Fundamental Physics Beyond Colliders

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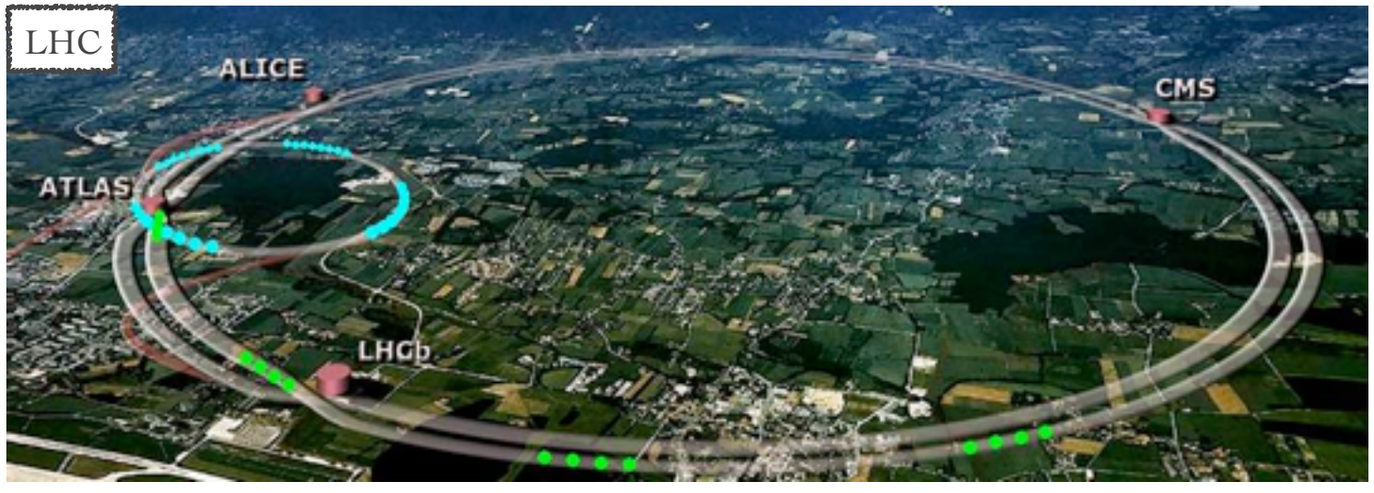
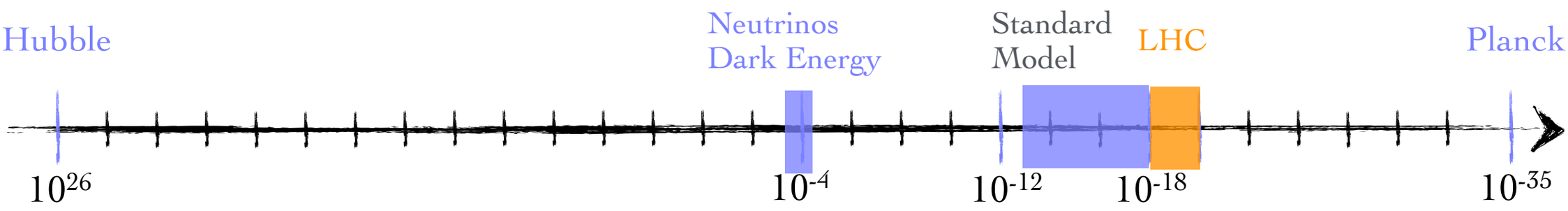
Perimeter Institute

The High Energy Frontier



The Length Scales in the Universe



Scale in m

80% of the energy scale left to explore

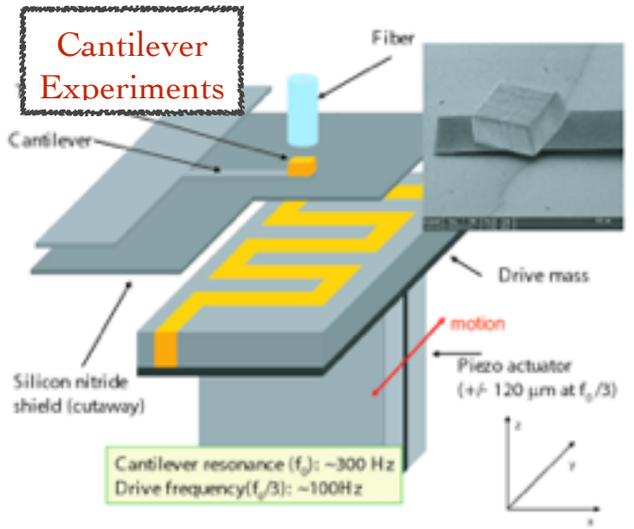
The Low Energy Frontier

- In the Standard Model
  - Gravitons
  - Cosmic Neutrinos

- In String Theory
  - Axion(s)
  - Photons kinetically mixing with our photon
  - Dilaton, moduli, new dimensions

Opportunities to probe the low energy frontier

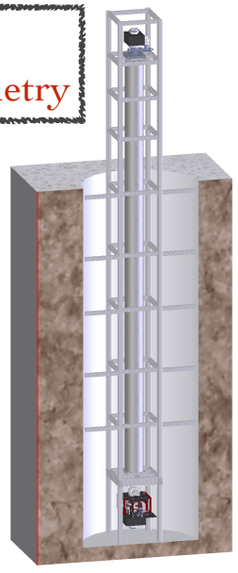
Cantilever Experiments



Dimopoulos, Kapitulnik (1997)

- Short Distance Tests of Gravity
- Extra Dimensions

Atom Interferometry



- Tests of Gravity
- Gravitational Wave detection at low frequencies
- Tests of Atom Neutrality at 30 decimals

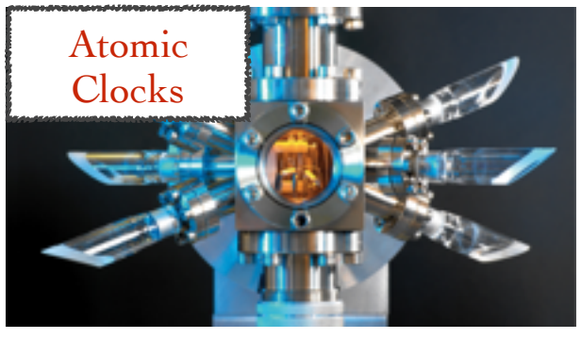
Dimopoulos, Geraci (2003)
Dimopoulos, Kasevich et. al.(2006-2008)

- Axion Dark Matter Detection
- Axion Force Detection

NMR

Graham et. al. (2012)
AA, Geraci (2014)

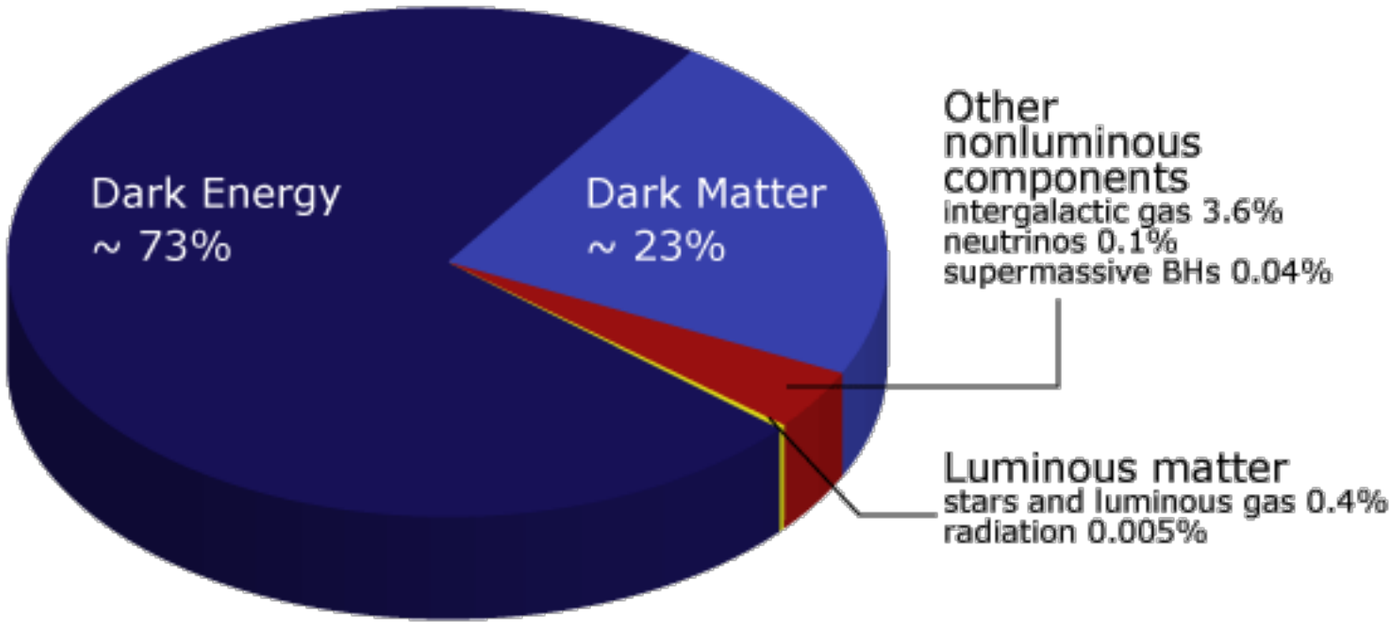
Atomic Clocks



- Setting the Time Standard
- Dilaton Dark Matter Detection

AA, Huang, Van Tilburg (2014)

The Mystery of Dark Matter



Properties of Dark Matter

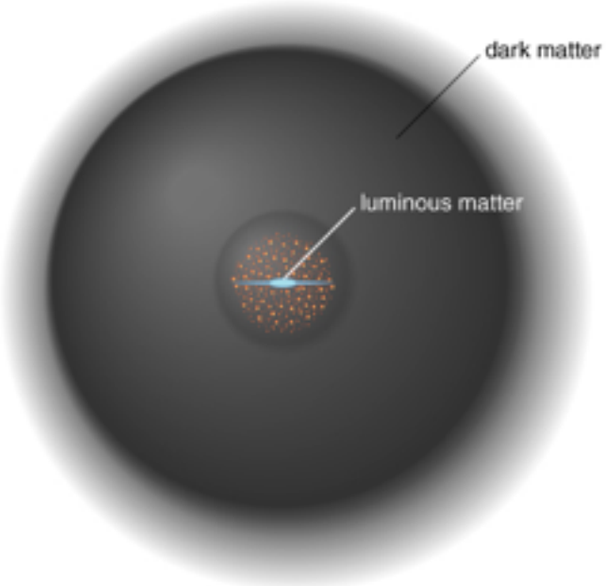
- What is it?

- How is it produced?

- Does it have interactions other than gravitational?

What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



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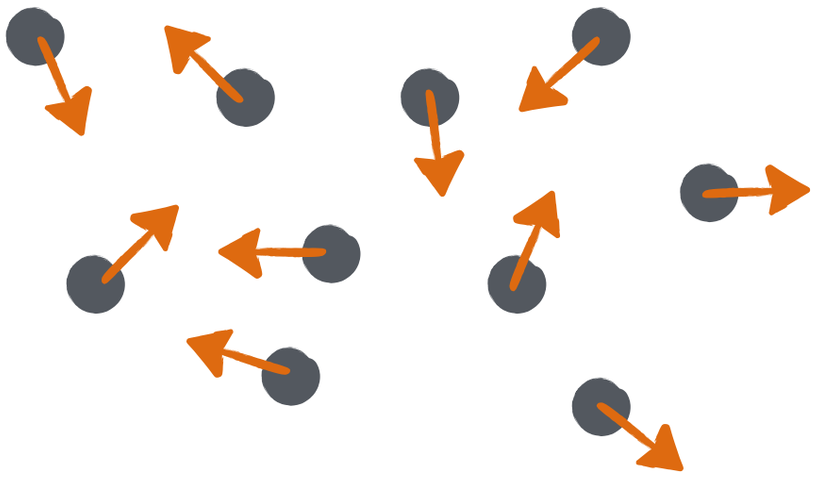

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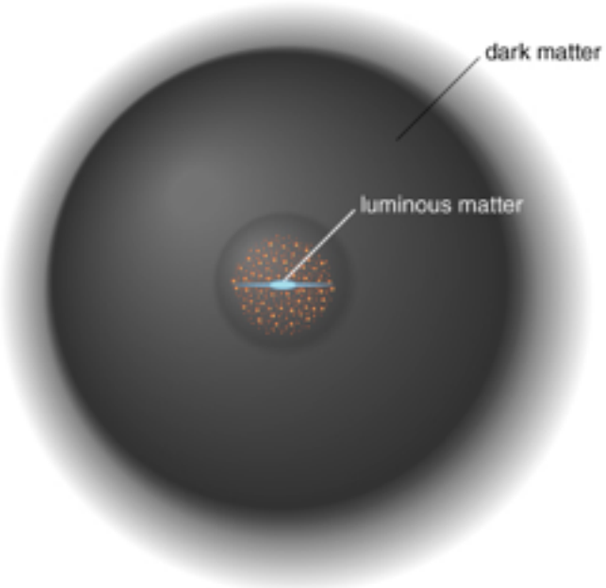

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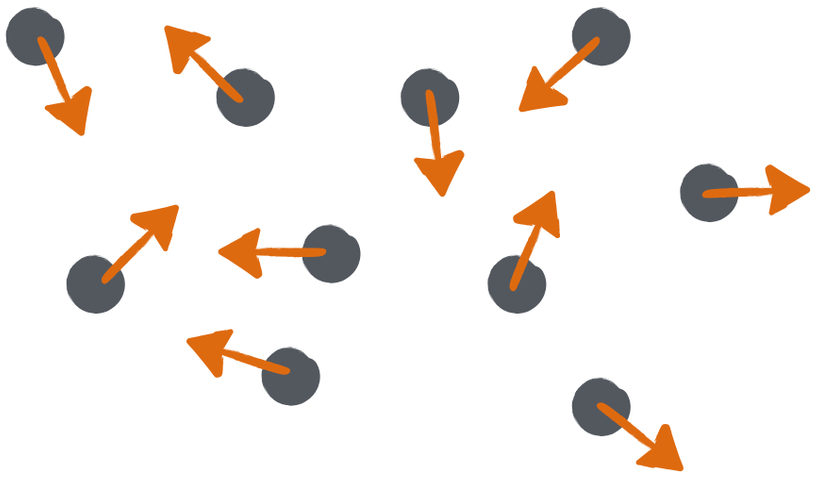
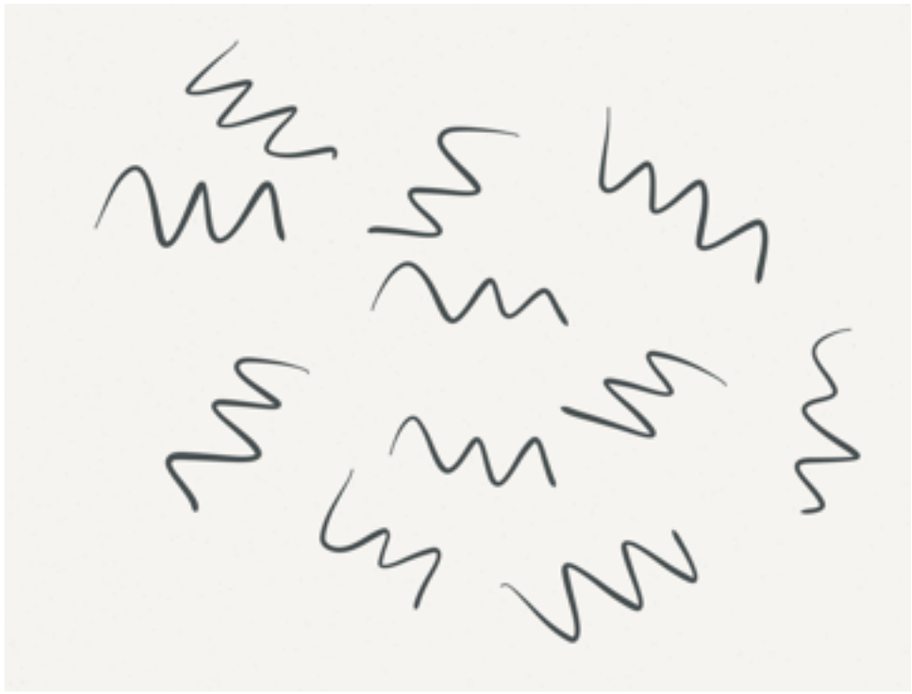


instead of…



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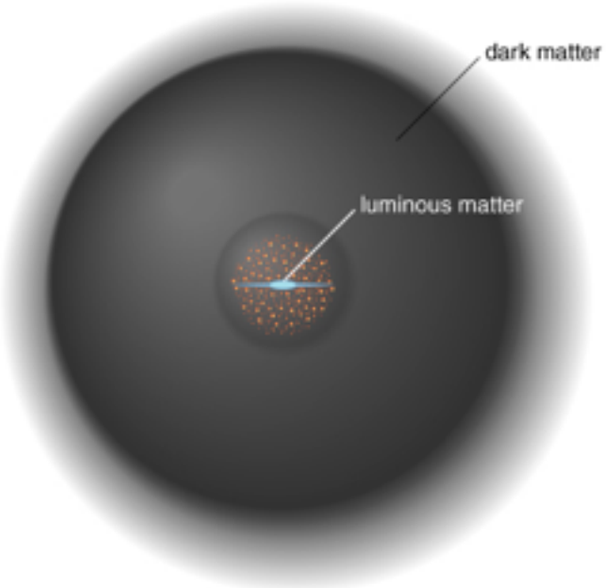
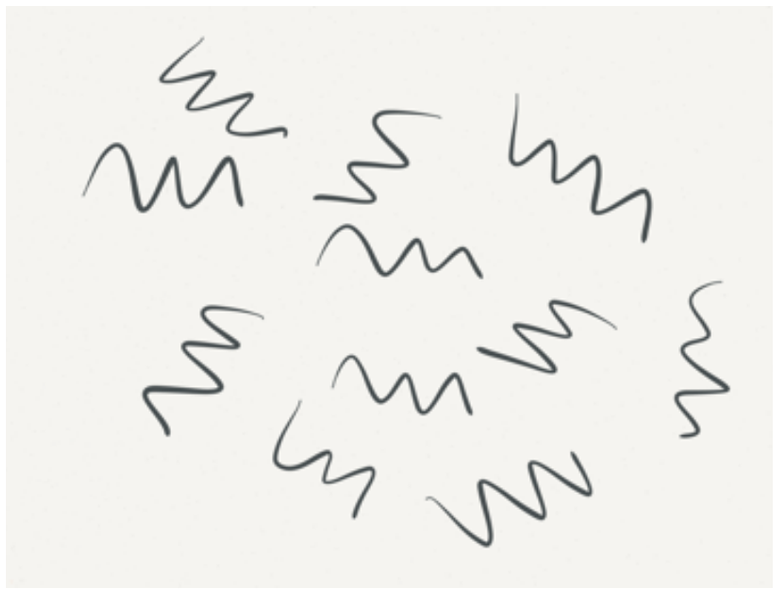
Dark Matter Particles in the Galaxy

