Problems of Modern Physics

Lecture 4

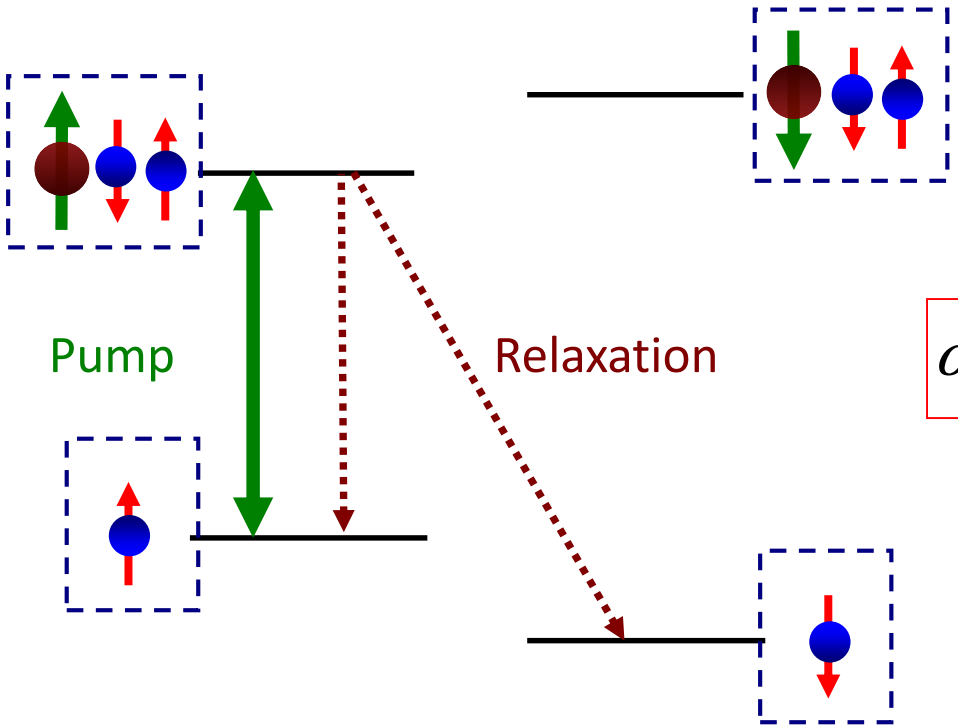
Semion K. Saikin
Department of Chemistry and Chemical Biology
Harvard University

Email: saikinsk@gmail.com

Spin qubits in QDs

Fast initialization

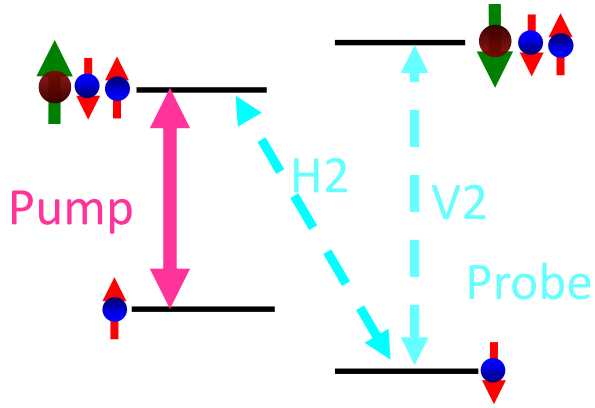
Whenever an electron is in the state flip it to the state.

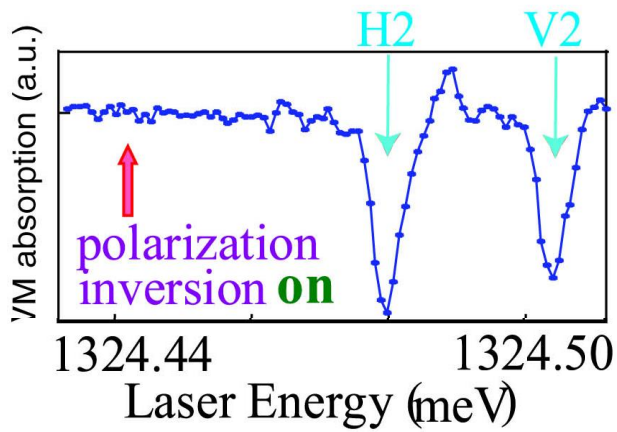


$$\alpha|\uparrow\rangle + \beta|\downarrow\rangle \Rightarrow |\downarrow\rangle$$

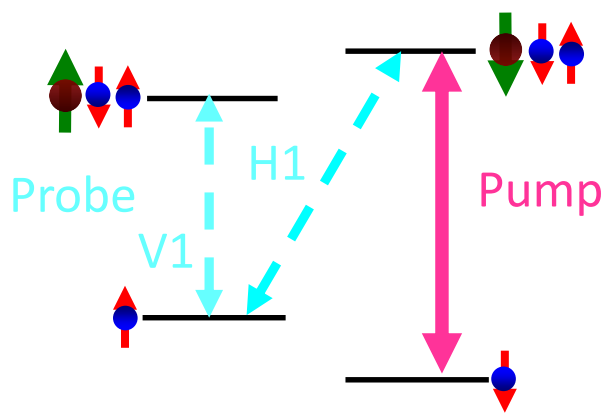
C. Emary, et. al. Phys. Rev. Lett. 98, 047401 (2007)

