Probing dark sector with atomic clocks

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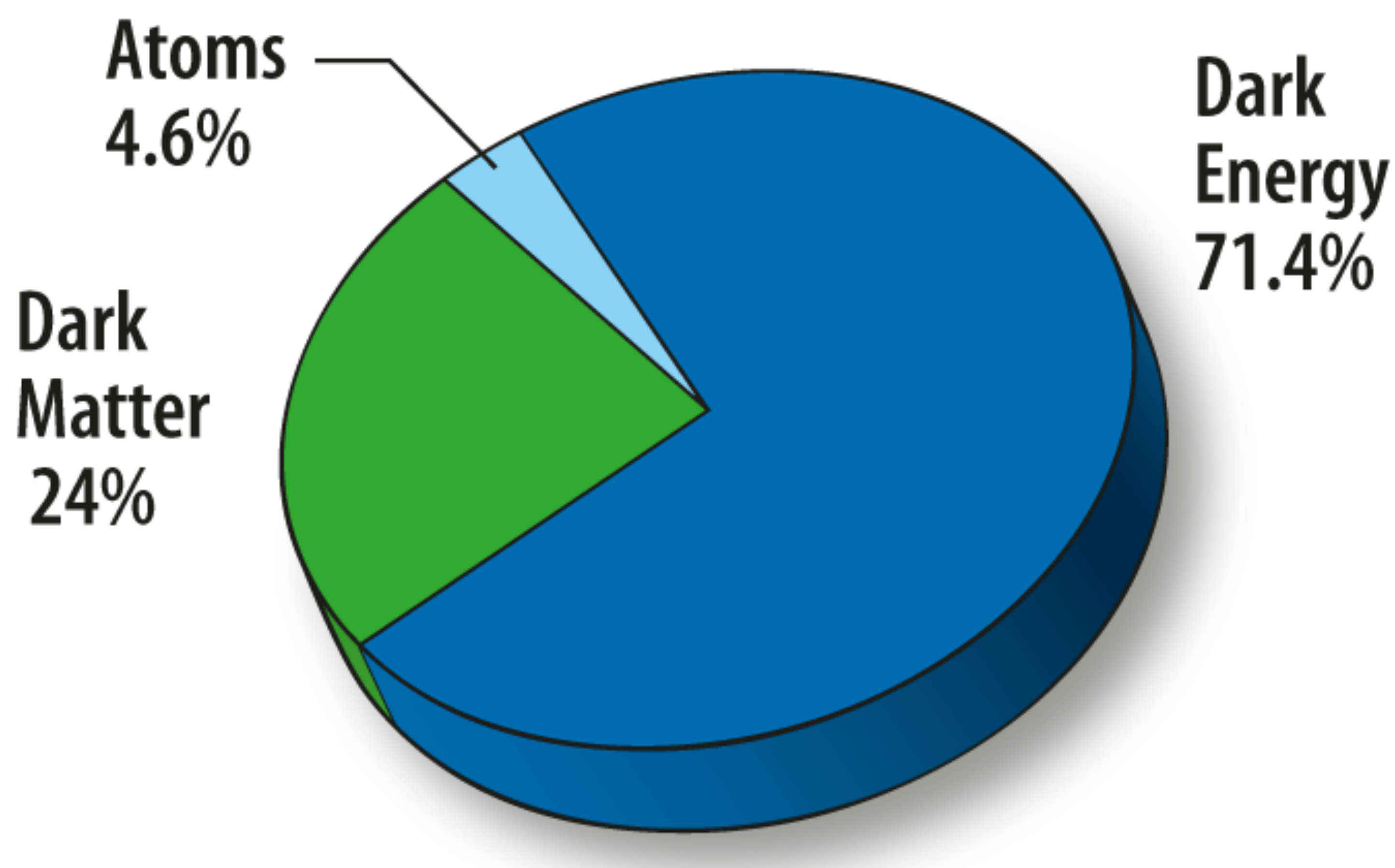
Problem of dark matter/dark energy



Fundamental constants mask our ignorance

Fundamental constant is any parameter **not** determined by the theory in which it appears

- Standard model: 28 parameters (masses, α, $\hbar$, c, …)
- Cosmology: +12 parameters (e.g., Hubble)

SM: constants are constant
BSM: constants become dynamical variables (fields)
can vary in space and time

Reviews:

J.-P. Uzan, Living Rev. Relativ. 14, (2011)
J.-P. Uzan, Comptes Rendus Phys. 16, 576 (2015)

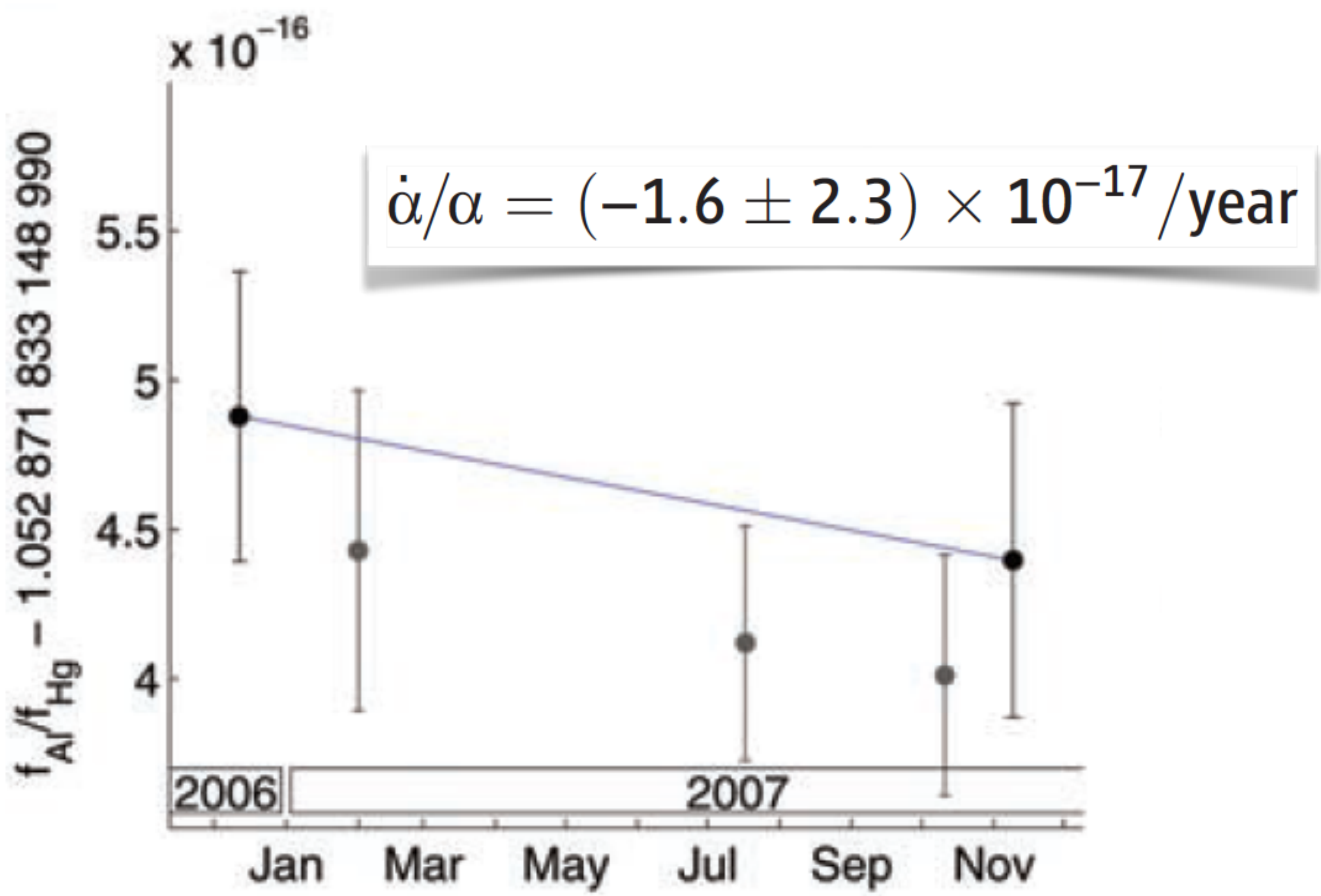
What if dark matter and/or dark energy fields drive fundamental constants?

