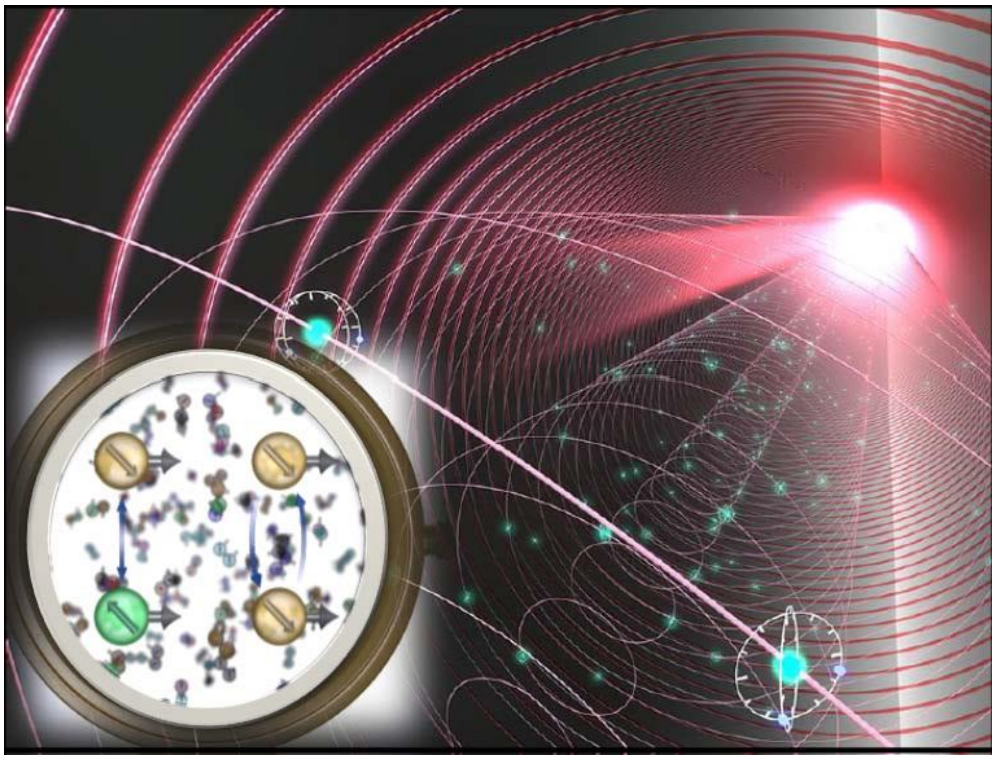
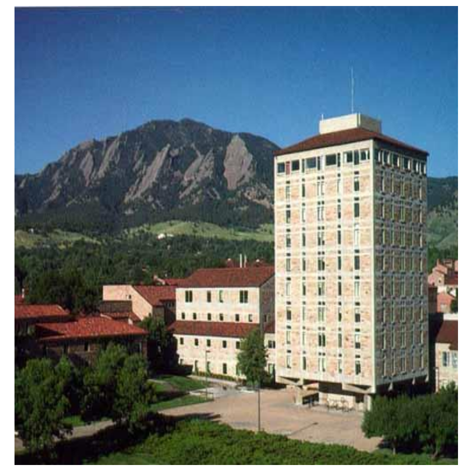
New Perspectives on Quantum Simulation with Alkaline-Earth Atoms

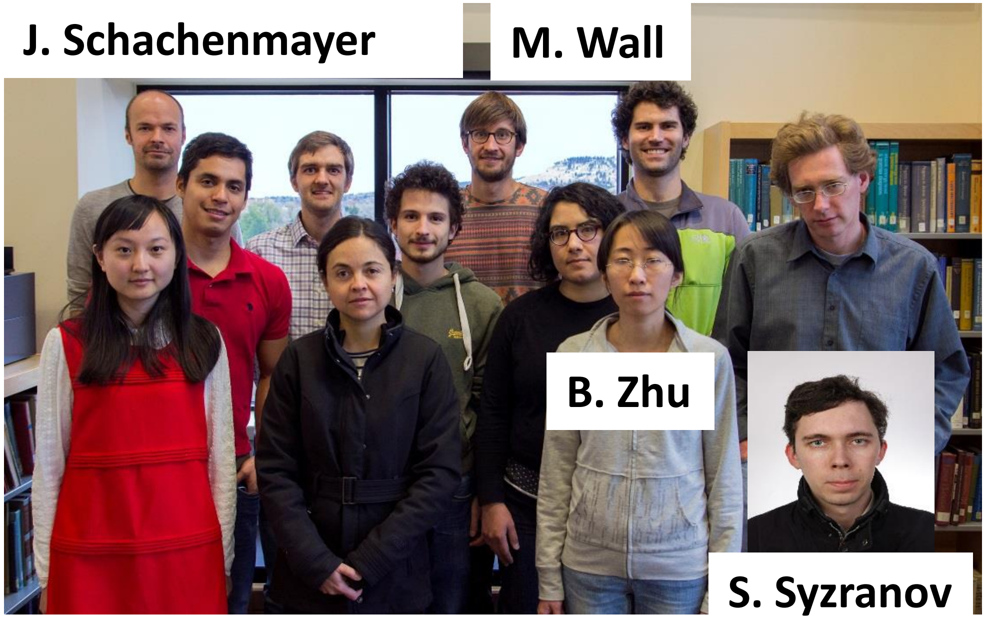
Ana Maria Rey





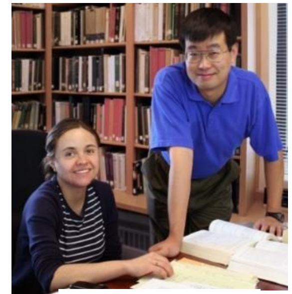
Solvay Workshop on quantum simulation with cold matter and phonons, February 8-11, 2016

Theory:

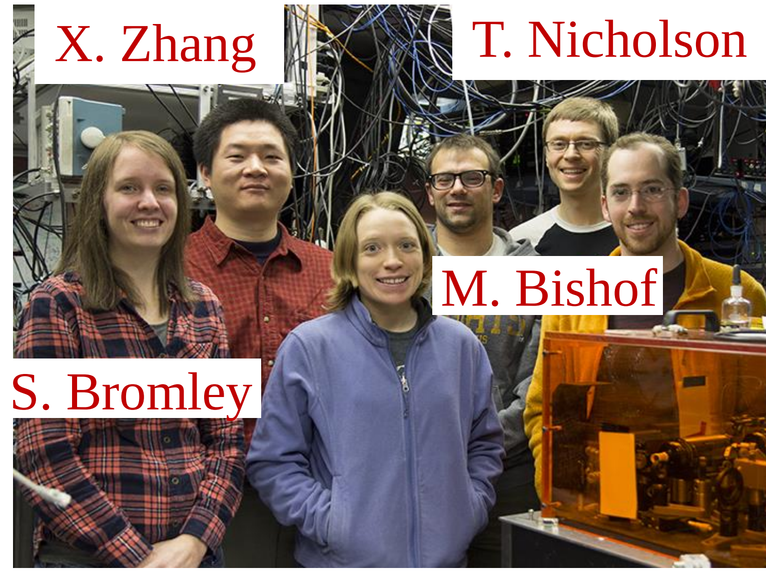


V. Gurarie, R. Kaiser, S. F. Yelin, M. D. Lukin

The JILA Sr team:

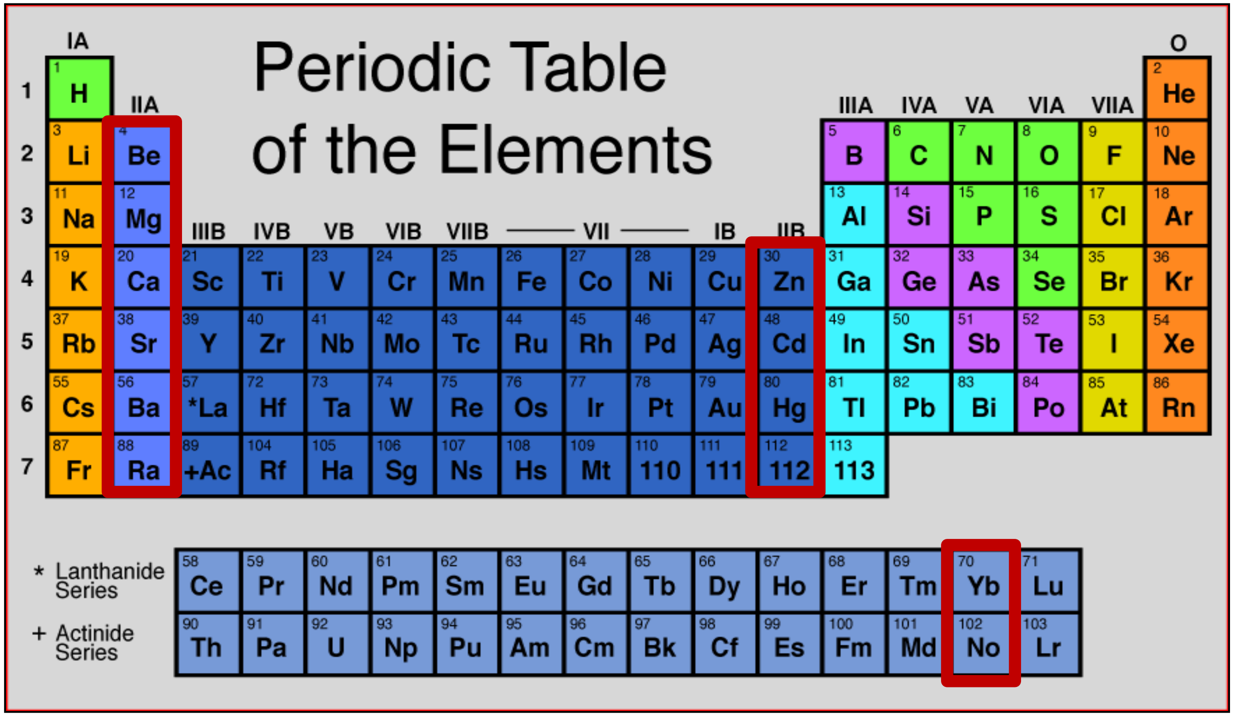


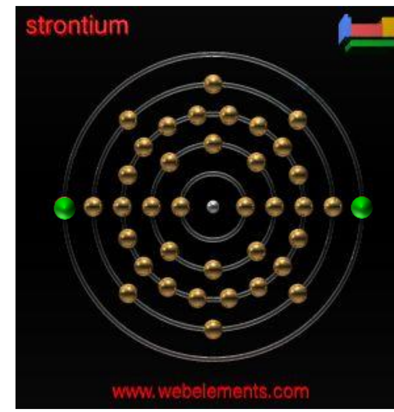
Jun Ye



Alkaline Earth (-like) Atoms: AEA

A TALE OF TWIN ELECTRONS





Can alkaline earth atoms be used in quantum computing?

2007

THANK YOU PETER!!!

Many body physics with clocks ?

Optical AEA Clock

Many-body Physics

Super-coherence

$^3P_0$ (e)

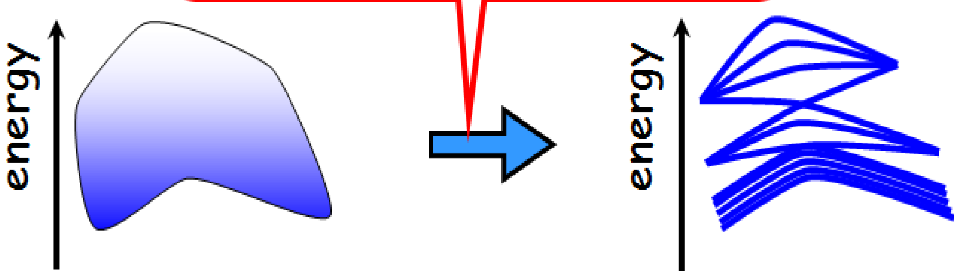
ν_0=5x10^{14} Hz

$^1S_0$ (g)

