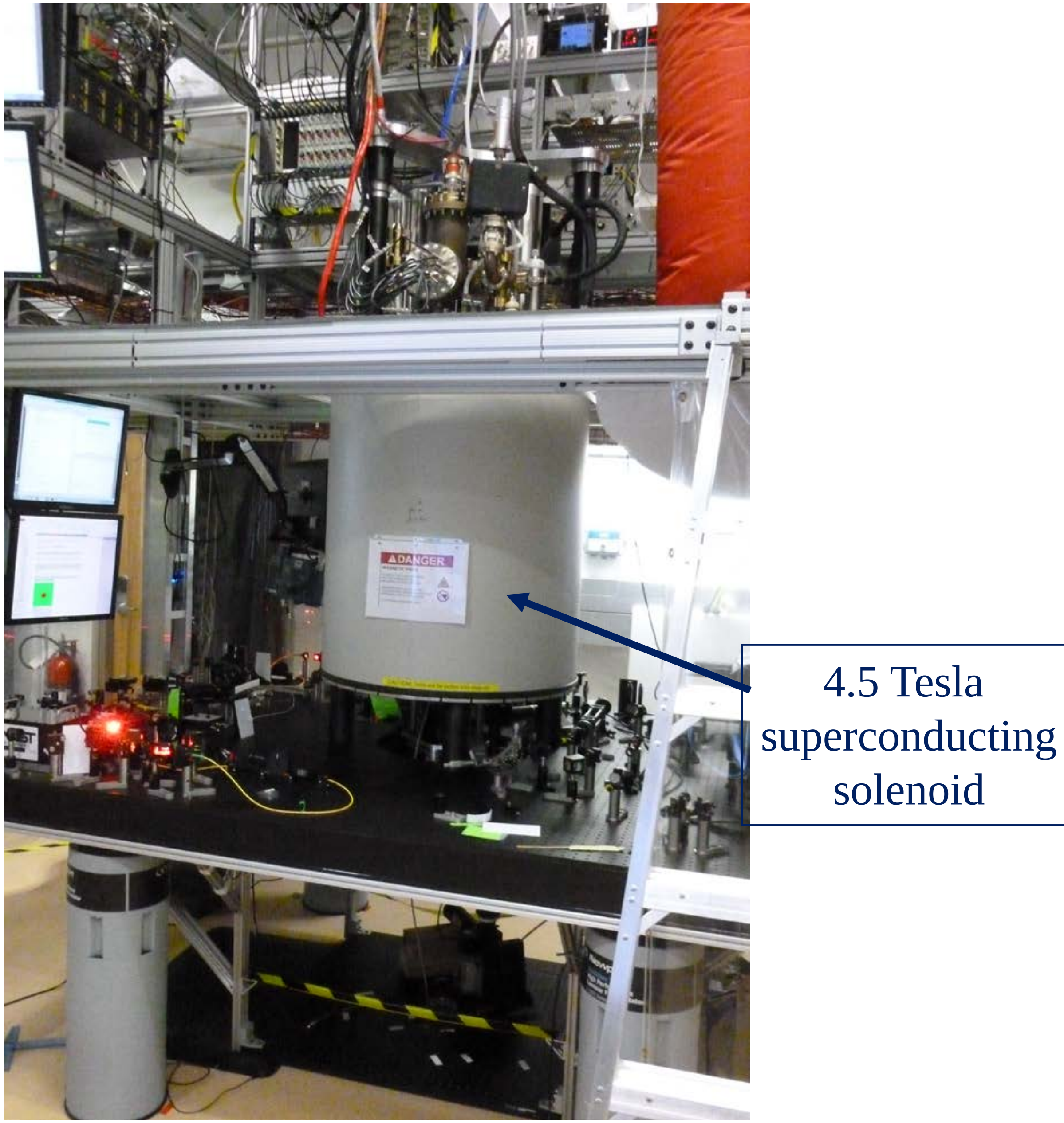
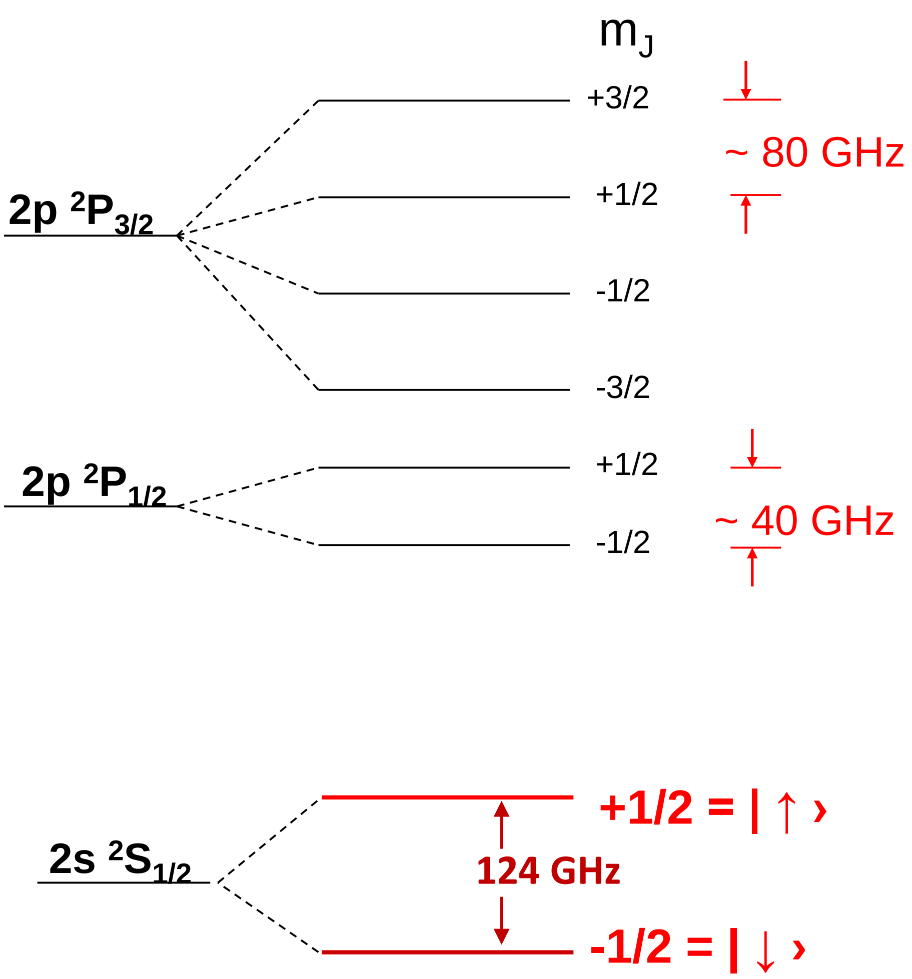
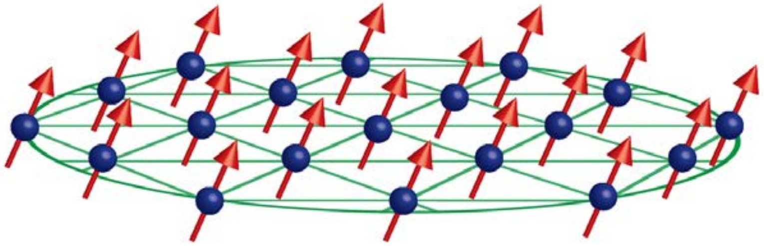




Be^+ high magnetic field qubit

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



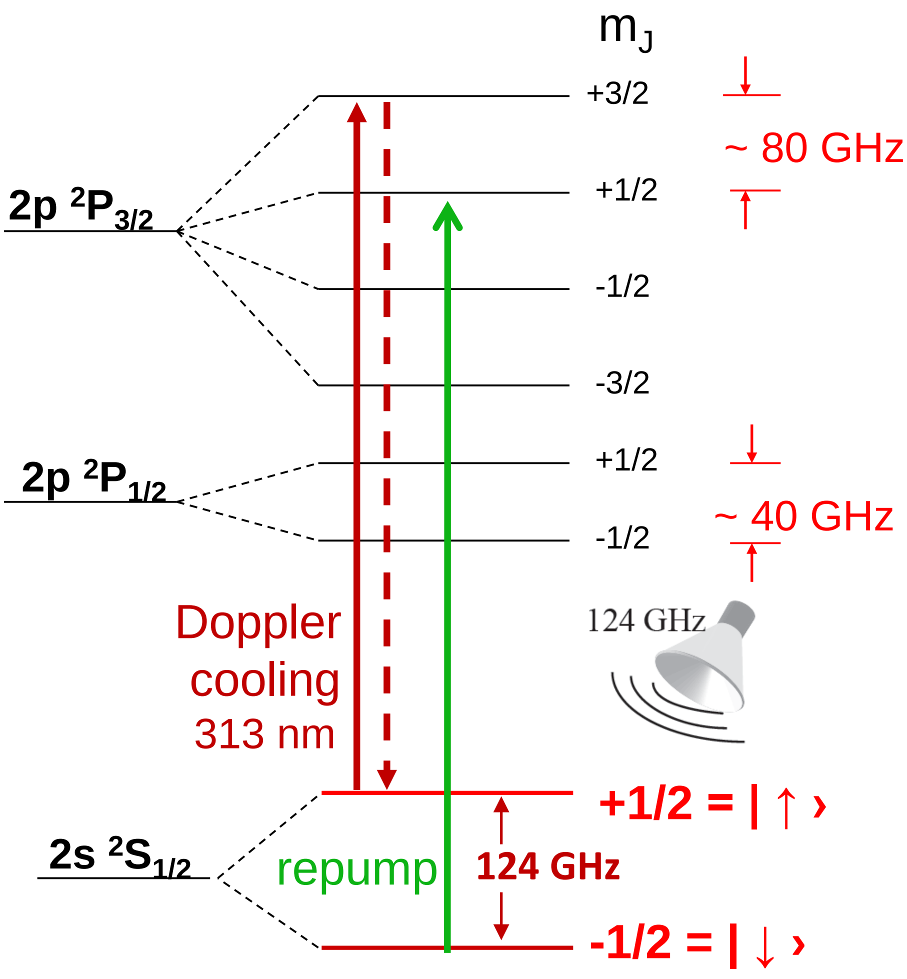


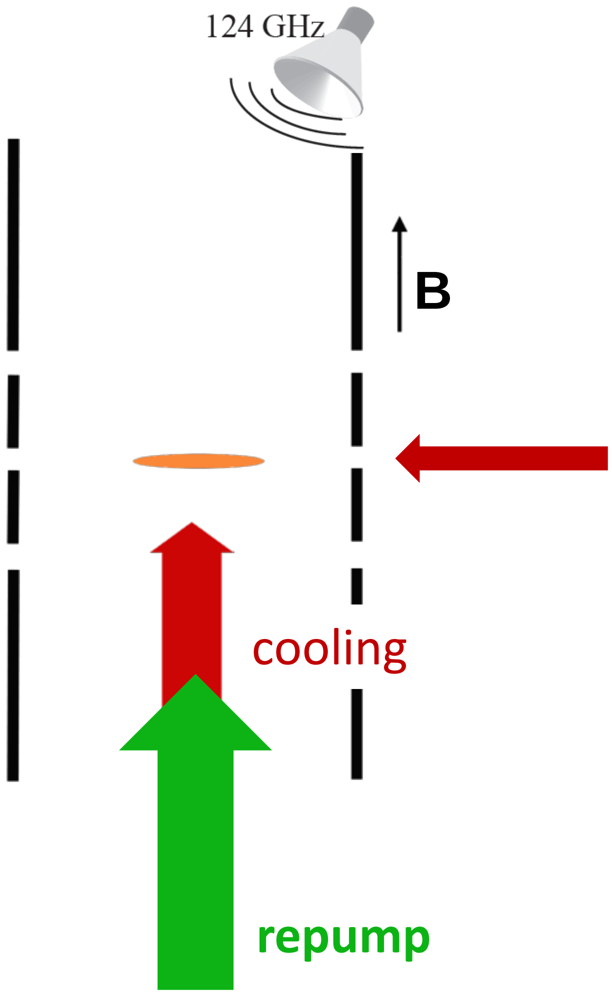
Be^+ high magnetic field qubit

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

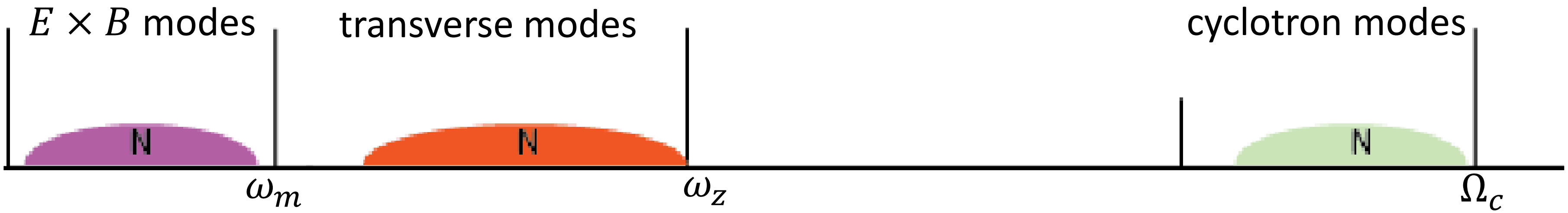
$$H_{\mu W} = \sum_i B_\perp \hat{\sigma}_i^x \,,$$

