Probing the relaxed relaxion \w luminosity & precision

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Outline

- Intro, 21st century log crisis/opportunity
- Case study, relaxed-relaxion, a few lessons
- Relaxion searches \w energy, luminosity on Earth, the sun (XENON1T)
- Precision (isotope shift spectroscopy + ultra light dark matter)
- Conclusions

Intro, (potential) hints from theory

- Our current 21st century puzzle:

knowledge that new physics (NP) exists vs our safest bets (LHC, WIMP,…) that came empty

- Motivates us to look for new paradigms

- Motivates us to look for new search strategies

Intro, (potential) hints from theory

- Our current 21st century puzzle:

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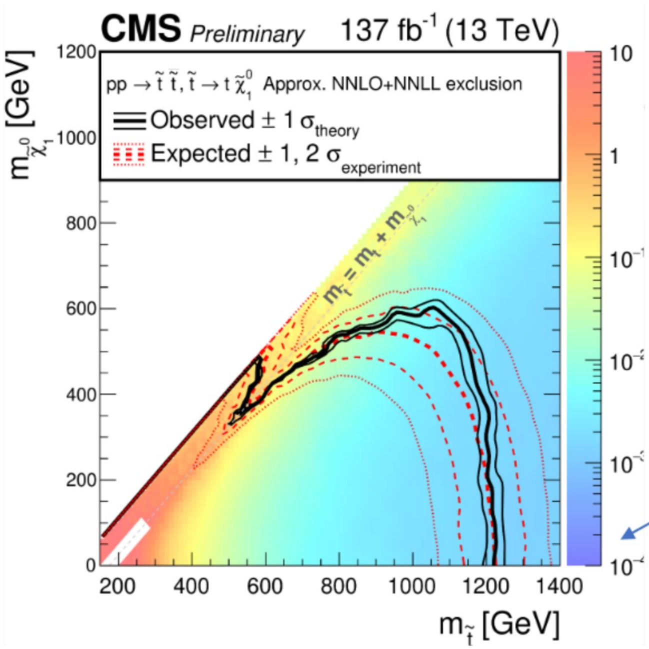
- Motivates us to look for new search strategies

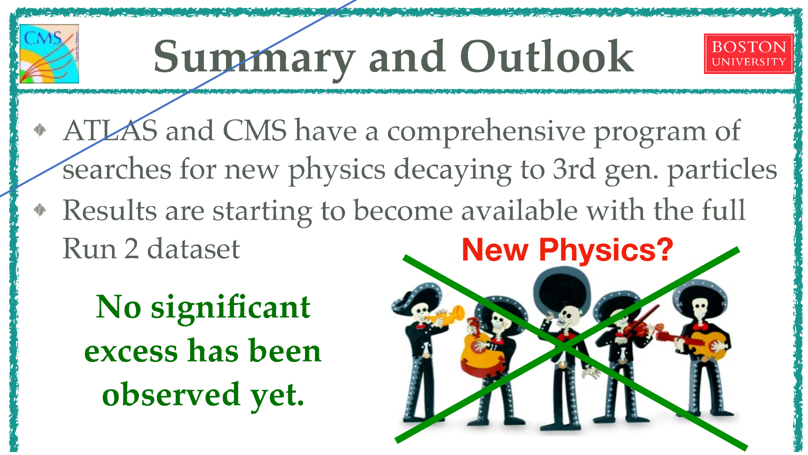
Conventional wisdom

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

  Sym' based solution to Naturalness <=> TeV NP (still the most compelling)

- Conventional NP searches @ E-frontier, polynomial time-progress, linear scale 2019:





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 solutions ? Is it satisfying for the weak scale?

Giudice, Kehagias & Riotto; Kaloper & Westphal; Dvali (19);
Agrawal, Barr, Donoghue & Seckel (98); Arkani-Hamed, Dimopoulos & Kachru (05);
Harnik Kribs & GP (06); Gedalia, Jenkins & GP (11);

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- 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.

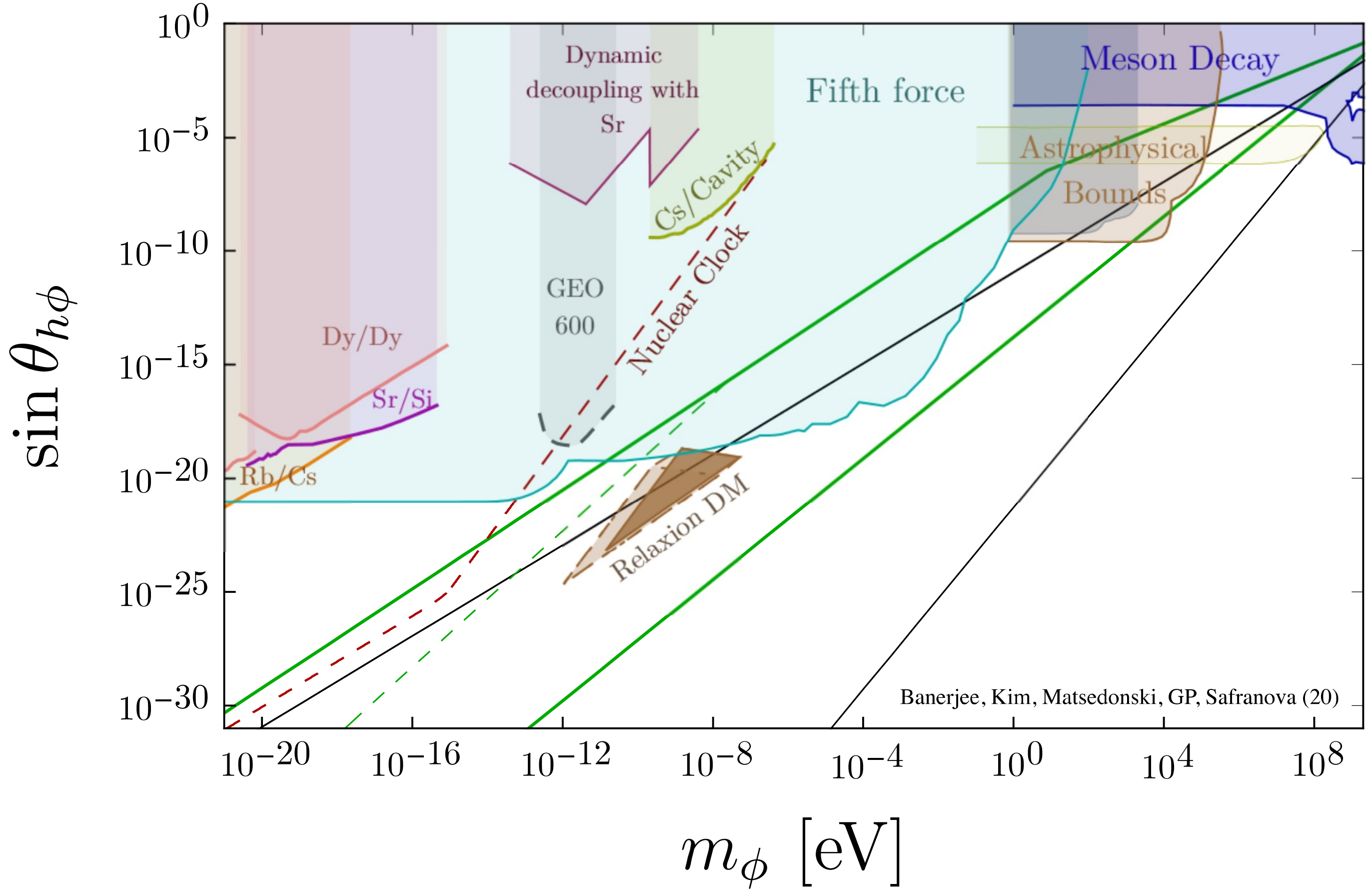
- Bottomline here: relaxion is axion-like-particle (ALP)-DM that (due to CP violation) can be described as scalar mixes \w the Higgs but with weird (shallow) potential.

