Looking for light scalar dark matter with rods and clocks

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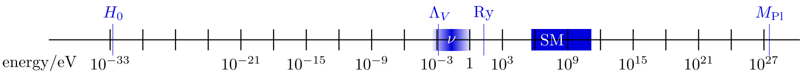
arXiv:1405.2925
with Asimina Arvanitaki (Perimeter), Junwu Huang (Stanford)

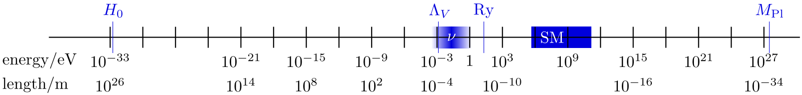
arXiv:1503.06886
with Nathan Leefer, Lykourgos Bougas, Dmitry Budker (Berkeley, Mainz)

arXiv:1508.01798
with Asimina Arvanitaki, Savas Dimopoulos (Stanford)

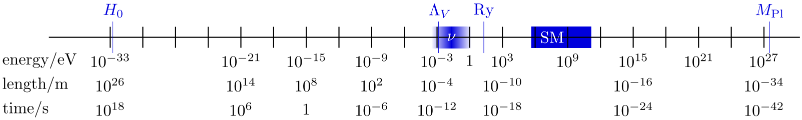
scales of Universe & DM



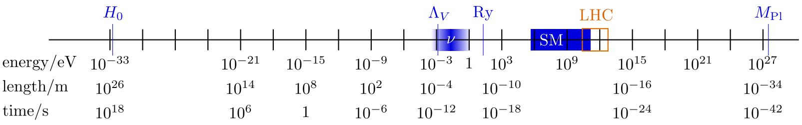
scales of Universe & DM



scales of Universe & DM



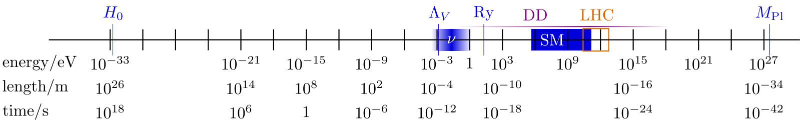
scales of Universe & DM



frontiers:

- high-energy $\to$ LHC

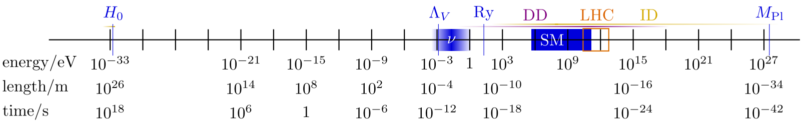
scales of Universe & DM



frontiers:

- high-energy → LHC
- intensity → direct detection

scales of Universe & DM



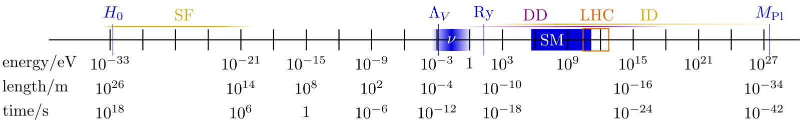
frontiers:

- high-energy → LHC
- intensity → direct detection
- cosmic → indirect detection

dark matter:

- fermionic → $m_{\text{fermion}} \gtrsim$ keV

scales of Universe & DM



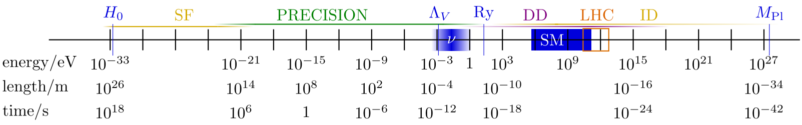
frontiers:

- high-energy → LHC
- intensity → direct detection
- cosmic → indirect detection
- cosmic → structure formation

dark matter:

- fermionic → $m_{\rm fermion} \gtrsim$ keV
- bosonic → $m_{\rm boson} \gtrsim 10^{-22}$ eV

scales of Universe & DM



frontiers:

- high-energy $\rightarrow$ LHC
- intensity $\rightarrow$ direct detection
- cosmic $\rightarrow$ indirect detection
- cosmic $\rightarrow$ structure formation
- precision!

dark matter:

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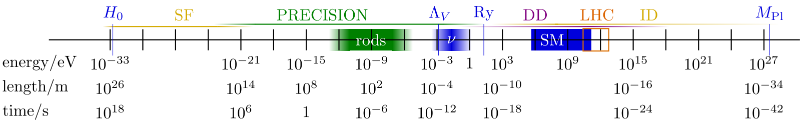
scales of Universe & DM



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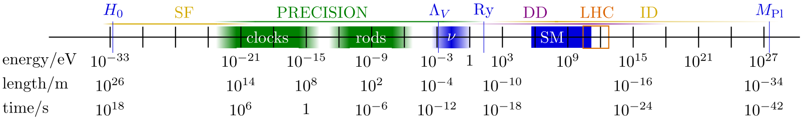

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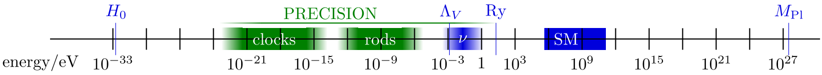
overview: 4 main points

1. light scalar fields
   theory: how do they arise?
   phenomenology: oscillating length and time scales (+forces)

2. rods
   acoustic resonators: absorbers of modulus waves

3. clocks
   atomic clocks: probes of adiabatic changes in modulus field values

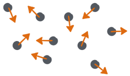
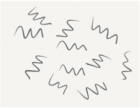


4. other probes
   force tests: from DM background and from virtual exchange
   astrophysical signatures: black-hole superradiance and pulsar timing
   cosmology

light scalar DM as classical oscillations

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2$$

correspondence principle: classical wave description


$$\text{occ. } \# = \frac{\Delta N}{(\Delta x)^3 (\Delta p)^3} = \frac{n}{(\Delta p)^3} = \frac{\rho}{m (\Delta p)^3} \sim \frac{\rho}{m^4 v_{\text{vir}}^3} \approx 2 \times 10^3 \left(\frac{\text{eV}}{m_\phi} \right)^4$$

$$\rho_{\text{DM}} \approx 0.3 \text{ GeV cm}^{-3} \qquad v_{\text{vir}} \sim 10^{-3}$$

$$\phi(t, \mathbf{x}) \simeq \phi_0 \cos\left(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x}\right) + \mathcal{O}(v^2) \text{ dispersion}$$

$$\rho = \frac{m_\phi^2 \phi_0^2}{2} = \rho_{\text{DM}} \quad \Rightarrow \quad \sqrt{4\pi G_N}\, \phi_0 \approx 6 \times 10^{-16} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right)$$

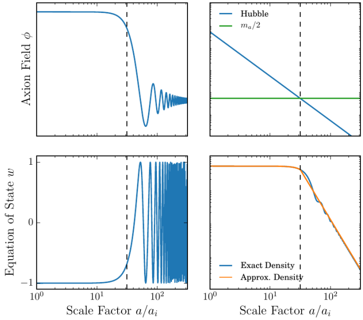
How does light scalar dark matter arise in the **Universe?**

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

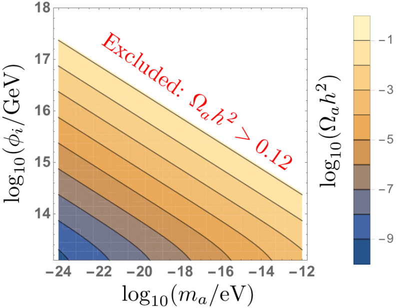
$$H(a_{\rm osc}) \sim m_\phi$$

$$\rho_\phi(a) \simeq \rho_\phi(a_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3$$

$$\rho_\phi(a_{\rm osc}) \simeq \frac{m_\phi^2}{2}\langle \phi_i^2 \rangle = \frac{m_\phi^2}{2}\left[\phi_i^2 + \left(\frac{H_I}{2\pi}\right)^2\right]$$



$$H_I = 10^{14}\ \text{GeV}$$



[arXiv:1510.07633]

How do light moduli arise in **UV theories?**

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + \sum_i d_i \sqrt{4\pi G_N}\, \phi\, \mathcal{O}_{\mathrm{SM},i} \qquad (1)$$

- Higgs portal: $b\phi H^\dagger H \;\Rightarrow\; d_m \sqrt{4\pi G_N} \sim \frac{b}{m_H^2}$ [arXiv:1003.2313]
- dilaton, least coupling principle: $4\pi G_N\, \phi^2\, \mathcal{O}_{\mathrm{SM}}$ [arXiv:hep-th/9401069]
- QCD axion: $d_{m_q} \sqrt{4\pi G_N} \sim \frac{\bar{\theta}_{\mathrm{QCD}}}{f_a}$
- radion component of extra-dimensional graviton
- any light Yukawa or gauge modulus!

