# Quantum Information Experiments in Penning traps

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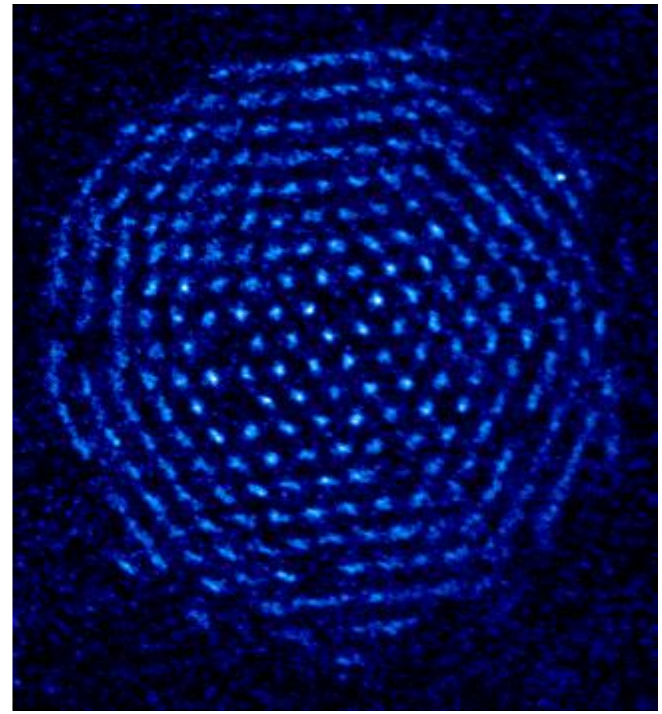
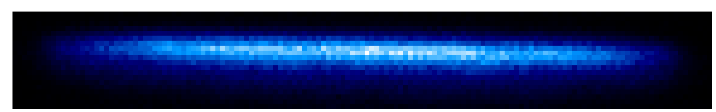
**NIST-Boulder**
**Ion storage group**

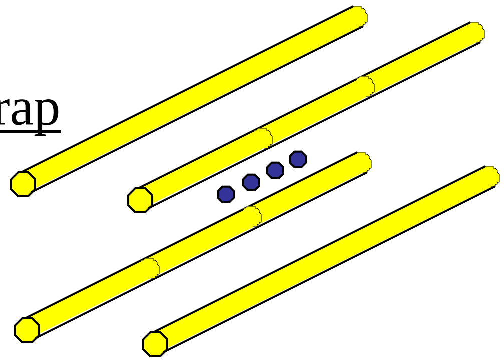
Wayne Itano, David Wineland, Jospeh Tan, Pei Huang, Brana Jelenkovic, Travis Mitchell, Brad King, Jason Kriesel, Marie Jensen, Taro Hasegawa, Nobuysau Shiga, Michael Biercuk, Hermann Uys, Joseph Britton, Dan Dubin – UCSD(theory)



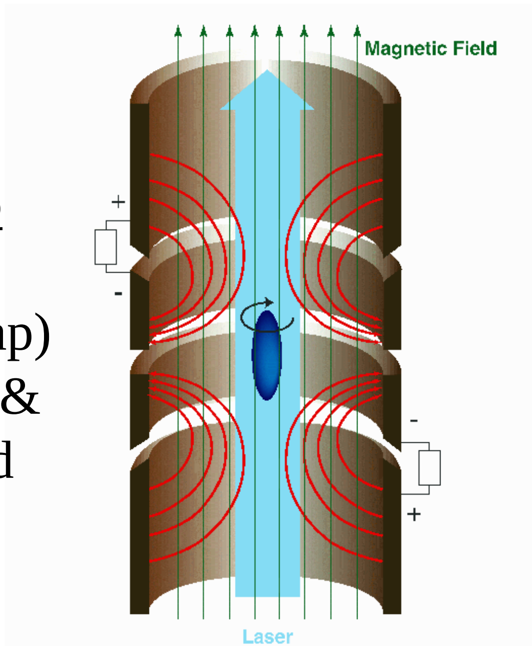


# Trapped Ions

<u>Rf or Paul Trap</u>
RF & DC
Voltages

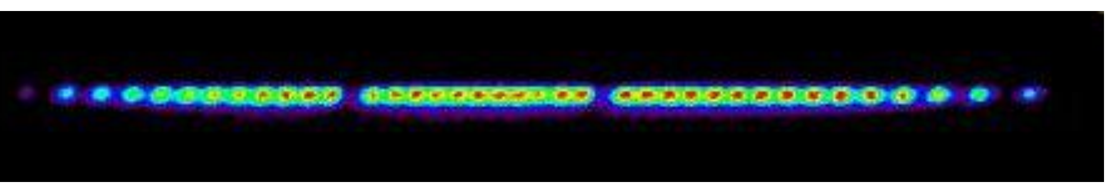


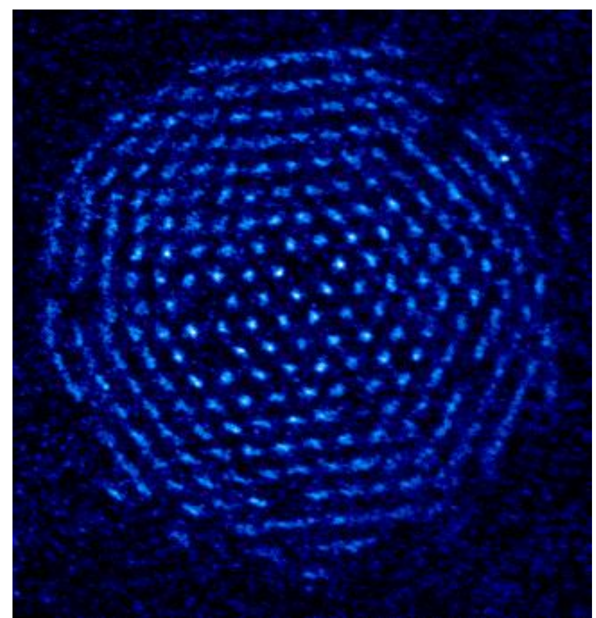
<u>Penning Trap</u>
(or Penning-
Malmberg trap)
DC Voltages &
Static B-Field




good for tight confinement and laser cooling smaller numbers of particles;
quantum computing;
optical and microwave clocks; 1-d ion arrays

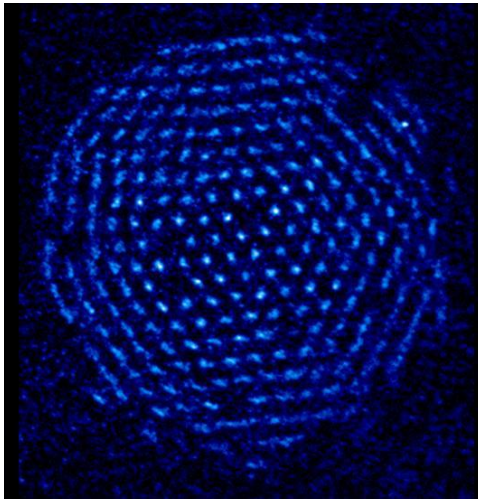
good for laser cooling larger numbers ;
microwave clocks; cold plasma studies; 2-d and 3-d ion arrays





quantum simulation experiments:
Schaetz group, Nature Physics 4, 757 (2008)
Monroe group, Nature 465, 590 (2010)

# Quantum simulation or computation ?



**quantum computation with trapped ion crystals:**

"Quantum manipulation of trapped ions in 2-d Coulomb crystals," Porras and Cirac, PRL 96, 250501 (2006)

"Wigner crystals of ions as quantum hard drives," Taylor and Calarco, PRA 78, 062331 2008

"Investigation of planar Coulomb crystals for quantum simulation and computation," Georgescu, Buluta, Kitaoka, Hasegawa, PRA 77, 06320 (2008)

**quantum simulation of magnetic spin systems with trapped ion crystals:**

Effective spin systems with trapped ions
Porras and Cirac, PRL 92, 207901 (2004)

Effective spin quantum phases in systems of trapped ions
Deng, Porras, and Cirac, PRA 72, 063407 (2005)

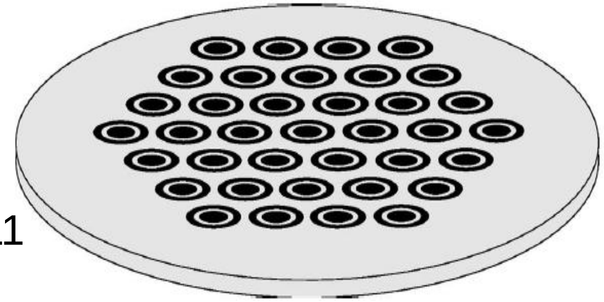
} does not require individual addressing

**Another approach: quantum comp/simulation with planar Penning trap arrays:**

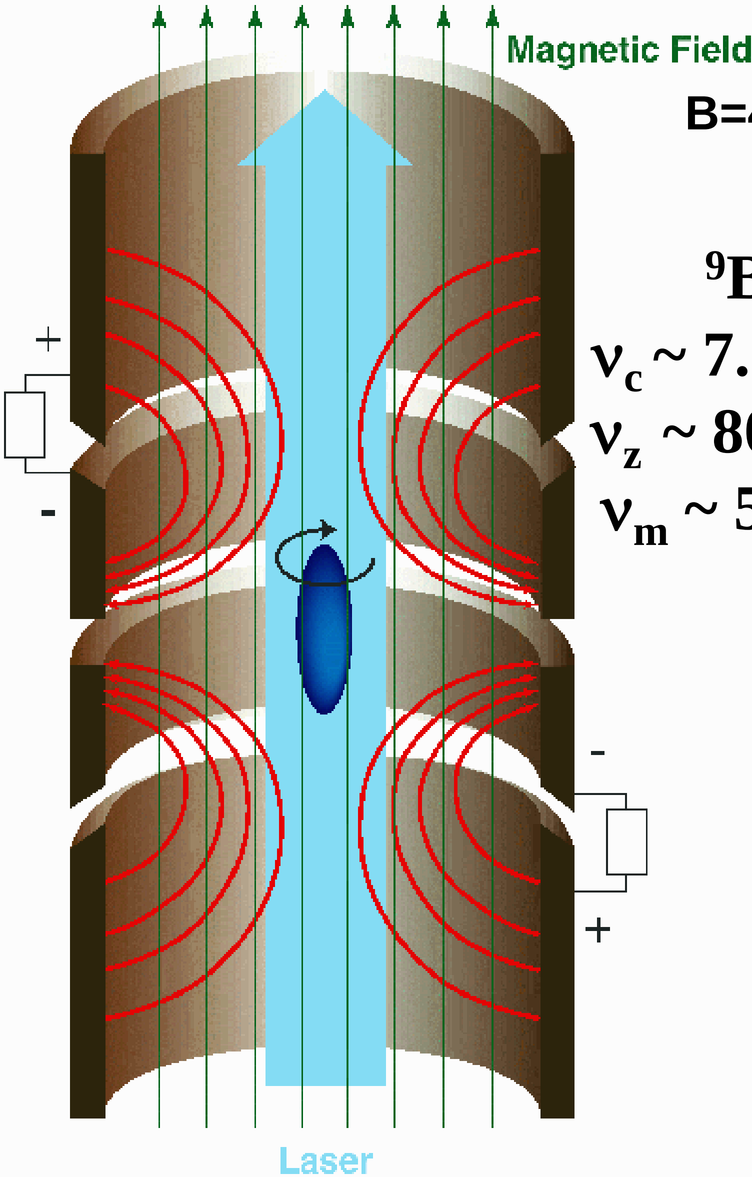
Ciaramicoli, Galve, Marzoli, and Tombesi, PRA **72**, 042323 2005

Marzoli, Tombesi, .., Werth,.., Schmidt-Kaler, et al.,J Physics B42, 154010 (2009)

Crick, Donnellan, Ananthamurthy, Thompson, Segal, RSI 81, 013111 (2010)



