SynQS

1st day: How to go ultracold

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Overview

Why go for ultracold ?

see also the talk by Bill Philipps called
‚Einstein, time and the coolest stuff in the Universe‘

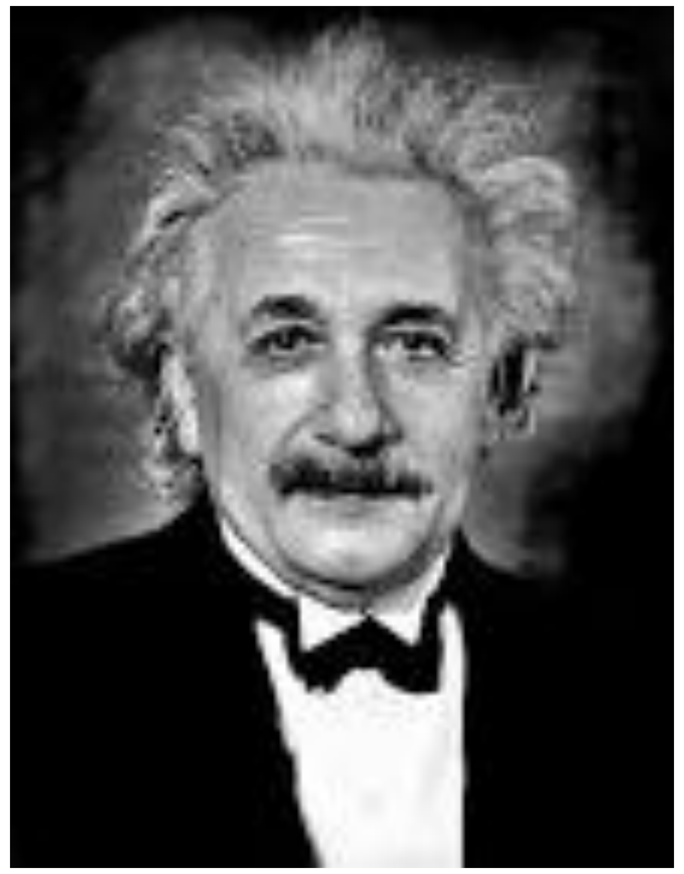
The first step: Getting ultracold by laser cooling

The second step: Get degeneracy by collisions

Good reads

- **Lecture notes on AMO physics** by *Mikhail Lukin*
- **Making, probing understanding Bose-Einstein condensates** by *W. Ketterle*
- **Laser cooling and trapping** by *Metcalf and van der Straten*
- **Theory of Bose-Einstein condensation in trapped gases** by *Dalfovo et al.*
- **Bose-Einstein condensation in dilute gases** by *Pethick and Smith*

What is time ?



Einsteins' special relativity:

Time is what a clock measures.

Experimentalists dilemma: What is a clock ?

Something that ‚ticks', i.e. provides a regular series of events

Traditional clocks

1 tick = 1 day

1 tick = few seconds

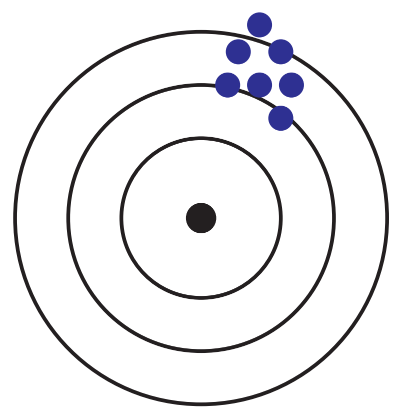
1 tick = 0.1 ms

<u>Problems:</u>

- Not very stable
- Very slow ticking
- Reprodicility

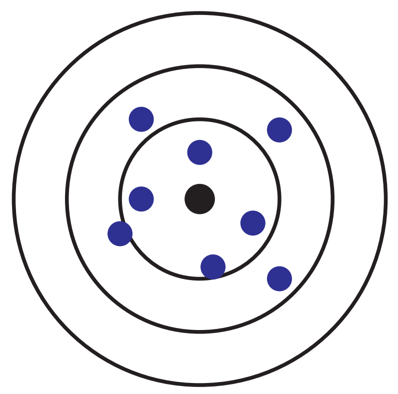
What is a good clock ?