Tuning? $\Delta m_\phi^2 \sim \sum_i \frac{4\pi G_N}{16\pi^2} d_i^2 \left\{ \Lambda^4, m_i^2 \Lambda^2, \frac{y_i^2}{16\pi^2} \Lambda^4, \ldots \right\}$

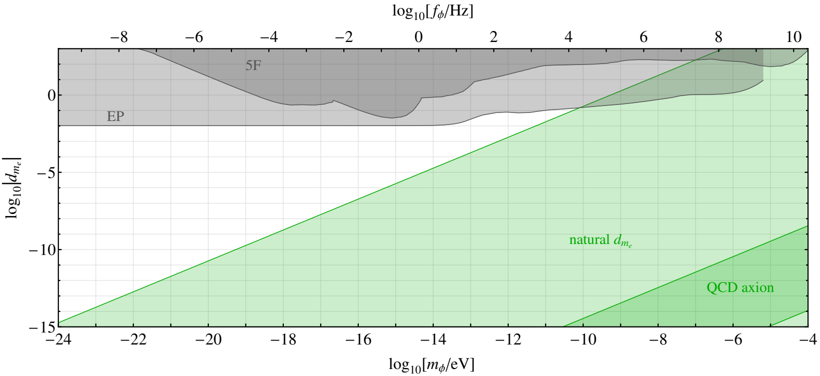
What are the observable effects of ultralight scalars?

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + \sqrt{4\pi G_N}\,\phi \Big[\underbrace{+\frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu}}_{\alpha \text{ changes}} \underbrace{- \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu} G^{A\mu\nu}}_{\Lambda_{\rm QCD} \text{ changes}} \underbrace{- d_{m_e} m_e \bar{e} e - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i}_{\text{electron and quark masses change}} \Big]$$

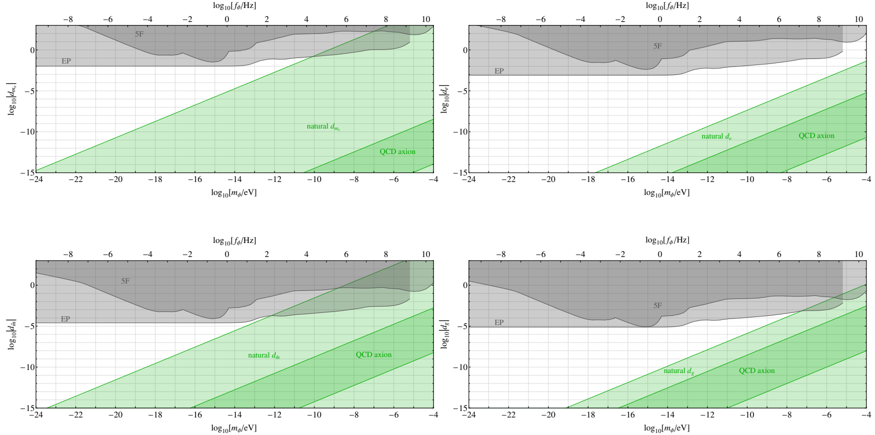
- oscillating masses and couplings
  $m_e(t) = m_e \left[1 + d_{m_e} \sqrt{4\pi G_N}\, \phi_0 \cos(m_\phi t)\right]$
  $\alpha(t) = \alpha \left[1 + d_e \sqrt{4\pi G_N}\, \phi_0 \cos(m_\phi t)\right]$
  $\rightarrow$ length scales $\propto$ Bohr radius $= 1/\alpha m_e$
  $\rightarrow$ frequency scales $\sim \left\{\alpha^2 m_e F(\alpha), \alpha^4 m_e^2/m_p, \ldots\right\}$
- equivalence-principle-violating forces
  $\rightarrow$ from scalar exchange: $V_{\rm AB} = -G_N \frac{m_{\rm A} m_{\rm B}}{r_{\rm AB}} (1 + \alpha_{\rm A}\alpha_{\rm B} e^{-m_\phi r})$ [arXiv:1007.2792]
  $\alpha_{\rm A} \sim d_g + 10^{-1} d_{m_q} + 10^{-3} d_e + \frac{m_e}{2m_p} d_{m_e} + \ldots$
  $\rightarrow$ from DM: $V_{\rm A} = m_{\rm A} \left[1 + \alpha_{\rm A} \sqrt{4\pi G_N} \phi_0 \cos\left(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x}\right)\right]$
- purely gravitational effects

  structure formation, black-hole superradiance, pulsar timing

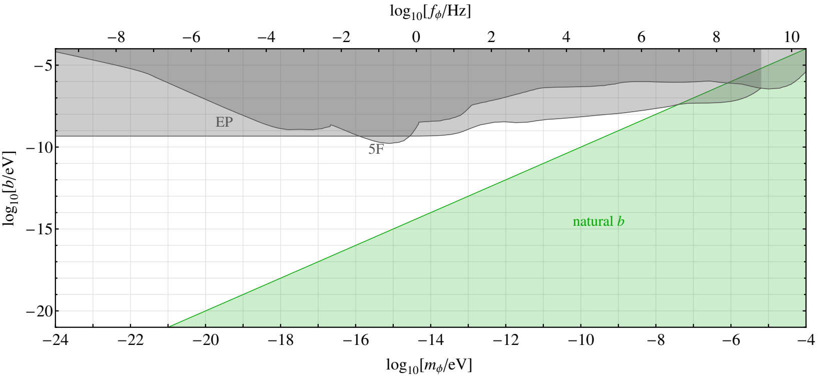
static forces from scalar exchange + naturalness



parameter space: primary couplings



parameter space: higgs portal



Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors

arXiv:1508.01798, Phys. Rev. Lett. 116, 031102 (2016)

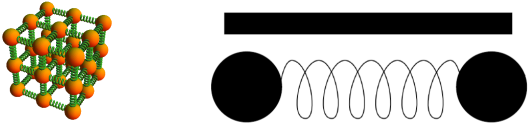
Asimina Arvanitaki (PI), Savas Dimopoulos (Stanford)

$$L_0 \sim \frac{N}{\alpha m_e}$$

- tiny fractional change → macroscopic objects

$$h \equiv \frac{\delta L}{L_0} = \frac{\delta \alpha}{\alpha} + \frac{\delta m_e}{m_e} = (d_{m_e} + d_e)\sqrt{4\pi G_N}\phi_0 \approx 10^{-18}(d_{m_e} + d_e)\left(\frac{10^{-12}\ \text{eV}}{m_\phi}\right)$$

