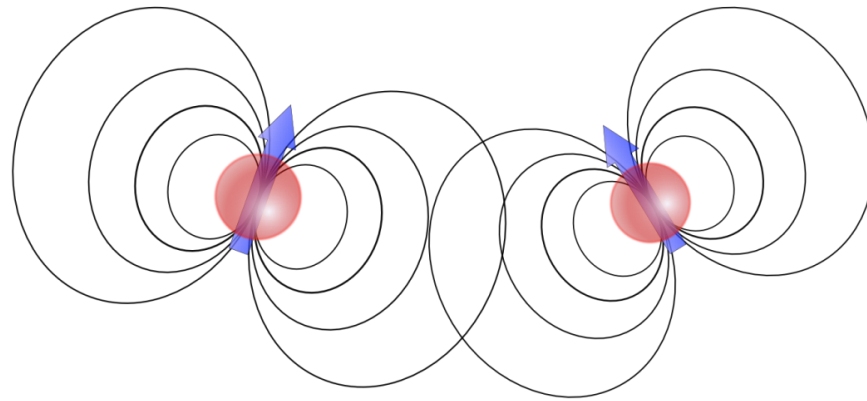


iQsim 2013

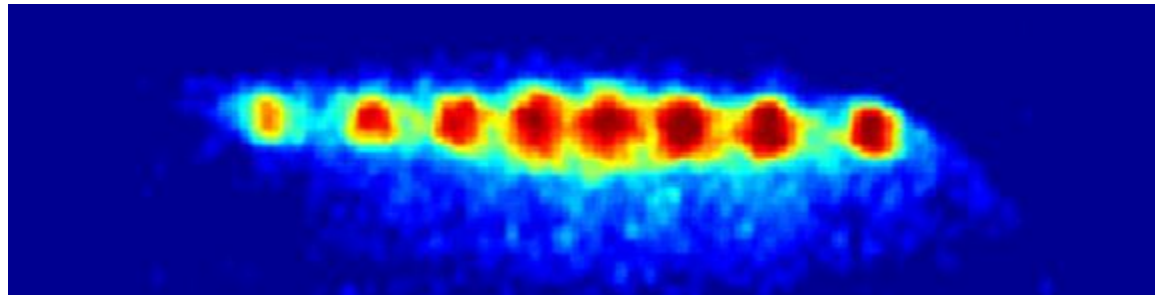
Weak Dipolar interactions in trapped-ion crystals



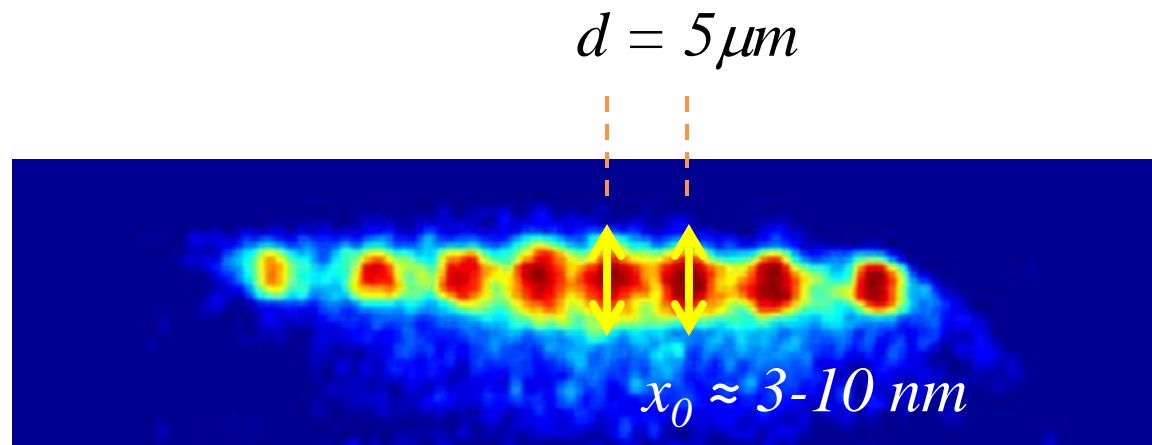
Roe Ozeri
Nitzan Akerman
Shlomi Kotler
Yinnon Glickman
Yehonatan Dallal
Tomas Sikorsky
Boaz Nissan-Cohen

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



- Spin dependent forces

$$x_0 = \sqrt{\frac{\hbar}{2m\omega}}$$

- Dipole moment $\approx 200 ea_0$

- Dipole-dipole interaction: $\hbar\omega_{int} = \frac{e^2}{2\pi\epsilon_0 d^3} x_0^2$

$\approx 10's - 100's \text{ kHz}$

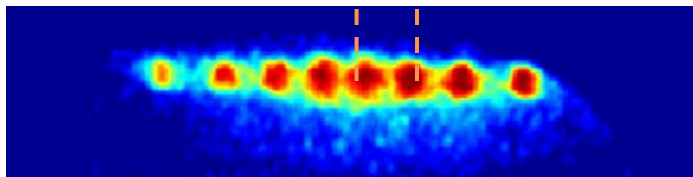


Magnetic spin-spin interactions:

- Magnetic dipole: spin. equivalent $\sim ea_0/137$ $ea_0 = \frac{\mu_B}{\alpha c}$
- Dipole-dipole interaction: $\xi = \mu_0(g\mu_B/2)^2/4\pi\hbar d^3$

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

$$d = 5\mu m$$



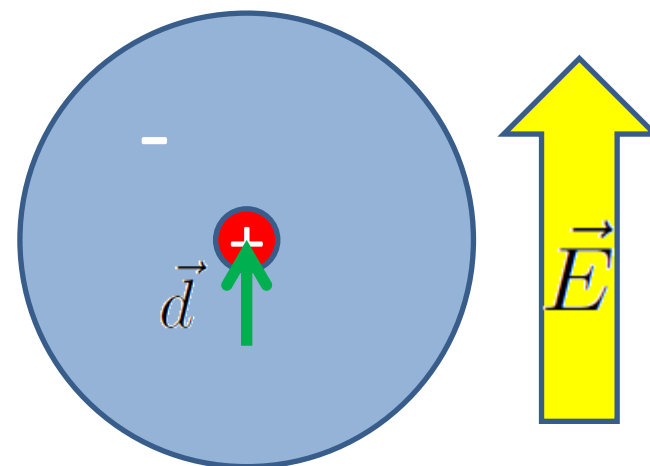
$$\xi/2\pi = 0.1 \text{ mHz}$$

Electric dipole-dipole interactions:

- Eigenstates are symmetric under parity:
no permanent dipole moment
- A field induces a dipole moment:

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

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

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

hydrogen 1 H 1.0079																					helium 2 He 4.0026	
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180					
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948					
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80					
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29					
caesium 55 Cs 132.91	barium 56 Ba 137.33	lanthanum 57 La 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]					
francium 87 Fr [223]	radium 88 Ra [226]	actinium 89 Ac [227]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnium 110 Uun [271]	ununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]									

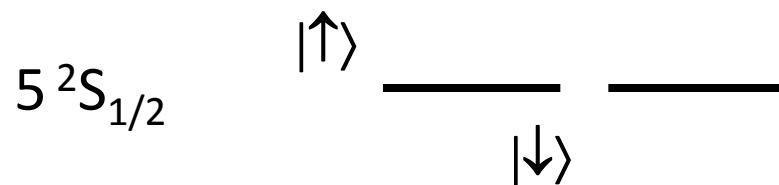
* Lanthanide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

** Actinide series



- 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)



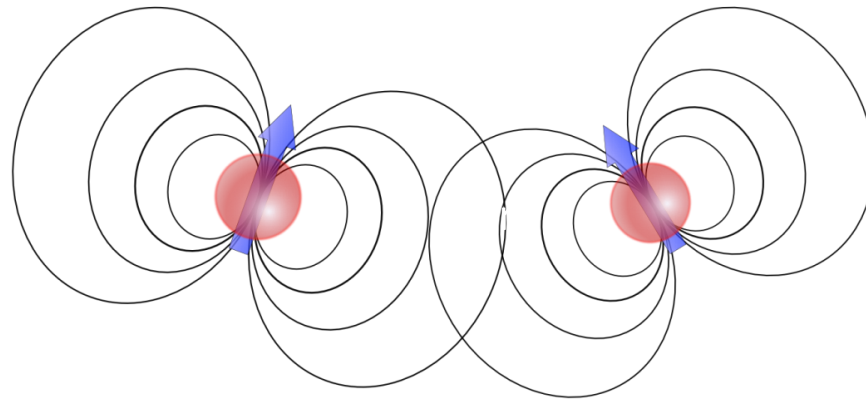
Turn on small B field
2.8 MHz/G



Electronic Spins

$$\vec{B} \parallel \vec{r}$$

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



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

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



Electronic Spins



$$\vec{B} \parallel \vec{r}$$

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

- Conserves $\sigma_{z,1} + \sigma_{z,2}$

$$\underline{|\uparrow\uparrow\rangle}$$

- Eigenstates:

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

$$\underline{4\xi} \updownarrow$$

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

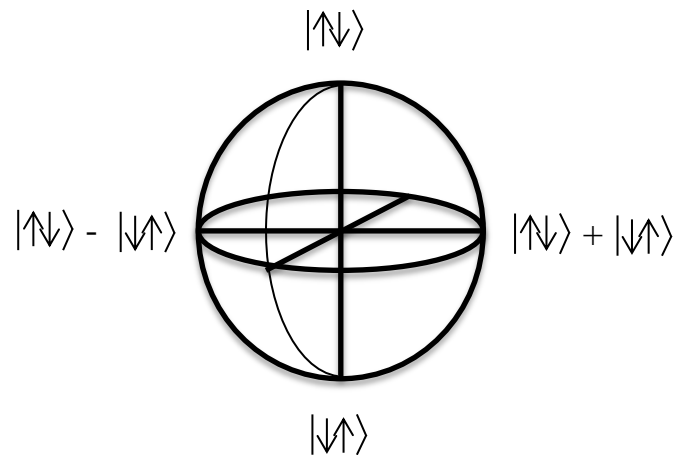
- $(\sigma_{x,1}\sigma_{x,2} + \sigma_{y,1}\sigma_{y,2})$ Remove the degeneracy between $|\Psi_{\pm}\rangle$

$$\underline{|\downarrow\downarrow\rangle}$$

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

$$|\Psi+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2} \quad (\text{triplet; } m=0)$$

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



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

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

Spin-Spin eigenstates:

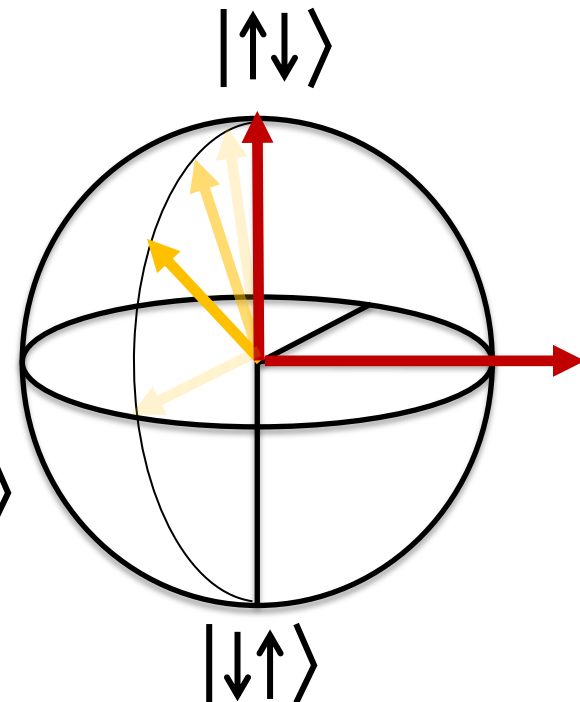
$$|\Psi+\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$$

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




\longleftrightarrow
2.4 μm

$$|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle$$

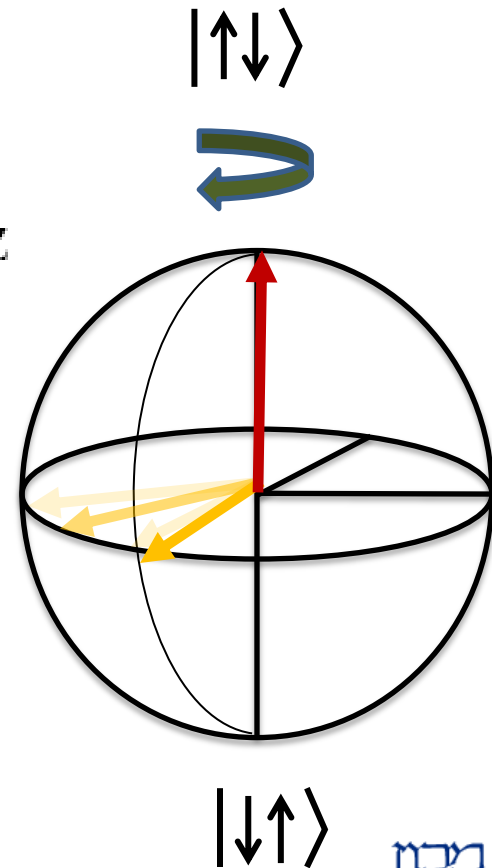


- $\Delta E = 4\xi = 3.8 \text{ mHz} \approx 200 \times 10^{-15} \text{ }^\circ\text{K} \approx 20 \times 10^{-18} \text{ eV}$
- B-field spins apply on each other nGauss; $10^6 <$ than noise

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

 $\Delta\omega_A = (2\pi)20 \text{ mHz}$

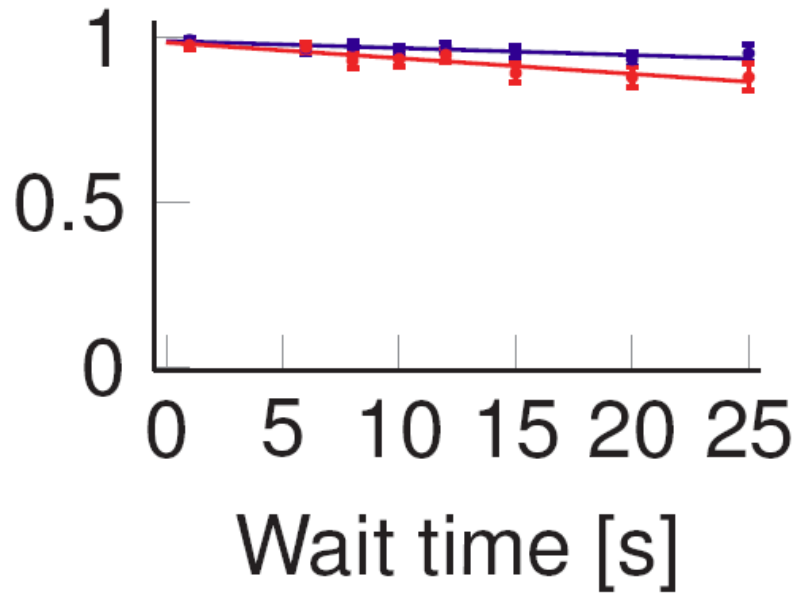
- Still overwhelms spin-spin
- Solution: Spin-Echo pulse-train
(2Hz rep. rate)