Slow drifts of fundamental constants

$$\nu_{\text{clock}}\left(\alpha, \frac{m_q}{\Lambda_{\text{QCD}}}, \frac{m_e}{m_p}\right)$$

$$\frac{\delta\nu(t)}{\nu_0} = \sum_{X=\text{fnd consts}} K_X \frac{\delta X(t)}{X} = K_\alpha \frac{\delta\alpha(t)}{\alpha} + \ldots$$

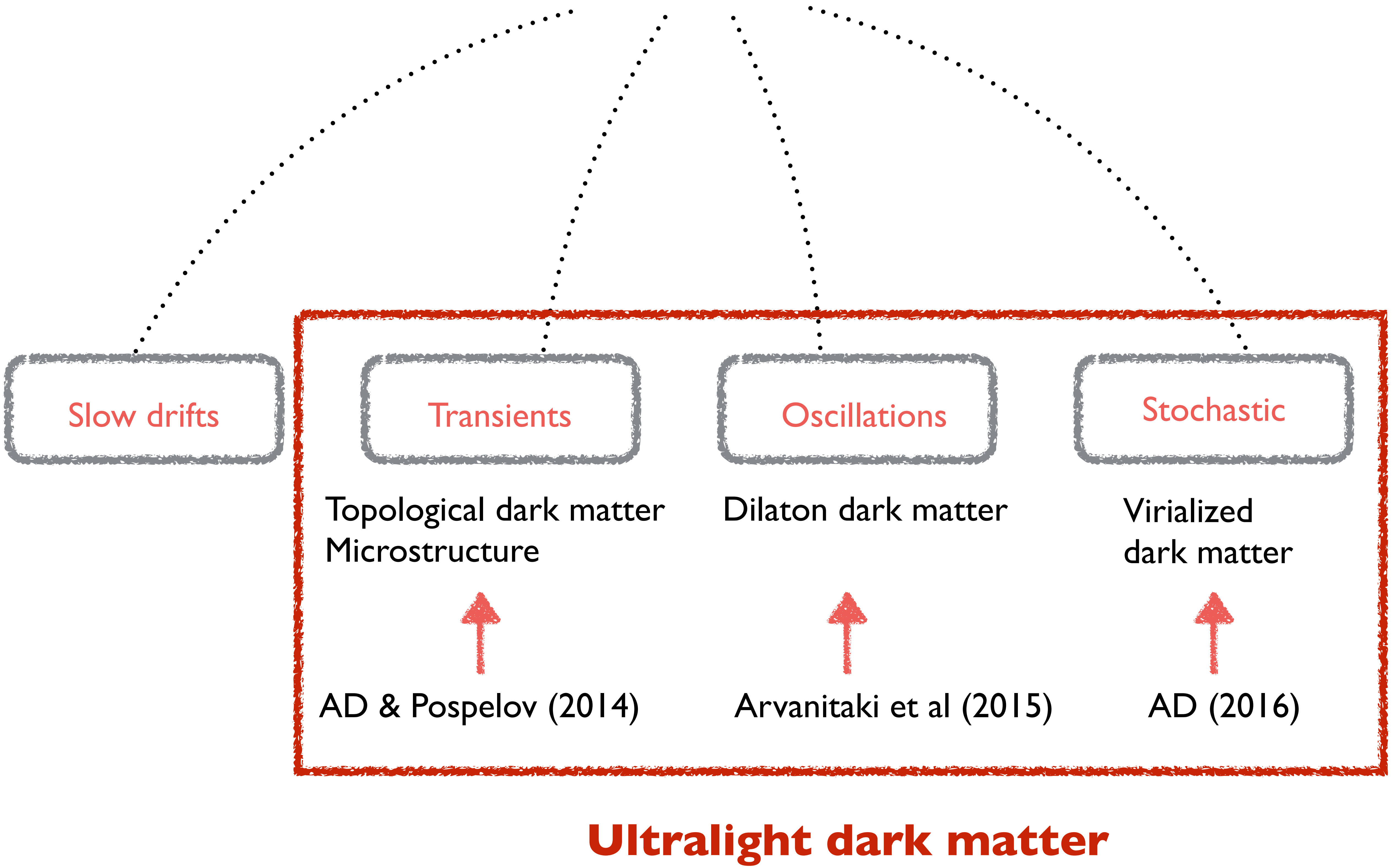
Compare ratio of frequencies of two clocks with different sensitivities



T. Rosenband, et al. Science 319, 1808 (2008)

Latest: *Godun,…Gill, PRL 113, 210801 (2014); Huntemann,… Peik, PRL 113, 210802 (2014)*

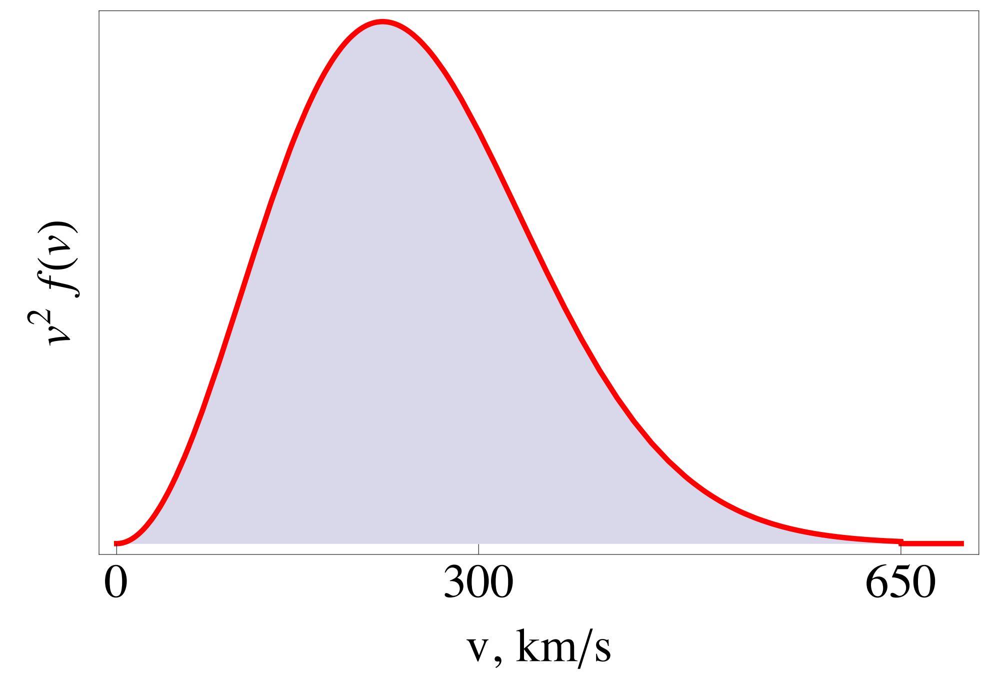
Variations of fundamental constants



What do we know about dark matter?