# NIST Penning trap



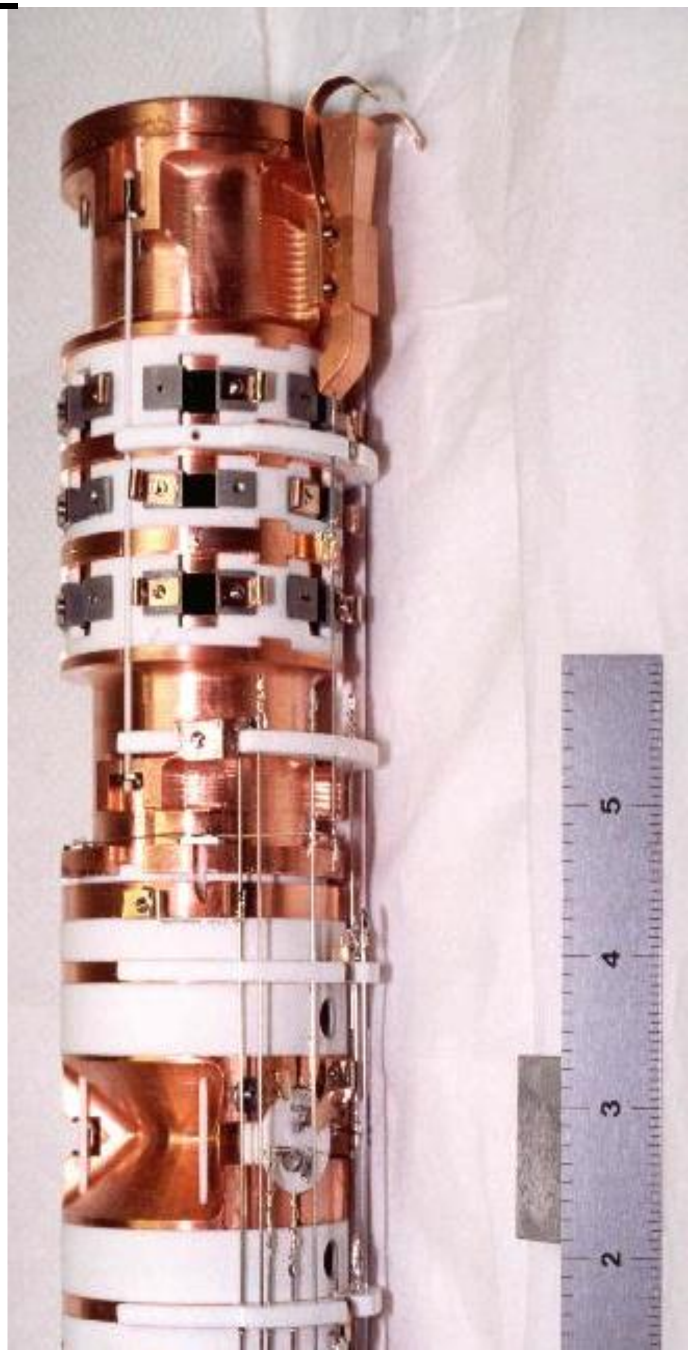

B=4.5 T

$^{9}Be^{+}$

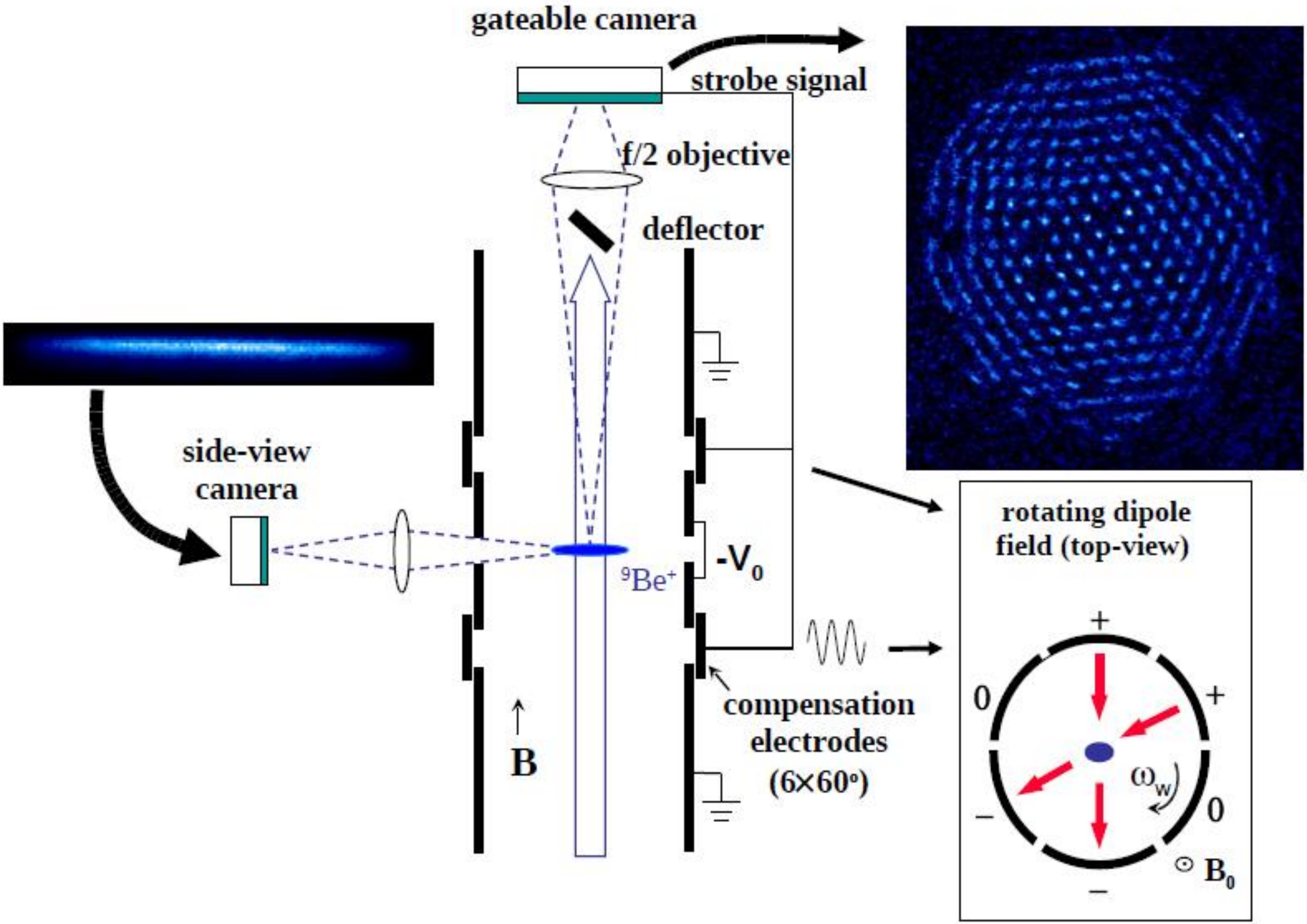
$\nu_c \sim 7.6$ MHz

$\nu_z \sim 800$ kHz

$\nu_m \sim 50$ kHz

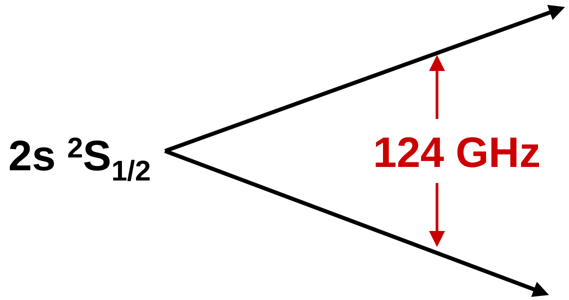


# NIST experimental set-up

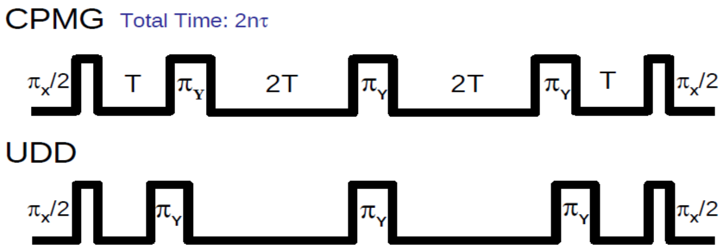


# Outline:

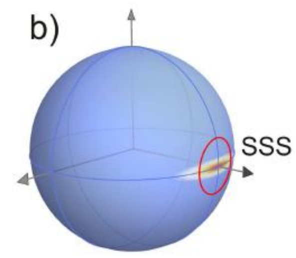
- High magnetic field qubit




- Dynamical decoupling demonstrations using 2-D ion crystals in a Penning trap




- Spin squeezing and quantum simulation (work in progress)



