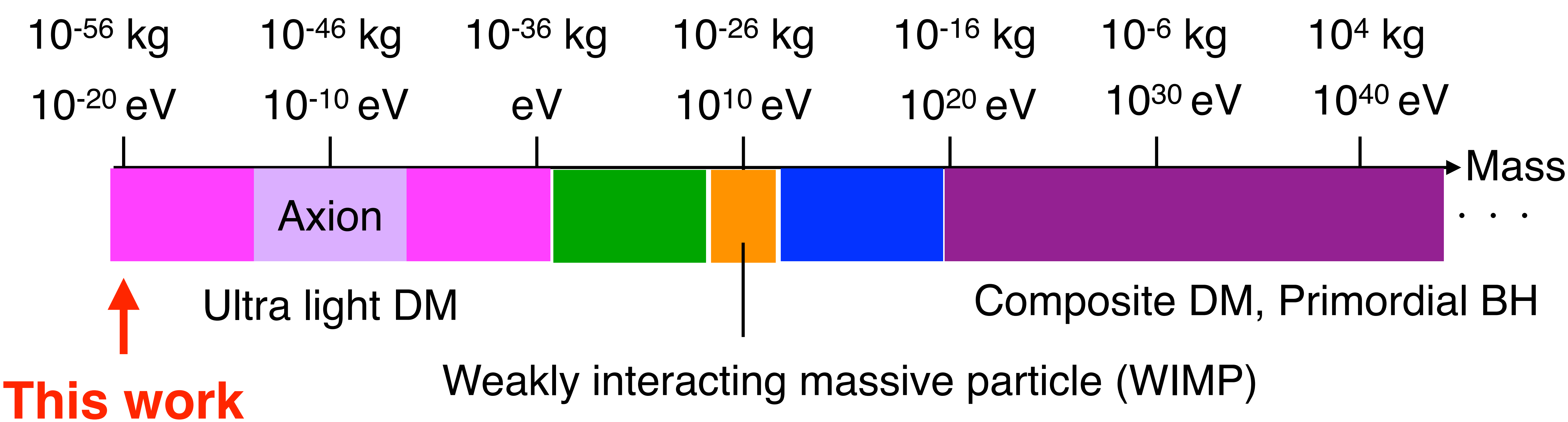
Search for ultralight dark matter with atomic clocks

National Metrology Institute of Japan (NMIJ), National Institute
of Advanced Industrial Science and Technology (AIST)

Takumi Kobayashi

Dark matter candidates

Objective of this work:
search for ultralight dark matter (mass~10^{-22} eV) using atomic clocks



Ultralight dark matter (dilatonlike particle)

e.g., W. Hu *et al.*, PRL **85**, 1158 (2000).

- **10^{-22} eV is the lowest mass limit** if ultralight dark matter is a major constituent

  de Brogile wavelength at ~ 10^{-22} eV is comparable to the sizes of dwarf galaxies

- **Behavior as a classical wave**

  Local dark matter density: 0.3 - 0.4 GeV/cm^3

  → de Brogile wavelength >> inter-particle separation

  → large occupation number per mode (Bose-Einstein condensation)

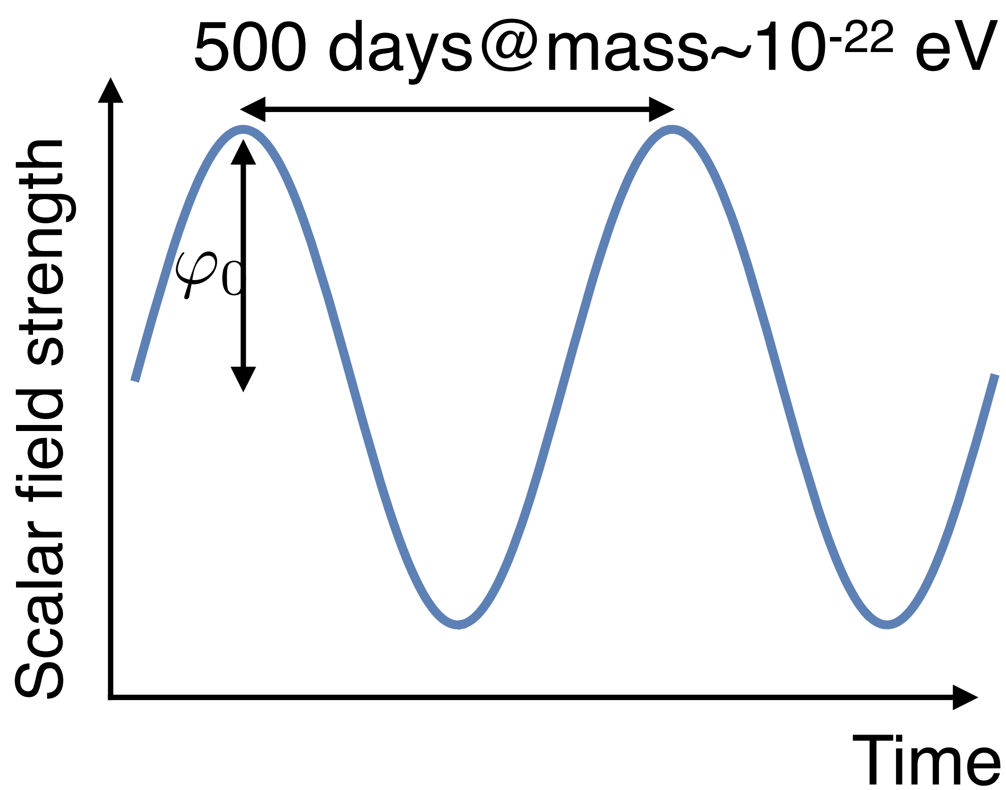
  → **Coherent oscillation of the scalar field**