- (almost) no DC response → excite acoustic modes

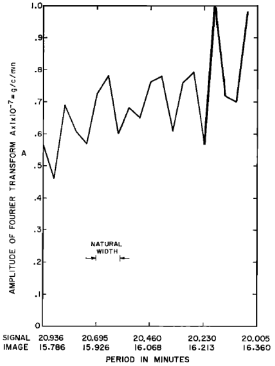


$$M\left[\ddot{x} + \frac{\omega}{Q}\dot{x} + \omega^2 (x - L)\right] = F_{\text{noise}} \qquad (D \equiv x - L)$$

$$M\left[\ddot{D} + \frac{\omega}{Q}\dot{D} + \omega^2 D\right] \simeq -M\ddot{L}_0 + F_{\text{noise}} = -ML_0\ddot{h} + F_{\text{noise}}$$

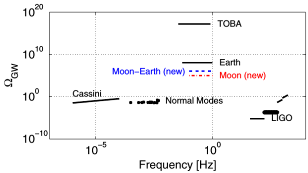
seismology

Earth: $T = 20.46$ min, $Q \approx 7,500$

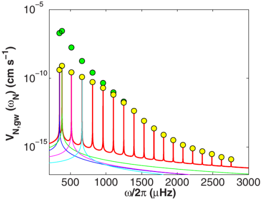


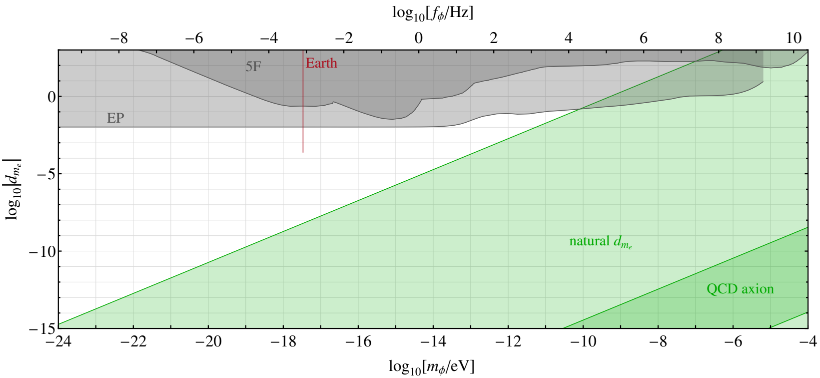
[Weiss, Block (1967)]

Earth crust + Moon [Coughlin, Harms (2014)]



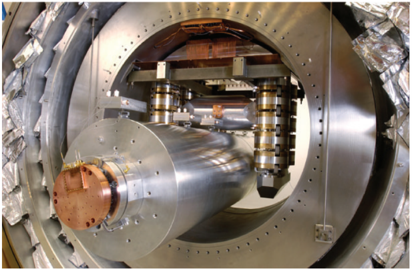
Sun: $Q \approx 10^8$–10^4 [Lopes, Silk (2014)]

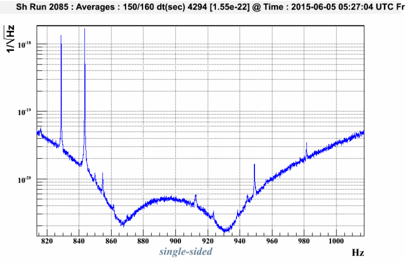



log10[fϕ/Hz]
−8 −6 −4 −2 0 2 4 6 8 10
5F
Earth
EP
natural dme
QCD axion
log10|dme|
0 −5 −10 −15
−24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4
log10[mϕ/eV]

AURIGA

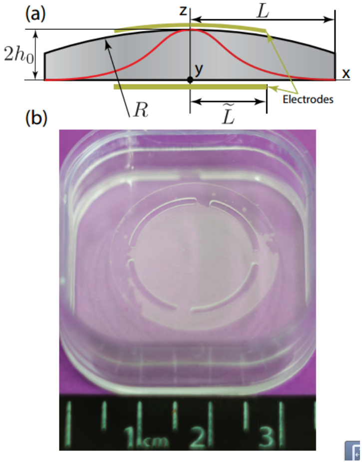
+ many other kHz-class cylindrical antennas: NAUTILUS, EXPLORER, MiniGRAIL, Schenberg, . . .

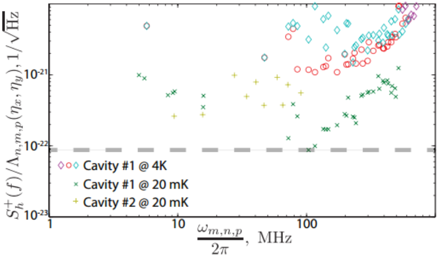


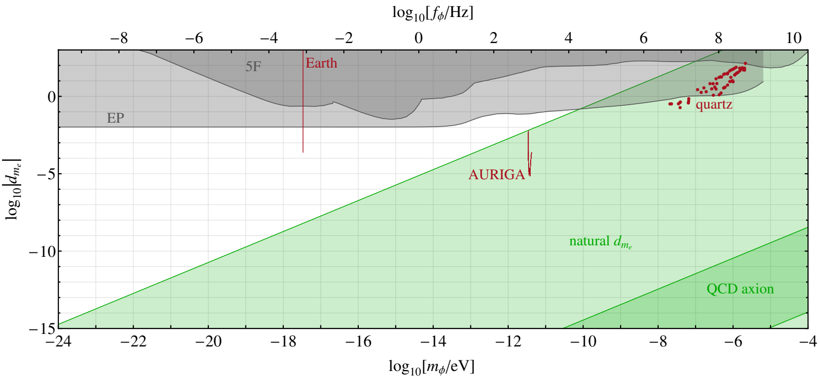


quartz crystal

"built-in" piezoelectric readout [arXiv:1410.2334]






$\log_{10}[f_\phi/\mathrm{Hz}]$
−8
−6
−4
−2
0
2
4
6
8
10
5F
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EP
quartz
AURIGA
natural d_{m_e}
QCD axion
$\log_{10}|d_{m_e}|$
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−10
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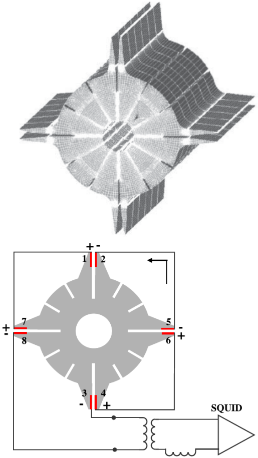
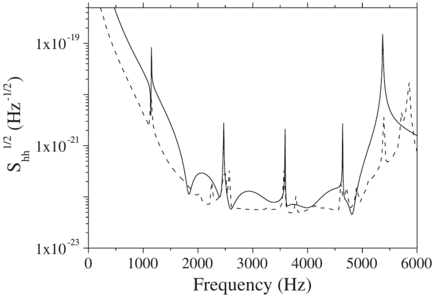
−6
−4
$\log_{10}[m_\phi/\mathrm{eV}]$

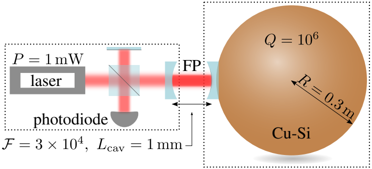
DUAL

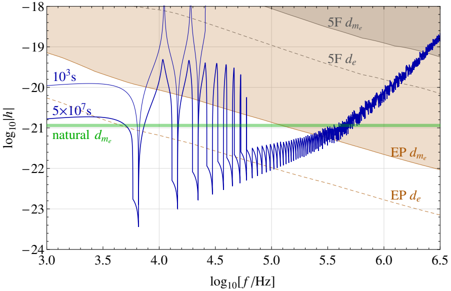




[Leaci+ (2008)]

