Searching for ultralight bosons using atomic clocks

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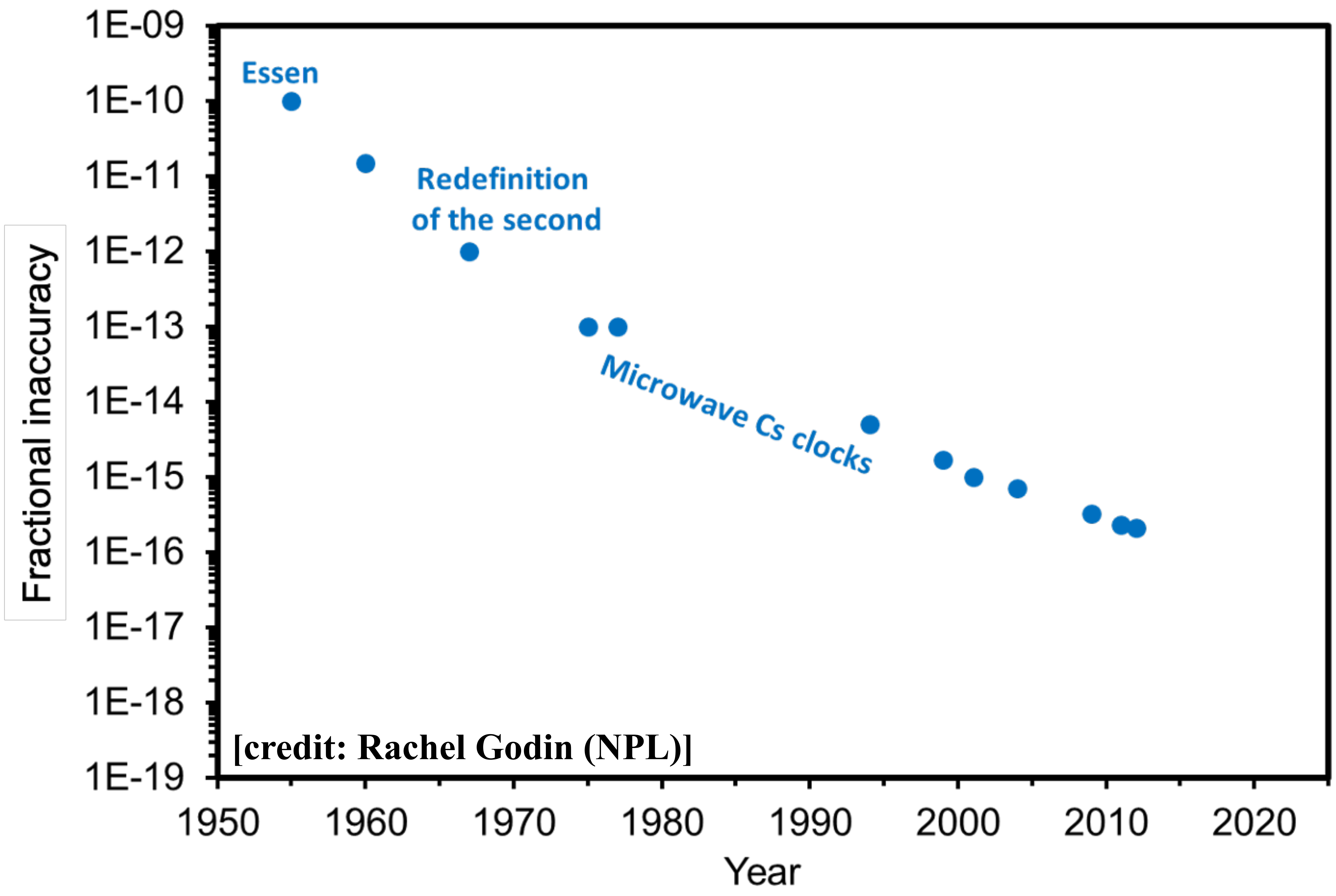
University of Sussex

axions++ 2023

Based on New J. Phys. 25, 093012 (2023)

In collaboration with the National Physical Laboratory (NPL)

Atomic clocks



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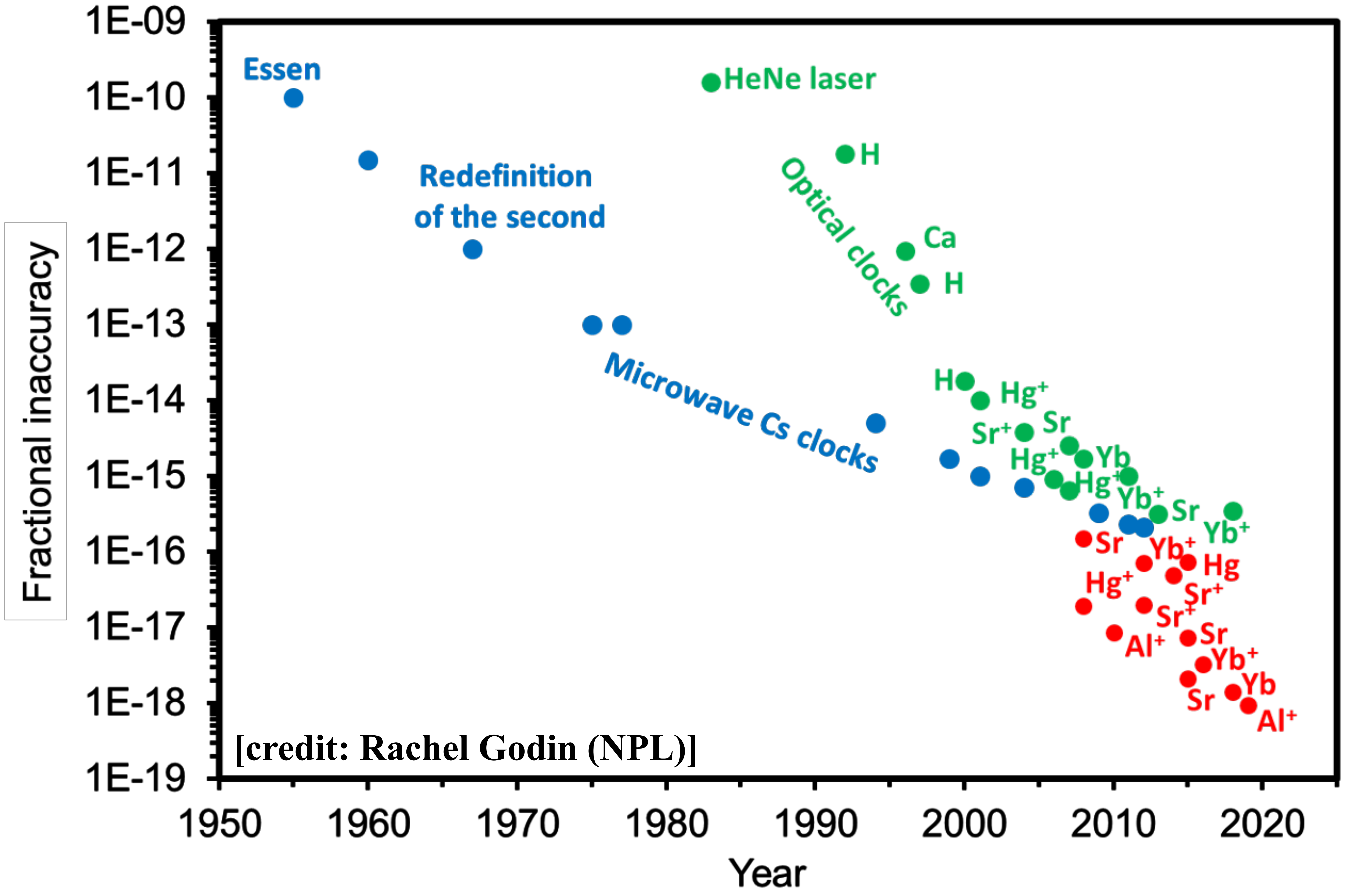

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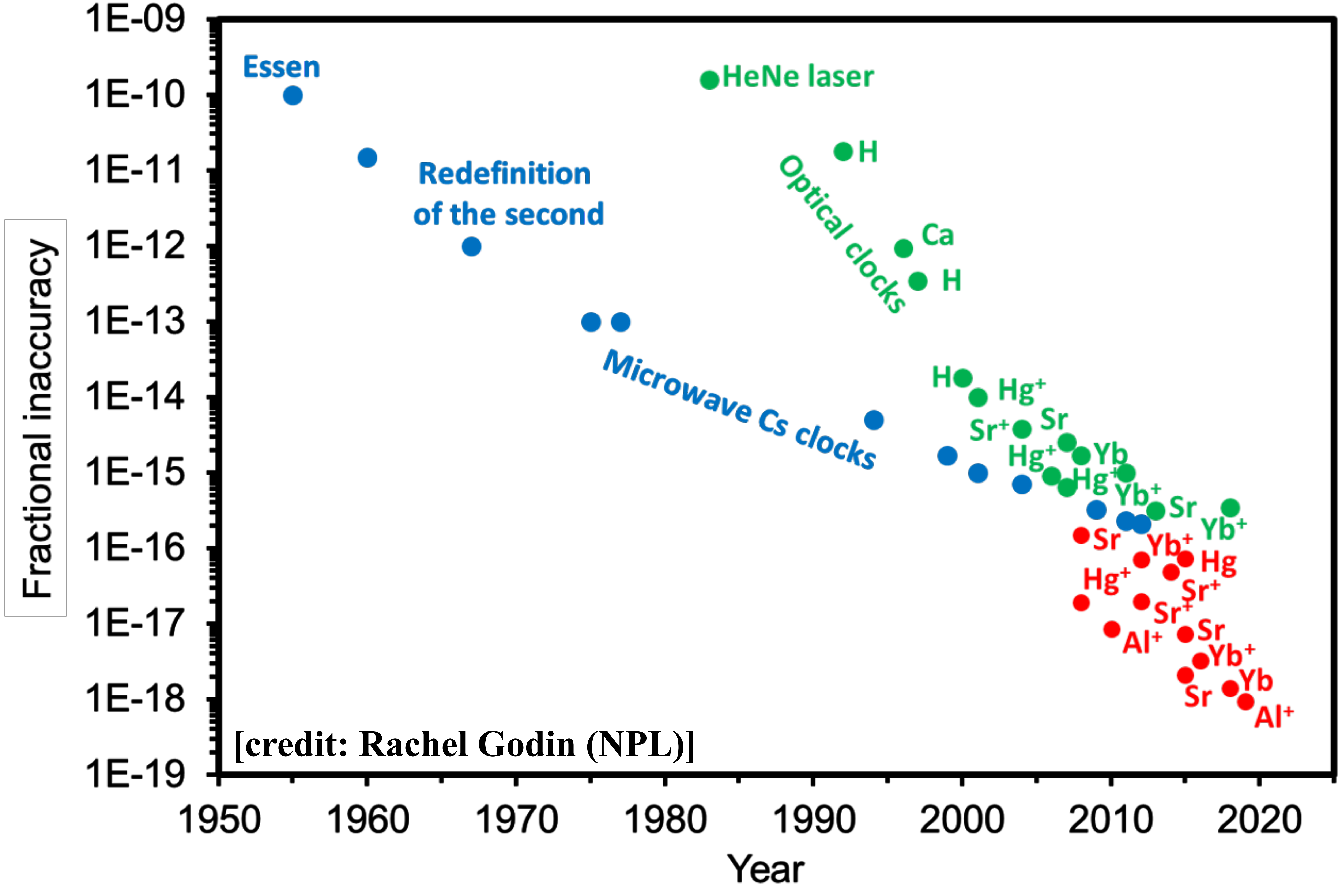

$$\nu_{\text{optical}} \sim 100 \text{ THz}$$

$$\nu_{\text{microwave}} \sim \text{GHz}$$

$$\nu_{\text{molecular}} \sim 10 \text{ THz}$$

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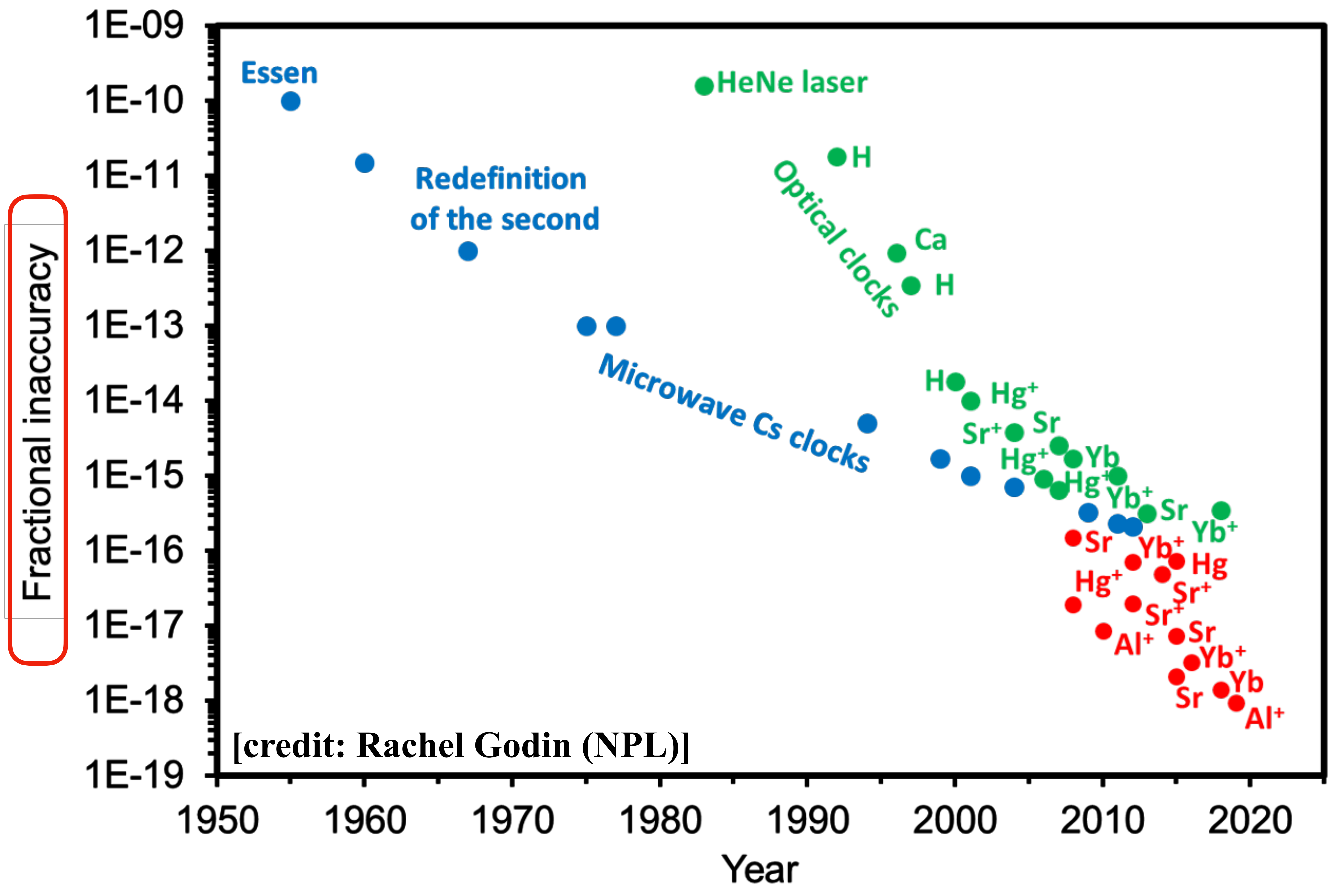

