The strong CP problem beyond the conventional axion

Gilad Perez

Weizmann

BBSM Ascona 2023

Outline

- Intro, strong CP problem (?), quality of spin-0 dark matter (DM)
- Searching for the QCD axion quadratically
- Interim summary

- New non-QCD axion (but that addresses the strong CP) pheno'

How serious is the strong CP problem ? (sorry if trivial)

- 3 levels of formulating the strong CP problem, *assuming CP is respected by the UV*:

(i) $\bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] \lesssim 10^{-10}$, is it a problem?

(who knows?)

(ii) $\bar{\theta} = \lesssim 10^{-10} \ll \theta_{\mathrm{KM}} = \arg\left\{\det\left[Y_u Y_u^{\dagger}, Y_d Y_d^{\dagger}\right]\right\}$, is it a problem?

(not if these are natural/protected and sequestered)

(iii) $\bar{\theta} = \lesssim 10^{-10} \ll \theta_{\mathrm{KM}}$, but $\bar{\theta} = \bar{\theta}_{\mathrm{bare}} + \epsilon\, \theta_{\mathrm{KM}} \ln\left(\Lambda_{\mathrm{UV}}/M_W\right)$, is it a problem?

(ϵ appears in 7 loops and contains several other suppression factor)

- Should we be more cautious / more generic? [at least till we reach $\mathcal{O}\left(10^{-16}\right)$ precision]

We nevertheless focus on axions & strong CP
Still let's first discuss some pheno of ultralight spin-0 DM

- Begin with ultralight dark matter (UDM), minimal model would be just a free massive scalar:

$$\mathscr{L} \in m_\phi^2 \phi^2 \,,\ \rho_{\rm Eq}^{\rm DM} \sim {\rm eV}^4 \sim m_\phi^2 \phi_{\rm Eq}^2 = m_\phi^2 \phi_{\rm init}^2 ({\rm eV}/T_{\rm osc})^3 \qquad \left[T_{\rm os} \sim \sqrt{M_{\rm Pl} m_\phi}\right]$$

- Assuming ("best case") MeV reheating: $\phi_{\rm init}\left(f_{\rm min}\right) = \begin{cases} 10^{17}\,{\rm GeV}\left(\dfrac{10^{-27}\,{\rm eV}}{m_\phi}\right)^{\frac{1}{4}} & m_\phi \lesssim 10^{-15}\,{\rm eV} \\ 10^{15}\,{\rm GeV}\left(\dfrac{10^{-15}\,{\rm eV}}{m_\phi}\right) & m_\phi \gtrsim 10^{-15}\,{\rm eV} \end{cases}$

- However, what if we allow Planck suppressed couplings? (generalized quality)

Planck suppression for ultralight spin 0 field

- Let's consider some dimension 5 operators, and ask if current sensitivity reach the Planck scale (assumed linear coupling and that gravity respects parity):

Graham, Kaplan, Rajendran;
Stadnik & Flambaum;
Arvanitaki Huang & Van Tilburg (15)

$\boxed{m_\phi = 10^{-18}\ \mathrm{eV}}$ (1/hour)

operator	current bound	type of experiment
$\frac{d_e^{(1)}}{4\,M_{\rm Pl}}\phi\, F^{\mu\nu}F_{\mu\nu}$	$d_e^{(1)} \lesssim 10^{-4}$ [58]	DDM oscillations
$\frac{\tilde{d}_e^{(1)}}{M_{\rm Pl}}\phi\, F^{\mu\nu}\tilde{F}_{\mu\nu}$	$\tilde{d}_e^{(1)} \lesssim 2\times 10^{6}$ [68]	Astrophysics
$\frac{\left\lvert d_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert d_{m_e}^{(1)}\right\rvert \lesssim 2\times 10^{-3}$ [58]	DDM Oscillations
$i\frac{\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert \lesssim 7\times 10^{8}$ [63]	Astrophysics
$\frac{d_g^{(1)}\beta(g)}{2M_{\rm Pl}\, g}\phi\, G^{\mu\nu}G_{\mu\nu}$	$d_g^{(1)} \lesssim 6\times 10^{-6}$ [67]	EP test: MICROSCOPE
$\frac{\tilde{d}_g^{(1)}}{M_{\rm Pl}}\phi\, G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\tilde{d}_g^{(1)} \lesssim 4$ [69]	Oscillating neutron EDM
$\frac{\left\lvert d_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert d_{m_N}^{(1)}\right\rvert \lesssim 2\times 10^{-6}$ [67]	EP test: MICROSCOPE
$i\frac{\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert \lesssim 4$ [69]	Oscillating neutron EDM

For updated compilation see: Banerjee, Perez, Safronova, Savoray & Shalit (22)

DDM = direct dark matter searches

Linear or quadratic axion coupling?

- (Linear) UDM scalar couplings are required to be super-Planckians
- The bounds on UDM scalar couplings are some ***12 orders of mag.*** stronger than axion's one
- Sensitivity to axion would be much better if it had linear scalar coupling (forbidden by CP)
- However, quadratic scalar couplings, $a^2/f^2 \times O^{\rm SM}_{\rm scalar}$, are allowed by CP
- In fact, $\theta \equiv \frac{a}{f} \sim \frac{\sqrt{\rho_{\rm DM}}}{m_a f} \sim 10^{-6} \times \frac{10^9\,{\rm GeV}}{f} \times \frac{10^{-15}\,{\rm eV}}{m_a}$, could be beneficial to go to $O(\theta^2)$

In passing: bounds on quadratic couplings are sub-Planckians:

$\frac{d_e^{(2)}}{8M_{\rm Pl}^2}\phi^2 F^{\mu\nu}F_{\mu\nu}$	$d_e^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE
$\frac{\left\|d_{m_e}^{(2)}\right\|}{2M_{\rm Pl}^2}\phi^2 m_e\psi_e\psi_e^c$	$\left\|d_{m_e}^{(2)}\right\| \lesssim 10^{12}$ [67]	EP test: MICROSCOPE
$\frac{d_g^{(2)}\beta_g}{4M_{\rm Pl}^2\, g}\phi^2 G^{\mu\nu}G_{\mu\nu}$	$d_g^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE.
$\frac{\left\|d_{m_N}^{(2)}\right\|}{2M_{\rm Pl}^2}\phi^2 m_N\psi_N\psi_N^c$	$\left\|d_{m_N}^{(2)}\right\| \lesssim 10^{11}$ [67]	EP test: MICROSCOPE

Banerjee, Perez, Safronova, Savoray & Shalit (22)

ALP quadratic UV scalar interactions

- The linear sigma model of an ALP $\left[\Phi \equiv \left(\frac{\rho + f}{\sqrt{2}}\right) e^{\frac{ia}{f}}\right]$ contains the coupling: $\rho\, \partial_\mu a\, \partial^\mu a$

- Thus: $\Phi \bar{f} f \;\Rightarrow\; \rho \bar{f} f \;\Rightarrow\; \partial_\mu a\, \partial^\mu a\, \bar{f} f$, however it is suppressed by extra m_a^2 / f^2, and thus negligibly small, $O(\theta^4)$ …

Oscillations of energy levels induced by QCD-axion-like DM

- QCD axion is special and the quadratic coupling are induced by IR effects
- Extracted via pion mass dependence: $m_\pi^2(\theta) \simeq m_\pi^2(0)\left(1 - \frac{m d m_u}{(m_d + m_u)^2}\theta^2\right)$ Brower, Chandrasekharanc, Negele & Wiese (03)

$$\mathrm{MeV} \times \theta^2 \bar{n} n \Rightarrow \frac{\delta f}{f} \sim \frac{\delta m_N}{m_N} \sim 10^{-16} \times \cos(2m_a) \times \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\frac{10^9\,\mathrm{GeV}}{f}\right)^2 \quad \mathrm{vs} \quad m_N \frac{a}{f}\bar{n}\gamma^5 n \Rightarrow \left(f \gtrsim 10^9\,\mathrm{GeV}\right)_{\mathrm{SN}}$$

(1/sec)

Kim & GP (22)

Exciting as we saw that clocks (& EP tests) are much more precise than magnetometers. Can possibly sense (slow) oscillation of energy levels due to change electron or QCD masses to precision of better than $1{:}10^{18}$

