The relaxion & its log crisis opportunities across frontiers

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New Physics on the Low-Energy Precision Frontier

Outline

- Intro: the (relaxion) log crisis/opportunity.
- Briefly: why collider might be important ? why accelerators are important ?
- The precision front:

  ultra light scalar dark matter (DM), halo => slow & fast oscillating VEVs;

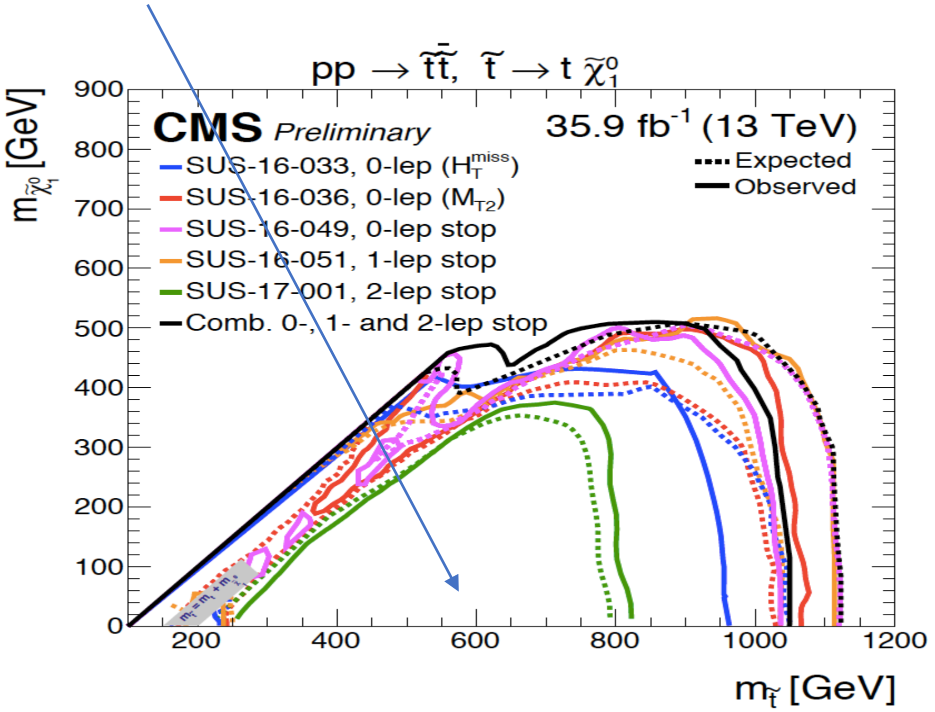
  ultra light pseudo scalar DM (halo)
- Conclusions.

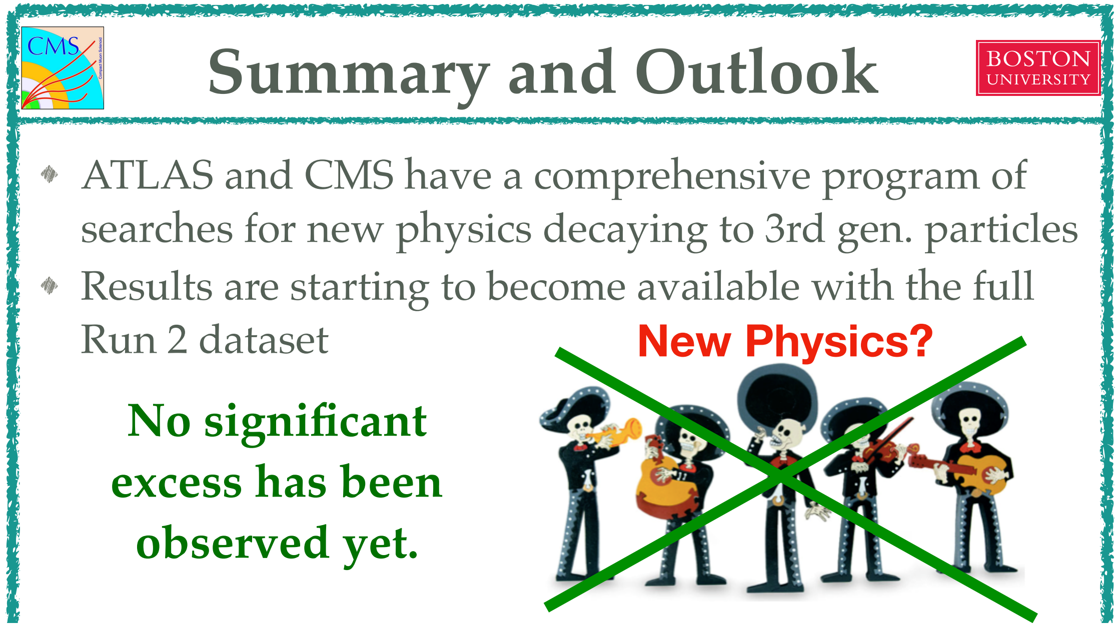
Higgs & new physics

- For > 40 yrs Higgs served us as anchor to determine the new phys. (NP) scale.

  Sym' based solution to Naturalness <=> TeV NP

- NP searches according to leading paradigm, driven by E-frontier on linear scale:





LHCP19: Suarez on behalf of the ATLAS & CMS

Higgs @ 21st century => crisis & opportunity

- New ideas & null LHC results cast tiny doubt on this paradigm.

  eg: “Cosmic attractors”, “dynamical relaxation”, “N-naturalness”, “relating the weak-scale to the CC” & “inflating the Weak scale”.

- Are they all anthropic solution for the weak scale ? Is it satisfying for the weak scale?

  Giudice, Kehagias & Riotto; Kaloper & Westphal; Dvali (19);
  Agrawal, Barr, Donoghue & Seckel (98) Harnik, Kribs & GP (06);
  Gedalia, Jenkins & GP (11)

Higgs @ 21st century => crisis & opportunity

- New ideas & null LHC results cast tiny doubt on this paradigm.

  eg: "Cosmic attractors", "dynamical relaxation", "N-naturalness", "relating the weak-scale to the CC" & "inflating the Weak scale".

- New scalar common to several of above: concretely let us consider the relaxion:

  Graham, Kaplan & Rajendran (15)

  under some assumption allows for a concrete QFT realisation.