Cu-Si sphere proposal

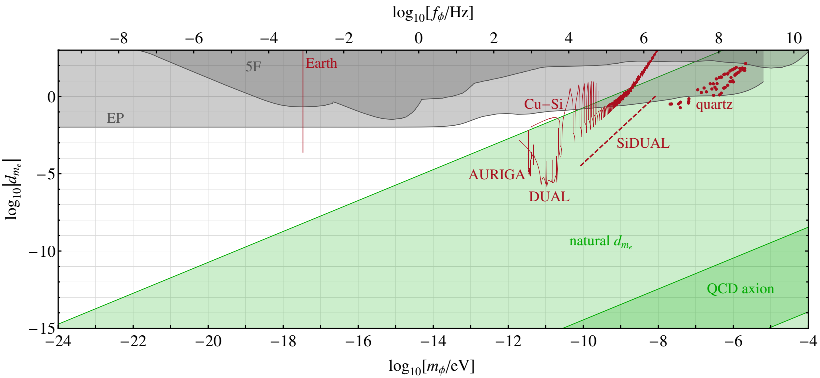




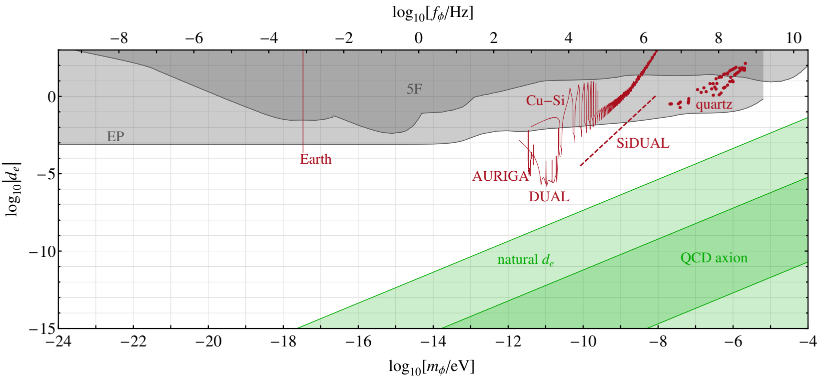
- broadband, non-resonant readout: $\sqrt{S_{xx}} \approx 10^{-19}\ \mathrm{m\,Hz}^{-1/2} \sim \sqrt{\lambda/\mathcal{F}^2 P}$
- multimode antenna: $\omega_n \sim n\pi c_l/R$
- temperature tuning: 5% c_l variation between 4–100 K

thermal noise power:

$$S_{hh}^{\mathrm{th}} = \frac{4TR}{MQc_l^3}\frac{M_n}{k_n^3 J_n^2}$$



with current acoustic detector technology, access to natural parameter space for electron mass moduli between 10^{-12} eV and 10^{-6} eV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Searching for light scalar dark matter with atomic clocks

arXiv:1405.2925, Phys. Rev. D 91, 015015 (2015)

with Asimina Arvanitaki (PI), Junwu Huang (Stanford)

arXiv:1503.06886, Phys. Rev. Lett. 115, 011802 (2015)

with Nathan Leefer, Lykourgos Bougas, and Dmitry Budker (Berkeley, Mainz)

Why use atomic clocks?

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oscillating scalar dark matter: $\phi(t) = \phi_0 \cos(m_\phi t)$

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$$\text{oscillating scalar dark matter: } \phi(t) = \phi_0 \cos(m_\phi t)$$
$$\Downarrow$$
oscillating masses and couplings

$$m_p(t) = m_p \left(1 + d_g \sqrt{4\pi G_N}\phi(t)\right), \; m_e(t) = m_e \left(1 + d_{m_e} \sqrt{4\pi G_N}\phi(t)\right),$$
$$\alpha(t) = \alpha \left(1 + d_e \sqrt{4\pi G_N}\phi(t)\right)$$

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$\Downarrow$

oscillating transition energies between atomic levels

$$f_\mathrm{A}(t) \propto m_e \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_\mathrm{A}} \alpha(t)^{2+\xi_\mathrm{A}}$$

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$$\Downarrow$$

oscillating ratios of atomic frequencies: $\frac{f_\text{A}}{f_\text{B}}(t) \simeq \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_\text{A}-\zeta_\text{B}}\alpha(t)^{\xi_\text{A}-\xi_\text{B}}$

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- atomic clock lasers provide monochromatic light with frequency stability of 1 part in 10^{18}

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$$\Downarrow$$

oscillating masses and couplings

$$m_p(t) = m_p\left(1 + d_g\sqrt{4\pi G_N}\phi(t)\right),\ m_e(t) = m_e\left(1 + d_{m_e}\sqrt{4\pi G_N}\phi(t)\right),$$

$$\alpha(t) = \alpha\left(1 + d_e\sqrt{4\pi G_N}\phi(t)\right)$$

$$\Downarrow$$

oscillating transition energies between atomic levels

$$f_{\mathrm{A}}(t) \propto m_e\left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_{\mathrm{A}}}\alpha(t)^{2+\xi_{\mathrm{A}}}$$

$$\Downarrow$$

oscillating ratios of atomic frequencies: $\frac{f_{\mathrm{A}}}{f_{\mathrm{B}}}(t) \simeq \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_{\mathrm{A}}-\zeta_{\mathrm{B}}}\alpha(t)^{\xi_{\mathrm{A}}-\xi_{\mathrm{B}}}$

- atomic clock lasers provide monochromatic light with frequency stability of 1 part in 10^{18}
- there exist optical synthesis elements to compare the frequencies of two different atomic clocks based on elements A and B

Why use atomic clocks?

oscillating scalar dark matter: $\phi(t) = \phi_0 \cos(m_\phi t)$

$$\Downarrow$$

oscillating masses and couplings

$$m_p(t) = m_p \left(1 + d_g \sqrt{4\pi G_N}\phi(t)\right), \; m_e(t) = m_e \left(1 + d_{m_e} \sqrt{4\pi G_N}\phi(t)\right),$$
$$\alpha(t) = \alpha \left(1 + d_e \sqrt{4\pi G_N}\phi(t)\right)$$

$$\Downarrow$$

oscillating transition energies between atomic levels

$$f_A(t) \propto m_e \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_A} \alpha(t)^{2+\xi_A}$$

$$\Downarrow$$

oscillating ratios of atomic frequencies: $\frac{f_A}{f_B}(t) \simeq \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_A - \zeta_B} \alpha(t)^{\xi_A - \xi_B}$

- atomic clock lasers provide monochromatic light with frequency stability of 1 part in 10^{18}
- there exist optical synthesis elements to compare the frequencies of two different atomic clocks based on elements A and B
  $\Rightarrow$ measure f_A/f_B as function of time

How do atomic transition frequencies change with varying masses and couplings?

$$f_A \propto \left(\frac{m_e}{m_p}\right)^{\zeta_A} (\alpha)^{\xi_A + 2} \tag{2}$$

ζ_A: 1 iff hyperfine; ξ_A: relativistic, spin-orbit, many-body, electric quadrupole effects

How do atomic transition frequencies change with varying masses and couplings?

