Quantum computation and quantum information

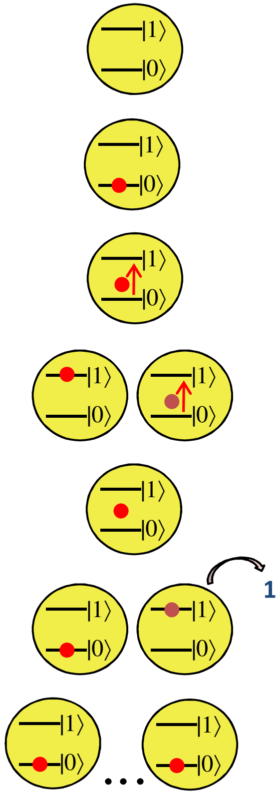
Chapter 7

- Physical Realizations
- Part 2

Ch. 7 – Physical Realizations

- Deviate from the book
- 2 lectures, 4h, 4 parts
  1) Overview, general info on implementations
  2) DiVincenzo criteria + Ion traps
  3) Rare-earth impurities – Lab exercise
  4) Other systems (linear optics/superconducting qubits)
- Summary and comparisons

Repetition - Di Vincenzo criteria



1) Qubit

2) Initialize

3) Single qubit gate

4) Two qubit gate

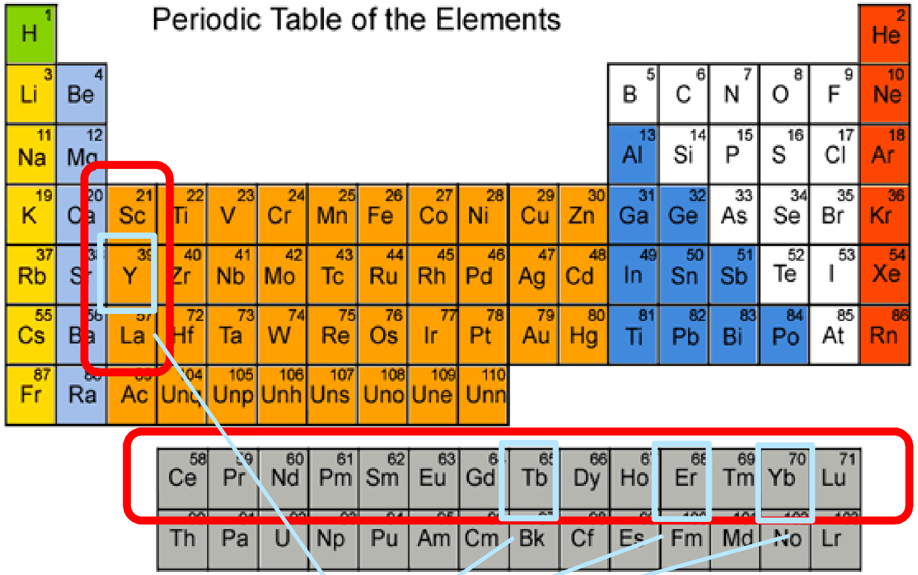
5) Long coherence time

6) Qubit readout

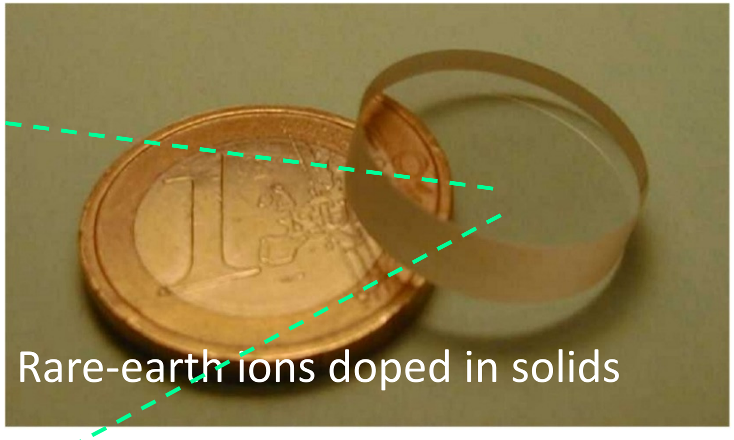
7) Scalability

Reformulated from: D. P. di Vincenzo, *The physical implementation of quantum computation*, Fortschritte der Physik, **48**, 771 (2000) (http://arxiv.org/abs/quant-ph/0002077)

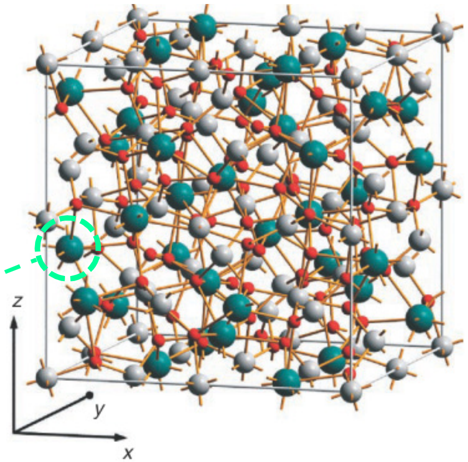
Rare-earth-ion quantum computing



4 of them named after Ytterby in Sweden

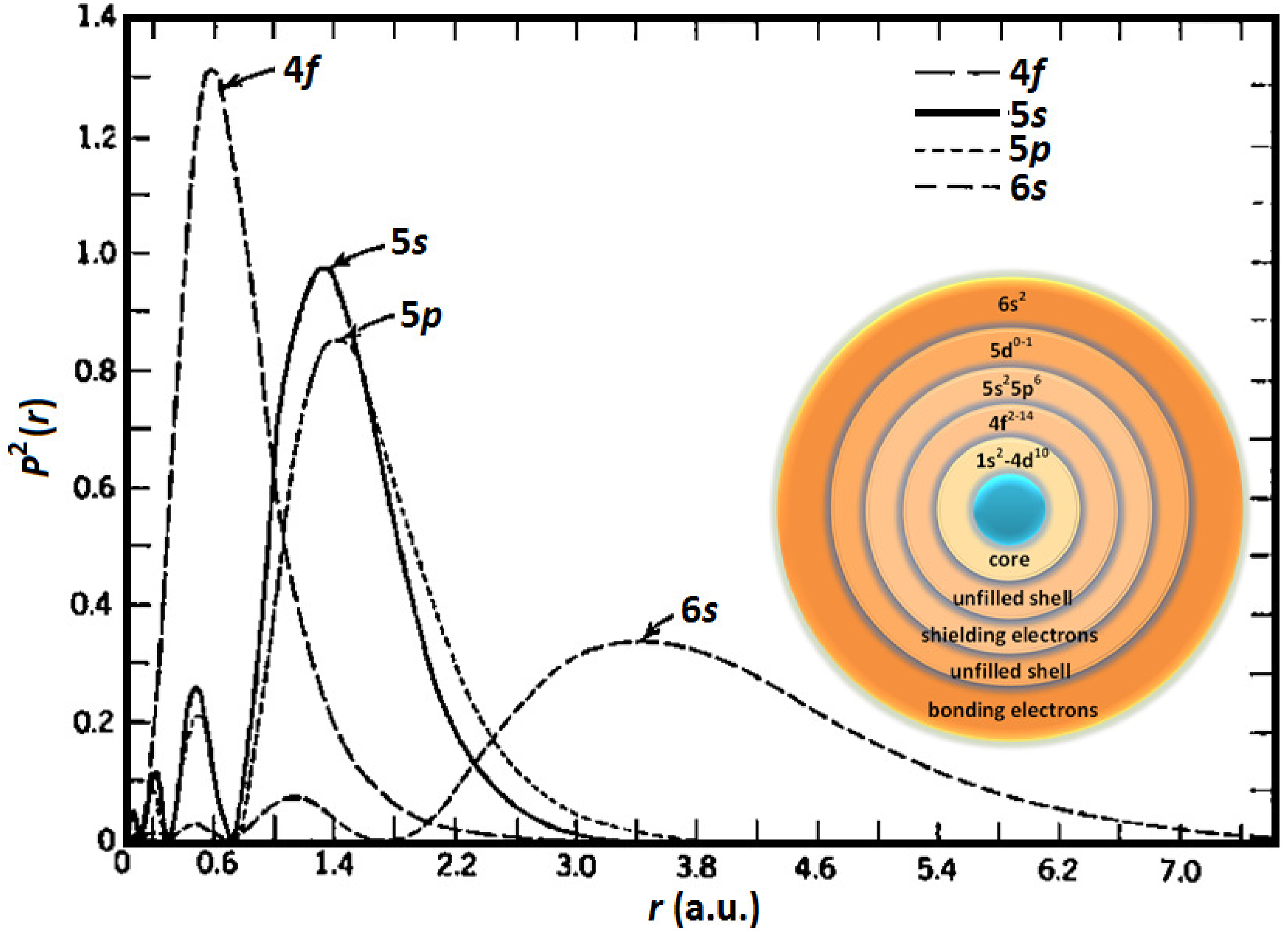


YAG unit cell structure



● = Rare-earth ion

Why Rare-earths? - Well shielded system!

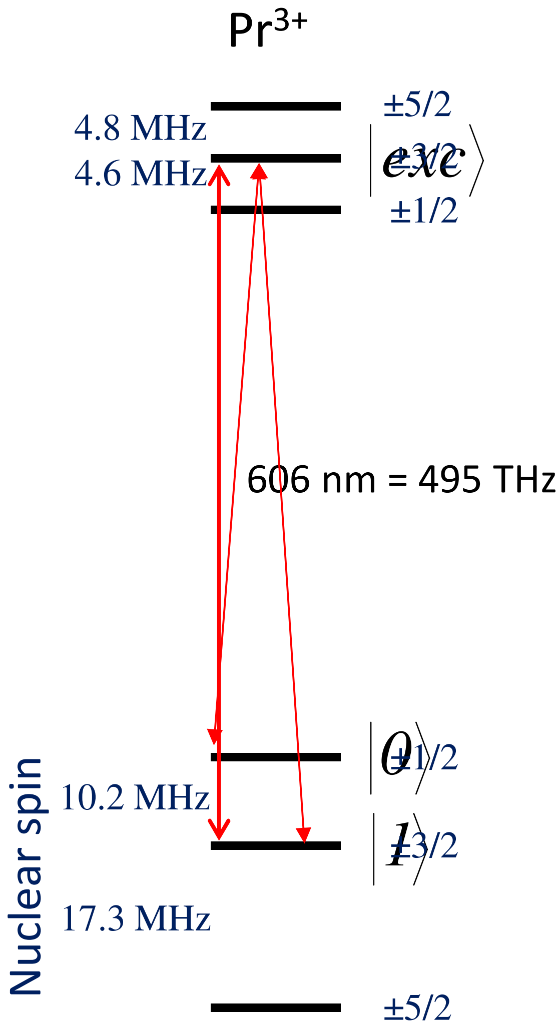


G. H. Dieke -> physics stackexchange

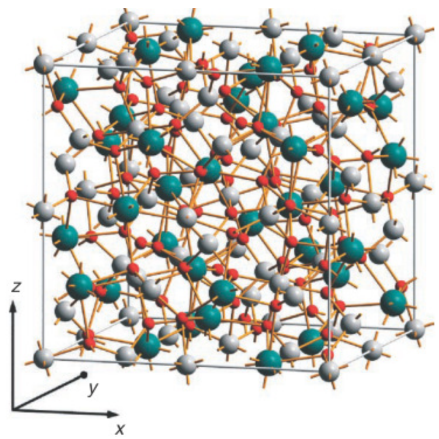
Element	4f electrons
La^{3+}	0
Ce^{3+}	1
Pr^{3+}	2
Nd^{3+}	3
Pm^{3+}	4
Sm^{3+}	5
Eu^{3+}	6
Gd^{3+}	7
Tb^{3+}	8
Dy^{3+}	9
Ho^{3+}	10
Er^{3+}	11
Tm^{3+}	12
Yb^{3+}	13
Lu^{3+}	14

Leads to long coherence times!