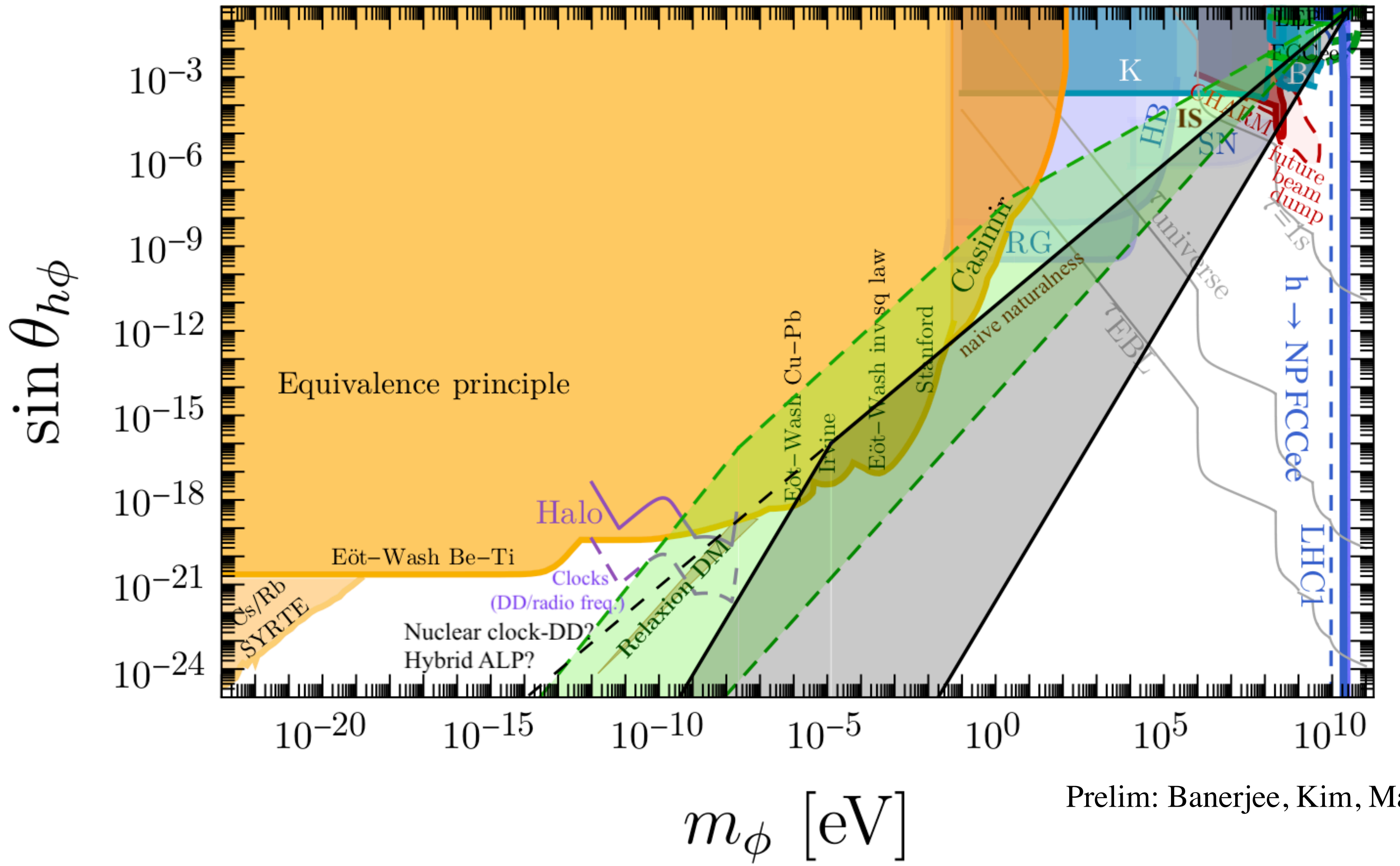
- Bottomline here: relaxion is ALP-DM that (due to CP violation) can be described as scalar mixes \w the Higgs (Kim's talk).

  Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)
  Banerjee, Kim & GP (18)

- However, searching the relaxion => *log crisis* as follows:

The relaxion (Higgs portal) parameter space & the *log crisis*

Overview plot: the relaxion 30-decade-open parameter space



Prelim: Banerjee, Kim, Matsedonski, GP, Safranova

Relaxion @ colliders & accelerators?

- They cover only small part of the parameter space.
- They nevertheless can potentially cover the whole relevant range.

The relaxion parameter space

- As effective relaxion models can be described as a Higgs portal:

$$L_S \in m_S^2 SS + \mu S H^\dagger H + \lambda S^2 H^\dagger H \,, \quad \text{with } S = \text{light scalar \& } H = \text{SM Higgs} \,.$$

Naive naturalness implies: $\sin\theta \simeq \mu/\langle H\rangle \lesssim \dfrac{m_S}{\langle H\rangle}$ & $\lambda \lesssim \dfrac{m_S^2}{\langle H\rangle^2}$.

- However, as show in yesterday talk by H. Kim the “relaxed”-relaxion parameter space, goes well above the natural mixing region!

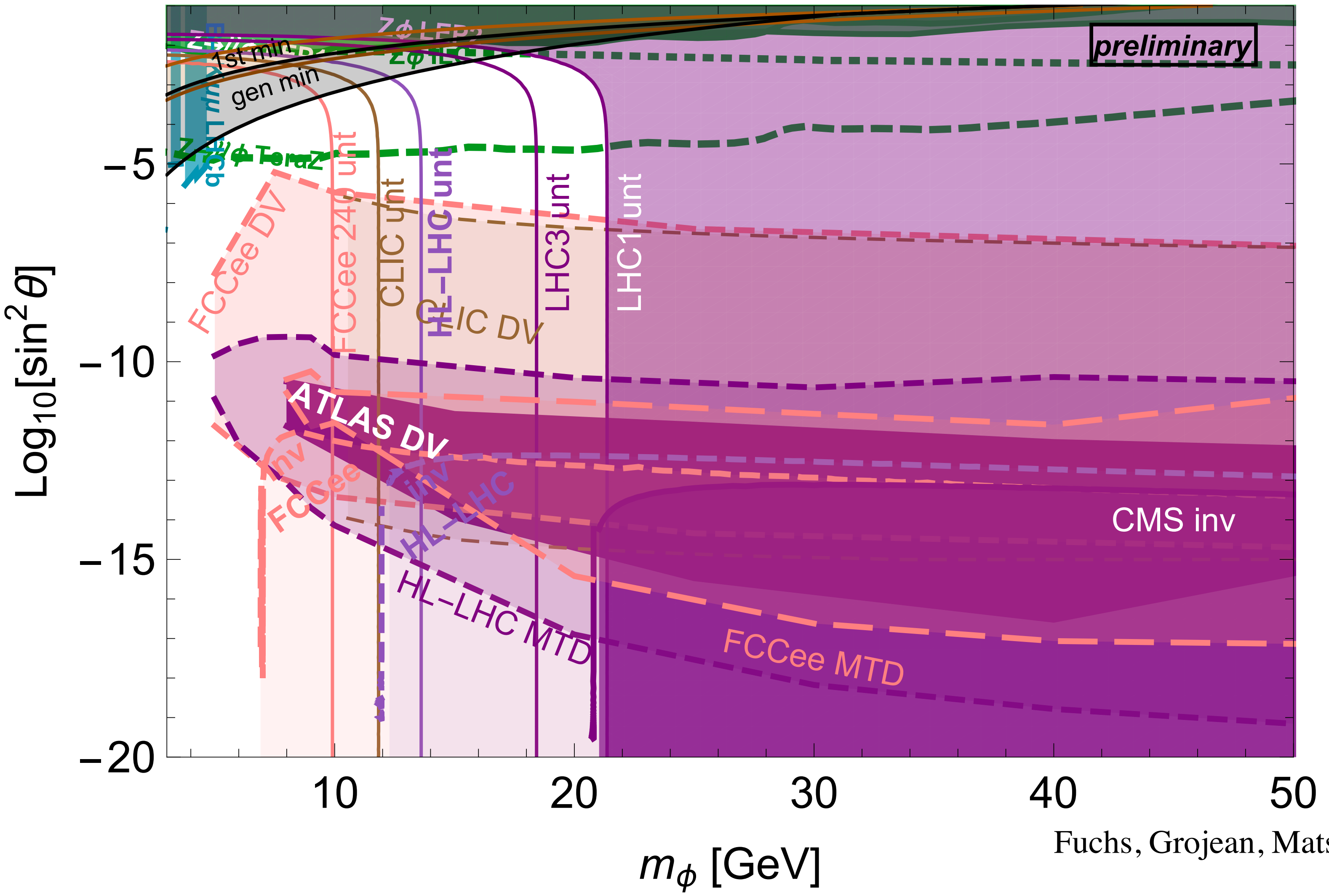
- As you see in following plot it is very hard to probe the natural region:

2 differences from generic Higgs portal

(i) Lower + upper bound on mixing angle (implications of compact parameter manyfold)

(ii) Parity-odd-ALP

Overview: collider probes of relaxion

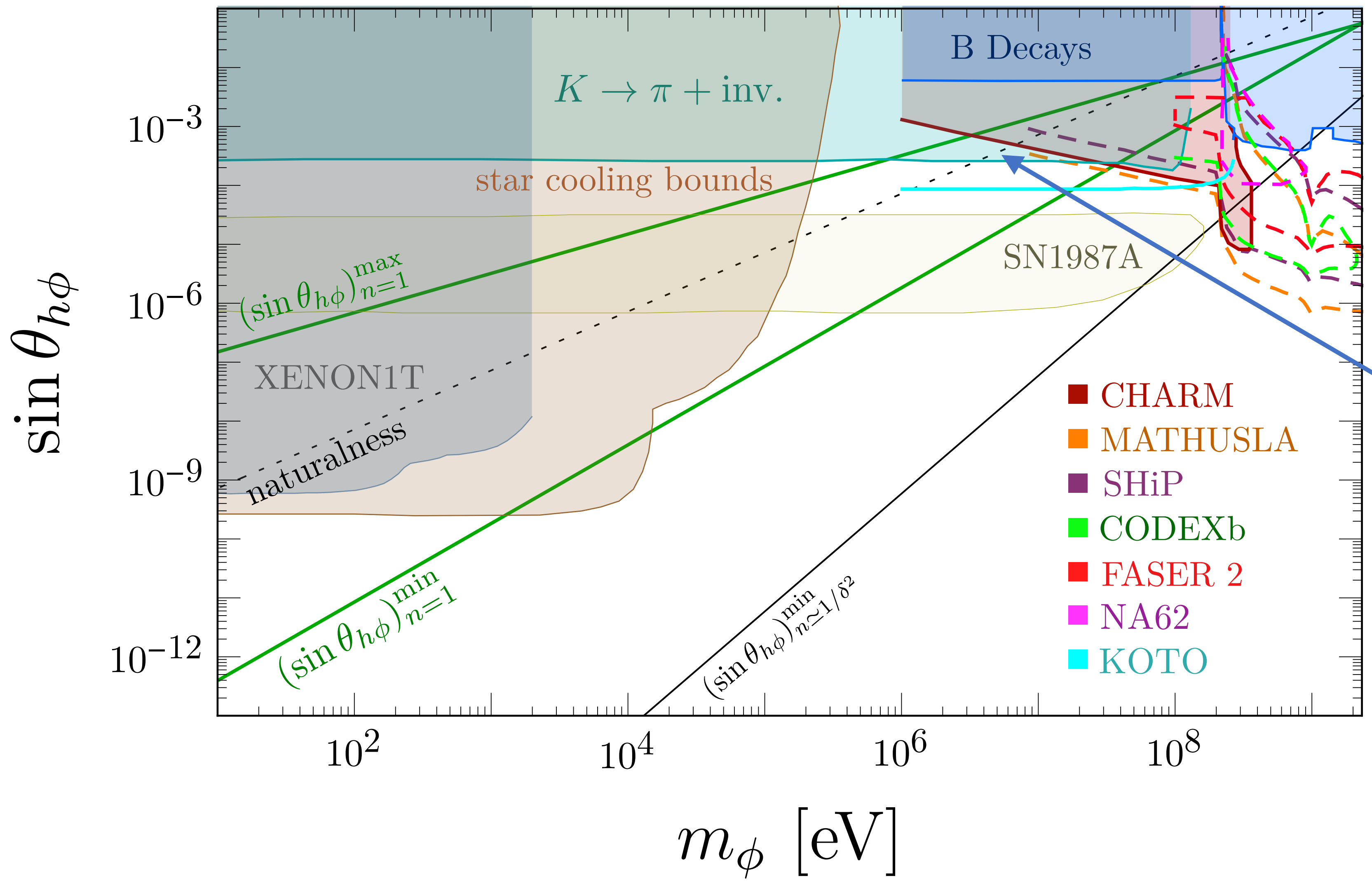


Fuchs, Grojean, Matsedonski, GP, Savoray, Schlaffer;

Frugiuele, Fuchs, GP & Schlaffer (18)