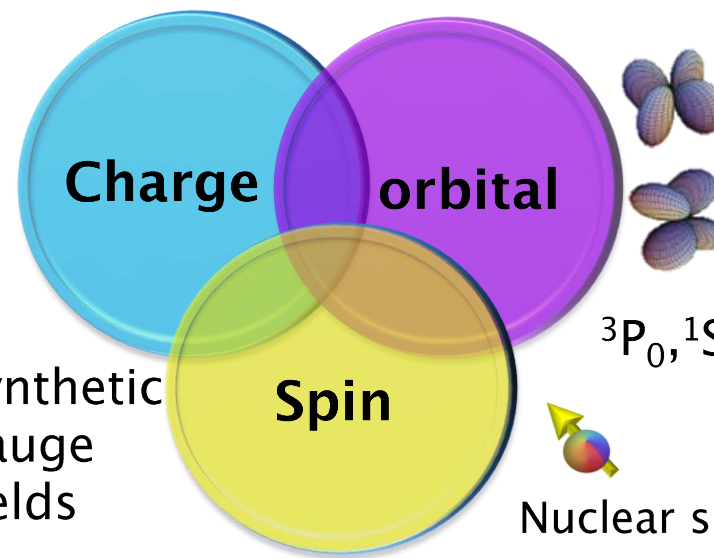
^{87}Sr $\Delta\nu_0$~ mHz

lifetime ~ 10^2 sec

Clock precision = 



Strongly correlated materials



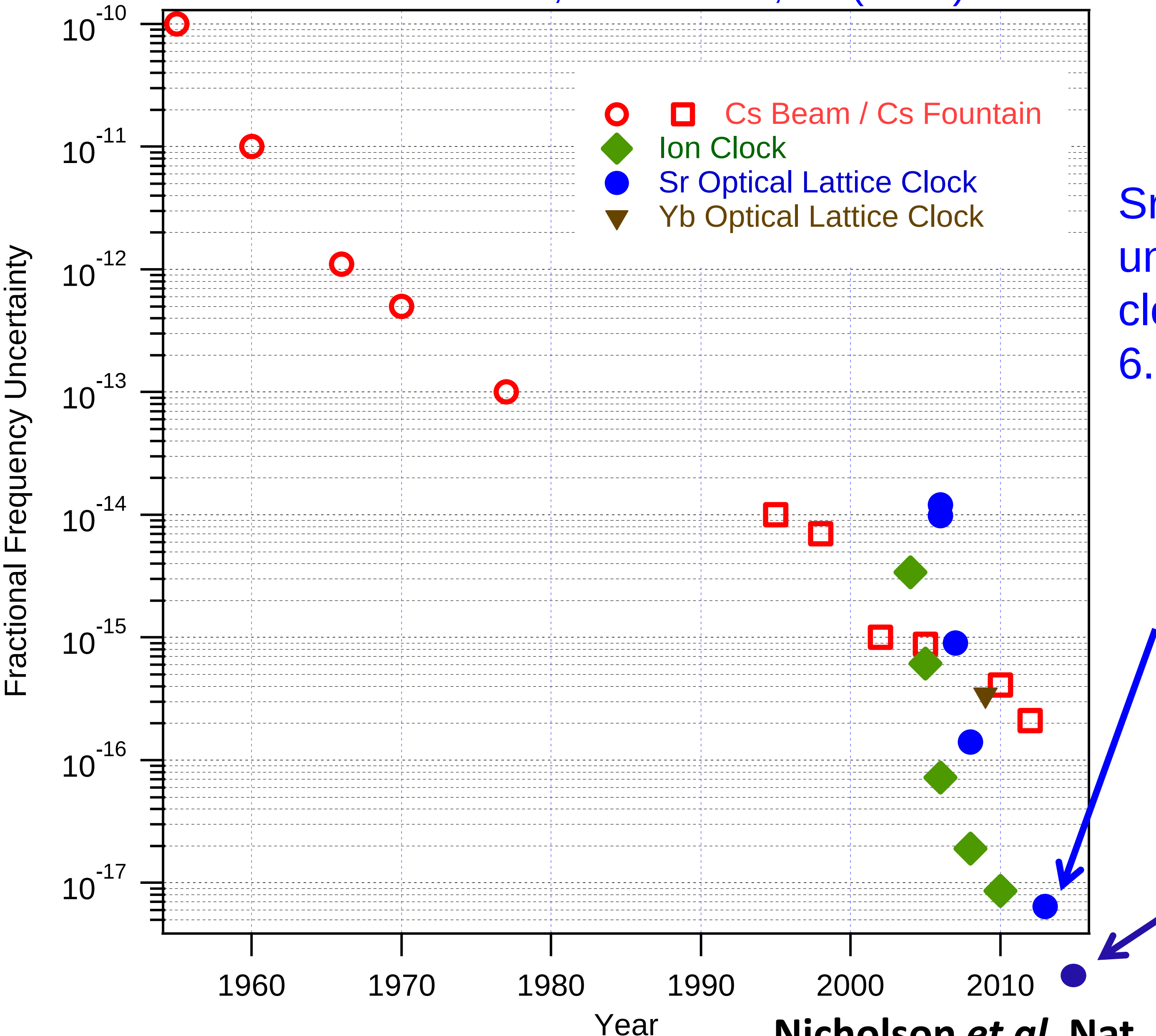
Synthetic gauge fields

$^3P_0$,$^1S_0$

Nuclear spins

A new frontier for clock stability & accuracy

Bloom *et al*., Nature **506**, 71 (2014).



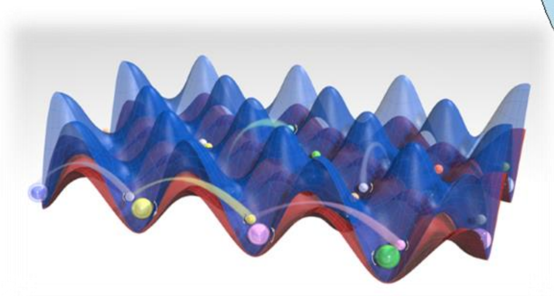
Sr: lowest uncertainty in atomic clocks: 6.4×10^{-18}

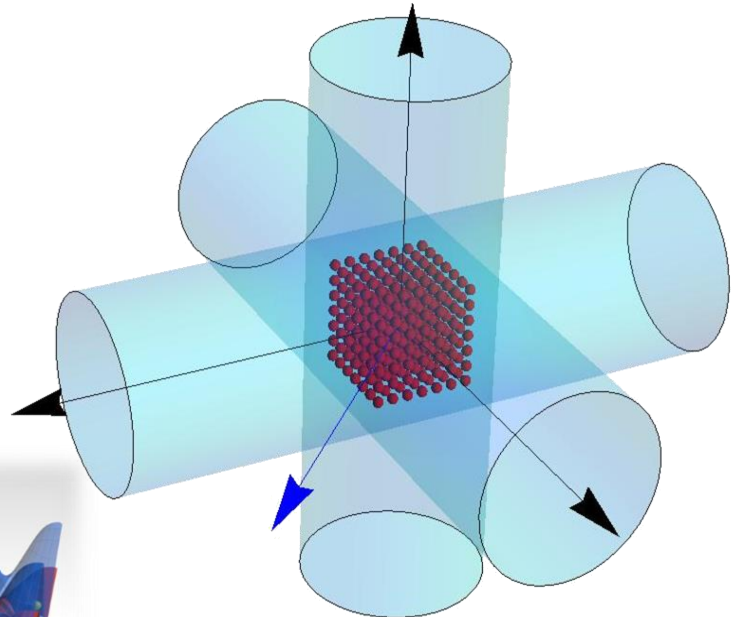
Achieving this 100x faster than other clocks

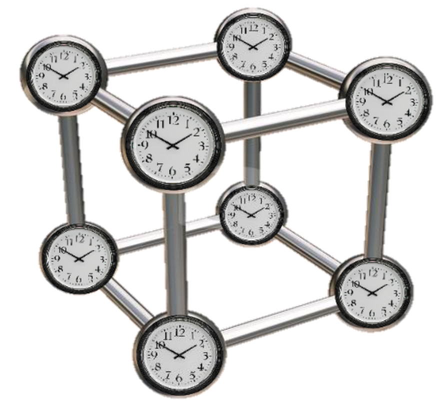
Now: 2.1×10^{-18}

Nicholson *et al*, Nat. Com., 6, 6896(2015)

Band (or Mott) Insulator clock







- For many-body physics
  - Single-site control & manipulation
  - SU(N) two orbital magnetism

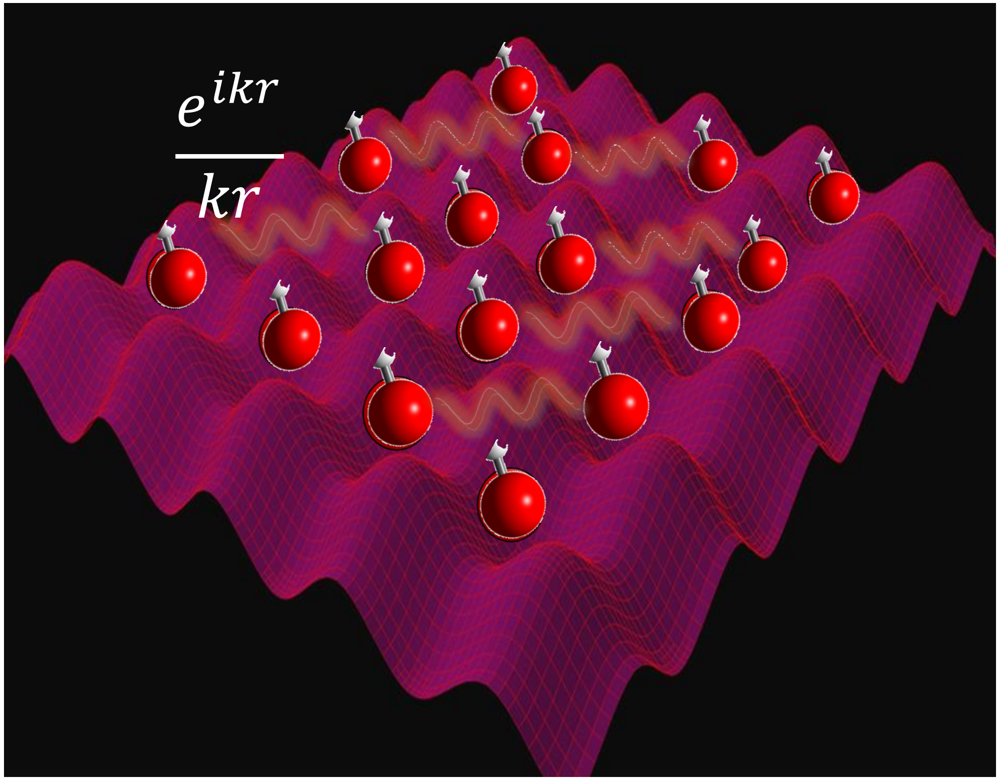
- For metrology
  - High accuracy at highest density
  - All degrees of freedom at quantum level
  - No contact interaction for shifts

But…..

Sr clock: the next systematic uncertainty - collective dipolar couplings

1 – 10 mHz clock shift for a unity filled lattice

(Chang, Ye, Lukin PRL 2004) relevant @10^{-18} sensitivity



Optical dipole moment

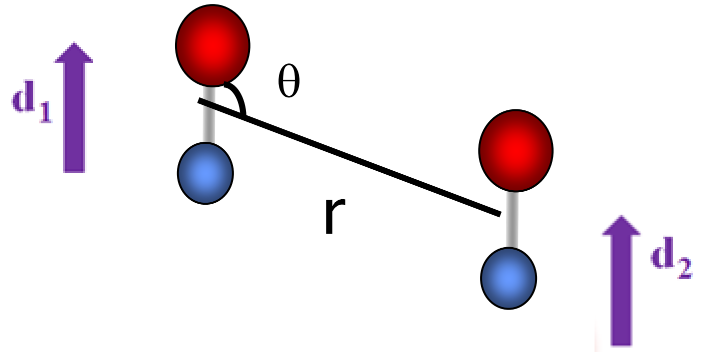
~ 10^{-4} – 10^{-5} Debye

We need to understand long-range dipolar coupling !

Dipole-Dipole Interactions

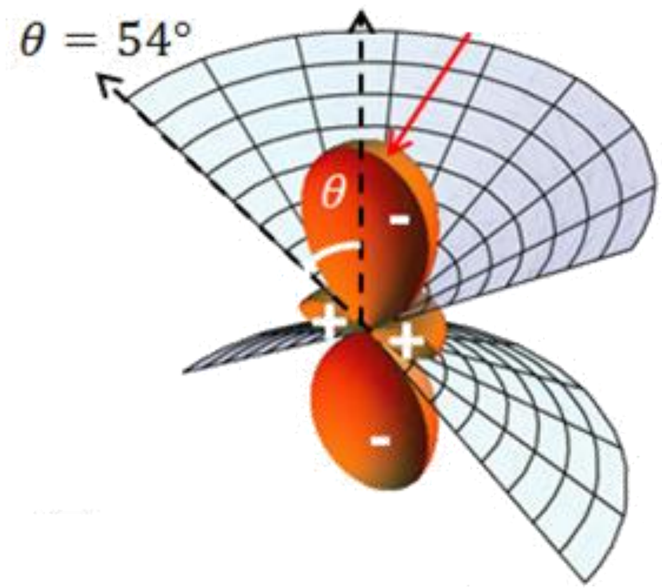
Communication channel dipolar interactions: exchange of virtual photons.

Instantaneous: r « λ elastic



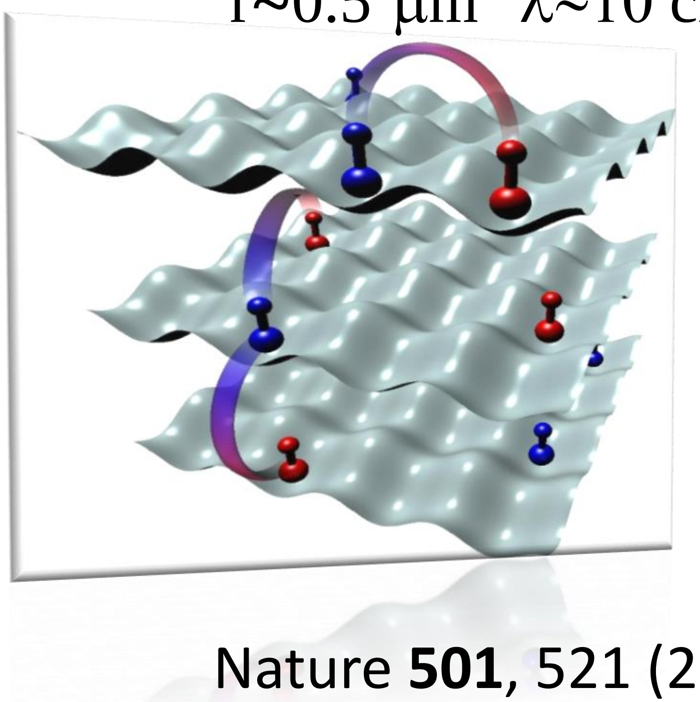
$$H_{dd} = d_1 d_2 V_{dd}^{12}$$

$$V_{dd}^{12} = \frac{(1-3\cos^2\theta\ )}{|r|^3}$$



e.g. rotational states polar molecules

r~0.5 µm λ~10 cm

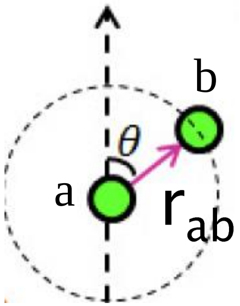


JILA KRb

Nature **501**, 521 (2013).

Radiating Dipoles

Retardation effects need to be consider when: $\zeta_{ab} = k_0 r_{ab} \sim 1$



$$H(\boldsymbol{r}_{ab}) = g(\boldsymbol{r}_{ab}) + \mathrm{i}\, f(\boldsymbol{r}_{ab})$$

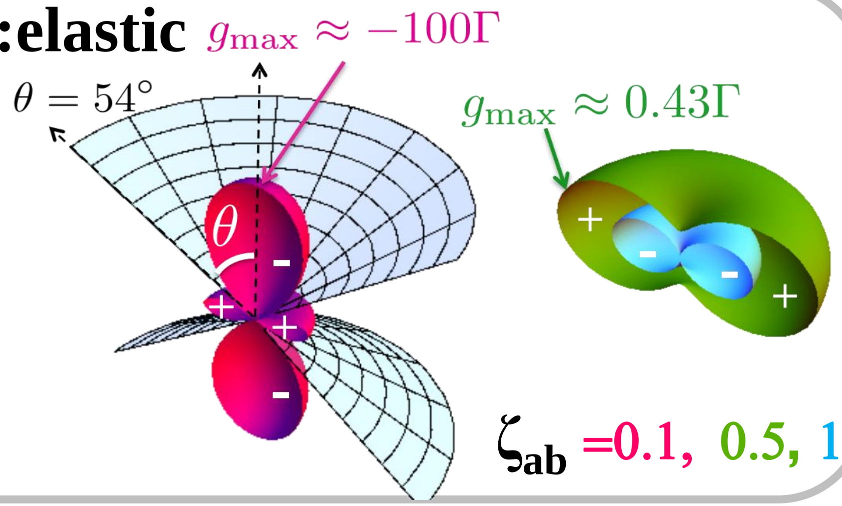
$$g(\mathbf{r}_{ab}) = -\frac{3\Gamma_0}{2}\left\{\sin^2\theta\frac{\cos\zeta_{ab}}{\zeta_{ab}} + (3\cos^2\theta - 1)\left[\frac{\cos\zeta_{ab}}{(\zeta_{ab})^3} + \frac{\sin\zeta_{ab}}{(\zeta_{ab})^2}\right]\right\}$$

$$f(\mathbf{r}_{ab}) = \frac{3\Gamma_0}{2}\left\{\sin^2\theta\frac{\sin\zeta_{ab}}{\zeta_{ab}} + (3\cos^2\theta - 1)\left[\frac{\sin\zeta_{ab}}{(\zeta_{ab})^3} - \frac{\cos\zeta_{ab}}{(\zeta_{ab})^2}\right]\right\},$$

