Constraining ultralight oscillators with atomic clocks

Nathaniel Sherrill
University of Sussex

Based on: arXiv:2302.04565

In collaboration w/Xavier Calmet and National Physical Laboratory (NPL)

Joint Theory Seminar
NBI, 11 May 2023

Fundamental constants

There are two types of physical constants

- **Dimensionful:** $G, \hbar, c, \ldots$
- **Dimensionless:** $\alpha, \mu = m_e/m_p$, CKM matrix elements, …

The latter type are convention independent ⇒ “fundamental constants”

Standard Model

$$\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}^j\gamma^\mu D_\mu\psi^j + \left(\bar{\psi}^i_L V_{ij}\Phi\psi^j_R + \text{h.c.}\right) - |D_\mu\Phi|^2 - V(\Phi)$$

Parametrized by 18 dimensionless constants

(+1 more for θ_{QCD}, + 7 more for massive νs, …)

General Relativity

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

No dimensionless constants!

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They *cannot* be calculated, must be measured!

Fundamental constants

FCs associated with deep questions

Eddington, Dirac, Jordan, Teller, Fierz, … many others

- How many are there?
- Can they be explained dynamically (e.g. strings)?
- Intuition of measured values? Hierarchies?
- Are there patterns between them?
- **Are they "only" numbers, or more generally, functions of spacetime?**

"Large numbers hypothesis"

P. A. M. Dirac, Nature 139, 323 (1937)

Explicit or apparent fundamental constant variations can be described by very light bosons interacting with the SM

$$\mathscr{L}_{\text{int},\phi} \supset -\frac{1}{4} g(\phi) F_{\mu\nu} F^{\mu\nu}$$

$$\alpha \to \alpha(\phi)$$

Ultralight bosons

Integer-spin fields with very small masses

$$10^{-33}\ \text{eV} \lesssim m \lesssim 1\ \text{eV}$$

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J. Uzan, Living Rev. Rel. 14, 2 (2011)

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  - scalars & axion-like particles
  - dark photons, dark spin-2

  } $10^{-22}\ \text{eV} \lesssim m \lesssim 1\ \text{eV}$

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Recent white papers

Axion DM

Ultralight spin-0,1 DM

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Parametrize varying constant $g(x^\mu)$ for low-energy probes **arXiv:2302.04565**

$$g(x^\mu) = g_0 + \frac{1}{\Lambda}\phi(x^\mu) + \cdots$$

(c.f. $g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$)

couplings to fields $g_0 \to g(\phi)$

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E.g. Bekenstein electrodynamics

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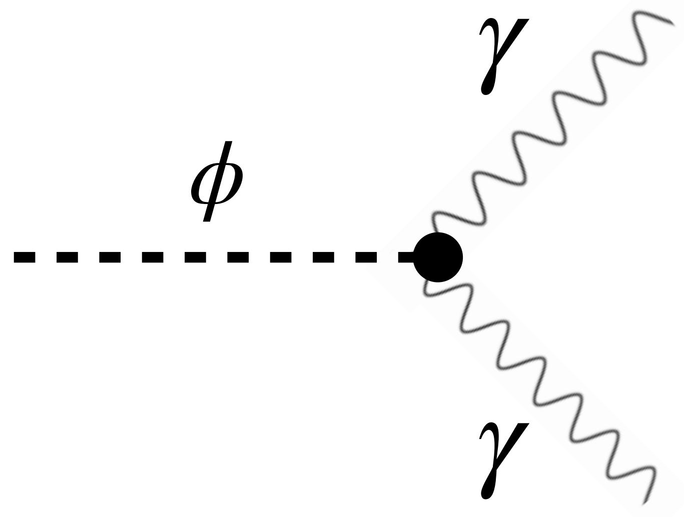
J. D. Bekenstein, Phys. Rev. D 25, 1527 (1982)

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



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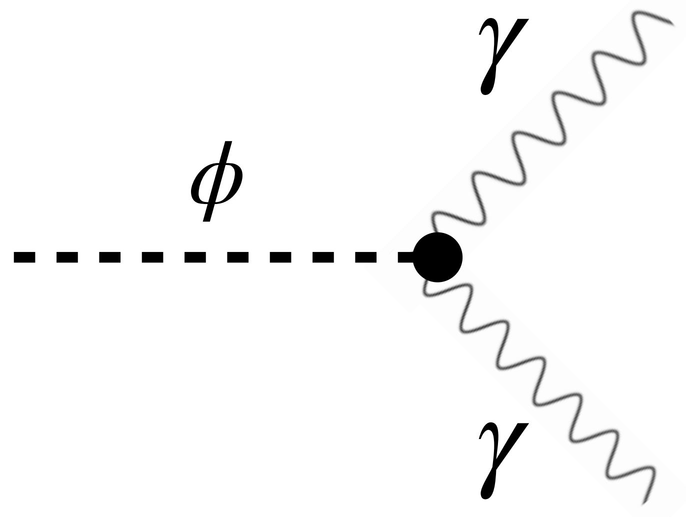
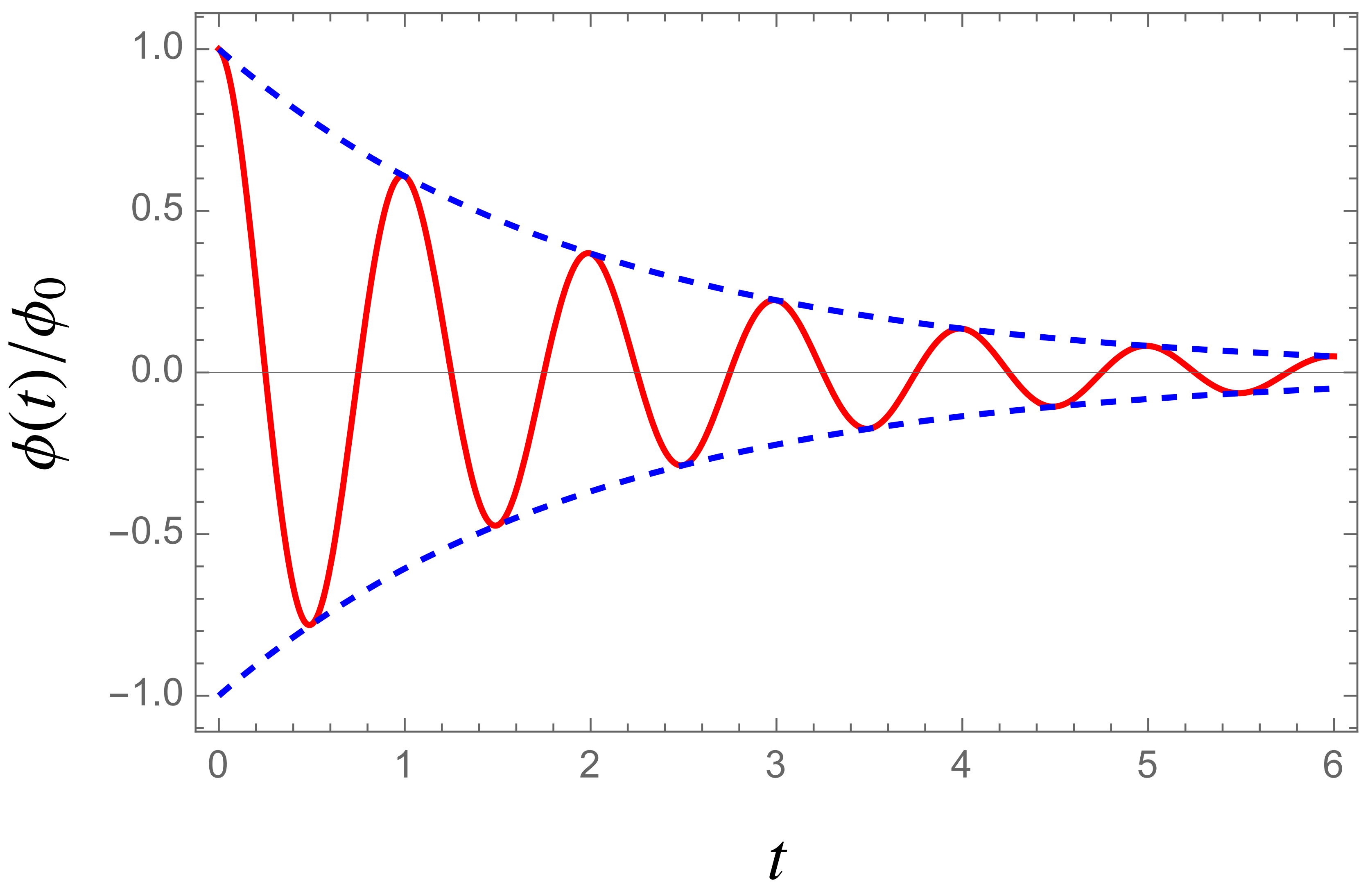


Description in terms of conventional theories with new interactions

Effective description

Primarily interested in temporal variations

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



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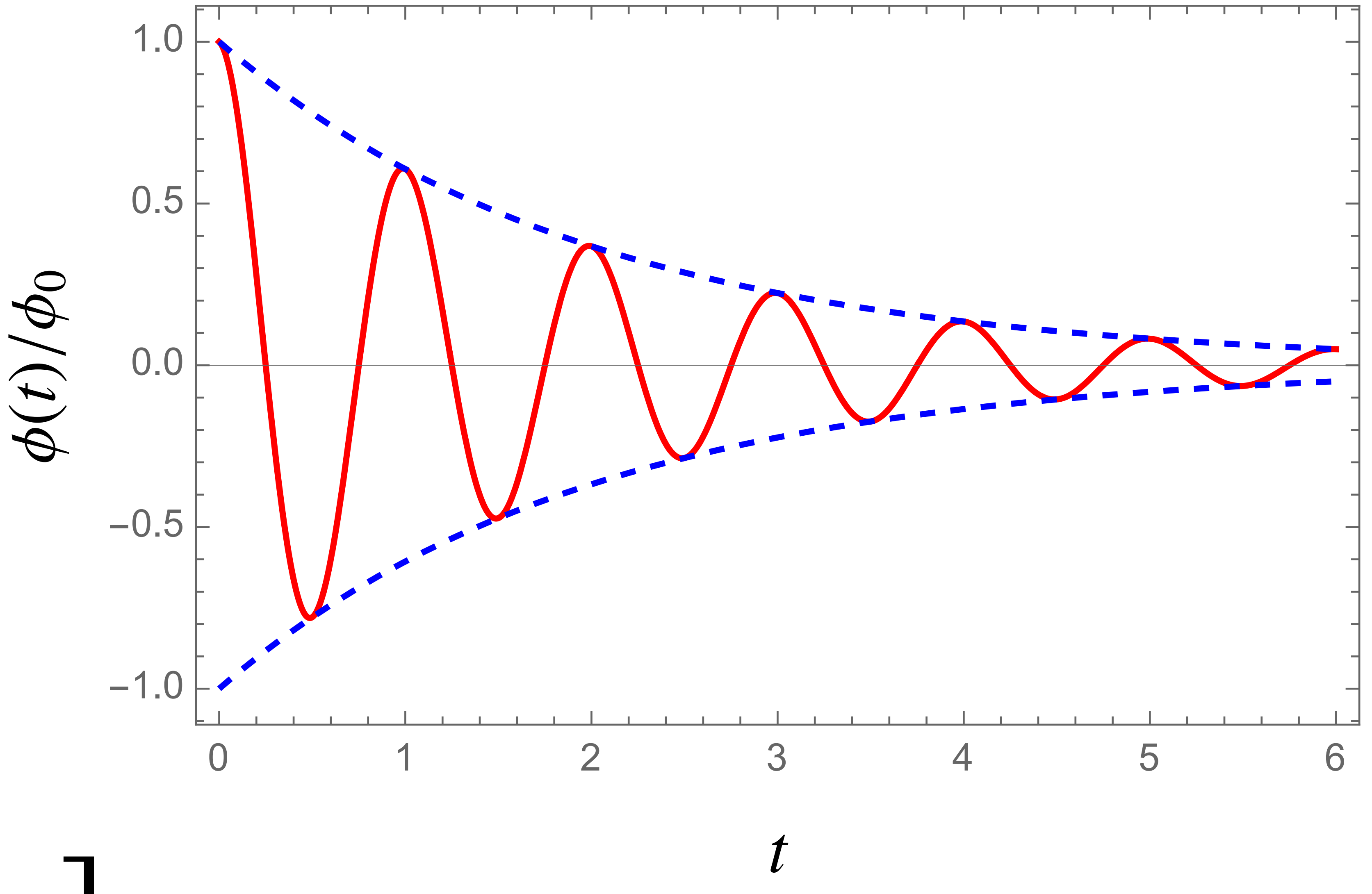

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controls frequency of oscillations

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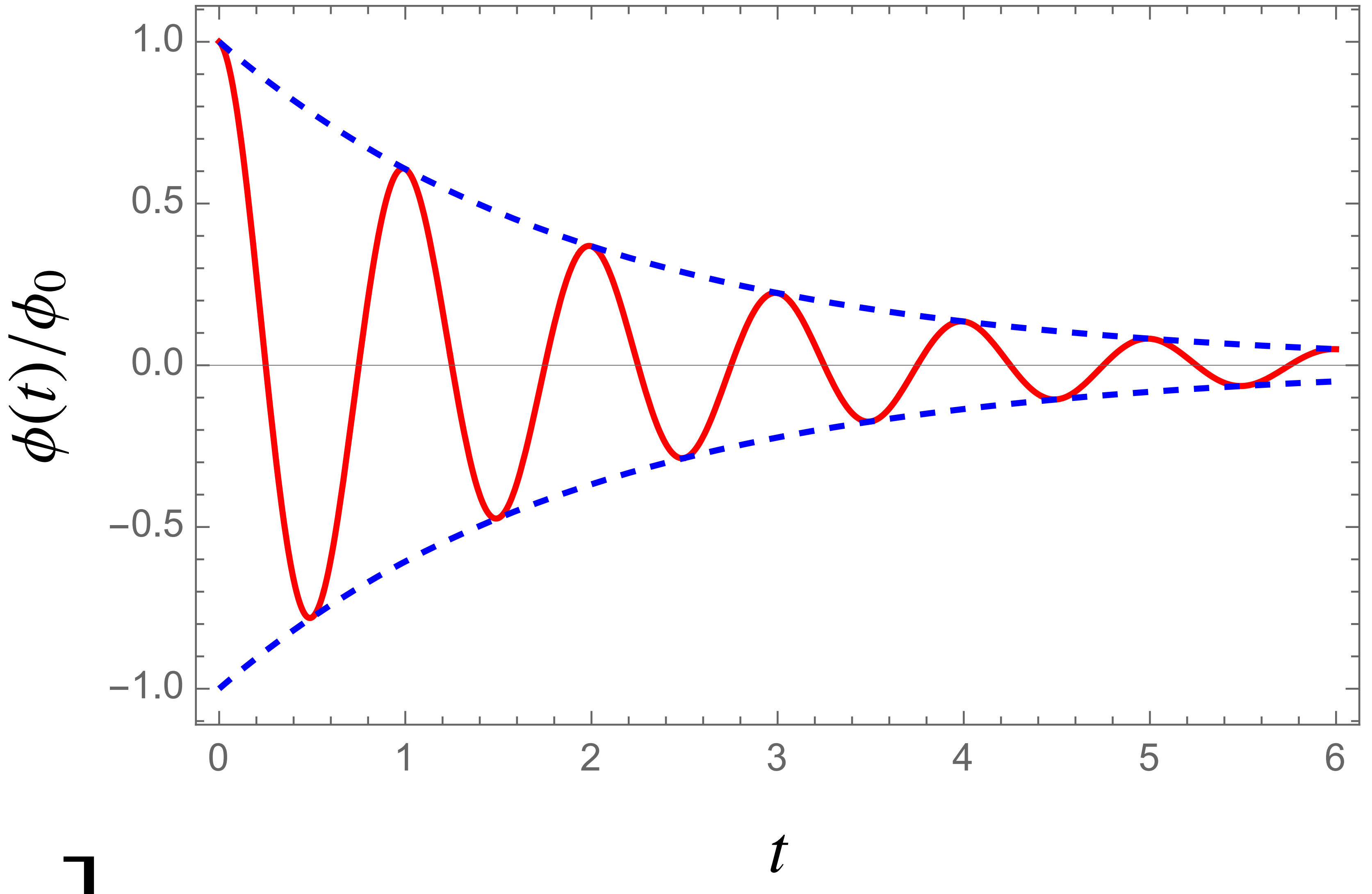

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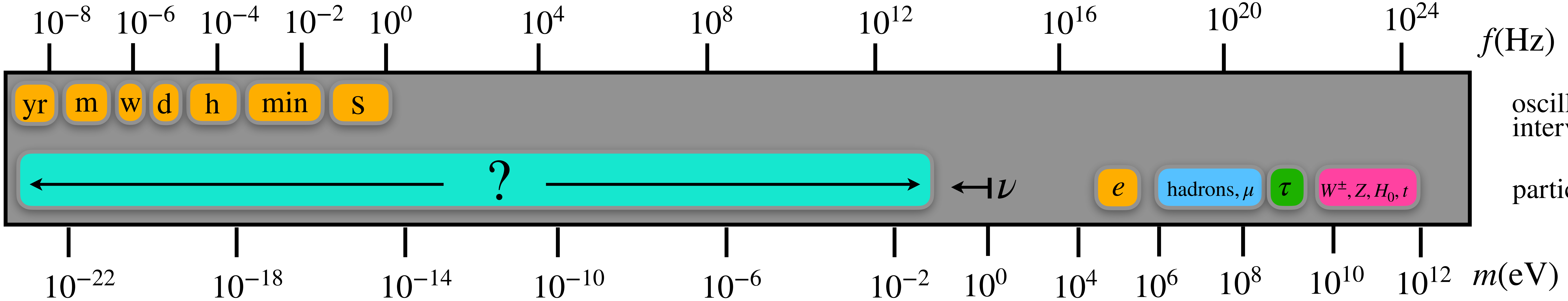