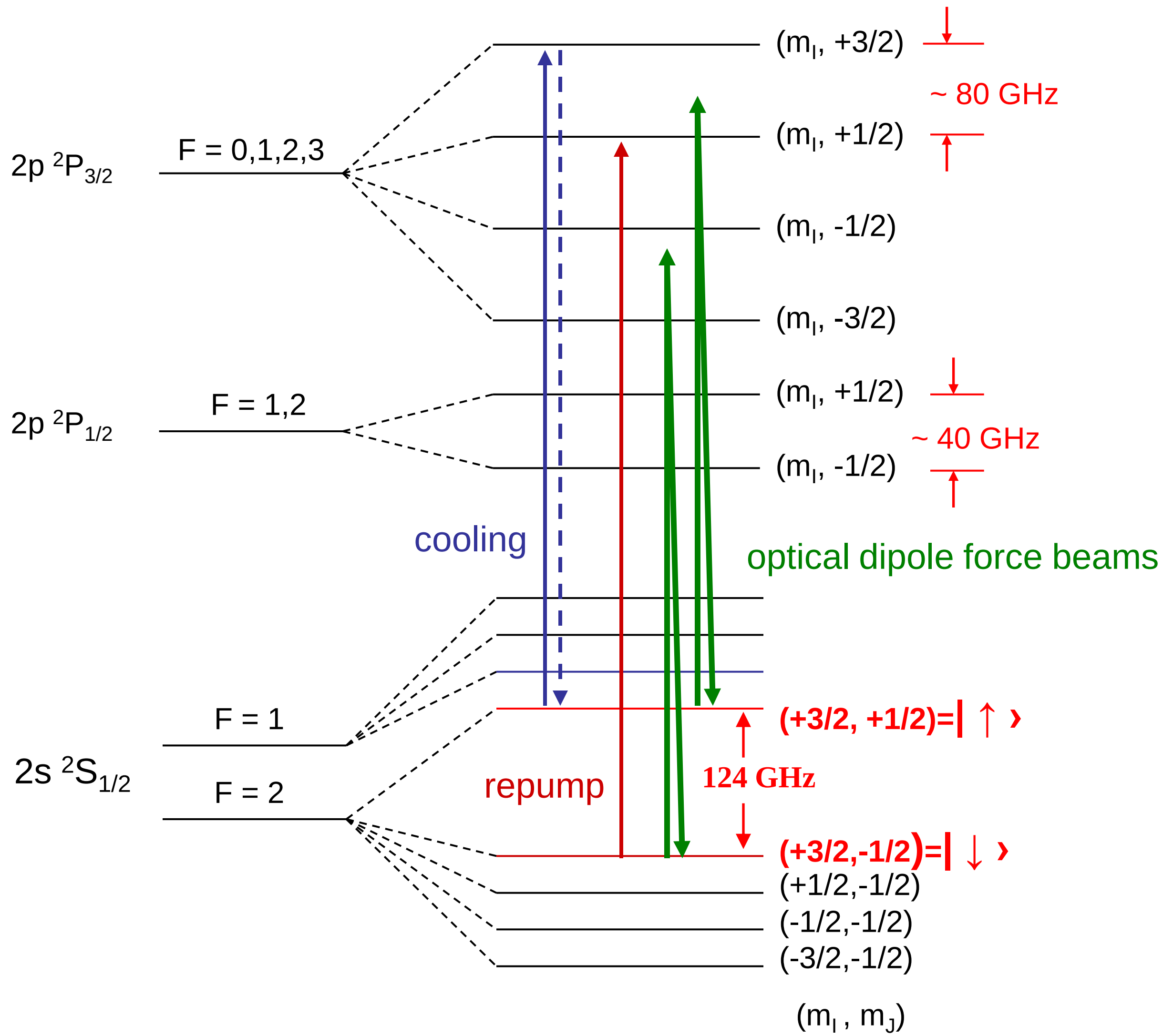

- Decoherence due to elastic Rayleigh scattering

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

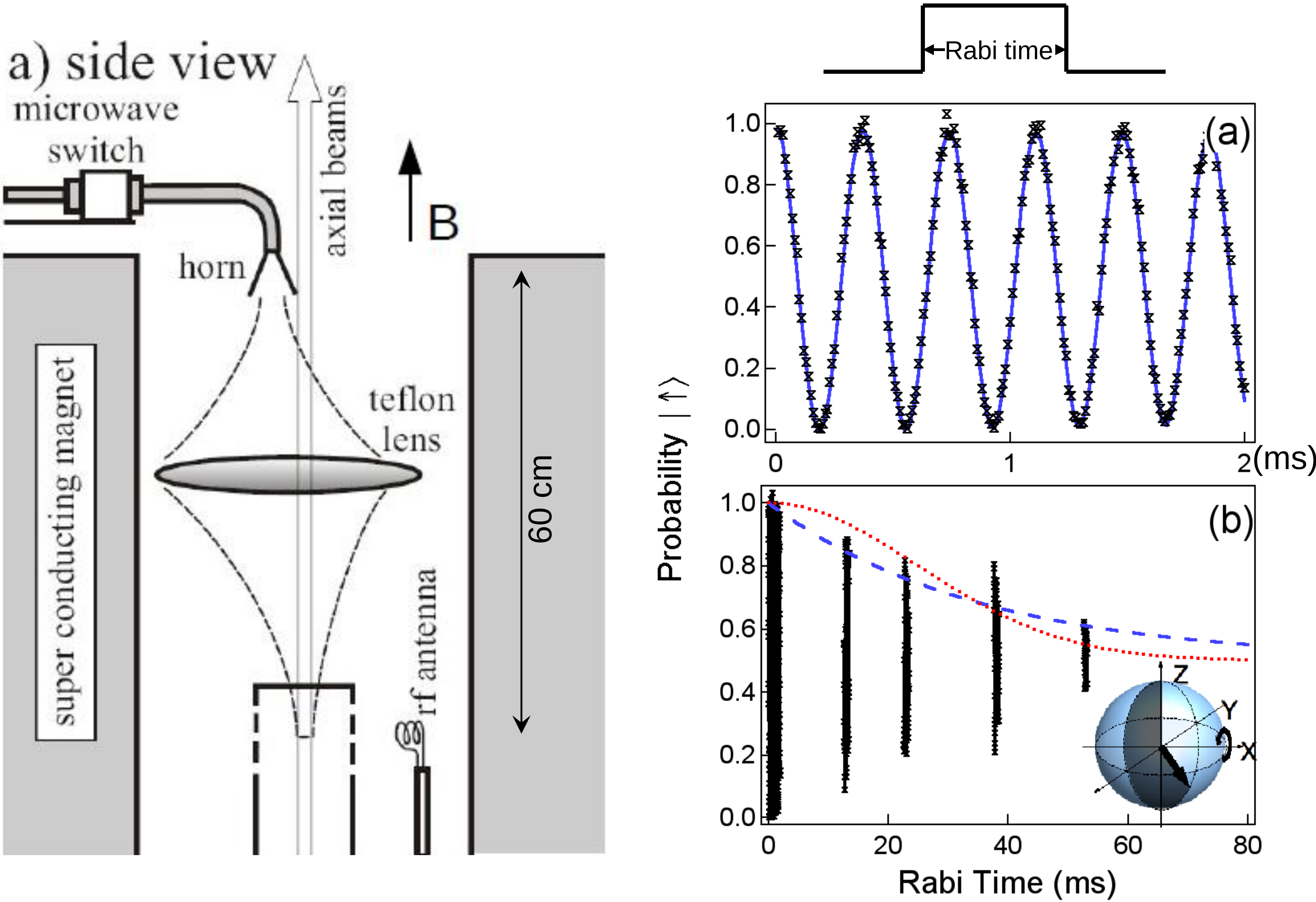
# High magnetic field qubit

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

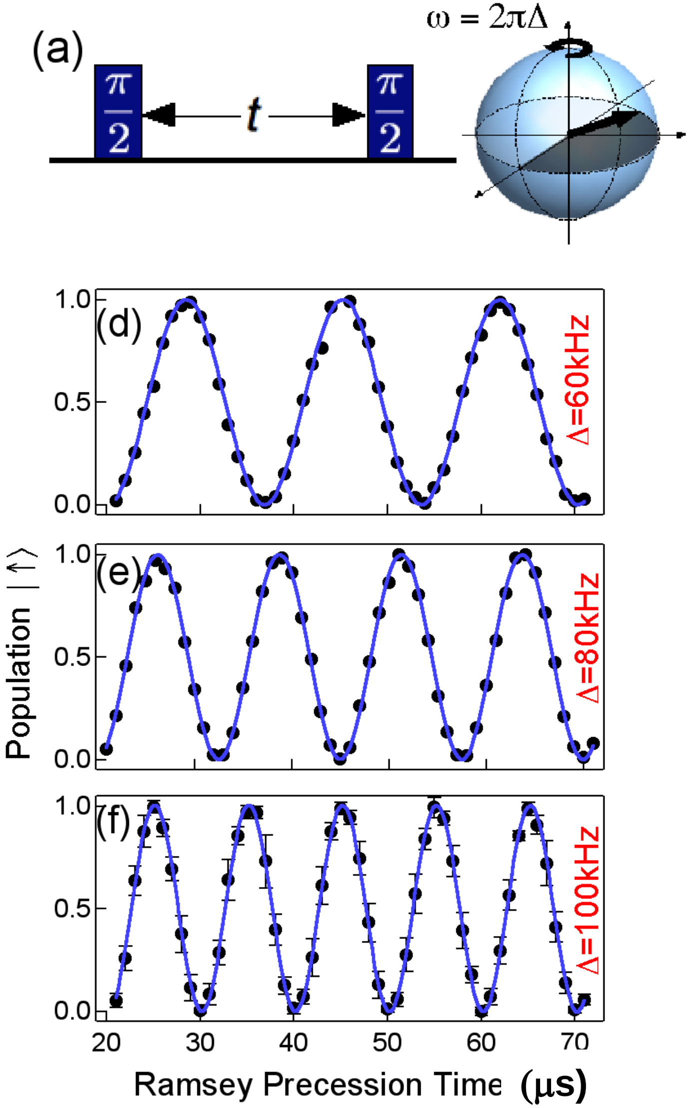
**our qubit:**

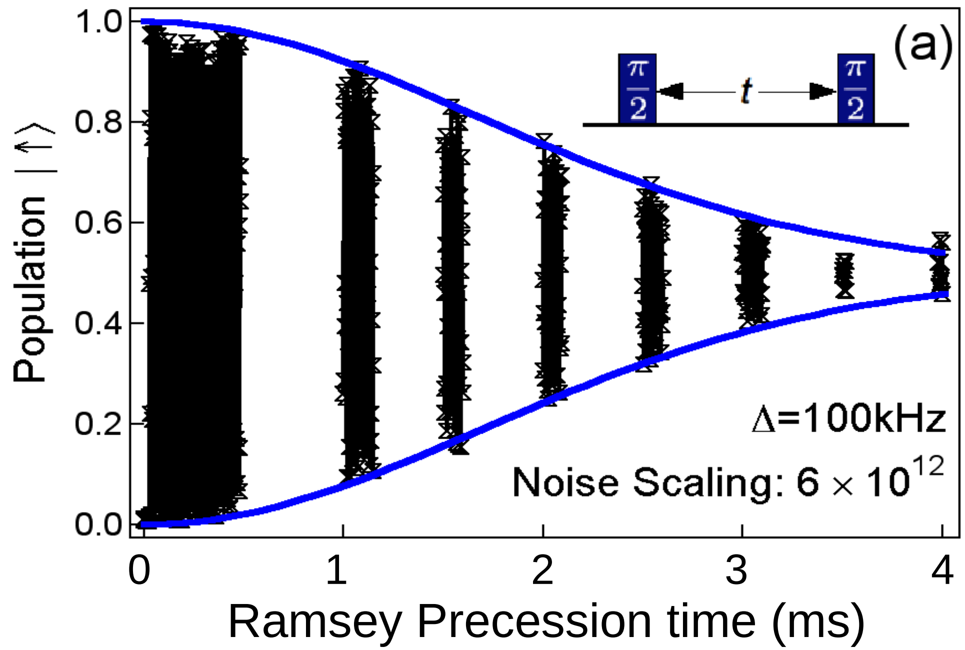


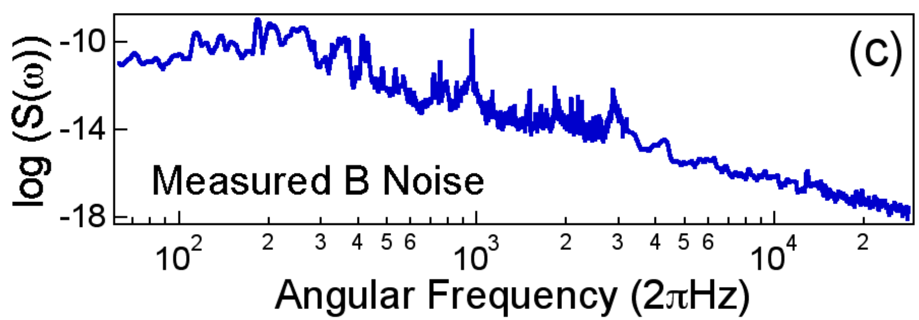
# Rabi flopping on 124 GHz electron spin flip



# Ramsey ($T_2$) coherence on 124 GHz electron spin flip



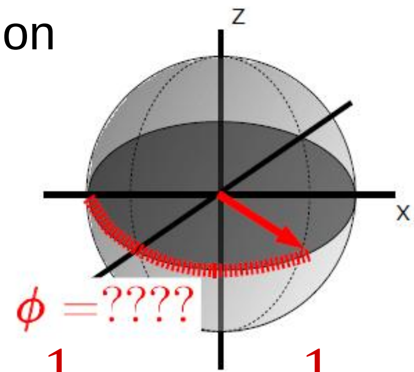

$$\frac{\delta B}{B} \sim 10^{-9}, \quad T_2 \sim 2\,\mathrm{ms}$$

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

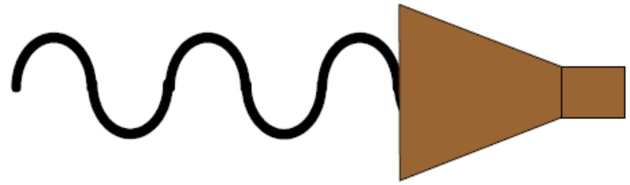
Biercuk, Uys, VanDevender, Shiga, Itano, Bollinger, Nature 458, 996 (2009)

