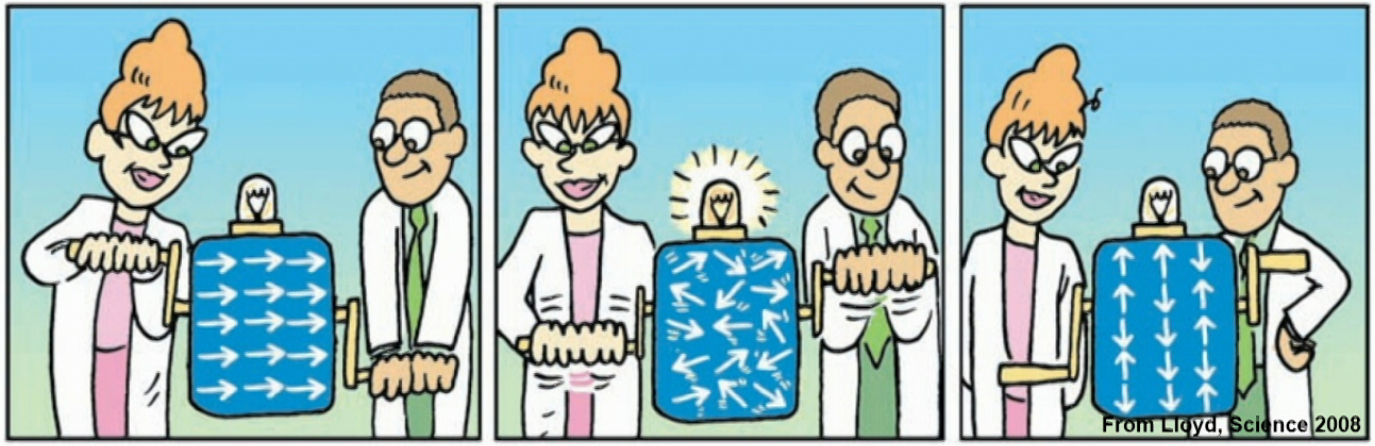
Title: Quantum simulation with laser-cooled trapped ions

Date: Feb 22, 2017 02:00 PM

URL: http://pirsa.org/17020012

Abstract: Laser-cooled trapped ions are among the most versatile experimental platforms for exploring quantum information. In this talk, I will give a brief overview of this system and its capabilities to simulate non-trivial interacting quantum models. Internal states of these ions, such as hyperfine states, constitute well isolated qubit (or spin-1/2) states, with quantum coherence demonstrated up to fifteen minutes. Individual qubits states can be detected by laser beams with near perfection. Quantum logic gates and interacting spin Hamiltonians are engineered by coupling internal states of multiple ions to their collective vibrational modes using optical forces. By suitably tailoring these spin-phonon couplings, interactions between ion-spins can be tuned in magnitude, range, and sign. The laboratory for Quantum Information with Trapped Ions at IQC aims to build a highly flexible quantum simulator with dozens of spins, and explore problems in quantum information and many-body physics in a regime that is intractable with classical computers.

Quantum Simulation with Laser-cooled Trapped Ions



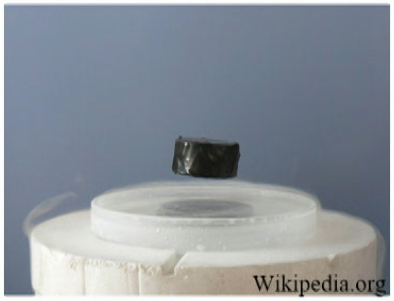
K. Rajibul Islam

research.iqc.uwaterloo.ca/qiti/

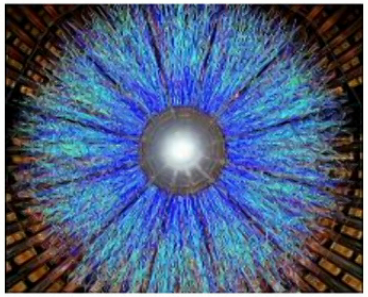
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Perimeter Institute for Theoretical Physics Feb 22, 2017

Strongly interacting quantum systems



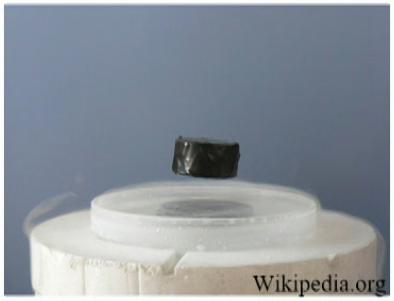
High Temperature superconductor



Quark Gluon ‘plasma’

Microscopic description?

Strongly interacting quantum systems



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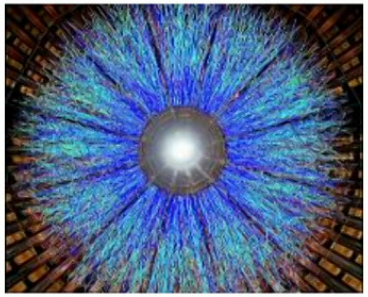
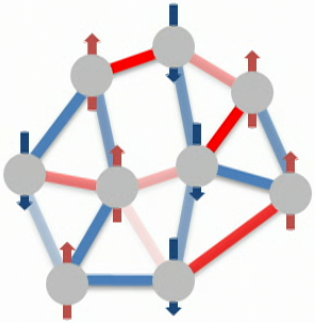


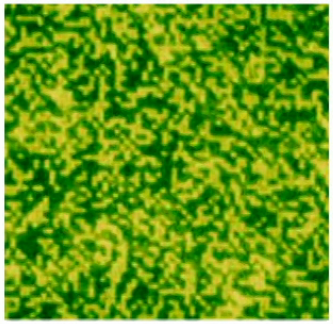
Quark Gluon ‘plasma’

Microscopic description?

Macroscopic phenomenon?



Spin network



Interacting atoms

Quantum Superposition

Exponential growth of Hilbert space

Exponential growth of Hilbert space
For *N* qubits - No. of states = 2^N

N = 40 2^{40} ~ 1 Tb

Quantum Superposition

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Entanglement

Quantum Superposition

Exponential growth of Hilbert space

Exponential growth of Hilbert space
For *N* qubits - No. of states = 2^N

N = 40 2^{40} ~ 1 Tb

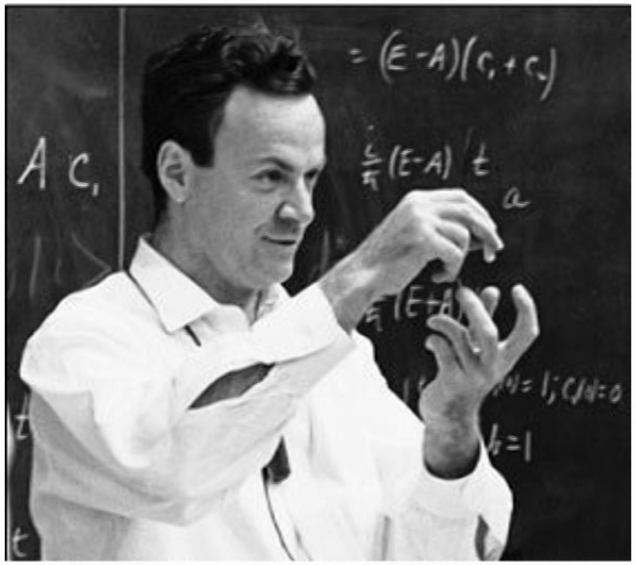
Entanglement

Growth of Entanglement – hard to compute

Solving Quantum dynamics of interacting spin models
currently limited to about 30 - 40 spins.

Quantum Simulation

One quantum system mimics another



International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

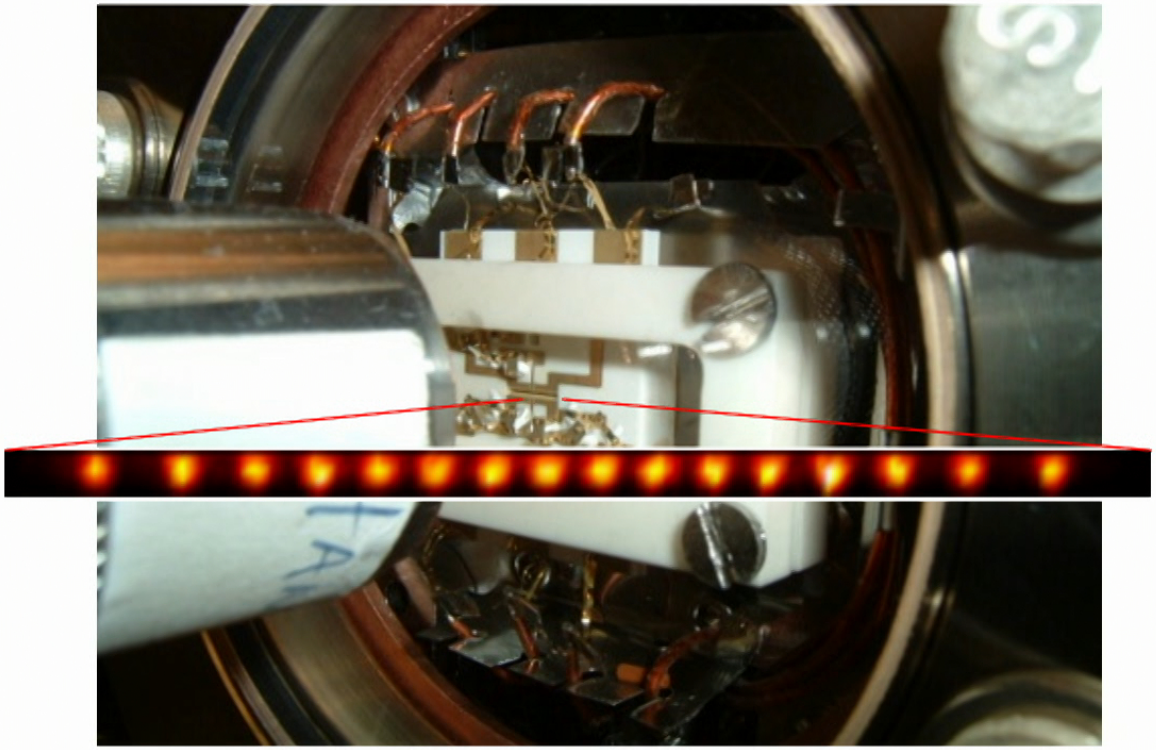
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

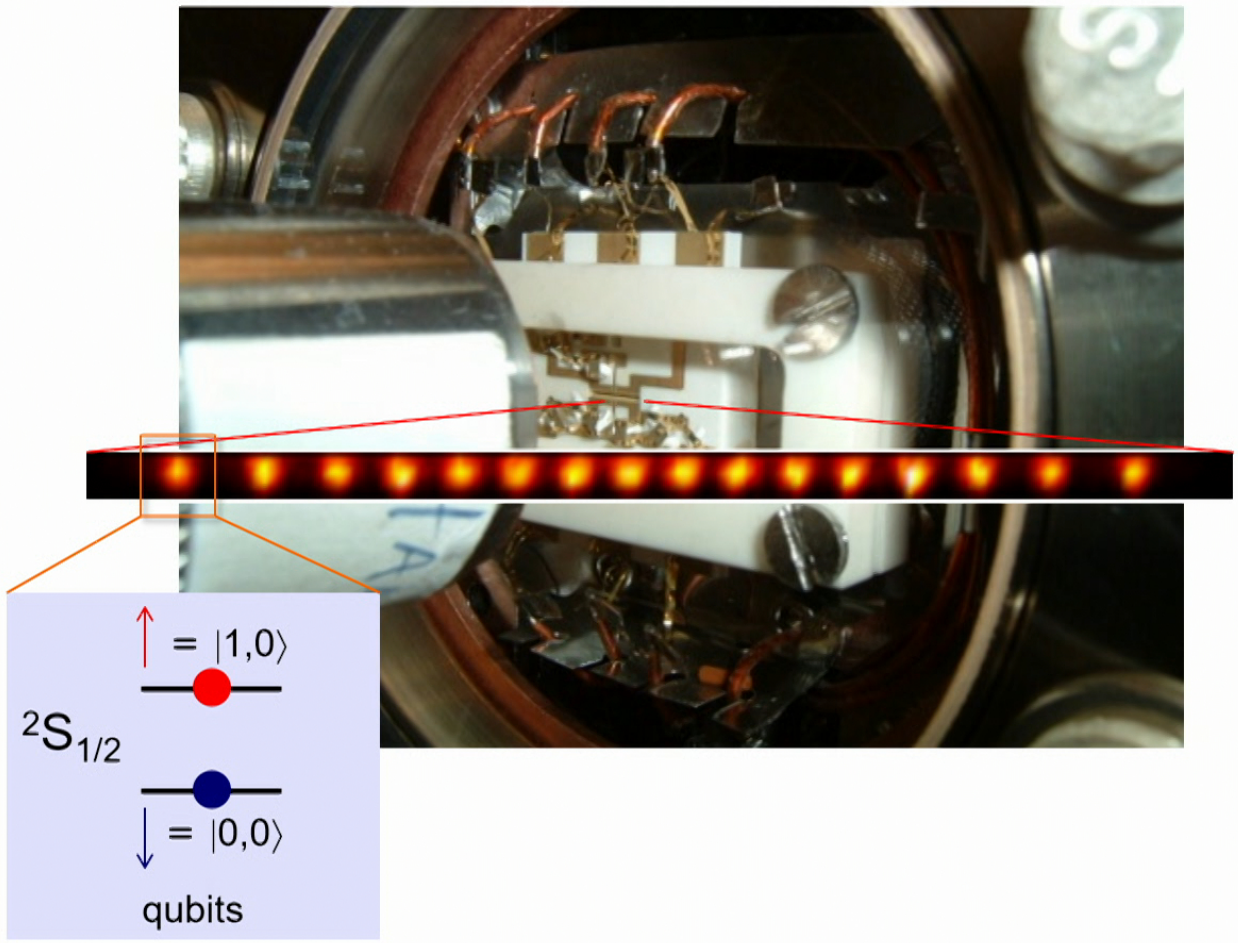
"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."

Foundational work by Lloyd, Science (1996)