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





Transverse (drumhead) modes



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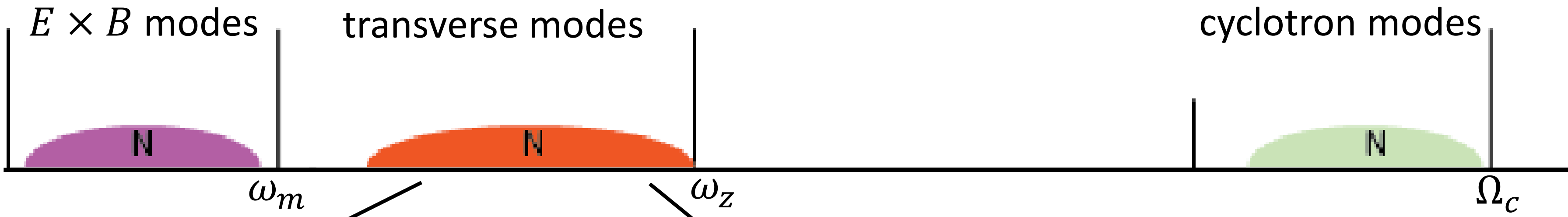
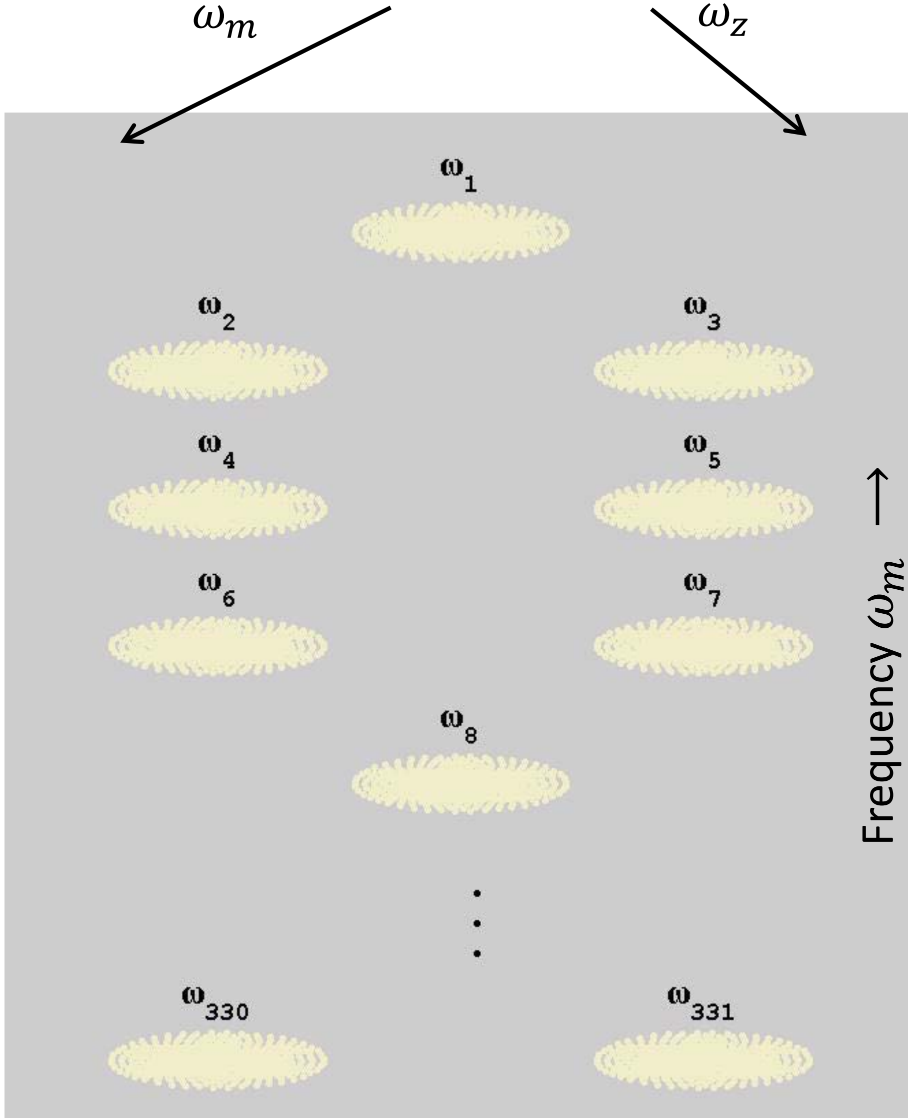




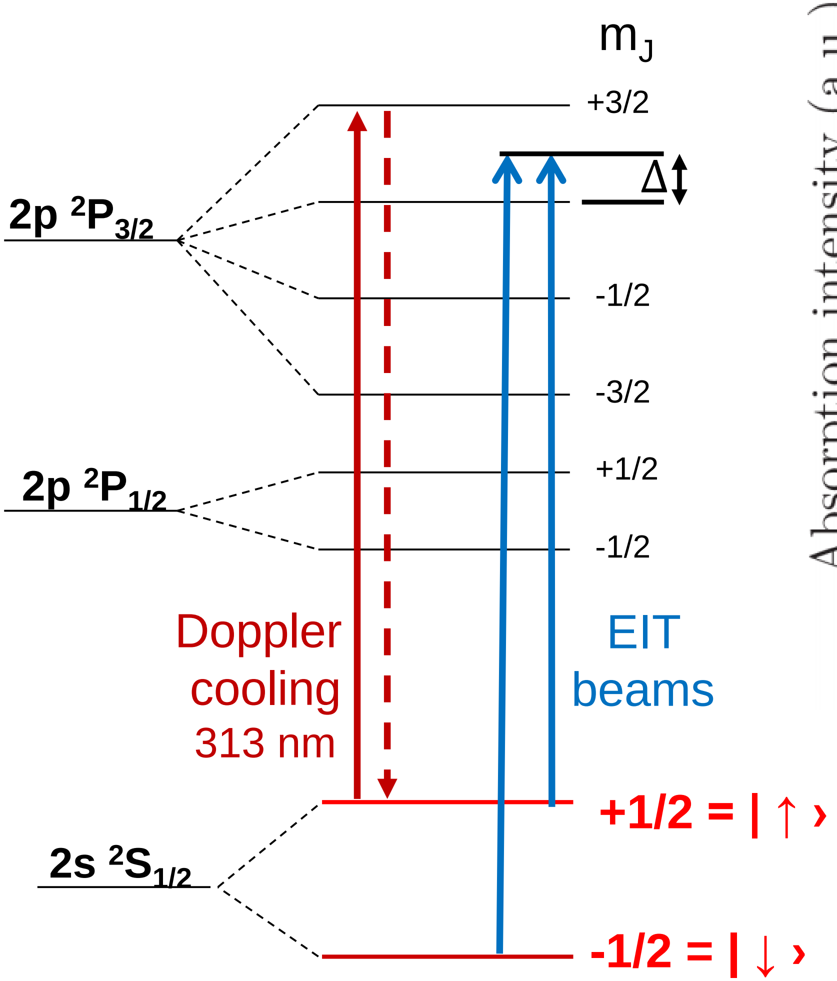
Freericks group, PRA (2013)
Baltrush, Negretti, Taylor, Calarco, PRA (2011)
Dubin, UCSD

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

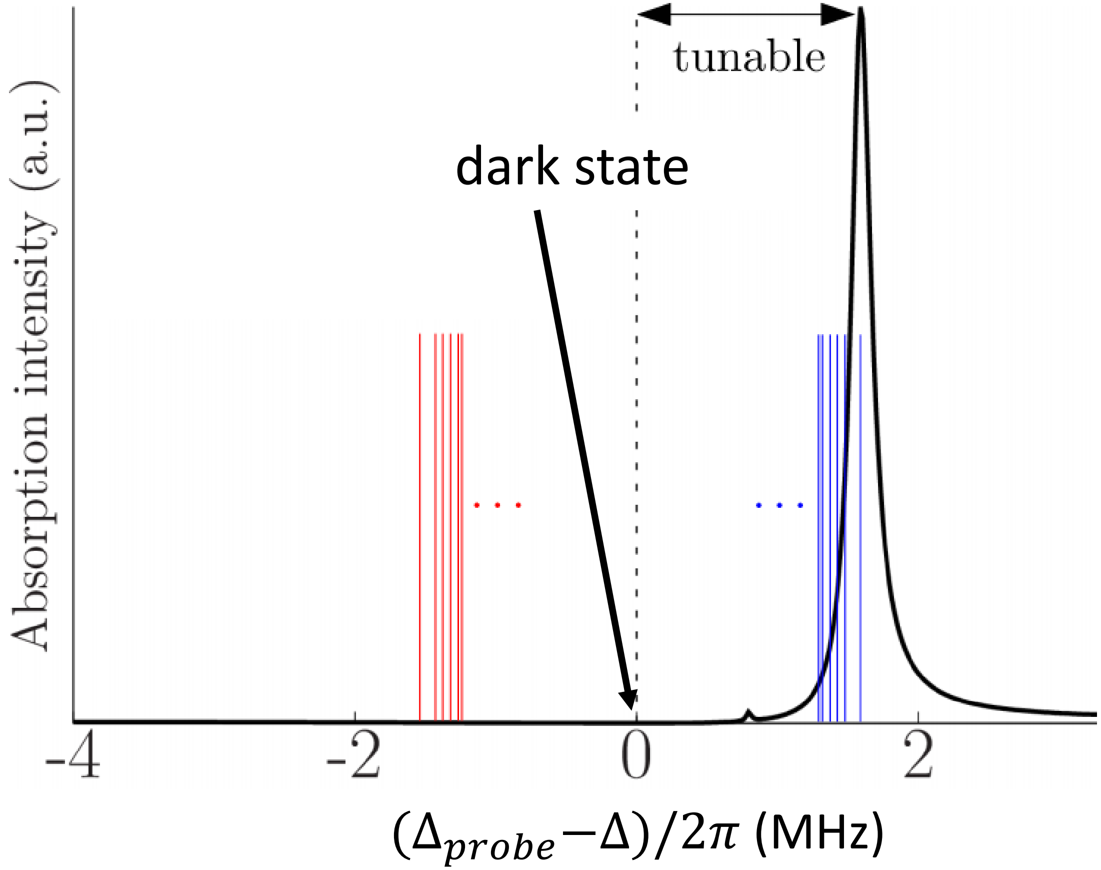
Ground-state cooling of the drumhead modes

EIT cooling

Morigi et al., PRL 2000
PRA 2003



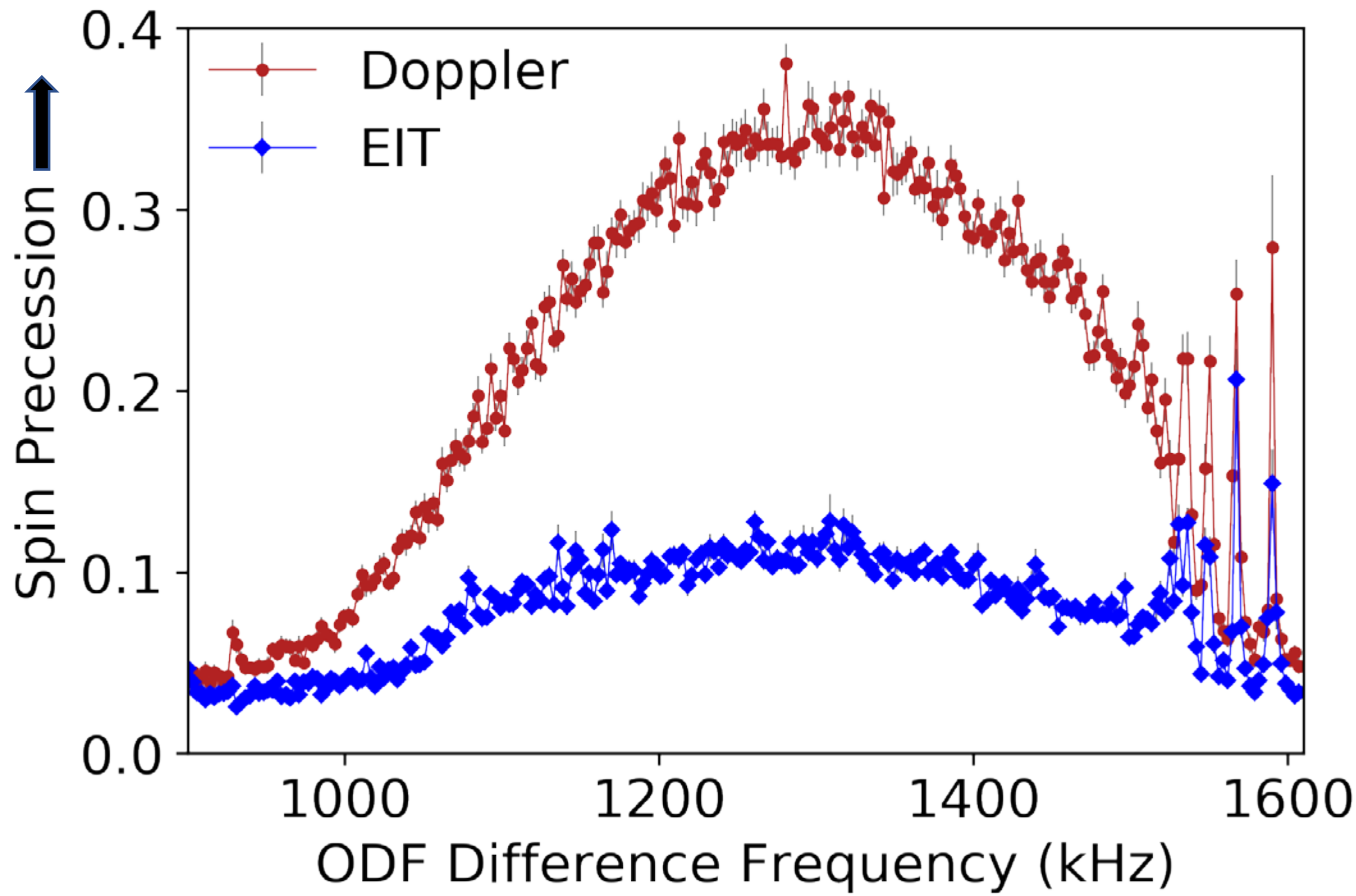
EIT absorption spectrum



Shankar et al., arXiv:1809.05492
Phys. Rev. A 99, 023409 (2019)

