Quantum Simulation and Sensing with Large Trapped-Ion Crystals

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Ion storage group

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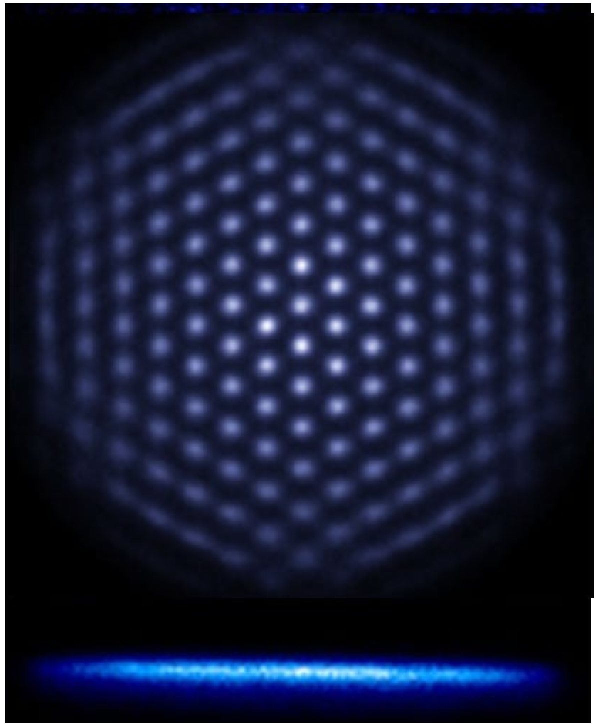
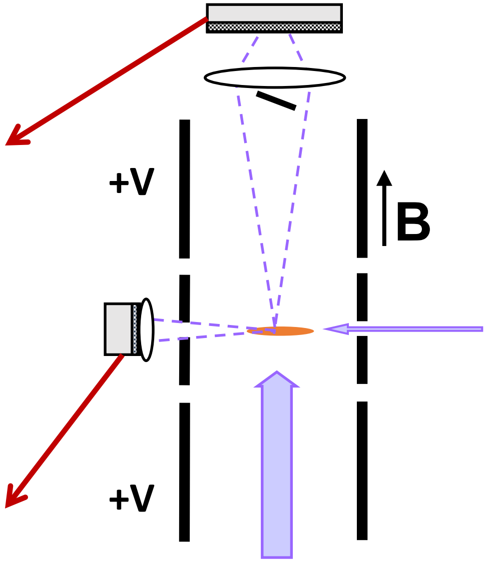
theory –Rey group (JILA/NIST)
Holland group (JILA/NIST)
Freericks group (Georgetown)
Michael Foss-Feig (Honeywell)
Dan Dubin (UCSD)

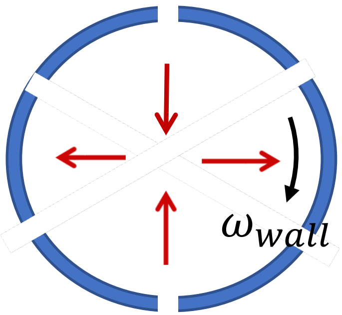
- Penning trap ⟺ system for controlling large ion crystals
- global single- and multi-qubit operations
- potential NISQ platform with intro of single σ_z rotations
- quantum sensing of displacements; weak electric fields





Outline:

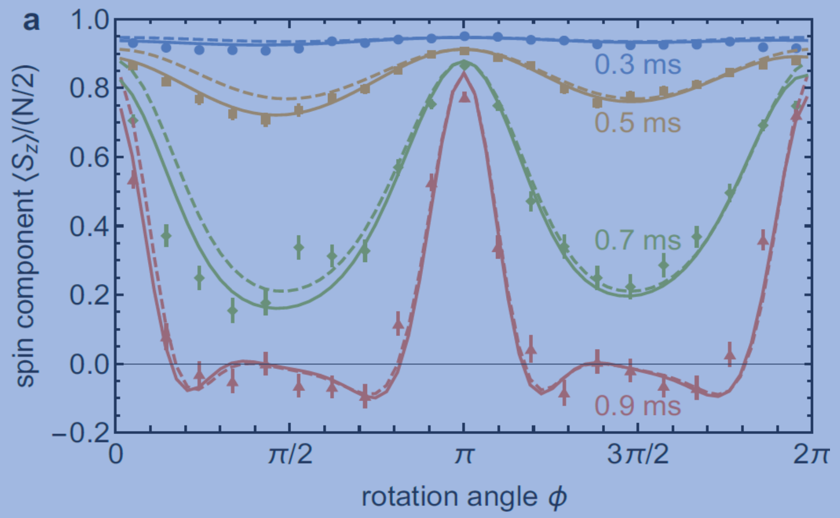
- ion crystals in Penning traps
  - high (4.5 T) magnetic field qubit
  - modes



- engineering tunable Ising interactions

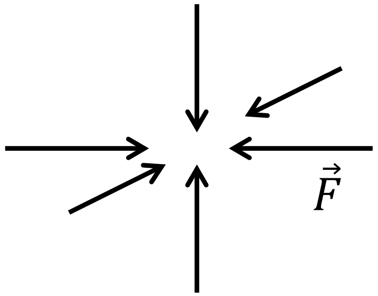
$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

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



- measuring weak motional excitations and electric fields

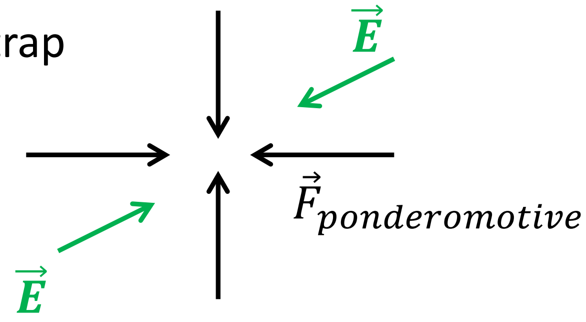
rf (Paul) trap vs Penning trap

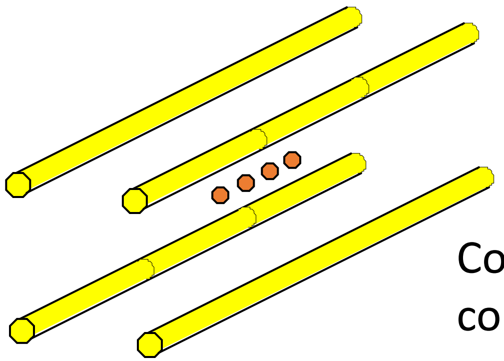


ideal ion trap

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

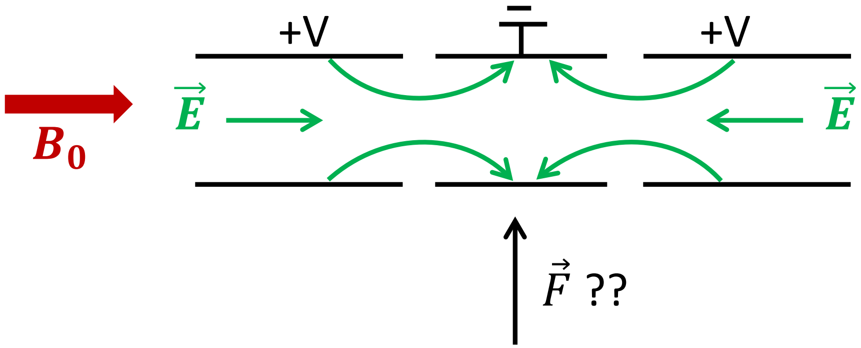
linear rf trap





Confinement due to conservation of energy

Penning trap

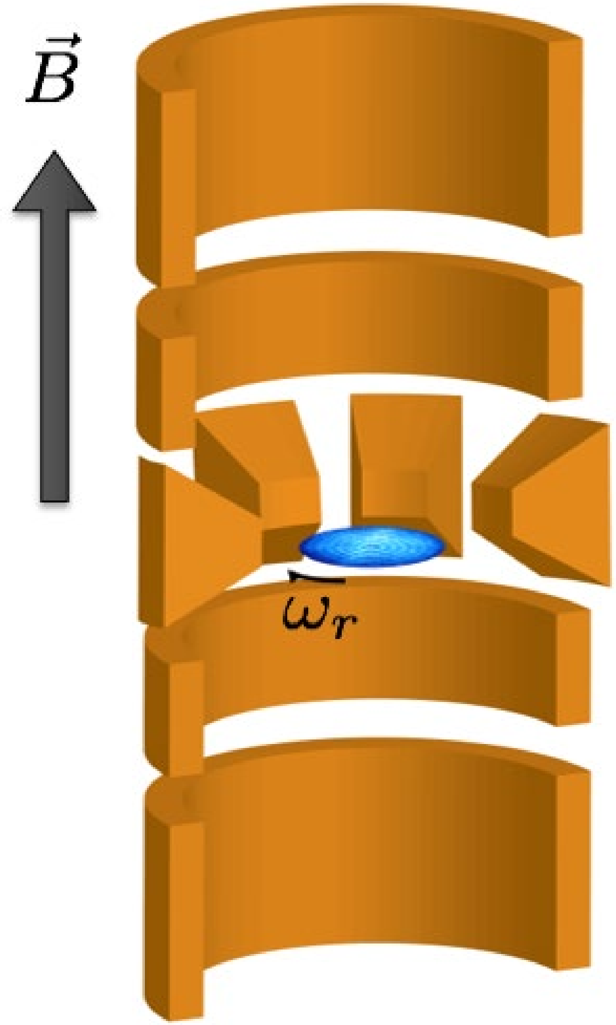


Dubin and O'Neil, RMP 71 (1999)

Radial confinement from conservation of angular momentum:

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

Penning trap: many particle confinement with static fields

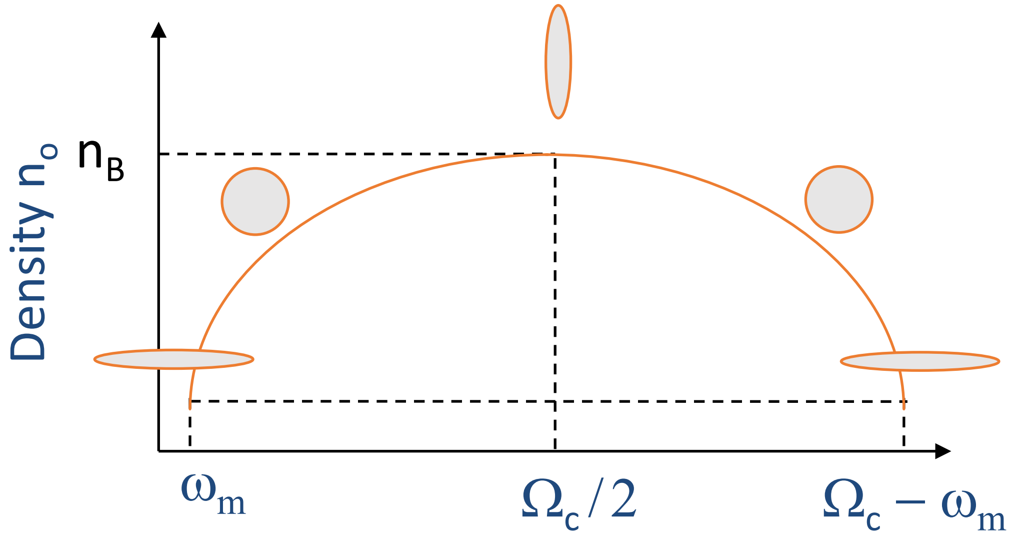


- radial confinement due to rotation –
  ion plasma rotates $v_\theta = \omega_r r$ due to ***ExB*** fields

  Lorentz force from rotation is directed radially inward

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

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



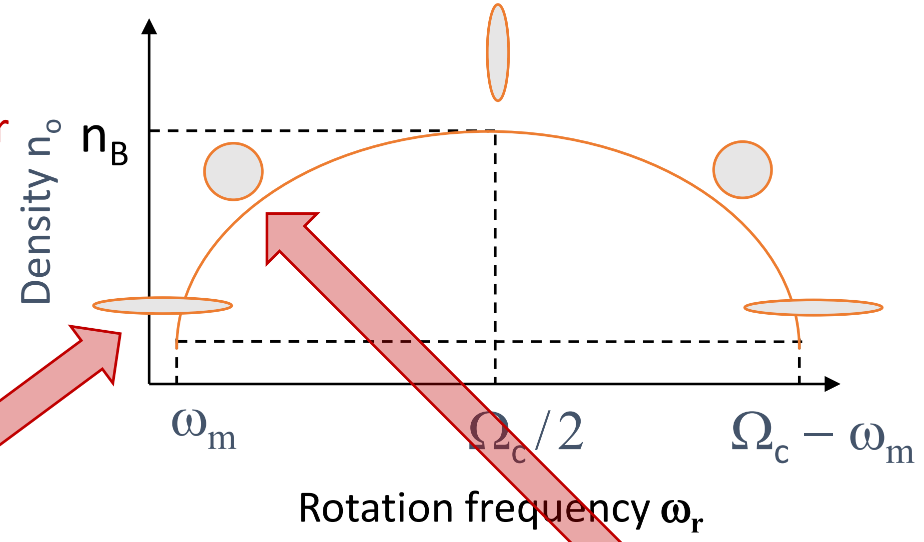
$^9Be^+$, B_0 = 4.5 T

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

Ion crystals form as a result of minimizing Coulomb potential energy

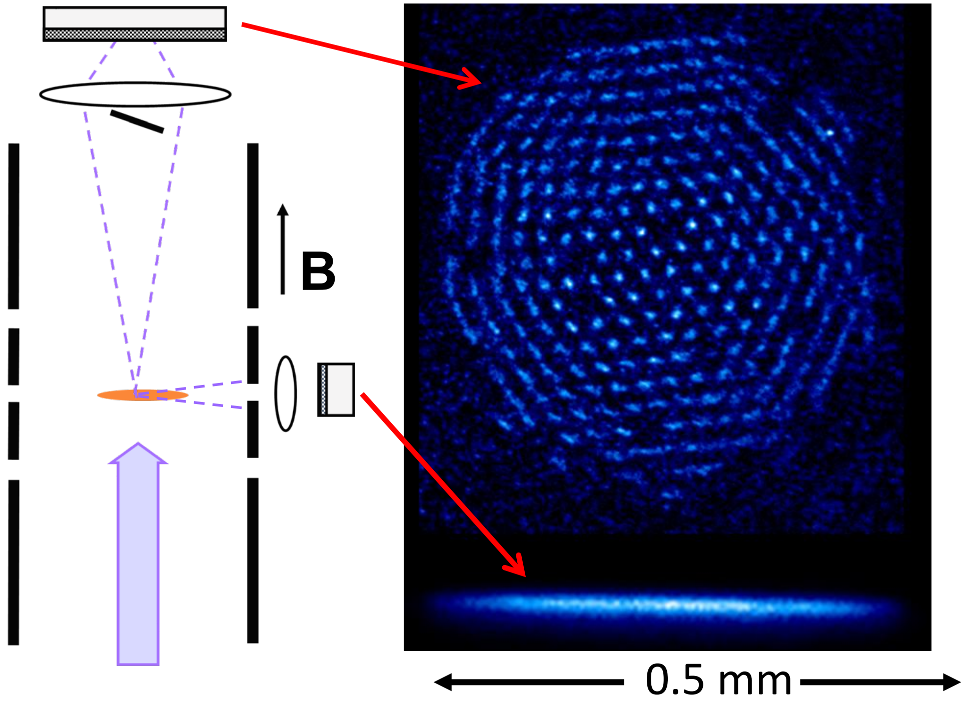
T→ 0.4 mK (Doppler laser cooling) ⇒ ${q^2}/{a_{WS}} \gg k_B T, 2a_{WS} \sim$ ion spacing

type of crystal, nearest neighbor ion spacing depend on ω_r



Mitchell et.al., Science (1998)

single planes

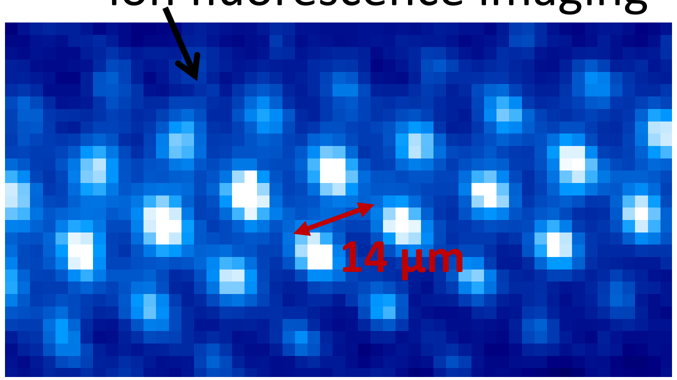


bcc crystals with N>100 k

observed with:

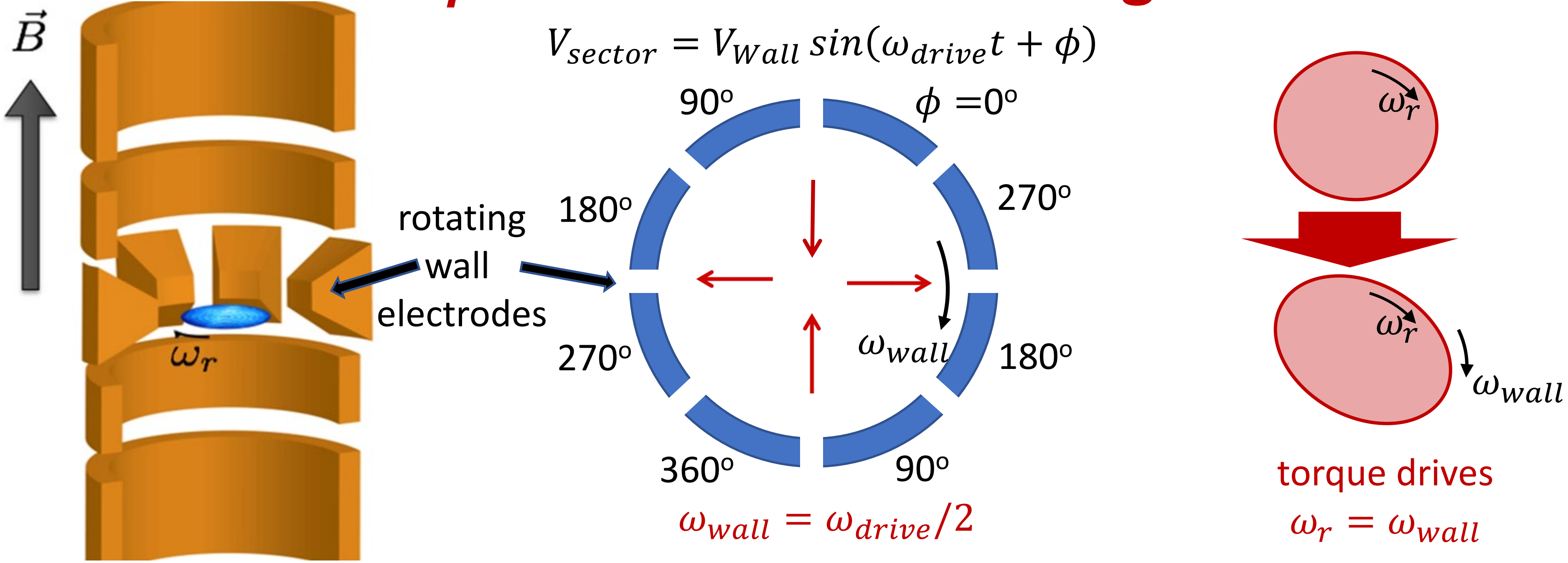
Bragg scattering

ion fluorescence imaging



Precise ω_r control with a rotating electric field

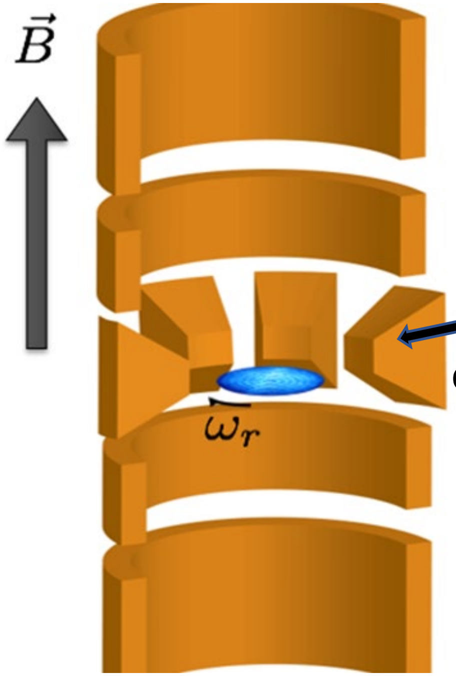
$$V_{sector} = V_{Wall}\, sin(\omega_{drive} t + \phi)$$



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

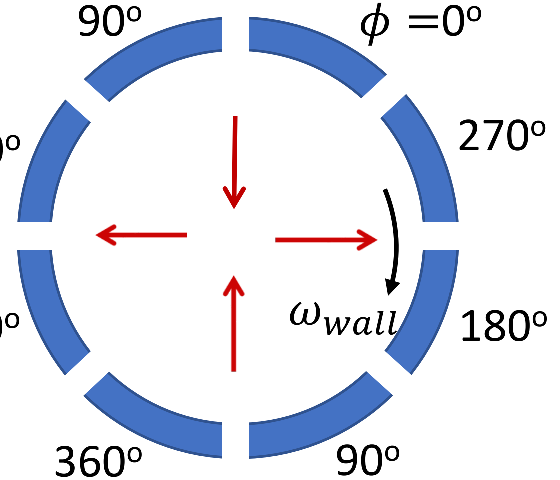
torque drives
$\omega_r = \omega_{wall}$