Dark Matter halo

Velocity distribution



Galactic orbital motion

$$v_g \sim 300\,\mathrm{km/s}$$

Energy density

$$\rho_{\mathrm{DM}} \approx 0.4\,\mathrm{GeV/cm^3}$$

Dark matter signatures and atomic clocks

Clocks monitor atomic transition frequencies

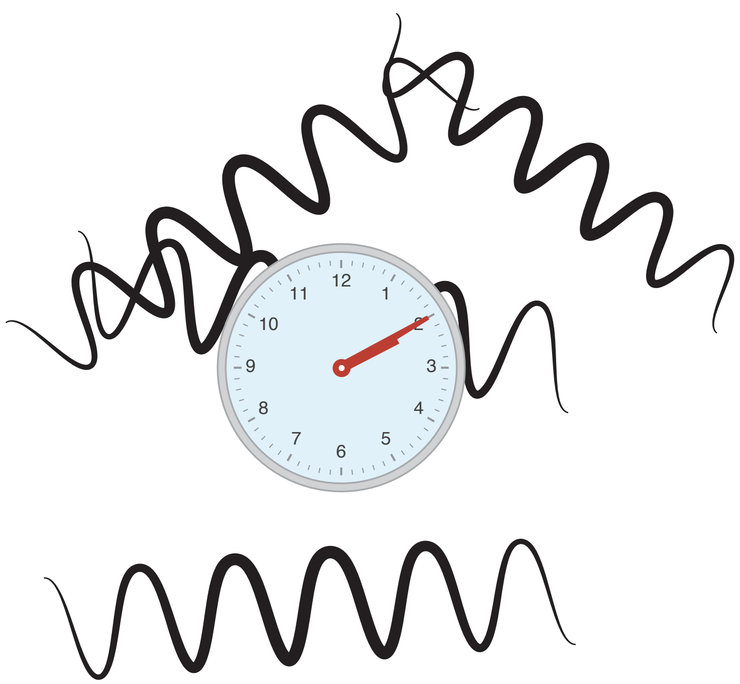
These depend on fundamental constants

$$\Rightarrow$$

Search for variation of fundamental constants
that is consistent with DM models

Ultralight DM and atomic clocks

non-interacting fields

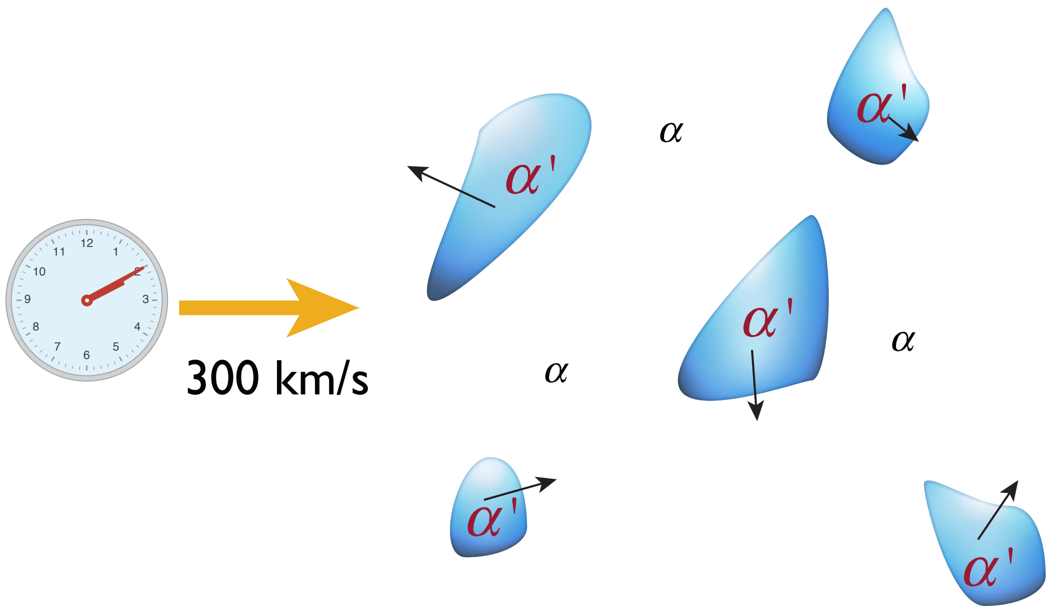


Oscillating variations of fund. const

Arvanitaki et al. PRD 91, 15015 (2015)

[Really stochastic]

self-interacting fields

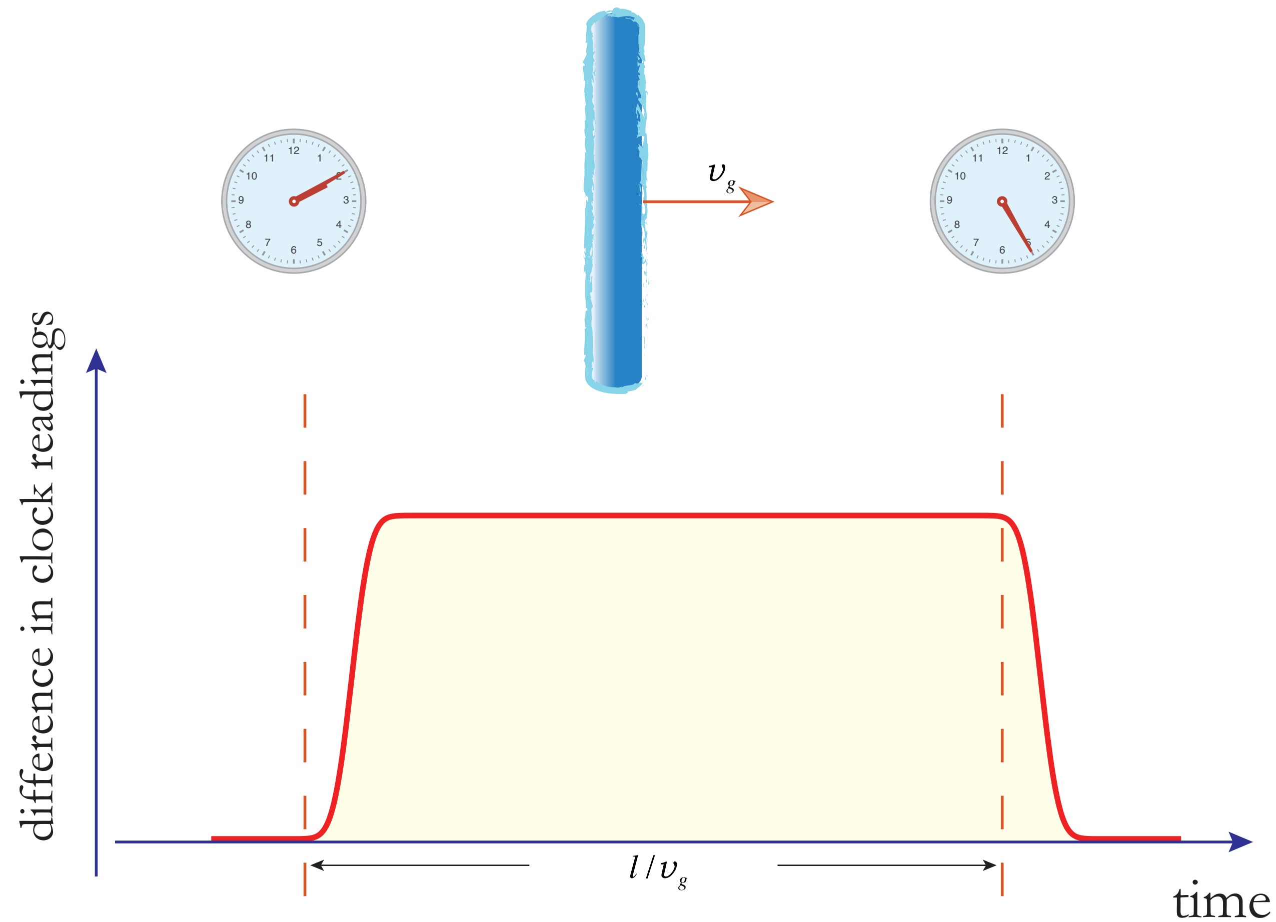


Transient variations of fund. const

Derevianko & Pospelov, Nature Phys. 10, 933 (2014)