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= uncertainty of shift $\nu_{\text{output}} - \nu_0$

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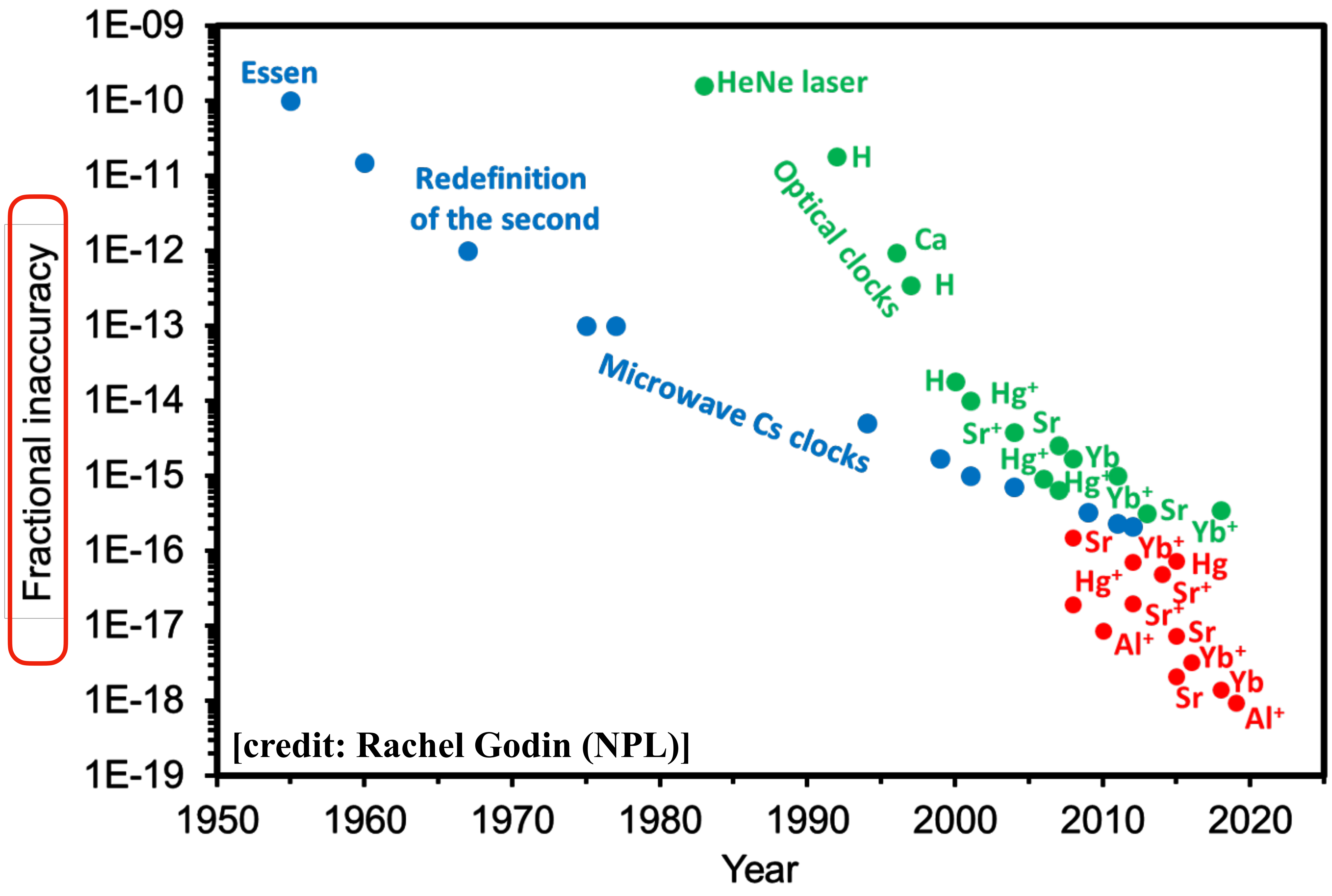

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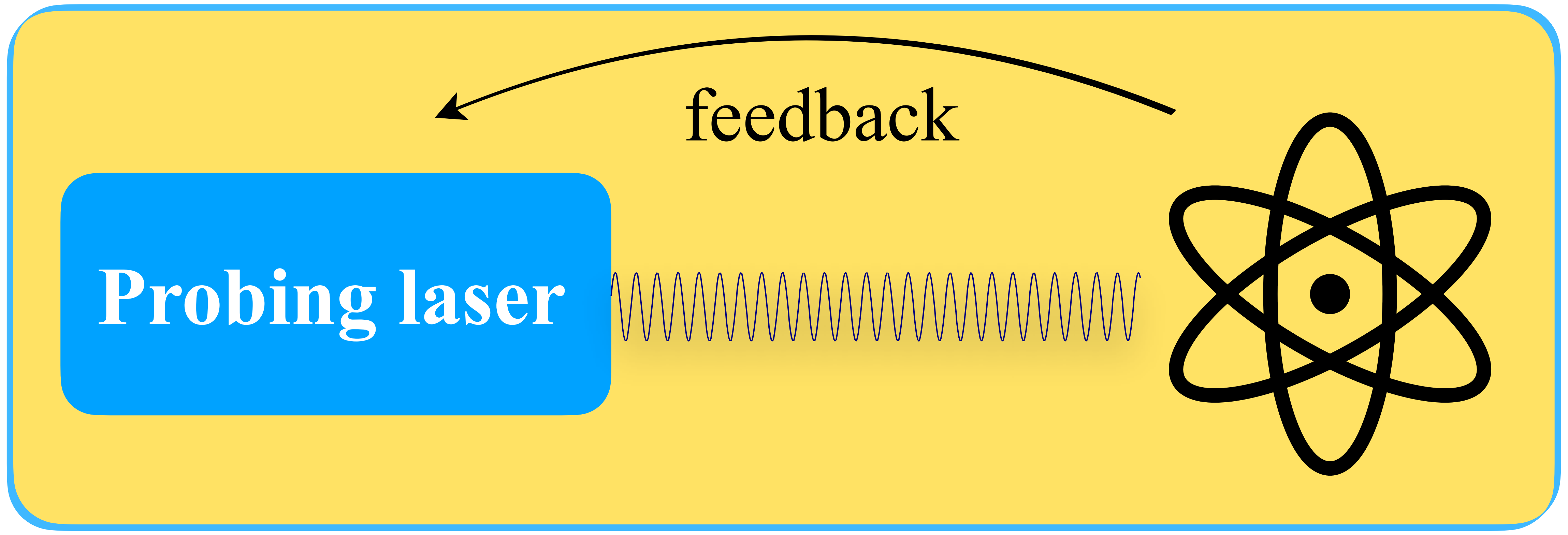
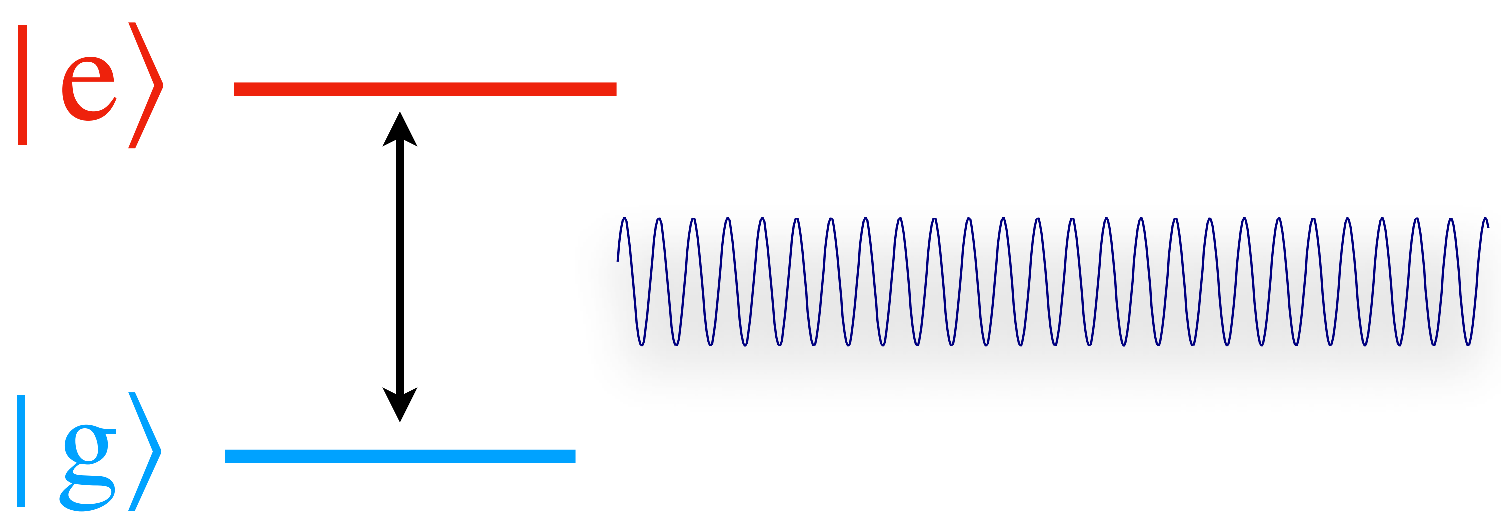
Smaller inaccuracies +
high-frequency transitions

Atomic clocks

Basic components



Clock transition



Measured* radiation

$$= h\nu_{\text{output}}$$

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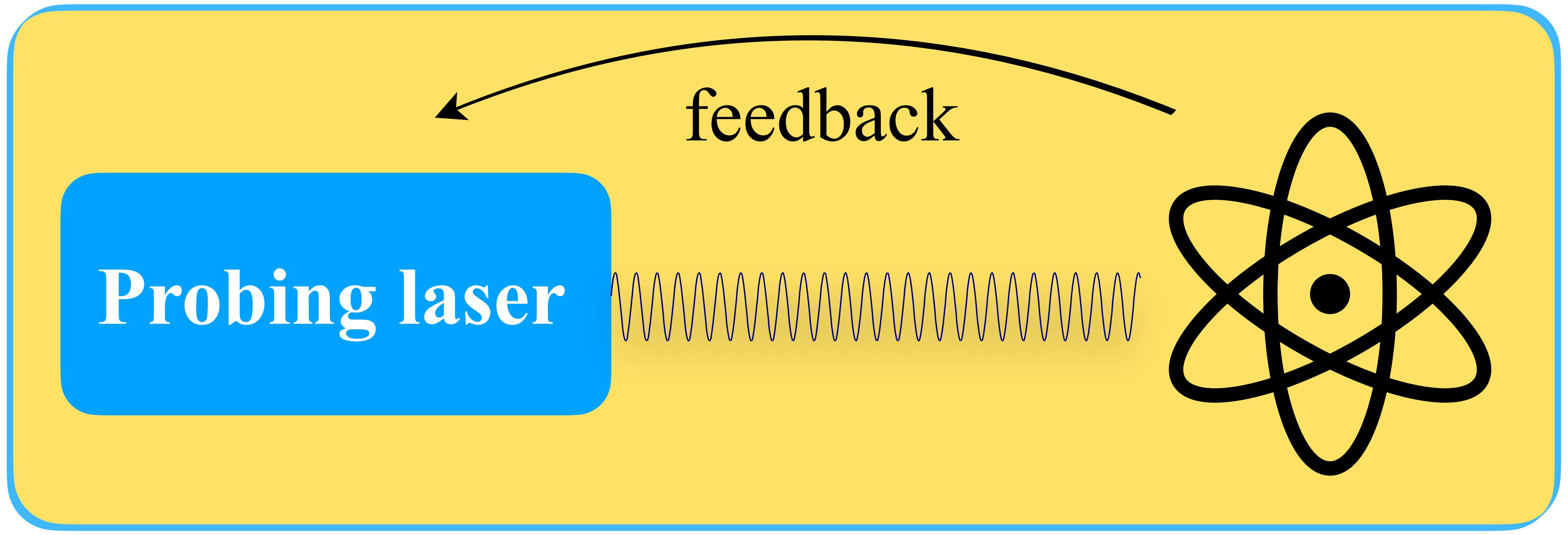

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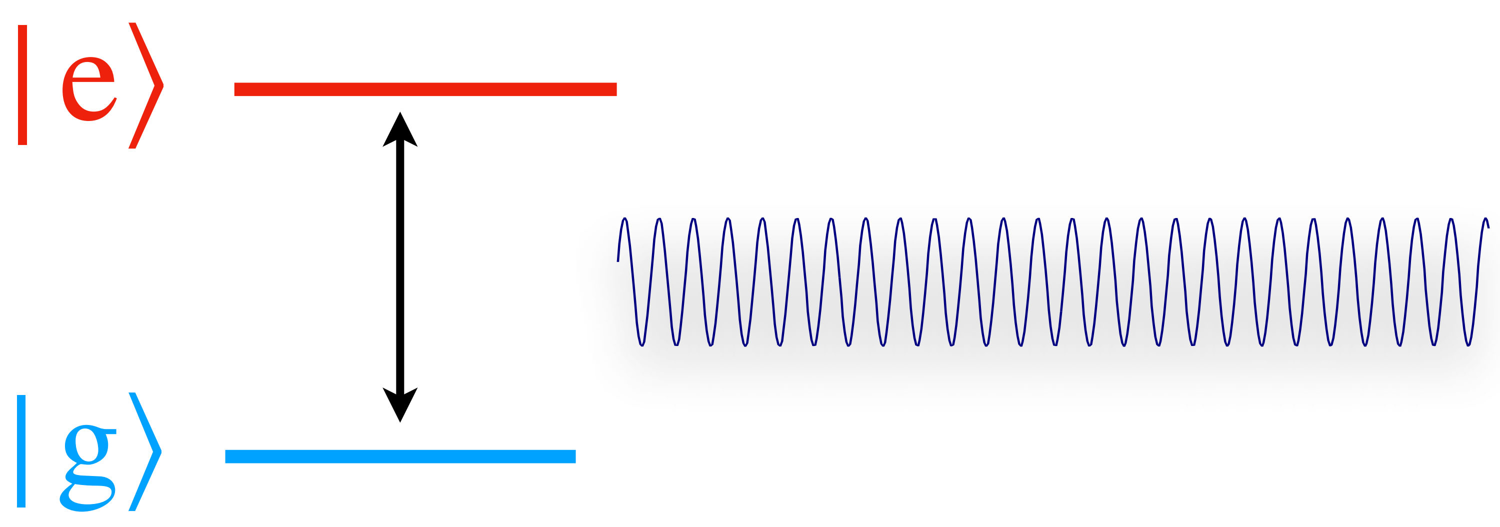