Overview: accelerator probes of relaxion

Prelim: Banerjee, Kim, Matsedonski, GP, Safranova

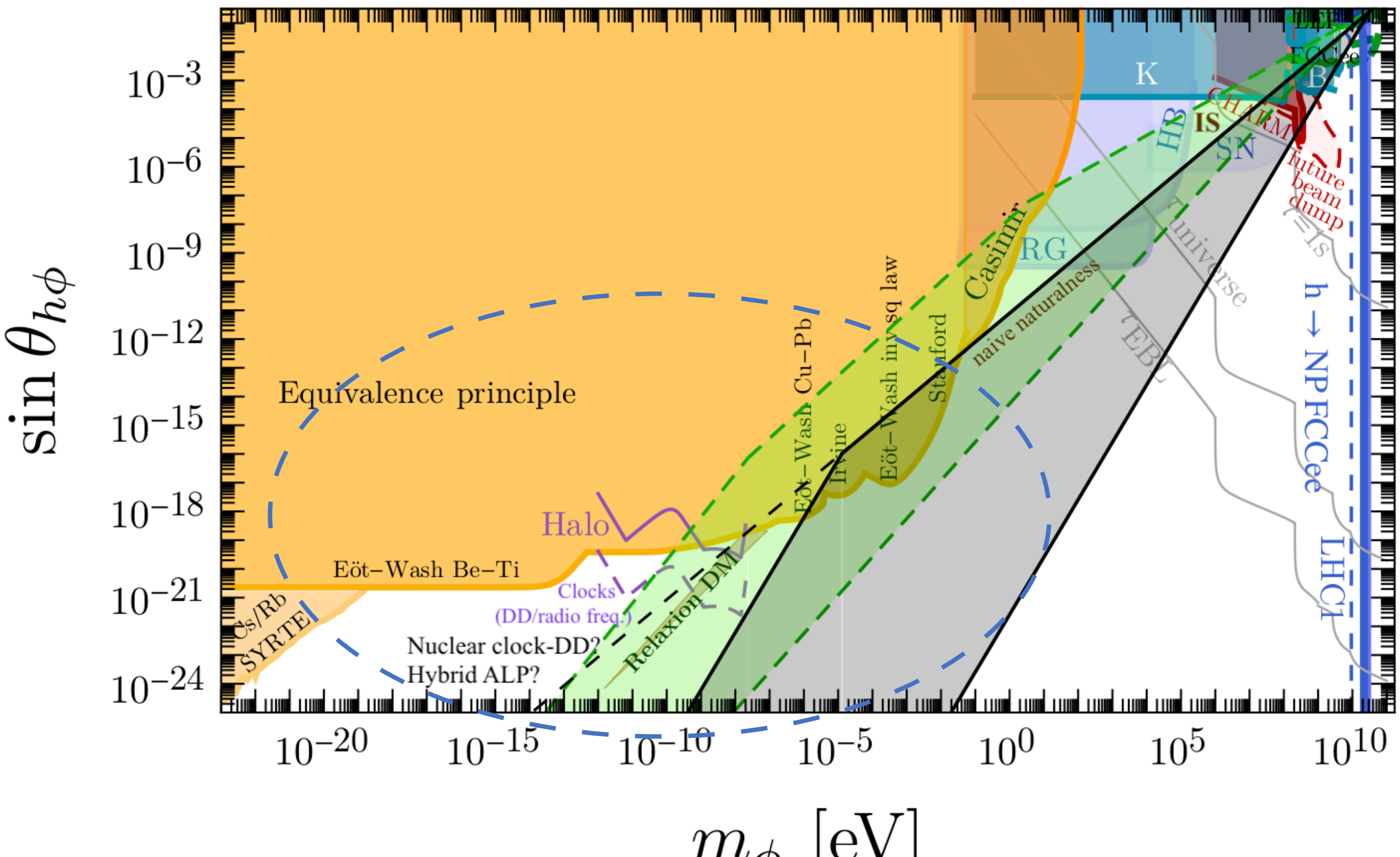


KOTO anomaly

Kitahara, Okui, GP, Soreq & Tobioka (19)

The log-crisis => precision front plays critical role

Prelim: Banerjee, Kim, Matsedonski, GP, Safranova



Hunting for ultra light relaxion DM - roadmap

- Scalar effects:

[(i) 5th force/equivalence principles;]
(ii) DM, slow oscillations - clock-clock comparison;
(iii) DM, rapid oscillation - clock-clock & clock-cavity & cavity-cavity (?!) comparisons;
(iv) DM properties (local density vs halo).

- Pseudo scalar, axial effect:

[(i)long range axion coupling;]
(ii) correlated axion DM signals;
(iii) DM property (local density vs halo)

Scalar DM & oscillating of constants

- Generically, time-varying scalar => variations of fundamental constants.

Damour & Polyakov (94); Barrow, (99)

- Scalar (dilaton) DM could induce an oscillation of fundamental constants.

Arvanitaki, Huang & Van Tilburg (15)

- We can use local quantum field theory (QFT) description to avoid confusions <=> scalar background is the only object that oscillates.

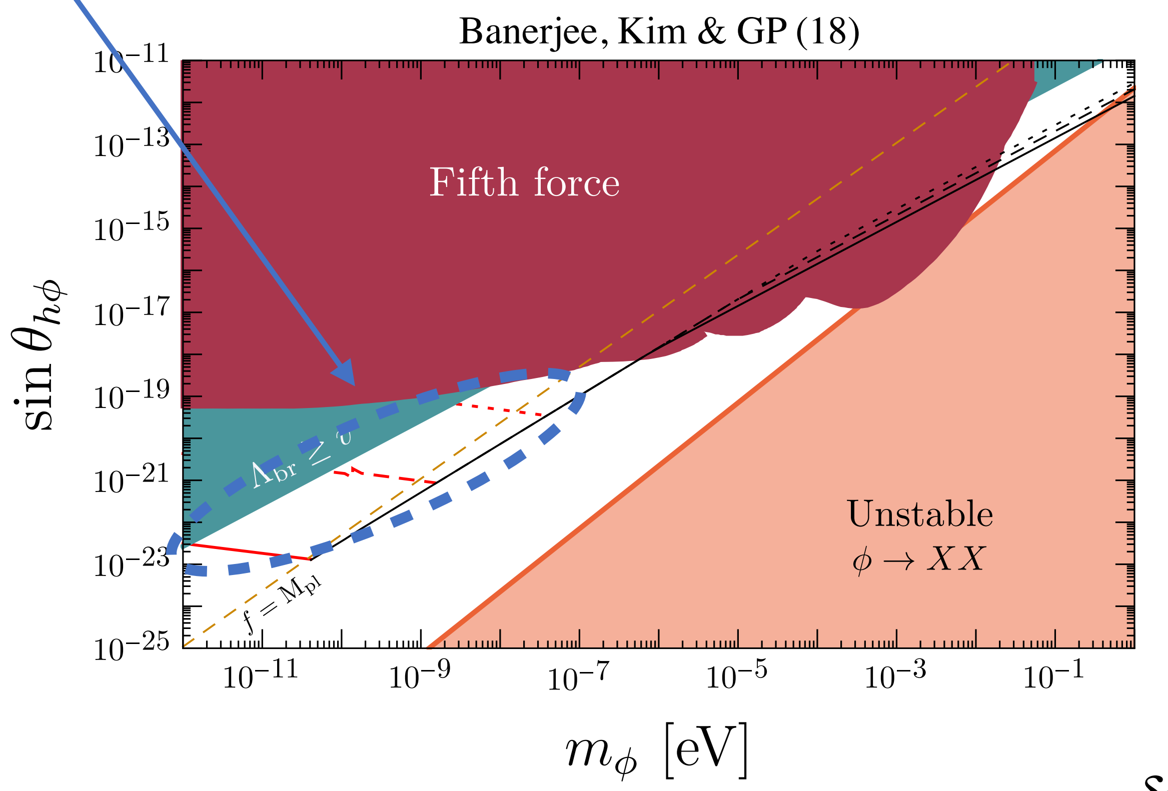
Antypas, Budker, Flambaum, Kozlov, GP & Ye (19)