Ground-state cooling of the drumhead modes

- N≈160 ions
- Simultaneously cool all drumhead modes
- 200 μs EIT cooling
- $\bar{n}_{COM} \approx 0.3\ (0.2)$



Elena Jordan, et al., arXiv:1809.06346
Phys. Rev. Lett. 122, 053603 (2019)

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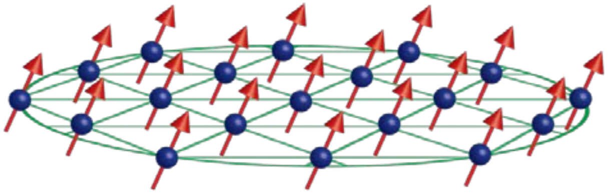

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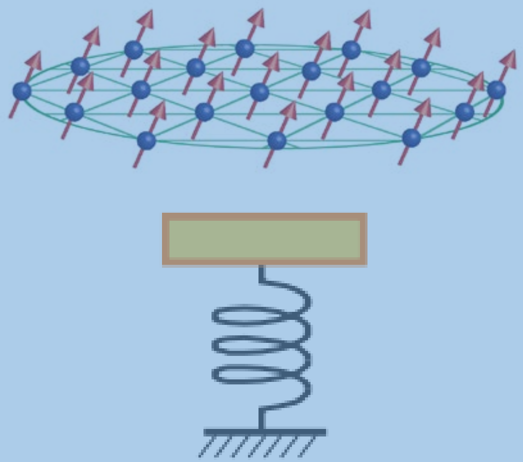

- Sensing small COM (center-of-mass) motion
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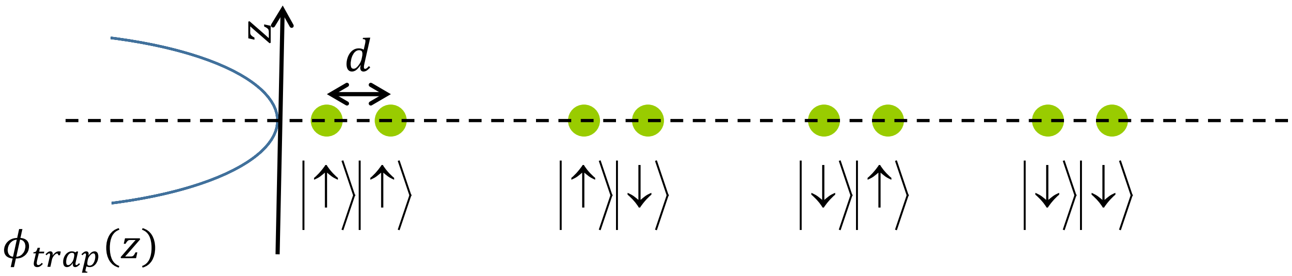
Engineering quantum magnetic couplings

Simple example – adiabatic spin-dependent force

Calarco, Cirac, Zoller, PRA (2001)

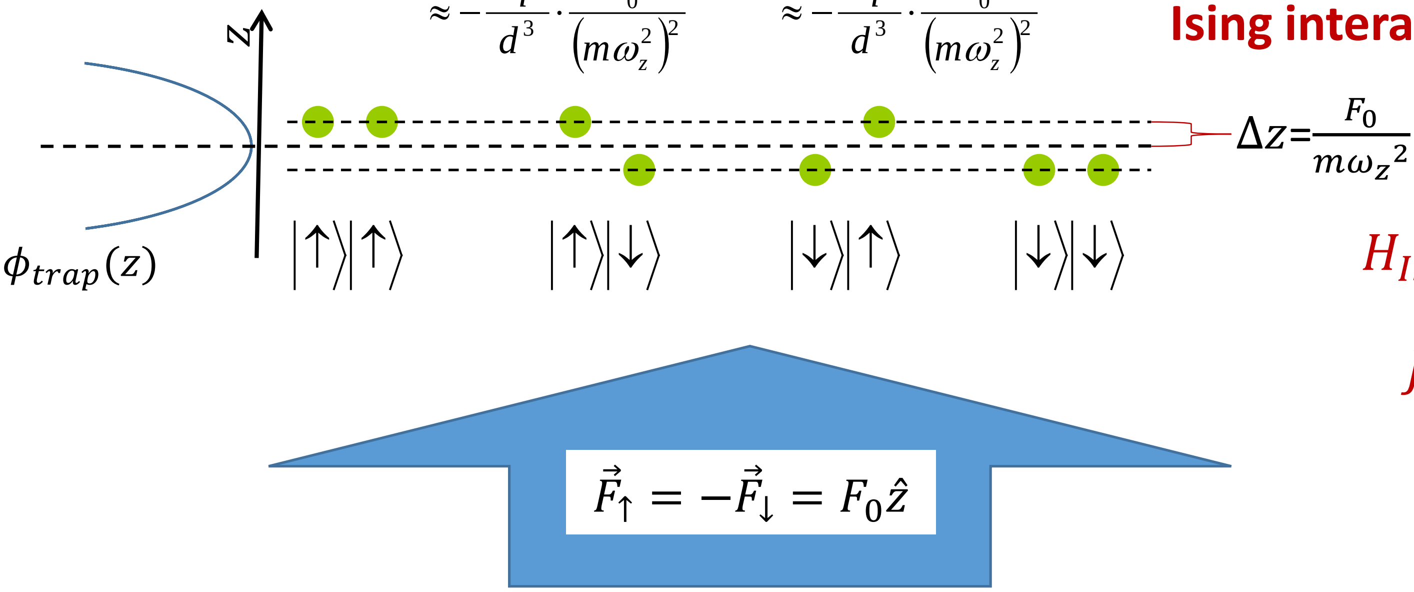


$$E_{Coulomb} \propto q^2/d$$

0 | $\frac{q^2}{d} - \frac{q^2}{\sqrt{d^2 + (2\cdot\Delta z)^2}}$ | $\frac{q^2}{d} - \frac{q^2}{\sqrt{d^2 + (2\cdot\Delta z)^2}}$ | 0 ← $\Delta E_{Coulomb}$

$$\approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad \approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2}$$

$\Delta E_{Coulomb} \leftrightarrow$ antiferromagnetic Ising interaction

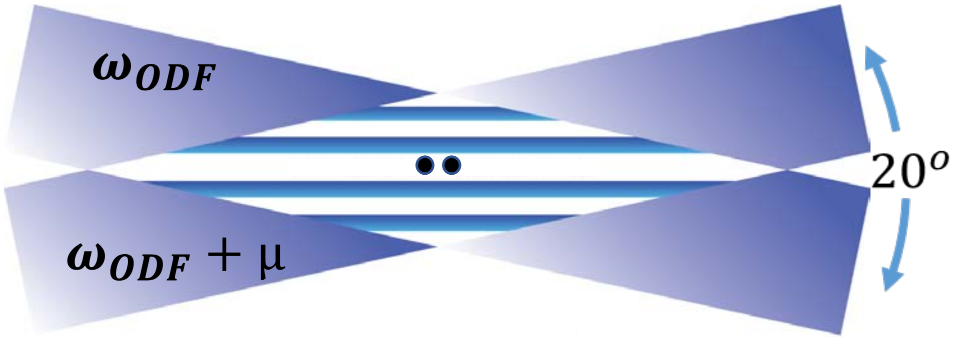


$$H_{Ising} = J\sigma^z{}_1 \cdot \sigma^z{}_2,$$

$$J = \frac{q^2}{d^3}\frac{F_0{}^2}{(m\omega_z{}^2)^2}$$

quantum magnetic couplings – geometric phase picture

Spin-dependent forces from optical dipole forces (ODFs)



- $F_{\uparrow}(t) = -F_{\downarrow}(t)$

  $F_{\uparrow}(t) = F_0 \cos(\mu t)$

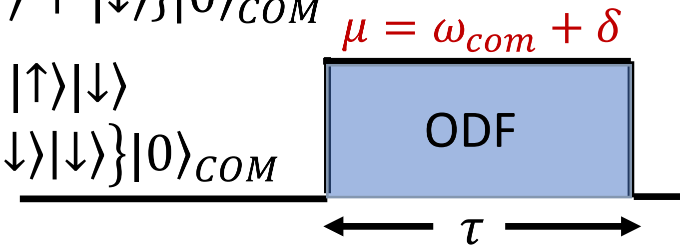
$$\hat{H}_{ODF}(t) = F_0 \cos(\mu t) \sum_{j=1}^{2} \hat{z}_j \cdot \hat{\sigma}_j^z$$

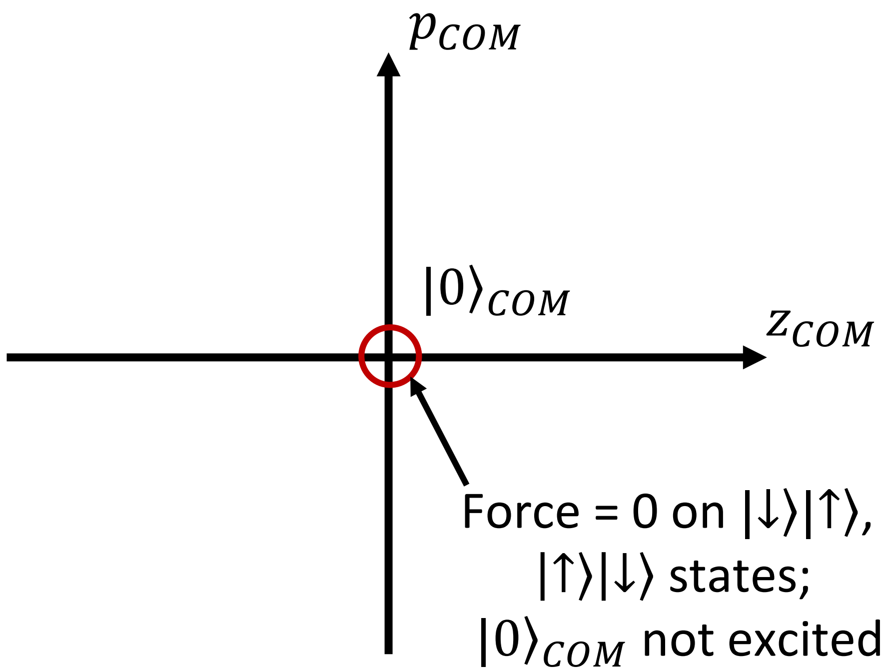
Consider $\mu = \omega_{COM} + \delta$

Prepare

$$\{|\uparrow\rangle + |\downarrow\rangle\}\{|\uparrow\rangle + |\downarrow\rangle\}|0\rangle_{COM}$$

$$= \{|\uparrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle\}|0\rangle_{COM}$$