# Dynamical decoupling - maintaining coherence in the presence of noise

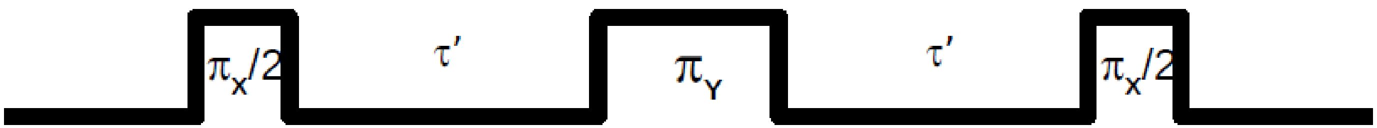
Ion

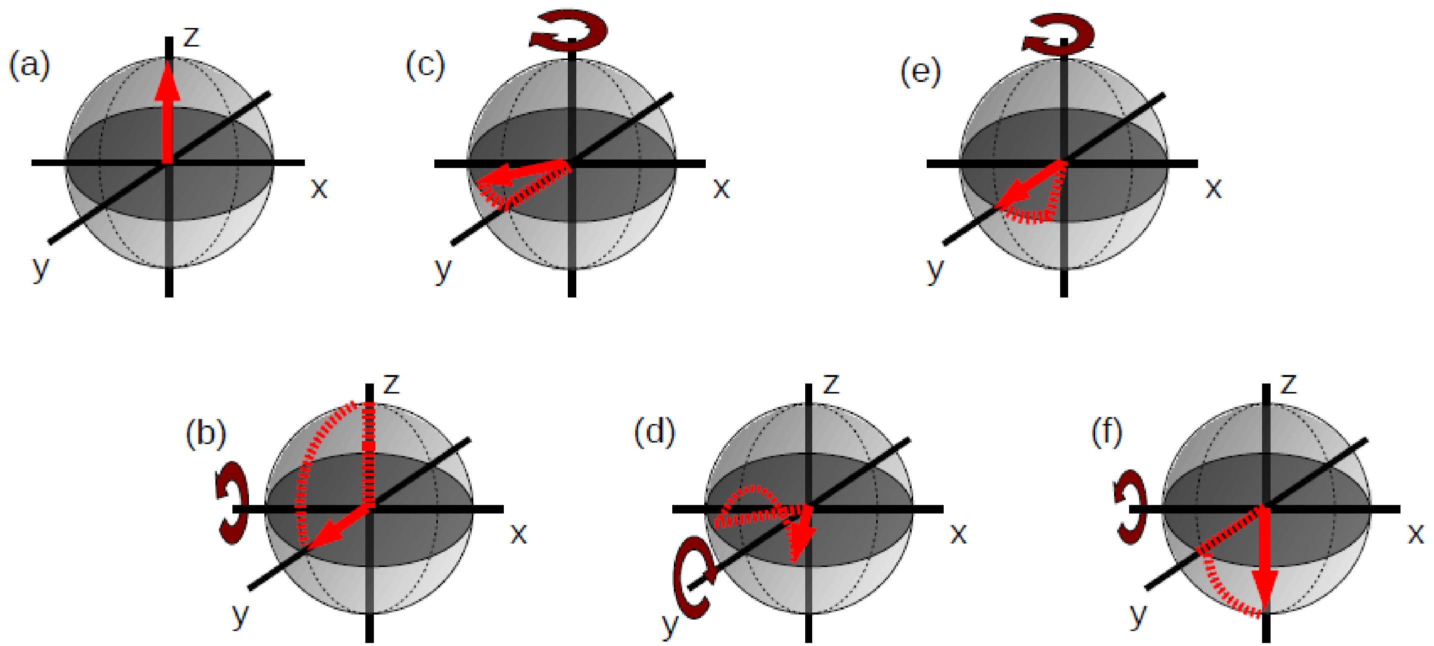



Microwaves



$$H = \frac{1}{2}\hbar\omega_o\sigma_z + \frac{1}{2}\beta(t)\sigma_z$$

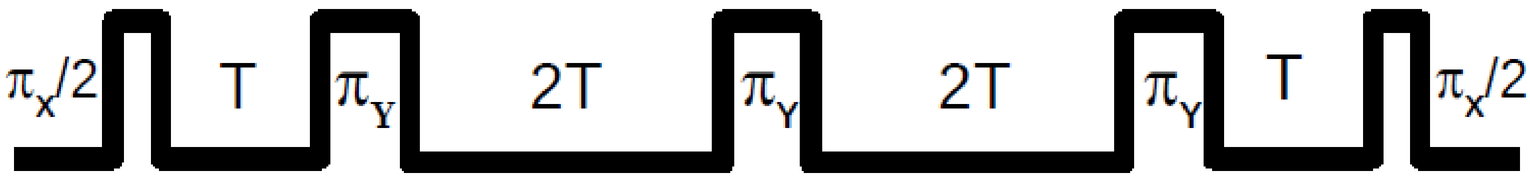


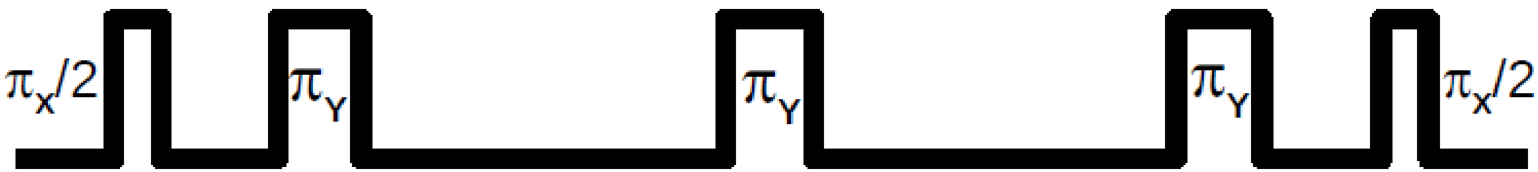

**E. L. Hahn, Phys. Rev. 80, 580 (1950)**

# Dynamical decoupling: evenly vs unevenly spaced π -pulses

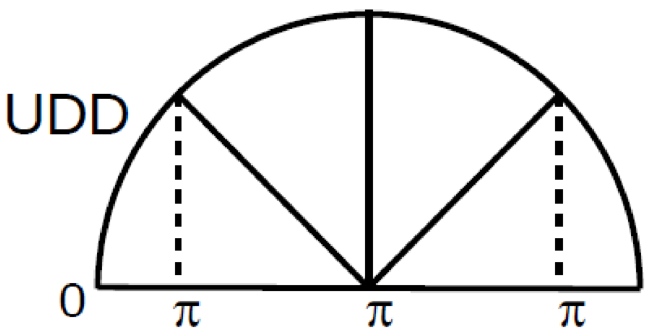
CPMG (Carr-Purcell-Meiboom-Gill)  Total sequence time n(2T), n=# of π-pulses




UDD (Uhrig Dynamical Decoupling) – Uhrig, PRL **98**, 100504 (2007)




UDD construction




For n π –pulses, UDD cancels 1st n derivatives of noise

$$H = \frac{1}{2}\sigma_z\left[\omega_0 + \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 + \cdots\right]$$

1π-pulse spin echo

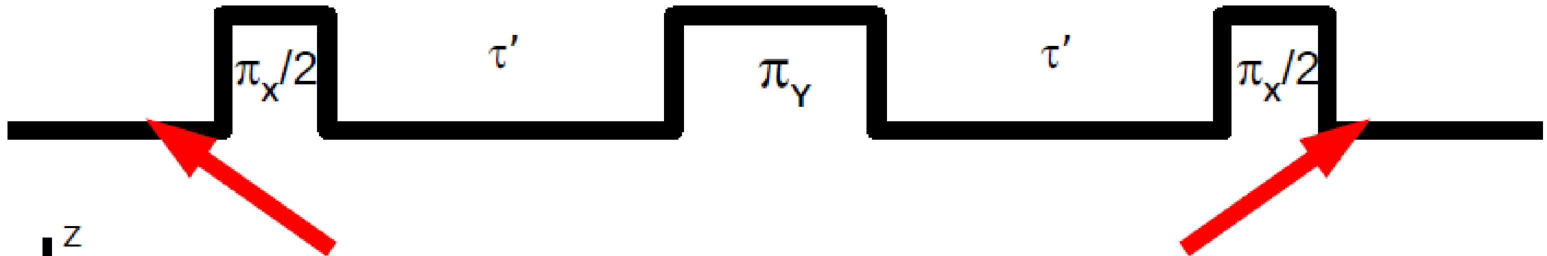
2π-pulse CPMG or UDD

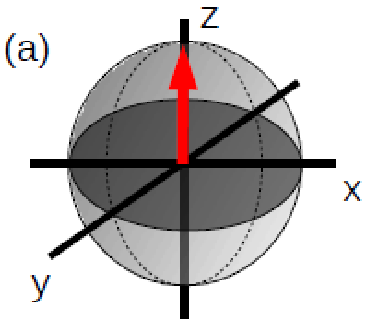
3π-pulse UDD

UDD Predicted to outperform CPMG by orders of magnitude in suppressing errors, for some noise spectra.

# Dynamical decoupling demonstrations with our set-up

1. prepare $|\uparrow\uparrow\uparrow\ldots\uparrow\uparrow\rangle$ and measure ion fluorescence
2. apply dynamical decoupling sequence
3. adjust phase of last pulse to rotate spins to $|\downarrow\downarrow\downarrow..\downarrow\rangle$ under full coherence
4. loss of coherence measured from ion fluorescence after sequence



