Building a Quantum Experiment: Fundamental Physics with Atomic Clocks

National Tsing Hua University

16th Particle Physics Phenomenology Workshop

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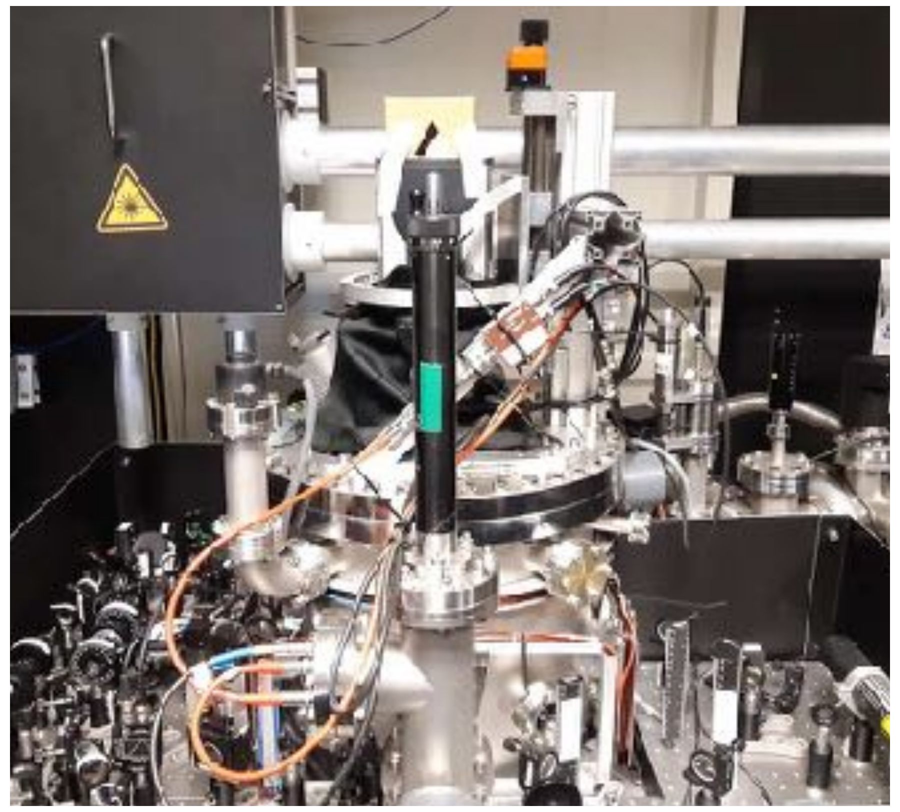
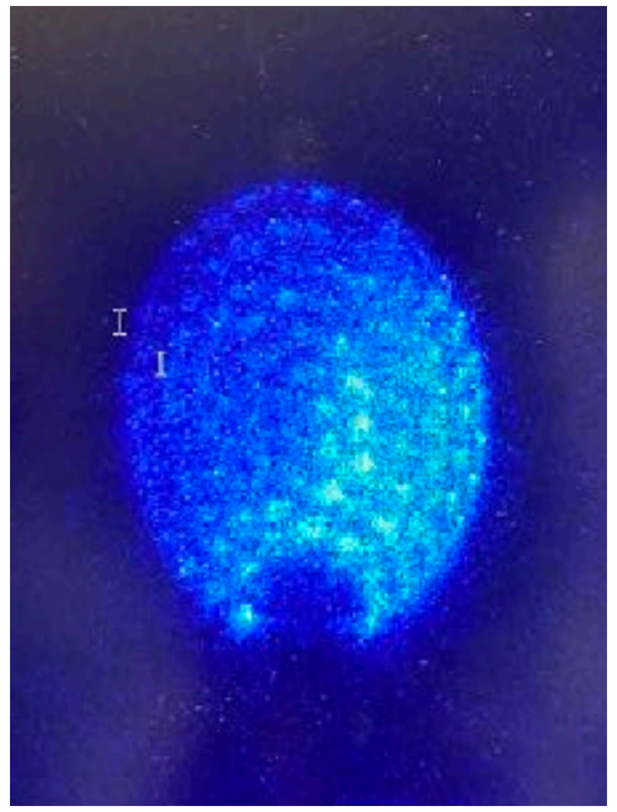
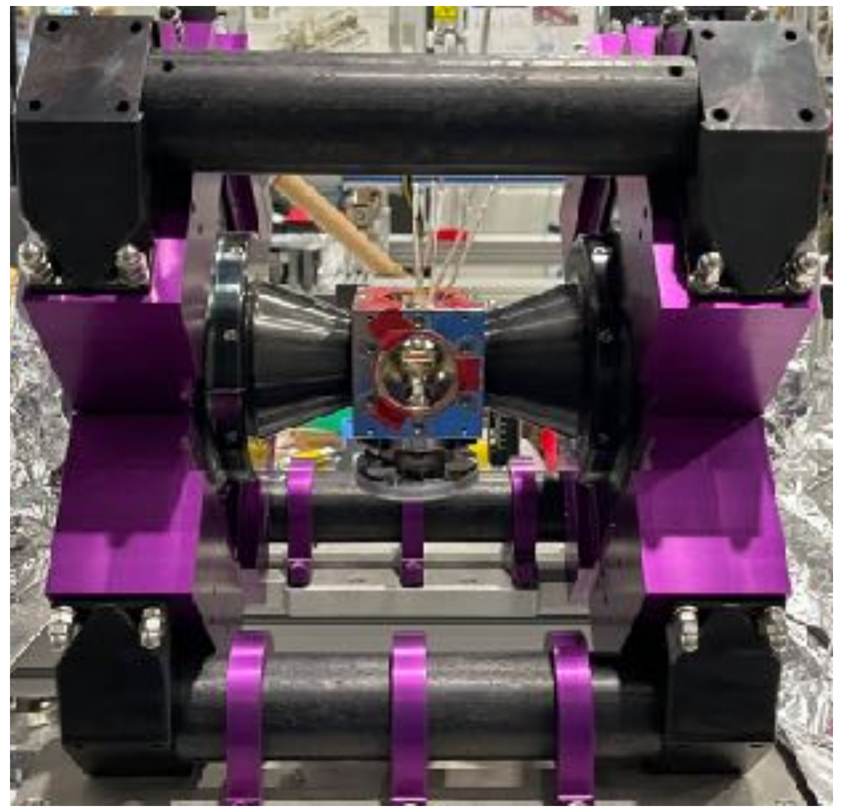
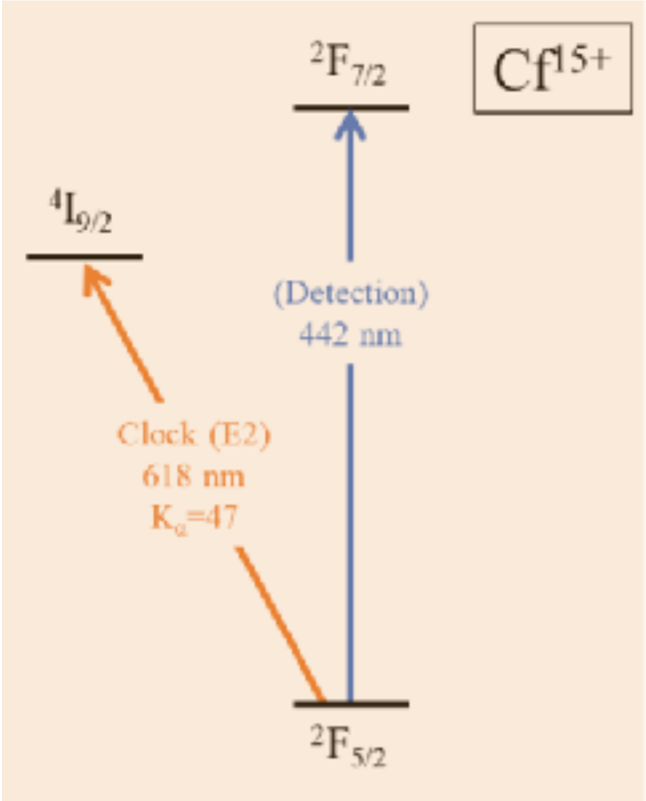
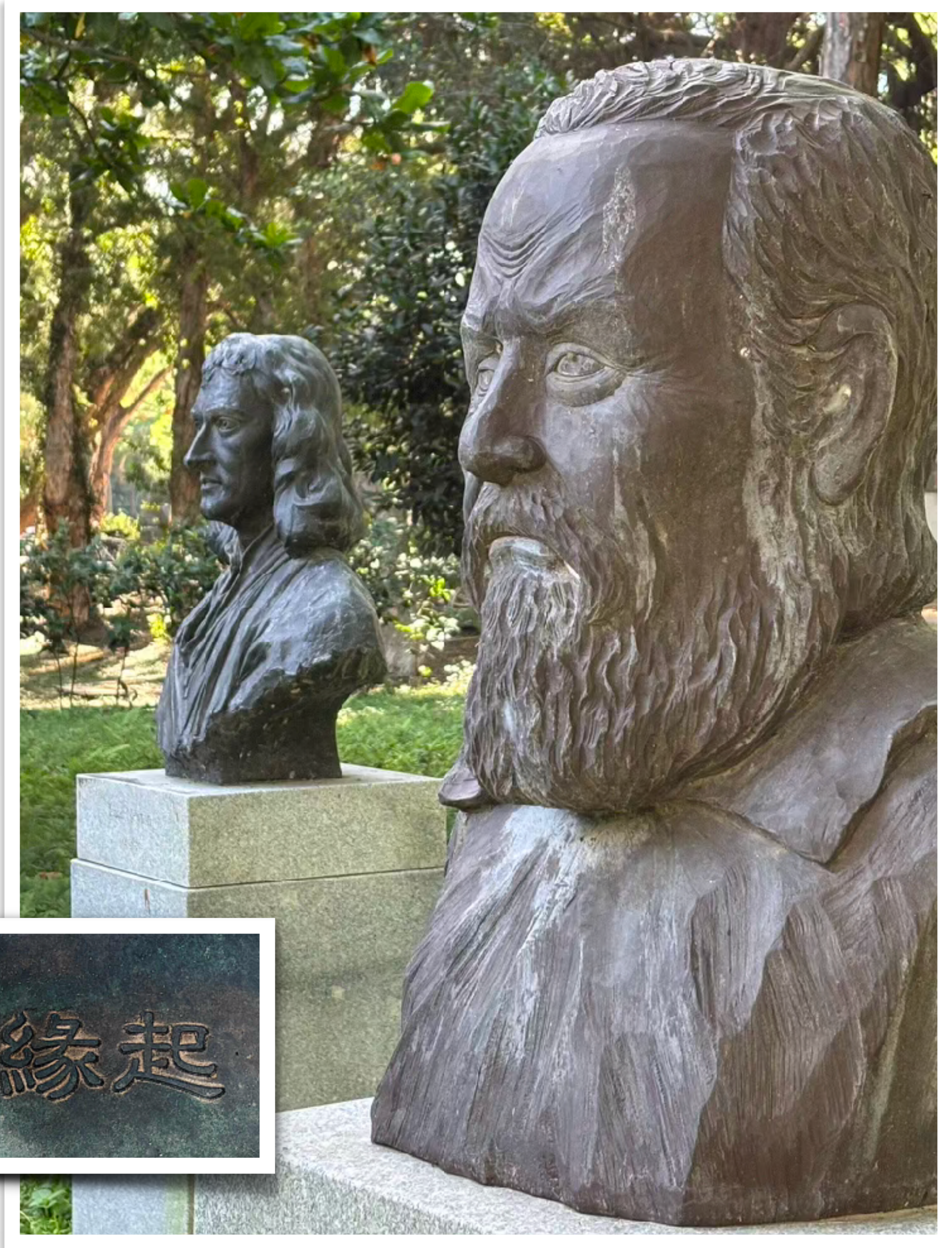






Outline

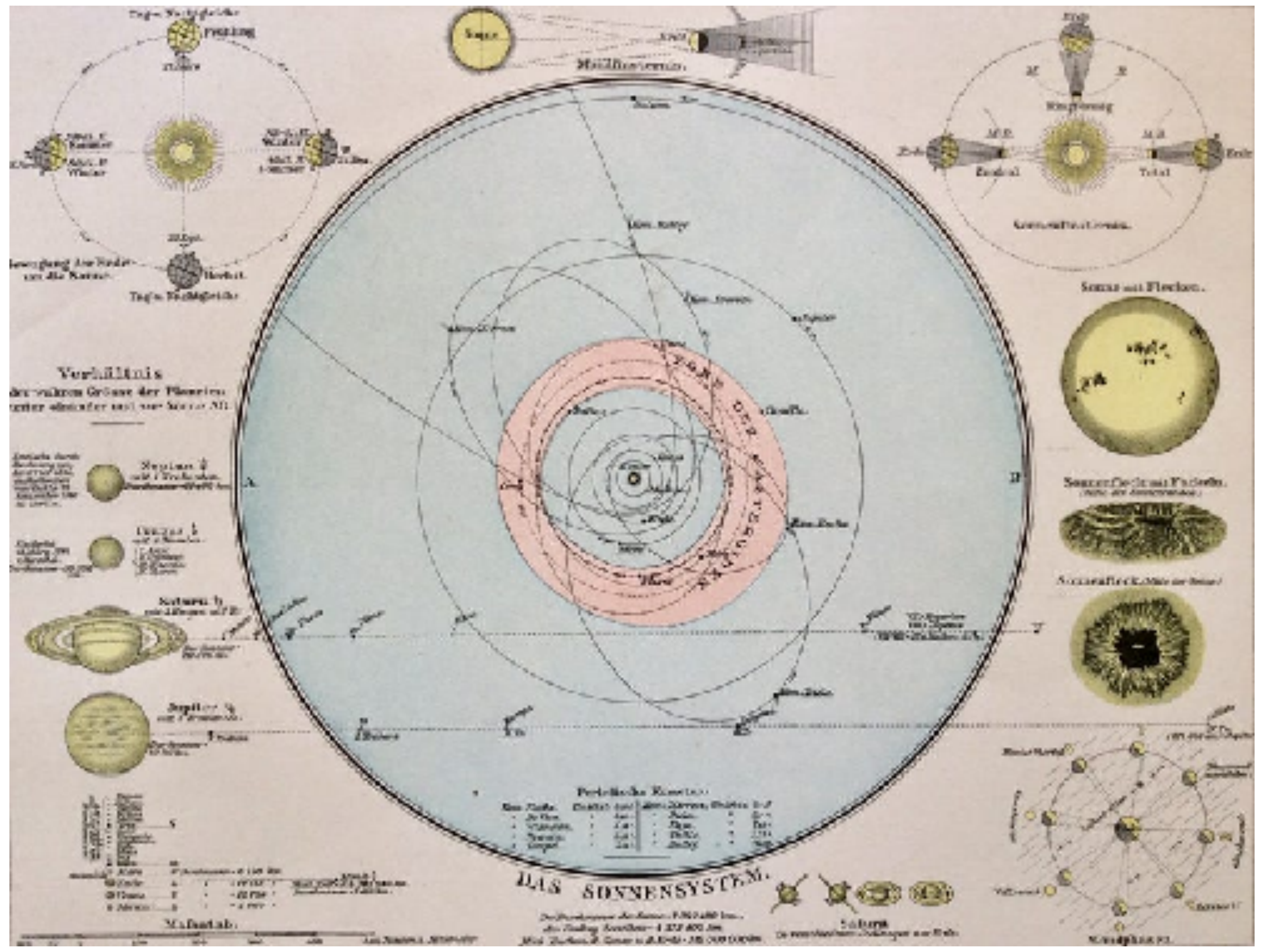
- Clocks in History
- Clock Basics
- What makes a good clock?
- Physics with a Clock
- Networks of Clocks
- The Future?

Galileo & Newton in the Garden

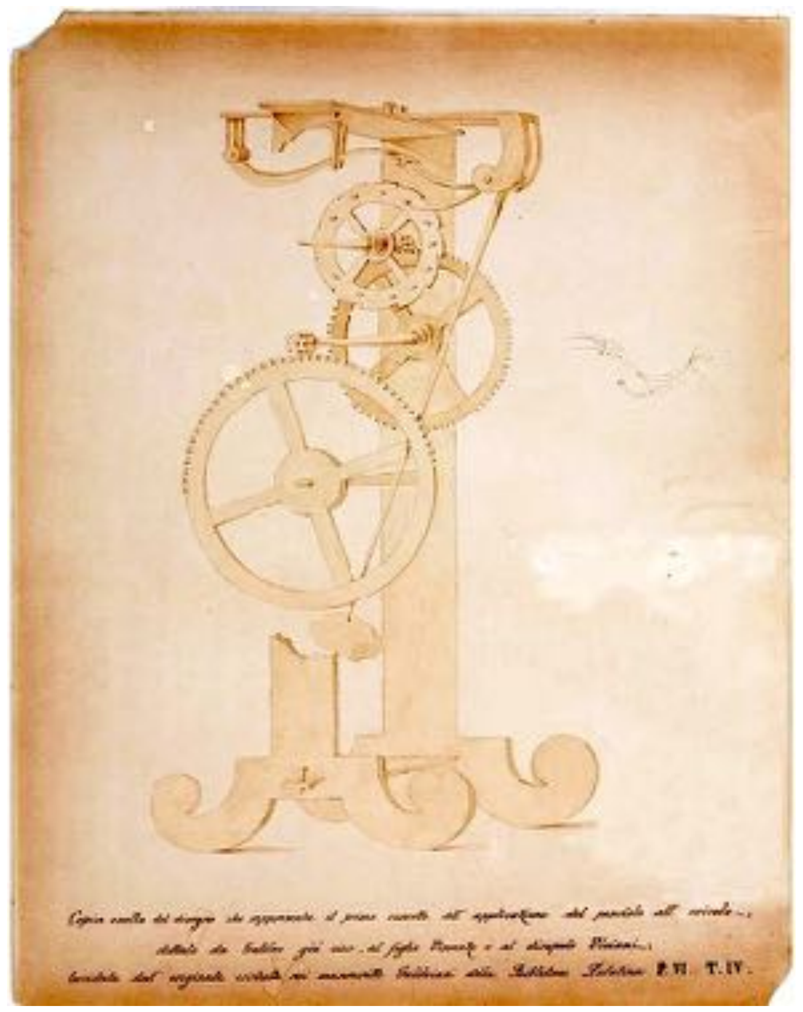


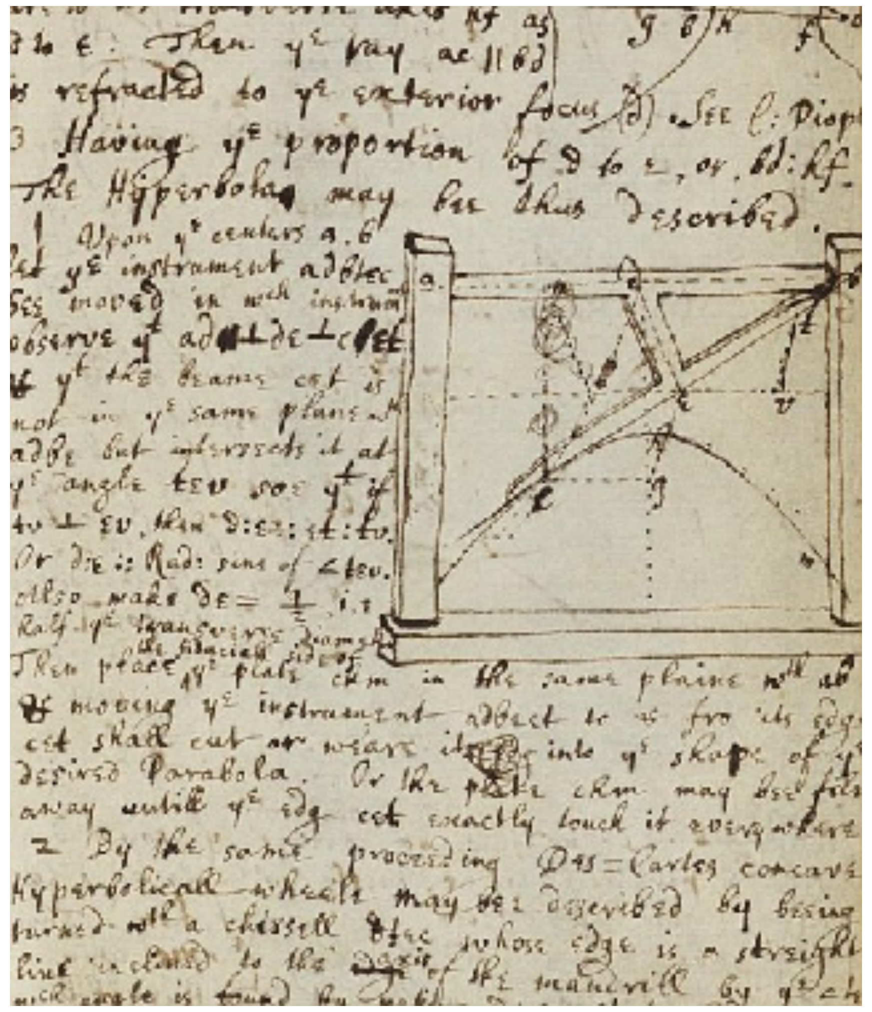
Revolutionary Clocks for Science

- 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

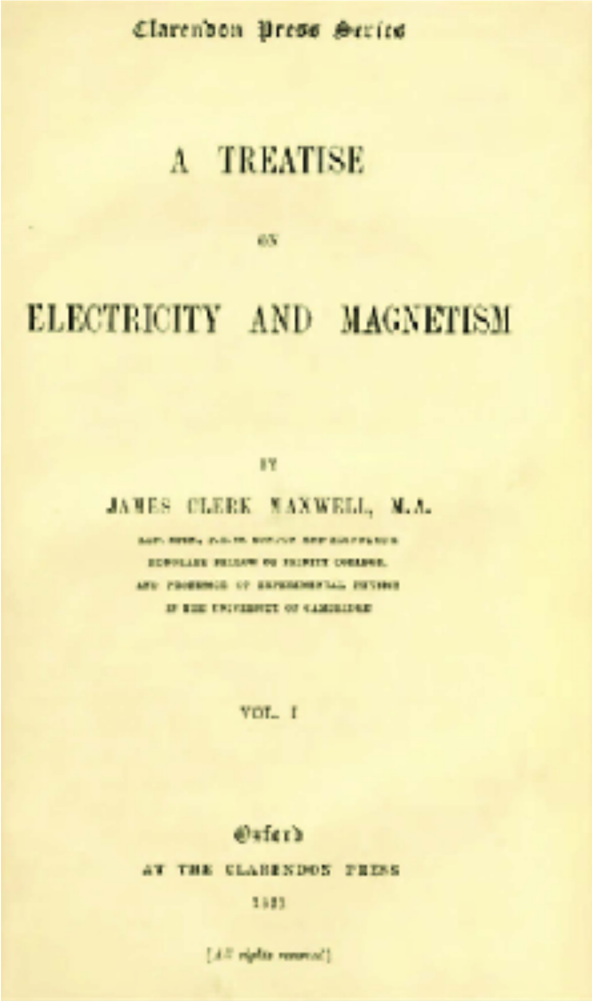


Astronomical predictions for the Solar System


Galileo's pendulum clock design


Newton's tests of gravity

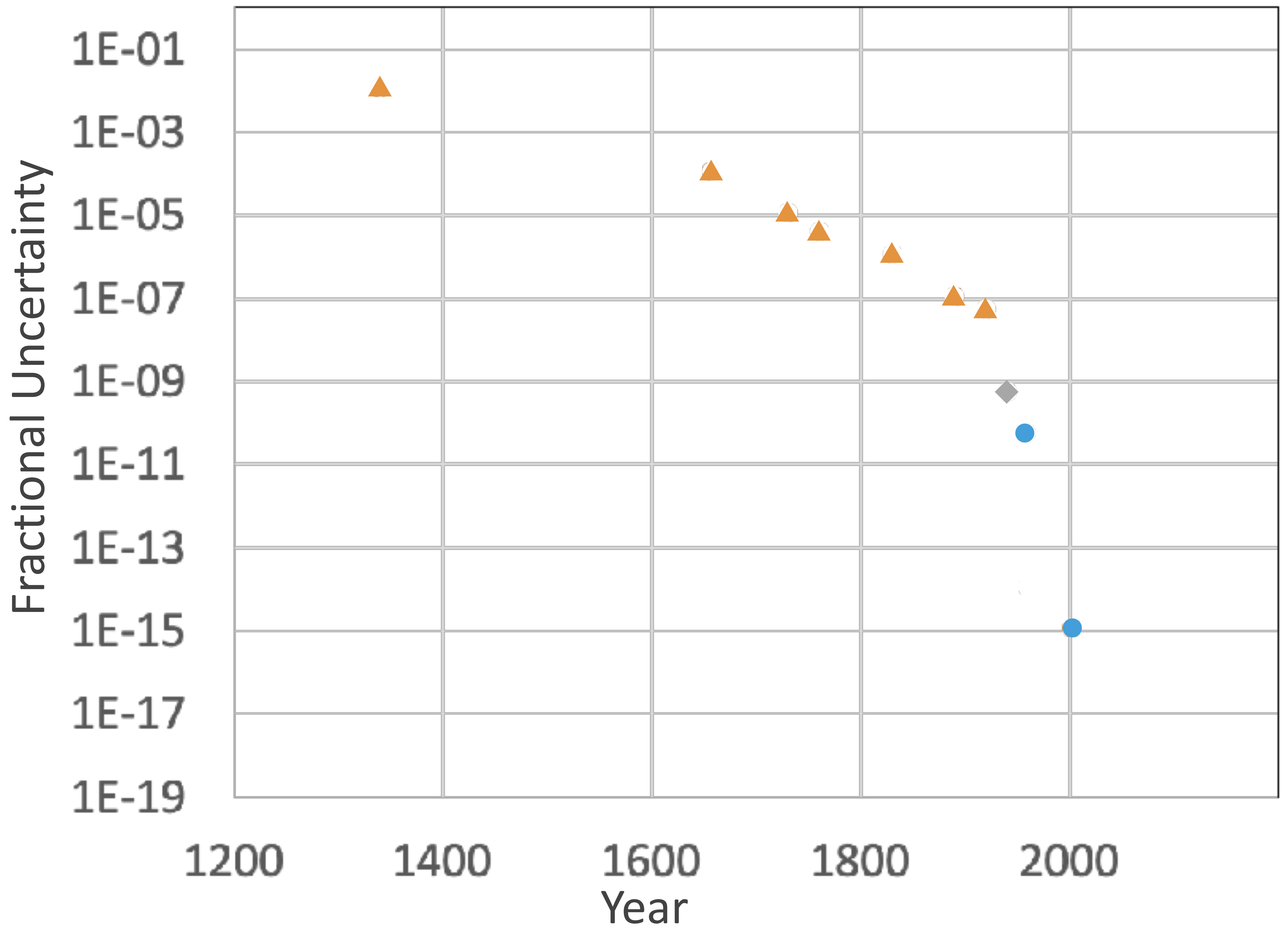
Remapping of France with pendulum clocks



Maxwell: atoms as clocks?

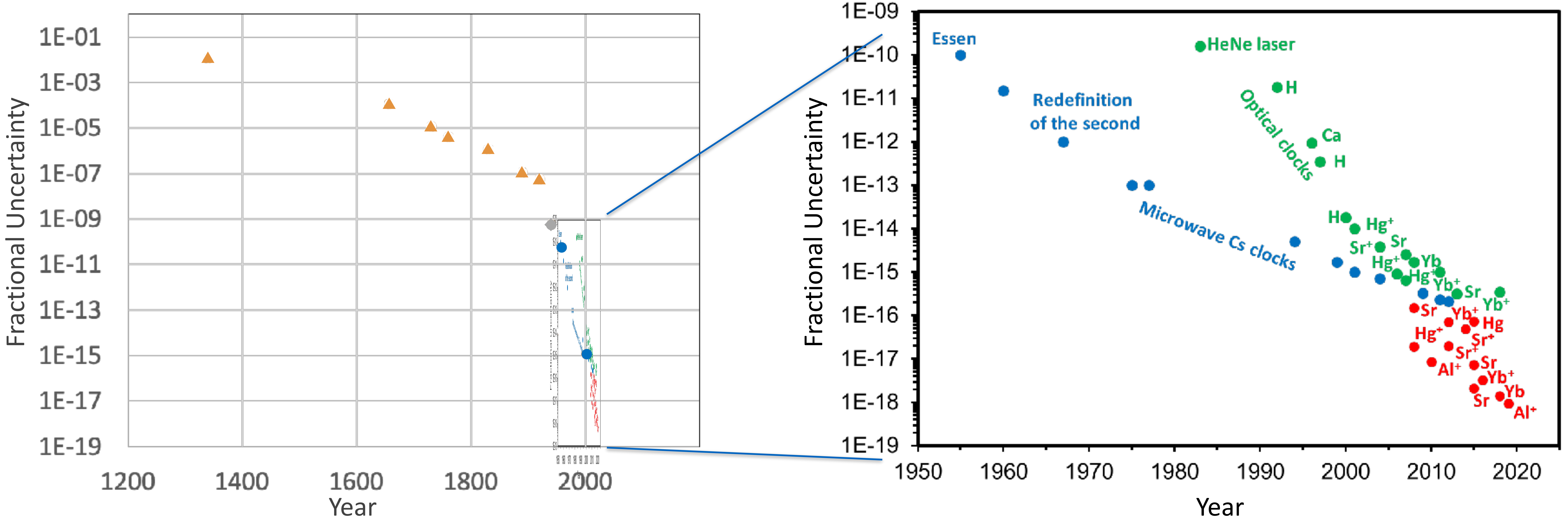
Fractional Uncertainty of Clocks vs. Year

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

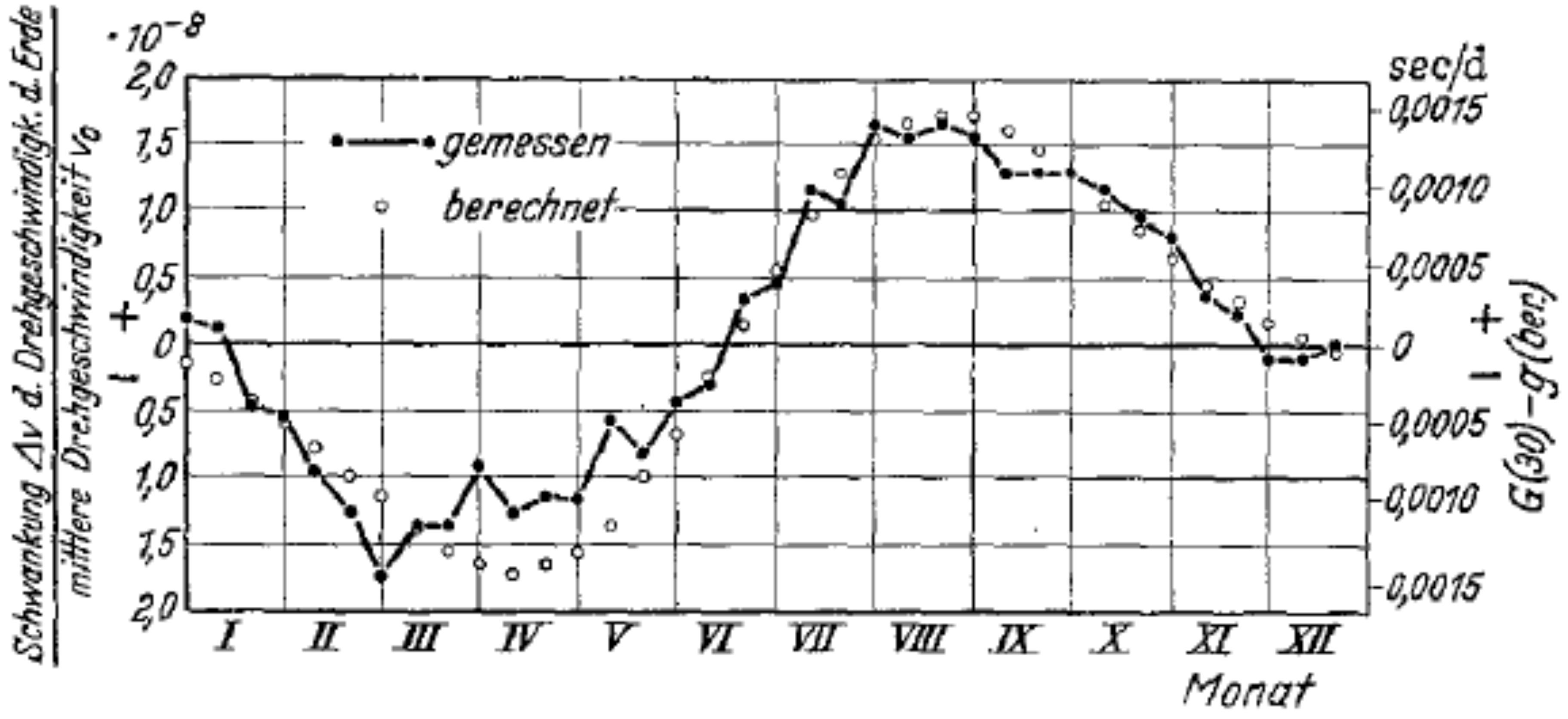


Fractional Uncertainty of Clocks vs. Year

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



What Science can you do with an Optical Atomic Clock?