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

- Searching the relaxion => *log crisis* as follows:

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

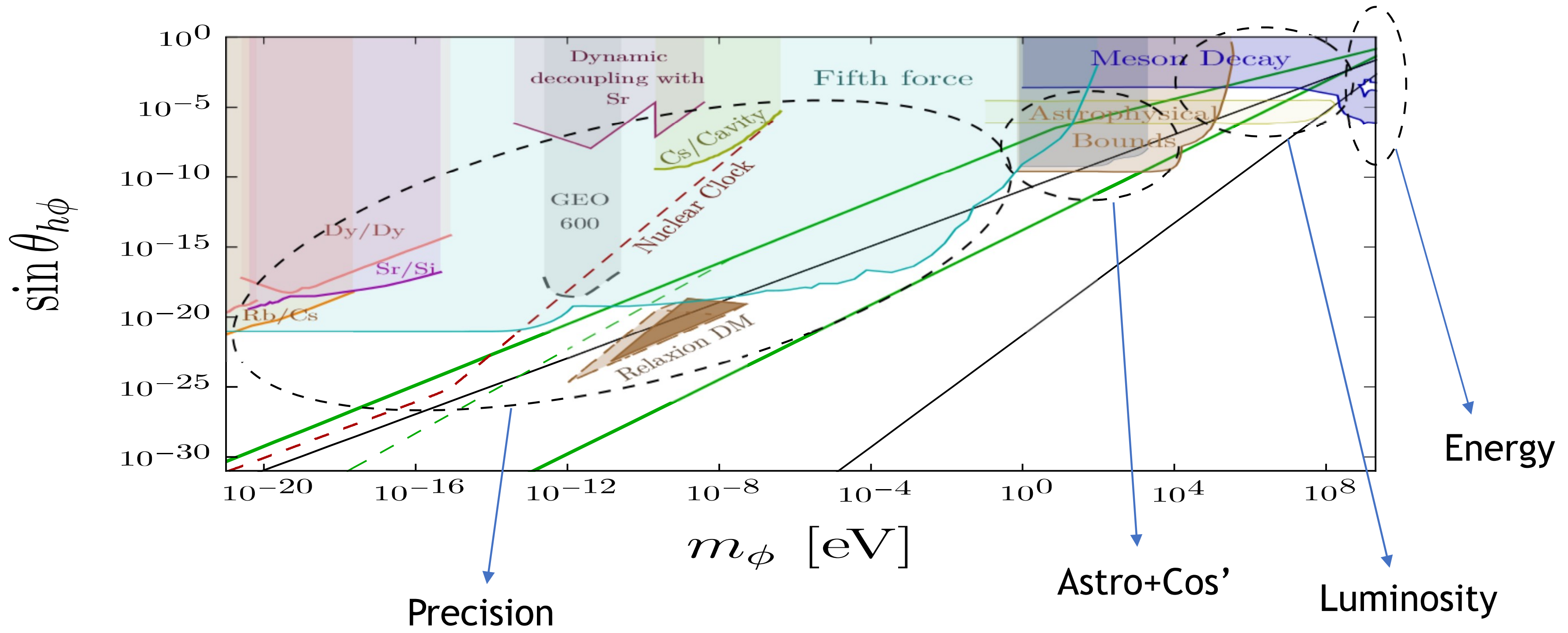
Overview plot: the relaxion 30-decade-open parameter space



The log crisis, toy example, lessons

- Lesson 1 - finding NP requires diverse approach, searches across frontier

- Lesson 2 - experimentally, worth checking where many decades are covered:

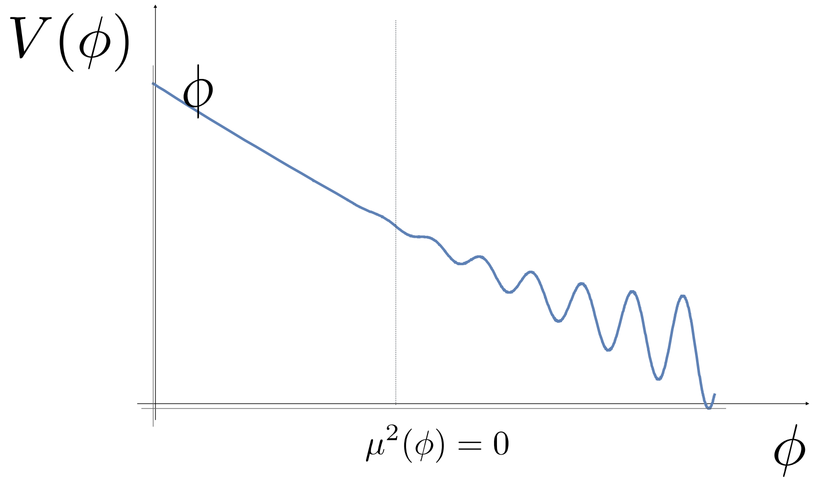


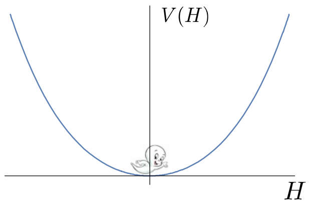
Relaxion mechanism (inflation based)

Graham, Kaplan & Rajendran (15)

(i) Add an ALP (relaxion) Higgs dependent mass (focussing on non-QCD variant): $\left(\overbrace{\Lambda^2 - g^2\phi^2}^{\mu^2(\phi)}\right) H^\dagger H$

(ii) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.





A comment about the hierarchy problem

(i) Add an ALP (relaxion) Higgs dependent mass: $$\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H.$$

The hierarchy problem: we need to understand why today $\mu^2(\phi_{\text{today}}) \ll \Lambda^2$

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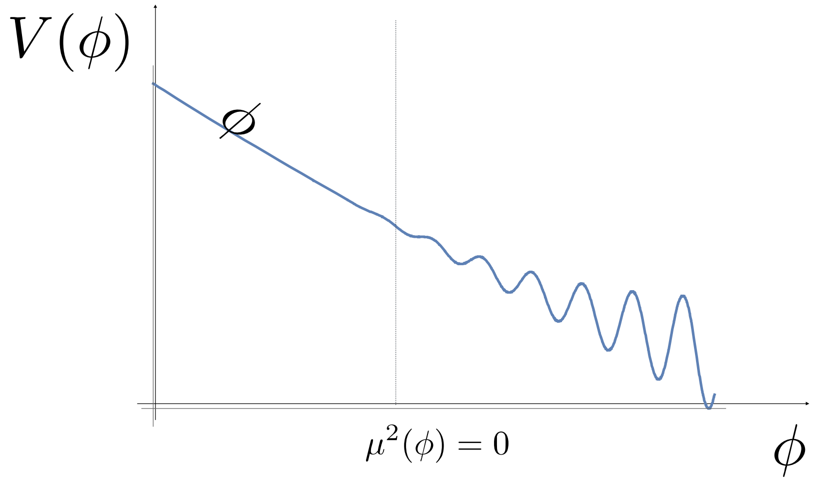