Dark matter transients

Dark matter signature

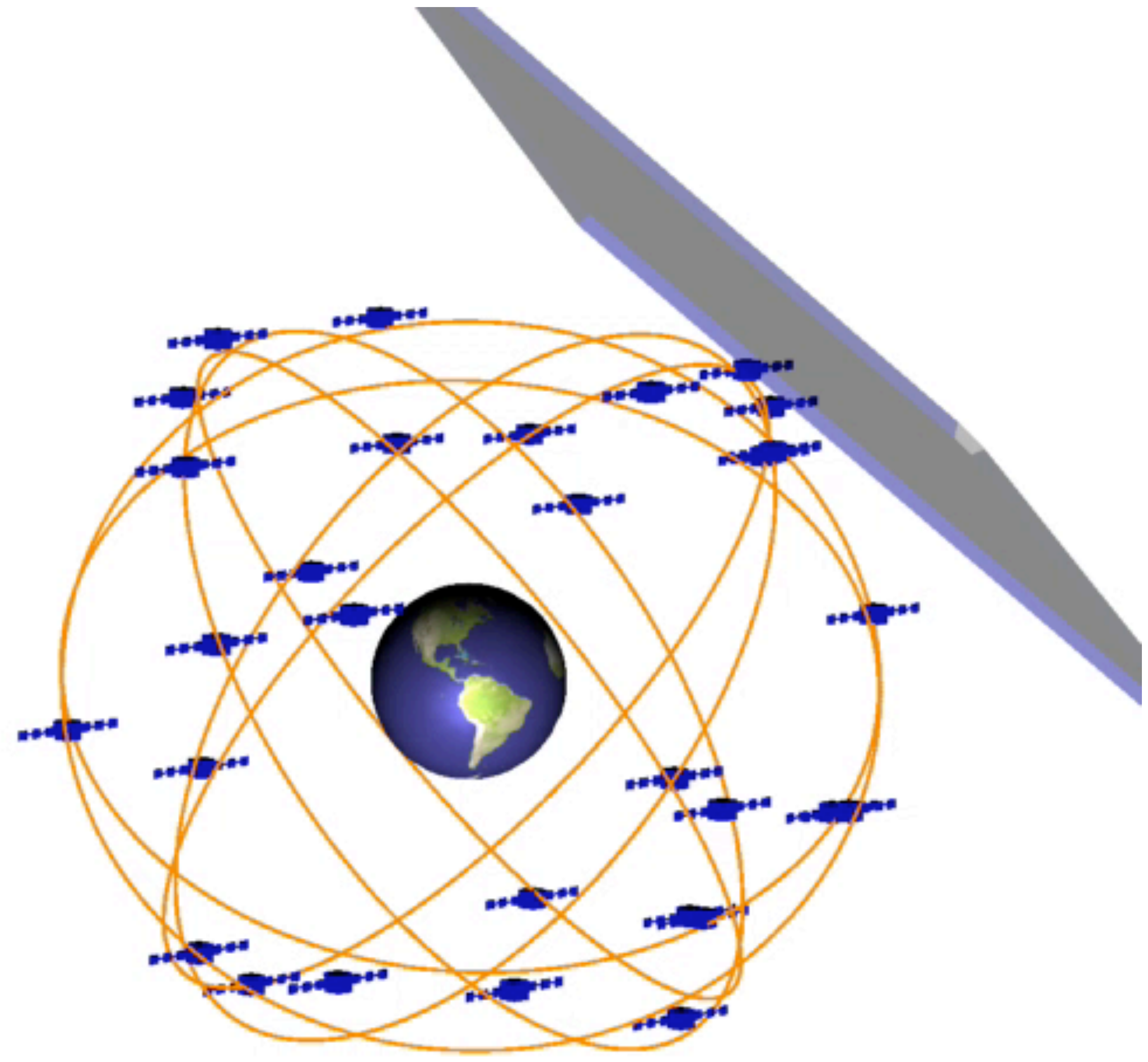


Monitor time difference b/w two spatially-separated clocks
⇒ persistent clock discrepancy for over time l/v_g

GPS aperture =50,000 km => l/v_g~ 150 sec

Derevianko & Pospelov, Nature Phys. 10, 933 (2014)

Domain wall GPS sweep

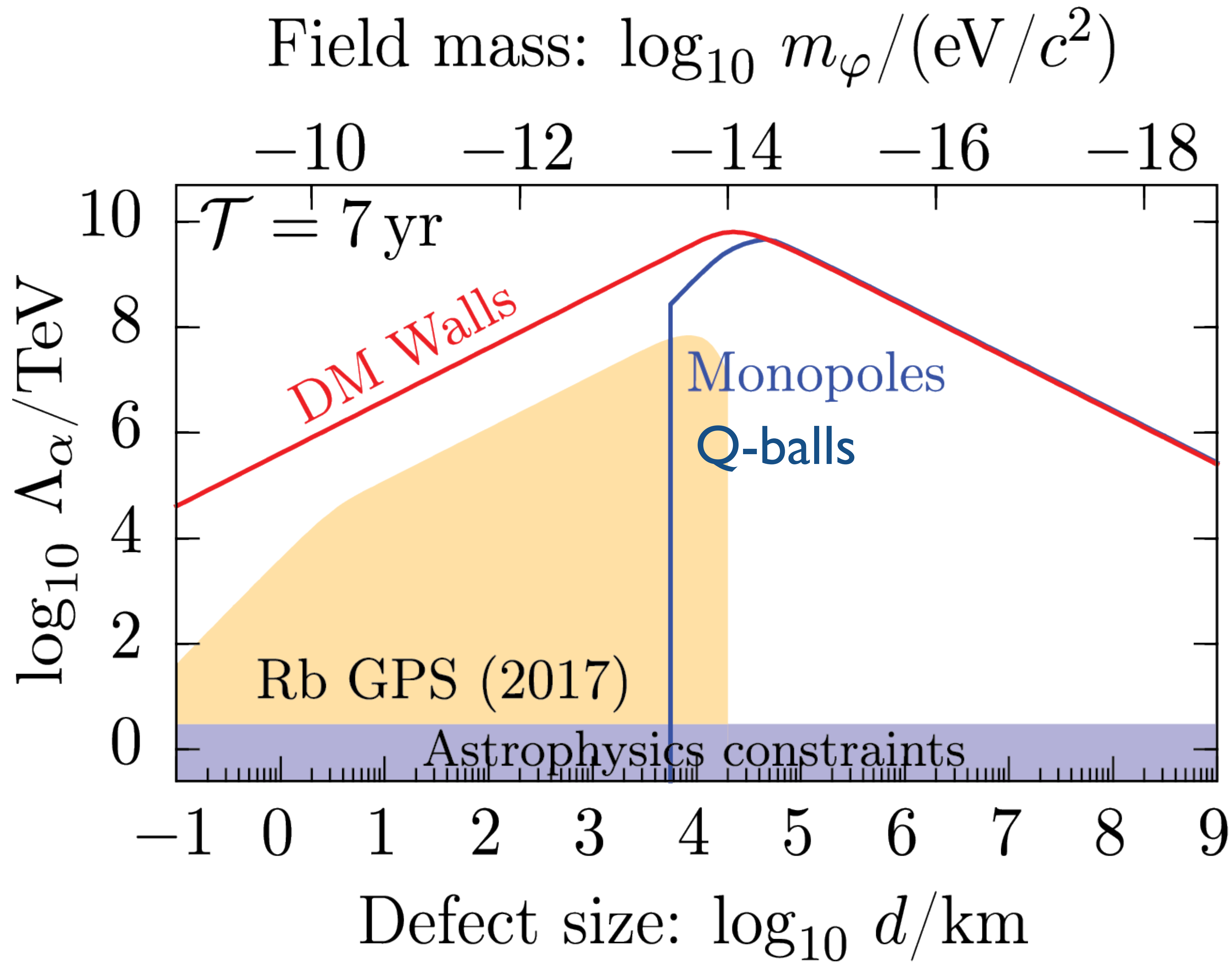


Credit: Conner Dailey

GPS.DM collaboration: mining of ~20 years of archival data for atomic clocks onboard GPS satellites

Relevant parameters:
coupling strength + average time b/w encounters + width of the object

