

Building a Quantum Experiment: Searching for Dark Matter with Atomic Clocks

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Physikzentrum Bad Honnef

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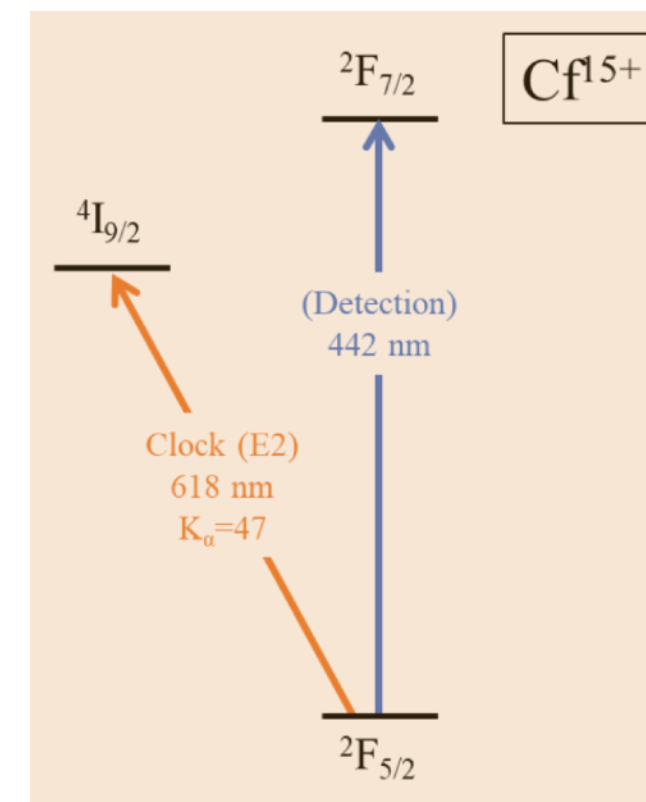
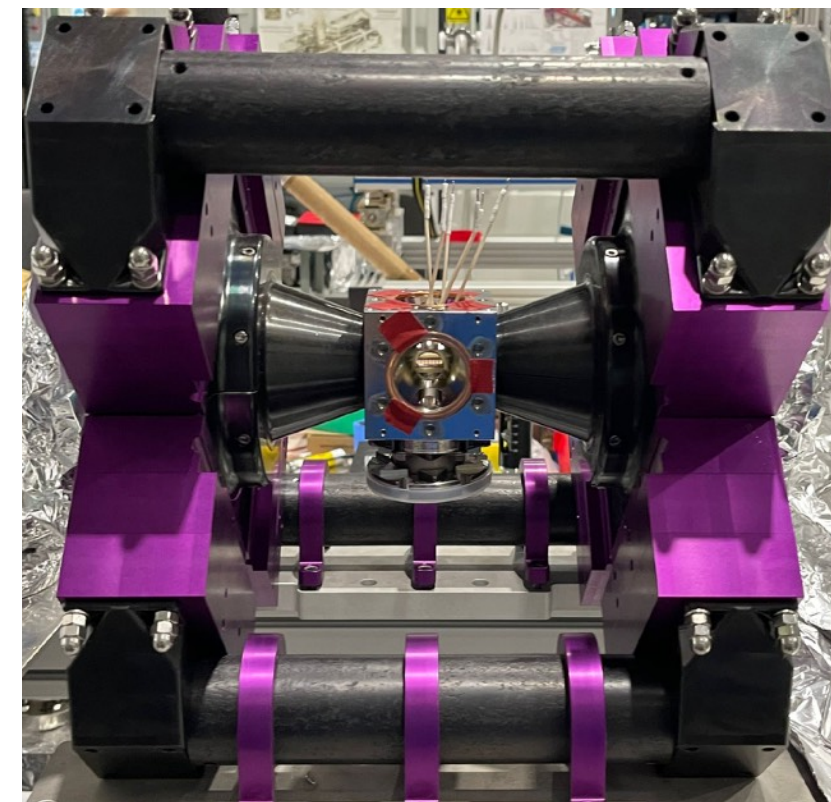
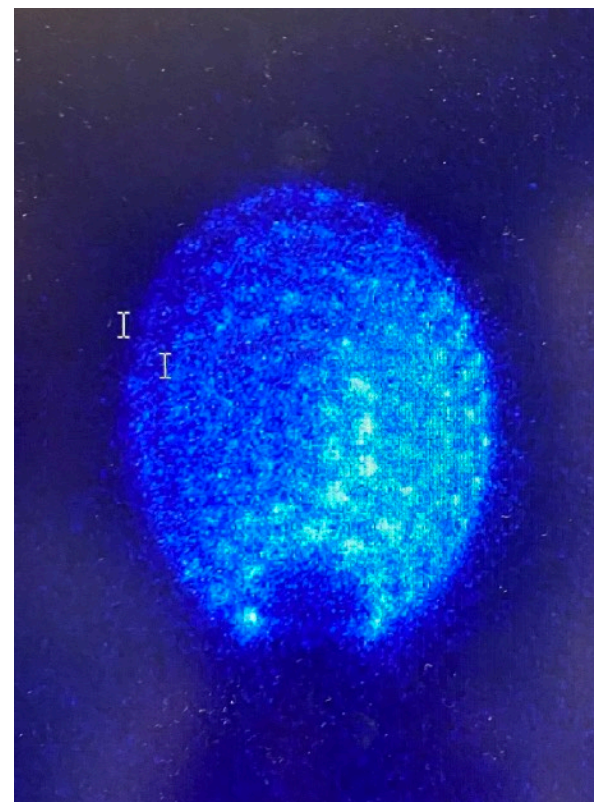
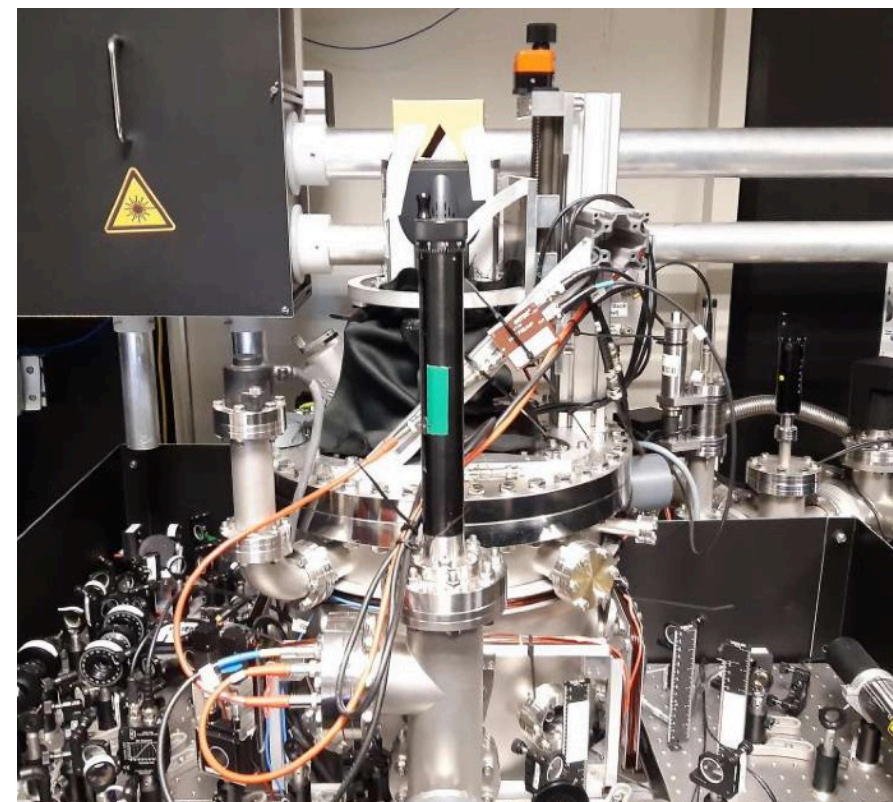
Deutsches Elektronen-Synchrotron (DESY) / Humboldt-Universität zu Berlin

September 10, 2026



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Center for
Quantum Technology
and Applications

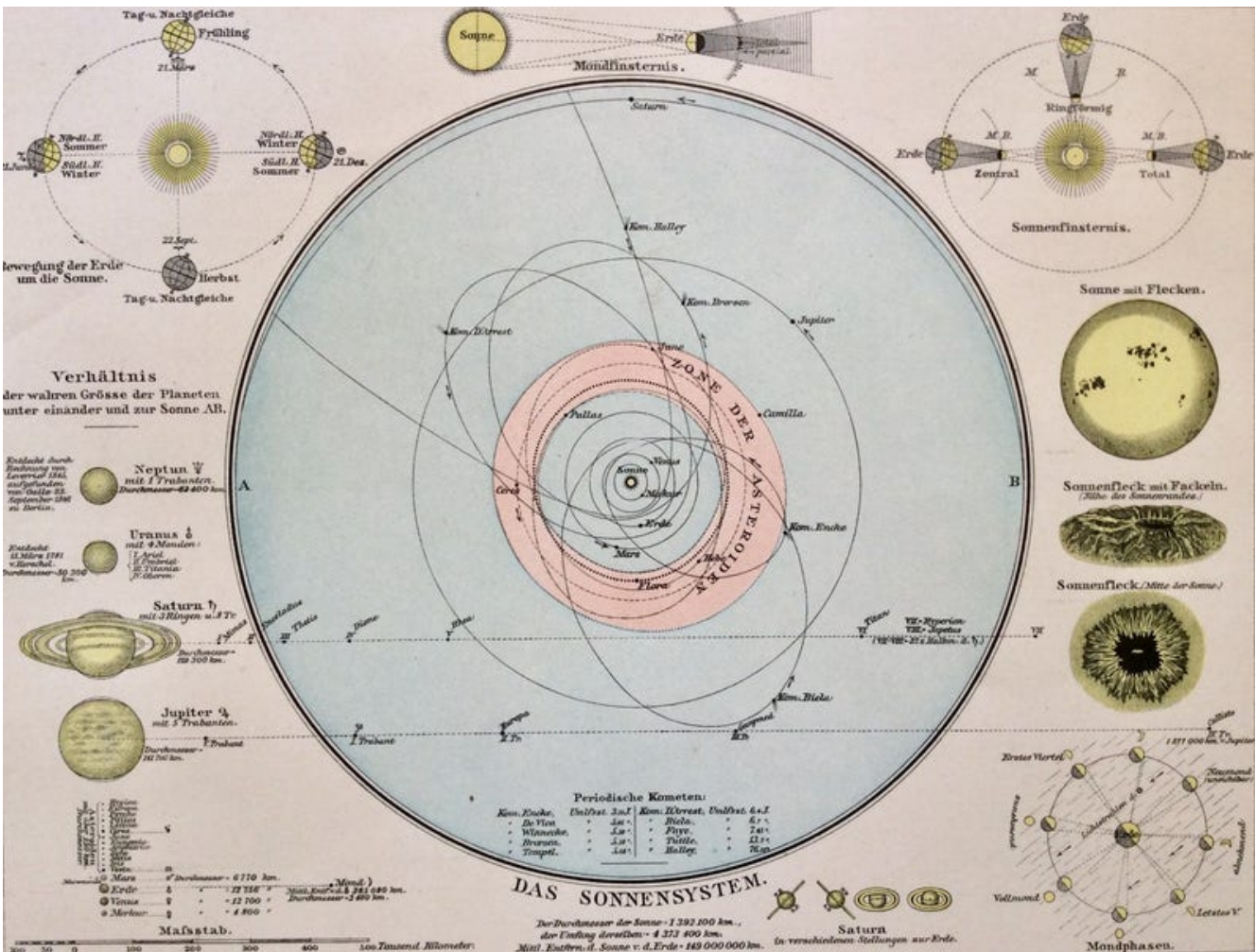


Outline

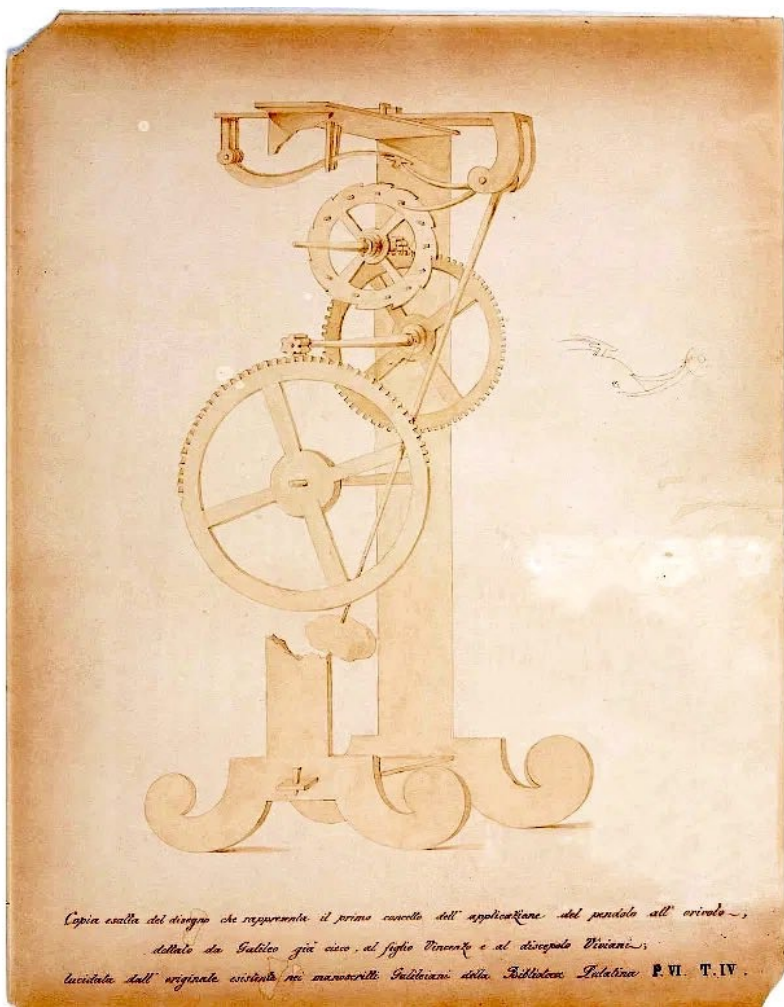
- Clocks in History
- Clock Basics
- What makes a good clock?
- Physics with a Clock
- Networks of Clocks
- The Future?

Revolutionary Clocks for Science

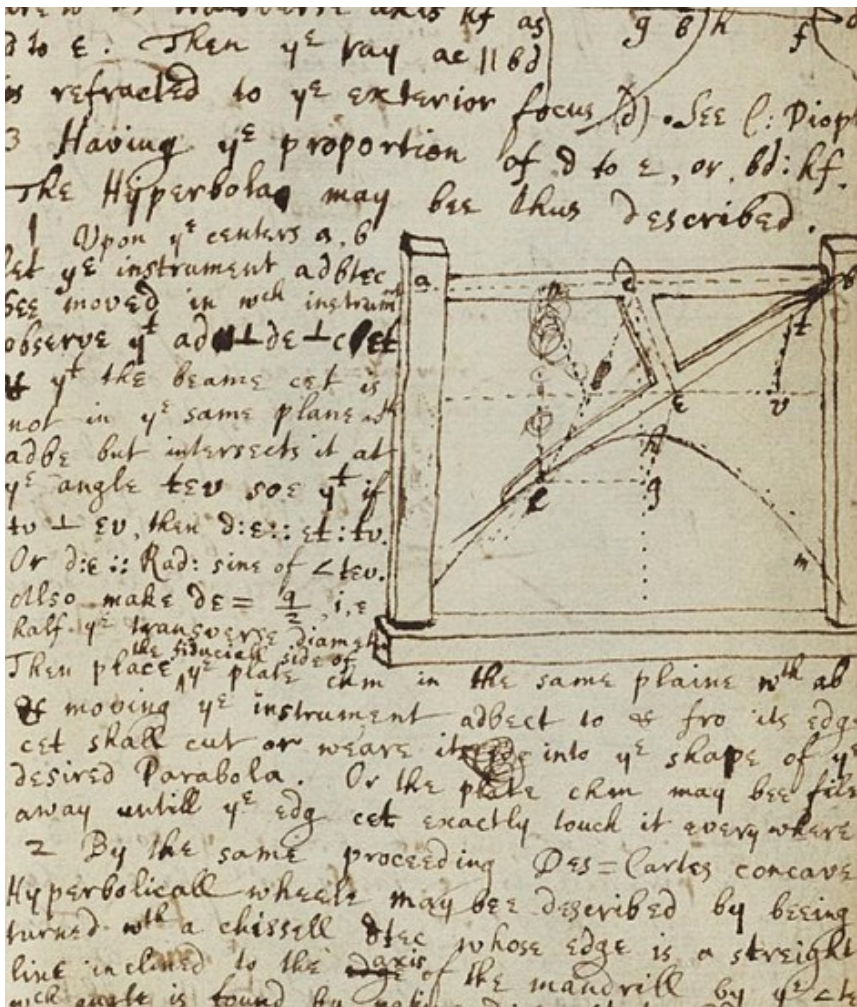
- Galileo proposed the pendulum clock - to fix longitude for astronomical observations (1637)
- Huygens made the first pendulum clocks (1656); essential for astronomy, navigation, mapping the earth
- Newton used pendulum clocks for gravity experiments (1687)
- Maxwell proposed using atoms as natural standard units of time (and length) in 1879
- Many advances driven by science needs/discoveries, which in turn enables new science



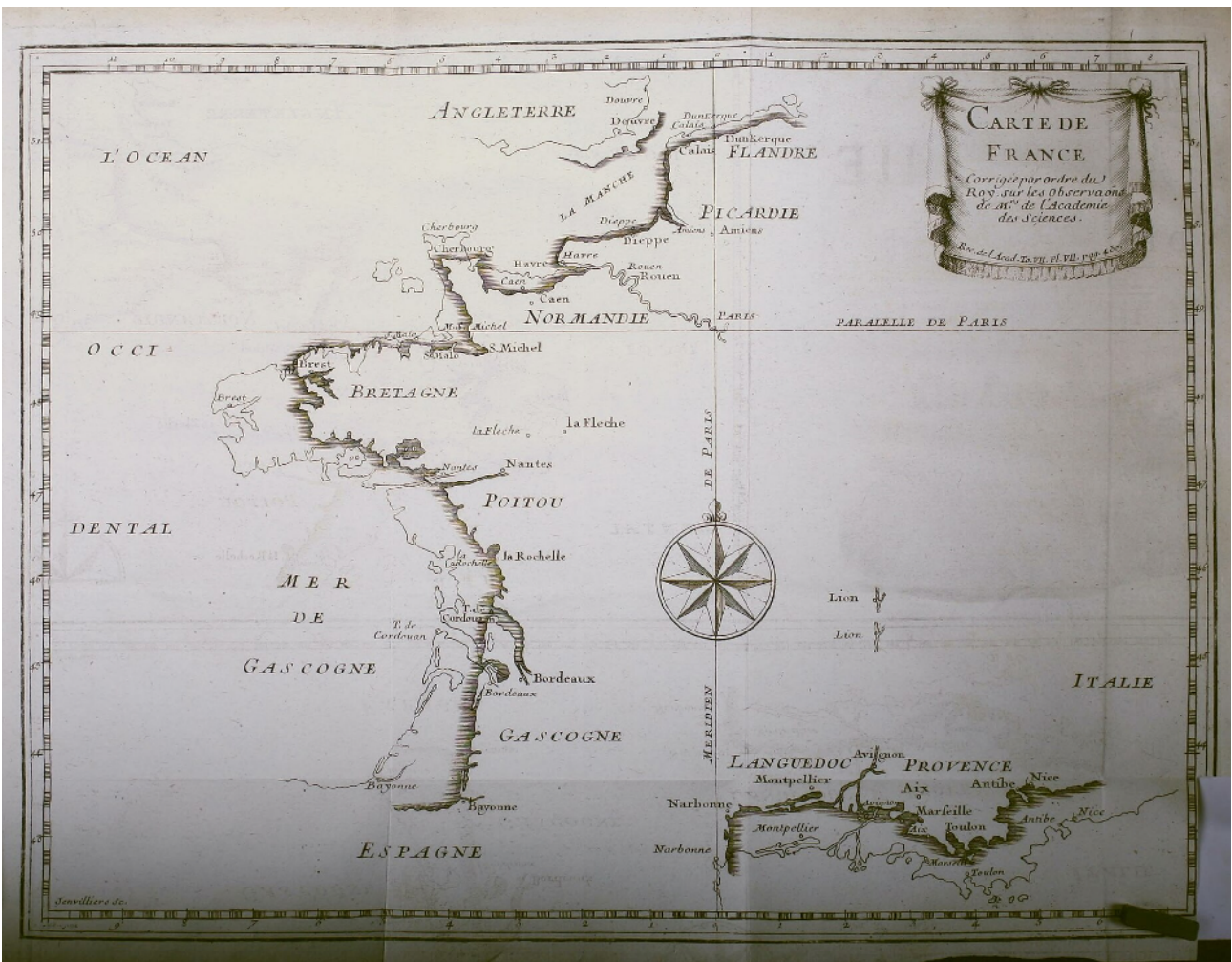
Astronomical predictions for the Solar System



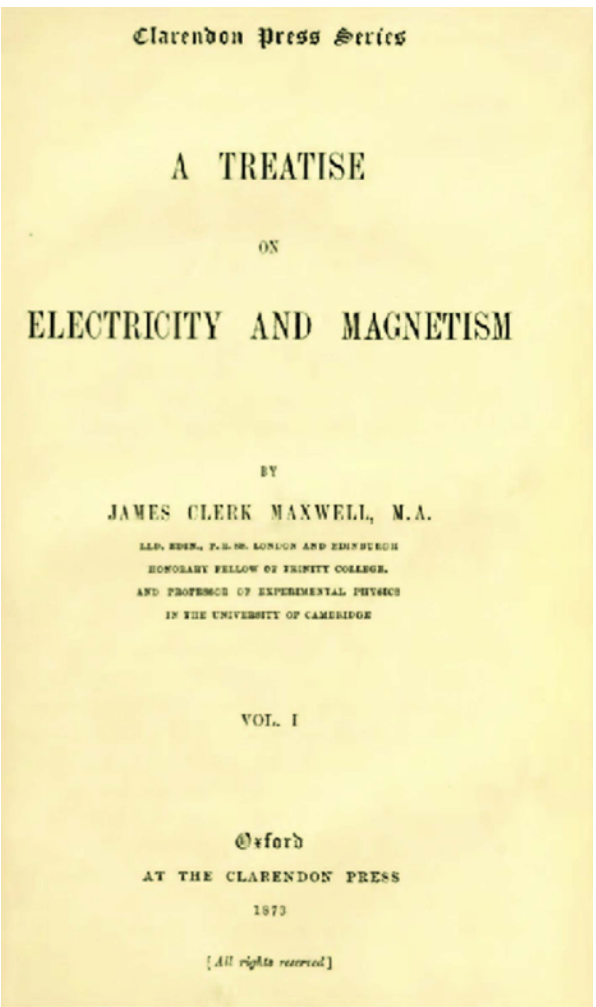
Galileo's pendulum clock design



Newton's tests of gravity



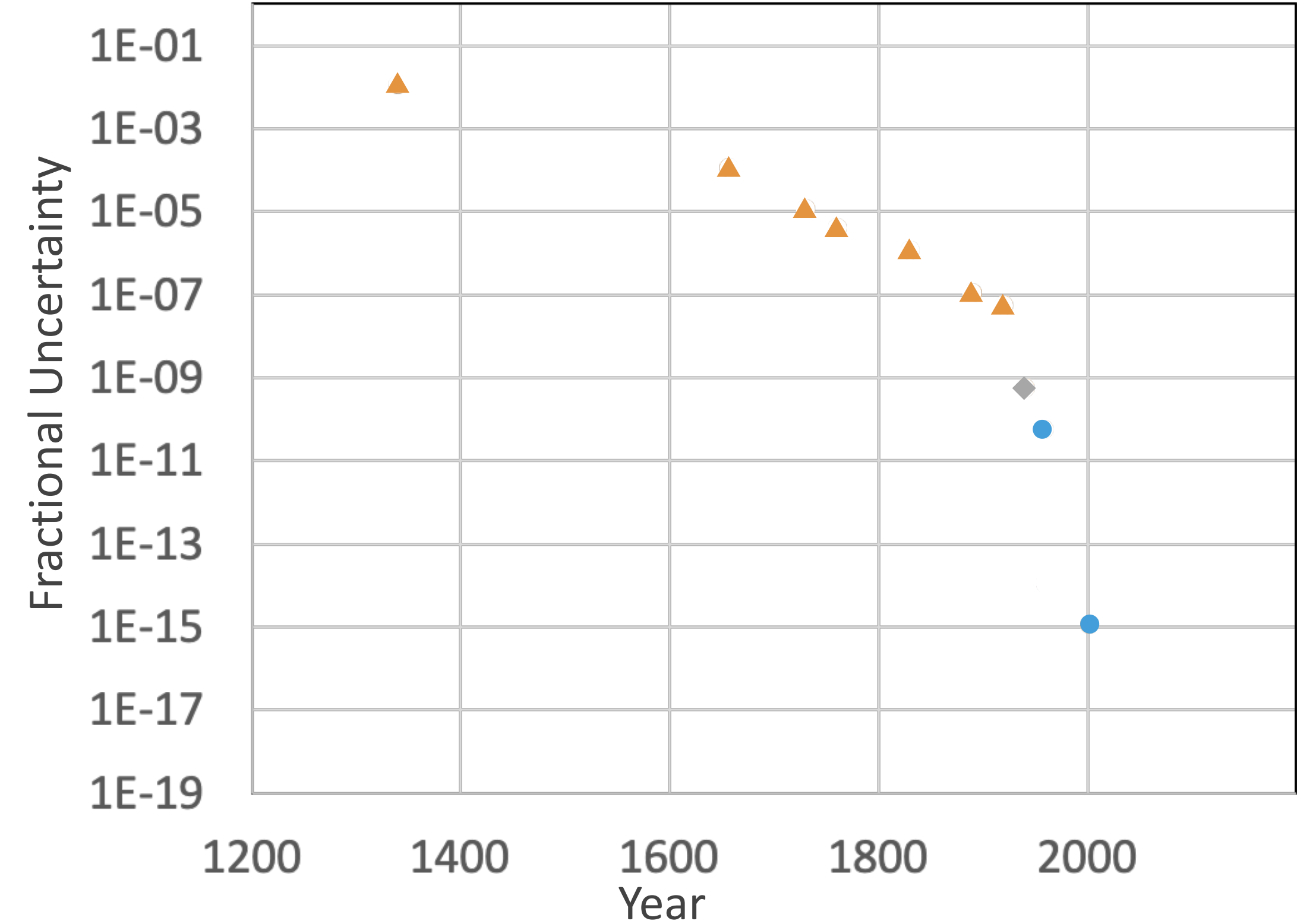
Remapping of France with pendulum clocks



Maxwell: atoms as clocks?