Natural linewidth $\Gamma_0 = \dfrac{k_0^3 d^2}{3\pi\hbar\epsilon_0}$

k_0: photon wave-vector
d: dipole moment

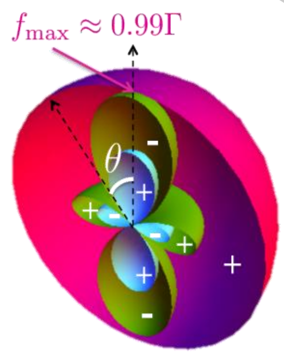
g:elastic



ζ_{ab} =0.1, 0.5, 1

f: Inelastic

superradiance



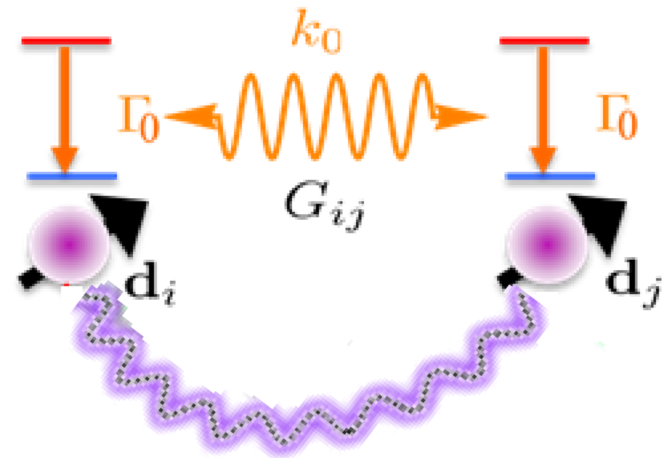
ζ_{ab} =0.1, 0.5, 1

Dipolar Interactions

$$G_{ij} = \frac{3\Gamma_0}{4}[(\hat{\mathbf{d}}_i \cdot \hat{\mathbf{d}}_j)A_{ij}(r) + (\hat{\mathbf{d}}_i \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_j \cdot \hat{\mathbf{r}})B_{ij}(r)]$$

$$A_{ij}(r) = -\frac{e^{ik_0 r}}{k_0 r} - i\frac{e^{ik_0 r}}{k_0^2 r^2} + \frac{e^{ik_0 r}}{k_0^3 r^3}$$

$$B_{ij}(r) = \frac{e^{ik_0 r}}{k_0 r} + 3i\frac{e^{ik_0 r}}{k_0^2 r^2} - 3\frac{e^{ik_0 r}}{k_0^3 r^3}$$



--Include both elastic and dissipative interactions

--Include near-field and far-field interactions:

- near-field physics $k_0 r \ll 1$ $A(r),B(r) \rightarrow \frac{1}{k_0^3 r^3}$ Microwave transitions

- far-field physics $k_0 r \gg 1$ $A(r),B(r) \rightarrow \rightarrow \frac{e^{ik_0 r}}{k_0 r}$ Optical transitions

Radiating Dipoles

$$G_{ij} = \frac{3\Gamma_0}{4}\left[(\hat{\mathbf{d}}_i \cdot \hat{\mathbf{d}}_j)A_{ij}(r) + (\hat{\mathbf{d}}_i \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_j \cdot \hat{\mathbf{r}})B_{ij}(r)\right]$$

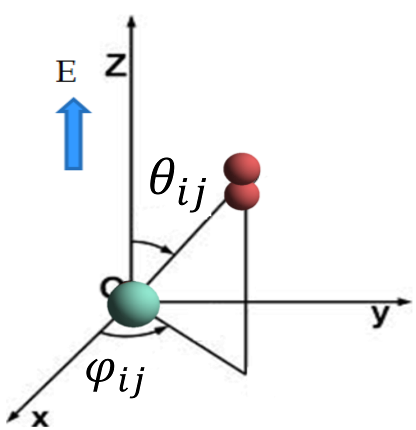
$$\hat{\mathbf{d}}_i^{\pm} = \mp\left(\frac{\hat{\mathbf{d}}_i^{x} \pm i\hat{\mathbf{d}}_i^{y}}{\sqrt{2}}\right)$$

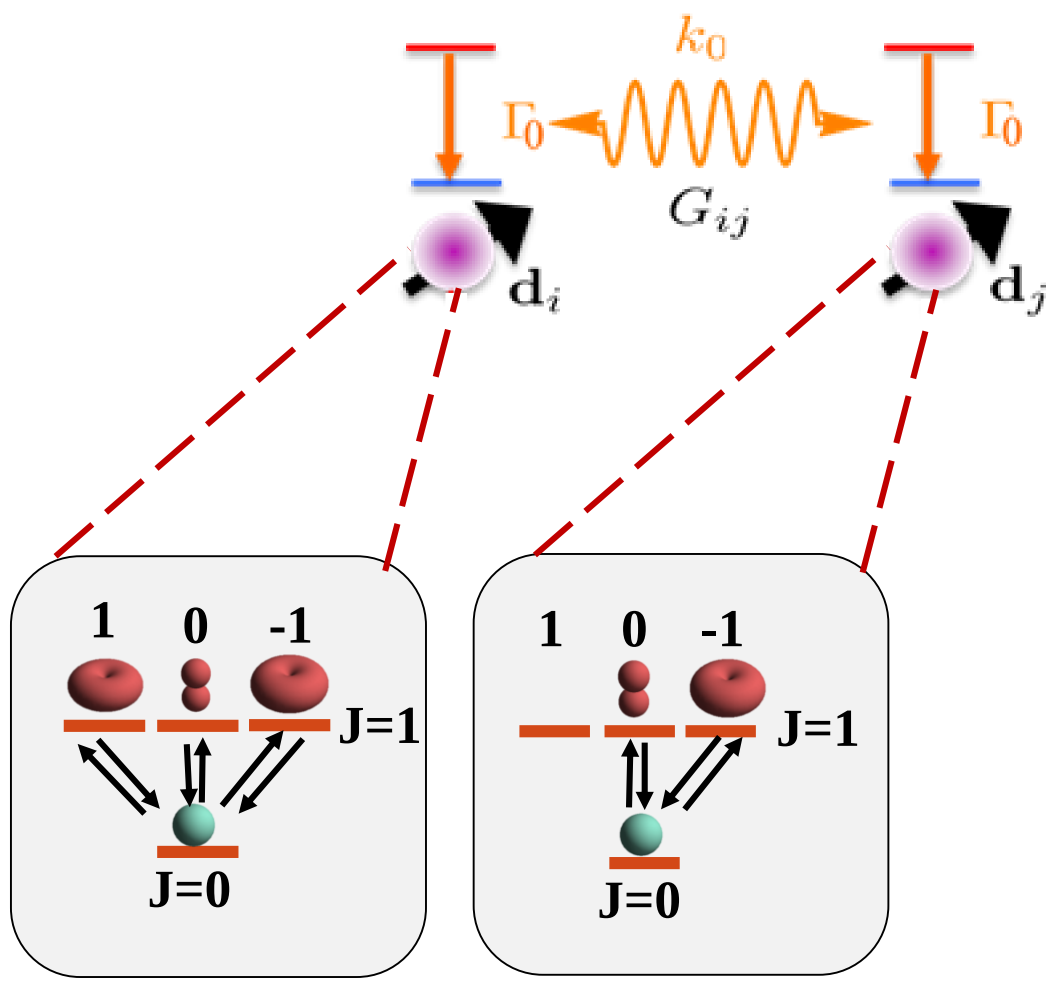
Project $\hat{\mathbf{d}}$ in J=0,J=1 manifolds

$$G_{ij}^{0} \propto \left(d_i^- d_j^+, d_i^+ d_j^-, d_i^z d_j^z\right)$$

$$G_{\mathbf{ij}}^{\pm 2} \propto e^{\mp 2\varphi_{ij}} d_i^{\pm} d_j^{\pm}$$

$$G_{\mathbf{ij}}^{\pm 1} \propto e^{\mp \varphi_{ij}} d_i^{\pm} d_j^{z}$$





Dipolar demagnetization

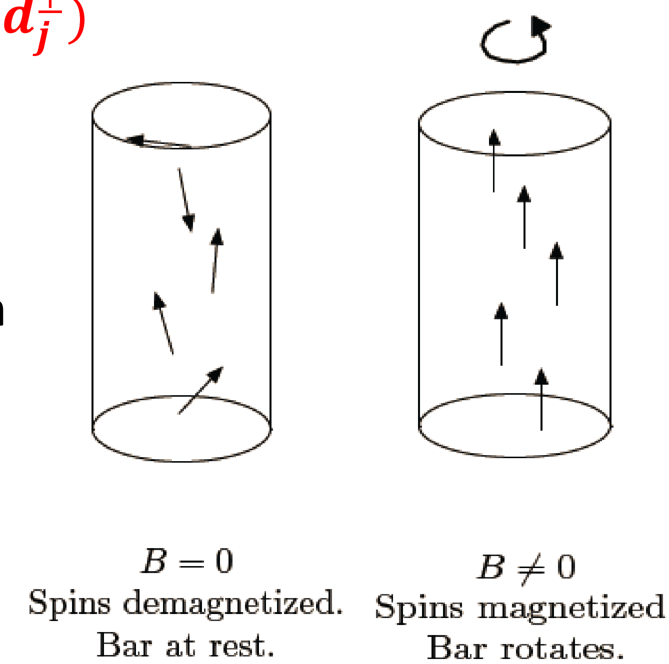
$$H_{dd}^{\pm 2} \propto \sin^2\theta e^{\mp i2\varphi}(d_i^{\pm} d_j^{\pm})$$

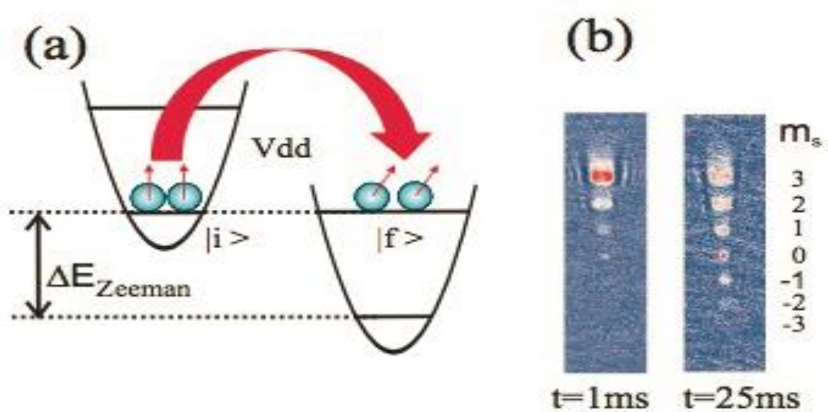
Einstein De-Hass effect

Conservation of total angular momentum:
Coupling spin and motional degrees of freedom

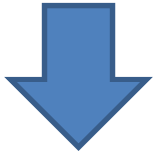
Various proposals to see the effect in **bosonic magnetic atoms.**

- Vortex formation: Santos, Ueda
  Not seen yet.
- Demagnetization: Laburte-Tolra, Pfau





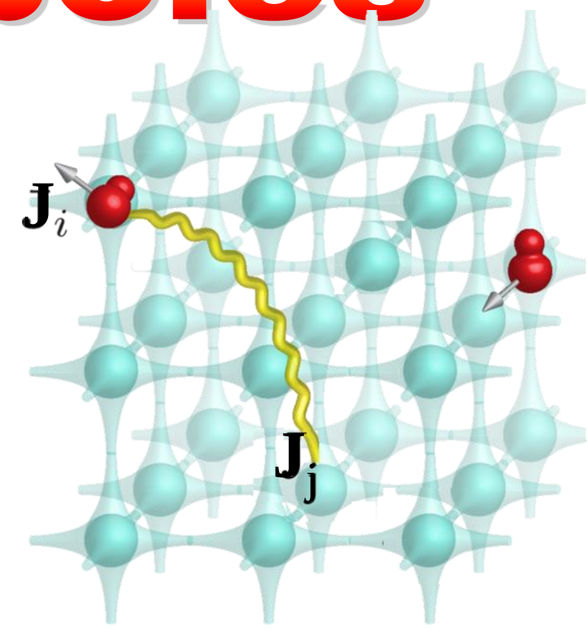
Phys. Rev. A 87, 051609(R) (2013)



Pinned particles ?

Radiating Dipoles

$$G_{ij} = \frac{3\Gamma_0}{4}[(\hat{\mathbf{d}}_i \cdot \hat{\mathbf{d}}_j)A_{ij}(r) + (\hat{\mathbf{d}}_i \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_j \cdot \hat{\mathbf{r}})B_{ij}(r)]$$

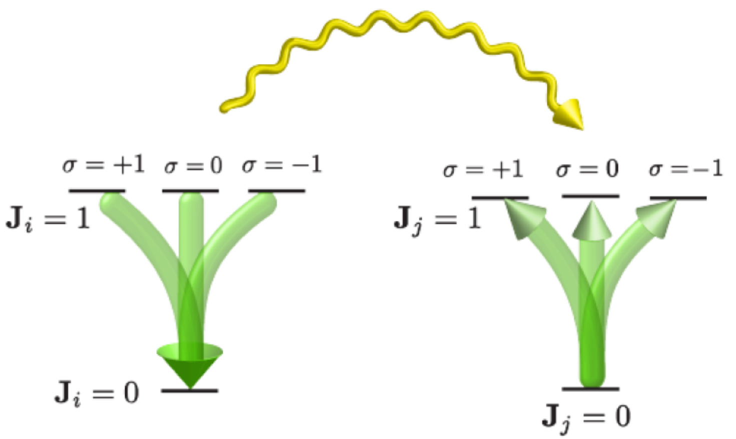


Dilute: most particles in $\mathbf{J}_i$=0: vacuum

An excitation $\hat{b}^{\dagger}_{i,\boldsymbol{\sigma}} = |\mathbf{J}_i\text{=}1, \sigma = \pm 1,0\rangle\langle \mathbf{J}_i\text{=}0,0|$