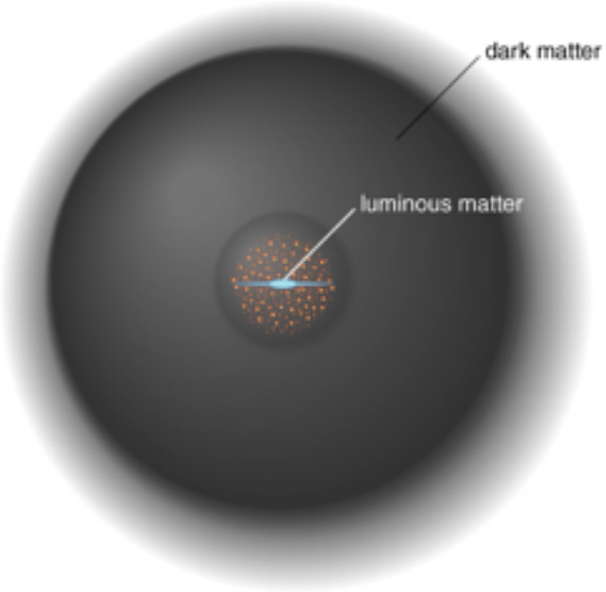


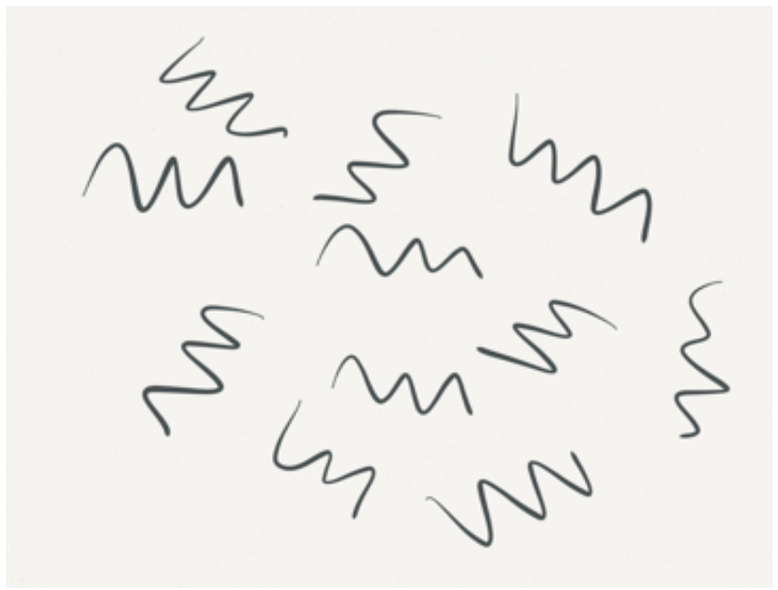


Decreasing DM Mass

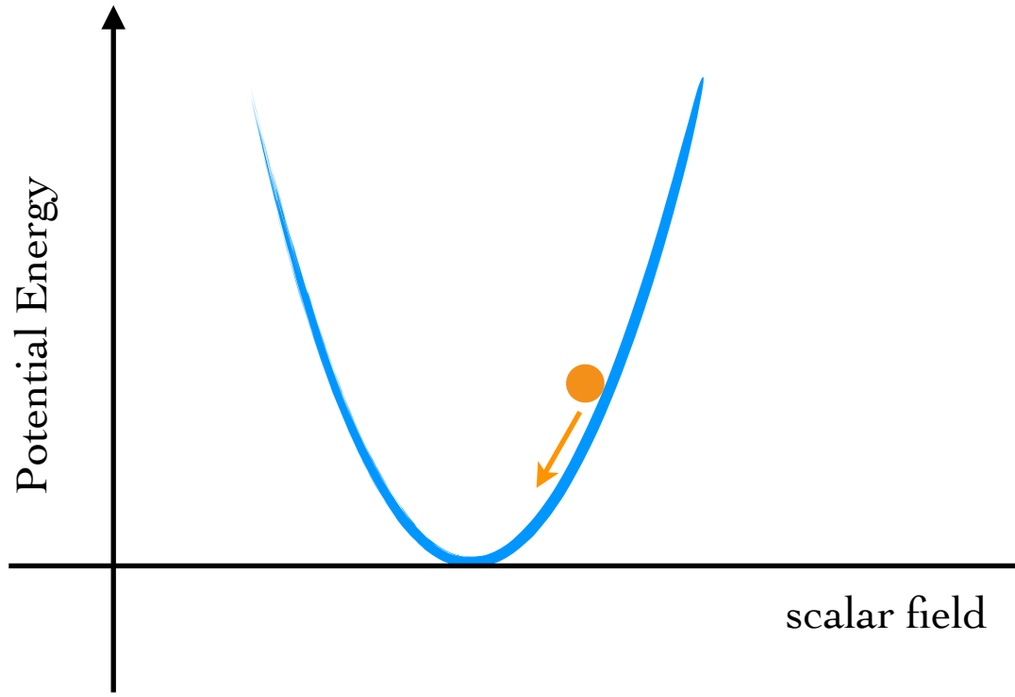
What If It Is a Boson and Very Light?

Dark Matter Particles in the Galaxy





Decreasing DM Mass



Equivalent to a Scalar Wave

Frequency set by DM mass and Amplitude set by DM abundance

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

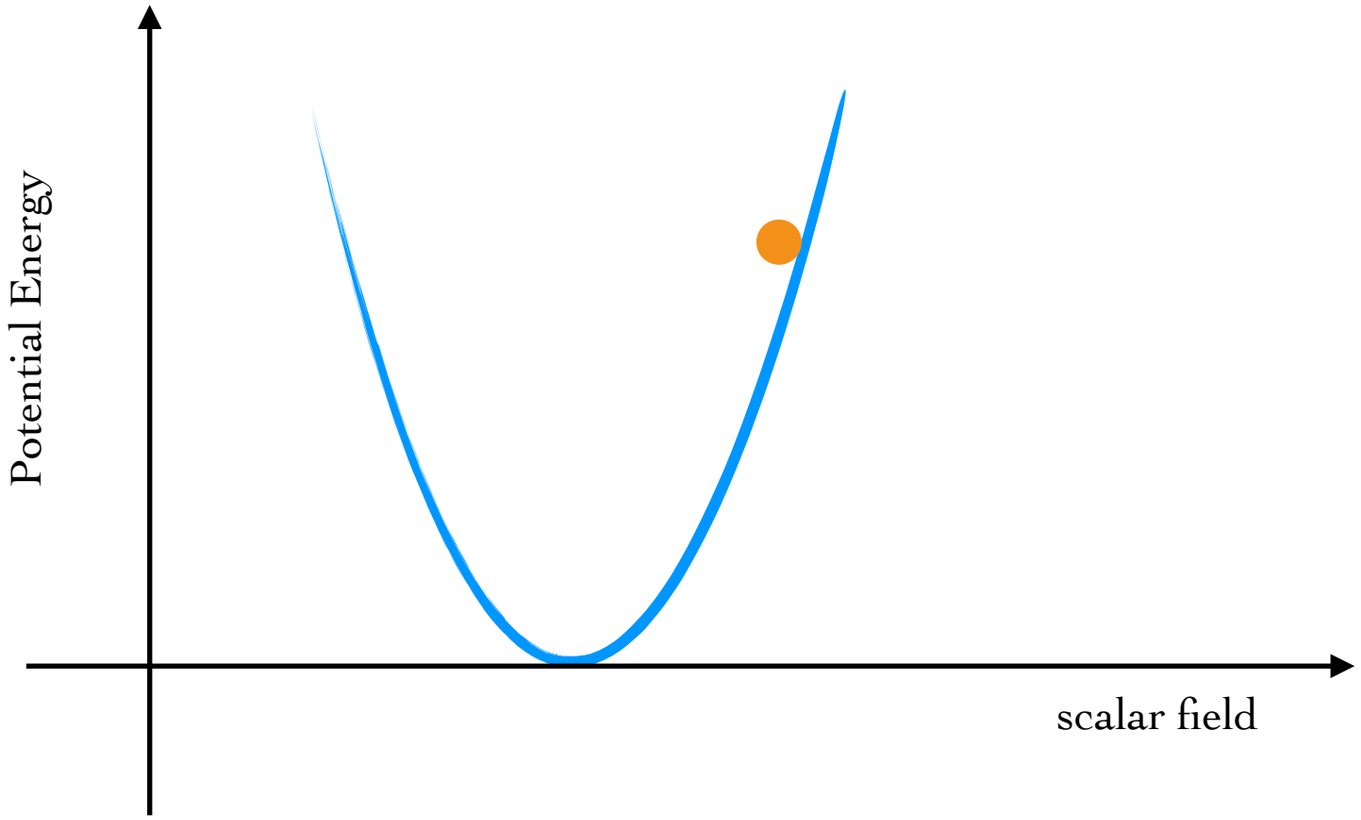
  - Generates a fifth force in matter

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

  - Generates Equivalence Principle violation

Light Scalar Dark Matter

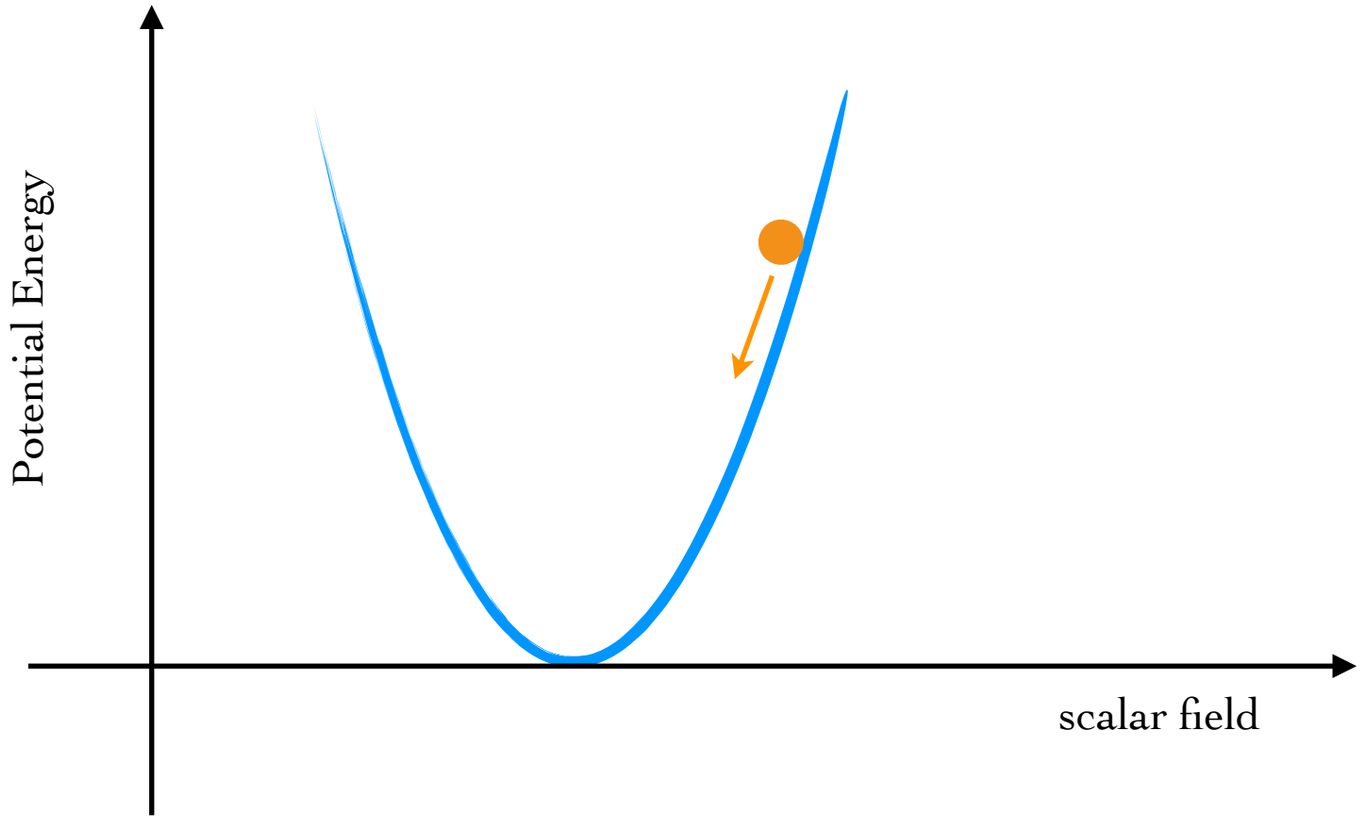
- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

Light Scalar Dark Matter

- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

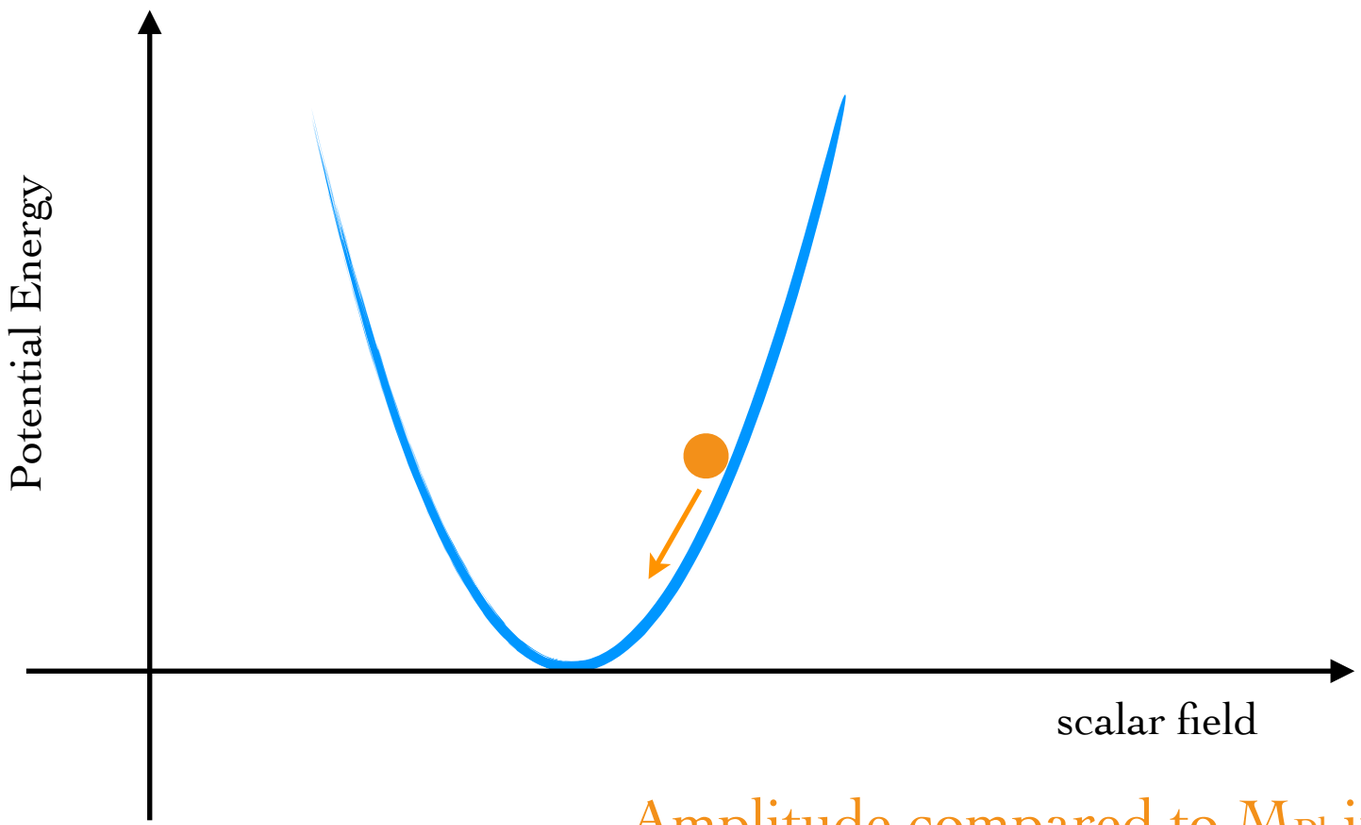
Oscillates when:
Hubble < m_ϕ

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

Initial conditions set by inflation

Light Scalar Dark Matter Today

- If $m_\phi < 1$ 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:

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

Oscillating Fundamental Constants

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e} \frac{\phi}{M_P l} m_e e \bar{e}$$

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

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

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

- ARIADNE

Keeping the DM time with Atomic Clocks

with Junwu Huang
and Ken Van Tilburg (2014)

Oscillating Atomic and Nuclear Energy Splittings

- Optical Splittings

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

- Hyperfine Splittings

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

- 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

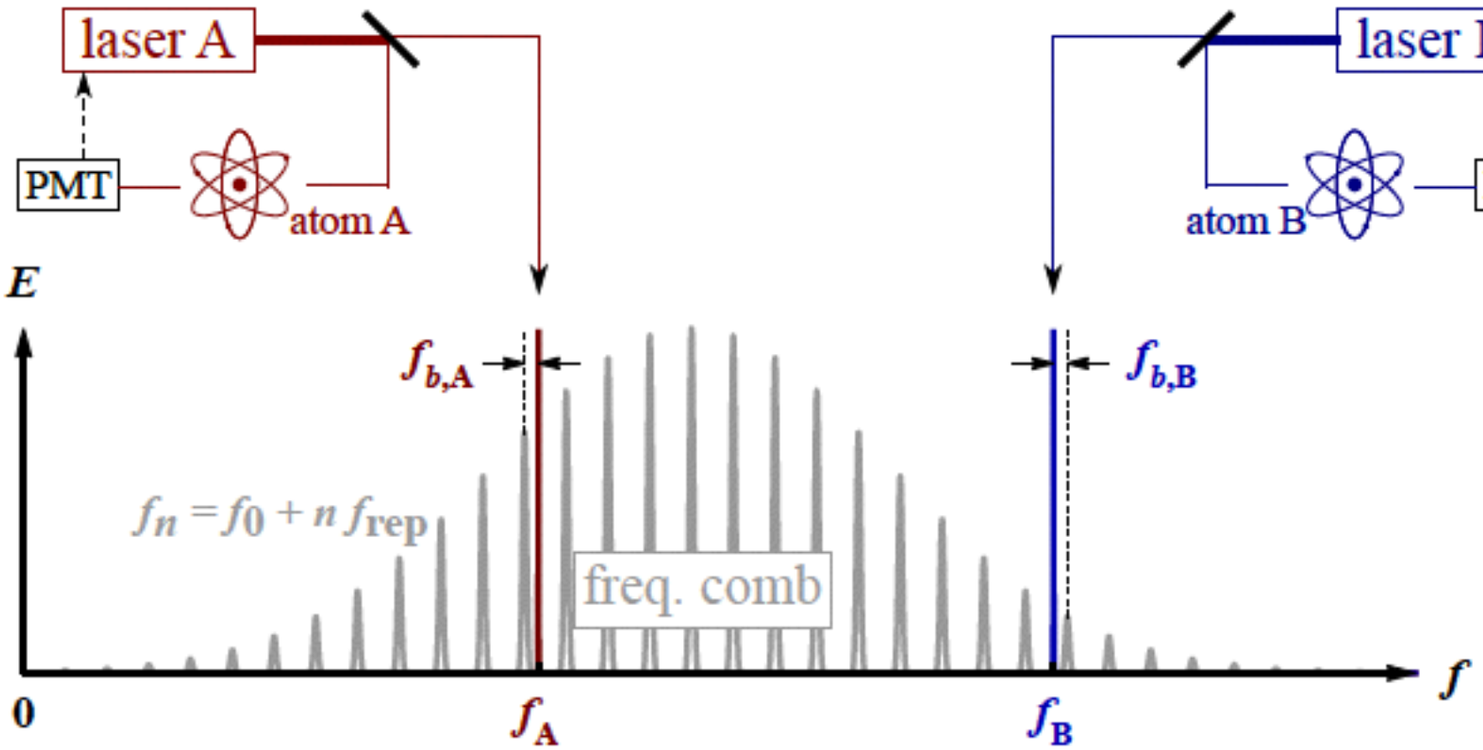
- Have shown stability of 1 part in 10^{18}

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

- Have won several Nobel prizes in the past 20 years

How does an Atomic Clock Work?

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

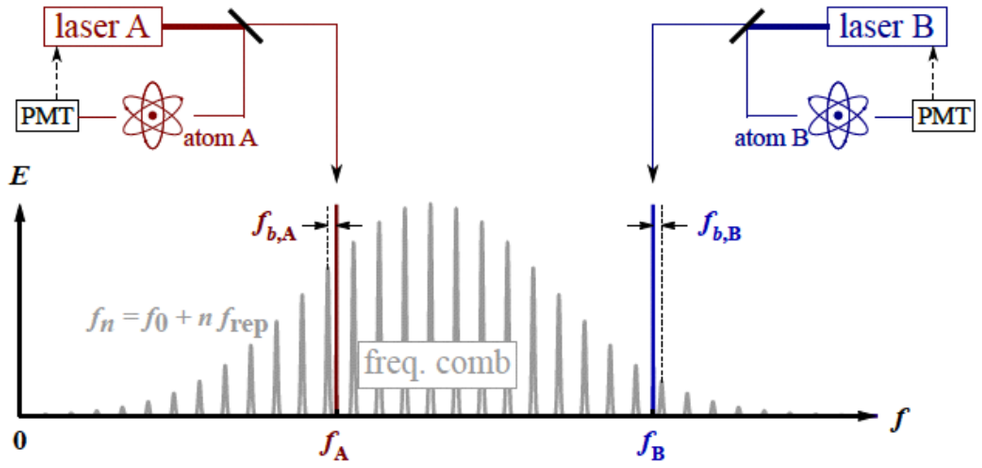


$$\frac{\delta f}{f} \sim \frac{\Gamma_{\text{atom}}}{f} \frac{1}{\sqrt{N_{\text{atoms}}}} \sqrt{\frac{\tau_{\text{cycling}}}{t_{\text{experiment}}}}$$

τ_{cycling} of order the lifetime

How do you take the measurements?

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



- Calculate ratio of frequencies taking into account:

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

- 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 $\left(\frac{10^{-15}}{\sqrt{\text{Hz}}}\right)$	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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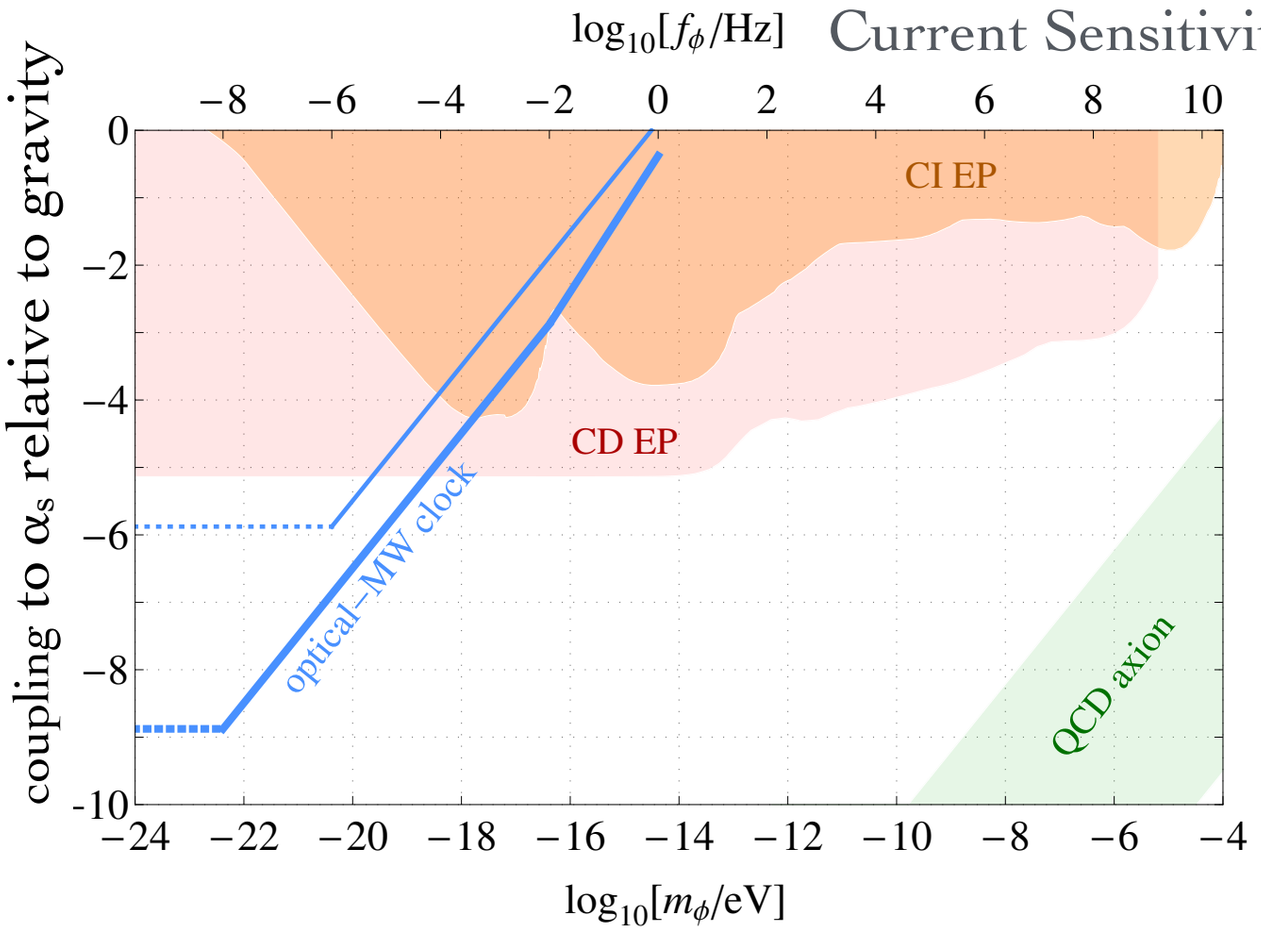
Thorium nuclear transition cancellations
increase sensitivity to EM coupling and quark mass coupling variations
Not measured yet…

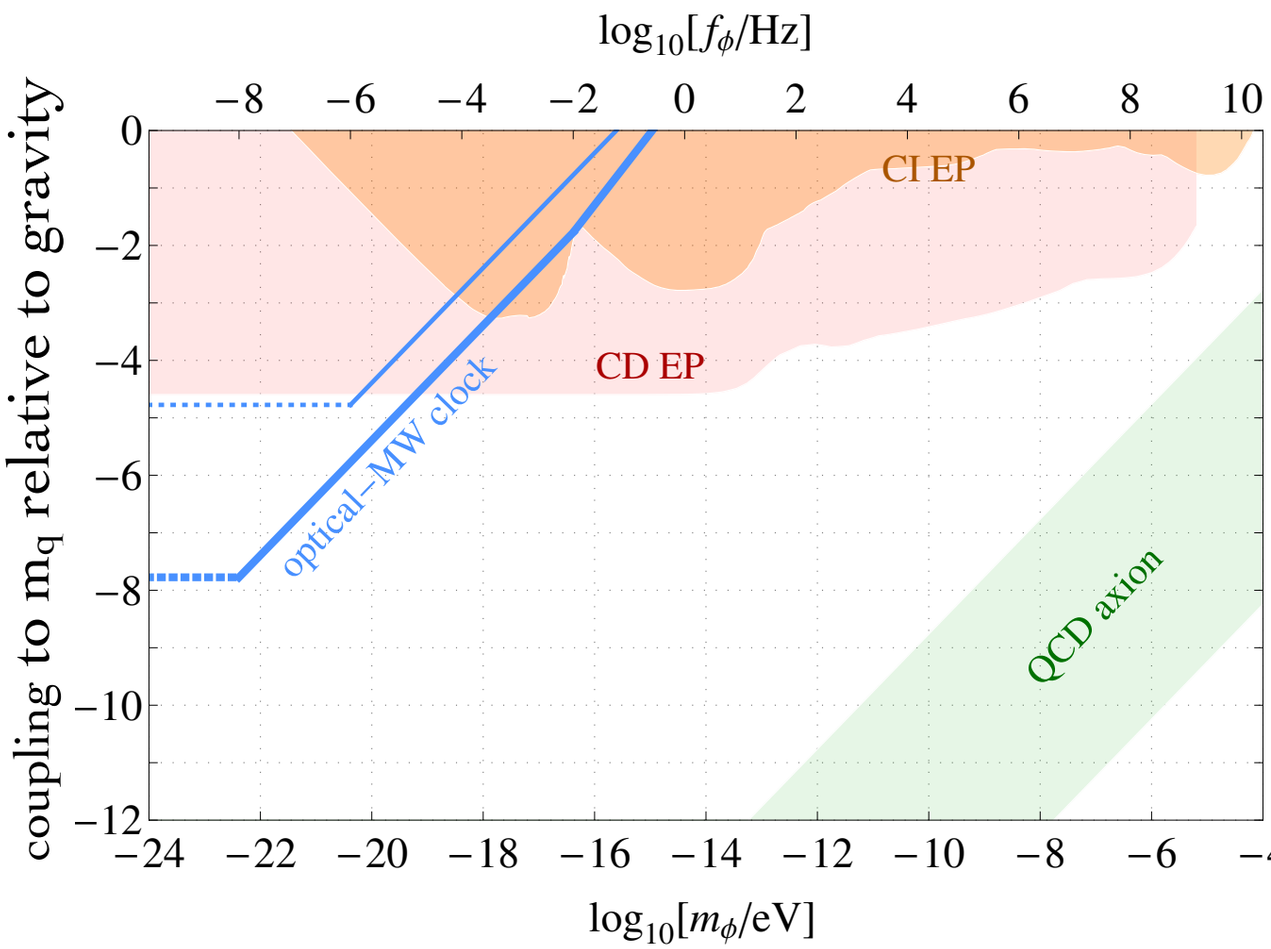
What type of comparisons can we do?