Stable



repeat with the same clock lots of
measurements and get similar results

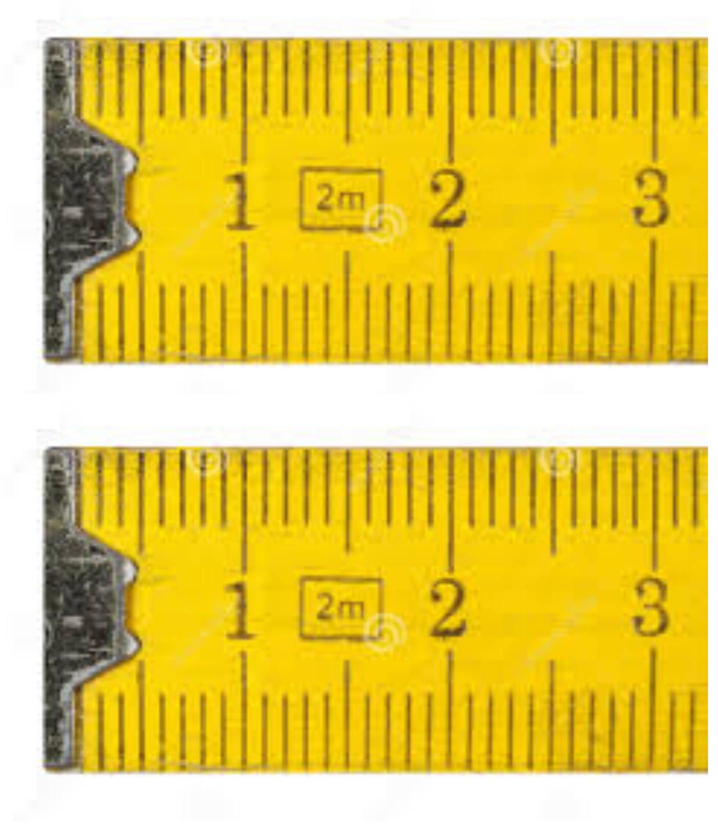
Precise

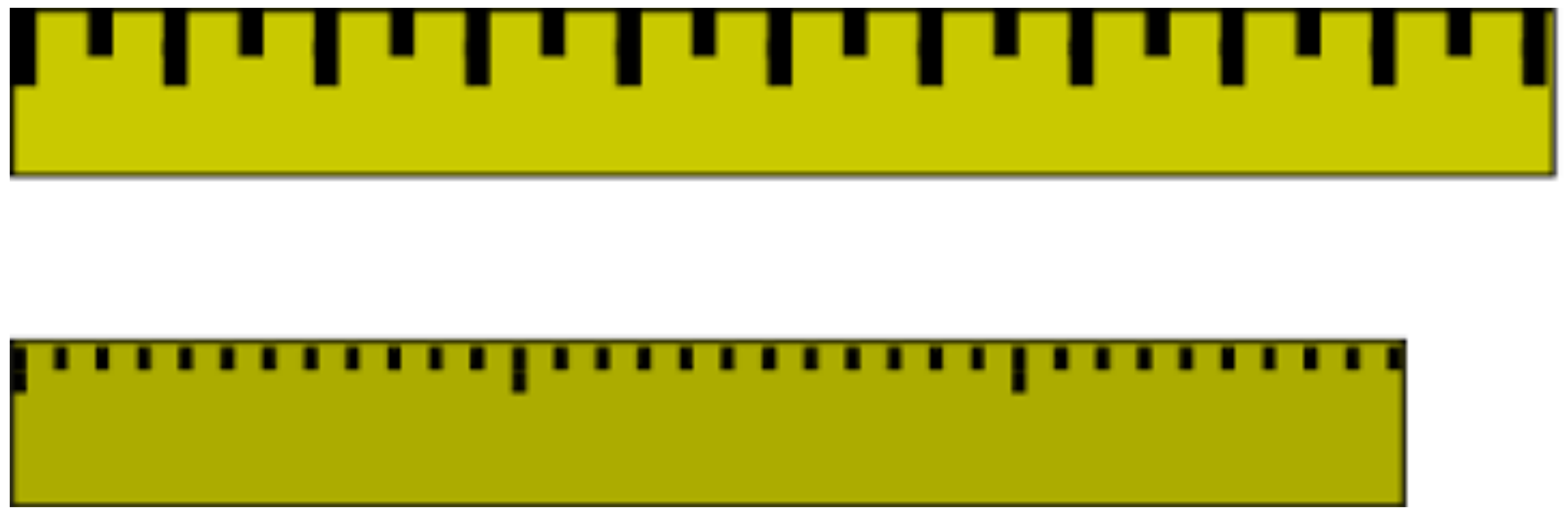


build several clocks
and obtain same results

most of the time much, much
harder to estimate

Characterization of clocks





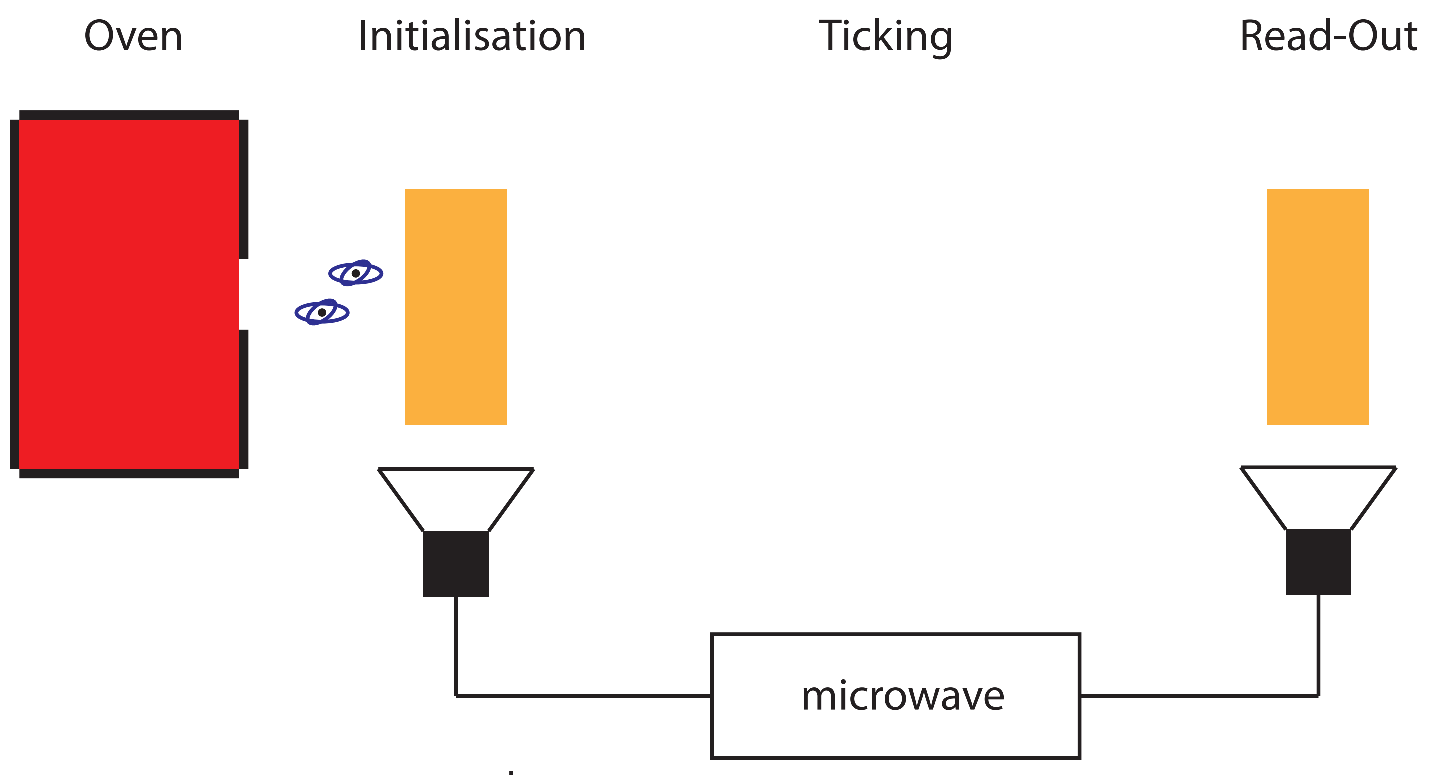
let them tick for a long time

compare the result

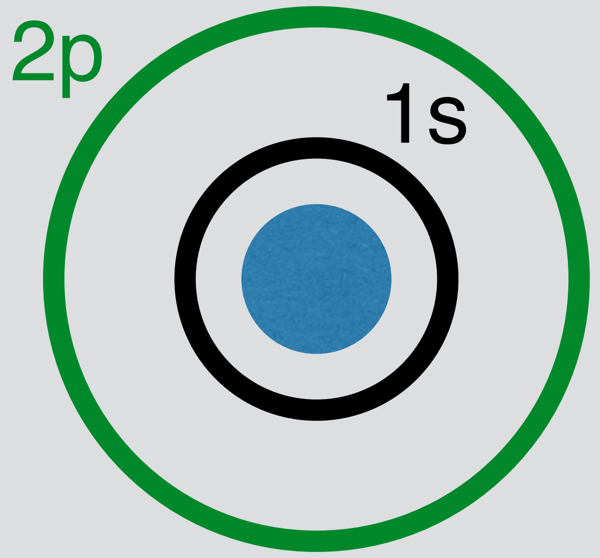
<u>What about precision?</u>

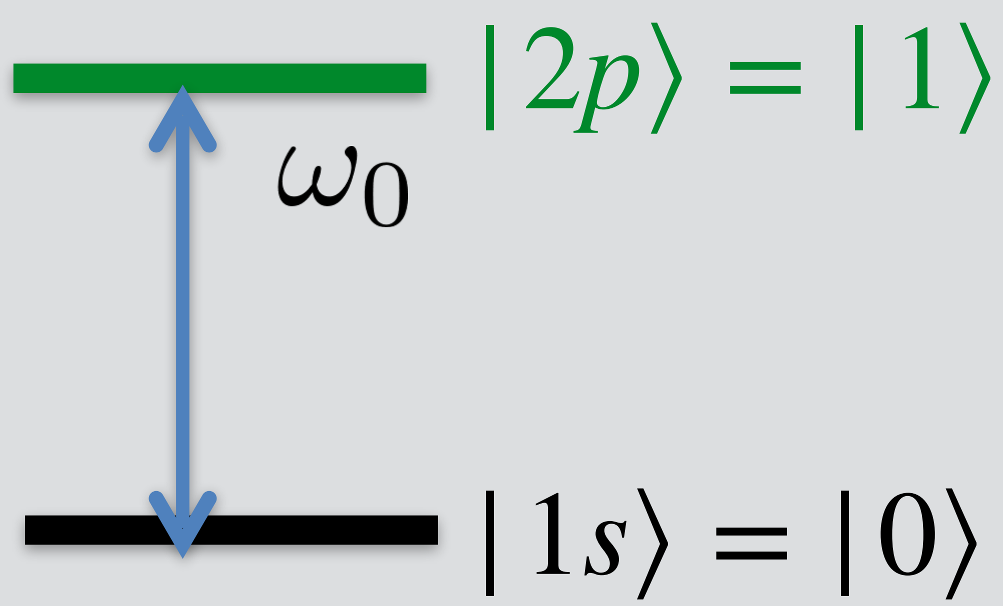
We need a good standard and atoms give this