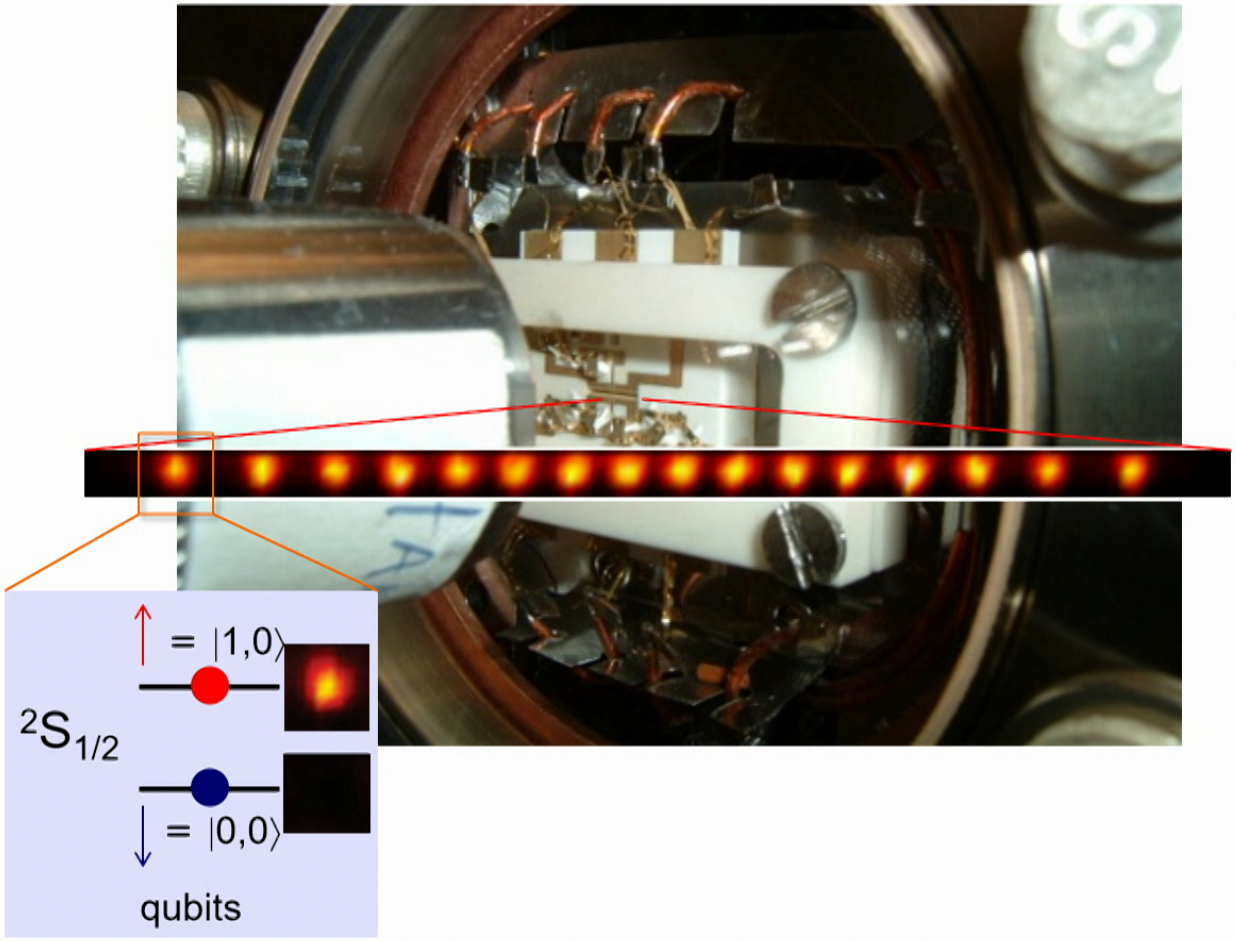
Quantum Simulation



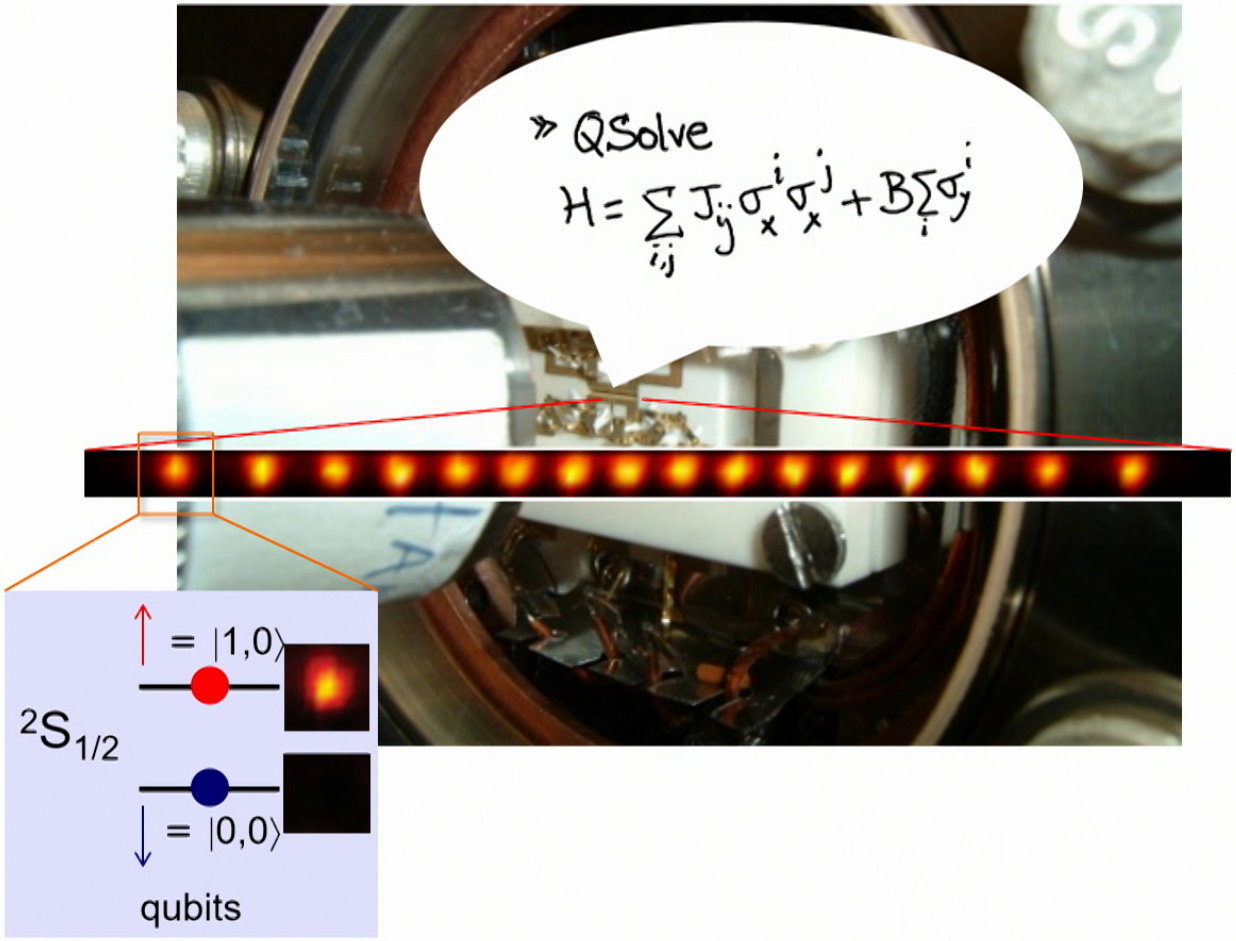
Quantum Simulation



Quantum Simulation

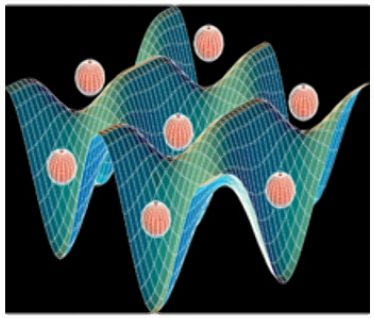


Quantum Simulation

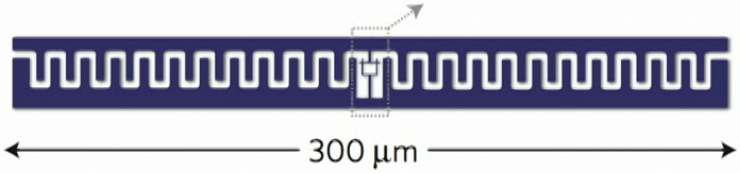


Quantum Simulation : Platforms

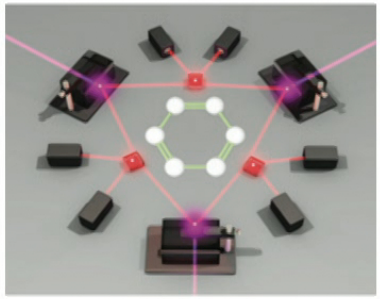
Trapped ions
Nature Physics 8, 277–284 (2012)



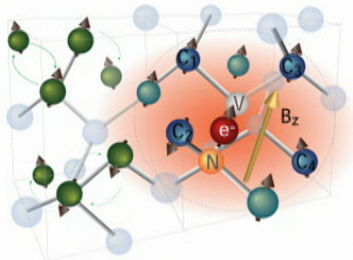
Neutral atoms
in optical lattices
Nature Physics 8,
267–276 (2012)



Superconducting circuits
Nature Physics 8,
292–299 (2012)

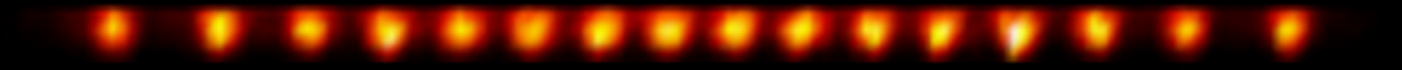


Photonic
networks
Nature Physics
8, 285–291 (2012)



NV defects in diamonds
Physics Today 67(10), 38(2014)

Features of cold atomic systems



- All qubits are identical
- Well isolated from the environment (levitated in vacuum)
- Access to laser-cooling techniques (~ few milliseconds to cool to ground state)
- Slow dynamical time scales (energy scales are kHz - MHz)
- Extreme dilution – optical imaging (length scale ~ micron)

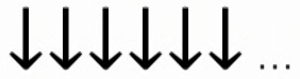
Trapped ions as a quantum simulator

1. Well-defined spin states/qubits

Also called Divincenzo's criteria in the context of Quantum Computation

Trapped ions as a quantum simulator

1. Well-defined spin states/qubits

2. Initialization of spin states 

Trapped ions as a quantum simulator

1. Well-defined spin states/qubits

2. Initialization of spin states

3. Tunable interactions

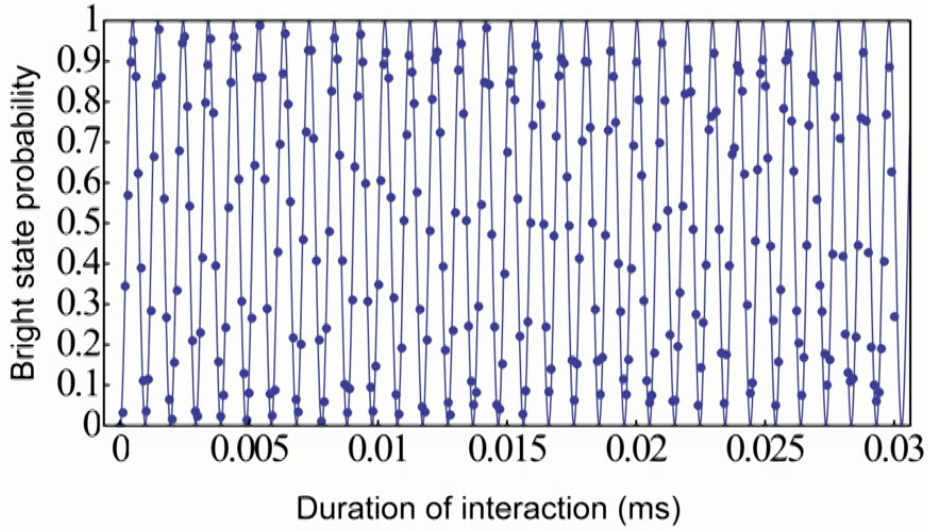
   Quantum Ising, XY, XYZ, …

   Controlled coupling (range, magnitude, sign)

   Synthetic fields

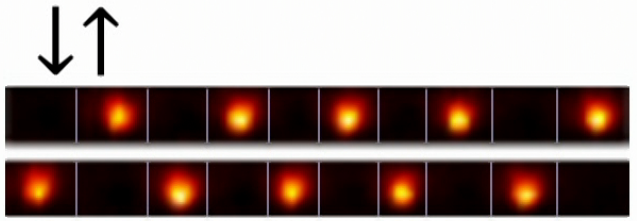
Trapped ions as a quantum simulator

1. Well-defined spin states/qubits
2. Initialization of spin states
3. Tunable interactions
4. Quantum coherence

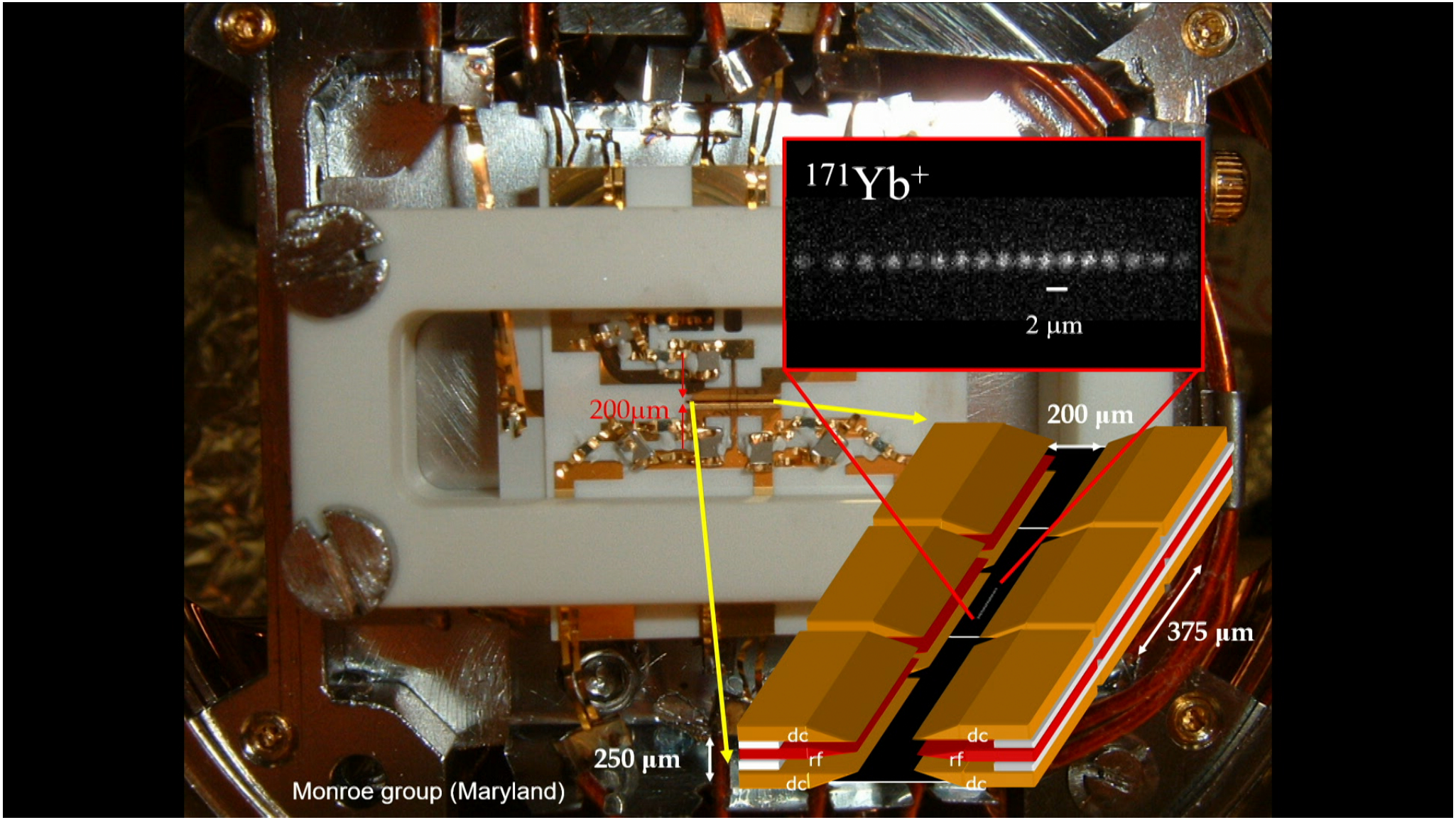


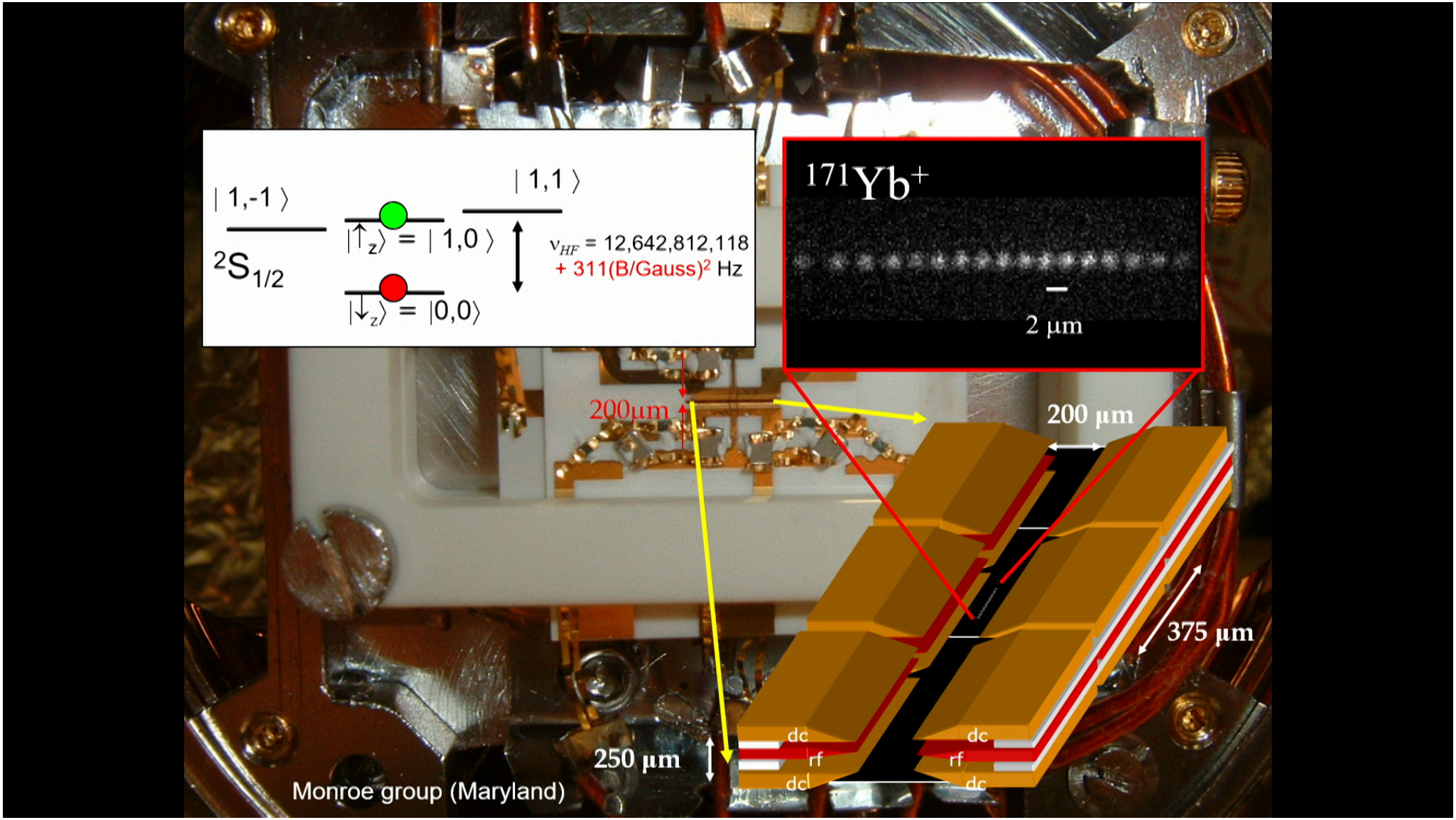
Trapped ions as a quantum simulator

1. Well-defined spin states/qubits
2. Initialization of spin states
3. Tunable interactions
4. Quantum coherence
5. Detection of spin states