$$\varphi(t) \sim \varphi_0 \cos(2\pi f t)$$

Compton frequency

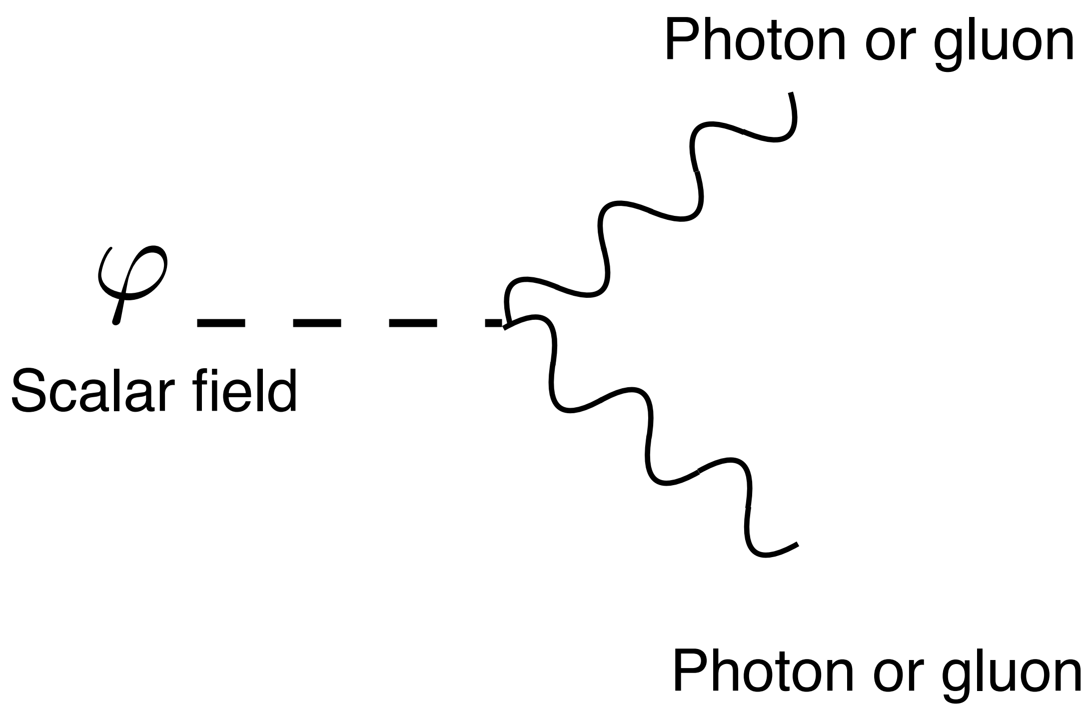
$$f = m_\varphi c^2 / h$$

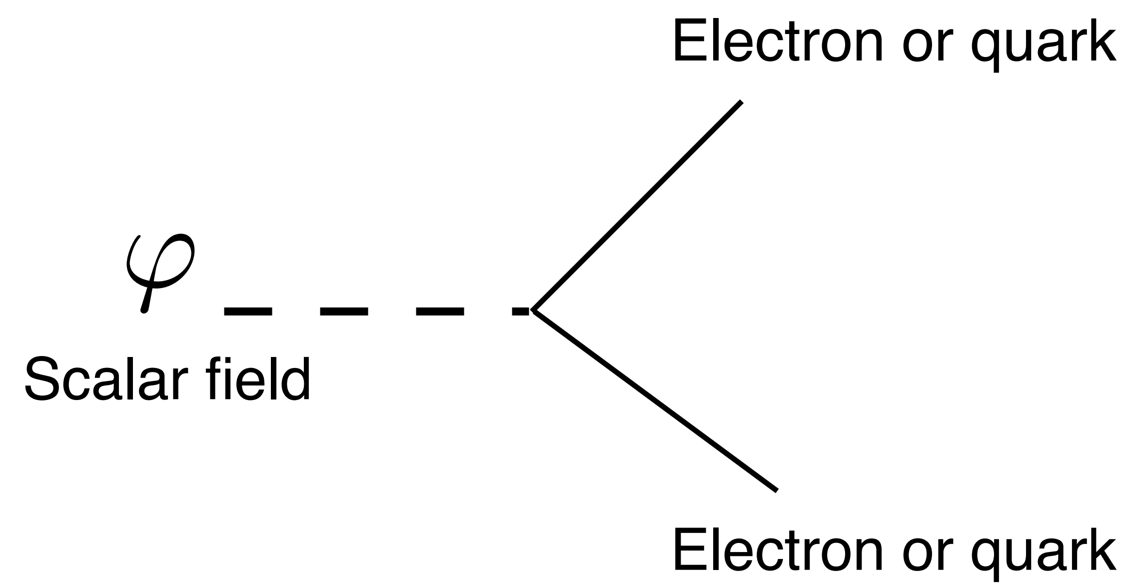
mass of the scalar dark matter



How to detect ultralight dark matter?

Let us assume that dark matter interacts with standard model particles.



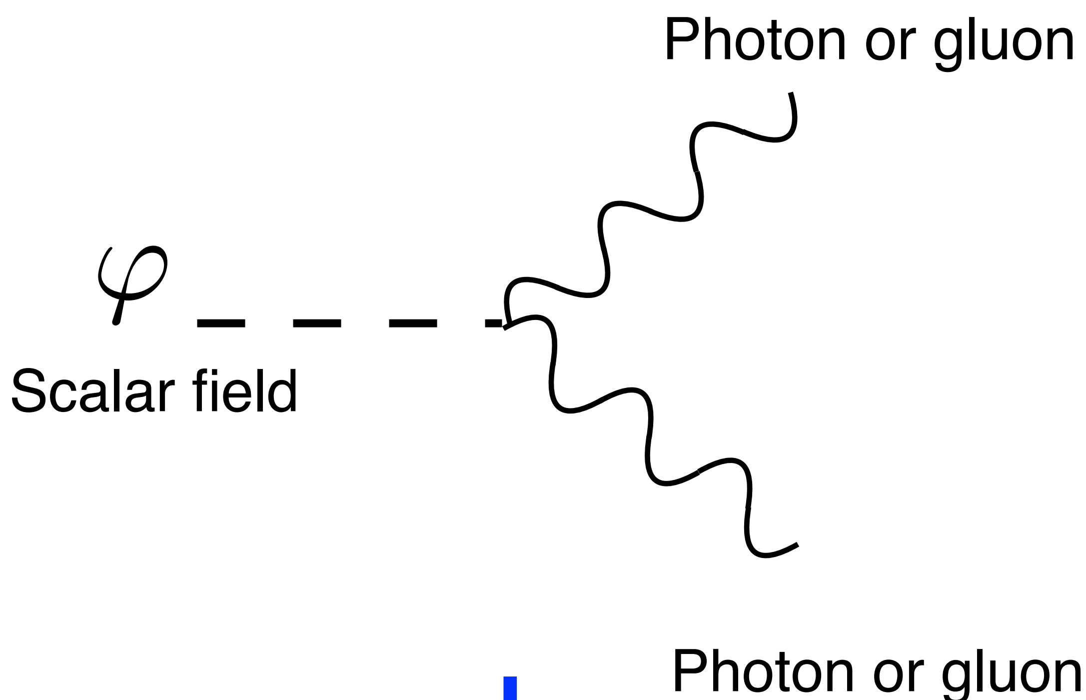


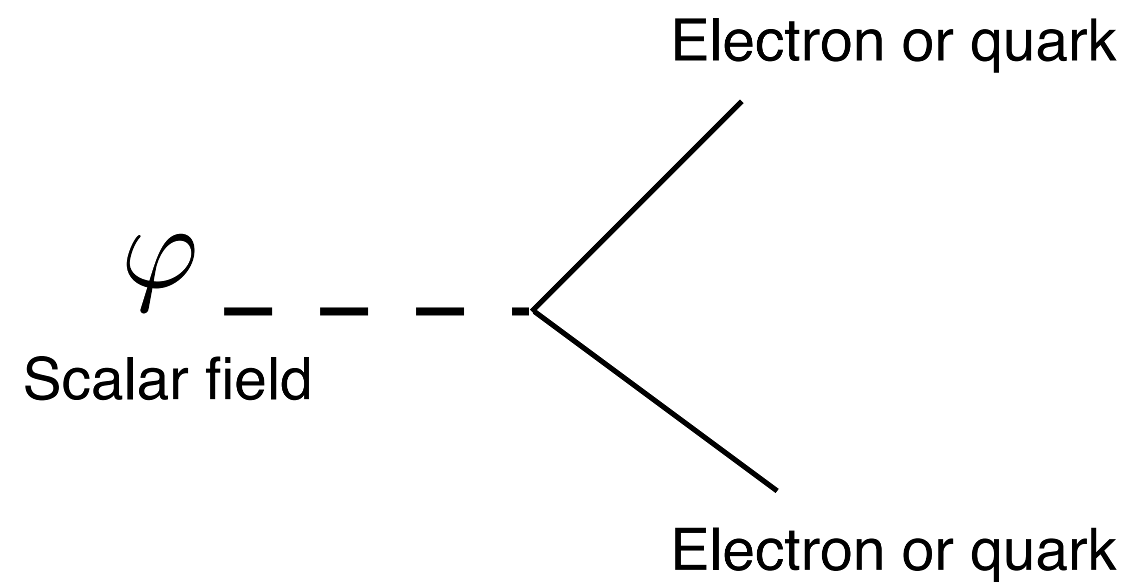
How to detect ultralight dark matter?

Let us assume that dark matter interacts with standard model particles.

$\rightarrow$ **Variations of fundamental constants** might be detected.

T. Damour *et al.*, PRD **82**, 084033 (2010).





Fine structure constant

$$\alpha(\varphi) = \alpha(1 + \underline{d_\alpha}\varphi)$$

QCD energy scale

$$\Lambda_{\mathrm{QCD}}(\varphi) = \Lambda_{\mathrm{QCD}}(1 + \underline{d_g}\varphi)$$

Electron mass

$$m_e(\varphi) = m_e(1 + \underline{d_{m_e}}\varphi)$$

Quark mass

$$m_q(\varphi) = m_q(1 + \underline{d_{m_q}}\varphi)$$

Dimensionless coupling coefficient *d* (<< 1)

Goal of the experiment: detection of these variations

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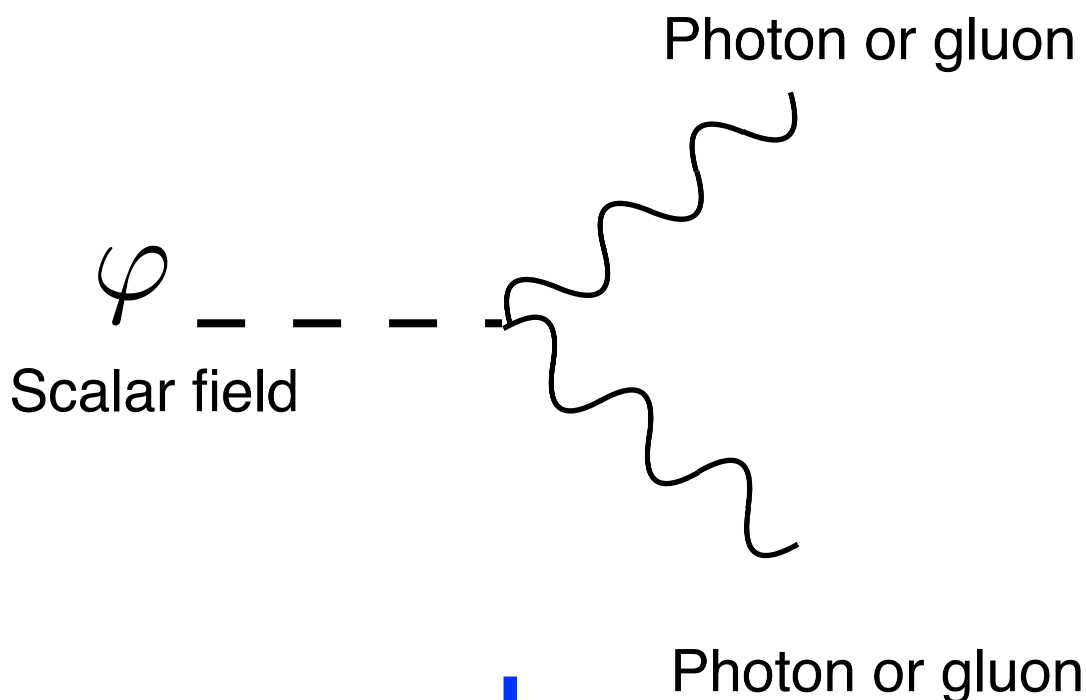

