Title: Quantum Computation and Simulation: Recent Progress in the Trapped Ion System

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Abstract: In this talk, I will briefly review the recent progress on quantum computation and simulation in the trapped ion system, with particular emphasis on the idea of scaling (how to scale up the number of qubits). I will discuss ideas towards large-scale quantum computation/simulation based on the network approach or the use of transverse phonon modes in anharmonic traps and then review the recent experimental progress along this direction. At the end of the talk, I will also briefly mention recent activities in Tsinghua-Michigan Joint Institute for quantum information.

Quantum Computation and Simulation: Recent Progress in the Trapped Ion System

Luming Duan

Department of Physics, University of Michigan

& Center for Quantum Information, Tsinghua University

DARPA IARPA AFOSR -MURI FOCUS MCTP Michigan Center for Theoretical Physics

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Why do we need a quantum computer?

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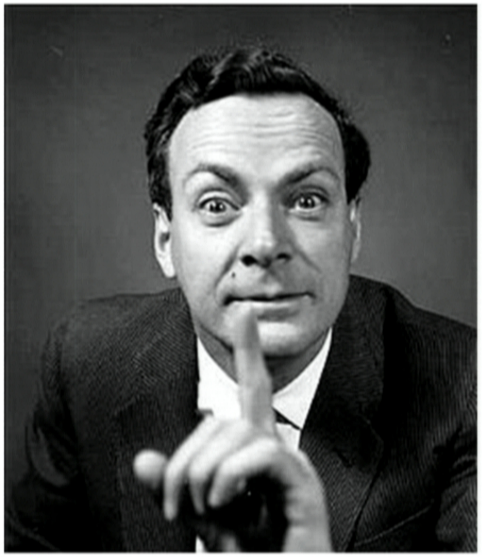
Limit of a classical computer:

- **Integration limit**



Richard Feynman

"We have plenty of room at the bottom"

But, **Quantum Mechanics!**

Limit of a classical computer:

- **Principle limit**

Some problems are hard! (NP)

Exponential scaling

Limit of a classical computer:

- **Principle limit**

Some problems are hard! (NP)

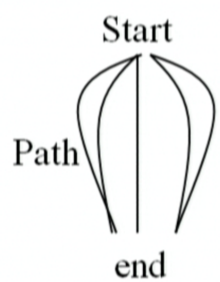
Exponential scaling

Physical example: strongly correlated system

Go to a quantum computer!!!

Possible exponential speedup

$$|\Psi\rangle = \sum_{i_1, i_2, \cdots, i_n} c_{i_1, i_2, \cdots, i_n} |i_1, i_2, \cdots, i_n\rangle$$



Quantum parallelism!

Example: Shor's factorization.

How to build a quantum computer?

Requirements:

- A scalable system of qubits
- Good isolation and precise control of individual qubits
- Controllable interaction between qubits

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Candidate physical systems

AMO systems
- ✓ Trapped ions
- ✓ Neutral atoms
- ✓ Photons

Solid-sate systems
- ✓ Quantum dots
- ✓ Superconducting qubits
- ✓ Nuclear spins

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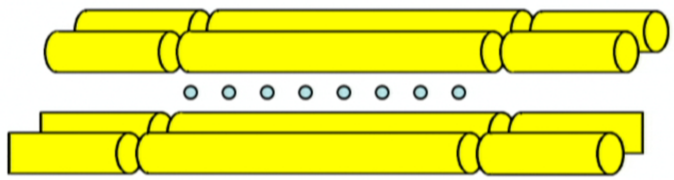
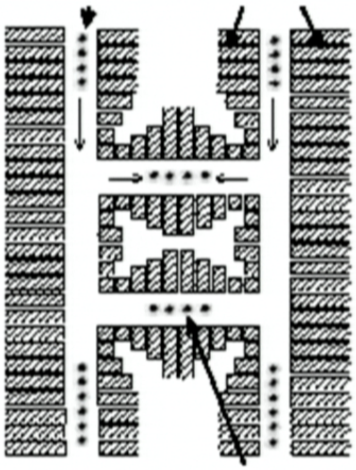
Linear Paul trap



How to scale up the system

1. Ion shuttling:



Kielpinksi, Monroe, Wineland,
Nature 417, 709 (2002)

How to scale up the system

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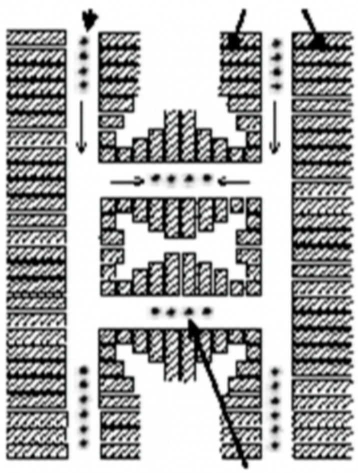
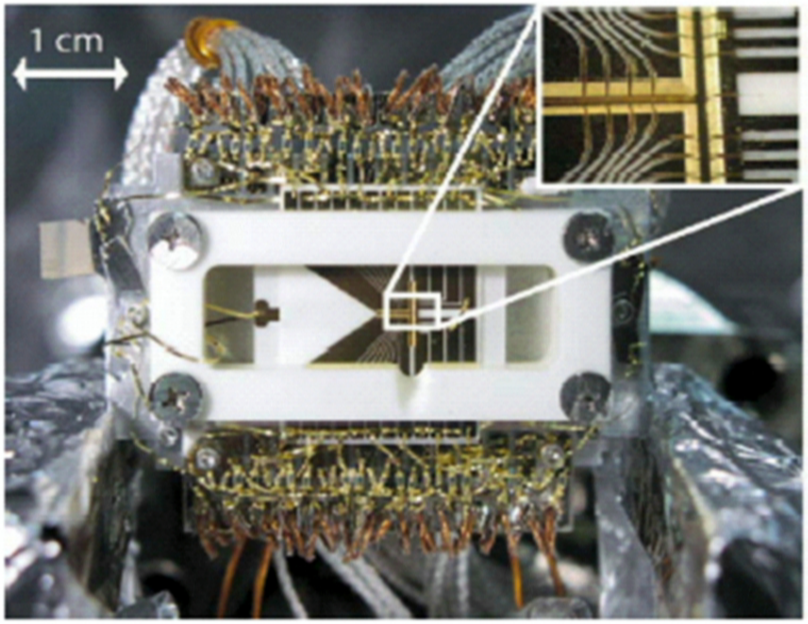


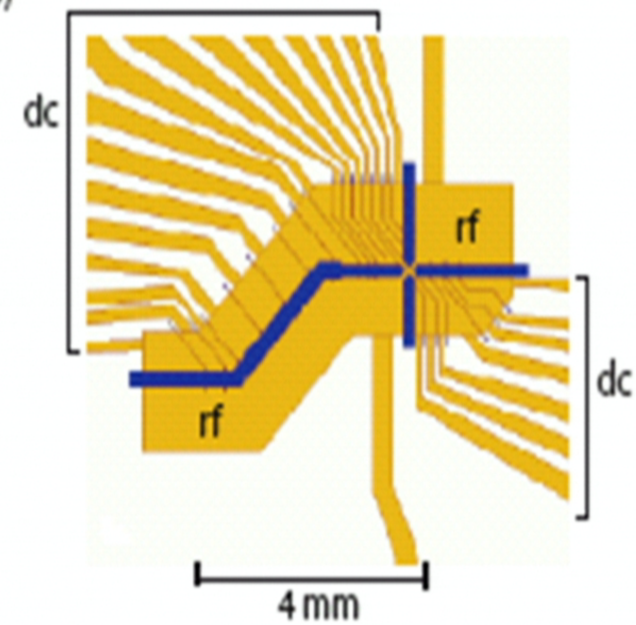


Kielpinksi, Monroe, Wineland,
Nature 417, 709 (2002)

More advanced traps

(a)

(b)



Wineland NIST group, chip trap, 2009

How to scale up the system

- **Quantum network approach through probabilistic photon coupling**

  Duan, Blinov, Moehring, Monroe, QIC 2003

  Duan and Monroe, Rev Mod Phys. (2010).

- **Transverse mode ion computation in anharmonic ion traps**

  Zhu, Monroe, Duan, PRL, 2006

  G.-D. Lin, S.-L. Zhu, Islam, Kim, Chang, Korenblit, Monroe, Duan , EPL, 2009

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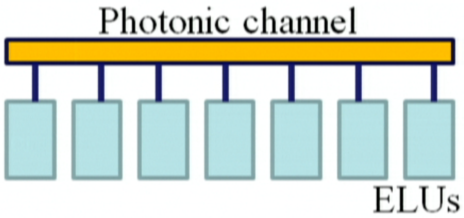
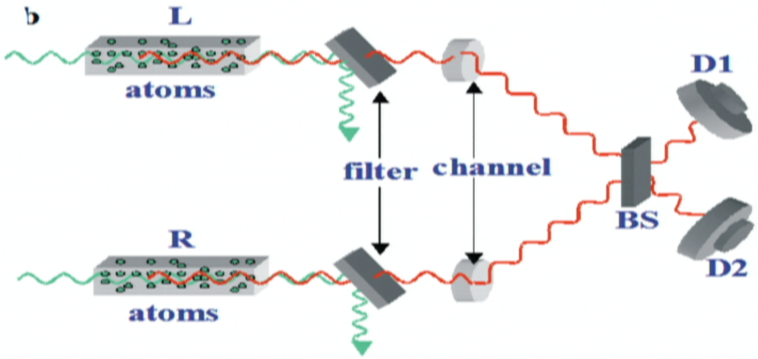
MUSIQC team (IARPA)

Modular Universal Scalable Ion-trap Quantum Computer



Inspiration from the DLCZ protocol

Duan, Lukin, Cirac, Zoller, (DLCZ), Nature 2001

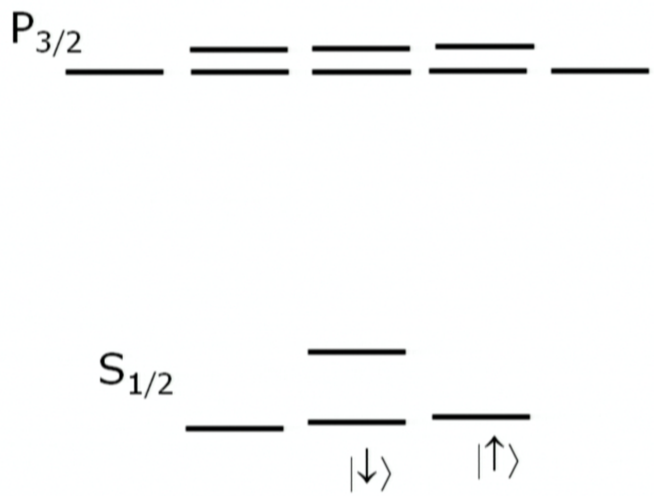


Experimental implementation:

Caltech group
Harvard group
Stanford group
Heidelberg group

Georgia Tech
USTC group
MIT group
Marx-Planck Institute

Experimental entanglement between 1 ion and 1 photon



Blinov, Moehing, Duan, Monroe
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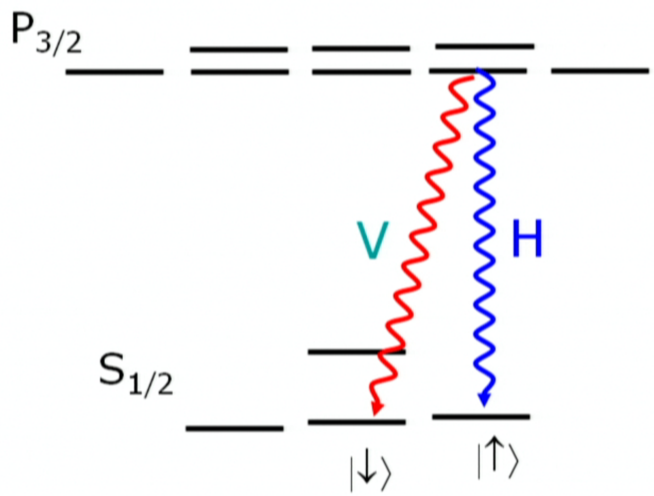
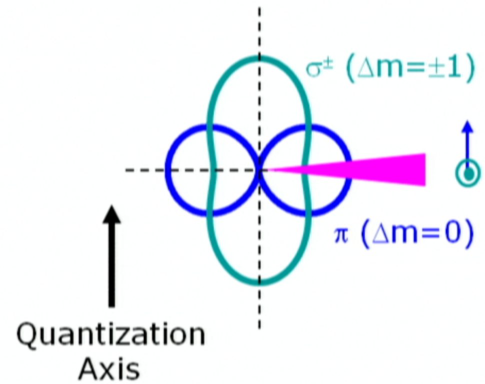
Experimental entanglement between 1 ion and 1 photon





$$|\psi\rangle = |\downarrow\rangle|V\rangle + |\uparrow\rangle|H\rangle$$

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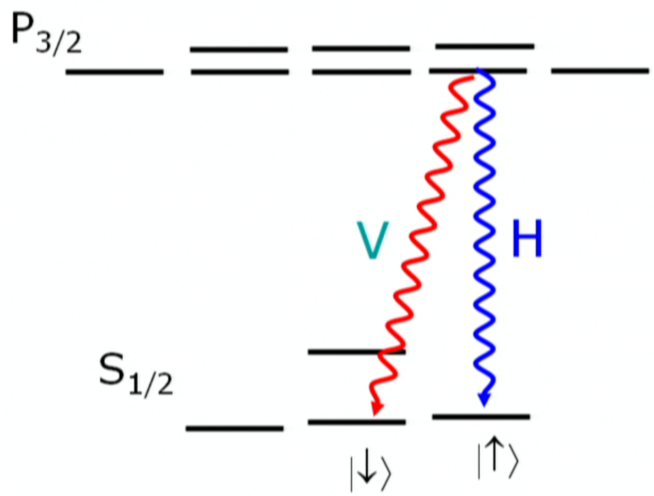

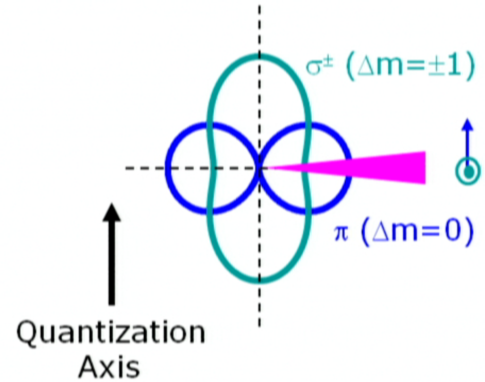

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Blinov, Moehing, Duan, Monroe
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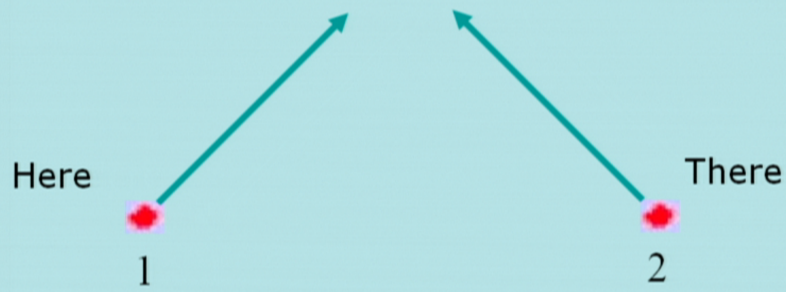
Probabilistic entanglement between two remote ions

$$|\Psi\rangle = \left(|\downarrow\rangle_1|V\rangle_1 + |\uparrow\rangle_1|H\rangle_1\right)\otimes\left(|\downarrow\rangle_2|V\rangle_2 + |\uparrow\rangle_2|H\rangle_2\right)$$



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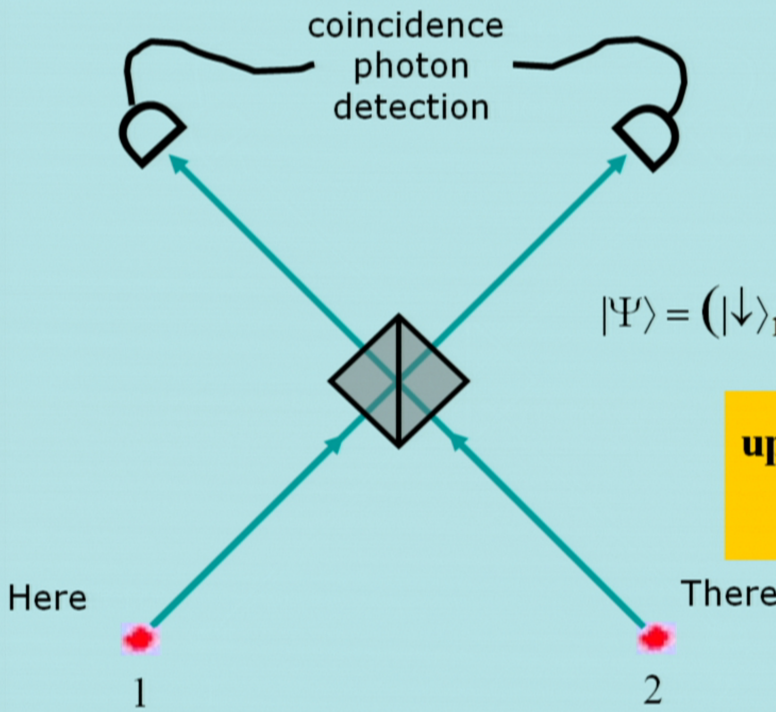

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upon coincidence photon detection

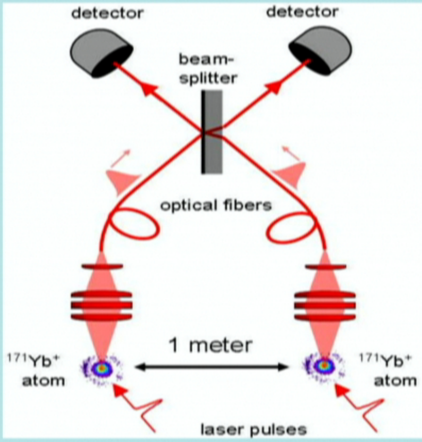
$$|\Psi\rangle \Rightarrow |\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_2|\downarrow\rangle_2$$

Rate $= R\,p^2$ *(R= 500 kHz)*
$= 0.1$ Hz

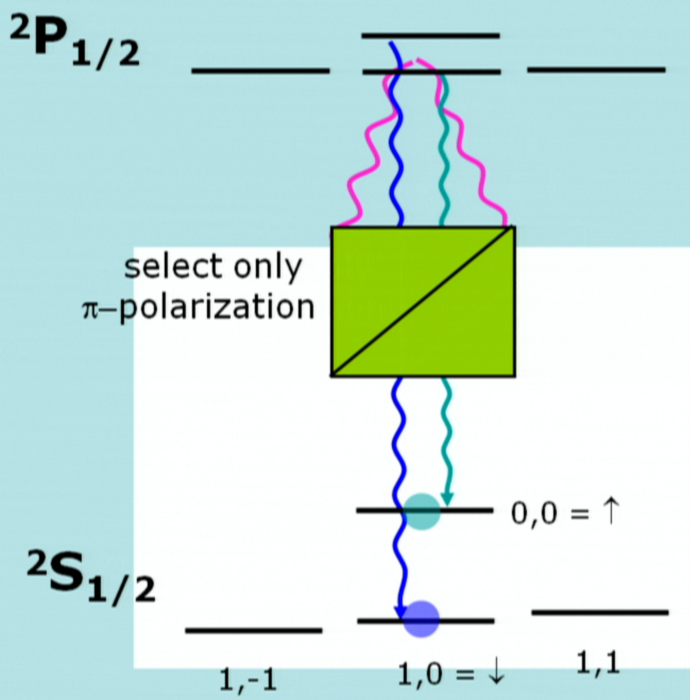
Entanglement of remote ions:

D. L. Moehring, P. Maunz, S. Olmschenk, K. C. Younge, D. N. Matsukevich, L.-M. Duan, and C. Monroe, Nature 449, 68 (2007).

Entanglement fidelity: 87(2)%



Probabilistic ion Gate (Duan et al, PRA, 2006)
Frequency Qubit



$|\psi_0\rangle = c_0|\downarrow\rangle + c_1|\uparrow\rangle$

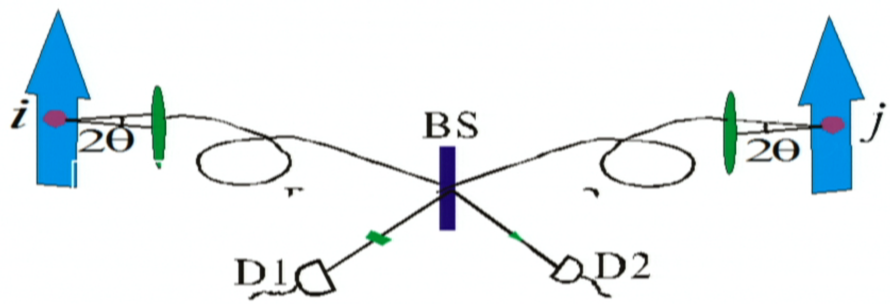
Given photon is emitted into polarizer

$|\psi\rangle = c_0|\downarrow\rangle|\text{blue}\rangle + c_1|\uparrow\rangle|\text{green}\rangle$

Keep track of information of the initial state !!

Probabilistic gates on remote ion qubits

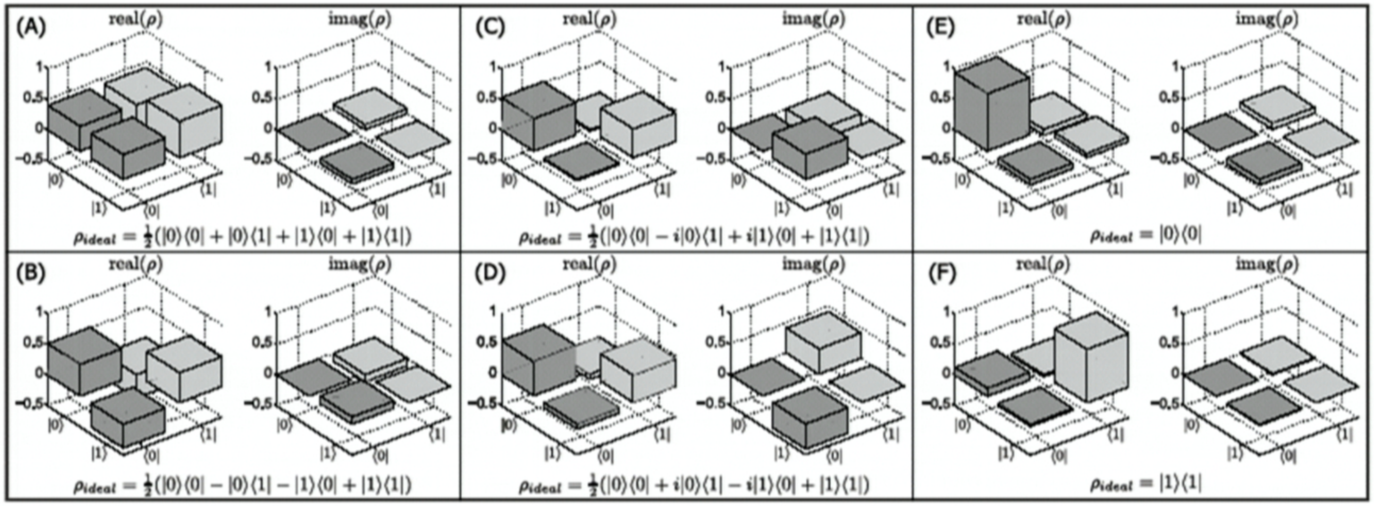
Duan et al., PRA, 2006



Joint measurements of emitted photons

- ✓ ions in arbitrary initial states
- ✓ probabilistic ZZ gate (projection to |01> and |10> subspace)
- ✓ Probabilistic ZZ is a gate that is universal and efficient for quant. Computation

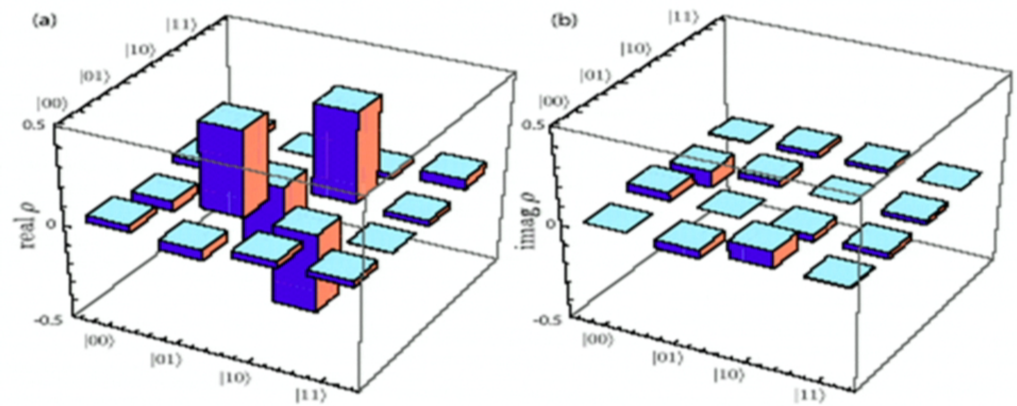
Quantum teleportation between remote ions



Average fidelity of teleported state: $90 \pm 2\%$.

S. Olmschenk, D. N. Matsukevich, P. Maunz, D. Hayes, L.-M. Duan, C. Monroe
arXiv:0907.5240, Science, 2009

Experimental demonstration of a remote gate



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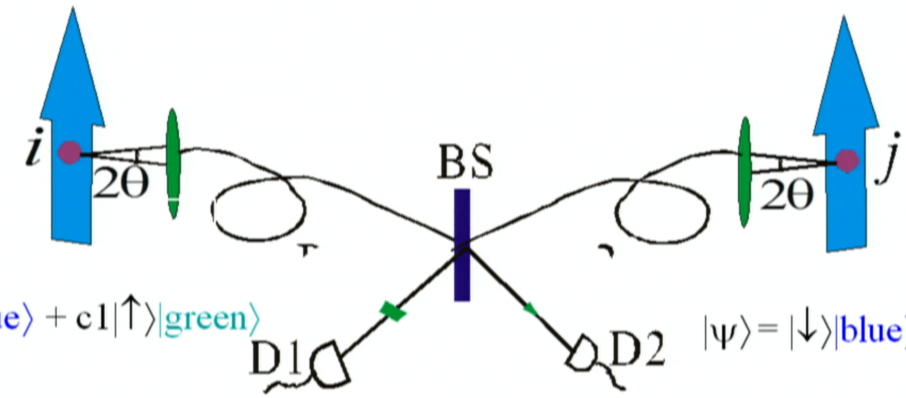
Teleportation of ion states

$|\psi\rangle = c0|\downarrow\rangle + c1|\uparrow\rangle$



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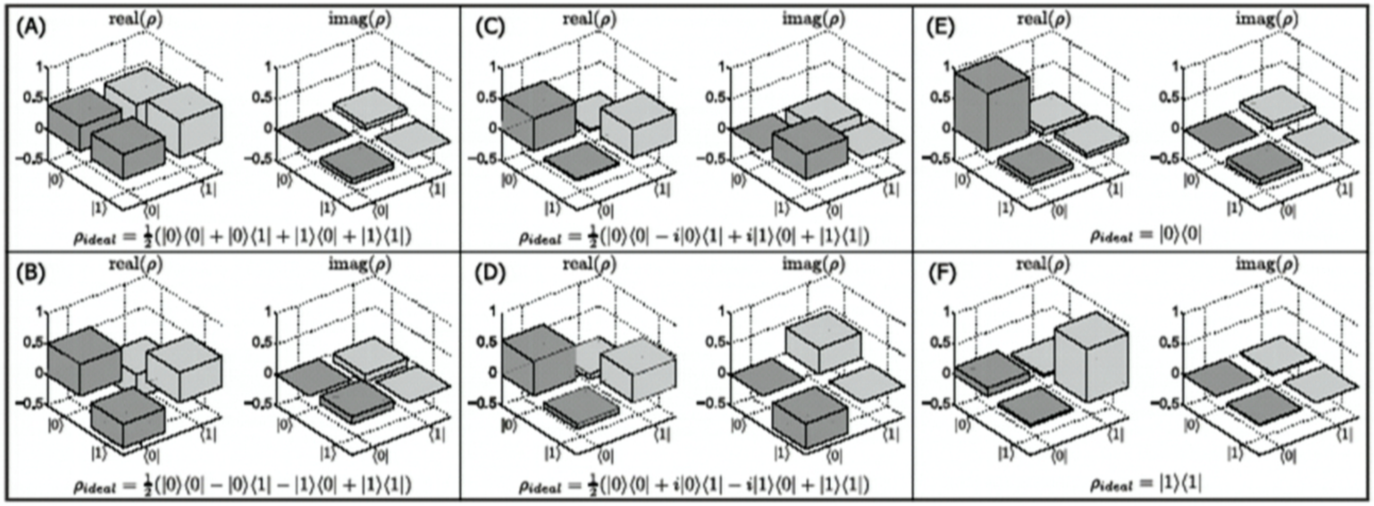

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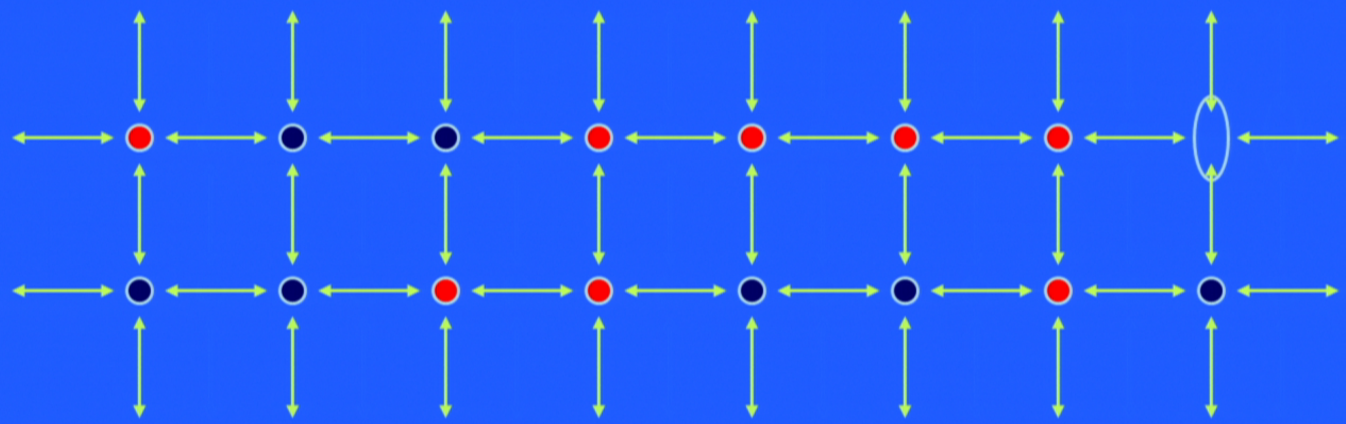
Quantum computing
with probabilistic ion-photon gate

Duan and Raussendorf, Phys. Rev. Lett. 95, 080503 (2005)



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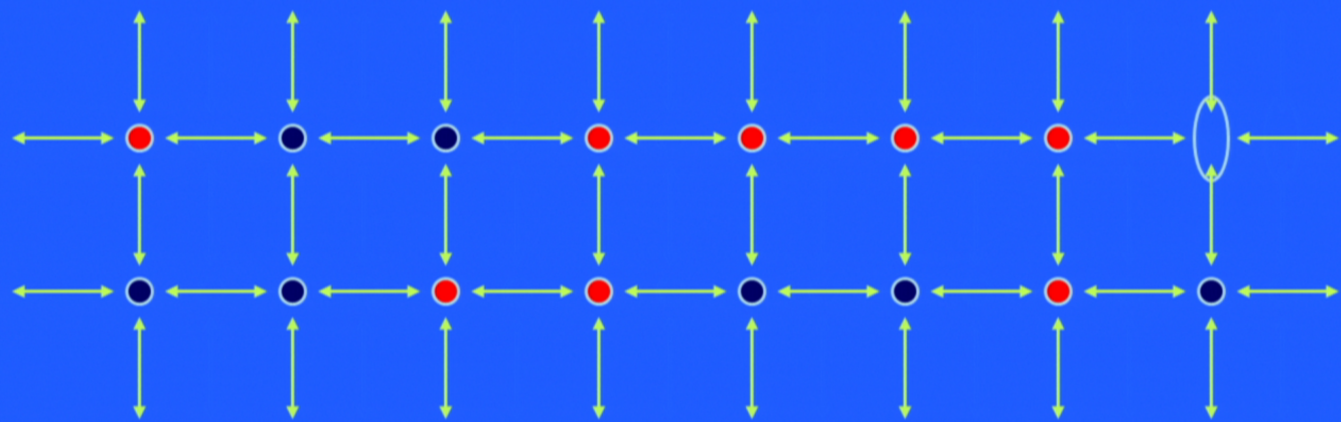
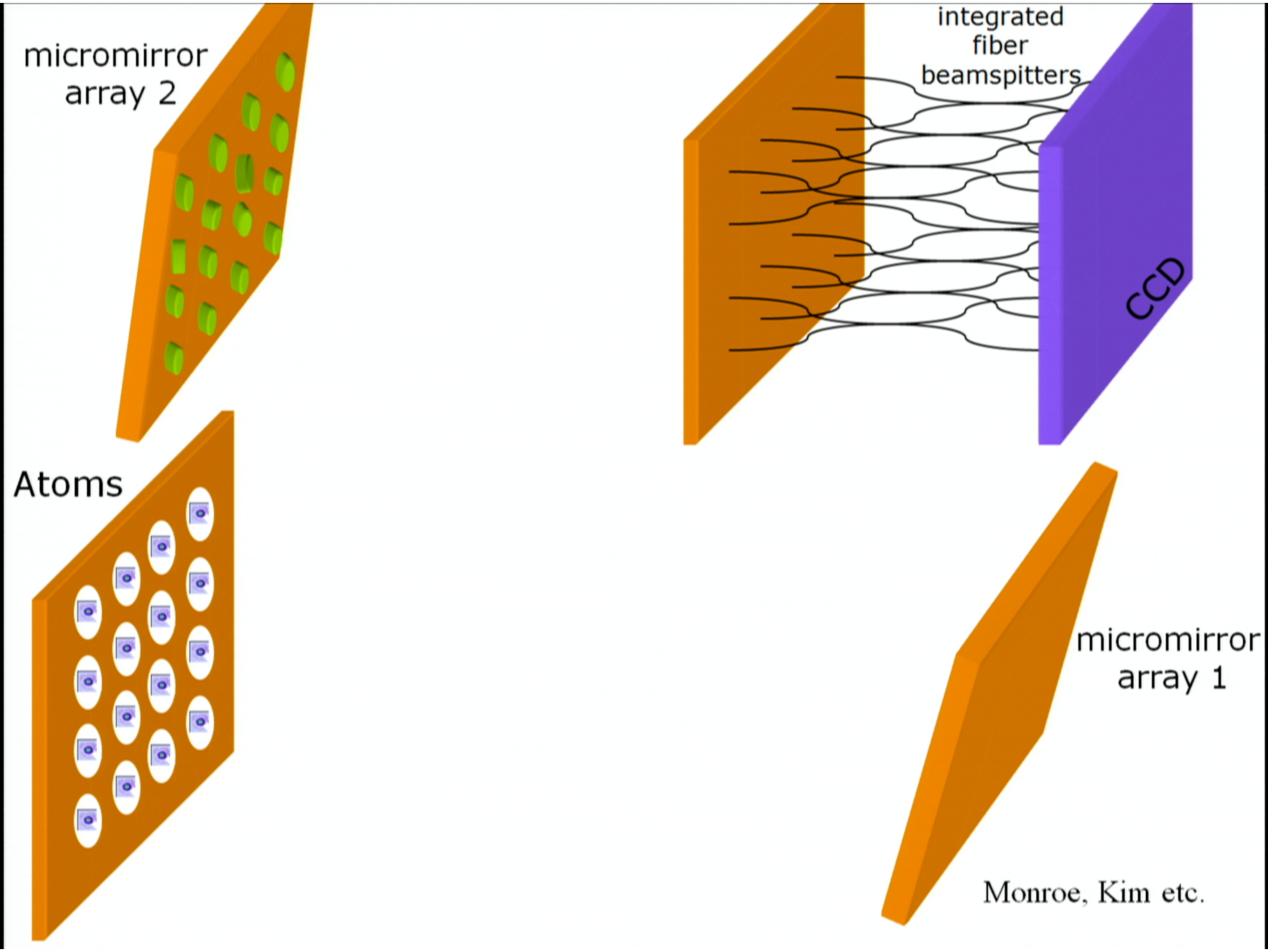


Efficient scaling with probabilistic gates:

$$M \propto n \ln(n/\varepsilon)\left(\frac{2}{p}\right)^{\log_2(4/p)+2}$$


micromirror
array 2
integrated
fiber
beamsplitters
CCD
Atoms
micromirror
array 1
Monroe, Kim etc.

How to scale up the system

- **Quantum network approach through probabilistic photon coupling**

  Duan, Blinov, Moehring, Monroe, QIC 2003

  Duan and Monroe, Rev Mod Phys. (2010).

- **Transverse mode ion computation in anharmonic ion traps**

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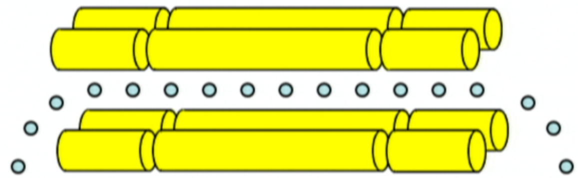
Scale up in a single linear trap

What is the difficulty?



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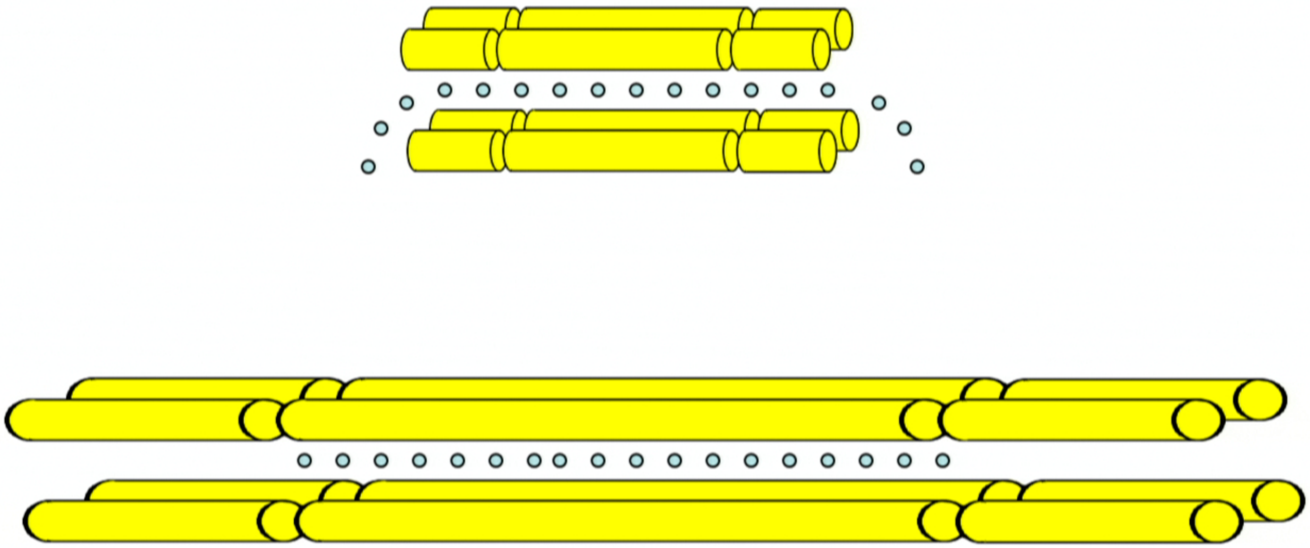

Scale up in the linear trap

The real problems:

1. Chain instability due to structural phase transition

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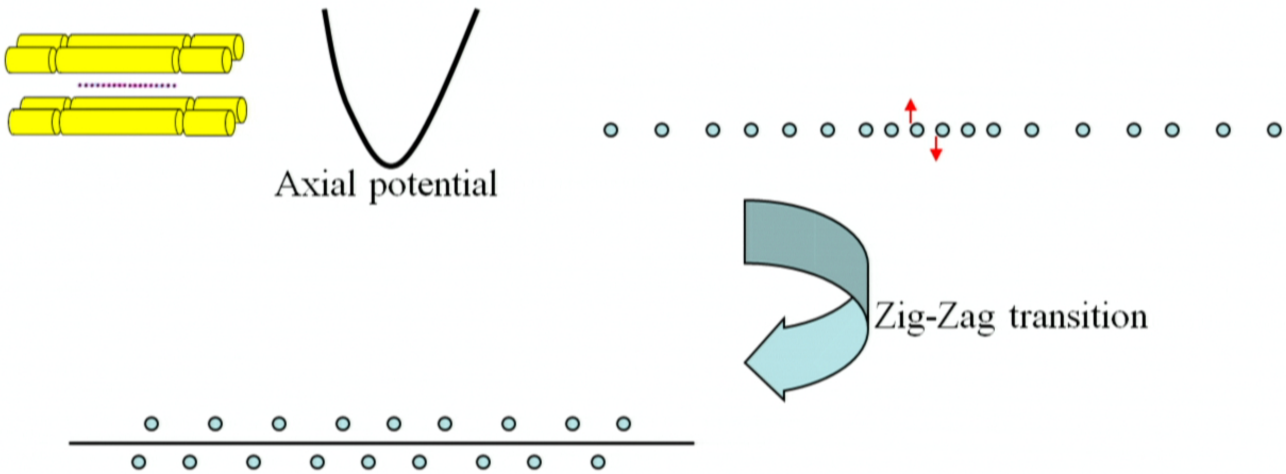

Scale up in the linear trap

Solutions to all the problems:

G.-D. Lin, S.-L. Zhu, Islam, Kim, Chang, Korenblit, Monroe, Duan

arXiv:0901.0579, EPL, 2009

Scale up in the linear trap

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An Uniform Ion Trap

Design of a large-scale uniform trap

No sideband cooling

Solution to Problem 2: Sideband cooling

We require no sideband cooling for the gates

Only Doppler Cooling!

No sideband cooling

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Thermal vibration outside of the Lamb-Dicke limit

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Solution to Problem 2: Sideband cooling

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Only Doppler Cooling!

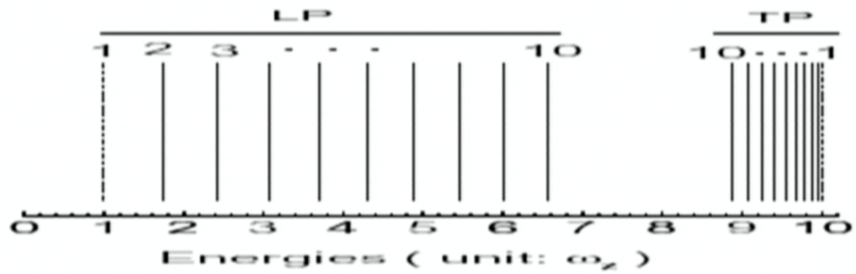
Thermal vibration outside of the Lamb-Dicke limit

We use transverse photon modes instead of the axial ones

Stronger confinement leads to more robustness to vibrational noise

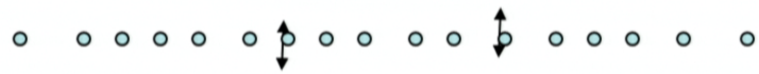
Transverse phonon modes

Phonon mode structure:



Multi-mode quantum gates

Solution to Problem 3: multiple phonon modes

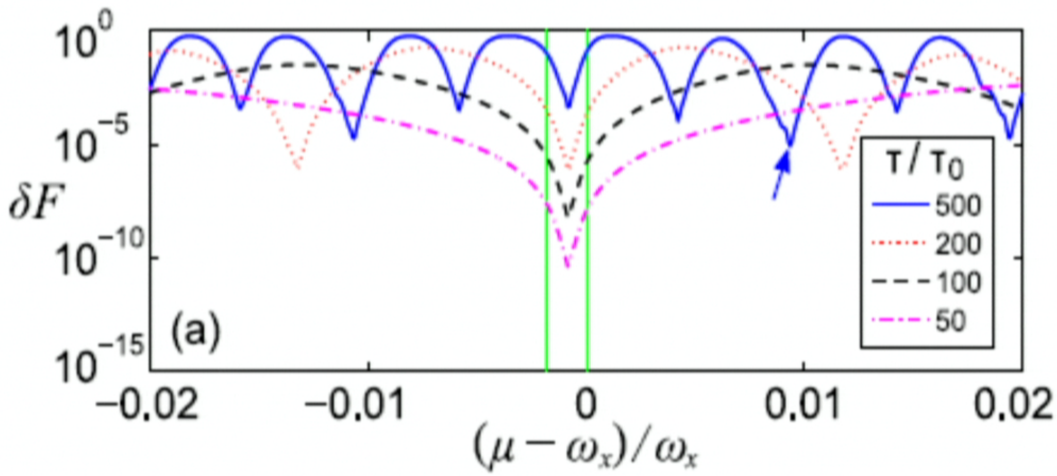


- **Through laser pulse control, high–fidelity Quantum gates can be achieved with involvement of all phonon modes**

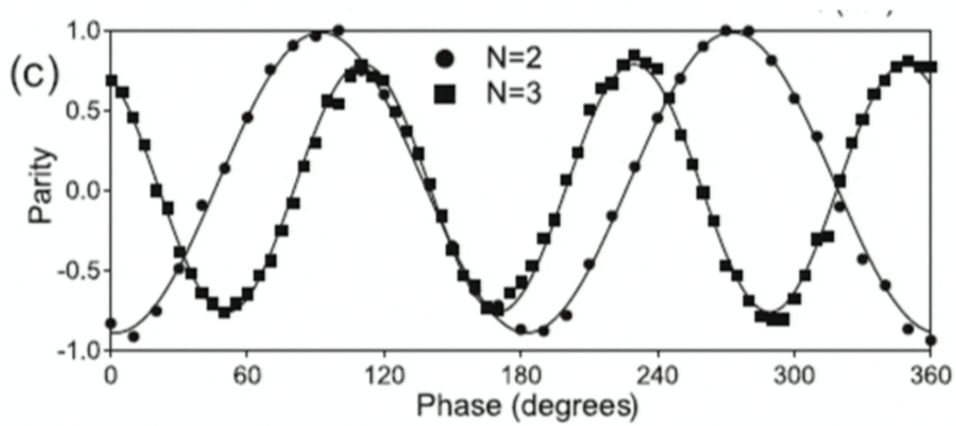
- **The required control can be pretty simple**

Laser control for the gate

The gate infidelity



Experimental demonstration of transverse mode quantum gate



Fidelity: F2>96%, F3>84%

K. Kim, M.-S. Chang, R. Islam, S. Korenblit, L.-M. Duan, C. Monroe
arXiv:0905.0225, PRL (2009).

Quantum Simulation

Solve fundamental many-body models: (important for new materials)

Quantum Simulation

Solve fundamental many-body models: (important for new materials)

Quantum Simulation

Solve fundamental many-body models: (important for new materials)

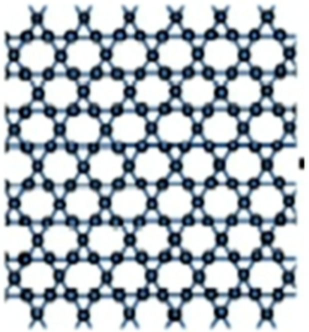
Examples:

Hubbard model (relevant for high-Tc physics)

$$H_{weak} = t\sum_{\langle i,j\rangle} a_{i\sigma}^{+} a_{j\sigma} + u\sum_{i} a_{i\uparrow}^{+} a_{i\downarrow}^{+} a_{i\downarrow} a_{i\uparrow}$$

Frustrated magnetic model

$$H_0 = J\sum_{\langle i,j\rangle} \mathrm{S}_i \cdot \mathrm{S}_j$$



Examples of simulation with ultracold atoms

Bose-Hubbard model:

Jaksch, Gardiner, Cirac, Zoller, PRL 1998.
Bloch's group, Nature (2002)

Quantum magnetic model:

Duan, Demler, Lukin, PRL (2003).
Bloch's group, Nature (2007);

Fermion Hubbard model:

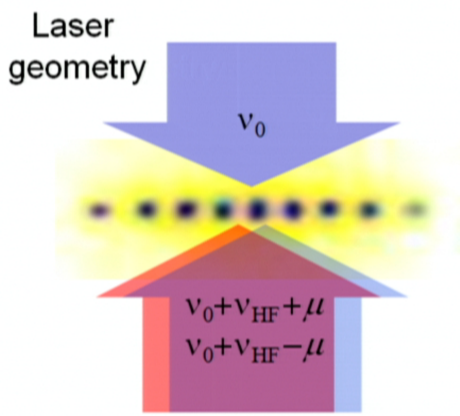
under weak interaction

Hofstetter, Cirac, Zoller, Demler, Lukin, PRL 2003

under strong interaction

Duan, PRL (2005).
Ketterle's group, Nature (2007).

Quantum Simulation with trapped ions



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

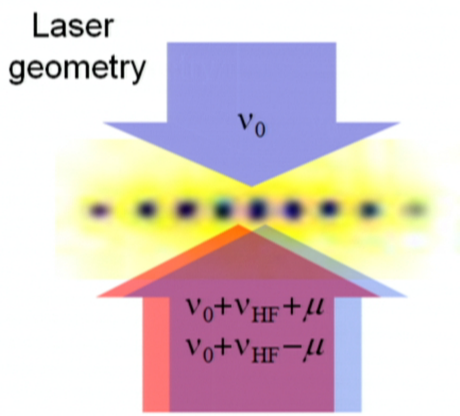
$$J_{i,j} = \Omega_i\Omega_j \frac{\hbar(\delta k)^2}{2M}\sum_m \frac{b_{i,m}b_{j,m}}{\mu^2-\omega_m^2}$$

μ= laser detuning

μ controls range and form of interaction

Porras,Criac, PRL, 2004
Zhu, Monroe, Duan, PRL, 2006

Quantum Simulation with trapped ions



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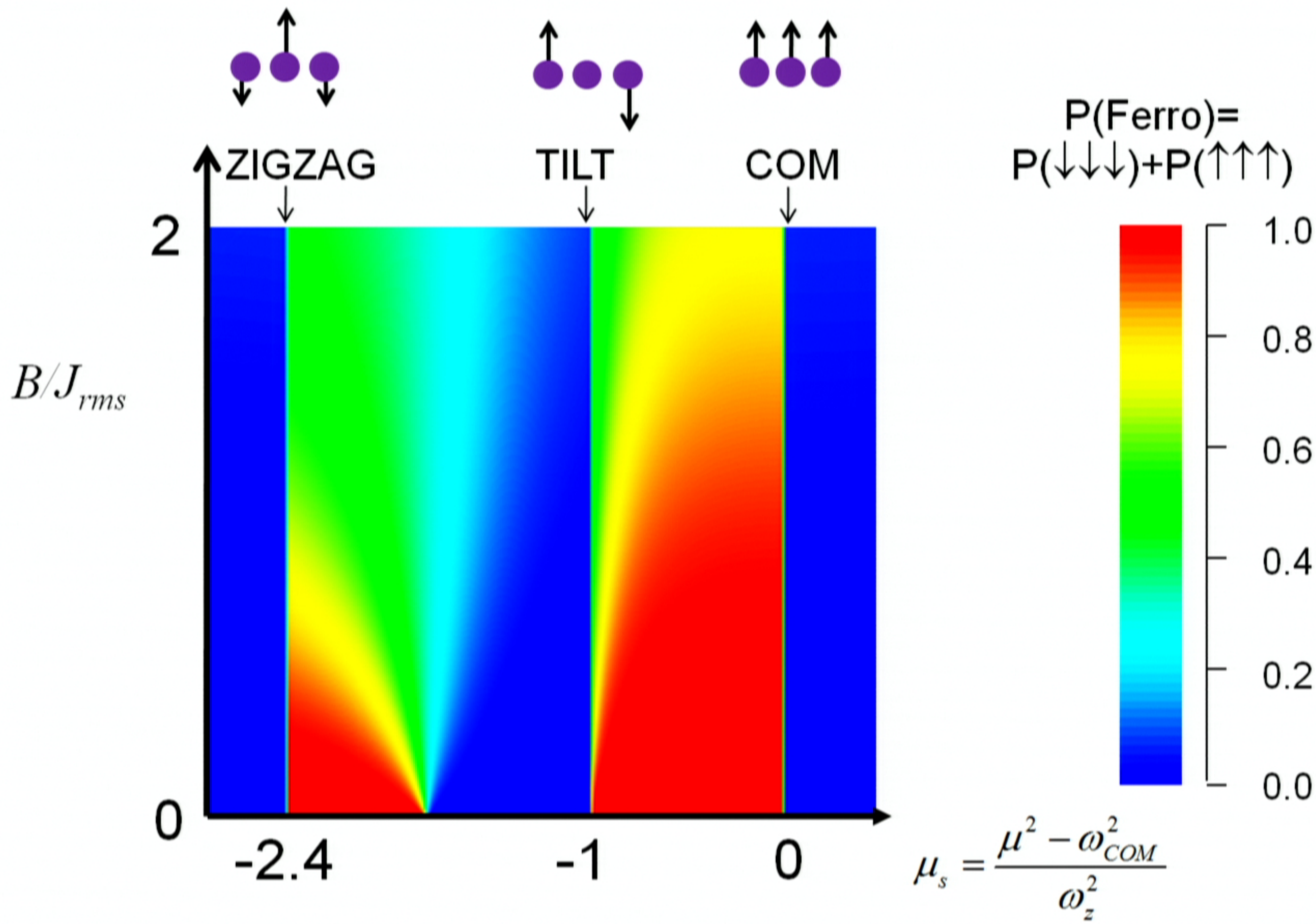
3-ion "phase diagram"



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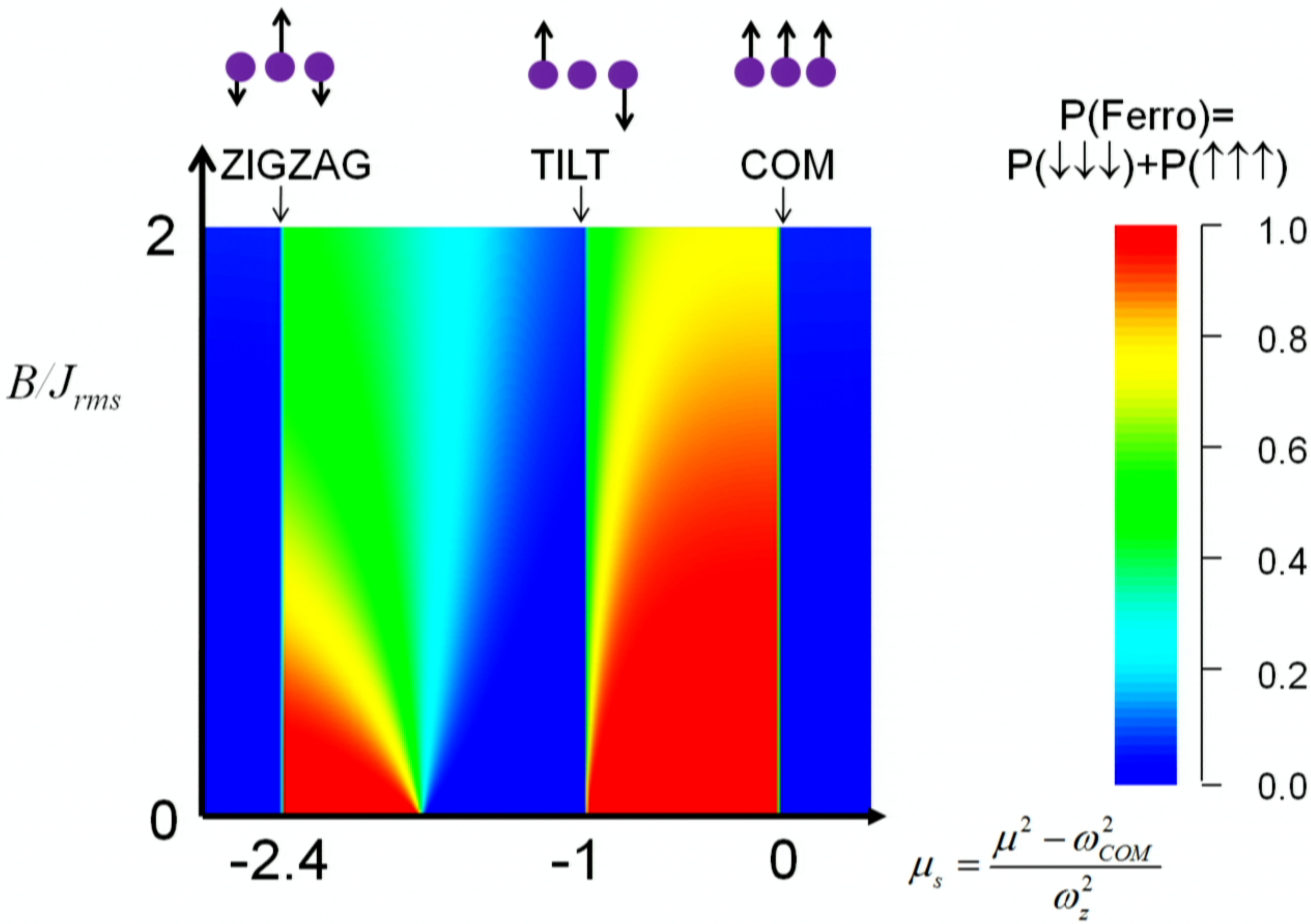
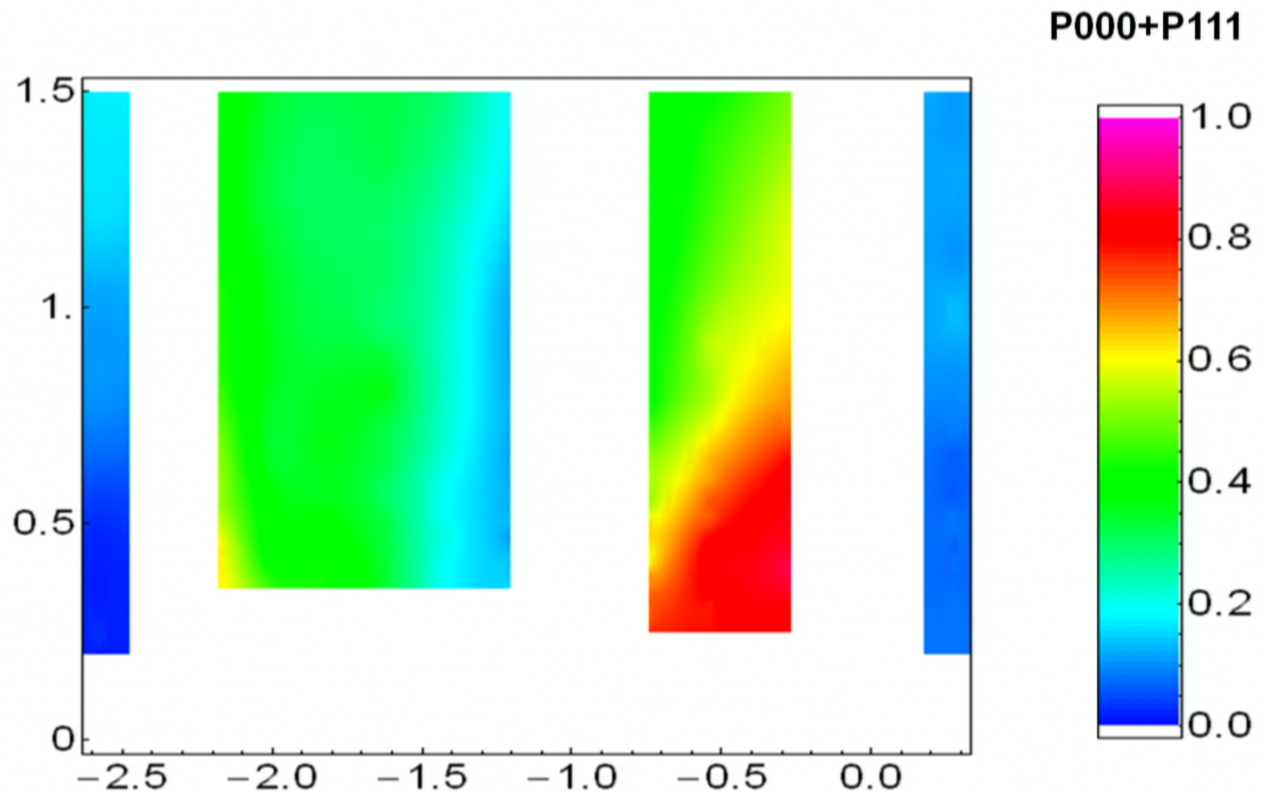
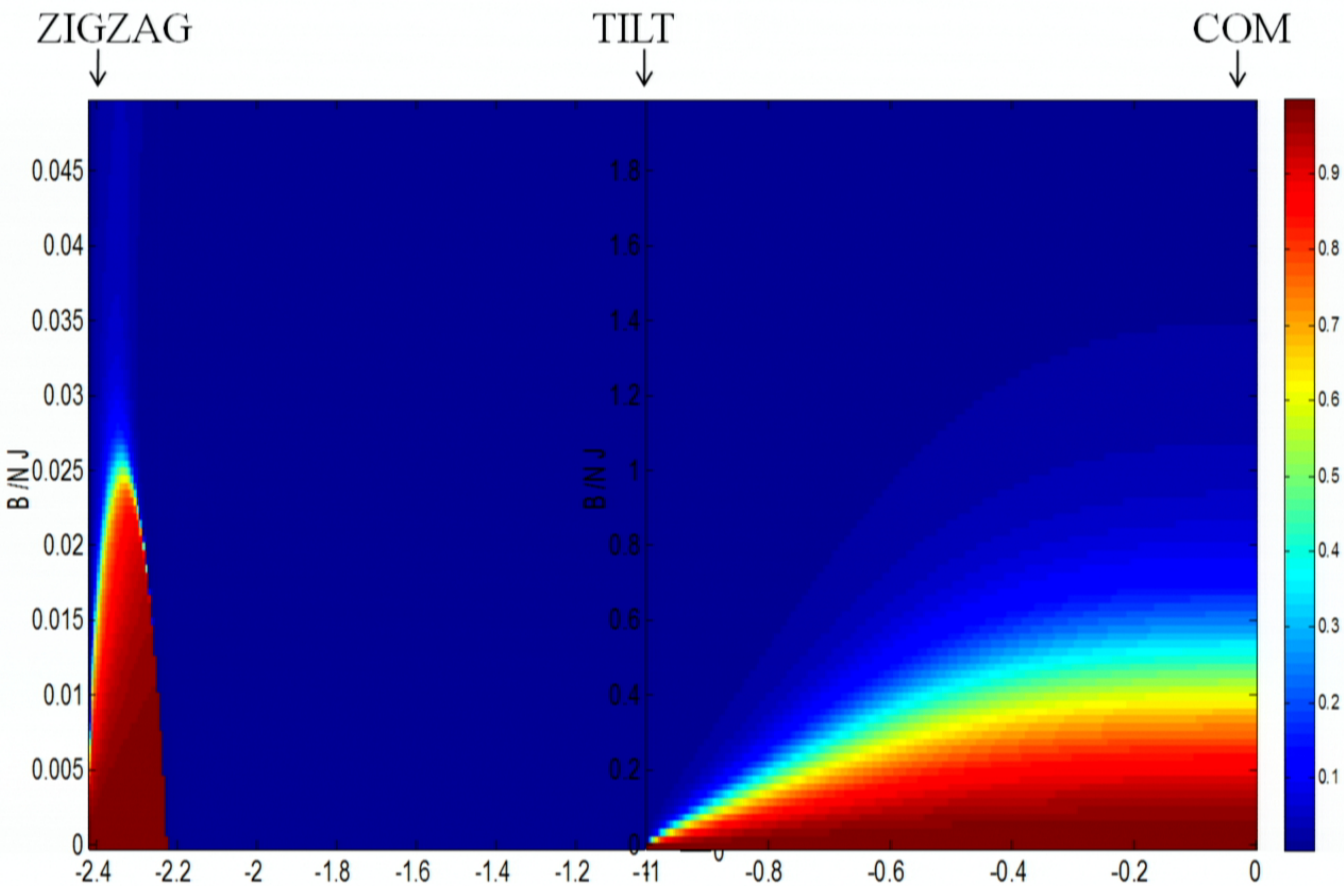


Experimental Phase Diagram (PMT) with P000+P111

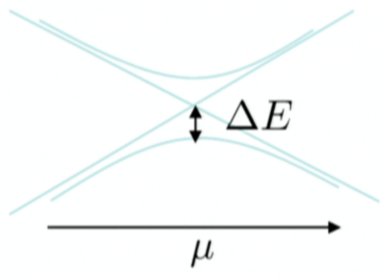


Kim, Chang, Korenblit, Islam, Edwards, Freericks, Lin, Duan, Monroe, Nature 465, 590 (2010).

9-ion phase diagram



Exponentially sharp phase boundary



$$\Delta E \sim \left(\frac{B}{NJ}\right)^{\frac{N-1}{2}}$$

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量子信息中心 Center for Quantum Information

Mission of CQI

- **A world-class research center for quantum informationm**

- Vibrant research culture with generous support
- International: more than half faculty are of non-Chinese origin
- Independence of junior faculty
- Interdisciplinary and integrated


量子信息中心
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ITCS: Strong theoretical computer science program
Experimental QI platform:
✓ Trapped ion quantum computation
✓ Photonic quantum network at the telecom
✓ Atom-Photon Quantum interface
✓ Ultracold atom quantum simulator
Andrew YAO
Amy WANG
Bo Zheng
Duan LM
Kihwan Kim
Zhe Zhang
Chong Zu
Ke Liu

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5
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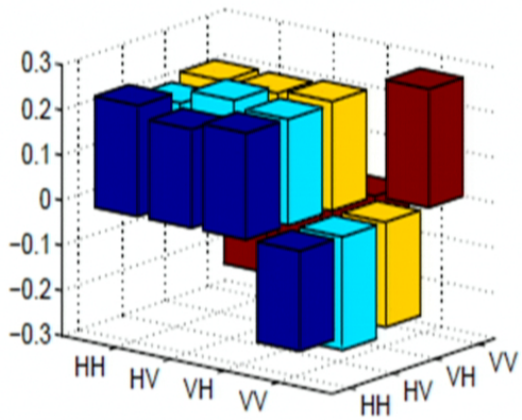
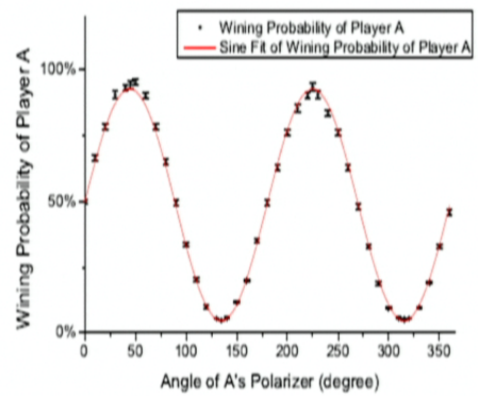
$$\left(|00\rangle_{ab} + |01\rangle_{ab} + |10\rangle_{ab} - |11\rangle_{ab}\right)/2$$

Demonstration of quantum game

NJP (2012)





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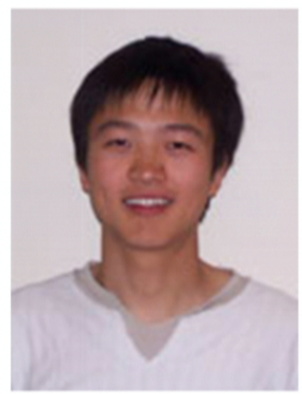
Giulio Chiribella

Alioscia Hamma

New Members

Hongcheng Jiang



Xiongfrng Ma

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