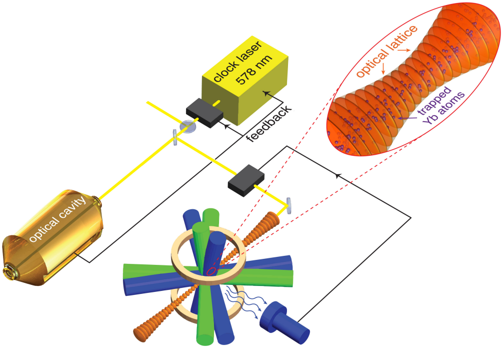
$$f_A \propto \left(\frac{m_e}{m_p}\right)^{\zeta_A} (\alpha)^{\xi_A + 2} \quad (2)$$

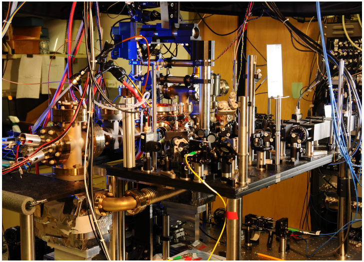
ζ_A: 1 iff hyperfine; ξ_A: relativistic, spin-orbit, many-body, electric quadrupole effects

species	transition	λ [nm]	short $\left[\frac{10^{-15}}{\sqrt{\tau}}\right]$	long $\left[10^{-18}\right]$	ζ_A	ξ_A
^{133}Cs	hyperfine	$3.3 \cdot 10^7$	$2 \cdot 10^2$	360	1	2.83
^{27}Al$^+$	$3s^2\,{}^1S_0 \leftrightarrow 3s3p\,{}^3P_0$	267	2.8	8.6	0	0.008
^{87}Sr	$5s^2\,{}^1S_0 \leftrightarrow 5s5p\,{}^3P_0$	698	0.34	6.4	0	0.06
^{171}Yb	$6s^2\,{}^1S_0 \leftrightarrow 6s6p\,{}^3P_0$	578	0.32	1.6	0	0.31
^{88}Sr$^+$	$5s\,{}^2S_{\frac{1}{2}} \leftrightarrow 4d\,{}^2D_{\frac{5}{2}}$	674	16	25	0	0.43
^{171}Yb$^+$	$4f^{14}6s\,{}^2S_{\frac{1}{2}} \leftrightarrow 4f^{13}6s^2\,{}^2F_{\frac{7}{2}}$	467	2.0	71	0	-5.30
^{199}Hg$^+$	$5d^{10}6s\,{}^2S_{\frac{1}{2}} \leftrightarrow 5d^9 6s^2\,{}^2D_{\frac{5}{2}}$	282	2.8	19	0	-3.19
^{162}Dy	$4f^{10}5d6s \leftrightarrow 4f^9 5d^2 6s$	$4.0 \cdot 10^8$	$4.0 \cdot 10^6$	-	0	$8.5 \cdot 10^6$
^{164}Dy	$4f^9 5d^2 6s \leftrightarrow 4f^{10}5d6s$	$1.3 \cdot 10^9$	$1.3 \cdot 10^7$	-	0	$-2.6 \cdot 10^6$
^{229m}Th^{3+}	nuclear	26	1	1	10^5	10^4

necessary tools for precise frequency comparisons:
2 stable atomic clocks + frequency comparison method

optical clock laser



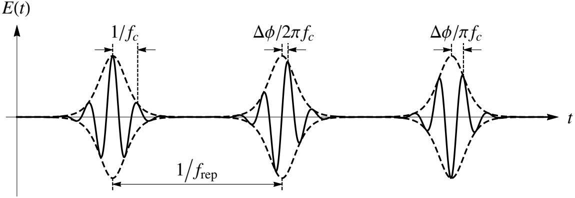


Hinkley et al '13

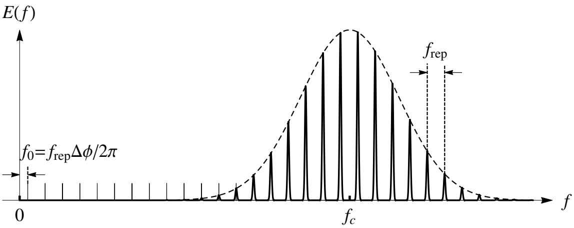
optical clocks: Yb, Al, Sr, Ca, Hg
microwave clocks: Cs, Rb, H, Dy
nuclear clocks: Th, U

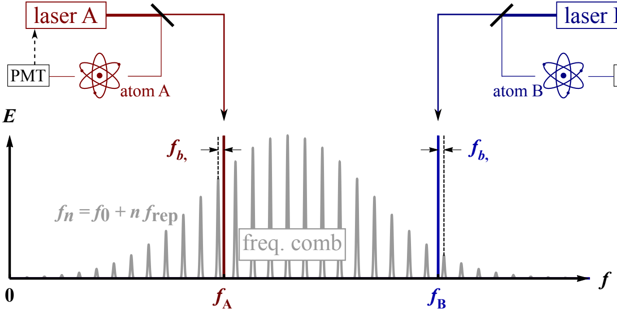
necessary tools for precise frequency comparisons:

2 stable atomic clocks + frequency comparison method



↓ fourier transform ↓



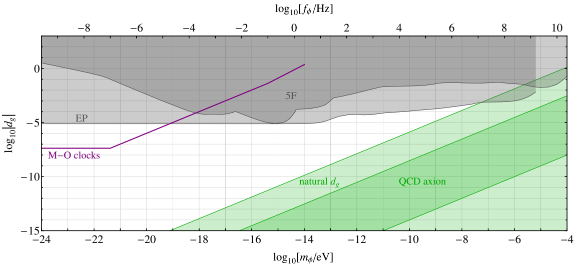


$$\frac{f_A}{f_B}(t) \simeq \left(\frac{m_e(t)}{m_p(t)}\right)^{\zeta_A - \zeta_B} \alpha(t)^{\xi_A - \xi_B};$$

$$\left.\frac{f_A}{f_B}\right|_{expt} = \frac{f_0 + n_A f_{rep} + f_{b,A}}{f_0 + n_B f_{rep} + f_{b,B}} \text{ (optical–optical)}; \qquad \left.\frac{f_A}{f_B}\right|_{expt} = \frac{f_0 + n_A f_{rep} + f_{b,A}}{f_B} \text{ (optical–MW)}$$

data $=$ time series of $\frac{f_A}{f_B}$ measurements *sensitivity to gluon coupling:* $\mathcal{L} \supset -\sqrt{4\pi G_N}\phi \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu} G^{A\mu\nu}$

$$\frac{\text{signal}}{\text{noise}} = 1$$



Cs–Yb comparison

$$\left(\frac{\delta f_A/f_B}{f_A/f_B}\right)_0 \simeq -d_g\sqrt{4\pi G_N}\phi_0$$

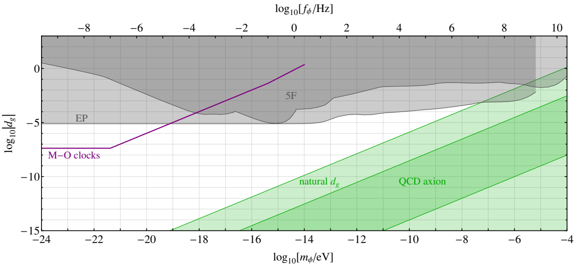
$$\phi_0 \propto \sqrt{\rho_\phi}$$

$$\sigma_n \approx \frac{2\cdot 10^{-13}}{\sqrt{\text{Hz}}}$$

$$t_{\text{int}} = 10^7\ \text{s}$$

sensitivity to gluon coupling: $\mathcal{L} \supset -\sqrt{4\pi G_N}\phi \frac{d_g \beta_3}{2 g_3} G^A_{\mu\nu} G^{A\mu\nu}$

$$\frac{\text{signal}}{\text{noise}} = 1 \quad \Rightarrow \quad \left(\frac{\delta f_A/f_B}{f_A/f_B}\right)^2_0 \min\{t_{\text{int}}, \tau_\phi\} = \frac{\sigma_n^2}{\max\left\{1, \sqrt{t_{\text{int}}/\tau_\phi}\right\}}$$



