Quantum logic Spectroscopy with trapped $^{40}Ca^{+}$ and $^{27}Al^{+}$

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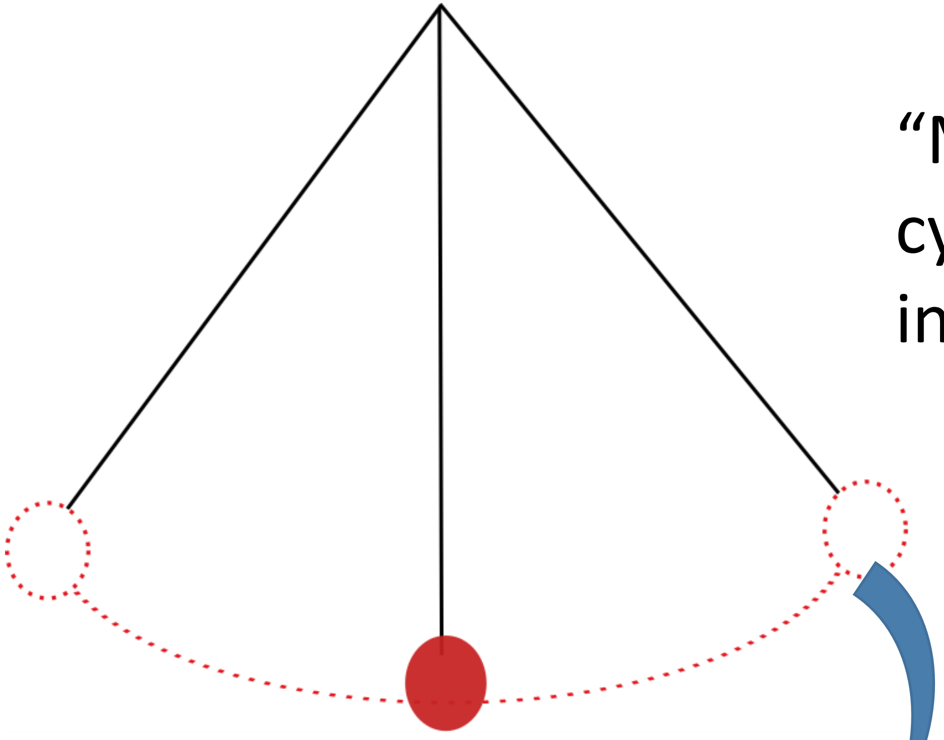
Quantum Optics and Spectroscopy

Supervisors:

Rainer Blatt and Christian Ross

“Never measure anything but frequency!”

PASSION FOR PRECISION
Nobel Lecture, December 8, 2005
Theodor W. Hänsch

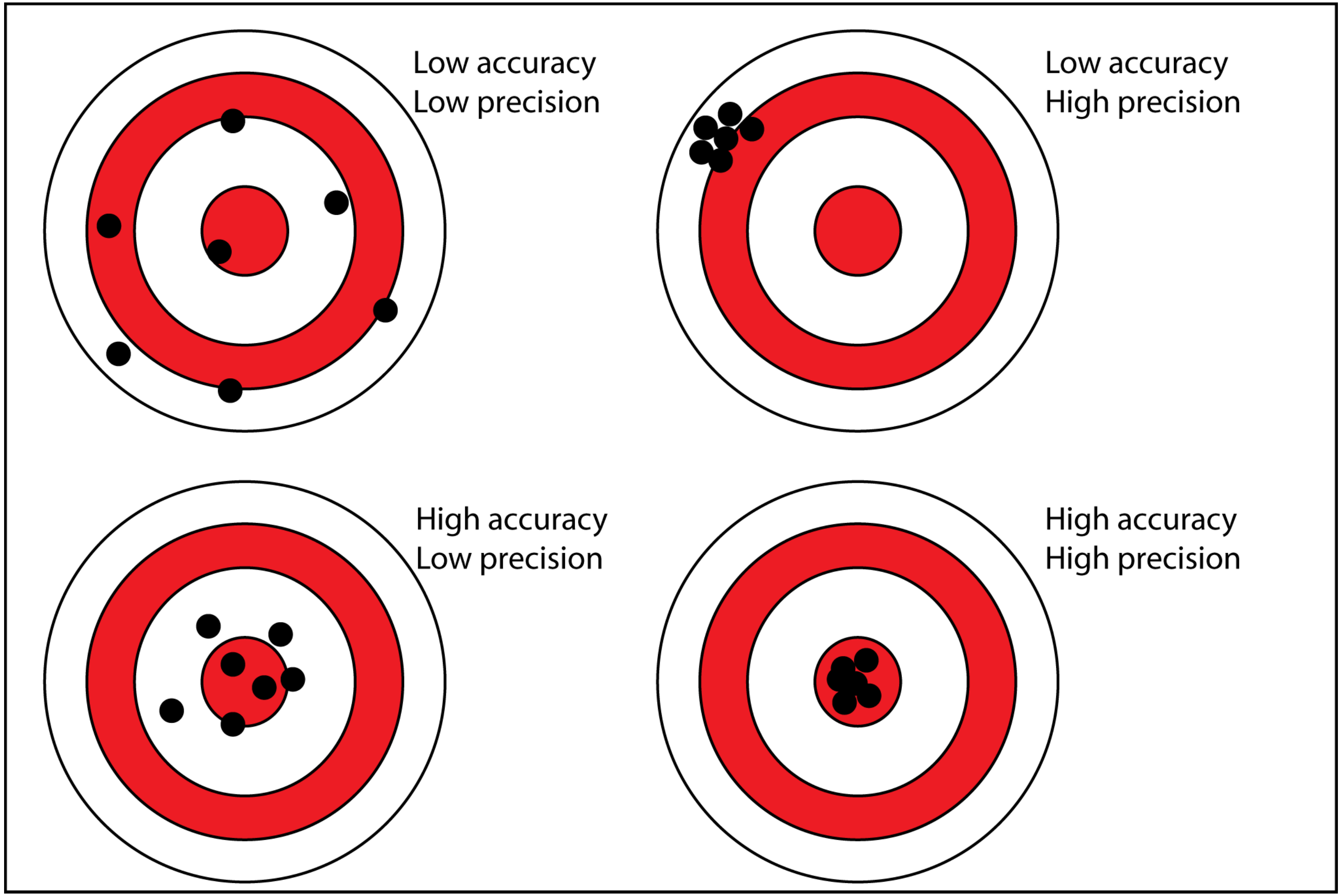


“Measuring the number of cycles during a given interval…”

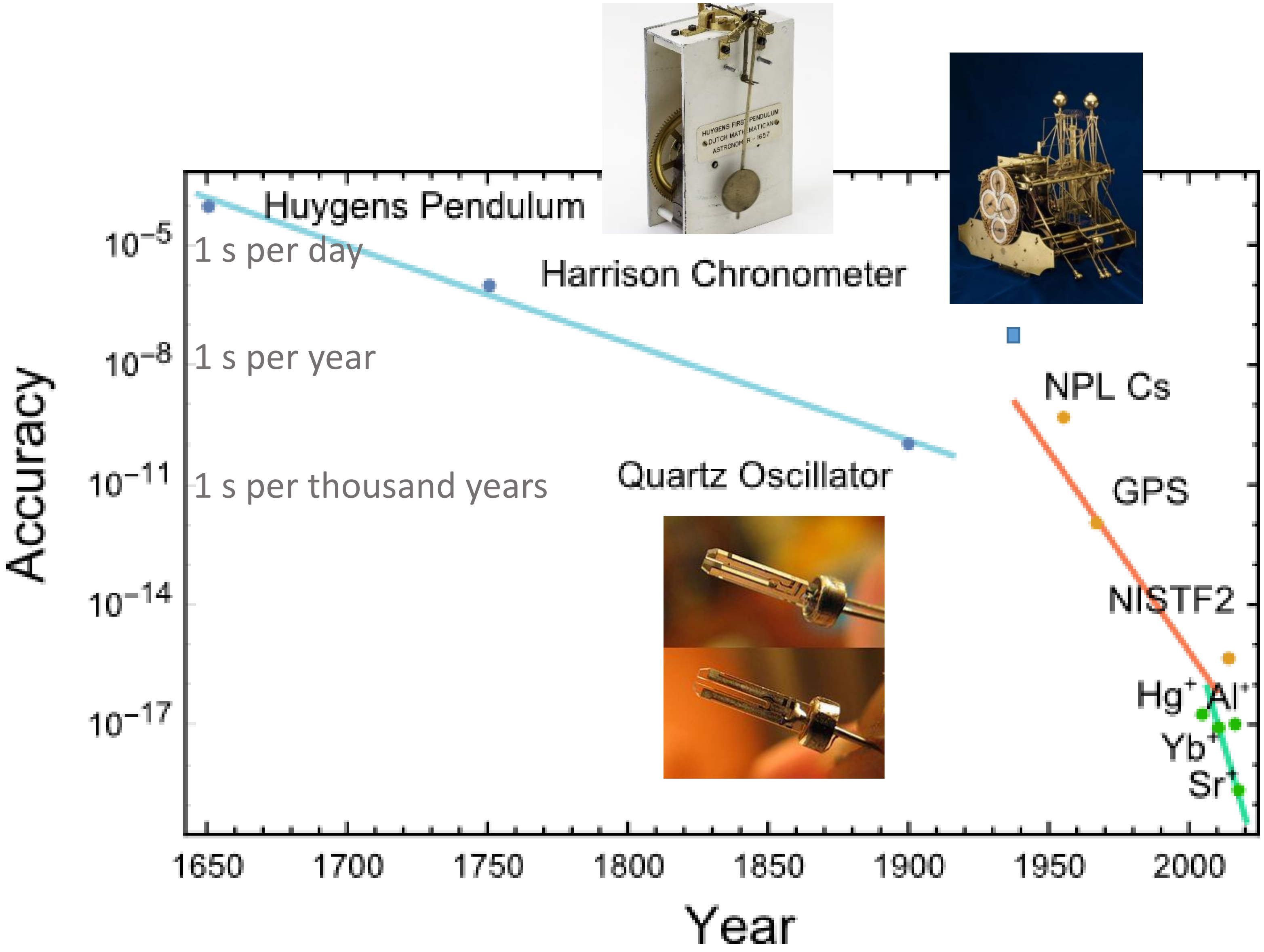
The most **accurate** and **precise oscillator** is actually the most **accurate** and **precise SENSOR**….