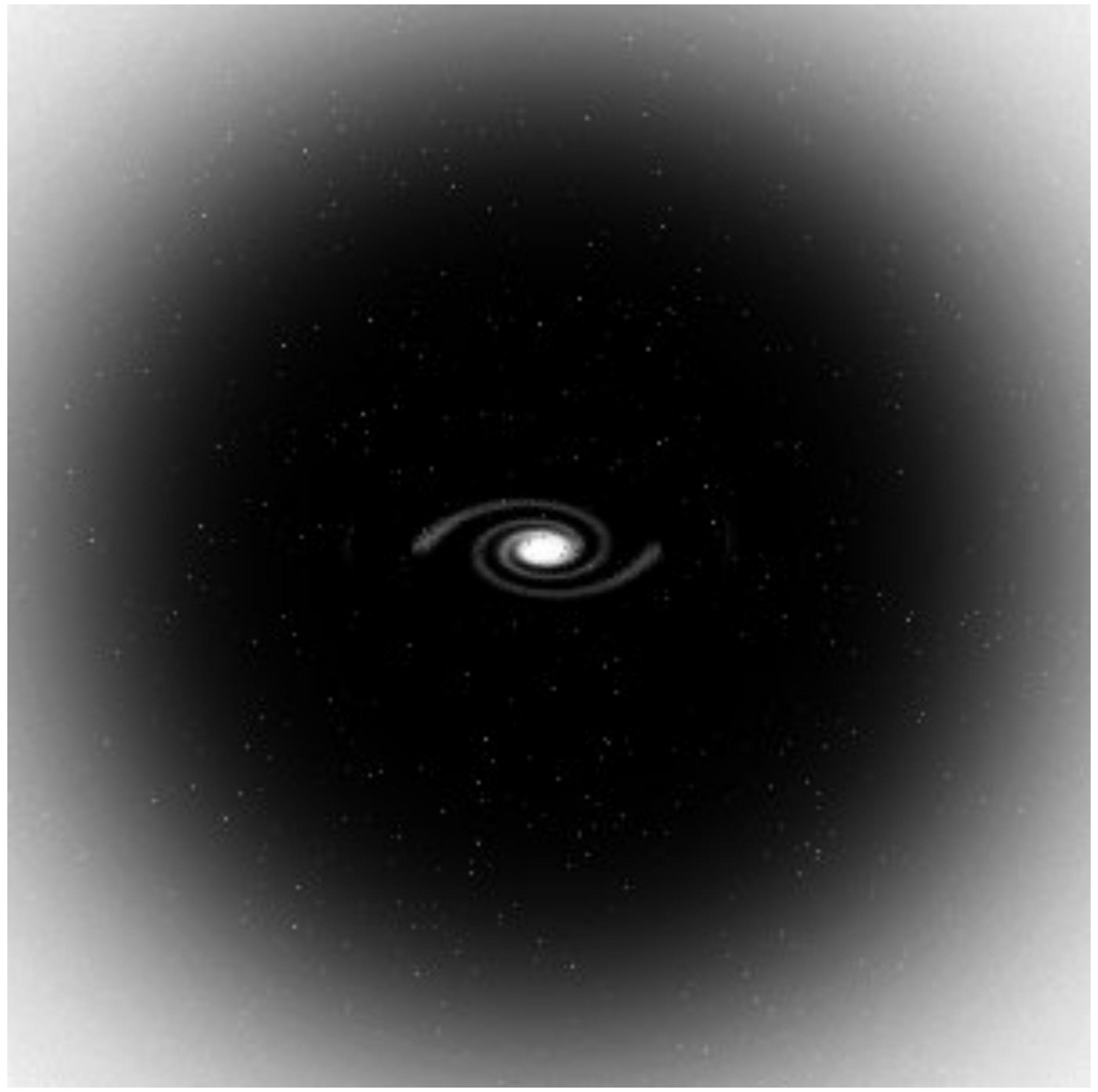


earth rotation variation: ±1.5 ms

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
- …



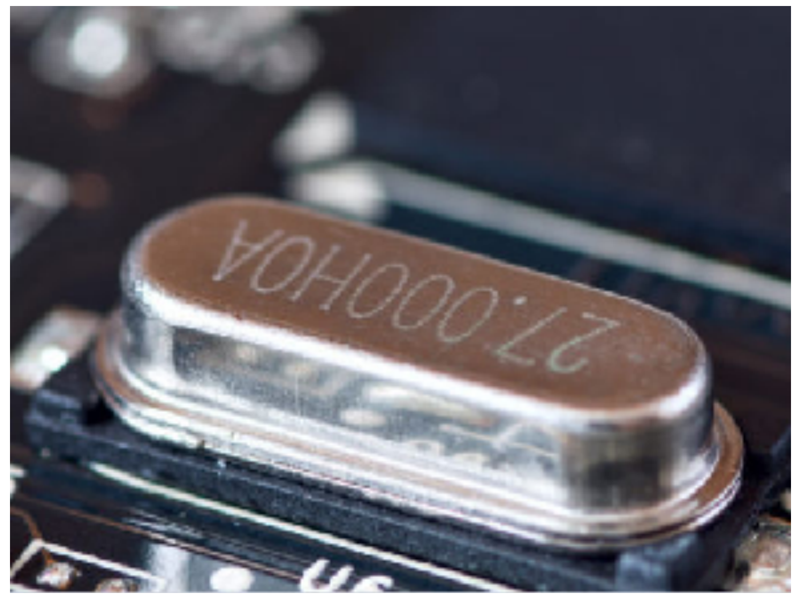
[A. Scheibe and U. Adelsberger, Z. Phys. 127, 416 (1950)]

Clock Basics

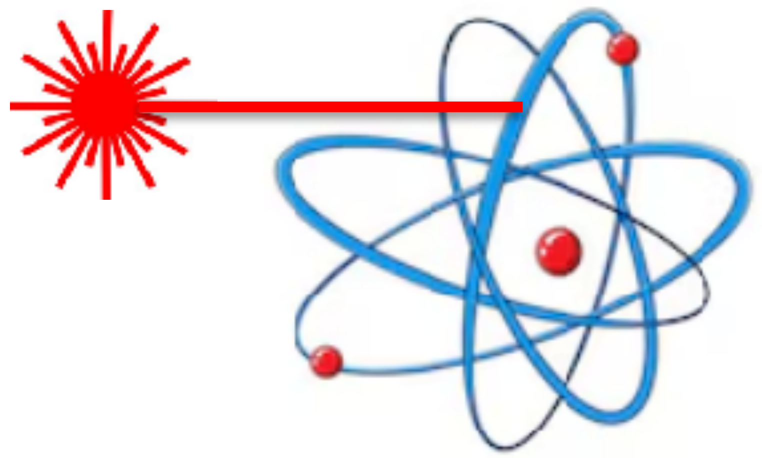
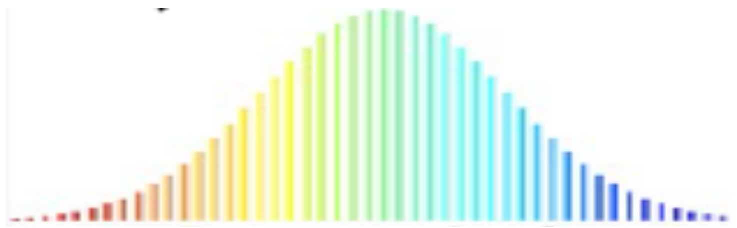
- Clock parts: oscillator and counter
- Both parts are important, true especially for atomic clocks
- Earth is imperfect oscillator, same for man-made resonators
- Many different atoms available, and they are all the same


minutes


seconds



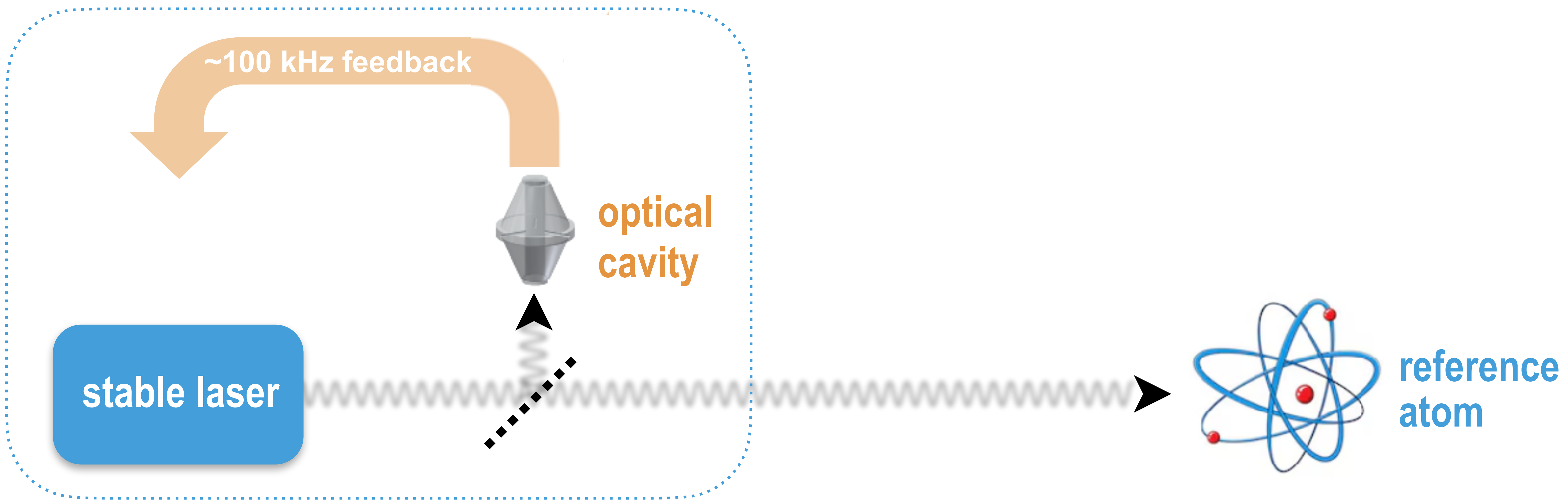

microseconds

< nanoseconds

Optical Atomic Clocks

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

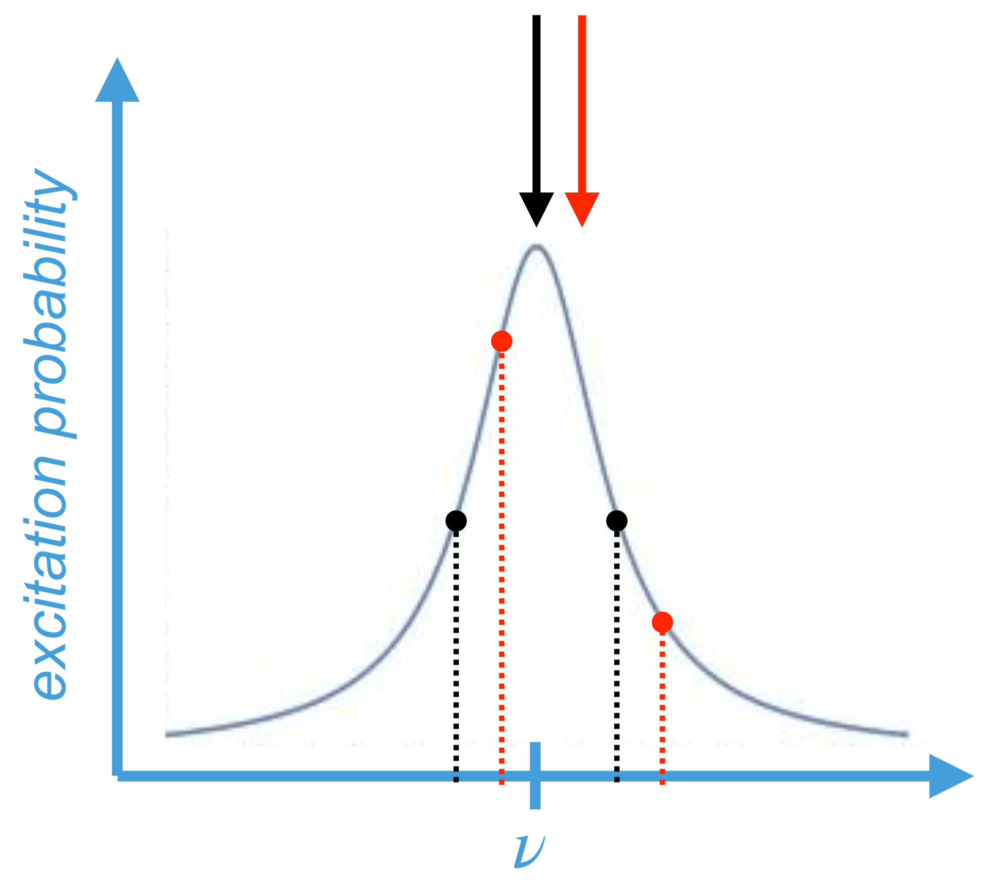


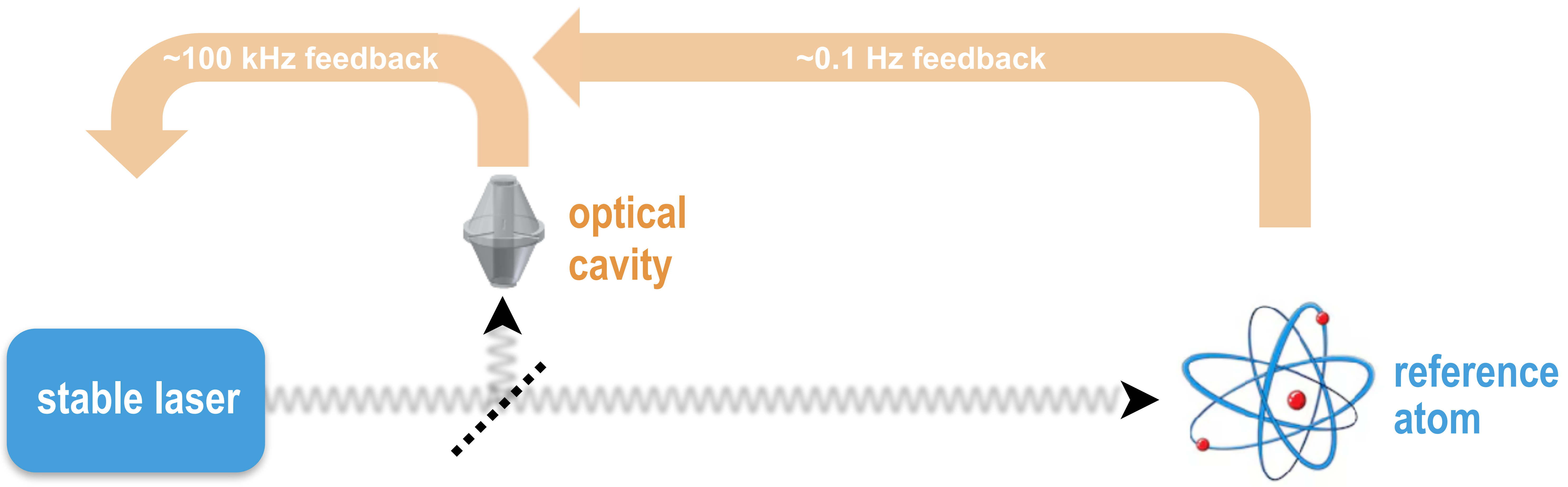
ultra-stable, narrow laser:

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

Optical Atomic Clocks

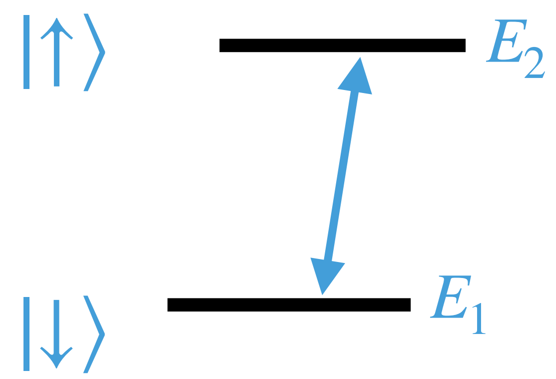
- Laser for oscillator, usually a narrow frequency around atomic transition
- Ultra-stable laser needed (e.g. referenced to a cavity)
- Locked to atomic transition: frequency detuned/offset (e.g. $\pm\Delta\nu$) to find max





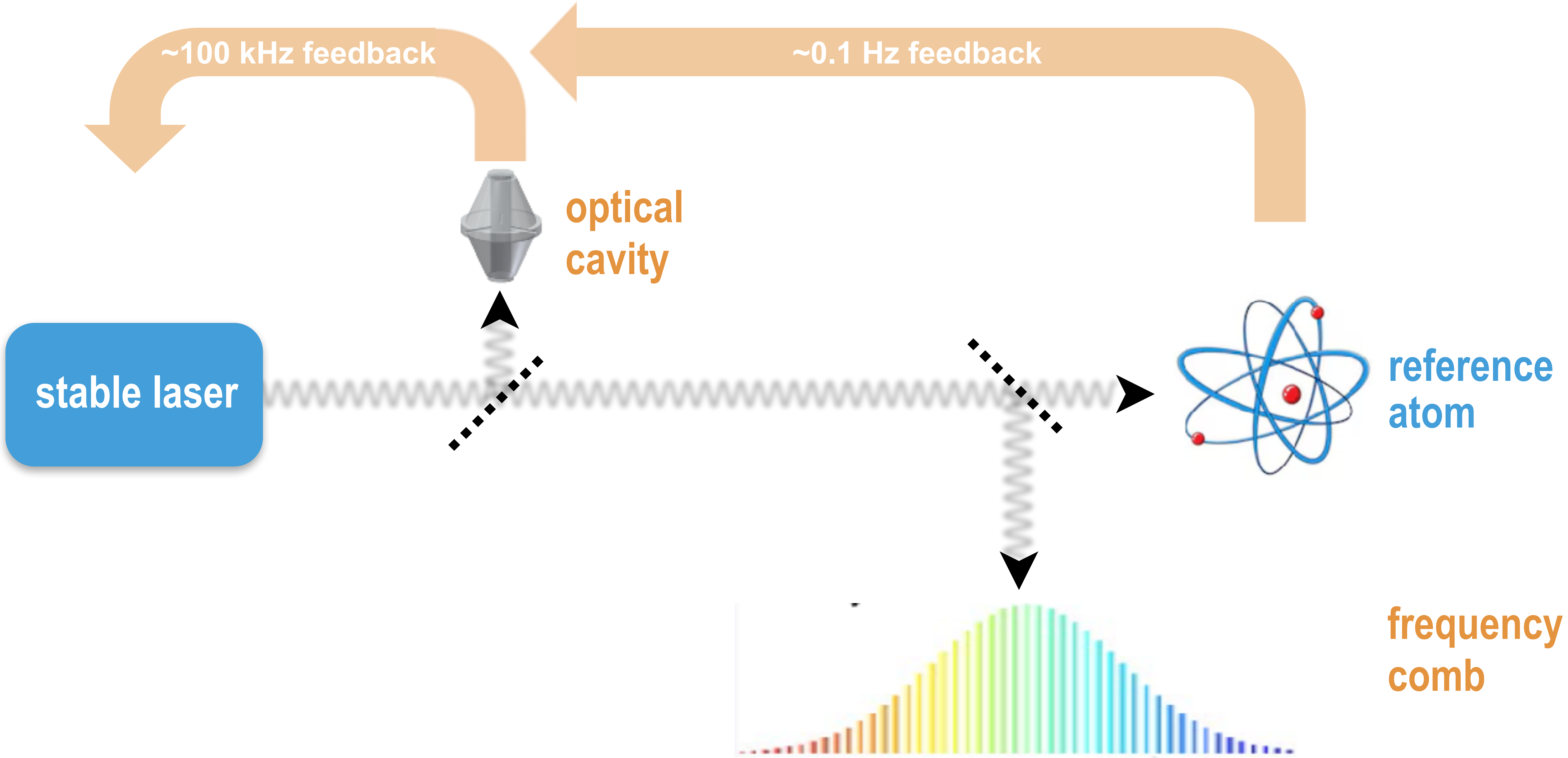
optical ν :

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



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



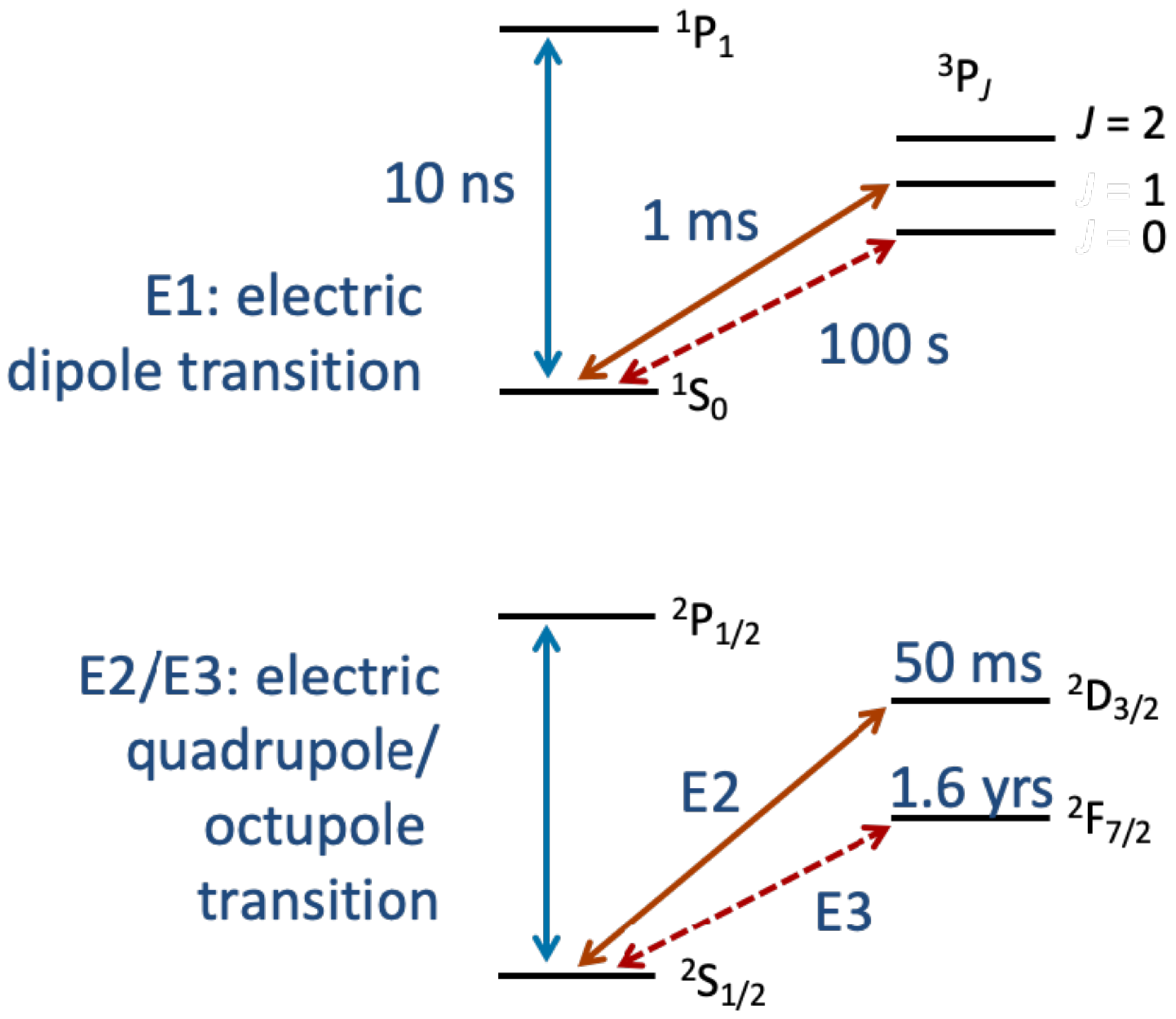
What Makes a Good Atomic Clock?

- 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)

[https://www.bbc.com/future/article/20220721-the-super-clocks-that-define-what-time-it-is]

Selecting an Atomic Reference

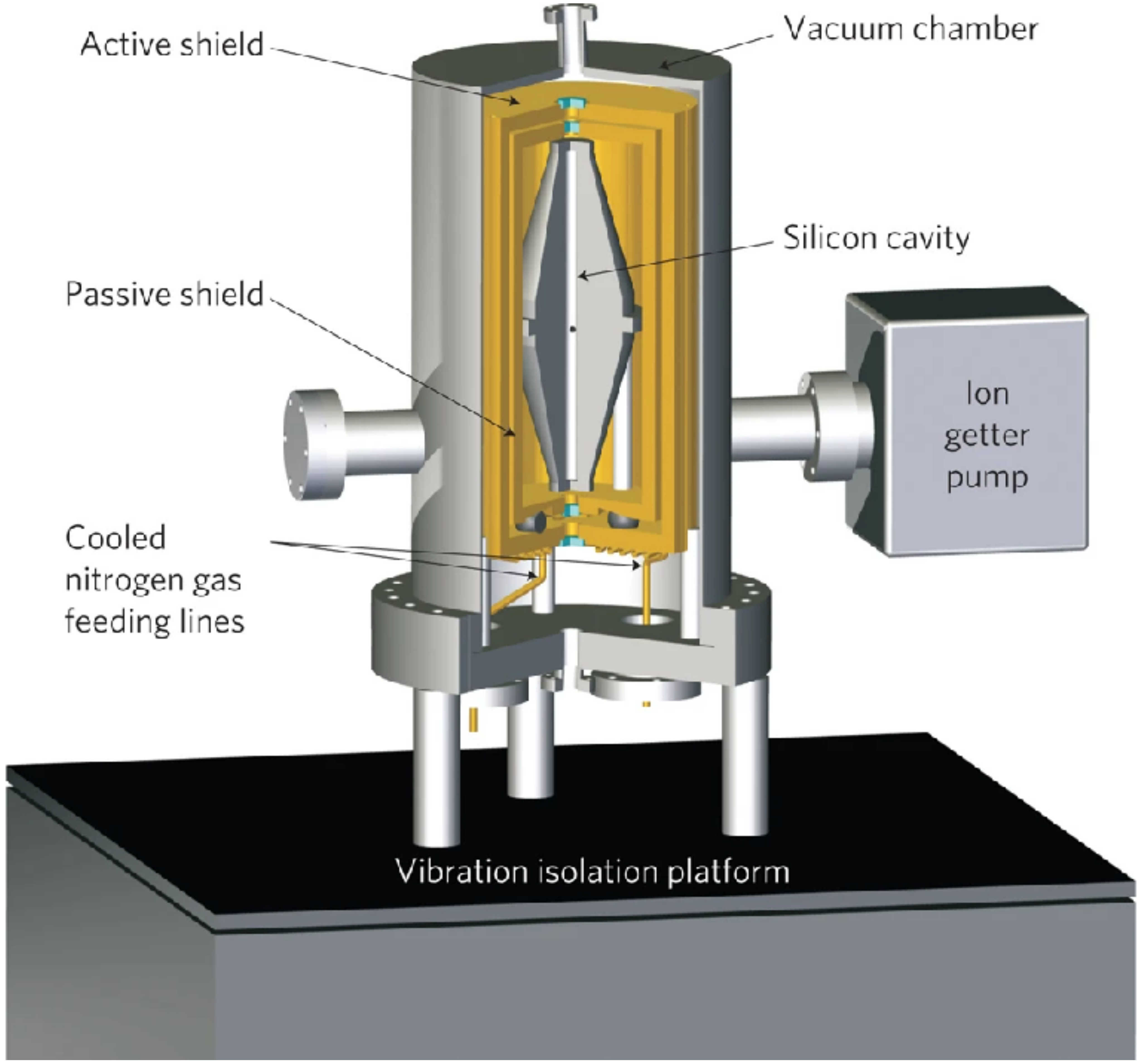
- Two requirements for the atom/transition:
  - long observation/interrogation time
  - narrow transition (can find the peak more precisely)
- Long-lived transitions are favourable
  - one minute or more… "forbidden" transitions
  - possible in some atoms with dipole transitions
  - more common for quadrupole/octupole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

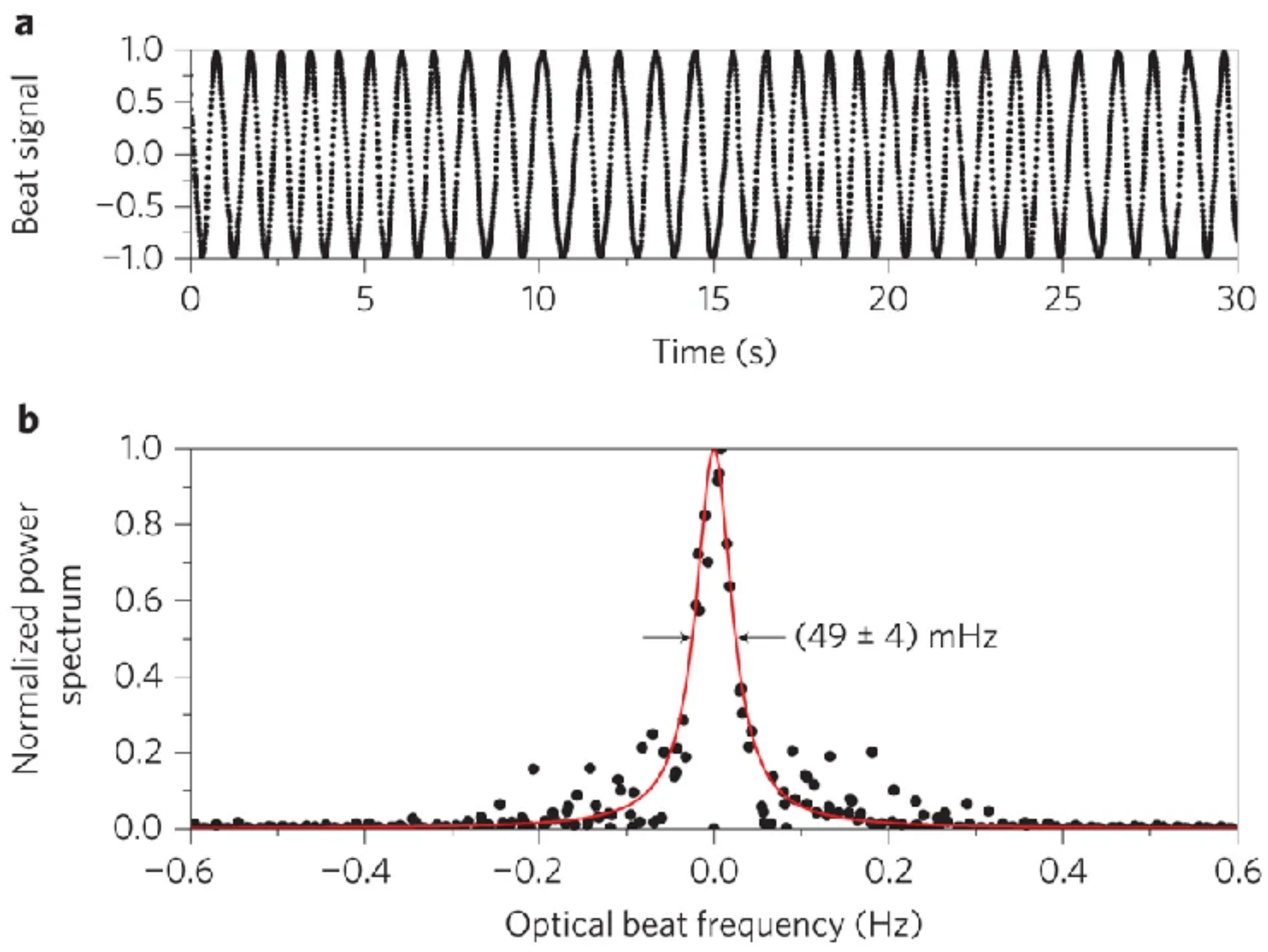


Strontium Level Diagrams

[Lisdat: Optical Clocks: An Introduction]

