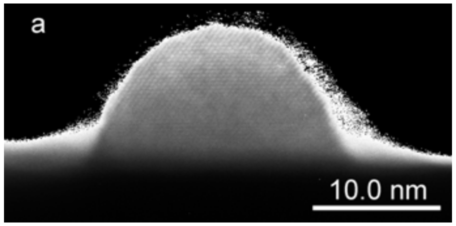
OPTICAL QUANTUM DOTS FOR QUANTUM INFORMATION



Tom Reinecke
Naval Research Laboratory
Washington, DC , USA
reinecke@nrl.navy.mil

outline
- single spin qubits
- two qubit gates
- entanglement in QD molecules

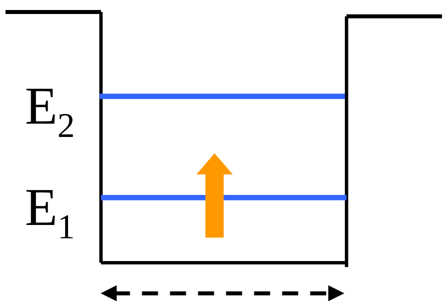
NRL theory: S. Economou, D. Solenov, T. Reinecke
NRL expt: D. Gammon, A. Bracker, S. Carter

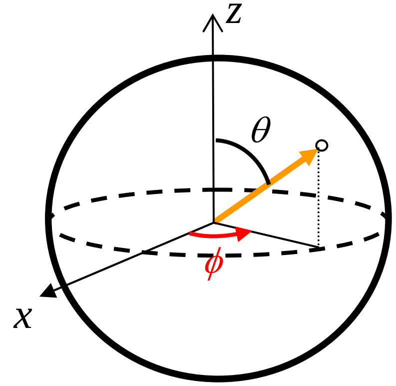
U. Wuerzburg: fabrication, expt
U. Dortmund: expt

support: DARPA, NSA and ONR

Optical quantum dots

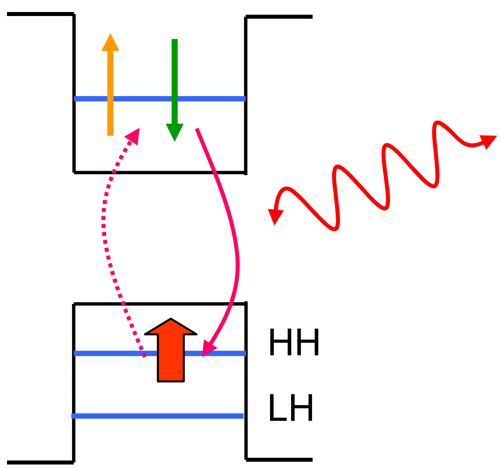
spin in QD





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

optical properties, control (trion)

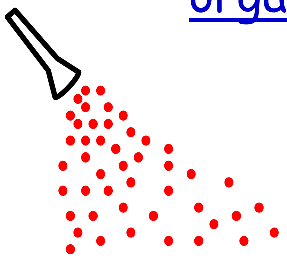


Quantum dots

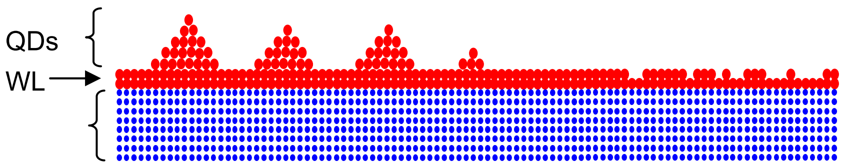
- spin natural qubit
- 'long' coherence
- fast optical manipulations
- integrate into semiconductor technology
- potentially scalable
- fixed locations

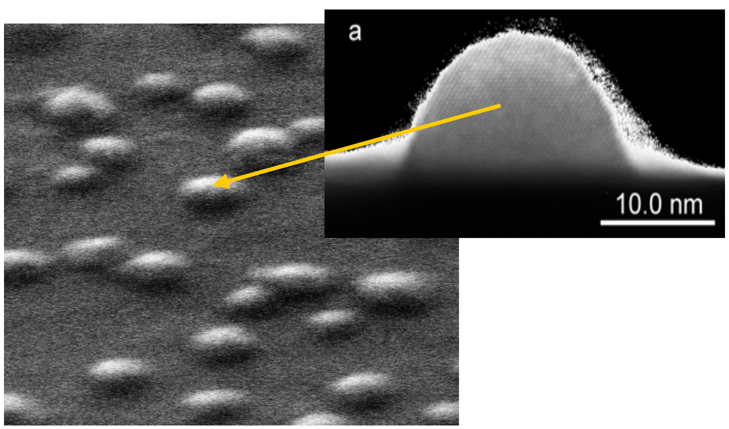
Quantum dots

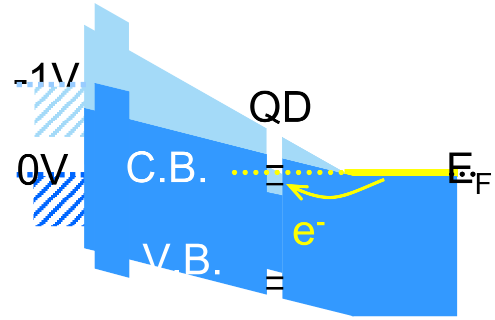
Stranski-Krastanov 'self organized' QDs



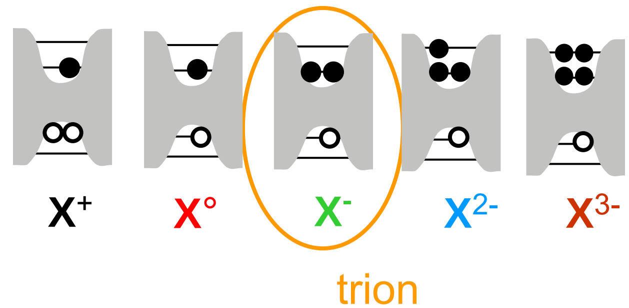
- substrate **GaAs**: small lattice constant
- deposited Material **InAs**: large lattice constant