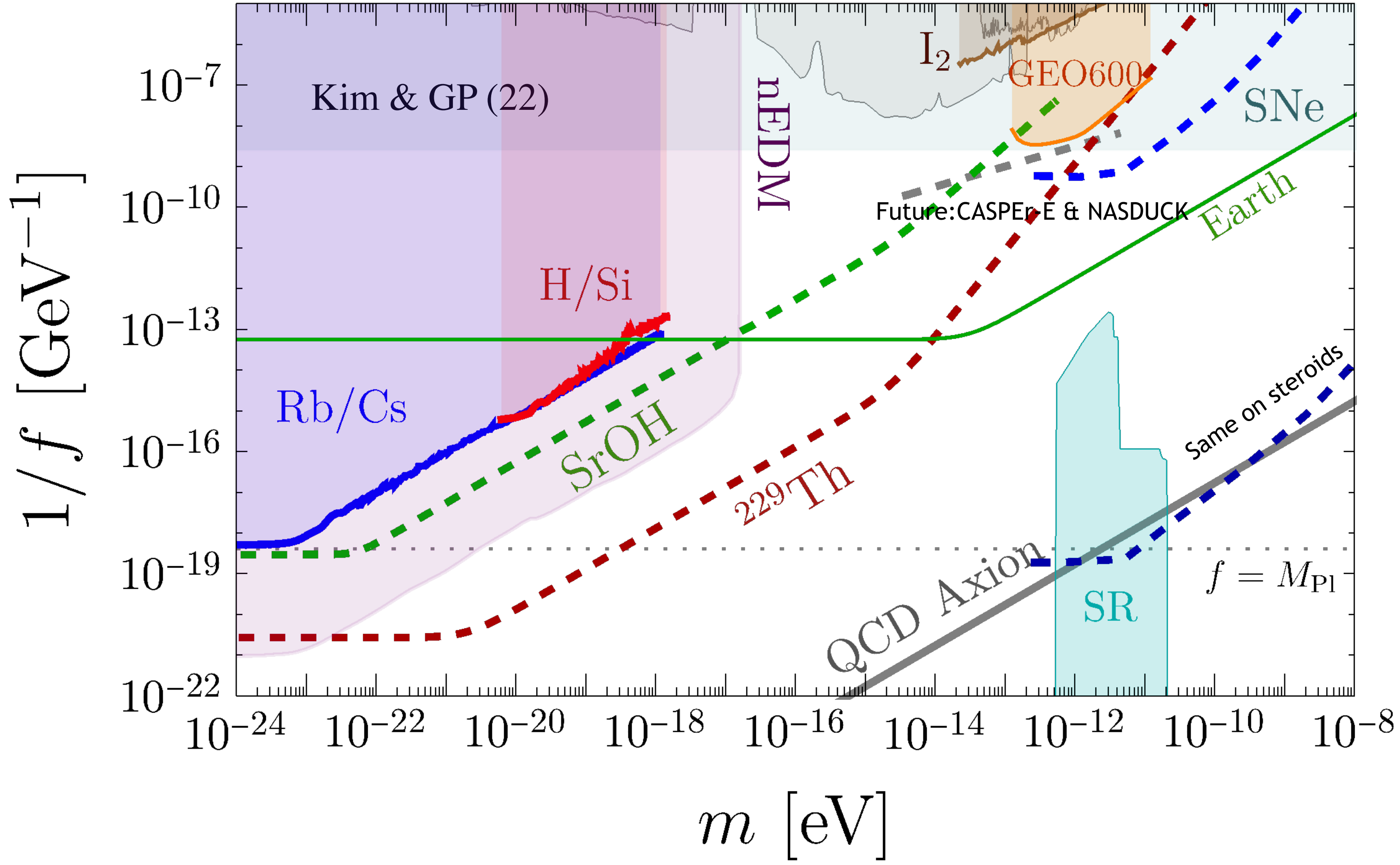
Oscillations of energy levels induced by QCD-axion-like DM

$$\frac{\delta m_\pi^2}{m_\pi^2} \sim \frac{1}{2}\theta^2$$

$$\frac{\delta m_N}{m_N} \simeq 0.13\frac{\delta m_\pi}{m_\pi}$$

$$\frac{\delta f_{Th}}{f_{Th}} \simeq 2\times 10^5\frac{\delta m_\pi^2}{m_\pi^2}$$

Snapshot terrestrial bounds (see later complete)



Two extra interesting ingredients (one trivial one less)

Kim, Lenoci, Perez & Ratzinger (23)

1. Quadratic coupling to hadrons => quadratic coupling to QED (1-loop) ~ same sensitivity

See also Beadle et. al (23)

2. Due to velocity dispersion, $\theta^2(t)$ => sharp resonance + continuum at lower frequencies

Masia-Roig et. al (23)

- To understand the point qualitatively, let's consider first linear coupling, say that changes α:

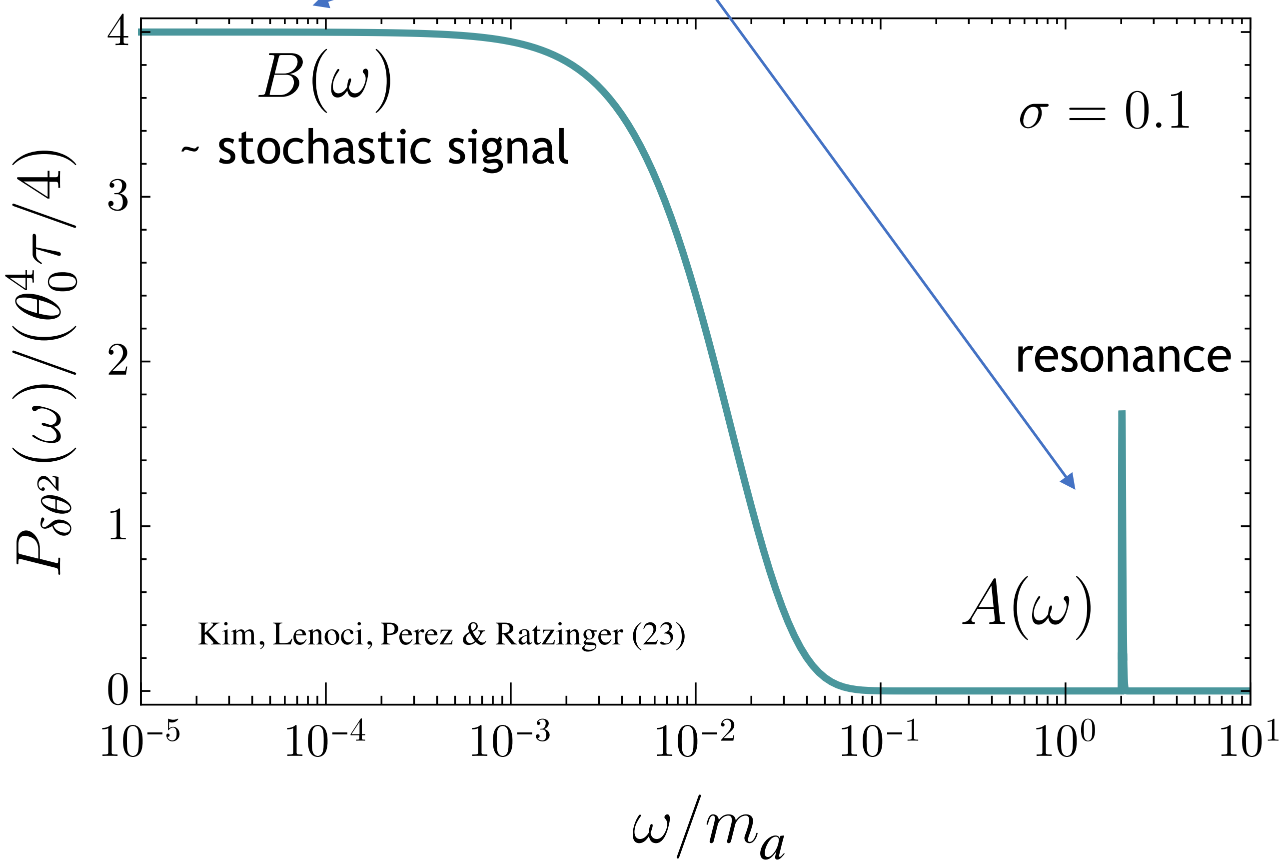
$$\delta E(t) \leftrightarrow m_e \alpha^2 (1+\theta(t)) \propto \frac{\rho_{\rm DM}}{m_a} \cos wt\,, \text{with } w \approx m_a \left(1+\frac{v^2}{2}\right), \text{ and } P(v) \propto \exp\left(\frac{-v^2}{\sigma^2}\right), \text{ with } \sigma \sim 10^{-3}$$