Building a quantum simulator with trapped ions


$^{171}Yb^{+}$
2 μm
200μm
200 μm
375 μm
250 μm
dc
rf
dc
dc
rf
dc
Monroe group (Maryland)


| 1,-1 ⟩
| 1,1 ⟩
$^2S_{1/2}$
$|\uparrow_z\rangle = |1,0\rangle$
$|\downarrow_z\rangle = |0,0\rangle$
ν_{HF} = 12,642,812,118
+ 311(B/Gauss)^2 Hz
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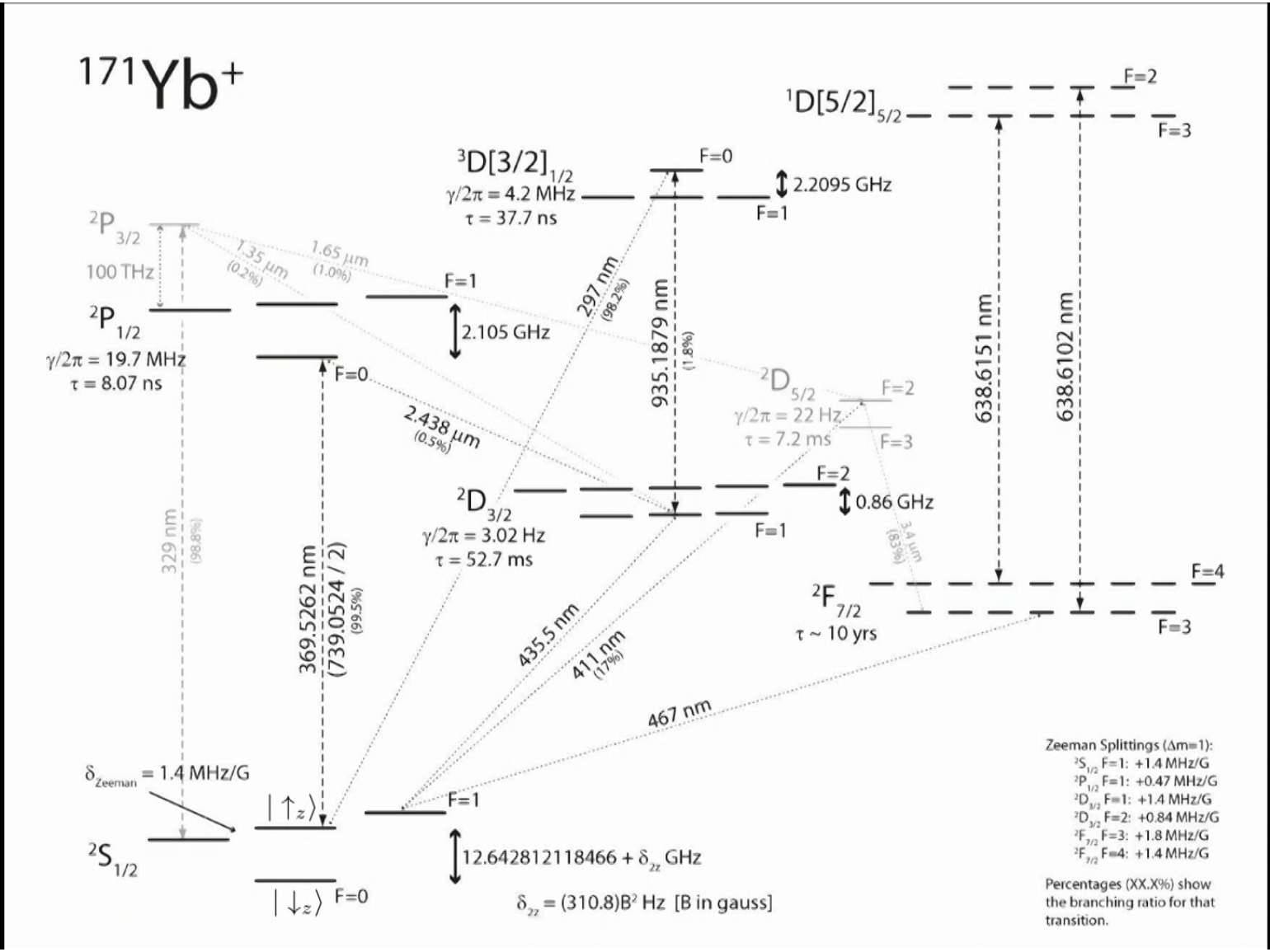
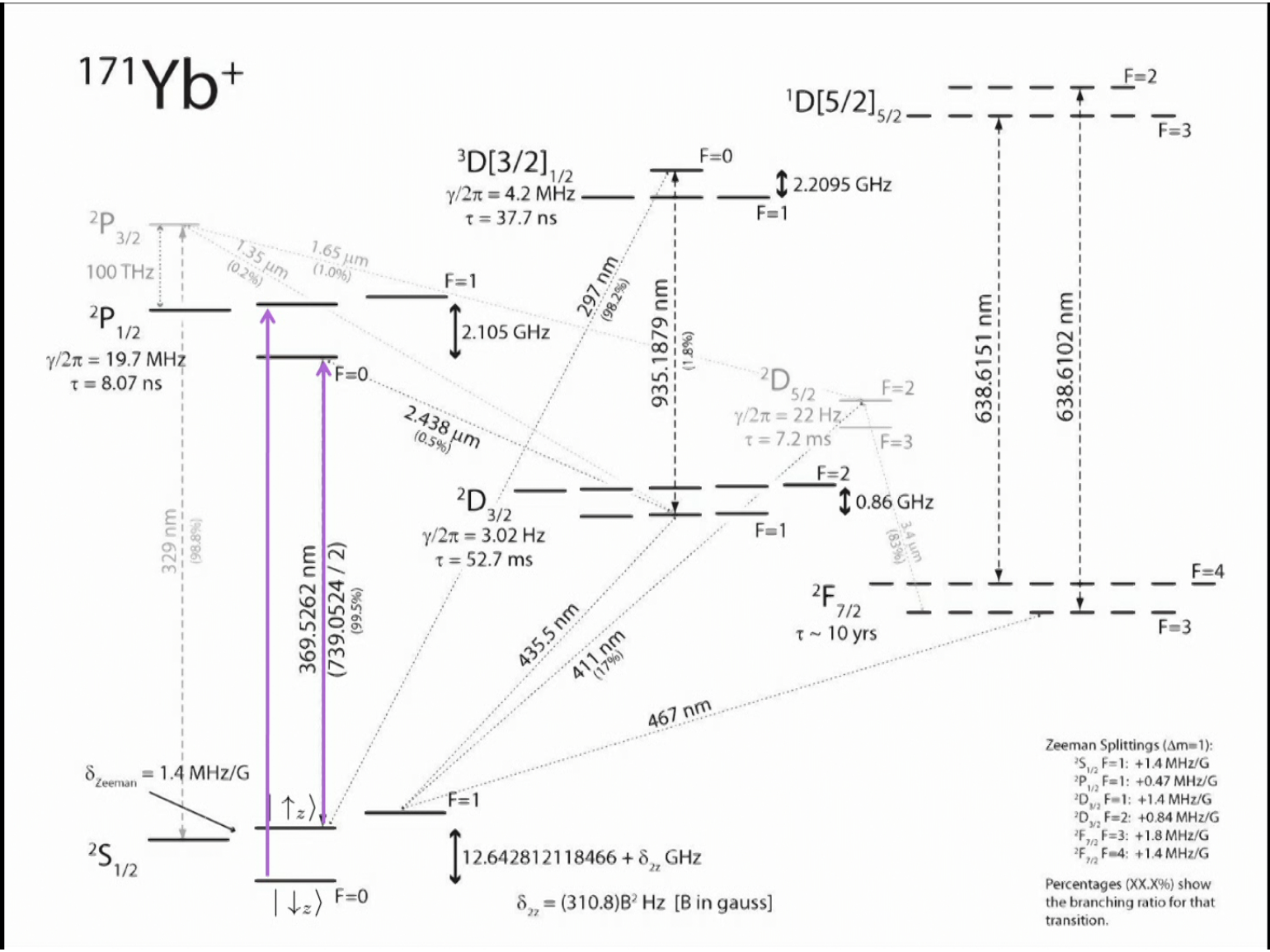

171Yb+
1D[5/2]5/2
F=2
F=3
3D[3/2]1/2
γ/2π = 4.2 MHz
τ = 37.7 ns
F=0
F=1
2.2095 GHz
2P3/2
100 THz
1.35 μm (0.2%)
1.65 μm (1.0%)
297 nm (98.2%)
935.1879 nm (1.8%)
2P1/2
γ/2π = 19.7 MHz
τ = 8.07 ns
2.105 GHz
2D5/2
γ/2π = 22 Hz
τ = 7.2 ms
638.6151 nm
638.6102 nm
2.438 μm (0.5%)
2D3/2
γ/2π = 3.02 Hz
τ = 52.7 ms
0.86 GHz
3.4 μm (83%)
329 nm (98.8%)
369.5262 nm (739.0524 / 2) (99.5%)
435.5 nm
411 nm (17%)
467 nm
2F7/2
τ ~ 10 yrs
F=4
δZeeman = 1.4 MHz/G
|↑z⟩
|↓z⟩
2S1/2
12.642812118466 + δzz GHz
δzz = (310.8)B² Hz [B in gauss]
Zeeman Splittings (Δm=1):
2S1/2 F=1: +1.4 MHz/G
2P1/2 F=1: +0.47 MHz/G
2D3/2 F=1: +1.4 MHz/G
2D3/2 F=2: +0.84 MHz/G
2F7/2 F=3: +1.8 MHz/G
2F7/2 F=4: +1.4 MHz/G
Percentages (XX.X%) show the branching ratio for that transition.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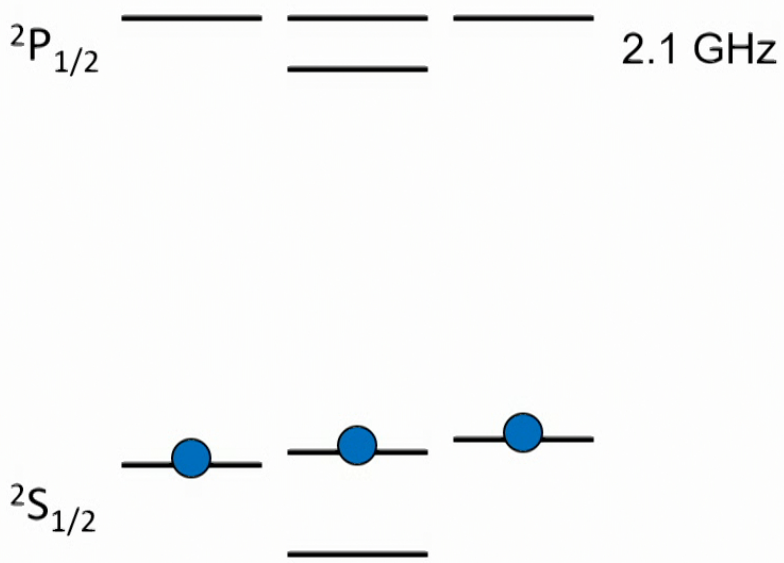
Initialization of spin states

Optical pumping



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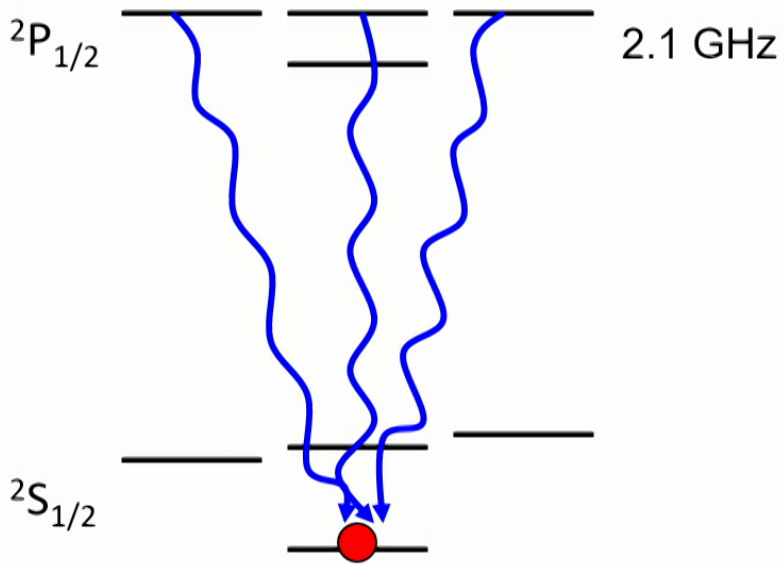
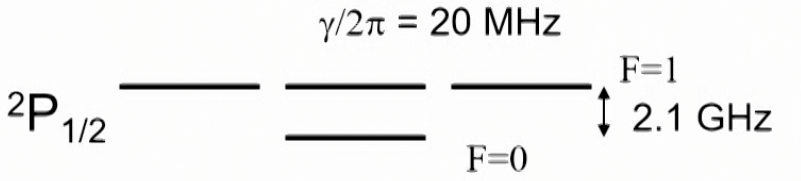
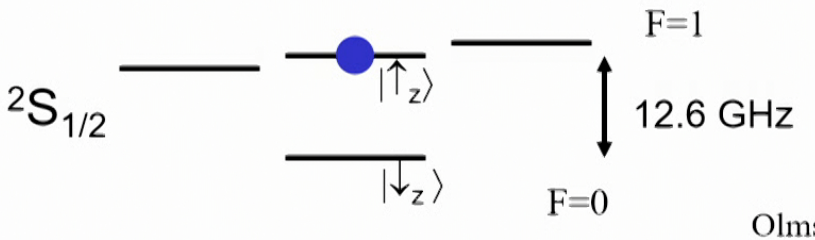


Detection of spin states

Spin dependent fluorescence





Olmschenk, S., *et al*, Phys. Rev. A 76, 052314 (2007).