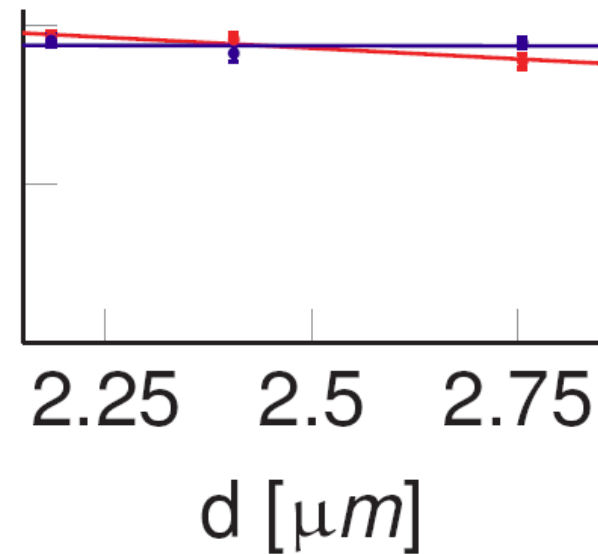
Detection fidelity

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

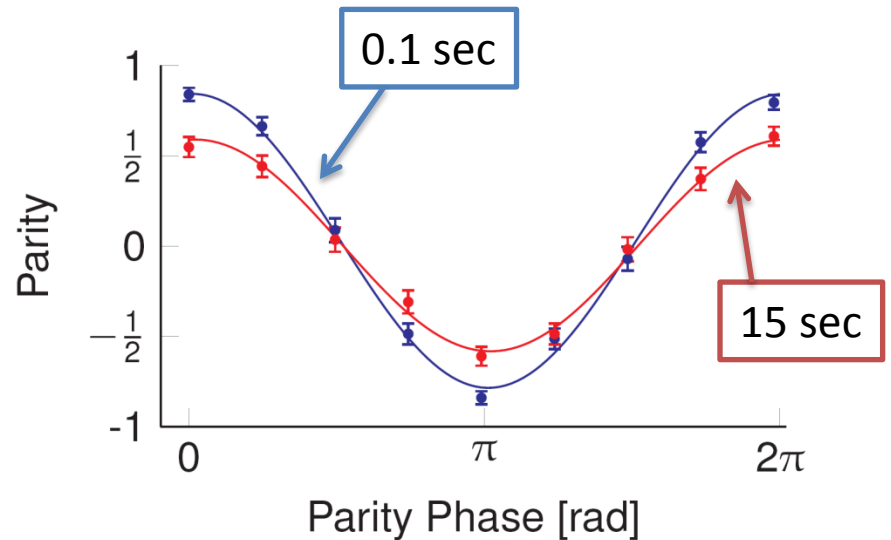
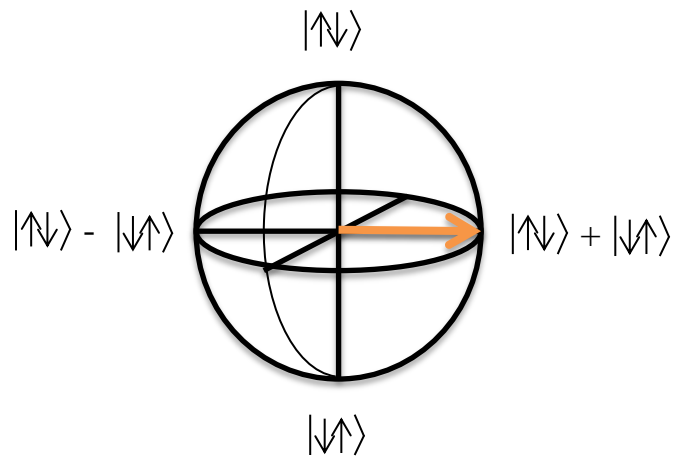
$|\downarrow\downarrow\rangle$ (blue)



@ 2.4 μm



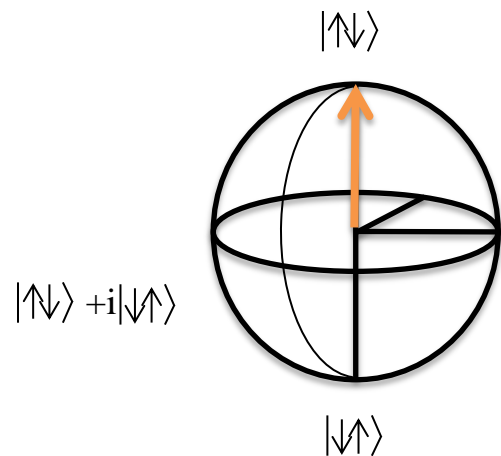
@ 15 sec

Echo coherence in DFS

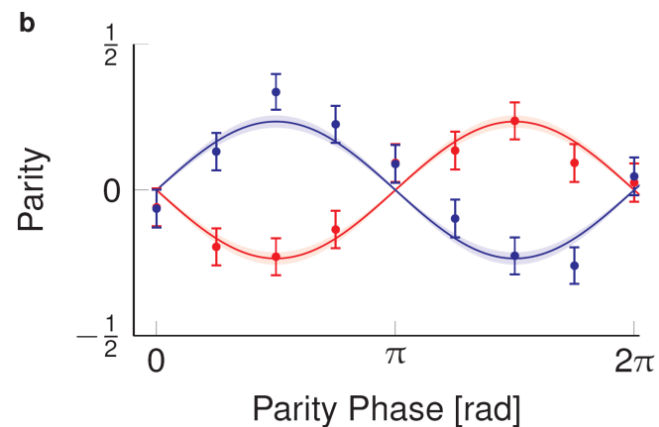
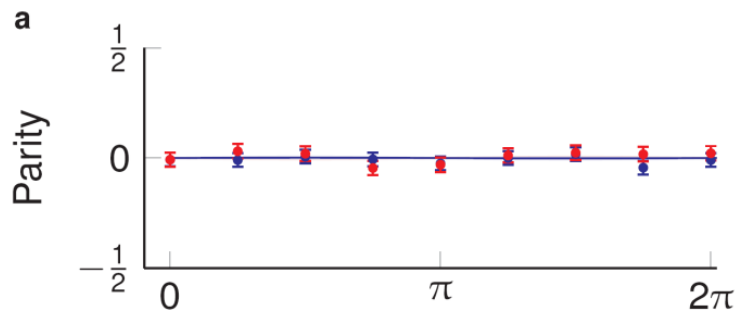
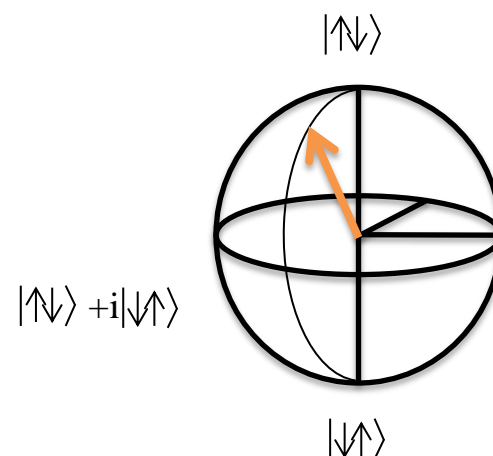
Coherence time = 44 Sec
(Consistent with detection error)



