Non-equilibrium many-body physics with alkaline earth atoms and polar molecules

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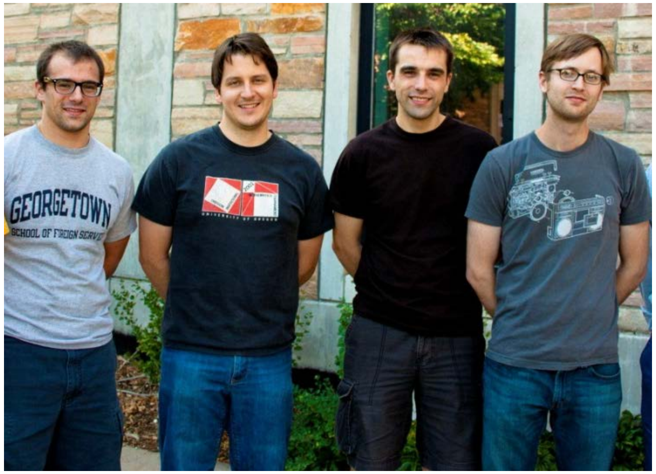
The 11th US-Japan Joint Seminar 2013

"Ultimate Quantum Systems of Light and Matter- Control and Applications"

The Sr team:



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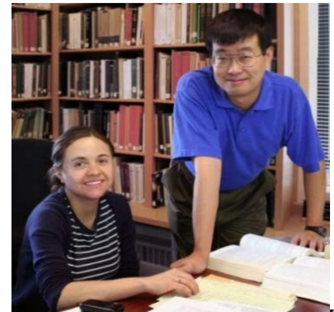
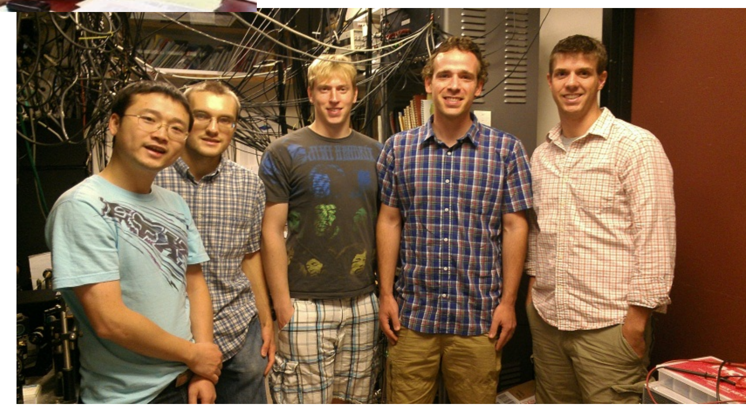
Jun Ye

KRb team:

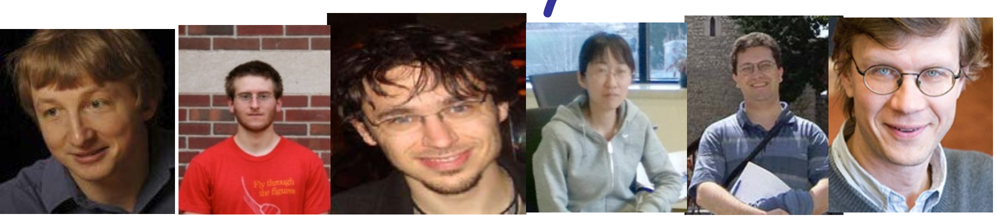


D. Jin



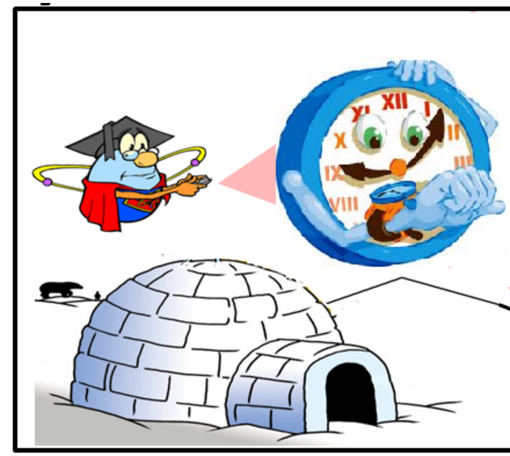
B. Yan, S. Moses, J. Covey, B. Neyenhuis and B. Gadway

Theory team:



A. Gorshkov, M. Foss-Feig, K. Hazzard, B. Zhu, S. Manmana, M. Lukin

Ultra-cold Matter



- Fully controllable quantum systems

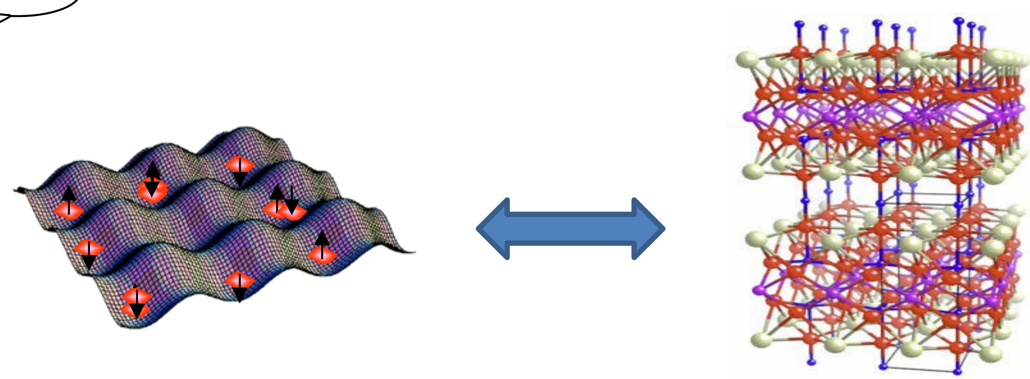
  The most precise measurements,
  e.g. clocks
  Quantum sensors

- A tool for understanding quantum complexity

Quantum simulation

Atomic Simulator

Richard Feynman



Atoms ↔ Electrons

Optical lattice ↔ Ionic Crystal

Ultra-cold atomic Simulator

Possible but challenging

Atoms heavier than electrons

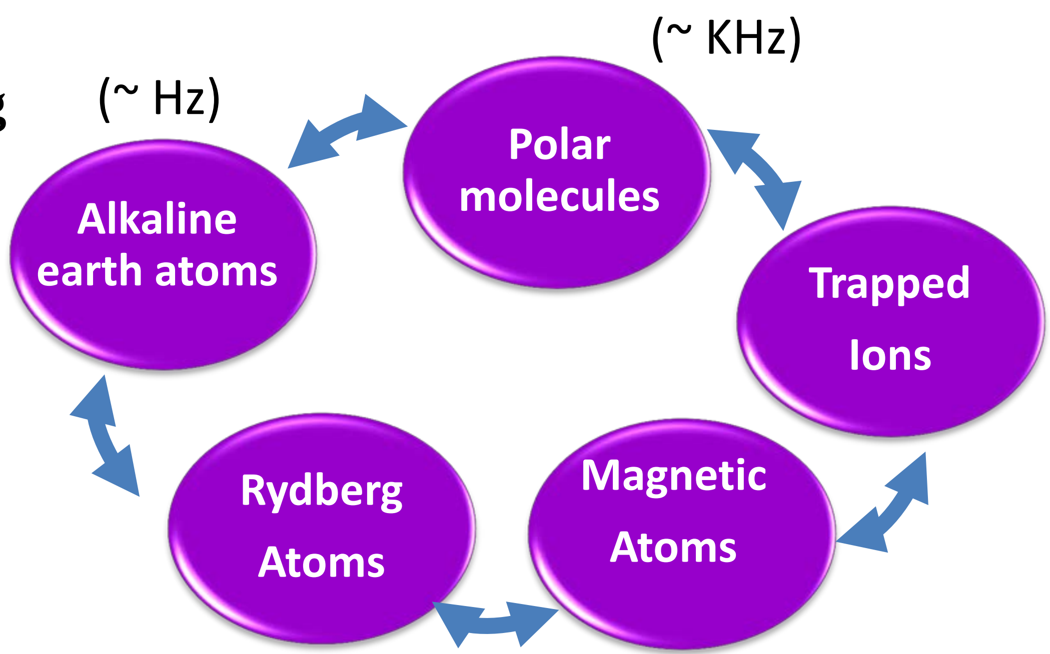
Optical lattice spacing much larger than ionic lattice spacing