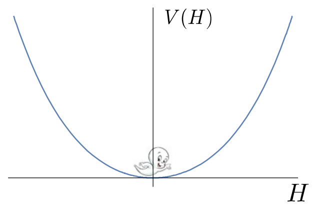

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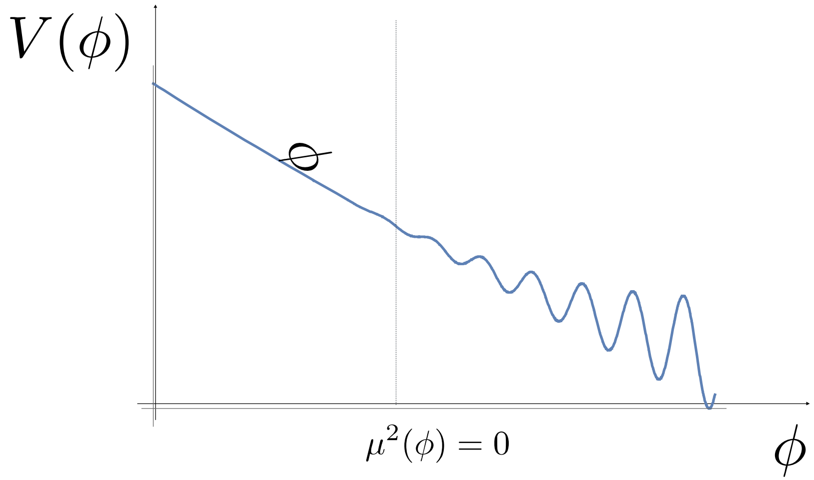

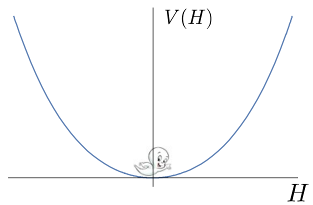

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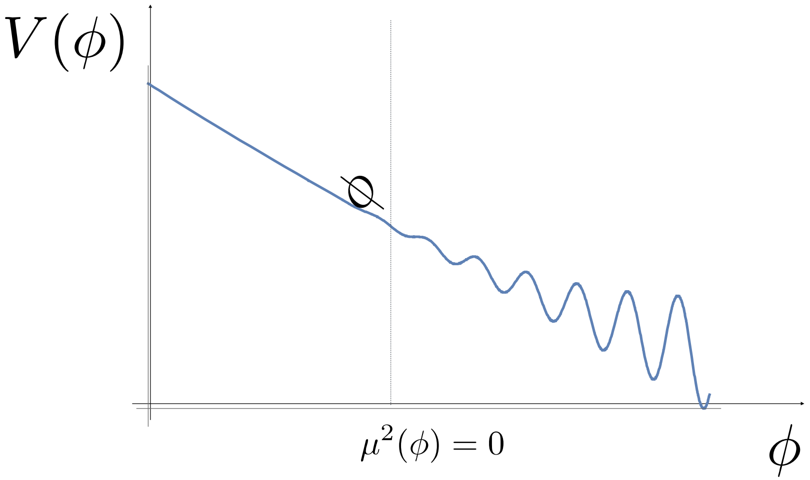

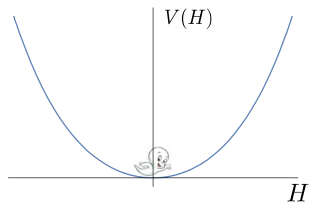

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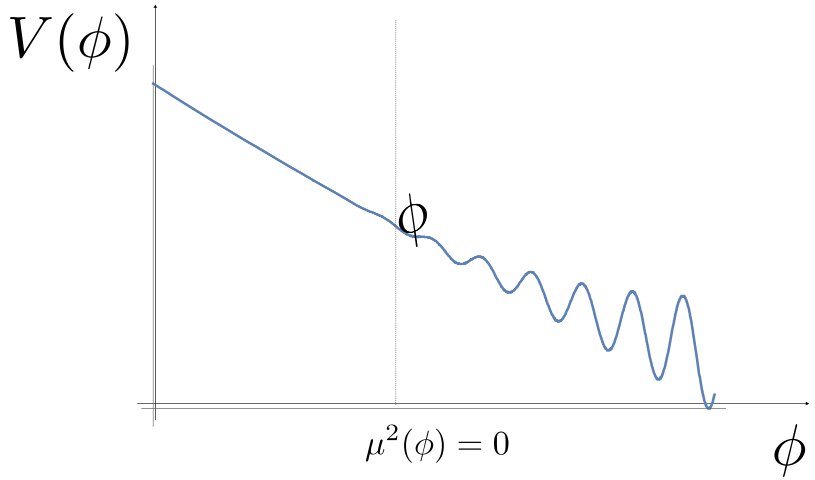

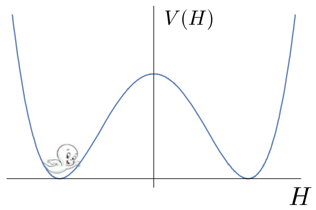

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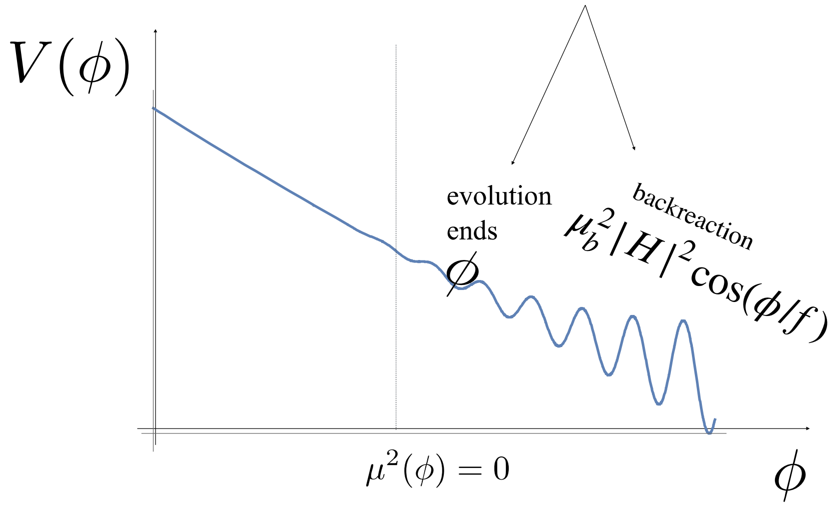
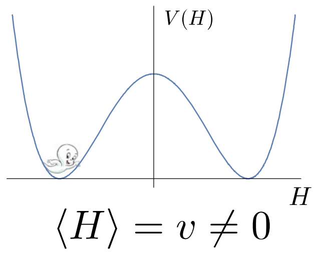




The relaxion parameter space

- 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: $\sin\theta \simeq \mu/\langle H\rangle \lesssim \dfrac{m_S}{\langle H\rangle} \quad \left(\& \quad \lambda \lesssim \dfrac{m_S^2}{\langle H\rangle^2}\right)$.

- However, the ("relaxed") relaxion parameter space, goes well above the natural mixing region => interesting & encouraging for pheno.