After 0.1 seconds

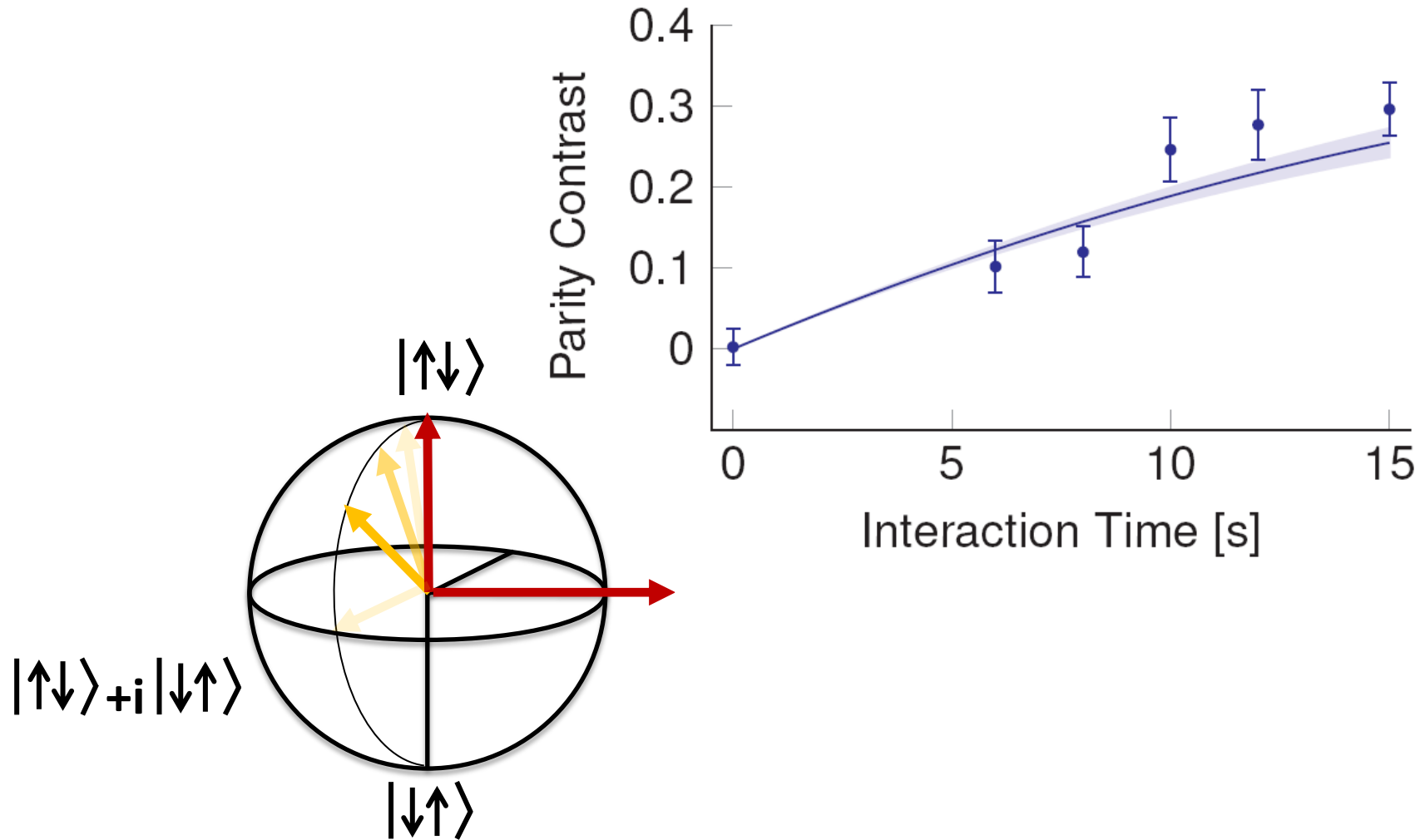


After 15 seconds



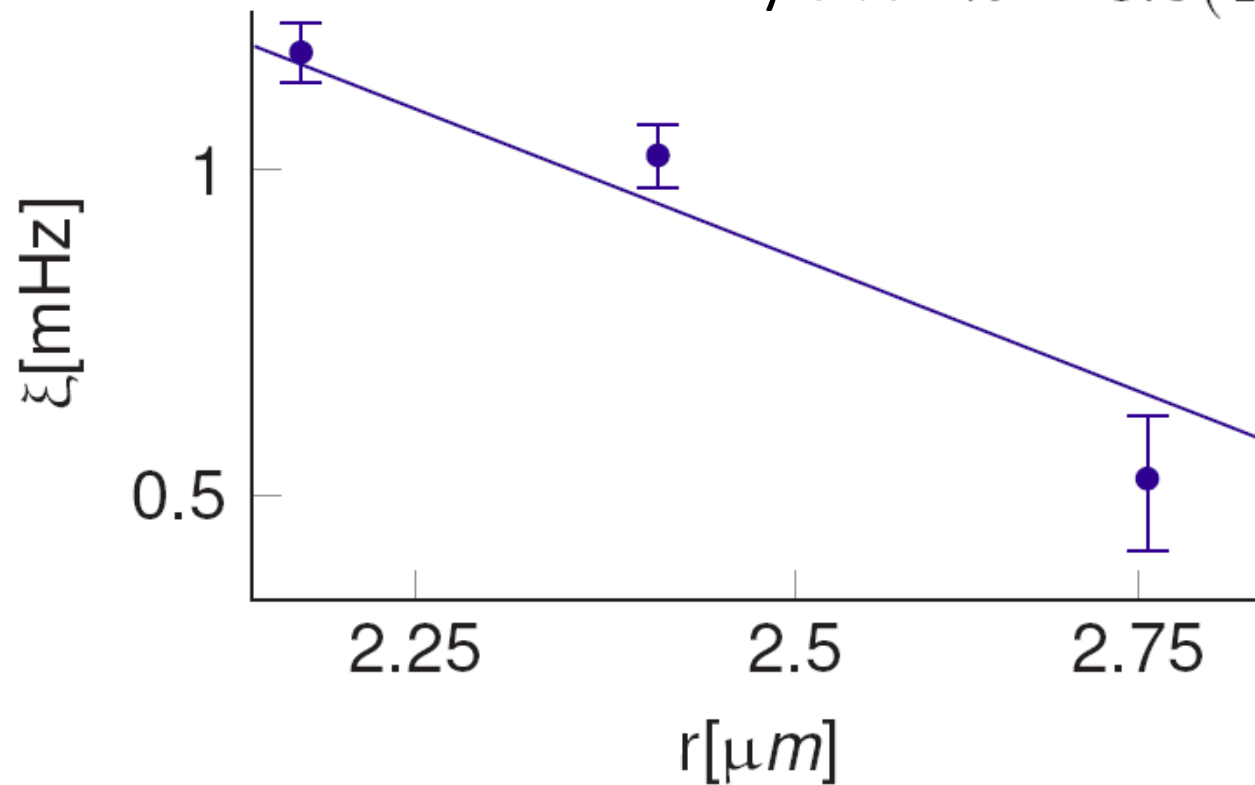
Initializing to: $|\uparrow\downarrow\rangle$ (blue) $|\downarrow\uparrow\rangle$ (red)





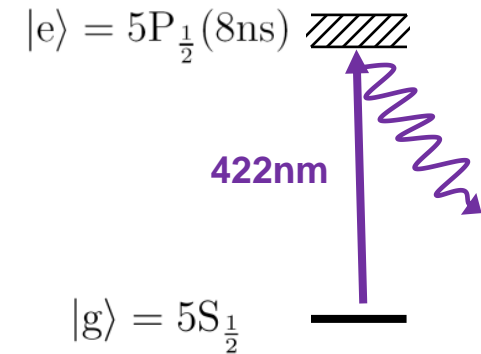
Fit to: $\xi = \mu_0(g\mu_B/2)^2/4\pi\hbar d^n$

yields: $n = 3.0(4)$

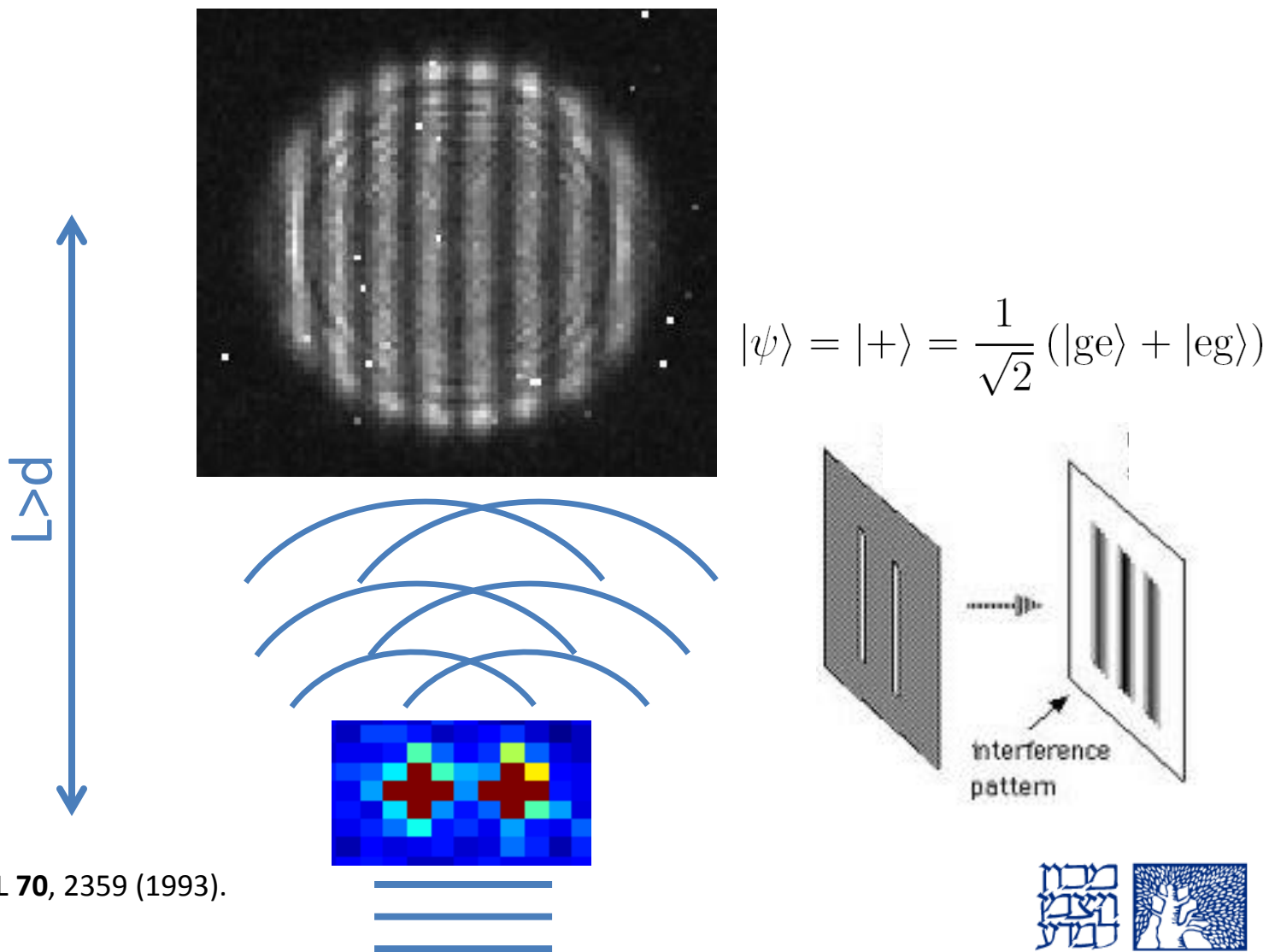


Electric dipole-dipole interactions

- 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)



