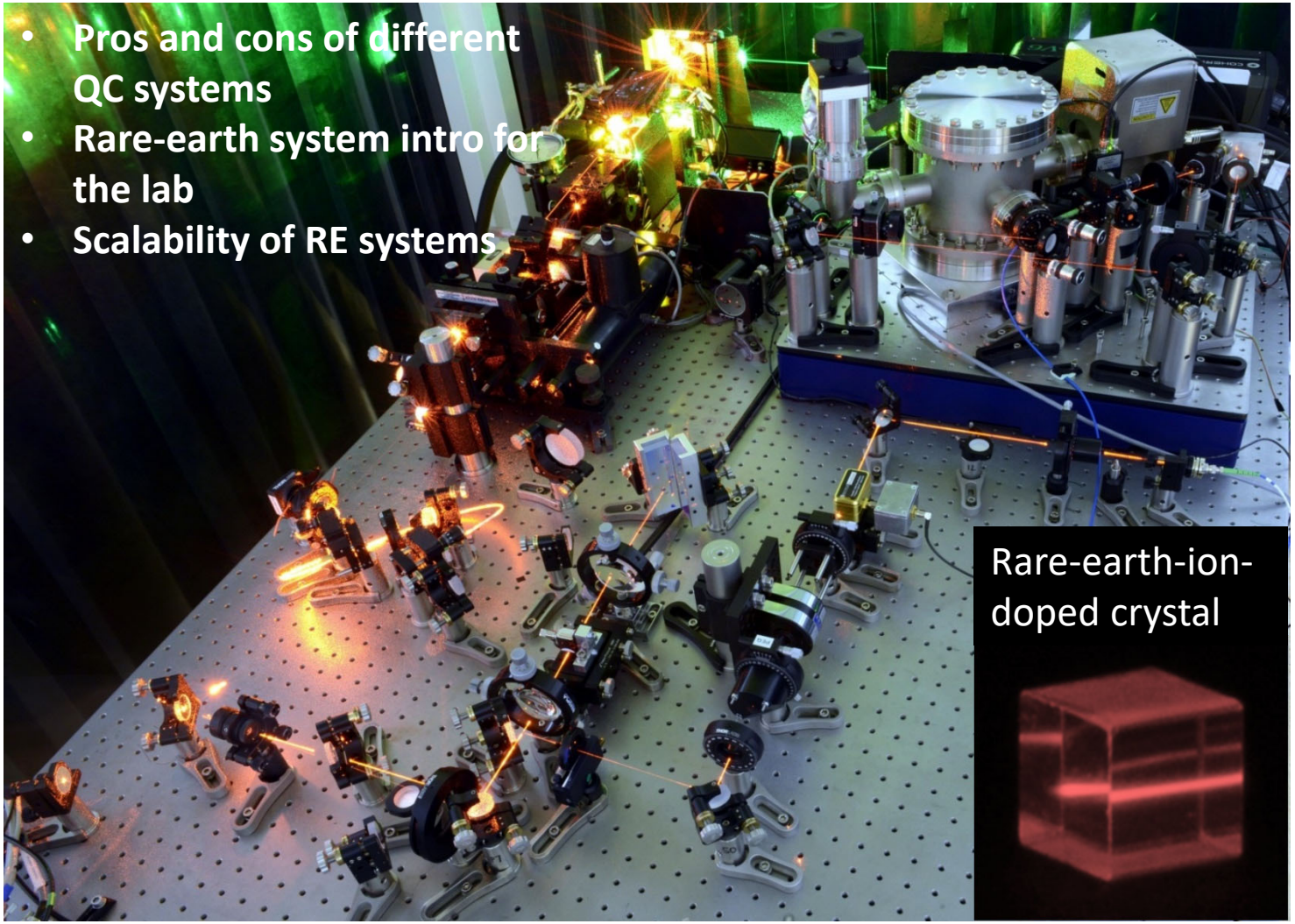
Quantum computing in Rare-earth-ion systems

By Andreas Walther, Lund University



Motivation: Why are rare-earth systems interesting?

Very versatile system

- Quantum communication
  - Quantum memories
    - 6 hours coherence time
    - High bandwidth of 50 GHz
    - Highly multimode (>1000 temporal modes)
  - Interface between atom/photon or between microwave/optical
    - Rare-earth connected to a SQUID demonstrated
- Quantum Sensing
  - Slow light structures
    - Filters for medical diagnostics (WACQT)
    - Laser Stabilization
  - Very sensitive local field probe
    - Sensing field from single ions of spins
- Quantum computing (QC)
  - Long term approach

QUANTUM FLAGSHIP

SQUARE

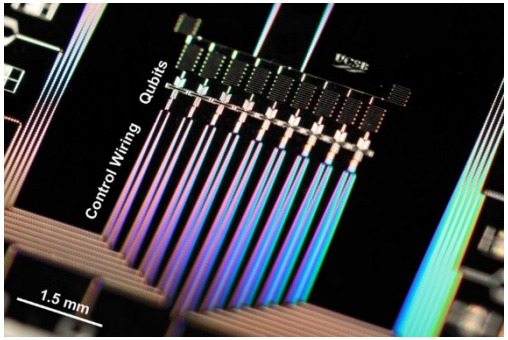
Scalable QUAntum computing nodes using Rare-Earth ions (SQUARE)

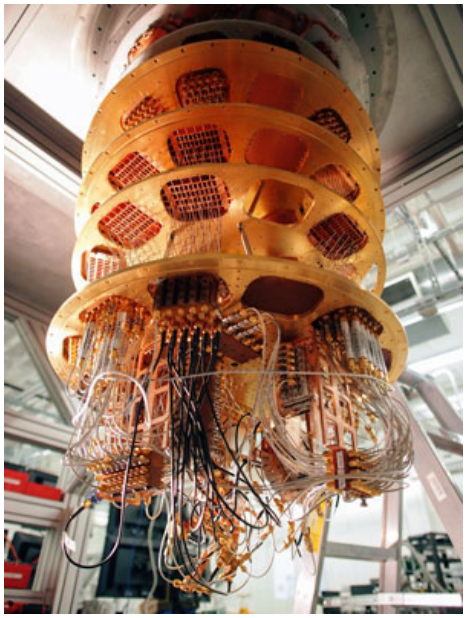
Quantum computing approaches

Leading approaches to QC in the Flagship

Superconducting qubits

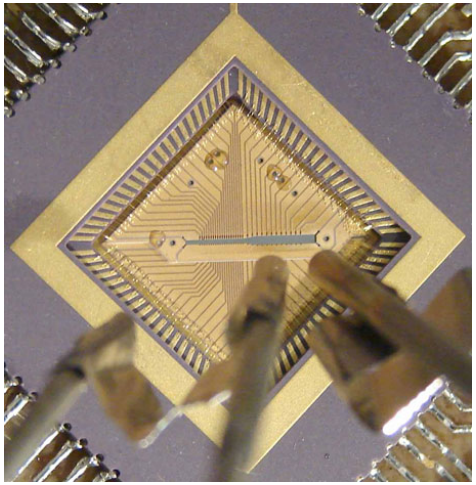
- Straightforward to add more qubits
- Solid state



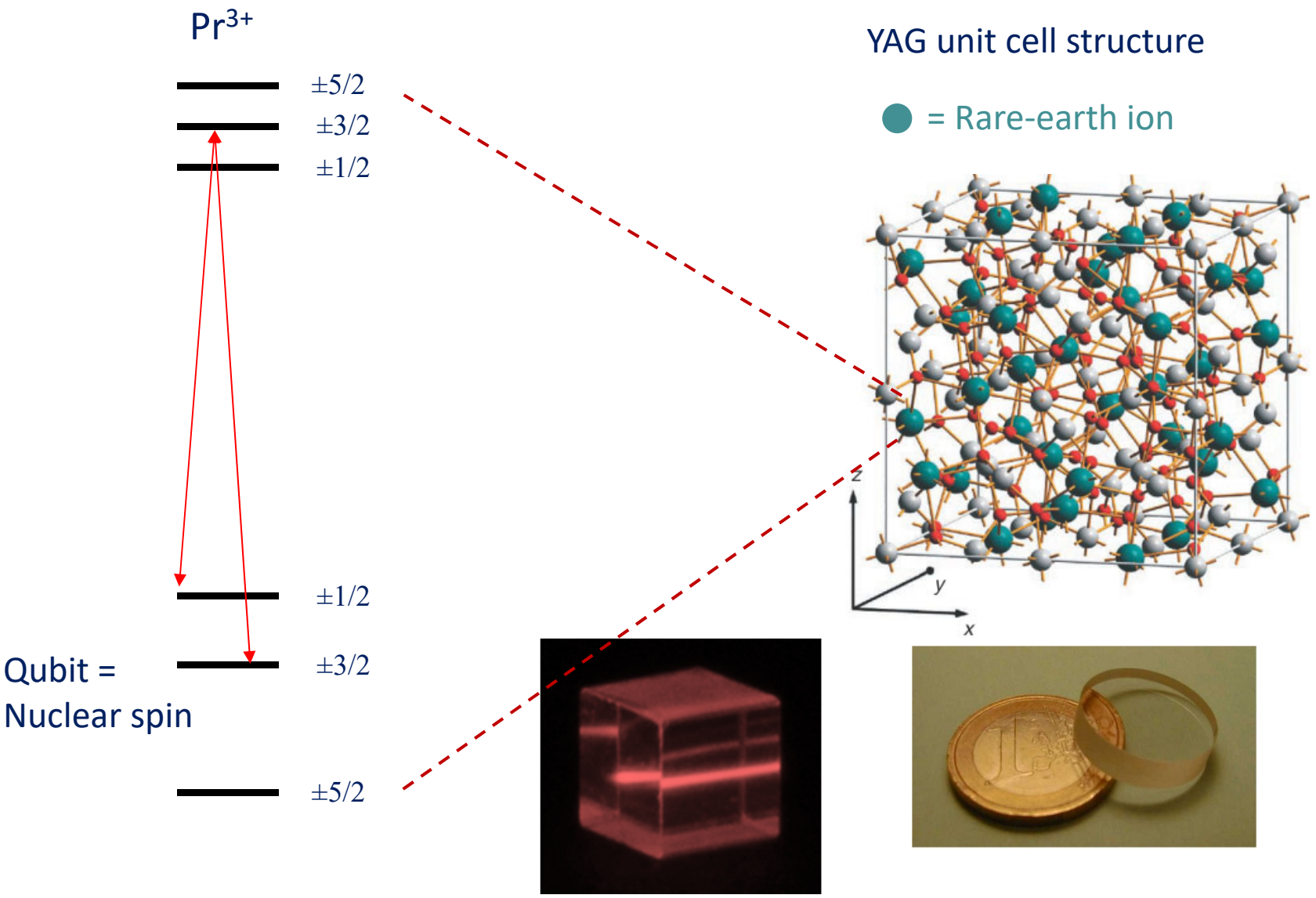


Artificially trapped ions

- High fidelity
- High connectivity



Rare-earth QC – naturally trapped ions

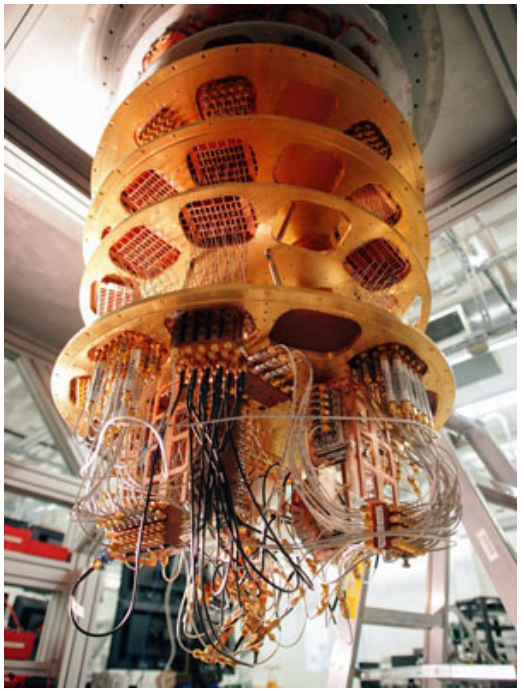


Current status of quantum computing

Superconducting qubits

- 20 qubit chips
- 3-12 qubit entangled chains

– Only nearest neighbor interactions
– Are currently mm in size
– Hard to scale cooling to mK