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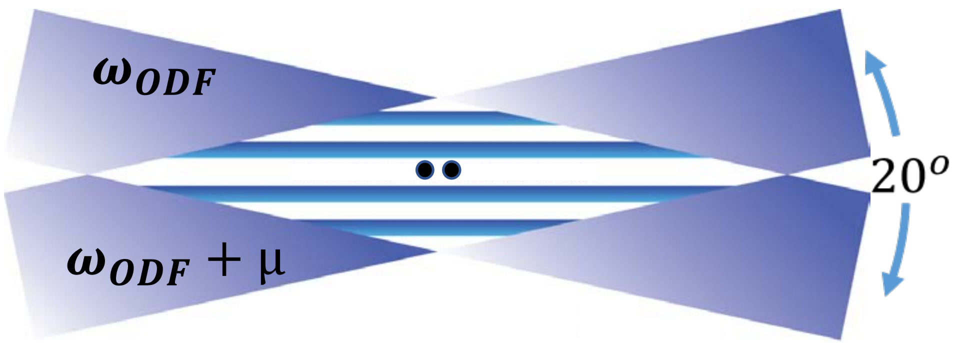
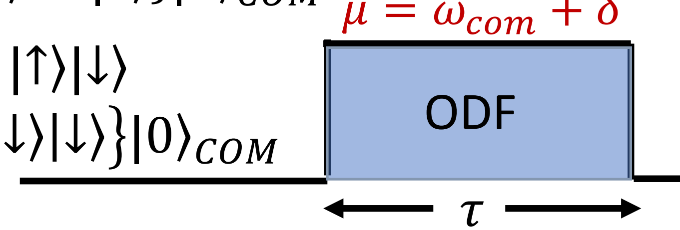
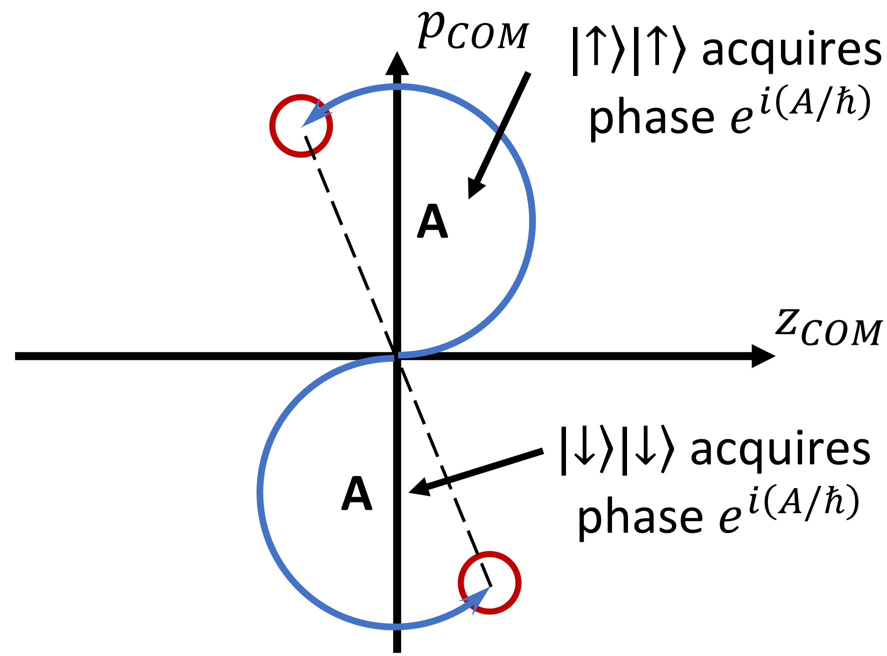


Prepare

$$\{|\uparrow\rangle + |\downarrow\rangle\}\{|\uparrow\rangle + |\downarrow\rangle\}|0\rangle_{COM}$$
$$= \{|\uparrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle\}|0\rangle_{COM}$$





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  $F_\uparrow(t) = F_0 \cos(\mu t)$

$$\hat{H}_{ODF}(t) = F_0 \cos(\mu t) \sum_{j=1}^{2} \hat{z}_j \cdot \hat{\sigma}_j^z$$

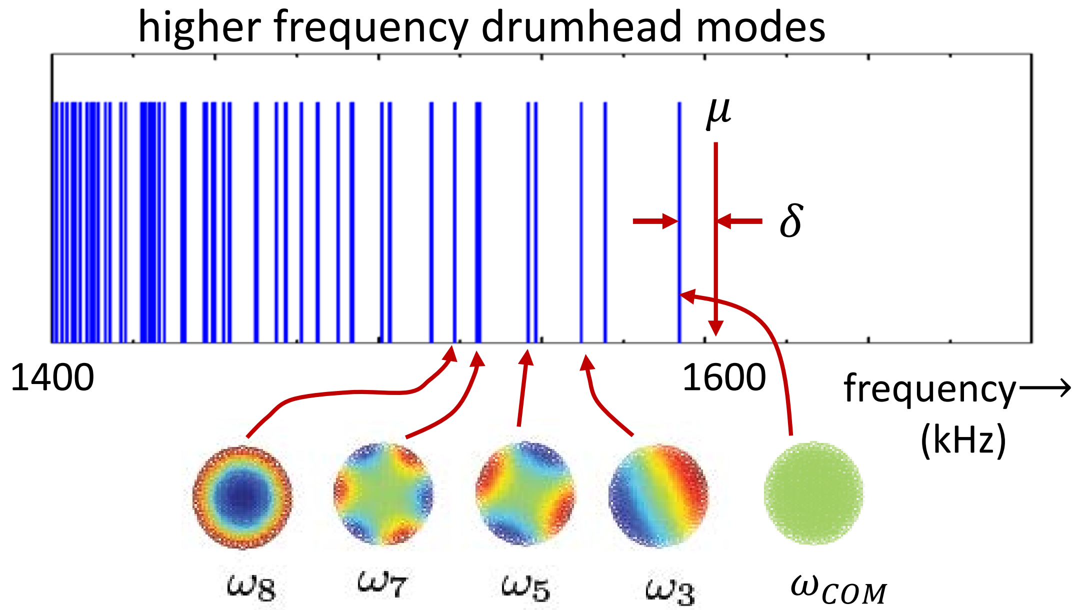
Consider $\mu = \omega_{COM} + \delta$

At $\tau = (2\pi)/\delta$, realize $H_{Ising} = \frac{J}{2}\sigma_1^z\sigma_2^z$,

$$J = \frac{F_0^2}{4\hbar m \omega_{COM}} \cdot \frac{1}{\mu - \omega_{COM}}$$

Engineering quantum magnetic couplings

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



For $\delta \gg \omega_{COM} - \omega_{m>1}$, realize effective $H_{Ising} = \frac{J}{N}\sum_{i<j}\sigma_i^z\sigma_j^z$

$$J = \frac{F_0^2}{4\hbar m \omega_{COM}} \cdot \frac{1}{\mu - \omega_{COM}}$$

Infinite range ⟹ Single axis twisting

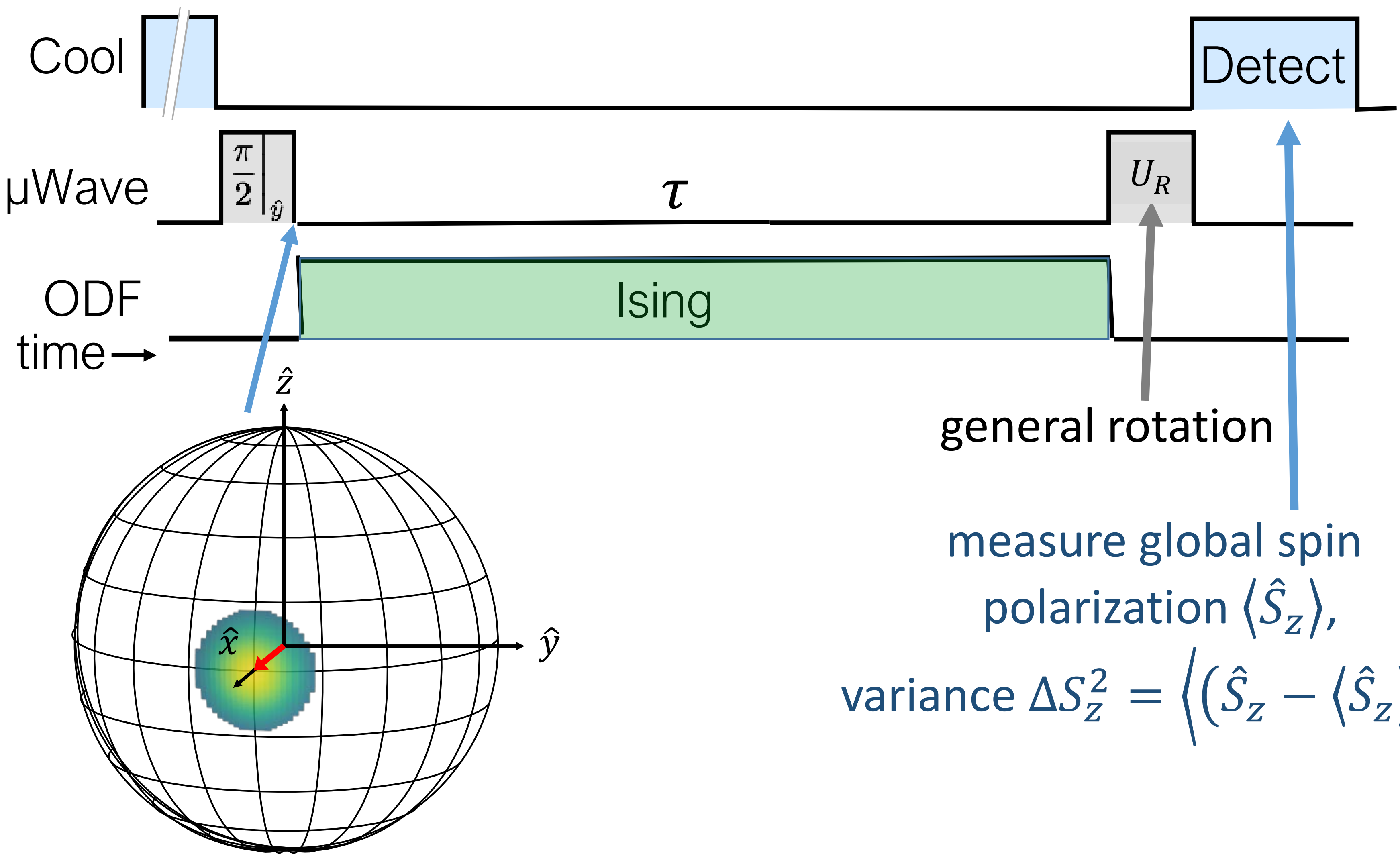
$H_{Ising} = \frac{J}{N}\sum_{i<j}\sigma_i^z\sigma_j^z = \frac{2J}{N}S_z^2$ where $S_z = \sum_i \frac{\sigma_i^z}{2}$

generates a "cat state" $\frac{1}{\sqrt{2}}\{|\uparrow\uparrow\uparrow\cdots\uparrow\rangle_x + |\downarrow\downarrow\downarrow\cdots\downarrow\rangle_x\}$

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

Benchmarking quantum dynamics

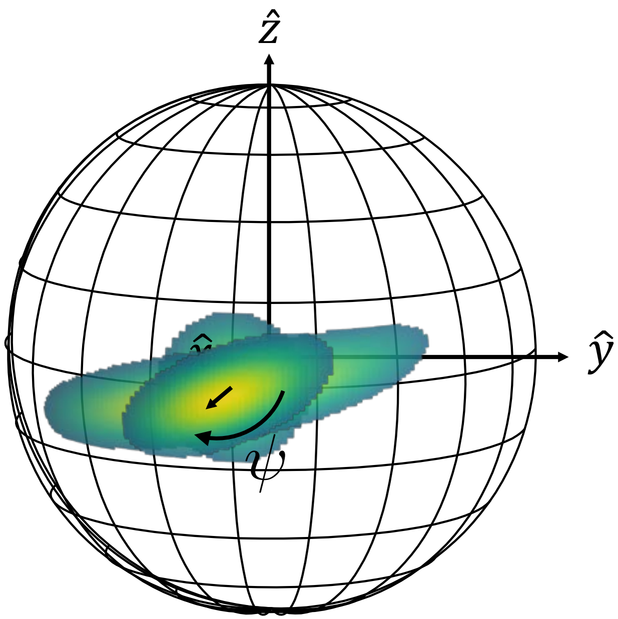
- employ infinite range interactions $H_{Ising} \approx \frac{2J}{N} S_z^2$, $S_z \equiv \sum_i \sigma_i^z / 2$
- prepare eigenstate of $H_{\perp} = \sum_i B_{\perp} \hat{\sigma}_i^x$, turn on H_{Ising}

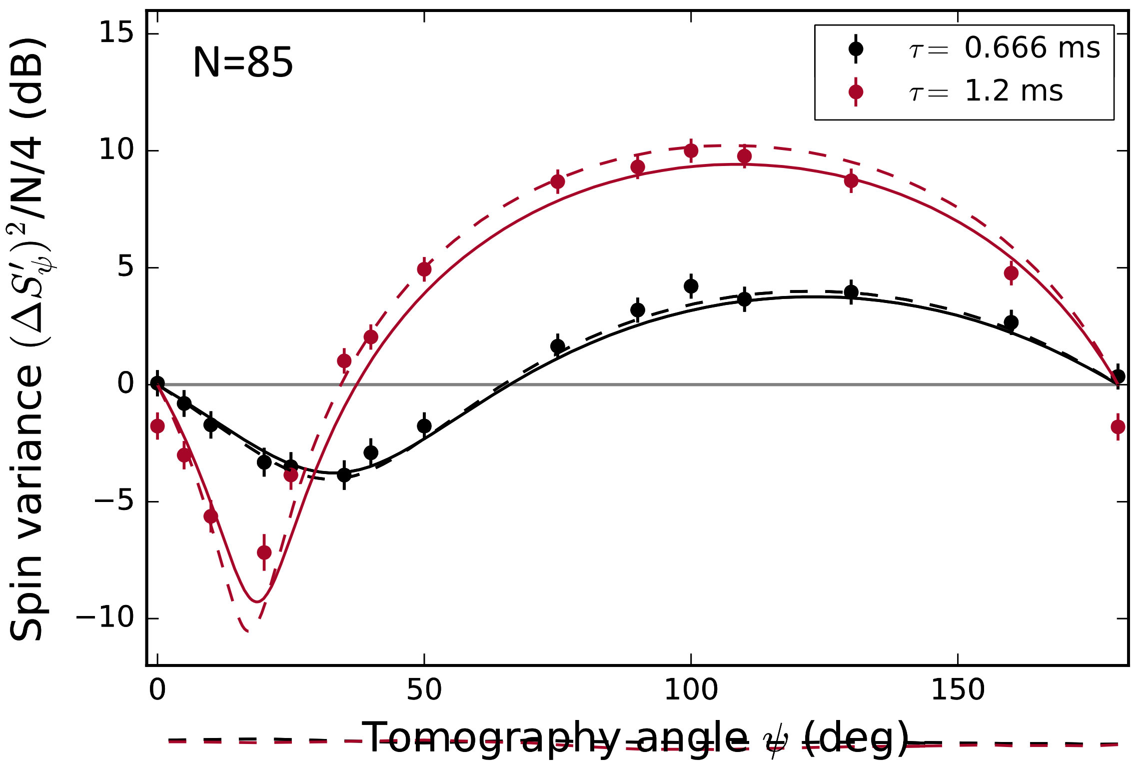


measure global spin polarization $\langle \hat{S}_z \rangle$,
variance $\Delta S_z^2 = \left\langle \left(\hat{S}_z - \langle \hat{S}_z \rangle \right)^2 \right\rangle$