GPS.DM discovery reach

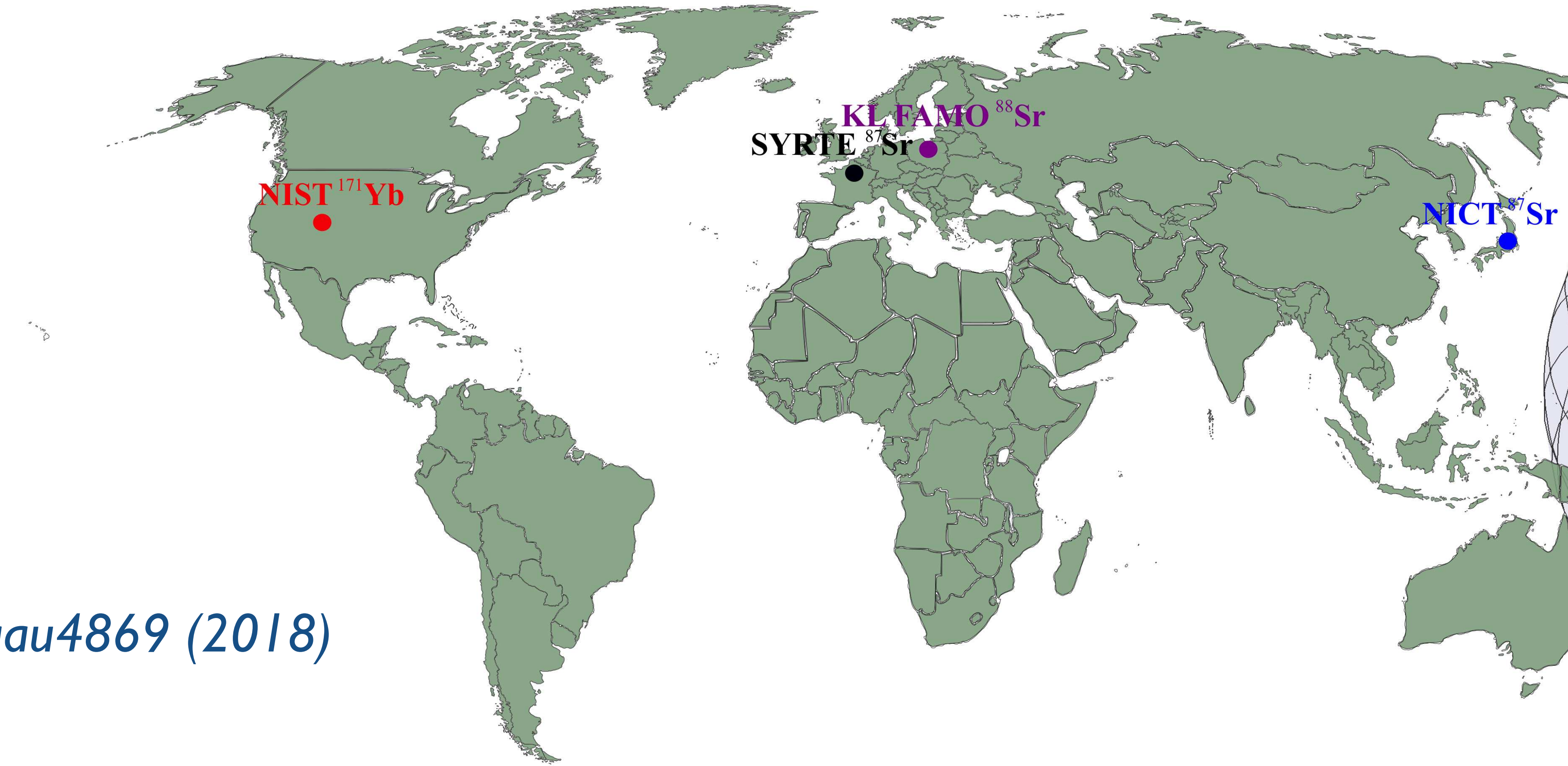


B. M. Roberts, G. Blewitt, C. Dailey, and A. Derevianko, *PRD 97, 83009 (2018)*

Nature Commun. ***8***, *1195 (2017)*

Global networks of laboratory clocks

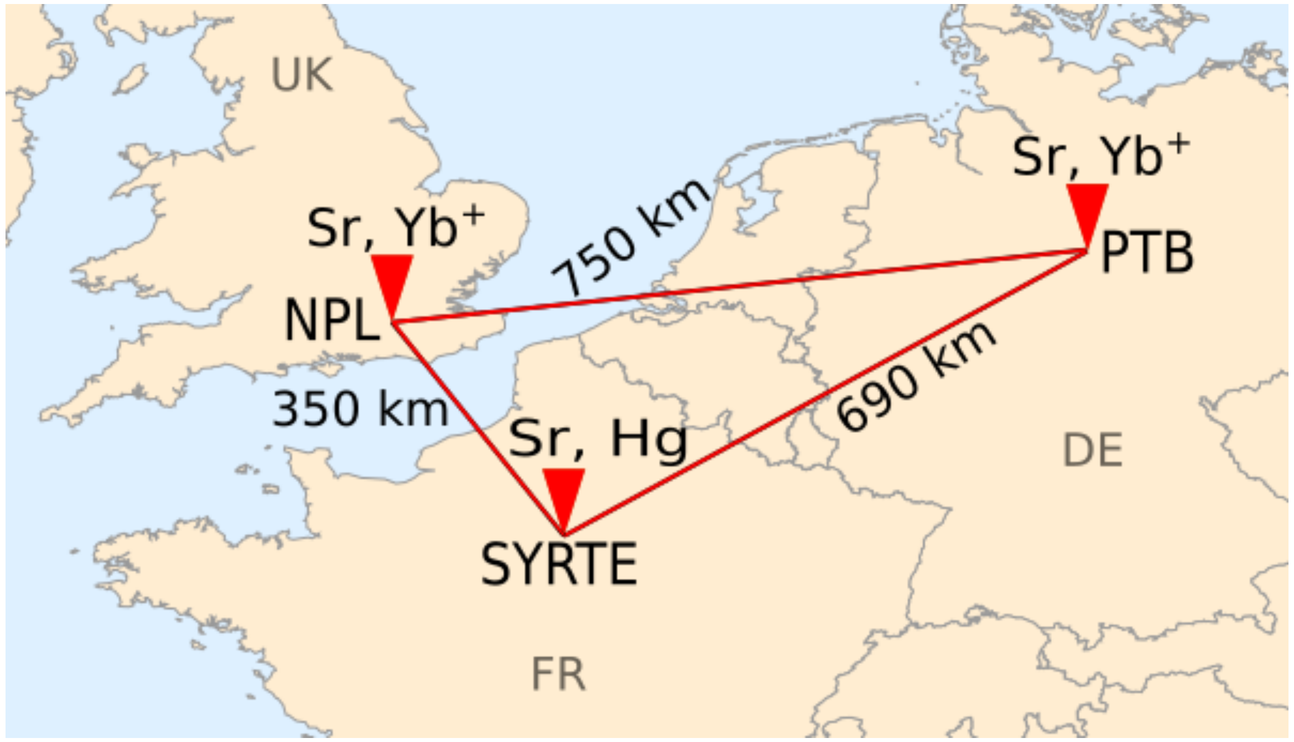
Laboratory clocks + GPS time-stamping



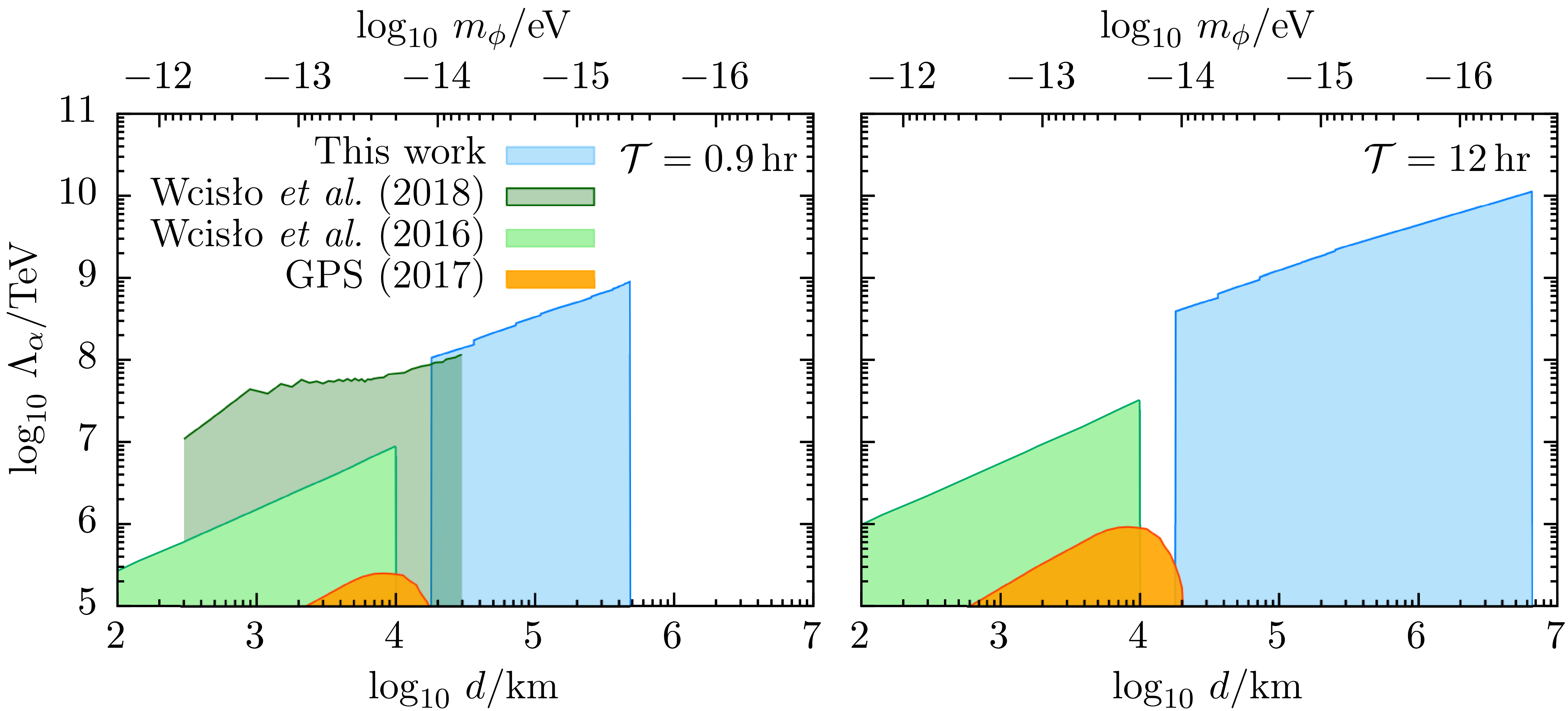
Wcisclo ... Zawada, Sci. Adv. 4, eaau4869 (2018)

Roberts…Wolf, 1907.02661

Fiber linked clocks



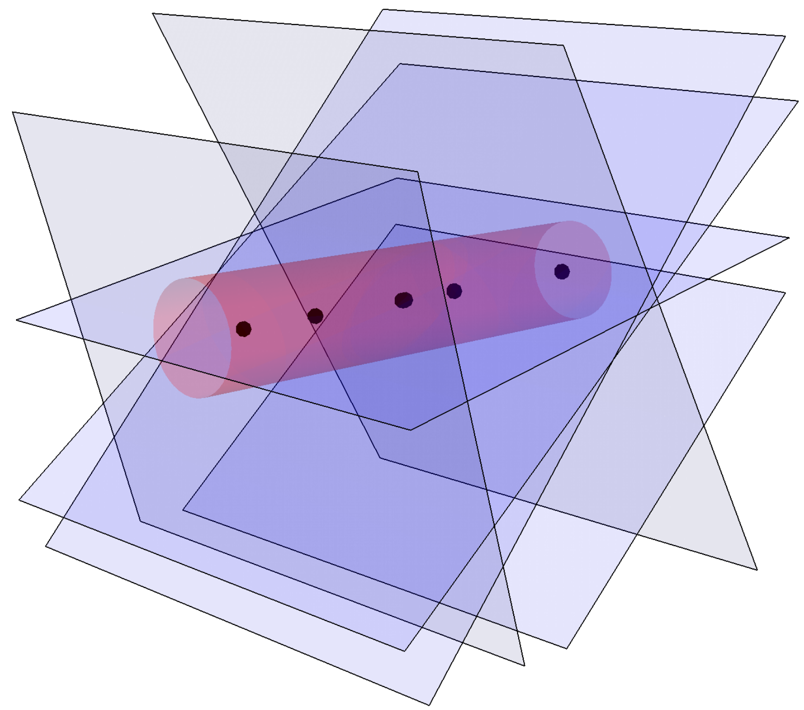
Constraints for short times b/w encounters



Roberts…Wolf, 1907.02661

For T > ~ a month GPS.DM still is the only network with any constraints.
+ GPS clocks are microwave clocks

Common mistake (all papers)



- Multiple (!) encounters
- Poisson processes
- Sensitivity ~ $\sqrt{N_{\text{events}}} = \sqrt{\frac{\text{Total observation time}}{\text{time between encounters}}}$
- All published constraints on Λ need to be rescaled by

$$\left(\frac{\text{Total observation time}}{\text{time between encounters}}\right)^{1/4}$$

Panelli, Roberts, Derevianko, arXiv:1908.03320

DM-induced oscillating/stochastic variation of fundamental constants