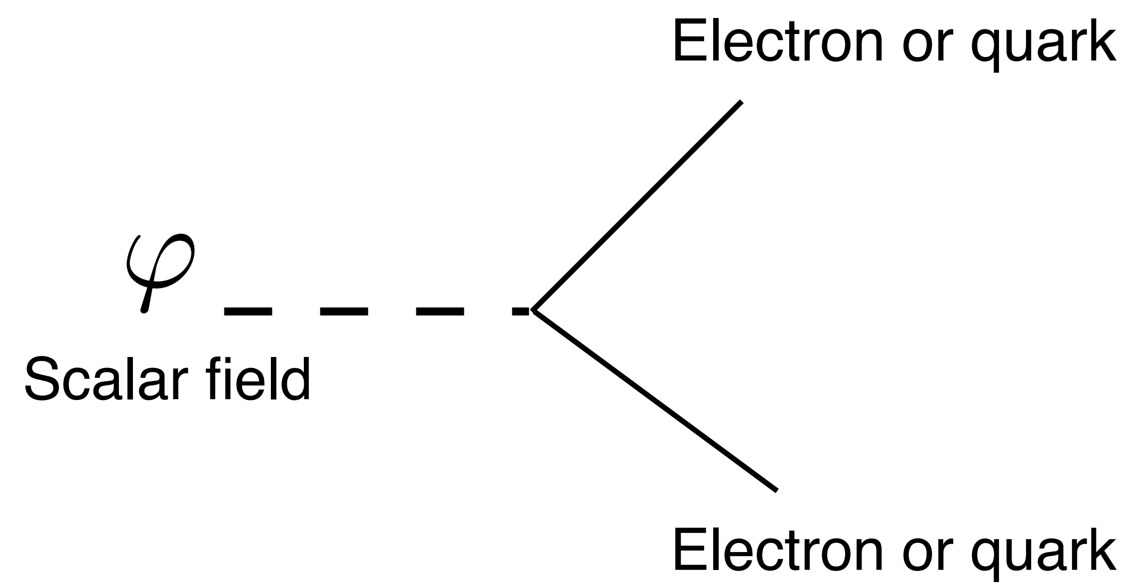

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Dimensionless coupling coefficient *d* (<< 1)

Goal of the experiment: ~~detection of these variations~~ if not

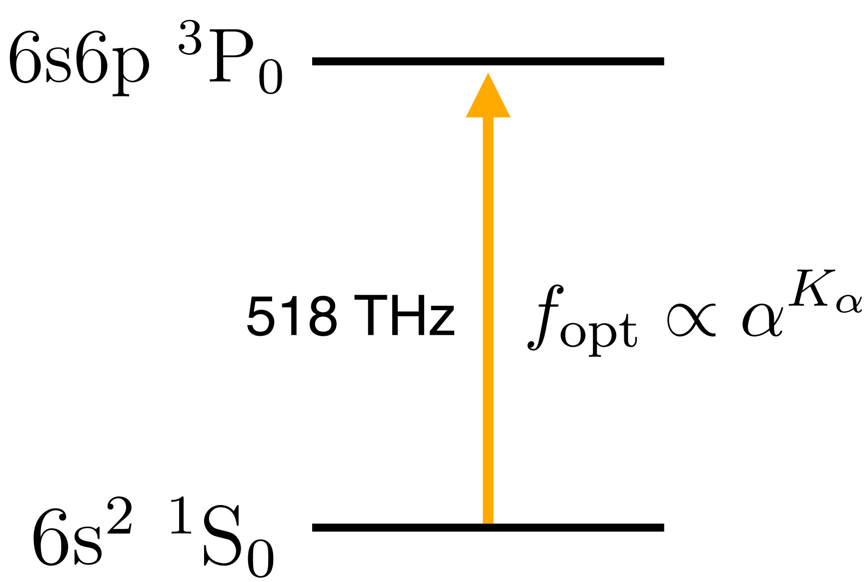
set new limits on coupling coefficients

Detection of variations of fundamental constants
→ Frequency ratio of atomic clocks with different atomic species

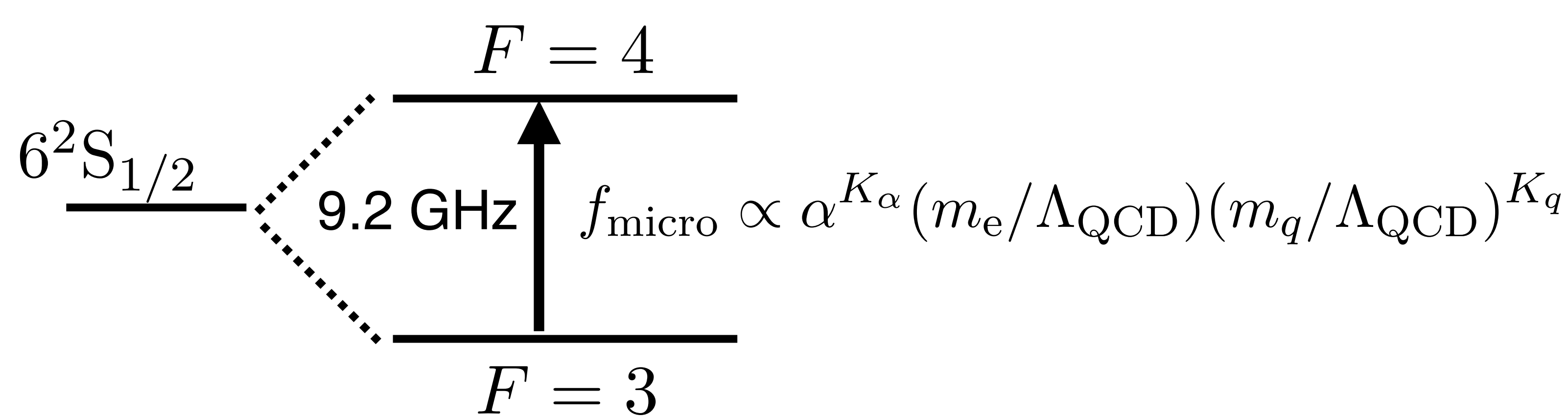
This work: Yb optical lattice clock and Cs fountain clock

$$\frac{\delta(f_{\mathrm{Yb}}/f_{\mathrm{Cs}})}{f_{\mathrm{Yb}}/f_{\mathrm{Cs}}} = -2.52\frac{\delta\alpha}{\alpha} - \frac{\delta(m_e/\Lambda_{\mathrm{QCD}})}{\underline{(m_e/\Lambda_{\mathrm{QCD}})}} + 0.046\frac{\delta(m_q/\Lambda_{\mathrm{QCD}})}{(m_q/\Lambda_{\mathrm{QCD}})}$$

Sensitive to the electron mass variation in the optical-microwave comparison



Electronic transition of Yb



Hyperfine transition of Cs

V. V. Flambaum *et al.*, PRD **69**, 115006 (2004).

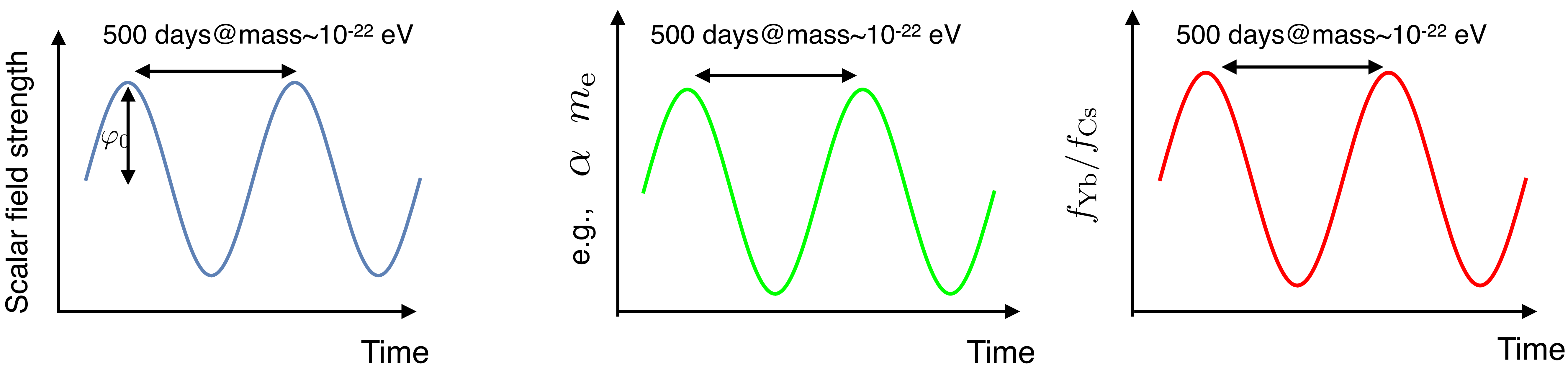
Search for harmonic oscillation signals from the Yb/Cs data

Long-term comparison is essential to detect the dark matter at ~10^{-22} eV.