Single-Crystal Silicon Optical Cavity



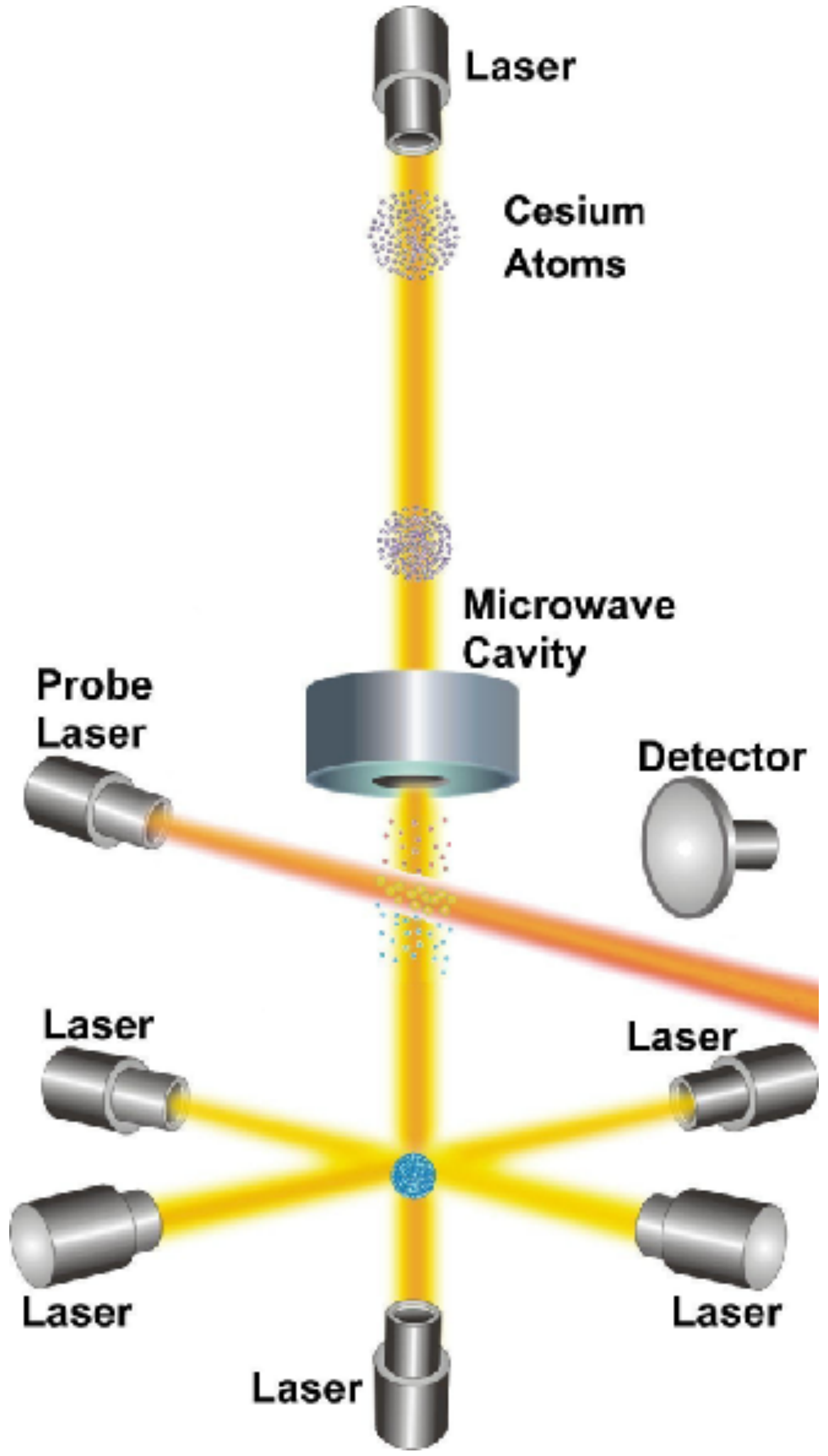


Normalized fast Fourier transform of the beat signal recorded with a HP 3561A FFT analyser (37.5 mHz resolution bandwidth, Hanning window). A Lorentzian fit is indicated by the red line. The combined result of five consecutive recordings of the beat signal (black dots) is displayed here, demonstrating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

[T. Kessler et al.. Nature Photon **6**, 687–692 (2012)]

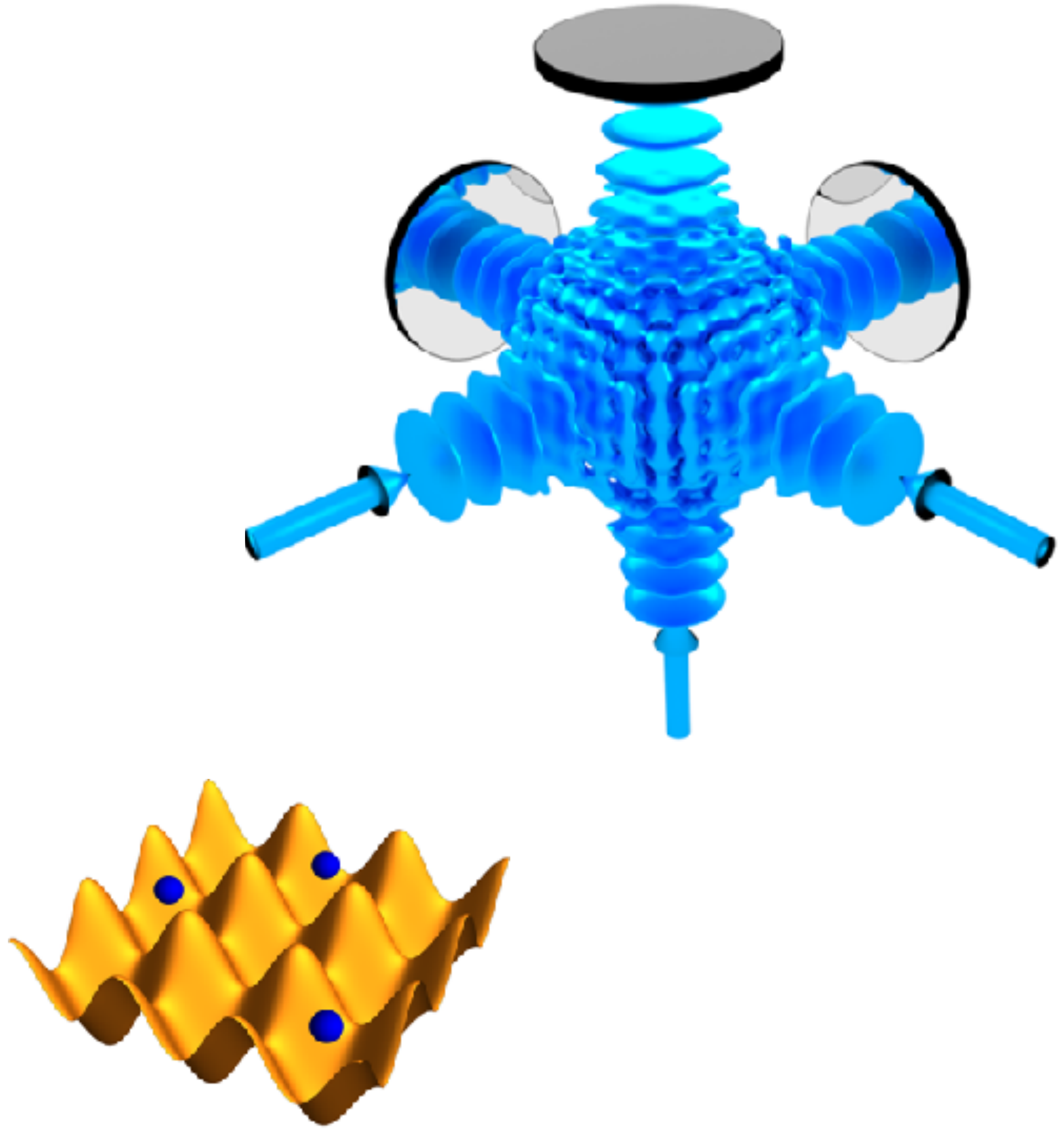
Manipulation and Trapping of Atoms

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



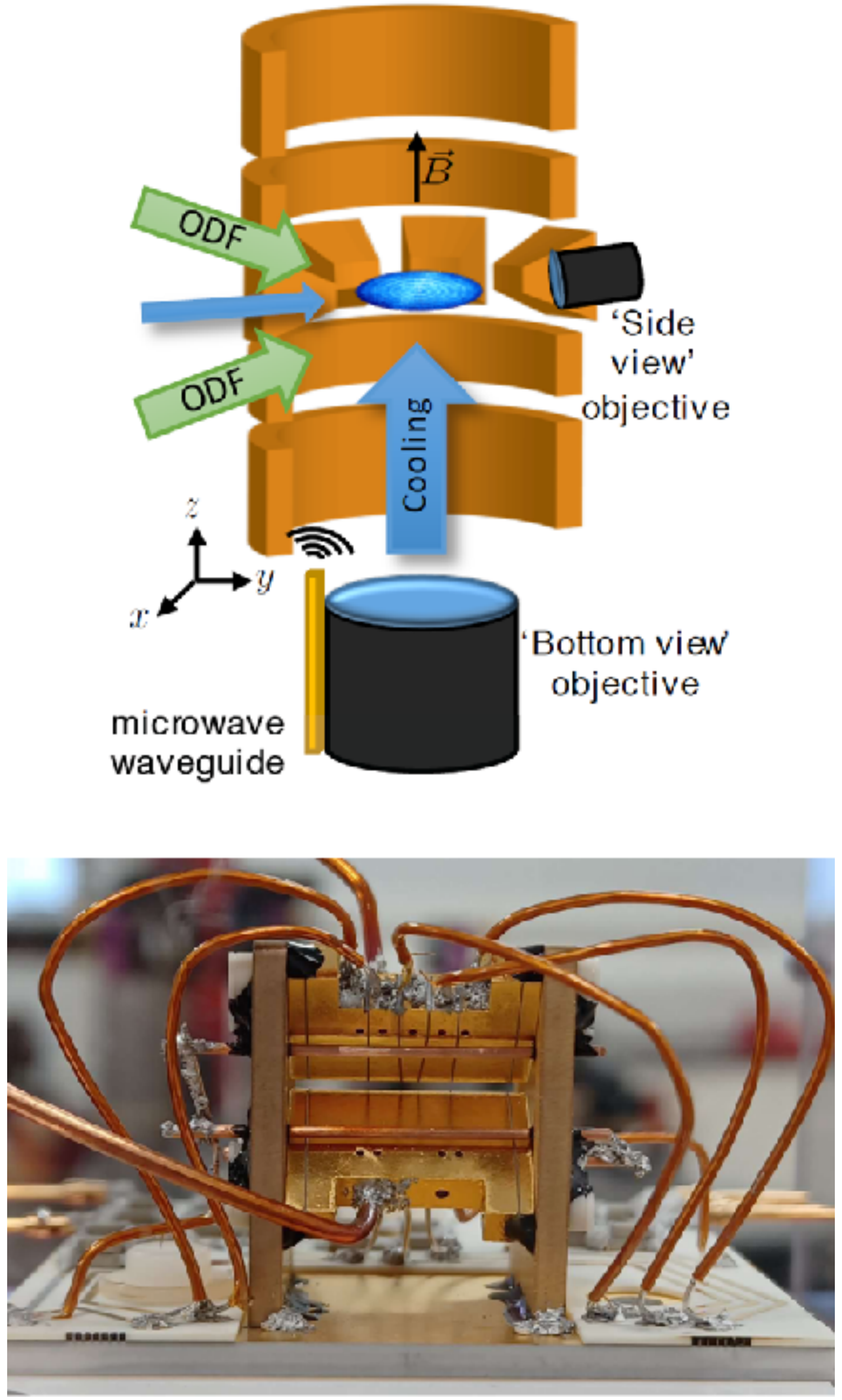
Atomic Fountain (Cesium)

[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/]

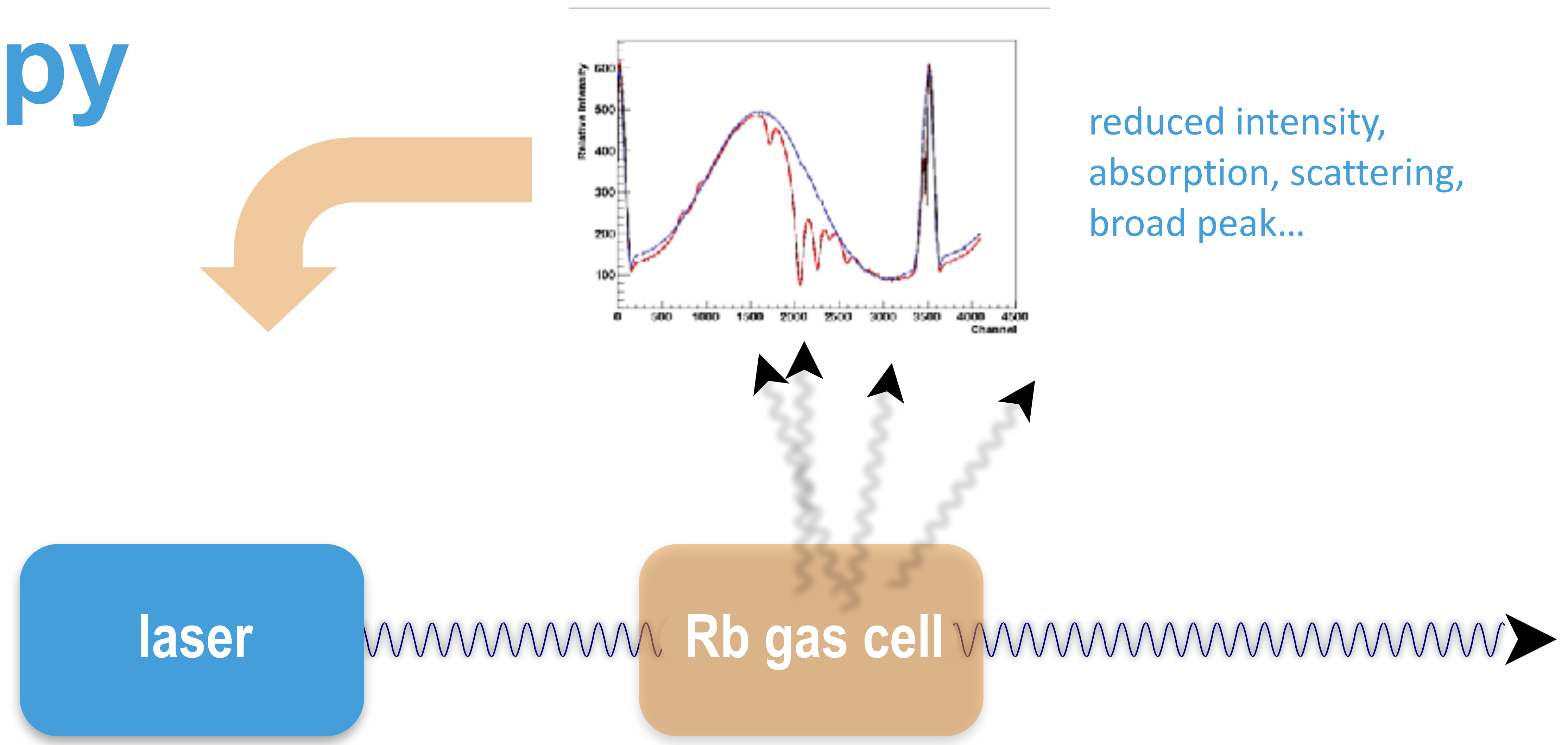


Penning and Paul Traps

[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 $\Longrightarrow$ short lifetime $\Longrightarrow$ 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: $\frac{\mathrm{d}}{\mathrm{d}t}\vec{b} = \vec{\Omega}_{\mathrm{eff}} \times \vec{b}$

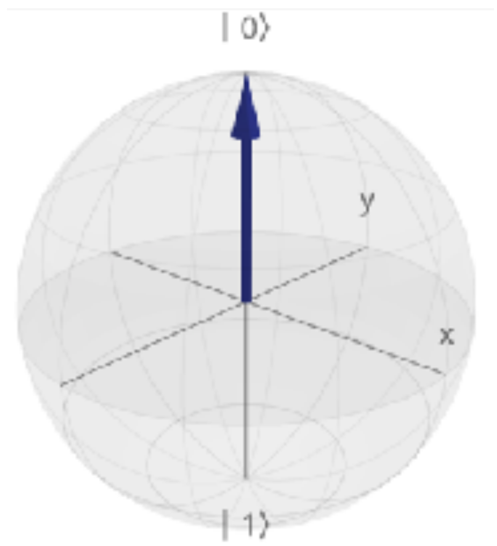
$\Omega = \langle g | \, \vec{d} \cdot \vec{E}_0 \, | e \rangle$

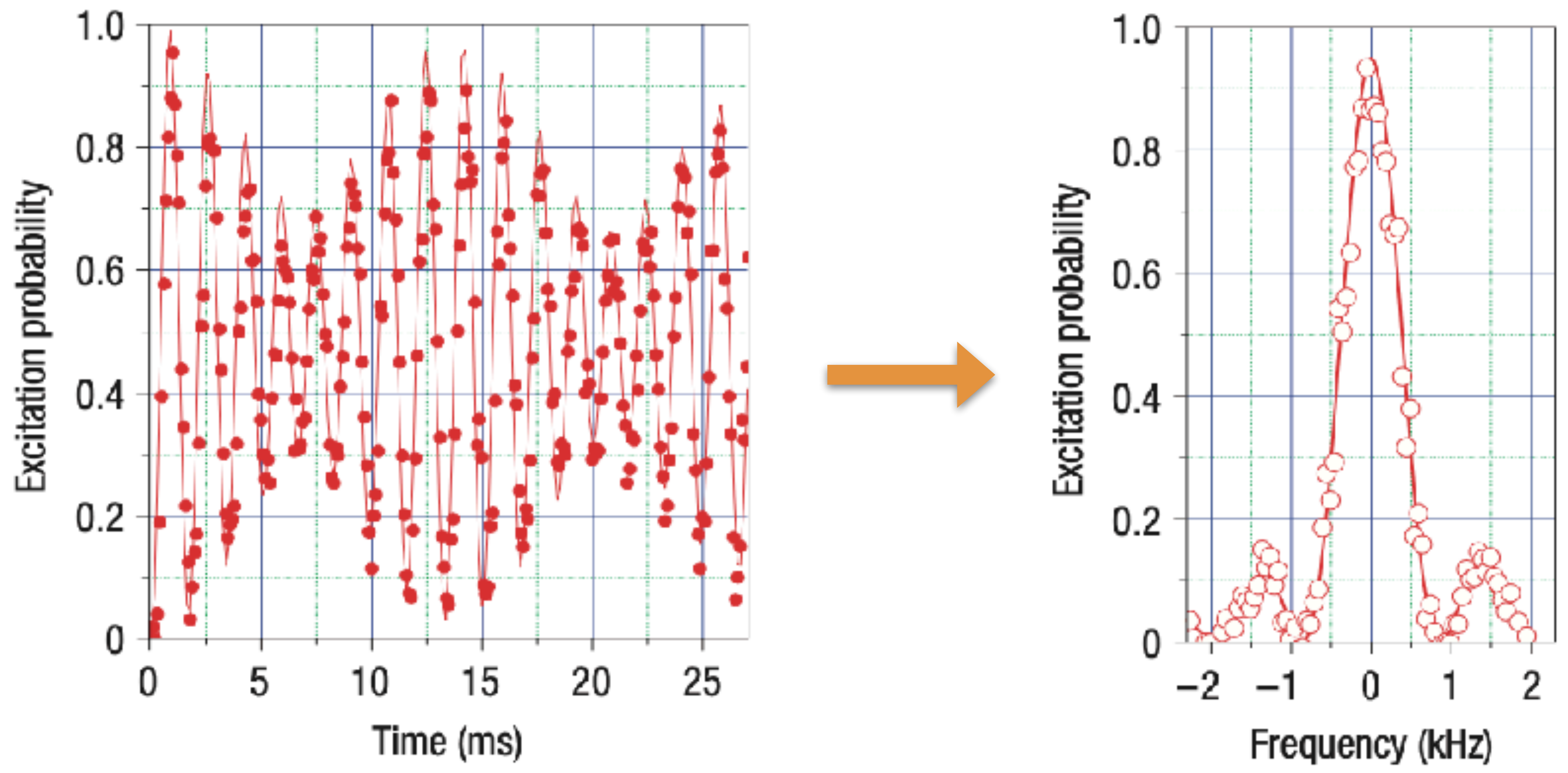
$\delta = \omega - \omega_0$

$\delta \ll \Omega$

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

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

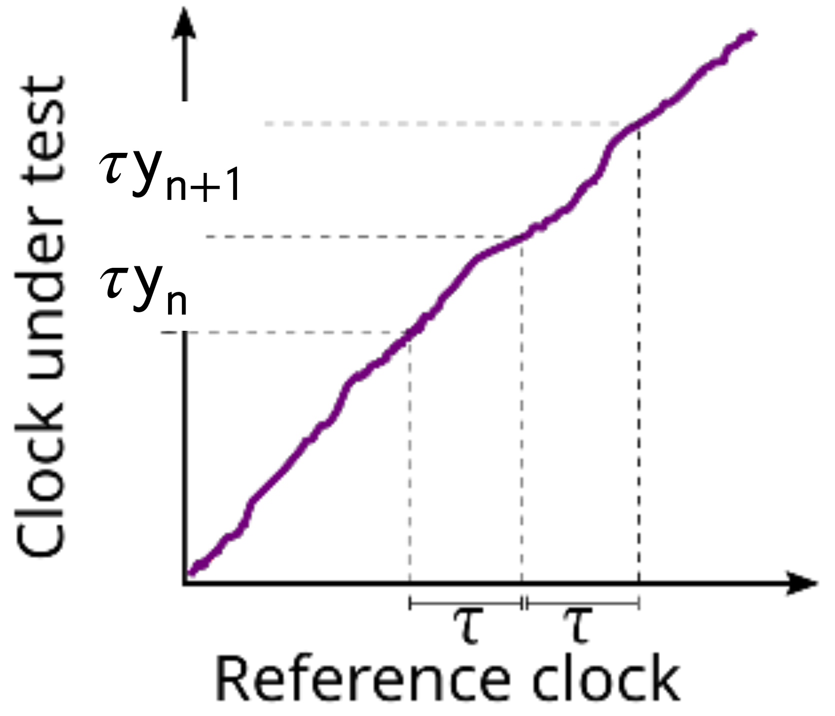




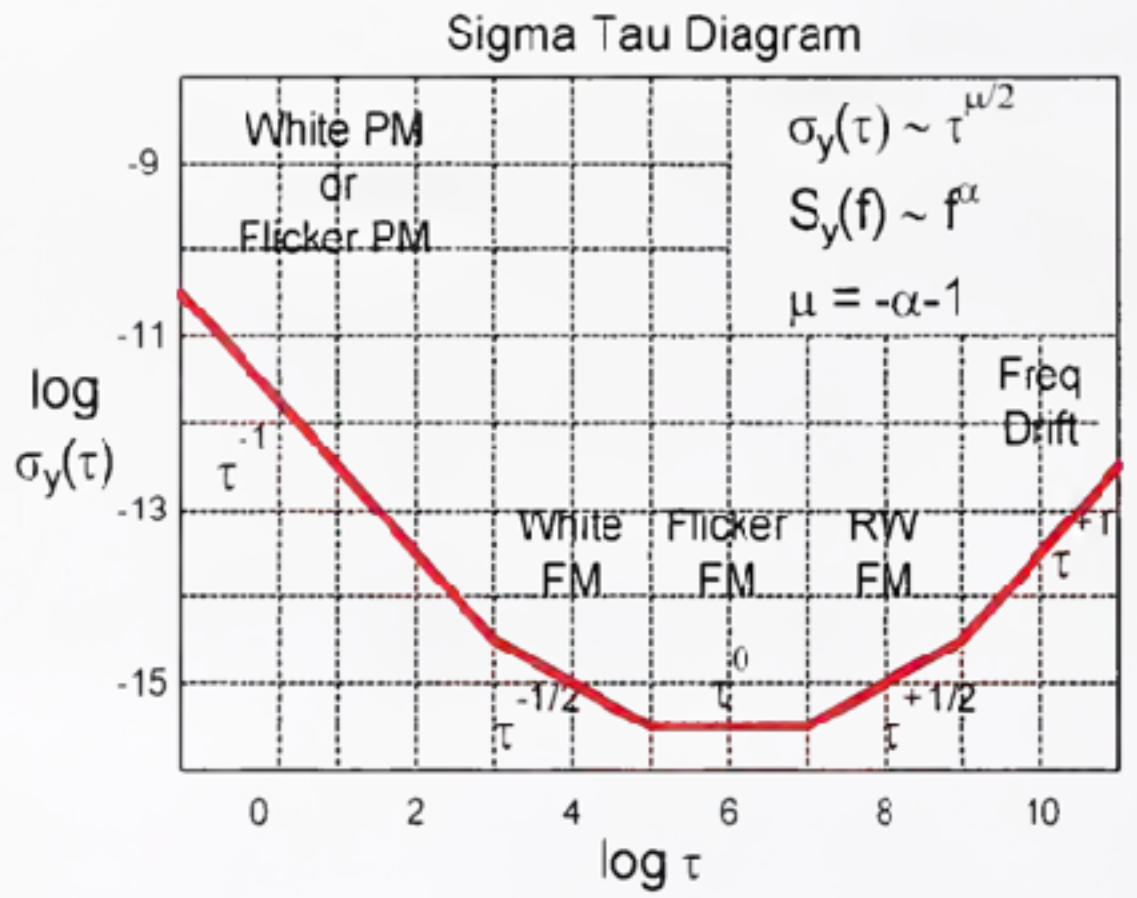
[Akatsuka et al, Nature Phys. 4, 954 (2008); Lisdat: Optical Clocks: An Introduction]

Clock Performance: Allan Deviation

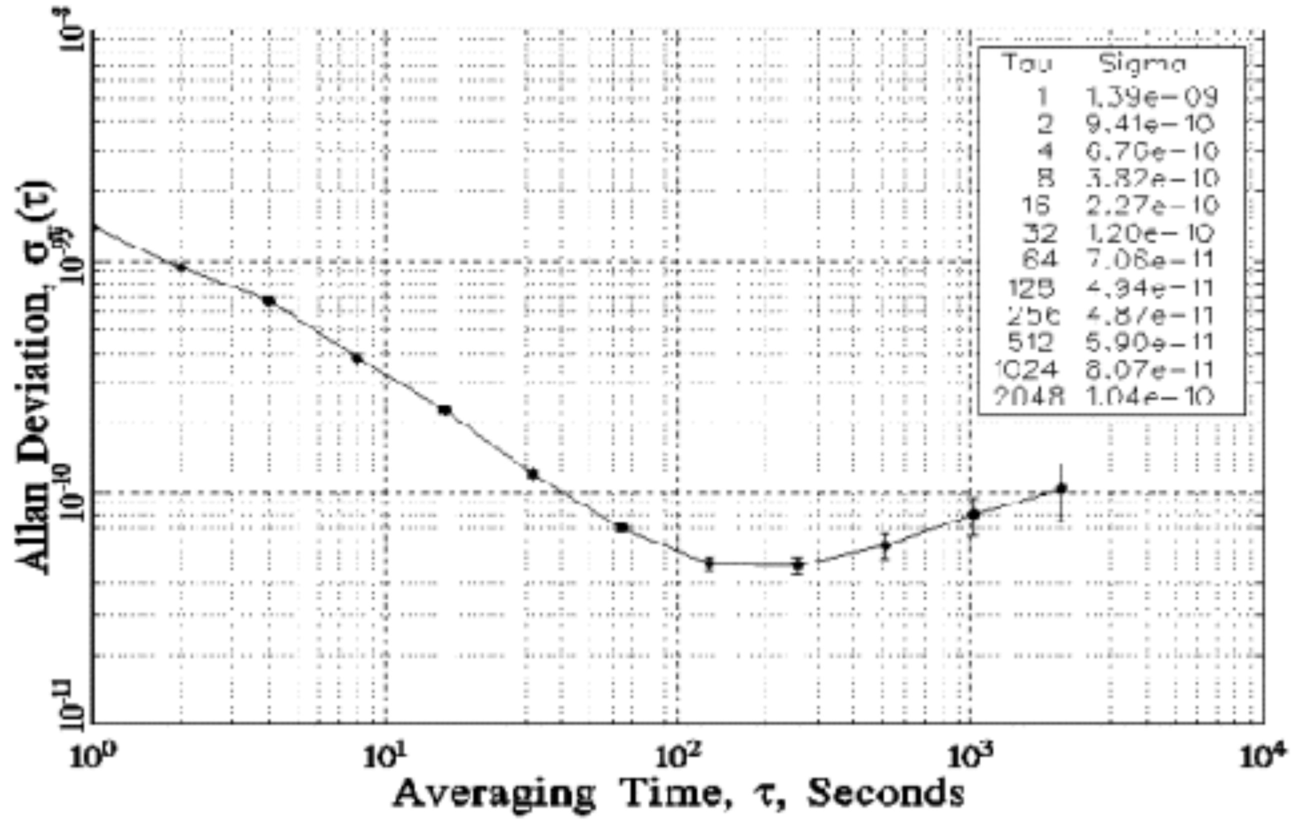
- Allan or two-sample variance better suited to oscillators than e.g. standard deviation
- Used to measure frequency stability in clocks, characterise (non-systematic) noise