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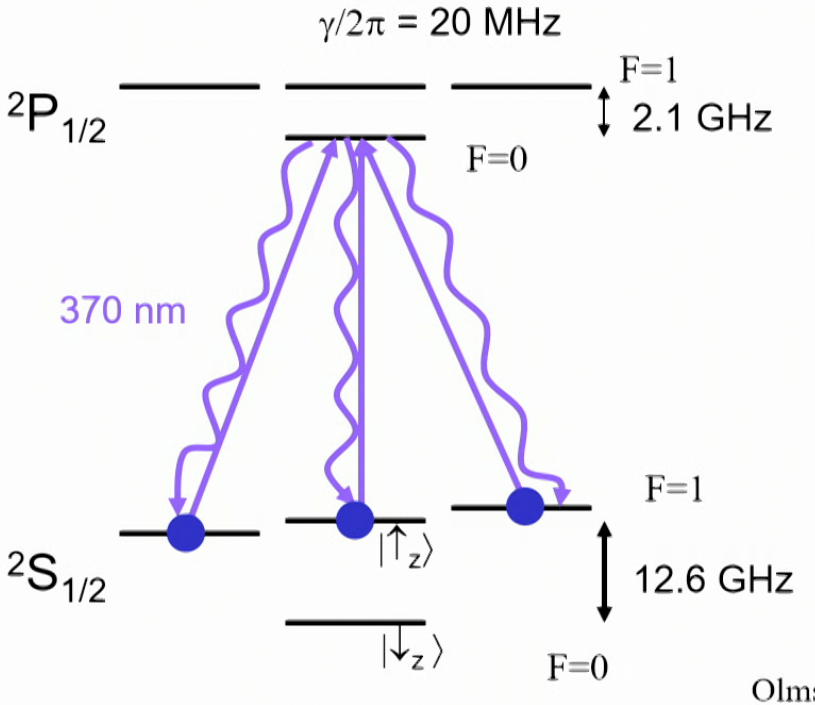

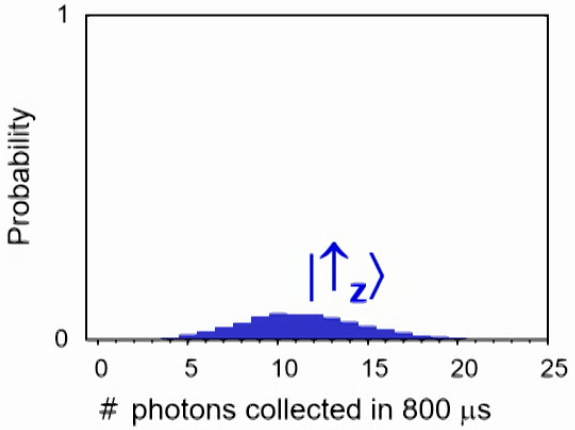

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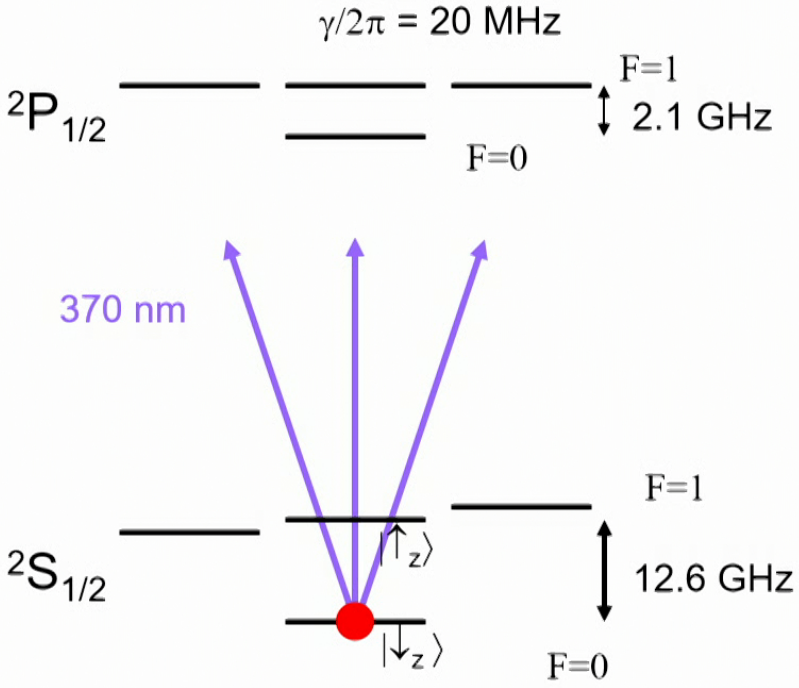
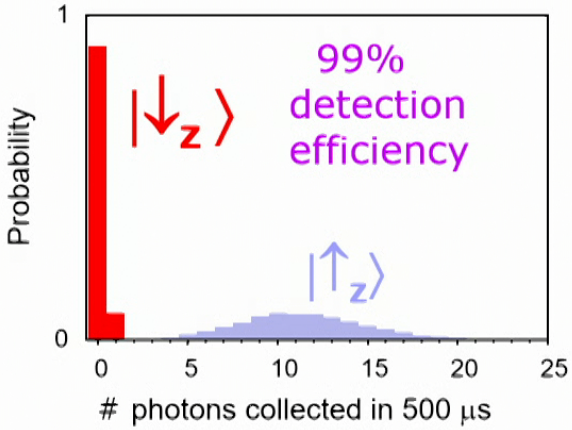
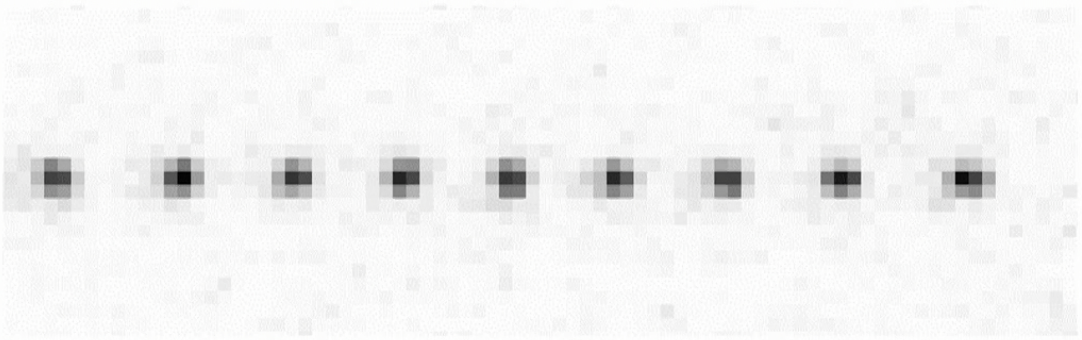




Manipulating trapped ion qubits/spins



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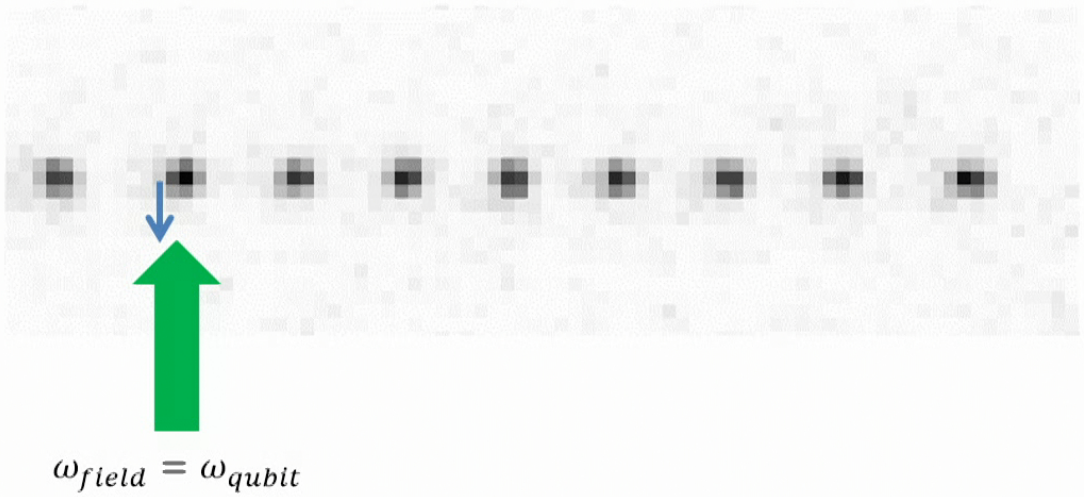
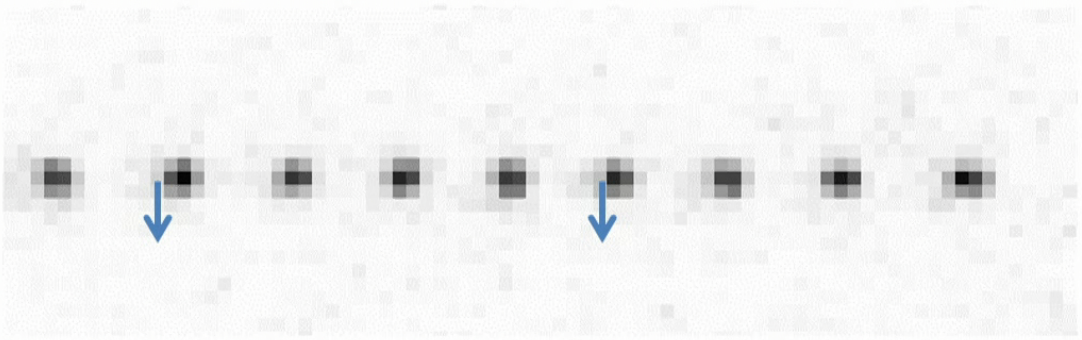


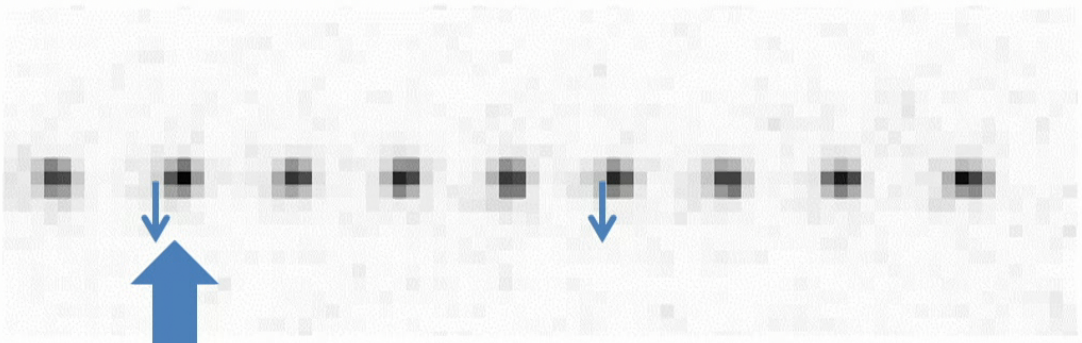
$\omega_{field} = \omega_{qubit}$

Manipulating trapped ion qubits/spins



Couple two qubits/spins?

Manipulating trapped ion qubits/spins

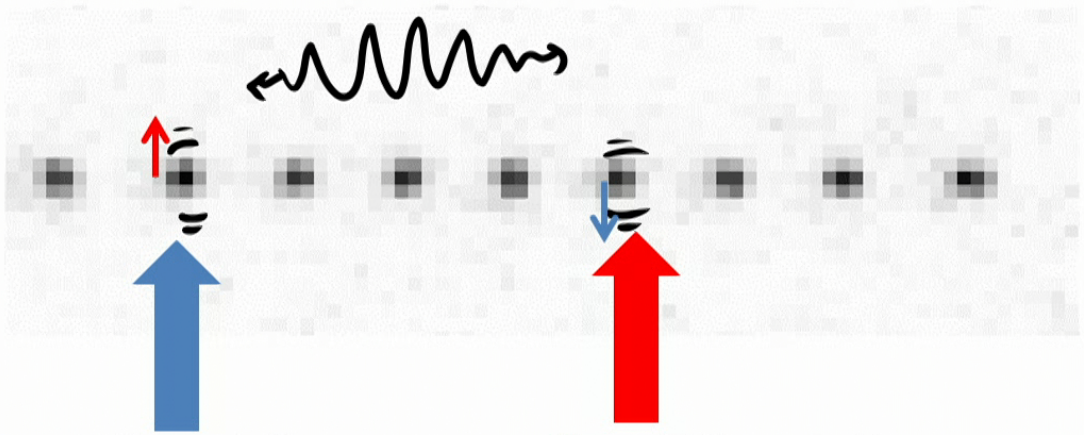


$$\omega_{field} = \omega_{qubit} + \omega_{vibration}$$

Manipulating trapped ion qubits/spins

$$\omega_{field} = \omega_{qubit} + \omega_{vibration}$$

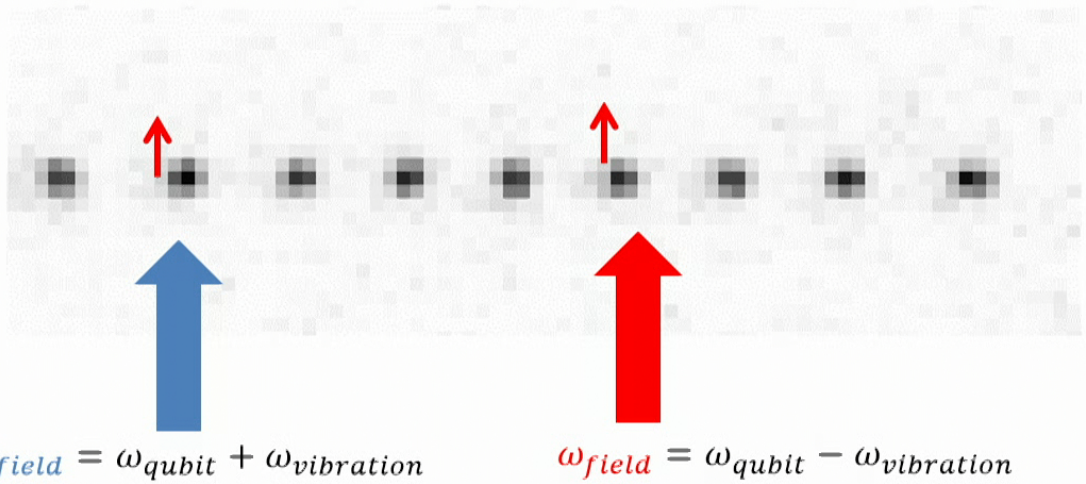
Manipulating trapped ion qubits/spins



$\omega_{field} = \omega_{qubit} + \omega_{vibration}$

$\omega_{field} = \omega_{qubit} - \omega_{vibration}$

Manipulating trapped ion qubits/spins



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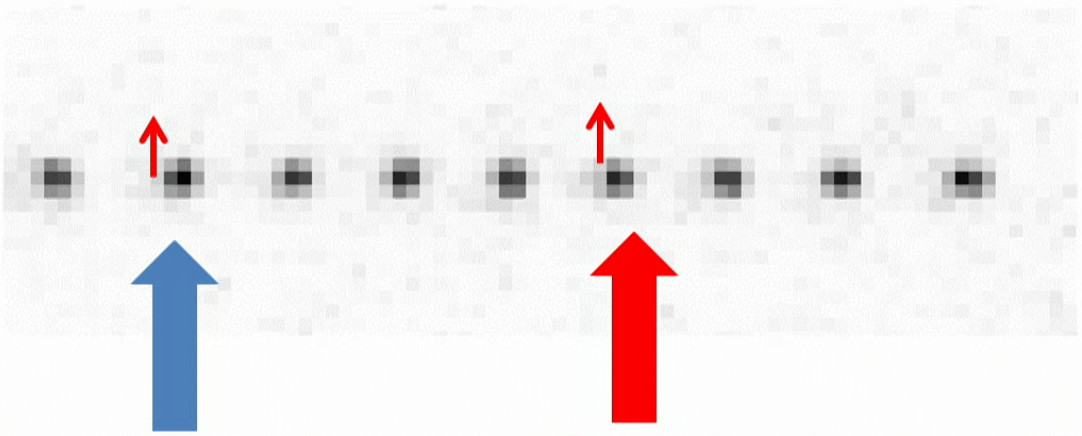
Manipulating trapped ion qubits/spins



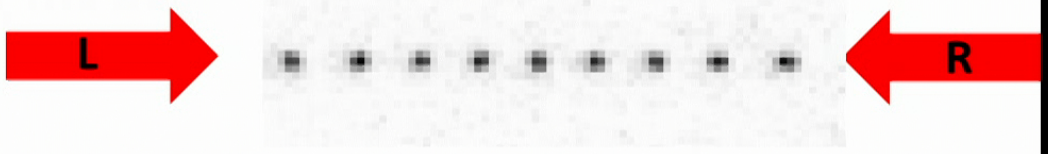
$\omega_{field} = \omega_{qubit} + \omega_{vibration} + \delta$ $\omega_{field} = \omega_{qubit} - \omega_{vibration} - \delta$

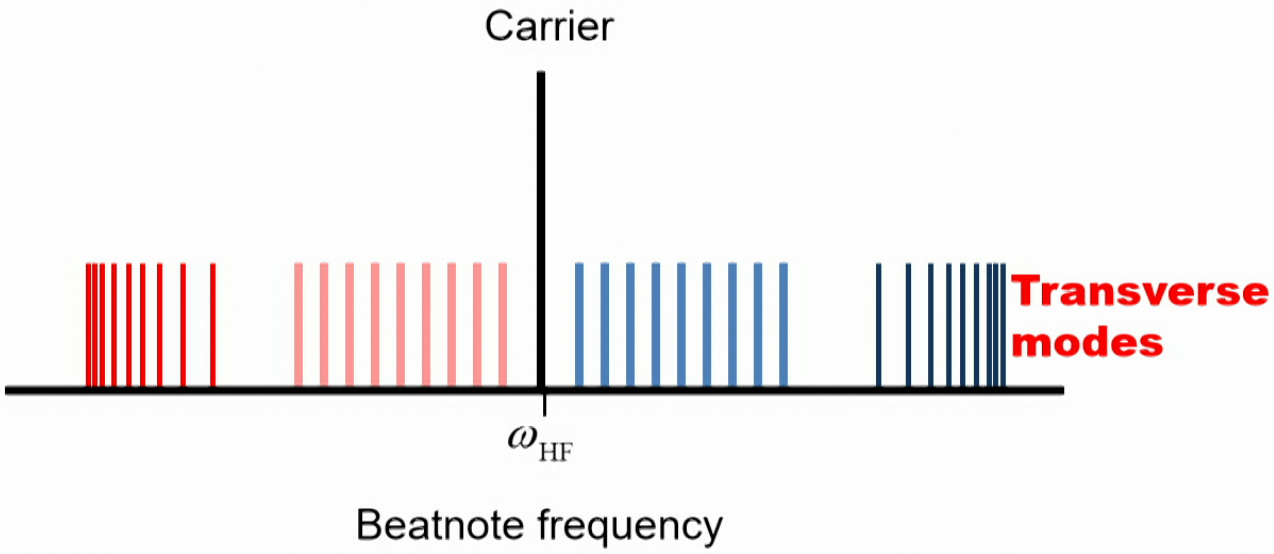
$$H_{eff} = \sum_{j<i} J_{i,j} \sigma_x^i \sigma_x^j$$

