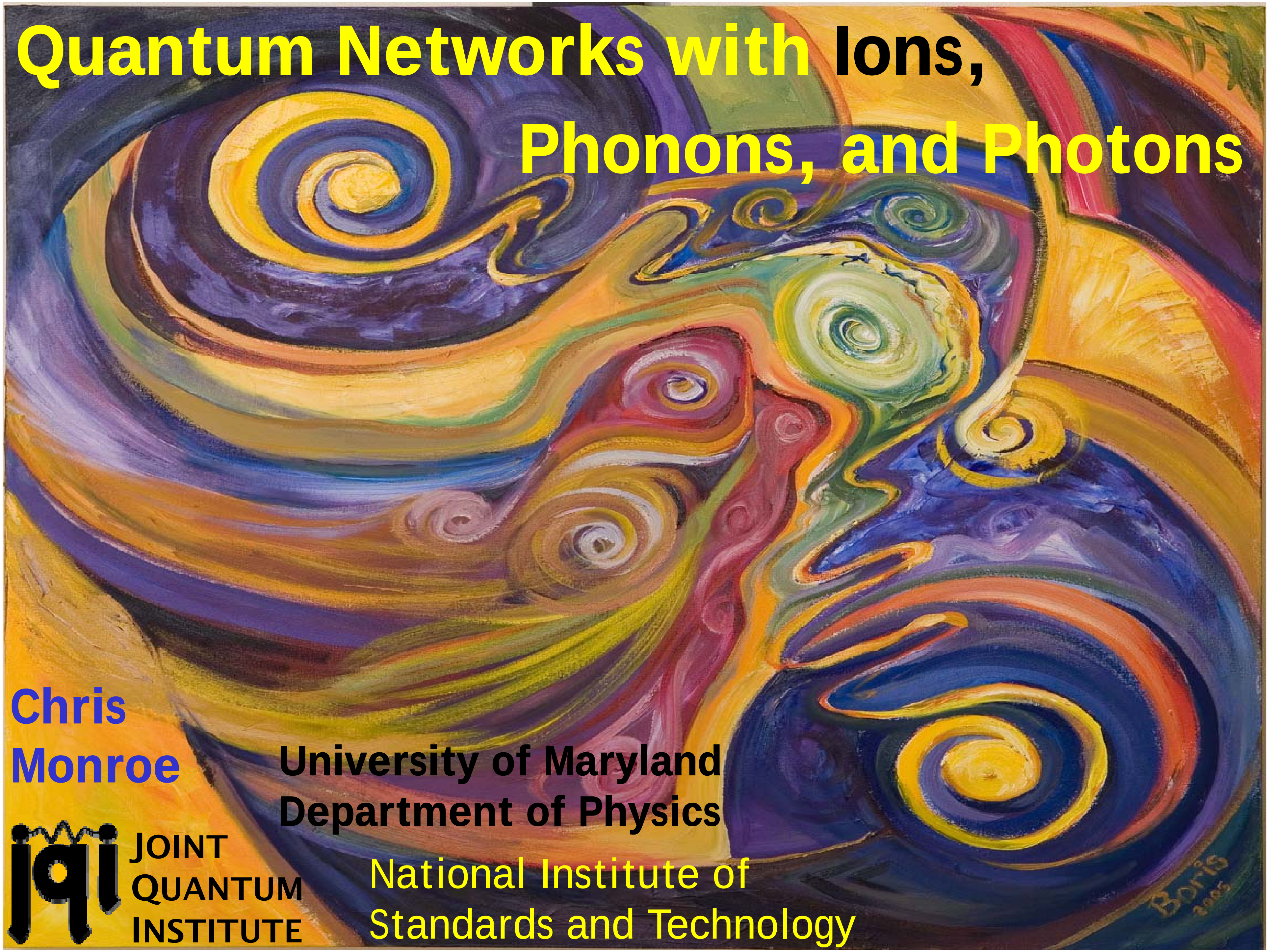
Quantum Networks with Ions, Phonons, and Photons

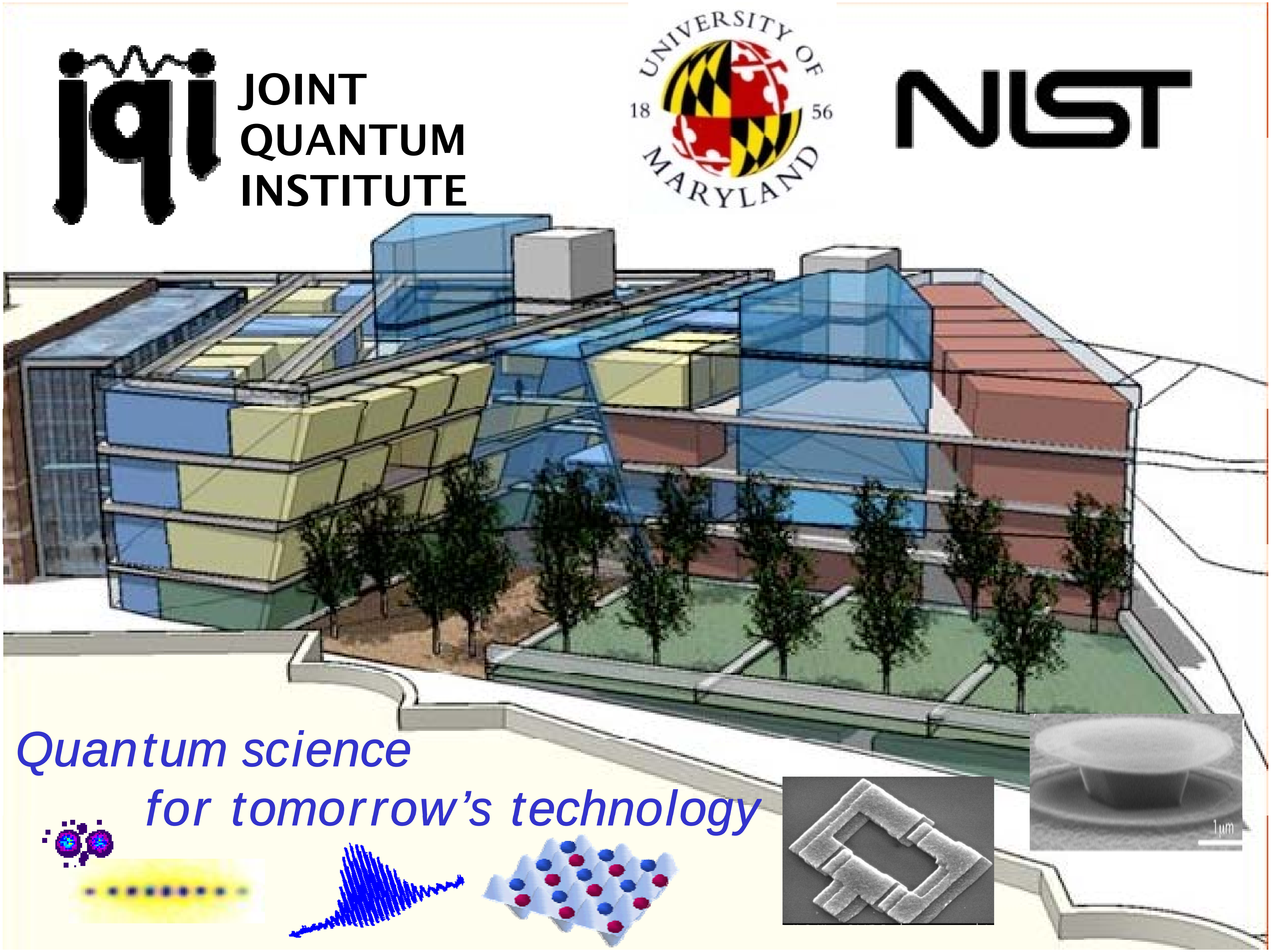


Chris Monroe

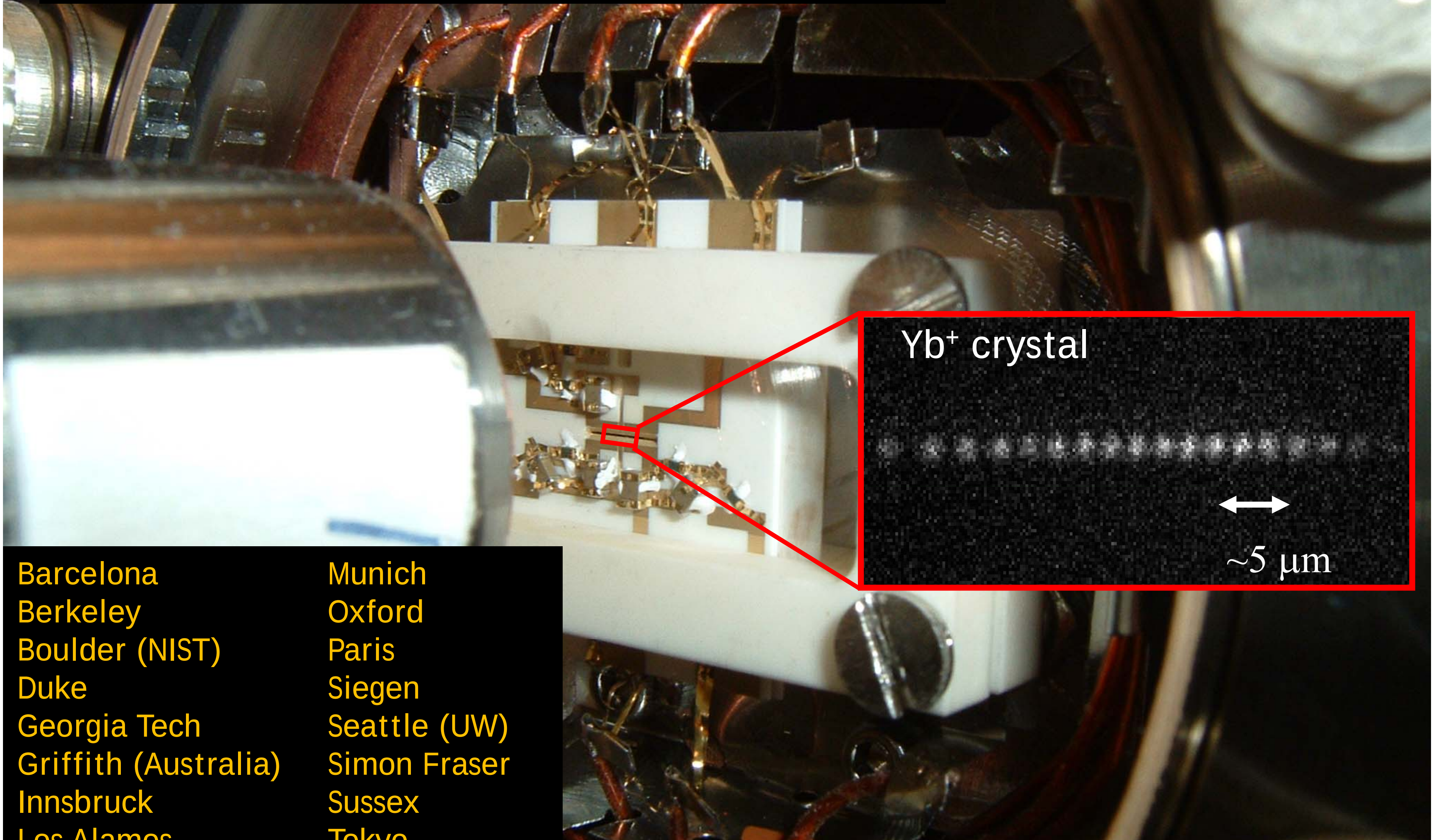
University of Maryland
Department of Physics

JOINT QUANTUM INSTITUTE

National Institute of Standards and Technology


jqi
JOINT
QUANTUM
INSTITUTE
UNIVERSITY OF MARYLAND
18 56
NIST
Quantum science
for tomorrow's technology
1μm

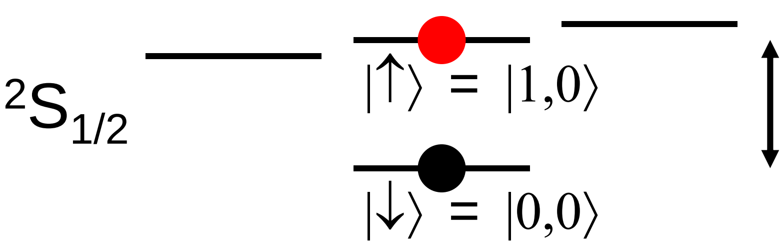
Trapped Atomic Ions



Barcelona	Munich
Berkeley	Oxford
Boulder (NIST)	Paris
Duke	Siegen
Georgia Tech	Seattle (UW)
Griffith (Australia)	Simon Fraser
Innsbruck	Sussex
Los Alamos	Tokyo
Maryland/JQI	Ulm
MIT	Weizmann Inst.

C.M. & D. J. Wineland, *Sci. Am.*, 64 (Aug 2008)
R. Blatt & D. J. Wineland, *Nature* **453**, 1008 (2008)

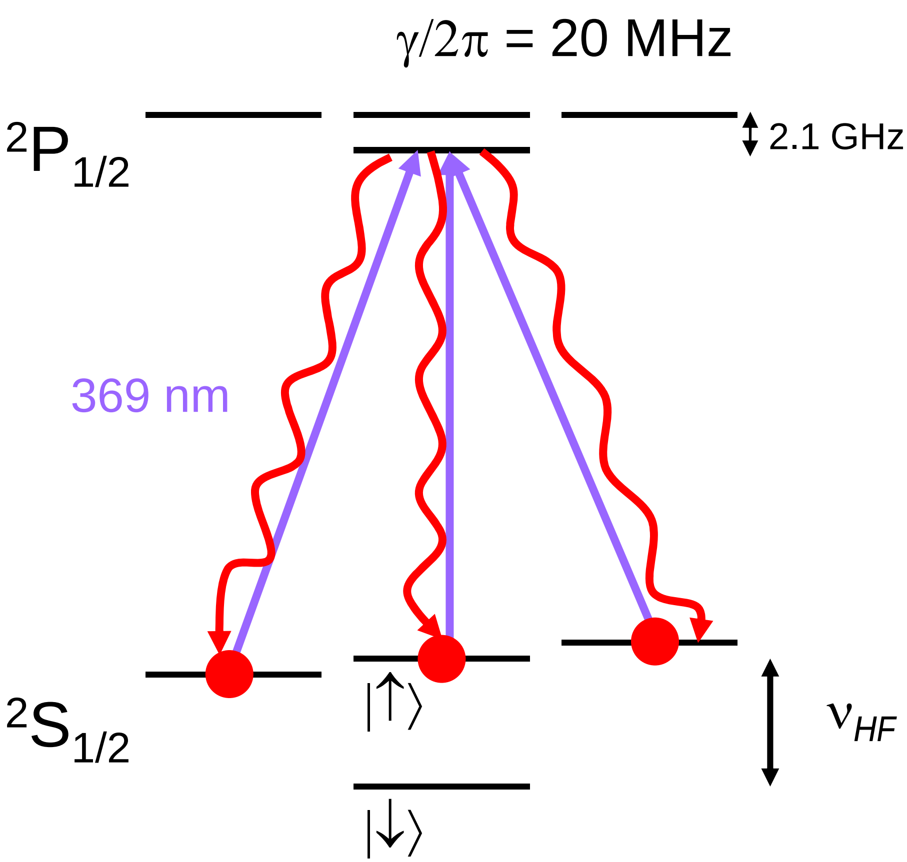
$^{171}Yb^{+}$ hyperfine qubit

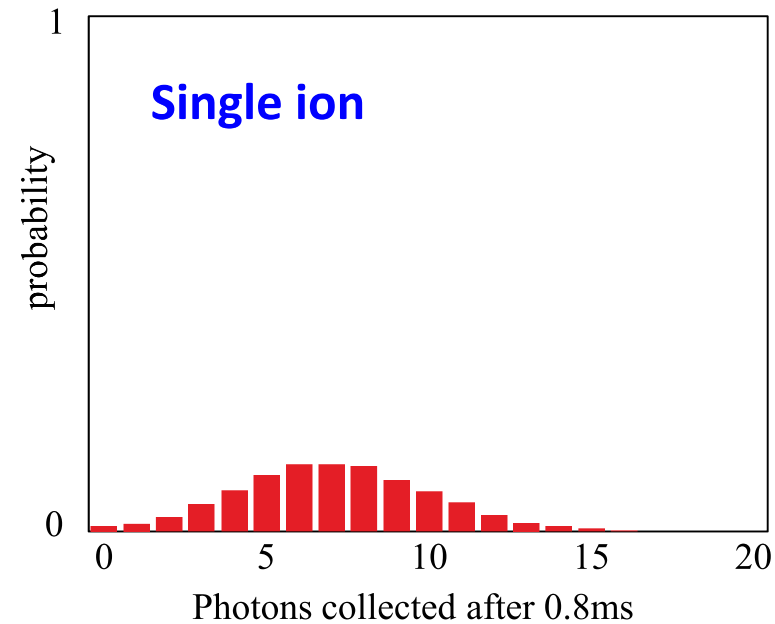


ν_{HF} = 12 642 812 118 + $311B^2$ Hz

(600 Hz/G @ 1 G)