Precise ω_r control with a rotating electric field



rotating wall electrodes

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



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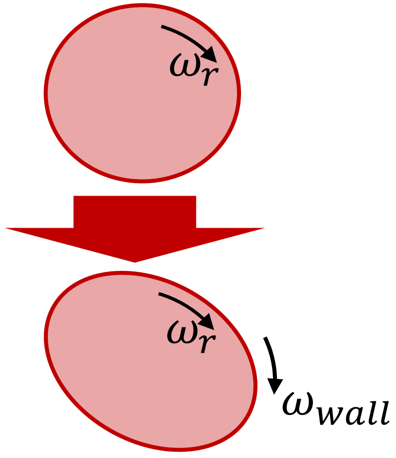
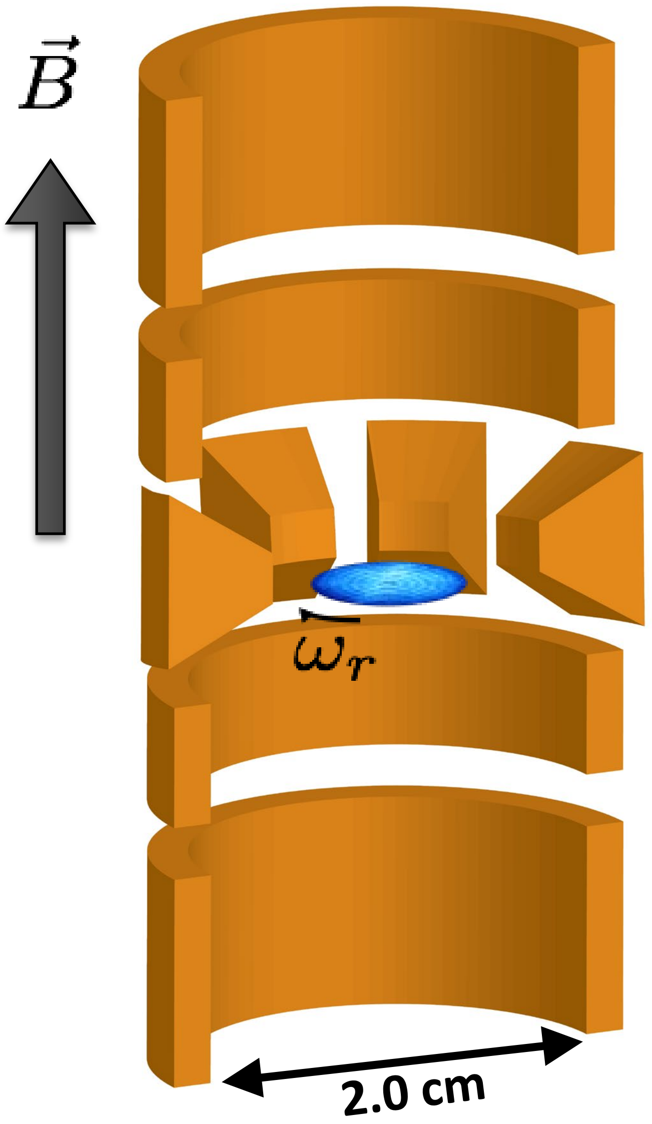
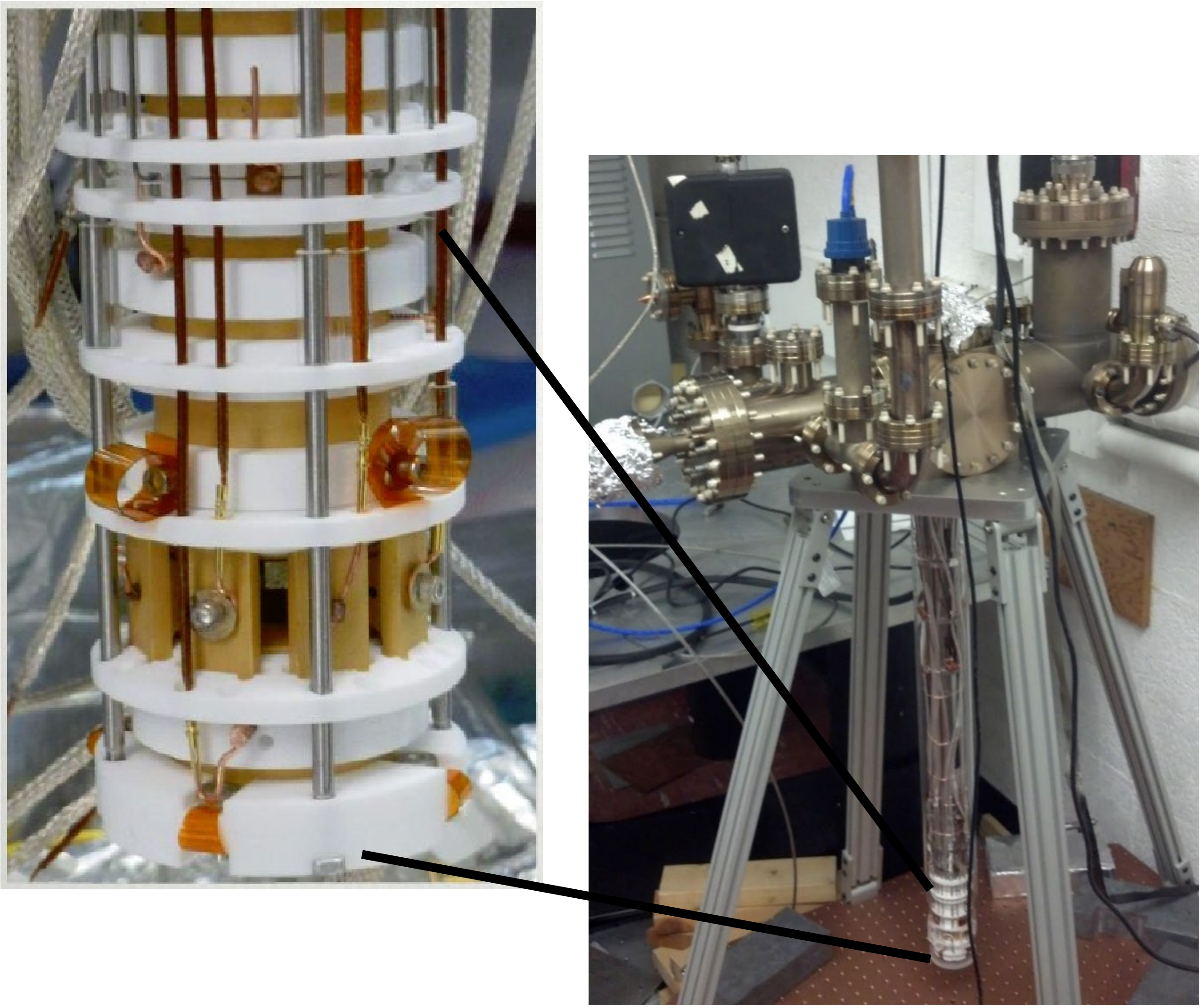


torque drives
$\omega_r = \omega_{wall}$

NIST Penning trap





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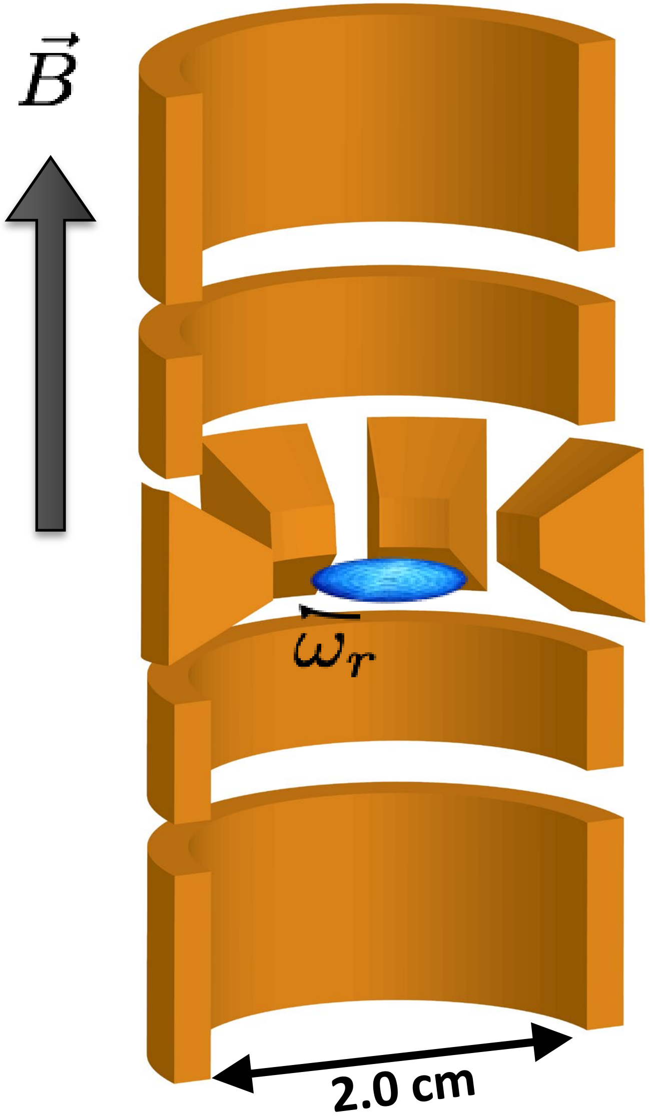
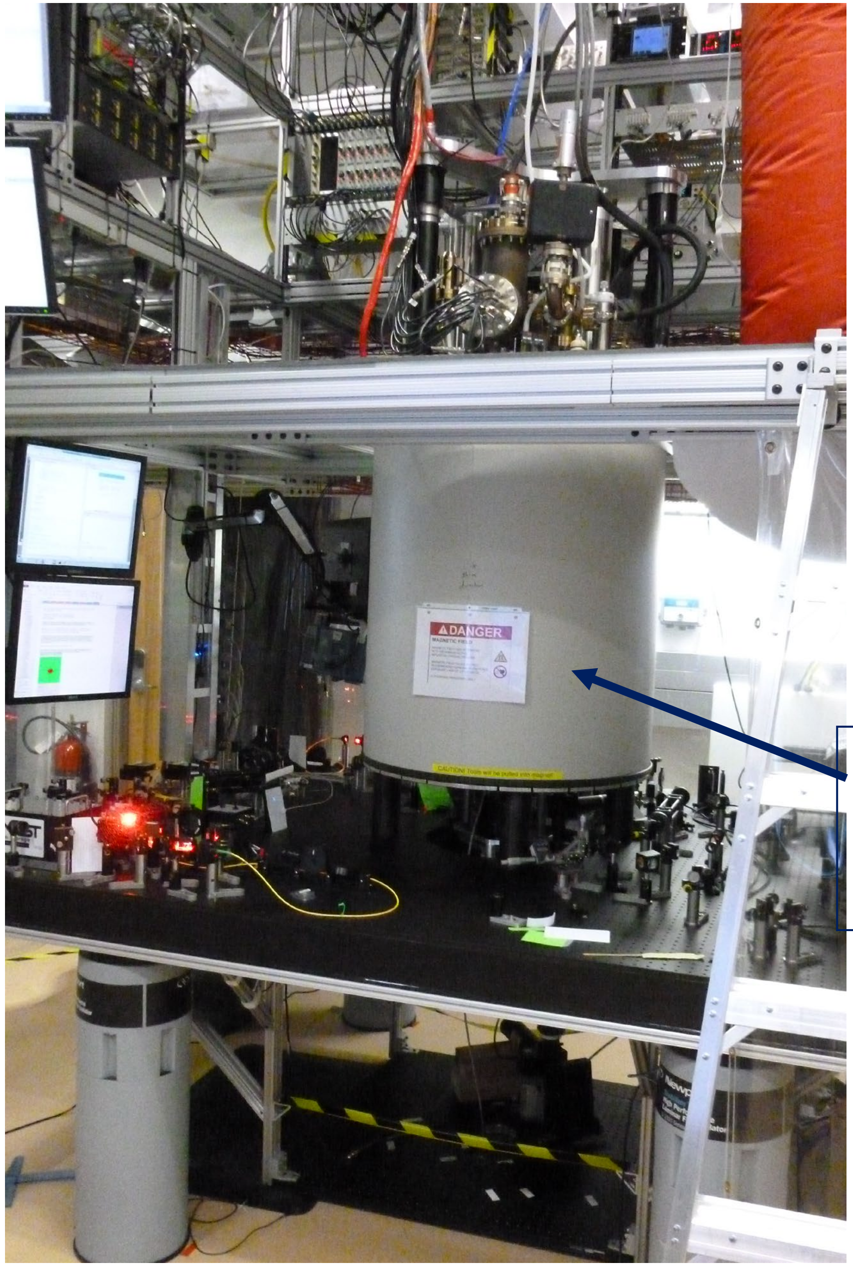




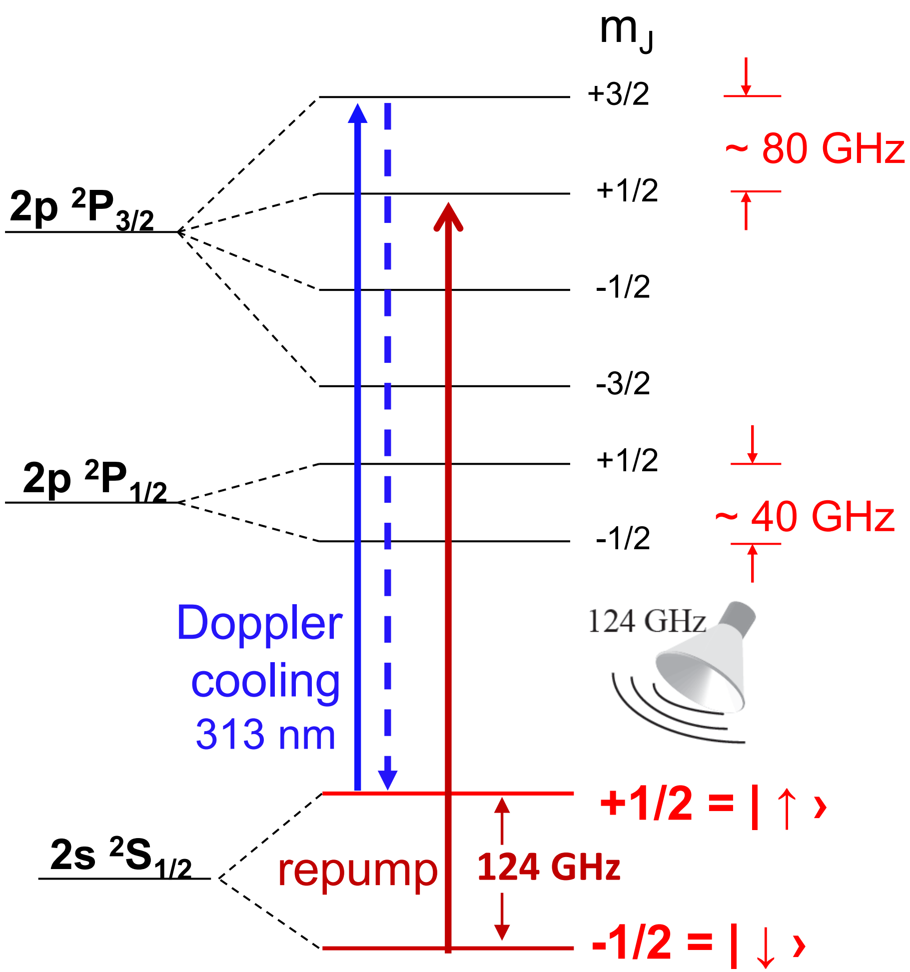
4.5 Tesla superconducting solenoid

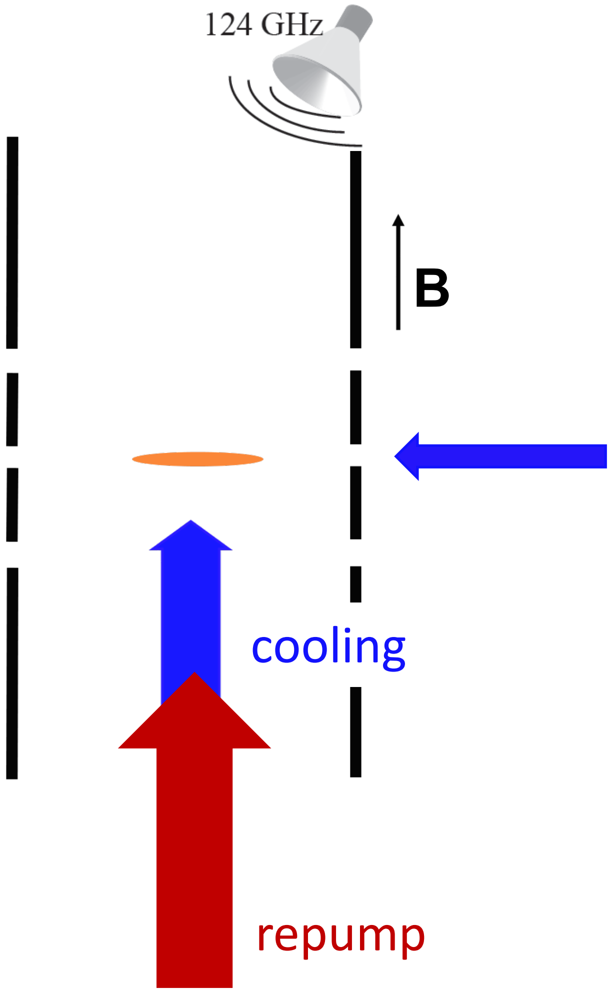
Be$^+$ high magnetic field qubit

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

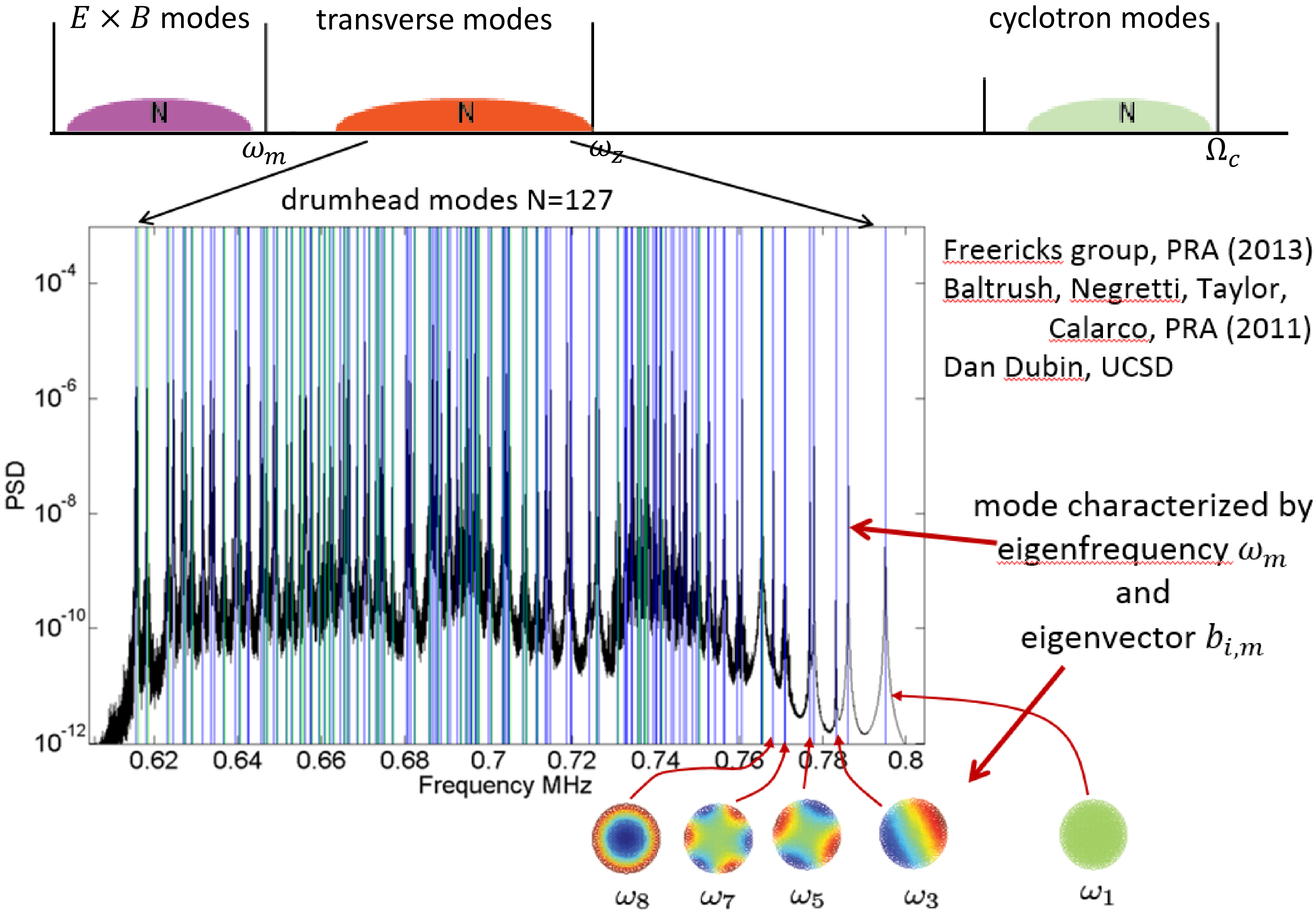
$$H_{\mu W} = \sum_i B_\perp \hat{\sigma}_i^x \, ,$$

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





Transverse (drumhead) modes



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

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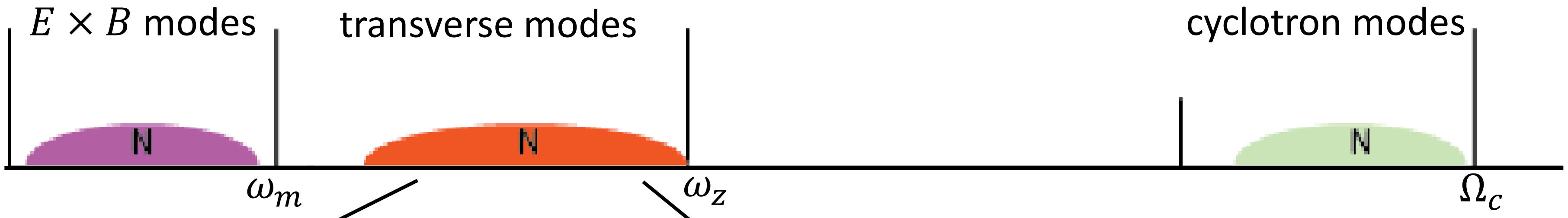