- Cirac, Zoller **PRL** 4091 (1995)
- Molmer, Sorensen **PRL** 1835 (1999)

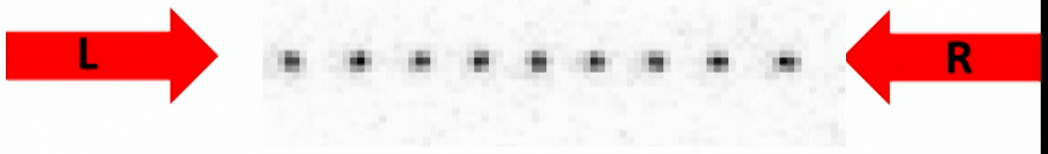
Qubits/spins interact by exchanging (virtual) phonons

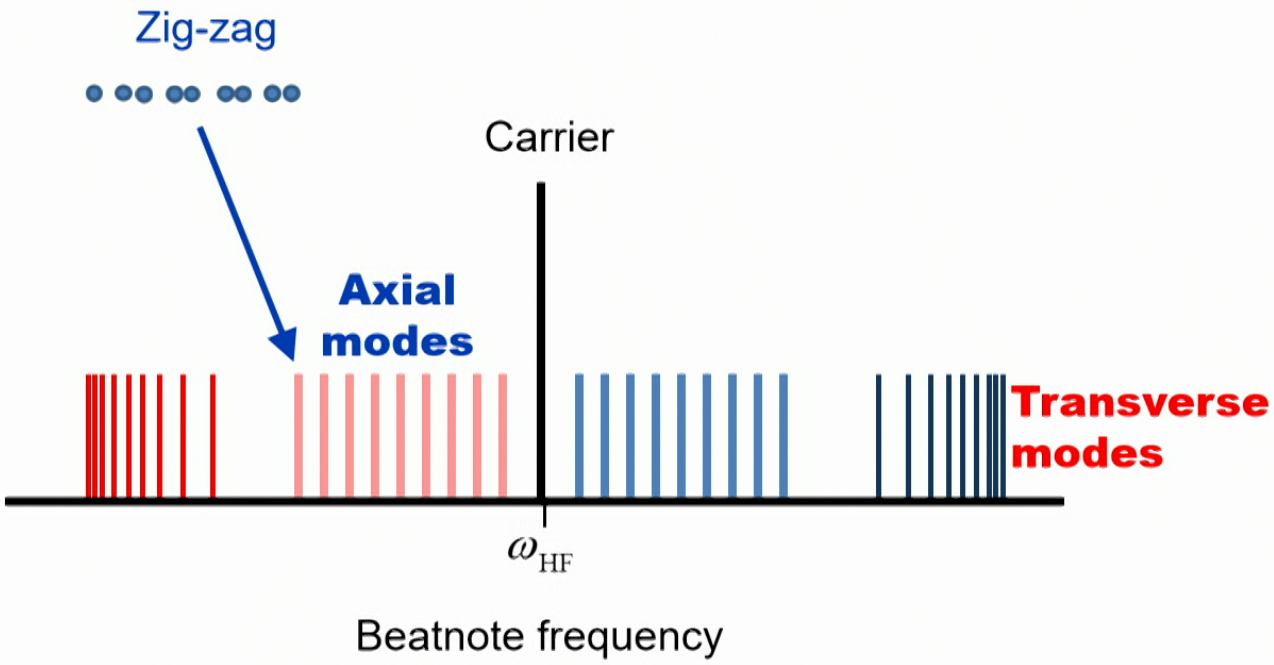
Multiple phonon modes



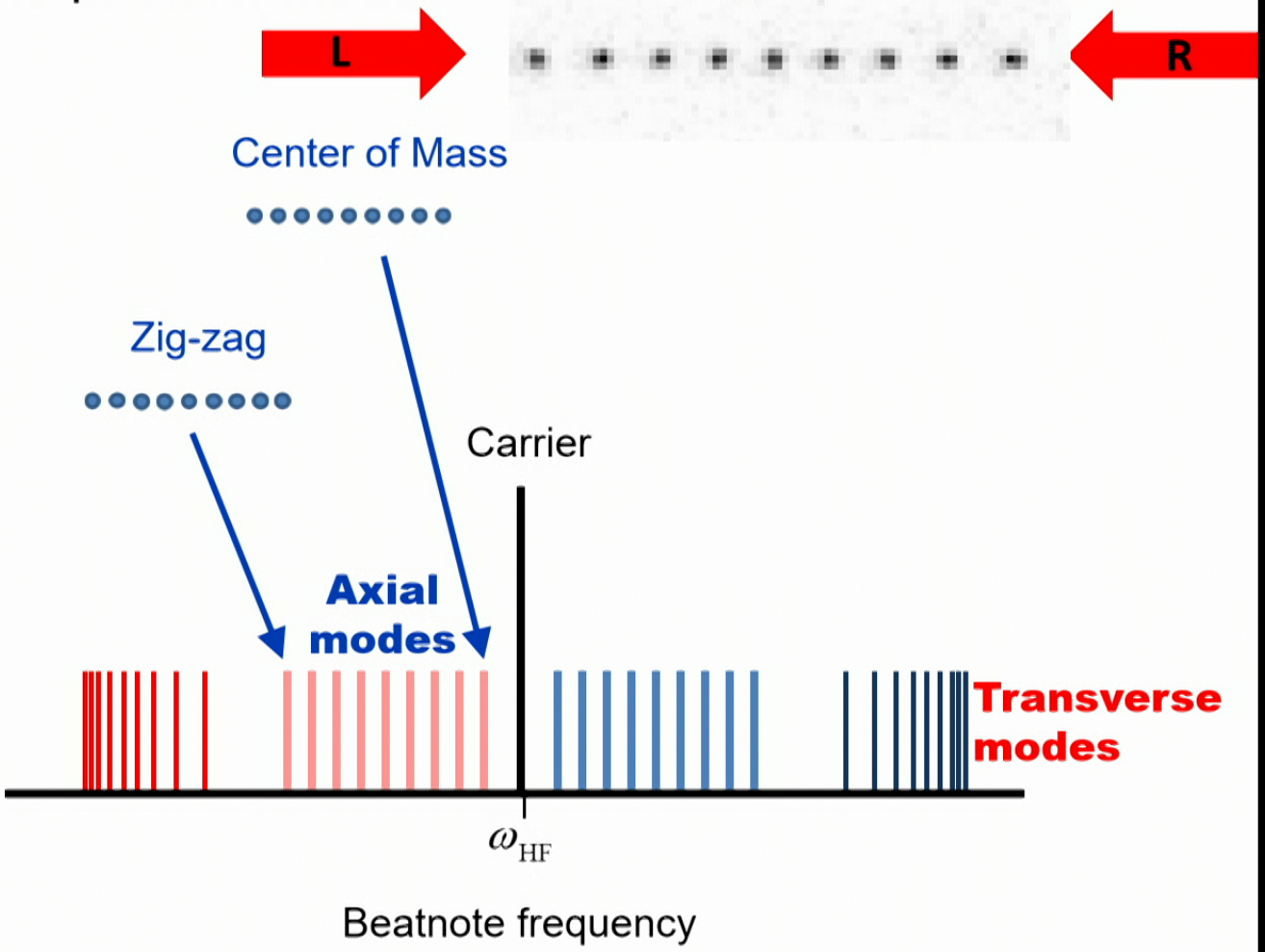


Multiple phonon modes

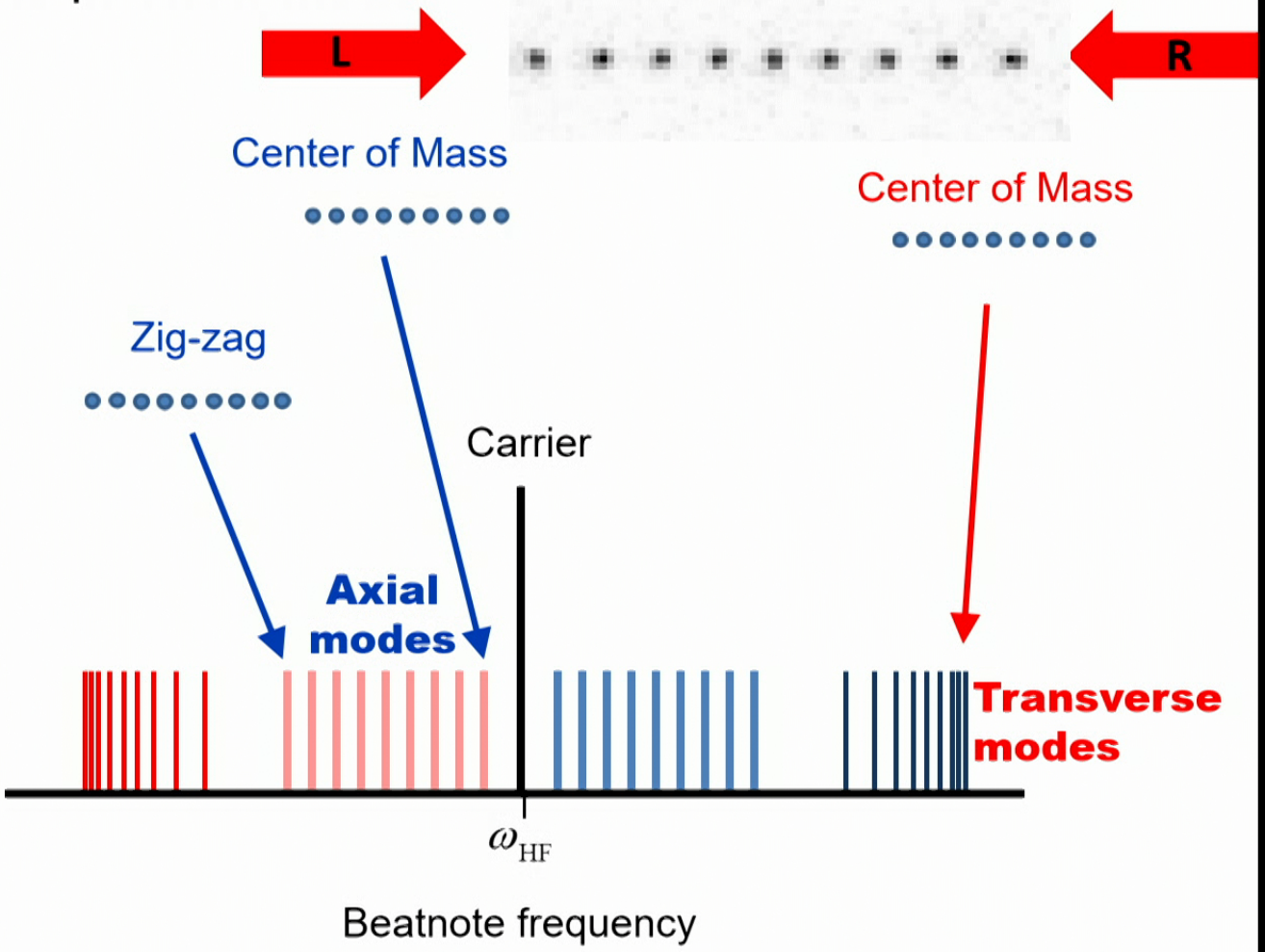




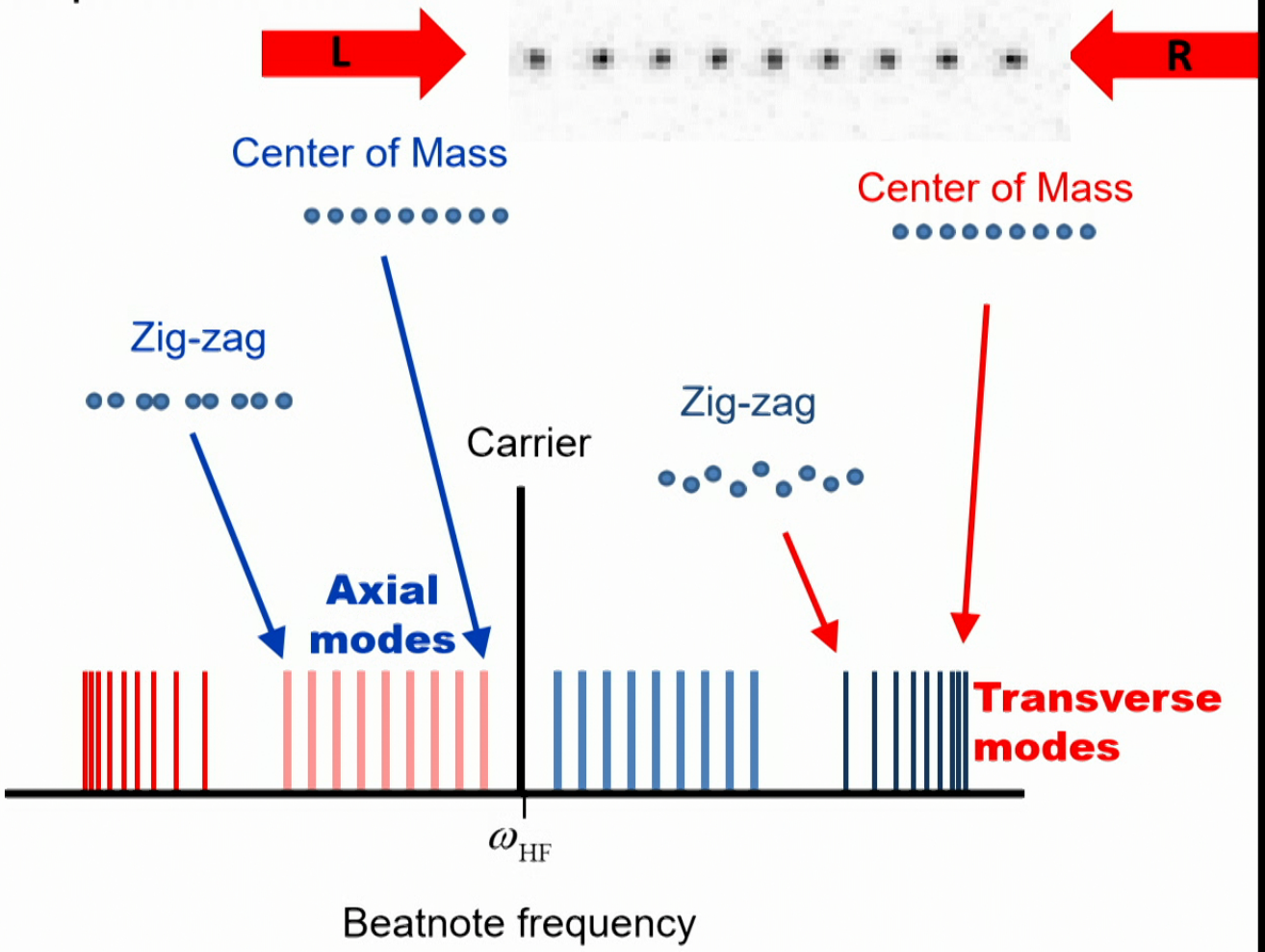
Multiple phonon modes



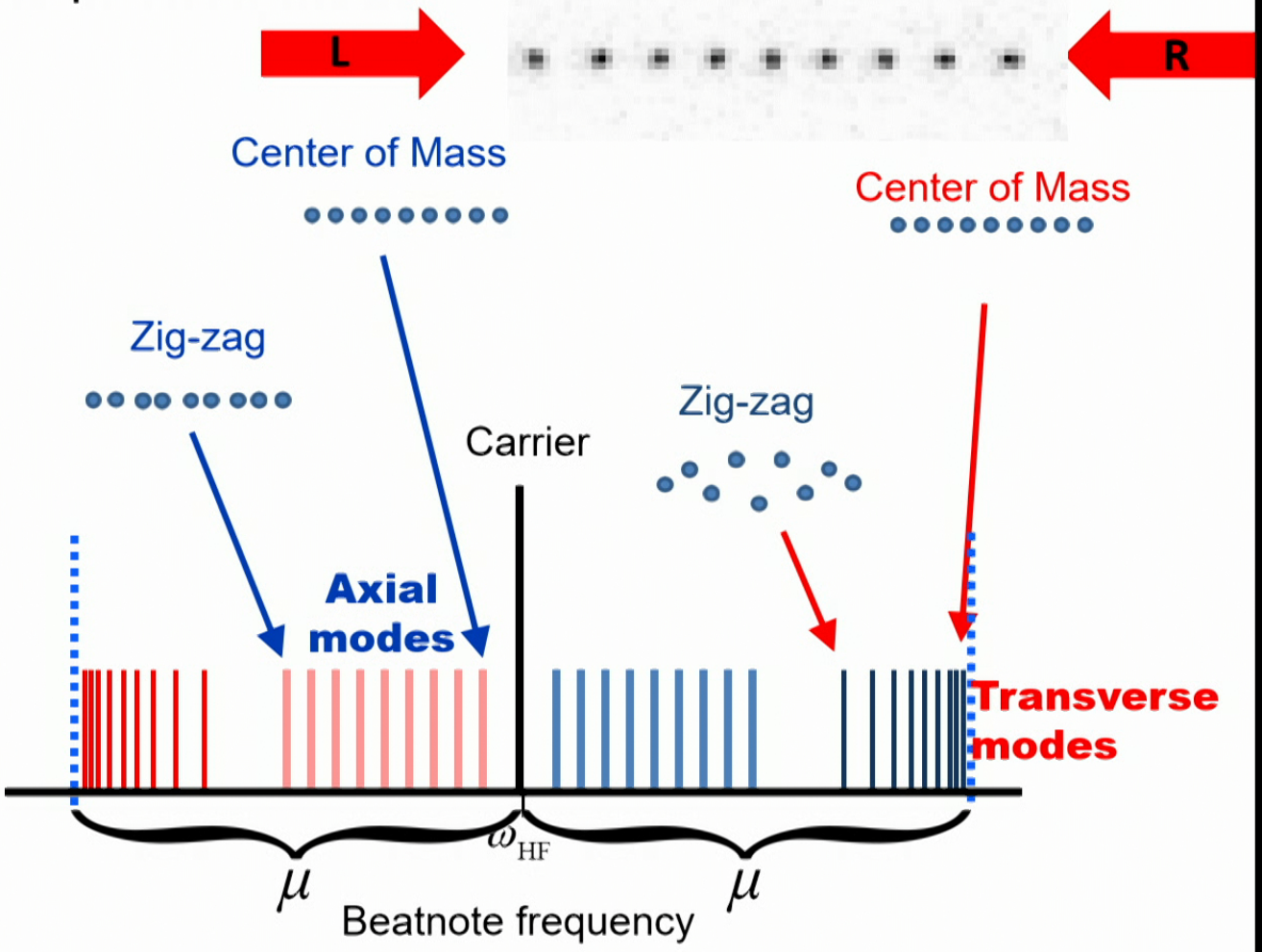
Multiple phonon modes



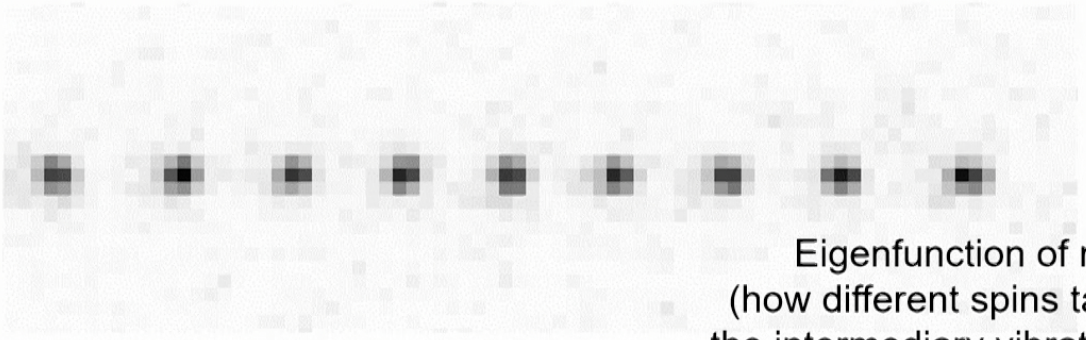
Multiple phonon modes



Multiple phonon modes



Tunable interaction strength



Eigenfunction of modes
(how different spins take part in