Virialized ultra-light fields (VULFs)

Example: S=0 fields, no self-interaction

- True scalars: dilatons/moduli
- Pseudo scalars: axions/ALPs

Single mode (fixed velocity)

$$\phi(t,\mathbf{r}) = \Phi_0 \cos\left(\omega_\phi t - \mathbf{k}\cdot\mathbf{r} + \theta\right)$$

$$\hbar\omega_\phi \approx mc^2 + \frac{1}{2}mv^2$$

Compton frequency

$$\rho_{\mathrm{DM}} = \frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \Phi_0^2$$

average over many oscillations

Many modes ⇒Stochastic field

$$\frac{\#\text{ of particles}}{\text{mode}} \sim \left(\frac{\rho_{\text{DM}}}{mc^2}\right) \times \left(\lambda_{\text{de Broglie}}\right)^3 \gg 1$$

$m \ll 10\,\text{eV}$ ⇒ ultra-light DM

$$\phi(t,\mathbf{r}) = \sum_{\text{modes}} \text{many waves with random phases}$$

⇒ Gaussian random fields (radiophysics, CMB, stochastic GW background,…)

- Correlation time and length
- Statistics is fully determined by 2-point correlation function

Stochastic approach: 2-point correlation function

$$\hbar \omega_\phi = \sqrt{\left(mc^2\right)^2 + \left(\frac{kc}{\hbar}\right)^2} \approx mc^2 + \boxed{\frac{mv^2}{2}}$$