Cs–Yb comparison

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$$\phi_0 \propto \sqrt{\rho_\phi}$$

$$\sigma_n \approx \frac{2 \cdot 10^{-13}}{\sqrt{\text{Hz}}}$$

$$t_{\text{int}} = 10^7 \text{ s}$$

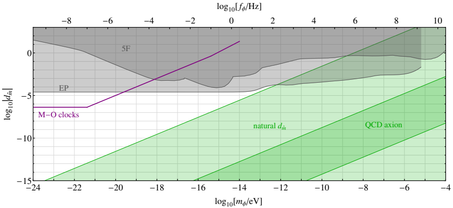
$$\tau_\phi \sim \frac{10^6}{f_\phi}$$

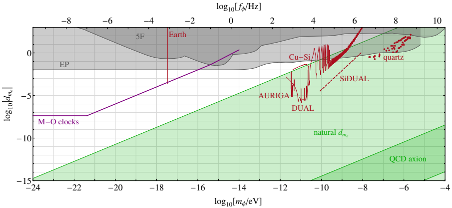
projected sensitivity to quark and electron mass couplings

Cs–Yb comparison

$$\mathcal{L} \supset -\sqrt{4\pi G_N}\phi d_{\hat{m}} m_i \bar{\psi}_i \psi_i \quad (i = u, d)$$

$$\mathcal{L} \supset -\sqrt{4\pi G_N}\phi d_{m_e} m_e \bar{e} e$$

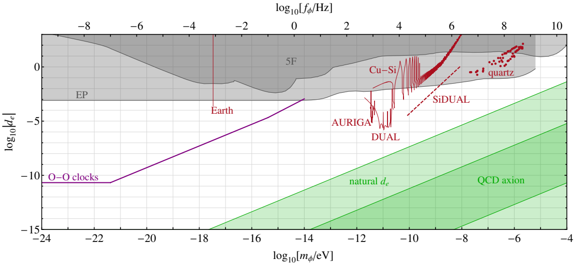




$$\left(\frac{\delta f_A/f_B}{f_A/f_B}\right)_0 \simeq +0.07 d_{\hat{m}} \sqrt{4\pi G_N}\phi_0$$

$$\left(\frac{\delta f_A/f_B}{f_A/f_B}\right)_0 \simeq +d_{m_e} \sqrt{4\pi G_N}\phi_0$$

projected sensitivity to electromagnetic coupling $\mathcal{L} \supset +\sqrt{4\pi G_N}\phi \frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu}$

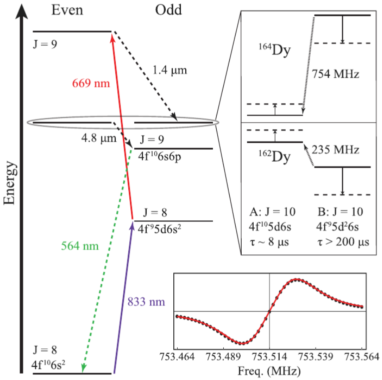


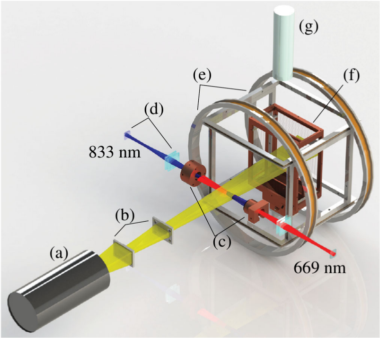
Yb$^+$–Al$^+$ comparison: $\left(\frac{\delta f_A/f_B}{f_A/f_B}\right)_0 \simeq -5.3 d_e \sqrt{4\pi G_N}\phi_0$;

$\sigma_n \approx \frac{3.4\cdot 10^{-15}}{\sqrt{\text{Hz}}}$

new limit on electric coupling $\mathcal{L} \supset +\sqrt{4\pi G_N}\phi \frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu}$

Dy^{162}/Dy^{164}: $\Delta f \approx \pm 2 \cdot 10^{15}\,\mathrm{Hz}\frac{\Delta\alpha}{\alpha}$ vs. Cs clock





new limit on electric coupling $\mathcal{L} \supset +\sqrt{4\pi G_N}\phi \frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu}$

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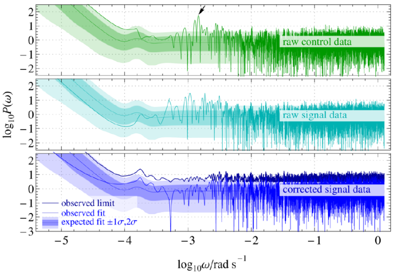
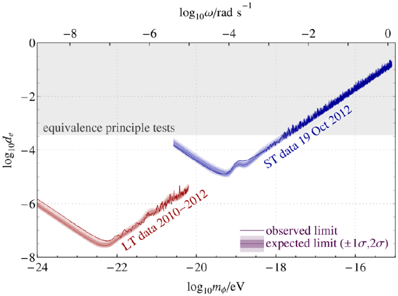
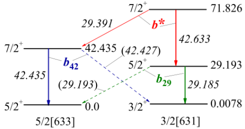




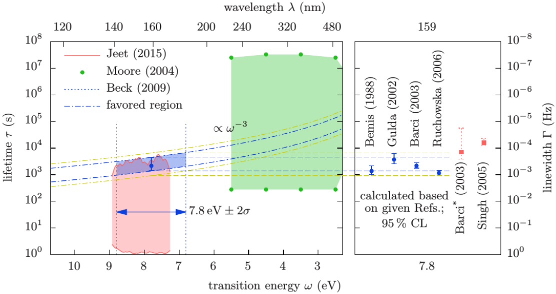
nuclear transitions

typically $\mathcal{O}(100\ \text{keV})$, except:

- ..., ^{201}Hg: 2150 eV; ^{183}W: 544 eV; ^{235}U: 73 eV;
- ^{229}Th: 7.8 ± 0.5 eV ← accessible to UV lasers!



⇒ extreme stability/accuracy, $\mathcal{O}(10^5)$ enhancement in sensitivity to d_g, $d_{\hat{m}}$, d_e

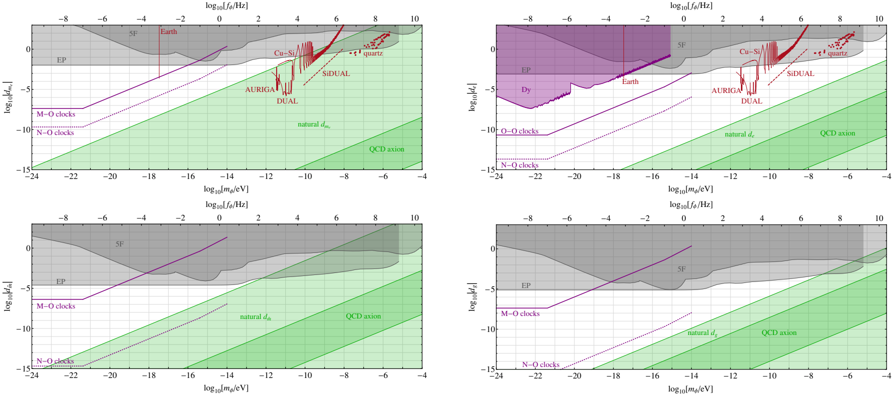


[arXiv:1509.09101]

projected sensitivity with future nuclear clock based on thorium

Th–Yb comparison

$$\left(\frac{\delta f_A/f_B}{f_A/f_B}\right)_0 \simeq (10^6 d_g - 10^5 d_{\hat{m}_q} + 4\times 10^4 d_e - d_{m_e})\sqrt{4\pi G_N}\phi_0; \qquad \sigma_n \sim \frac{10^{-15}}{\sqrt{\text{Hz}}}$$