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***Cannot measure absolute energies**

$$r_{\text{observable}} = \frac{\nu_1}{\nu_2}$$

Different transitions of same system or distinct systems

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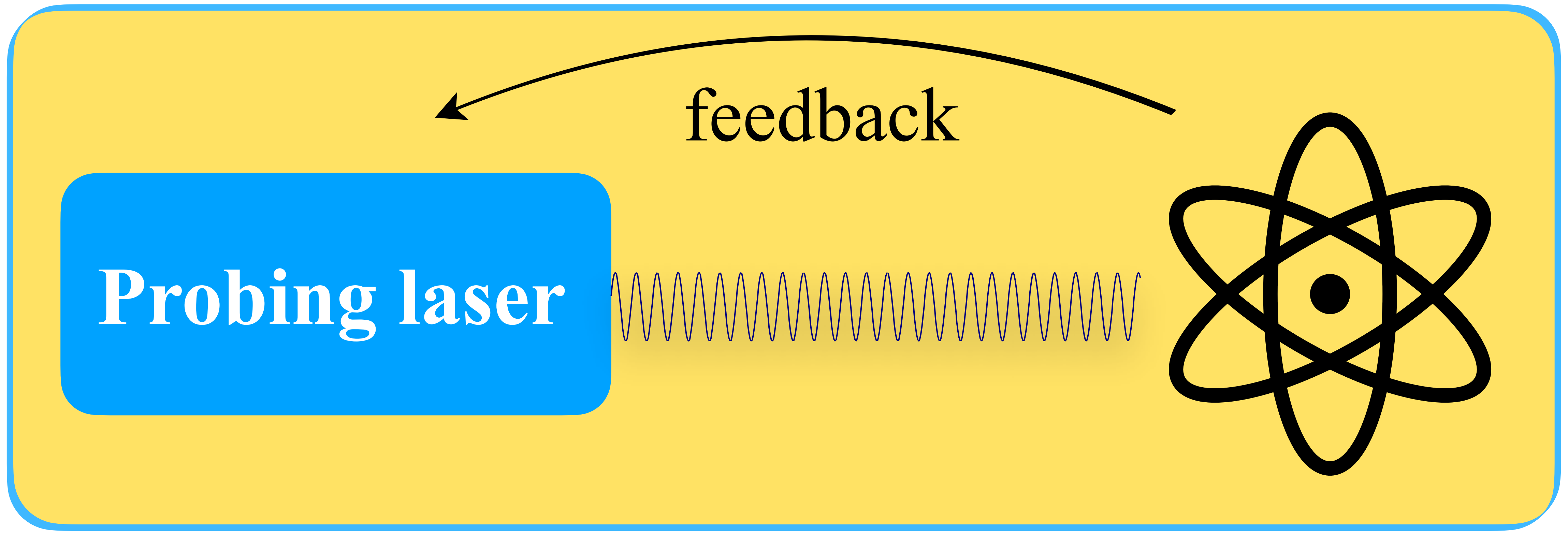

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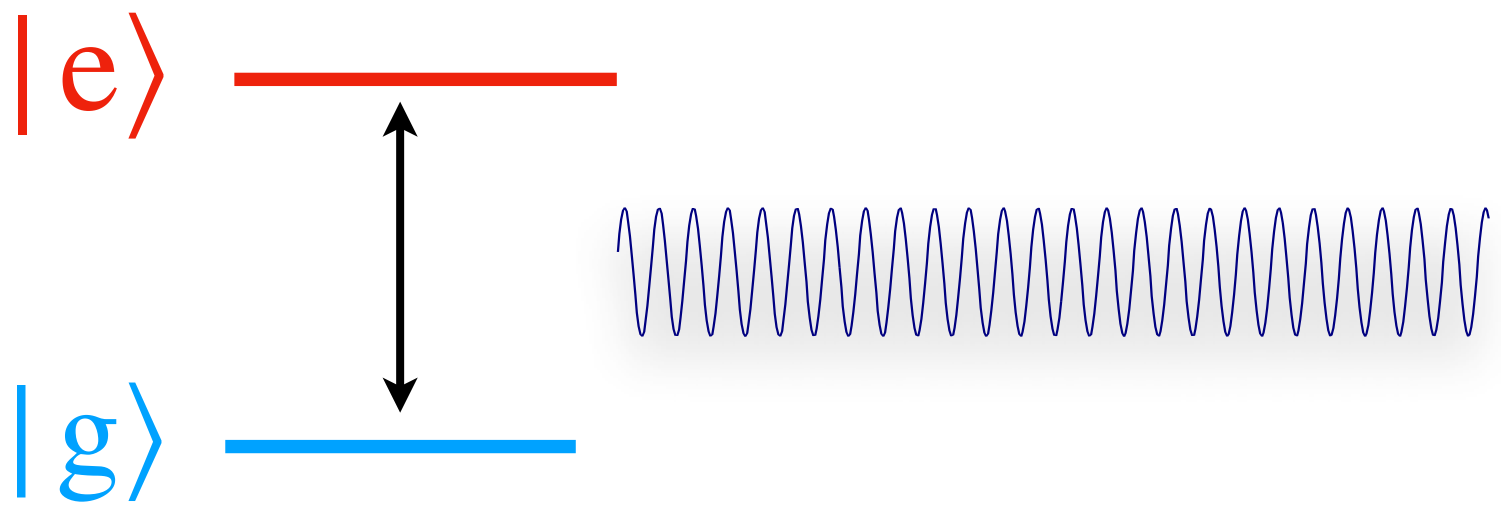

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Different transitions of same system or distinct systems

Common clock transitions

$$\nu_{\text{optical}} = A \cdot (cR_\infty) \cdot F_{\text{opt}}(\alpha)$$

$$\nu_{\text{microwave}} = B \cdot (cR_\infty) \cdot \alpha^2 F_{\text{MW}}(\alpha) \cdot g_N \cdot \mu$$

$$\nu_{\text{molecular}} = C \cdot (cR_\infty) \cdot \mu^{1/2}$$

$\mu = m_e/m_p$

Atomic clocks

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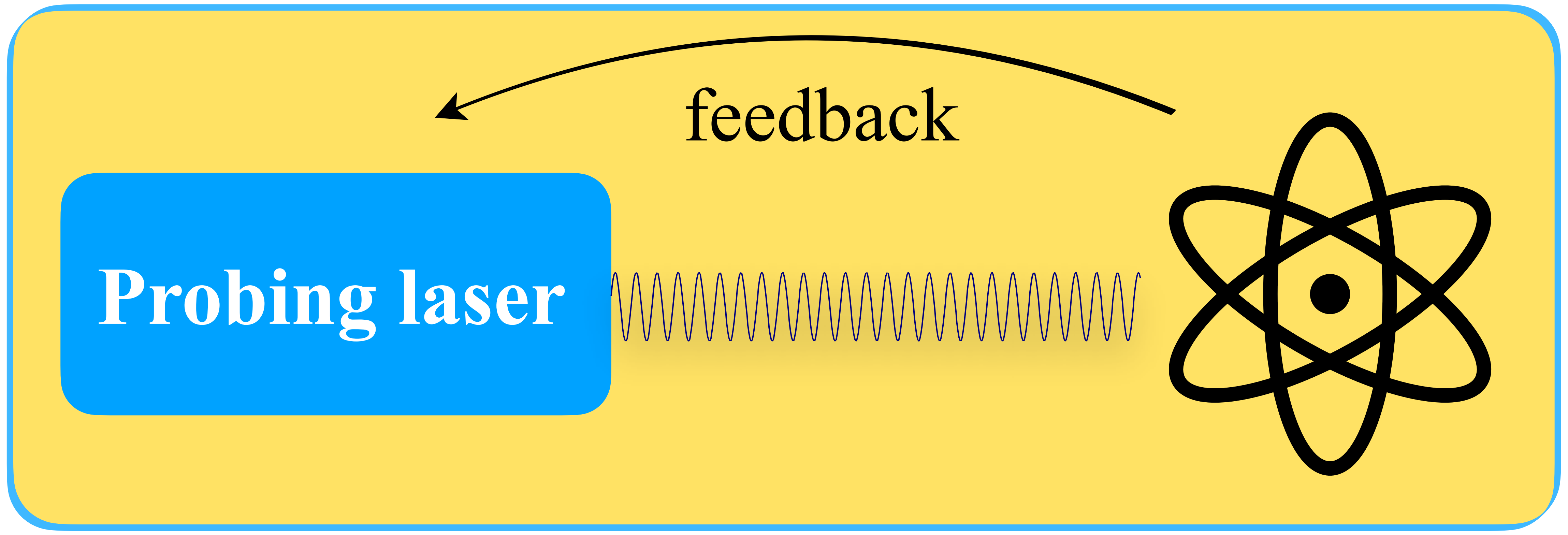

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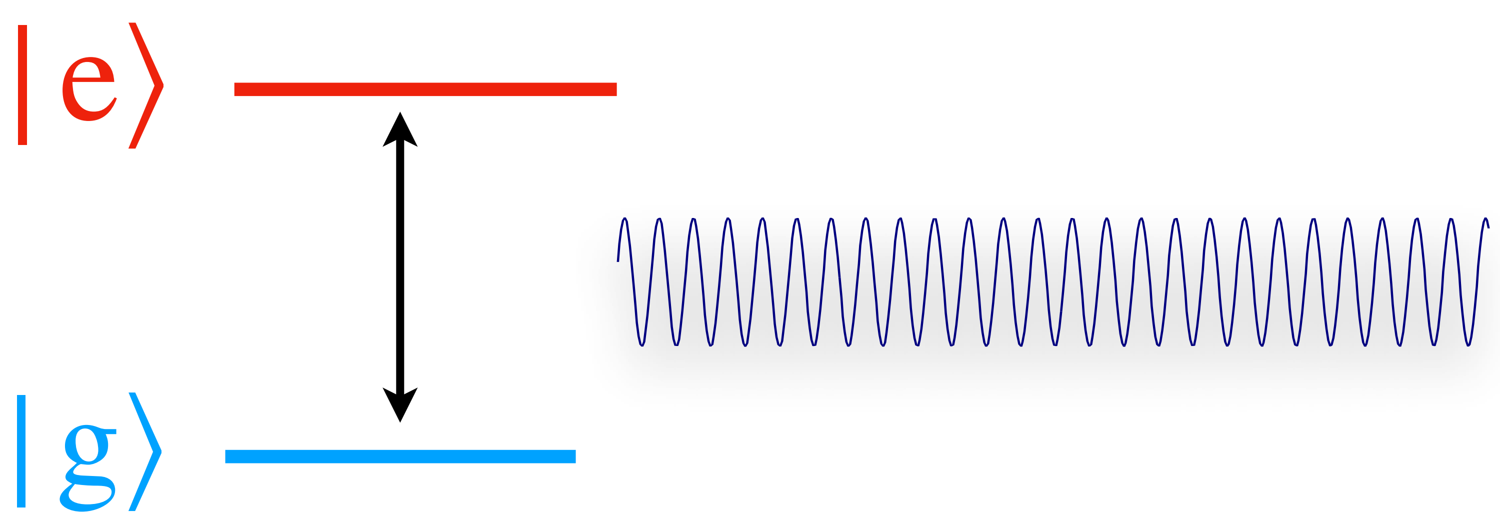

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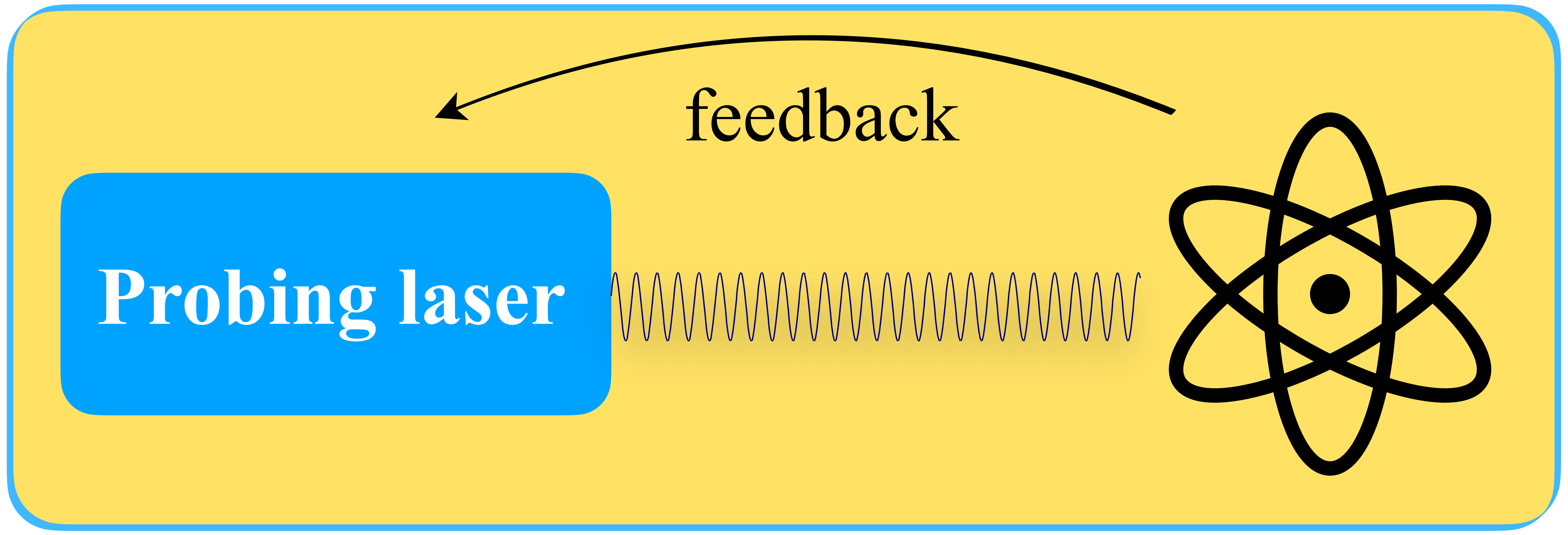