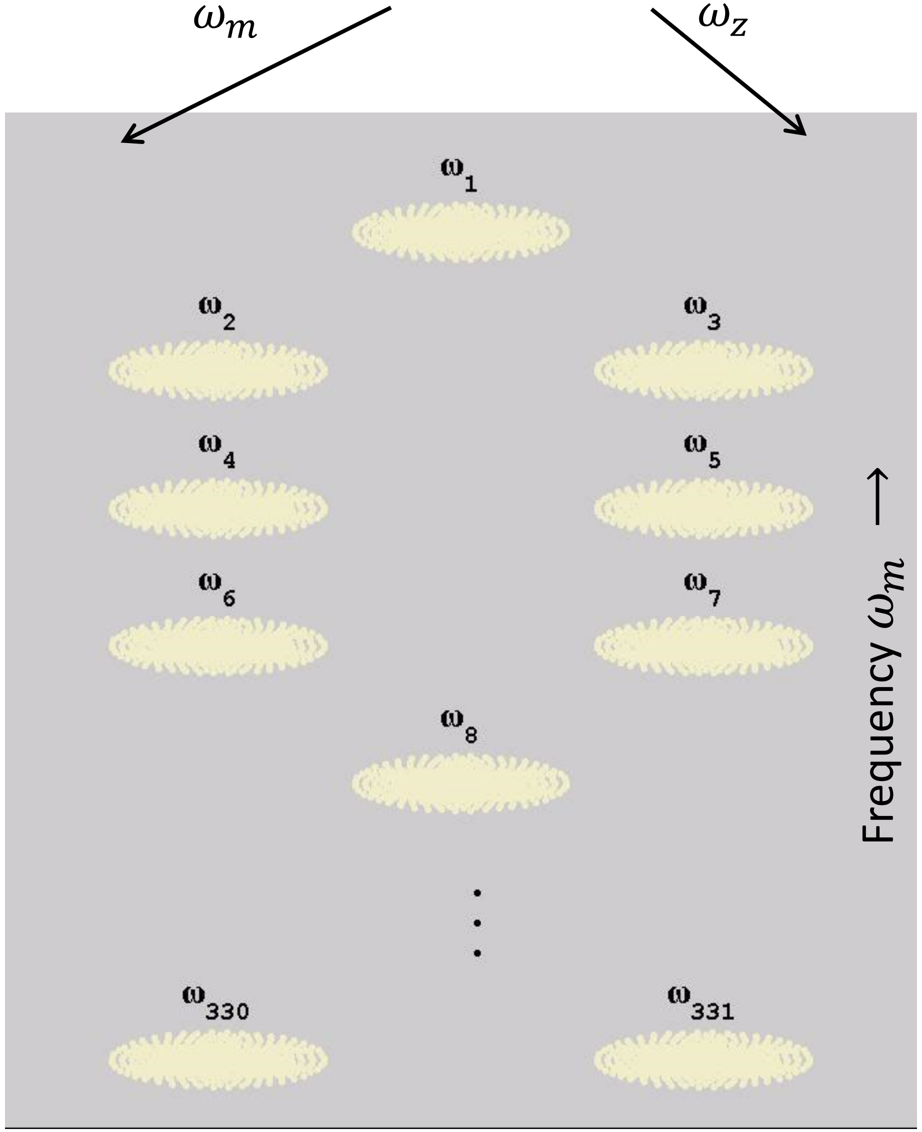

Freericks group, PRA (2013)
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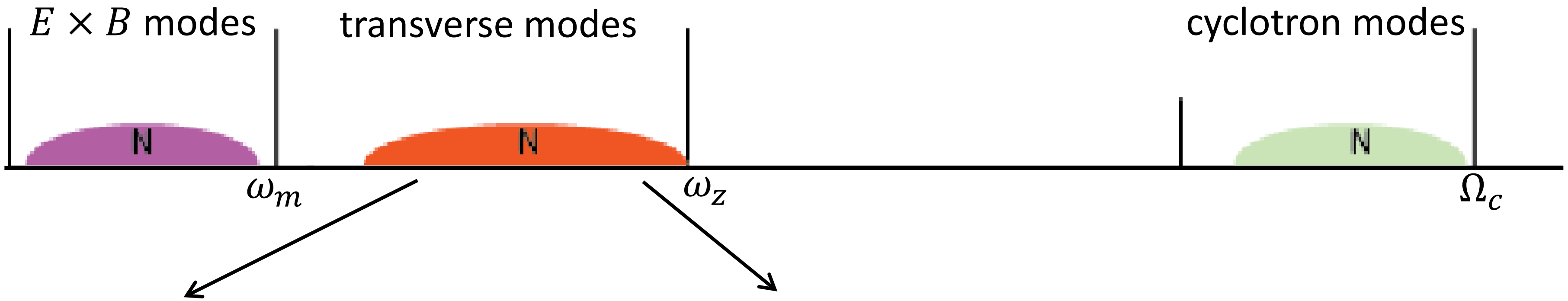
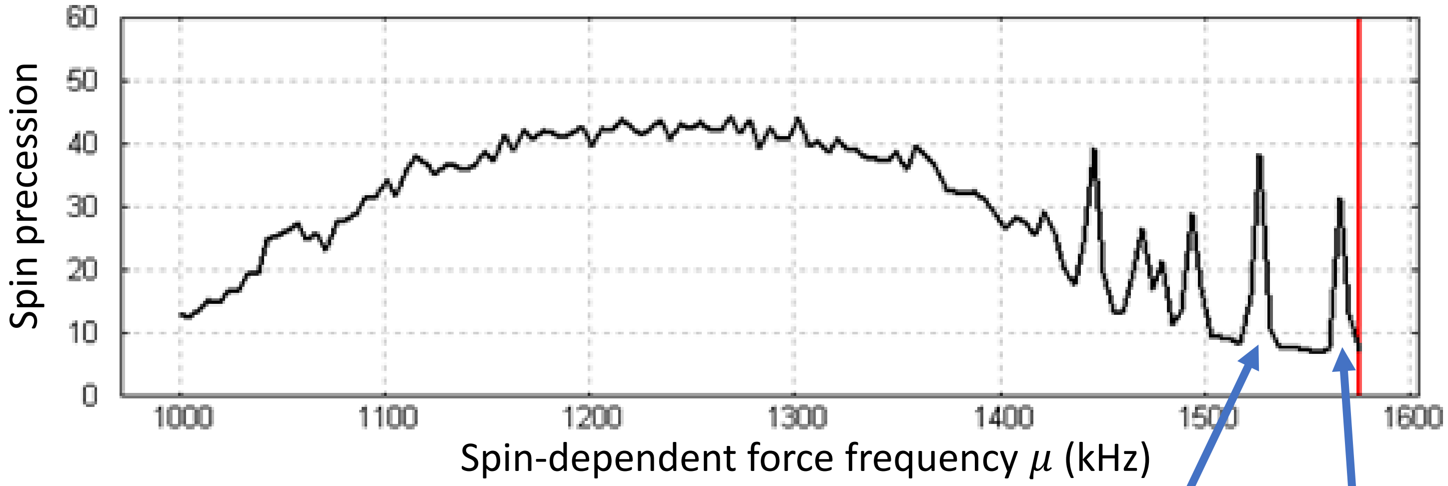
Dubin, UCSD

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

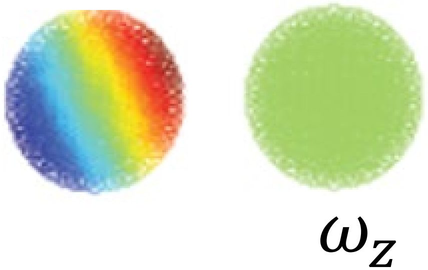
Transverse (drumhead) modes





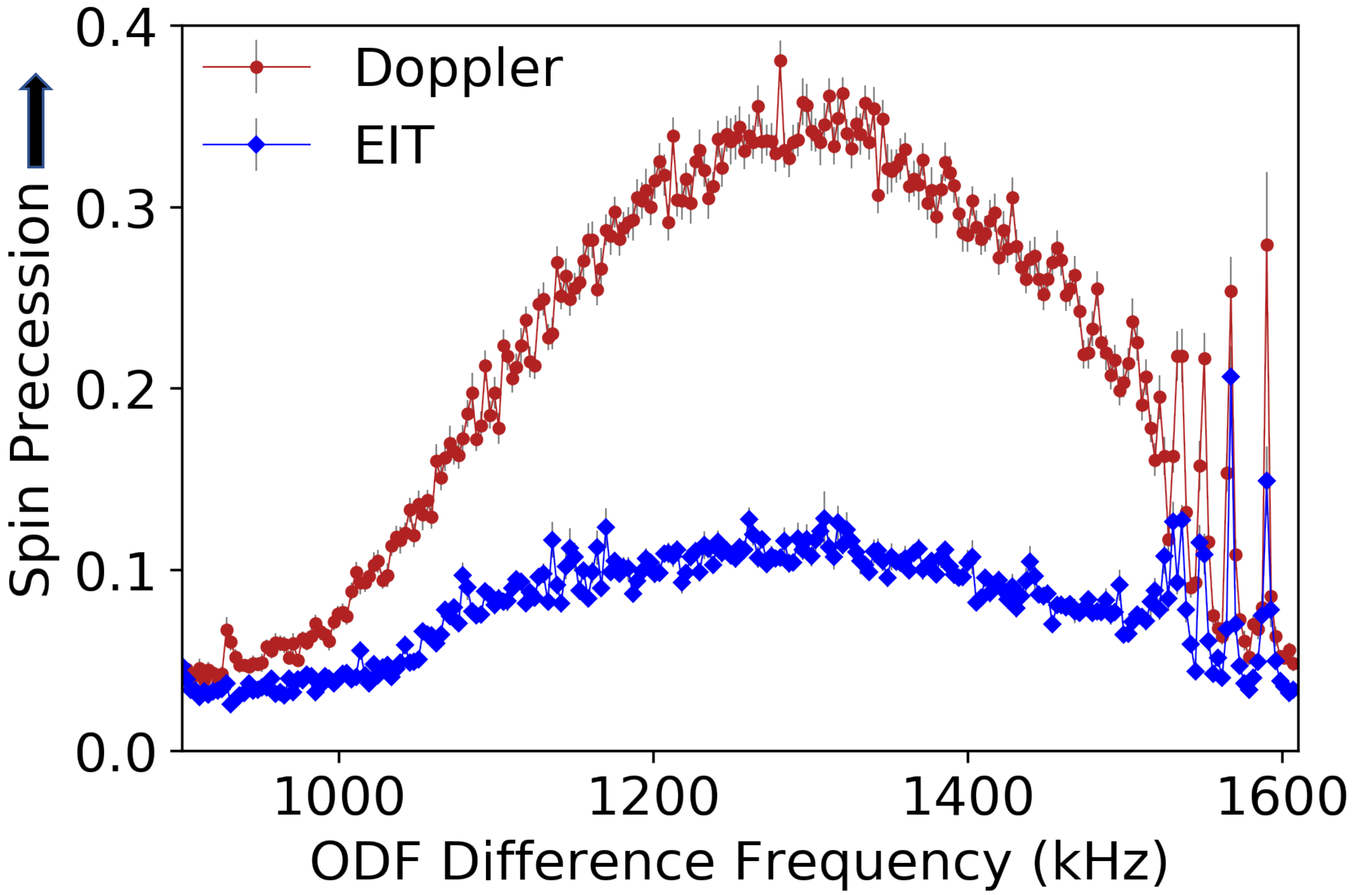
Measure mode spectrum with spin-dependent force

tilt mode COM mode



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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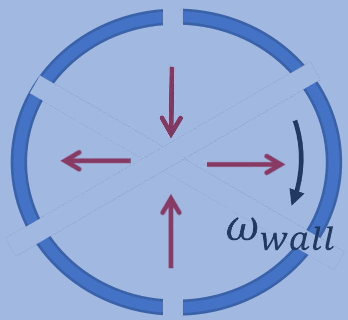

- engineering tunable Ising interactions

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

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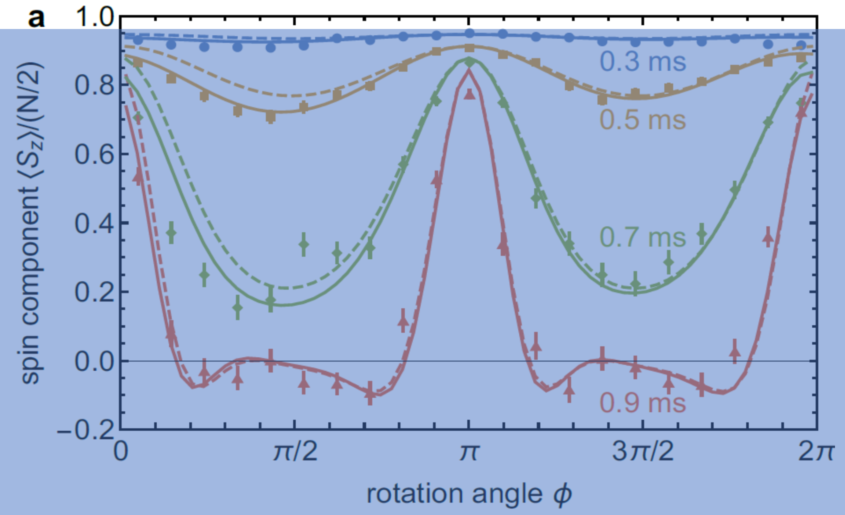
  - out-of-time-order correlations (OTOC)

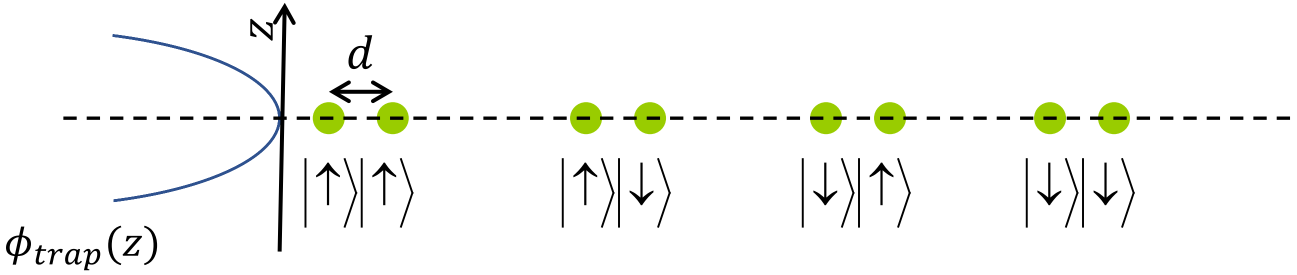


- measuring weak motional excitations and electric fields

Generating entangled states with spin-dependent forces

Simple example – adiabatic spin-dependent force

Calarco, Cirac, Zoller, PRA (2001)

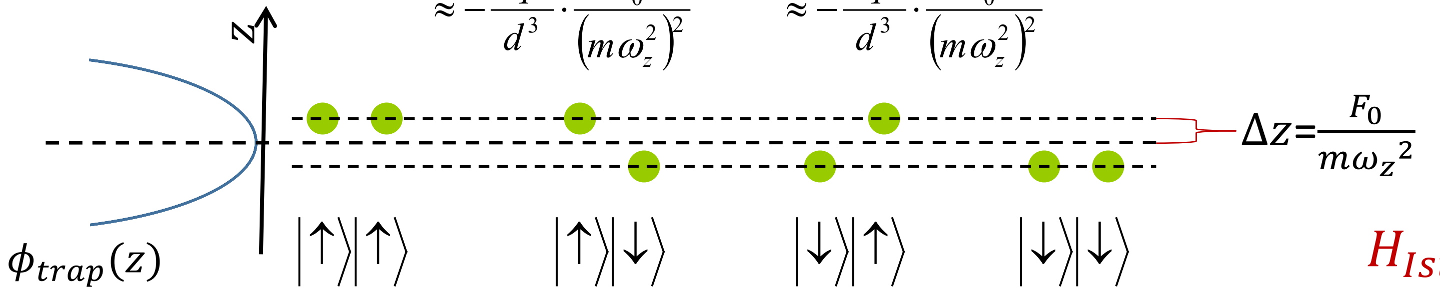


$$E_{Coulomb} \propto q^2/d$$

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

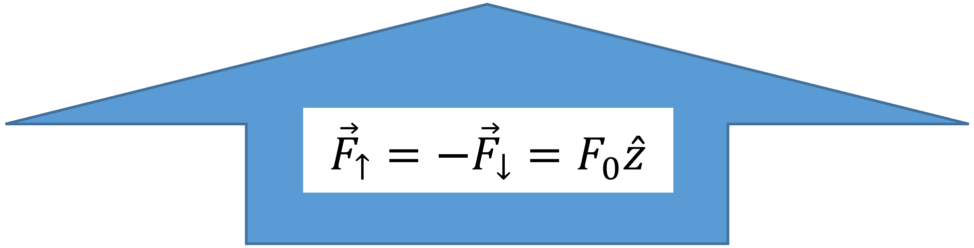
$$\approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad \approx -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2}$$

$\Delta E_{Coulomb} \longleftrightarrow$ **antiferromagnetic Ising interaction**



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

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



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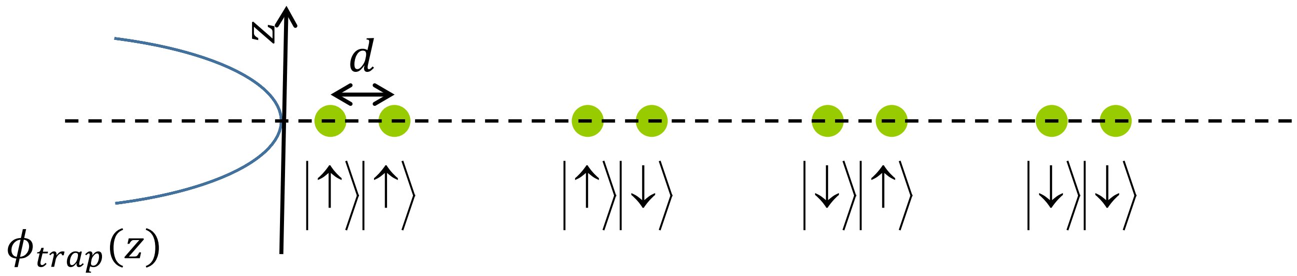
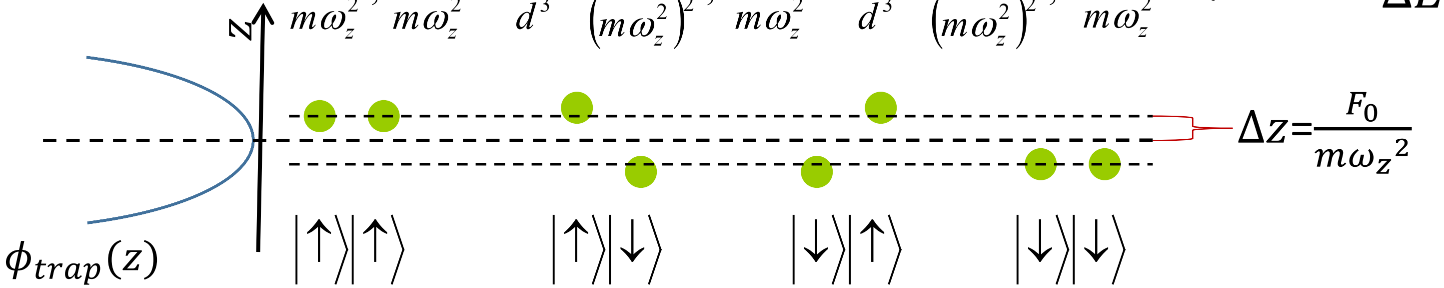


$E_{Coulomb} \propto q^2/d$

Spin-dependent push can be enhanced by the remaining ion!

$$0 \qquad -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad -\frac{2q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2} \qquad 0 \longleftarrow \Delta E_{Coulomb}$$

$$\frac{F_0^2}{m\omega_z^2}, \quad \frac{F_0^2}{m\omega_z^2}+\frac{4q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2}, \quad \frac{F_0^2}{m\omega_z^2}+\frac{4q^2}{d^3}\cdot\frac{F_0^2}{(m\omega_z^2)^2}, \quad \frac{F_0^2}{m\omega_z^2} \longleftarrow \Delta E_{Trap}$$



$\Delta E_{Coulomb} + \Delta E_{Trap} \Longrightarrow$ ferromagnetic interaction

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

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

$$\vec{F}_\uparrow = -\vec{F}_\downarrow = F_0\hat{z}$$

Generating entangled states with spin-dependent forces

Oscillating spin-dependent force: $\vec{F}_\uparrow(t) = -\vec{F}_\downarrow(t) = F_0 \cos(\mu t)\,\hat{z}$

- $\mu < \omega_z$, ion oscillation, $\vec{F}_{\uparrow,\downarrow}(t)$ in phase

  $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ have larger oscillation amplitude and energy

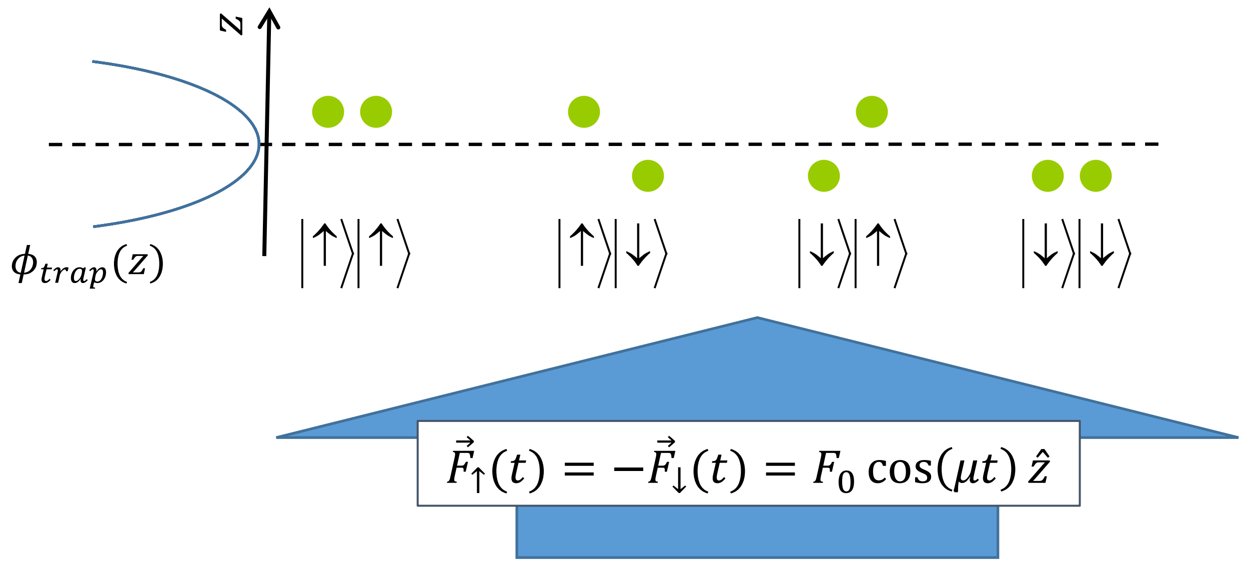
  $\Rightarrow$ ferromagnetic interaction

- $\mu > \omega_z$, ion oscillation, $\vec{F}_{\uparrow,\downarrow}(t)$ 180º out of phase

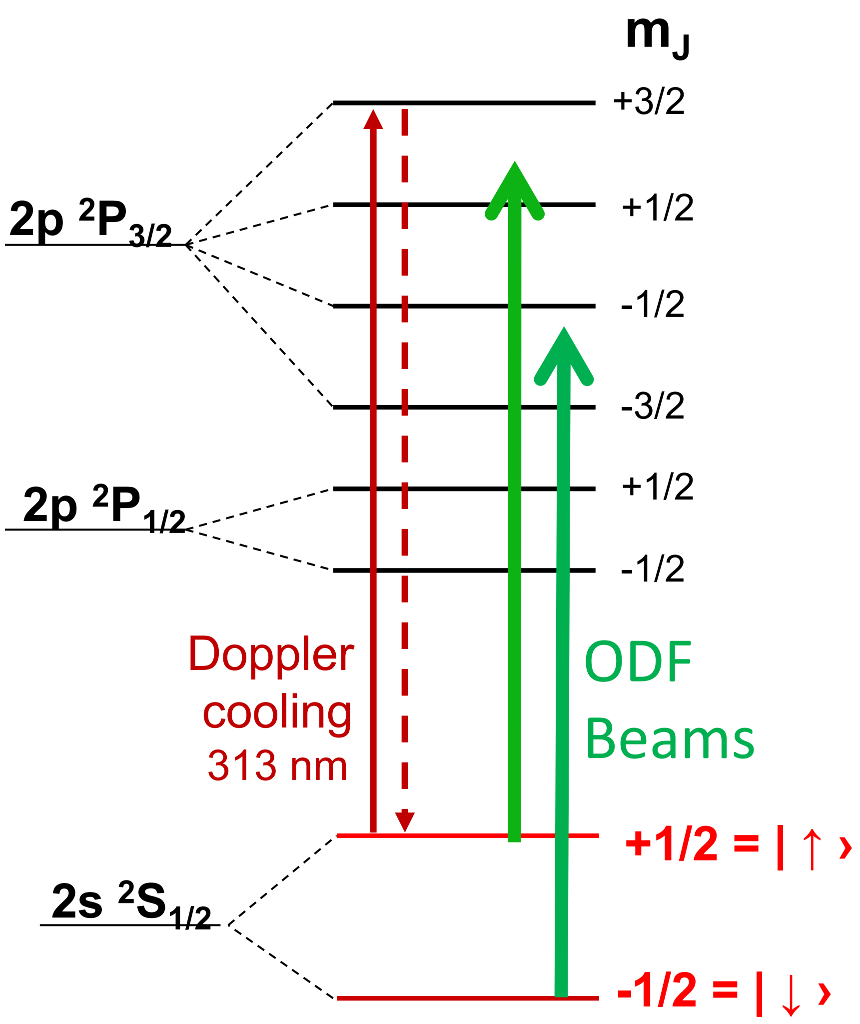
  Coulomb force opposes $\vec{F}_{\uparrow,\downarrow}(t)$ for $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ states,