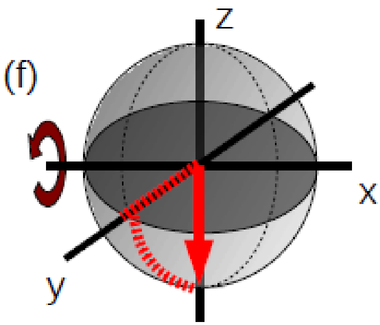




Measure fluorescence

$$\text{Error} = \frac{\text{Counts after}}{\text{Counts before}}$$

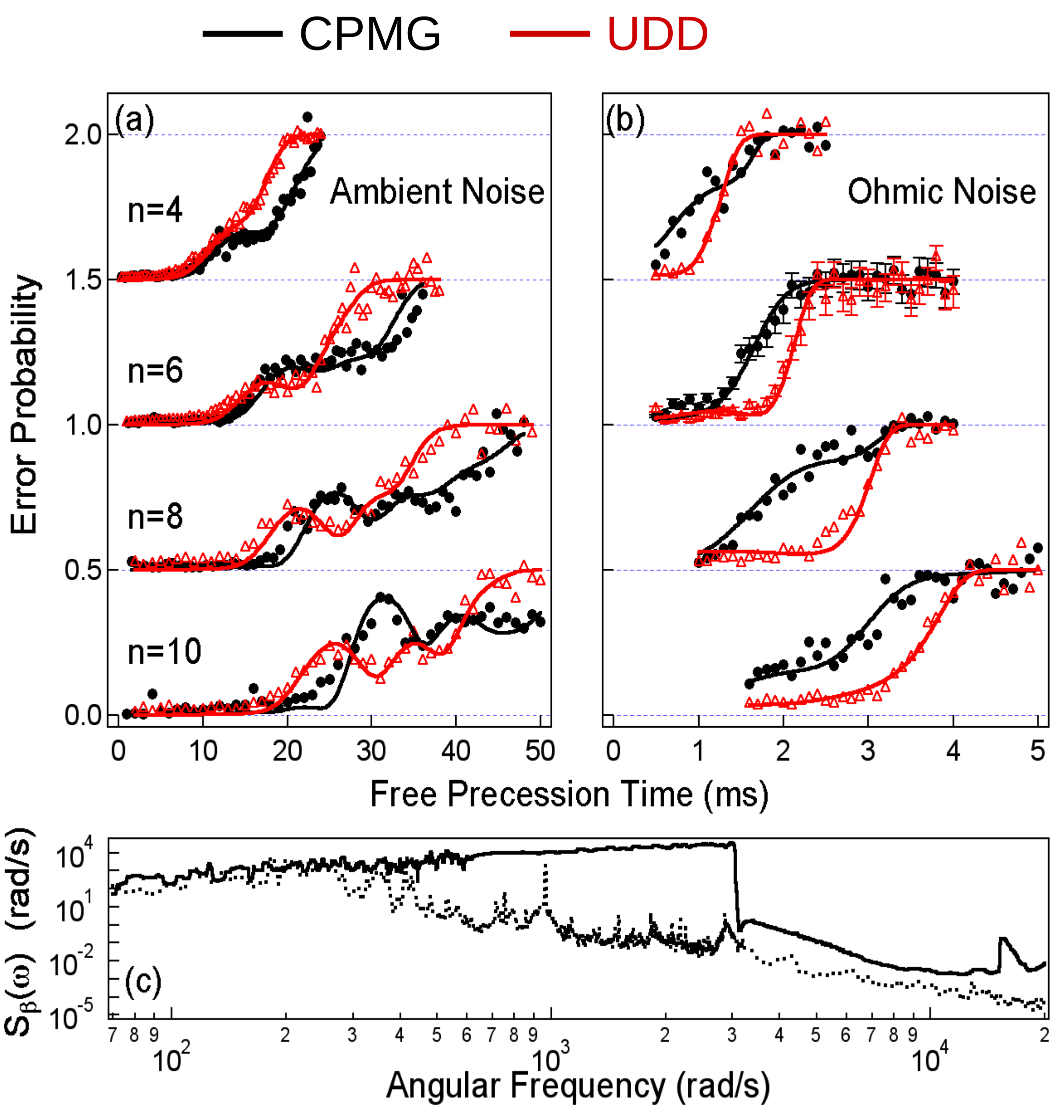
No dephasing: Error=0

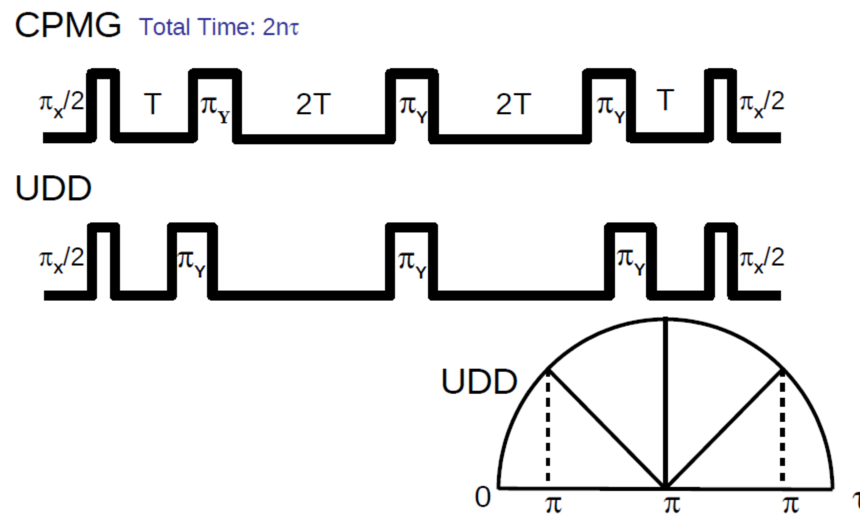
Complete dephasing: Error=0.5



# Qubit coherence extended and accurately predicted by dynamical decoupling

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

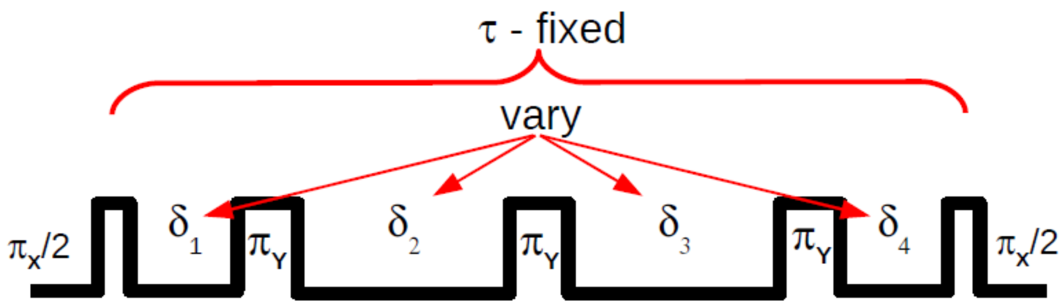


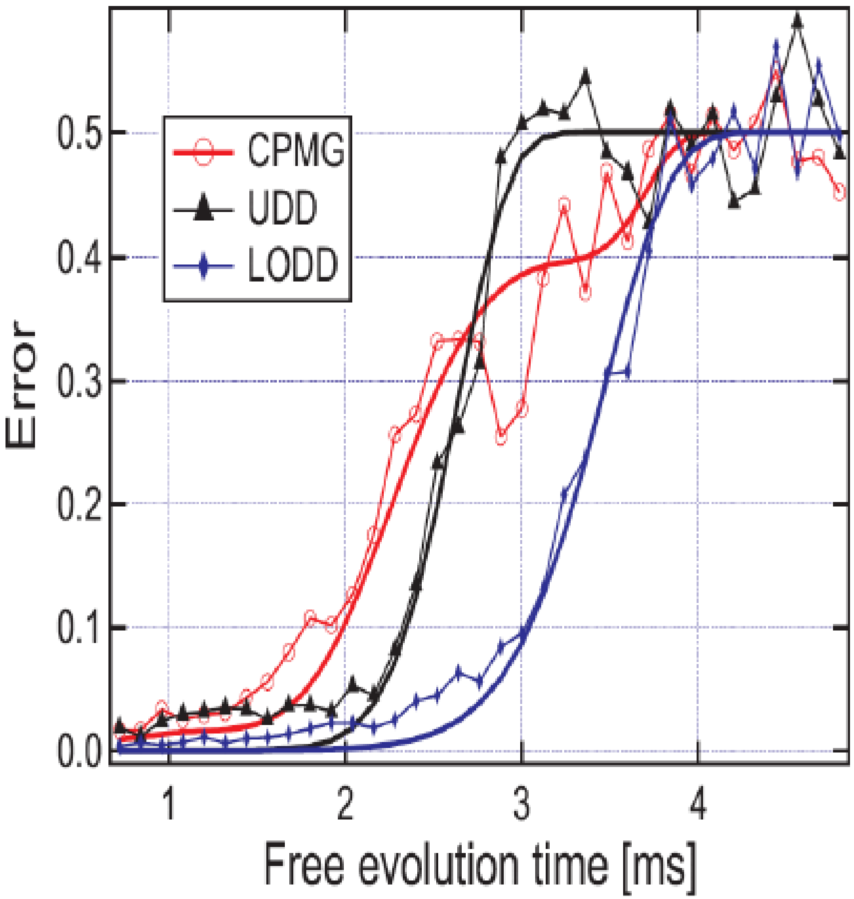




- **Fits use analytical filter function and measured noise spectrum**
- **CPMG, UDD perform similarly for $1/f^2$ ambient noise**
- **UDD performs better for noise spectra with sharp cutoffs**
- **Ohmic noise with sharp cutoff injected**

# Locally optimized dynamical decoupling

- 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 $S(\omega)$ required**

# Spin squeezing and quantum simulation – work in progress

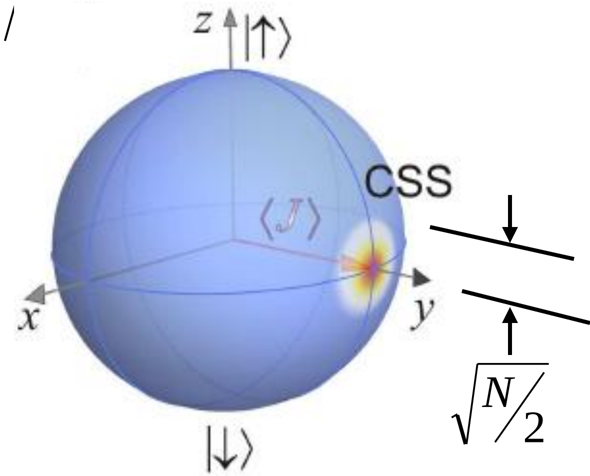
Spin squeezing:

consider N spin ½ systems $\vec{\sigma}_i, i = 1, ..., N \quad \vec{J} = \sum_{i=1}^{N} \vec{\sigma}_i / 2$

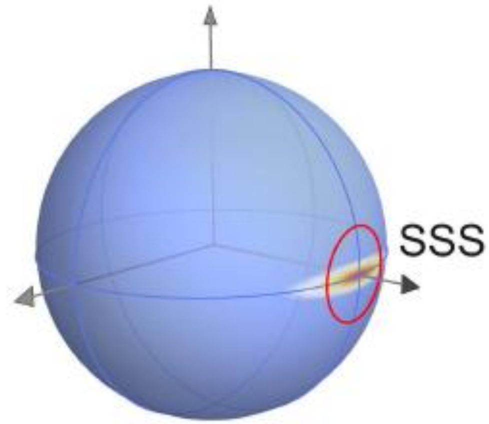
initialize coherent spin state $\left|\uparrow\uparrow\uparrow \; ..... \uparrow\right\rangle = \left| J = \frac{N}{2}, M_J = \frac{N}{2} \right\rangle$

rotate about x-axis by 90º

$$\left|\Psi\right\rangle_{CSS} \rightarrow \frac{1}{2^{N/2}} \sum_{M_j=-N/2}^{N/2} \binom{N}{N/2+M_J}^{1/2} \left| \frac{N}{2}, M_J \right\rangle$$




squeezed spin state –
reduction in the variance of some components of $\vec{J} \perp \left\langle \vec{J} \right\rangle$



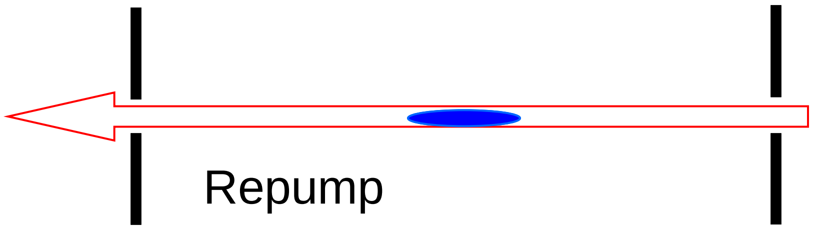

potential applications:
atomic clocks, magnetometry

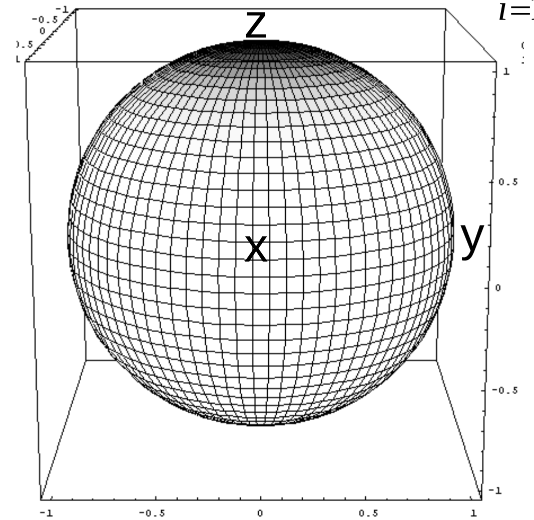
# Implementation of spin squeezing – single axis twisting

single axis twisting - Kitigawa and Ueda, PRA 47, 5138 (1993)

1. **prepare** $|\uparrow\uparrow\uparrow\cdots\uparrow\rangle = |J=\frac{N}{2}, M_J=\frac{N}{2}\rangle$ , **$T_{motional}$ ~ 0.5 mK**

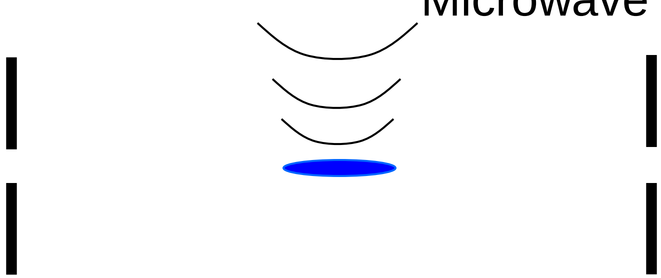
$$\vec{J} = \sum_{i=1}^{N} \sigma_z^{\,i}/2$$