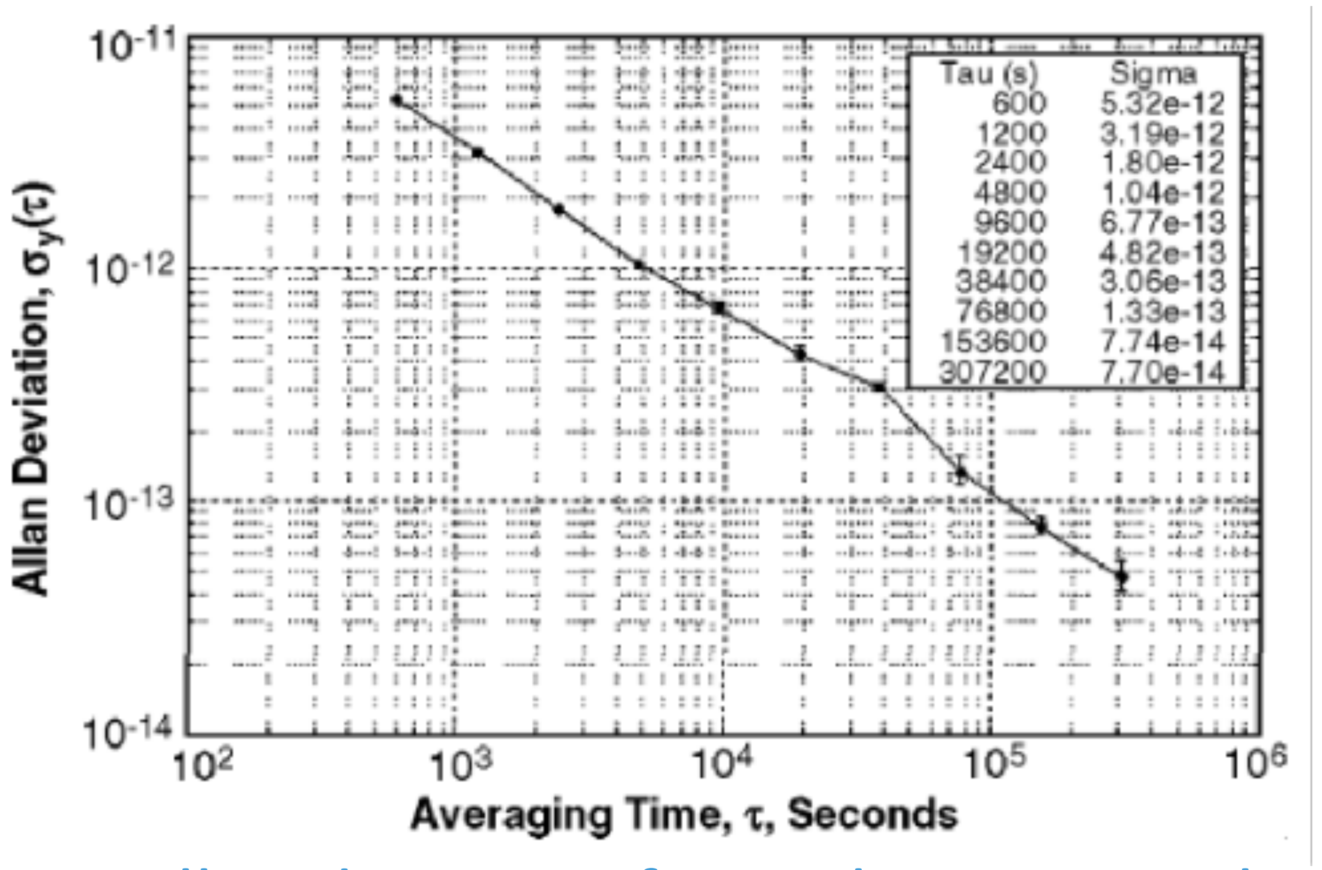
$$\sigma_y(\tau) = \sqrt{\sigma_y^2(\tau)} = \frac{1}{2}\langle(\bar{y}_{n+1} - \bar{y}_n)^2\rangle$$



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



Example Allan deviation plot



Allan deviation for early GPS signals

[Lombardi, Fundamentals of Time and Frequency; NIST Pub 1065, Handbook of Frequency Stability Analysis, 2008; Wikipedia]

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)

5028 J. Appl. Phys., Vol. 83, No. 10, 15 May 1998

effects from micromotion

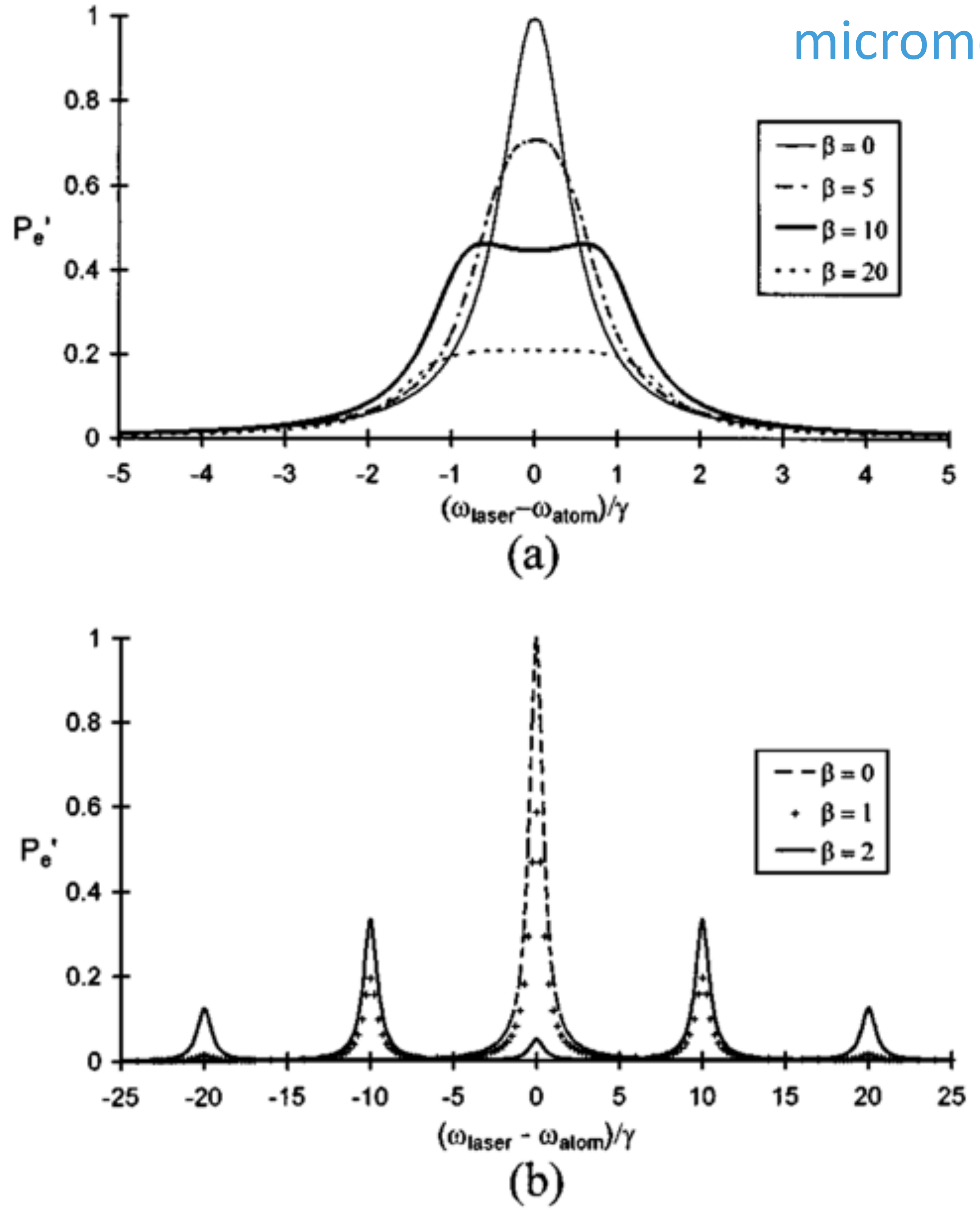


FIG. 2. Effect of micromotion on the spectrum of P_e (excited state population). We plot $P_e' = P_e[\hbar\gamma/(2\mathscr{P}|E_0|)]^2$ for various values of β. For both graphs, we assume that the ion is driven below the saturation limit. (a) $\Omega/\gamma = 0.1$. For $\beta = 10$, heating occurs in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

[Berkeland et al., Journal of Applied Physics, Vol 83, 10 (1998); Safranova et al., Phys. Rev. A 87, 012509]

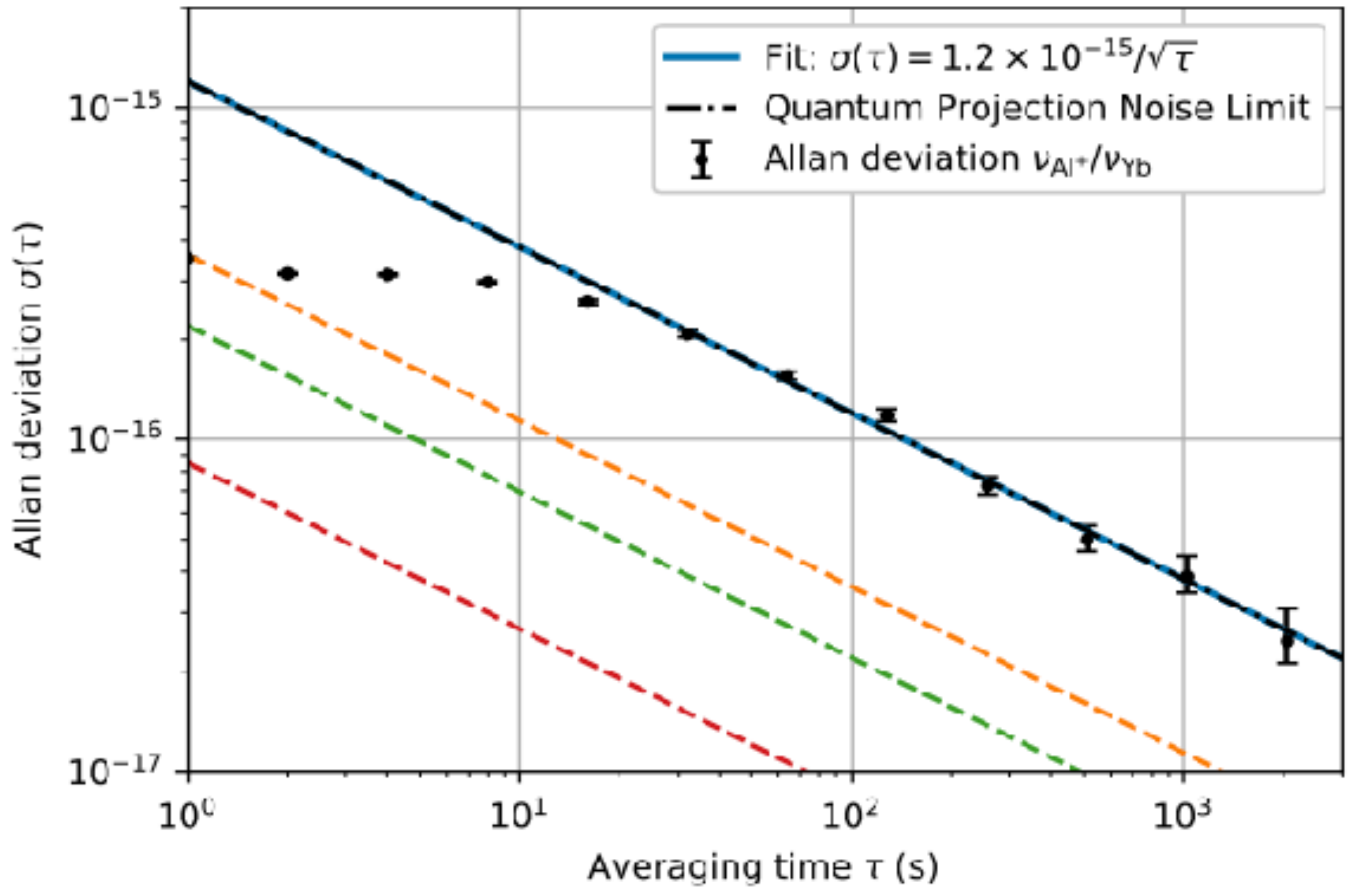
Optical Clock Uncertainties

- 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 $^{27}Al^+$ Quantum-Logic Clock

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

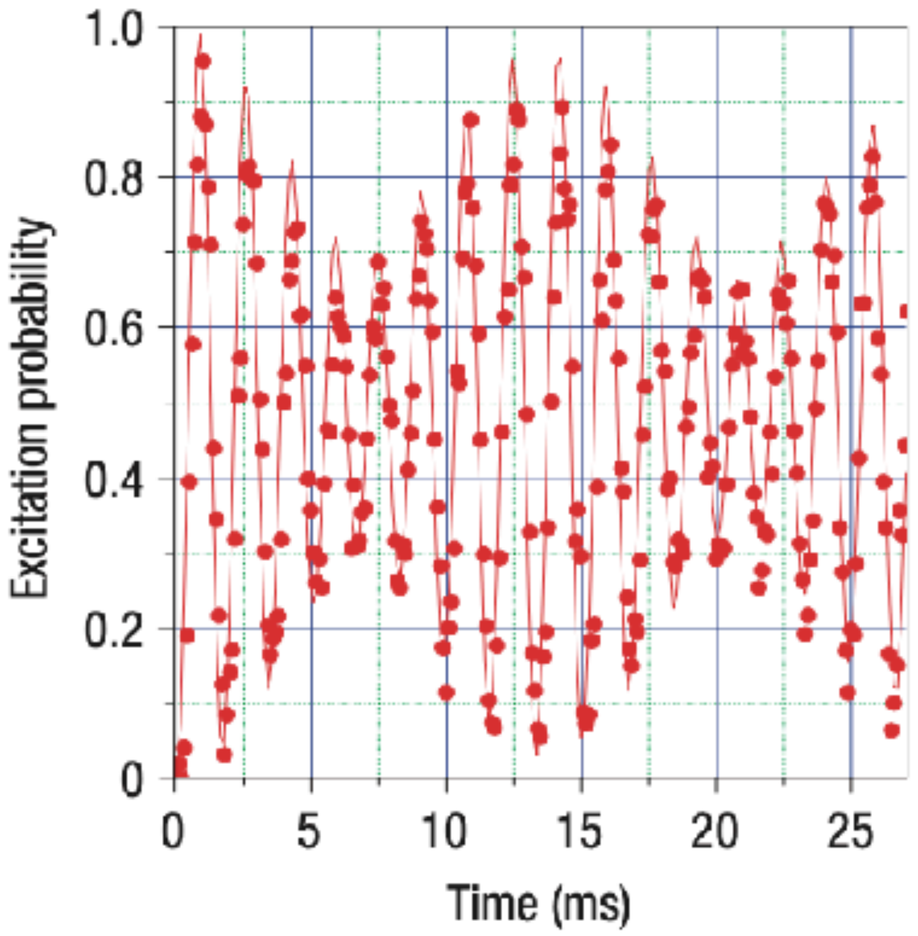
Effect	Shift (10^{-19})	Uncertainty (10^{-19})
Excess micromotion	−45.8	5.9
Blackbody radiation	−30.5	4.2
Quadratic Zeeman	−9241.8	3.7
Secular motion	−17.3	2.9
Background gas collisions	−0.6	2.4
First-order Doppler	0	2.2
Clock laser Stark	0	2.0
AOM phase chirp	0	<1
Electric quadrupole	0	<1
Total	−9336.0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

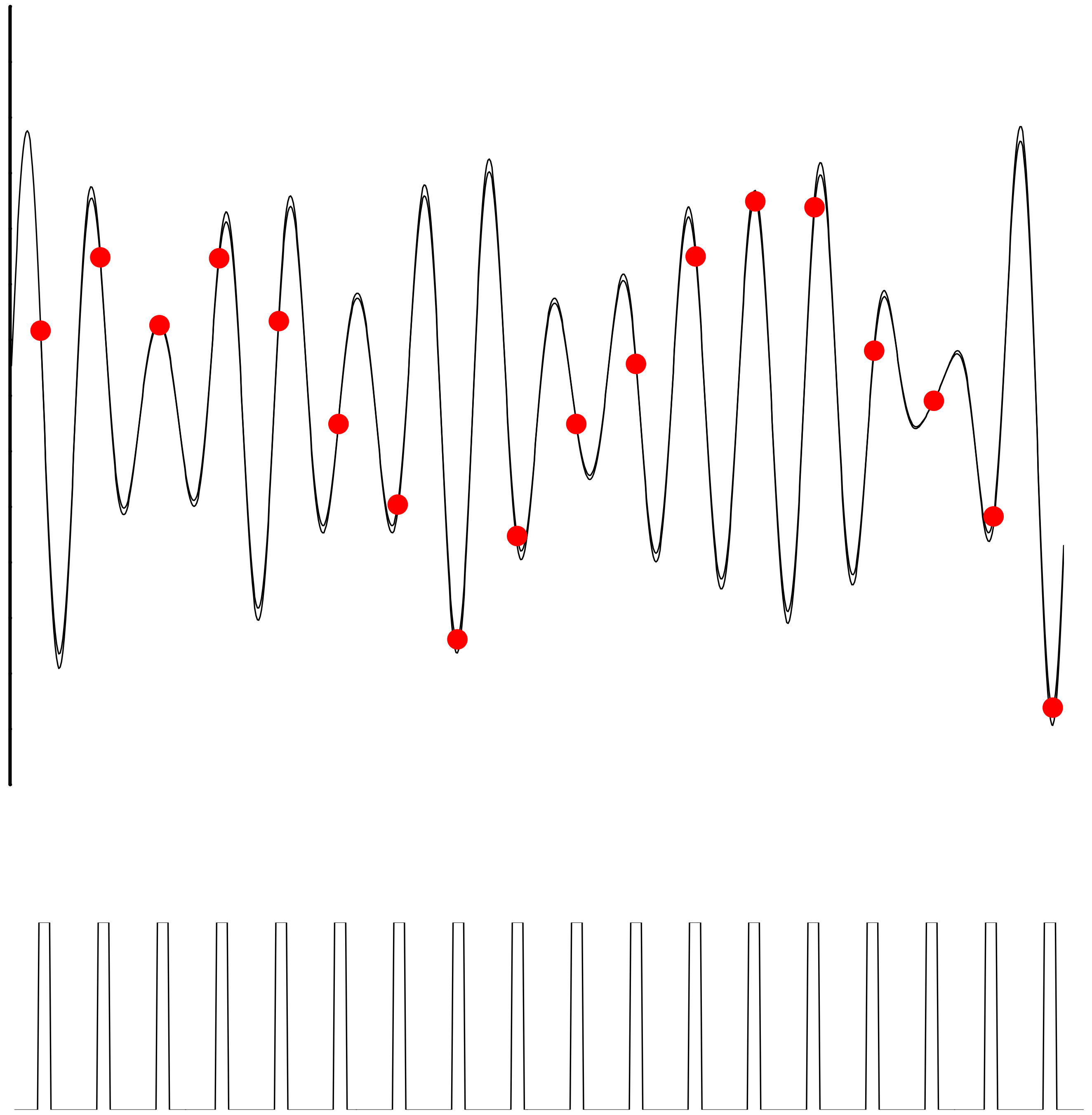


[Brewer at al, PRL 123, 033201 (2019)]

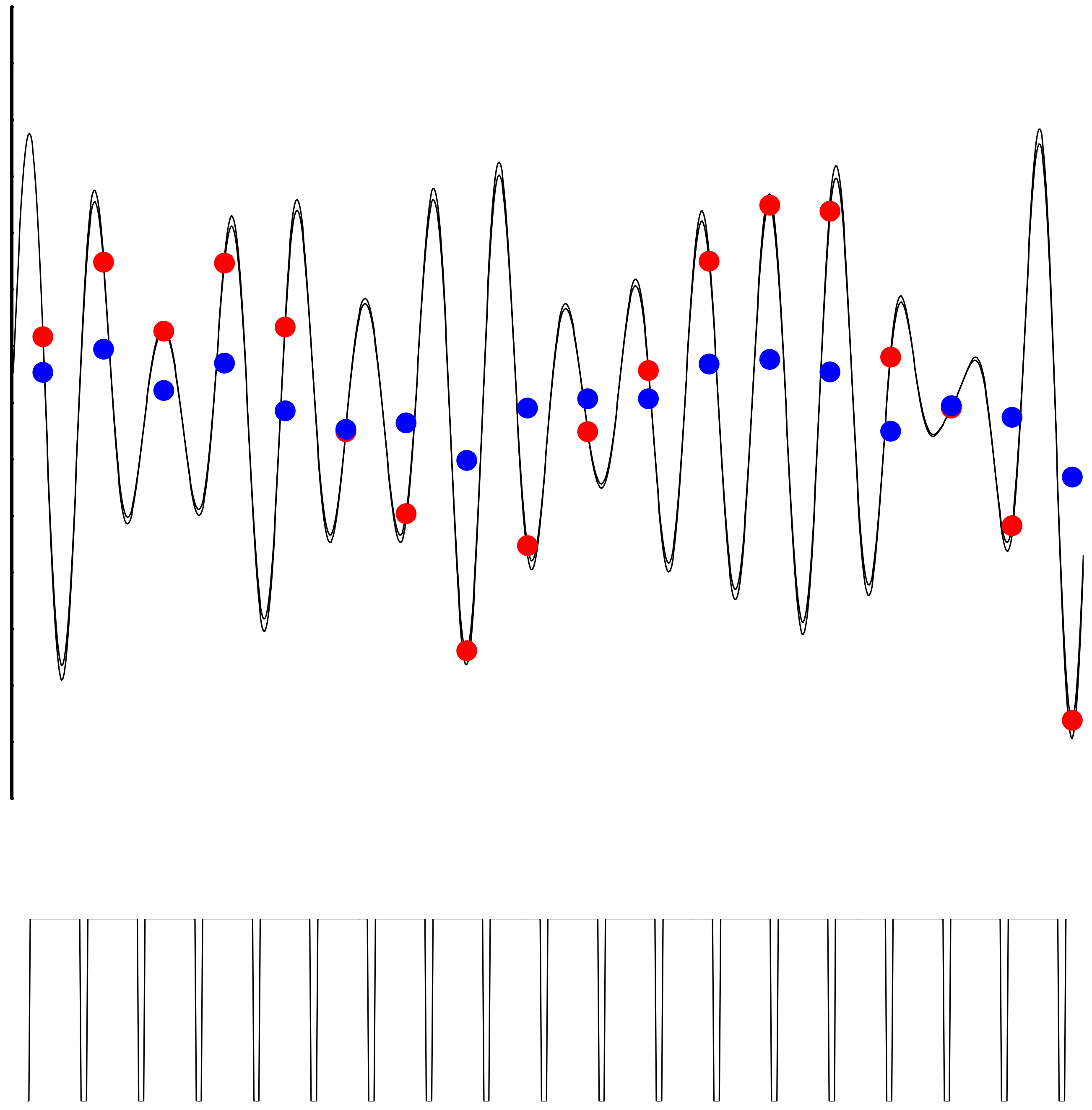
Deadtime-Related Uncertainty

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





probe time + long dead time

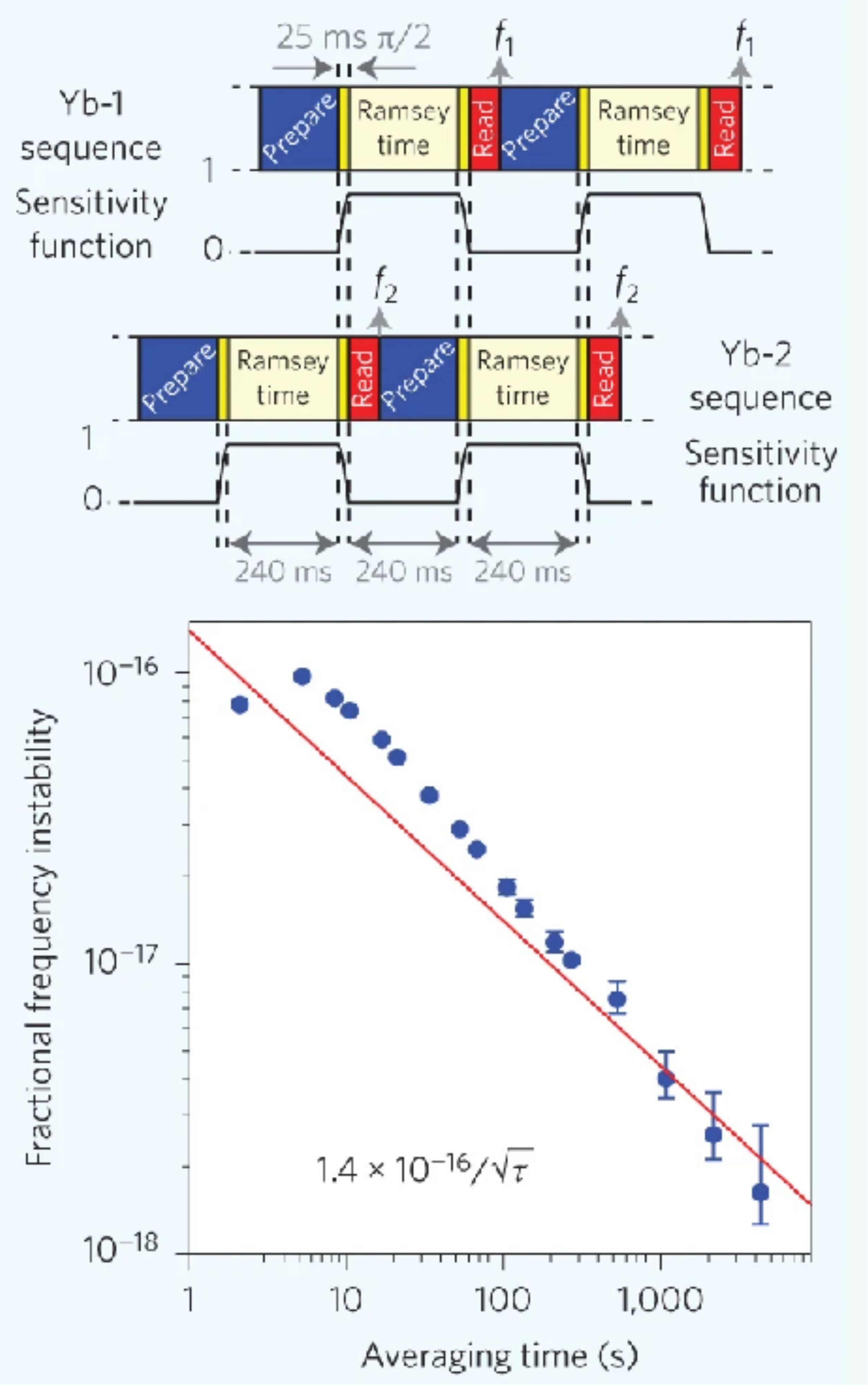


probe time + short dead time

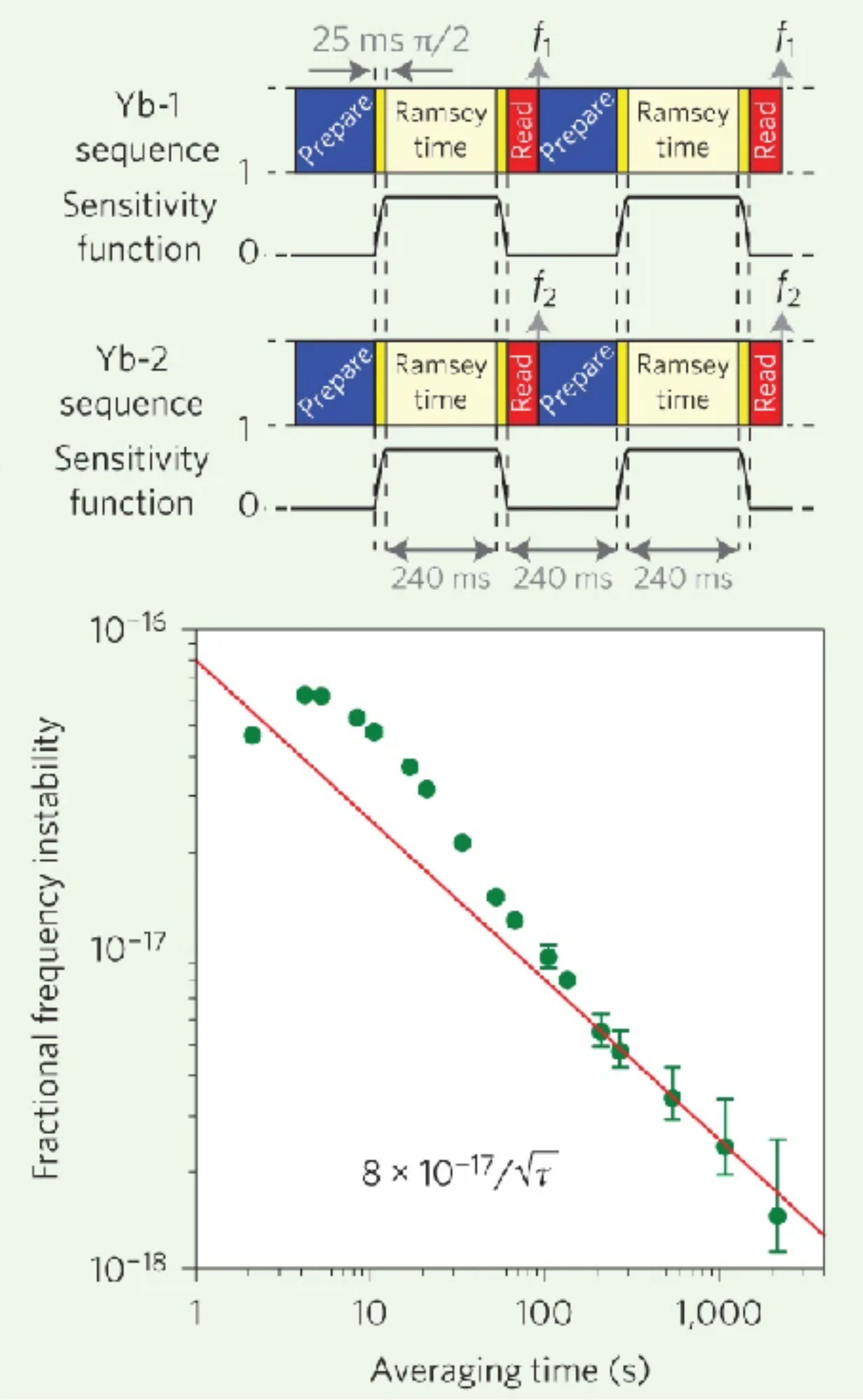
[Santarelli et. al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control 45, 887 – 894 (1998); M. Schioppo et al., Nature Phot. 11, 48 (2017)]

