Quantum Information Experiments with Ion Crystals in Penning Traps

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Ion storage group

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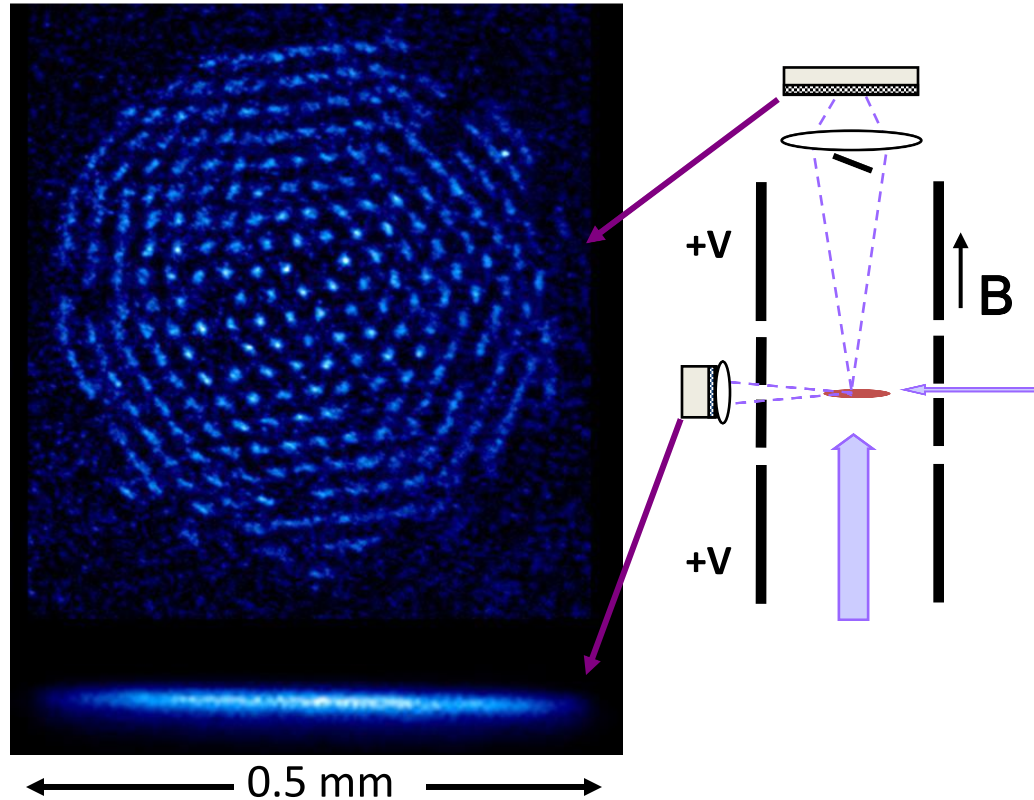
Dan Dubin – UCSD(theory)



National Institute of Standards and Technology

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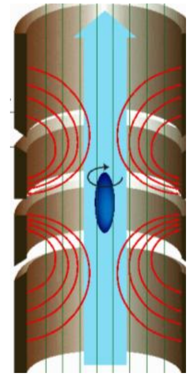
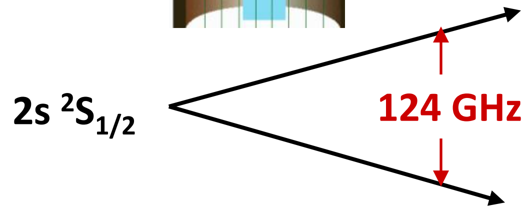
BE THE FUTURE

Outline:

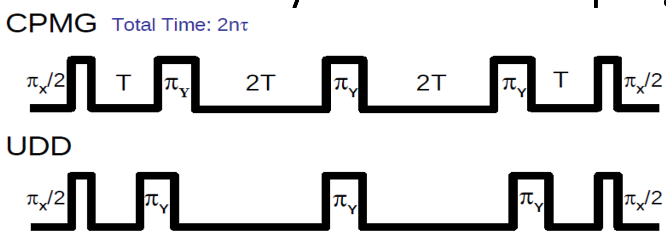
- Penning traps
  - Monday: Quint, Wada
  - Tuesday: Charlton
  - Friday: Schweikhard



- High magnetic field qubit

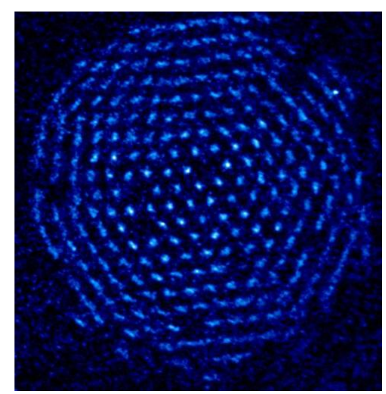


- Qubit coherence and dynamical decoupling techniques



- Current effort: quantum simulation

$$H = -B_x \sum_i \sigma_i^x + \chi J_z^2$$

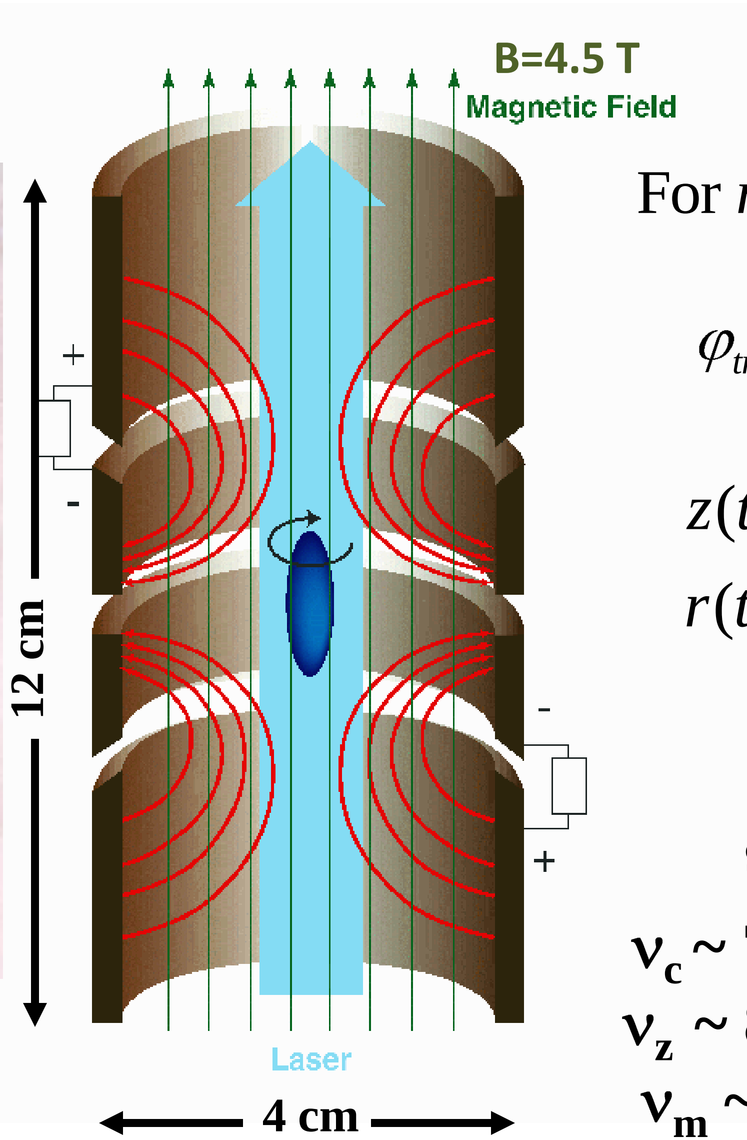


- Decoherence due to elastic Rayleigh scattering

$$\Gamma_{Rayleigh} = \Omega_R^{\,2} \gamma \left(\sum_J a_{d\to d}^J - \sum_{J'} a_{u\to u}^{J'} \right)^2$$

Penning trap

NIST Penning trap



For $r, z <<$ trap dimensions ,

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

$$z(t) = z_o \sin(2\pi\nu_z t + \varphi_z)$$

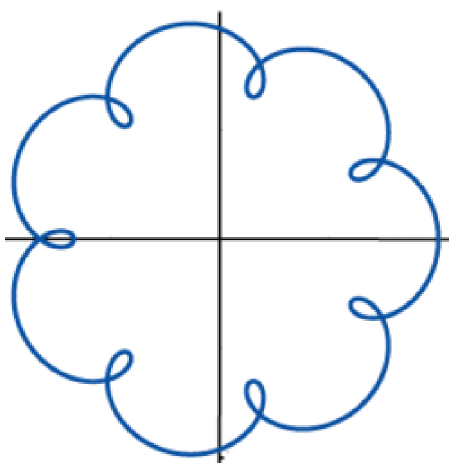
$$r(t) = r_c \sin(2\pi(\nu_c - \nu_m)t + \phi_c) + r_m \sin(2\pi\nu_m t + \phi_m)$$

$^9Be^+$

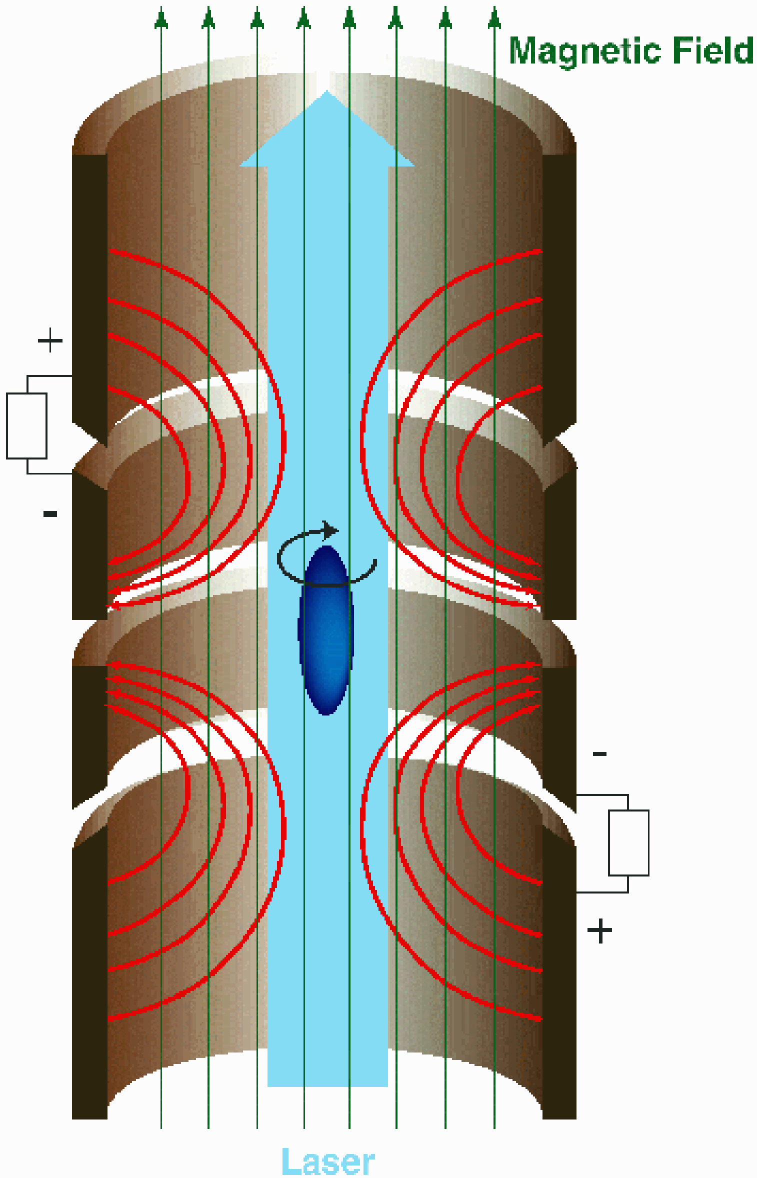
$\nu_c \sim$ 7.6 MHz

$\nu_z \sim$ 800 kHz,

$\nu_m \sim$ 40 kHz



Penning trap: many particle confinement



axial confinement ⟷ conservation of energy

radial confinement ⟷ conservation of angular momentum

$$P_\theta = \sum_j \left(m v_{\vartheta_j} + \frac{q}{c} A_\theta(r_j) \right) r_j$$