the intermediary vibrational mode)

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Couling between
spins i and j

Laser power
(Rabi frequency)

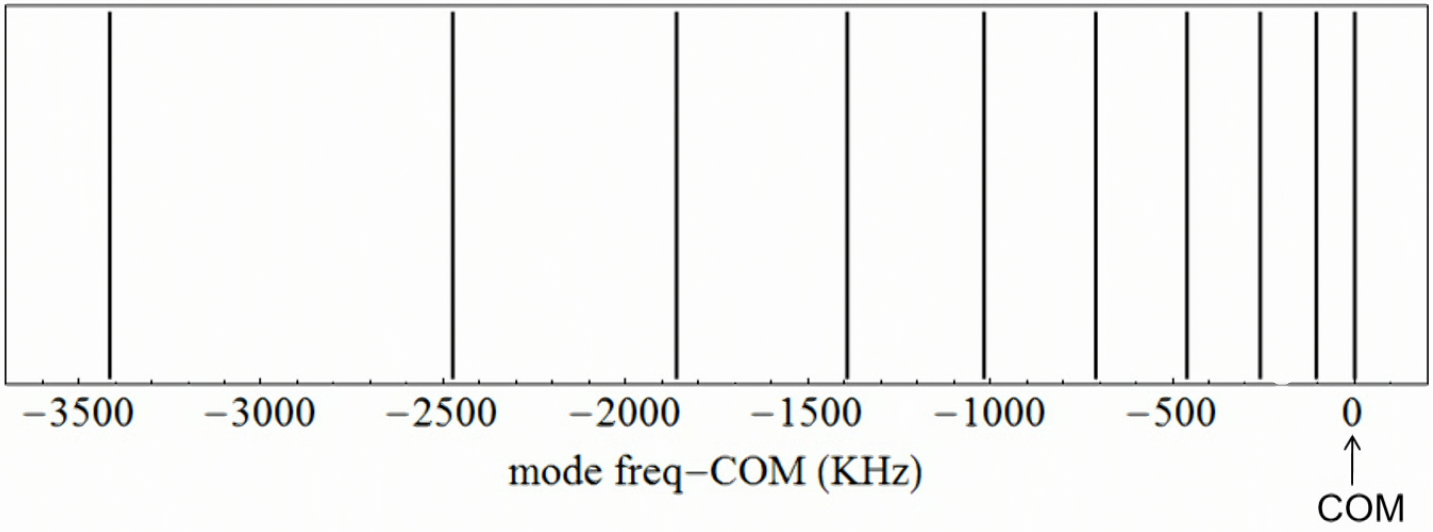
Recoil frequency

~ laser detuning (δ)

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

$J_{i,j} > 0 \quad - Antiferromagnetic$

$J_{i,j} < 0 \quad - Ferromagnetic$



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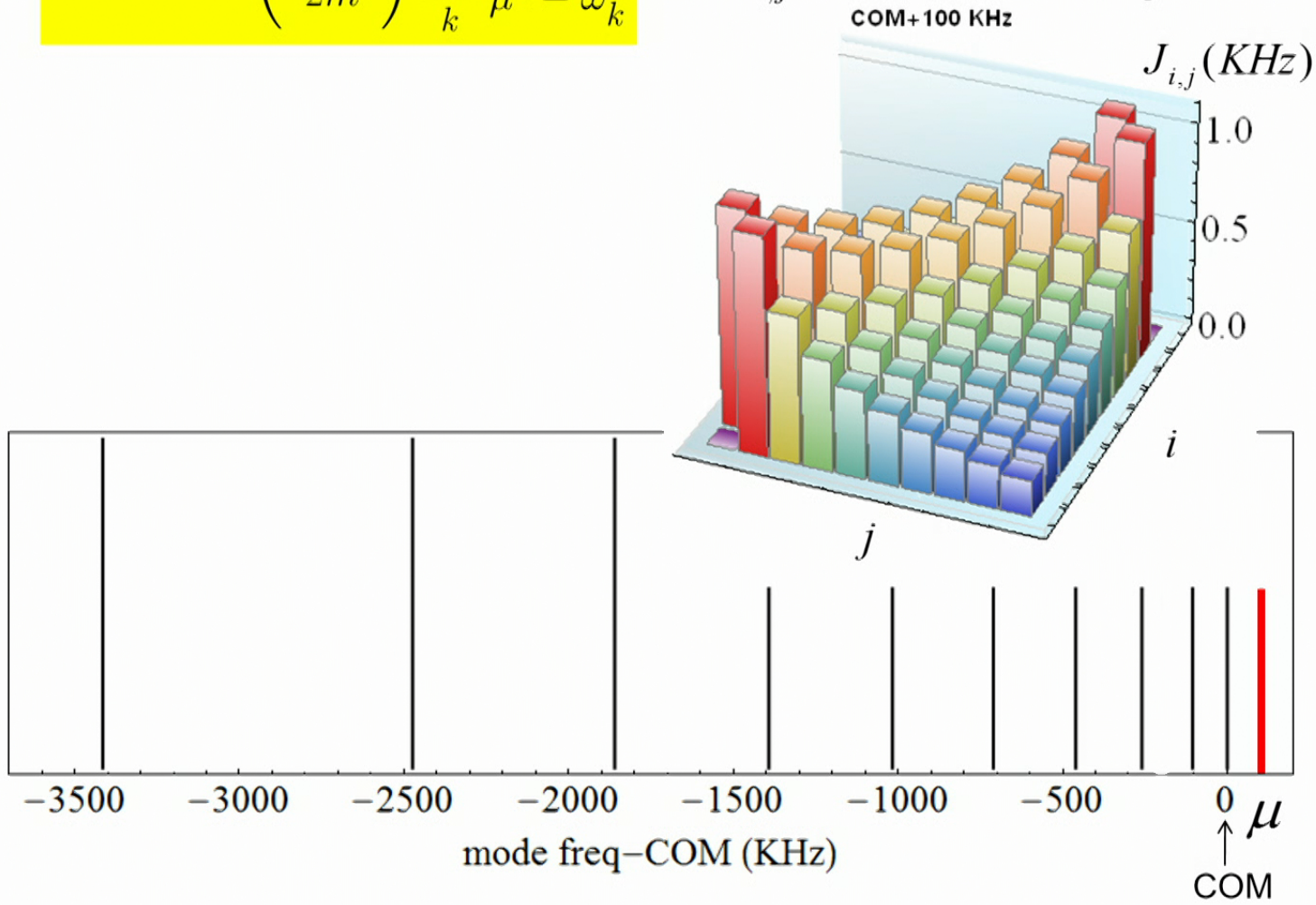

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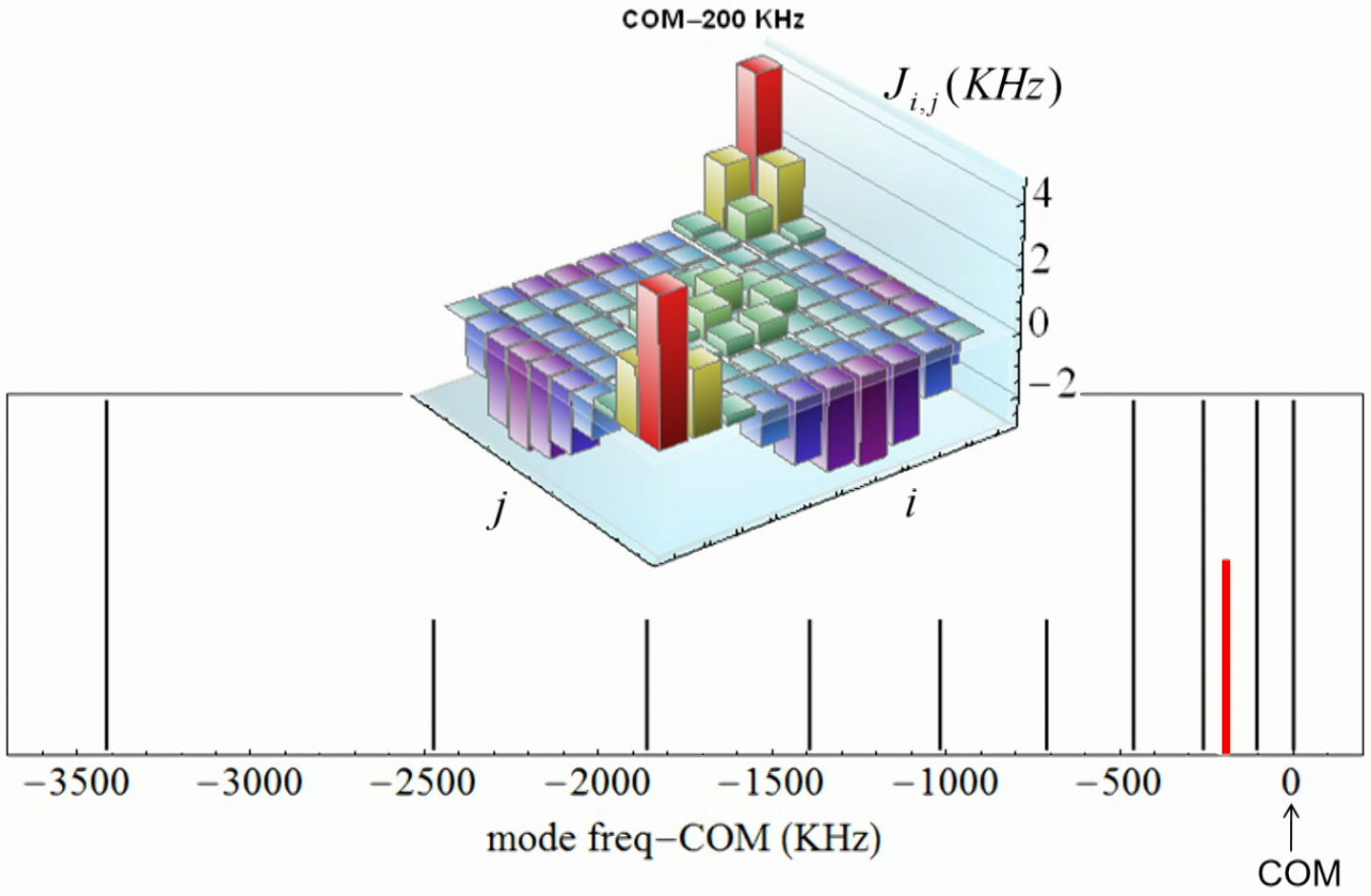

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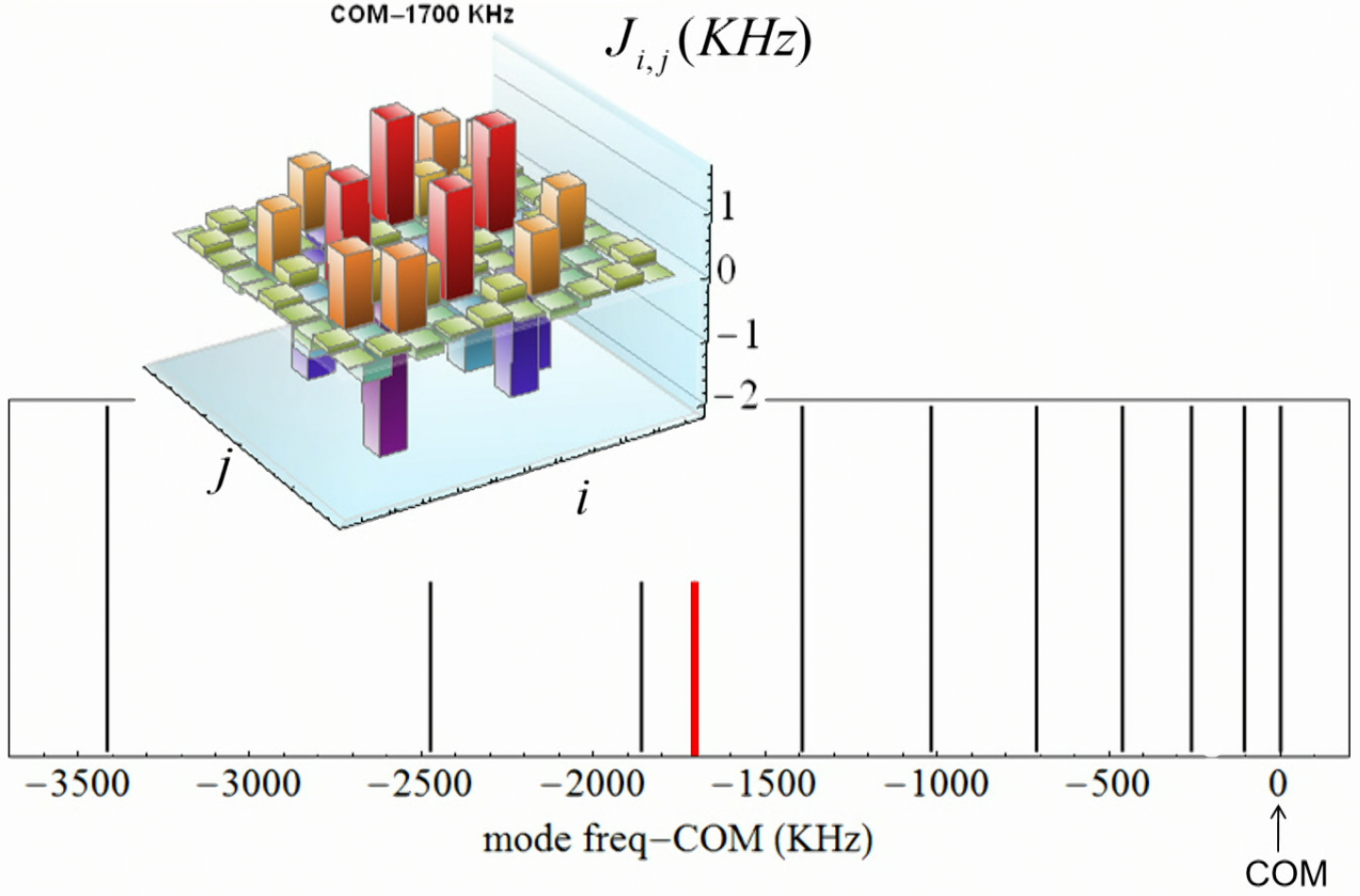

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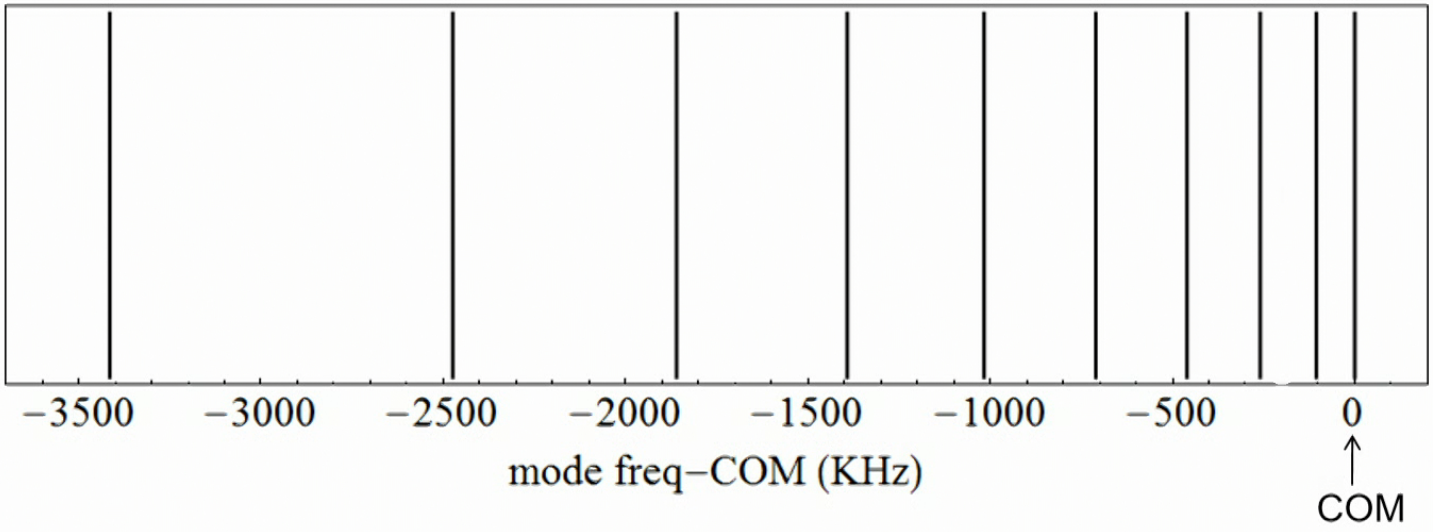

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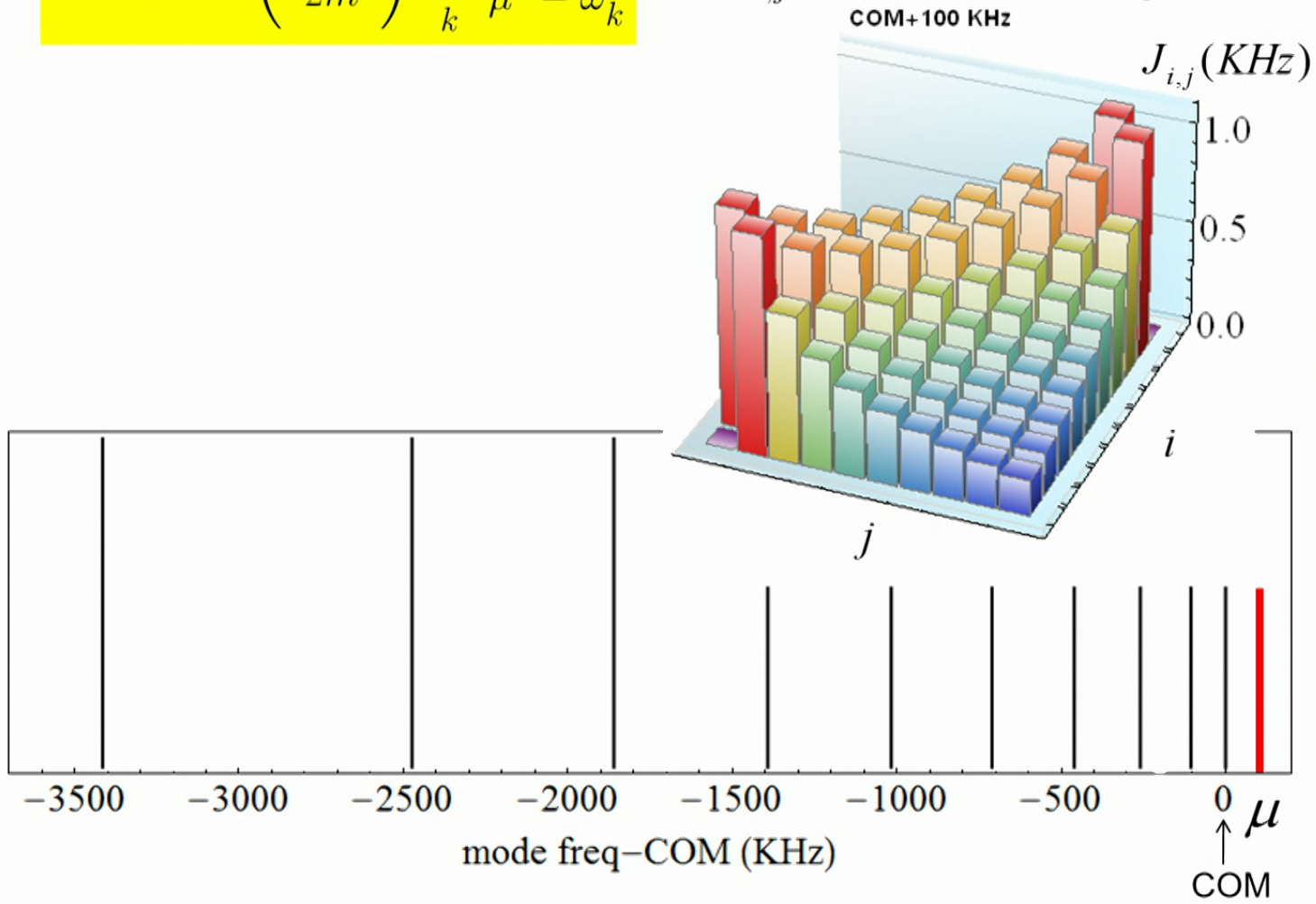
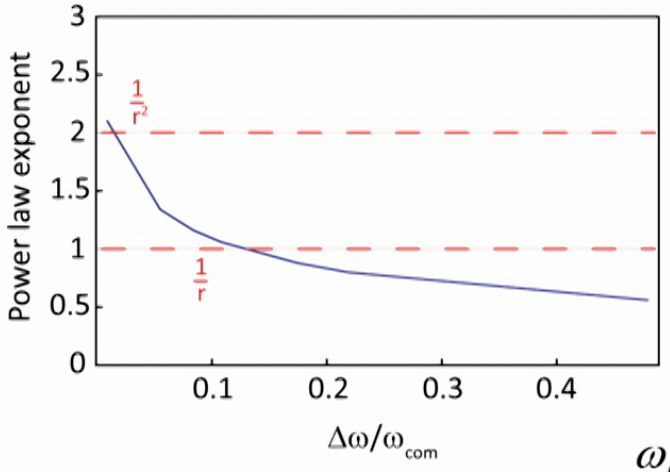
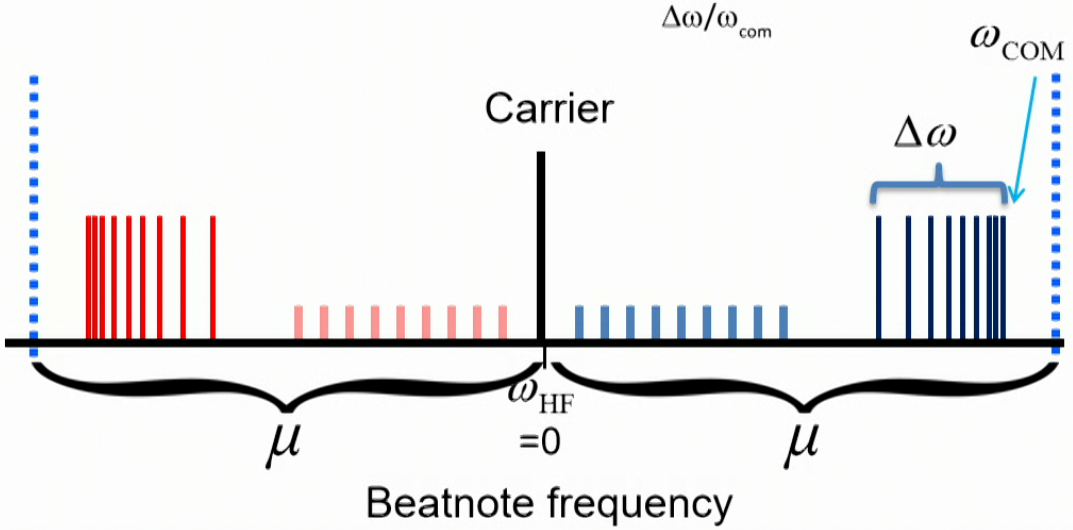


Control of Range of Interaction

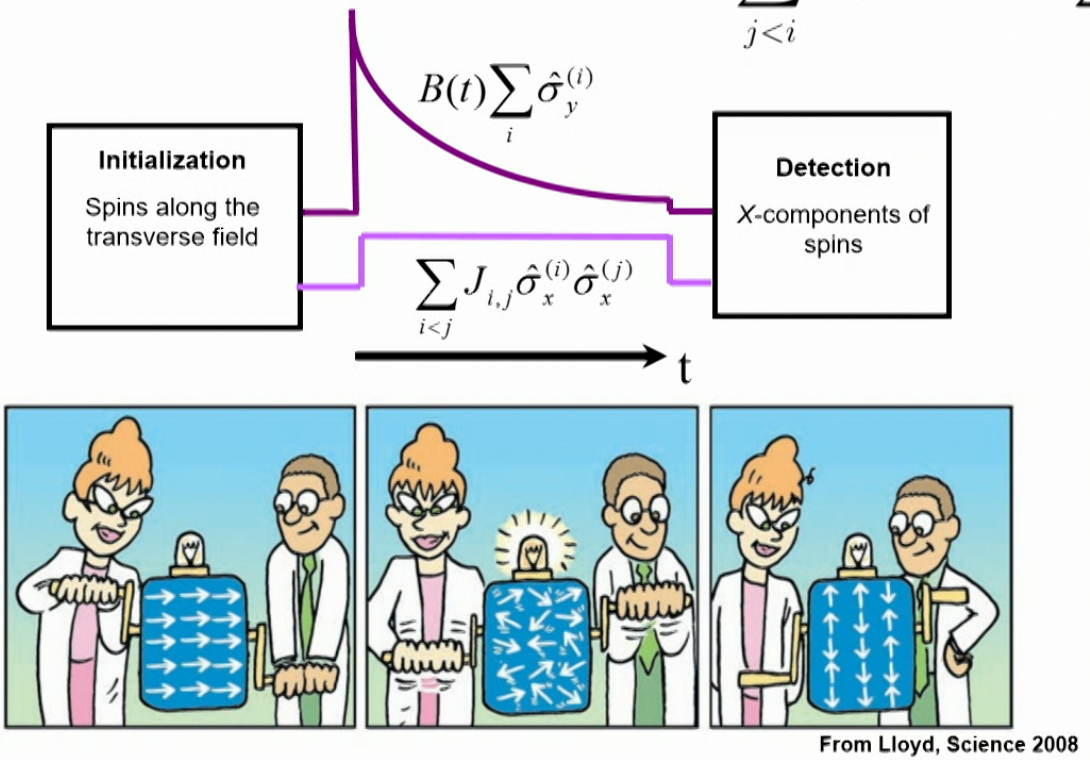
$$J_{i,j} \sim \frac{1}{|i-j|^{\alpha}}$$