Any small change or “perturbation” of the system is going to affect the frequency

Accuracy and Precision

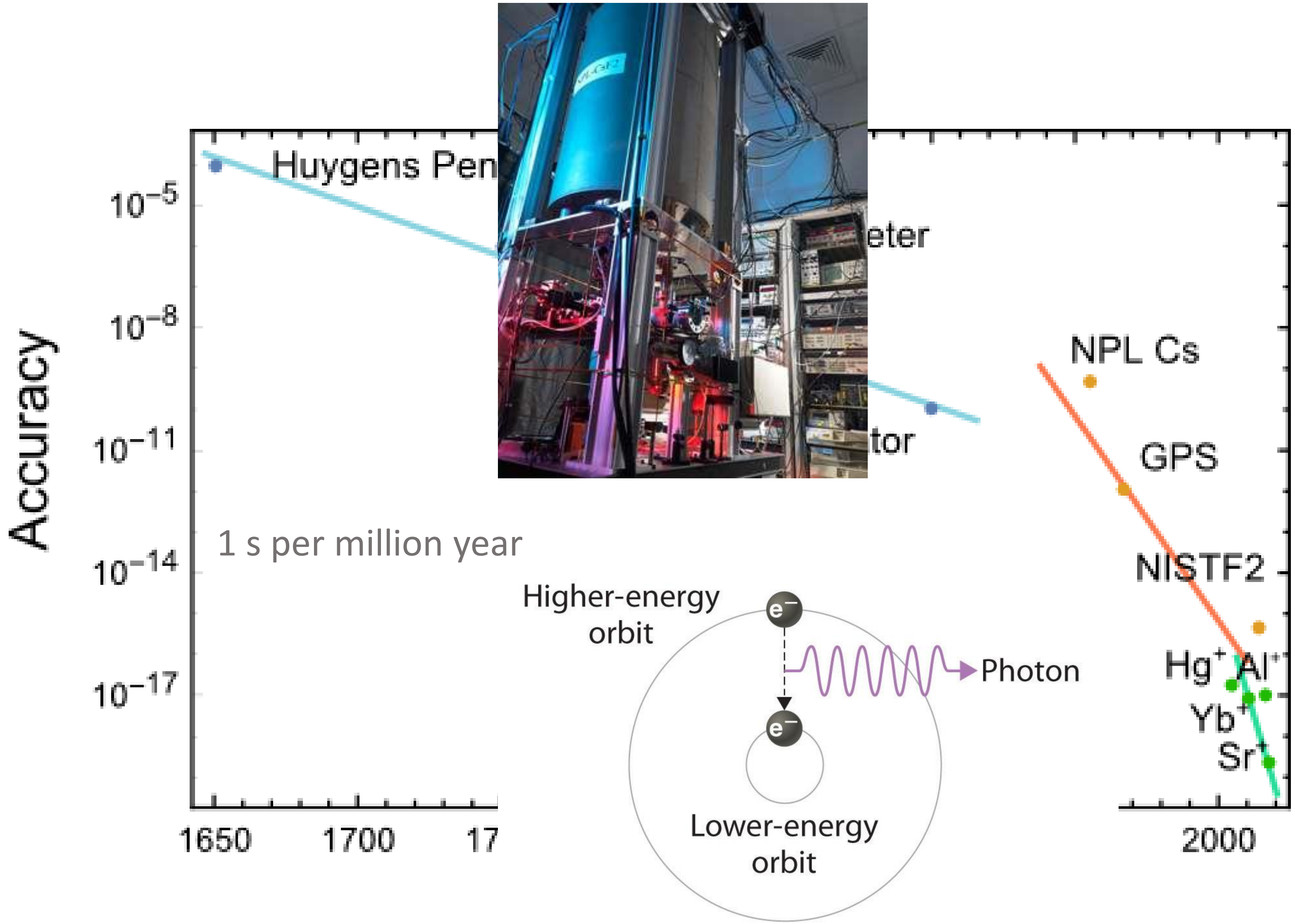


Clock accuracy and applications



Celestial navigation (~1 km accuracy)

Clock accuracy and applications

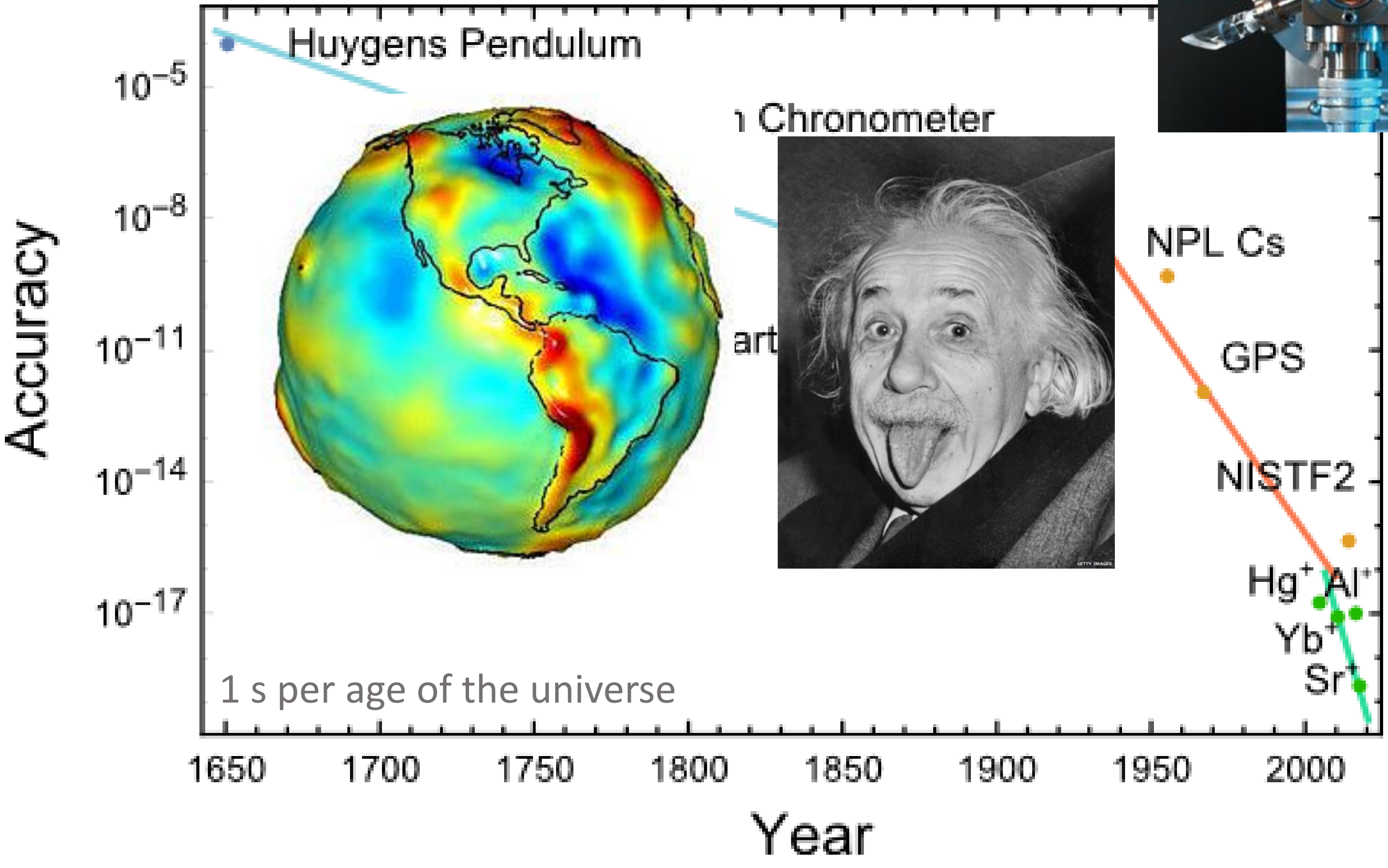


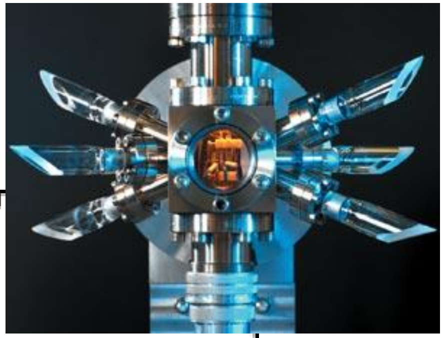
Modern telecommunications

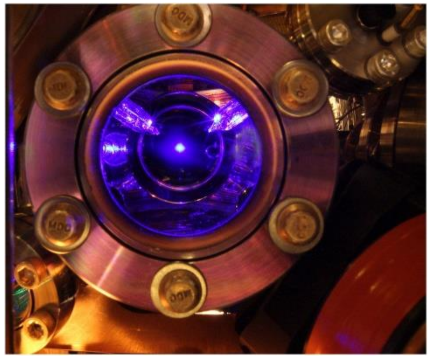
Satellite navigation (~10 m)