$$\approx \frac{qB}{2c} \sum_j r_j^{\,2} \text{ for } A_\theta(r) = \frac{Br}{2} \text{ and } B \text{ large}$$

O'Neil, Dubin, UCSD

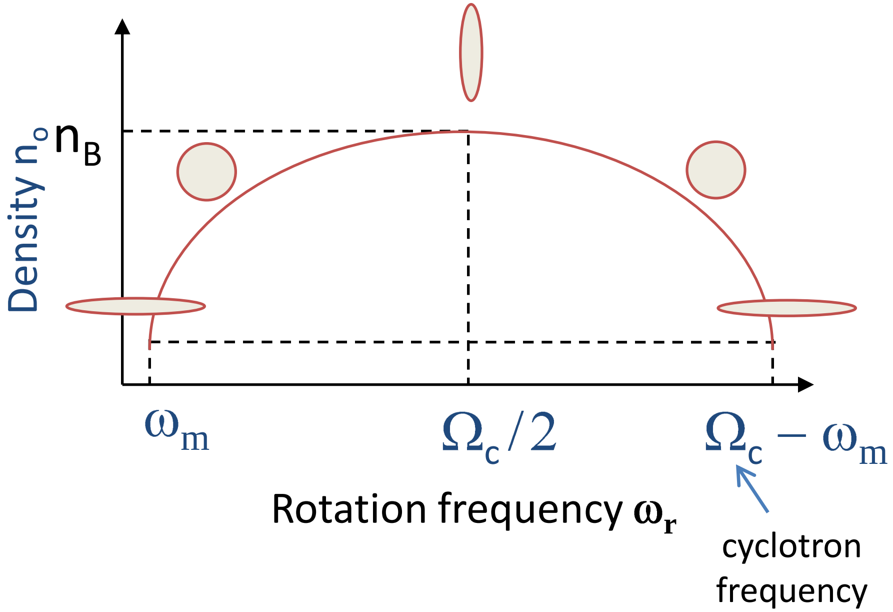
axial symmetry important – trap and B field aligned to 0.01°

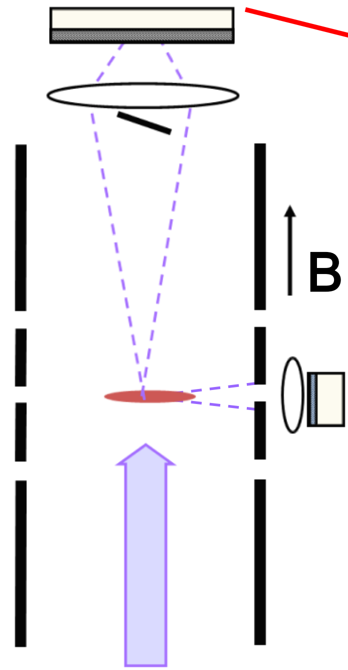
radial confinement due to rotation – ion plasma rotates $v_\theta = \omega_r r$ due to ***ExB*** fields

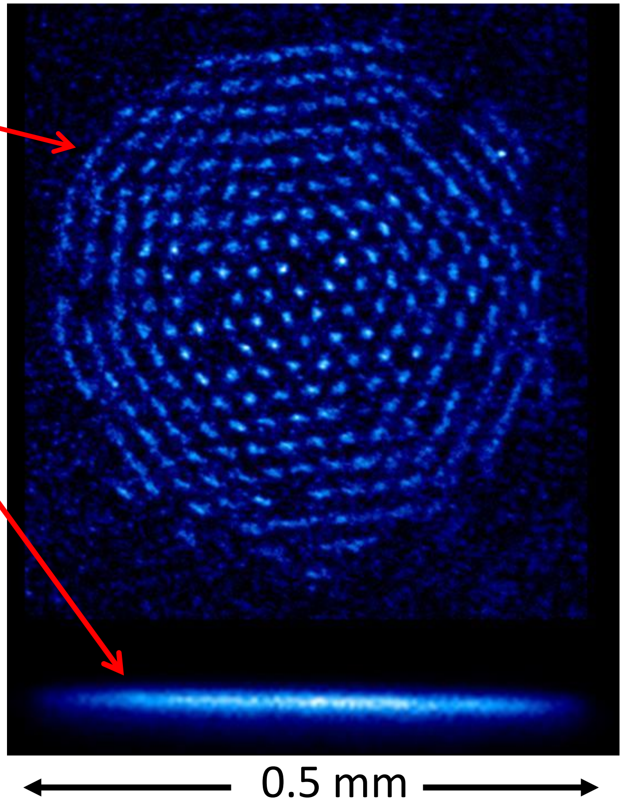
in rotating frame, $\omega_r r \hat{\theta} \times B \hat{z}$ Lorentz force is directed radially inward

precisely control ω_r (and the radial binding force) with a rotating electric field (rotating wall)

Planar ion arrays in Penning traps





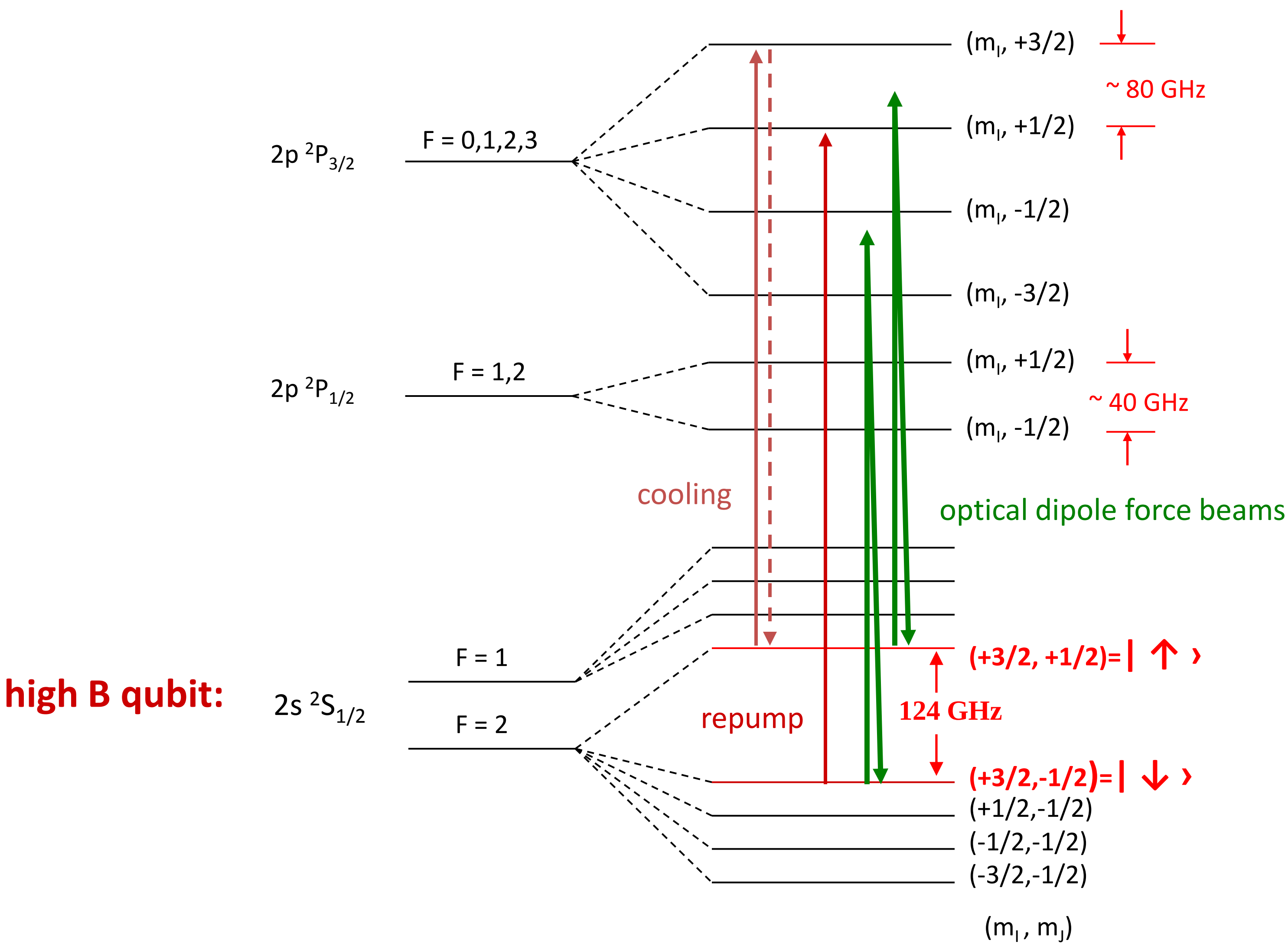


Features of Penning traps for quantum information/simulation experiments:

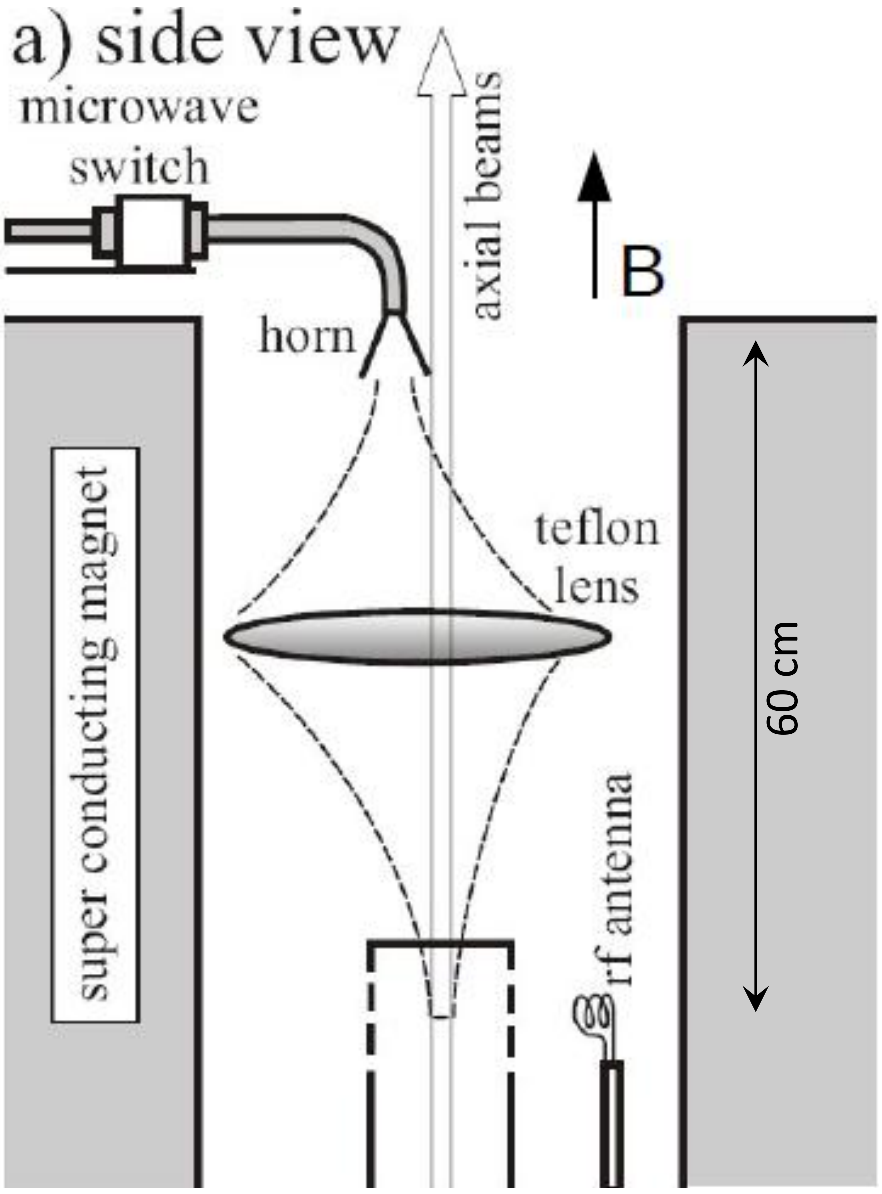
- static trapping fields enable large traps to be used; ions are far from electrode surfaces ⇨ low heating rates
- ion crystals form naturally from minimization of the Coulomb potential energy
- for a single plane, the minimum energy lattice is triangular ⇨ good for magnetically frustrated simulations
- ion crystals rotate (~50 kHz) but rotation precisely controlled ⇨ individual particle detection still possible

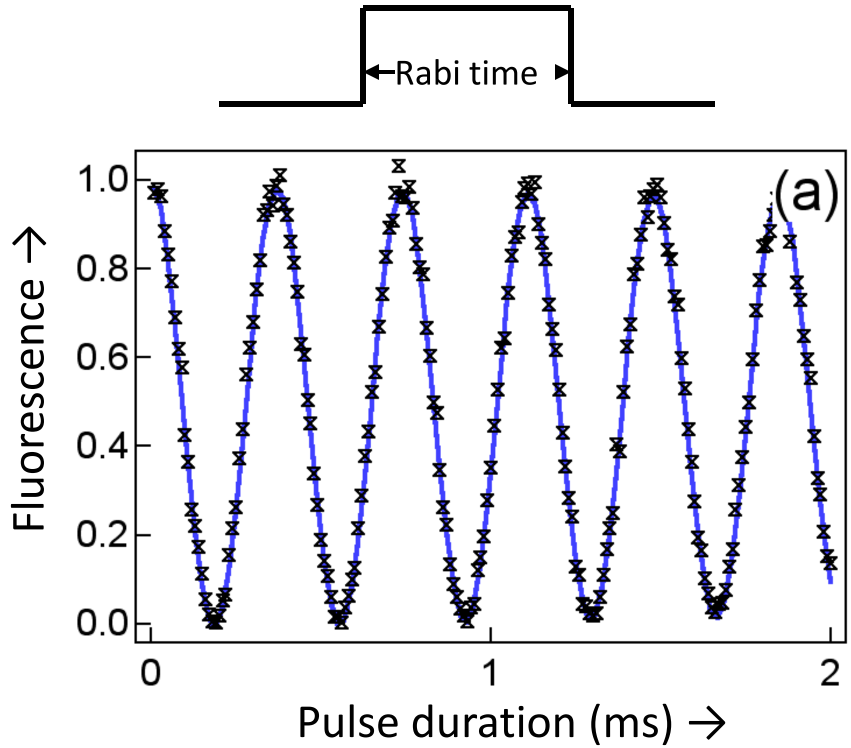
High magnetic field qubit

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



Rabi flopping on 124 GHz electron spin flip



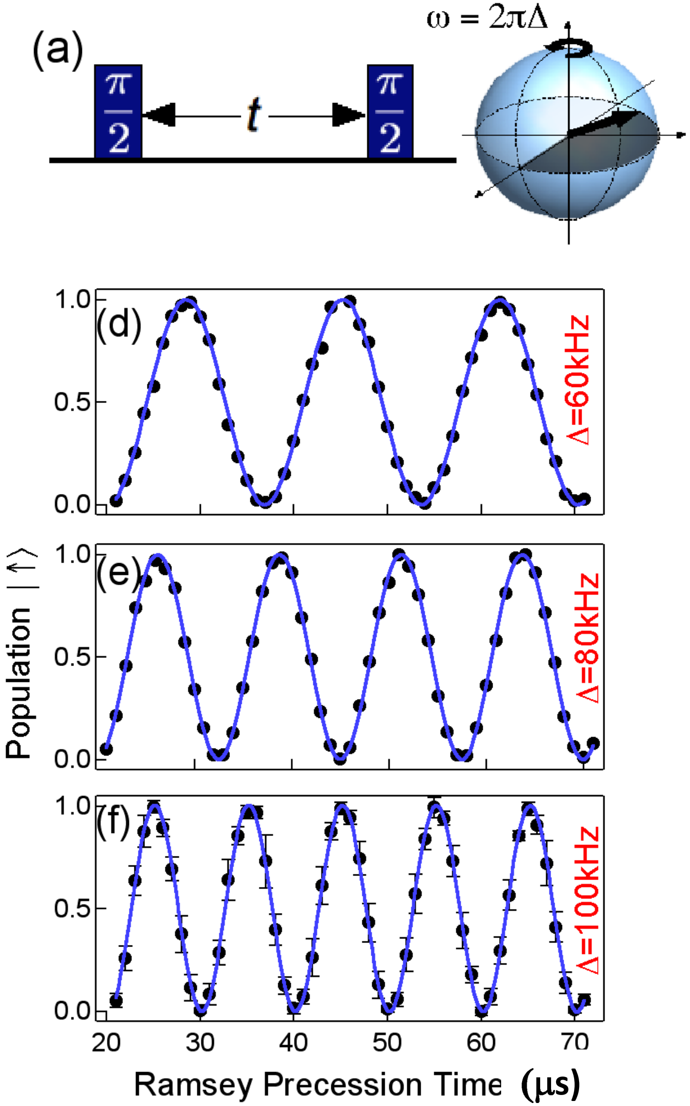


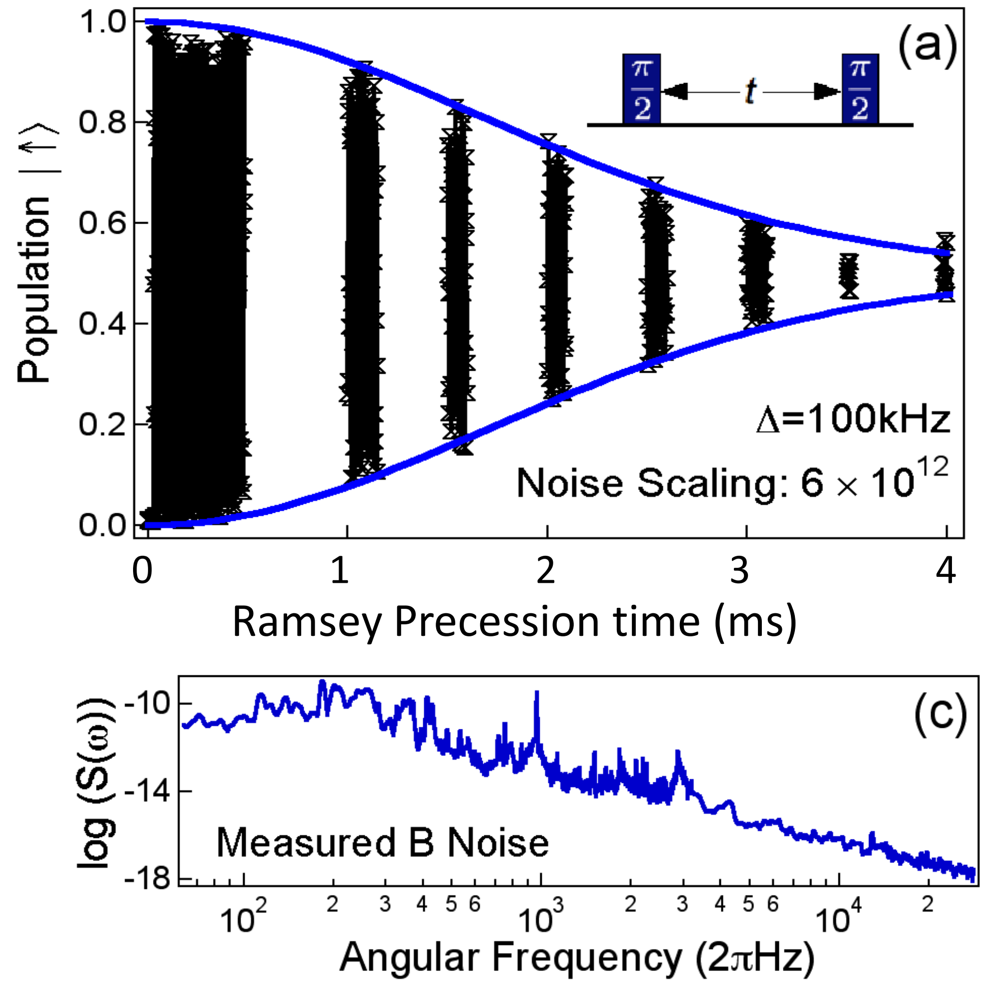
random benchmarking experiment:

Biercuk, *et al.*, Quantium Information and Control 9, 920 (2009).

