A photonic cluster state

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Imperial College London

arXiv: 0810.2587

Weizmann, March 2009

Proposal for conversion of single photon sources into devices which emit large strings of photonic cluster states in a controlled and pulsed-on-demand manner

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Outline

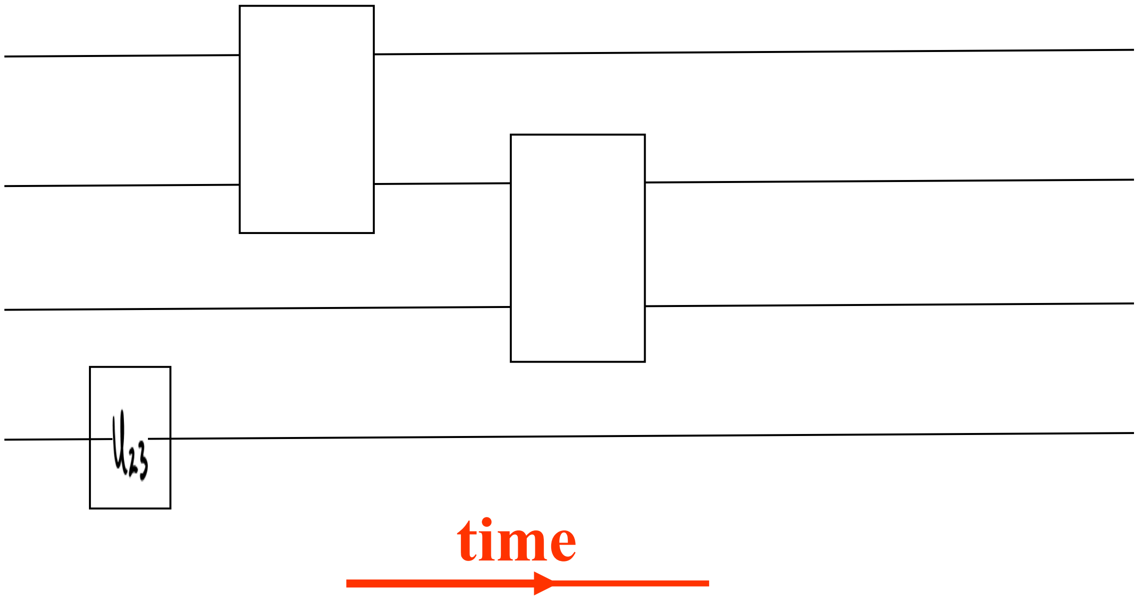
- Cluster states and quantum computation
- Photonic cluster states
- Optical transitions in quantum dots
- The idealized “machine gun”
- Decoherence processes
- Outlook

Quantum Computation

$$U(t)$$

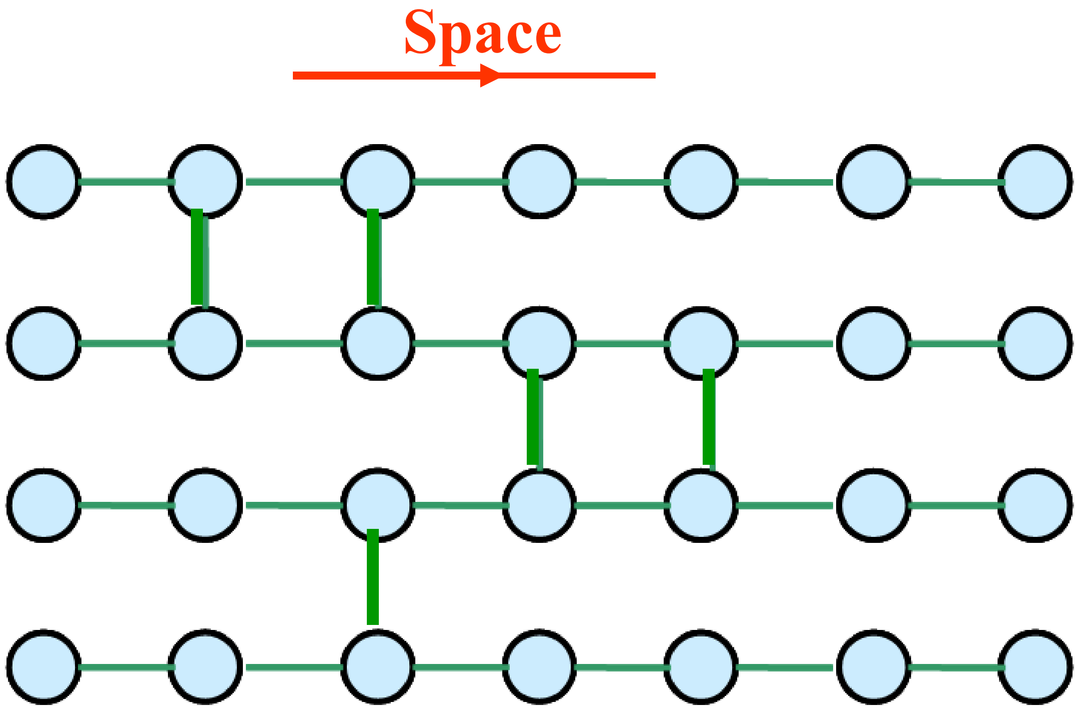
$$|\Psi_0\rangle$$

Measurement



A one way quantum computer

- Start from a many body entangled state
- Evolve by performing single particle measurements



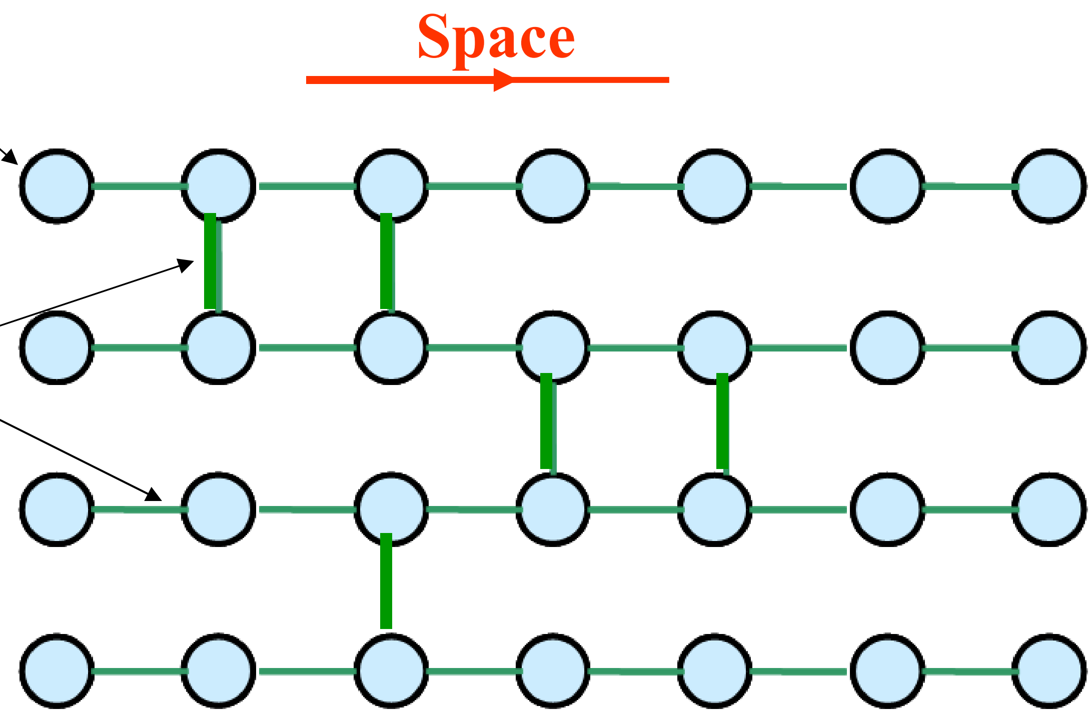
R. Raussendorf & H. Breigel PRL 86, 5188 (2001)

A one way quantum computer

- Start from a many body entangled state
- Evolve by performing single particle measurements

Initialize qubits into |0>+|1>

Apply Controlled-Z (CPHASE) unitary



R. Raussendorf & H. Breigel PRL 86, 5188 (2001)

So how do we build a photonic cluster state?

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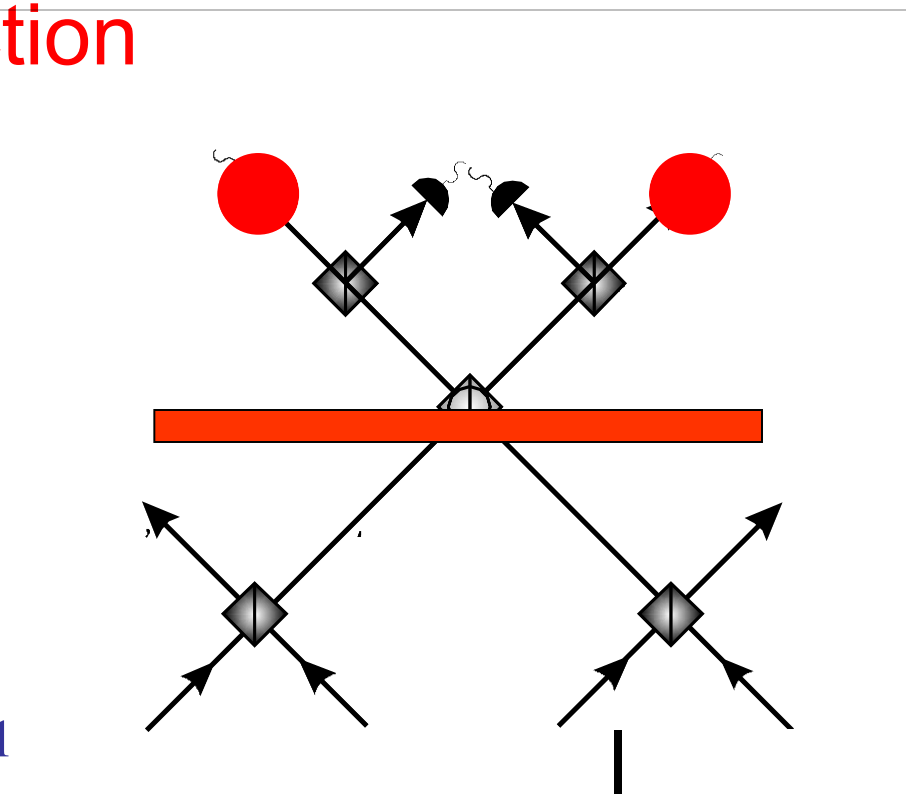
So how do we build a photonic cluster state?