Banerjee, Kim, Matsedonski, GP & Safranova (20)

3 differences from generic Higgs portal

(i) Lower + upper bound on mixing angle, apparent unnaturalness

(ii) Tiny "distance" between 1st minimum & maximum

(iii) [Relaxion has also parity-odd-ALP (axion-like-particle) couplings]

Point i: Relaxion's naive parameters (similar to ALP, backreaction domination)

$$m_\phi^2 \sim \partial_\phi^2 V_{br}(\phi, h) \sim \frac{\mu_b^2 v_{\rm EW}^2}{f^2} \cos\frac{\phi_0}{f}$$

$$\sim 1$$

$$\sin\theta_{h\phi} \sim \partial_\phi \partial_h V_{br}(\phi, h)/v_{\rm EW}^2 \sim \frac{\mu_b^2}{f v_{\rm EW}} \sin\frac{\phi_0}{f}$$

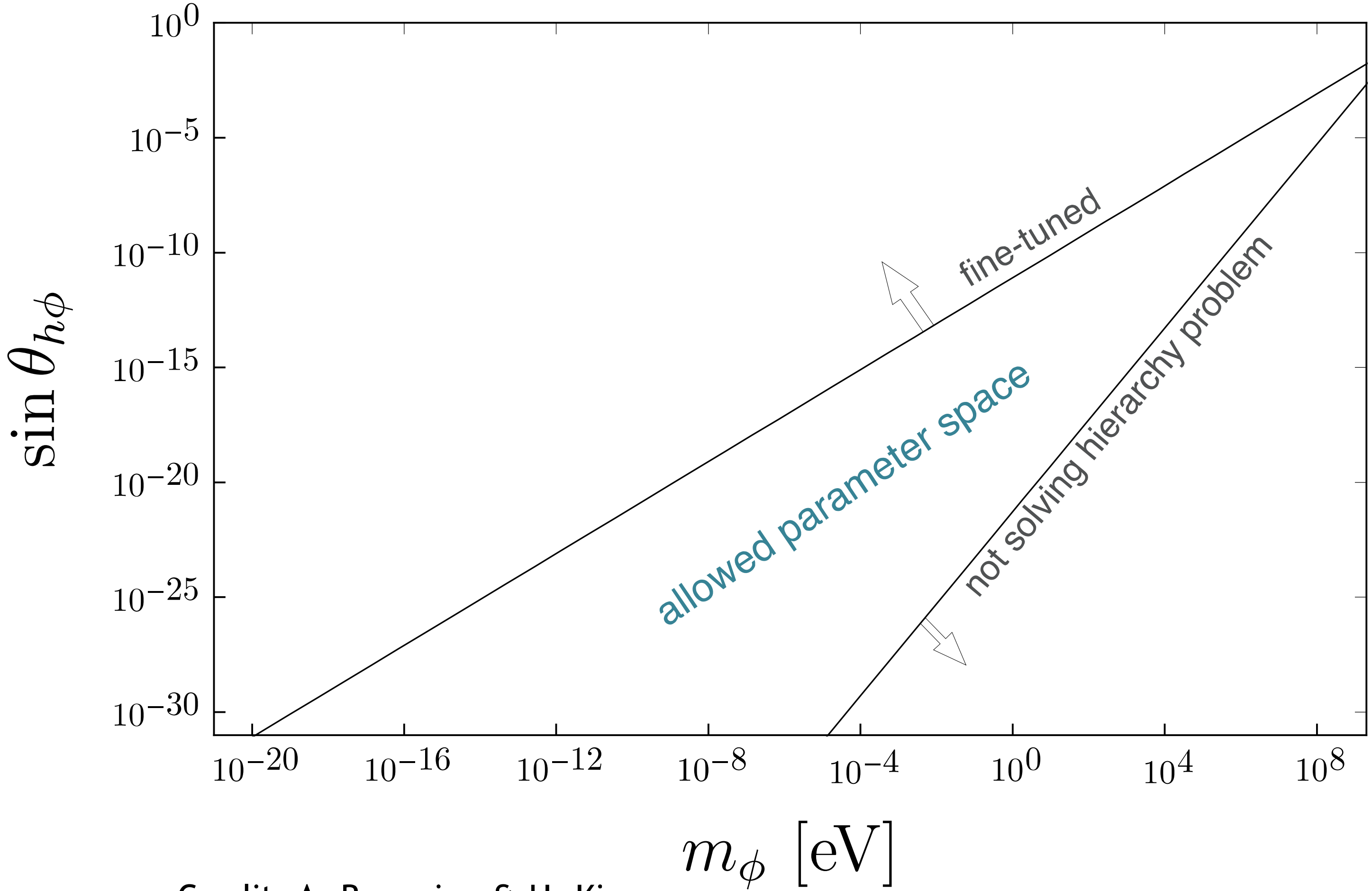
Naively: mixing angle in terms of mass $\sin\theta_{h\phi} \sim \frac{m_\phi}{v_{\rm EW}} \frac{\mu_b}{v_{\rm EW}}$

Maximum mixing angle $(\sin\theta_{h\phi})_{\rm max} \sim \frac{m_\phi}{v_{\rm EW}}$

Naturalness bound

Minimum mixing angle $(\sin\theta_{h\phi})_{\rm min} \sim \frac{m_\phi^2 \Lambda_{\rm min}}{v_{\rm EW}^3}$

The relaxion's naive parameter space



Credit: A. Banerjee & H. Kim

(Less naive treatment)

$$V(\phi, h) = (\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}})|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi - \mu_{\rm b}^2 |H|^2 \cos\frac{\phi}{f} \qquad v^2(\phi) = \begin{cases} 0 \ \text{ when } \phi < \mathrm{f_{eff}} \\ > 0 \text{ when } \phi > \mathrm{f_{eff}} \end{cases}$$

Relaxion stopping point determines the EW scale $\quad \frac{\Lambda^4}{f_{\rm eff}} \sim \frac{\mu_{\rm b}^2 v_{\rm EW}^2}{f}$

Resolution parameter

Higgs mass change for $\Delta\phi = 2\pi f \quad \frac{\Delta v^2}{v^2} \sim \frac{\Lambda^2}{f_{\rm eff}}\frac{f}{v^2} \sim \boxed{\frac{\mu_b^2}{\Lambda^2}} \equiv \delta^2 \ll 1$

$$V_{\rm br} = -\mu_{\rm b}^2 |H|^2 \cos\frac{\phi}{f} \quad \Rightarrow$$

Potential height grows incrementally

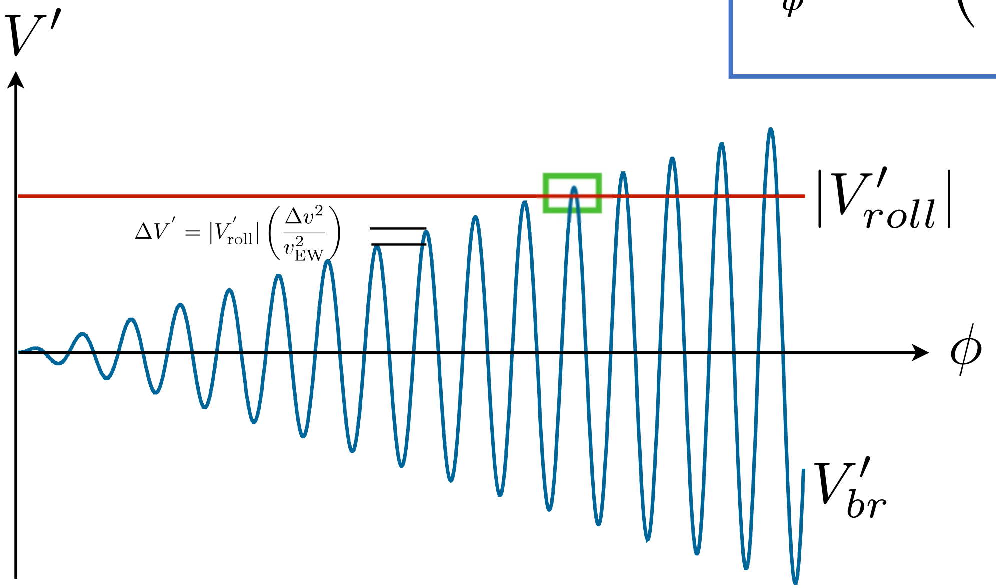
Stopping condition, fine resolution => tuned (relaxed) mass