The atomic clocks must be robust for long-term comparison.

Oscillating scalar field → Oscillating fundamental constants → Oscillating frequency ratio

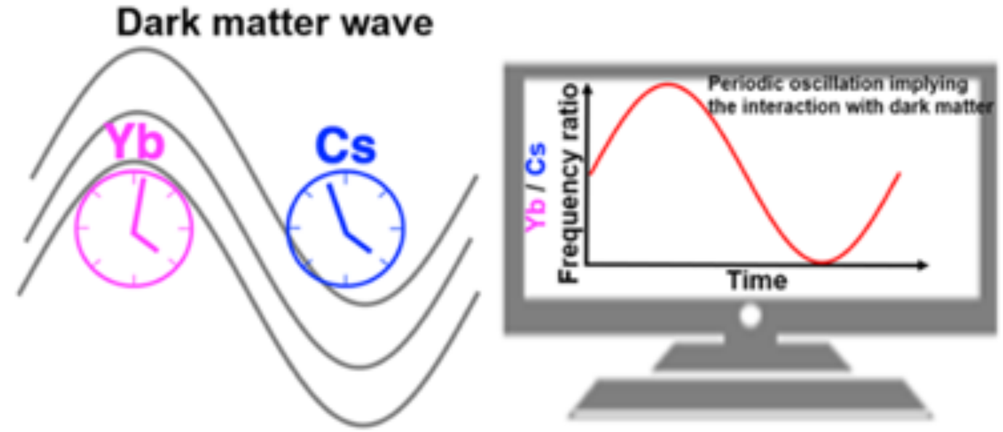
$f = m_\varphi c^2/h$



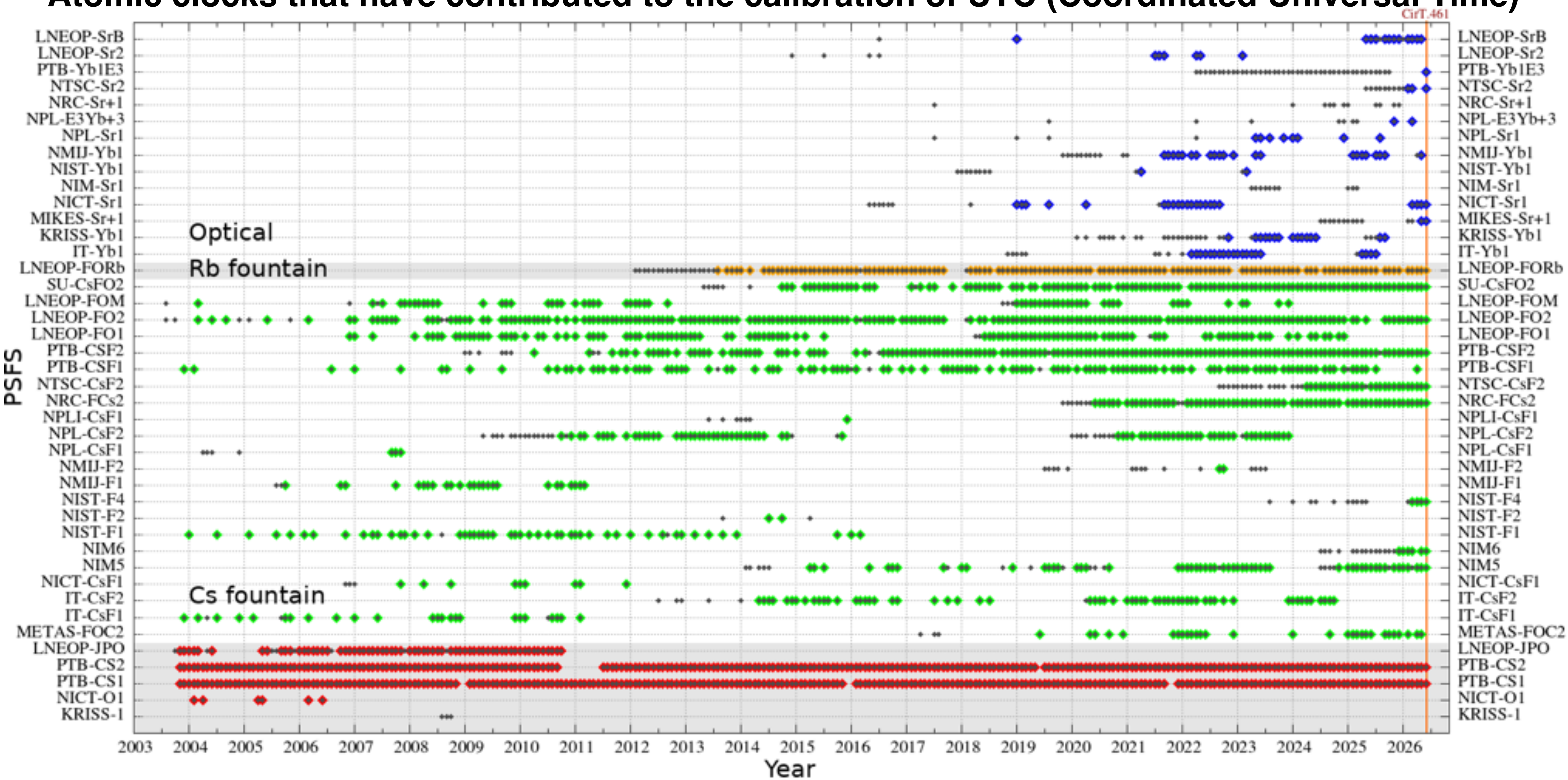
A. Arvanitaki *et al.*, PRD **91**, 015015 (2015).

Metrology → Search for dark matter

→



Atomic clocks that have contributed to the calibration of UTC (Coordinated Universal Time)



Metrology → Search for dark matter

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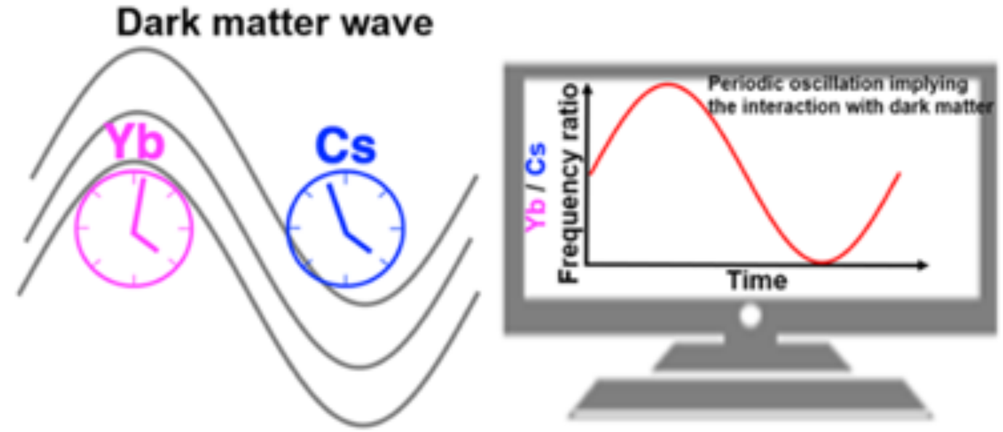

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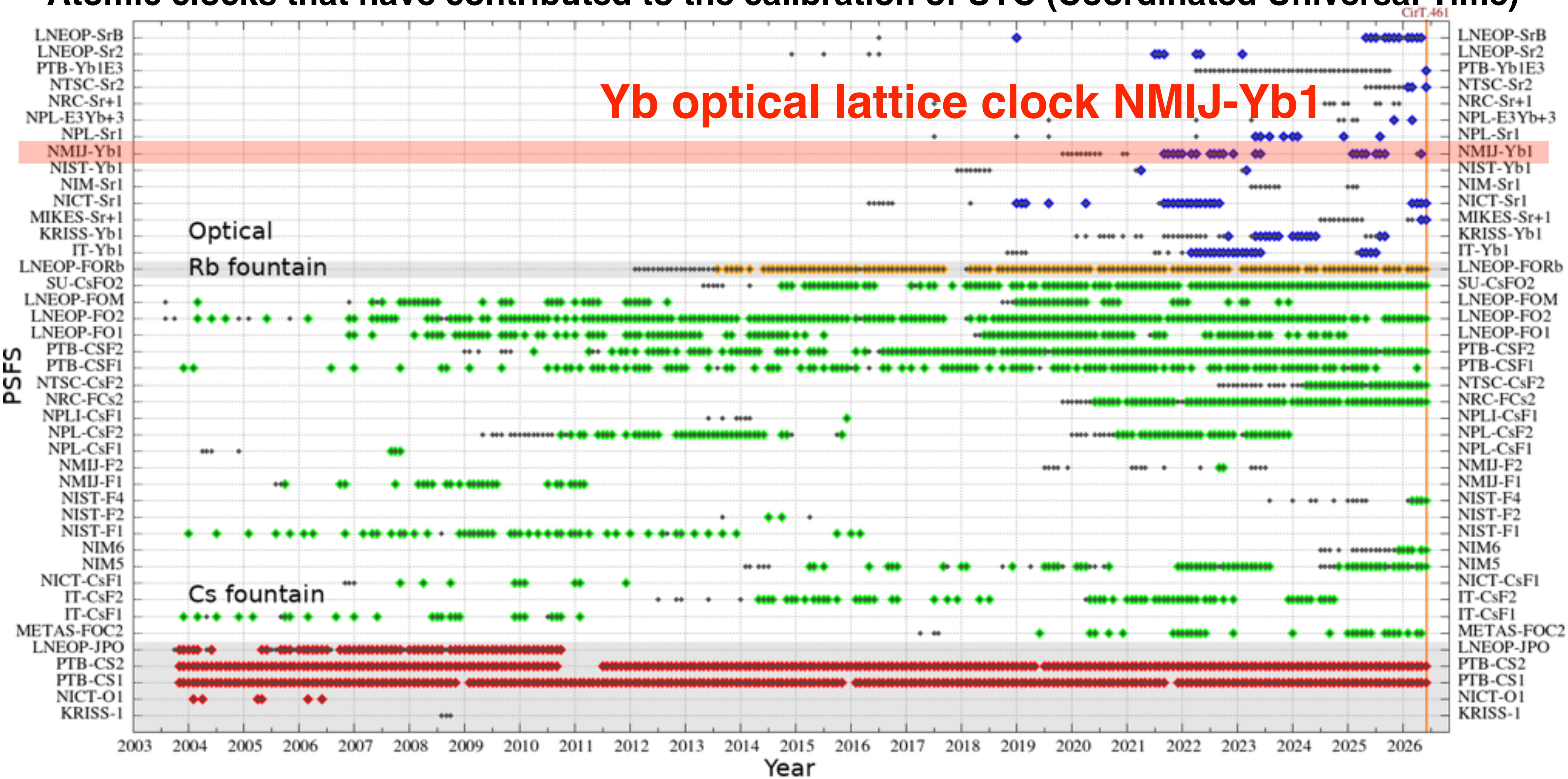