$^{171}Yb^+$ qubit detection

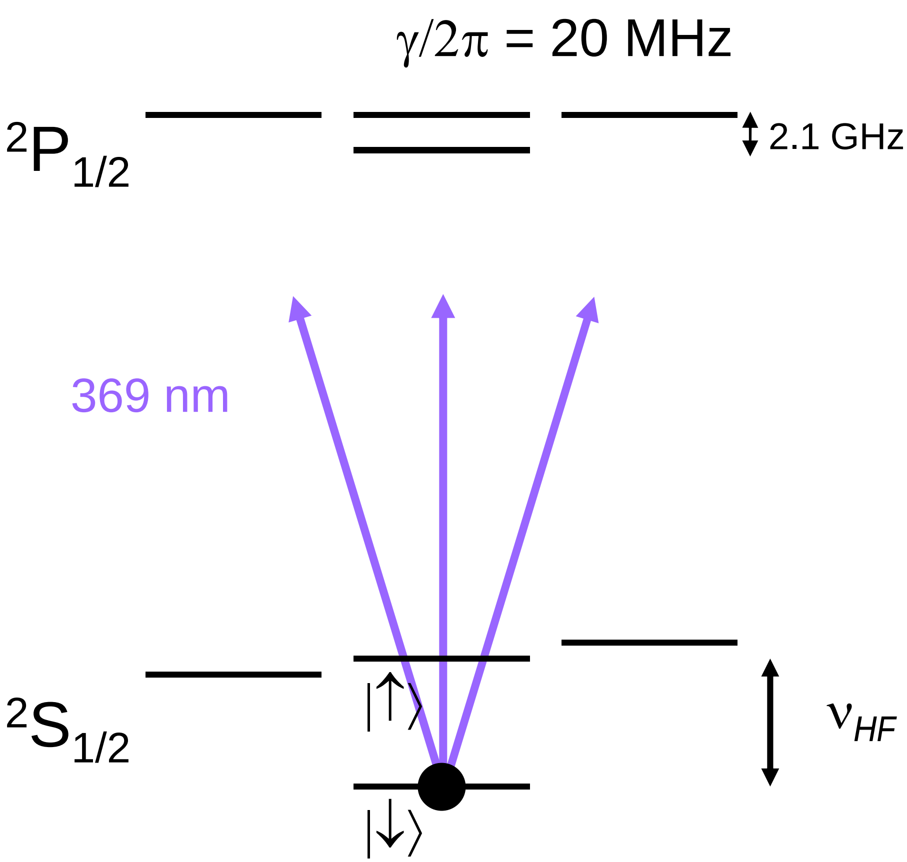




ν_{HF} = 12 642 812 118 + 311B^2 Hz

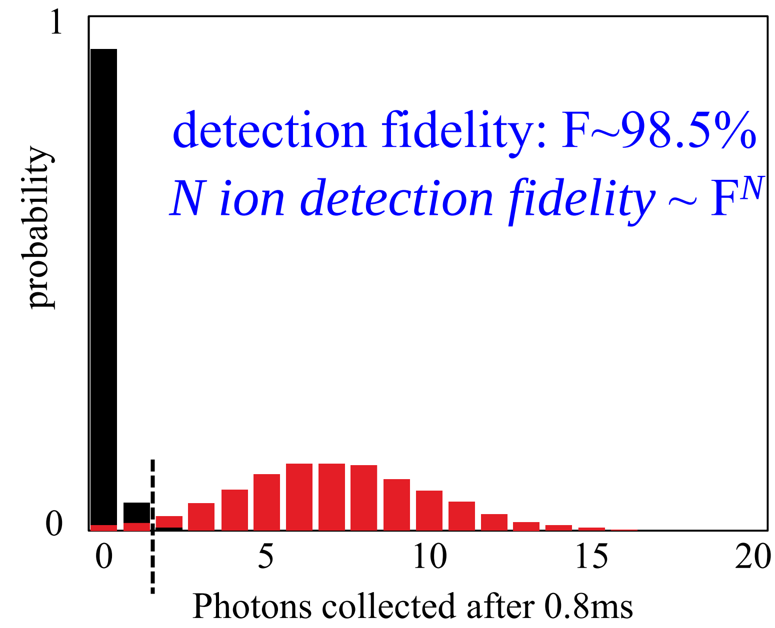
(600 Hz/G @ 1 G)

$^{171}Yb^+$ qubit detection

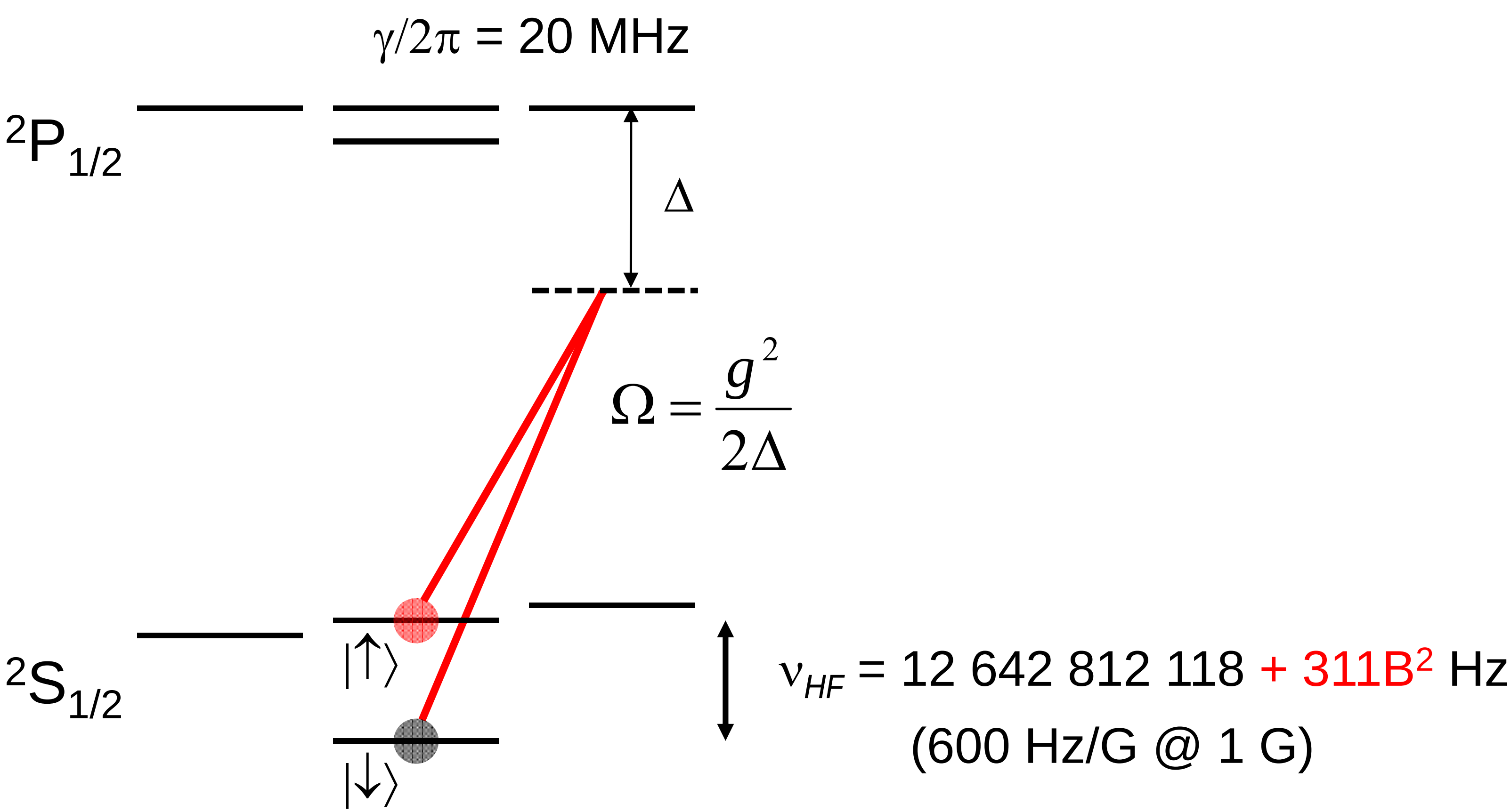


ν_{HF} = 12 642 812 118 + 311B^2 Hz

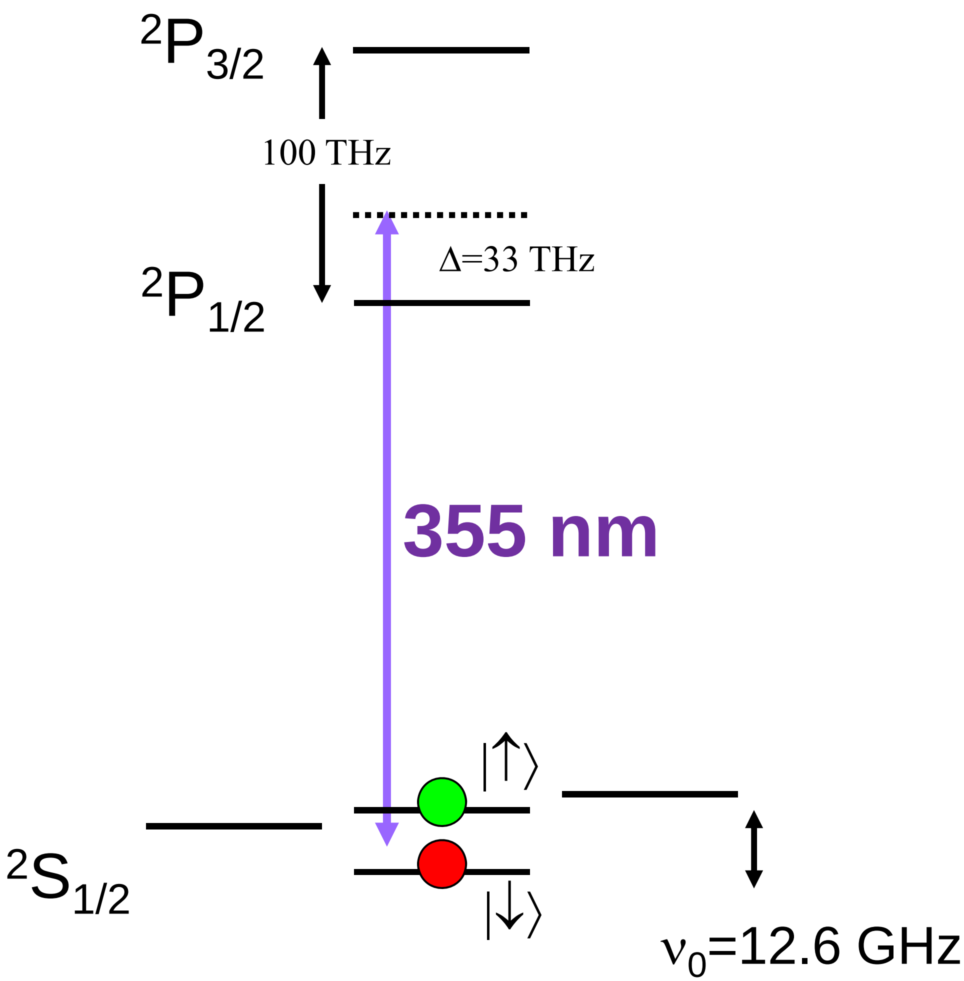
(600 Hz/G @ 1 G)

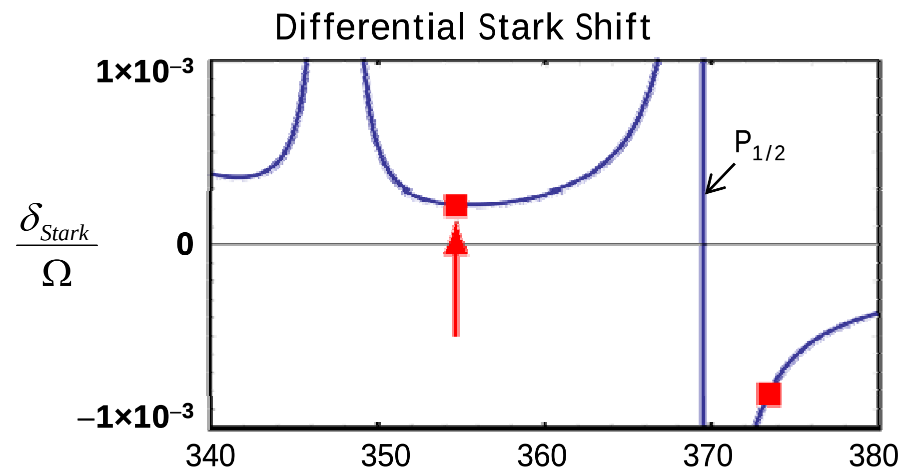


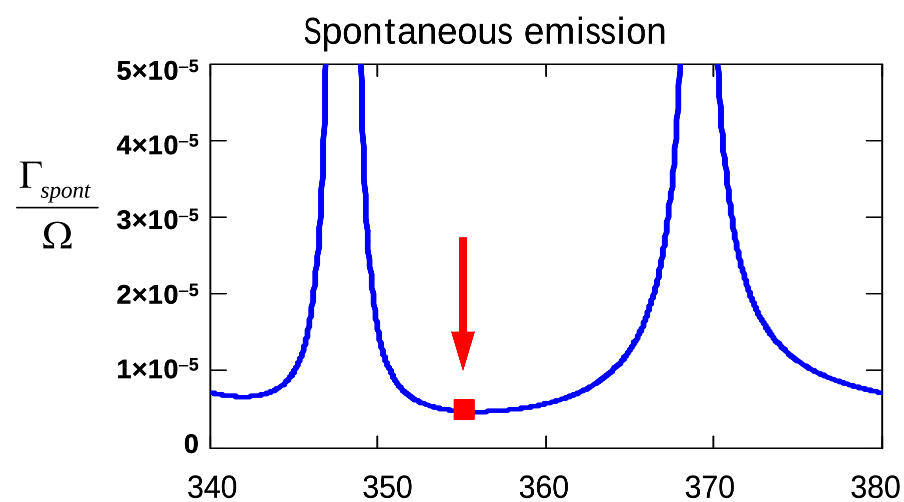
$^{171}Yb^{+}$ qubit manipulation



Suppressing Spontaneous emission: 355nm







National Ignition Facility (LLNL) 355nm

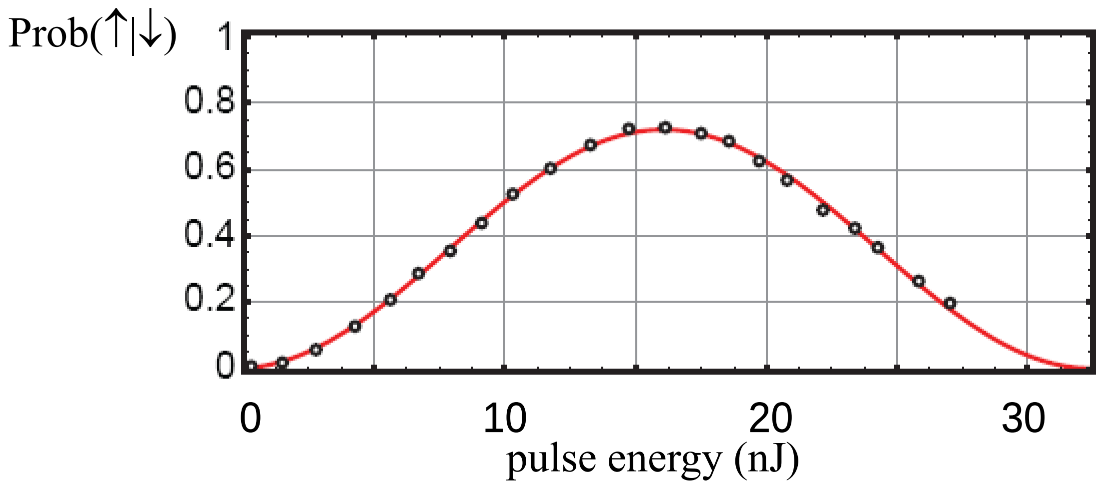
P_{avg}=4W at 355nm
120MHz rep rate
10 psec pulses