- Frequency transformed: it would result in a sharp signal at $\omega \sim m_a$ with width of $O\left(10^{-6}\right)$

- However our signal is quadratic $\delta E(t) \leftrightarrow \theta(t)^2 \sim \cos\left[2m_a t\right] + \cos\left[m_a\left(\frac{v_1^2 - v_2^2}{2}\right)\right]$

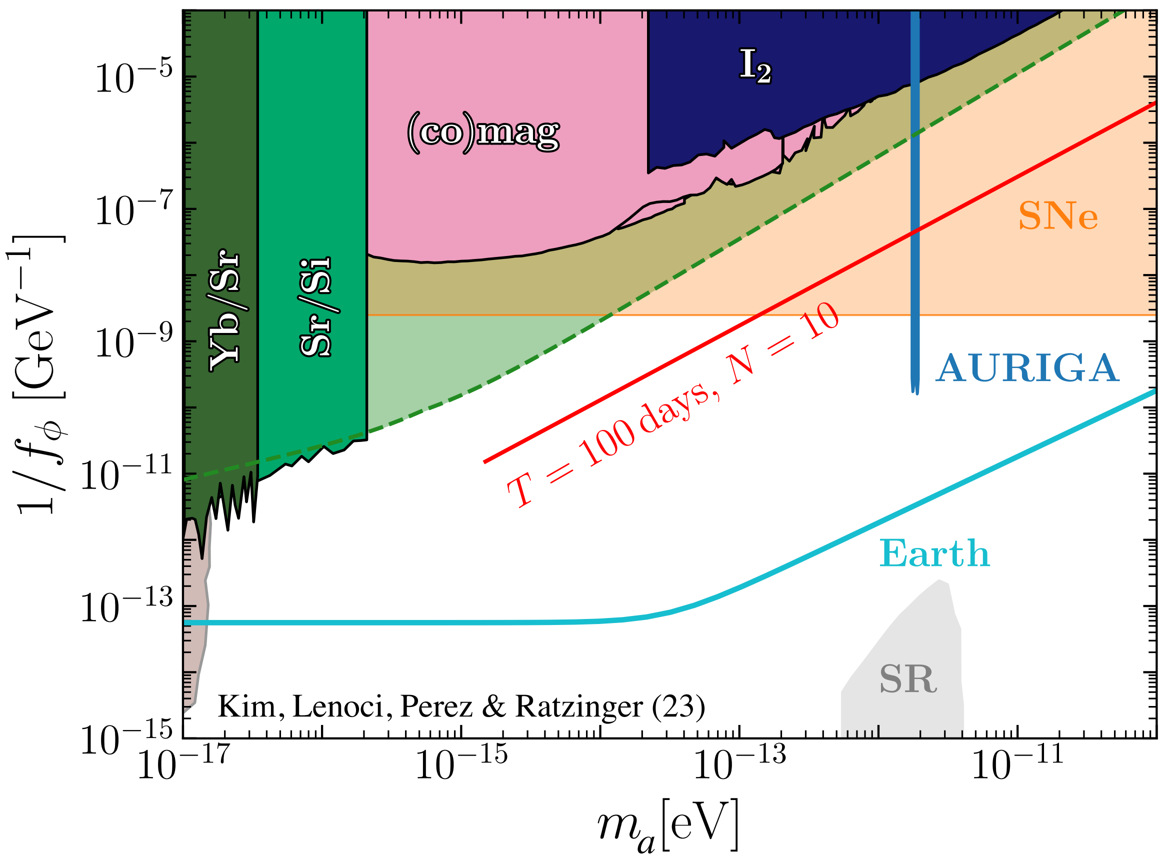
Power spec' of signal after integrating over Maxwell-Boltzmann velocity dist' , QCD-axion

$$\delta E(t) \leftrightarrow \theta(t)^2 \sim \cos\left[2m_a t\right] + \cos\left[m_a\left(\frac{v_1^2 - v_2^2}{2}\right)\right]$$

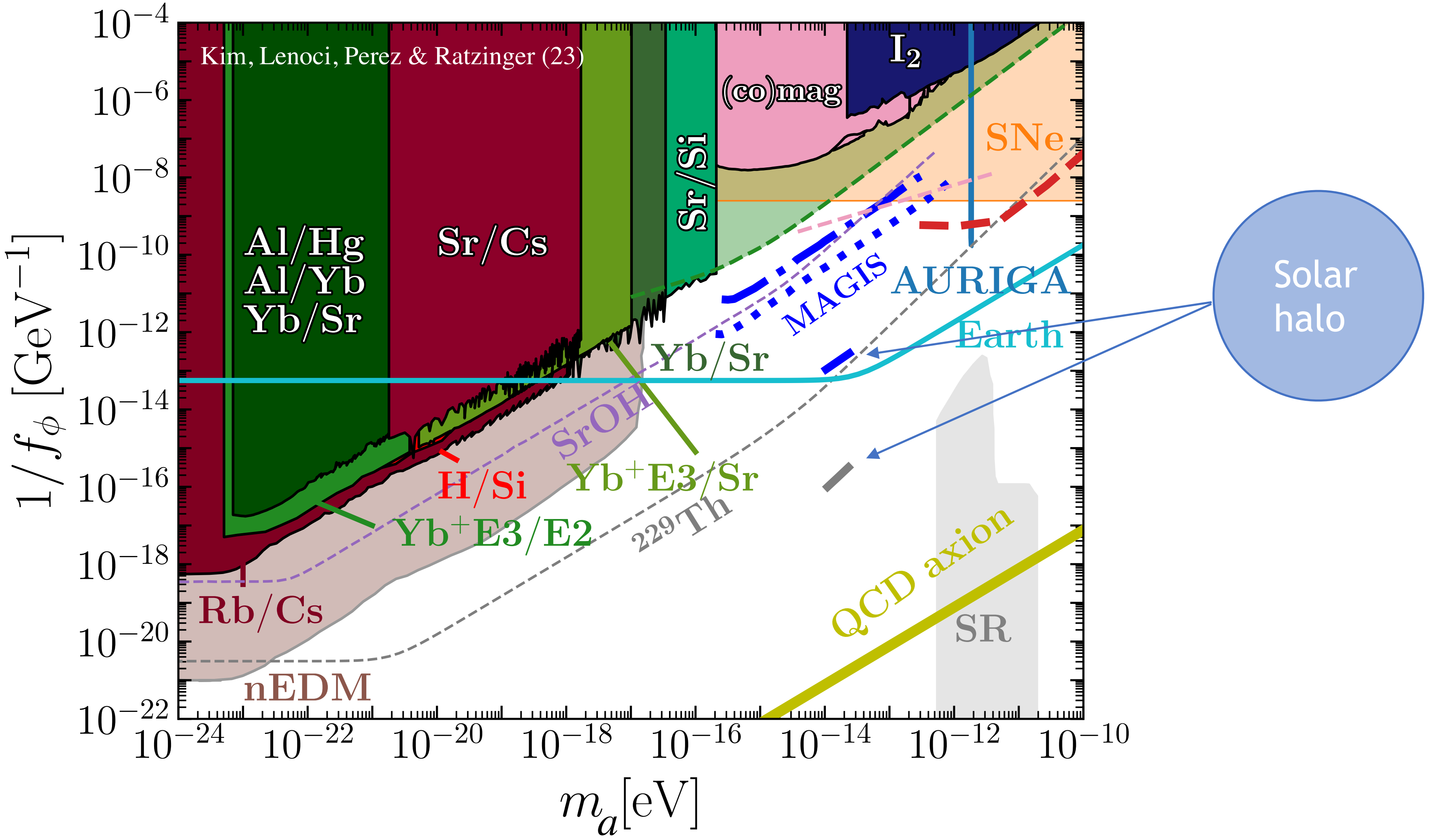


Bottom line

- We can use noise to bound QCD axion due to quadratic part — Flambaum & Samsonov (23)
- This is not noise, cont' signal is correlated among several detectors, improve sensitivity



Combining everything (on Earth)



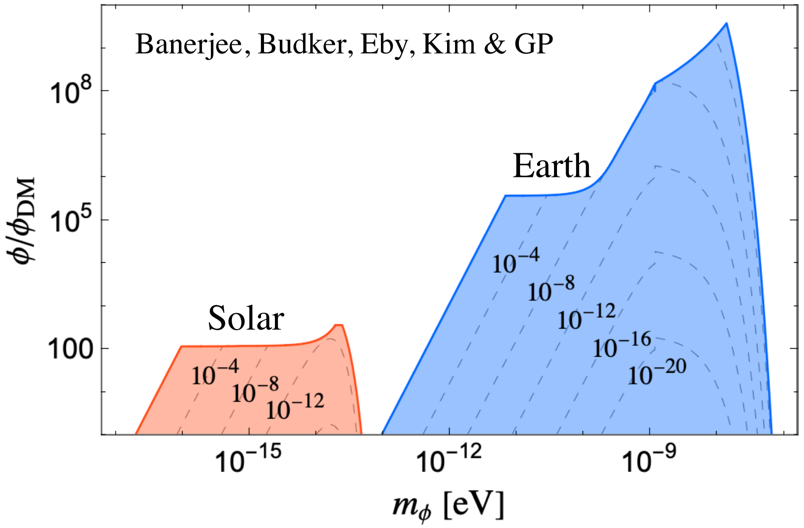
For related bounds not shown for simplicity, see e.g- Astro/cosmo: Blum, Tito D'Agnolo, Lisanti & Safdi (14); Rogers & Peiris (20); Density effects: Hook & Huang (17); Balkin, Serra, Springmann & Weiler (20)

Simple mechanism for formation of UDM solar halo

Budker, Eby, Gorghetto, Minyuan & GP (23)

- One can find stable configuration of UDM bounded to external gravitational potential such as stars or planets.
- These objects would lead to very different properties of UDM: Banerjee, Budker, Eby, Kim & GP (19)

  larger densities; different line shape, bigger coherent time; no stochasticity …



Simple mechanism for formation of UDM solar halo

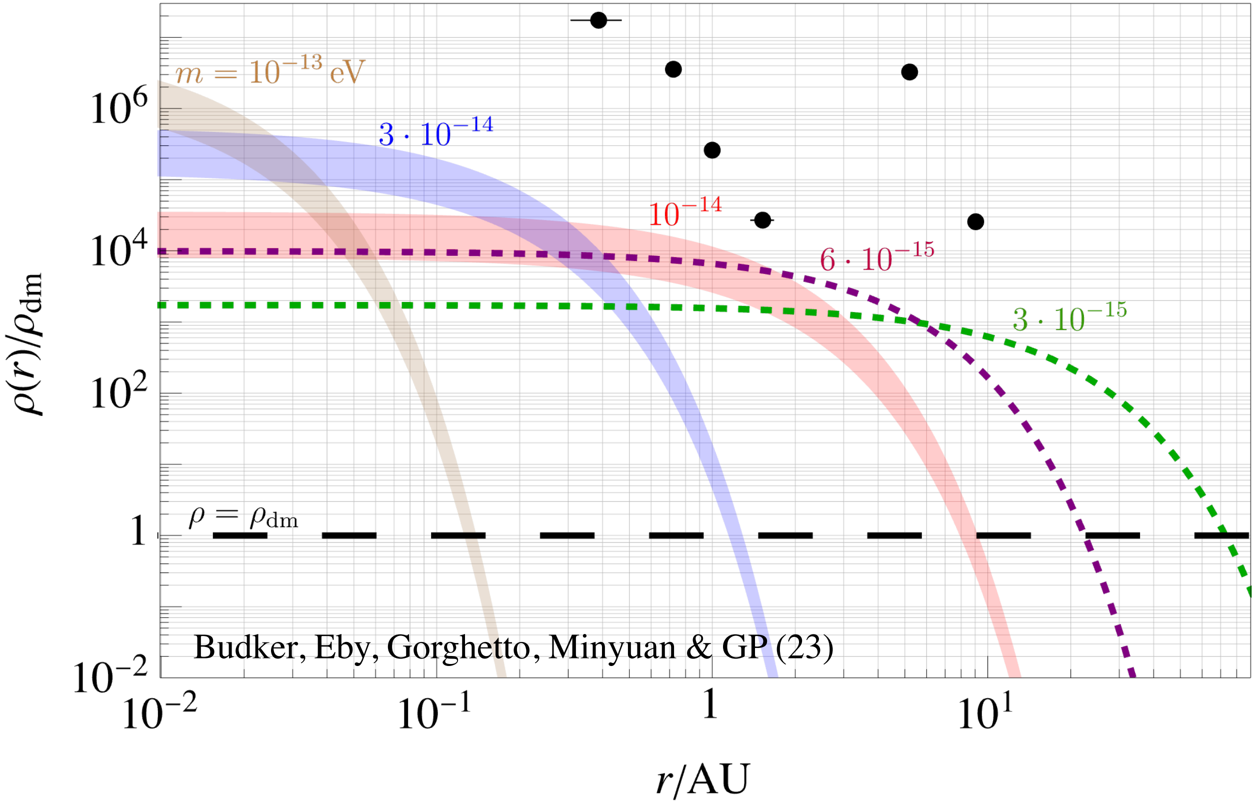
Budker, Eby, Gorghetto, Minyuan & GP, (23)

- However, as the escape velocity say at AU is around 30 km/s & the incoming DM is coming to us at 300 km/s trapping it seems hard.
- Yet recently understood that quartic interactions in the presence of strong gravitational potential lead to enhanced coupling, in the region that focusing is active:

$$\xi_{\rm foc} = \frac{\lambda_{\rm dB}}{R_\star} = \frac{2\pi\alpha}{v_{\rm dm}} \simeq \left[\frac{m}{1.7\times 10^{-14}\,{\rm eV}}\right]\left[\frac{M}{M_\odot}\right]\left[\frac{240\,{\rm km/s}}{v_{\rm dm}}\right] \qquad R_\star = 1\,{\rm AU}\left[\frac{1.3\cdot 10^{-14}\,{\rm eV}}{m}\right]^2\left[\frac{M_\odot}{M}\right]$$

$$\alpha \equiv GMm$$

Simple mechanism for formation of UDM solar halo



In the red, blue, and brown shaded regions, the DM-velocity parameters are varied from $v_{dm} = \sigma/2 = 240$km/s to 50km/s, where σ is the variance of the velocity distribution. The purple and green dashed lines are the density functions for $m < 10^{-14}$ eV, which are only exponentially growing when $v_{dm} \ll 240$ km/sec.

2/3rd summary

- Strong CP problem is only marginally a problem
- The simplest ultralight dark matter (UDM) solution is under pressure due to generalized quality argument, due to scalar interactions
- Low-mass QCD axions can be efficiently probed via their quadratic scalar interactions (even at higher masses using the continuum part); in passing: these models suffer from a severe quality problem
- Is there another class of models which addresses the strong CP problem? Maybe of better quality and different pheno?

The other path

- There's a class of models where CP is UV-sym' and at tree level we find:

$$\bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] = 0 \quad \& \quad \theta_{\mathrm{KM}} = \arg\left\{\det\left[Y_u Y_u^{\dagger}, Y_d Y_d^{\dagger}\right]\right\} = \mathcal{O}(1)$$

- This is realized if:

1. Yukawas are Hermitian (left-right models or wave function renorm')

Hiller & Schmaltz (01); Harnik, GP, Schwartz & Shirman (04); Cheung, Fitzpatrick & Randall (08)

2. Structure/sym. => det(0), concretely, Nelson-Barr (NB)

Nelson; Barr (84)

- We focus on NB, which are easy to control & of higher quality

Nelson-Barr (crash course)

- $\mathscr{L}_{\text{NB}} = \mu q^c q + (g_i\Phi + \tilde{g}_i\Phi^*)d_i^c q + Y_d HQd^c + Y_u\tilde{H}Qu^c \quad (\text{with } q, q^c, \Phi \subset Z_2 - \text{odd})$

- Assume that theory is real and only $\Phi = \frac{f+\rho}{\sqrt{2}}\exp\left(\frac{ia}{f}\right)$; $\langle a\rangle \neq 0$ breaks CP, then:

1. $\mathscr{M}_d = \begin{pmatrix} \mu & B_i \\ 0 & m_d \end{pmatrix}$; $m_d \equiv Y_d v$; $B_i \equiv (g_i\Phi + \tilde{g}_i\Phi^*)$ => det $\left[\mathscr{M}_d\right] \in$ Real

2. At low energy ($v \ll \mu, g_i f$), effective m_d satisfies $m_d^{\text{eff}} m_d^{\text{eff}\dagger} = m_d\left(\mathbf{1}_3 + \frac{B_i^* B_j}{\mu^2 + B_f B_f^\dagger}\right)m_d^\dagger$,

   which if g_i isn't parallel to $\tilde{g}_i$ and $\mu \lesssim B_i$ lead to $\theta_{\text{KM}} = \mathcal{O}(1)$

Nelson-Barr axion-like pheno for the CP breaking

Discussion with: M. Dine, Y. Nir, W. Ratzinger, I. Savoray

- $\mathscr{L}_{\rm NB} = \mu q^c q + (g_i\Phi + \tilde{g}_i\Phi^*)d_i^c q + Y_d HQd^c + Y_u\tilde{H}Qu^c$ (with $q, q^c, \Phi \subset Z_2-$odd)
- Assume approx' flavor sym' such that $g_i \propto (1,0,0)$ & $\tilde{g}_i \propto (0,0,1)$
- Then a is a pseudo-Nambu-Goldstone-boson, with suppressed potential, but with $\langle a\rangle = 0$
- Furthermore, one can show that $\theta_{\rm KM} = \dfrac{a}{f}$

$$\left\{ m_d^{\rm eff} m_d^{\rm eff\dagger} \sim m_d \left[\mathbf{1}_3 + r \begin{pmatrix} 1 & 0 & e^{\frac{2ia}{f}} \\ 0 & 0 & 0 \\ e^{\frac{-2ia}{f}} & 0 & 1 \end{pmatrix} \right] m_d^T \right\}$$

- Also, mixing angles develop quadratic dependence on a (but not masses)

Nelson-Barr ultralight-DM pheno

With: M. Dine, Y. Nir, W. Ratzinger, I. Savoray (also discussion with Surjeet)

- In case another sector breaks the shift sym' (say Planck suppress or other) then the minimum of potential generically would lead to $\langle a \rangle \neq 0$ and spontaneous breaking of CP => $\bar{\theta} = 0 \quad \& \quad \theta_{\rm KM} = \mathcal{O}(1)$

Relaxion: Graham, Kaplan & Rajendran (15)

NB-relaxion - Davidi, Gupta, GP, Redigolo, & Shalit (17)

- Now if we tip the NB-axion from it's minimum it'd behave as a new type of ultralight DM (UDM)

$\Downarrow$

New type of pheno: *time dependent CKM angles*

While the strong CP is always zero

NB-UDM signature & parameter space

- What is the size of the effect? $\delta\theta_{\mathrm{KM}} \sim \frac{\sqrt{\rho_{\mathrm{DM}}}}{m_{\mathrm{NB}} f}\cos(m_{\mathrm{NB}} t) \sim 10^{-3} \times \frac{10^{10}\,\mathrm{GeV}}{f} \times \frac{10^{-19}\,\mathrm{eV}}{m_{\mathrm{NB}}} \times \cos(m_{\mathrm{NB}} t)$

- Currently (PDG): $\theta_{\mathrm{KM}} = 1.14 \pm 0.03$

- How to search such signal? Need time dependence CP violation, perfect for B-asym

- Bound from EP: $\frac{\Delta m_u}{m_u} \approx \frac{3}{32\pi^2} y_b^2 |V_{ub}^{\mathrm{SM}}|^2 \frac{a}{f} \Rightarrow f \gtrsim 10^{10}\,\mathrm{GeV}$

- Minimal misalignment DM bound, can't be satisfied: $f \gtrsim 10^{15}\,\mathrm{GeV} \left(\frac{10^{-19}\,\mathrm{eV}}{m_\phi}\right)^{\frac{1}{4}}$

- Naive naturalness => sub-MeV cutoff , $\Delta m_a \approx \frac{y_b |V_{ub}| m_u \Lambda_{\mathrm{UV}}}{16\pi^2 f}$ => current B-factories probe finely tuned region

Backups

Time dependent CP asym.

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle,$$
$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle,$$

$$A_f = \langle f|\mathcal{H}_d|B^0\rangle, \quad \bar{A}_f = \langle f|\mathcal{H}_d|\bar{B}^0\rangle$$

$$a_{f_{\rm CP}}(t) = \frac{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{\rm CP}) - \Gamma(B^0_{\rm phys}(t) \to f_{\rm CP})}{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{\rm CP}) + \Gamma(B^0_{\rm phys}(t) \to f_{\rm CP})}$$

$$a_{f_{\rm CP}}(t) = -\frac{1-|\lambda_{f_{\rm CP}}|^2}{1+|\lambda_{f_{\rm CP}}|^2}\cos(\Delta m_B t) + \frac{2{\rm Im}\lambda_{f_{\rm CP}}}{1+|\lambda_{f_{\rm CP}}|^2}\sin(\Delta m_B t) \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$a_{f_{\rm CP}}(t) = {\rm Im}\lambda_{f_{\rm CP}}\sin(\Delta m_B t) \qquad \left(\lambda_{B\to\psi Ks/\eta} \simeq 1\right)$$

Ex. Babar: Measurements of CPV Asymmetries and BFs in B Meson Decays to η ′ K Article in Physical Review Letters · October 2003

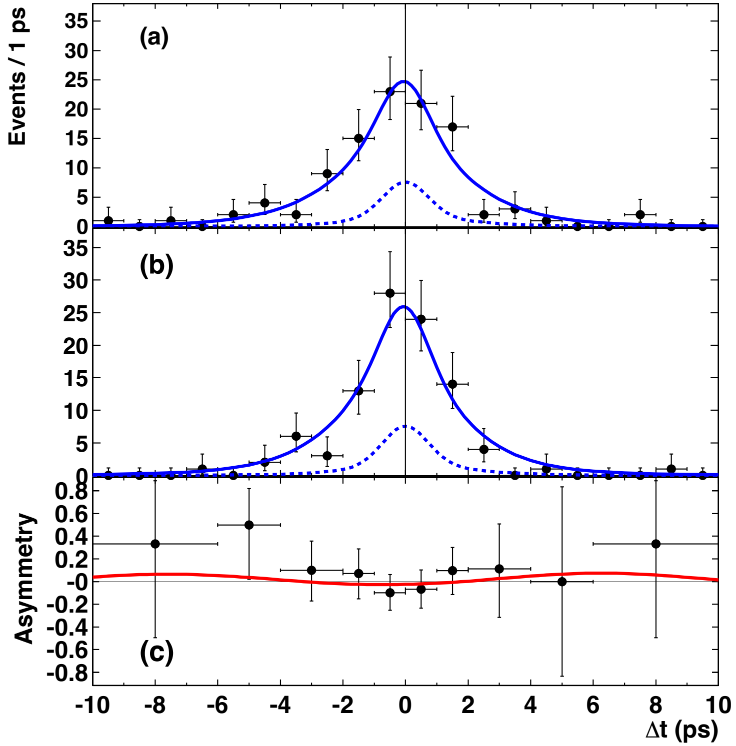


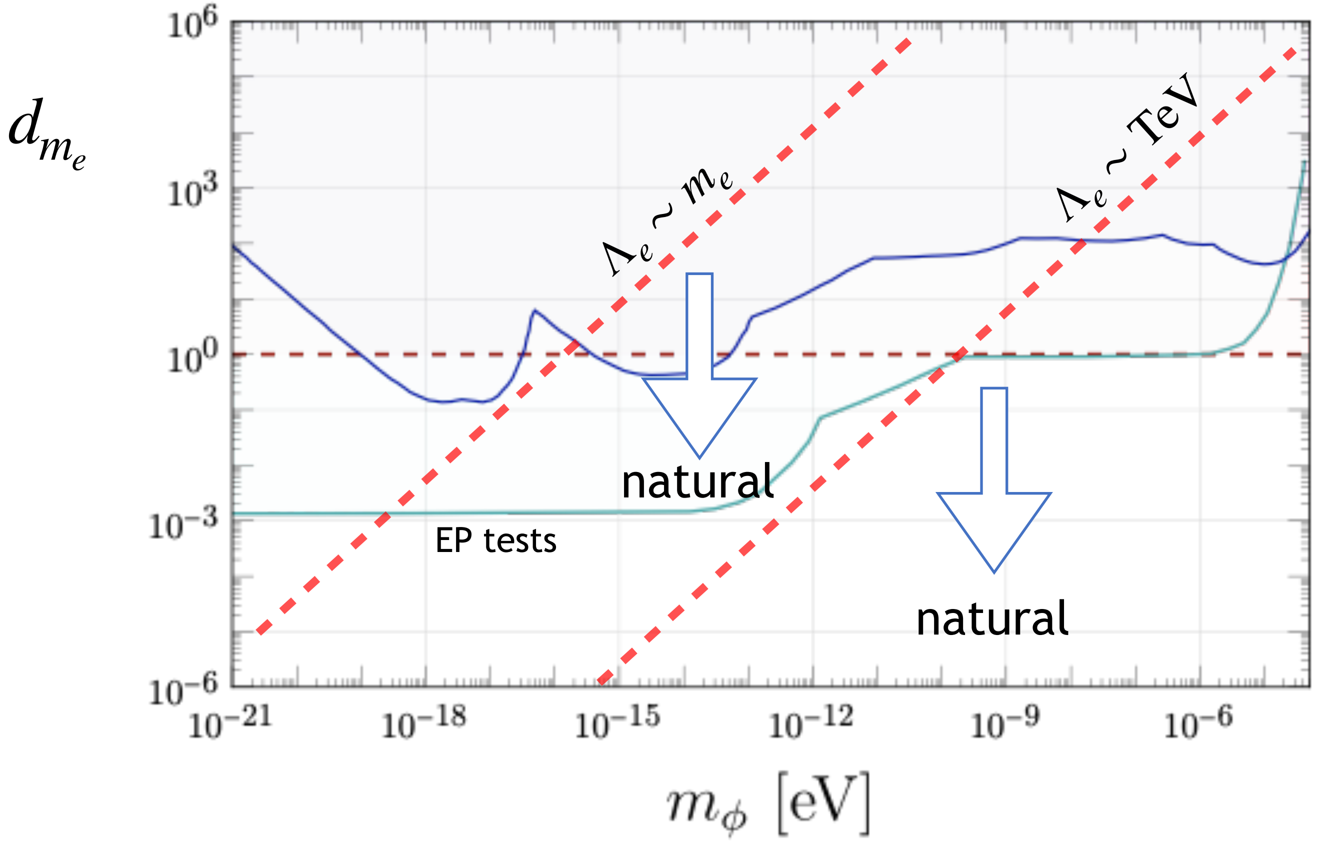
FIG. 2: Projections onto Δt for $B^0 \to \eta' K^0_S$ data (points with errors), the fit function (solid line), and background function (dashed line), for (a) B^0 and (b) $\overline{B}^0$ tagged events, and (c) the asymmetry between B^0 and $\overline{B}^0$ tags.

Naturalness problem ULDM scalars

- For this action there's also an issue of naturalness: $d_{m_e} < 4\pi m_\phi/\Lambda_e \times M_{\rm Pl}/m_e$

With $\Lambda_e \gtrsim m_e$ (for mirror model) => $d_{m_e} \lesssim 10^{6,0} \times \dfrac{m_\phi}{10^{-10}\,\mathrm{eV}} \times \dfrac{m_e, \mathrm{TeV}}{\Lambda_e}$

$\mathscr{L}_{\rm Pl} \in d_{m_e}\dfrac{\phi}{M_{\rm Pl}} m_e \bar{e} e + d_g \dfrac{\phi}{2g M_{\rm Pl}} \beta_g G G$



However it's not easy to probe the UDM coupling to hadrons \w clocks

- The energy levels are proportional to $E_{\rm Ryd} \sim m_{\rm reduced}\,\alpha^2/2n^2$
- \w $m_{\rm reduced} \simeq m_e(1 + m_e/m_{\rm nuc})$ effect decouple like number of nucleons A^{-1})-;
- (Molecular) vibrational modes are a bit better, $E_{\rm vib} \propto \sqrt{\frac{m_e}{m_{\rm nuc}}} \propto A^{-\frac{1}{2}}$

Oswald, Nevsky, Vogt, Schiller, Figuerora, Zhang, Tretiak, Antypas, Budker, Banerjee & GP (21)

So what else can be done ? (while waiting for the nuclear clock to be built)

Oscillating charge radius

Banerjee, Budker, Filzinger, Huntemann, Paz, GP Porsev & Safronova (23)

- Finite nucleus size (charge radius): $\Delta E_{\text{radius}} \propto \langle r^2_{\text{nuc}} \rangle \propto A^{\frac{2}{3}}$

- We propose to use optical atomic clock in an heavy atom to search for the QCD axion DM and/or scalar DM-nucleon interaction using the Charge radius effect:

The total electronic energy of an atomic state

$$E_{\text{tot}} = E_0 + E_{\text{MS}} + E_{\text{FS}}$$

dominant effect | Reduced mass effect | finite nucleus size (charge radius)

For heavy atoms

$$\left.\frac{\Delta E_{\text{tot}}}{E_{\text{tot}}}\right|_{\text{nuc}} \simeq \frac{E_{\text{FS}}}{E_{\text{tot}}} \frac{\Delta \langle r_N^2 \rangle}{\langle r_N^2 \rangle}$$

$$E_{\text{FS}} = K_{\text{FS}} \langle r_N^2 \rangle$$

The scaling and observable

Banerjee, Budker, Filzinger, Huntemann, Paz, GP, Porsev & Safronova (23)

- To understand why it works consider Hydrogen like *ns* energy level:

$$\Delta E_{\mathrm{MS},n} = \frac{m_e^2 \alpha^2}{2\, m_{\mathrm{nuc}}\, n^2} \simeq \frac{1}{2\, A\, m_N\, a_0^2\, n^2} \qquad [a_0 = (m_e \alpha)^{-1}]$$

$$(\Delta E)_{\mathrm{FS},\, n} = \frac{2\pi}{3} \left|\psi_s(0)\right|^2 Z\alpha \left\langle r_N^2 \right\rangle = \frac{2\pi}{3\, n^3} \frac{Z^2 \alpha}{a_0^3} \left\langle r_N^2 \right\rangle$$

$\Rightarrow$ Field shift dominates over Mass shift for $A \gtrsim 50\, n^{\frac{3}{11}}$

- Experimental comparison between two optical clock transition:

$$\frac{\Delta(\nu_a/\nu_b)}{(\nu_a/\nu_b)} = \frac{\Delta \nu_a}{\nu_a} - \frac{\Delta \nu_b}{\nu_b} = \left(\frac{K_{\mathrm{FS}}^{\nu_a} \left\langle r_N^2 \right\rangle}{\nu_a} - \frac{K_{\mathrm{FS}}^{\nu_b} \left\langle r_N^2 \right\rangle}{\nu_b} \right) \frac{\Delta \left\langle r_N^2 \right\rangle}{\left\langle r_N^2 \right\rangle}$$

Suppression factor $\sim 10^{-3}$ (Instead of 10^{-5})