Adiabatic quantum simulation

$$H = \sum_{j<i} J_{i,j}\sigma_x^i\sigma_x^j + B\sum_i \sigma_y^i$$

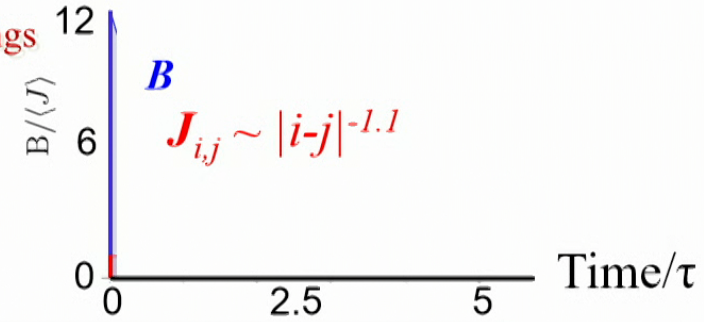


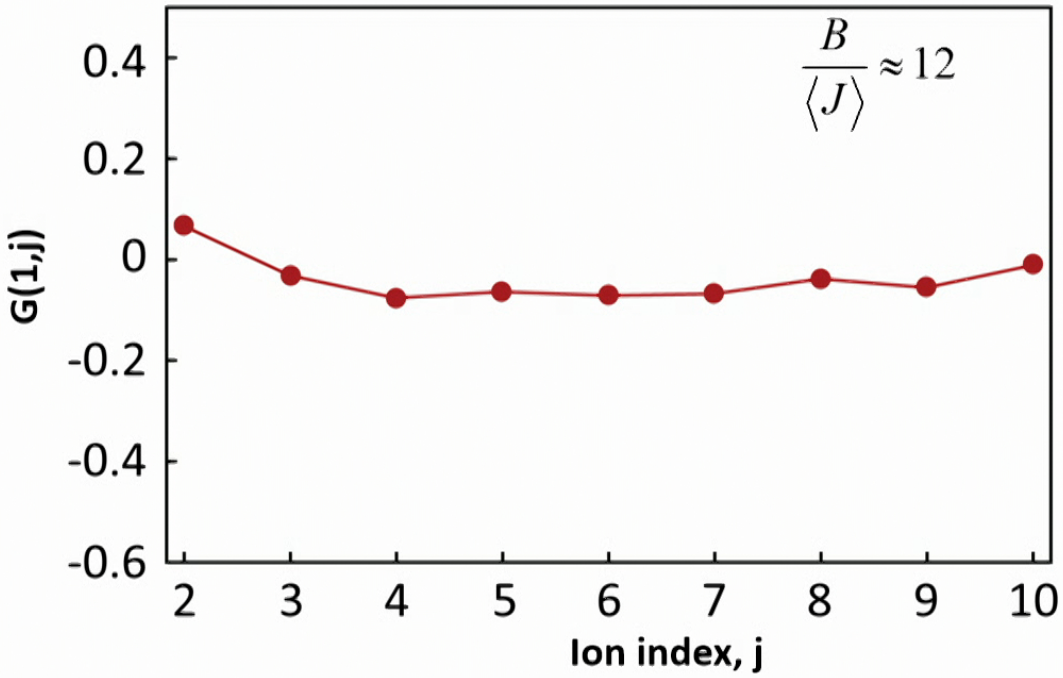
From Lloyd, Science 2008

Frustrated Ising model

Long range **anti-ferromagnetic** Ising couplings

$$H_{eff} = \sum_{j<i} J_{i,j}\sigma_x^i\sigma_x^j + B\sum_i \sigma_y^i$$





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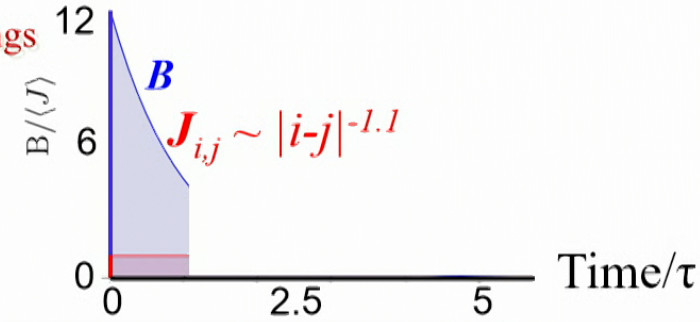
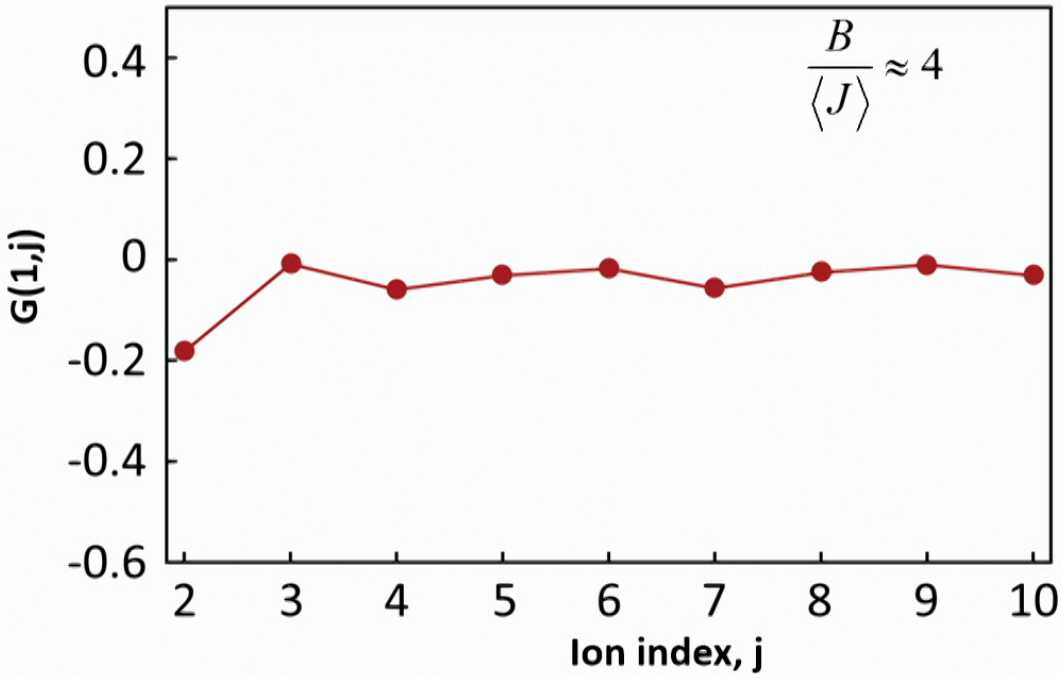
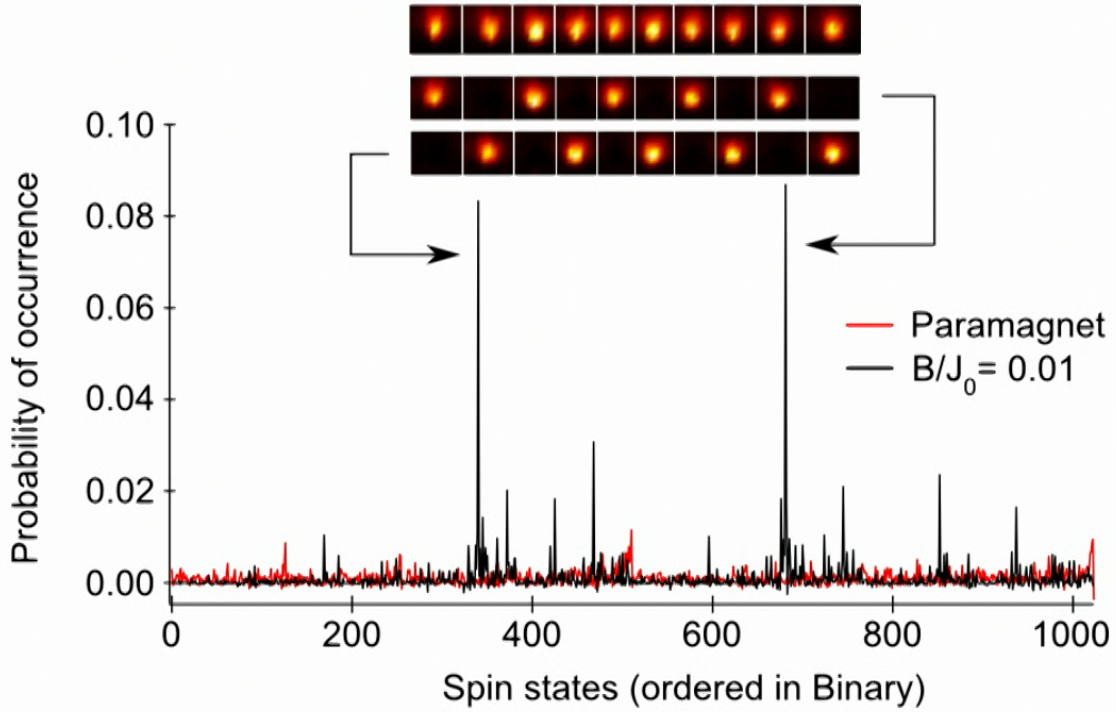




Onset of Neel order (N=10)

Population of all 1024 states

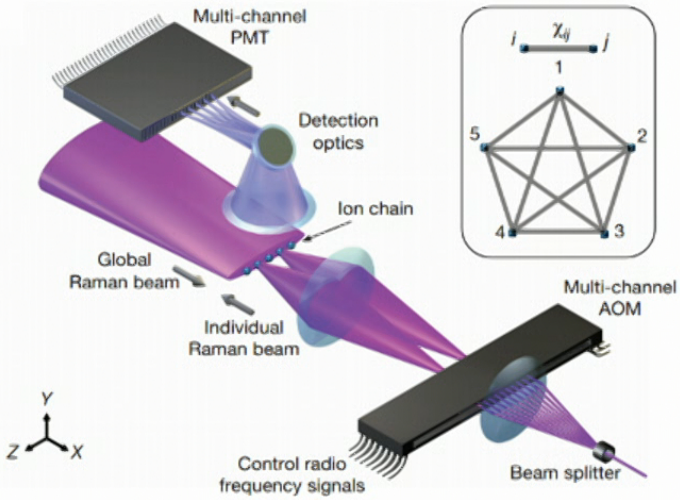


R. Islam, C. Senko, W. C. Campbell, S. Korenblit, J. Smith, A. Lee, E. E. Edwards, C.-C. J. Wang, J. K. Freericks, and C. Monroe, ***Science*** *340 583* (2013).

Control over individual particles and interactions

Individual addressing

Move around a focused beam
(Multi channel AOM)



S. Debnath et al Nature 536, 63 (2016)

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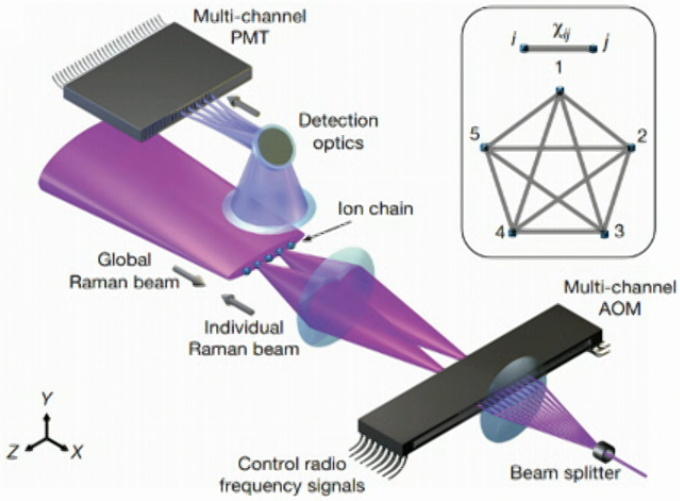
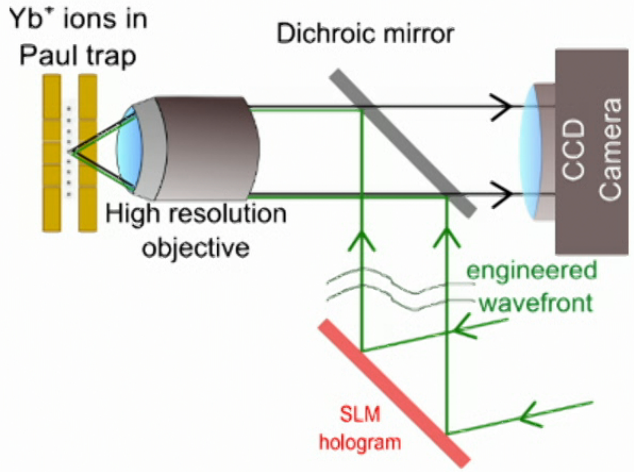


S. Debnath et al Nature 536, 63 (2016)

Precisely engineer the intensity
(and phase) pattern of the field

Fourier holography using
Spatial Light Modulation



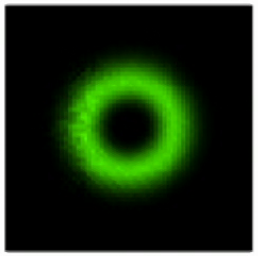
Fourier holography used in
R. Islam et al Nature 528, 77 (2015)
to directly measure entanglement entropy

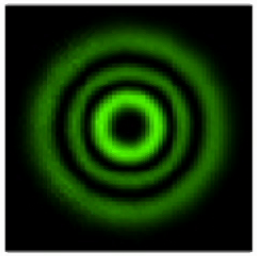
Individual addressing also allows measuring arbitrary correlation functions

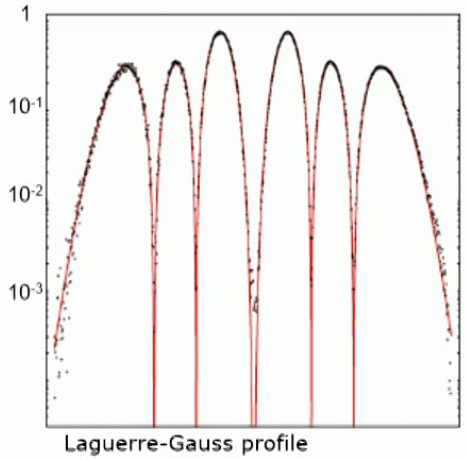
Arbitrary beam shaping

- Weitenberg et al., **Nature** 471, 319-324 (2011)
  Zupancic, P., Master's Thesis, LMU Munich/Harvard 2013
- Cizmar, T *et al.*, **Nature Photonics** 4, 6 (2010)

High-order Laguerre Modes







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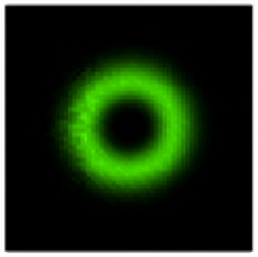
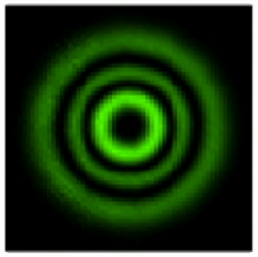
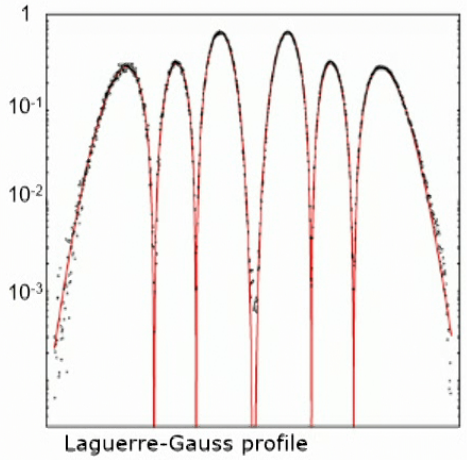
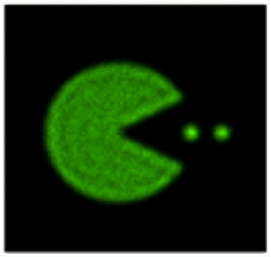




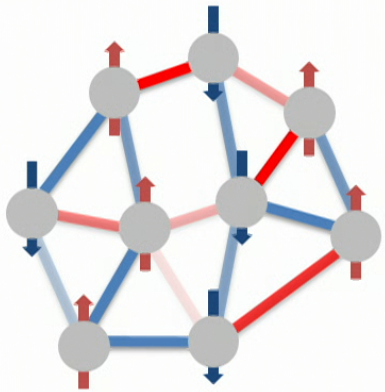


Laguerre-Gauss profile



Towards an arbitrary spin network

Need control at the level of individual spins



Analog way

$$J_{i,j} = \Omega_i \Omega_j \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Laser power (Rabi frequency)

Individual addressing

~ laser detuning (δ)

Excite multiple modes selectively

S. Korenblit et al, *New J. Phys.* 14 (9), 095024 (2012)

Towards an arbitrary spin network

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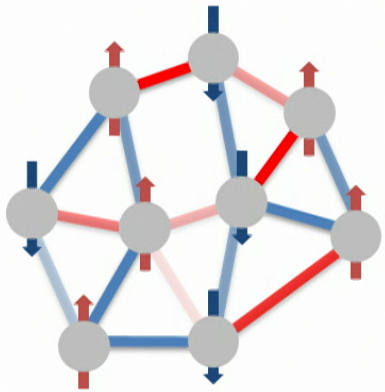
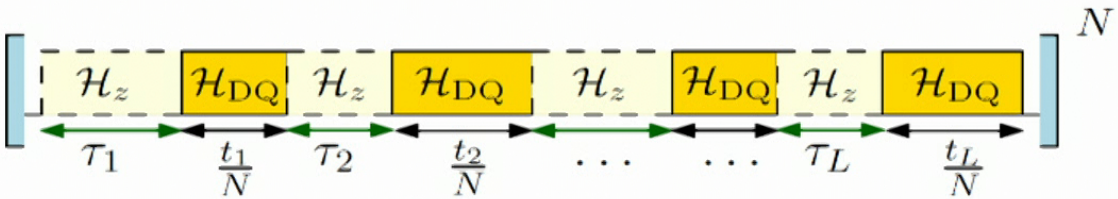


Analog + Digital way



$$\mathcal{H}_{\rm DQ} = \sum_{i<j} J_{ij}(S_i^+ S_j^+ + S_i^- S_j^-) \qquad \mathcal{H}_z = \sum_j \omega_j Z_j$$

where $S^{\pm} = X \pm iY$

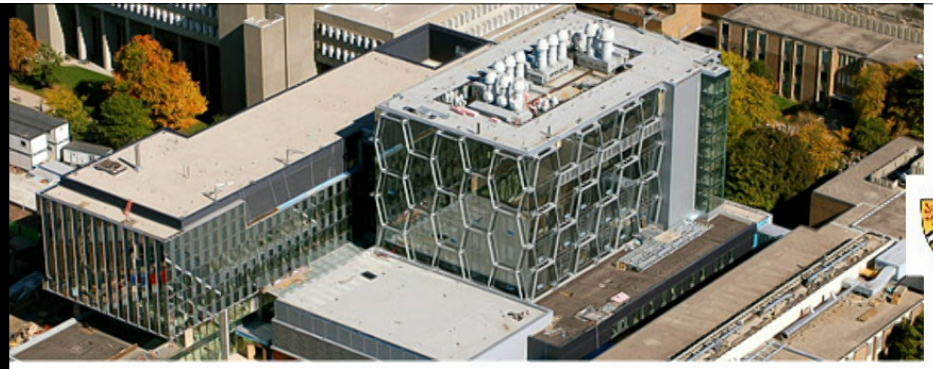
Ashok Ajoy (UC Berkeley)

Also: D. Hayes et al, *New J. Phys.* **16**, 083027 (2014)

Prospects/questions

1. Simulation of various Hamiltonians - Quantum Ising, XY, Heisenberg – phase diagrams
2. Probing collective spin excitations
3. Entanglement in magnetic phases
4. Quantum phase transitions – using entanglement to characterize them
5. Add controlled dissipation – new spin phases and phase transitions
6. Alternate to adiabatic quantum simulation? Can we engineer a bath to cool a many-body system directly to its (entangled) ground state?
7. Speed of information propagation in a quantum network
8. Digital quantum simulation – creation of very non-local Hamiltonians (multi-spin operators), phase diagram of such Hamiltonians
9. Phase transitions in excited states
10. And many more ….

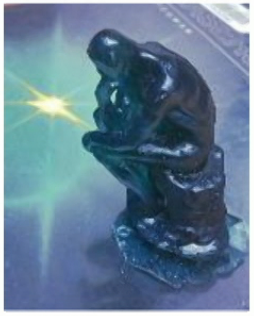
Thank you!



UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Quantum Information with Trapped Ions

research.iqc.uwaterloo.ca/qiti/



Current group members :

Undergraduates – Tony Kappen, Kaleb Ruscitti

Students, Postdocs wanted! (krislam@uwaterloo.ca)