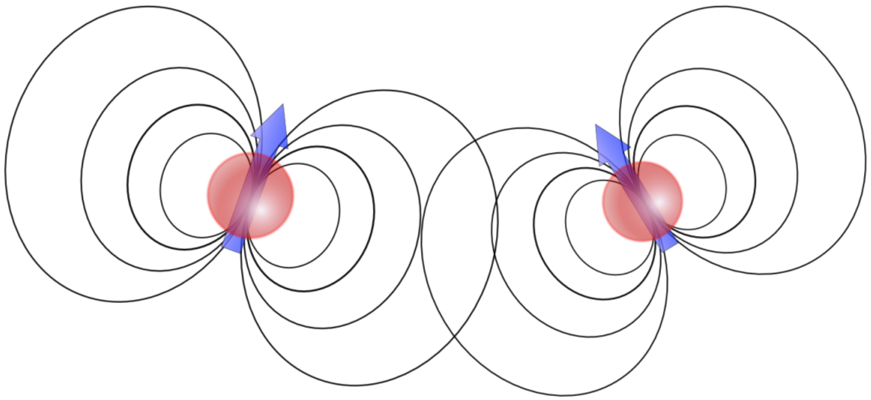
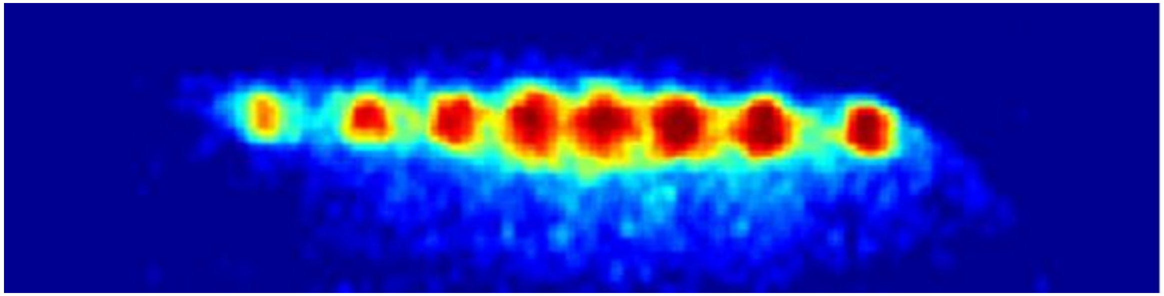
iQsim 2013

Weak Dipolar interactions in trapped-ion crystals



Roee Ozeri
Nitzan Akerman
Shlomi Kotler
Yinnon Glickman
Yehonatan Dallal
Tomas Sikorsky
Boaz Nissan-Cohen
Nir Navon
Ravid Shaniv
Osip Schwarz
Ziv Meir
Anna Keselman
Roy Patael
Collaboration with Dan Oron

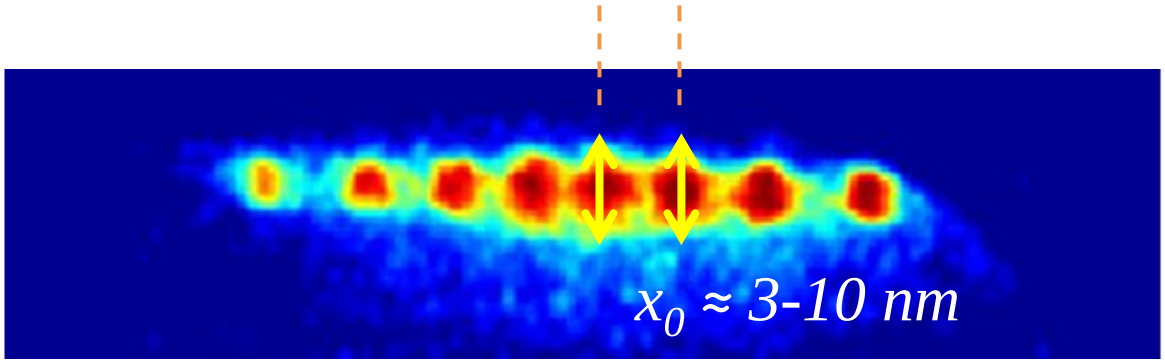


- Localized qubits (“spins”)
- Realization of correlated spin models requires spin-spin interactions
- Didi says: “natural” spin-spin interactions are very weak

Trapped-ions

Phonon-mediated (synthetic) spin-spin interactions

$d = 5\mu m$



- Spin dependent forces $x_0 = \sqrt{\frac{\hbar}{2m\omega}}$
- Dipole moment ≈ 200 ea_0
- Dipole-dipole interaction: $\hbar\omega_{int} = \frac{e^2}{2\pi\epsilon_0 d^3} x_0^2$

≈ 10’s - 100’s kHz

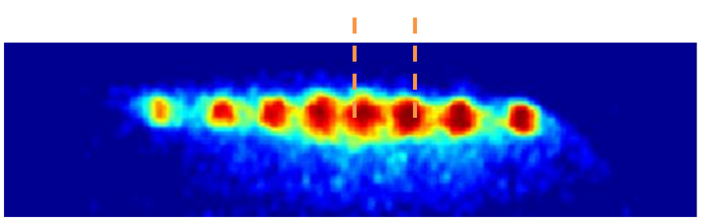
Magnetic spin-spin interactions:

- Magnetic dipole: spin. equivalent ~ $ea_0 / 137$ $\quad ea_0 = \frac{\mu_B}{\alpha c}$

- Dipole-dipole interaction: $\xi = \mu_0 (g\mu_B/2)^2 / 4\pi\hbar d^3$

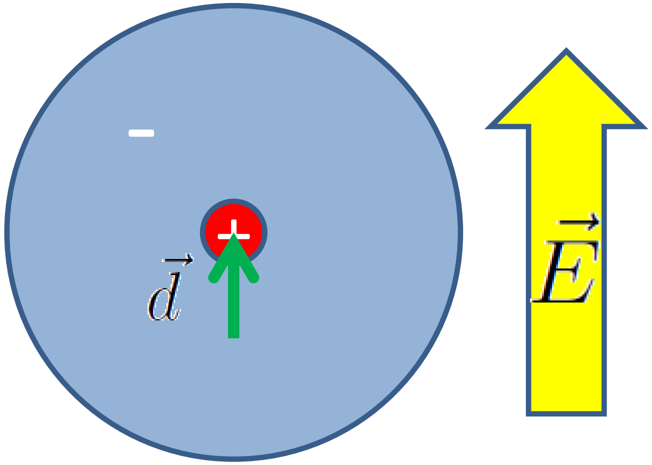
$$\xi/2\pi = \frac{13}{(r/1\mu m)^3} \quad mHz$$

$d = 5\mu m$



$$\Rightarrow \quad \xi/2\pi = 0.1\ mHz$$

Electric dipole-dipole interactions:



- Eigenstates a symmetric under parity:

  no permanent dipole moment

- A field induces a dipole moment:

$$\vec{d} = \alpha \vec{E}$$

Typically with $E \approx 10^6$ V/m ⇒ $d \approx 10^{-3}\, ea_0$

Possible Enhancements:

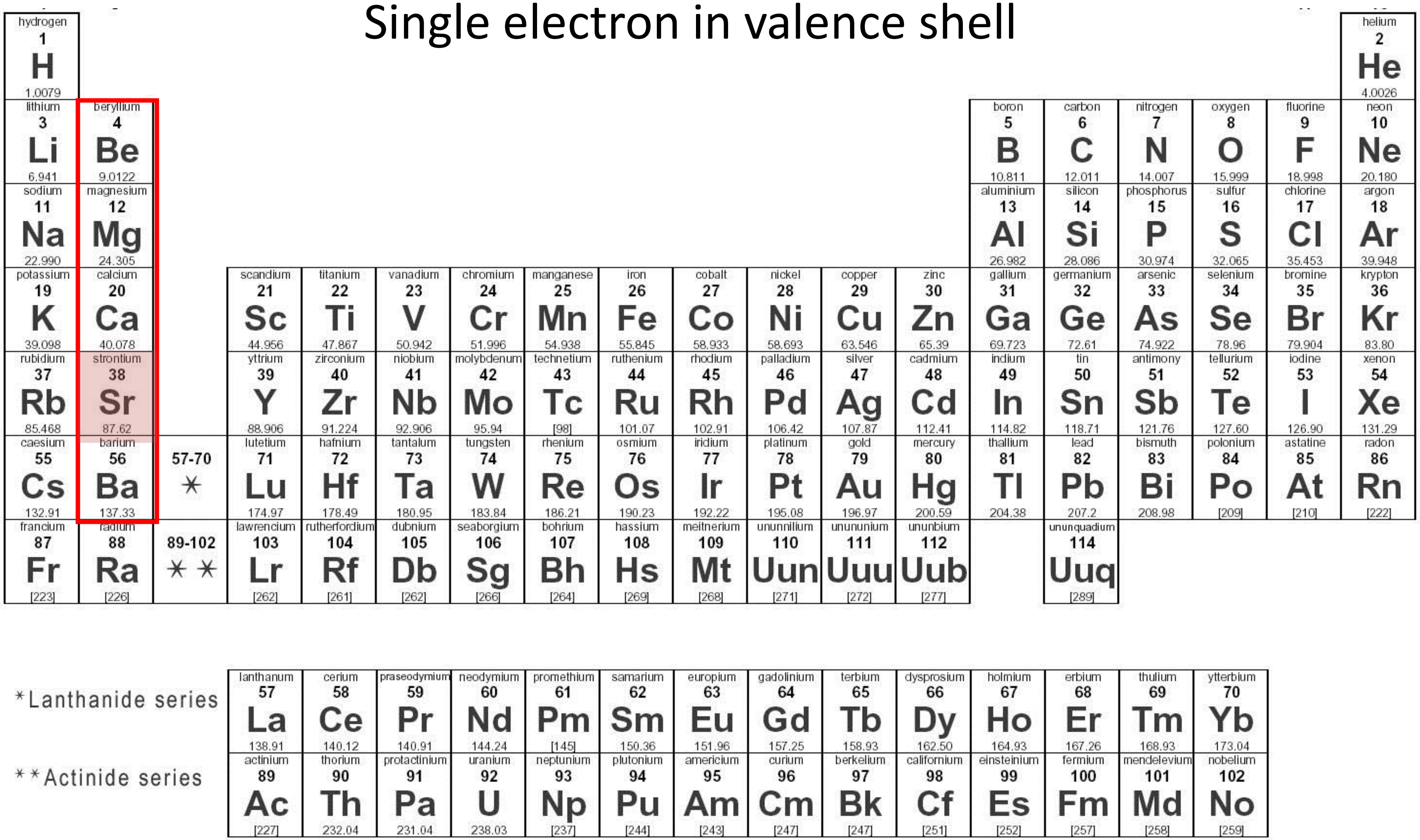
- Rydberg states
- Oscillating fields: resonance enhancement; far field $1/d$

Magnetic dipole-dipole interactions

Magnetic Spin-Spin interactions

Which ions?