- 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

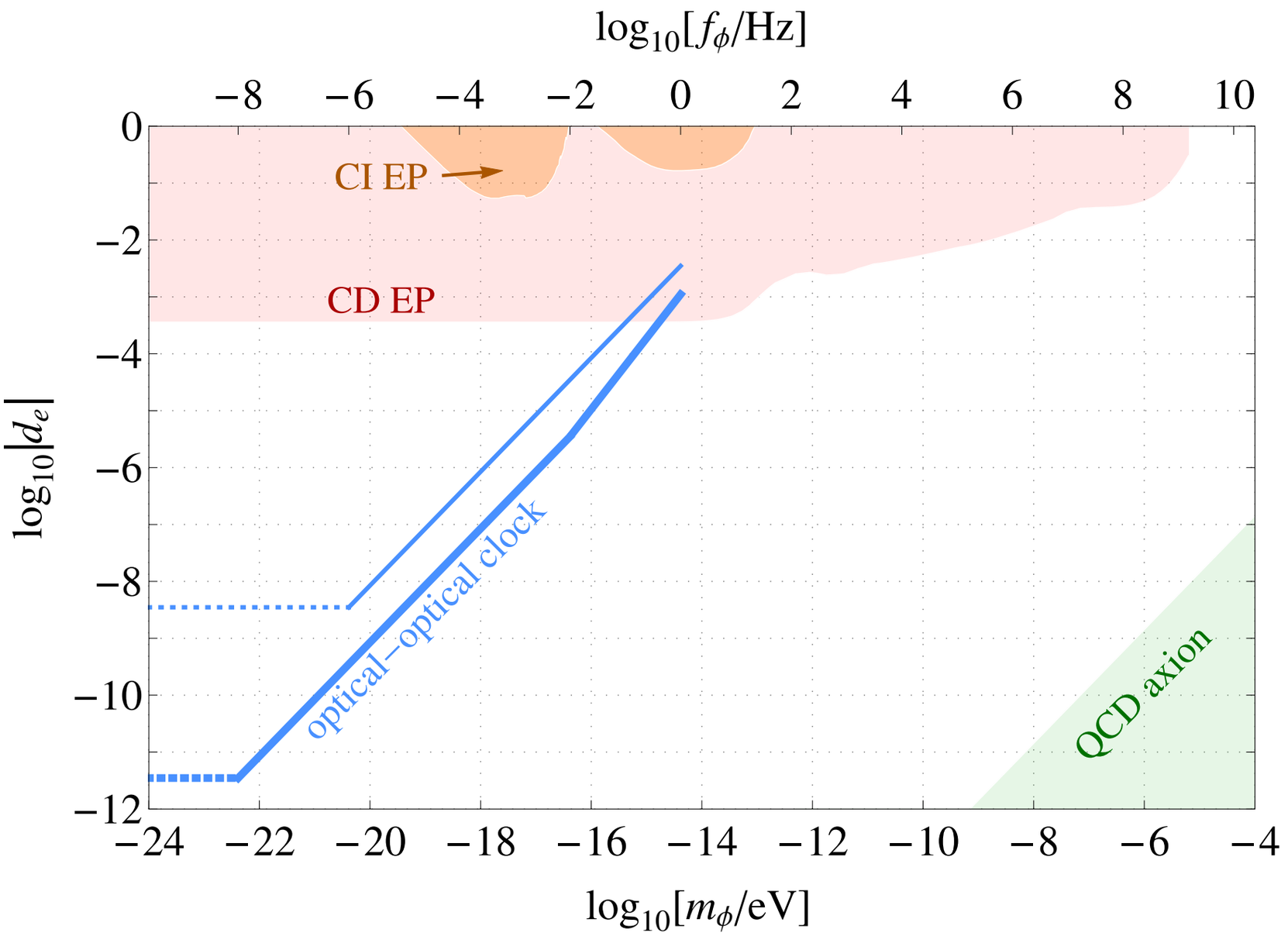


Experiments run for 10^6 sec or ~ year



Optical to Optical Comparison

Current sensitivity to α_{EM} variations

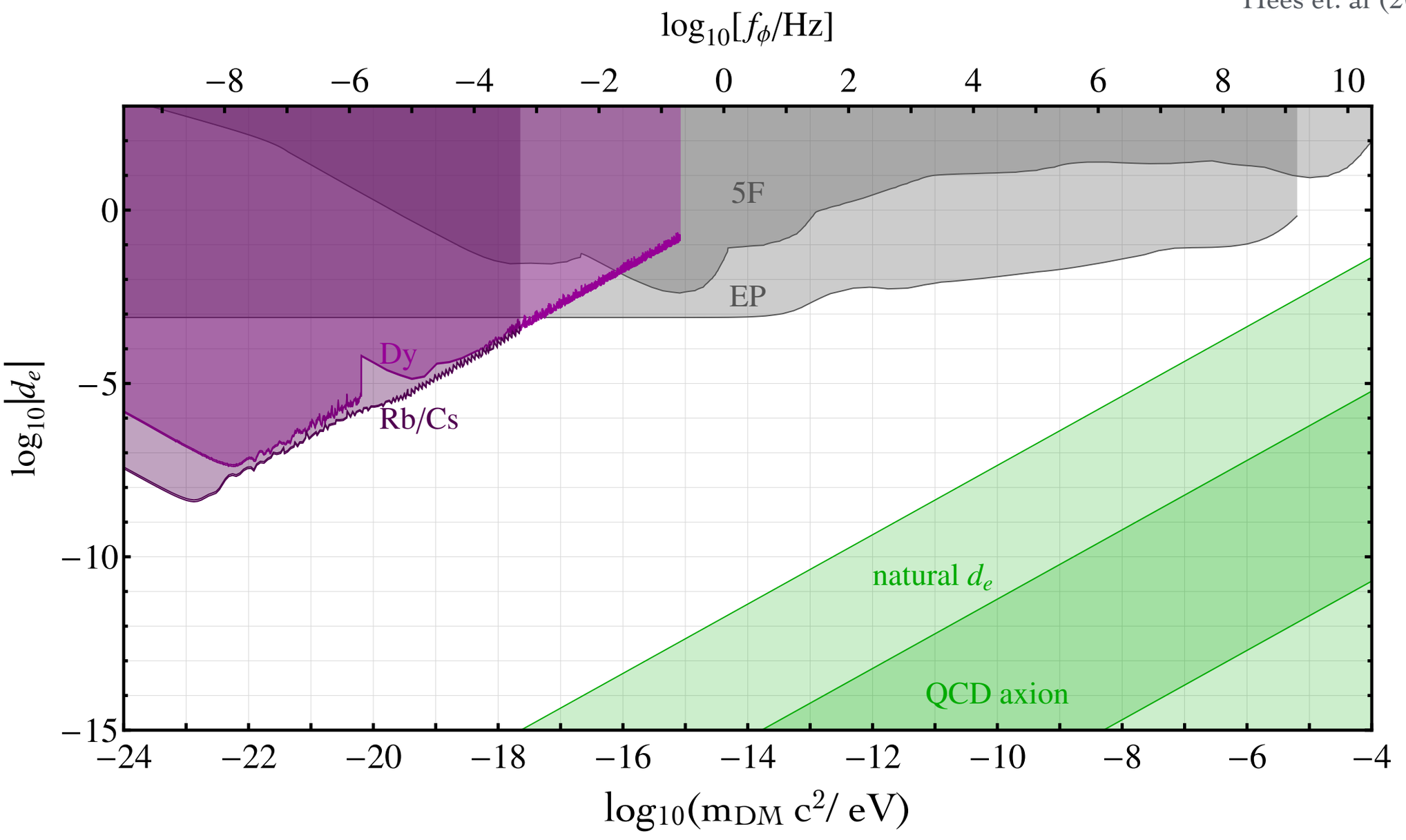


The Dy isotope and Rb/Cs Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

sensitivity to α_{EM} variations

Hees et. al (2016)



Analysis performed with existing data

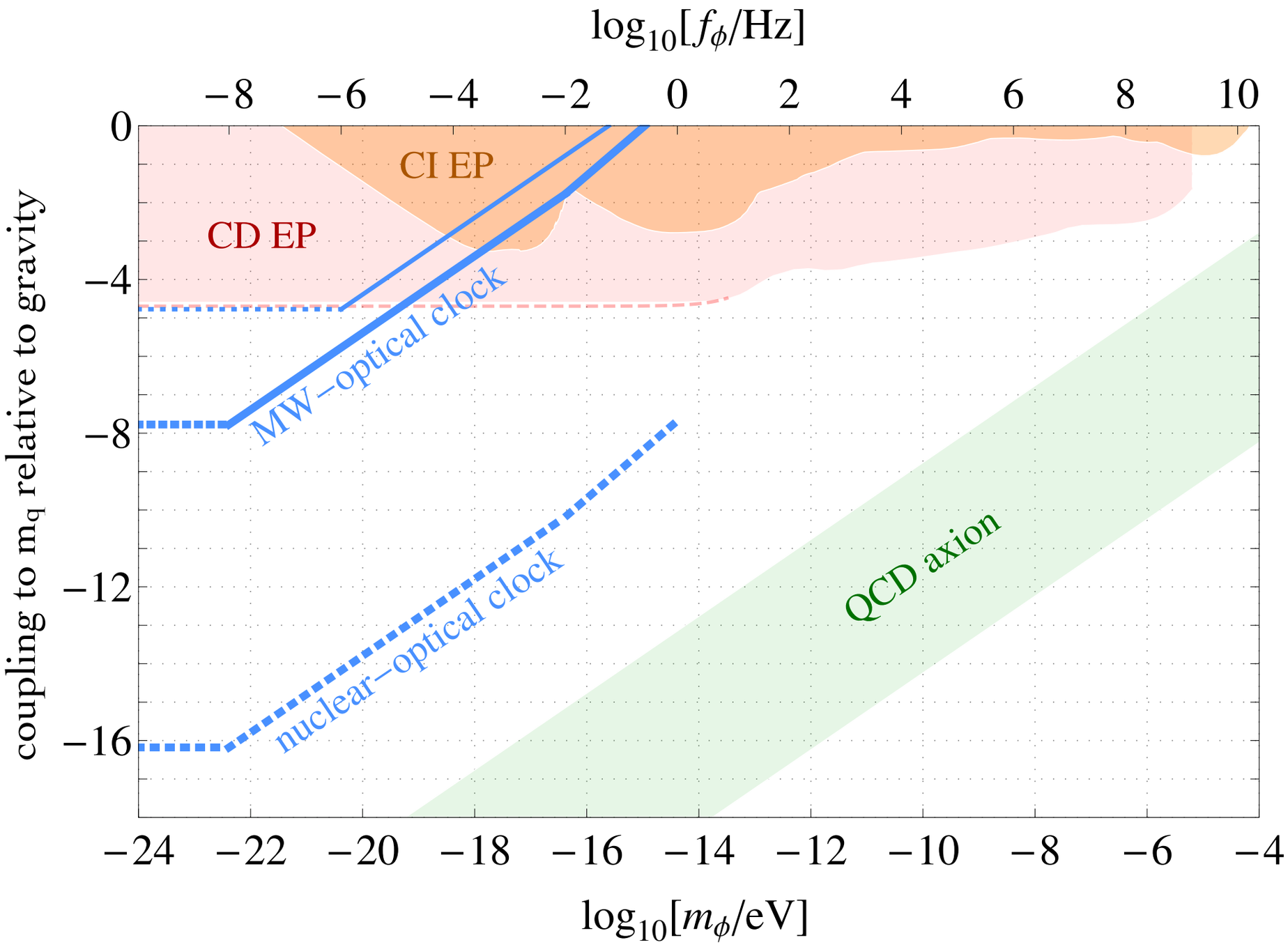
What are possible future improvements?

- 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

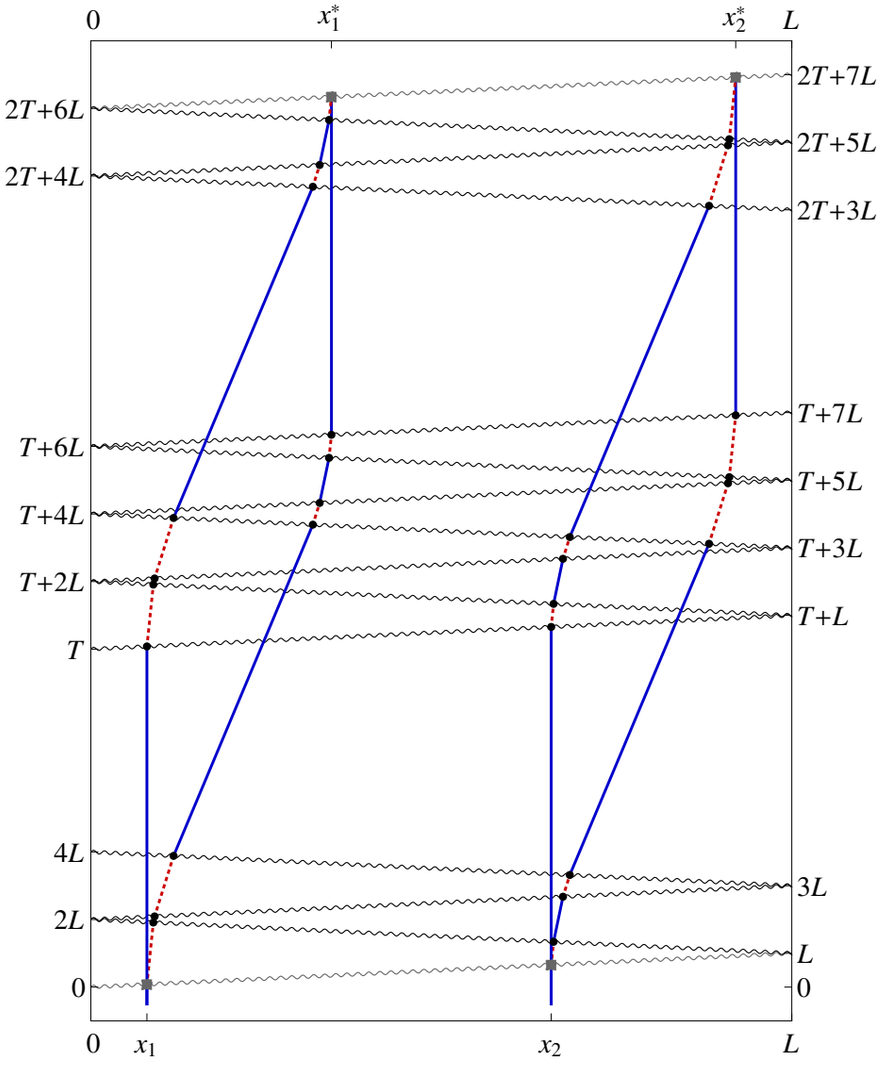
Nuclear to Optical Clock Comparison

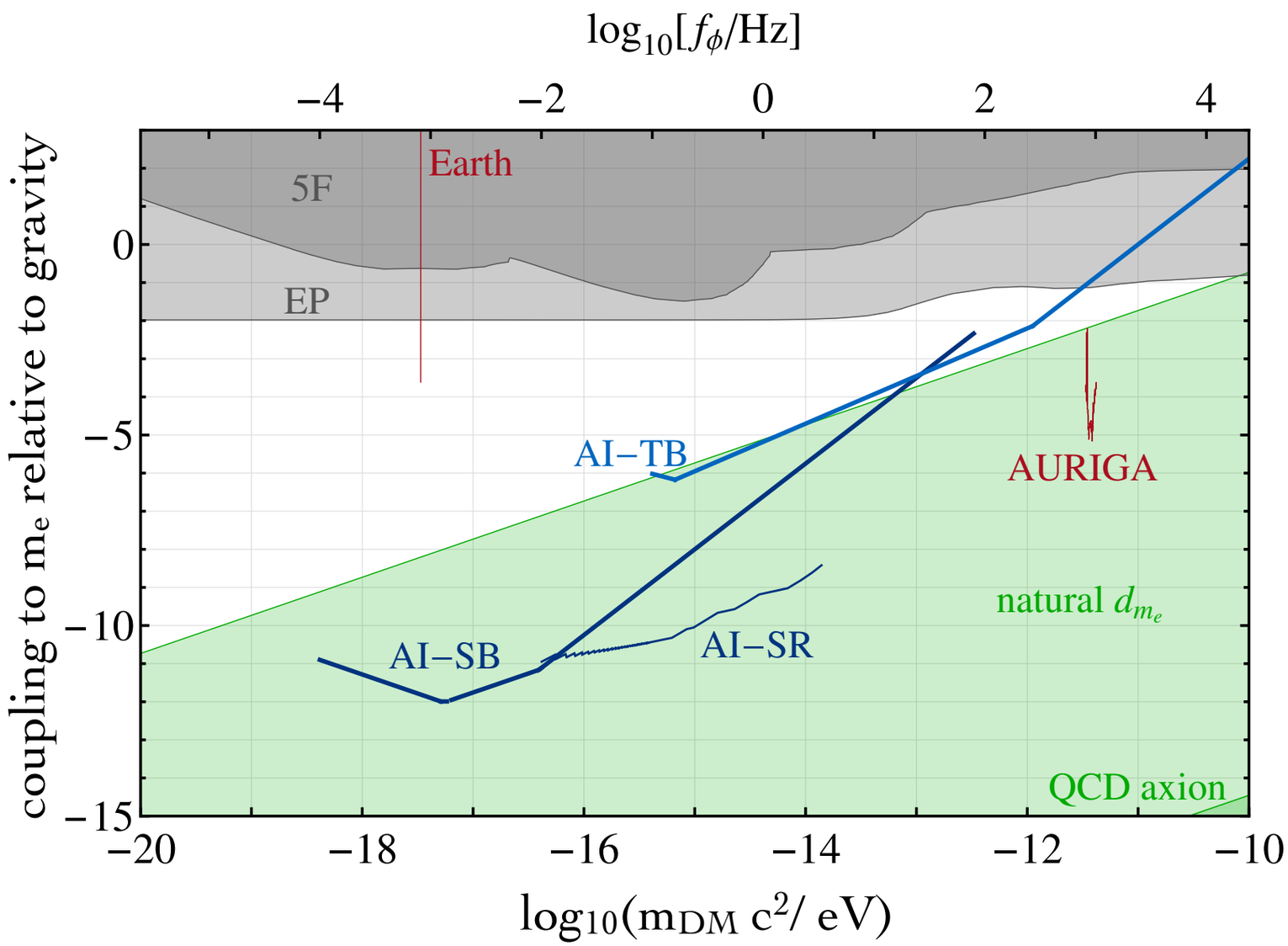
Future Sensitivity of a ^{229}Th clock with $10^{-15}/\mathrm{Hz}^{-1/2}$ noise