Dephasing

⇒ coherence time & length

$\phi\left(t', \mathbf{r}'\right)$ $\phi\left(t, \mathbf{r}\right)$

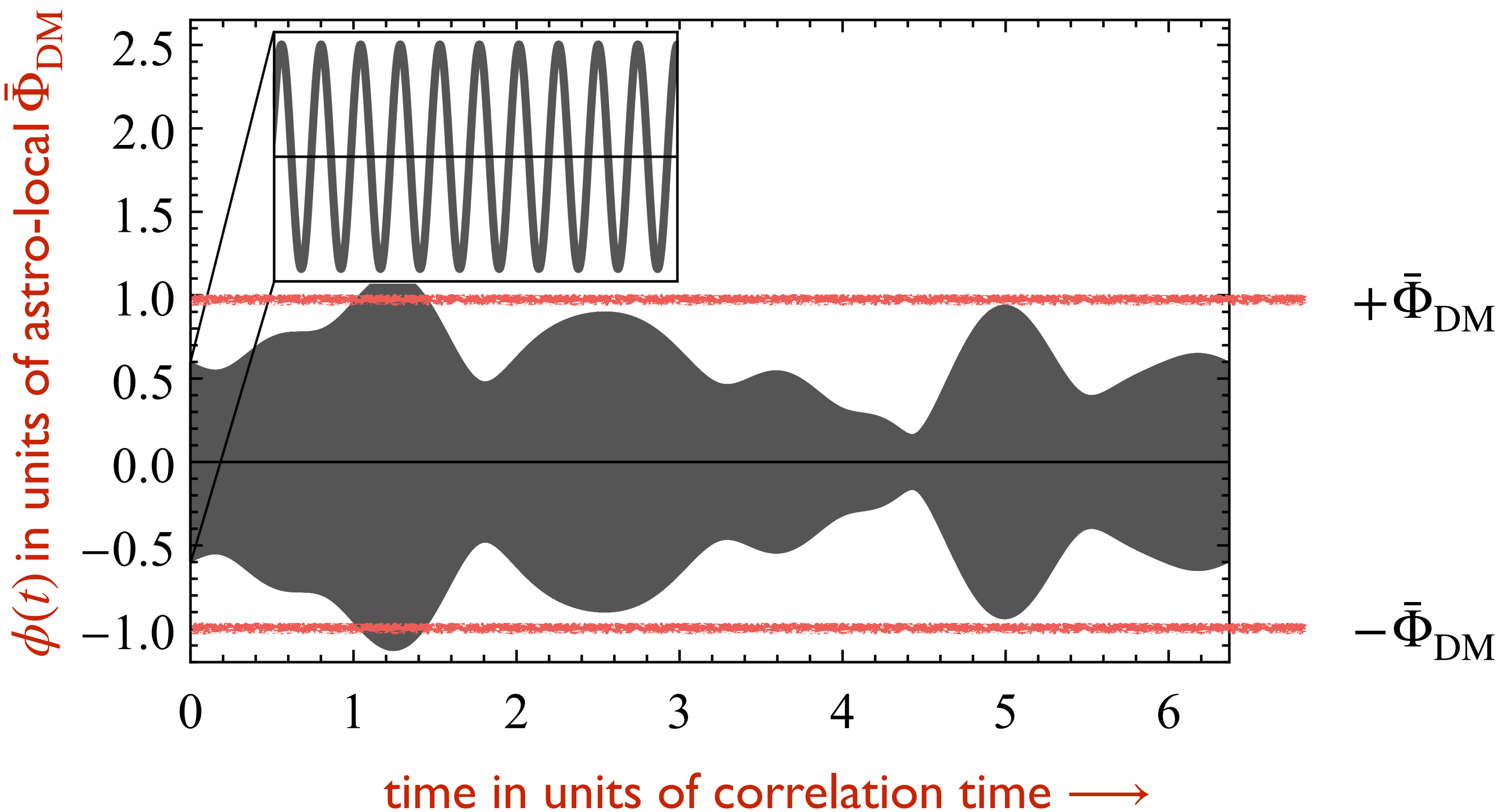
$$\boxed{g\left(\tau, \mathbf{d}\right) = \left\langle \phi\left(t' = t + \tau, \mathbf{r} = \mathbf{r}' + \mathbf{d}\right) \phi\left(t, \mathbf{r}\right) \right\rangle}$$

Stochastic variation of fundamental constants

$$\frac{\langle \alpha(t',\mathbf{r}')\alpha(t,\mathbf{r})\rangle}{\alpha^2} = 1 + \hbar c\,\Gamma_\alpha^2\, g(\tau,\mathbf{d})$$

arXiv:1605.09717

How does the DM field look like?



If the observation time ≪ correlation time

$$\phi(t,\mathbf{r}) \approx \Phi_0 \cos(\omega_\phi t + \theta)$$

Unlucky experimentalist may encounter near-zero amplitudes

arXiv:1905.13650

Time scales

mass	oscillation period	correlation time
10^{-15} eV	~ 5 seconds	~10 days
10^{-20} eV	~ 6 days	~ 2000 years

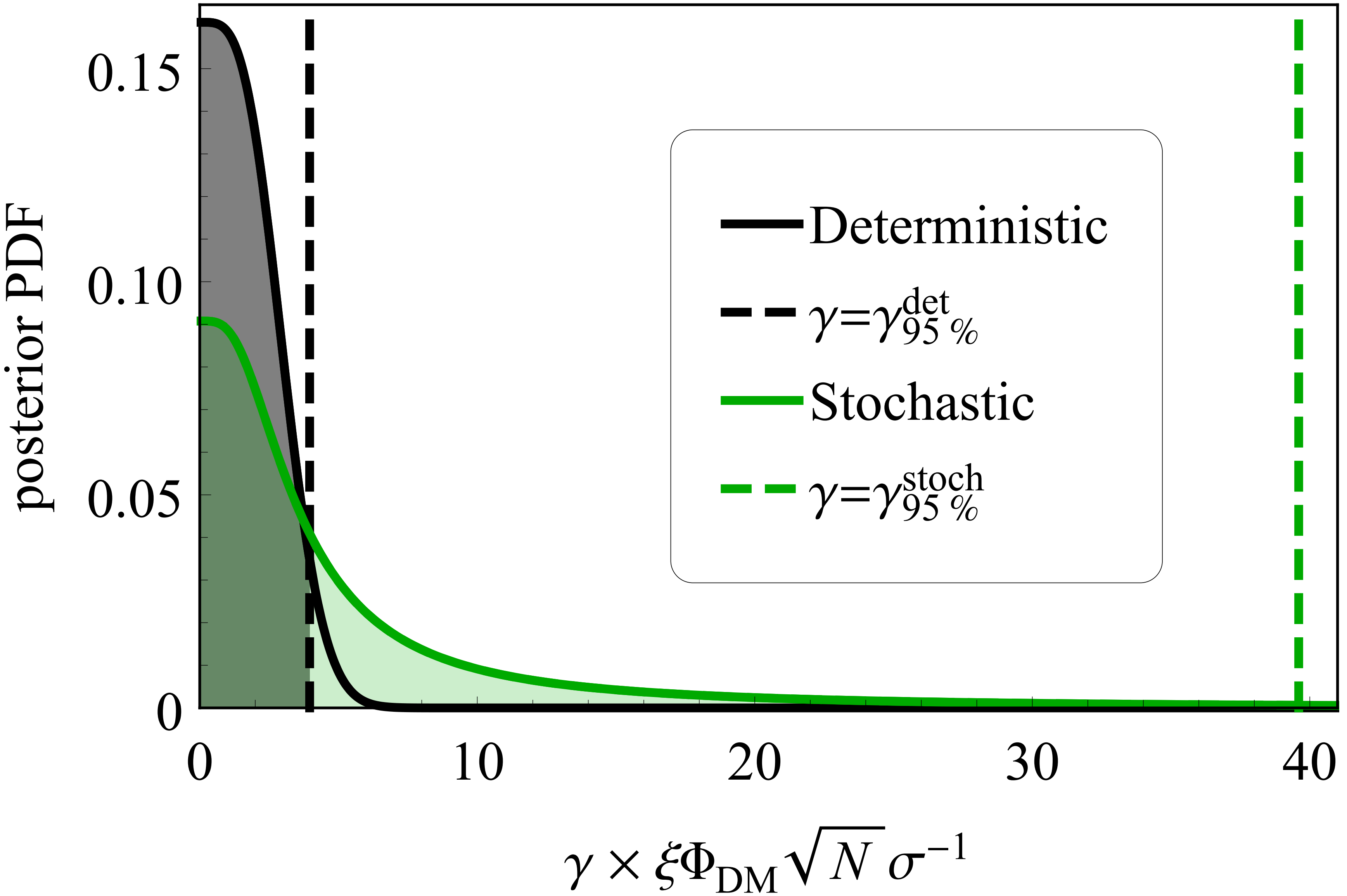
Uncertainty in the amplitude is an issue for $m \ll 10^{-14}\,\mathrm{eV}$