Atomic clocks



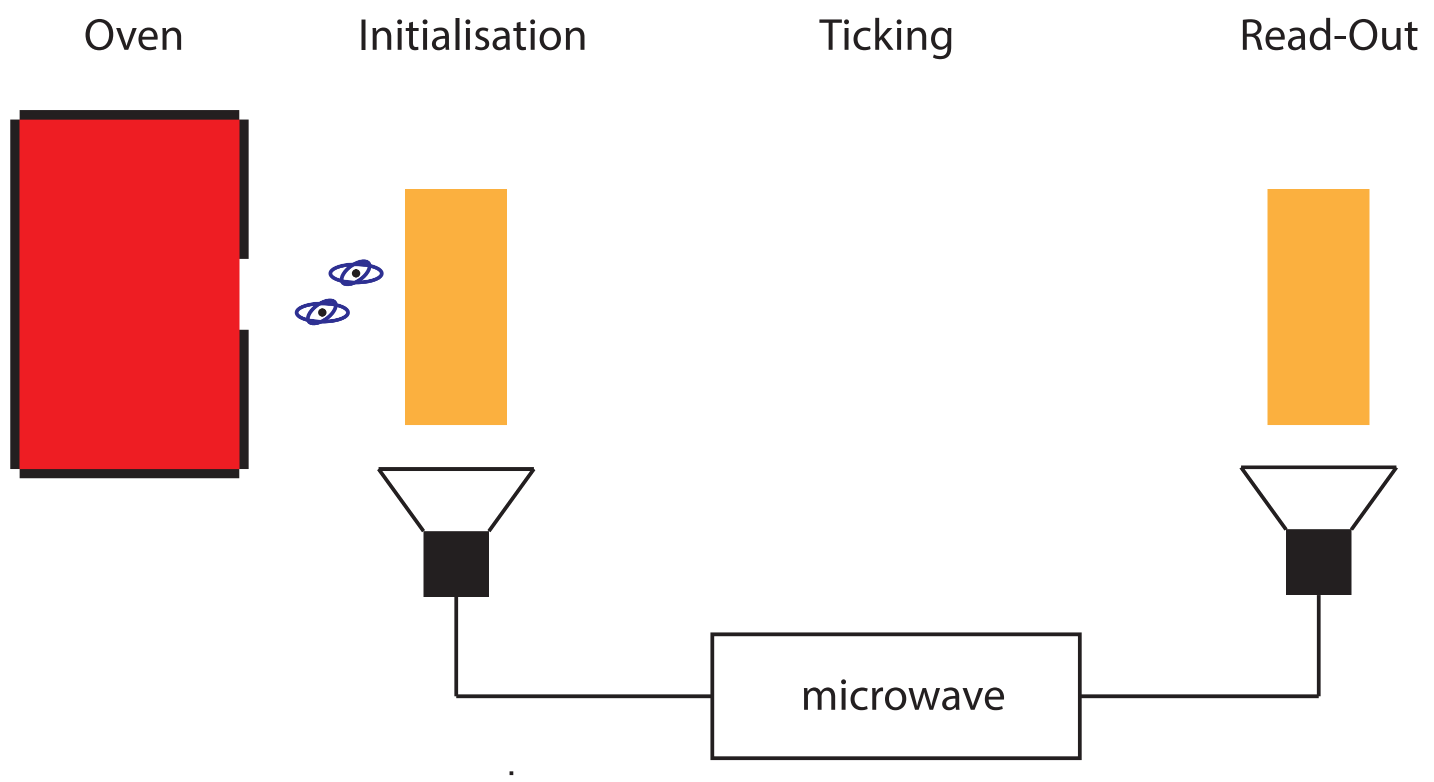
The Atom



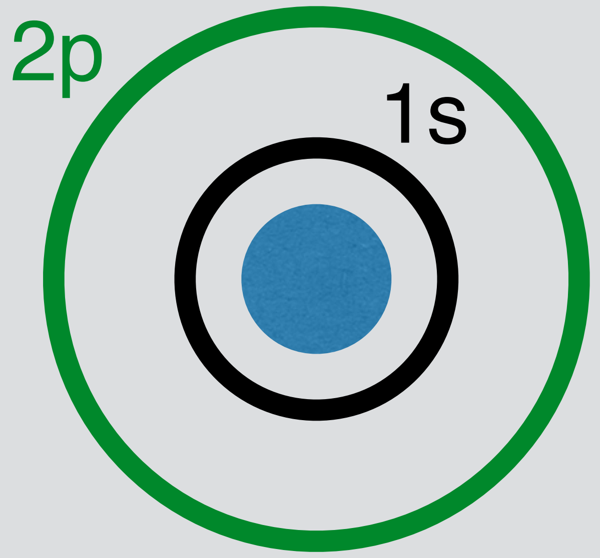


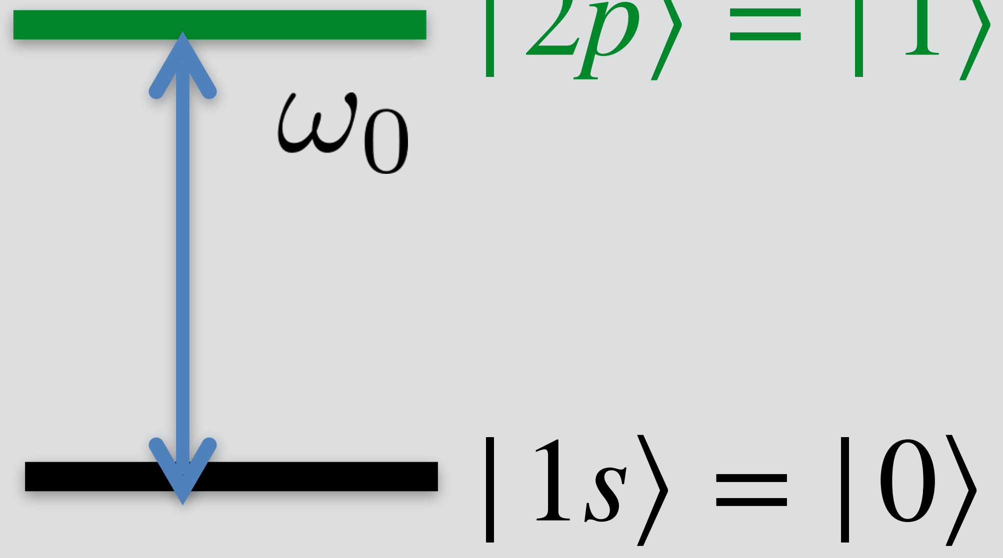
$$\mathscr{H} = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1|$$

Atomic clocks



The Atom

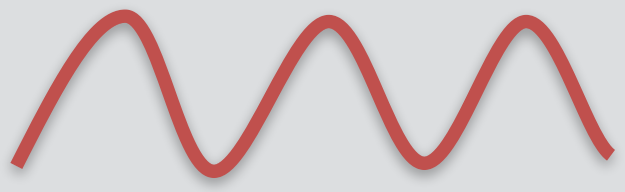




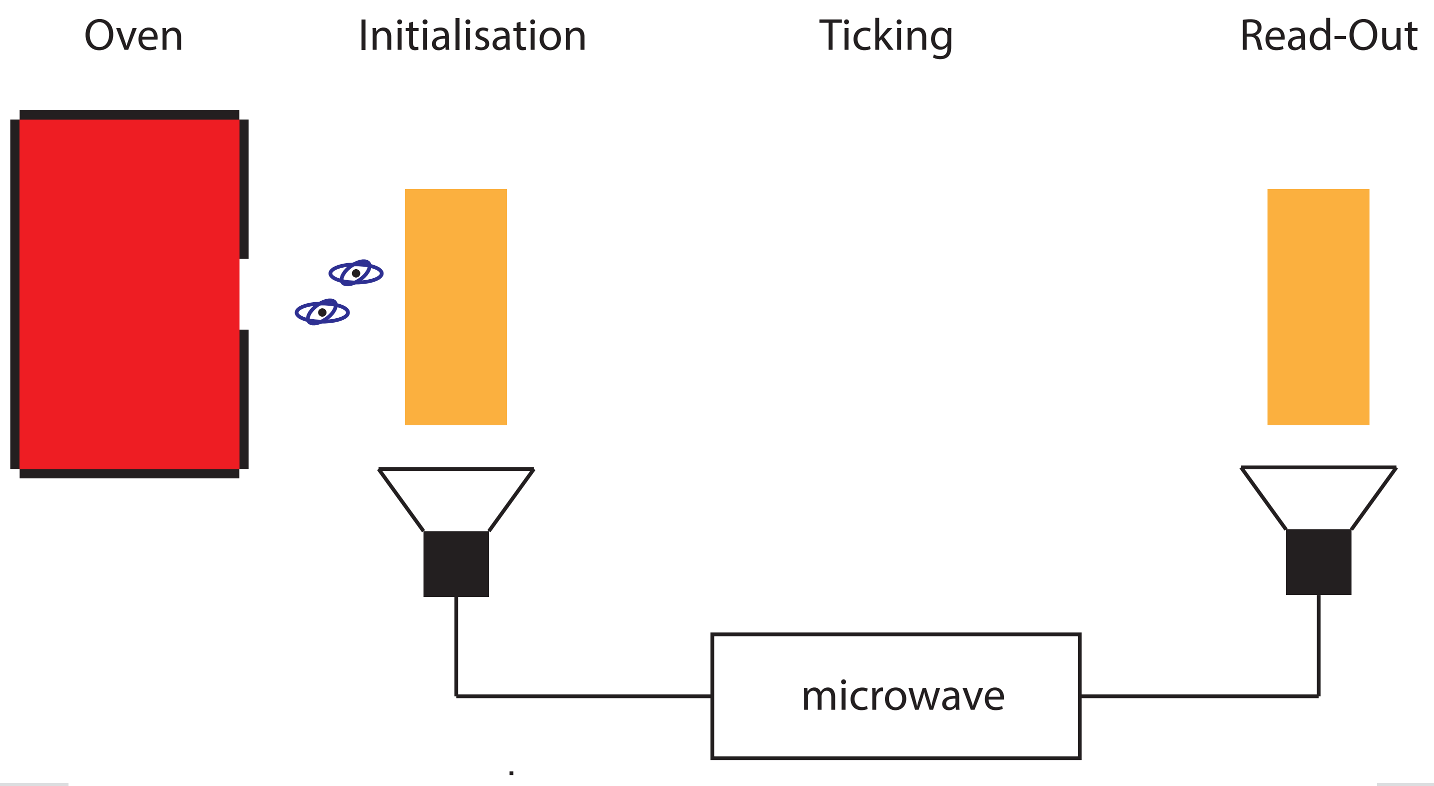
$$\mathscr{H} = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1|$$

