Searching for a fifth force with atomic and nuclear clocks

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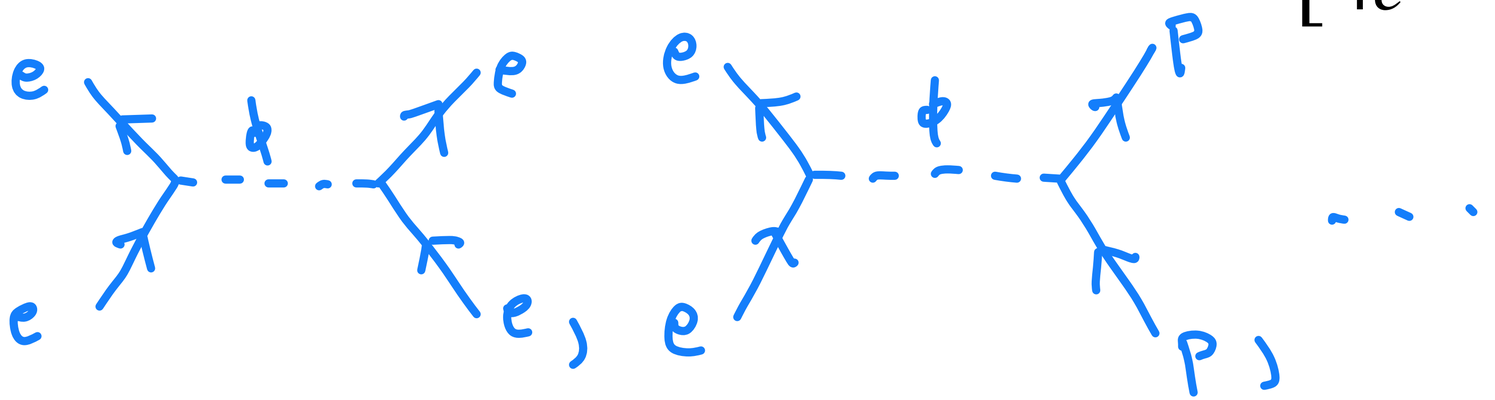
Properties of generic scalar interaction

- If linearly coupled to the SM, expect $\mathscr{L} \supset \kappa\phi \left[\frac{d_e}{4e^2} F^2 + d_{m_e} m_e \bar{e} e + \cdots \right]$



- Couplings don't need to be the same -> EP violation

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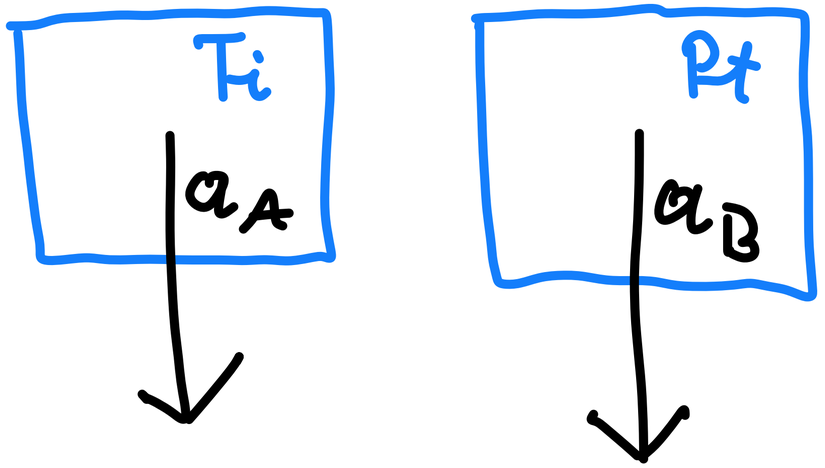
Testing the new force

[Source: John Lienhard]