Artificially trapped ions qubits Fewer qubits needed

- 20 qubit strings
- Up to 14 qubit entangled chains

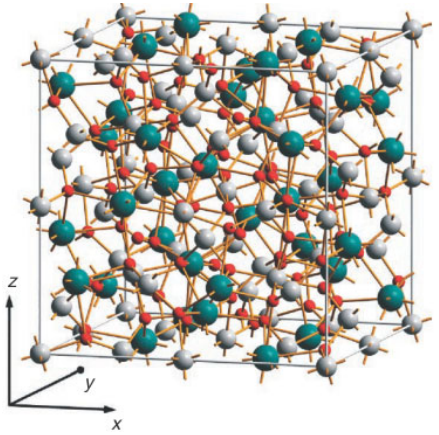
– but you can't put more than 10-20 in the same trap

Naturally trapped RE ion qubits Fewer qubits needed

- Only 1 qubit

Are nm in size
Very high potential qubit density

– Single ions are hard to detect



A technologically relevant QC algorithm (for SC qubits) requires $\gtrsim 200$ million qubits

Fowler et al, PRA 86, 032324 (2012)

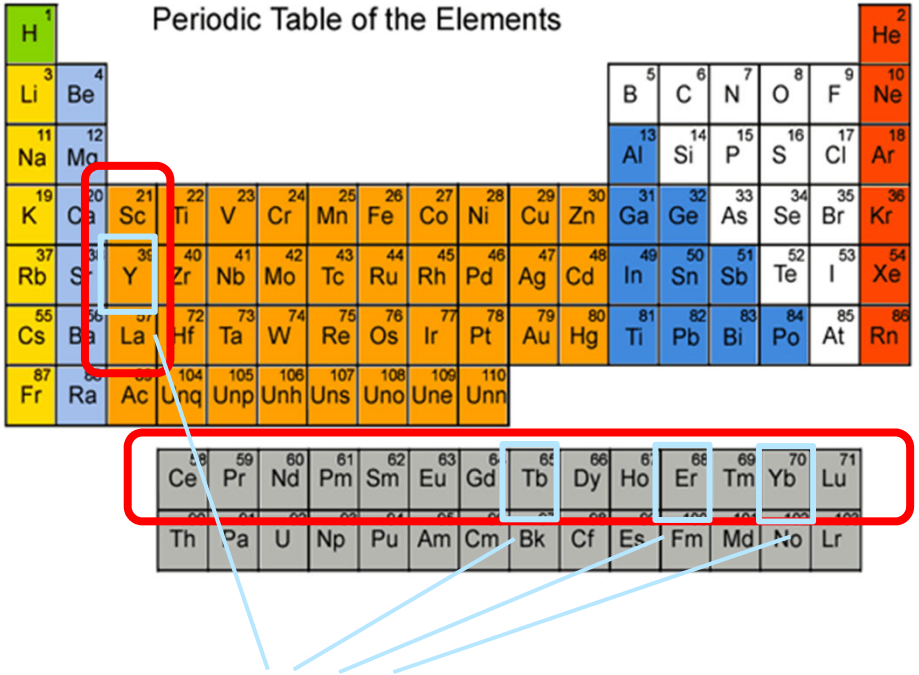
It’s difficult to predict technological development

- “This 'telephone' has too many shortcomings to be seriously considered as a means of communication.”
  - *Western Union internal memo, 1876*

- “I think there is a world market for maybe five computers.”
  - *Thomas Watson, chairman of IBM, 1943*

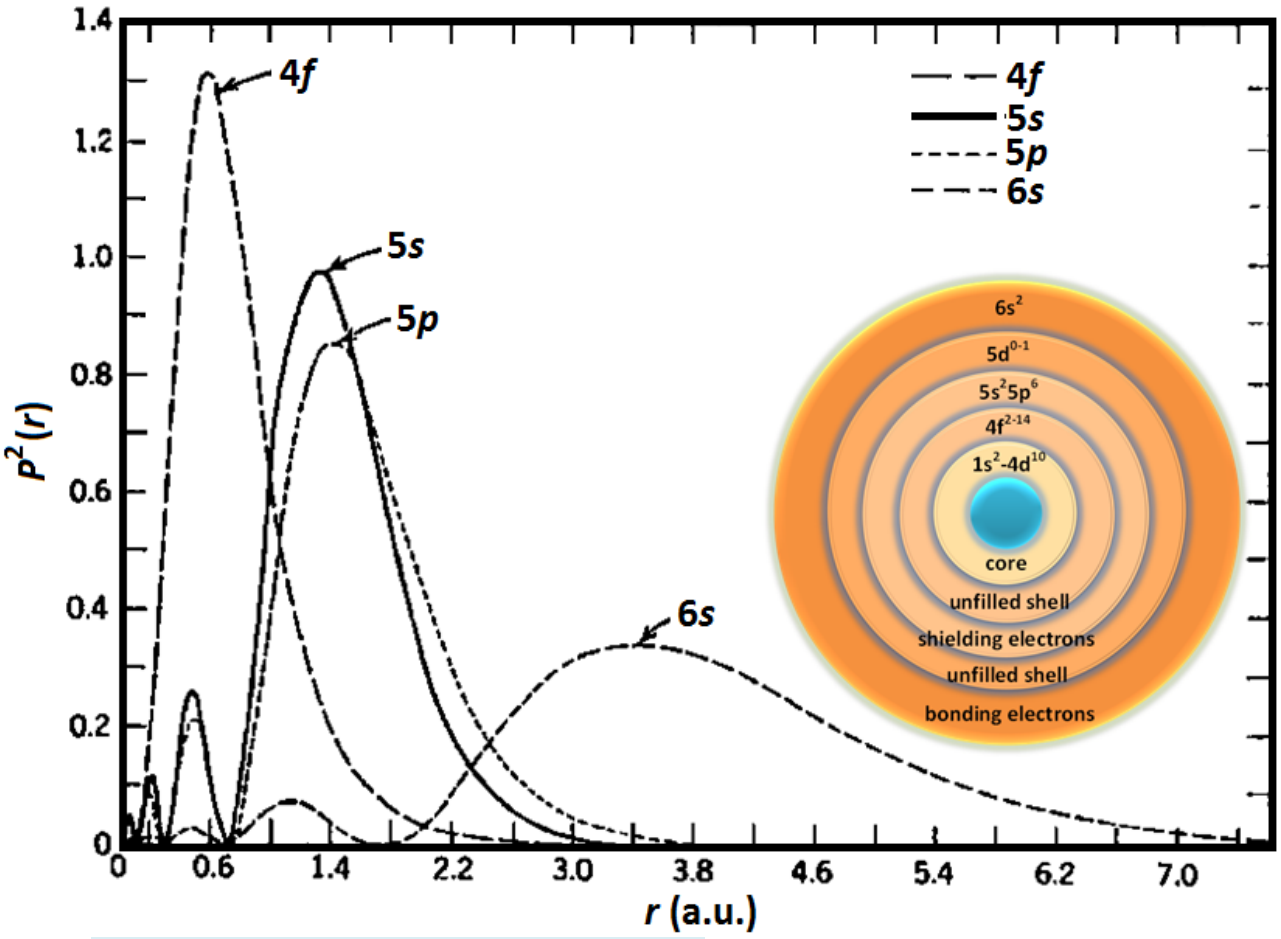
Paradigm shift: Electron tubes → transistors very hard to predict

Rare-earth-doped crystals



4 of them named after Ytterby in Sweden

Why RE ions?

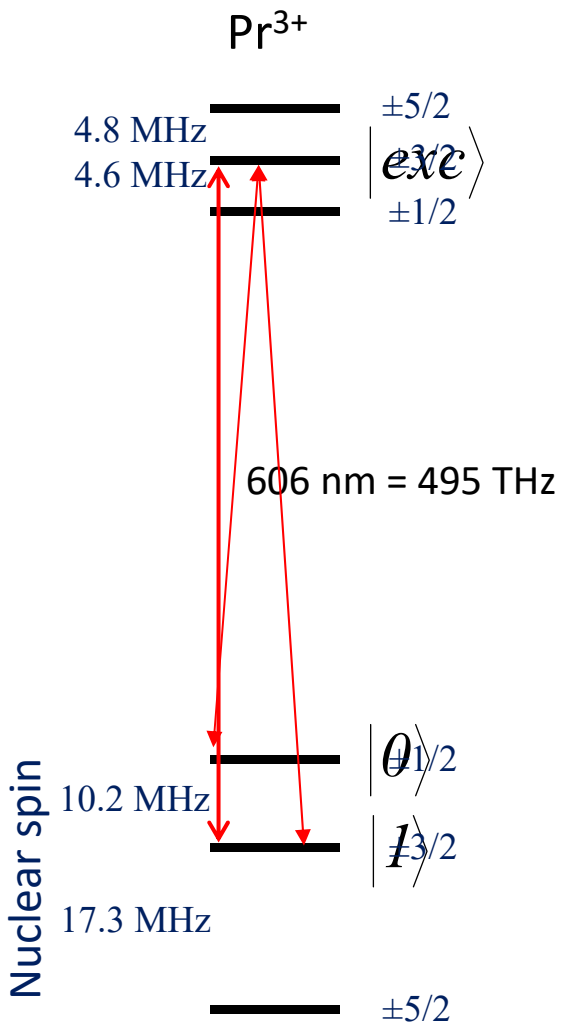


G. H. Dieke -> physics stackexchange

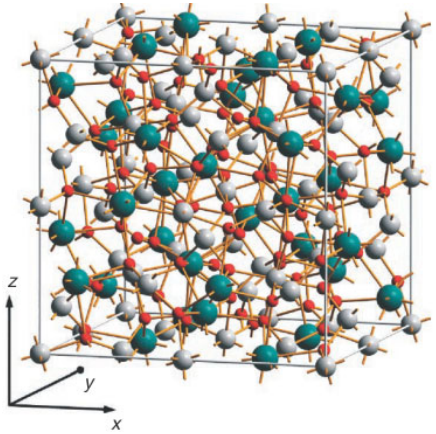
Element	4f electrons
La^{3+}	0
Ce^{3+}	1
Pr^{3+}	2
Nd^{3+}	3
Pm^{3+}	4
Sm^{3+}	5
Eu^{3+}	6
Gd^{3+}	7
Tb^{3+}	8
Dy^{3+}	9
Ho^{3+}	10
Er^{3+}	11
Tm^{3+}	12
Yb^{3+}	13
Lu^{3+}	14

Leads to long coherence times!

Rare-earth ion qubits



- Long coherence times:
  - Up to 6 h for spin
  - Several ms for excited state
- Spatially close:
  - strong interactions



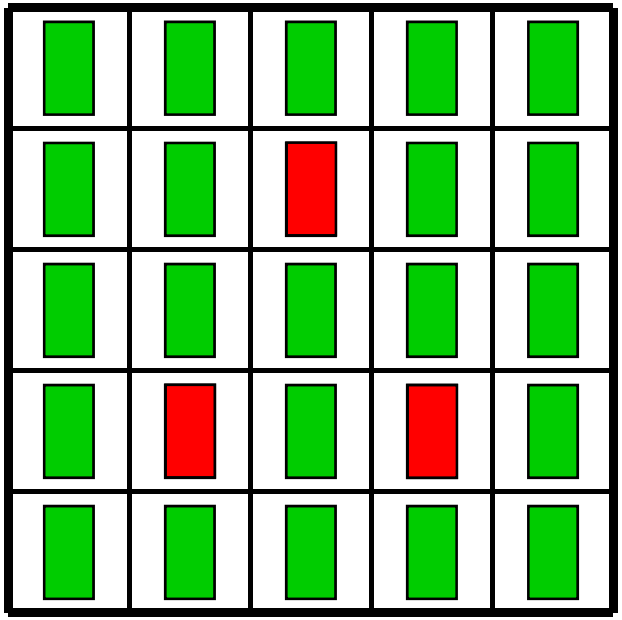
1 ion = 1 qubit is ultimate goal, but not there yet