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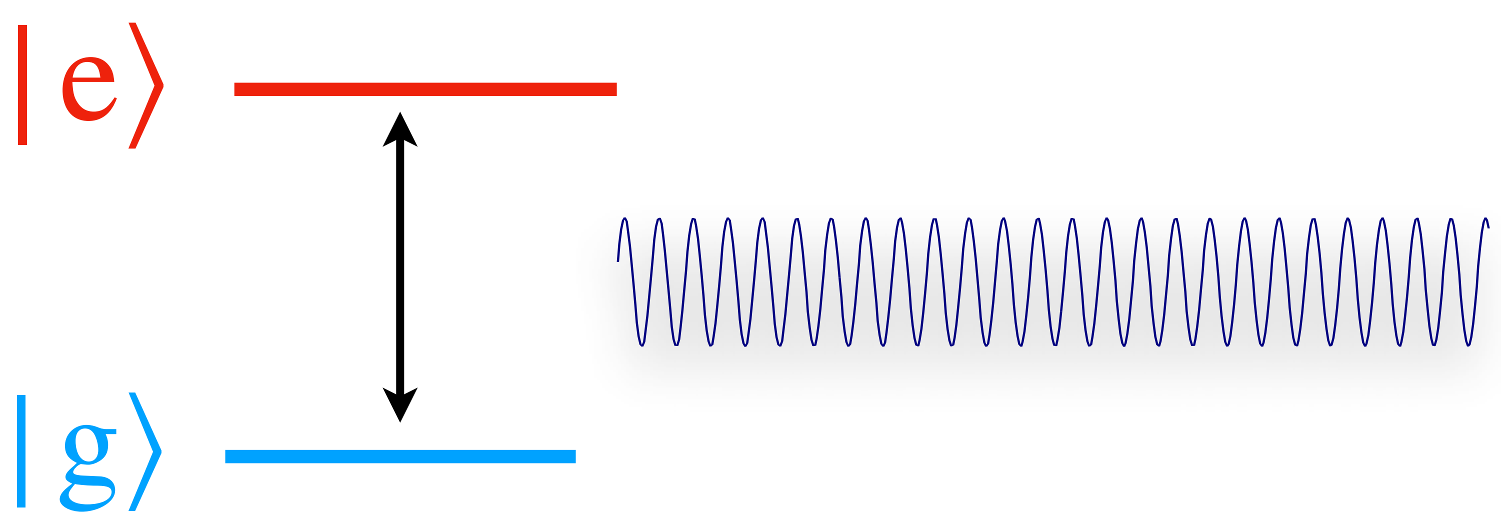

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Atomic clocks are sensitive to "variations" of fundamental constants

Bosonic interactions

Additional bosons can source variations $\mathscr{L}_{\text{int},\phi} \supset -\frac{1}{4} g(\phi) F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \quad \alpha \rightarrow \alpha(\phi)$

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E.g. "Bekenstein electrodynamics" $e(x) = e_0 \epsilon(x) \approx e_0 + \frac{\phi}{\Lambda'}$

J. D. Bekenstein, Phys. Rev. D 25, 1527 (1982)

$$\mathcal{L} = \mathcal{L}_{\text{QED}} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 + \frac{1}{2\Lambda'} \phi F_{\mu\nu} F^{\mu\nu}$$

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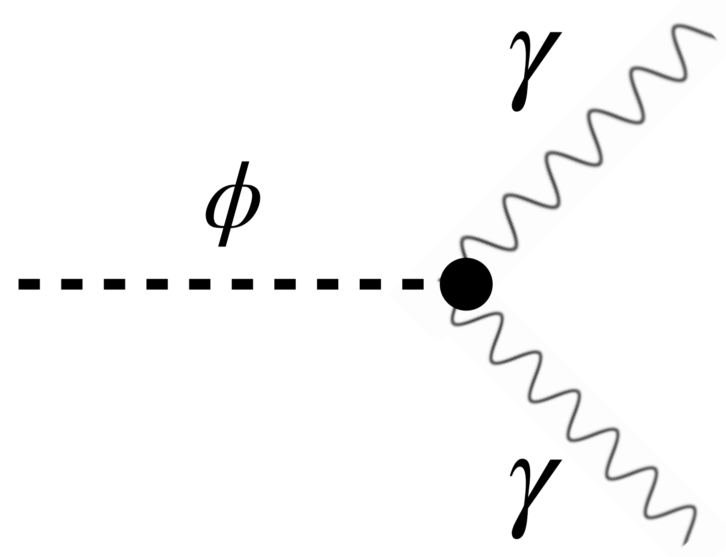

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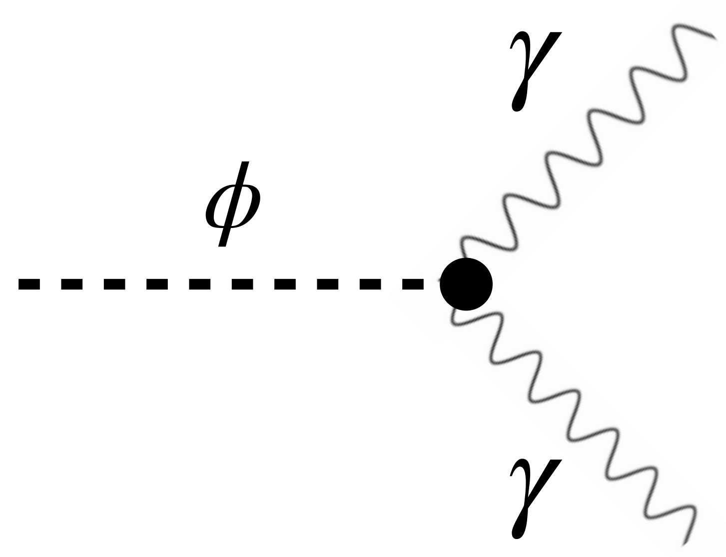

Theories with varying constants ⇔ conventional physics + additional interactions

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Effective ϕ−SM interactions

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$\kappa = \sqrt{4\pi G} = \left(\sqrt{2}M_P\right)^{-1}$

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(see, e.g.)

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Shifts in fundamental constants

$$\alpha(\phi) = \alpha\left(1 + d_\gamma^{(n)}(\kappa\phi)^n\right) \Rightarrow \frac{\delta\alpha}{\alpha} = d_\gamma^{(n)}(\kappa\phi)^n$$

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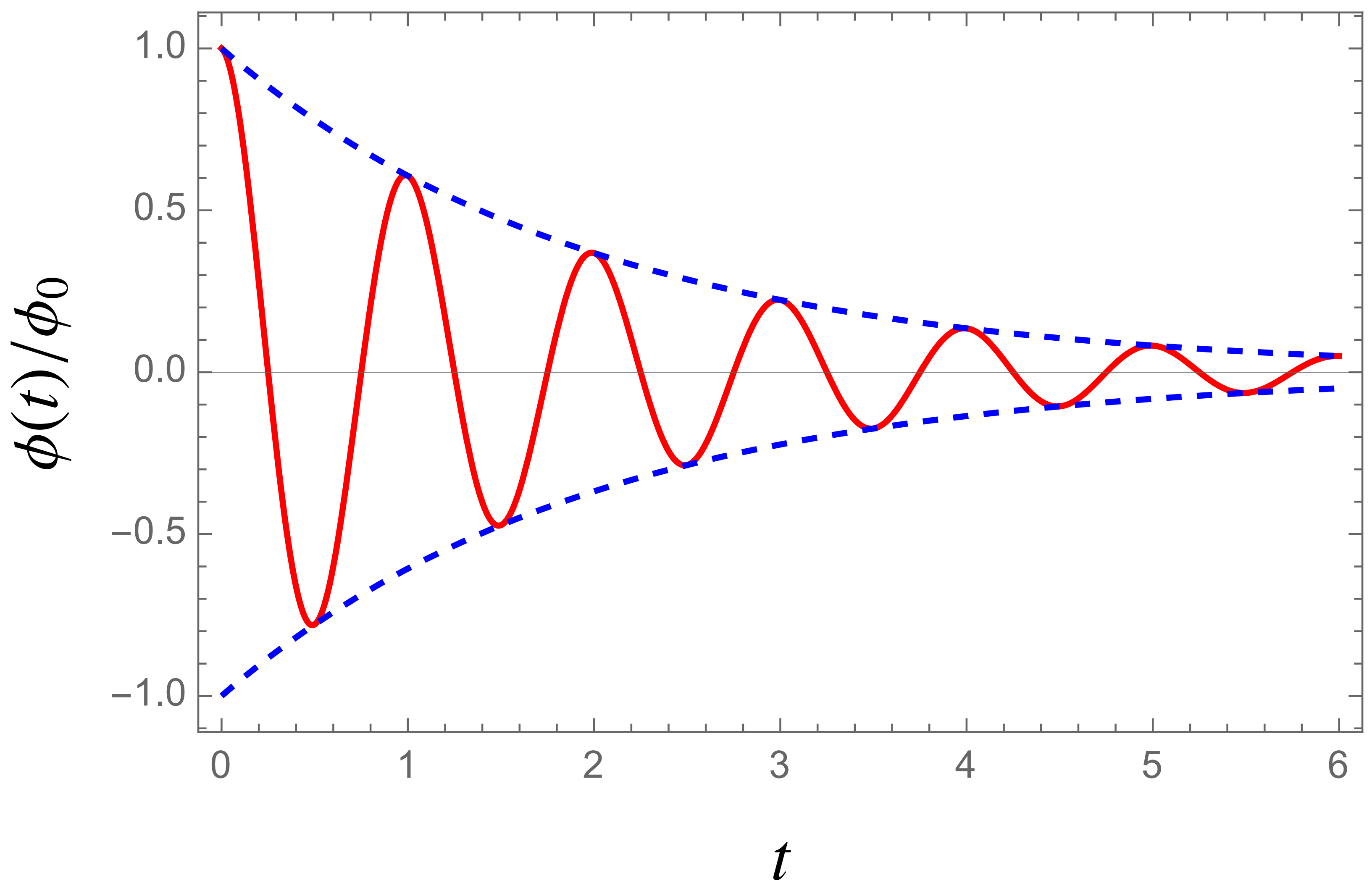
Boson EOM controls character of variations

Bosonic interactions

Damped oscillator covers many models of interest

- Dark matter $\Gamma = 0$
- Dark energy: $\Gamma = 3H(t)$
- Generic hidden sector: $\Gamma \neq 0$
- …

$$\ddot{\phi} + \Gamma\dot{\phi} + m^2\phi \approx 0$$



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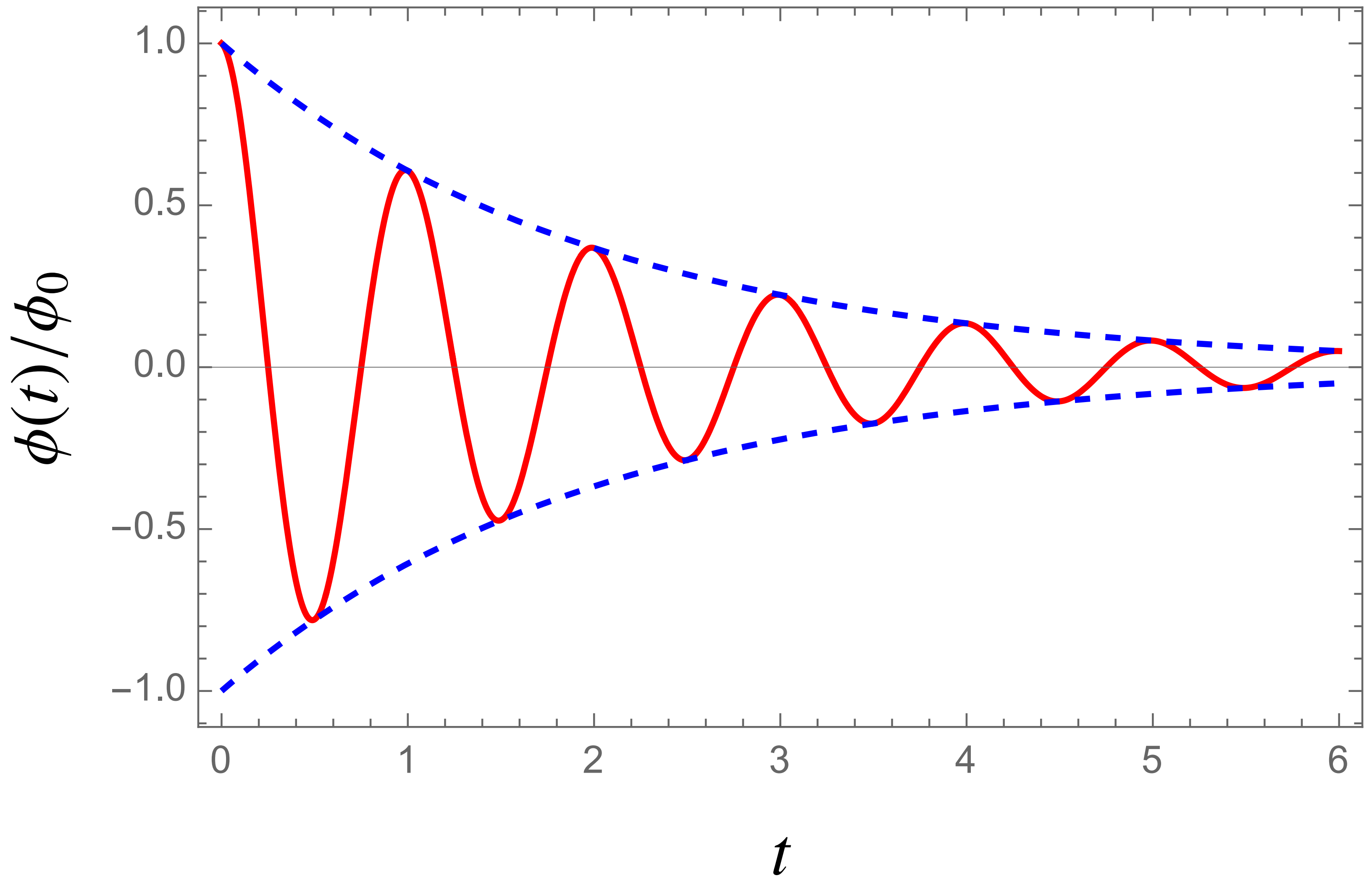