Deadtime Mitigation

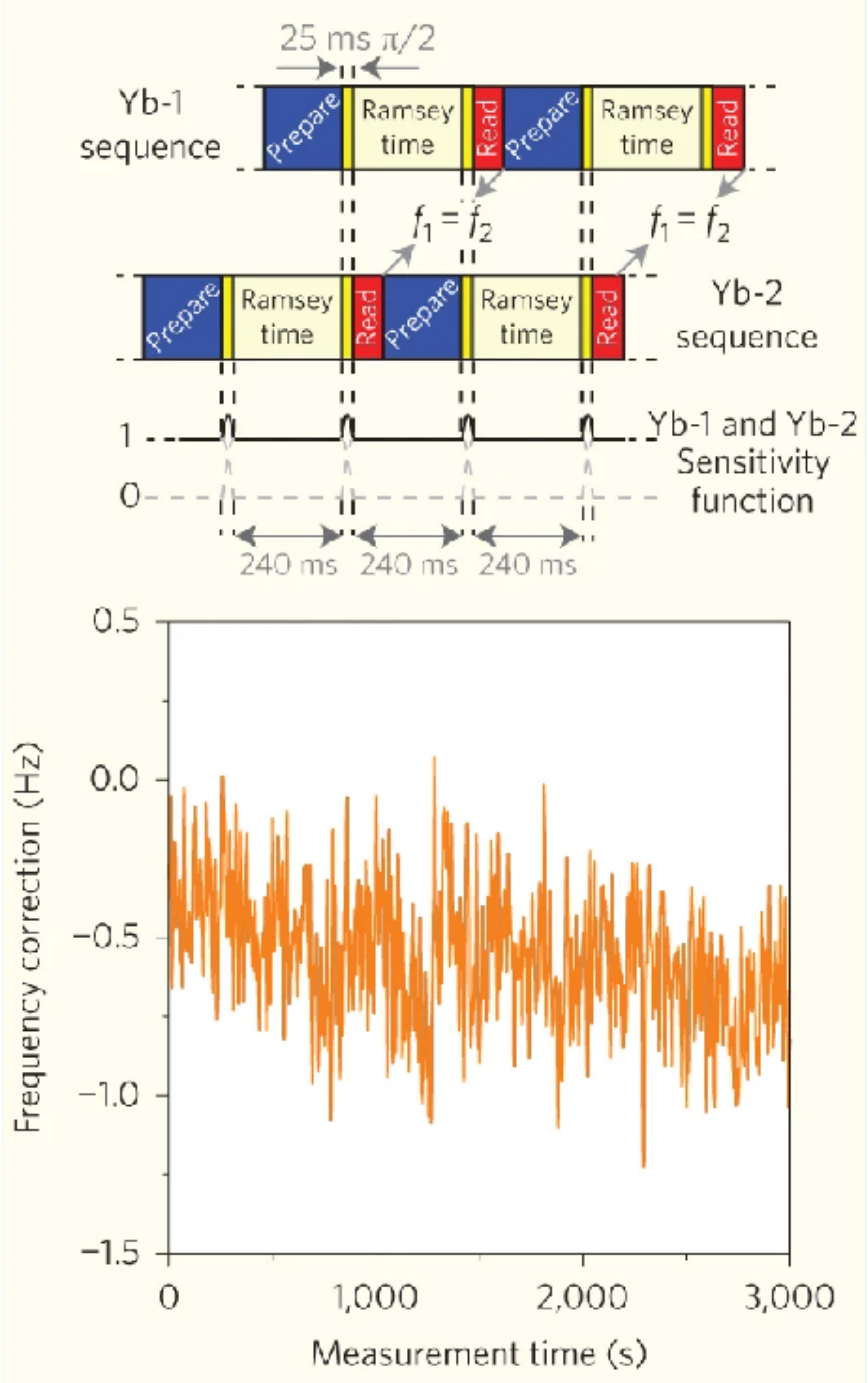
- Example of recent efforts to overcome the effect



asynchronous readout



synchronous readout



readout w/ active feedback corrections

[M. Schioppo et al., Nature Phot. 11, 48 (2017)]

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)

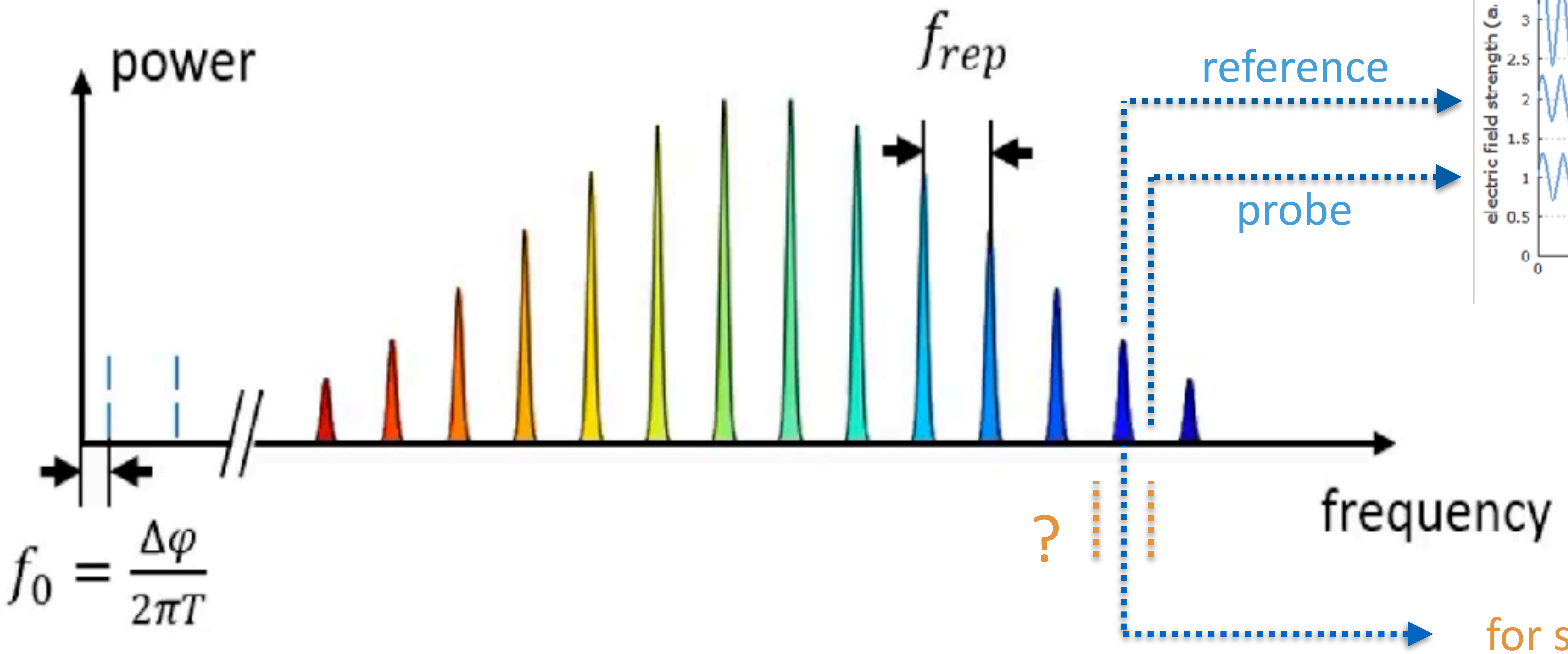
$$f_n = nf_{rep} + f_0$$

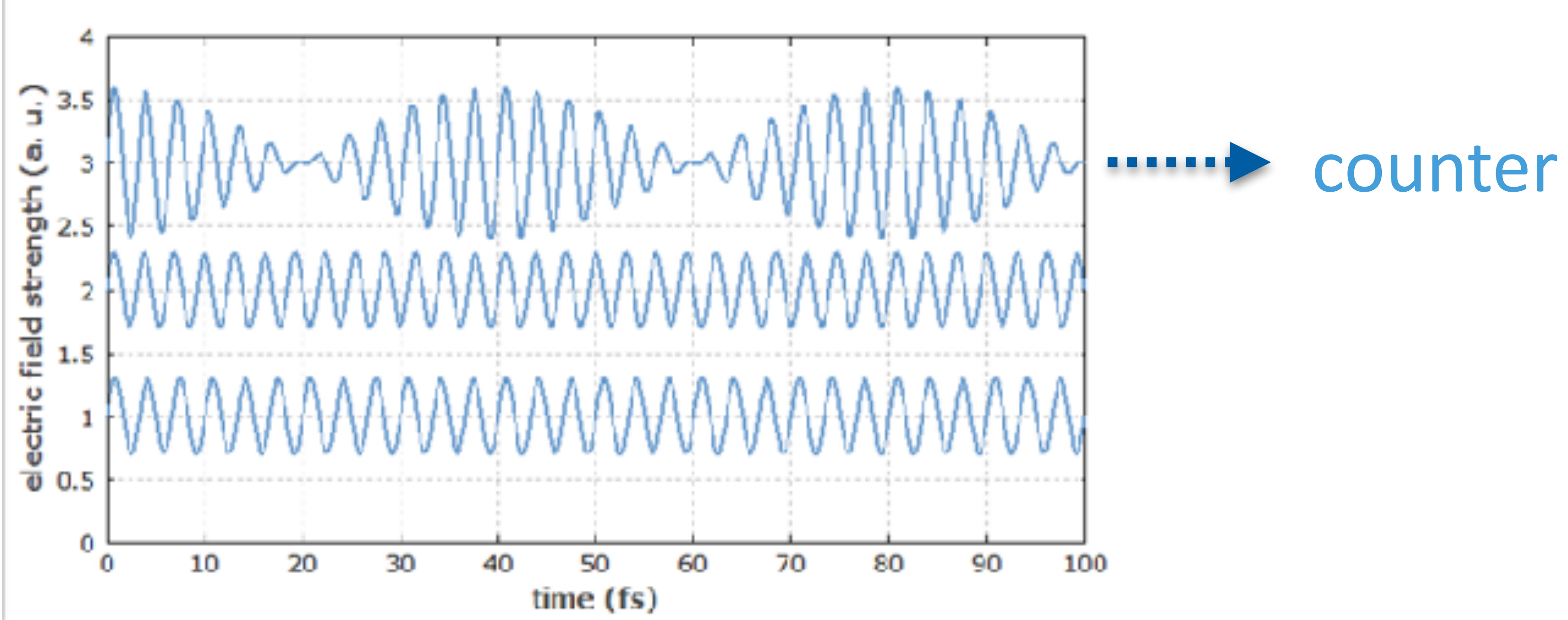
- Repetition frequency f_{rep} typically larger than CEO-frequency f_0 (e.g. 200 MHz vs. 50 MHz)
- Both frequencies are tunable, defined in relation to a frequency reference for high-end applications

[https://www.nobelprize.org/prizes/physics/2005/popular-information/]

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 -





for small increase of f_{rep}:

smaller beat, use $f_n = nf_{rep} + f_0 + f_b$

larger beat, use $f_n = nf_{rep} + f_0 - f_b$

Why Measure a Frequency Ratio?

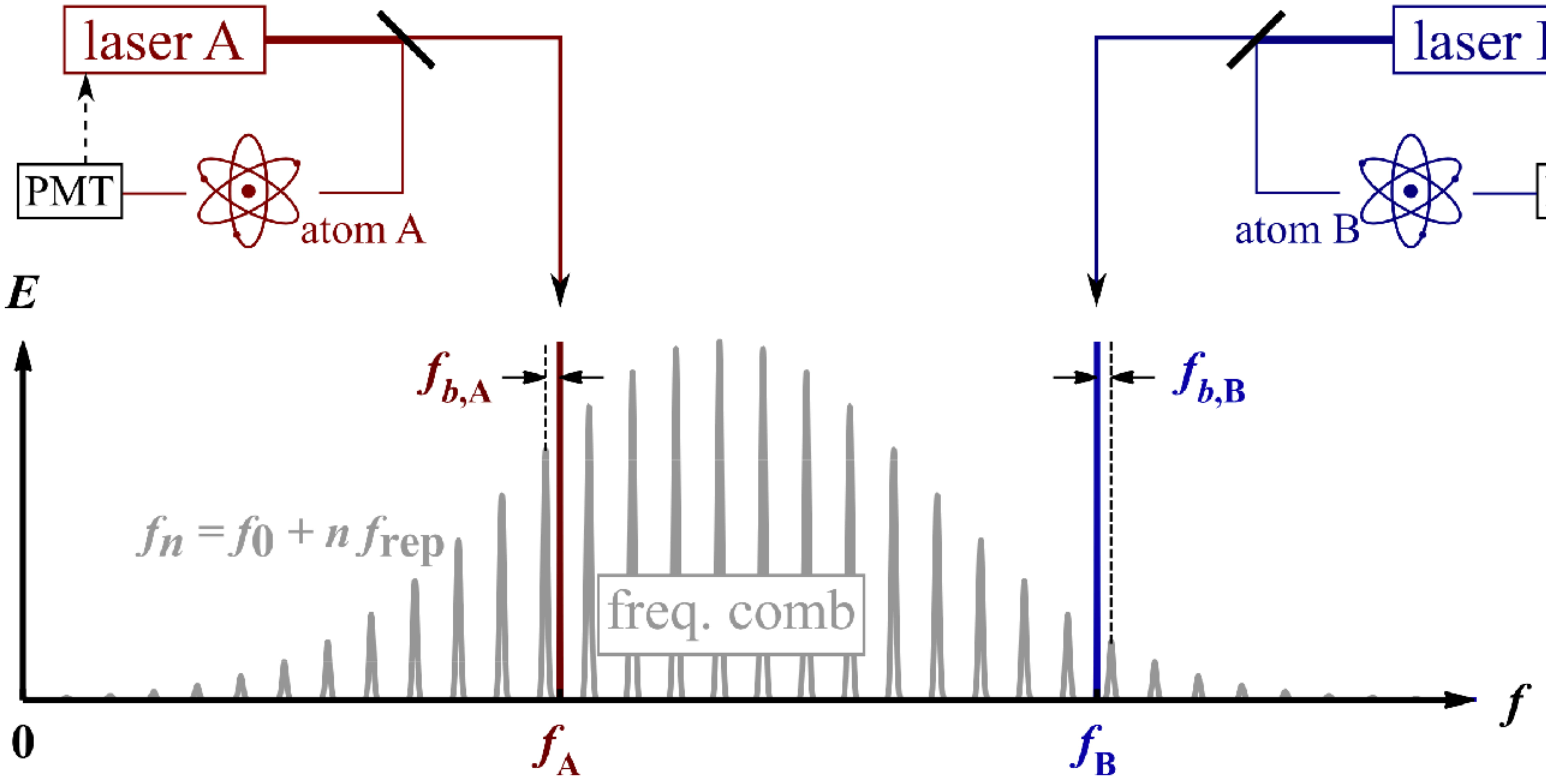
- Unitless: Ratios are not limited by the definition/accuracy of the SI second
- Transportable: Frequencies depend on gravity (et al); ratios can be used for comparison
- Measurable: Even at optical frequencies, can use a frequency comb to measure with accuracy and stability limited by the clocks themselves
- 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

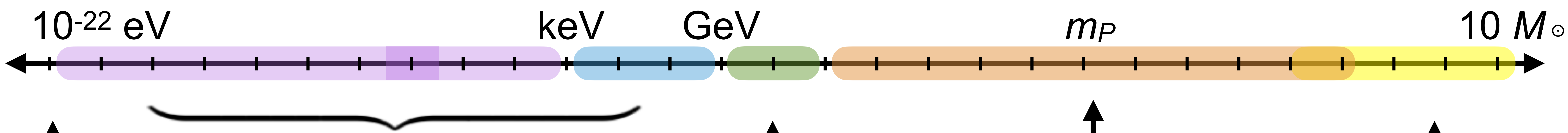
Typical Experiment Setup



[Arvanitaki et al., Phys. Rev. D 91, 015015 (2015)]

Particle Physics Example: Mass Scales for Dark Matter

Quantum Sensing needed for Light/Ultralight Dark Matter



Light and Ultra-light Dark Matter
Axions, ALPs
Quantum Sensing

Composite Dark Matter
WIMPzillas, Q-balls, bound states
CMB, Cosmic Rays

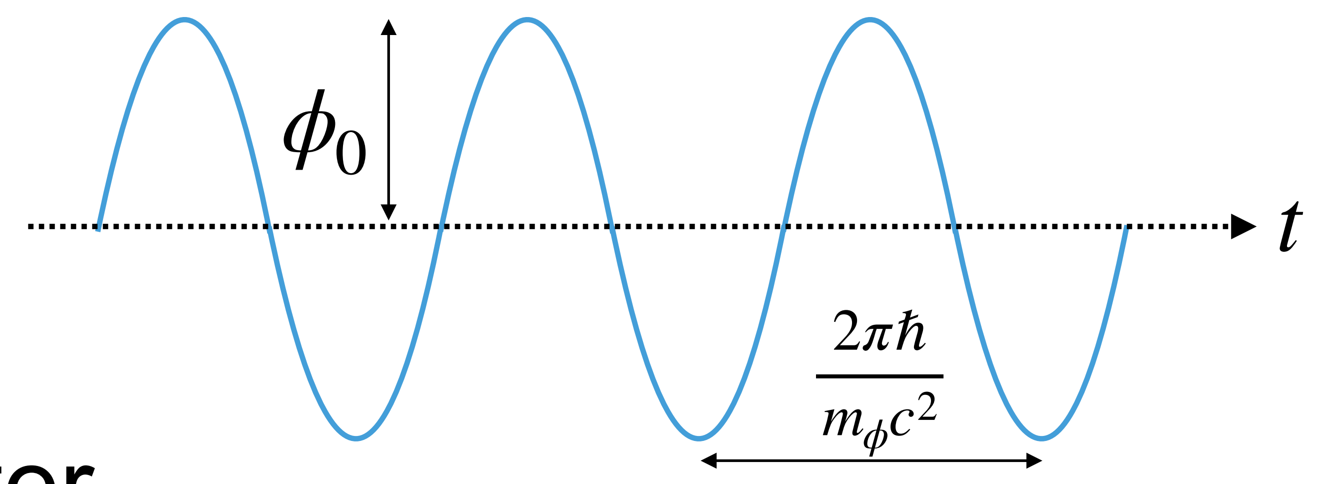
probably not below:
de Broglie wavelength too long

Standard Model Particle Scale
Weakly Interacting Massive Particles
Collider Searches

Superheavy Dark Matter
Primordial Black Holes
Gravitational Lensing

[T. Lin, arXiv:1904.07915]

Ultra-Light Dark Matter: Phenomenology



- Starting with Standard Model Lagrangian, adding new DM interaction (field)
- Bosonic: Ultra-light DM must be bosonic in nature
- Non-relativistic ($\sim 10^{-3}c$): so it neither leaves the galaxy or clumps near the center
- Oscillating classical field: coherent, practically monochromatic → wave-like

$$\phi(t) \approx \phi_0 \cos(m_\phi c^2 t/\hbar)$$

$$\mathcal{L}_{int} = \frac{4\pi\phi}{M_{pl}}\left(\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e}m_e\bar{e}e - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right)$$

- Coupling to Lagrangian is linear (in ϕ) for lowest order interaction w/ scalar field (or quadratic with $\phi \leftrightarrow -\phi$ symmetry)

$$\mathcal{L}_{DM} = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e}m_e\bar{\psi}\psi \qquad \mathcal{L}_{DM} = \frac{\phi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi^2}{(\Lambda'_e)^2}m_e\bar{\psi}\psi$$

- At the effective new physics energy scales Λ_α and Λ_e, α and m_e appear to oscillate

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0\cos(m_\phi t)}{\Lambda_\gamma}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0\cos(m_\phi t)}{\Lambda_e} \qquad \frac{d\alpha}{\alpha} \approx \frac{\phi_0^2\cos^2(m_\phi t)}{(\Lambda'_\gamma)^2}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0^2\cos^2(m_\phi t)}{(\Lambda'_e)^2}$$

[Damour & Donoghue, PRD 82, 084033 (2010); Arvanitaki et al., Phys. Rev. D 91, 015015 (2015); Safranova et al., RMP 90, 025008 (2018)]

Clock Transitions and Sensitivities

Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

- Atomic transition scale set by Rydberg constant $R_\infty = \alpha^2 m_e c/4\pi\hbar$, also fine structure constant α and proton-to-electron mass ratio μ

  Hyperfine transitions: $\nu_{\mathrm{hf}} = A \cdot \mu\alpha^2 F_{\mathrm{hf}}(\alpha) \cdot R_\infty$

  Optical transitions: $\nu_{\mathrm{opt}} = B \cdot F_{\mathrm{opt}}(\alpha) \cdot R_\infty$

  Vibrational transitions: $\nu_{\mathrm{vib}} = C \cdot \mu^{1/2} \cdot R_\infty$

- Transitions have different sensitivities to variations in α or μ, given by K_α and K_μ

$$K_\alpha = \frac{\partial \ln\left(\frac{\nu}{cR_\infty}\right)}{\partial \ln \alpha} = \begin{cases} 2 + \partial \ln F_{hf}/\partial \ln \alpha & \text{for hyperfine transitions} \\ \partial \ln F_{opt}/\partial \ln \alpha & \text{for optical transitions} \end{cases}$$

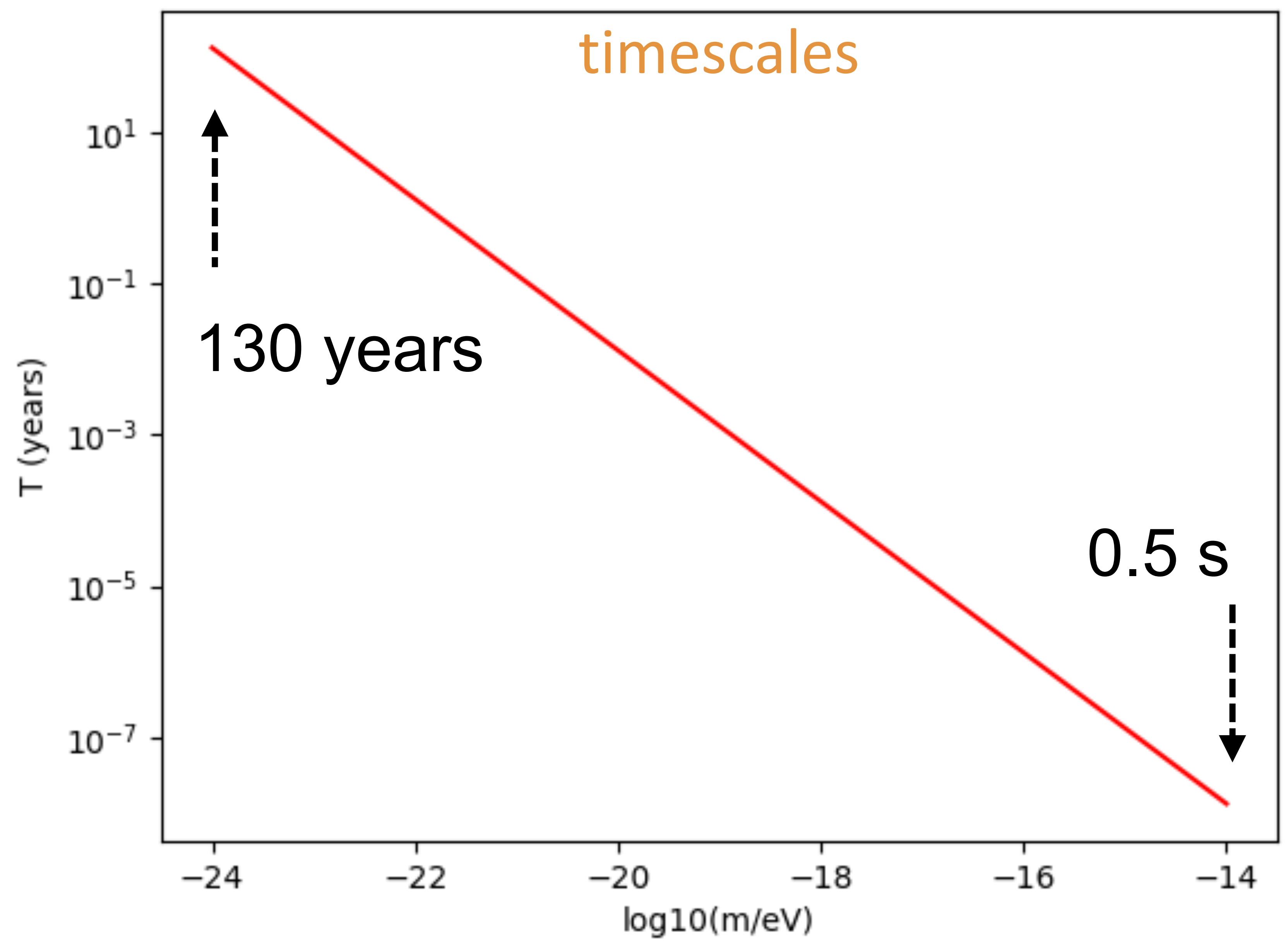
- Measure ratios of frequencies of two transitions ($R = \nu_1/\nu_2$)
- So for α and simple case of scalar field ϕ and linear coupling, ratio oscillates with frequency $f = m_\phi c^2/h$

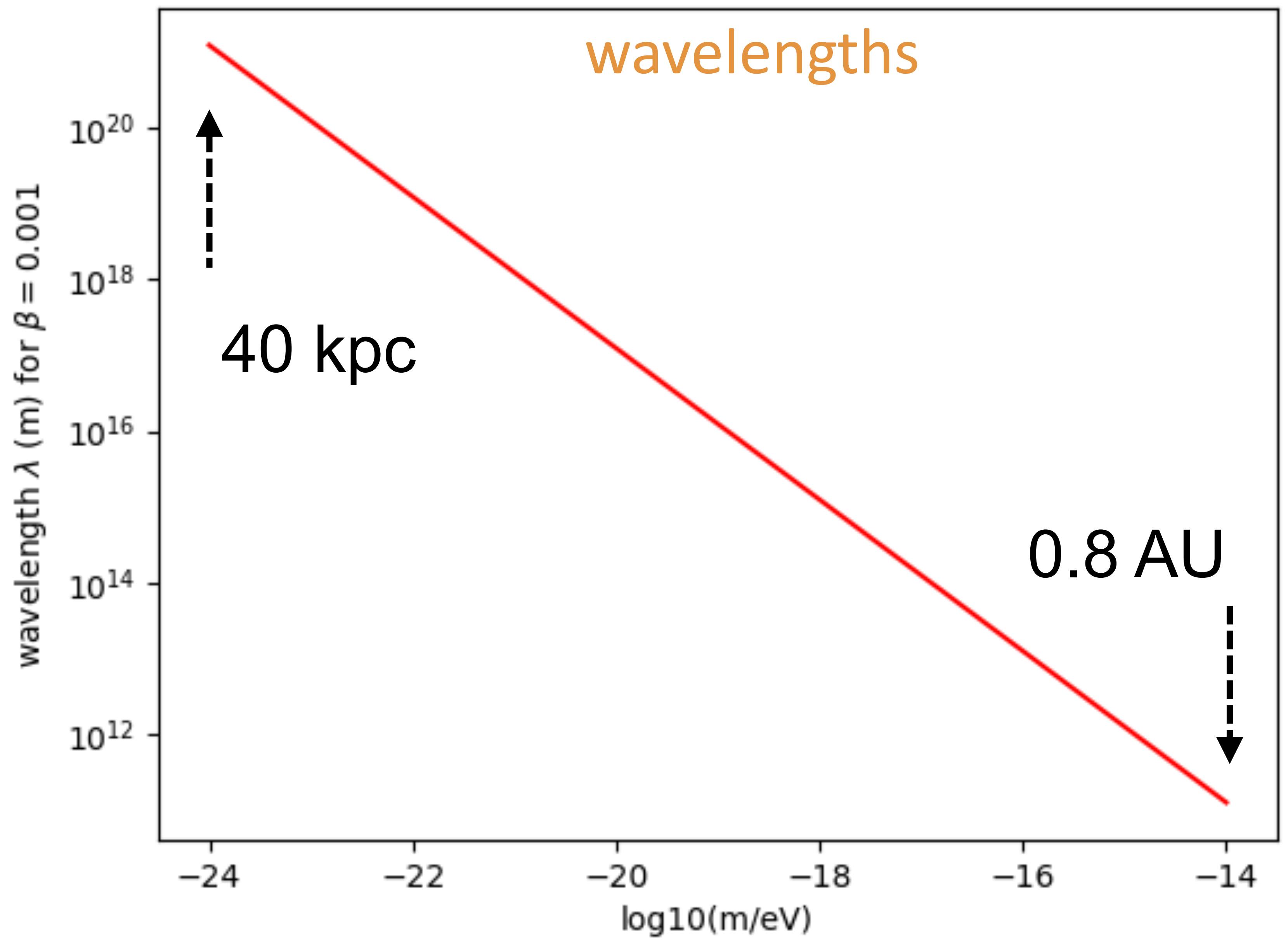
$$\frac{dR}{R} = [K_{\alpha,1} - K_{\alpha,2}]\frac{d\alpha}{\alpha}$$
$$= [K_{\alpha,1} - K_{\alpha,2}]\frac{\phi_0 \cos(m_\phi t)}{\Lambda}$$

Sensitivity estimates for $\delta\alpha/\alpha$ for different clock transitions… similar for and $\delta\mu/\mu$

Wave-like Dark Matter

- Dark Matter with clock experiments—oscillation timescales and wavelengths





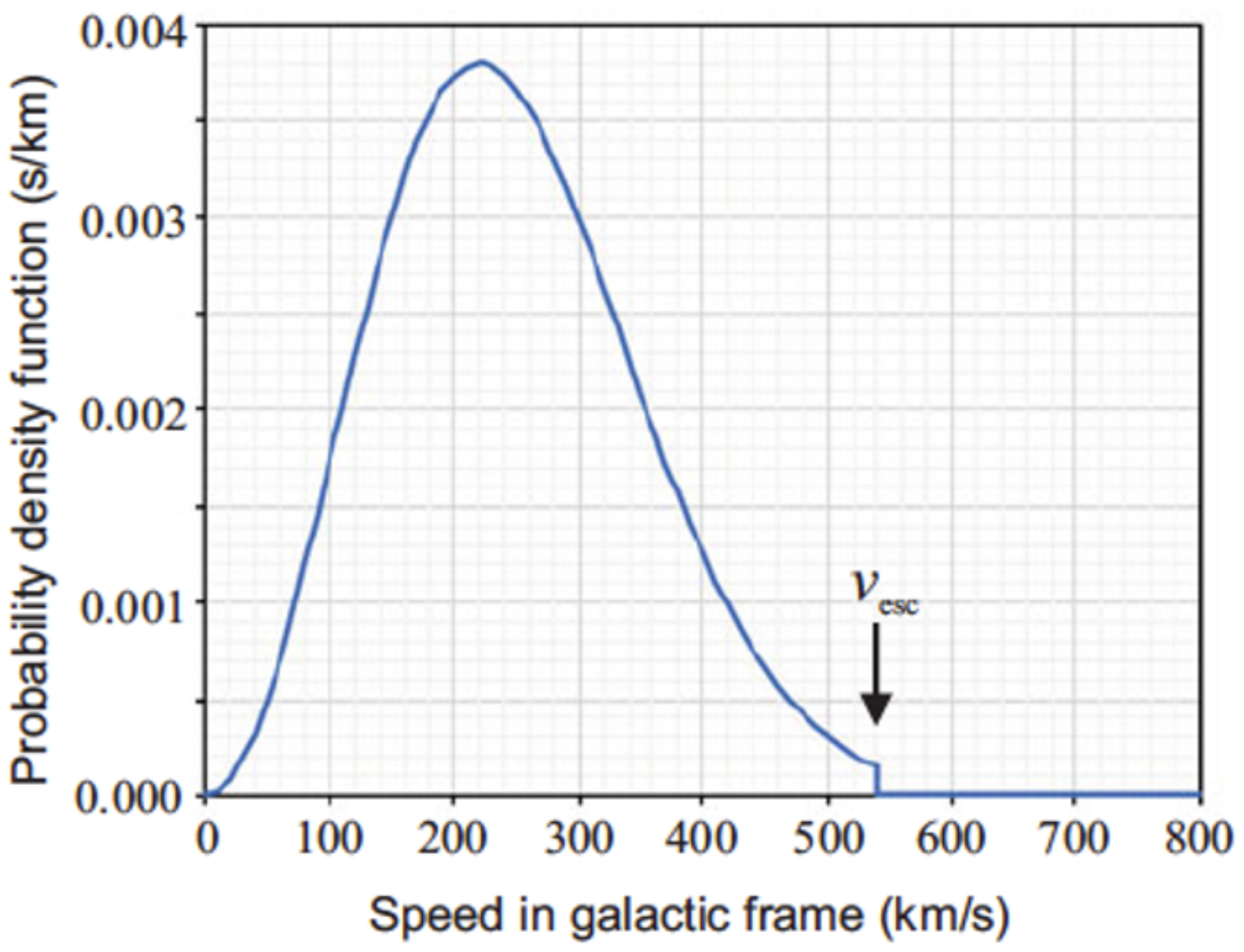
$$E = \hbar\omega = mc^2 = \frac{h}{T} \implies T = \frac{2\pi\hbar}{mc^2}$$

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

- 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

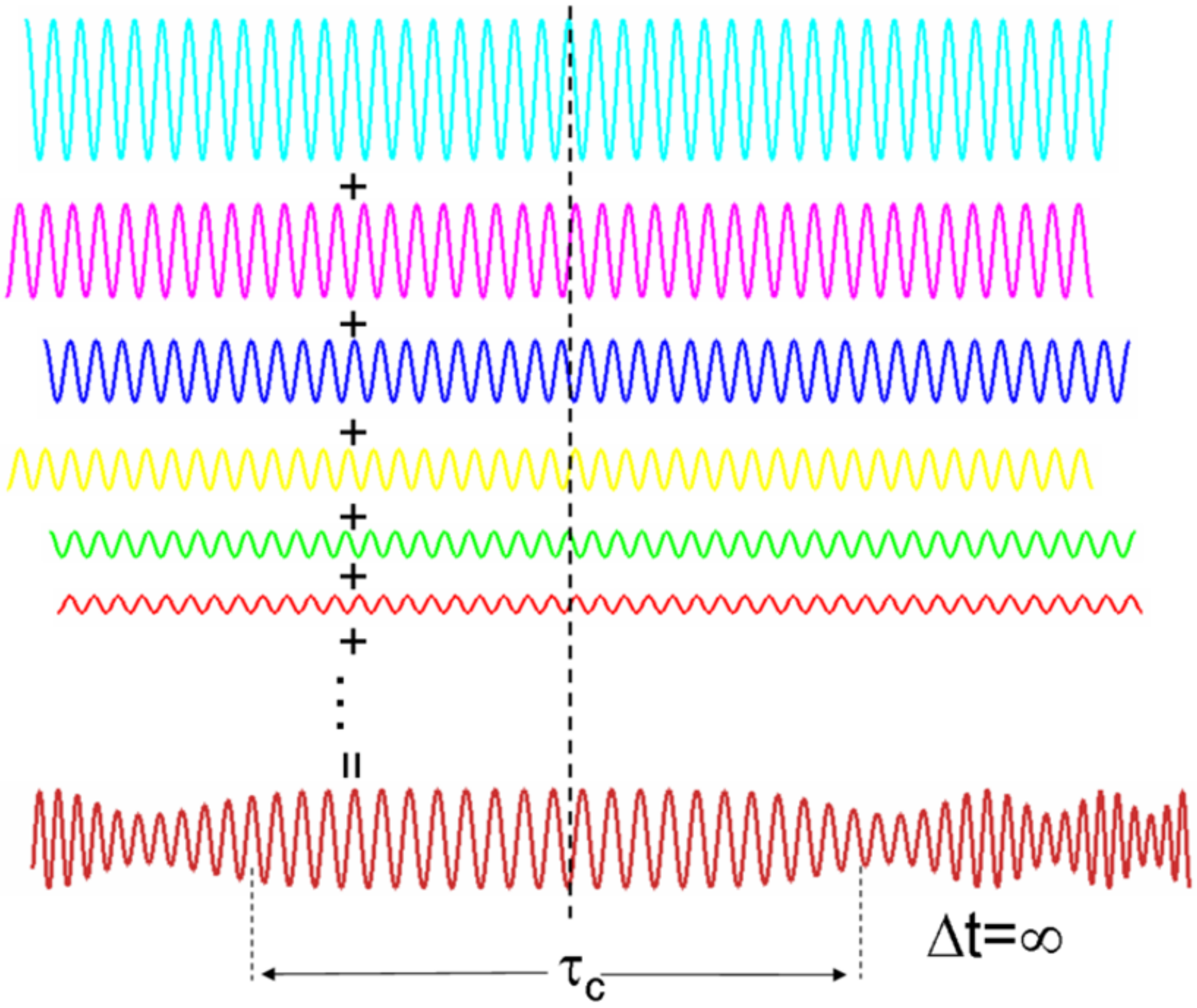
- DM makes up most of the Milky Way mass, and density at the solar circle is 0.3-0.4 GeV cm^{-3}
- Velocity dispersion is large, around 300 km/s (DM is virialised, not thermalised)
- Velocity distribution has cutoff at 544 km/s
- Sun moves with 220 km/s toward constellation Cygnus
- Earth moves around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



[U. Schwanke; G. Centers et al., Nature Communications 12, 7321 (2021)]

Ultra-Light Dark Matter as Semi-Coherent Waves?

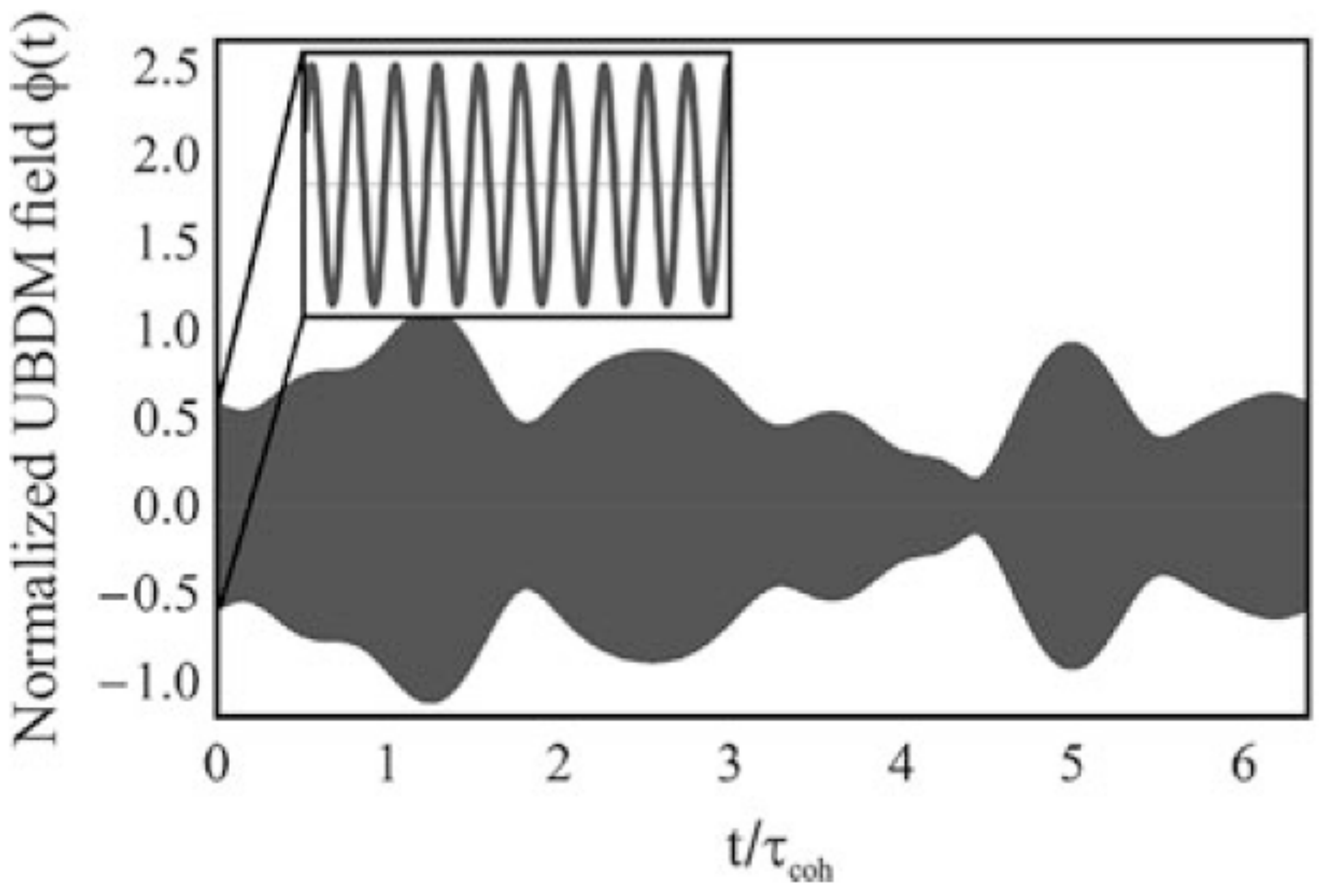
- Simple case: DM is coherent and frequency completely determined by mass (previous page)
- This picture is too simple… the frequency is also a function of velocity (Milky Way, local rest frame)
- The result is a superposition of DM waves and a time dependence
- Amplitude of DM signal only approx. constant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

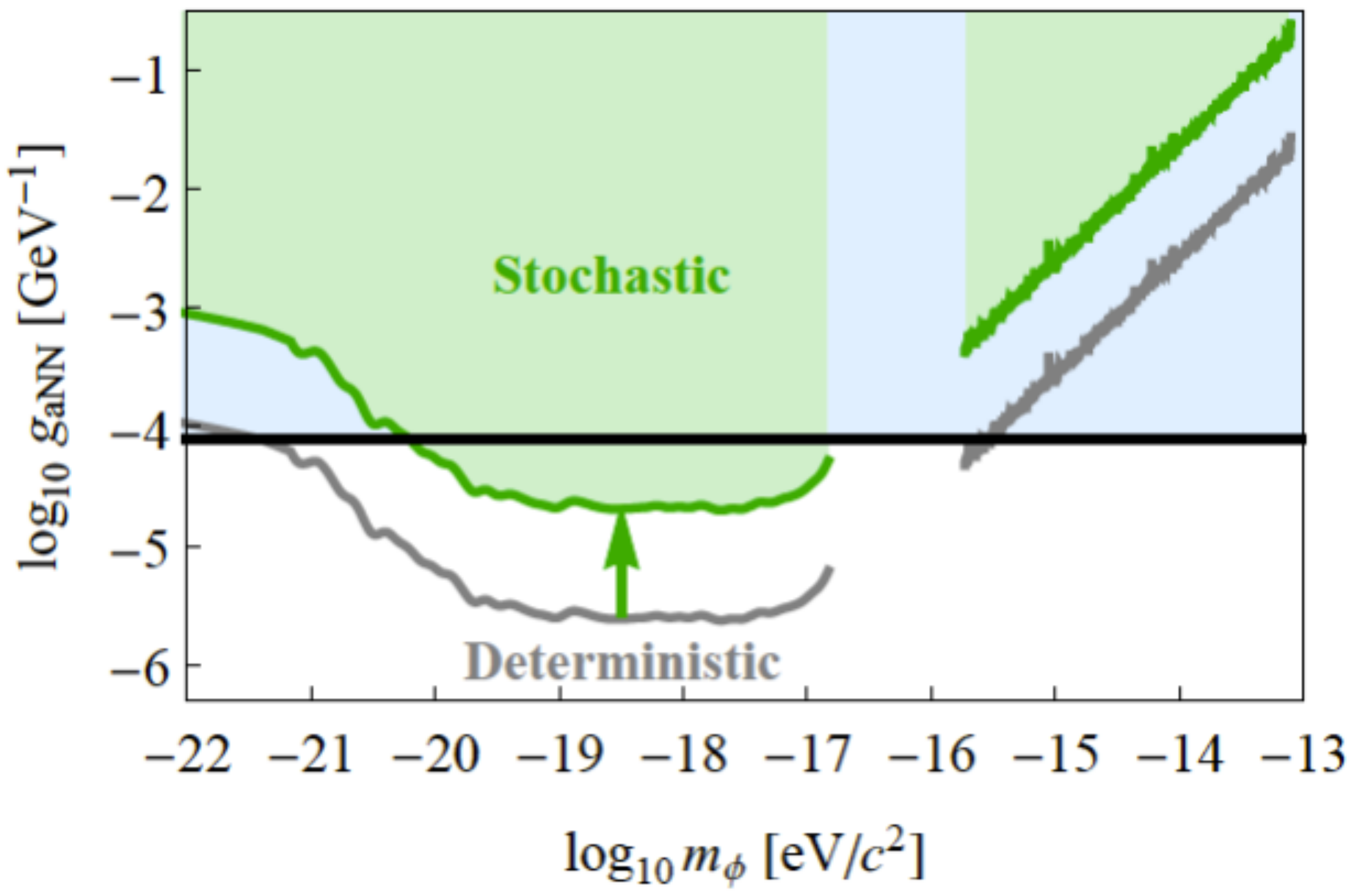


[fig: Wikipedia]

Dark Matter Coherence Time vs T_{data}

- Field amplitude varies stochastically with time
- For $T_{data} < \tau_c$: oscillation occurs at same frequency, but field amplitude not same as average DM density
- For $T_{data} > \tau_c$: 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





[U. Schwanke; G. Centers et al., Nature Communications 12, 7321 (2021)]

Data Analysis Challenge

- One frequency ratio R measurement per s for $\mathcal{O}$(1 year), i.e. 3×10^7 data points → 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

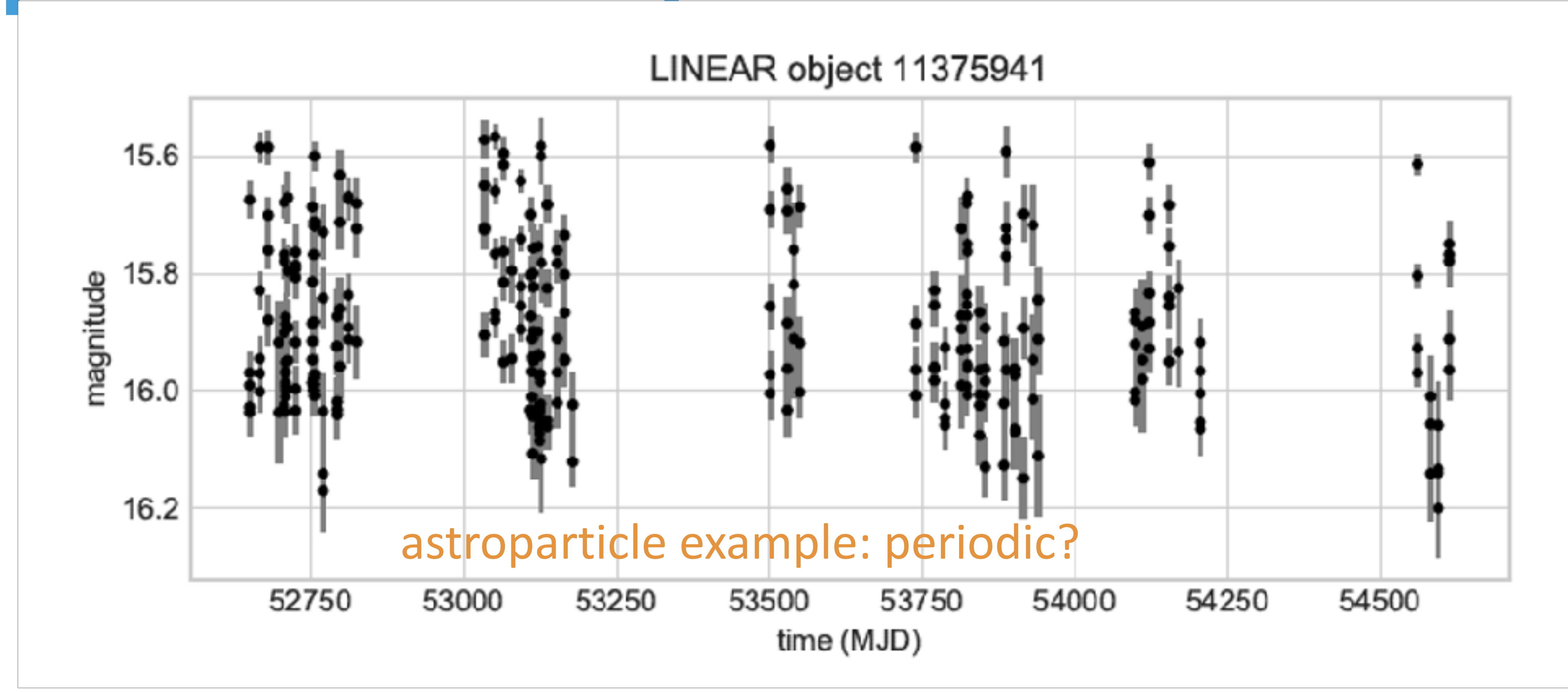
$$\frac{dR}{R} = [K_{\alpha,1} - K_{\alpha,2}]\frac{\phi_0 \cos(m_\phi t)}{\Lambda}$$

- *The challenge:*
- Limited time steps: discreet (~1s) 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

[U. Schwanke]

Fourier Transform and Power Spectral Density

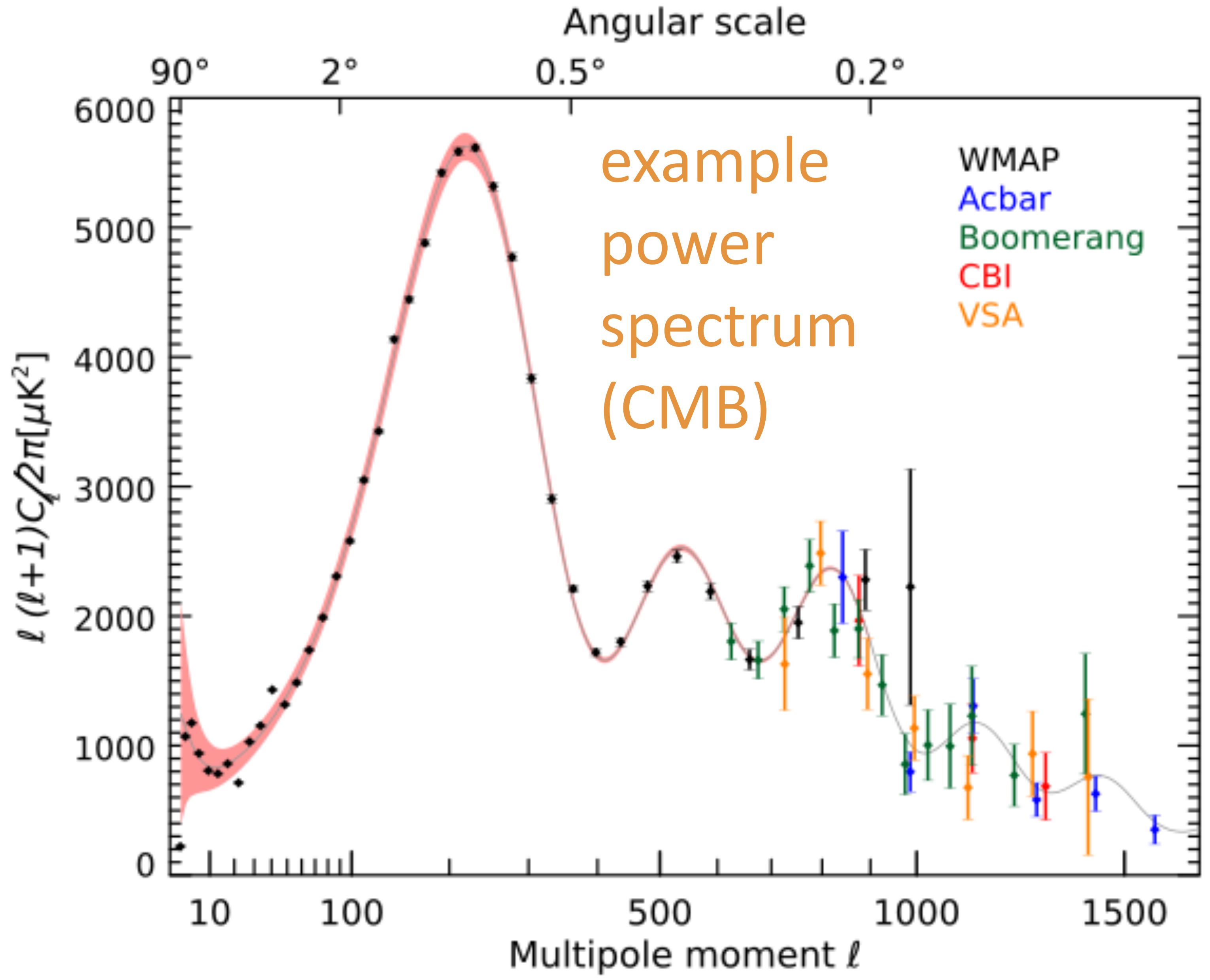
- There are many techniques to identify periodicity
- Signal is often folded/convolved with a windowing function resulting from experimental constraints
- Suitable analysis method depends on many factors (frequency known or not, phase known or not, cadence of observations)
- Our case: frequency unknown,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

$$P(\omega) = \lim_{T\to\infty} \frac{1}{T} |F(\omega)|^2$$ power spectral density



[Astro-ph arXiv: 1703.09824; Wikipedia for CMB]

Periodogram and Lomb-Scargle

- Periodogram: serves as an estimate of the power spectral density for the case of discreet 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

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

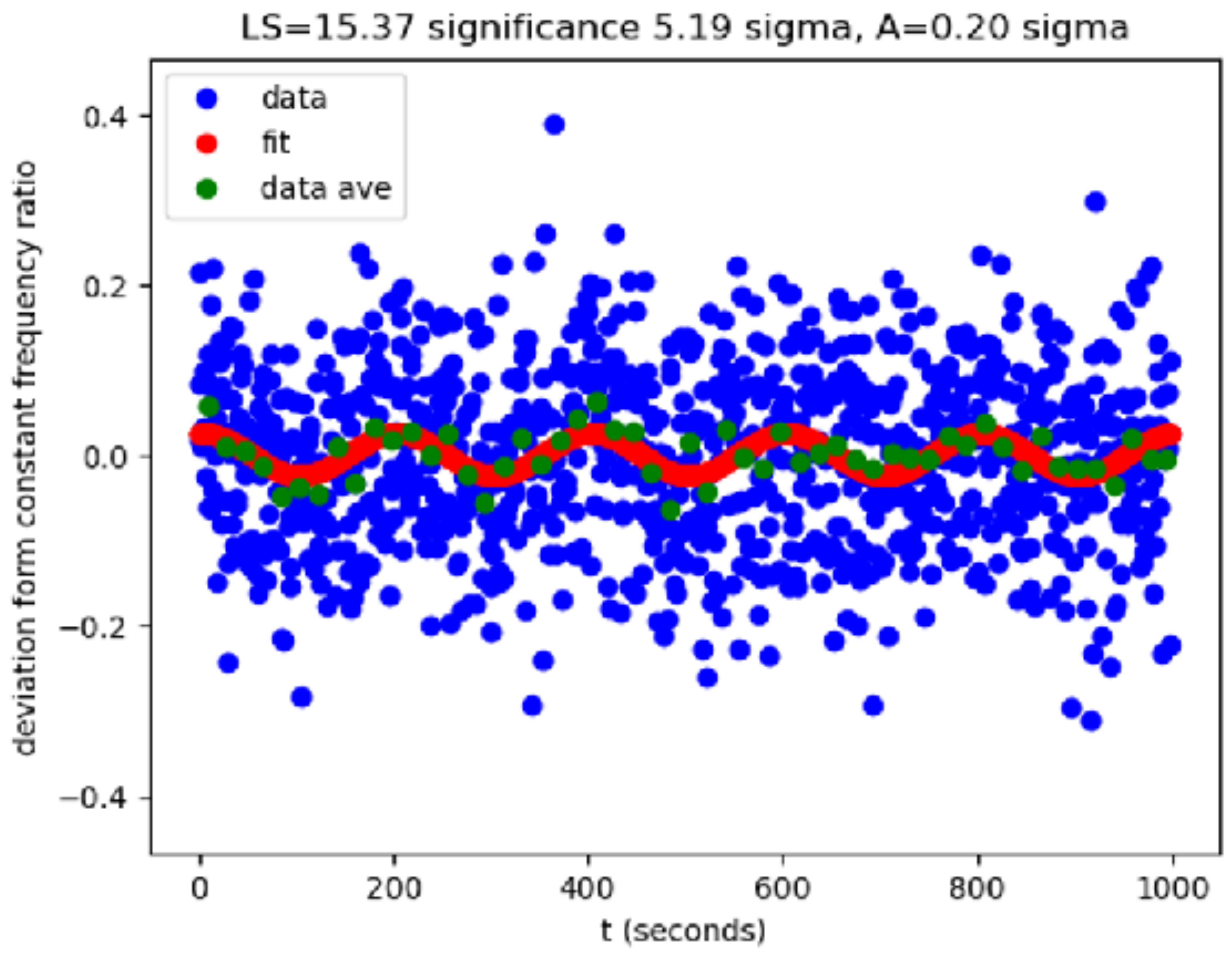
power spectral density

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

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

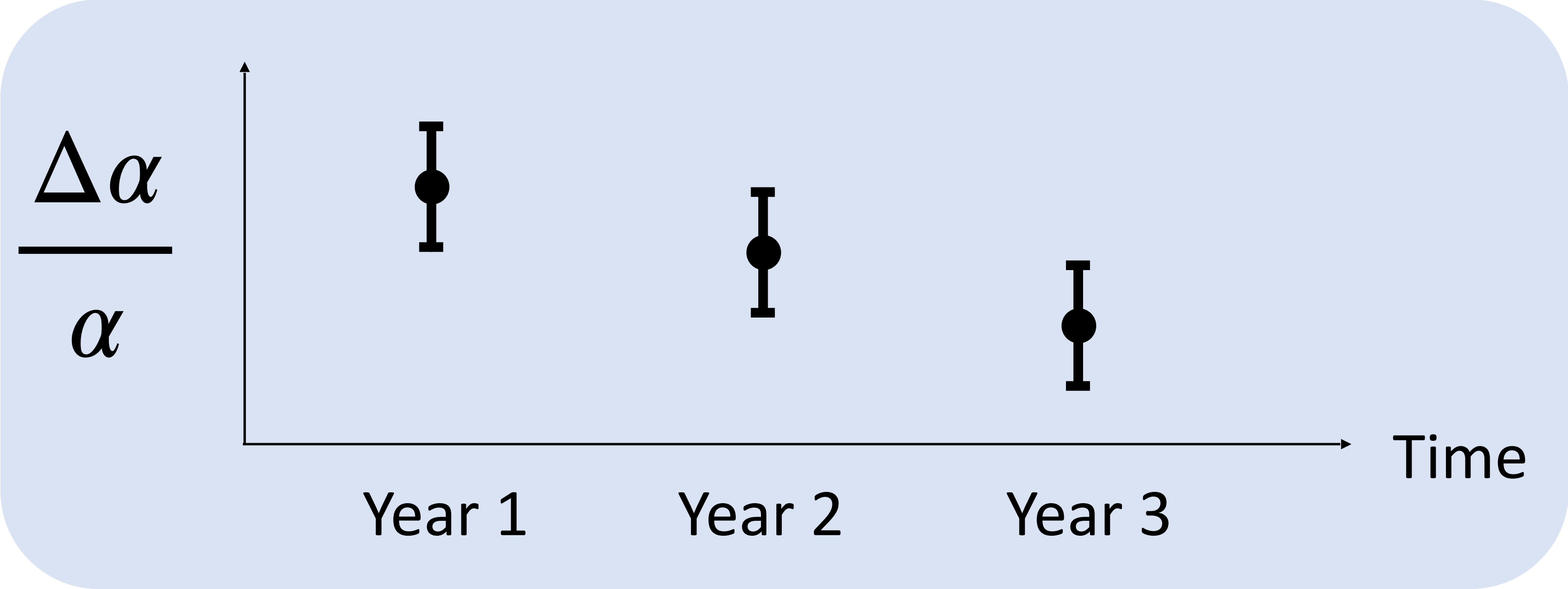


Simulation w/ Lomb-Scargle fit (red)
1 Hz sampling, σ=0.1, N=10^3, T=200 s

[U. Schwanke]

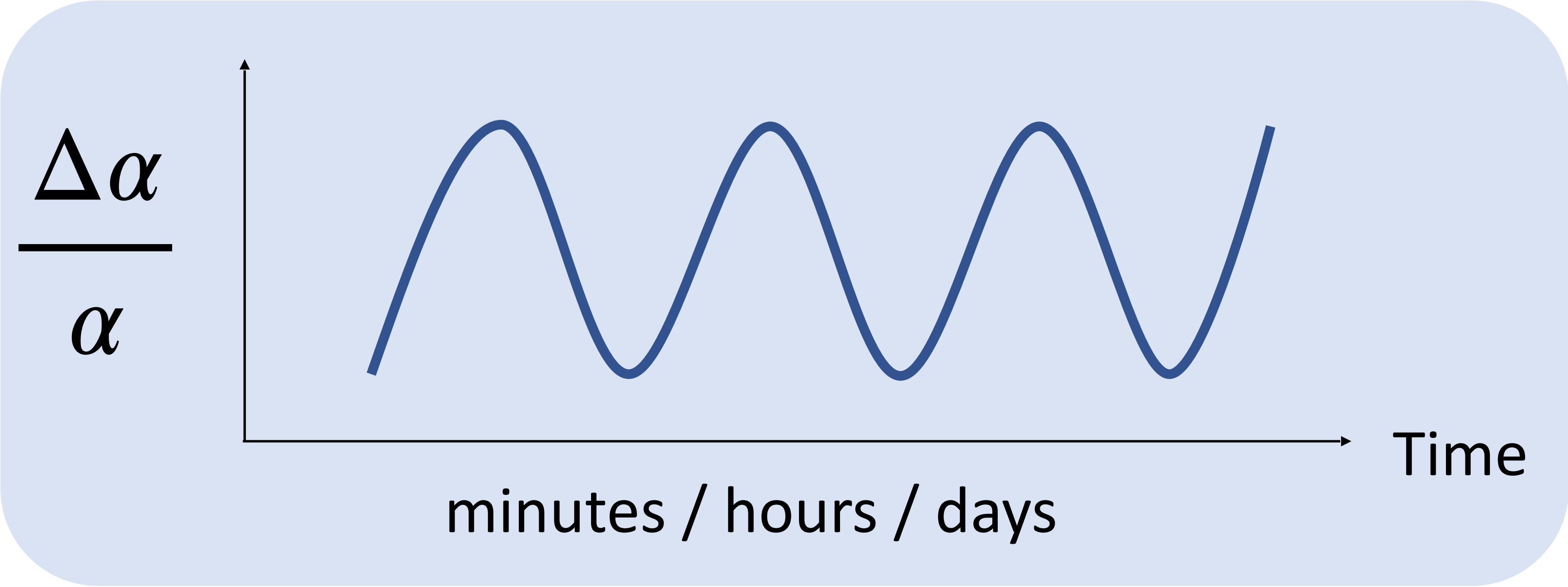
Clock-based Search for α Variations at Different Timescales