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

But...
compensation needed for inhomogeneities

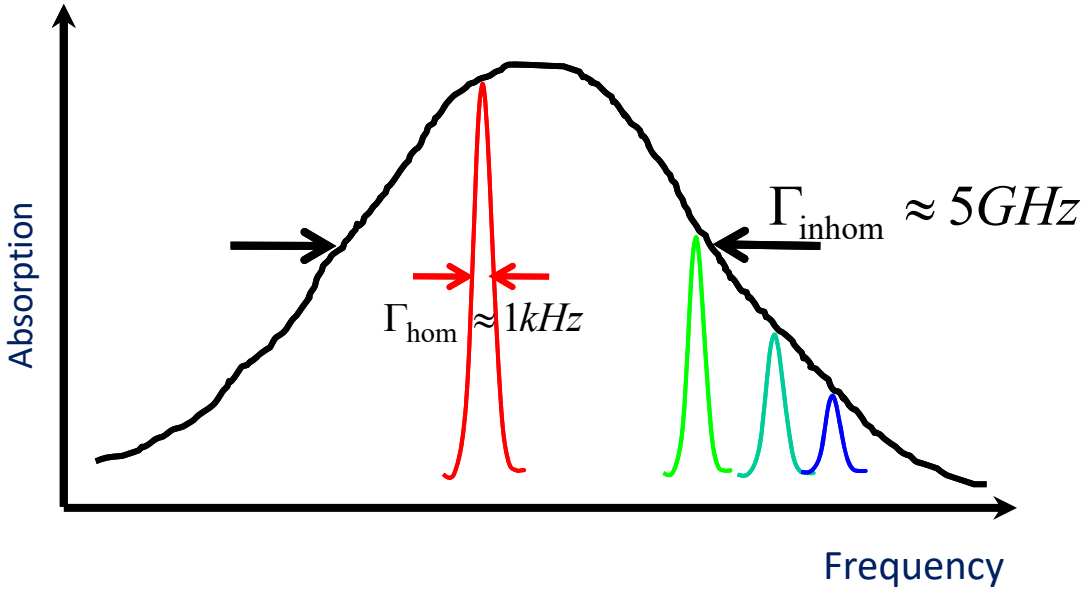
Rare-earth ion ensemble qubits

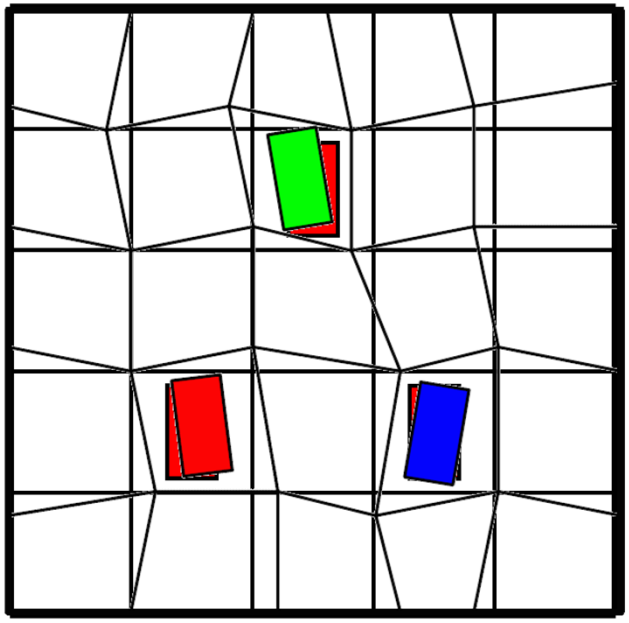
Conceptual picture of crystal



$Pr^{3+}:Y_2SiO_5$

Rare-earth ion ensemble qubits





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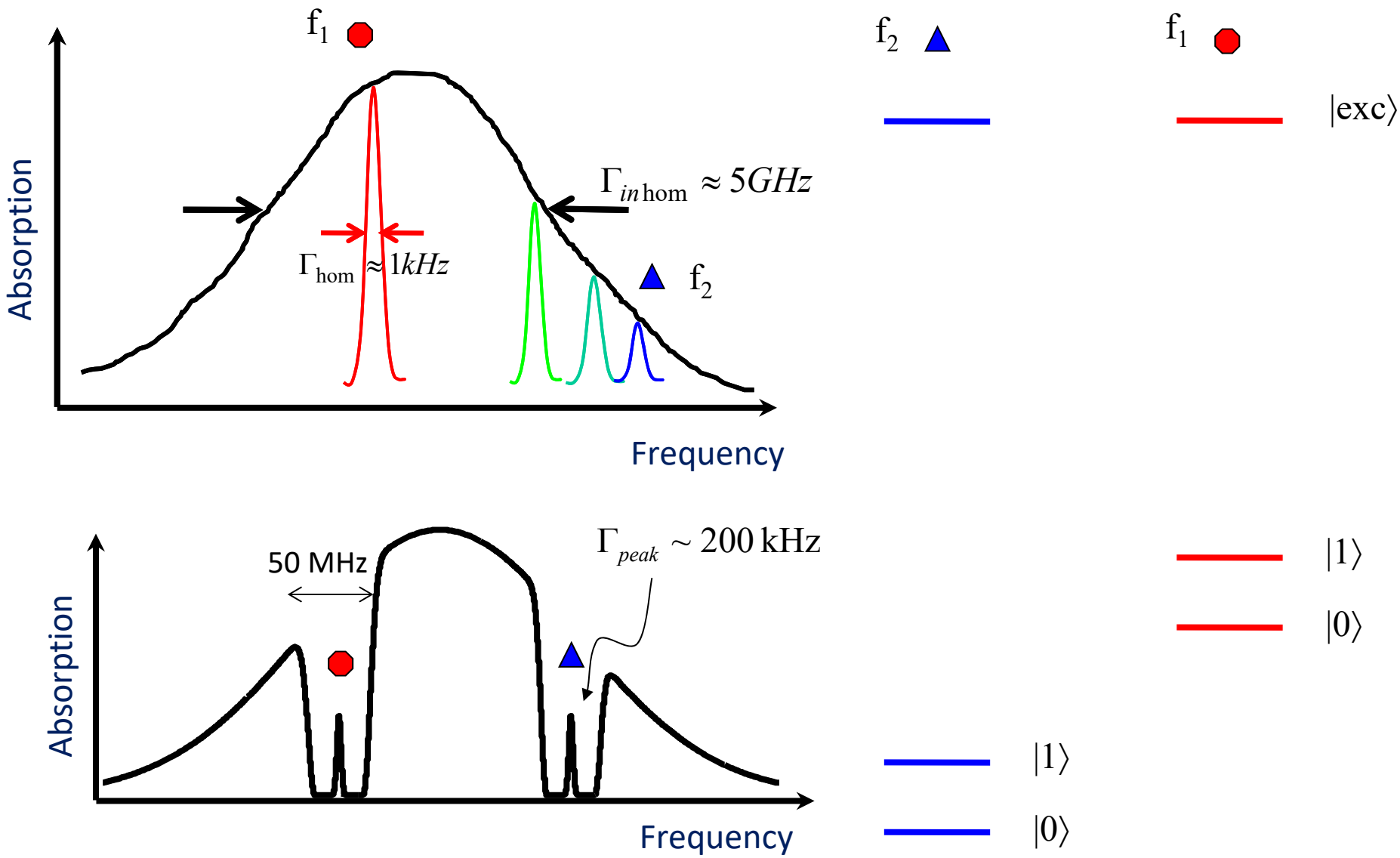
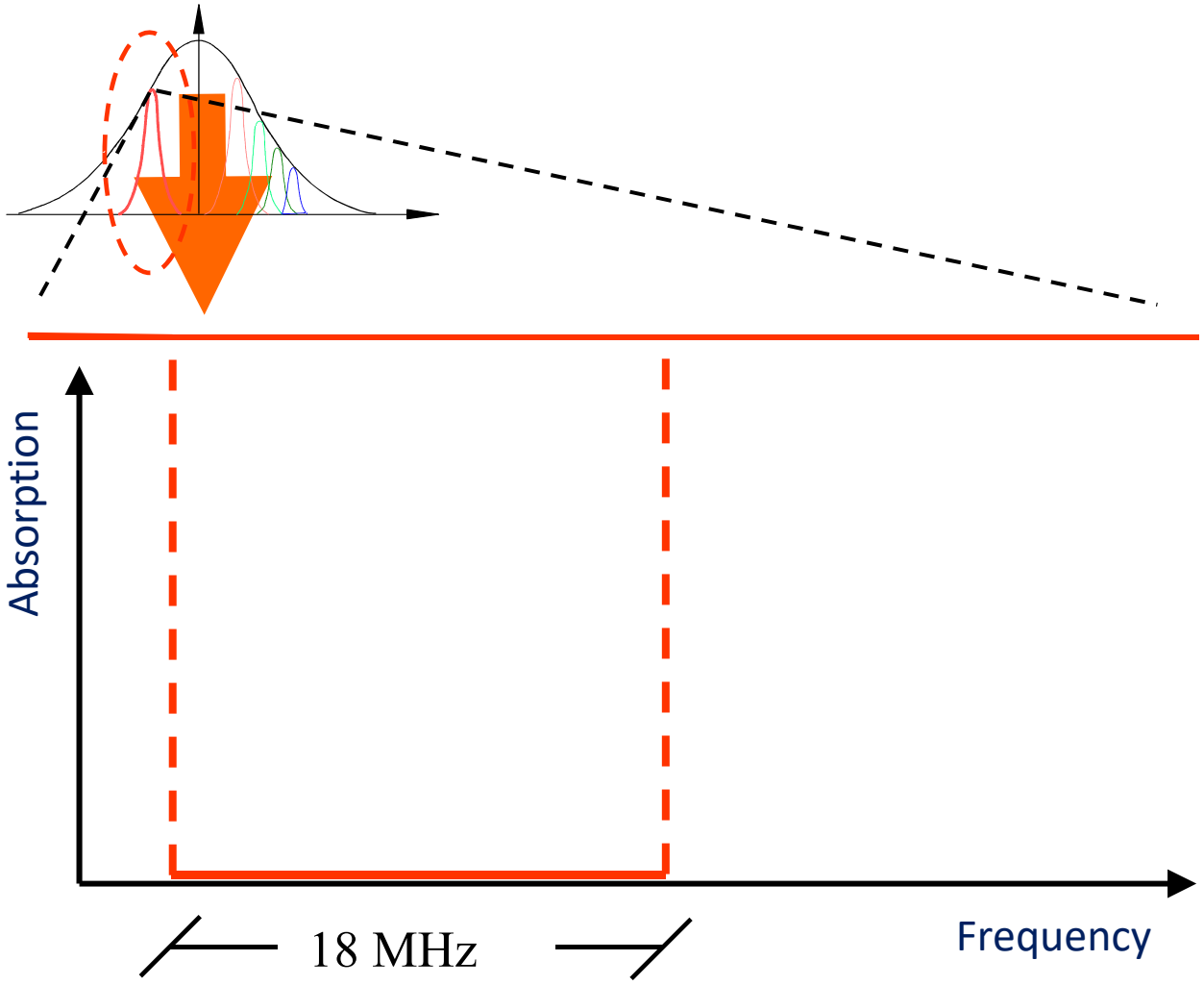
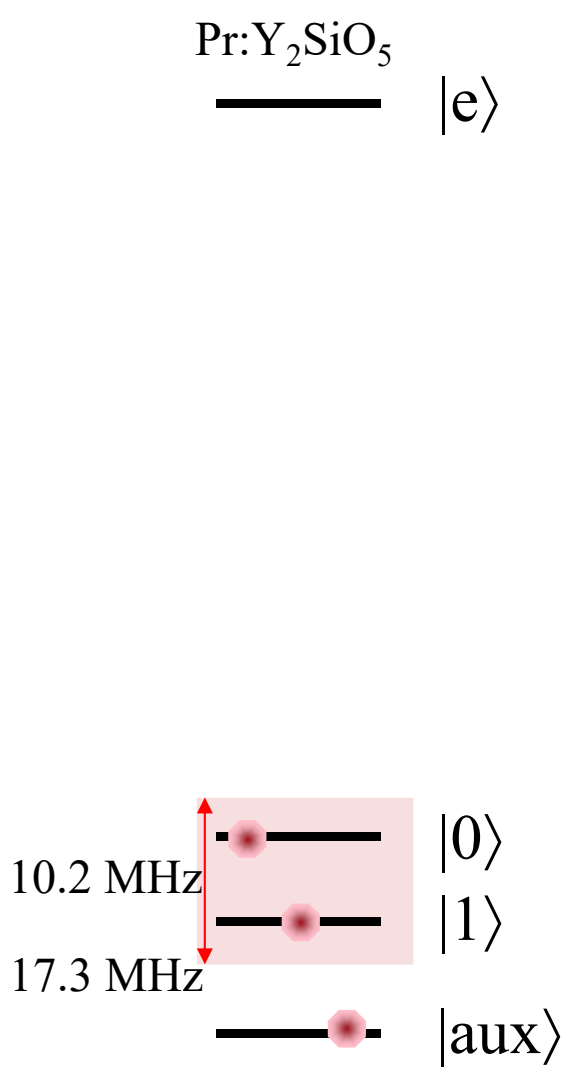
Rare-earth ion ensemble qubits

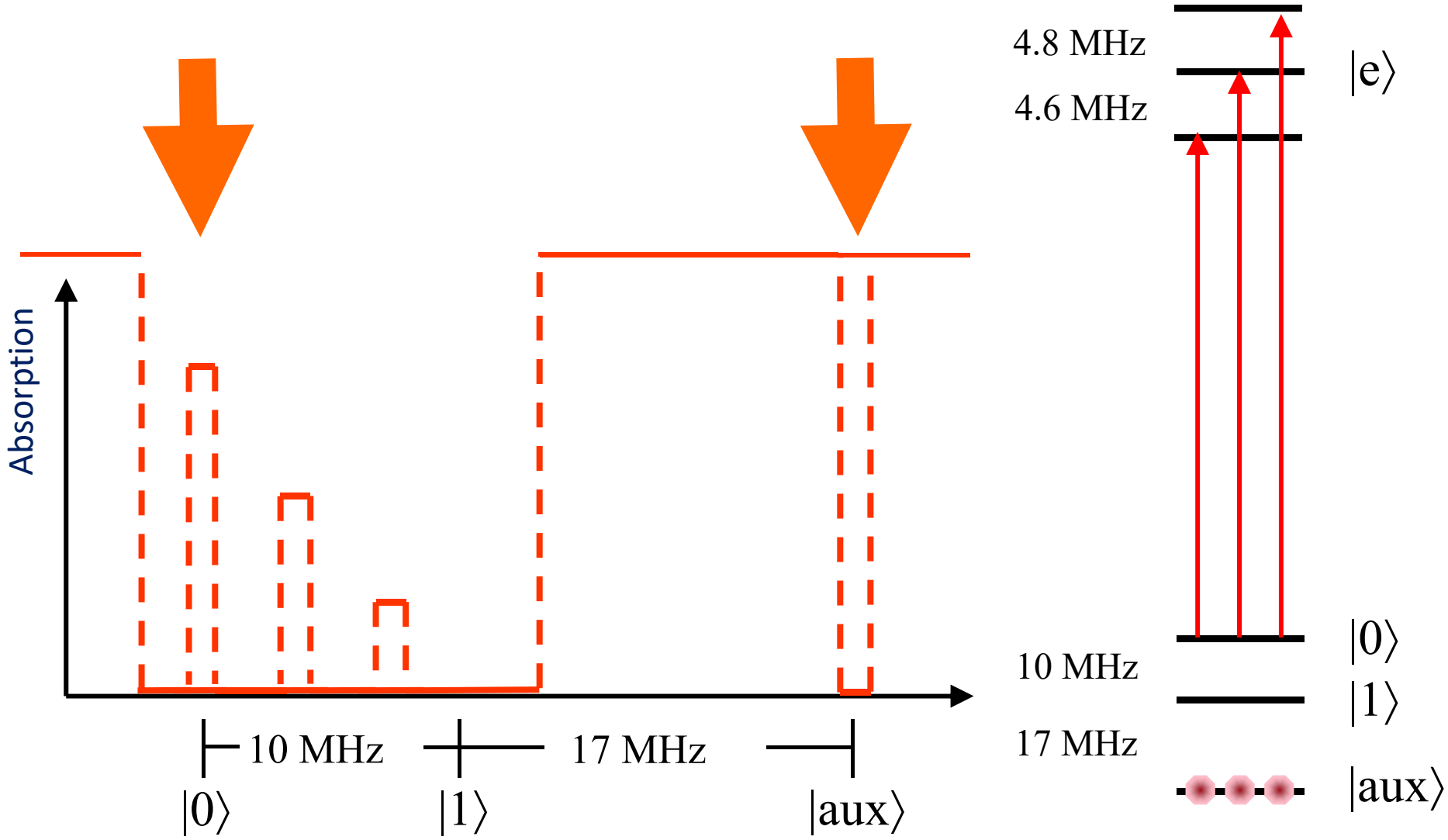


RE ensemble qubits: Initialization

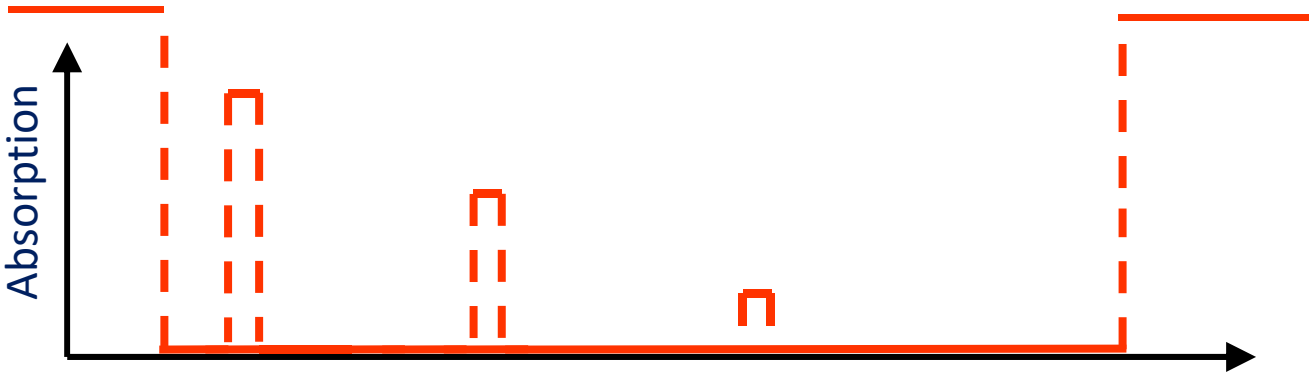




RE ensemble qubits: Initialization

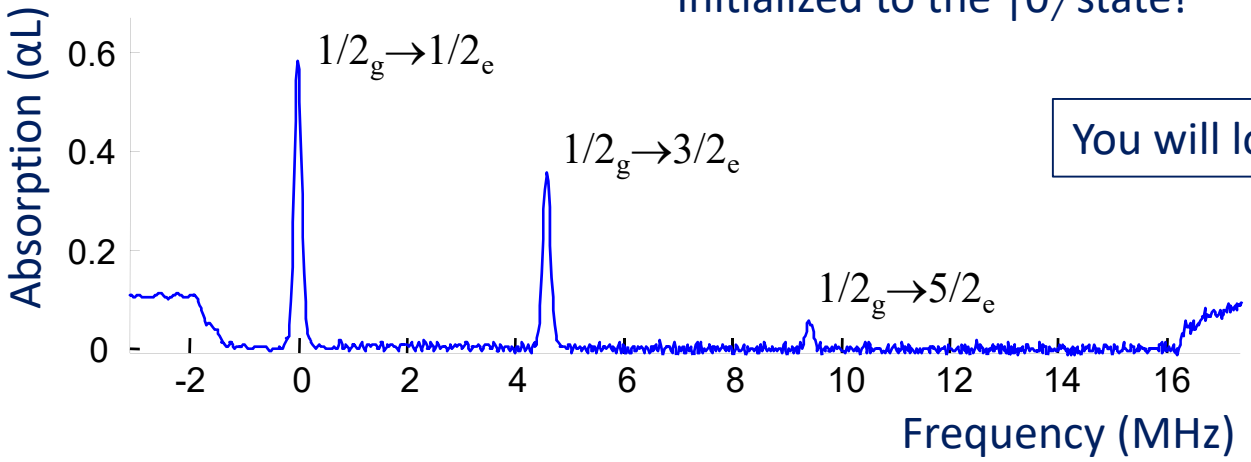


RE ensemble qubits: Initialization



633 pulses later...

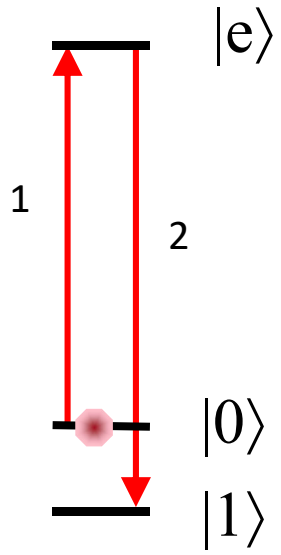
Initialized to the $|0\rangle$ state!

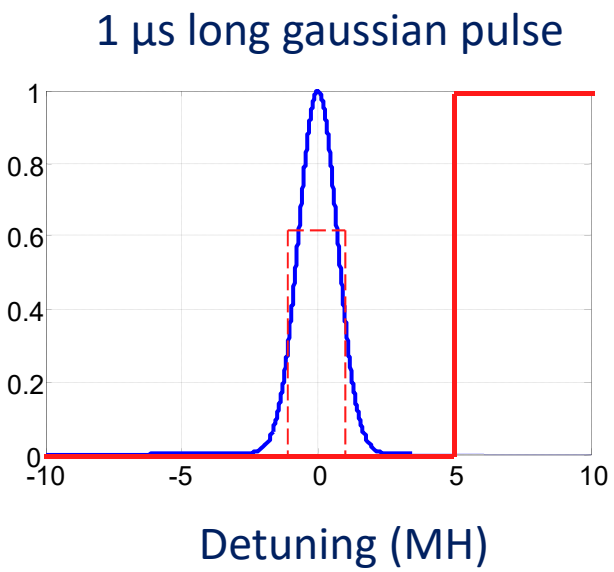


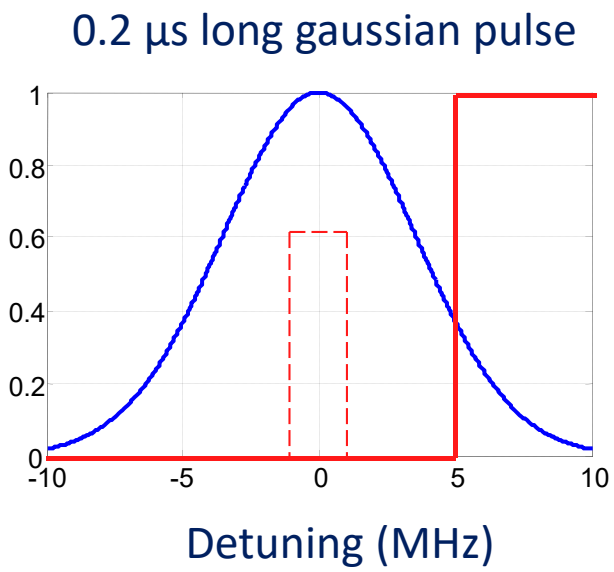
You will look at this during the lab!

Single qubit gates

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



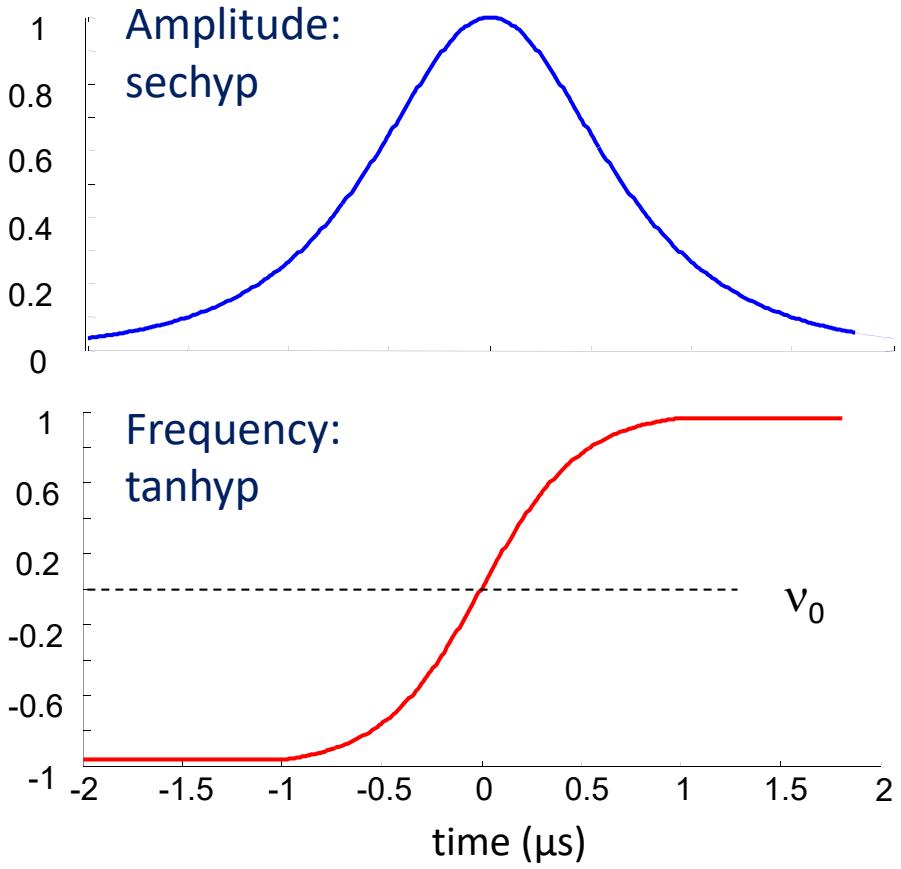




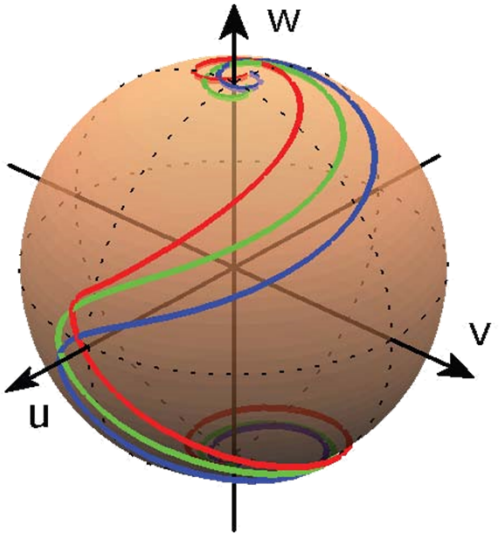
- Problem #1: Not the same Rabi frequency everywhere
- Problem #2: Dephasing due to the inhomogeneous width
- Problem #3: Wings excite non-initialized ions

Single qubit gates

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

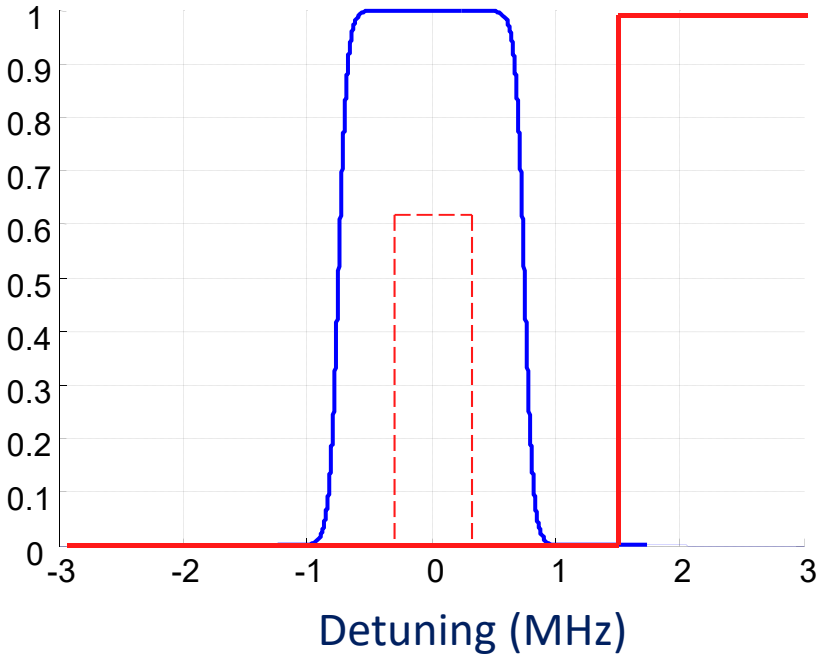


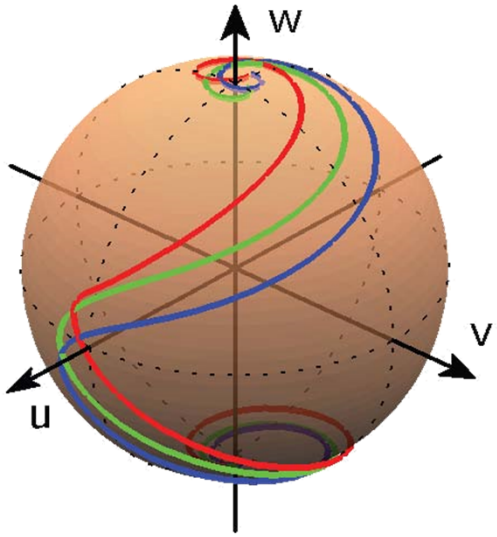
Path on Bloch sphere:



Single qubit gates

Sechyp pulses:

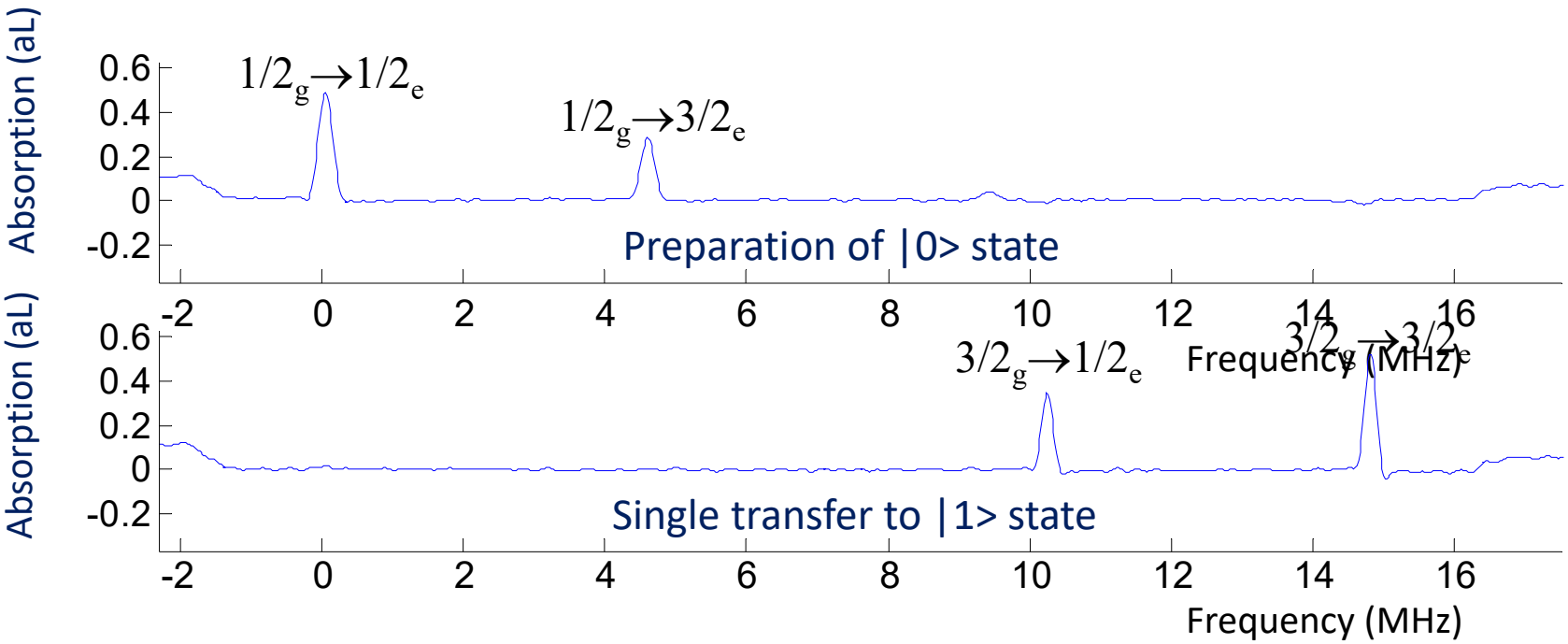




+ Solve the problem with different rabi frequencies
+ Solve the problem with dephasing due to inhomogeneous broadening
+ No excitation outside initialized region

- Can only handle pole to pole transfers

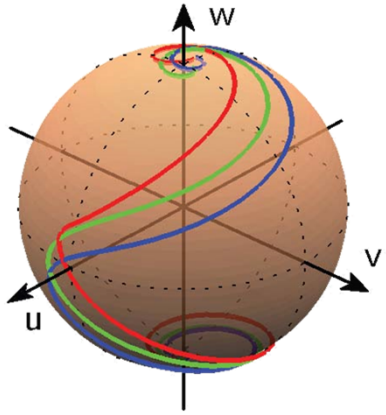
Single qubit gates



97.5% single transfer efficiency!

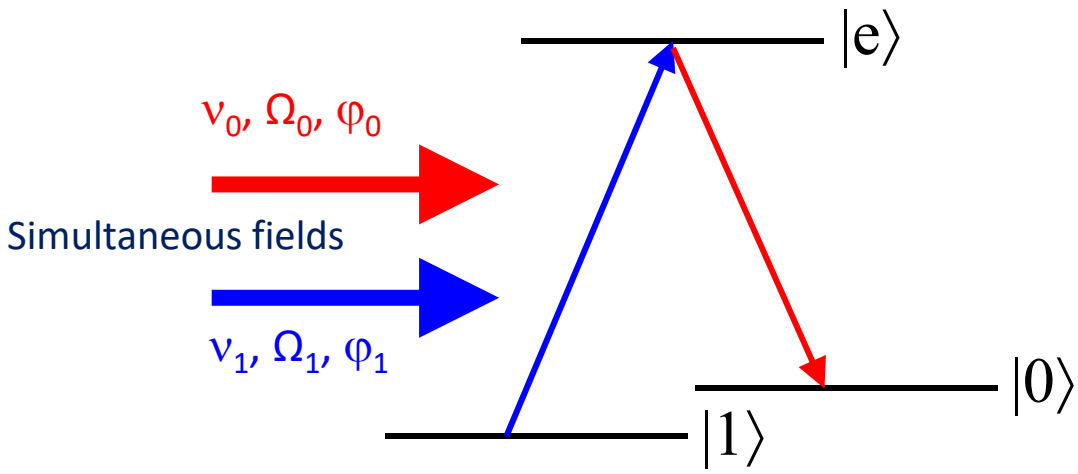
(Limited by Pr ion, Eu would be much better)

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



Single qubit gates

The ”most” complicated scheme: Dark state pulses



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

Superpositions:

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

Interactions:

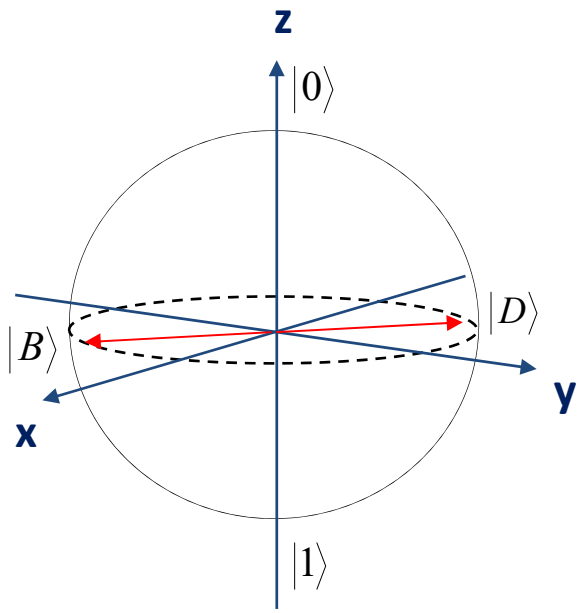
$$\langle e|H_{int}|B\rangle = 2c$$
$$\langle e|H_{int}|D\rangle = 0$$

Single qubit gates

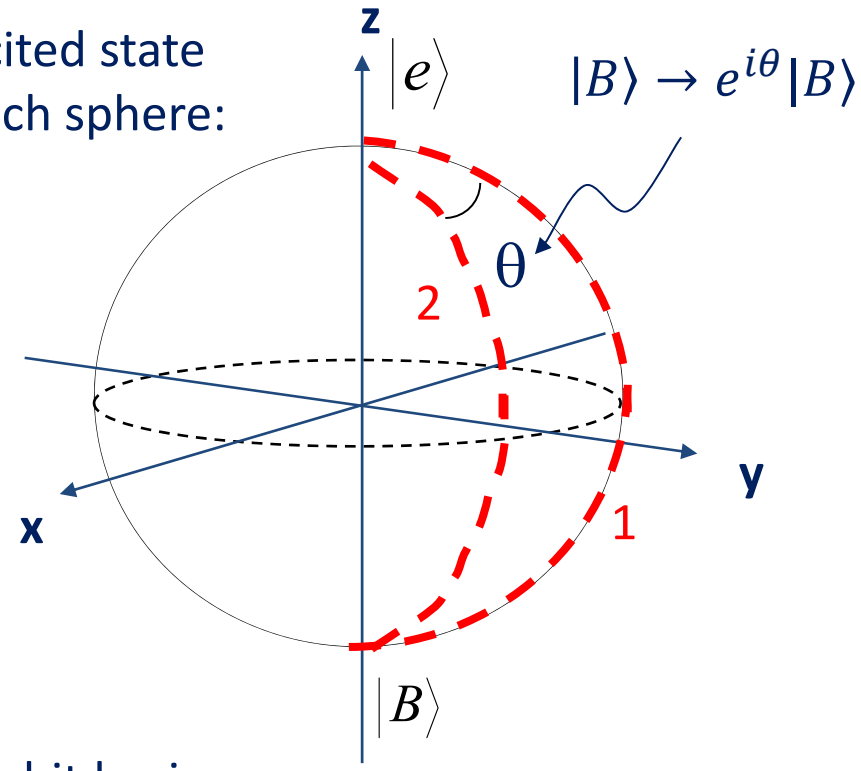
Dark state pulses

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

Qubit Bloch sphere:



Excited state Bloch sphere:

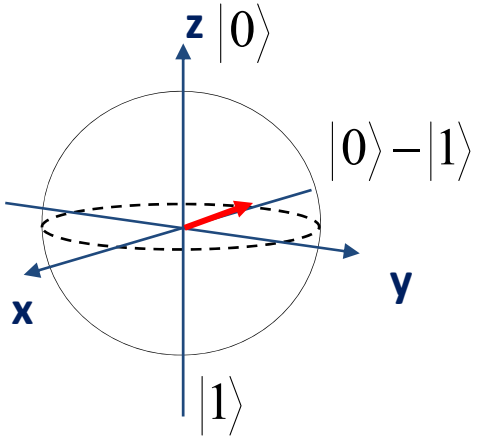


Qubit basis:

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

= Arbitrary rotation around an axis on the equator

Reading out qubit states

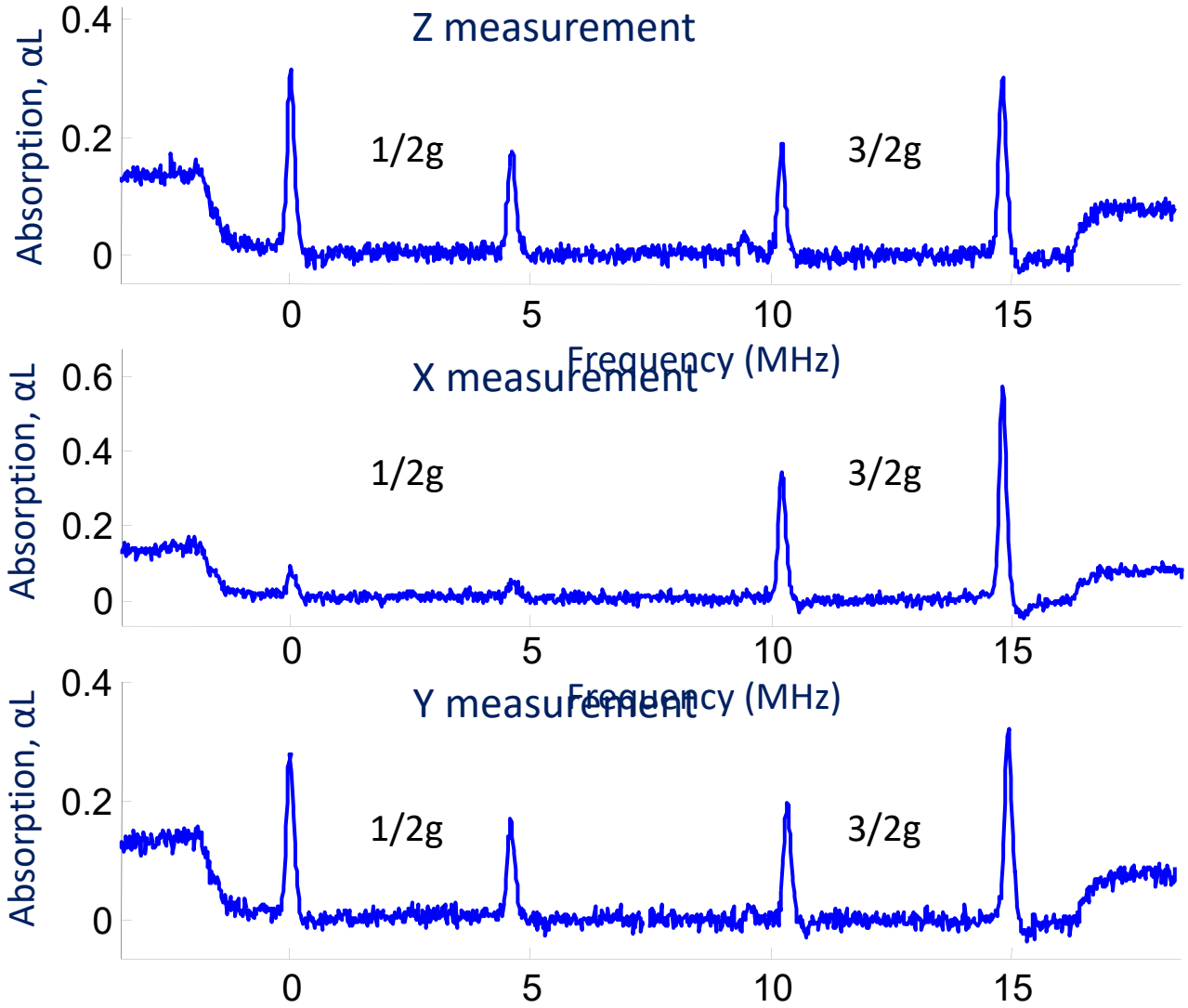


$F_{op} = 0.93$

Rippe et al, PRA 77, 022307 (2008)

Limited by Pr ion T_2

Eu prediction: F > 99.9%



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

(Eq 8.148 in Nielsen and Chuang)

Two qubit gates

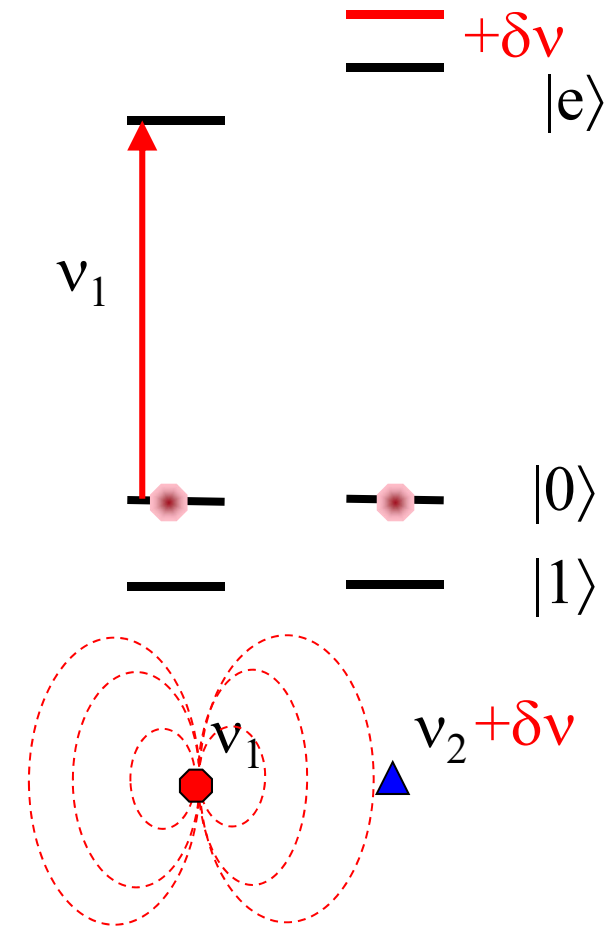
→ need to find a conditional mechanism

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 $\frac{1}{r^3}$

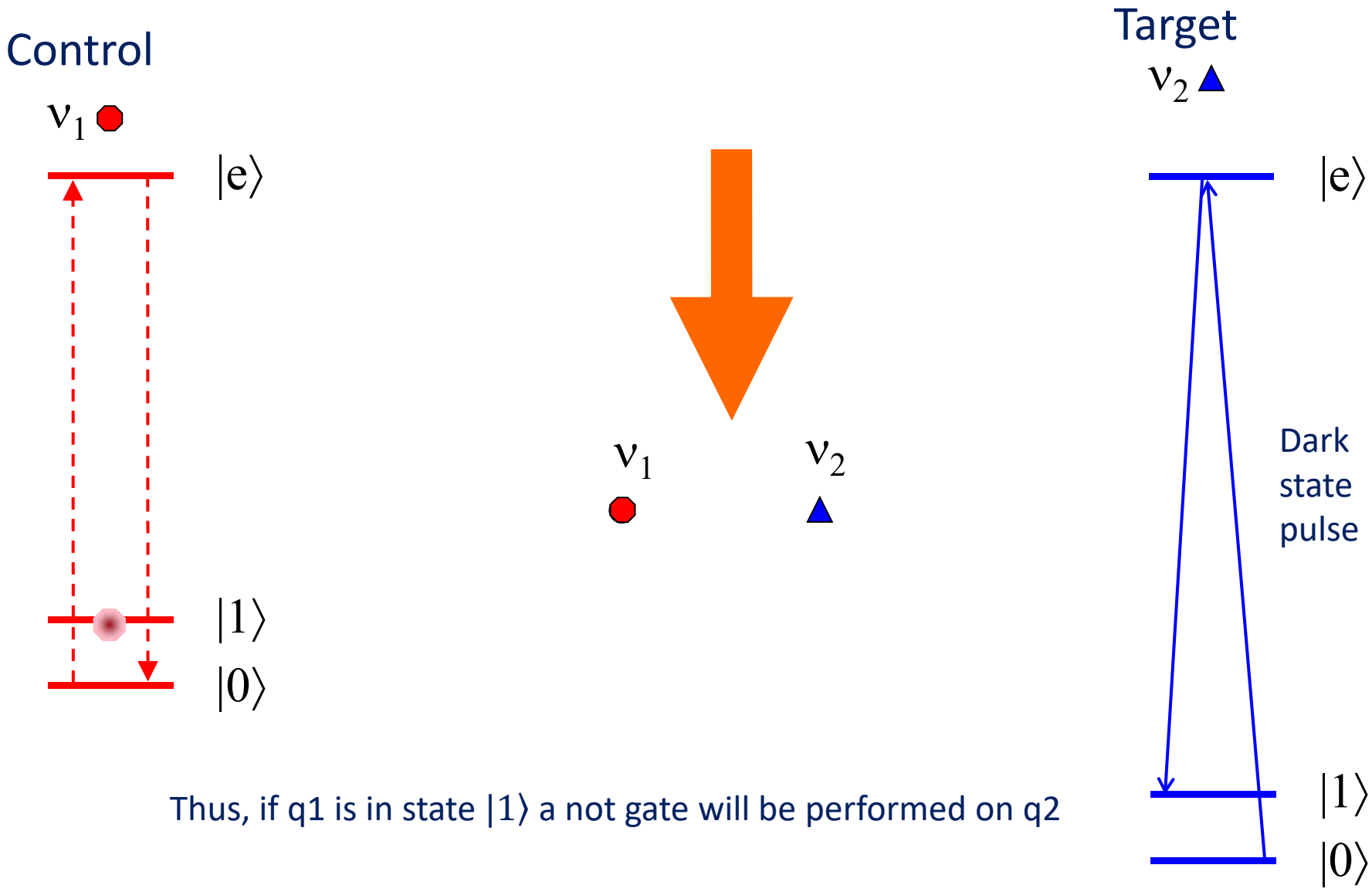


Ion distance	frequency shift
100 nm	1 line width
10 nm	1000 line widths
1 nm	1000000 line widths

Artificial trap: ~ µm

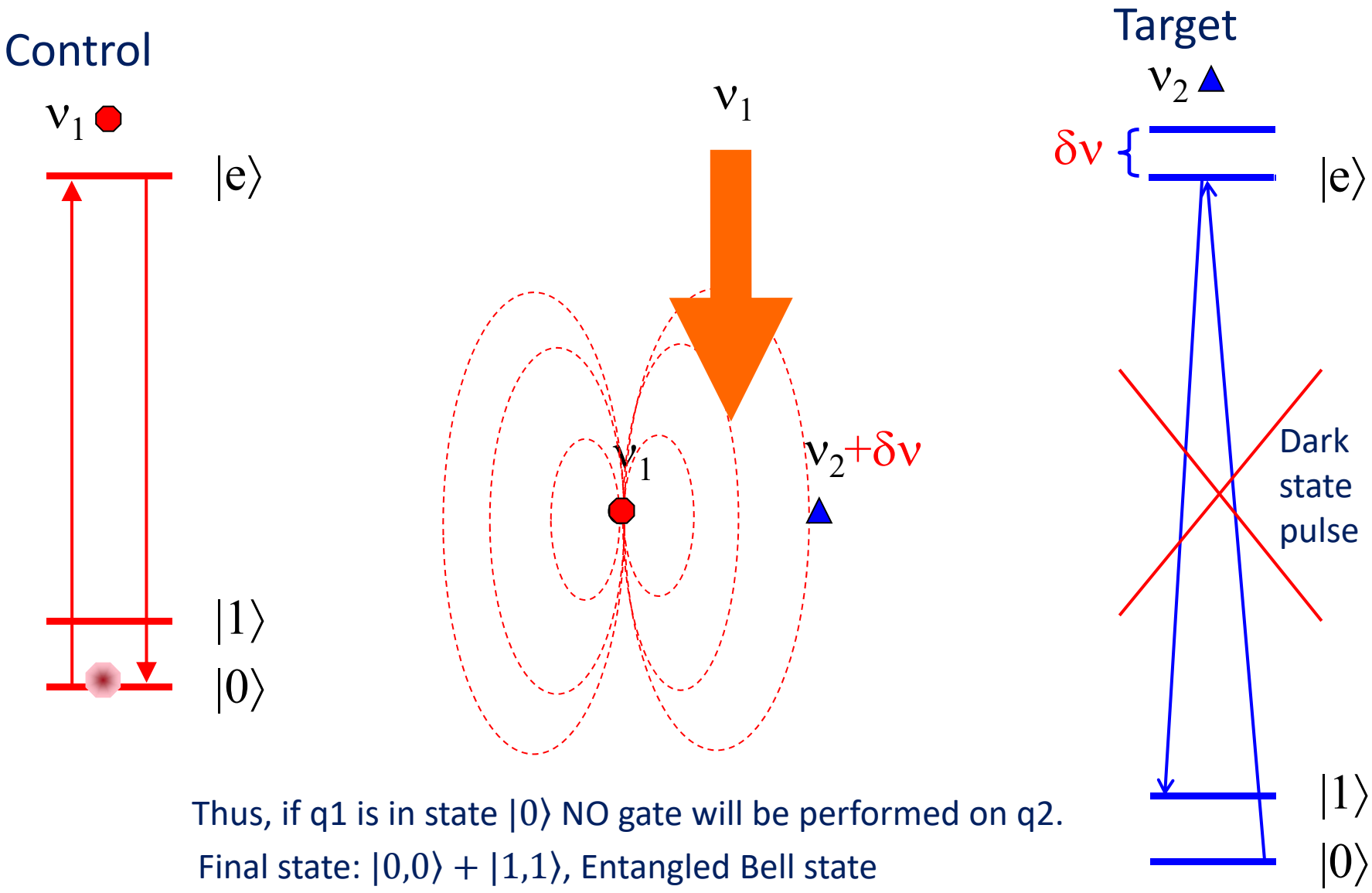
Natural trap: ~ nm

Two qubit CNOT gate



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

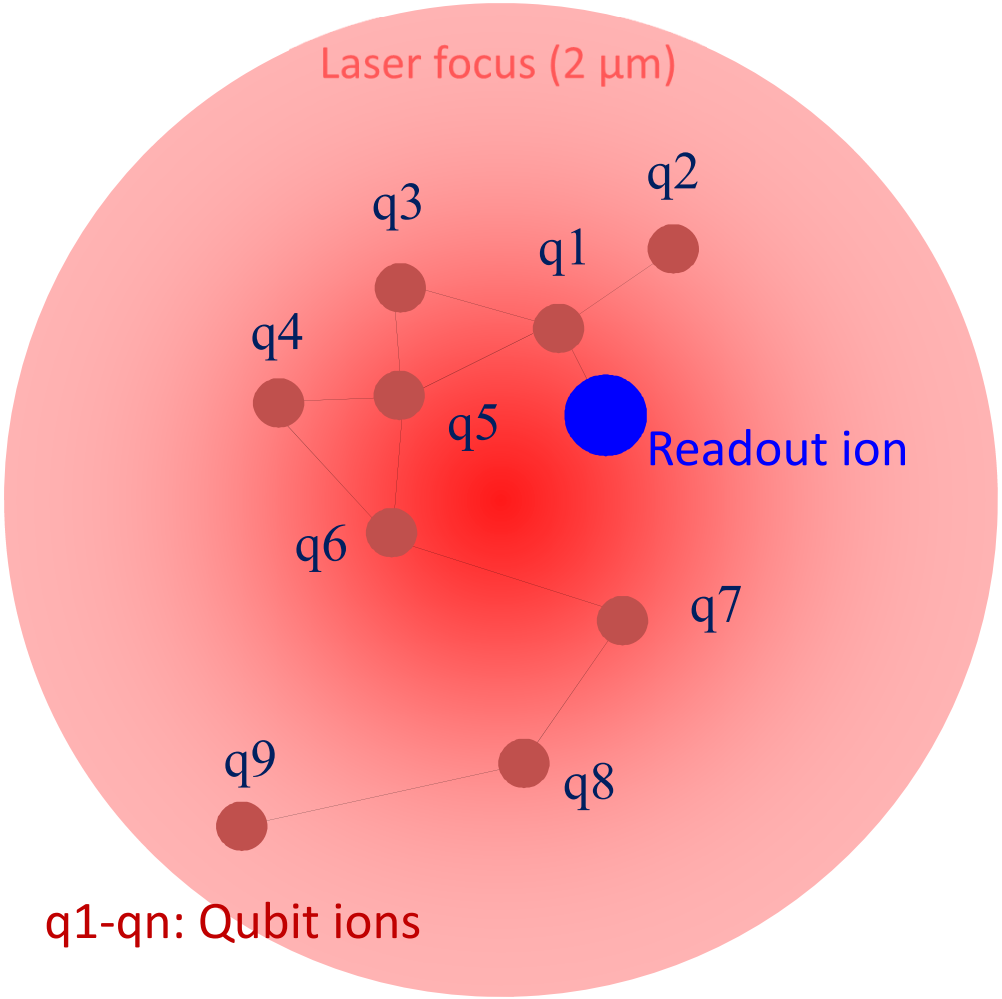
Two qubit CNOT gate



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

Scalability – single instance



Scalability question:

What is the expected qubit chain length?
(with unique frequencies)

Answer: ~1000 qubits

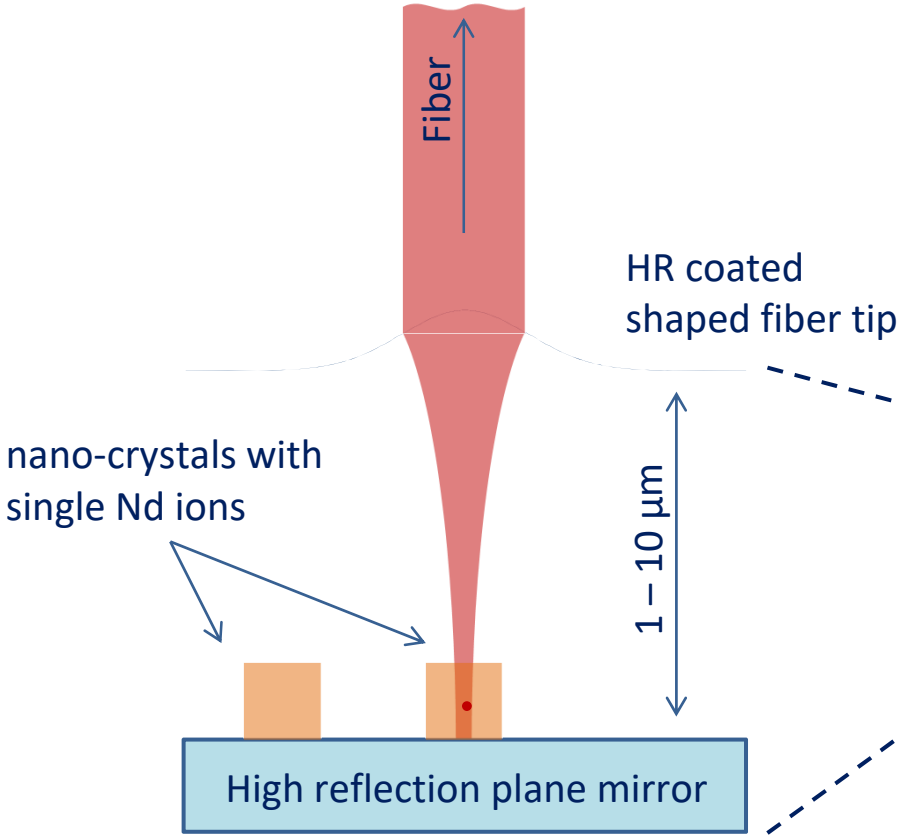
– Depends on species, concentration, host, schemes etc.

Additional questions

- How to scale the system further?
- How to read out the weak RE ions?

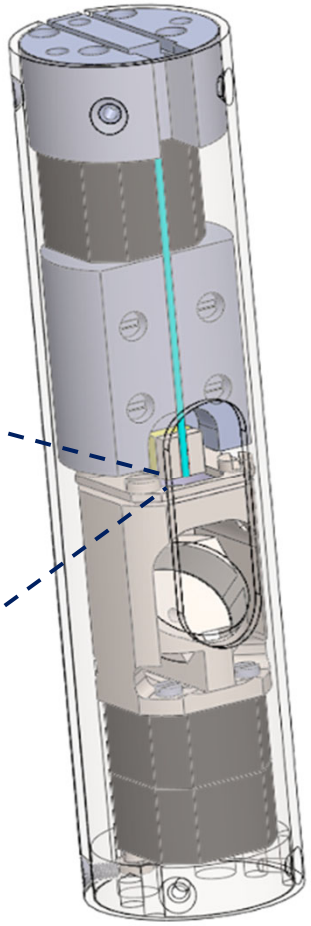
Scalability – current approach

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



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

Current experimental progress:



Scalability – current approach

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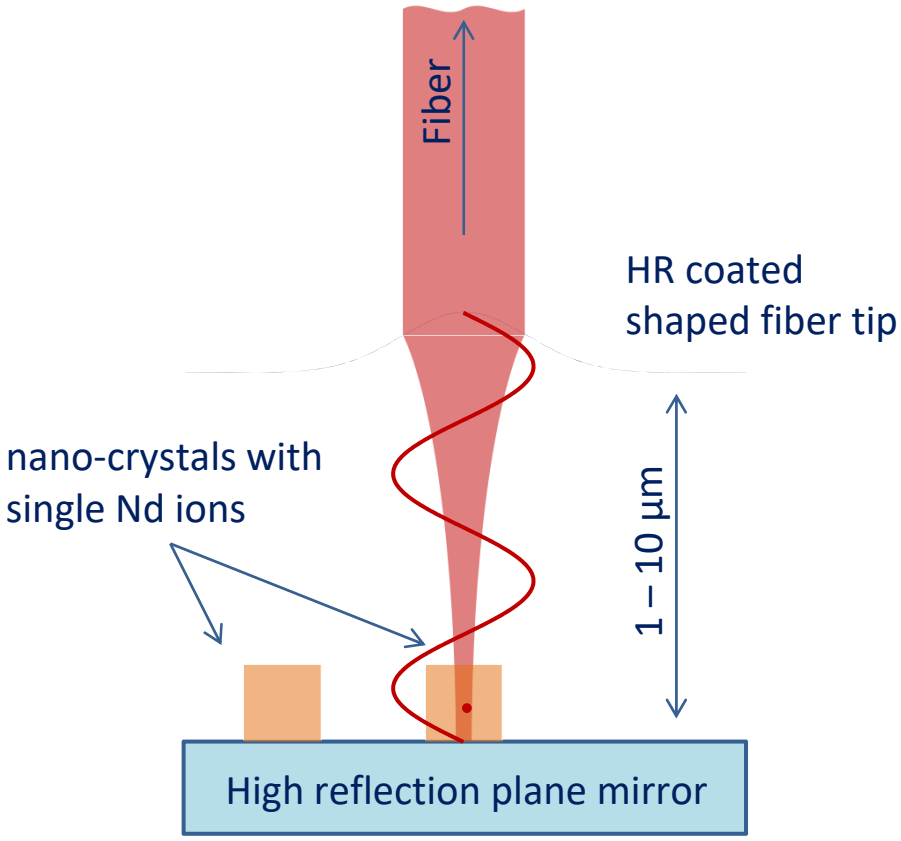


- When the mode volume ~ λ^3 the vacuum modes are modified
- Fermi golden rule:

Decay rate = matrix element * density of states

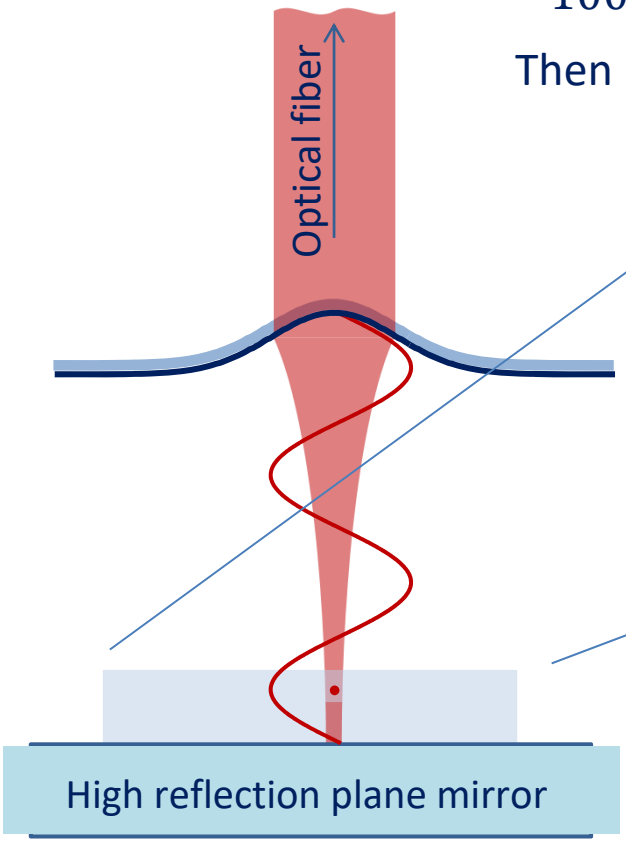
- The spontaneous emission is then enhanced (Purcell effect)
  - Q-value > 10^6
  - Estimated fluorescence enhancement: 10^4

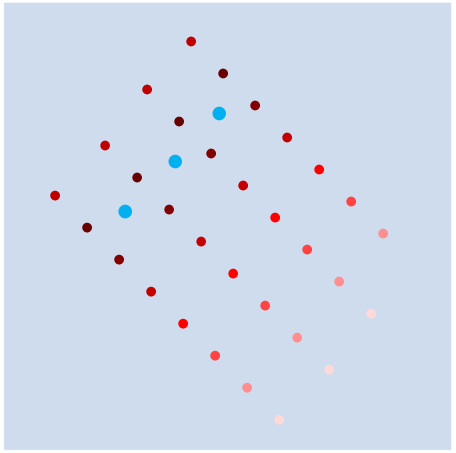
Kaupp *et al*, PRA **88**, 053812 (2013)

Scalability – with cavity QED

~1000 qubits in one focus of 2 μm

Then move one focus to a new spatial location

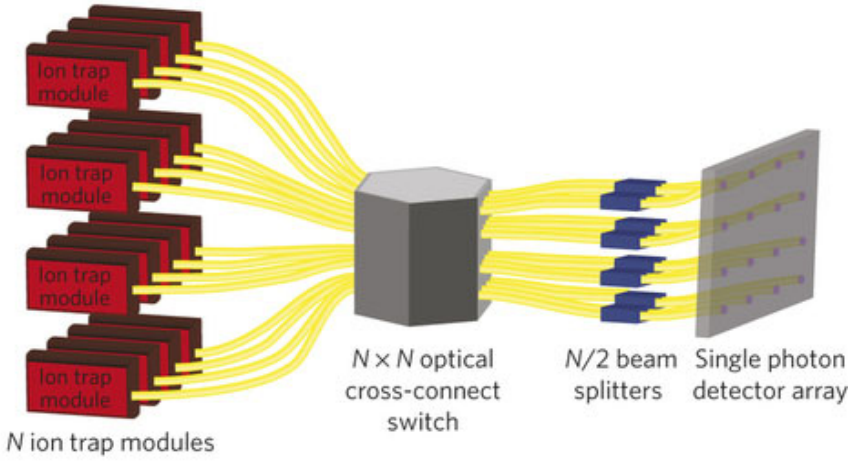




2D thin film

Future further scaling:

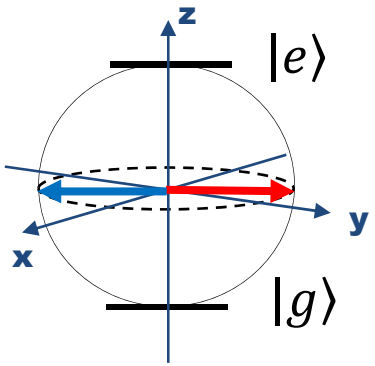
Monroe *et al*, Science 339, 1164 (2013)



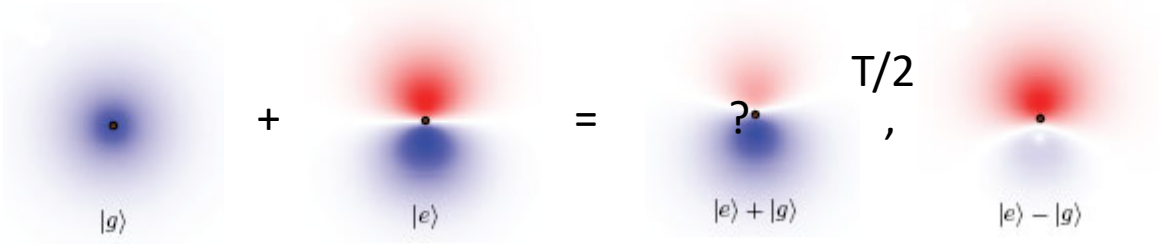
What is a superposition state physically?

- General properites of systems that can encode quantum information

$$|\psi\rangle = \alpha|e\rangle + \beta|g\rangle$$



Example: electron density:



What is a superposition state physically?

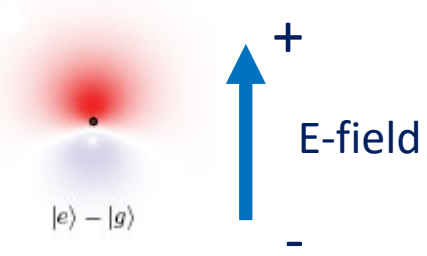
Consider charge distribution ρ as a function of time (and space).
– two-level system with energies E_g and E_e.

$$\psi_g(r,t) = g_g(r)e^{-iE_g t/\hbar}$$
$$\psi_e(r,t) = g_e(r)e^{-iE_e t/\hbar}$$
$$, \Delta E = \hbar\omega$$

$$\rho \sim |\psi_{\text{total}}|^2 = |\psi_g + \psi_e|^2 = |g_g|^2 + |g_e|^2 + g_g g_e^* e^{i(\omega_e-\omega_g)t} + g_g^* g_e\, e^{-i(\omega_e-\omega_g)t}$$

$$= |g_g|^2 + |g_e|^2 + 2\tilde{g}_g\tilde{g}_e \cos(\omega_{ge}t - \varphi_{ge})$$

T/2
,



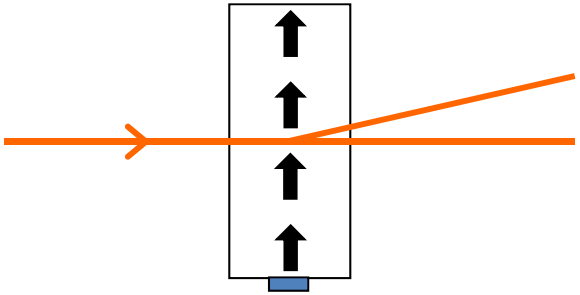
- An atom in a superposition will radiate (oscillating dipole)
- The phase of the electric field (light) changes the interaction

- What is the corresponding physical nature of decoherence?

How do we change the phase of the light field?

- Difficult because the light has a frequency of $\sim 10^{15}$ Hz

Acousto Optic Modulator (AOM):



$f_0 + f_{\text{sound}}$, $\varphi_0 + \varphi_{\text{sound}}$

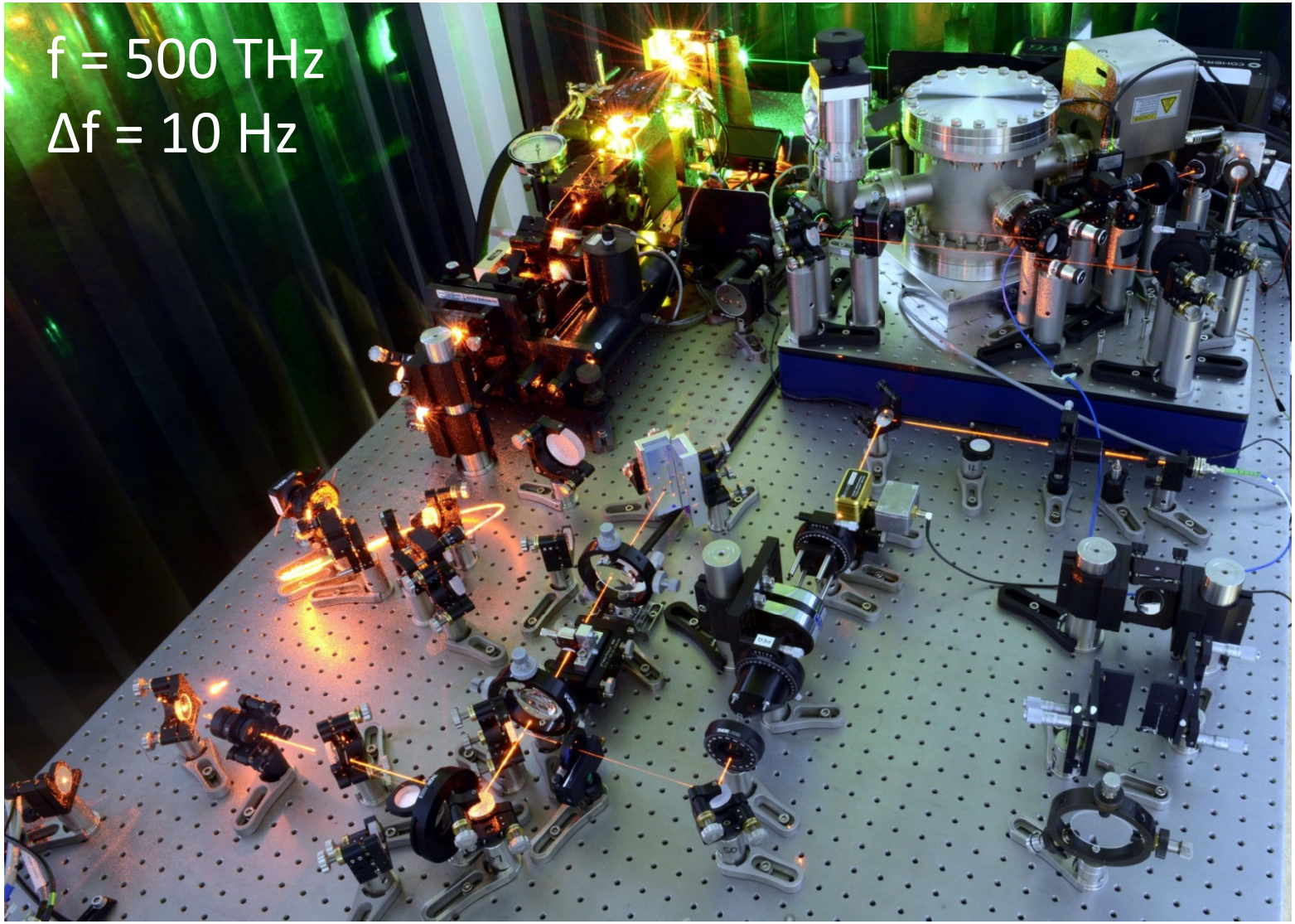
f_0

Works when laser is stabilized!

Beam deflection from grating
or
Photon and phonon collision

- Momentum conservation
- Energy conservation

→

- Beam is deflected
- Frequency of light is changed
- Phase of light is changed

Frequency stable light source