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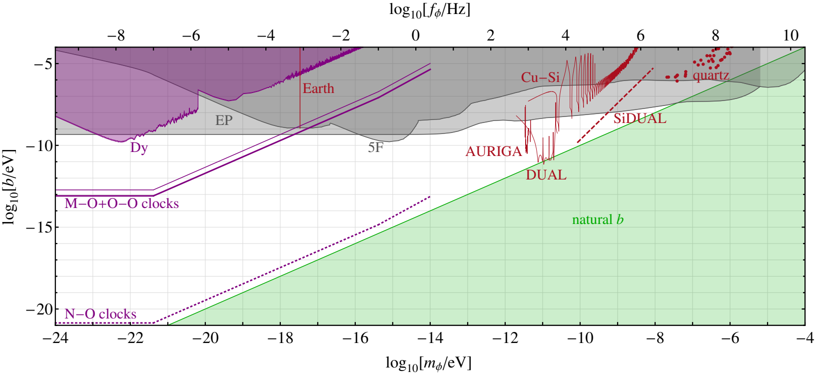
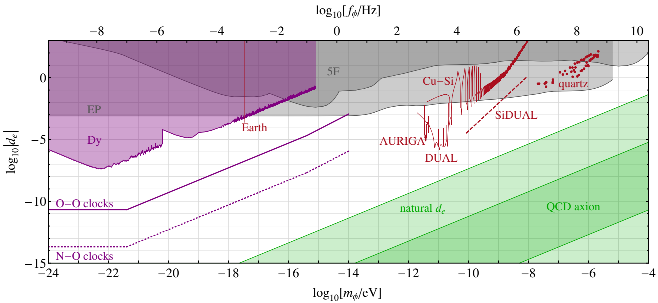


sensitivity of equivalence principle and fifth force tests

$$V = -G_N \frac{m_A m_B}{r_{AB}}\left(1 + \alpha_A \alpha_B e^{-m_\phi r_{AB}}\right); \quad \alpha_A \simeq d_g + \ldots \qquad (3)$$

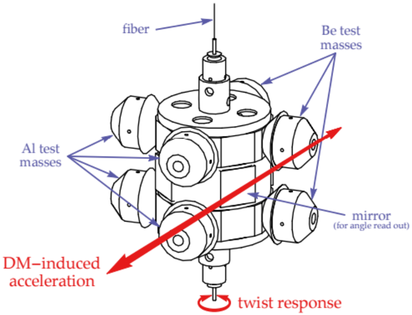
– EötWash: $\left|\frac{\Delta a}{a}\right|_{\text{Be–Ti}} \simeq |\alpha_{\text{Earth}}(\alpha_{\text{Be}} - \alpha_{\text{Ti}})| \lesssim 3.6 \cdot 10^{-13}$ at 95% CL
– Lunar Laser Ranging: $\left|\frac{\Delta a}{a}\right|_{\text{Earth–Moon}} \simeq \alpha_{\text{Sun}}(\alpha_{\text{Earth}} - \alpha_{\text{Moon}})| \lesssim 2.8 \cdot 10^{-13}$
– atom interferometry: differential acceleration of ^{85}Rb & ^{87}Rb at 10^{-15} level?

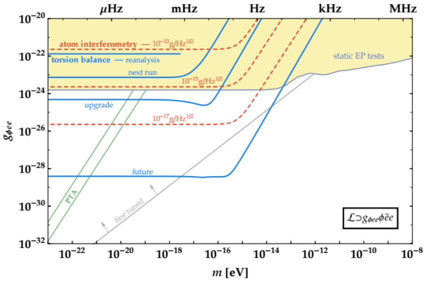


DM-induced forces in accelerometers

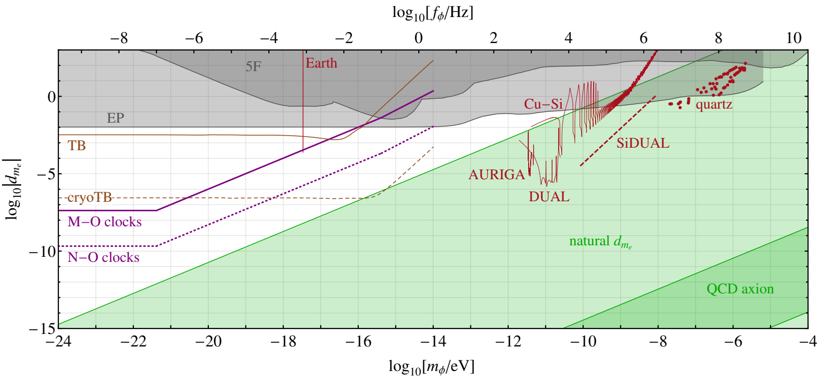
$$V_A = m_A \left[1 + \alpha_A \sqrt{4\pi G_N} \phi_0 \cos\left(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x} \right) \right]$$

$$\alpha_A \sim d_g + 10^{-1} d_{m_q} + 10^{-3} d_e + \frac{m_e}{2 m_p} d_{m_e} + \dots$$





[arXiv:1512.06165]

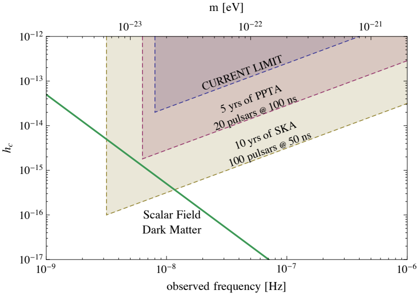

$\log_{10}[f_\phi/\text{Hz}]$
$\log_{10}[m_\phi/\text{eV}]$
$\log_{10}|d_{m_e}|$
5F
Earth
EP
TB
cryoTB
M–O clocks
N–O clocks
Cu–Si
AURIGA
DUAL
SiDUAL
quartz
natural d_{m_e}
QCD axion

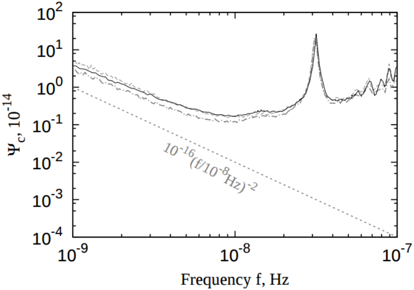
sensitivity of pulsar timing to oscillating gravitational strain

not pressureless on short time scales: $T_{ij} = \delta_{ij} p(\vec{x}, t) = -\delta_{ij} \frac{1}{2} m_\phi^2 \phi_0^2 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x})$

oscillating scalar metric strain with amplitude $\Psi_0 = \frac{1}{2} \pi G_N \phi_0^2$

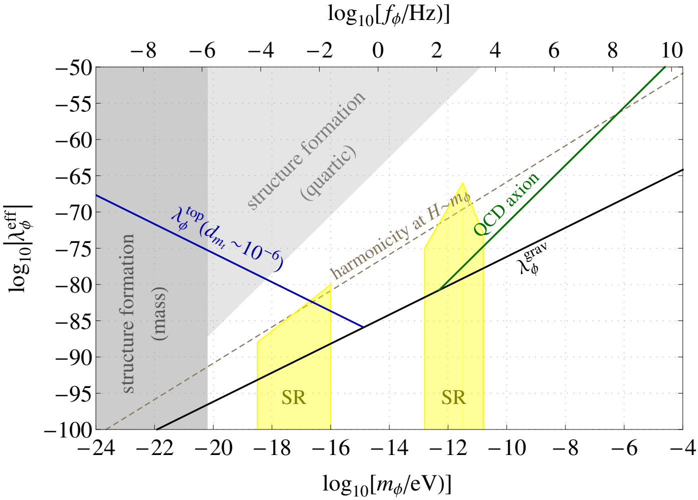
timing delay/advance of pulsar signals: $\delta t \sim 2 \frac{\Psi_0}{m_\phi} \approx 30\,\text{ns} \left(\frac{10^{-23}\,\text{eV}}{m_\phi} \right)^3$





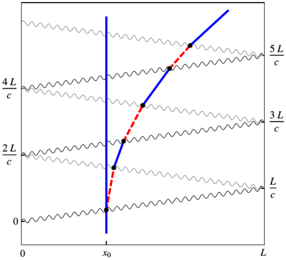
[arXiv:1309.5888] [1408.4670]