Rare-earths: 1) Qubit



- Long coherence times:
  up to 6 h demonstrated
- Spatially close:
  strong interactions

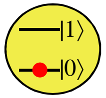


1 ion = 1 qubit is ultimate goal, but not there yet

Instead: Ensembles of many ions = 1 qubit
→ good photon interaction

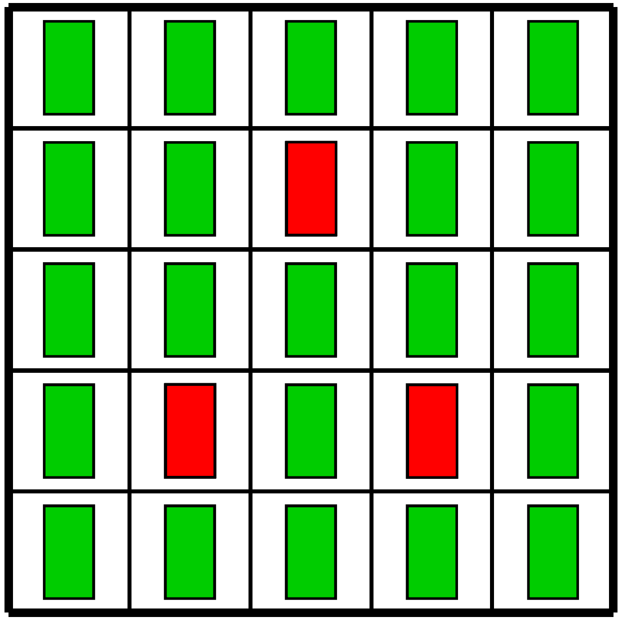
But...
compensation needed for inhomogeneities

Rare-earths:



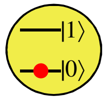
2) Initialize

Conceptual picture of crystal

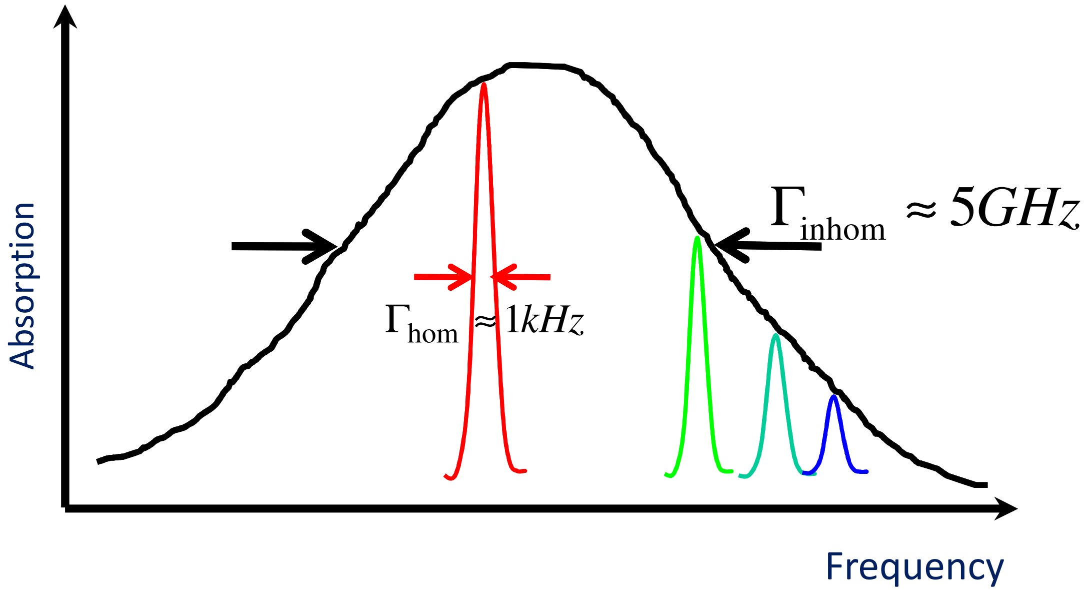


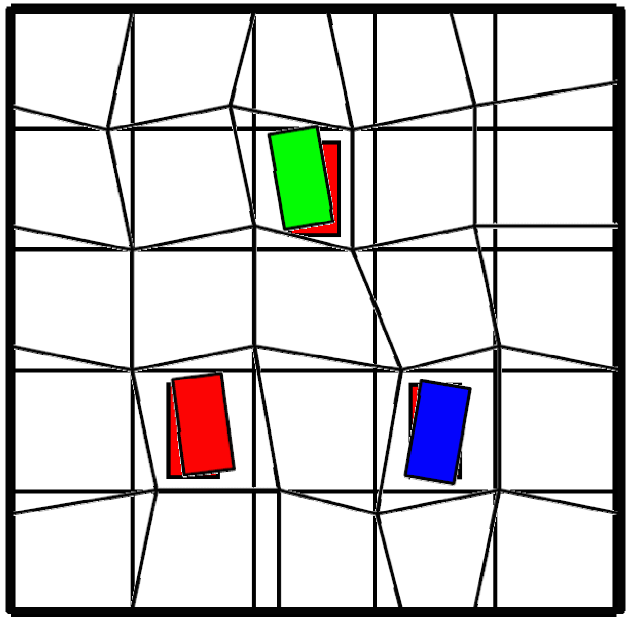
$Pr^{3+}:Y_2SiO_5$

Rare-earths:



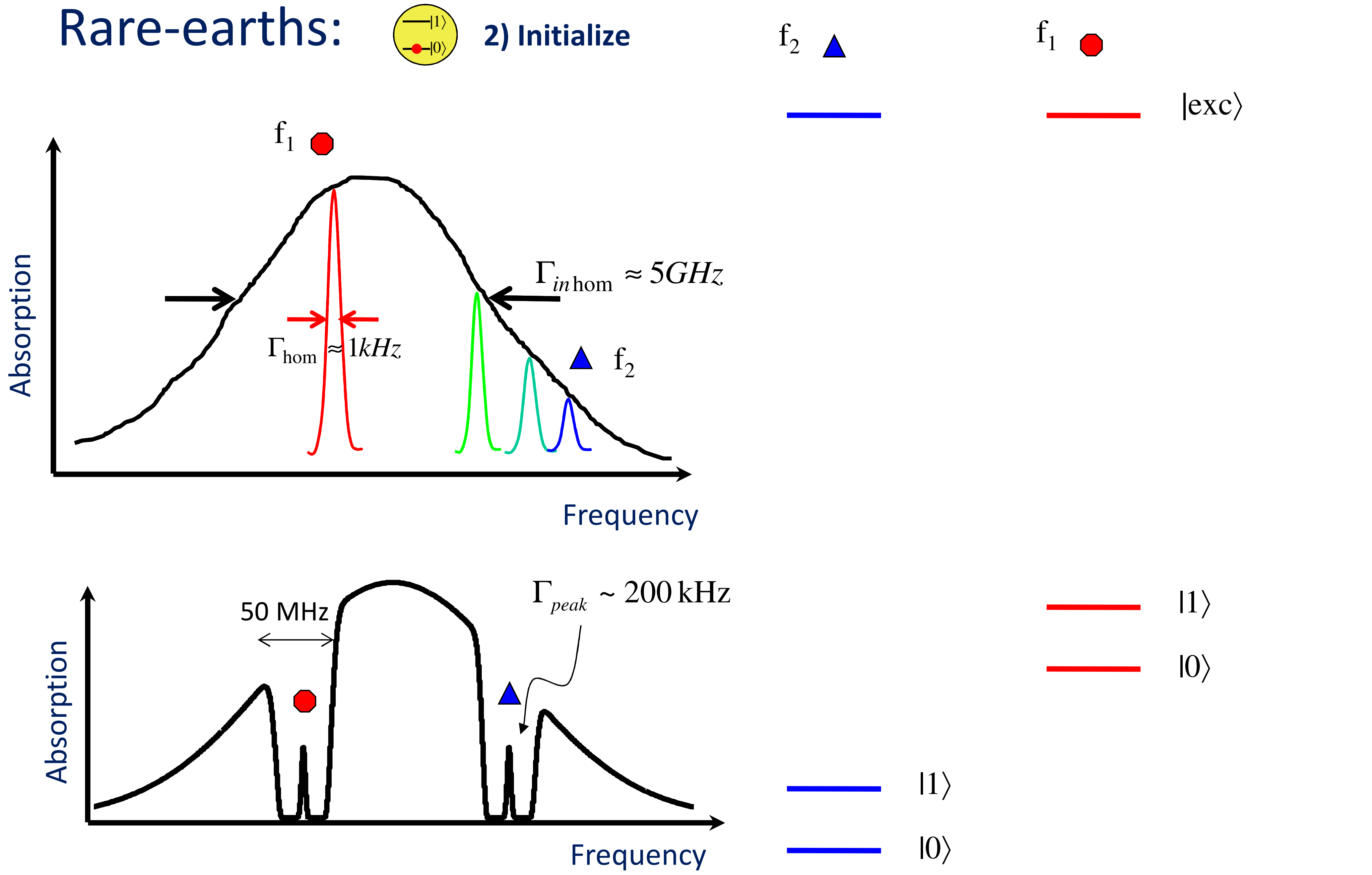
2) Initialize



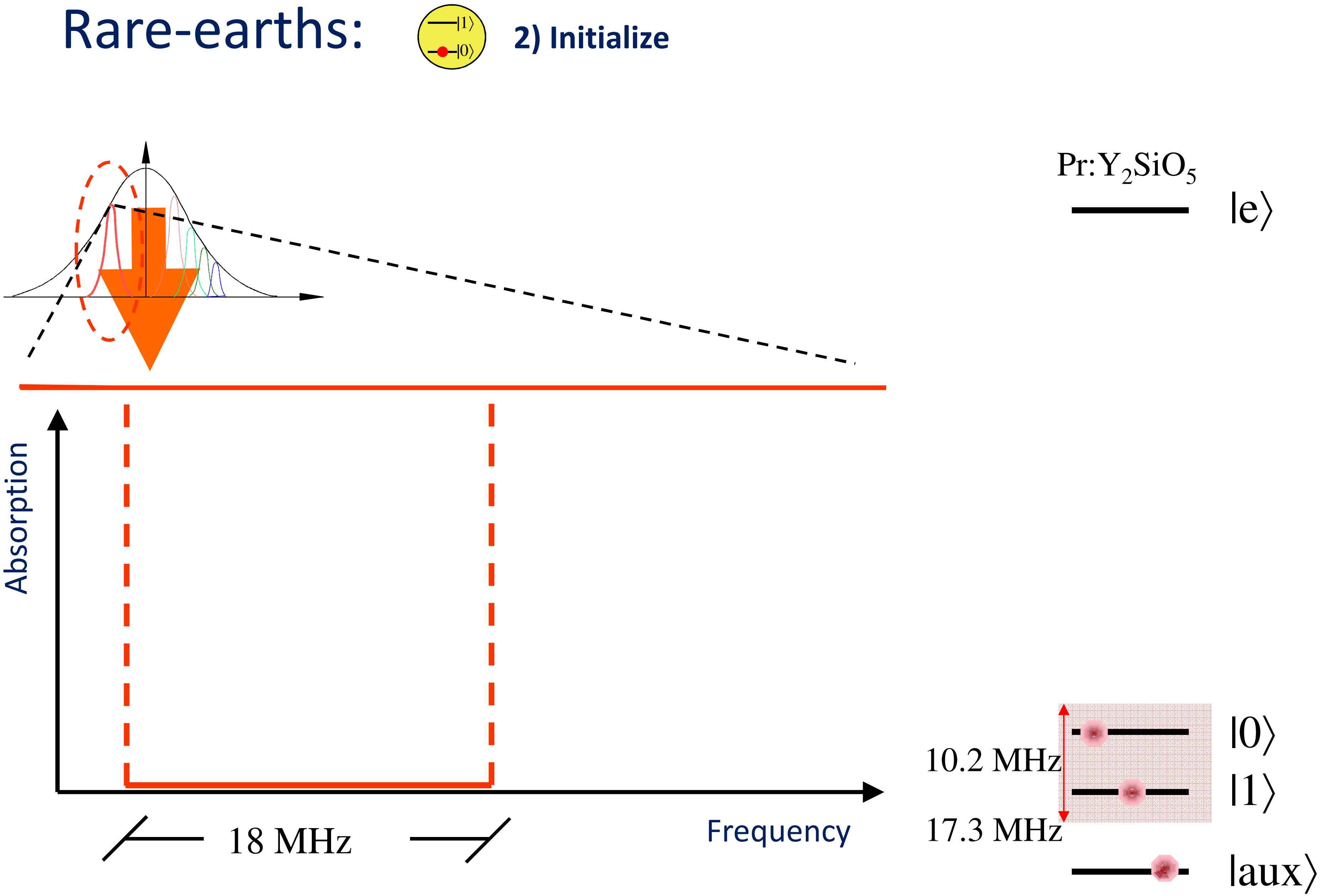


$Pr^{3+}:Y_2SiO_5$

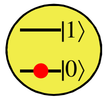
Rare-earths: 2) Initialize



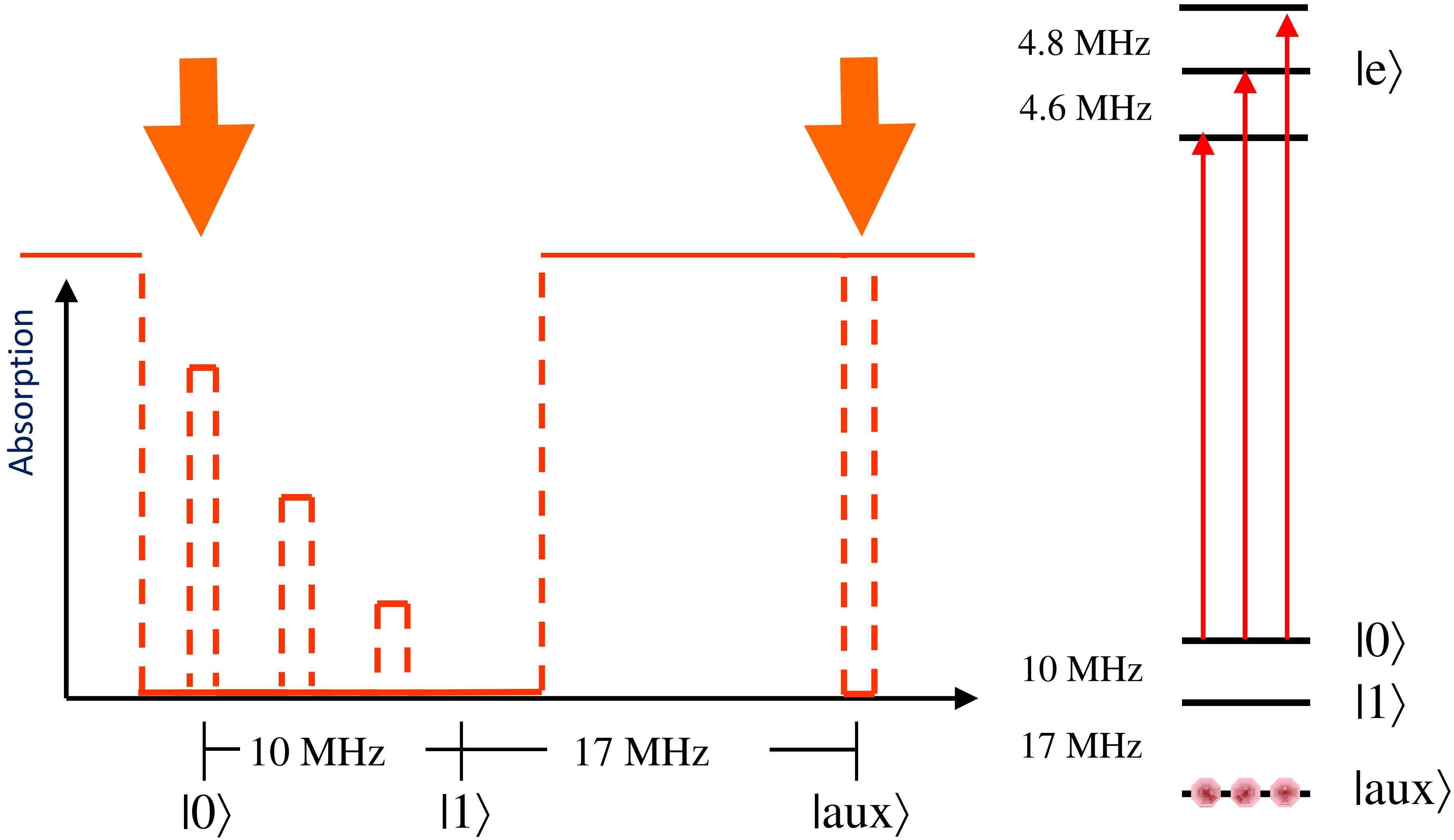
Rare-earths: 2) Initialize



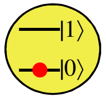
Rare-earths:



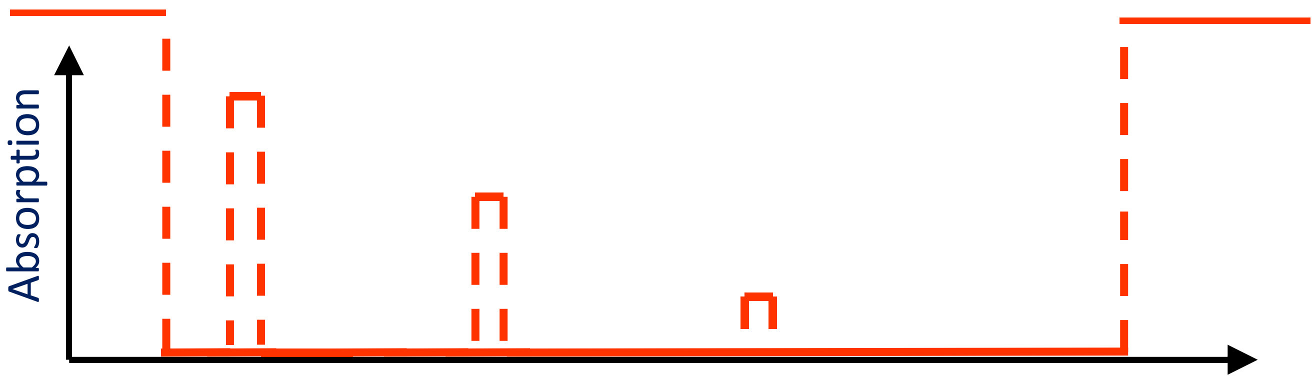
2) Initialize



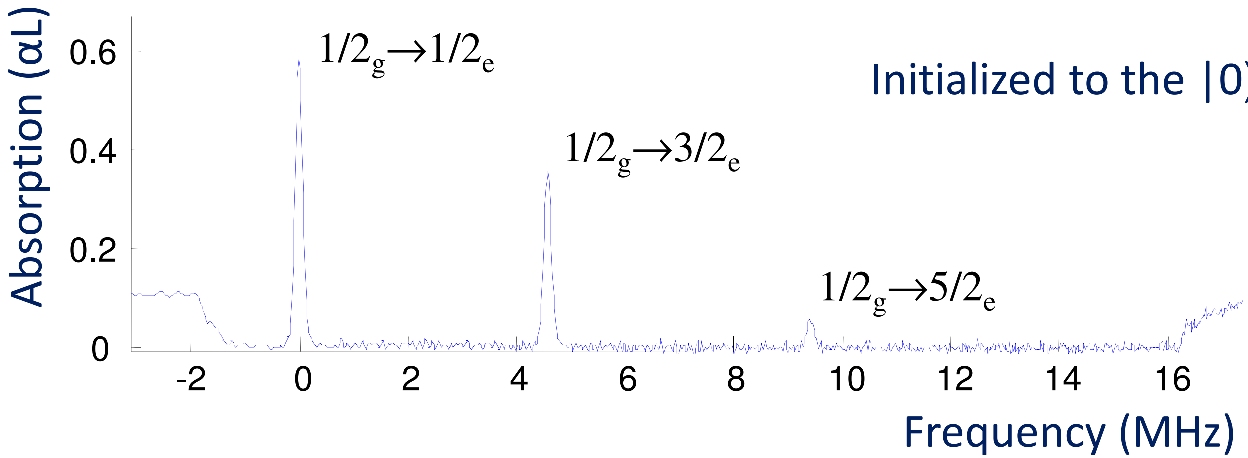
Rare-earths:



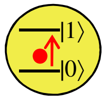
2) Initialize



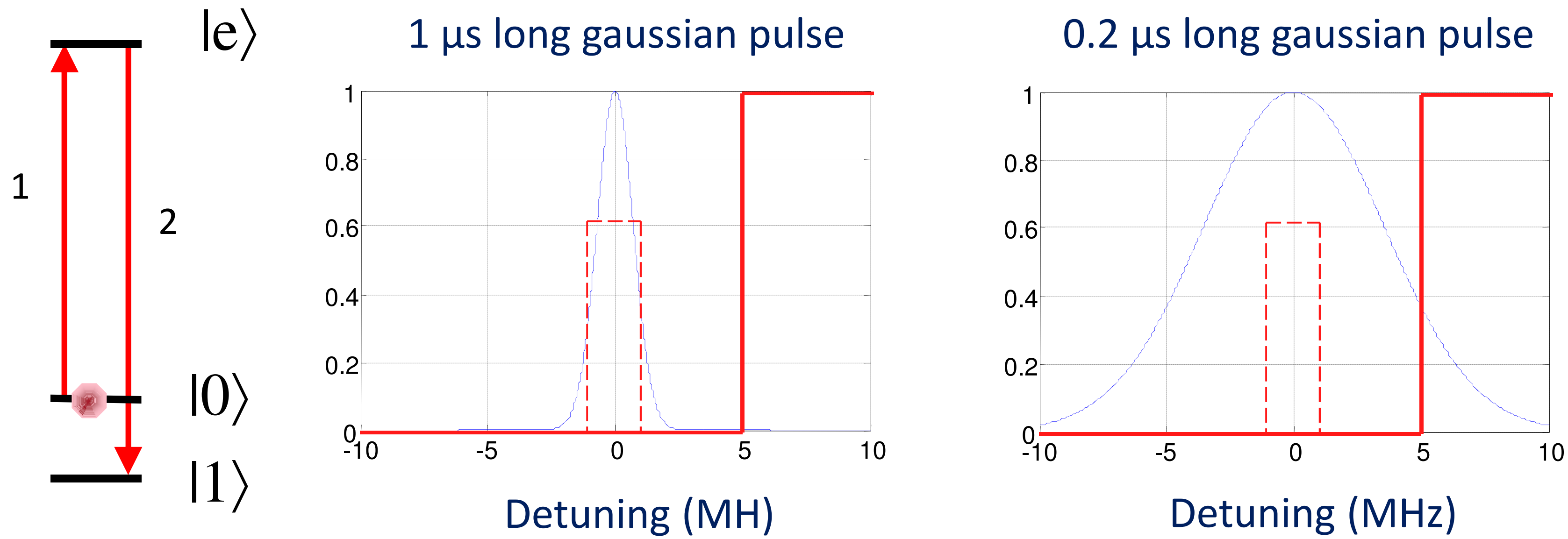
633 pulses later...



Initialized to the |0⟩ state!

Rare-earths:  3) Single qubit gate

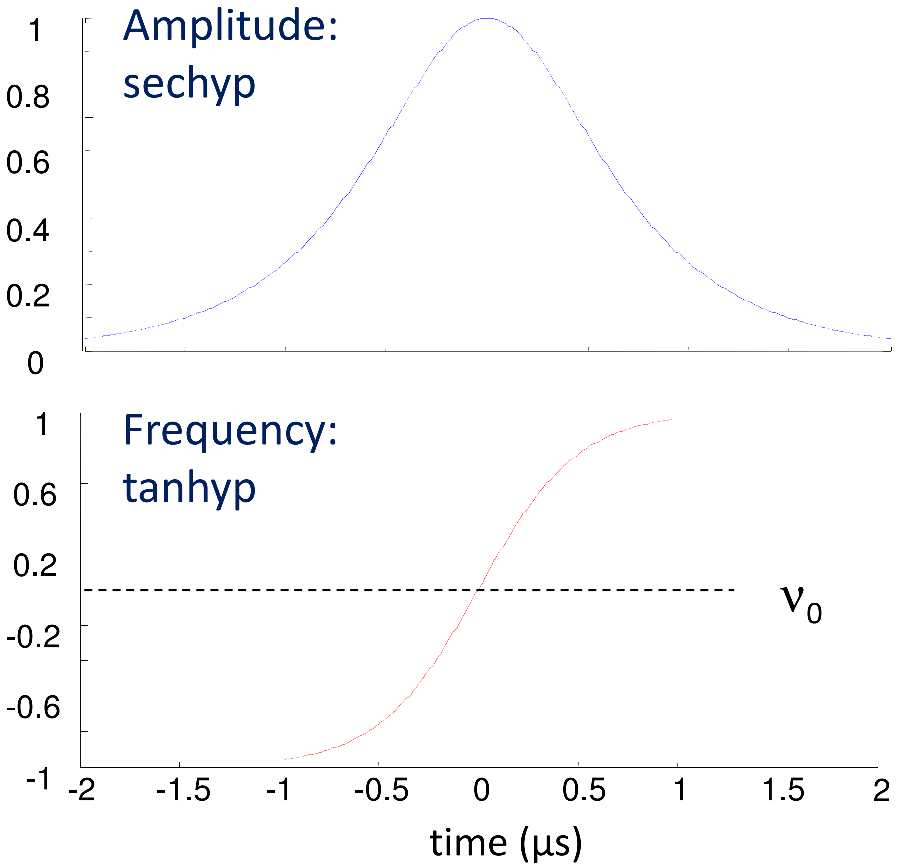
First, let's try a simple approach:
Gaussian pulses

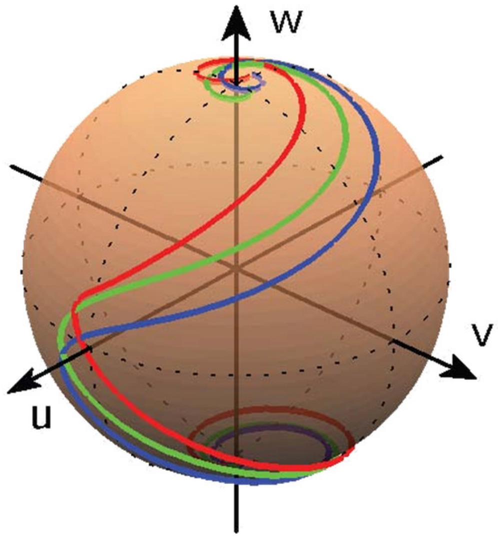


- Problem #1: Not the same Rabi frequency everywhere
- Problem #2: Dephasing due to the inhomogeneous width
- Problem #3: Wings excite non-initialized ions

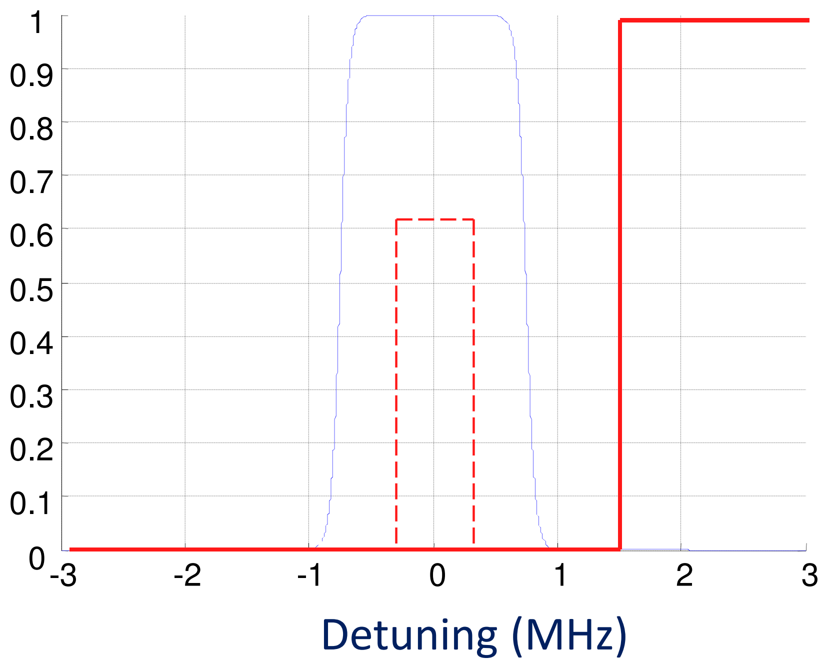
Rare-earths: **3) Single qubit gate**

Second, let's try something more complicated:
Complex hyperbolic secant pulses (sechyp)