→ **Extra low temperatures**

10^{-11} K in atomic systems ~ K in solid state systems

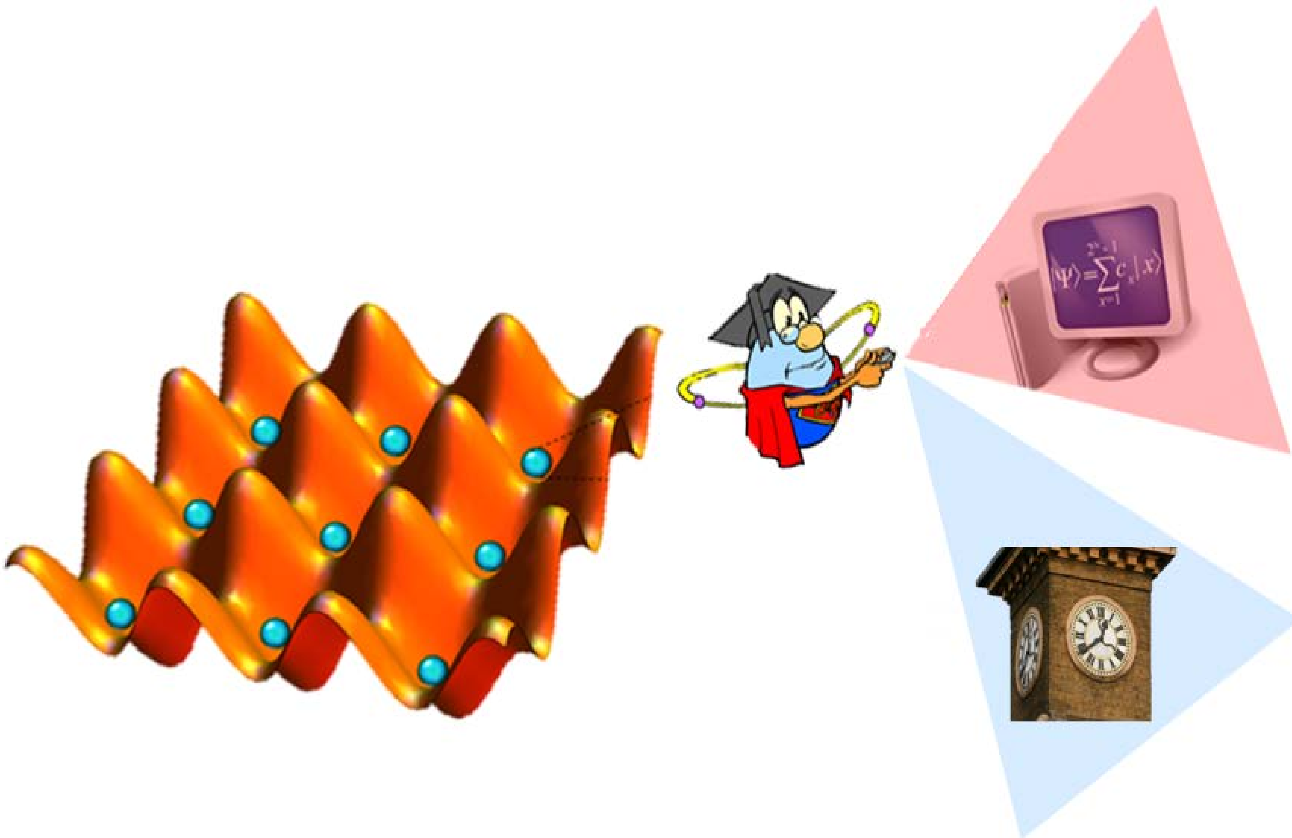
Solutions

- **Develop sophisticated cooling methods**
- **Explore new type of systems**
- **Take advantage of ultra-precise tools**



Many body physics with clocks

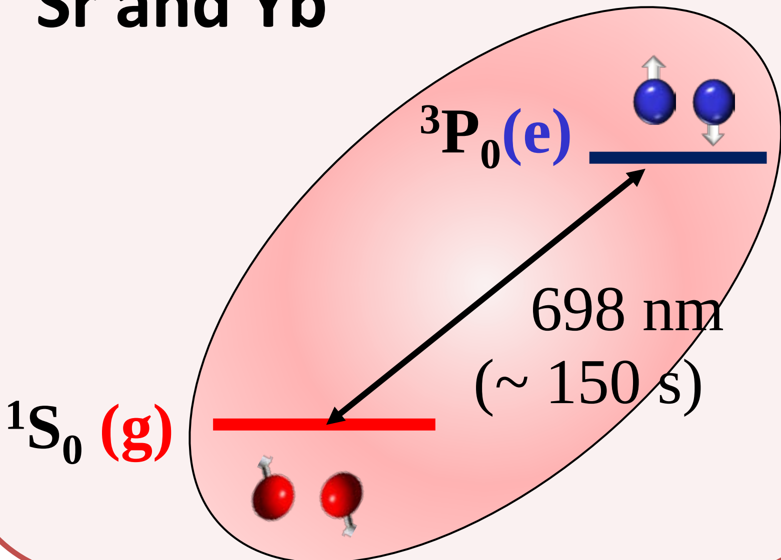
Understanding quantum systems from few- to many-body with “clock” precision and control



Alkaline earth – super coherence

Metastable state

Sr and Yb

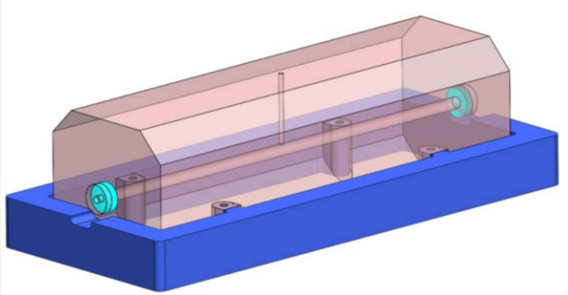


JILA Ultra-coherent spectroscopy:

Nicholson *et al*., Phys. Rev. Lett. 109 (2012) 230801

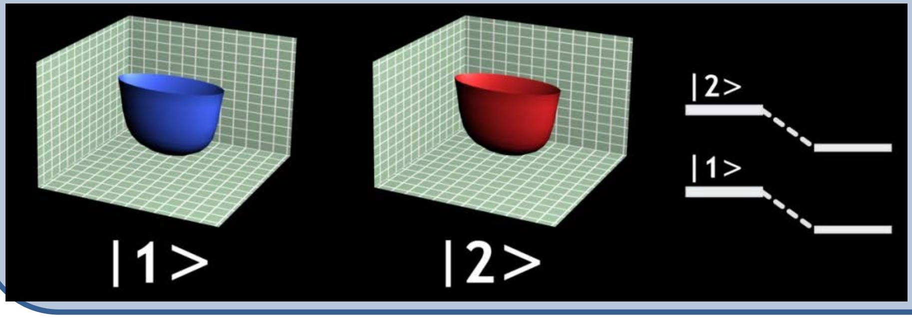
Ye's talk this afternoon

Q~10^{15}, seconds coherence time



Magic wave length

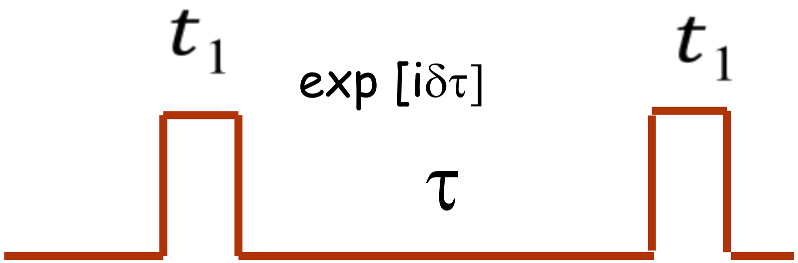
Ye, Kimble, & Katori, Science **320**, 1734 (2008).