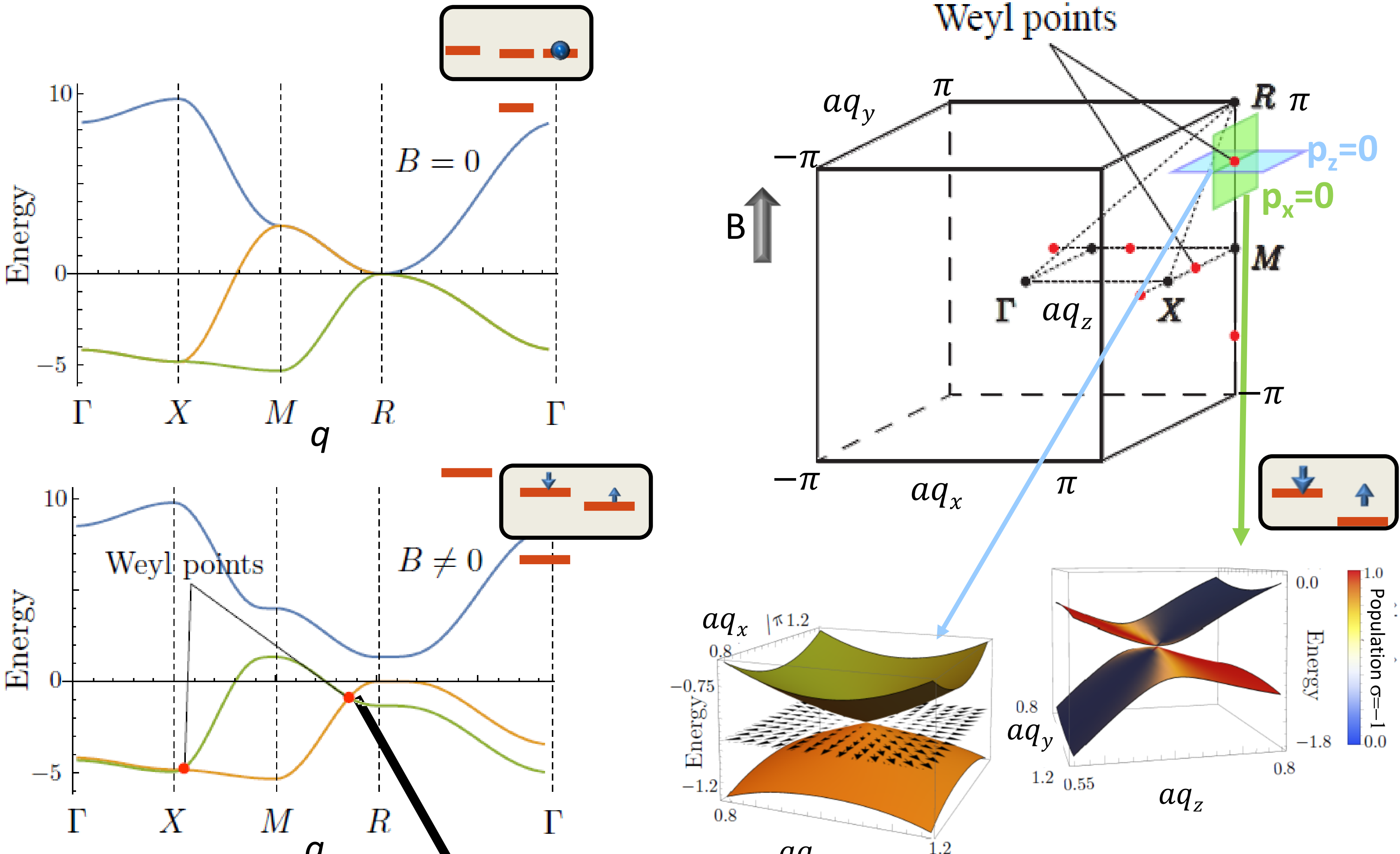
$$\boldsymbol{H_{ef}} = \sum_{ij\tilde{\sigma}} G_{ij}^{\tilde{\boldsymbol{\sigma}}\boldsymbol{\sigma}} \hat{b}^{\dagger}_{i,\tilde{\sigma}} \hat{b}_{j\sigma}$$

Excitation can propagate even for pinned particles in a lattice while flipping their spin



Spin-orbit coupling

Weyl particles with dipoles: $k_0 a \ll 1$



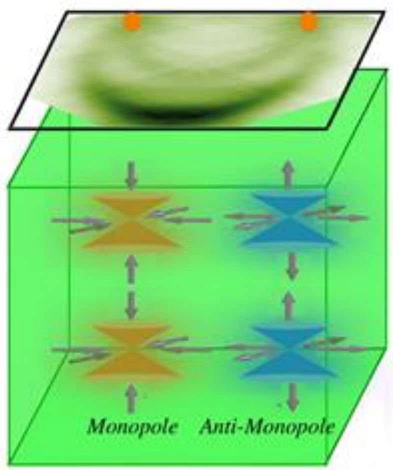
$\boldsymbol{q} = \boldsymbol{p} + \boldsymbol{K}_R$

arXiv:1601.01004

$$\hat{h}\,(\boldsymbol{p}) \sim \xi(\boldsymbol{p})I + v_\perp(K_R)(\hat{\sigma}_x p_x + \hat{\sigma}_y p_y) + v_\parallel(K_R)\hat{\sigma}_z p_z$$

Weyl excitations

Weyl fermions are fundamental massless particles with a definite handedness that were first predicted by Hermann Weyl back in 1929, but they have never been observed in high-energy experiments.



Weyl Fermion Crystal

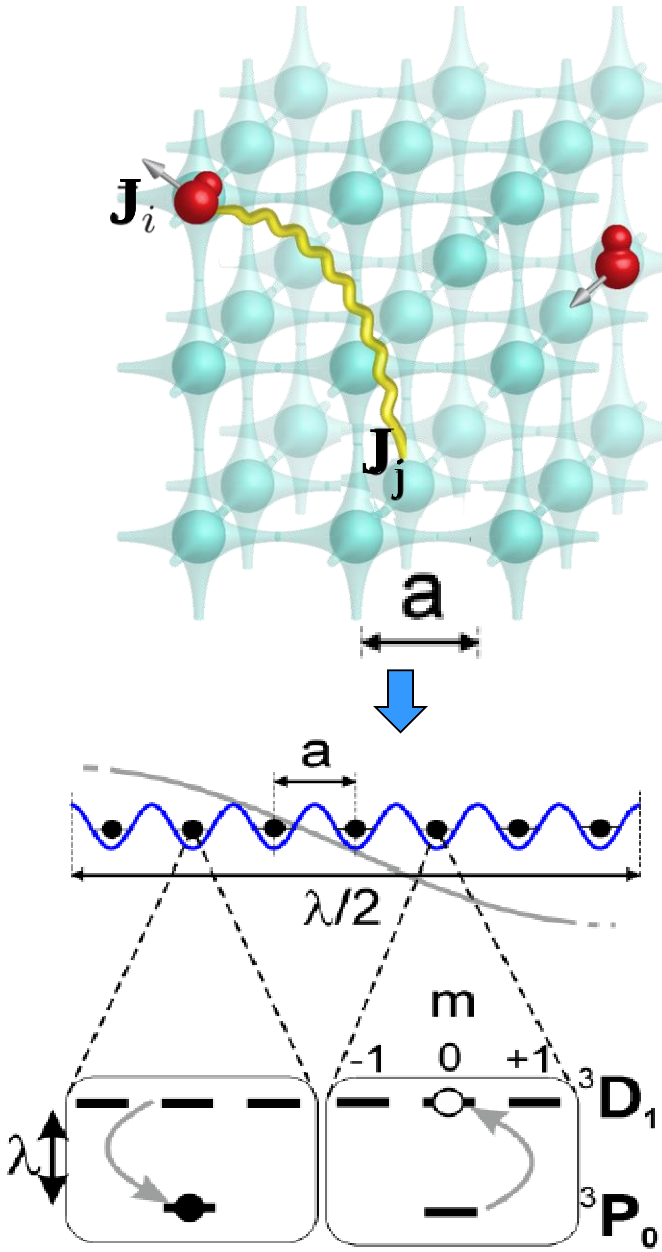
Recently found in solid materials
(TaAs --Princeton & Beijing--, Photonic crystals –MIT--)
Naturally appear in excitations of dipolar systems

Possible issues:

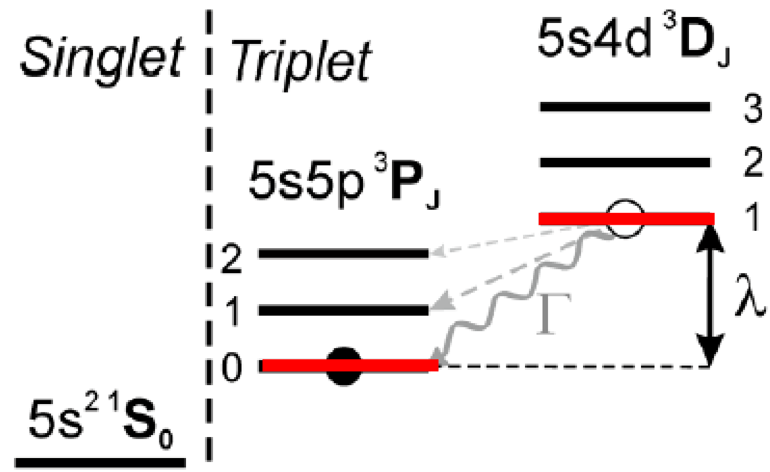
- ✓ Disorder: perfect system requires unit filling
- ✓ Dissipative process from dipolar interactions: radiative dipoles

Indication that Weyl points survive

Experimental Implementation



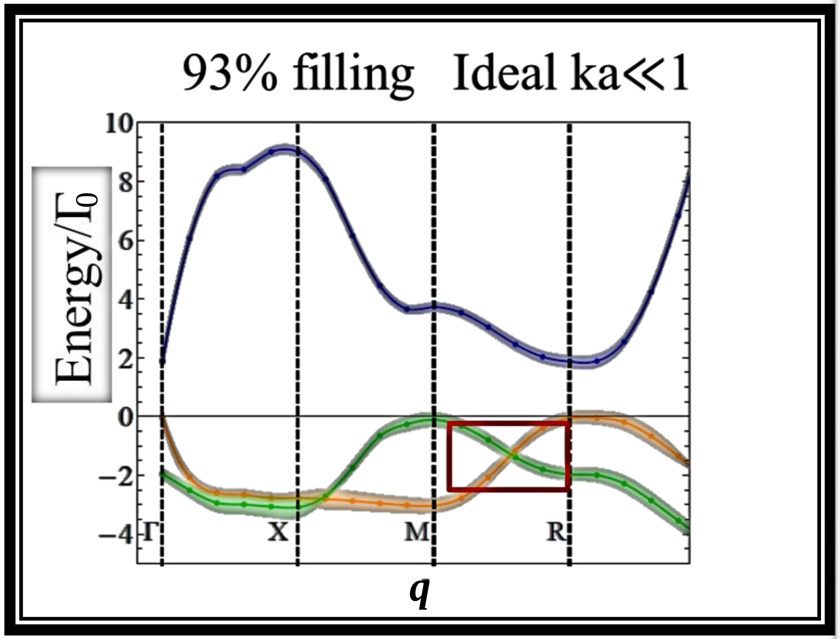
- Mott Insulator of Sr atoms
- Trapped in a magic wave lattice