The electric field

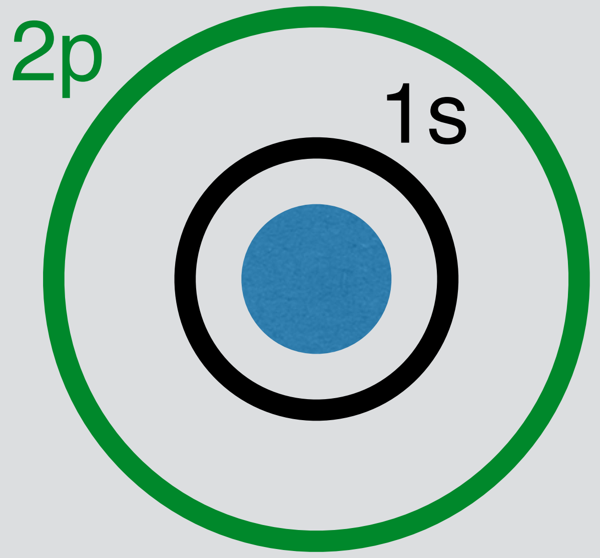
$$\mathbf{E} = E_0\left(e^{i\omega_L t + i\varphi} + e^{-i\omega_L t - i\varphi}\right)$$

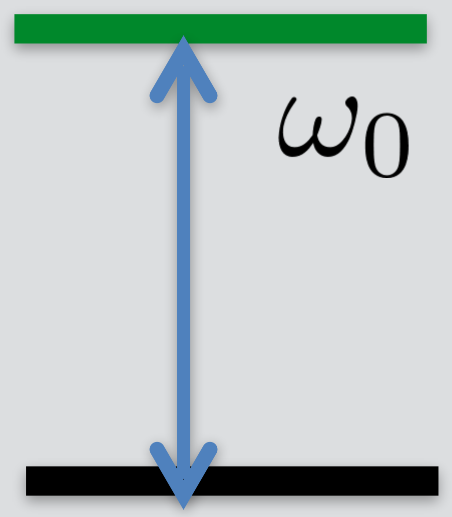


Atomic clocks



The Atom





$|2p\rangle = |1\rangle$

ω_0

$|1s\rangle = |0\rangle$

$$\mathscr{H} = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1|$$

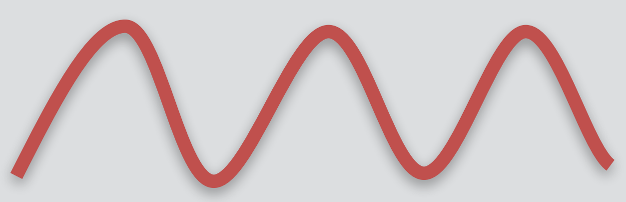
Interaction via

$$\mathcal{H} = -\mathbf{d} \cdot \mathbf{E}$$

$$\mathbf{d} = d\left(|0\rangle\langle 1| + |1\rangle\langle 0|\right)$$

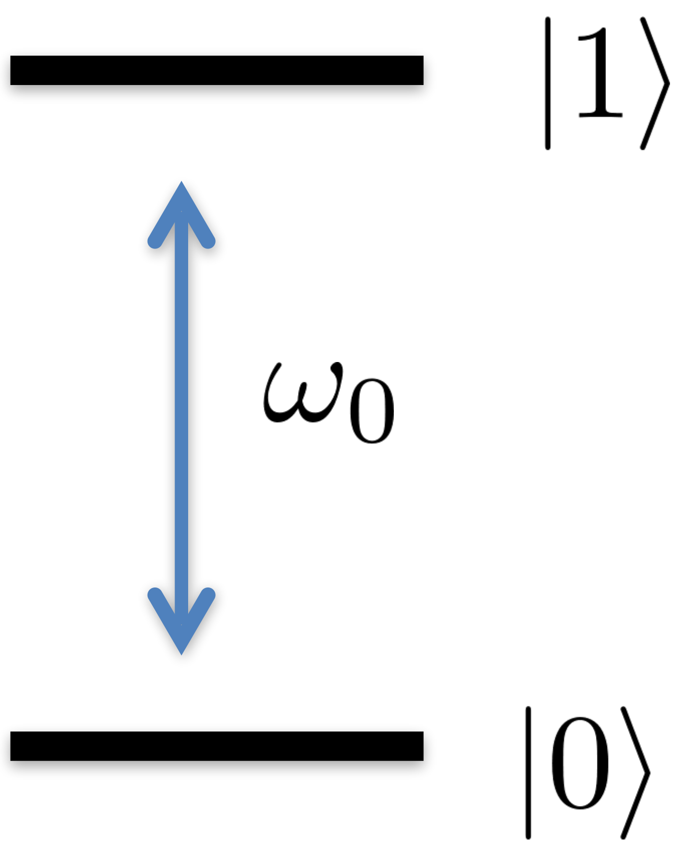
The electric field

$$\mathbf{E} = E_0\left(e^{i\omega_L t + i\varphi} + e^{-i\omega_L t - i\varphi}\right)$$



The atom as a qubit

$$\mathcal{H} = E_0 |0\rangle \langle 0| + E_1 |1\rangle \langle 1|$$



$$\mathcal{H} = \frac{\hbar\omega_0}{2} |1\rangle \langle 1| - \frac{\hbar\omega_0}{2} |0\rangle \langle 0|$$

$$\mathcal{H} = \frac{\hbar\omega_0}{2}\sigma_z$$

$\rightarrow$ write everything in terms of spins

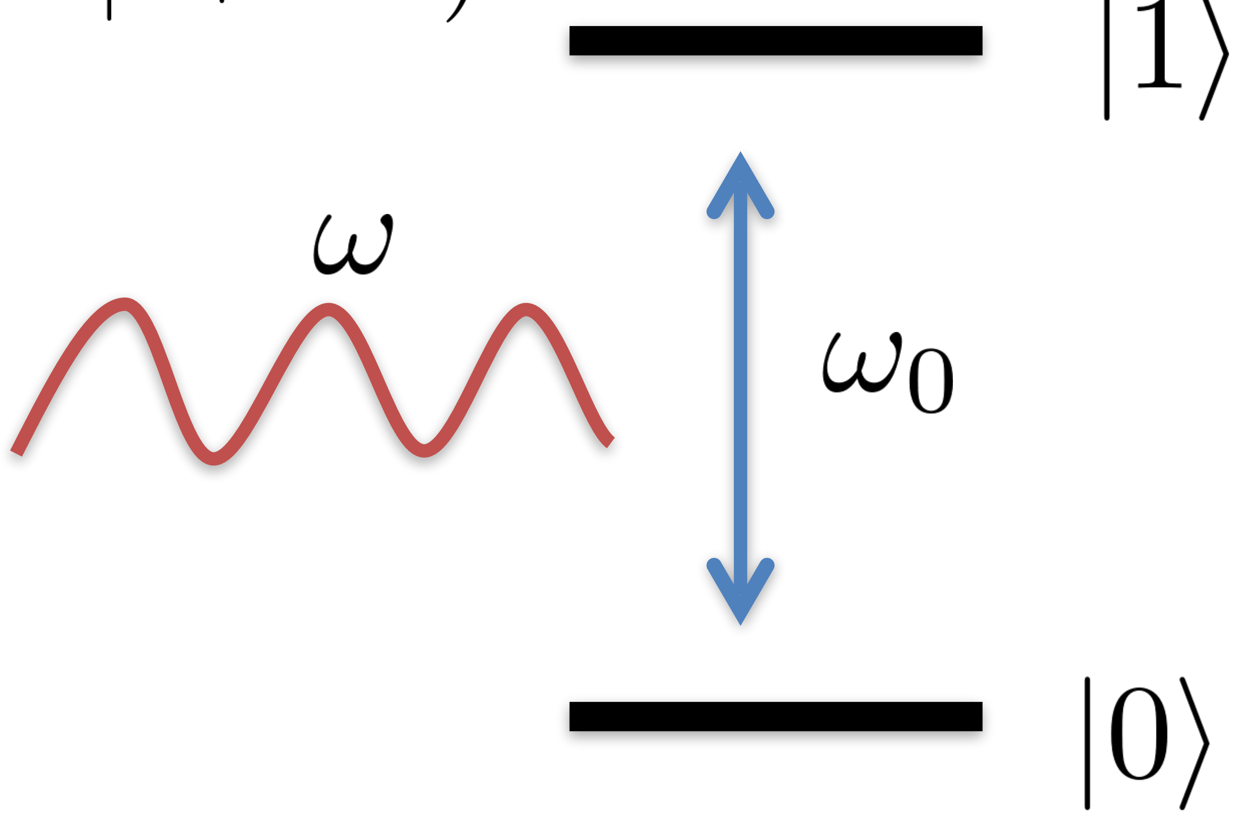
$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Interaction Hamiltonian

$$\mathcal{H} = -\mathbf{d}\cdot\mathbf{E}$$

$$\mathbf{E} = E(\mathrm{e}^{\mathrm{i}\omega t+\mathrm{i}\varphi} + \mathrm{e}^{-\mathrm{i}\omega t-\mathrm{i}\varphi})$$

$$\mathbf{d} = d(\sigma_+ + \sigma_-)$$



Rotating frame:

$$\mathcal{H} = \frac{dE}{2}(\sigma_+\mathrm{e}^{\mathrm{i}\varphi} + \sigma_-\mathrm{e}^{-\mathrm{i}\varphi})$$

$$\mathcal{H} \sim \hbar\Omega(\sigma_+\mathrm{e}^{\mathrm{i}\varphi} + \sigma_-\mathrm{e}^{-\mathrm{i}\varphi})$$