- Here we only focus on leading order, linear, with respects to scalar DM, as the scalar has quantum number can be "glued" to any SM operator:

$$\mathscr{L}_\phi \in \frac{\phi}{v}\left[-\bar{m}_f \bar{f} f + \frac{c_\gamma}{4\pi} FF + \frac{c_g}{4\pi} GG\right] + \ldots$$

Relaxion/Higgs-portal & benchmarking

- The relaxion DM provides us with a concrete & simple realisation of the idea (via dynamical misalignment, see yesterday's talk), via it is Higgs mixing:

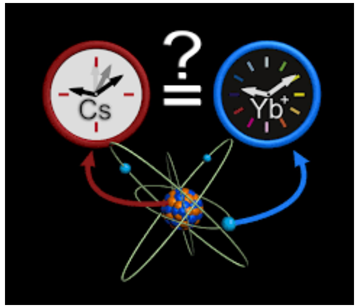


$$\mathcal{L} \supset \sin\theta_{h\phi}\frac{\phi}{v}\left[-m_f\bar{f}f + \frac{c_\gamma}{4\pi}FF + \frac{c_g}{4\pi}GG\right];$$

for instance: $$\frac{\delta m_e}{m_e} \lesssim y_e \sin_{\phi h}\frac{\sqrt{\rho_{\rm DM}}}{m_e m_\phi}\sin\left(m_\phi t\right)$$

Hunting oscillating DM, strategy & scales

- How to search for the time variation?
- General: find 2 systems \w different dependence of scalar background.
- Classical ex.: clock comparisons: $\delta E_{1,2} \equiv \nu_{1,2} = f_{1,2}(\alpha^{\xi_\alpha^{1,2}}, \alpha_s^{\xi_{\alpha_s}^{1,2}}, m_e^{\xi_{m_e}^{1,2}}, m_q^{\xi_{m_q}^{1,2}})$



PTB (14)

Fractional change of the frequency ratio: $\frac{\Delta\left(f_A/f_B\right)}{f_A/f_B}$

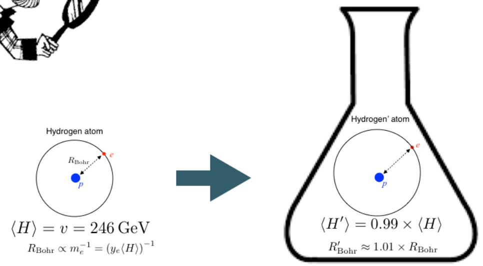
[see Safronova,Budker, DeMille, Kimball, Derevianko & Clark (18) for recent review]

$$R_\infty \propto \alpha^2 \left(m_e + O(m_e/m_A)\right) \,, R_{\rm Bohr}^{-1} \propto \alpha(m_e + \ldots)\,, \ldots$$

Relaxion oscillating DM, scales

- Relaxion-Higgs mixing => Higgs VEV oscillation:

$$\mathcal{L} \supset \sin\theta_{h\phi}\frac{\phi}{v}\left[-m_f\bar{f}f + \frac{c_\gamma}{4\pi}FF + \frac{c_g}{4\pi}GG\right]$$



Blog, Nat. Ast., Eby (20)

Banerjee, Budker, Eby, Kim & GP (19)

- Problem with several scales: (for instance we use below)

DM oscillating time: $\tau_{\rm DM} \sim 1{\rm s} \times \frac{10^{-15}{\rm eV}}{m_{\rm DM}}$

DM coherent time: $\tau_{\rm DM}^{\rm co} \sim 10^6{\rm s} \times \frac{10^{-15}{\rm eV}}{m_{\rm DM}} \times \frac{10^6}{\beta^2}$

Exp. ave stability time: $\tau_{\rm sta} \sim 1{\rm s}; T \sim 10^6$ s - total integration time

Exp. cycle time: $\tau_{\rm cyc} \sim 10^{-3}{\rm s}$

Slow oscillation, long DM coherence, clock comparisons

- Let us assume for simplicity that $\tau_{\rm DM}^{\rm co}$ is the longer scale in problem.

- The sensitivity will be give by:

$$\mathrm{SNR} = \frac{\Delta(f_A/f_B)/(f_A/f_B)}{\sigma_y(\tau_{\rm sta})} \times \sqrt{T} \qquad \left(\sigma_y(\tau) = 10^{-15}/\sqrt{\tau\,\mathrm{Hz}}\right)$$

- As the signal goes like $\phi \sim 1/m_\phi$, we find that $\sin\theta_{h\phi}^{\rm bound} \propto 1/m_\phi$.

Arvanitaki, Huang & Van Tilburg (15)

Rapid oscillation vs. cycle time

- If $\tau_{\rm cyc} < \tau_{\rm DM} < \tau_{\rm ave}$ we can't average over full ave. time, instead we optimise result by averaging of "DM-cycle" time.

  The sensitivity will be give by $\sin\theta_{h\phi}^{\rm bound} \propto 1/m_\phi^{3/2}$.

- If $\tau_{\rm DM} < \tau_{\rm cyc} < \tau_{\rm ave}$ we only get residual contribution from last oscillation.

  The sensitivity will be give by $\sin\theta_{h\phi}^{\rm bound} \propto 1/m_\phi^{2}$. Derevianko (16),

Ideal system

- The largest coupling of the relaxion is to the gluons.

- The strongest sensitivity would be via a clock where the energy levels are prop to the QCD scale => (^{229}Th) nuclear clock (there's big uncer.!):

$$\Delta\left(\frac{f_A/f_B}{f_A/f_B}\right) \simeq 10^{5-6}\frac{\Delta(m_q/\Lambda_{\rm QCD})}{(m_q/\Lambda_{\rm QCD})} \propto 10^{5-6}\sin\theta_{h\phi}$$

Flambaum (06); Berengut & Flambaum (10)

where m_q is the light quark mass, and $\Lambda_{\rm QCD}$ is the QCD scale

What about the size of the scalar DM amplitude itself ?

