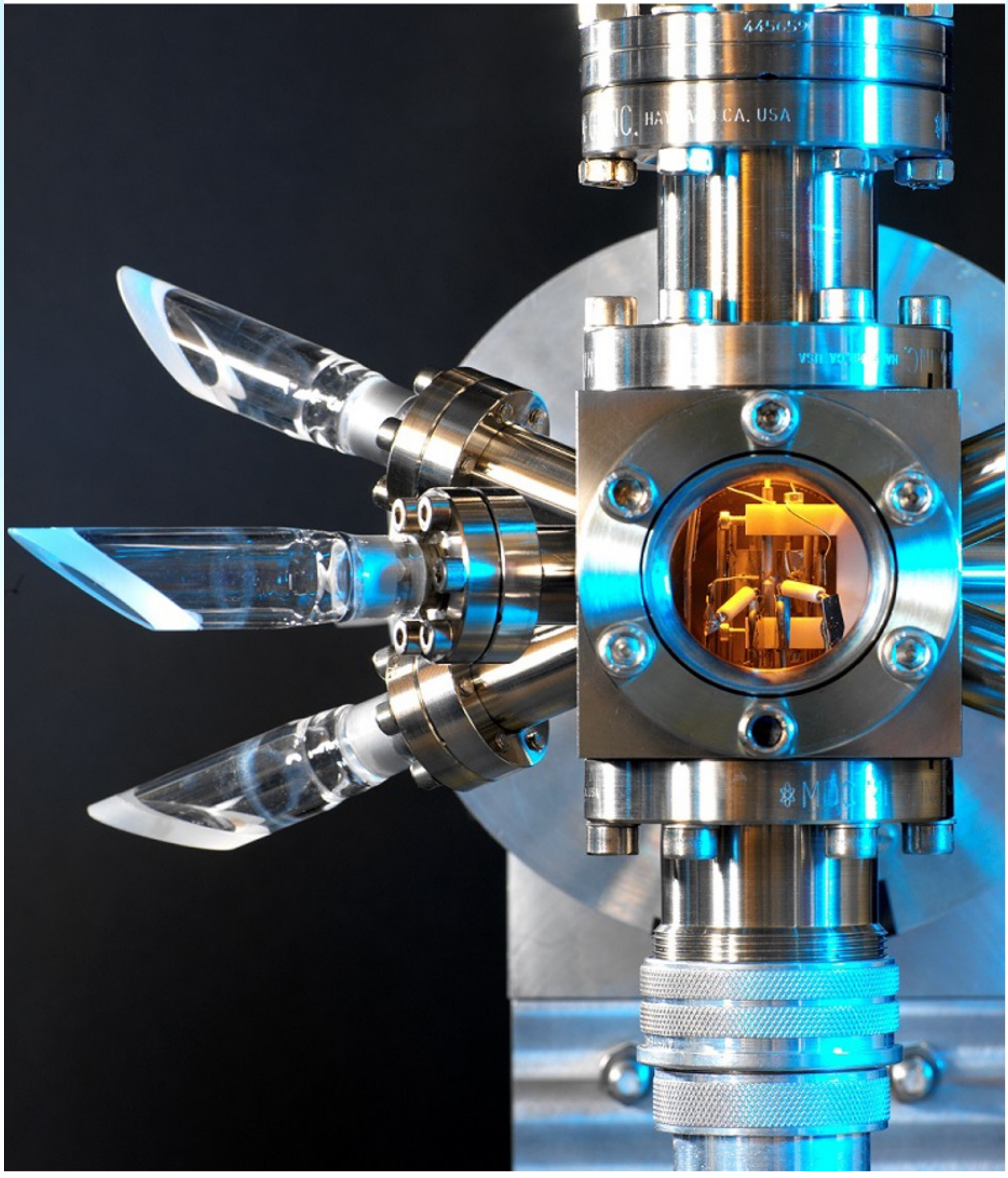
Constraints on ultralight scalars and axions using atomic clocks

Nathaniel Sherrill

University of Sussex

SUSY 2023

based on arXiv:2302.04565



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Integer-spin fields with very small masses

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This talk: search for ultralight bosons by measuring "variations" of fundamental constants

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Consider ϕ-SM interactions

$$\mathscr{L}_{\mathrm{int},\phi} \supset -\left(\frac{\phi}{\Lambda}\right)^n \cdot \mathscr{O}_{\mathrm{SM}}$$

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

$$\kappa^n d_j^{(n)} \leftrightarrow 1/\Lambda^n$$

see, e.g.,

P. W. Graham et al., PRD 93, 075029 (2016)

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Terms induce shifts in FCs

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

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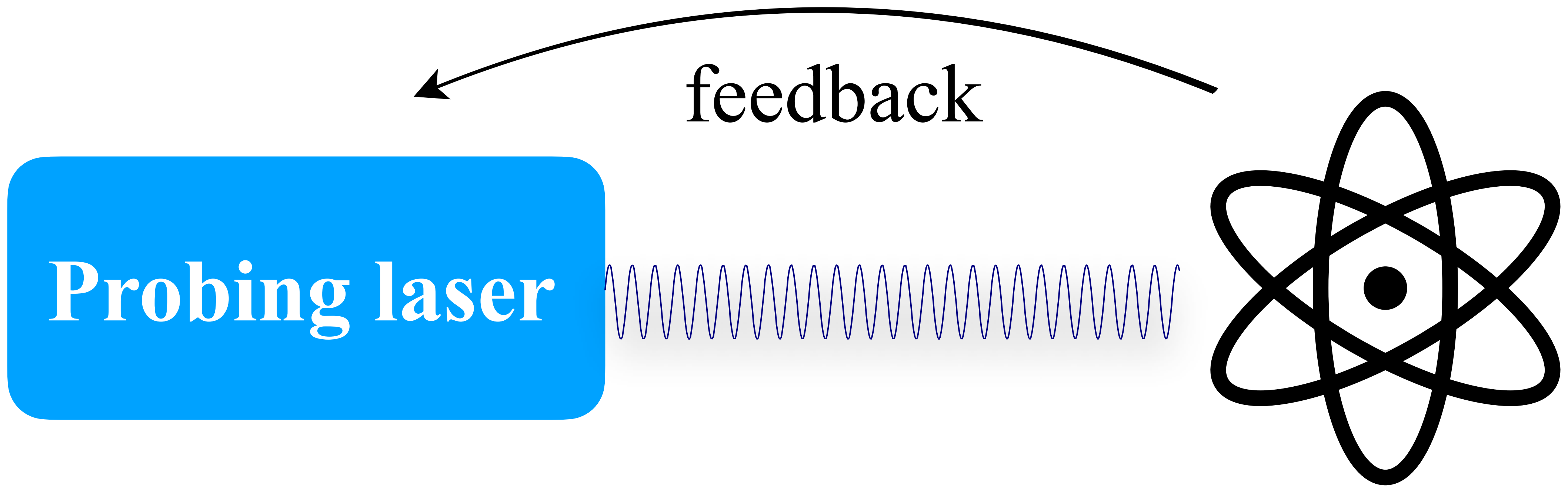
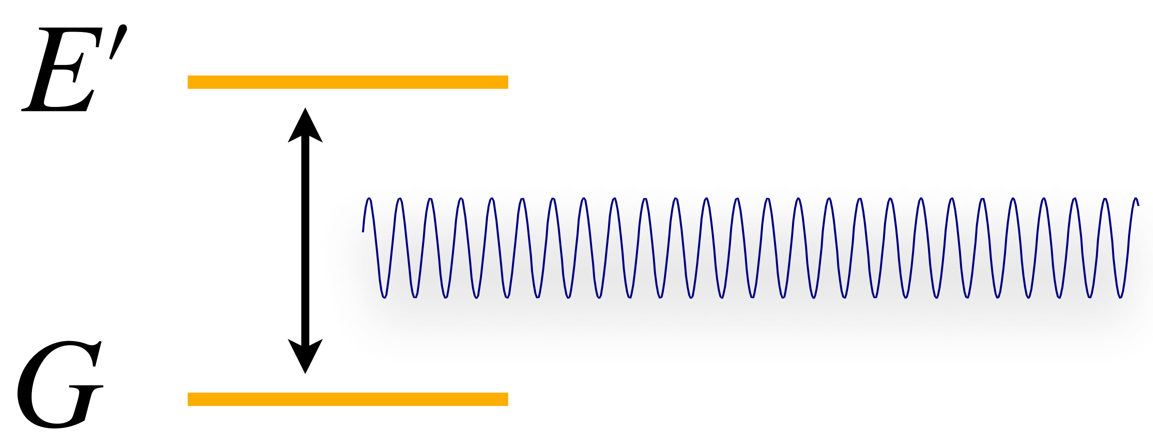
How does one measure with clocks?