Illustrative case: stable, nonrelativistic limit

$$\begin{matrix}\Gamma \to 0 \\ v \ll c\end{matrix} \Rightarrow \phi(t) \approx \phi_0 \cos\left[m(1+\tfrac{1}{2}v^2)t + \delta\right] \Rightarrow m \propto f$$

main driver of oscillations

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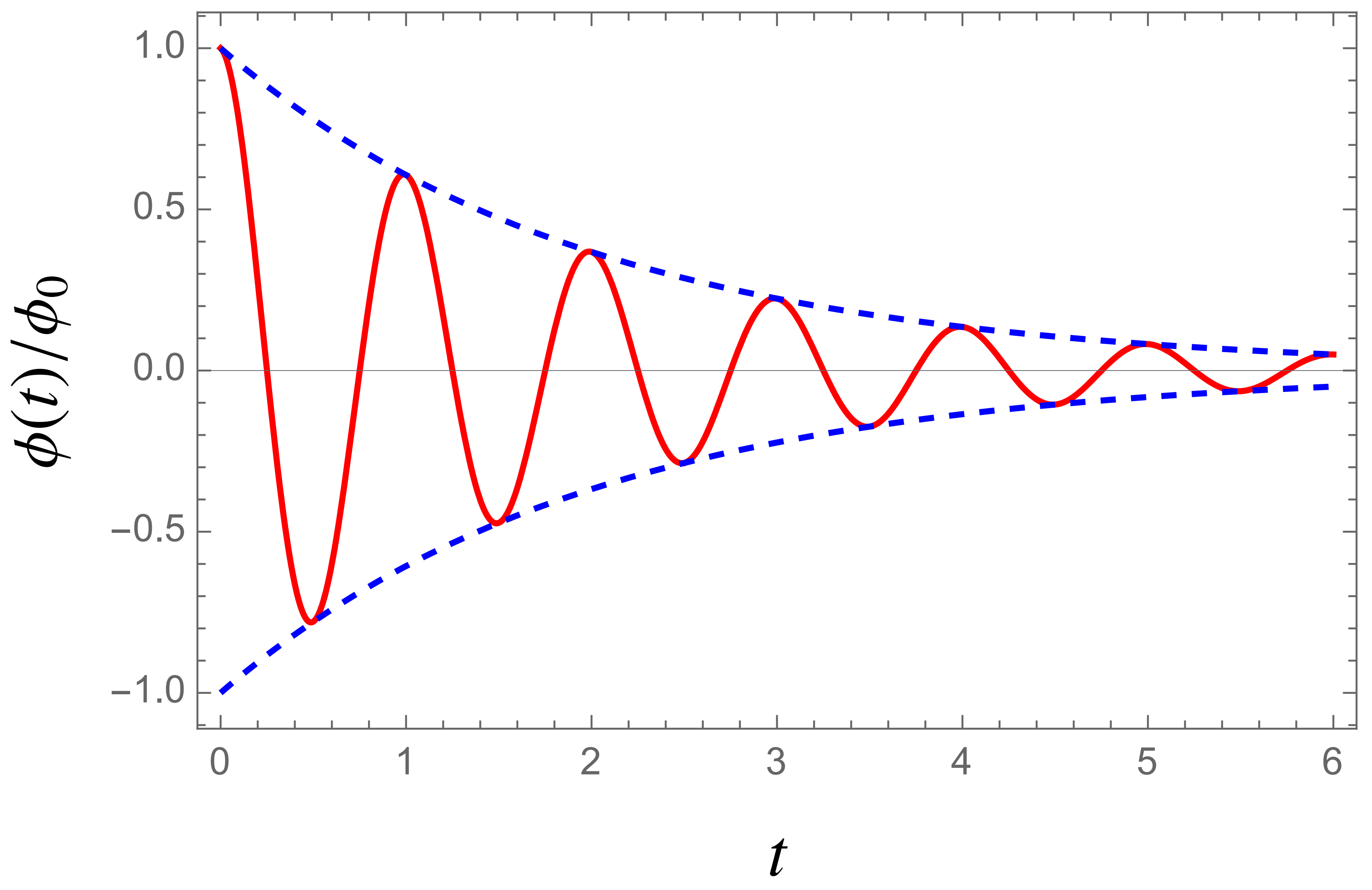

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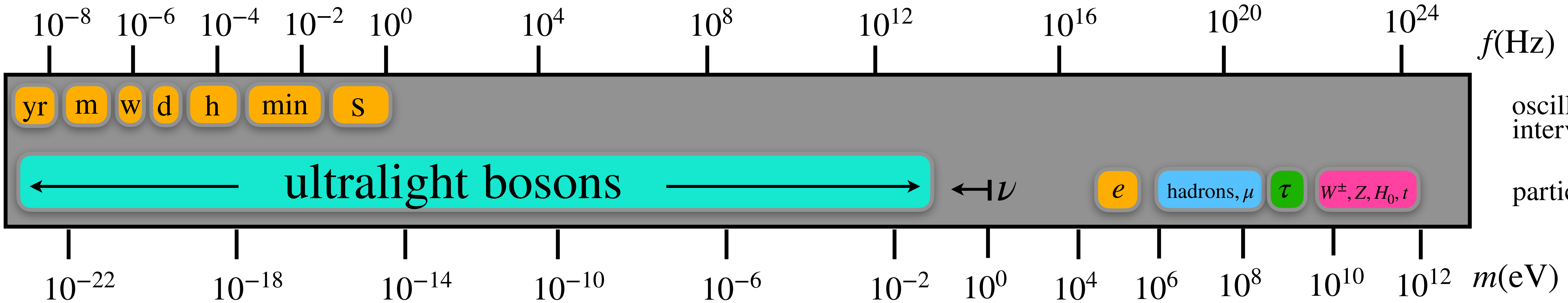

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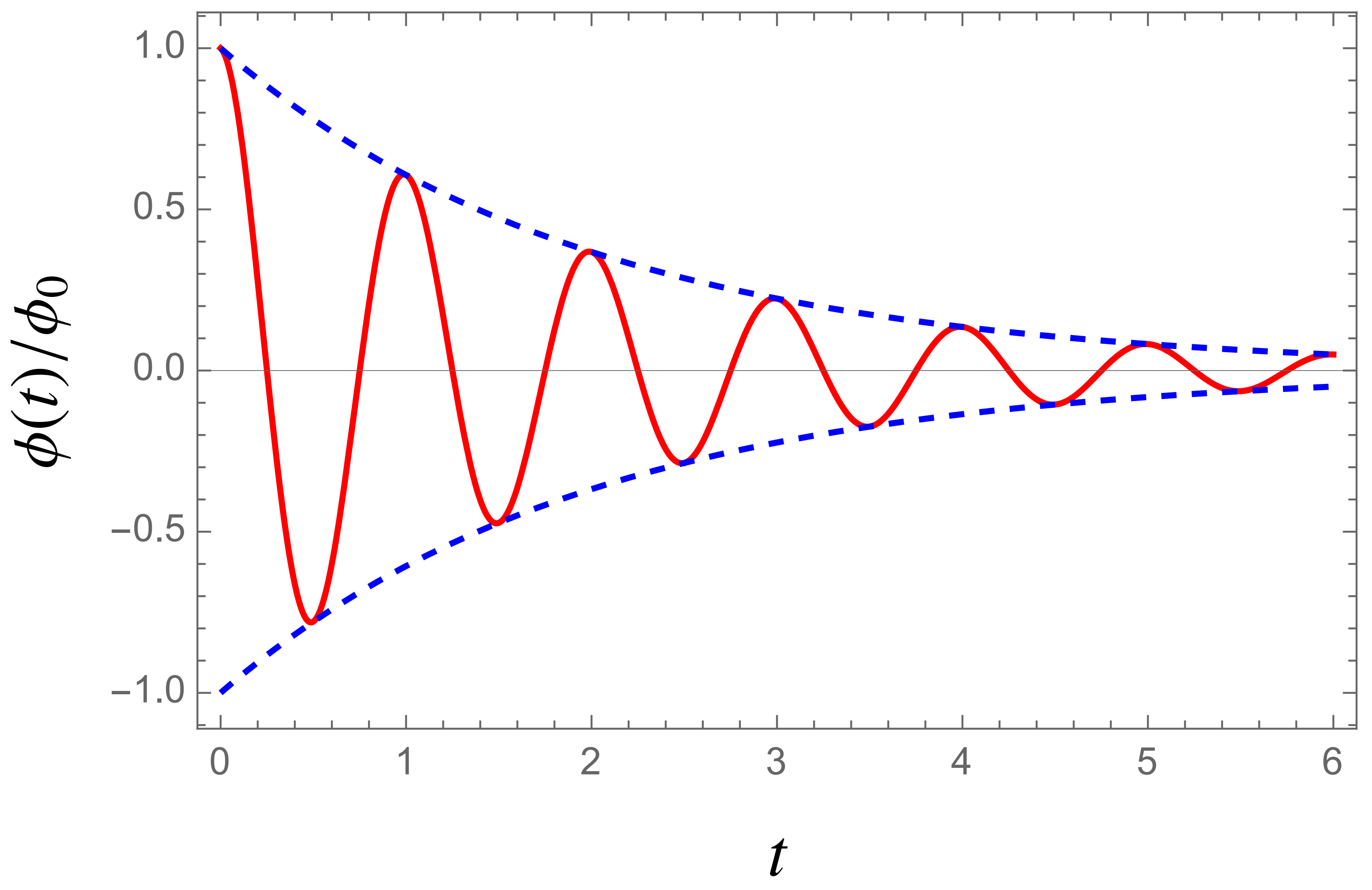

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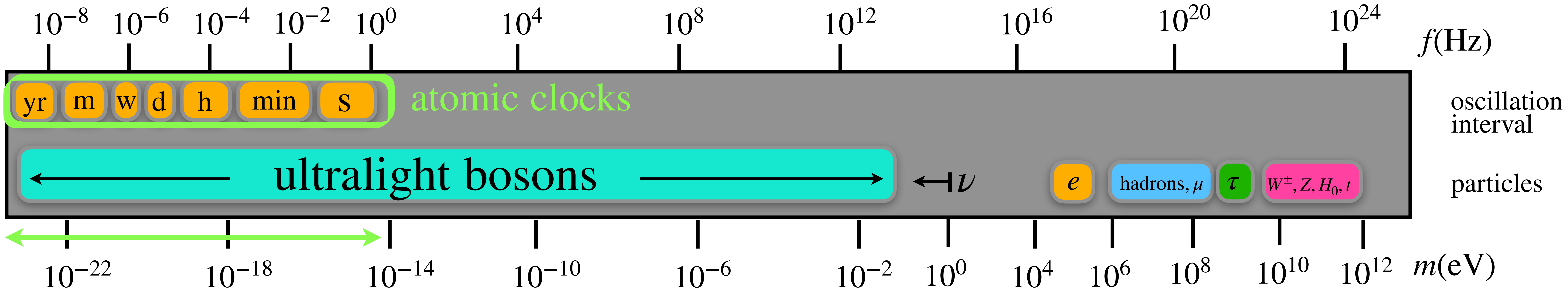
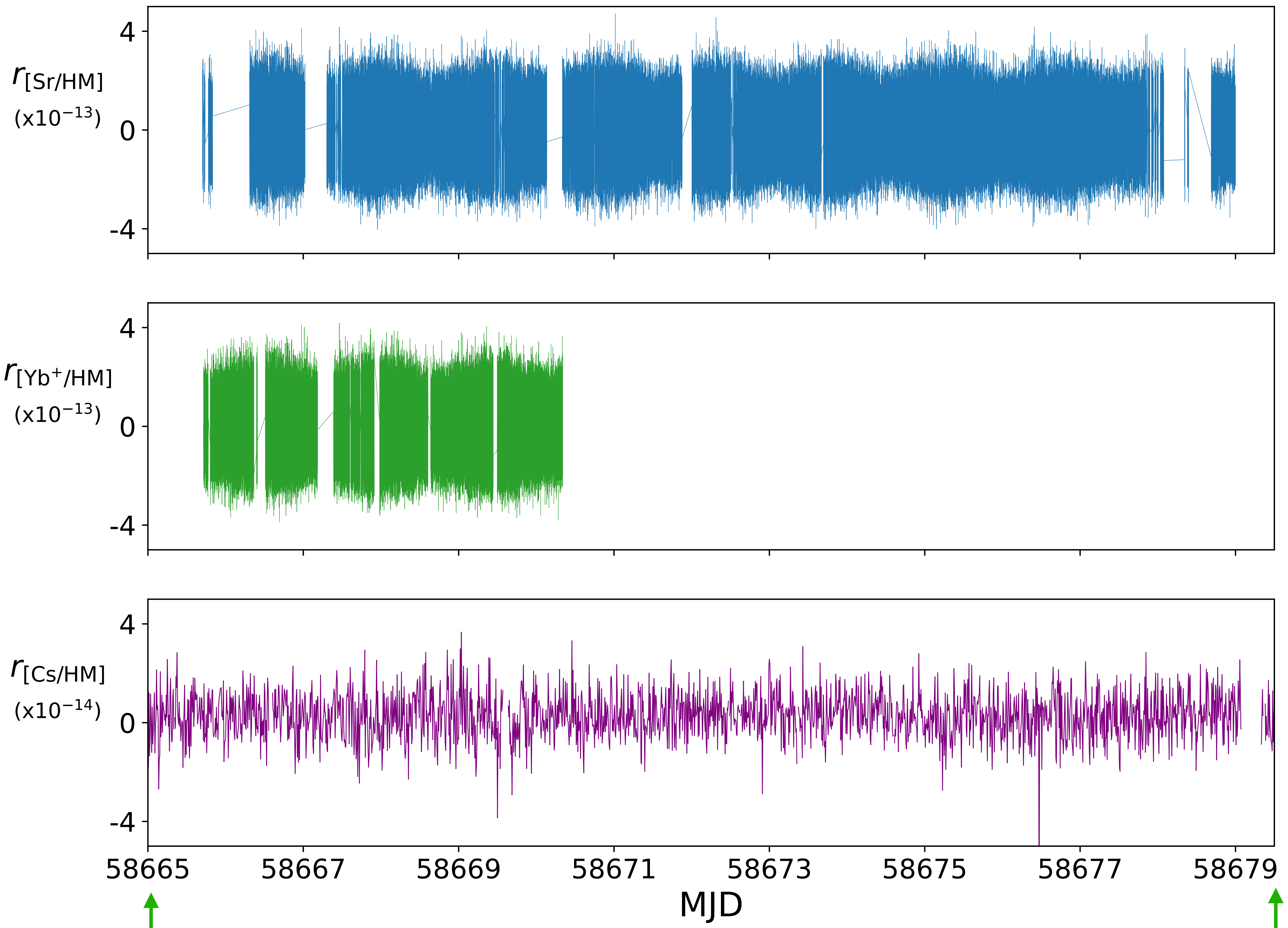


NPL frequency ratios

[New J. Phys. 25, 093012 (2023)]



01 July 2019

15 July 2019

$$r_{[i/j]} = \frac{\nu_i/\nu_j - R^*_{ij}}{R^*_{ij}}$$

- ~ 2 weeks of measurements, roughly every second with 75% uptime
- Observations made over same window