From GKR (15): "… in the non-QCD case, the field φ may be stopped right when the barriers first appear and therefore the mass of the axion particle may be naturally tuned to be small. This small mass improves the observability of the axion dark matter …"

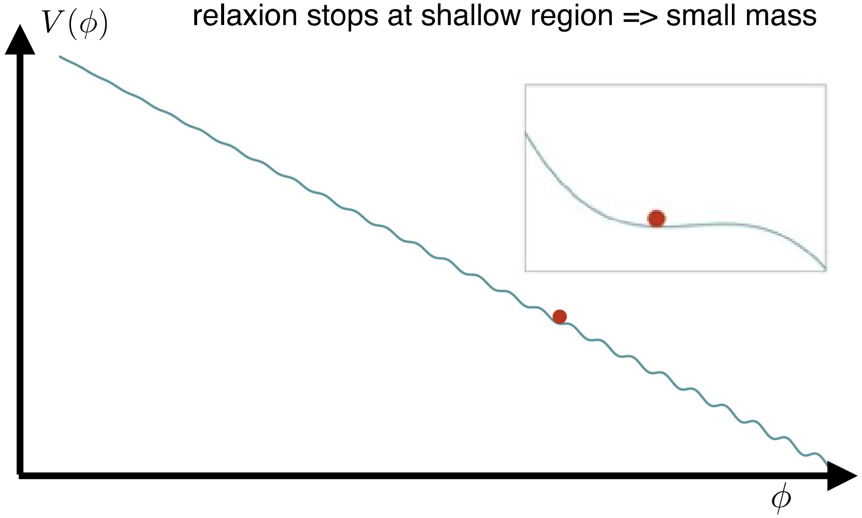
Banerjee, Kim, Matsedonski, GP, Safranova (20)

$$\boxed{V_\phi^{'} = 0 \Rightarrow \sin\theta = \frac{v_{\rm EW}^2}{v^2(\phi)} + \frac{v_{\rm EW}^2}{\Lambda^2}} \quad \Longrightarrow \quad \boxed{\frac{\phi_0}{f} \sim \frac{\pi}{2} \ \text{upto resolution factors}}$$

$$\boxed{m_\phi^2 \approx \delta \times \left(m_\phi^2\right)_{\rm naive} \ll \left(m_\phi^2\right)_{\rm naive}}$$



Relaxion: barriers increase incrementally:
relaxion stops at shallow region => small mass

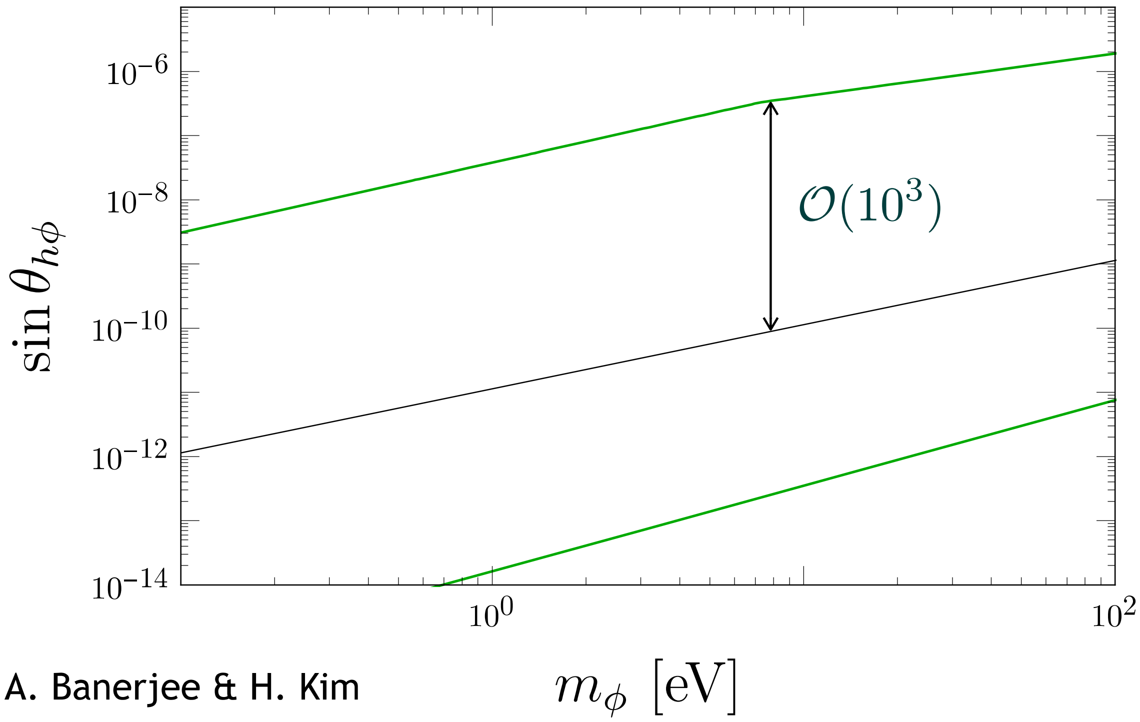


Credit: A. Banerjee & H. Kim

Relaxed mass => natural violation of naturalness bound

Banerjee, Kim, Matsedonski, GP, Safranova (20)

Max. Mixing angle: $\sin\theta_{h\phi}^{\max} = \left(\frac{m_\phi}{v_{EW}}\right)^{\frac{2}{3}} \gg \left(\frac{m_\phi}{v_{EW}}\right)_{\text{naturalness}}$



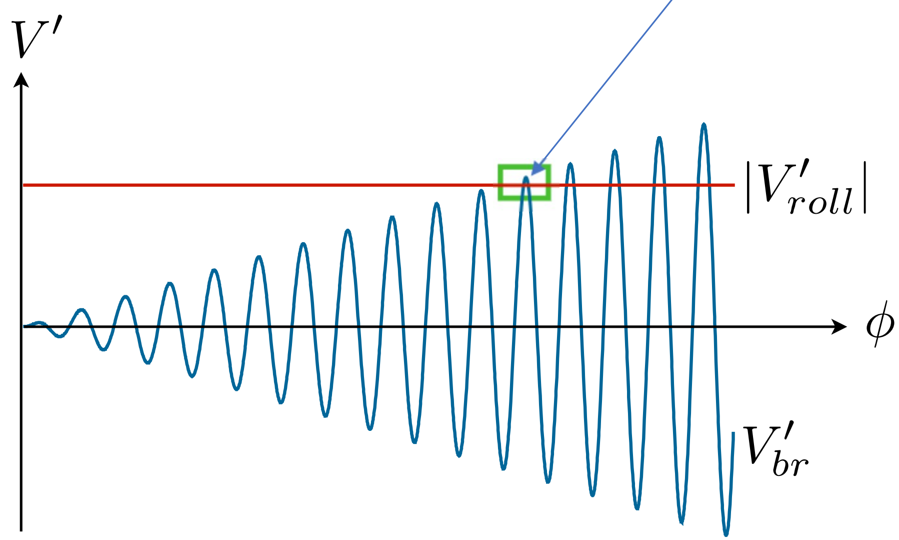
Credit: A. Banerjee & H. Kim

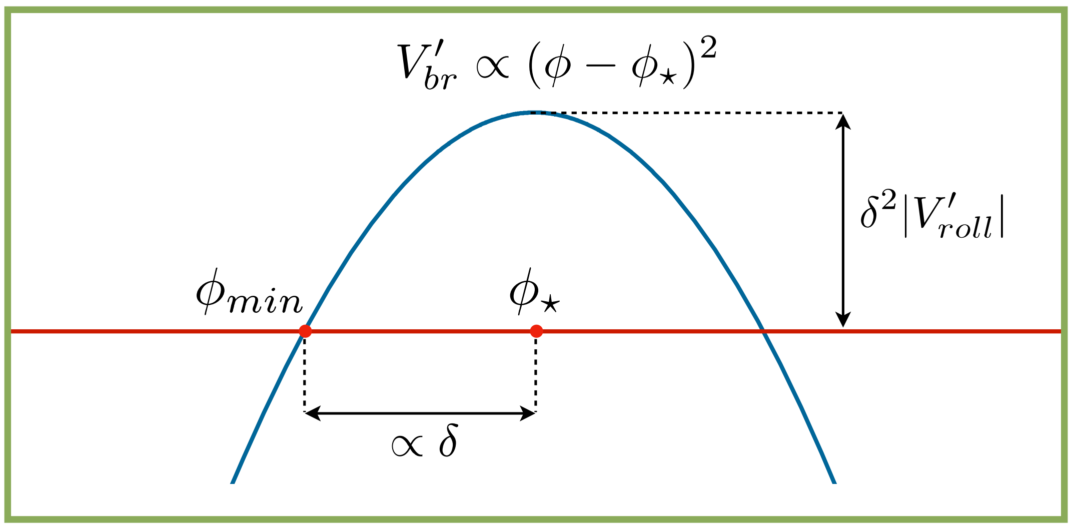
Point ii: Distance between 1st min. & max. & relaxion as chameleon

1st min. & maximum are very close, environmental effects may destabilised:

$$\Delta\phi_{\rm mima}/f \sim \delta \;\Rightarrow\; \Delta\phi_{\rm mima} \sim \sin\theta_{h\phi}\, v^{5/3}/m_\phi^{2/3} \ll f$$

Budnik, Kim, Matsedonski, GP & Soreq (20)





Credit: A. Banerjee & H. Kim

Intro, new search strategies

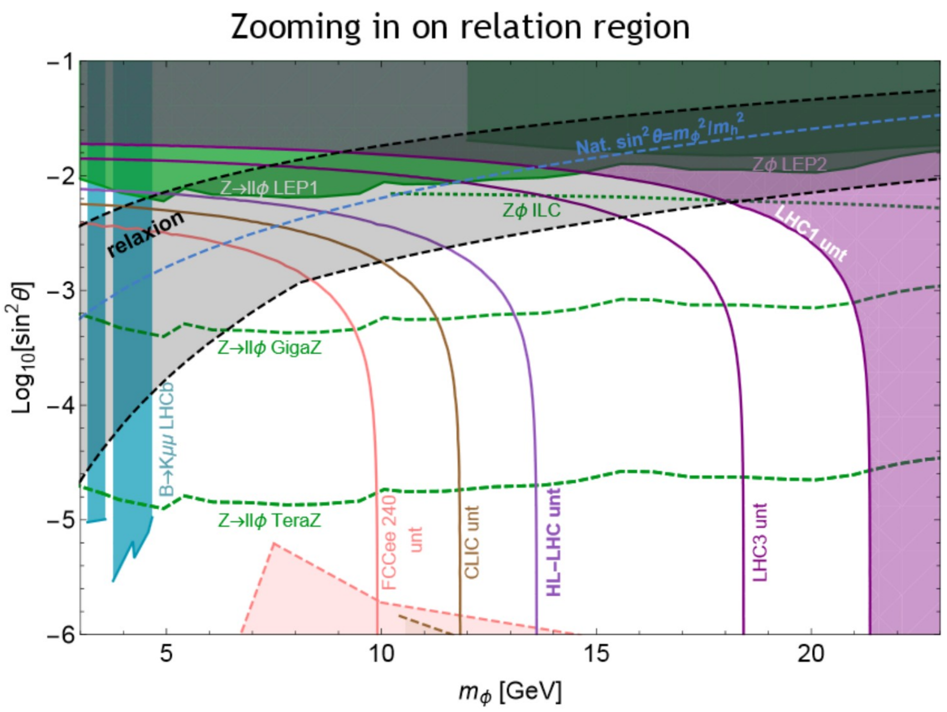
- Our current 21st century puzzle:

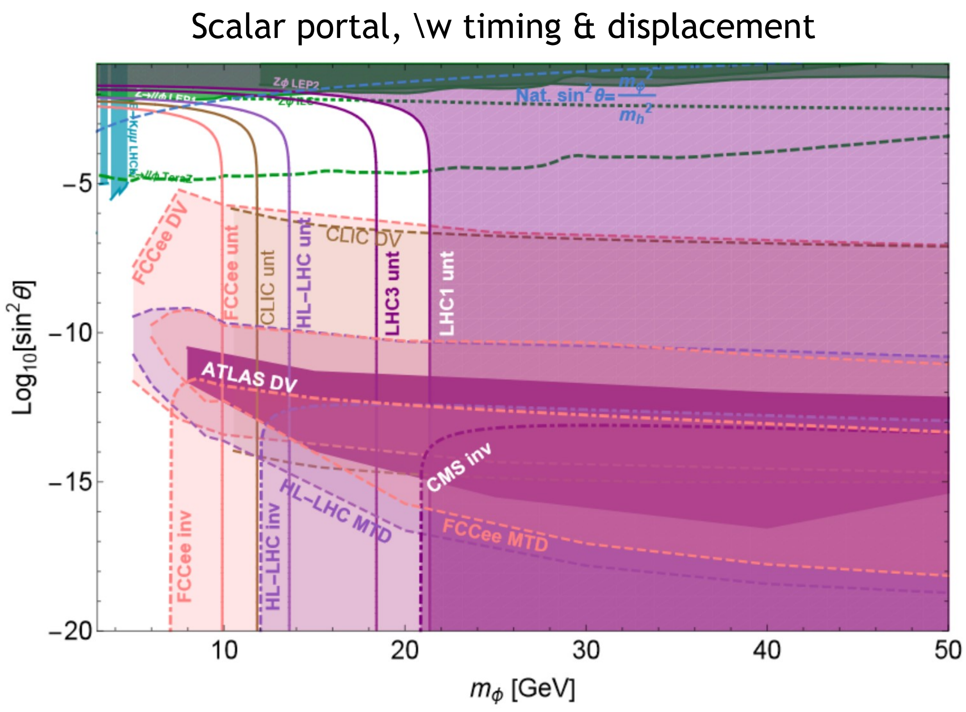
knowledge that new physics (NP) exists vs our safest bets (LHC, WIMP,…) that came empty