Benchmarking quantum dynamics

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

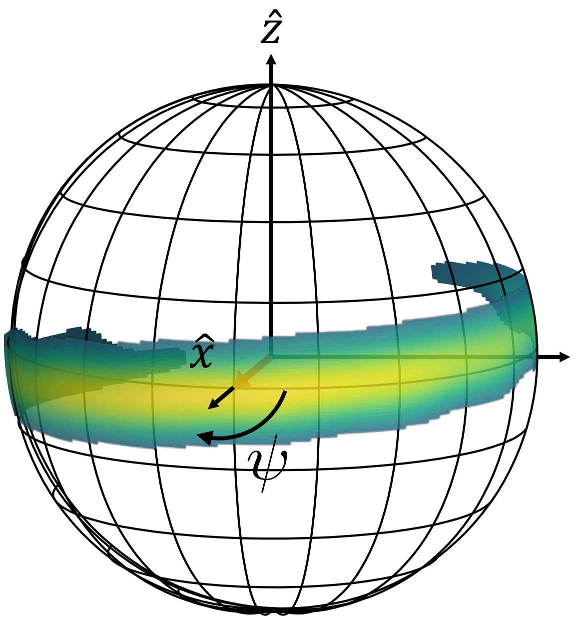


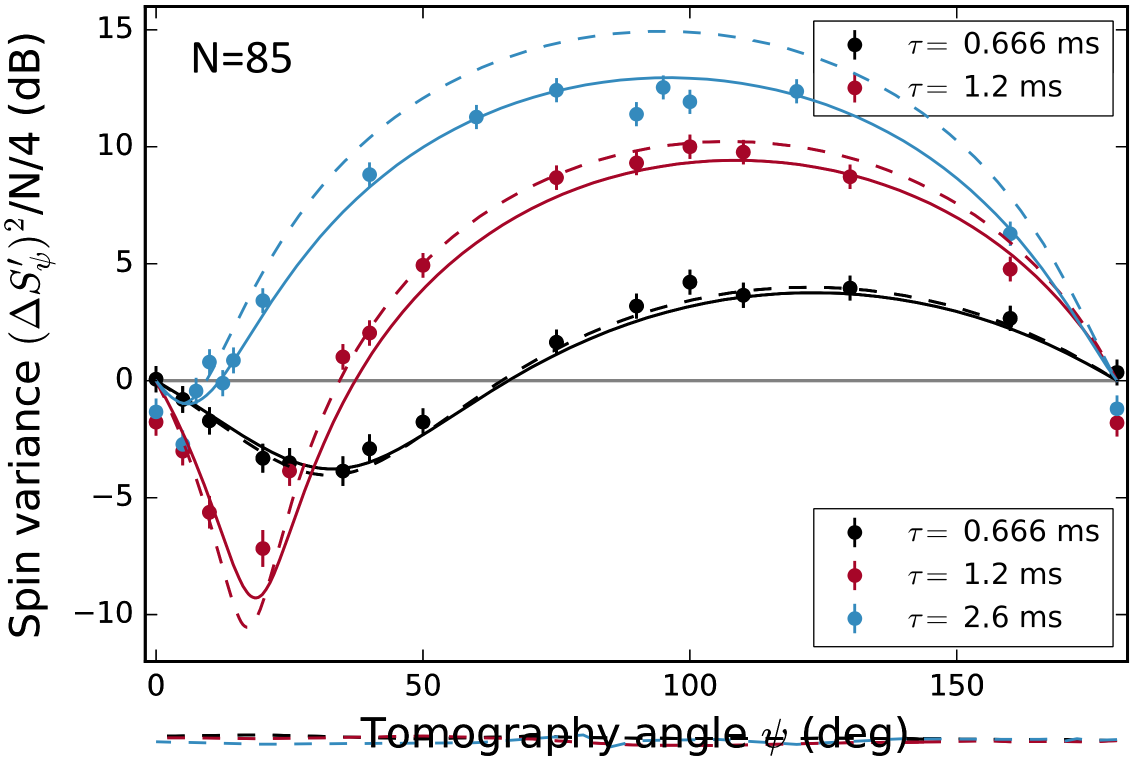


- Measurements of Ramsey squeezing parameter ⇒ prove entanglement for $25 < N < 220$
- Largest inferred squeezing: -6.0 dB

Benchmarking quantum dynamics

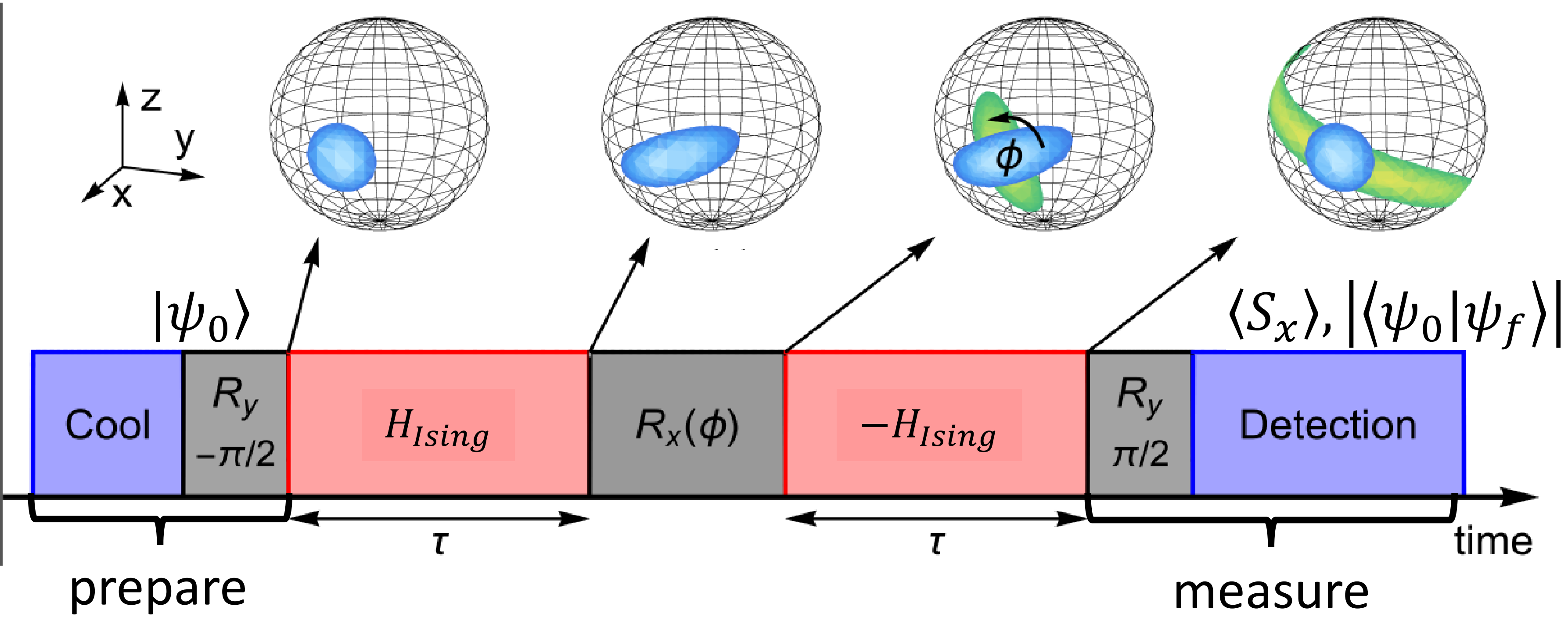
Bohnet *et al.*, *Science* 352, 1297 (2016)





Multiple quantum coherence protocol

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



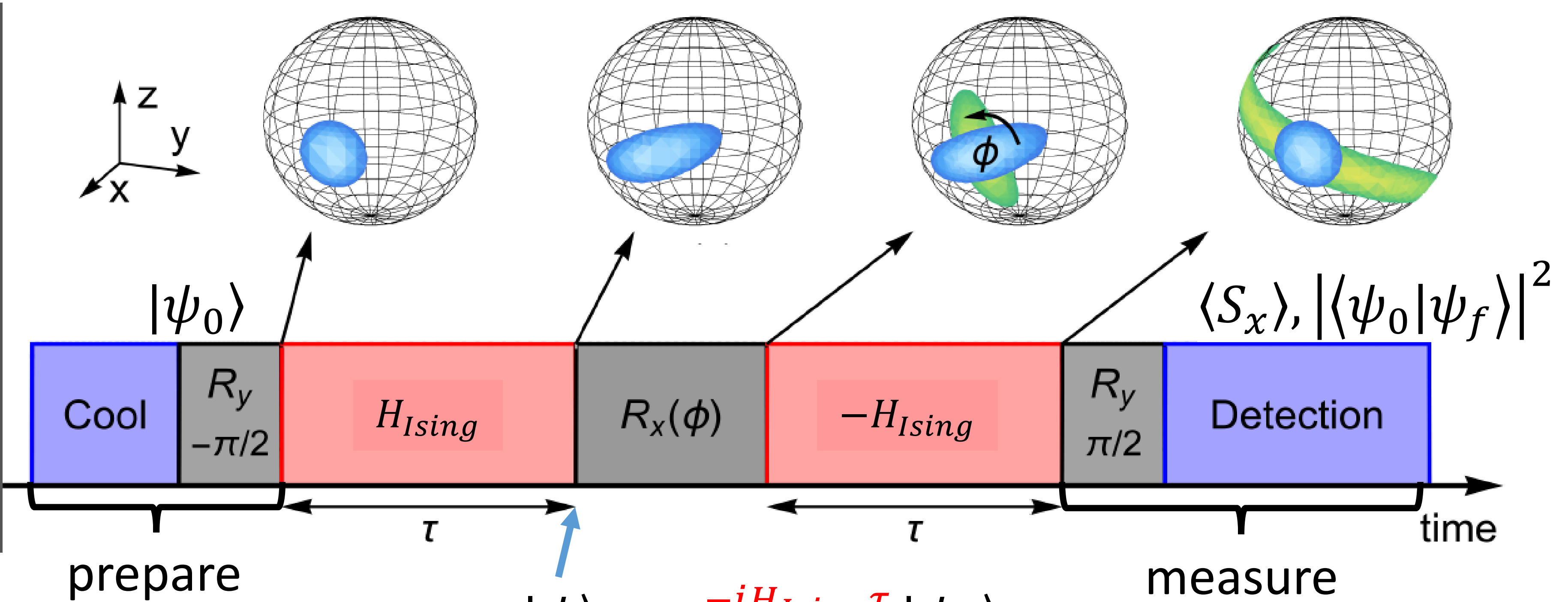
Time reversal of the Ising dynamics

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

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)