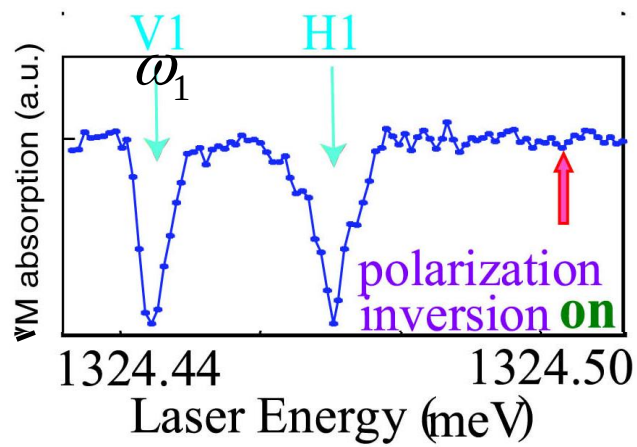
Pump-probe of initialization





State preparation efficiency 98.9%



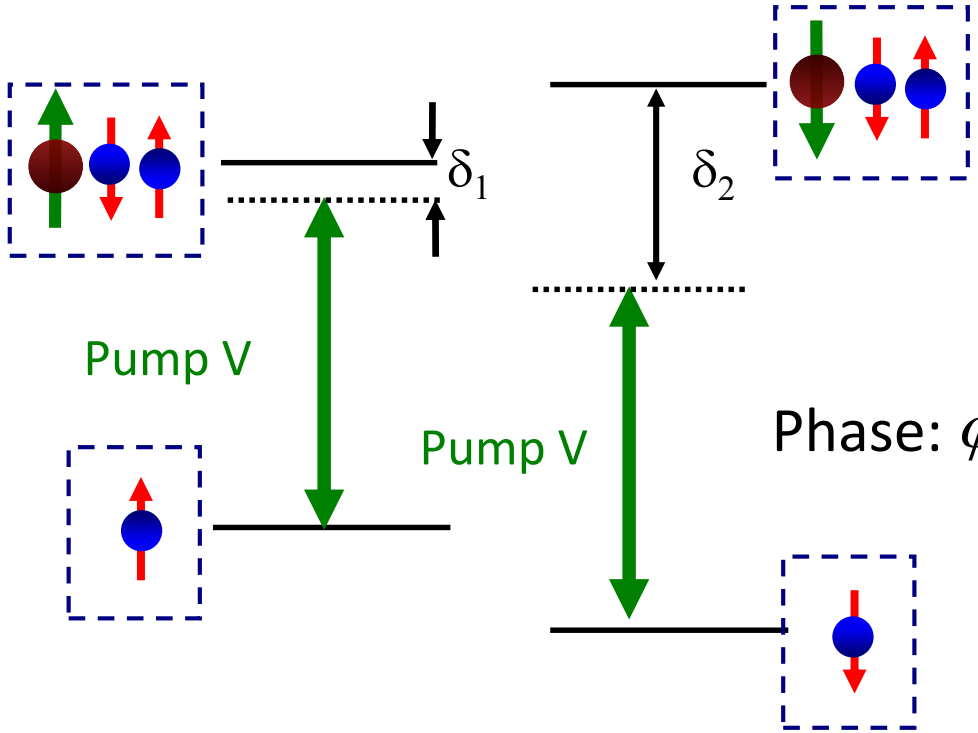


D. Steel, U. Michigan
D. Gammon, NRL

X. Xu, *et. al.*, PRL **99**, 097401 (2007)

Single qubit phase gate

Phase: $\varphi_1 \propto \frac{V^2}{\delta_1} t_{pulse}$



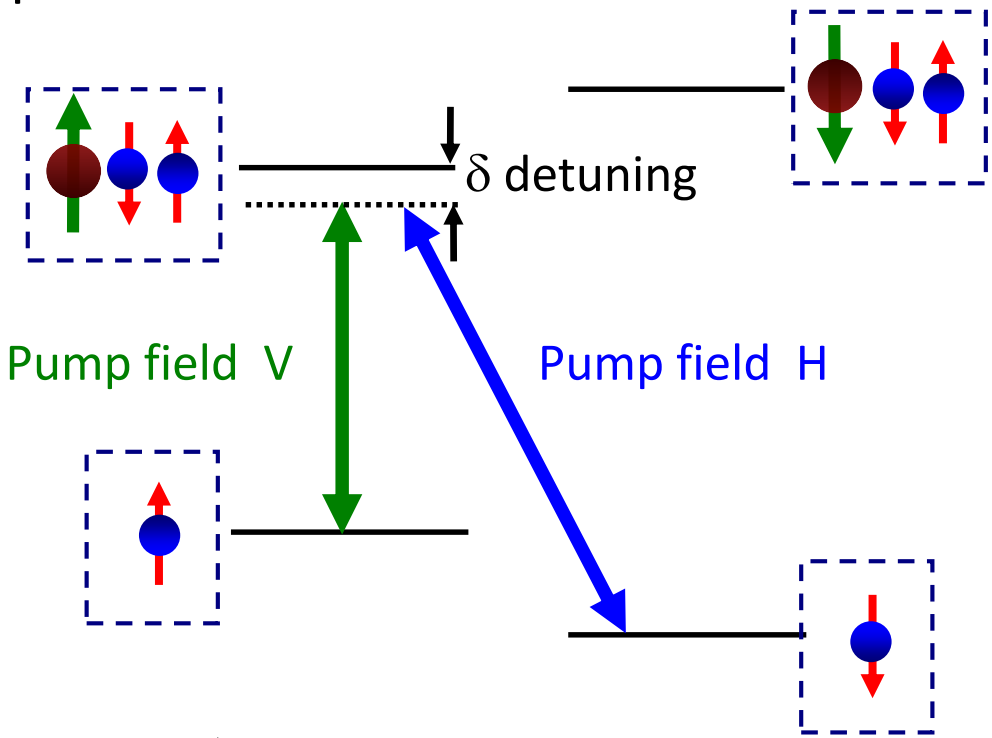
Phase: $\varphi_2 \propto \frac{V^2}{\delta_2} t_{pulse}$

$$H_{gate} = \begin{pmatrix} -\frac{V^2}{\delta_1} & 0 \\ 0 & -\frac{V^2}{\delta_2} \end{pmatrix}$$

$$\boxed{\alpha|\uparrow\rangle + \beta|\downarrow\rangle \Rightarrow \alpha e^{-i\varphi_1}|\uparrow\rangle + \beta e^{-i\varphi_2}|\downarrow\rangle}$$

Single qubit operations

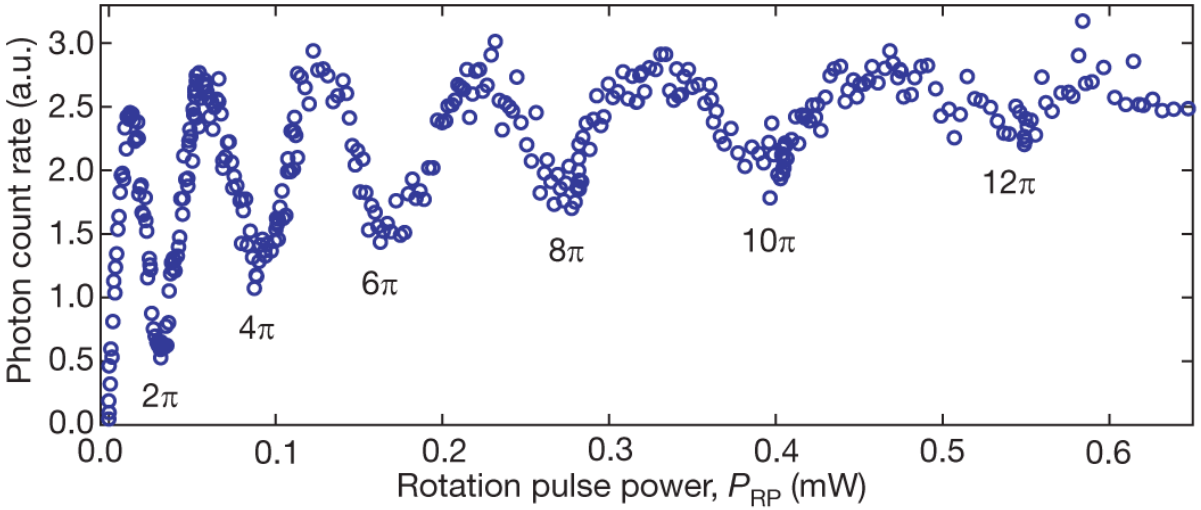
Use frequency and polarization selection



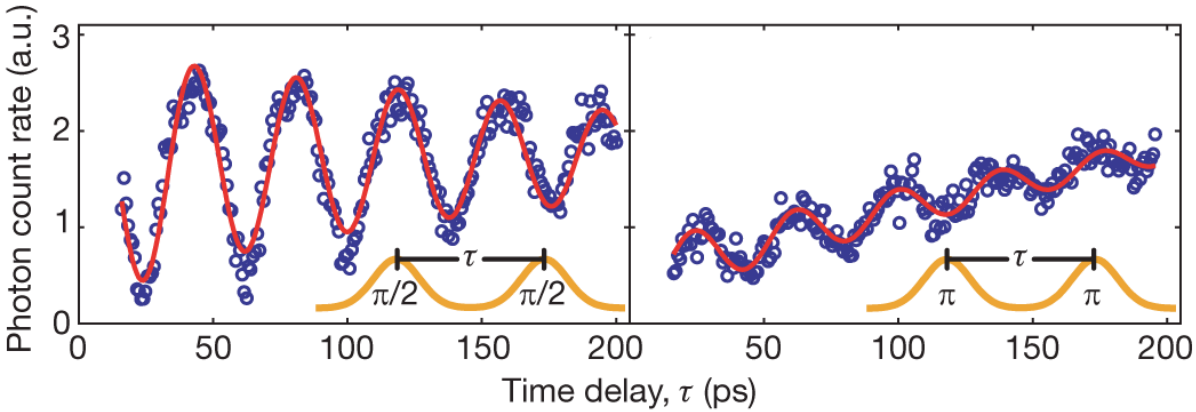
$$H_{gate} = \begin{pmatrix} 0 & -\frac{VH}{\delta} \\ -\frac{VH}{\delta} & 0 \end{pmatrix}$$

