Atomic Clocks -

How well can we measure time?

A presentation as part of the Master Seminar „Your passion for AMO-physics“ given by Lasse Kundy

18.05.2021

[1, from Pyramidtimessystems]

Motivation – What is time?

[2, KIDPID…]

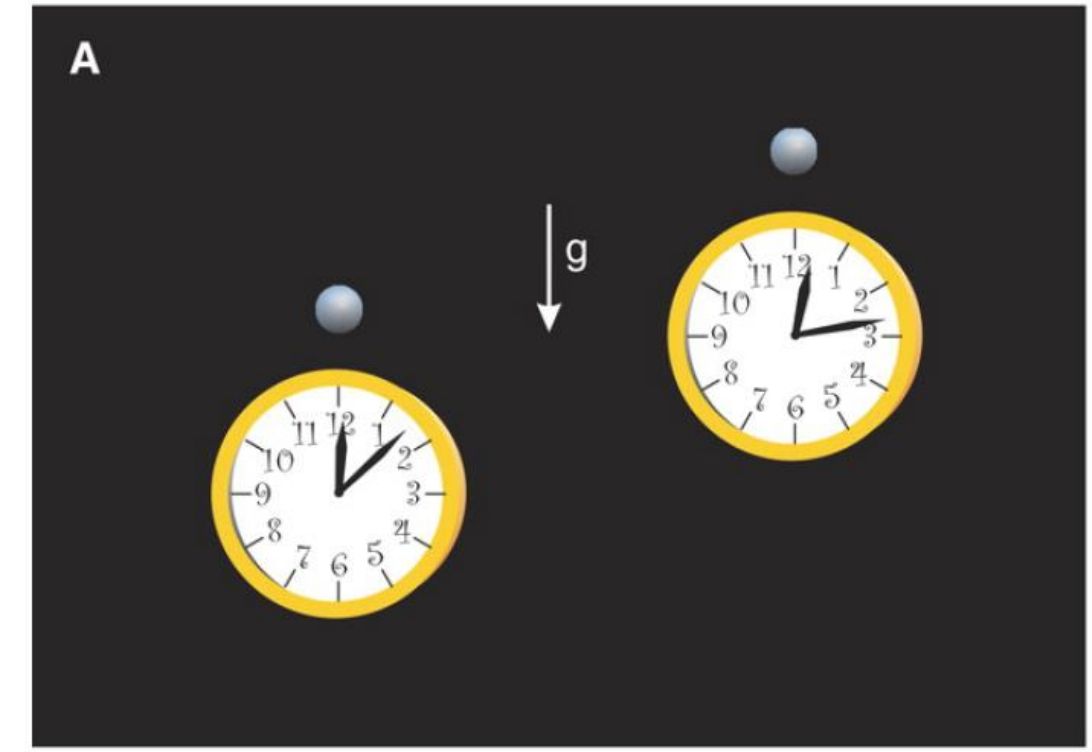
Height difference of $h = 33\text{cm}$

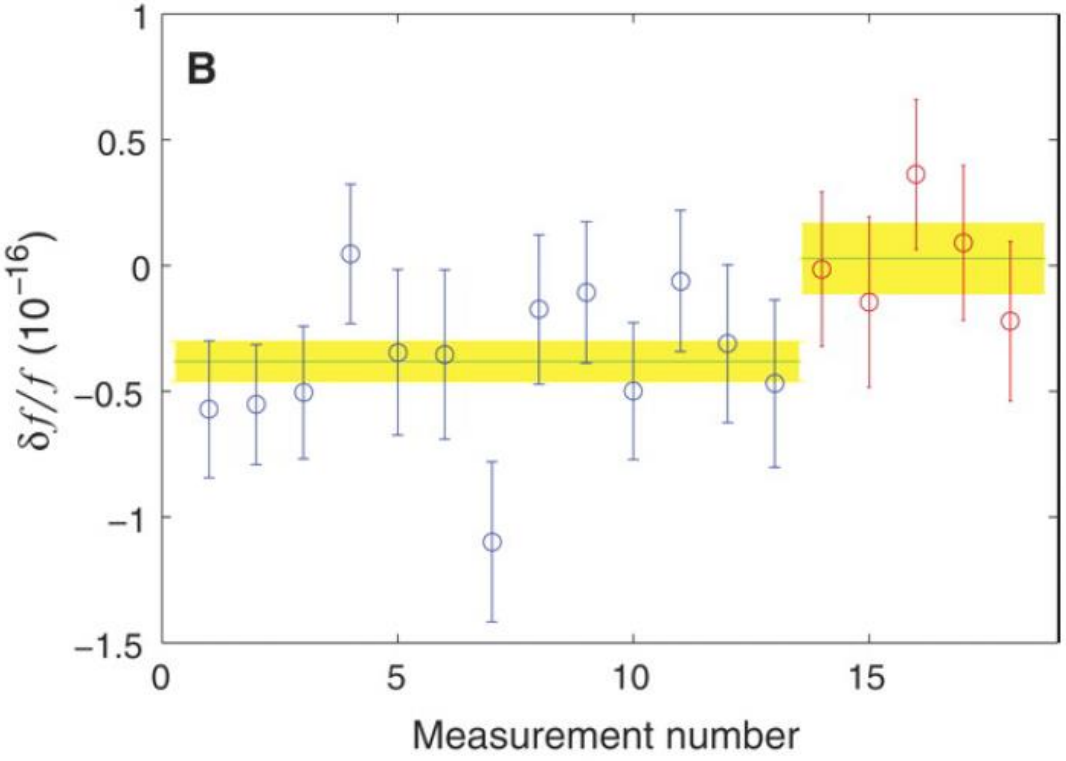
$$\Delta E = mgh = \frac{E}{c^2}gh$$

$$\frac{\Delta E}{E} = \frac{gh}{c^2} \rightarrow \frac{\Delta f}{f}$$

$$\approx 4 * 10^{-17}$$

Motivation





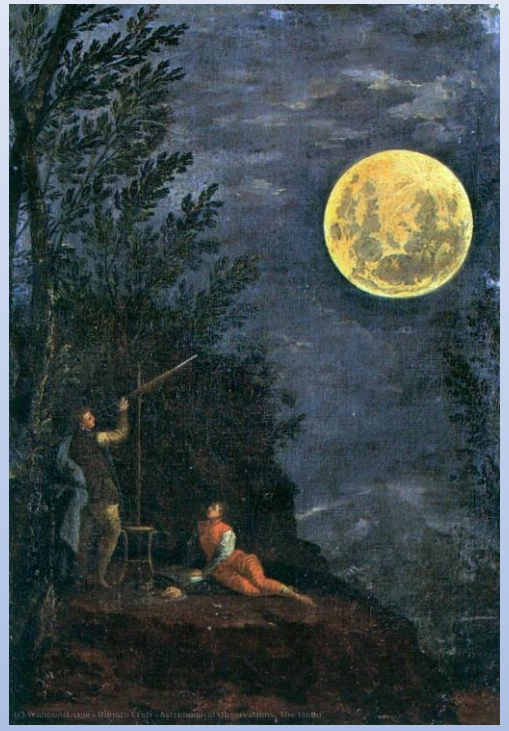
[3, C.W. Chou et al, Optical Clocks and Relativity]

Structure

- History of timekeeping
- How does an atomic clock work?
- Example: CSF1 atomic clock
- Discussion

- Optical Clocks
- CryPTEx-2 at MPIK
- Applications
- Summary
- Discussion

History of timekeeping



[4, Usuem by Creti]
Astronomical observations

[5, Uhren-Hidding]
Pendulum Clock

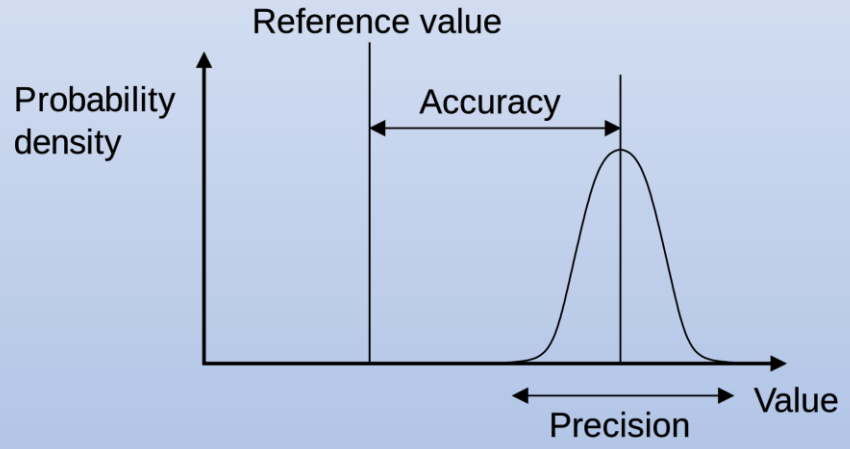
$\sim 10^{-5}$

[6, Wikipedia Quartz Clock]