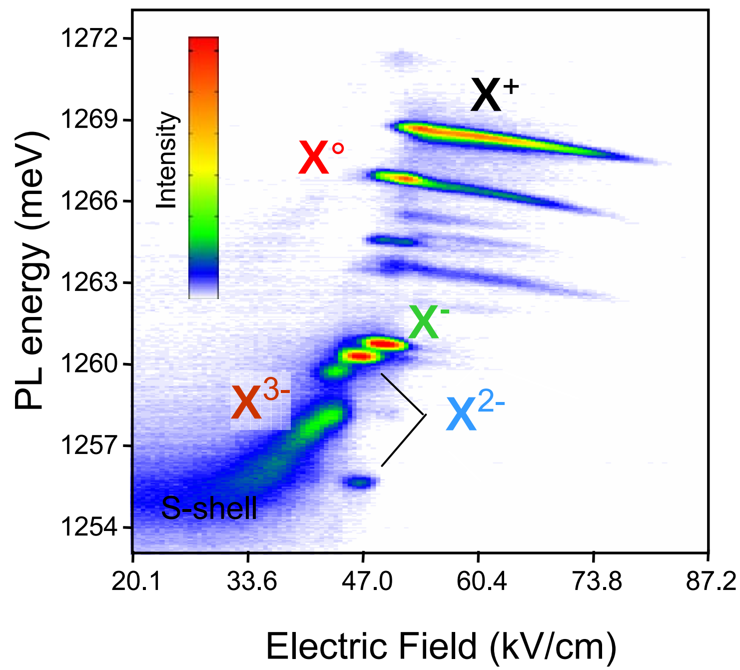




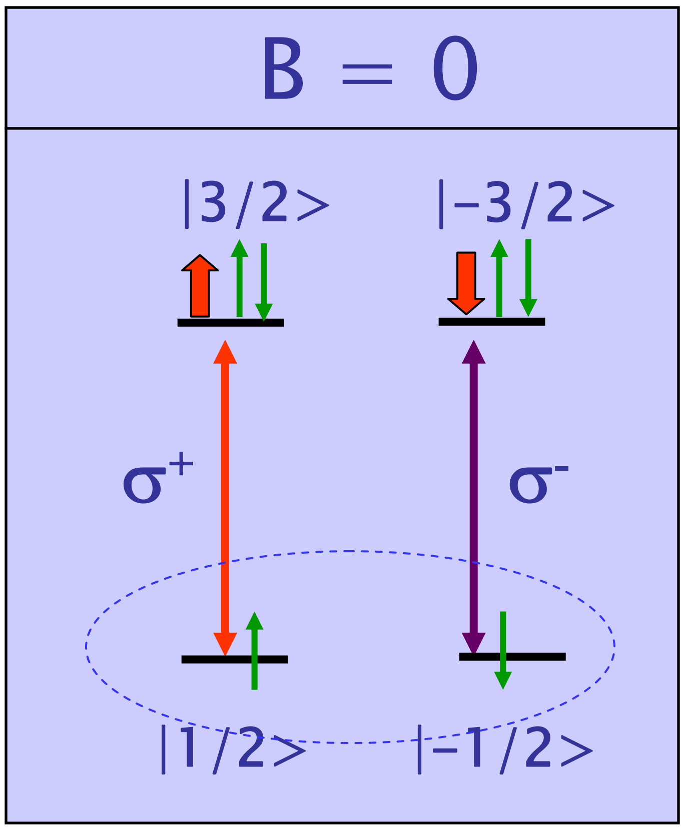


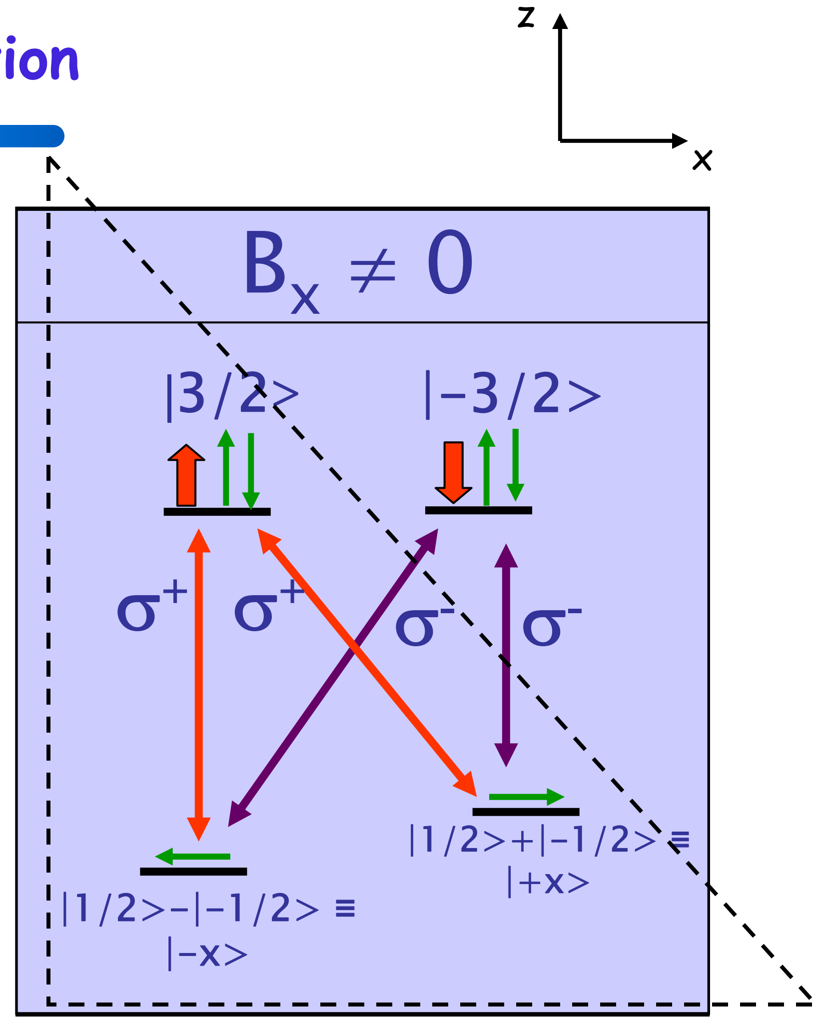
spins in low states in QDs





Spin initialization, manipulation





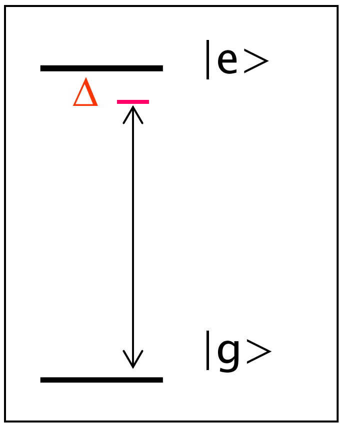
- No Raman transitions |1/2> → |-1/2>
- Cannot make arbitrary spin rotation

('z basis' - growth direction/optical axis)

- Voigt field mixes spin states & enables Raman transitions
- optical pumping gives initialization

('x basis')

Useful feature of 2-level systems

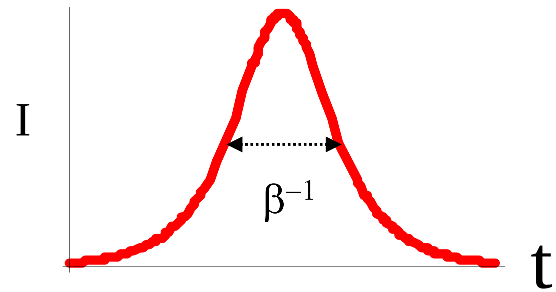


$$H(t) \sim \begin{pmatrix} 0 & V_{ge}(t) \\ V_{ge}(t)^* & (E_e - E_0) \end{pmatrix}$$

analytical solution

$$V_{ge} = \Omega \operatorname{sech}(\beta t) e^{i\Delta t}$$

Δ = detuning
β = pulse bandwidth



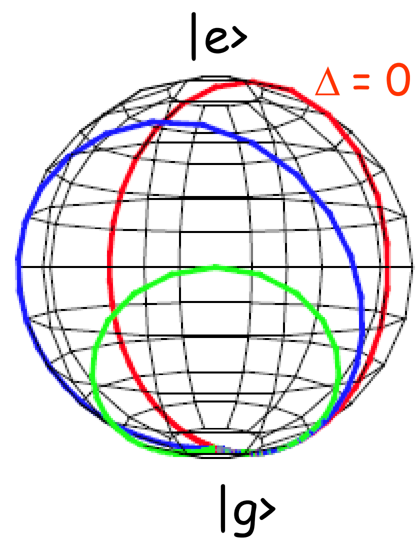
properties:

(ι) $\Omega = \sigma \rightarrow 2\pi$, no excitation left in |e>

(ii) pulse area indep of detuning

(iii) |g> acquires phase

$$\tan(\phi) = \frac{2\beta\Delta}{\Delta^2 - \beta^2}$$



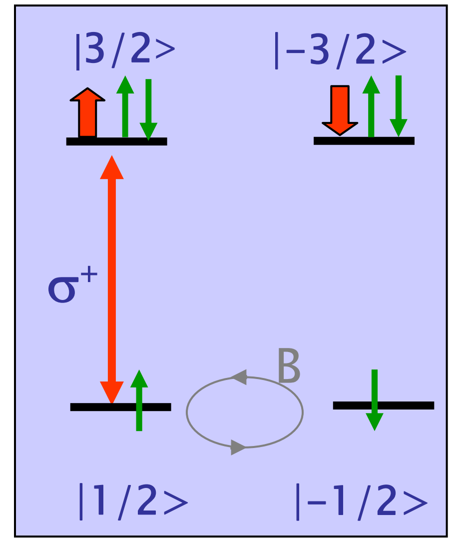
(Rosen & Zener, Phys. Rev., 1932)

Spin rotations around one axis (z)

$$H(t) \sim \begin{pmatrix} 0 & \omega_B & 0 \\ \omega_B & 0 & \Omega(t)e^{i\omega_0 t} \\ 0 & \Omega^*(t)e^{-i\omega_0 t} & \varepsilon_T \end{pmatrix}$$

'z-basis' $\{|\bar{z}\rangle, |z\rangle, T\}$

Pulses: $V_{ge} = \Omega \operatorname{sech}(\beta t) e^{i\Delta t}$



B_x

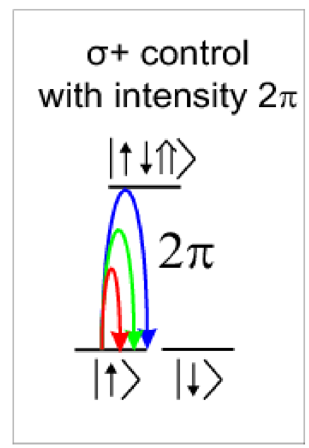
(fast pulses: $\beta >> \omega_B$)

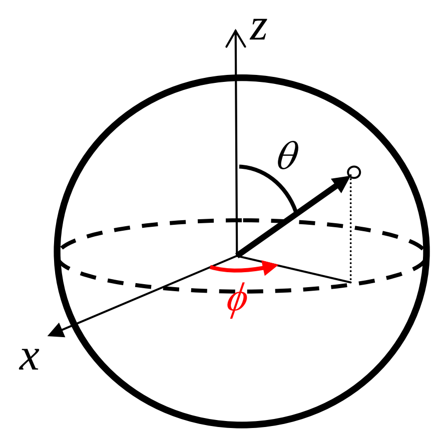
Properties:

(i) 2π pulses return to spin subspace with no trion excitation

(ii) 2π pulses give phase ϕ of |z> wrt |z'> equivalent to a z rotation

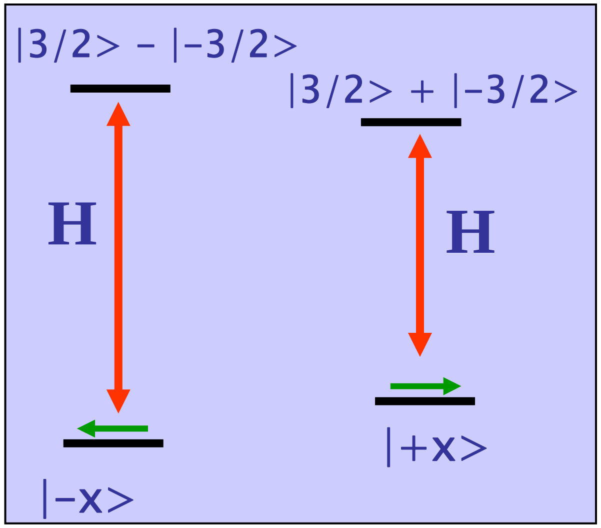
$$\phi = 2\arctan(\beta / \Delta)$$



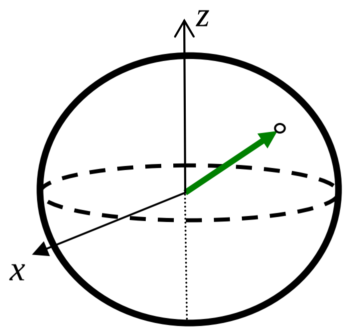


Rotations around another axis (x)

- <u>single</u>, broad band, linearly polarized pulse couples both transitions
- <u>different</u> phase |x> and |x'>
- pulse area independent of detuning
- gives rotation $(\phi_1 - \phi_2)$



π_x polarizations



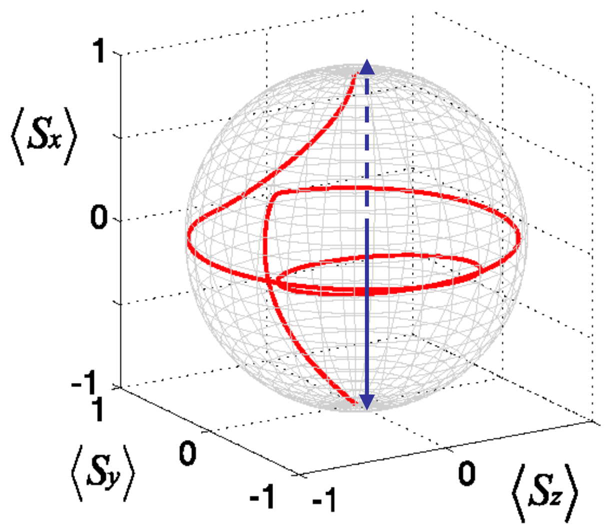
general rotations from those about z and x

general rotations, full solutions

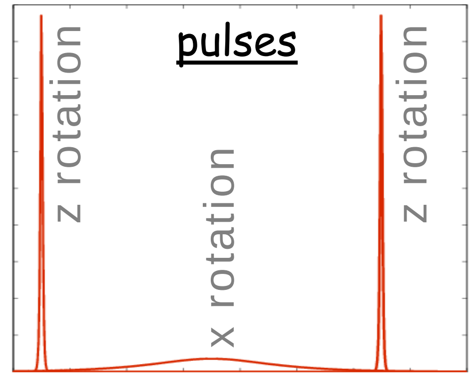
- density matrix calculations including mixing, losses
- arbitrary rotation from rotations around two axes

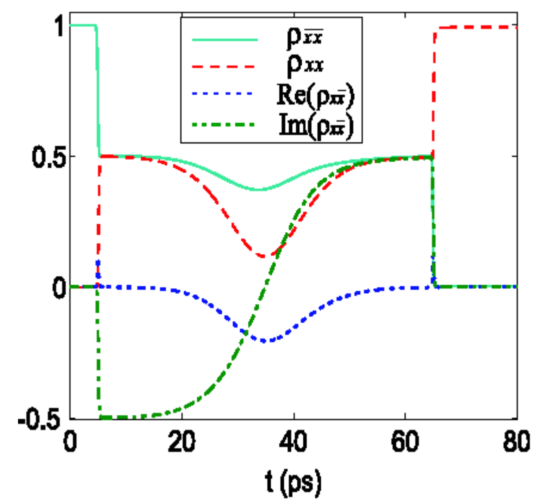
$$R_y(\phi) = R_z^+(\pi/2)\, R_x(\phi)\, R_z(\pi/2)$$

Fidelity 99.28%



parameters for InAs QDs

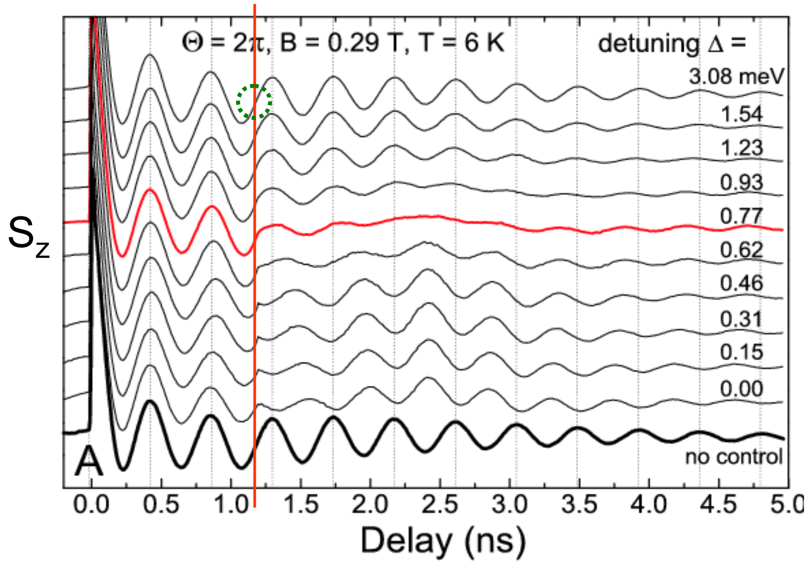


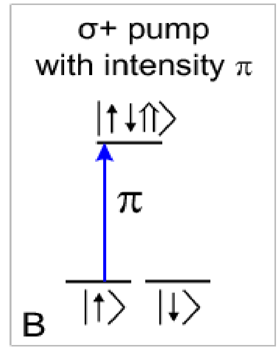


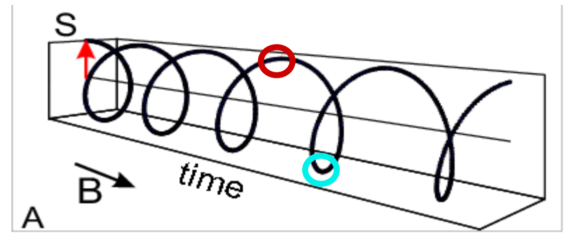
fast gates ~ 60 psec

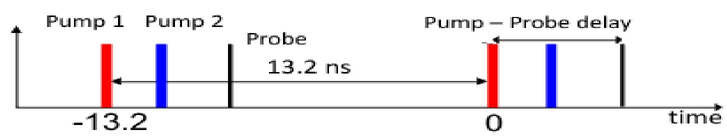
Economou & Reinecke, PRL (2007)

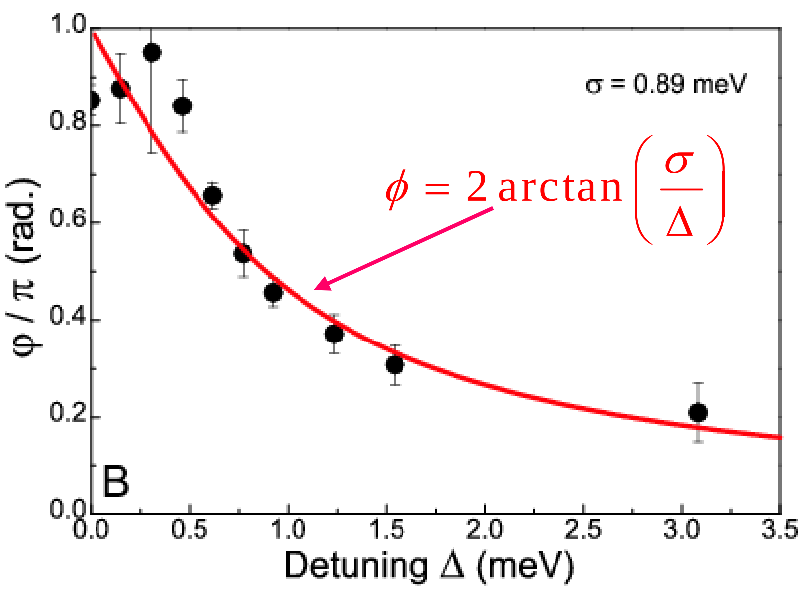
Spin rotations – ϕ vs Δ

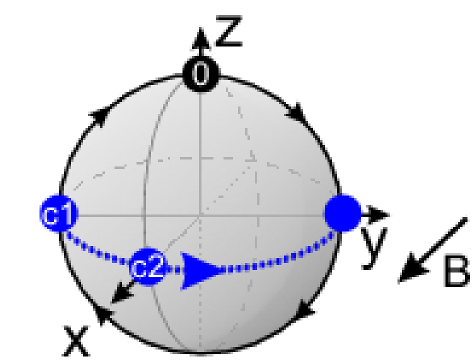












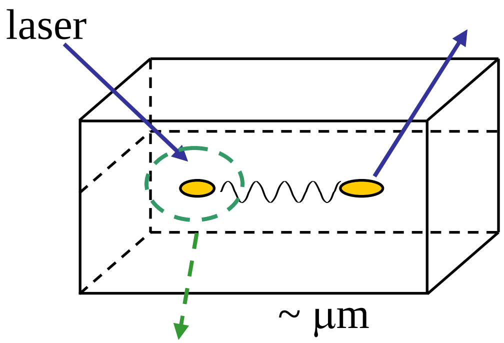
general rotations demonstrated by varying precession

Greilich *et al*, Nature Physics **5**, 262 (2009)

Cavity coupling

Cavity development

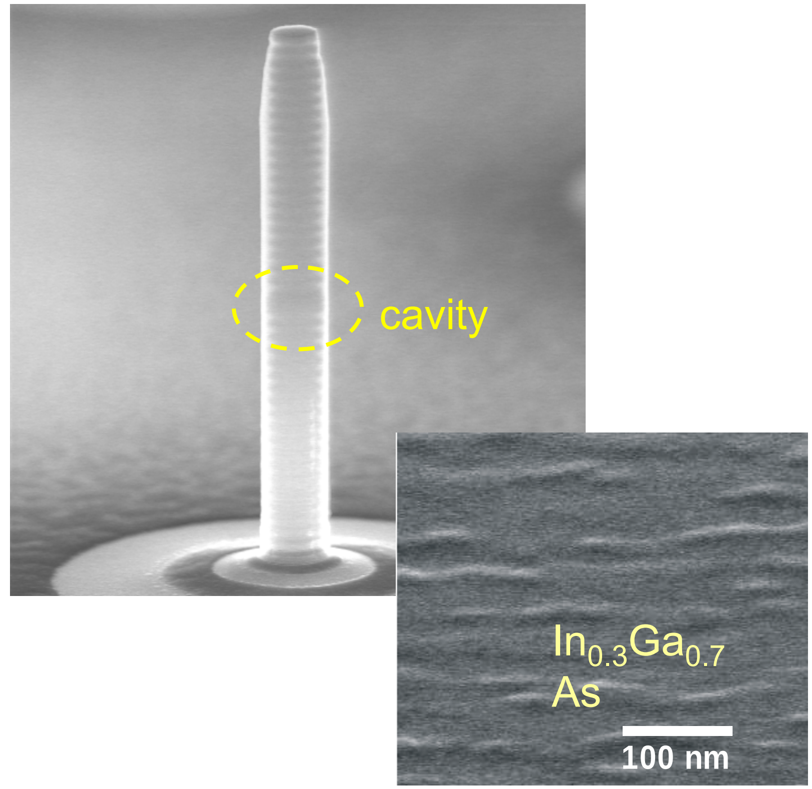
fast, distant, frequency selective coupling and architectures

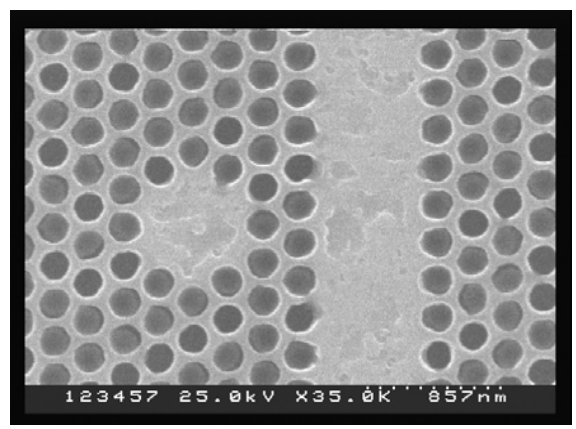


strong coupling (coherent)
weak coupling (Purcell)

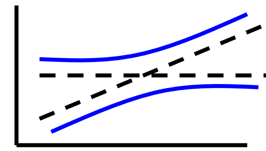
$$\omega_{\pm} = \omega_c \pm \sqrt{g_{e-p}{}^2 - (\gamma_c + \gamma_e)^2 / 4}$$

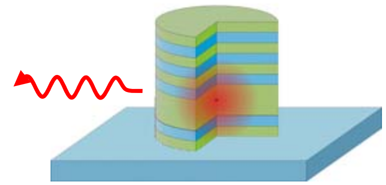
$$g = \sqrt{\frac{e^2 f}{4\pi\kappa\varepsilon_0 V_m}}$$



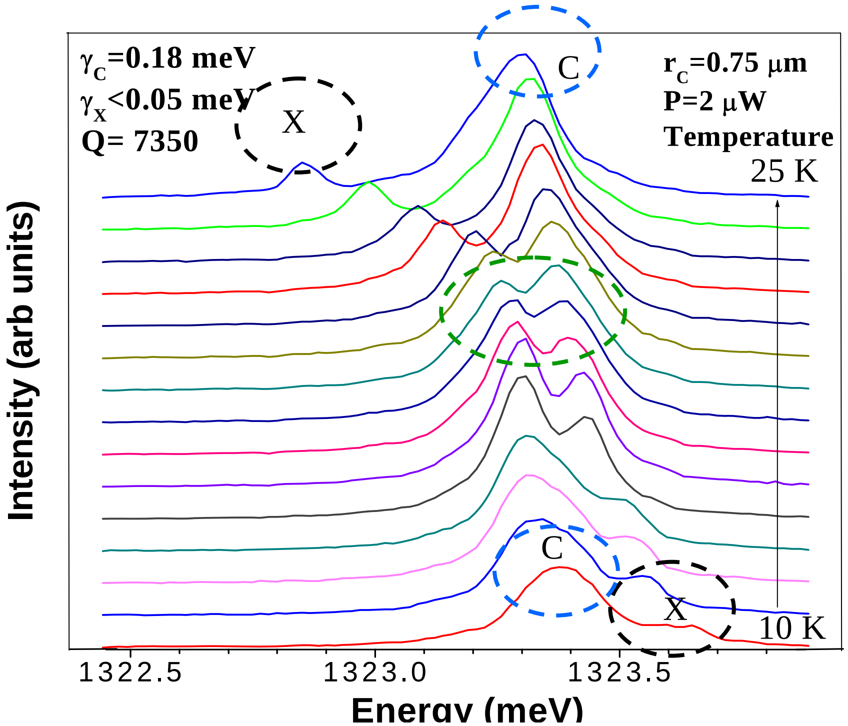


Strong coupling

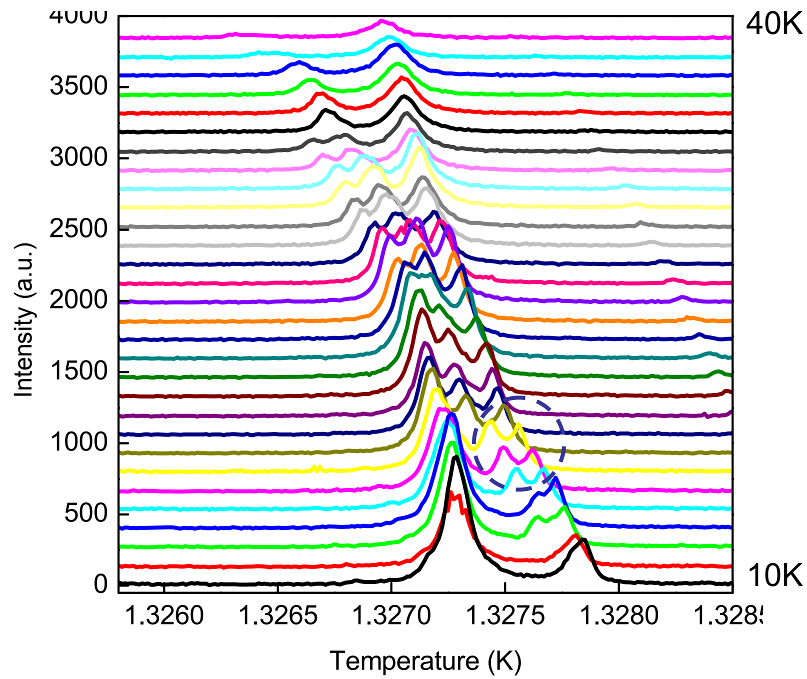




one dot spectra



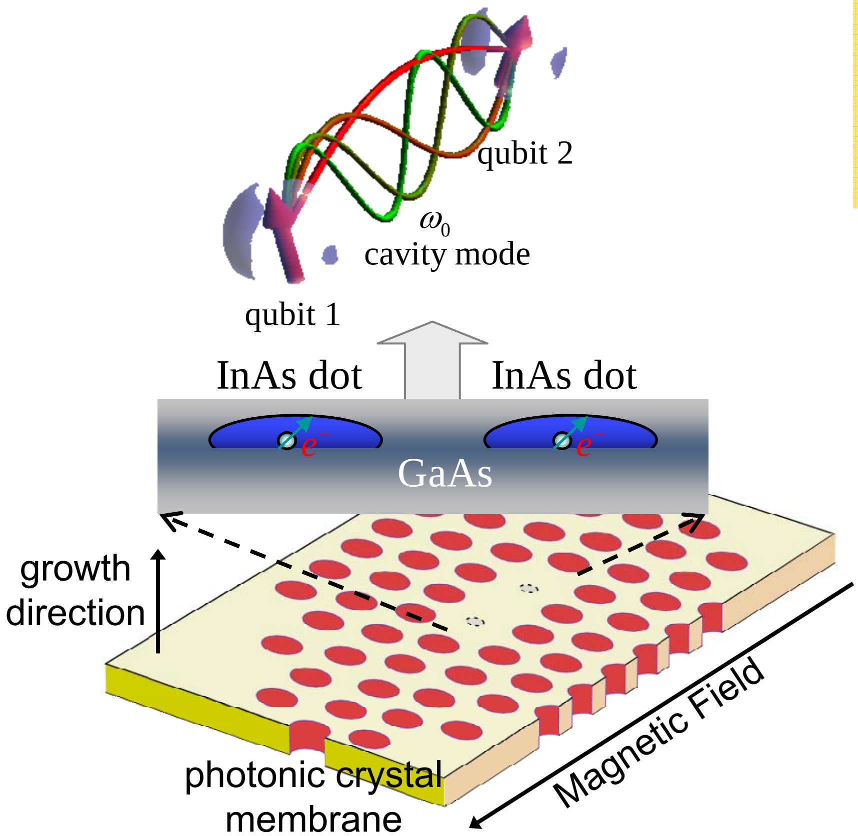
one dot spectra



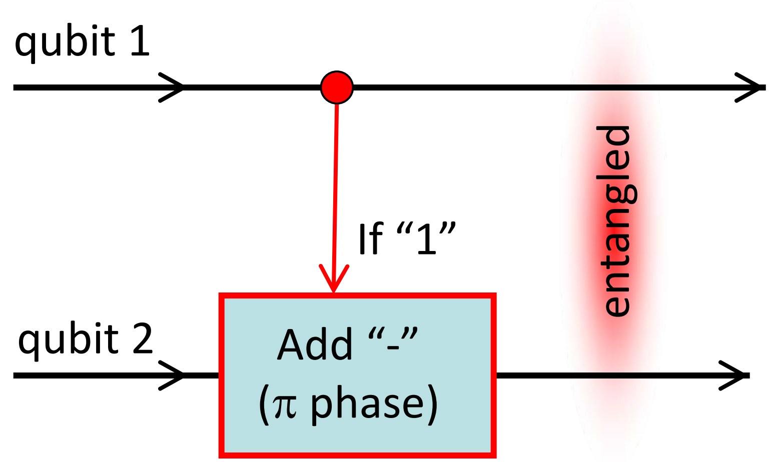
- $g_{ex\text{-}p}$ ~ 100-200 meV
- 40 pillars from several wafers with $g_{ex\text{-}p}$ > 50 meV
- confirmed by intensity and linewidths

*Reithmaier et al, Nature **432**, 197 (2005)*

Two qubit entangling gate (theory)

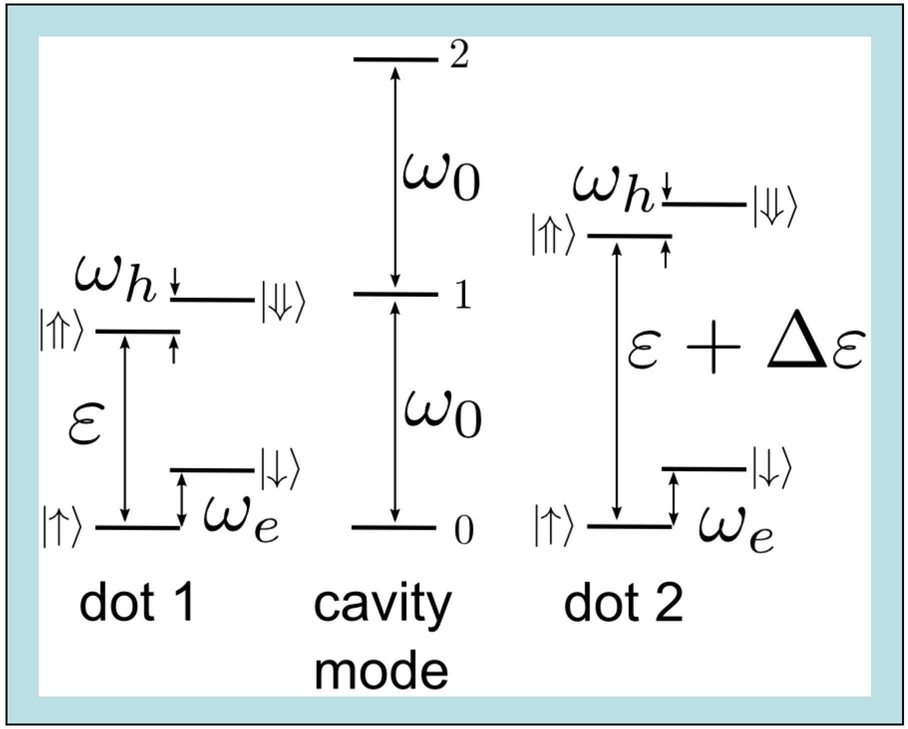


Requirements for two qubit (entangling) gate:
- (Long-range) physical interaction
- Dynamical control of interaction
- Conditionality (control-U operation)
- Scalability



compatible with one qubit operations

system



System $(n=1,2)$

$$H_{e-t,n} = -\omega_e c_{n\uparrow}^{\dagger} c_{n\uparrow} + \omega_e c_{n\downarrow}^{\dagger} c_{n\downarrow}$$

$$+\left(\varepsilon_n - \omega_h\right) t_{n\uparrow}^{\dagger} t_{n\uparrow} + \left(\varepsilon_n + \omega_h\right) t_{n\downarrow}^{\dagger} t_{n\downarrow}$$

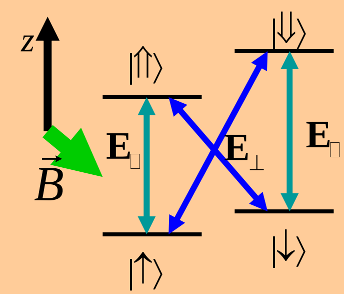
$$H_c = \omega_0 a^{\dagger} a$$

$$H_{e-c,n} = g\left(t_{n\uparrow}^{\dagger} c_{n\uparrow} + t_{n\downarrow}^{\dagger} c_{n\downarrow} + h.c.\right)\left(a^{\dagger} + a\right)$$

Pulses

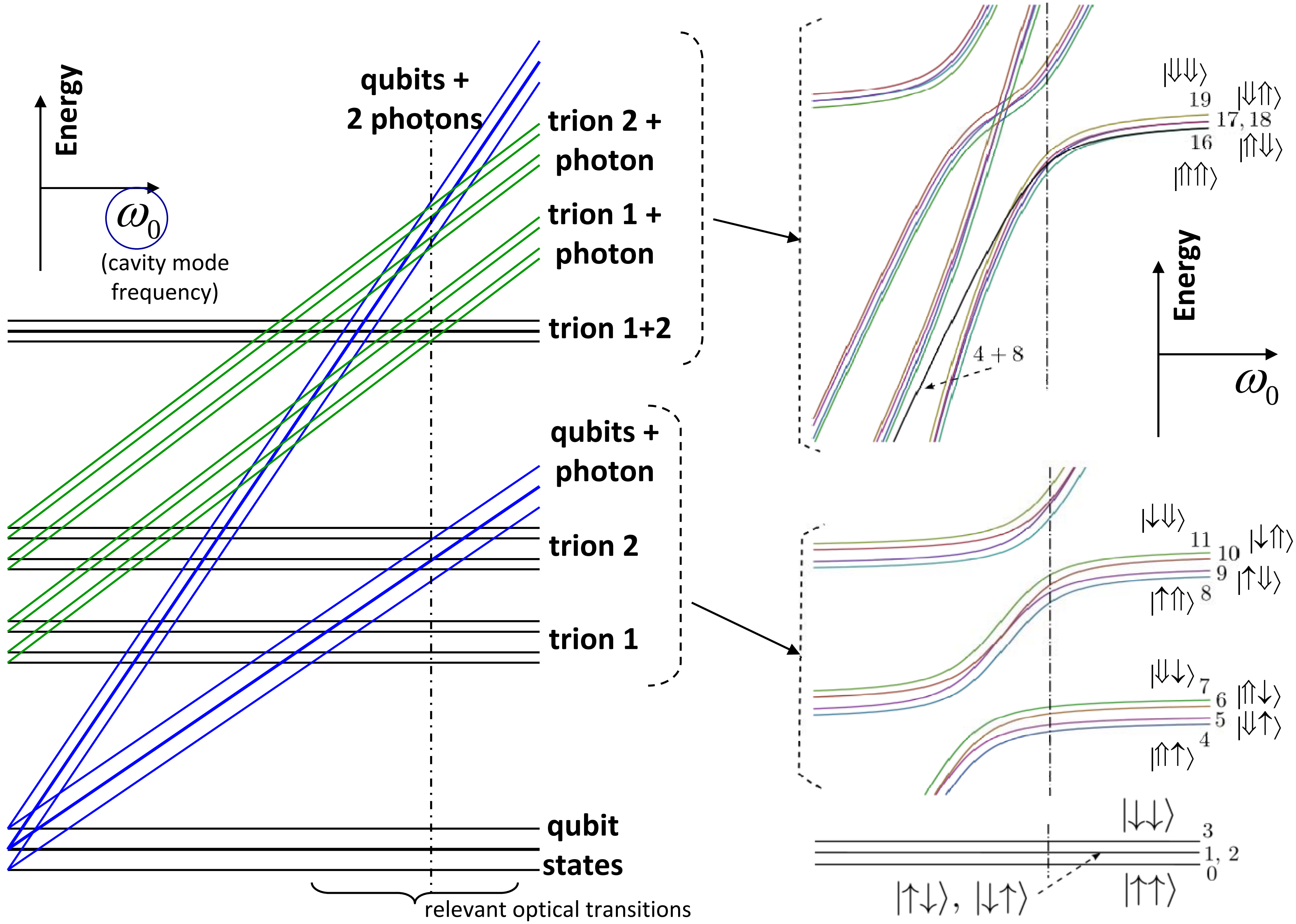
$$V(t) = \sum_{\substack{p \\ \xi\xi'=\uparrow,\downarrow \\ n=1,2}} \Omega_{p(\xi\xi')}(t - t_p) \cos \omega_p t \left(t_{n\xi}^{\dagger} c_{n\xi'} + h.c.\right)$$

Magnetic field perpendicular to the growth axis (z)



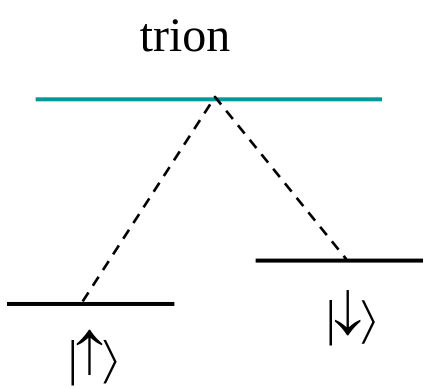
$$H_{qubits} = \frac{\omega_e}{2}\sigma_z^{(1)} + \frac{\omega_e}{2}\sigma_z^{(2)}$$

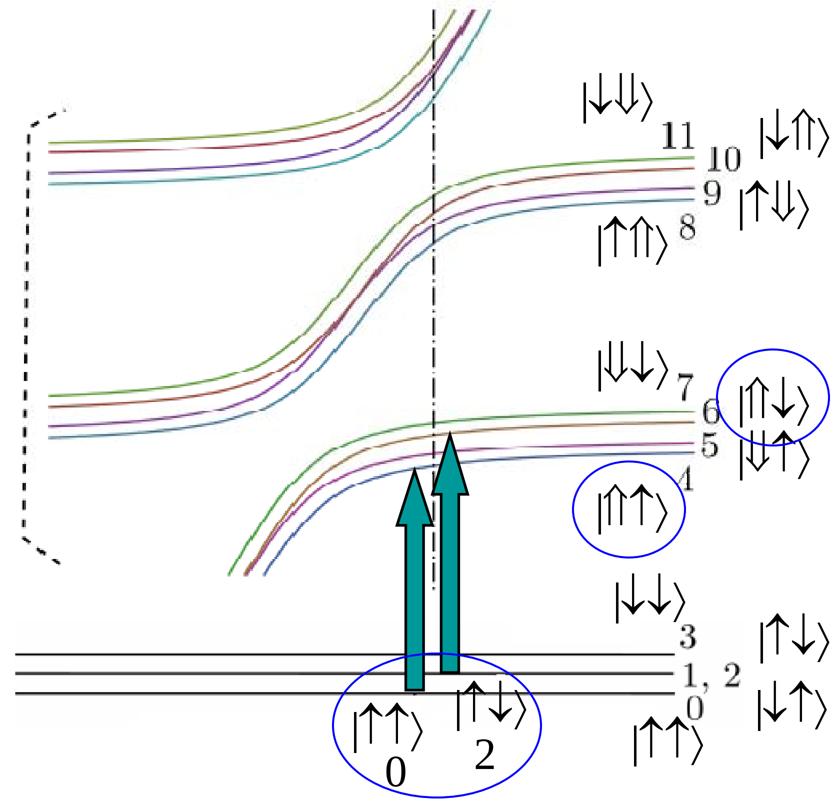
spectra


Energy
ω_0
(cavity mode frequency)
qubits + 2 photons
trion 2 + photon
trion 1 + photon
trion 1+2
qubits + photon
trion 2
trion 1
qubit states
relevant optical transitions
19
17, 18
16
4 + 8
11
10
9
8
7
6
5
4
3
1, 2
0
Energy
ω_0

Single qubit operations: compatibility

- effects of cavity-induced splitting in one-particle sector negligible for <u>short</u> pulses
- single qubit operations same as previously
- need single and two-qubit operations for complete set of operations

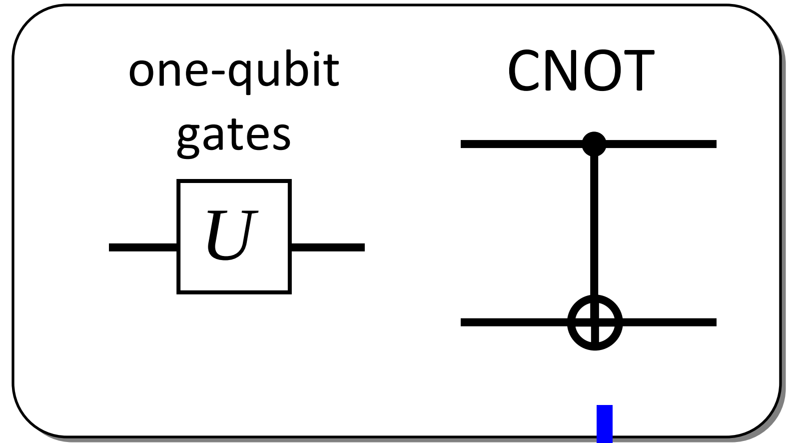


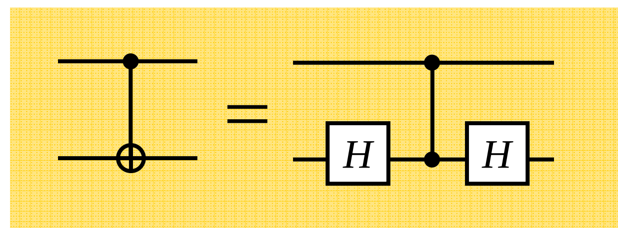


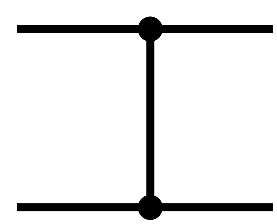
fast pulses

Two-qubit gates: CZ gate

universal





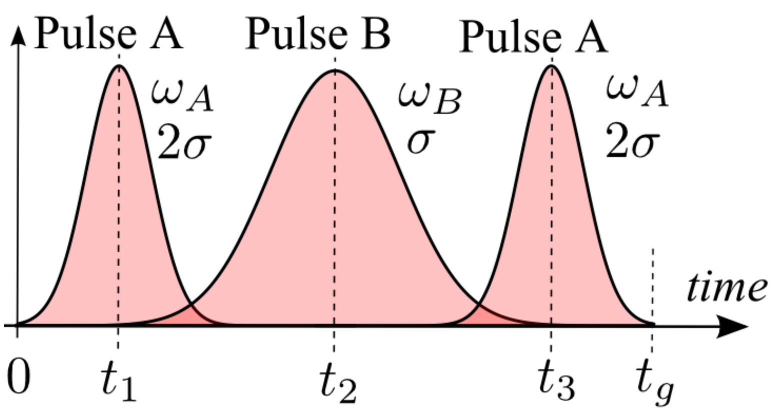


$$U_g = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

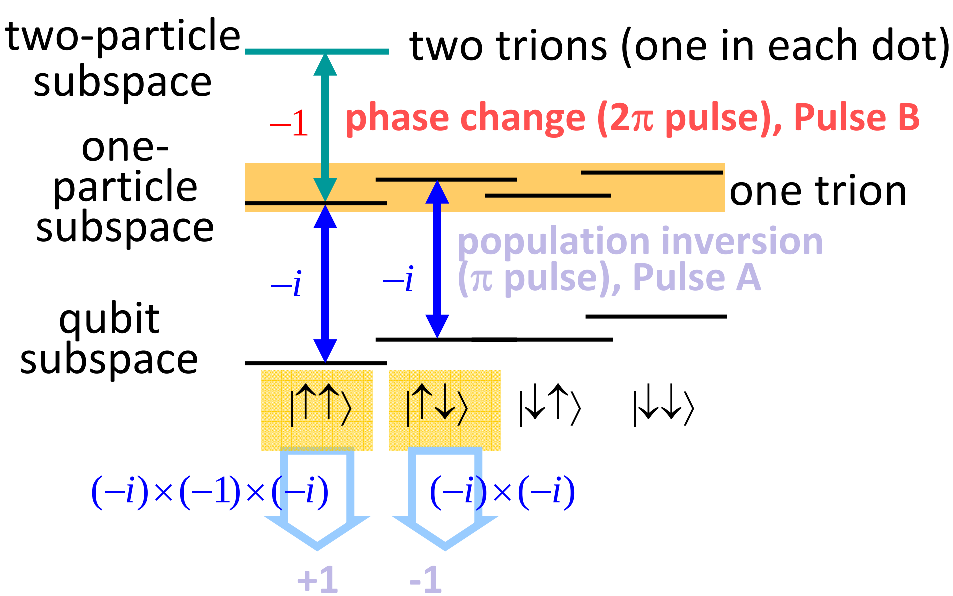
$$|\psi\rangle = \alpha|\uparrow\uparrow\rangle + \beta|\uparrow\downarrow\rangle + \delta|\downarrow\uparrow\rangle + \gamma|\downarrow\downarrow\rangle$$

$$|\psi\rangle = \alpha|\uparrow\uparrow\rangle - \beta|\uparrow\downarrow\rangle + \delta|\downarrow\uparrow\rangle + \gamma|\downarrow\downarrow\rangle$$

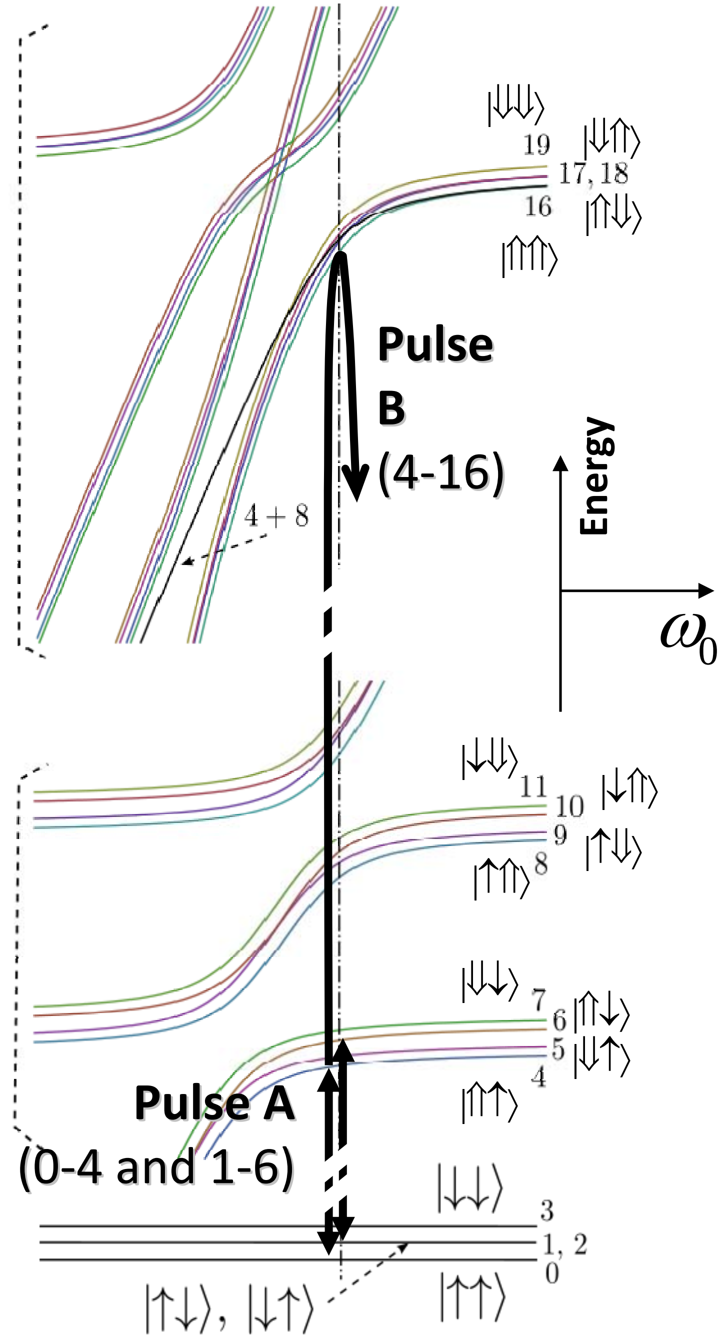
CZ gate



Pulse A
Pulse B
Pulse A
ω_A
2σ
ω_B
σ
ω_A
2σ
time
0
t_1
t_2
t_3
t_g



two-particle subspace
two trions (one in each dot)
–1
phase change (2π pulse), Pulse B
one-particle subspace
one trion
–i
–i
population inversion (π pulse), Pulse A
qubit subspace
|↑↑⟩
|↑↓⟩
|↓↑⟩
|↓↓⟩
(–i)×(–1)×(–i)
(–i)×(–i)
+1
-1

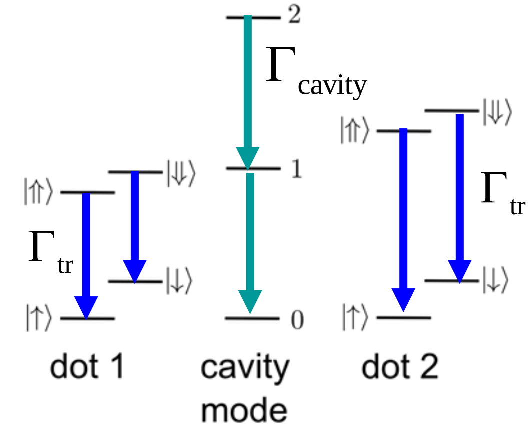


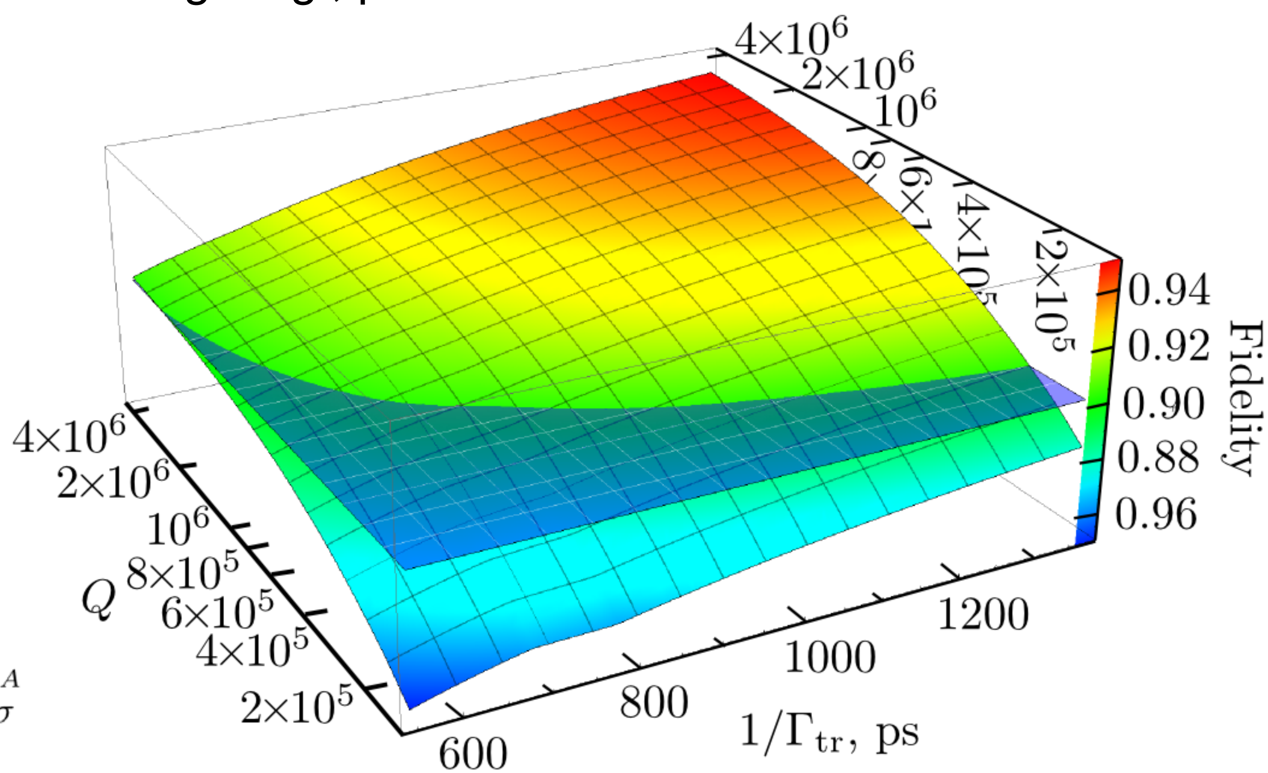
Pulse B (4-16)
Pulse A (0-4 and 1-6)
Energy
ω_0
4 + 8
19
17, 18
16
11
10
9
8
7
6
5
4
3
1, 2
0
|↑↓⟩, |↓↑⟩
|↑↑⟩
|↓↓⟩

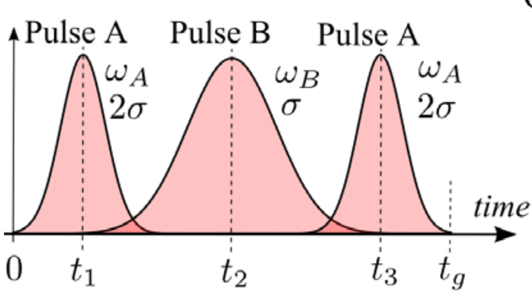
Fidelity

1. losses due to unwanted coherent dynamics of off-resonant transitions
2. losses due to carrier recombination and cavity losses

-- can be improved through e.g., pulse shaping



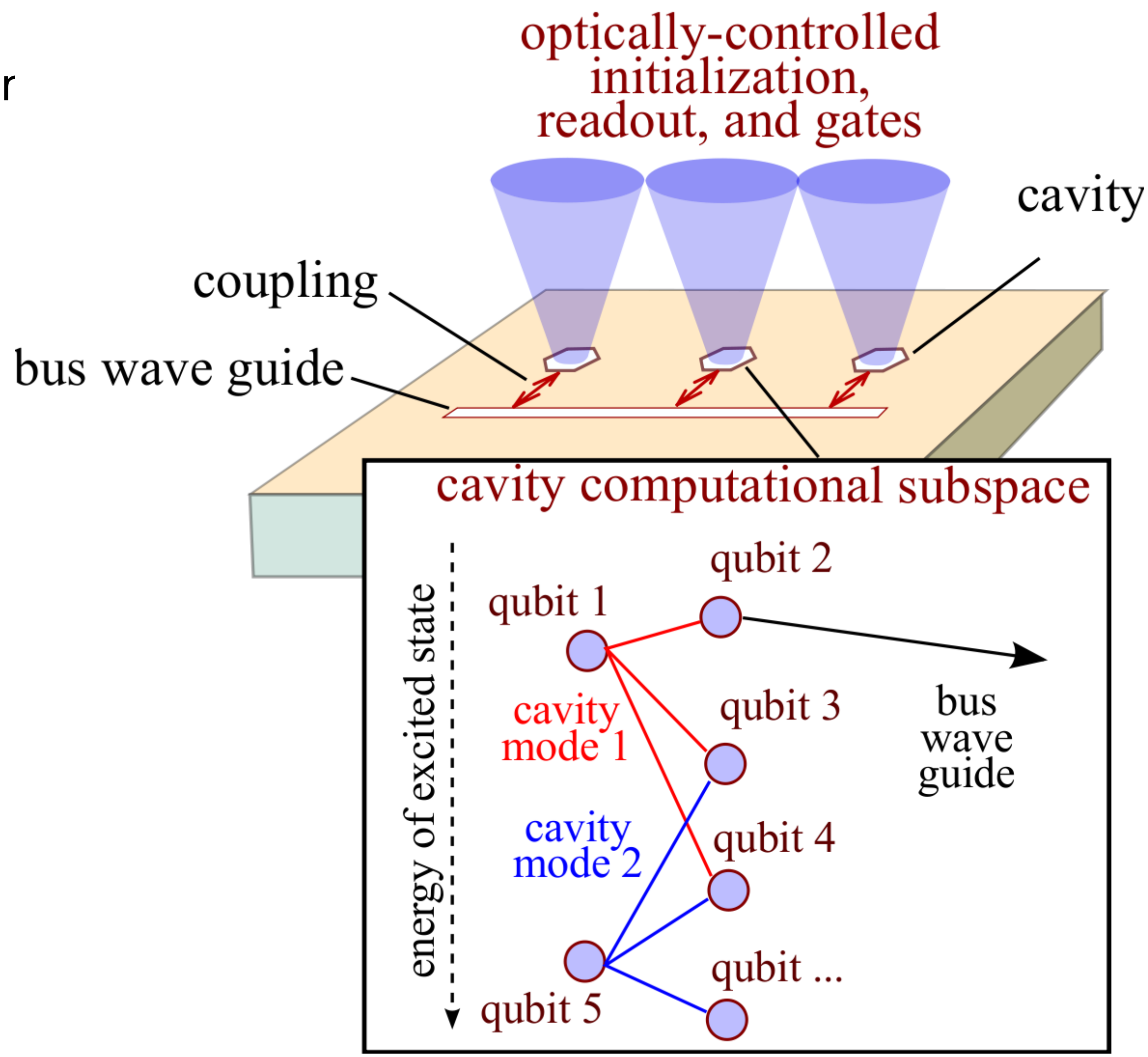




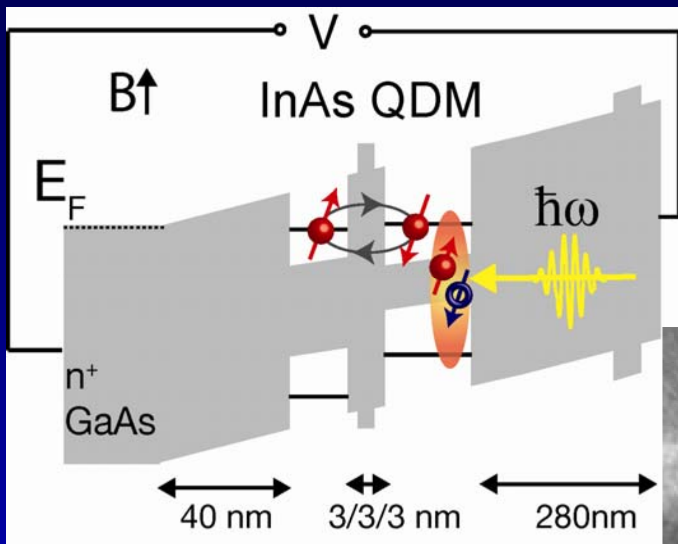
Solenov, Economou and Reinecke, to be published

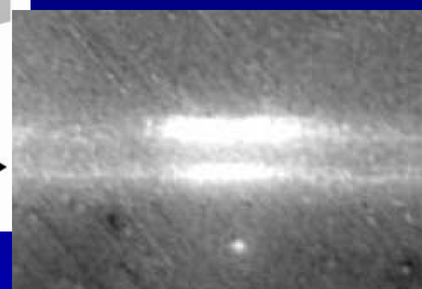
Scalability

- gates for unequal dot excitation energies allow coupling between multiple dots
- multiple confined photon exist modes in cavities



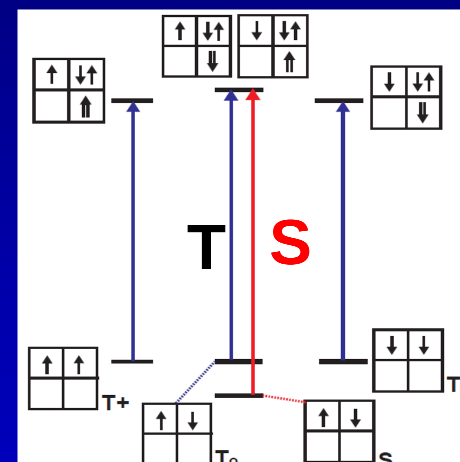
2 electron spins in two dots

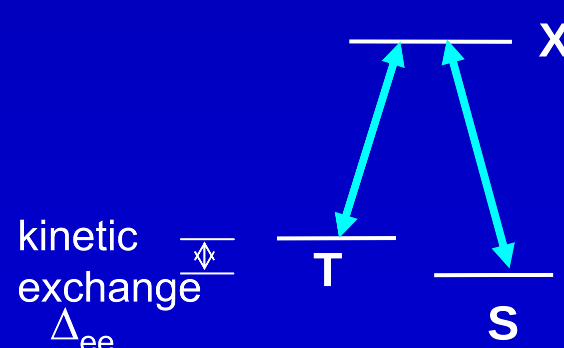




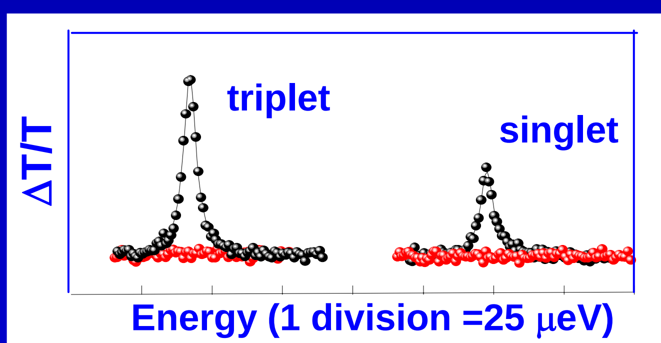
- Tunnel coupled QDs
- Exchange interaction always on
- Can access optically single qubit and two-qubit states

Energy diagram



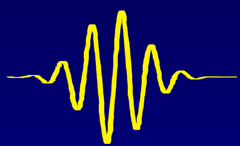


Initialization



Short vs. Long optical pulses

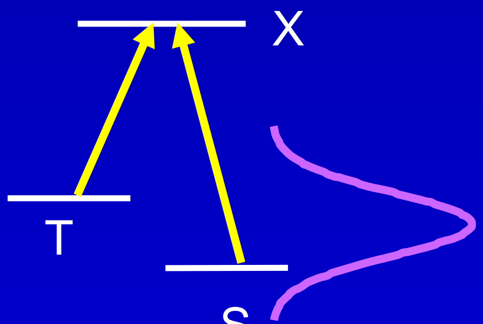
Short pulses



Time domain:

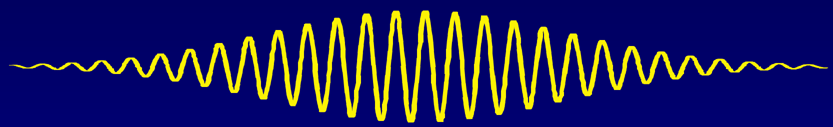
• Acts on *single* spin state because *faster* than exchange interaction

Frequency domain:



Acts on S + T

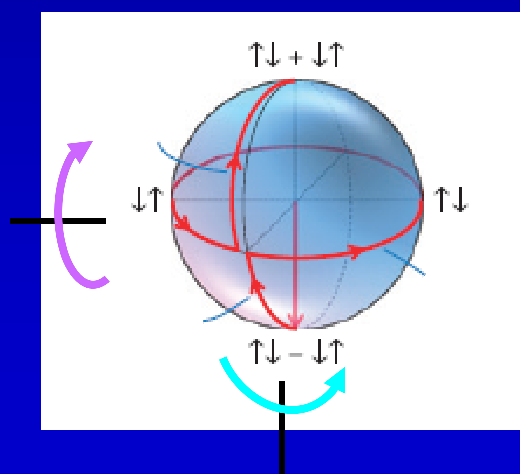
Long pulses

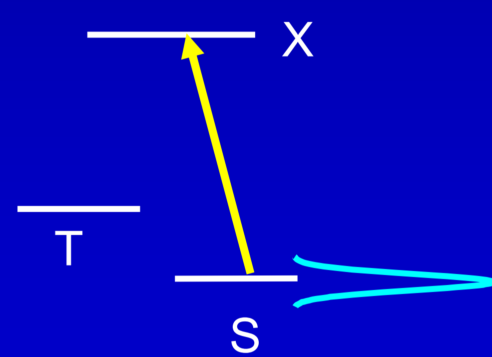


Time domain:

• Acts on *joint* spin state because *slower* than exchange interaction

Frequency domain:





Acts just on S

Optical 2-qubit phase gate

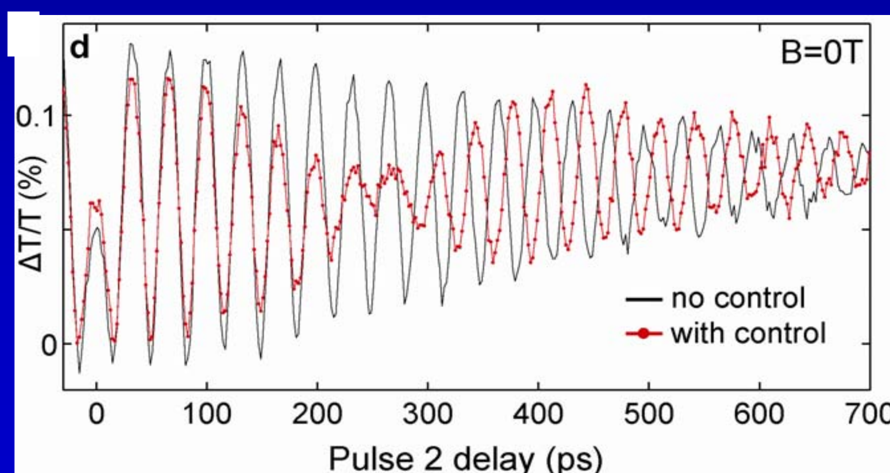
$$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \Rightarrow e^{i\phi}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

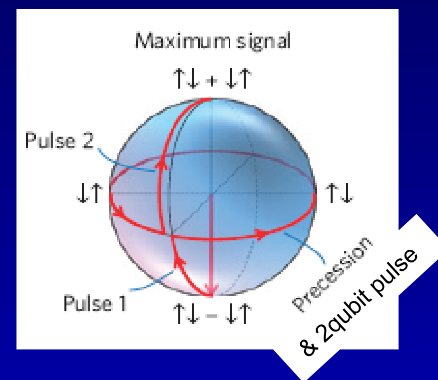
$$|\uparrow\downarrow\rangle \Rightarrow |\uparrow\downarrow\rangle - i|\downarrow\uparrow\rangle, \text{ for } \varphi = \pi/2$$

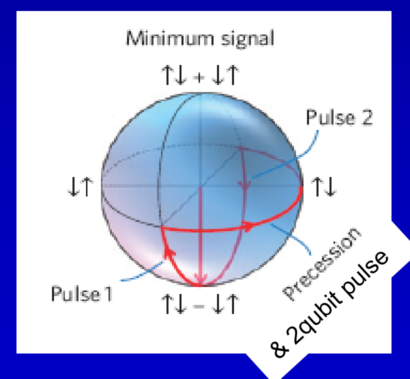
→ $\sqrt{\text{SWAP}}$ gate

Pulse sequence

Ramsey fringes with control pulse





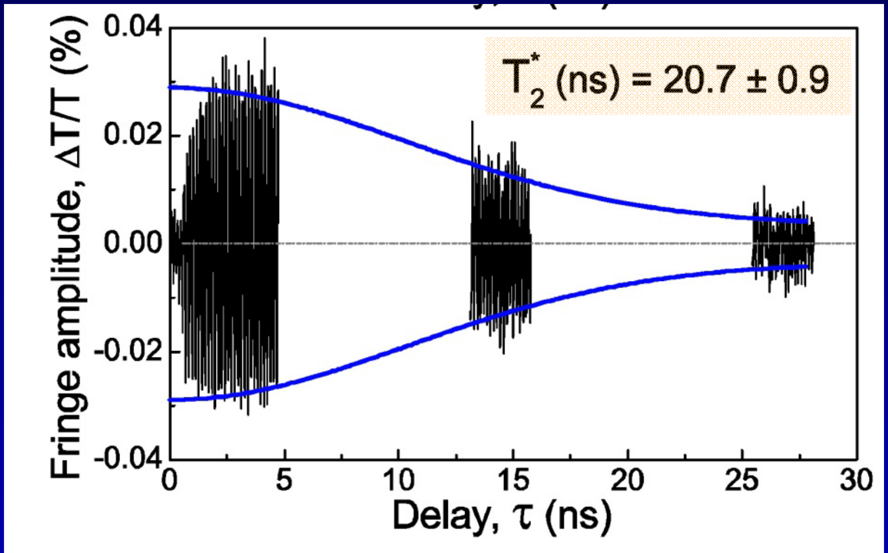


Can vary phase change from -180° to +180° with pulse detuning

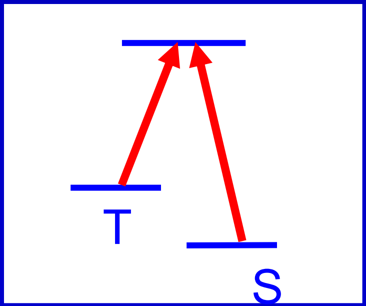
Kim *et al*, Nat. Physics, 7, 223 (2011)

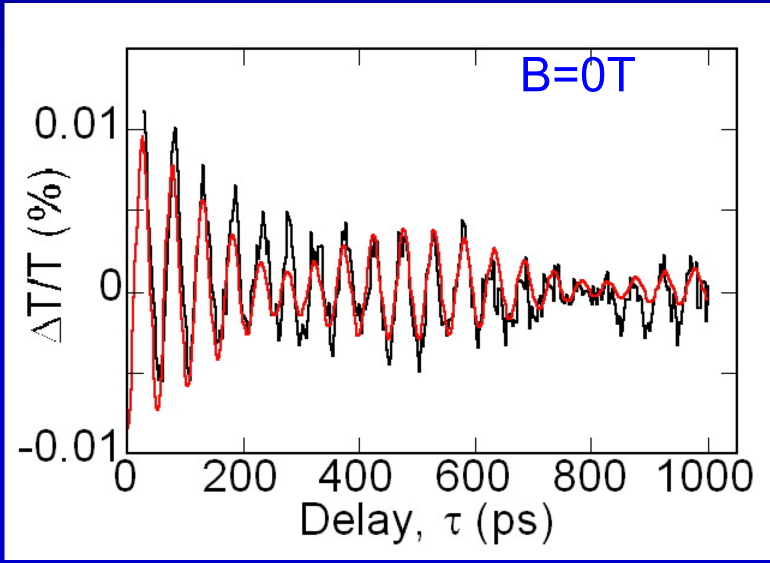
Alternative qubit: hole spin

Ramsey fringes of single hole qubit



Coupled hole qubits



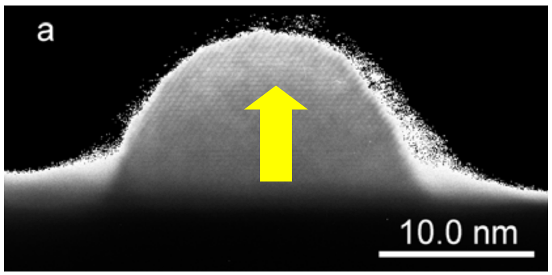


SUMMARY

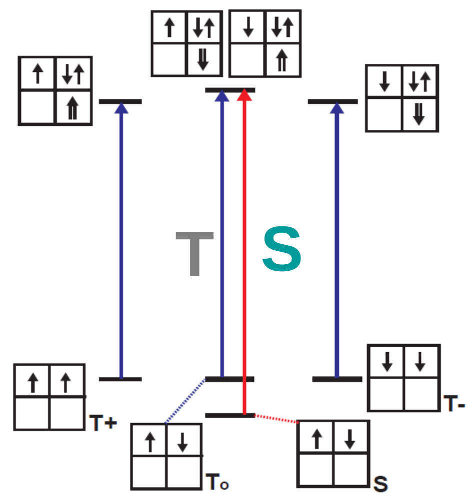
- Two qubit phase gate

$$U_g = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

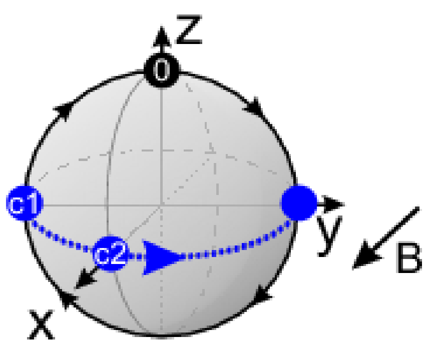
- Spins in quantum dots



- entanglement in QD molecules



- single qubit operations



Acknowledgements

NRL

Sophia Economou

Dmitry Solenov

Dan Gammon

Sam Carter

Allan Bracker

Wuerzburg University

Alfred Forchel group

Dortmund University

Manfred Bayer group

Alex Greilich

Support:

ONR

DARPA

NSA