Deep space navigation

Clock accuracy and applications







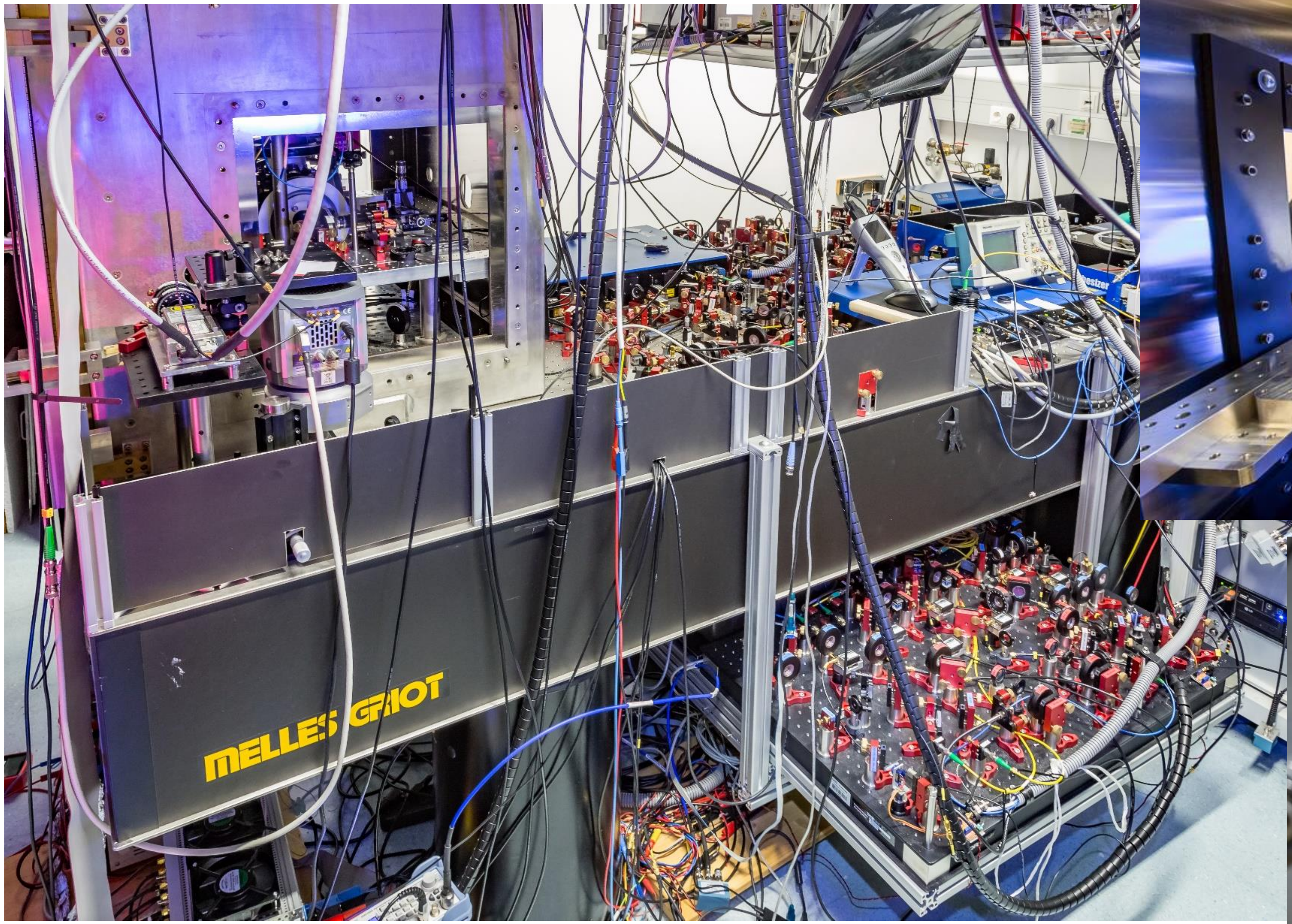
Fundamental physics measurements

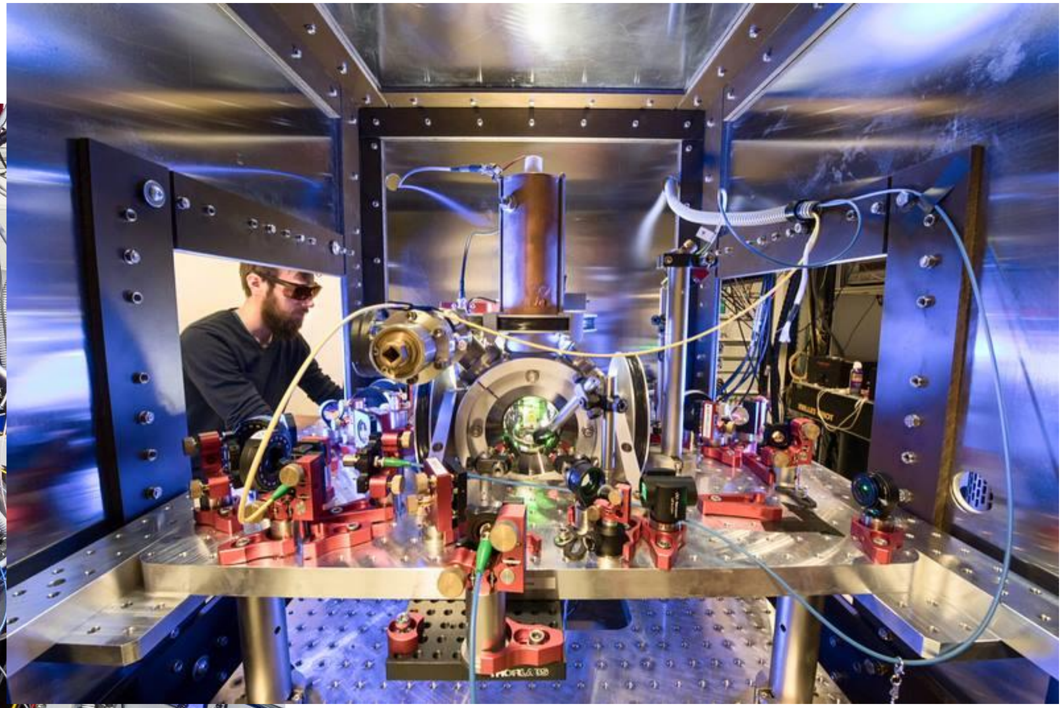
- -Gravitational potential measurements (1 cm accuracy)
- -Dark matter detection
- -Gravitational wave detection

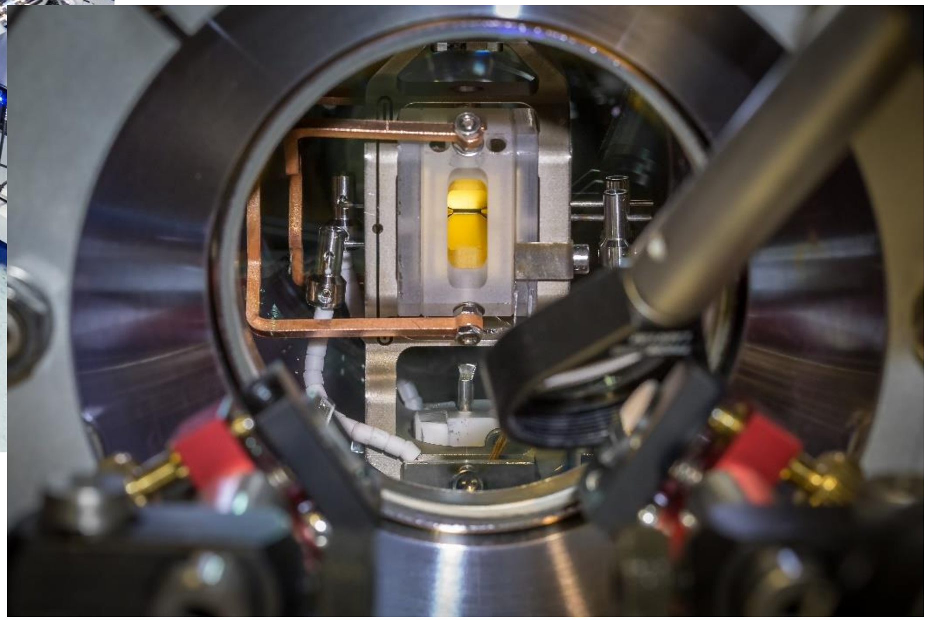
Outlook

- Quantum logic spectroscopy of Al^+
  - Trapping ions: trapping and cooling techniques
  - Why Al^+?
  - Sympathetic cooling
  - Quantum logic spectroscopy
- Frequency measurement of the $^1S_0 \leftrightarrow {}^3P_1$ transition of $^{27}Al^+$
- Characterization of the background gas
- Absolut frequency measurements via GNSS link

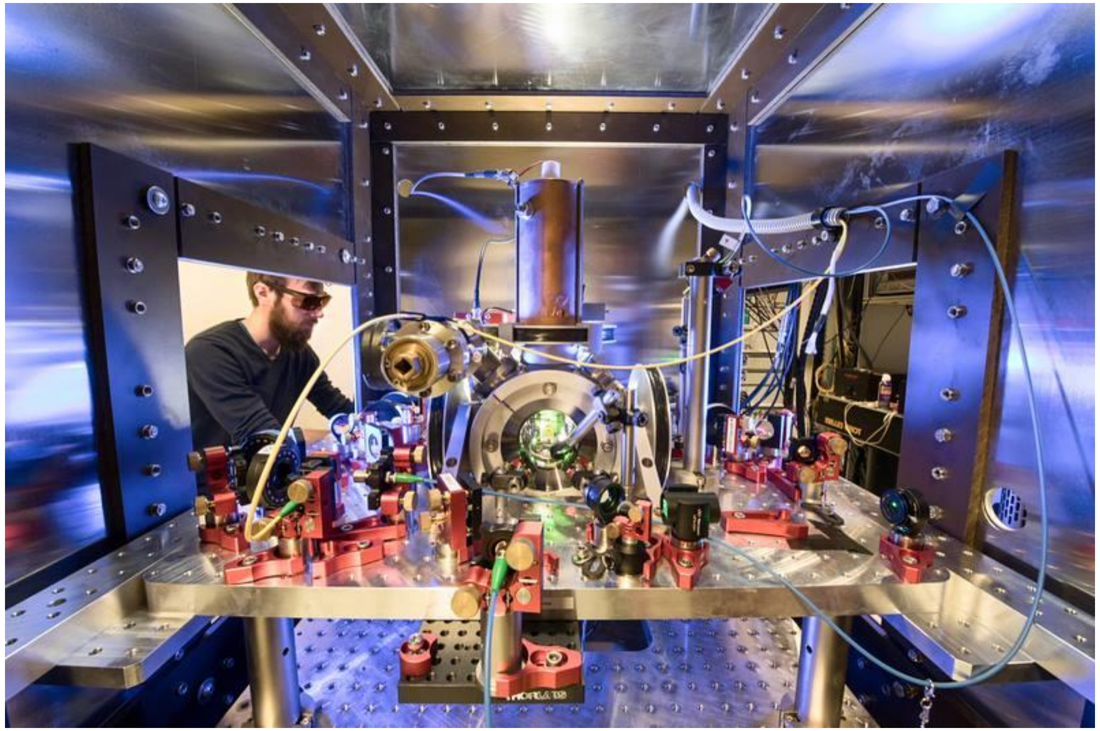
Trapping and cooling ions

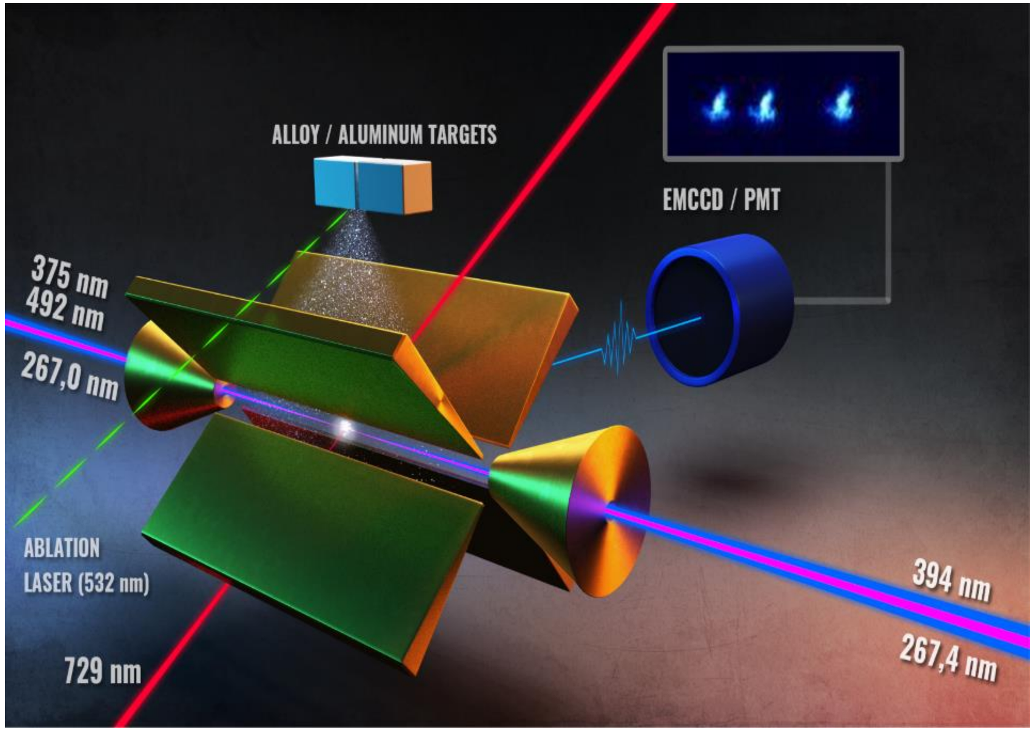


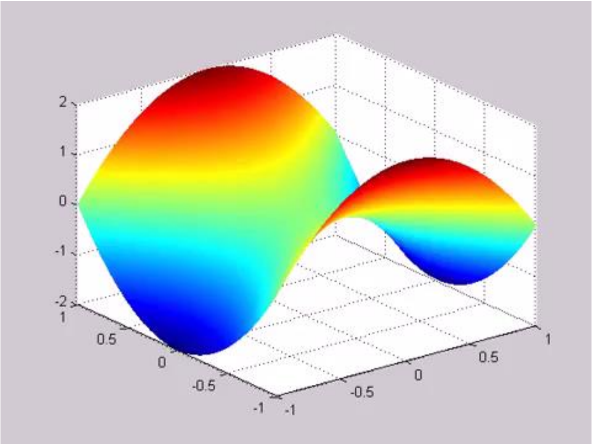


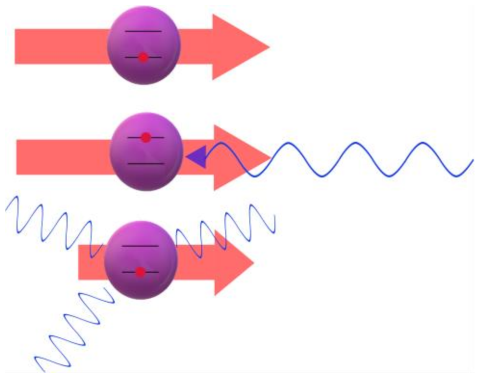


Trapping and cooling of single ions

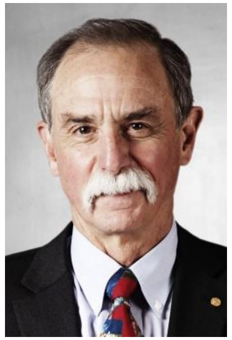








Wolfgang Paul
(1913-1993)

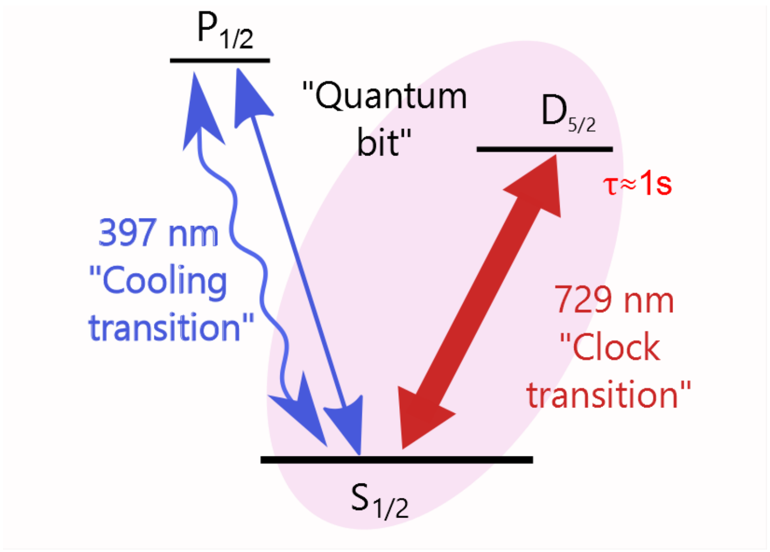


David J Wineland
(1944-)

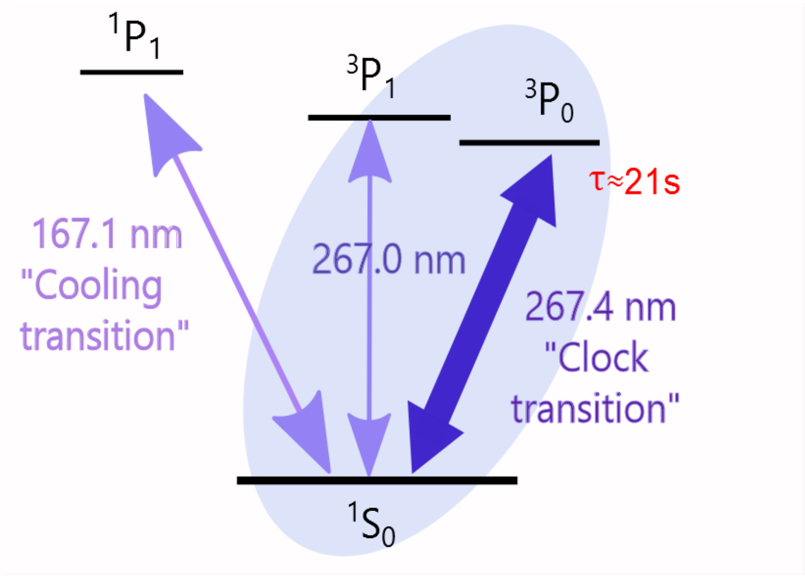
William
Phillips
(1948-)

Why Al^+ and Ca^+?

Ca^+ Clock



Al^+ Clock



Advantages:

-High line Q: $\frac{f}{\Delta f} \approx 3\ x\ 10^{14}$

-Available lasers for cooling transitions

Disadvantage:

-High sensitivity to quadrupole shifts

- Large first-order Zeeman shift

Advantages:

-High line Q: $\frac{f}{\Delta f} \approx 2\ x\ 10^{17}$

-Small Quadrupole shift

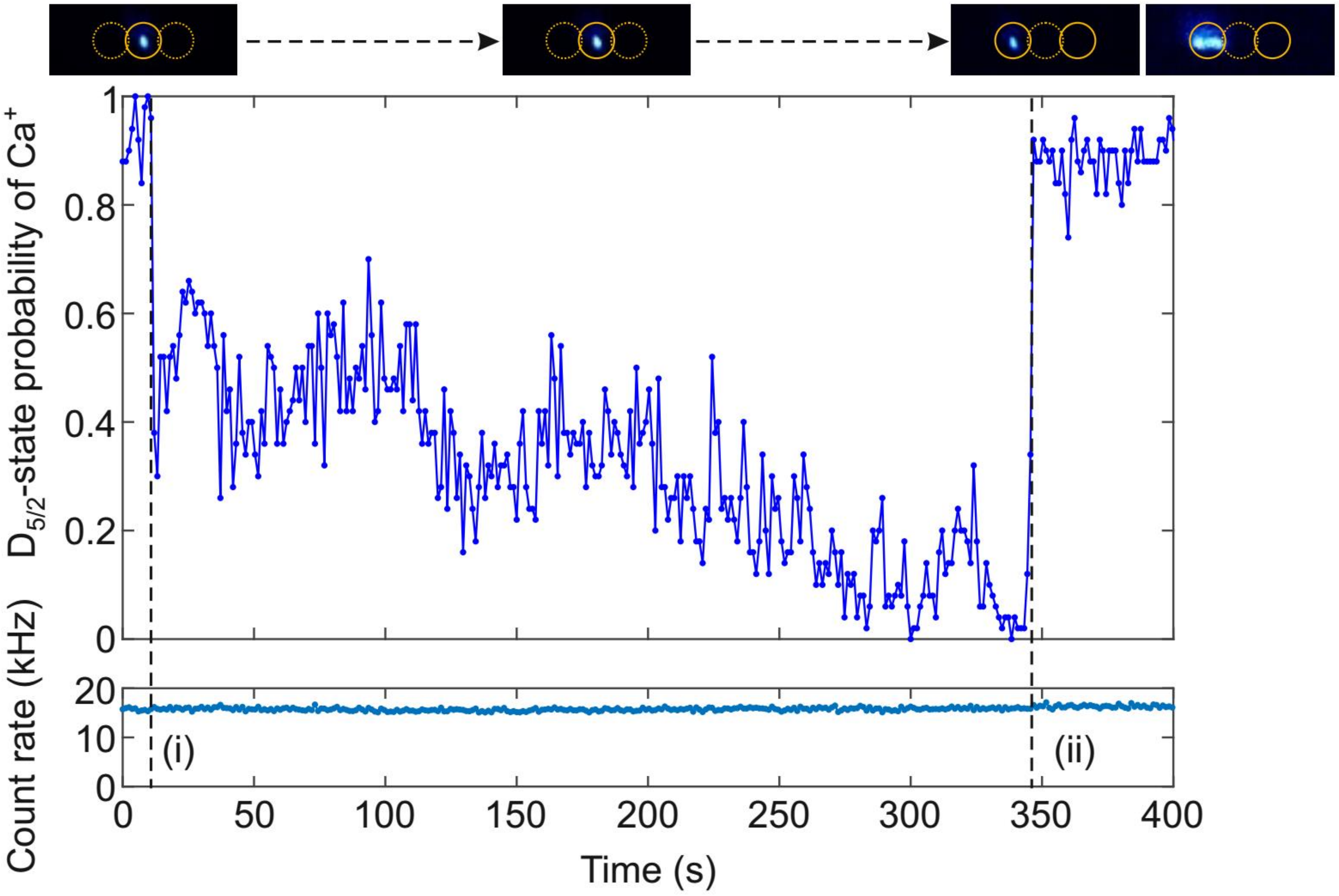
-Low AC Stark shift by black body radiation

-Small Zeeman shifts

Disadvantage:

-Cooling transition

Sympathetic cooling

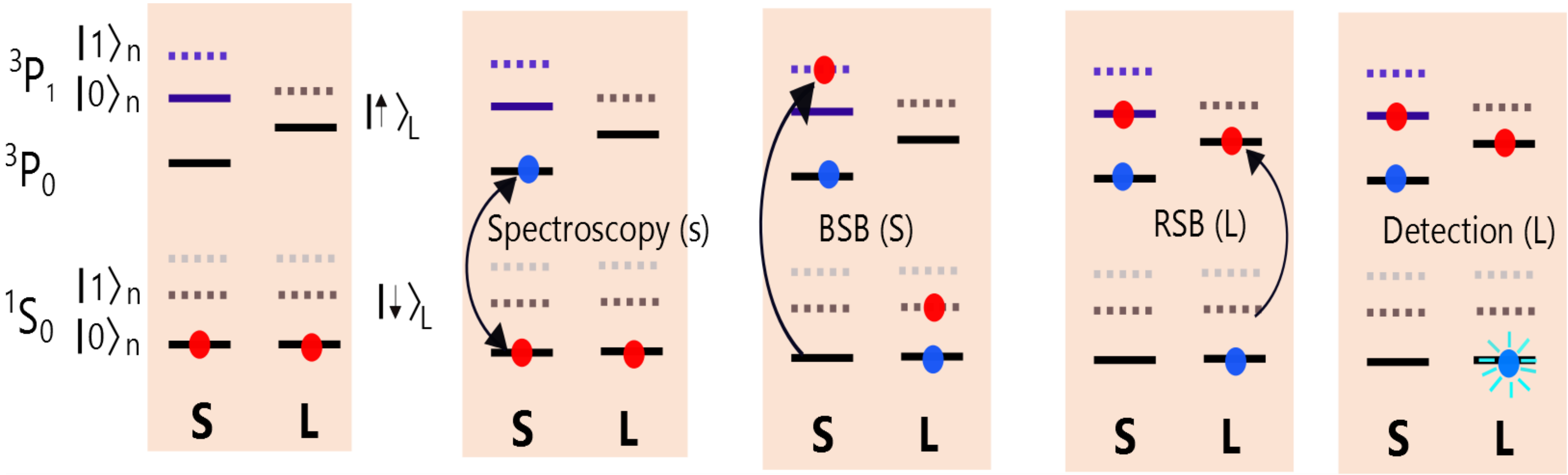


Guggemos, M., Heinrich, D., Herrera-Sancho, O. A., Blatt, R., & Roos, C. F. (2015). Sympathetic cooling and detection of a hot trapped ion by a cold one. *New Journal of Physics*, *17*(10), 103001.

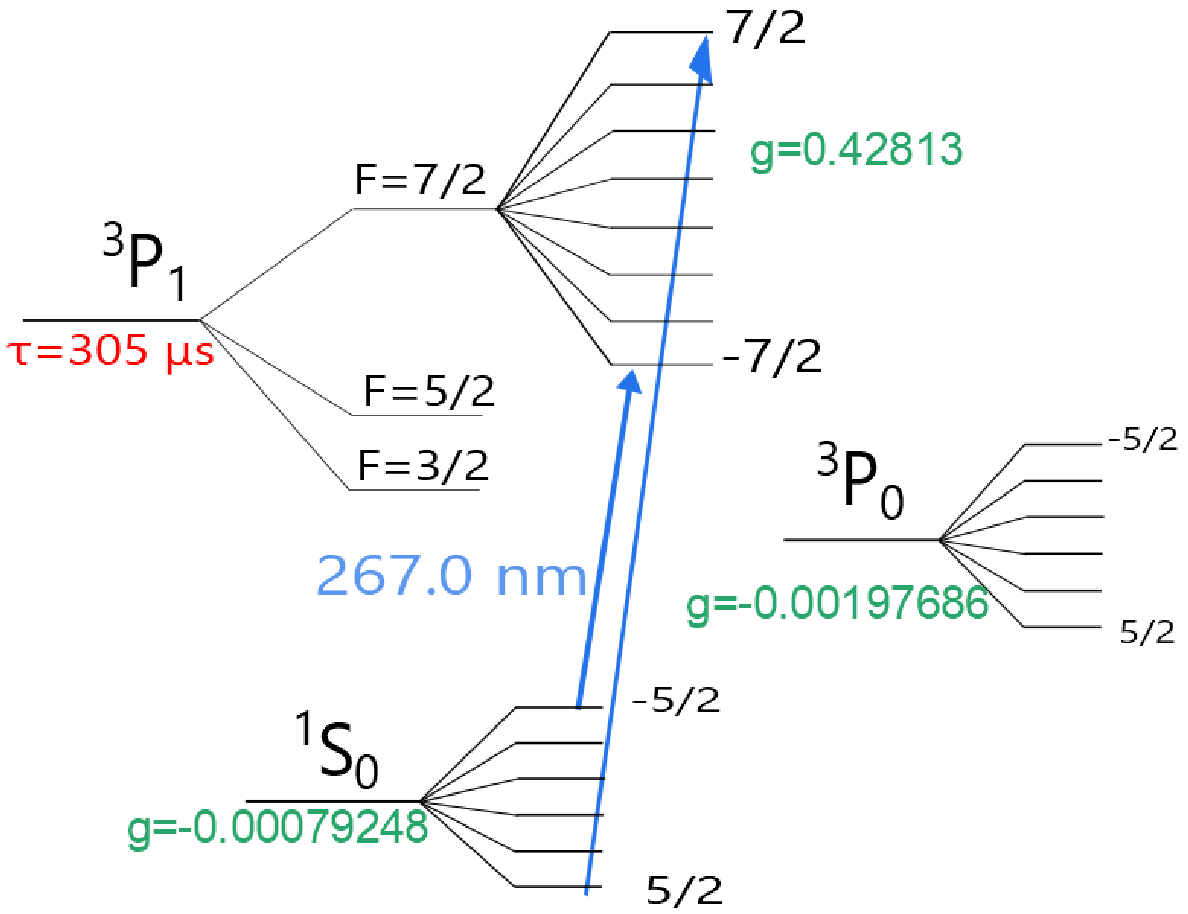
Quantum logic spectroscopy

S: Spectrocopy Ion Al^+

L: Logic ion Ca^+



Frequency measurement of the $^1S_0 \leftrightarrow {}^3P_1$ of $\boldsymbol{Al^+}$ with $\boldsymbol{Ca^+}$



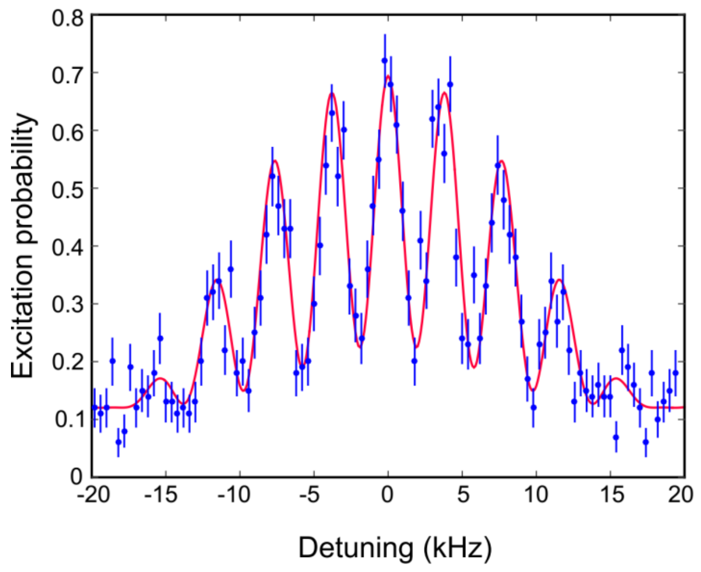
Importance of the **intercombination line:**

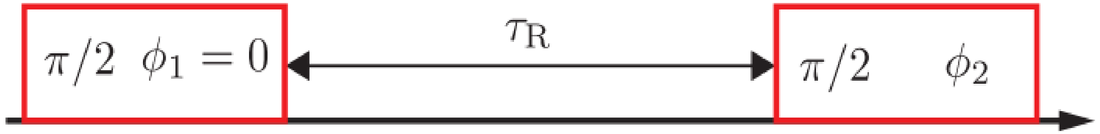
- Initialization of the ion in a pure electronic state by optical pumping

- High fidelity state detection by repetitive quantum demolition measurements based on QLS

Measurement

Interleaved Ramsey experiments on Al^+ and Ca^+

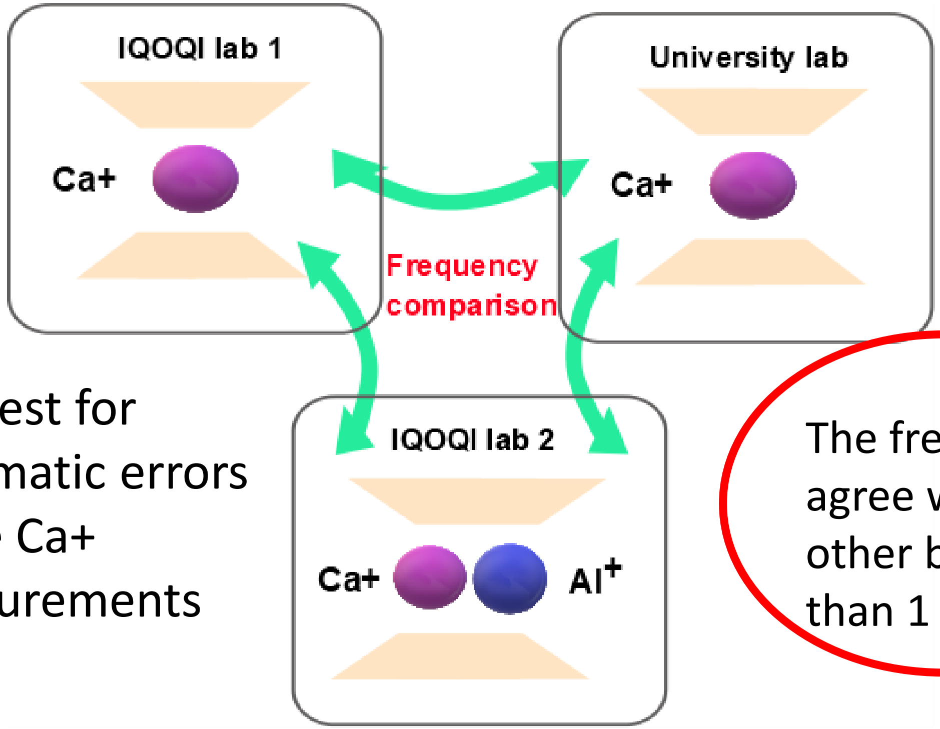




The phase of the second $^{\pi}/_{2}$ pulse is shifted by $0, \pm\, ^{\pi}/_{2}$ and π in order to measure:

- Laser detuning
- Contrast of the ramsey fringe

Frequency comparison of Ca^+ between 3 labs:



As a test for systematic errors in the Ca+ measurements

The frequencies agree with each other better than 1 Hz

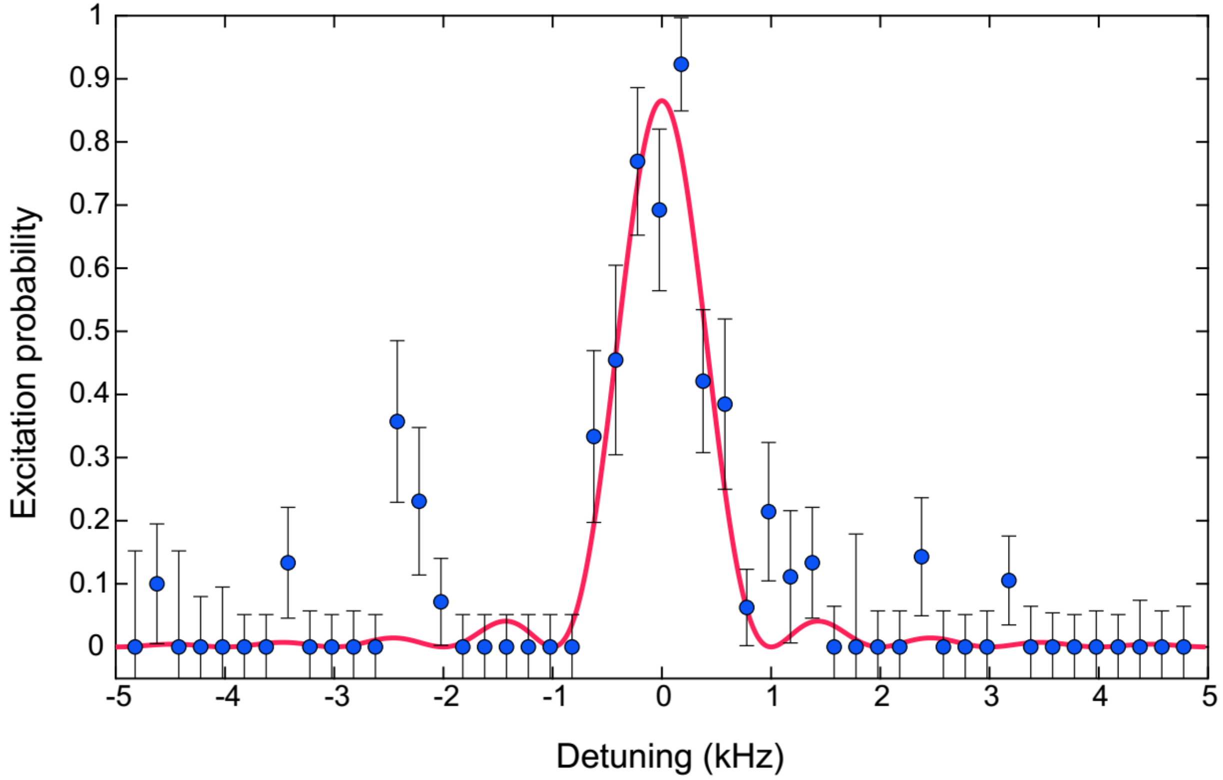
We determine the frequency of the *intercombination line* to be:

$$\nu_{\,^1S_0 \leftrightarrow \,^3P_{1,F=7/2}} = 1\,122\,842\,857\,334\,736\,(93)\ Hz$$

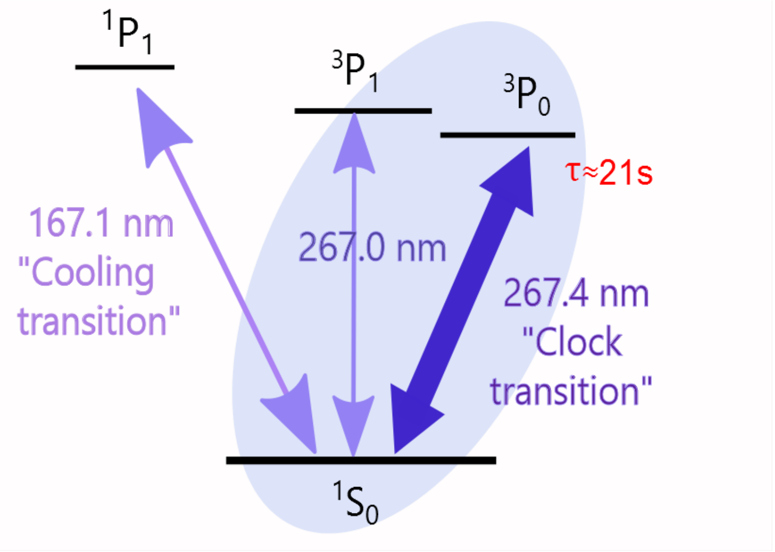
And the Landé g factor of the excited state:

$$g_{\,^3P_{1,F=7/2}} = 0.428132(2)$$

Frequency measurement of the *clock transition*



Al^+ Clock



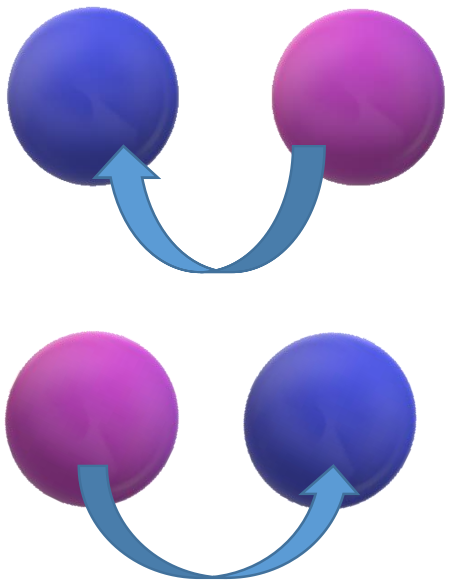
Limitations:

- Formation of molecules(every 15 mins)
- Cooling times (Sympathetic cooling time (Aprox 15 mins)
- Stability of lasers

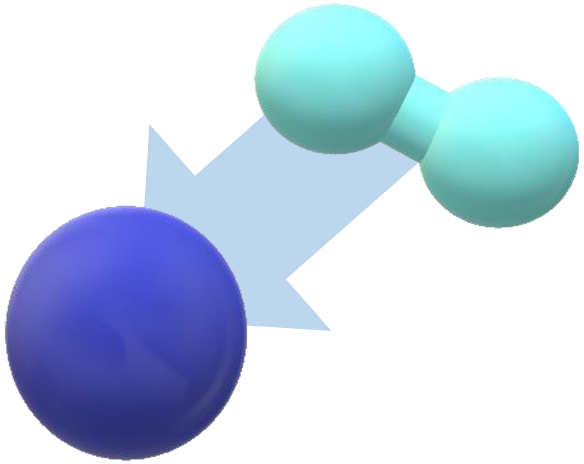
Dynamics of background gas collisions

Through the study of the collisions of the background particles with the Ca^+ and Al^+ we search to ***characterize the composition of the background gas in our chamber***

Swapping rate of Al^+-Ca^+

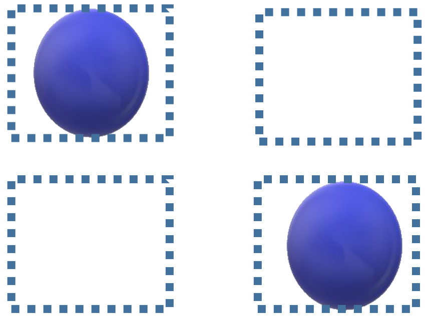


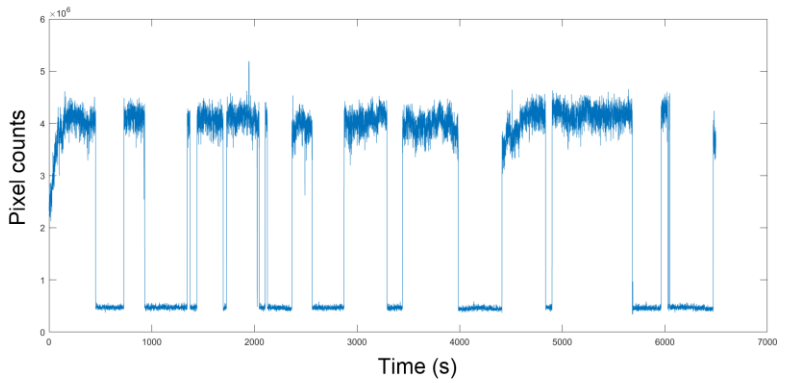
Cooling dynamics of Ca^+ after background gas collisions



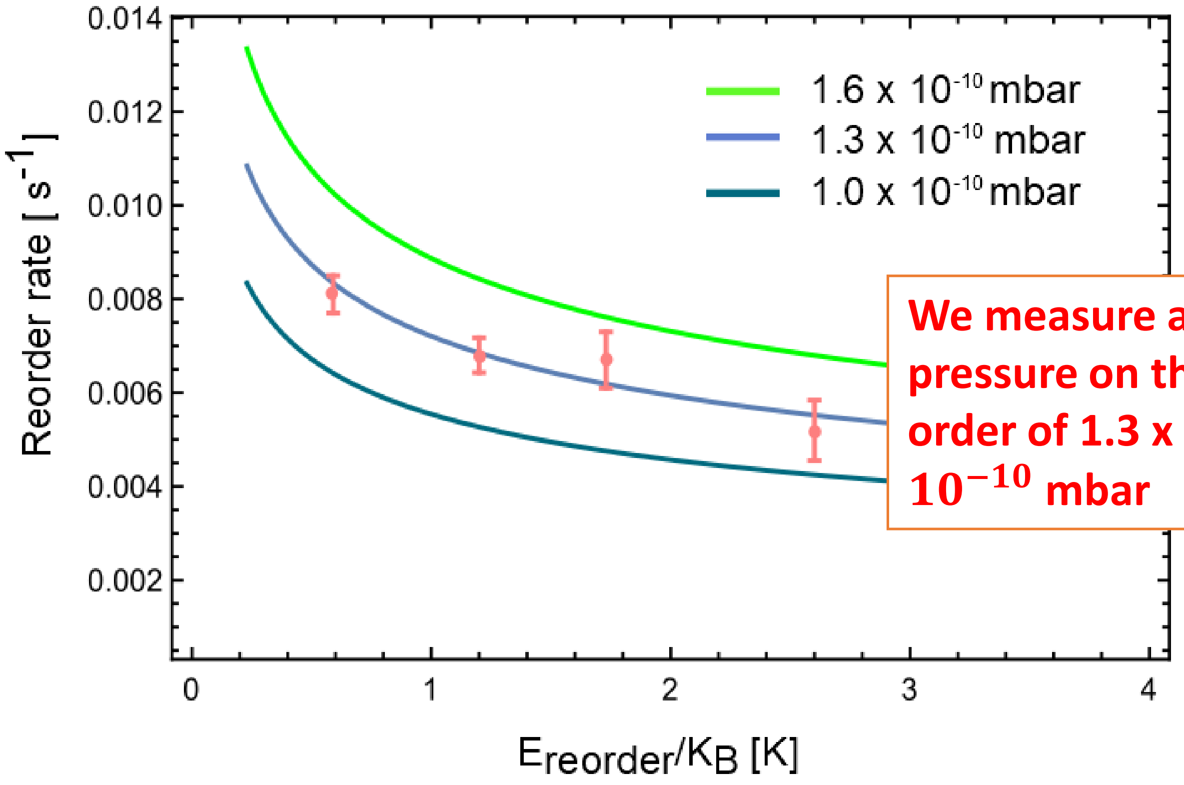
Swapping rate of the position of $Al^+ - Ca^+$

Measurement: We use the camera and determine 2 ROI at the position of the Al+ And the Ca+ and measure the amount of pixels in each region as a function of time





Pixels counts as a function of time in ROI 1

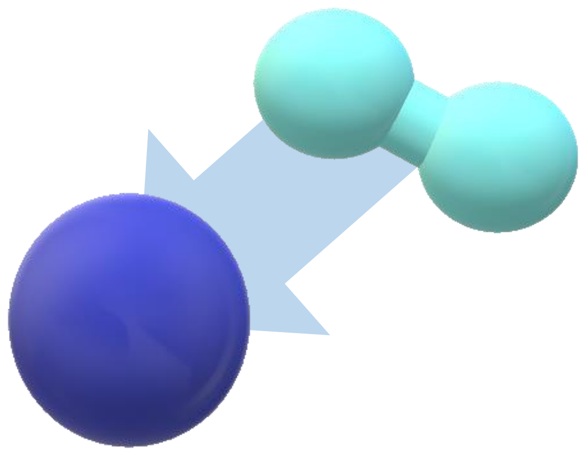


We measure a pressure on the order of 1.3 x 10^{-10} mbar

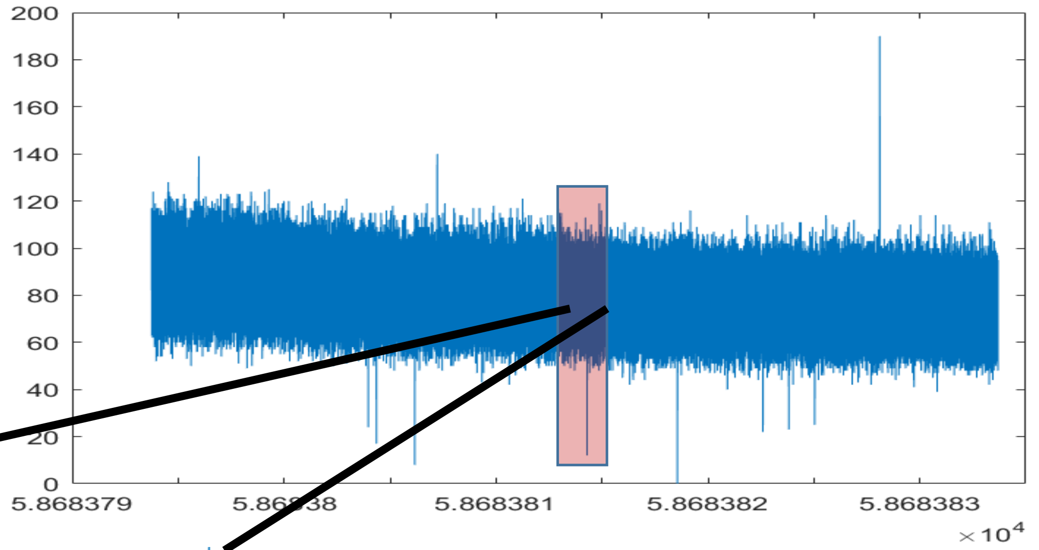
$$\Gamma_{\text{reorder}} \lessapprox \frac{1}{2}\left(\frac{p}{902\ \text{nPa}\cdot\text{s}}\right)\left(\frac{E_{\text{reorder}}}{1\ \text{K}\times \text{k}_\text{B}}\right)^{-0.278}$$

Collisions with Ca^+

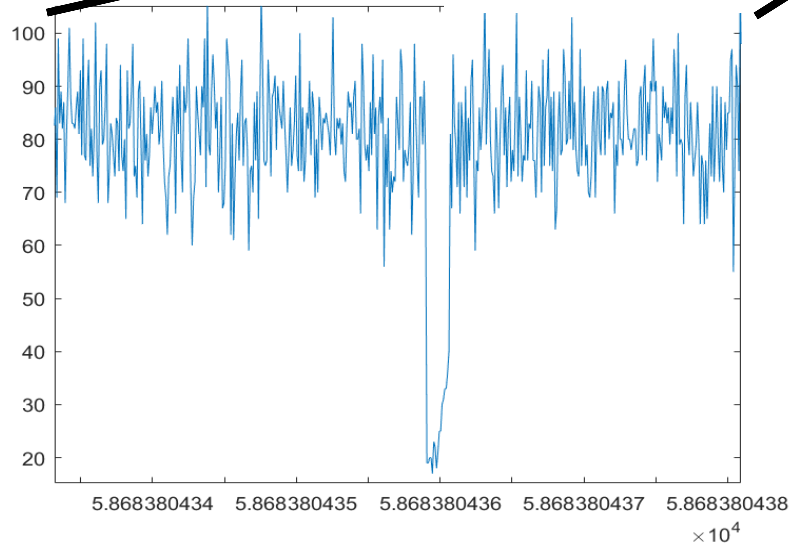
Doppler cooling thermometry: Ions' kinetic energy influences the fluorescence rate due to the Doppler effect.
As the ion scatters photons its energy decreases towards the Doppler cooling limit and its fluorescence increases [1]



We look only at the fluorescence rate emitted by the Ca^+ during Doppler cooling



During a collision the ion gets warmed consequently the fluorescence decays. When the ion cools back the fluorescence recovers.

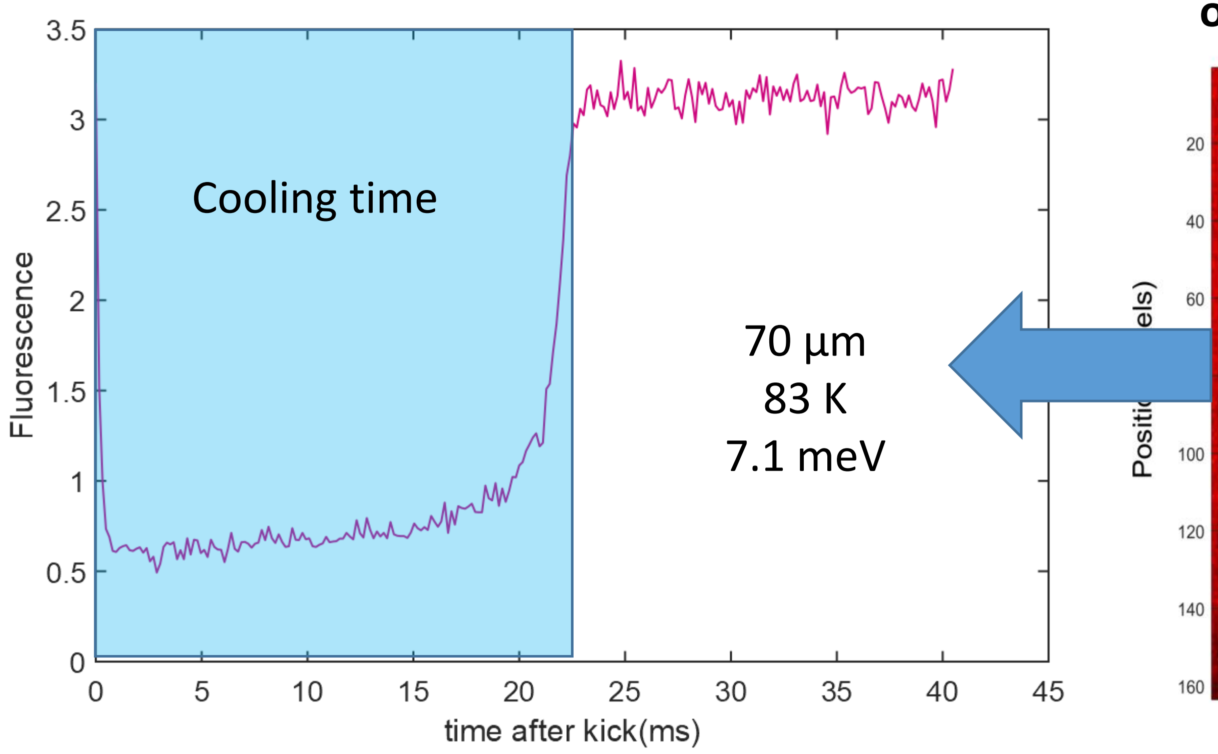


Through the observation of the recooling dynamics we can extract the energy of the collision and consequently the mass of the particle that collided with the Ca+ ion

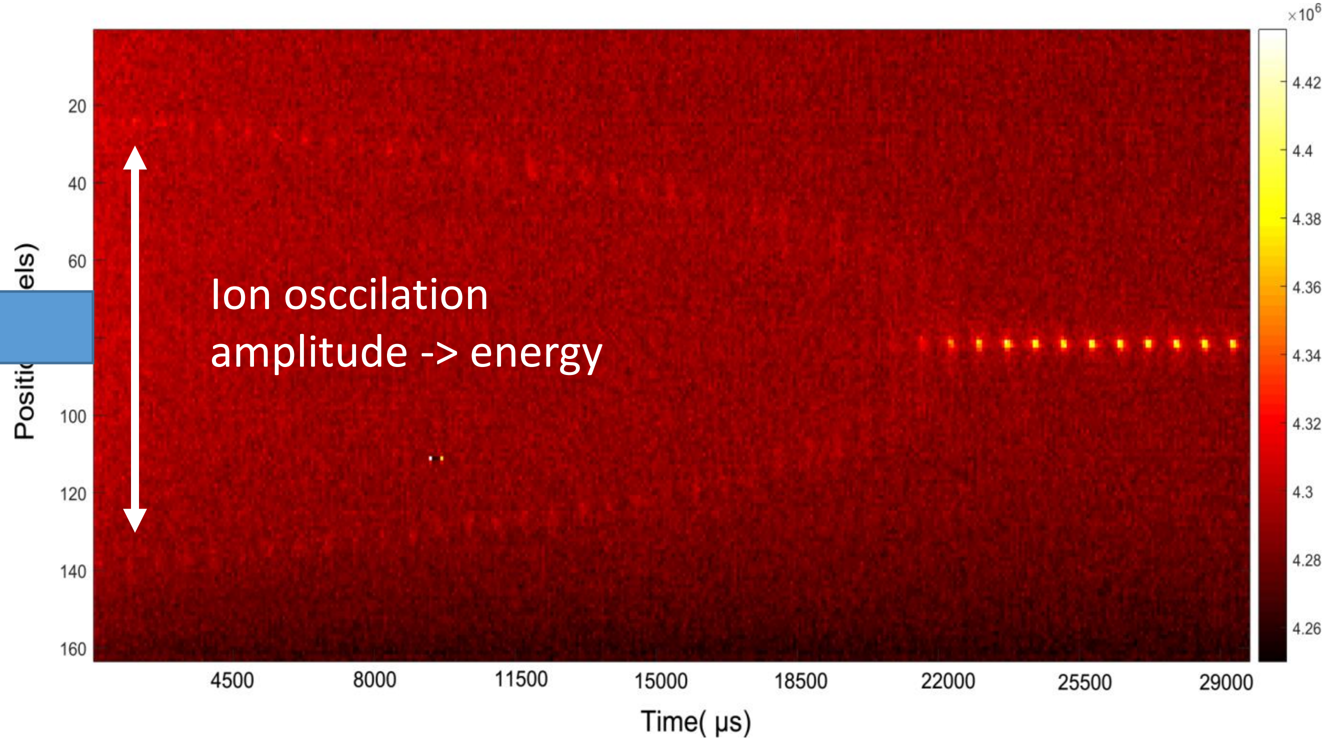
[1] Sikorsky, Tomas, et al. "Doppler cooling thermometry of a multilevel ion in the presence of micromotion." *Physical Review A* 96.1 (2017): 012519

Characterization of cooling dynamics

Evolution of fluorescence counts as a function of time

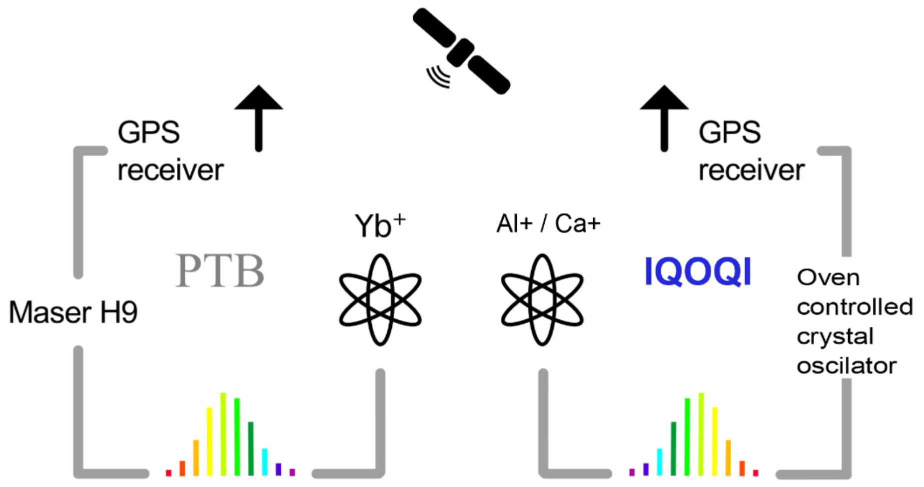


Imaging of the fluorescence spatial distribution as a function of time detected with a CCD camera



GNSS link Innsbruck-PTB

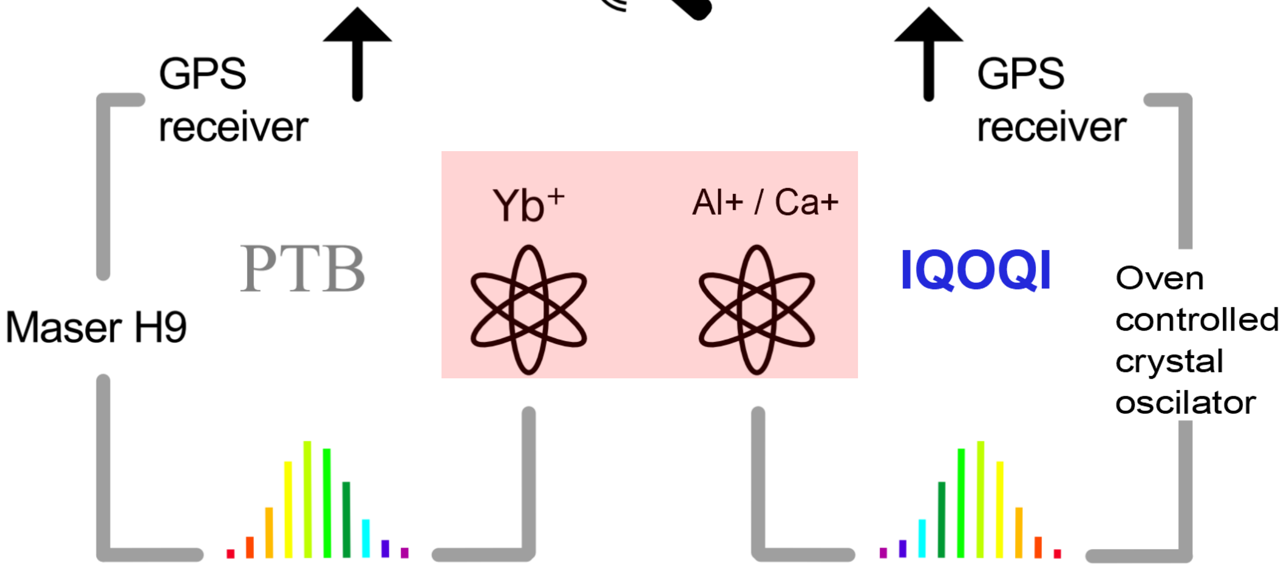
- Absolute frequency measurements
- Experimental set up
- First results: characterization of Passive Hydrogen MASER
- Future: absolute frequency measurement of the Ca^+ transition-Comparison with Asian groups



Absolute frequency measurement via PPP

Frequency:
Satellite – Maser

Frequency:
Satellite – Maser



Frequency:
Maser-Yb^+

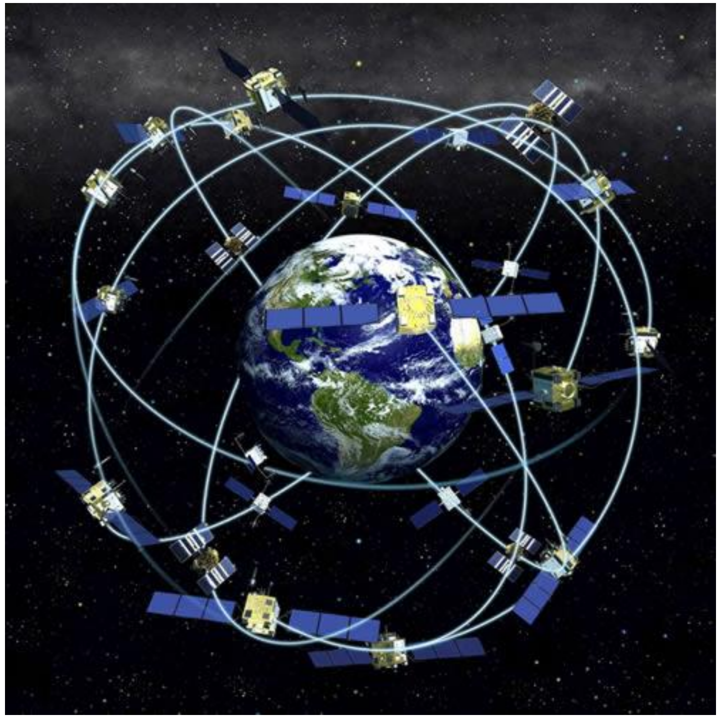
Frequency:
Maser-$Al^+/\,Ca^+$

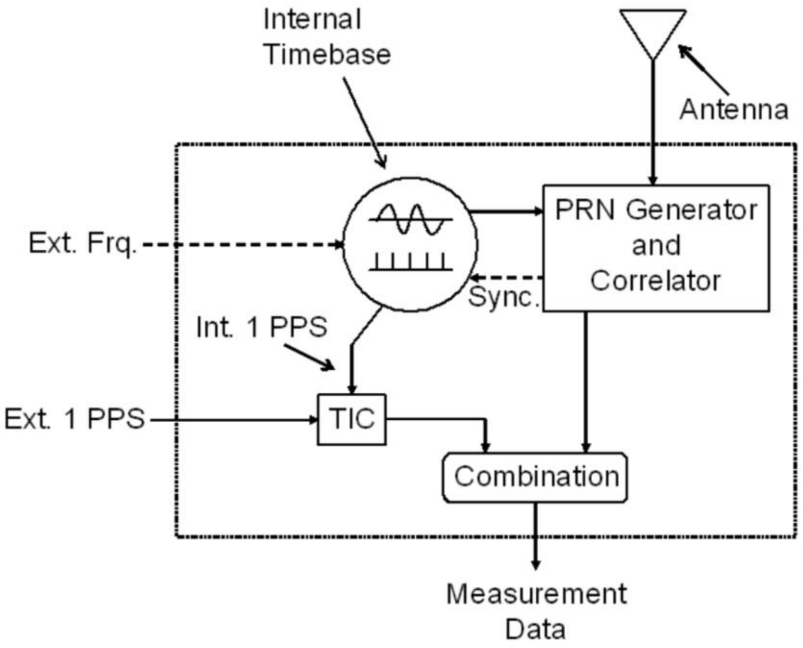
Frequency comparison Yb^+ and $Al^+/\,Ca^+$

Experimental set up

GPS satellites

GNSS Antenna + GNSS receiver

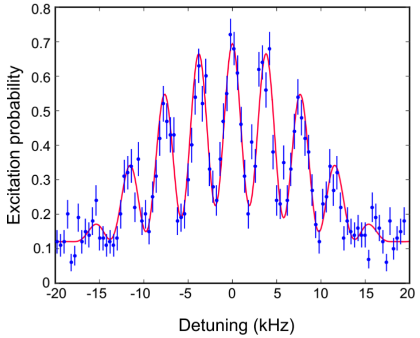




Summary

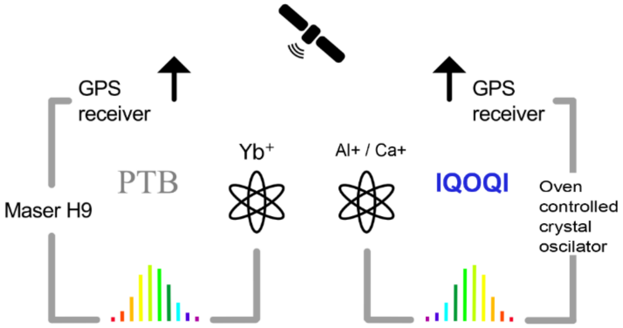
Quantum logic Spectroscopy with trapped $^{40}Ca^{+}$ and $^{27}Al^{+}$

Frequency measurement of the $^{1}S_{0} \leftrightarrow \,^{3}P_{1}$ of Al^{+} with Ca^{+}



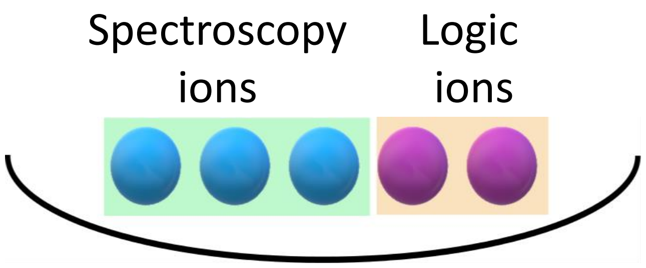
Background gas in trapped-ion optical clocks

Absolut frequency measurements Via GNSS link

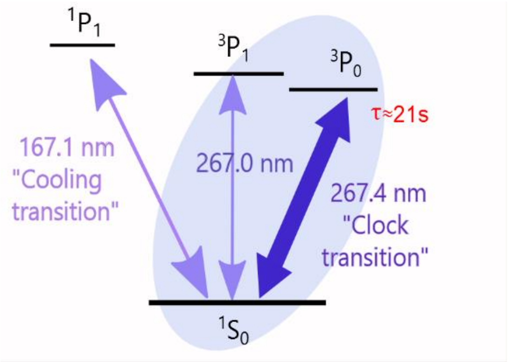


Future

Entanglement protocol for Multi ion read out



Absolut frequency measurement of the Al+ clock transition



Thank you!