π –pulse fidelity > 99.9%

Ramsey (T_2) coherence on 124 GHz electron spin flip





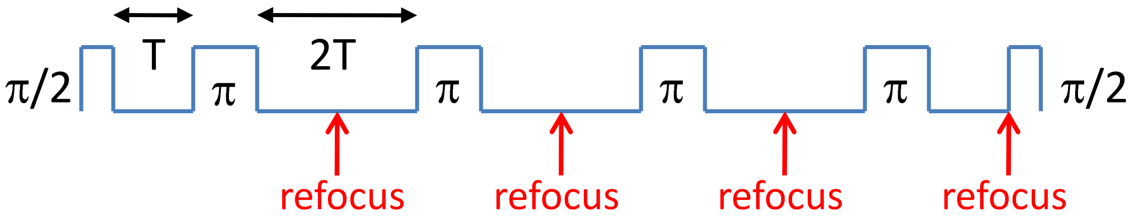
$$\frac{\delta B}{B} \sim 10^{-9}, \quad T_2 \sim 2\,\mathrm{ms}$$

coherence can be extended to 10's of ms with spin echo (dynamical decoupling)

Biercuk, Uys, VanDevender, Shiga, Itano, Bollinger, Nature 458, 996 (2009)

Dynamical decoupling sequences

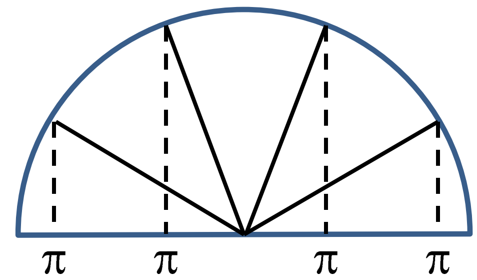
- Carr-Purcell-Meiboom-Gill (CPMG) sequence – evenly spaced π-pulses



usually only need refocusing at sequence end ⇒ π-pulses need not be evenly spaced

- Uhrig sequence (UDD) - Uhrig, PRL **98**, 100504 (2007)

UDD construction



n π-pulse UDD sequence cancels lowest n-1 derivatives of the noise

B(t) = B(0) + B'(0)t +(1/2)B''(0)t² + (1/6)B'''(0)t³ + …..

- Theoretical determination of coherence:
  - Uhrig
  - Cywinski, Das Sarma
  - Martinis

$F(\omega\tau) =$ noise filtration function of sequence

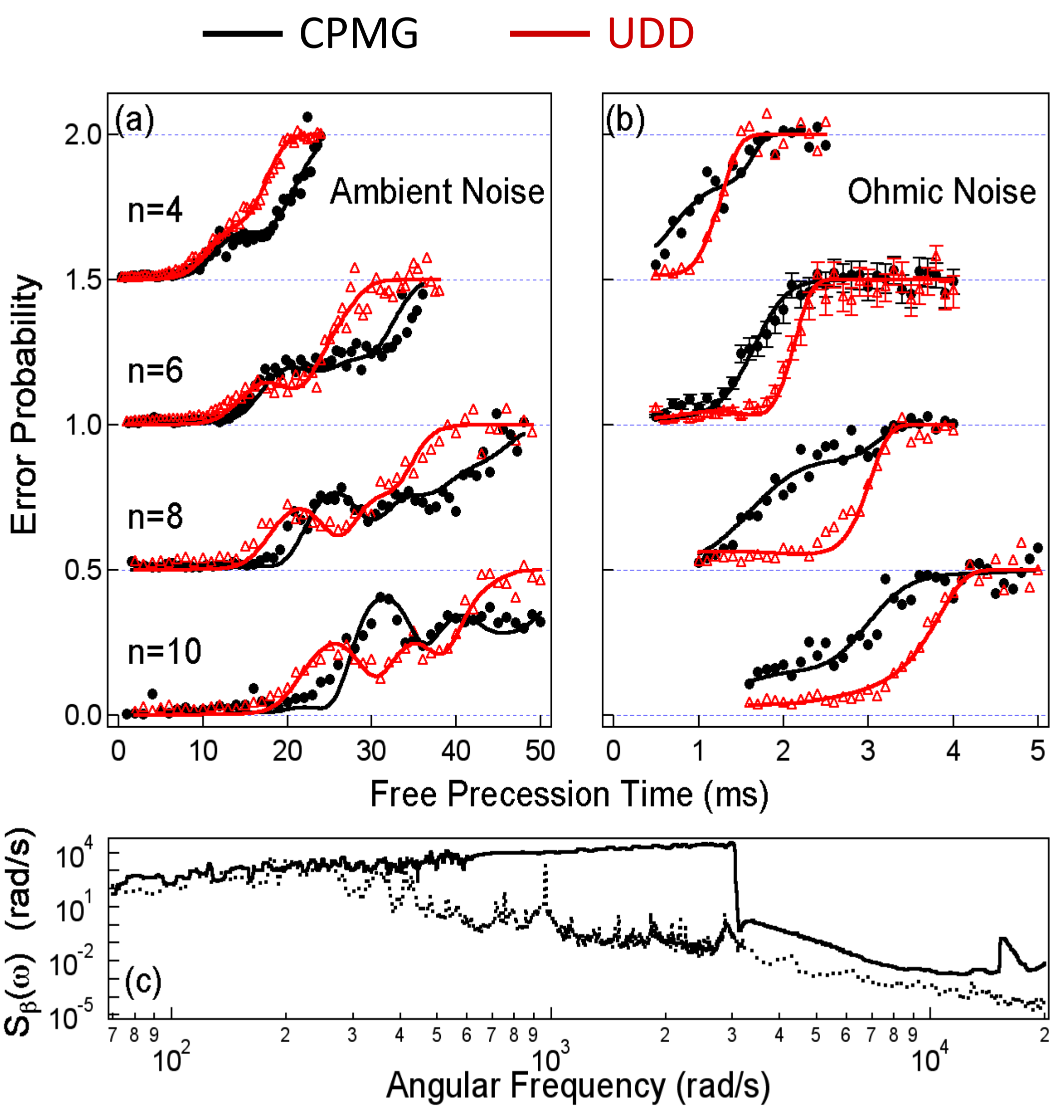
$S(\omega) =$ noise power spectrum

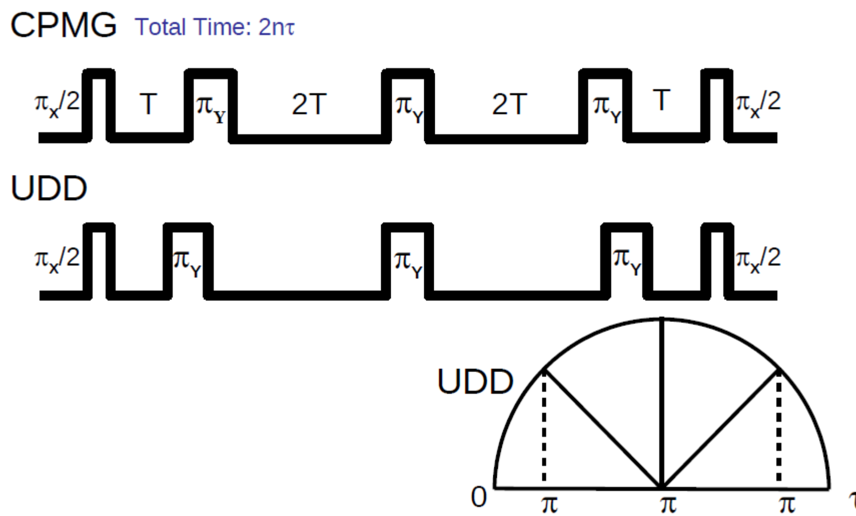
$$\text{coherence} = e^{-\chi(\tau)},\ \chi(\tau) = \frac{2}{\pi}\int_0^\infty \frac{S(\omega)}{\omega^2} F(\omega\tau)\, d\omega$$

Qubit coherence extended and accurately predicted by dynamical decoupling

Biercuk, et al., Nature 458, 996 (2009)

Uys, et al., PRL 103, 040501 (2009)

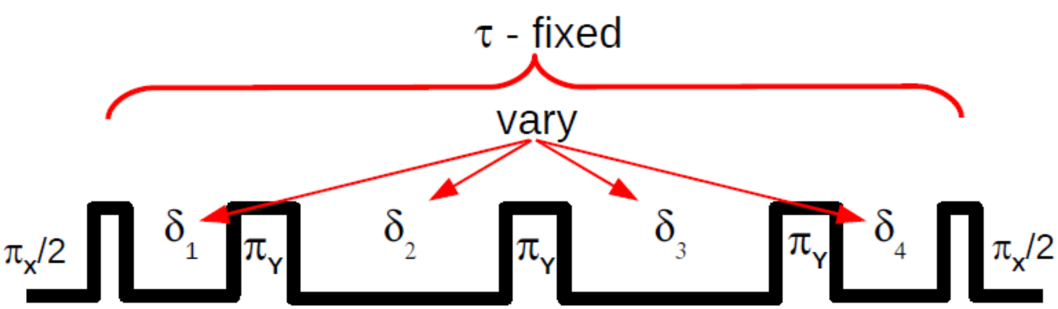


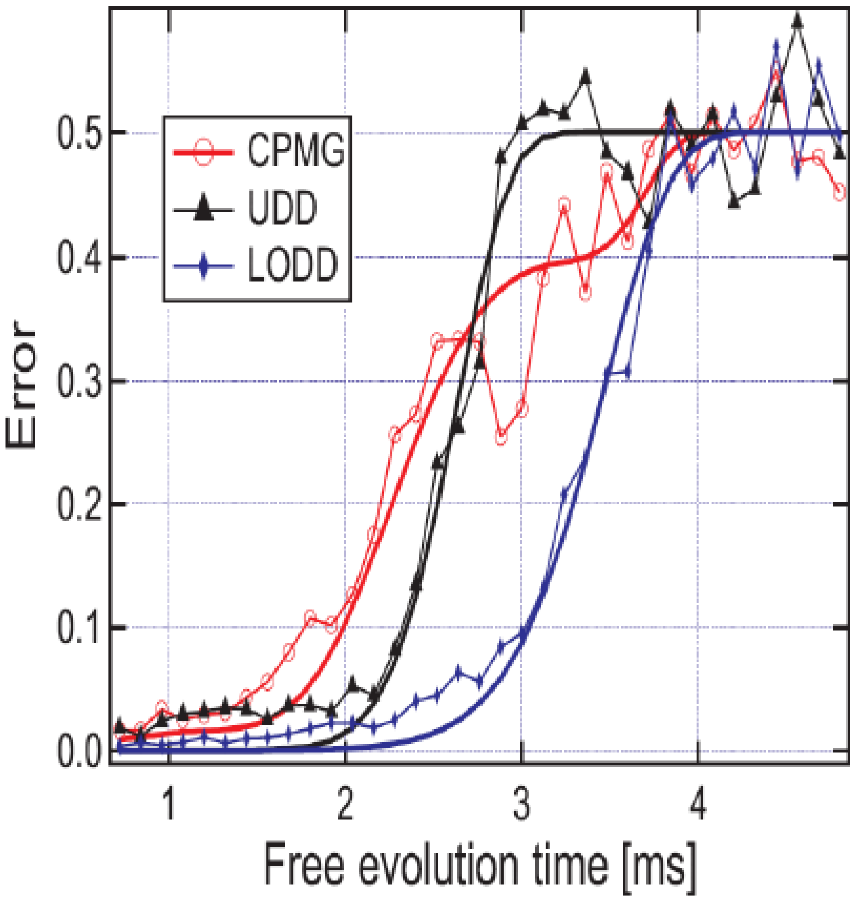


- Fits use analytical filter function and measured noise spectrum
- CPMG, UDD perform similarly for $1/f^2$ ambient noise
- UDD performs better for noise spectra with sharp cutoffs
- Ohmic noise with sharp cutoff injected

improved performance through feedback optimization

- vary inter-pulse delays for fixed precession time (Nelder-Mead simplex method)