$\varphi = 0$

$$\mathcal{H} \sim \hbar\Omega(\sigma_+ + \sigma_-)$$

$$\mathcal{H} \sim \hbar\Omega\sigma_x$$

$\varphi = \pi/2$

$$\mathcal{H} \sim \hbar\Omega(\sigma_+ - \sigma_-)$$

$$\mathcal{H} \sim \hbar\Omega\sigma_y$$

Clocks as extremely precise qubits

Rotation about z-axis
Detuning

$$\mathscr{H} = \hbar\Delta\hat{\sigma}_z$$

$Z_{\pi/2}$

$$\Delta t = \frac{\pi}{2}$$

Rotation about x-axis
Laser intensity

$$\mathscr{H} = \hbar\Omega_x\hat{\sigma}_x$$

$X_{\pi/2}$

$$\Omega_x t = \frac{\pi}{2}$$

Rotation about y-axis
Laser intensity with phase adjusted

$$\mathscr{H} = \hbar\Omega_y\hat{\sigma}_y$$

$Y_{\pi/2}$

$$\Omega_y t = \frac{\pi}{2}$$

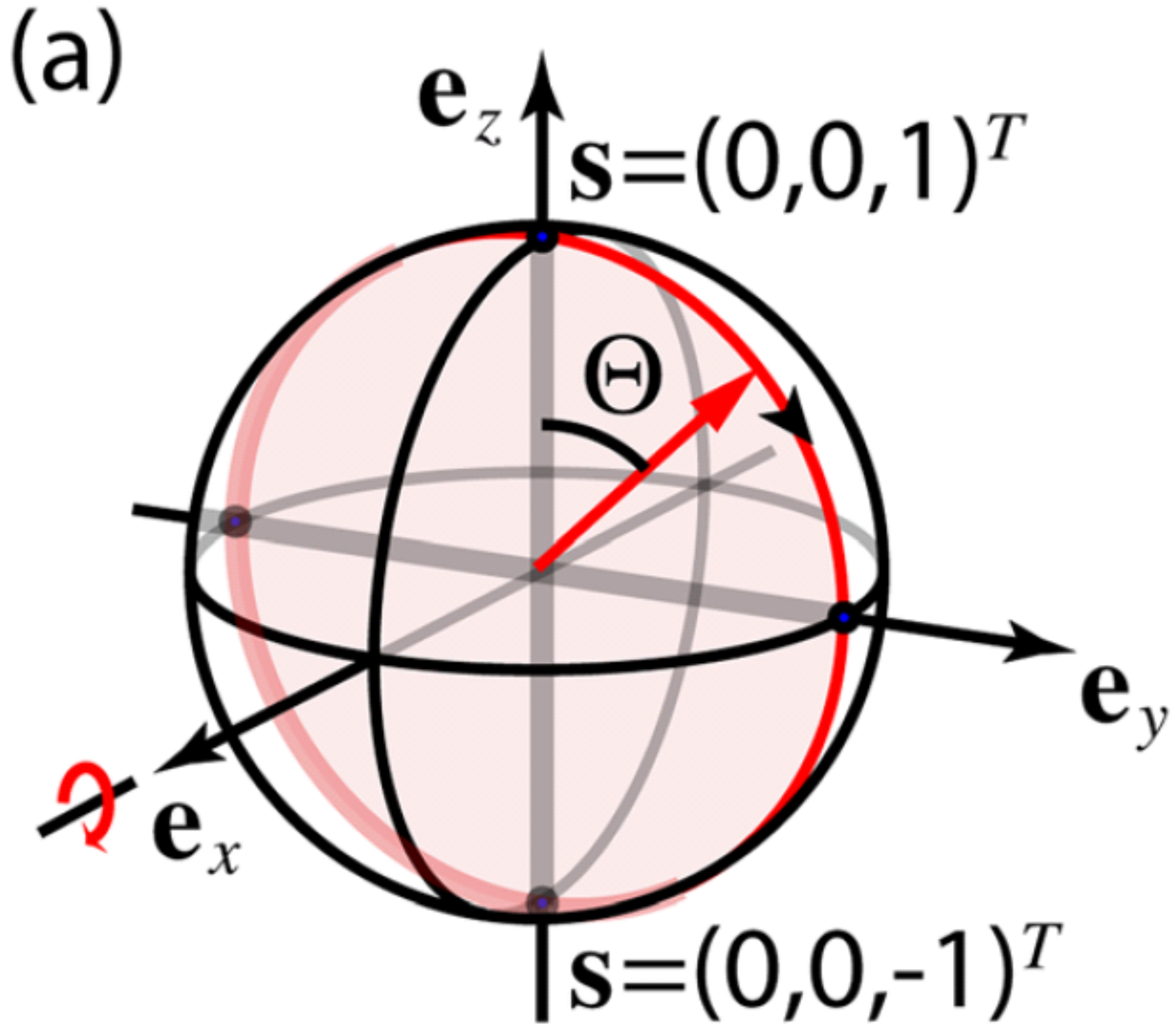
$$U = e^{i\mathscr{H}t/\hbar}$$

Example: Rabi oscillations

$\mathcal{H} = \hbar\Omega S_x$

time evolution: $\mathrm{e}^{\mathrm{i}\Omega\sigma_x t}$

Rotation about **x-axis** angle $\Theta = \Omega t$



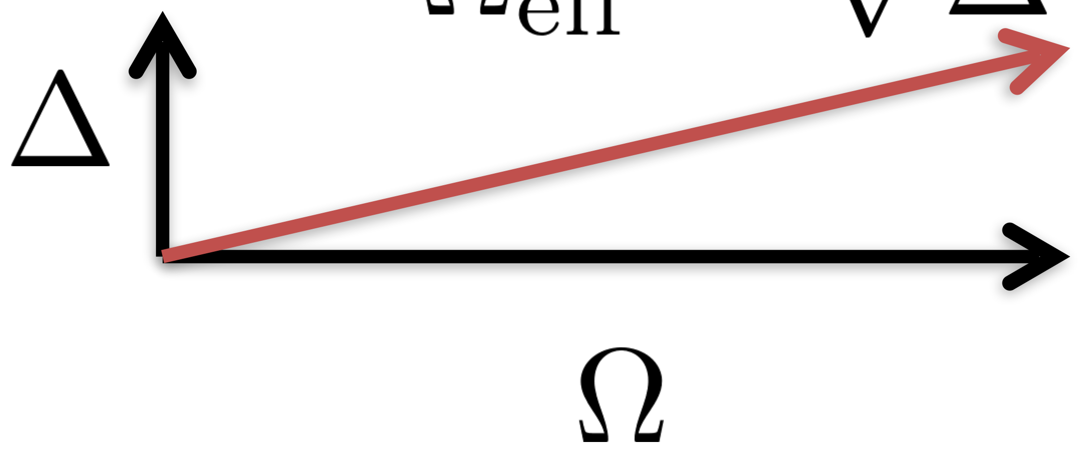
Example: Offresonant Rabi oscillations

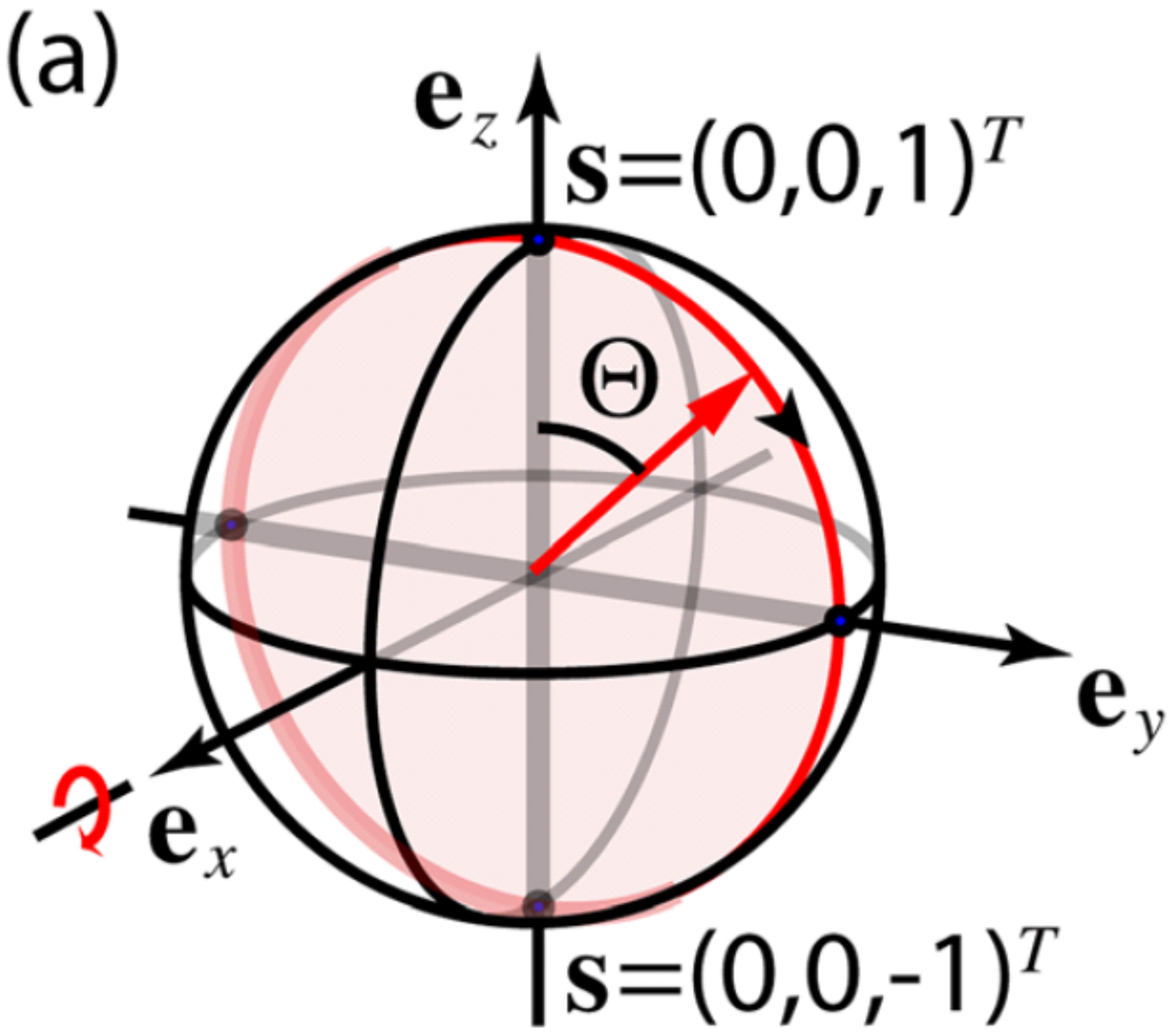
$$\mathcal{H} = \hbar\Omega S_x + \hbar\Delta S_z$$

detuning

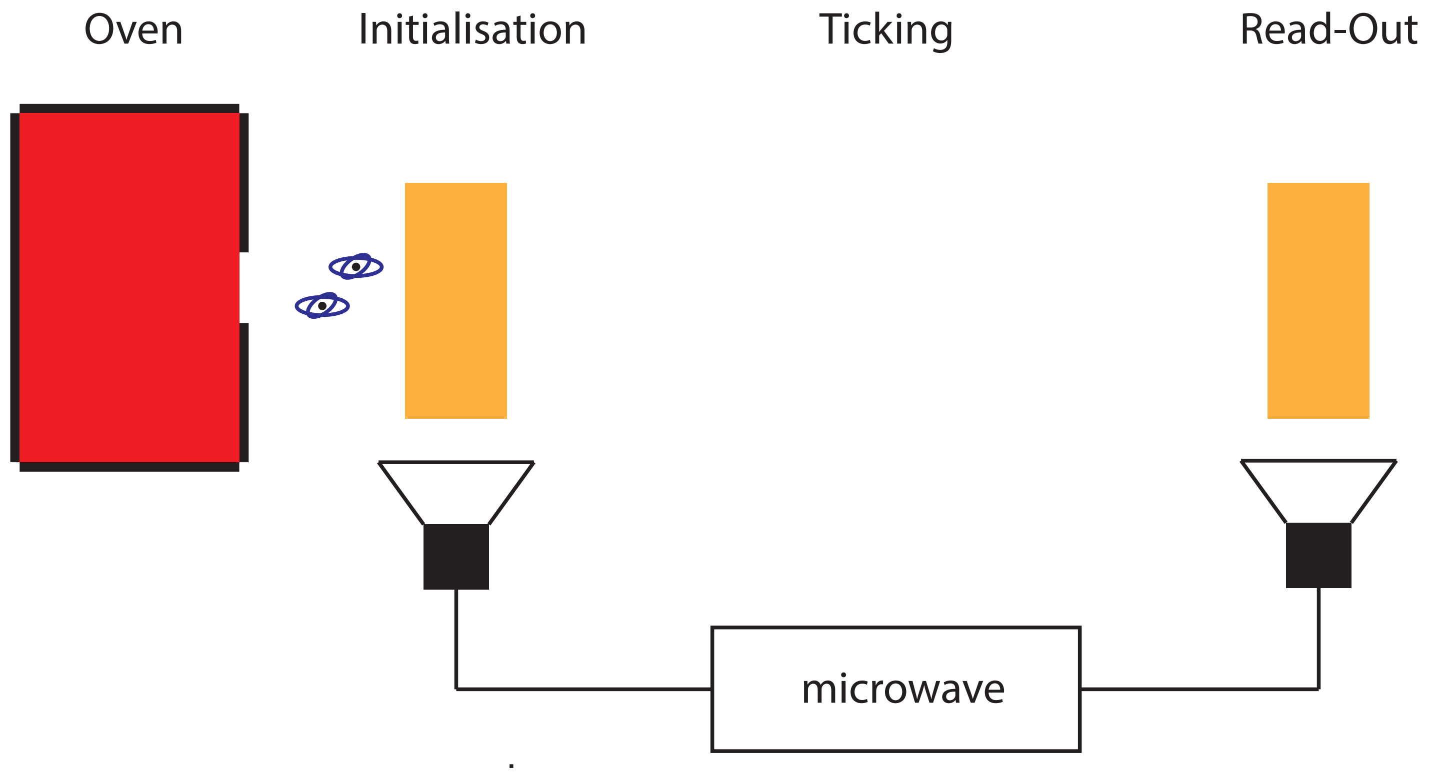
tilted rotation axis $J = \begin{pmatrix} \Omega \\ 0 \\ \Delta \end{pmatrix}$

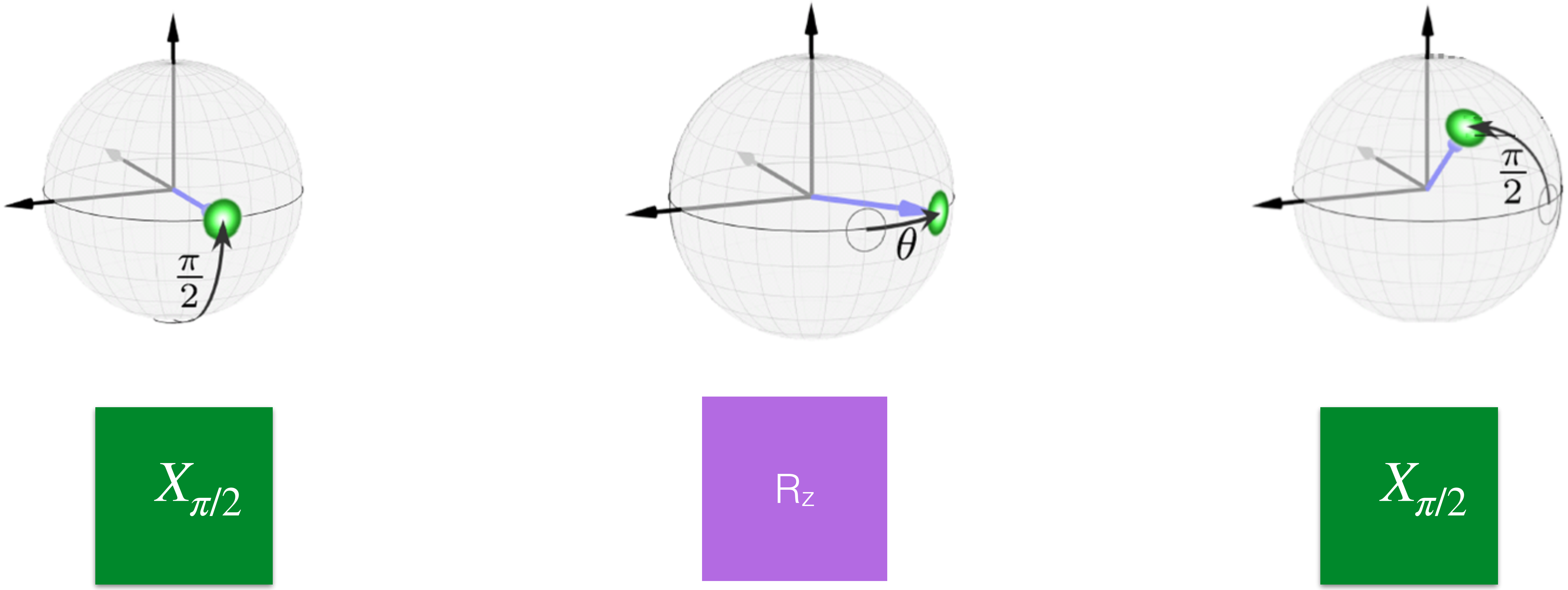
$$\Omega_{\text{eff}} = \sqrt{\Delta^2 + \Omega^2}$$