A natural way to look for these interactions is to compare accelerations of two test masses of different chemical compositions



$$\eta = \frac{2(a_A - a_B)}{a_A + a_B}$$

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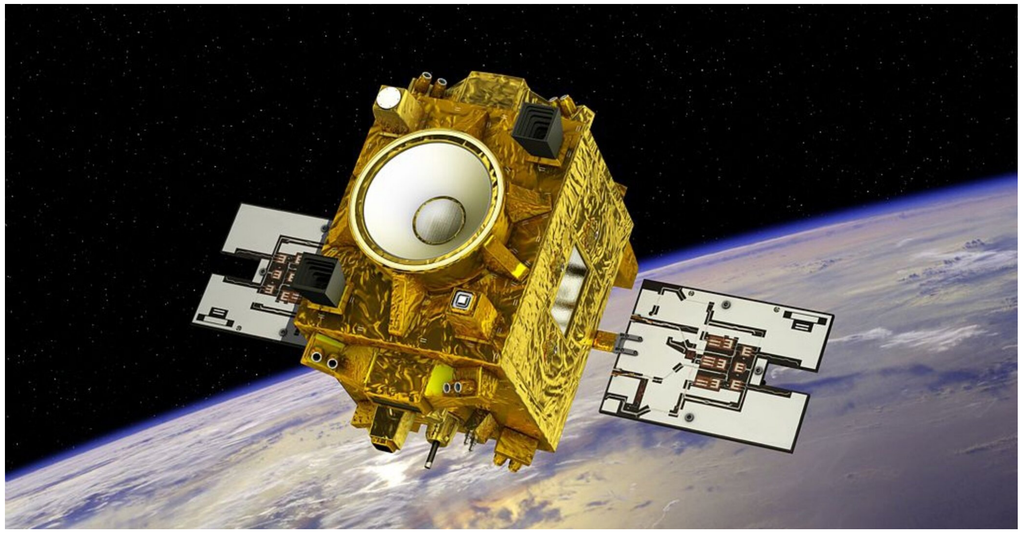
MICROSCOPE



[Source: esa.int]

$$\eta = \frac{2(a_A - a_B)}{a_A + a_B} \lesssim 10^{-15}$$

$$m_\phi \lesssim 10^{-14}\ \text{eV}$$

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How clocks enter the picture?

- We can rewrite Lagrangian as

$$\mathscr{L} \supset \kappa\phi \left[\frac{d_e}{4e^2} F^2 + d_{m_e} m_e \bar{e} e + \cdots \right] = \frac{1}{4e(\phi)^2} F^2 + m_e(\phi) \bar{e} e + \cdots$$

- Background value of ϕ affects fundamental parameters such as fine structure constant α, electron mass m_e, etc.
- Energy levels in atoms are sensitive to these changes.
- We can compare energies of two clock transitions to look for them

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Scalar field background

- The most compelling background is due to the scalar being the DM

$$\phi(t) = \sqrt{\frac{\rho}{2m_\phi^2}} \cos m_\phi t$$

- This naturally leads to the variation of the fundamental parameters with the same frequency

$$\alpha(t) = \alpha_0 + \delta\alpha \cos(m_\phi t) \qquad m_e(t) = m_e + \delta m_e \cos(m_\phi t)$$

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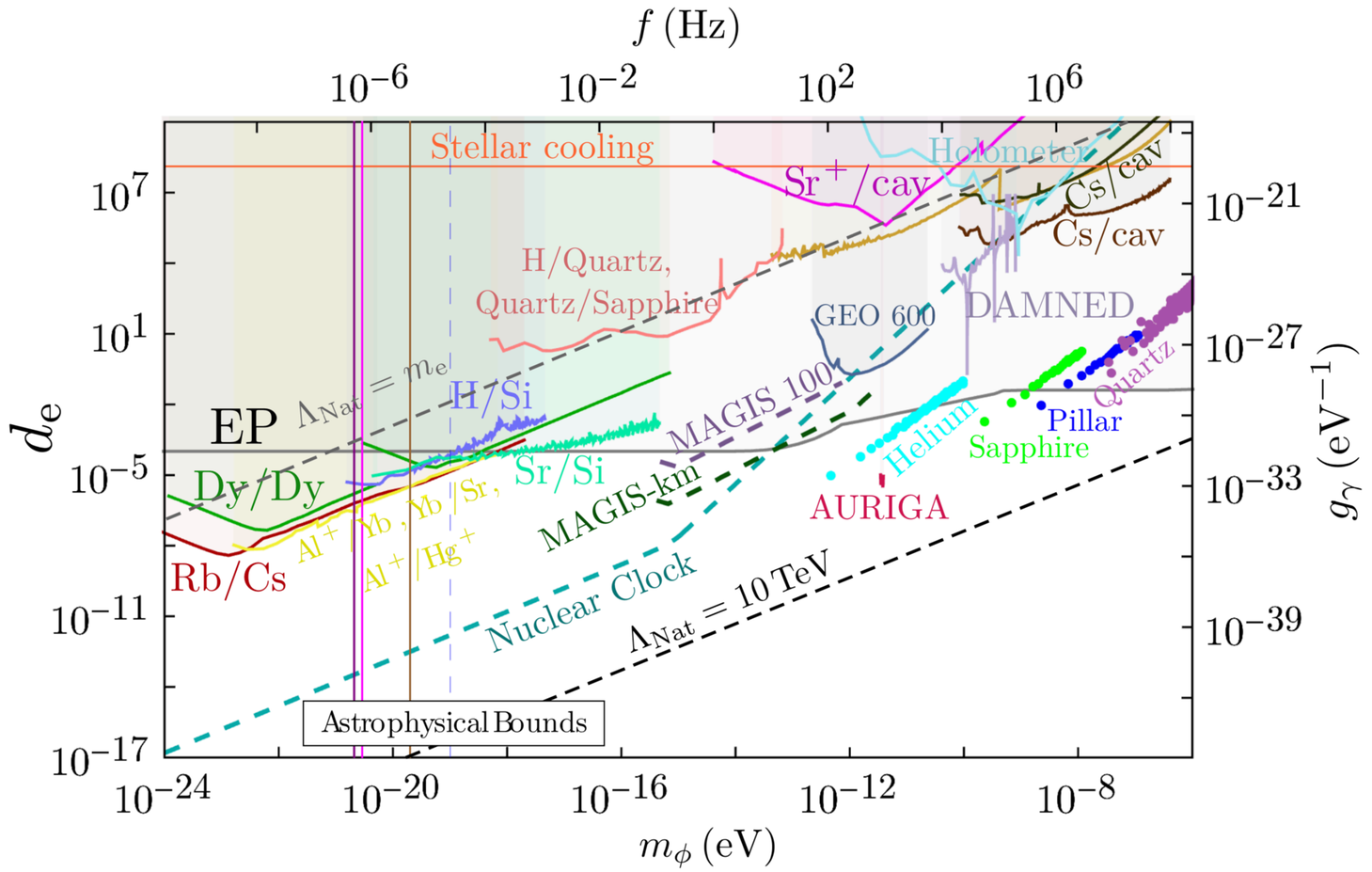
DM Bounds



[2203.14915]