No Doppler, No Recoil

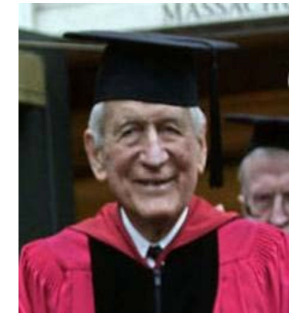
No Stark shift

Ramsey Spectroscopy

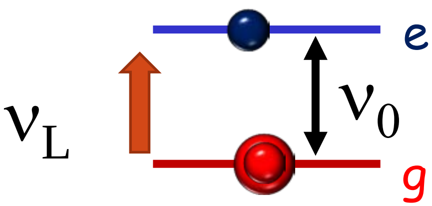


$B=2\pi(\nu_L - \nu_0)=\delta$

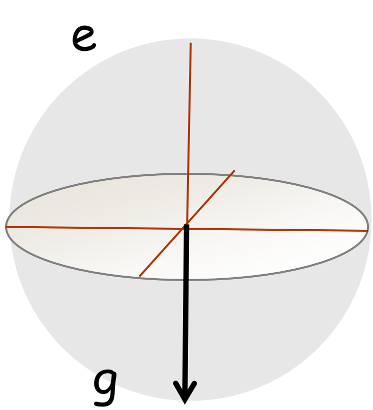
Measure # of e atoms

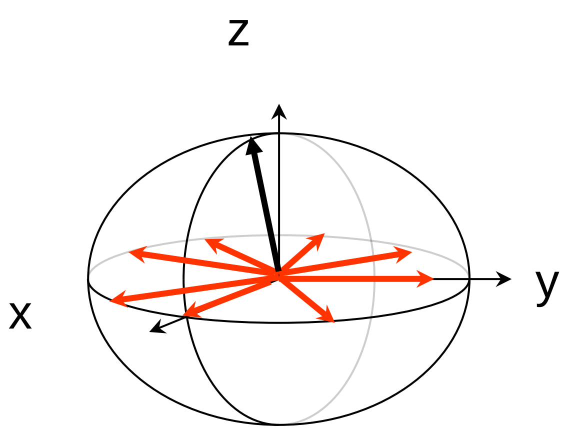


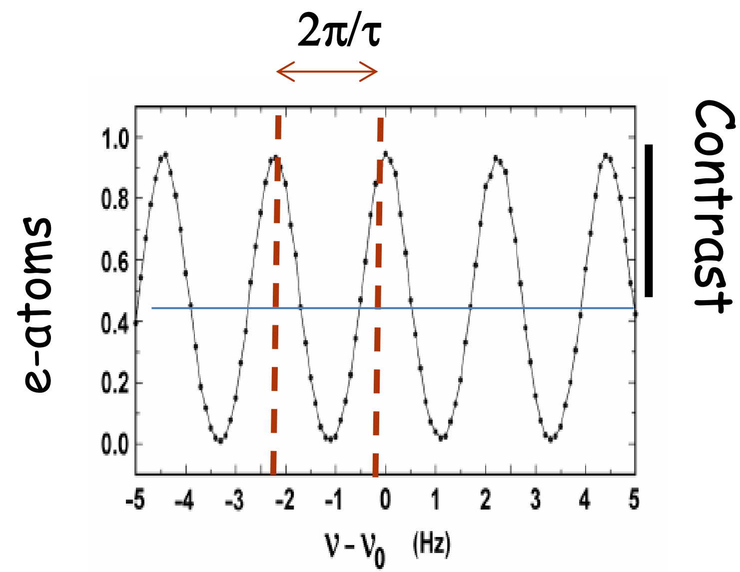
N. Ramsey. Nobel prize 1989



δ: Detuning





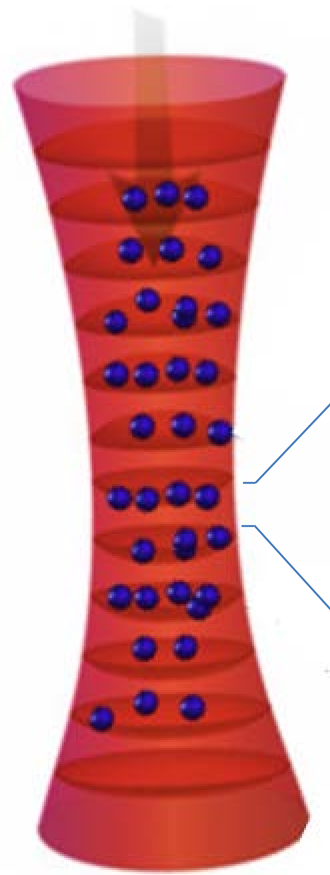


What happens in the real experiment with N particles?

Non-interacting: Collective-spin $S = N/2$ $S_{\mathbf{x,y,z}} = \sum_n S_{\mathbf{n}}^{x,y,z}$ Interactions?

$^3P_0$ (e) 1D lattice clock: @ T~μK

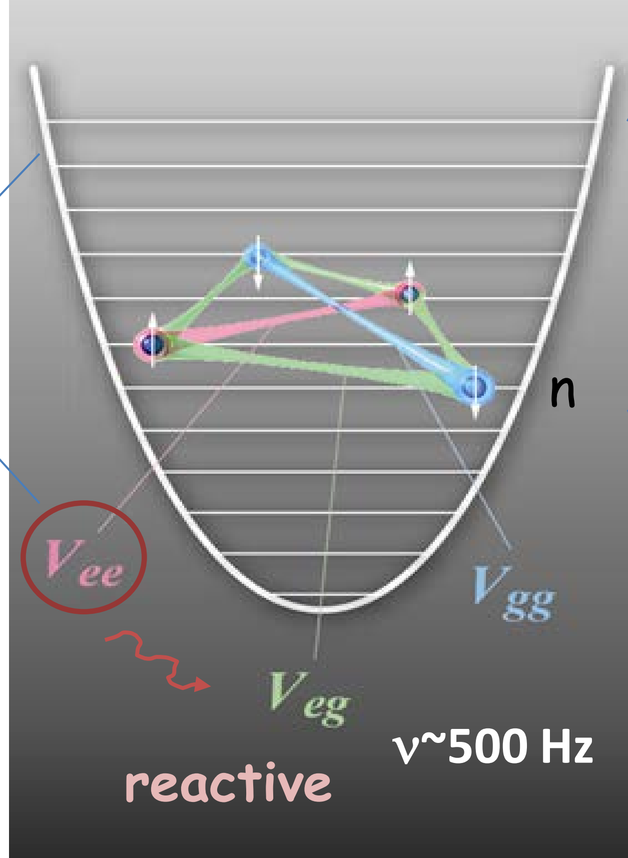
$^1S_0$ (g) Effective spin 1/2 system during clock interrogation



Array of pancakes

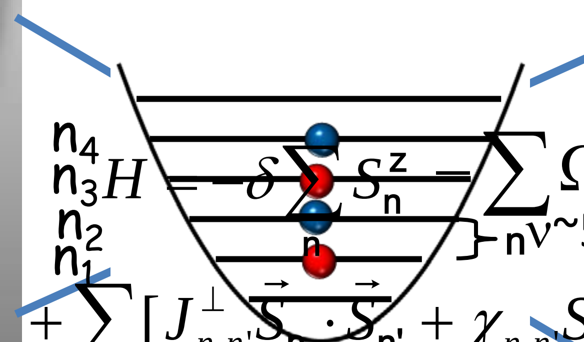
Dominant p-wave collisions

Both elastic and inelastic



Mode occupation is conserved. No laser/interaction induced mode changing collisions.

Decoupled motional/spin



$$H = -\delta \sum_n S_n^z - \sum_n \Omega_n S_n^x + \sum_{n,n'} [J^{\perp}_{n,n'} \vec{S}_n \cdot \vec{S}_{n'} + \chi_{n,n'} S_n^z S_{n'}^z + B_{n,n'} S_n^z]$$

ν~500 Hz, V~ 1 Hz

δ: Detuning

Ω_n: Rabi Frequency

Interaction parameters

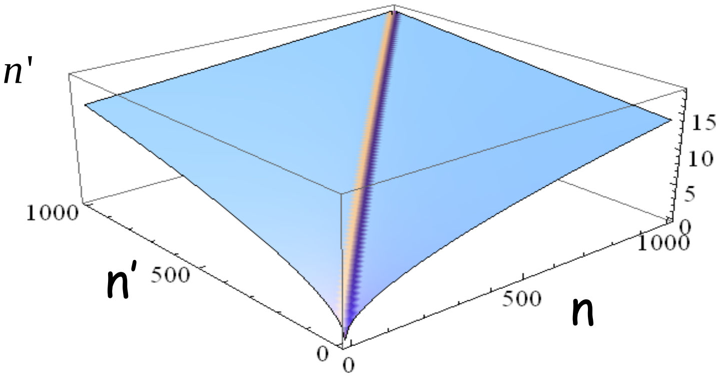
$$J^{\perp}_{n,n'} = \left(V^{eg}_{n,n'} - U^{eg}_{n,n'}\right)$$

$$\chi_{n,n'} = \left(2V^{eg}_{n,n'} - V^{ee}_{n,n'} - V^{gg}_{n,n'}\right)$$

$$B_{n,n'} = (V^{ee}_{n,n'} - V^{gg}_{n,n'})$$

Spin Model: Collective Mode approximation

$J^{\perp}_{n,n'}, \chi_{n,n'}$



$J^{\perp}_{n,n'}, B_{n,n'}, \chi_{n,n'} \rightarrow \bar{J}^{\perp} + \Delta J^{\perp}_{n,n'},$

$\bar{B} + \Delta B_{n,n'}$

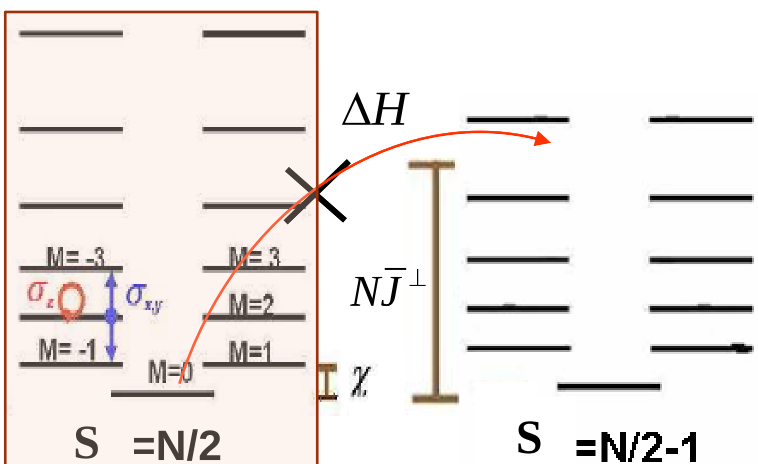
$\bar{\chi} + \Delta \chi_{n,n'}$

Long range!!