- Motivates us to look for new paradigms

- *Motivates us to look for new search strategies*

Overview: collider probes of relaxion





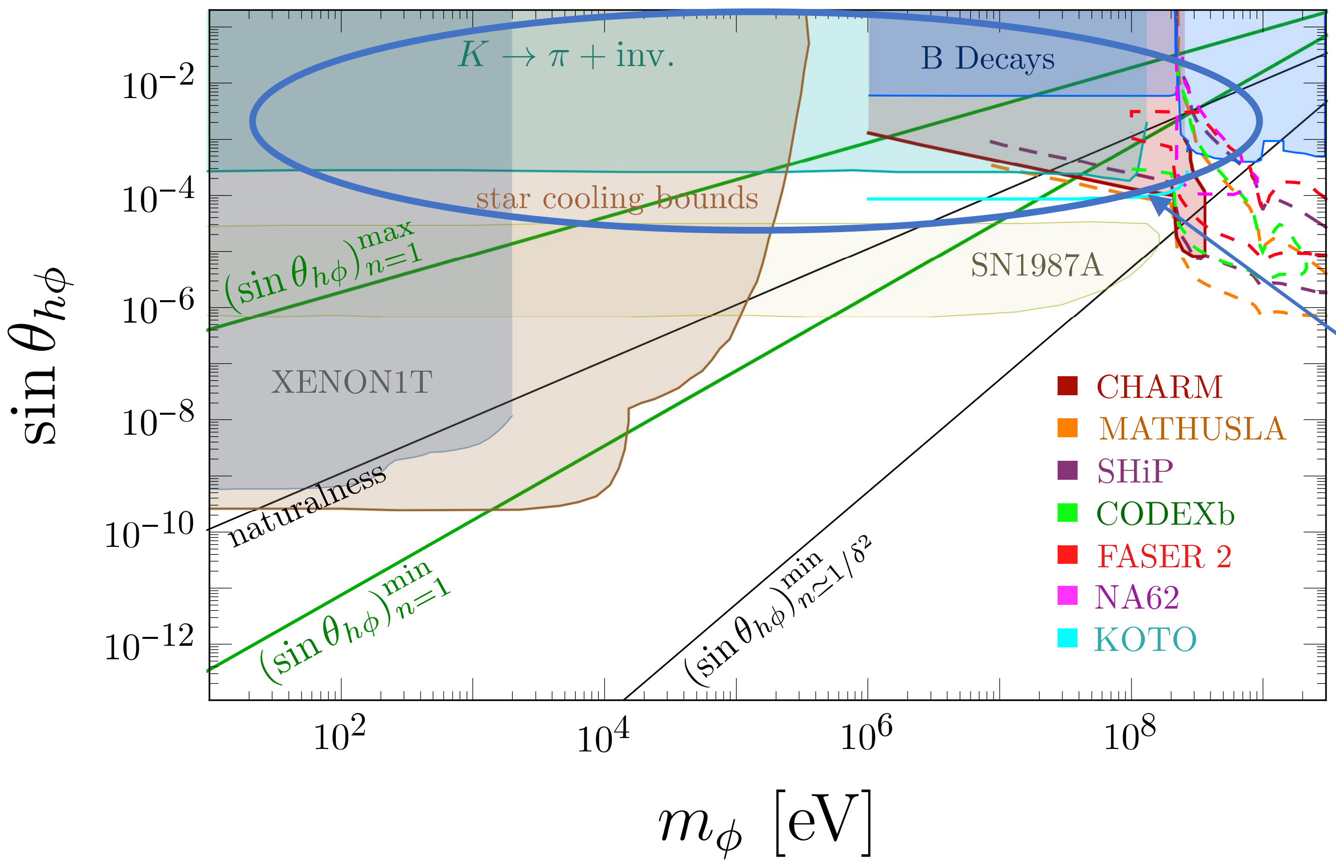
Fuchs, Matsedonski, Savoray, Schlaffer (20)

Frugiuele, Fuchs, GP & Schlaffer (18)

Luminosity & precision: the era of Kaon factories

For this brief discussion, relaxion = scalar that mixes with the Higgs.

Banerjee, Kim, Matsedonski, GP & Safranova (20)



Region probed via Kaon factories 2020

Luminosity & precision: the era of Kaon factories

CERN

J-PARC

The Kaon factories:

- No. of Kaon of $O(10^{13})$, \w world record of 10^{19} proton on targets
- Aiming for BR of $O(10^{-11})$ soon (factor $10^{2\text{-}3}$)!

What are they searching for [within the Standard Model (SM)]:

- Super-rare events - NA62 : $K^+ \to \pi^+ \nu \bar{\nu}$ KOTO : $K_L \to \pi^0 \nu \bar{\nu}$
- Super clean: $\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (9.1 \pm 0.7) \times 10^{-11}$, $\mathrm{BR}\left(K_L \to \pi^0 \nu \bar{\nu}\right) = (3.0 \pm 0.3) \times 10^{-11}$

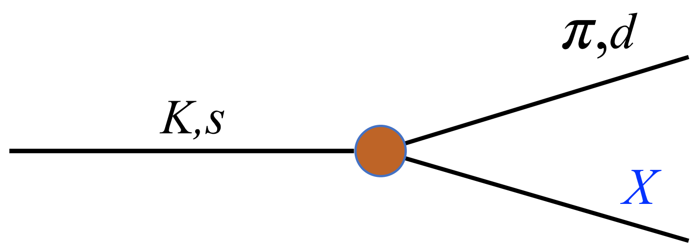
Buras, Buttazzo, Girrbach-Noe & Knegjens, (JHEP 15)

Kaon factories & dark sector searches

- NP models with new light particles that only feebly interacts (FIPs) with SM fields are very motivated (relaxion is one ex. out of many)

- However, such dark sectors (FIPs) are very hard to discover, requires high luminosity & precision <=> Kaon factories:

$$\text{KOTO/NA62}: (K \to \pi\nu\bar{\nu}) \Leftrightarrow (K \to \pi X)$$



NA62 vs. KOTO, SM & beyond

- The Grossman-Nir (GN) bound (97):

  SM, $K_L \to \pi^0 \nu\nu$ and $K^+ \to \pi^+ \nu\nu$ are related via sym., $\mathrm{BR}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 4.3\,\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$

- Relation holds (saturates) in NP (scalar), say in 2 body, or heavy particles:

  Leutwyler and M. A. Shifman (90), $\mathrm{BR}\left(K_L \to \pi^0 S\right) = 4.3\,\mathrm{BR}\left(K^+ \to \pi^+ S\right)$

Experimental status, NA62 vs KOTO

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{\mathrm{NA62}} = (11.0 \pm 4.0) \times 10^{-11} \implies 3.5\,\sigma\,! \quad \left[\mathrm{SM}: \ (9.1 \pm 0.7) \times 10^{-11}\right]$$

$$\text{"}\,\mathrm{BR}\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{\mathrm{KOTO}} \lesssim 4 \times 10^{-9}\,\text{"} \quad \left[\mathrm{SM}: \ (3.0 \pm 0.3) \times 10^{-11}\right]$$

Update (last month) 2012.07571:

$$\mathrm{BR}\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{\mathrm{KOTO}} \lesssim 5 \times 10^{-9}$$

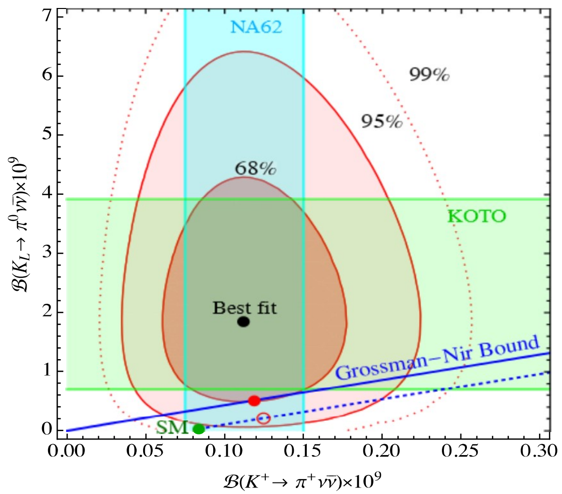
$$\mathrm{BG} \sim 1.22$$

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

Tobiaka, POST ICHEP 20:

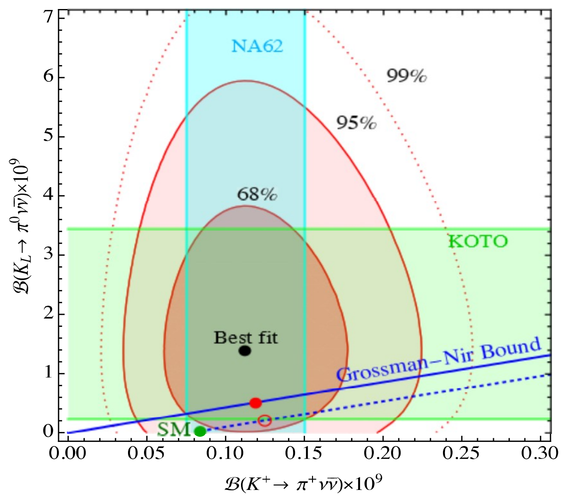
(A) K⁺ BG based on MC

B=**0.39**±0.10



(B)K⁺ BG MC **x3** [special run]