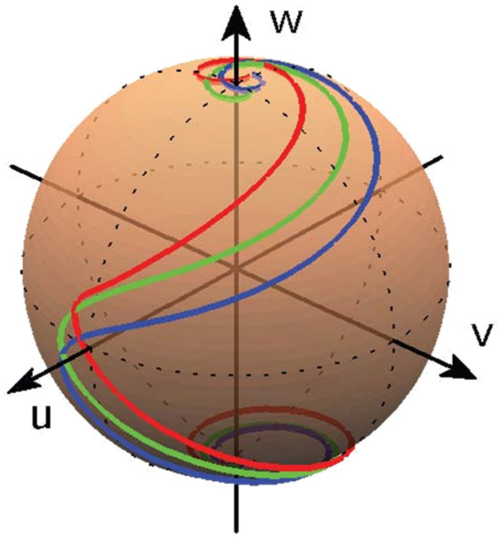




Rare-earths: 3) Single qubit gate

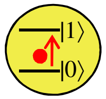


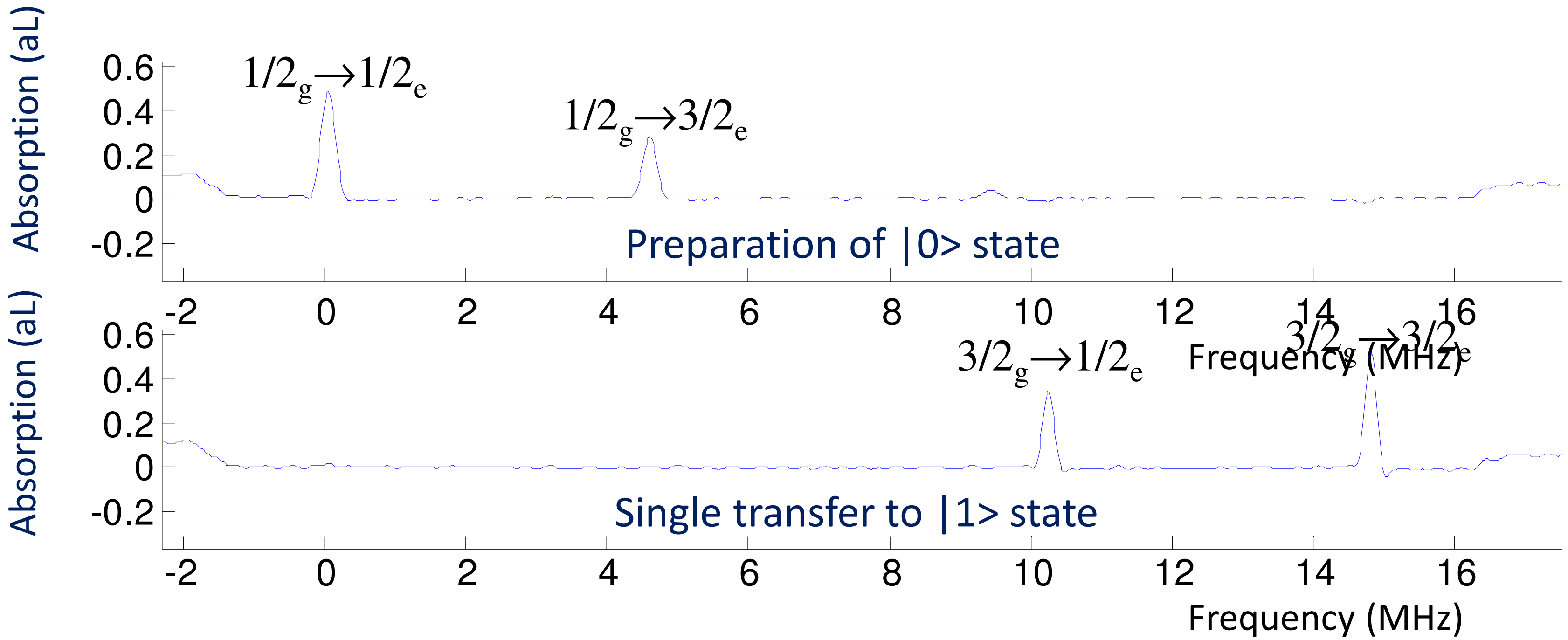
Sechyp pulses



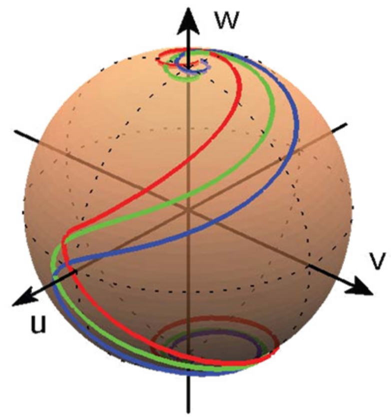
+ Solve the problem with different rabi frequencies
+ Solve the problem with dephasing due to inhomogeneous broadening
+ No excitation outside initialized region

- Can only handle pole to pole transfers

Rare-earths:  3) Single qubit gate



97.5% single transfer efficiency!

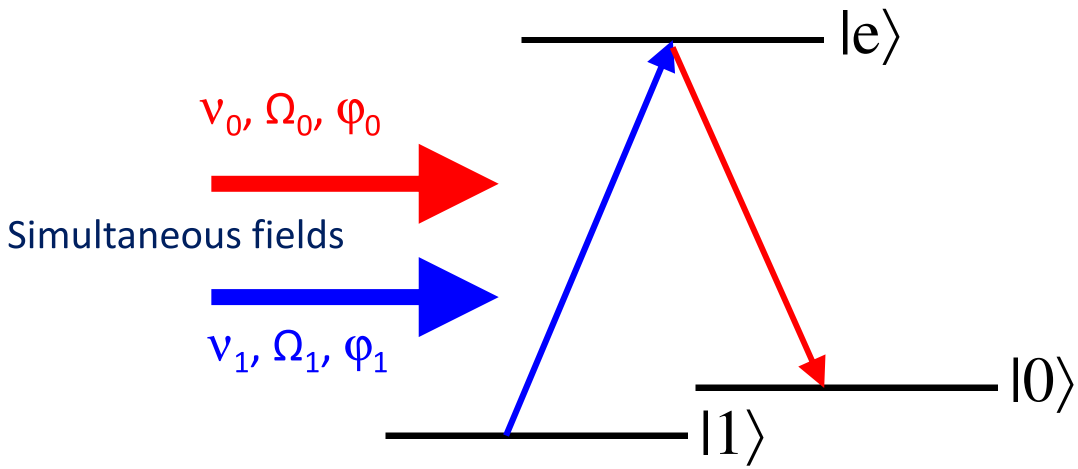


... but only pole to pole transfers. Arbitrary states require a yet more complicated approach.

Rare-earths:

3) Single qubit gate

The ”most” complicated scheme: Dark state pulses



$$H_{int} = c\big(|e\rangle\langle 0| + |e\rangle\langle 1|\big)$$

Superpositions:

$$\begin{cases} |B\rangle = |0\rangle + |1\rangle \\ |D\rangle = |0\rangle - |1\rangle \end{cases}$$

Interactions:

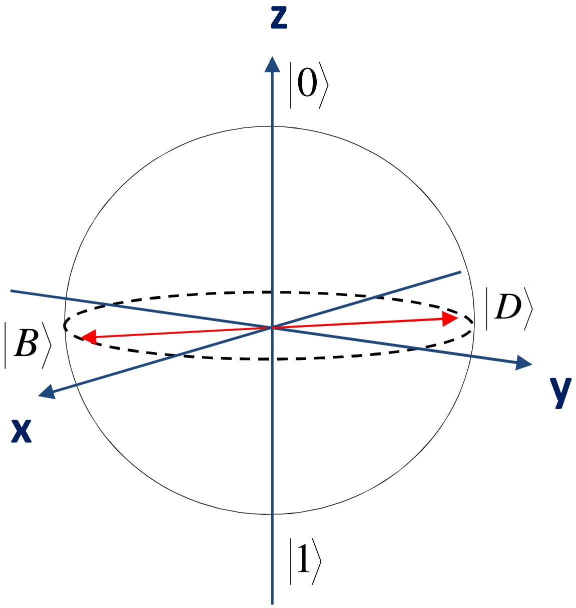
$$\langle e|H_{int}|B\rangle = 2c$$
$$\langle e|H_{int}|D\rangle = 0$$

Rare-earths: 3) Single qubit gate

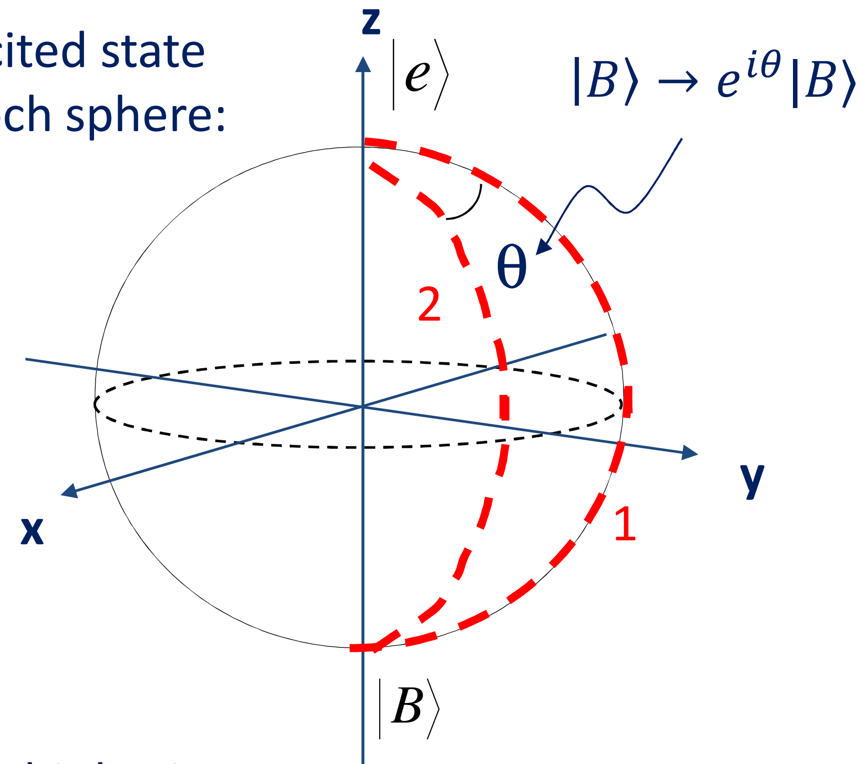
Dark state pulses

$$\begin{cases} |B\rangle = |0\rangle + e^{-i\varphi}|1\rangle \\ |D\rangle = |0\rangle - e^{-i\varphi}|1\rangle \end{cases}$$

Qubit Bloch sphere:



Excited state Bloch sphere:

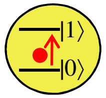


Qubit basis:

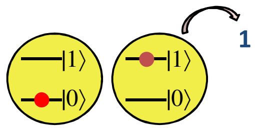
$$U = e^{\frac{i\theta}{2}} \begin{pmatrix} \cos(\theta/2) & ie^{i\phi}\sin(\theta/2) \\ ie^{-i\phi}\sin(\theta/2) & \cos(\theta/2) \end{pmatrix}$$

= Arbitrary rotation around an axis on the equator

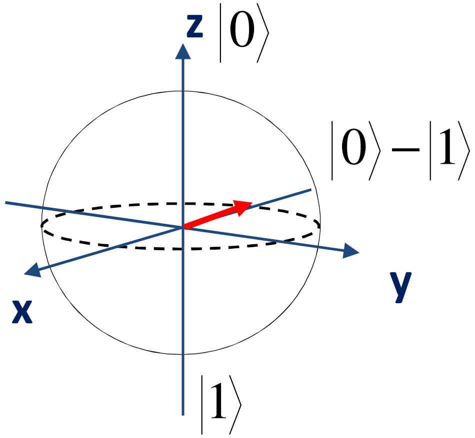
Rare-earths:

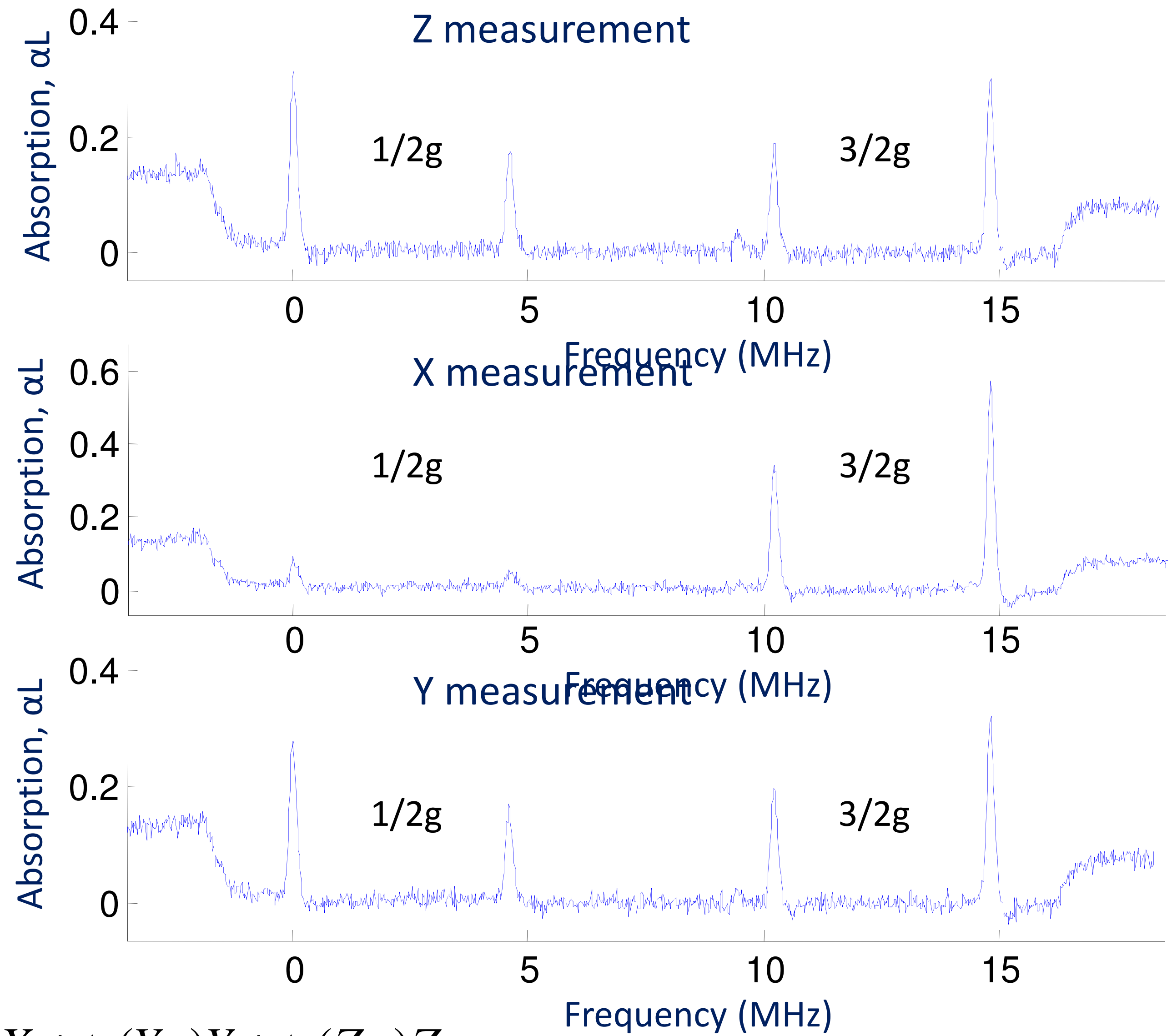


3) Single qubit gate +



6) Qubit readout





$F_{op} = 0.93$

$$\rho = \frac{tr(\rho)I + tr(X\rho)X + tr(Y\rho)Y + tr(Z\rho)Z}{2}$$

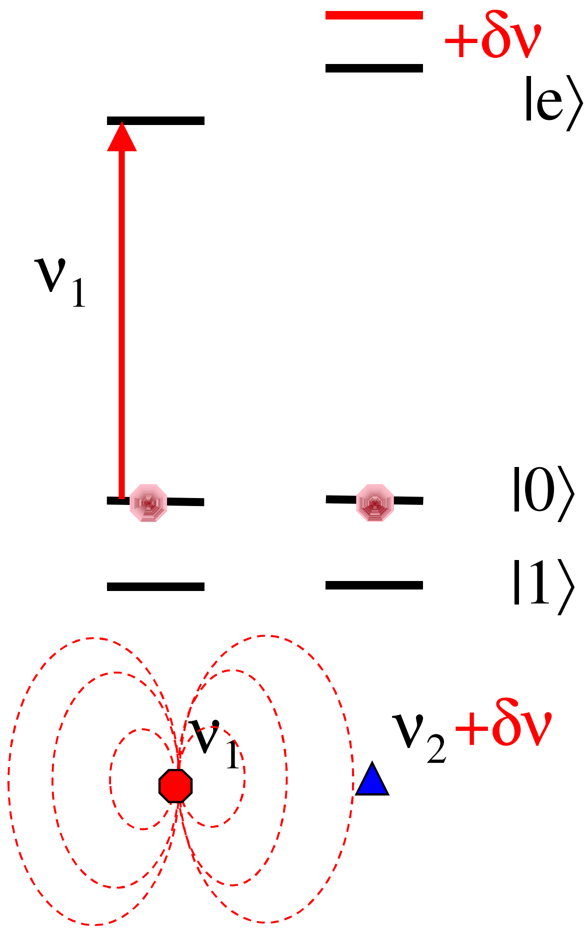
Eq 8.148 in Nielsen and Chuang

Rare-earths:

4) Two qubit gate

→ need to find a conditional mechanism

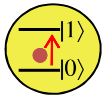
1. Consider two ions in the crystal that are spatially close
2. One of the ions is excited on its optical transition
3. The dipole moment is different in the excited state. This leads to a shift of the second ion energy levels
4. Static dipole-dipole interaction scales as $\frac{1}{r^3}$

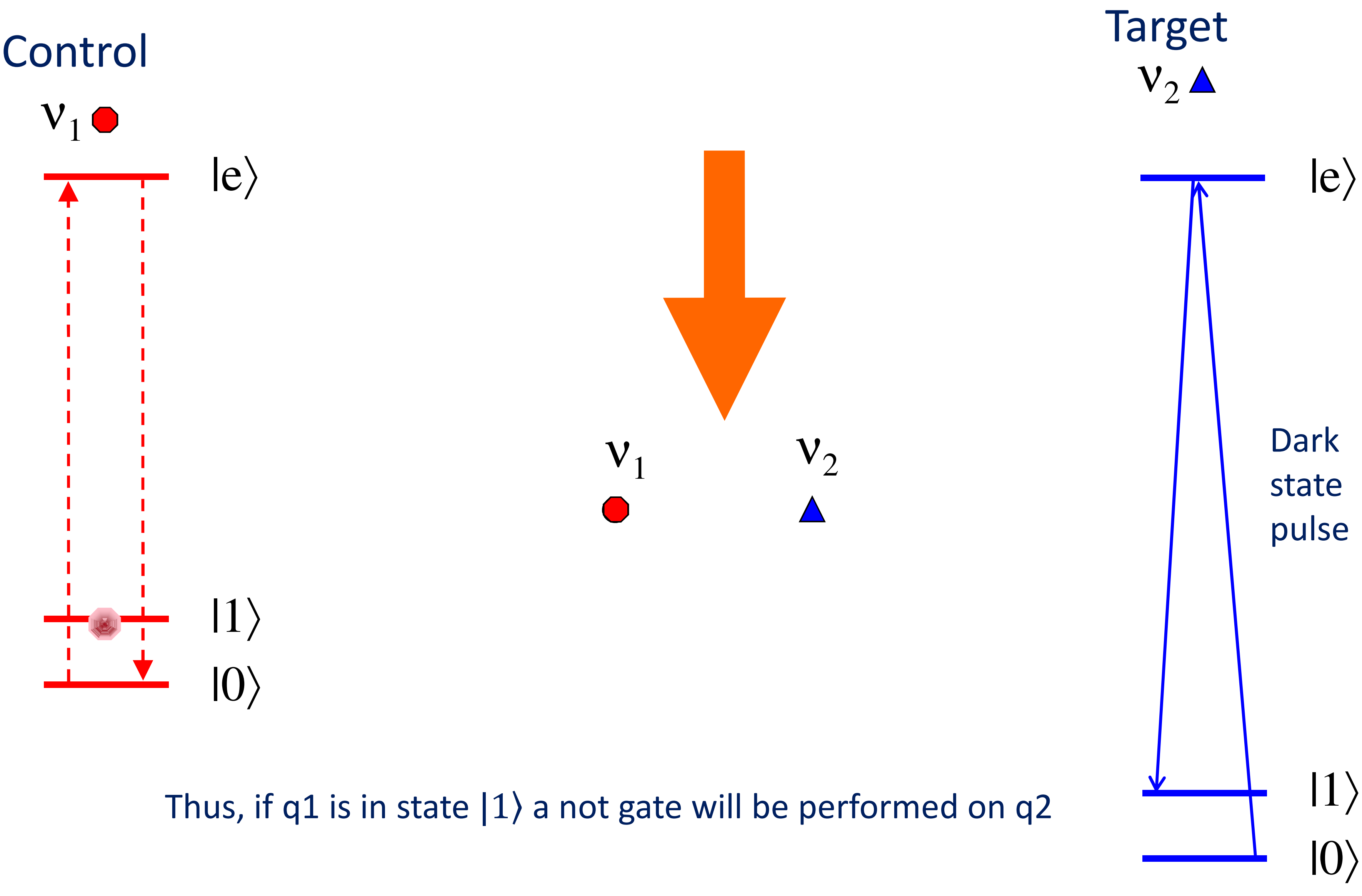


Ion distance	frequency shift
100 nm	1 line width
10 nm	1000 line widths
1 nm	1000000 line widths

Artificial trap: ~ μm

Natural trap: ~ nm

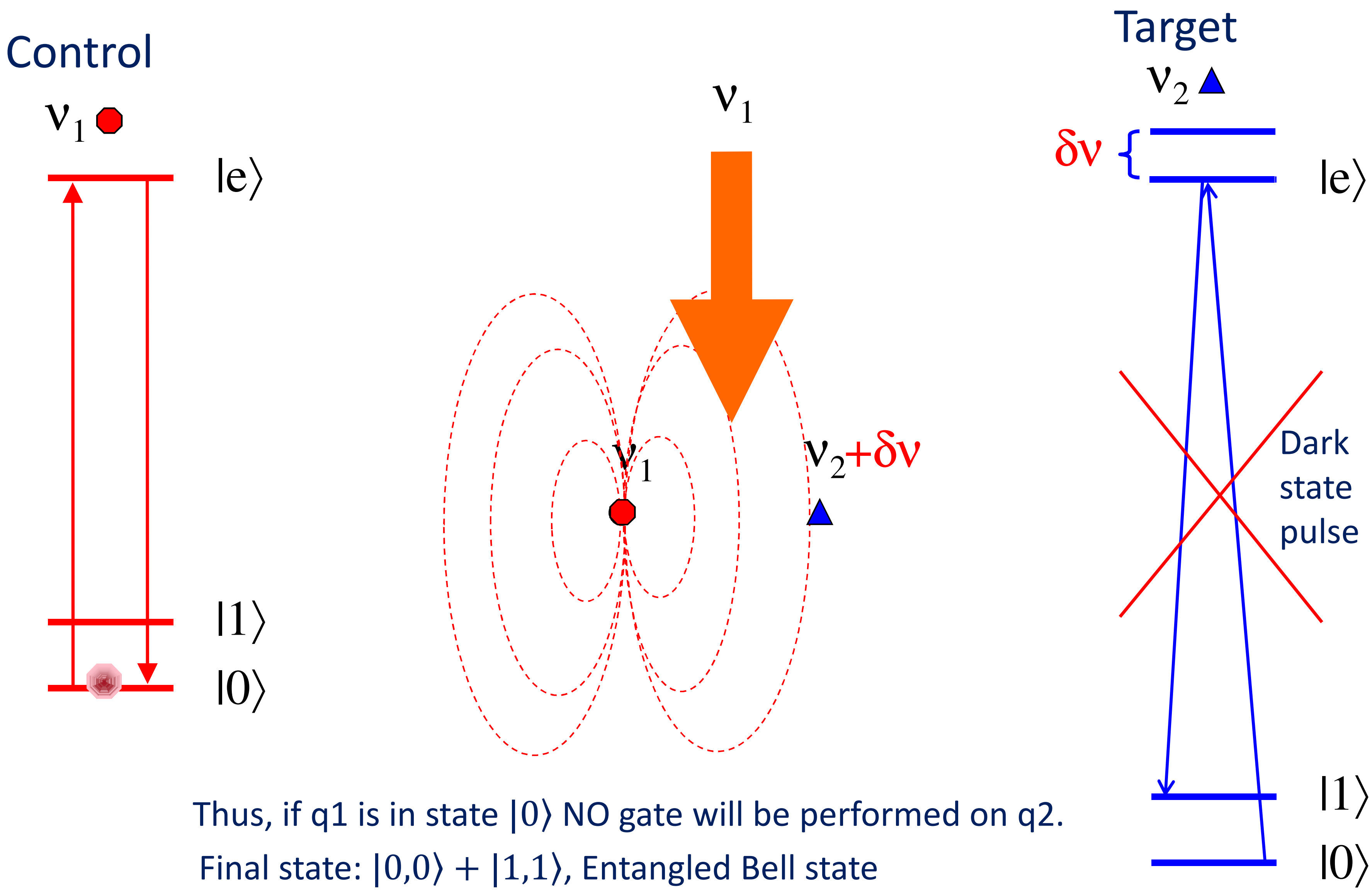
Rare-earths:  4) Two qubit gate



Thus, if q1 is in state $|1\rangle$ a not gate will be performed on q2

Rare-earths:

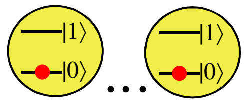
4) Two qubit gate



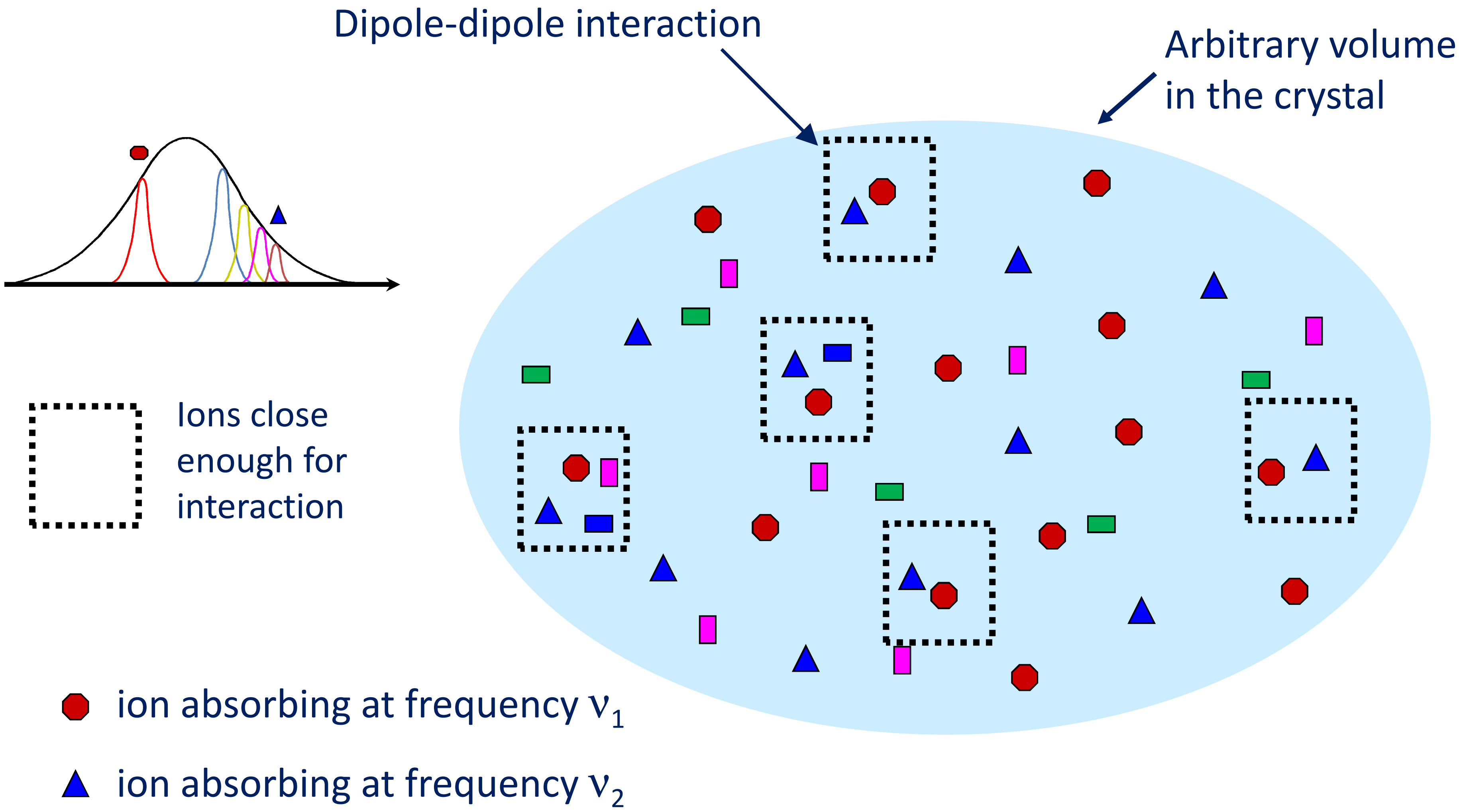
Thus, if q1 is in state $|0\rangle$ NO gate will be performed on q2.