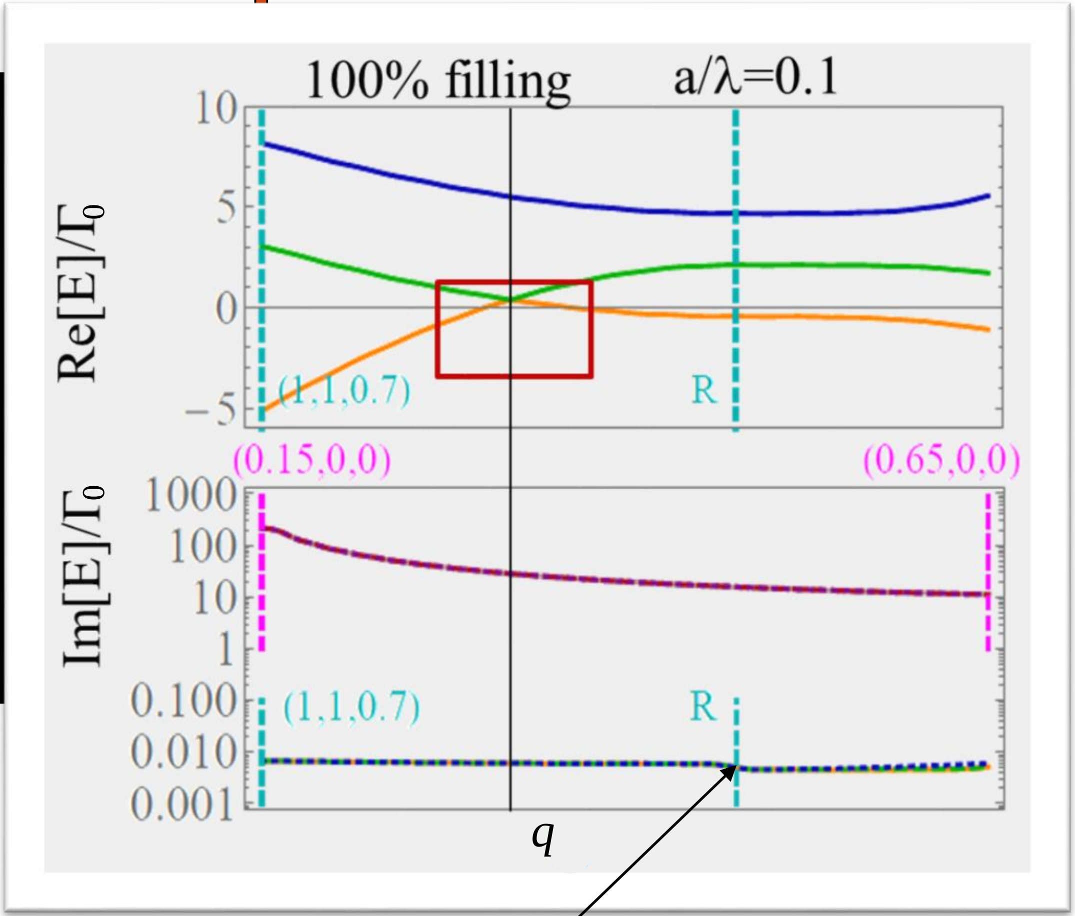


B. Olmos, et al PRL. **110**, 143602 (2013)

- Dipole moment d=4.03 D
- Γ_0=2.9 x10^5 s $^{-1}$
- a/λ=0.1 Near field physics

Weyl particles with dipoles



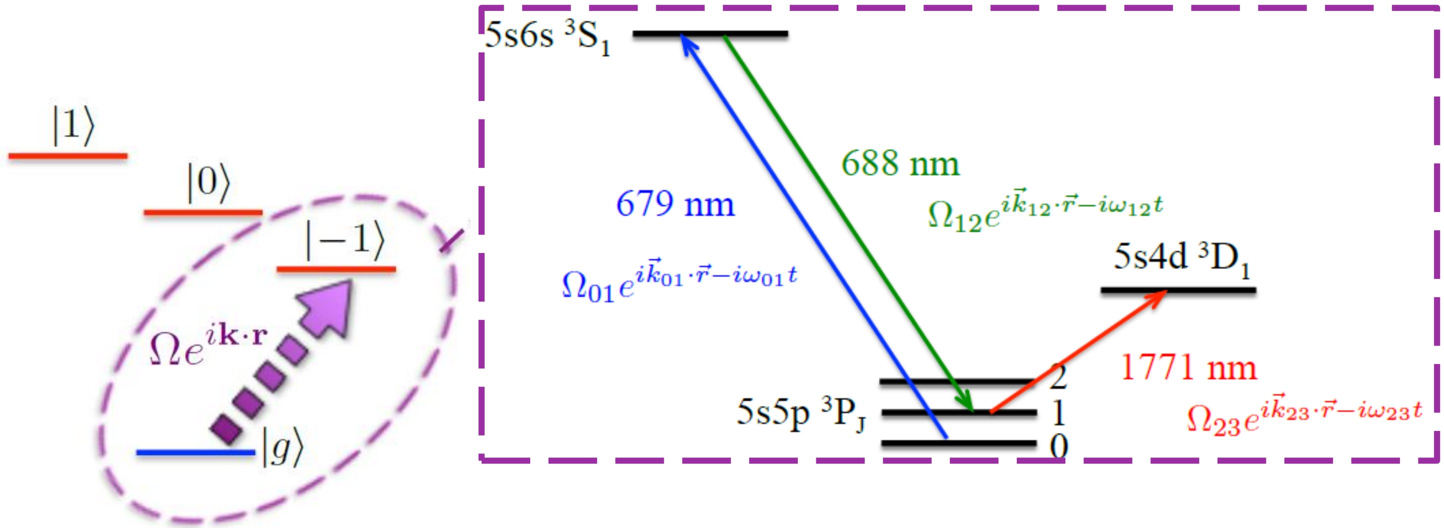


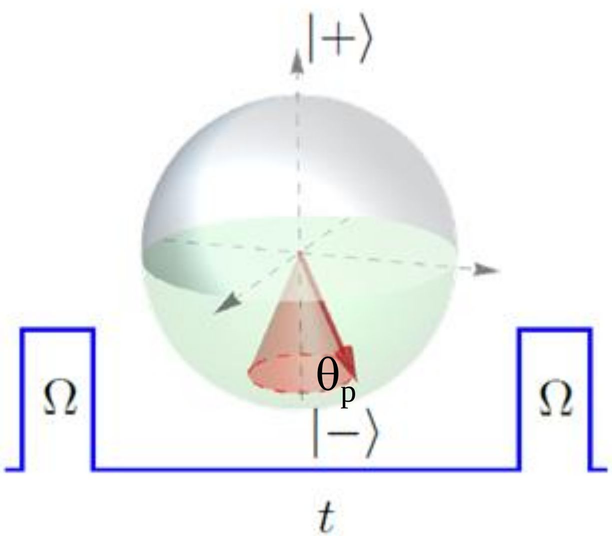
Spontaneous decay suppressed at Weyl points: "subradiance"

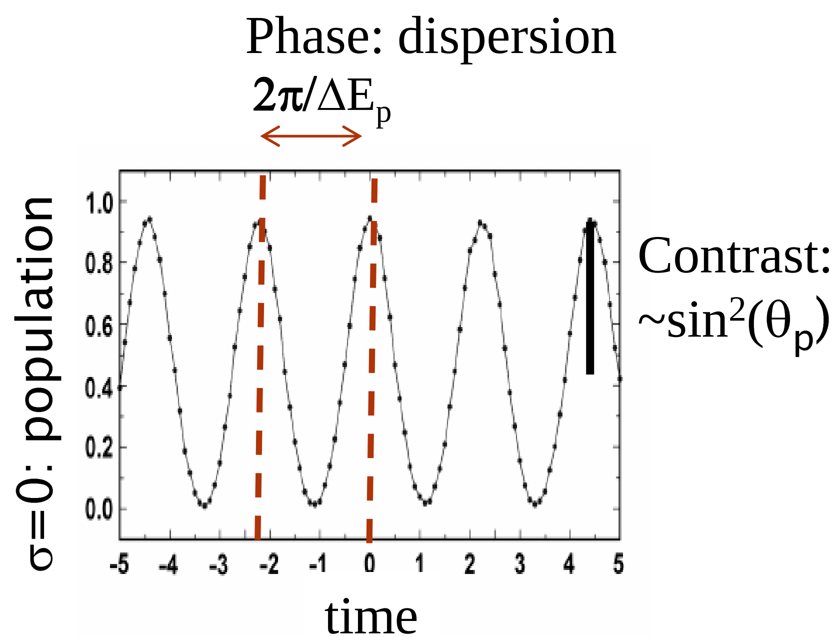
Decay orders of magnitude smaller than elastic part

Weyl particles: Detection

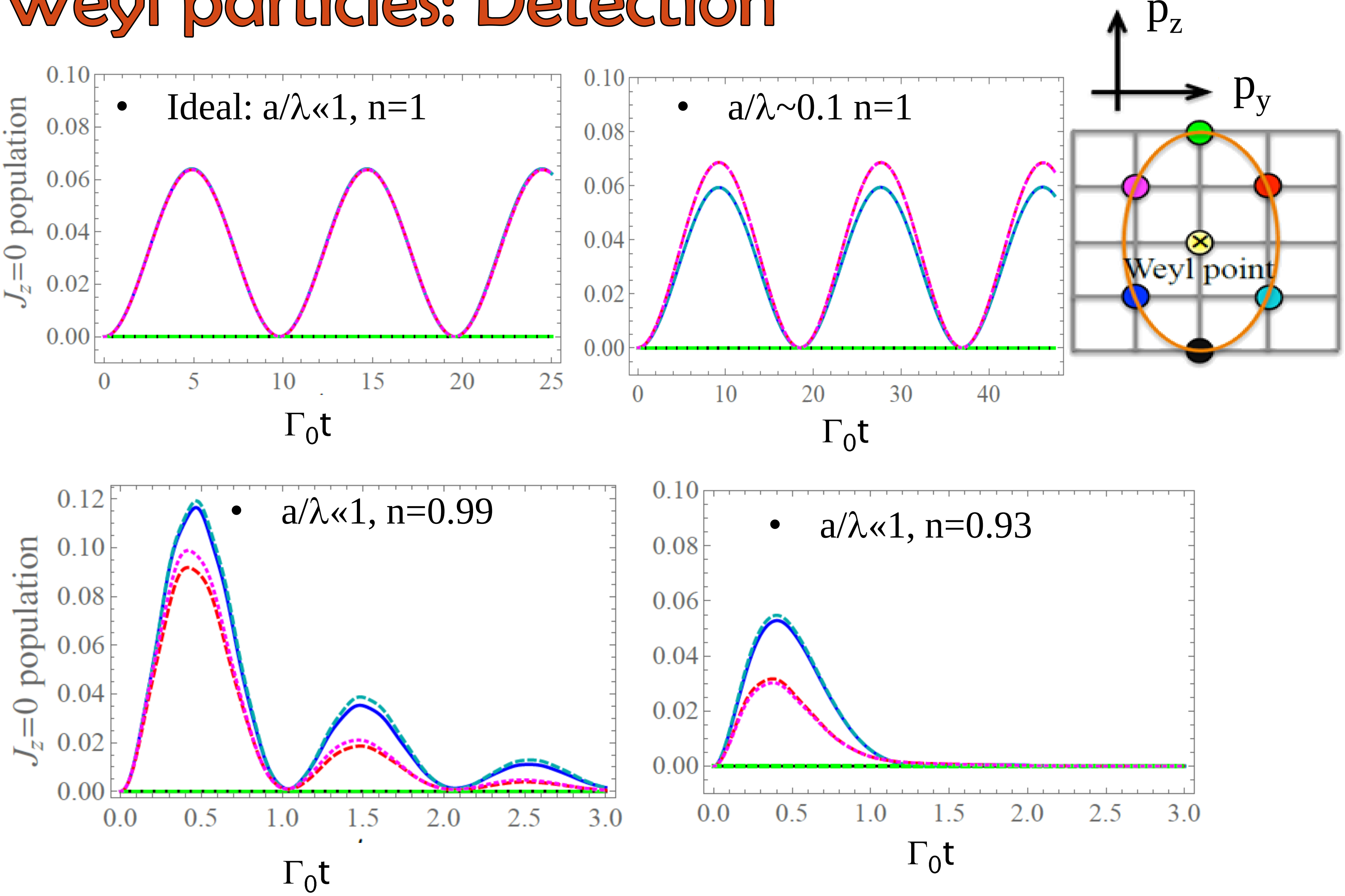
Use momentum resolves Ramsey spectroscopy





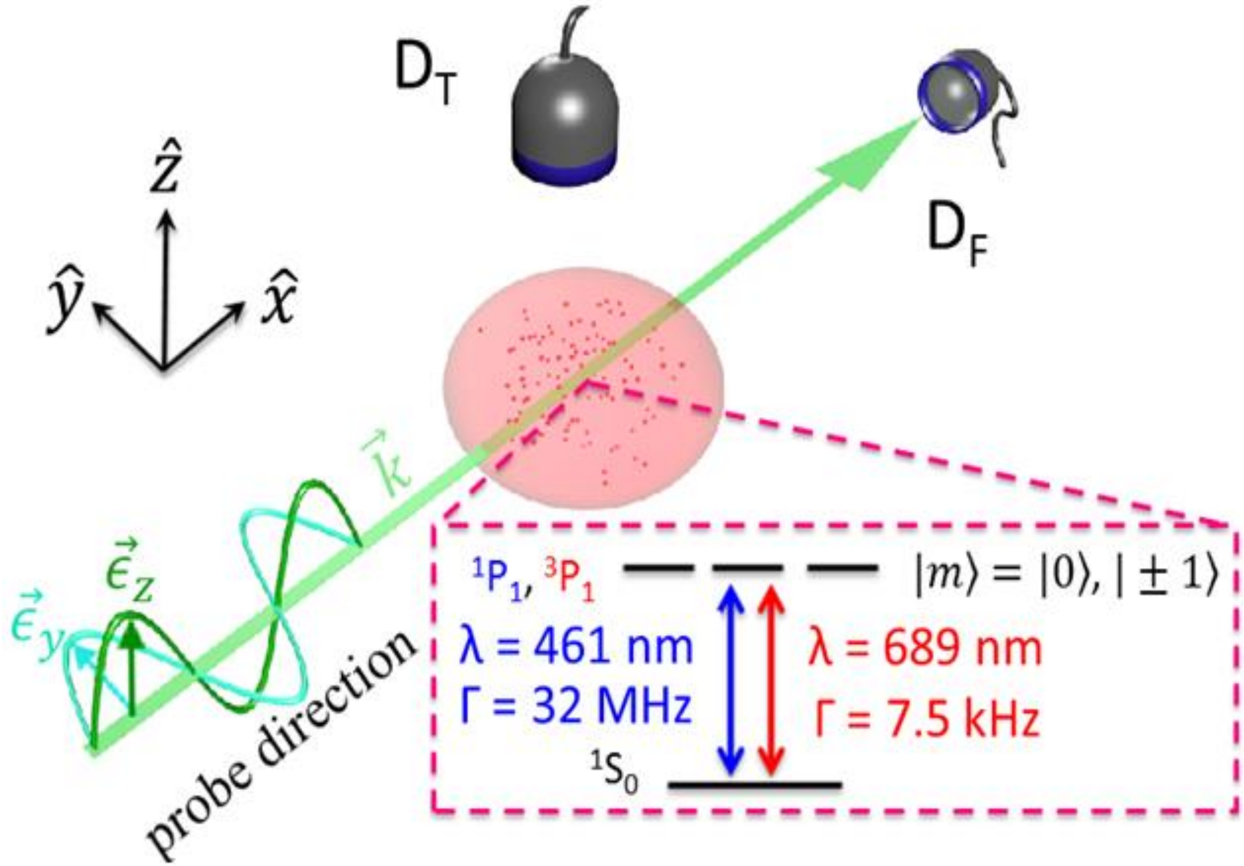


Weyl particles: Detection



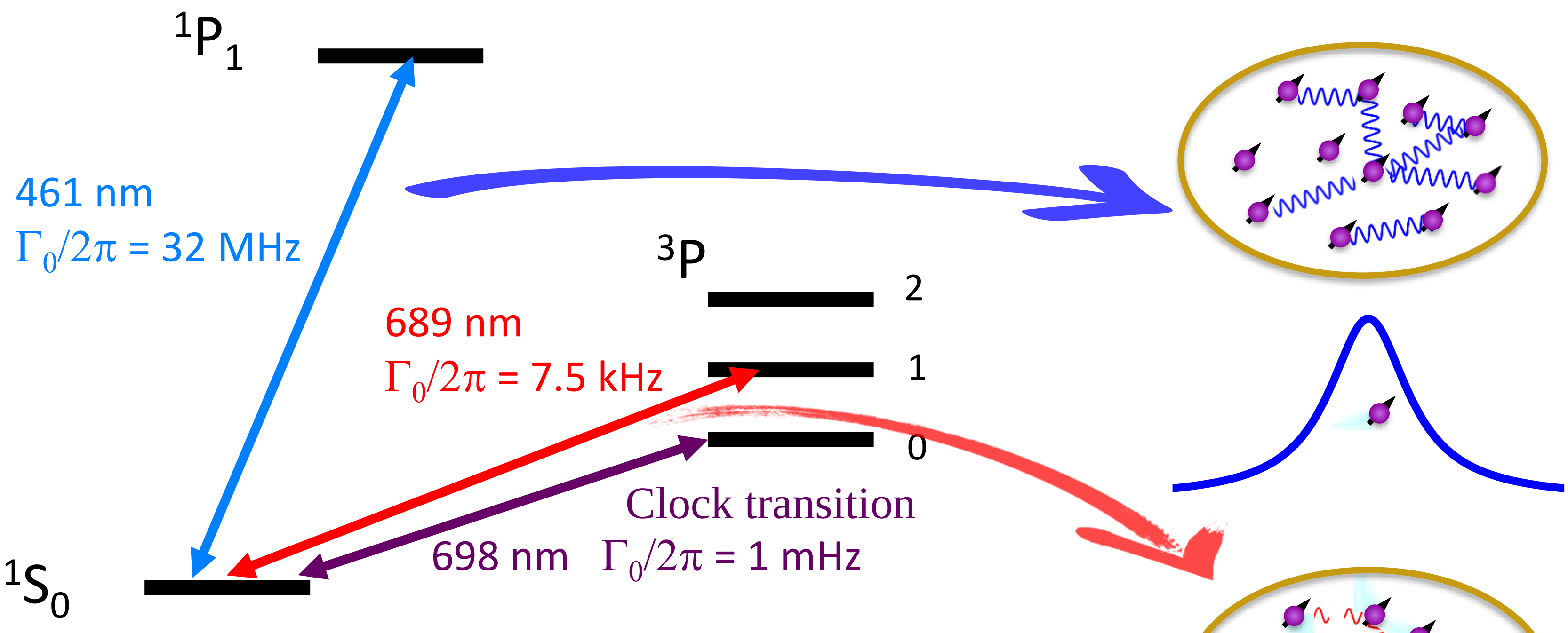
First test be experiments at JILA

Cooperative fluorescence of ^{88}Sr atoms



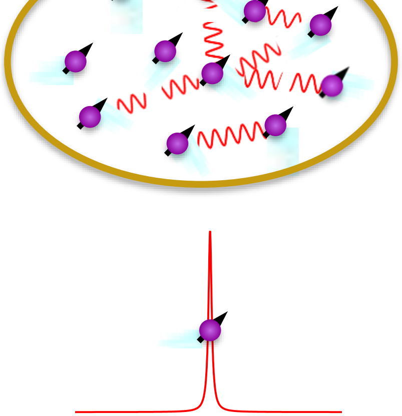
arXiv:1601.05322 Accepted Nat. Comm.

Sr level structure: weak and strong interactions



- Two simple $J = 0 \rightarrow J' = 1$ transitions providing strong and weak dipole interactions $\propto \Gamma_0$

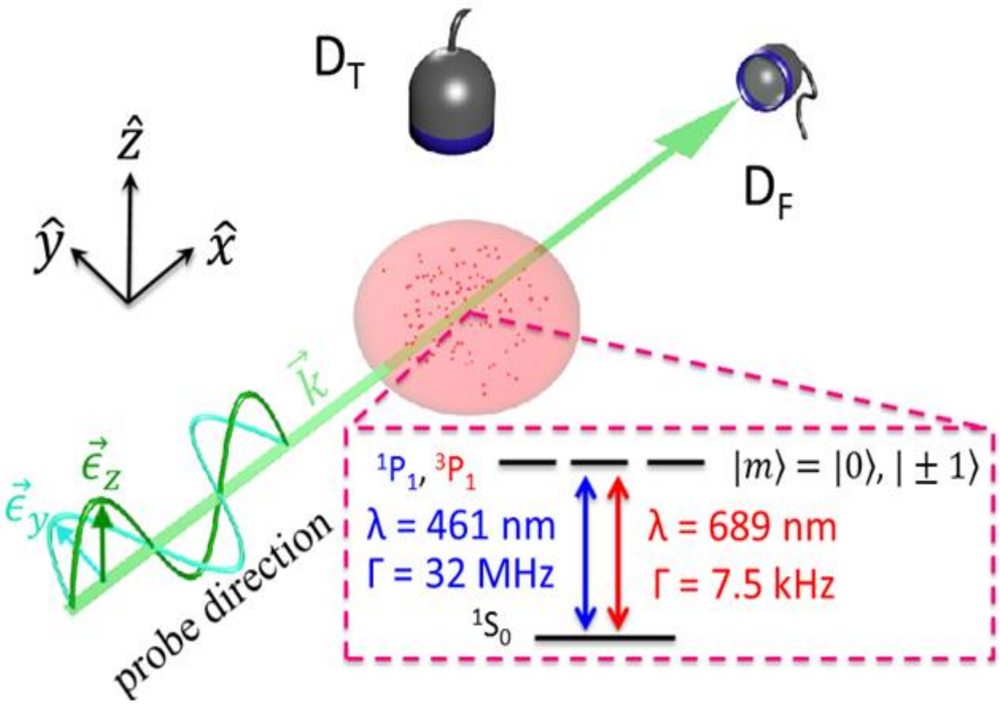
$$\frac{\Gamma_0^{\text{blue}}}{\Gamma_0^{\text{red}}} \sim 1000$$



- Temperature ~ 1μK , Doppler broadening ~ 50 kHz
  → Negligible for the blue transition, but important for the red transition

Cooperative fluorescence of ^{88}Sr atoms

First test bed experiments at JILA



- Coherent dipole coupling: Probe model
- Motional effects: Frozen particles (blue)
- No lattice: Random position, far field
- Dipolar effects: Intensity, line broadening and line center shift

Measure: forward and transverse fluorescence

Vary probe laser polarization

Tune density and optical depth by time of flight

TOF	Peak density (cm^{-3})	OD_{av}	ka
1ms	1.5×10^{12}	21	11
25ms	1.5×10^{11}	4.3	25

Coherent dipole model

- Weak driving field
  $\Omega \ll \Gamma_0$

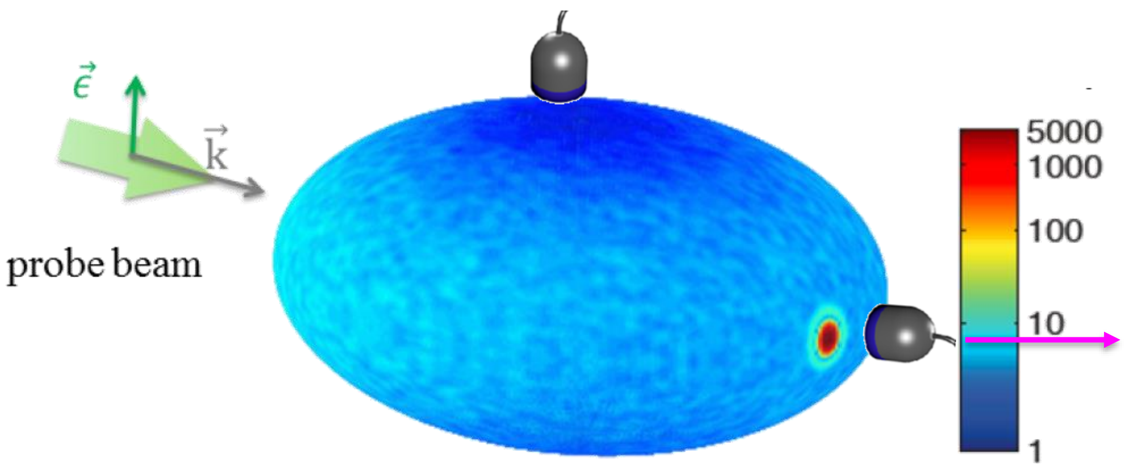
$$\boldsymbol{H_{ef}} = \sum_{j\sigma} (\Omega_j^{\sigma} b_{j,\sigma}^{\dagger} + h.c) + \sum_{j\sigma} \Delta^{\boldsymbol{\sigma}} b_{j,\sigma}^{\dagger} b_{j\sigma} + \sum_{jn\sigma\tilde{}} G_{jn}^{\tilde{\boldsymbol{\sigma}}\boldsymbol{\sigma}} b_{j,\tilde{\sigma}}^{\dagger} b_{n\sigma}$$

Driving Laser　　Detuning　　Dipole Coupling

$\hat{b}_{i,\boldsymbol{\sigma}}^{\dagger} = |\mathbf{J}_i{=}1, \sigma = \pm 1, 0\rangle\langle \mathbf{J}_i{=}0, 0|$

- Fluorescence at far-field $I(\mathbf{r}_s) \propto \sum_{j,m} [\mathbf{b}_j \cdot \mathbf{b}_m^* - (\mathbf{b}_j \cdot \hat{\mathbf{r}}_s)(\mathbf{b}_m^* \cdot \hat{\mathbf{r}}_s)] e^{i\mathbf{k}_s \cdot (\mathbf{r}_j - \mathbf{r}_m)}$

- Steady-state $\langle b_{j\sigma} \rangle = \dfrac{\Omega^{\sigma} e^{ik_0 x_j}}{2(\Delta^{\sigma} + i\Gamma_0/2)} + \sum_{n \neq j\tilde{}} \dfrac{G_{jn}^{\sigma\tilde{\sigma}} \langle b_{n\tilde{\sigma}} \rangle}{i(\Delta^{\sigma} + i\Gamma_0/2)}$

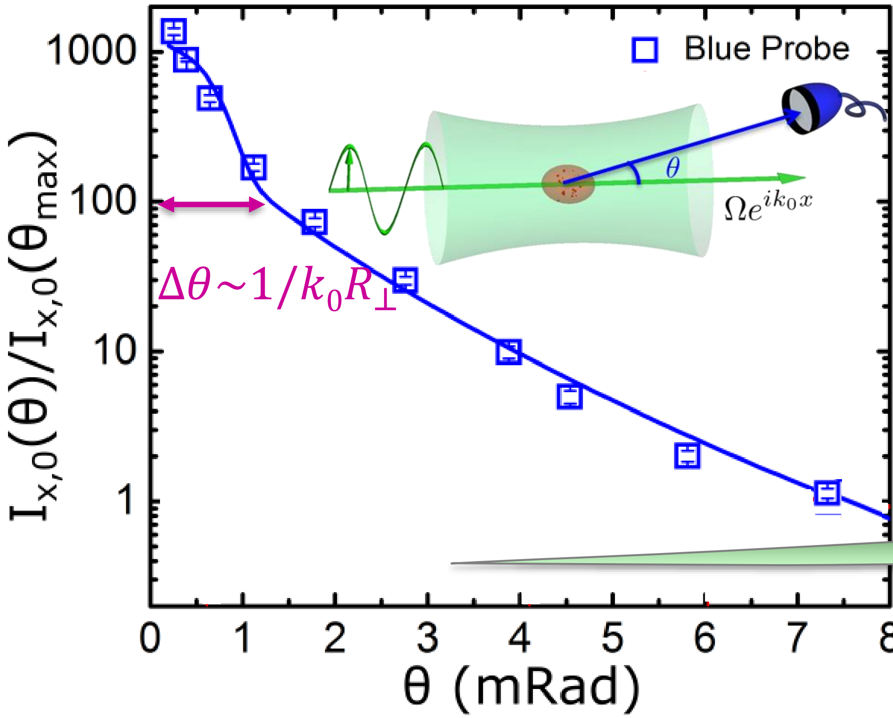


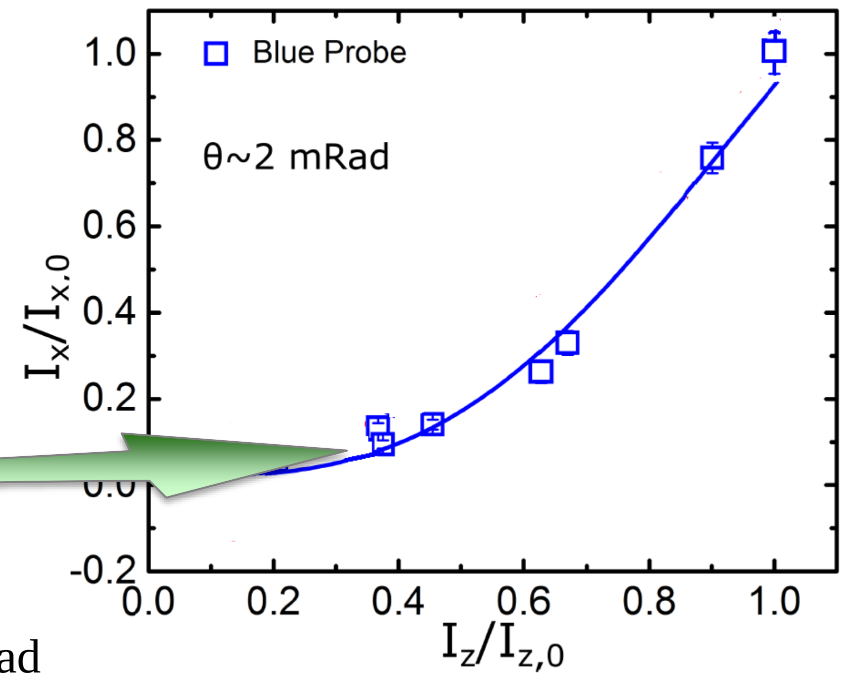
forward fluorescence: Coherent emission

Forward fluorescence intensity

— Coherent dipole model
□ Experiment

$$I \sim \frac{|\Omega^{\sigma}|^2}{|\Delta|^2 + (\Gamma_0/2)^2}\left(N + N^2 e^{-|\boldsymbol{k}_S - \boldsymbol{k}_0|^2 R_\perp^2}\right)$$