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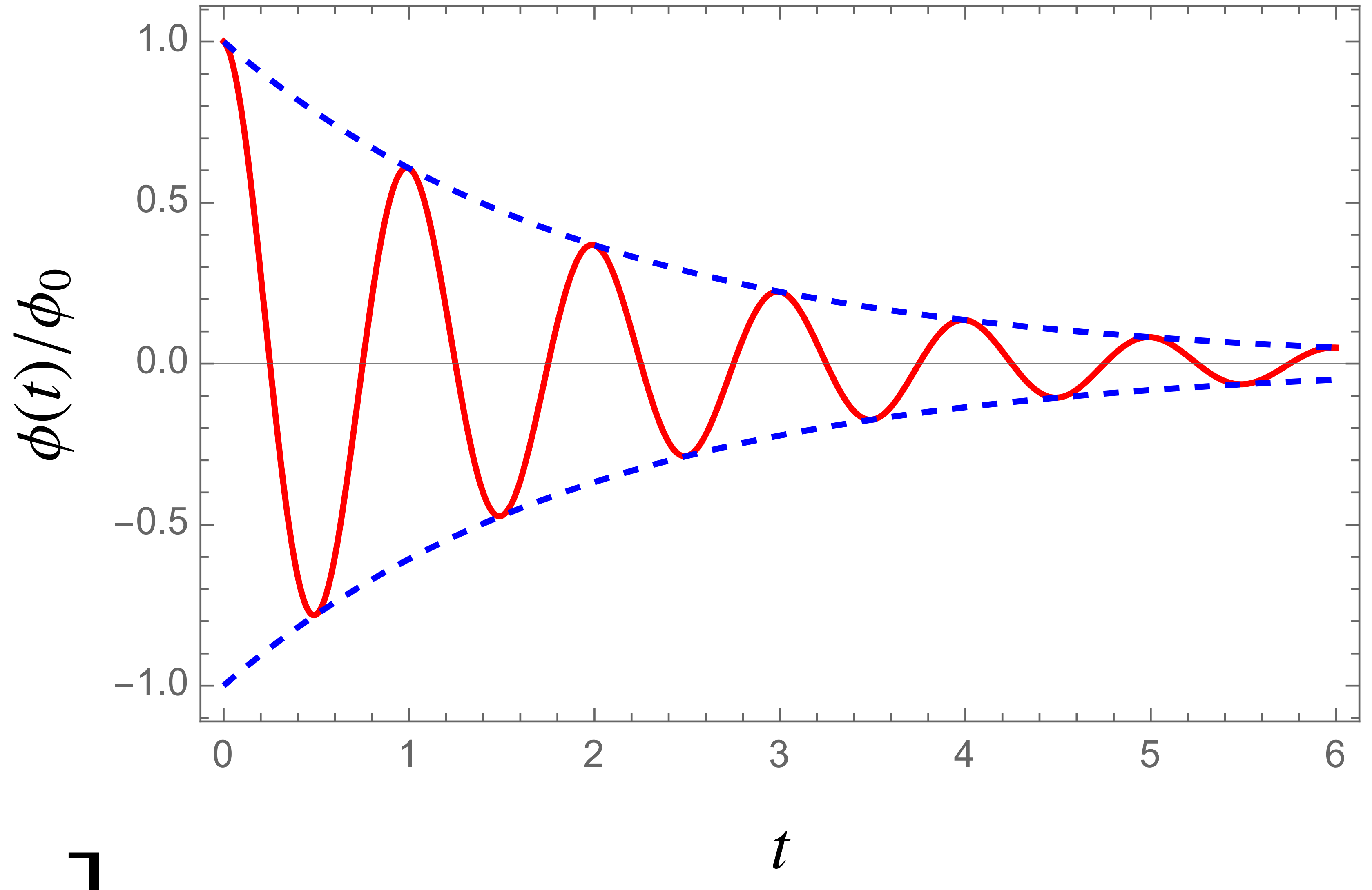

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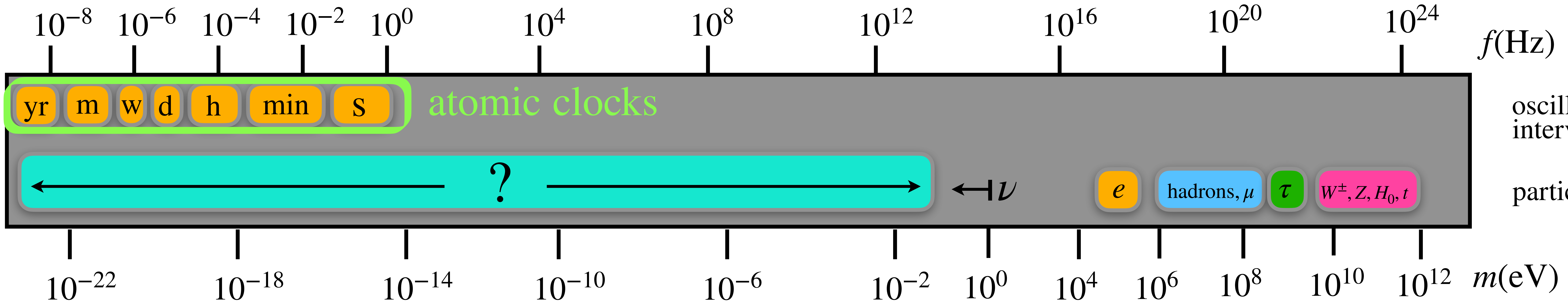

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Search for ϕ couplings to SM

$$S = \int d^4x \sqrt{-g}\,\mathscr{L}_{\mathrm{int},\phi} \qquad \mathscr{L}_{\mathrm{int},\phi} \supset -\left(\frac{\phi}{\Lambda}\right)^n \cdot \mathscr{O}_{\mathrm{SM}}$$

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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

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$$m_j(\phi) = m_j\left(1 + d_{m_j}^{(n)}(\kappa\phi)^n\right) \Rightarrow \frac{\delta m_j}{m_j} = d_{m_j}^{(n)}(\kappa\phi)^n \quad (j = e, u, d)$$

$$\Lambda_{\mathrm{QCD}}(\phi) = \Lambda_{\mathrm{QCD}}\left(1 + d_g^{(n)}(\kappa\phi)^n\right) \Rightarrow \frac{\delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} = d_g^{(n)}(\kappa\phi)^n$$

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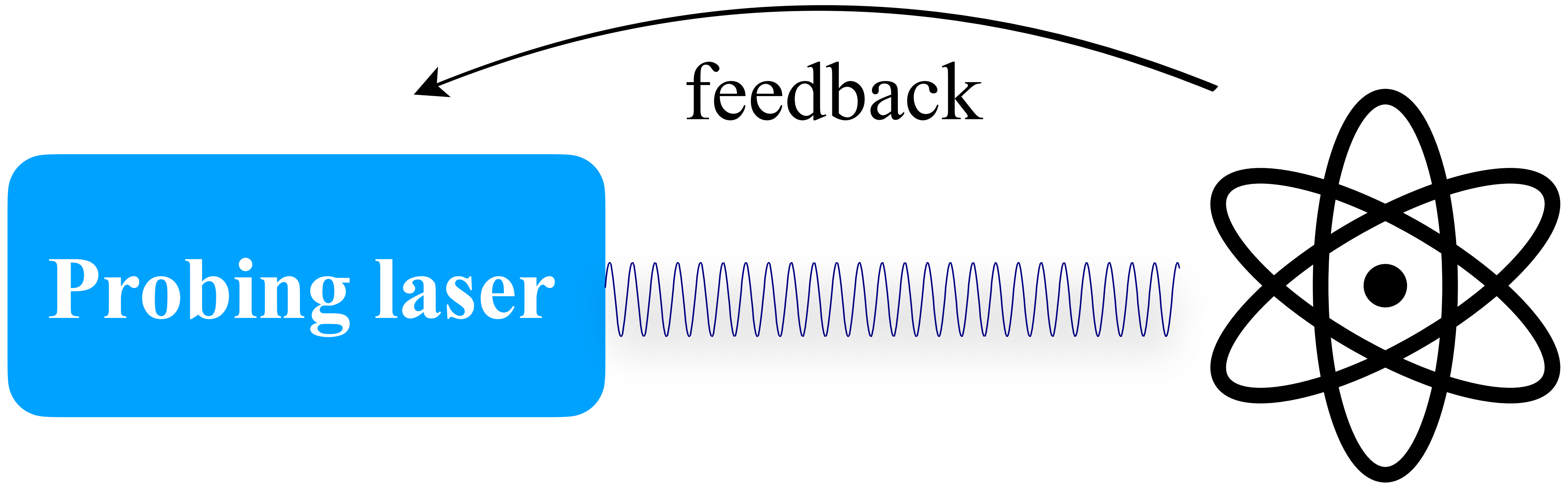
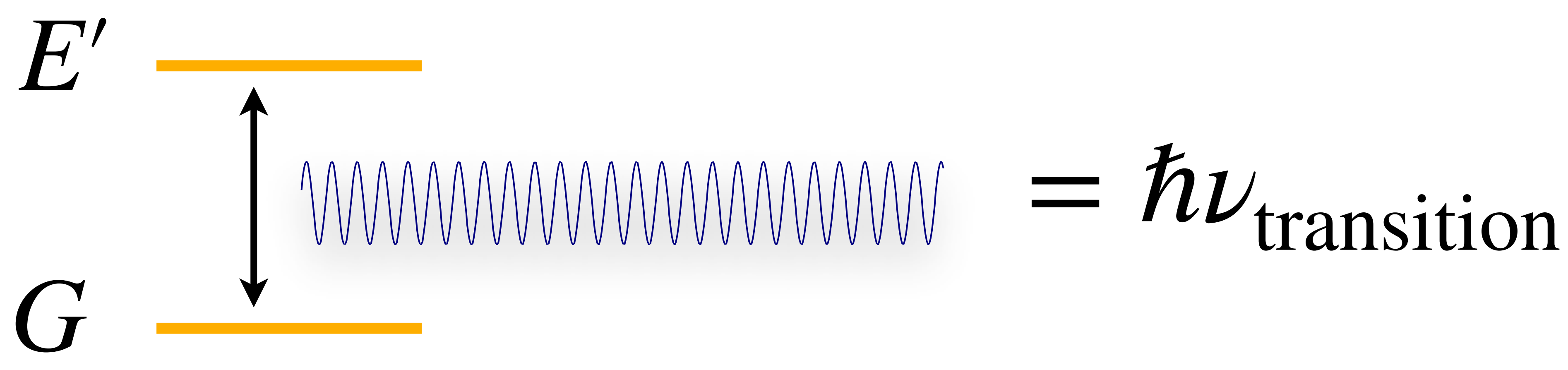
...but how does one measure with clocks?

Atomic clocks

Atomic clocks count cycles of EM radiation emitted from suitable transitions





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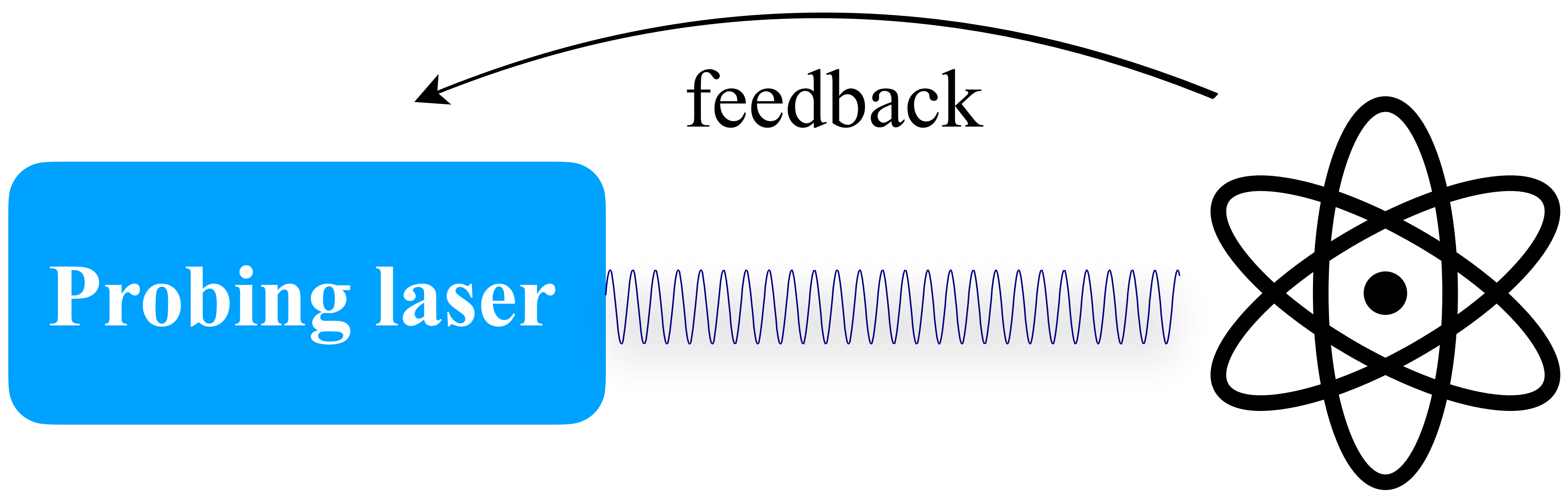

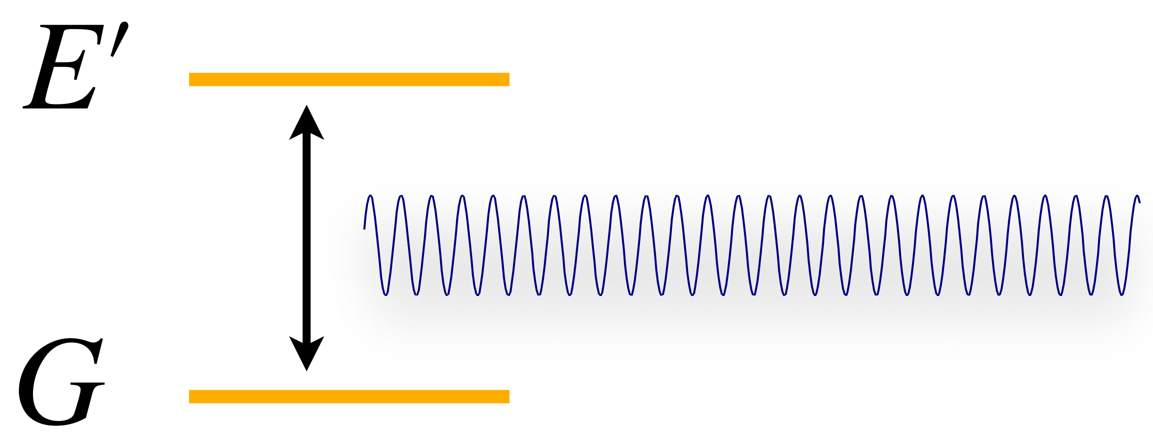

$= \hbar\nu_{\text{transition}}$

E.g. $\left.\frac{\delta\nu}{\nu}\right|_{\mathrm{Yb}^+} \approx 10^{-18}$

"Off by 1 second after $T_{\text{Universe}} \approx$ 14 billion yr"

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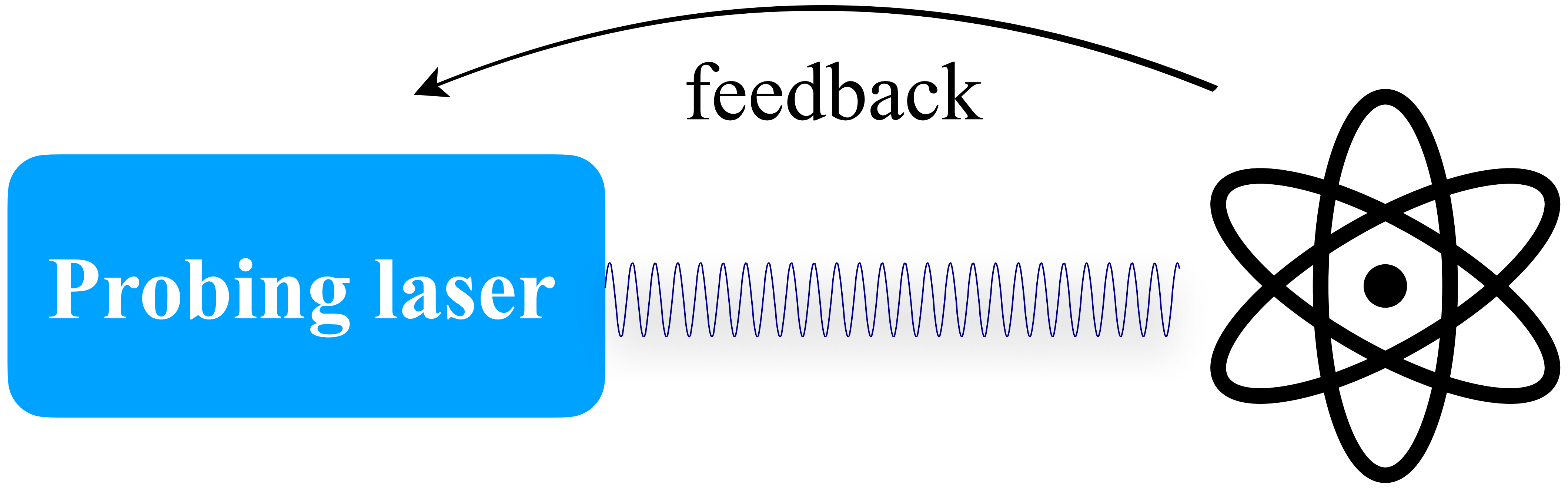

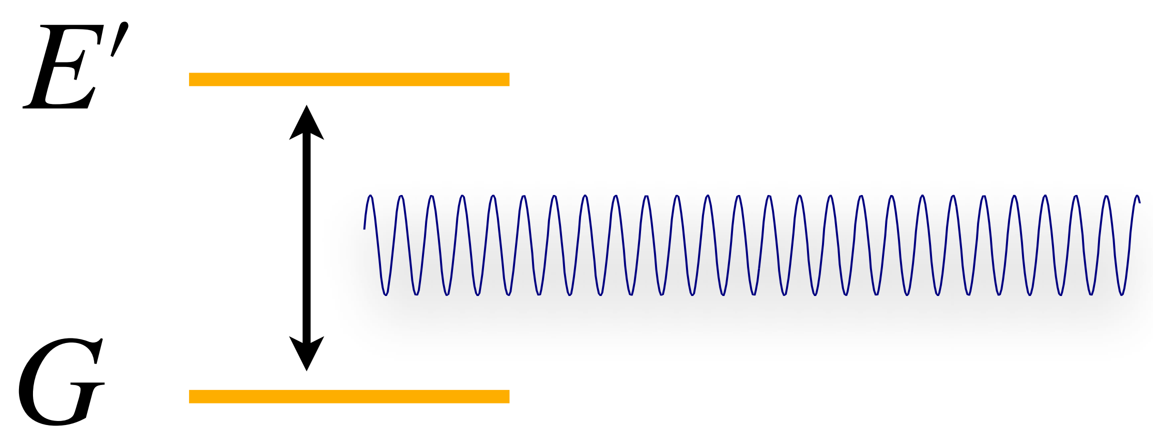

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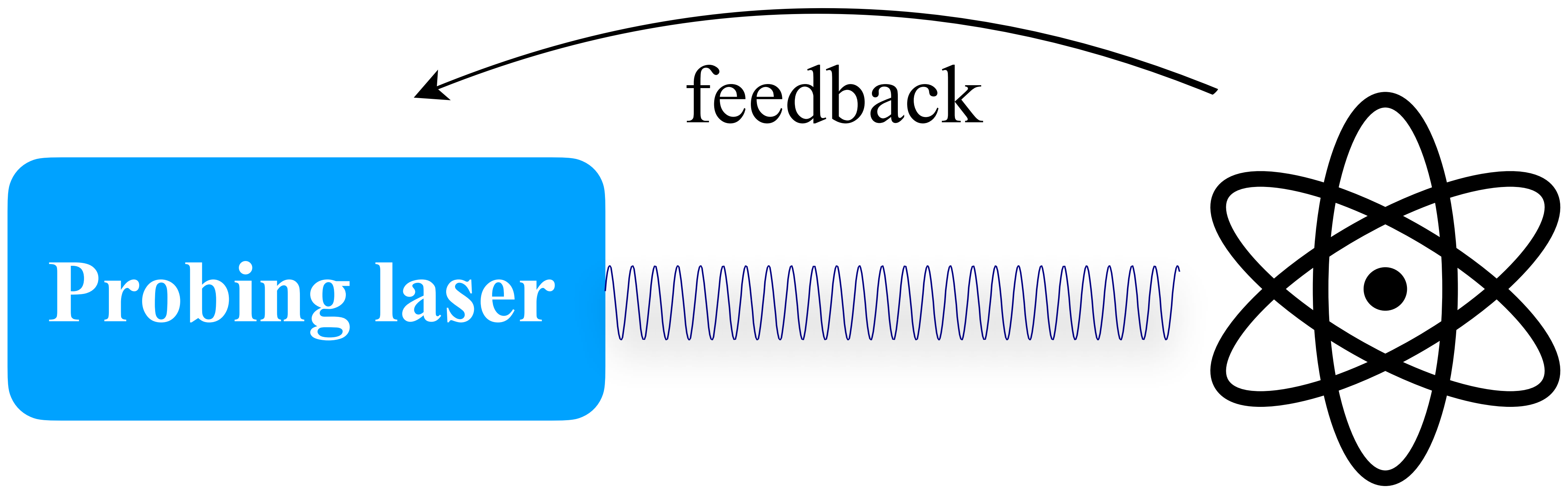