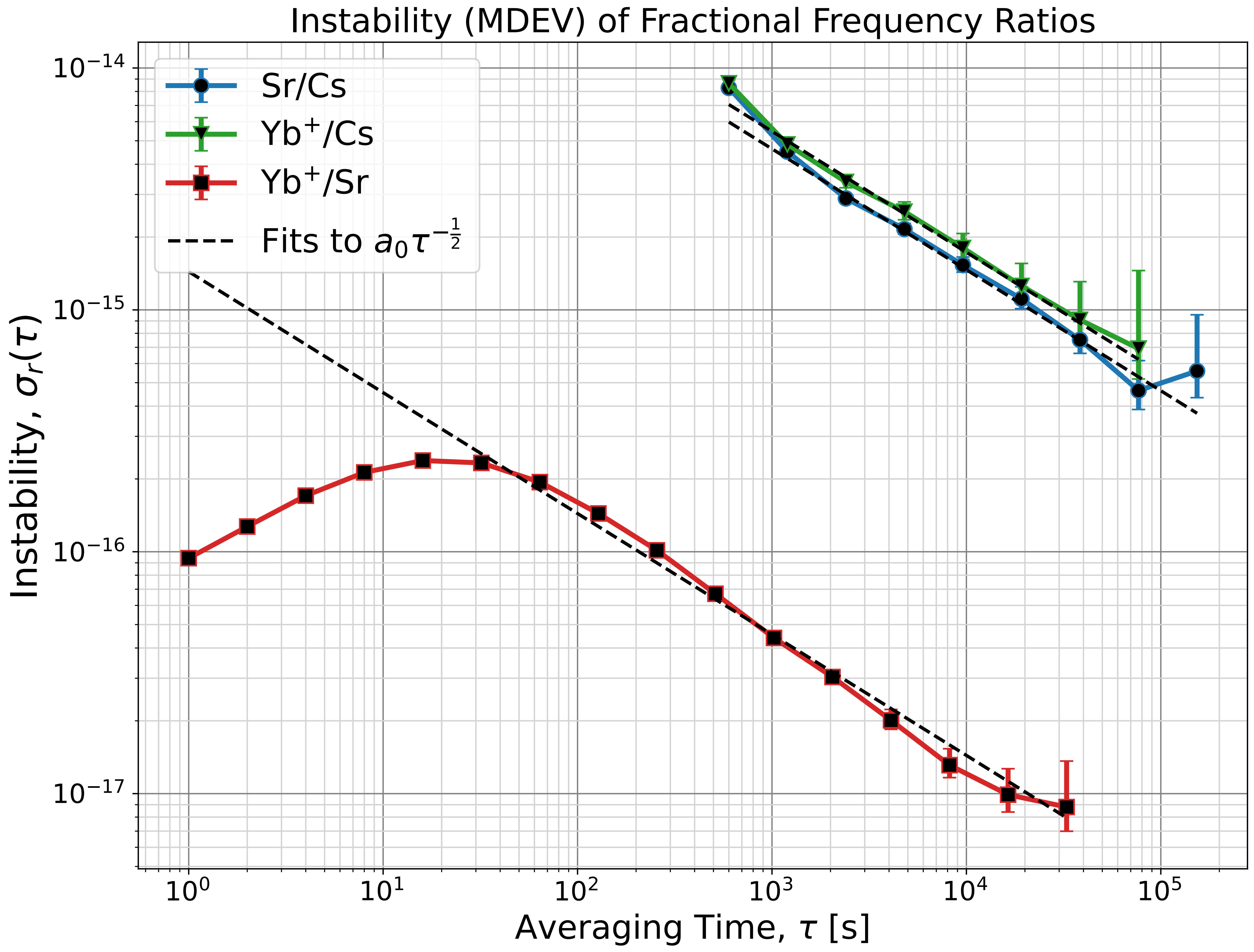
Divide out HM

⇙ ⇘

Yb^+/Sr ⇓ $\frac{\delta\alpha}{\alpha}$

Sr/Cs ⇓ $\frac{\delta\alpha}{\alpha}, \frac{\delta\mu}{\mu}, \frac{\delta g_N}{g_N}$

NPL clock instabilities



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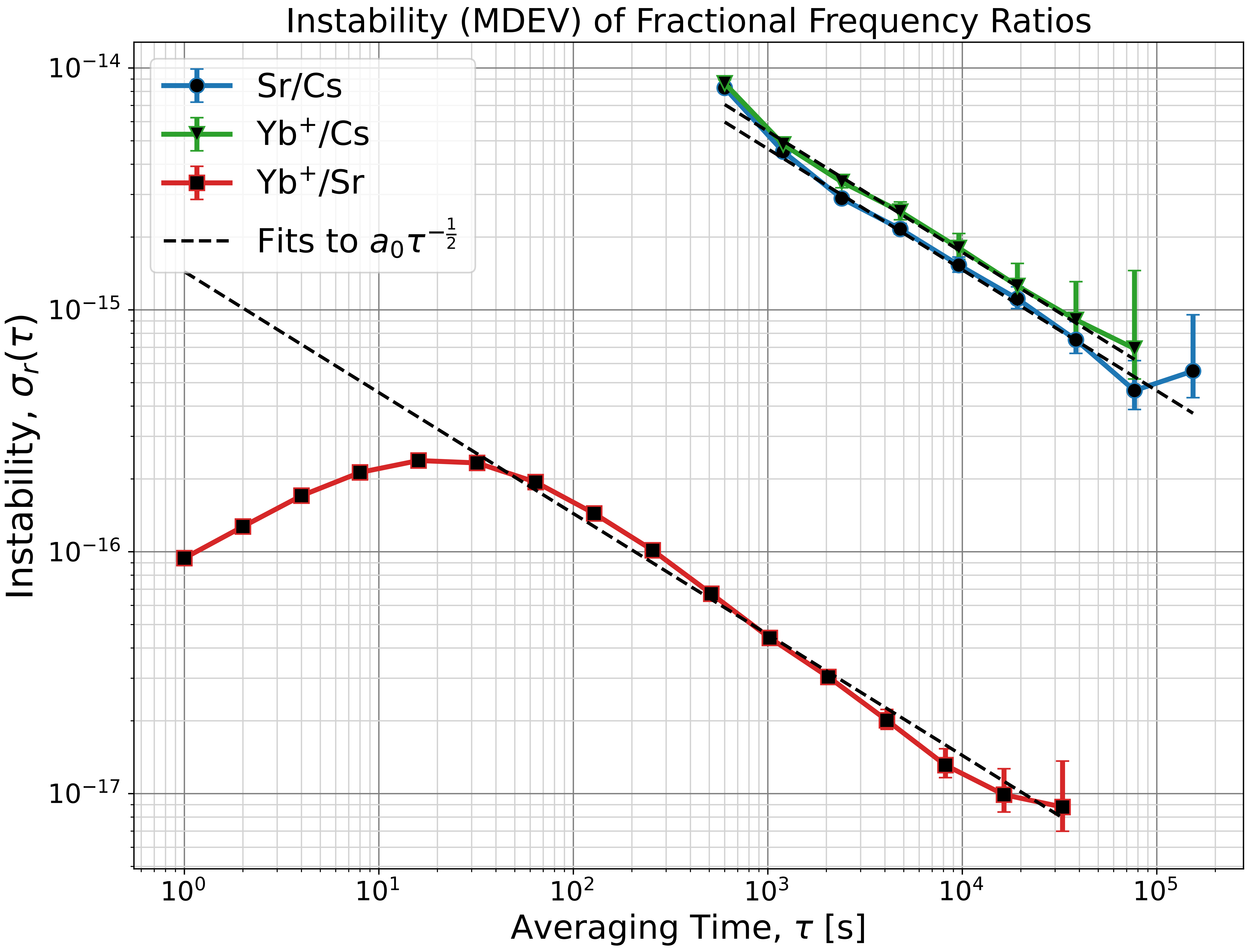

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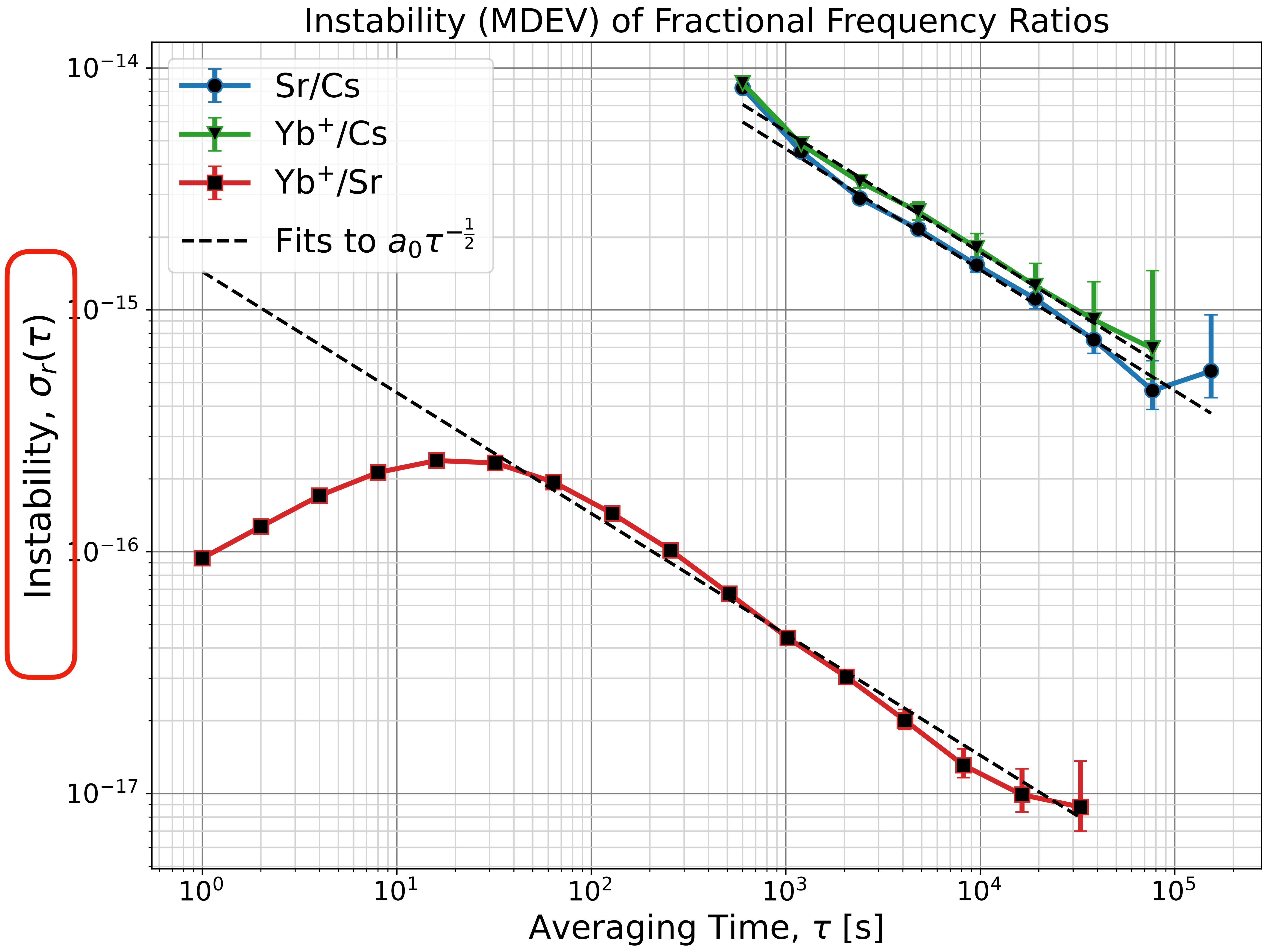

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measure of frequency ratio variations $\frac{\delta r}{r}$

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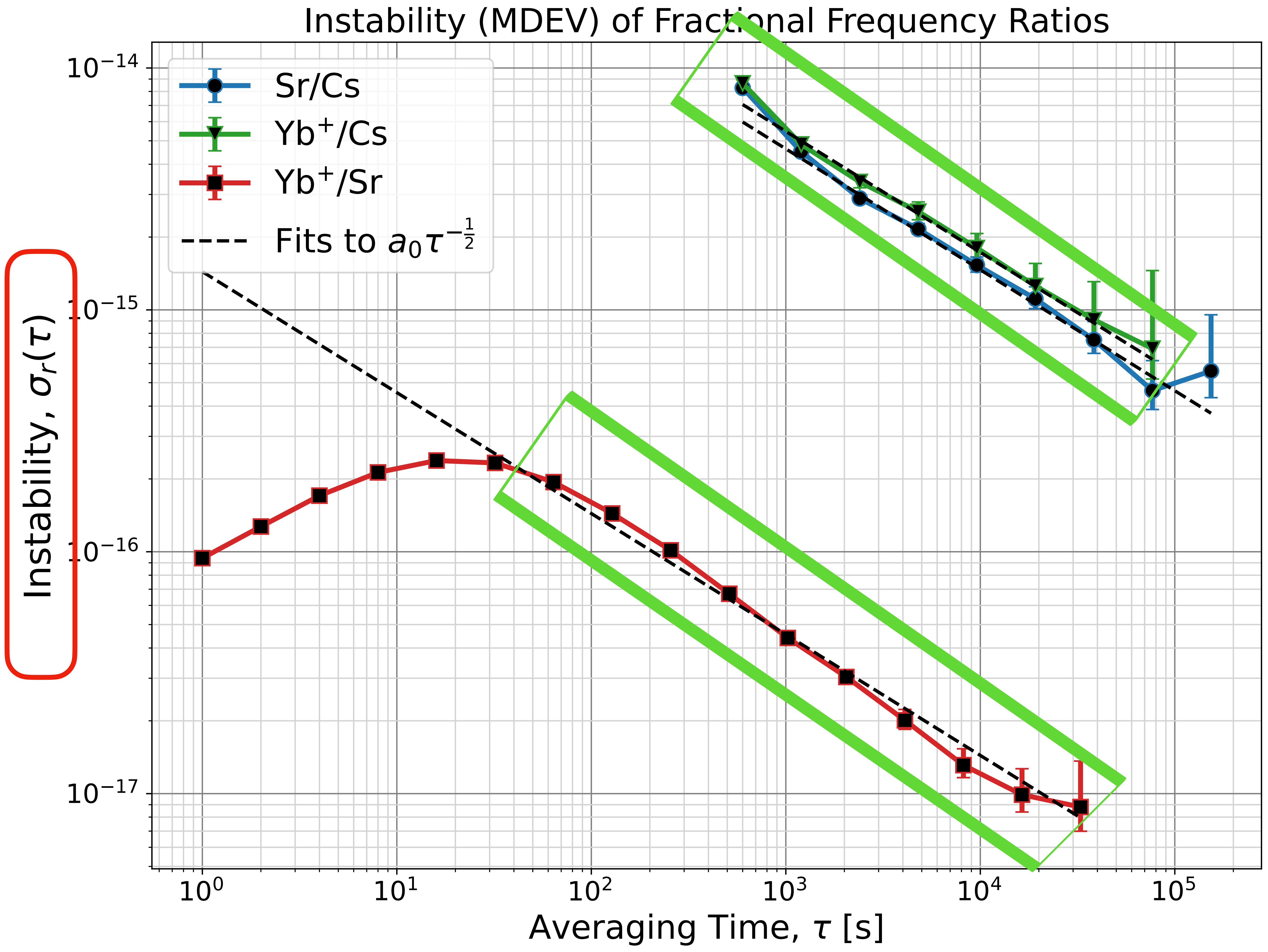