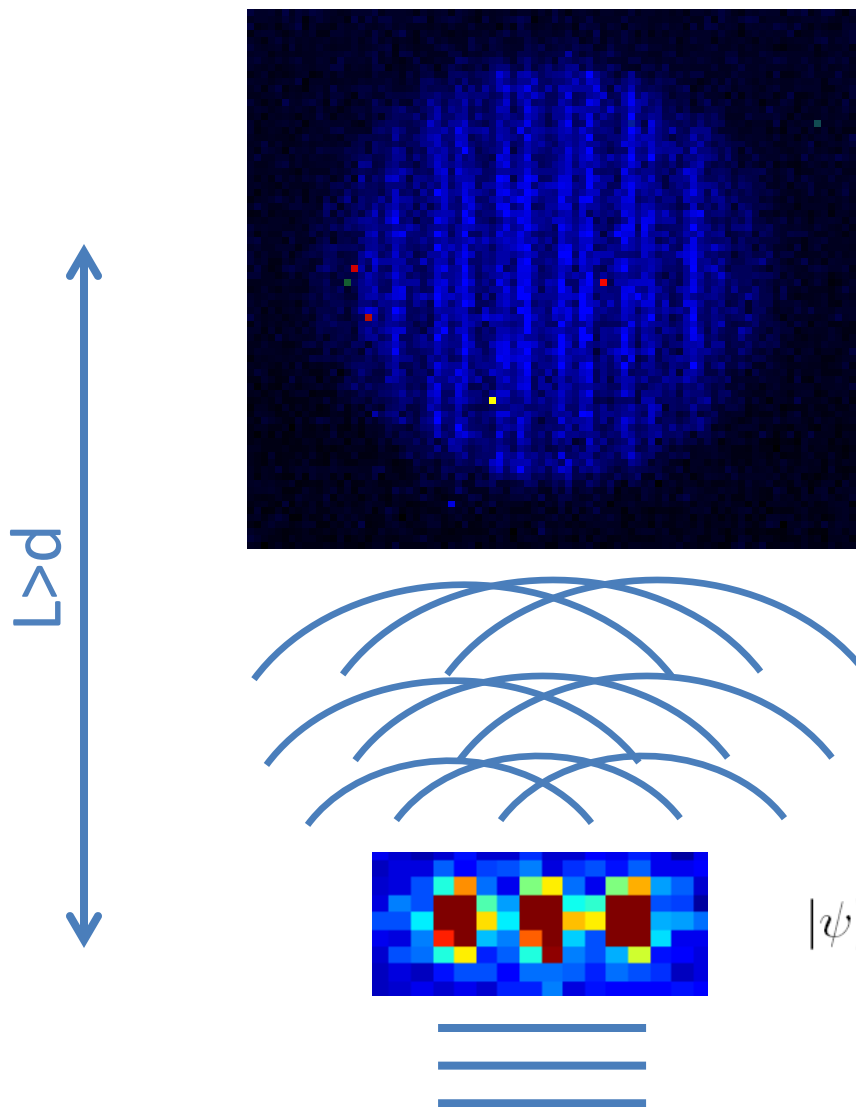
Two-ion far field interference



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

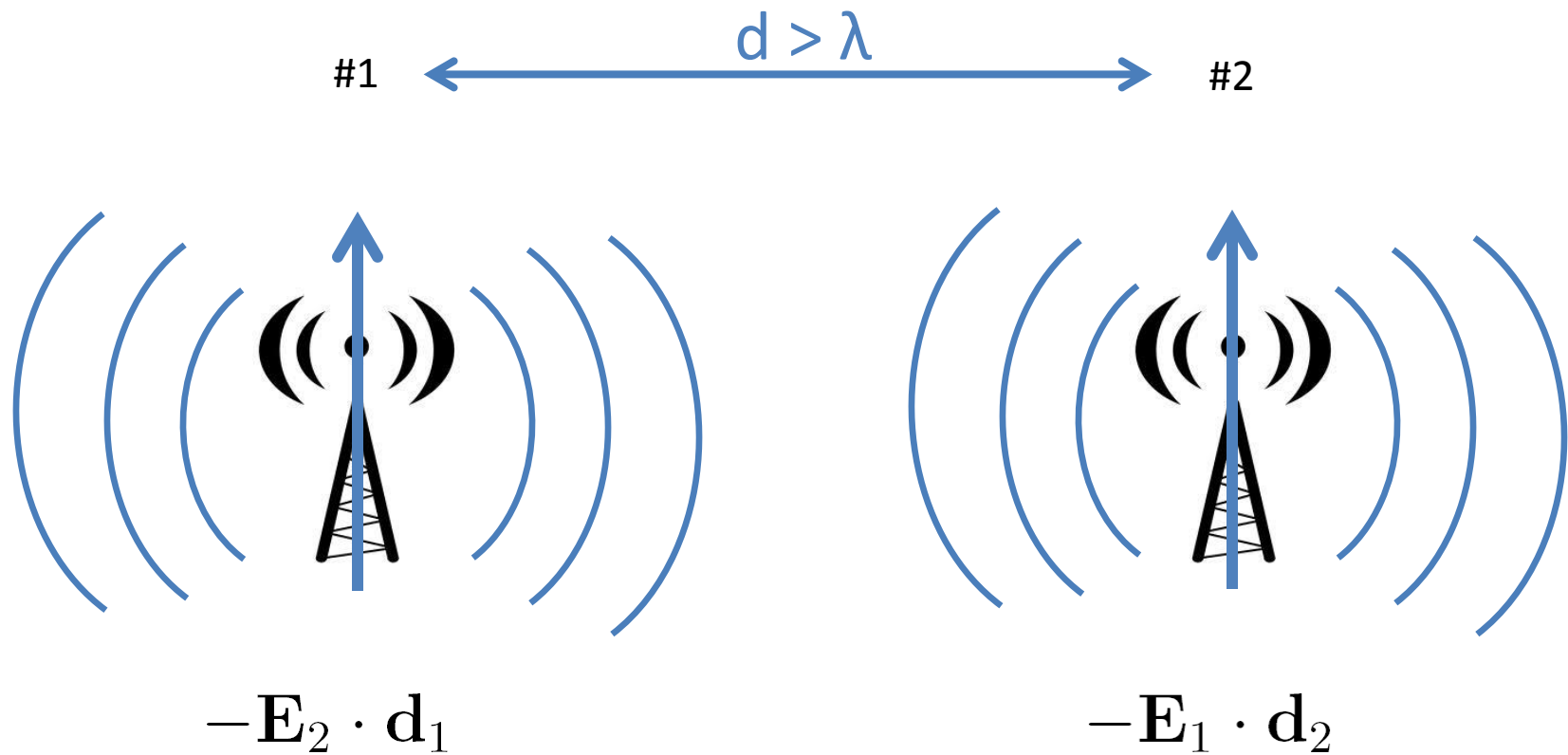


Three-ion far field interference



$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_j |g_1 g_2 \dots e_j \dots g_N\rangle$$





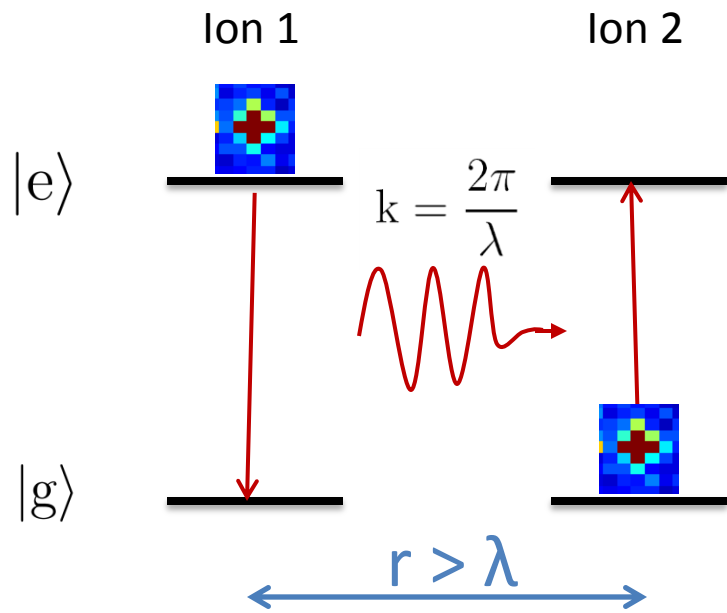
$$\mathbf{E}_{\text{dipole}} \sim \frac{e^{ikr}}{r} \sin(\theta) \hat{\theta}$$

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



Electric dipole-dipole interaction

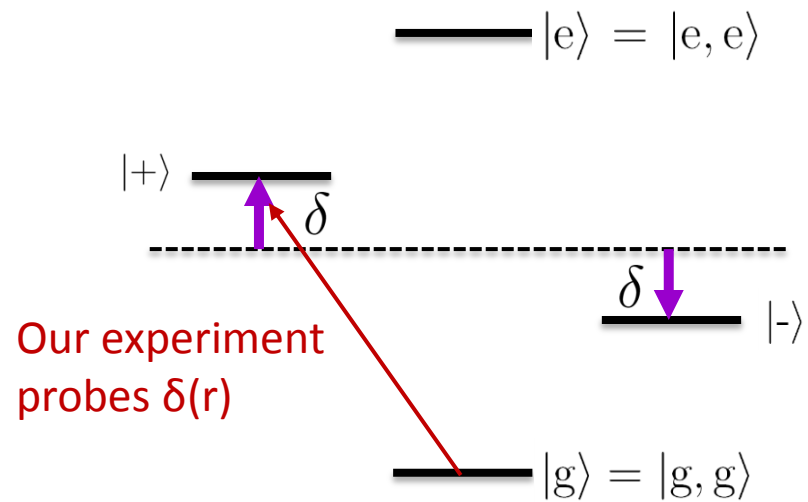
Resonant dipole-dipole interactions

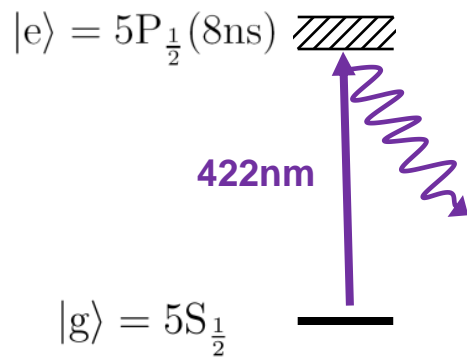


$$\mathbf{E}_{\text{dipole}} \sim \frac{e^{ikr}}{r} \sin(\theta) \hat{\theta}$$

$$\delta = -\frac{3}{8} A_{\uparrow\downarrow} \frac{\cos(kr)}{kr} + O(kr^{-2}).$$