No easy way to get photons to interact

Starting from single photons

- Use interference and measurement to make effective interaction
  (lesson from KLM)



4 single photons

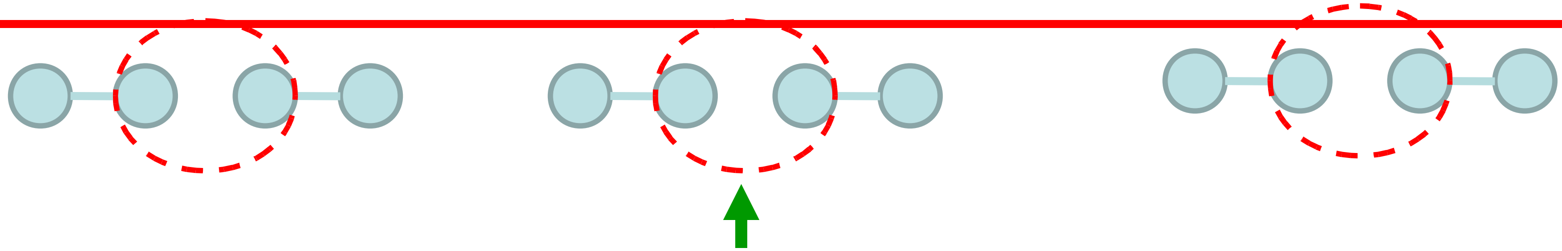
One Bell pair

Probability = 1/4

D. E. Browne and T. Rudolph PRL **95**, 010501 (2005).
Q. Zhang et. al., PRA 77, 062316 (2008)

LOQC Starting from Bell pairs

LOQC Starting from Bell pairs

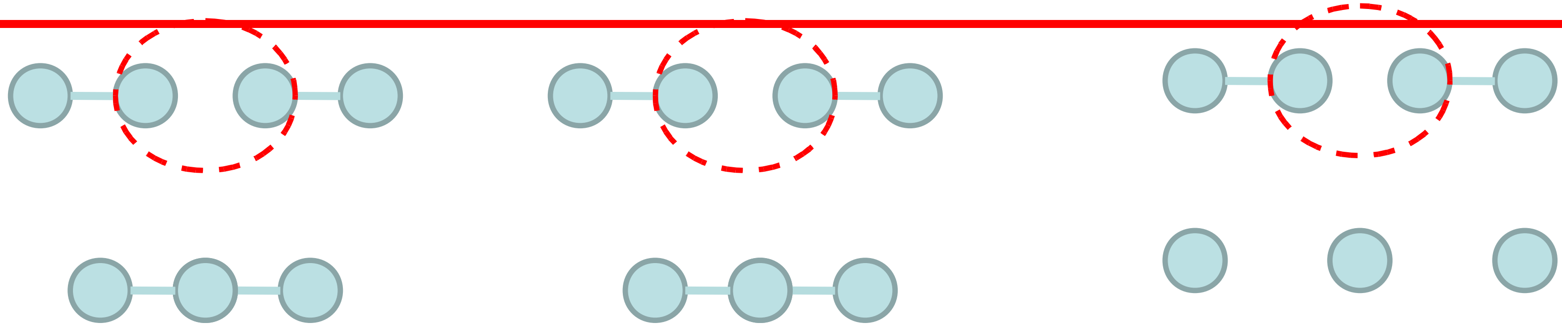


Interference and measurement of **one** photon

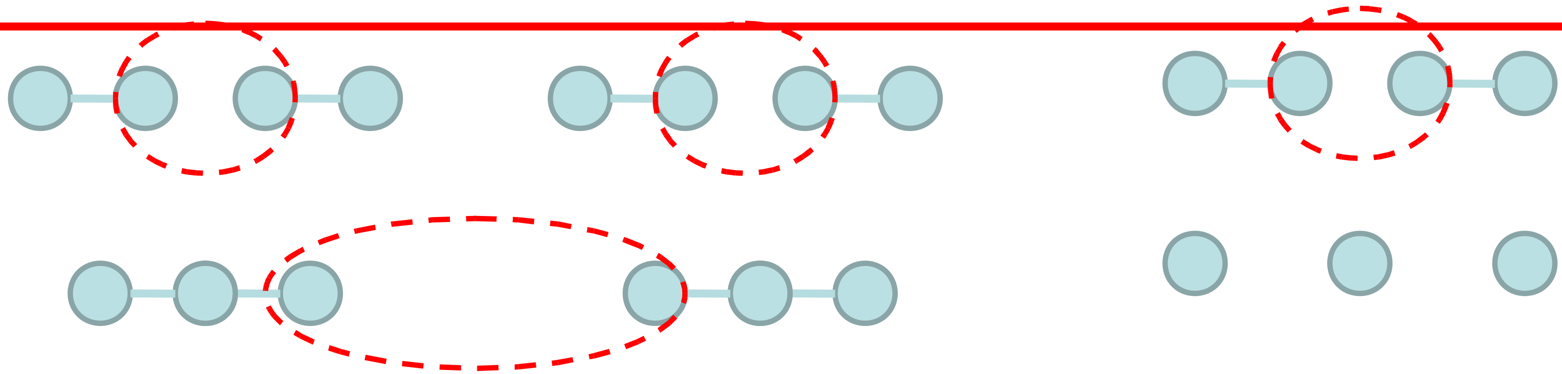
Probability = 1/2

D. E. Browne and
T. Rudolph PRL 95,
010501 (2005).

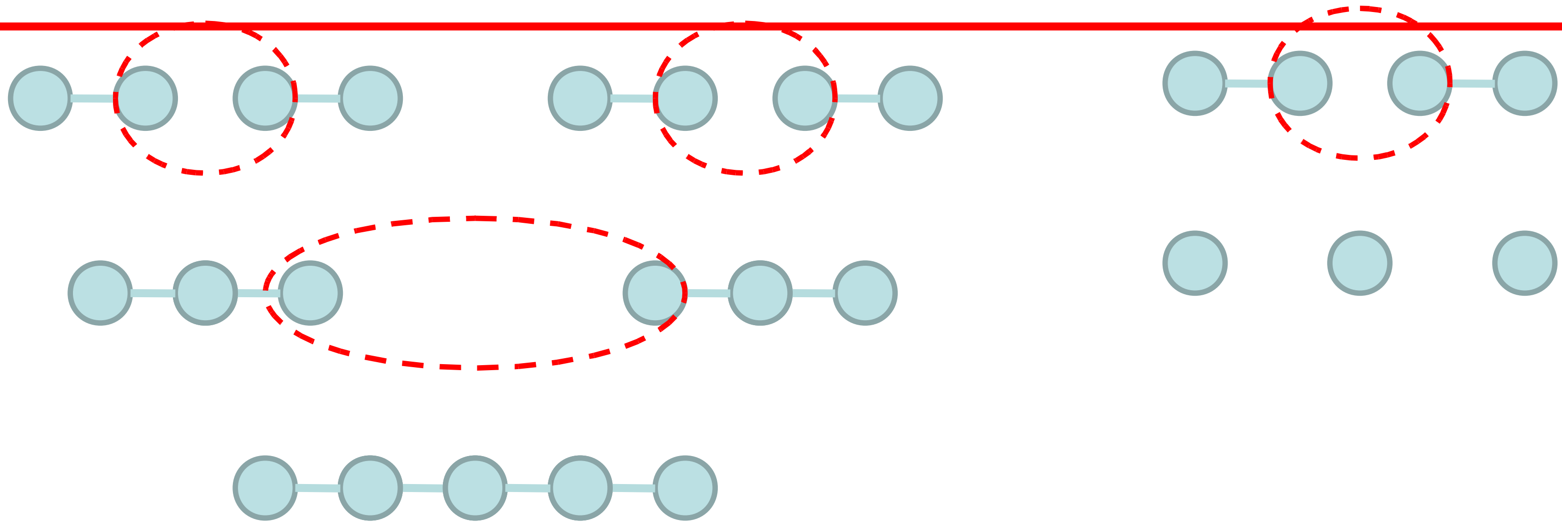
LOQC Starting from Bell pairs



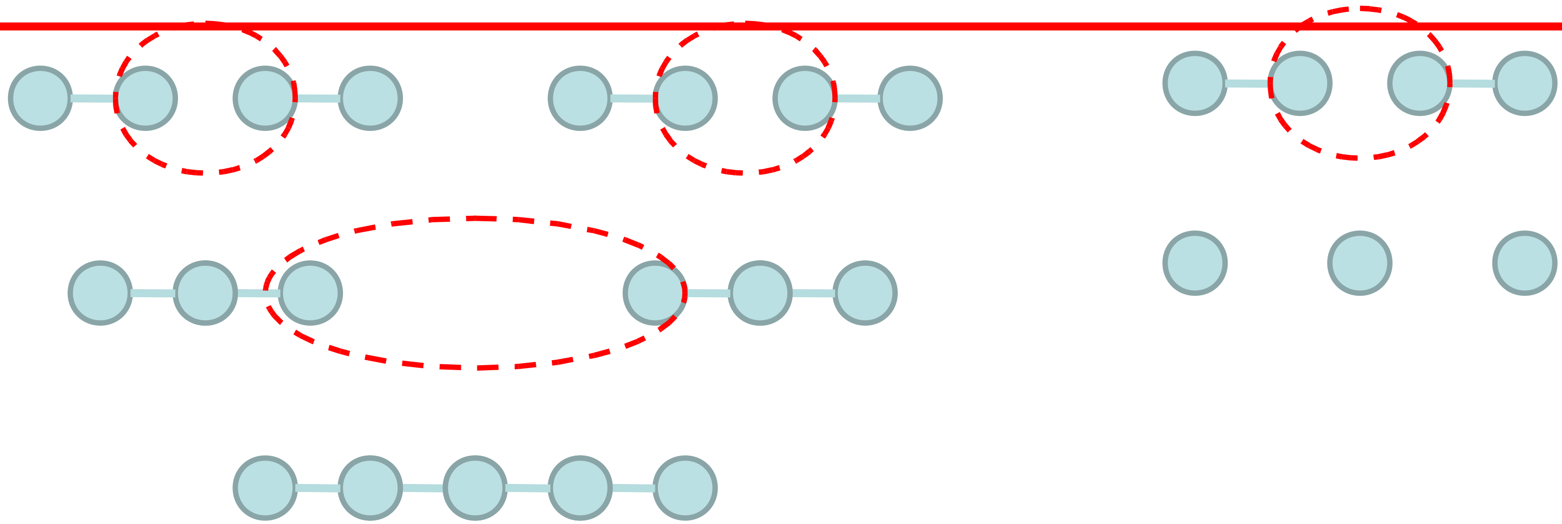
LOQC Starting from Bell pairs



LOQC Starting from Bell pairs



LOQC Starting from Bell pairs



Efficient but still resource intensive, requiring lots of quantum memory etc

LOQC Starting from Bell pairs

· Bell pairs produced directly from quantum dots via biexciton cascade?

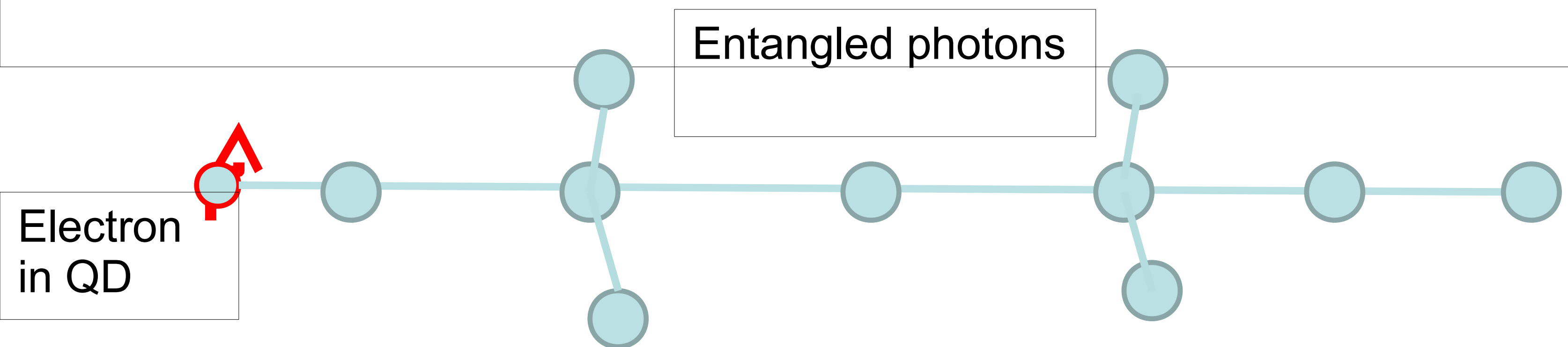
· Problems:
(i) Exciton dephasing
(ii) Removes only the inefficiency of the first step

LOQC Starting from Bell pairs

· Bell pairs produced directly from quantum dots via biexciton cascade?