- Slow drifts



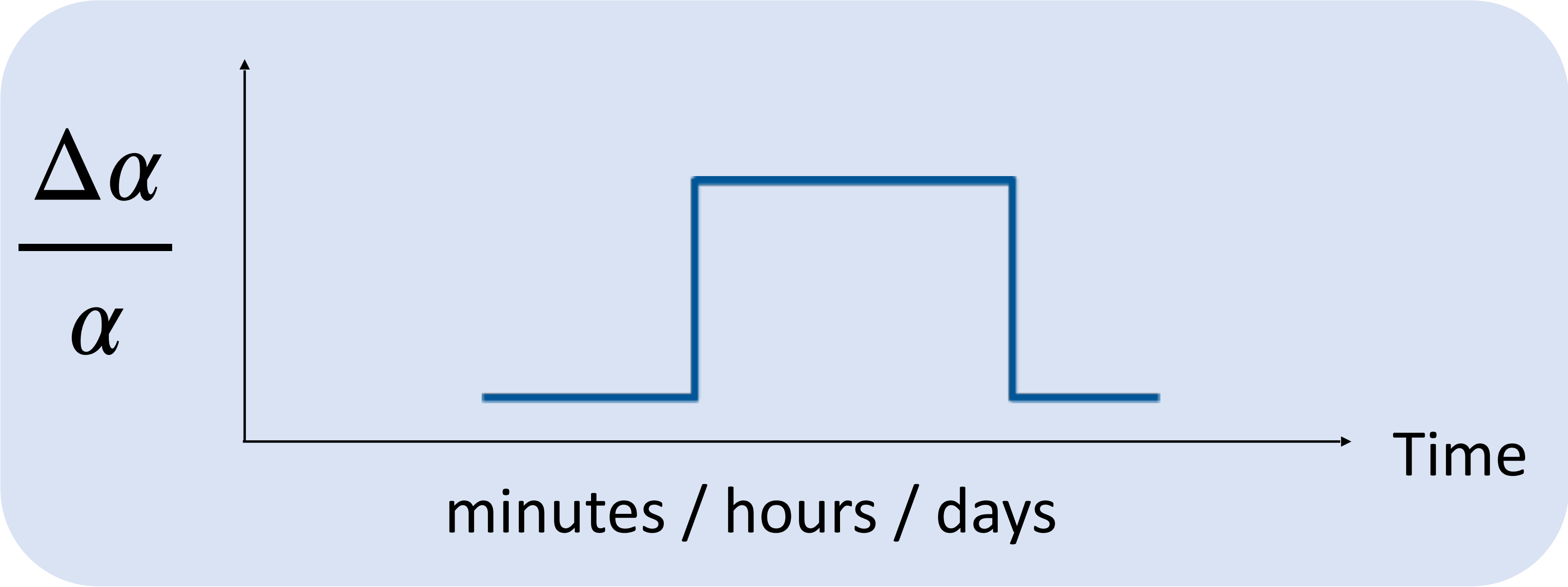
➡ New physics

- Oscillations



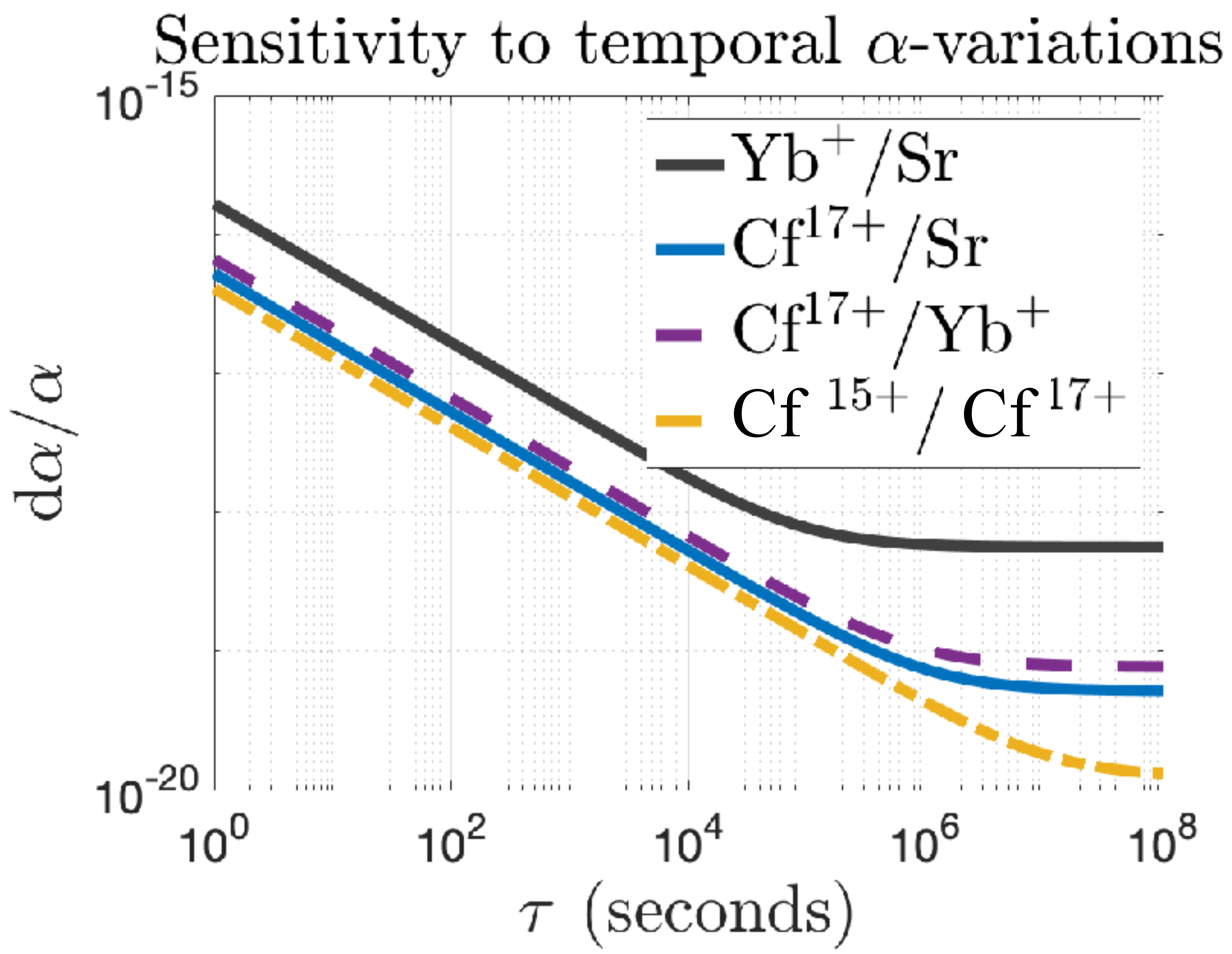
➡ Very light dark matter

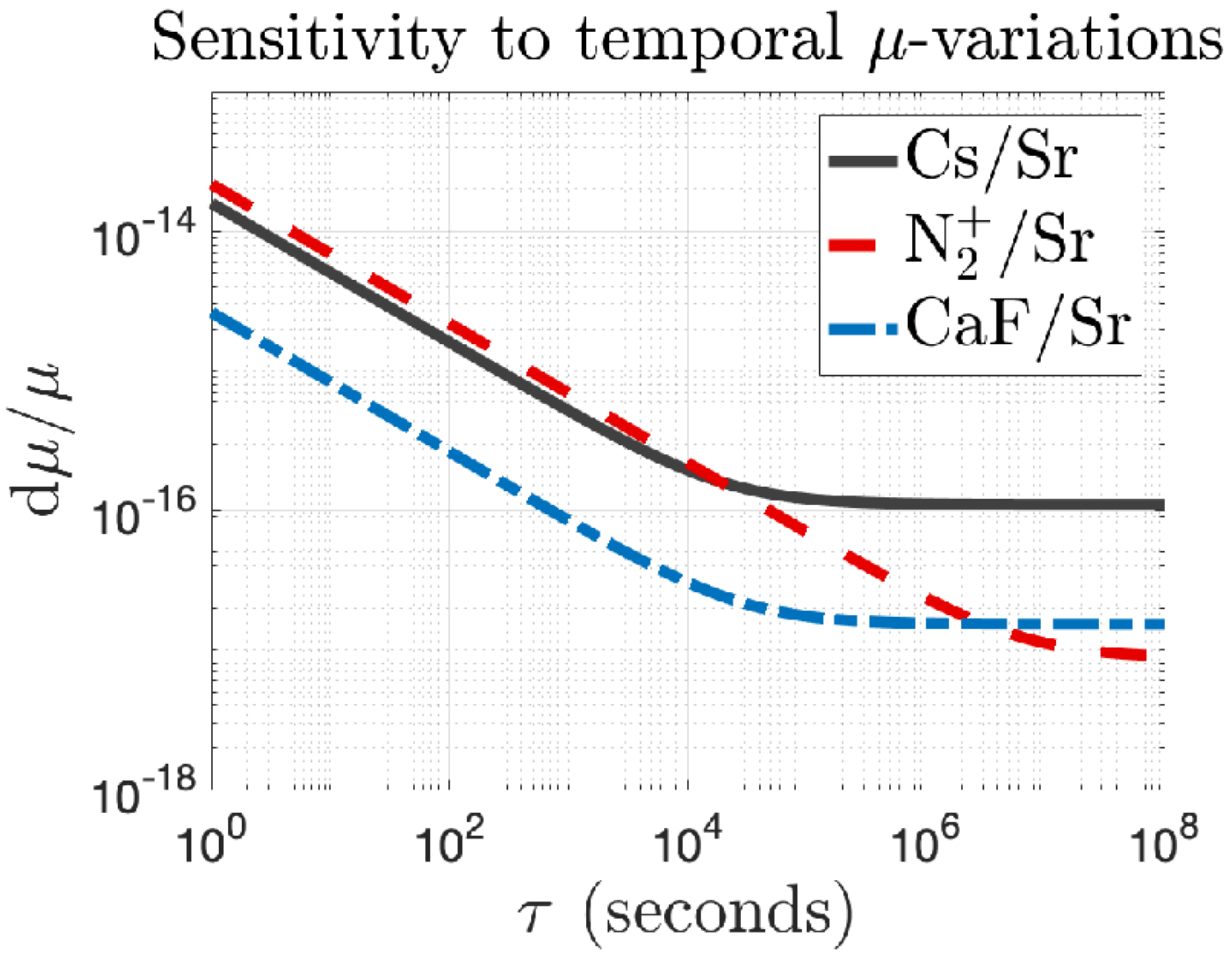
- Fast transients



➡ Dark matter, topological defects

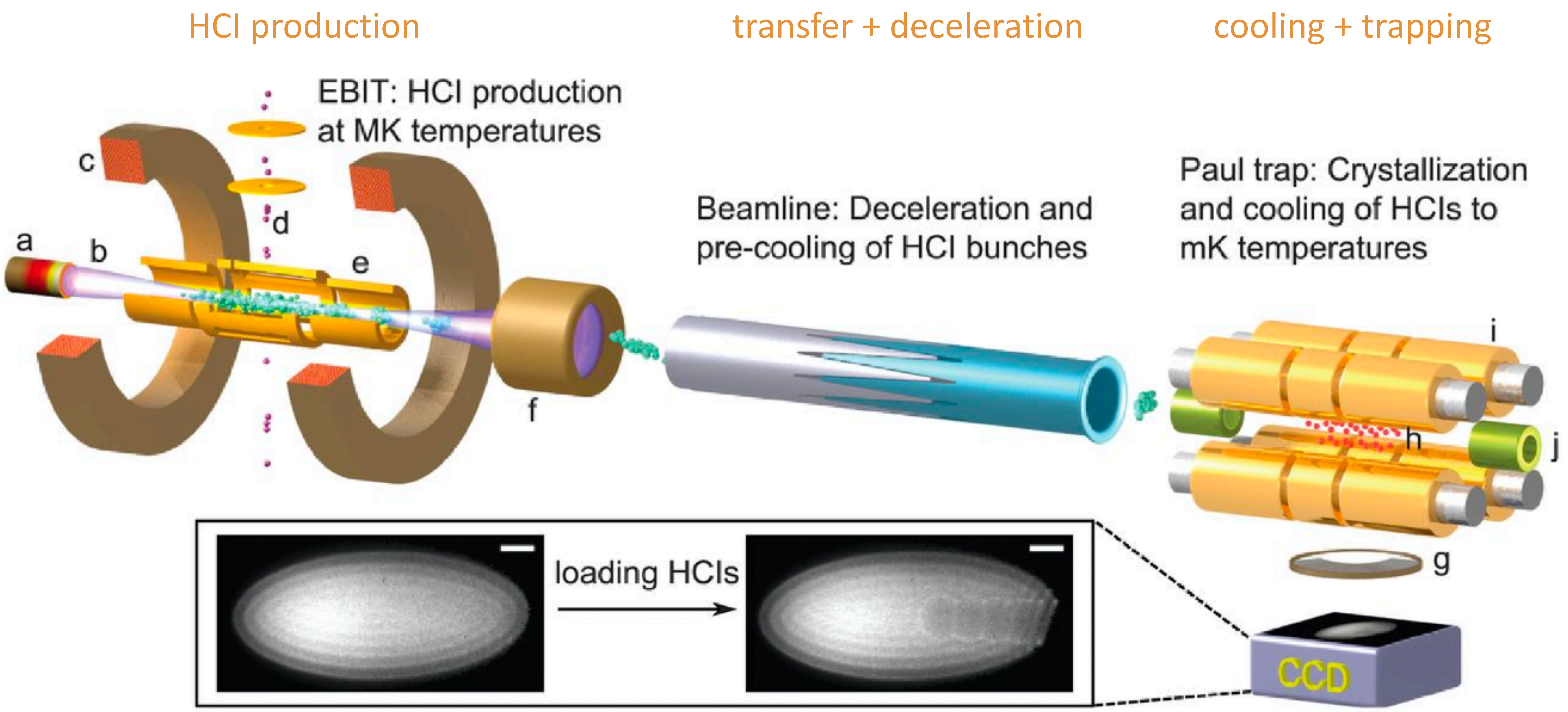
Sensitivities to Temporal Variations of α, μ





[EPJ Quant.Technol. 9 (2022) 1,12]

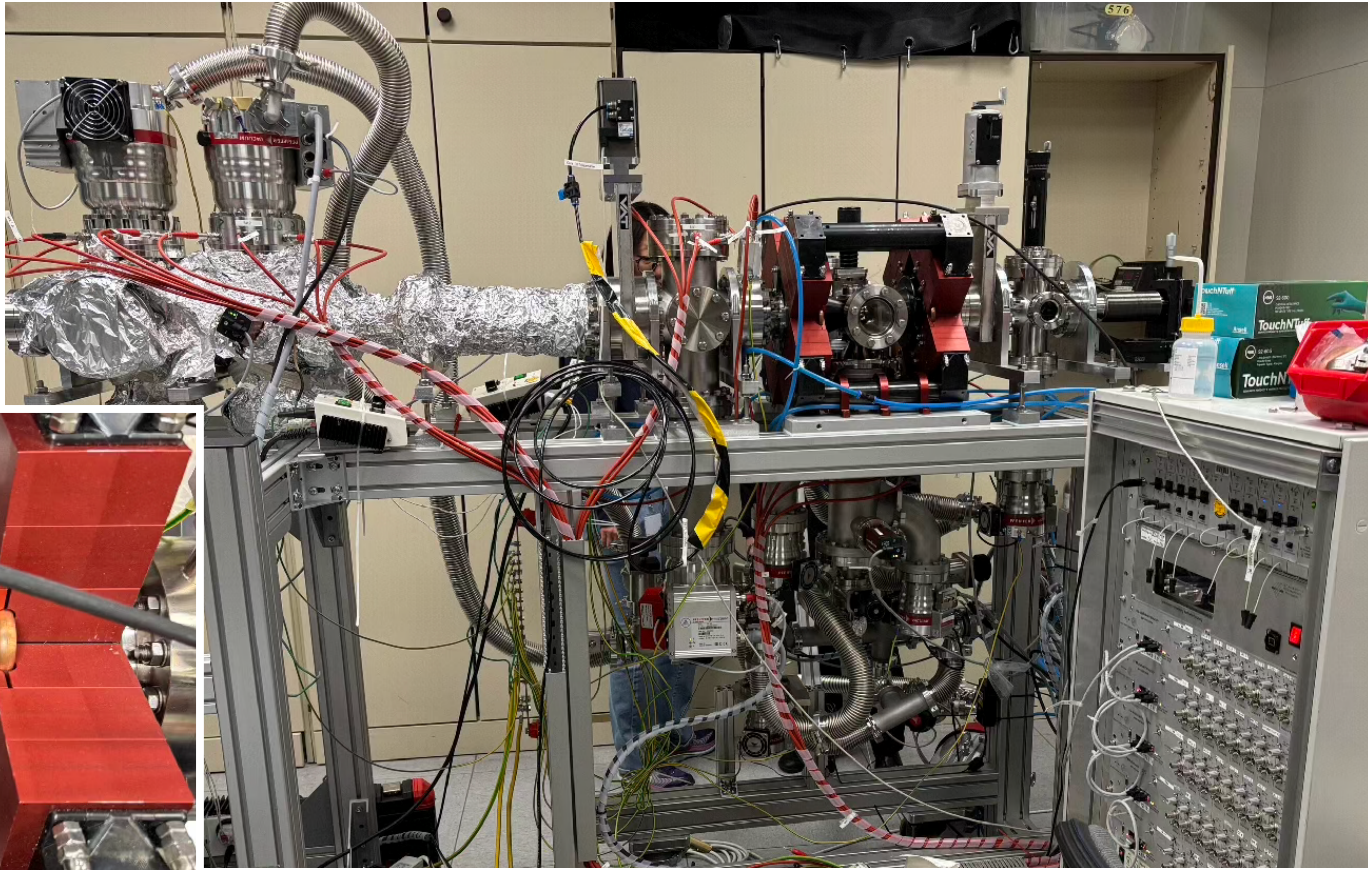
Highly Charged Ions: Production, Cooling and Trapping

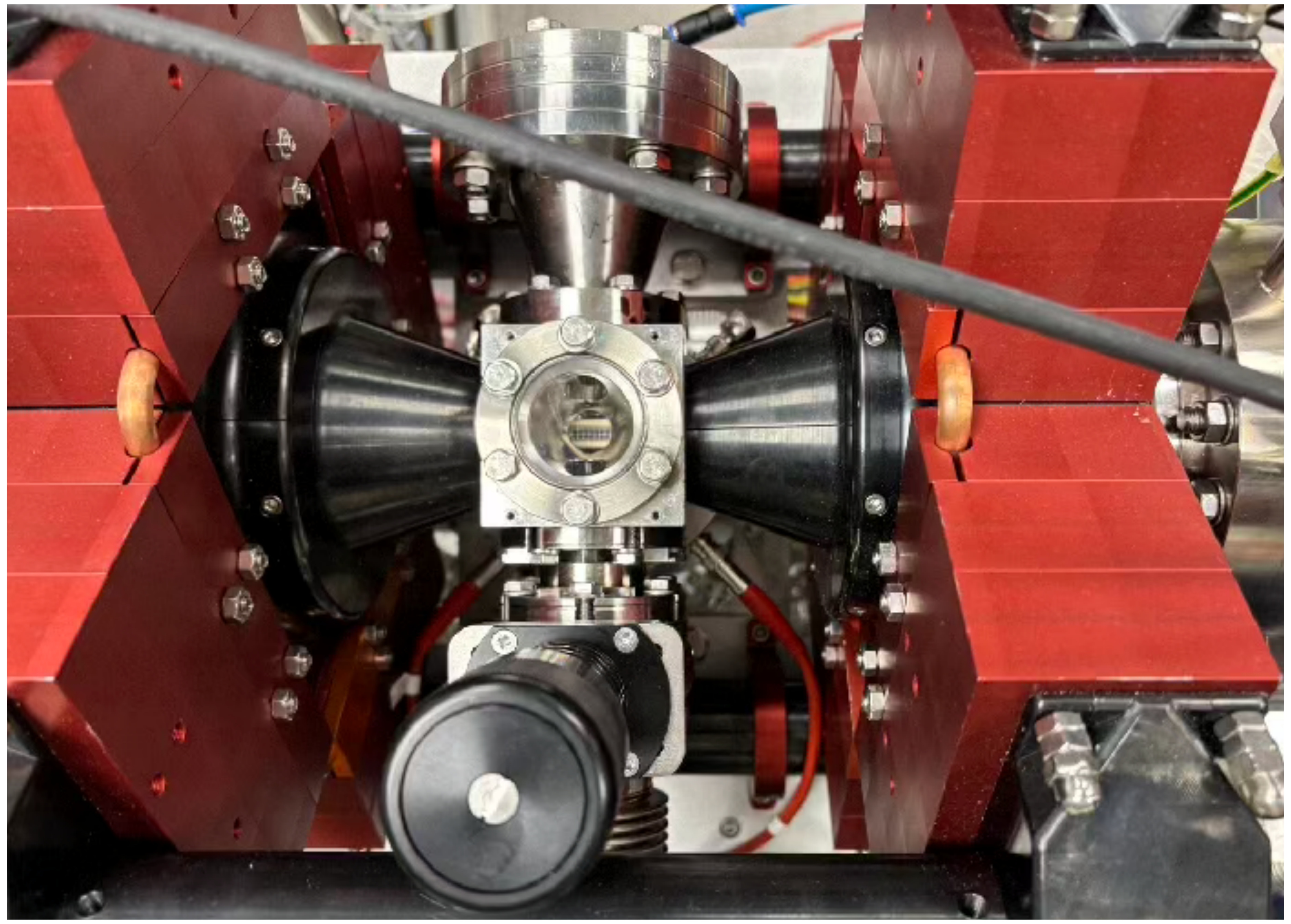


- EBIT: Electron Beam Ion Trap (used as a source of HCI)
- HCI bunches are loaded into a linear Paul Trap on demand (HCI lifetimes can be hours)
- Laser and Sympathetic Cooling e.g. with Be+, Ca+ (lots of lasers for cooling/preparation/readout)

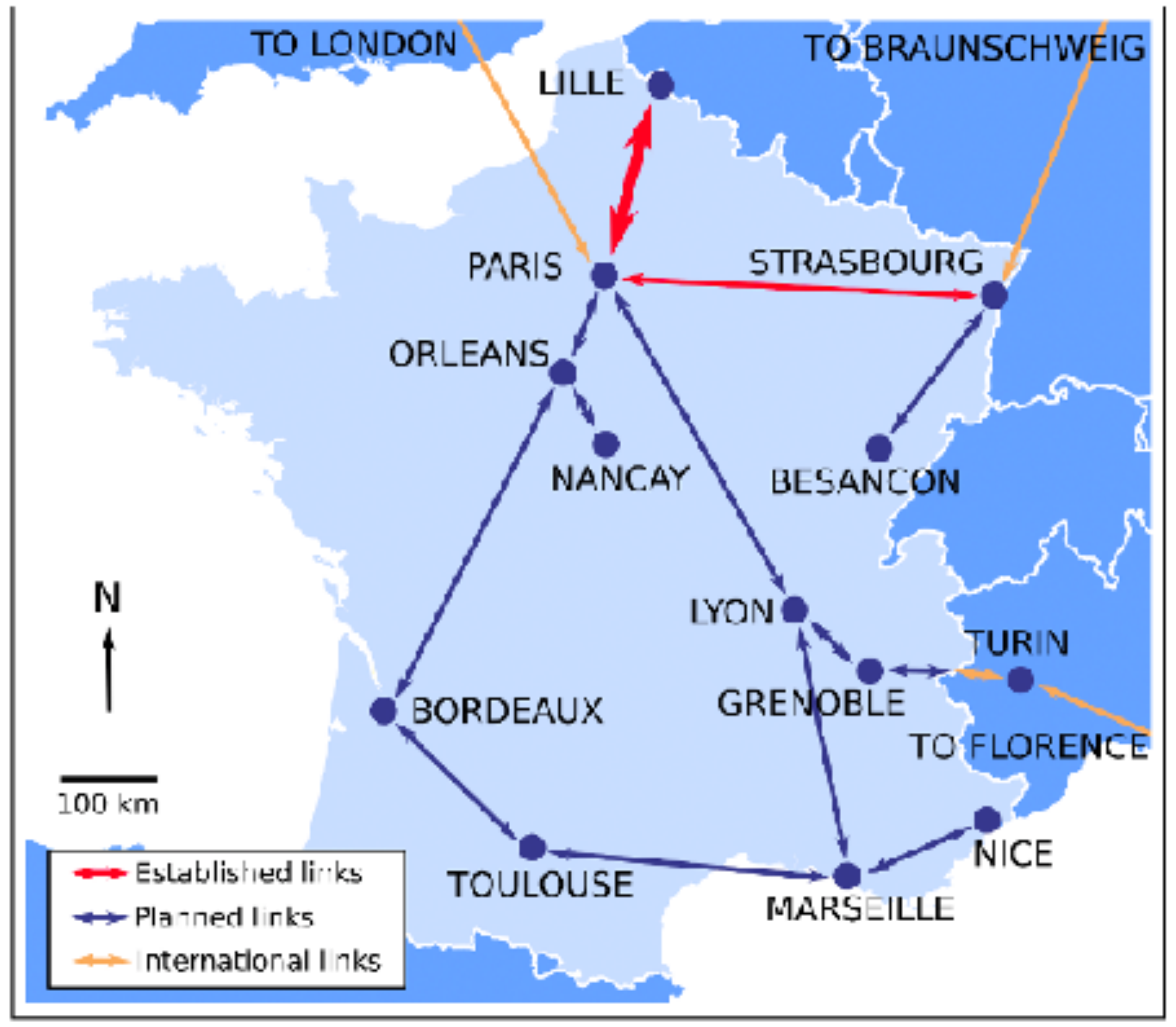
[L. Schmöger et al., Science 347, 6227 (2015); P. Micke et al., Nature 578, 2020]

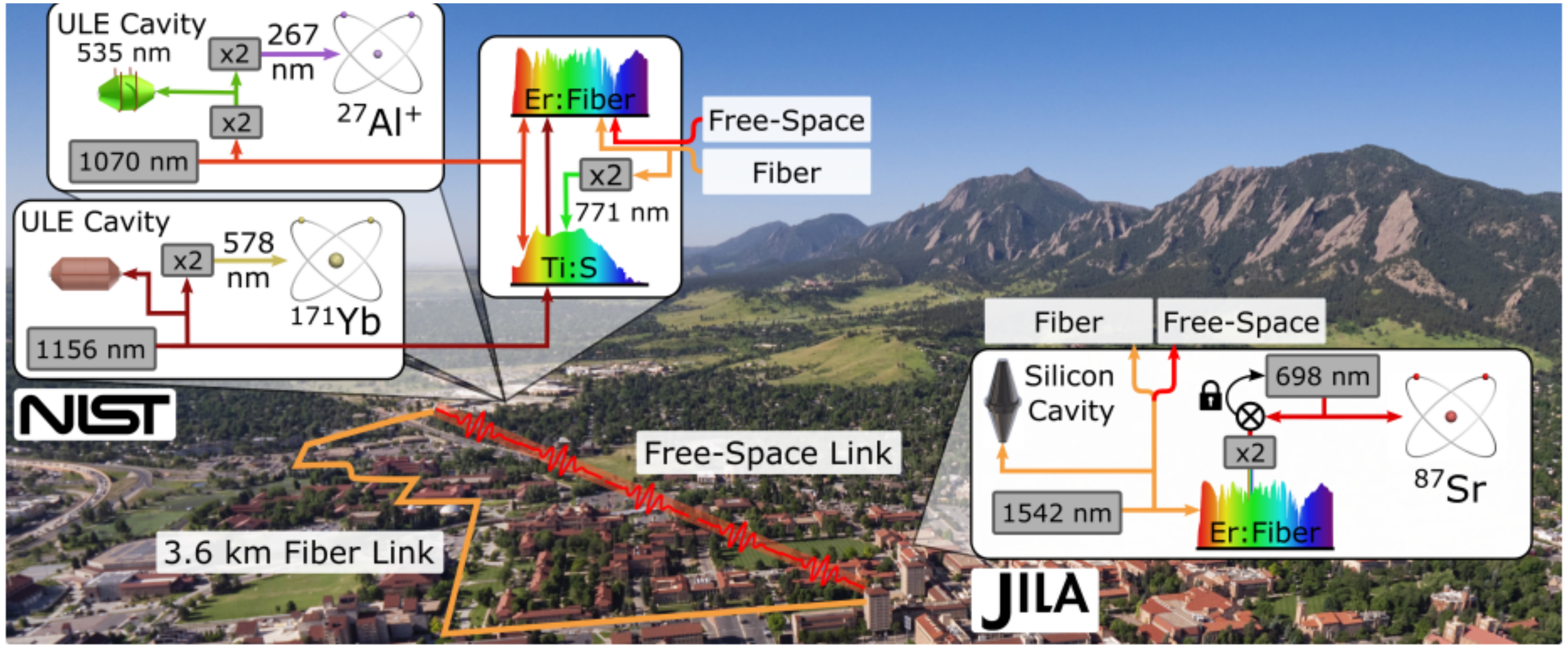
TIQTOC: Trapped Ion Quantum Test Of fundamental Constants