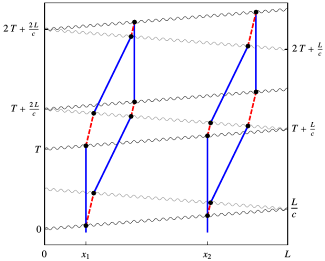
cosmological and astrophysical constraints



[arXiv:1411.2263]

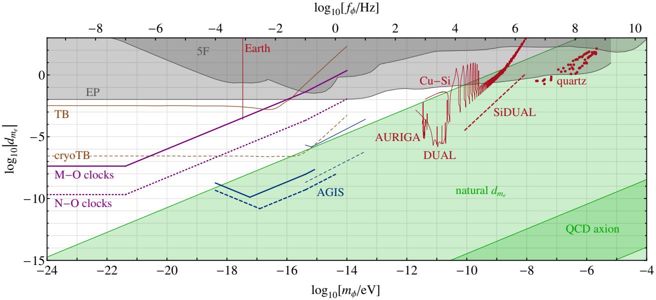
preliminary: atom interferometry





$$\Delta\Phi \simeq \frac{8}{\pi}\Delta\omega_0 N L \sin^2\left(\frac{m_\phi T}{2}\right)$$

[arXiv:0712.1250,1206.0818,1501.06797]



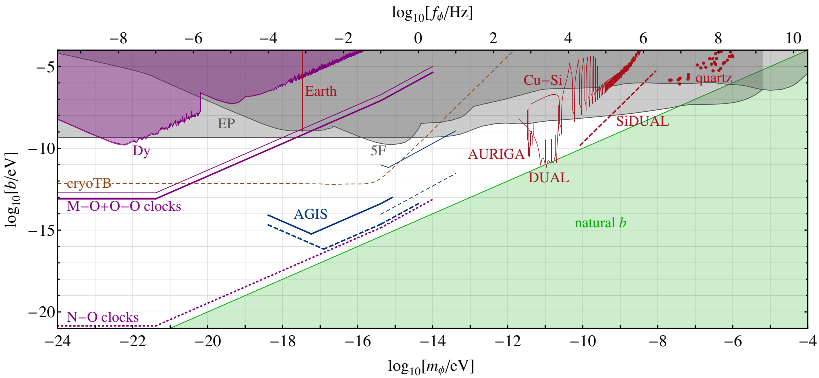
conclusions

1. light moduli fields are good dark matter candidates and can arise in many extensions of the Standard Model

2. **acoustic resonators** are sensitive probes of temporal changes in atomic length scales: **absorbers of modulus waves**
   – compilation of medium-band and tunable setups could cover to 6 decades in mass ($f \gtrsim 100$ Hz)
   – (astero)seismology can provide a window at $f \lesssim 1$ Hz
   – signal scales as $\sqrt{\rho_\phi/\rho_{\rm DM}}$, linear in modulus couplings d_{m_e}, d_e
   – current technology provides a reach way beyond existing constraints
   – already sensitive to natural parameter space for electron mass modulus!

3. **atomic clock pairs** are sensitive probes of temporal changes in atomic energy scales: **measures of modulus field values**
   – broadband searches sensitive to $\gtrsim 8$ decades in mass ($f \lesssim 1$ Hz)
   – signal scales as $\sqrt{\rho_\phi/\rho_{\rm DM}}$, linear in modulus couplings d_g, d_{m_q}, d_{m_e}, d_e
   – already leading limits on electromagnetic gauge modulus
   – future $\rightarrow$ natural parameter space for quark mass modulus!

4. complimentary probes: EP tests, structure formation, superradiance, accelerometers, pulsar timing, atom interferometry, ...


log10[fϕ/Hz]
−8
−6
−4
−2
0
2
4
6
8
10
−5
−10
−15
−20
log10[b/eV]
Earth
Cu−Si
quartz
EP
SiDUAL
Dy
5F
AURIGA
DUAL
cryoTB
M−O+O−O clocks
AGIS
natural b
N−O clocks
−24
−22
−20
−18
−16
−14
−12
−10
−8
−6
−4
log10[mϕ/eV]

Backup slides

cosmic evolution

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0, \tag{4}$$

$$\delta a_{\phi,\mathrm{SM}} \sim -\frac{(d_{m_i}\kappa m_i)^3\, m_i}{16\pi^2} \sim -10^{-58}\,\mathrm{eV}\left(\frac{d_{m_t}}{10^{-6}}\right)^3 \tag{5}$$

$$\delta \lambda_{\phi,\mathrm{SM}} \sim +\frac{(d_{m_i}\kappa m_i)^4}{16\pi^2} \sim +10^{-92}\left(\frac{d_{m_t}}{10^{-6}}\right)^4 \tag{6}$$

$$\lambda_\phi^{\mathrm{eff}} \equiv \delta\lambda_{\phi,\mathrm{SM}} - \frac{10\delta a^2_{\phi,\mathrm{SM}}}{9m_\phi^2} + \delta\lambda_{\phi,\mathrm{grav}}$$
$$\sim +10^{-92}\left(\frac{d_{m_t}}{10^{-6}}\right)^4 - 10^{-80}\left(\frac{d_{m_t}}{10^{-6}}\right)^6\left(\frac{10^{-18}\,\mathrm{eV}}{m_\phi}\right)^2 - 10^{-92}\left(\frac{m_\phi}{10^{-18}\,\mathrm{eV}}\right)^2, \tag{7}$$

$$\left|\lambda_\phi^{\mathrm{eff}}\right| \lesssim \frac{m_\phi^2}{\phi_{0,i}^2} \lesssim 10^{-86}\left(\frac{\rho_{\mathrm{DM,U}}}{\rho_\phi}\right)\left(\frac{m_\phi}{10^{-18}\,\mathrm{eV}}\right)^{5/2}. \tag{8}$$

structure formation

pressure $p_\phi \equiv \dot{\phi}^2/2 - V(\phi) = (\gamma + \gamma_p - 1)\rho_\phi$ can have non-zero average

$$\gamma = \frac{1}{T}\int_0^T \frac{\dot{\phi}^2}{V(\phi)}dt \simeq 2\frac{\int_{-\phi_0}^{+\phi_0}\left[1-\frac{V(\phi)}{V(\phi_0)}\right]^{+1/2}d\phi}{\int_{-\phi_0}^{+\phi_0}\left[1-\frac{V(\phi)}{V(\phi_0)}\right]^{-1/2}d\phi} \approx 1 + \frac{3\lambda_\phi^{\text{eff}}\phi_0^2}{16m_\phi^2} + \mathcal{O}\left(\frac{\lambda_\phi^{\text{eff}\,2}\phi_0^4}{m_\phi^4}\right) \tag{9}$$

$$\ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} \simeq \left[\frac{4\pi\rho_{\text{tot}}}{M_{\text{Pl}}^2} - \left(\frac{\mathbf{k}^2}{4m_\phi^2 a^2} + \frac{3\lambda_\phi^{\text{eff}}\phi_0^2}{16m_\phi^2}\right)\frac{\mathbf{k}^2}{a^2}\right]\delta_{\mathbf{k}}. \tag{10}$$

$$L_{J,(m)} \simeq \left(\frac{\pi^3 M_{\text{Pl}}^2}{\rho_\phi m_\phi^2}\right)^{1/4} \;;\; L_{J,(\lambda)} \simeq \left(\frac{3\pi|\lambda_\phi^{\text{eff}}|M_{\text{Pl}}^2}{8m_\phi^4}\right)^{1/2}, \tag{11}$$

$$m_\phi \gtrsim 6\cdot 10^{-21}\,\text{eV}; \quad |\lambda_\phi^{\text{eff}}| \lesssim 3\cdot 10^{-79}\left(\frac{m_\phi}{10^{-18}\,\text{eV}}\right)^4. \tag{12}$$