Atomic clocks





$= \hbar\nu_{\text{transition}}$

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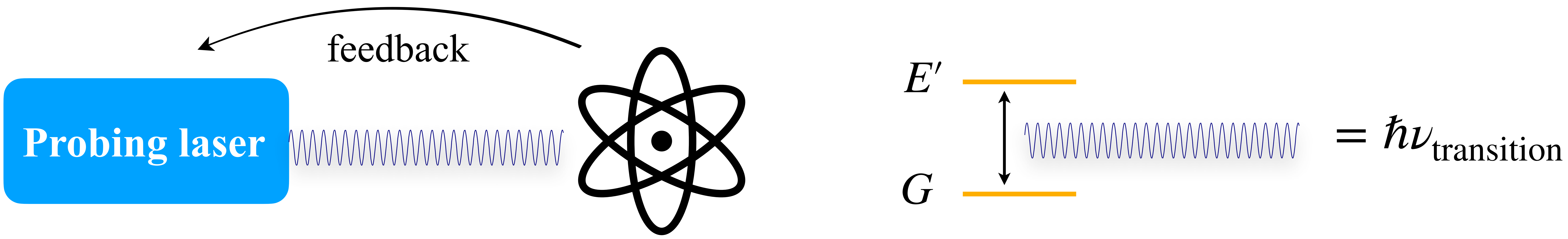

Common clock transitions

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

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

$\mu = m_e/m_p$

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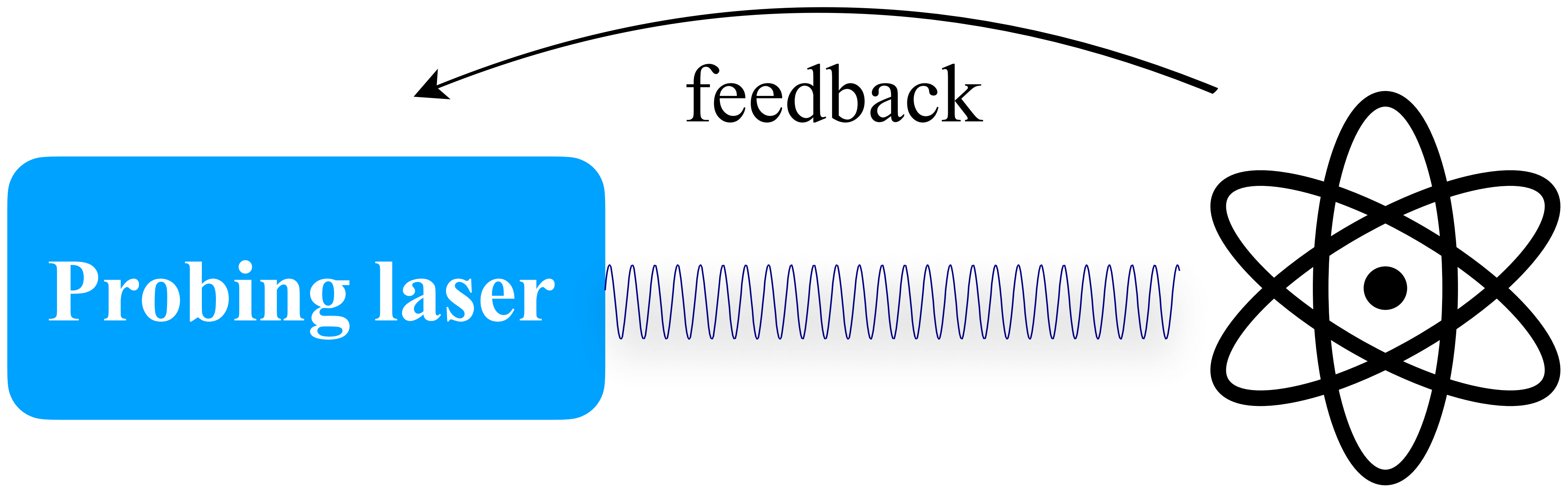

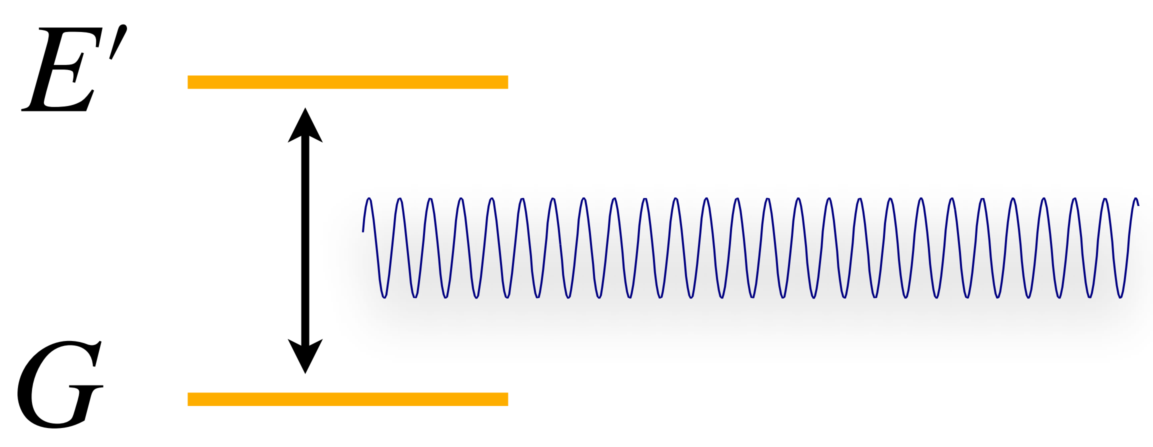

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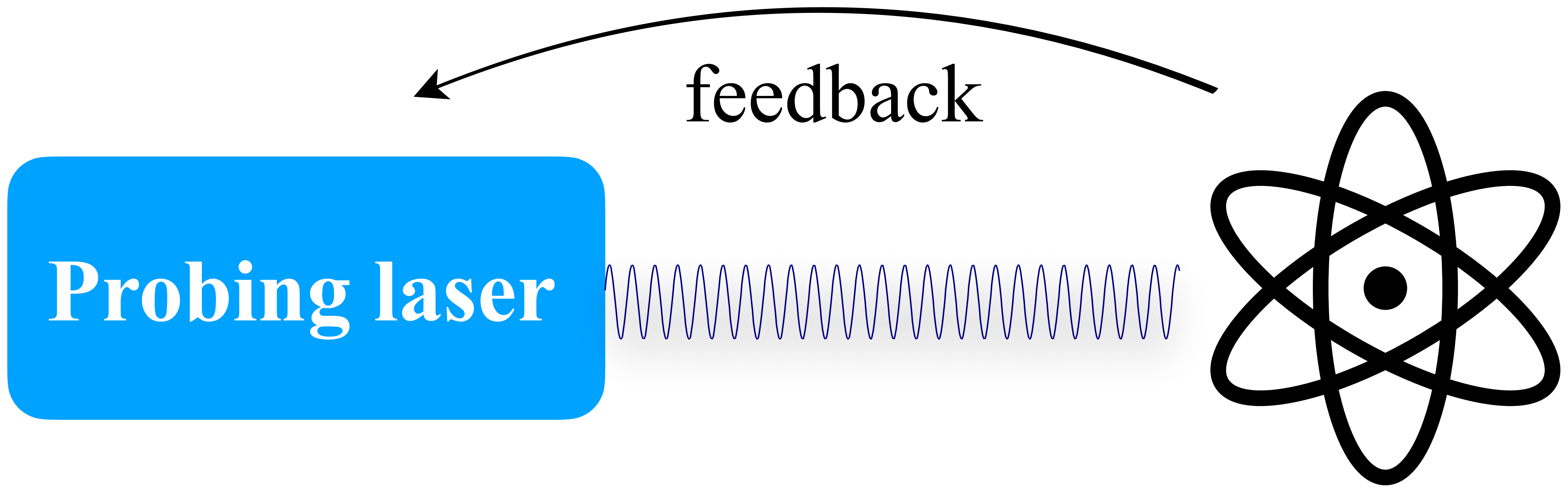