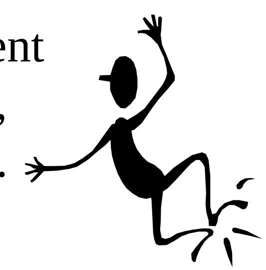
constant

$$H = -(\delta - (N-1)\bar{B})S_z - \bar{\Omega} S_x + \bar{J}^{\perp} \vec{S} \cdot \vec{S} + \bar{\chi} S_z^2 + \sum_{n.n'} \Delta H_{n,n'}$$

$$S_{x,y,z} = \sum_n S_n^{x,y,z}$$



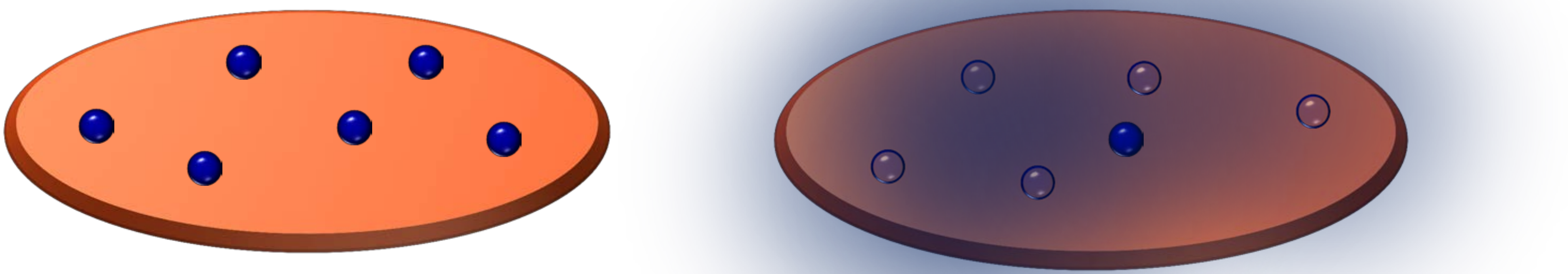
Same Hamiltonian that two component Bose Einstein Condensate: Sorensen, Moller, Cirac, Zoller, Lewenstein, …



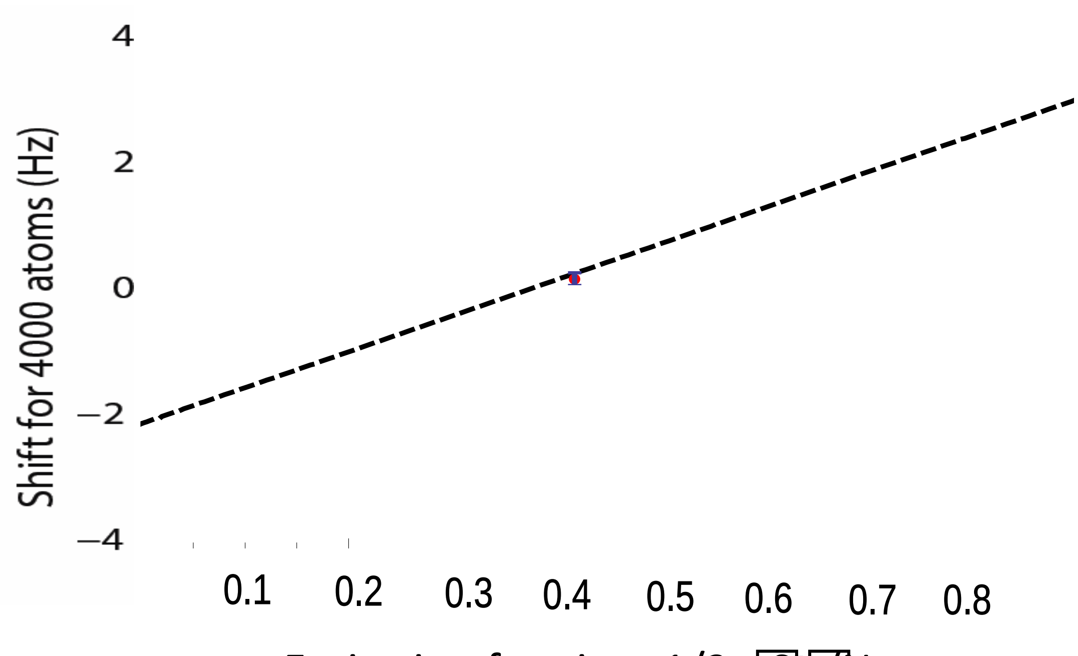
A. M. Rey, L. Jiang, M. Fleischhauer, E. Demler, and M. D. Lukin, PRA 77, 052305 (2008) .

Mean Field

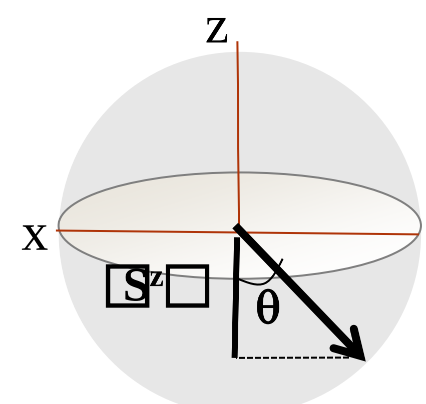
Treat other surrounding atoms as an average



$$H=-\chi(S^z)^2 \rightarrow 2\chi\langle S^z\rangle S^z = B\, S^z \qquad B=-2\chi\langle S^z\rangle = -N\chi\cos\theta$$



Spin precesses with a modified rate with depends on atom number



θ controlled by first pulse

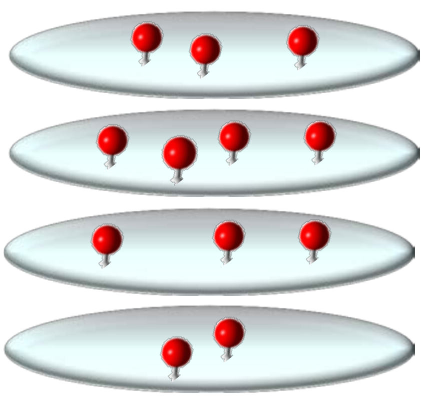
M. Martin *et al* arXiv:1212.6291

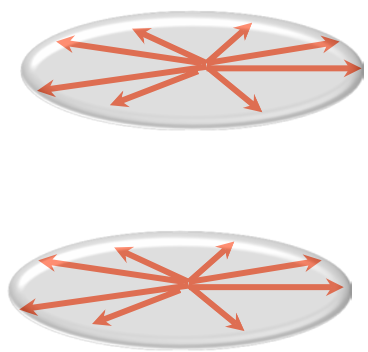
Quantum correlations – beyond mean field

Quantum correlations should manifest on the amplitude of the oscillations

- At the mean field level interactions only affect the precession rate.
- Amplitude remains constant

But….. in the experiments there are many pancakes with different atom number. Due to interactions the pancakes with more atoms precess faster.





Signal adds → amplitude of the oscillations decay due to dephasing or destructive interference between pancakes

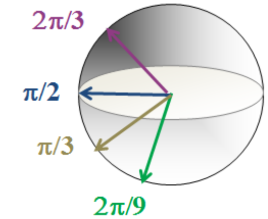
- Atom number decay aslo leads to decay of the amplitude

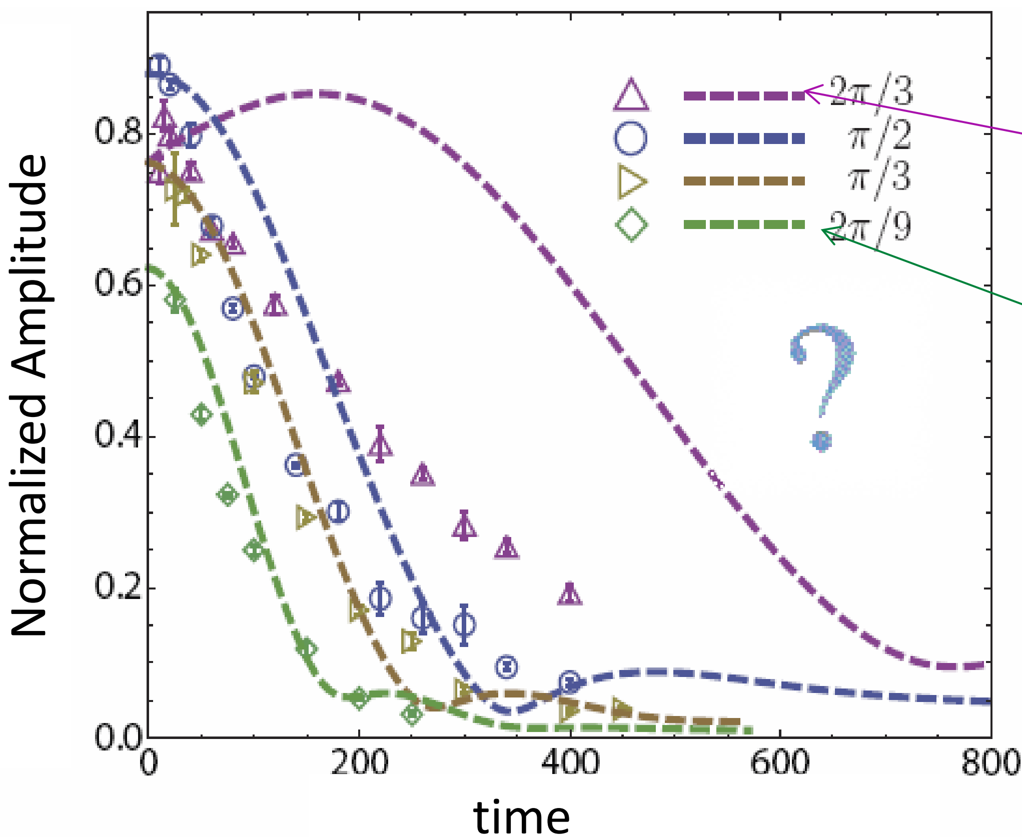
M. Martin *et al* arXiv:1212.6291

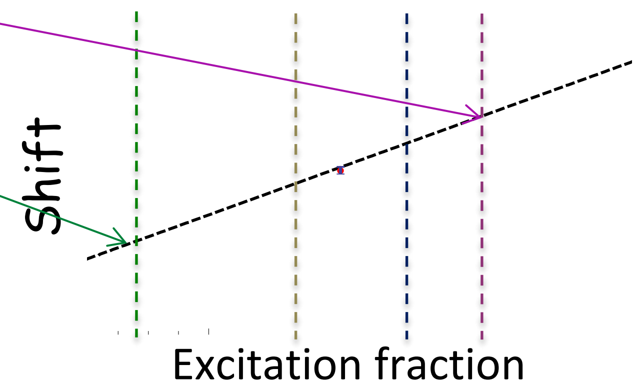
Comparisons with experiment

Ramsey fringe decay vs. the spin tipping angle

To eliminate the effect of decay we normalize the amplitude with atom number





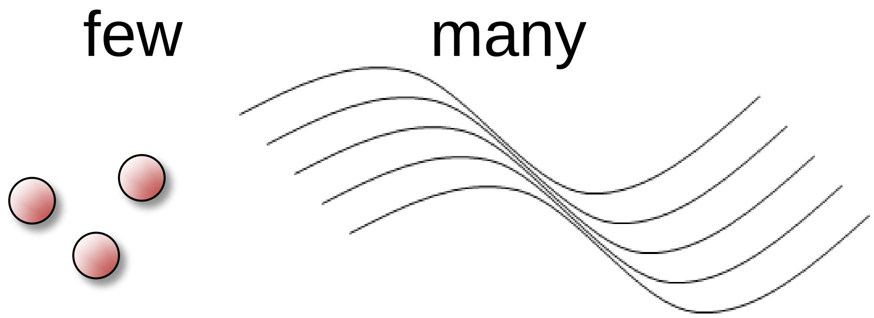


Mean filed fails to reproduce the amplitude decay at tipping angles where the density shift vanishes

M. Martin *et al* arXiv:1212.6291

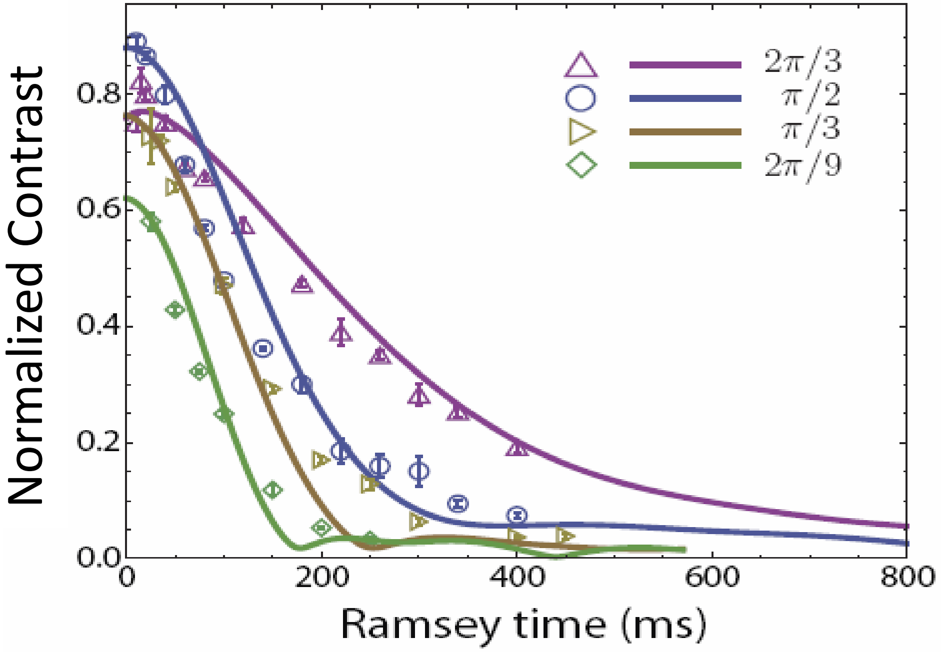
Quantum fluctuations – beyond mean field

Interplay between interactions and decoherence: complicated

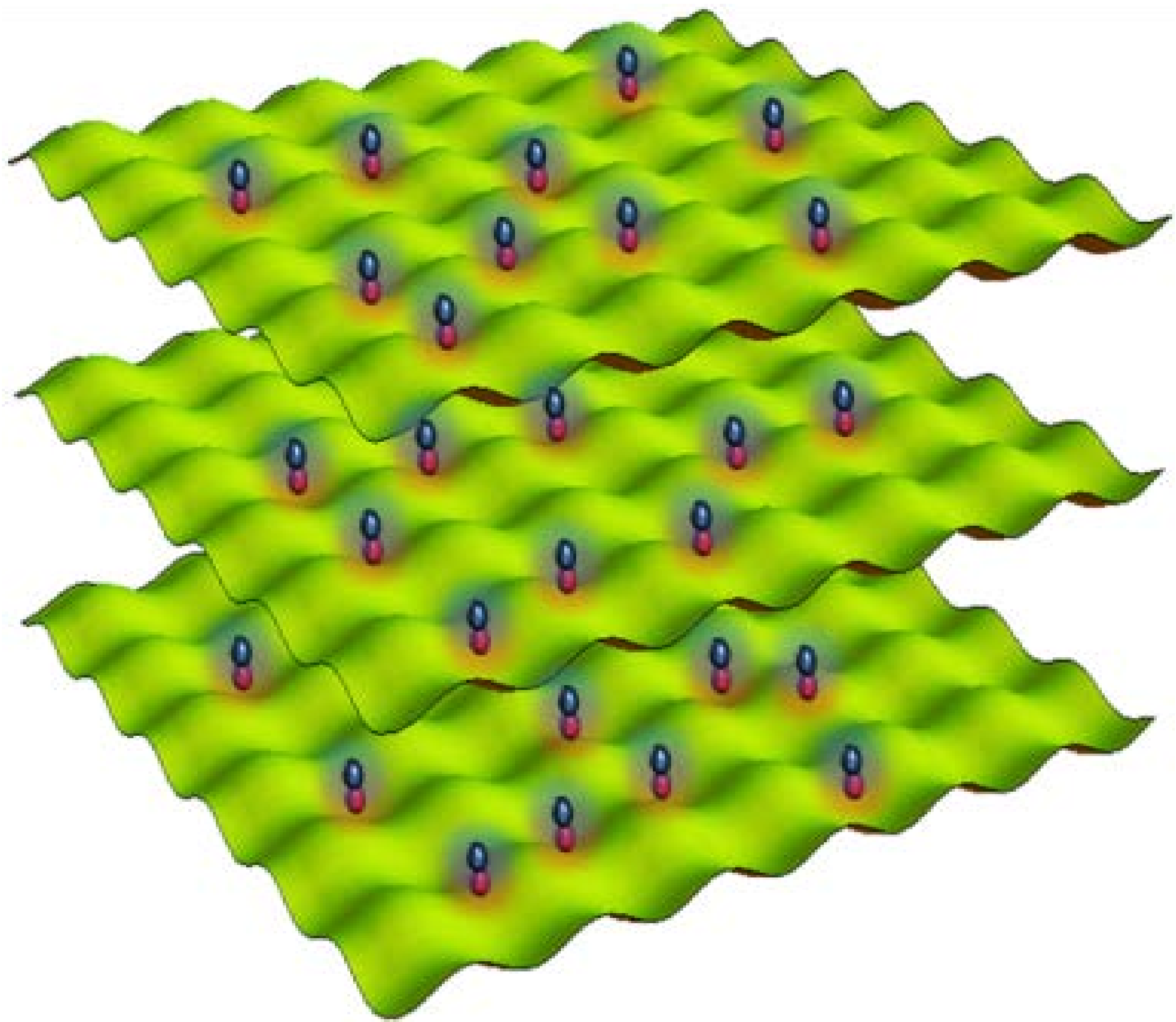


Quantum correlations induce faster decay of the amplitude

We were able to solve the full master Eq for the collective model.



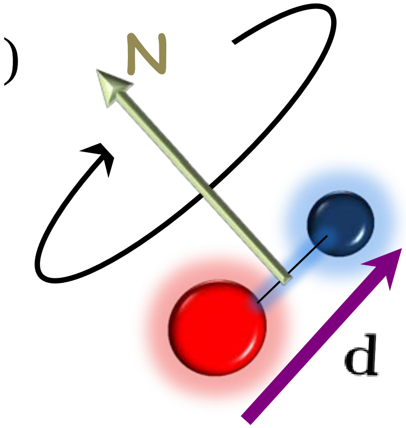
Polar molecules



Quantum Magnetism

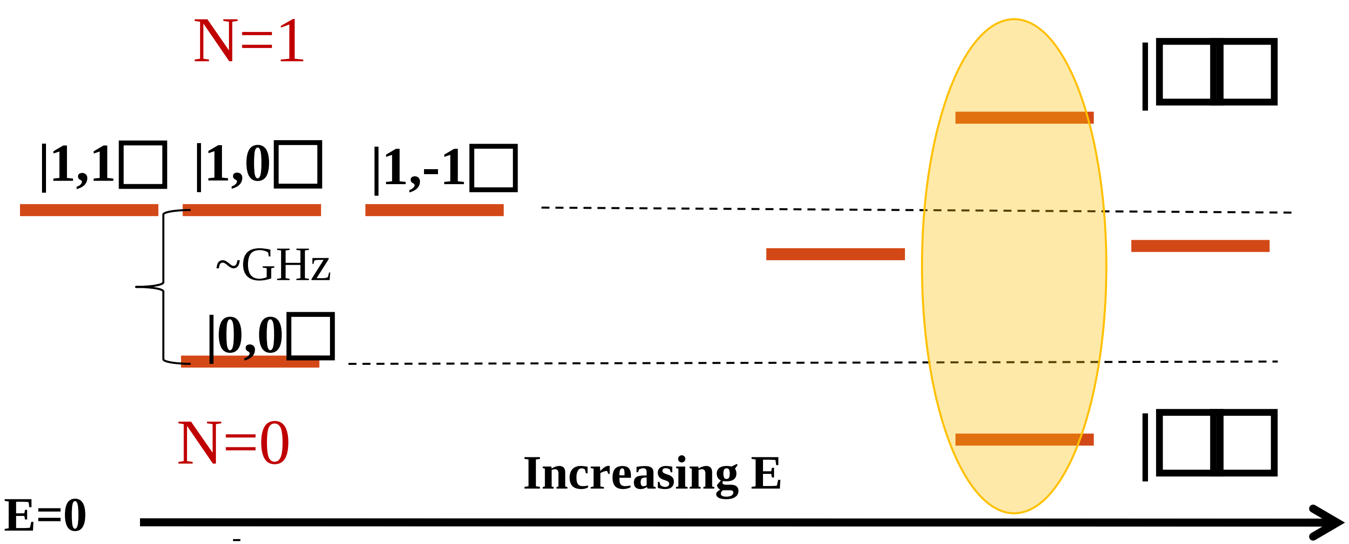
Gorshkov *et al*: PRL.107.115301(2011), PRA 84,033619 (2011)

Rotation $\Rightarrow$ "spin"



dipole moment

Rigid Rotor $H_i^{rot} = BN_i^2 - \vec{d}_i \cdot \vec{E}$

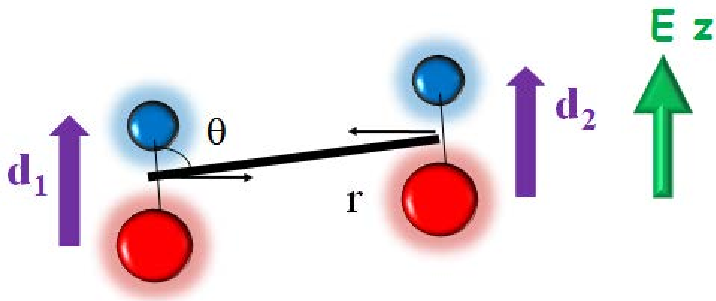


Select two dressed levels : Effective spin ½ system

Related previous work

Other schemes: *Micheli* et al, *Nat. Phys.* ***2*** *341 (2006); Brennen* et al, *NJP* ***9*** *138 (2007); Buechler* et al, *Nat. Phys.* ***3*** *726 (2007); Perez-Rios*, et al *NJP* ***12****, 103007; Wall-Carr Phys. Rev. A 82, 013611 (2010)…*

Spin model: Frozen molecules in a lattice



$$H_{dd} = d_i d_j V_{dd}^{ij} \qquad V_{dd}^{ij} = \frac{(1-3\cos^2\theta)}{|r_i - r_j|^3}$$

- Project d_i on the two selected rotational levels

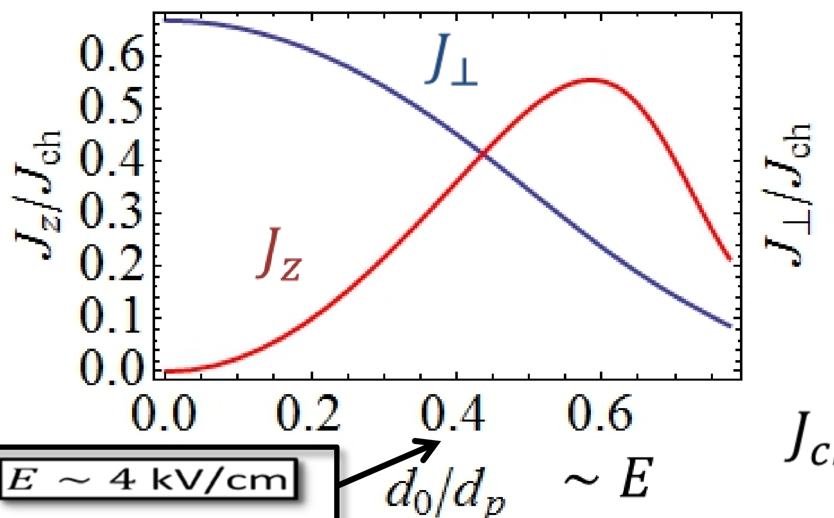
$$|\uparrow\rangle = |N=1, M=0\rangle$$

$$|\downarrow\rangle = |N=0, M=0\rangle$$

$$d_i = \hat{z}\sum_{\sigma,\sigma'} d_{\sigma,\sigma'} |\sigma_i\rangle\langle\sigma_i'| \quad d_{\sigma\sigma'} = \langle\sigma|d|\sigma'\rangle$$

$$H_{dd} = \sum_{i,j} V_{dd}^{ij}\left[J_z(d_{\sigma\sigma'}) S_i^z S_j^z + J_\perp(d_{\sigma\sigma'})\left(S_i^x S_j^x + S_i^y S_j^y\right)\right]$$

Ising **Flip-flop**



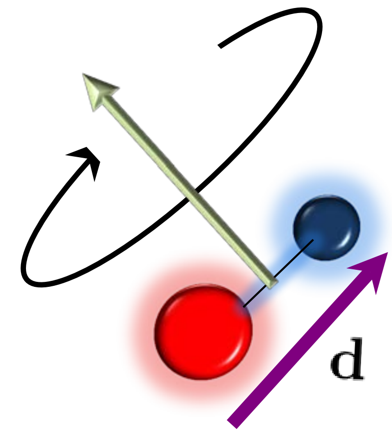
$E \sim 4$ kV/cm

$$J_\perp = 2(d_{\uparrow\downarrow})^2$$

$$J_z = (d_{\uparrow\uparrow} - d_{\downarrow\downarrow})^2$$

$J_{ch} \sim 2\pi \times 250$Hz → 1ms

Quantum Magnetism



- Use direct dipole-dipole interaction to generate direct strong (~KHz) spin exchange interaction:

  10-100 larger than super-exchange or magnetic dipoles

- Fully tunable coefficients by E field (microwaves)

  Gorshkov *et al*: PRL.107.115301(2011),
  PRA 84,033619 (2011)

- Long-range ($1/r^3$) and anisotropic interactions:

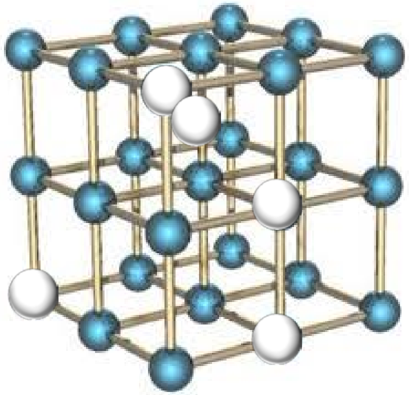
  S. R. Manmana *et al* PRB 87, 081106(R) (2013),
  A. V. Gorshkov *et al* arXiv:1301.5636

- Spin *temperature*, not motional *temperature* matters:

  Relevant ratio is interaction time (~ms) to cloud lifetime (25 sec!):
  K. R.A. Hazzard et al PRL 110, 075301 (2013)

Filling factor: f

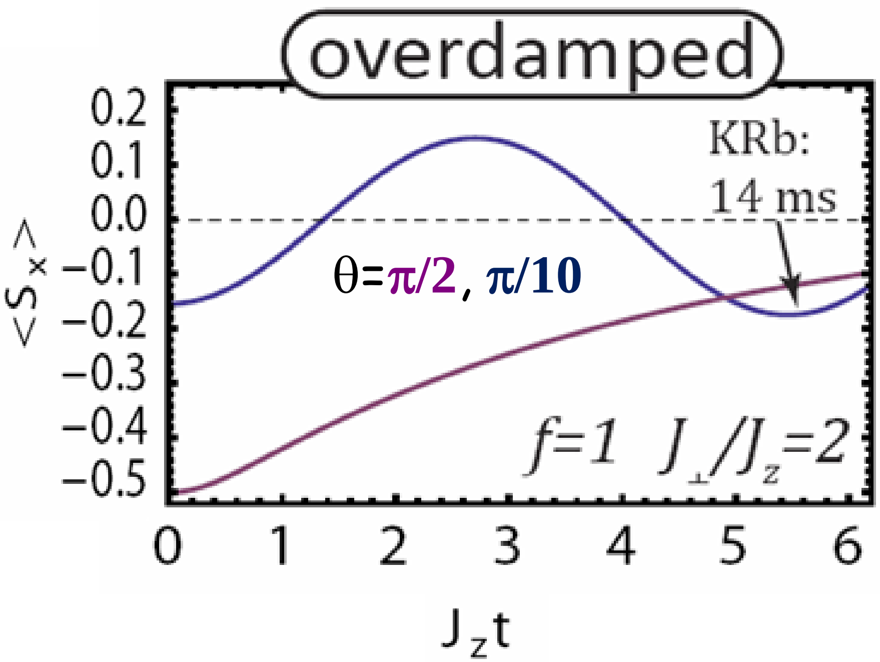
- Empty sites act as defects
- Need to perform disorder average