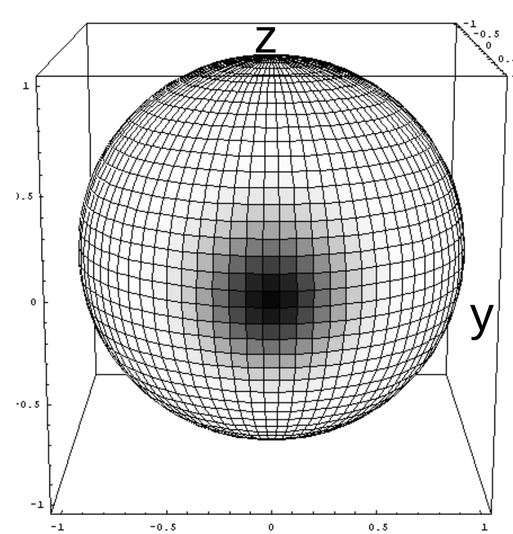



2. **π/2 pulse of 124 GHz microwaves**

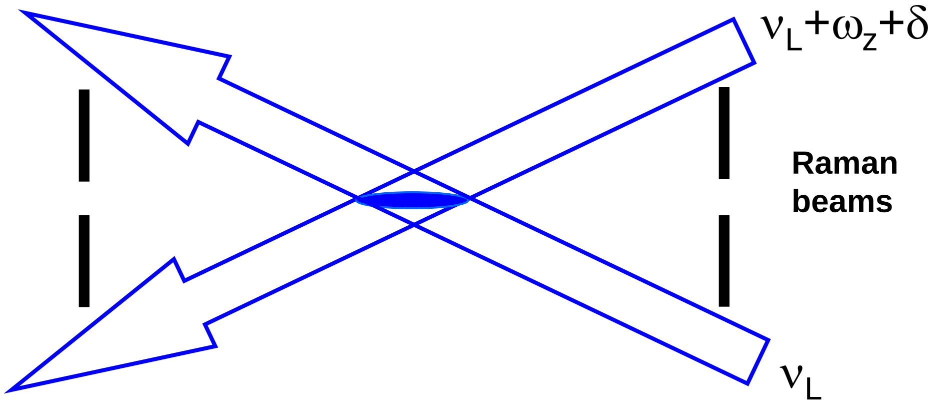
$$|J=\frac{N}{2}, M_J=\frac{N}{2}\rangle \rightarrow \sum_{M_J=-\frac{N}{2}}^{\frac{N}{2}} c(N, M_J)|J, M_J\rangle$$

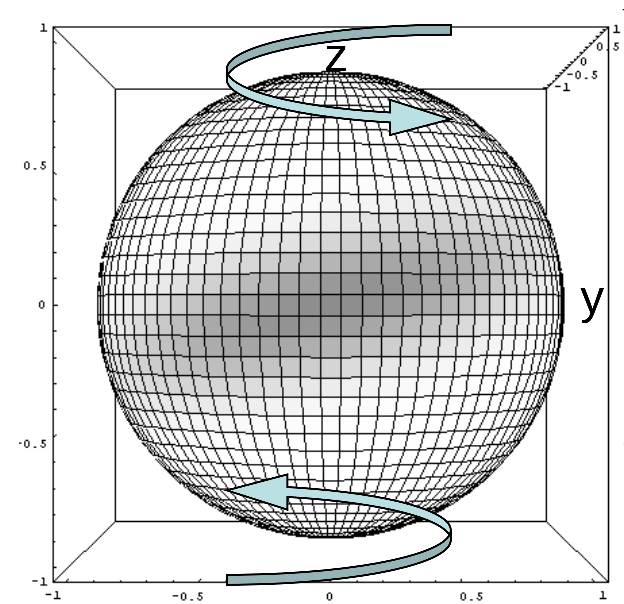


# Spin squeezing through single axis twisting

3. **Apply $\exp(i\chi \{J_z\}^2 t)$ "push" gate on the axial center-of-mass mode of a single ion plane**



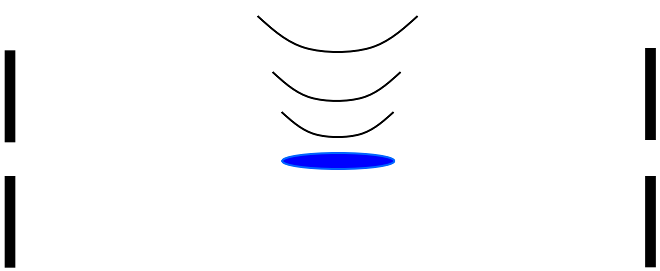

D.Leibfried, et al., Science **304**, 1476 (2004)

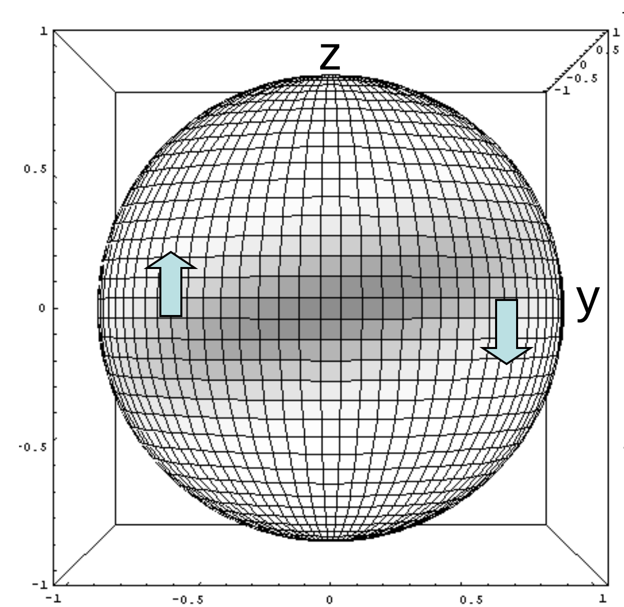
$$\chi = \frac{(\eta\Omega)^2}{\delta}$$

$$t = m\frac{2\pi}{\delta}, \quad m = 1, 2, 3, \ldots$$

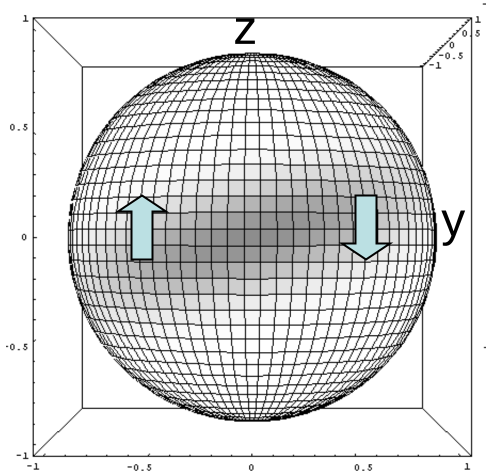
4. **Measure $\Delta J_z$ as a function of rotation about x-axis (mean spin vector direction)**

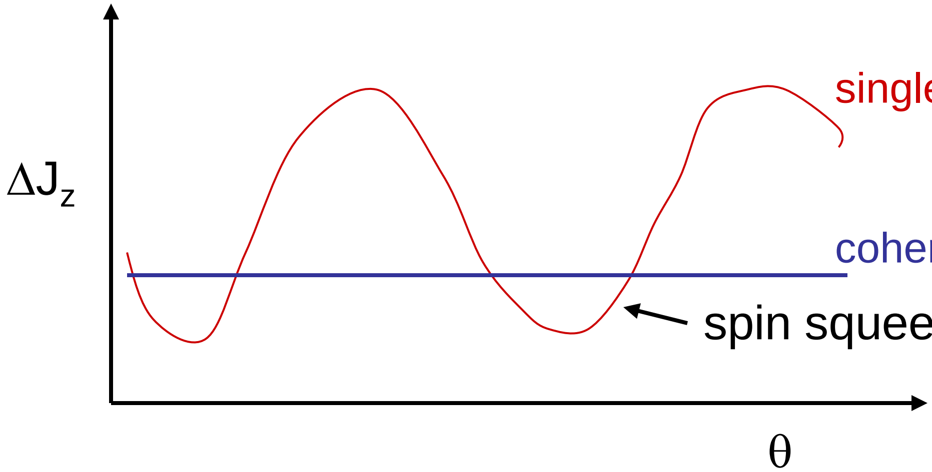
Microwave with
90°Phase shift





# Spin squeezing through single axis twisting




recent spin squeezing demonstrations: Polzik, Vuletic, Treutlein, Oberthaler, ..

features of spin squeezing with trapped ions:

- precise knowledge of ion number N
- enables quantitative analysis of the depth of entanglement

single-axis twisting Hamiltonian $H = \chi J_z{}^2$ is a uniform Ising model

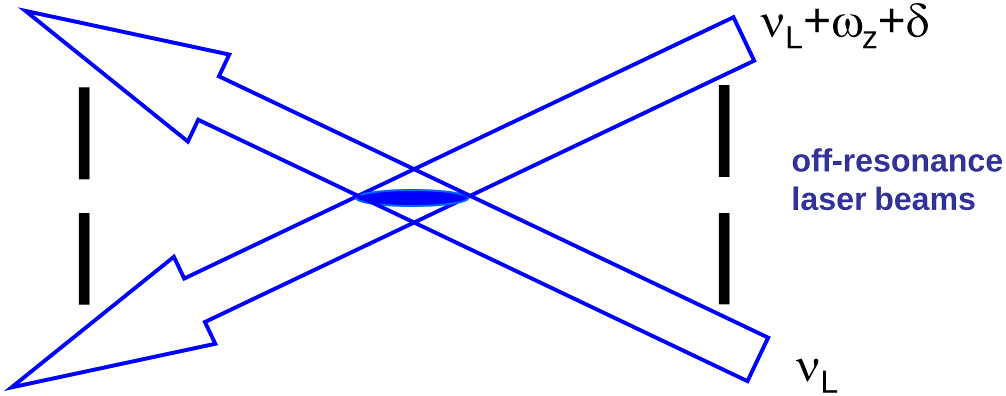
$$J_z{}^2 = \left(\sum_i \sigma_z{}^i / 2\right)\left(\sum_j \sigma_z{}^j / 2\right) = \frac{1}{4}\sum_{i,j} \sigma_z{}^i \sigma_z{}^j$$

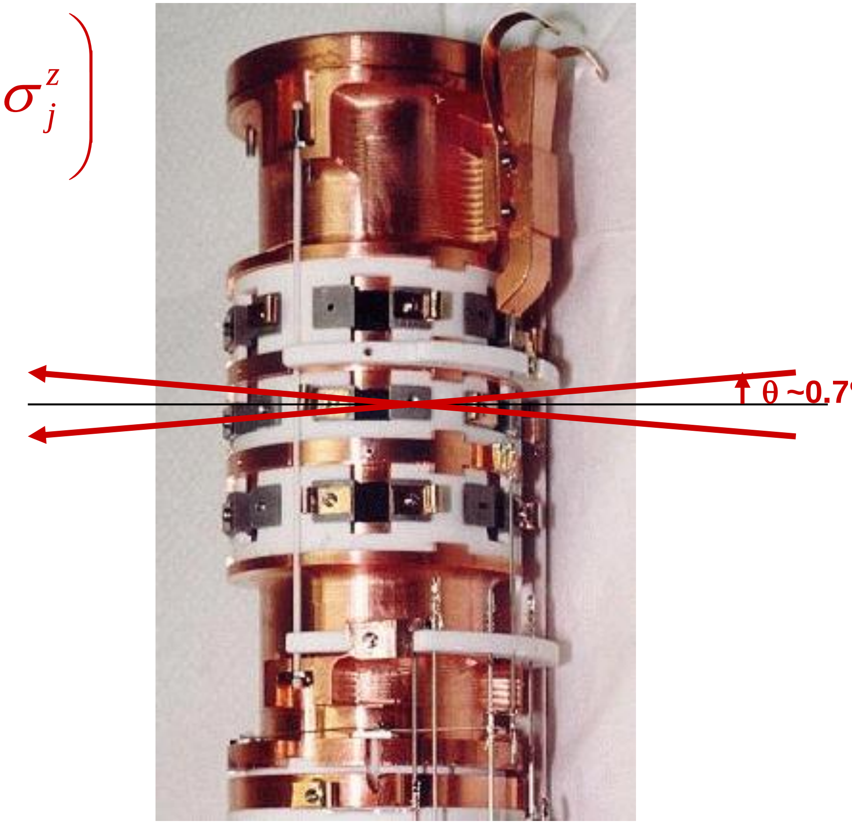
- interaction strength independent of distance between ion pairs
- evolution exactly calculable; enables test of fidelity of implementation

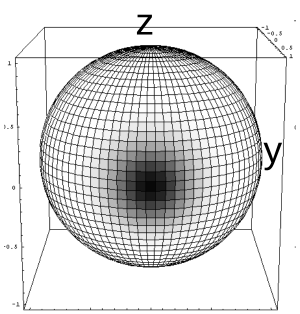
# Optical dipole force implementation of $J_z^2$

$$J_z = \sum_i \sigma_i^z/2, \quad H = \chi J_z^2 = \chi\left(N/4 + \tfrac{1}{4}\sum_{i\neq j}\sigma_i^z\sigma_j^z\right)$$