Now we need to estimate dependence of the charge radius on the DM

- We can write it as follows:

$$\frac{\Delta \left\langle r_N^2 \right\rangle}{\left\langle r_N^2 \right\rangle} \approx \alpha \frac{\Delta \Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} + \beta \frac{\Delta m_\pi^2}{m_\pi^2}$$

scalar part

axion part

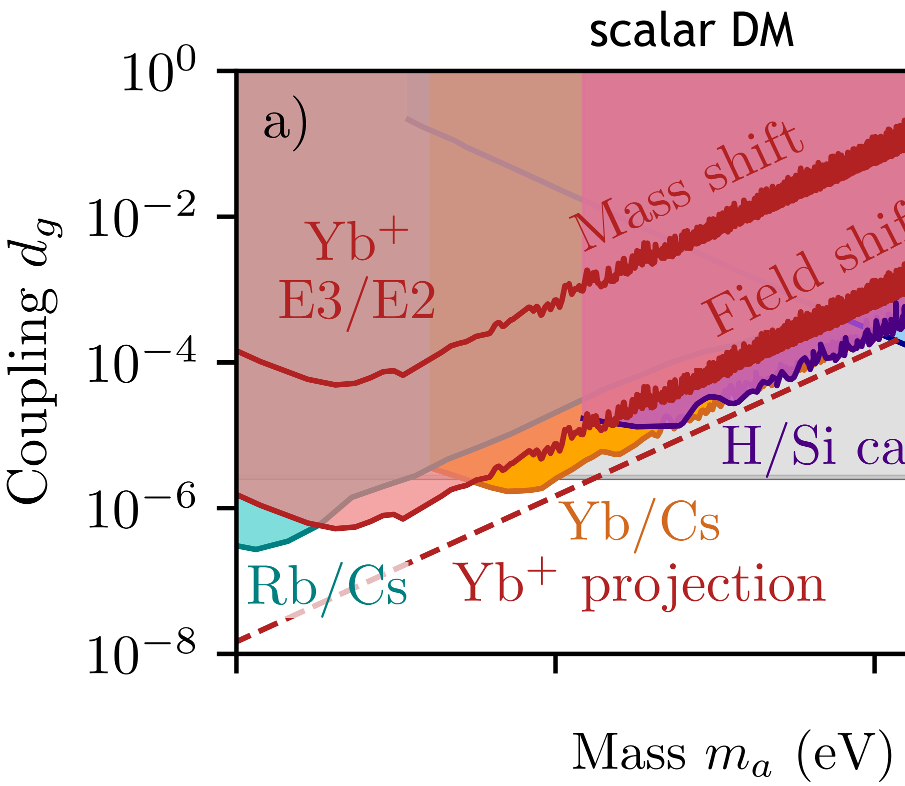
- It is easy to conclude that $\alpha = 2$

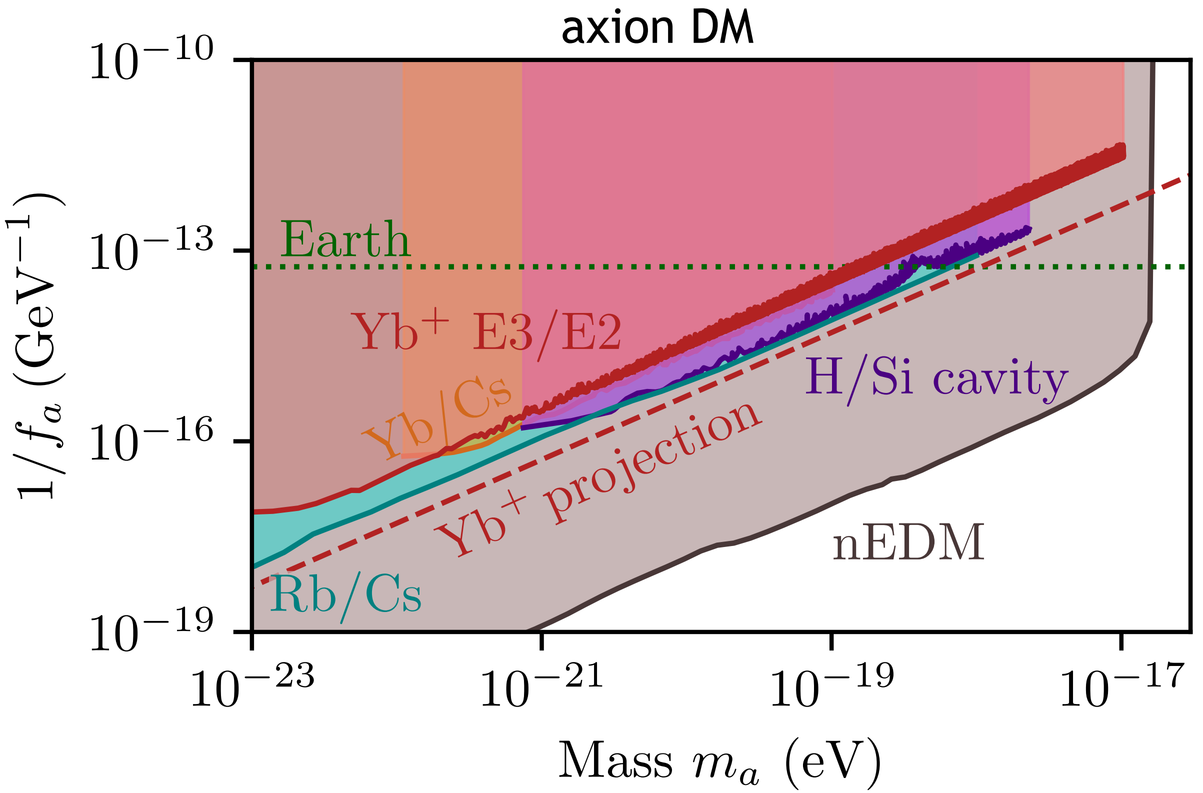
- For β we have used 2 extreme naive models of the nuclear (puffy and stiff) resulting with

$\beta \sim 2, 0.02, 0.003$, in the plot you see we went for the middle choice

The bounds

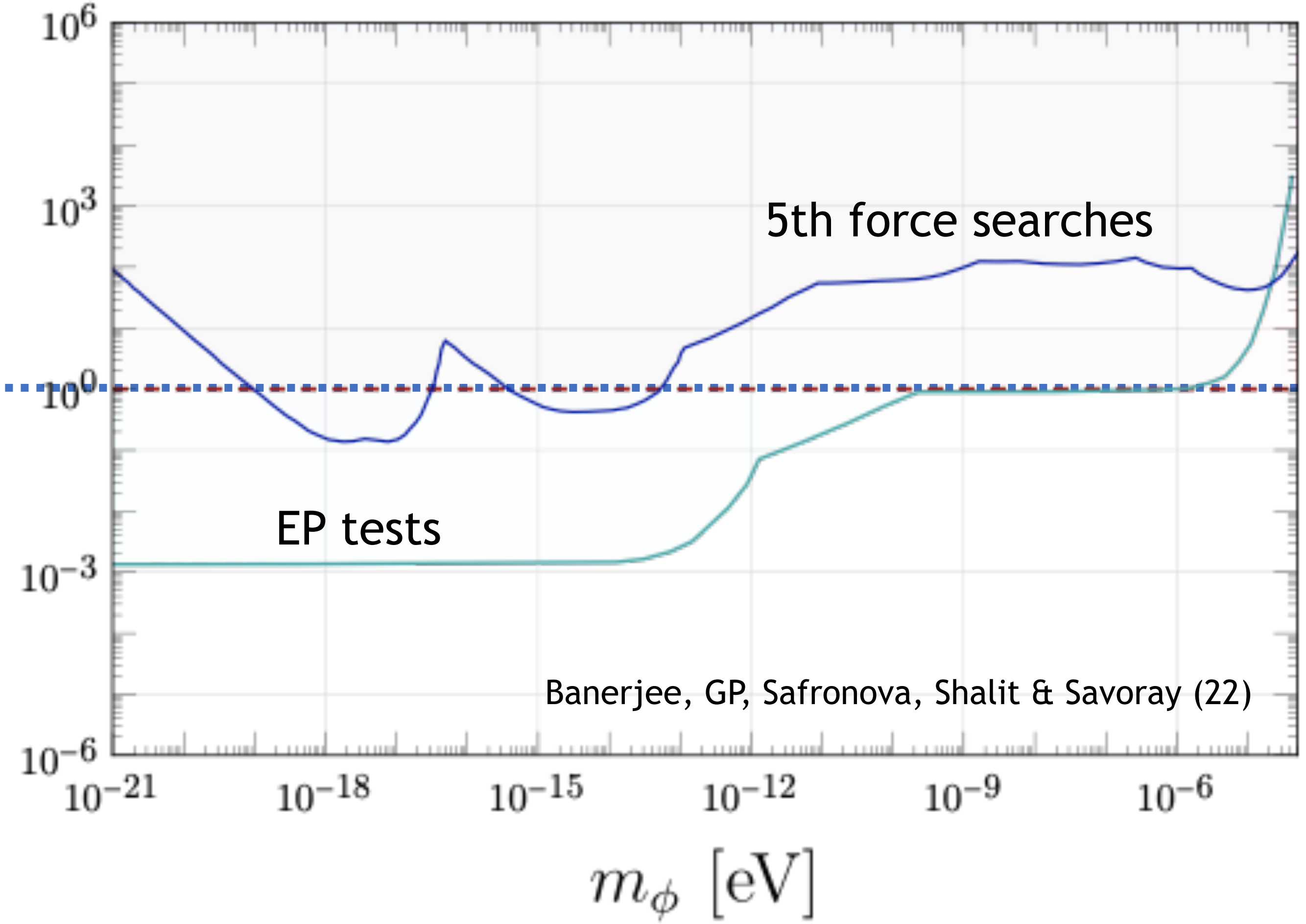
Banerjee, Budker, Filzinger, Huntemann, Paz, GP, Porsev & Safronova (23)