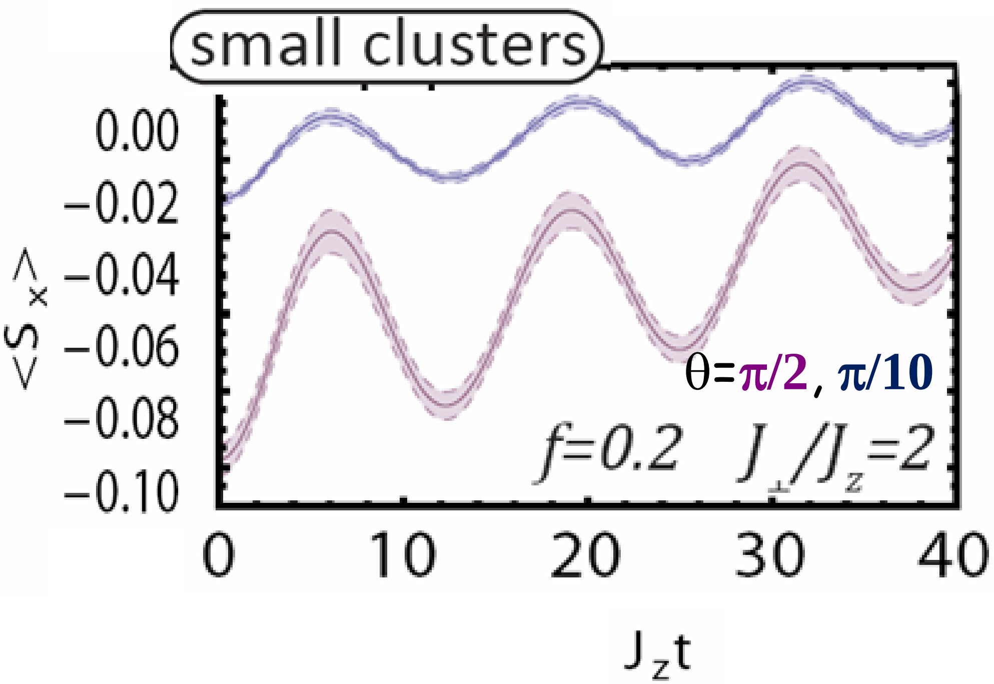


Dipolar interactions will be visible in the Ramsey fringe contrast even in dilute samples

Full solution 1D-DMRG

K. R.A. Hazzard et al PRL 110, 075301 (2013)





3D-KRb lattice experiment

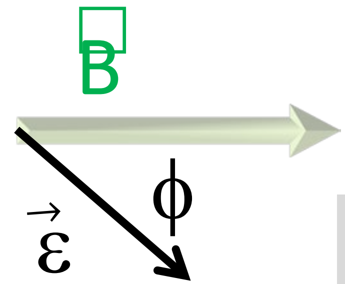
Current experiments are carried out in a 3D lattice with a B field

B: determines quantization axis

|□□⟩ = |N=1,M=-1□

|□□⟩ = |N=0,M=0□

Polarization trapping light

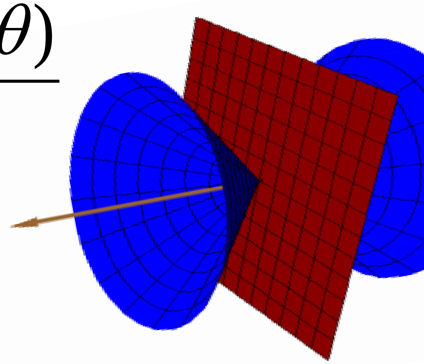


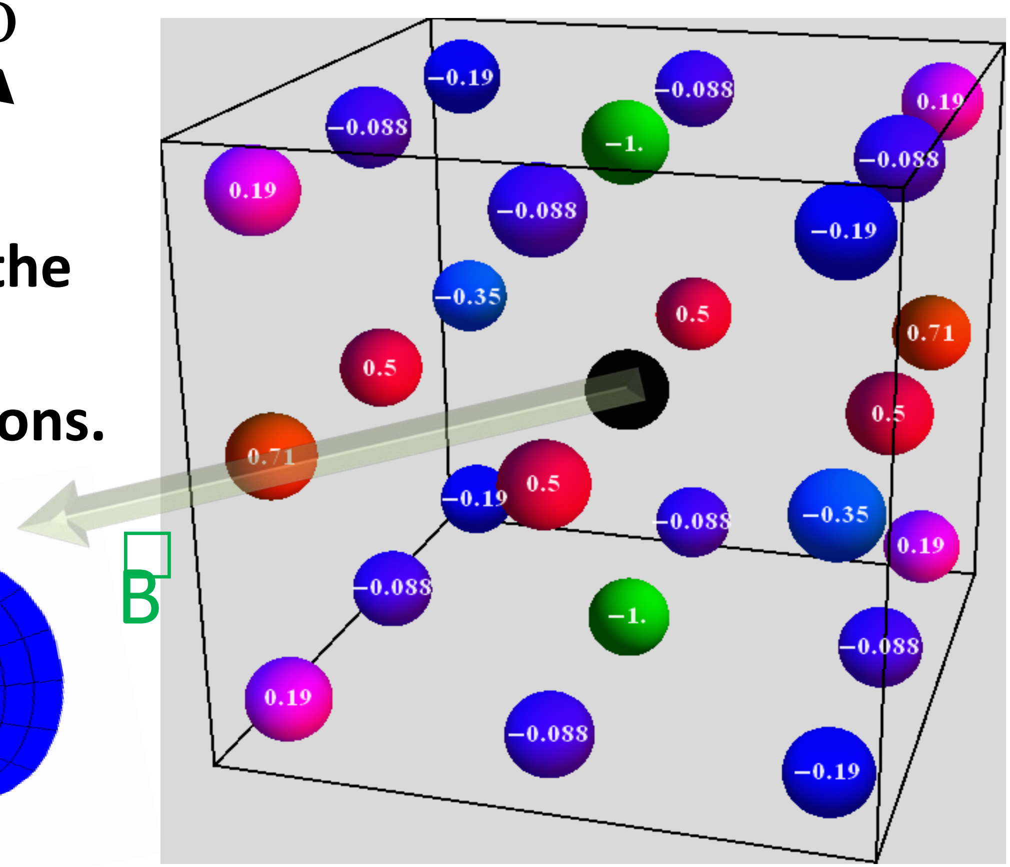
Magic wavelength for their lattice

B. Neyenhuis *et al* Phys. Rev. Lett. 109, 230403 (2012)

- **Non-trivial dependence on the geometry due to the anisotropic dipolar interactions.**