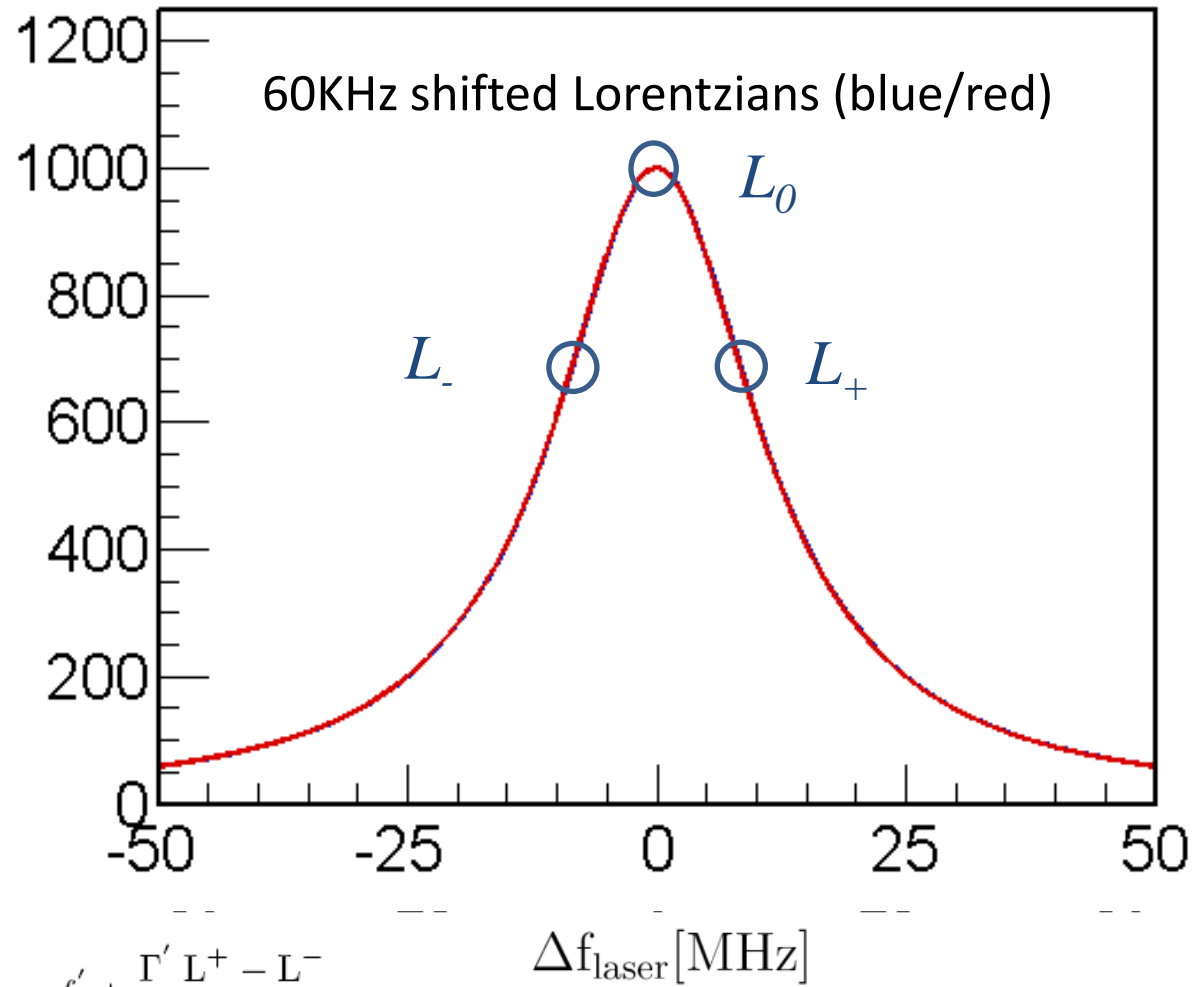
A - Coupling strength



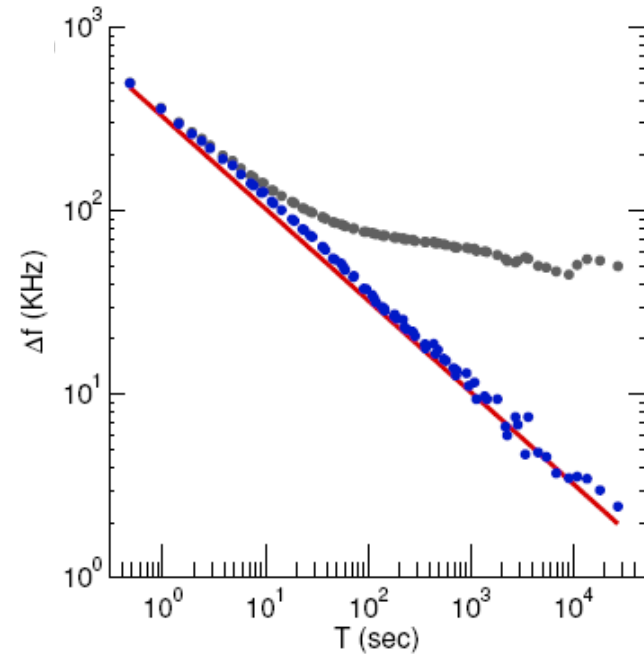
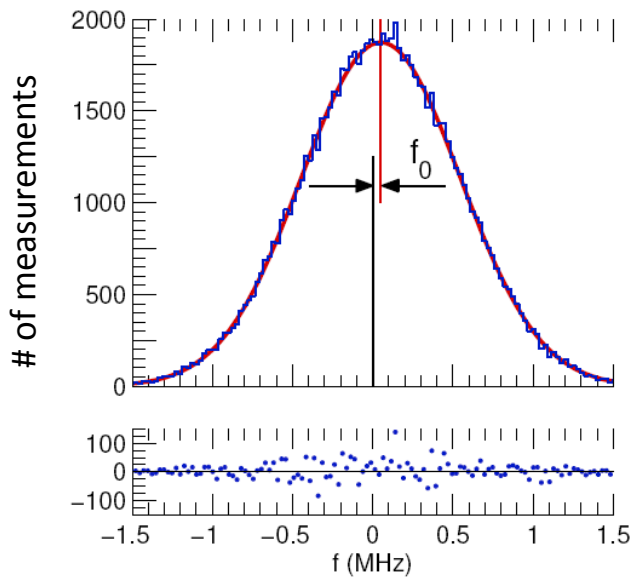


$$L(\nu) = \frac{A}{1 + \left(\frac{\nu - f_0}{\frac{\Gamma}{2}}\right)^2}$$

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



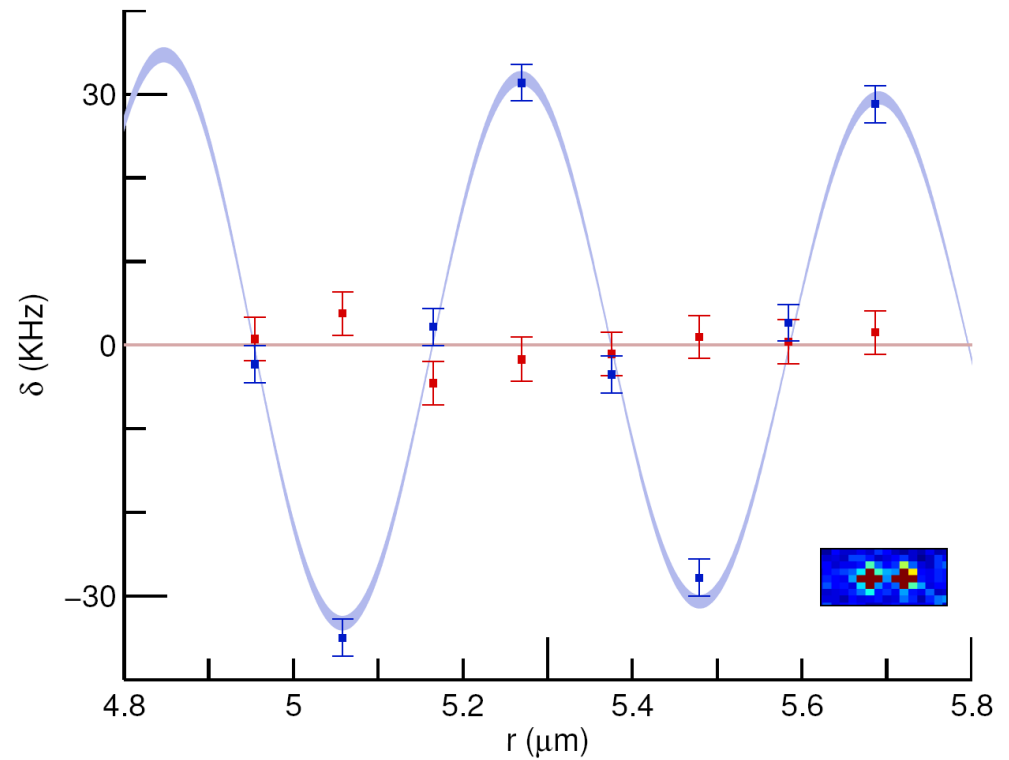
- The transition/laser drifts.
- Interlacing distance points (30 sec per point)
- Few days integration