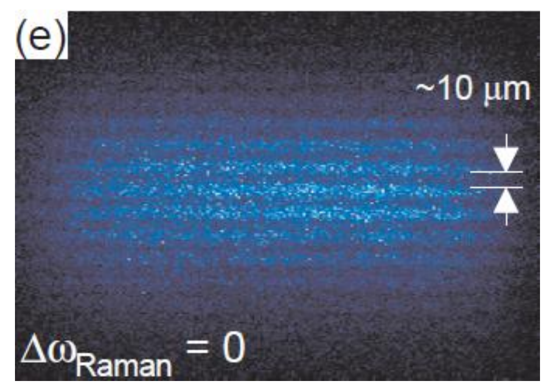
**use optical dipole force to near resonantly drive the axial COM mode**




$$\rightarrow \sum_{M_j=-N/2}^{M_J=+N/2} c(N.M_J)\,|J,M_J\rangle$$




with $F_\downarrow = -F_\uparrow$, $|J,M_J\rangle$ acquires a phase ~ $M_J^2$

For θ ~ 0.7°, squeezing will be limited by spontaneous emission

# Quantum simulation

**Effective spin systems with trapped ions**
**Porras and Cirac, PRL 92, 207901 (2004)**

→ **dipolar Ising interaction obtained by tuning beat note far from resonance with any modes**

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

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

present 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

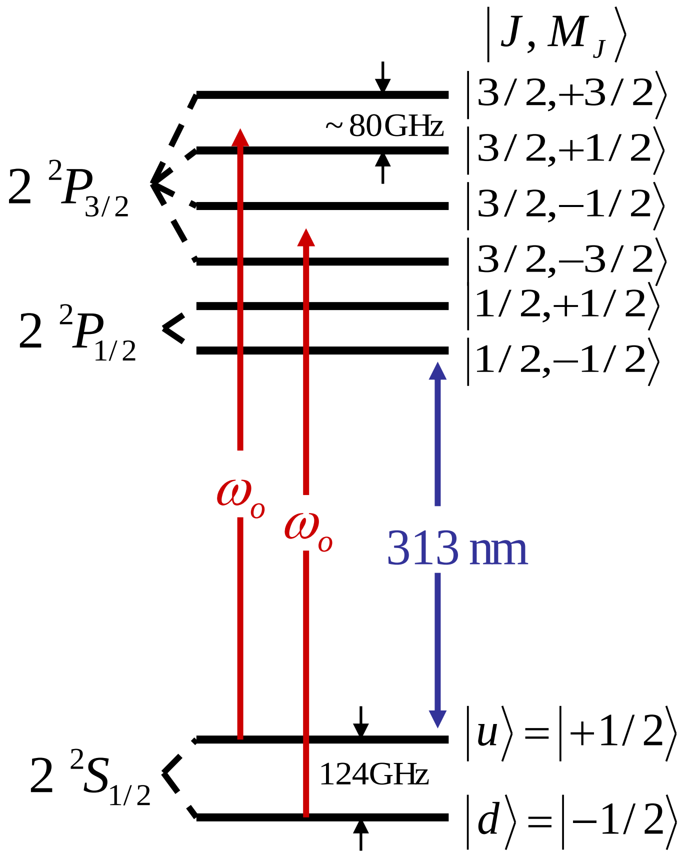
θ → 5°, 10 mW/beam
waist ~ 500 μm x 50 μm

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

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




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 ($\omega_o$) scattering causes decoherence,

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

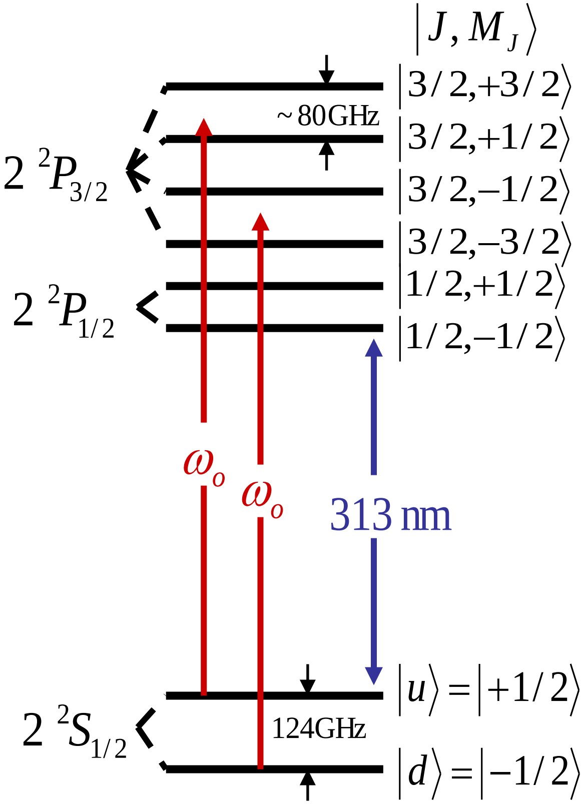
$$\Gamma = ???$$

# 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

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

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

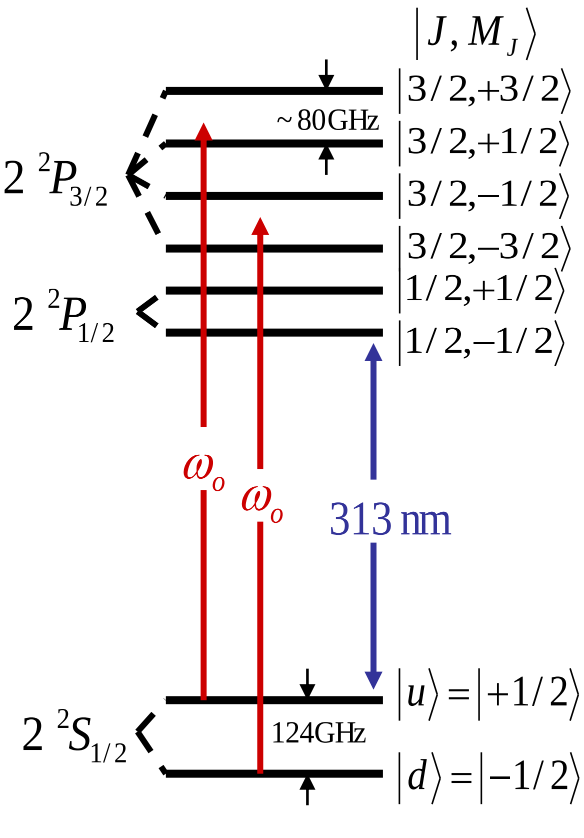
Ozeri *et al.* , Phys. Rev. Lett. **95**, 030403 (2005) –

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)

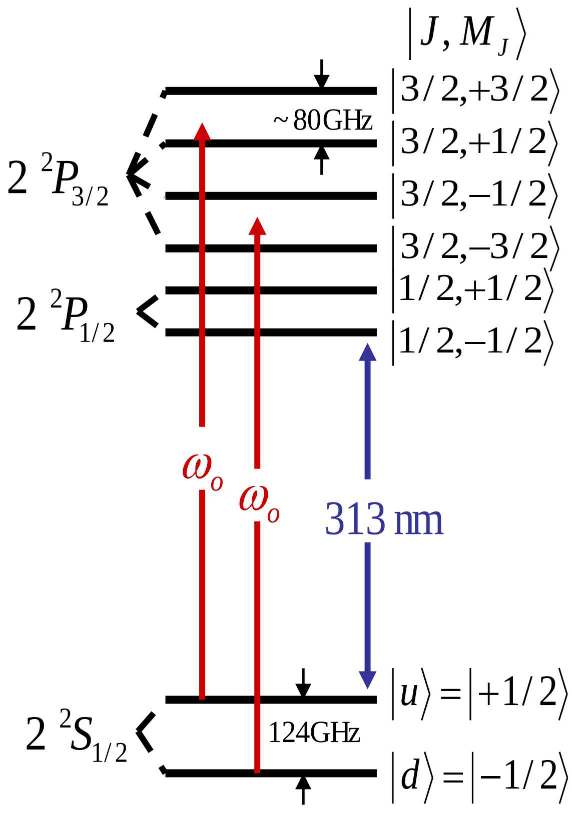
$$\Gamma_{Rayleigh,diff} \sim \frac{(\Gamma_{uu} - \Gamma_{dd})^2}{(\Gamma_{uu} + \Gamma_{dd})/2}$$

# Master equation treatment of decoherence due to light scattering

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

- credit to: Hermann Uys

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




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

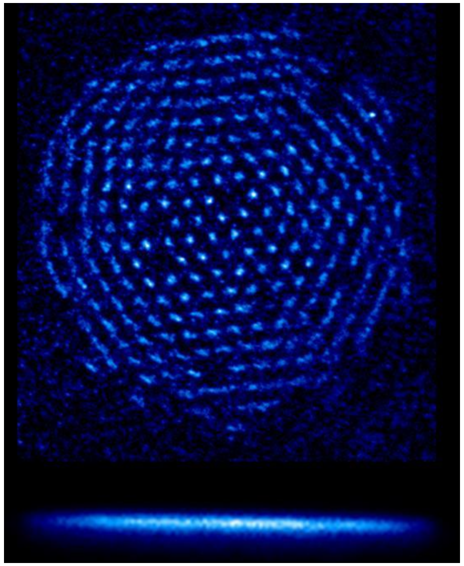
decoherence due to difference in the elastic scattering *amplitudes* !

- large decoherence expected if scattering amplitudes have opposite sign

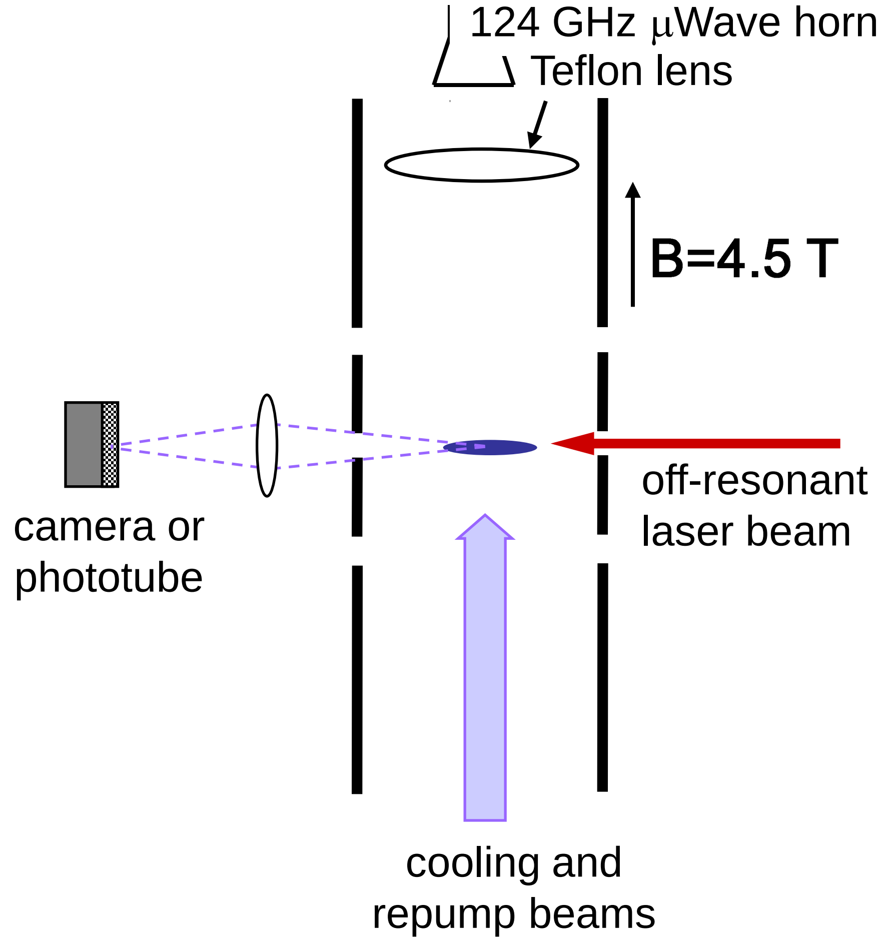
- sign of scattering amplitude determined by the detuning