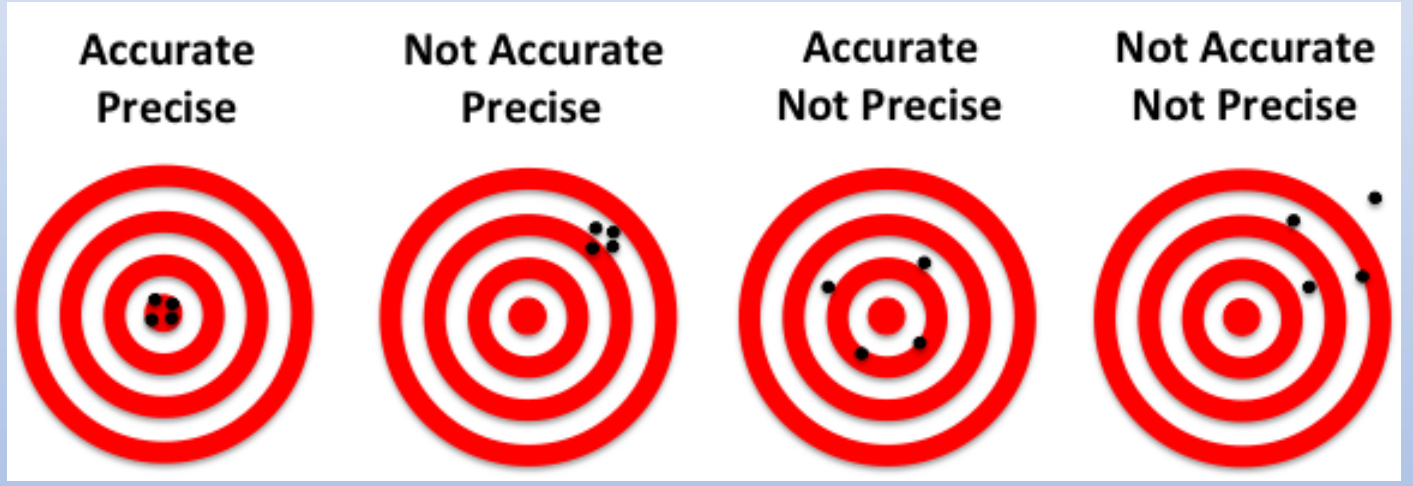
$\sim 10^{-8}$

→ **Relative uncertainty** $= \frac{\Delta t}{t}$

Accuracy vs. Precision

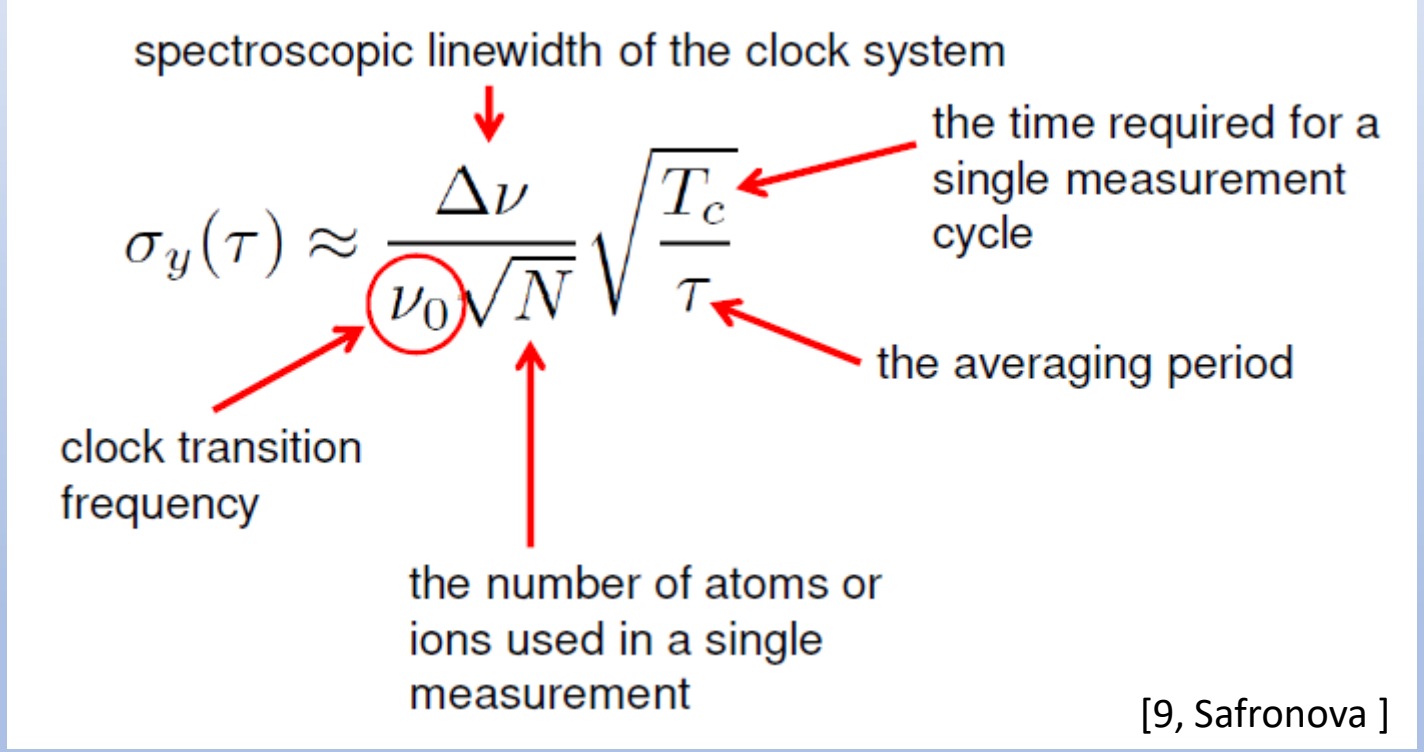


[7, Wikipedia, Accuracy and Precision]

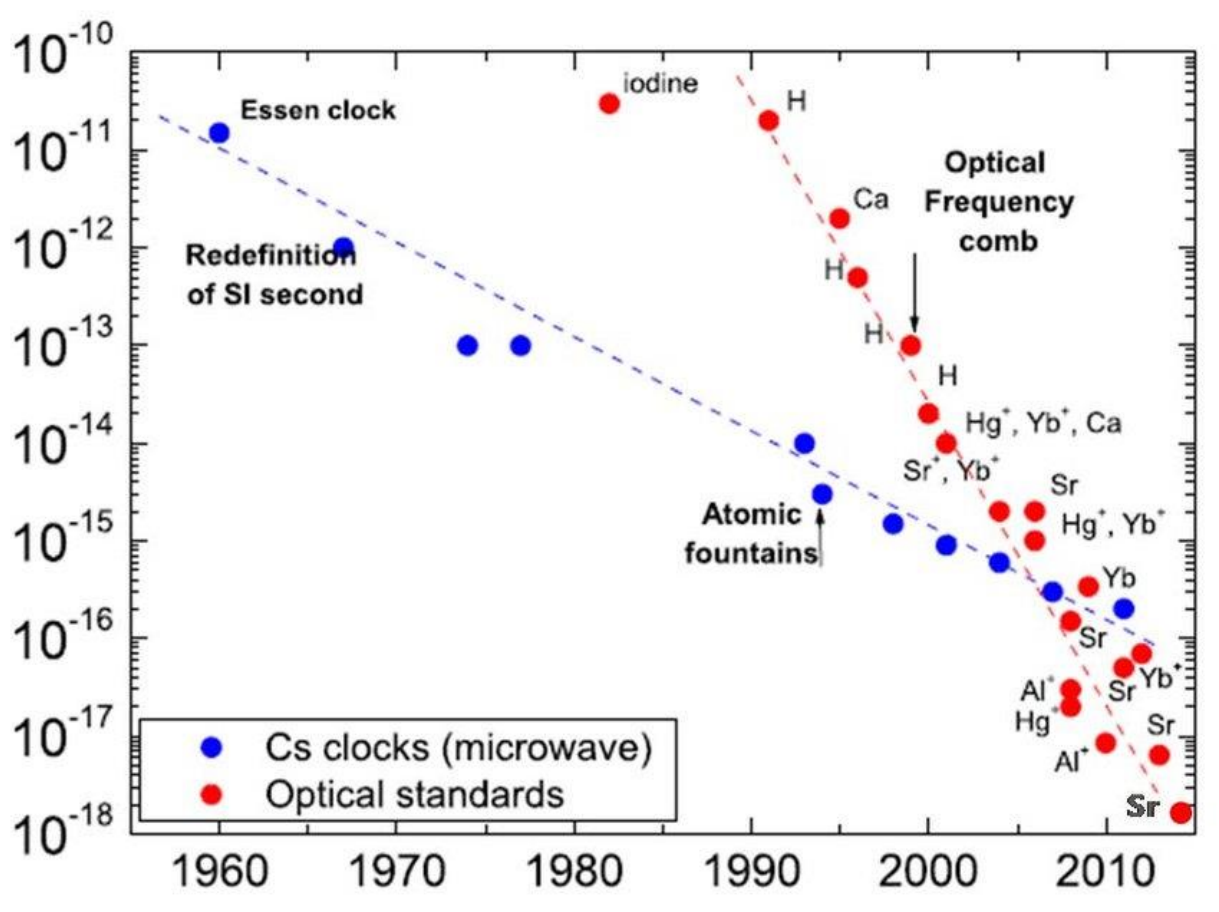


[8, dnasoftware]

Clock instability ~ relative uncertainty



History of timekeeping



[10, IEEE, Arias et. Al.]

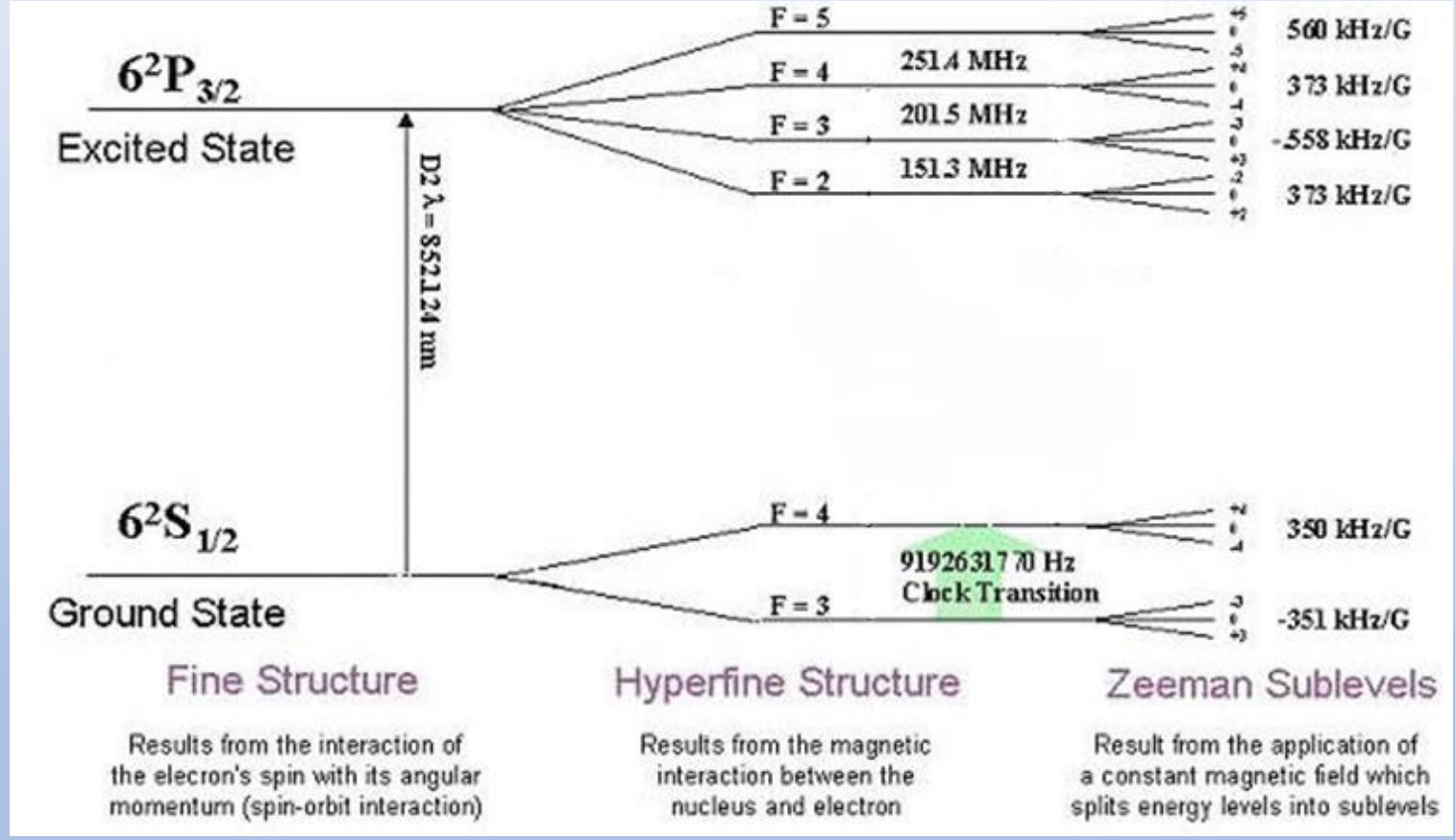
"The second is defined as being equal to the time duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine-levels of the fundamental unperturbed ground-state of the caesium-133 atom"

- International Bureau of Weights and Measures

2019, NIST, Al^+

How does an atomic clock work?

- Interaction between light and internal electronic states of an atom
- In the case of Cs-133: hyperfine-transition is probed by microwaves
- $J = {}^{1}/_{2}$
- $I = {}^{7}/_{2}$

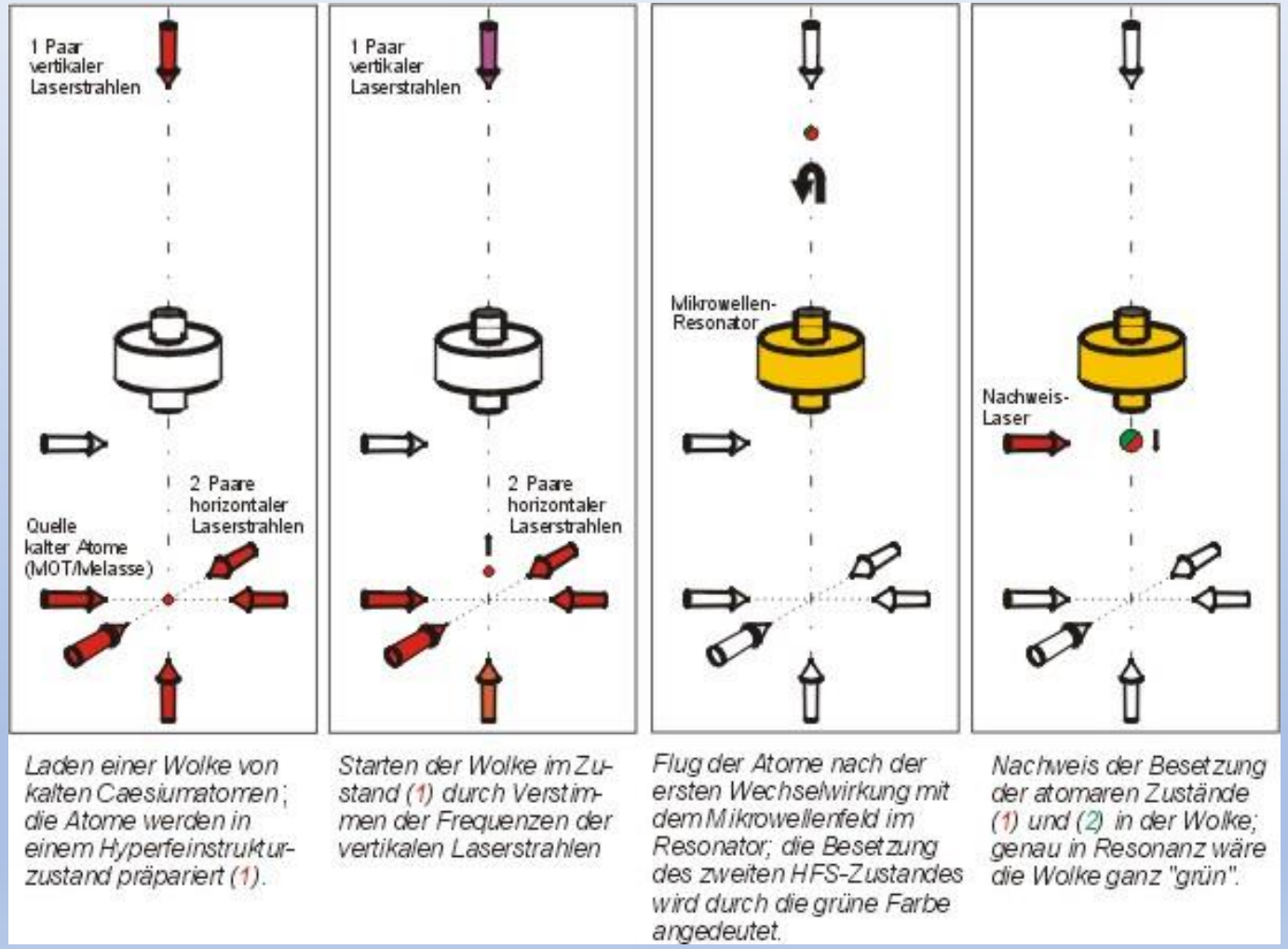


[11, PHARAO, Moric et.al.]

Example: CSF1 clock of PTB

[12, PTB, CSF1 and CSF2]

“9.192.631.770 oscillations”

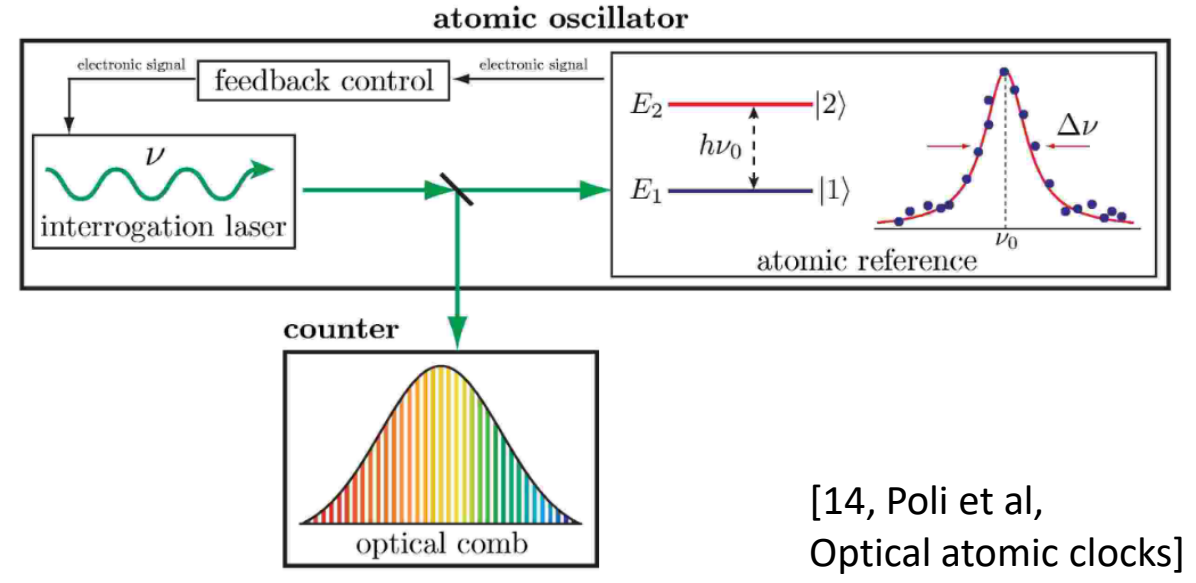


[13, PTB]

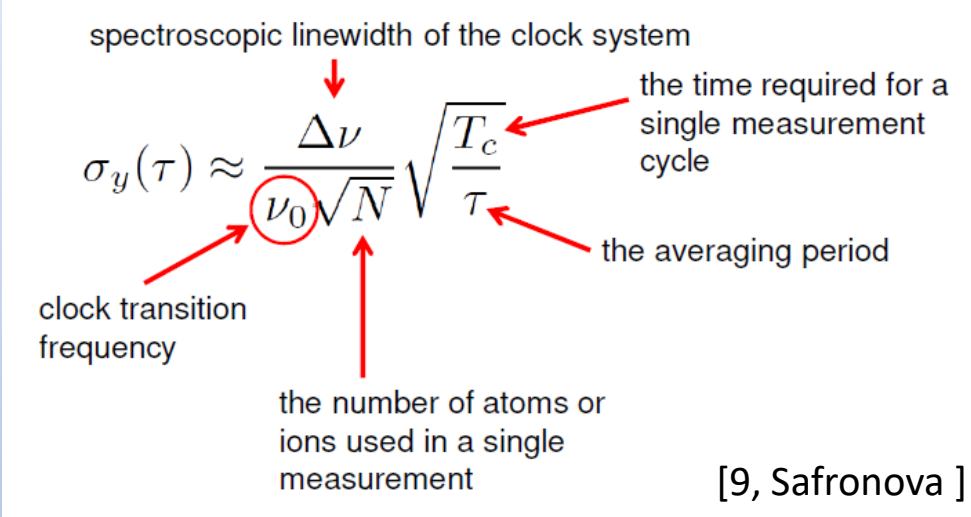
Discussion

Optical Clocks

- Transitions with optical frequencies $\sim 10^{15}$Hz
- Only measurable by **frequency comb**



[14, Poli et al, Optical atomic clocks]

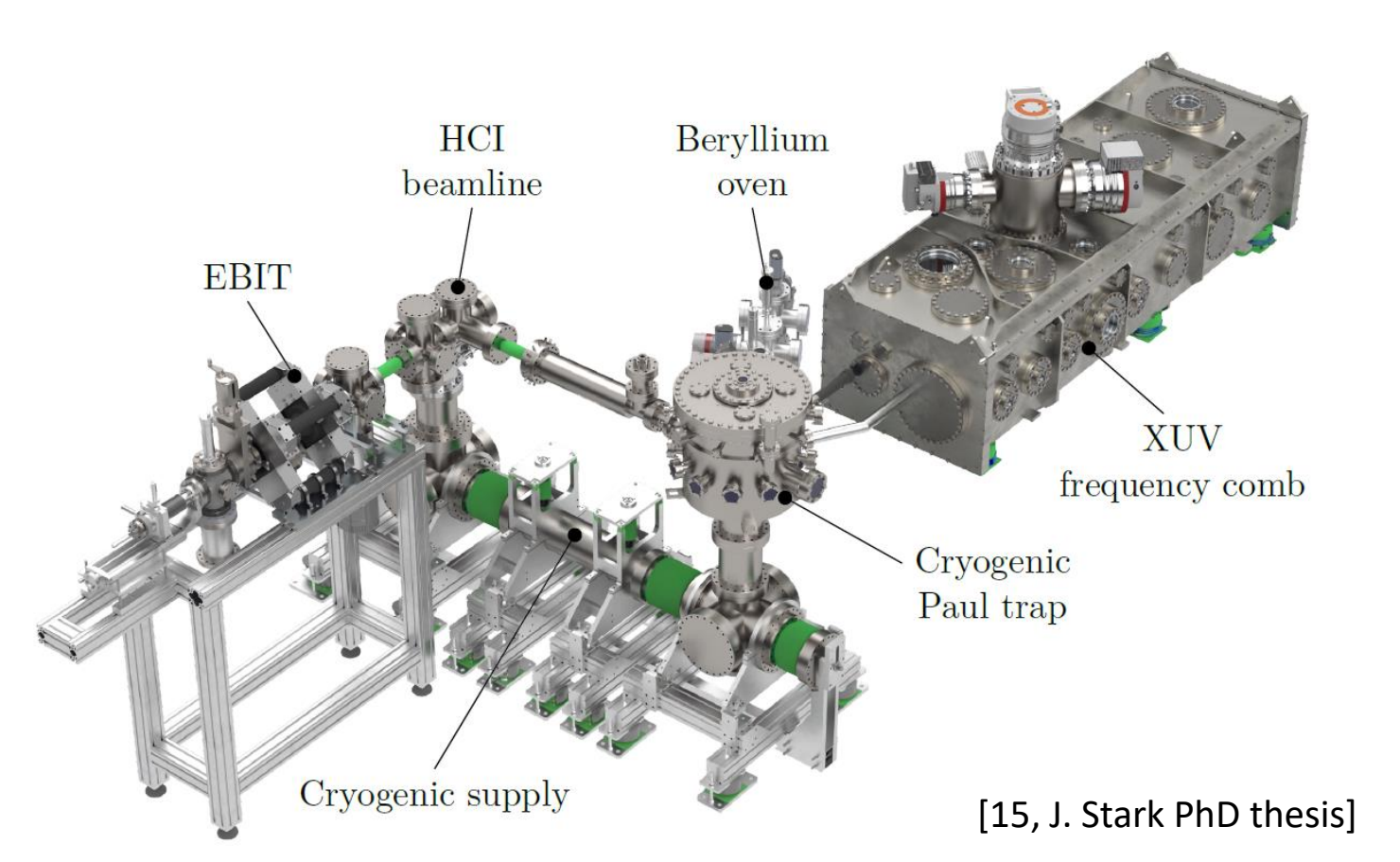


[9, Safronova]

Highly Charged Ions (HCI)

- Less sensitive for perturbations
- Dipole forbidden transitions in the optical regime
  - Fine and Hyperfinetransitions
  - levelcrossings
- Very sensitive for possible α-variation
- Relative Change of $\frac{\dot{\alpha}}{\alpha} \sim 10^{-19}$ per year ?

CryPTEx-2 at MPIK



[15, J. Stark PhD thesis]

- Spectroscopy of cold HCI in the XUV
- Candidate for new frequency standards
- Testing QED/SM

Applications

- International Atomic Time (TAI)
- Coordinated Universal Time (UTC)
- Global Positioning System (GPS)
- Geodesy
- PHARAO
- Goal: smaller, cheaper, portable, energy efficient and more stable

[16, googleapis]

Summary

- We can measure time very well

  → achieved **relative uncertainty** $\sim 10^{-19}$
- Definition of 1s is based on a hyperfinetransition of Caesium
- Next generation of **optical clocks**
- Many applications e.g. navigation systems
- Related experiments such CryPTEx-2
- Testing **Standard Model**, **Special** and **General Relativity**

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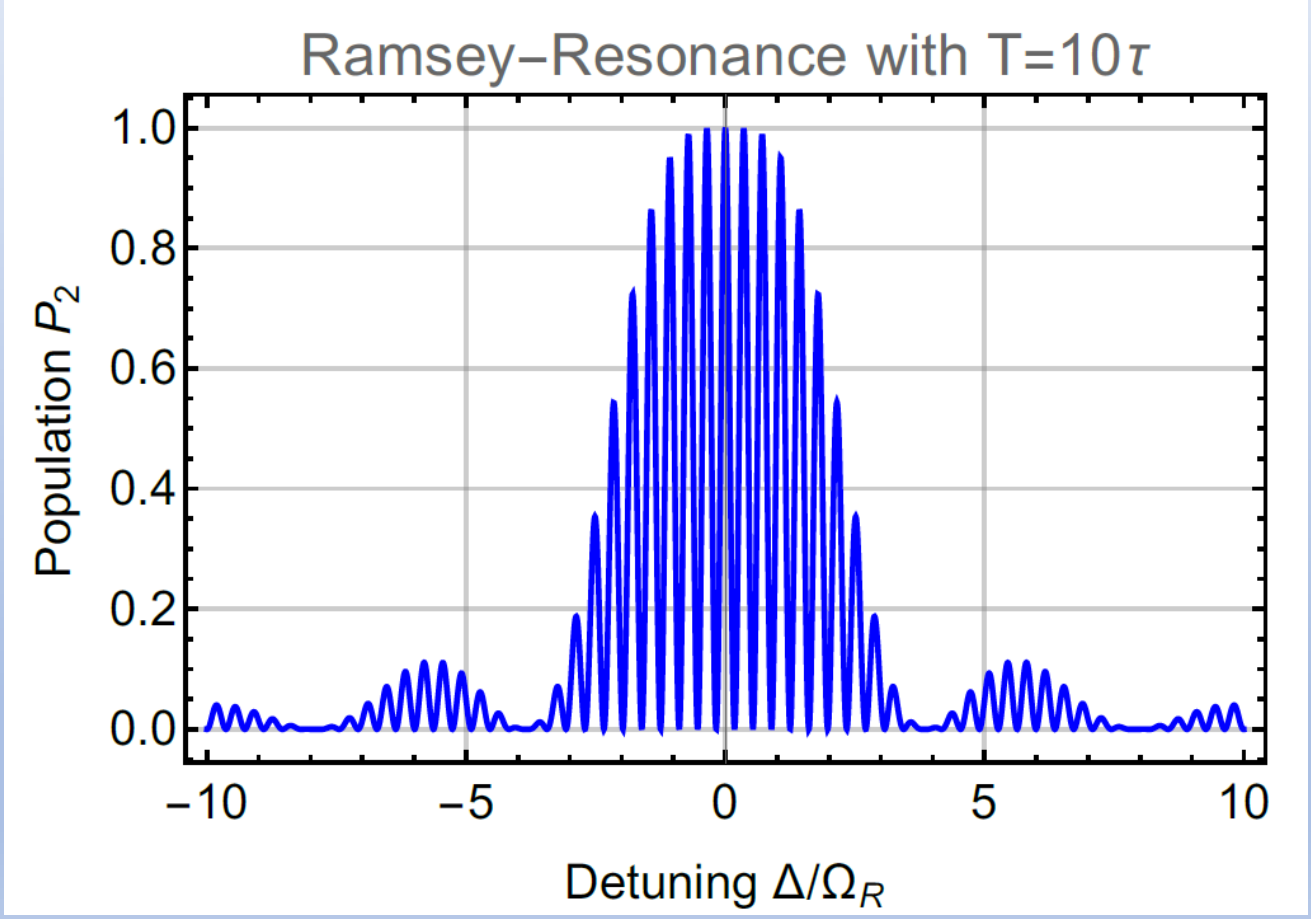
[1, from Pyramidtimessystems]

