Title: Small scale gadgets for large scale processing

Date: Jun 15, 2007 05:15 PM

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Abstract:

Small quantum gadgets for large-scale processing

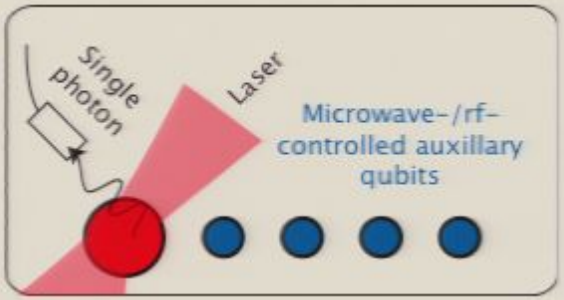
Jake Taylor (MIT)

Massachusetts Institute of Technology

IQSE Institute for Quantum Science and Engineering

Focus of this talk

Quantum registers for distributed computation



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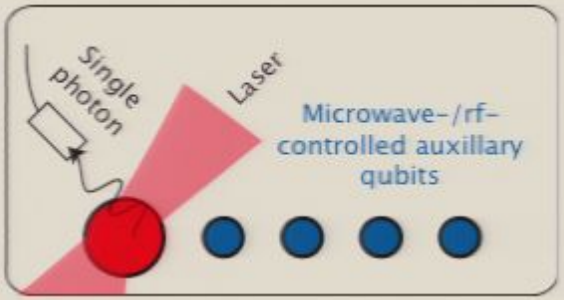
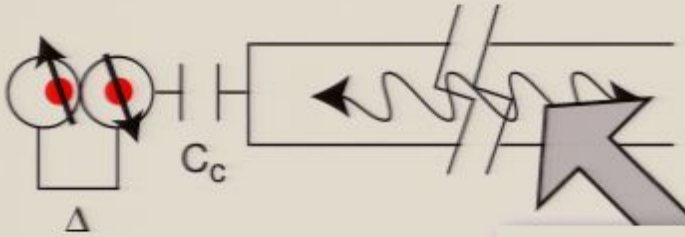
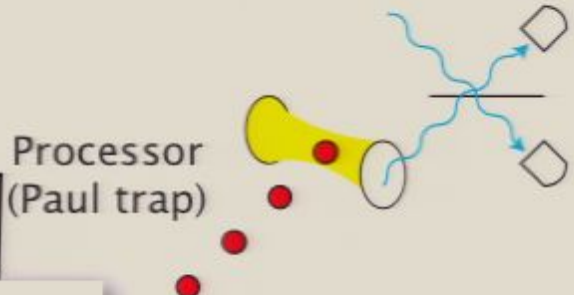
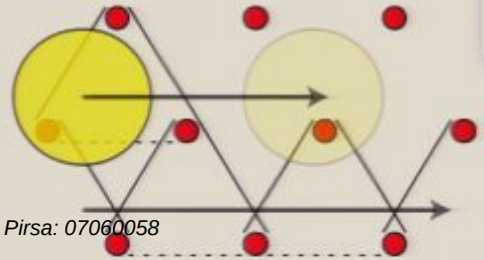
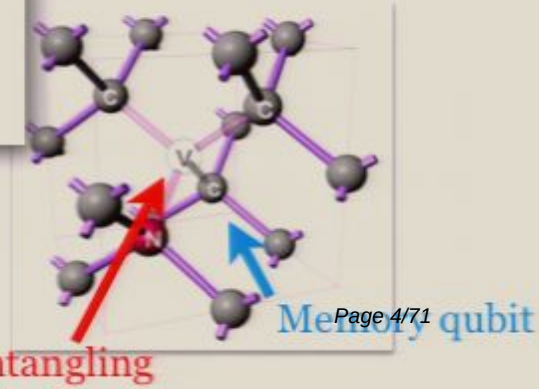




Some example approaches







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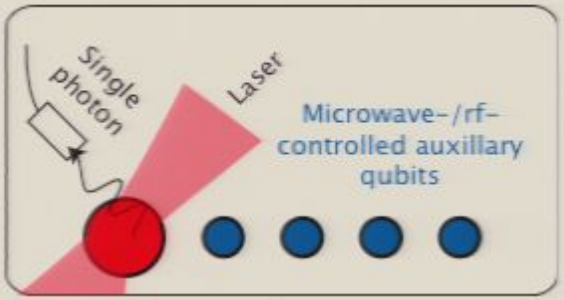

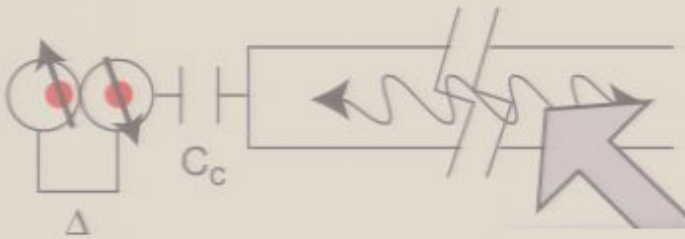

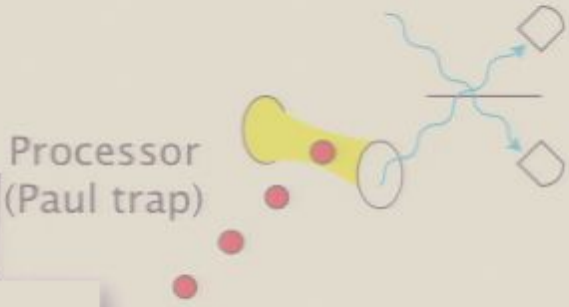

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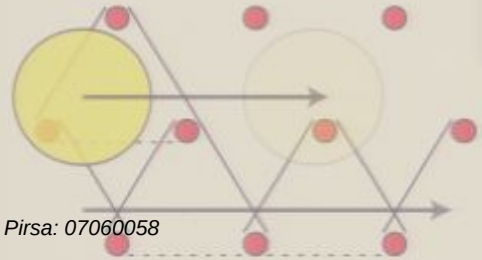
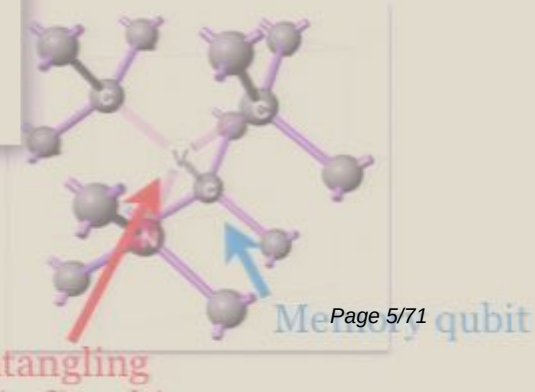




Distributed quantum computation

- Problem: apparatus for many qubits?
  - limited coupling strengths in a NMR molecule (frequency selectivity)
  - quantum control in a dilution refrigerator

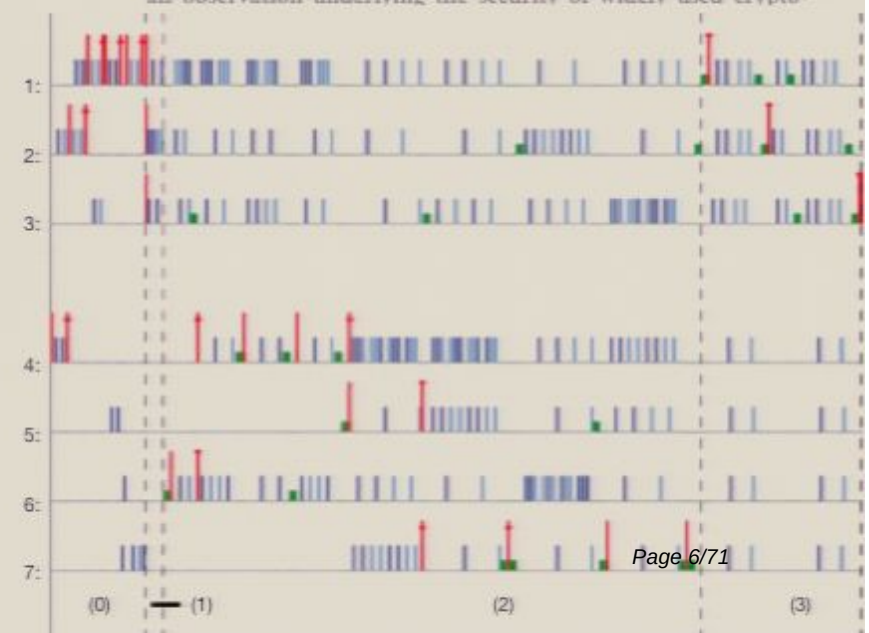
[image from Janis.com]

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

* IBM Almaden Research Center, San Jose, California 95120, USA
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

The number of steps any classical computer requires in order to find the prime factors of an l-digit integer N increases exponentially with l, at least using algorithms known at present[1]. Factoring large integers is therefore conjectured to be intractable classically, an observation underlying the security of widely used crypto-



Distributed quantum computation

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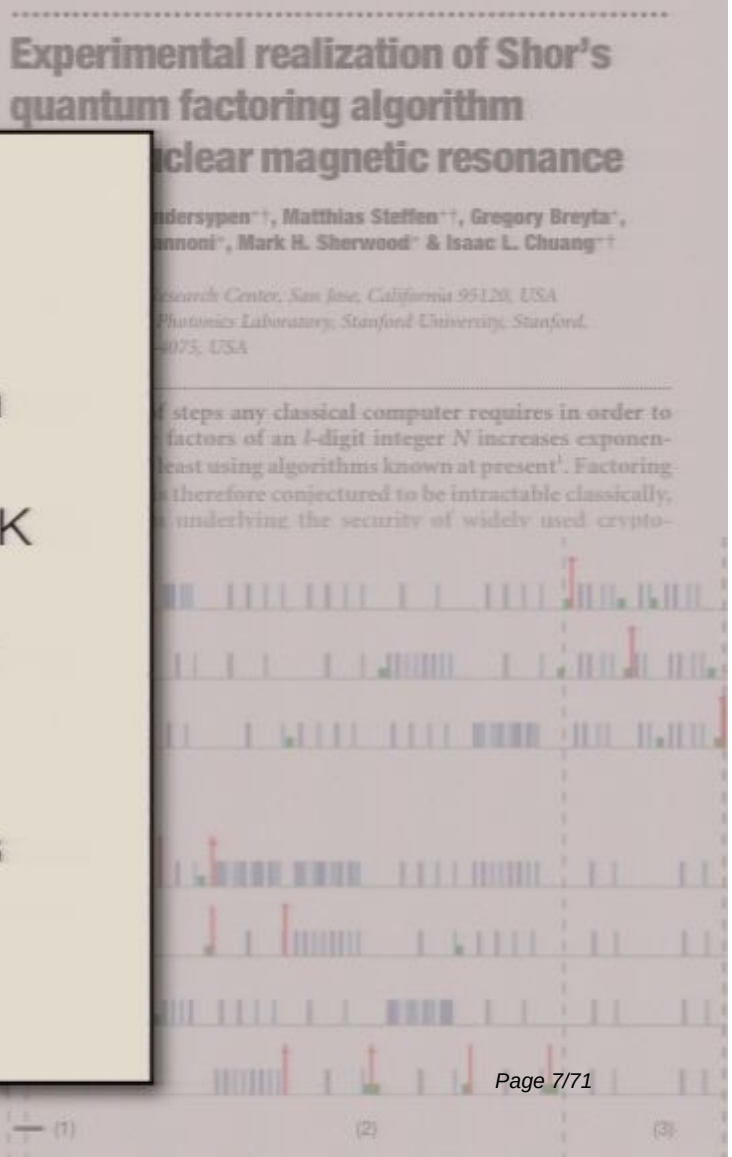
Approach: build a
Quantum Register

Use quantum communication between registers
- noisy, failure prone, still OK

Have good local operation of a given register

Use many local operations to improve (faulty) inter-register operations



Early ideas (monolithic architecture)

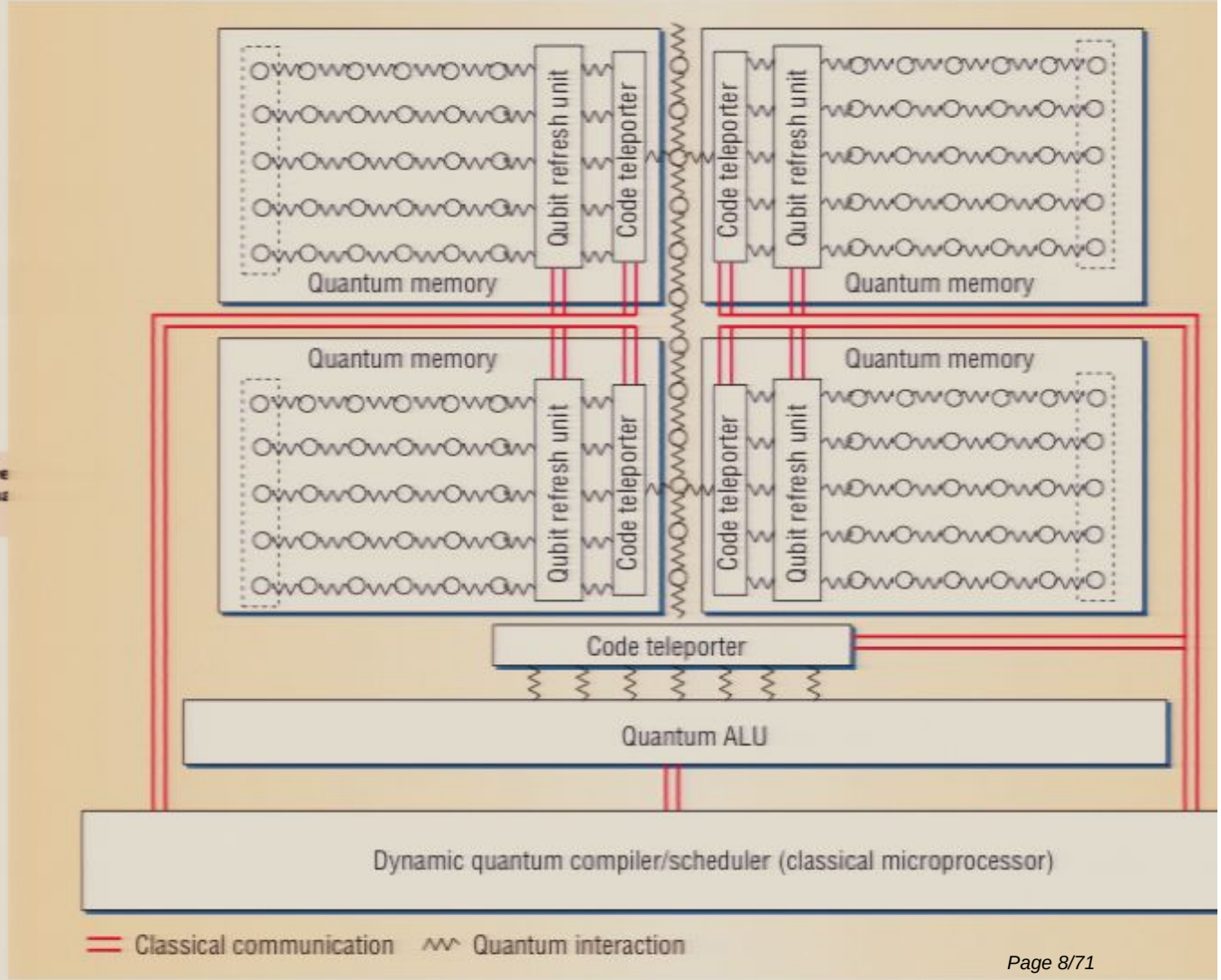
A Practical Architecture for Reliable Quantum Computers

Quantum computation has advanced to the point where solutions can help close the gap between emerging qua and real-world computing requirements.

Mark Oskin
University of Washington

Frederic T. Chong
University of California, Davis

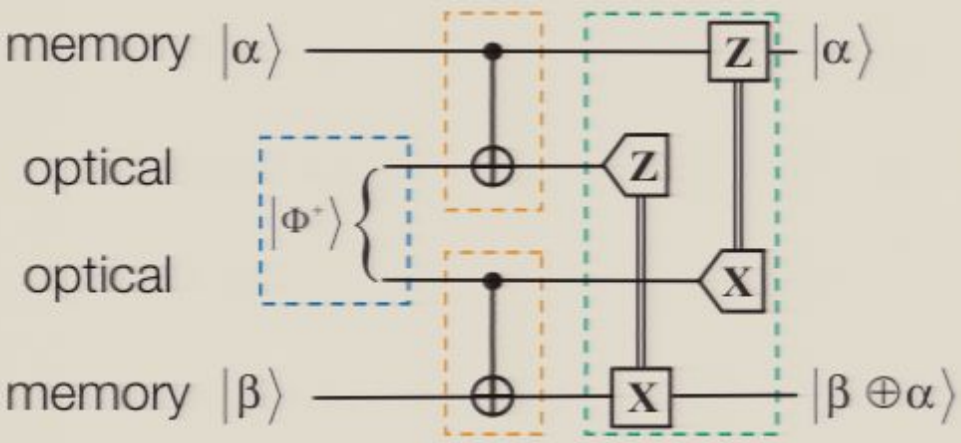
Isaac L. Chuang
Massachusetts Institute of Technology



[Oskin et al., IEEE 2002]

Teleportation, gates, and bandwidth

Teleportation-based CNOT



[Gottesman & Chuang]

Entanglement +
Local operations +
Classical communication =

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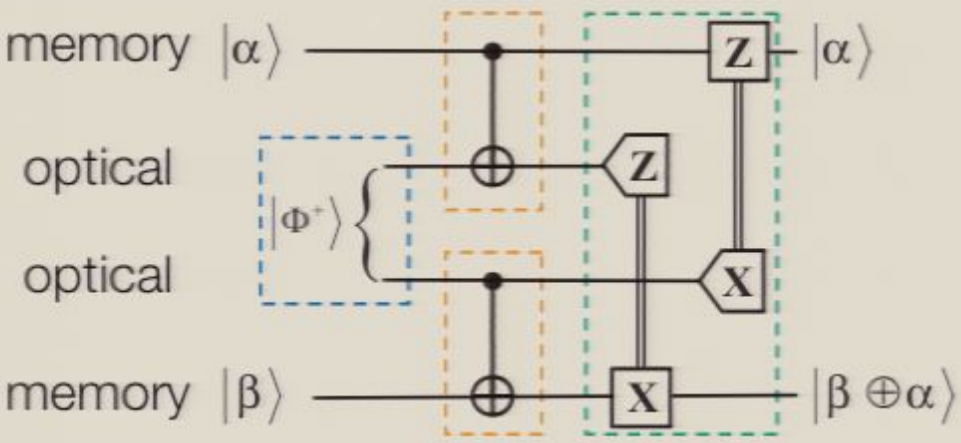

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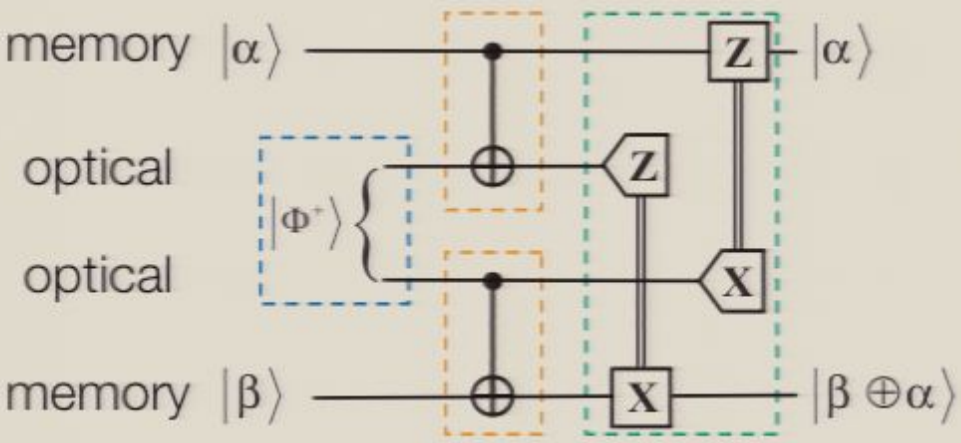

[Gottesman & Chuang]

Entanglement +
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Deterministic gates
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(quantum) bandwidth *in advance*

Using photons to build entanglement

State-selective
transition
(atom, ion, etc.)

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Using photons to build entanglement

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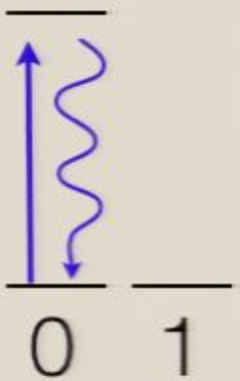

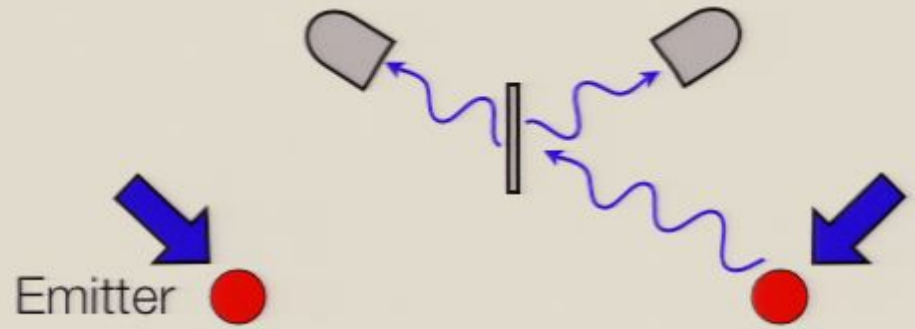

$$(\sqrt{p}|0\rangle + |1\rangle) \otimes (\sqrt{p}|0\rangle + |1\rangle) \rightarrow$$
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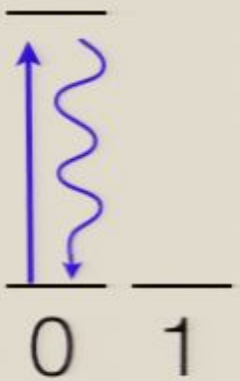
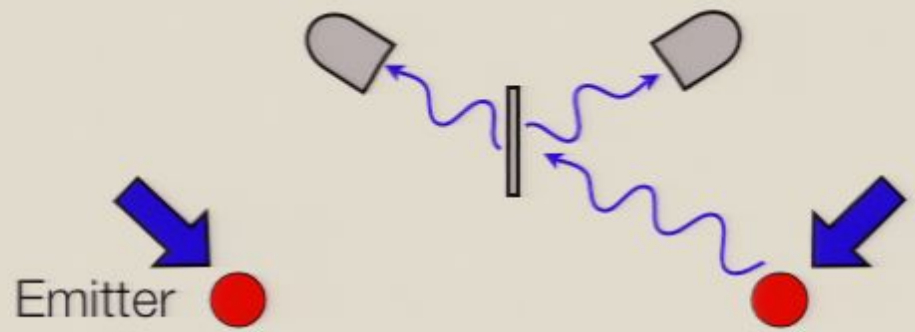
Using photons to build entanglement

State-selective transition (atom, ion, etc.)





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- Single "click" with no which-path information
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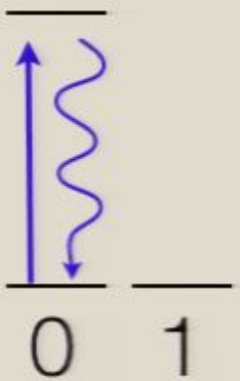

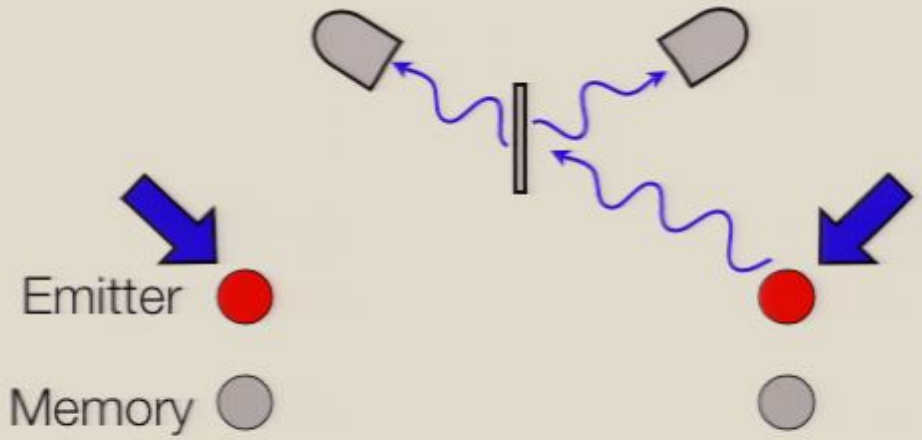

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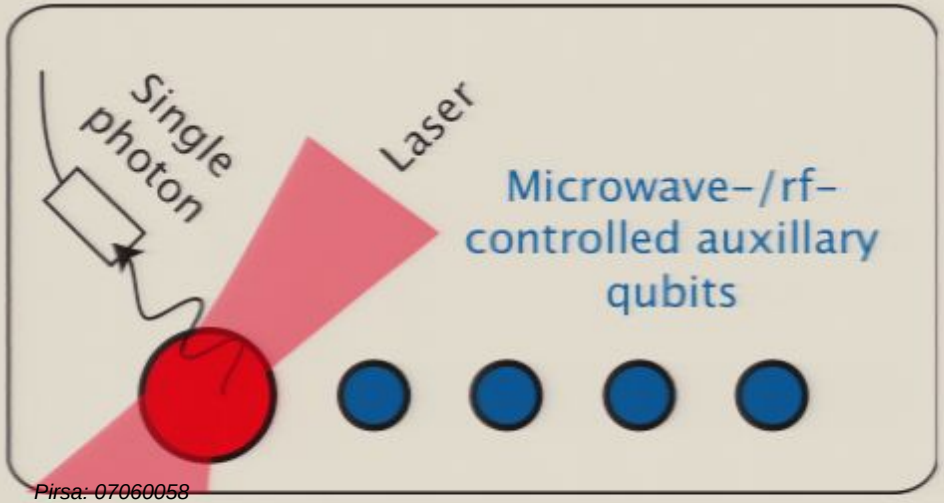
A minimal register

Minimum requirements:

- "optical" qubit
  - entanglement generation
  - measurement / initialization
- "memory" qubit
- very good local control
- reasonable optical interface



[Jiang et al. quant-ph/0703029]

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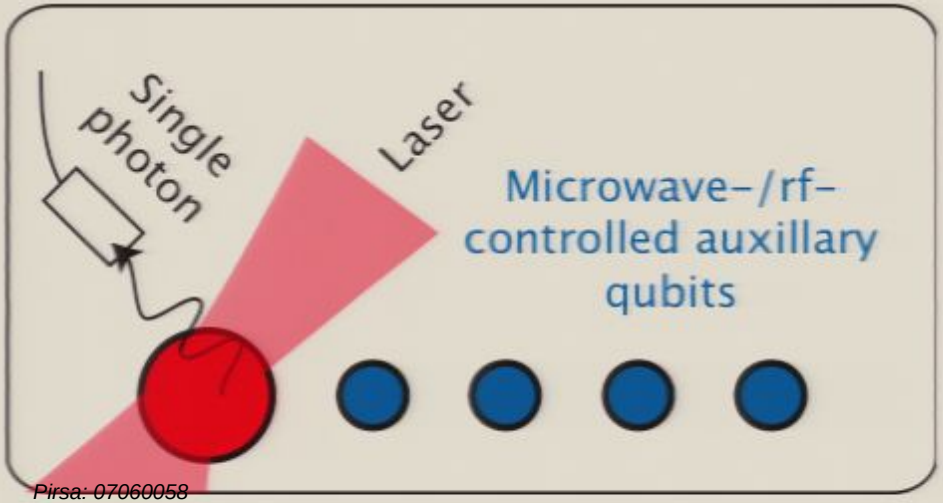

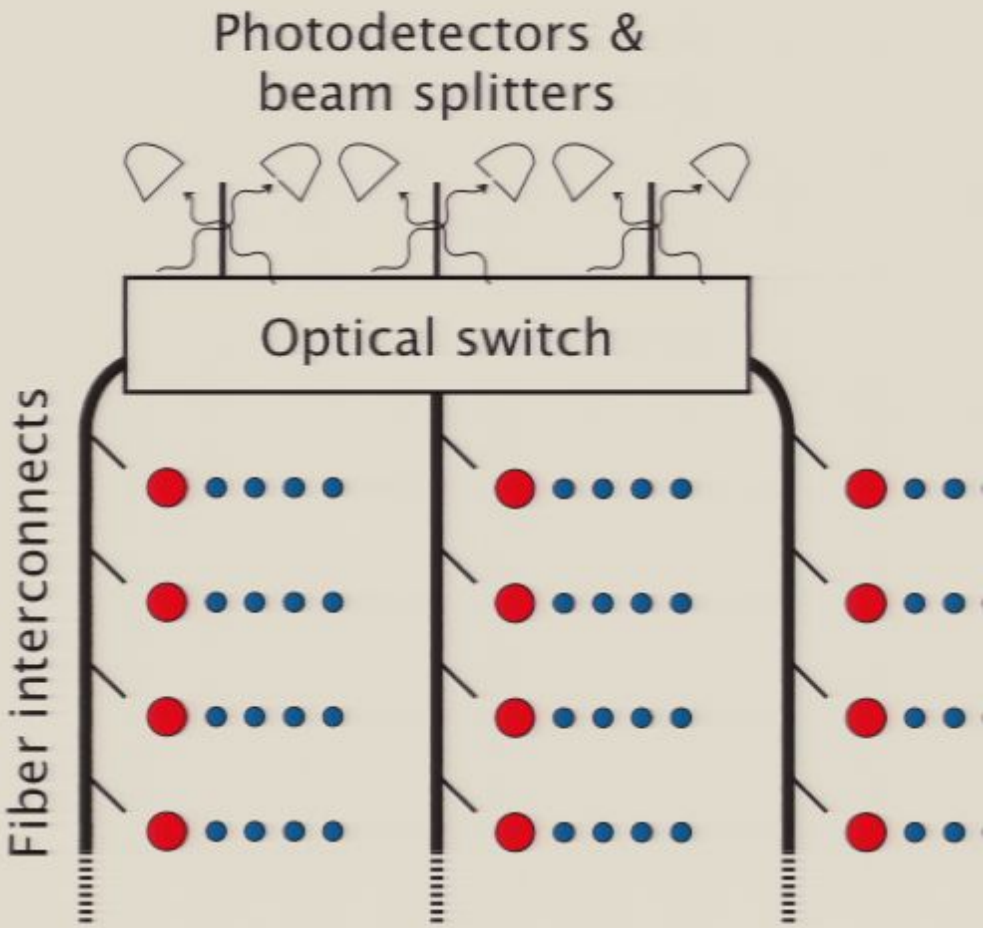

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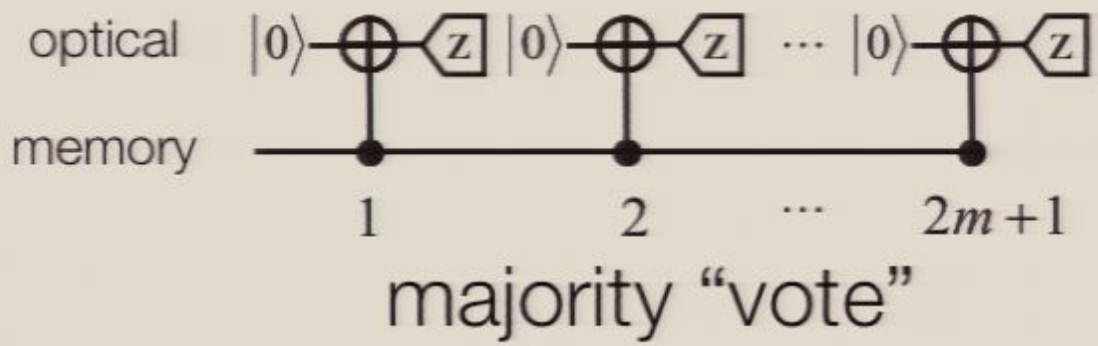
Dealing with imperfections

Robust measurement:
bit verification

- Trade measurement errors for local errors and time
- Phase errors in C irrelevant
- Also initializes memory bit



Robust entanglement generation

- use entanglement purification
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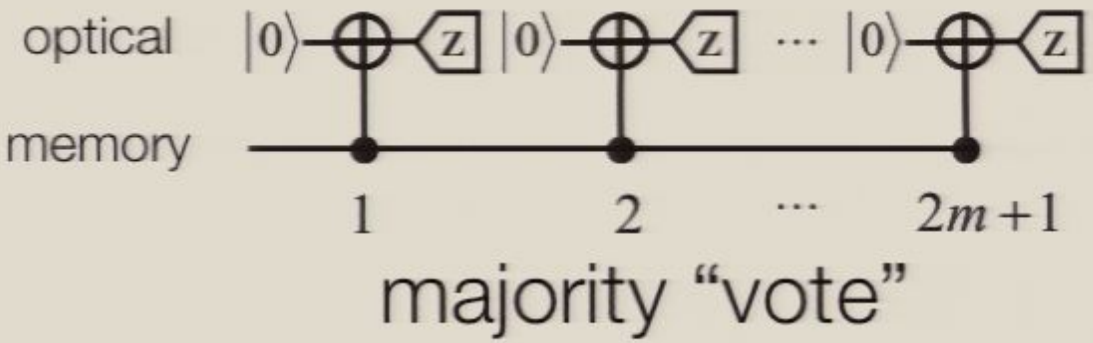

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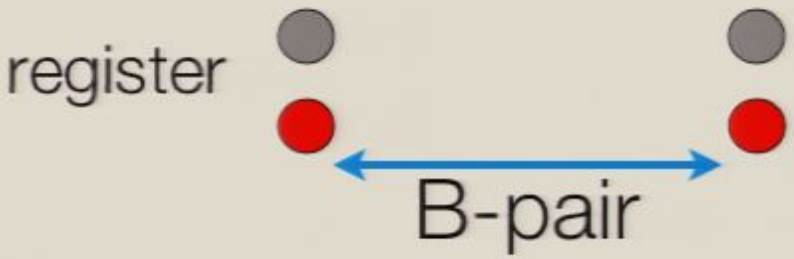

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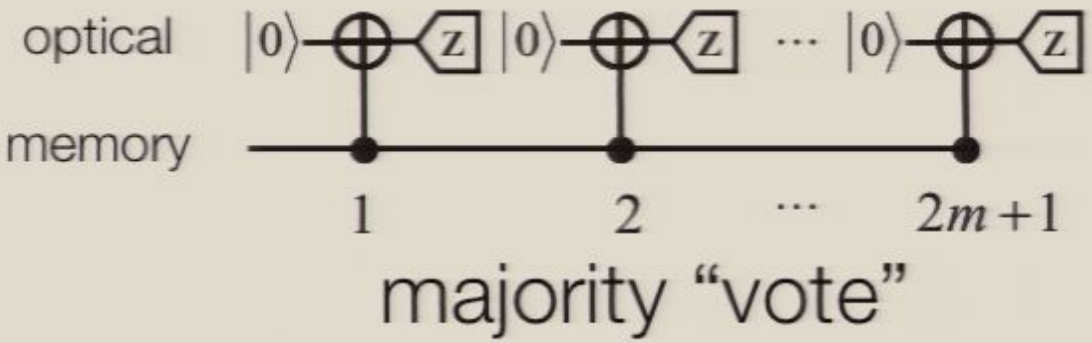

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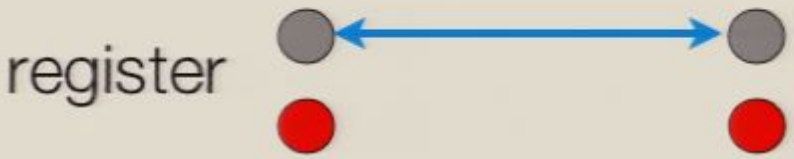

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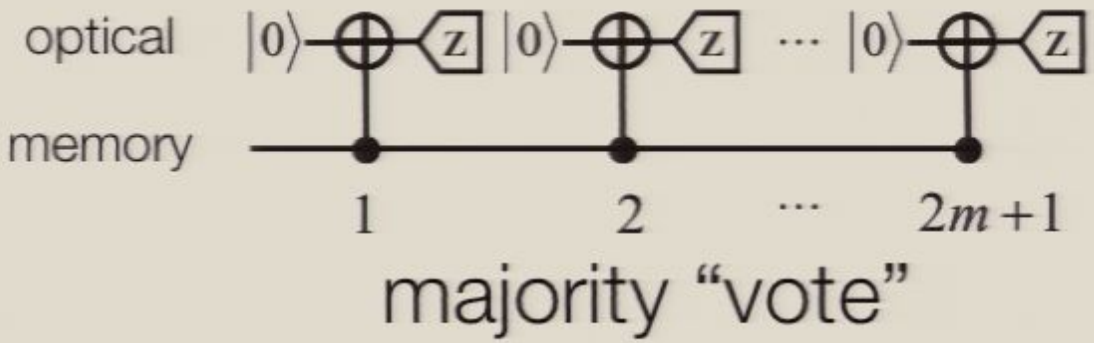

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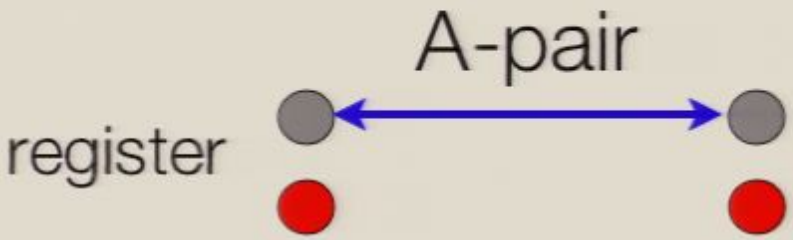

Dealing with imperfections

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bit

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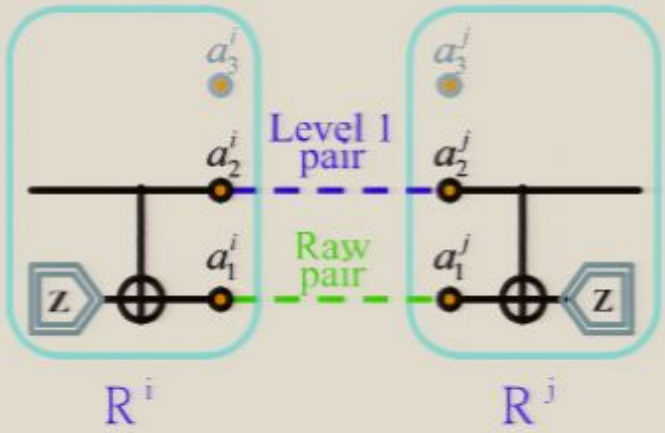

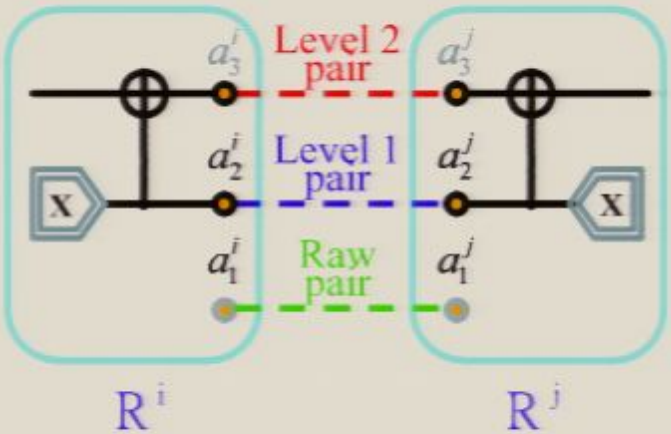

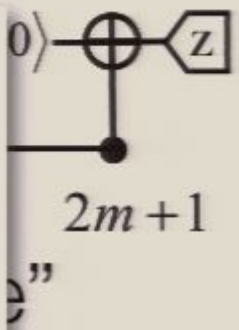

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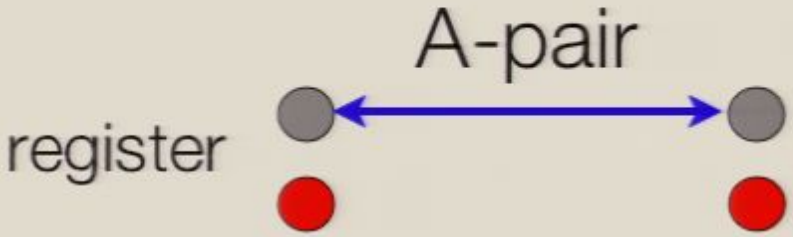

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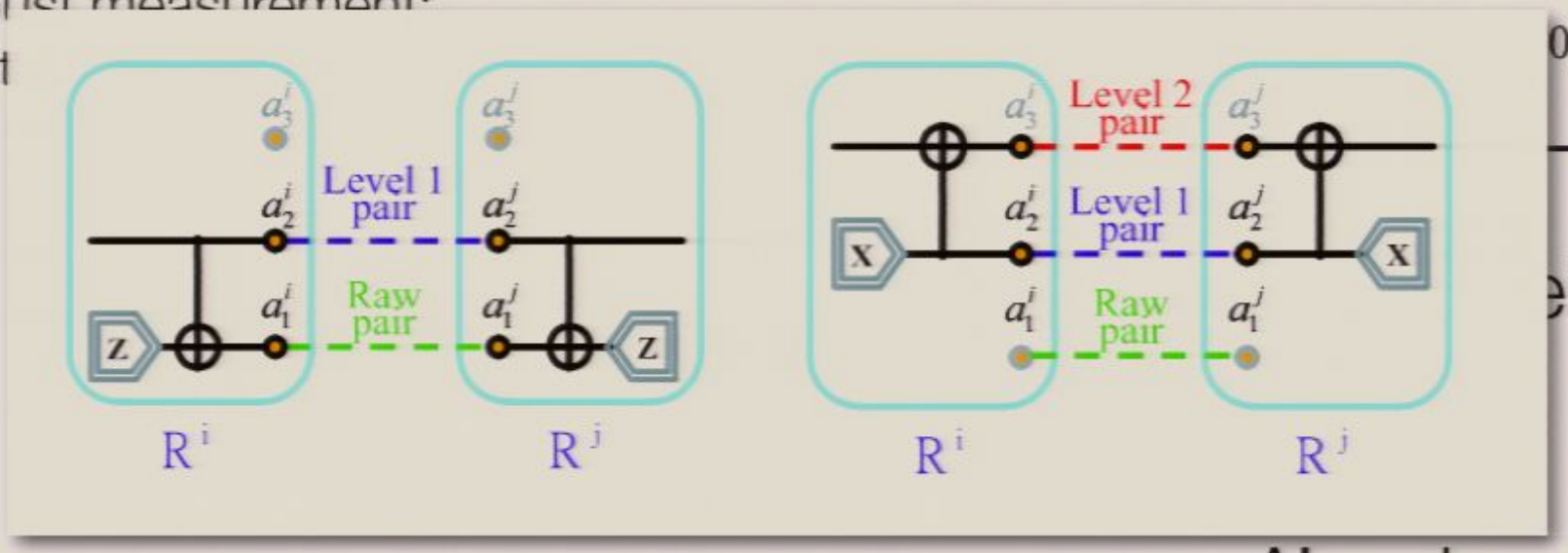

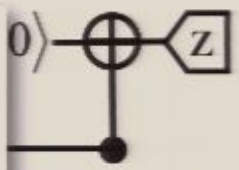

$2m+1$

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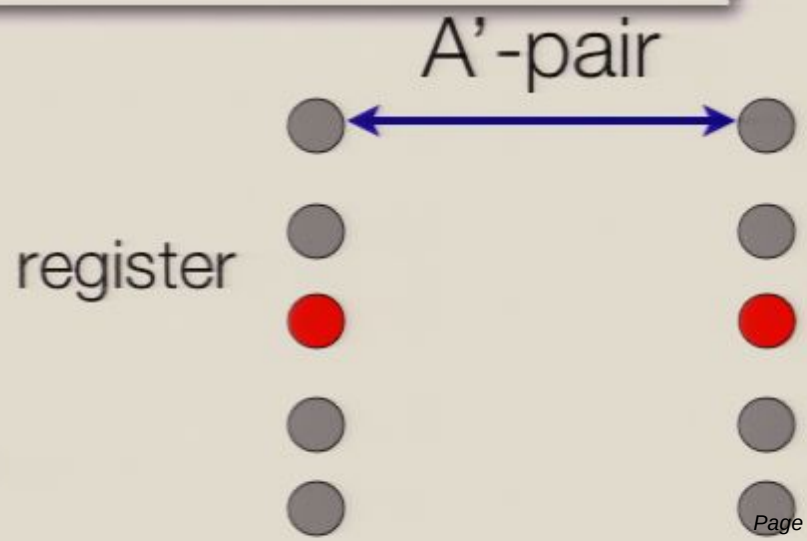
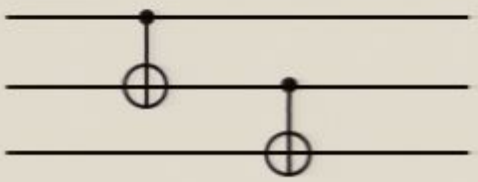


Deterministic distributed computation

desired (logical) circuit



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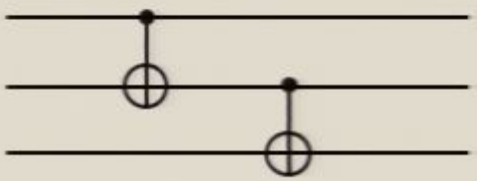

Idea:

- Break into pairwise gates
- Set a “clock cycle” time
  - can have “did not succeed” errors
  - can have logical errors

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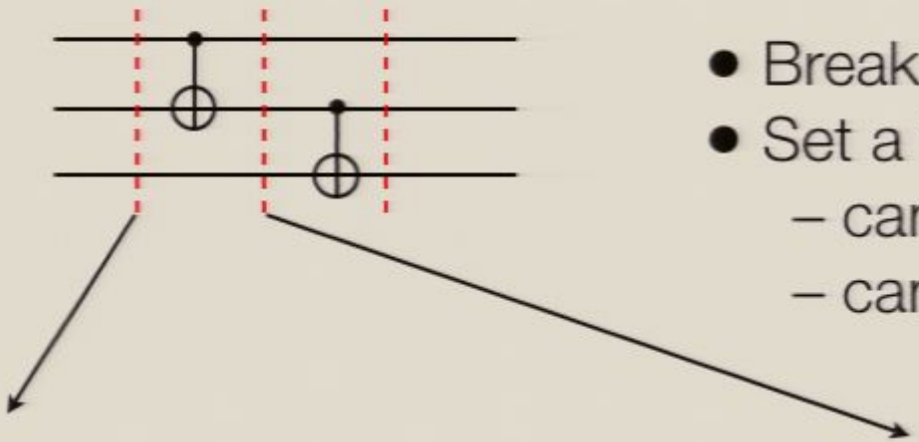

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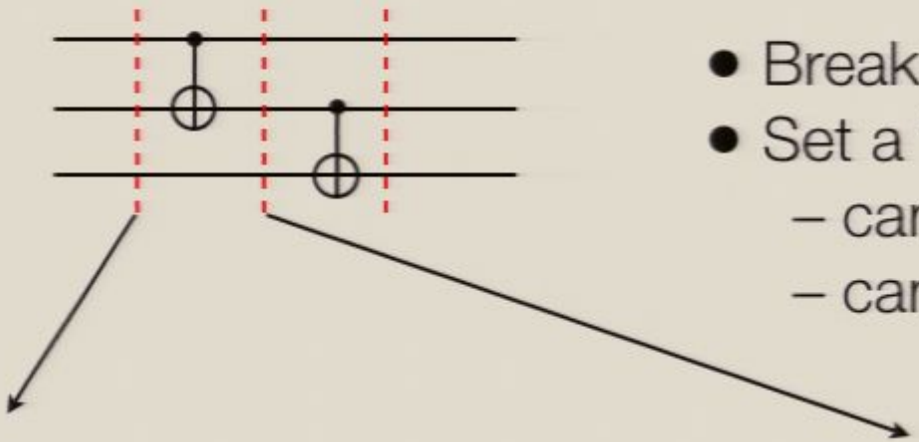

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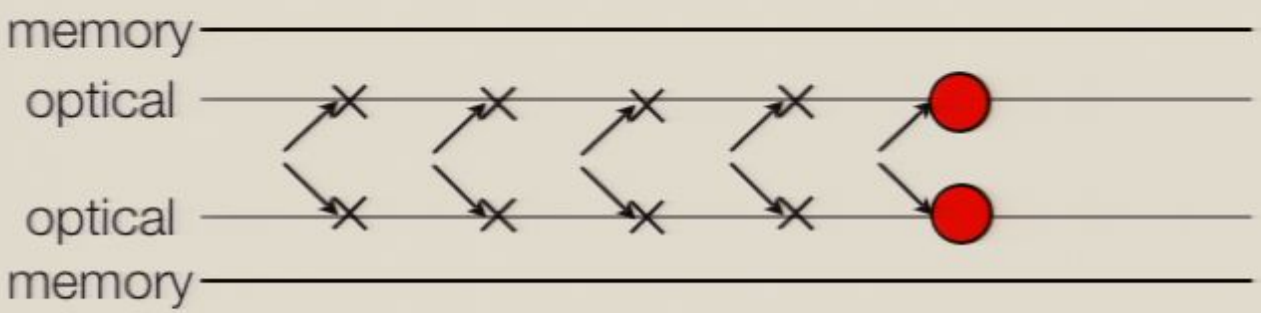

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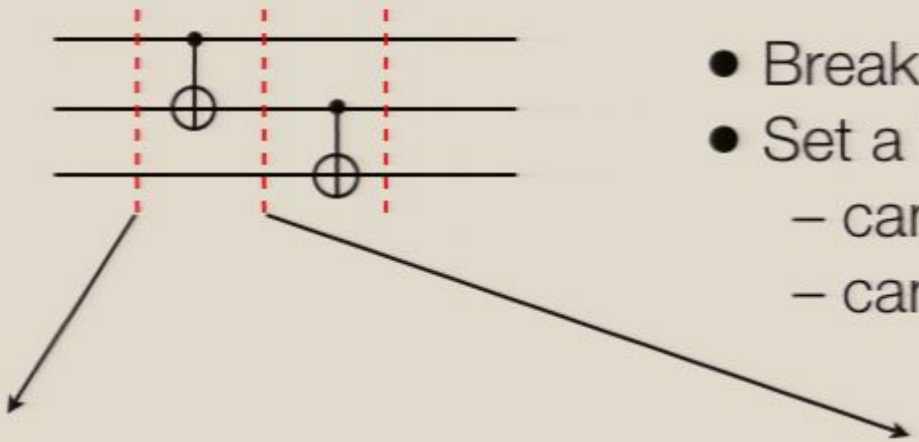

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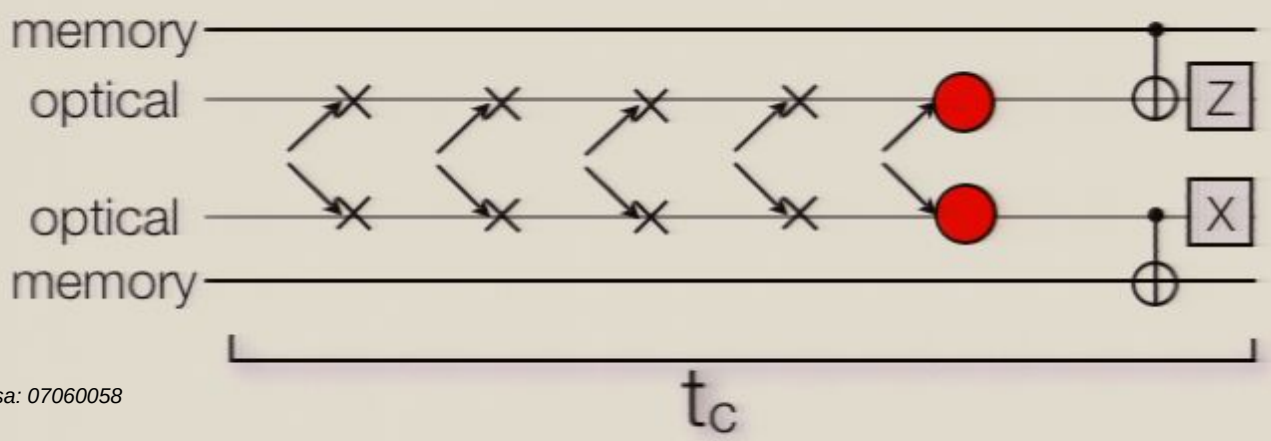

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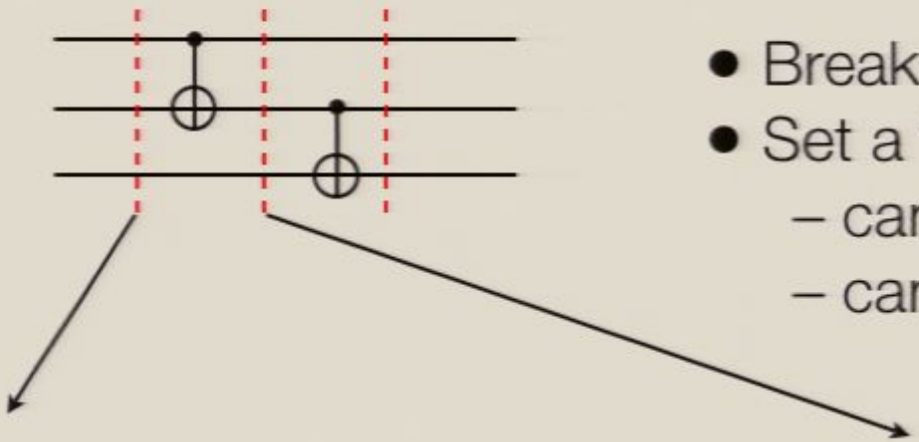

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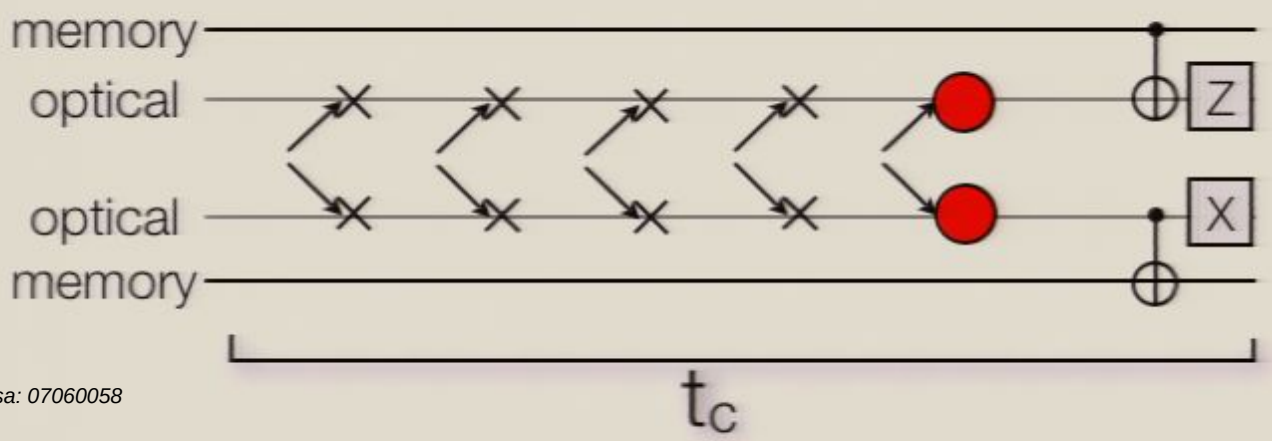

time/gate = t_c

error/gate = $N_{eff}\, p_L$

Performance for 5-qubit registers

Robust measurement

- imperfect initialization, measurement (p_I,p_M ~ 5%)
- near-perfect local operation (p_L ~ 0.01%)

$$\tilde{\varepsilon}_M \approx \binom{2m+1}{m+1} (p_I + p_M)^{m+1} + (2m+1)\, p_L$$

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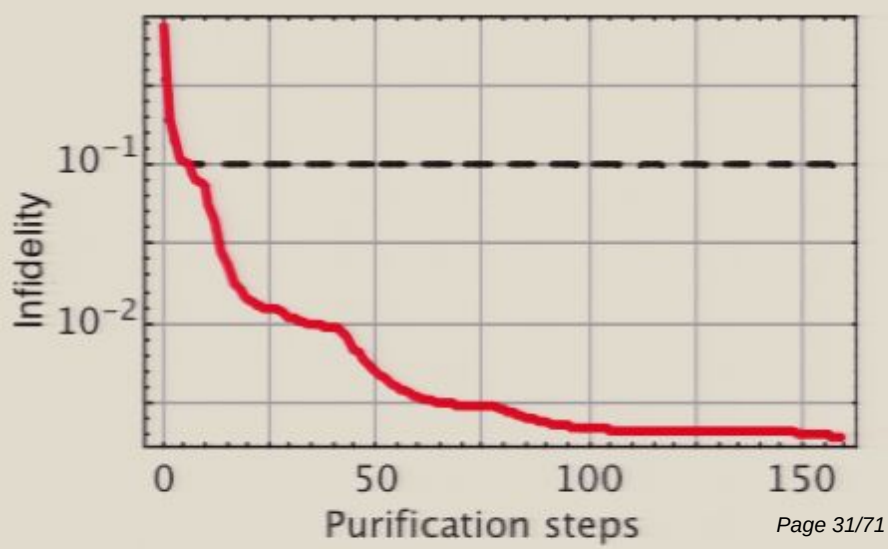
- Large time overhead
  (t_C ~100–1000 t_L)
- Initial F=0.9 gives final F>0.995
  (N_{eff} ~ 20)
- Good quantum memory *critical*



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Further improvements:
better collection efficiency via
optical cavities (Purcell effect)
— improves both speed and fidelity

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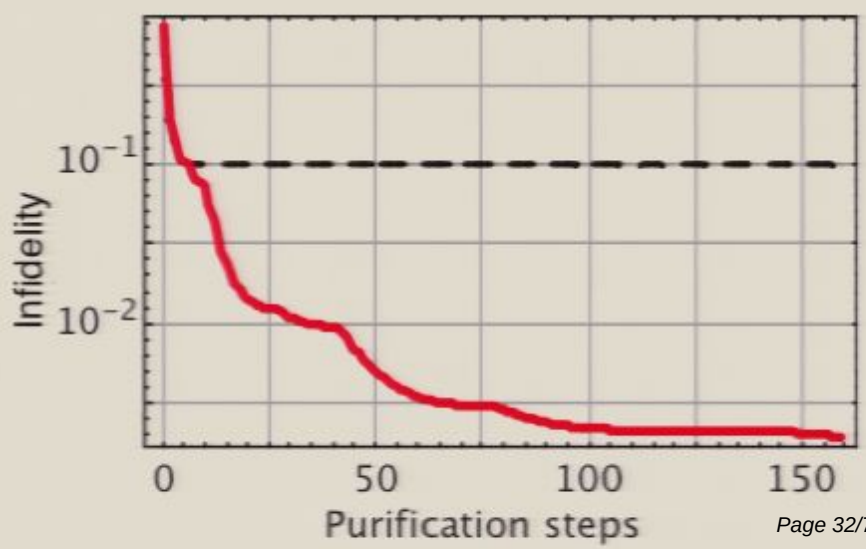

Approaches towards commodity gadgets

- Commodity good: cheap, interchangeable, ubiquitous
- Finite size control problem *per register*.
  - GRAPE pulses [Khaneja et al.], feedback & filtering, composite pulses, etc.
- Optical or other "distributed qubit" interconnect system can be faulty (<50% errors after post-selection sufficient; for <10%, only 5 qubits needed)
- Implementations:
  - NEED: few coupled, controllable qubits with fantastic quantum memory; optical (or phononic, or qubit-bus) interconnection possible
  - Ion traps, NV centers, Quantum dots, neutral atoms(?)
- FUTURE: better use of post-selected computing; better purification protocols (c.f. n-bit purification approaches); direct, multi-qubit entanglement protocols

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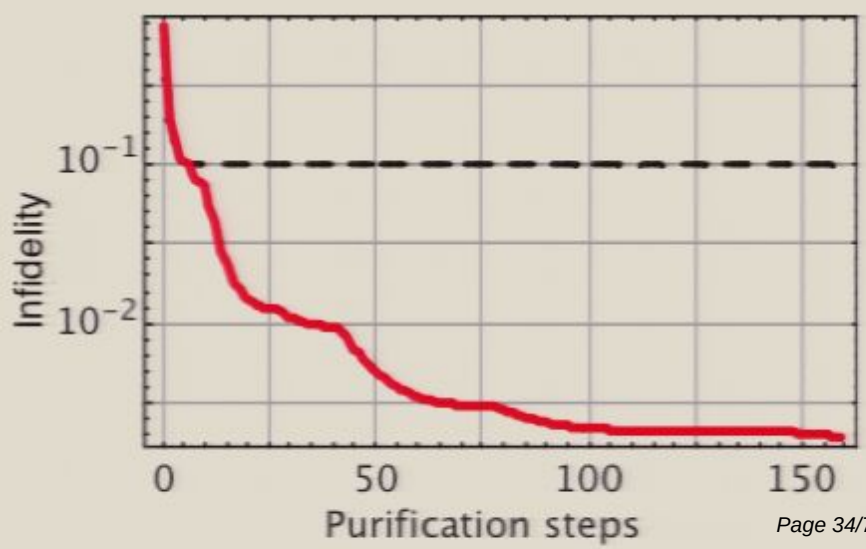

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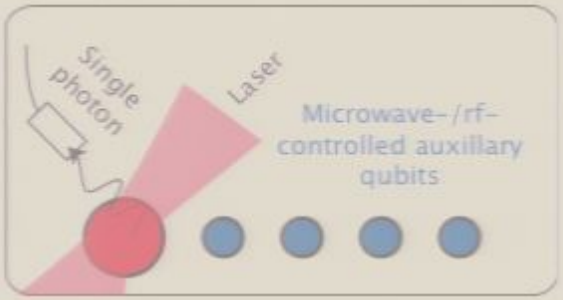
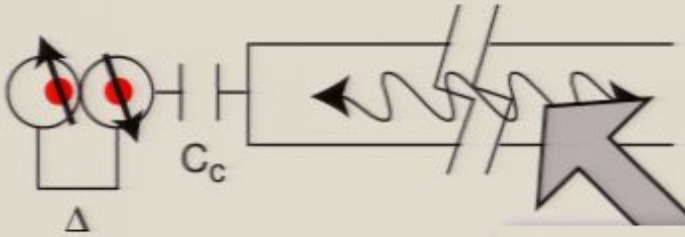
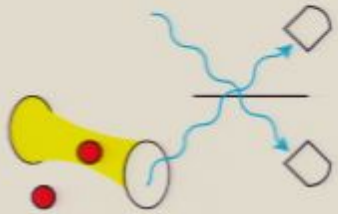
Focus of this talk

Quantum registers for distributed computation

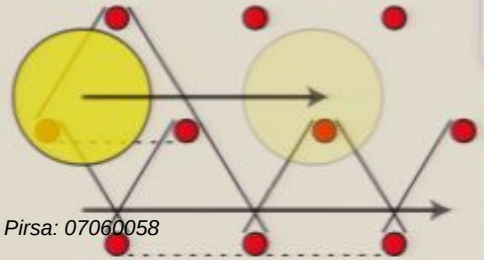


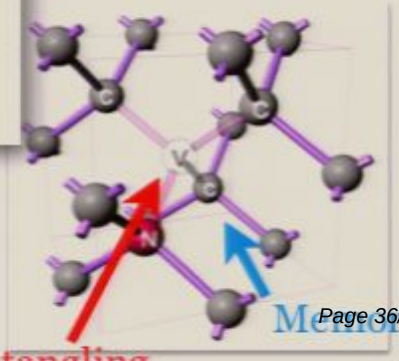


Processor (Paul trap)

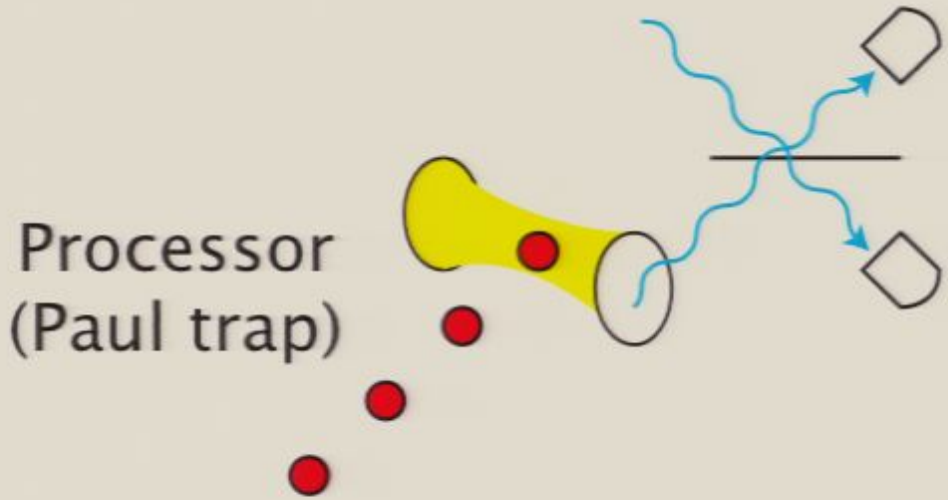


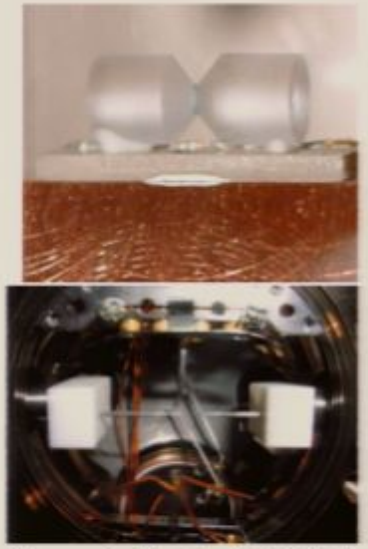
Some example approaches





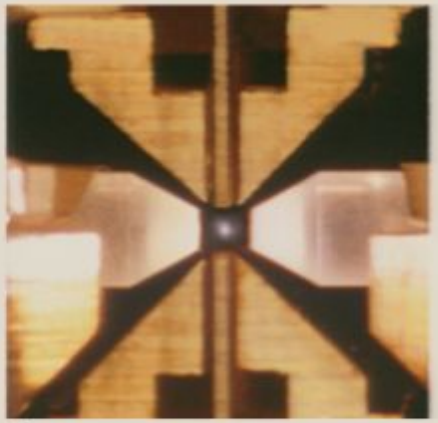
Linear paul traps + cavity





Georgia Tech / U Mich

Innsbruck



Sussex

Nitrogen-vacancy color center in diamond

Color centers as qubits
(NV centers in diamond)

Nitrogen-vacancy color center in diamond

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Entangling
(optical) qubit

Nitrogen-vacancy color center in diamond

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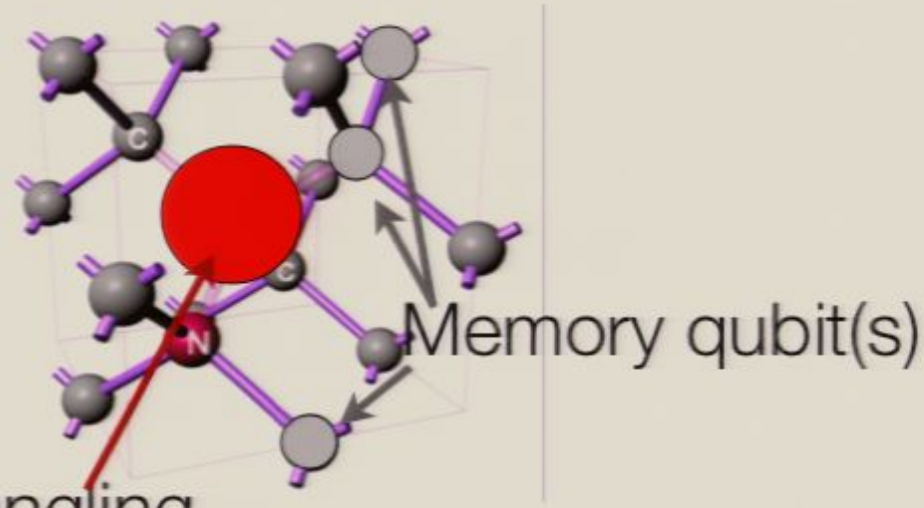

Nitrogen-vacancy color center in diamond

Color centers as qubits
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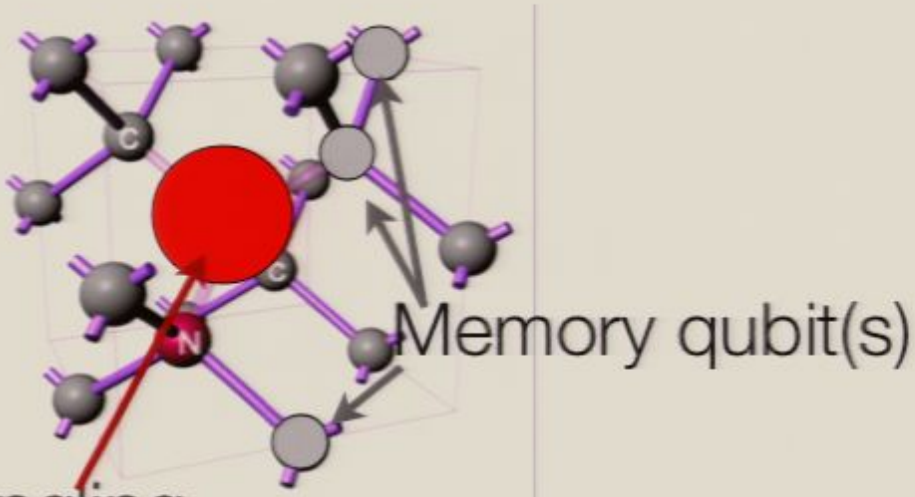
- ^{13}C provides NMR-based memory



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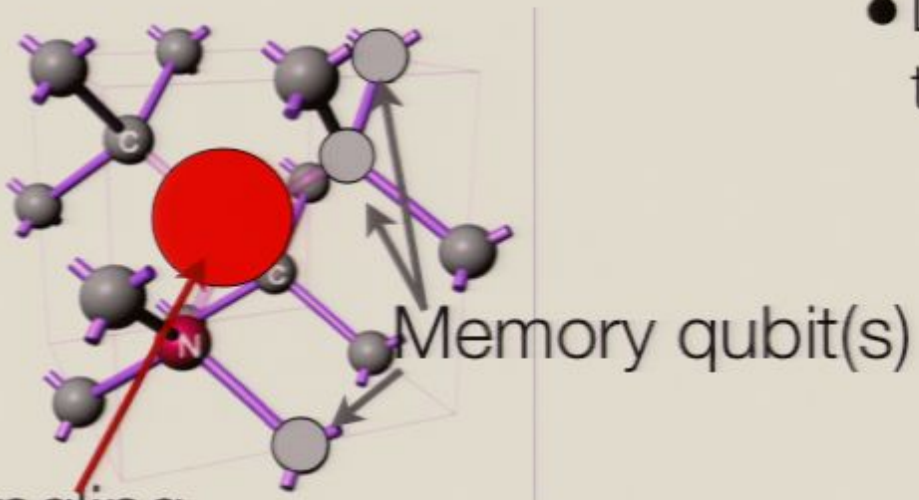

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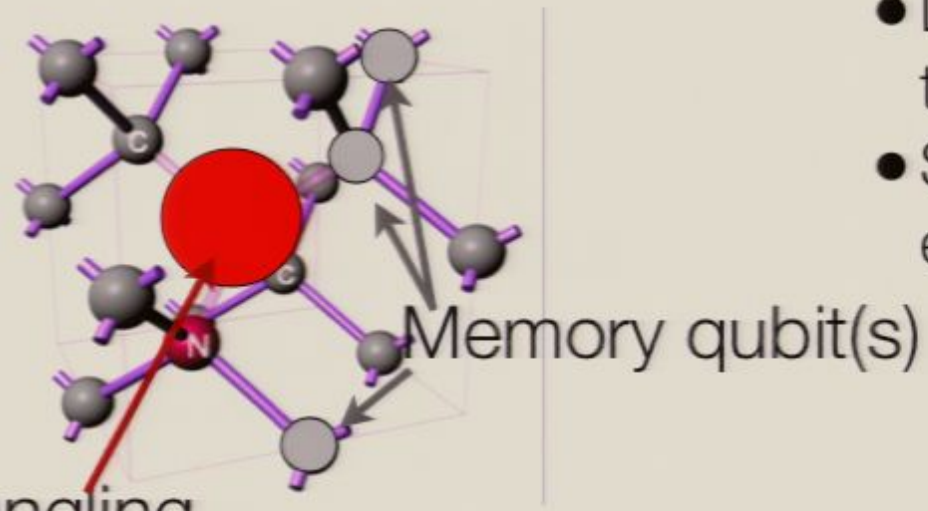

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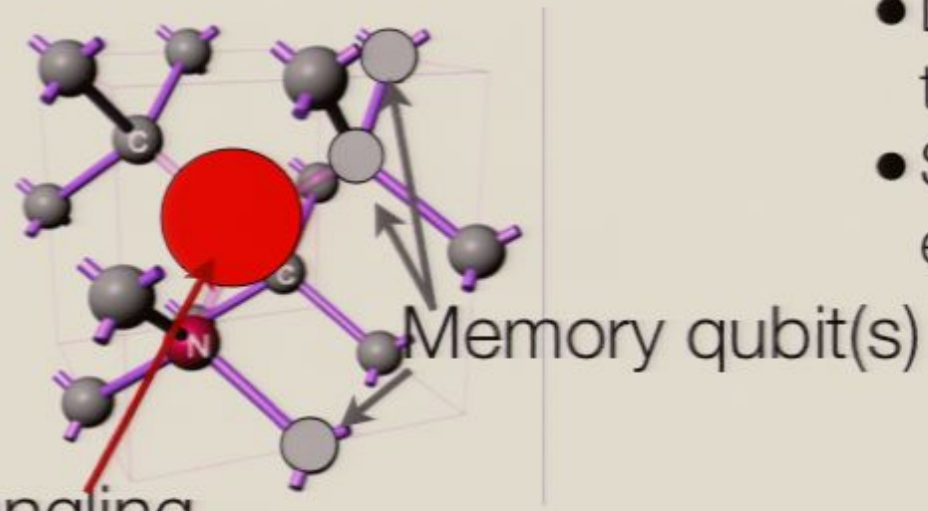


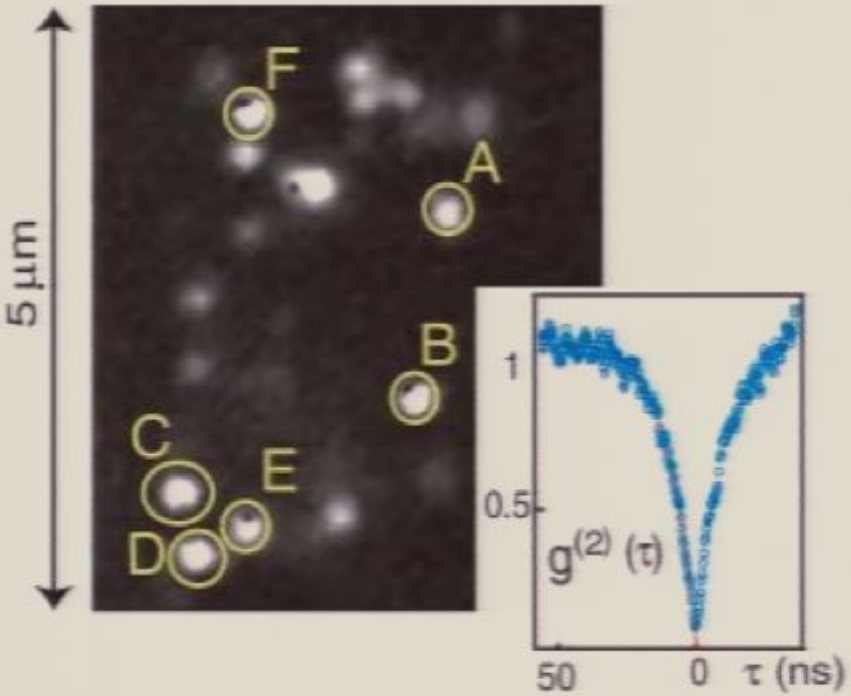
Entangling
(optical) qubit

NMR molecule
in a lattice

State-selective fluorescence

[Lenef & Rand; Kennedy; Jelezko; Grangier; ...]

Confocal microscope image and $g^{(2)}$



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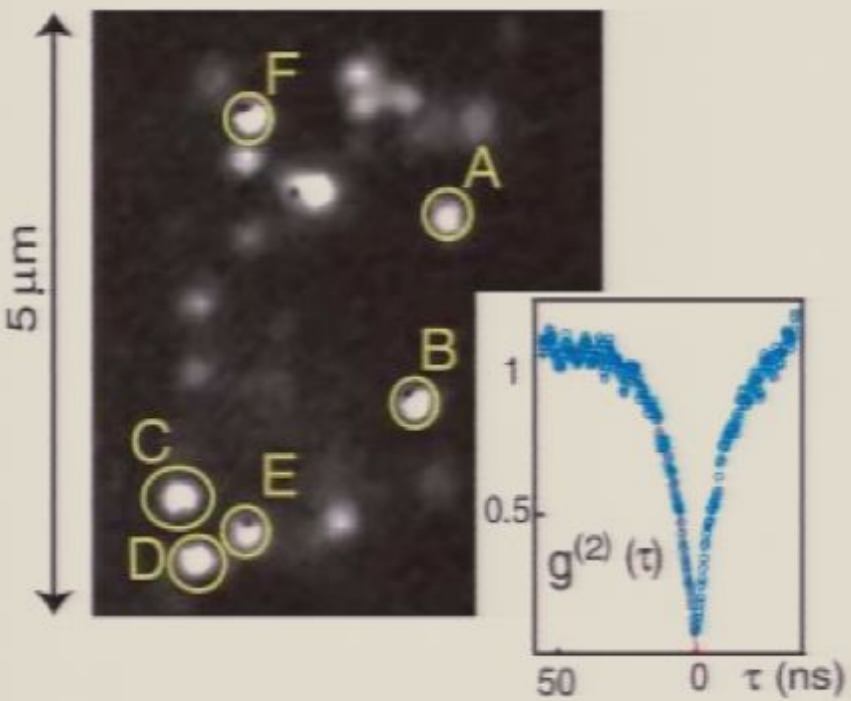

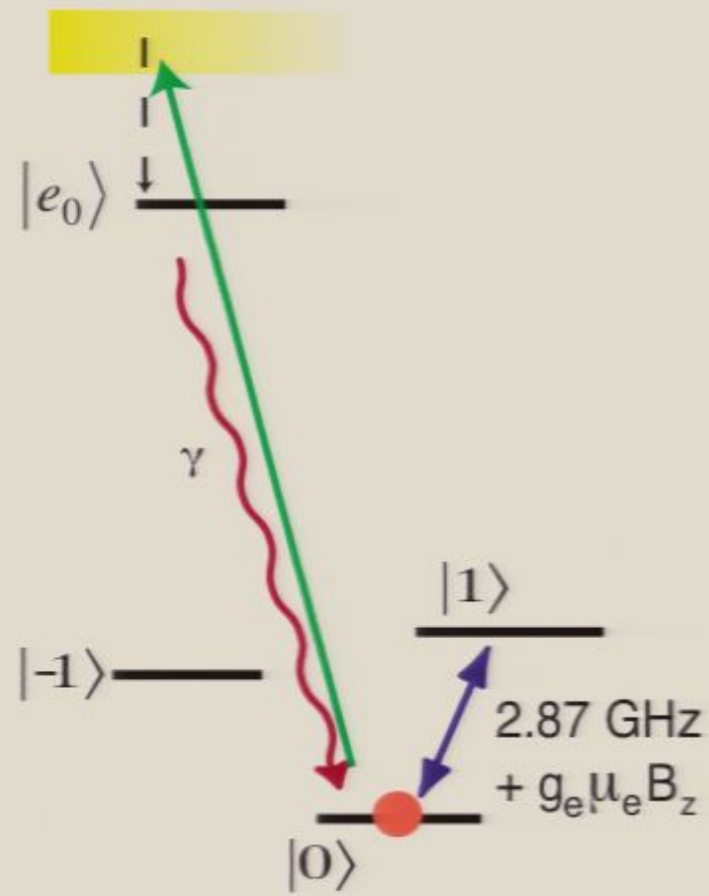

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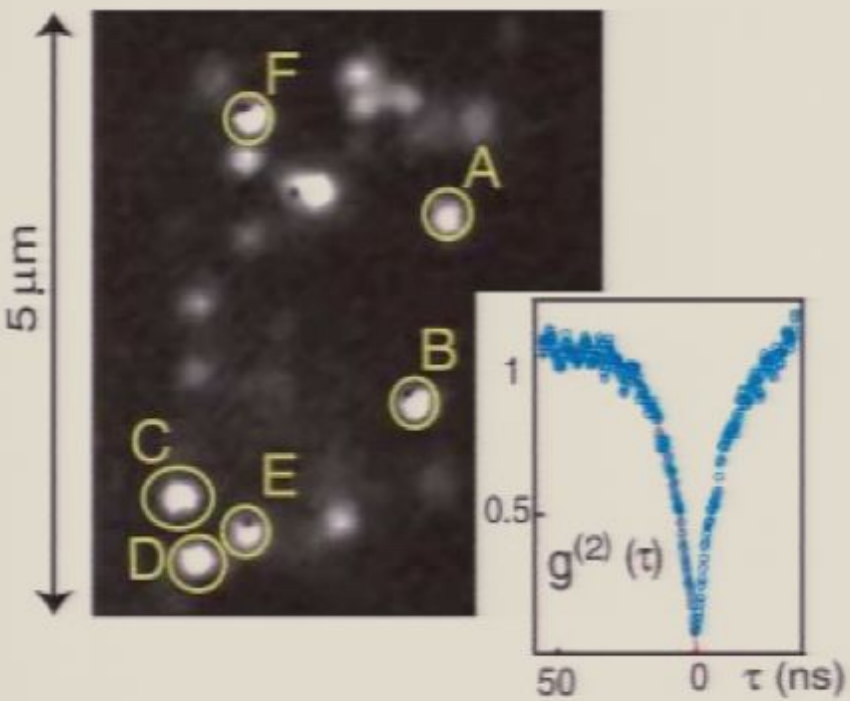

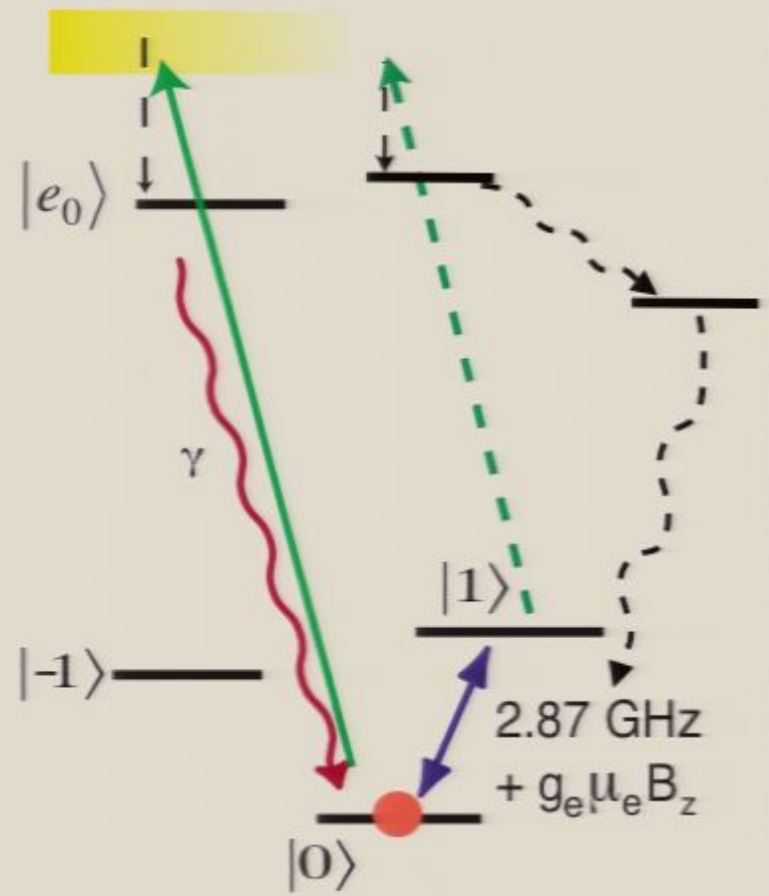

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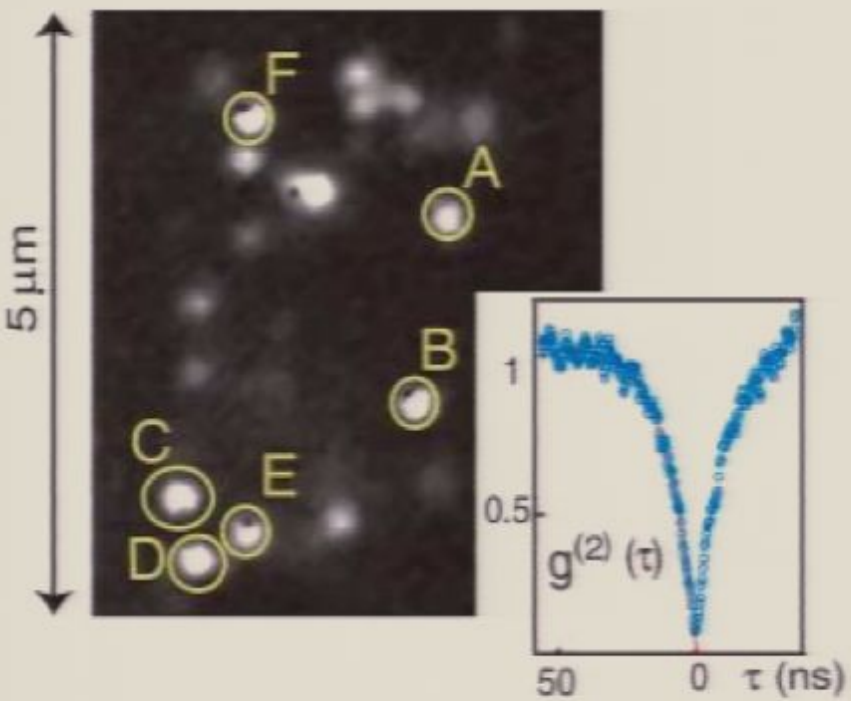
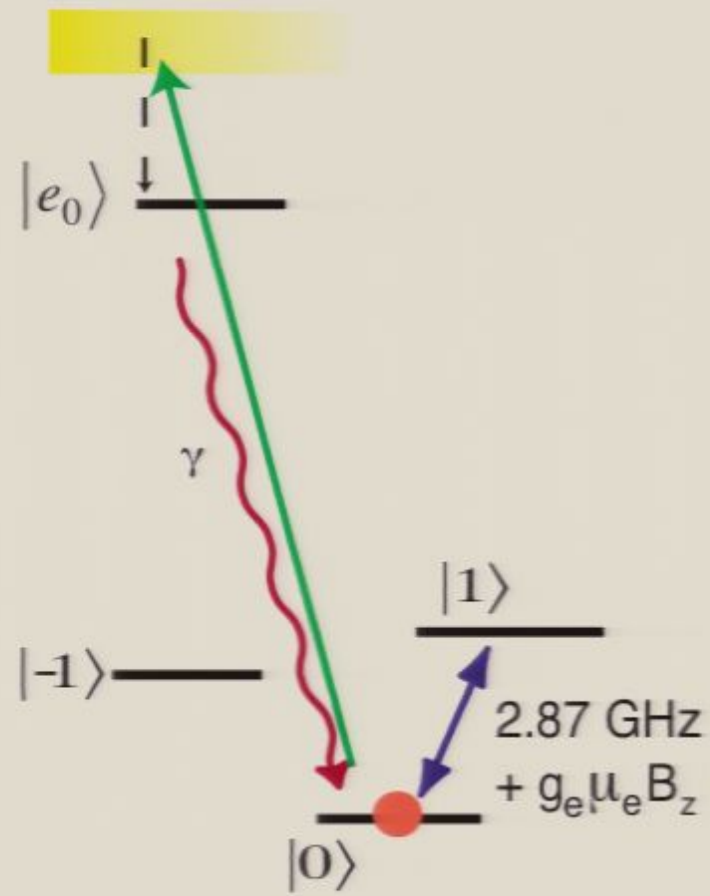
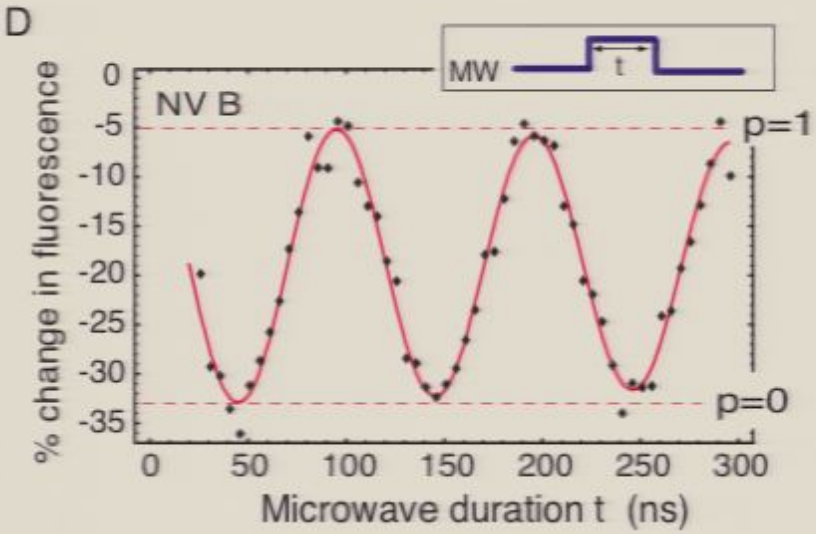
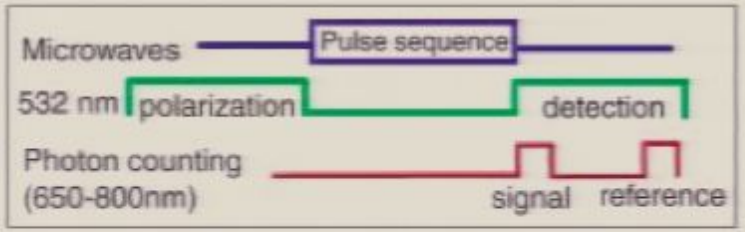




Optically detected single-center ESR

[Childress et al. Science (2006)]





- Driven oscillations (Rabi)

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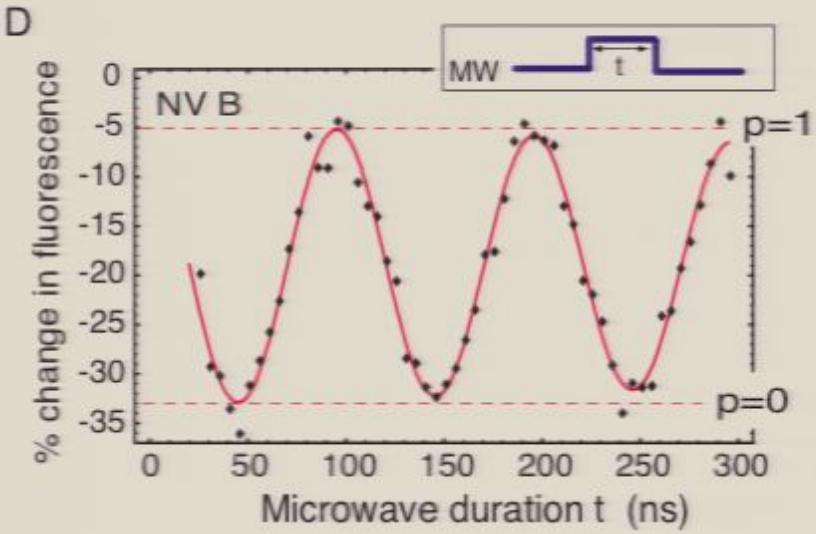
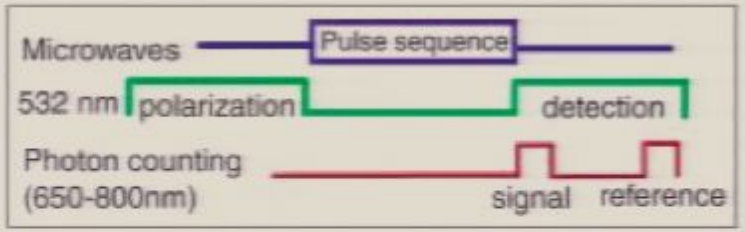
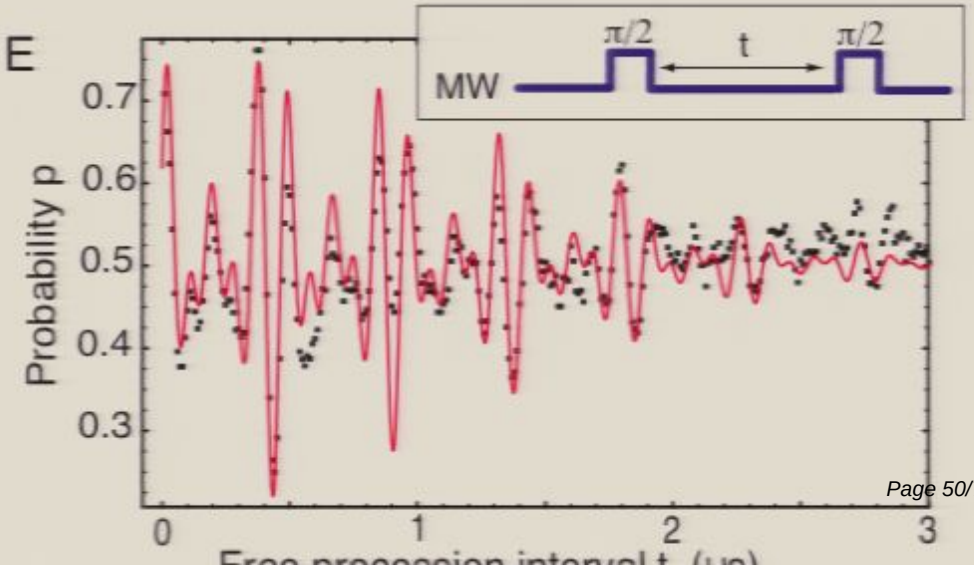




- Driven oscillations (Rabi)

- Free precession (Ramsey)



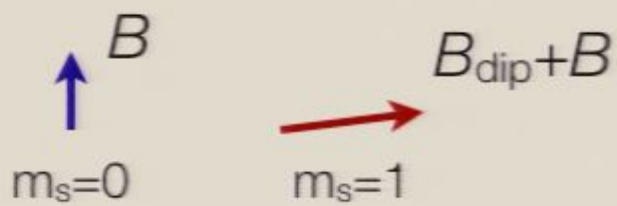
Electron spin echo

- Electron spin–nuclear spin dipole-dipole interaction

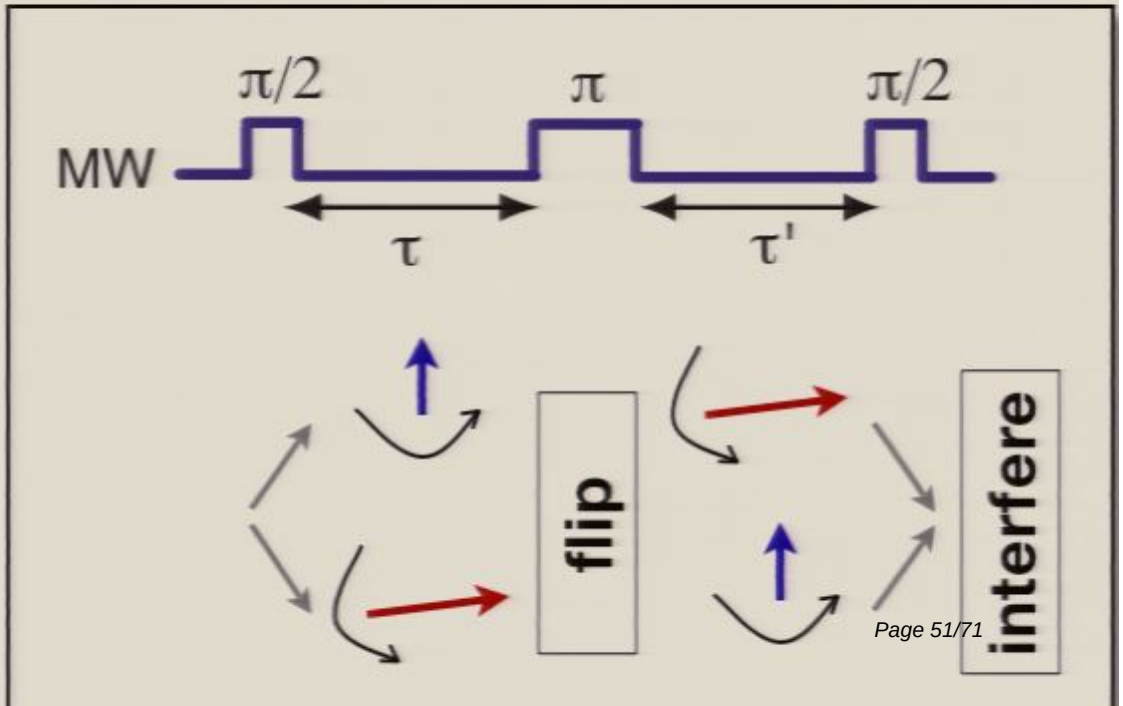
$$\hat{H} = \Delta \hat{S}_z^2 - B_z \hat{S}_z + \hat{S}_z \sum_k \alpha_{z\nu}^k \hat{I}_\nu^k + \gamma_{\mathrm{nuc}} \sum_k \vec{B} \cdot \hat{\vec{I}}^k$$

- For nuclear spin j

$$\hat{H}^j = \hat{S}_z \vec{B}_{\mathrm{dip}}^j \cdot \hat{\vec{I}}^j + \gamma_{\mathrm{nuc}} \vec{B} \cdot \hat{\vec{I}}^j$$



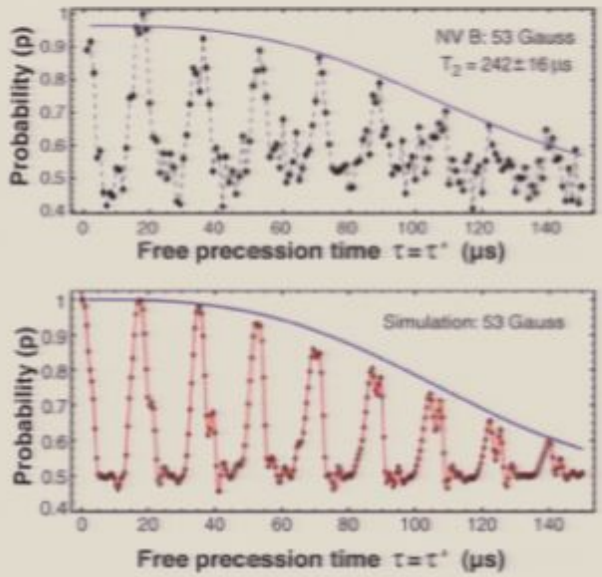
- Coupling leads to echo decay
  [Mims 1977, van Oort et al. 1989, Childress et al. Science (2006)]

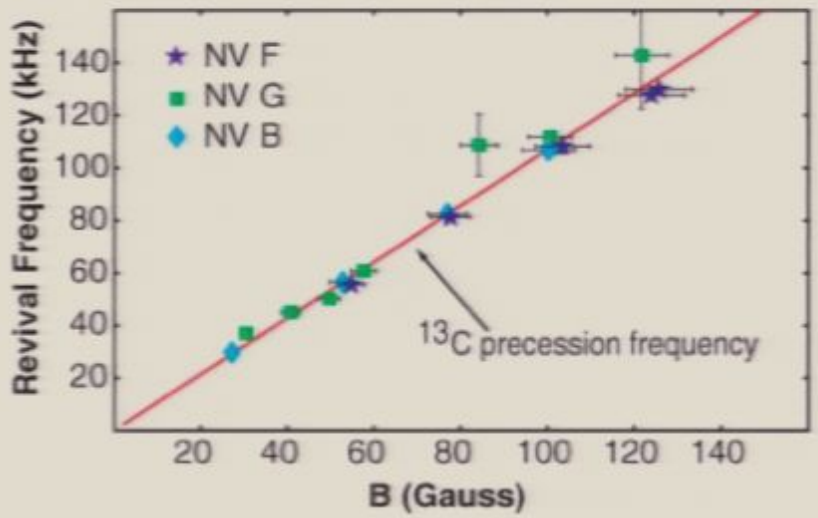


Electron spin echo

- E

- F





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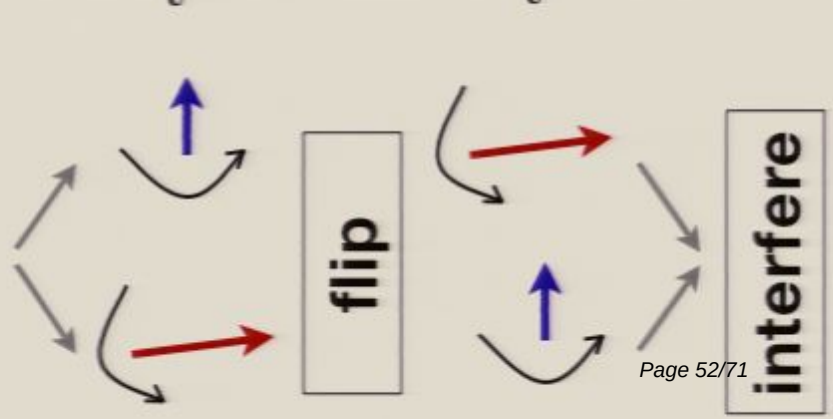
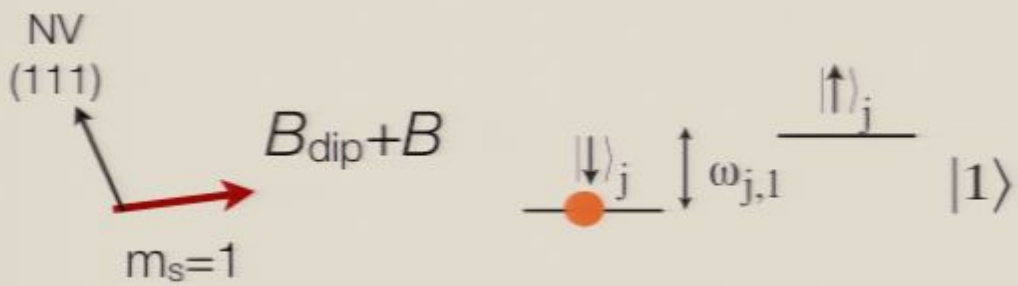
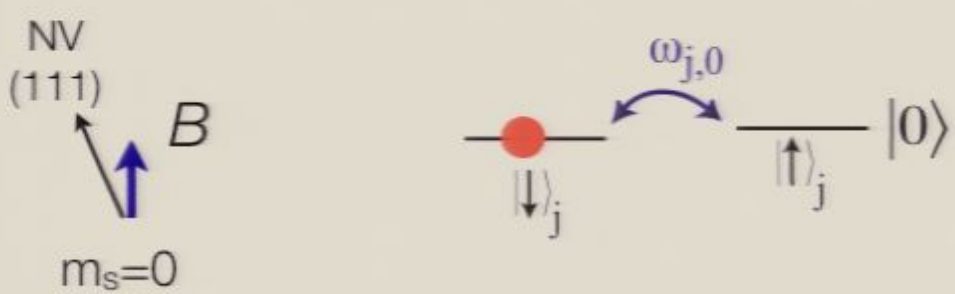


Local addressing of Carbon-13

Recall: large 0–1 splitting (RWA)

- First correction ~ B_{xy}





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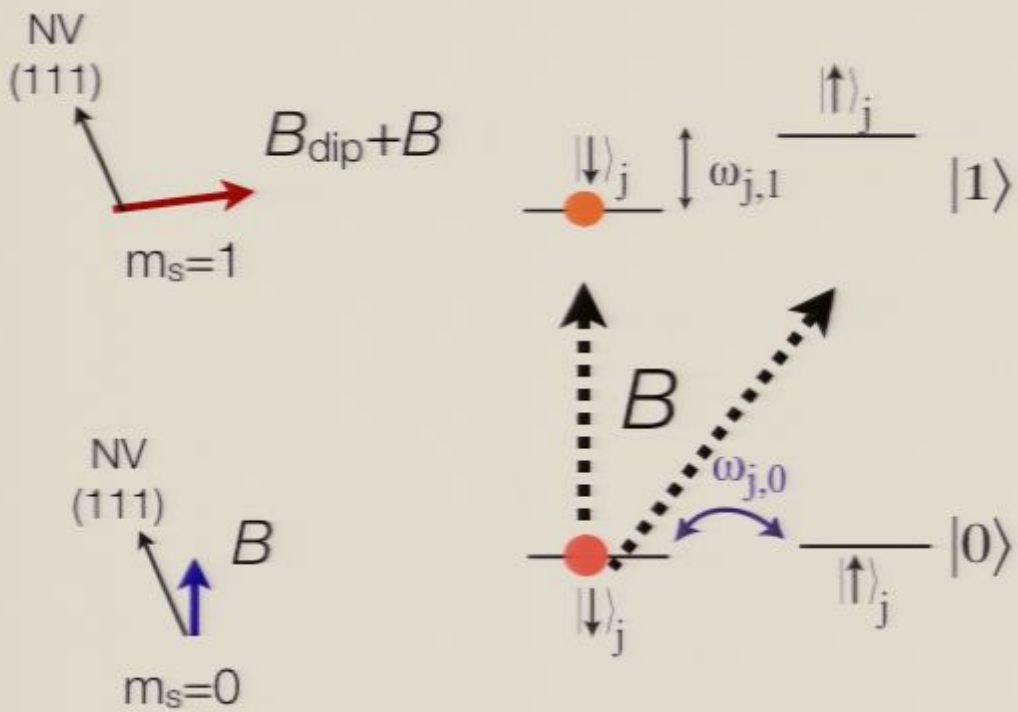

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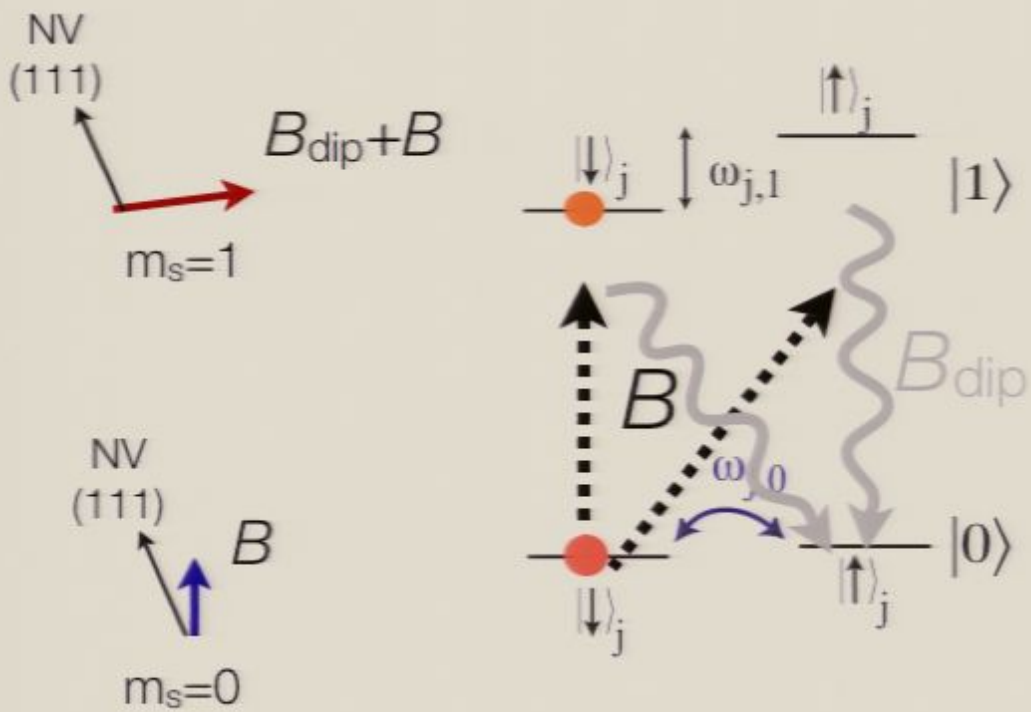
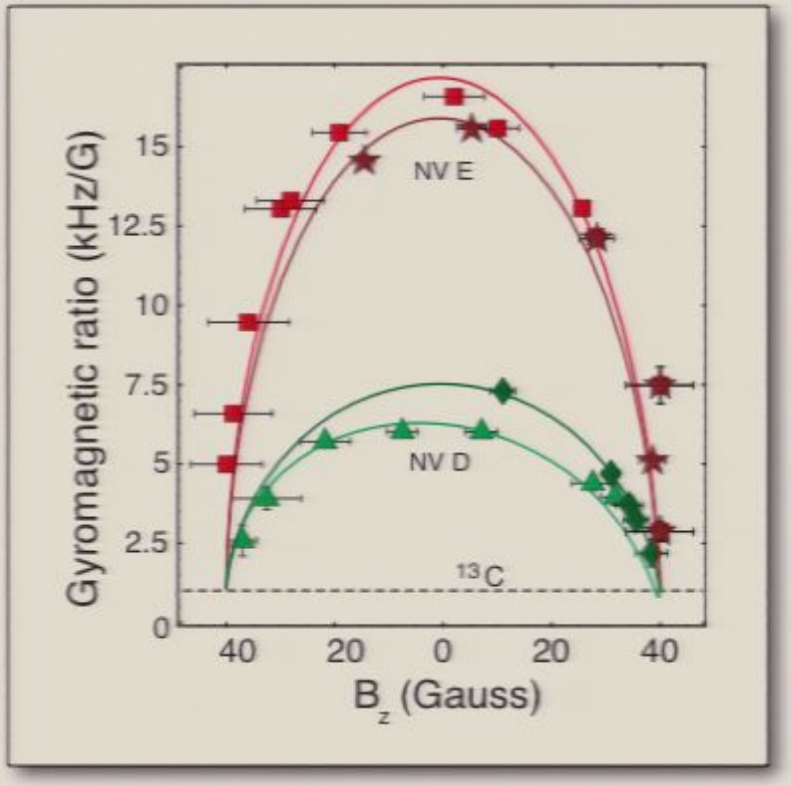
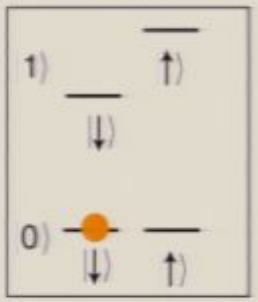




A ^{13}C quantum memory

[Dutt et al., Science (2007)]

Initialize



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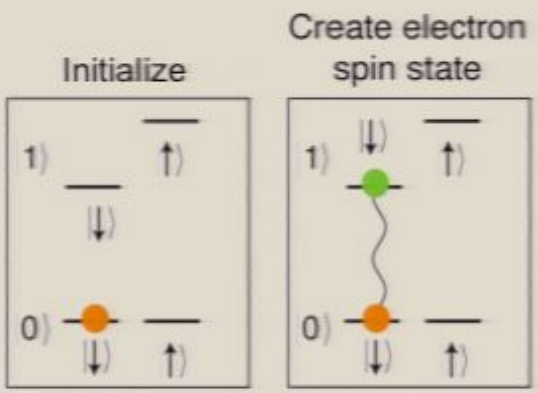

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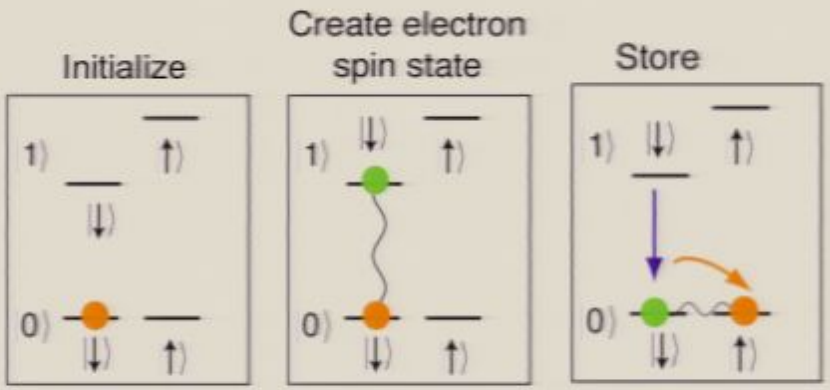

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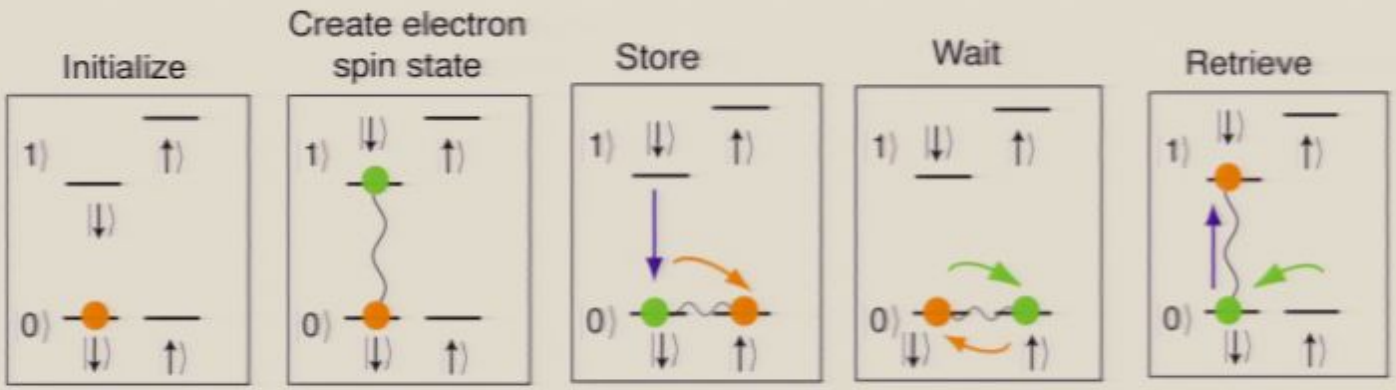

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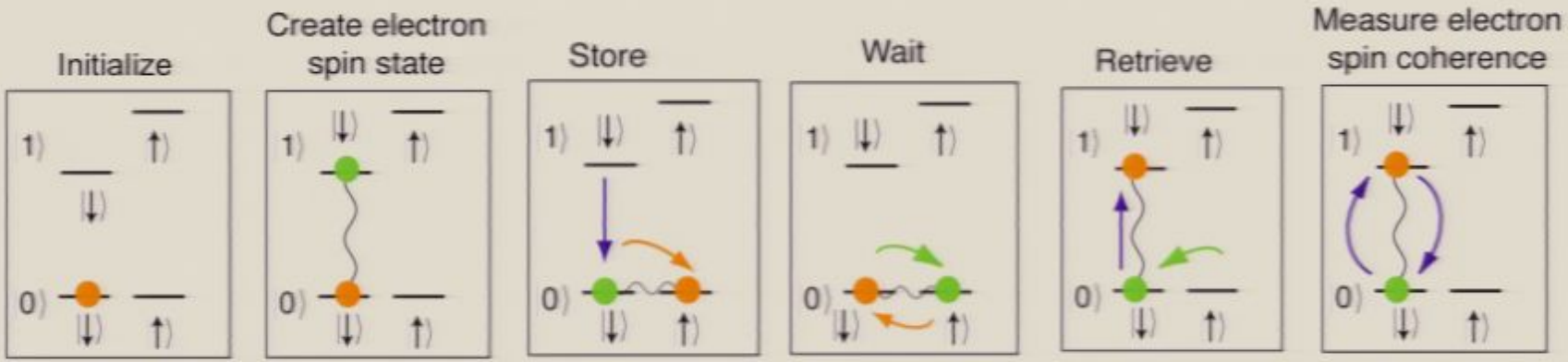

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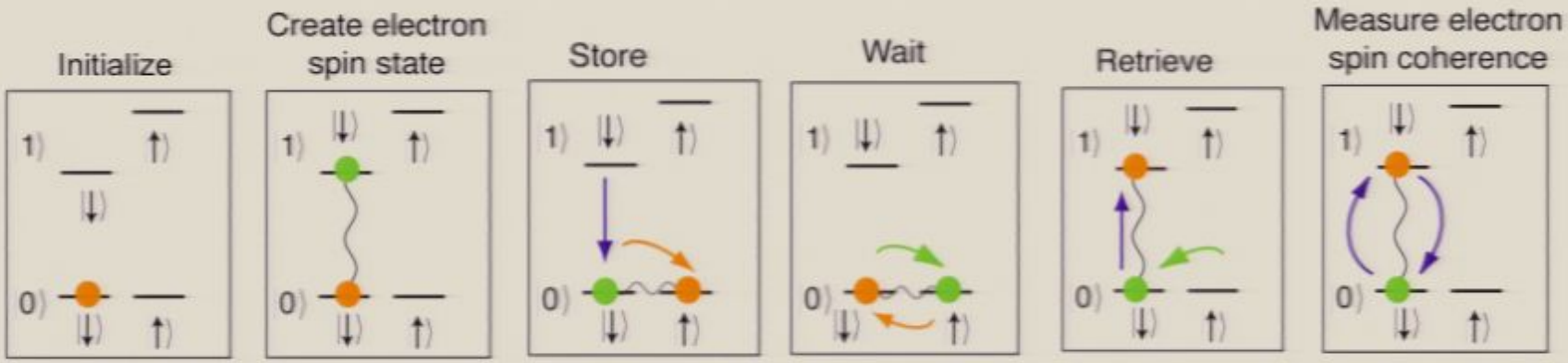
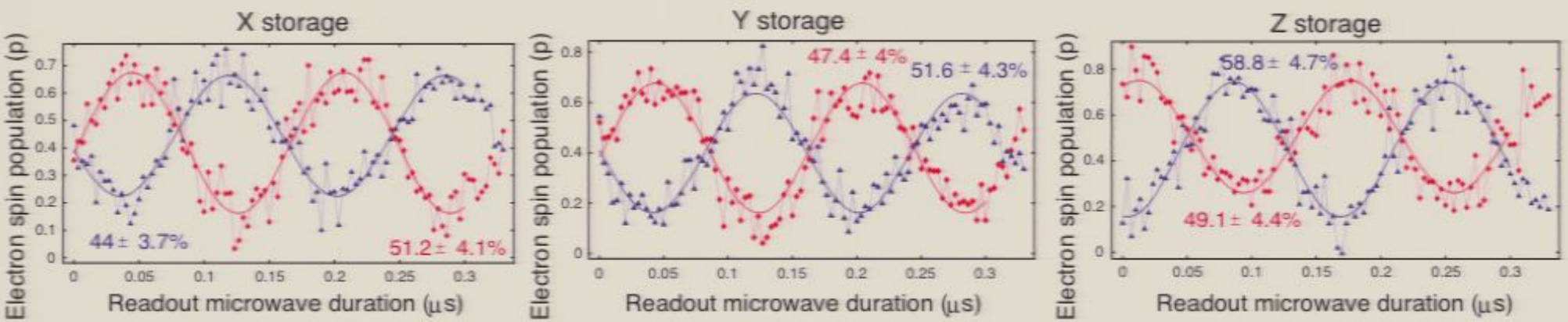
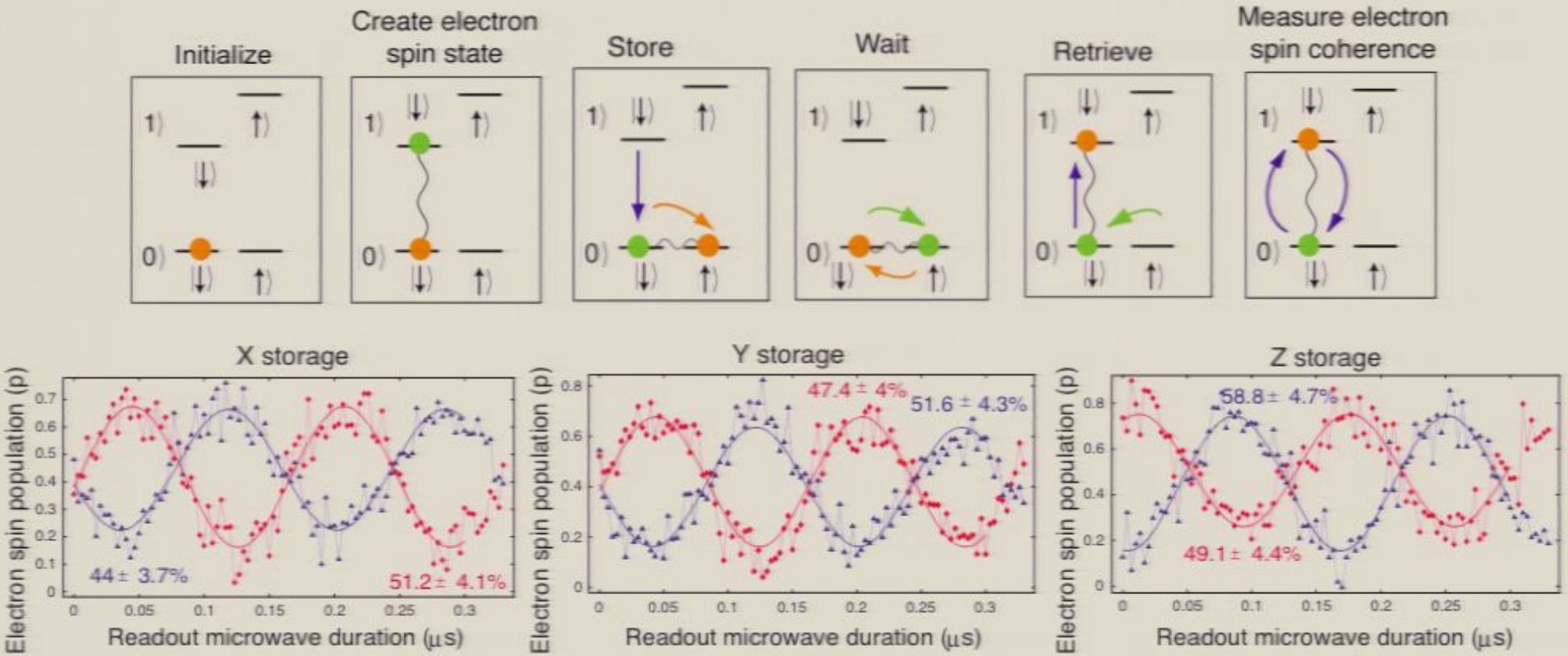




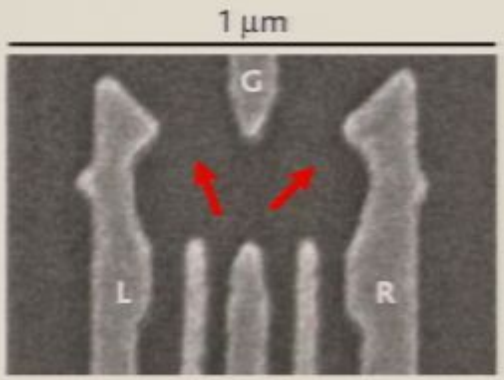
A ^{13}C quantum memory

[Dutt et al., Science (2007)]



- Storage fidelity F~0.75
- NMR echo lifetime >> 2 ms

Other directions? Spins in quantum dots



Local confinement in a semiconductor

- Trap single electrons in controlled potentials
- Electron spin provides a quantum bit

[Loss & DiVincenzo 1998]

$$|\text{“0”}\rangle = |\uparrow\rangle\,, |\text{“1”}\rangle = |\downarrow\rangle$$

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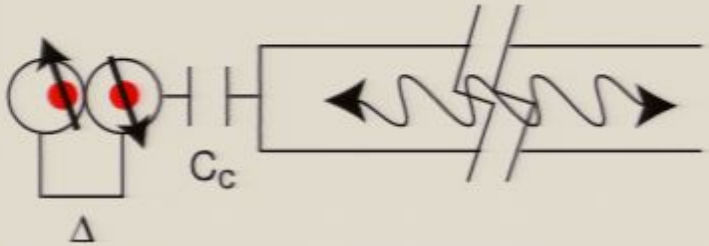
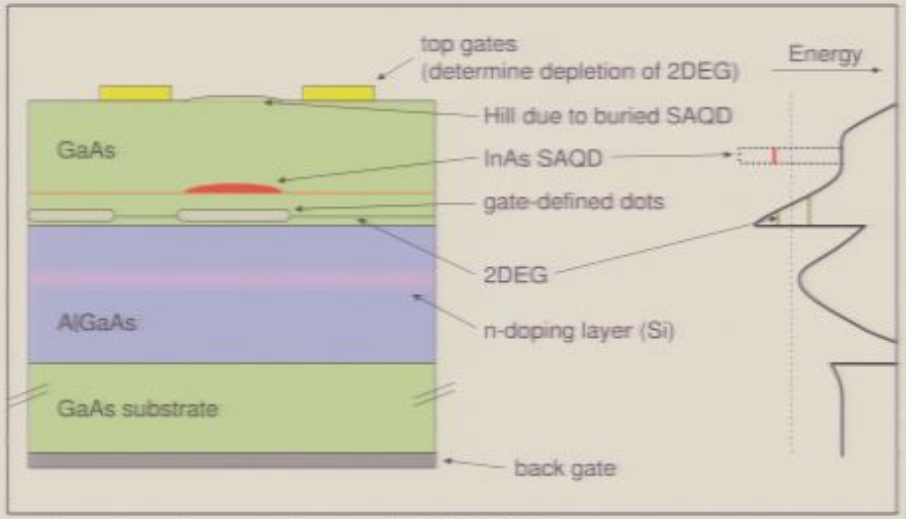
Couple to photons or phonons



[Burkard & Imamoglu, PRB (2006), Taylor & Lukin, cond-mat/0605144]



[Engel et al., cond-mat/0612700]

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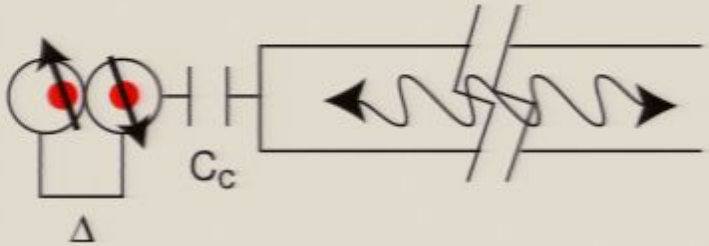

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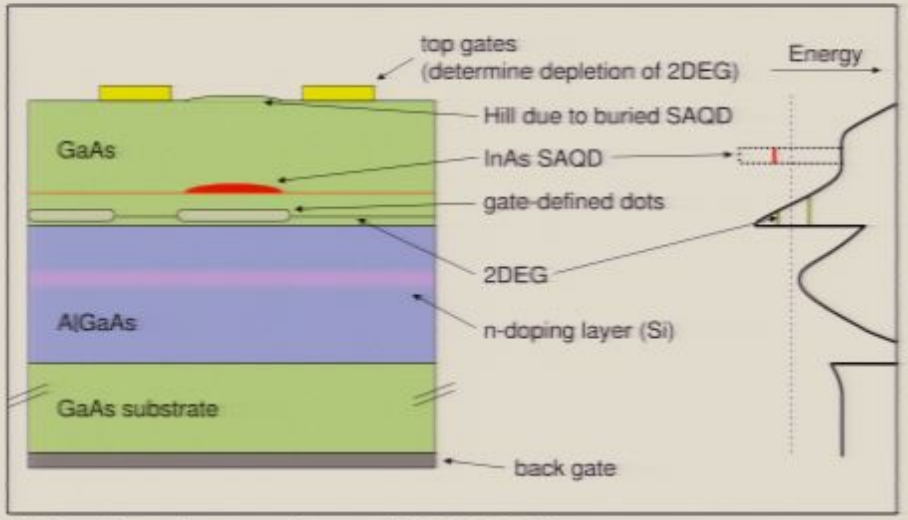

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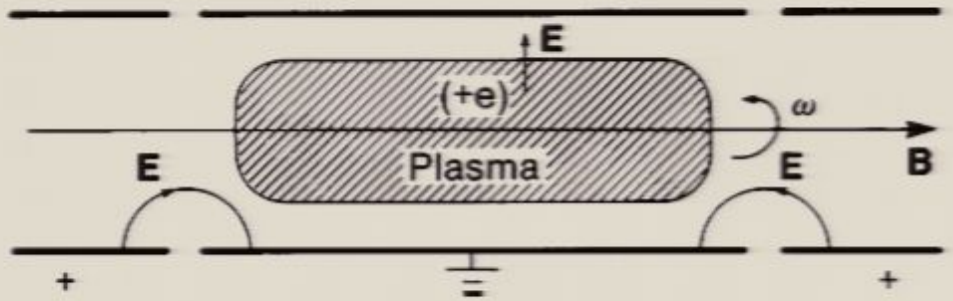
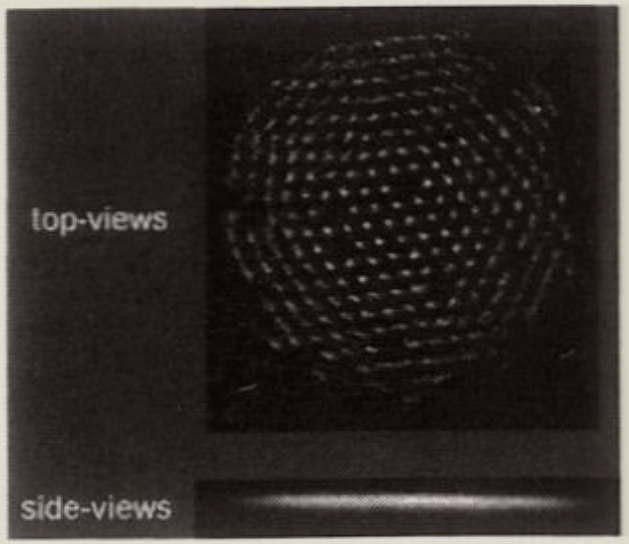
Other directions? Wigner crystals of ions



[Dubin & O'Neil, RMP (1999)]

Progress toward making spin squeezed states with ions in a Penning-Malmberg trap.

N. Shiga, W.M. Itano and J.J. Bollinger
National Institute of Standard and Technology,
325 Broadway, Boulder, CO 80305, USA
e-mail: shiga@boulder.nist.gov



[OCMC 2006]

Advantages:

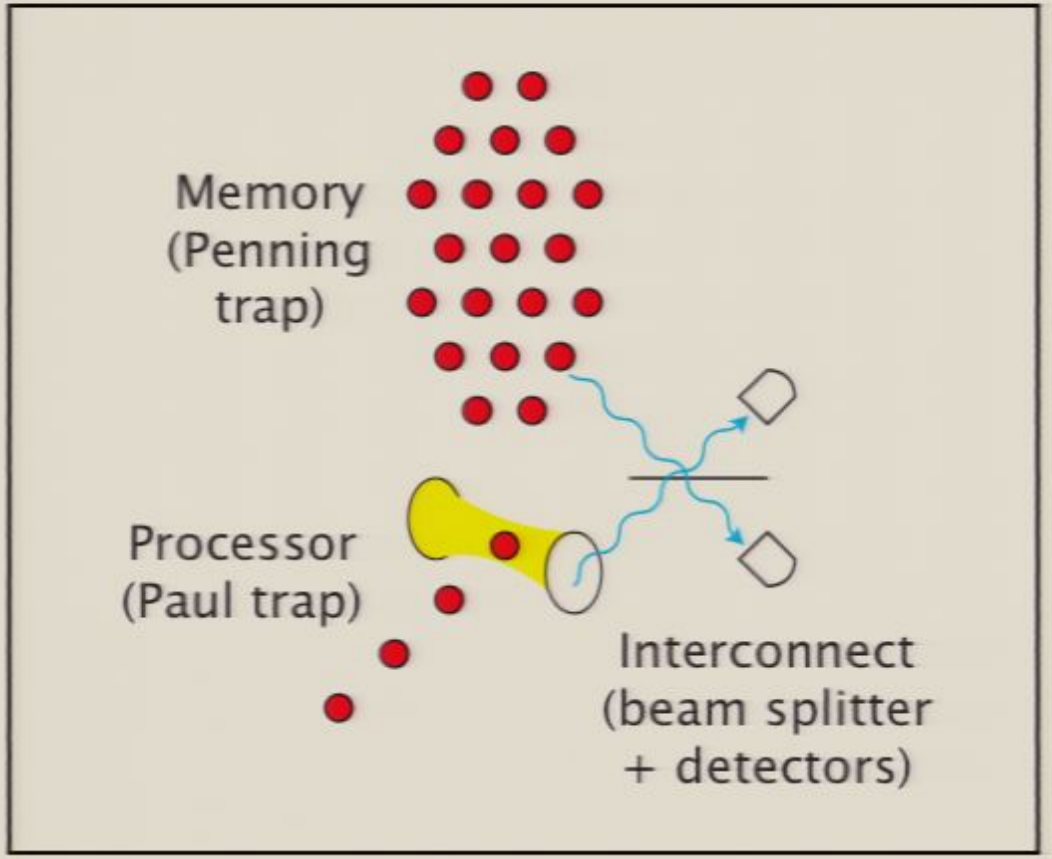
- many ions (good memory)
- self-organized, stable
- optically resolved sites

Problems:

- high temperature
- finite size
- low collection efficiency

[Taylor & Calarco (0706.1951)]

Other directions? Wigner crystals of ions



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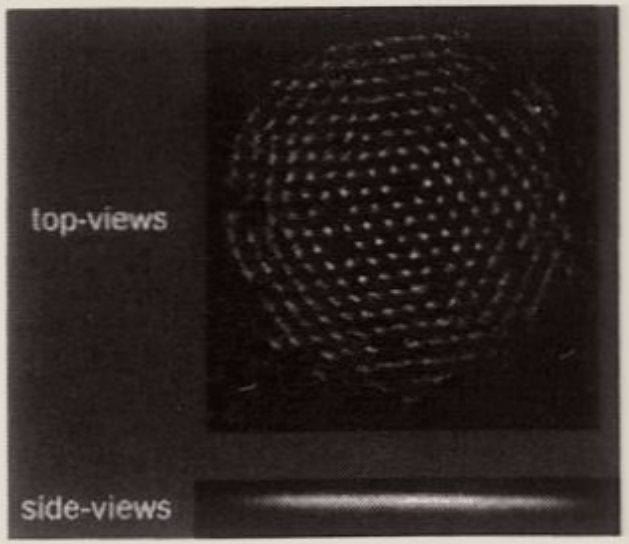

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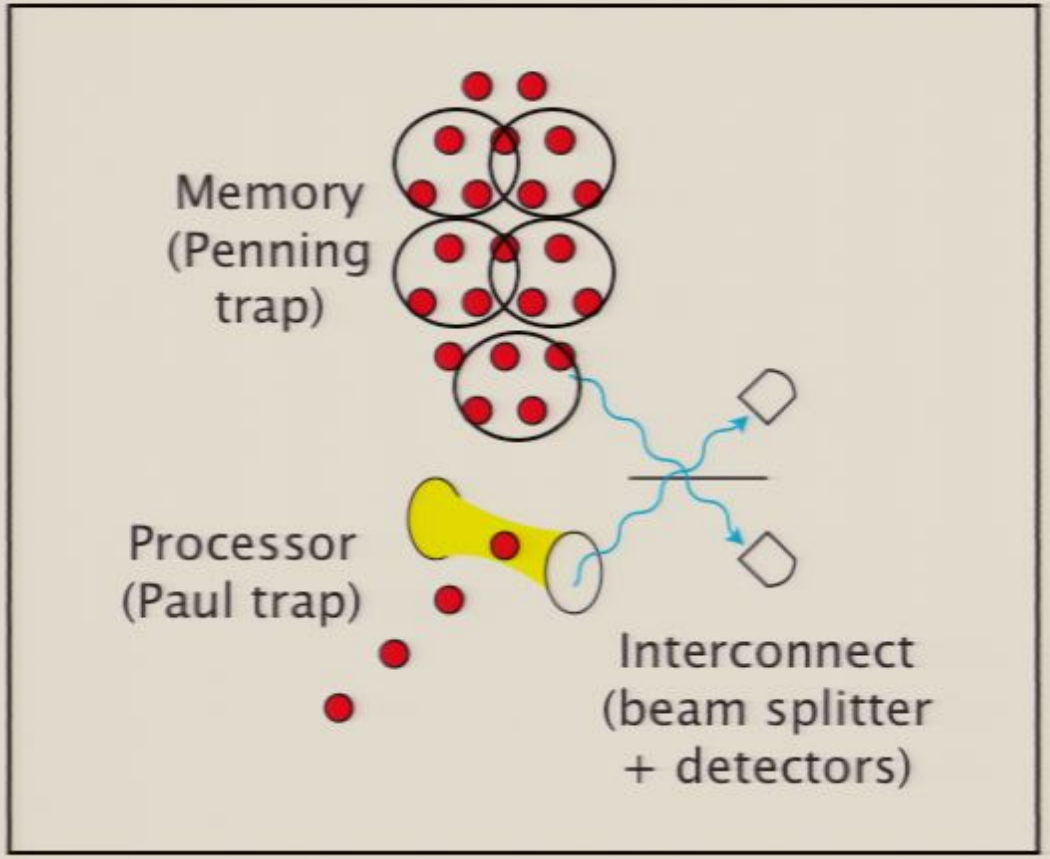

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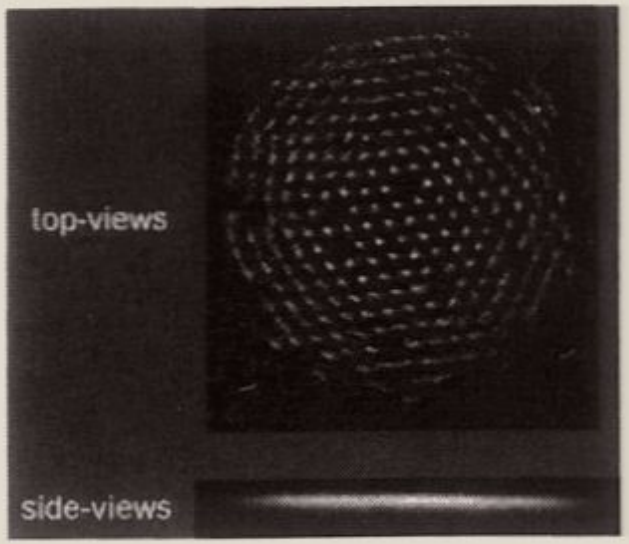

[OCMC 2006]

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[Taylor & Calarco (0706.1951)]

Outlook

- Few qubit register sufficient for computation

Use remote CNOTs,
purification =>
high fidelity,
deterministic CNOT
possible

Application in:
ion-based computation
(linear Paul traps + cavities)
NV centers
Quantum dots
Neutral atoms?
Superconducting qubits??
???

- Progress in implementations

Long memory times, some local operations demonstrated

but, still need atom-atom entanglement generation,
more qubits per node

Collaborators

$$$: Pappalardo, ARO, DARPA-QIST, NSF, ...

Harvard:

T. Calarco

J. R. Petta (->Princeton)
D. Reilly
A. C. Johnson
E. A. Laird
A. Yacoby (<- Weizmann)
C. M. Marcus

H.-A. Engel
L. Jiang

L. I. Childress
M. G. Dutt
A. S. Zibrov
M. D. Lukin

Elsewhere:

W. Dür
P. Zoller (Innsbruck)

A. Imamoglu (ETH Zürich)

C. Flindt
A. Sørensen (NBI Copenhagen)

F. Jelezko
J. Wrachtrup (Stuttgart)

P. R. Hemmer (Texas A&M)

M. P. Hanson
A. C. Gossard (UCSB)