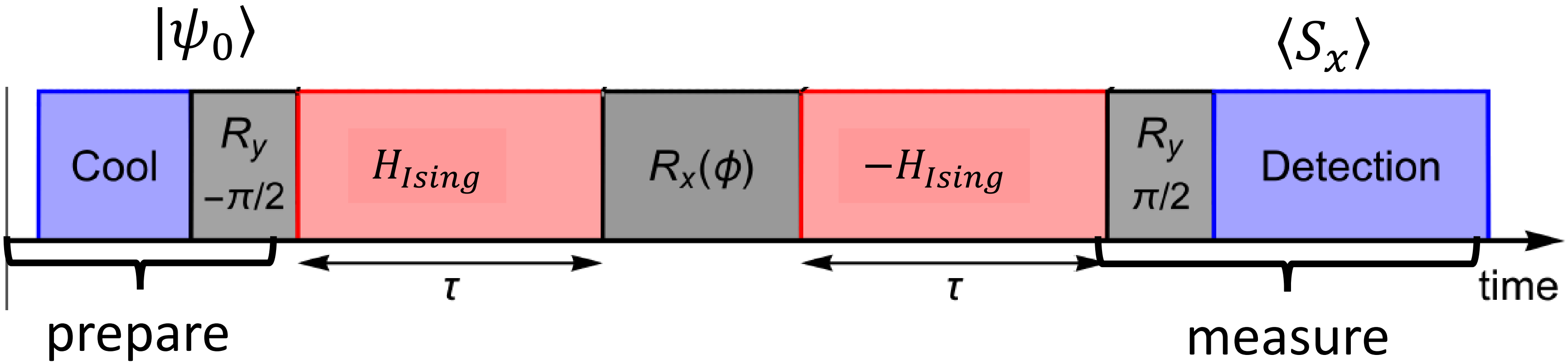


$$|\psi\rangle \equiv e^{-iH_{Ising}\tau} |\psi_0\rangle$$

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

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

Multiple quantum coherence protocol



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

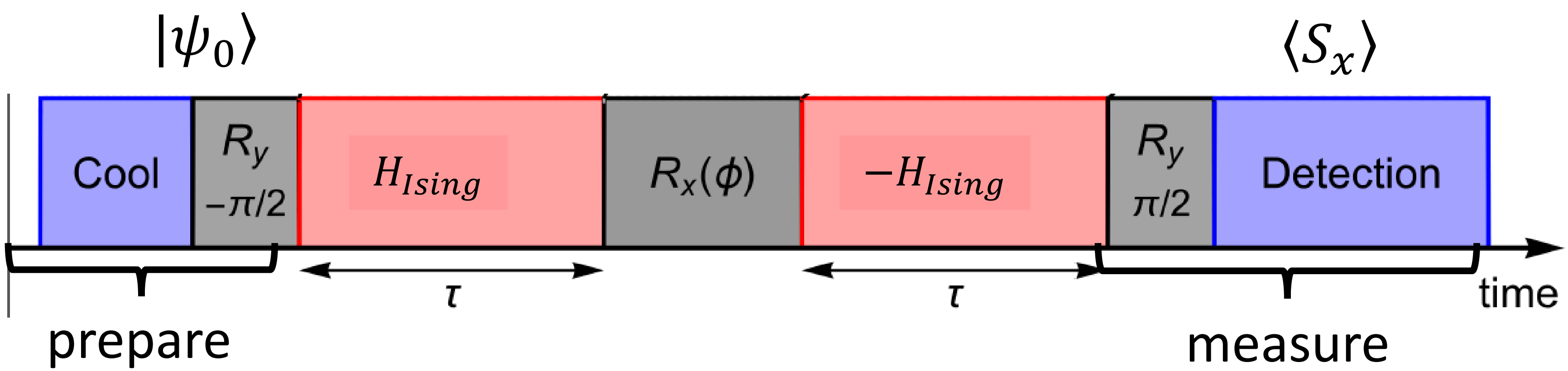
$$= \frac{2}{N} \langle \Psi_0 | \, \underbrace{e^{iH_{Ising}\tau} \, W^\dagger \, e^{-iH_{Ising}\tau}}_{W^\dagger(t)} \underbrace{V^\dagger}_{V^\dagger(0)} \, \underbrace{e^{iH_{Ising}\tau} \, W \, e^{-iH_{Ising}\tau}}_{W(t)} \underbrace{V}_{V(0)} | \Psi_0 \rangle$$

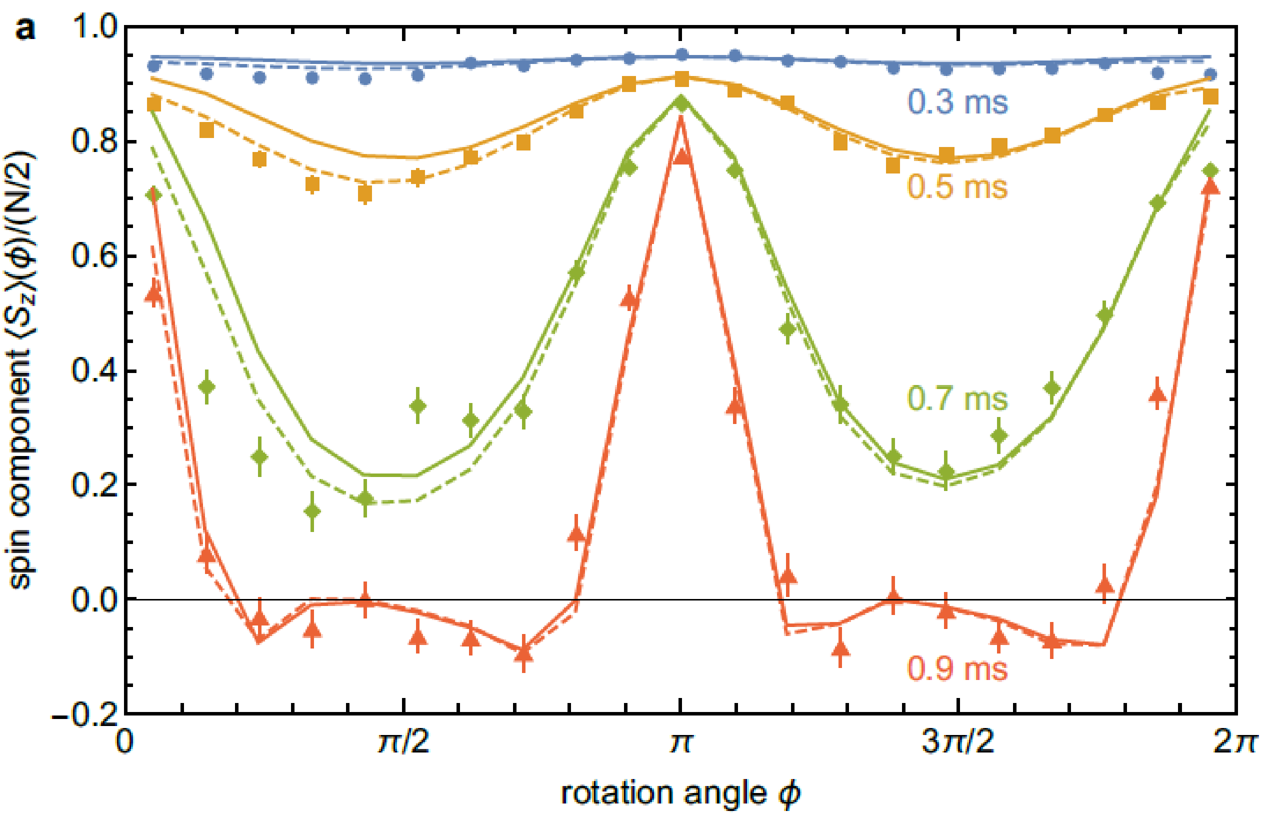
Out-of-time-order correlation (OTOC) function

$\Rightarrow$ **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)

MQC protocol – $\langle S_x \rangle$ measurement





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

$J \lesssim 5kHz$

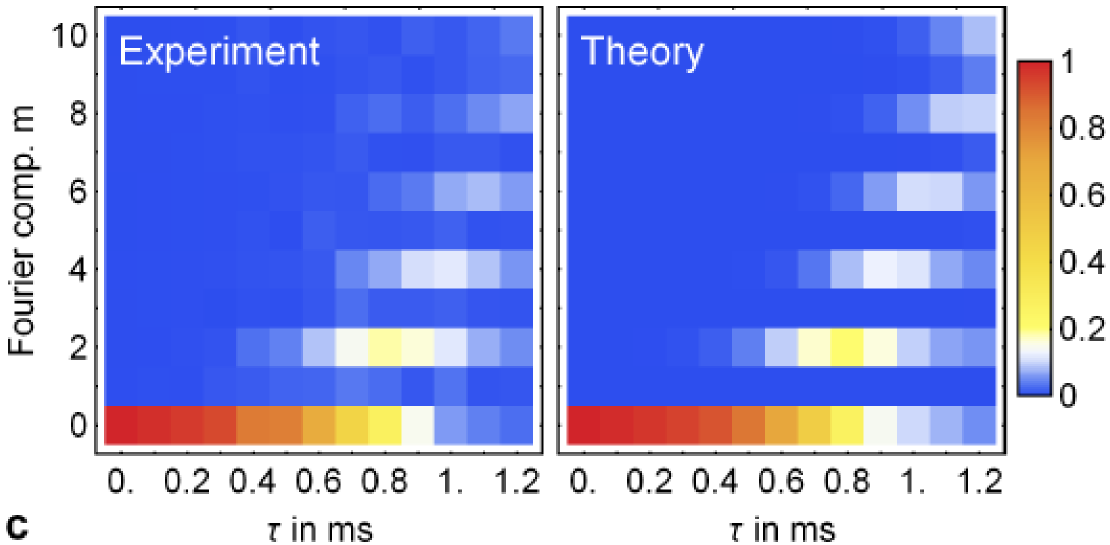
$N = 111$

$\Gamma = 93Hz$

[Gärttner, Bohnet et al. Nature Physics 2017]

Fourier transform of magnetization

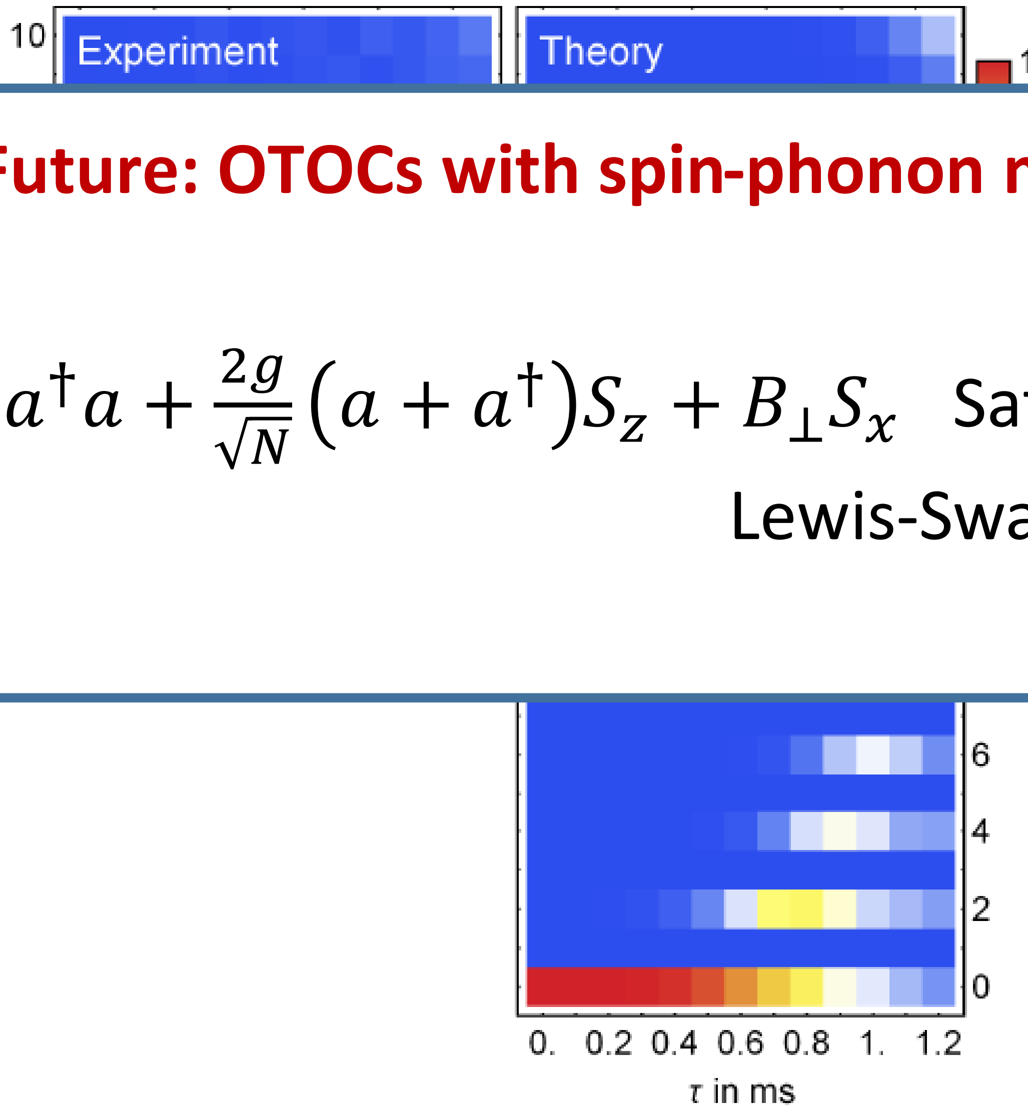
[Gärttner, Bohnet et al. Nature Physics 2017]



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

Fourier transform of magnetization

[Gärttner, Bohnet et al. Nature Physics 2017]



- Measure build-up

spread of quantum information

Future: OTOCs with spin-phonon models (Dicke model)

$$\delta a^\dagger a + \frac{2g}{\sqrt{N}}(a + a^\dagger)S_z + B_\perp S_x$$

Safavi-Naini, ..PRL (2018)