Comparison of two spatially separated Sr clocks

with Peter Graham, Jason Hogan,
Surjeet Rajendran and Ken Van Tilburg(2016)





Gravitational Wave interferometers such as aLIGO not sensitive enough due to laser noise

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

  - $L \sim N\,(\alpha\, m_e)^{-1}$

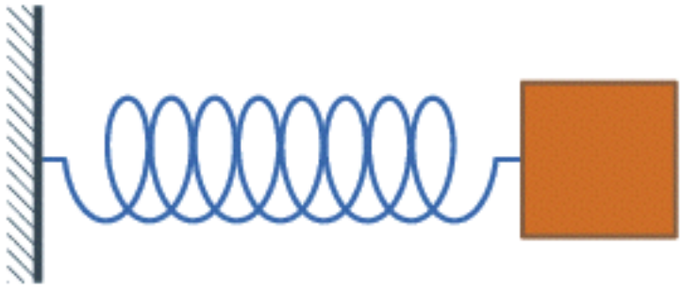
$$\frac{\delta L}{L} = -\left(\frac{\delta \alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

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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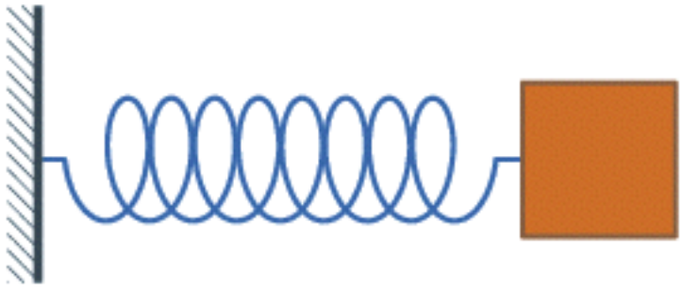

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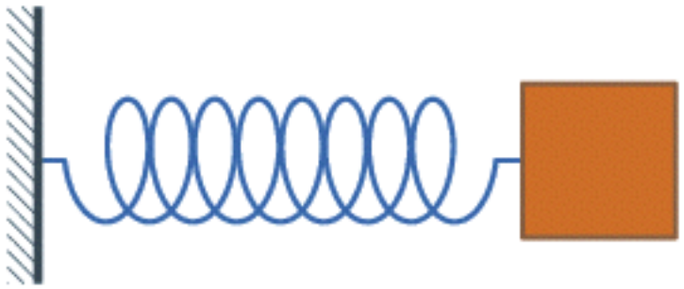
Driving force from change in the equilibrium position

The Simple Harmonic Oscillator



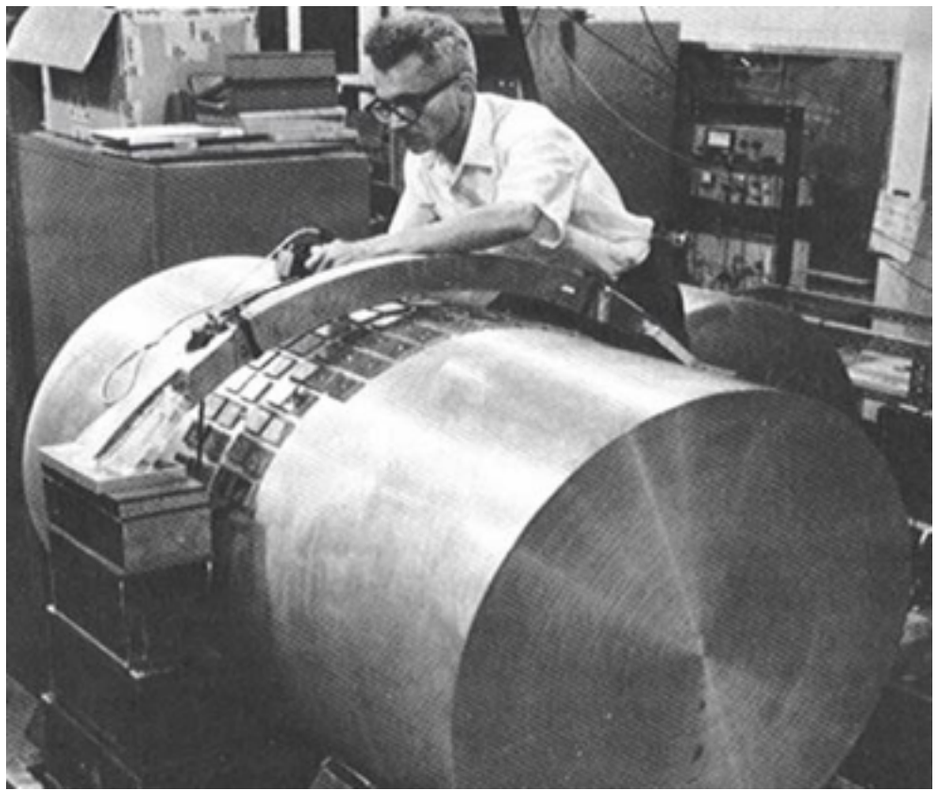
Dark Matter Driving Force:

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

with

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

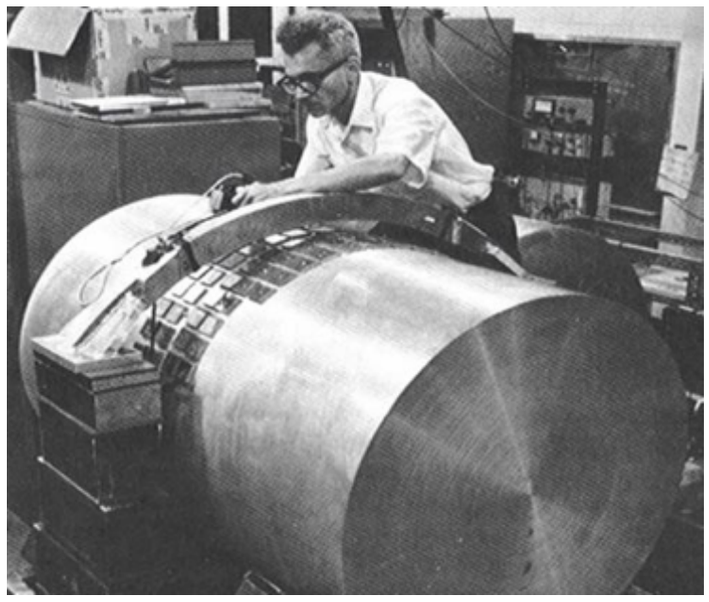
Just like a scalar gravitational wave of same strain



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

$$h_{\min} \sim \sqrt{\frac{4T}{MQ_n\omega_n^3 R^2 J_n^2}}$$

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 100 MHz
  - Need to worry about bandwidth coverage

The Sun and The Earth as Resonant-Mass Detectors

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

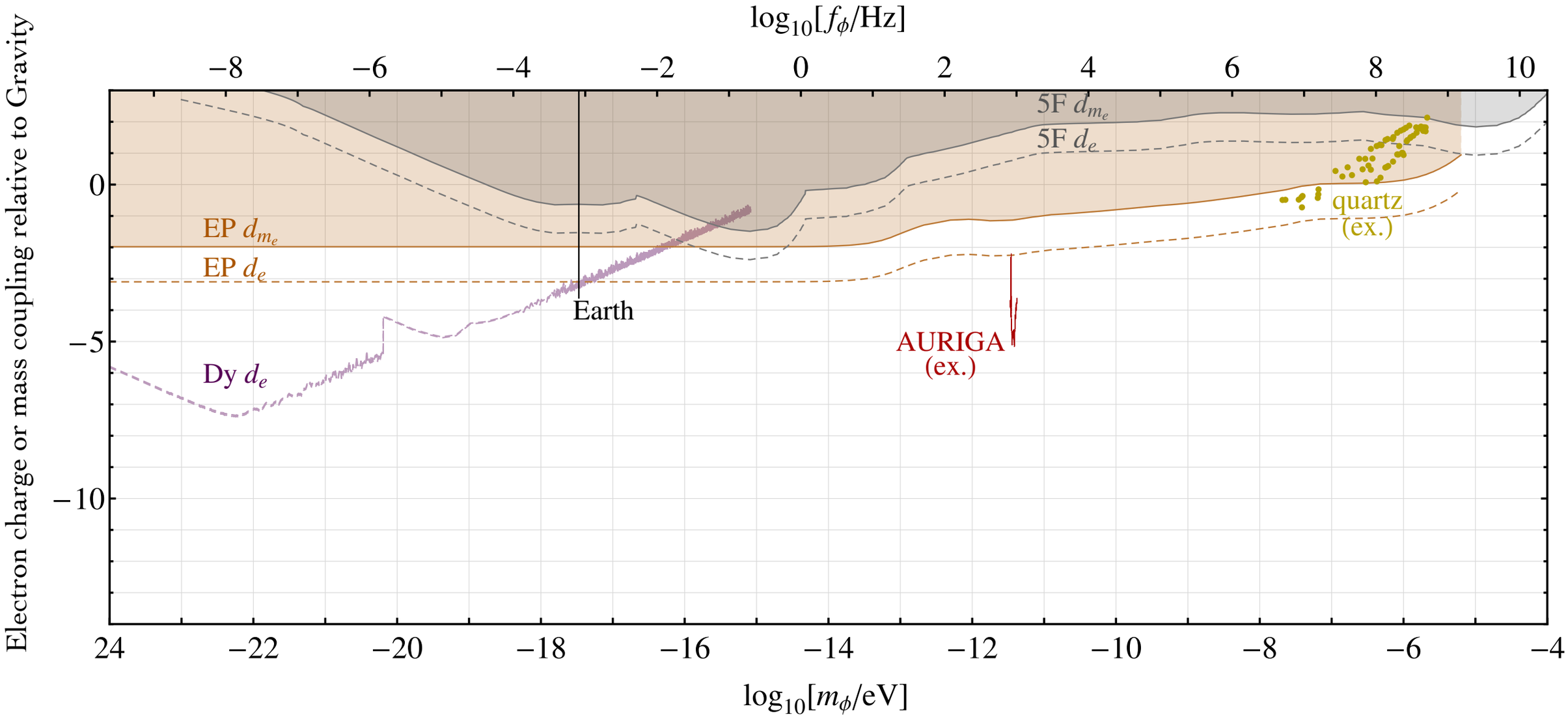
Strain sensitivity $h \sim 10^{-17}$

- 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

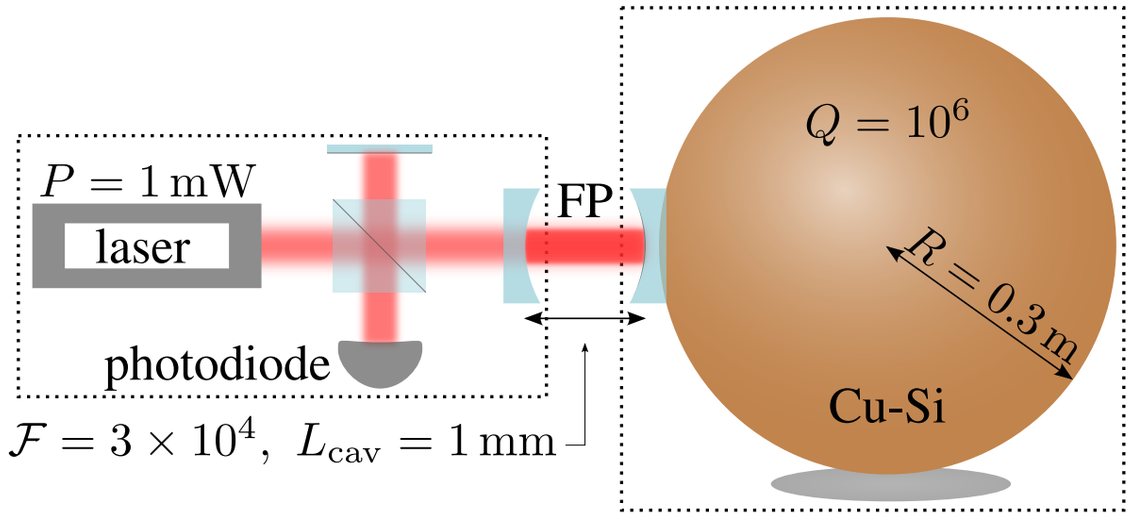
What can be done in the future?

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

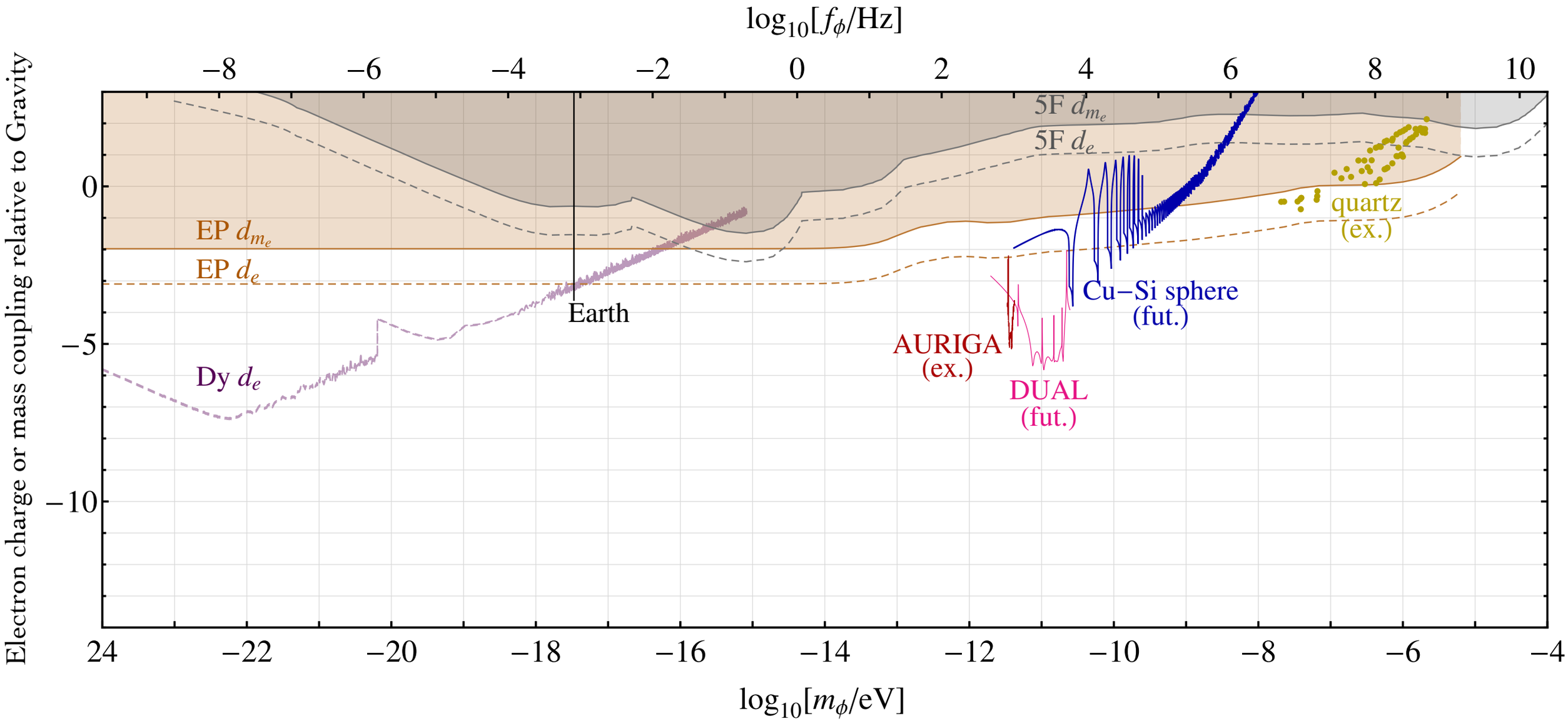


- Use Fabry-Perot cavity to pick up displacement as small as 10^{-19} m/(Hz)$^{1/2}$