Quality problem, 5th force vs EP violation, electron coupling

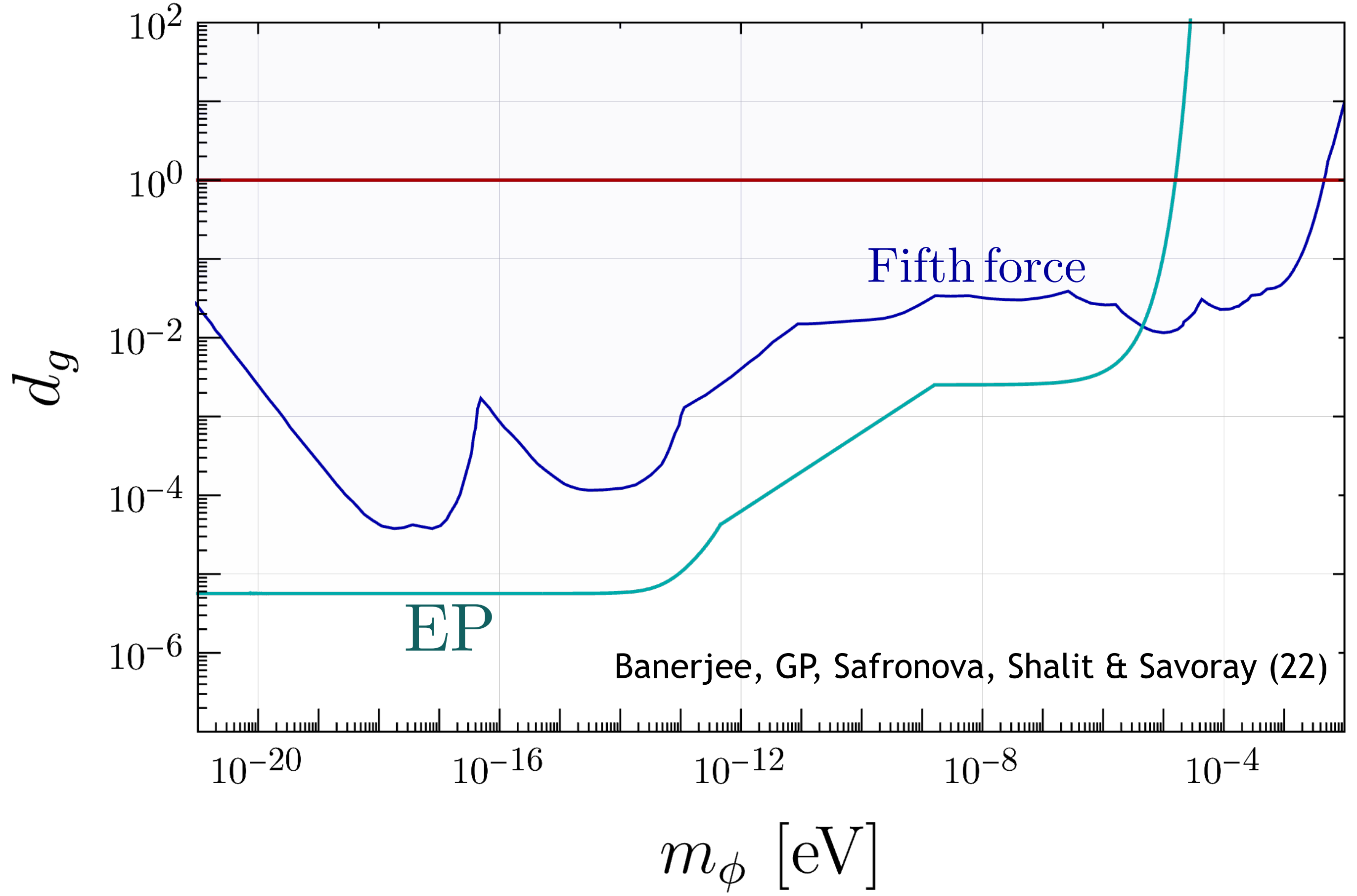
$$d_{m_e} \sim 1 \text{ or } g_e \sim \frac{m_e}{M_{\rm Pl}}$$



EP: Planck suppressed operators are excluded for $m_\phi \lesssim 10^{-6}\,\mathrm{eV}$

5th force: ***operators are excluded for*** $10^{-19} \lesssim m_\phi \lesssim 10^{-13}\,\mathrm{eV}$

Quality problem, 5th force vs EP violation, gluon



EP: Planck suppressed operators are excluded for $m_\phi \lesssim 10^{-5}\,\mathrm{eV}$

5th force: ***operators are excluded for*** $m_\phi \lesssim 10^{-3}\,\mathrm{eV}$

Quality and naturalness of axions

- Example of a quality problem for the QCD axion:

$$V = \Lambda_{\rm QCD}^4 \cos(a/f + \bar{\theta}) + \frac{\Phi^n}{M_{\rm Pl}^n} \overbrace{(\Phi^\dagger \Phi)^2}^{\left[\Phi \equiv \left(\frac{\rho+f}{\sqrt{2}}\right) e^{\frac{ia}{f}}\right]} \quad \Rightarrow \quad \Lambda_{\rm QCD}^4 \sin\delta\theta \sim \overbrace{\epsilon^N f^4}^{\left[\epsilon \equiv \frac{f}{M_{\rm Pl}}\right]} \quad \Rightarrow_{f \to 10^{10}\,{\rm GeV}} \quad \left(\frac{\Lambda_{\rm QCD}}{10^{10}\,{\rm GeV}}\right)^4 10^{-10} \sim \left(\frac{10^{10}\,{\rm GeV}}{M_{\rm Pl}}\right)^n$$

where with $n < 7$ operators, $\delta\theta > 10^{-10}$ and the strong CP problem is not solve!

This may be solved if one impose a (gauged) discrete symmetry, respected by gravity

- Even more general axion-like-particles are not immune:

$$\frac{\Phi^n}{M_{\rm Pl}^n}(\Phi^\dagger \Phi)^2 \quad \Rightarrow \quad \delta m_{\rm ALP} \sim \epsilon^{\frac{n}{2}} f \sim 10^{-4n} \times \left(\frac{f}{10^{10}\,{\rm GeV}}\right)^{\frac{n}{2}} \times 10^{10}\,{\rm GeV} =_{f=10^{10}\,{\rm GeV}} 10^{19-4n}\,{\rm eV}$$

natural eV ULDM requires n>4 operators

Still reasonable motivation to search for UDM Furthermore, specific models typically yield larger couplings to the SM in particular to its QCD sector

- QCD axion: $\frac{a}{f} G\tilde{G}$
- Dilaton: $d_g \frac{\phi}{2gM_{\rm Pl}} \beta_g GG$
- Higgs portal: $\sin\theta_{h\phi}\, g_{hGG}\, GG$
- I'll argue that, generically, all ALPs

$\Longleftrightarrow$

Claim: all of these couplings can be probed using oscillation of energy levels in quantum sensors, such as clocks