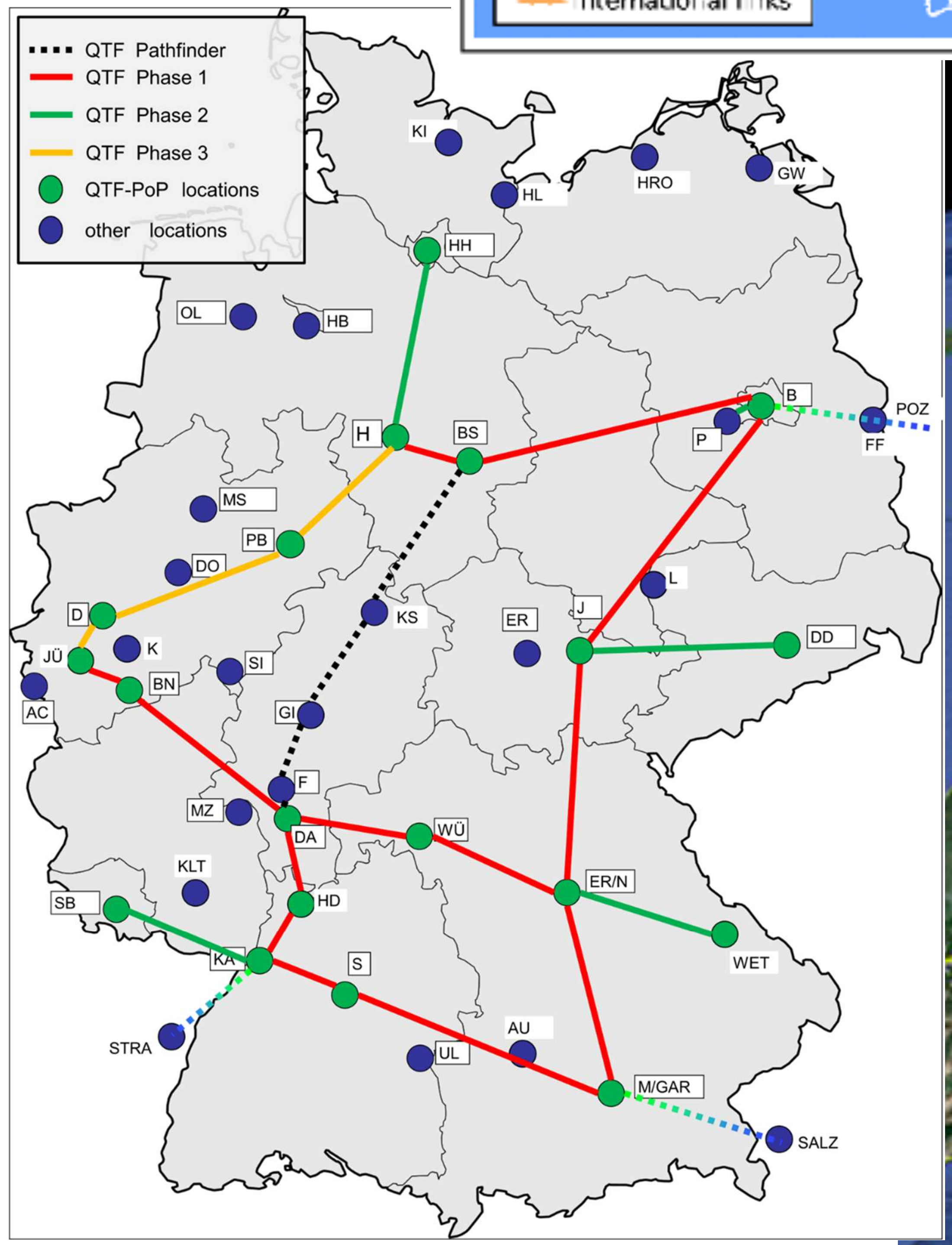


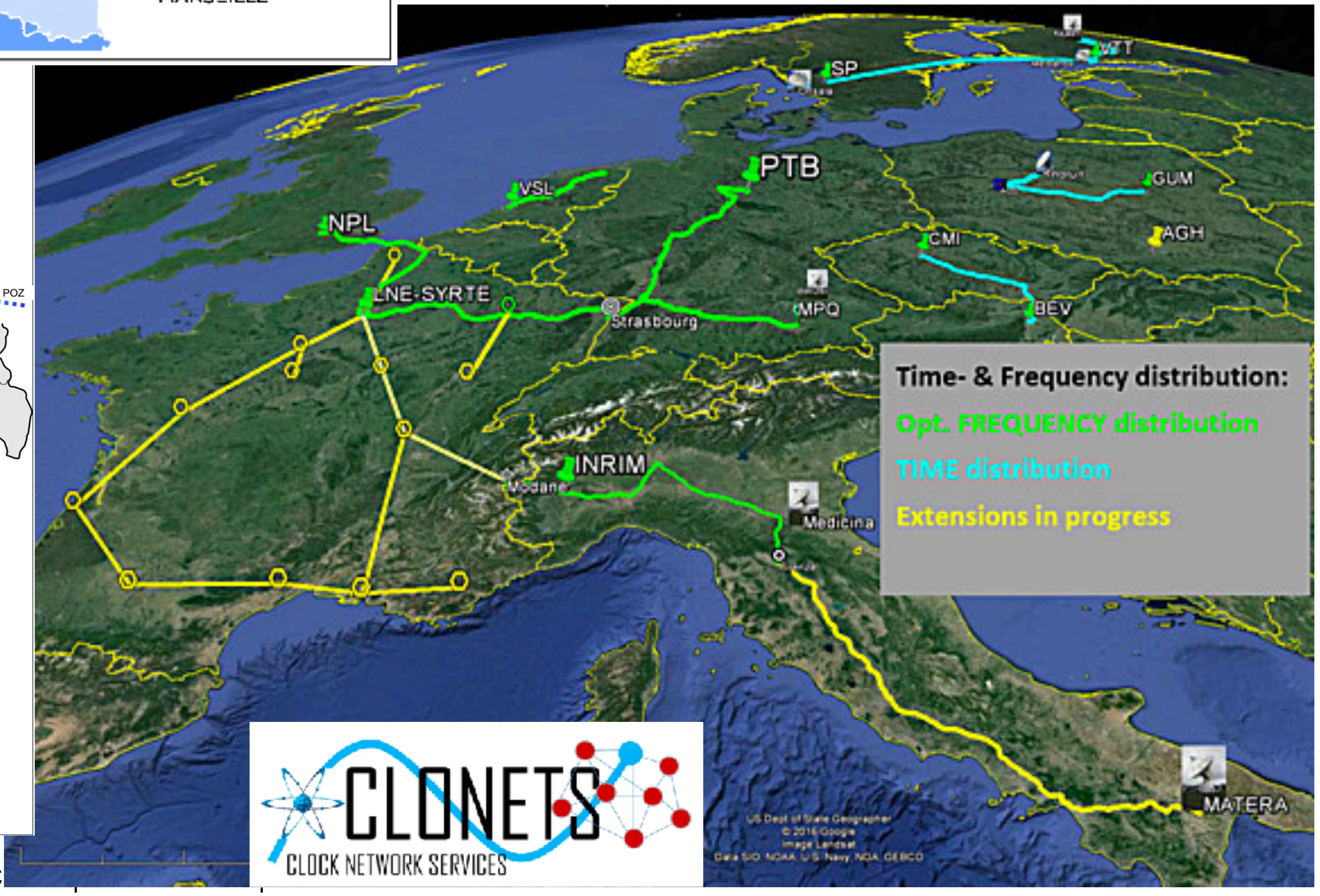


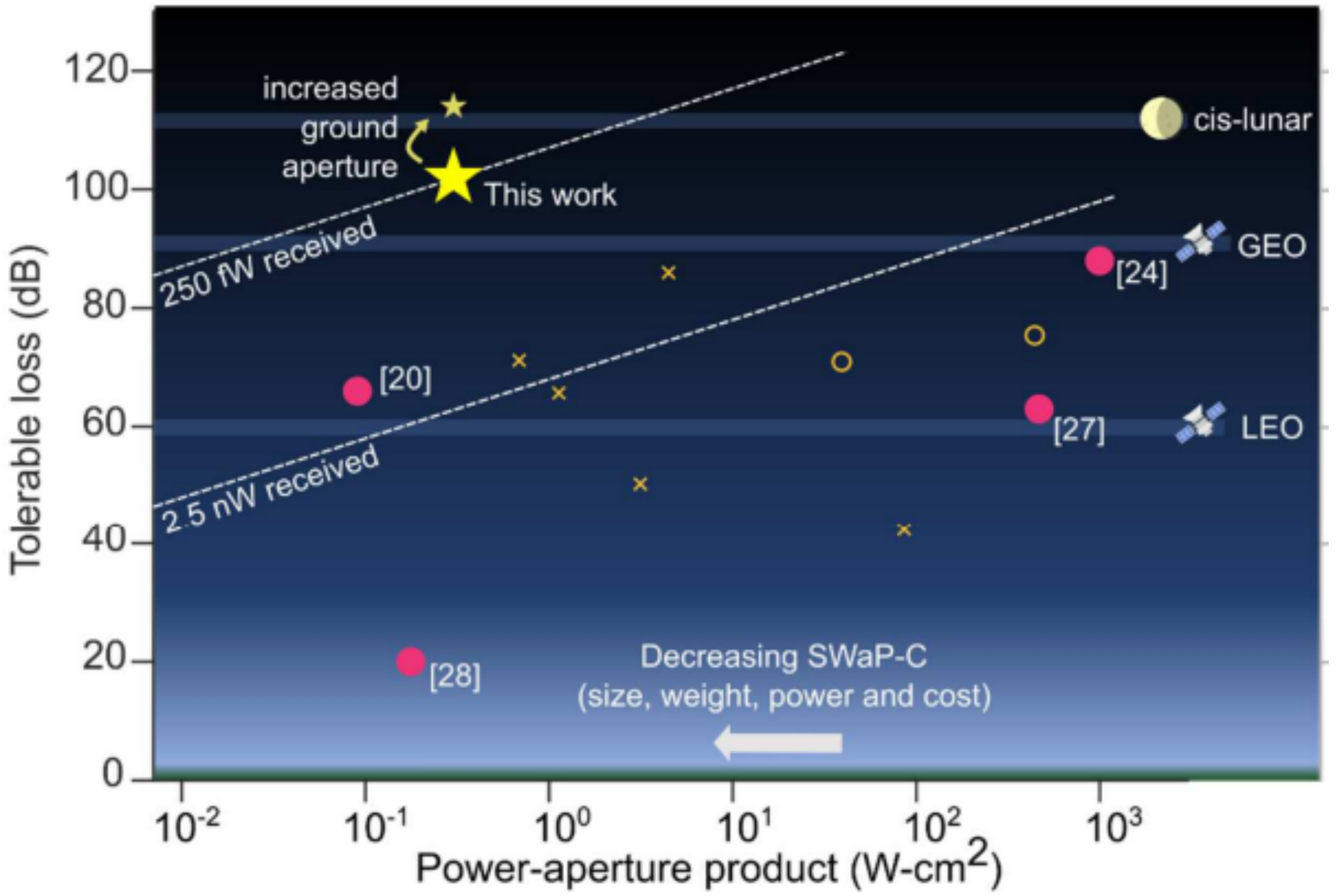
Time/Frequency Networks







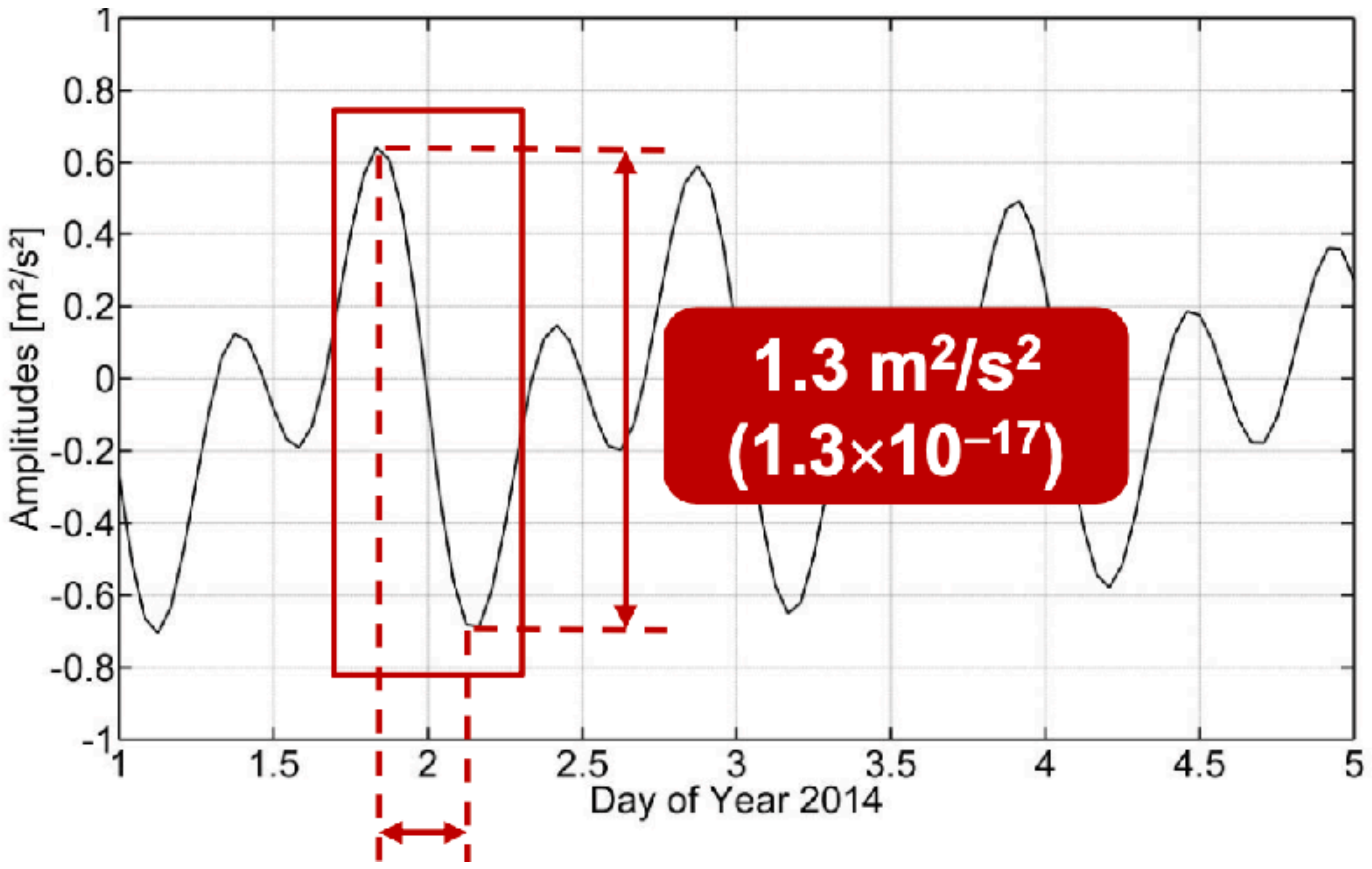




Clock Networks and Fast Transients

- NPL-SYRTE-PTB demonstrated an optical clock network with dark fibres
- Comparing clocks with different sensitivities to variations of α
- Clock-clock comparisons over optical fibres features excellent long-term stability
- Previously unconstrained parameter space for quadratic coupling

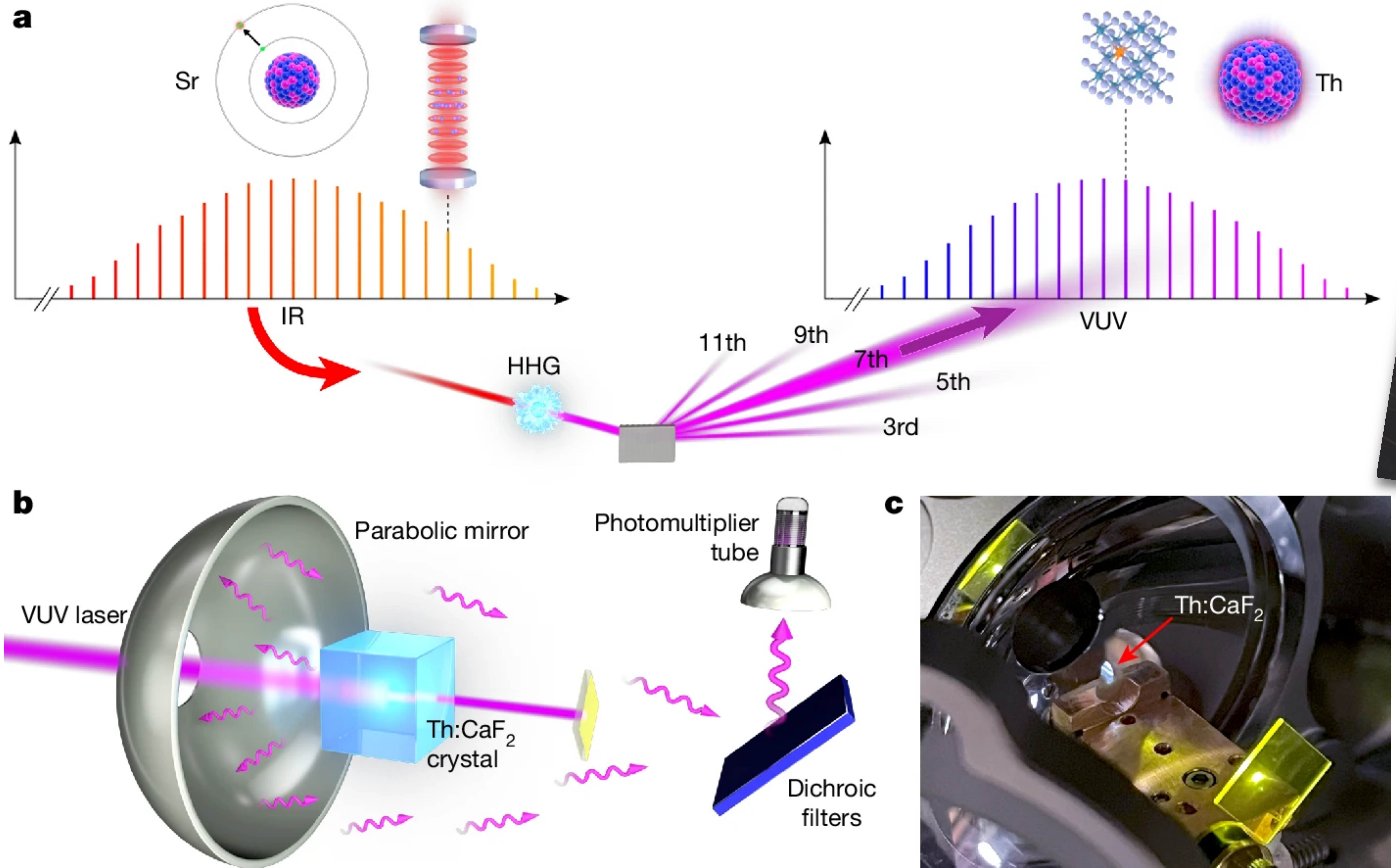
gravity potential difference NPL-PTB



7 hours

[Roberts et al, New J. Phys. 22, 093010 (2020); P. Delva et al., Phys. Rev. Lett., 118 221102 (2017)]

^{229m}Thorium Clock

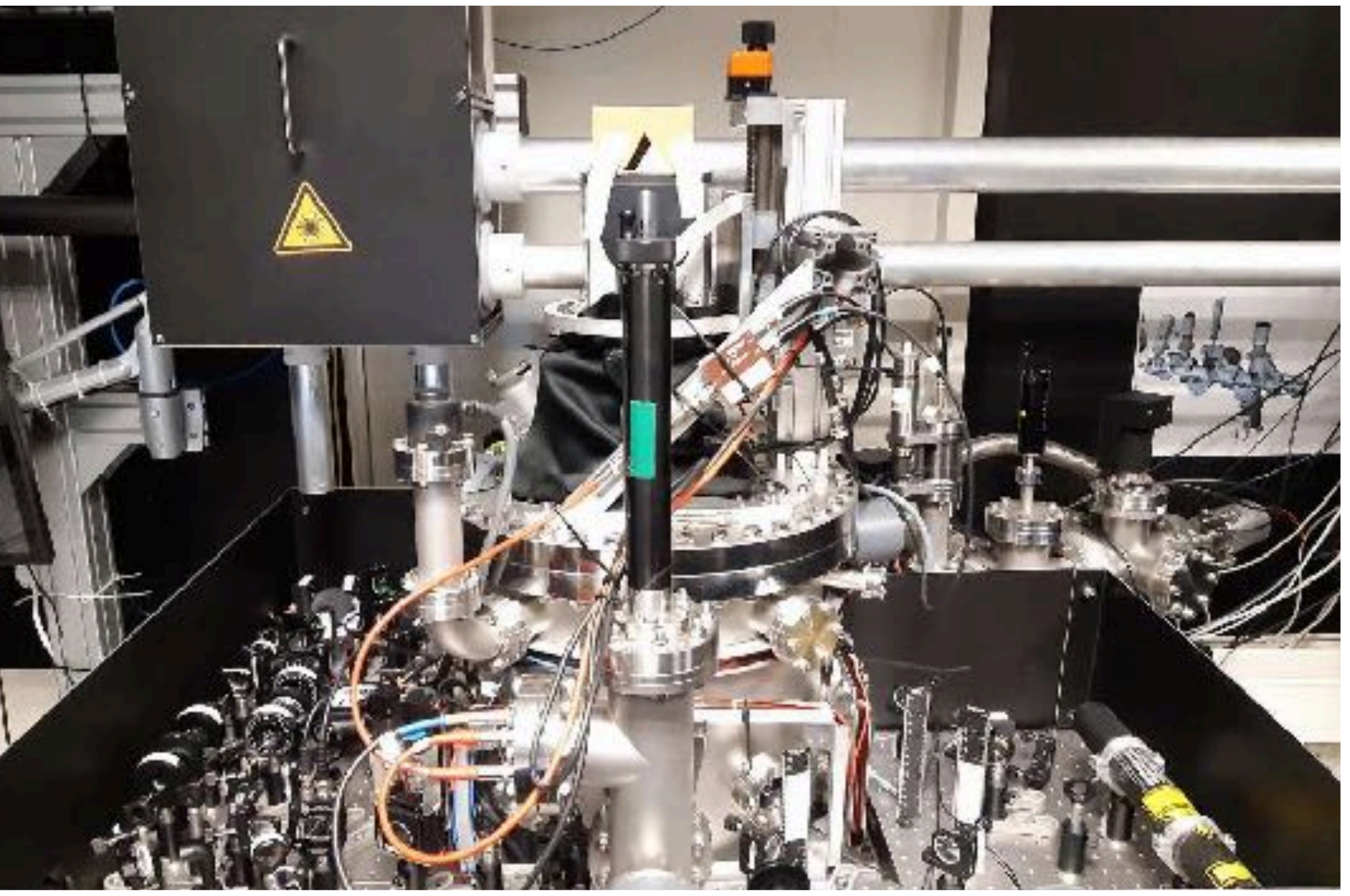


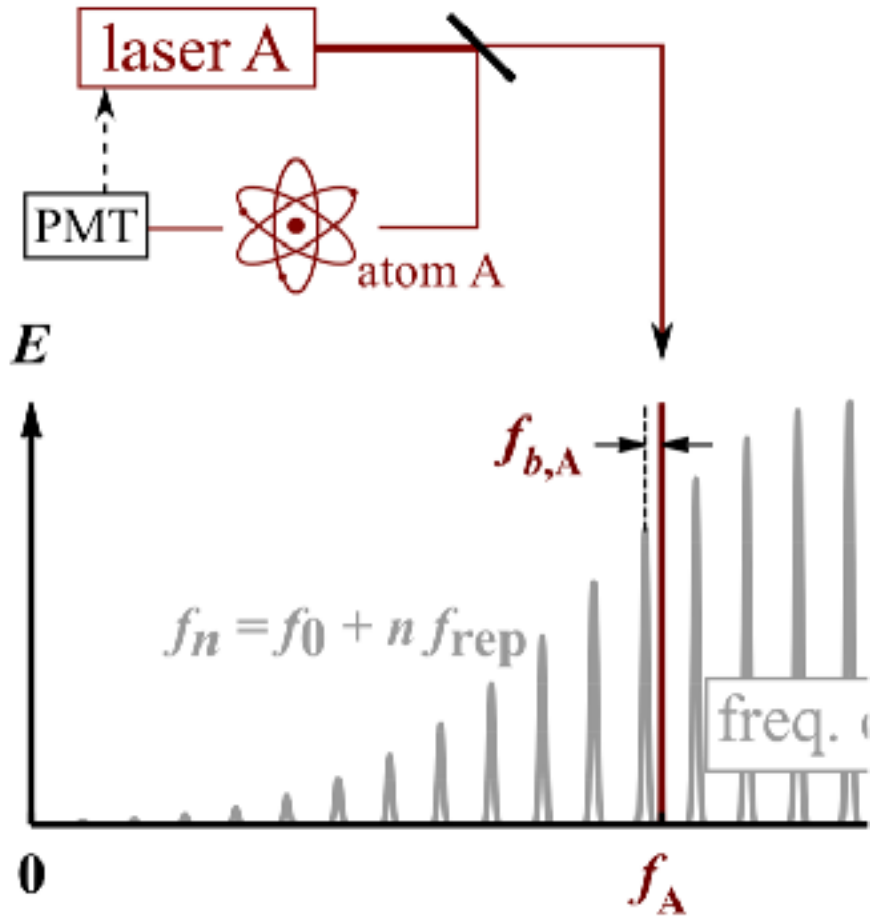
Nuclear clocks are here!

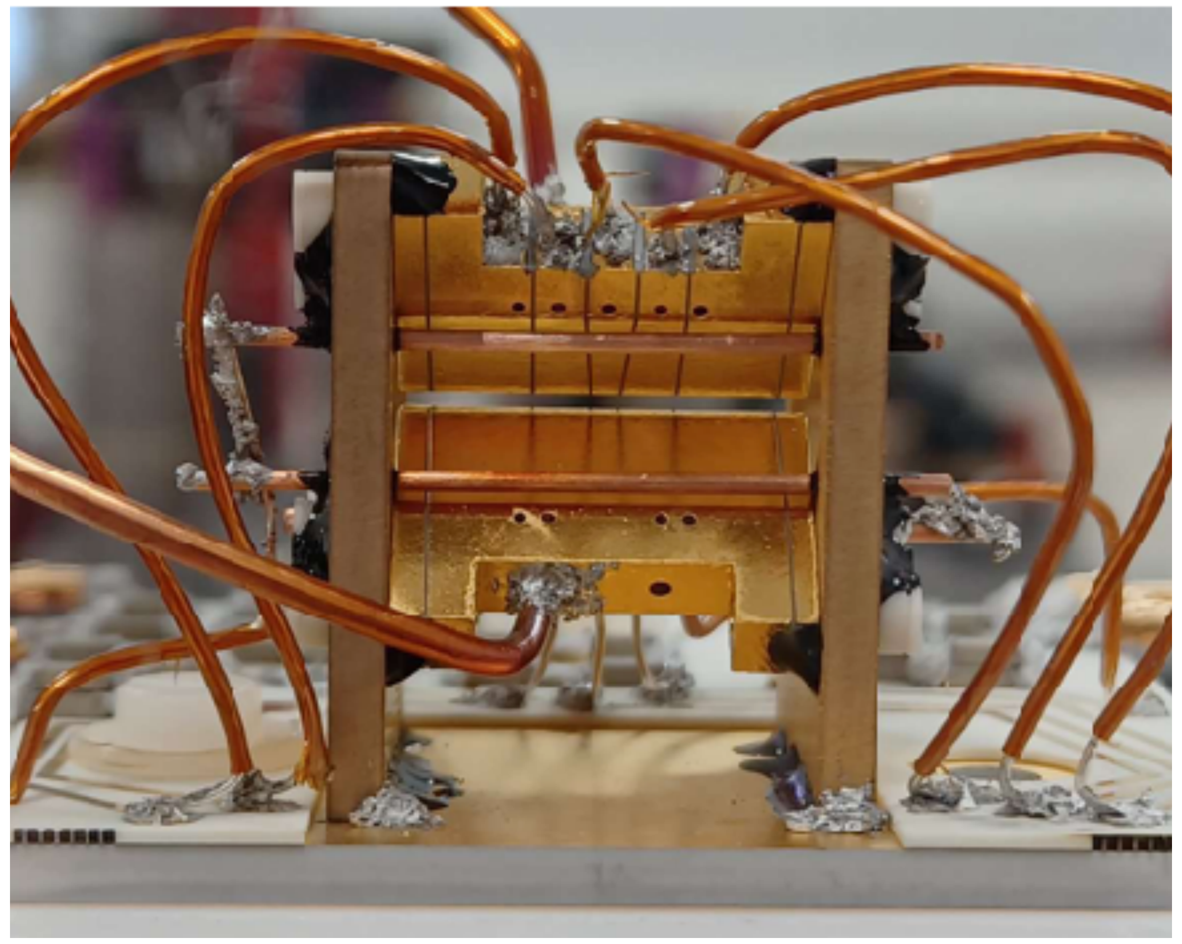
C. Zhang et al., Nature 633, 63 (2024)

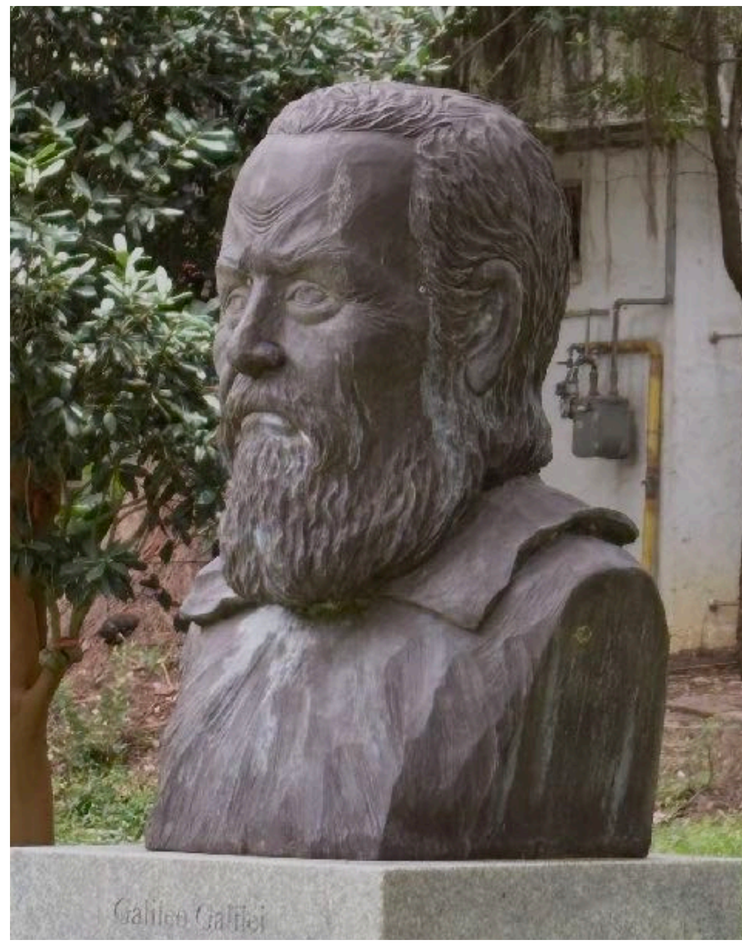
Conclusions

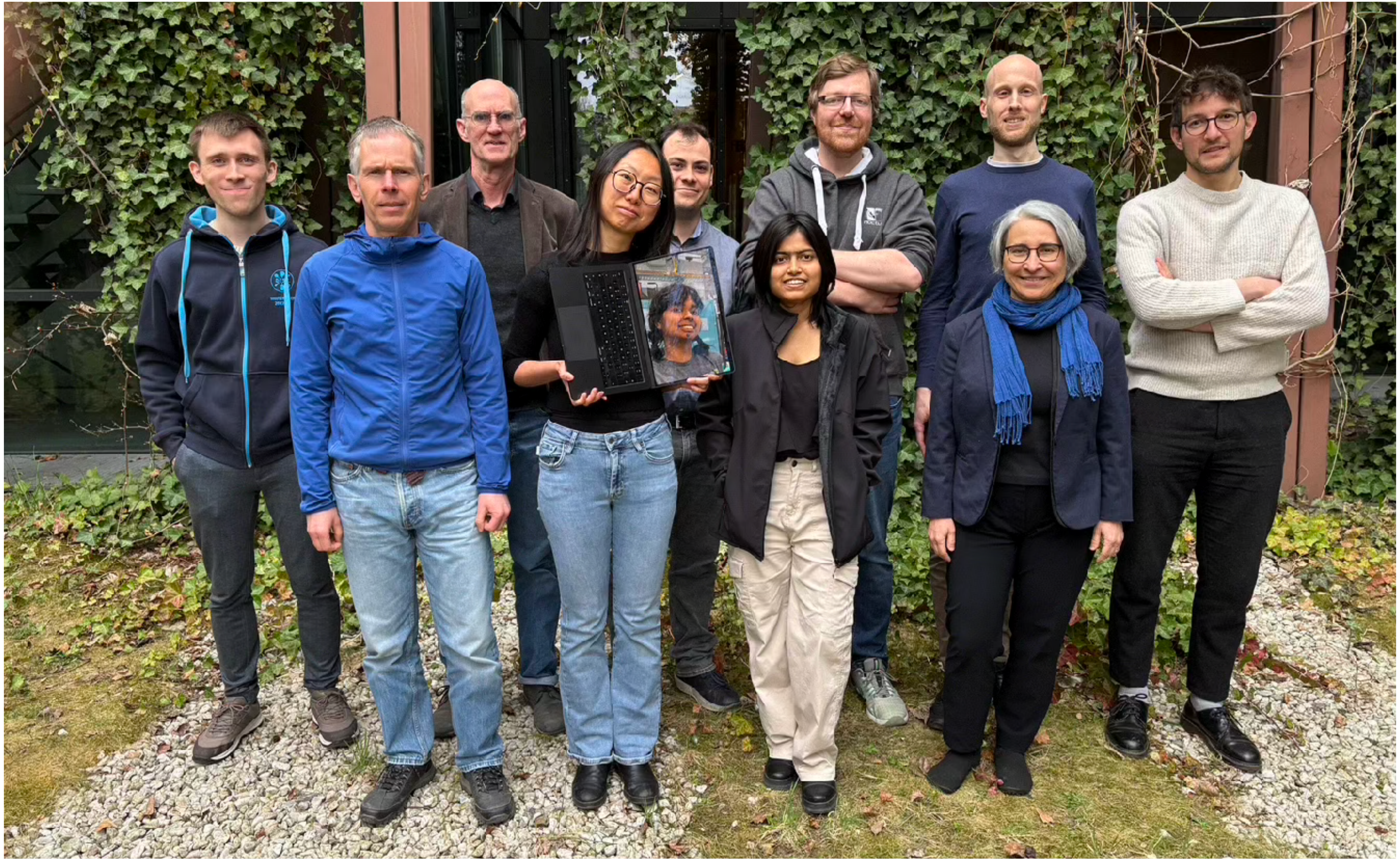
- Optical Atomic Clocks are some of the most sensitive instruments available
- Fantastic testbed for all sorts of new physics, for example ultra-light dark matter
- Lots of new ideas to follow and new innovations… new clocks, networks, and opportunities!











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