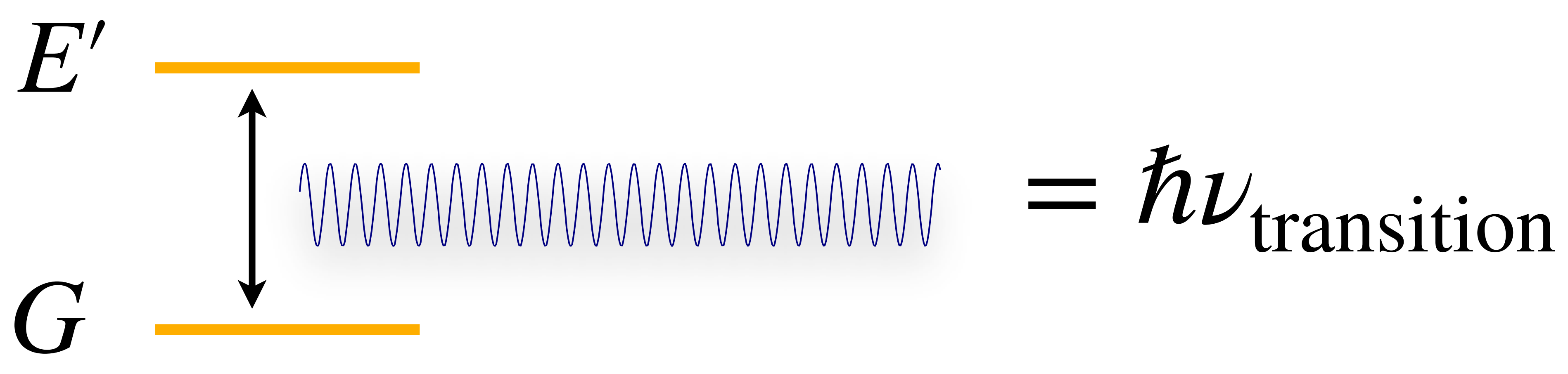

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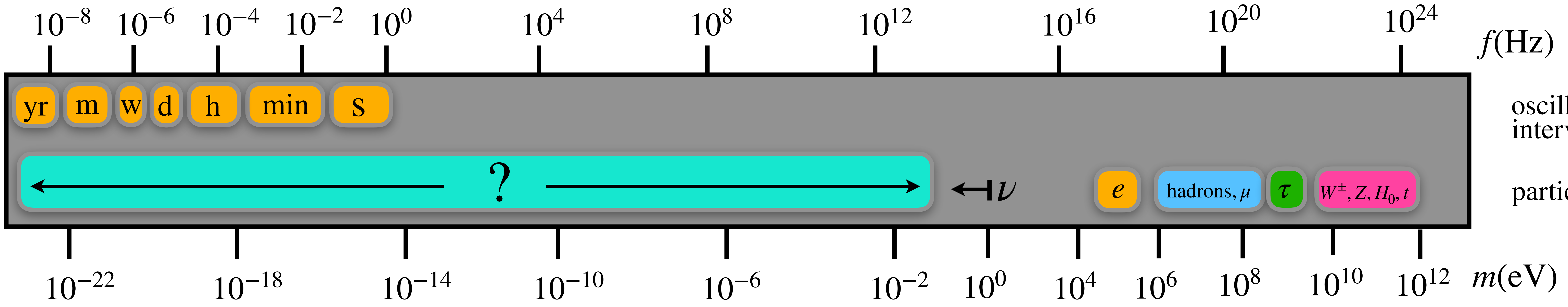

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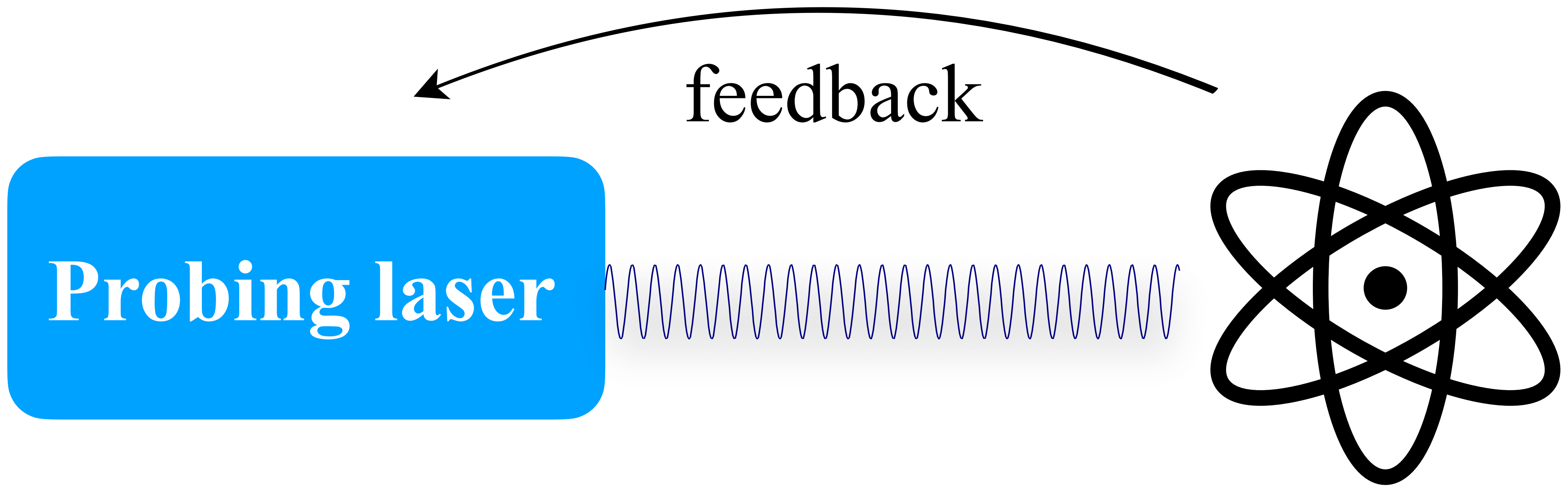

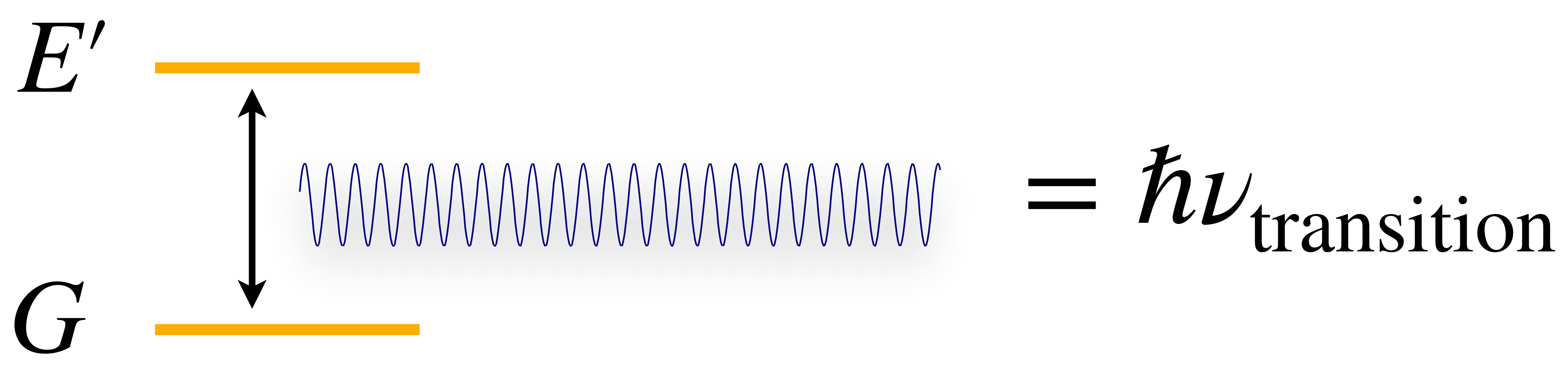

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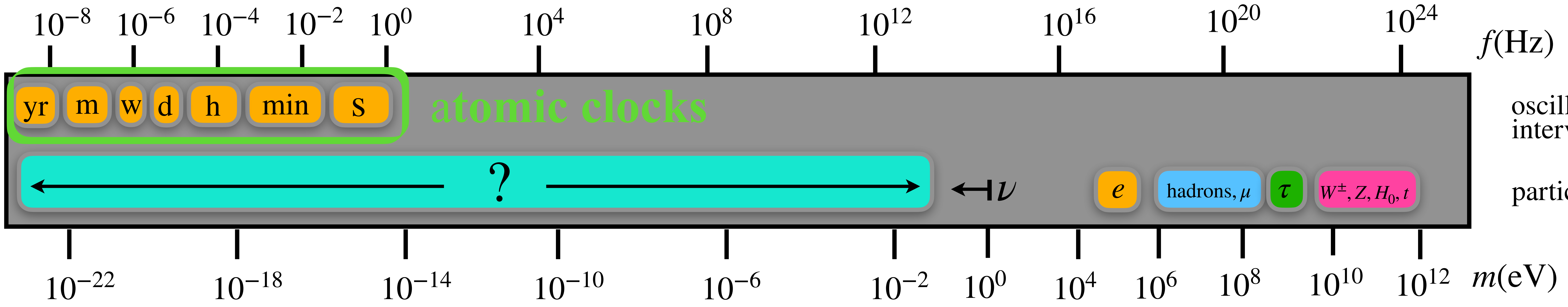