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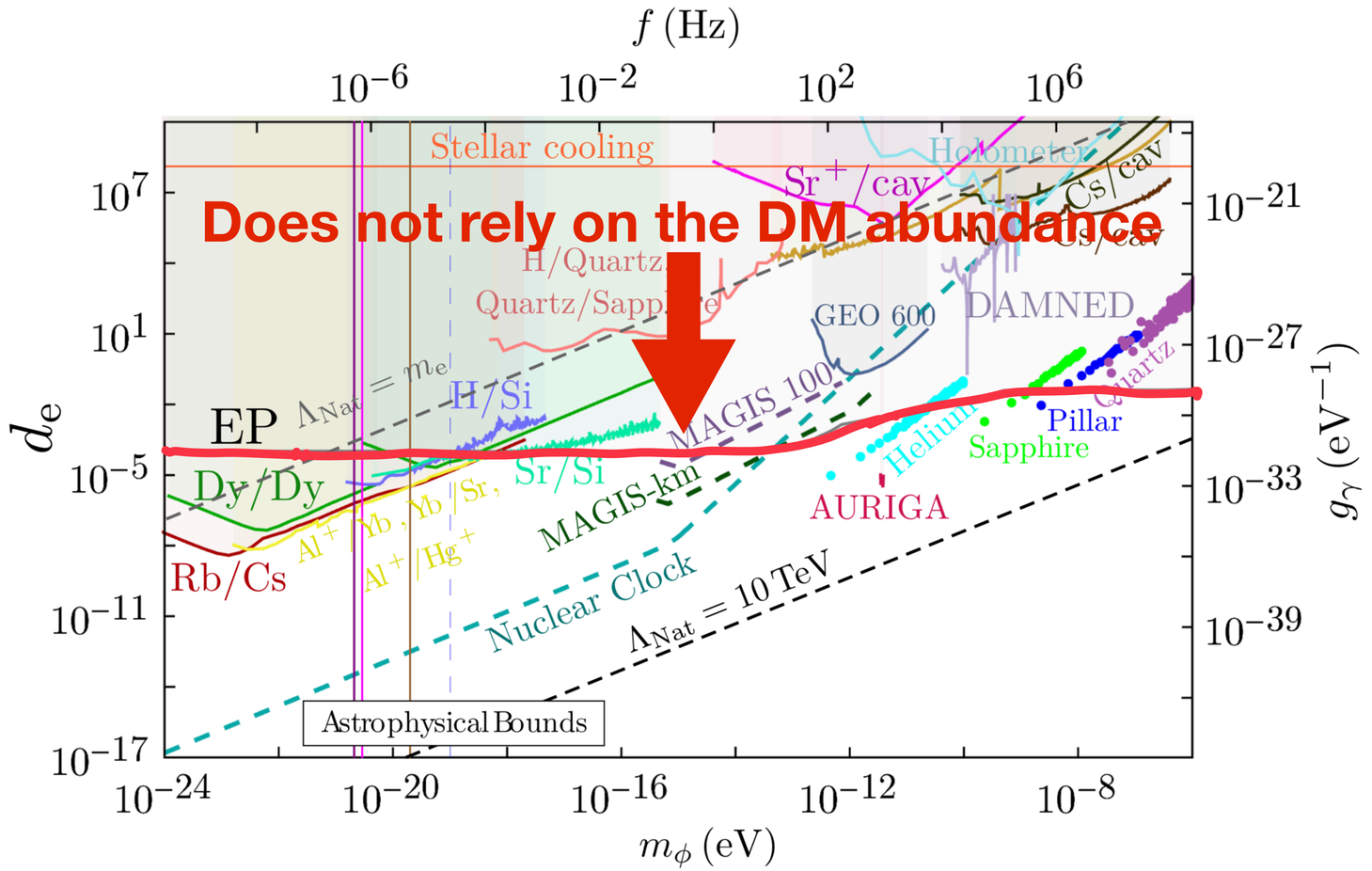
DM Bounds



[2203.14915]

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Can we get DM independent results with clocks?

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Scalar field background II

- $\mathscr{L} \supset \kappa\phi \left[\frac{d_e}{4e^2} F^2 + d_{m_e} m_e \bar{e} e + \cdots \right]$ means that every macroscopic body sources the scalar field
- E.g. around earth or sun we expect $\phi = -\frac{q}{4\pi r} e^{-m_\phi r} \propto U e^{-m_\phi r}$
- Similarly for the fundamental parameters $\frac{\delta\alpha}{\alpha} \propto U e^{-m_\phi r}$, $\frac{\delta m_e}{m_e} \propto U e^{-m_\phi r}$
- The idea is to exploit the spatial variation of these parameters

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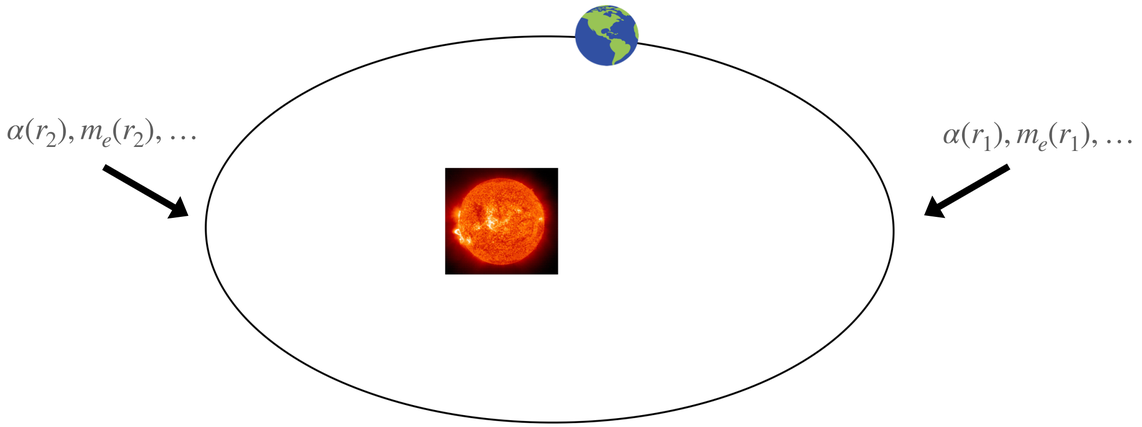
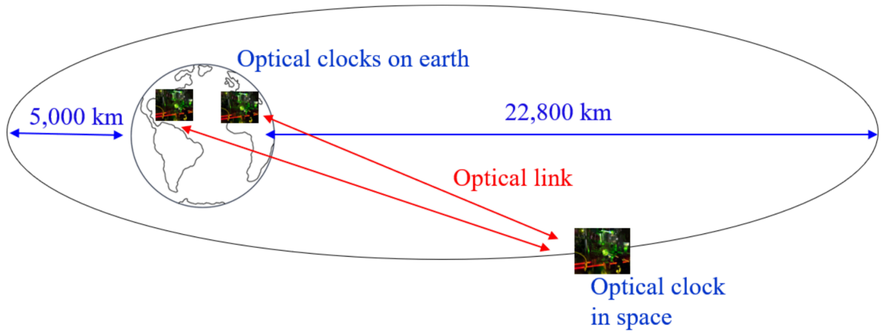
Measuring the background

- Earth based: seasonal change of fundamental parameters



- Space based: eccentric orbit around earth, transit towards sun



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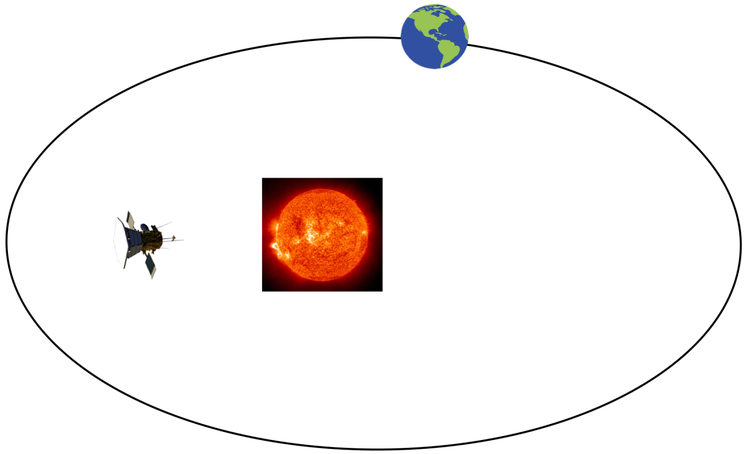

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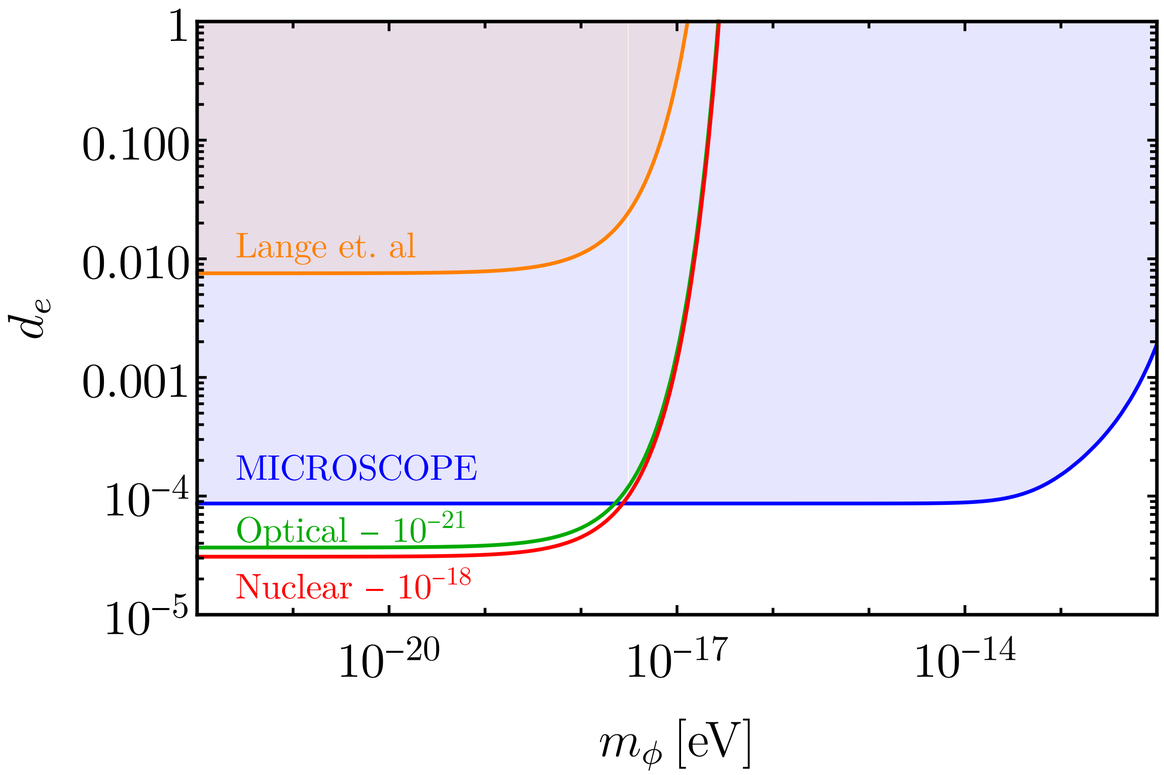
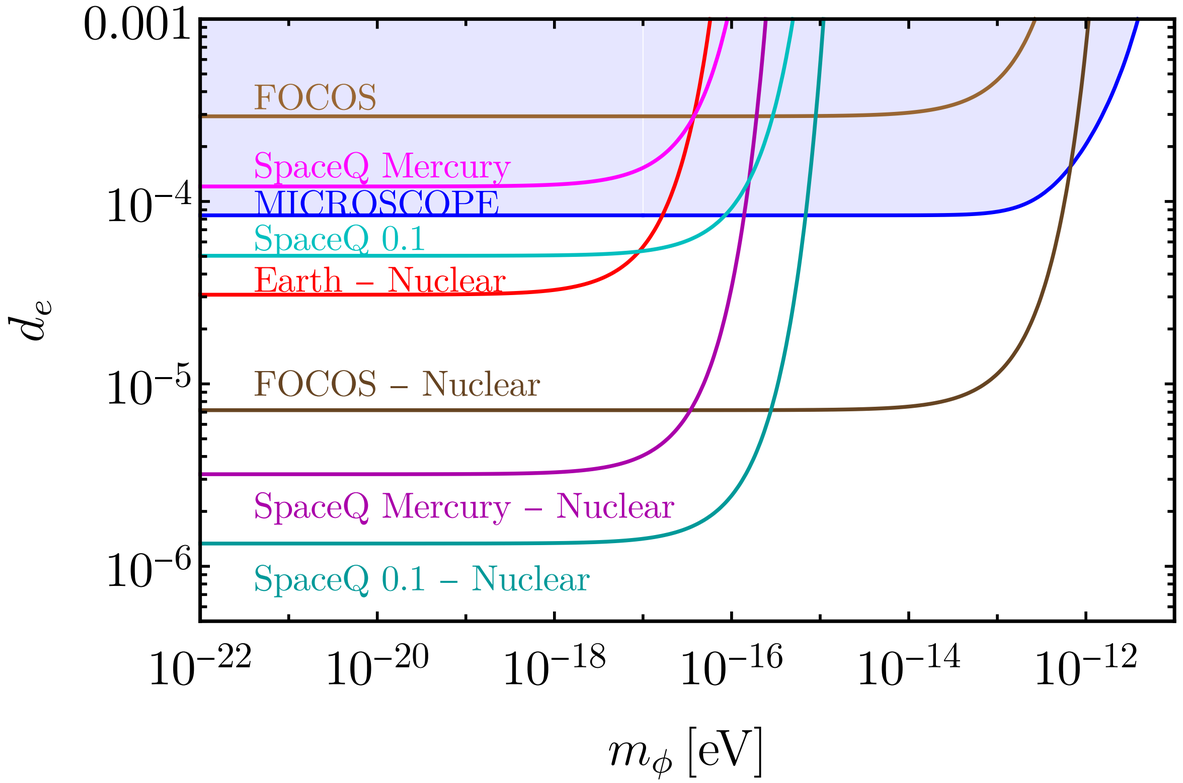
Experimental prospects





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Conclusions

- Experiments involving atomic or nuclear clocks can be used to look for a fifth force without assuming DM background
- In about a decade, earth based optical clock experiments can reach sensitivity of MICROSCOPE
- Nuclear clocks have potential to significantly improve fifth force constraints

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Thank you!