θ_{max}=7.5 mRad

- Narrow interference cone shows phase coherence, wavelength dependent

  $R_\perp$: cloud size perpendicular to $\mathbf{k_0}$

- Collective enhancement of forward fluorescence

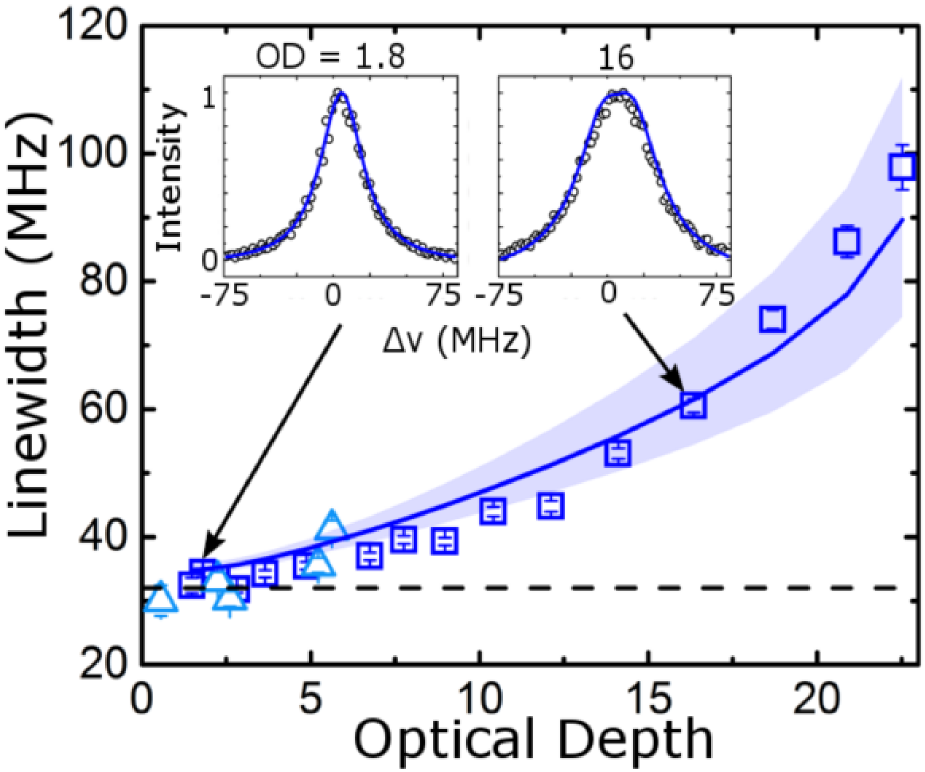
  $I_x \sim I_z^2 \quad I_z \sim N$

- Well captured by coherent dipole model

Significant linewidth with increasing OD

Coherent dipole model
Experiment

Forward Direction



Atom#
N ~1.7×10^7
¼ atom number

$$\mathrm{OD} = \frac{3N}{2k^2R_\perp^2}$$

$R_\perp$: cloud size perpendicular to $\mathbf{k_0}$

- Collapse as a function of OD

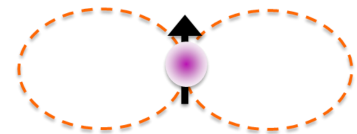
Shadow: 20% atom number uncertainty

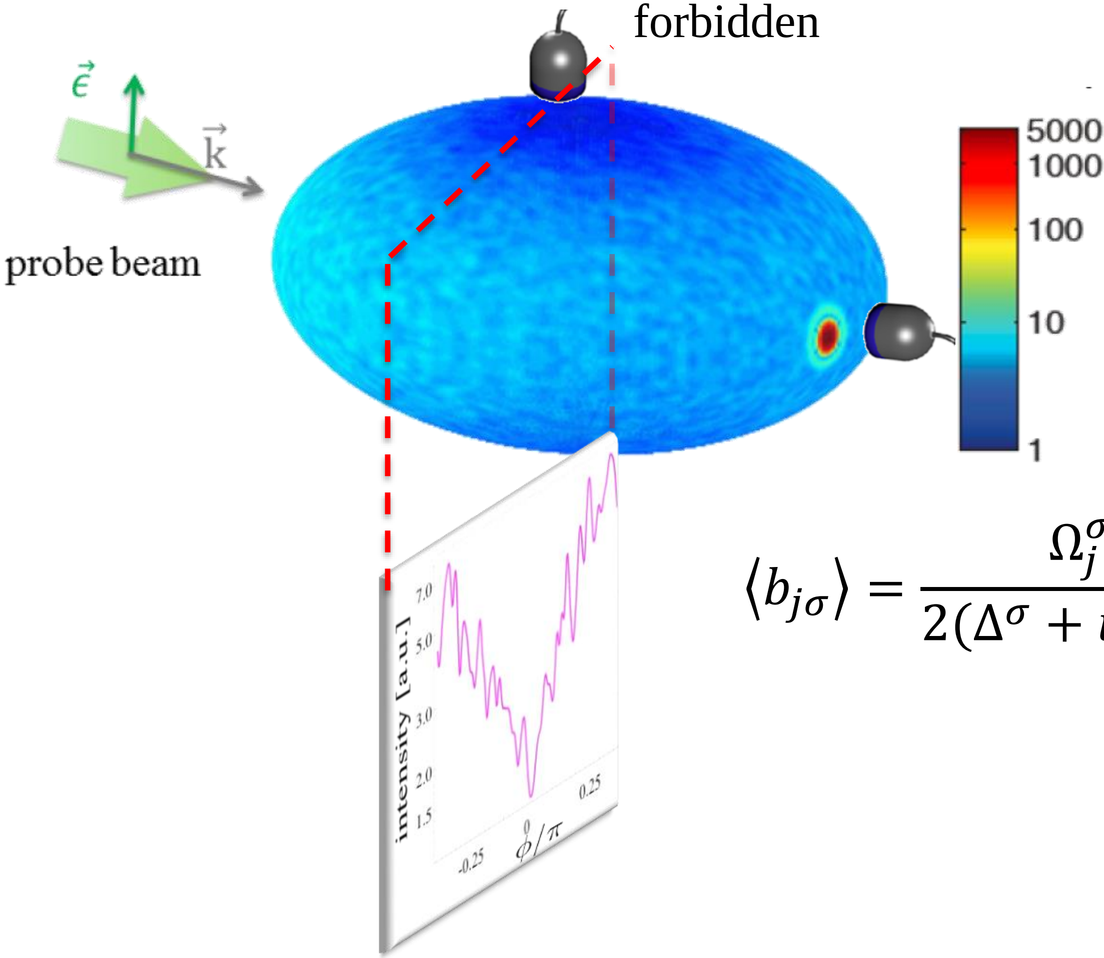
Coherent dipole model

- Weak driving field

  $\Omega \ll \Gamma_0$

For one dipole emission parallel to polarization is forbidden





But is allowed for many-dipoles:

$$\langle b_{j\sigma} \rangle = \frac{\Omega_j^\sigma}{2(\Delta^\sigma + i\Gamma_0/2)} + \sum_{n \neq j} \frac{G_{jn}^{\sigma\tilde{\sigma}} \langle b_{n\tilde{\sigma}} \rangle}{i(\Delta^\sigma + i\Gamma_0/2)}$$

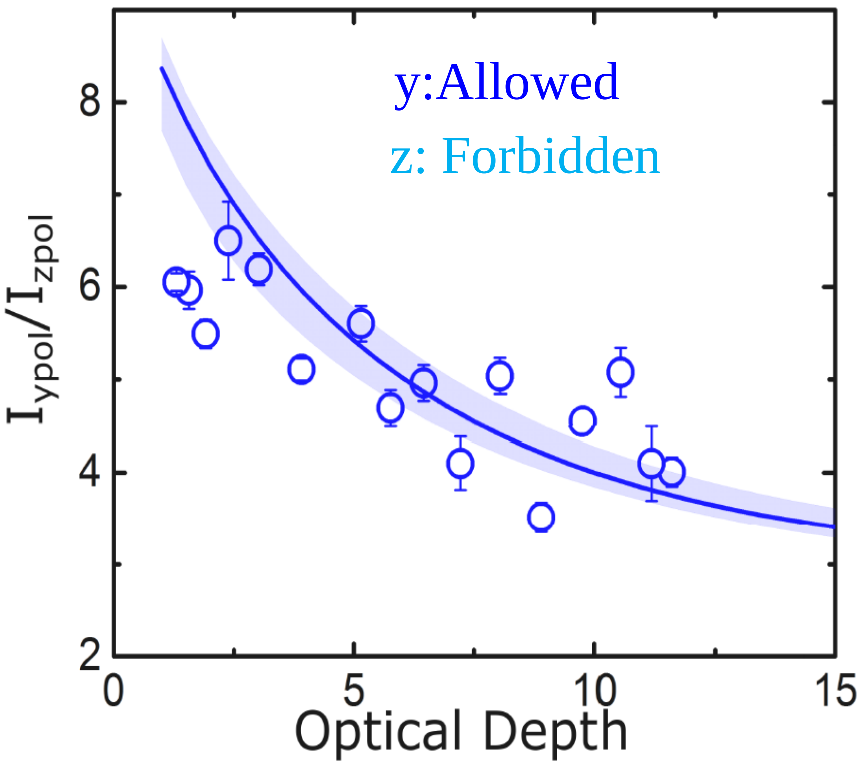
Transverse fluorescence

- Experiment agree well with “spin-orbit” coherent dipole model
- Anisotropy of dipole-dipole interactions: polarization and geometry dependent linewidth and intensity

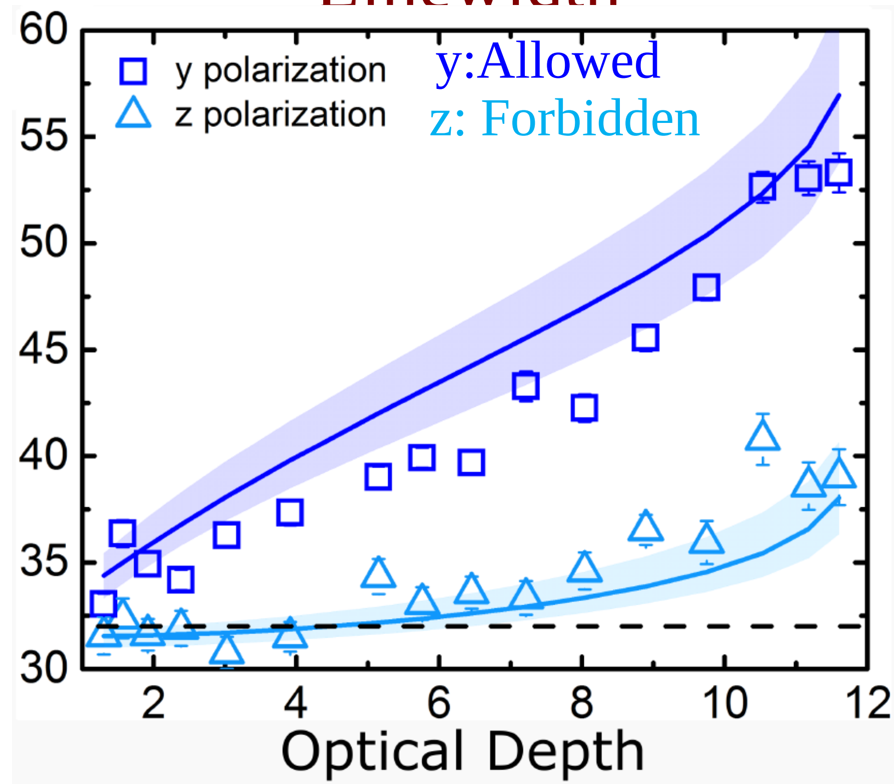
Coherent dipole model

Experiment

Intensity Ratio

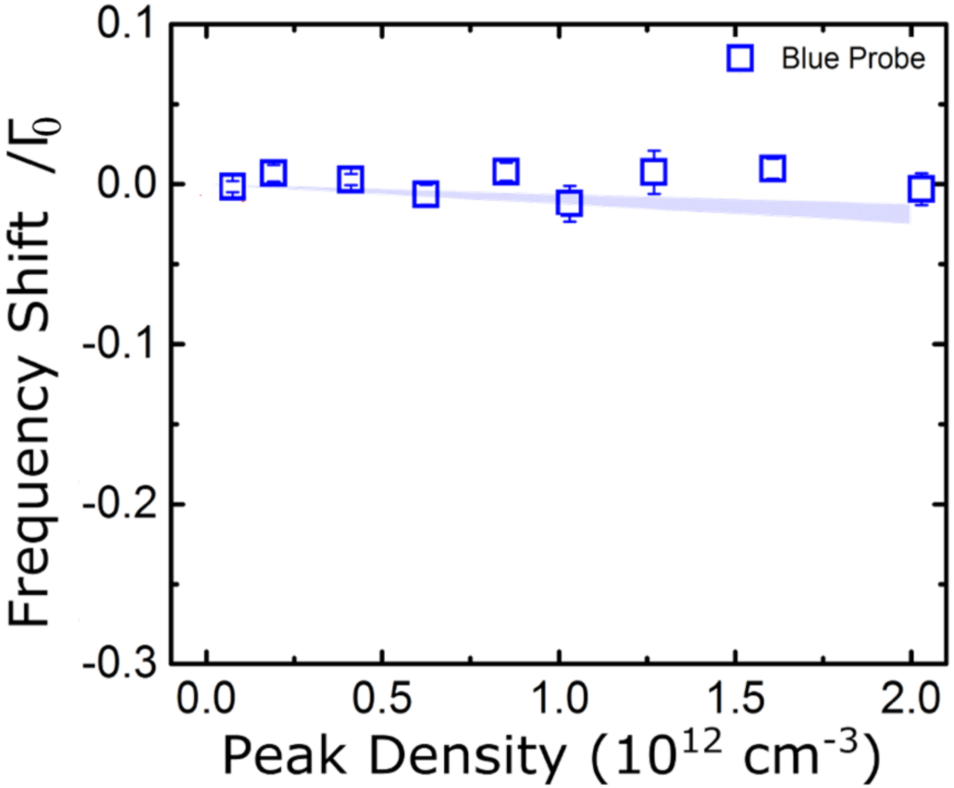


Linewidth



Fluorescence intensity and linewidth are collective enhanced for the forbidden polarization

Transverse fluorescence



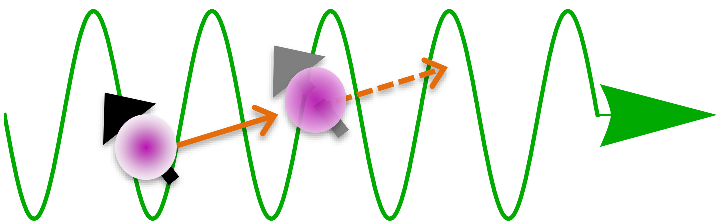
- Coherent dipole model prediction: frequency shift on the order of $\Gamma_0 n k_0^{-3}$ $\quad nk_0^{-3} = 4 \times 10^{-4}$

- Frequency shift agrees with theory

- What about the red transition? Motion effects not negligible

Doppler broadening ~ 50 kHz $\qquad \Gamma_0$~ 7.5 kHz

Coherent dipole model



- Lowest order correction from motion: atomic motion accounted by as random detunings

$$\langle b_{j\sigma} \rangle = \frac{\Omega_j^{\sigma}}{2(\Delta^{\sigma} + \delta_j + i\Gamma_0/2)} + \sum_{n \neq j} \frac{G_{jn}^{\sigma\tilde{\sigma}} \langle b_{n\tilde{\sigma}} \rangle}{i(\Delta^{\sigma} + \delta_j + i\Gamma_0/2)}$$

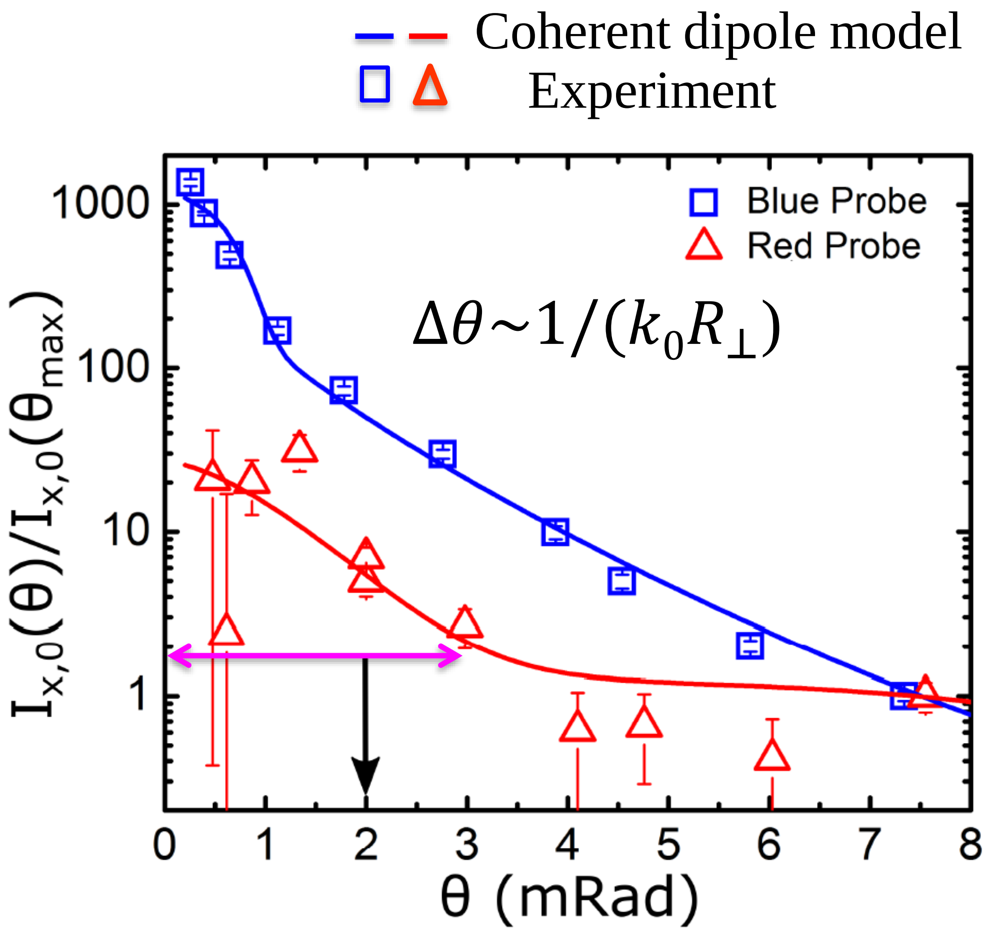
$$P(\delta_j) \propto e^{-\frac{(\delta_j)^2}{2w_D^2}}$$

random detuning for each atom

w_D : Doppler width
Δ^{α} : detuning of probe laser
$G_{\alpha,\alpha'}$: dipole-dipole interaction