Single qubit operations: experiment

Rabi oscillations

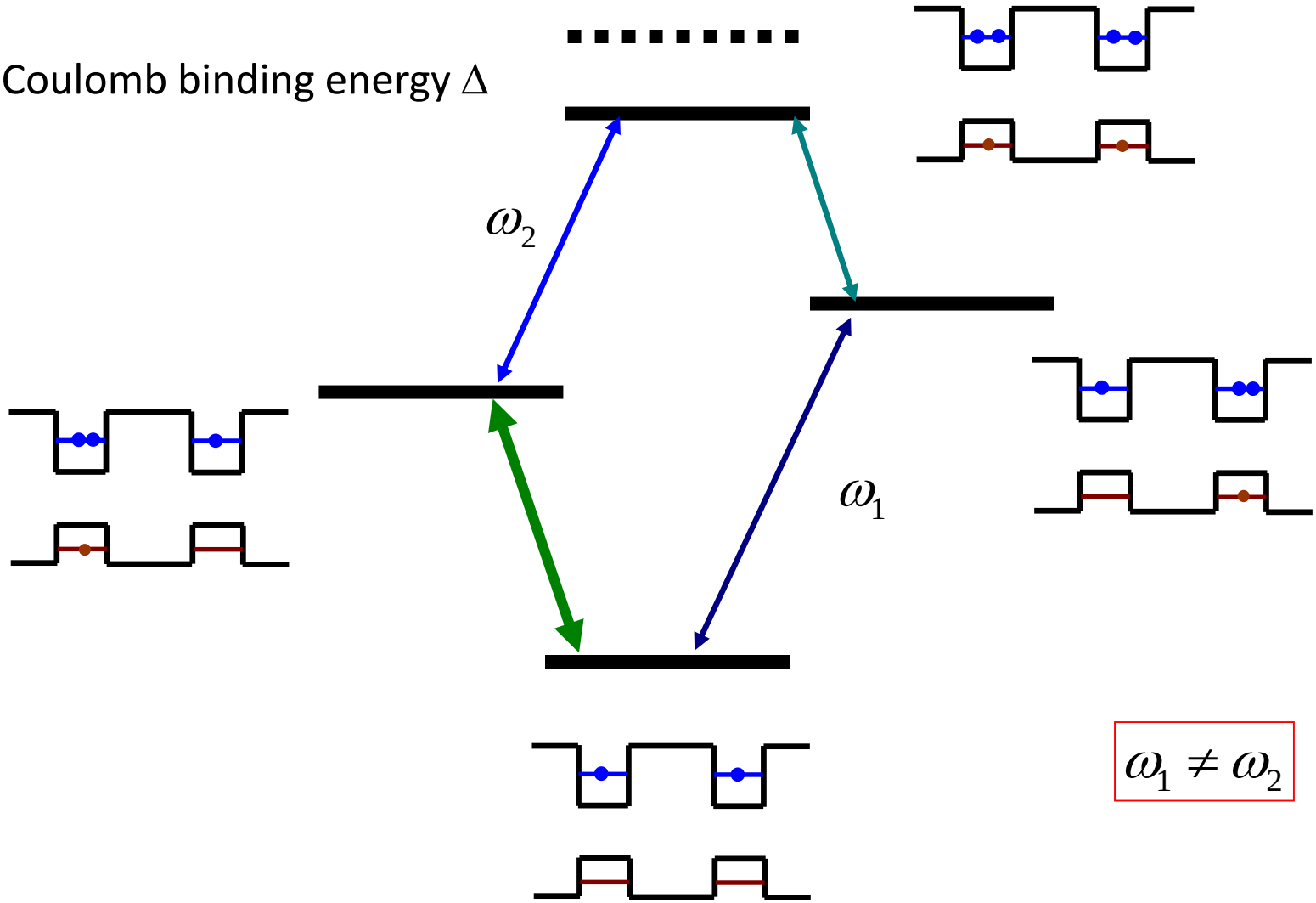


Ramsey fringes



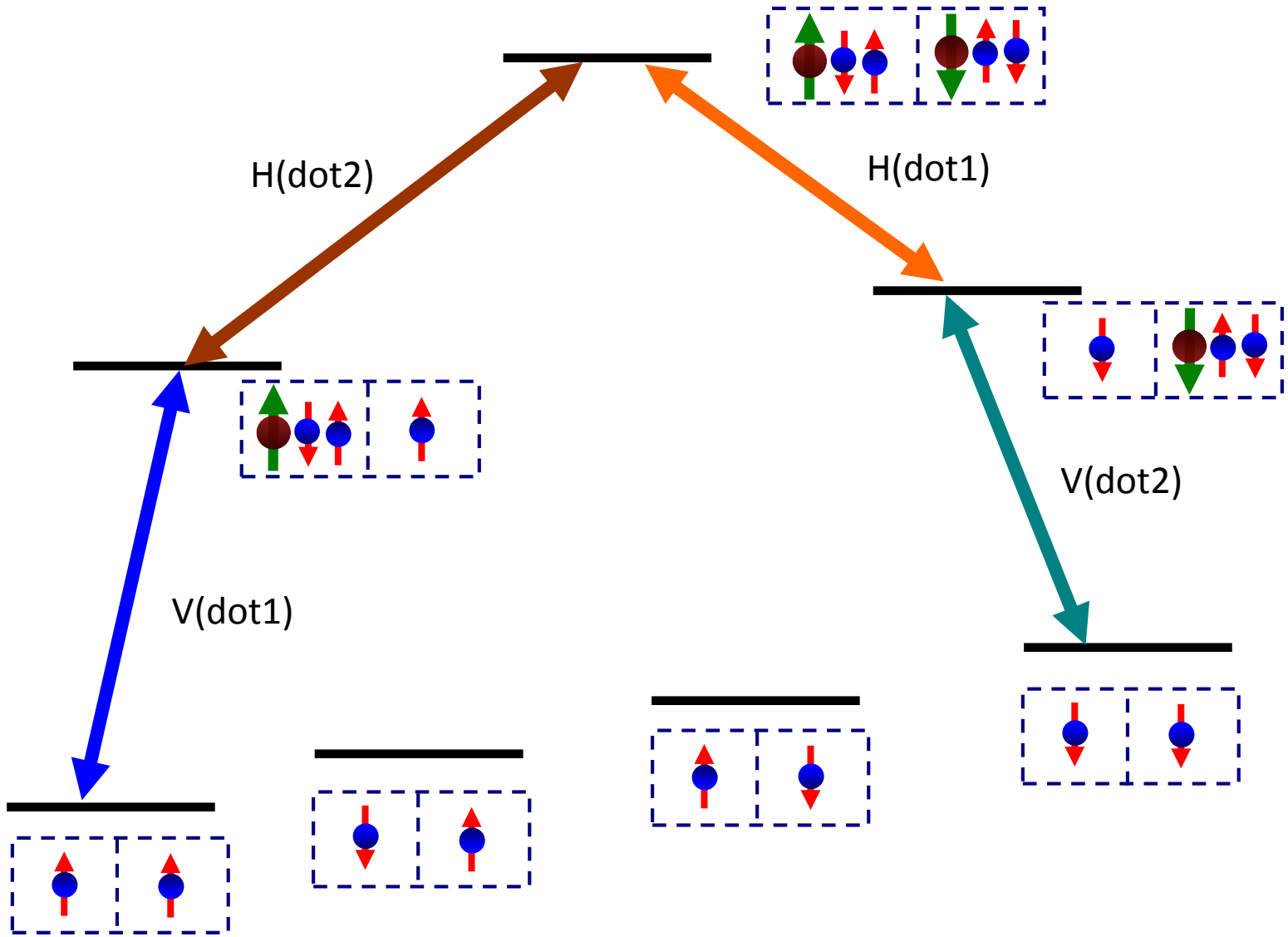
D. Press, et. al. Nature 456, 218 (2008)

Two-qubit systems: conditional phase gate



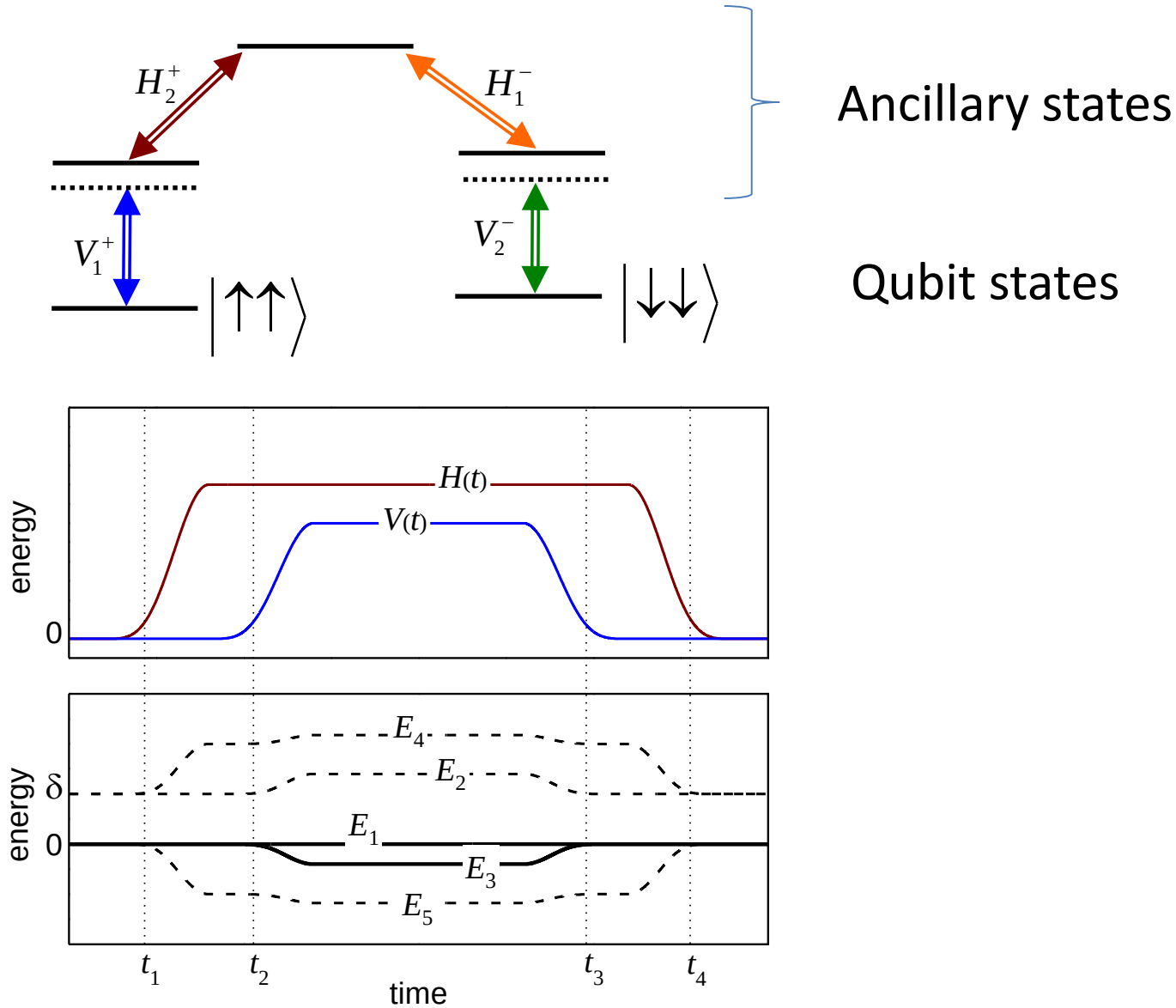
$\omega_1 \neq \omega_2$

Two-qubit systems: SWAP gate



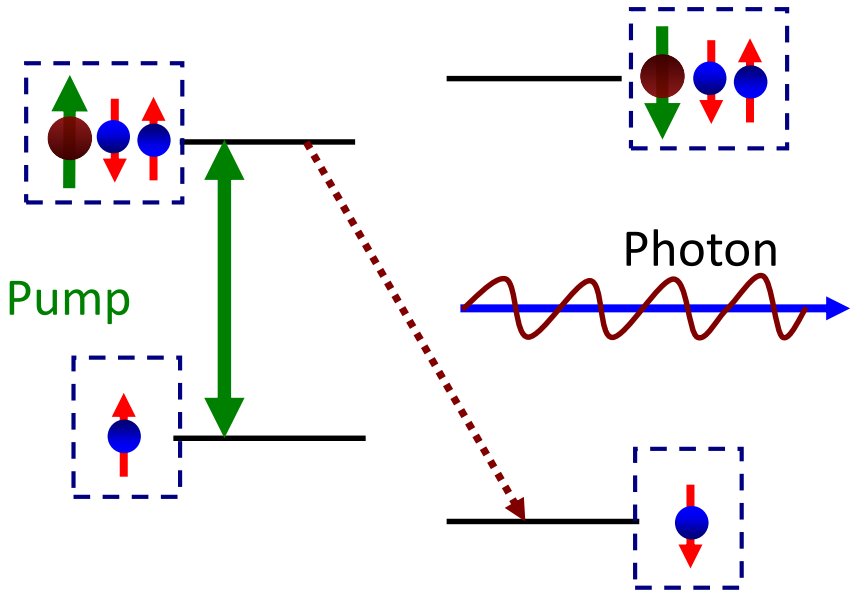
- Frequency and polarization selection of a particular coupling

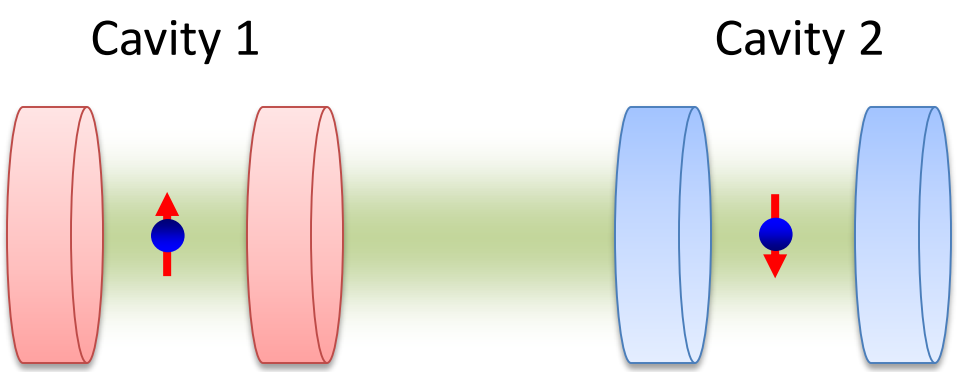
Adiabatic SWAP gate

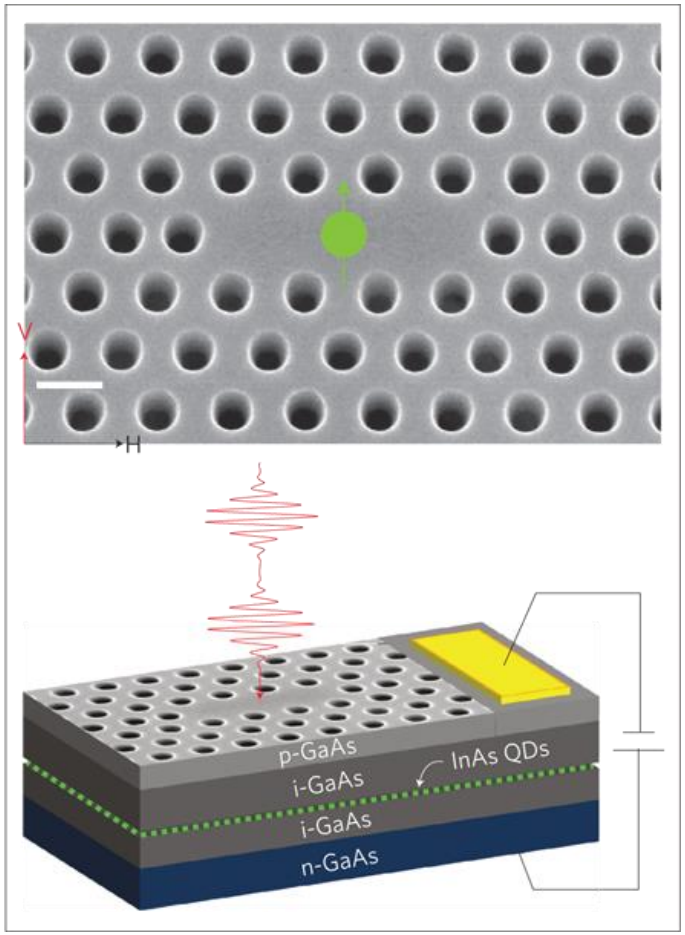


S.K.Saikin, et. al. PRB 78, 235314 (2008)

Two-qubit hybrid SWAP gate





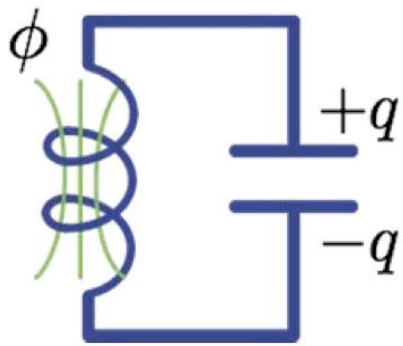


S. G. Carter, et. al. Nature Photonics 7, 329 (2013)

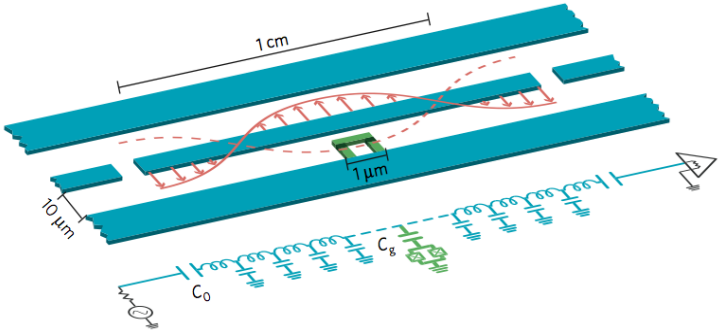
Superconducting qubits

Quantization of e/m field

LC-contour



Transmission line resonator

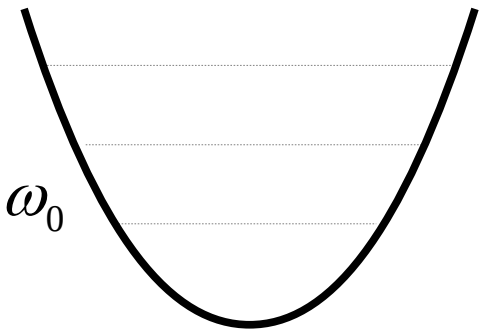


Single photon mode

$$\omega_0 = \frac{1}{\sqrt{LC}}$$ ~ 5 GHz

Photon band

~ 2-10 GHz



Harmonic oscillator

Canonical variables:

Charge: q

Flux: ϕ

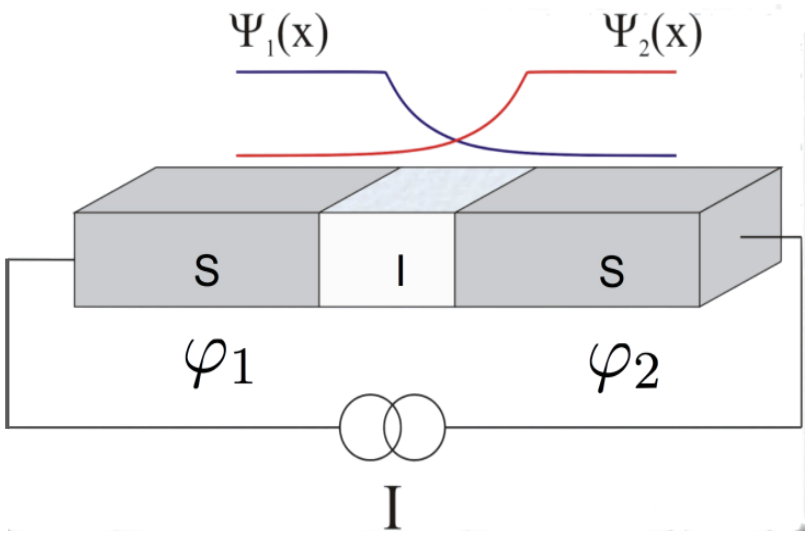
Hamiltonian

$$H = \frac{1}{2C}q^2 + \frac{1}{2L}\phi^2$$

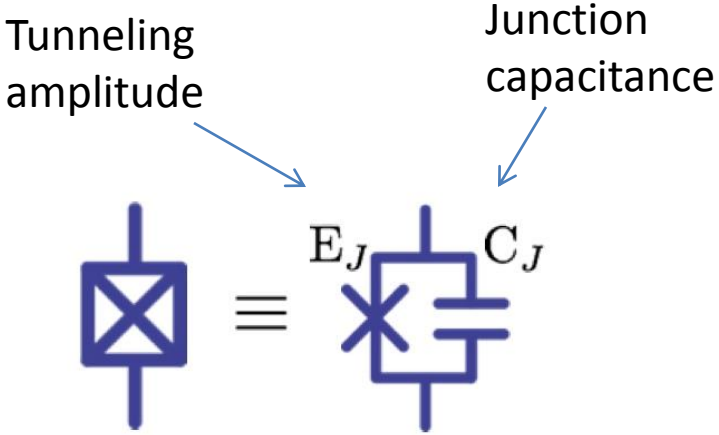
Josephson junction

Adding anharmonic terms

- Non-linear, dissipationless, inductive element
- Coherent tunneling of Cooper pairs
- Oscillating current between superconductors