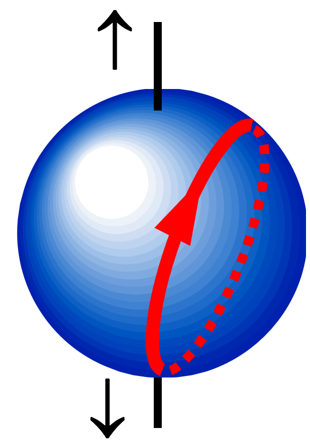
Ultrafast/ultraclean control of a single spin

$$H = \frac{\omega_{HF}}{2}\hat{\sigma}_z + \frac{\Omega(t)}{2}\hat{\sigma}_x$$

single pulse
at 355nm

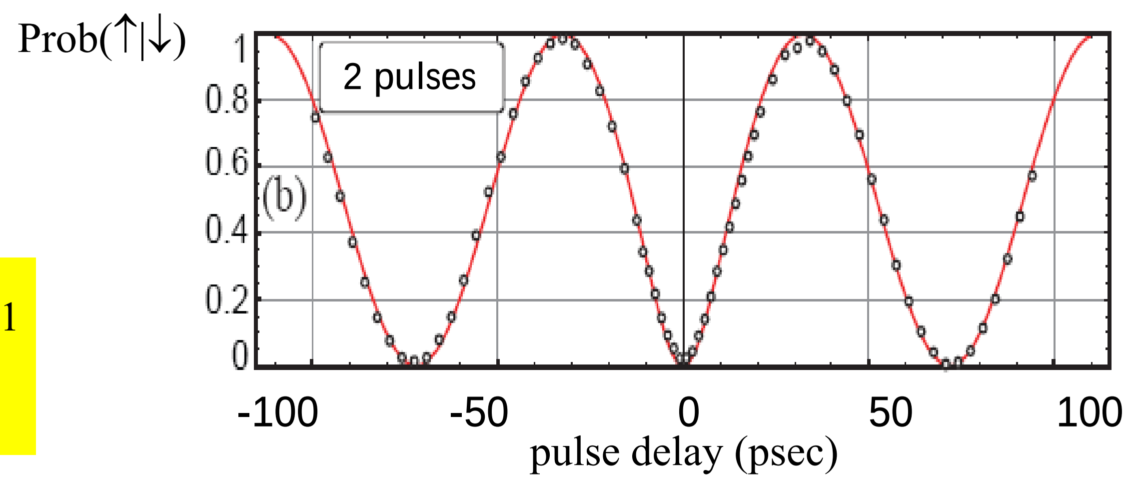
τ ~ 10 psec

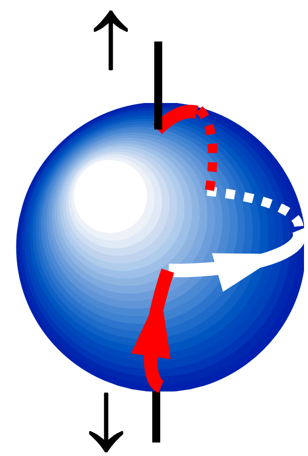




two pulses
at 355nm

$$\frac{\tau_{decoh}}{\tau_{control}} > 10^{11}$$

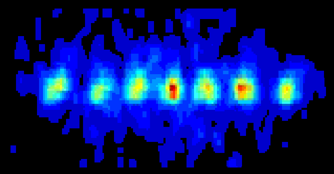




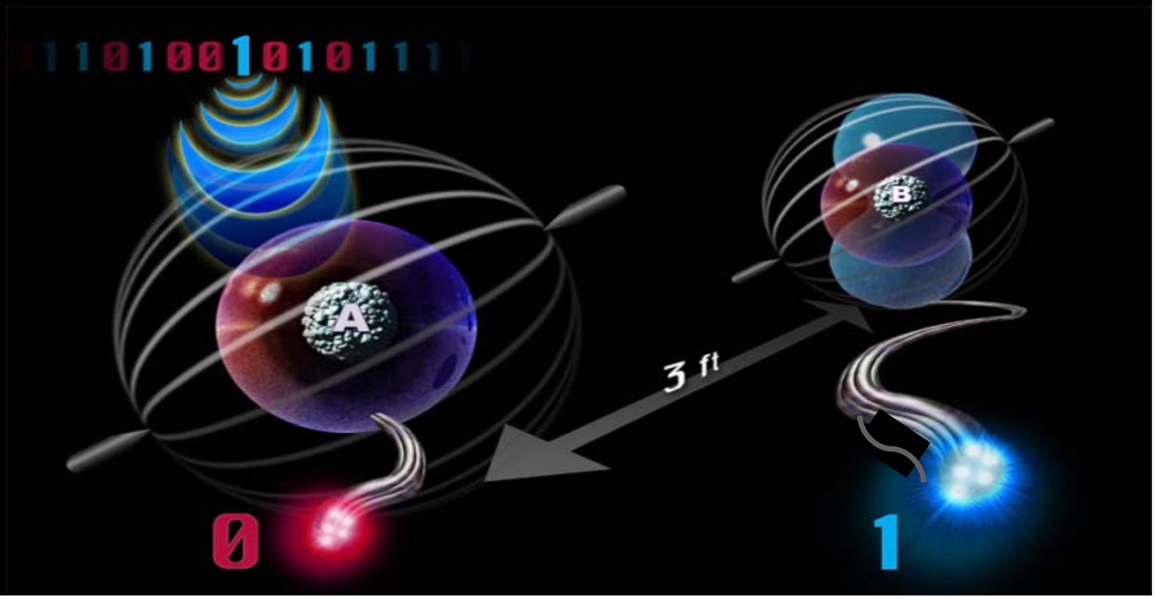
W. Campbell et al., Phys. Rev. Lett. 105, 090502 (2010)

Ion Trap Quantum Networks

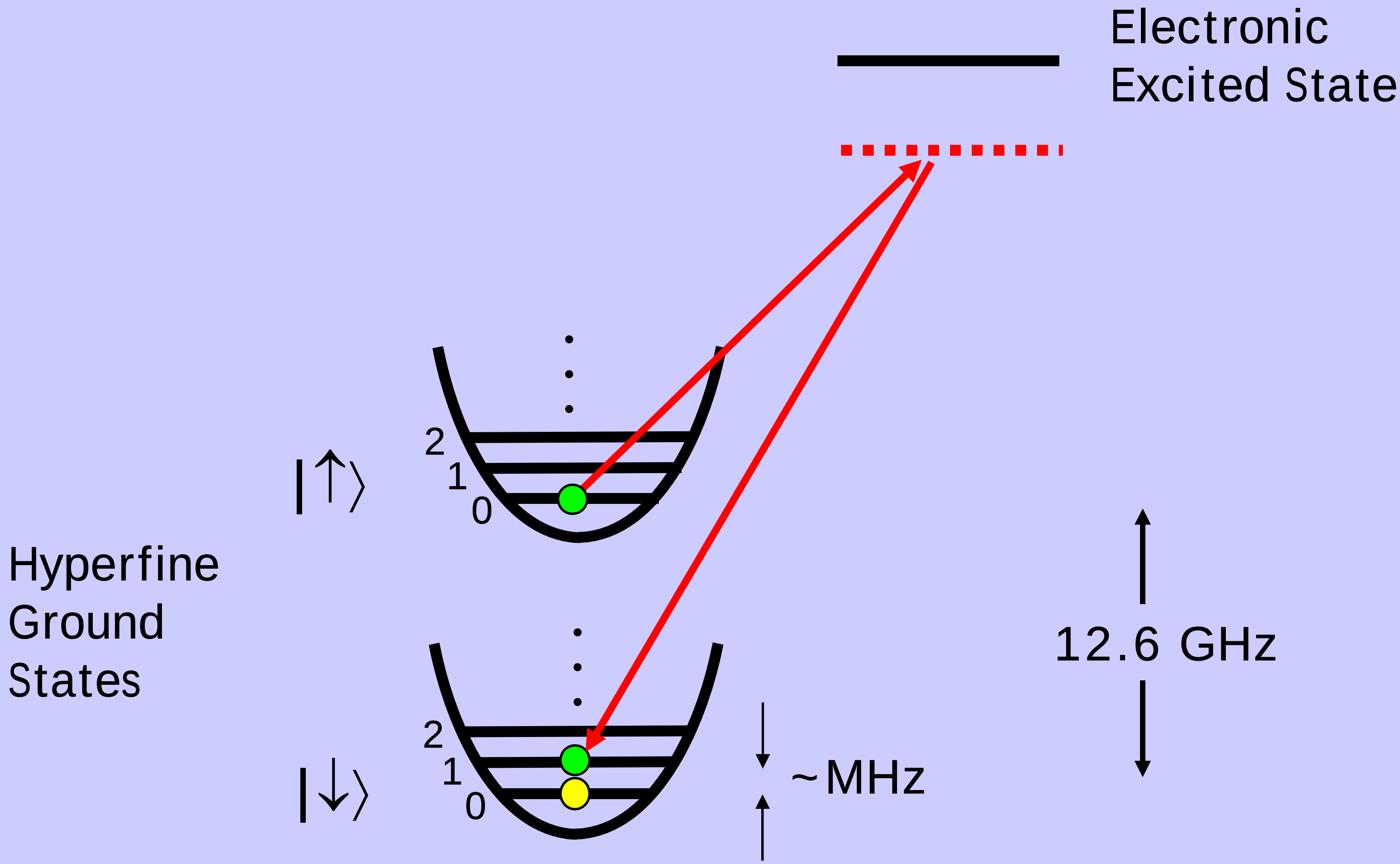
- Local connections through the Coulomb/dipole interaction



- Nonlocal connections with photons



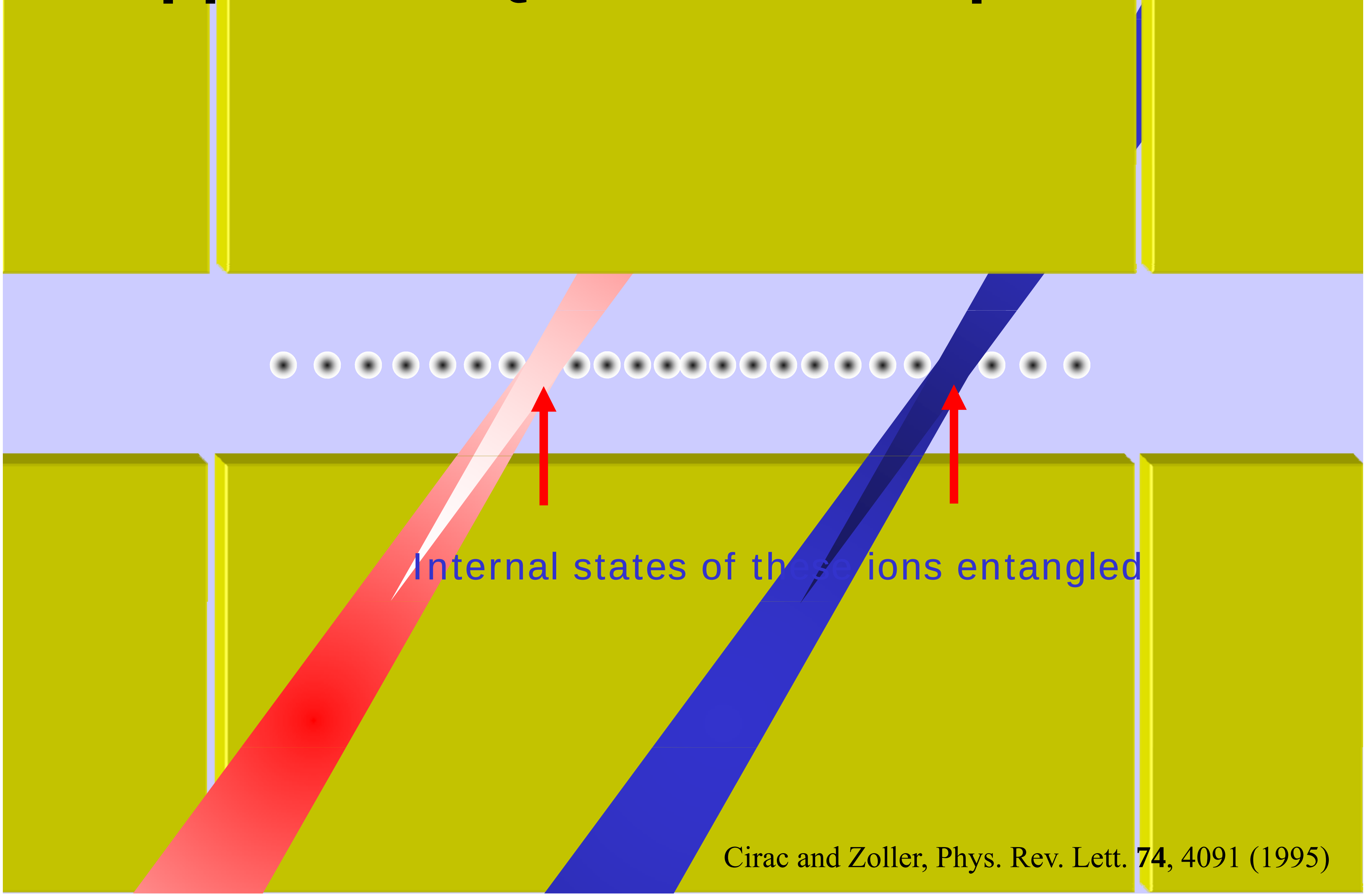
$^{171}Yb^{+}$ qubit with motion



Mapping: $\boxed{(a|\downarrow\rangle + b|\uparrow\rangle)}\,|0\rangle_m \;\rightarrow\; |\downarrow\rangle\boxed{(a|0\rangle_m + b|1\rangle_m)}$

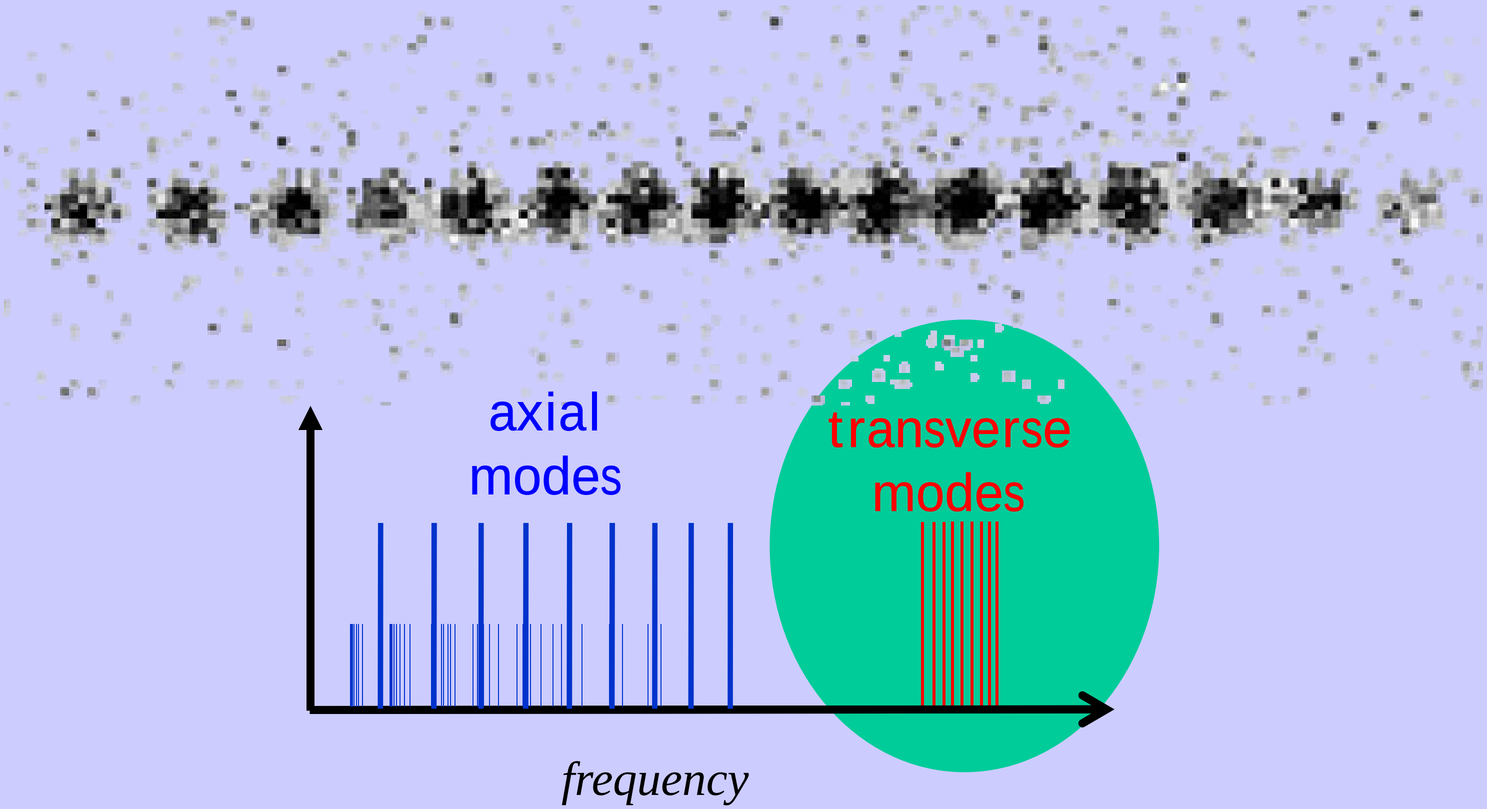
Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

Trapped Ion Quantum Computer



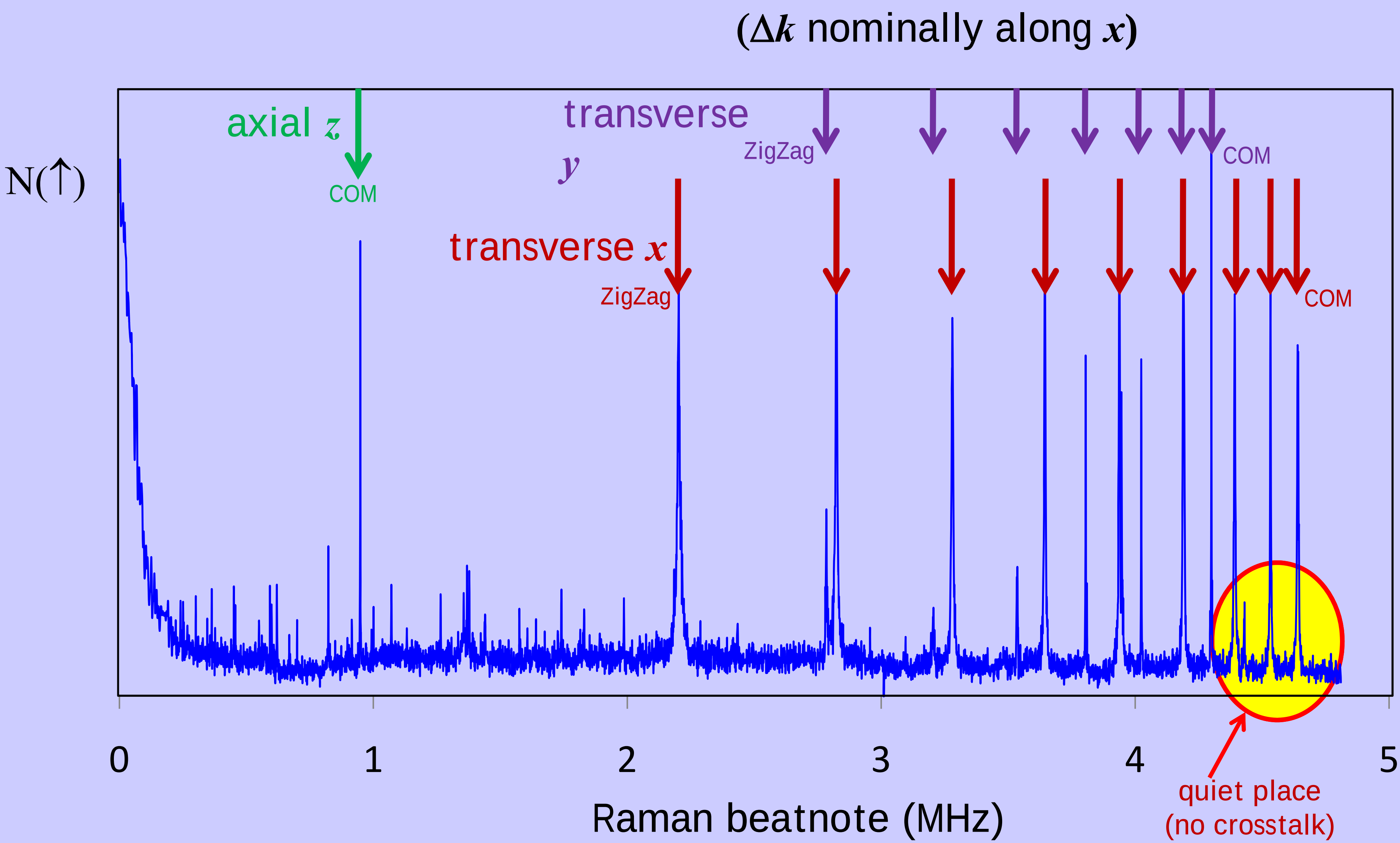
Cirac and Zoller, Phys. Rev. Lett. **74**, 4091 (1995)

Transverse Modes in a linear trap

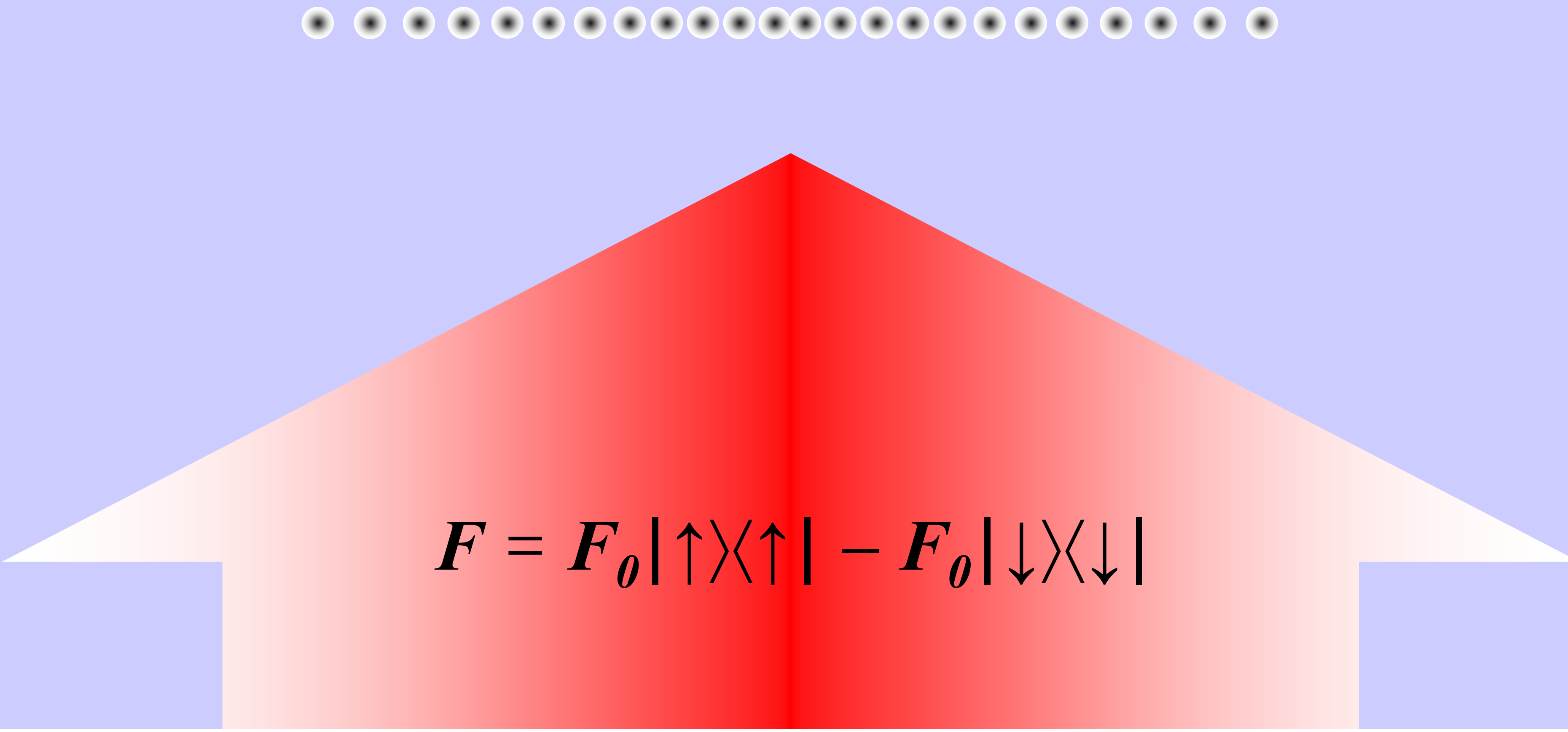


- higher frequency (cooling easier; less motional decoherence)
- controllable bandwidth
- little crosstalk between modes

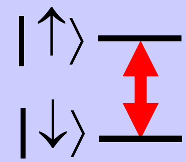
Raman spectrum of N=9 ions



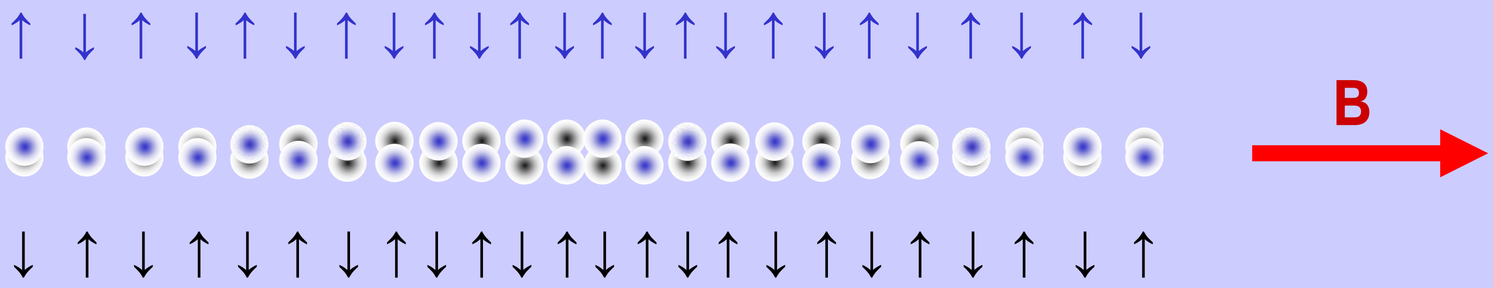
Global spin-dependent force



Global spin-dependent force



ADD: Independent spin flips



$$F = F_0 |\uparrow\rangle\langle\uparrow| - F_0 |\downarrow\rangle\langle\downarrow|$$

Resonant-enhanced force

$\sqrt{\frac{\hbar}{2m\omega_k}}$

normal mode matrix
ion i, mode k

$$H = F \cdot x = \Delta k \sum_{i,k} \Omega_i \hat{\sigma}_x^{(i)} x_0^k b_i^k [a_k^\dagger e^{i(\mu-\omega_k)t} + a_k e^{-i(\mu-\omega_k)t}]$$

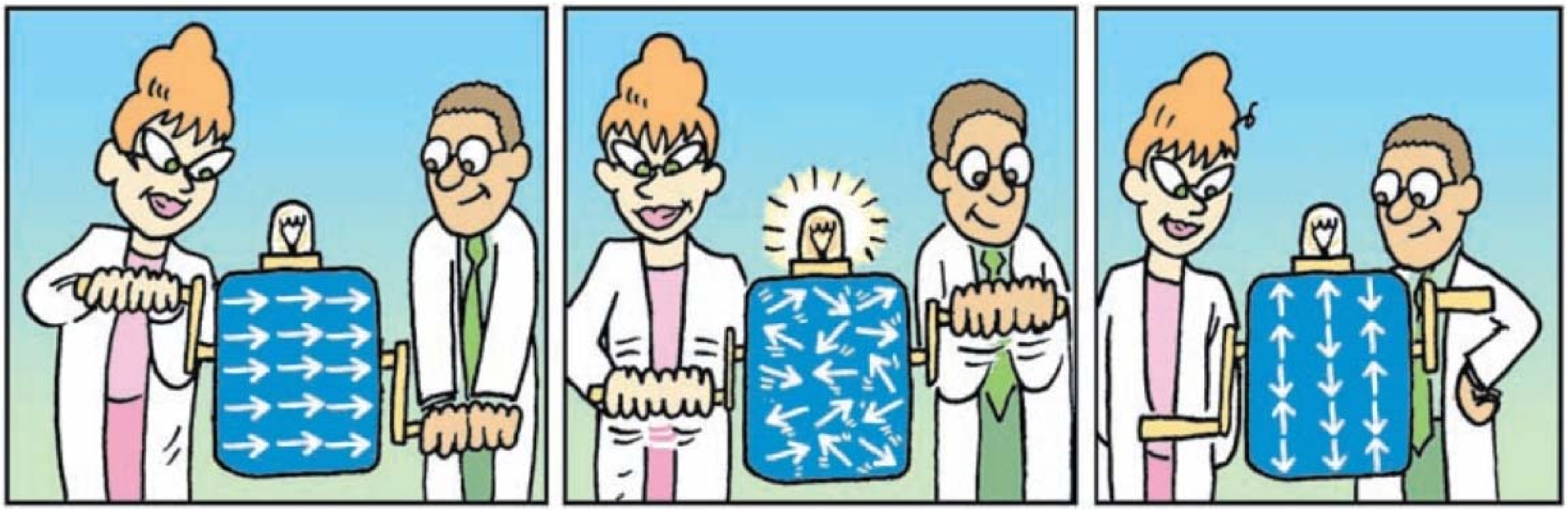
Adiabatic elimination of phonons: $|\mu - \omega| >> \Omega_0$

$$H_{eff} = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B \sum_i \hat{\sigma}_y^{(i)}$$

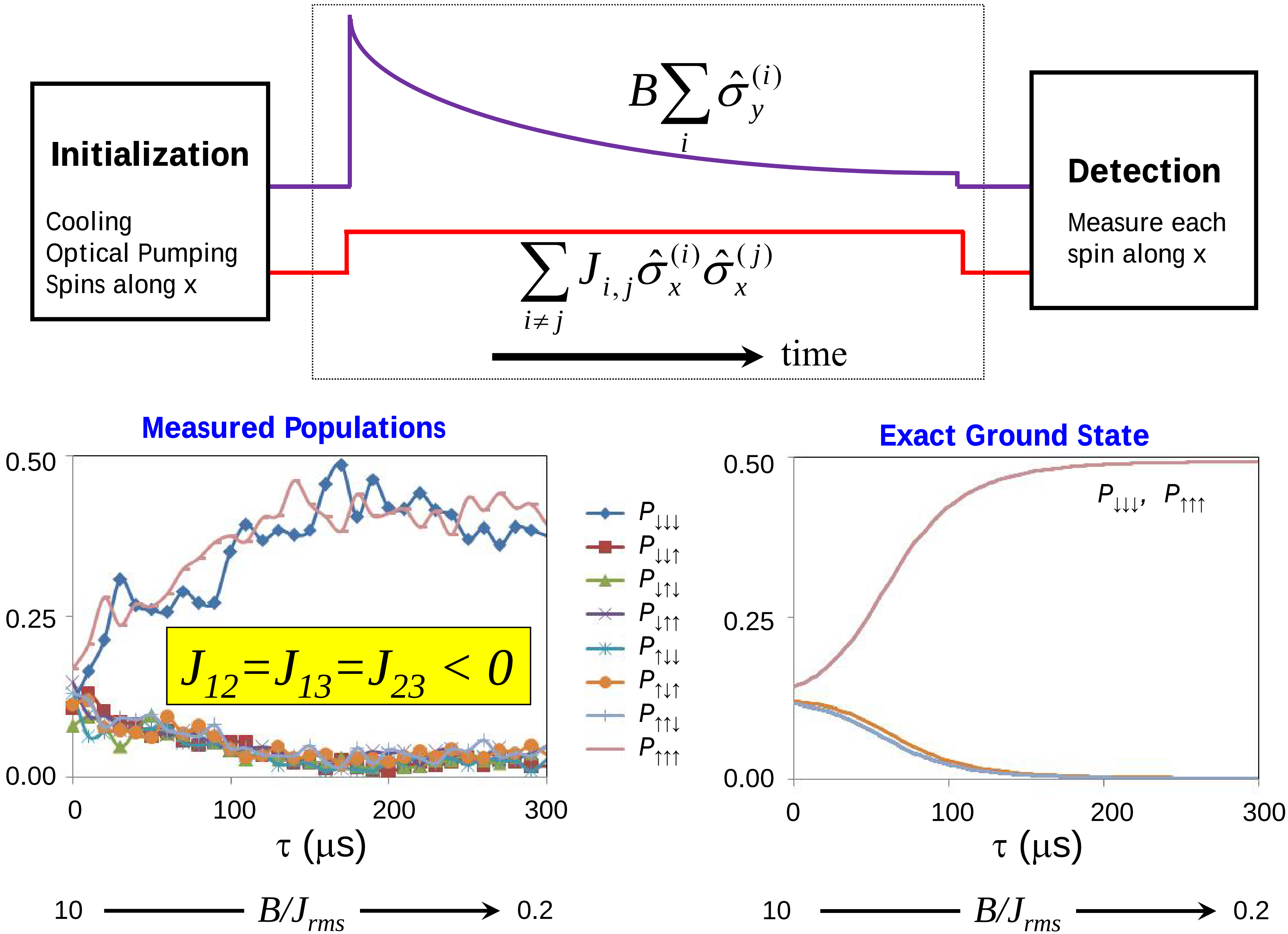
$$J_{i,j} = \frac{\hbar \Omega_i \Omega_j (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Quantum simulations with ions

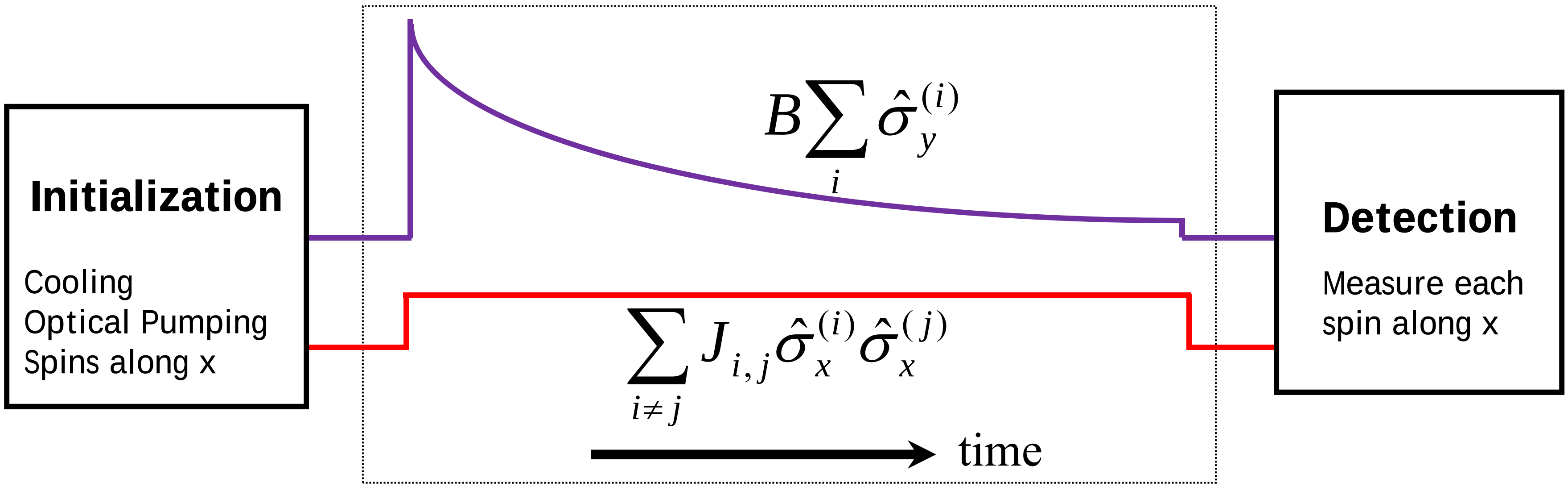
D. Porras and J. I. Cirac, Phys. Rev. Lett. **92**, 207901 (2004)
A. Friedenauer,... T. Schaetz, Nature Physics **4**, 757 (2008)
K. Kim et al., Phys. Rev. Lett. **102**, 250502 (2009)
K. Kim et al., Nature **465**, 590 (2010)
E. Edwards et al., Phys. Rev. B **82**, 060412 (2010)

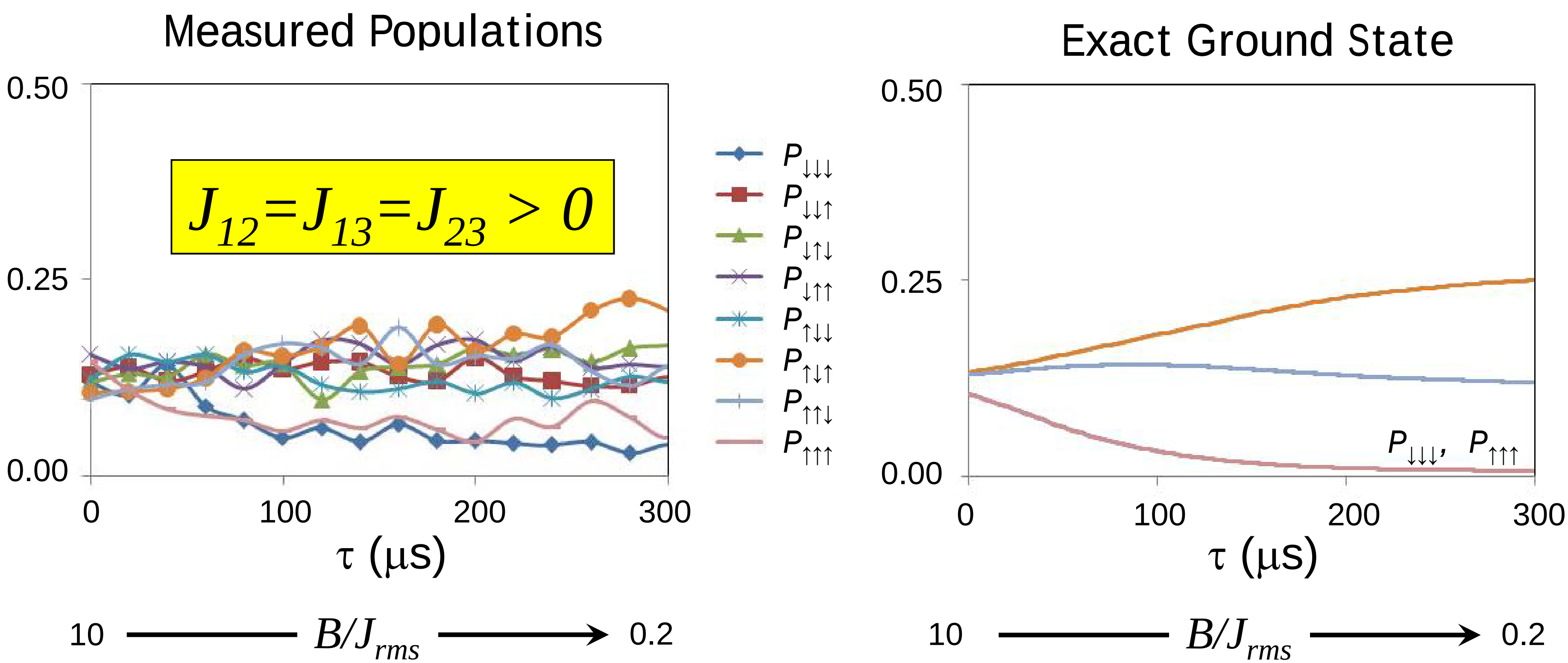


from S. Lloyd, Science **319**, 1209 (2008)



E. Edwards, et al., Phys. Rev. B (2010); ArXiv 1005.4160

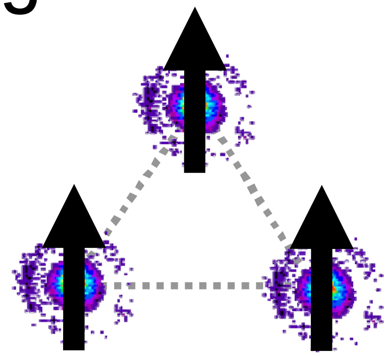


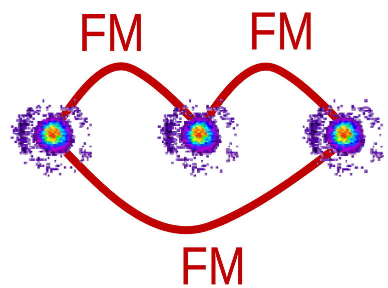


K. Kim, et al., Nature **465**, 590 (2010)

Ferromagnetic couplings

$J_{12}=J_{13}=J_{23} < 0$





ground state is *entangled*

$$|\Psi\rangle = |\uparrow\uparrow\uparrow\rangle+|\downarrow\downarrow\downarrow\rangle$$

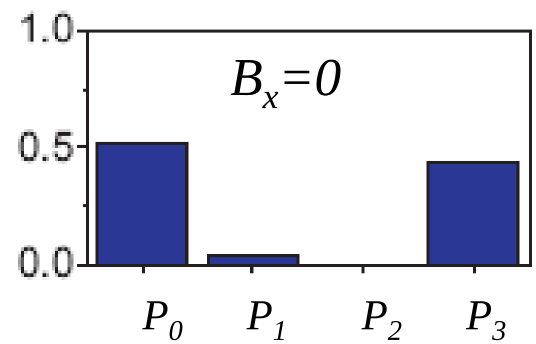
symmetry breaking field B_x

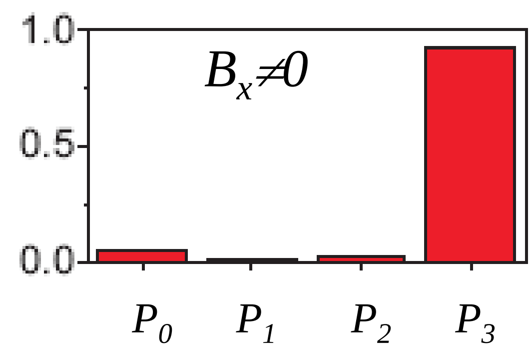
$$|\Psi_1\rangle = |\uparrow\uparrow\uparrow\rangle$$

no entanglement

$$|\Psi_2\rangle = |\downarrow\downarrow\downarrow\rangle$$

no entanglement

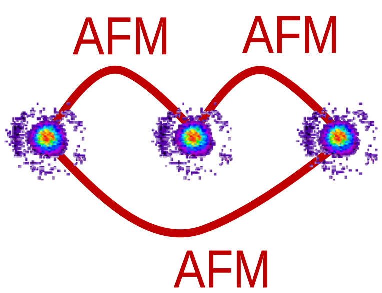


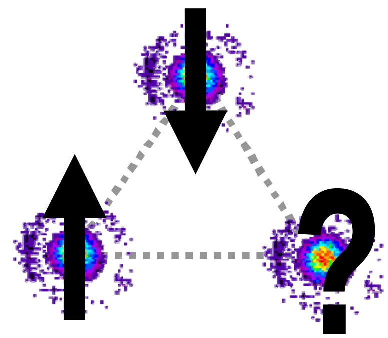


K. Kim, et al., Nature **465**, 590 (2010)

Simplest case of spin frustration

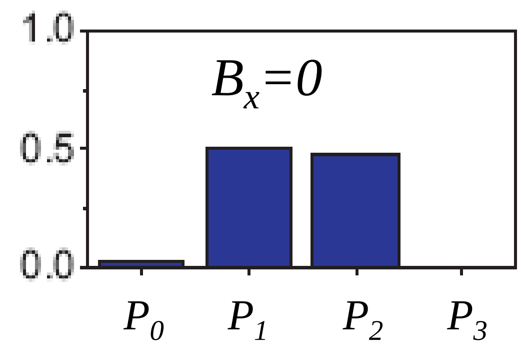
$J_{12}=J_{13}=J_{23} > 0$





ground state is *entangled*

$|\Psi\rangle = |\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle + |\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle$



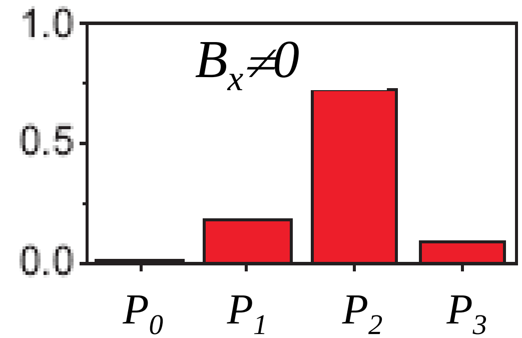
symmetry breaking field B_x

$|\Psi_1\rangle = |\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle$

still entangled!

$|\Psi_2\rangle = |\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle$

still entangled!

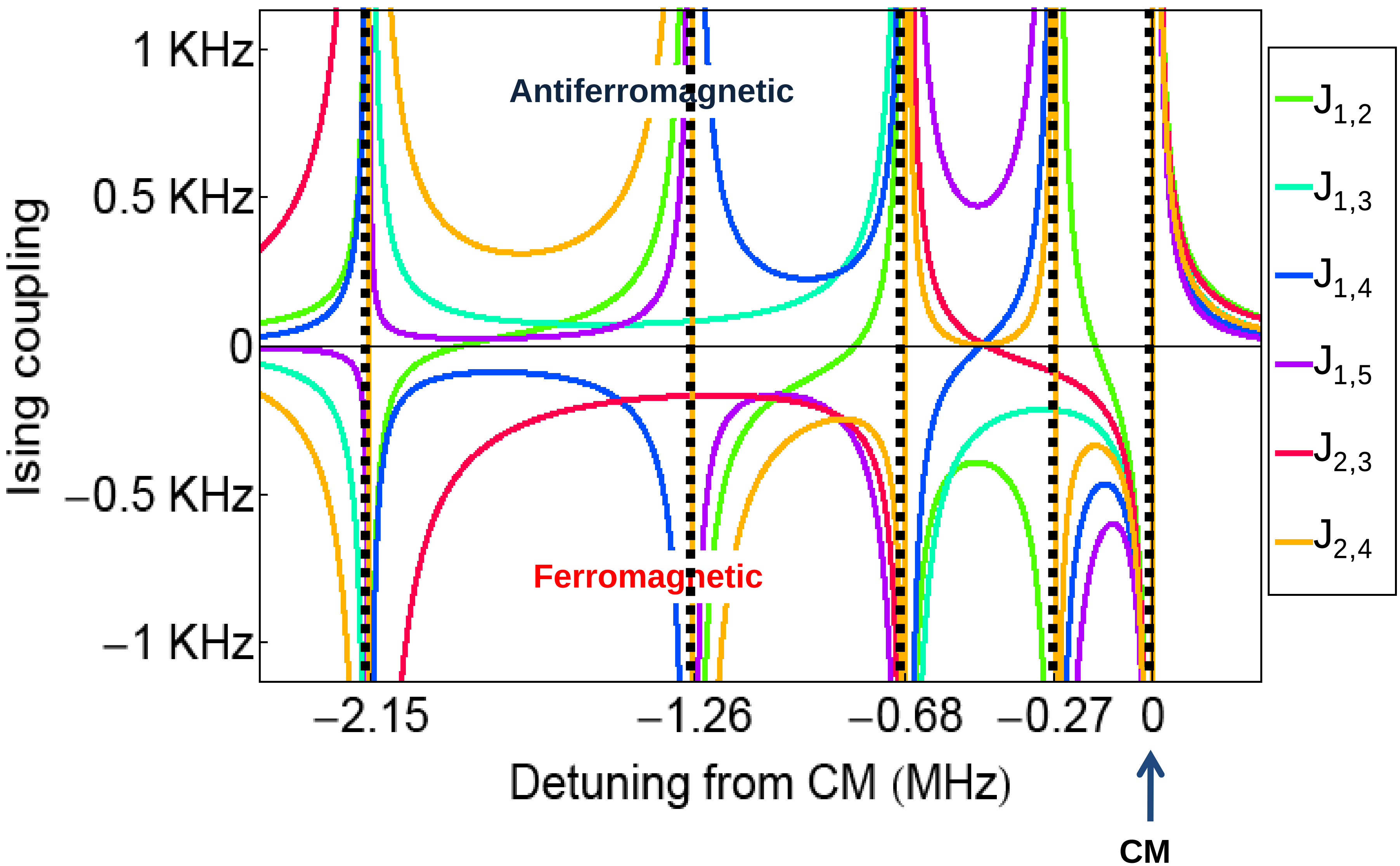


Frustration ⇔ Entanglement

K. Kim, et al., Nature **465**, 590 (2010)

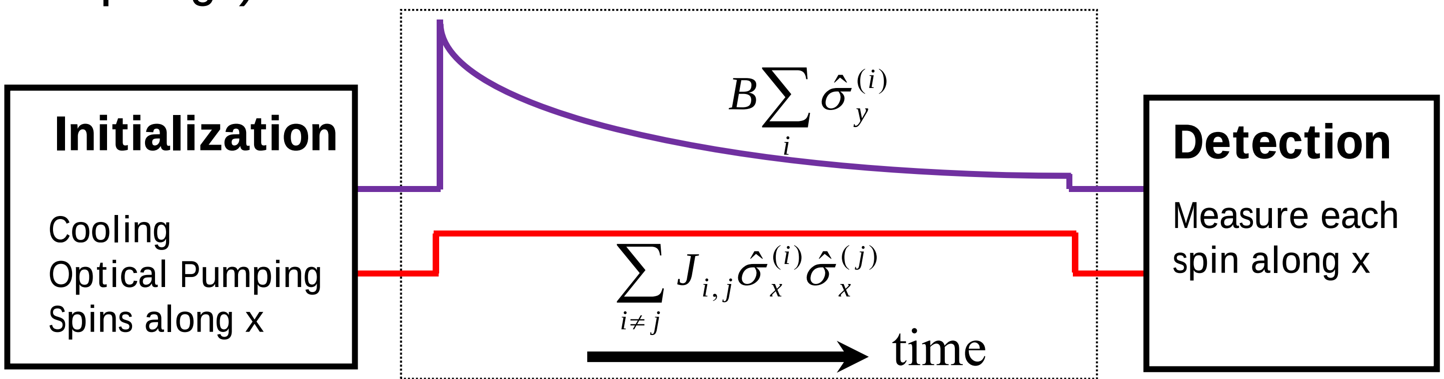
Ising couplings for 5 spins

$$H = \sum_{i \neq j} J_{i,j} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)} + B \sum_i \hat{\sigma}_x^{(i)}$$

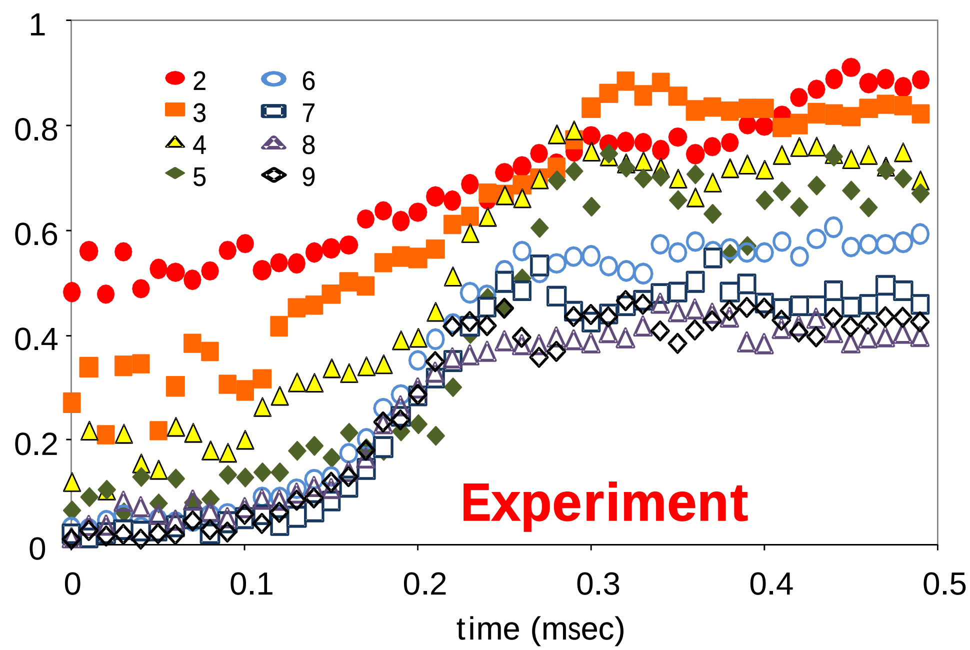


Emergence of ferromagnetism vs. N

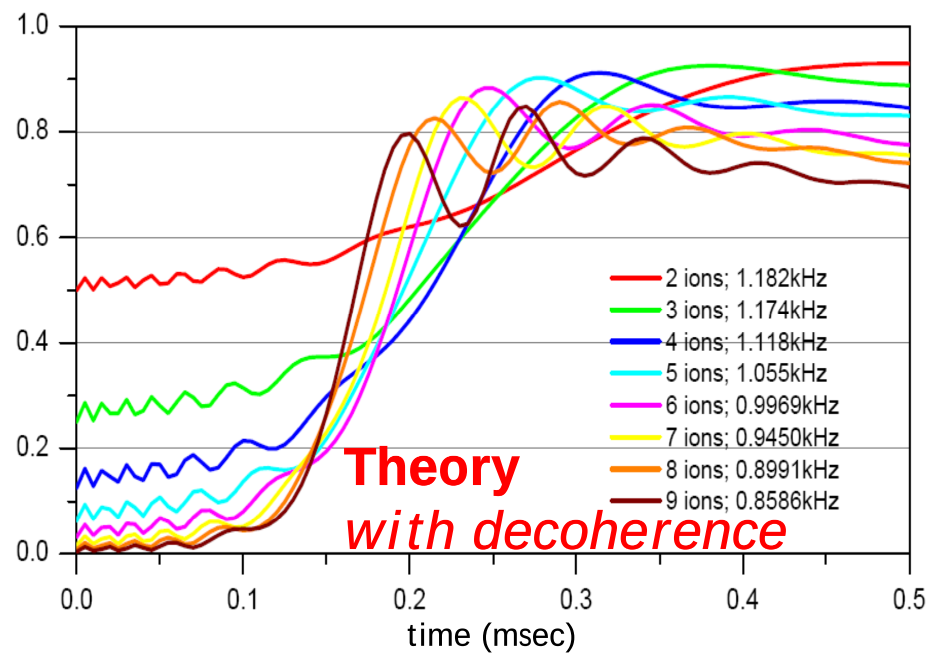
(uniform couplings)



P(FM) = P(↑↑↑...↑) + P(↓↓↓...↓)



P(FM) = P(↑↑↑...↑) + P(↓↓↓...↓)

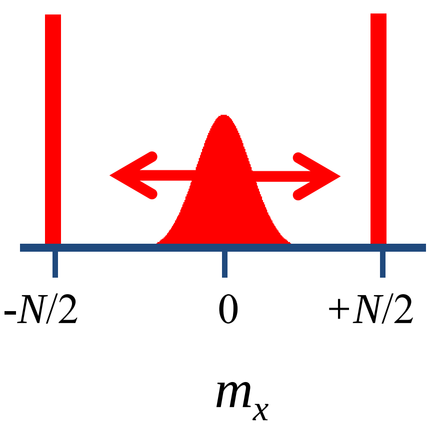


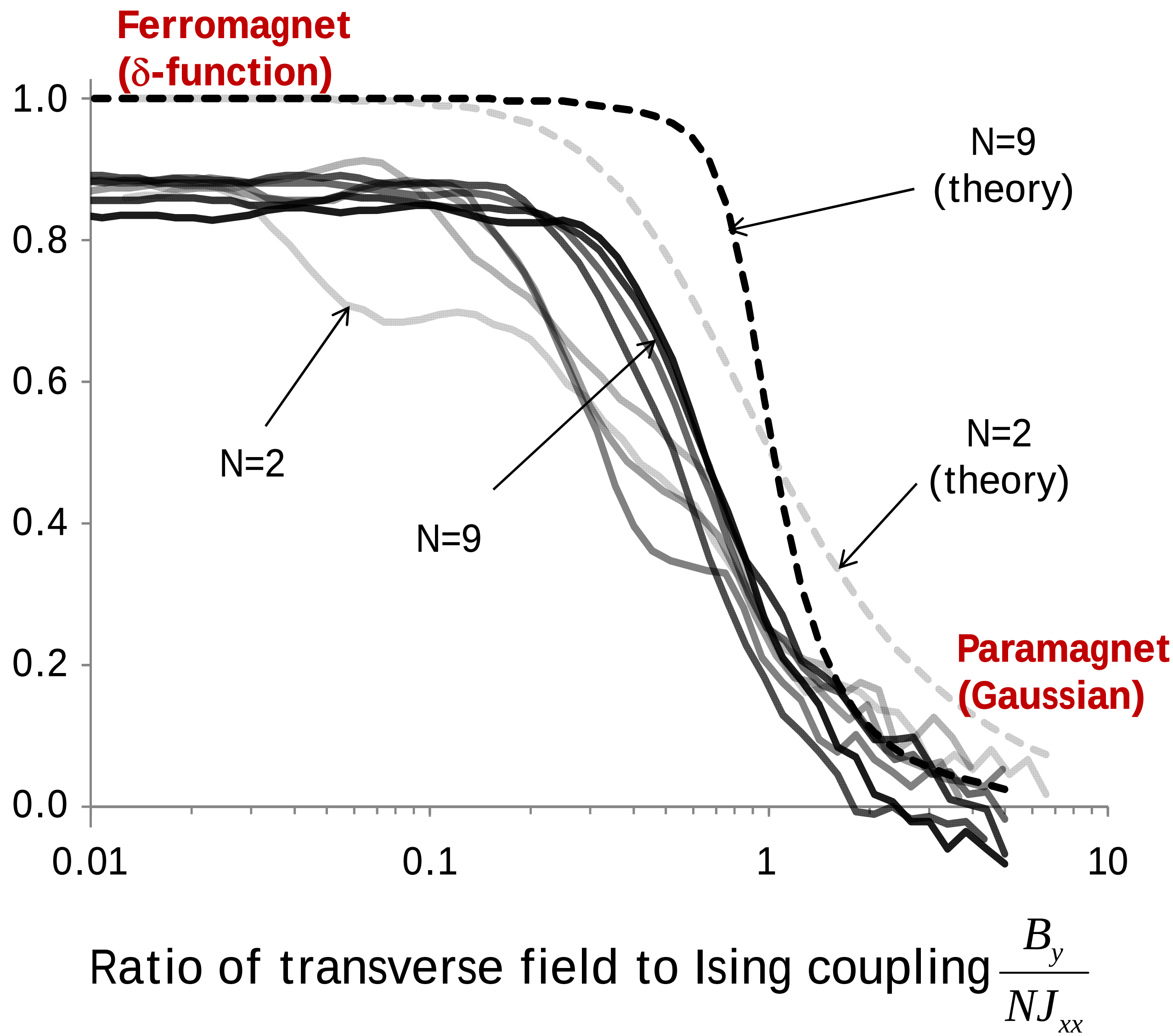
H. Carmichael

Distribution of magnetization for N=2,3,..9 spins (Uniform FM couplings)

"Binder Ratio"

$$\frac{3\langle m_x^2\rangle^2 - \langle m_x^4\rangle}{2\langle m_x^2\rangle^2}$$





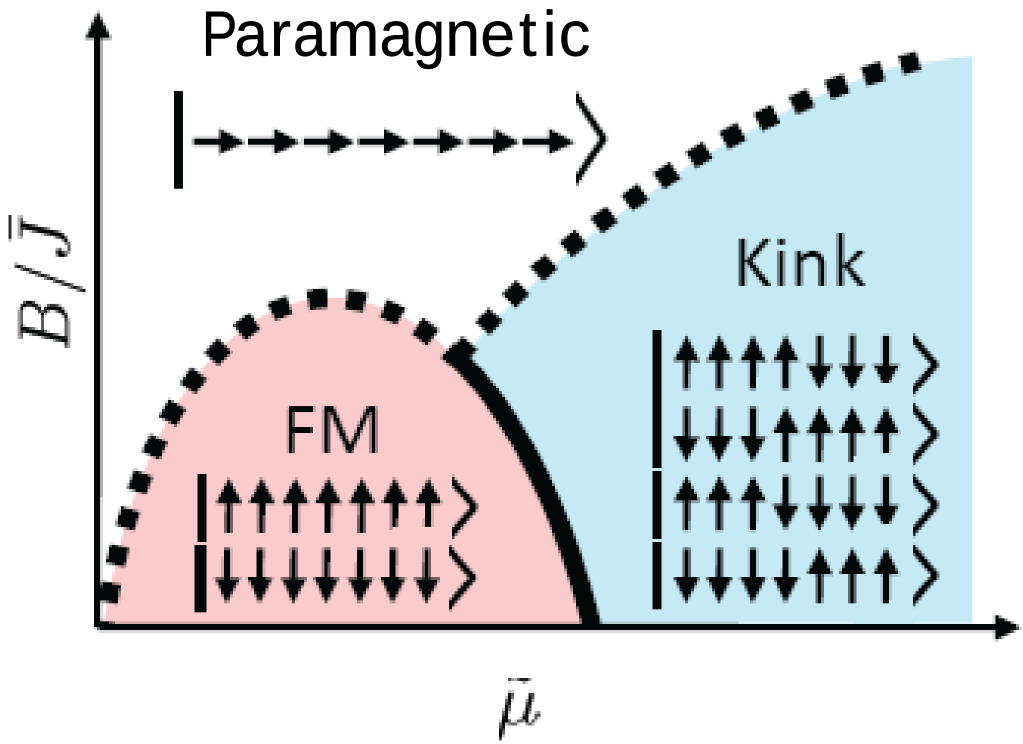
Sharp phase transitions in a small spin network of trapped ions with frustrated coupling

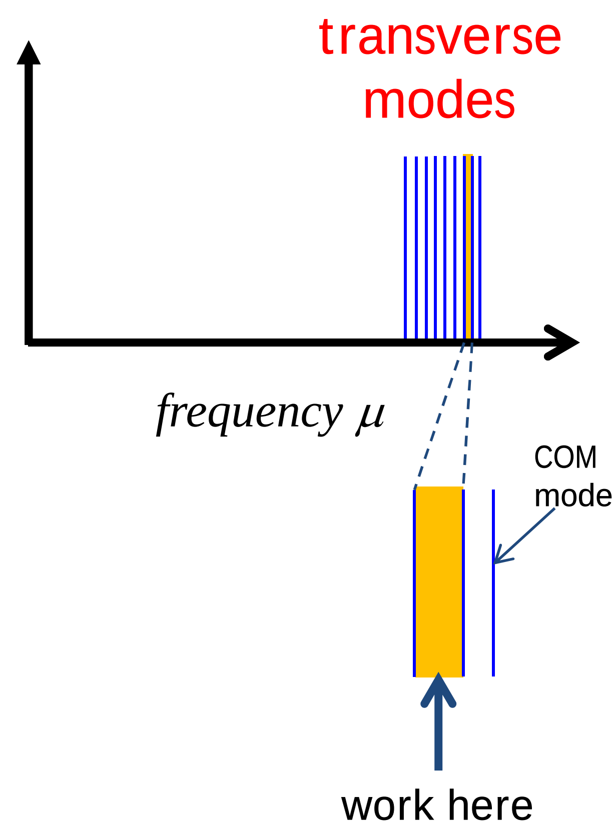
G.-D. Lin[1], C. Monroe[2], and L.-M. Duan[1]

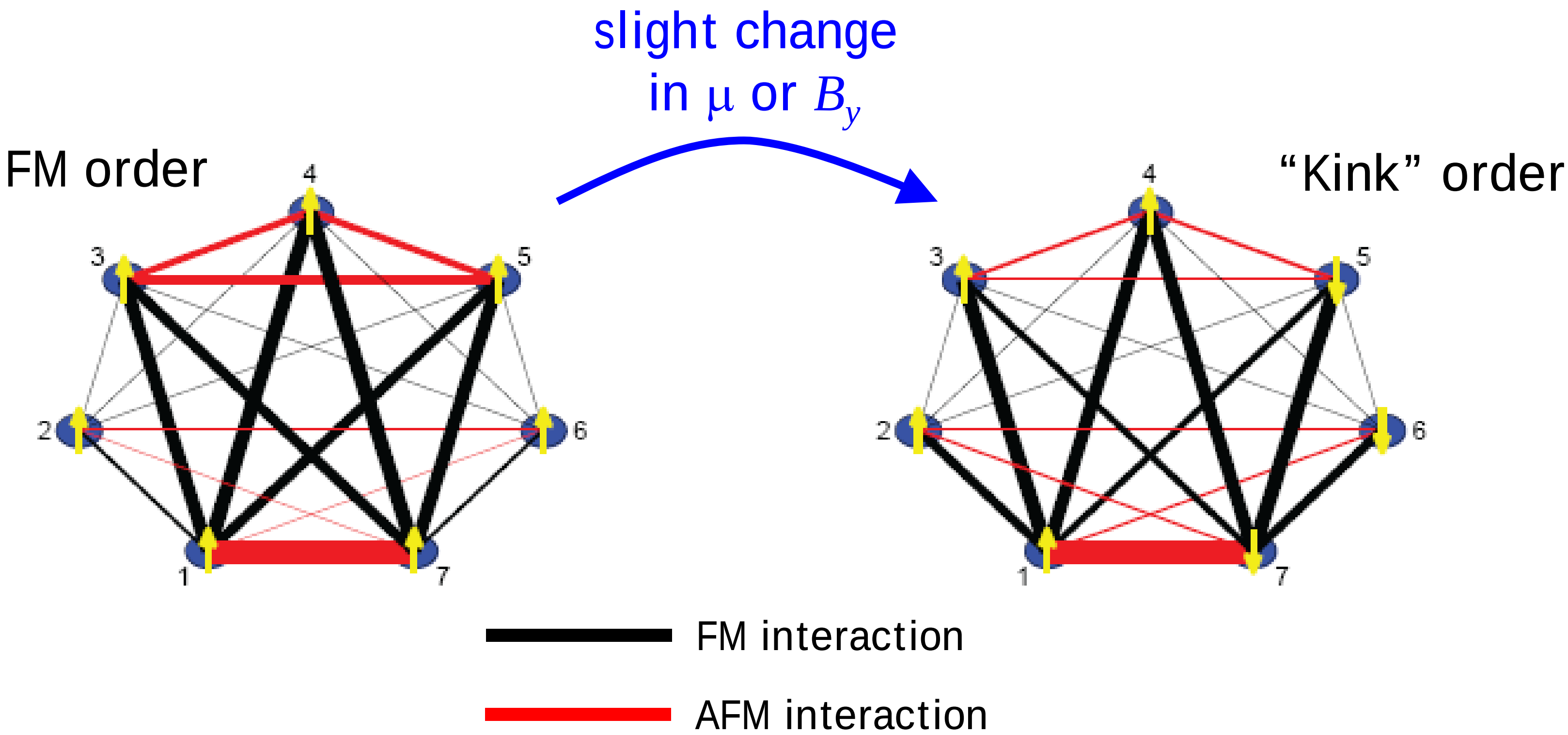
1. *Department of Physics and MCTP, University of Michigan, Ann Arbor, Michigan 48109*

2. *Joint Quantum Institute, University of Maryland Department of Physics and National Institute of Standards and Technology, College Park, Maryland 20742 USA*

(Dated: May 18, 2010)







from *SIAM News*, Volume 33, Number 6

The Ising Model Is NP-Complete

By Barry A. Cipra

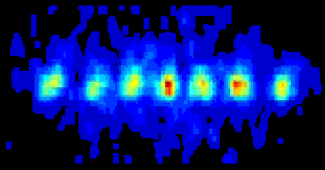
In 1925, the German physicist Ernst Ising introduced a simple mathematical model of phase transitions, the abrupt changes of state that occur, for example, when water freezes or a cooling lump of iron becomes magnetic. In the 75 years since, the Ising model has been analyzed, generalized, and computerized—but never, except in special cases, solved. Researchers managed to get exact answers for physically unrealistic, two-dimensional systems, but have never been able to make the leap out of the plane.

There could be a good reason: The Ising model, in its full, nonplanar glory, is NP-complete.

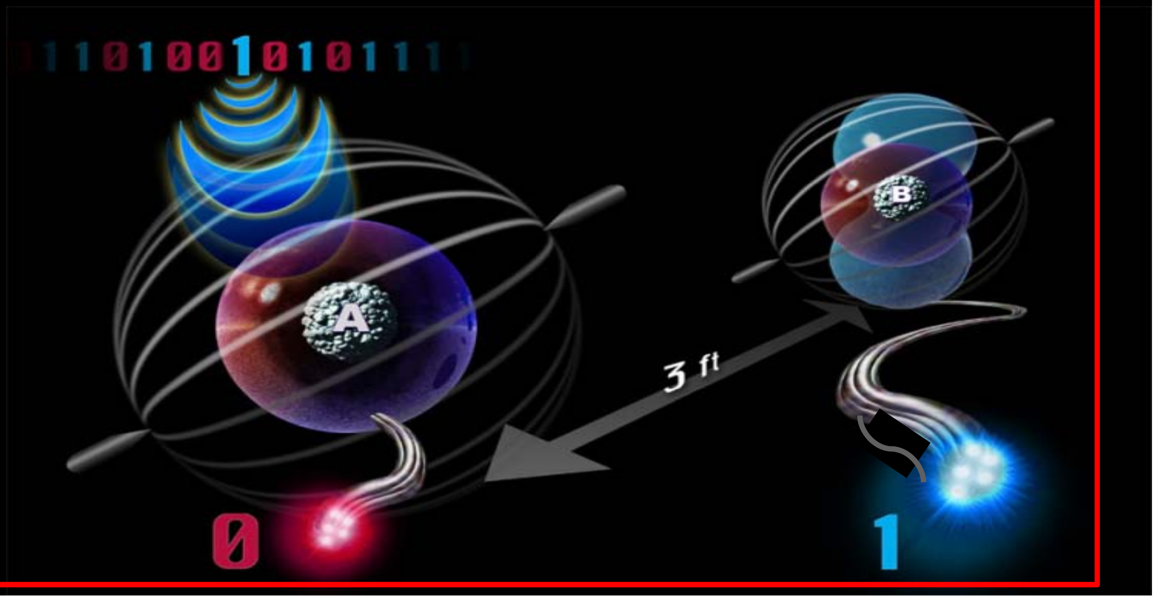
Can quantum computers solve NP-complete problems?

Ion Trap Quantum Networks

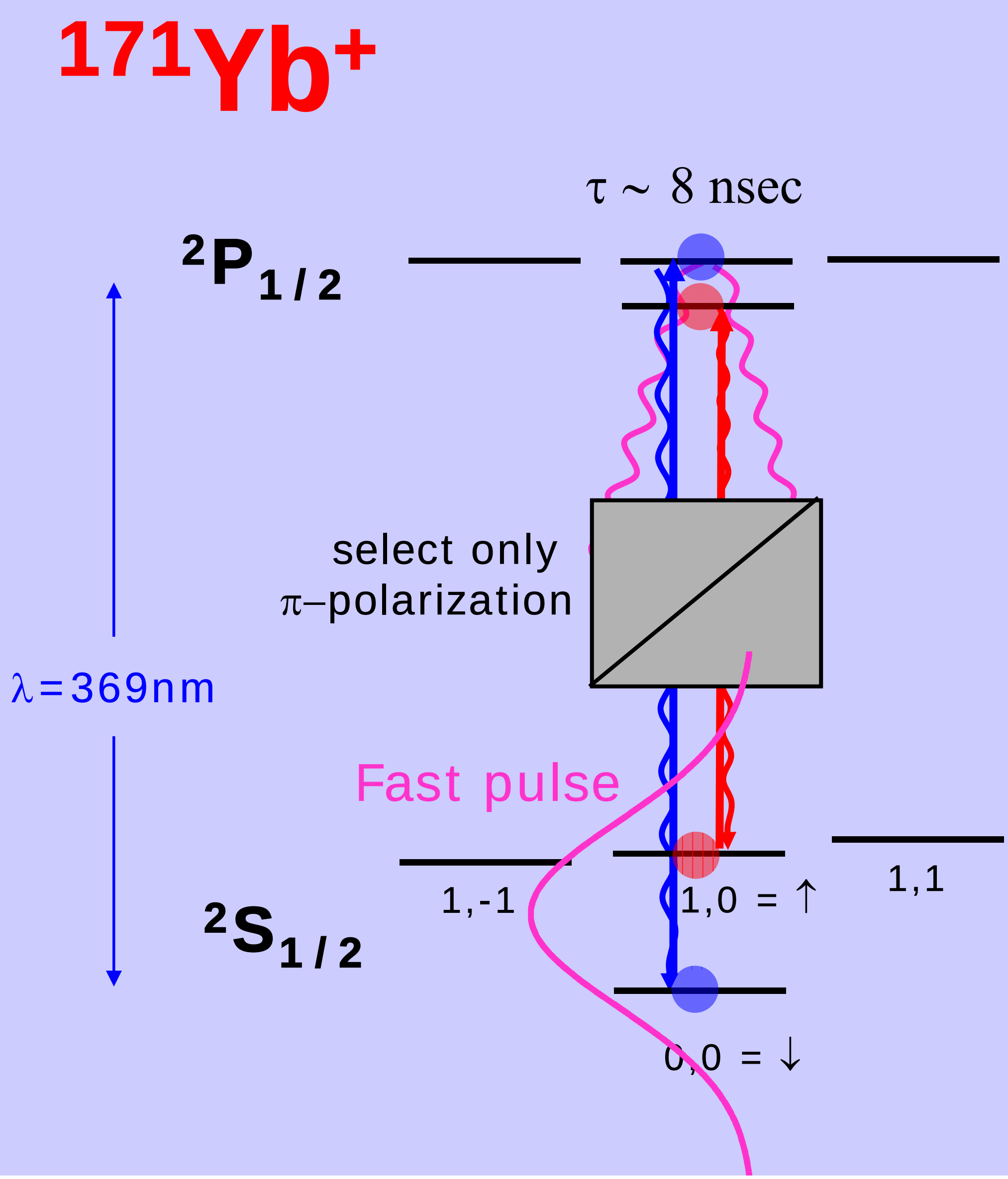
- Local connections through the Coulomb/dipole interaction



- Nonlocal connections with photons



Linking atoms with ~~phonons~~ photons



Given photon emerges from polarizer

$|\psi\rangle = |\downarrow\rangle|\text{blue}\rangle + |\uparrow\rangle|\text{red}\rangle$

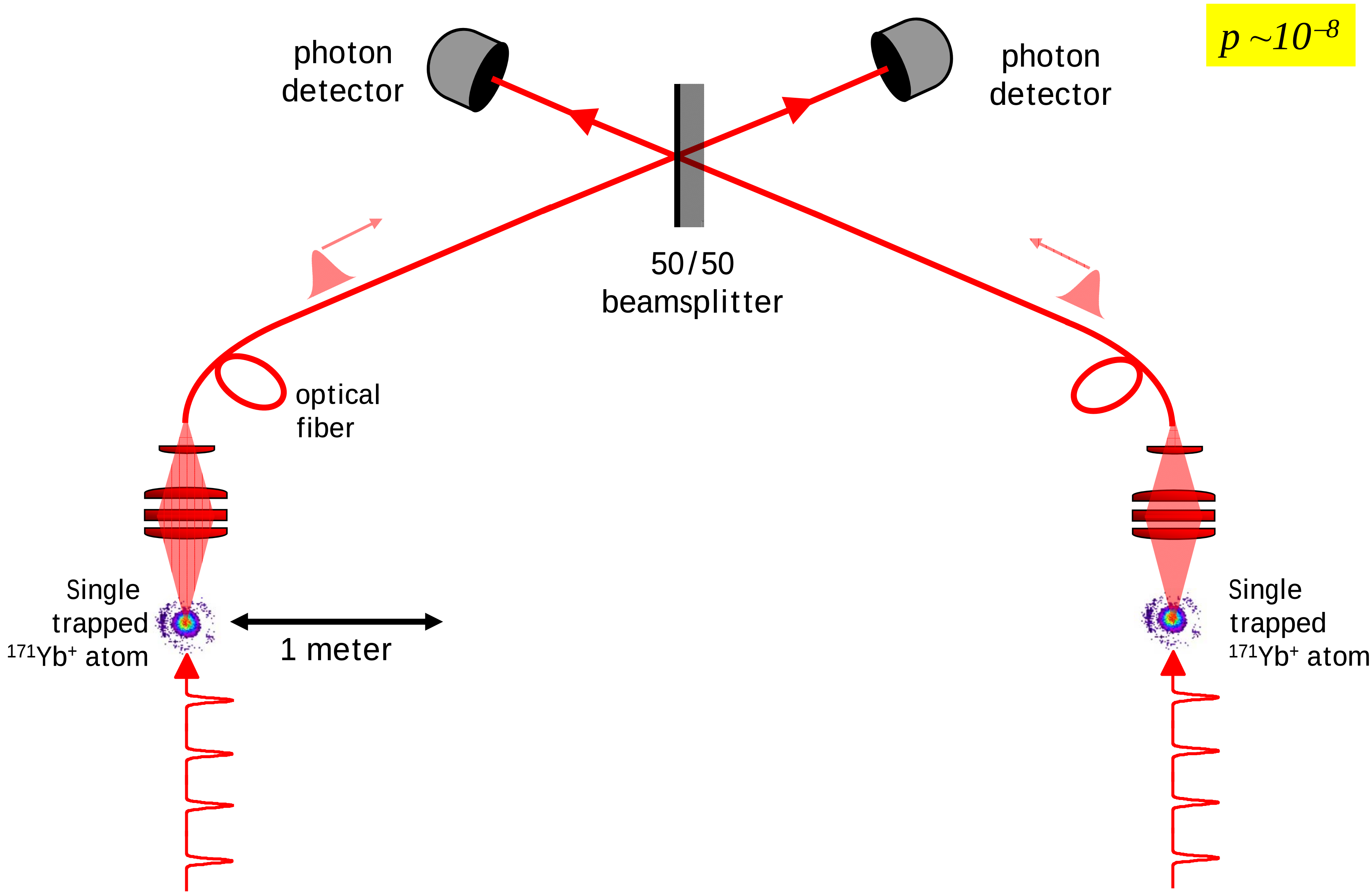
(post-selected)

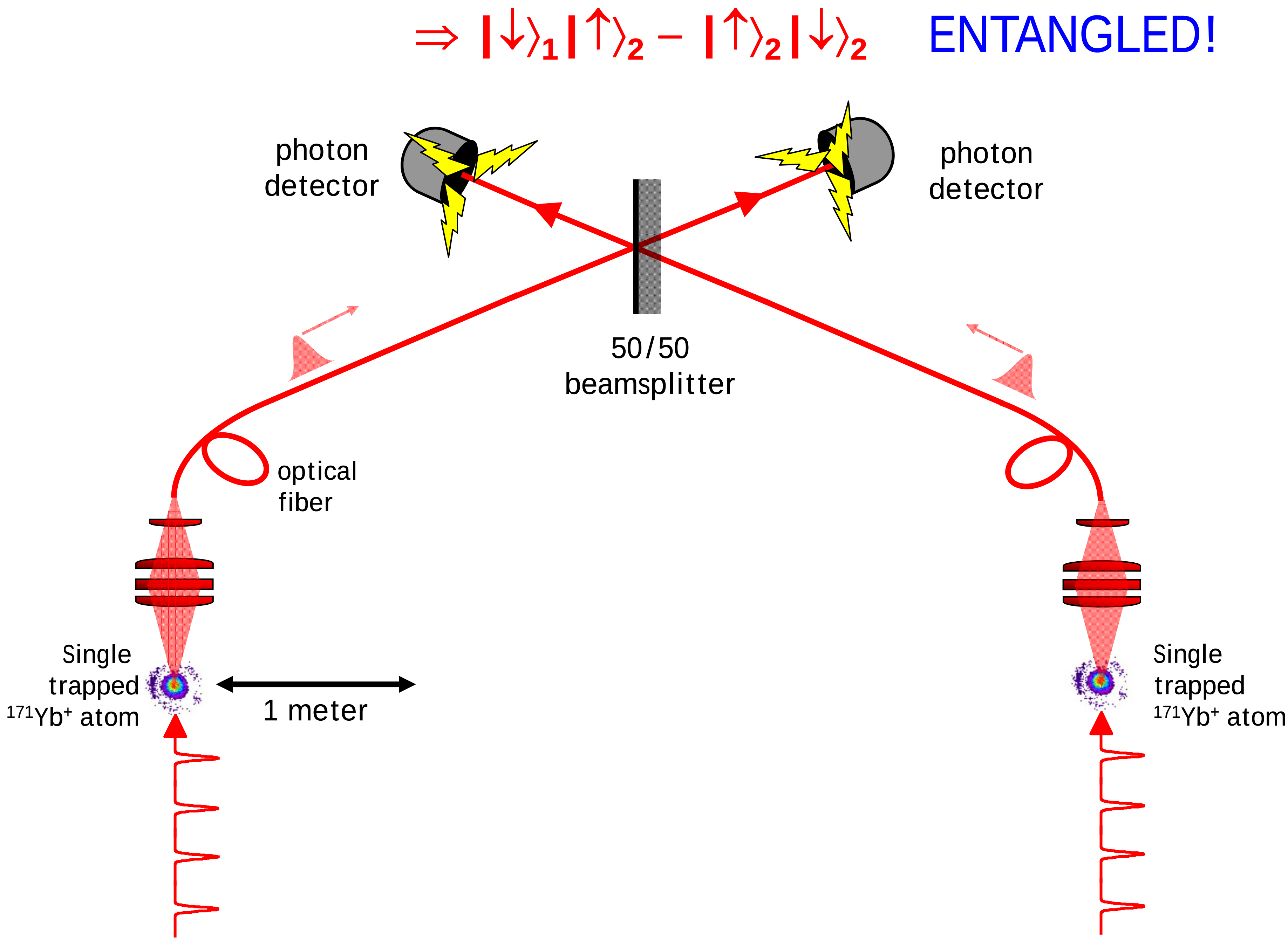
$p \sim 10^{-4}$

12.6 GHz

Blinov, et al., *Nature* **428**, 153 (2004)
Madsen, et al., PRL **97** 040505 (2006)

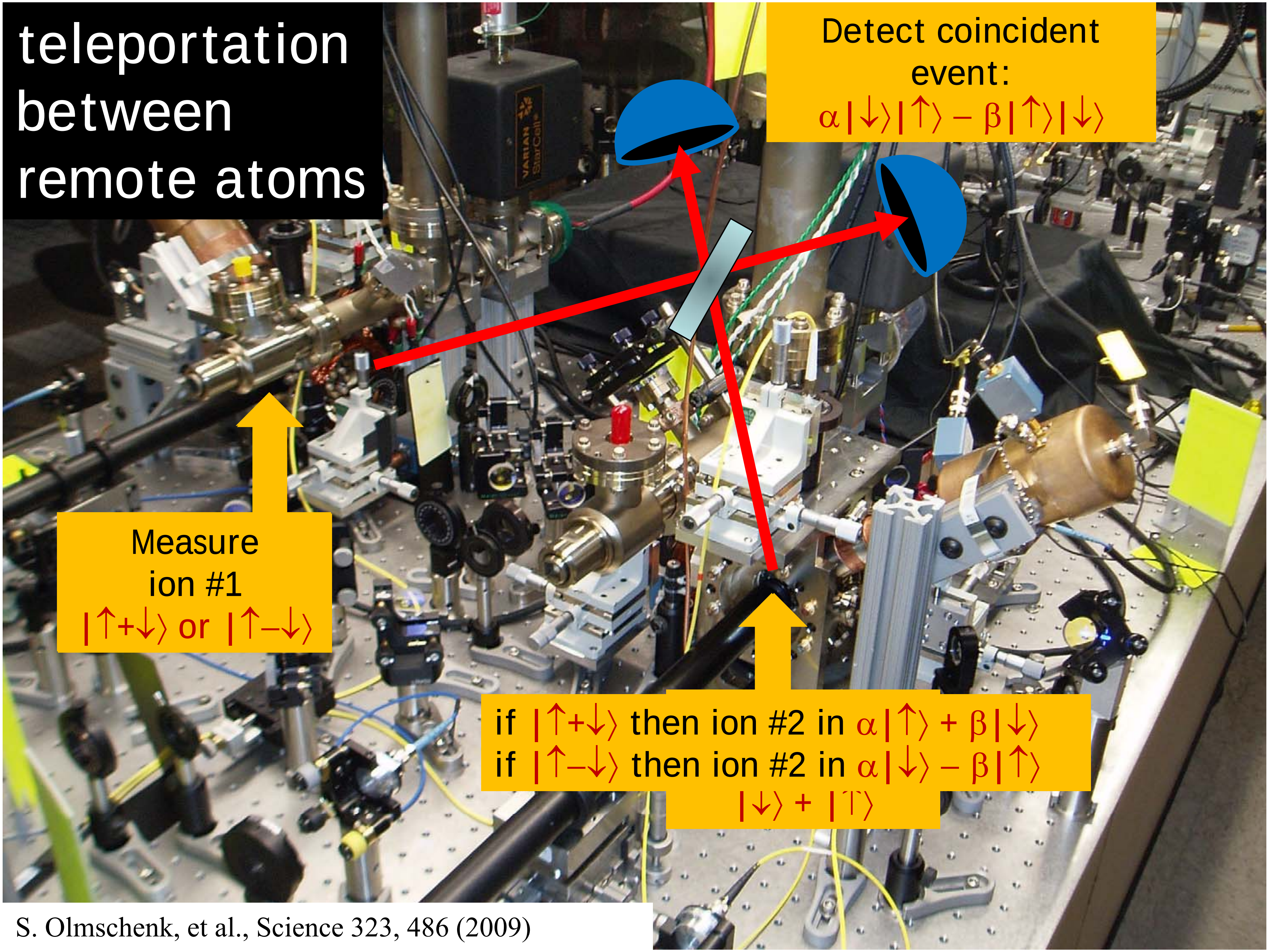
$$(|\downarrow\rangle_1 |\text{blue}\rangle_1 + |\uparrow\rangle_1 |\text{red}\rangle_1) \otimes (|\downarrow\rangle_2 |\text{blue}\rangle_2 + |\uparrow\rangle_2 |\text{red}\rangle_2)$$



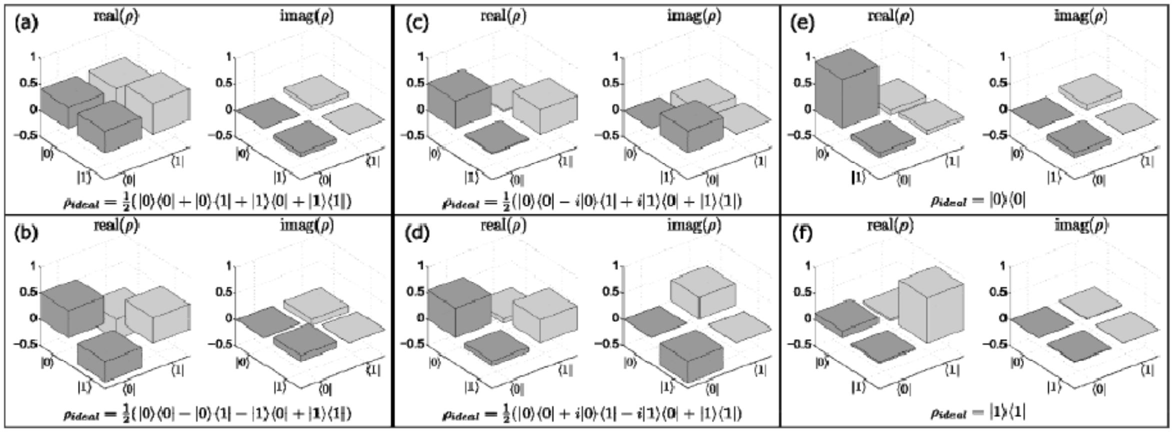


$\Rightarrow |\downarrow\rangle_1 |\uparrow\rangle_2 - |\uparrow\rangle_2 |\downarrow\rangle_2$
ENTANGLED!
photon detector
photon detector
50/50 beamsplitter
optical fiber
Single trapped $^{171}Yb^+$ atom
1 meter
Single trapped $^{171}Yb^+$ atom

teleportation between remote atoms



S. Olmschenk, et al., Science 323, 486 (2009) tomography of teleported state



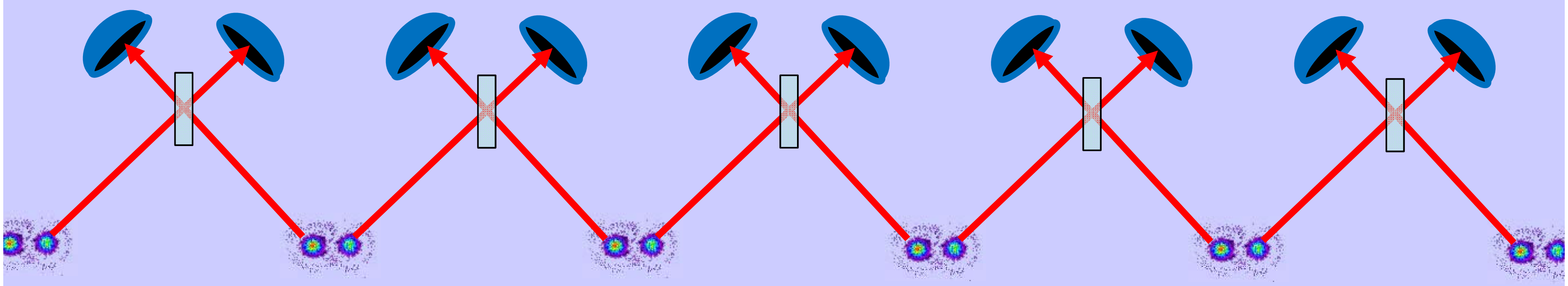
State Teleported	Fidelity
$\lvert\downarrow\rangle$	0.93(4)
$\lvert\uparrow\rangle$	0.88(4)
$\lvert\downarrow\rangle + \lvert\uparrow\rangle$	0.91(3)
$\lvert\downarrow\rangle - \lvert\uparrow\rangle$	0.88(4)
$\lvert\downarrow\rangle + i\lvert\uparrow\rangle$	0.92(4)
$\lvert\downarrow\rangle - i\lvert\uparrow\rangle$	0.91(4)

$\langle$Fidelity$\rangle > 0.90$

<u>Teleportation:</u> S. Olmschenk, et al., *Science* **323**, 486 (2009)
<u>General Gate:</u> P. Maunz, et al., *Phys. Rev. Lett.* 102, 250502 (2009)
<u>***private*** random number generation</u>: S. Pironio, et al., *Nature* 465, 590 (2010)

1 bit: 12 minutes
1500 events = 300 hours

Quantum networking with probabalistic entanglement



Quantum repeaters

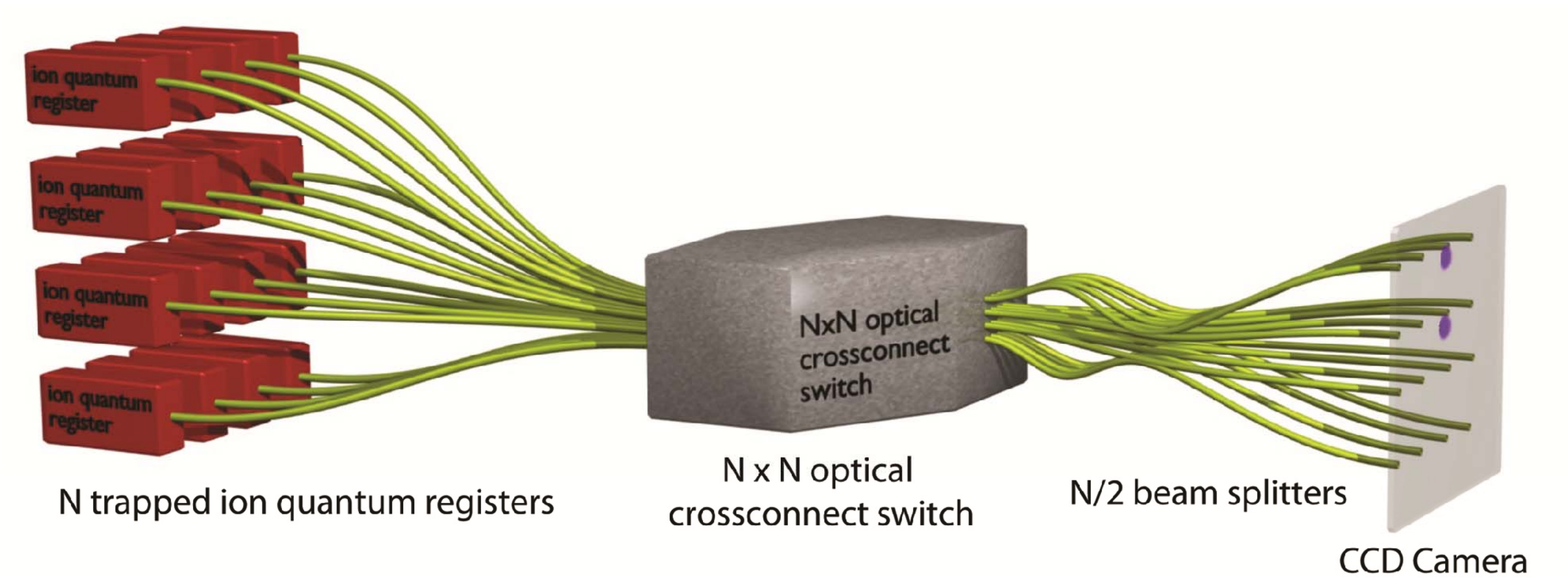
Briegel *et al.*, PRL **81**, 5932 (1998)

Distributed quantum computing with hybrid gates

Duan, et al., Quant. Inf. Comp. 4, 165 (2004)

Connection time: $\tau \sim \dfrac{\log N}{p}$

Large scale vision (10^3 – 10^6 atomic qubits)



JOINT QUANTUM INSTITUTE

www.iontrap.umd.edu

UNIVERSITY OF MARYLAND 1856

Grad Students

Shantanu Debnath
Dave Hayes
David Hucul
Rajibul Islam
Simcha Korenblit
Andrew Manning
Jonathan Mizrahi
Steven Olmschenk
Crystal Senko
Jon Sterk

Undergrads

Brian Fields
Kenny Lee

NSF

pfc@jqi

Res. Scientist

Peter Maunz

Postdocs

Susan Clark
Emily Edwards
Dmitry Matsukevich
Kihwan Kim
Wes Campbell
Le Luo
Qudsia Quraishi

Collaborators

Luming Duan (Michigan)
Jim Freericks (Georgetown)

DARPA IARPA BE THE FUTURE

NATIONAL SECURITY AGENCY UNITED STATES OF AMERICA

SCIENCE TO SHAPE THE FUTURE OF THE ARMY · ARMY RESEARCH OFFICE · 1951