Void-profile line shape: Convolution Gaussian and Lorentzian

Forward fluorescence intensity



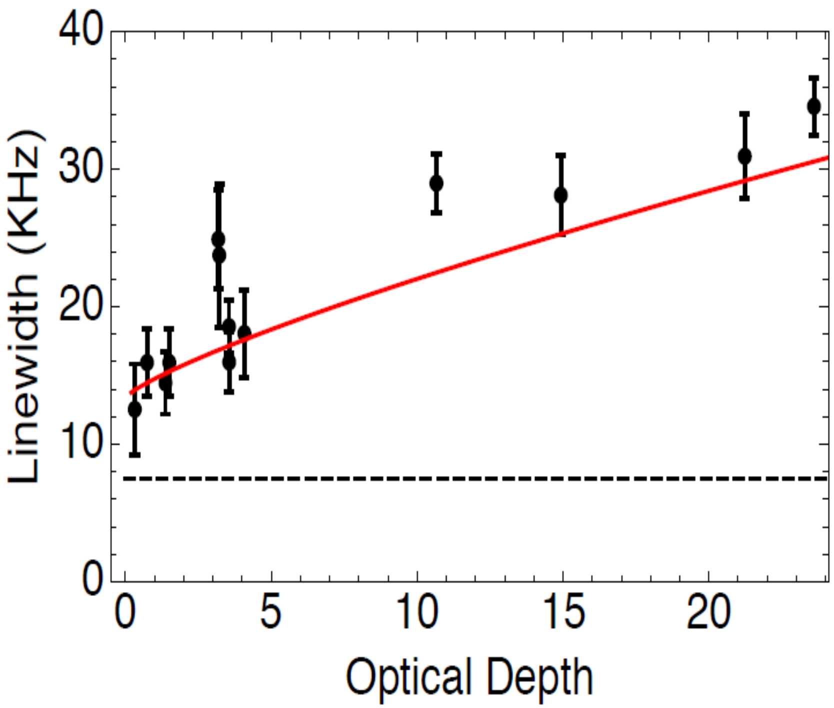
- Interference cone: k_0 dependence
- Motion decreases phase coherence
- Well captured by coherent dipole model

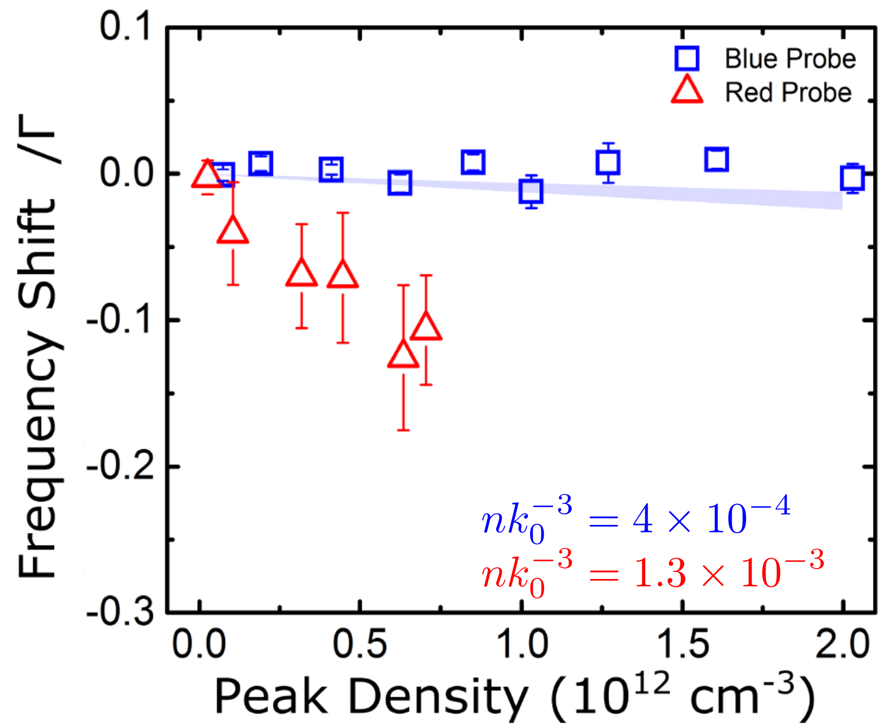
Transverse fluorescence intensity

— Coherent dipole model+ random detunning

●△ Experiment: T. Ido, *et al* PRL 94, 153001(2005).

$\Omega/\Gamma_0 \sim 0.3 - 0.6$



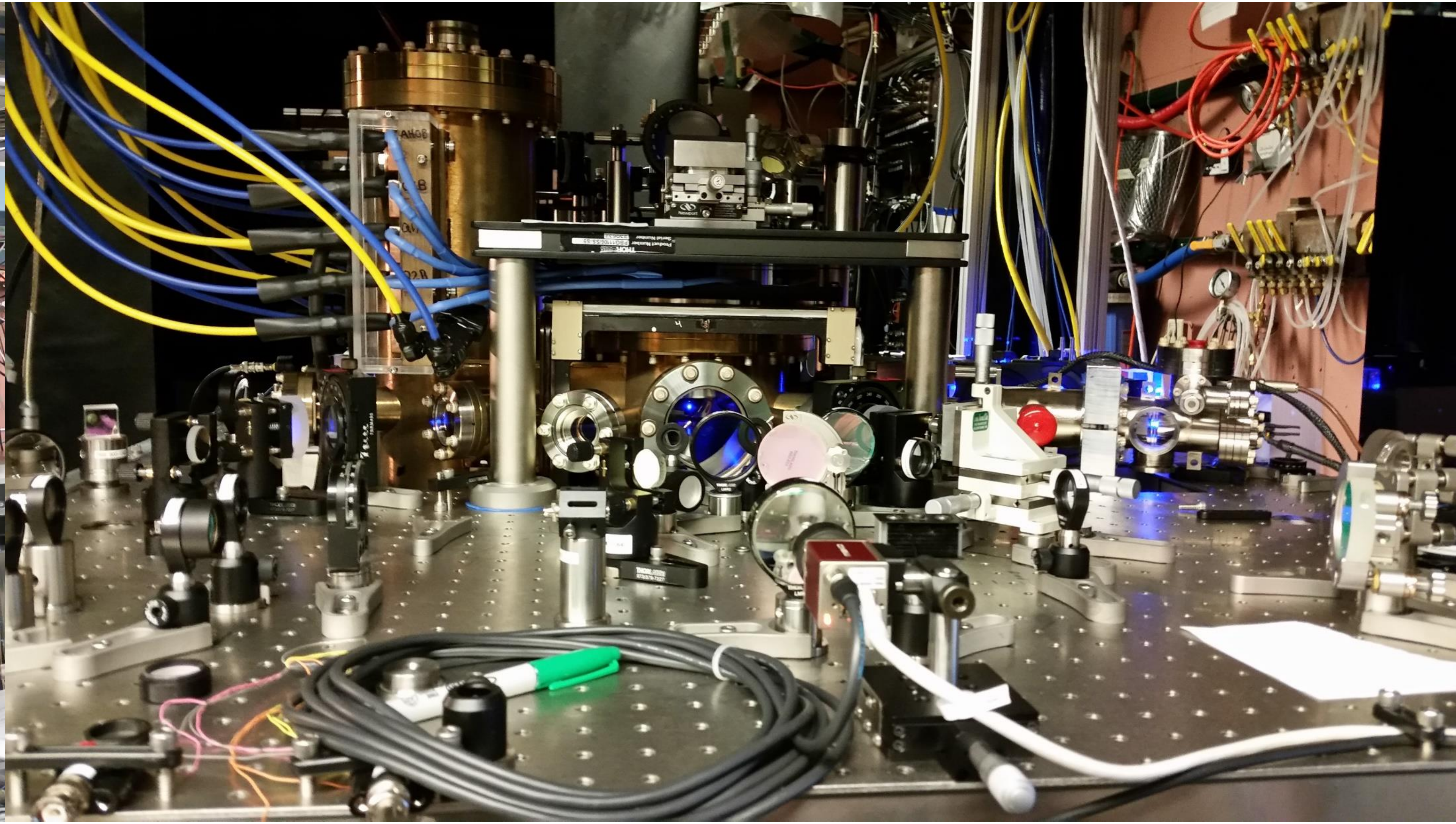


- Weak transition: Large frequency shift exceeding theory prediction
- Other effects caused by motion (such as recoil, momentum diffusion), nonlinearity, short-range physics?

Red transition: Complex regime

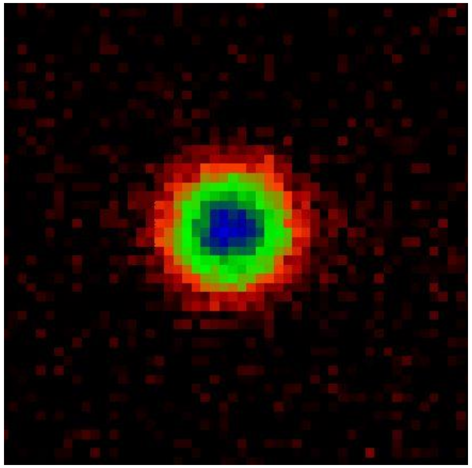
Single photon recoil energy ~ linewidth~ Rabi frequency

Progress towards quantum degeneracy

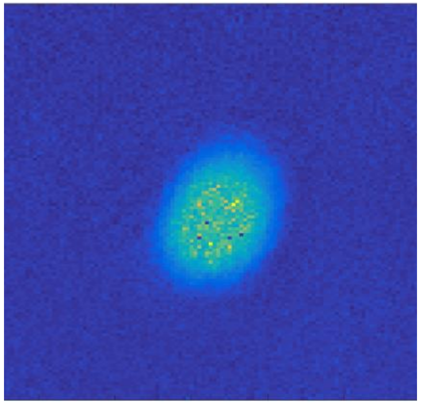


Progress quantum degeneracy: ^{87}Sr lab @JILA

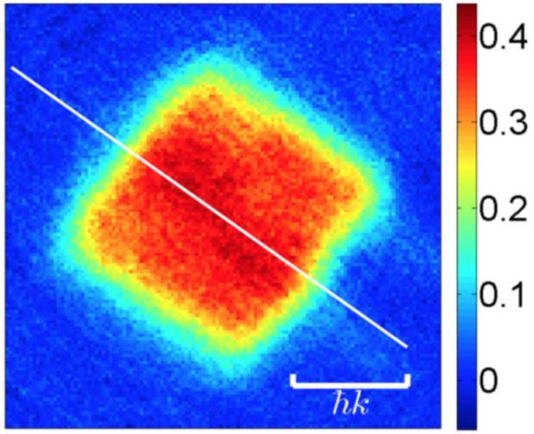
5 x 10^5 atoms at 1.5 mK (crossed dipole trap)



~ 10^4 atoms, T< 80 nK, T/T_F ~ 0.3 for each nuclear spin component (after evaporation in dimple)

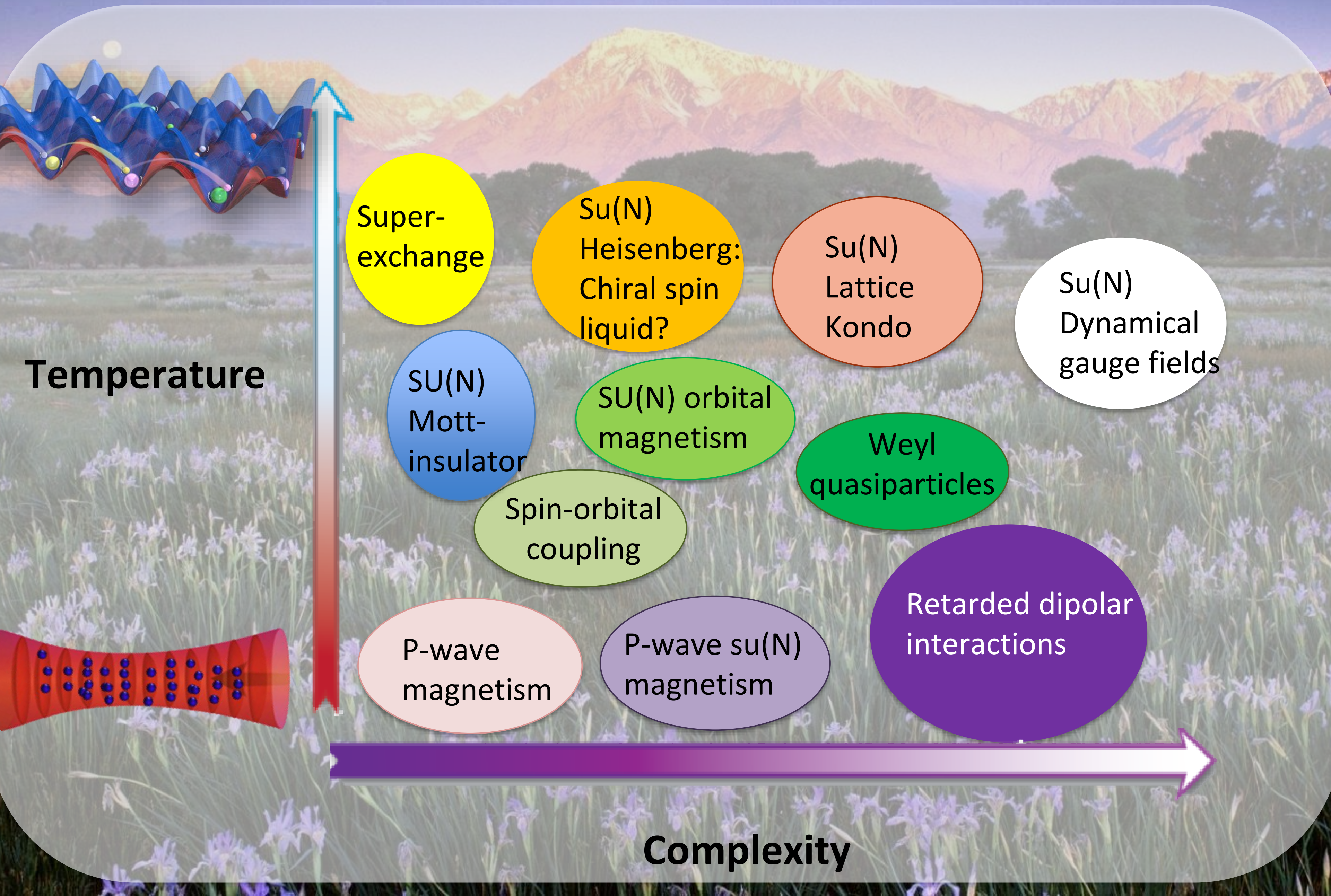


Then loaded in a lattice



Preliminary, January 2016

Alkaline earth atoms: A great vista ahead !



Thanks for your attention

Congratulations Peter!!!!