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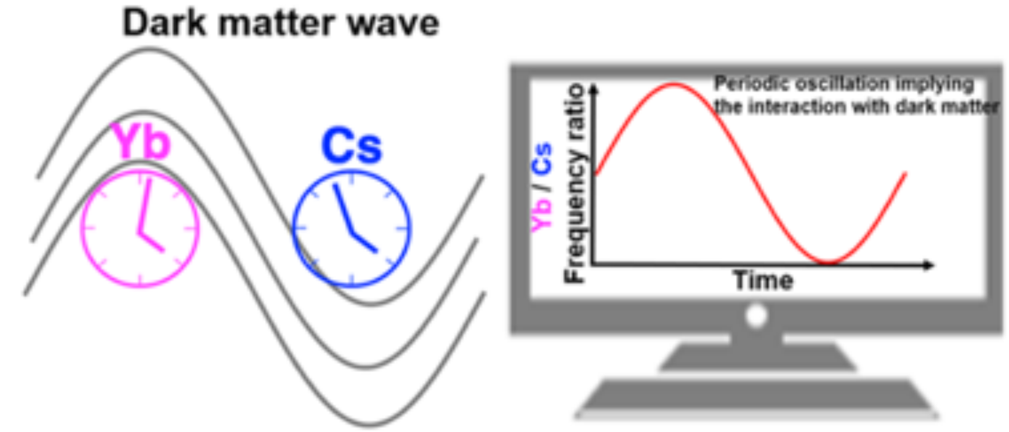

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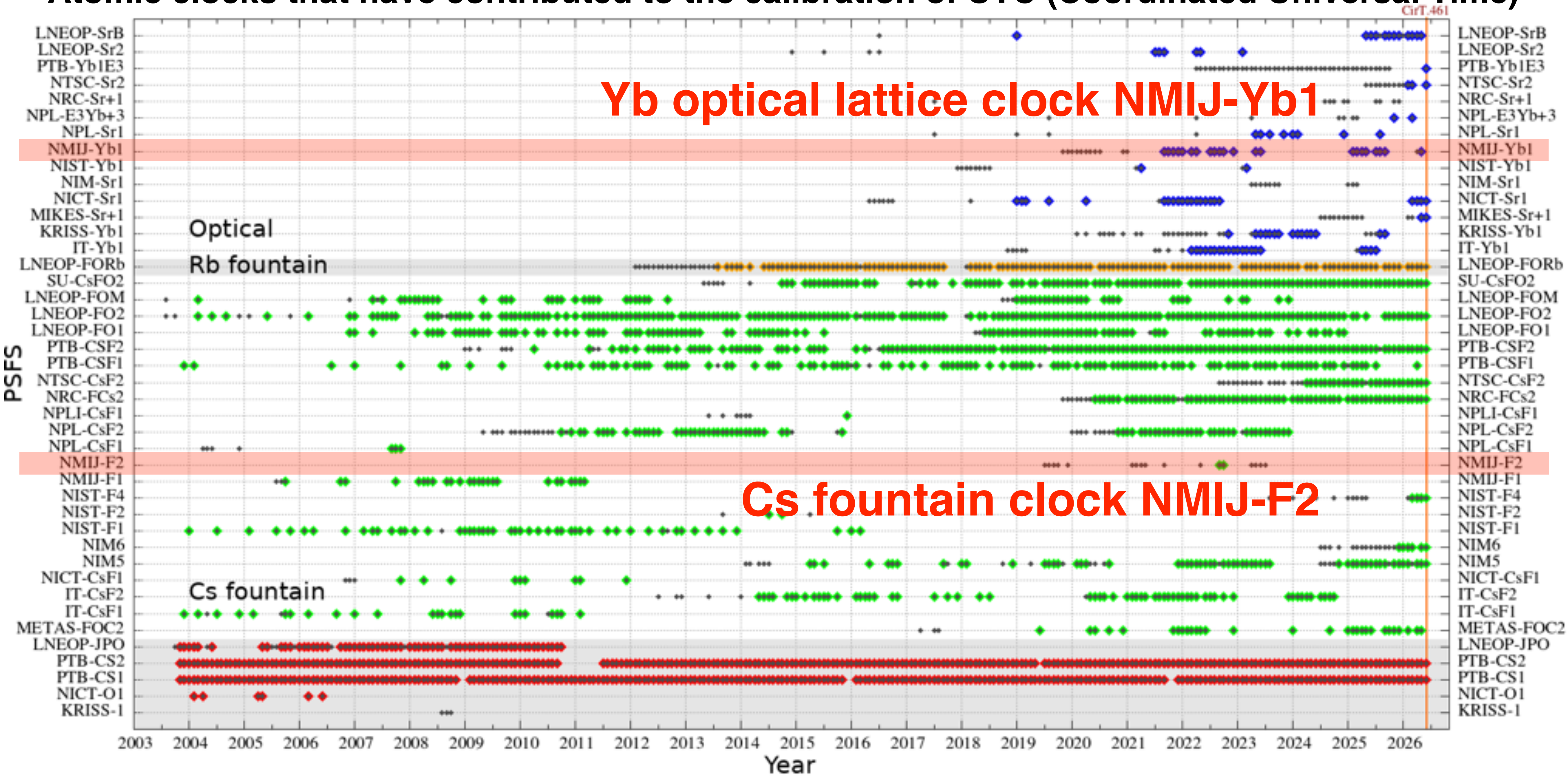
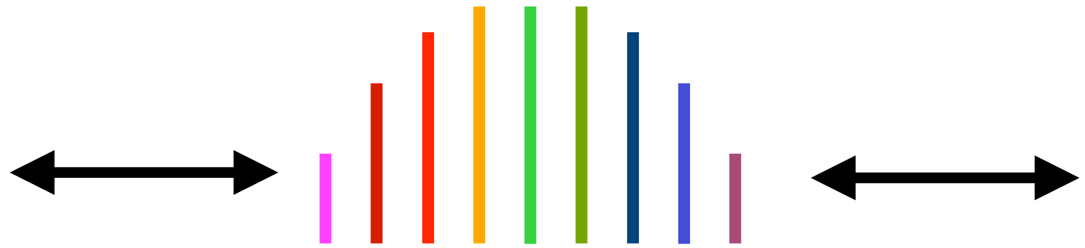