Back to our atomic clocks





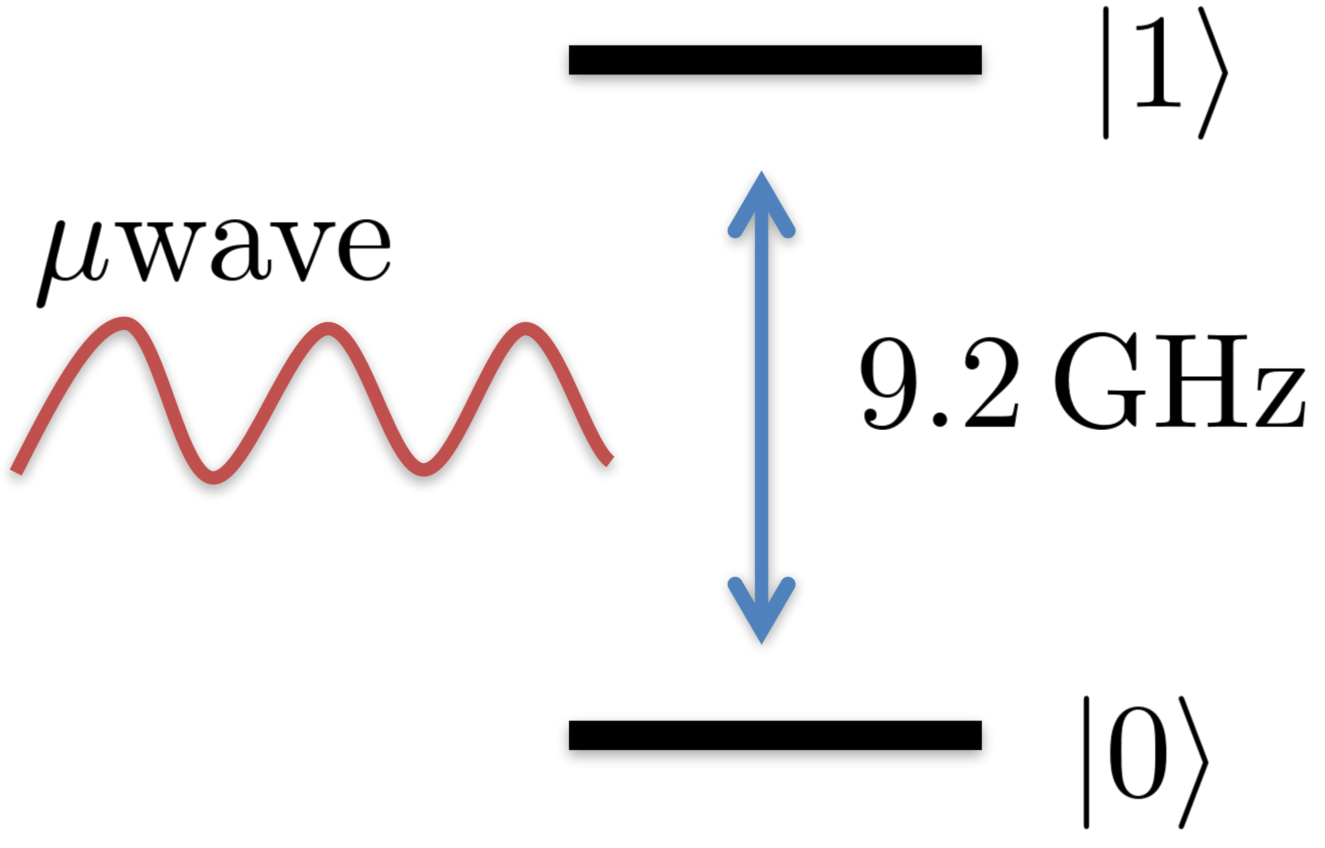
Application: Time standard with Cesium fountain clock

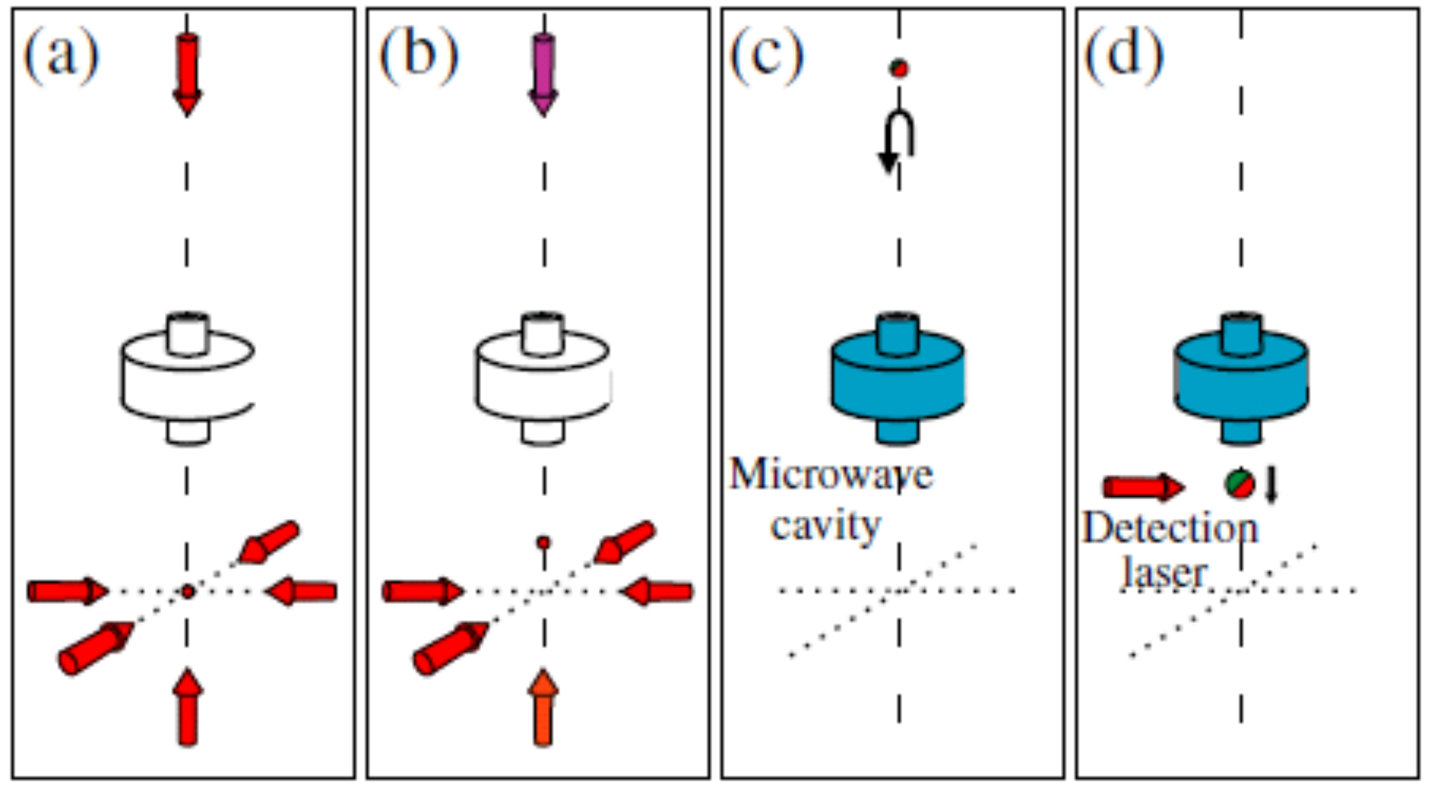
$^{133}\mathrm{Cs}$: Hyperfine splitting 9.2 GHz