Need to marginalize over unknown amplitude

Posteriors for coupling strength γ

$$2\int_0^{\gamma_{95\%}} p(\gamma)d\gamma = 0.95$$

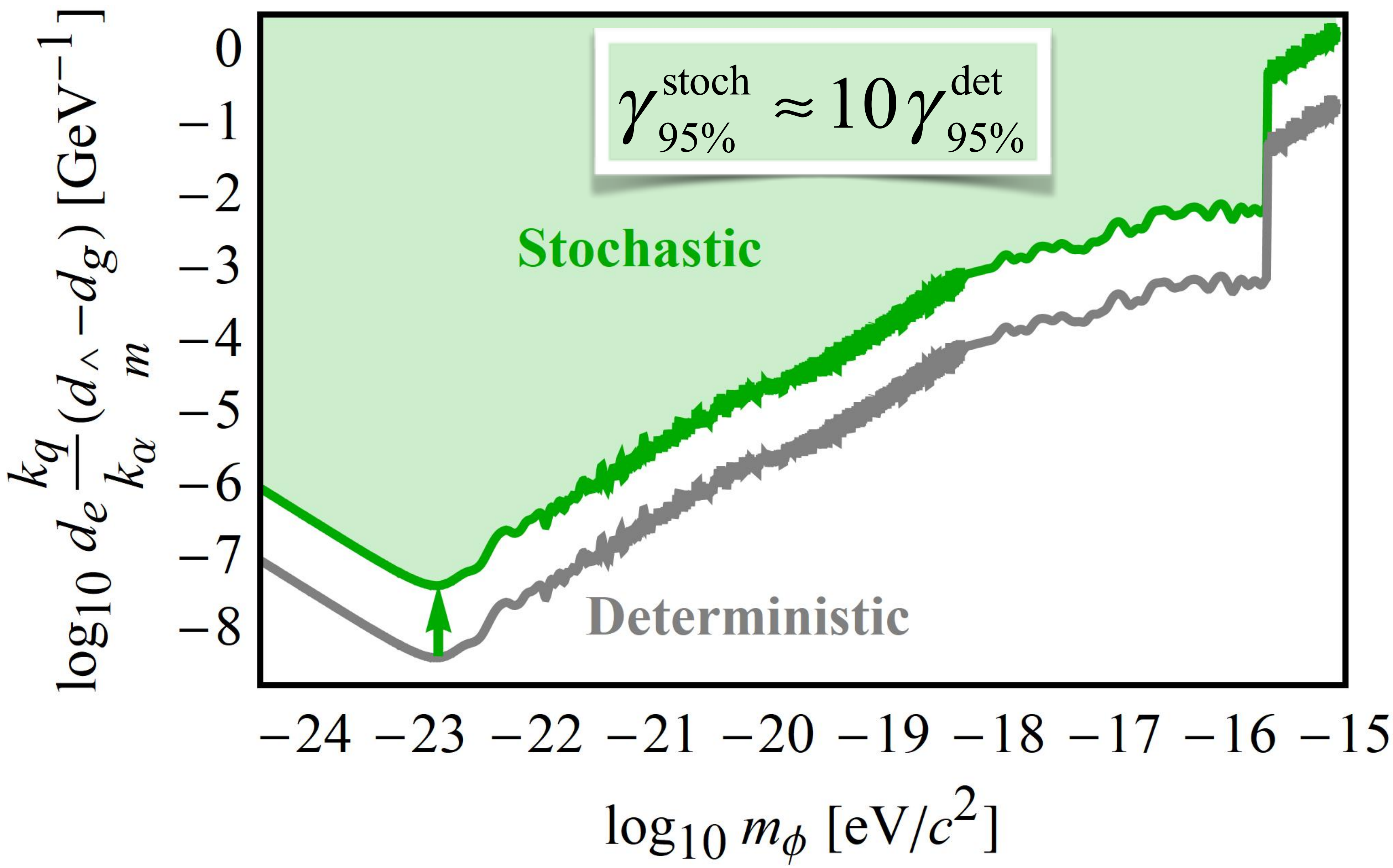
95% Confidence level



$$\gamma^{\rm stoch}_{95\%} \approx 10\,\gamma^{\rm det}_{95\%}$$

arXiv:1905.13650

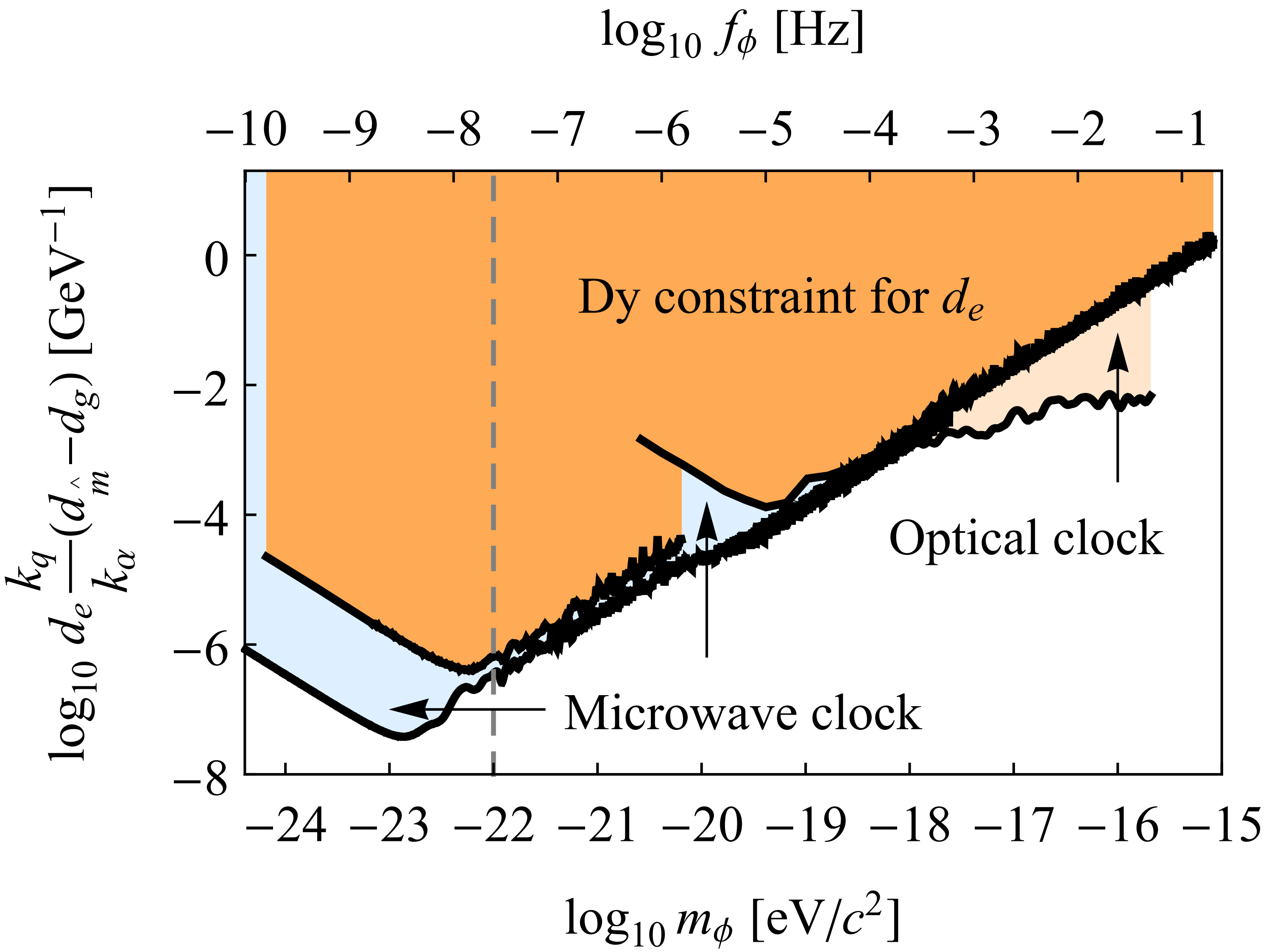
Effect on exclusion plots



Previous bounds (microwave clocks)

A. Hees, J. Guena, M. Abgrall, S. Bize, and P. Wolf, PRL 117, 061301 (2016)

Revised dilaton coupling



Previous bounds from:

Van Tilburg ... Budker, PRL 115, 011802 (2015)
Hees...Wolf, PRL 117, 061301 (2016)
Wcislo...Zawada, Science Advances 4, eaau4869 (2018)

PHYSICAL REVIEW A **97**, 042506 (2018) arXiv:1605.09717

Editors' Suggestion

Detecting dark-matter waves with a network of precision-measurement tools

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Limits on the coupling strengths

All nodes within coherence length

$$\Gamma_X^{(network)} < \Gamma_X^{(1)} / N^{1/2}$$

Incoherent limit

$$\Gamma_X^{(network)} < \Gamma_X^{(1)} / N^{1/4}$$

Can ACES mission lead to further improvements in the search for DM?