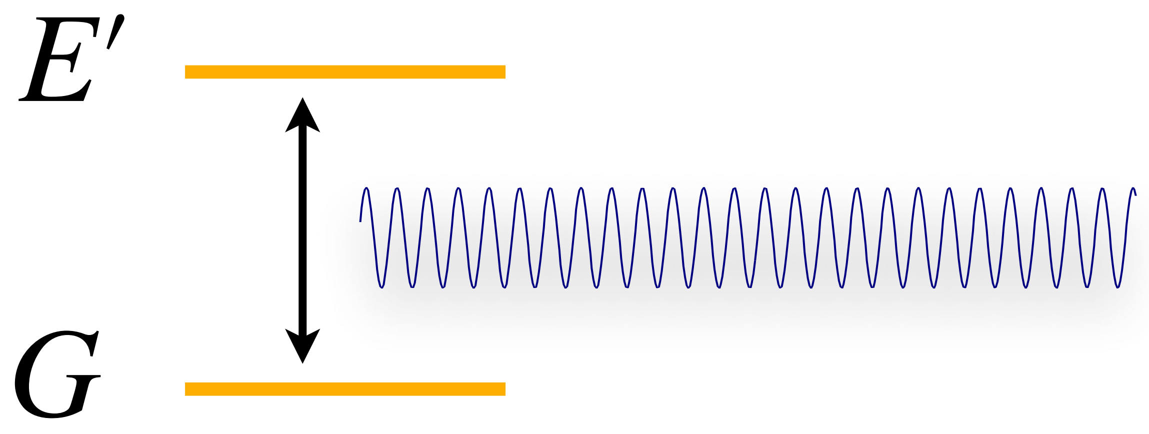

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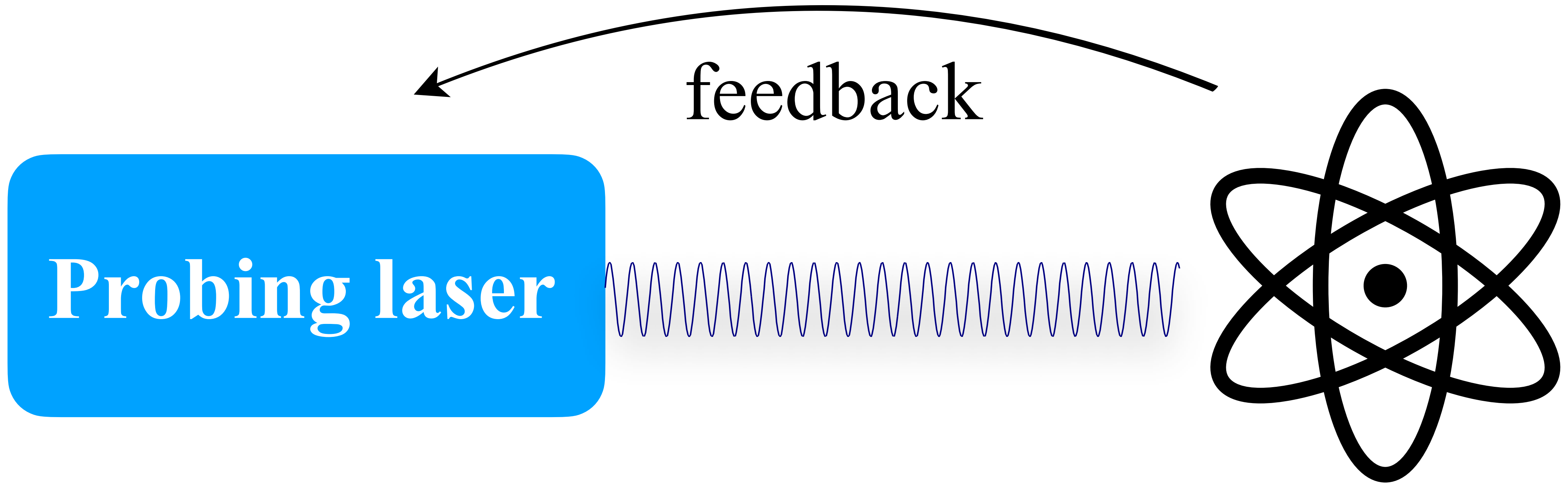

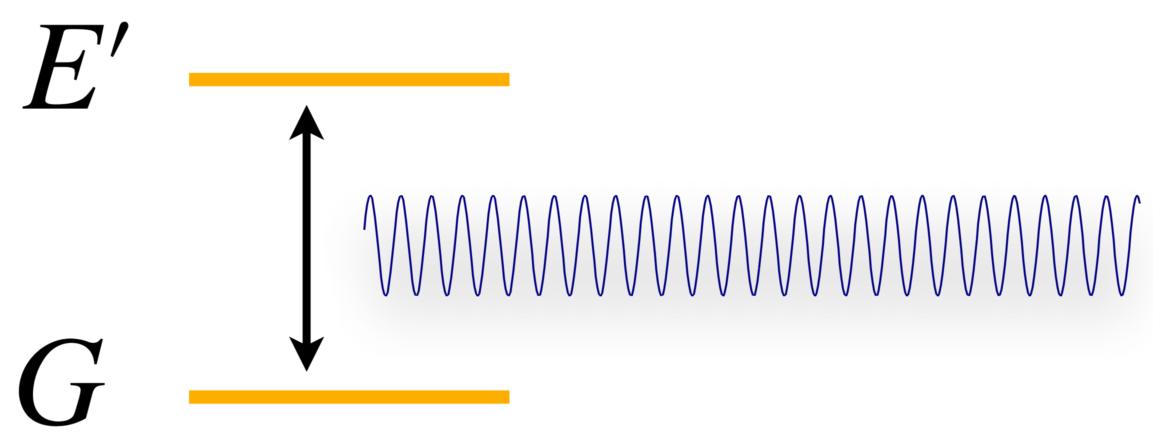

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"sensitivity factor"
dependent on atom/transition

V.V. Flambaum, V. A. Dzuba, Can. J. Phys. 87, 25 (2009)

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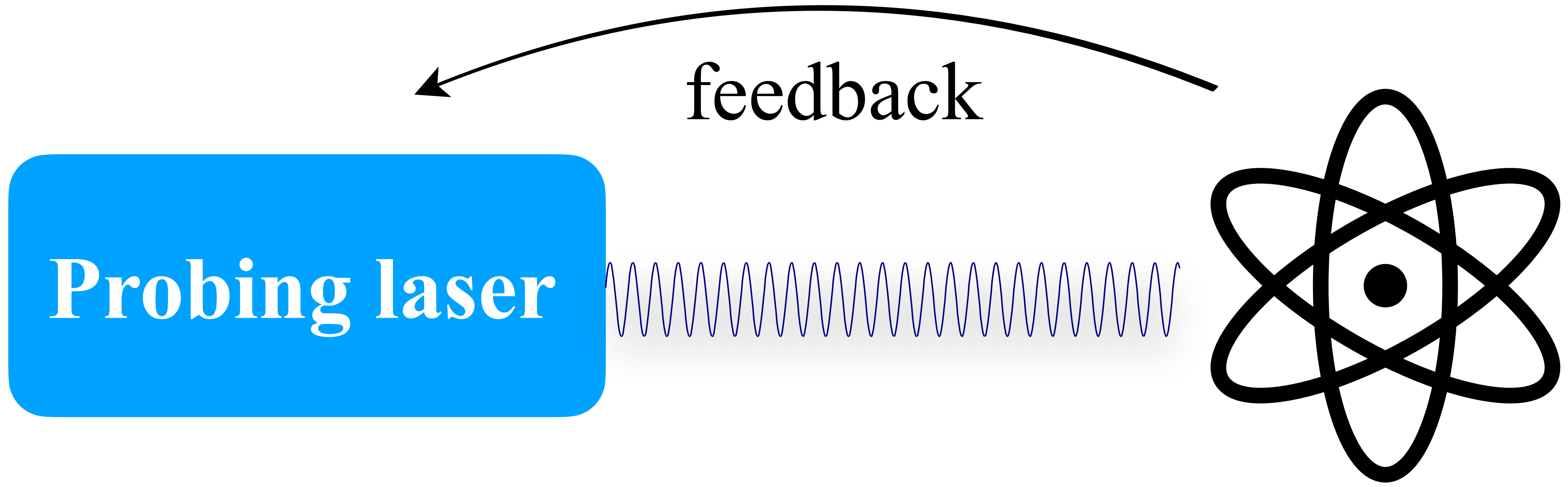

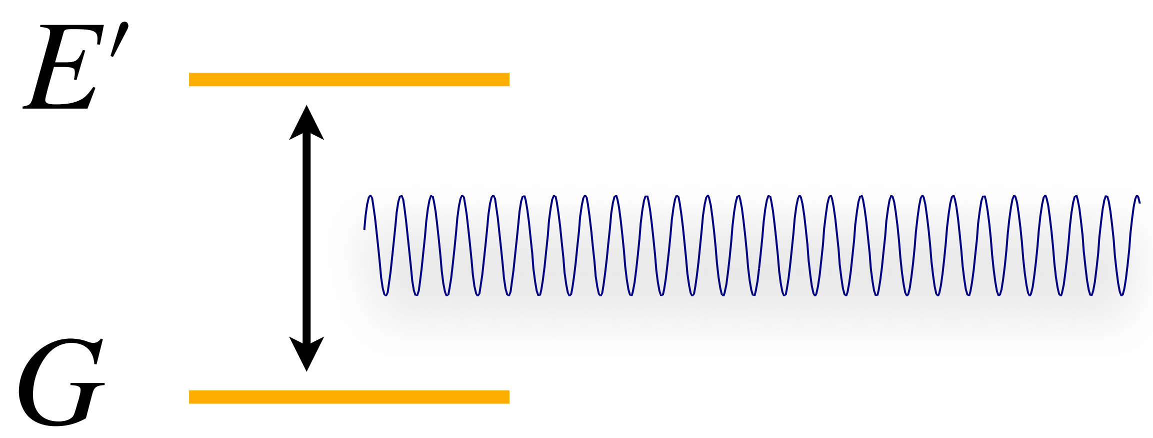

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Measurements involve *comparisons*

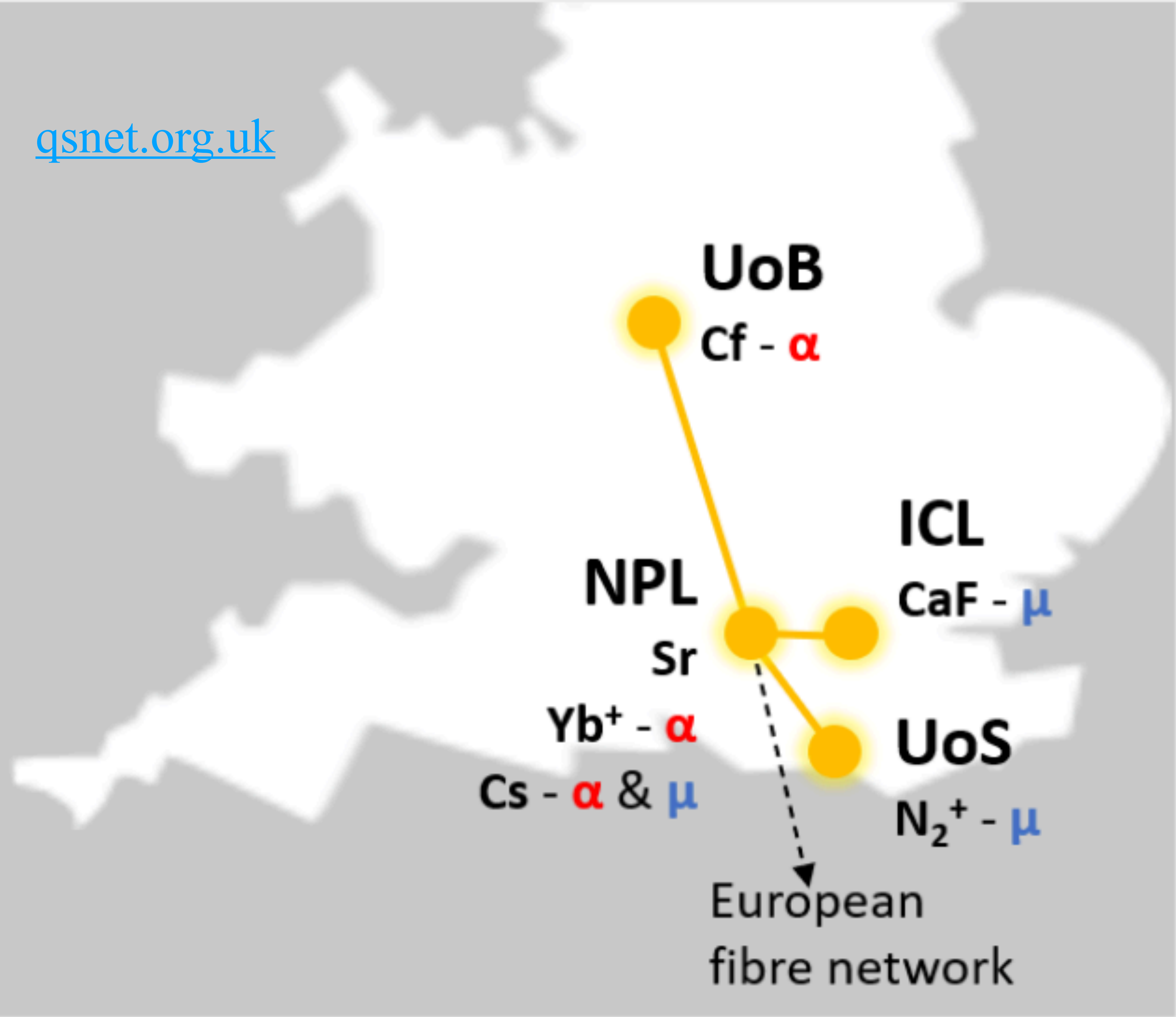
- Need reference that has distinct sensitivity
- $r = \nu_1/\nu_2$ is dimensionless observable
- *Difference* $\Delta K_{1,2}$ is relevant

QSNET

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

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

qsnet.org.uk



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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 (Yb+, Sr, Cs)

Under construction (CaF, N2+, Cf15+, Cf17+)

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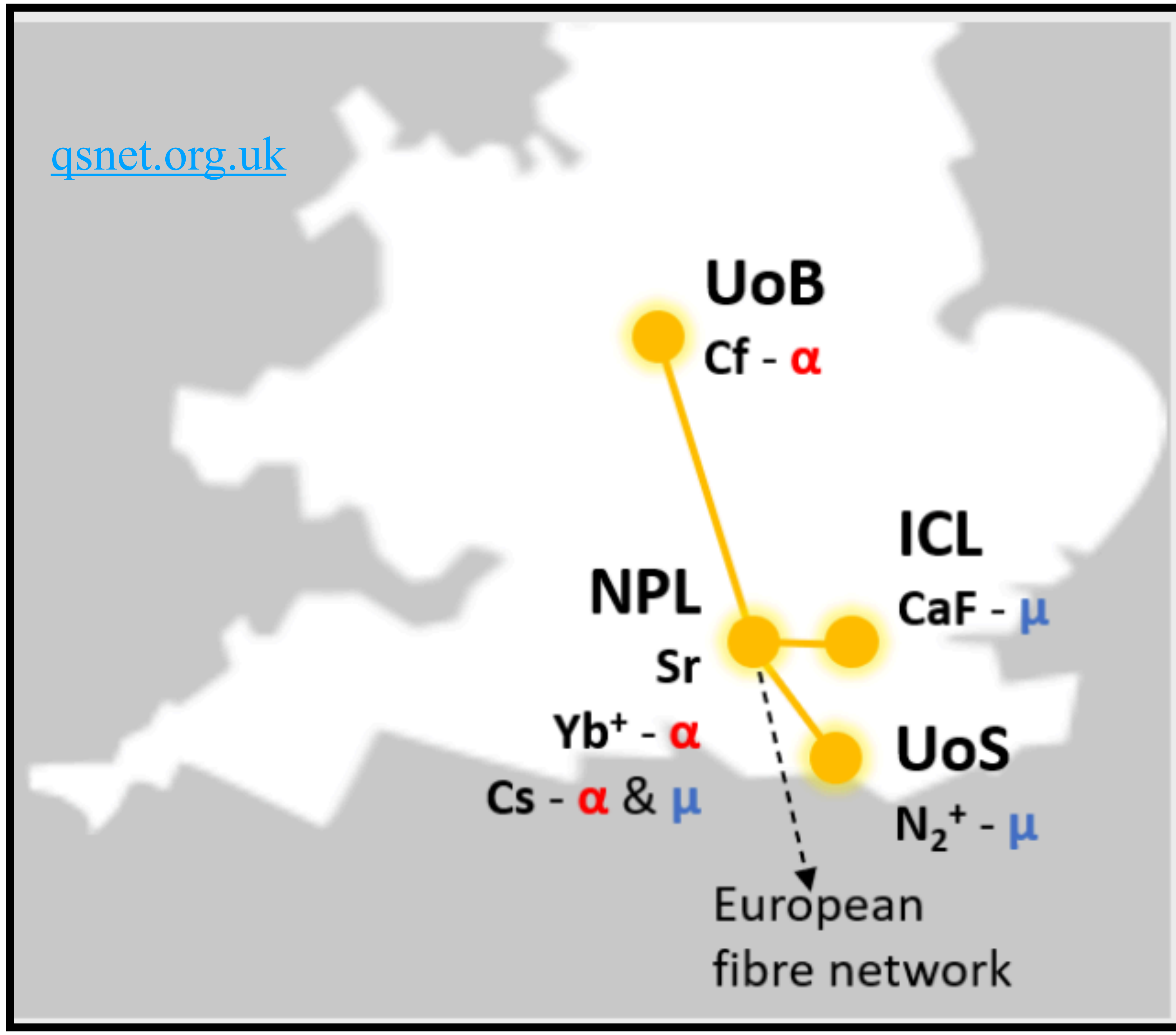

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*New data from NPL

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Under construction: CaF, N_2^+, Cf^{15+}, Cf^{17+}

Ratio variations

Parametrization of atomic frequency

V.V. Flambaum et al., Phys. Rev. D 69, 115006 (2004)

$$\nu = (\text{const.})\,(cR_\infty)\cdot\alpha^{K_\alpha}\cdot(m_e/\Lambda_{\text{QCD}})^{K_\mu}\cdot(m_q/\Lambda_{\text{QCD}})^{K_q}$$

$q \equiv (u+d)/2$

$m_p \approx A\cdot\Lambda_{\text{QCD}} + \text{light quarks}$

quark masses + magnetic moments

$$\Rightarrow \quad \frac{\delta r}{r} = \Delta K_\alpha d_\gamma^{(n)}(\kappa\phi)^n + \Delta K_\mu(d_{m_e}^{(n)} - d_g^{(n)})(\kappa\phi)^n + \Delta K_q(d_{m_q}^{(n)} - d_g^{(n)})(\kappa\phi)^n$$

Ratio variations

Parametrization of atomic frequency

V.V. Flambaum et al., Phys. Rev. D 69, 115006 (2004)

$$\nu = (\text{const.})\,(cR_\infty)\cdot \alpha^{K_\alpha}\cdot (m_e/\Lambda_{\text{QCD}})^{K_\mu}\cdot (m_q/\Lambda_{\text{QCD}})^{K_q}$$

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For NPL clocks

$$\left(\frac{\delta r}{r}\right)_{\text{Yb}^+/\text{Sr}} = -\,6.01 d_\gamma^{(n)}(\kappa\phi)^n$$

$$\left(\frac{\delta r}{r}\right)_{\text{Sr/Cs}} = -\left(2.77 d_\gamma^{(n)} + d_{m_e}^{(n)} - d_g^{(n)} + 0.07(d_q^{(n)} - d_g^{(n)})\right)(\kappa\phi)^n$$

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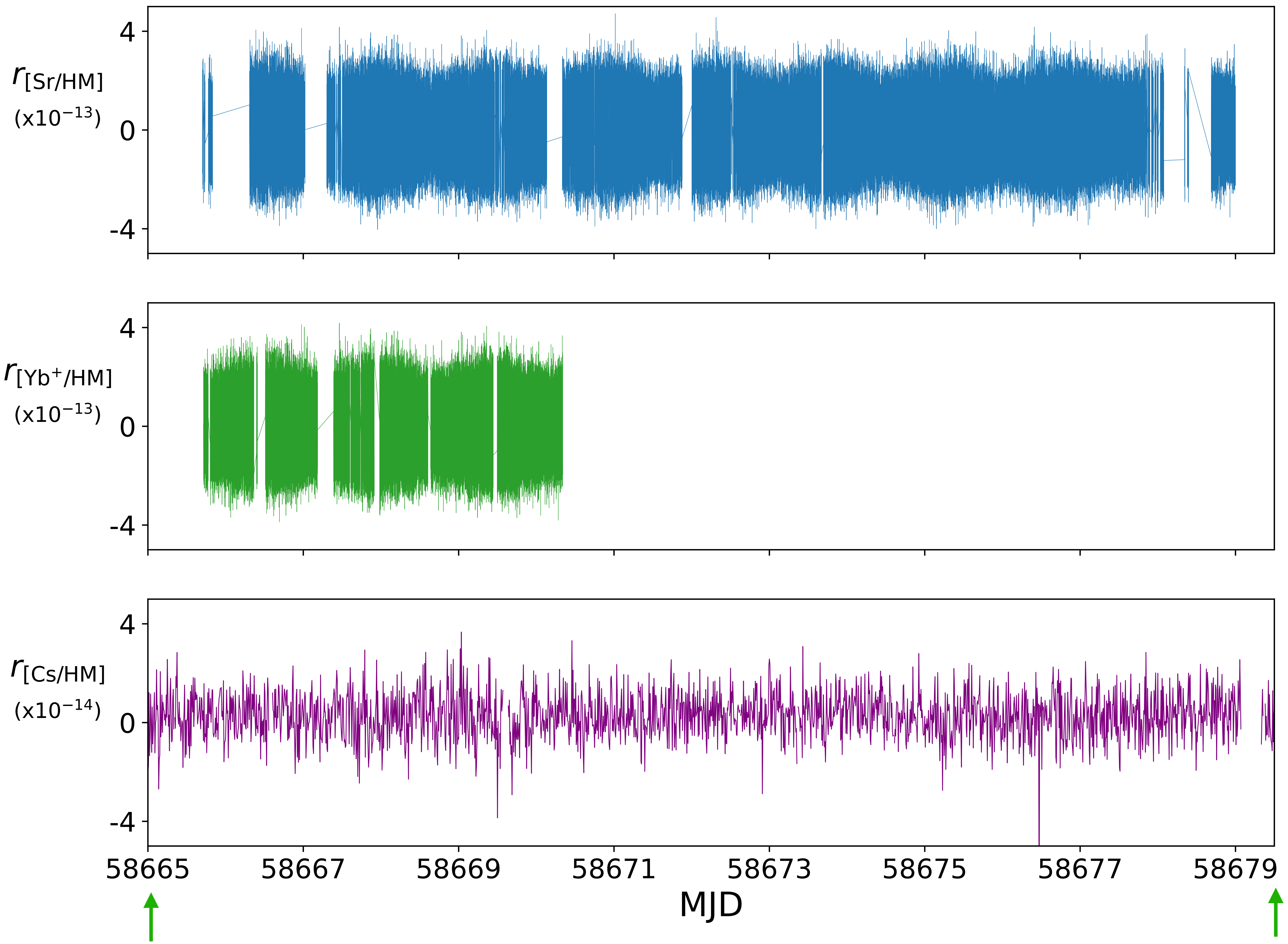
NPL data: time series

arXiv:2302.04565



01 July 2019

15 July 2019

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

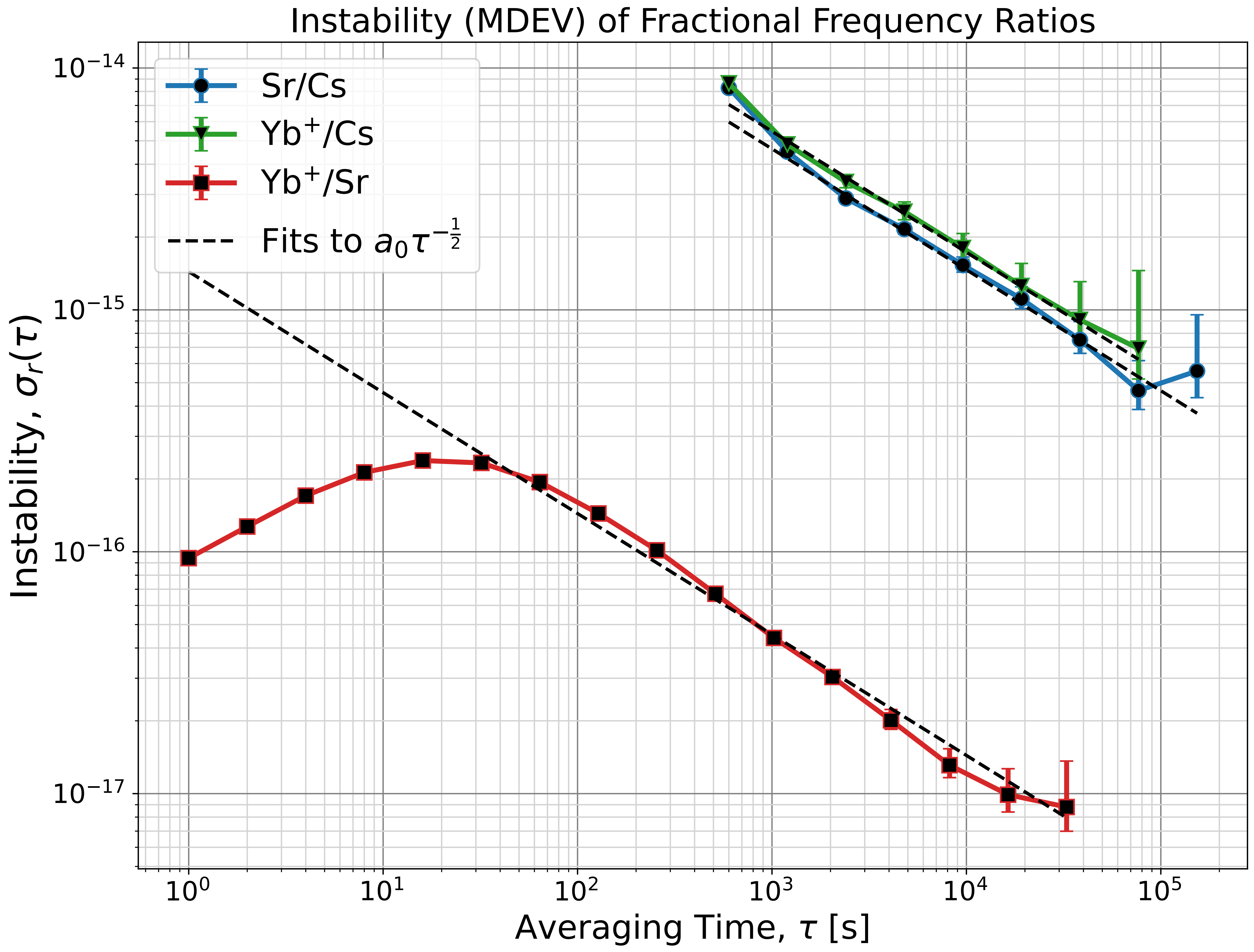
- ~ 2 weeks of measurements, roughly every second with 75% uptime
- Observations made over same window

$$\Downarrow$$

Yb⁺/Sr and Sr/Cs constructed

$$\propto \overbrace{\frac{\delta\alpha}{\alpha}} \quad \propto \overbrace{\frac{\delta\mu}{\mu}, \frac{\delta g_N}{g_N}}$$

NPL data: clock instabilities



Mean ratios not constant over time

Instability = 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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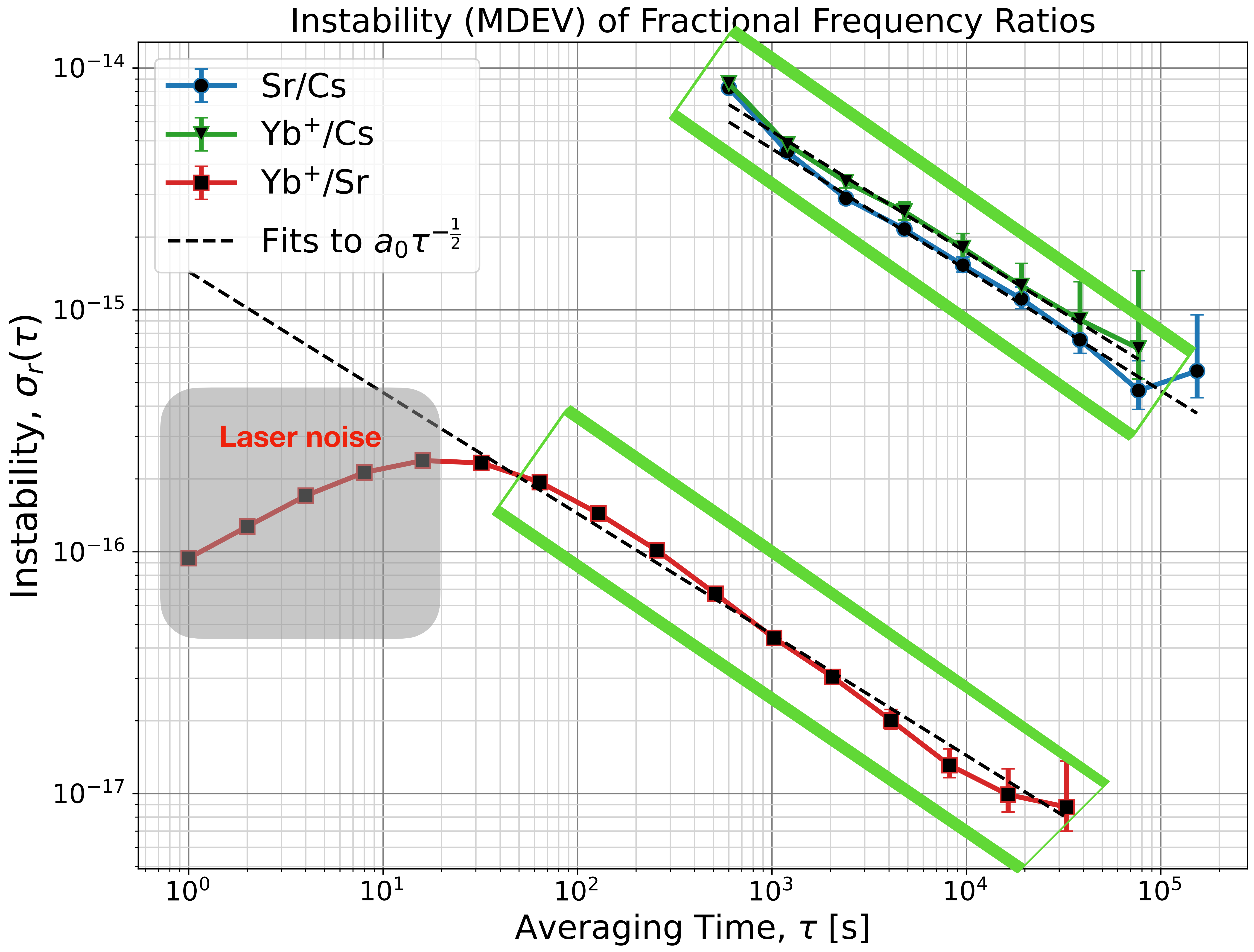

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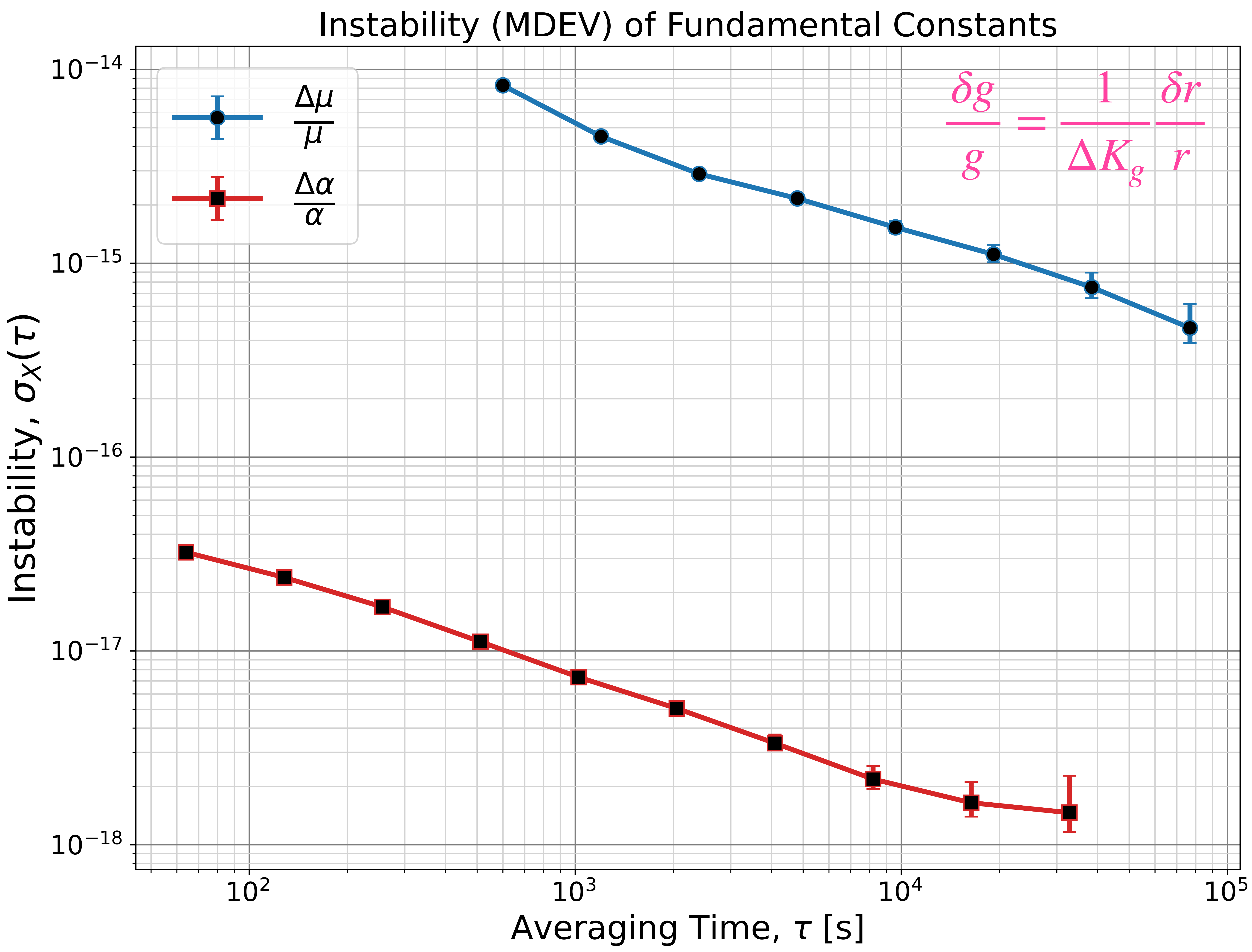
Data characteristic of Gaussian white noise (stat uncertainties dominant)

$\Rightarrow$ **Representative of operating @ the atomic transition!**

Model-independent constraints



Translate instabilities 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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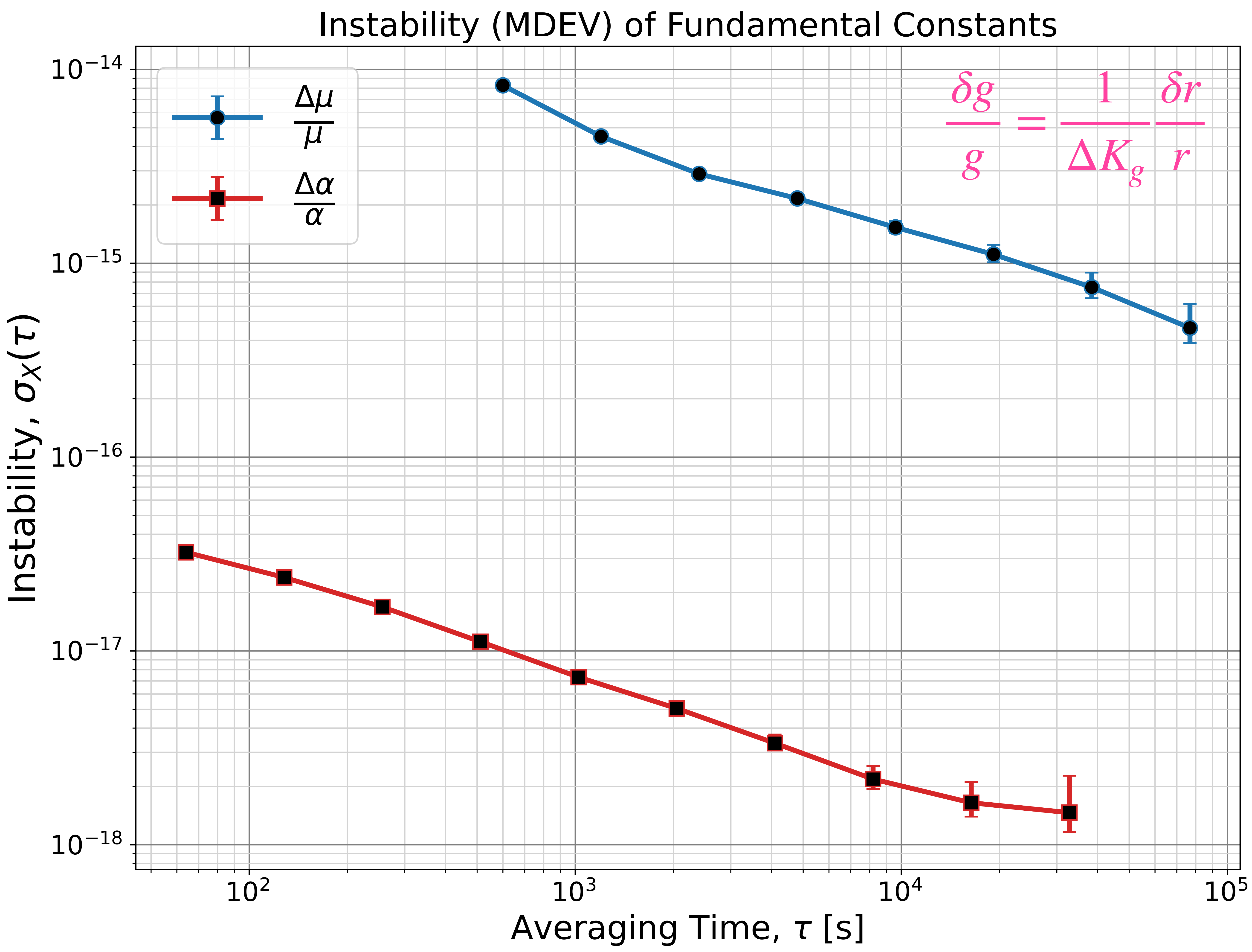

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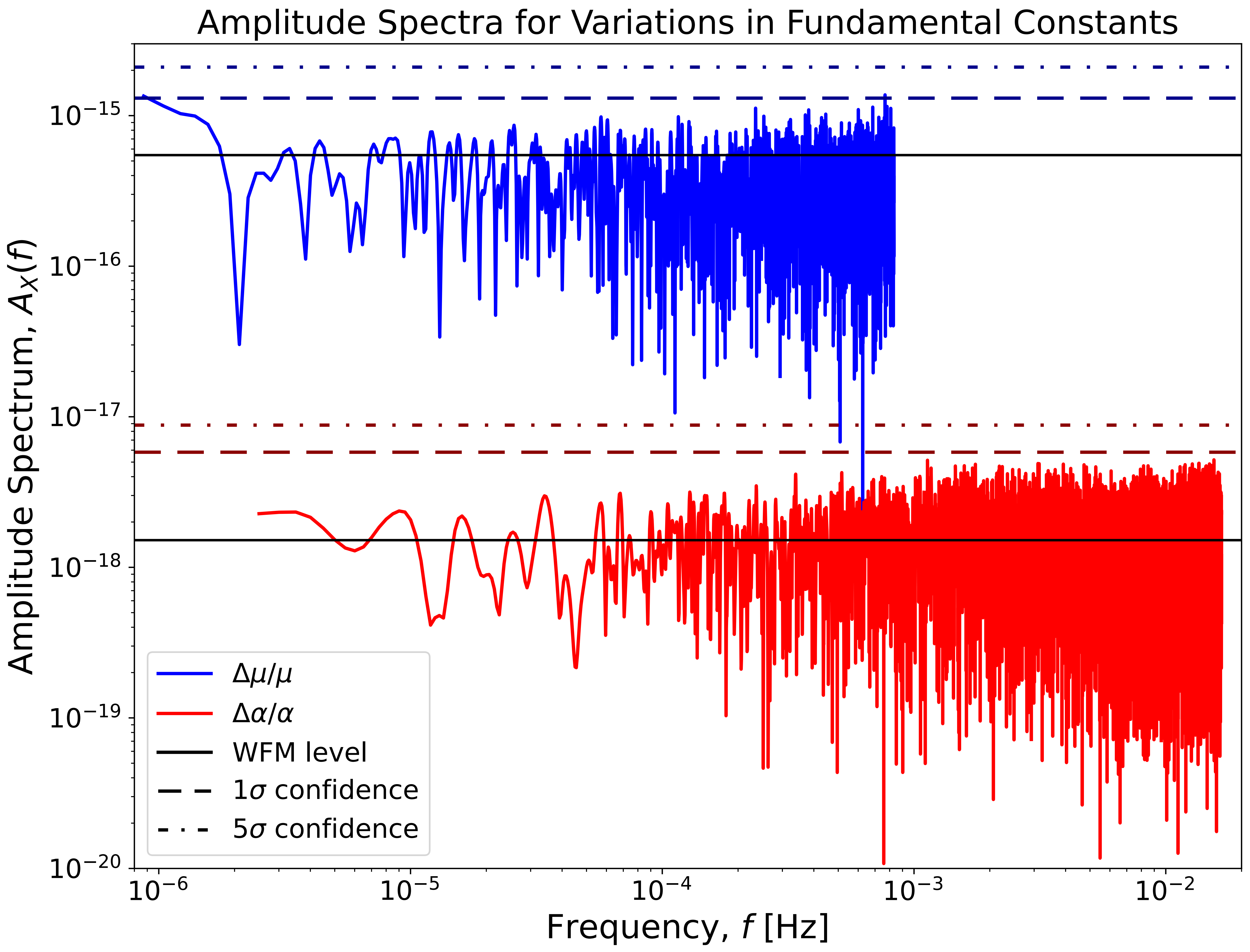
E.g. for two times separated by 1000 seconds

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

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

NPL data: amplitude spectra



$$4 \times 10^{-21}\ \text{eV} \lesssim m_\phi \lesssim 8 \times 10^{-17}\ \text{eV}$$

Assuming underlying oscillatory signal

- Fourier transform time-series data
- Fit to signals

$$\sim \text{Amp} \cdot \cos(2\pi f t)$$

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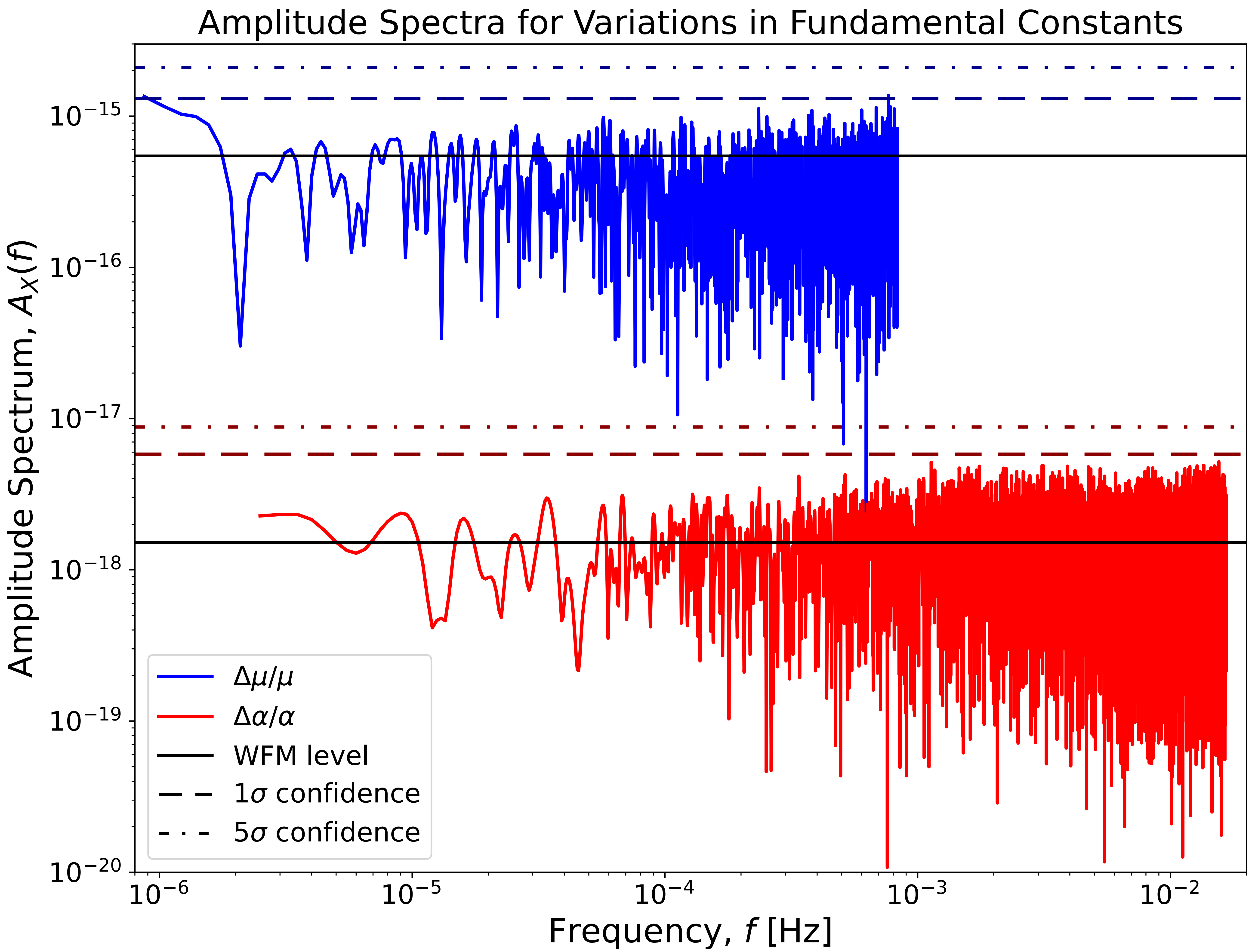

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peak width $\propto \Gamma$ $\quad \phi(t)/\phi_0 \sim e^{-(3\Gamma/2)t} \cos(m_\phi t + \delta)$

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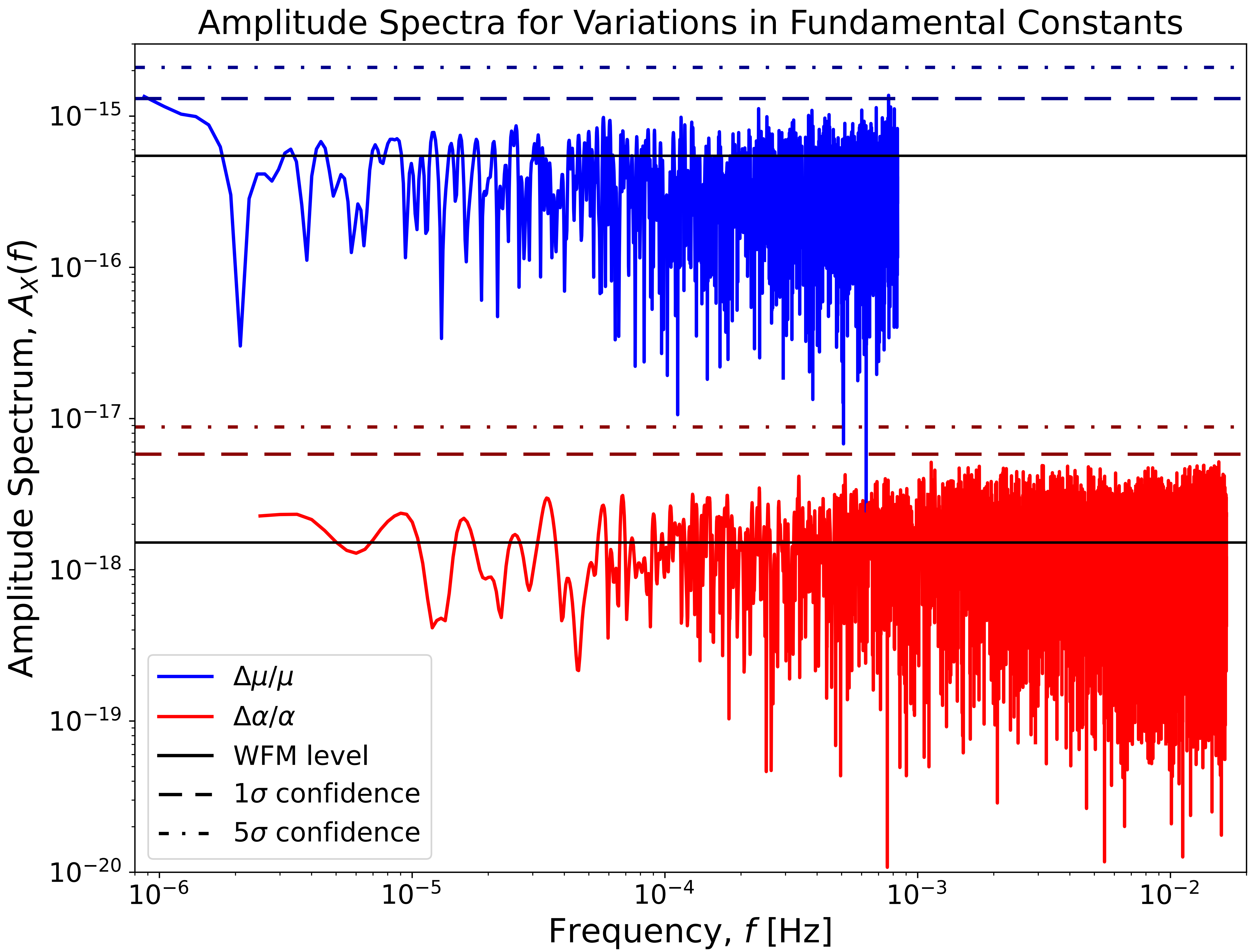

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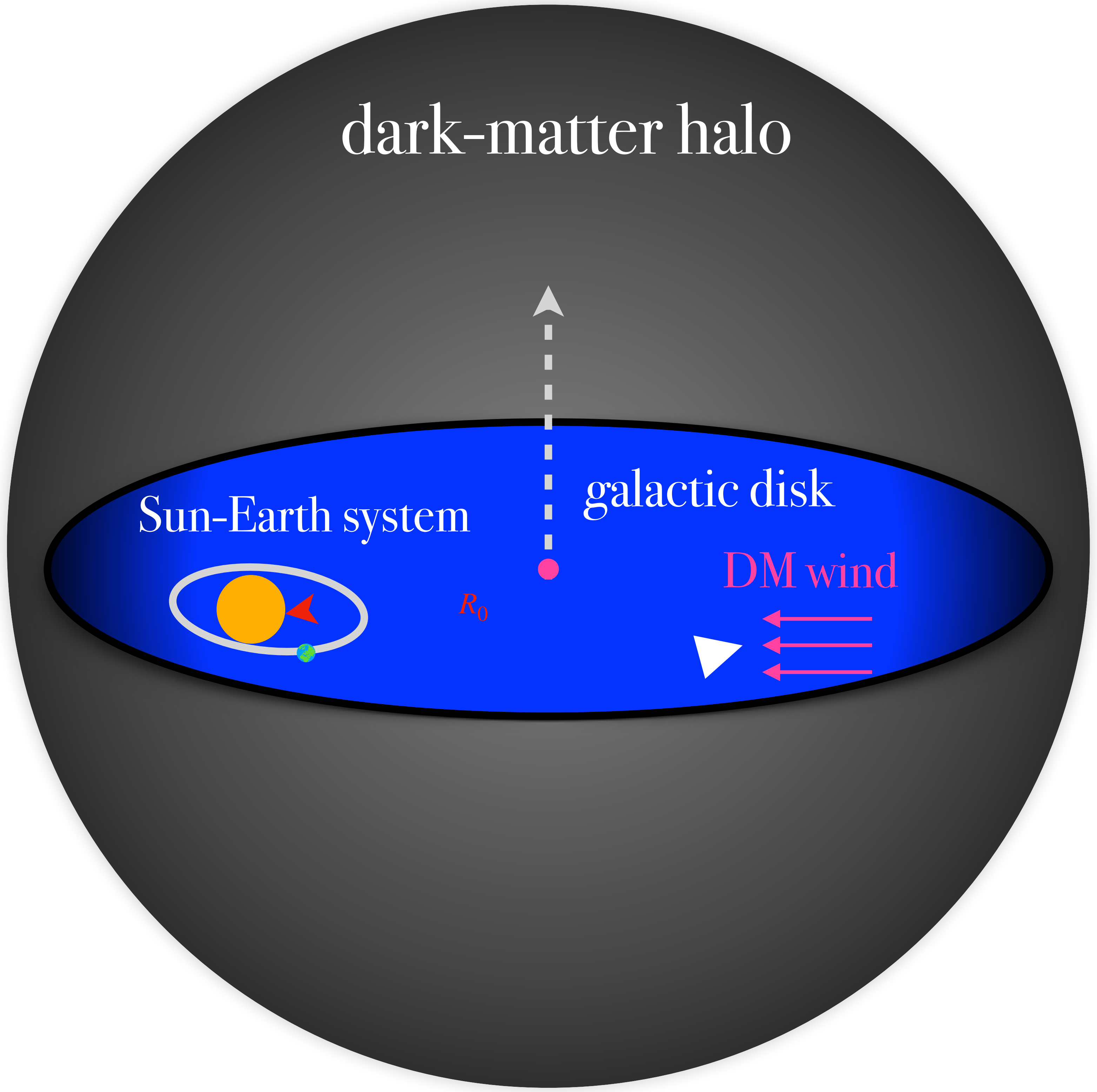
Data consistent with stat uncertainties (no signal)

$\Rightarrow$ **set constraints on ultralight DM**

Ultralight DM

$\Delta x \Delta p \sim 1$

$n \cdot \lambda_{\mathrm{DB}}^3 \gg 1$



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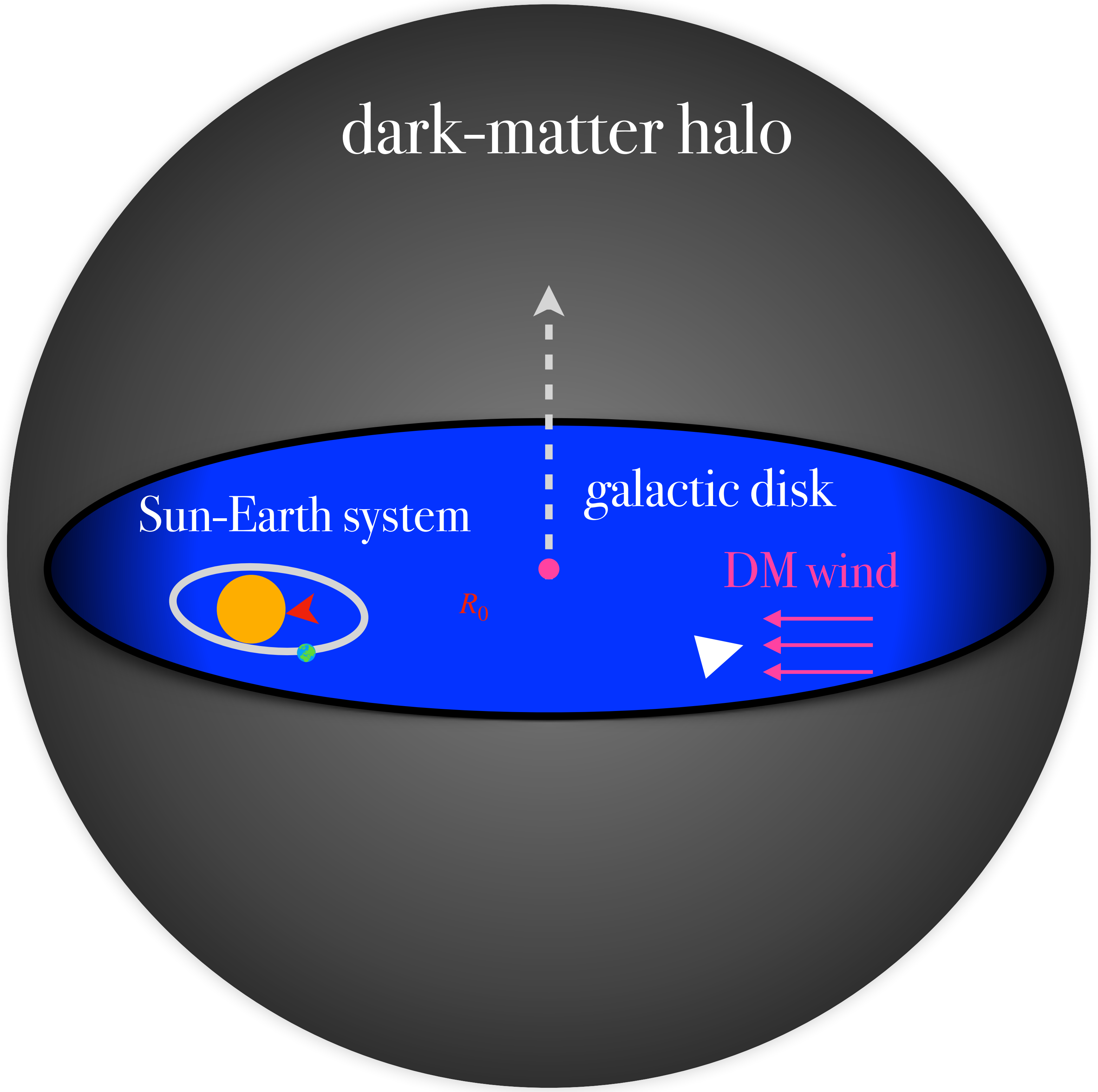
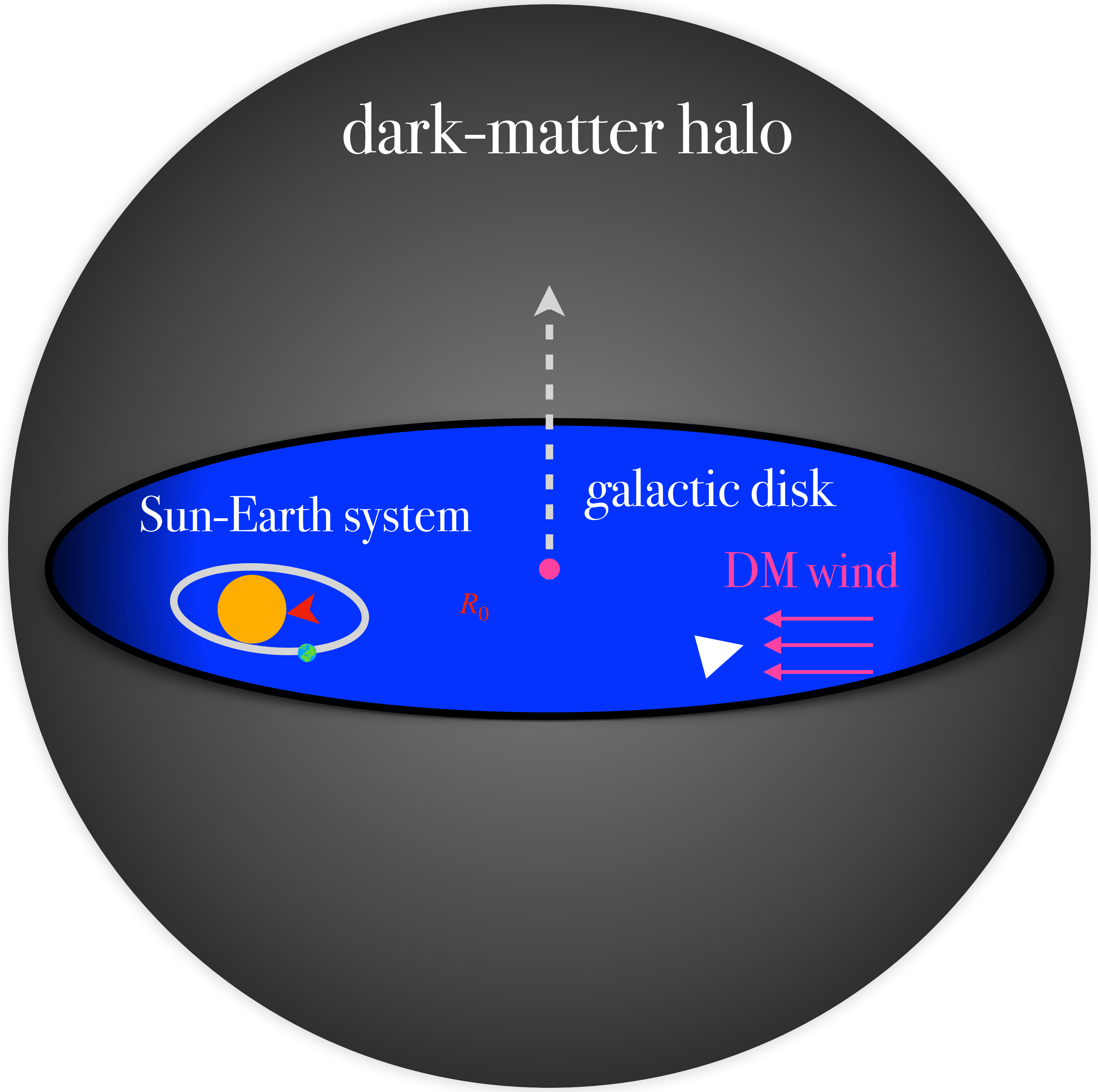


Compton frequency ∝ rest mass $\quad m_\phi = 2\pi f_\phi = 2\pi f_C = \dfrac{2\pi}{T_C}$

Oscillations are *coherent*

$$\begin{cases} \tau_C = \dfrac{2\pi}{\frac{1}{2} m v_{\mathrm{DM}}^2} \gtrsim 10^6 T_C \gg T_{\mathrm{experiment}} \\ \lambda_C = \dfrac{2\pi}{m v_{\mathrm{DM}}} \gg R_{\mathrm{solar\ system}} \end{cases}$$

Ultralight DM



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$\rho_{\rm DM} = \rho_{\rm DM}(R_0) \approx 0.3\ {\rm GeV/cm^3}$

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ULDM = macroscopic coherently oscillating field $\quad \phi(t) \approx \phi_0 \cos(m_\phi t) \quad \phi_0 = \dfrac{\sqrt{2\rho_{\rm DM}^{\rm local}}}{m_\phi}$

Constraints

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

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

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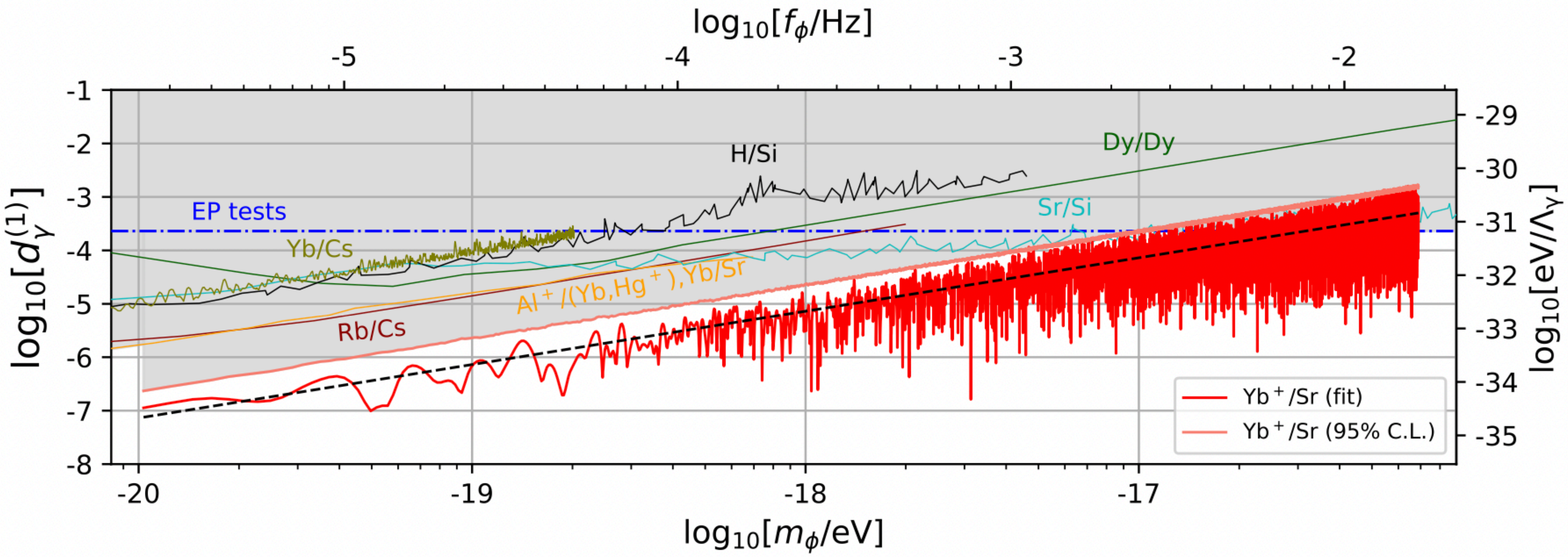

$n = 1\ (f = f_\phi)$

$$\frac{1}{\Delta K_\alpha} \frac{\delta r}{r}\bigg|_{\rm Yb^+/Sr} = d_\gamma^{(1)} (\kappa\phi)^1$$

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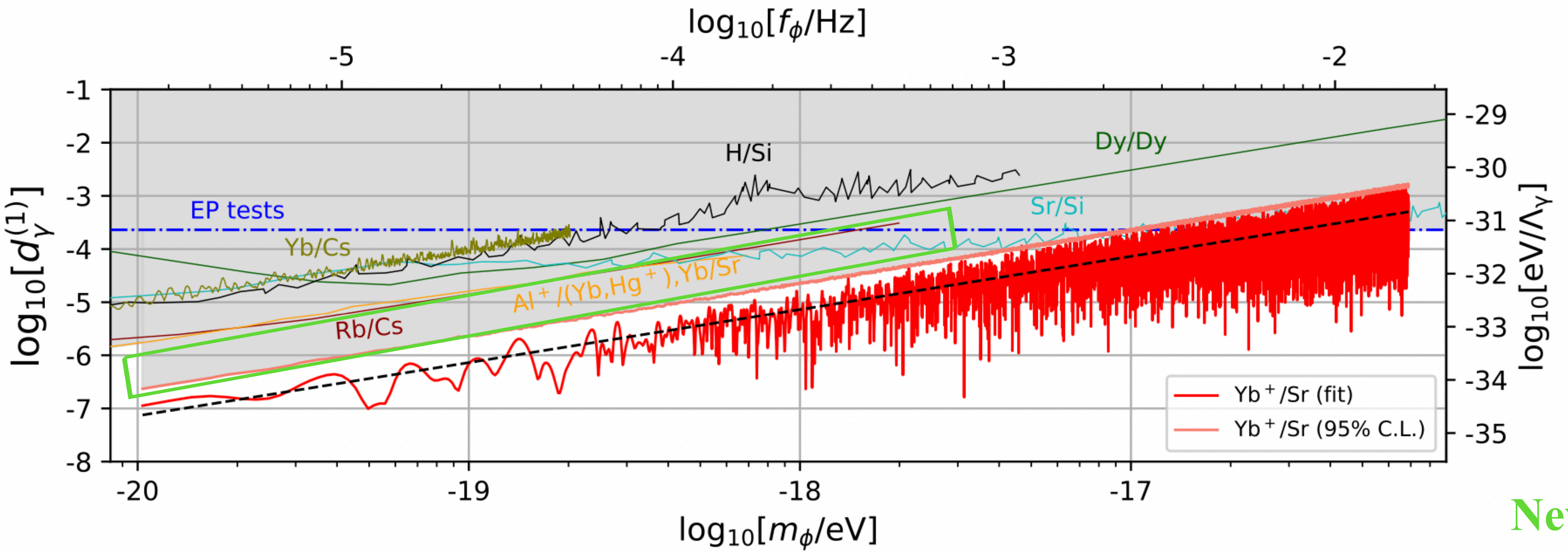

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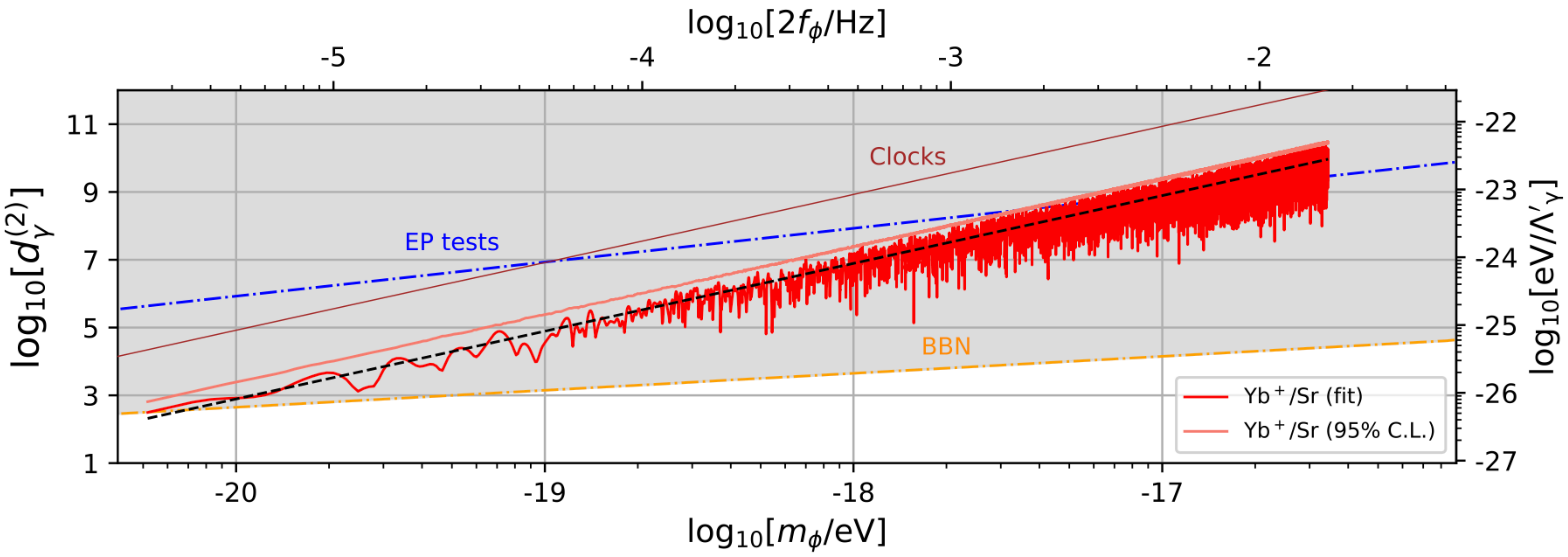
New parameter space probed

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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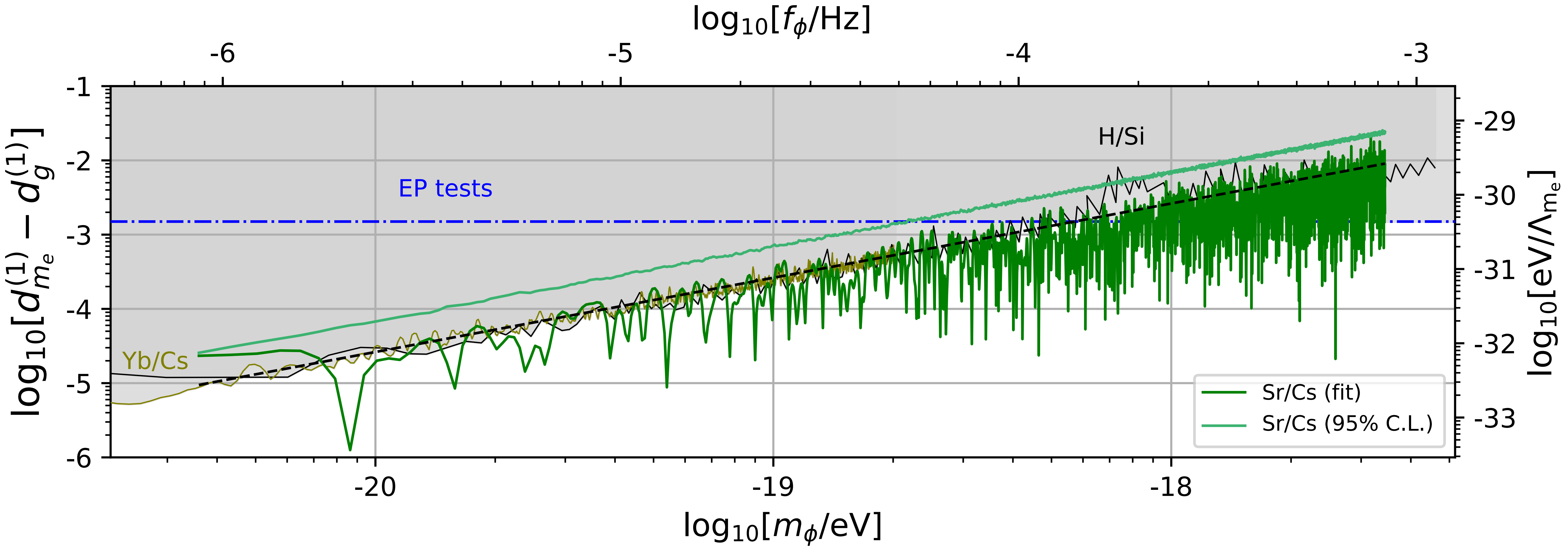

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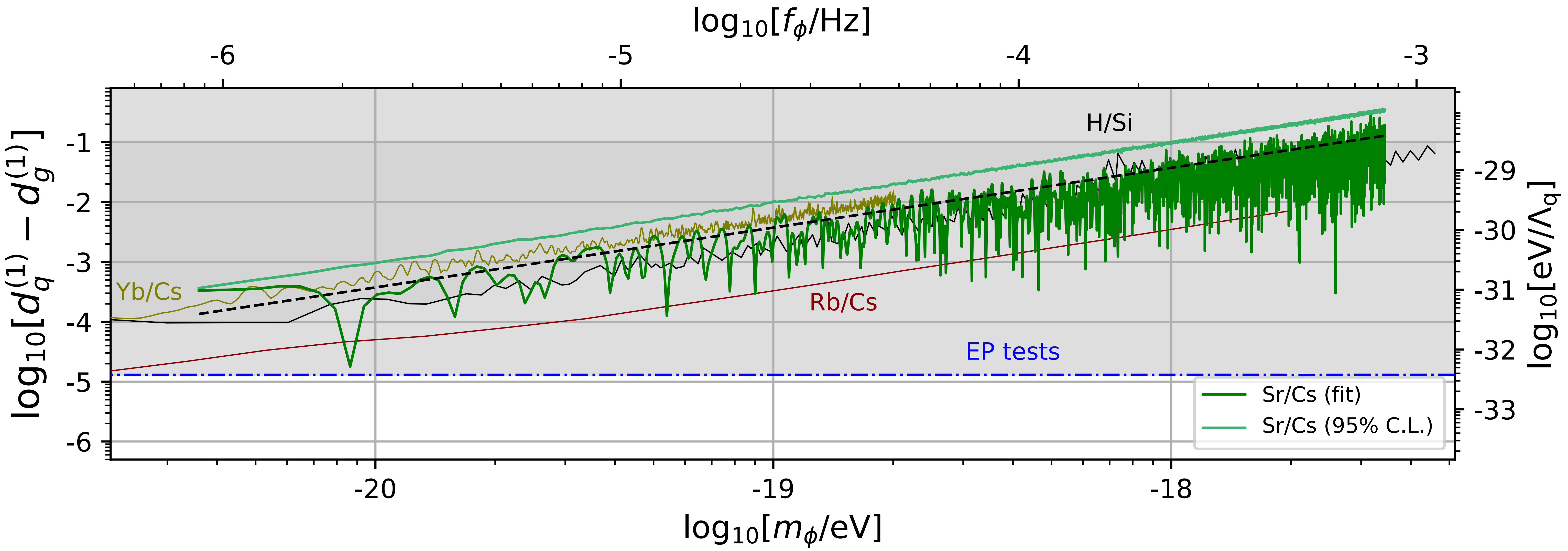

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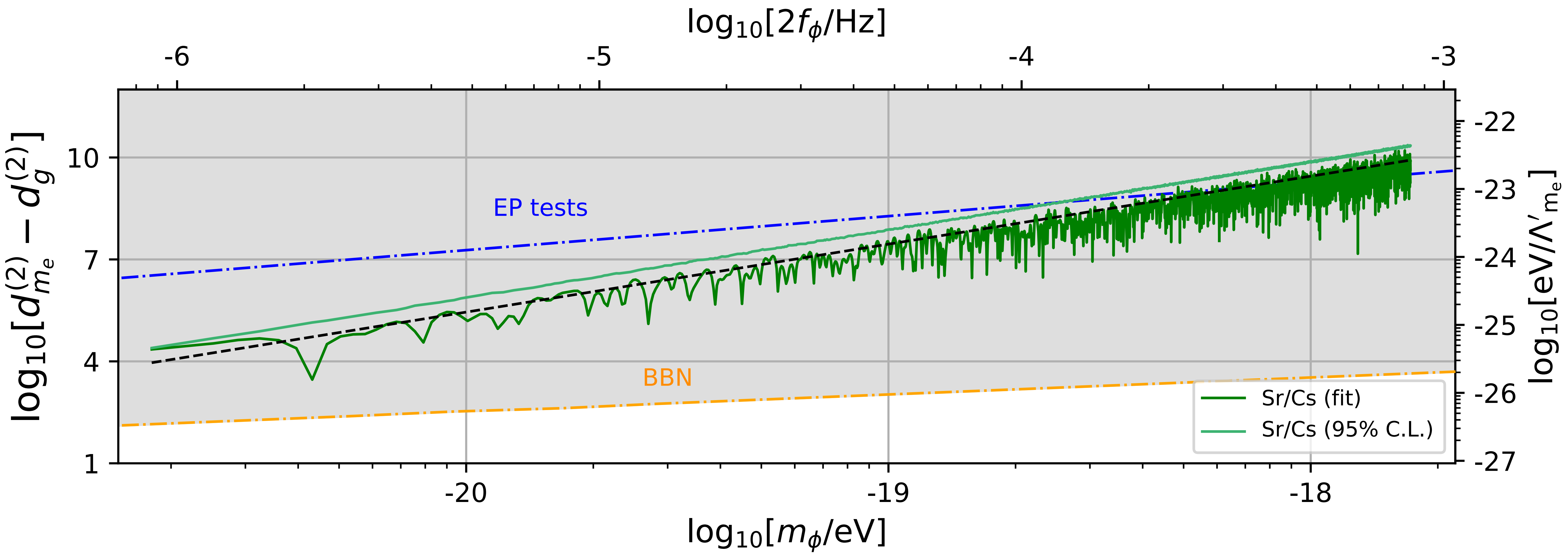

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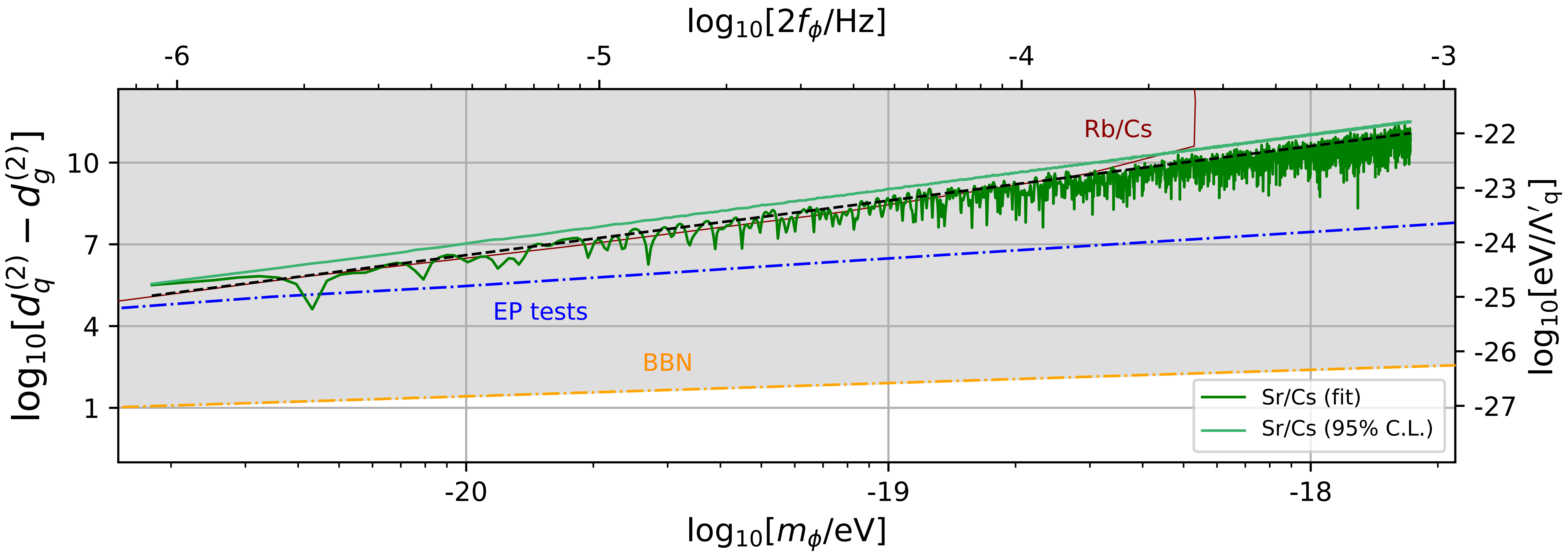

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Constraints

May also consider ϕ – Higgs couplings $\mathscr{L}_H = -A\phi H^\dagger H$ F. Piazza, M. Pospelov, Phys. Rev. D 82, 043533

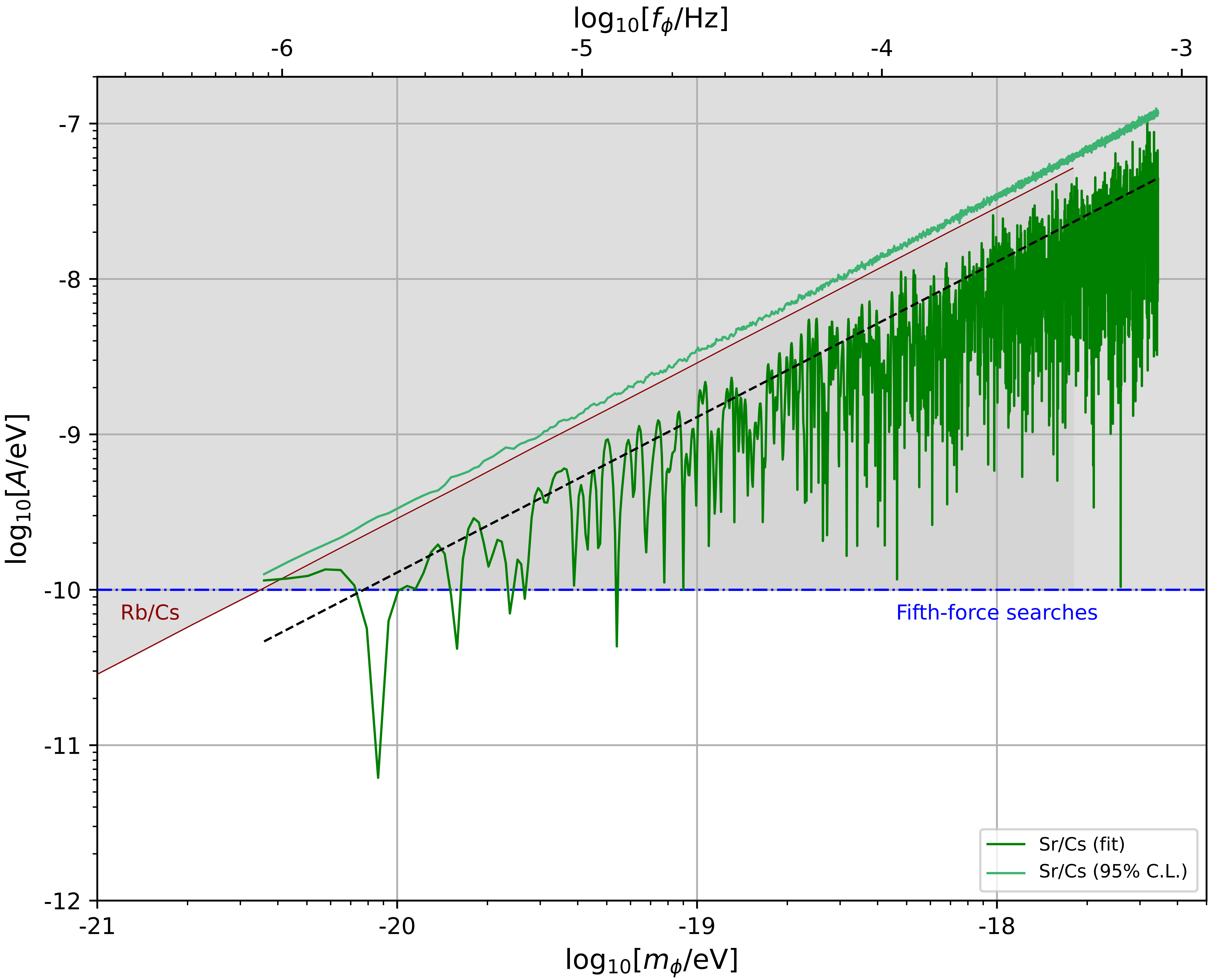
Mixing generates effective interactions $\mathscr{L}_{\text{Higgs,eff.}} = \frac{A\langle h\rangle}{m_h^2}\phi\left(\sum_f g_{hff}\bar{\psi}_f\psi_f + \frac{g_{h\gamma\gamma}}{\langle h\rangle}F_{\mu\nu}F^{\mu\nu}\right)$

Y. V. Stadnik, V. V. Flambaum, PRA 94, 022111 (2016)

$$\frac{\delta r}{r} = \Delta K_H \frac{A}{m_h^2}\frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi}\cos(m_\phi t) \qquad K_H = \frac{\alpha}{2\pi}K_\alpha - (1-b)K_{m_e} - 1.05(1-b)K_{m_q}$$

With $\Delta K_H\Big|_{\text{Sr/Cs}} \approx 0.5$ constraints on A are obtained

Constraints



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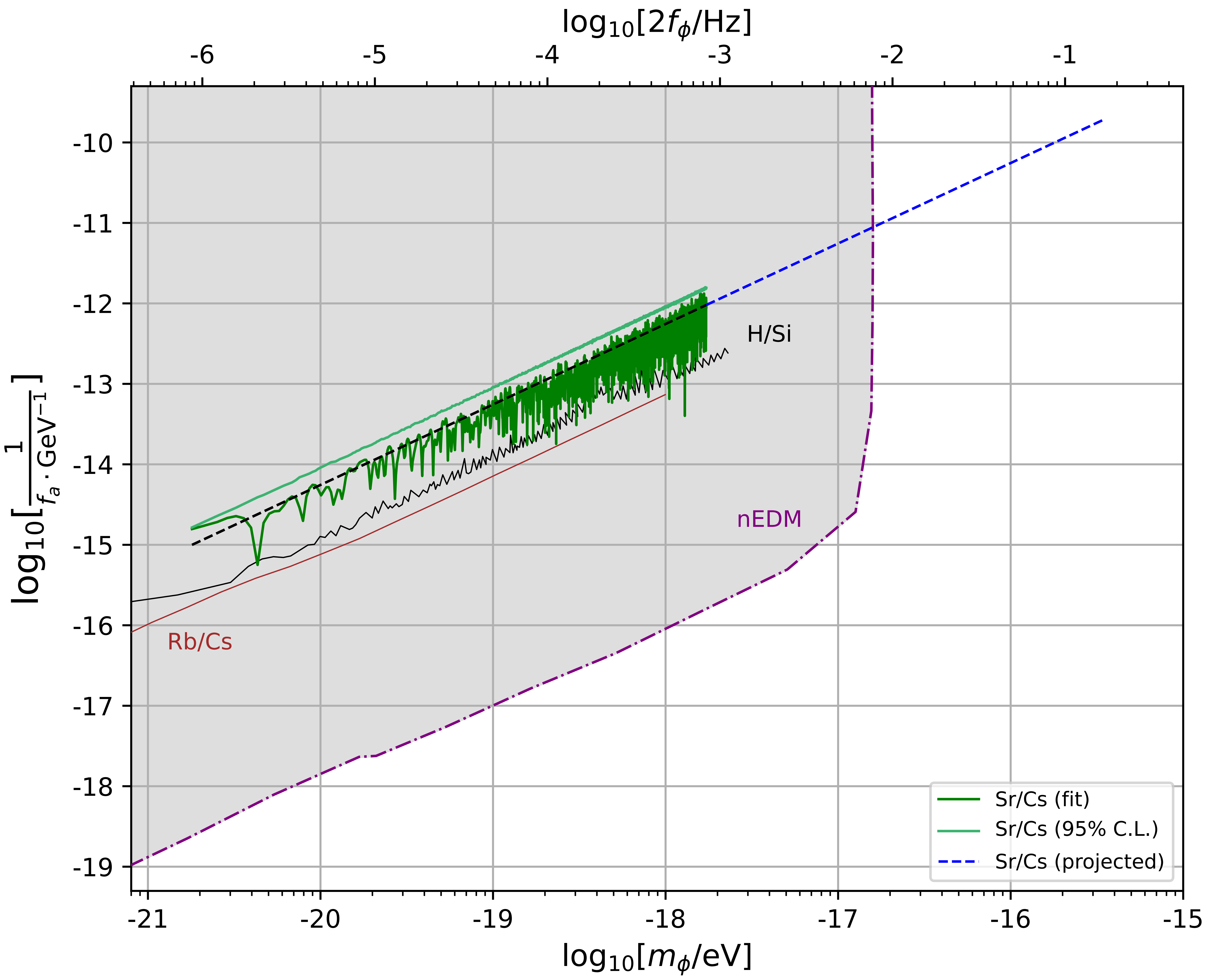

Kim, Perez, 2205.12988

Clocks can also probe axion-like couplings

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

Induces oscillations in nucleon mass and nuclear g factor

transmits to sensitivity from Sr/Cs ratio

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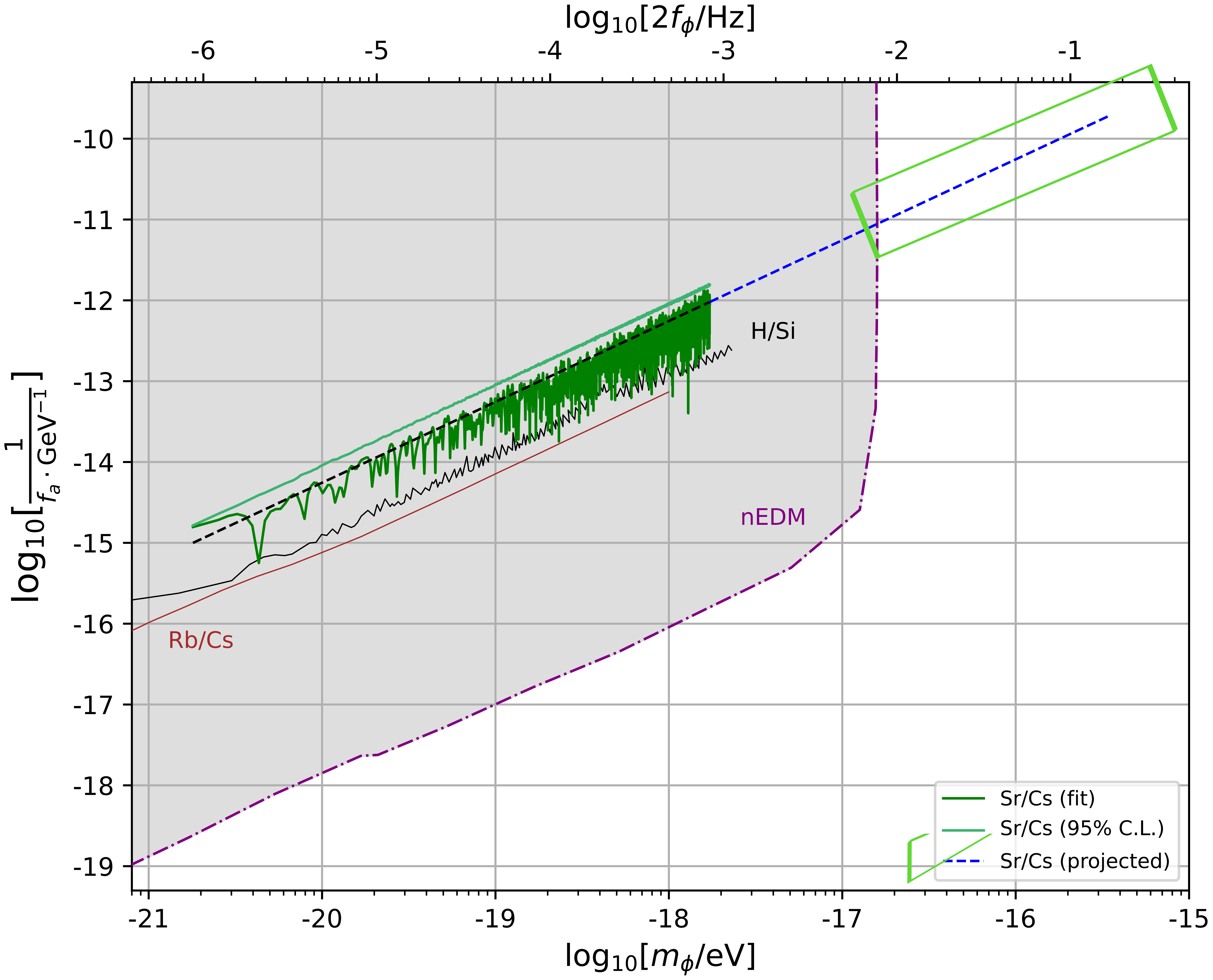

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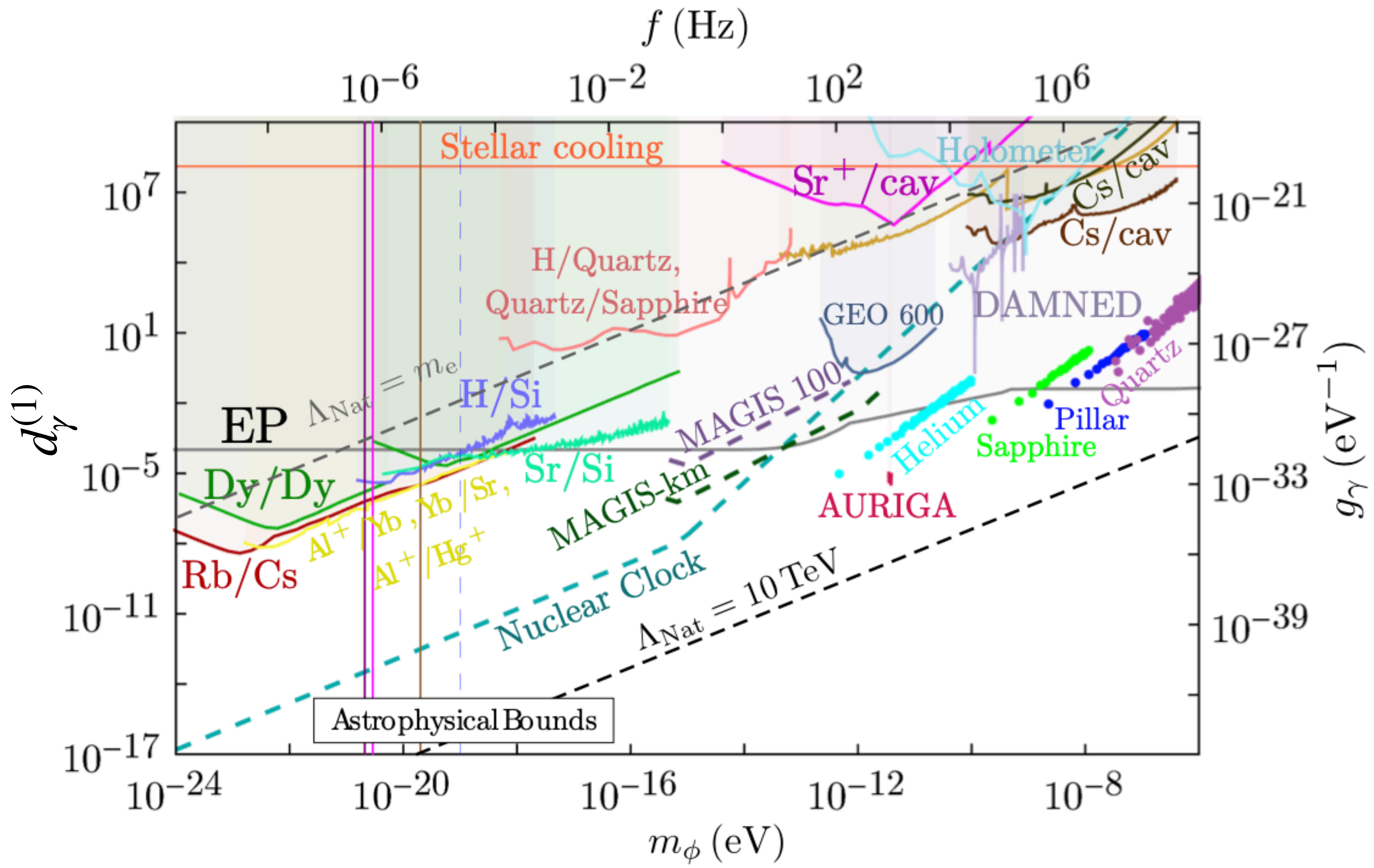
Recap and conclusions

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

- Lots of recent theory activity (ULDM, ALPs, …)
- Experimental funding/capabilities rapidly increasing

New Horizons: Scalar and Vector Ultralight Dark Matter, 2022 Snowmass Summer Study



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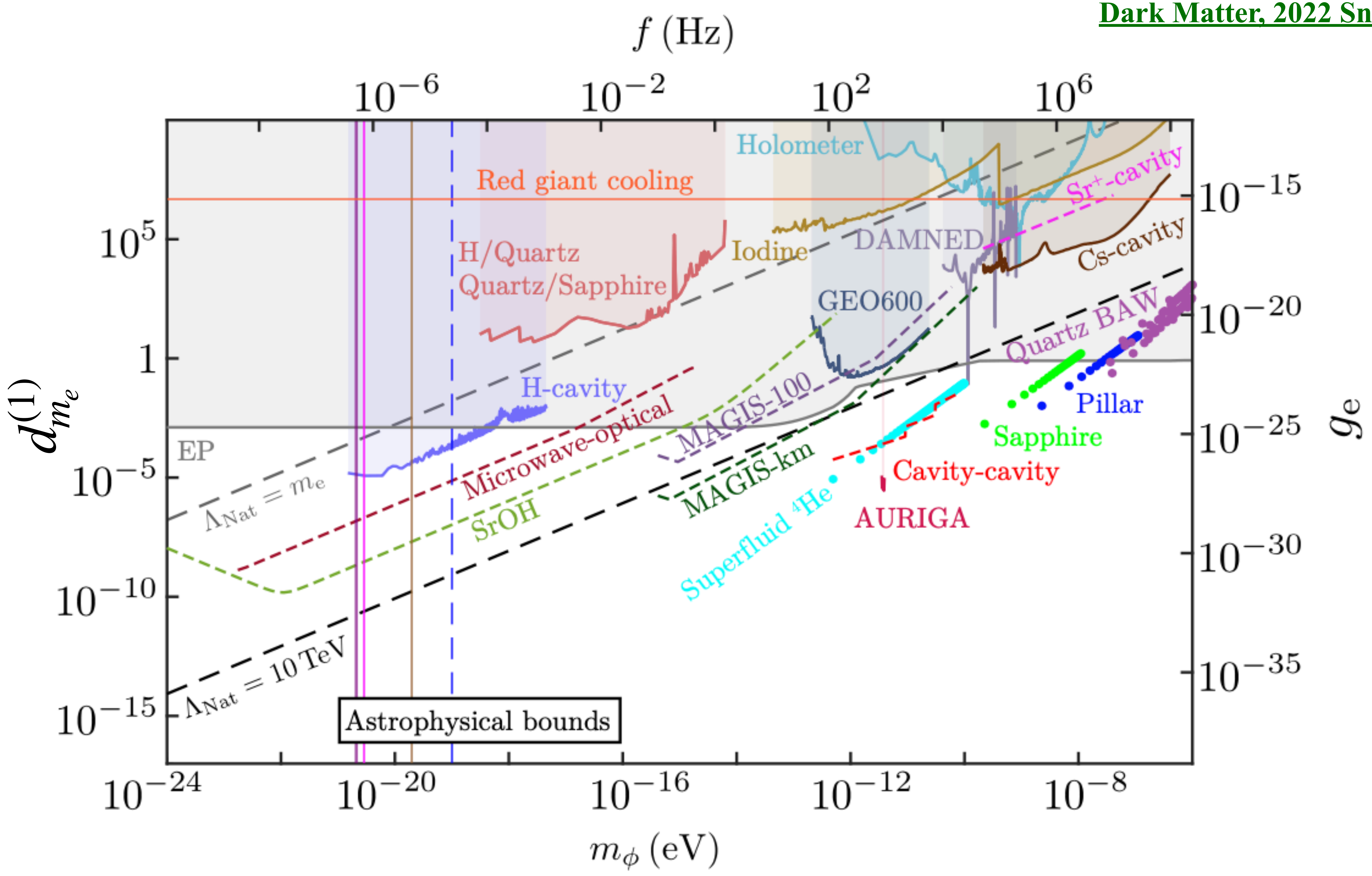

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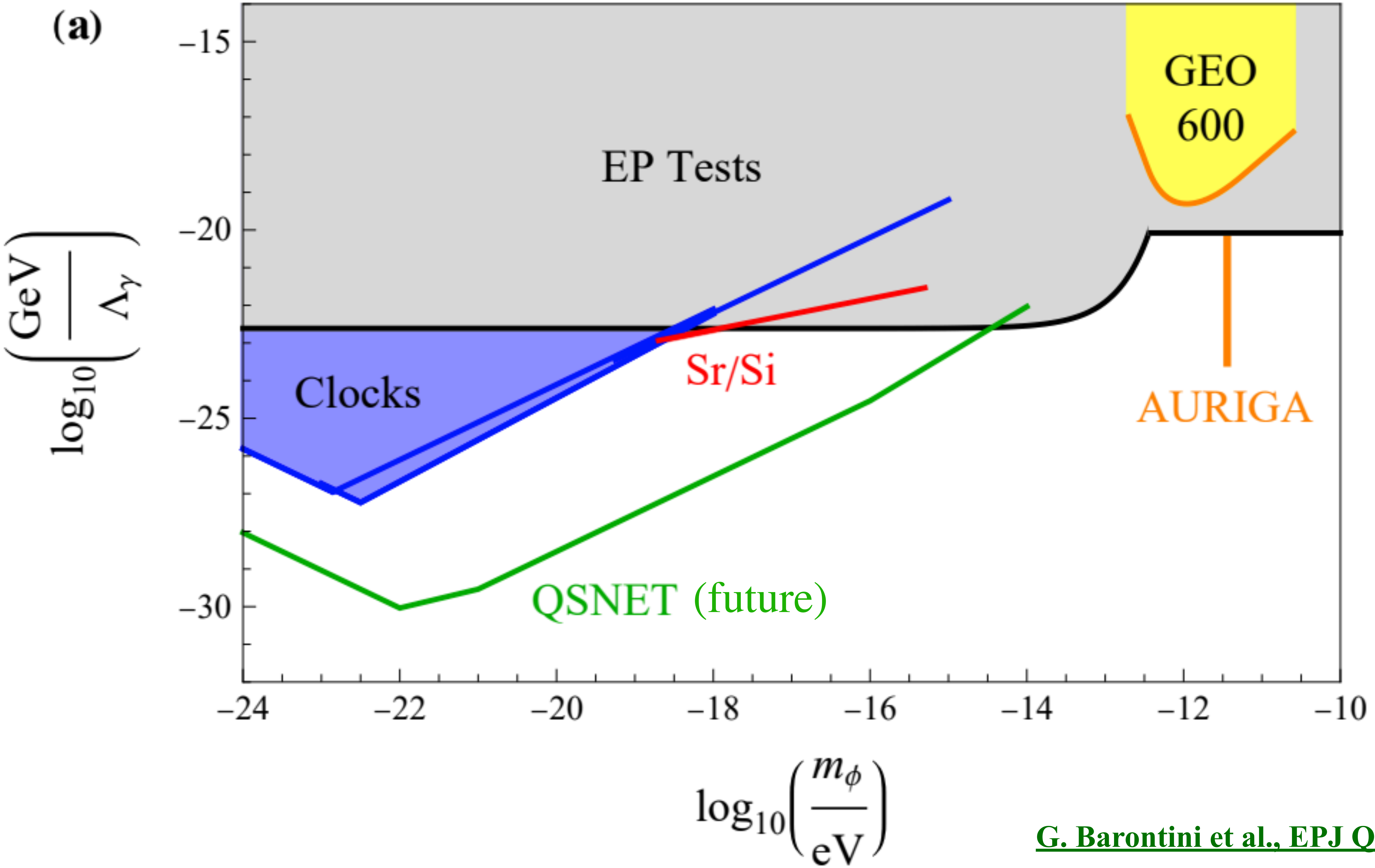
Excellent future prospects

- ☐ Longer datasets give access to *lighter* masses
- ☐ New QSNET clocks w/larger K factors $\Rightarrow$ drive exclusion regions *downward*

$$(\kappa\phi)\, d_\gamma^{(1)} \frac{1}{4} F_{\mu\nu}F^{\mu\nu} \leftrightarrow \frac{\phi}{\Lambda_\gamma} \frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$



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

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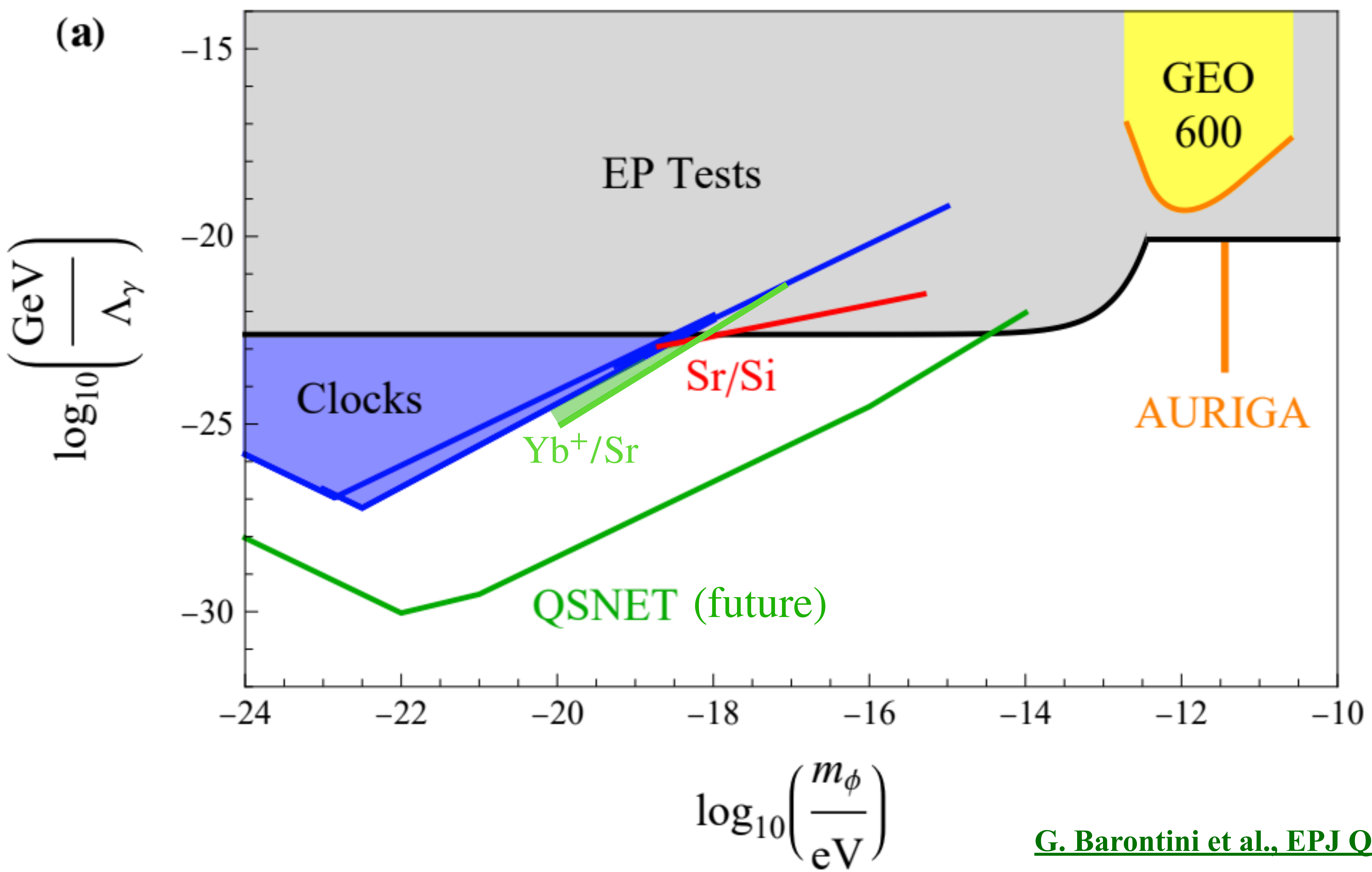

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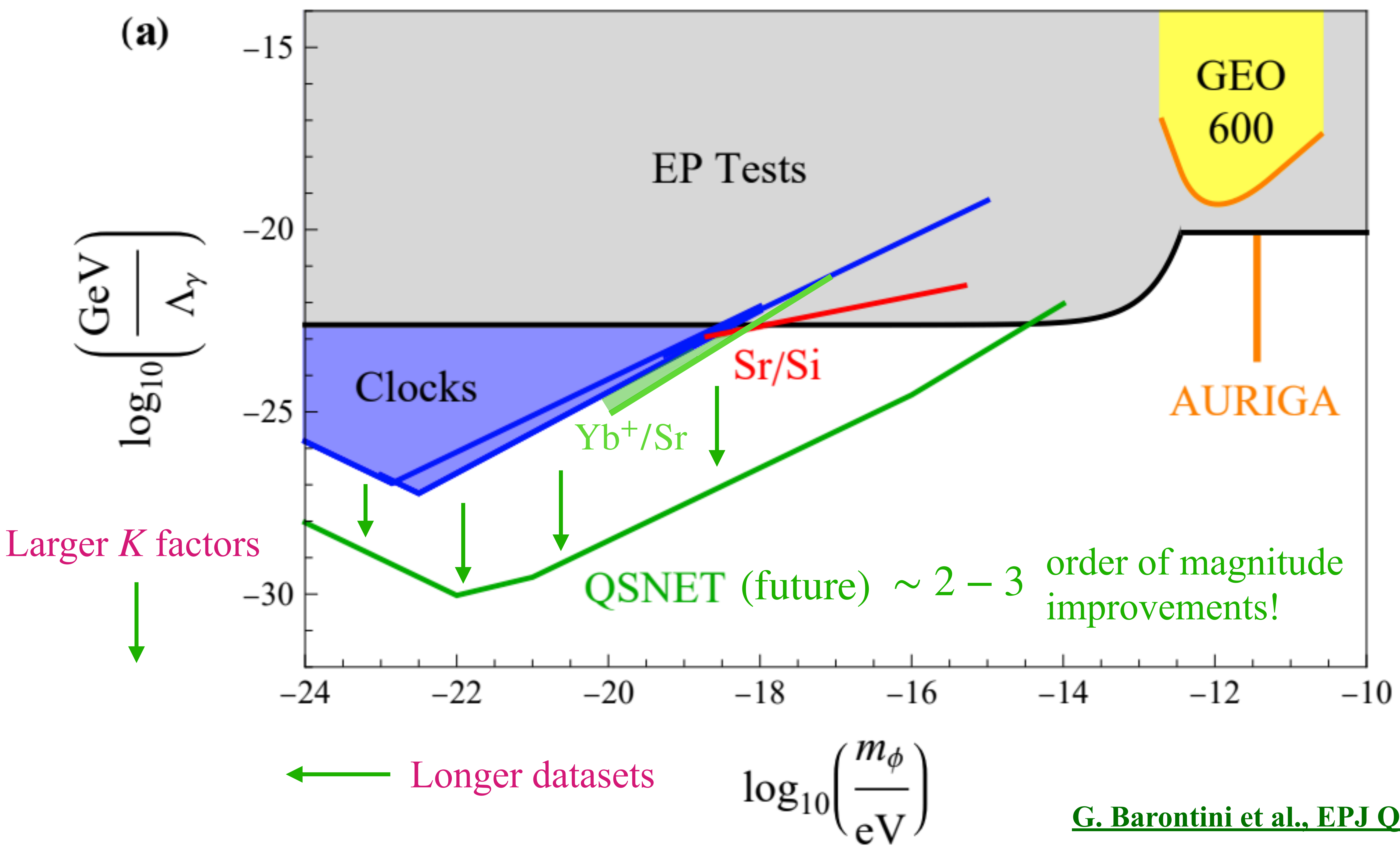

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