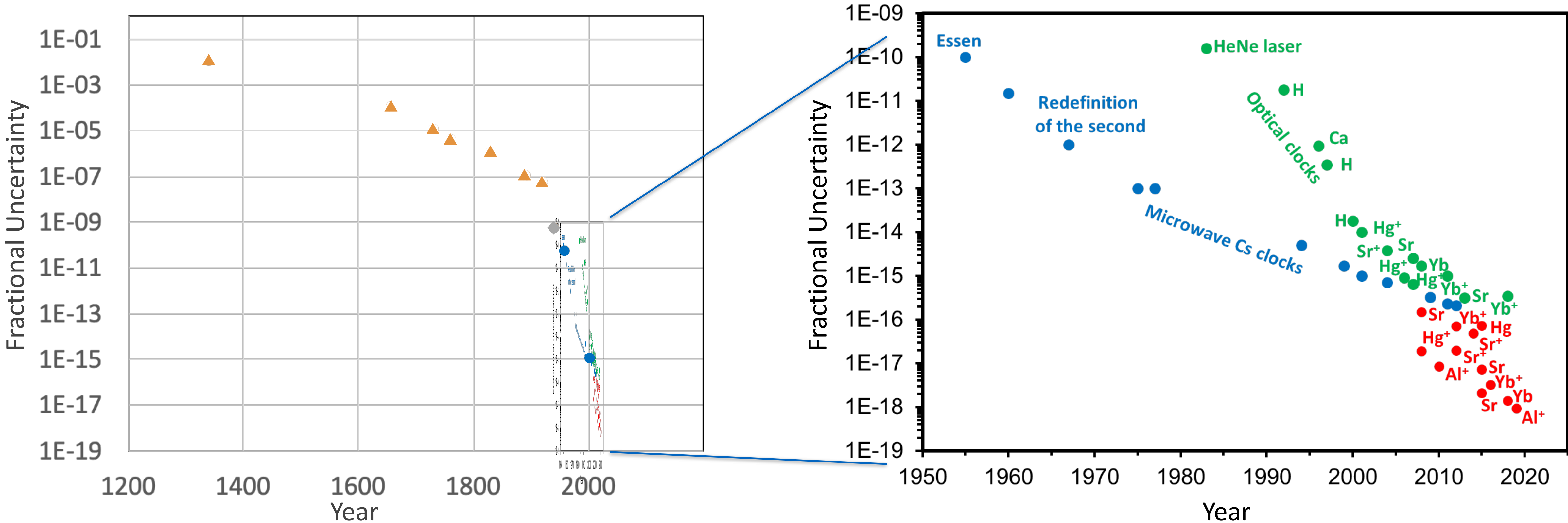
Fractional Uncertainty of Clocks vs. Year

- Mechanical ▲
- Crystal ◆
- Atomic (microwave) ●



Fractional Uncertainty of Clocks vs. Year

- Mechanical ▲
- Crystal ◆
- Atomic (microwave) ●
- Atomic (optical in Hz) ●
- Atomic (optical w/ estimated uncertainty) ●

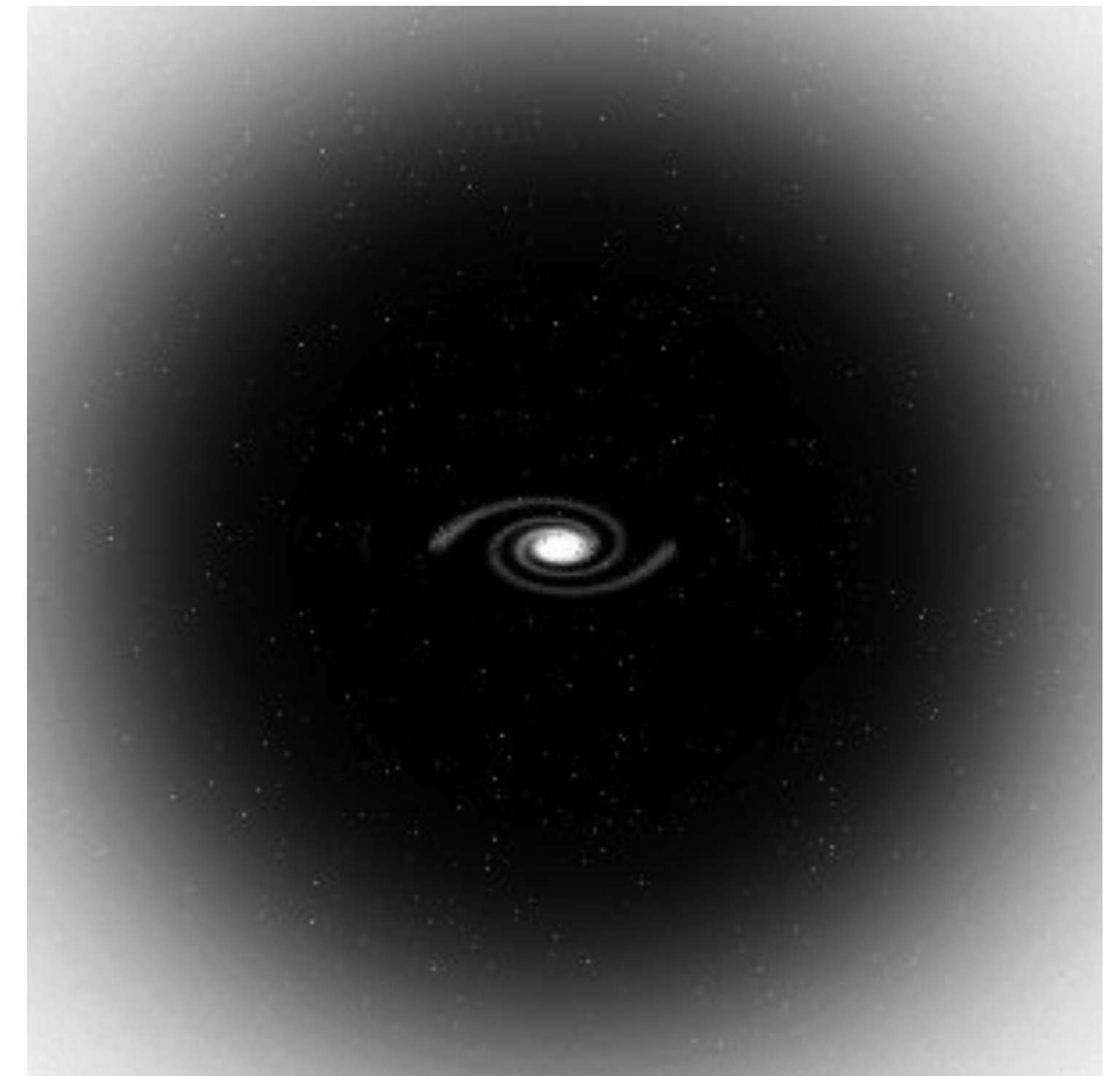
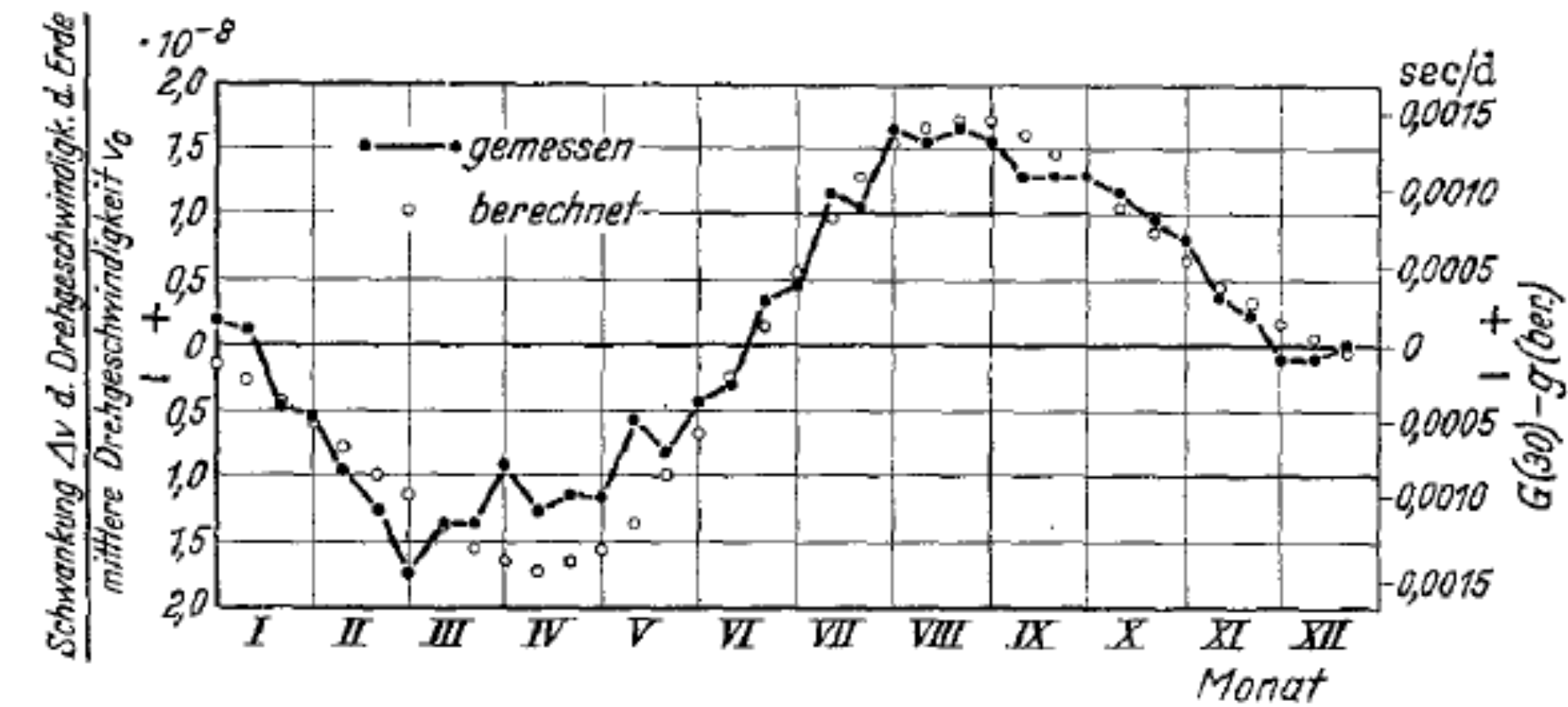


What Science can you do with an Optical Atomic Clock?

Q: What (science) can you do with such a good clock??

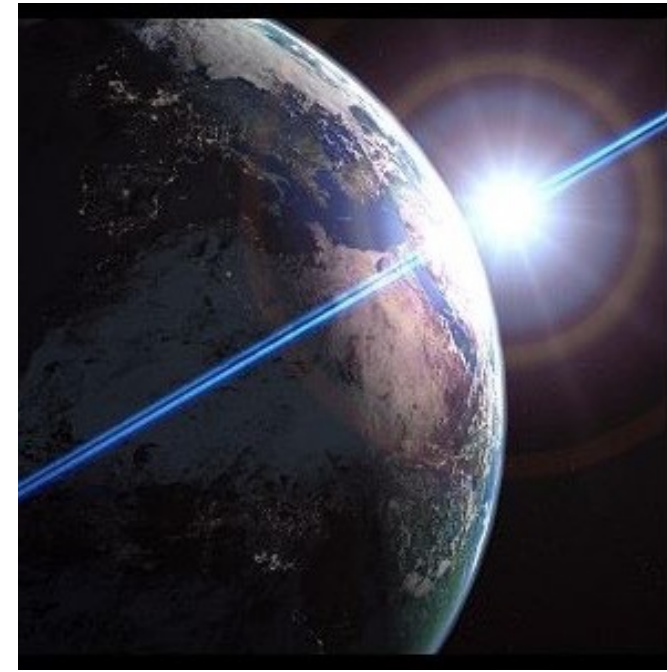
A: Discover new stuff!

- Ultra-light Dark Matter, topological defects Dark Matter
- Local Lorentz Invariance
- 5th Forces
- Gravitational redshift
- Change in fundamental constants
- Dark Energy
- Gravitational Waves
- Equivalence Principle
- ...



Clock Basics

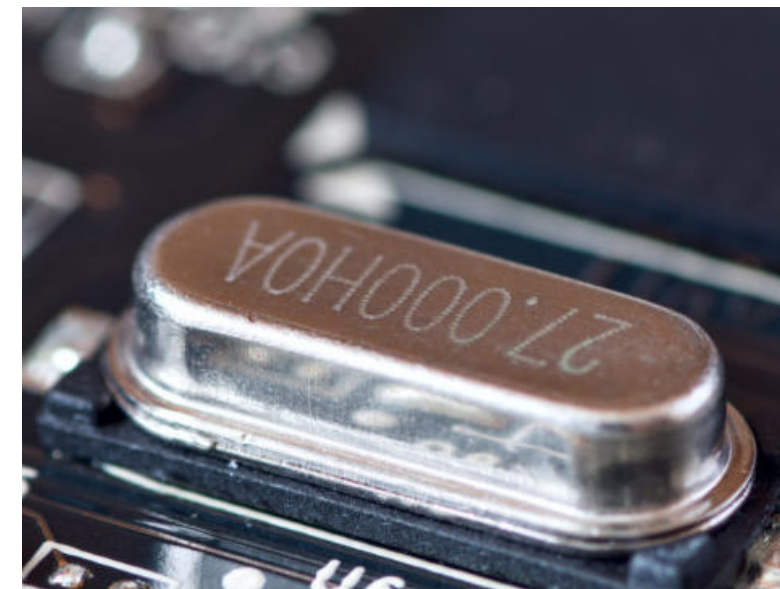
- Clock parts: **oscillator** and **counter**
- Both parts are important, true especially for atomic clocks
- Earth is imperfect oscillator, same for man-made resonators
- Many different atoms available, and they are all the same



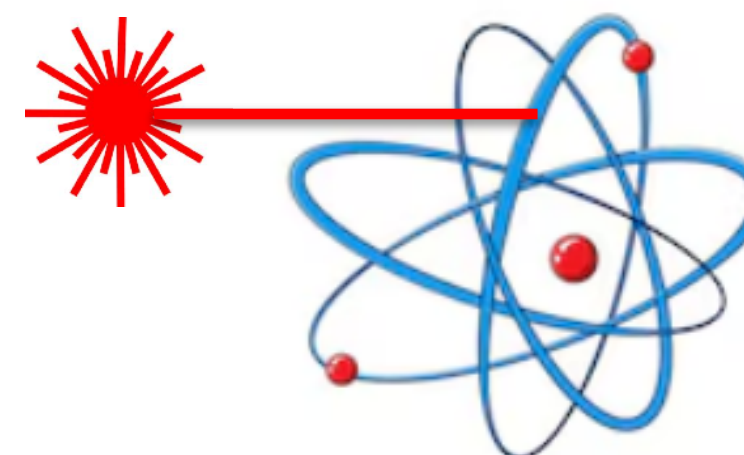
minutes



seconds



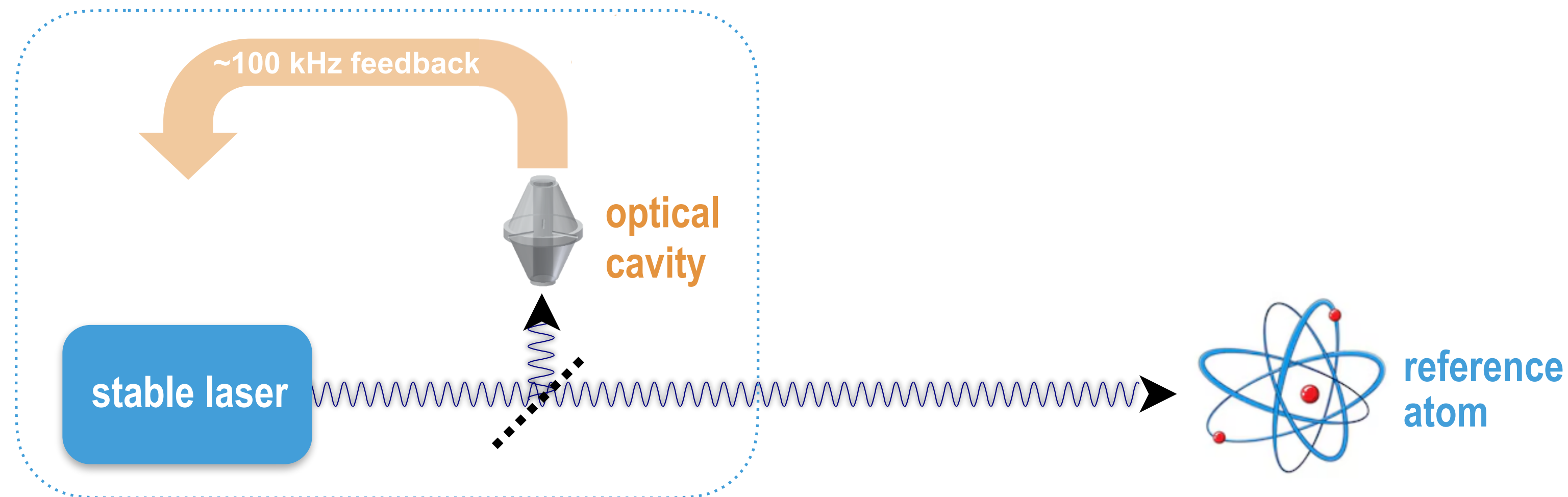
microseconds



< nanoseconds

Optical Atomic Clocks

- Laser for oscillator, usually a narrow frequency around atomic transition
- Ultra-stable laser needed (e.g. referenced to a cavity)

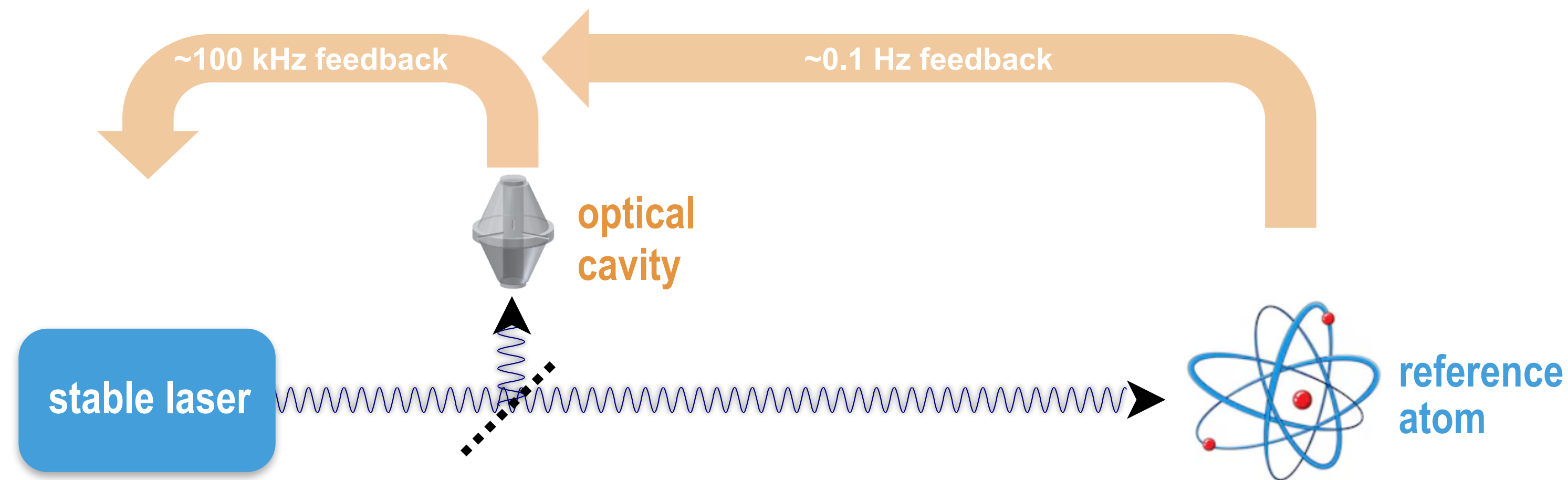
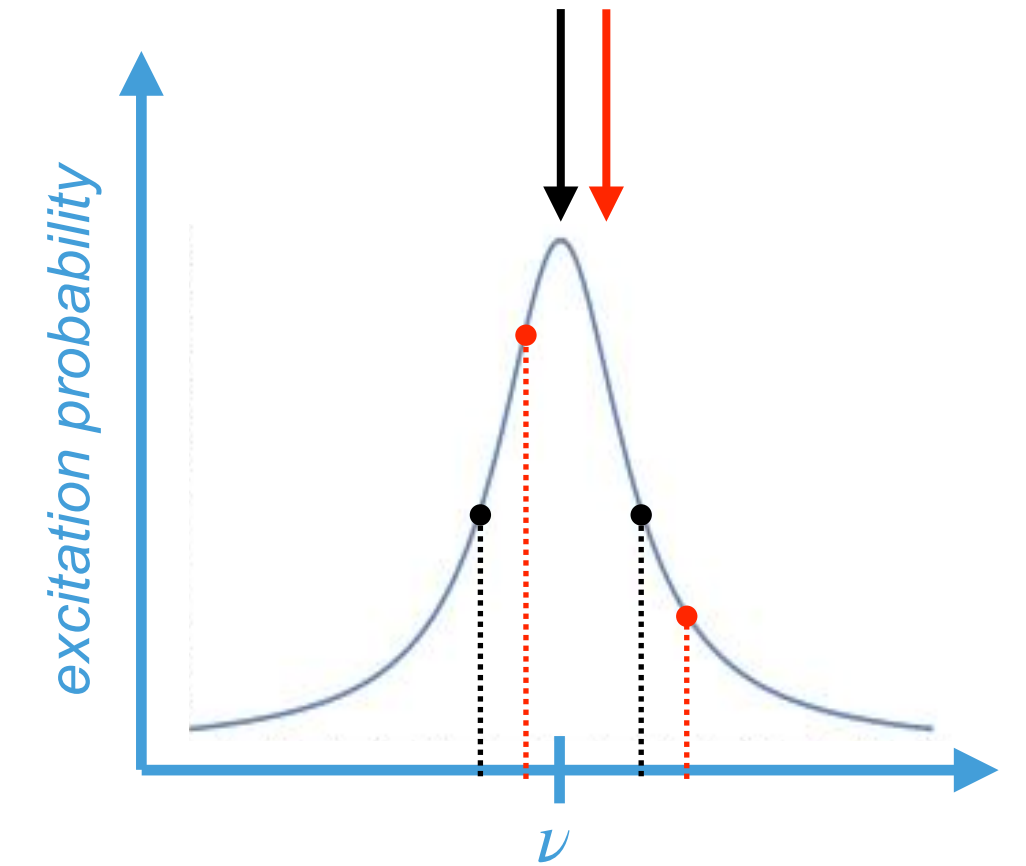


ultra-stable, narrow laser:

$$\Delta\nu \approx \mathcal{O}(1 \text{ Hz})$$

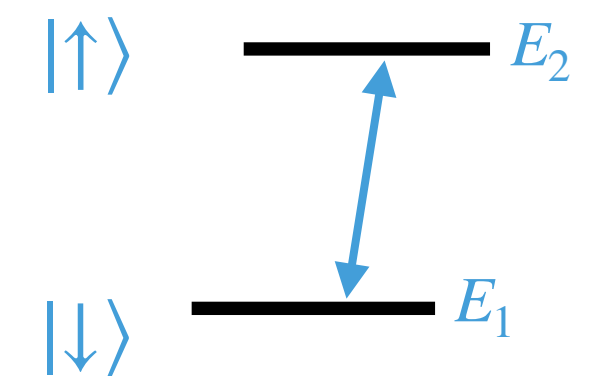
Optical Atomic Clocks

- Laser for oscillator, usually a narrow frequency around atomic transition
- Ultra-stable laser needed (e.g. referenced to a cavity)
- Locked to atomic transition: frequency detuned/offset (e.g. $\pm\Delta\nu$) to find max



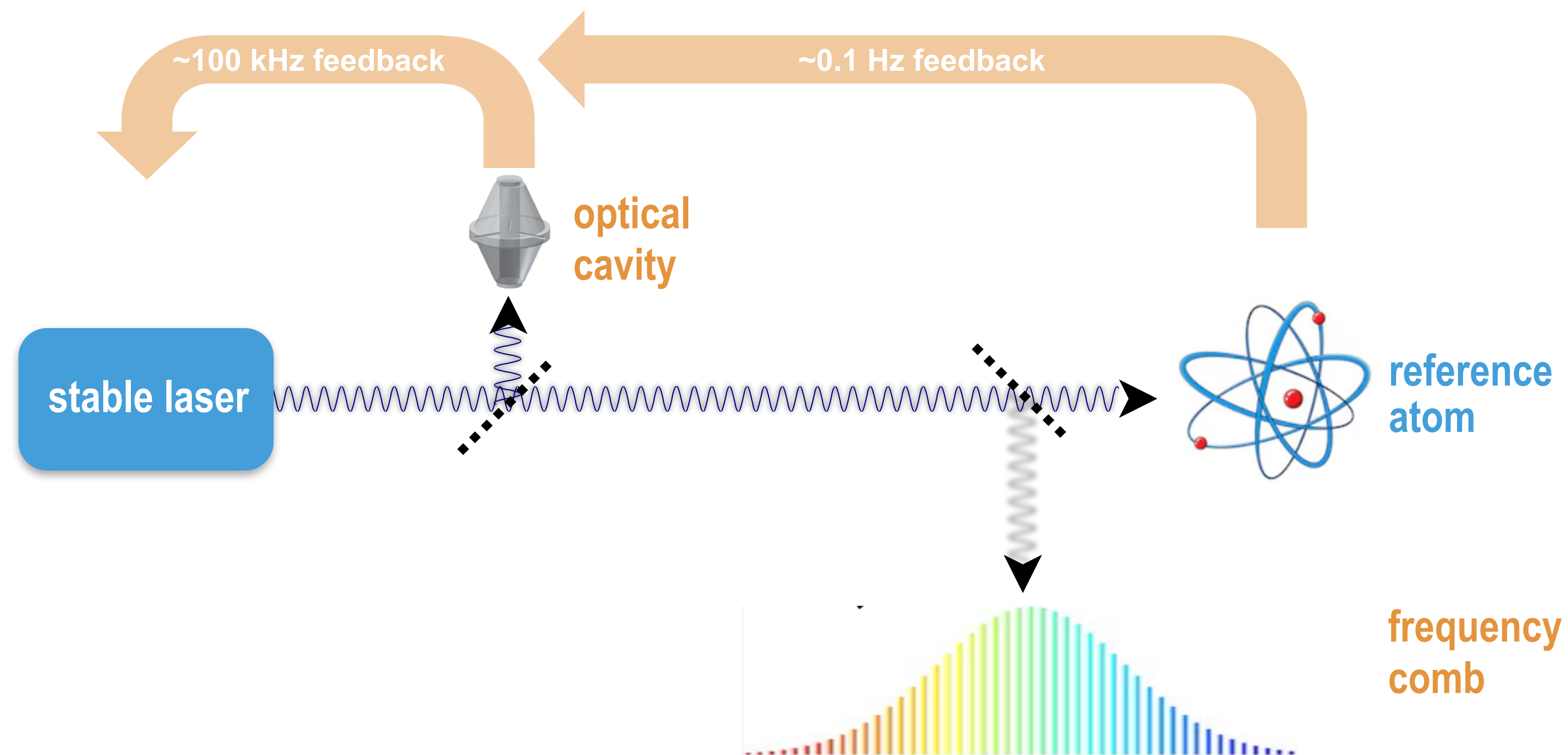
optical ν :

$$\nu = \frac{E_2 - E_1}{h} \approx \mathcal{O}(10^{15} \text{ Hz})$$



Optical Atomic Clocks

- Laser for oscillator, usually a narrow frequency around atomic transition
- Ultra-stable laser needed (e.g. referenced to a cavity)
- Locked to atomic transition: frequency detuned/offset (e.g. $\pm\Delta\nu$) to find max
- Frequency comb used to link optical frequencies to countable microwave



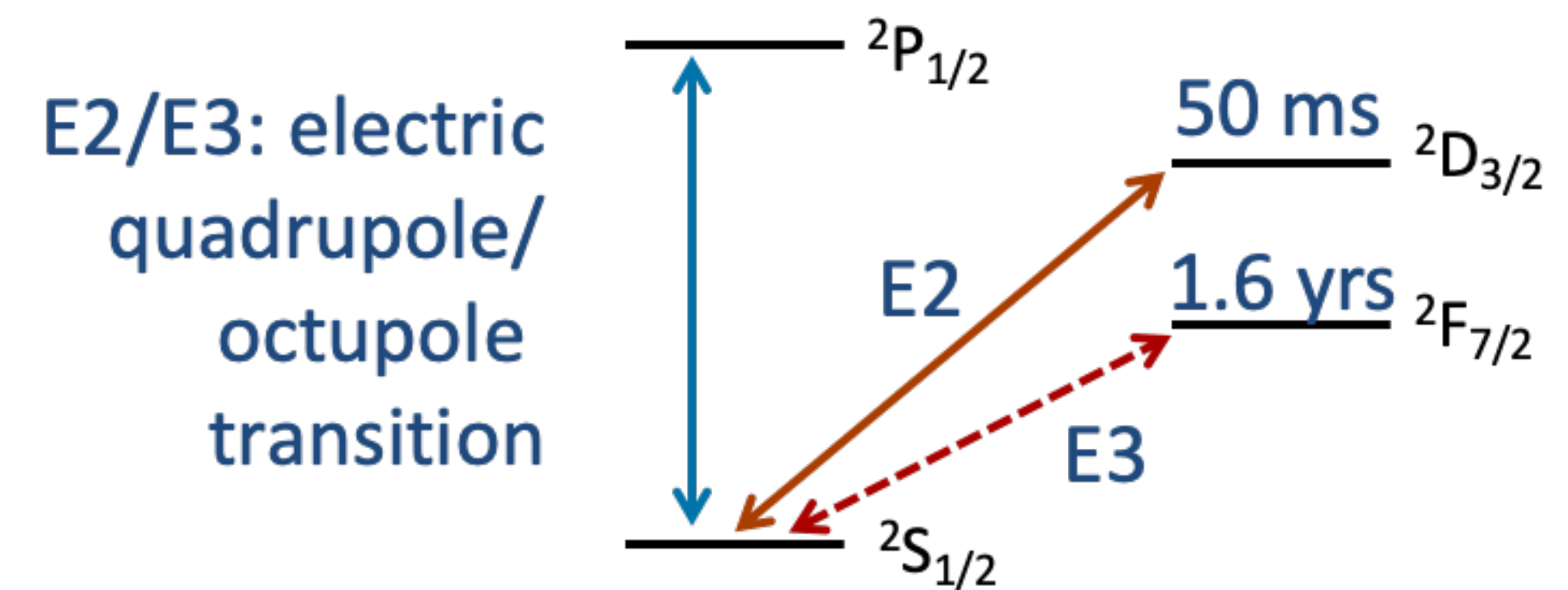
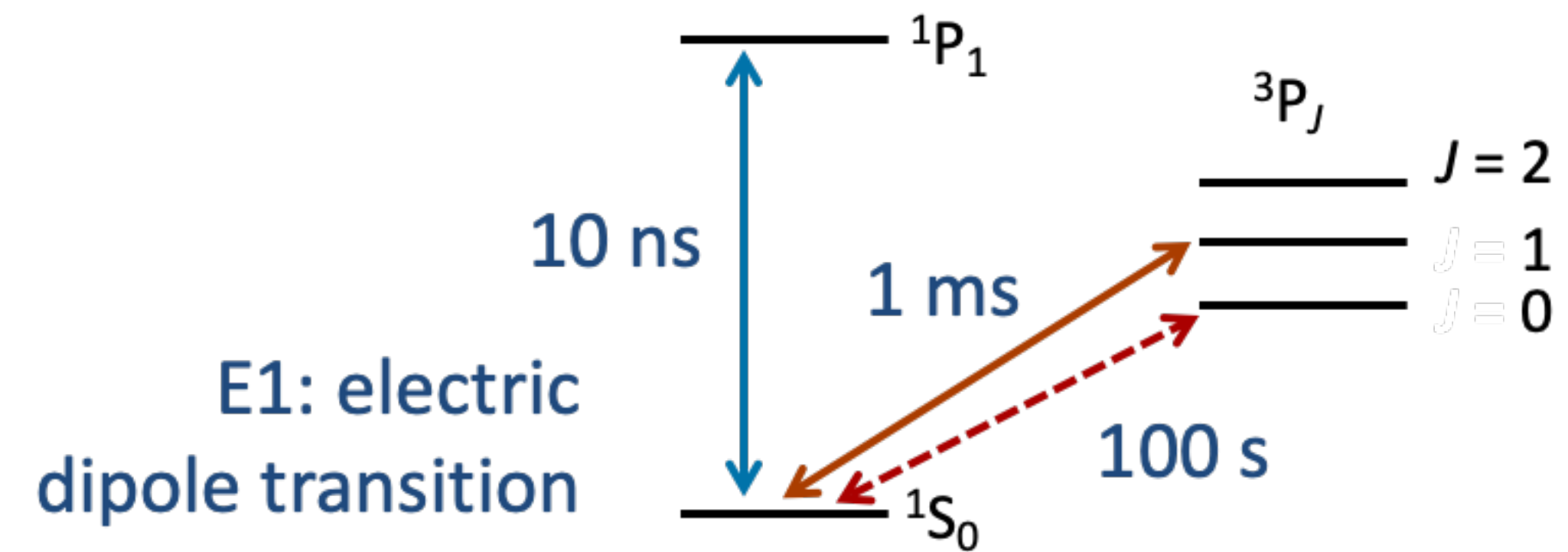
What Makes a Good Atomic Clock?