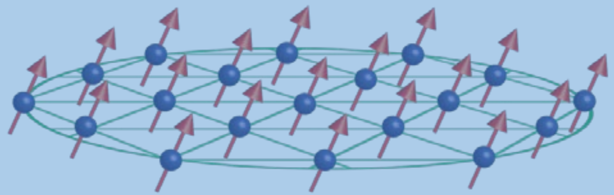
Lewis-Swan, .. arXiv:1808.07134

Outline:

- Penning trap features
  - high field qubit, modes, ground-state cooling

- Quantum simulation - engineering Ising interactions with spin-dependent forces

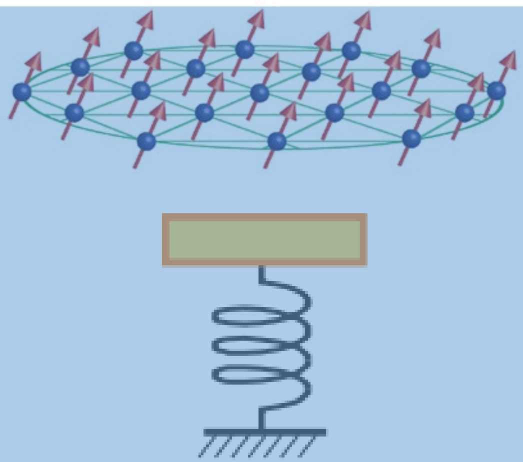
$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$



  - benchmark quantum dynamics through spin-squeezing and multi-quantum coherence protocol (Loschmidt echo)

- Stronger interactions – parametrically drive the phonons

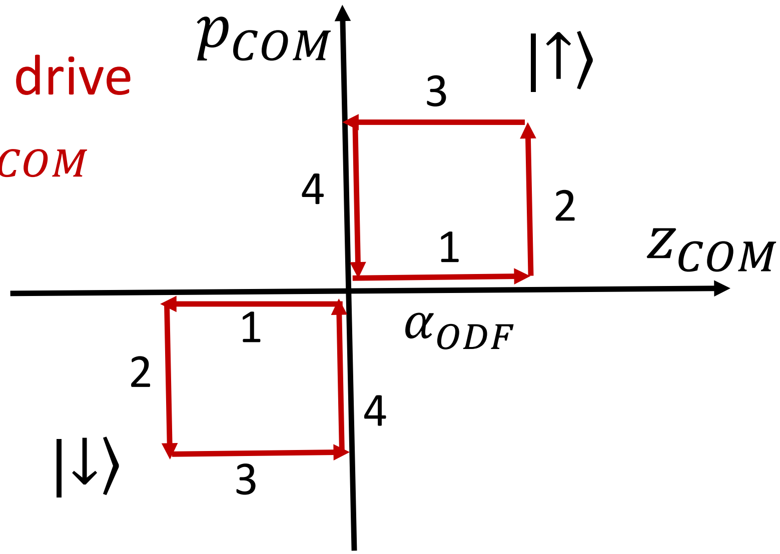
- Sensing small COM (center-of-mass) motion
  - spin-dependent forces



Stronger interactions by parametric amplification

- Spin interactions induced by spin-dependent acquisition of a geometric phase

resonant drive
$\mu = \omega_{COM}$



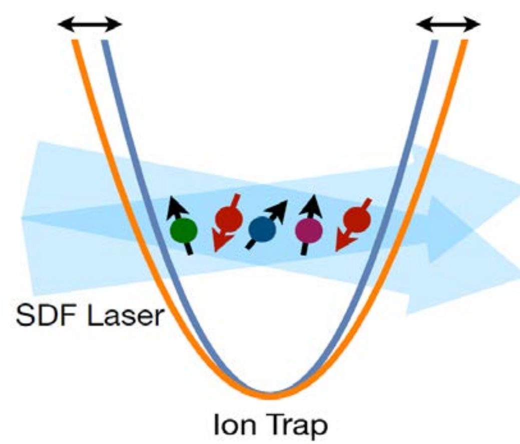
1. ODF(0)
2. ODF($\frac{\pi}{2}$)
3. ODF(π)
4. ODF($-\frac{\pi}{2}$)

geometric phase
$\propto \alpha_{ODF}^2$

- Spin independent amplification of ODF displacements by squeezing $S(\xi)$

Squeezing operator $S(\xi) = \exp\left(\frac{1}{2}\left(\xi^* \hat{a}^2 - \xi \hat{a}^{*2}\right)\right), \xi = re^{i\theta} \equiv (g \cdot \Delta t)e^{i\theta}$

Generated by modulating the trap potential
at $2\omega_{COM}$ (a parametric drive)



Burd et al., arXiv:1812.0182 $\quad g/2\pi > 50$ kHz

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resonant drive

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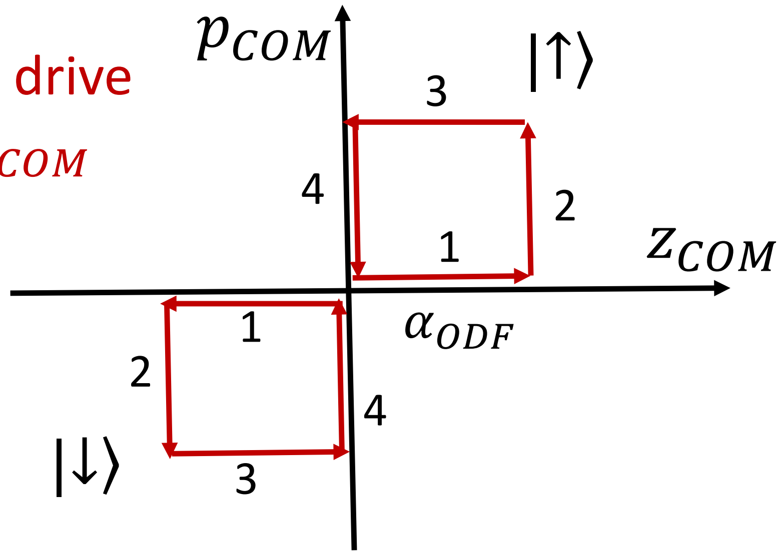

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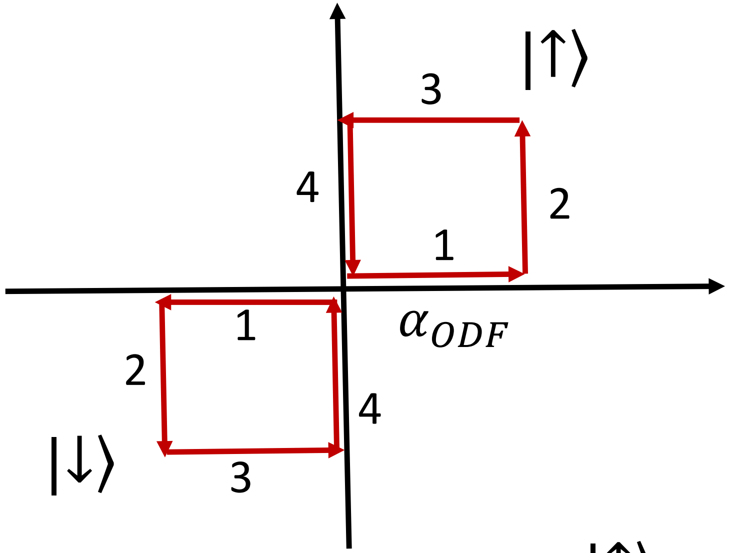
Spin-independent amplification:

$$S^\dagger\left(re^{i\theta}\right) \cdot ODF(\alpha_{ODF}) \cdot S\left(re^{i\theta}\right) = ODF(\alpha_{ODF}e^r)$$

Stronger interactions by parametric amplification

- Spin interactions induced by spin-dependent acquisition of a geometric phase

resonant drive $\mu = \omega_{COM}$



1. ODF(0)
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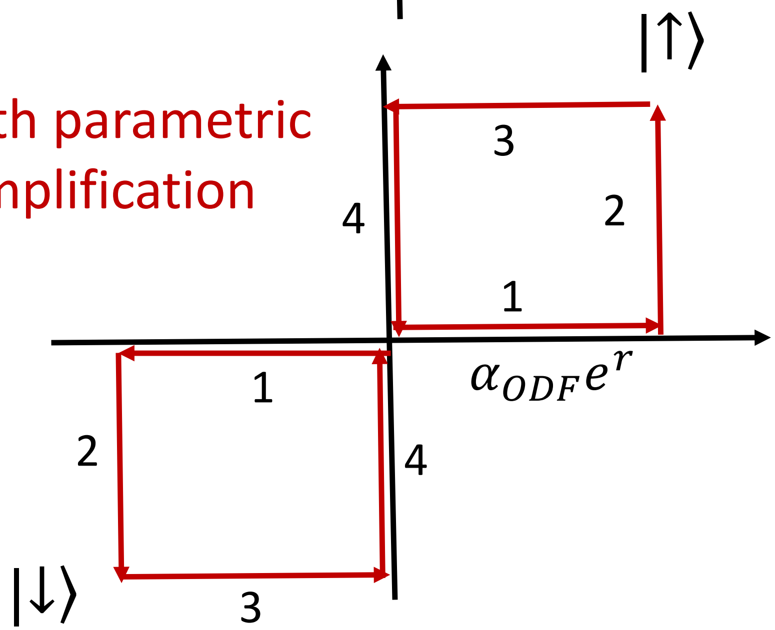
4. ODF($-\frac{\pi}{2}$)

geometric phase $\propto \alpha_{ODF}^2$

with parametric amplification



1. $S^\dagger(\xi_1)\cdot$ODF(0)$\cdot\, S(\xi_1)$
2. $S^\dagger(\xi_2)\cdot$ODF($\frac{\pi}{2}$)$\cdot\, S(\xi_2)$
3. $S^\dagger(\xi_3)\cdot$ODF(π)$\cdot\, S(\xi_3)$
4. $S^\dagger(\xi_4)\cdot$ ODF($-\frac{\pi}{2}$)$\cdot\, S(\xi_4)$

geometric phase $\propto \alpha_{ODF}^2 e^{2r}$

Stronger interactions by parametric amplification

Trapped Ion Quantum Information Processing with Squeezed Phonons, Wenchao Ge, Brian C. Sawyer, Joseph W. Britton, Kurt Jacobs, John J. Bollinger, and Michael Foss-Feig, Phys. Rev. Lett. **122**, 030501 (2019)

Wenchao Ge

Michael Foss-Feig

- continuous protocol with ODF and PA simultaneously applied

- ODF and PA drives off-resonant with the ion crystal mode

- sensitivity trade-offs with ODF and PA relative phase, mode frequency stability, Lamb-Dicke breakdown, ….

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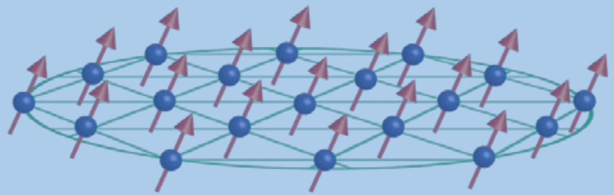

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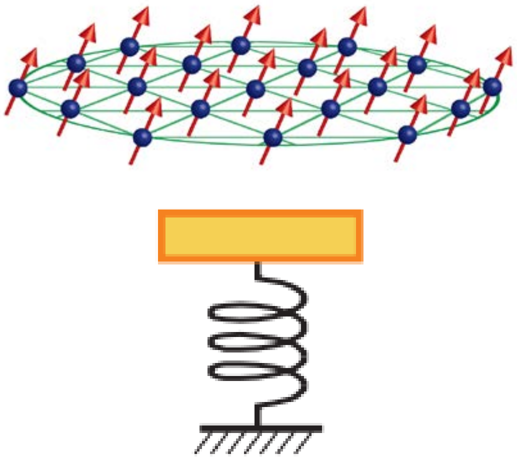


Motional amplitude sensing or
Trapped ions as sensitive $\vec{E}$-field and force detectors

Maiwald, *et al*., Nature Physics 2009 – 1 yN $Hz^{-1/2}$

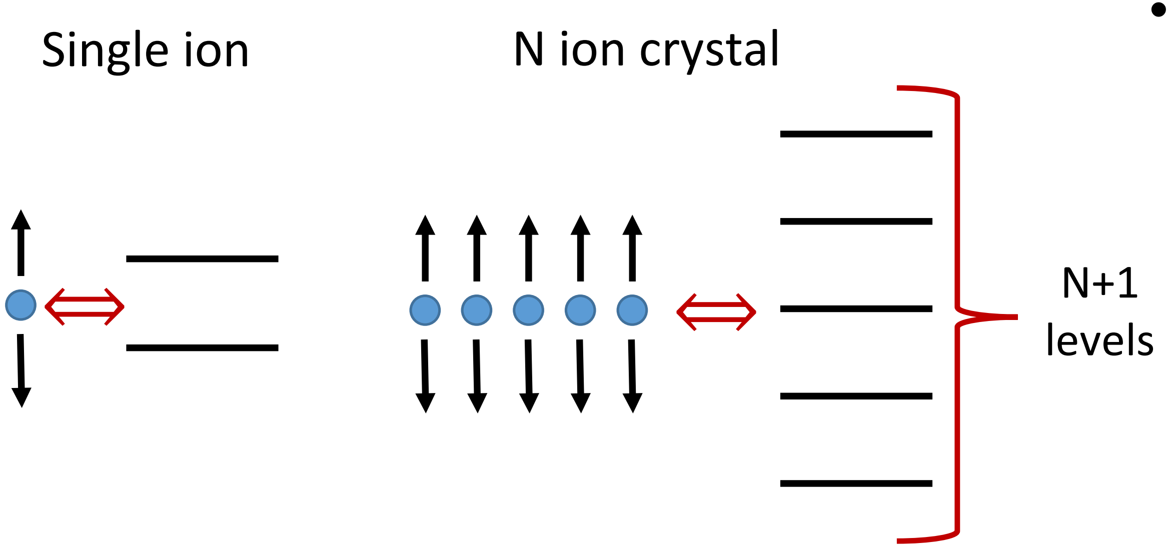
Hempel *et al*., Nature Photonics 2013 – detect single photon recoil