- 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

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

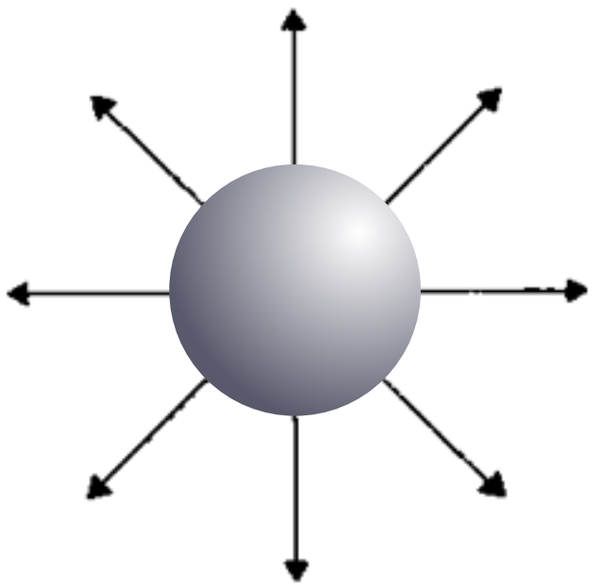
ARIADNE:

Axion Resonant InterAction DetectioN Experiment

with Andrew Geraci (2014)
and A. Kapitulnik, Chen-Yu Liu,J. Long, Y. Semertzidis, M. Snow (to be built)

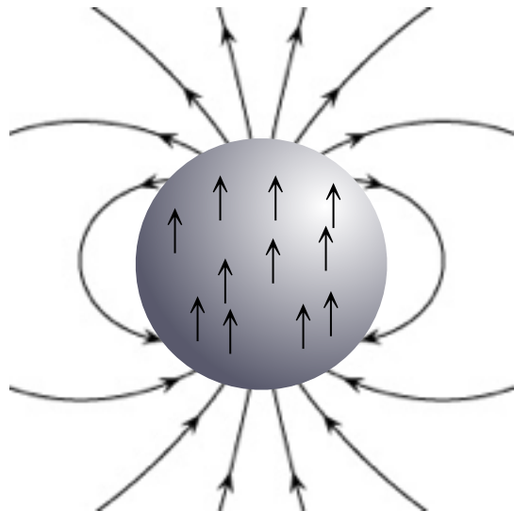
Short Range Interactions of the Axion

Moody and Wilczek (1984)



Monopole Interaction

Mass with N nucleons



Dipole Interaction

N spins

$$a(r) \approx \frac{g_s N}{4\pi} \frac{e^{-m_a r}}{r}$$

$$a(r) \approx \frac{g_p N}{4\pi m_f} \frac{e^{-m_a r}}{r^2} (\vec{\sigma} \cdot \hat{r})$$

$$6 \times 10^{-27} \left(\frac{10^9\ GeV}{f_a}\right) \lesssim g_s \lesssim 10^{-21} \left(\frac{10^9\ GeV}{f_a}\right)$$

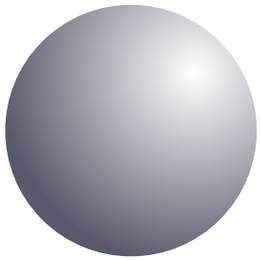
From CP violation in the Standard Model

From CP violation allowed by experiment

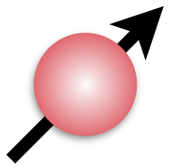
$$g_p \approx 10^{-9} \left(\frac{m_f}{1\ \text{GeV}}\right) \left(\frac{10^9\ \text{GeV}}{f_a}\right)$$

Short Range Interactions of the Axion

Monopole-Dipole Interaction

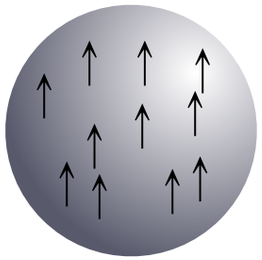


Mass with N nucleons

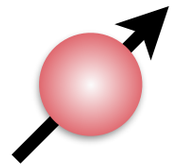


Spin

Dipole-Dipole Interaction



N spins



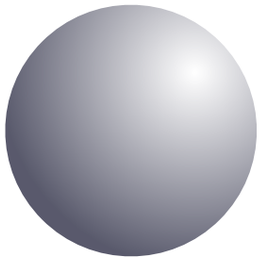
Spin

Interaction energy:

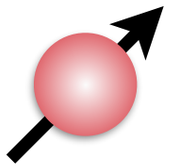
$$\frac{g_p \nabla a}{m_f} \cdot \vec{\sigma}$$

Short Range Interactions of the Axion

Monopole-Dipole Interaction



Mass with N nucleons



Spin

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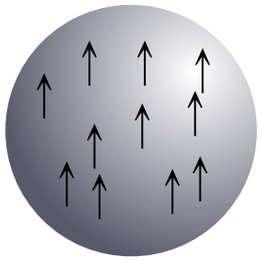
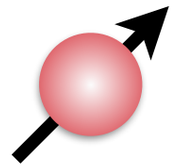


N spins



Spin

Interaction energy:

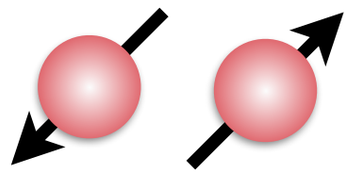
$$\frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma} \qquad \frac{\vec{\nabla} a}{\mu_f f_a} \cdot \vec{\mu_f} \equiv \vec{B}_{eff} \cdot \vec{\mu_f}$$

Just like a magnetic field

- B_{eff} is 2000 times bigger for nucleons than it is for electrons
- B_{eff} cannot be screened

Precision Magnetometry

Nuclear Magnetic Resonance



Precision Magnetometry

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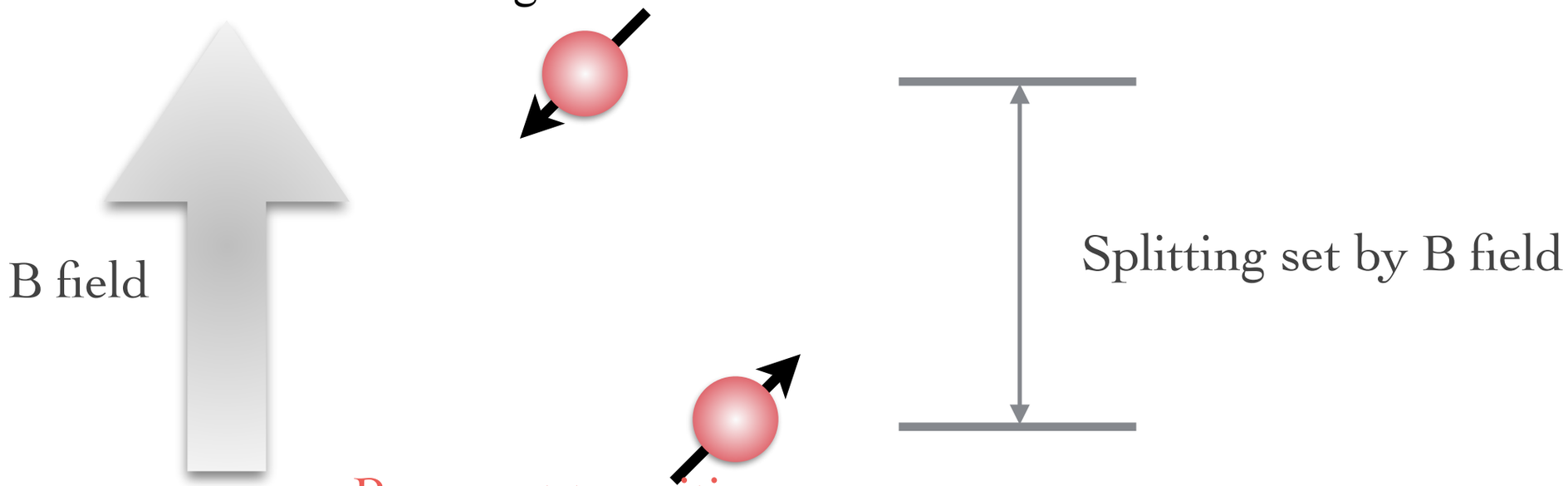

Resonant transition:

Perturbation at the splitting frequency of the spins

Precision Magnetometry

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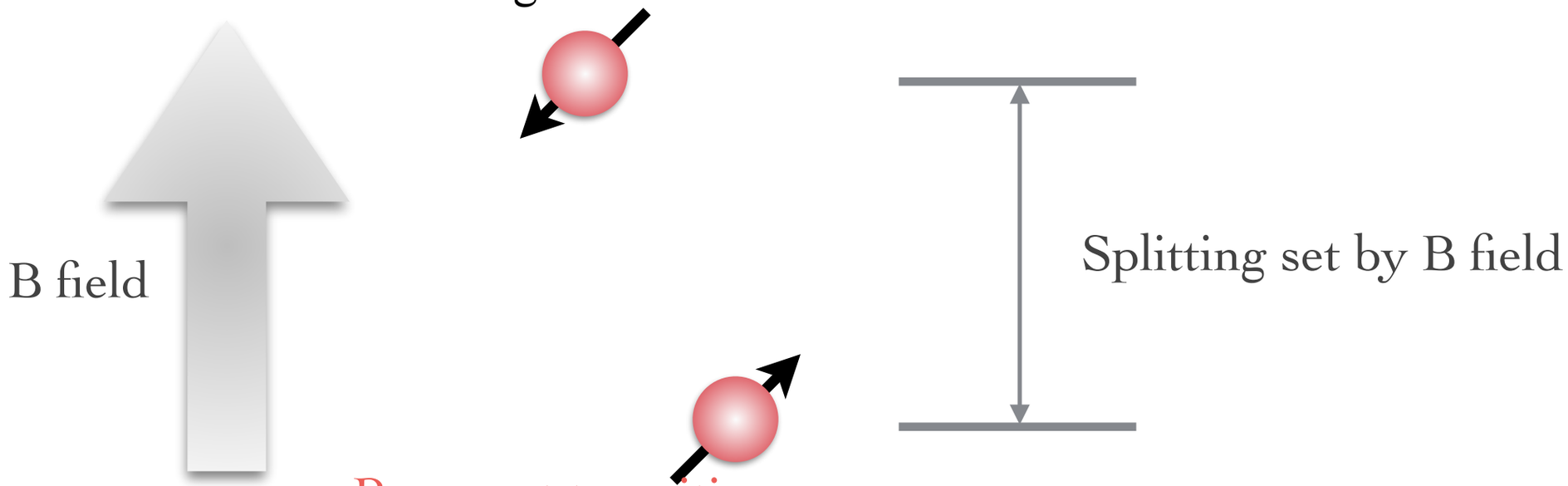

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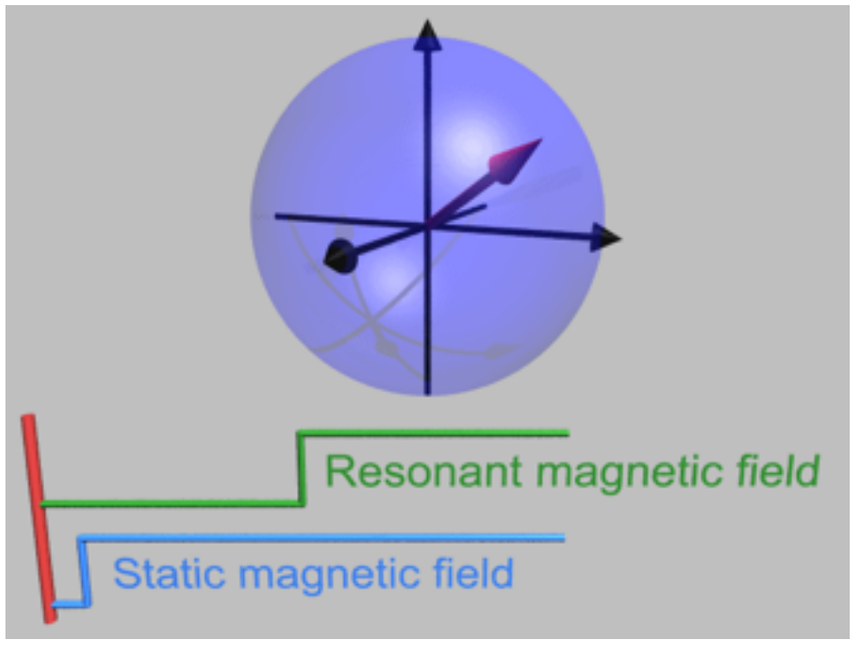
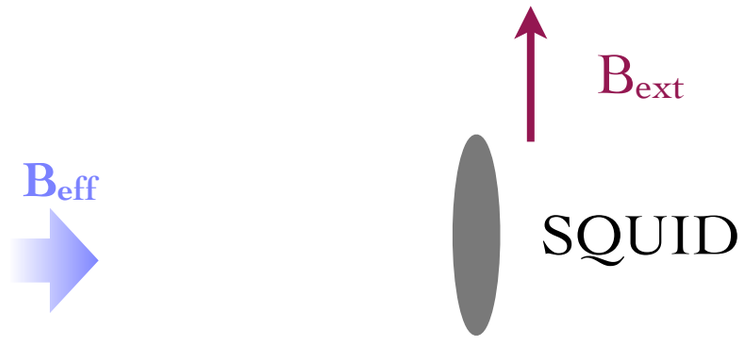


In the classical picture: Spins precessing around the perturbing magnetic field

Detection Strategy

Just like a magnetic field



Oscillating Source Mass NMR

$$\Delta E_{NMR} = \frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

On resonance:

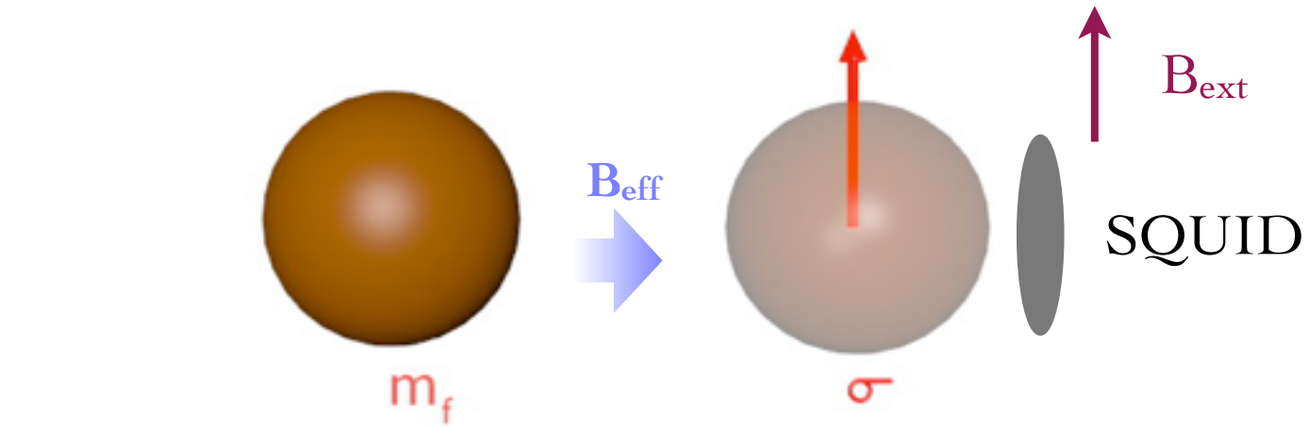
$$\vec{M}(t) = n_{NMR}\, p\vec{\mu}\, \Delta E_{NMR}\, t \sin \omega t$$

Signal grows till T_2

p: polarized fraction, n_{NMR}: density of spin in the detector, T_2: spin relaxation time

Detection Strategy

Just like a magnetic field



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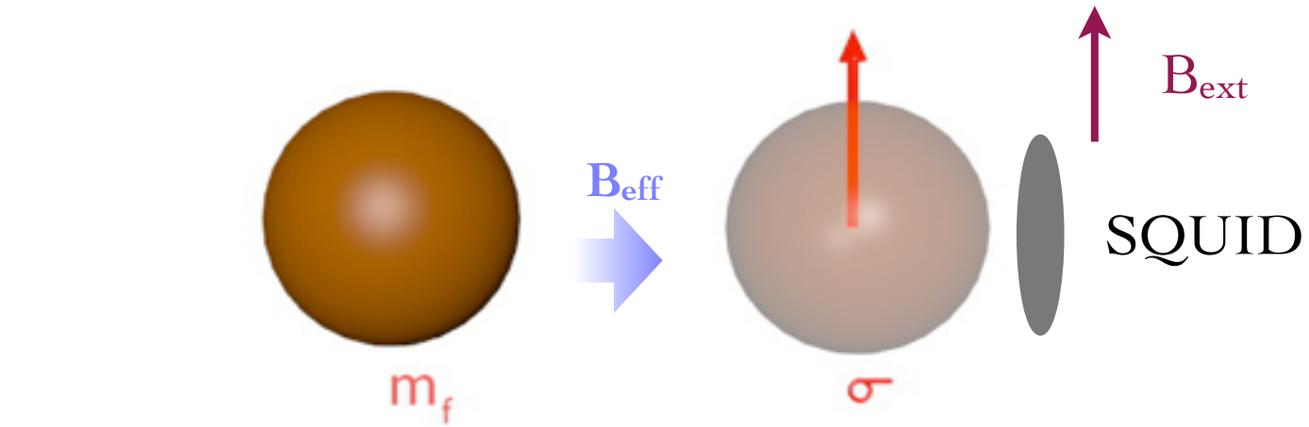