- Choice of atom
- How to stabilise the oscillator
- Arrangement of atoms (trap, fountain, ...)
- Measurement choices & measuring ratios
- How to characterise the clock (Allan deviation, noise sources, etc)
- How to count really fast (Frequency Comb)



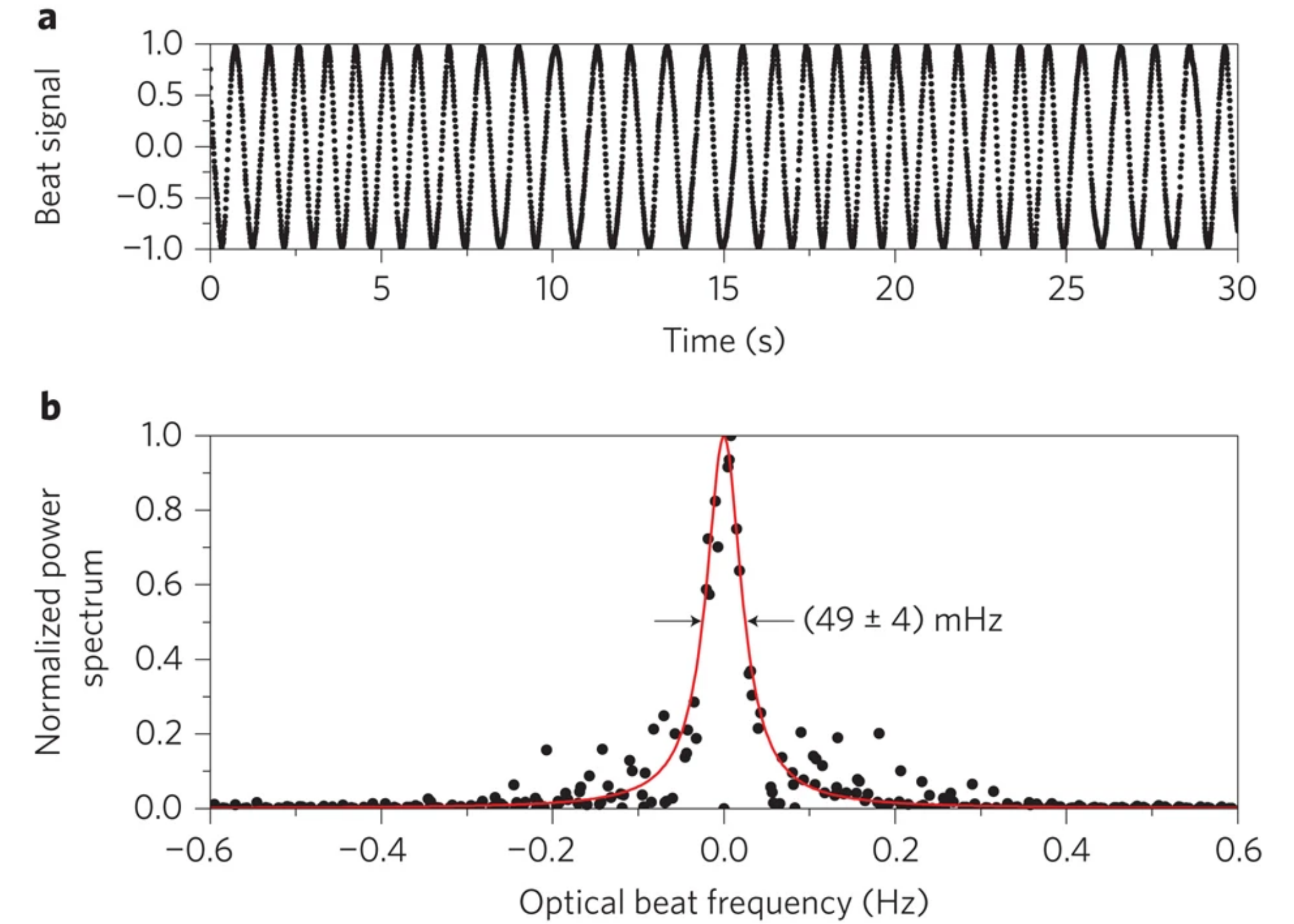
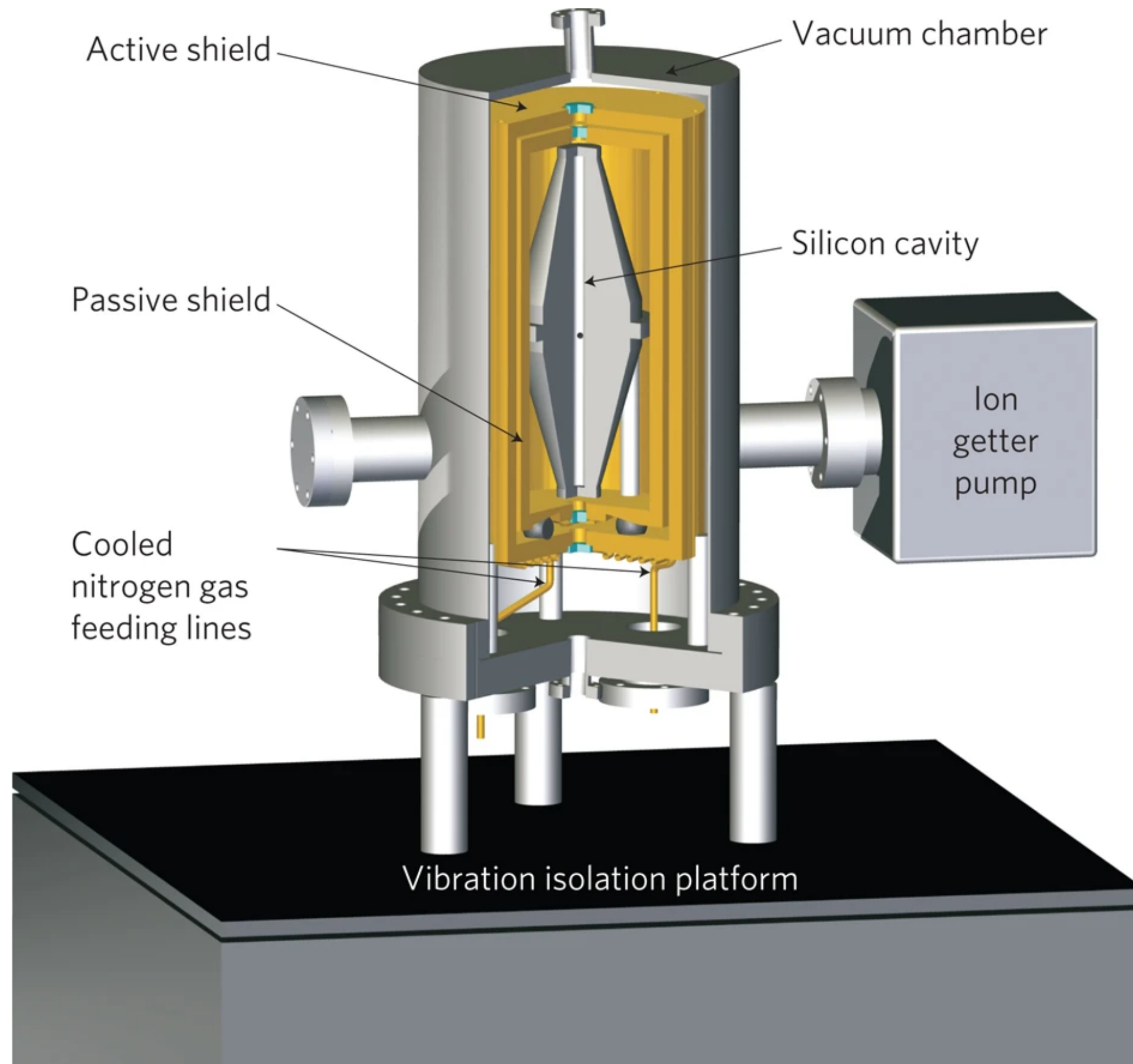
Selecting an Atomic Reference

- Two requirements for the atom/transition:
 - long observation/interrogation time
 - narrow transition (can find the peak more precisely)
- Long-lived transitions are favourable
 - one minute or more... “forbidden” transitions
 - possible in some atoms with dipole transitions
 - more common for quadrupole/octupole transitions
- Other considerations:
 - convenient optical wavelengths
 - ease of preparation/operation
 - availability of atoms
 - sensitivity to external effects (low or high)



Strontium Level Diagrams

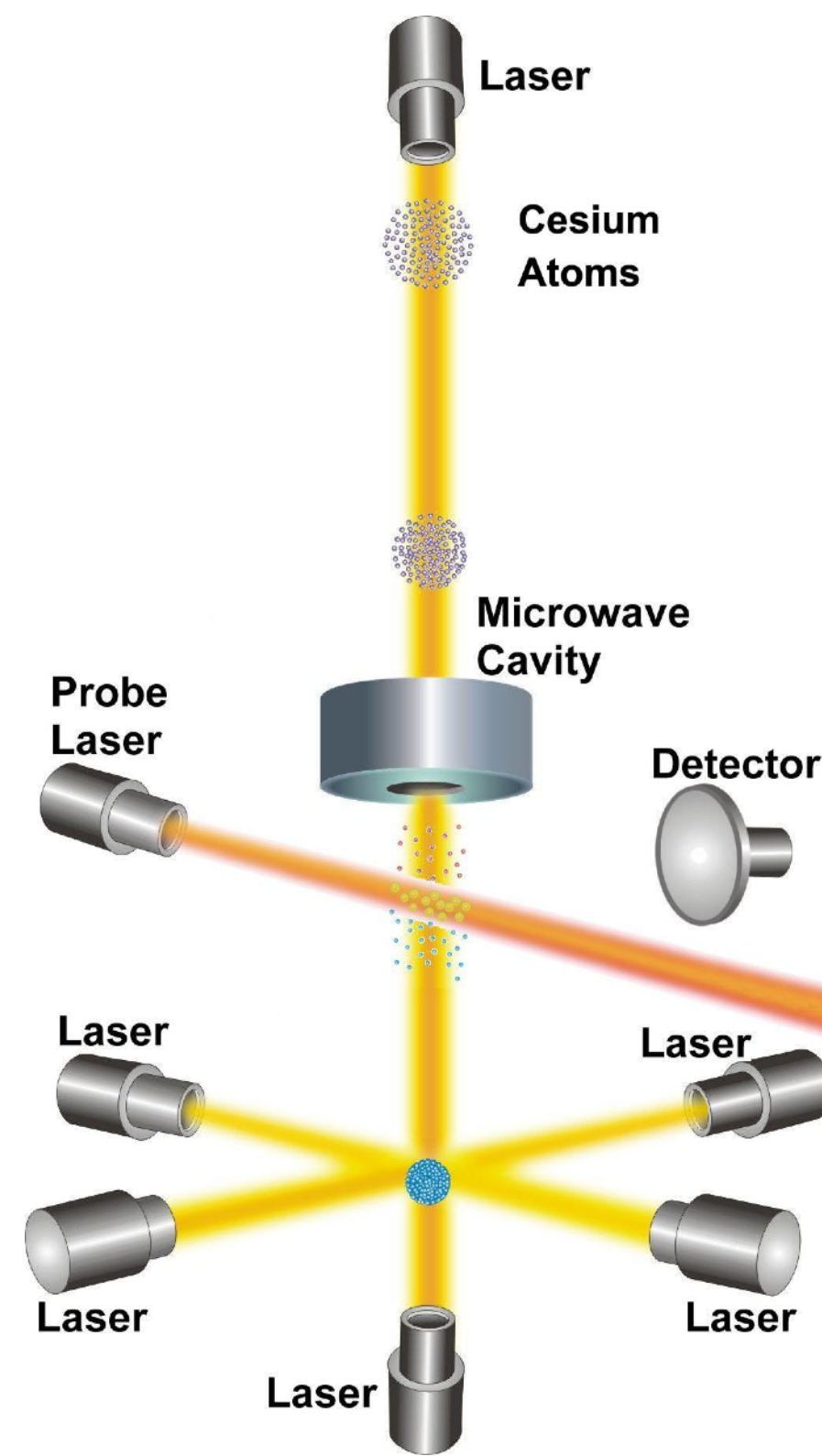
Single-Crystal Silicon Optical Cavity



Normalized fast Fourier transform of the beat signal recorded with a HP 3561A FFT analyser (37.5 mHz resolution bandwidth, Hanning window). A Lorentzian fit is indicated by the red line. The combined result of five consecutive recordings of the beat signal (black dots) is displayed here, demonstrating the robustness of this record-setting linewidth.

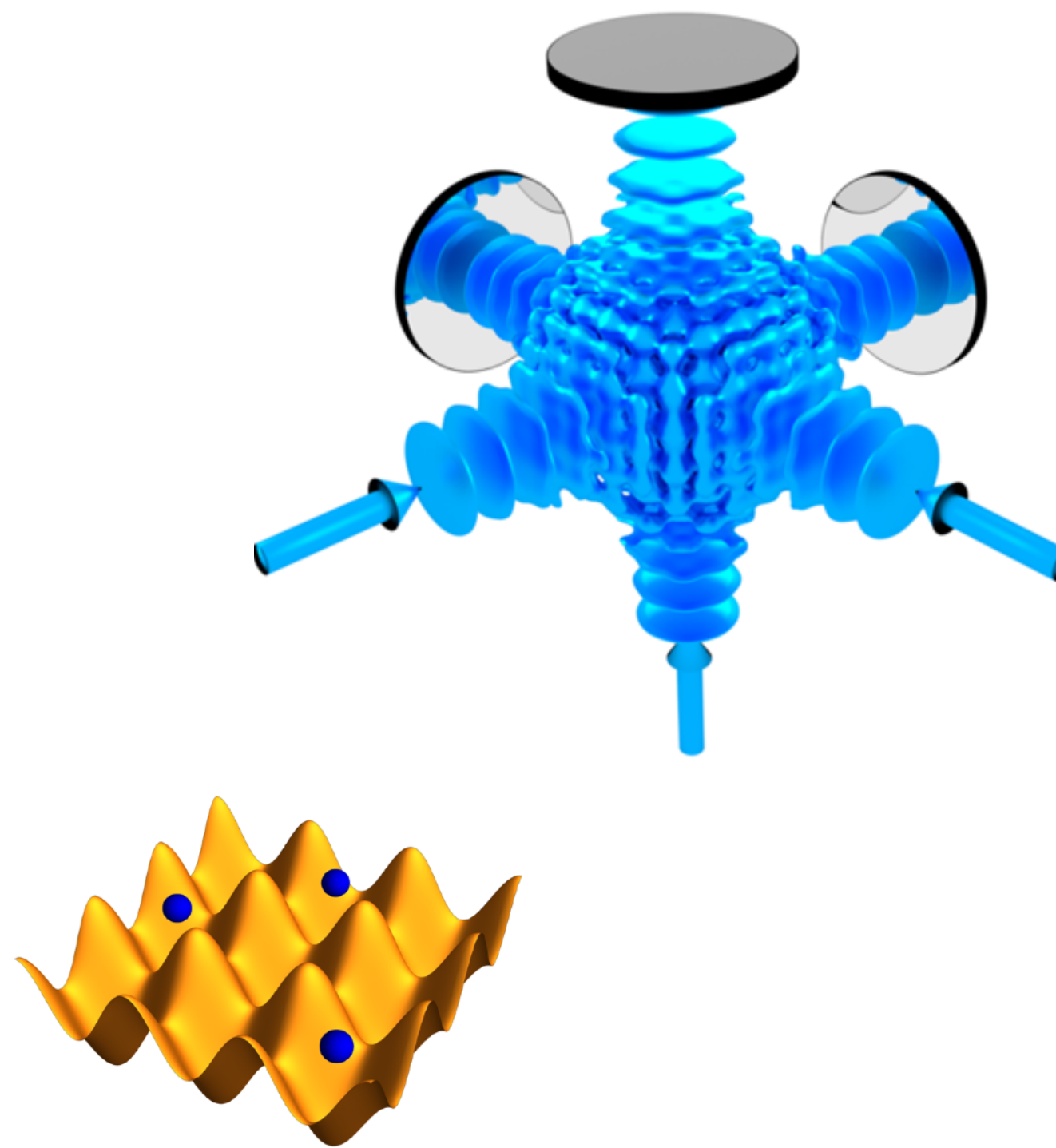
Manipulation and Trapping of Atoms

- Fountains (or ovens): e.g. Cesium Fountain Clock
- Neutral atoms in optical lattice: e.g. Strontium Lattice Clock
- Ions held in electromagnetic trap:



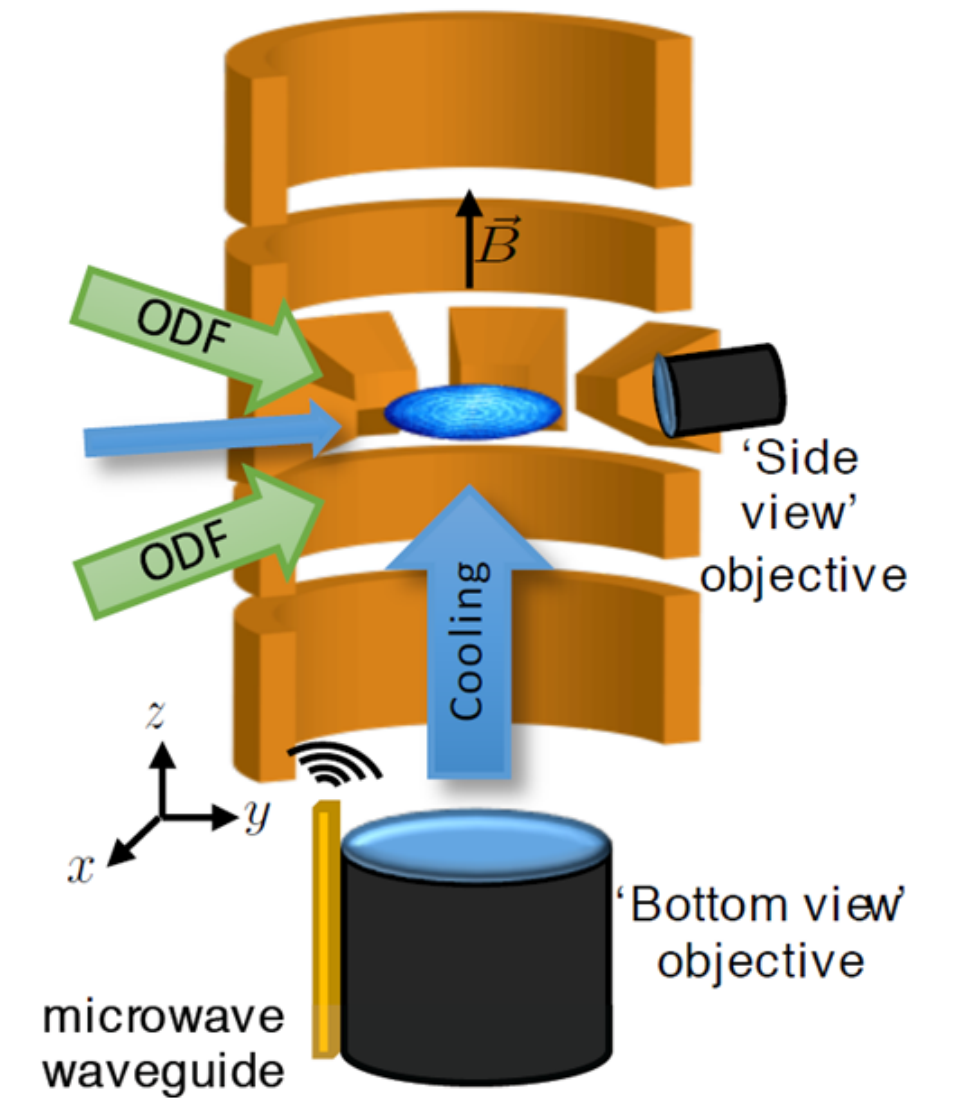
Atomic Fountain (Cesium)

[<https://www.nist.gov/news-events/news/1999/12/nist-f1-cesium-fountain-clock>]



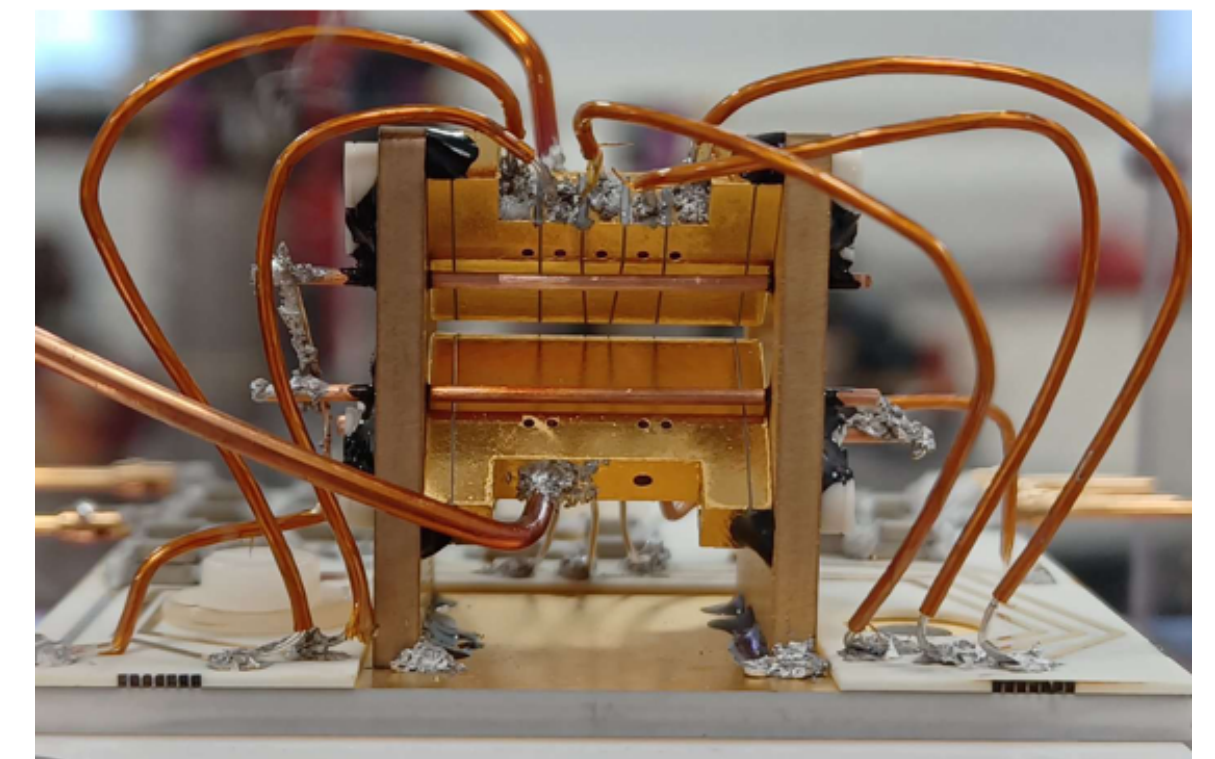
2D and 3D Lattice Potentials

[Wikipedia, <https://www.amop.phy.cam.ac.uk/>]



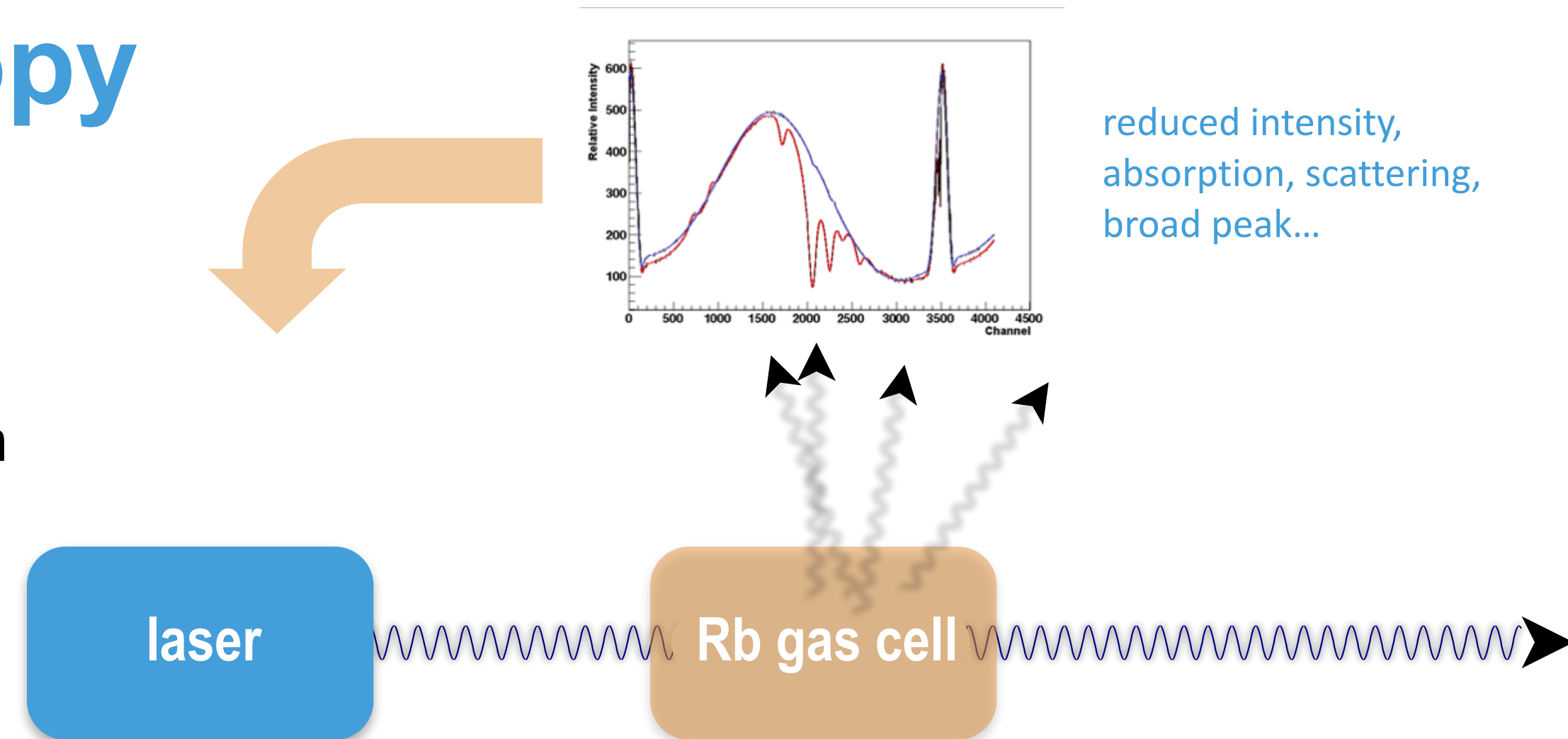
Penning and Paul Traps

[Barontini/PTB, <https://www.nist.gov/image/penningtrappng>]