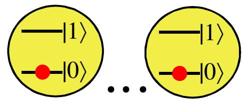
Final state: $|0,0\rangle + |1,1\rangle$, Entangled Bell state

Rare-earths:

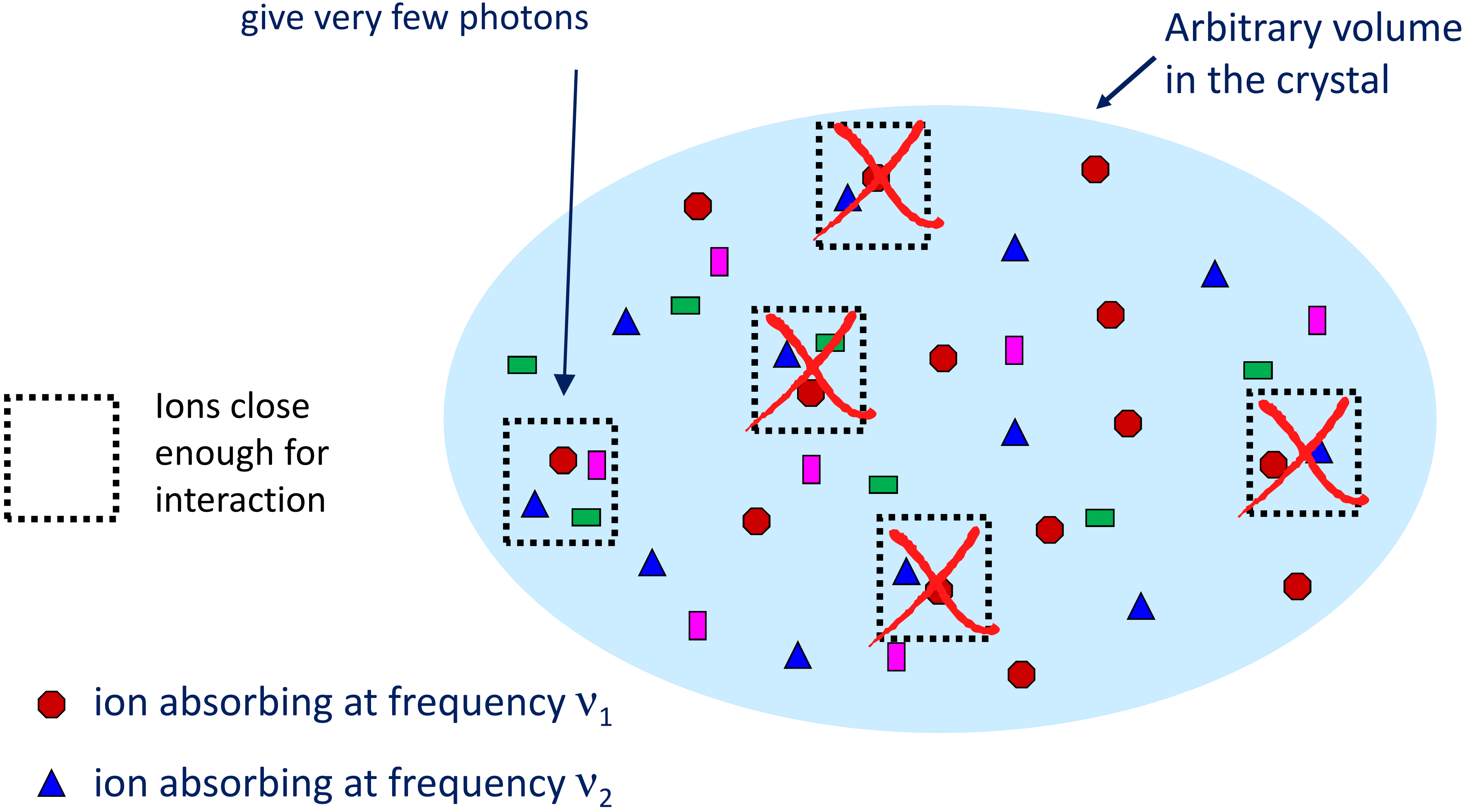


7) Scalability

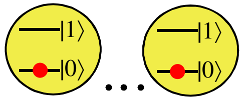


Rare-earths:  7) Scalability

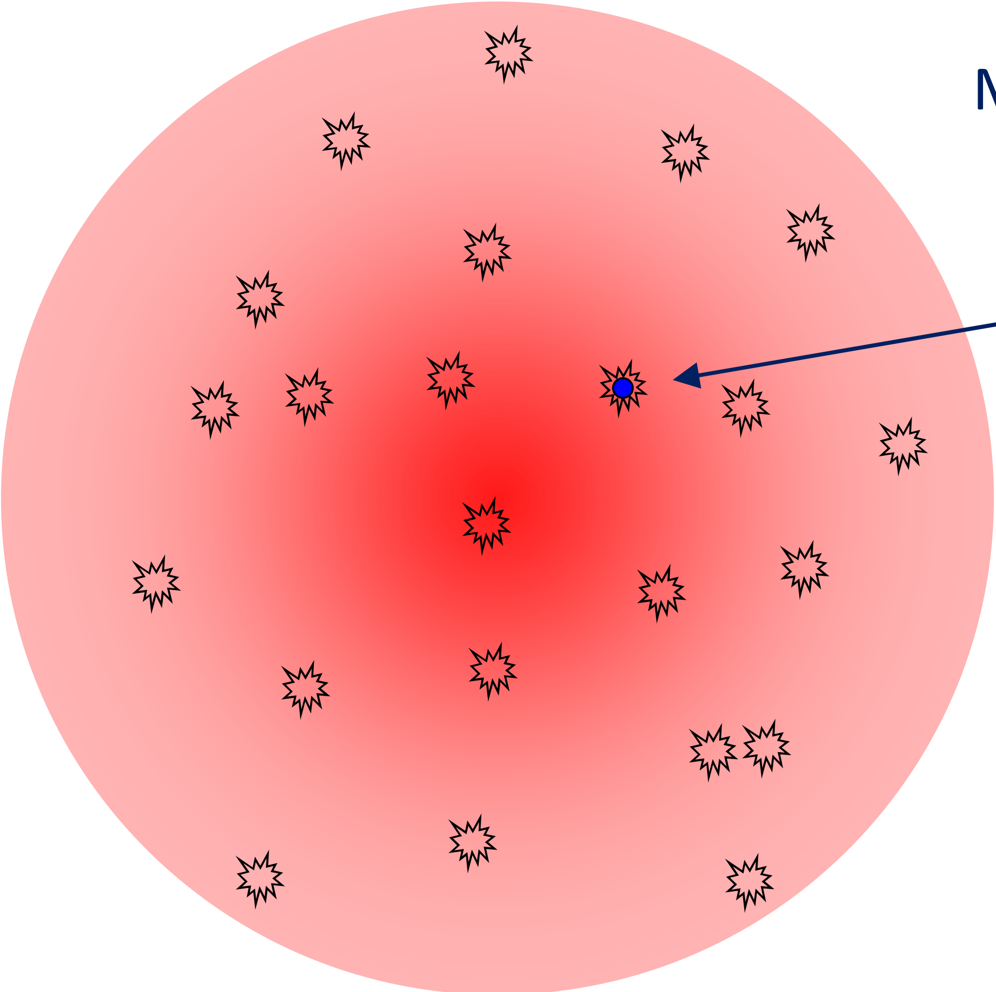
Single instance!
Hard to readout because the long qubit lifetimes give very few photons



Rare-earths:



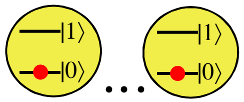
7) Scalability



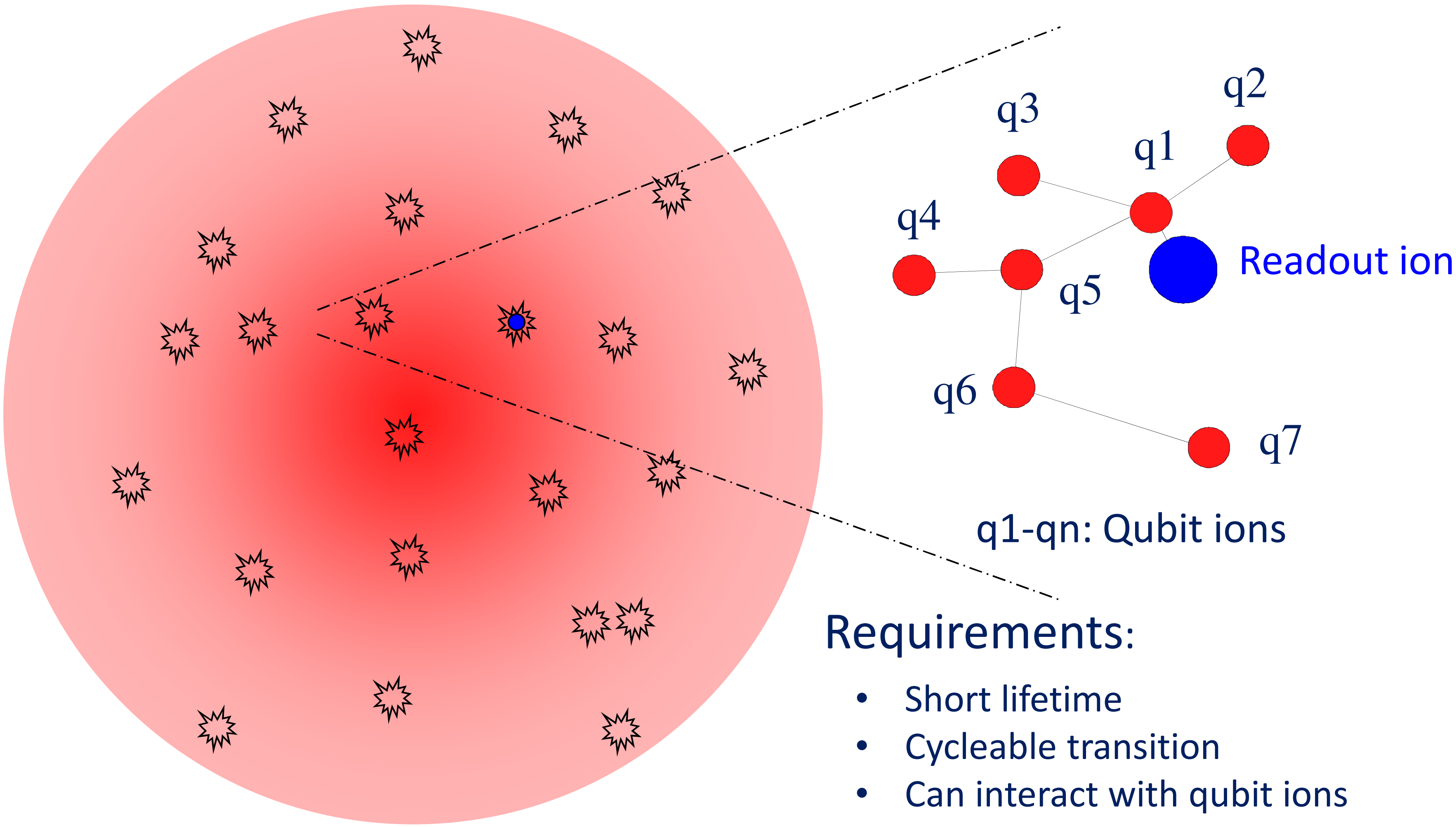
Minimal laser focus

Read out ion of different species

Rare-earths:



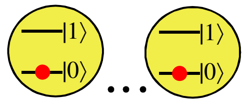
7) Scalability



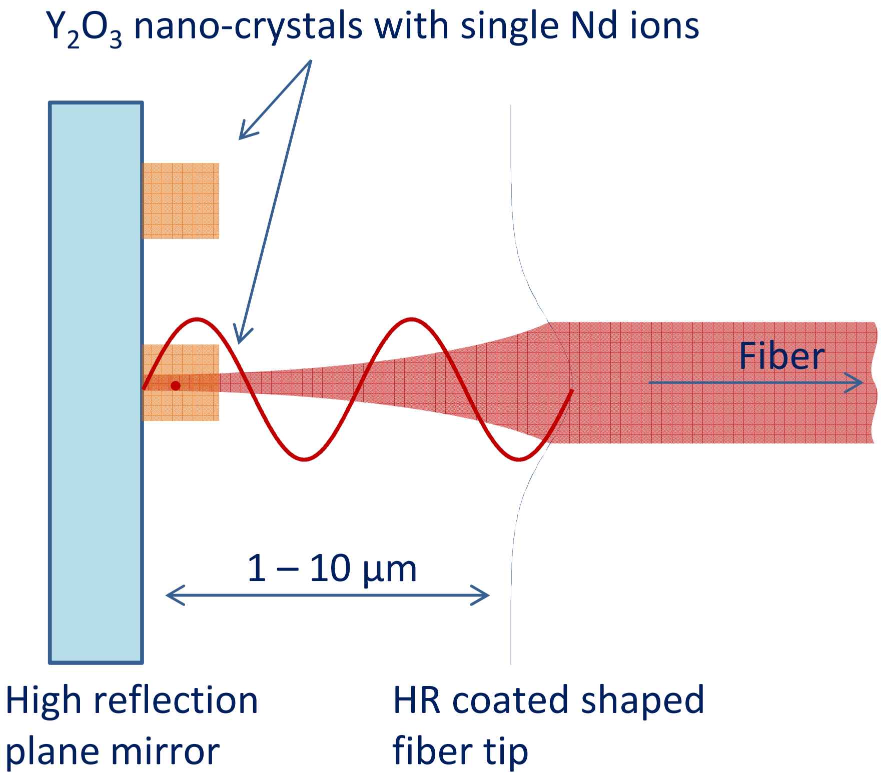
Requirements:

- Short lifetime
- Cycleable transition
- Can interact with qubit ions

One possible approach: Cerium

Rare-earths:  7) Scalability

New approach: use micro-cavity to enhance emission from qubit ions



Kaupp *et al*, PRA **88**, 053812 (2013)

- When the mode volume ~ λ^3 the vacuum modes are modified

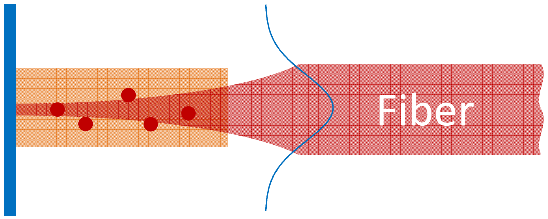
- Fermi golden rule:

Decay rate = matrix element * density of states

- The spontaneous emission is then enhanced (Purcell effect)
  - Q-value > 10^6
  - Estimated fluorescence enhancement: 10^4

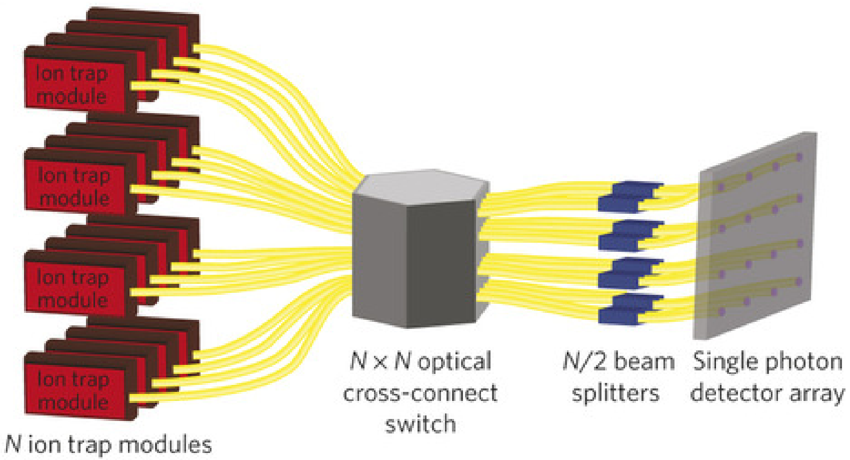
Scaling with cavity QED:

Multi qubit QC



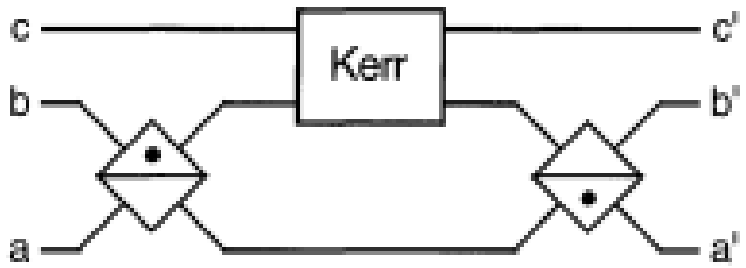
- High ion density gives many potential qubits

Further scaling through a network:



Quantum computing with linear optics

- Advantage: Photons are good information carriers, little decoherence
- One of the first proposals for quantum gates:
  - Non-linear optics by Milburn (1989)
- Described in the book (photonic QC)



- Two-qubit interactions via an intensity dependent Kerr-nonlinearity
- Doesn't work: Impossibly small phase shift of $\sim 10^{-18}$
- Knill, Laflamme, Milburn (KLM) shows in 2001 that QC possible with only linear optical elements

Quantum computing with linear optics

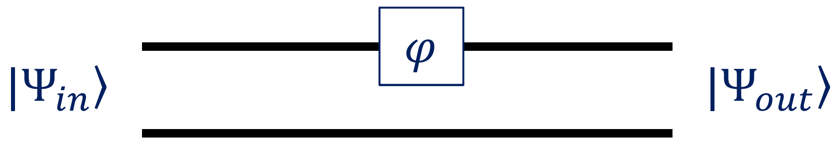
- Qubits via a single photon:
  - Single line with 0 or 1 photons is no good – n not conserved
  - Perpendicular polarizations (1 photon either way)
  - Dual rail (1 photon in two modes):
    - Spatial/Polarization/Time-bin/Frequency bin

$|0\rangle$ - photon is in the upper path
$|1\rangle$ - photon is in the lower path

Quantum computing with linear optics

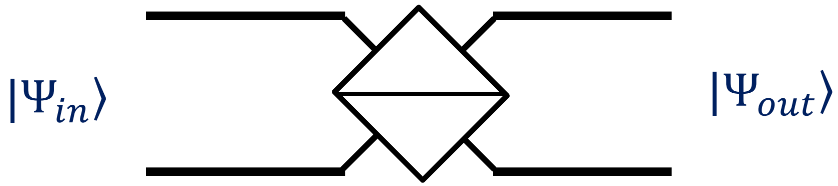
Single qubit gates with dual-rail:

Phase shifter:



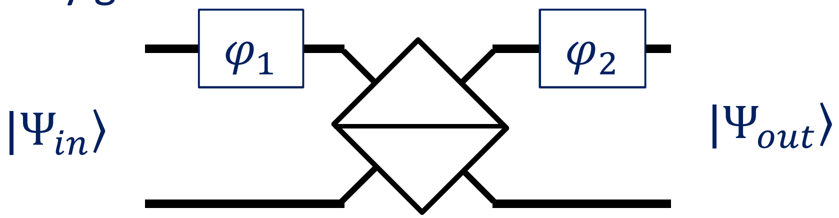
Can be accomplished by e.g. a medium with n>1

Beam splitter:



Can be made by partial mirror

Arbitrary gate:



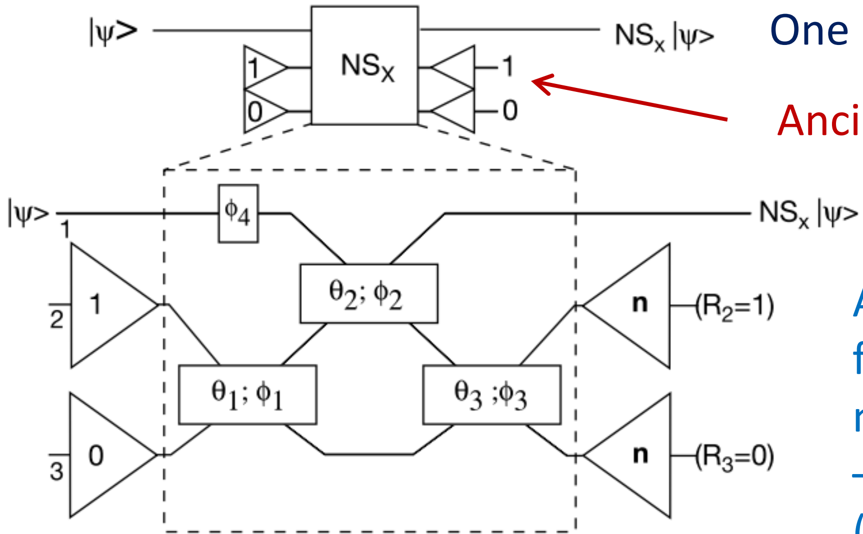
Combining the two elements can create any superposition state

Very simple components!

Quantum computing with linear optics

- The difficult part: a Multi-qubit gate
- Despite name, a non-linear component is needed: Detectors!

C-phase gate
(from KLM 2001):



One rail gets a phase shift

Ancilla qubits

Ancillas are detected, and for some answers, the main qubit is used.
– otherwise thrown away (probabilistic gate)

How can detection increase entanglement?

Consider the state : $|00\rangle + |01\rangle + |10\rangle + |11\rangle$, no entanglement

Add one qubit: $|001\rangle + |010\rangle + |100\rangle + |111\rangle$, partially entangled

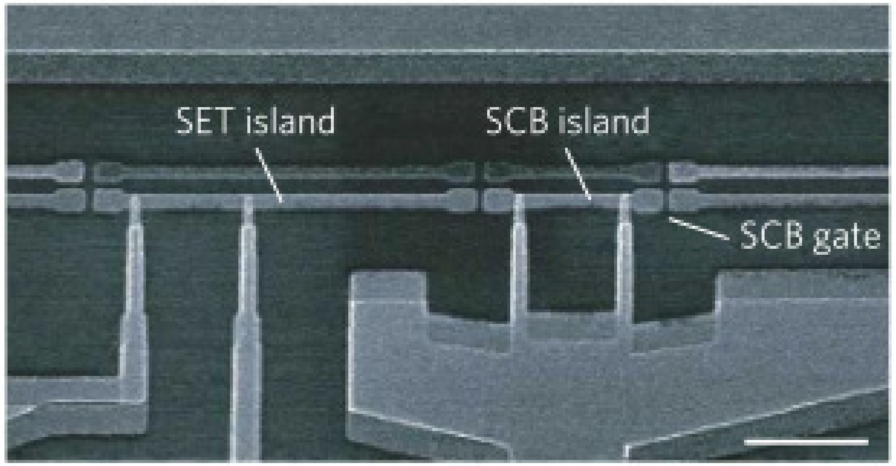
Post-select q3=1: $|00\rangle + |11\rangle$, Maximally entangled!

Another option: Start with multi-qubit entanglement –> cluster states

QC with superconducting qubits

Introduction

Motivation: QC scheme based on electronics might integrate better with conventional technology

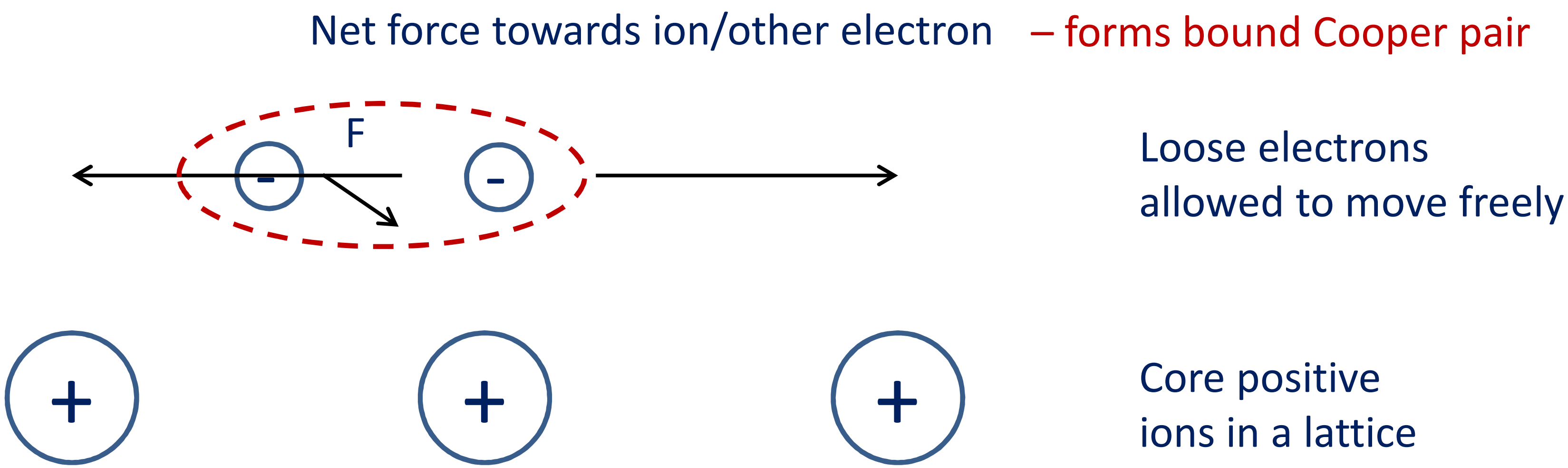


- Basic mechanism: superconductivity via Cooper pairing + Josephson junction
- Fully explained by BCS theory (Nobel prize 1972 to Bardeen, Cooper and Schrieffer)
- Tunneling barrier – Josephson *et al*. 1962, Nobel prize 1973

QC with superconducting qubits

Superconductivity – a hand-waving explanation

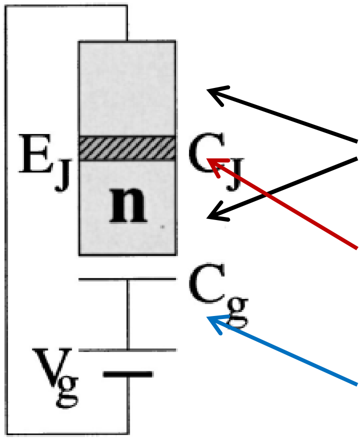
Consider a metallic structure:



- Paired electrons are Bosons and can thus be in the same state
- Electron scattering vanishes → No resistance, superconductivity
- Simple picture, a proper description requires full many body interactions
- Weak effect, requires very low temperatures to form bound

QC with superconducting qubits

Qubits based on superconducting patches:

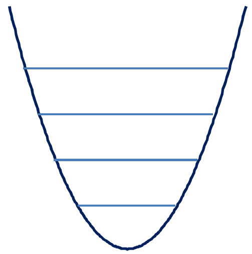


superconducting

Barrier

Controlling the bias allows different number of Cooper pairs, **n**, on island

Josephson effect – quantization of charges



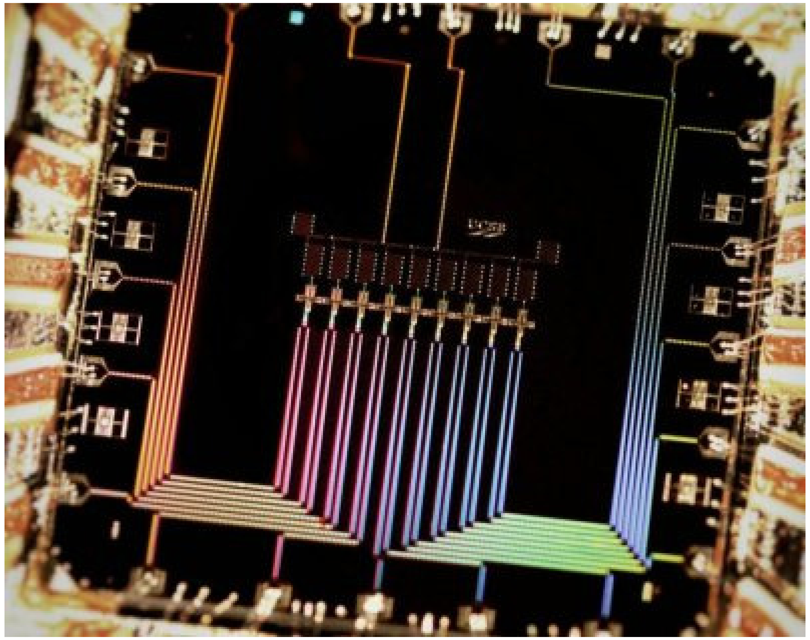
$\Delta E \sim$ 0.5 K

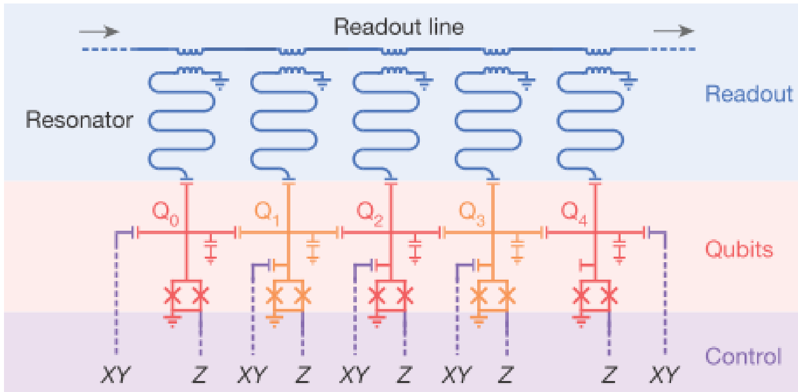
- Cooper pairs can coherently tunnel between the patches
- Requires very low temperature ~ 10-30 mK
- Can be readout by a Single Electron Transistor coupled to the island

QC with superconducting qubits

Multi-qubit gates

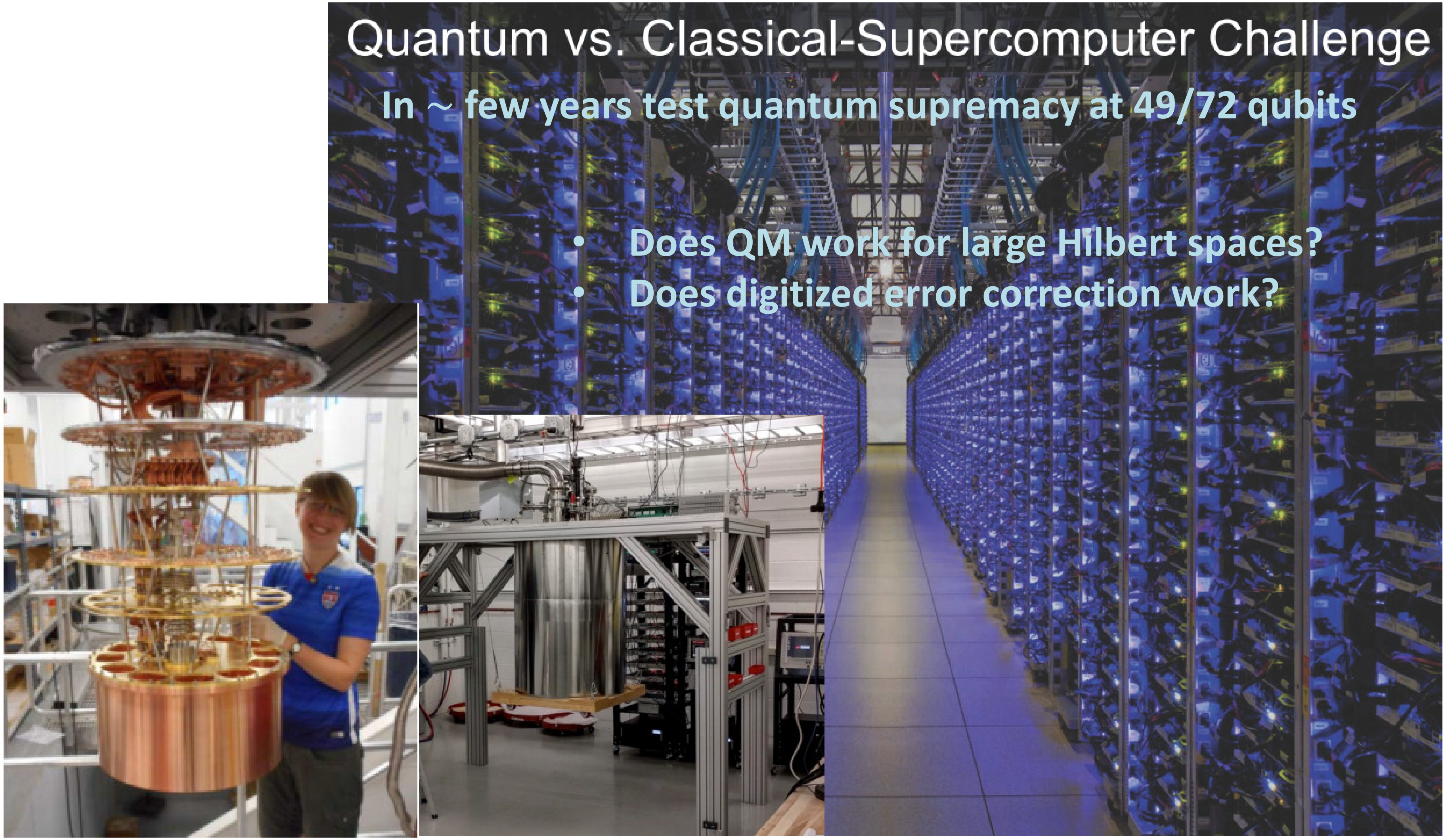
9 ”Xmon” qubits (Martinis group, now at Google):





- Each qubit has a distinct resonance frequency
- Multi-qubit gates by tuning near qubits into resonance
- Seemingly scalable architecture
- Good coherence vs. gate time

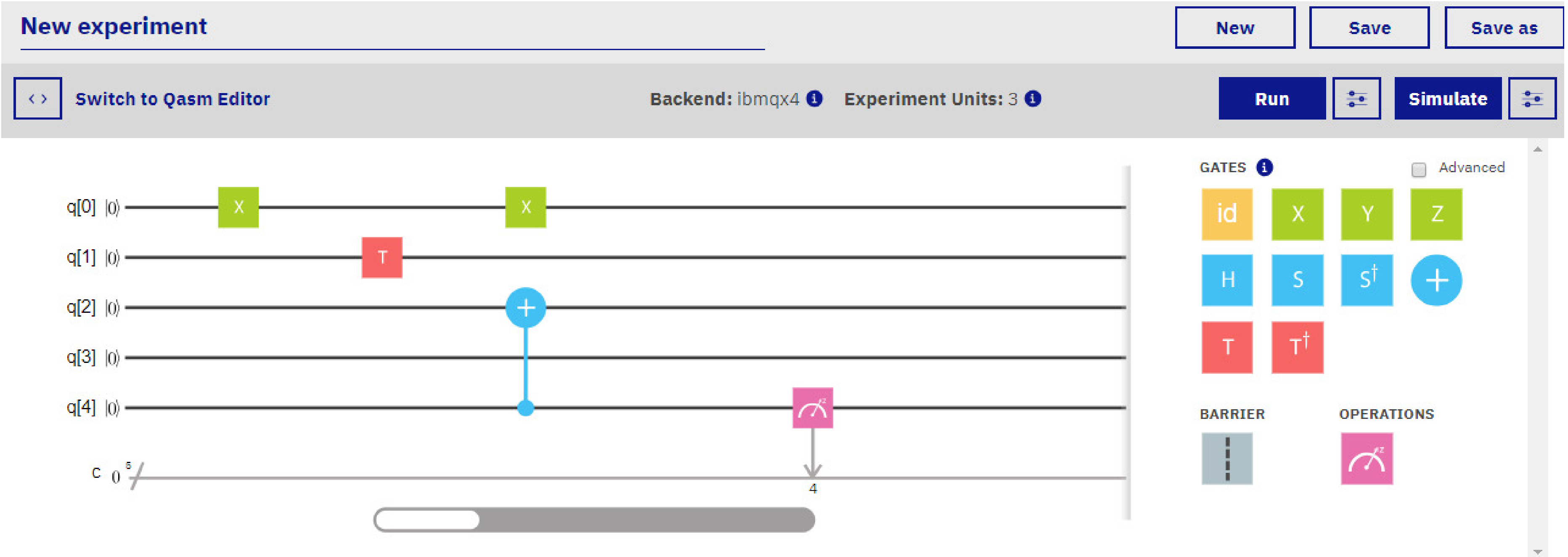
The future is already here?



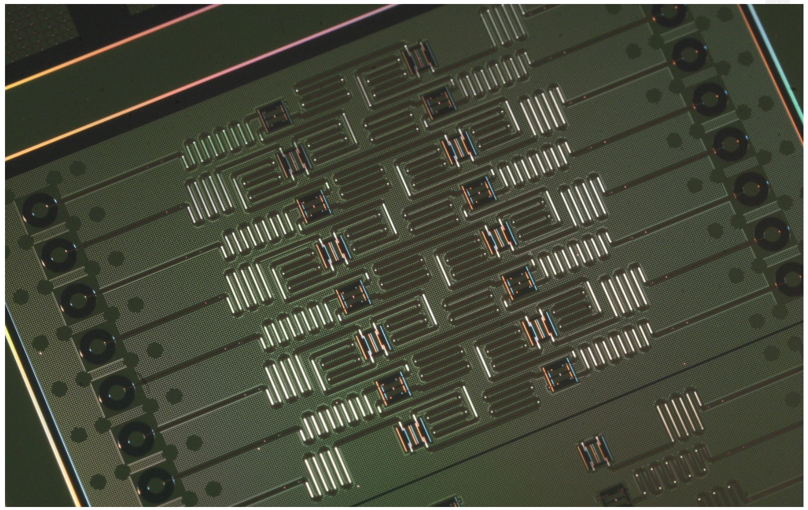
From John Martinis at Google

The future is already here?

IBM: The Quantum Experience, online SC quantum computer



- 5 and 14-qubit chips are open to public:
- 20 qubit chip available at a cost



EU Flagship on Quantum Technologies

- 10 years: Started in 2018 and lasts to 2028
- Budget: 1 billion €

- Has generated much national investment

  In Sweden: WAllenberg Center for Quantum Technologies (WACQT)

  Budget: 600 MSEK over 10 years

- 4 major areas:
  - Quantum communication
  - Quantum simulation
  - Quantum sensing
  - Quantum computing
    - Superconducting qubits
    - Artificially trapped ions
    - Rare-earth ions

Scalable QUAntum computing nodes using Rare-Earth ions (SQUARE)

Summary – Many systems will work together!

• Ion traps	• Early success with many qubits (8-14) • Very good single operation fidelity • Drawbacks: resource heavy, difficult scaling
• Rare-earth systems	• Simpler system + solid state • High density, strong interactions • Drawbacks: single ion regime is difficult
• Superconducting qubits (Google, IBM)	• Solid system/electronics • Fast and good operations, best scalability • Drawbacks: serious cooling, no flying qubits
• Linear optics photonics	• Simple components • Photons are good qubits (Long T_2 and flying) • Drawbacks: probabilistic makes it very slow
• NV-centers in diamond	• Simple system • Some room temperature operation • Drawbacks: Limited scalability around NV
• Nuclear Magnetic Resonance (NMR)	• Early success but no real quantum scaling

- Quantum dots
- Topological quantum computing (Microsoft) – Majorana qubits