Sources of figures

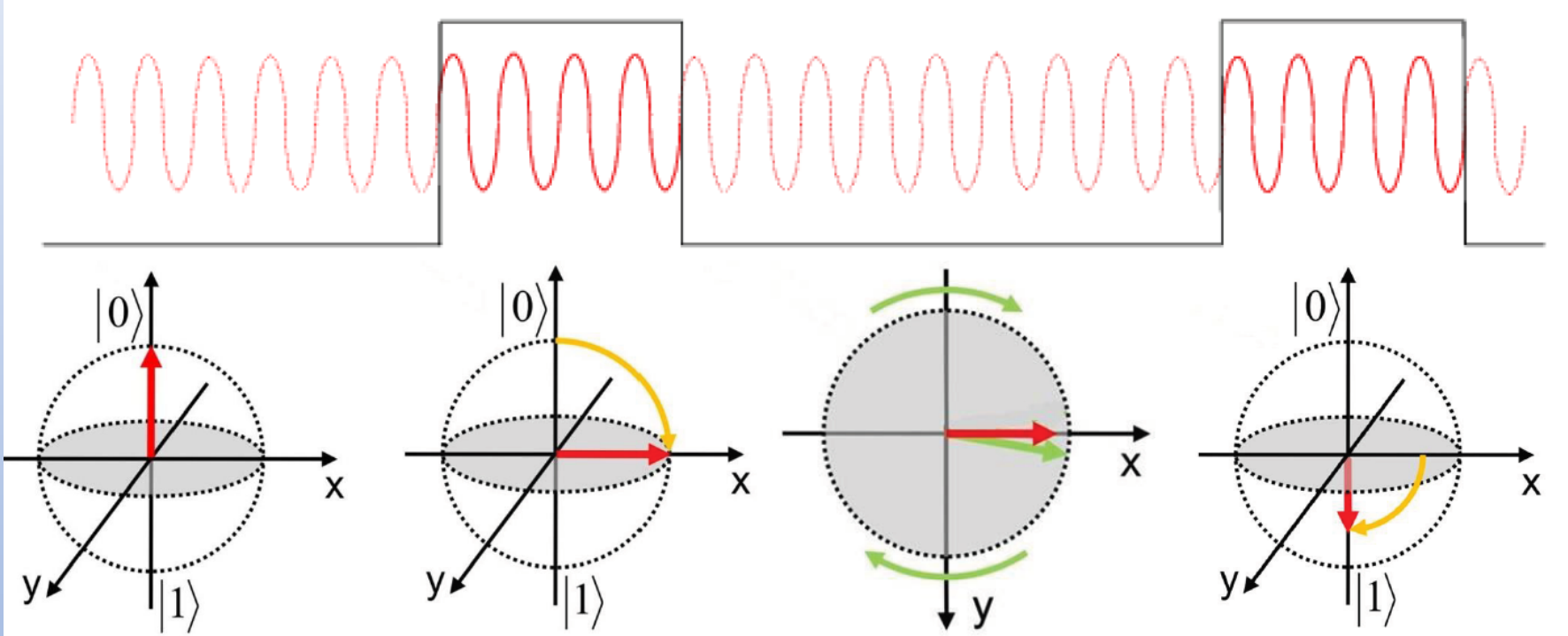
- [1] https://www.pyramidtimesystems.com/media/wysiwyg/atomic_clock_1.jpg
- [2] https://www.kidpid.com/what-is-time-travel-is-it-possible/
- [3] Chou CW, Hume DB, Rosenband T, Wineland DJ. Optical clocks and relativity. Science. 2010 Sep 24;329(5999):1630-3. doi: 10.1126/science.1192720. PMID: 20929843.
- [4] https://useum.org/artwork/Astronomical-Observations-the-Moon-Donato-Creti-1711
- [5] https://uhren-hidding.de/en/startseite/258-riefler-precision-pendulum-clock.html
- [6] https://upload.wikimedia.org/wikipedia/commons/thumb/0/03/Clock_lock.jpg/1024px-Clock_lock.jpg
- [7] https://en.wikipedia.org/wiki/Accuracy_and_precision#/media/File:Accuracy_and_precision.svg
- [8] https://www.dnasoftware.com/our-products/copycount-qpcr-analysis-copynumber/precision-and-accuracy/
- [9] Atomic Clock, presentation by Marianna Safronova, University of Delaware
- [10] The 50th Anniversary of the Atomic Second - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Reported-accuracy-of-atomic-transitions-from-BIPM-website_fig1_324253222 [accessed 10 May, 2021]
- [11] On-ground characterization of the cold atoms space clock PHARAO - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/The-energy-levels-of-cesium-energy-level-used-for-clock-transition-and-cooling_fig5_281534634 [accessed 30 Apr, 2021]
- [12] https://www.ptb.de/cms/fileadmin/_processed_/csm_4_-_Uhren_13bfebd041.jpg
- [13] https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_4/4.4_zeit_und_frequenz/4.41/sequcsf1.jpg
- [14] Poli, Nicola, et al. "Optical atomic clocks." *La Rivista del Nuovo Cimento* 36 (2013): 555-624.
- [15] Julian Stark. “An Ultralow-Noise Superconducting Radio-Frequency Ion Trap for Frequency Metrology with Highly Charged Ions”. Diss. Ruprecht-Karls-Universität,Heidelberg, 2020.
- [16] https://storage.googleapis.com/geotab_wfm_production_cms_storage/CMS-Images-production/Blog/NA/_2020/May/GPS-update/blog-what-is-gps-hero@2x.png

Appendix A – Ramsey Fringe Pattern



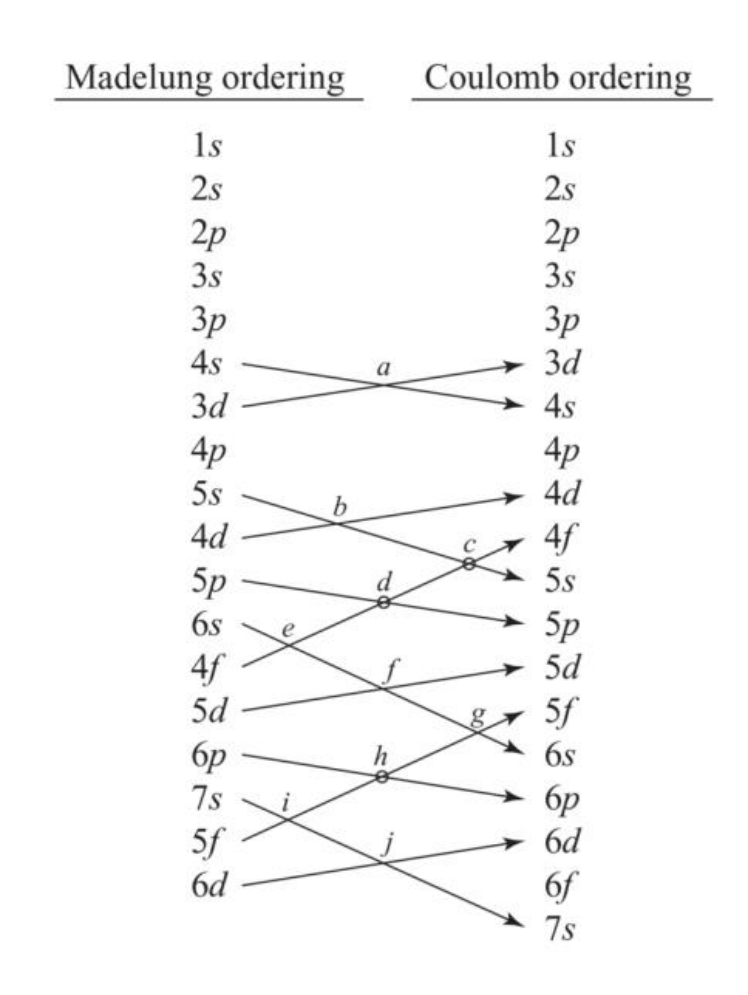
http://www.phys.cwru.edu/events/mppl/Hanneke/MPPL_clocks.pdf

Appendix B – Ramsey Resonance method



From: R. Gross: Control of quantum two-level systems (2013).

Appendix C - Levelcrossings



https://www.quantummetrology.de/fileadmin/quest/quest_institute/Projects/HCI/level_crossing.png