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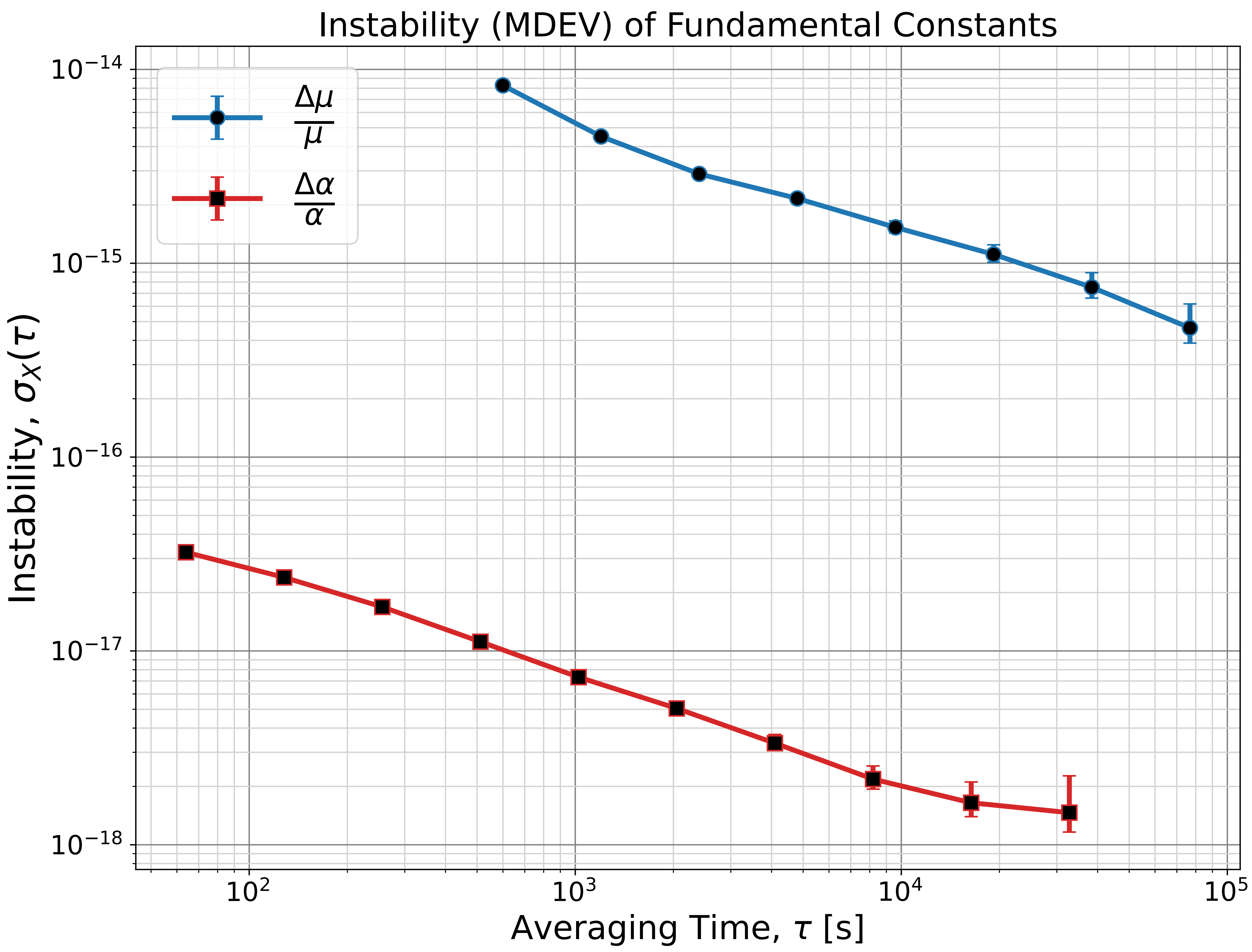
Data characteristic of white noise
⇒ operating on atomic transition!

Model-independent constraints



Translate instabilities to bounds on shifts

$$\frac{\delta r}{r} \propto \frac{\Delta g}{g} \sim \kappa^n d_g^{(n)} \phi^n(t)$$

$$\kappa^n \, |d_{\mathrm{Sr/Cs}}^{(n)}| \, \sigma_{\phi^n}(\tau) \lesssim 1.6 \times 10^{-13} / \sqrt{\tau/\mathrm{s}}$$

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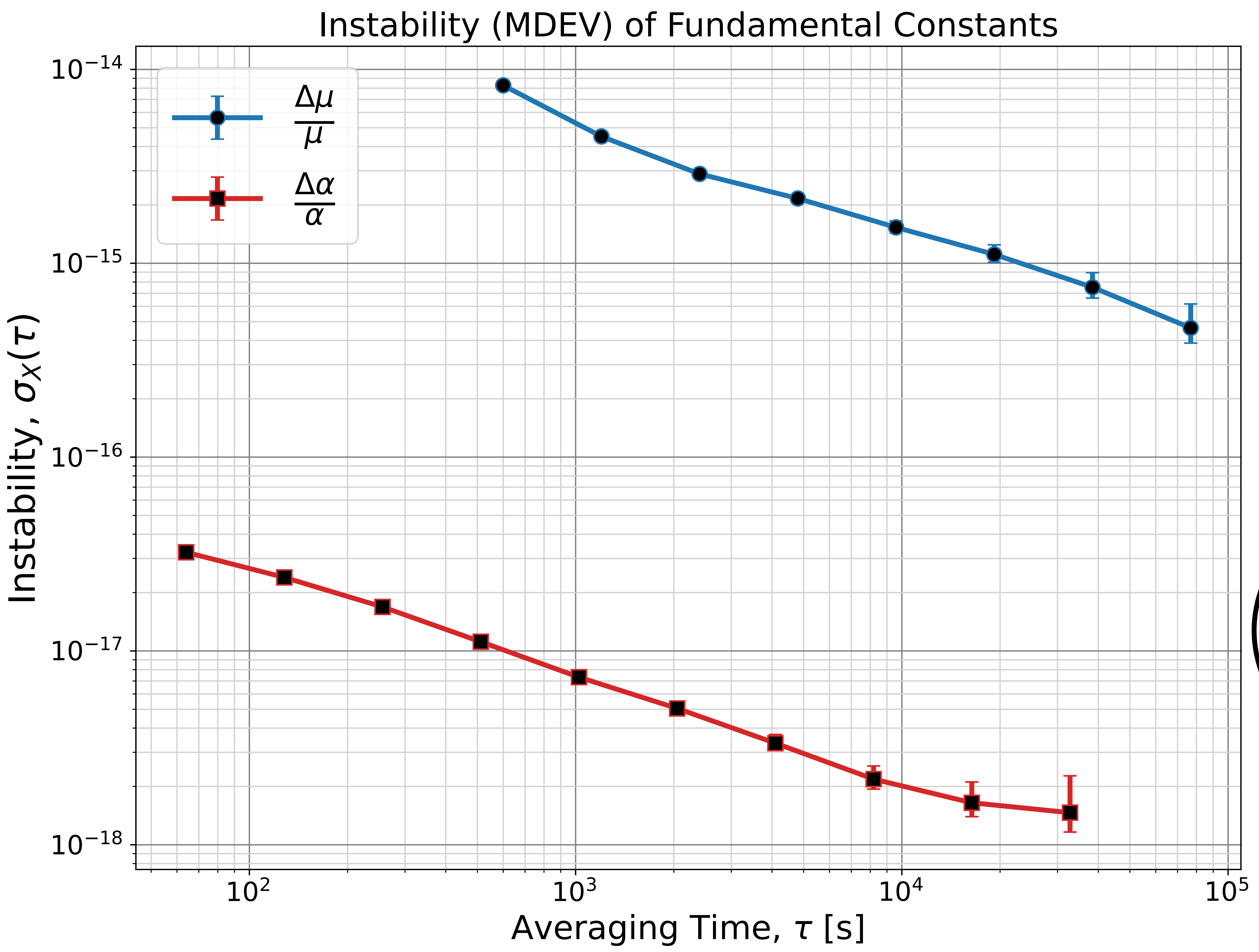

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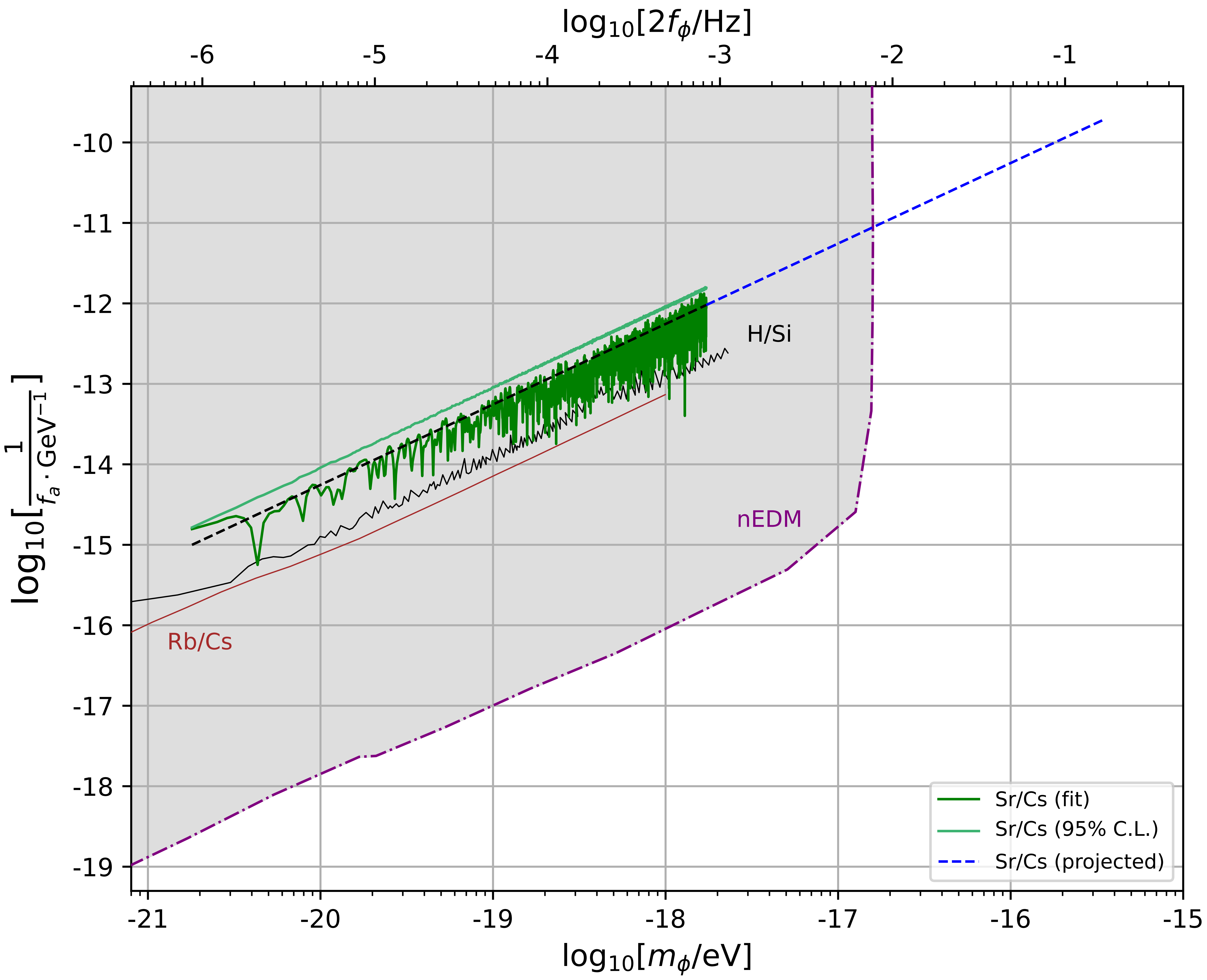
E.g. for two times separated by 1000 seconds

$$\approx \kappa^n \,|\, d^{(n)}_{\gamma} \,|\, [\phi^n(t+\tau) - \phi^n(t)] \lesssim 7 \times 10^{-18}$$

No functional form of $\phi(t)$ assumed

ALP constraints



H. Kim and G. Perez, arXiv:2205.12988

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Axion is coherently oscillating field

$$a(t) \approx \frac{\sqrt{2\rho_{\rm DM}^{\rm local}}}{m}\cos(mt) \qquad \rho_{\rm DM}^{\rm local} \approx 0.3\ {\rm GeV/cm^3}$$

Can induce oscillations in nucleon mass and nuclear g factor

transmits to sensitivity from Sr/Cs ratio

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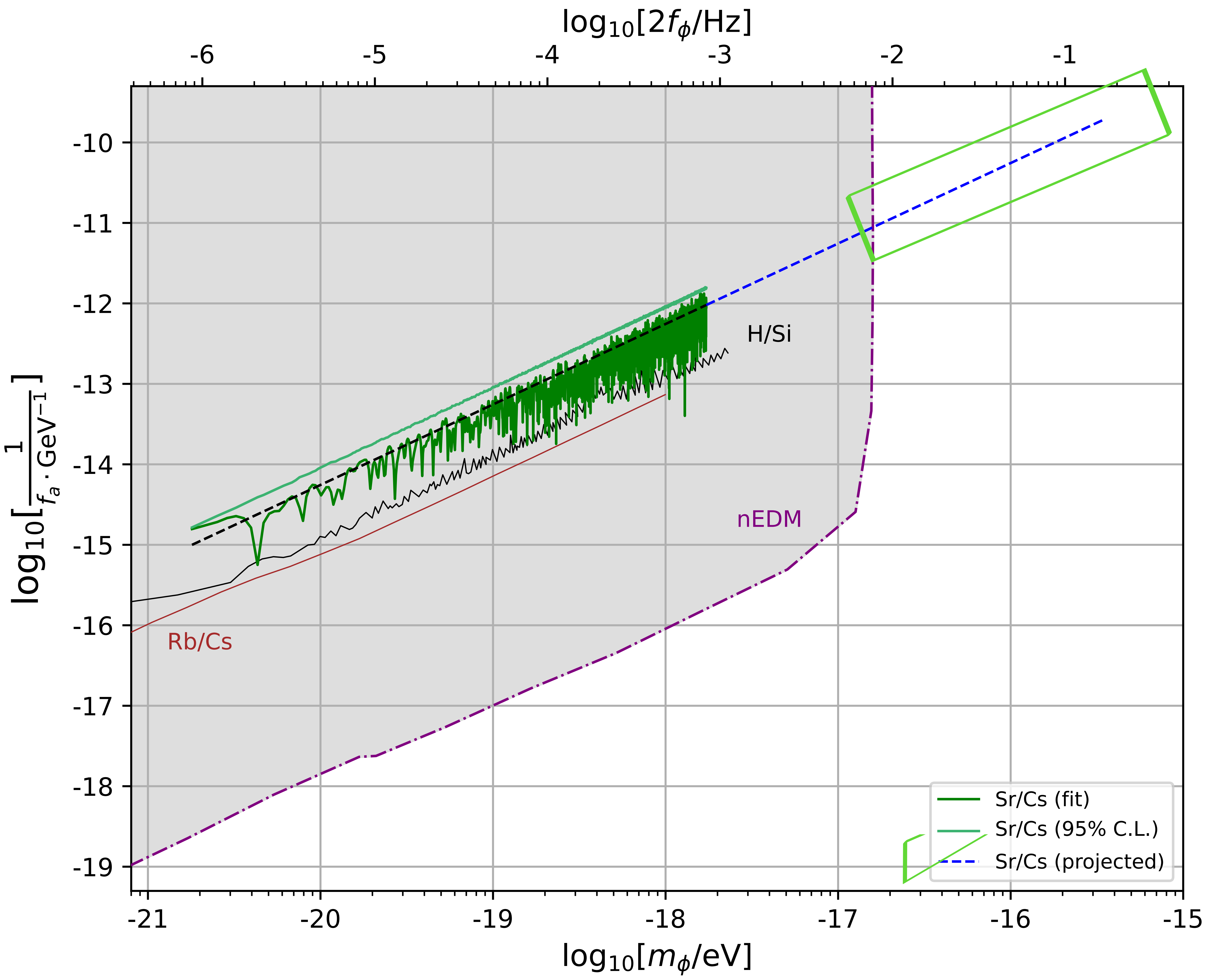