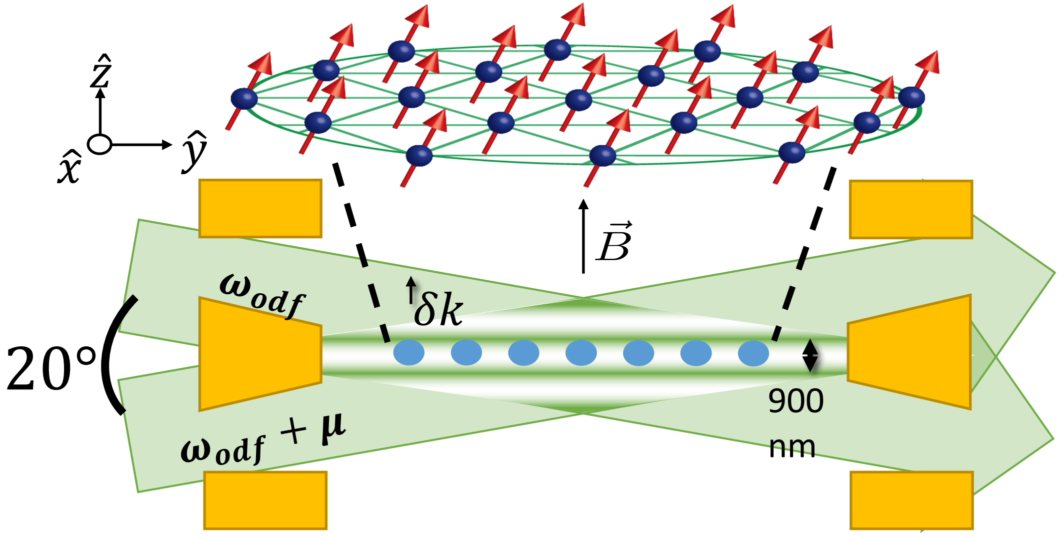
  $|\uparrow\rangle|\downarrow\rangle, |\downarrow\rangle|\uparrow\rangle$ have smaller oscillation amplitude and energy

  $\Longrightarrow$ anti-ferromagnetic interaction



Engineering quantum magnetic couplings with spin-dependent forces





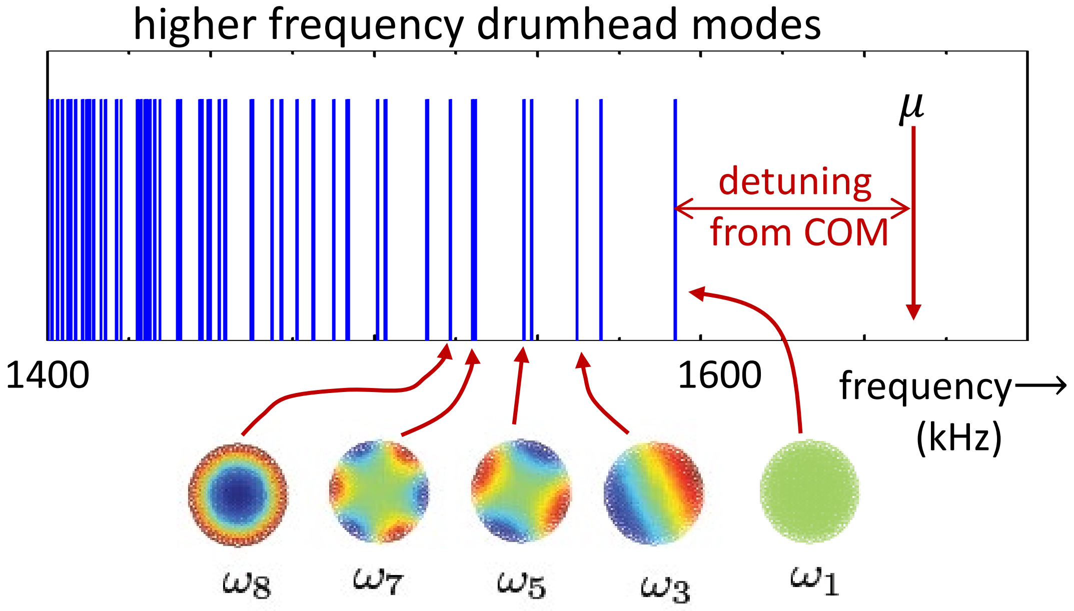
- $F_{\uparrow}(t) = -F_{\downarrow}(t)$
  $F_{\uparrow}(t) = F_0 \cos(\mu t)$
- alignment of 1D lattice and ion plane

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

Engineering quantum magnetic couplings

$$\hat{H}_{ODF}(t) = -F_0 \cos(\mu t) \sum_{j=1}^{N} \underbrace{\hat{z}_j}_{\sum_{m=1}^{N} b_{jm} \sqrt{\frac{\hbar}{2M\omega_m}} \left(\hat{a}_m^\dagger e^{i\omega_m t} + \hat{a}_m e^{-i\omega_m t}\right)} \cdot \hat{\sigma}_j^z =$$

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



Produces spi
- useful metrolo
- source of deco

Infinite range ⟹Single axis twisting

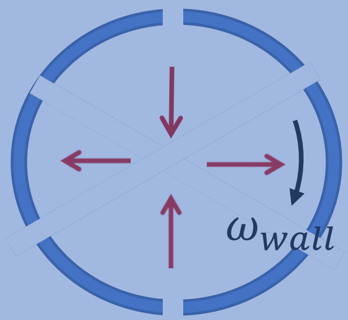
$$H_{Ising} = \frac{J}{N} \sum_{i<j} \sigma_i^z \sigma_j^z = \frac{2J}{N} S_z^2$$

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 $\frac{2J}{N}\tau = \frac{\pi}{2}$

Outline:



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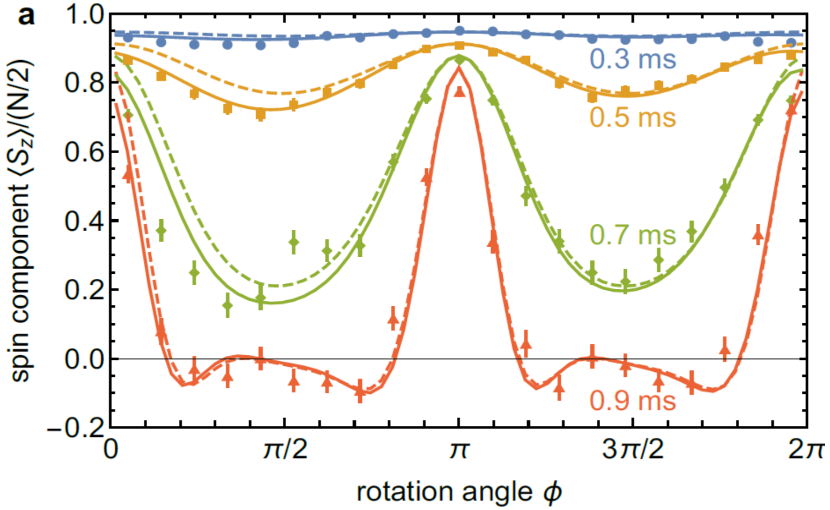
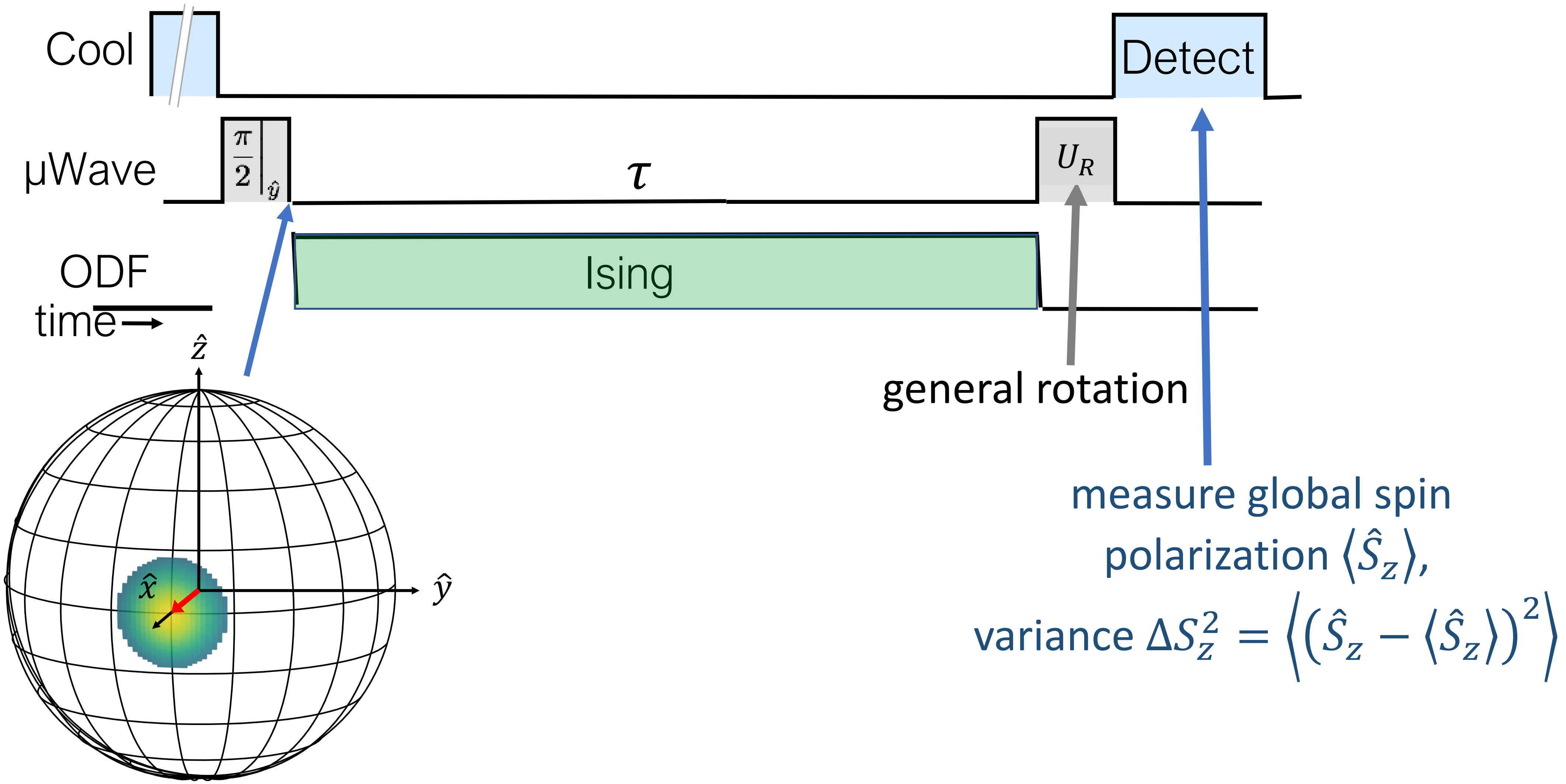


- measuring weak motional excitations and electric fields

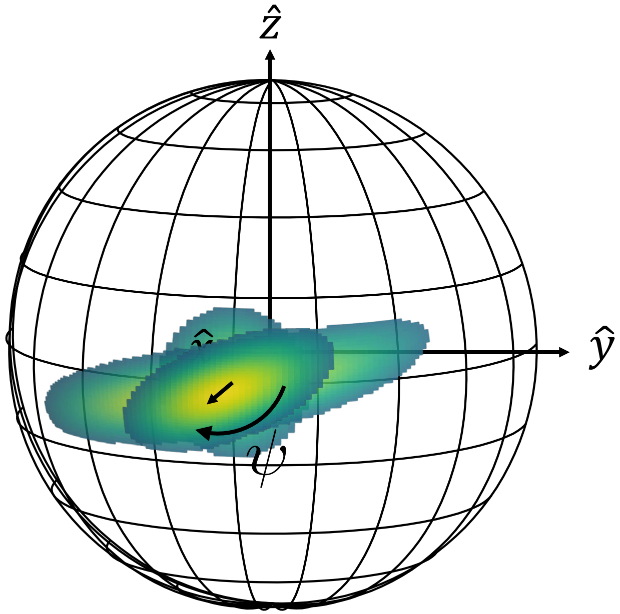
Benchmarking quantum dynamics

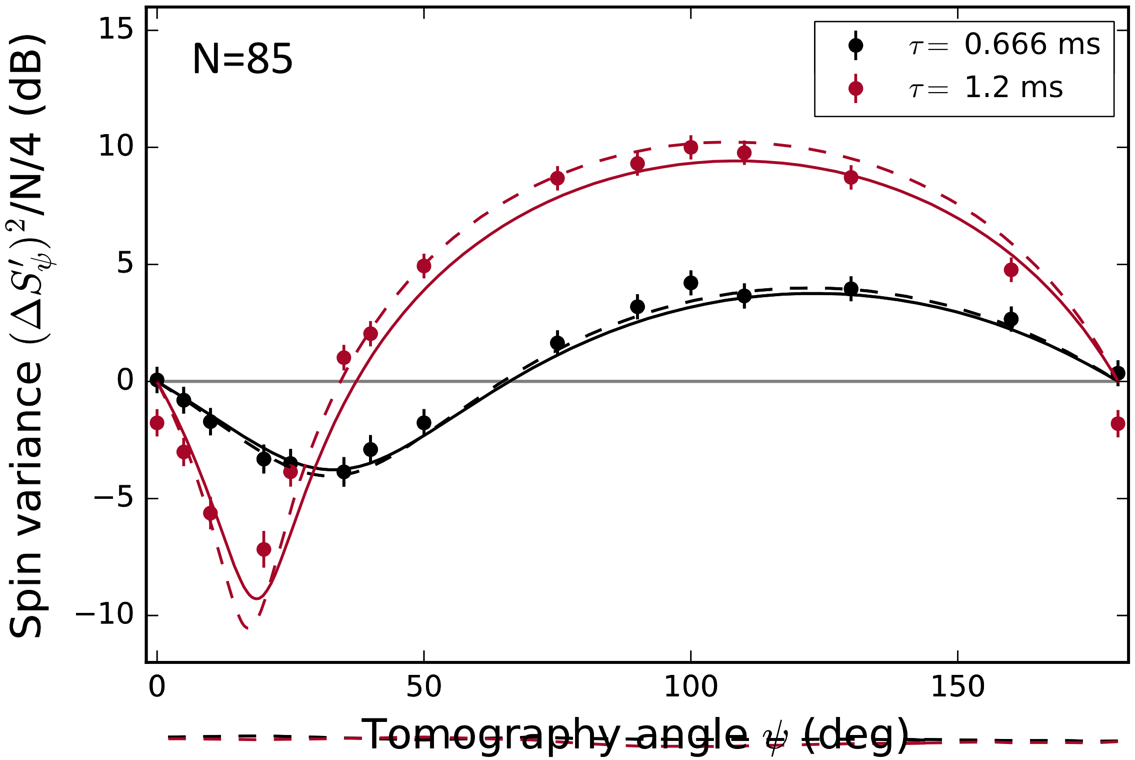
- employ infinite range interactions $H_{Ising} \approx \frac{2J}{N} S_z^2, S_z \equiv \sum_i \sigma_i^z /2$
- prepare eigenstate of $H_\perp = \sum_i B_\perp \hat{\sigma}_i^x$, turn on H_{Ising}



Benchmarking quantum dynamics

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

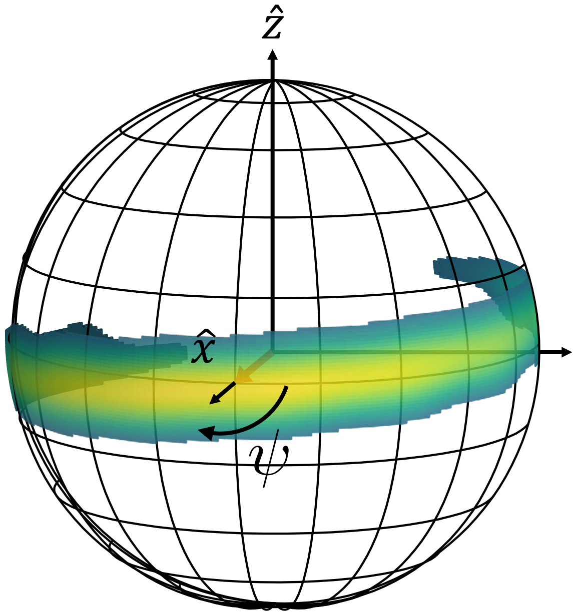


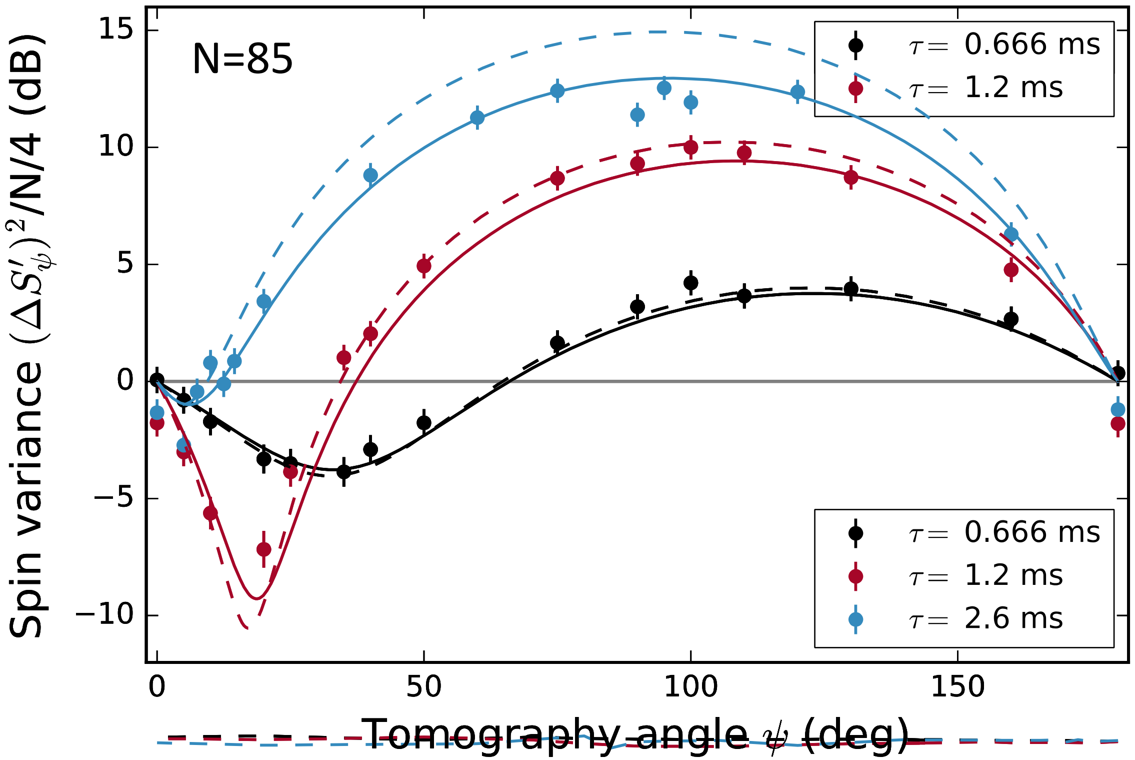


- Measurements of Ramsey squeezing parameter $\Rightarrow$ prove entanglement for $25 < N < 220$
- Largest inferred squeezing: -6.0 dB

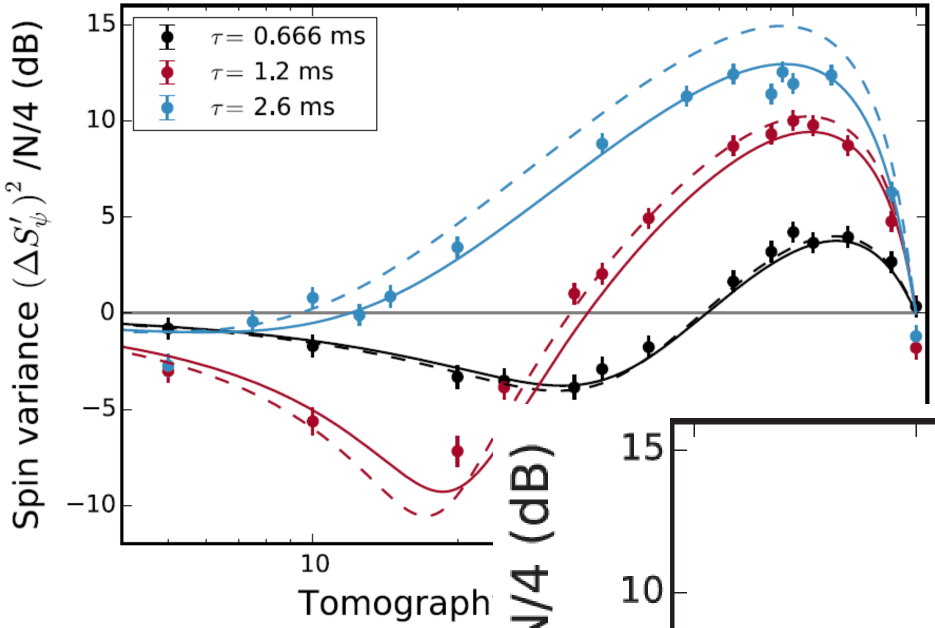
Benchmarking quantum dynamics

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



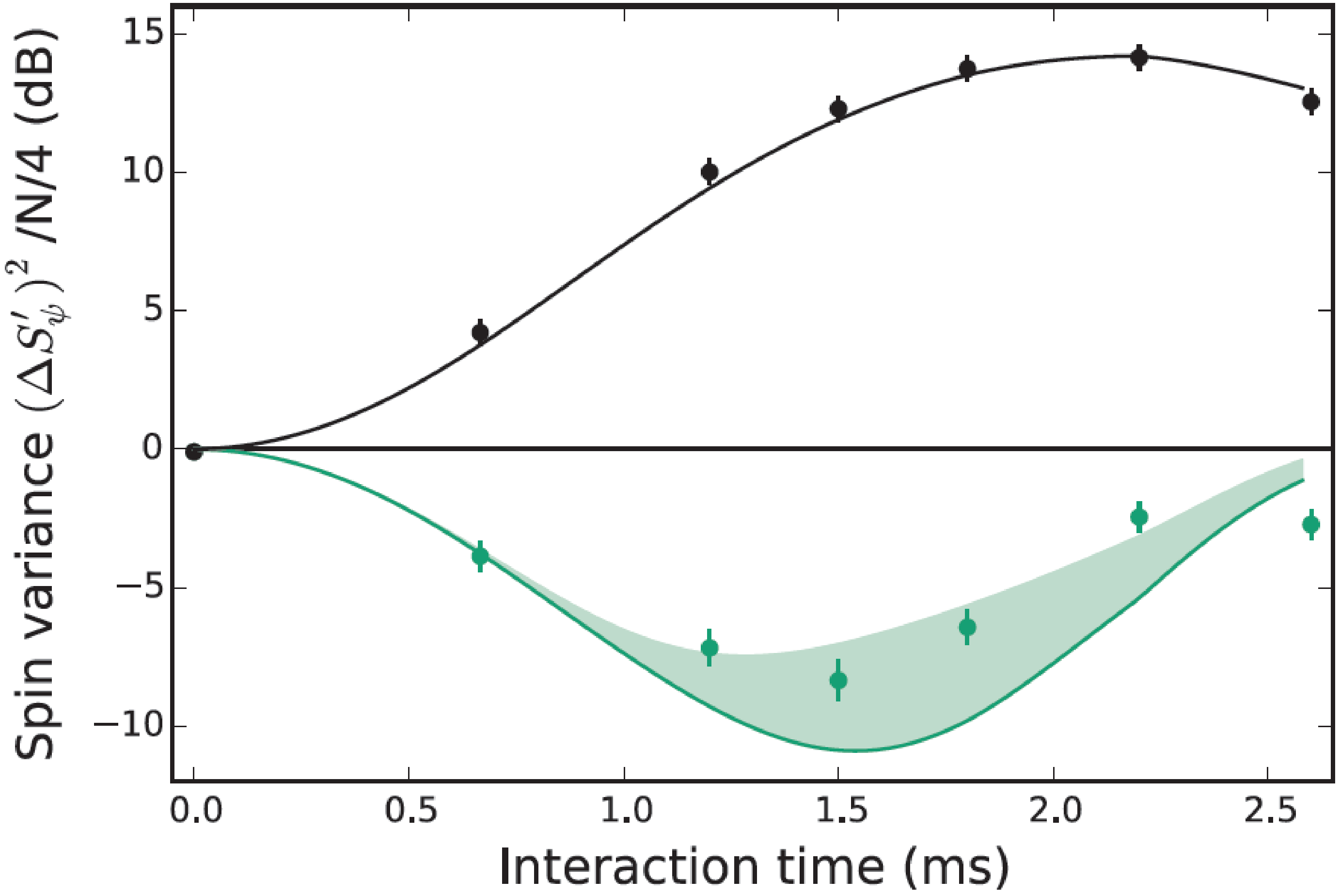


Benchmarking quantum dynamics



N = 86

Time dependence of squeezed and anti-squeezed variance



Bohnet *et al.*, Science352 (2016)

Out-of-time-order correlation functions

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

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

$\Rightarrow$ **measures failure of initially commuting operators to commute at later times**

$\Rightarrow$ **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)

Difficult to measure $\Leftrightarrow$ requires time-reversal of dynamics

time reversal is possible in many quantum simulators!