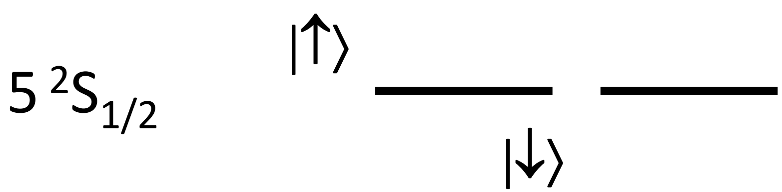
Single electron in valence shell



Magnetic Spin-Spin interactions

$^{88}Sr^{+}$ electronic spin

- No nuclear spin $S = 1/2$
- Magnetic dipole moment: $\mu_e = -g\mu_B \frac{S}{\hbar}$
- Bound electron g: 10^{-4} correction vs. free electron (Breit 1928)

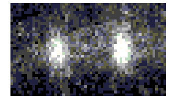


Turn on small B field
2.8 MHz/G

Magnetic Spin-Spin interactions

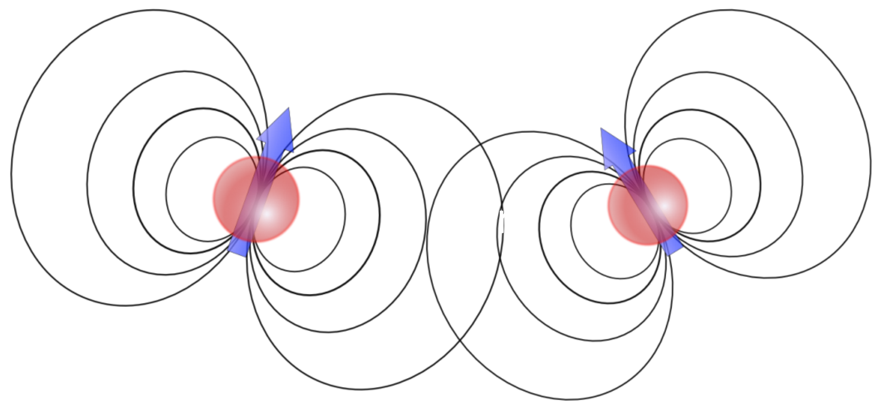
Hamiltonian

<u>Electronic Spins</u>



$\vec{B} \,||\, \vec{r}$

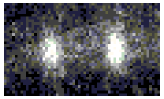
$$H = \frac{\hbar\omega_A}{2}(\sigma_{z,1} + \sigma_{z,2}) + 2\hbar\xi\sigma_{z,1}\sigma_{z,2} - \hbar\xi(\sigma_{x,1}\sigma_{x,2} + \sigma_{y,1}\sigma_{y,2})$$



$$\hbar\xi = \tfrac{1}{2}k\lambda_c^2 \qquad \lambda_c = \tfrac{h}{m_e c} \equiv 2.4 \times 10^{-12}\ m \qquad \xi/2\pi = \frac{13}{(r/1\mu m)^3}\ mHz$$

- Was never directly measured: dominated by exchange interaction
- If measured with high precision: search for anomalous spin forces

Electronic Spins



$\vec{B} || \vec{r}$

$$H = \frac{\hbar\omega_A}{2}(\sigma_{z,1} + \sigma_{z,2}) + 2\hbar\xi\sigma_{z,1}\sigma_{z,2} - \hbar\xi(\sigma_{x,1}\sigma_{x,2} + \sigma_{y,1}\sigma_{y,2})$$

- Conserves $\sigma_{z,1} + \sigma_{z,2}$
- Eigenstates:
- $(\sigma_{x,1}\sigma_{x,2} + \sigma_{y,1}\sigma_{y,2})$ Remove the degeneracy between $|\Psi_{\pm}\rangle$

$|\uparrow\uparrow\rangle$

$|\Psi+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$

4ξ

$|\Psi-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

$|\downarrow\downarrow\rangle$

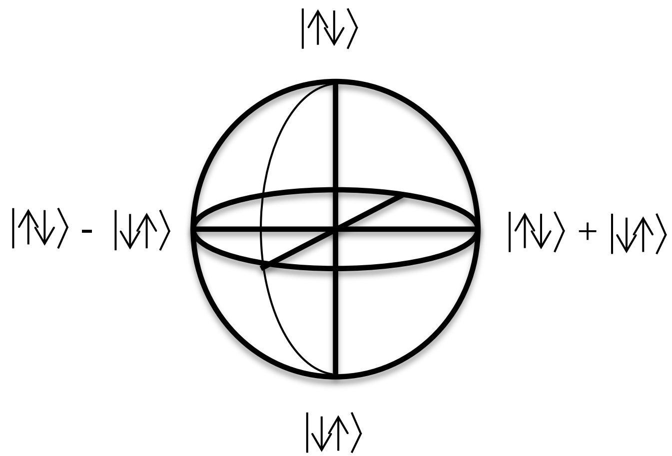
Magnetic Spin-Spin interactions

Decoherence-Free subspaces

All the states in the sub-space, spanned by the two states,

$$|\Psi+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$$ (triplet; m=o)

$$|\Psi-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$ (singlet)



- Subspace invariant under spin-spin coupling
- Remain coherent under collective magnetic field noise.

Haffner *et. al.* Appl. Phys. B, **81,** 151 (2005)
Langer *et. al.* Phys. Rev. Lett., **95,** 060502 (2005)

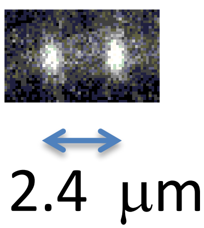
Rotation in DFS

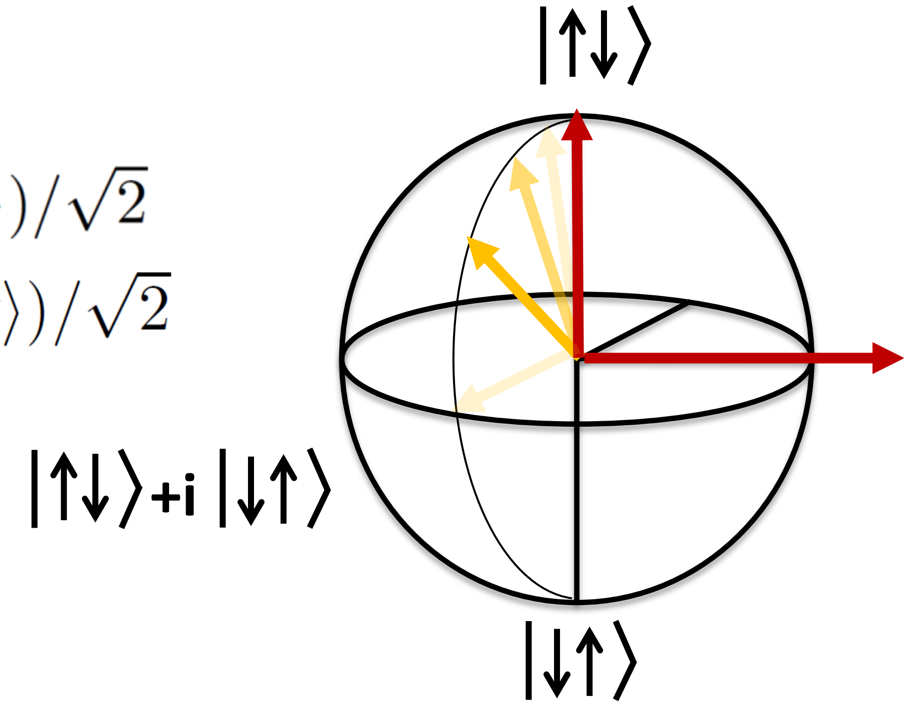
$$H = 2\hbar\xi\left(|\uparrow\downarrow\rangle\langle\downarrow\uparrow| + |\downarrow\uparrow\rangle\langle\uparrow\downarrow|\right)$$

<u>Spin-Spin eigenstates:</u>

$$|\Psi+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$$

$$|\Psi-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$





- *ΔE= 4ξ = 3.8 mHz ≈ 200×10⁻¹⁵ ˚K ≈ 20×10⁻¹⁸ eV*
- B-field spins apply on each other nGauss; 10^6 < than noise

Magnetic Spin-Spin interactions

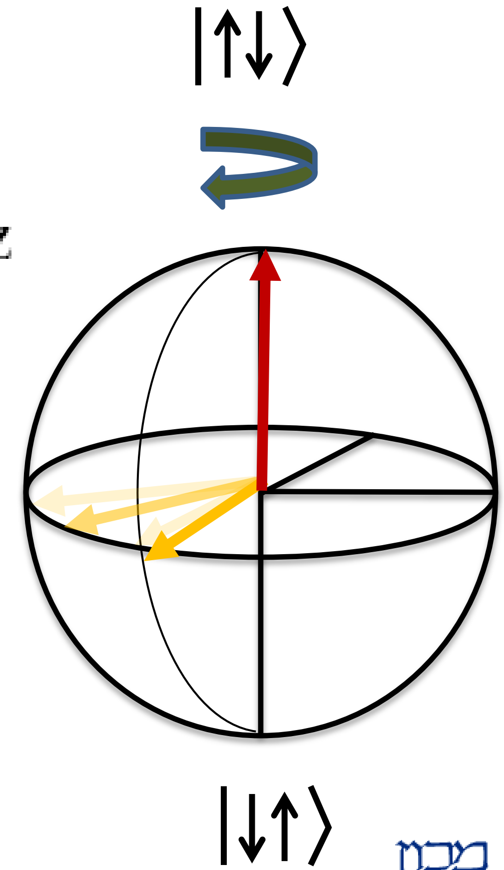
Difficulties: magnetic Field gradient

- Magnetic field gradient removed degeneracy between $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$
- Detunes spin-spin coupling from resonance
- After careful nulling: $3 \times 10^{-7}\mathrm{T/m}$

$$\Rightarrow \quad \Delta\omega_A = (2\pi)20\ \mathrm{mHz}$$

- Still overwhelms spin-spin
- Solution: Spin-Echo pulse-train

(2Hz rep. rate)