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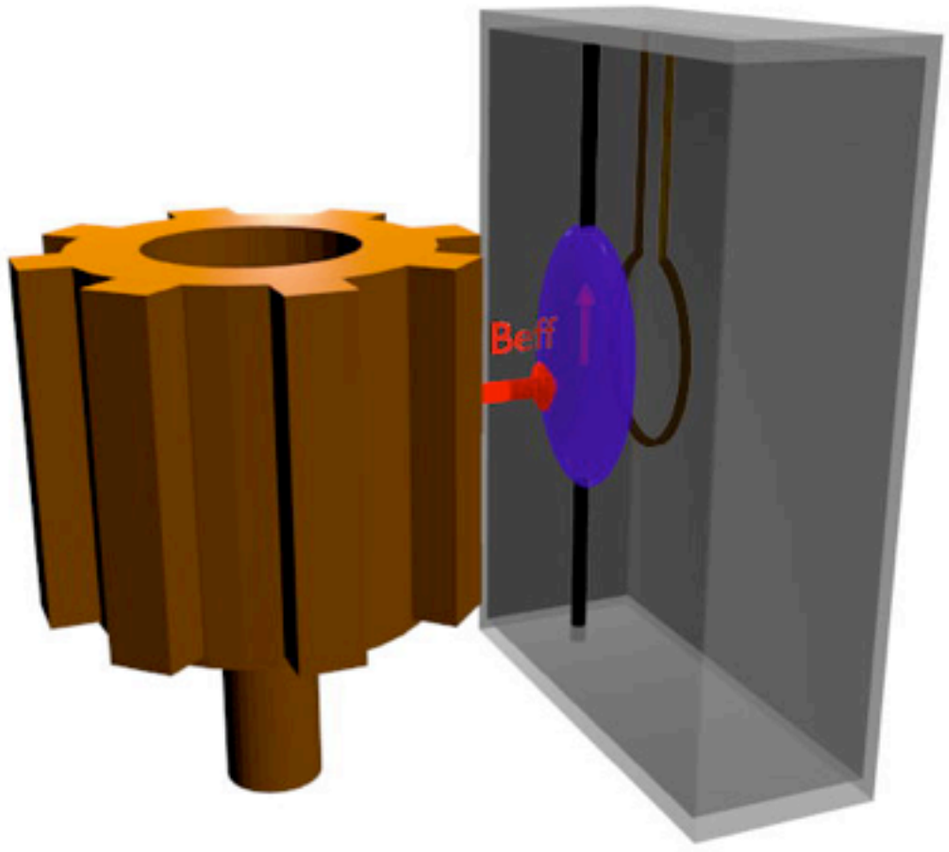
ARIADNE:

Axion Resonant InterAction DetectioN Experiment



He-3 NMR sample with
T_2 up to ~1000 sec

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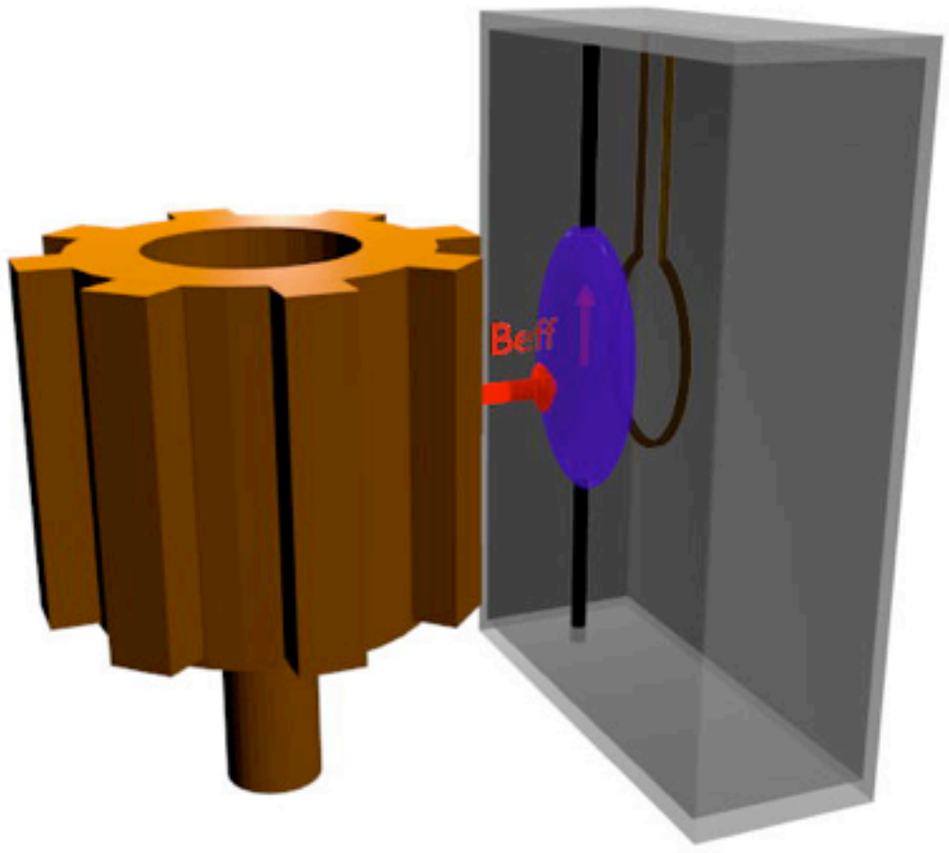
Axion Resonant InterAction DetectioN Experiment



He-3 NMR sample with
T_2 up to ~1000 sec

$$B_{\min} \approx p^{-1}\sqrt{\frac{2\hbar b}{n_s \mu_{^3\mathrm{He}} \gamma V T_2}} = 3\times 10^{-19}\ \mathrm{T}\times$$

$$\left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{mm}^3}{V}\right)\left(\frac{10^{21}\ \mathrm{cm}^{-3}}{n_s}\right)\left(\frac{1000\ \mathrm{s}}{T_2}\right)}$$

B_{min} = 10^{-16} T/(Hz)$^{1/2}$
for SQUIDs

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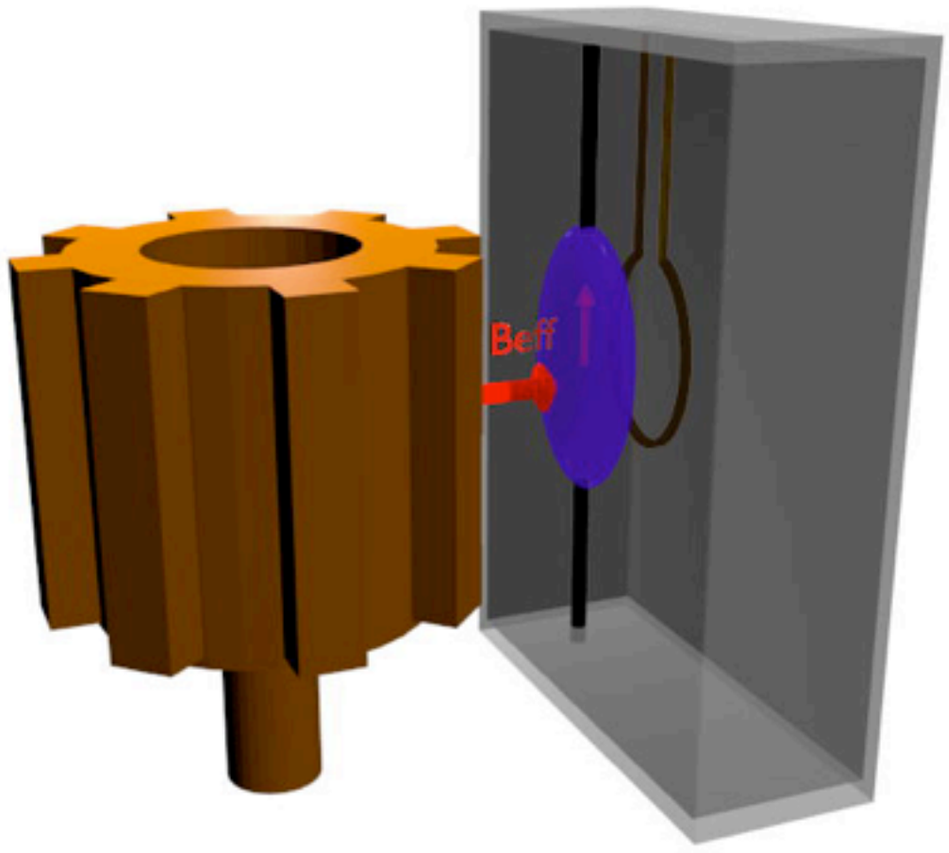

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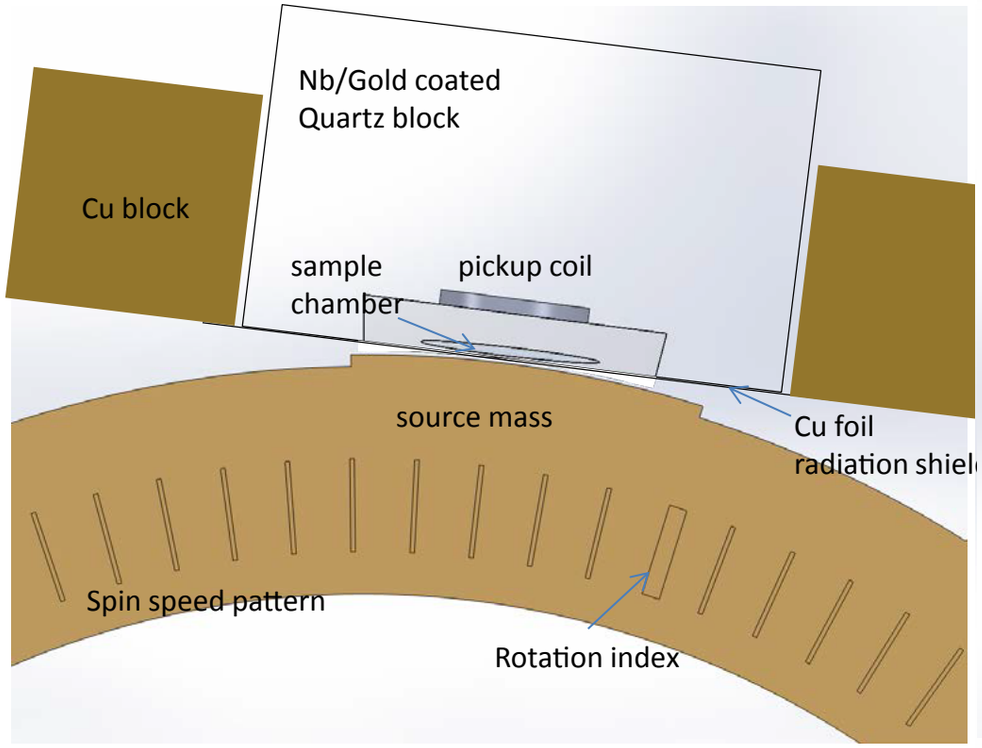
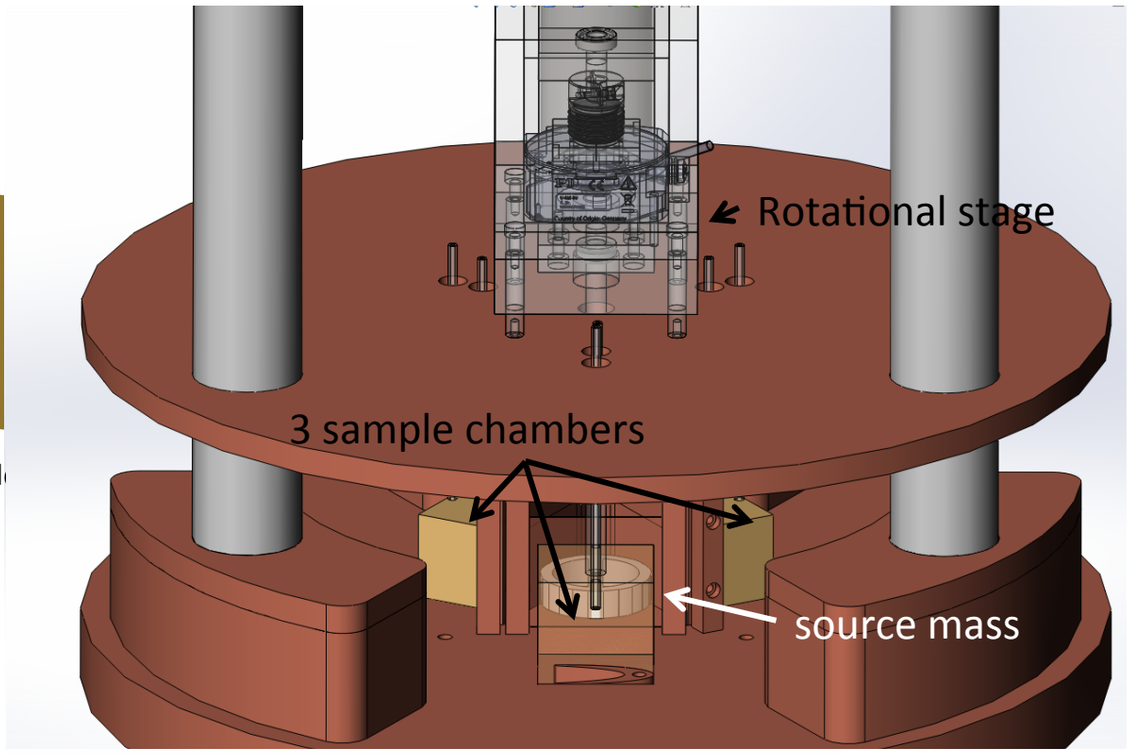
Experimental Setup

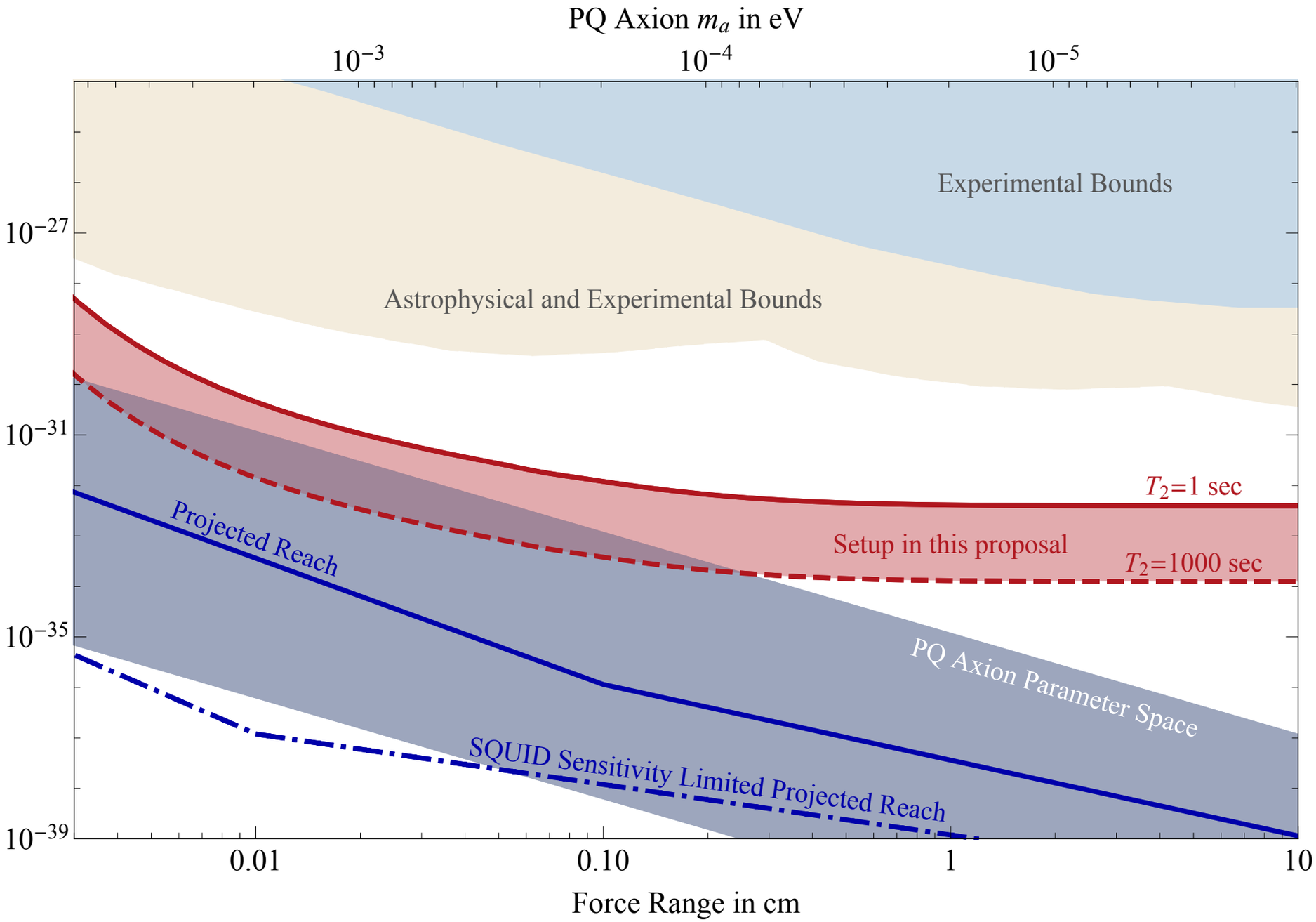




- 99 Hz Larmor precession frequency for ^{3}He nuclei
- $2x10^{21}$ / cc ^{3}He polarized spin density
- 10 mm x 3 mm x 150 μm NMR sample size
- Tungsten (or nuclear - electron spin polarized He or Fe) source mass