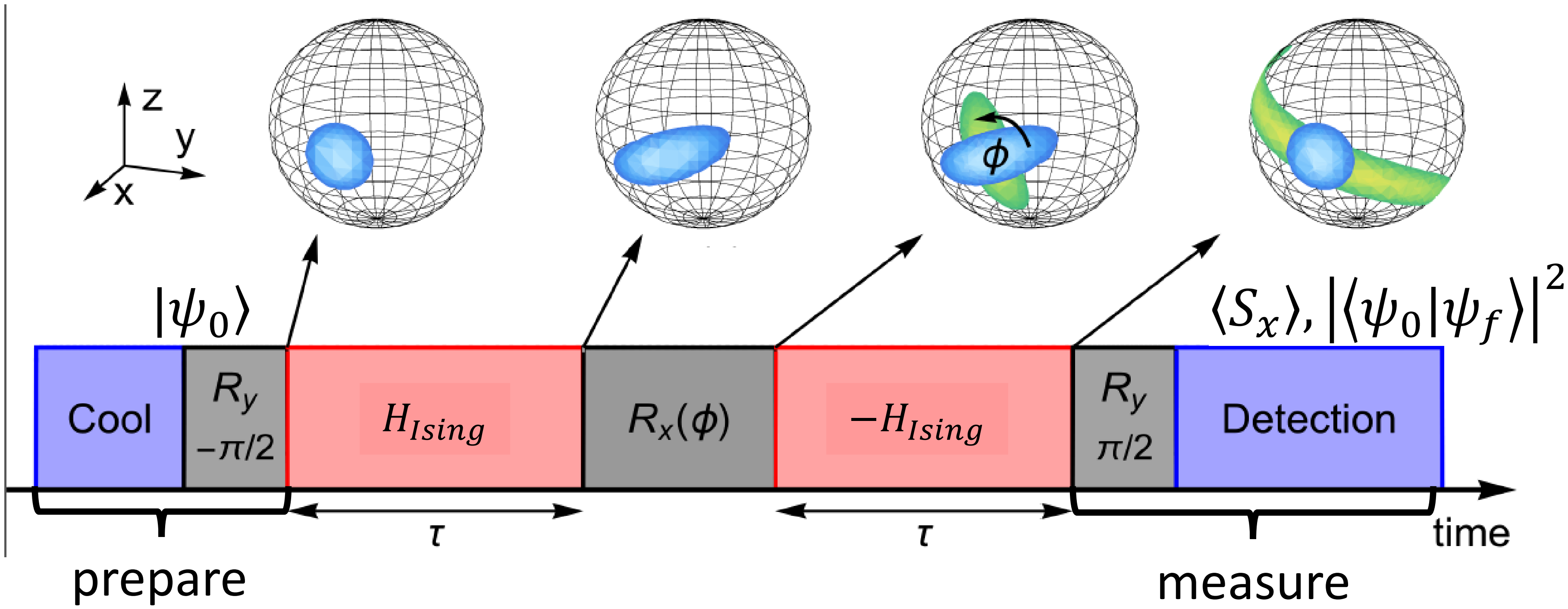
Time reversal of the Ising dynamics

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

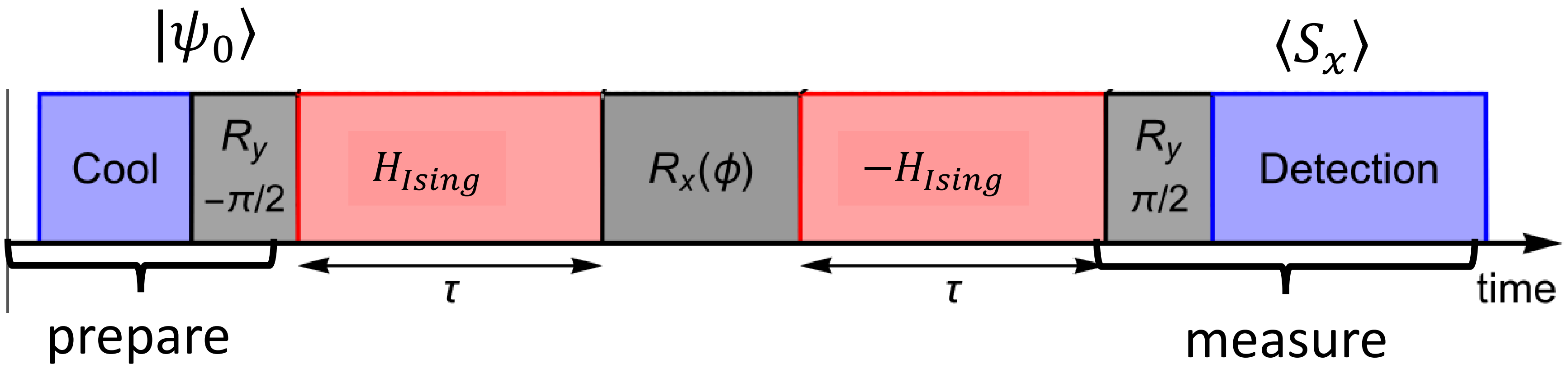
Change $\mu = \omega_z + \delta$ (antiferromagnetic)
to $\mu = \omega_z - \delta$ (ferromagnetic)

Multiple quantum coherence protocol

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



Multiple quantum coherence protocol



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

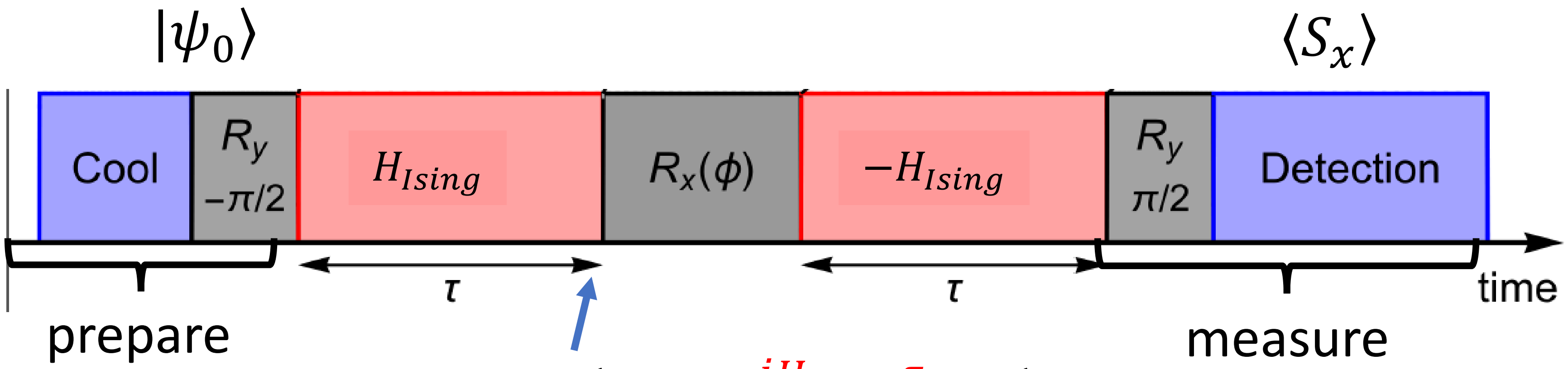
$$= \frac{2}{N}\langle\Psi_0|\, \underbrace{e^{iH_{Ising}\tau}\, W^\dagger\, e^{-iH_{Ising}\tau}}_{W^\dagger(t)} \underbrace{V^\dagger}_{V^\dagger(0)}\, \underbrace{e^{iH_{Ising}\tau}\, W\, e^{-iH_{Ising}\tau}}_{W(t)} \underbrace{V}_{V(0)} |\Psi_0\rangle$$

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



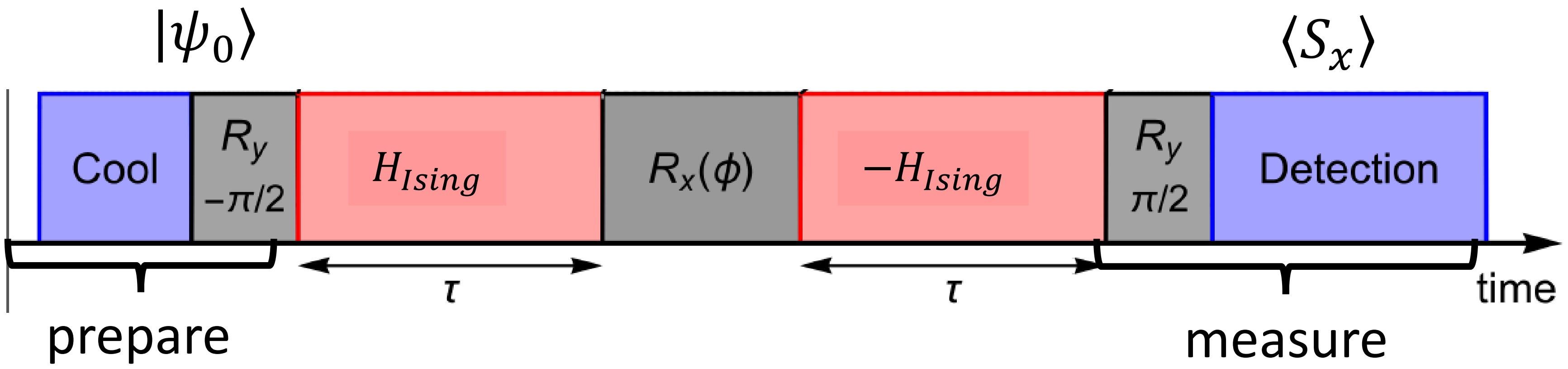
$$|\psi\rangle \equiv e^{-iH_{Ising}\tau}\,|\psi_0\rangle$$

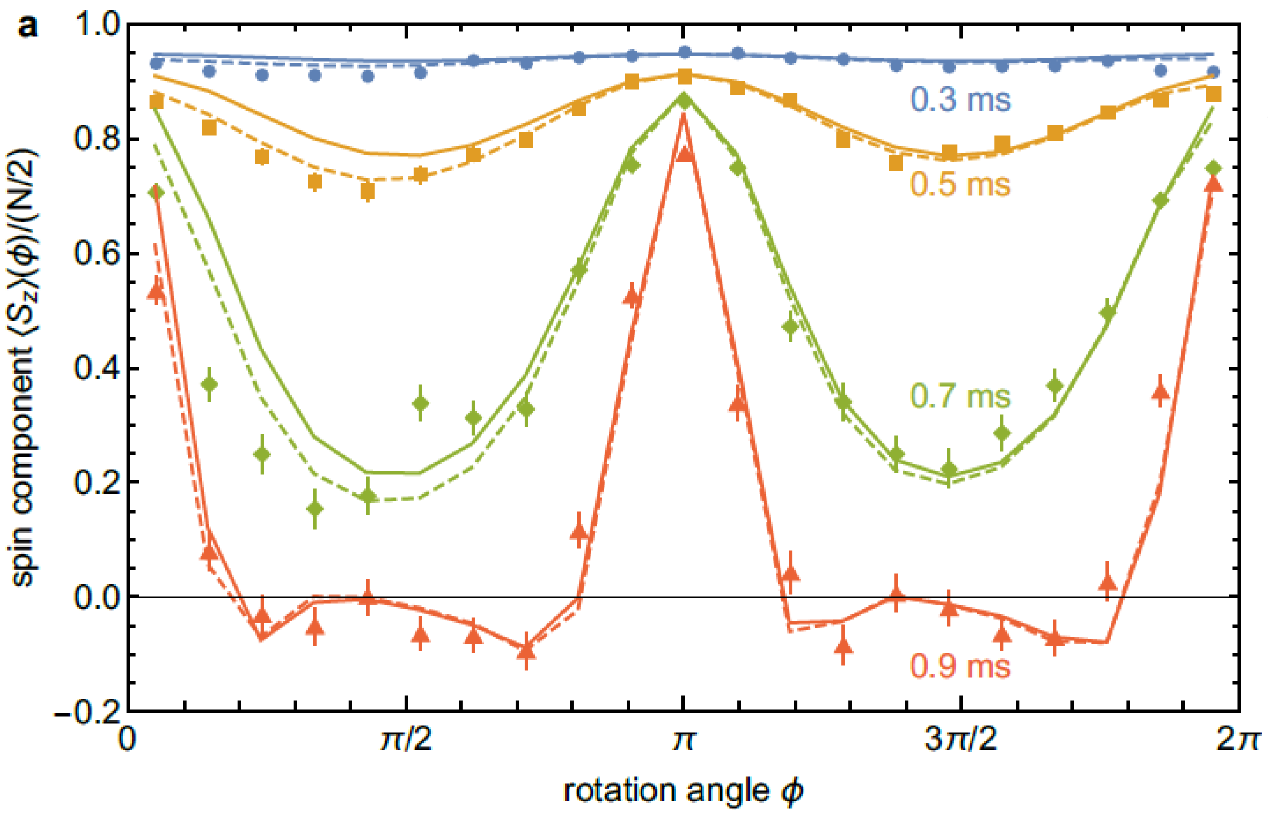
$$\langle S_x\rangle = \langle \Psi_0|\, e^{iH_{Ising}\tau}\, e^{i\phi S_x}\, e^{-iH_{Ising}\tau} S_x\, e^{iH_{Ising}\tau}\, e^{-i\phi S_x}\, \underbrace{e^{-iH_{Ising}\tau}|\Psi_0\rangle}_{\equiv |\Psi\rangle}$$

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

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





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

$J \lesssim 5kHz$

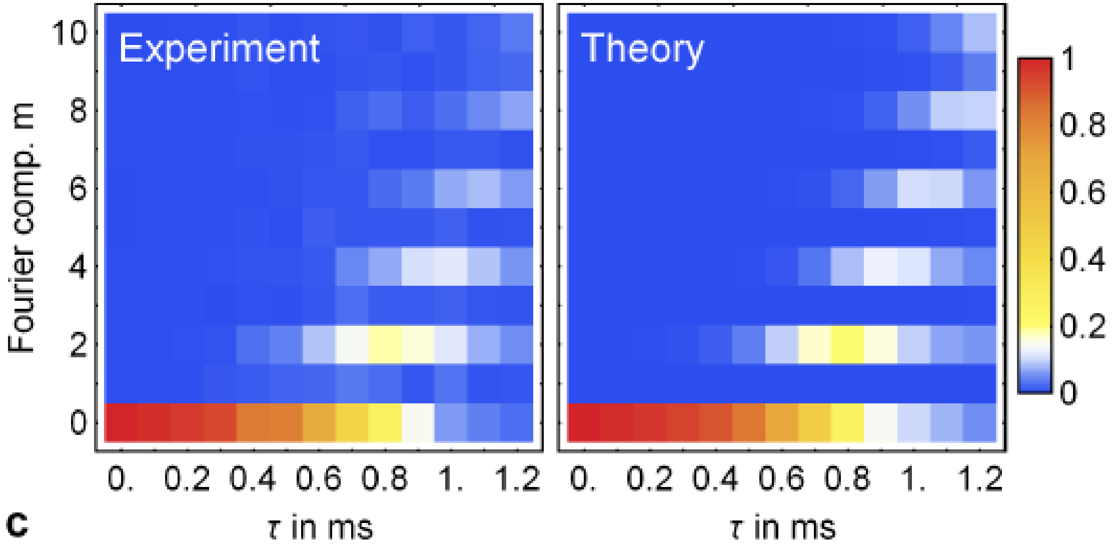
$N = 111$

$\Gamma = 93Hz$

[Gärttner, Bohnet et al. Nature Physics 2017]

Fourier transform of magnetization

[Gärttner, Bohnet et al. Nature Physics 2017]

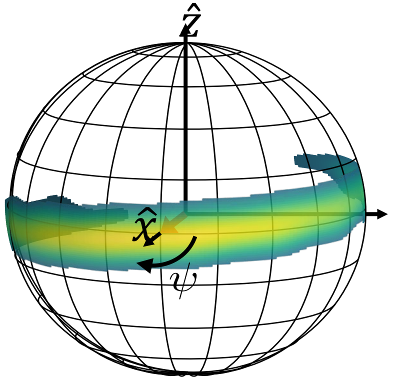


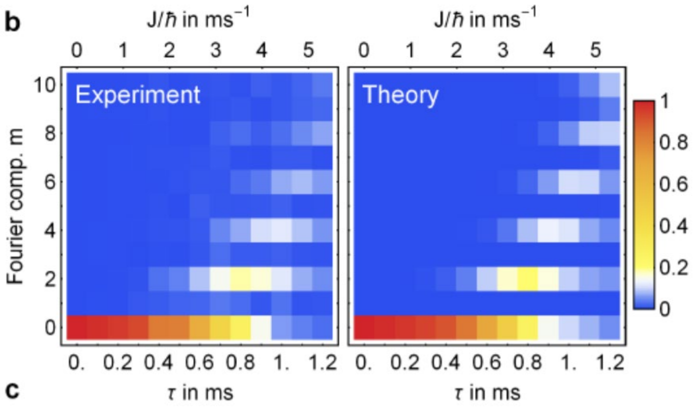
- Measure build-up of 8-body correlations
- Only global spin measurement
- Illustrates how OTOCs measure spread of quantum information

Summary:

- Penning traps good for controlling large ion crystals (> 200; 3D, $> 10^5$)

- employed spin-squeezing, OTOCs to benchmark quantum dynamics with long range Ising interactions





Future directions ⇔ increase coherence, complexity!

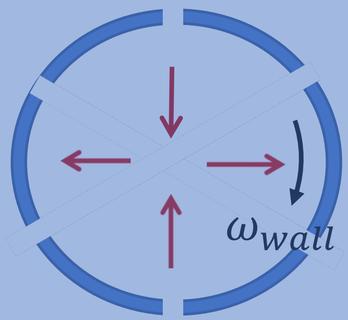
- increase entangling operation coherence with parametric amplification (W. Ge, et al., PRL (2019))

- implement single-site σ_z - rotations (potential NISQ platform)

- transverse field, spin-phonon models

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

Outline:

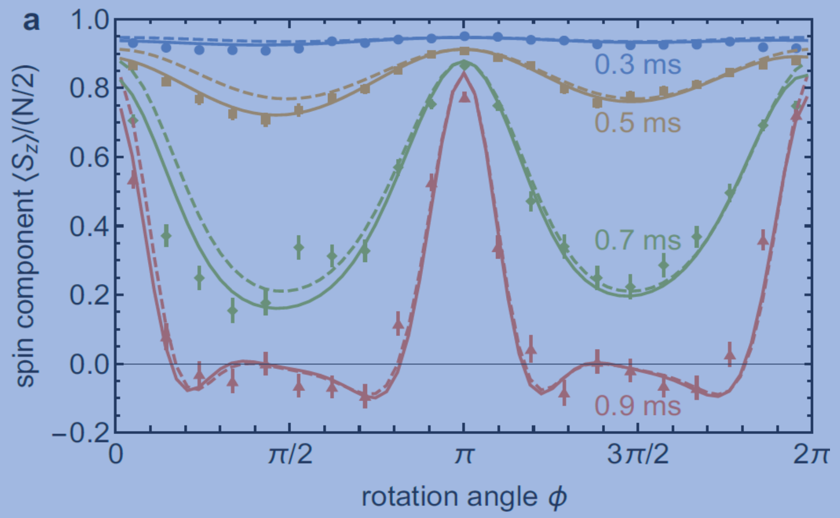


- ion crystals in Penning traps
  - high (4.5 T) magnetic field qubit
  - modes

- engineering tunable Ising interactions

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

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

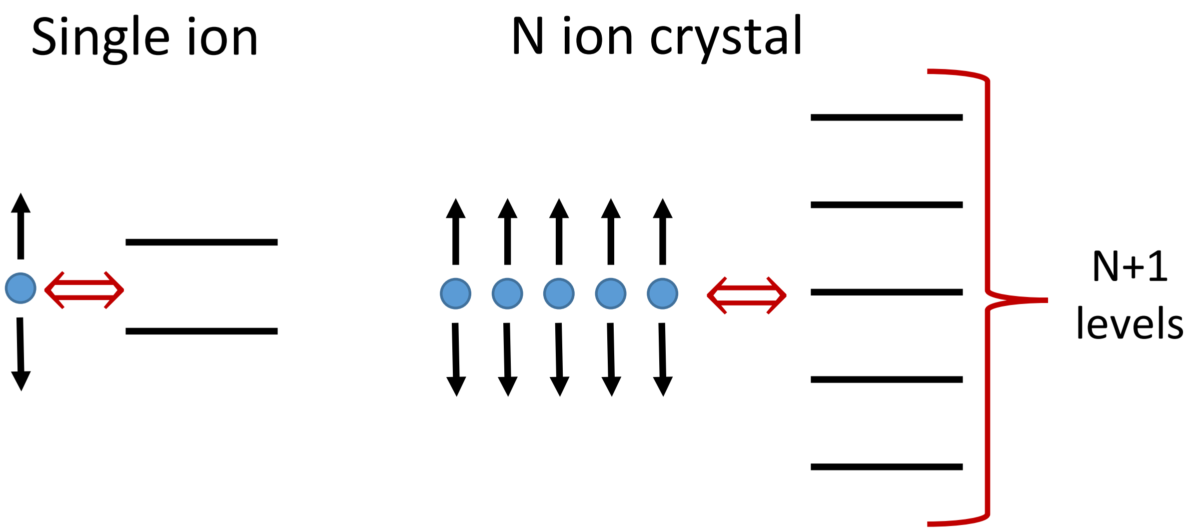


- measuring weak motional excitations and electric fields

Motional amplitude sensing /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 ($\sim$28 zN Hz$^{-1/2}$) at low frequencies
⋮
Biercuk *et al.*, Nature Nanotechnology, 2010 – 100-ion crystal (400 yN Hz$^{-1/2}$)

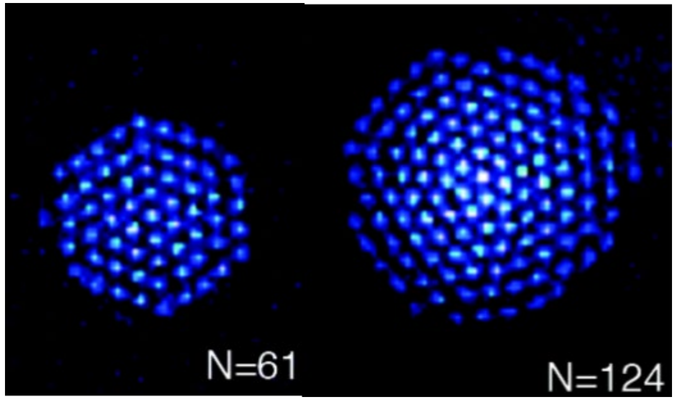
Basic idea: map motional amplitude onto spin precession



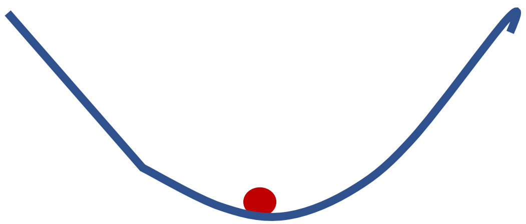
<u>N ion crystal</u>

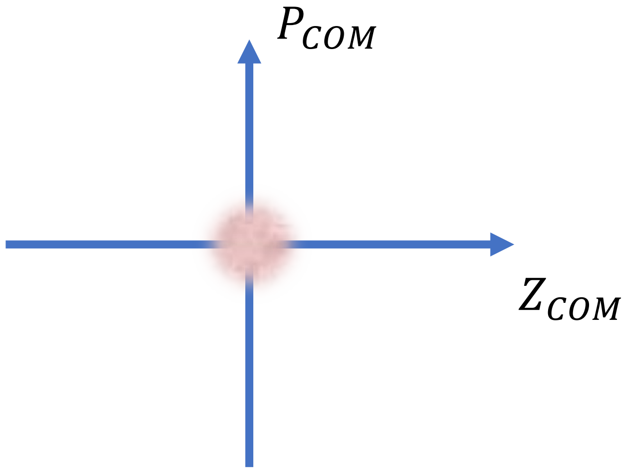
- Less projection noise
- Smaller zero-point motion, $z_{zpt} \approx 2$ nm for N=100

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



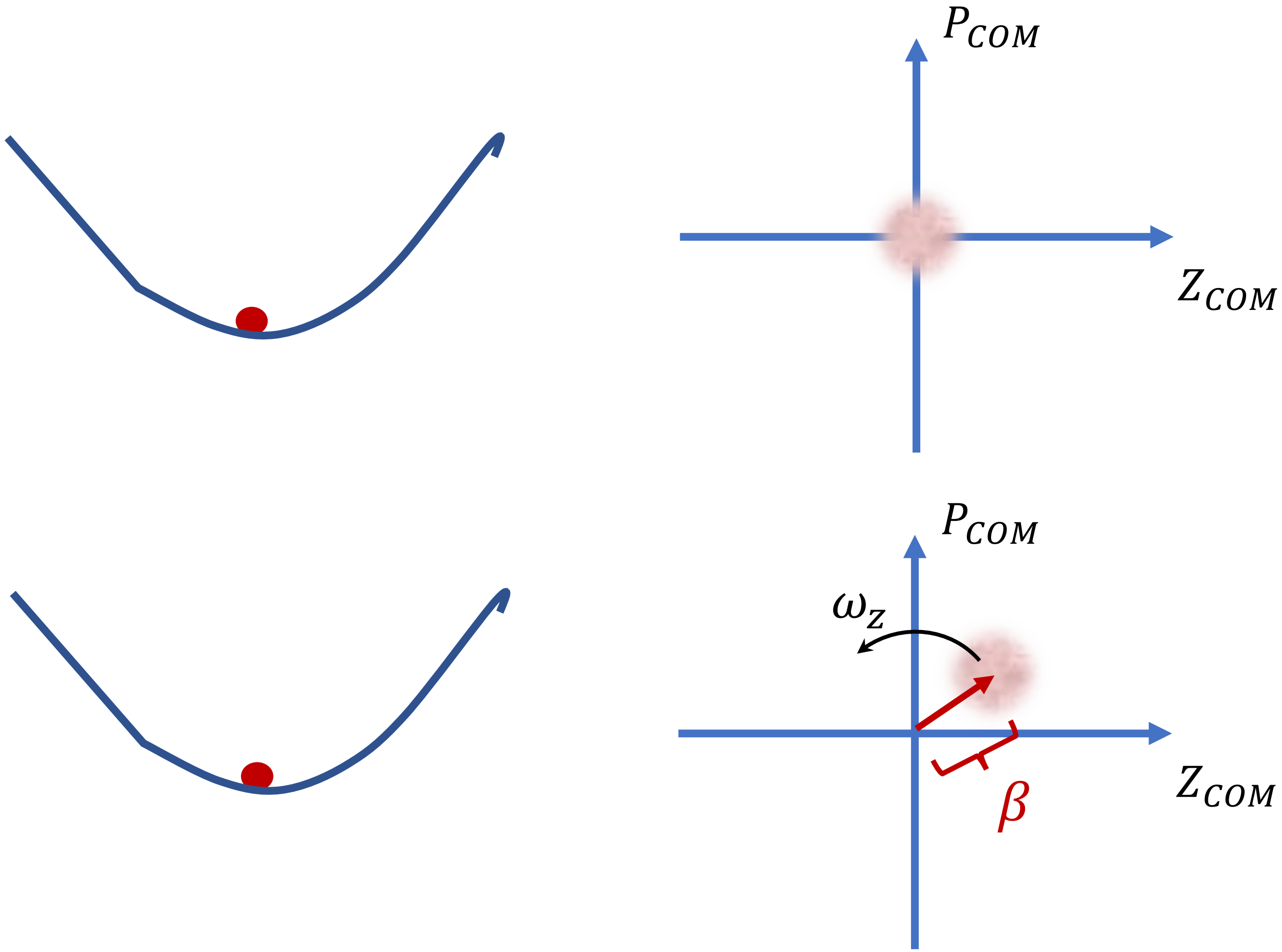
Conventions





$$z_{zpt} = \frac{1}{\sqrt{N}}\sqrt{\frac{\hbar}{2m\omega_z}}$$

Conventions



$$z_{zpt} = \frac{1}{\sqrt{N}}\sqrt{\frac{\hbar}{2m\omega_z}}$$

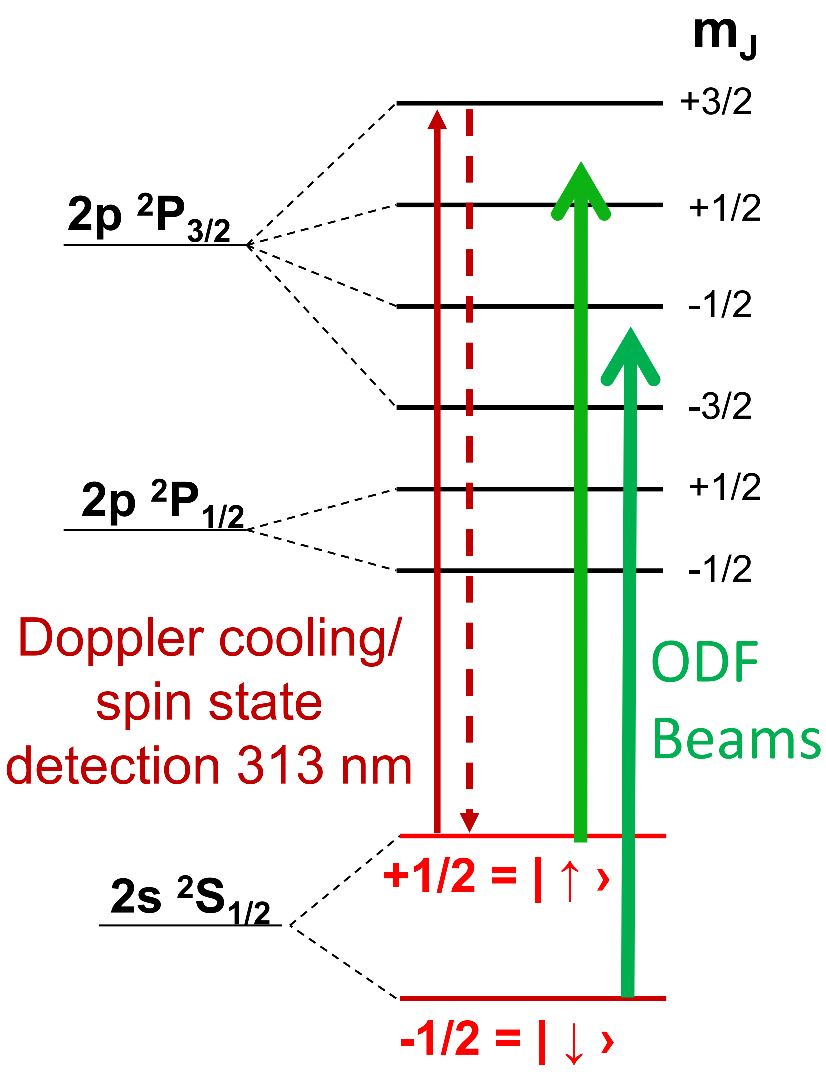
motional coherent state $|\beta\rangle$

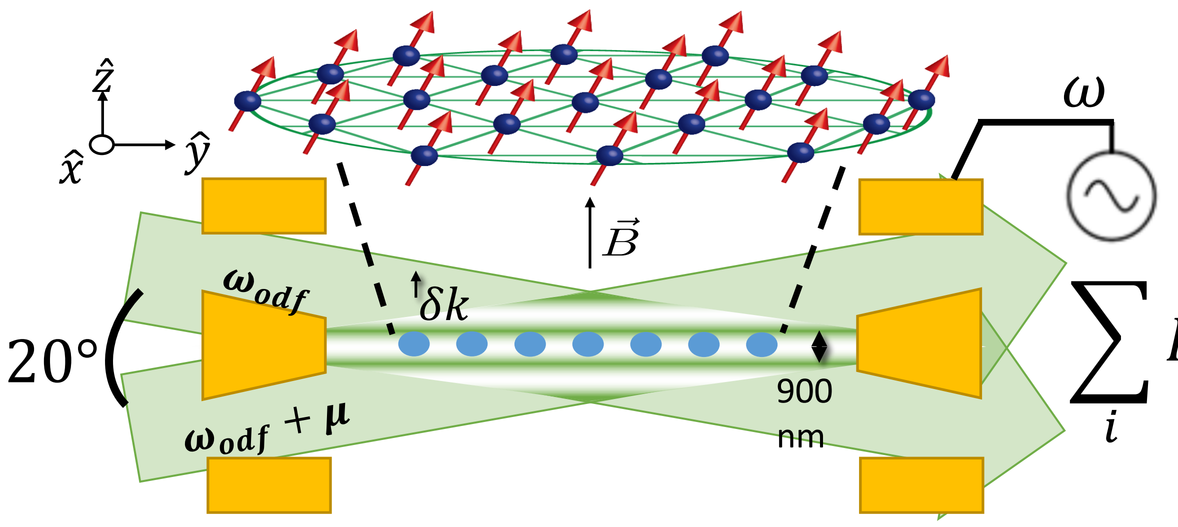
$\beta \equiv$ dimensionless displacement amplitude

in dimensionless units $z_{zpt} = 1/2$

The standard quantum limit (SQL) for sensing (or measuring) β in a single measurement is 1/2

Motional sensing through spin precession





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

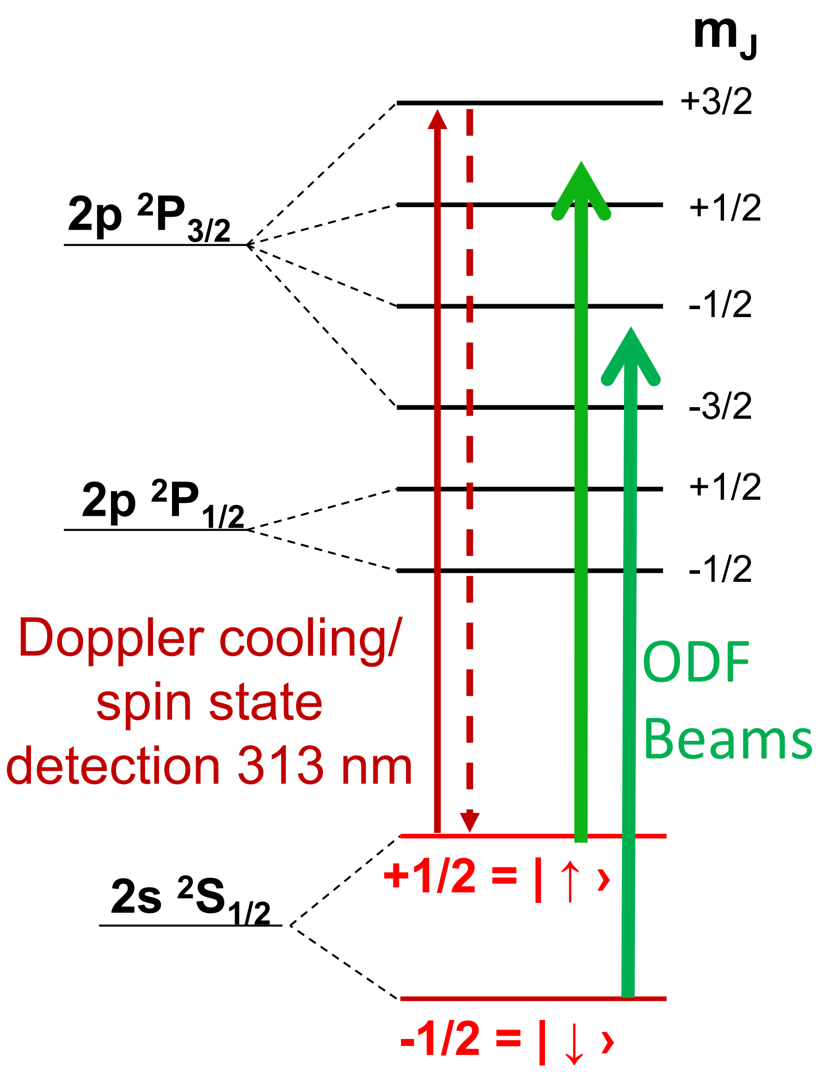
Implement classical COM oscillation: $\hat{z}_i \to \hat{z}_i + Z_c\, cos(\omega t + \phi)$

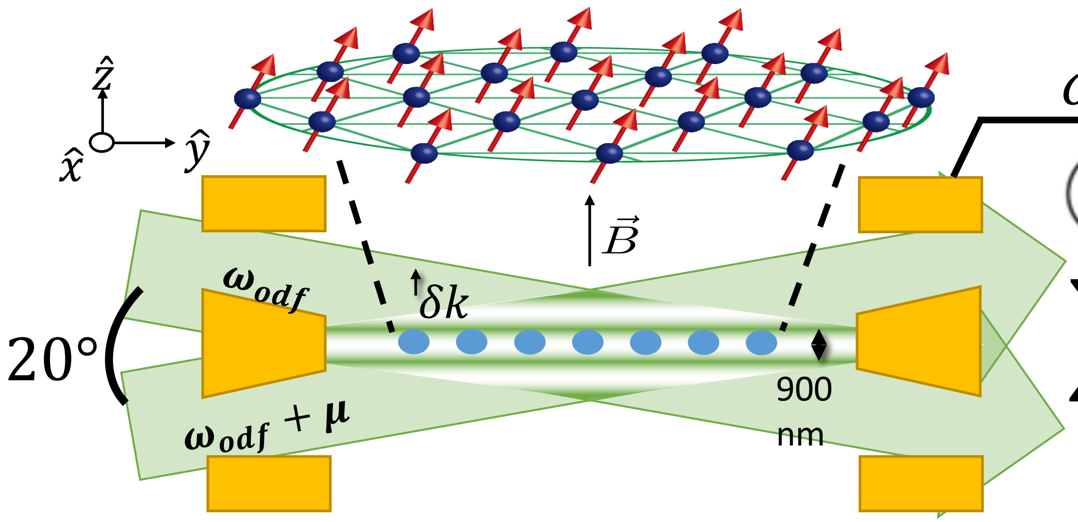
$$H_{ODF} \cong F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi] \sum_i \frac{\hat{\sigma}_i^z}{2}$$

$$= F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi]\ \hat{S}_z$$

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

Motional sensing through spin precession





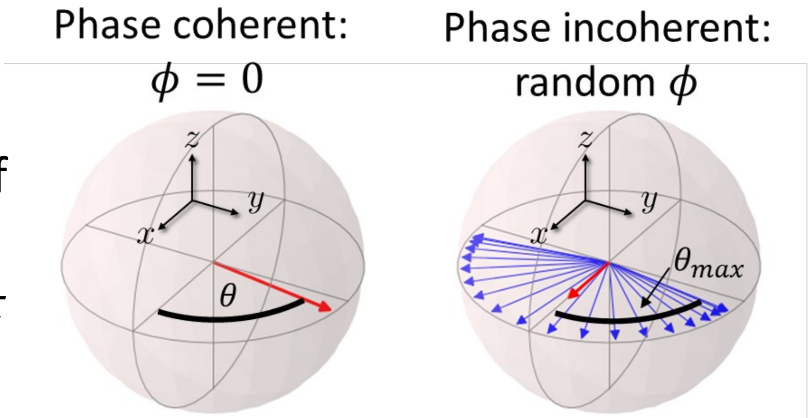
$$H_{ODF} = \sum_i F_0 \cos(\mu t)\, \hat{z}_i \hat{\sigma}_i^z$$

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

$$H_{ODF} \cong F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi]\ \hat{S}_z$$

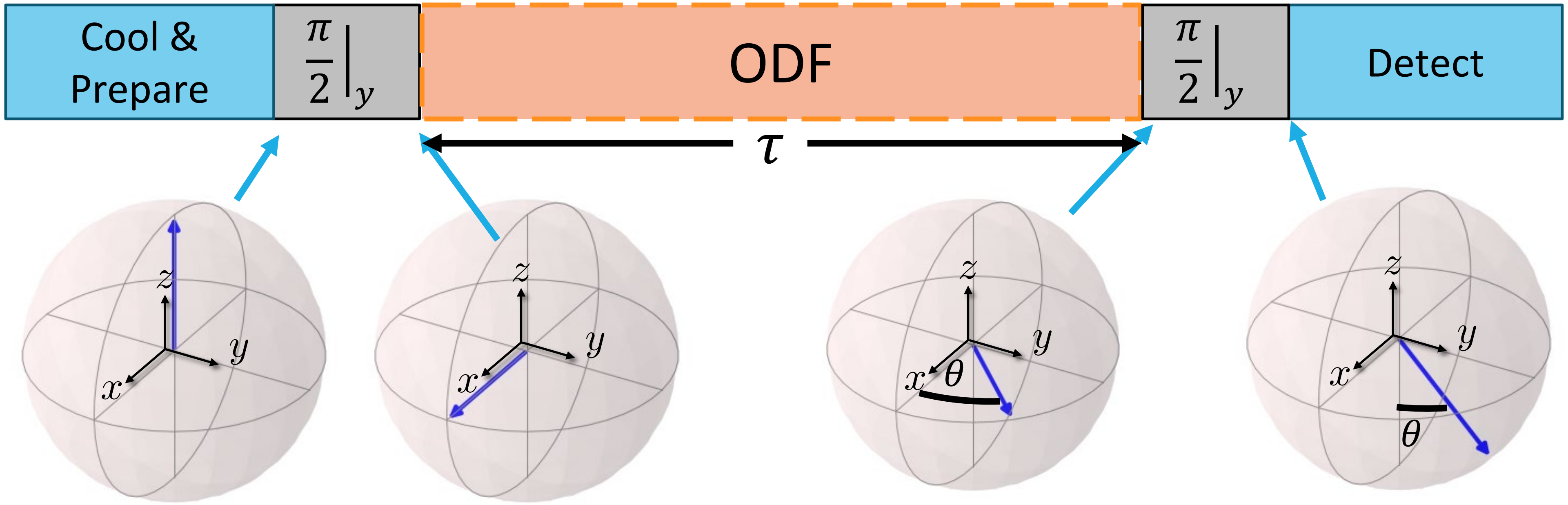
For $\mu = \omega$, produces spin precession with rate $\propto F_0 \cdot Z_c \cos(\phi)$

application of H_{ODF} for duration τ



$$\theta_{max} = F_0 Z_c \tau$$

Measuring spin precession (phase incoherent)



Precession θ,

$$\theta = \frac{F_0}{\hbar} Z_c \tau \cos(\phi)$$

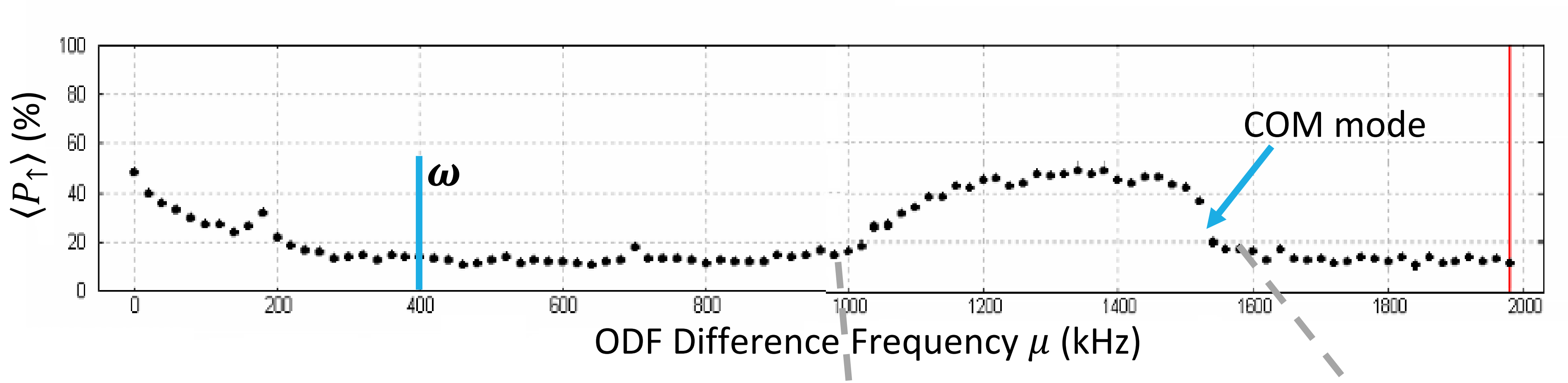
$$-\frac{F_0}{\hbar} Z_c \tau < \theta < \frac{F_0}{\hbar} Z_c \tau$$

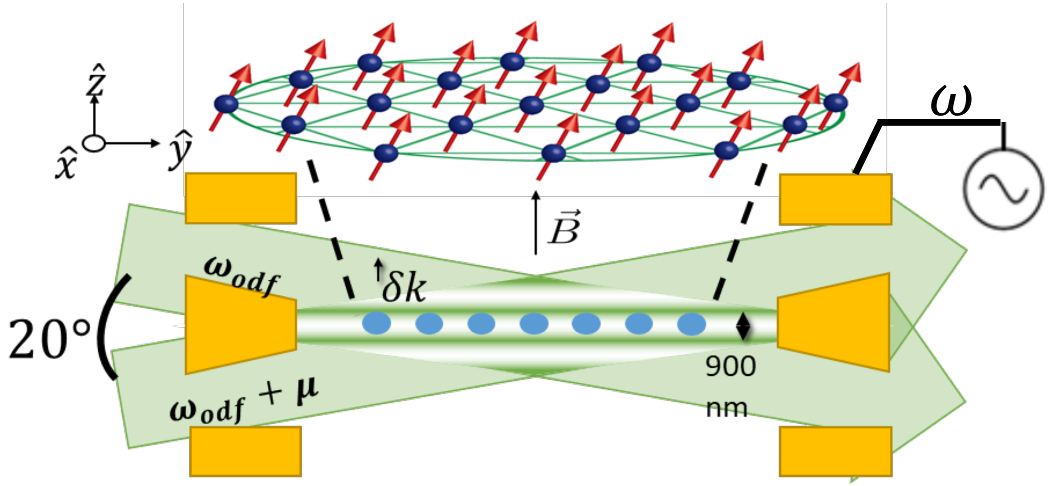
Probability of measuring spin up:

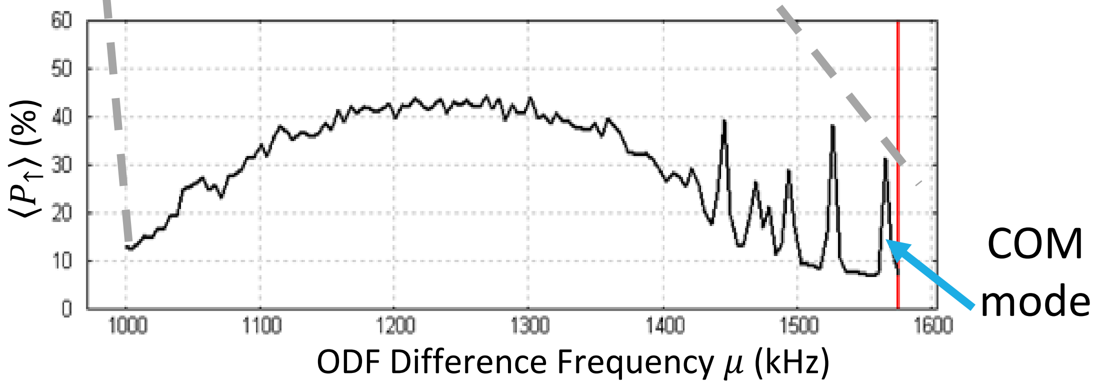
$$\langle P_\uparrow \rangle = \frac{1}{2}\left(1 - e^{-\Gamma\tau} \langle \cos\theta \rangle\right)$$

$$= \frac{1}{2}\left(1 - e^{-\Gamma\tau} J_0\left(\frac{F_0}{\hbar} Z_c \tau\right)\right)$$

Measuring spin precession (phase incoherent)







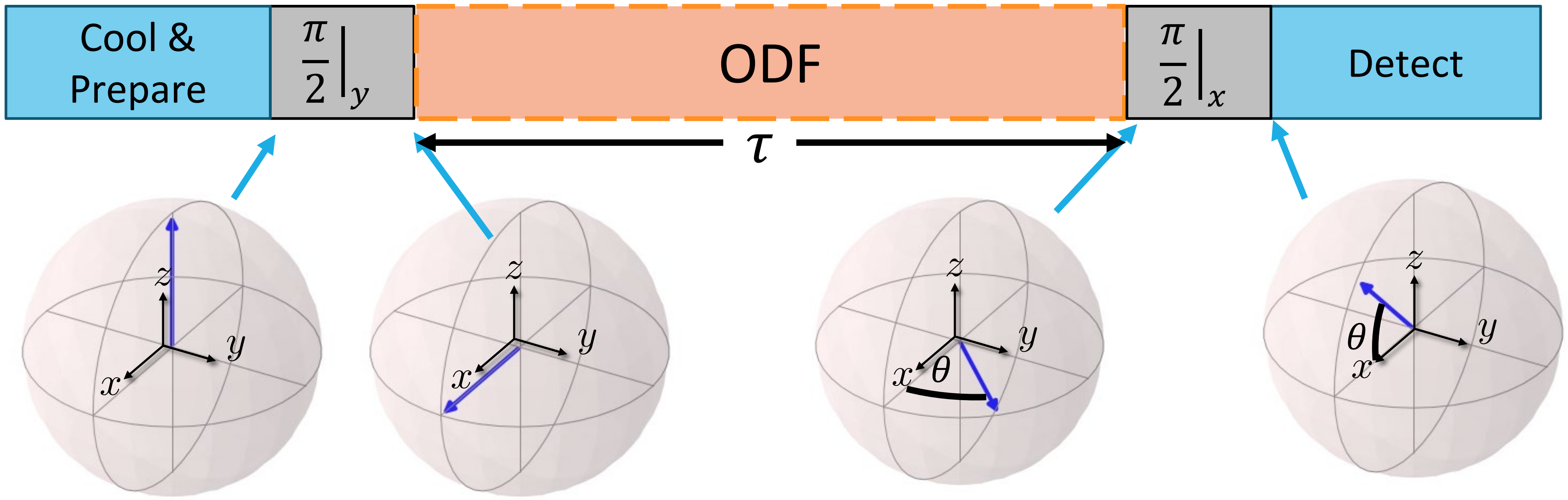
Gilmore et al.,
PRL 2017

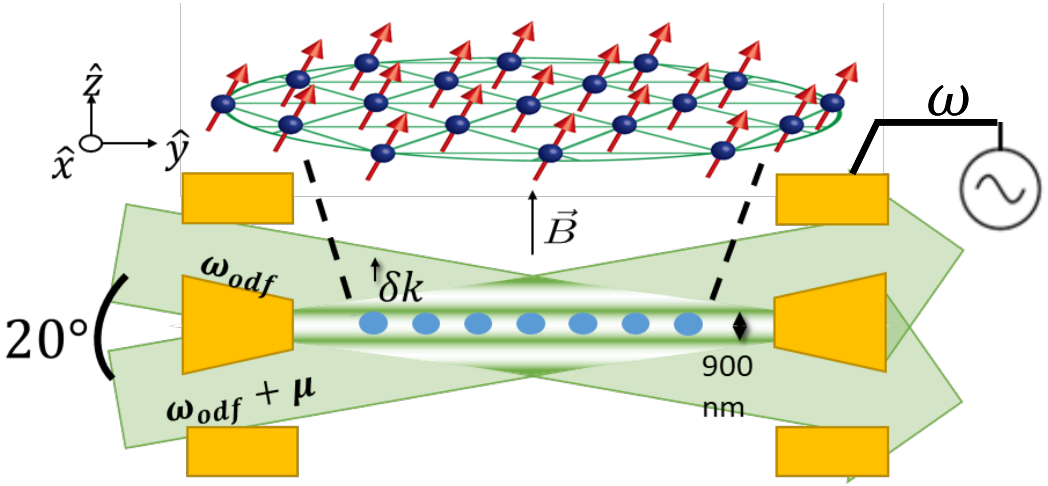
$$\left.\frac{Z_c^2}{\delta Z_c^2}\right|_{\text{limiting}} \approx \left[\frac{Z_c}{0.2\text{nm}}\right]^2$$

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

$\boldsymbol{\phi}$ **random**

Measuring spin precession (phase coherent)





Phase coherent sensing
first order sensitive to Z_c!

Affolter et al.,
PRA 2020

$$\left.\frac{Z_c}{\delta Z_c}\right|_{\text{limiting}} \approx \left[\frac{Z_c}{0.050\text{ nm}}\right]$$

$\boldsymbol{\omega \neq \omega_z}$
$\boldsymbol{\phi}$ fixed

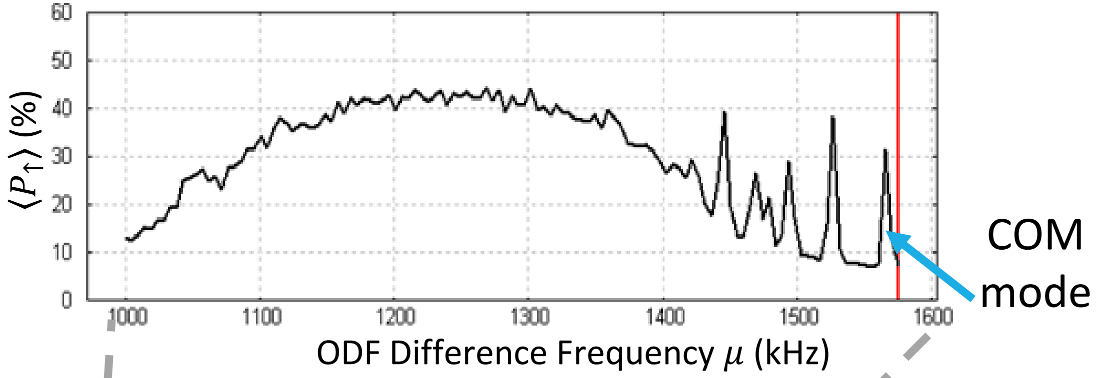
40x smaller than $z_{zpt} \approx 2$ nm

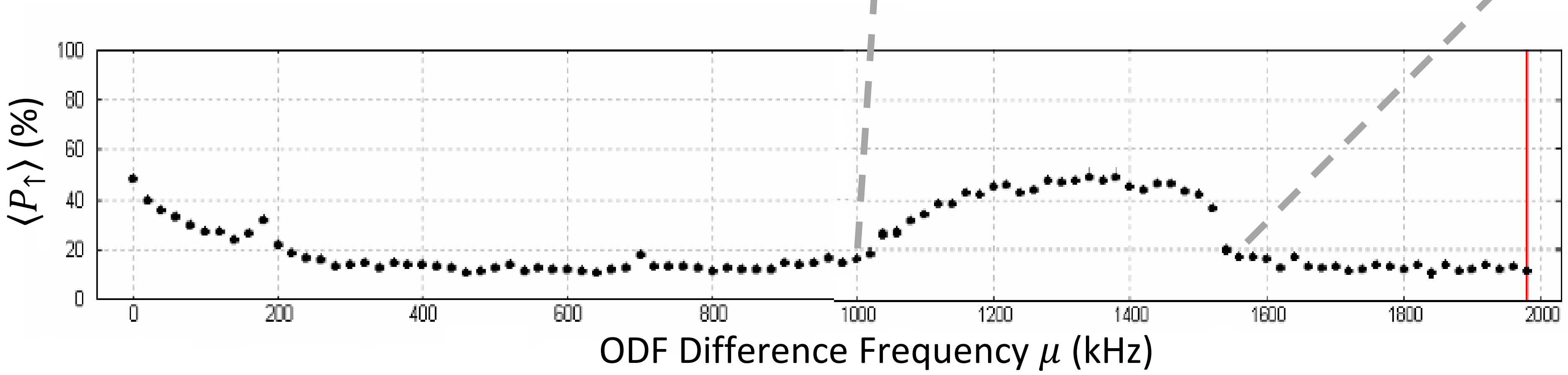
On resonance motional sensing: sensitivity to noise

Sensing motion resonant with ω_z much more sensitive to weak forces and electric fields

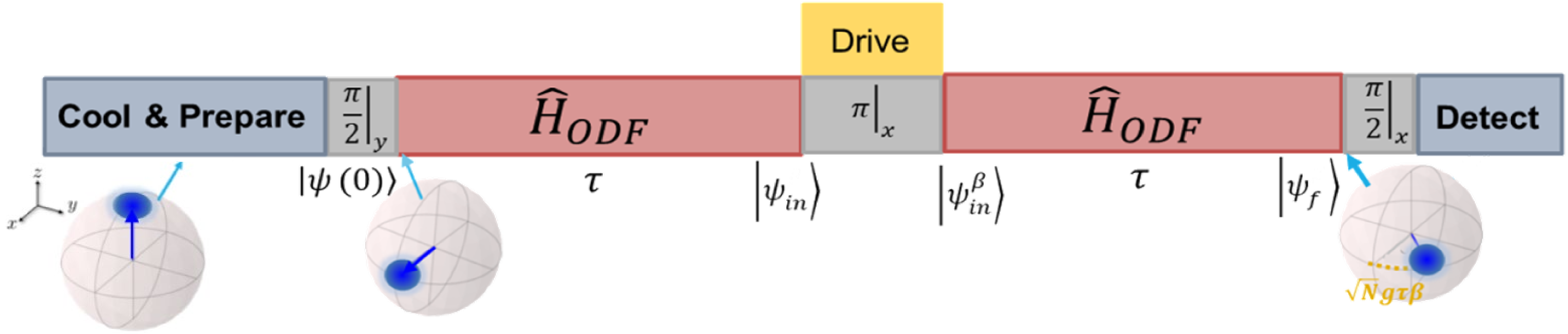
BUT

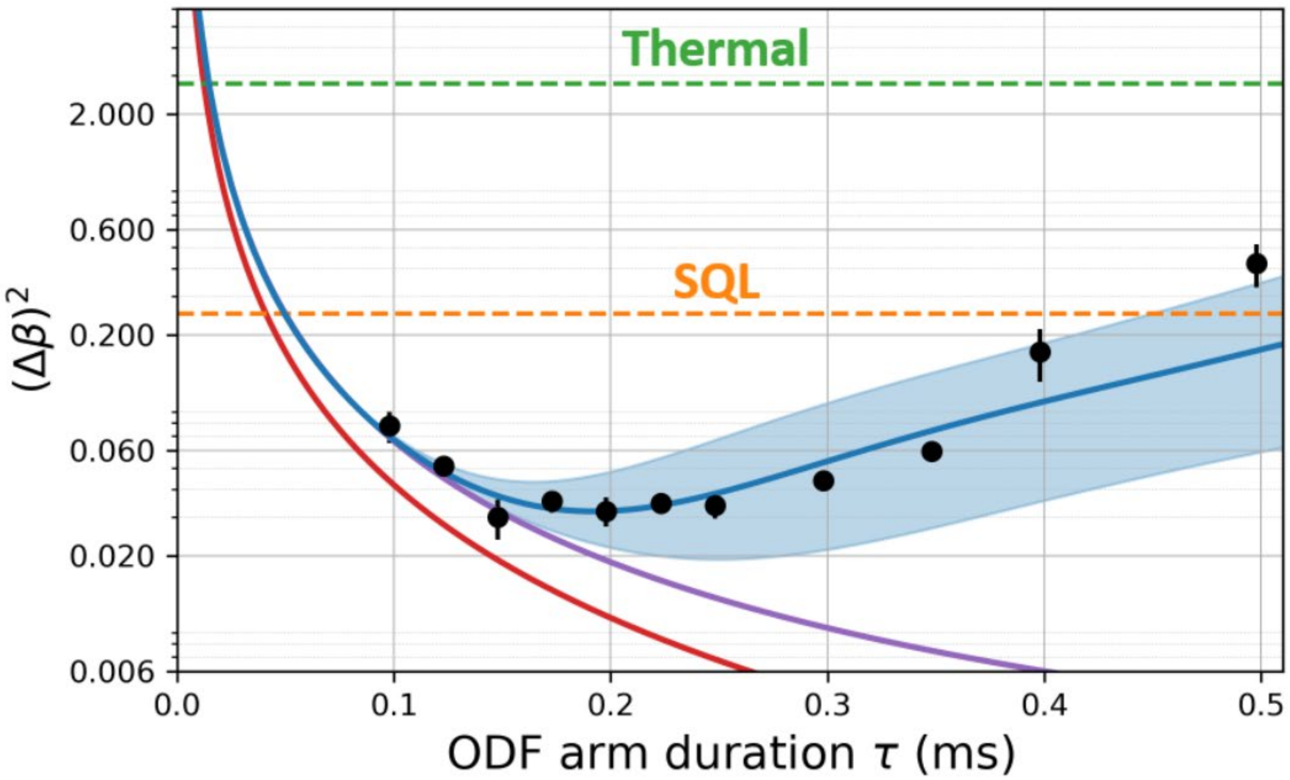
now also sensitive to thermal noise,
zero-point noise,
back action, …





On resonance motional sensing: use time reversal





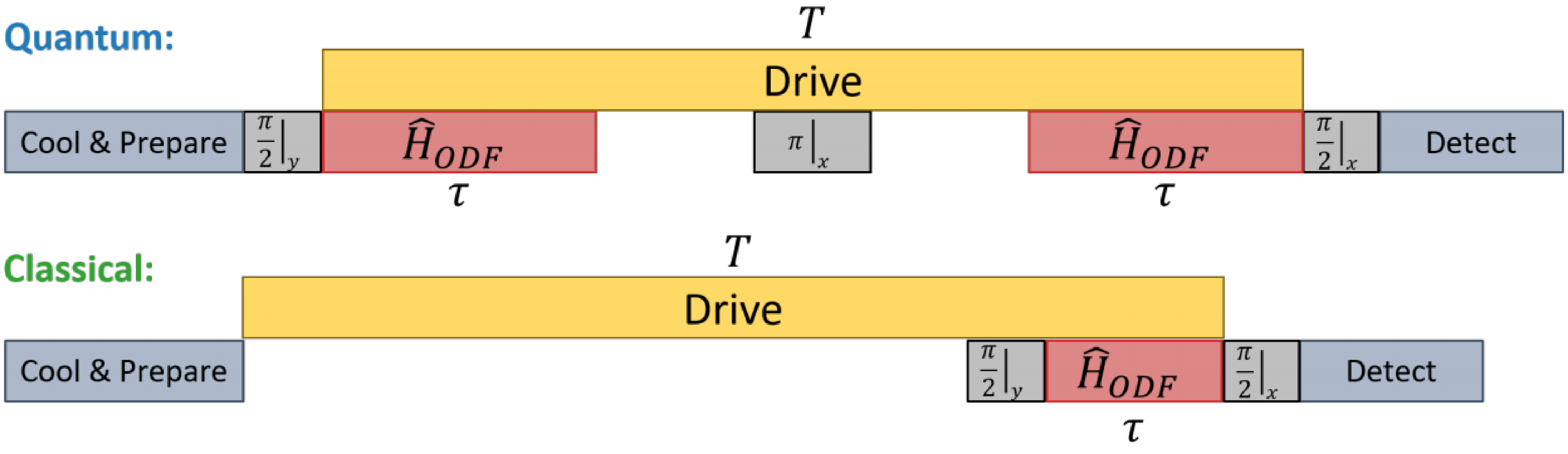
$$\Delta\beta_{Th}^{2} = \frac{(2\overline{n(0)}+1)}{4}$$

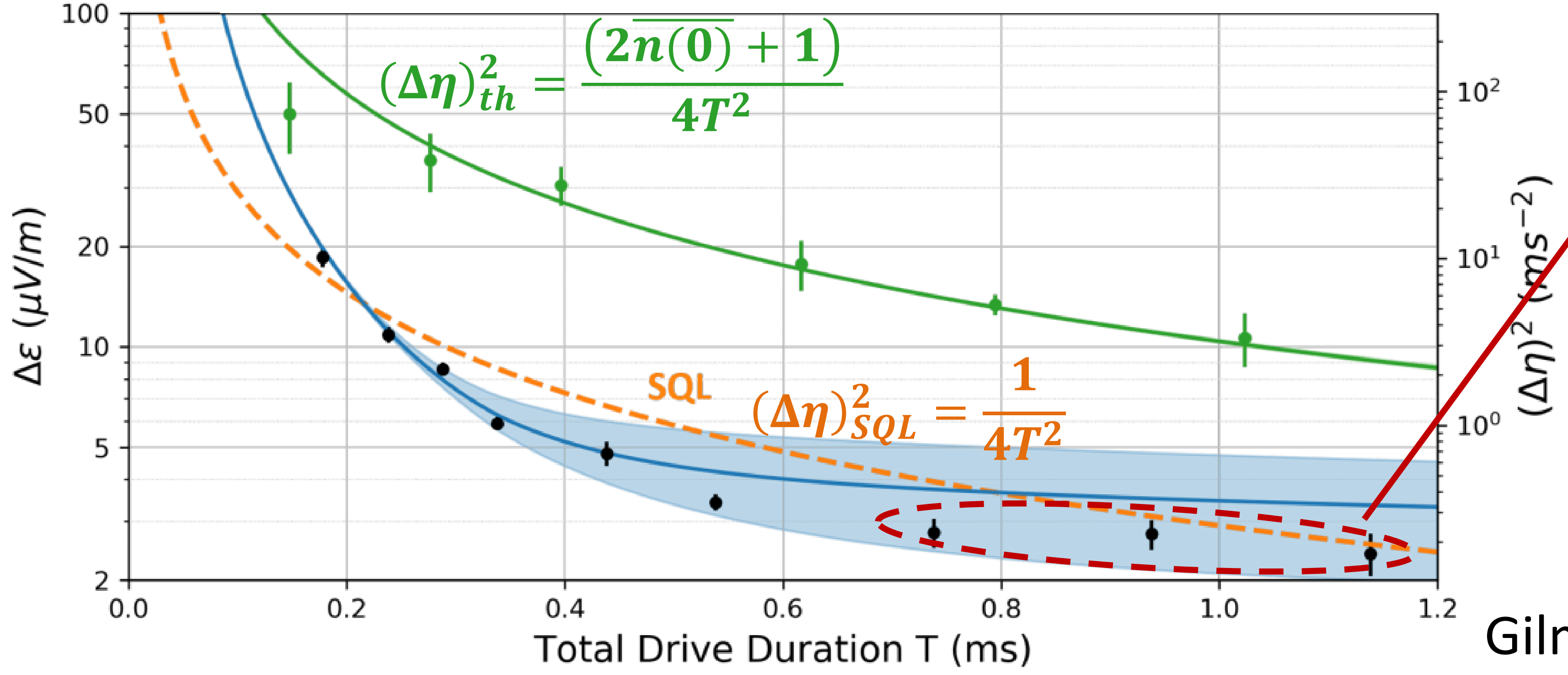
$$\Delta\beta_{SQL}^{2} = \frac{1}{4}$$

See:
Hempel, et al., Nat. Photonics 7 (2013)
Toscano, et al., PRA 94 (2006)

Gilmore et al., arXiv:2103.08690,
Science (to appear)

On resonance $\vec{E}$-field sensing: increase drive duration T





$(240 \pm 10)\frac{(nV/m)}{\sqrt{Hz}}$ @ 1.6 MHz

Favorable comparison with state-of-the-art Rydberg sensors

$\Delta E \sim 5.5\frac{(\mu V/m)}{\sqrt{Hz}}$ @10 GHz

Gilmore et al., arXiv:2103.08690

Summary

- Demonstrated quantum-enhanced sensor of mechanical displacements and weak electric fields in a crystal composed of $\sim$150 trapped ions.

Sensitivities @ 1.6 MHz:

✓ Displacement: $\mathbf{36 \pm 1.5 \frac{pm}{\sqrt{Hz}}}$ [**8.8±0.4 dB** below SQL (**19 dB** below thermal bound)]

✓ Electric Field: $\mathbf{240 \pm 10 \frac{nV/m}{\sqrt{Hz}}}$ [**4±0.5 dB** below SQL (**14 dB** below thermal bound)]

- Limitations: COM fluctuations $\sigma(\delta) \sim (20-60)\mathrm{Hz}$
  COM Doppler cooled $\bar{n} \sim 4.5$

- Improvements: $\left.\begin{array}{l}\text{Reduce COM fluctuations to } \sigma(\delta) \sim 1\ \text{Hz} \\ \text{Near gnd state cooling of COM}\end{array}\right\} \Rightarrow 10 \frac{(n\mathrm{V/m})}{\sqrt{Hz}}$

- Further improvements: ion number $N \sim 10^6$; employ spin squeezed states

Detection of hidden photons and axions @ frequencies [10 kHz to 10 MHz] ??