Interacting with Atoms: Spectroscopy

- **Incoherent:** absorption spectroscopy for laser stabilisation
 - Signal is continuous (timing is not an issue)
 - Absorption/scattering method $\implies$ short lifetime $\implies$ broad linewidth
- **Coherent:** interactions via Rabi oscillations
 - Very long lifetime—usually limited by other effects
 - Setup, query and read-out is not continuous
 - Oscillation between ground and excited states (rotation around Bloch sphere)



Bloch vector: $\frac{d}{dt}\vec{b} = \vec{\Omega}_{\text{eff}} \times \vec{b}$

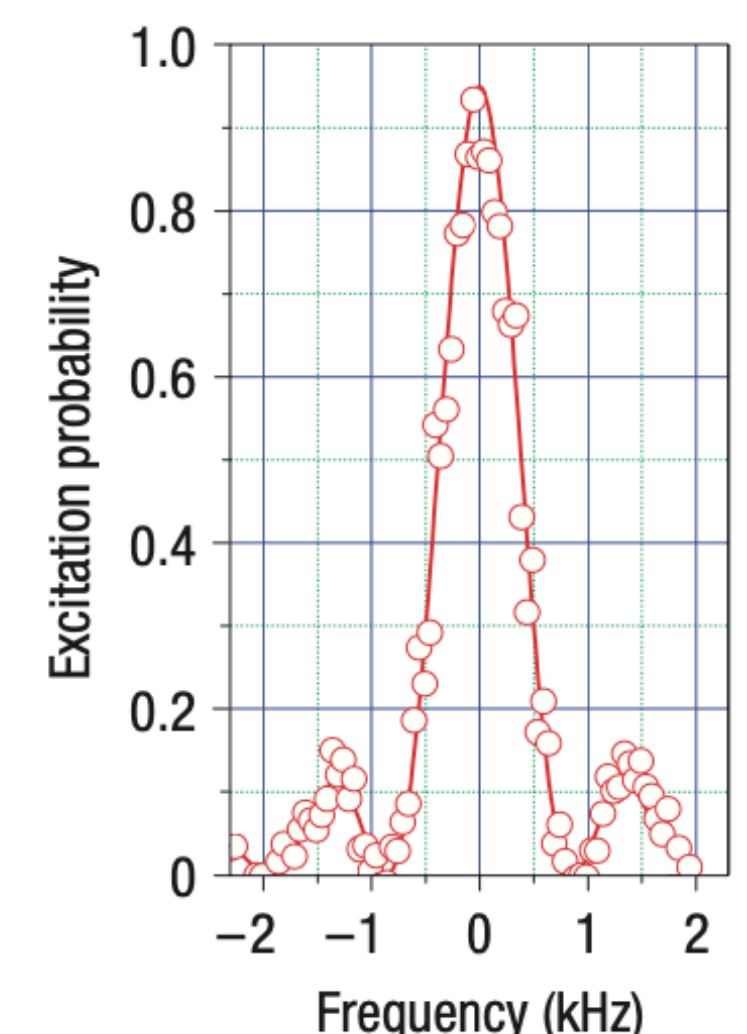
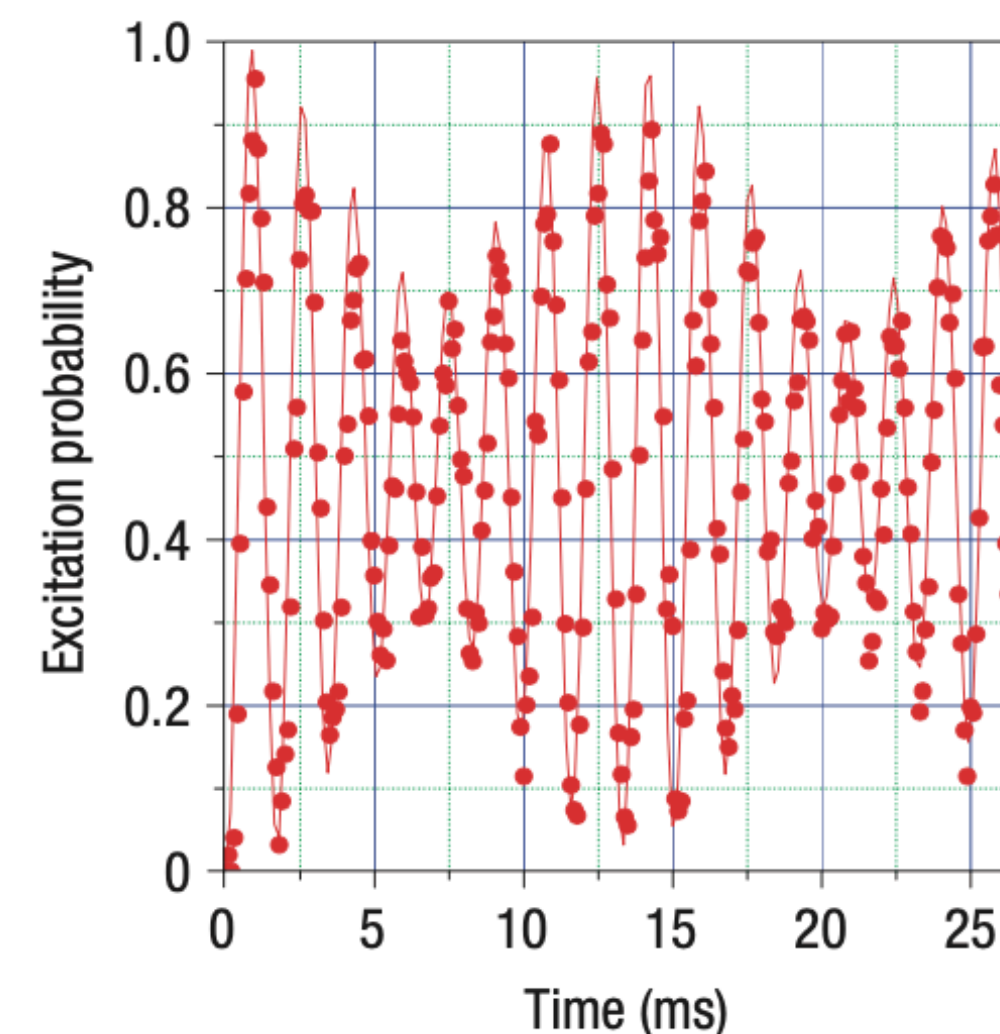
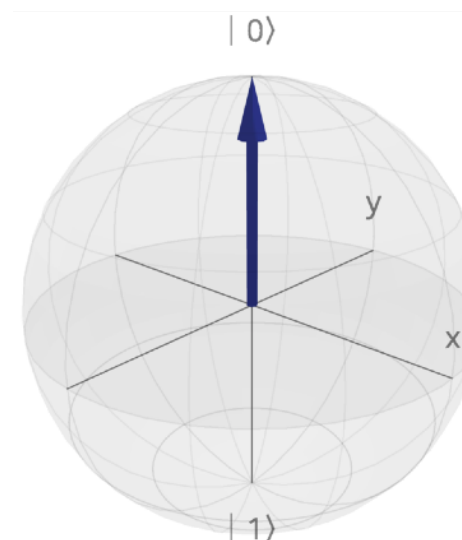
Rabi Frequency: $\vec{\Omega}_{\text{eff}} = \begin{pmatrix} \Omega \\ 0 \\ -\delta \end{pmatrix}$

Pulse: $\vec{\Omega}_{\text{eff}} \approx \begin{pmatrix} \Omega \\ 0 \\ 0 \end{pmatrix}$ free evolution: $\vec{\Omega}_{\text{eff}} = \begin{pmatrix} 0 \\ 0 \\ -(\pm\delta) \end{pmatrix}$

$$\Omega = \langle g | \vec{d} \cdot \vec{E}_0 | e \rangle$$

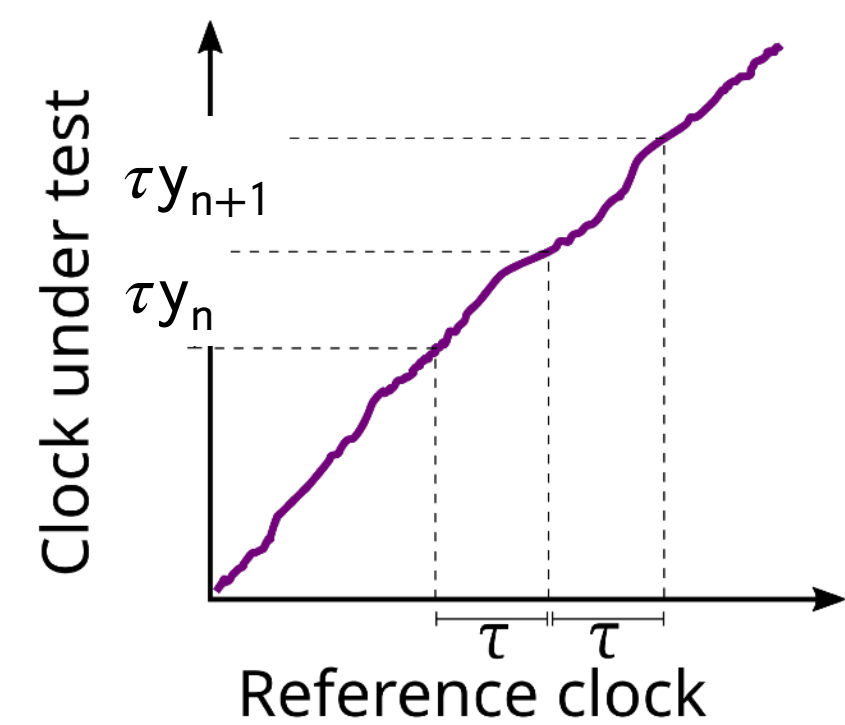
$$\delta = \omega - \omega_0$$

$$\delta \ll \Omega$$

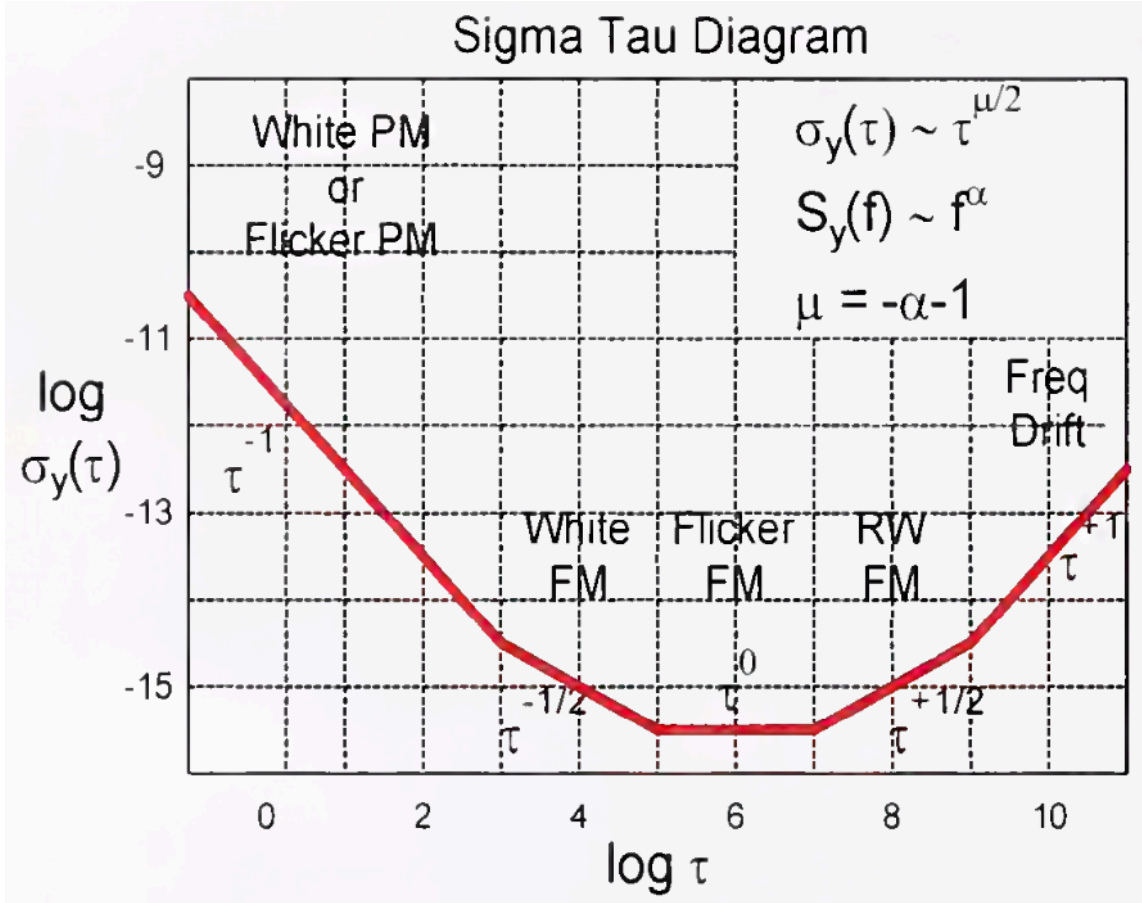


Clock Performance: Allan Deviation

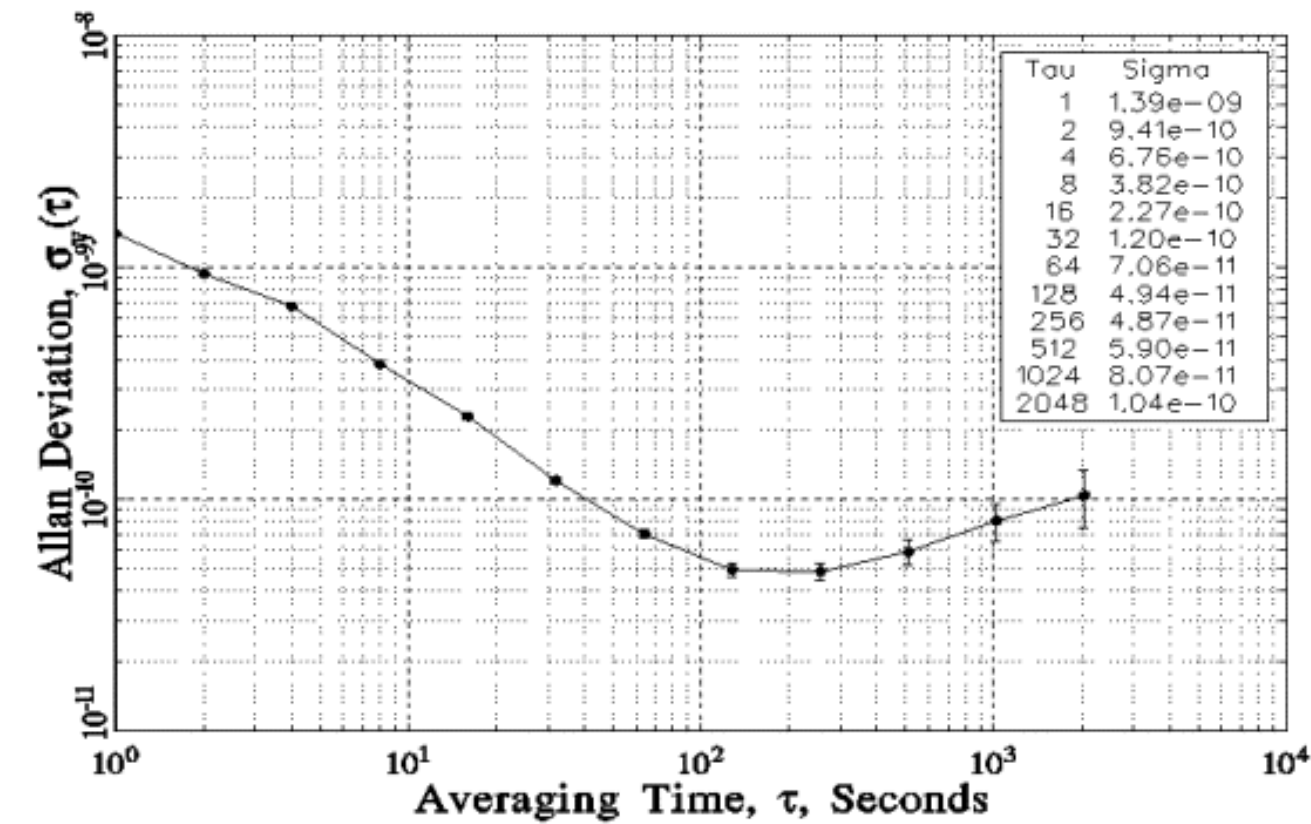
- Allan or two-sample variance better suited to oscillators than e.g. standard deviation
- Used to measure frequency stability in clocks, characterise (non-systematic) noise



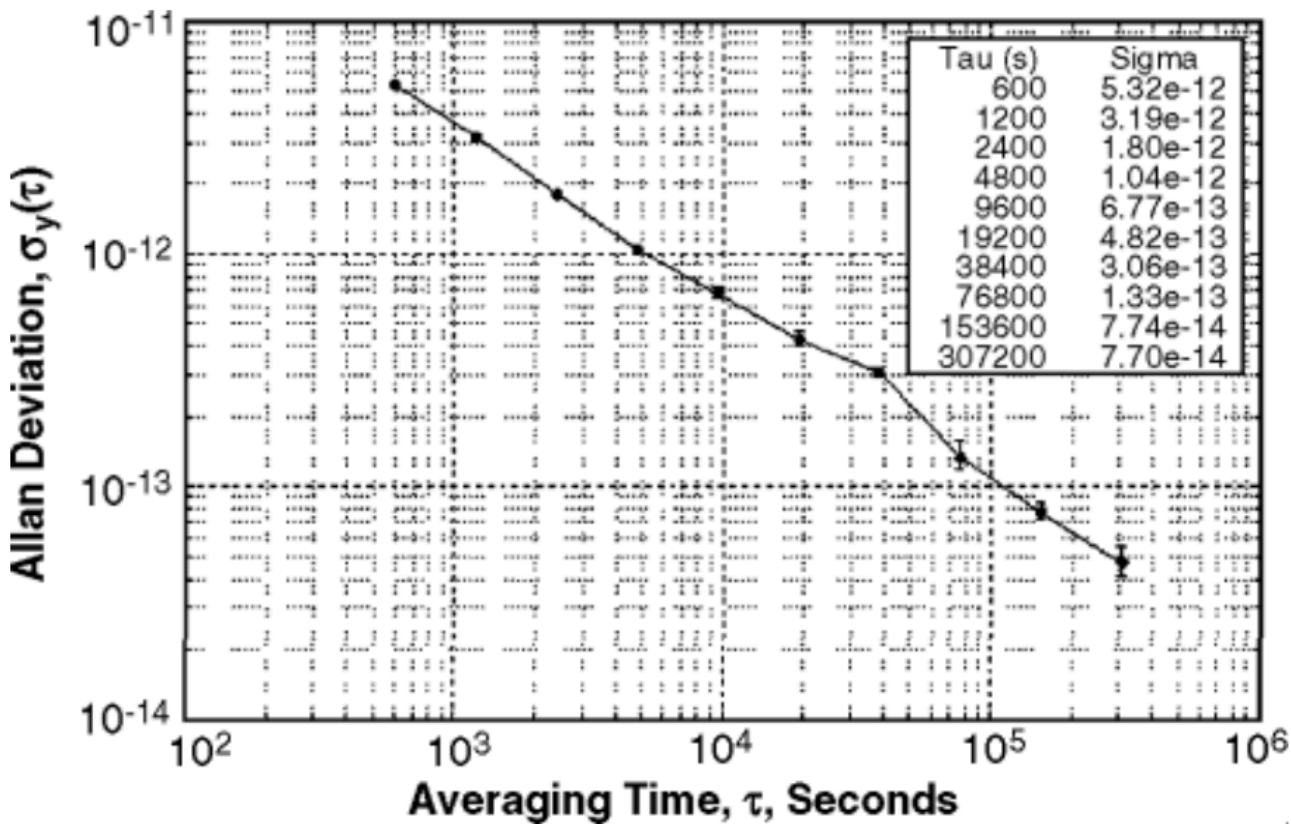
$$\sigma_y(\tau) = \sqrt{\sigma_y^2(\tau)} = \frac{1}{2} \langle (\bar{y}_{n+1} - \bar{y}_n)^2 \rangle$$



- Slope of the curve (log scale) gives different exponent-dependent noise source



Example Allan deviation plot



Allan deviation for early GPS signals

Uncertainties from Shifts and Broadening

- **Doppler broadening:** velocity distribution of atoms can cause spectral lines to shift
- An issue at low pressure, high temperature, small wavelengths
- Can be addressed by reducing the thermal motion: laser or sympathetic cooling
- **Collisional broadening:** electronic interactions with nearby particles can cause frequency shifts
- Suppressed by cryogenic temperatures, or with better vacuum
- Lattice potentials can be used to eliminate collisions and first-order Doppler shifts
- **Stark shift:** shift in atomic energy levels as a result of external electric fields
- Effects minimised by eliminating constant external fields (linear Stark shift)
- **Zeeman shift:** the split of energy levels in the presence of magnetic fields
- Can be reduced by local shielding, or by choosing transitions insensitive to first-order Zeeman shift

Micromotion & Black Body Radiation

- **Micromotion** is excess ion motion synchronous with trap AC field
 - Can change atomic transition line shapes
 - Induce significant second-order Doppler shifts
 - Limit confinement time (for room temp traps)
 - Stark shifts in atomic transitions from the AC field
 - Addressed by better trap design, better control of AC field
- **Black-Body Radiation** changes the energy levels in clock transitions
 - From heat: major source of uncertainty in room-temperature clocks
 - Shift atom's energy levels via the radiation's electric field (Stark shift)
 - Control by reducing local temperatures, heat sources, windows, etc
 - Advances in calculating the effects (theory)

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J. Appl. Phys., Vol. 83, No. 10, 15 May 1998

effects from
micromotion

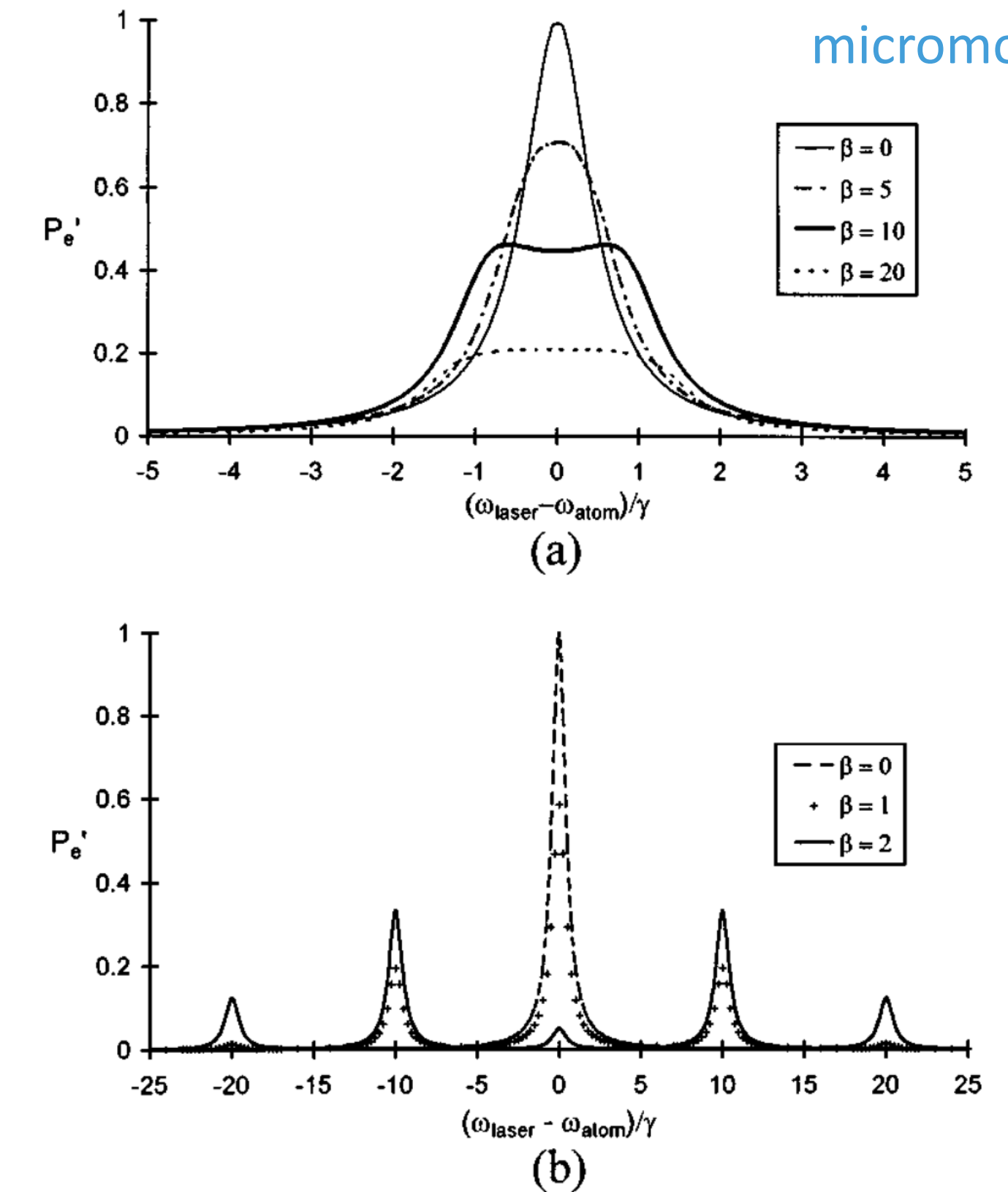


FIG. 2. Effect of micromotion on the spectrum of P_e (excited state population). We plot $P_e' = P_e [\hbar \gamma / (2 \mathcal{P} |E_0|)]^2$ for various values of β . For both graphs, we assume that the ion is driven below the saturation limit. (a) $\Omega/\gamma = 0.1$. For $\beta = 10$, heating occurs in the regions $-0.6 < (\omega_{\text{laser}} - \omega_{\text{atom}})/\gamma < 0$ and $(\omega_{\text{laser}} - \omega_{\text{atom}})/\gamma > 0.6$. (b) $\Omega/\gamma = 10$. For $\beta > 0$, heating can occur when the laser frequency is tuned near, but above the center of, any of the sideband frequencies.

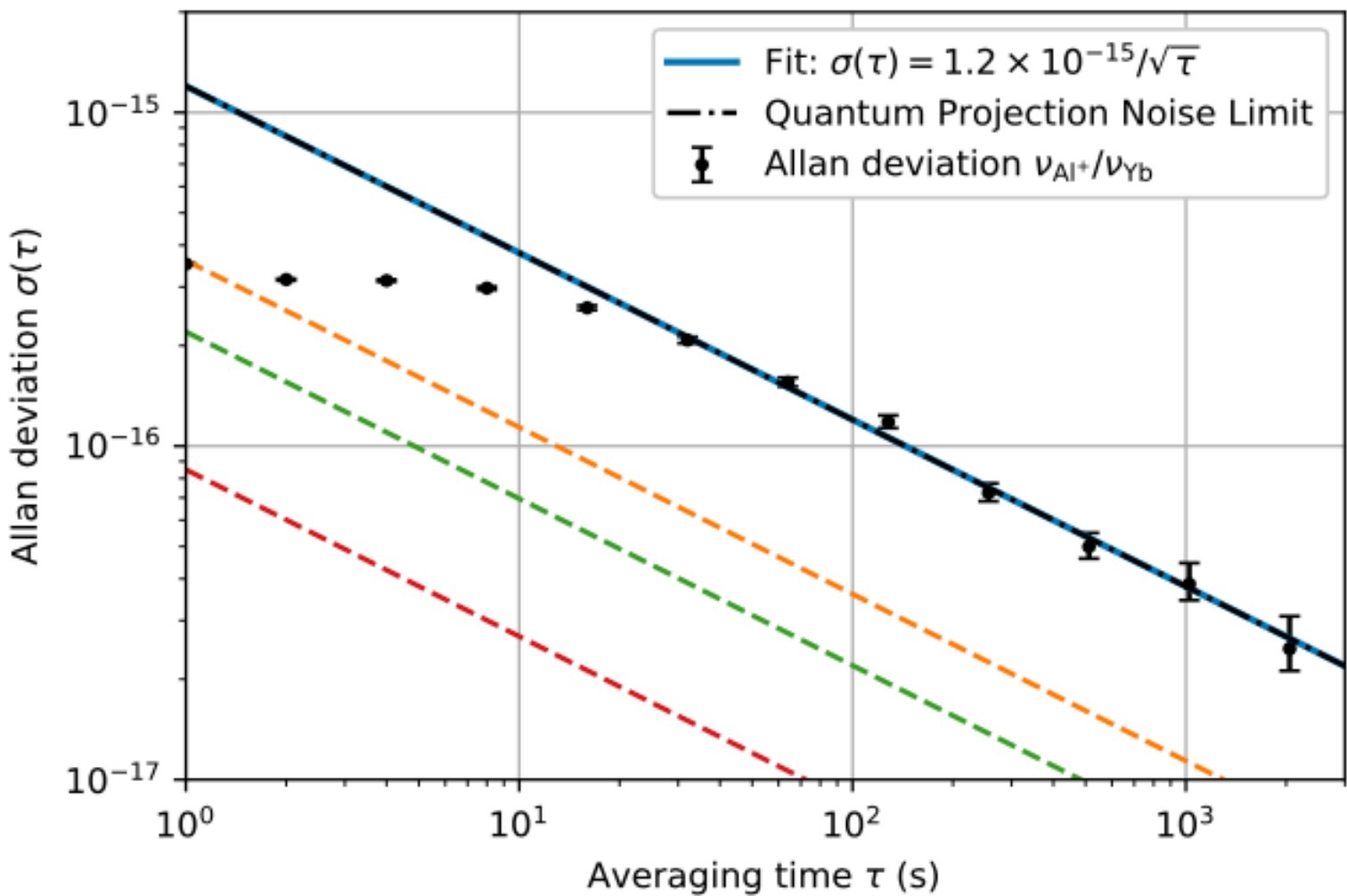
Optical Clock Uncertainties

- Typically many systematic noise sources
 - Blackbody radiation: local heat sources (e.g. for room temperature clocks)
 - Stark/Zeeman shift: know your fields very well
 - Motional uncertainty, background gas: better vacuum
 - Laser-induced effects: improve laser stability
 - Micromotion (ion motion in sync with trap AC field): better trap design, better control of AC field
- Quantum Projection Noise (shot noise)
 - After laser interrogation, you want to read out the state (either ground or excited, 0 or 1)
 - Binary, discrete nature of quantum leads to uncertainty $\sigma(\tau) = 1/f\sqrt{NT_p\tau}$, for frequency f , probe time T_p and measurement time τ
 - Can be reduced further using squeezing/entanglement ($\sim 1/N$), or more atoms!

NIST $^{27}\text{Al}^+$ Quantum-Logic Clock

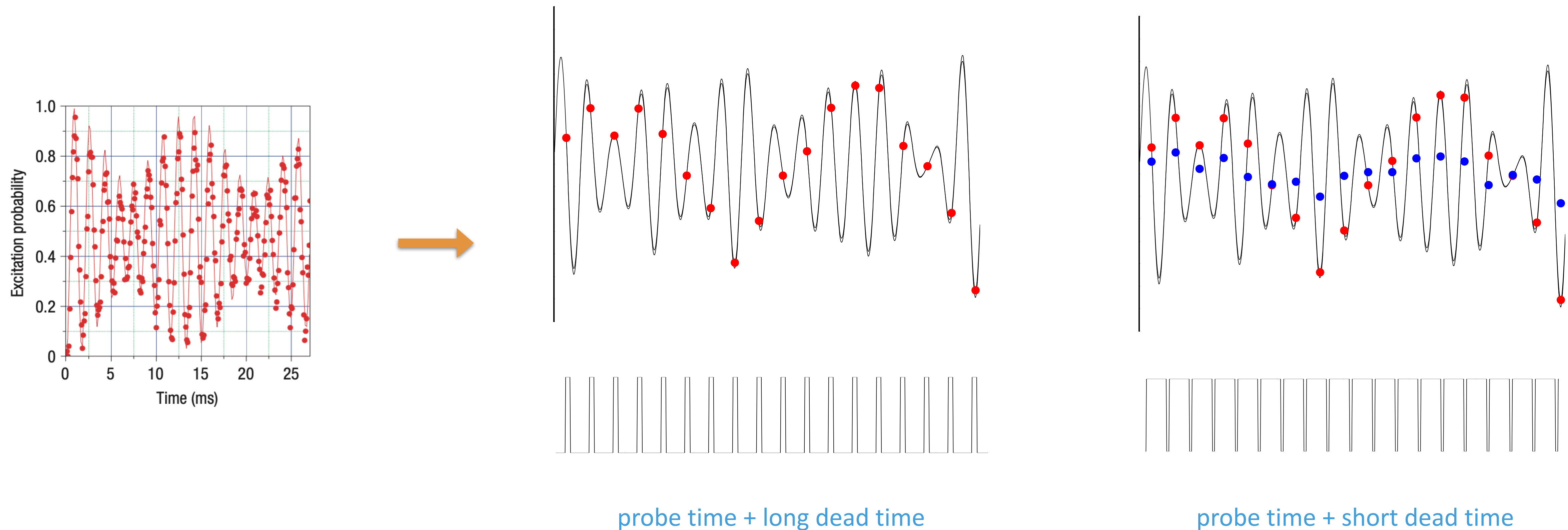
TABLE I. Fractional frequency shifts ($\Delta\nu/\nu$) and associated systematic uncertainties for the $^{27}\text{Al}^+$ quantum-logic clock.

Effect	Shift (10^{-19})	Uncertainty (10^{-19})
Excess micromotion	−45.8	5.9
Blackbody radiation	−30.5	4.2
Quadratic Zeeman	−9241.8	3.7
Secular motion	−17.3	2.9
Background gas collisions	−0.6	2.4
First-order Doppler	0	2.2
Clock laser Stark	0	2.0
AOM phase chirp	0	<1
Electric quadrupole	0	<1
Total	−9336.0	9.4



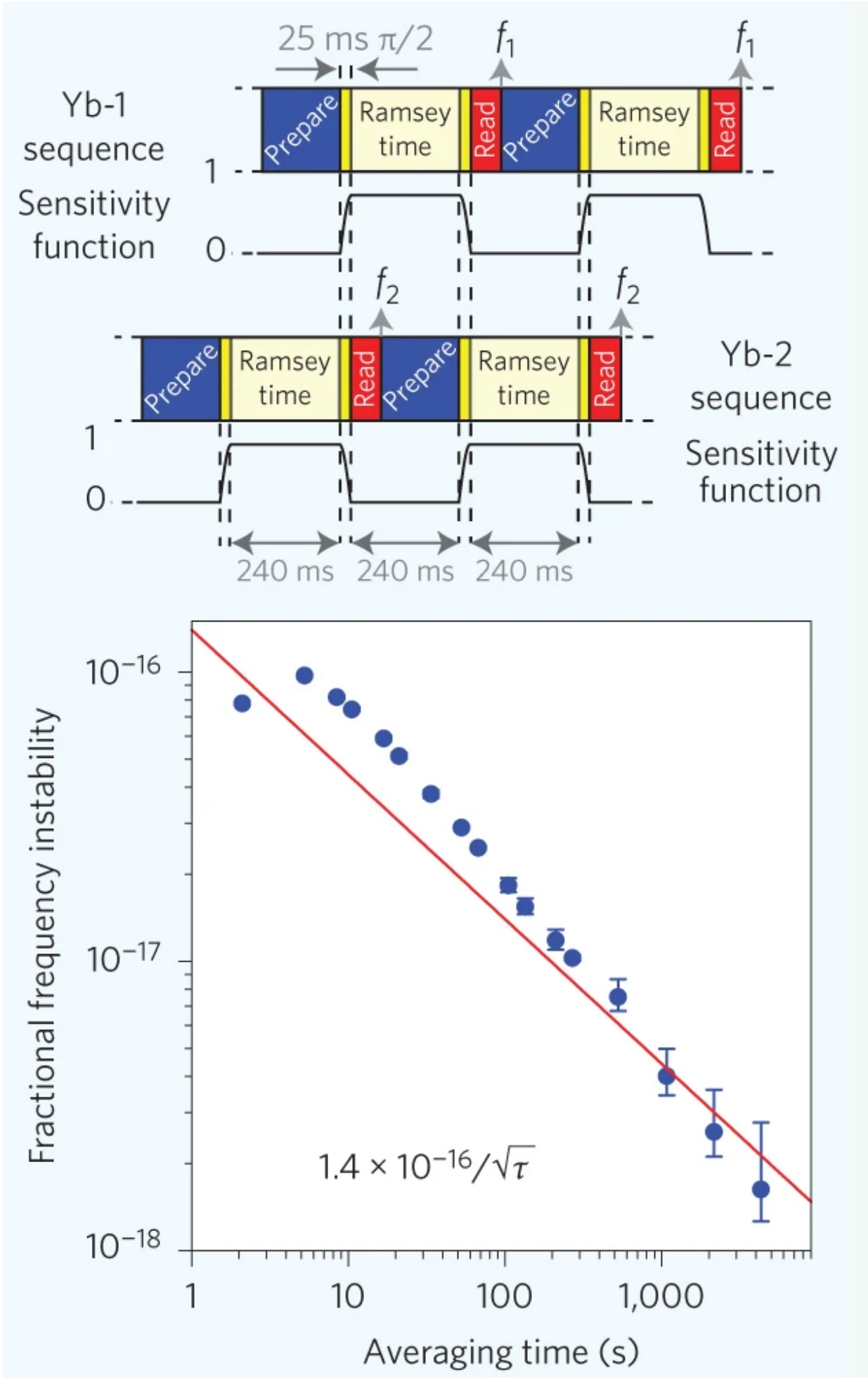
Deadtime-Related Uncertainty

- It takes some unavoidable time for interrogation (Rabi/Ramsey)
- The data acquisition also add dead time... net effect (Dick's effect) is added uncertainty

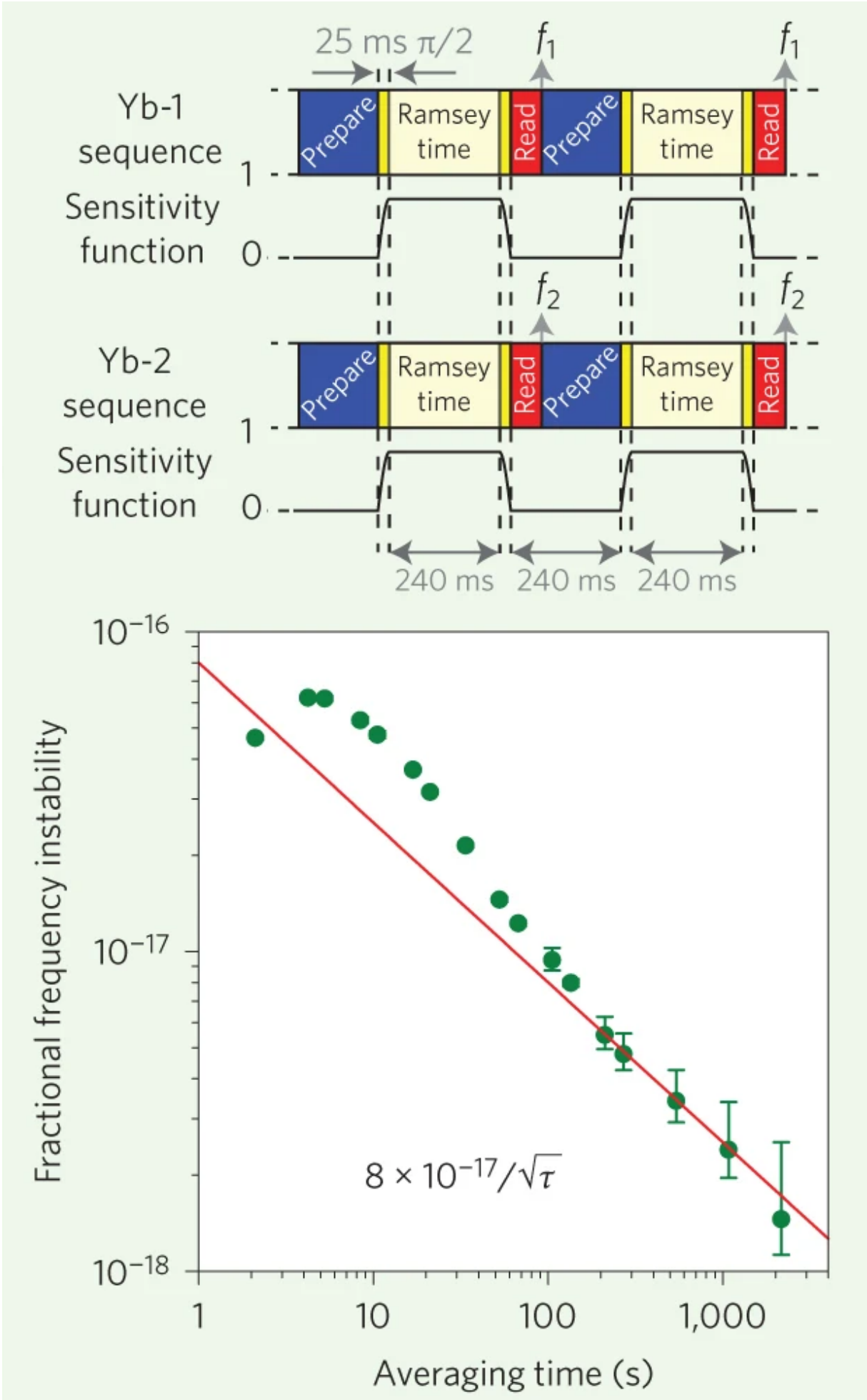


Deadtime Mitigation

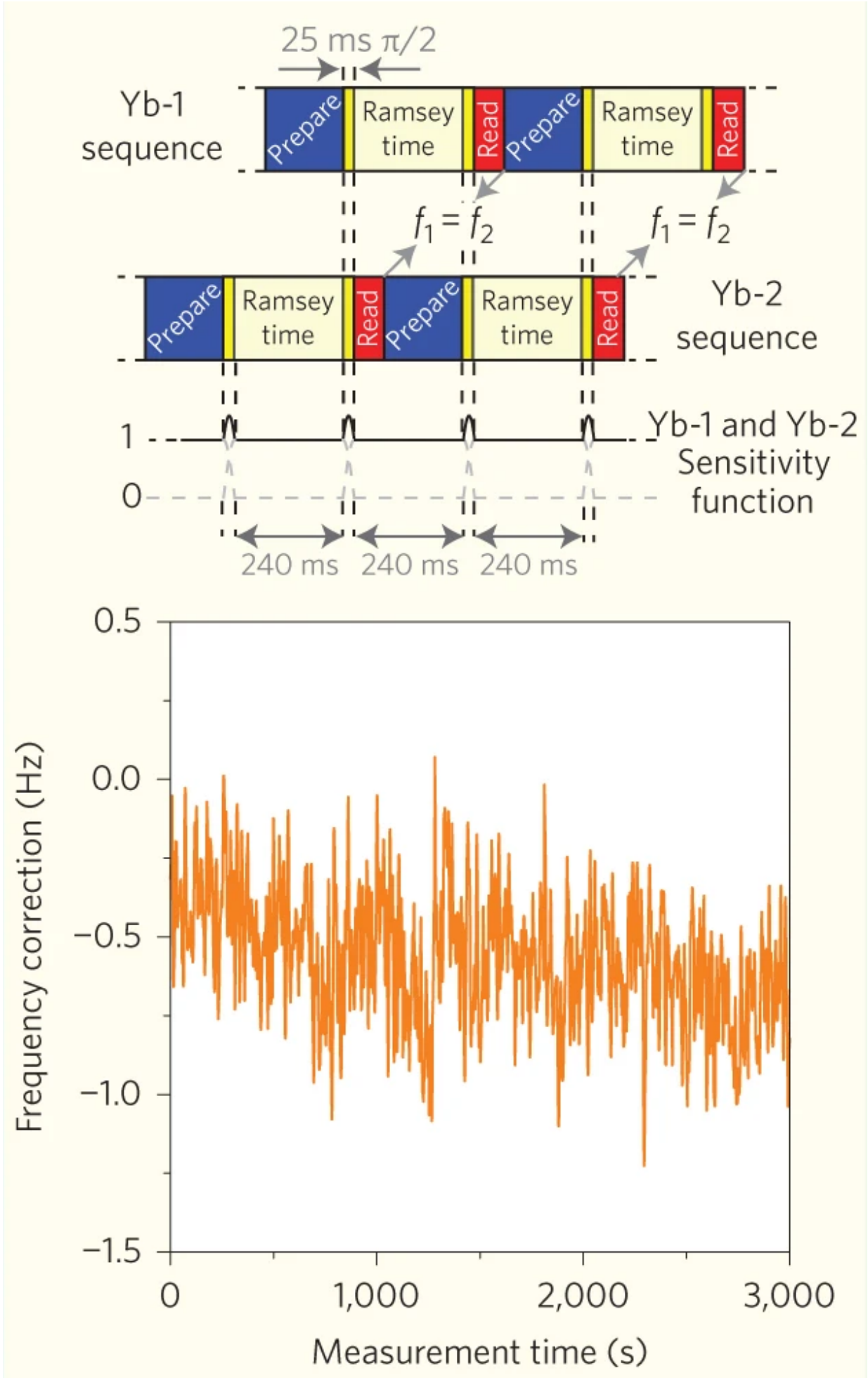
- Example of recent efforts to overcome the effect



asynchronous readout



synchronous readout



readout w/ active feedback corrections

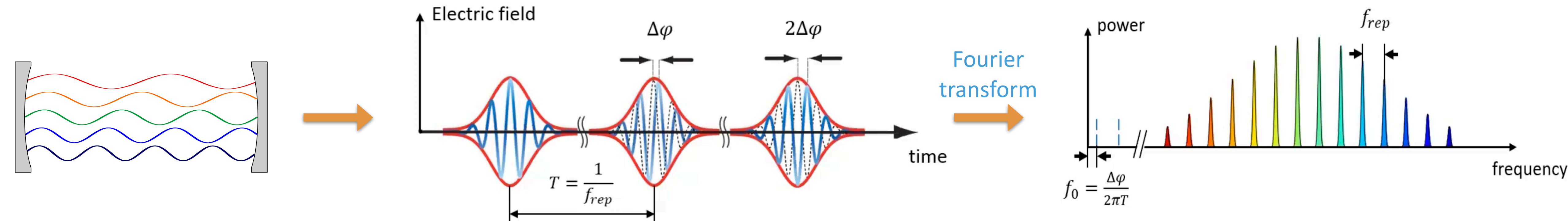
What about the Counter?

- Ok, so we have the oscillator and have characterised it, how do we count the clock “ticks”?
- The problem... we can count electronically up to microwave frequencies, but not the 100's of THz optical
- Al⁺ clock example from earlier: 1121015393207859 Hz!
- **Frequency combs** solve this problem, by translating/connecting the optical frequencies to countable microwave



Frequency Comb

- Q: How to precisely measure optical frequencies? The clock ticks? Compare to other clocks?



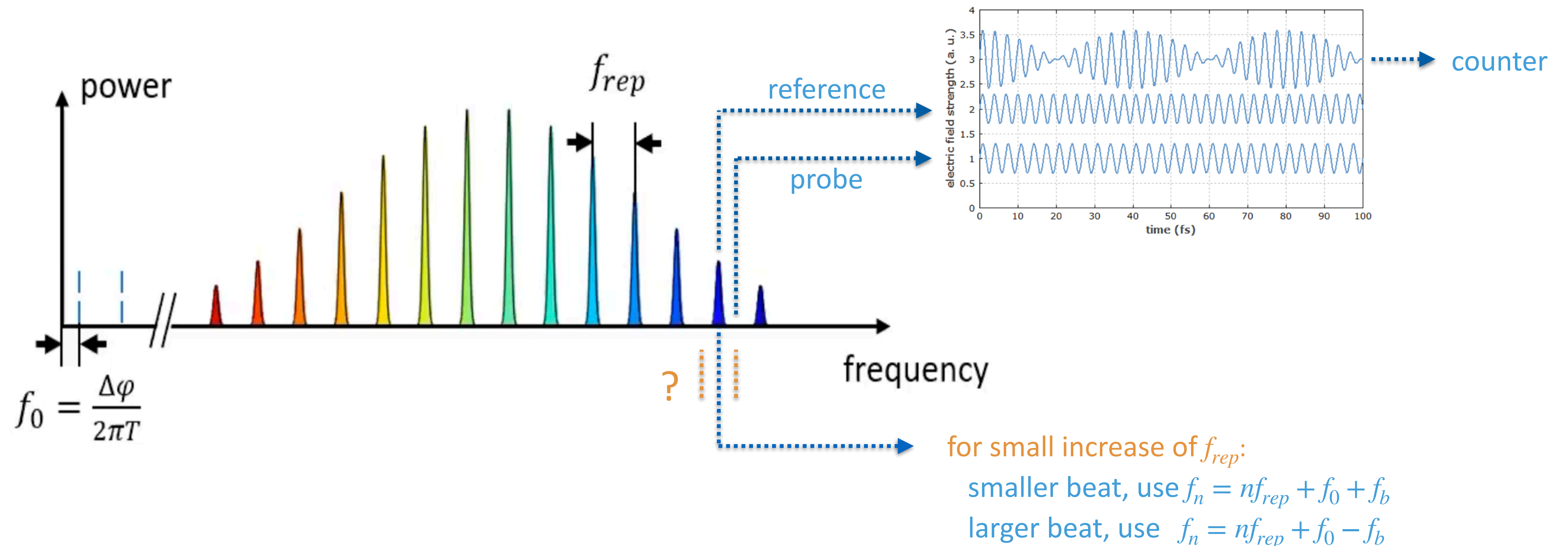
- Frequency comb:** mode-locked laser w/ stabilised rep rate (f_{rep}) and carrier-envelope-offset (f_0)

$$f_n = nf_{rep} + f_0$$

- Repetition frequency f_{rep} typically larger than CEO-frequency f_0 (e.g. 200 MHz vs. 50 MHz)
- Both frequencies are tunable, defined in relation to a frequency reference for high-end applications

Frequency Comb: Operation

- For a comb with f_0 and f_{rep} , an unknown frequency can be measured wrt one tooth by creating a beat note
- The integer n can be found using a wavemeter with an accuracy better than $f_{rep}/2$ (e.g. 40 MHz)
- Beat notes with additional teeth avoided by extracting only the relevant tooth (e.g. with a grating)
- One can slightly increase f_{rep} to find out whether the sign of the beat frequency is + or -



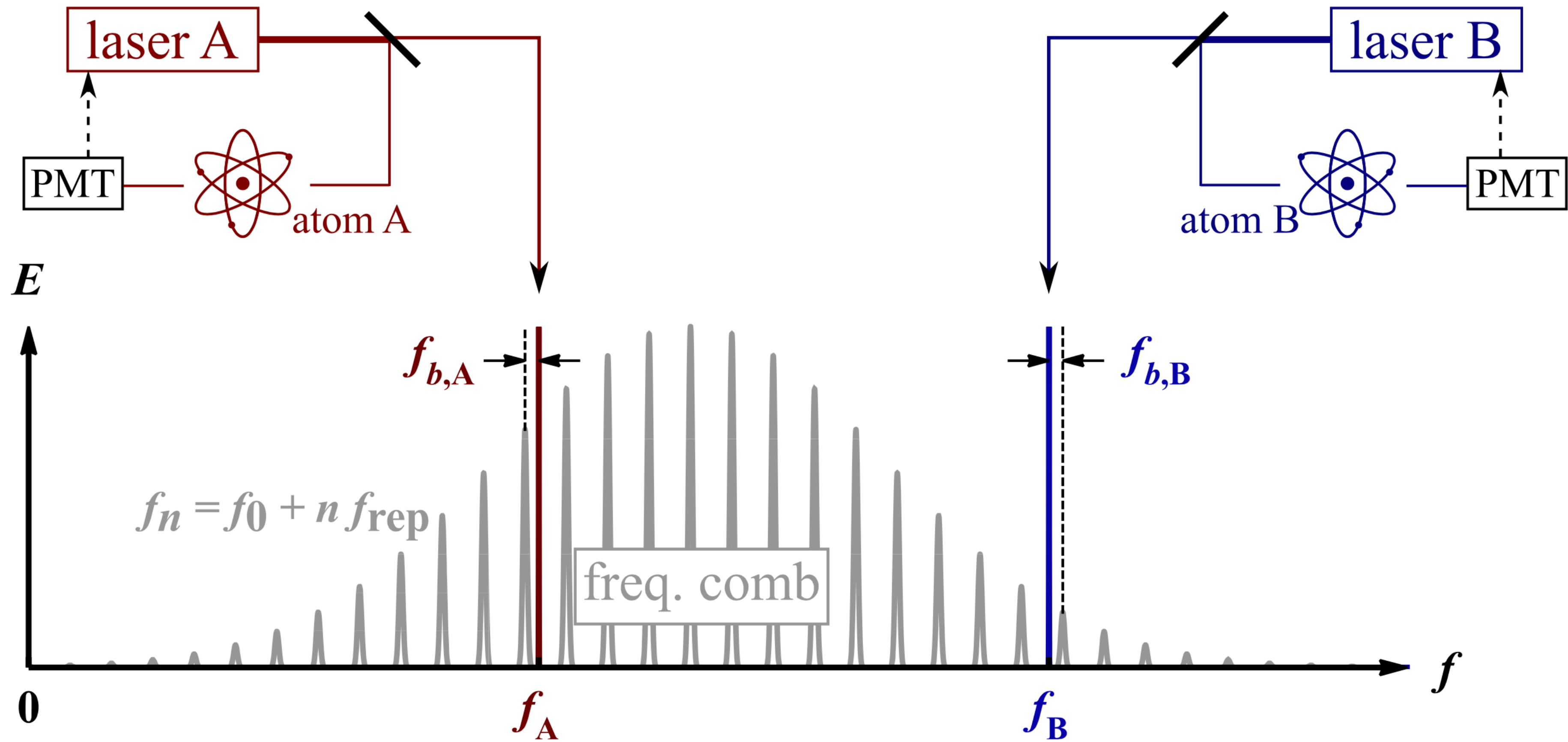
Why Measure a Frequency Ratio?

- **Unitless:** Ratios are not limited by the definition/accuracy of the SI second
- **Transportable:** Frequencies depend on gravity (et al); ratios can be used for comparison
- **Measurable:** Even at optical frequencies, can use a frequency comb to measure with accuracy and stability limited by the clocks themselves
- **Comparative:** Can be used to compare different atomic species and/or different reference frames
- **Sensitive:** Can be engineered to maximise sensitivity to fundamental constants, symmetries of nature
- ...also with 18 digits of precision, no predictions from theory!

“Never measure anything but frequency!”