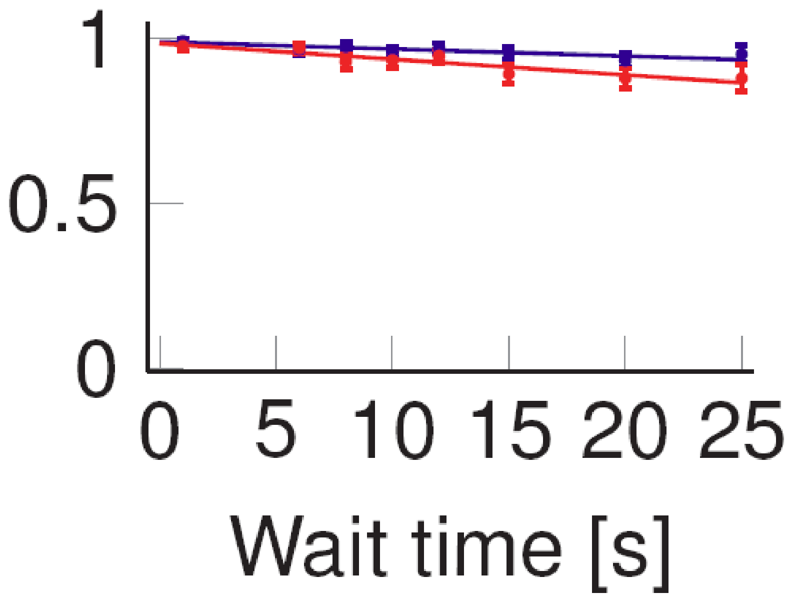


Magnetic Spin-Spin interactions

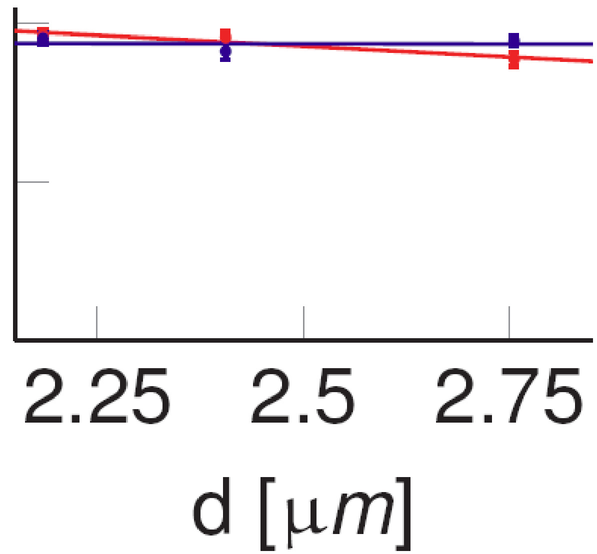
Difficulties: long experiments

Detection fidelity

$|\uparrow\uparrow\rangle$ (red) $|\downarrow\downarrow\rangle$ (blue)

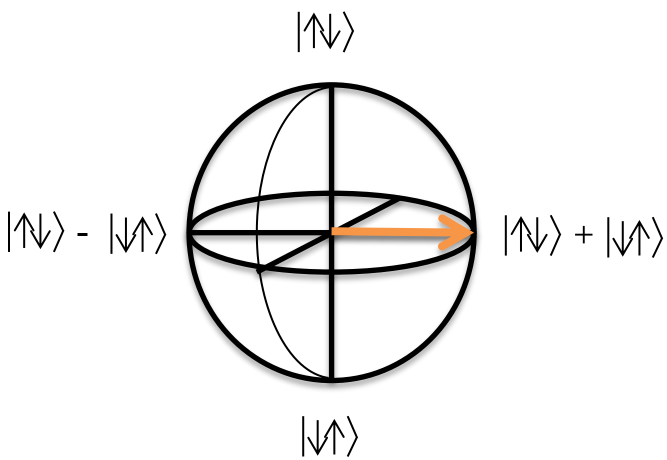


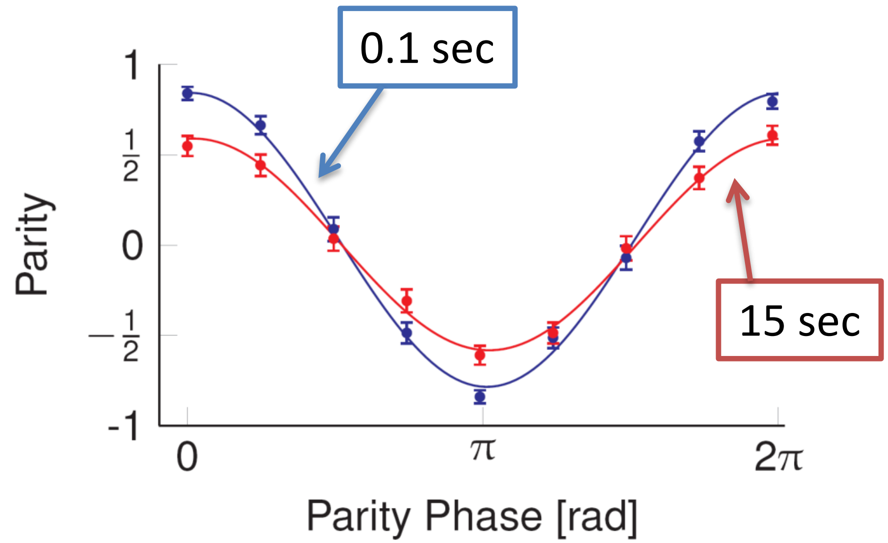
@ 2.4 μm



@ 15 sec

Echo coherence in DFS



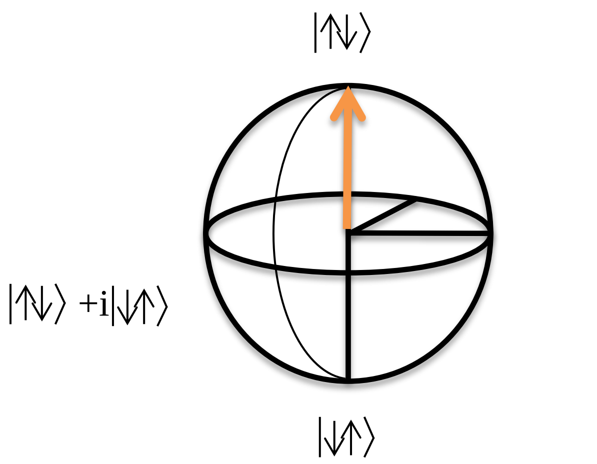


Coherence time = 44 Sec

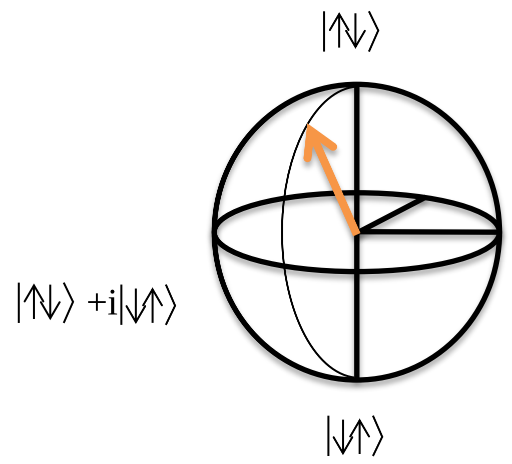
(Consistent with detection error)