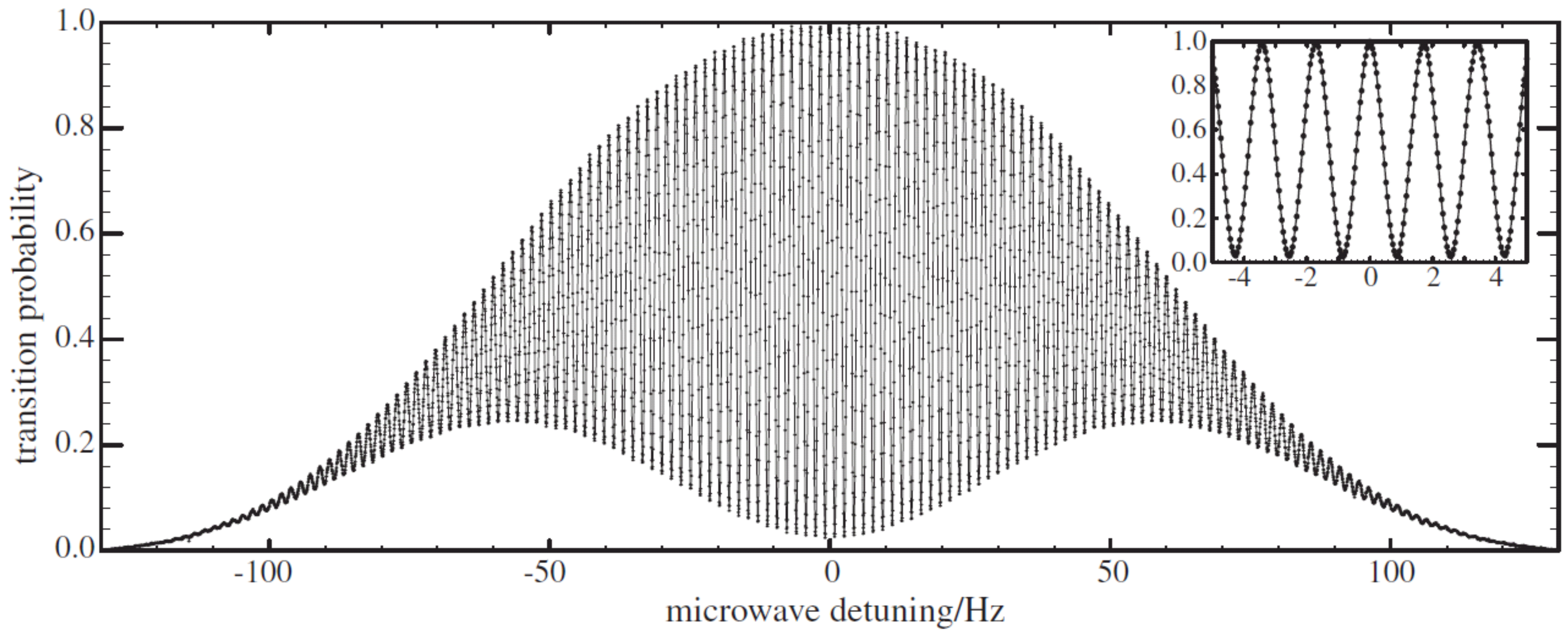
envelope $\times \cos \Delta E t/\hbar$

$\Delta\omega \times \Delta t \geq 1$

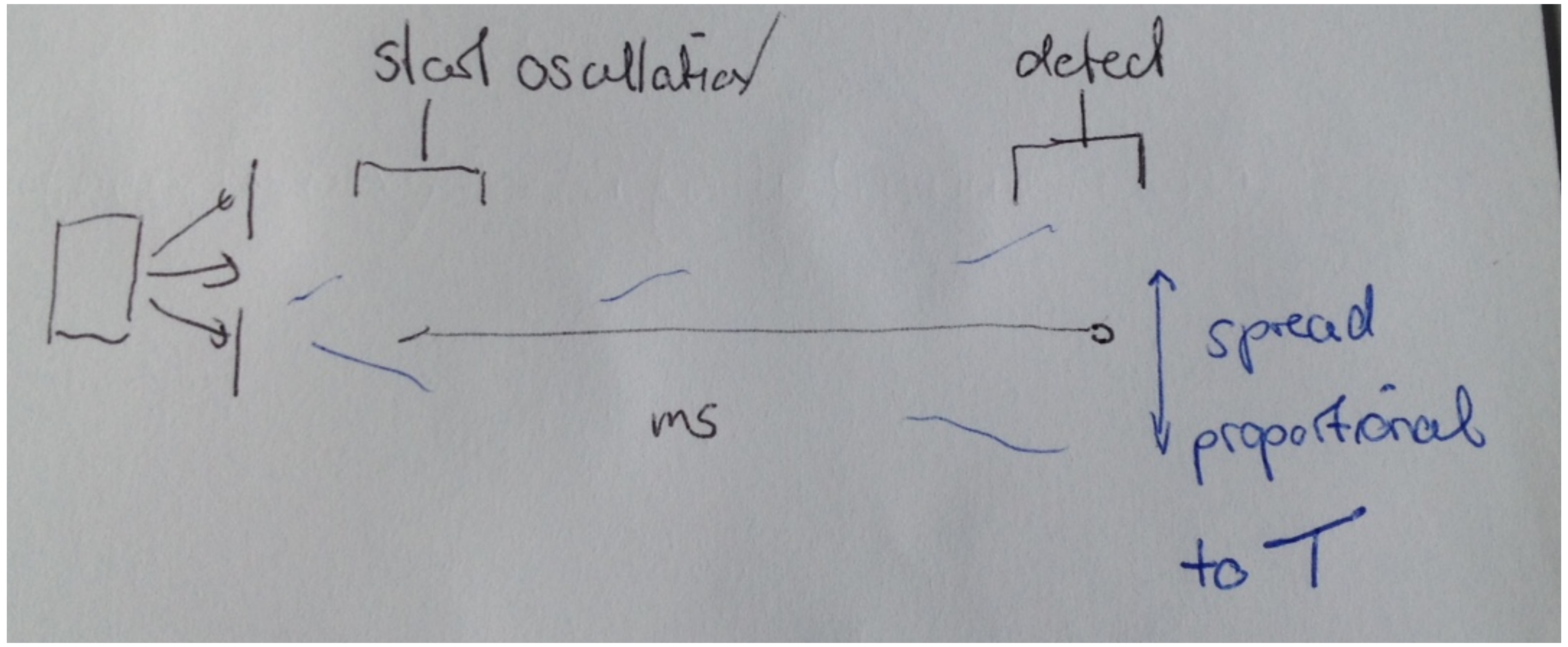
$\rightarrow$ precision: $\frac{\Delta\omega}{\omega} \times \frac{1}{\sqrt{N}} \approx 10^{-13}$





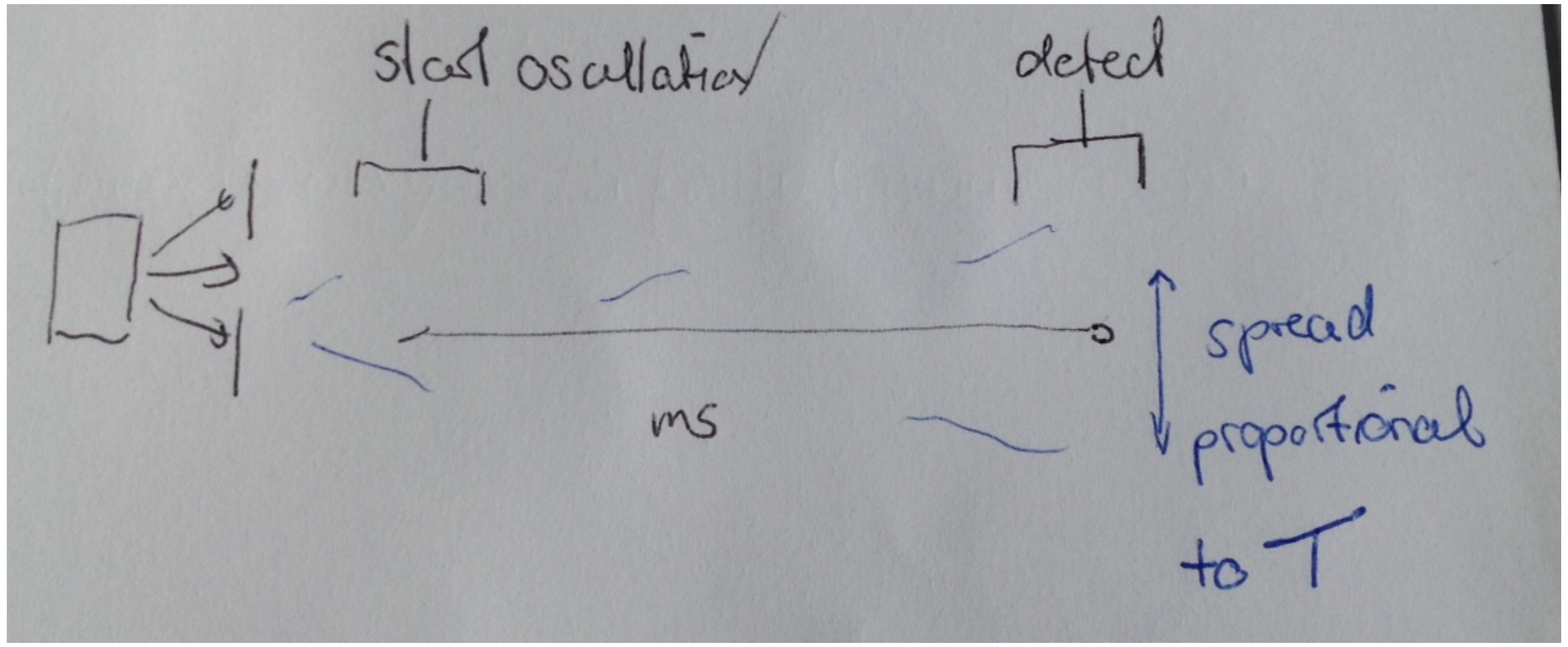


Ramsey limitations



Detection better if atoms are slower

Ramsey limitations



Detection better if atoms are slower

- We know how to perform qubit operation.
- How can we cool these atoms ?
- How can we trap them individually ?


ASK
learn
learn
learn
ask
ask
question
ASK
QUESTION
ASK
ask
question
ASK
question