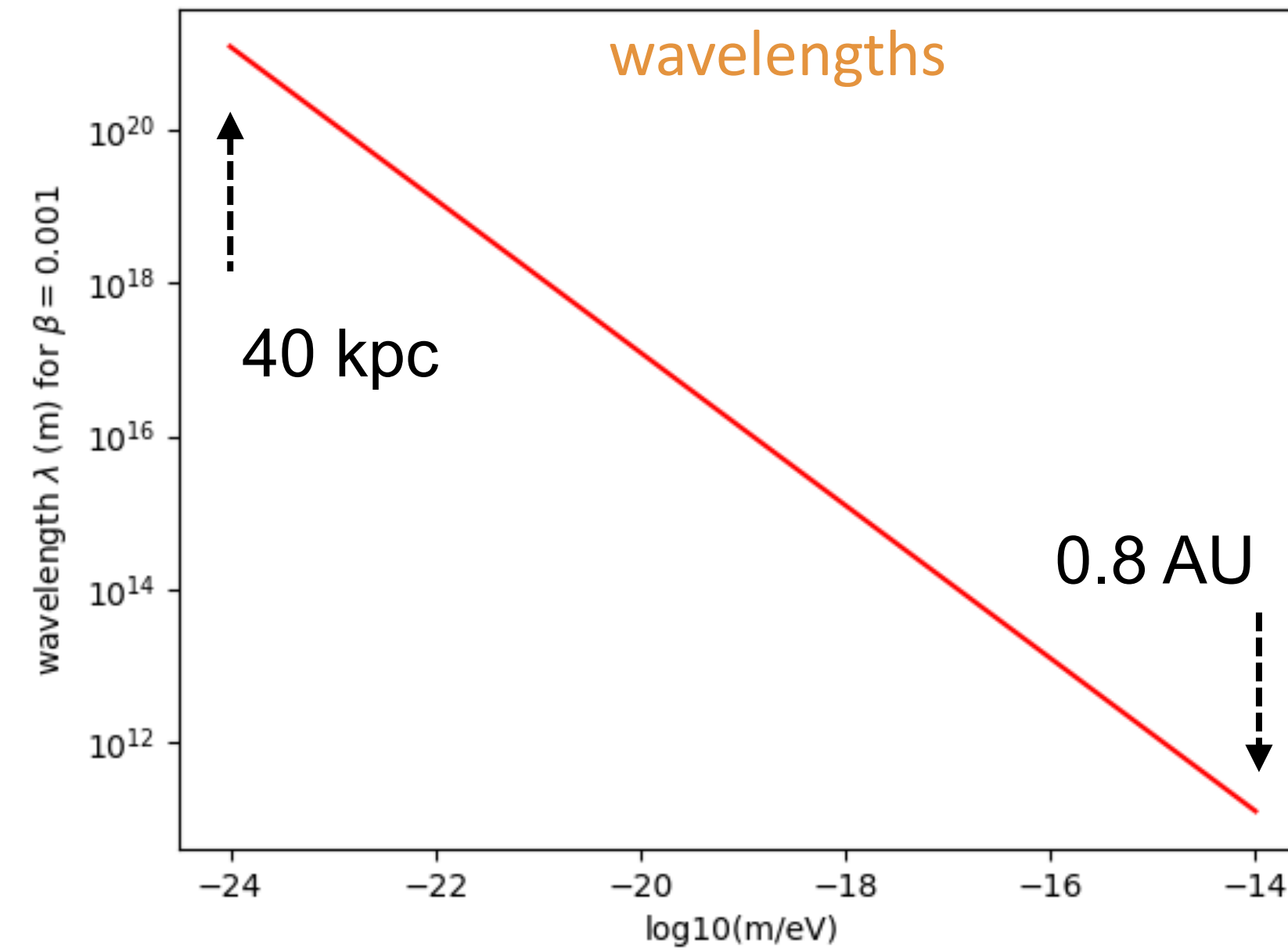
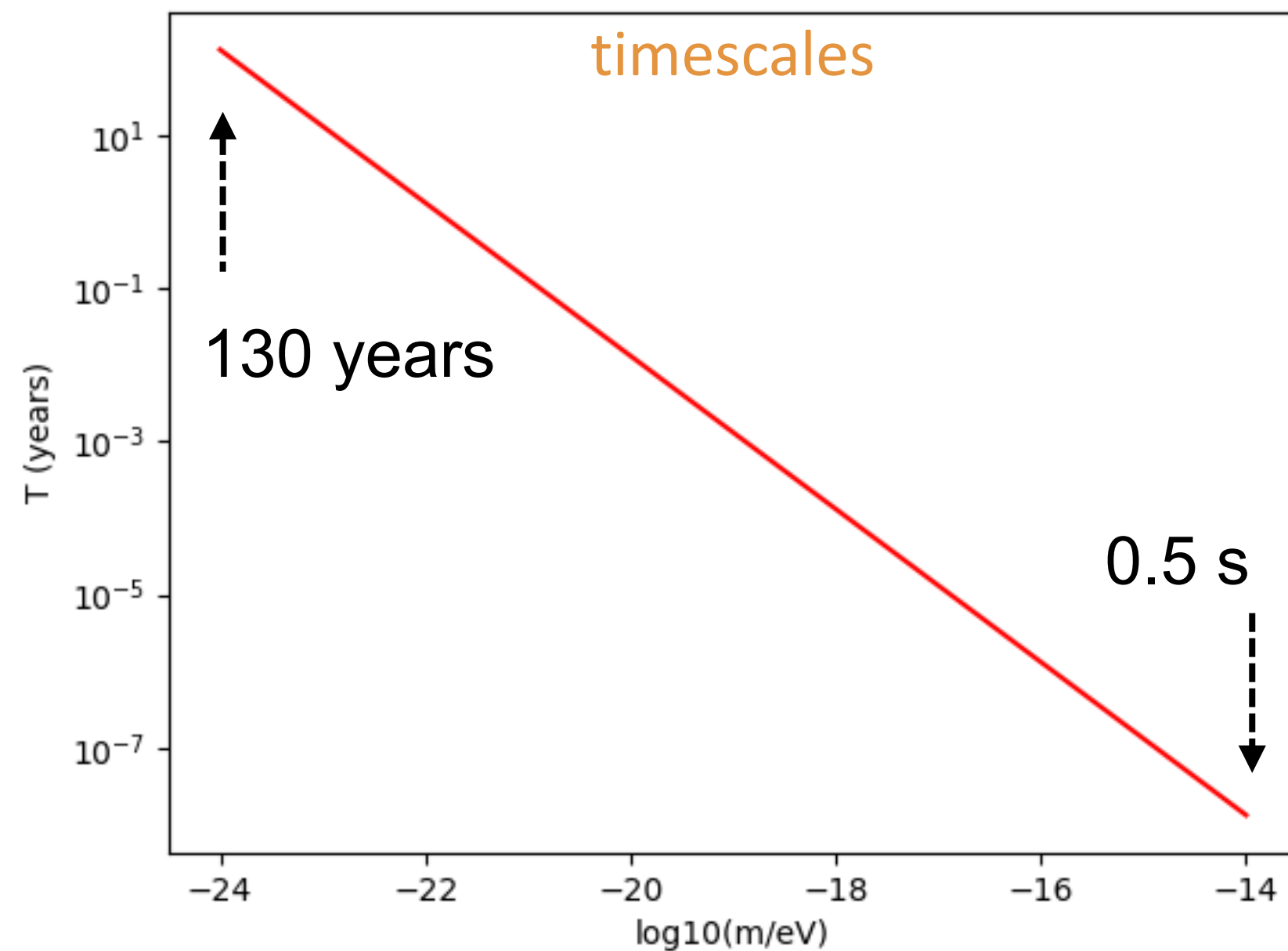
- Arthur Schawlow, Nobel 1981

Typical Experiment Setup



Wave-like Dark Matter

- Dark Matter with clock experiments—oscillation timescales and wavelengths



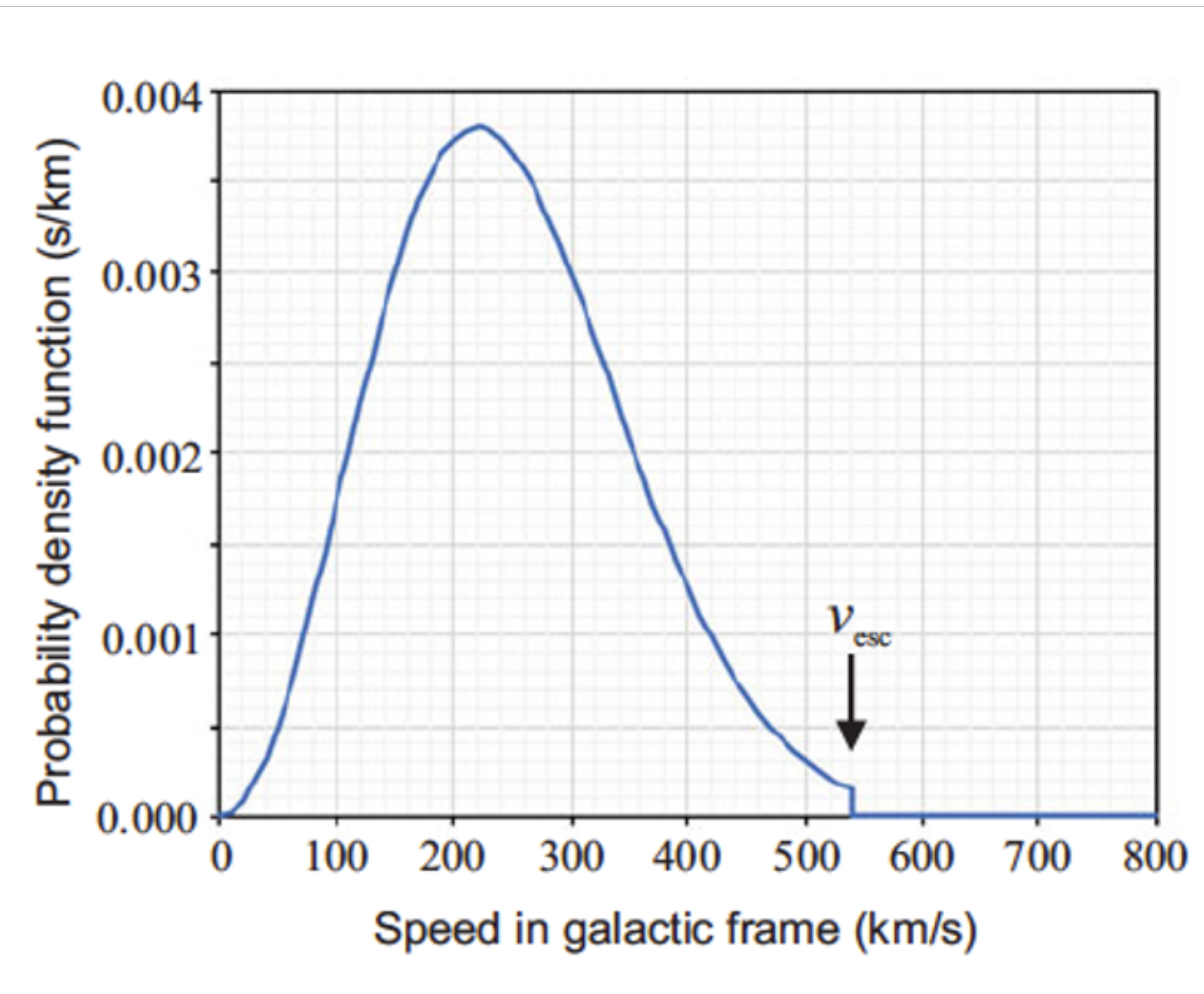
$$E = \hbar\omega = mc^2 = \frac{h}{T} \implies T = \frac{2\pi\hbar}{mc^2}$$

$$\lambda = \frac{h}{p}, \quad pc = \beta\gamma mc^2 \implies \lambda = \frac{2\pi\hbar c}{\beta\gamma mc^2}$$

- Below $m \approx 10^{-21}$ eV, the long wavelength is in tension with the existence of astrophysical DM halos

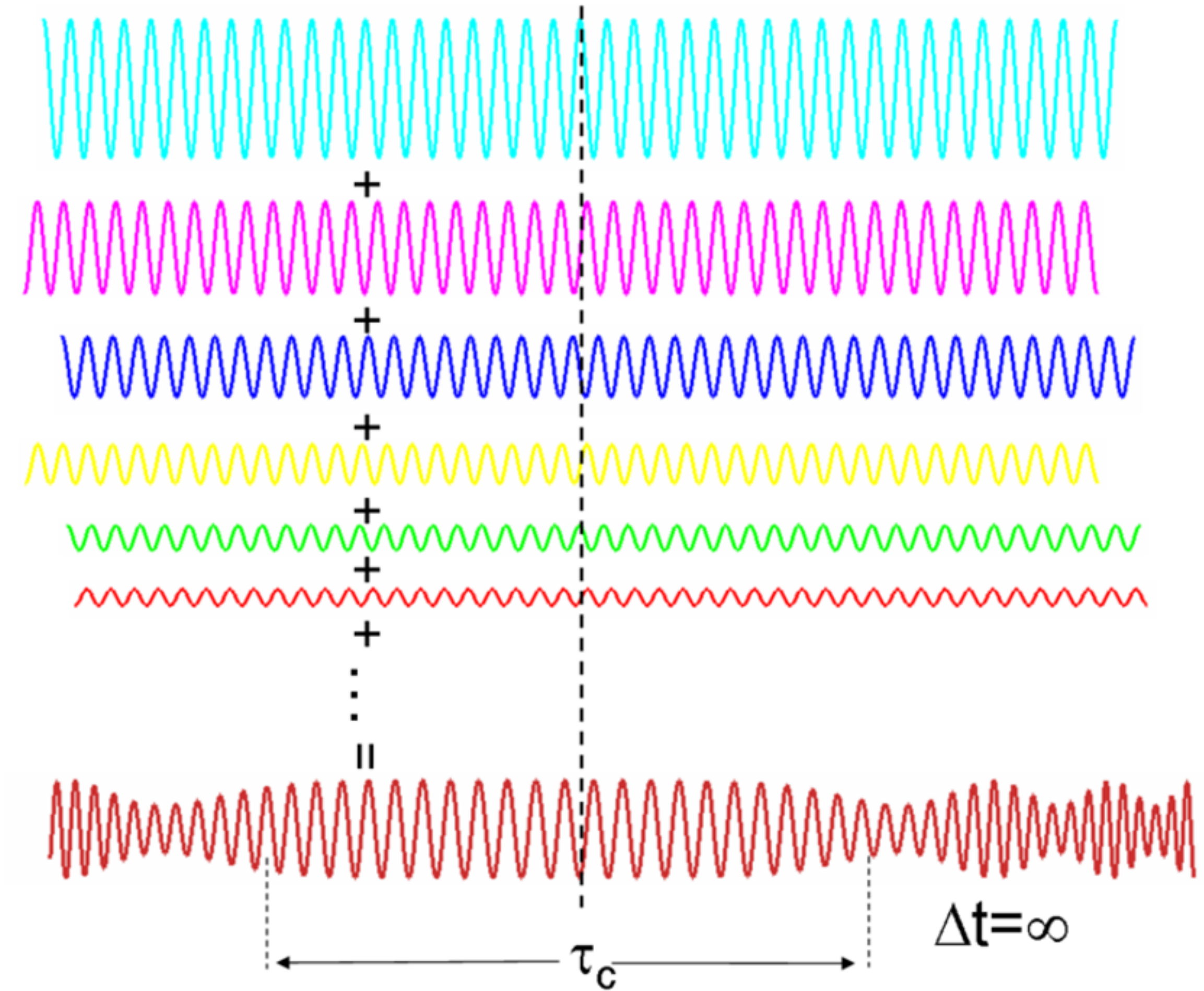
Dark Matter and the Milky Way

- DM makes up most of the Milky Way mass, and density at the solar circle is $0.3\text{-}0.4 \text{ GeV cm}^{-3}$
- Velocity dispersion is large, around 300 km/s (DM is virialised, not thermalised)
- Velocity distribution has cutoff at 544 km/s
- Sun moves with 220 km/s toward constellation Cygnus
- Earth moves around Sun at $\sim 30 \text{ km/s}$
- Mean velocity $\approx$ velocity dispersion $\approx 300 \text{ km/s} = 10^{-3} c$



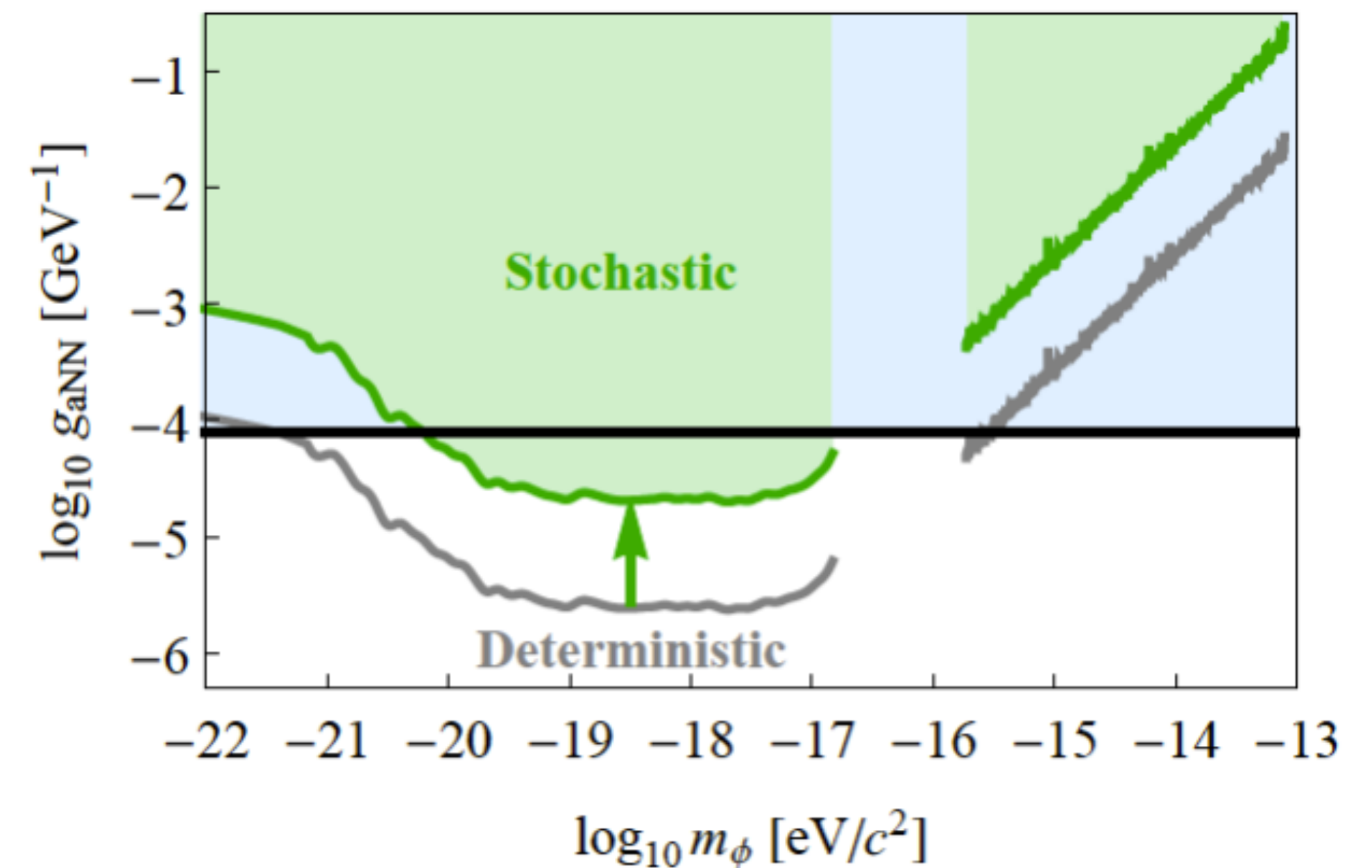
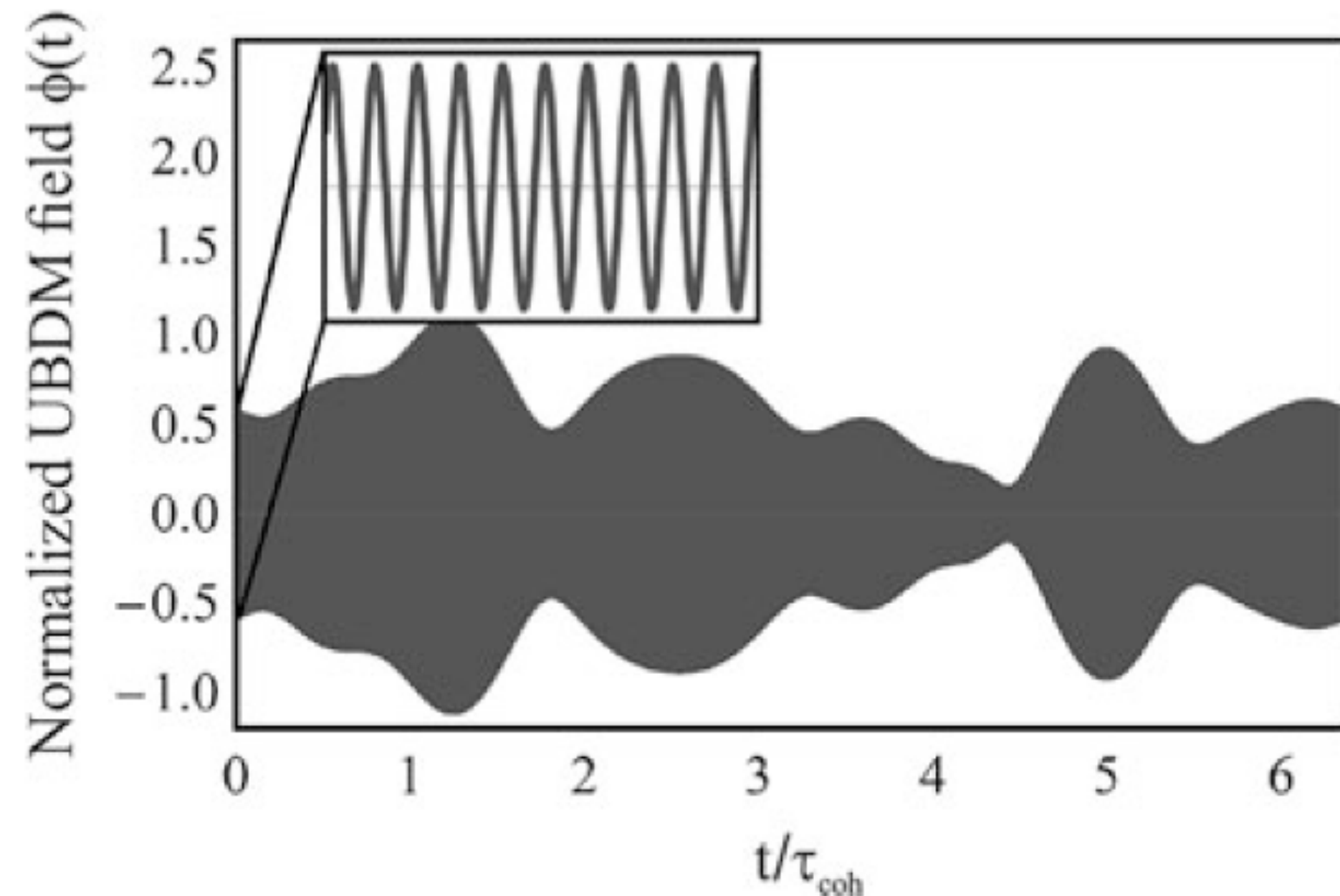
Ultra-Light Dark Matter as Semi-Coherent Waves?

- Simple case: DM is coherent and frequency completely determined by mass (previous page)
- This picture is too simple... the frequency is also a function of velocity (Milky Way, local rest frame)
- The result is a superposition of DM waves and a time dependence
- Amplitude of DM signal only approx. constant within coherence time τ_c



Dark Matter Coherence Time vs T_{data}

- Field amplitude varies stochastically with time
- For $T_{\text{data}} < \tau_c$: oscillation occurs at same frequency, but field amplitude not same as average DM density
- For $T_{\text{data}} > \tau_c$: assumption of a single frequency fails, but the amplitude is given by the average DM density
- Impact on clock experiments: Limits are weakened by about a factor of 3-10



Data Analysis Challenge

- One frequency ratio R measurement per s for $\mathcal{O}(1 \text{ year})$, i.e. 3×10^7 data points $\rightarrow$ time series analysis
- We can estimate the error on dR/R by adding in quadrature the fractional frequency error for the two clocks (each with e.g. probe time 1 s)
- Ultimately, we would like to measure/limit the signal frequency (thus m_ϕ) and also Λ

$$\frac{dR}{R} = [K_{\alpha,1} - K_{\alpha,2}] \frac{\phi_0 \cos(m_\phi t)}{\Lambda}$$

- *The challenge:*
- Limited time steps: discrete (~ 1 s) data points
- Limited resolution: can't say anything about periods much smaller than 1s
- Irregular gaps in data-taking periods
- Assumptions/model dependence/systematic errors in $K_{\alpha,1}$, $K_{\alpha,2}$, ϕ_0 , relation to Λ

Fourier Transform and Power Spectral Density

- There are many techniques to identify periodicity
- Signal is often folded/convolved with a windowing function resulting from experimental constraints
- Suitable analysis method depends on many factors (frequency known or not, phase known or not, cadence of observations)
- Our case: frequency unknown, but relatively high uptime and regularly spaced measurements

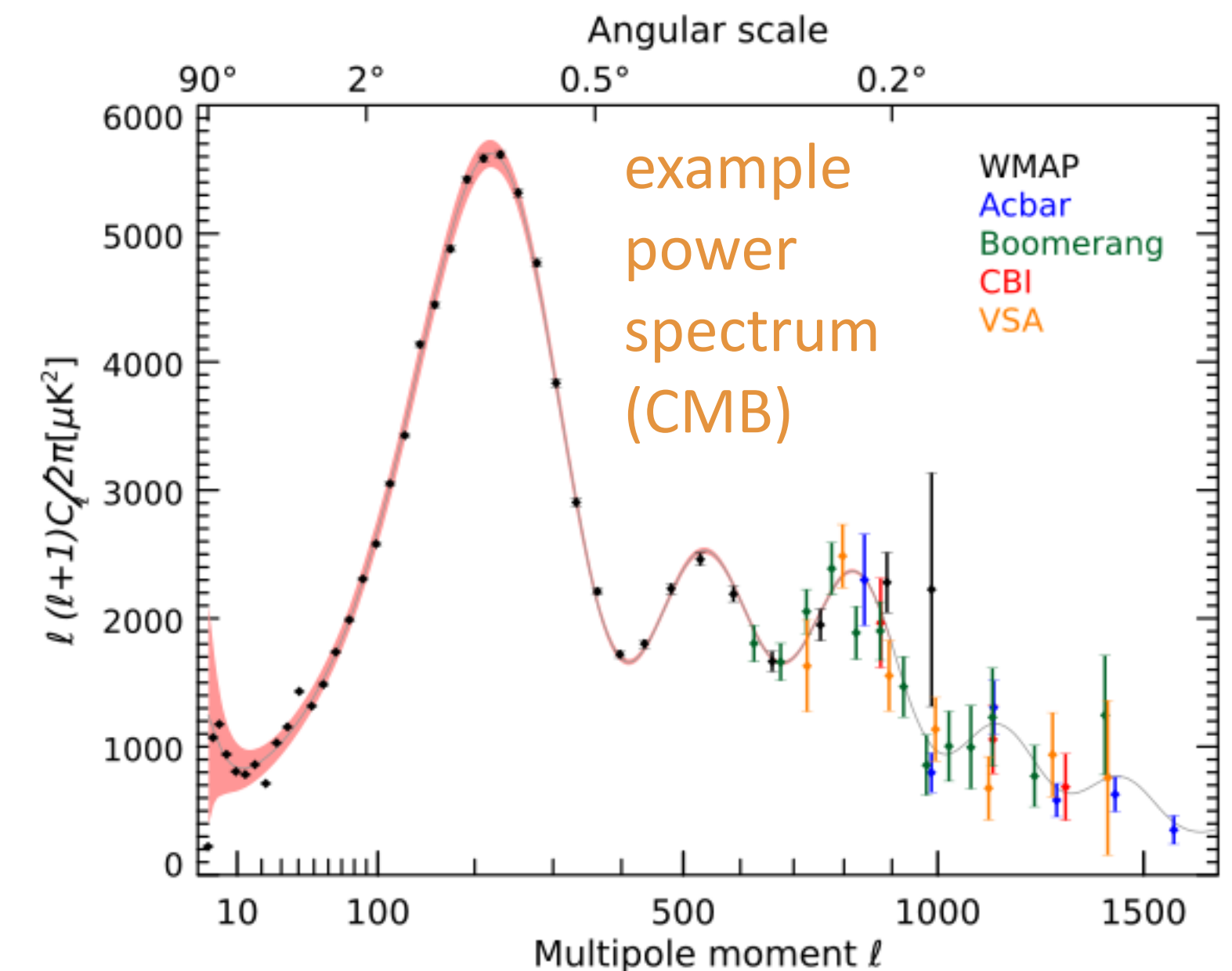
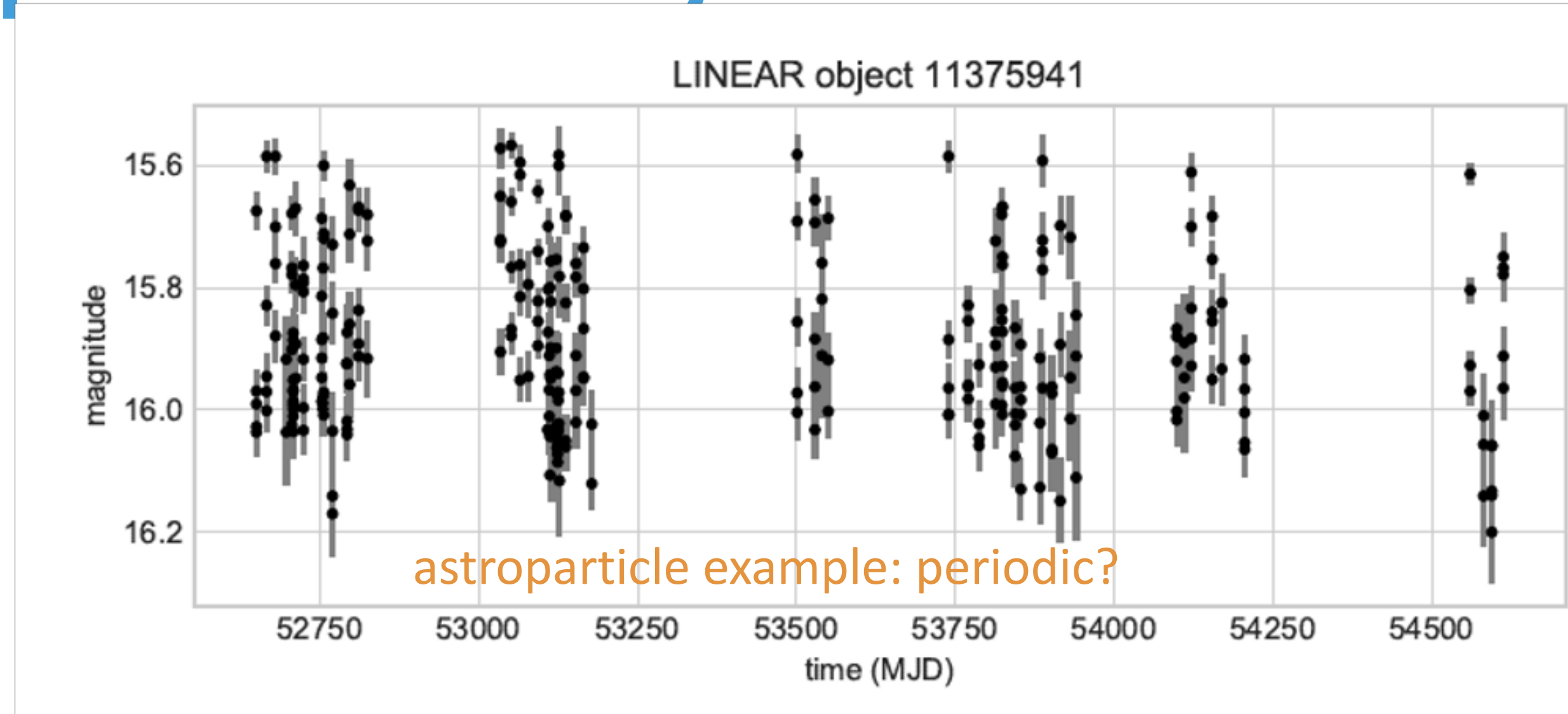
$$\frac{dR}{R} \propto A \cos(\omega t + \phi) = g(t)$$

$$F(\omega) = \int_{-\infty}^{+\infty} g(t) e^{-i\omega t} dt$$

Fourier transform

$$P(\omega) = \lim_{T \rightarrow \infty} \frac{1}{T} |F(\omega)|^2$$

power spectral density



Periodogram and Lomb-Scargle

- Periodogram: serves as an estimate of the power spectral density for the case of discrete data
- A periodogram is useful for finding the dominant periods (or frequencies) of a fixed-interval time series
- Lomb-Scargle Periodogram developed for cases where the sampling is irregular

$$P(\omega) = \lim_{T \rightarrow \infty} \frac{1}{T} |F(\omega)|^2 = \lim_{T \rightarrow \infty} \frac{1}{T} \left(\int g \sin \omega t dt \right)^2 + \left(\int g \cos \omega t dt \right)^2$$