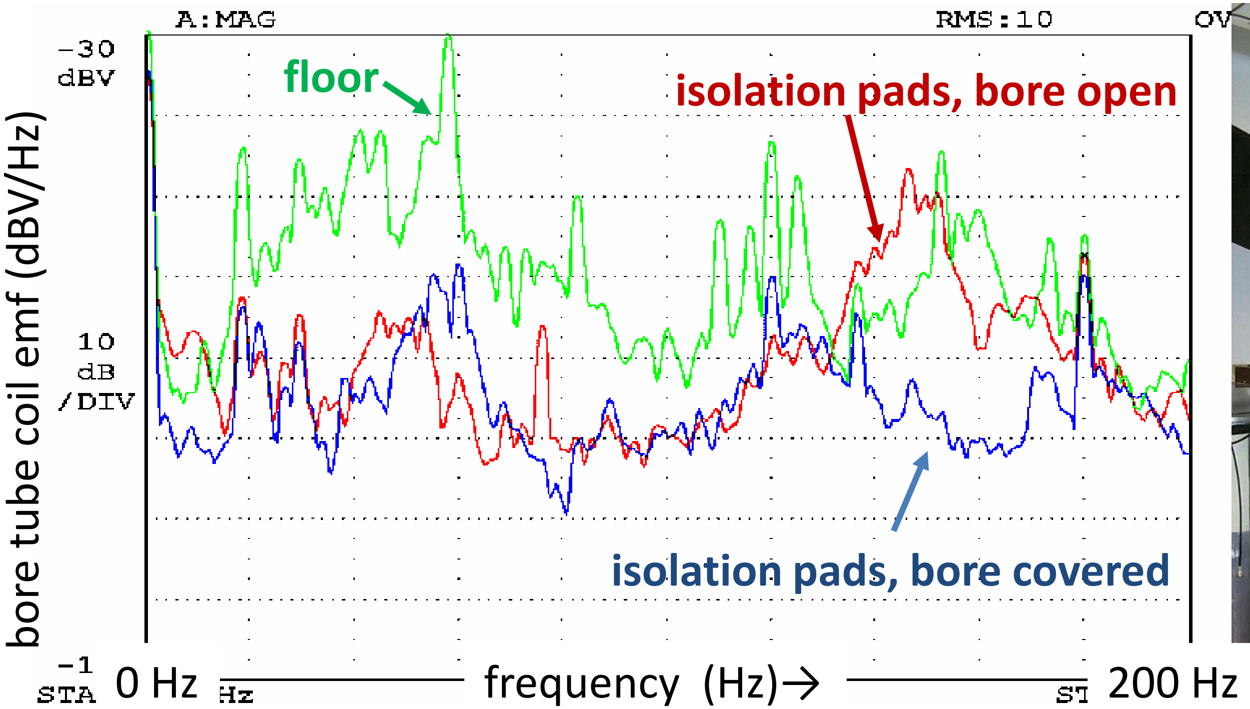


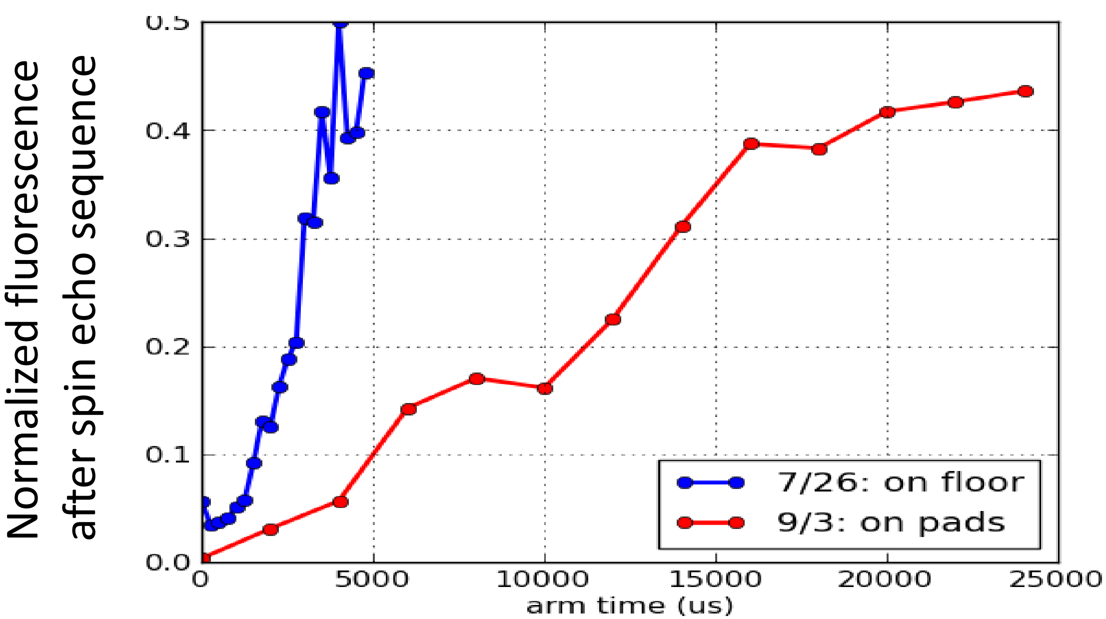
- results shown for injected Ohmic noise

- improved performance with feedback optimization at each total precession time

- no prior knowledge of S(ω) required

Magnetic field noise reduced through vibration reduction





3 ms → 15 ms increase in spin echo coherence time (single arm time)

Present effort: quantum simulation (see Thursday tutorial by Schaetz)

- Porras, Cirac, PRL 92 (2004); Deng, Porras, Cirac, PRA 72 (2005)
- Schaetz group, Nature Physics 4 (2008); Monroe group, Nature 465 (2010)

uniform Ising model

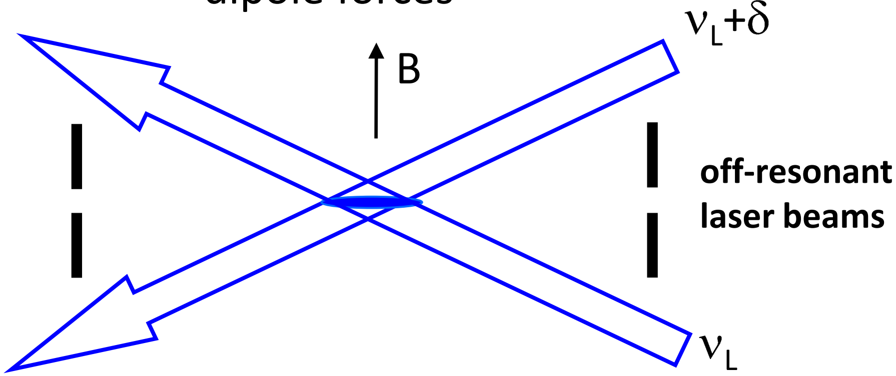
$$H = -B_x \sum_i \sigma_i^x + \chi J_z^2$$

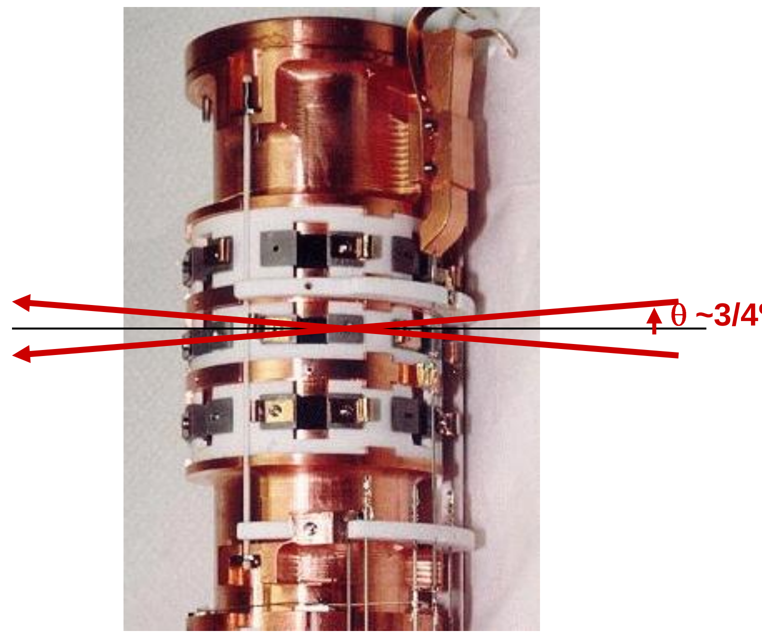
$$J_z^2 = \frac{1}{4}\left(\sum_i \sigma_z^i\right)\left(\sum_j \sigma_z^j\right) = \frac{N}{4} + \frac{1}{4}\sum_{i,j} \sigma_z^i \sigma_z^j$$

dipolar anti-ferromagnetic Ising interaction

$$H = -B_x \sum_i \sigma_i^x + J \sum_{i \neq j} \sigma_i^z \sigma_j^z \frac{d_o^3}{\left|\vec{r}_i - \vec{r}_j\right|^3}$$

- B_x derived from 124 GHz microwaves
- χ, J derived from state-dependent optical dipole forces

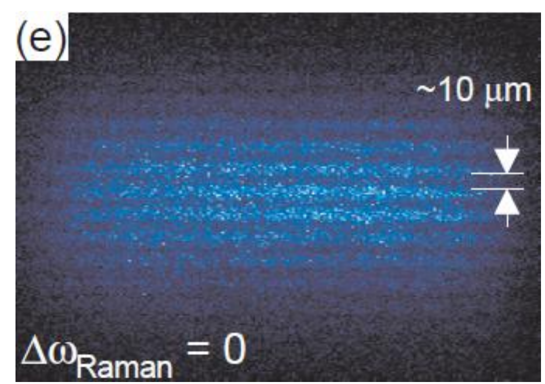




$\delta \approx \omega_z \Rightarrow \chi J_z^2$ uniform Ising interaction, squeezing

$\delta >> \omega_z \Rightarrow$ dipolar anti-ferromagentic Ising interation

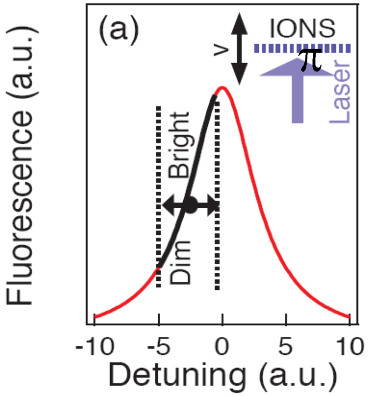
$\delta = 0$

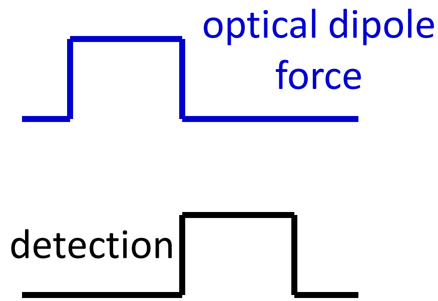


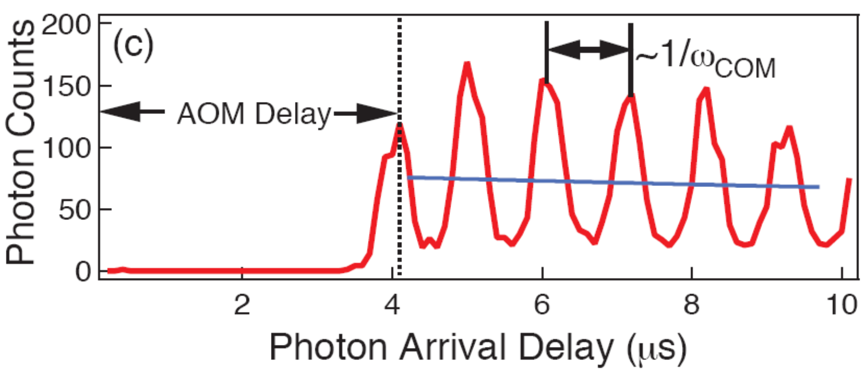
Optical dipole force excitation of ion planar arrays (N>100)

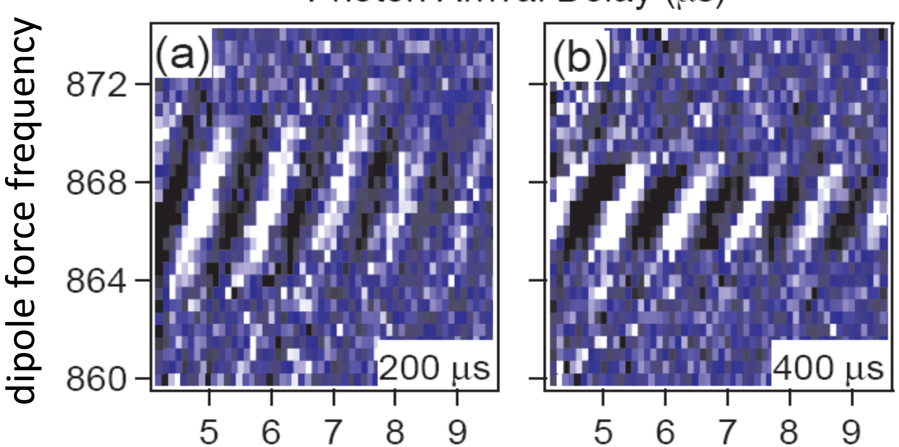
triggered Doppler velocimetry

Biercuk et al., Nature Nanotechnology 5 (2010)

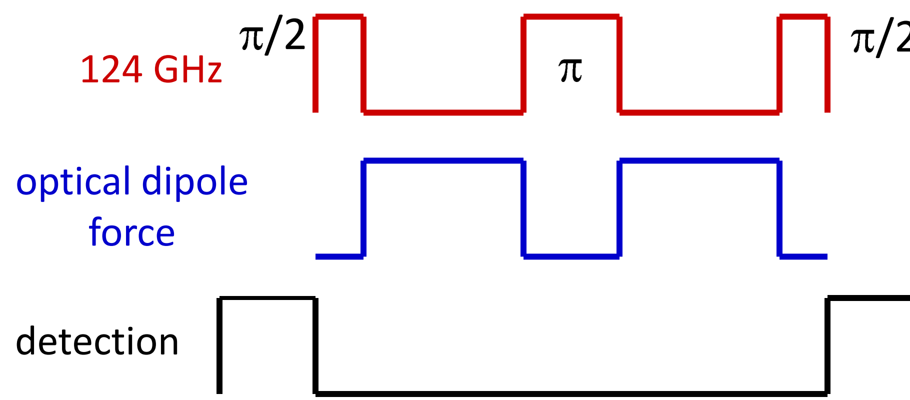




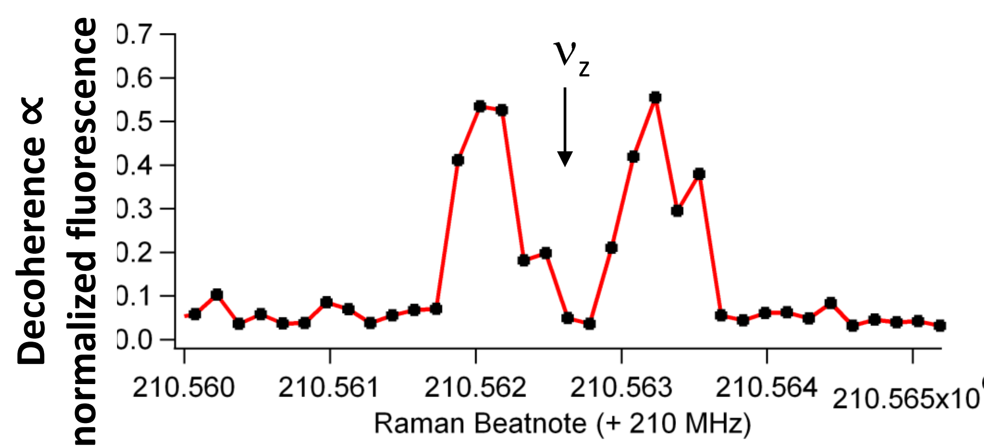




internal state dependence of optical dipole drive



decoherence due to spin/axial COM mode entanglement



Quantum simulation with planar ion arrays

uniform Ising model

$$H = -B_x \sum_i \sigma_i^x + \chi J_z^2$$

B_x = 5 kHz; > 50 kHz with new μwave source

dipolar anti-ferromagnetic Ising interaction

$$H = -B_x \sum_i \sigma_i^x + J \sum_{i \neq j} \sigma_i^z \sigma_j^z \frac{d_o^3}{\left|\vec{r}_i - \vec{r}_j\right|^3}$$

first configuration:
θ = 0.72°, 10 mW/beam
waist ~ 500 μm x 50 μm
Δ ~(2π)·20 GHz, N=100

χ ~ 2π ·36 Hz
J ~ 2π ·7 Hz
Γ/χ ~ 1

Spontaneous emission limits coherent interaction effects; squeezing and entanglement still possible at short times χt ~ 0.02(π/2), **but .....**

presently implementing:
θ → 5°, 10 mW/beam
waist ~ 500 μm x 50 μm

χ ~ 2π ·1.7 kHz
J ~ 2π ·320 Hz
Γ/χ ~0.07

future configuration?
θ → 35°, 10 mW/beam
waist ~ 500 μm x 300 μm
sub-Doppler cooling required

χ ~ 2π ·2.1 kHz
J ~ 2π ·380 Hz
Γ/χ ~0.01

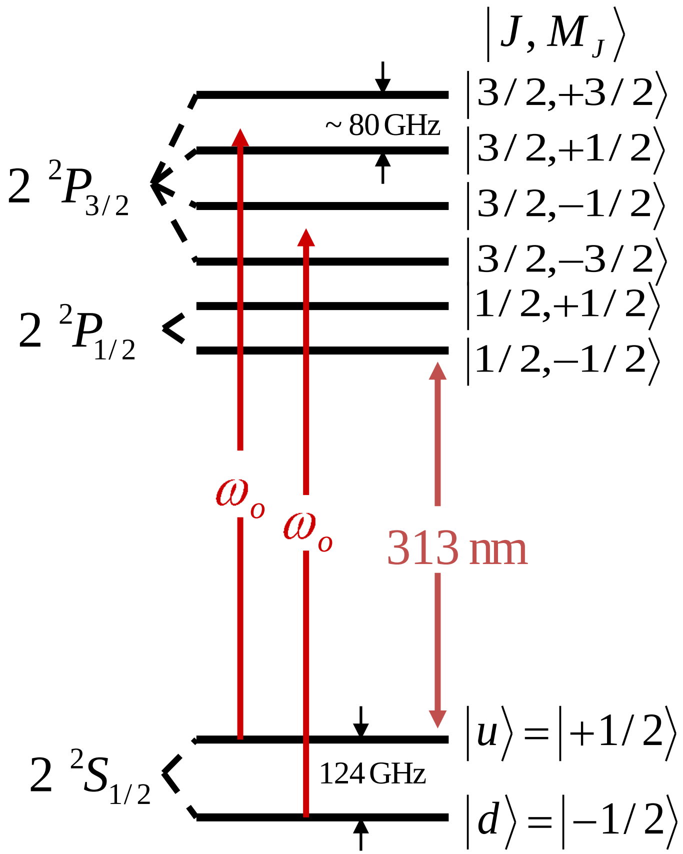
with high power fiber laser based system
10 mW/beam → 100 mW/beam

⇒

χ → 100·χ
J → 100·J

Decoherence due to elastic Rayleigh scattering

Uys, *et al.*, arXiv:1007.2661



Be$^+$ energy levels, B=4.5 T

qubit superposition state described by density matrix

$$\rho \equiv \begin{pmatrix} \rho_{uu} & \rho_{ud} \\ \rho_{du} & \rho_{dd} \end{pmatrix}$$

non-resonant light (ω_o) scattering causes decoherence,

$$\frac{d\rho_{ud}}{dt} = -\frac{\Gamma}{2}\rho_{ud}$$

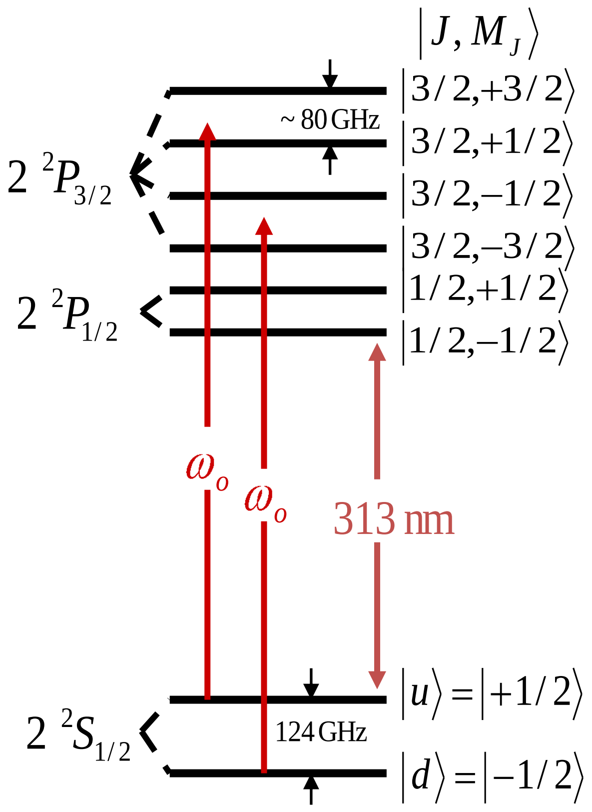
$$\Gamma = ???$$

Raman scattering vs Rayleigh scattering

Raman scattering: $|u\rangle \rightarrow |d\rangle; |d\rangle \rightarrow |u\rangle$

final qubit state entangled with the polarization or frequency of the scattered photon

⇒ decoherence after single scattering event



Raman scattering rate given by Kramers-Heisenberg formula

$$\Gamma_{ij} = \Omega_R^{\ 2}\gamma\left(\sum_J a^J_{i\rightarrow j}\right)^2, \quad a^J_{i\rightarrow j} = \frac{\langle j|\vec{d}\cdot\hat{\varepsilon}^*_{\lambda+(i-j)}|J,\lambda+i\rangle\langle J,\lambda+i|\vec{d}\cdot\hat{\varepsilon}_\lambda|i\rangle}{\delta_{i;J,\lambda+i}}$$

$$\frac{d\rho_{ud}}{dt} = -\frac{\Gamma_{Raman}}{2}\rho_{ud}, \quad \Gamma_{Raman} = \Gamma_{ud} + \Gamma_{du}$$

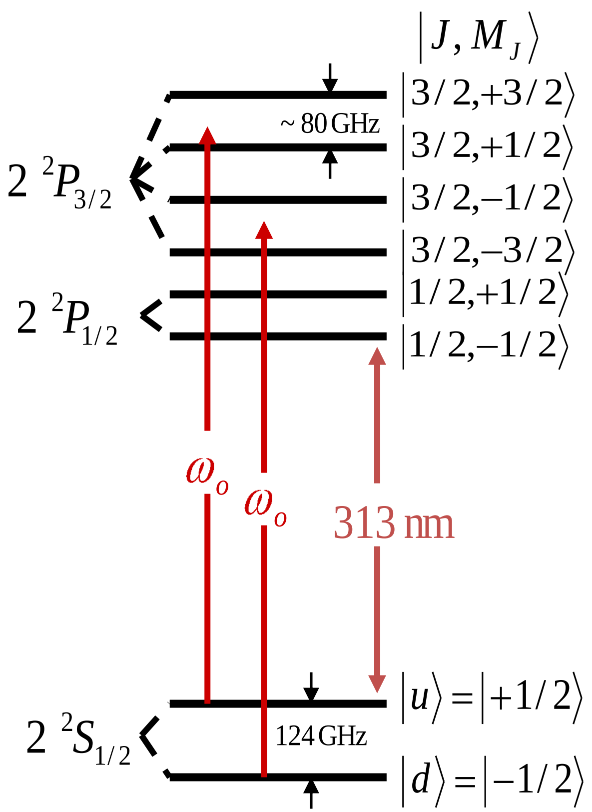
Ozeri *et al.* , Phys. Rev. Lett. **95**, 030403 (2005) –

precise test of the above prescription for calculating decoherence due to Raman scattering

Raman scattering vs Rayleigh scattering

elastic Rayleigh scattering: $|u\rangle \rightarrow |u\rangle; |d\rangle \rightarrow |d\rangle \quad \Gamma_{Rayleigh} = ???$

literature indicates that elastic Rayleigh scattering should not produce decoherence when the elastic scatter rates are equal



- "when of equal rate from both qubit levels, off-resonance Rayleigh scattering of photons did not affect the coherence of a hyperfine superposition", PRA 75, 042329 (2007)

- "In our system, Rayleigh scattering occurs at the same rate for the two clock states, does not reveal the atomic state, and so does not harm the coherence", PRL 104, 073602 (2010)

estimate based on difference in elastic scatter rates, from Ozeri *et al.*, PRA 75, 042329 (2007)

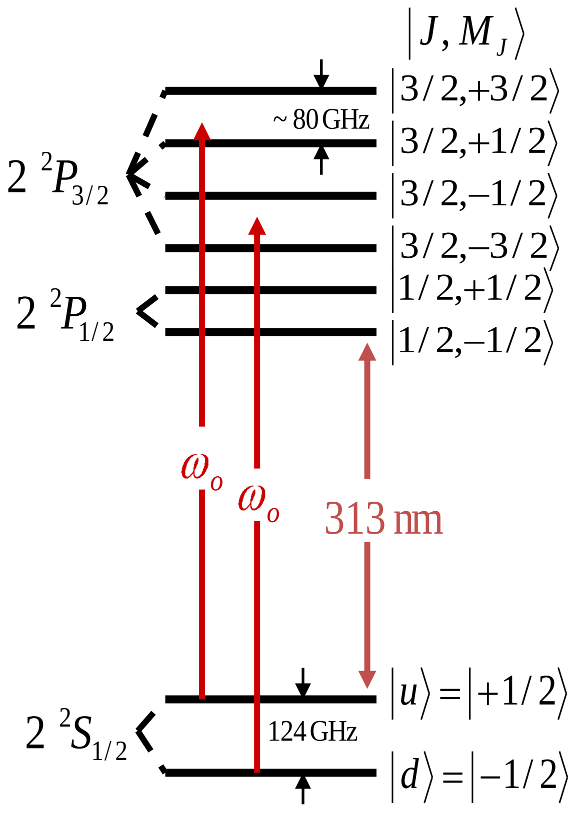
$$\Gamma_{Rayleigh,diff} \sim \frac{(\Gamma_{uu} - \Gamma_{dd})^2}{(\Gamma_{uu} + \Gamma_{dd})/2}$$

Master equation treatment of decoherence due to light scattering

- consistent treatment of decoherence due to both Raman and Rayleigh scattering

- credit to: Hermann Uys

$$\frac{\partial \rho}{\partial t} = \begin{pmatrix} -\Gamma_{ud}\rho_{uu} + \Gamma_{du}\rho_{dd} & -\frac{1}{2}(\Gamma_{Raman} + \Gamma_{Rayleigh})\rho_{ud} \\ -\frac{1}{2}(\Gamma_{Raman} + \Gamma_{Rayleigh})\rho_{du} & -\Gamma_{du}\rho_{dd} + \Gamma_{ud}\rho_{uu} \end{pmatrix}$$



$$\Gamma_{Rayleigh} = \Omega_R^{\,2}\gamma\left(\sum_J a^J_{d\to d} - \sum_{J'} a^{J'}_{u\to u}\right)^2$$

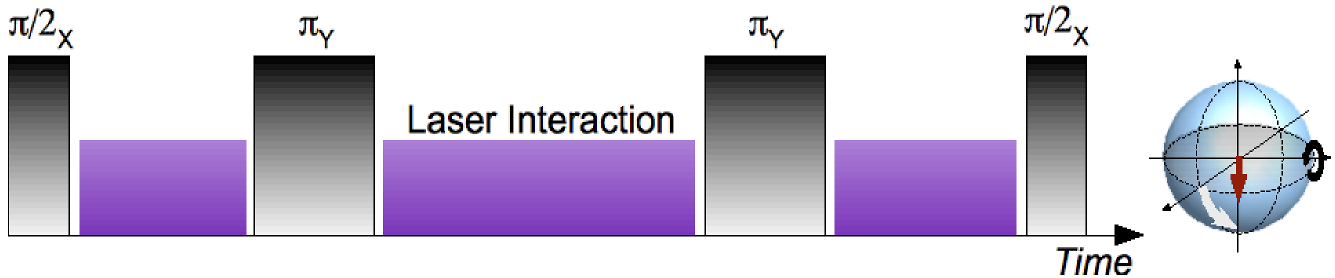
decoherence due to difference in the elastic scattering *amplitudes* !

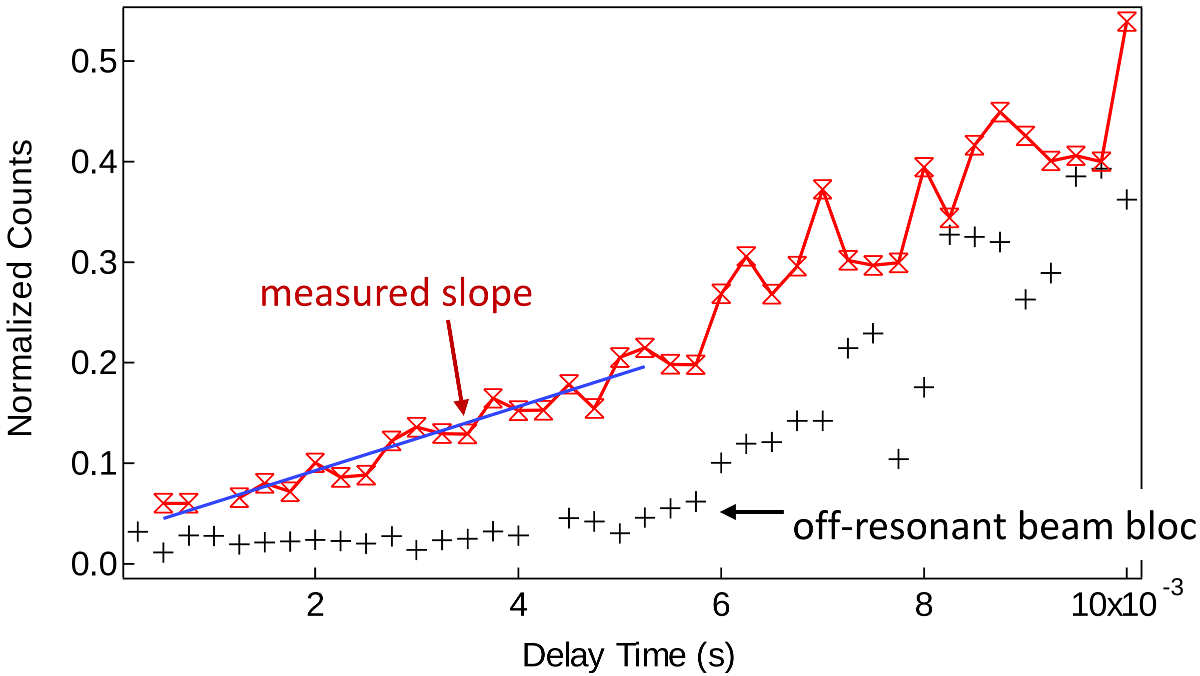
- large decoherence expected if scattering amplitudes have opposite sign