$$V_{dd}^{ij} = \frac{(1-3\cos^2\theta)}{|r_i - r_j|^3}$$

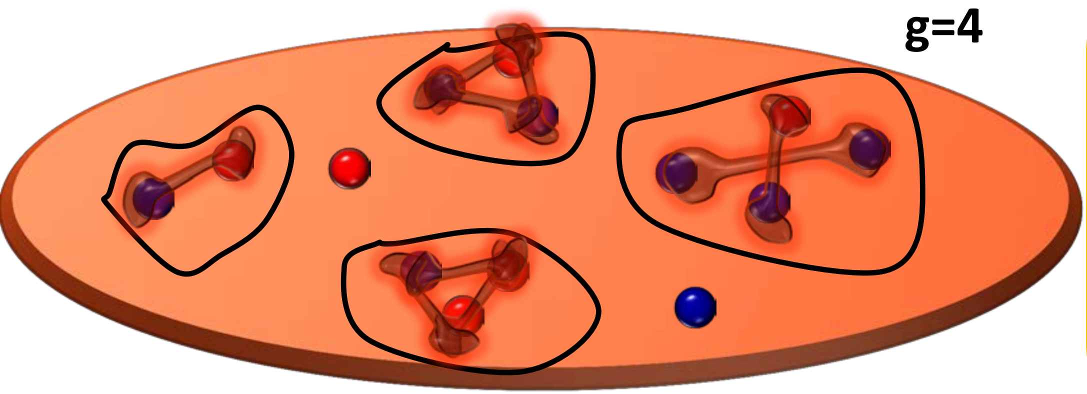




3D-lattice experiment in B field

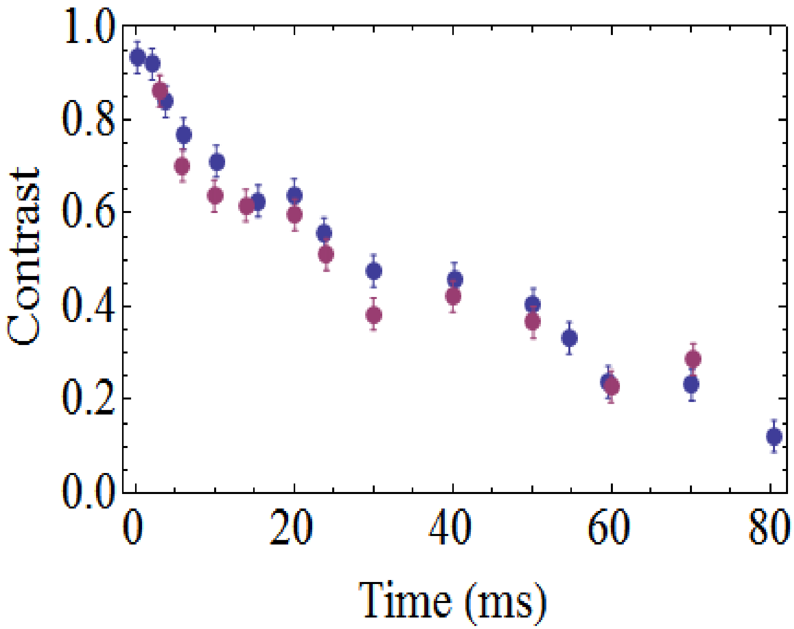
$$H = J_{\perp} \sum_{<i,j>} V_{ij}\left[S^{x}{}_{i}S^{x}{}_{j} + S^{y}{}_{i}S^{y}{}_{j}\right] \qquad J_{\perp} = -(d_{\uparrow\downarrow})^2$$

Cluster Expansion

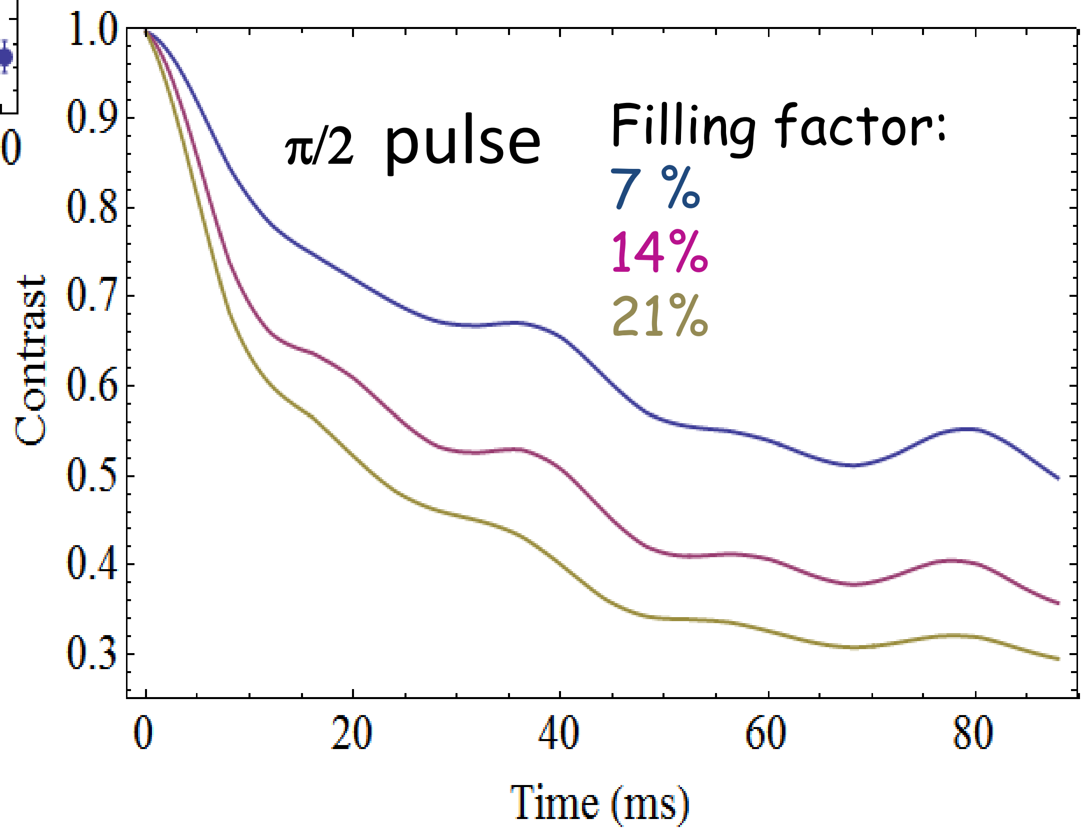


- Spins grouped in cluster of max size g.
- Intra-cluster interactions kept
- Inter-cluster interactions neglected or treated as a perturbation.

Preliminary comparisons with experiment

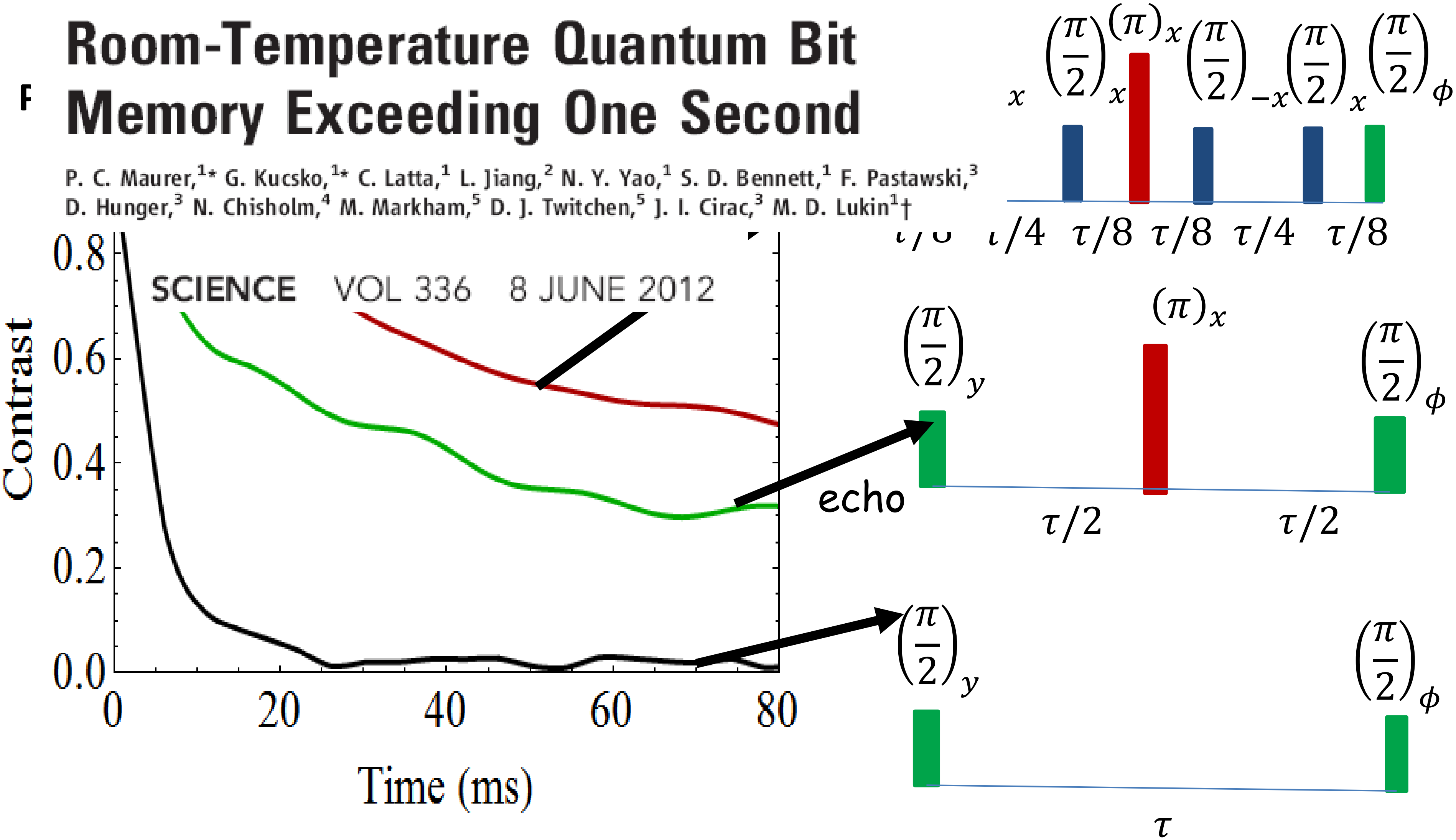


Solid lines: Cluster expansion g=10
Gaussian distribution:



Dynamical decoupling

Learn from NMR: By applying the proper pulse sequence it is possible to eliminate dipolar interactions.



Conclusions

- Ultra-cold polar matter offers a unique controllable laboratory for the exploration of many-body physics

Strongly interacting open driven quantum systems

- Manifestation of quantum magnetism observable even in a non-quantum degenerate gas

- Rich physics a lot to be understood

Thanks