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



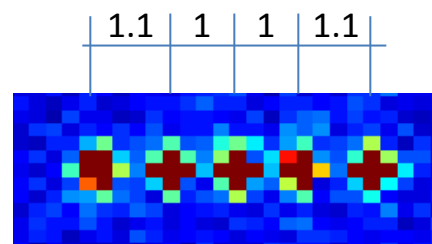
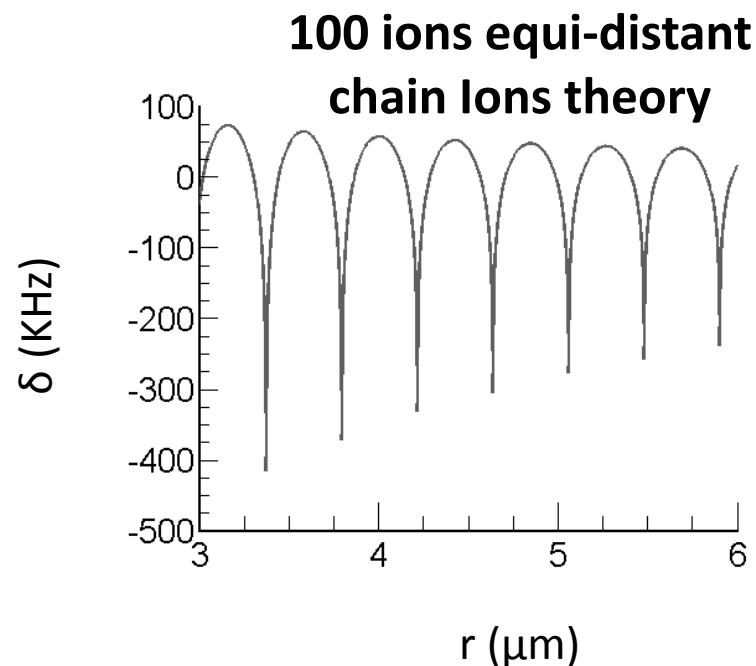
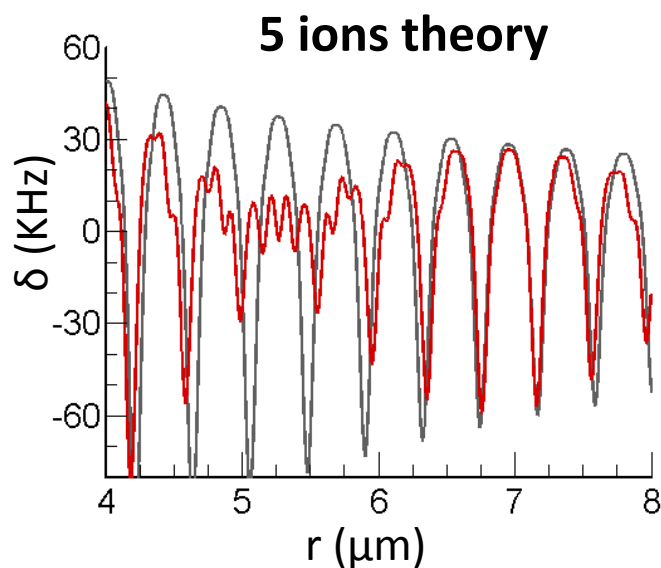
- Light blue – theory (no fit parameters)
- Small effect : 10^{-3} (60KHz)
- Acc. : 10^{-4} (<3KHz)
- Int. time : 8.6 hrs/point,
Almost a week for entire
data set
- Control via polarization



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

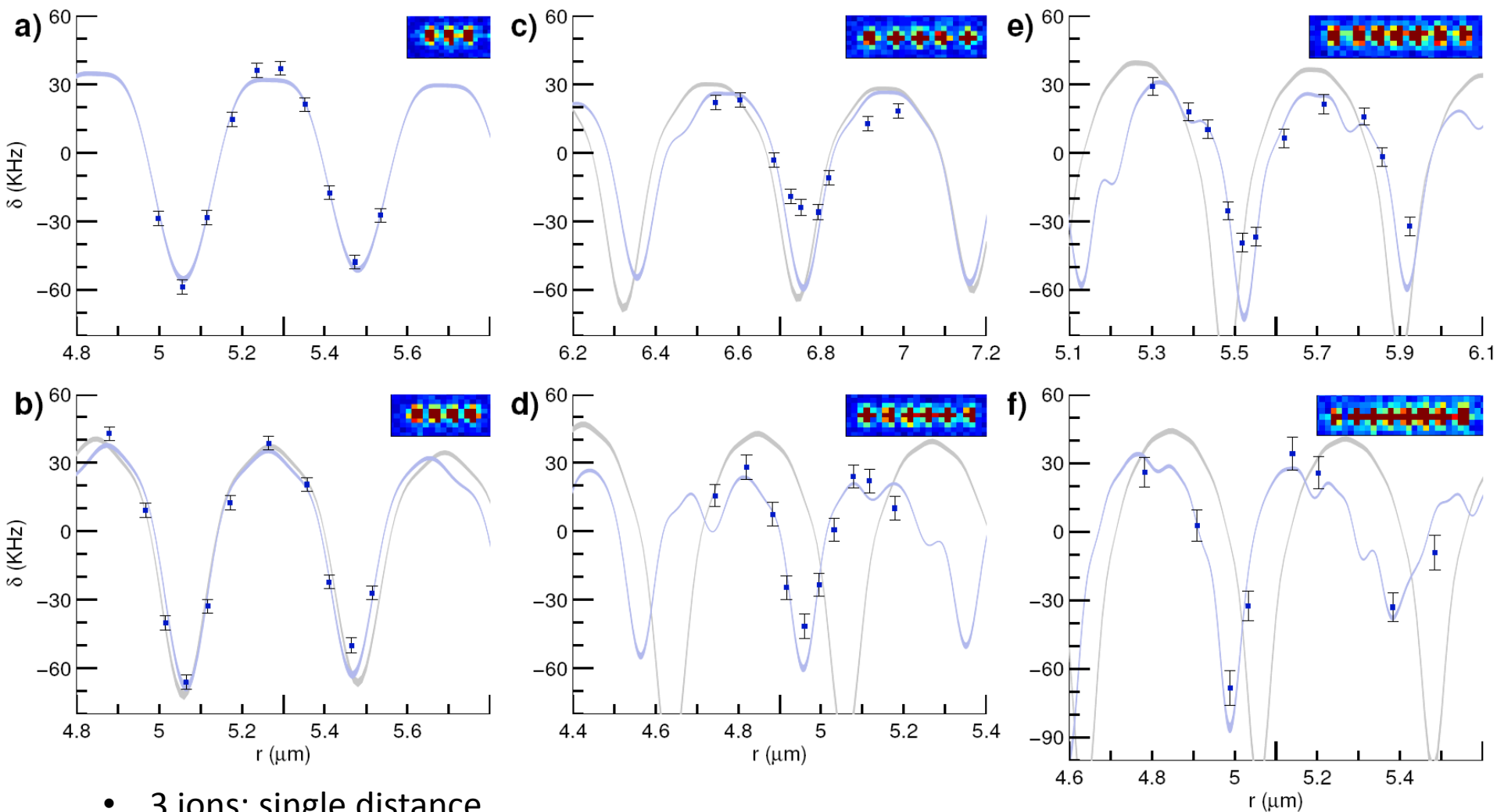
$$\delta_M = \frac{1}{M} \sum_{m \neq n} \delta(r_m - r_n)$$