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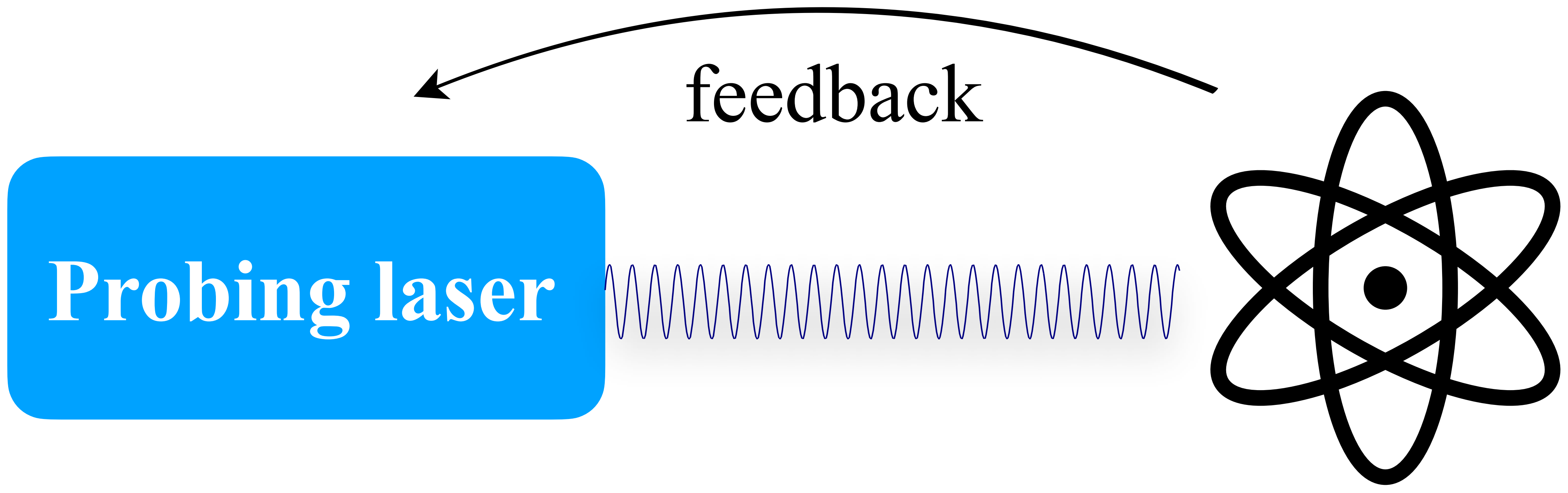

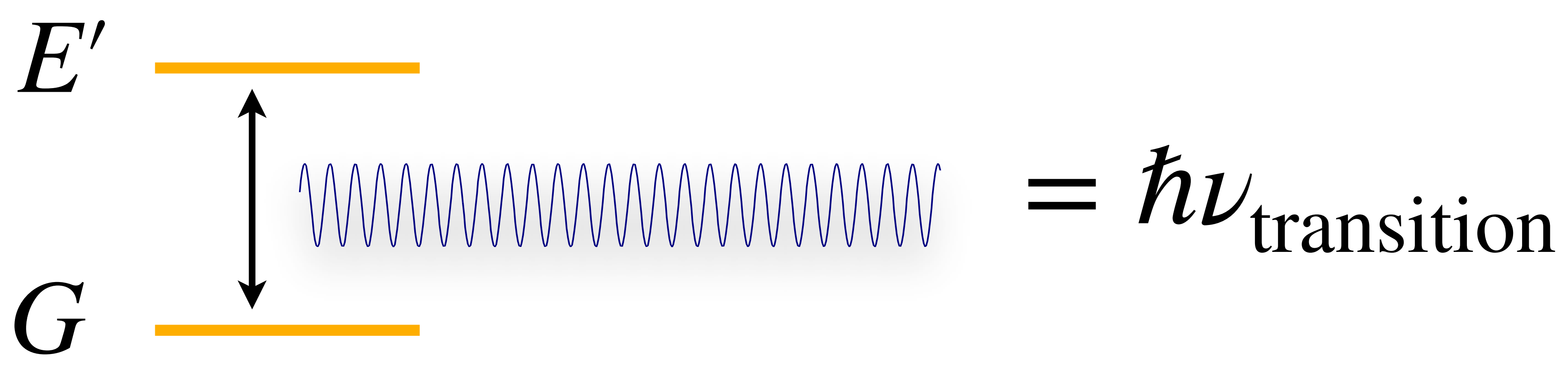

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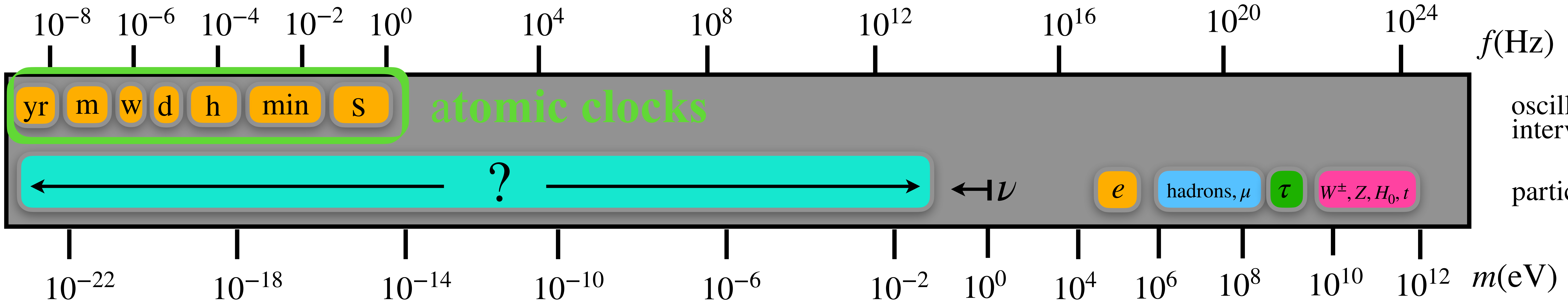
Measurements involve *comparisons!*

- Need reference with distinct sensitivity
- $r = \nu_1/\nu_2$ is dimensionless observable
- $\delta r_{\text{opt}}/r_{\text{opt}} \propto \delta\alpha/\alpha$



NPL clocks: Yb^+, Sr, and Cs

National Physical Laboratory (NPL) in UK has collected 2 weeks of Yb^+, Sr, and Cs measurements

Mean frequency ratios $\bar{r}$ *not* constant over time

Instability = good measure of frequency fluctuations

$$\sigma_r^2(\tau) \sim \frac{1}{2}\langle(\bar{r}_{i+1} - \bar{r}_i)^2\rangle$$

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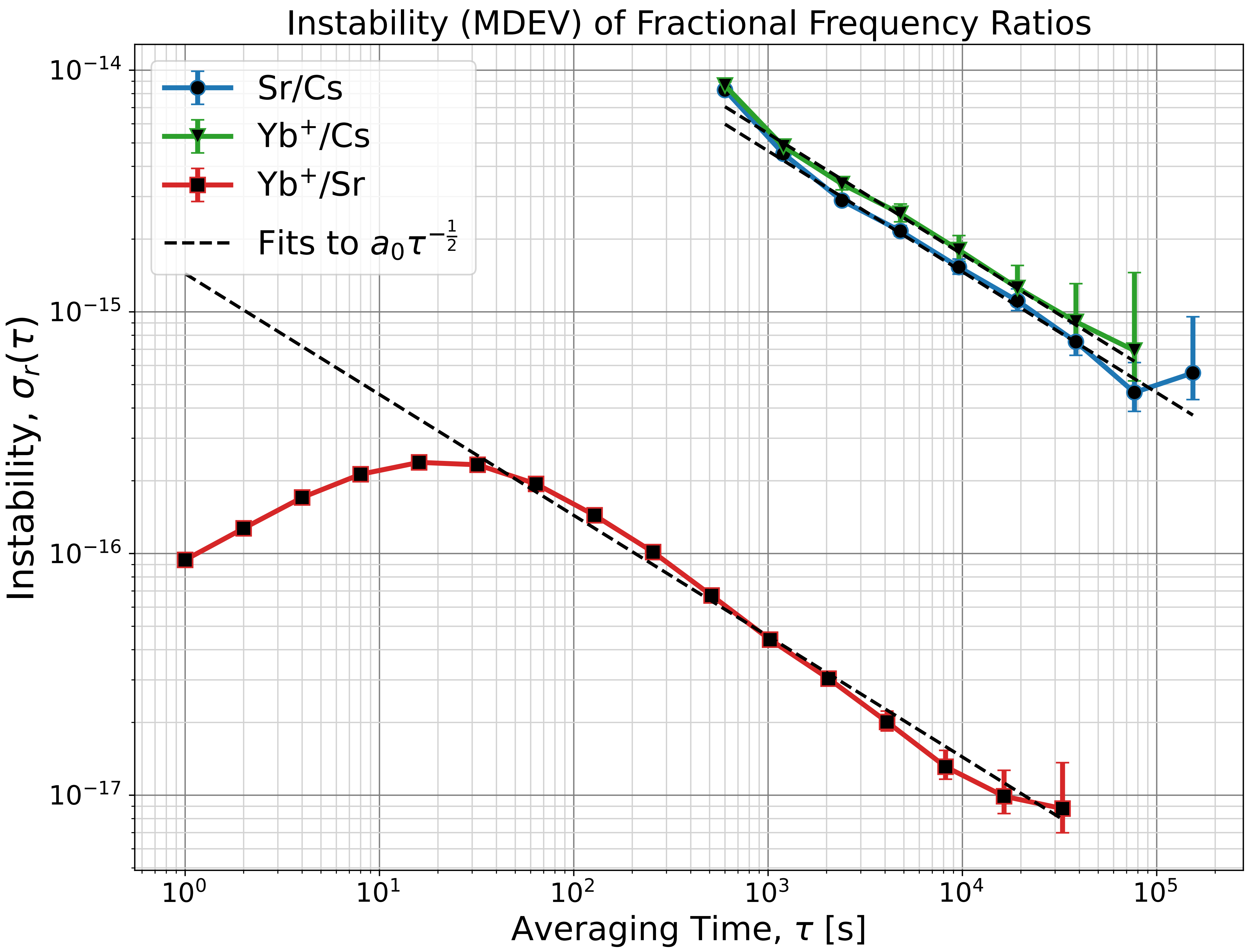

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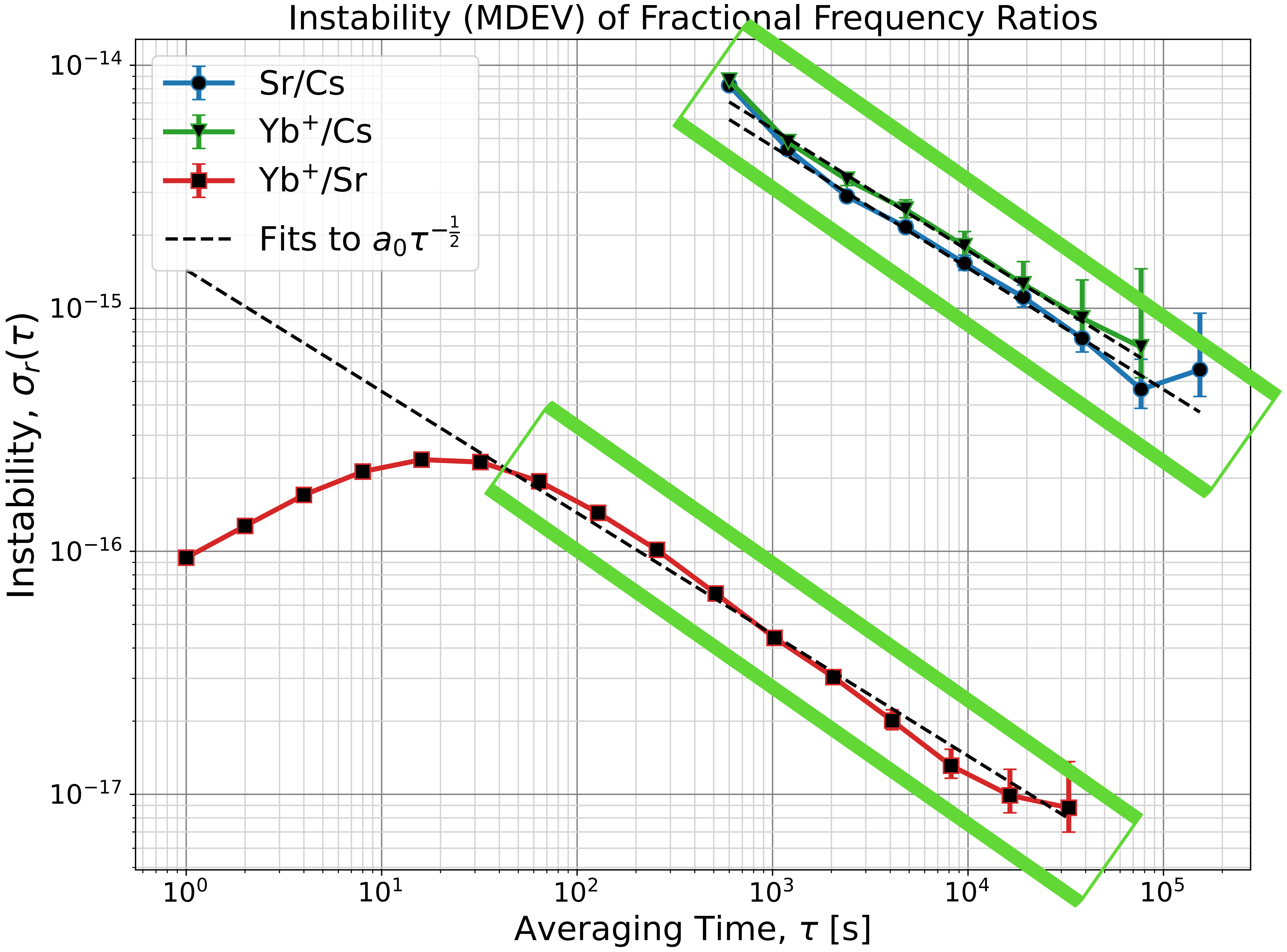

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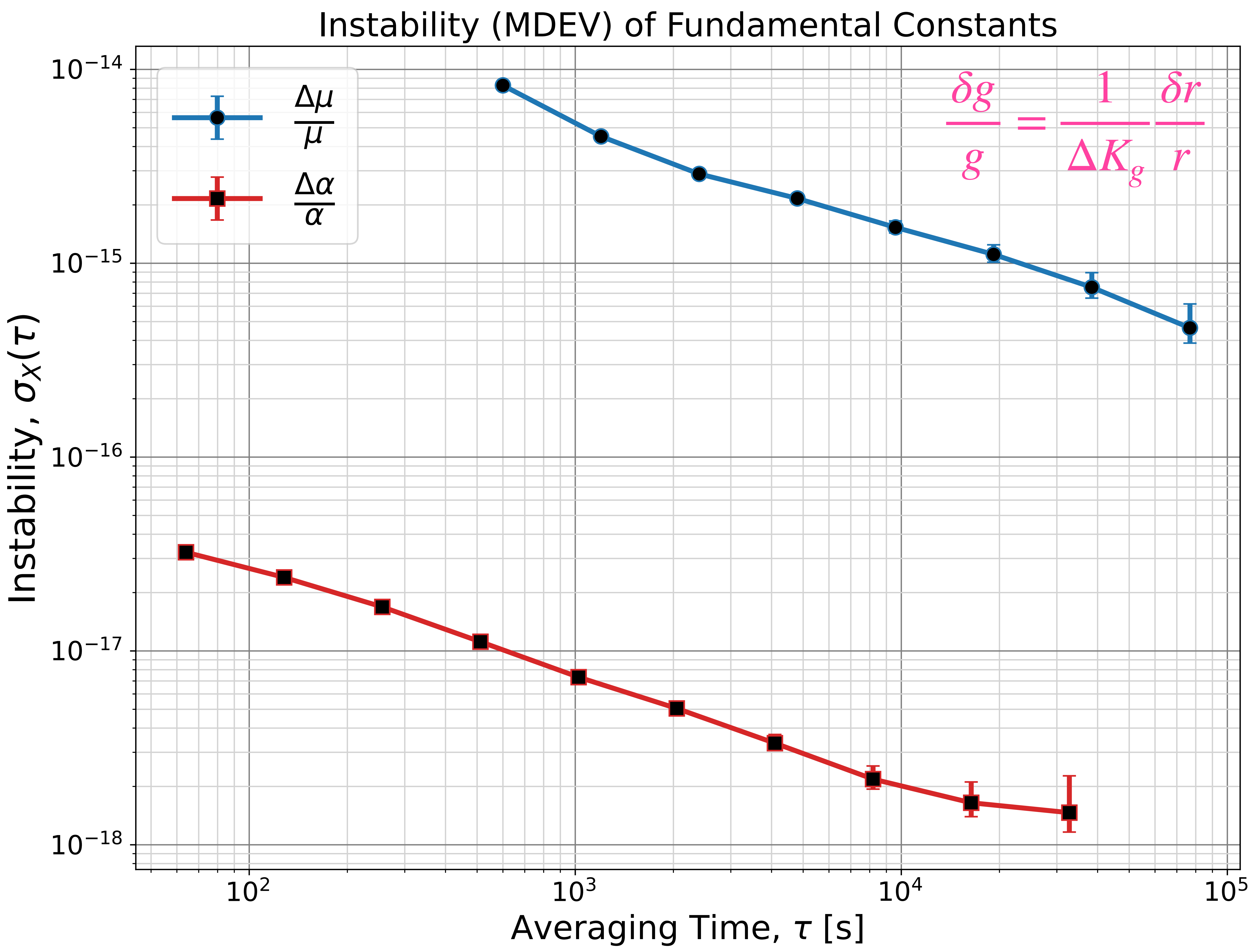
Data characteristic of Gaussian white noise (stat uncertainties dominant)

$\Rightarrow$ **Operating on atomic transition!**

Model-independent constraints



Instabilities translate to bounds on shifts

$$\kappa^n \,|\, d_\gamma^{(n)} \,|\, \sigma_{\phi^n}(\tau) \lesssim 2.3 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$$

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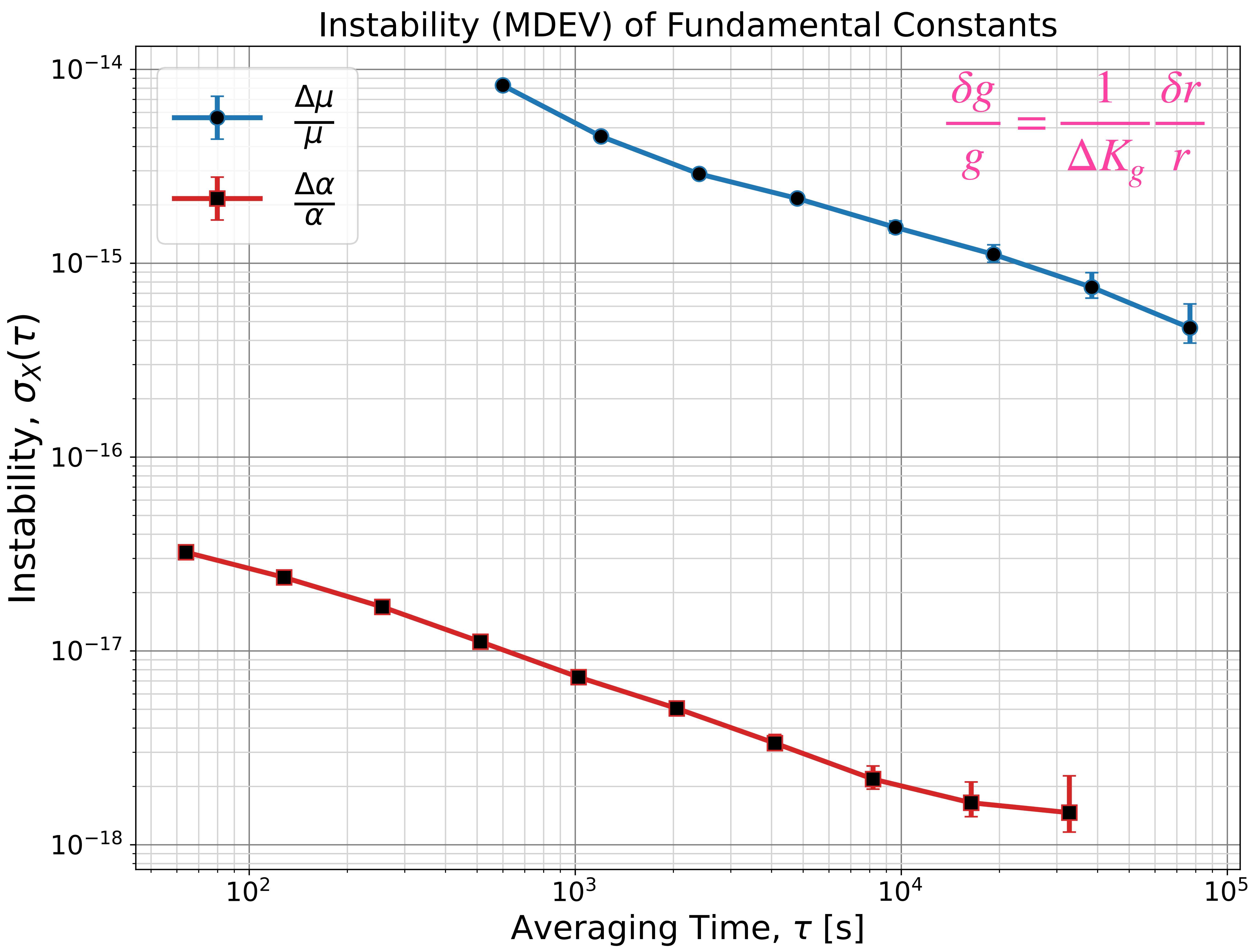

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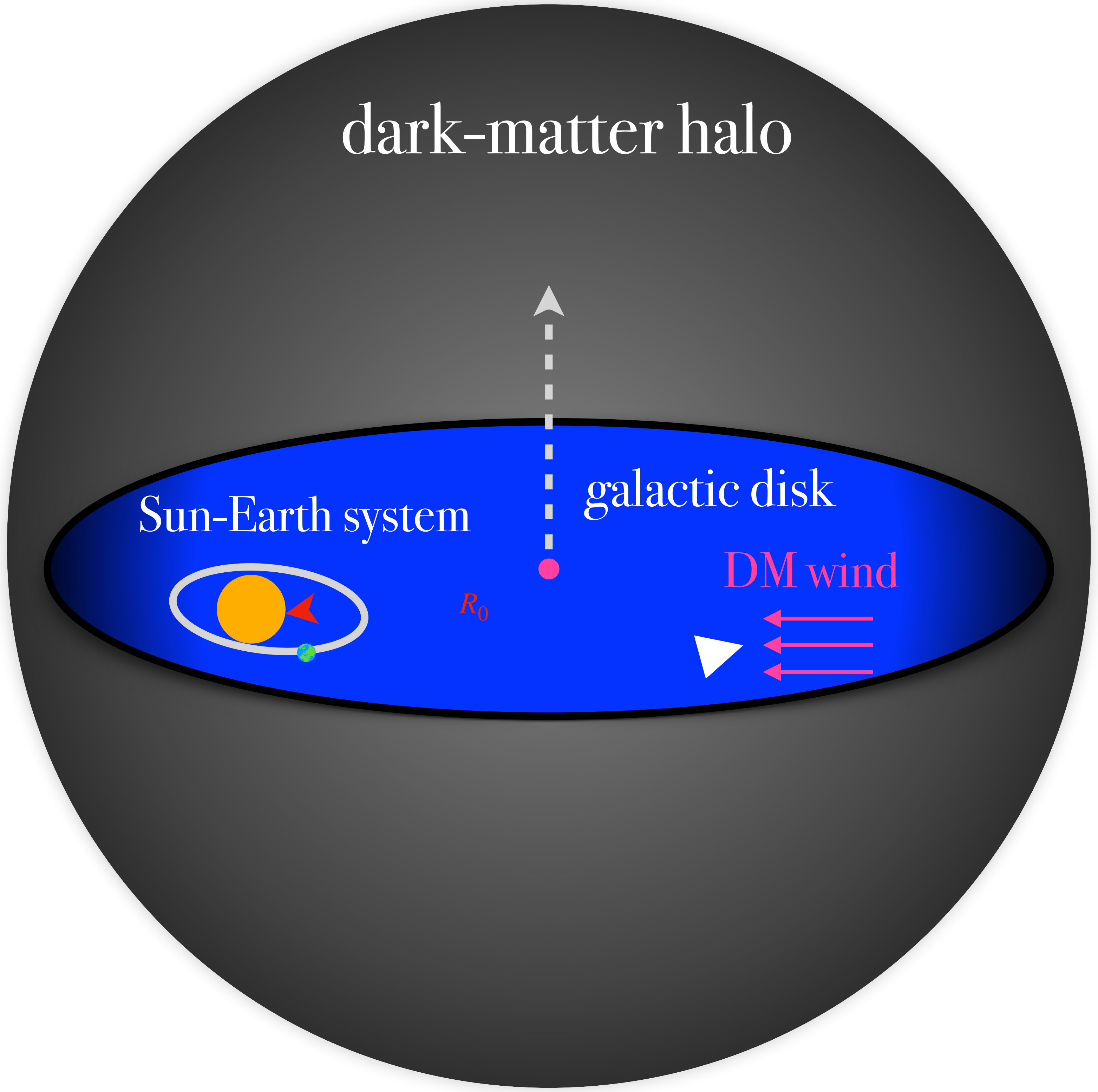
E.g. for two times separated by 1000 seconds

$$\approx\ \kappa^n\,|\,d_\gamma^{(n)}\,|\,[\phi^n(t+\tau)-\phi^n(t)] \lesssim 7\times10^{-18}$$

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

Ultralight DM

$\Delta x \Delta p \sim 1$ $\qquad$ $n \cdot \lambda_{\rm DB}^3 \gg 1$



ULDM = macroscopic coherently oscillating field

$$\phi(t) \approx \phi_0 \cos(m_\phi t) \qquad \boxed{\phi_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}} \qquad \rho_{\rm DM} = \rho_{\rm DM}(R_0) \approx 0.3\ {\rm GeV/cm^3}$$

Dark matter constraints

Because $\frac{\delta r}{r} = \sum_g \Delta K_g d_g^{(n)}(\kappa\phi)^n$ and $\phi(t) \approx \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_\phi}\cos(m_\phi t)$ $(m_\phi = 2\pi f_\phi)$

Map amp. spectrum onto magnitude of oscillations for lowest-order ($n = 1{,}2$) ints.

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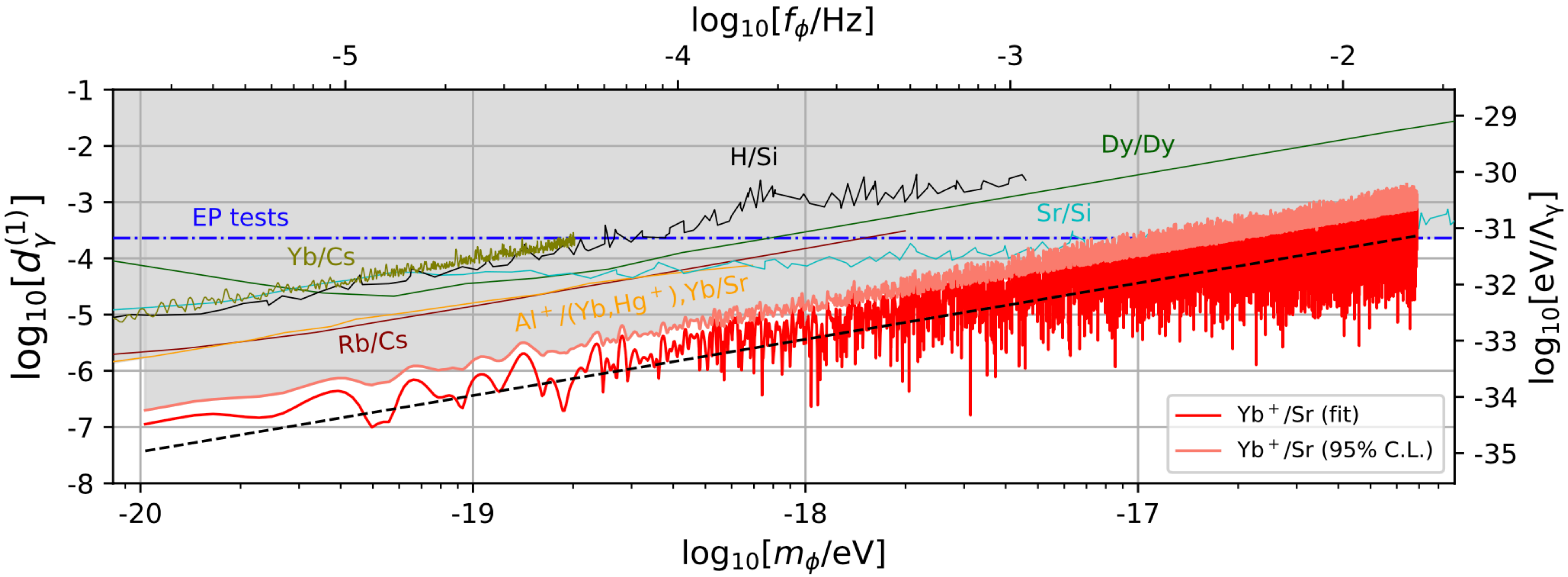

$n = 1\ (f = f_\phi)$

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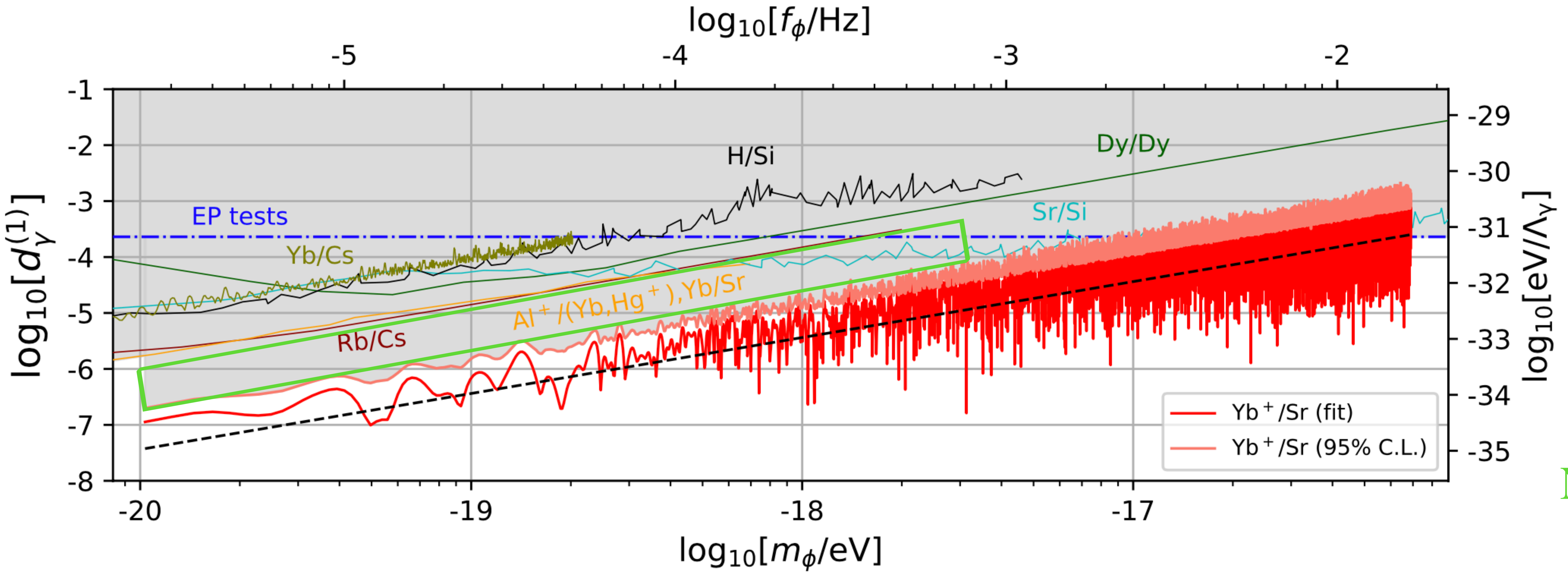

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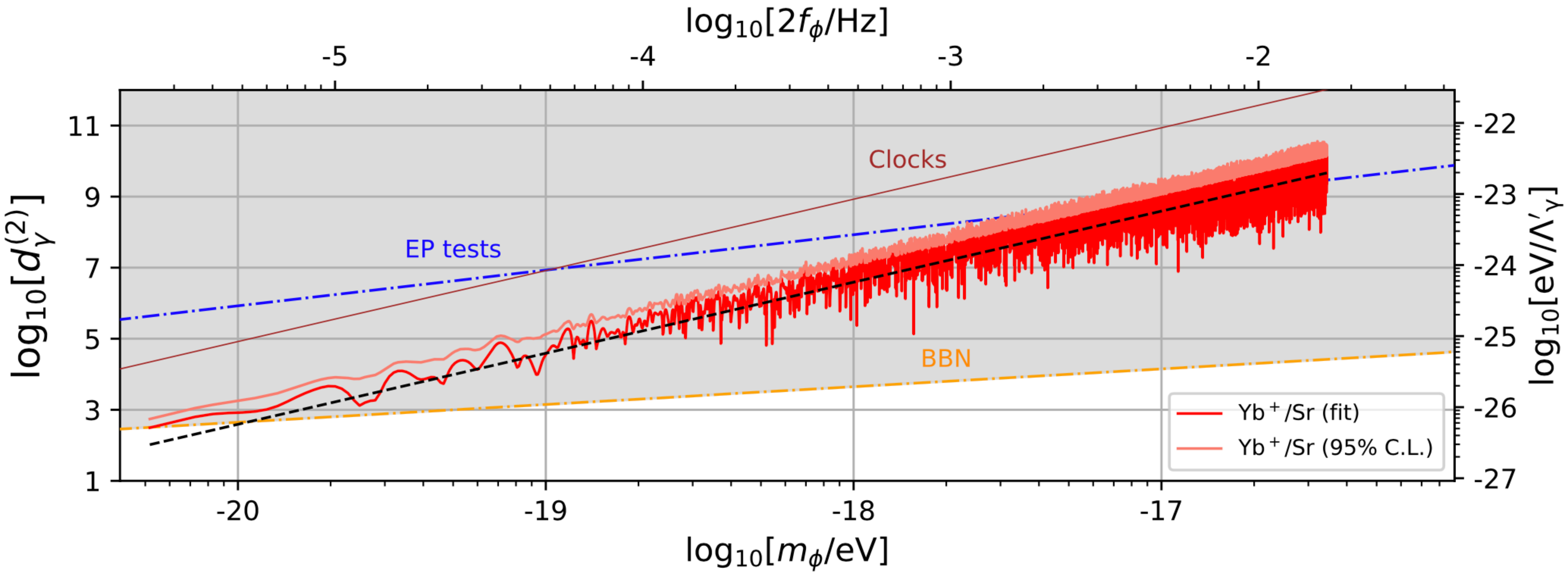
New parameter space probed

Dark matter constraints

For $n = 2$

$$\left.\frac{\delta r}{r}\right|_{\text{osc.}} \propto \frac{1}{M_P^2}\cos(2m_\phi t) \rightarrow f = 2f_\phi$$



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*Constraints on electron/gluon and quark/gluon parameters also studied (see paper)

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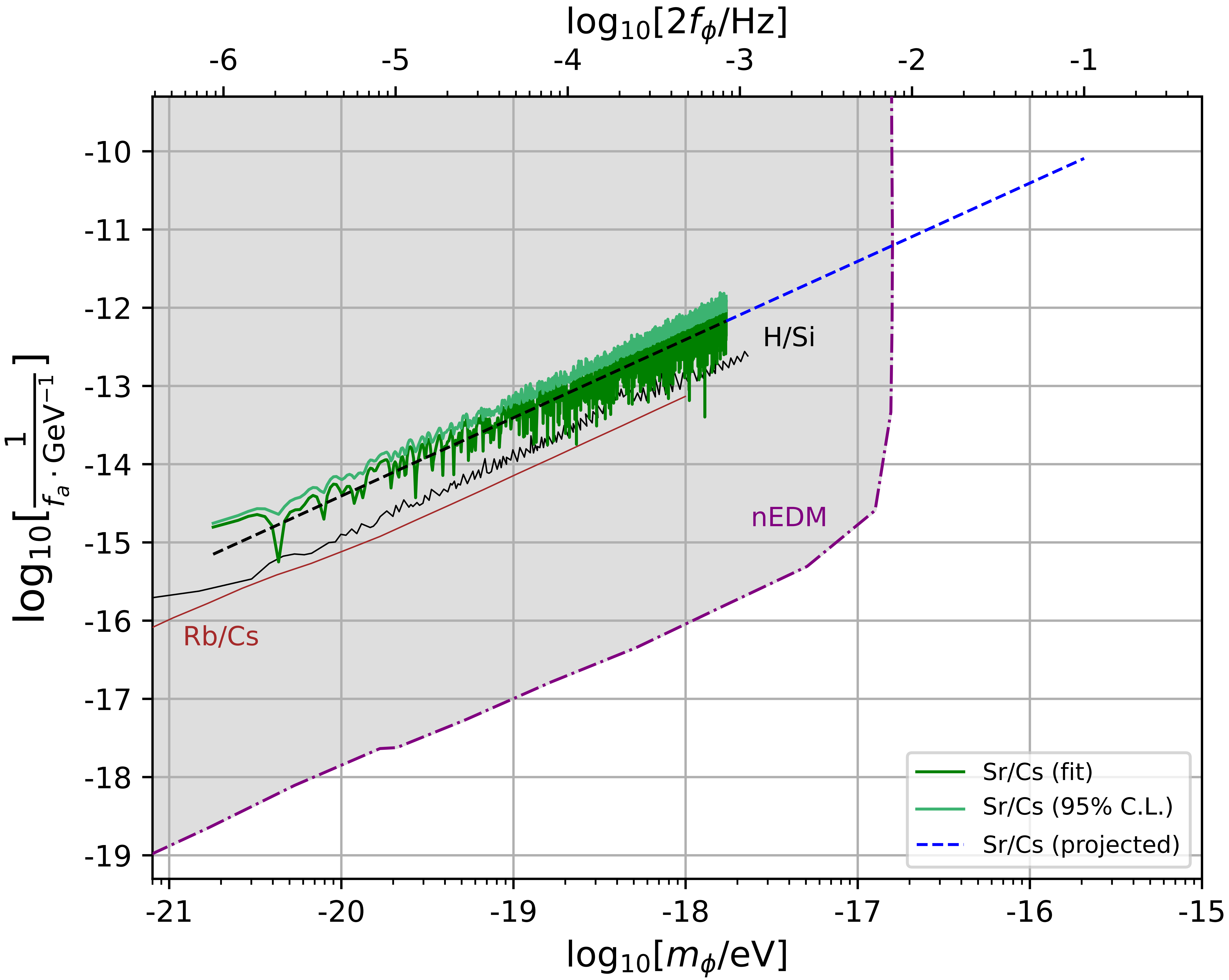

Kim, Perez, 2205.12988

Clocks also probe axion-like particles

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

Induces oscillations in nucleon mass and nuclear g factor

transmits to sensitivity from Sr/Cs **ratio**

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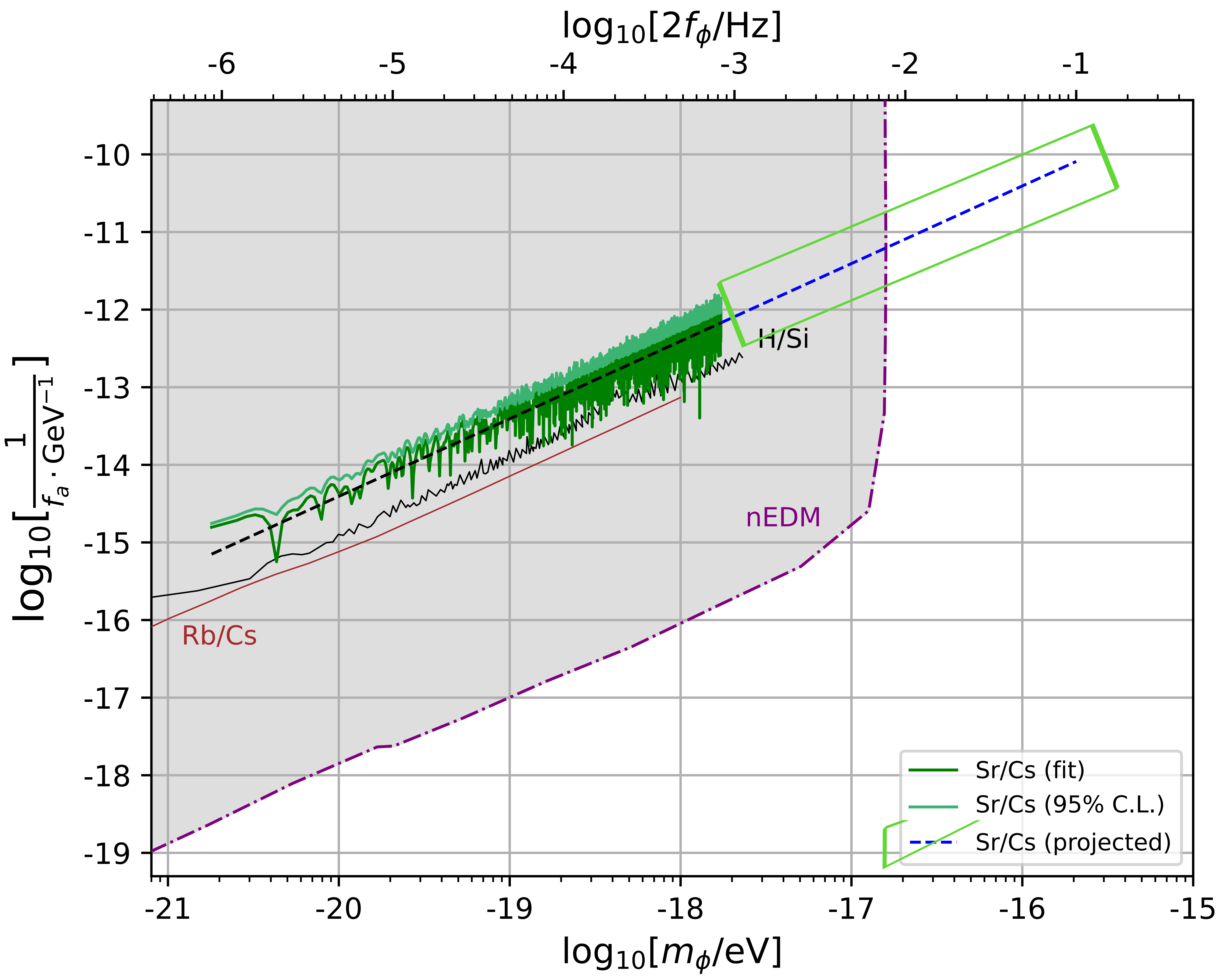

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Recap and conclusions

Ultralight bosons cover a wide range of well-motivated new physics

- ☐ Lots of recent theory activity (ULDM, ALPs, …)
- ☐ Experimental capabilities rapidly increasing (c.f. "quantum sensors")

New constraints from NPL data

- ☑ Model-independent constraints from instabilities of Yb^+, Sr, and Cs clocks
- ☑ New constraints on scalar and axion-like ULDM

Excellent outlook

- ☐ Longer datasets give access to *lighter* masses ($T \sim 1/f \sim 1/m$)
- ☐ New clocks with larger K factors $\Rightarrow$ drive exclusion regions *downward*