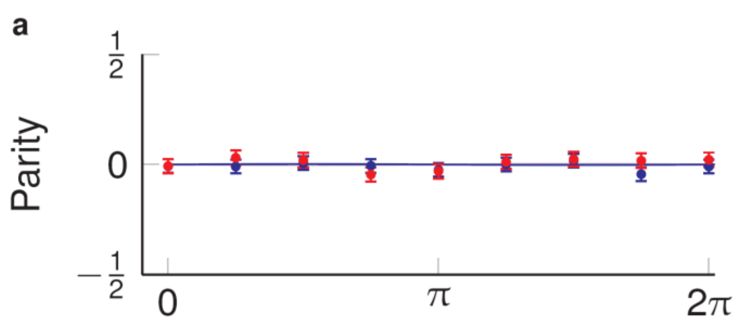
Spontaneously entangled spins

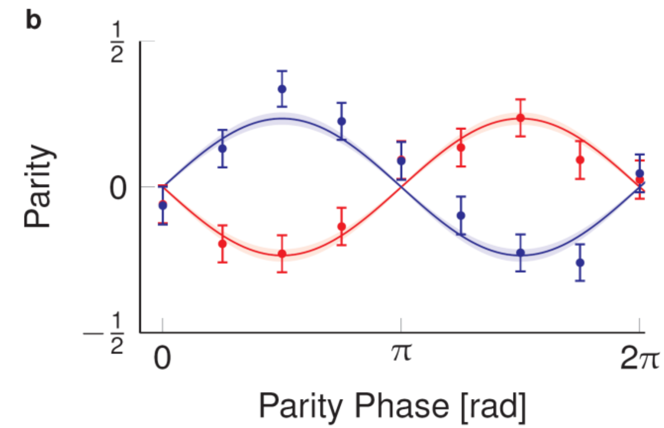
After 0.1 seconds



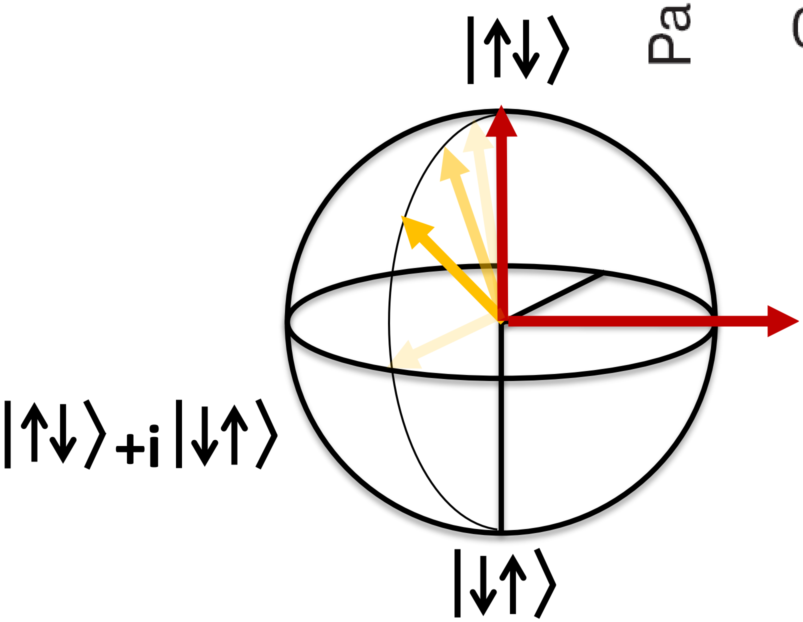
After 15 seconds

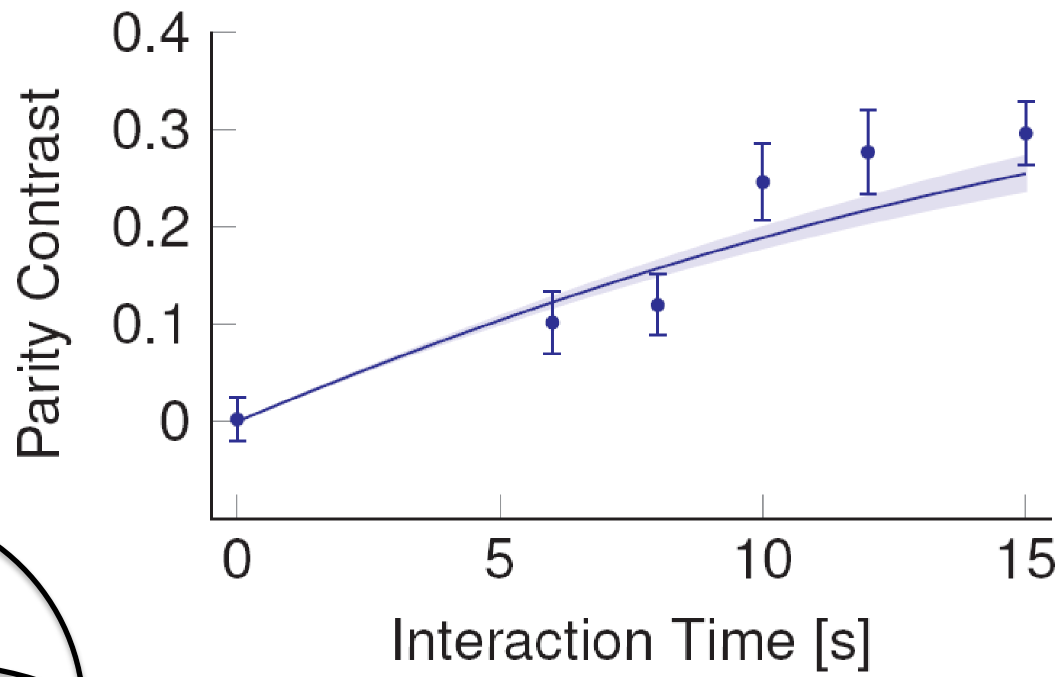






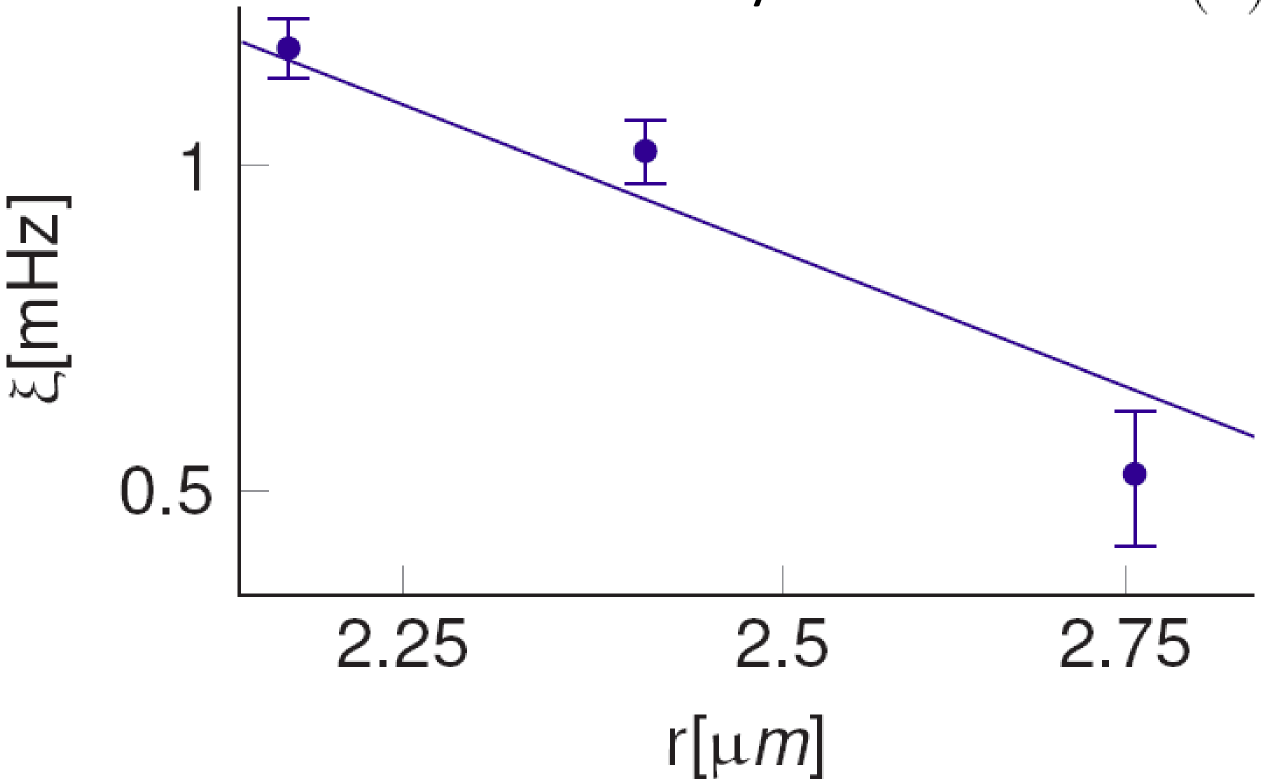
Initializing to: |↑↓⟩ (blue) |↓↑⟩ (red)


|↑↓⟩
|↑↓⟩+i|↓↑⟩
|↓↑⟩


Parity Contrast
0.4
0.3
0.2
0.1
0
0
5
10
15
Interaction Time [s]

Fit to: $\xi = \mu_0 (g\mu_B/2)^2/4\pi\hbar d^n$

yields: $n = 3.0(4)$



Electric dipole-dipole interactions

Resonance field excitation

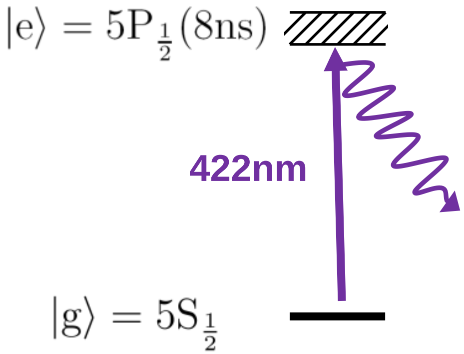
- Excite a dipole moment with a laser field,
  on resonance with an electric dipole transition

- Atomic polarizability resonantly enhanced

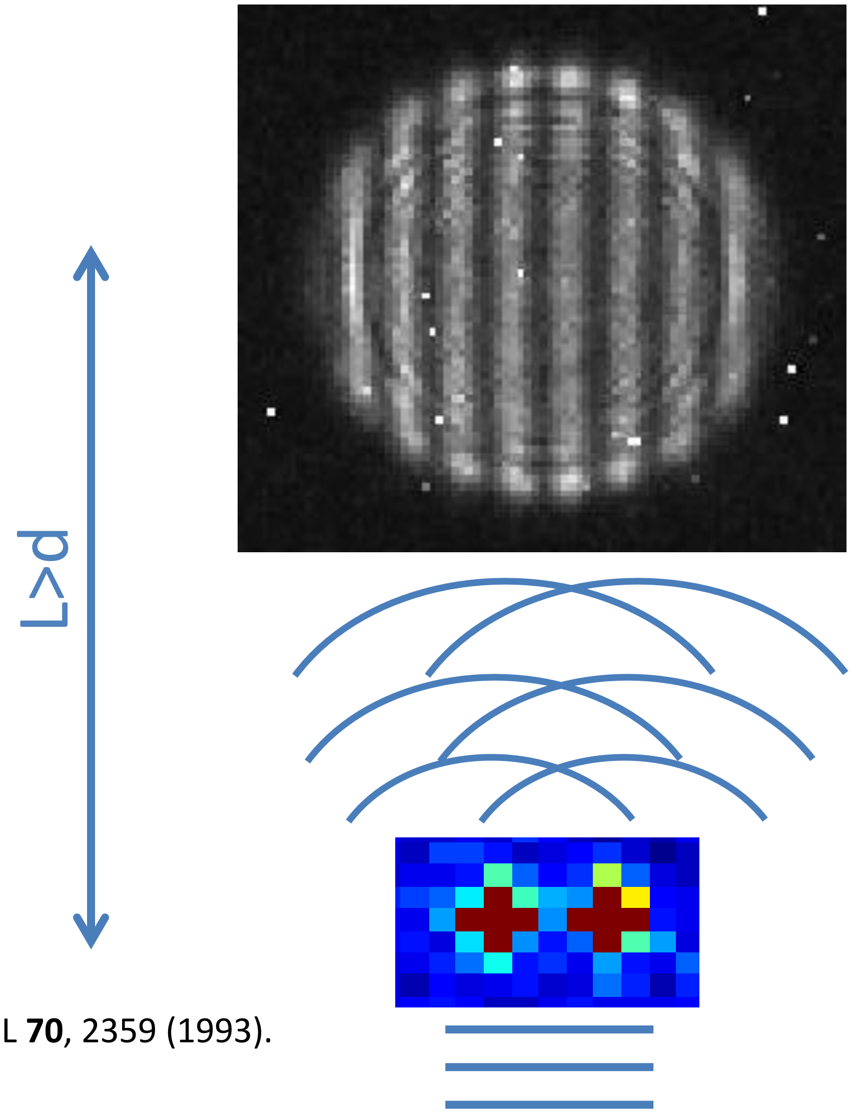
- Spontaneous photon scattering

- Far field regime $d \gg \lambda$ – non-trivial distance dependence $\neq \frac{1}{d^3}$