$$I = I_0 \sin\phi \qquad \phi \propto \varphi_1 - \varphi_2$$



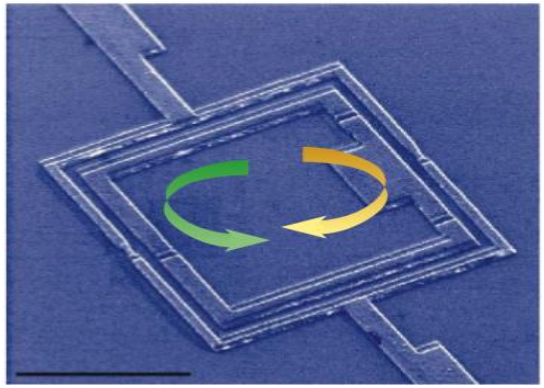
Hamiltonian

$$H = \frac{2e^2}{C} q^2 - I_0 \phi_0 \cos\phi$$

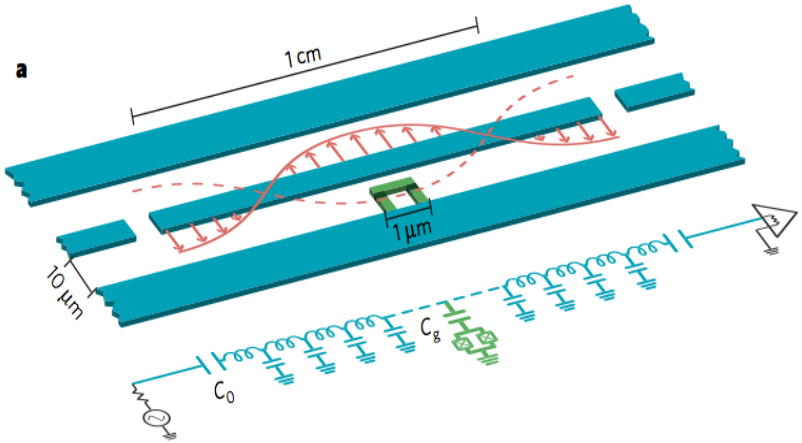
Anharmonicity

Flux qubit

Flux quantization



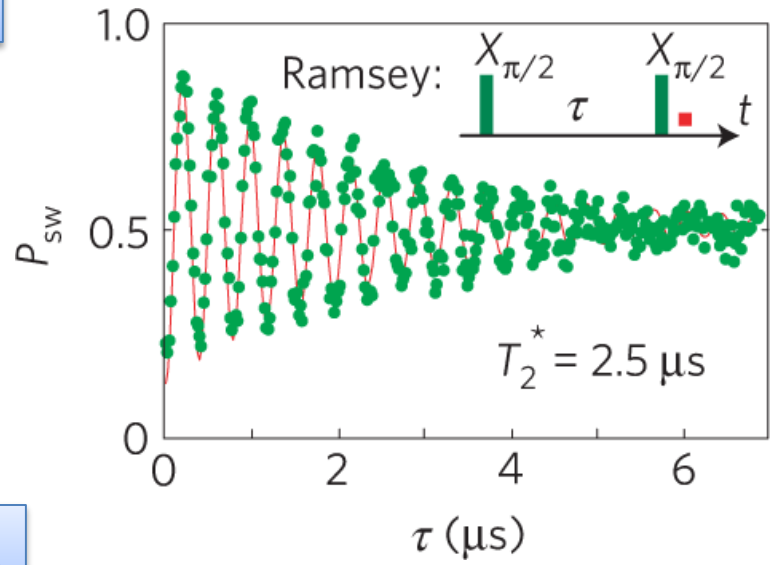
Capacitive coupling to transmission line



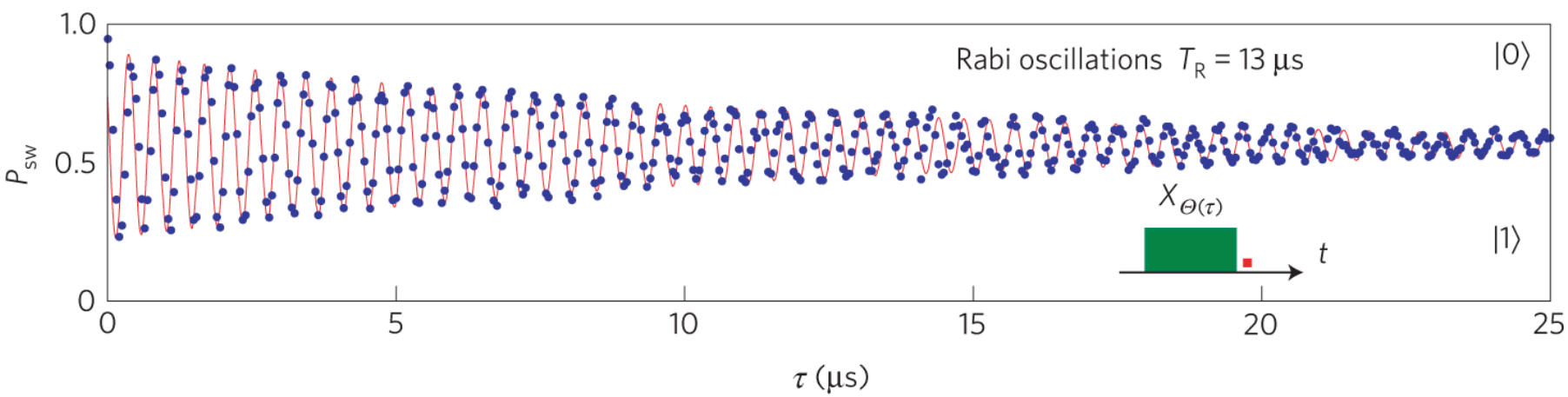
H. Mooij et. al. Science (2003) (Flux qubit)

Single qubit operations

Ramsey fringes



Rabi oscillations



J. Bylander, et. al. Nature Physics 7, 565 (2011)

Requirements for qubits

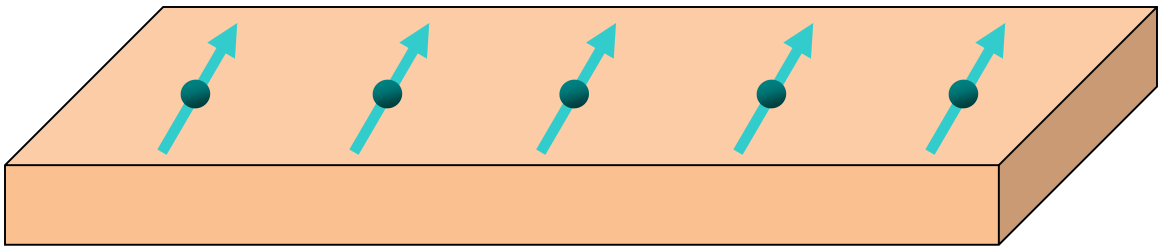
- Ability to scale the architecture to a large number of qubits.
- Initialization (set all qubits to 0) should be possible.
- Precise single and two-qubits quantum operations.
- Slow error rate (slow decoherence as compared to gate time).
- Reliable output of the final result.

Scaling of qubit systems

$$H_{ex} = \mathbf{S}_1 \mathbf{J}(E) \mathbf{S}_2$$

$$\mathbf{J}(E) \propto e^{-\alpha R_{12}}$$

Gate interaction is very sensitive to the relative position of qubits



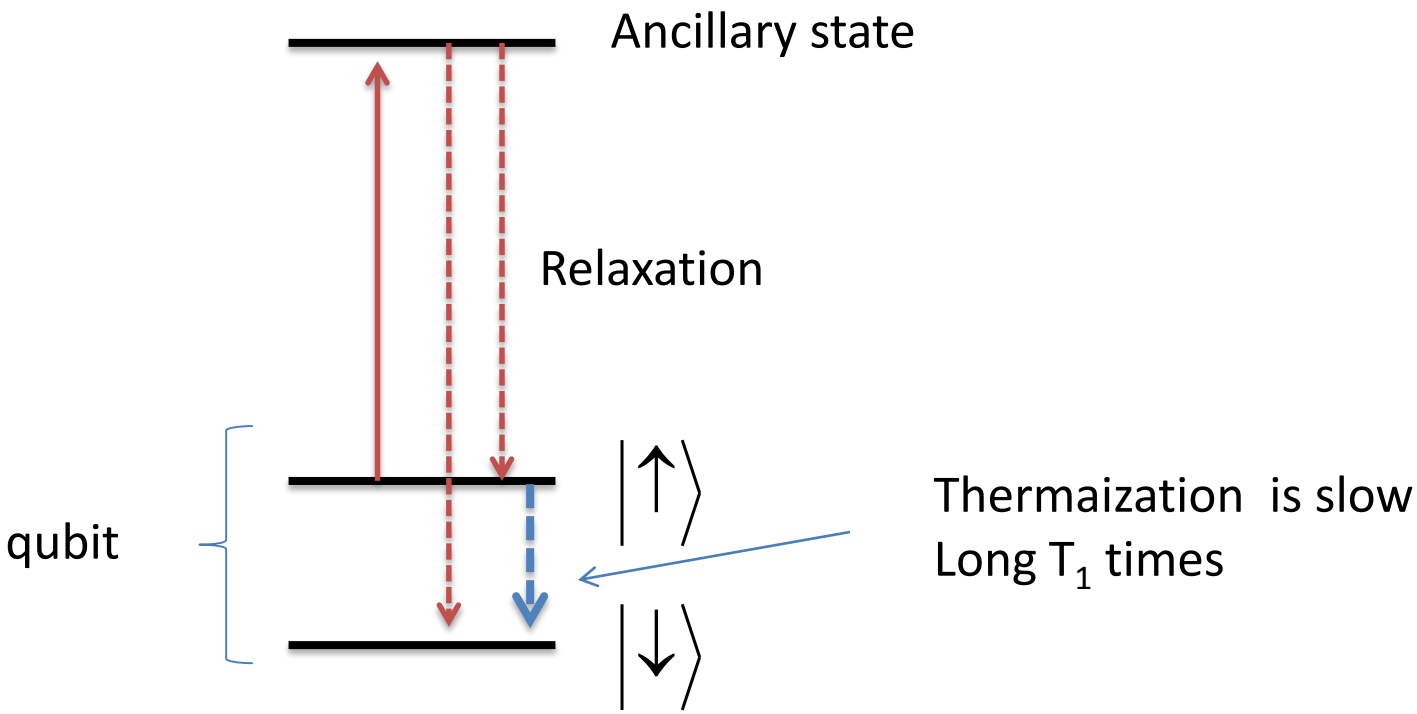
$$H_{dipole} = \mathbf{S}_1 D \mathbf{S}_2$$