Shaniv, Ozeri, Nature Communications, 2017 – high sensitivity (∼28 zN $Hz^{-1/2}$) at low frequencies

⋮

Biercuk *et al*., Nature Nanotechnology, 2010 – 100-ion crystal (400 yN $Hz^{-1/2}$)

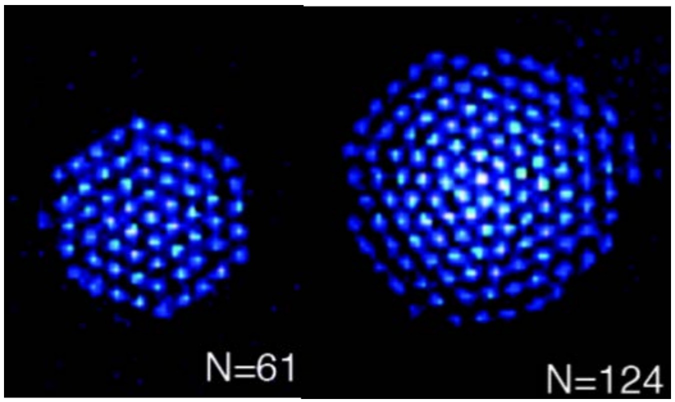
Basic idea: map motional amplitude onto spin precession



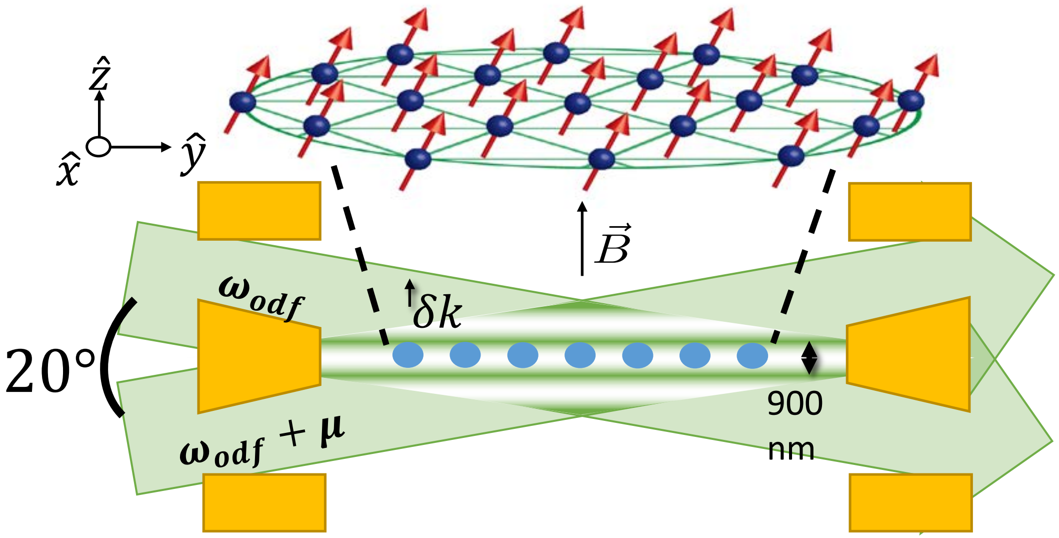
<u>N ion crystal</u>

- Less projection noise
- Smaller zero-point motion, $z_{zpt} \approx 2\ \text{nm}$ for N=100

$\sim \frac{1}{\sqrt{N}}$



Sensing small center-of-mass motion



$$F_\uparrow(t) = -F_\downarrow(t) = F_0 \cos(\mu t)$$

$$H_I = \sum_i F_0 \cos(\mu t)\, \hat{z}_i \hat{\sigma}_i^Z$$

Implement classical COM oscillation: $\hat{z}_i \rightarrow \hat{z}_i + Z_c\, cos(\omega t + \phi)$

$$H_I \cong F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi] \sum_i \frac{\hat{\sigma}_i^Z}{2}$$
$$= F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi]\ \hat{S}_z$$

For $\mu = \omega$, produces spin precession with rate $\propto F_0 \cdot Z_c \cos(\phi)$

Gilmore et al., PRL 2017

$$\left.\frac{Z_c^2}{\delta Z_c^2}\right|_{\text{limiting}} = \left[\frac{Z_c}{0.2\ \text{nm}}\right]^2$$

$\boldsymbol{\omega \neq \omega_z}$
ϕ random

Sensing small center-of-mass motion

Future:

- Fixed phase sensing off-resonance (i.e. fixed ϕ in $Z_c cos(\omega t + \phi)$)
  - 74 pm in single experimental trial (compared to 2 nm zero-point)
  - 18 pm/$\sqrt{Hz}$
  - Further sensitivity with spin squeezed states

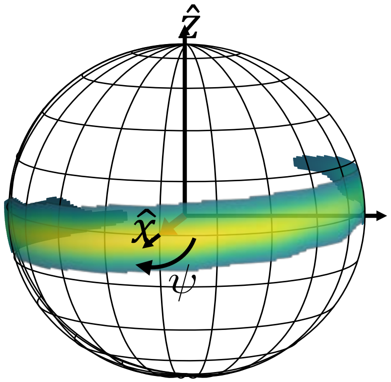
- On-resonance with COM mode
  - Enhance force and electric field sensitivities by $Q \sim 10^6$
  - Protocols for evading zero-point fluctuations, backaction ??
  - 20 pm amplitude from a resonant 100 ms coherent drive
    - force/ion of 5×10^{-5} yN
    - electric field sensitivity < 0.5 (nV/m)/$\sqrt{\mathrm{Hz}}$

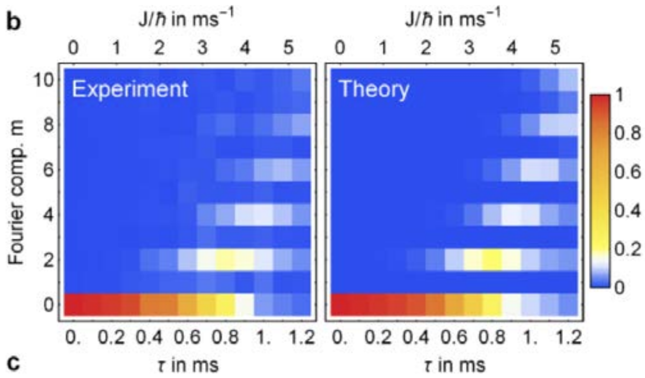
$\Rightarrow$ potential search for axion and hidden photon dark matter

Summary:

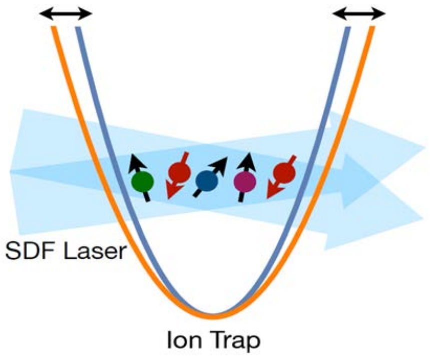
- Penning traps useful for generating large 2d ion crystals

- engineered global entangling gate; benchmarked through spin-squeezing, multi-quantum coherence protocol





- improve coherence with parametric driving



- spin-motion coupling enables weak electric field sensing and potential dark matter searches

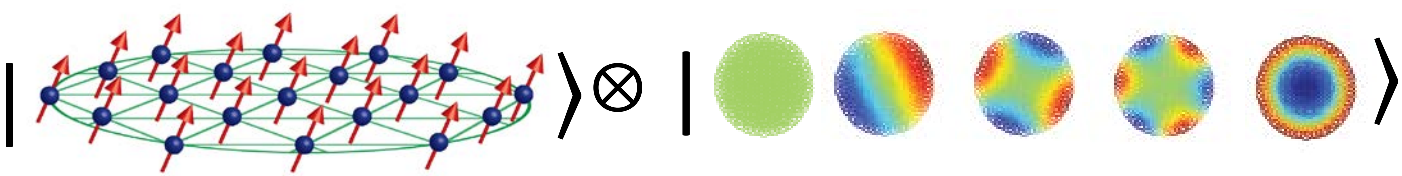
Open questions/unresolved issues

for quantum simulation and sensing with large trapped-ion crystals

- what is the best way to implement single-site control – rotations should be sufficient

- improve crystal stability – better in-plane cooling, …?

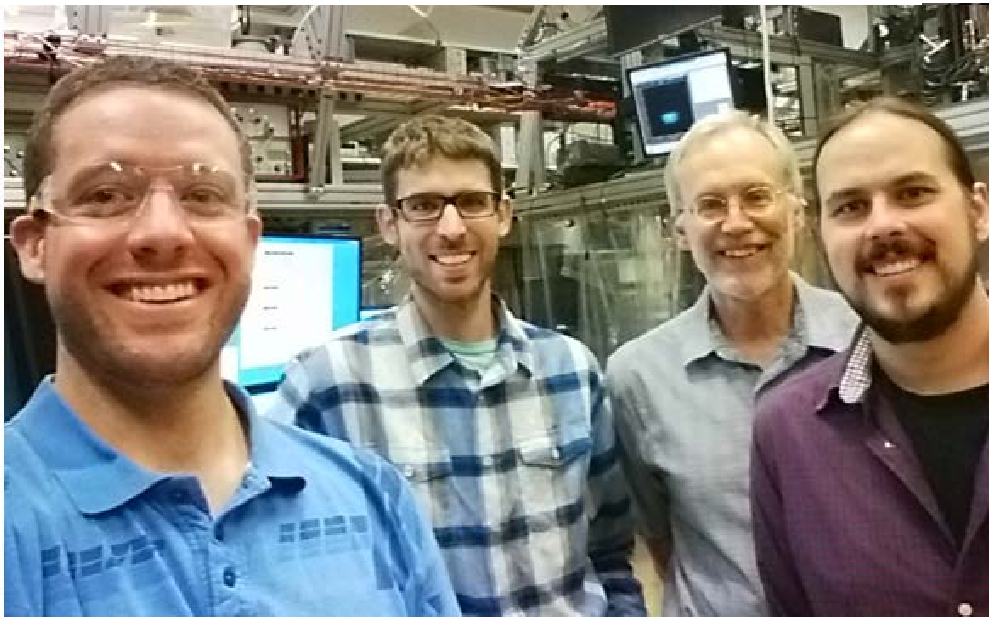
- in addition to PA, are there other manipulations of the phonons that are useful (or interesting)?



- extensions to 3-d crystals? – enables much larger N $(> 10^5)$ are there interesting experiments/questions to pursue with 3-d and large N ?

Lab selfie ~ 2014

2017



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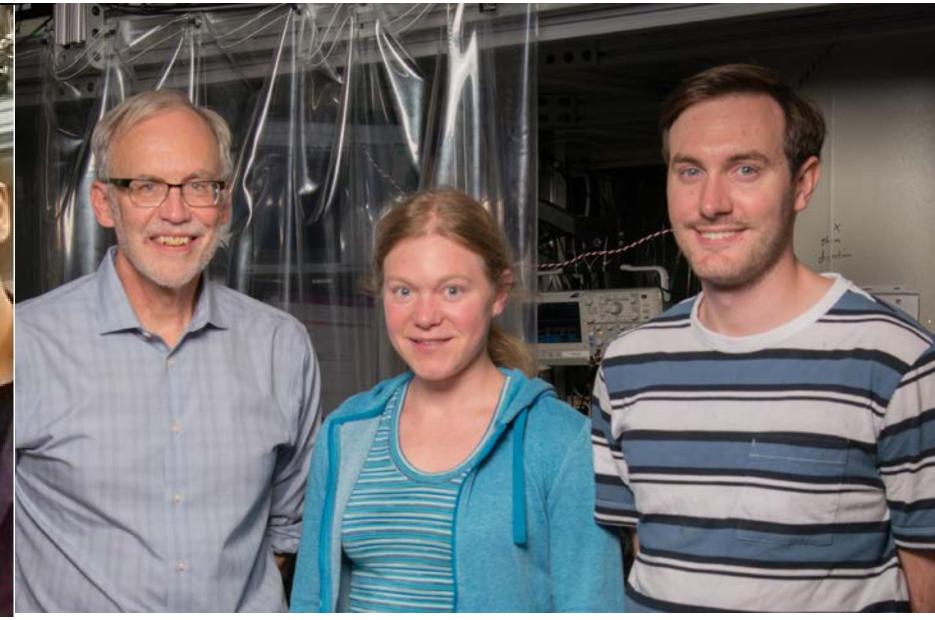

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