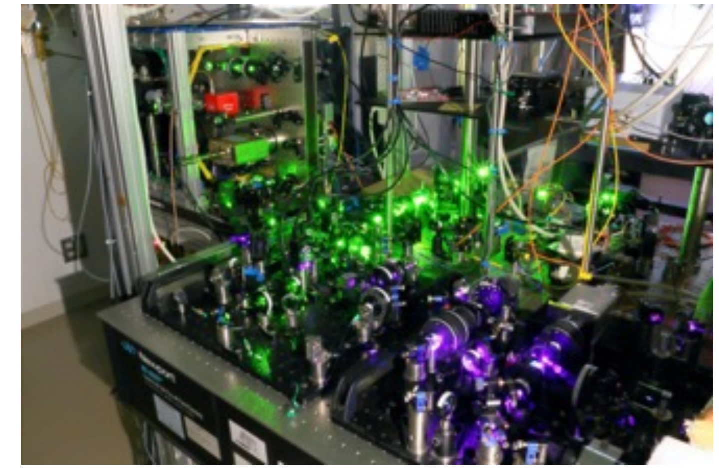
Yb/Cs comparison

Cs fountain clock
NMIJ-F2

A. Takamizawa *et al.*, Metrologia **59**, 035004 (2022).

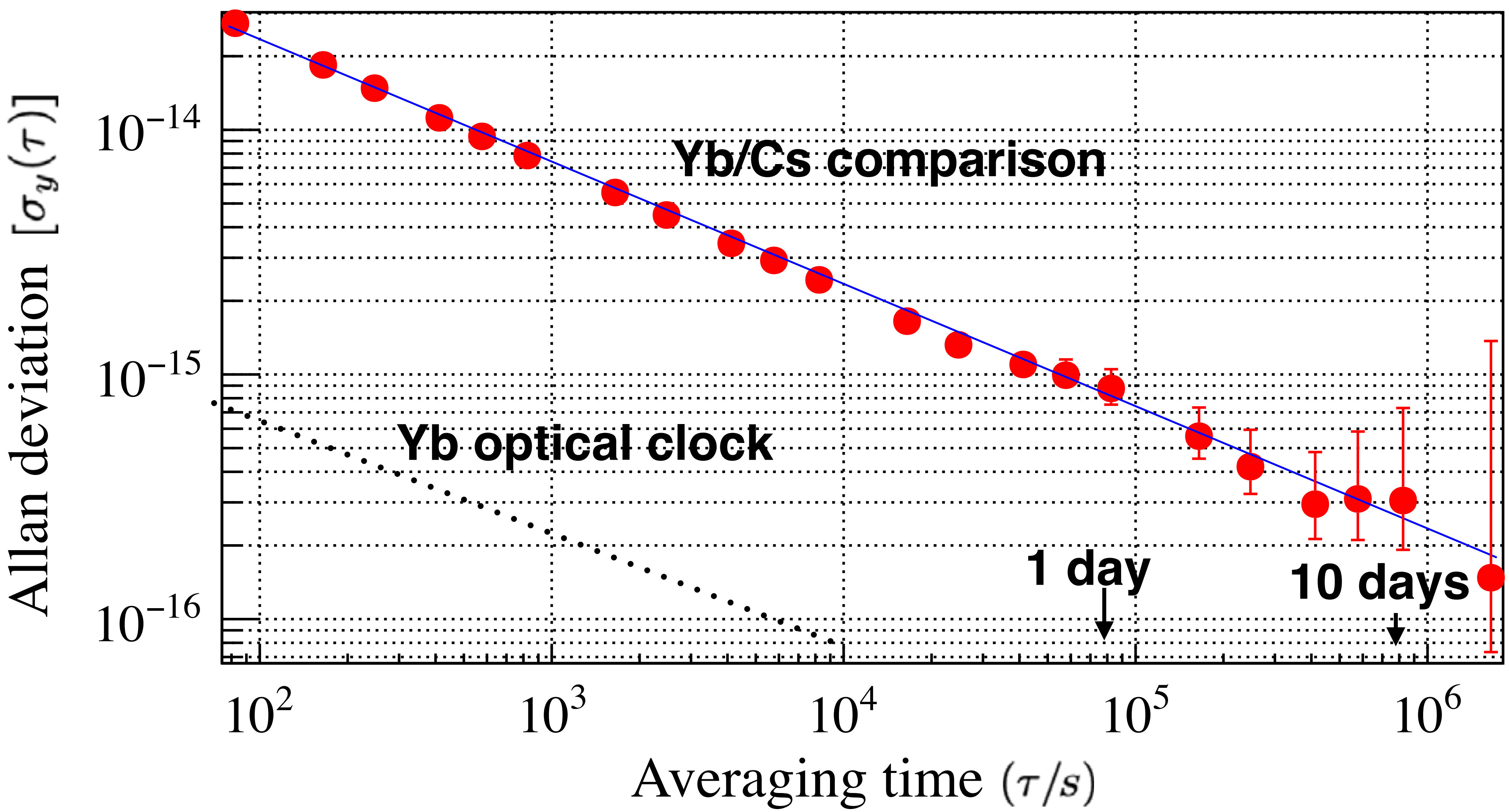


H. Inaba *et al.*, Opt. Express **12**, 5223 (2006).



Yb optical lattice clock
NMIJ-Yb1

T. Kobayashi *et al.*, Metrologia **57**, 065021 (2020).



Yb/Cs ratio data used for the dark matter search

Fitting was employed to obtain the amplitude of the oscillation signal

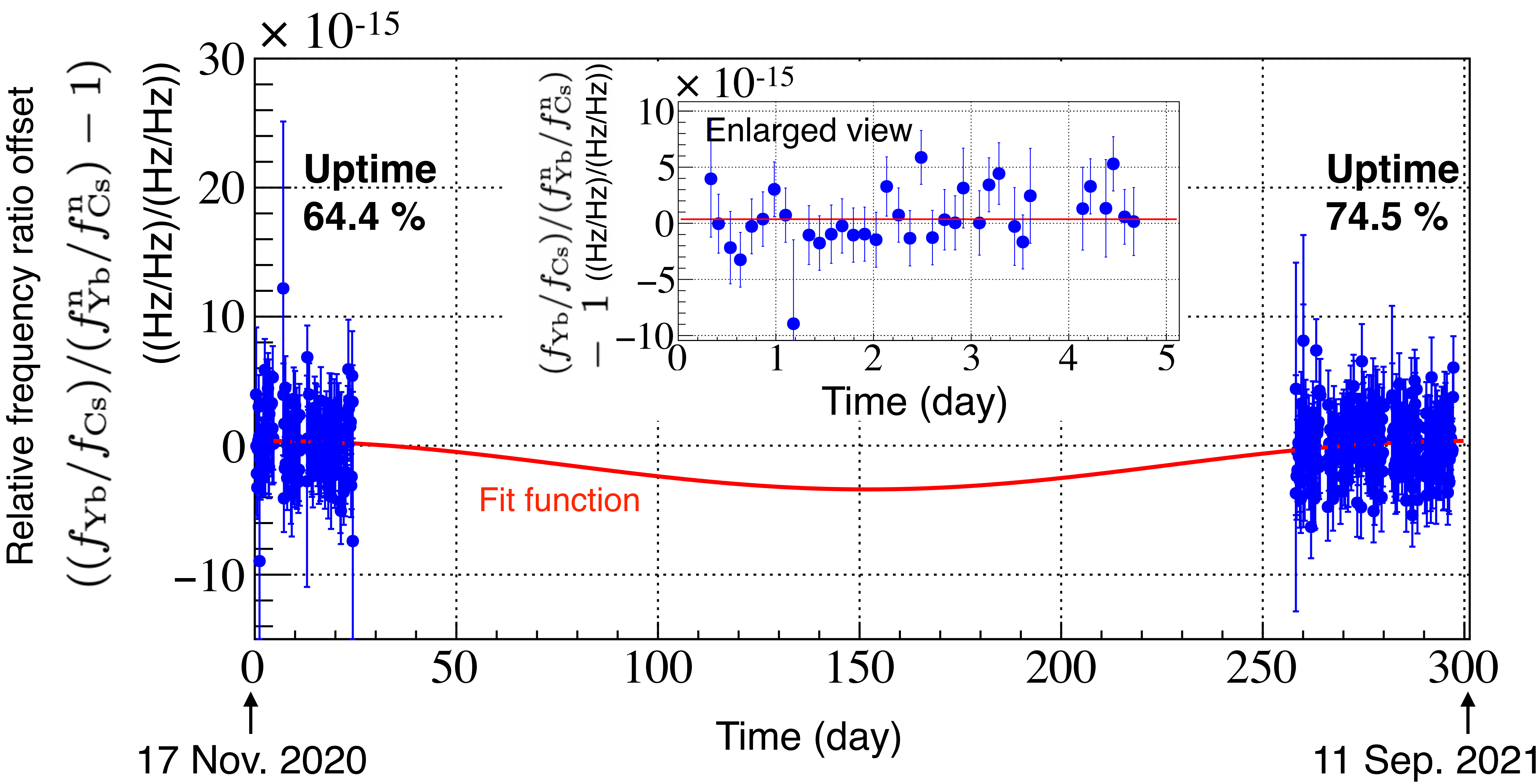
Fit function

$$\underline{p_1}\cos(2\pi f t) + \underline{p_2}\sin(2\pi f t) + \underline{p_3} \rightarrow$$