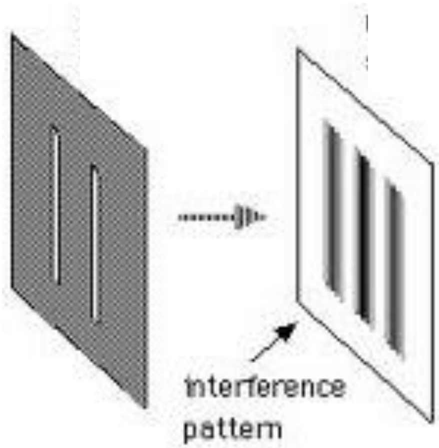
- Weak excitation intensity $I < I_{sat}$ to avoid multiple photon scattering (dipole linear in field)



Two-ion far field interference



$$|\psi\rangle = |+\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{ge}\rangle + |\mathrm{eg}\rangle\right)$$

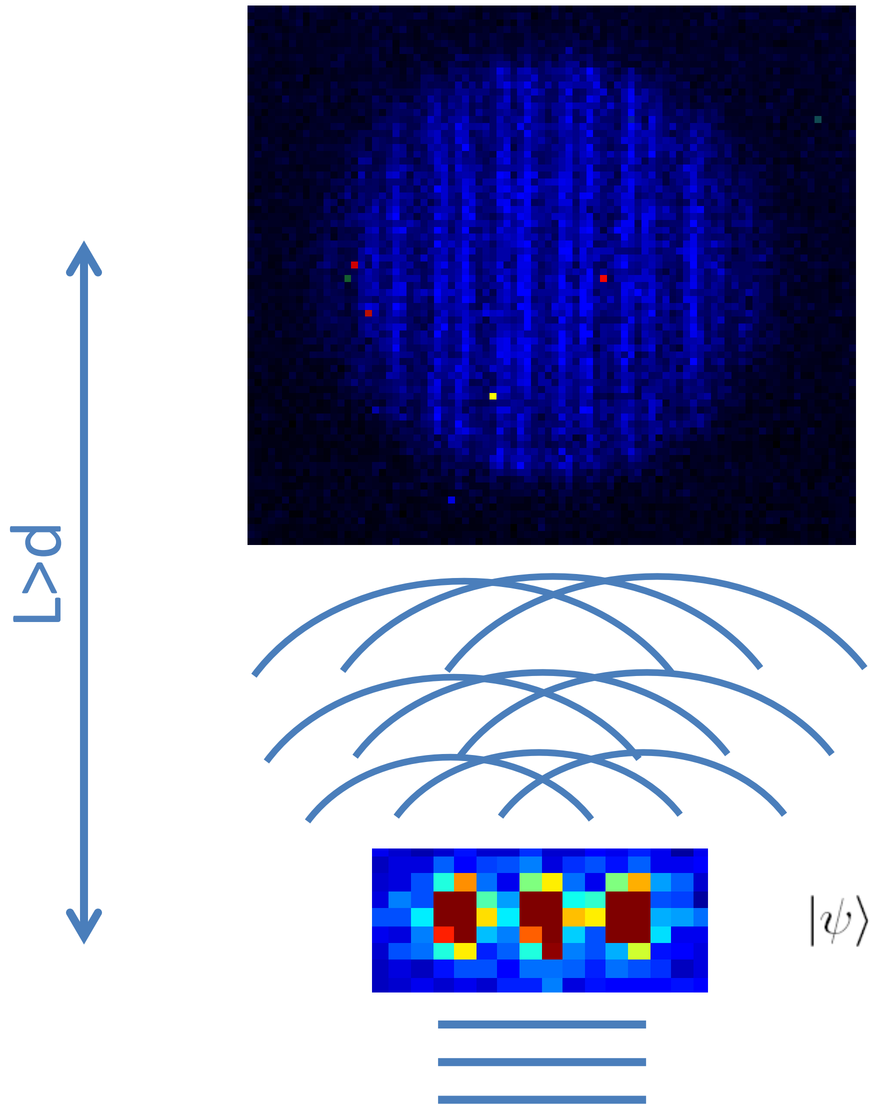


U. Eichmann et al., PRL **70**, 2359 (1993).

Electric dipole-dipole interaction

Ions as coherent field emitters

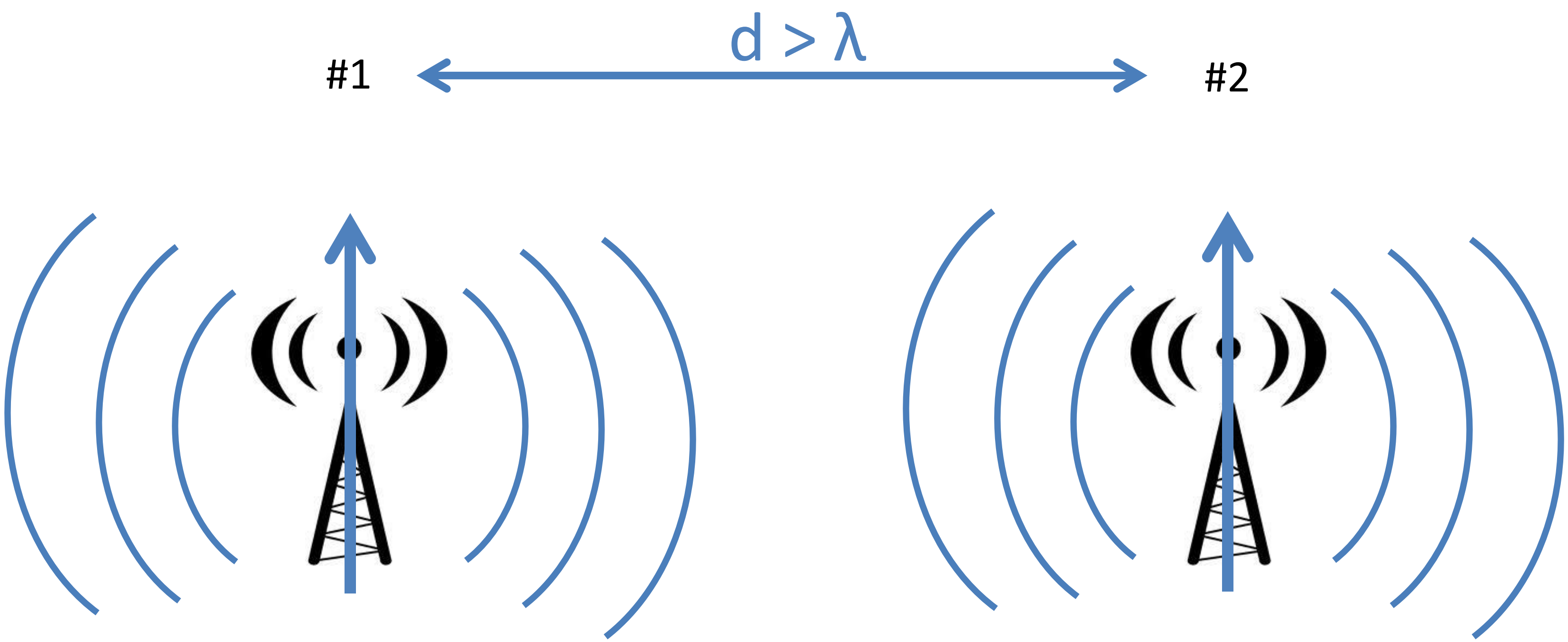
Three-ion far field interference



$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{j} |g_1 g_2 \ldots e_j \ldots g_N\rangle$$

Electric dipole-dipole interaction

Quantum coupled antennas

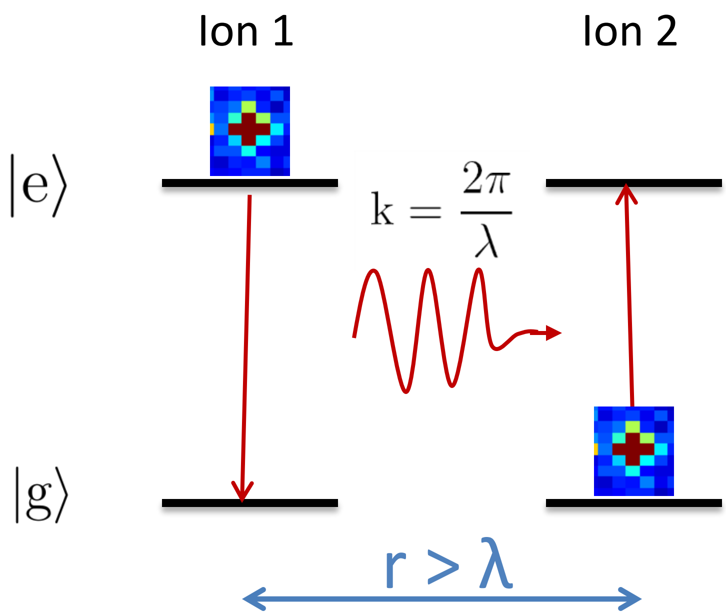


$-\mathbf{E}_2 \cdot \mathbf{d}_1$ $-\mathbf{E}_1 \cdot \mathbf{d}_2$

$$\mathrm{E}_{\mathrm{dipole}} \sim \frac{e^{ikr}}{r} \sin(\theta)\hat{\theta}$$

- Retardation: phase of emitted filed oscillates with a λ period.