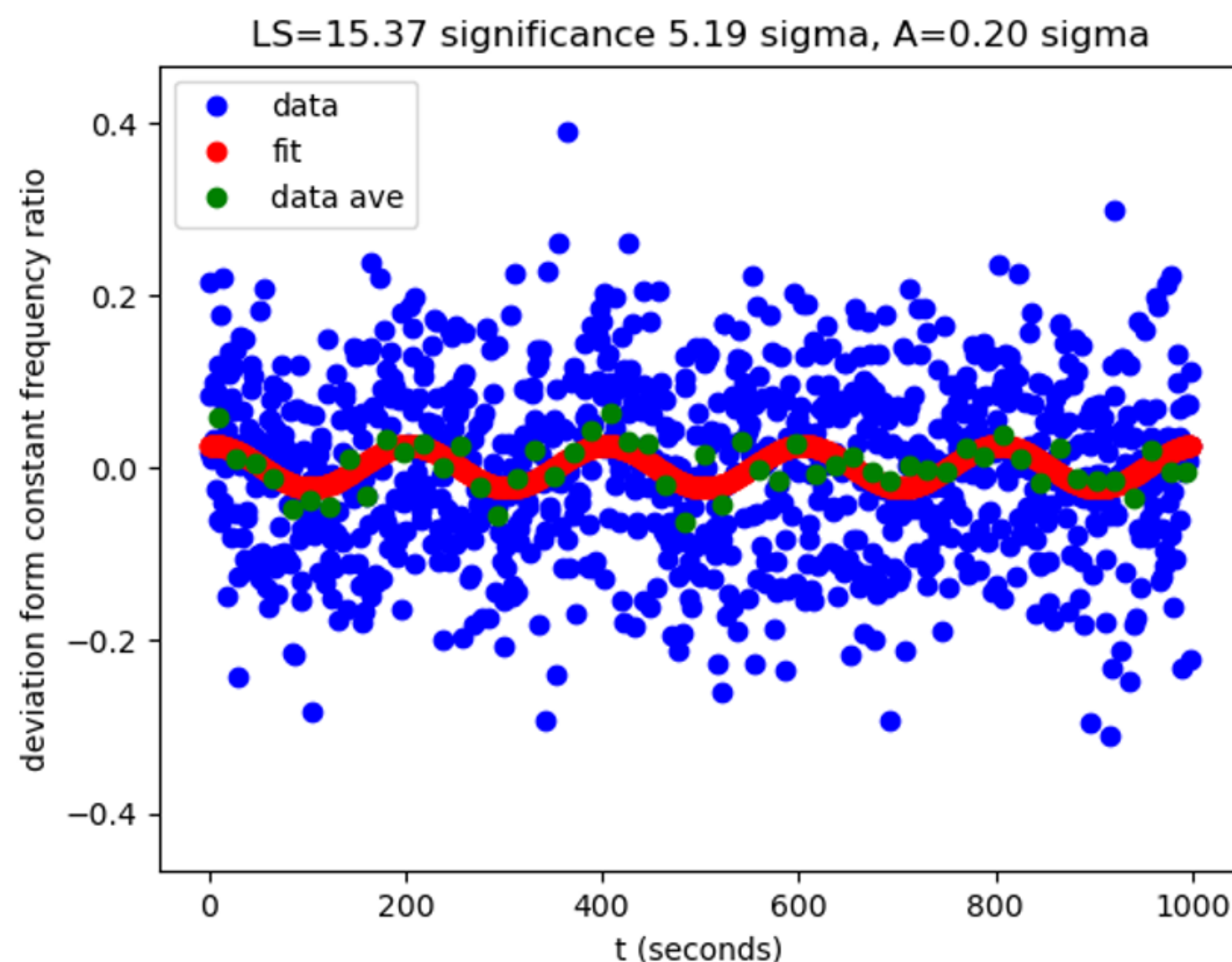
power
spectral
density

$$\frac{1}{N} \left\{ \left(\sum g_n \cos(\omega t_n) \right)^2 + \left(\sum g_n \sin(\omega t_n) \right)^2 \right\}$$

classic
periodogram

$$\frac{B_1^2}{2} \left(\sum g_n \cos(\omega(t_n - \tau)) \right)^2 + \frac{B_2^2}{2} \left(\sum g_n \sin(\omega(t_n - \tau)) \right)^2$$

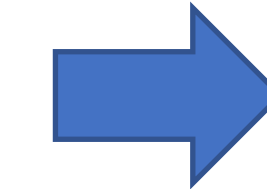
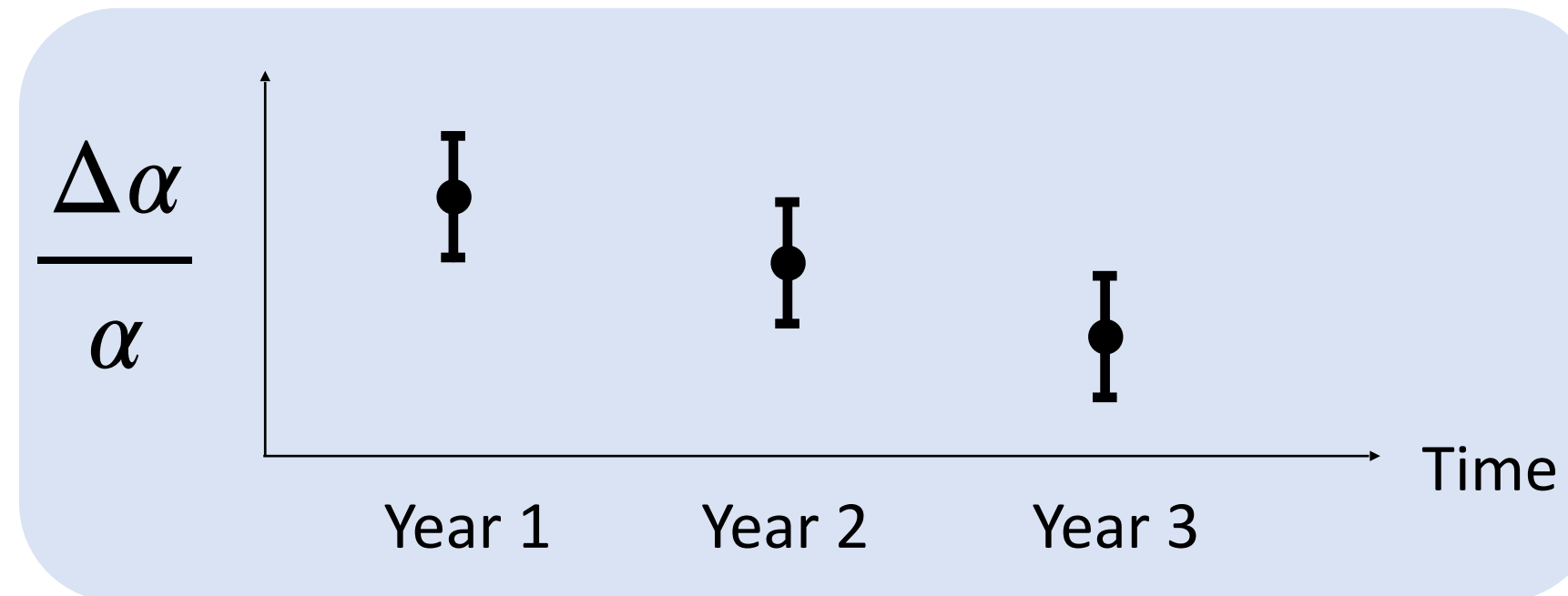
Lomb-Scargle
periodogram



Simulation w/ Lomb-Scargle fit (red)
1 Hz sampling, $\sigma=0.1$, $N=10^3$, $T=200$ s

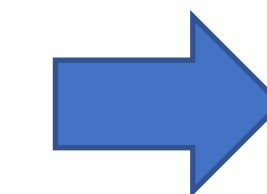
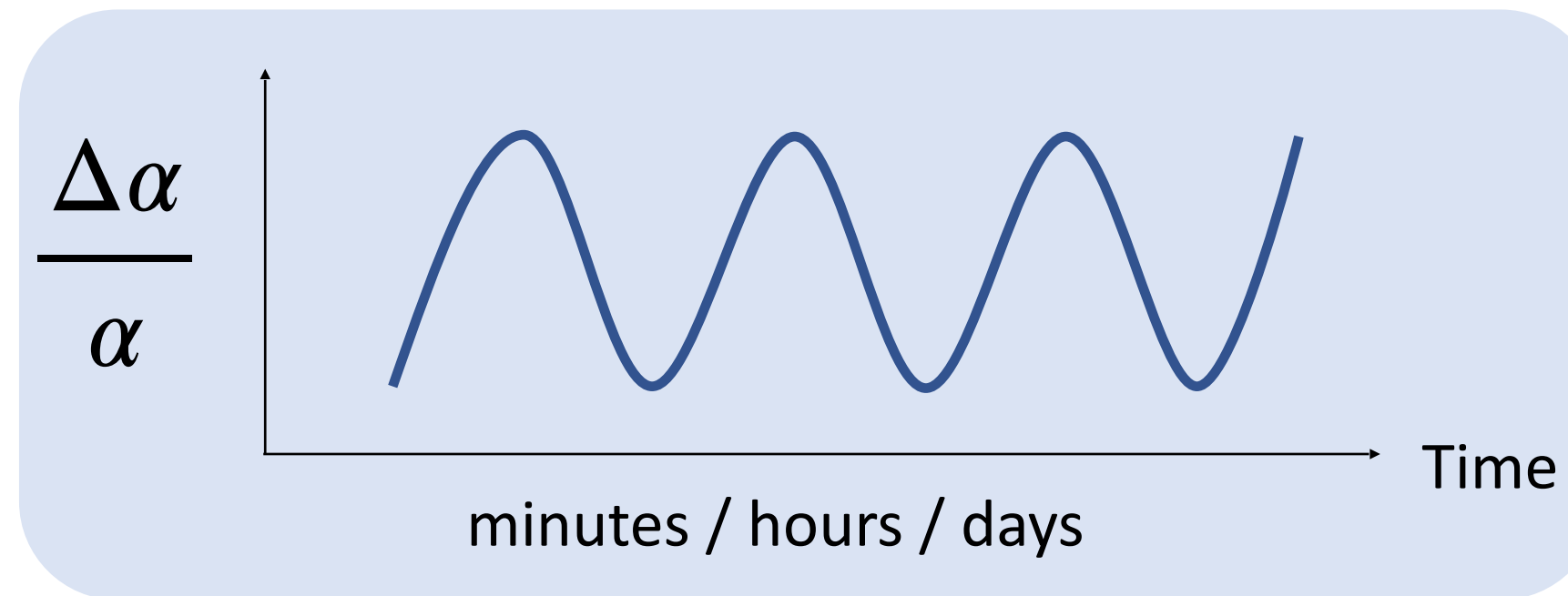
Clock-based Search for α Variations at Different Timescales

- Slow drifts



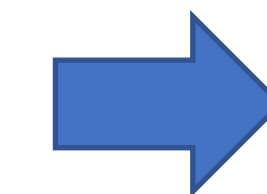
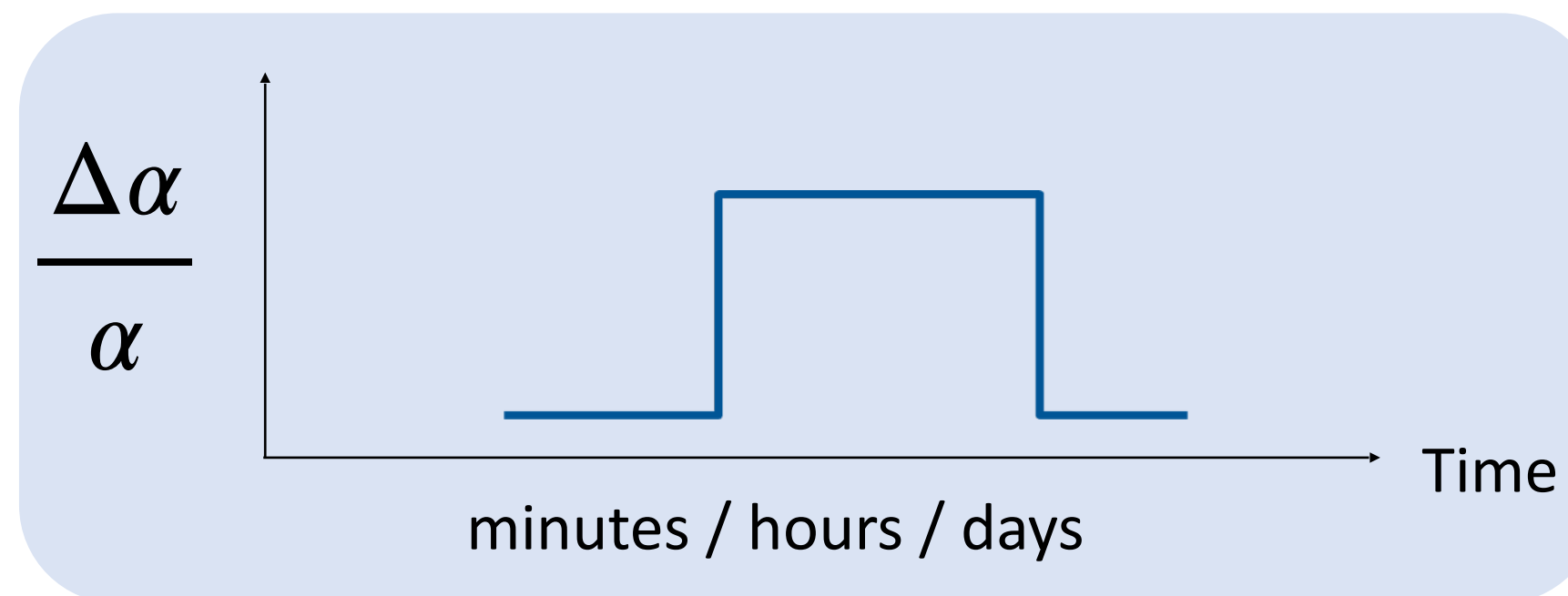
New physics

- Oscillations



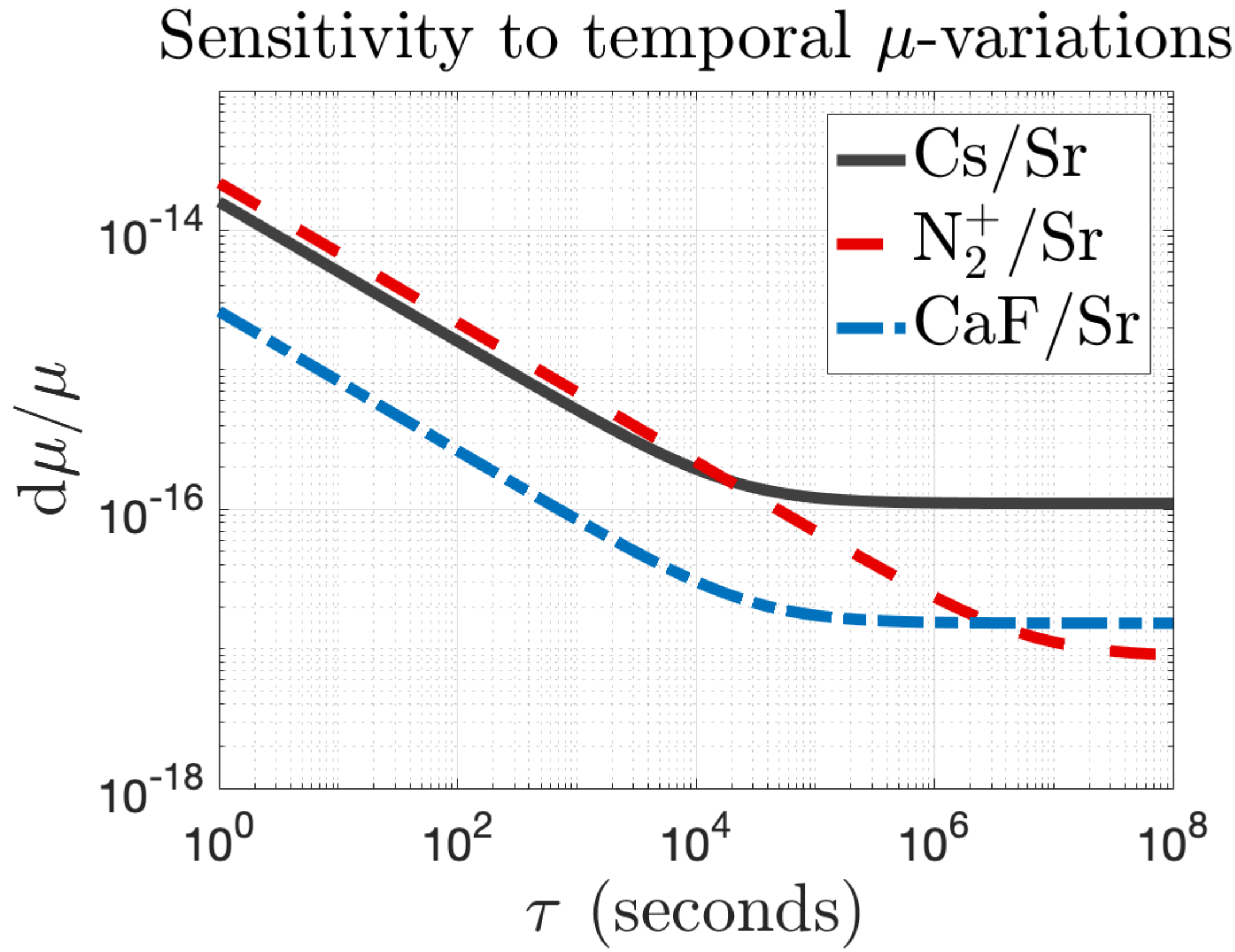
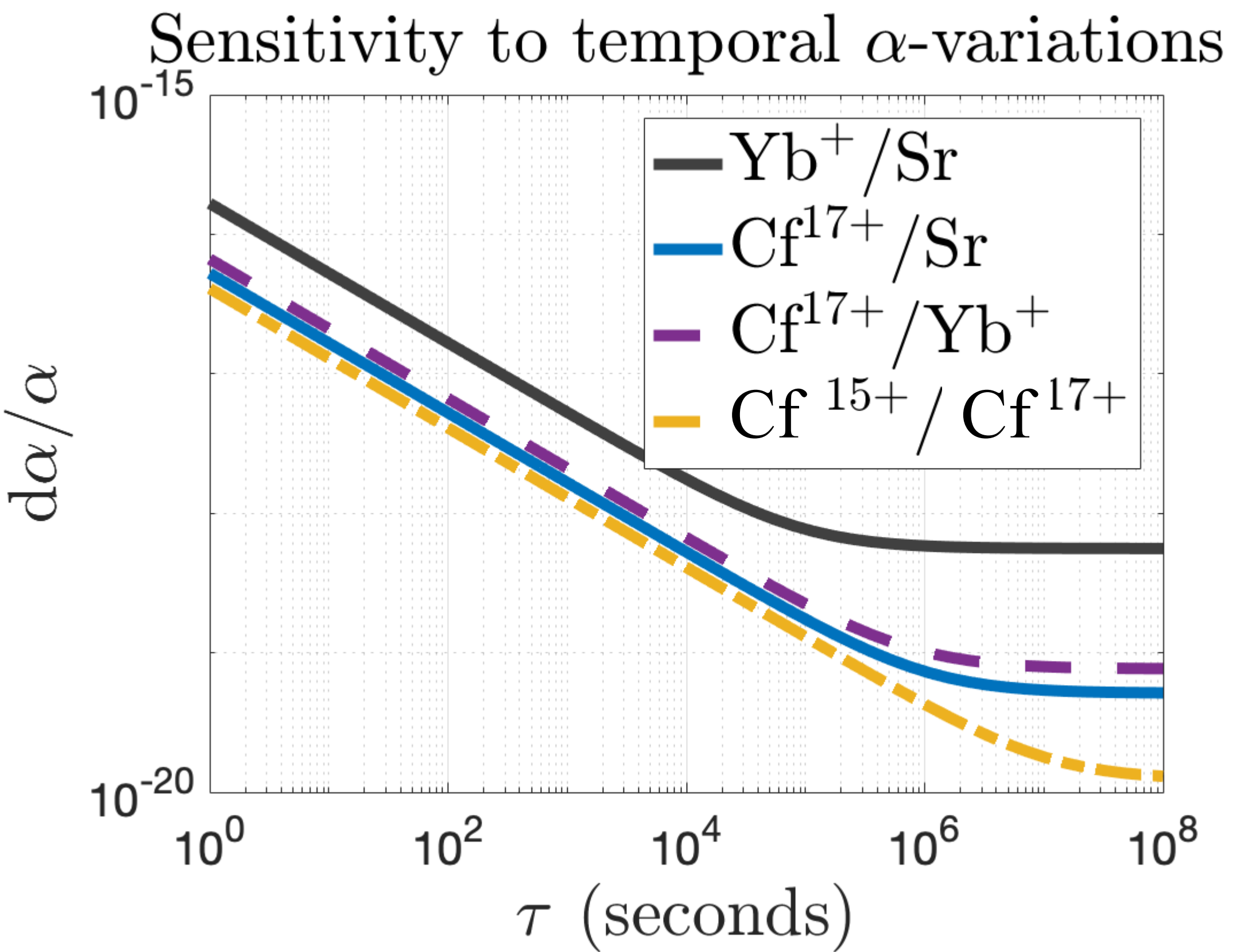
Very light dark matter

- Fast transients

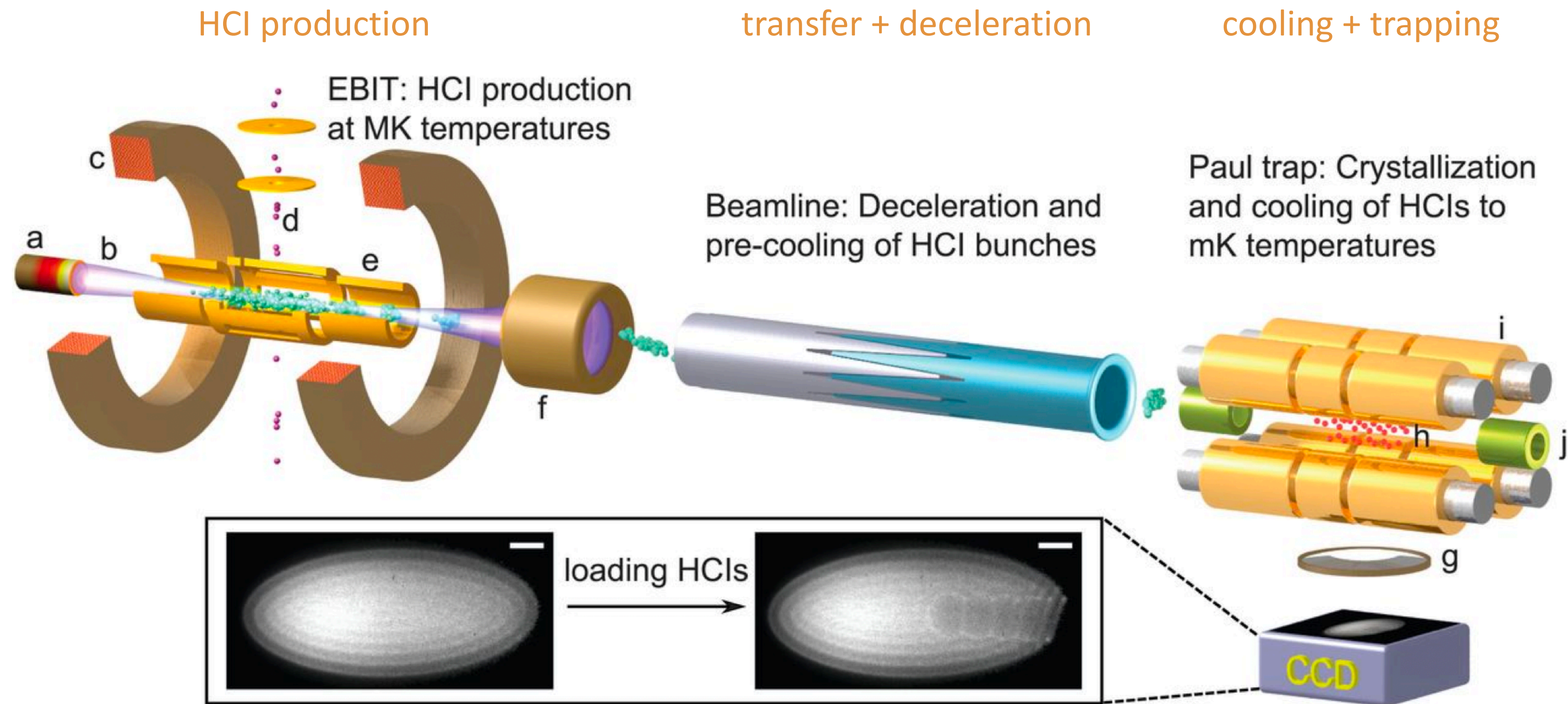


Dark matter, topological defects

Sensitivities to Temporal Variations of α, μ

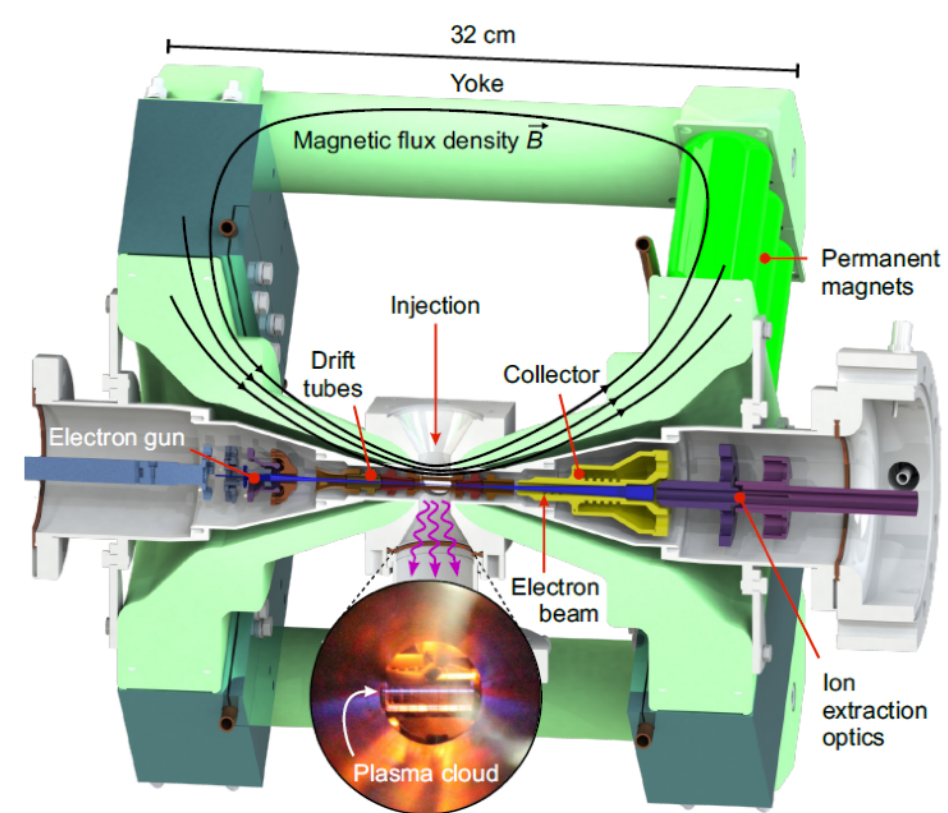


Highly Charged Ions: Production, Cooling and Trapping

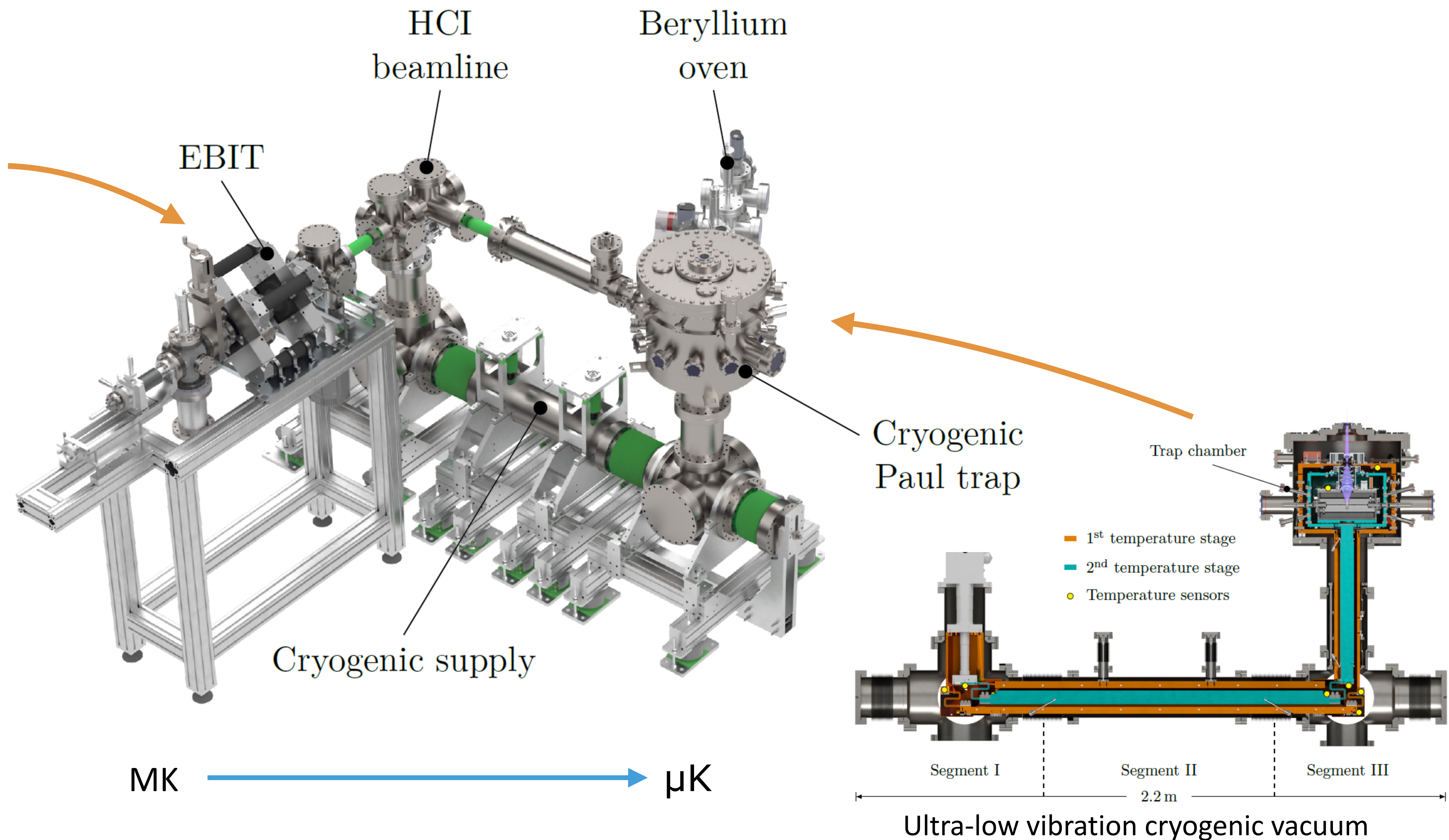


- EBIT: Electron Beam Ion Trap (used as a source of HCI)
- HCI bunches are loaded into a linear Paul Trap on demand (HCI lifetimes can be hours)
- Laser and Sympathetic Cooling e.g. with Be^+ , Ca^+ (lots of lasers for cooling/preparation/readout)

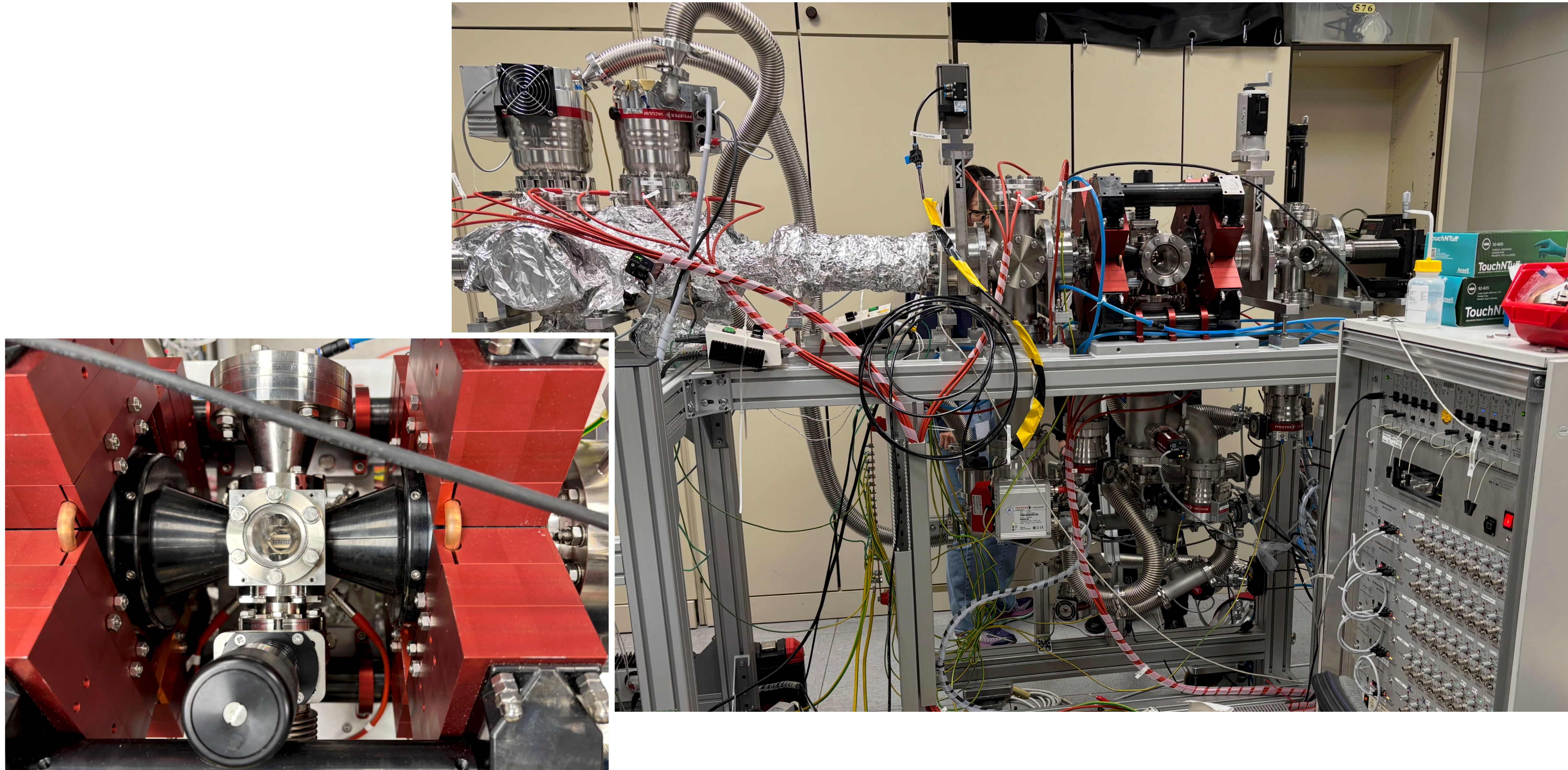
Highly Charged Ions: Production, Cooling and Trapping



Compact EBIT @ MPIK



TIQTOC: Trapped Ion Quantum Test Of fundamental Constants



Towards a Thorium Nuclear Clock

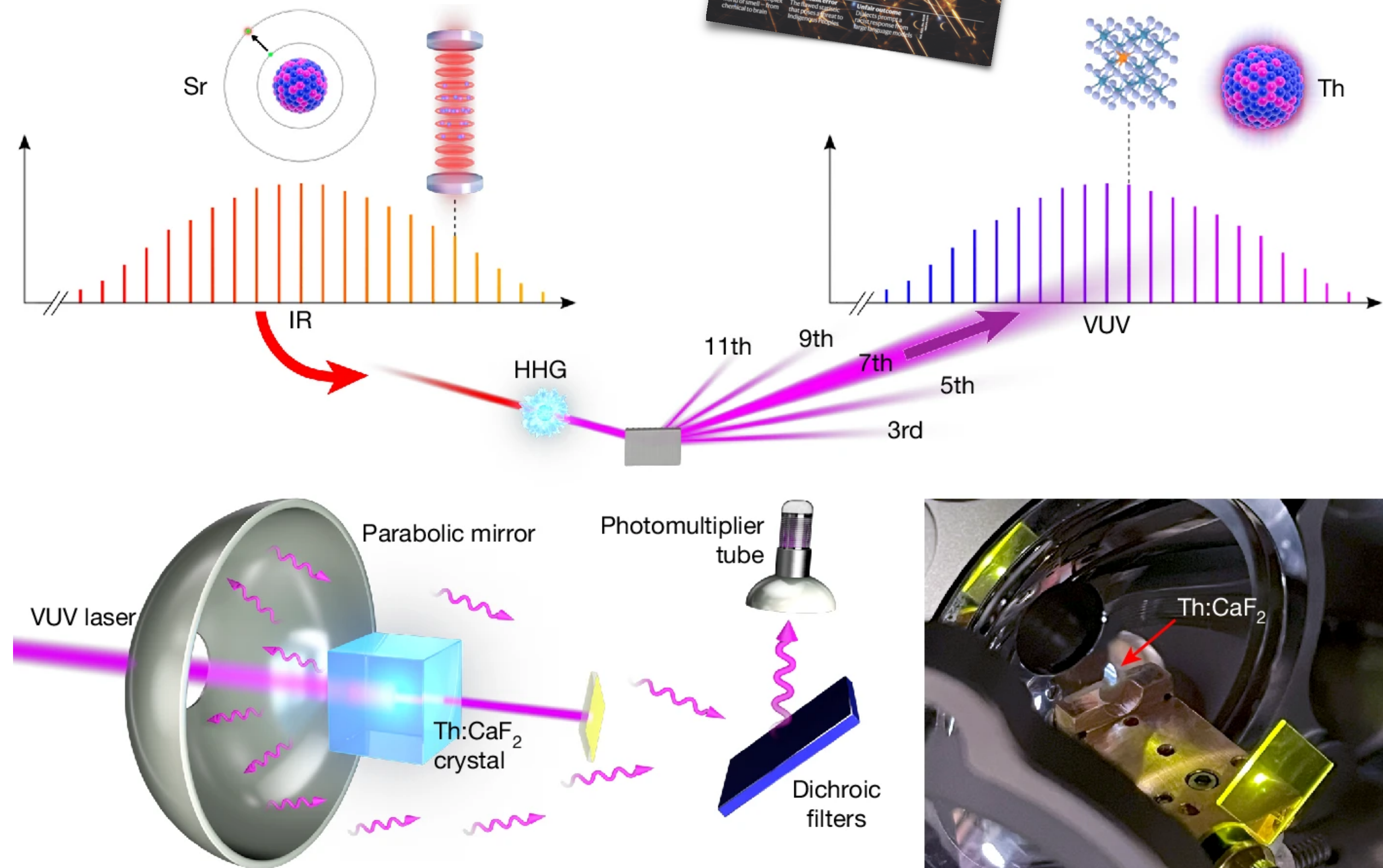
- Only one with an unusually low excitation energy: $^{229\text{m}}\text{Th}$
 - Excitation ≈ 8 eV $\rightarrow$ can be laser-excited
 - $^{229\text{m}}\text{Th}$: Lifetime $\approx 1/2$ h
- Measurement precision ($\delta\nu/\nu$) vs. time:
 - 2020: 10^{-1}
 - 2022: 10^{-3} (ISOLDE)
 - 2024, March: 10^{-6} (PTB)
 - 2024, June: 10^{-11} (JILA)
 - 2025, July: 10^{-13} (JILA)
- Next Challenges: make a clock
 - UV Laser & Frequency comb
 - Thorium preparation - crystal, trap, etc
 - How to estimate new physics sensitivity



Towards a Thorium Nuclear Clock

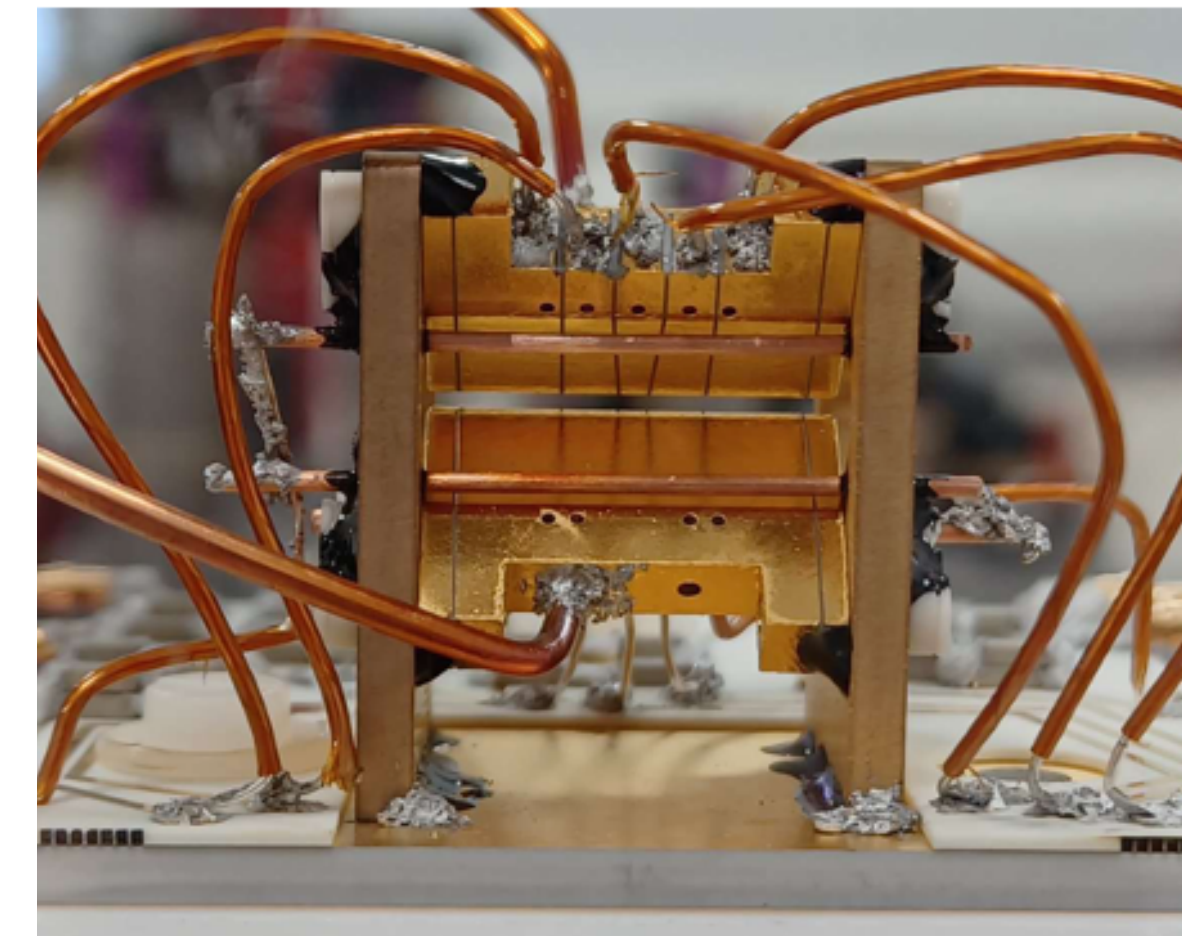
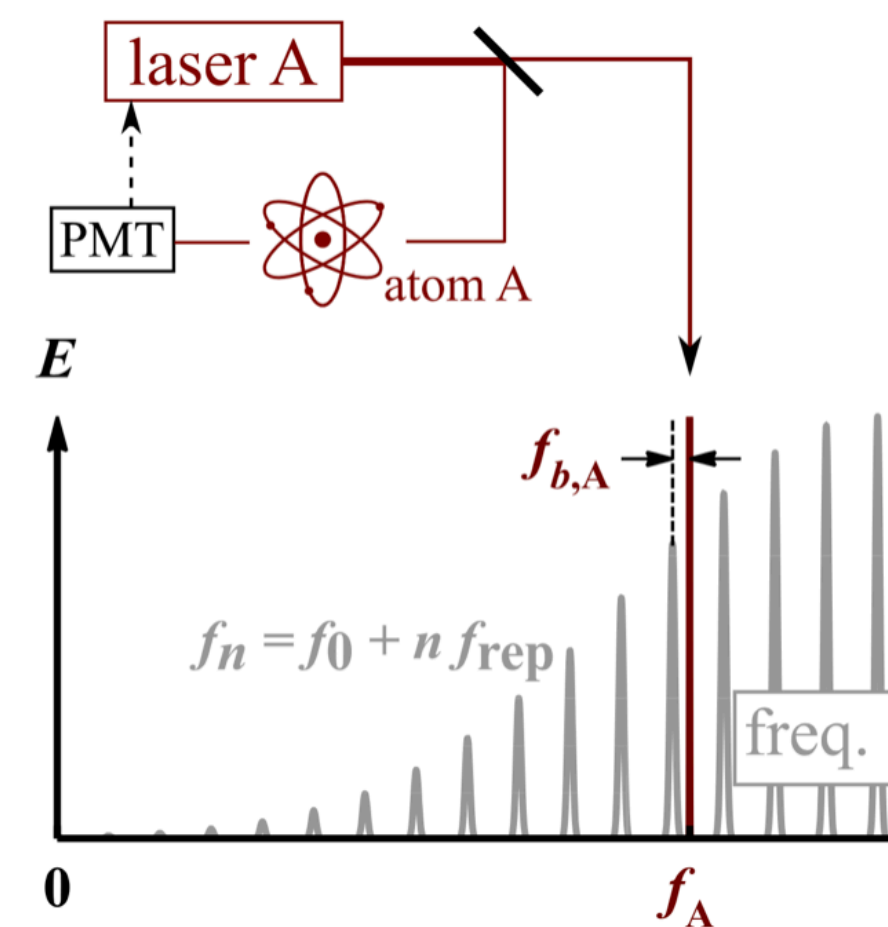
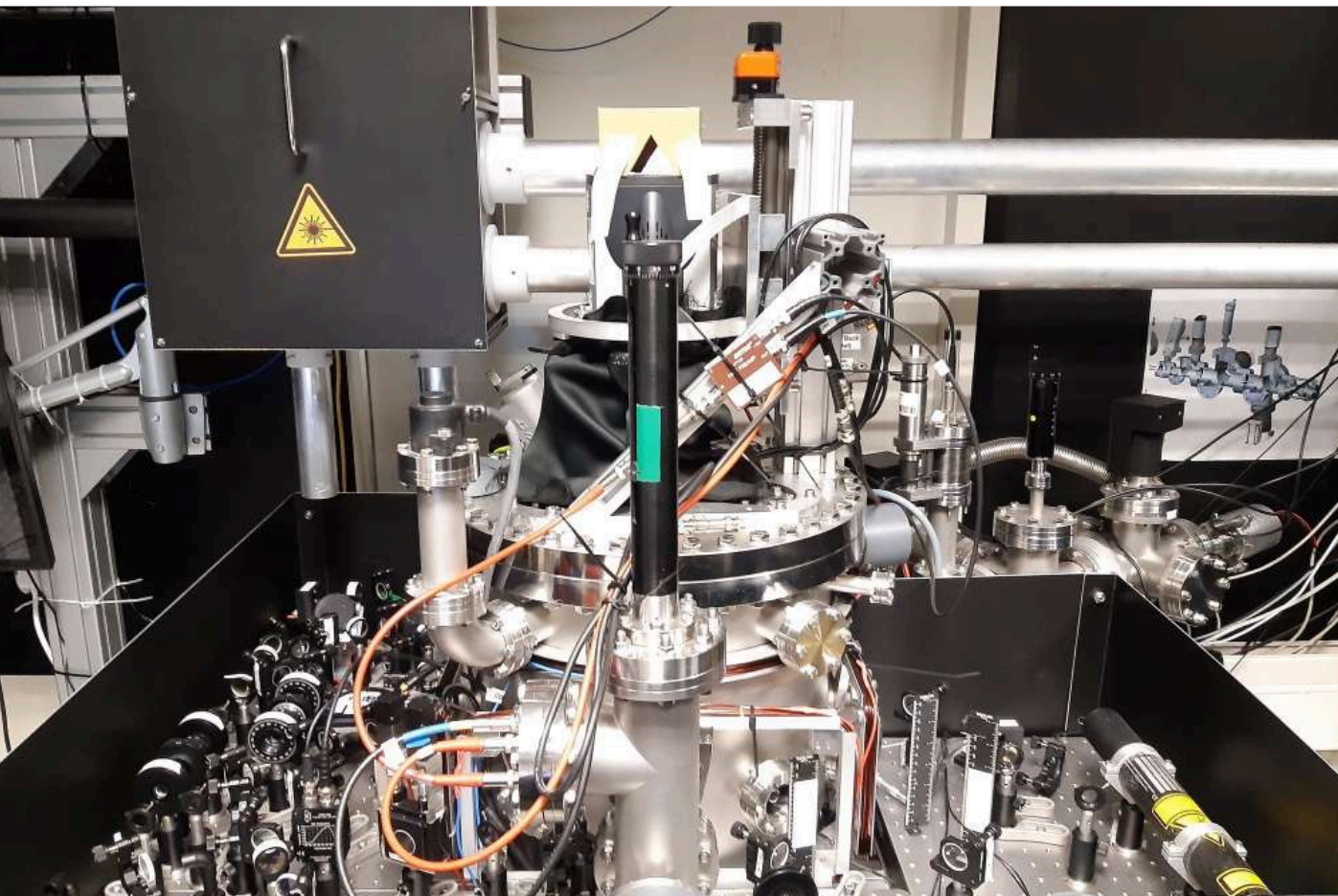
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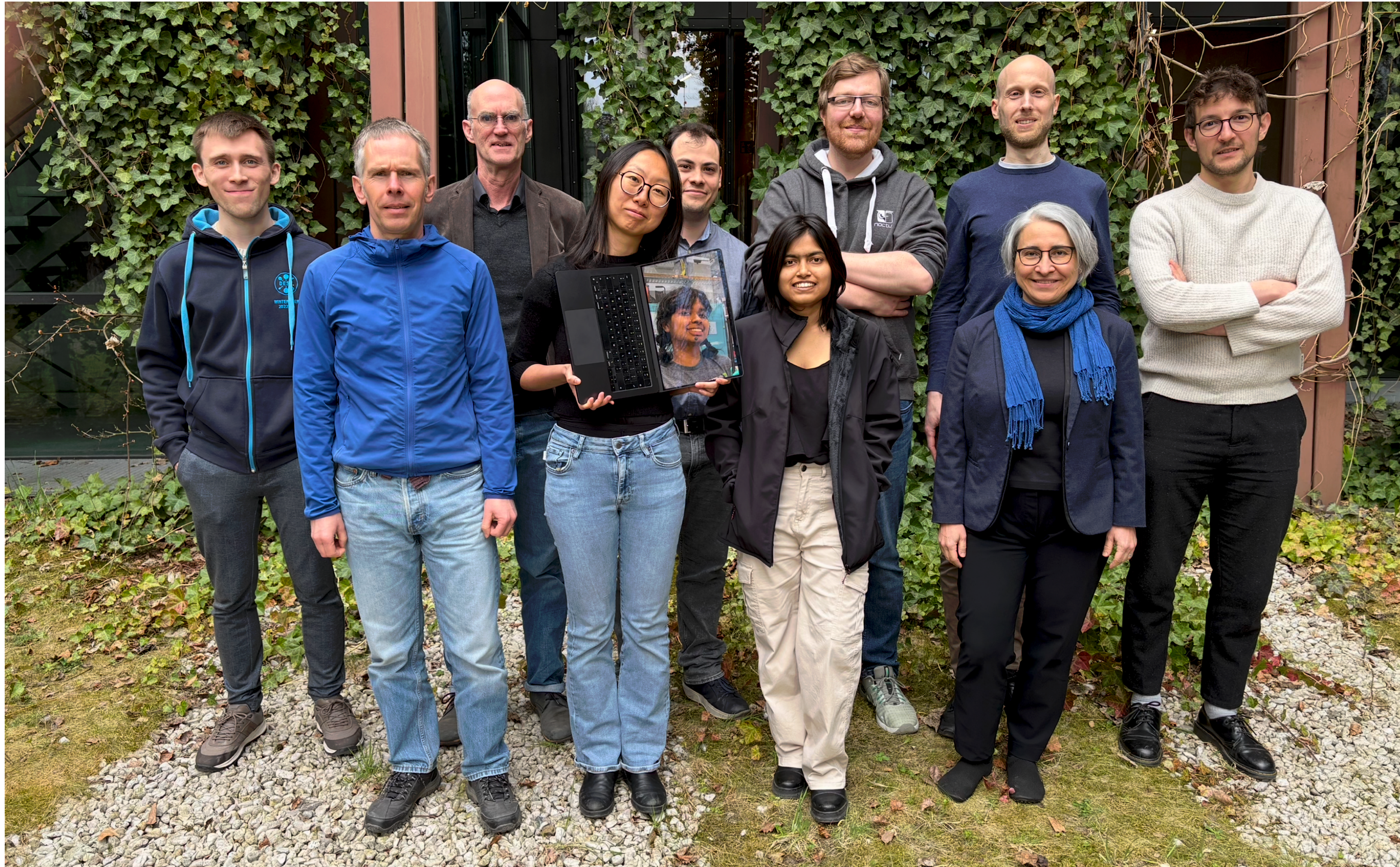
Nuclear clocks are here!



Conclusions

- Optical Atomic Clocks are some of the most sensitive instruments available
- Fantastic testbed for all sorts of new physics, for example ultra-light dark matter
- Lots of new ideas to follow and new innovations... new clocks, networks, and opportunities!





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