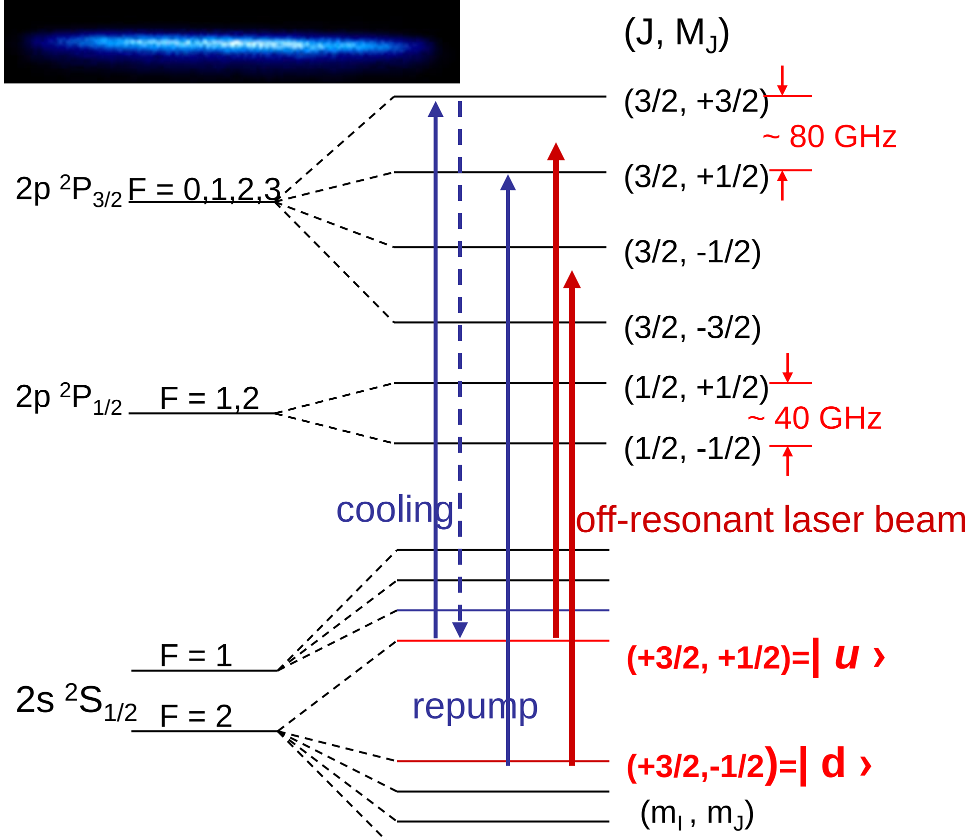
- physically the state of the qubit can be determined from the phase of the scattered photon

# Experimental test of decoherence theory



- use single plane arrays of N ~100 ions in a Penning trap

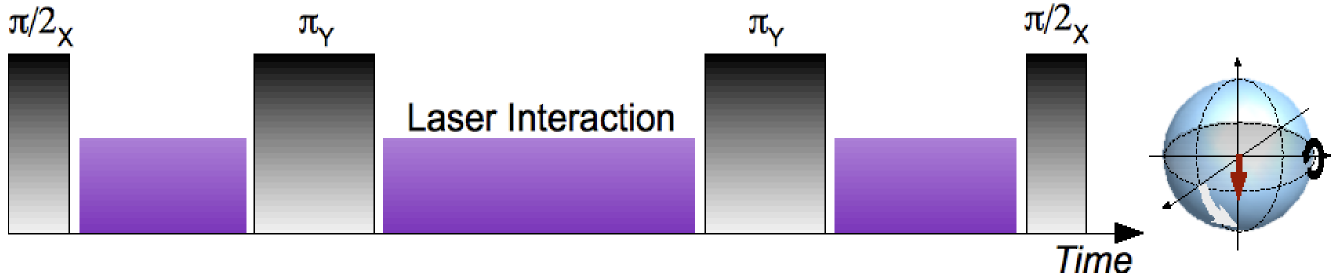


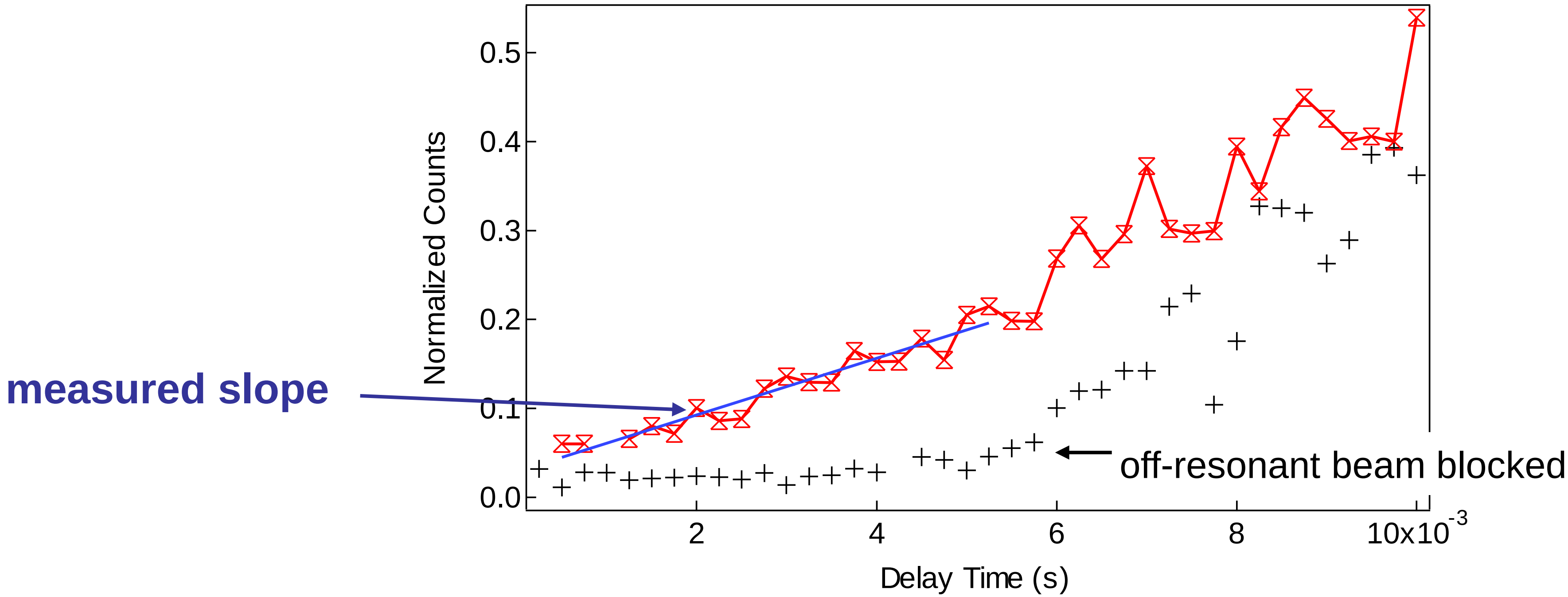




- ions Doppler laser cooled to ~0.5 mK

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

# Decoherence measured from decrease in the Bloch vector

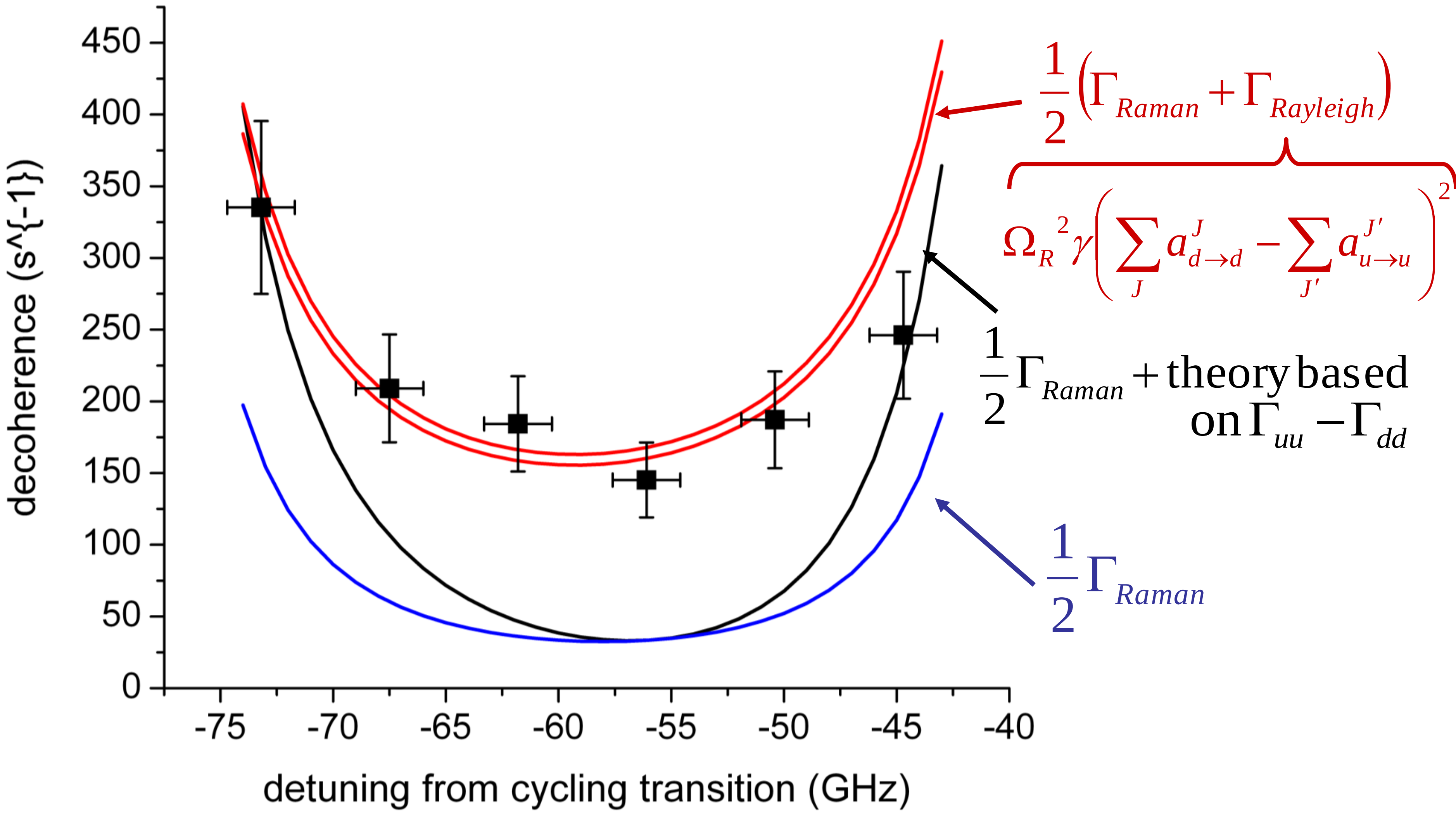



$$\text{Normalized counts} = \frac{1}{2}\left[1 - e^{-\frac{1}{2}(\Gamma_{Raman}+\Gamma_{Rayleigh})\tau}\right] \approx \frac{1}{2}\,\frac{\Gamma_{Raman}+\Gamma_{Rayleigh}}{2}\,\tau\,,\ \tau =$$ total laser on time

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

# Good agreement between theory and experiment

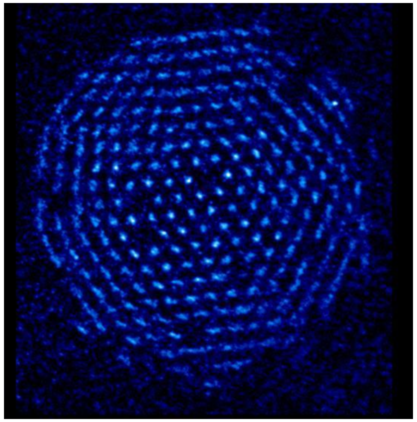



- Laser electric field calibrated from measured light shift and Raman rates

# Summary

- Penning traps appear to provide a platform for the simulation of quantum spin systems with N > 100 ions

- triangular lattice occurs naturally → enables simulation of spin frustration



- initial focus: uniform Ising model $J_z^2$

-eventual goal: short range (dipolar) Ising interaction