Axion coupling constant sensitivity estimate

The Axion-EM field interaction modifies Maxwell's equations:

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right) \qquad a(t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\sin(m_a t),$$

m_a: Axion mass

ρ_{DM}: 0.3 $\mathrm{GeV/cm^3}$

$g_{a\gamma\gamma}$: axion – photon coupling

For COM frequencies $\omega_z/(2\pi)$ < 10 MHz $\Rightarrow$ $\lambda^{\text{axion}}_{\text{Compton}} \gg R$(size of B_0 field region) $\Rightarrow$ axion electric field $\boldsymbol{E}_0$ suppressed to 2nd order in $(m_a R)^2$ (natural units)

$$E_0(t) \sim (m_a R)^2 g_{a\gamma\gamma} a(t) B_0$$

$\boldsymbol{B}_0$: External magnetic field ~ 4.5 T

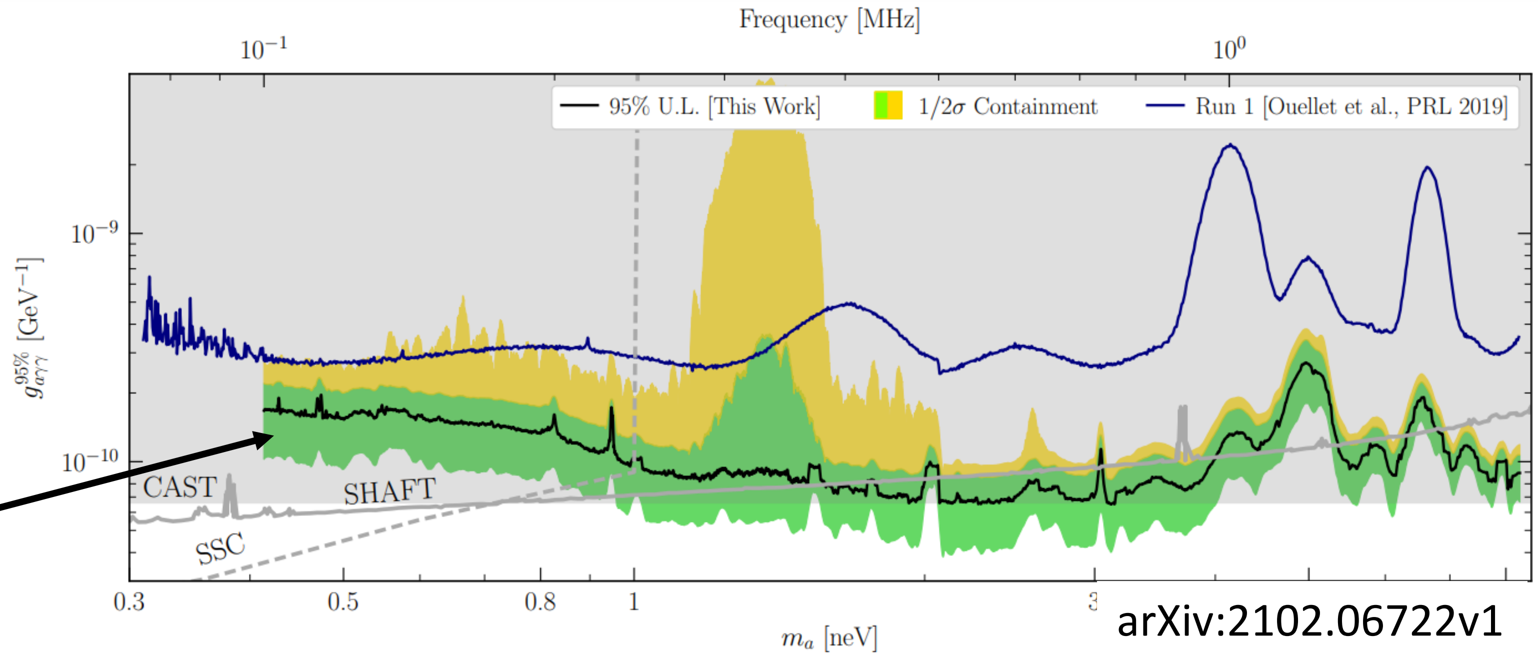
R: 6.5 cm radius of finite magnetic field region

$$\delta g_{a\gamma\gamma} = (\delta E)(m_a)\left(\frac{1}{B_0}\right)\left(\frac{1}{\sqrt{2\rho_{DM}}}\right)\left(\frac{1}{\quad}\right)^2$$

$$\delta g_{a\gamma\gamma} = 4.80 \times 10^{-9}\ \mathrm{GeV}^{-1} \times \sqrt{\frac{1\ \mathrm{s}}{t_{\mathrm{avg}}}}$$

$$\delta g_{a\gamma\gamma}(1\ \mathrm{day}) = 1.6 \times 10^{-11}\ \mathrm{GeV}^{-1}.$$

Compatible with state-of-the-art ABRACADABRA and BASE collaboration limits (PRL 126 (2021))



arXiv:2102.06722v1

NIST ion storage group (2019)

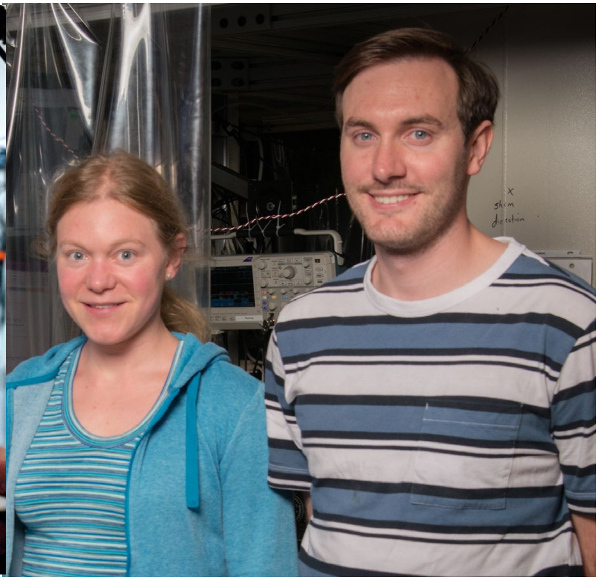
John Bollinger; James Chou; David Hume; Dietrich Leibfried; David Leibrandt; Daniel Slichter; Andrew Wilson; David J. Wineland;

Matt Affolter; James Bergquist; Kevin Boyce; Shaun Burd; Dalton Chaffee; Ethan Clements; Daniel Cole; Alejandra Collopy; Kaifeng Cui;

Robert Drullinger; Stephen Erickson; Kevin Gilmore; Panyu Hou; Wayne Itano; Elena Jordan; Jonas Keller; May Kim; Hannah Knaack;

Felix Knollman; Justin Niedermeyer; Julian Schmidt; Raghavendra Srinivas; Laurent Stephenson; Susana Todaro; Jose Valencia; Jenny Wu

Experiment

Matt Affolter Elena Jordan Kevin Gilmore

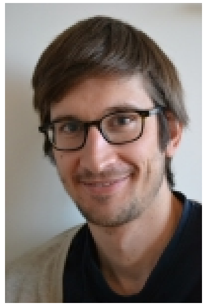
Justin Bohnet

Jennifer Lilieholm

Bryce Bullock

Theory

Ana Maria Rey



Martin Gärttner

Arghavan Safavi-Naini

Robert Lewis-Swan

Murray Holland

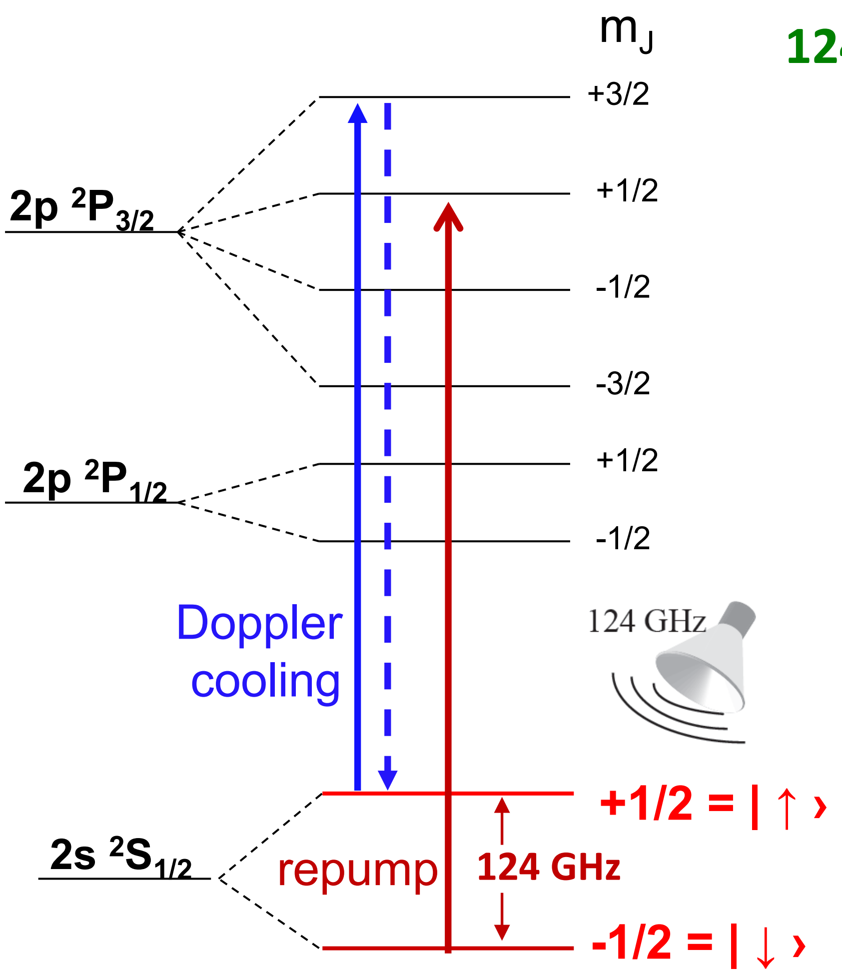
Athreya Shankar
Holland group

Diego Barberena

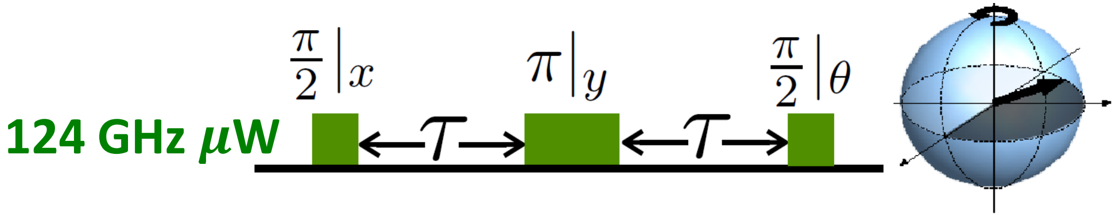
Extra Slides

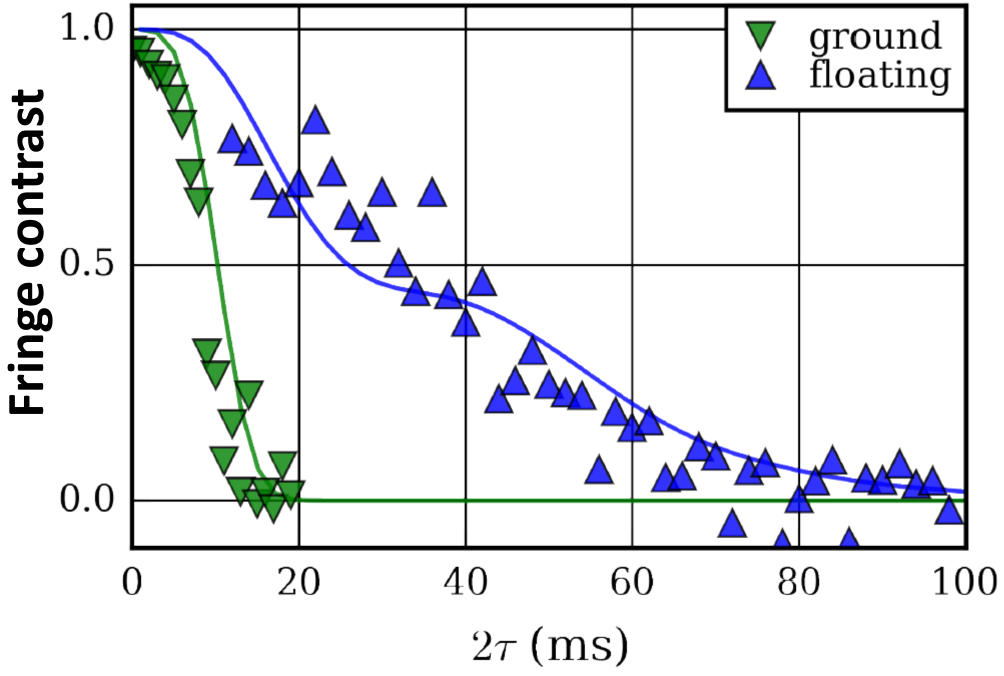
Be$^+$ high magnetic field qubit

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



T2 coherence



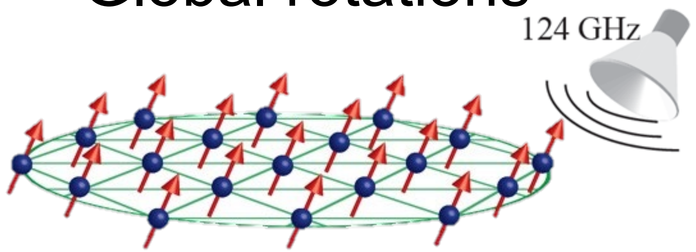


Spin-echo precession time →

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

Implementing single-site rotations

Global rotations



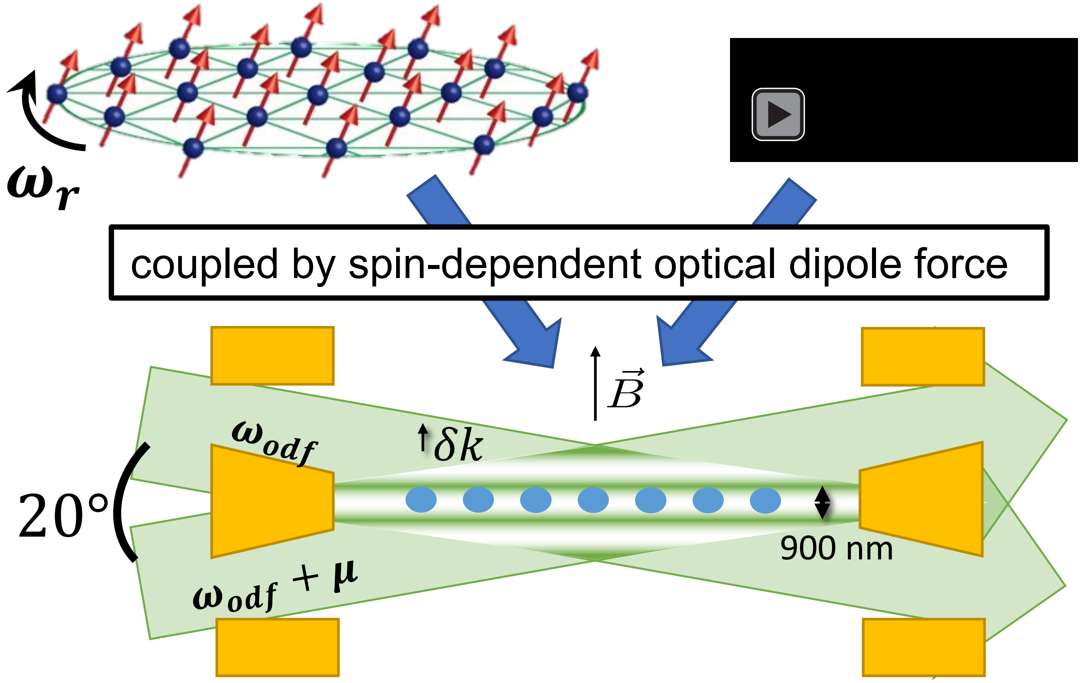
Global entangling gate
Global rotations
Single-site rotations

→ Universal gate set

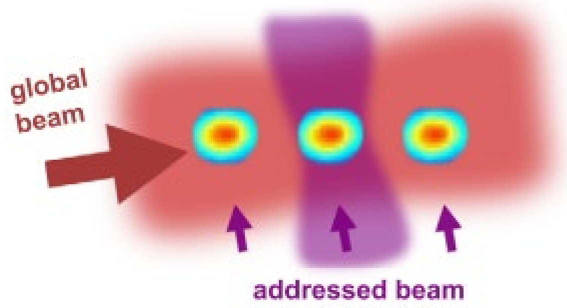
Global entangling gate

124 GHz spin qubit

Center-of-mass motion



With linear arrays, single-site σ_z- rotations with AC Stark shifts from focused laser beams



From Schindler et al 2013 New J. Phys. 15 123012

Implementing single-site rotations - σ_z rotations with patterned AC Stark shifts

$$\hat{H}_{ODF} = U\sum_i \sin\left(\delta k \hat{z}_i - \mu t + \psi\right)\hat{\sigma}_i^z. \quad \overset{\text{DM}}{\Longrightarrow} \quad \hat{H}_{ODF} = U\sum_i \sin\left[\delta k \hat{z}_i - \mu t + \psi + \delta(x_i, y_i)\right]\hat{\sigma}_i^z.$$

$$\delta(x,y) \equiv \delta(\rho, \phi^{lab}) := P^m(\rho)\cos(m\phi^{lab})$$

$$\xRightarrow[\phi_i^{lab} = \phi_i^{rot} - \omega_r t]{\mu = m\omega_r}$$

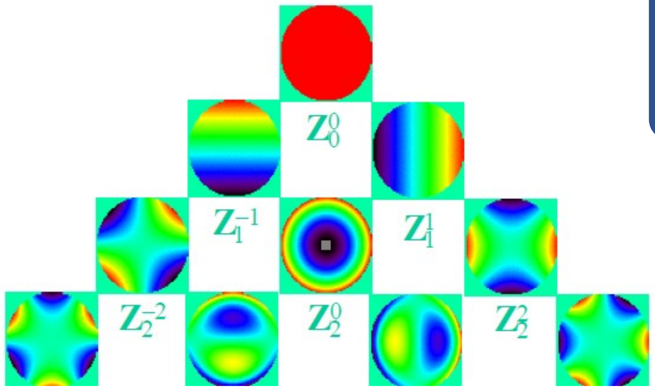
$$\hat{H}_{ODF} = U\sum_i J_1[P^m(\rho_i)]\sin(m\phi_i^{rot} - \psi)\hat{\sigma}_i^z$$

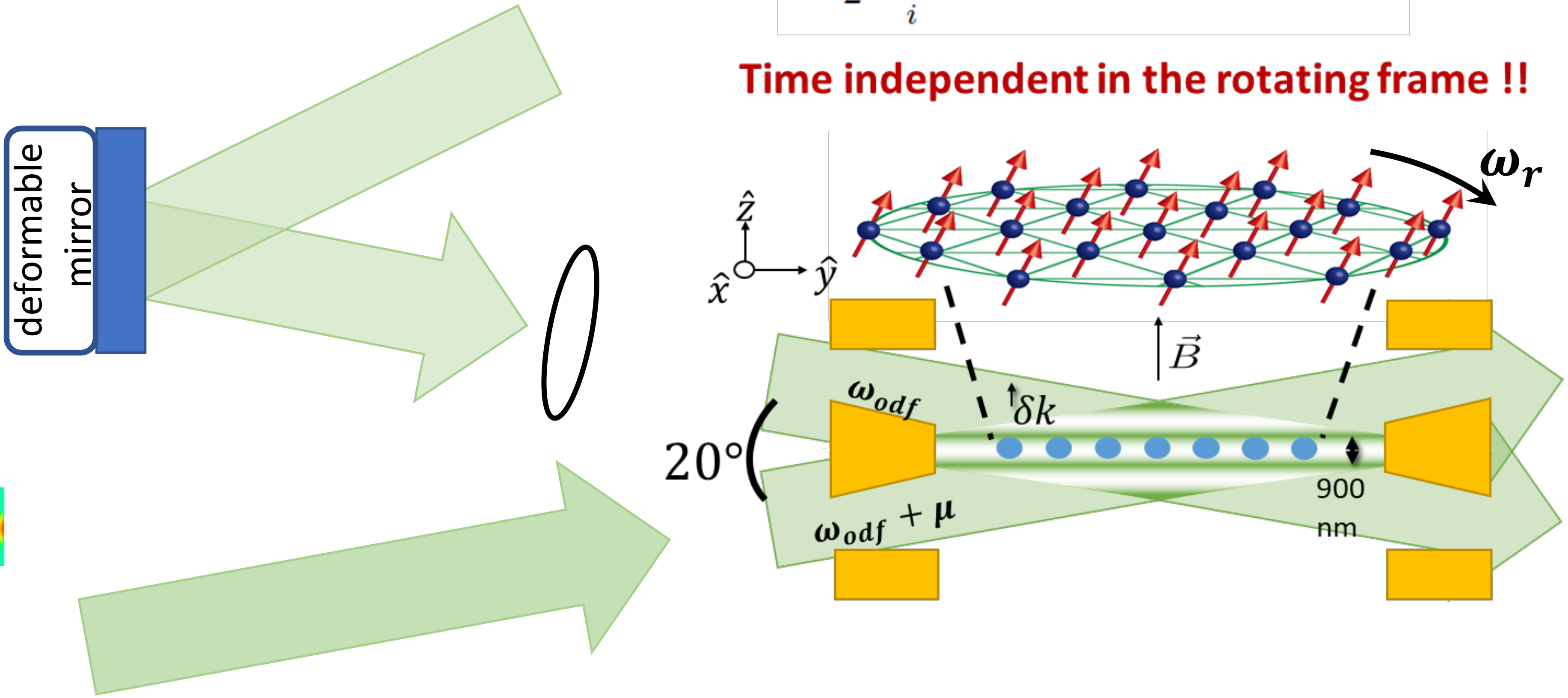
$$\approx \frac{U}{2}\sum_i P^m(\rho_i)\sin(m\phi_i^{rot} - \psi)\hat{\sigma}_i^z$$

Time independent in the rotating frame !!

Zernike polynomials

$$Z_n^m(\rho,\phi) = \begin{cases} N_n^m R_n^{|m|}(\rho)\cos(m\phi), \\ N_n^m R_n^{|m|}(\rho)\sin(m\phi), \end{cases}$$





Implementing single-site rotations - σ_z rotations with patterned AC Stark shifts

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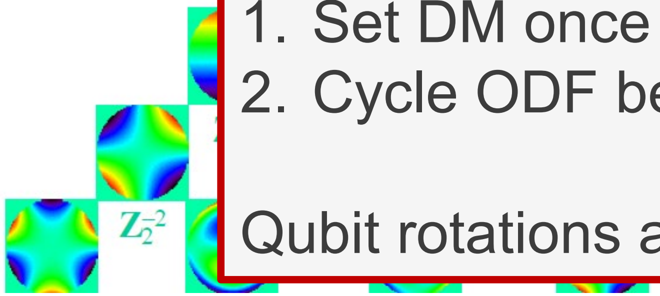

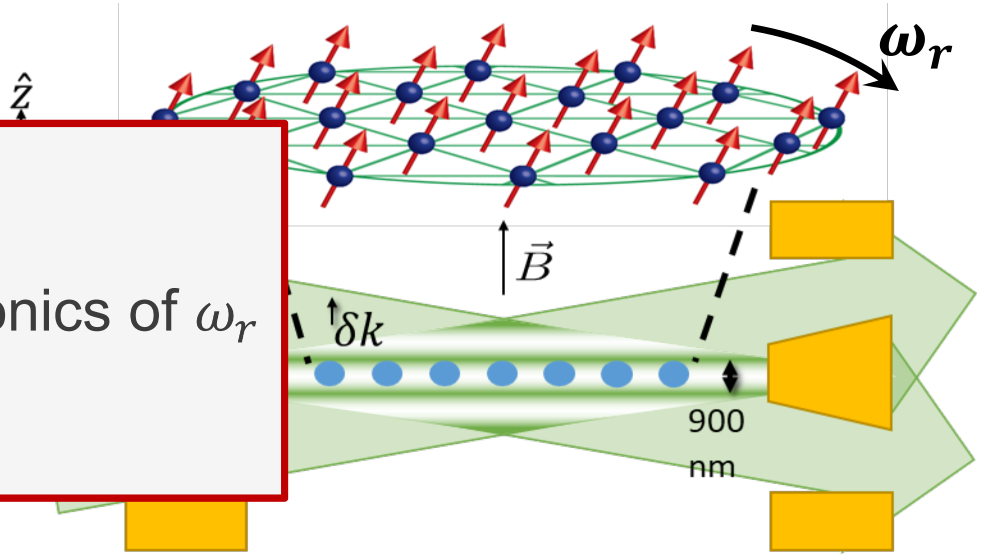

Simple protocol for small argument regime:

1. Set DM once
2. Cycle ODF beat note $\mu = m\omega_r$ through harmonics of ω_r

Qubit rotations are conducted in parallel