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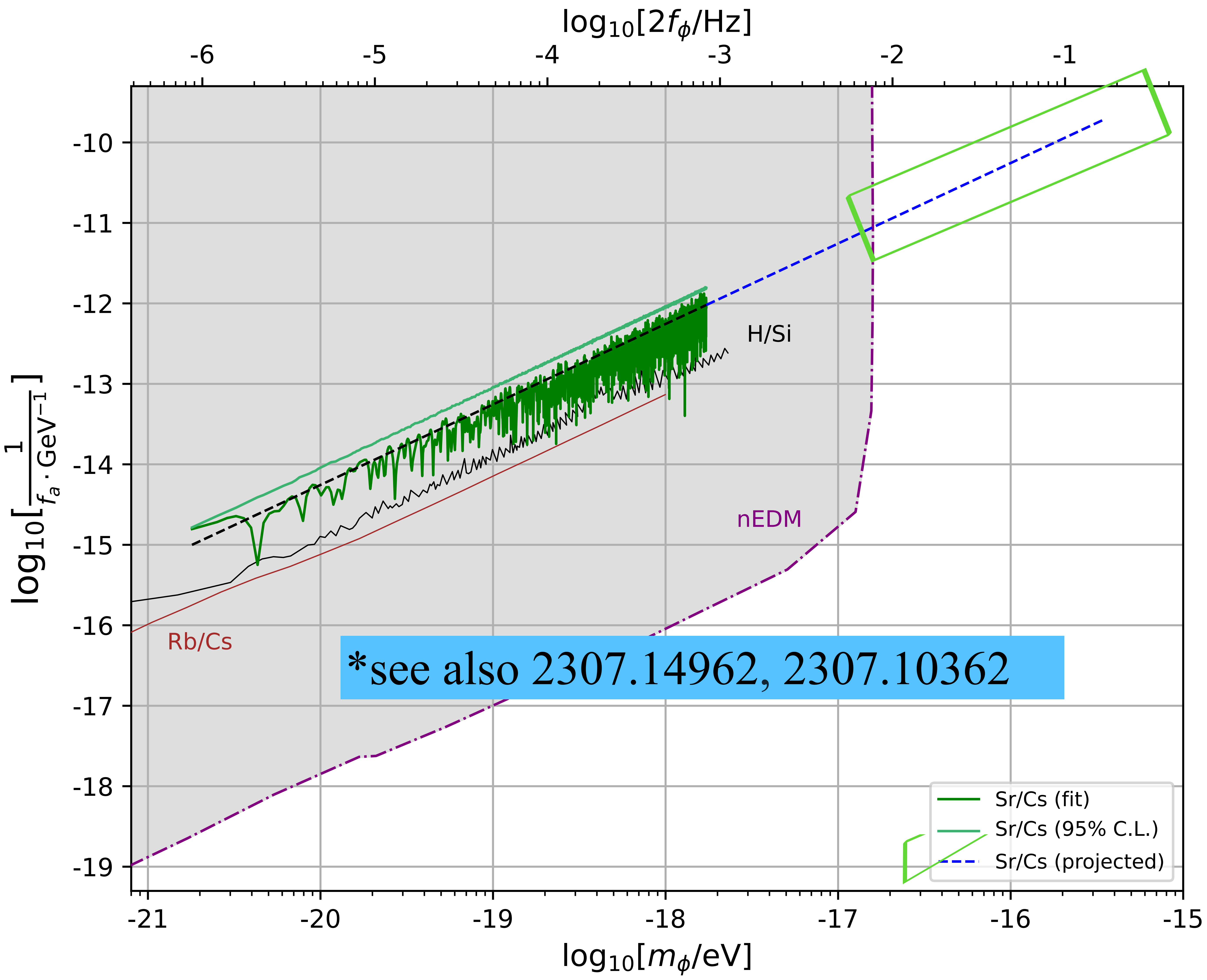

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$$\mathscr{L}_a = \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^b_{\mu\nu}\widetilde{G}^{b\mu\nu}$$

Axion is coherently oscillating field

$$a(t) \approx \frac{\sqrt{2\rho_{\rm DM}^{\rm local}}}{m}\cos(mt) \qquad \rho_{\rm DM}^{\rm local} \approx 0.3\ {\rm GeV/cm^3}$$

Can induce oscillations in nucleon mass and nuclear *g* factor

transmits to sensitivity from Sr/Cs ratio

$$\frac{1}{f_a \cdot {\rm GeV}^{-1}} = 10^{-10}\sqrt{\frac{m_{15}^2}{c_r \cdot 10^{-15}}\left|\frac{\delta r}{r}\right|_{\rm Sr/Cs}}$$

Conclusions

Atomic clocks are powerful probes of ultralight bosons

- ☐ Sensitive to "variations" of fundamental dimensionless constants
- ☐ Variations may be attributed to presence of ultralight bosons
- ☑ Model-independent constraints from instabilities of Yb^+, Sr, and Cs clocks
- ☑ New constraints on ALPs and scalar ultralight DM (see paper)

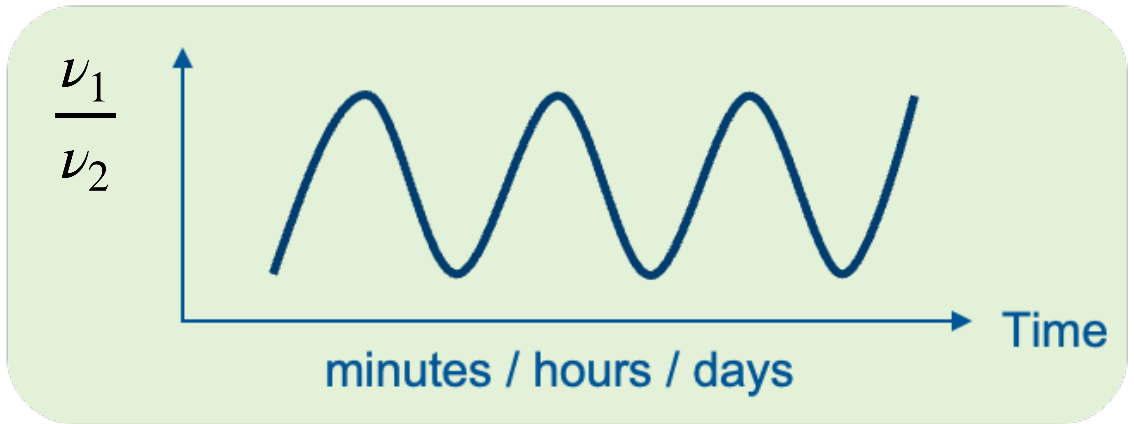
Excellent future prospects

- ☑ New clocks under construction, additional data-taking campaigns in progress
- ☑ New phenomenology connecting ultralight fields to atomic observables

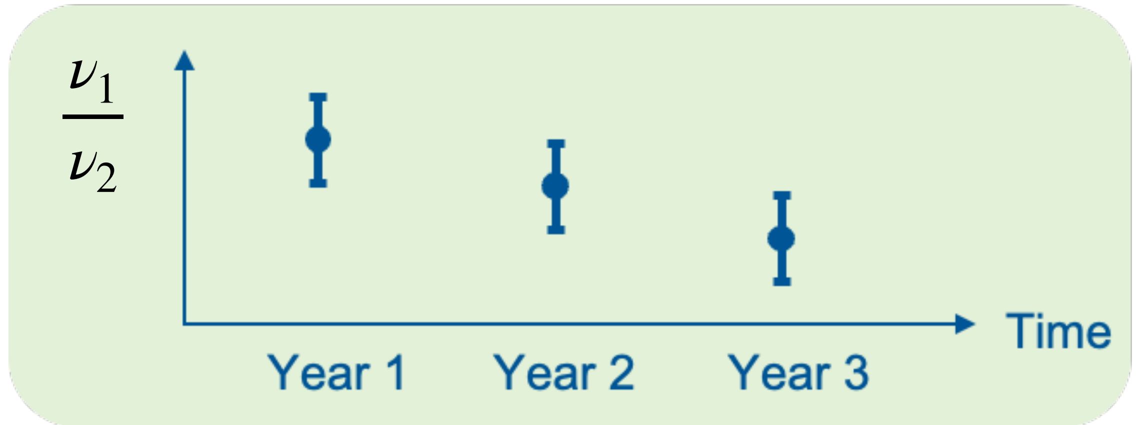
"A network of clocks measuring the stability of fundamental constants"

G. Barontini et. al. EPJ Quantum Technology 9, 12 (2022)

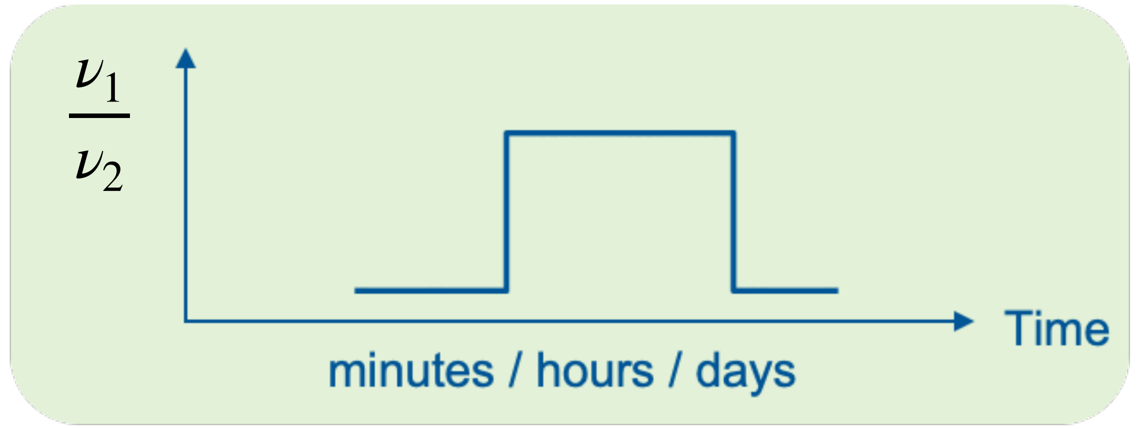
SNET



Oscillations



Drifts



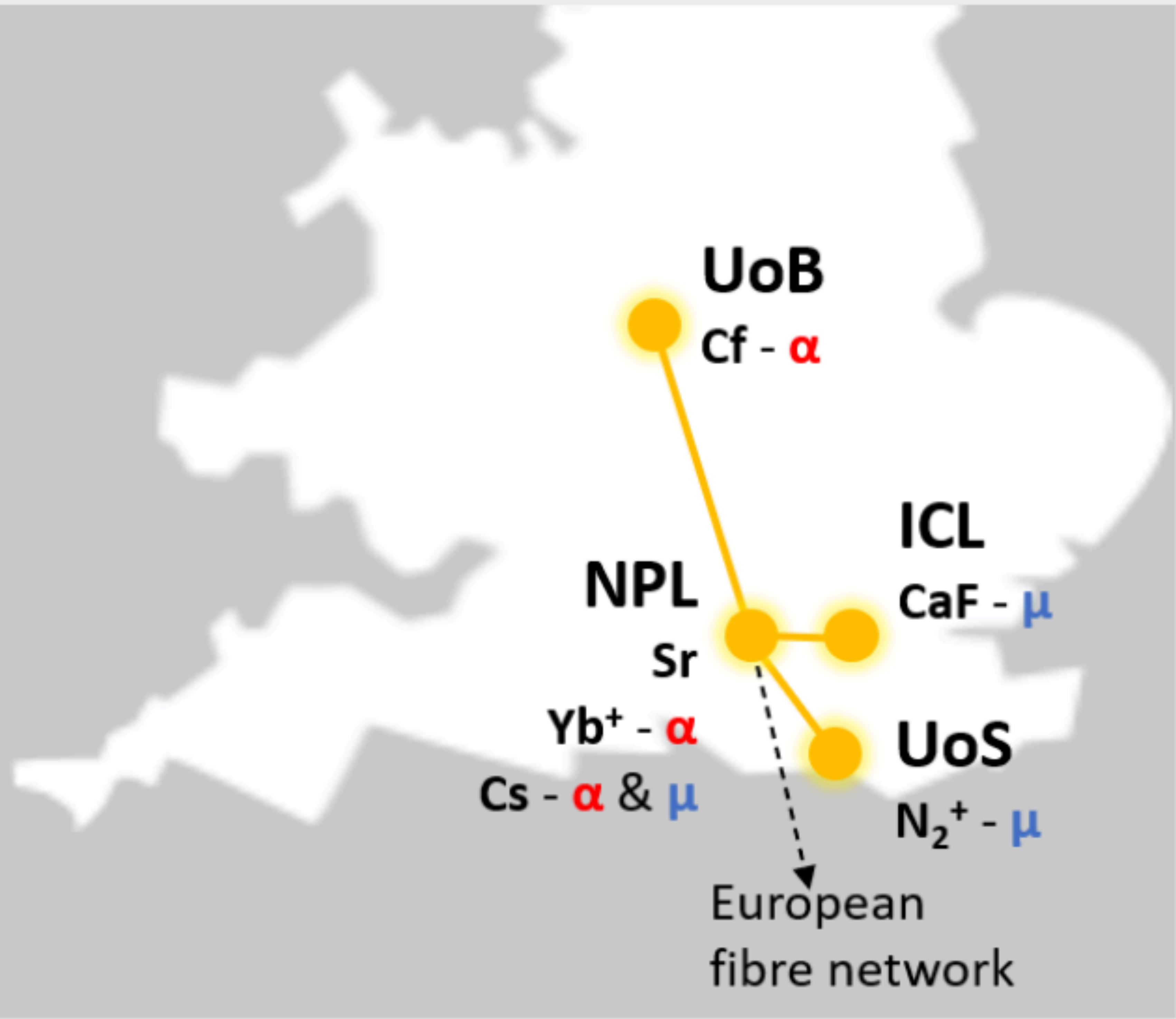
Transients

University of Birmingham

Imperial College London

University of Sussex

NPL



Clock	K_α	K_μ
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

Operational

Under construction