- The effects are linear with the scalar amplitude:

$$\mathcal{L} \supset \sin\theta_{h\phi} \frac{\phi}{v} \left[-m_f \bar{f} f + \frac{c_\gamma}{4\pi} FF + \frac{c_g}{4\pi} GG \right]$$

- This is astro stuff, there are considerable uncertainties.

- We consider 2 options:

Conventional - $\phi \sim \sqrt{\rho_{\rm DM}} / m_\phi$

Extreme - $\phi \sim \sqrt{\rho_{\rm halo}} / m_\phi$

Searching for a relaxion DM planet around us

- Massive object may trap the (rel)axion => stable solution of EOM, “gravitational hydrogen”:

Assume small DM density & large radius => mass-radii relation:

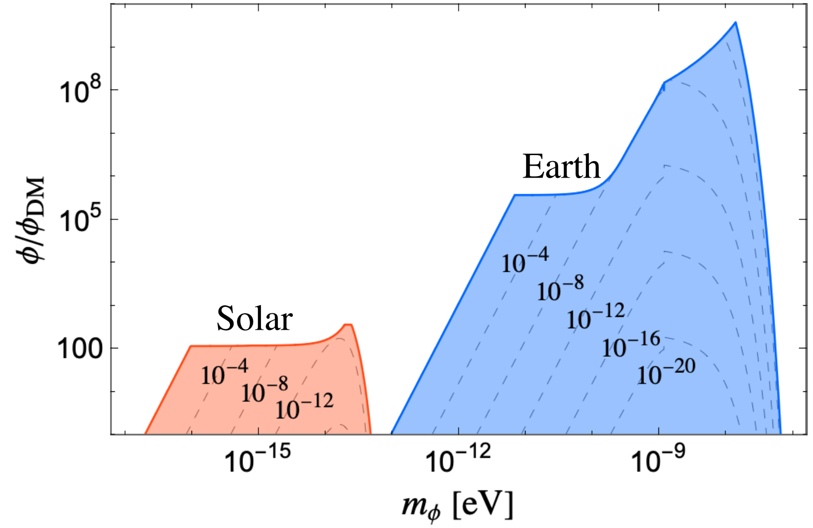
$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

Eby, Leembruggen, Street, Suranyi & Wijewardhana (18); Banerjee, Budker, Eby, Kim & GP (19)

Can obtain large density enhancement:

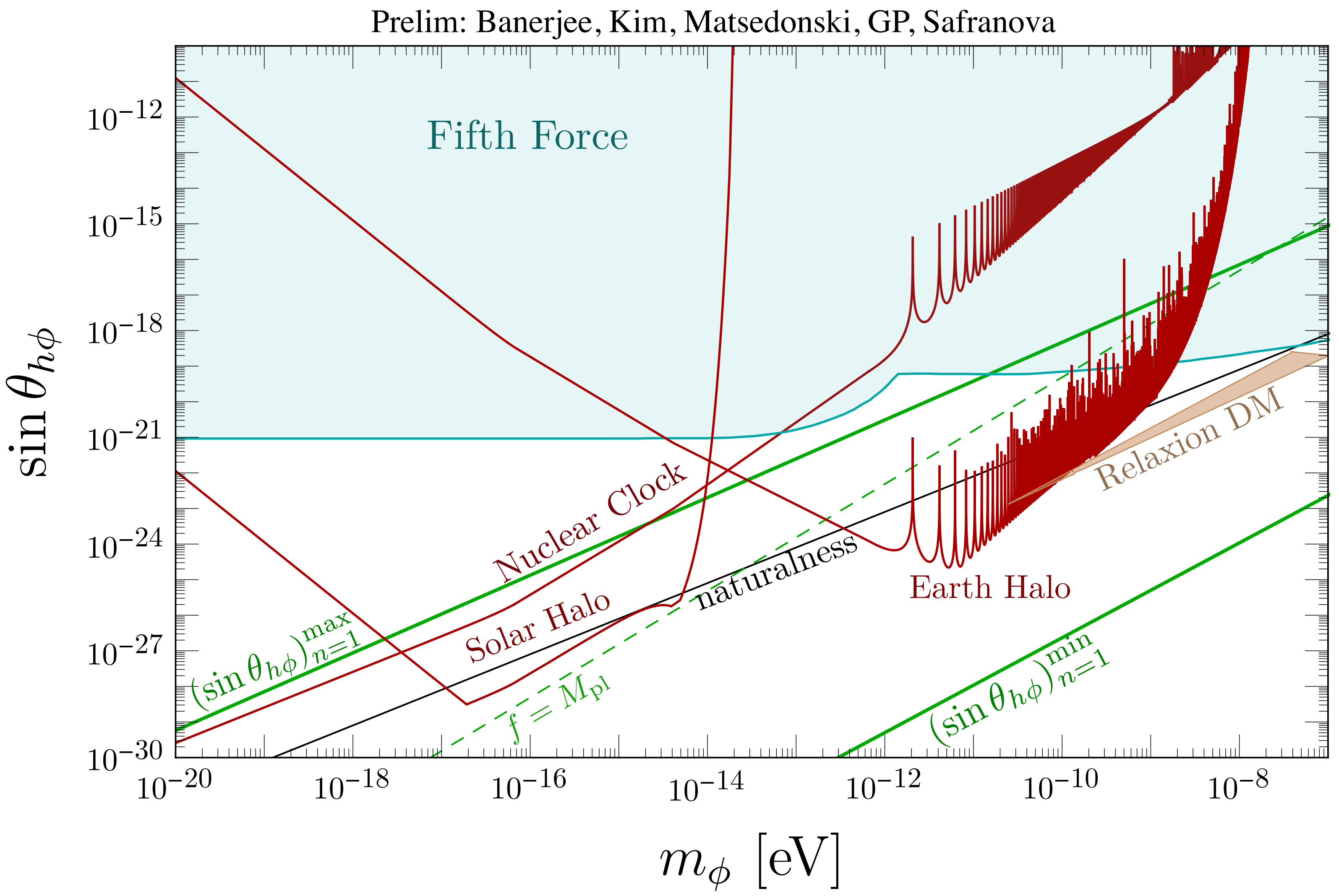
$$r \equiv \frac{\rho_{\rm star}}{\rho_{\rm loc-DM}} \sim \xi \frac{M_{\rm Earth}^4\, m_\phi^6}{M_{\rm Pl}^6\, \rho_{\rm loc-DM}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}}\right)^6$$

$$\xi \equiv M_{\rm star}/M_{\rm Earth}$$



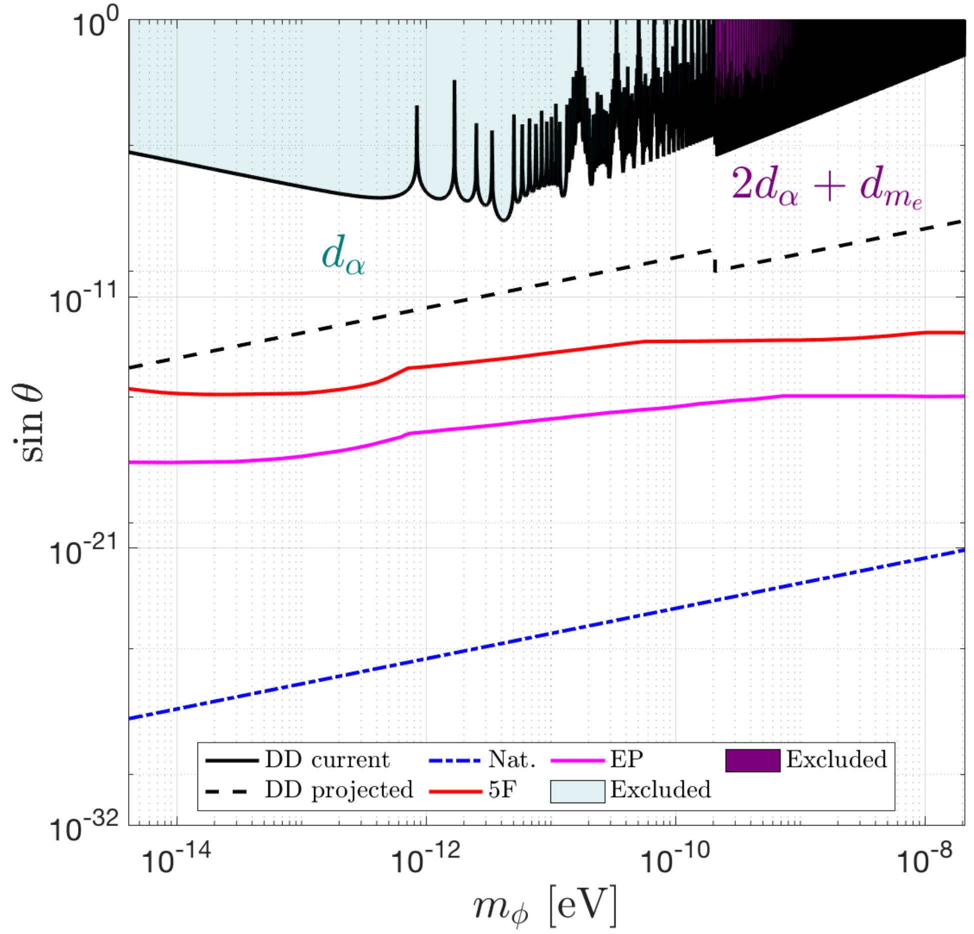
Enhancements in the axion halo scenario compared to the background DM case, in the field value for the Earth halo (blue) and solar halo (red) compared to the usual ALP DM case. Solid lines correspond to maximal halo mass M_* by gravitational constraints.

Ideal system, nuclear clock



Beyond 1Hz DM mass \w dynamical decoupling

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray (19) [via ion-cavity comparison]

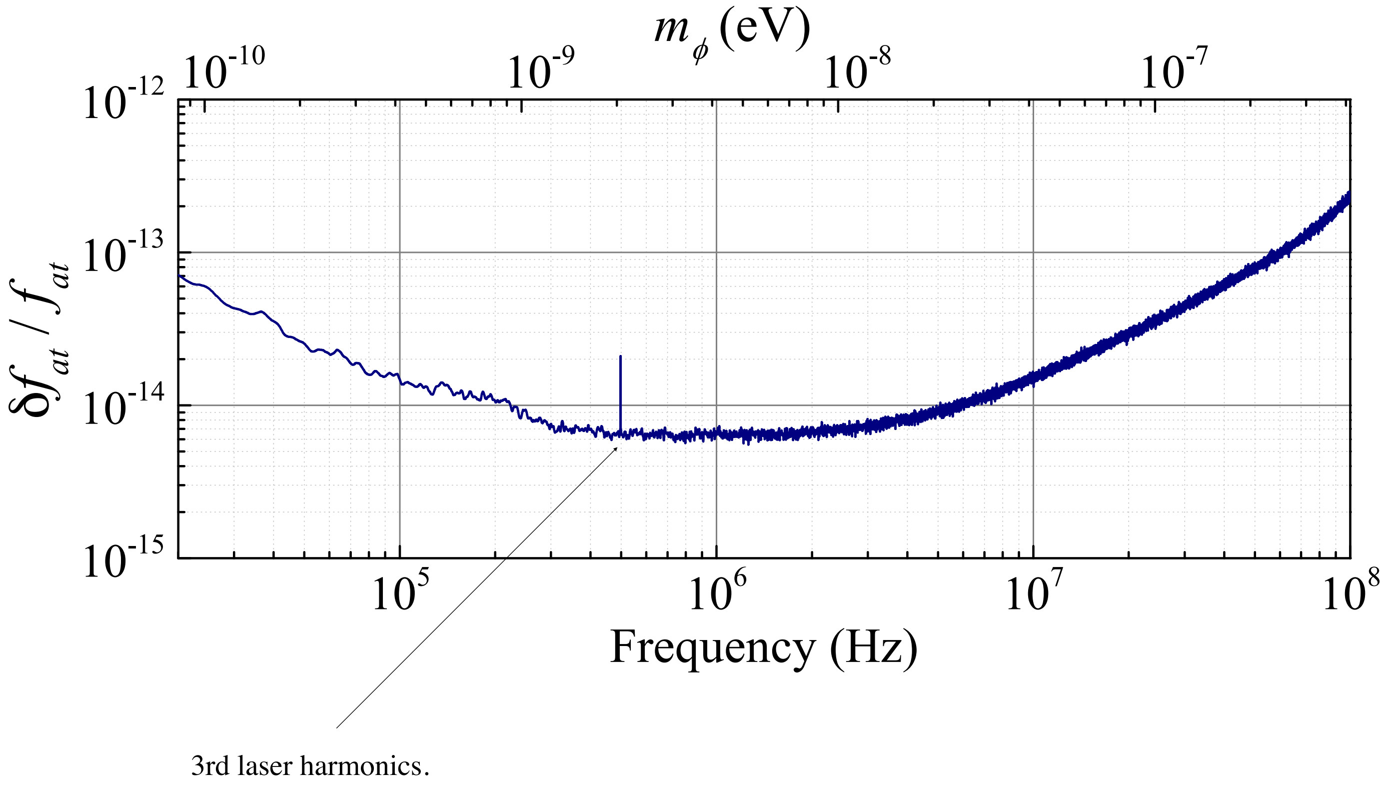


The bounds on the mixing angle of a relaxion DM: Black – current and projected bounds from DD experiments at 95% CL. Red – Bounds from fifth force experiments. Magenta – EP-tests bounds. Dash-dotted – Bounds from Naturalness.

Beyond 1Hz DM mass \w polarization spectroscopy

Antypas, Tretiak, Garcon, Ozeri, GP & Budker, (19)

Cs $6S_{1/2} \rightarrow 6P_{3/2}$ transition frequency (10 GHz)



Cavity-cavity comparisons - stay tune for Fri.

Stadnik & Flambaum (14); Grote & **Stadnik** (19) …

The (rel)axion frontier

Axial coupling searches of relaxion DM

- The relaxion being an axion-like-particle (ALP) obtain pseudo-scalar coupling to matter, that are model dependent.

  See e.g.: Graham, Kaplan & Rajendran; Gupta, Komargodski, GP & Ubaldi (15);
  Davidi, Gupta, GP, Redigolo & Shalit (17,18)

- Generically, one loop below backreaction scale we expect axial coupling to be induced.

Motivate us to search for an associated signal via “magnetometers”

Banerjee, Budker, Eby, Flambaum, Kim, Matsedonskyi & GP (19)

Axial coupling searches of relaxion DM

- One can look at signals at variety of experiments (we consider 2):

ABRACADABRA $\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} - g_{\phi\gamma\gamma}\left(\vec{E} \times \nabla\phi - \vec{B}\,\frac{\partial \phi}{\partial t}\right).$ Kahn, Safdi & Thaler (16); Ouellet et al (18) $\left(\mathcal{L} \supset -\frac{1}{4} g_{\phi\gamma\gamma}\,\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}\right)$

CASPEr(Wind) $H \simeq -[(d_a/I)\vec{I}\cdot\vec{E} + (\mu_n/I)\vec{I}\cdot\vec{B}_\phi]\cos(m_\phi t)\,.$

$$\vec{d}_a = g_{ad}\,\phi\,\vec{I}\,, \qquad \vec{B}_\phi = g_{\phi NN}\gamma_n^{-1}\nabla\phi\,.$$

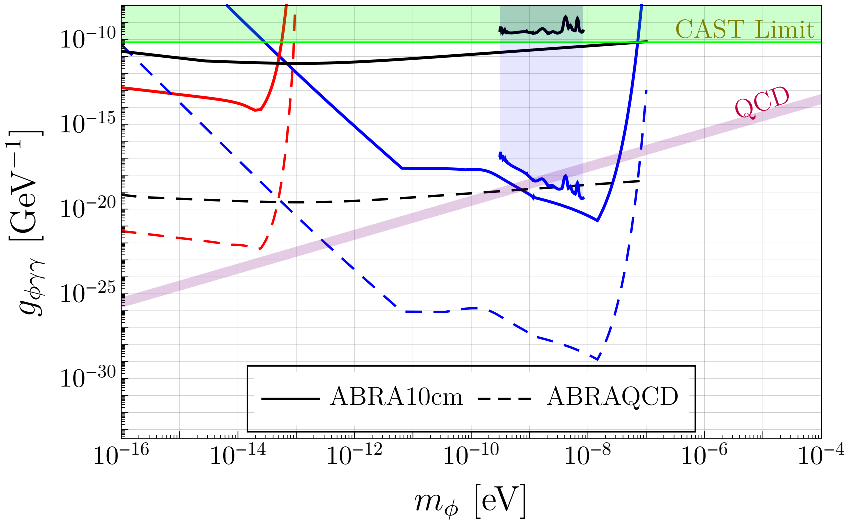
$\left(\mathcal{L} \supset g_{\phi NN}\partial_\mu\phi\bar{N}\gamma^\mu\gamma_5 N - \frac{\imath}{2} g_d\,\phi\,\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu} + ...,\right)$

Budker, Graham, Ledbetter, Rajendran & Sushkov (13); Jackson Kimball et al (2017)

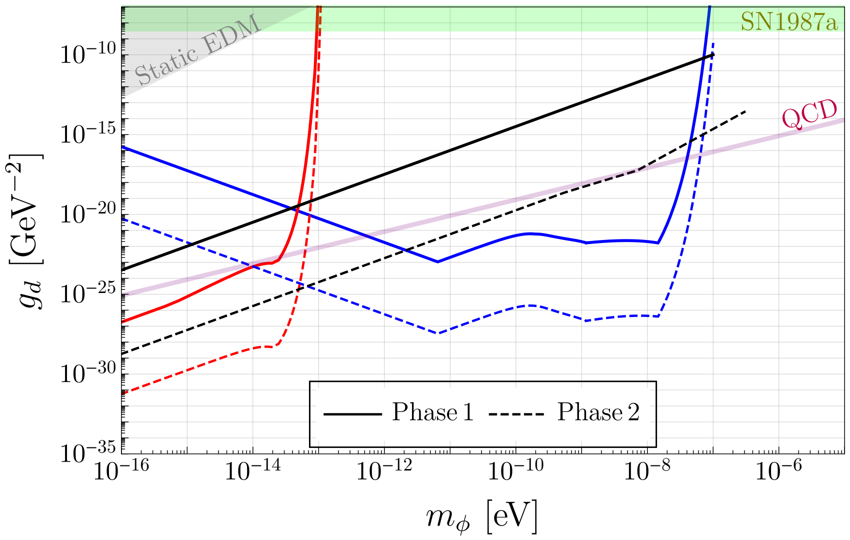
- In the case of axion-halo the “wind” is replaced by density gradient which is orientation-dependent => new type of signature.

Axial coupling searches of relaxion DM

Banerjee, Budker, Eby, Flambaum, Kim, Matsedonskyi & GP (19)



Sensitivity to $g_{\phi\gamma\gamma}$ in the ABRACADABRA experiment. Black lines: projected sen- sitivity for background axion dark matter; blue lines: sensitivity for Earth axion halo; red: sensitivity for solar axion halo. The shaded regions represent the QCD axion band (purple), the current CAST constraint (green), and the current ABRACADABRA constraint (black/blue).



Sensitivity to g_d in presence of an axion halo for CASPER-Electric; the blue (red) curves represent the Earth-based (Sun-based) halo, the black lines represent the standard back- ground DM density, and the shaded regions are current constraints from astrophysics (green) and static EDM searches (gray).

Conclusions

- Higgs physics has been always our beacon for new physics.
- Null-results + new theories (ex.: relaxion) => log crisis/opportunity, calls for experimental diversity.
- Accelerators provided a unique opportunity to search for (relaxed) relaxion.
- Ultra-light relaxion DM => Higgs VEV oscillating => exciting signals …
- Signals are correlated with axion-searches which is a unique property.