Free parameter

Amplitude

$$A = \sqrt{p_1^2 + p_2^2}$$

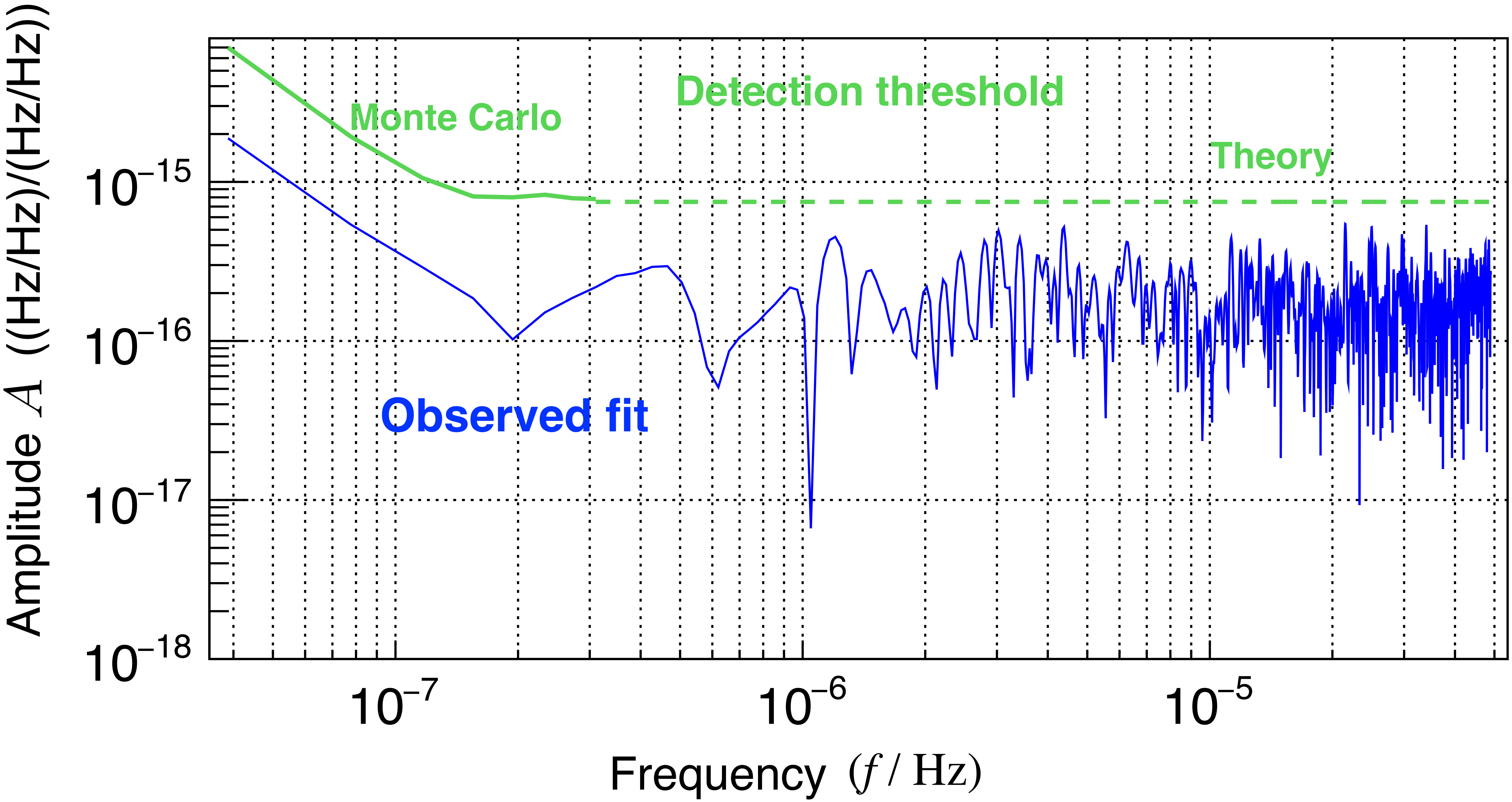


Amplitude spectrum

We define the detection threshold such that the probability of finding a noise above this threshold is 5% for a search involving many frequency bins (1262 bins in this case).

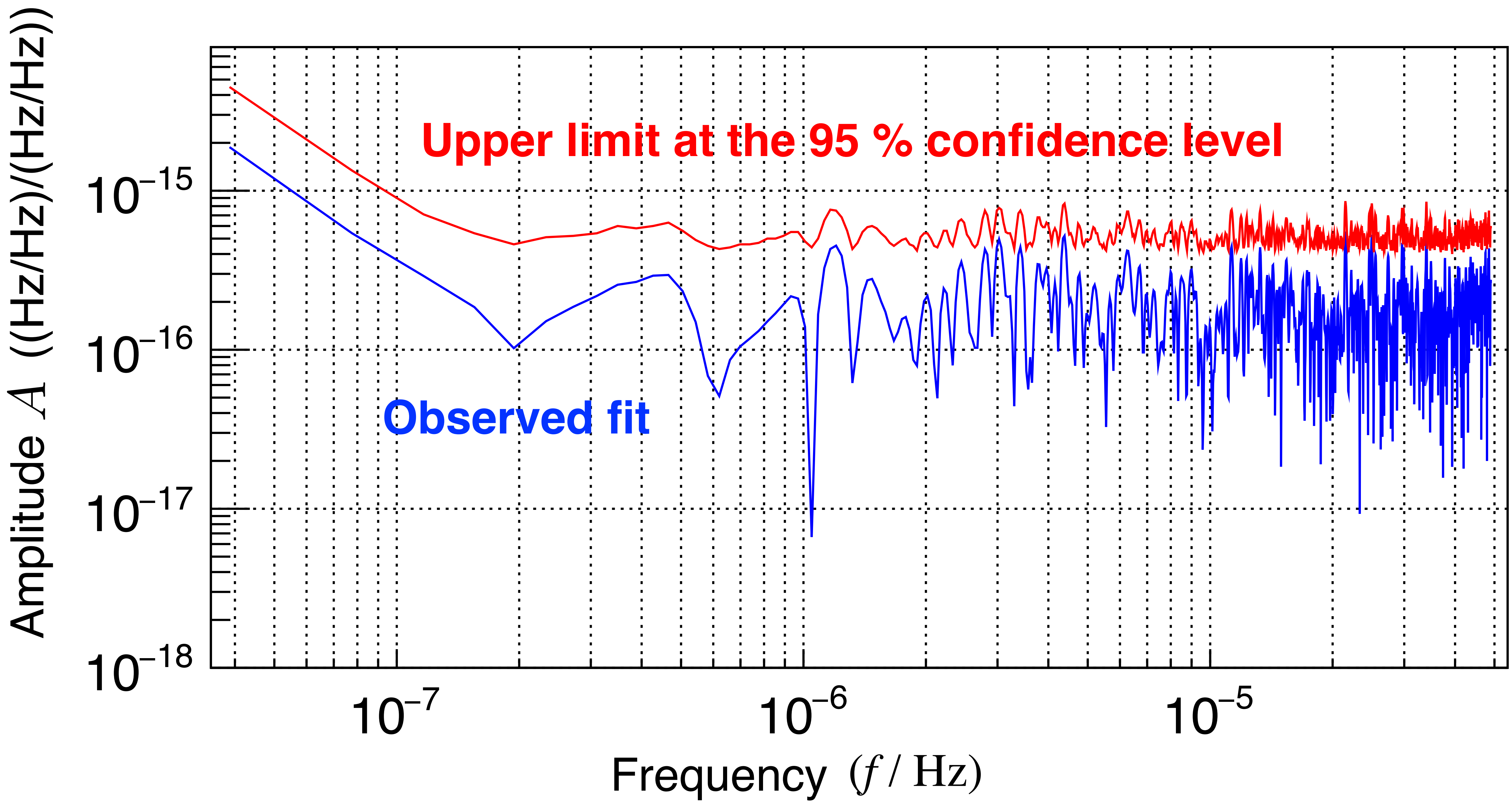
e.g., A. Hees *et al.*, PRL **117**, 061301 (2016).
P. Wscilo *et al.*, Sci. Adv. **4**, eaau4846 (2018).

No signals exceeding the detection threshold



Limits on the amplitudes of the oscillation signals

Monte Carlo method based on the white frequency noise model



Limits on *A* → Limits on the coupling coefficients

Variations of fundamental constants

Coupling coefficients

$$\alpha(\varphi) = \alpha(1 + \underline{d_\alpha}\varphi) \qquad m_q(\varphi) = m_q(1 + \underline{d_{m_q}}\varphi)$$

$$m_e(\varphi) = m_e(1 + \underline{d_{m_e}}\varphi) \qquad \Lambda_{\mathrm{QCD}}(\varphi) = \Lambda_{\mathrm{QCD}}(1 + \underline{d_g}\varphi)$$

Variation of the Yb/Cs frequency ratio

$$\frac{\delta(f_{\mathrm{Yb}}/f_{\mathrm{Cs}})}{f_{\mathrm{Yb}}/f_{\mathrm{Cs}}} = -2.52\frac{\delta\alpha}{\alpha} - \frac{\delta(m_e/\Lambda_{\mathrm{QCD}})}{(m_e/\Lambda_{\mathrm{QCD}})} + 0.046\frac{\delta(m_q/\Lambda_{\mathrm{QCD}})}{(m_q/\Lambda_{\mathrm{QCD}})}$$

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$$\varphi(t) \sim \varphi_0 \cos(2\pi f t)$$

Relationship between *A* and φ_0

$$A = [-2.52 d_\alpha - d_{m_\mathrm{e}} + 0.046 d_{m_q} + 0.954 d_g]\varphi_0$$

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φ_0 is estimated from the local dark matter density $\rho_{\rm DM}(= 0.3\,{\rm GeV/cm^3})$

$$\varphi_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m}\sqrt{\frac{4\pi G\hbar^2}{c^6}}$$