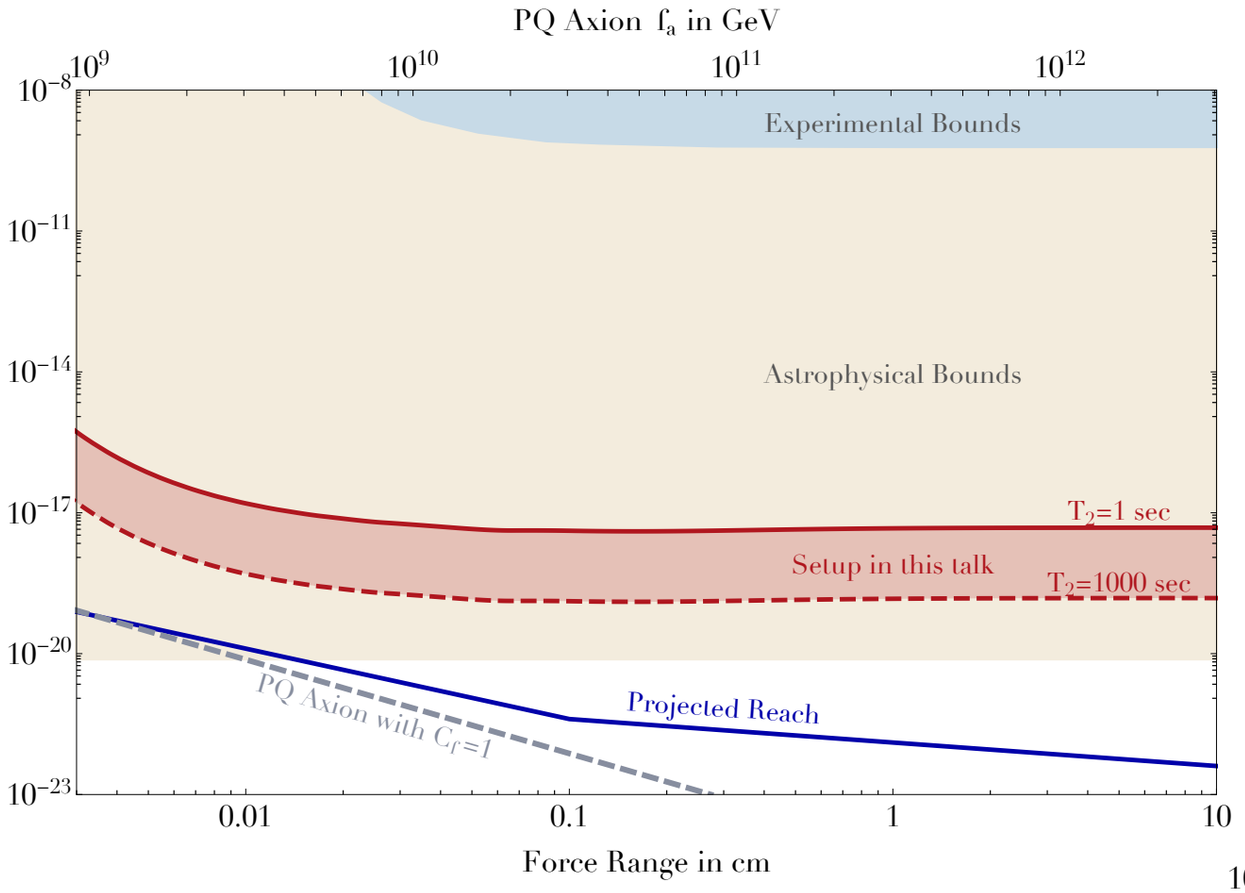
Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration



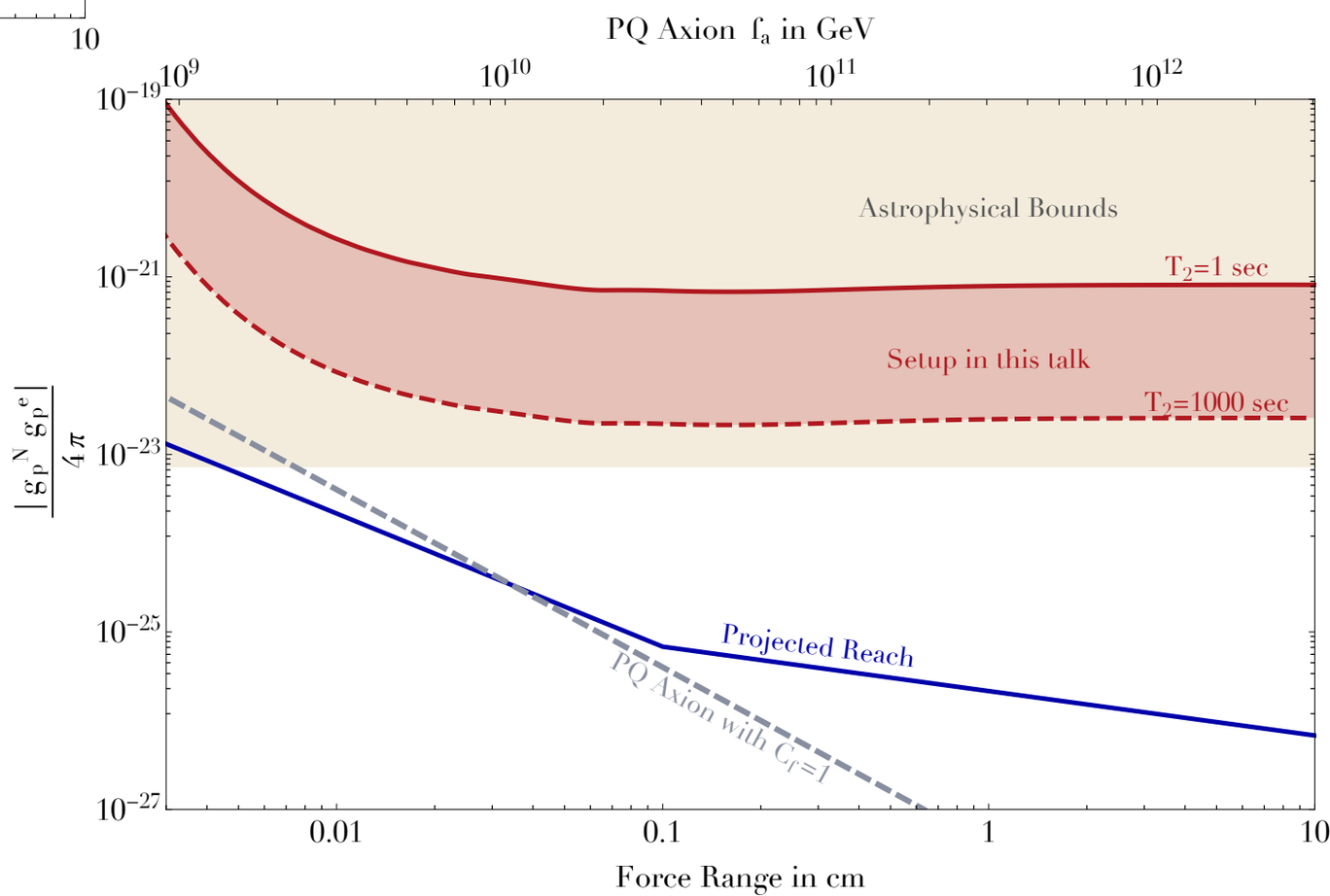
Projected Reach with increase of polarized spin density and larger NMR sample volume

Dipole-Dipole Interaction Reach



Nuclear Spin Polarized Source Mass
with 10^6 sec integration

Electron Spin Polarized Source Mass
with 10^6 sec integration



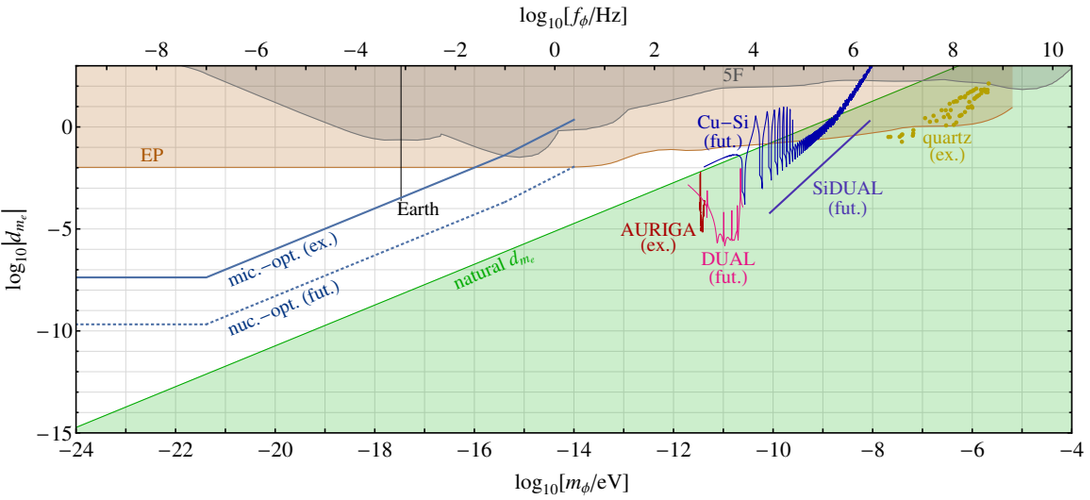
Major systematics

- Magnetic field screening
  (requires less than 10^{-16} - 10^{-17} T/(Hz)$^{1/2}$, ideally 10^{-19} - 10^{-20} T/(Hz)$^{1/2}$)
  - Use superconducting shields
  - Additional advantages since it is an AC measurement
- Magnetic field gradients
  - Shape of the shield, shimming
  - Spin Echo techniques

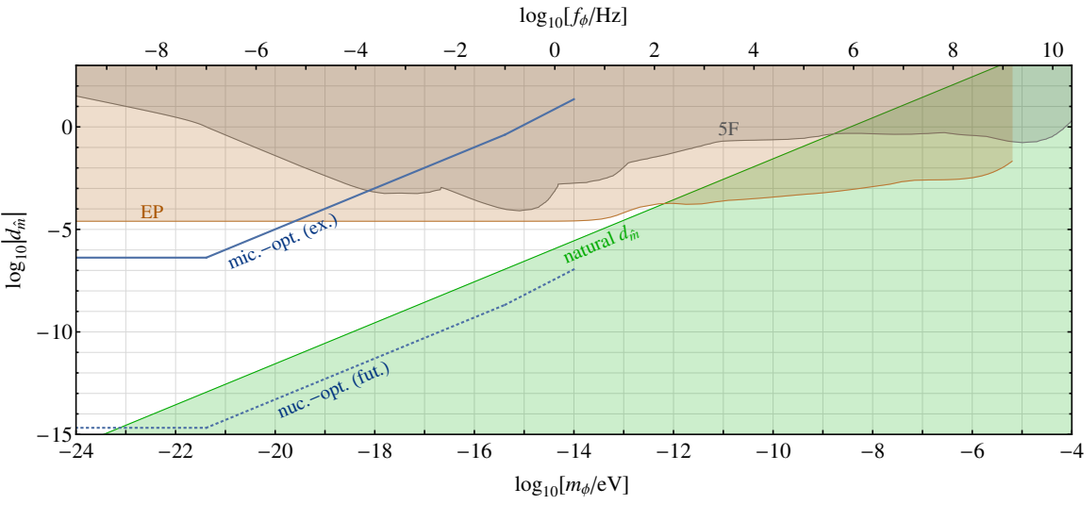
Summary for Light Scalar Searches

Searches for Dark Matter

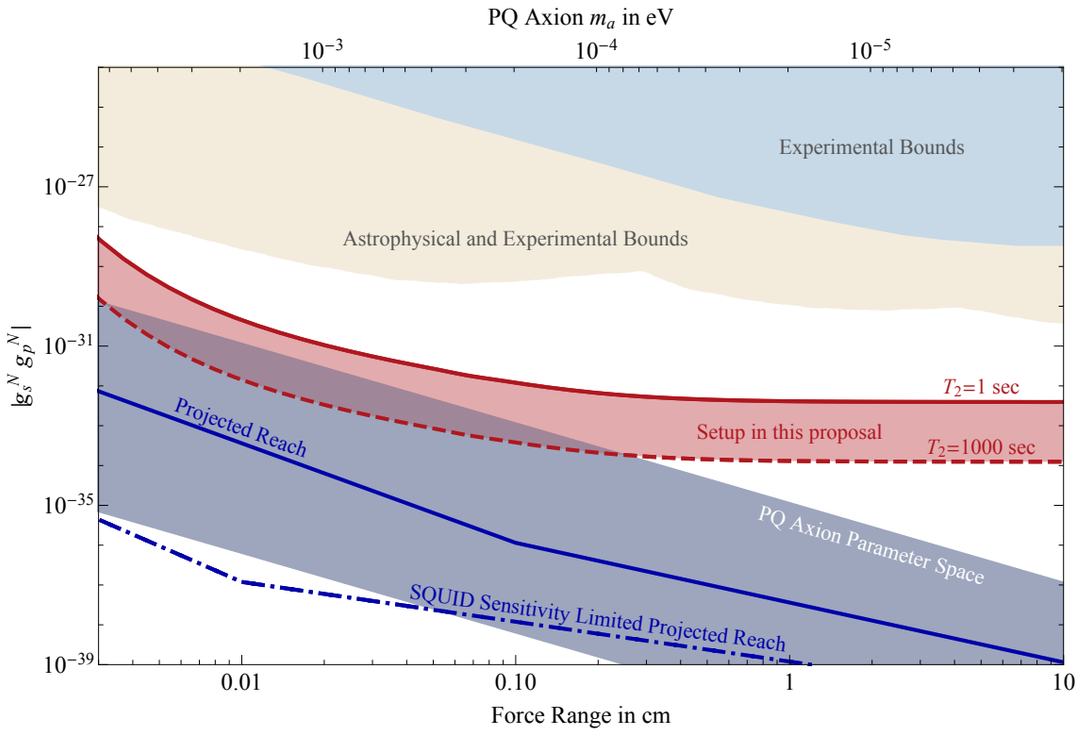
Electron charge or mass coupling relative to Gravity



Quark mass coupling relative to Gravity



Searches for Forces



Summary

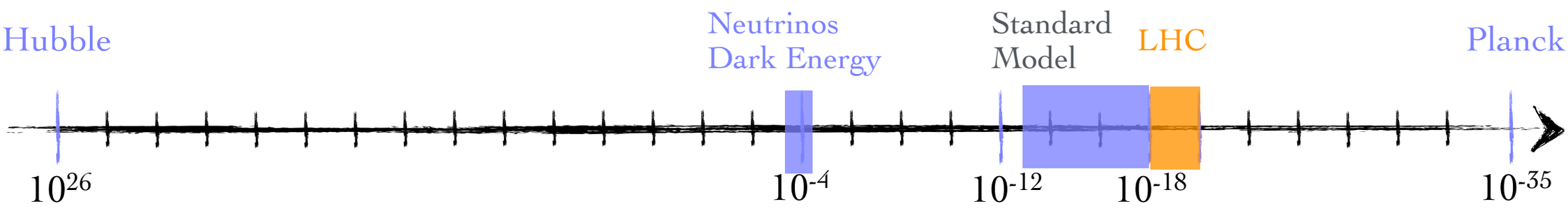
- Several orders of magnitude improvement in searches for scalar Dark Matter and the QCD axion

- Based on existing and well-established techniques

- There are several more possibilities

This is only scratching the surface…

Length Scales in the Universe



Scale in m

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet