Searching for Scalar Dark Matter

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Perimeter Institute

with
Ken Van Tilburg
Junwu Huang (2014)
and Savas Dimopoulos (2015)

Theories of Light Scalars

- Moduli, Dilaton, Axions…

- Couples non-derivatively to the Standard Model

$$\mathcal{L} \supset d_i \frac{\phi}{M_{Pl}} \mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, ...$$

Constraints on Light Scalars

- Mediates new interactions in matter

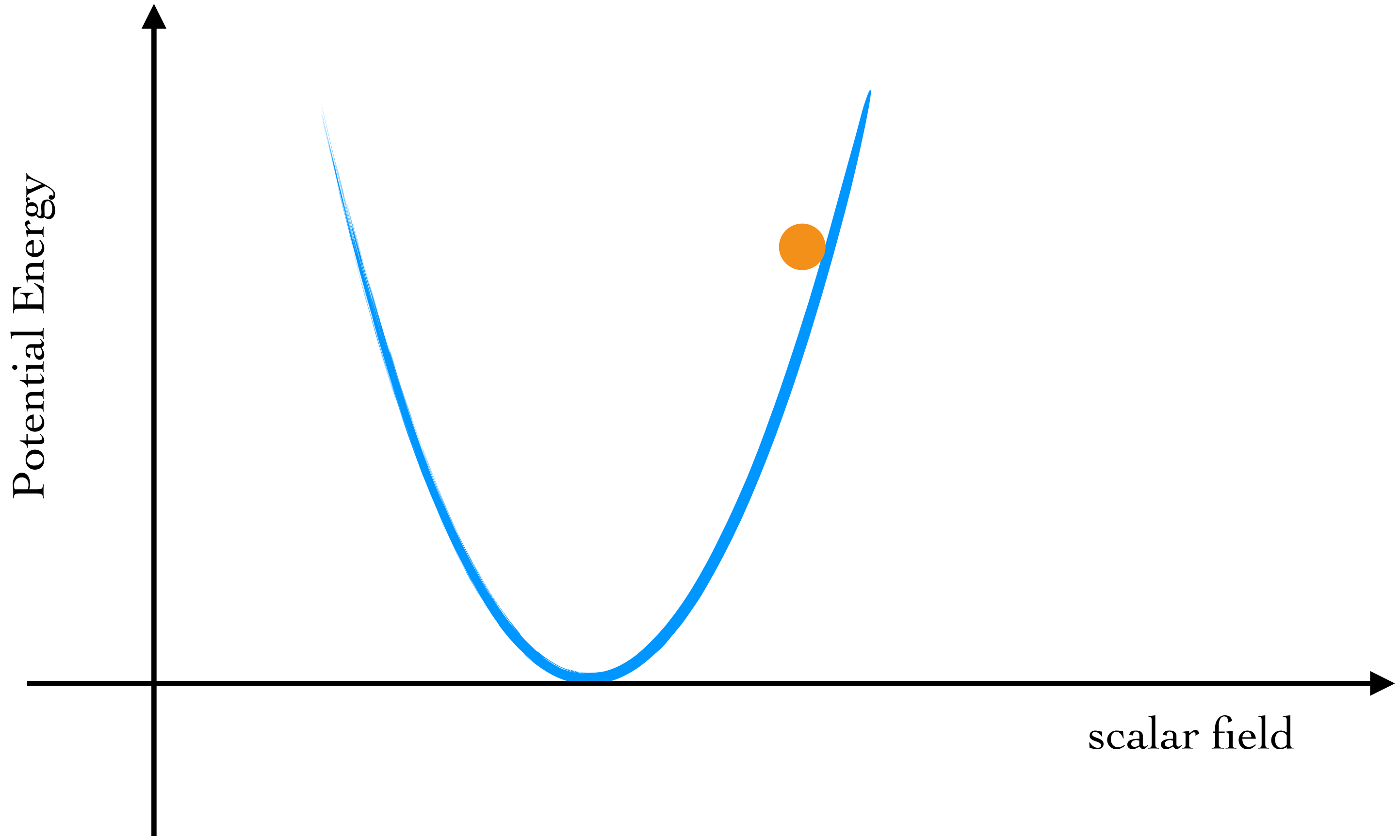
  - Generates a fifth force in matter

$$F \sim \frac{(d_i Q_i)^2}{4\pi M_{Pl}^2} \frac{M_1 M_2}{r^2} e^{-m_\phi r}$$

  - Generates Equivalence Principle violation

Light Scalar Dark Matter

- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

Light Scalar Dark Matter

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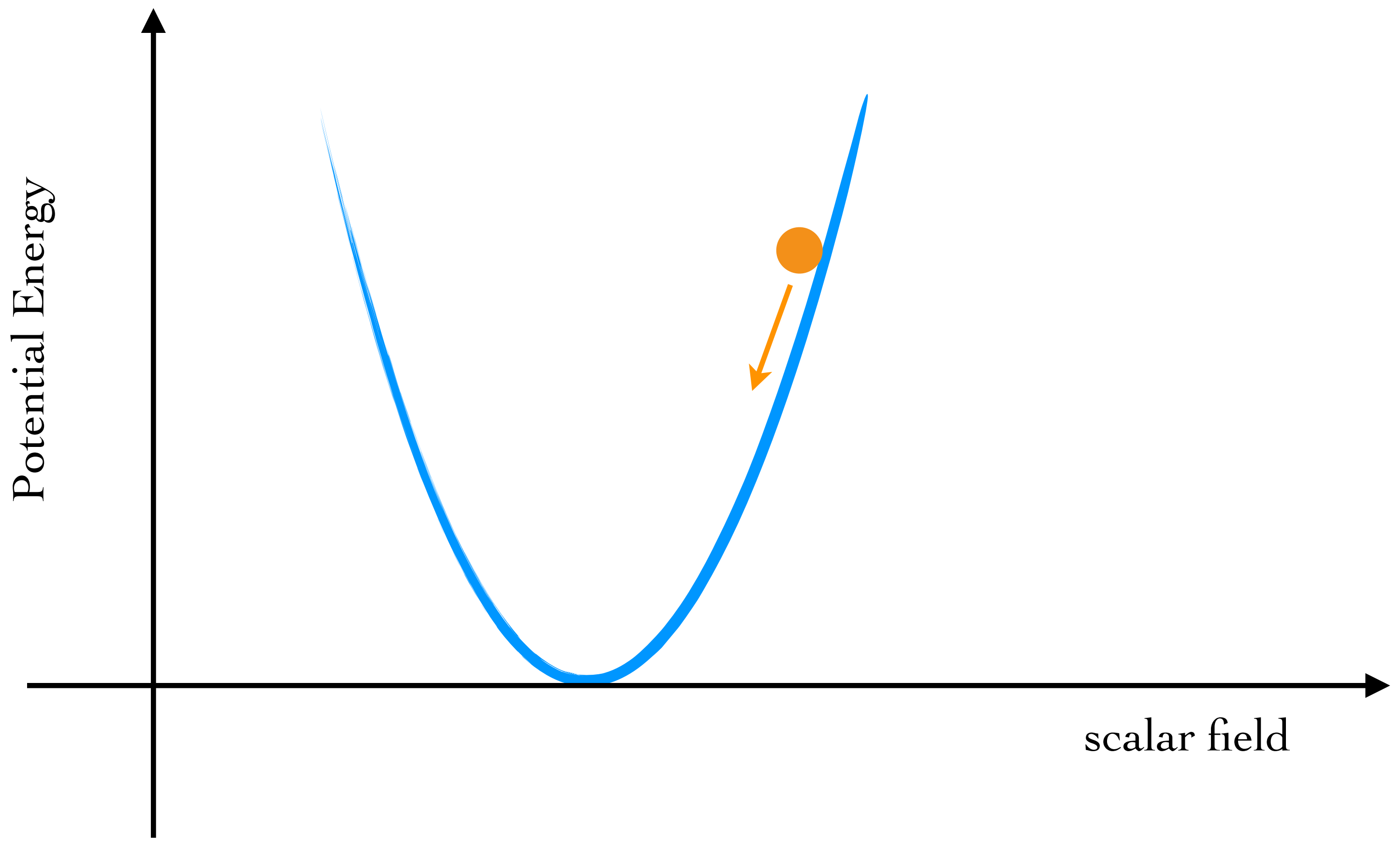


Frozen when:
Hubble > m_ϕ

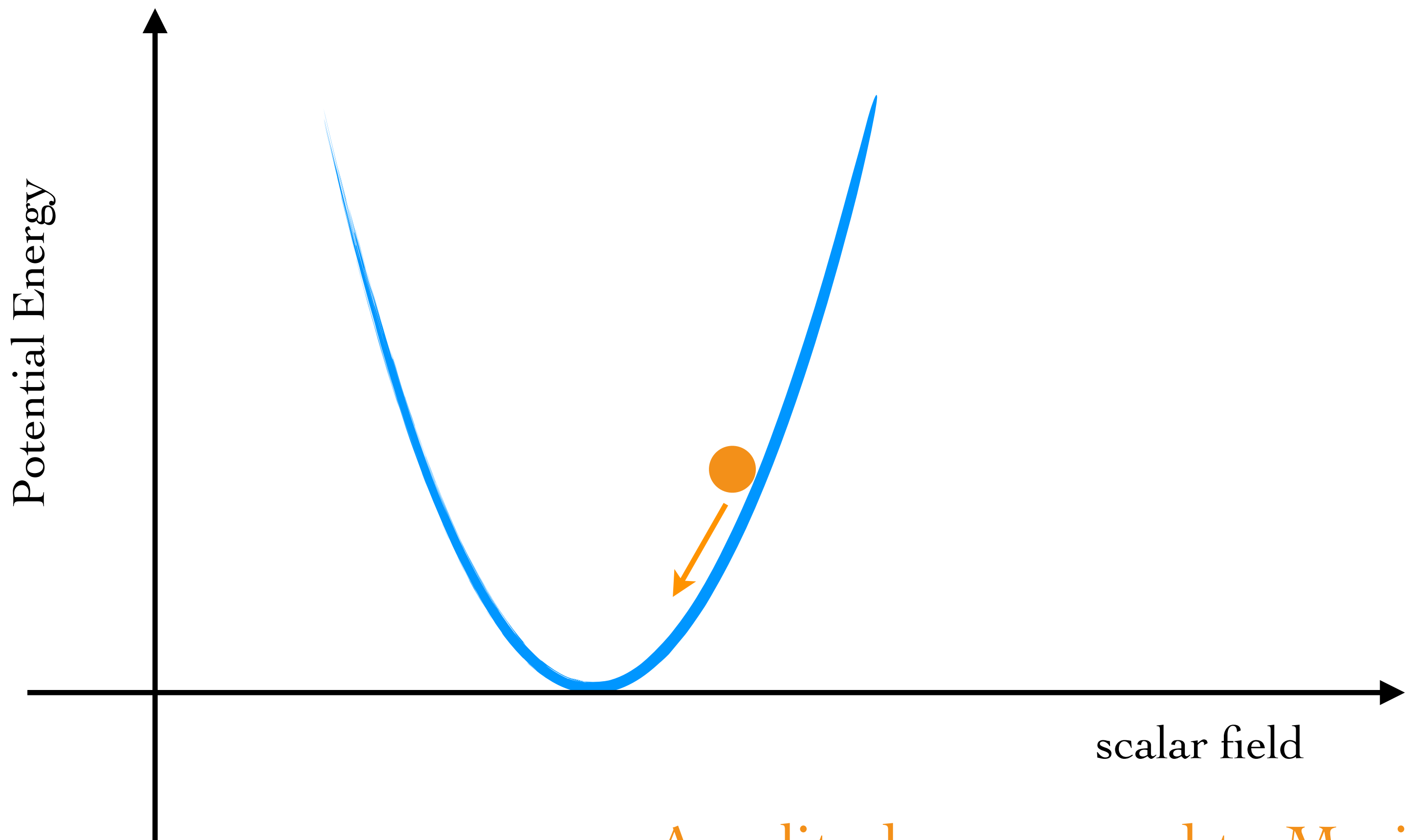
Oscillates when:
Hubble < m_ϕ

ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

Light Scalar Dark Matter Today

- If $m_\phi < 0.1$ eV, can still be thought of as a scalar field today



$m_\phi{}^2\ \phi_o{}^2\ \cos^2(m_\phi\, t) \sim \rho_\phi$

Coherent for $\upsilon_{vir}^{-2} \sim 10^6$ periods

Amplitude compared to M_{Pl} in the galaxy:

$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4\cdot 10^{-13}\left(\frac{10^{-18}\,\mathrm{eV}}{m_\phi}\right)$$

Oscillating Fundamental Constants

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e} \frac{\phi}{M_{Pl}} m_e e \bar{e}$$

$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e} \phi_o}{M_{Pl}} \cos(m_\phi t)$$

$$= 6 \times 10^{-13} \cos(m_\phi t) \frac{10^{-18} \text{ eV}}{m_\phi} \frac{d_{m_e}}{1}$$

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…

Light Scalar Dark Matter Detection

- Detecting Dark Matter with Atomic Clocks
- Detecting Dark Matter with Resonant-Mass Detectors

Keeping the DM time with Atomic Clocks

with Junwu Huang
and Ken Van Tilburg (2014)

Oscillating Atomic and Nuclear Energy Splittings

- Optical Splittings

$$\Delta E_{\rm optical} \propto \alpha_{EM}^2 m_e \ \sim \text{eV}$$

- Hyperfine Splittings

$$\Delta E_{\rm hyperfine} \propto \Delta E_{\rm optical}\alpha_{EM}^2 \left(\frac{m_e}{m_p}\right) \sim 10^{-6}\ \text{eV}$$

- Nuclear Splittings

$$\Delta E\ (m_p,\ \alpha_s,\ \alpha_{EM}) \sim 1\ \text{MeV}$$

DM appears as a signature in atomic (or nuclear) clocks

Atomic Clocks

- Kept tuned to an atomic energy level splitting

Current definition of a second:
the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom

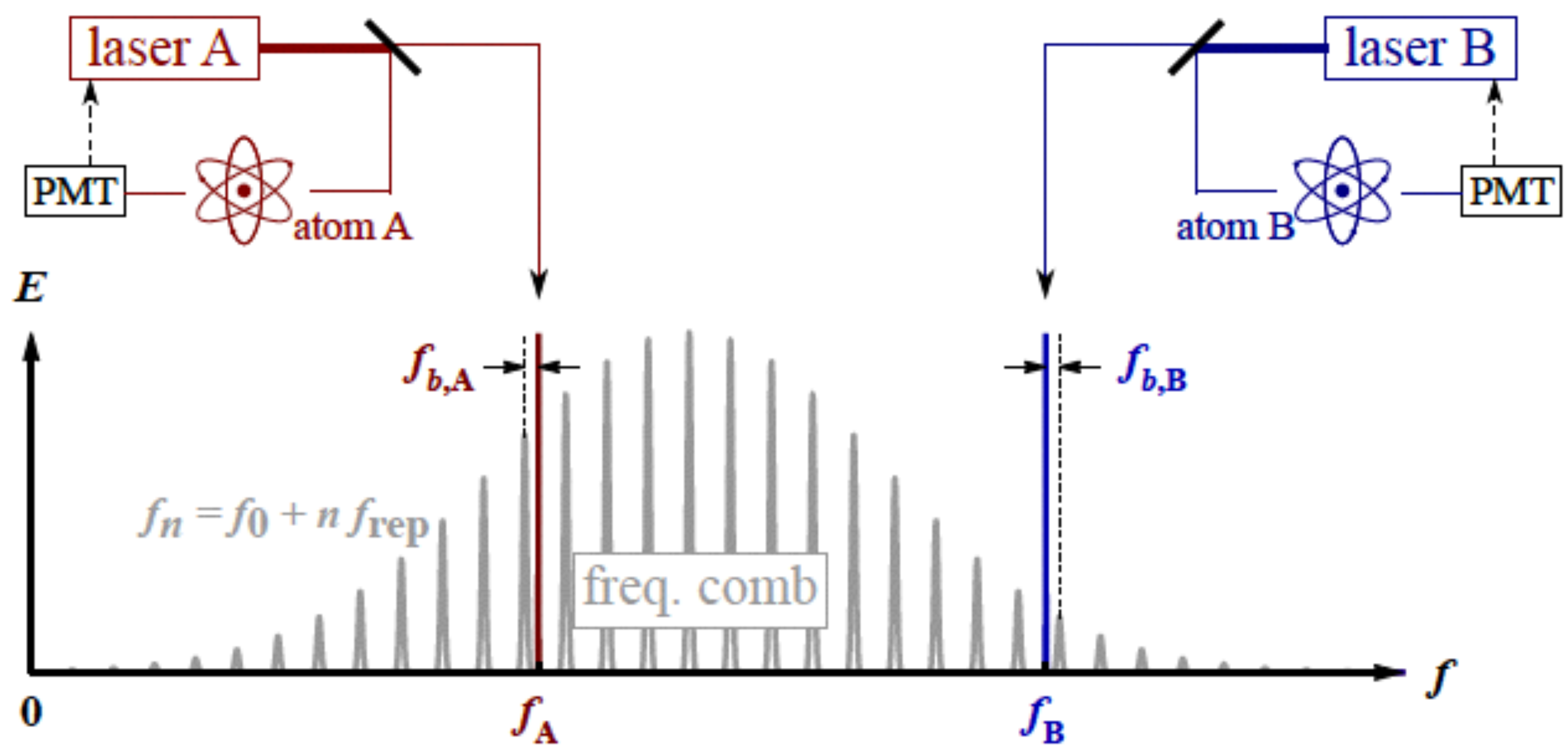
- Have shown stability of 1 part in 10^{18}

Compared to 1 part in 10^{13} expected by DM

- Have won several Nobel prizes in the past 20 years

How does and Atomic Clock Work?

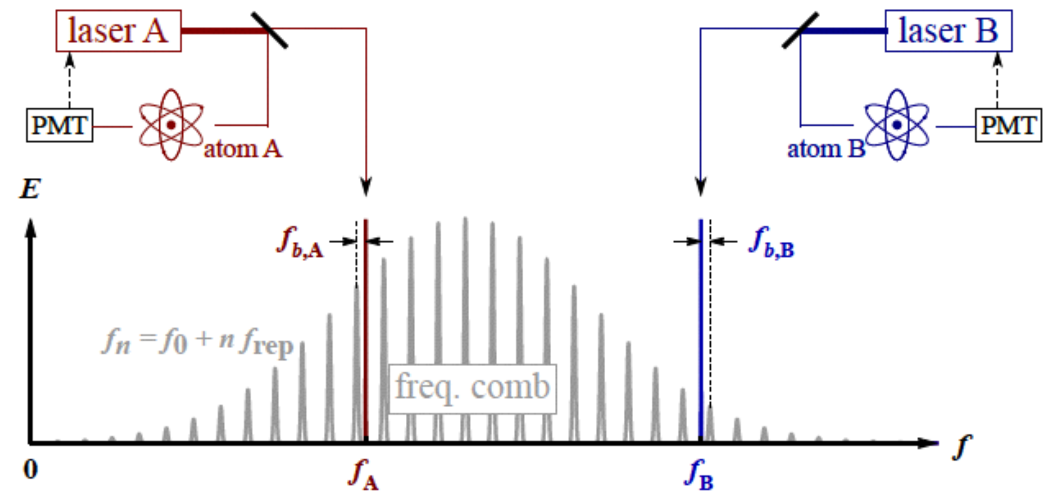
Keep a laser tuned to a long-lived (> minutes) atomic transition



$$\frac{\delta f}{f} \sim \frac{\Gamma_{\rm atom}}{f} \frac{1}{\sqrt{N_{\rm atoms}}} \sqrt{\frac{\tau_{\rm cycling}}{t_{\rm experiment}}}$$

$\tau_{\rm cycling}$ of order the lifetime

How do you take the measurements?



- Observe two clocks every $\tau_{cycling}$

- Calculate ratio of frequencies taking into account:

$$f_A = \alpha_{EM}^{\xi_A+2}\left(\frac{m_e}{m_p}\right)^{\zeta_A} \qquad \frac{\delta f_A}{f_A} = (\xi_A+2)\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \zeta_A\frac{\delta m_e}{m_e} - \zeta_A\frac{\delta m_p}{m_p}$$

- Take Fourier transform to look for oscillations with period longer than $\tau_{cycling}$

Atomic Clock DM searches are broadband searches

Table of atomic transitions used (or to be used)

$$\frac{\delta f_A}{f_A} = (\xi_A + 2)\frac{\delta \alpha_{EM}}{\alpha_{EM}} + \zeta_A \frac{\delta m_e}{m_e} - \zeta_A \frac{\delta m_p}{m_p}$$

Species	Transition	λ (nm)	Short $\left(\frac{10^{-15}}{\sqrt{\mathrm{Hz}}}\right)$	Long (10^{-18})	ζ_A	ξ_A
^{133}Cs [21]	hyperfine	$3.3 \cdot 10^7$	$2 \cdot 10^2$	360	1	2.83
^{199}Hg$^+$ [15]	$5d^{10}6s\,^2S_{\frac{1}{2}} \leftrightarrow 5d^9 6s^2\,^2D_{\frac{5}{2}}$	282	2.8	19	0	-3.19
^{171}Yb$^+$ [22]	$4f^{14}6s\,^2S_{\frac{1}{2}} \leftrightarrow 4f^{13}6s^2\,^2F_{\frac{7}{2}}$	467	2.0	71	0	-5.30
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^{229m}Th^{3+} [26]	nuclear	$\sim 1.6 \cdot 10^2$	~ 1	~ 1	-	$\sim 10^4$

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Accidental cancellations in Dysprosium optical transitions
are very sensitive to EM coupling variations

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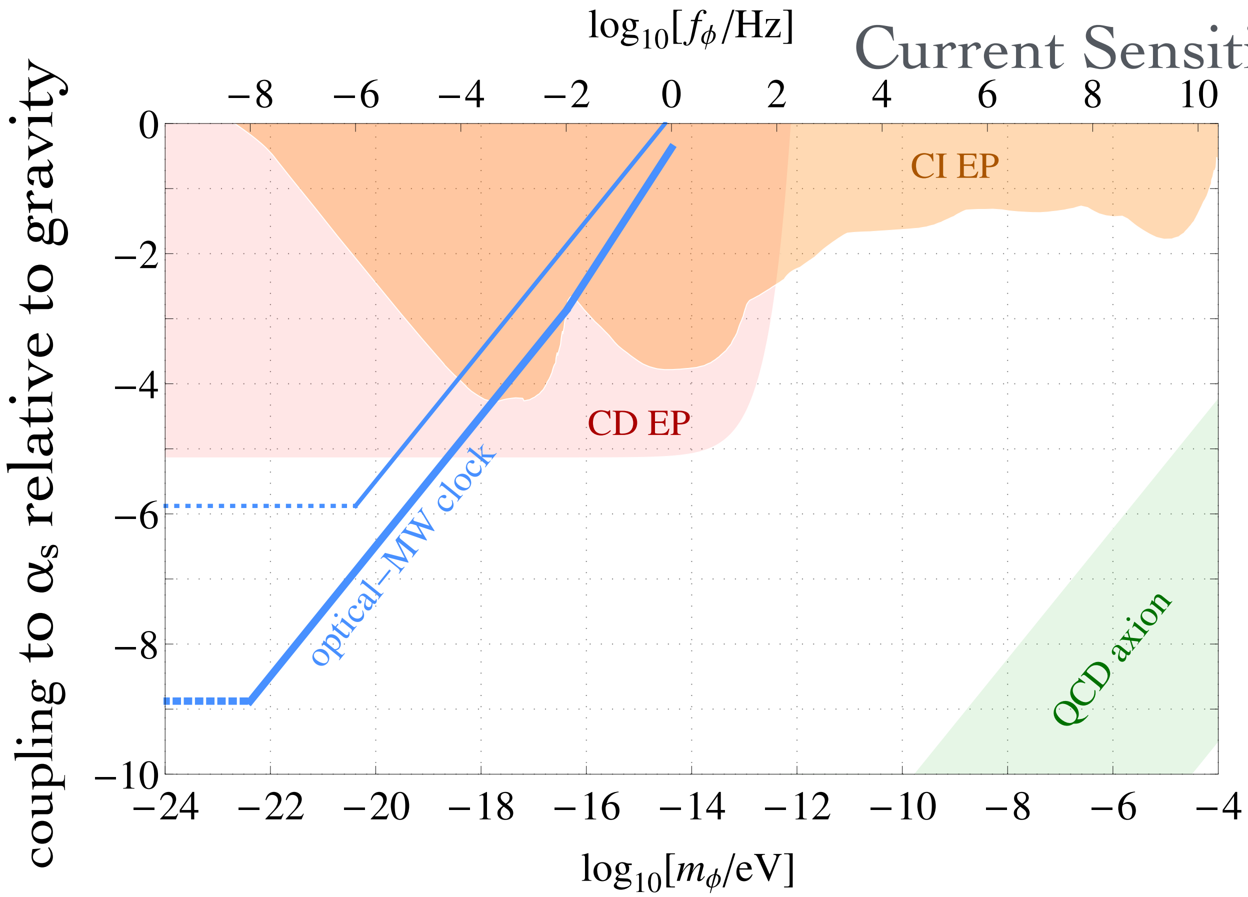
Thorium nuclear transition cancellations
increase sensitivity to EM coupling and quark mass coupling variations
Not measured yet…

What type of comparisons can we do?

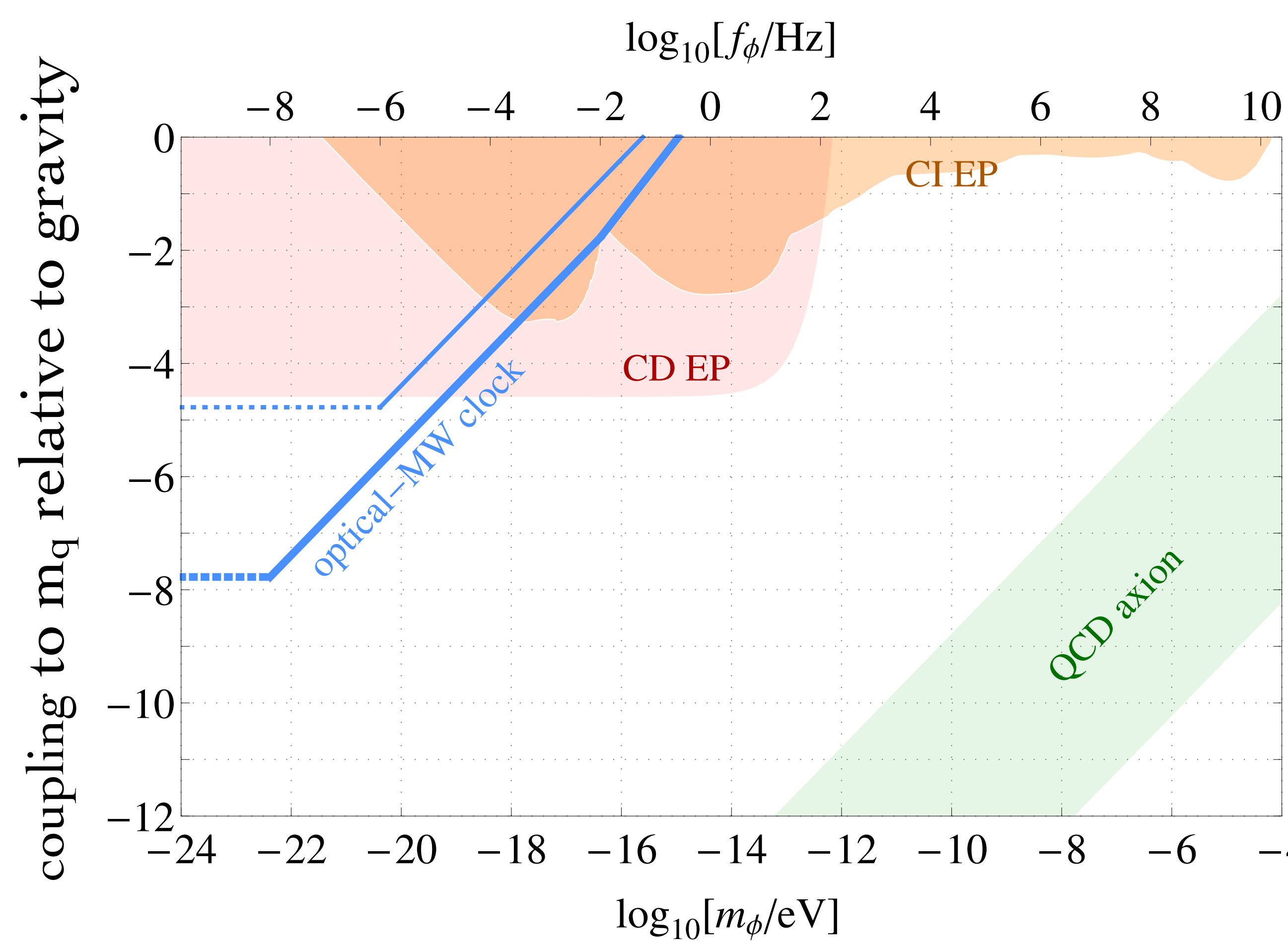
- Hyperfine to Optical transitions
  - Sensitive to m_e, m_q, and α_s (less to α_{EM})
- Optical to Optical transitions
  - Sensitive to α_{EM}
- Nuclear to Optical transitions
  - Sensitive to m_e, α_{EM}, m_q, and α_s

Hyperfine to Optical Transition Comparison

Current Sensitivity to α_s and m_q variations

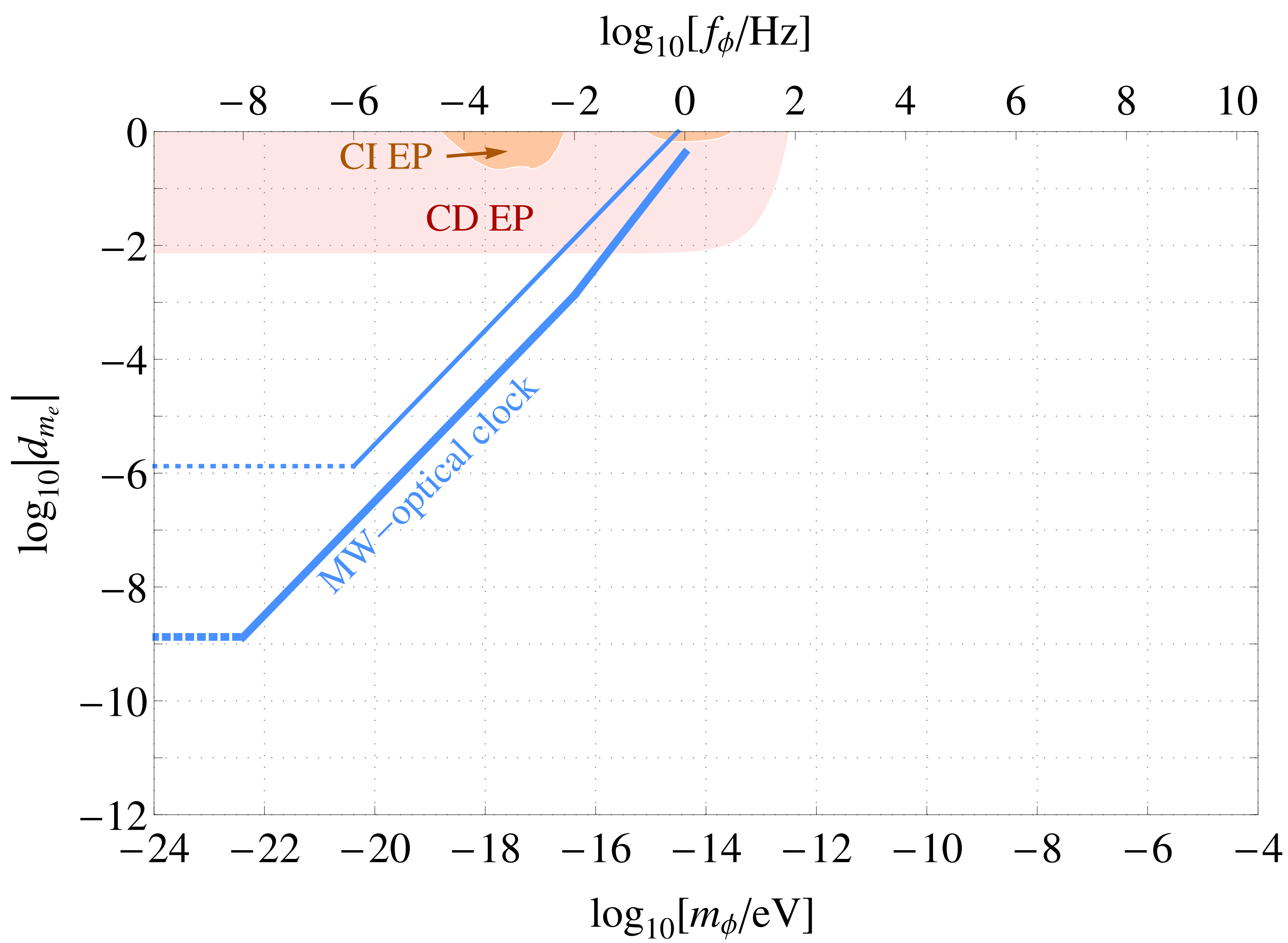


Experiments run for 10^6 sec or 3 years



Hyperfine to Optical Transition Comparison

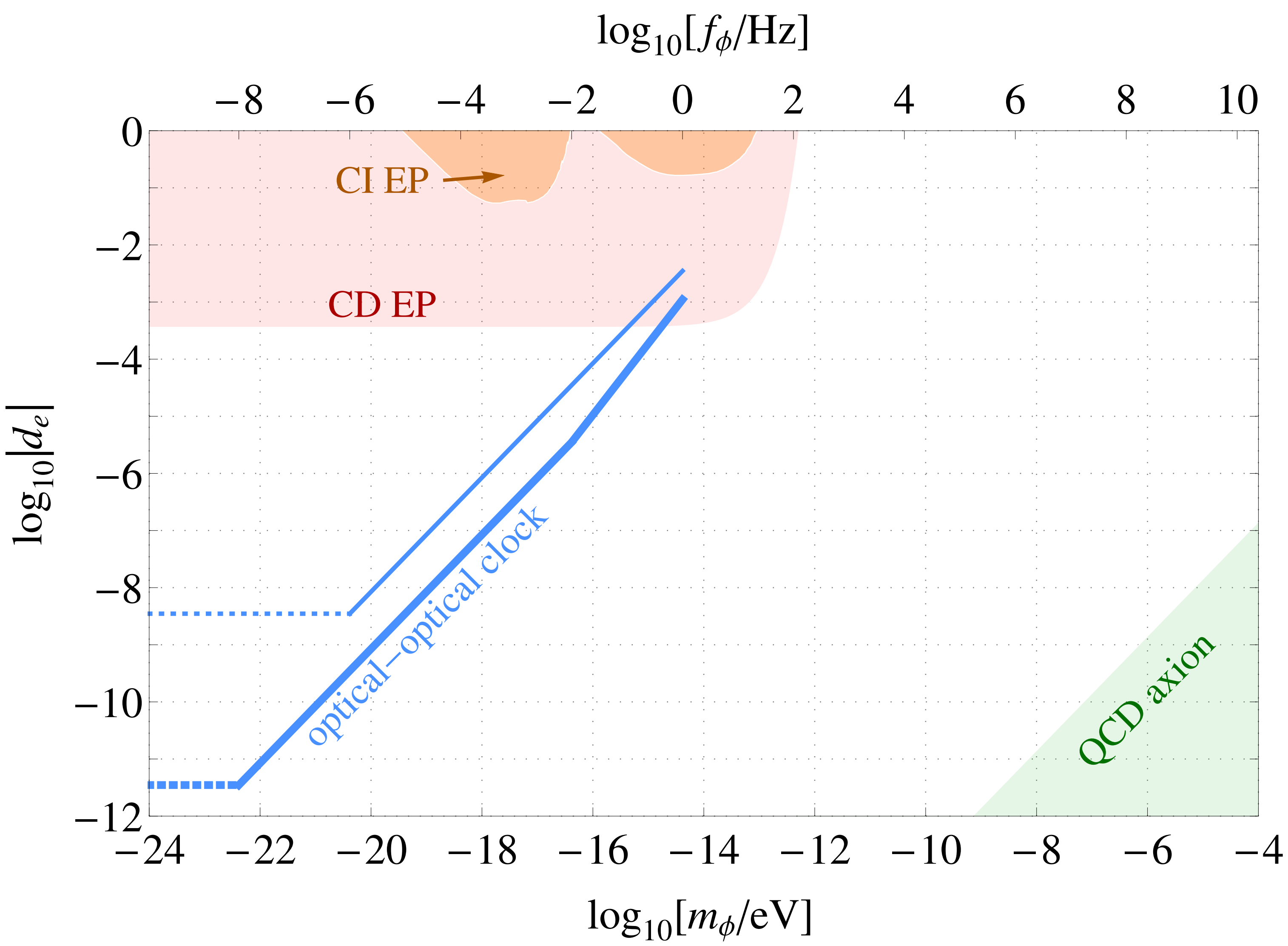
Current Sensitivity to m_e variations



Reduced sensitivity to variations of the EM coupling

Optical to Optical Comparison

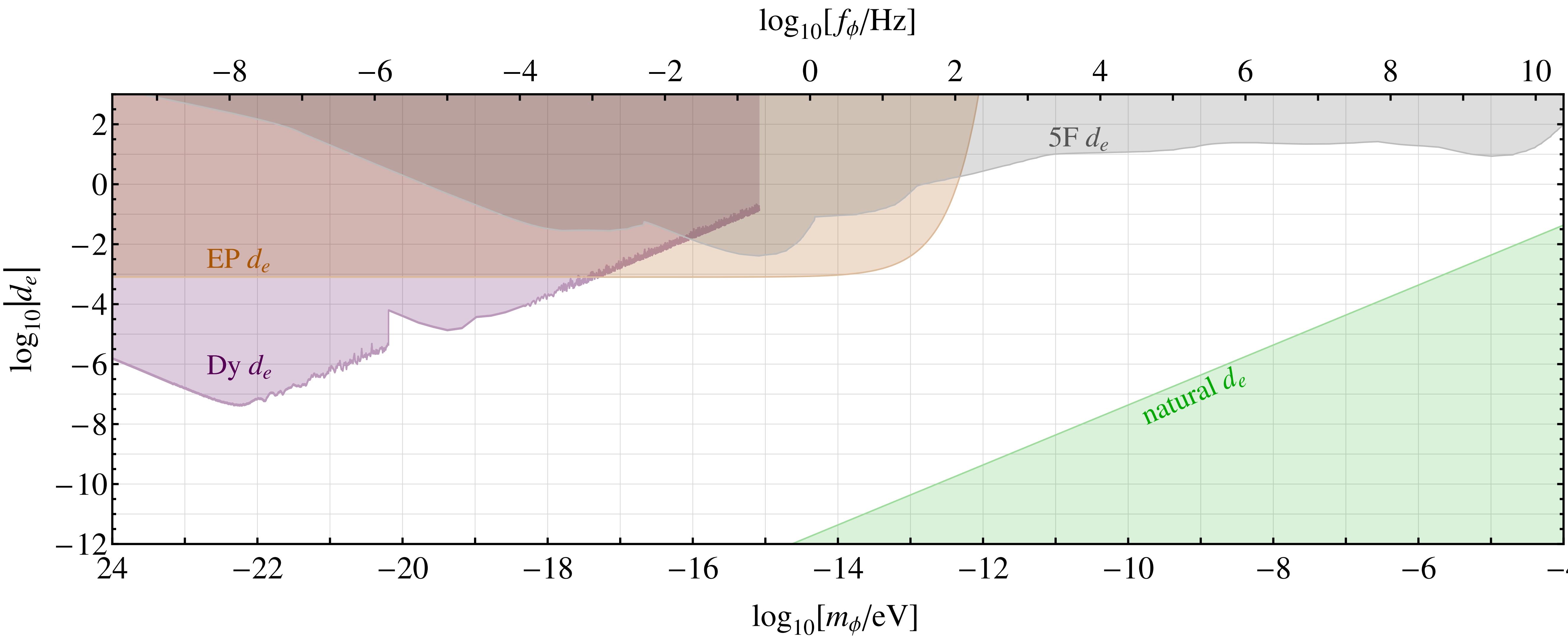
Current sensitivity to α_{EM} variations



The Dysprosium Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

sensitivity to α_{EM} variations



Analysis performed with existing data

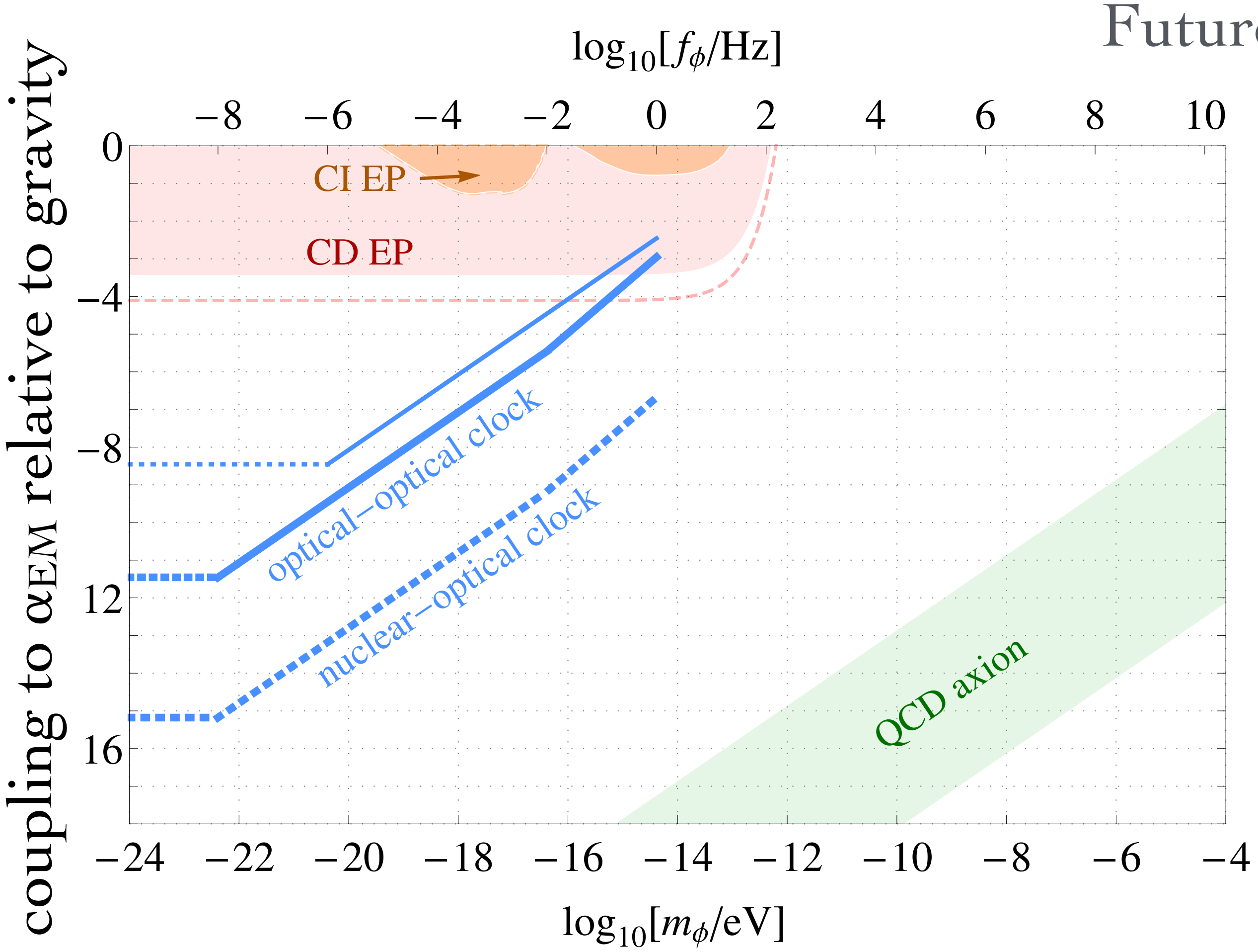
What are possible future improvements?

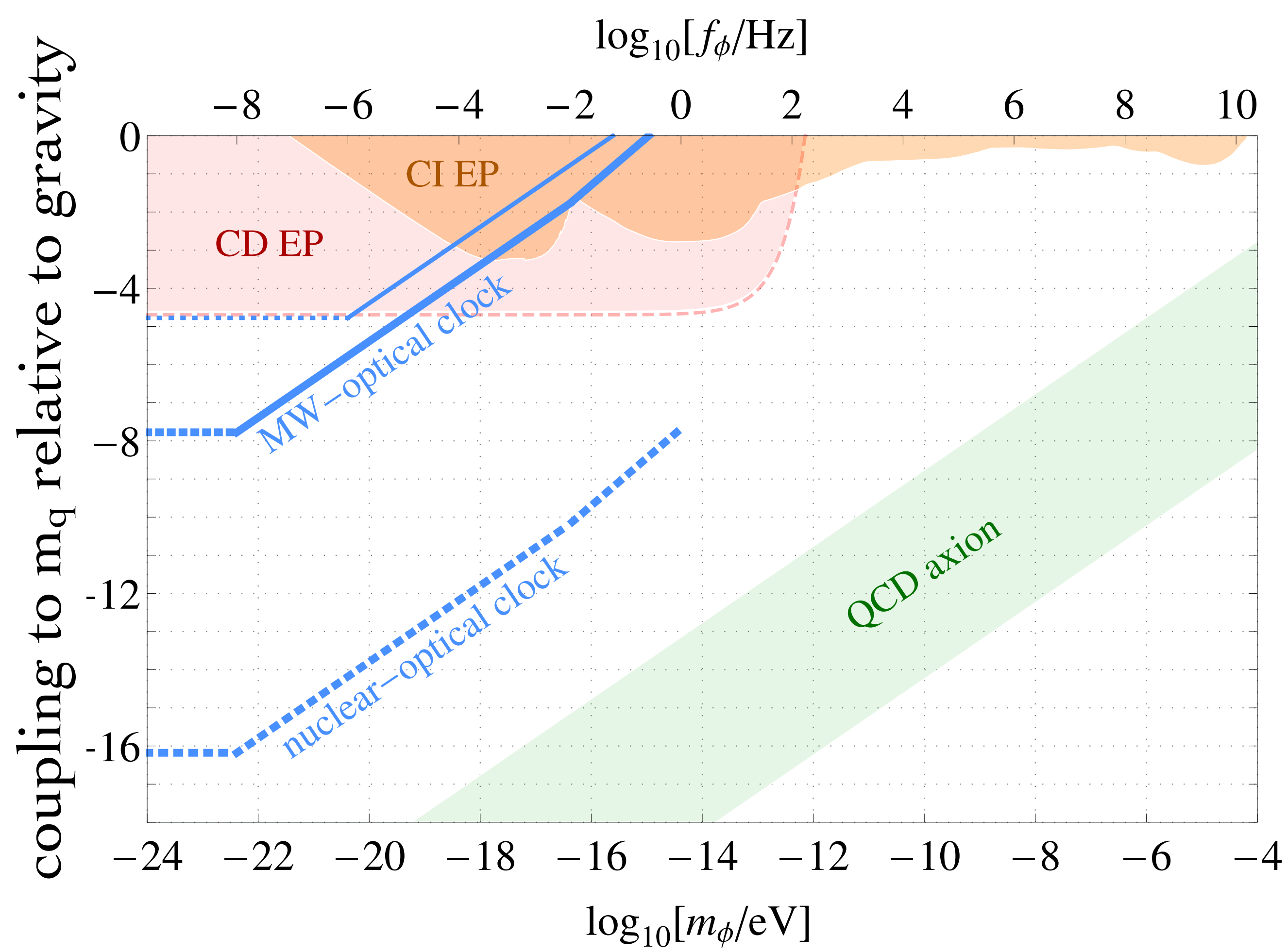
- Optical clock improvements by four orders of magnitude
    - Using more than one atom
    - Using entangled atoms

- The thorium clock under development:
  Nuclear-Optical Clock comparison

Nuclear to Optical Clock Comparison

Future Sensitivity





Keeping the DM time with Atomic Clocks

- Several orders of magnitude improvement possible now compared to 5th force and EP violation searches

- Nuclear clocks if ever built will give several orders of magnitude improvement in the reach

The Sound of Dark Matter

with Ken Van Tilburg
and Savas Dimopoulos (2015)

Oscillating interatomic distances

- The Bohr radius changes with DM
  - $r_B \sim (\alpha\, m_e)^{-1}$

$$\frac{\delta r_B}{r_B} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

- The size of solids changes with DM
  - $L \sim N\,(\alpha\, m_e)^{-1}$

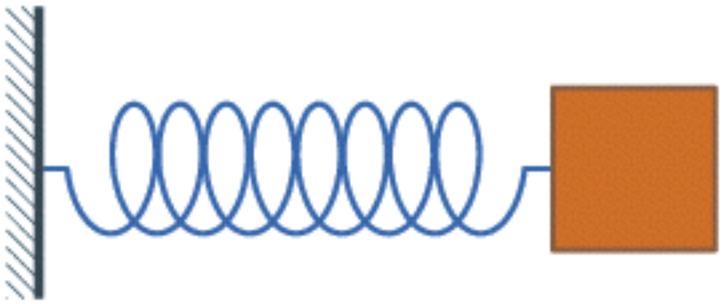
$$\frac{\delta L}{L} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

For a single atom $\delta r_B \sim 10^{-30}$ m

Need macroscopic objects to get a detectable signal

The simple harmonic oscillator

of mass M, resonant frequency ω and equilibrium length L



$$M\left[\ddot{x}+\frac{\omega}{Q}\dot{x}+\omega^2\left(x-L\right)\right]=F_{\rm th}+F_{\rm ext}$$

If the equilibrium size changes with time (with D=x-L):

$$L=L_o\left(1+\frac{\delta L}{L_o}\cos(m_\phi t)\right)$$

$$M\left[\ddot{D}+\frac{\omega}{Q}\dot{D}+\omega^2 D\right]\simeq -M\ddot{L}+F_{\rm th}+F_{\rm ext}$$

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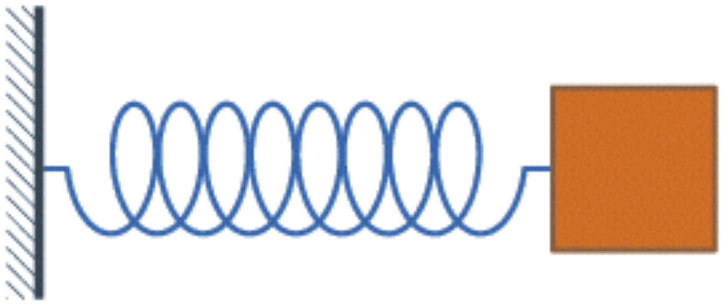

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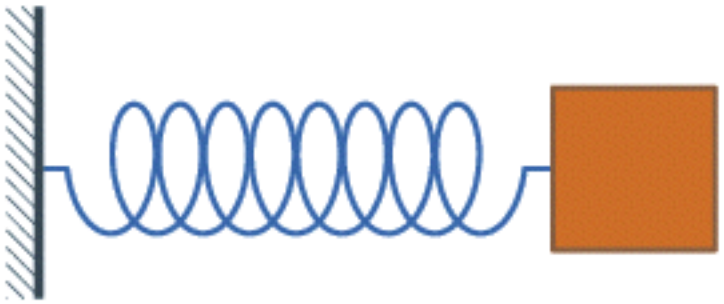
Driving force from change in the equilibrium position

The Simple Harmonic Oscillator



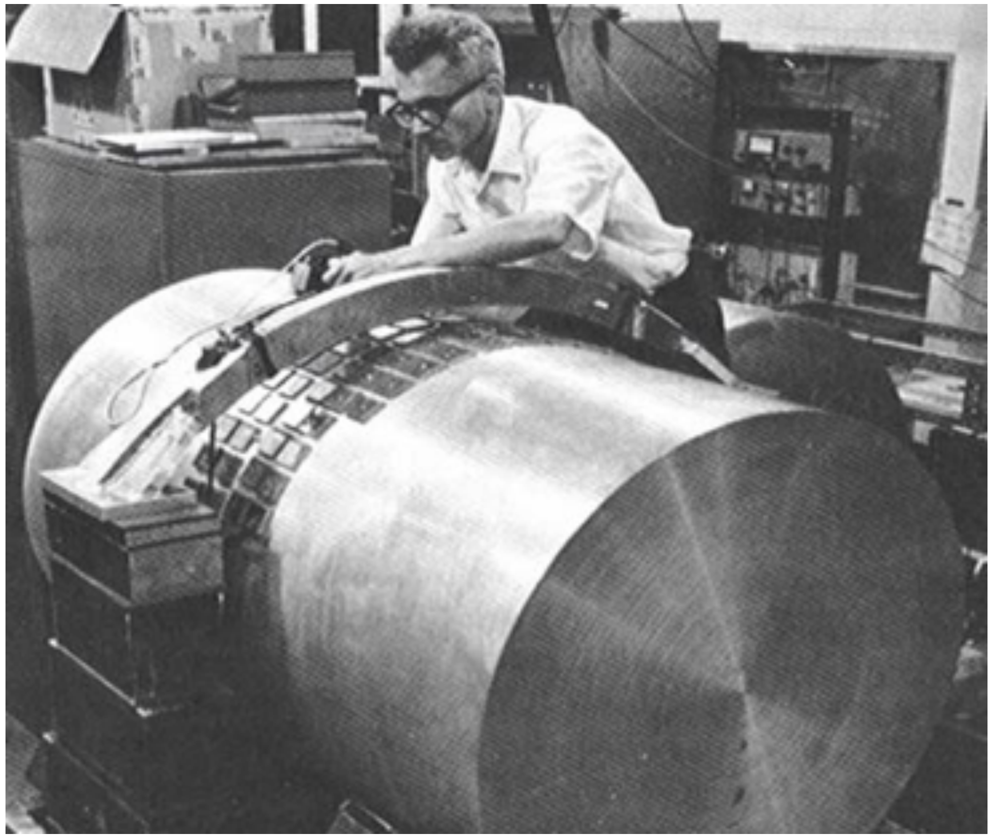
Dark Matter Driving Force:

$$F_{DM} = -M\omega^2 L_o h$$

with

$$h = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

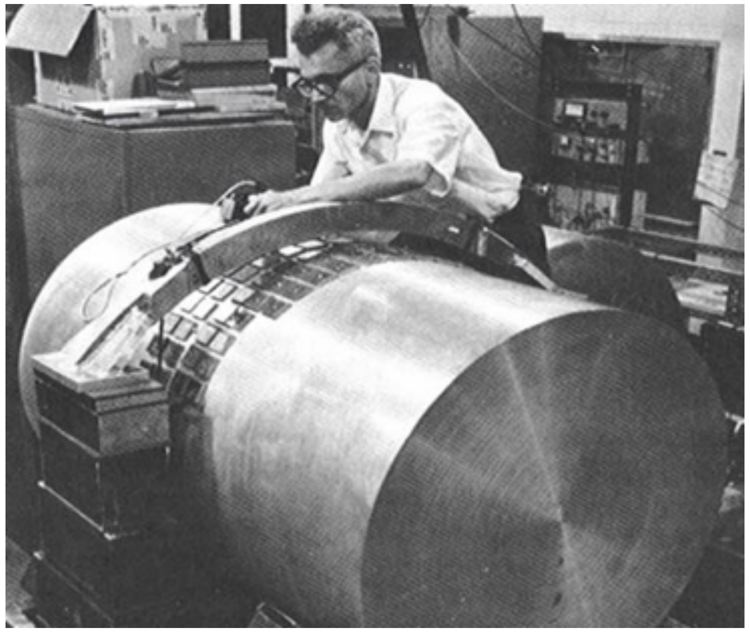
Just like a scalar gravitational wave of same strain



Can use resonant-mass detectors
to enhance and measure
the acoustic waves produced the signal

Resonant-Mass Detectors

- In the 1960's: The Weber Bar



Strain sensitivity $h \sim 10^{-17}$

- Today: AURIGA, NAUTILUS, MiniGrail

Strain sensitivity $h \sim 10^{-23}$

Resonant-Mass Detectors

- Resonant frequency set by size and speed of sound in the material
  - For sizes ~ 1 m resonant frequency of ~1 kHz
- Can take advantage of higher acoustic modes
  - Increases the bandwidth covered by a single device

Resonant-Mass Detectors

- Ultimate sensitivity limited by thermal noise

$$h_{\rm min} \sim \sqrt{\frac{4T}{M\omega_n^3 J_n^2 Q_n}}$$

Improves with higher quality factor object size and (effective) mass

J_n : mode overlap with DM signal —drops like n^{-2}

- Can cover frequencies from 1 kHz all the way to 1 GHz
    - Need to worry about bandwidth coverage

The Sun and The Earth as Resonant-Mass Detectors

- Earth's acoustic mode with frequency (20 min)$^{-1}$ and Q~7500

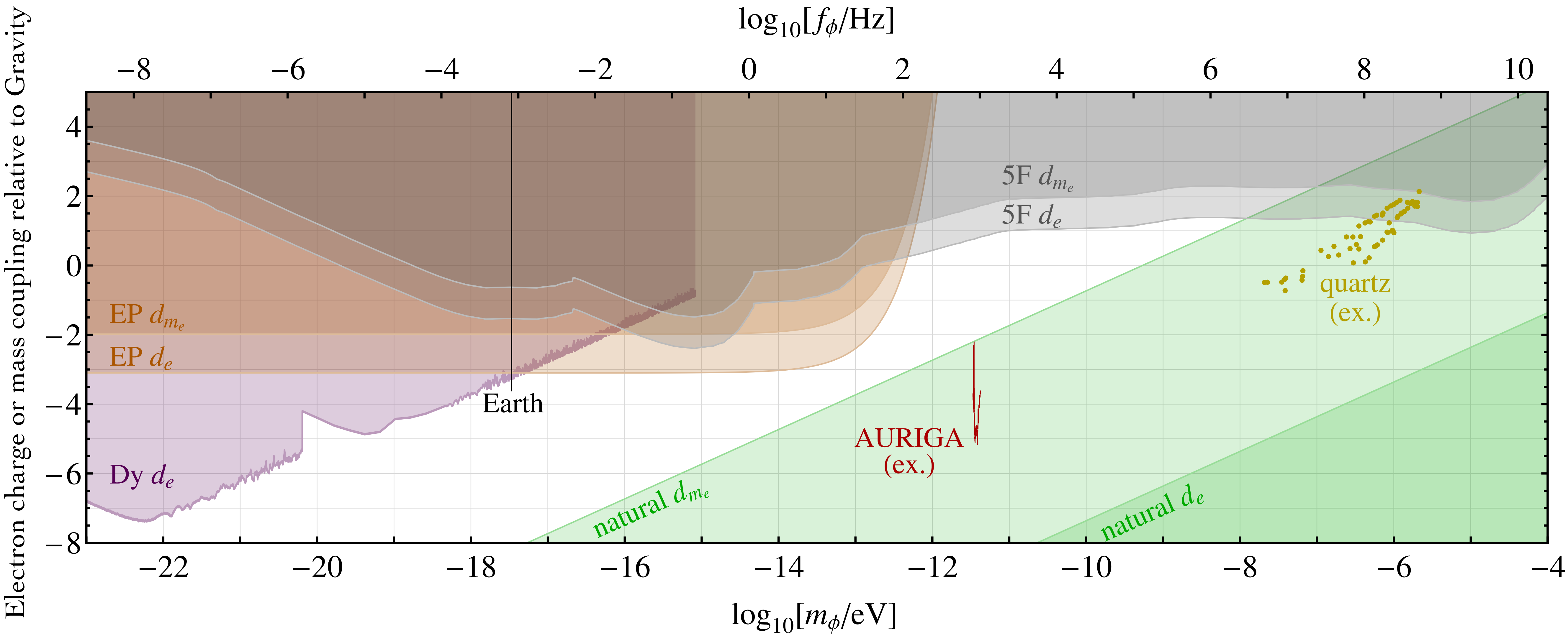
Strain sensitivity h~10^{-17}

- Sun's acoustic modes with frequency ~1 mHz and Q~1000

- Can potentially use other astrophysical objects

Good only for setting bounds

What can be done with current resonant-mass detectors?



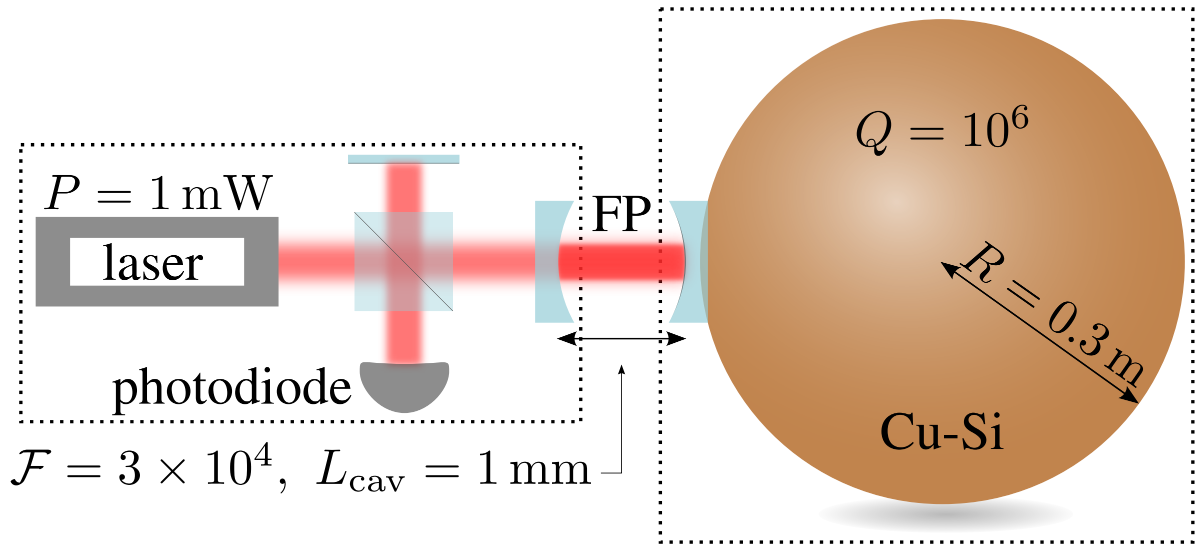
- AURIGA: Ten years of data taking available
- Quartz: Experiment by M. Tobar using Q > 10^{10} piezoelectrics
- Earth: Using a single monopole seismic mode observed over several months

What can be done in the future?

Need to increase bandwidth

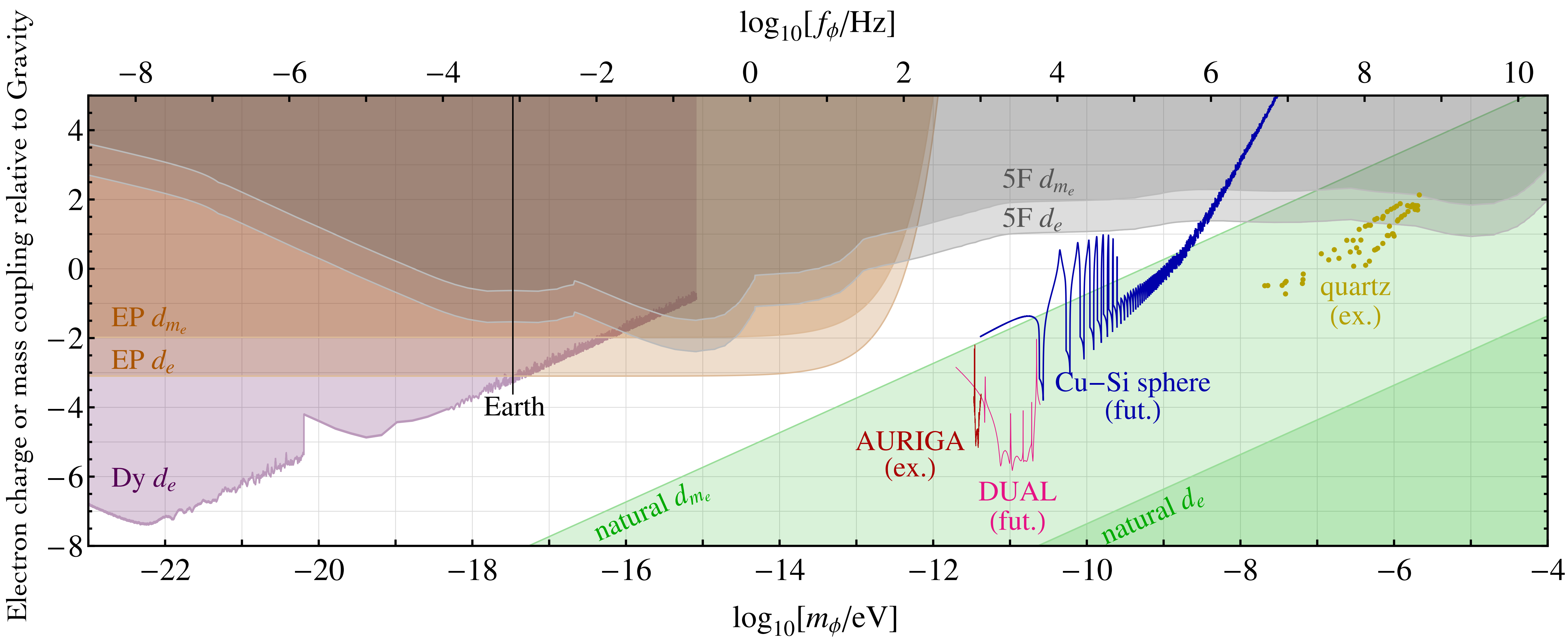
- Dual Mass detectors
- Xylophone
- Copper-Silicon alloy sphere: variations of few percent in sound speed between $4 - 100$ K
  - Use temperature to scan resonant frequency

The scanning resonant-mass detector



- Use Fabry-Perot cavity to pick up displacement as small as 10^{-19} m/(Hz)$^{1/2}$
- Change operating temperature between 4-100 K at 2 mK increments
- Pick up ALL modes at once: continuous coverage above 10kHz

What can be done in the future?

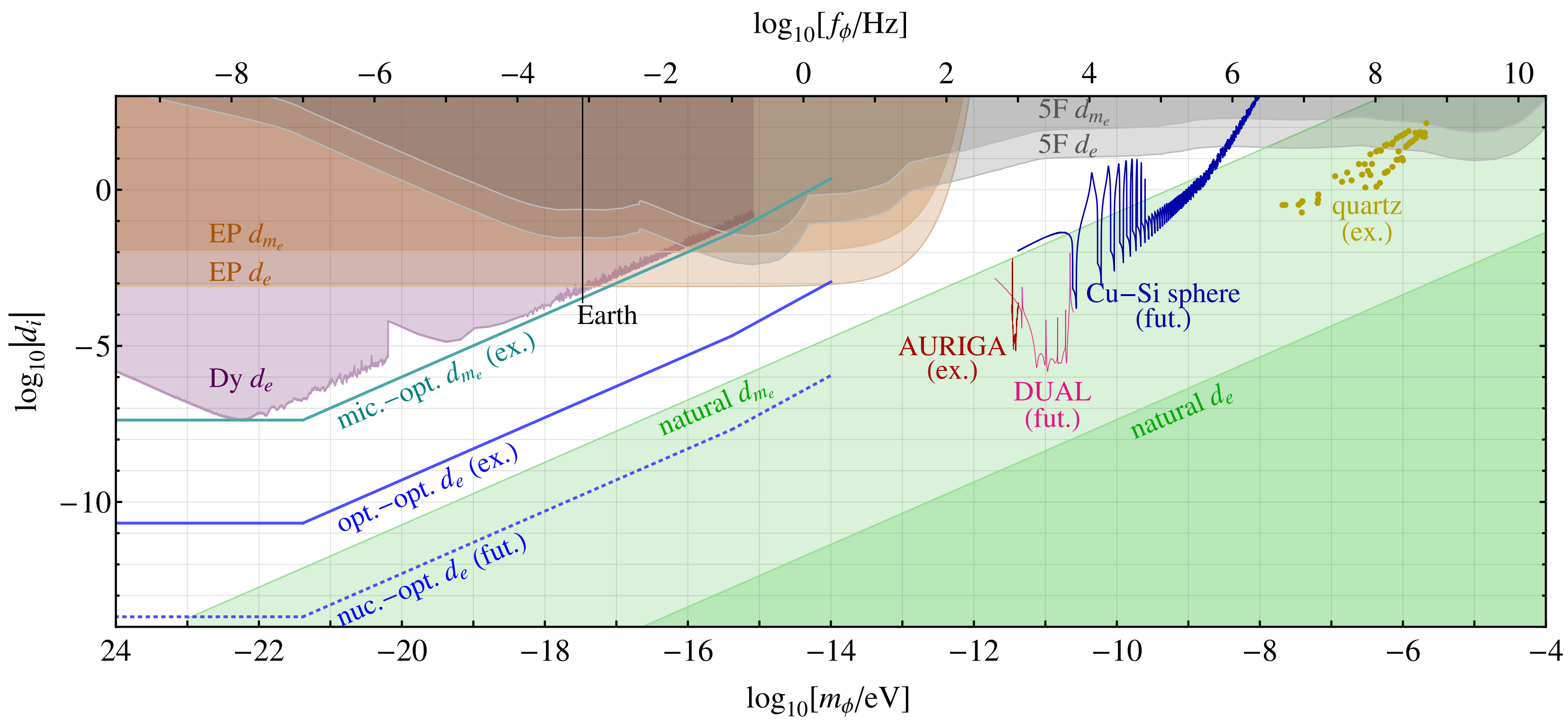


- Probe even the theoretically biased regime of natural couplings and masses

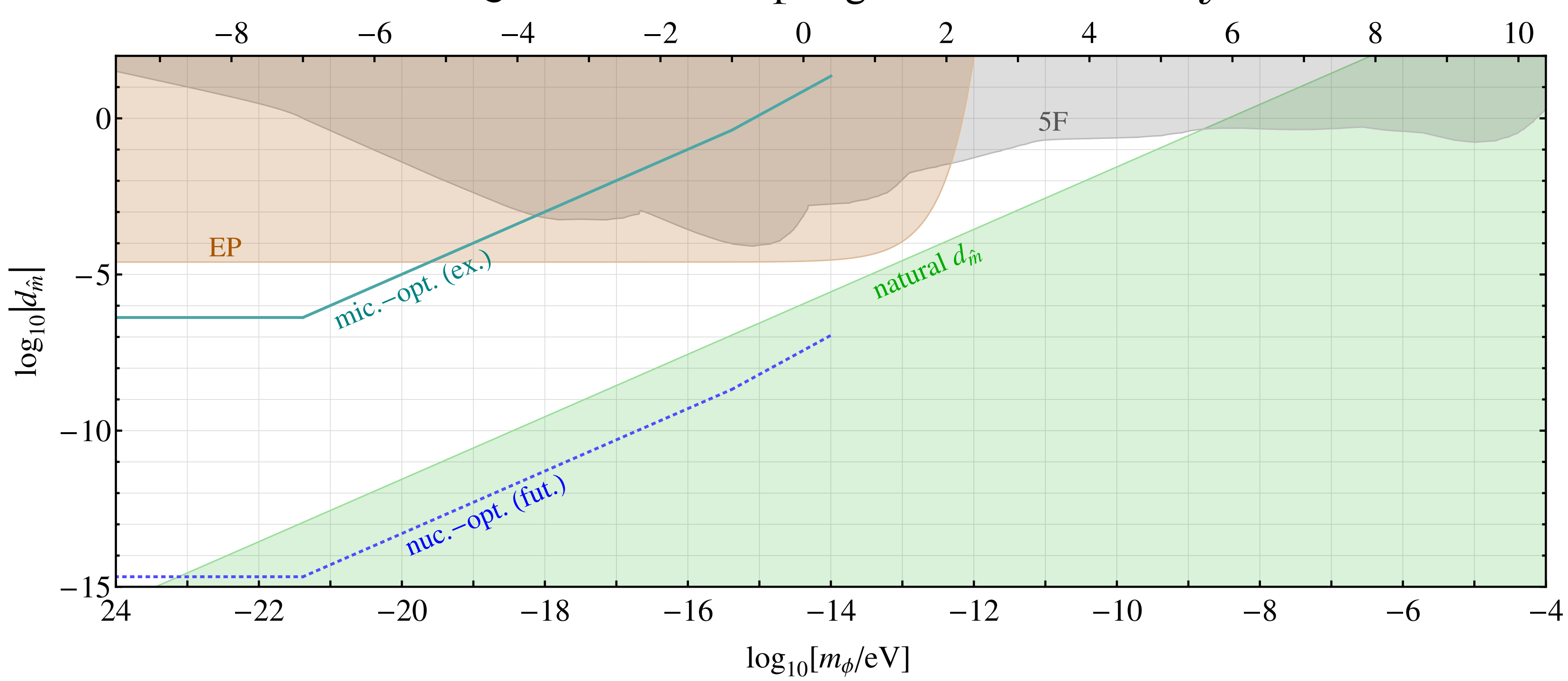
$$\text{Ex.} \qquad \frac{\delta m_e}{m_e} < 10^{-20} \left(\frac{10 \text{ TeV}}{\Lambda} \right)^2$$

What about naturalness?

Electron charge or mass coupling relative to Gravity



Quark mass coupling relative to Gravity



Summary

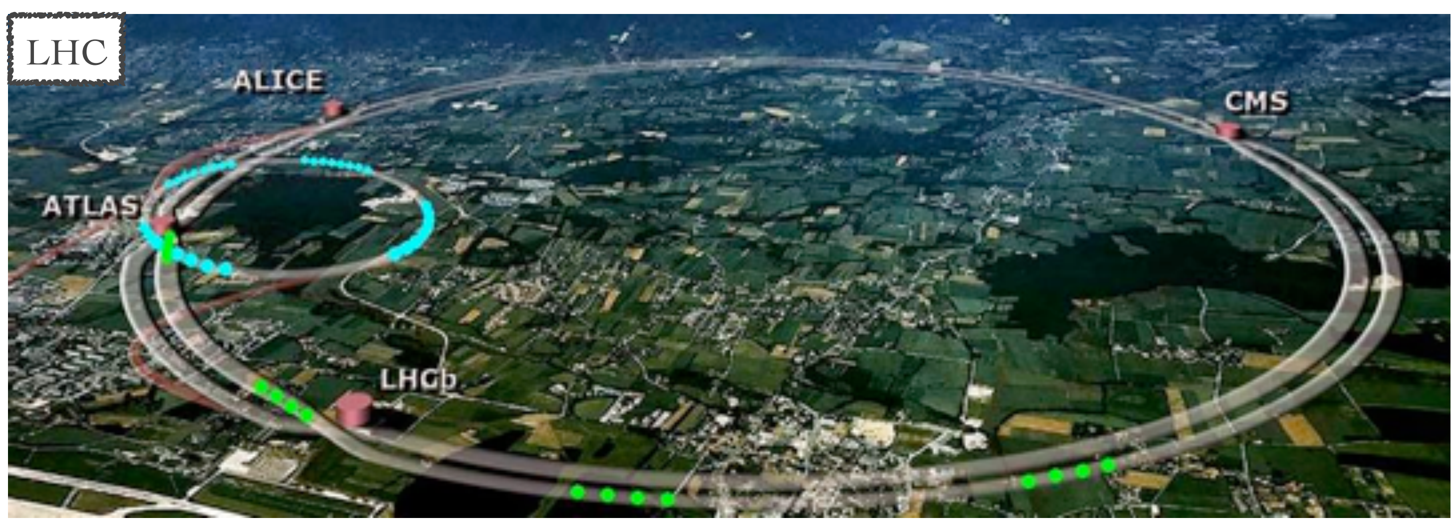
- Several orders of magnitude improvement in searches for moduli Dark Matter

- Based on existing and well-established techniques

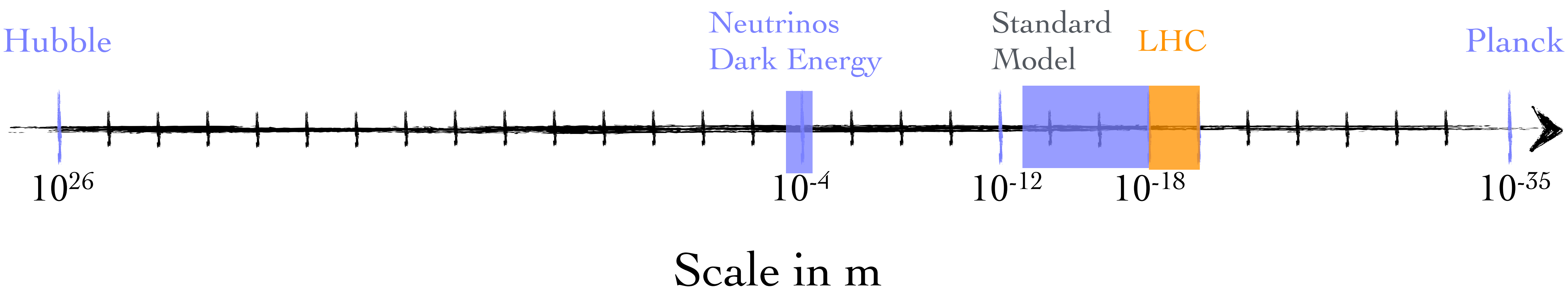
- There are several more possibilities in particular pushing to higher frequencies

This is only scratching the surface…

The High Energy Frontier



The Length Scales in the Universe



80% of the energy scale left to explore