· Problems:
(i) Exciton dephasing
(ii) Removes only the inefficiency of the first step

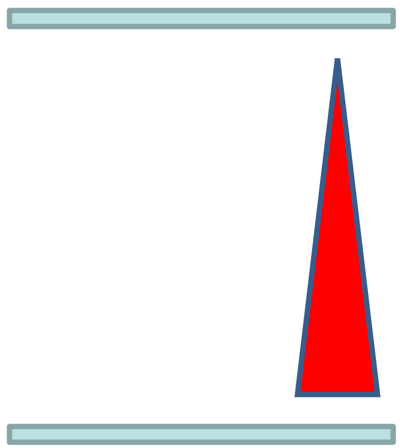
· Solution: Design a source which uses only single exciton recombination, but which can fire out optical cluster state:



Optical transitions in a quantum dot

$$J_z = +3/2$$

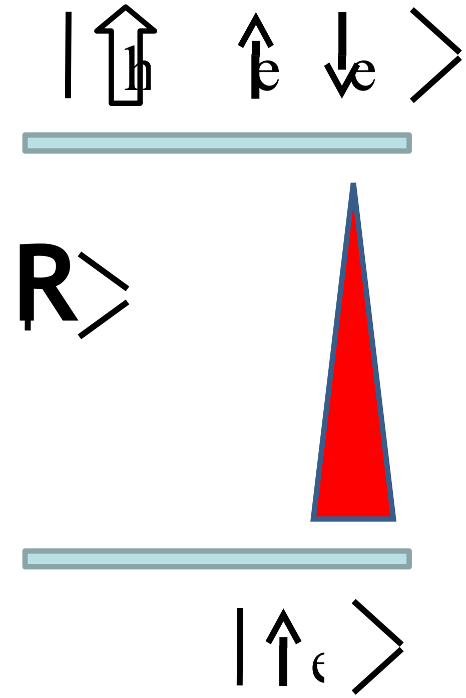
$$|\Uparrow_h \uparrow_e \downarrow_e\rangle$$



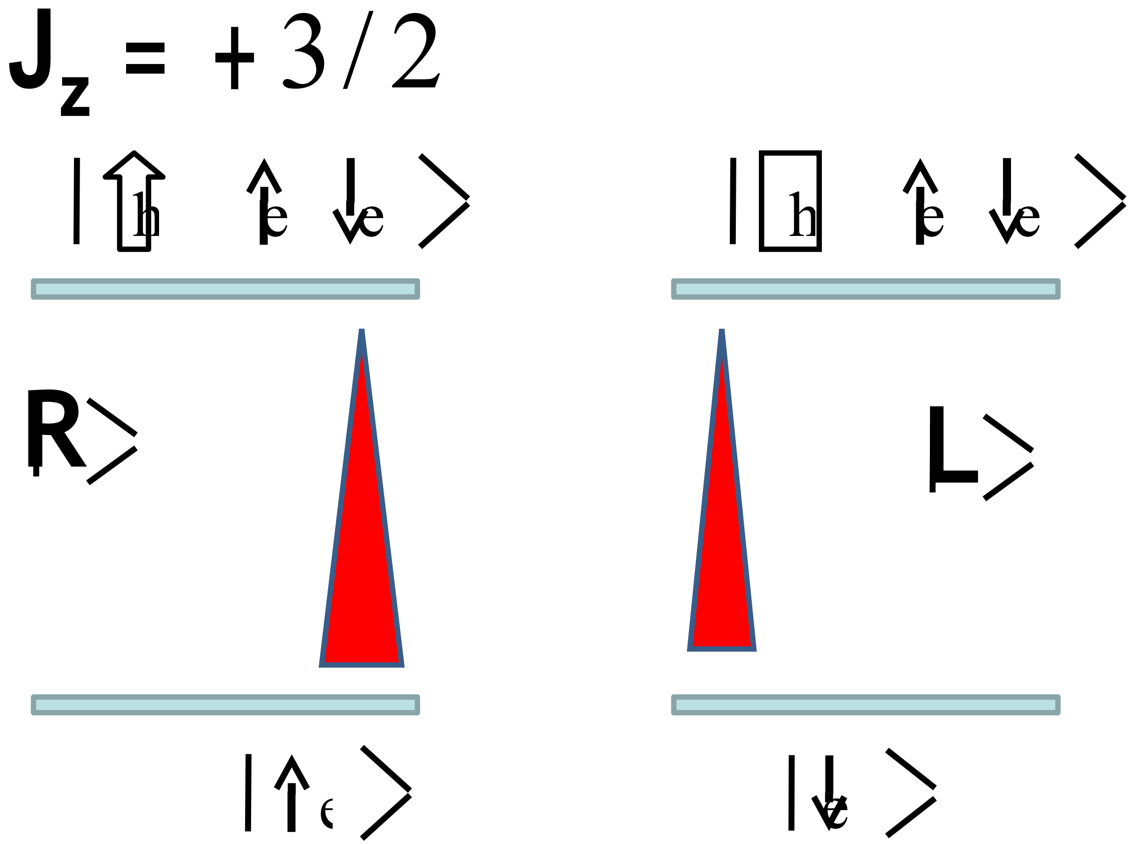
$$|\uparrow_e\rangle$$

Optical transitions in a quantum dot

$J_z = +3/2$

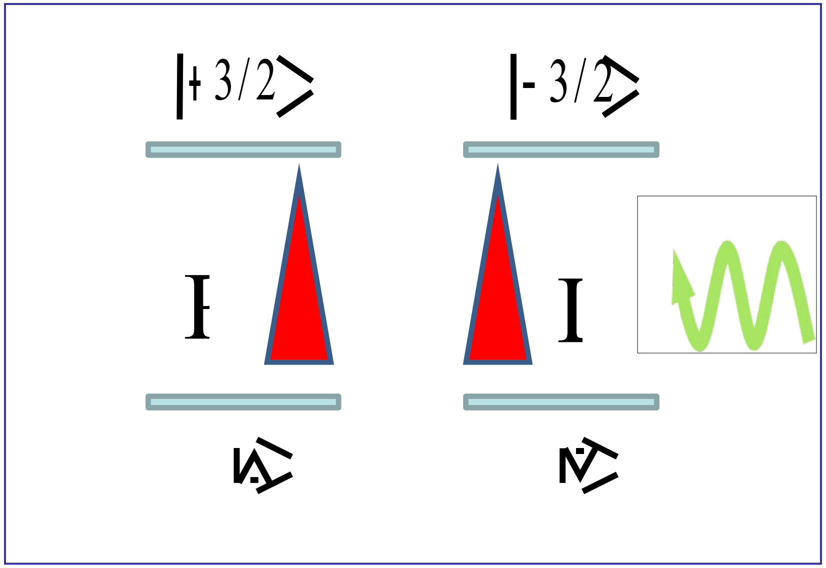


Optical transitions in a quantum dot

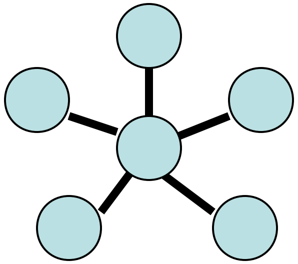


GHZ state machine gun

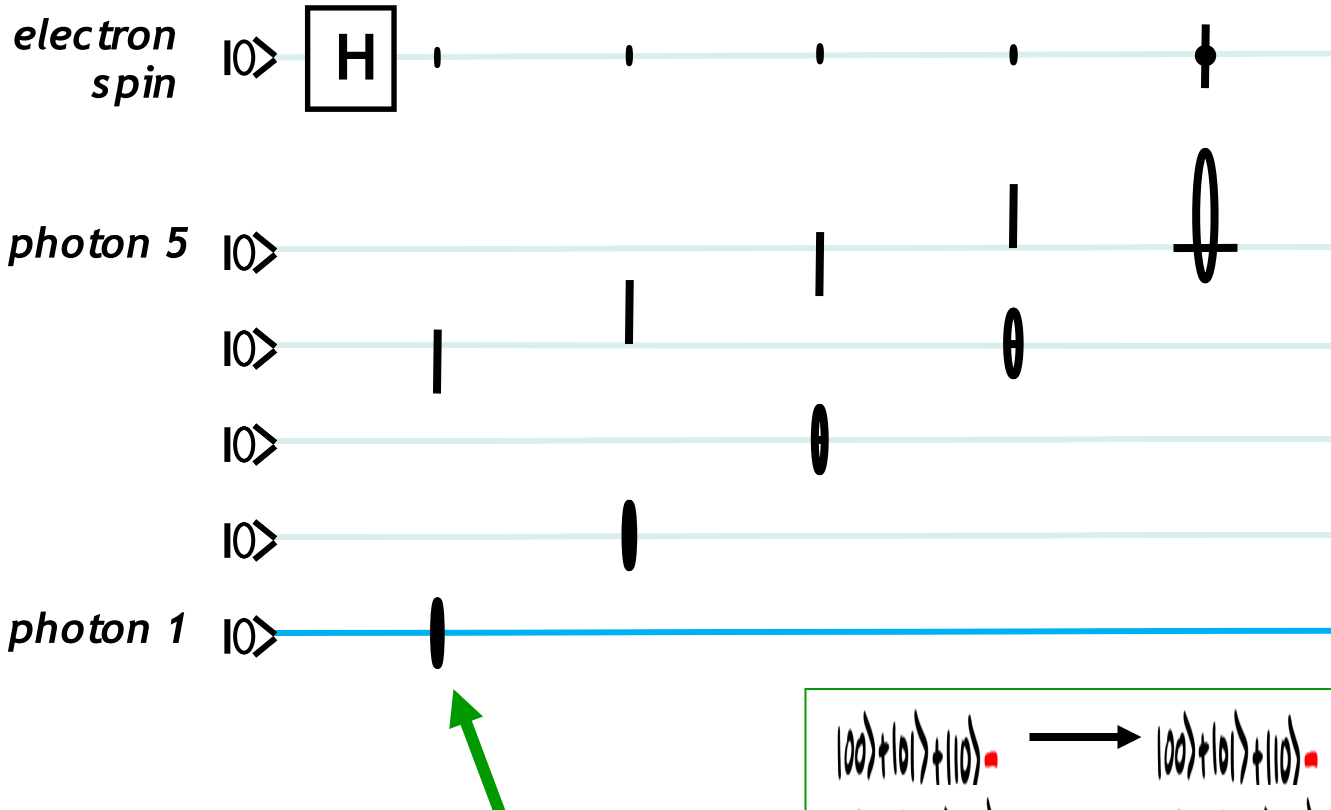
$$|\uparrow\rangle + |\downarrow\rangle \xrightarrow{\text{excitation}} |\Uparrow\rangle + |\Downarrow\rangle$$

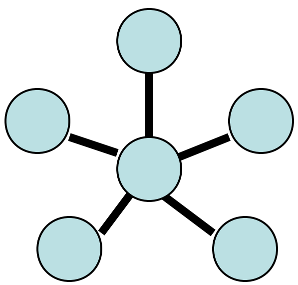


“Schrodinger’s cat” state:

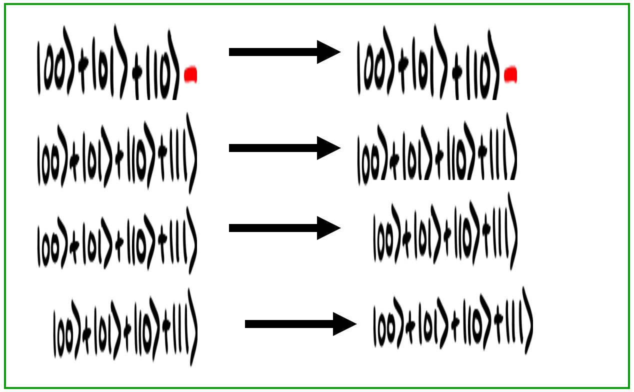


GHZ state machine gun



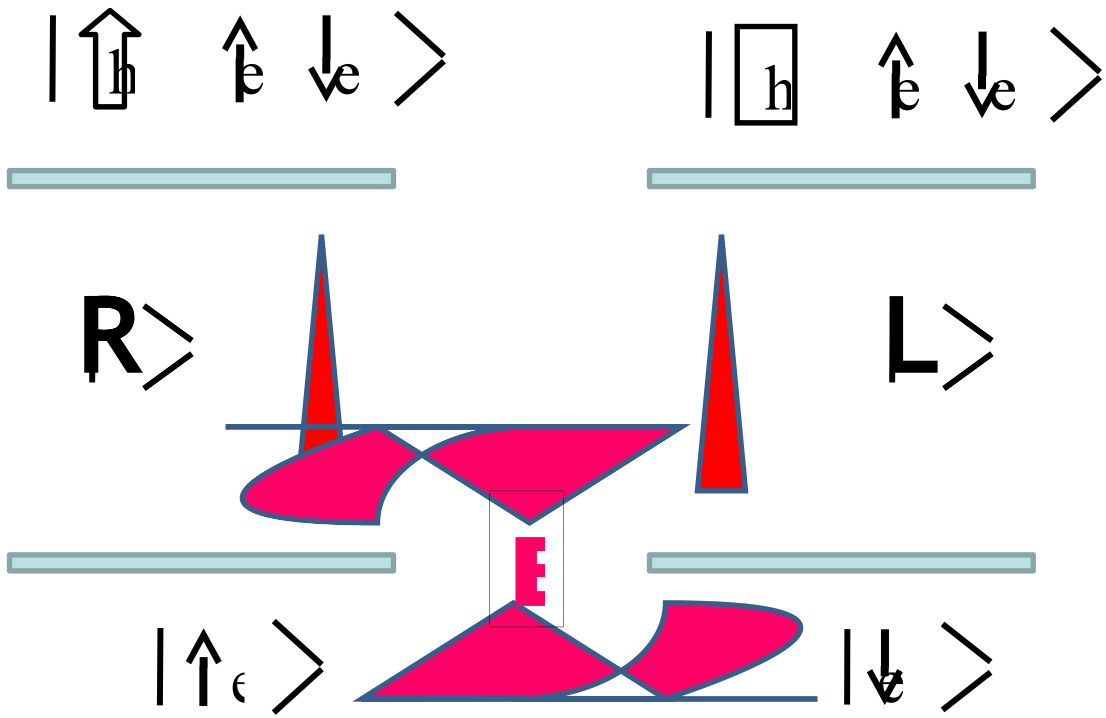


cNOT=



C. Schoen *et. al*., PRA 75, 032311 (2007);

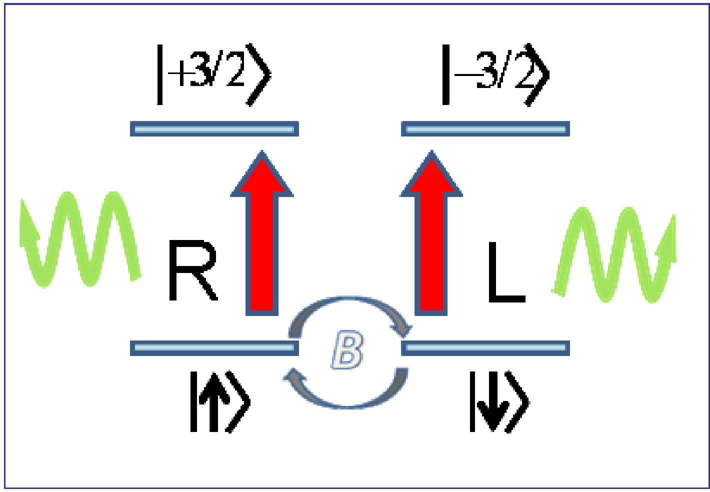
A cluster state machine gun



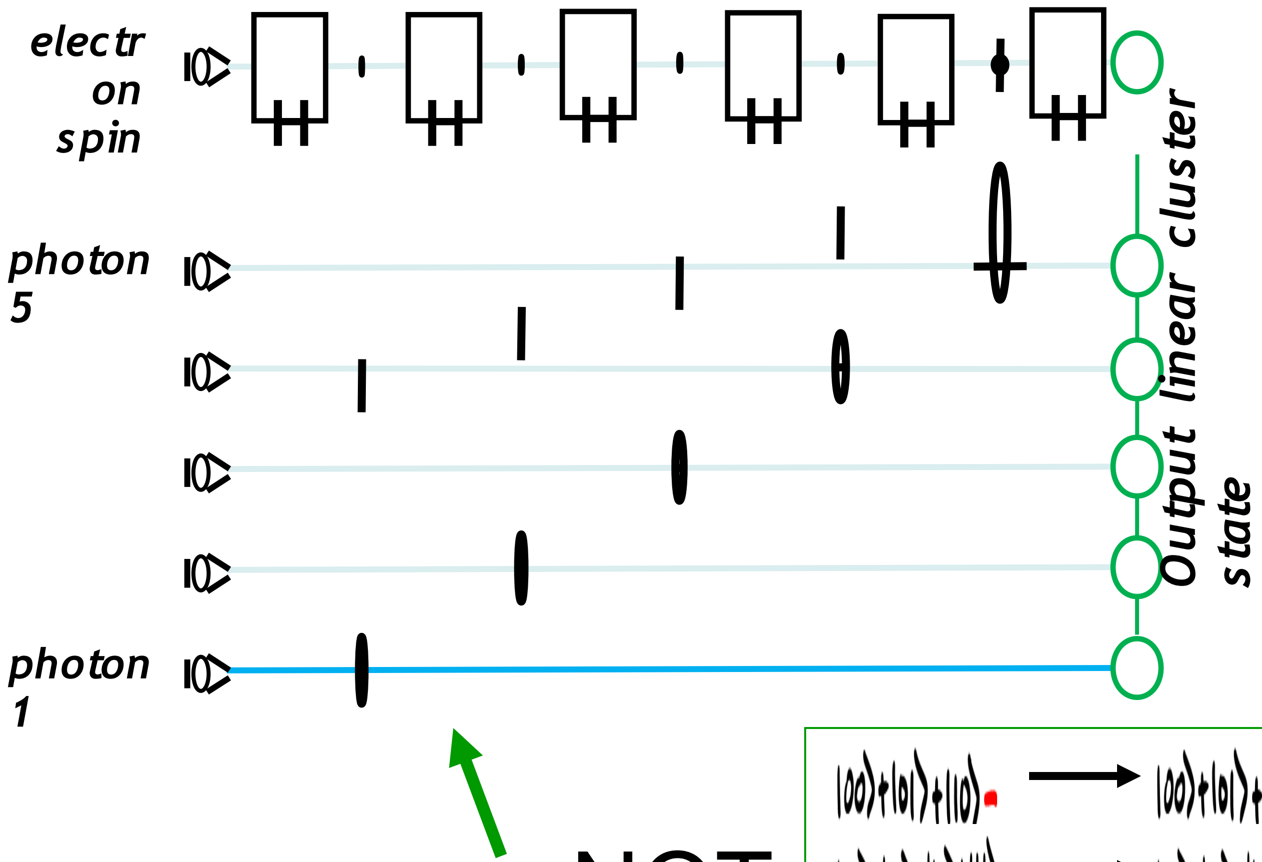
Add in-plane (xy) **static** Magnetic field

Ideal machine gun

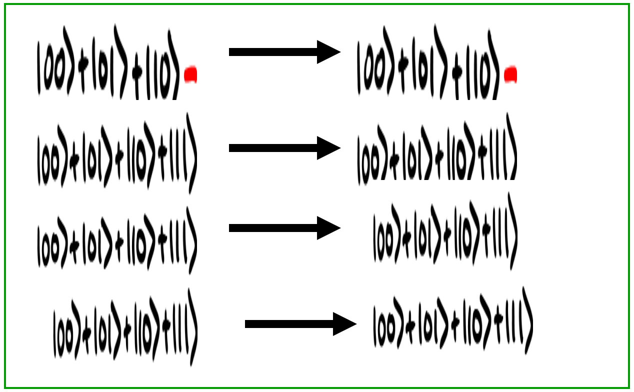
precess.



Ideal machine gun



cNOT=



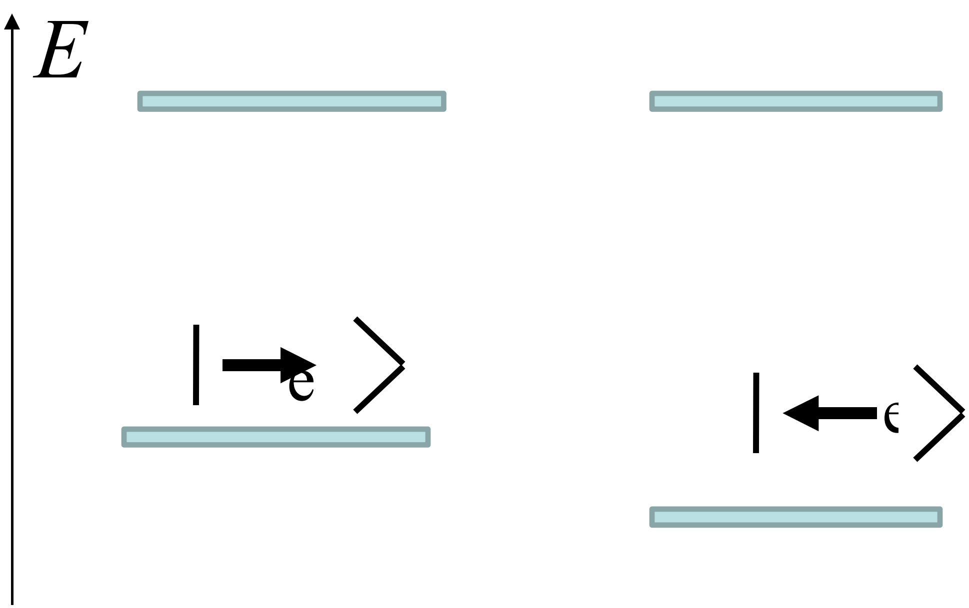
C. Schoen *et. al*., PRA 75, 032311 (2007);

Decoherence (1)

· Finite lifetime of the excited state

Zeeman splitting

spectral “which path” information

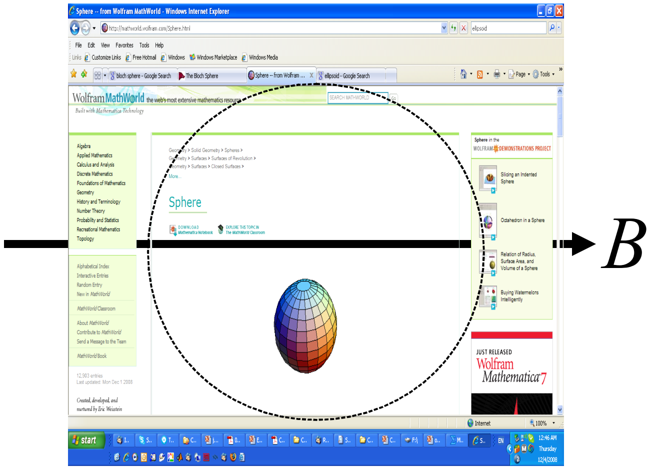


$$\Gamma_{\mathrm{decay}} > g\mu B$$

$$\tau_{\mathrm{decay}} < \hbar / g\mu B$$

Decoherence (2)

- Interaction of spin with its environment:
  - Dephasing ($T2$ time) (nuclear spins)
  - Spin relaxation ($T1$ time) (phonons)



$T1 >> T2 >> \tau_{decay}$

0.1sec 1μ sec 100psec

M. Kroutvar et. al., Nature 432, 81 (2004)

A. Greilich et al, Science 313, 341 (2006)

Limitation on the full process?

- **Does the state degrade with number of photons (time)?**
- **Is the process limited by the** ***T2/1 time?***

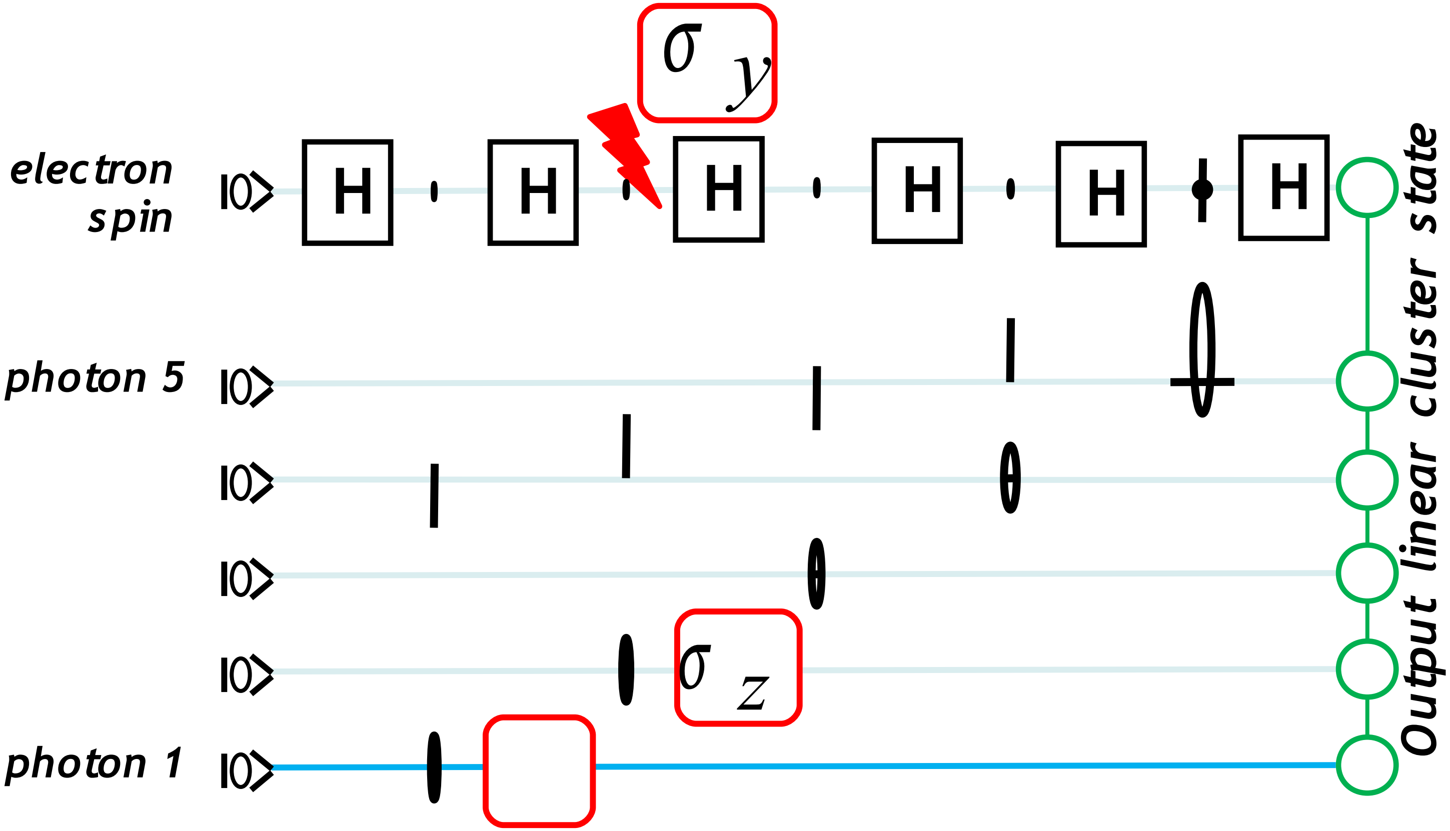
NO

- Errors **localize**: constant, independent probability of error on each photon.

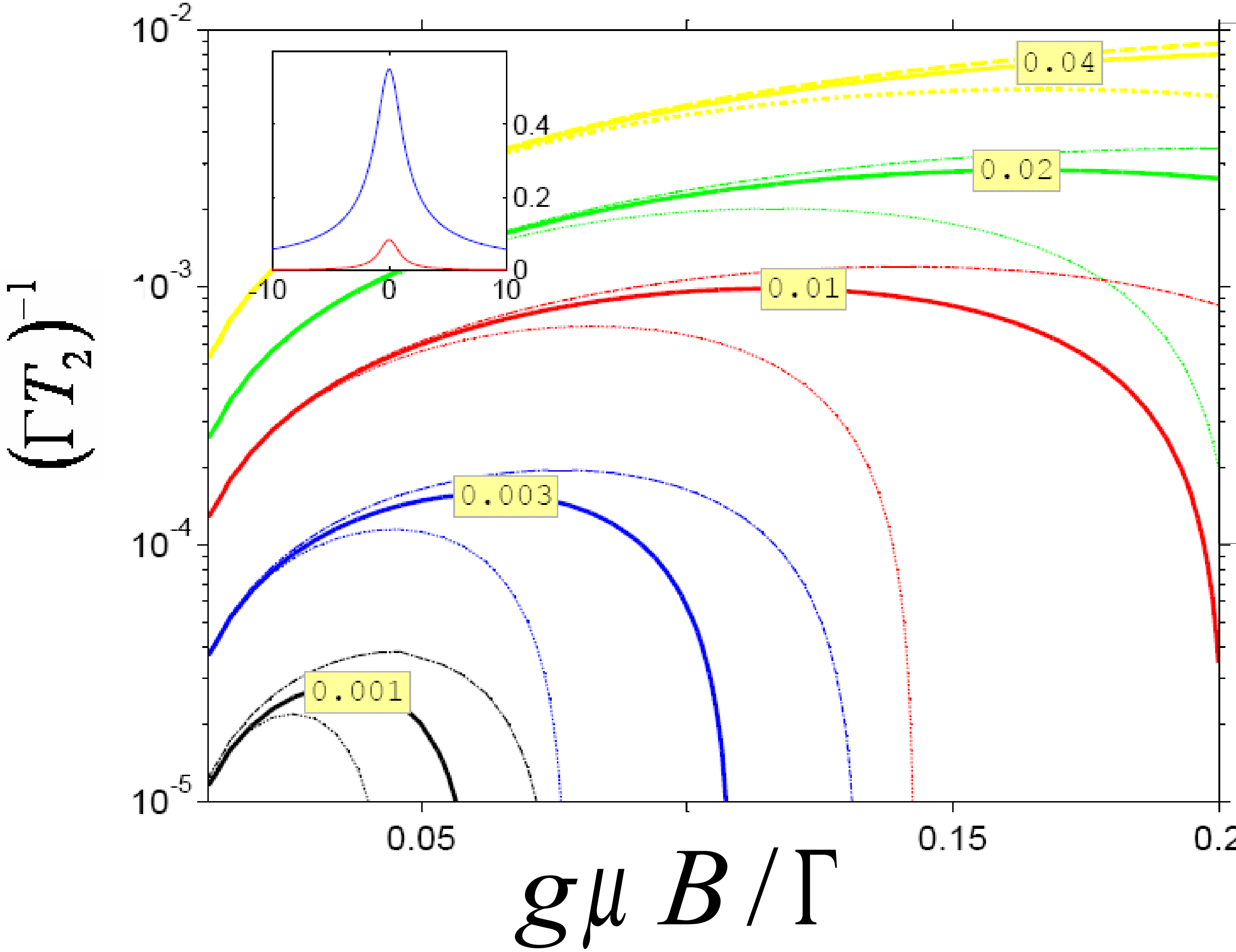
Process can continue irrespective of *T2/1*

Localization of errors (2)

dephasing: $\rho_{n+1} = (1-p)\tilde{\rho}_{n+1} + p\sigma_Y^{\text{spin}}\tilde{\rho}_{n+1}\sigma_Y^{\text{spin}}$



Error optimization



τ1 ~ 0.1sec

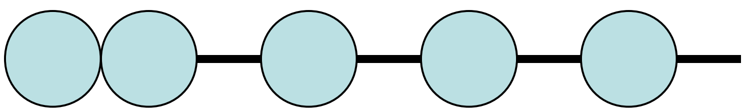
τ2 ~ 1μ sec

τ_{decay} ~100psec

B ~ 20mT

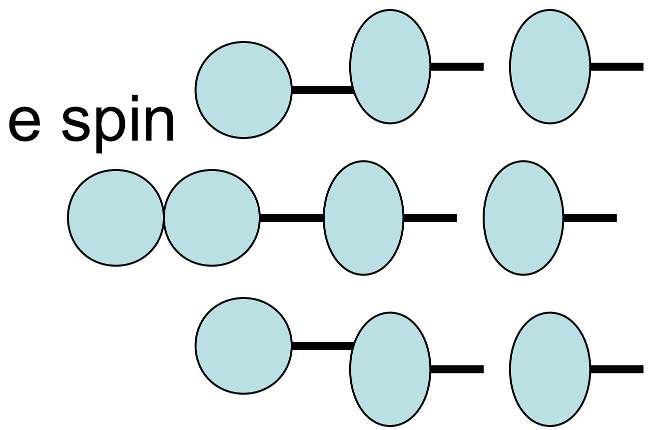
Constructing 2D cluster states

e spin



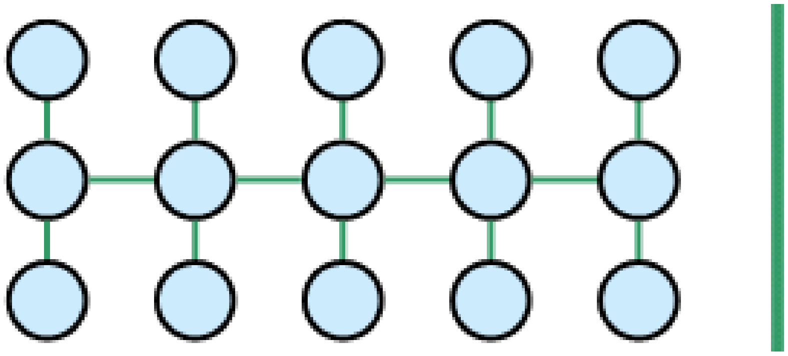
$\pi\ /2,$ $\pi\ /2,$

Constructing 2D cluster states



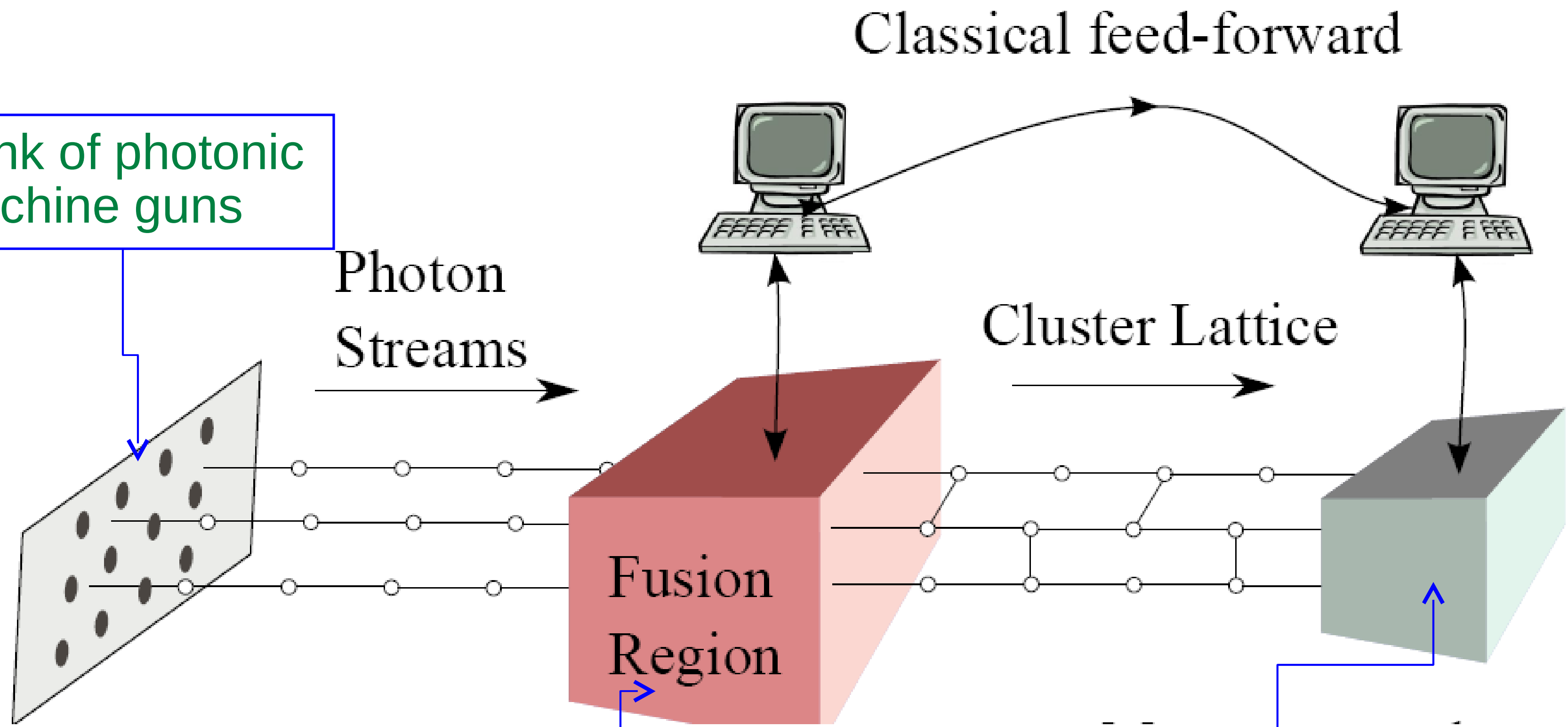
$\pi/2,$ $\pi/2, \pi, \pi, \pi/2, \pi, \pi,$

Constructing 2D cluster states



Eventual architecture?

Bank of photonic machine guns



LOQC style fusion gates create desired 3d cluster state lattice

Banks of detectors perform the braided measurements yielding the topologically protected computation

Summary and outlook

- Single quantum dots can emit large strings of 1D cluster states $\longrightarrow$ 2D clusters.
- Errors localize
- Process can proceed for times >> T2, T1

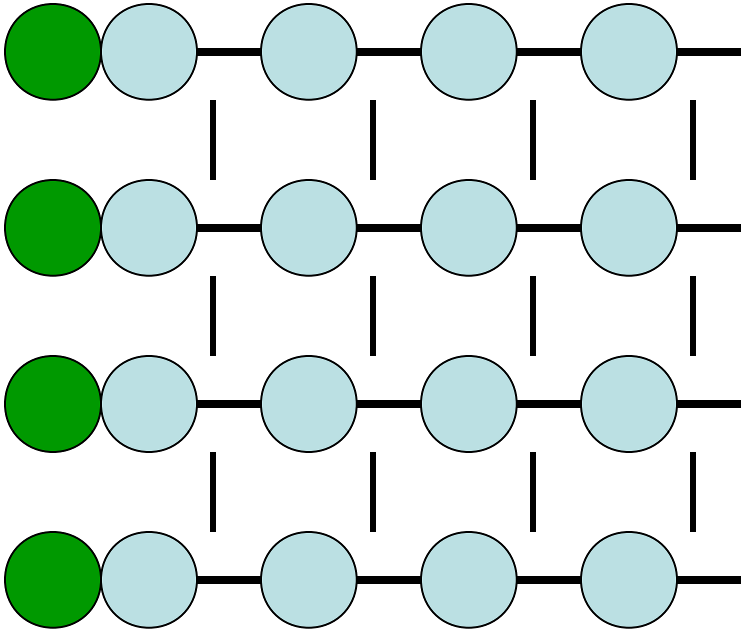
arXiv: 0810.2587

Summary and outlook

- Single quantum dots can emit large strings of 1D cluster states ⟶ 2D clusters.
- Errors localize
- Process can proceed for times >> T2, T1
- Outlook:
  - Coupling a number of quantum dots
  - Other single photon sources
  - Better bounds for non markovian environments.

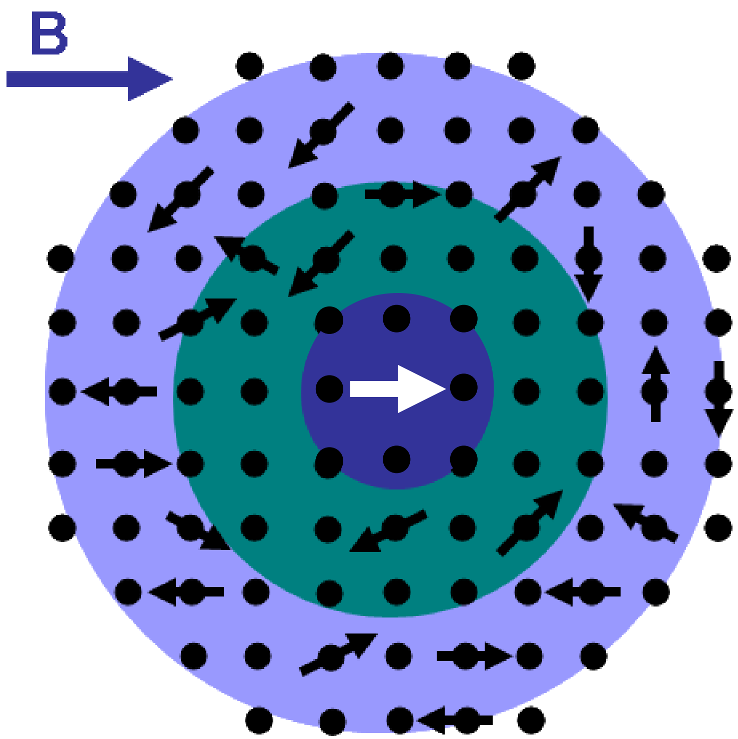
arXiv: 0810.2587

Parralel machine gun

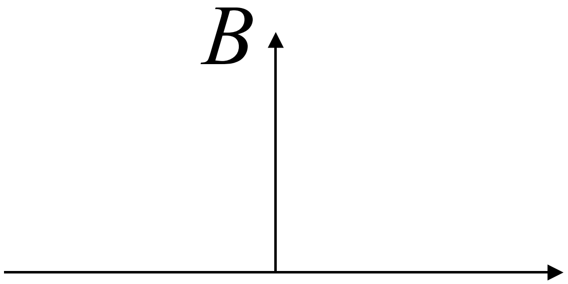


Spin-bath Hamiltonian

$$H = H_e + H_{eN} + H_N + H_{NN}$$



$H_e = \boldsymbol{B} \cdot \boldsymbol{S_e}$ Zeeman



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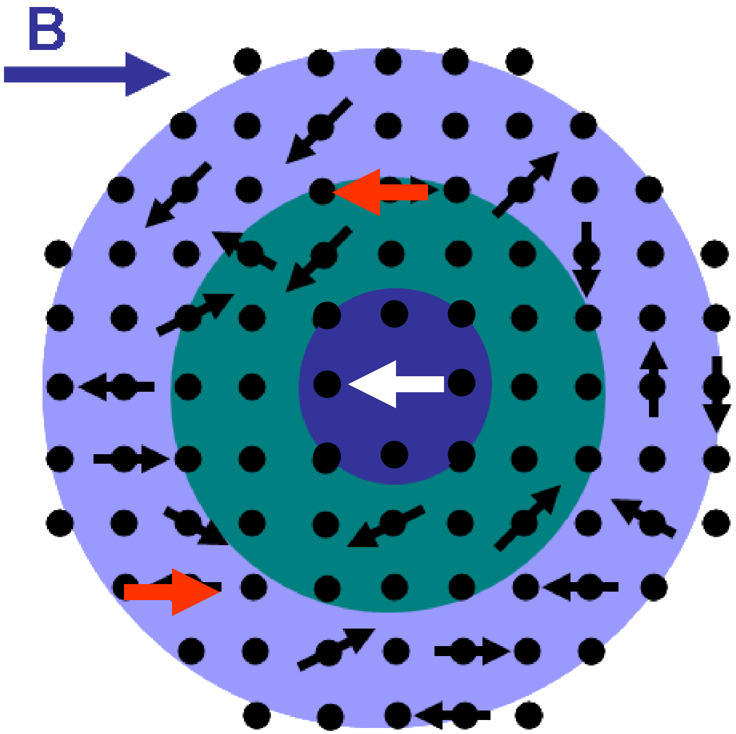
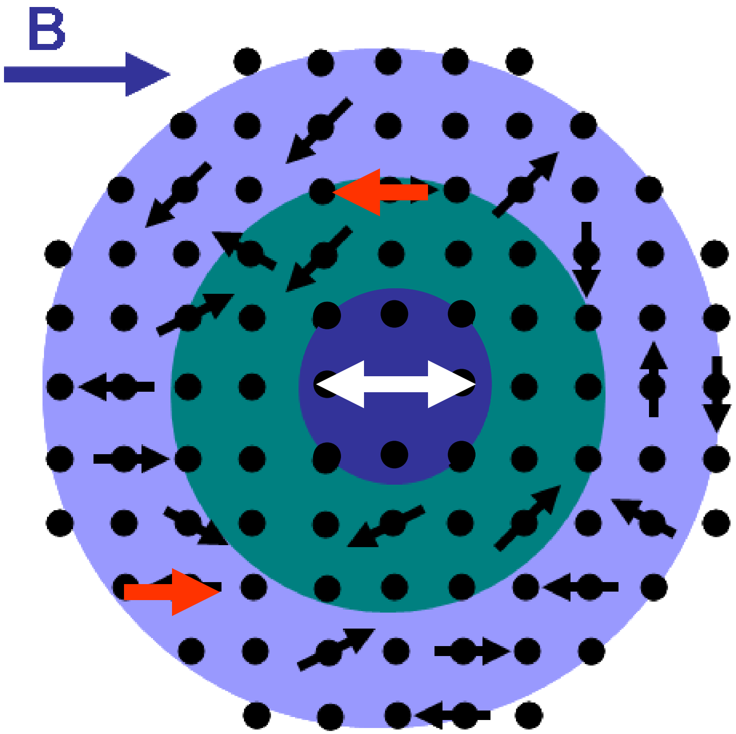


Energy scales

H_{eN}	$\alpha_n : 10^6 \sec^{-1}$
H_{NN}	$\beta_n : 10^2 \sec^{-1}$
H_e	$\mu_B : 10^{11} \sec^{-1} T^{-1}$

Spin-bath Hamiltonian

$$H = H_e + H_N + H_{eN} + H_{NN}$$



Effective Interaction Hamiltonian

Spin wave-packet entanglement

$$|\uparrow\rangle \longrightarrow \sum_t A_t |\Omega(t)\rangle |t\rangle$$

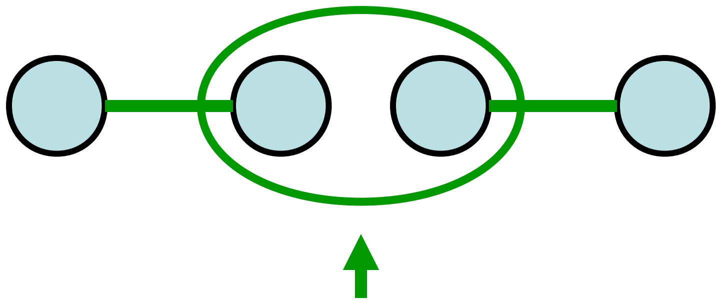
$$\rho(t_n + \tau) = U(\tau)\left(G^\dagger \rho(t_n) G + F^\dagger \rho(t_n) F \right) U^\dagger(\tau)$$

G= good mode function | F= bad mode function

$$g(k) = \frac{k - Z}{(k - Z)^2 - B^2}$$

Fuse larger clusters

- Two Bell pairs ▶ 3 photon C-state



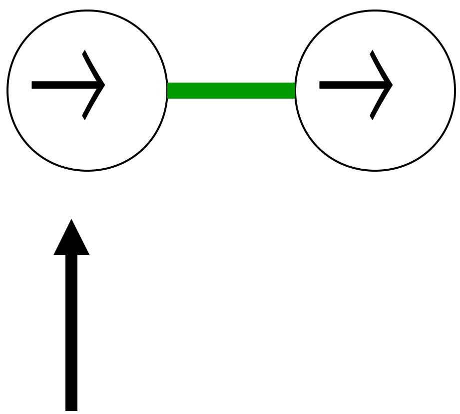
D. E. Browne and T. Rudolph PRL 95, 010501 (2005).

Interference and measurement of **<u>one</u>** photon

Probability = 1/2

- 3 photon C-state + Bell pair . . .

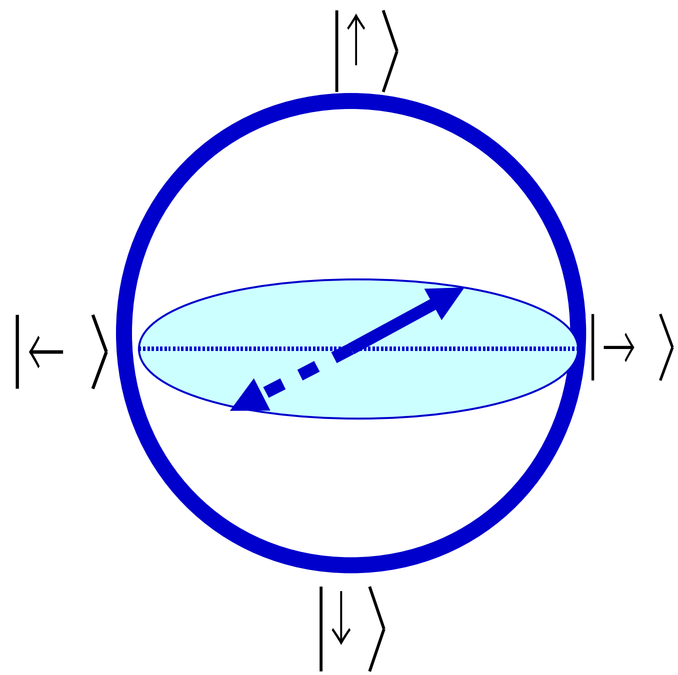
Two spins



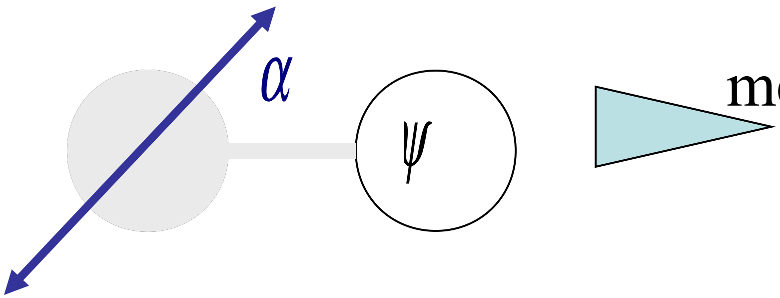
$$= \left| \rightarrow \uparrow \right\rangle + \left| \leftarrow \downarrow \right\rangle$$

measure left spin

in xy plane basis



Two spins



measurement result

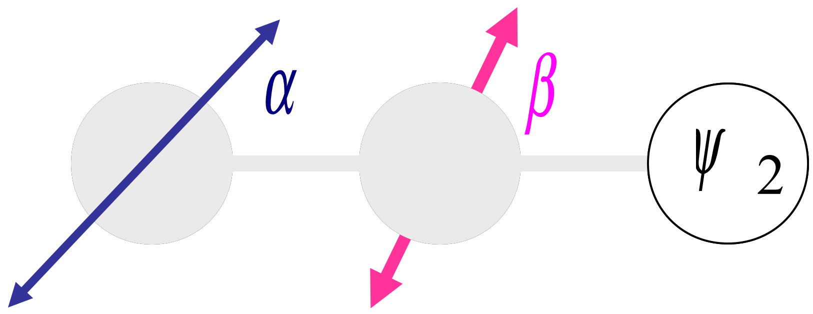
$$m = 0,1$$

$$|\psi\rangle = (\sigma_x)^m \left(\cos(\alpha)|\uparrow\rangle + \sin(\alpha)|\downarrow\rangle \right)$$

$$= (\sigma_x)^m H Z_\alpha |\rightarrow\rangle$$

$$Z_\alpha = \exp(i\alpha\sigma_z) \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

Three spins



$$|\psi_2\rangle = \sigma\, HZ_\beta\, HZ_\alpha\, |\rightarrow\rangle$$

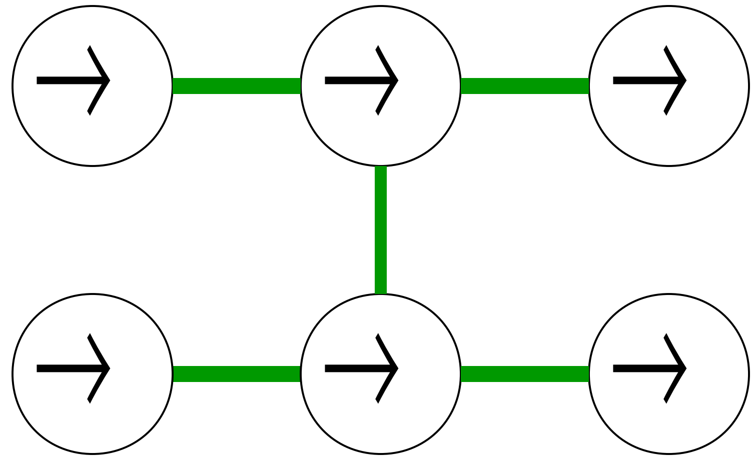
$$X_\beta = \exp(i\beta\,\sigma_x)$$

Cluster states

Array of spins:

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

$$|\Psi_C\rangle =$$



= control-σ_z

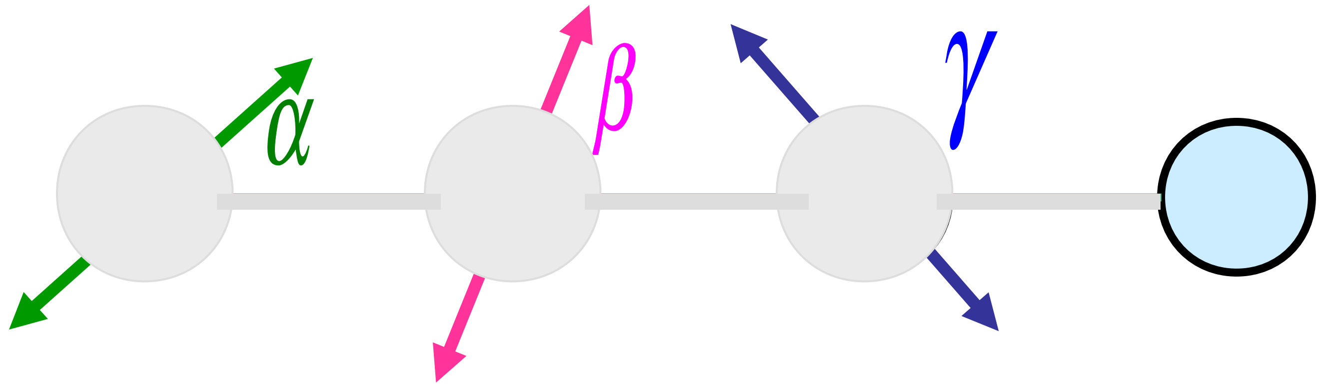
$$|\uparrow\uparrow\rangle \longrightarrow |\uparrow\uparrow\rangle$$

$$|\uparrow\downarrow\rangle \longrightarrow |\uparrow\downarrow\rangle$$

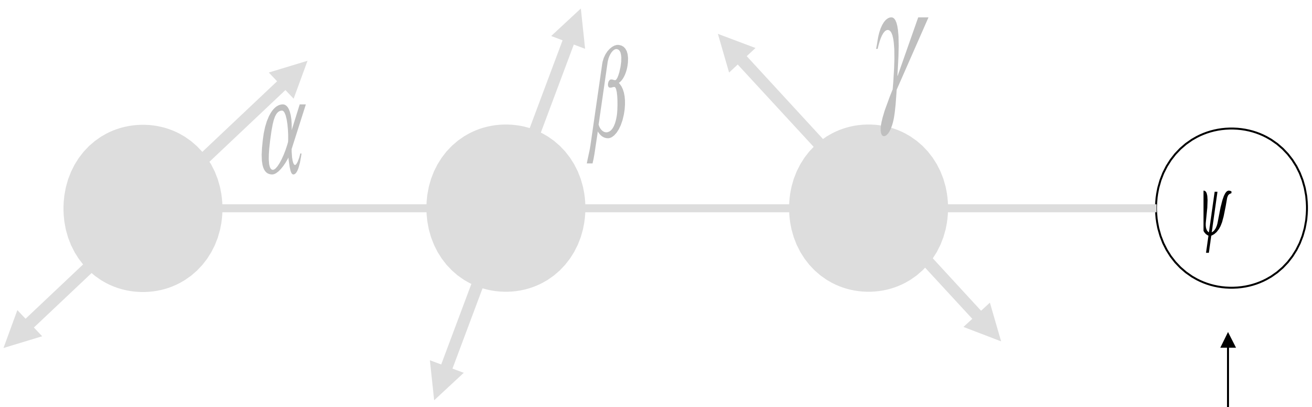
$$|\downarrow\uparrow\rangle \longrightarrow |\downarrow\uparrow\rangle$$

$$|\downarrow\downarrow\rangle \longrightarrow -|\downarrow\downarrow\rangle$$

1D chains



1D chains



Three measurements

Arbitrary rotation

$$|\psi\rangle = \sigma\, U(\alpha, \beta, \gamma)|\rightarrow\rangle$$

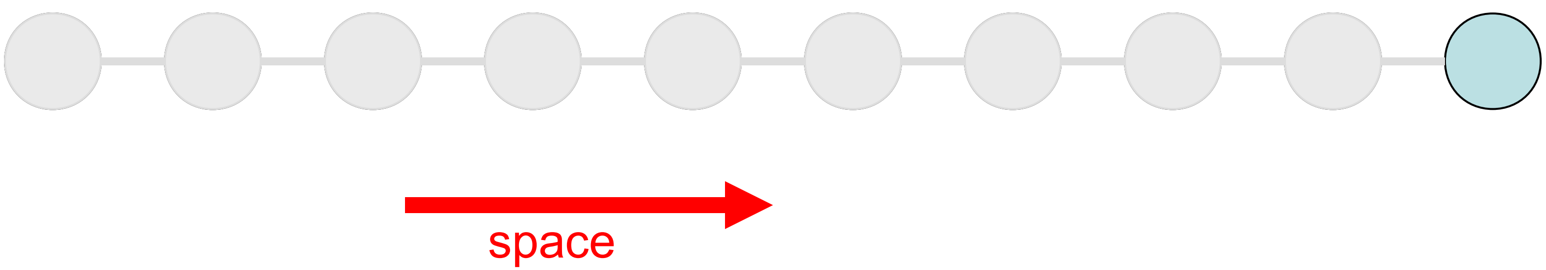
<u>Note</u>: Later angles depend on earlier measurement outcomes

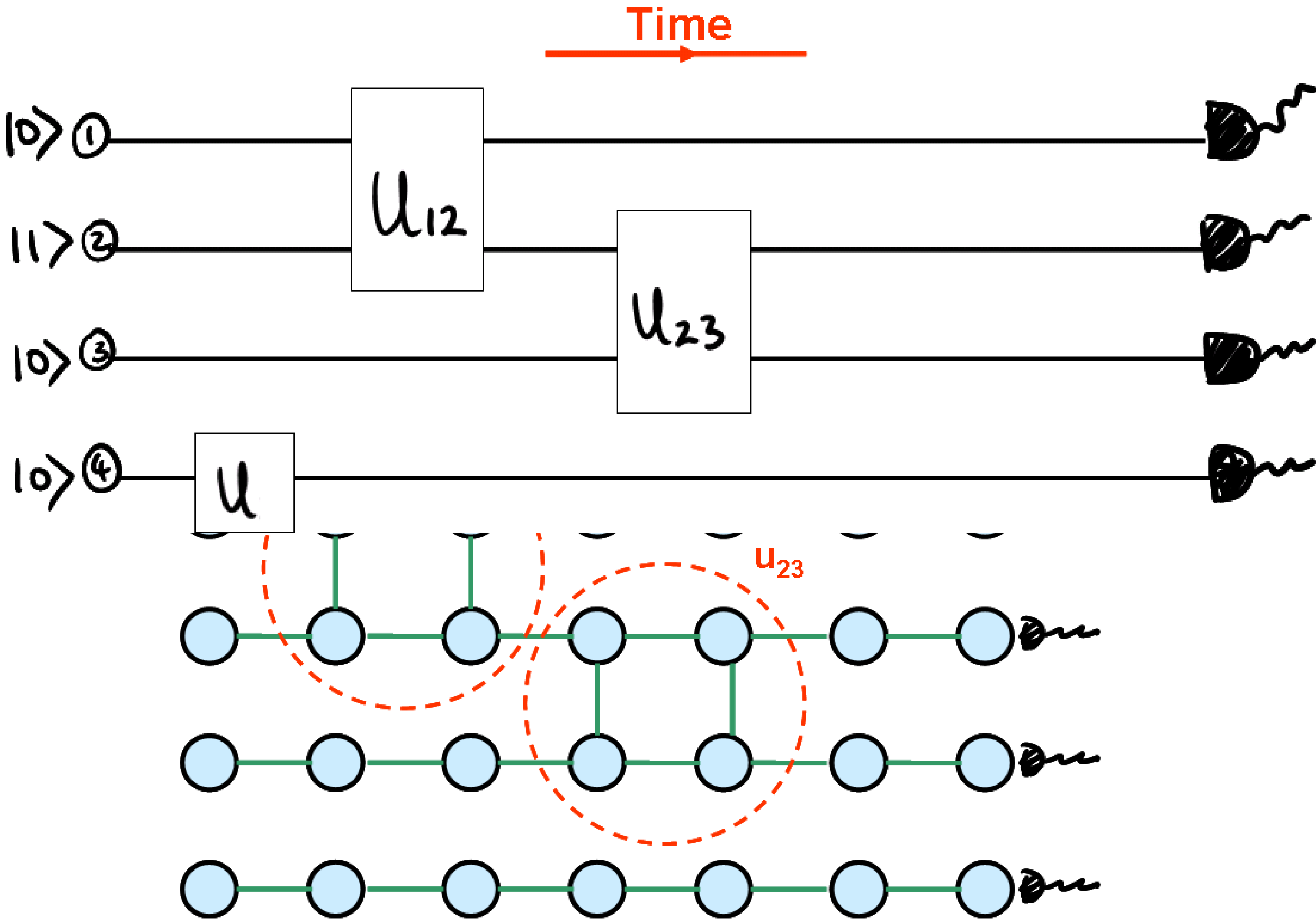
1D chains

Unitary time evolution

$$|\rightarrow\rangle \qquad U(t)|\rightarrow\rangle$$

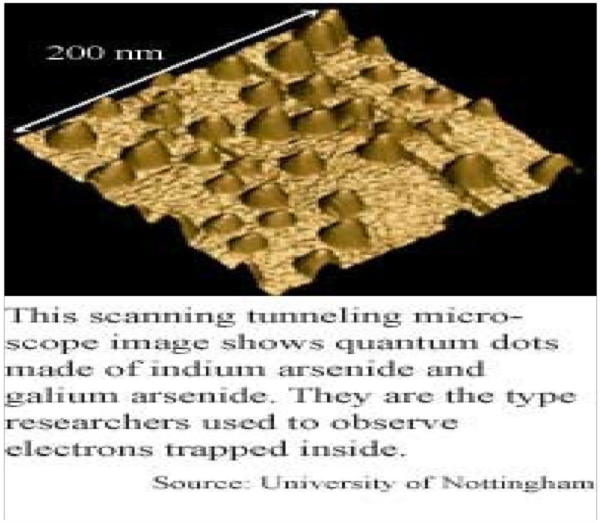
Evolution by measurements





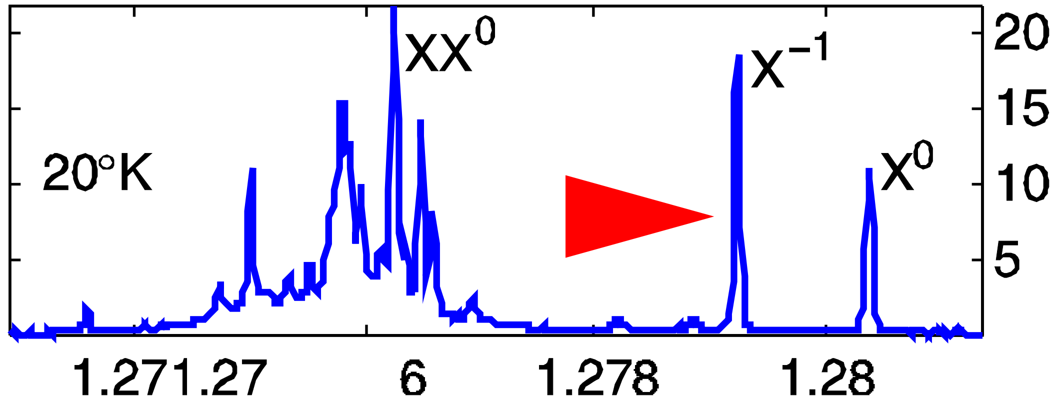
Time
|0⟩ ①
|1⟩ ②
|0⟩ ③
|0⟩ ④
U12
U23
U
u23

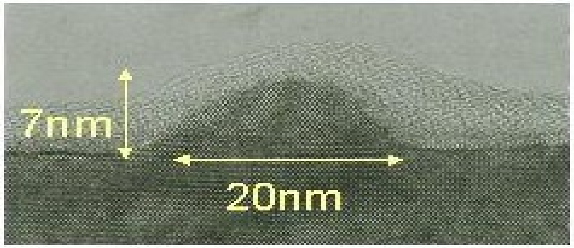
Strain induced self-assembled quantum dots



STM (Nottingham)

PL spectra (Technion, UCSB)

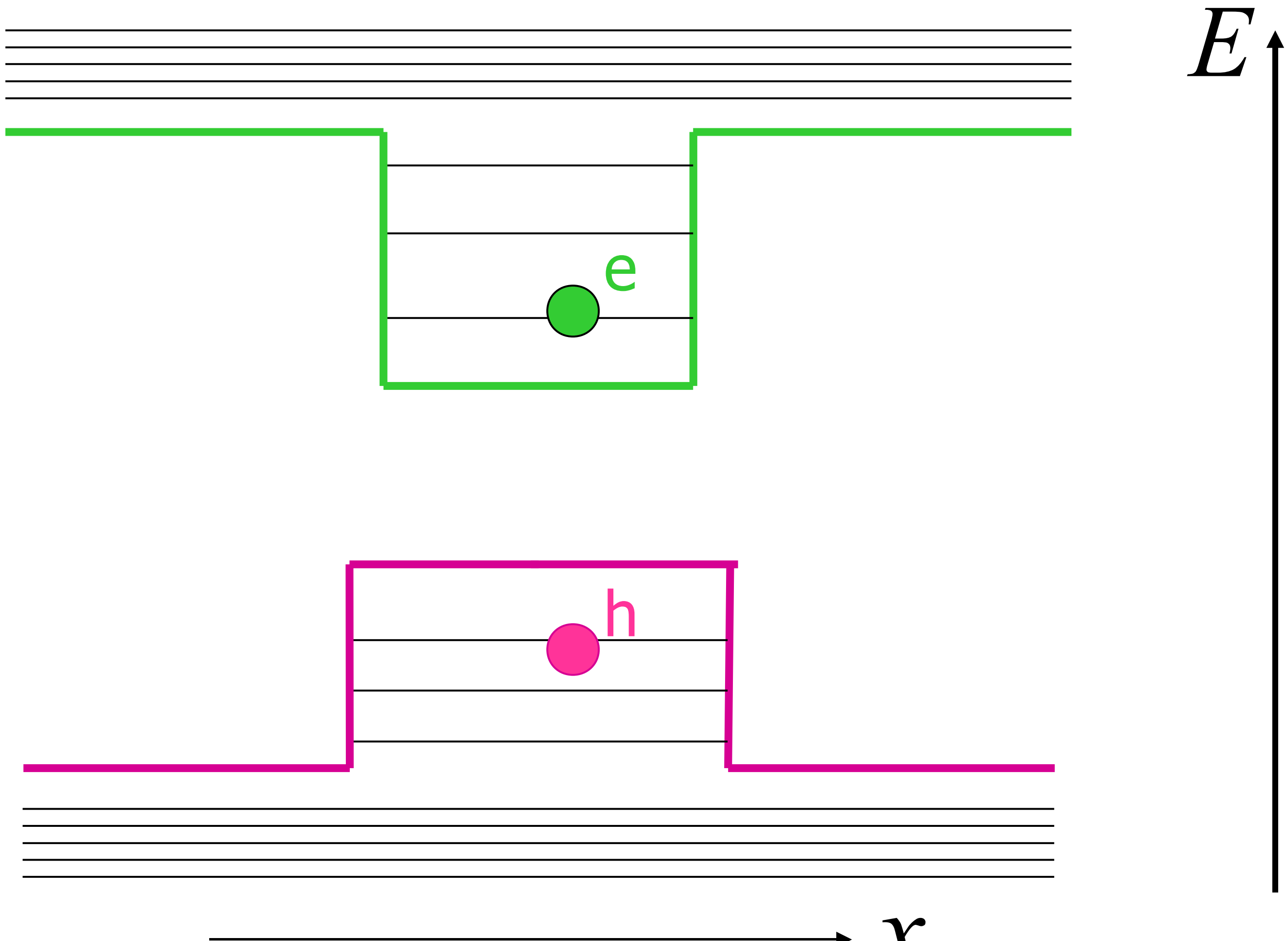




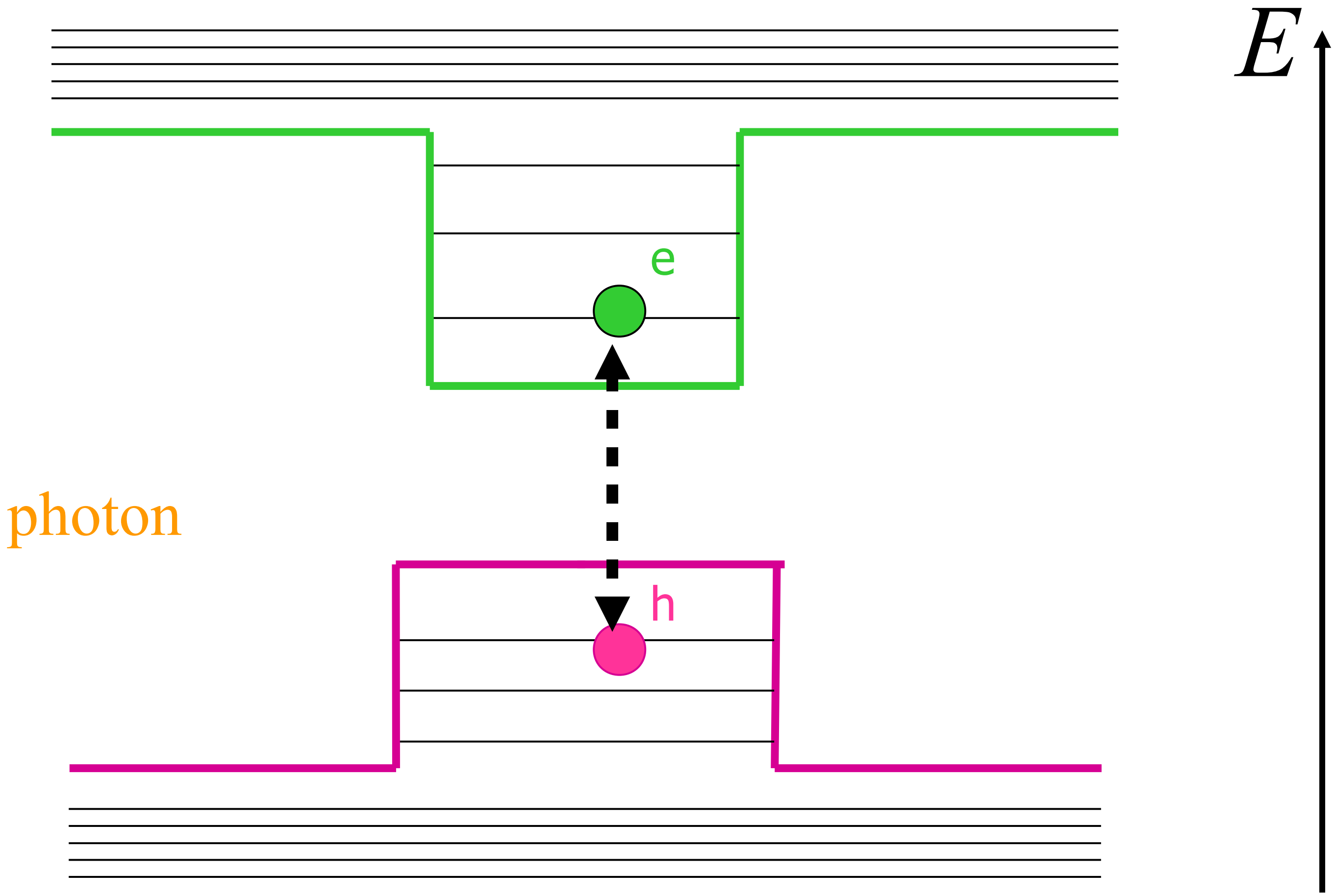
Cross-sectional TEM of an uncapped QD

N. Akopian *et. al*., PRL **90**, 130501 (2006)
Stevenson *et. al*., Nature **439**, 179 (2006)
M. Bayer *et. al*. PRB **65** 195315 (2002)
Stefan Strauf *et. al*, Nature Photonics **1**, 704 - 708 (2007)

Quantum dots



electron - hole recombination



Localization of errors (1)

ideally: $\tilde{\rho}_{n+1} = U^{\dagger} \rho_n U$

$\sum_k A_k^{\dagger} A_k = I$

decoherence:

dephasing: $\rho_{n+1} = (1-p)\tilde{\rho}_{n+1} + p\sigma_Y^{\text{spin}} \tilde{\rho}_{n+1} \sigma_Y^{\text{spin}}$