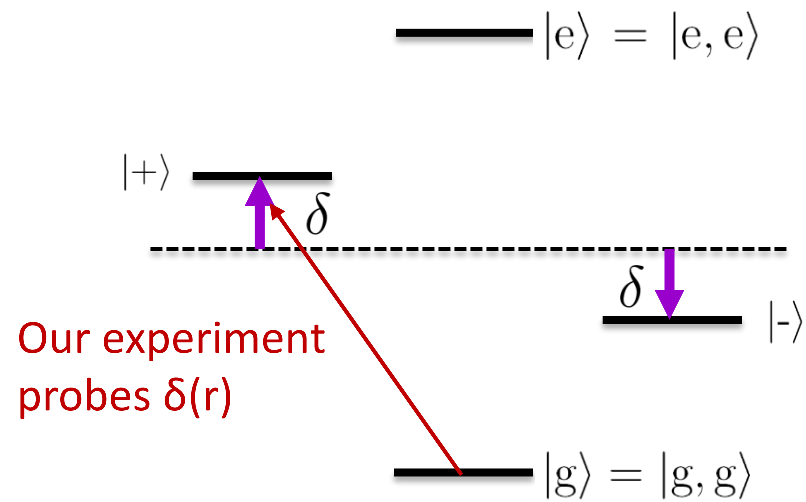
Resonant dipole-dipole interactions



$$\mathrm{E_{dipole}} \sim \frac{e^{ikr}}{r} \sin(\theta)\hat{\theta}$$

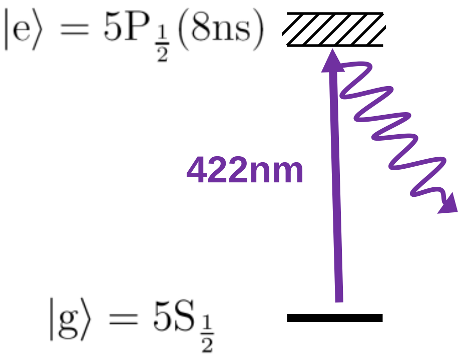
$$\delta = -\frac{3}{8} \mathrm{A}_{\uparrow\downarrow} \frac{\cos(\mathrm{kr})}{\mathrm{kr}} + \mathrm{O}\left(\mathrm{kr}^{-2}\right).$$

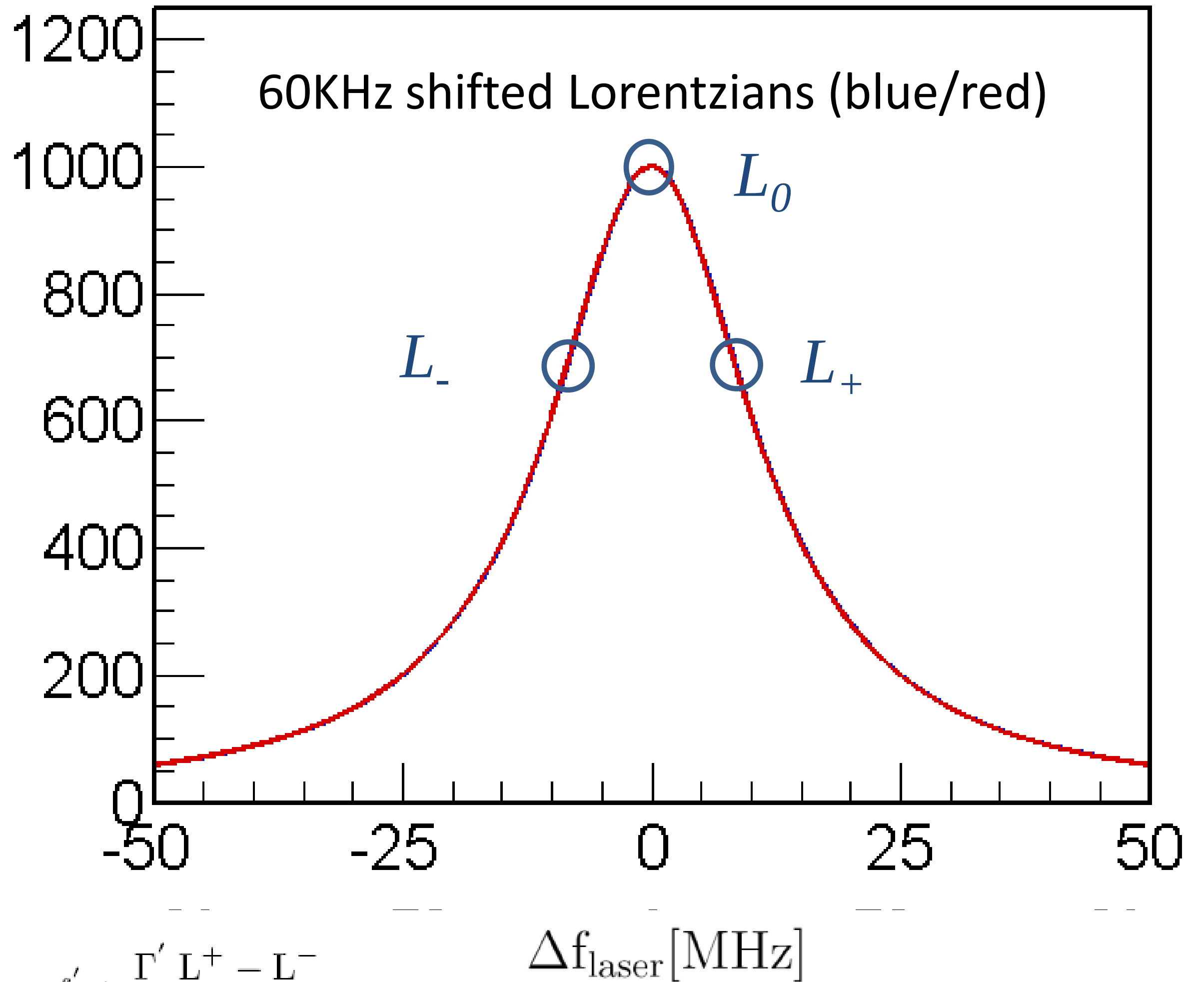
A - Coupling strength



Electric dipole-dipole interaction

Spectroscopy





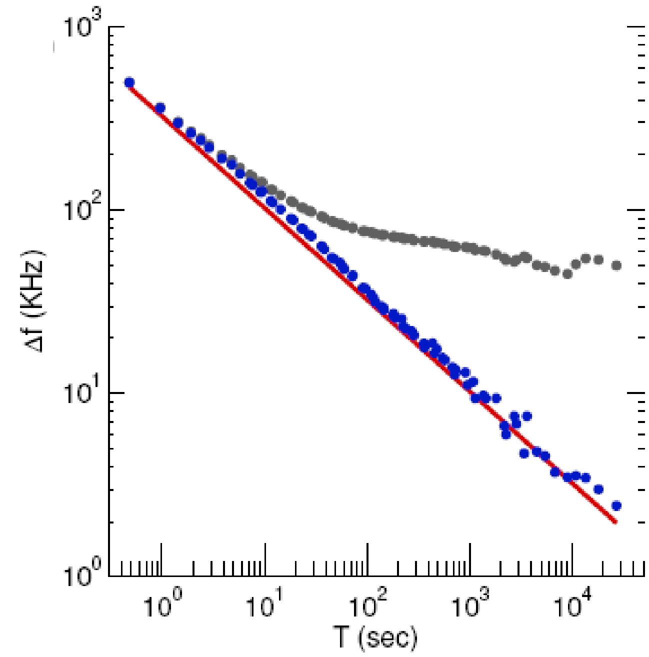
$$L(\nu) = \frac{A}{1 + \left(\frac{\nu - f_0}{\frac{\Gamma}{2}}\right)^2}$$

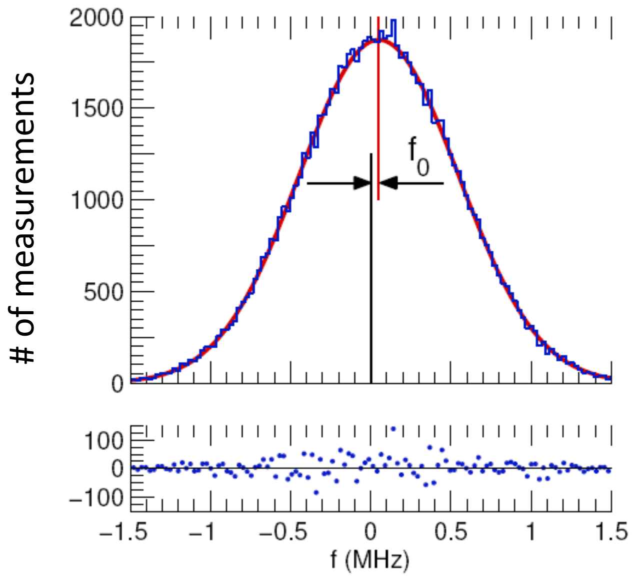
$$f = f' + \frac{\Gamma'}{2} \frac{L^+ - L^-}{2(L^+ + L^-) - \frac{4L^+L^-}{L^0}} \approx f' + \frac{\Gamma'}{2} \frac{L^+ - L^-}{L^0}$$

Electric dipole-dipole interaction

Spectral resolution

- The transition/laser drifts.
- Interlacing distance points (30 sec per point)
- Few days integration



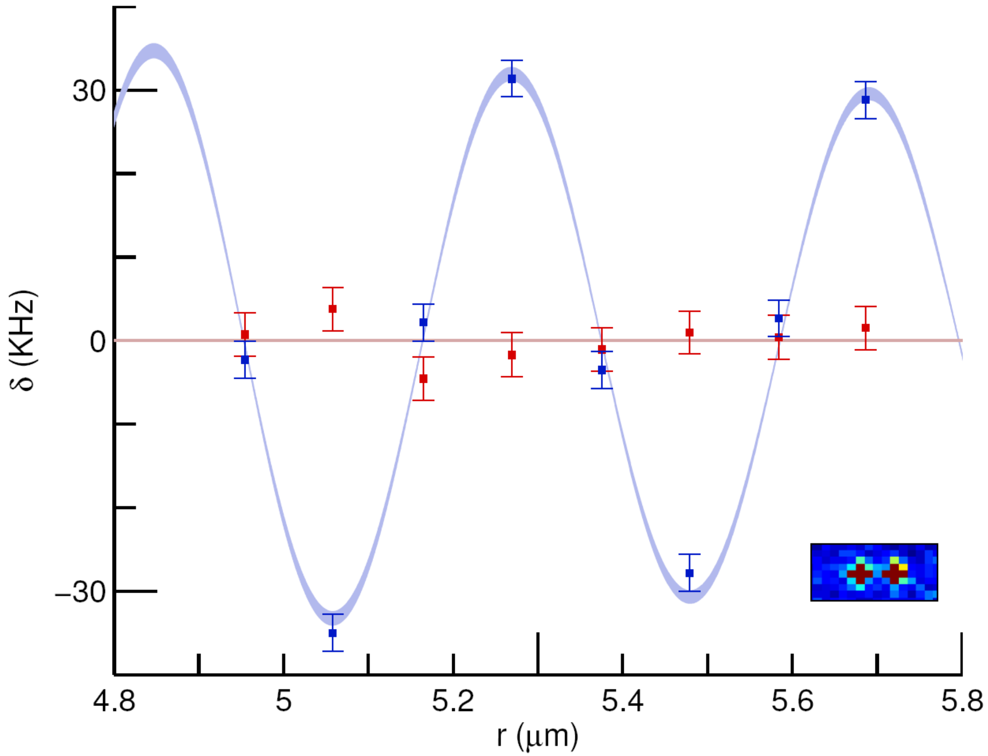


- 93300 measurements
- $n = 1325$ photons on average/meas.
- Gaussian width $0.4963(12)\mathrm{MHz}$
- Photon shot-noise $\frac{\Gamma}{2\sqrt{n}} = 0.469\mathrm{MHz}$
- Frequency shift $f_0 = 50.6 \pm 1.6$

- Light blue – theory (no fit parameters)
- Small effect : 10^{-3} (60KHz)
- Acc. : 10^{-4} (<3KHz)
- Int. time : 8.6 hrs/point,

  Almost a week for entire

  data set
- Control via polarization

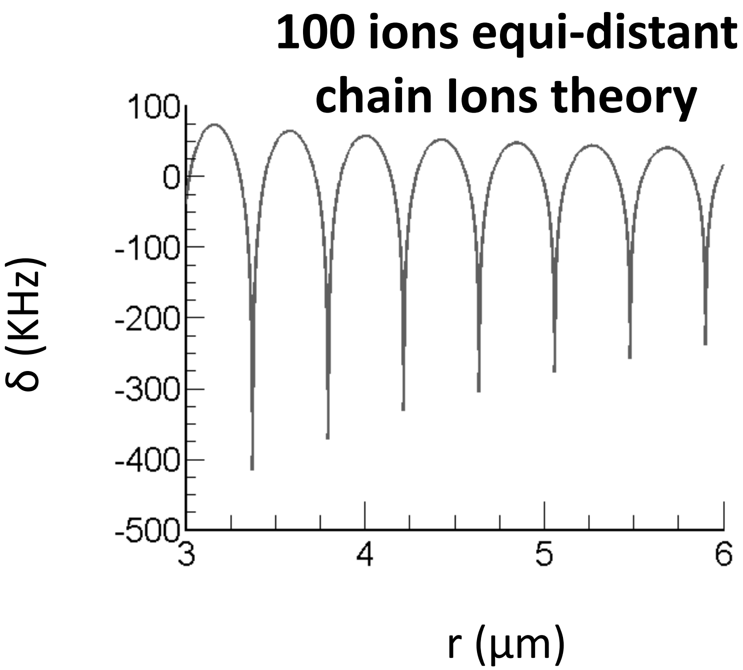


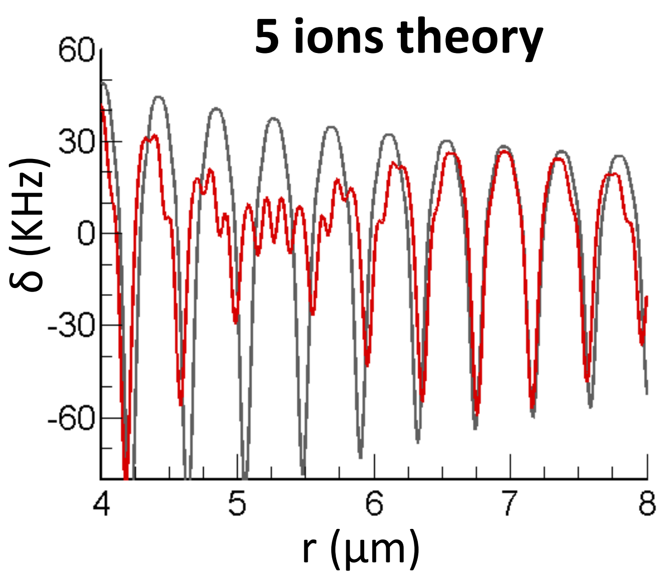
Multiple–ions theory

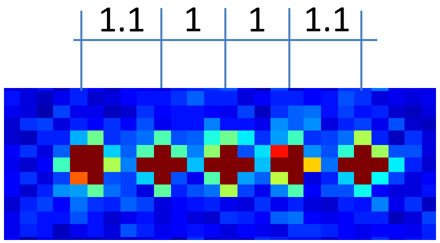
$$|\psi\rangle = \frac{1}{\sqrt{M}} \sum_i |g_1 \ldots e_i \ldots g_N\rangle$$

$$\delta_M = \frac{1}{M} \sum_{m \neq n} \delta(r_m - r_n)$$

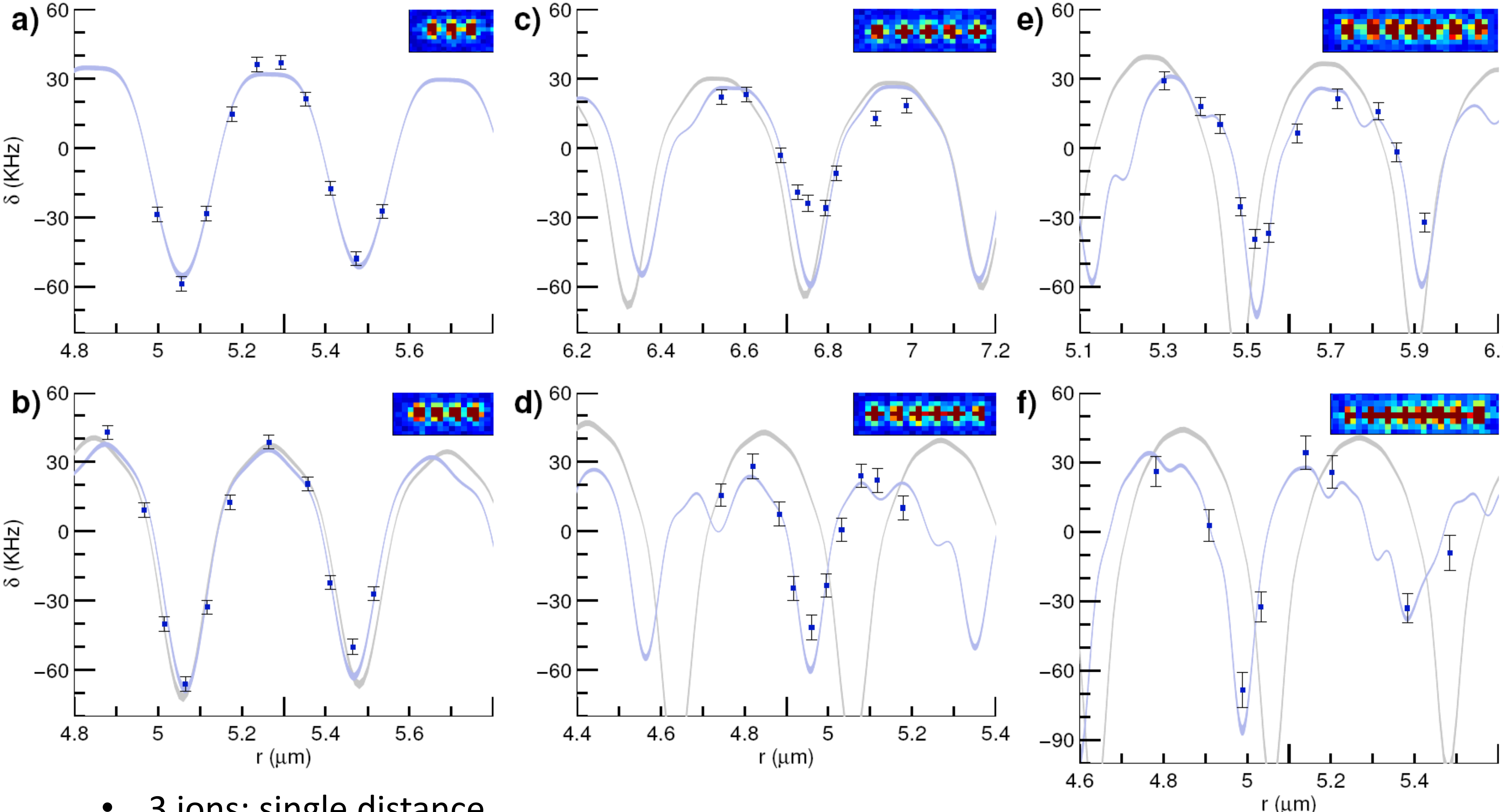
- Coherent sum of al pair-wise shifts
- Narrowing of resonances
- Not equidistant – Beating