$$\mathbf{D} \propto R_{12}^{-3}$$

Long-range interaction between qubits

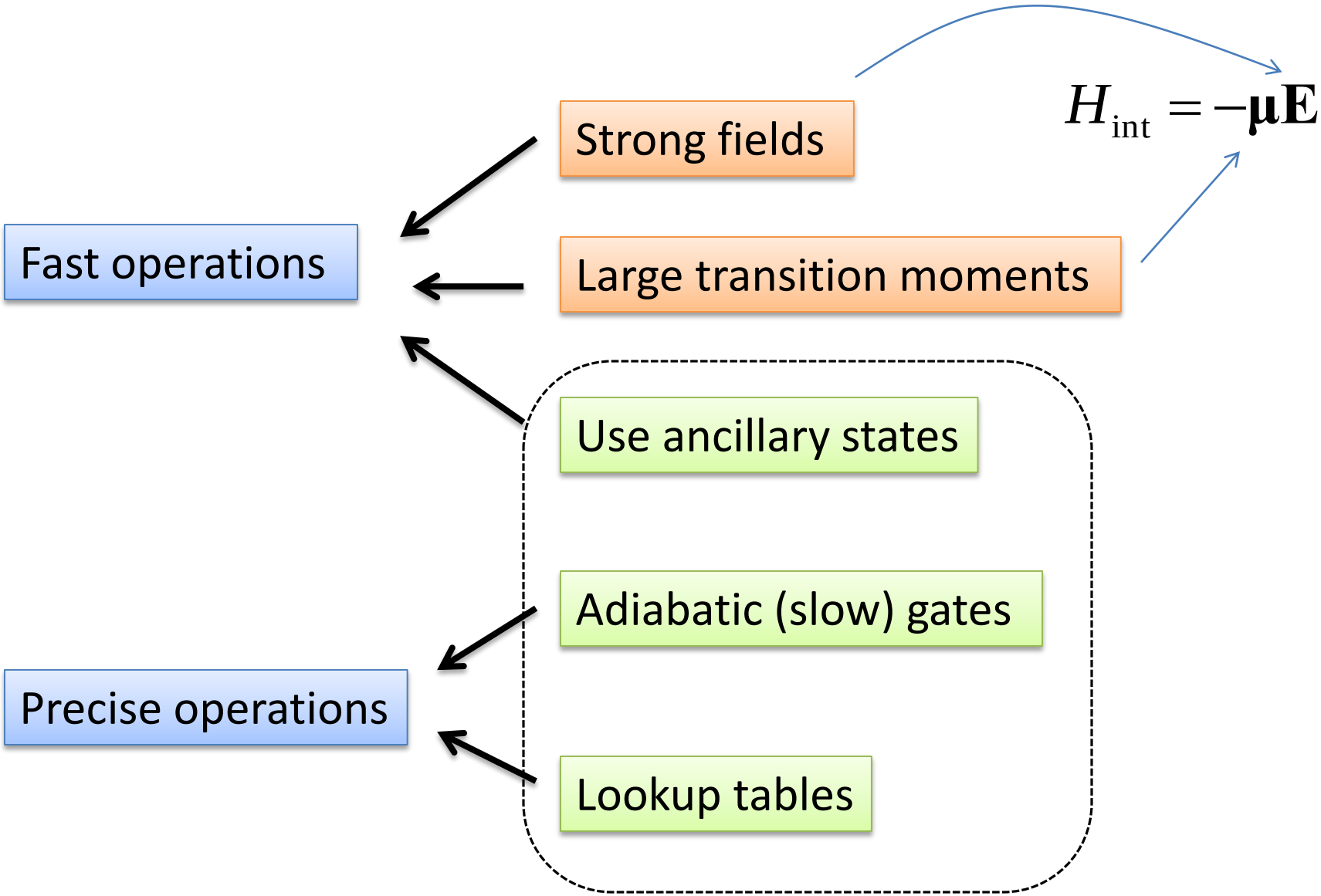
- Two-qubit gates are for nearest neighbors only
- Some implementations, e.g. nuclear spins in molecules or ions in e/m traps, may have natural limitations in scaling
- Hybrid systems with different types of qubits, e.g. spins and photons, should be used

Initialization/redout



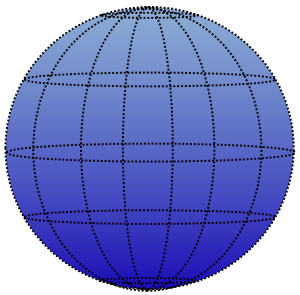
- Requires fast operations between qubit and ancillary states.

Precise and fast operations



Decoherence

System + Bath = Closed quantum system



Phonons,
Photons,
Electrons,
Spins…

Space available for the qubit evolution

System is entangled with the bath

<u>No-relaxation model</u>

$$|\Psi(0)\rangle = \left(\alpha|\uparrow\rangle + \beta|\downarrow\rangle\right)|J\rangle \longrightarrow |\Psi(t)\rangle = \alpha(t)|\uparrow\rangle|J_\uparrow\rangle + \beta(t)|\downarrow\rangle|J_\downarrow\rangle$$

system bath

$$\rho = \begin{pmatrix} |\alpha(t)|^2 \langle J_\uparrow|J_\uparrow\rangle & \alpha(t)\beta^*(t)\langle J_\downarrow|J_\uparrow\rangle \\ \beta(t)\alpha^*(t)\langle J_\uparrow|J_\downarrow\rangle & |\beta(t)|^2 \langle J_\downarrow|J_\downarrow\rangle \end{pmatrix}$$

D-Wave “quantum computer”

D-Wave machine

The quantum computer of our dreams:

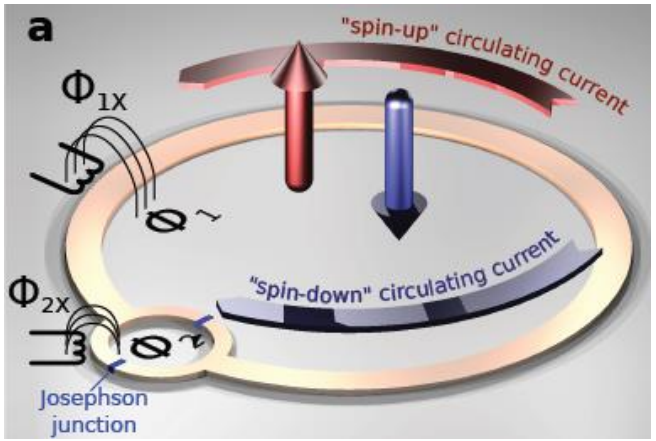
- Gate model
- Highly impractical
- Well characterized

The D-Wave "quantum computer" :

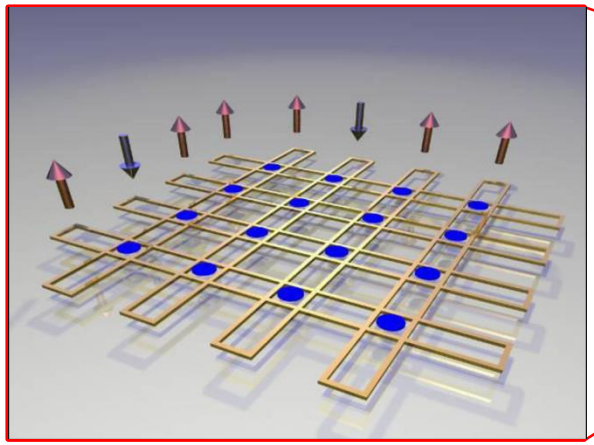
- Not universal
- Not characterized
- It definitely solves problems, has some quantum properties and **exists**

Architecture

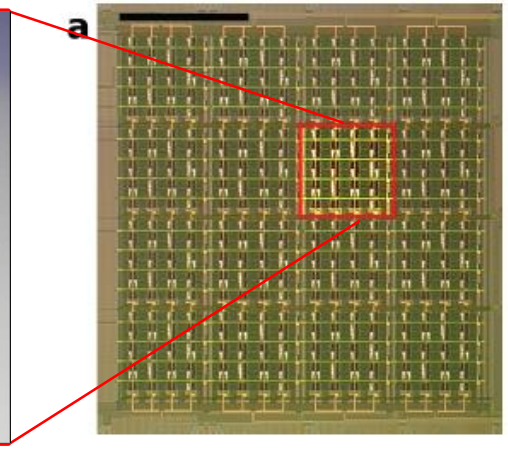
Superconducting flux qubit



8-qubit unit cell



Optical image: 128 qubit chip



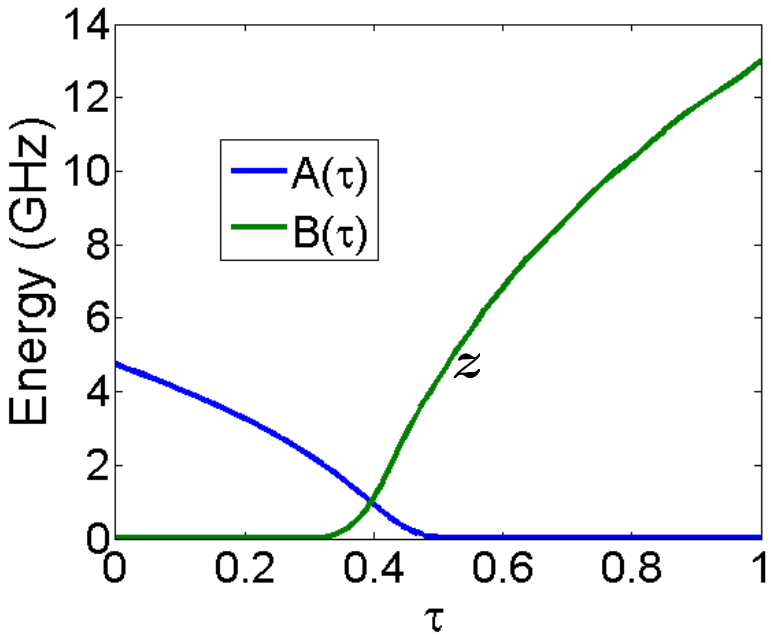
What is the device good for:

Design to solve **DISCRETE OPTIMIZATION**

Find the assignment $\mathbf{s} = s_1^*, s_2^*, \cdots, s_N^*$ which minimizes the objective function:

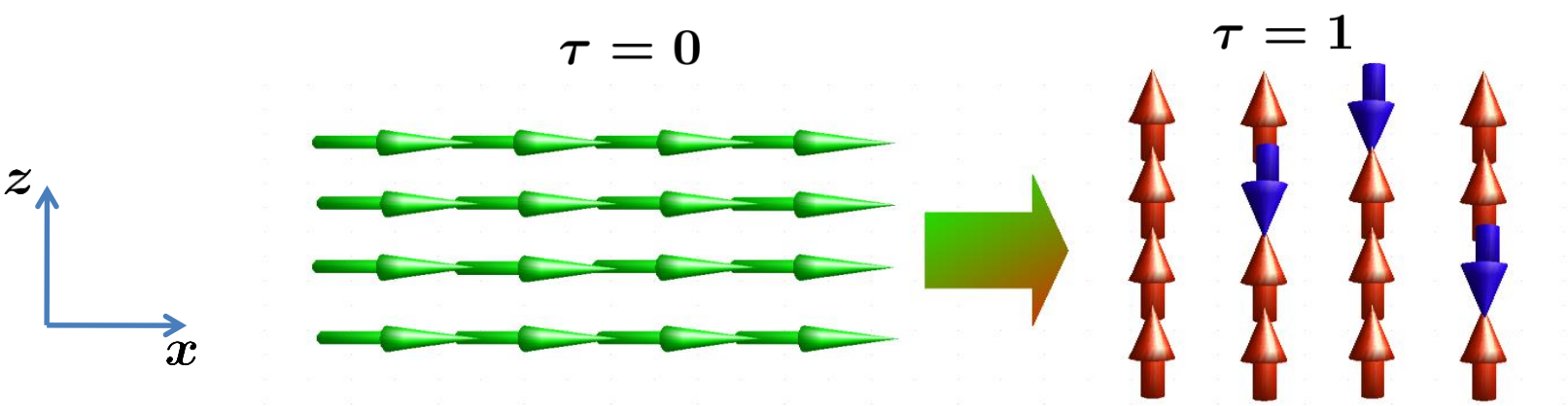
$$F = \sum_i^N h_i s_i + \sum_{j>i}^N J_{ij} s_i s_j, \qquad s_i \in \{-1, 1\}$$

Adiabatic quantum computing



$$H(\tau) = A(\tau)\sum_i \sigma_i^x + B(\tau)H_p$$

$$\tau = t/t_{run} \qquad t_{run} = 148\mu s$$

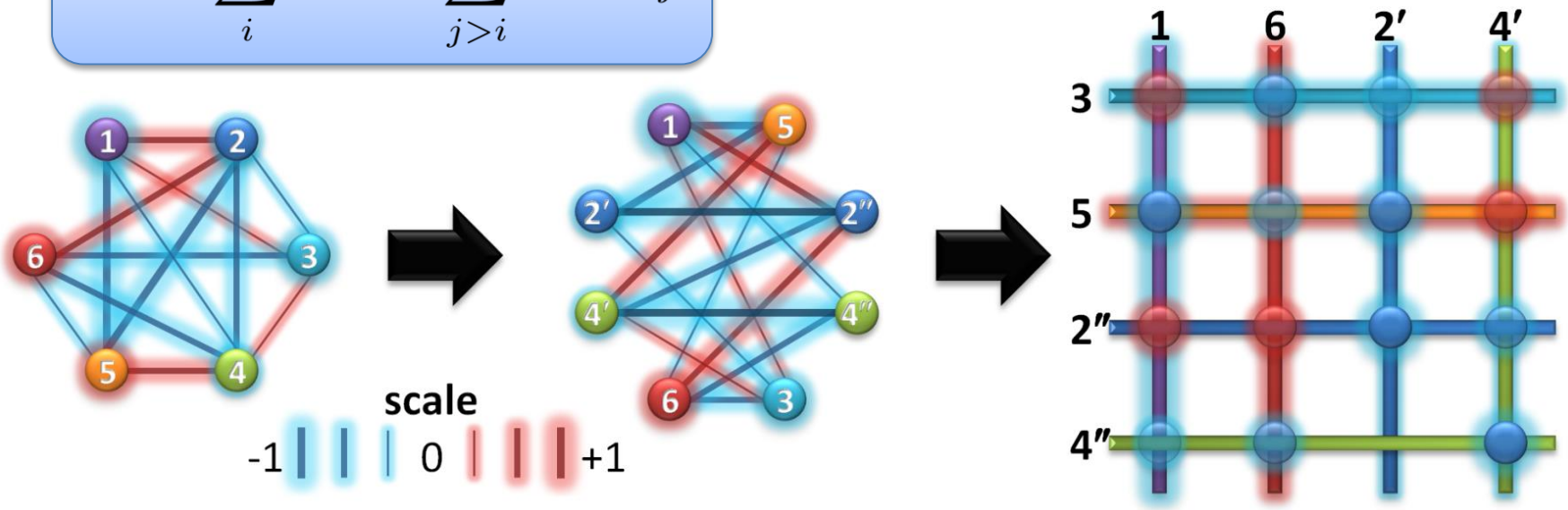


Transverse field ON
Longitudinal field OFF

Transverse field OFF
Longitudinal field ON

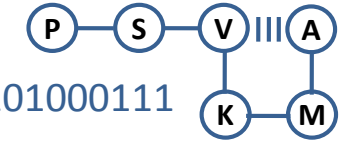
Mapping problem on quantum device

$$H_p = \sum_{i}^{N} h_i \sigma_i^z + \sum_{j>i}^{N} J_{ij} \sigma_i^z \sigma_j^z$$



Hardware dictates encoding strategy

Encode Problem

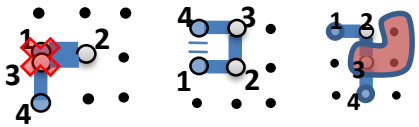


0101000111

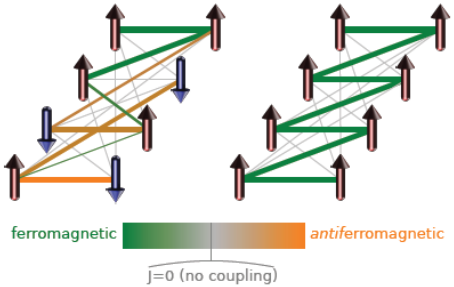
$$q = \underbrace{01}_{\text{turn 1}}\ \underbrace{0q_1}_{\text{turn 2}}\ \underbrace{q_2q_3}_{\text{turn 3}}\ \underbrace{q_4q_5}_{\text{turn 4}} \cdots \underbrace{q_{2(N-3)-1}q_{2(N-3)}}_{\text{turn N-1}}$$

