Problems of Modern Physics

Lecture 3

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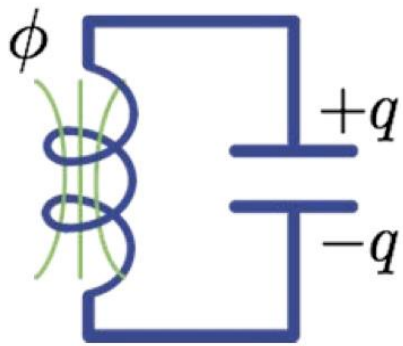
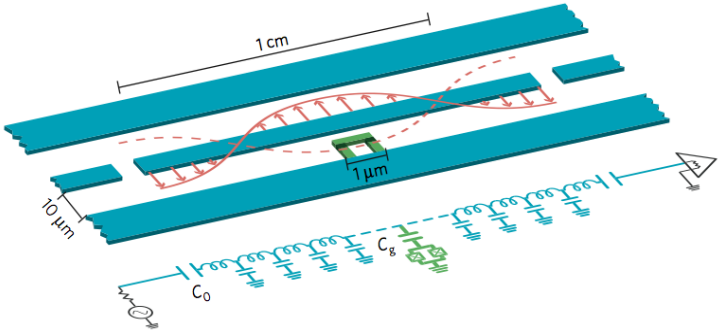
Superconducting qubits

Quantization of e/m field

LC-contour



Transmission line resonator

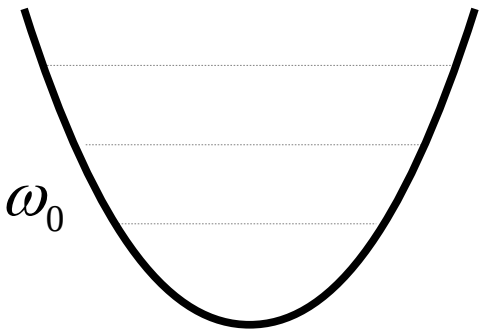


Single photon mode

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

Photon band

~ 2-10 GHz



Harmonic oscillator

Canonical variables:

Charge: q

Flux: ϕ

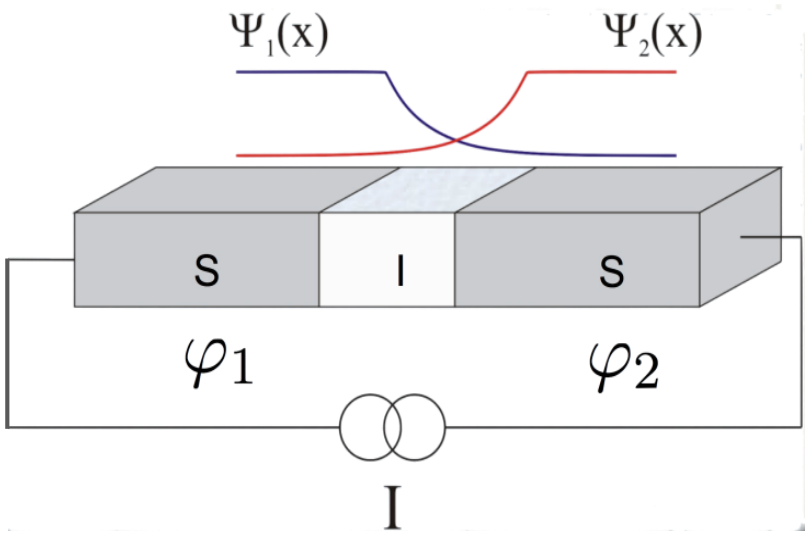
Hamiltonian

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

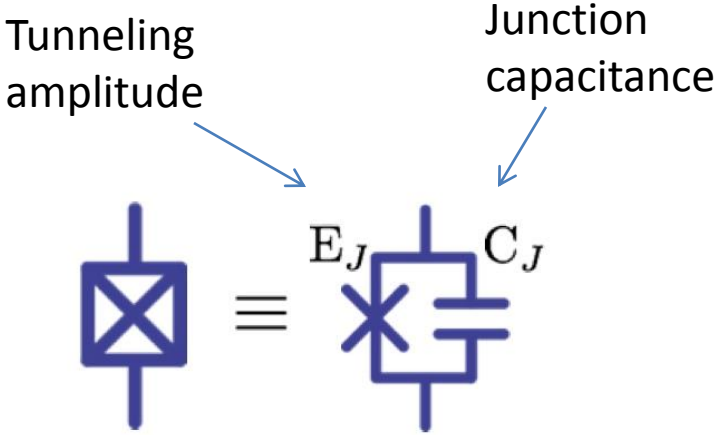
Josephson junction

Adding anharmonic terms

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



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



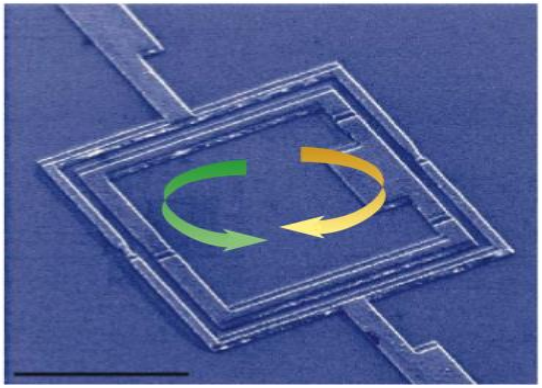
Hamiltonian

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

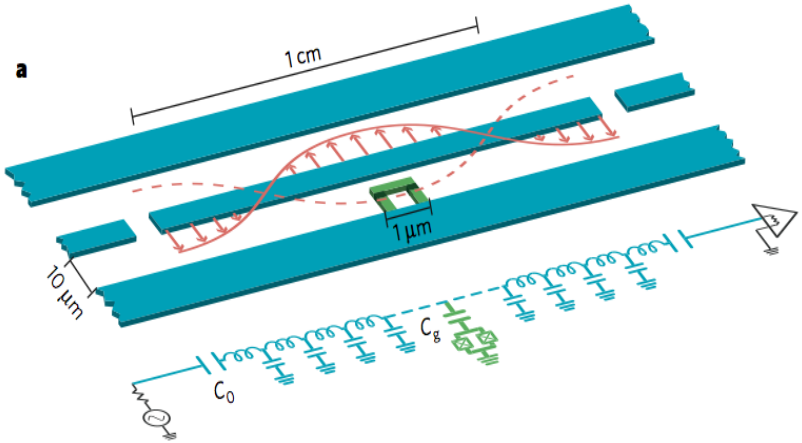
Anharmonicity

Flux qubit

Flux quantization



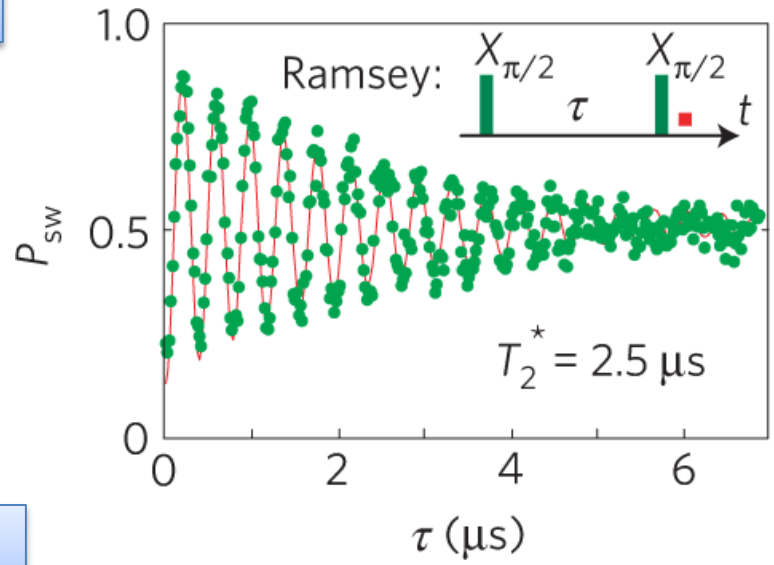
Capacitive coupling to transmission line



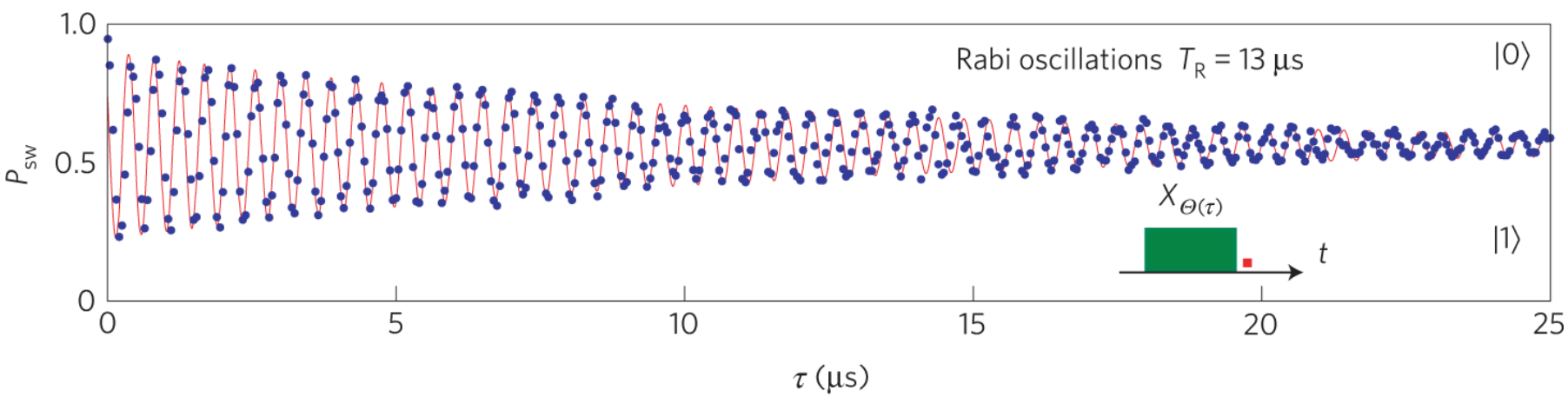
H. Mooij et. al. Science (2003) (Flux qubit)

Single qubit operations

Ramsey fringes



Rabi oscillations



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

D-Wave “quantum computer”

D-Wave machine

The quantum computer of our dreams:

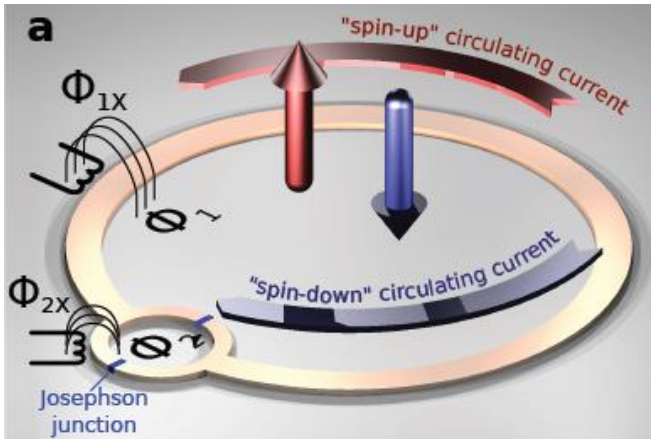
- Gate model
- Highly impractical
- Well characterized

The D-Wave "quantum computer" :

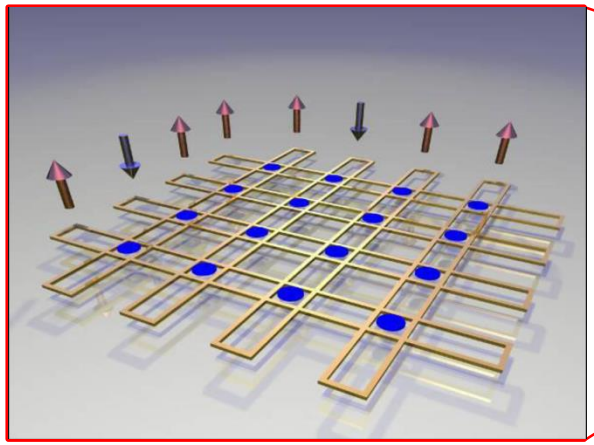
- Not universal
- Not characterized
- It definitely solves problems, has some quantum properties and **exists**

Architecture

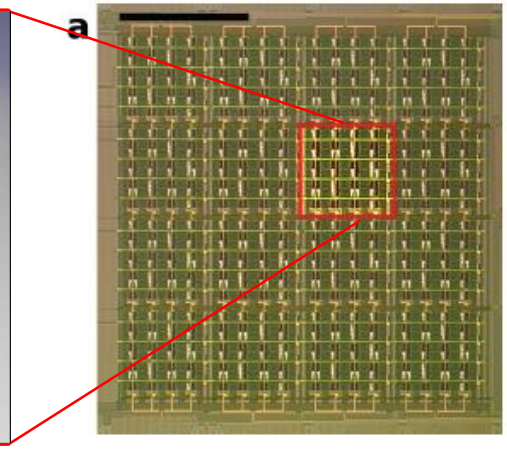
Superconducting flux qubit



8-qubit unit cell



Optical image: 128 qubit chip



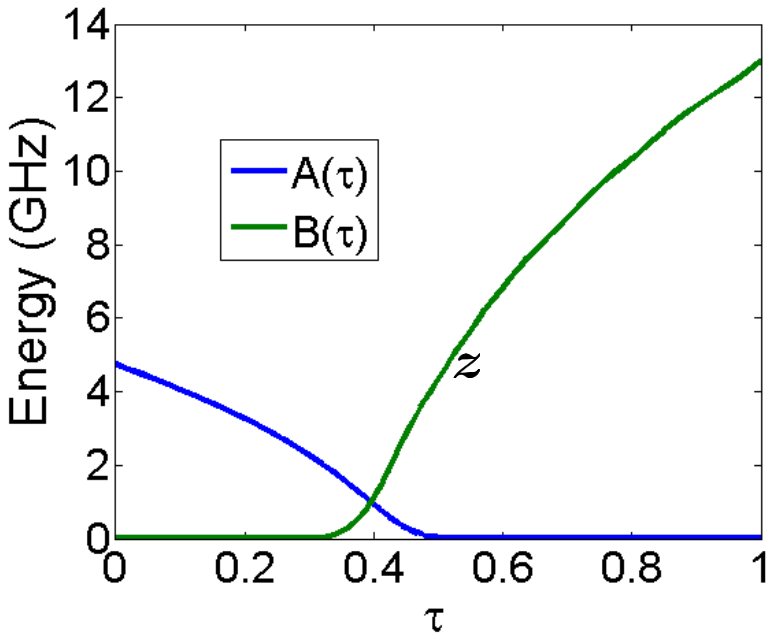
What is the device good for:

Design to solve **DISCRETE OPTIMIZATION**

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

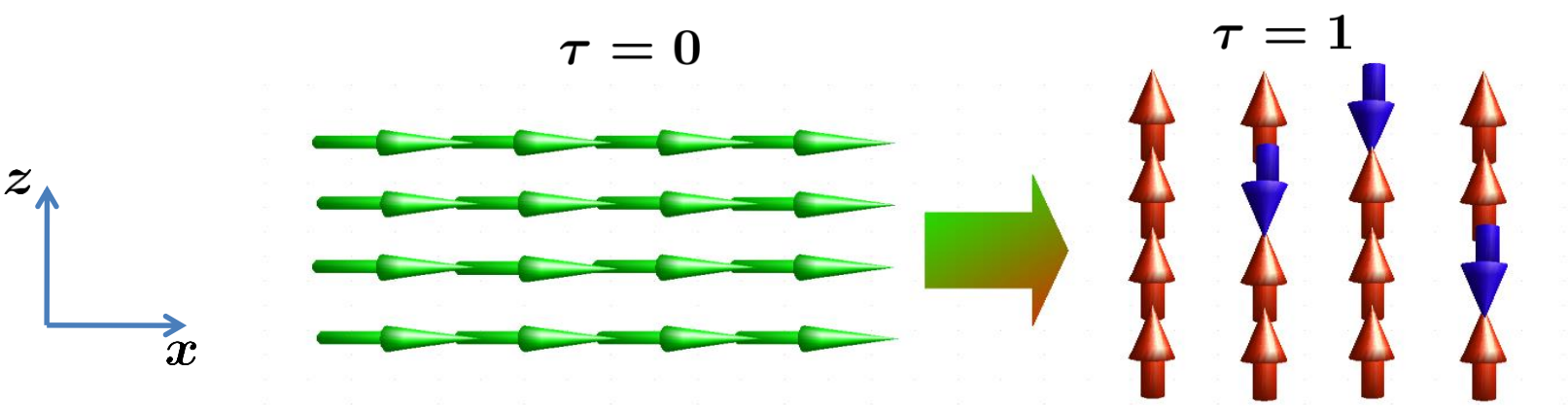
$$F = \sum_i^N h_i s_i + \sum_{j>i}^N J_{ij} s_i s_j, \qquad s_i \in \{-1, 1\}$$

Adiabatic quantum computing



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

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

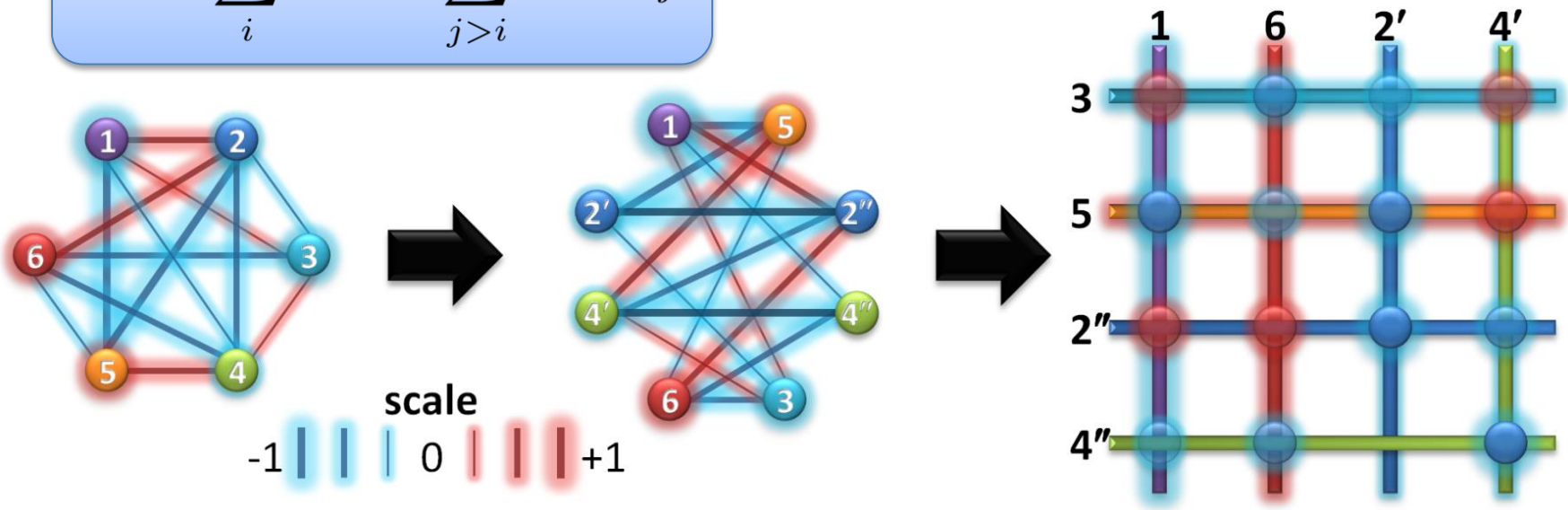


Transverse field ON
Longitudinal field OFF

Transverse field OFF
Longitudinal field ON

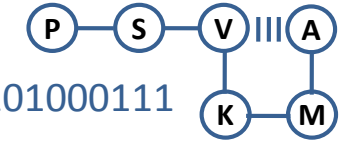
Mapping problem on quantum device

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



Hardware dictates encoding strategy

Encode Problem

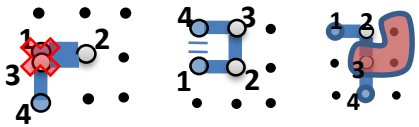


0101000111

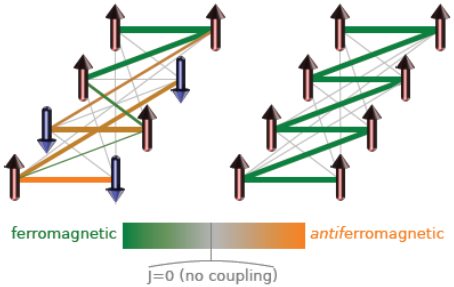
$$q = \underbrace{01}_{\text{turn 1}}\ \underbrace{0q_1}_{\text{turn 2}}\ \underbrace{q_2q_3}_{\text{turn 3}}\ \underbrace{q_4q_5}_{\text{turn 4}} \cdots \underbrace{q_{2(N-3)-1}q_{2(N-3)}}_{\text{turn N-1}}$$

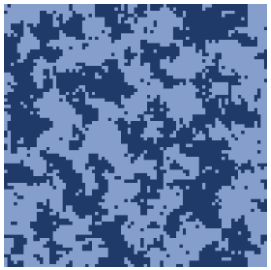
Create Objective Function

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

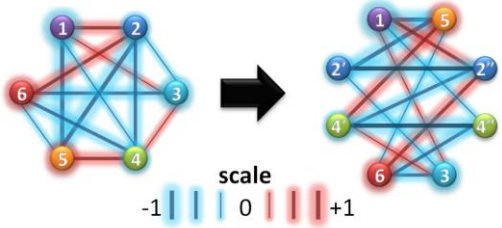


HARDWARE ABILITIES



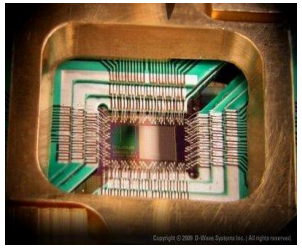


Embed in Hamiltonian



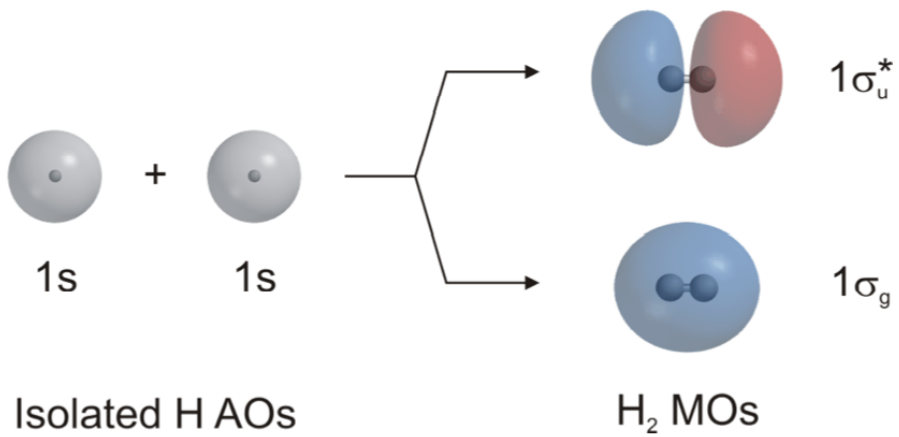
Map to device

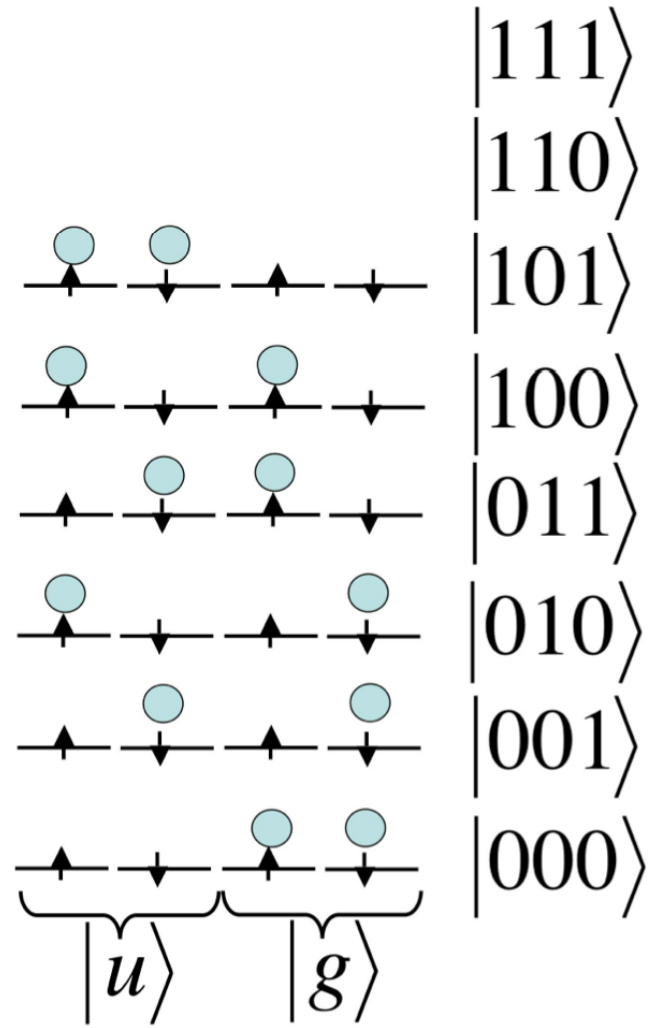
Solve on Device



Quantum simulators

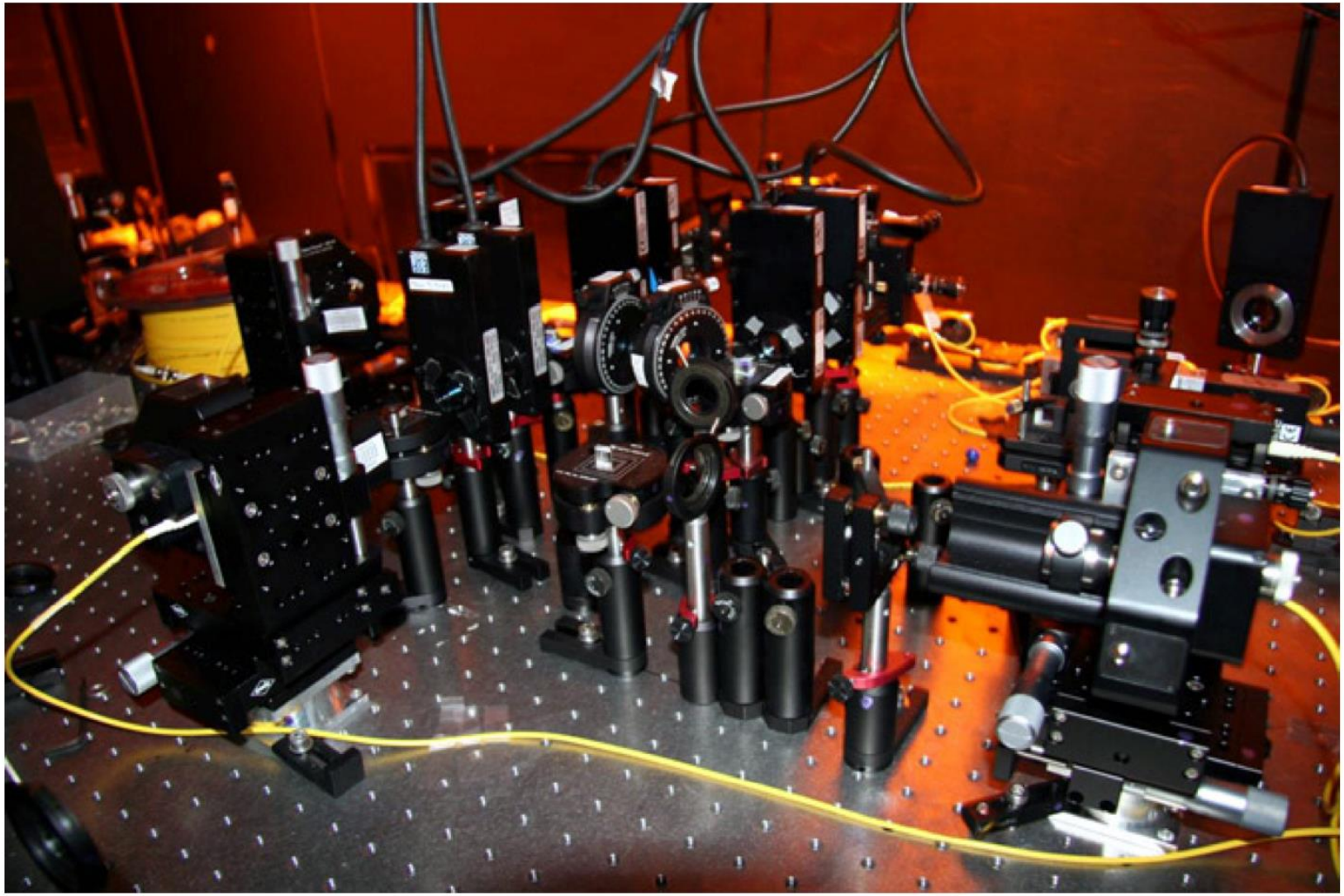
Electronic structure of Hydrogen molecule





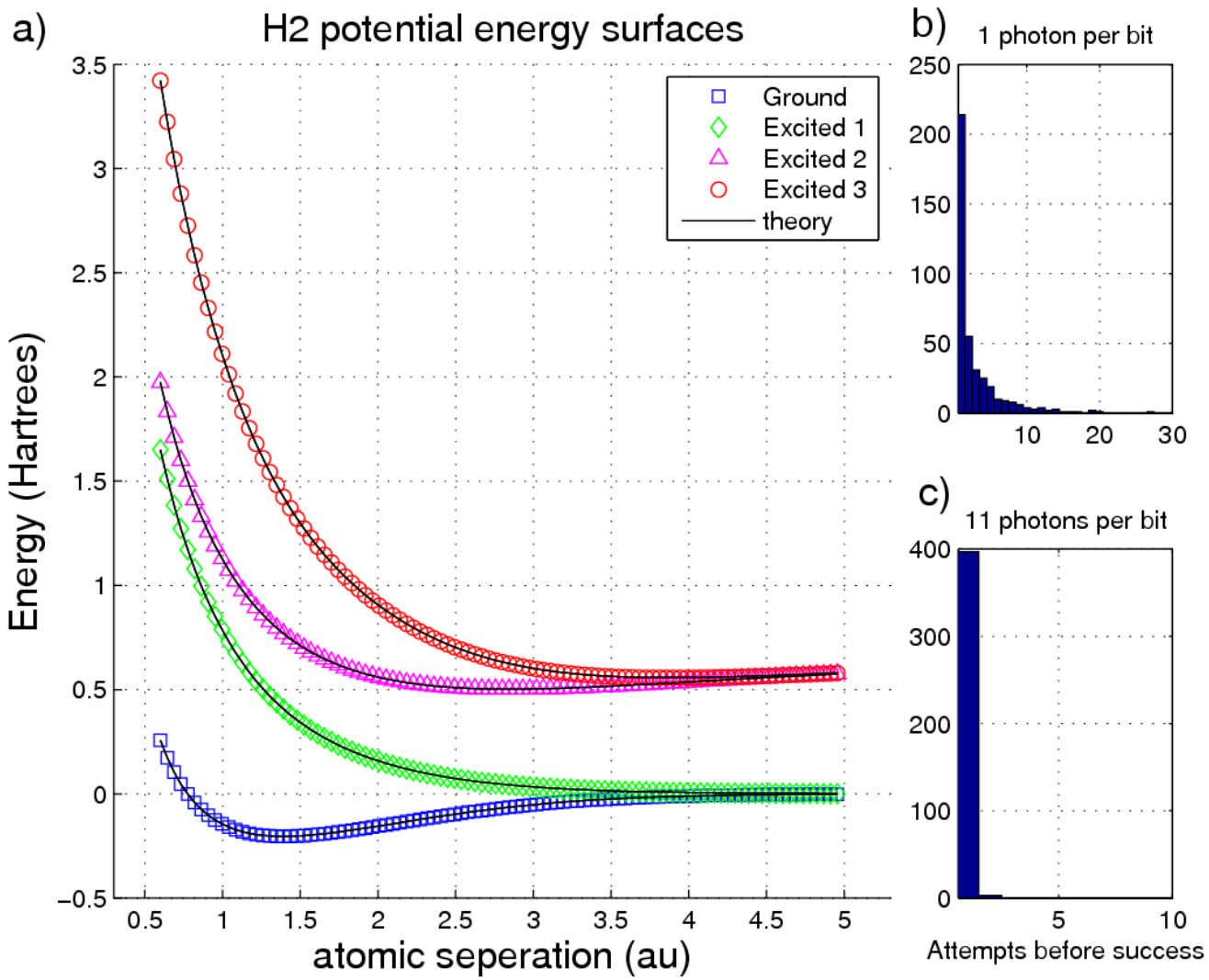
H is 6×6, but block-diagonal.
Need to diagonalize 2×2 matrices.

Optical setup



Lanyon et. al., Nature Chemistry (2010)

Energy curves

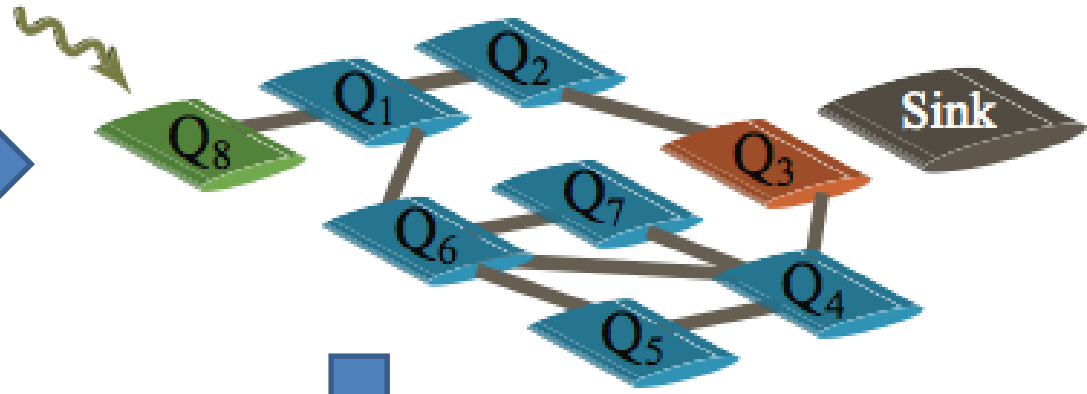


Towards simulation of open systems

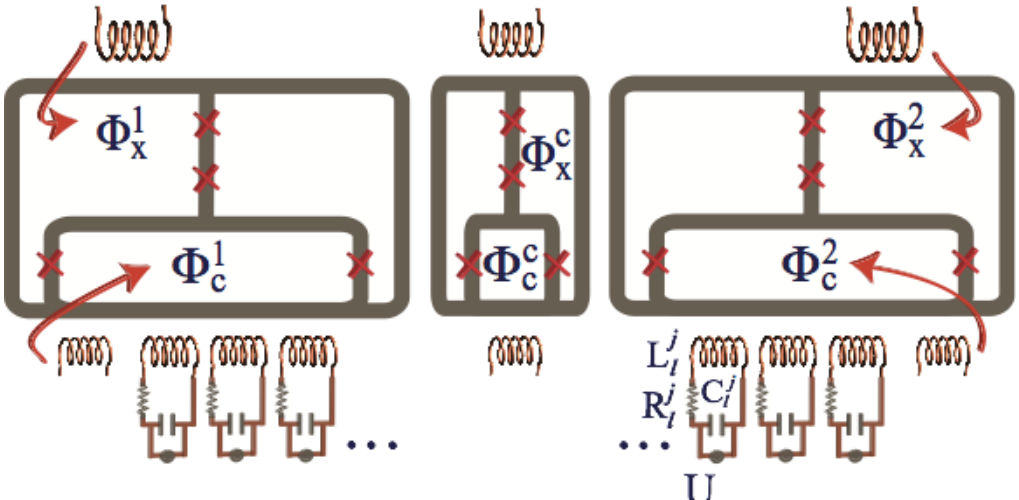
Light-harvesting antenna

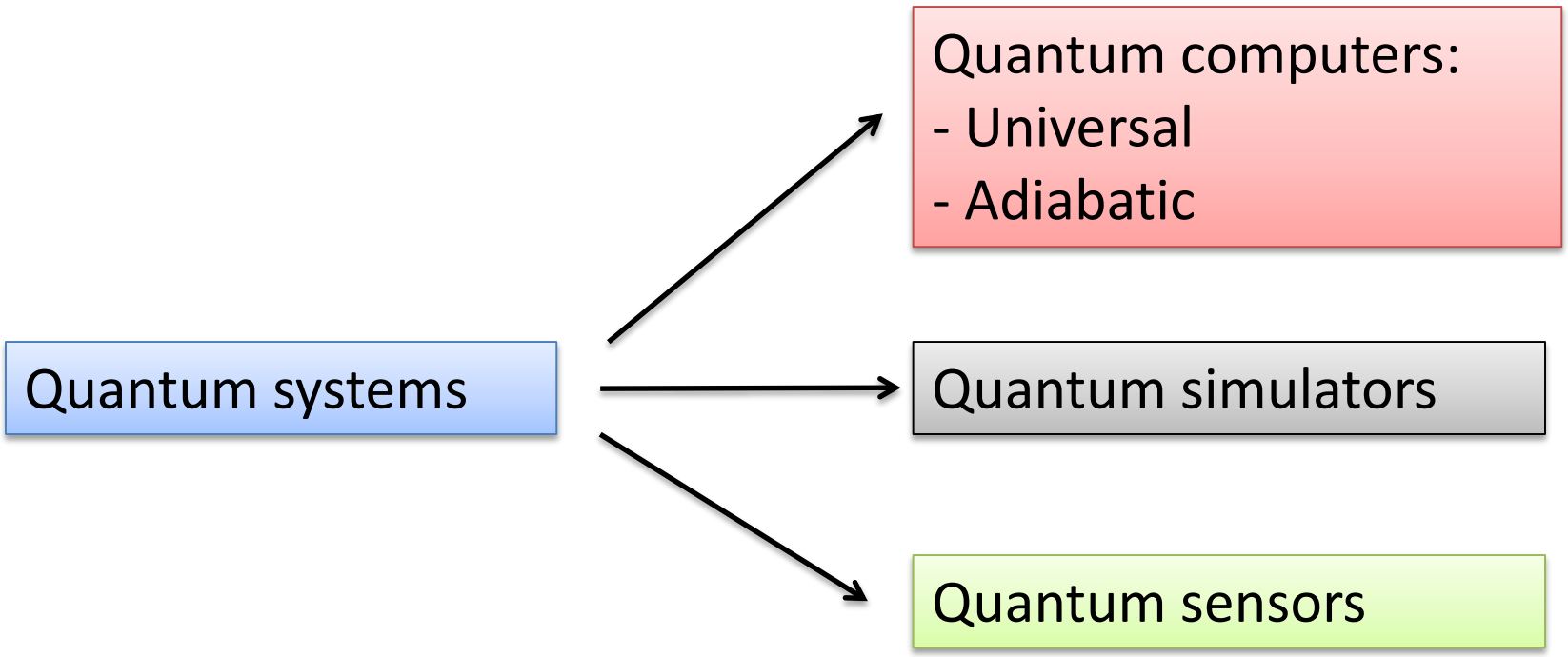
Pigments = qubits
Environment = bath

Quantum system



Superconducting architecture



S. Mostame, et. al. New J. Phys. 14, 105013 (2012)

Quantum information processing structures