Relationship between *A* and the coupling coefficients

$$A = [-2.52 d_\alpha - d_{m_e} + 0.046 d_{m_q} + 0.954 d_g]\sqrt{\frac{2G\rho_{\rm DM}}{\pi f^2 c^2}}$$

New limits on the electron and gluon couplings by our Yb/Cs measurement

T. Kobayashi *et al.*, Phys. Rev. Lett. **129**, 241301 (2022).

Shaded area: excluded at the 95% confidence level

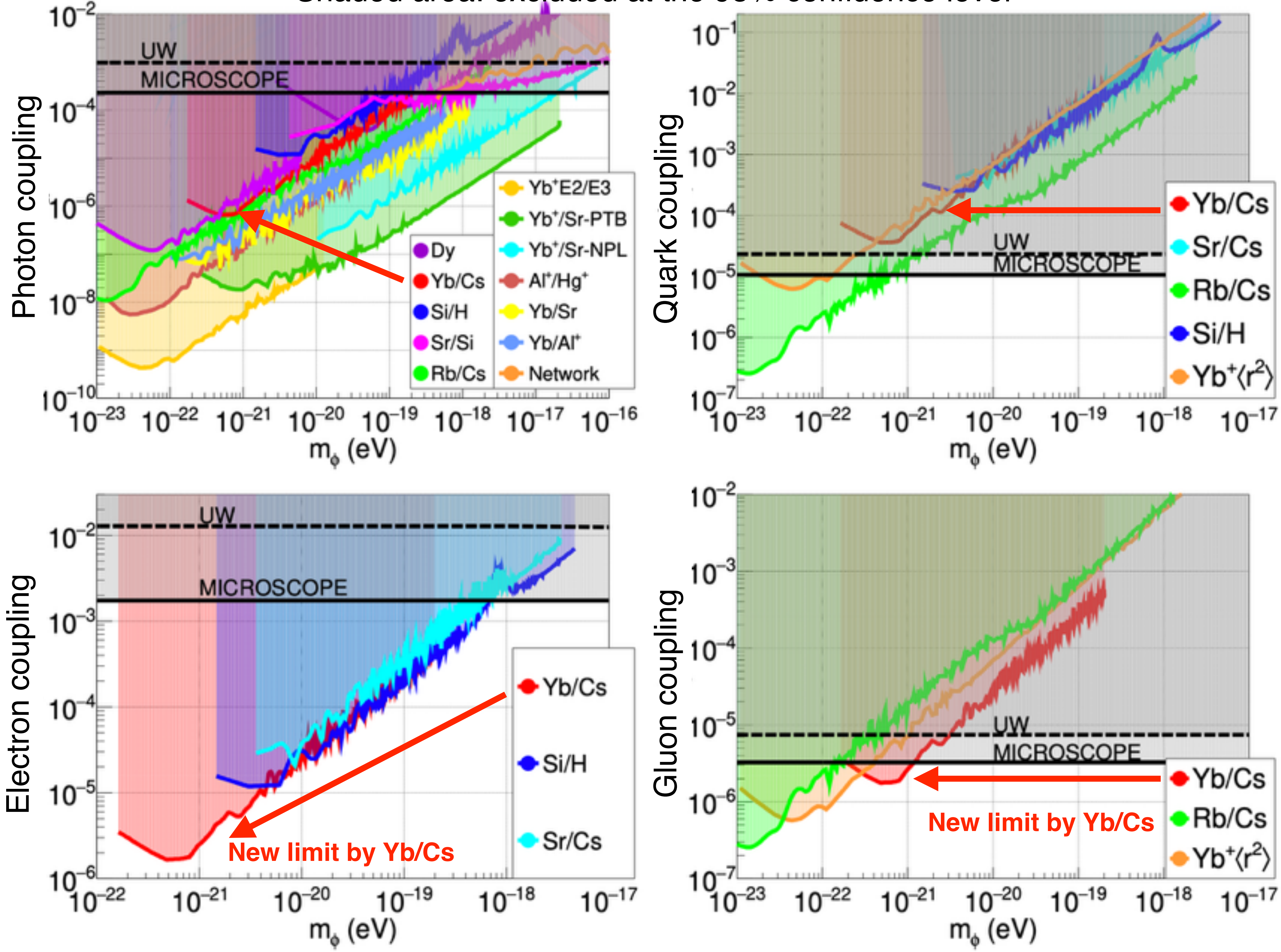
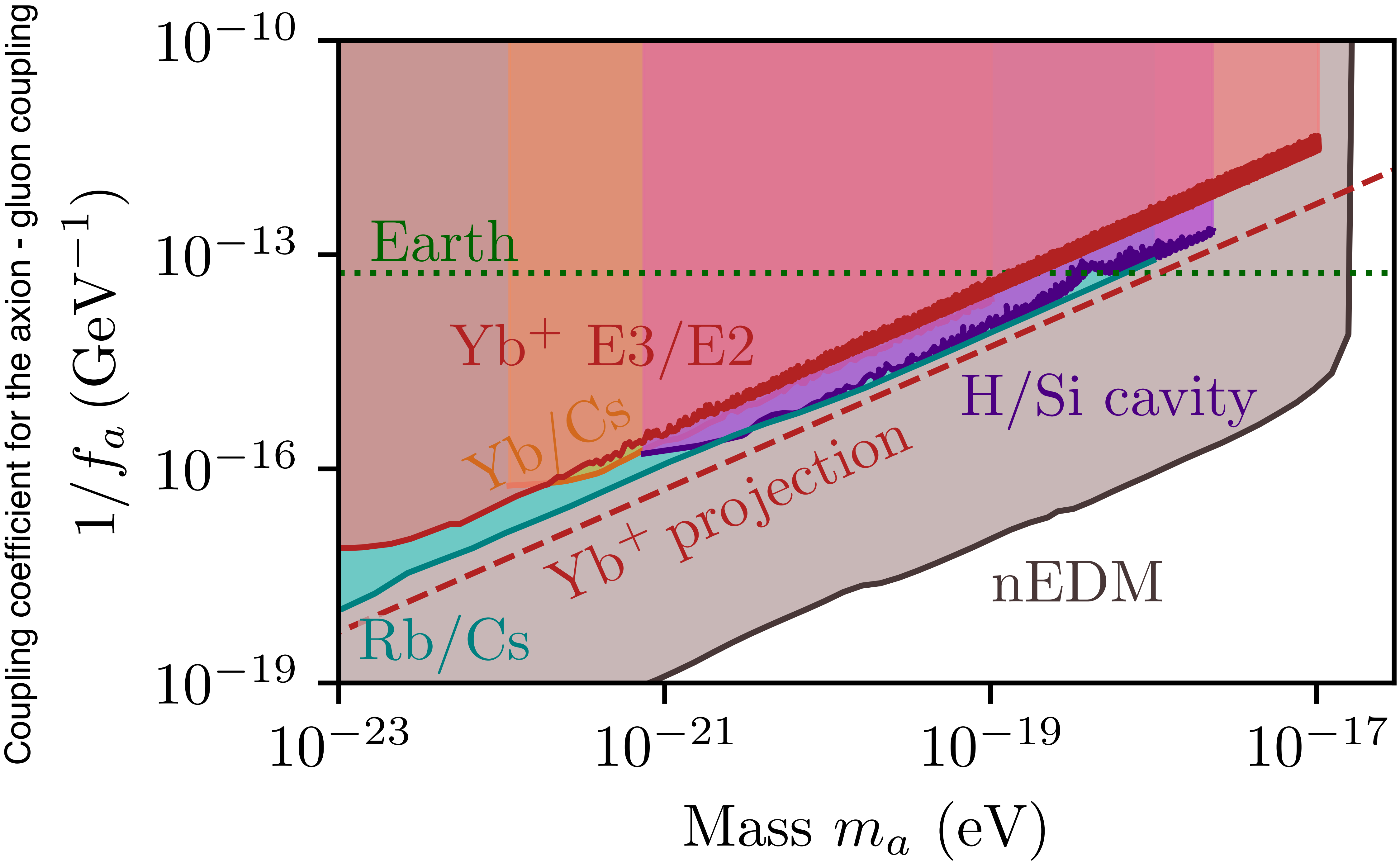


Figure taken from A. Kawasaki, Applied Physics Review **12**, 041331 (2025).

Axion - gluon coupling

Axion-gluon coupling changes the pion mass
→nuclear g-factor and proton mass are varied.

$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu},$$



H. Kim *et al.*, Phys. Rev. D **109**, 015005 (2024).

A. Banerjee *et al.*, Phys. Rev. Lett. **135**, 223001 (2025).

Summary

- Overview of the search for ultralight dark matter with atomic clocks

- Search for ultralight dark matter from long-term comparisons between an Yb optical lattice clock and a Cs fountain clock

T. Kobayashi *et al.*, Phys. Rev. Lett. **129**, 241301 (2022).

- Improved limit on the coefficient of the electron coupling by up to three orders of magnitude

- Plan to continue the operation of the atomic clocks and improve the limits in the future