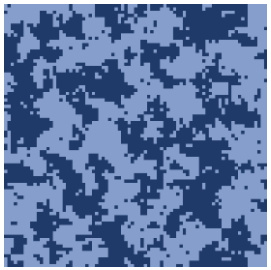
Create Objective Function

$$E(q) = E_{onsite}(q) + E_{pair}(q) + E_{ext}(q)$$

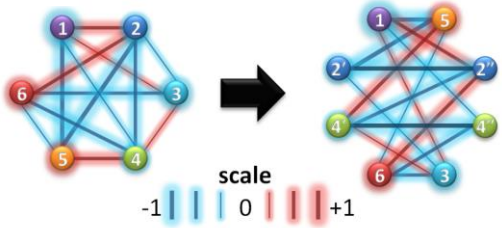


HARDWARE ABILITIES



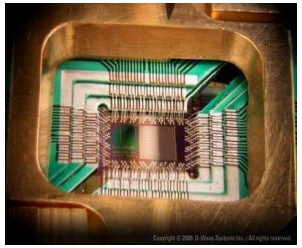


Embed in Hamiltonian



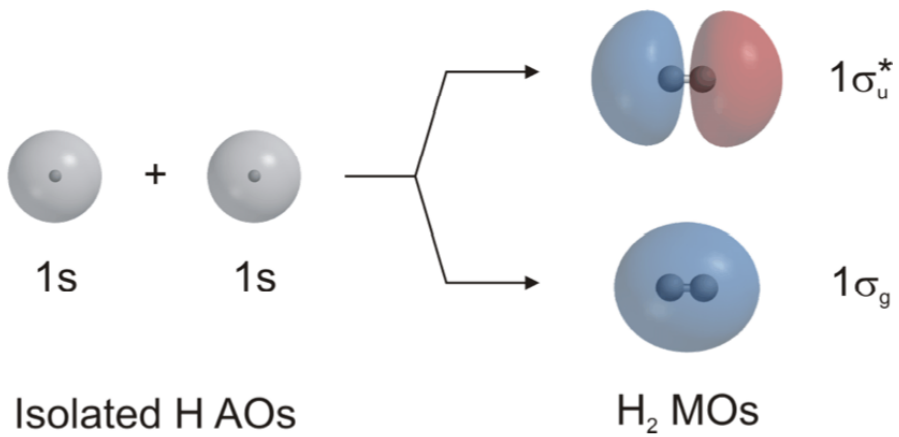
Map to device

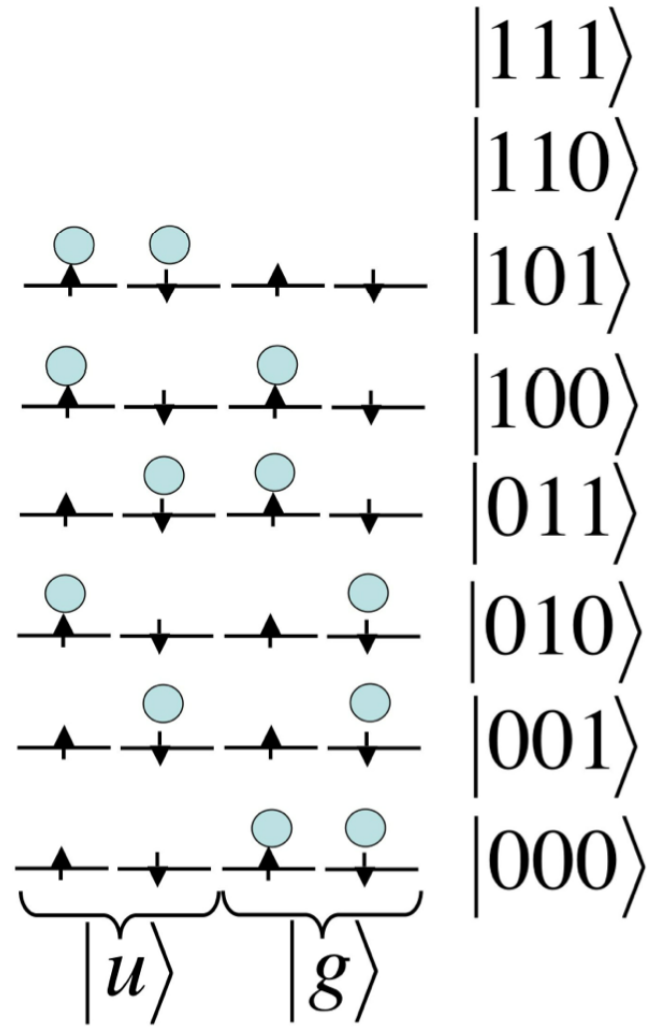
Solve on Device



Quantum simulators

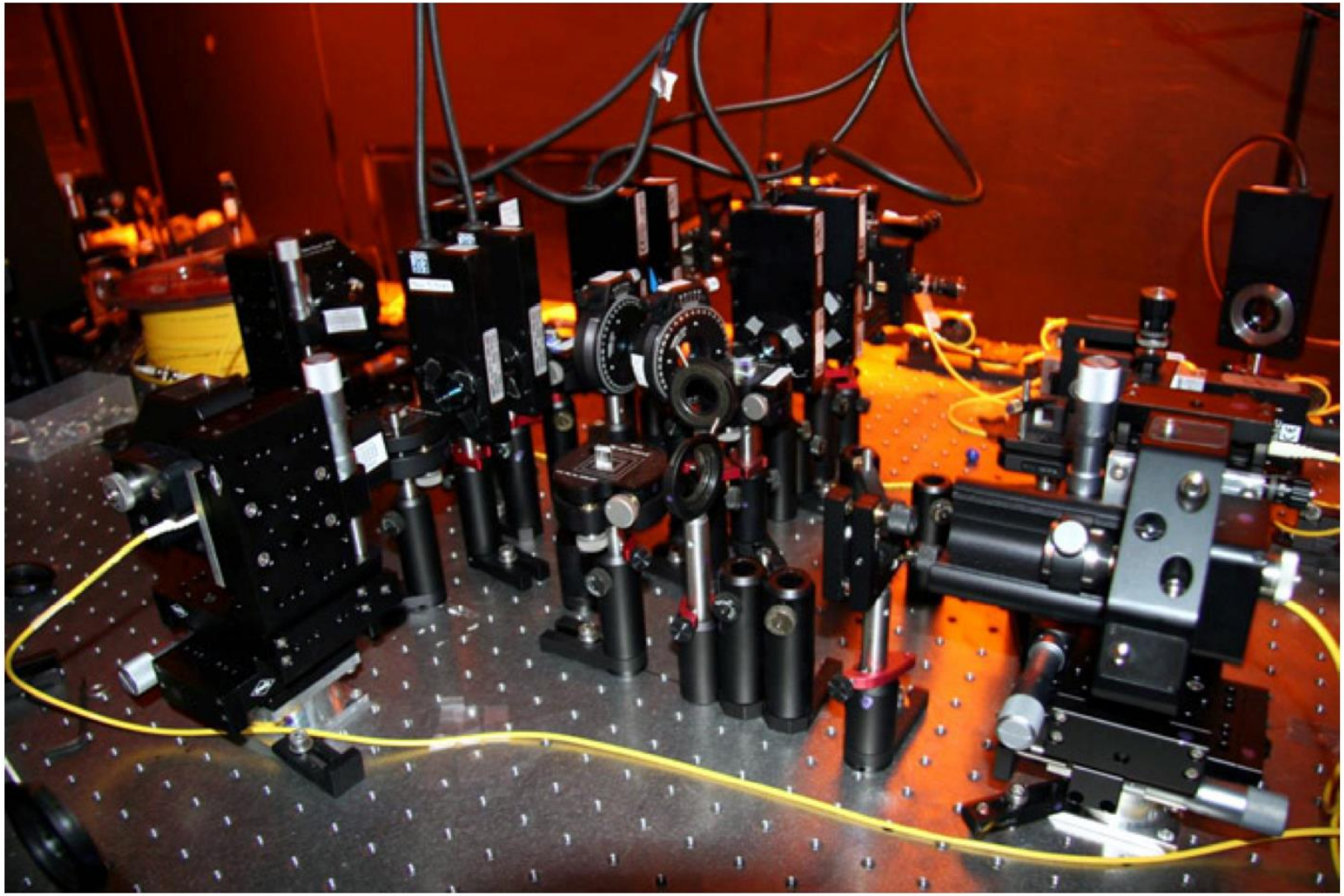
Electronic structure of Hydrogen molecule

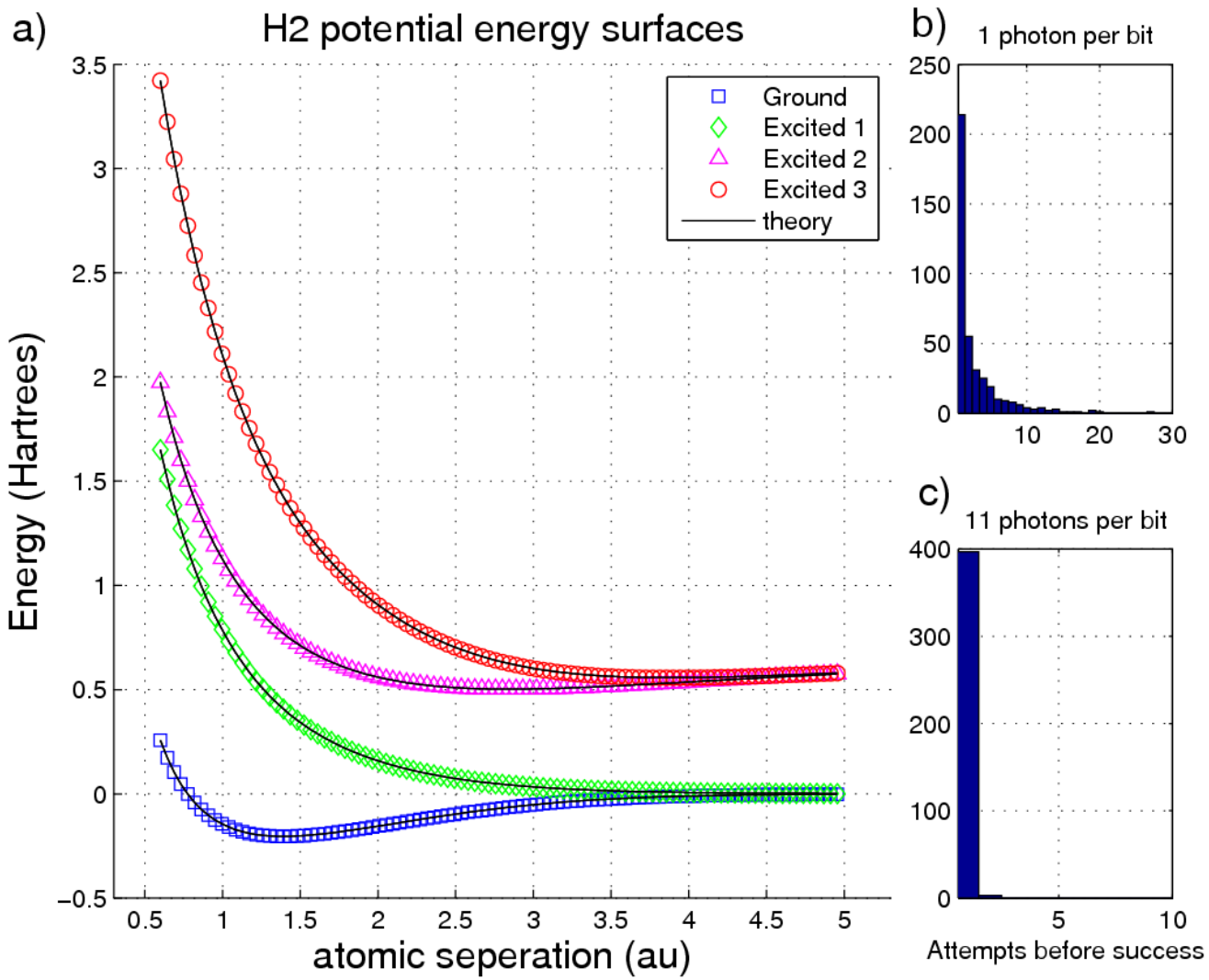




H is 6×6, but block-diagonal.
Need to diagonalize 2×2 matrices.

Optical setup



Lanyon et. al., Nature Chemistry (2010)

Energy curves