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



Electric dipole-dipole interaction

Multiple ions experiment



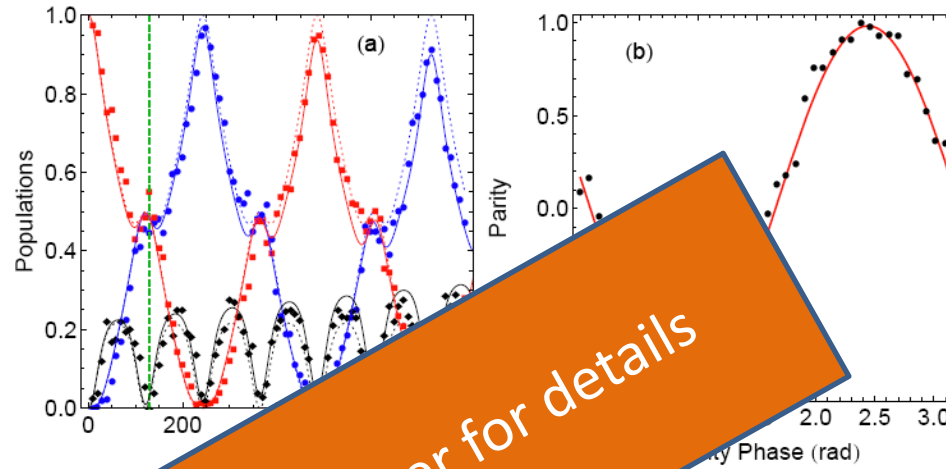
- 3 ions: single distance
- Blue lines: theory with no fit parameters
- Grey lines: equidistant-chain theory



Synthesized dipole-dipole interactions

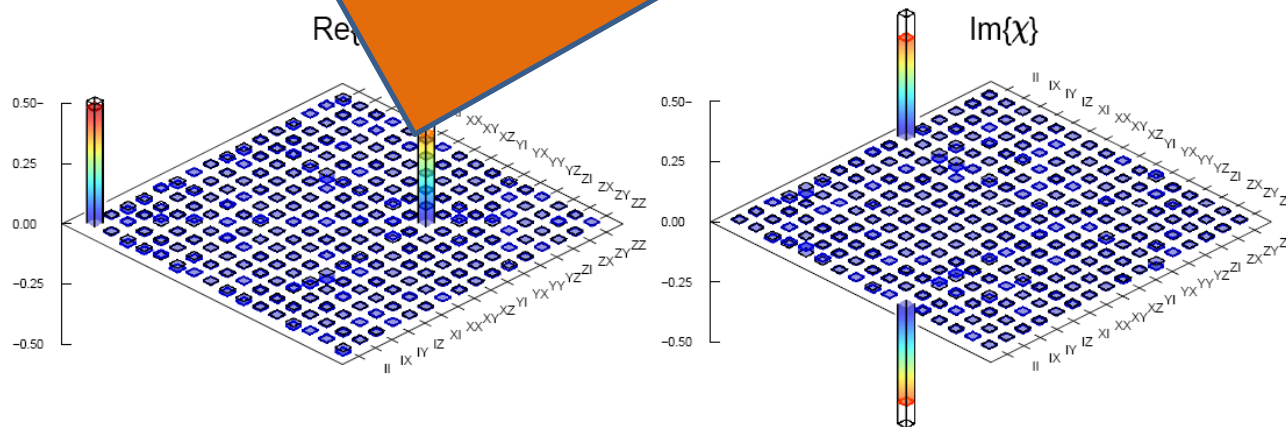
Laser-driven entanglement: Sørensen-Mølmer gate

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



See Poster for details

Quantum Process tomography

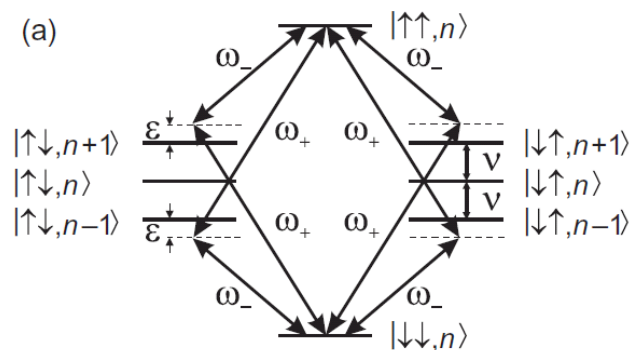


Navon, Akerman, Kotler, Glickman and RO, arXiv:1309.4502 (2013)

Benhelm, Kirchmair, Roos, Blatt, Nature Physics 4, 463 (2008)



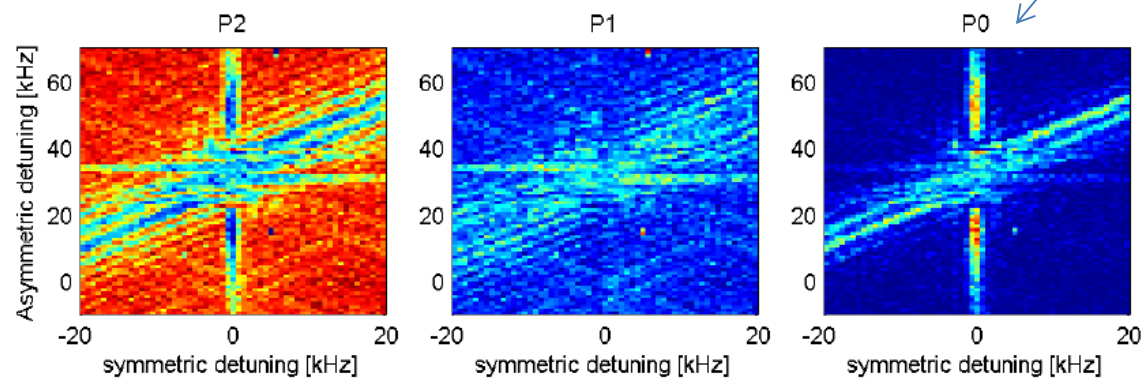
SM coupling



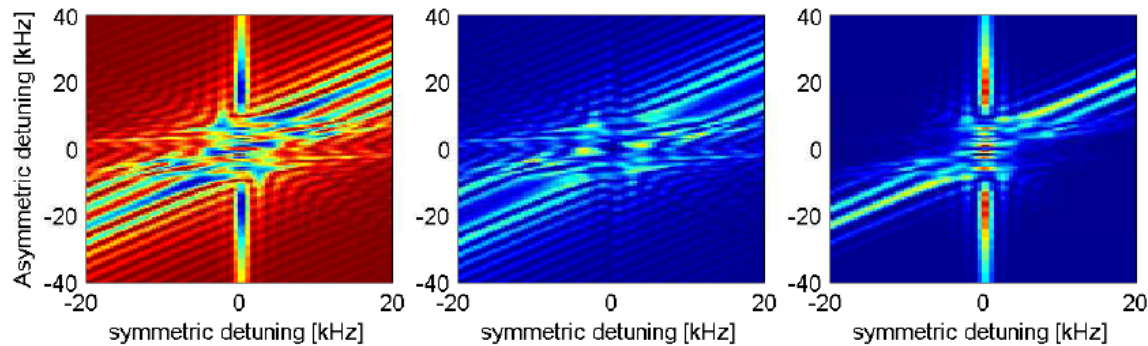
Two-photon spin-spin coupling

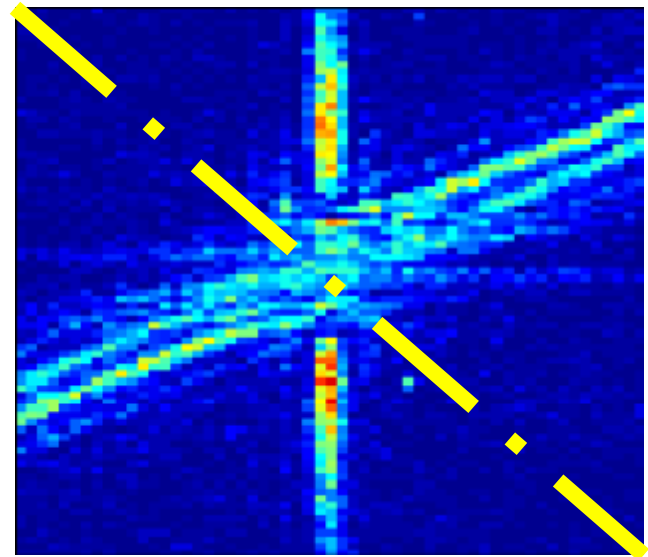
BSB

Data:



Calculation:





↳ Weak dipolar interactions in ion crystals

- **Weak interactions at the μm separation**

Magnetic \sim mHz; Electric $\sim 10^{-3}$ 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

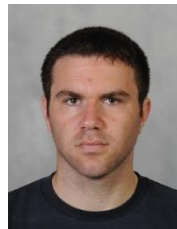
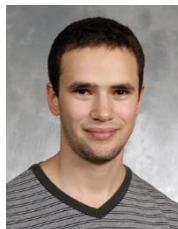
Frequency metrology



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
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