- sign of scattering amplitude determined by the detuning

- physically the state of the qubit can be determined from the phase of the scattered photon

Decoherence measured from decrease in the Bloch vector



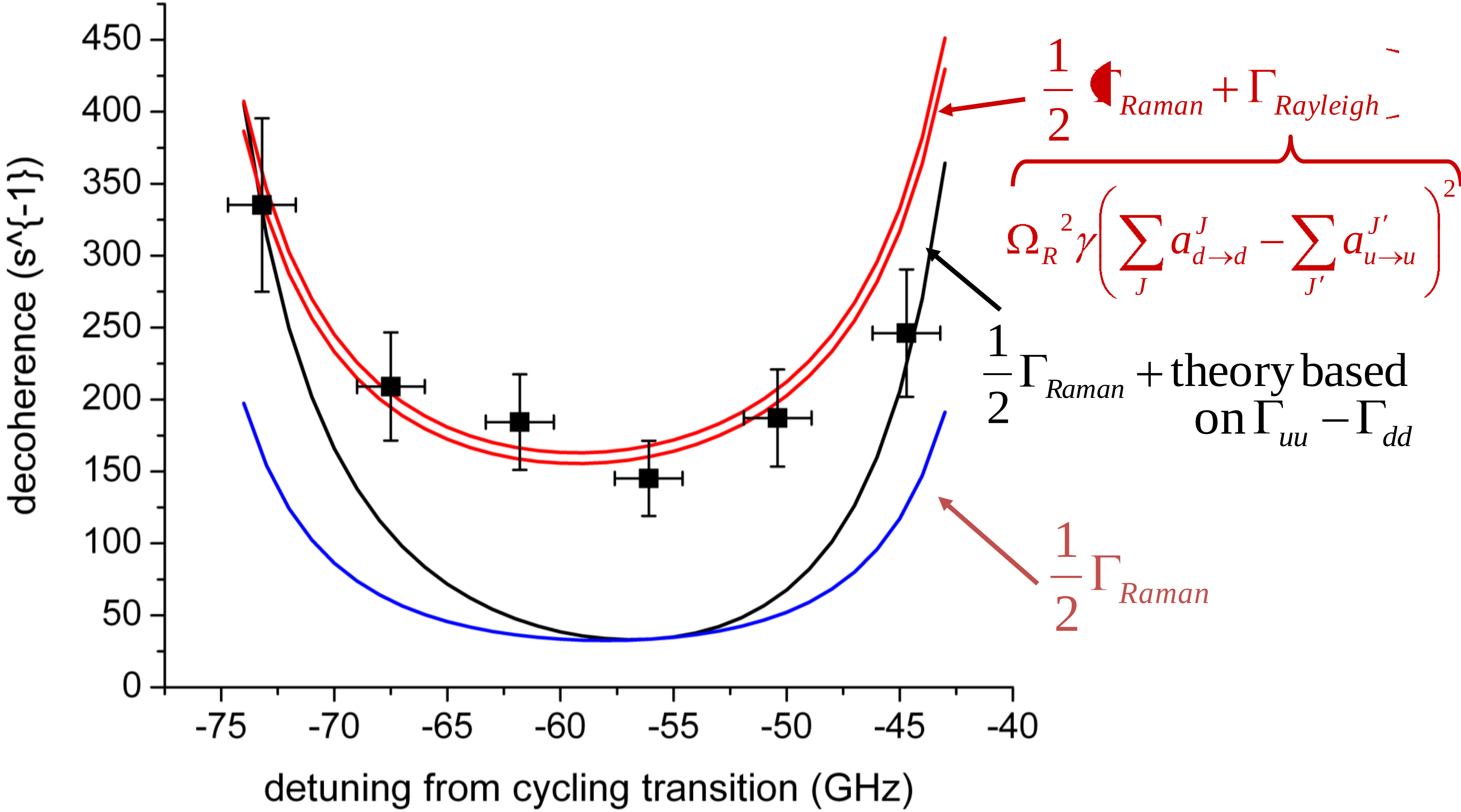


- off-resonant laser beam polarization adjusted to null light shift

$$\text{Normalized counts} = \frac{1}{2}\left[1 - e^{-\frac{1}{2}(\Gamma_{Raman}+\Gamma_{Rayleigh})\tau}\right] \approx \frac{1}{2}\frac{\Gamma_{Raman}+\Gamma_{Rayleigh}}{2}\tau\,,\ \tau =$$ total laser on time

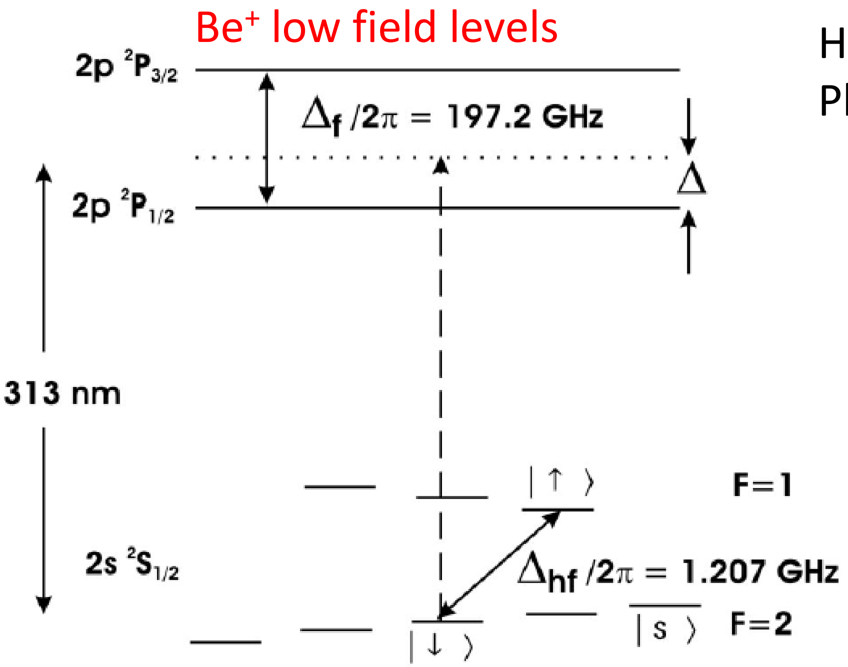
$$\text{decoherence} = \frac{\Gamma_{Raman}+\Gamma_{Rayleigh}}{2} \approx 2\times(\text{measured slope})$$

Good agreement between theory and experiment



- Laser electric field calibrated from measured light shift and Raman rates

Contribution of $\Gamma_{Rayleigh}$ to low field trapped ion experiments



Hyperfine Coherence in the Presence of Spontaneous Photon Scattering, Ozeri , *et al.*, PRL 95 (2005)

- no decoherence due to Rayleigh scattering
- conditions: 1. clock states
  2. $\Delta >> \Delta_{hf}$
- $\Gamma_{Raman} \sim 1/\Delta^4$ → gate errors due to spontaneous emission reduced with large detunings Δ

For clock states and $\Delta >> \Delta_{hf}$:

$$\Gamma_{Rayleigh} = \Omega_R{}^2 \gamma \left(\sum_J a^J_{d \to d} - \sum_{J'} a^{J'}_{u \to u} \right)^2 \sim \frac{1}{\Delta^2} \left(\frac{\Delta_{hf}}{\Delta} \right)^2 \sim \frac{1}{\Delta^4}$$

For qubits that are not clock states:

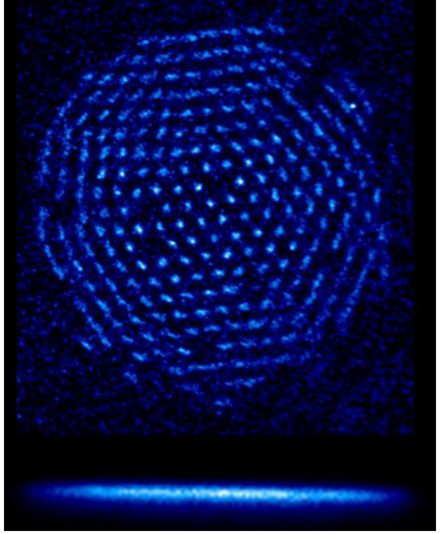
$$\Gamma_{Rayleigh} \sim \frac{1}{\Delta^2}$$

two-ion gate strength:

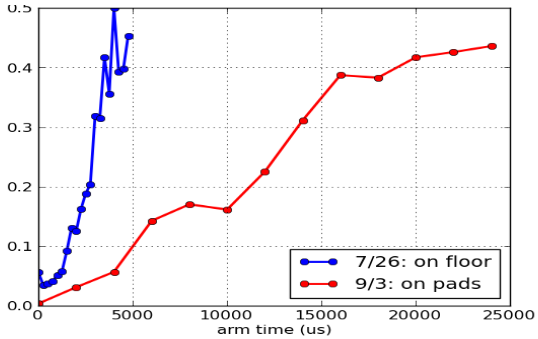
$$\chi \sim \frac{\eta^2}{\delta} \frac{V^2}{\Delta^2} \sim \frac{1}{\Delta^2}$$

No apparent advantage of large Δ if qubits are not clock states

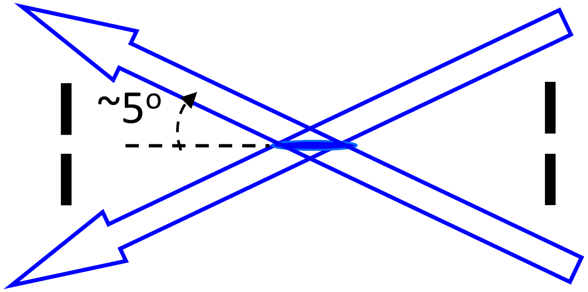
Summary:



- ion crystals in Penning traps look like a good platform for simulating quantum magnetic models with an intractable number of ions



- qubit coherence limited by 20 -200 Hz magnetic field fluctuations; 3 ms → 15 ms coherence time through vibration reduction



- current effort: Ising model simulation using state dependent optical dipole forces to push the ions in the axial direction