Multiple ions experiment

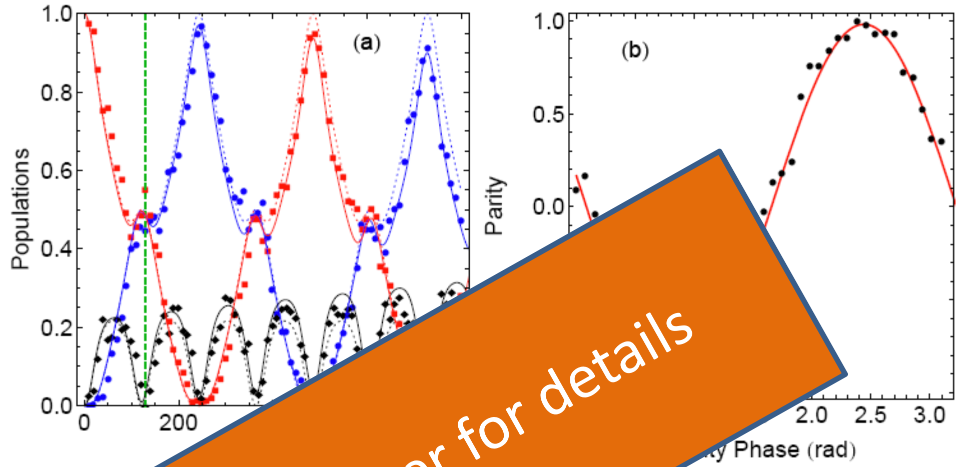


- 3 ions: single distance
- Blue lines: theory with no fit parameters
- Grey lines: equidistant-chain theory

Synthesized dipole-dipole interactions

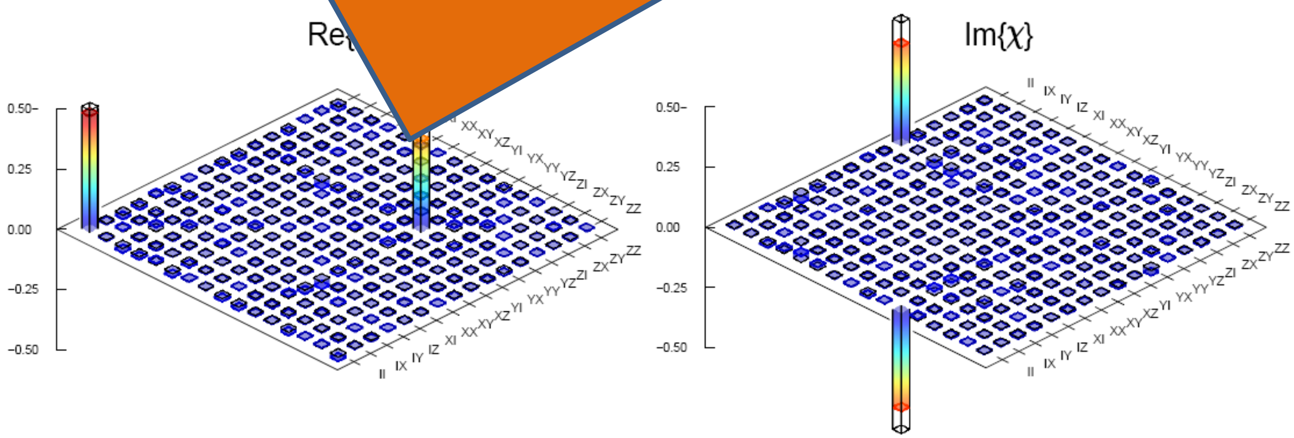
Laser-driven entanglement: Sørensem-Mølmer gate

For 2 ions:
$\mathcal{F} \cong 0.985(10)$



See Poster for details

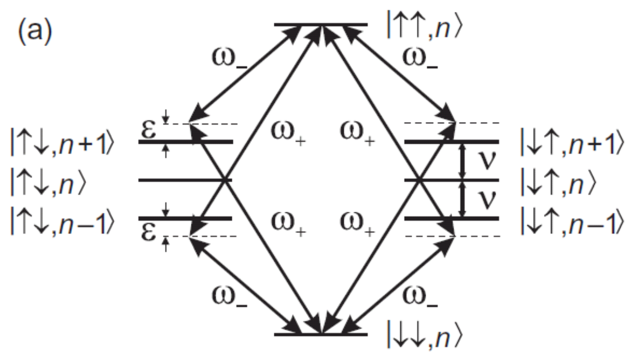
Quantum Process tomograp ... tes



Navon, Akerman, Kotler, Glickman and RO, arXiv:1309.4502 (2013)
Benhelm, Kirchmair, Roos, Blatt, Nature Physics 4, 463 (2008)

Mølmer-Sørensen coupling

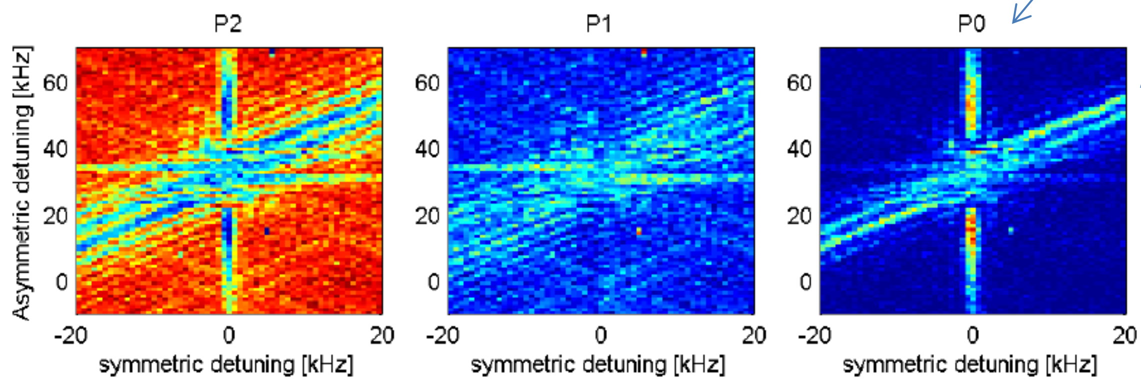
SM coupling



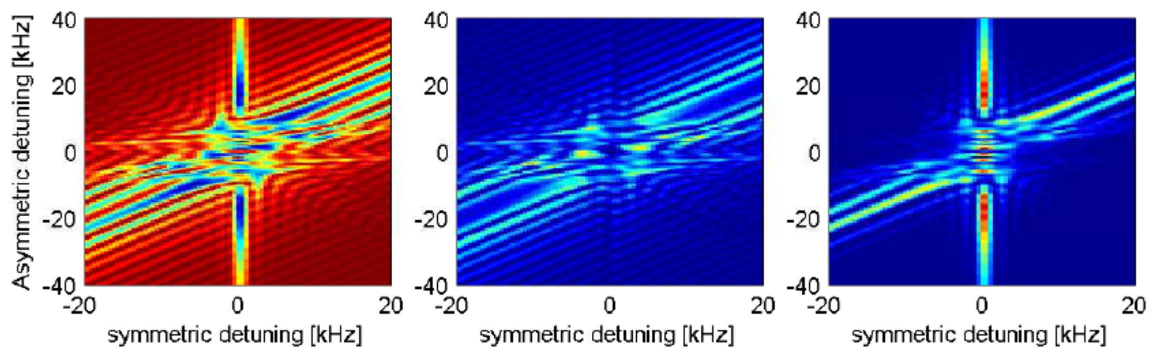
Two-photon spin-spin coupling

BSB

Data:

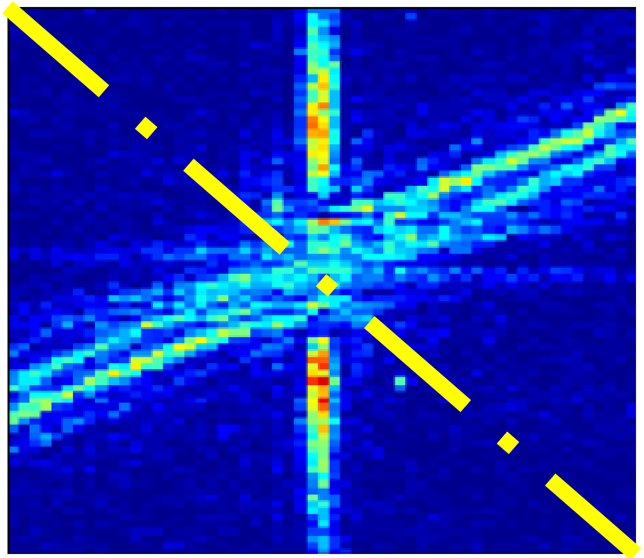


Calculation:



Synthetic dipole-dipole interactions

Union Jack



- **Weak interactions at the μm separation**

  Magnetic ~ mHz; Electric~ 10^{-3} of transition strength

- **Many future prospects**

  Magnetic coupling of excited states – coupled current loops

  Electric Quadrupolar coupling between ions

  Electric dipolar coupling in the quantum regime (multi-photon)

  Etc.

- **Possible error source in large ion arrays**

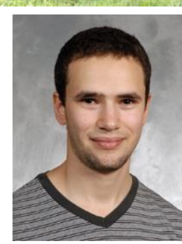
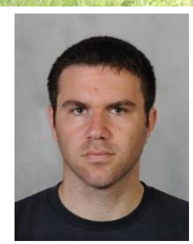
  Quantum computing

  Frequency metrology

Weizmann Institute Trapped-ion group

Open Postdoc and PhD positions at the Weizmann

- Nitzan Akerman
- Yinnon Glickman
- Shlomi Kotler
- Yehonatan Dallal
- Anna Keselman
- Ziv Meir
- Elad Kronstein
- Nir Navon
- Boaz Nissan-Cohen
- Osip Schwartz
- Tomas Sikorsky
- Roy Patael
- Roee Ozeri

ISRAEL SCIENCE FOUNDATION

i-CORE
Israeli Centers of Research Excellence

erc
European Research Council

MINERVA STIFTUNG
Gesellschaft für die Forschung m.b.H.