B=**1.05**±0.28



	(A)	(B)
● SM:	2.6σ	1.7σ
● GN tension:	1.5σ	0.9σ

The solar relaxion

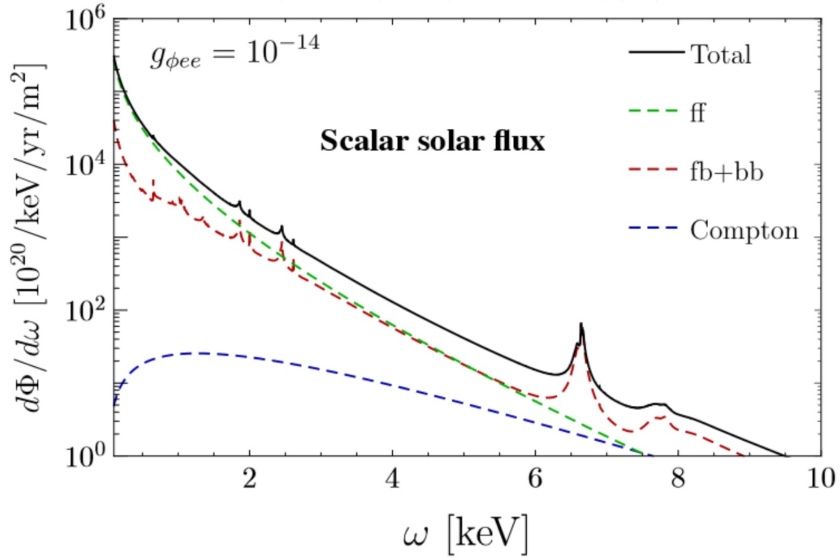
- The relaxion is copiously produced in the solar core. (via Bremsstrahlung & resonant processes)

Redondo (13)

- This flux can be absorbed by liquid xenon dark matter (DM) detectors.

- Used XENON (19) & LUX (17) to constrain the relaxion-electron couplings ($g_{\varphi ee}$):

Budnik, Davidi, Kim, GP & Priel, (19)

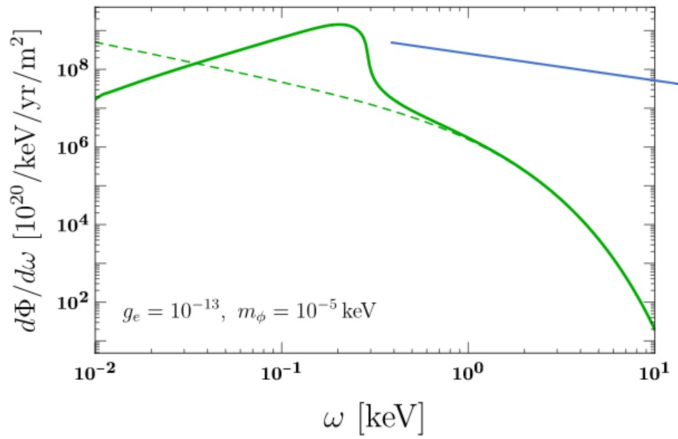


The coupling to electrons is chosen to be $g_{\phi ee} = 10^{-14}$, and scalar taken to be massless. Green dashed line is Bremsstrahlung flux from electrons interacting with hydrogen and helium ions, red dashed line is the flux due to recombination and transitions of bounded electrons in heavier elements, blue dashed line is the flux from Compton-like scattering, black line is the total scalar flux.

Can search for it with S1 (high threshold) & \w S2 (low threshold)

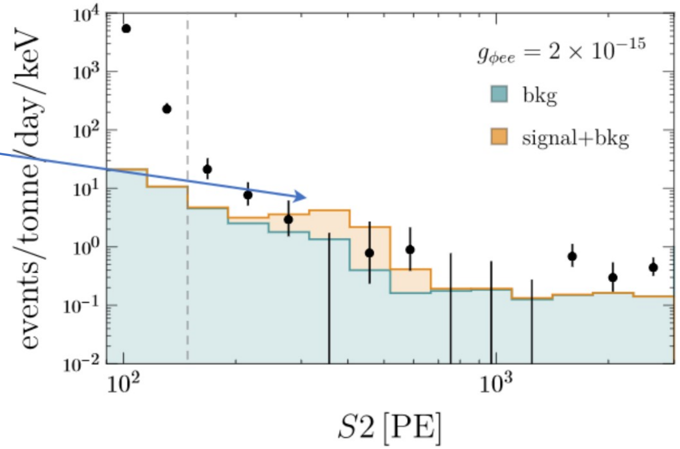
Hardy and R. Lasenby (17)

unpublished: resonant spectrum



The dashed line ignores the mixing between scalar and longitudinal photon excitation, while solid line includes it.

XENON1T (19) data + relaxion's resonant production



XENON1T data = black dots, blue histogram = partial background model, signal = orange histogram (massless scalar, $g_{\varphi ee} = 2 \times 10^{-15}$ - the peak around 400 PE corresponds scalar $E \sim 0.2$ keV.

Massless case: $g_{\varphi ee} < 2 \times 10^{-15}$

$\sin\theta < 7 \times 10^{-10}$

XENON1T result on S1 (not looking at scalars)

E. Aprile et al., "Observation of Excess Electronic Recoil Events in XENON1T," arXiv:2006.09721 [hep-ex].

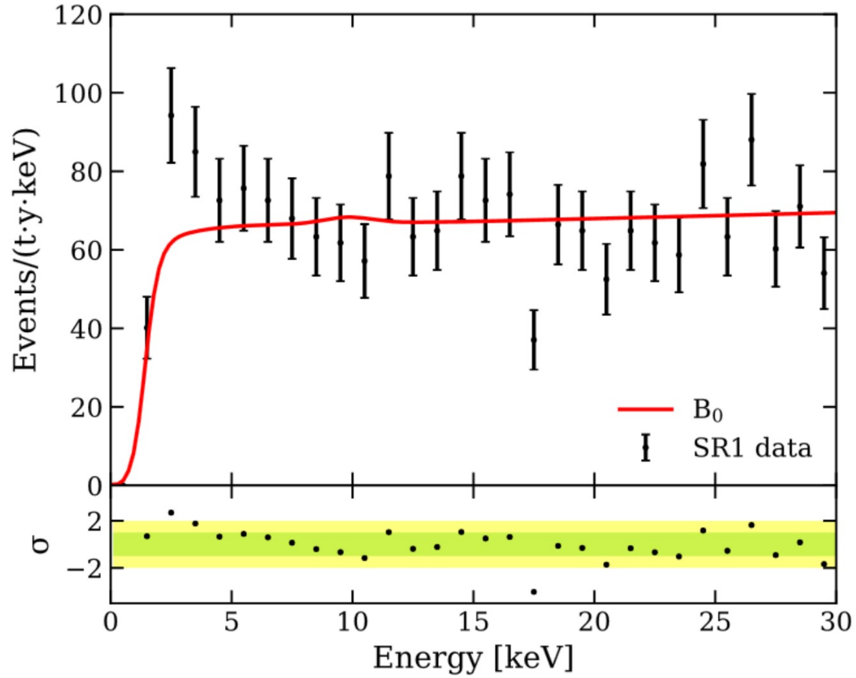
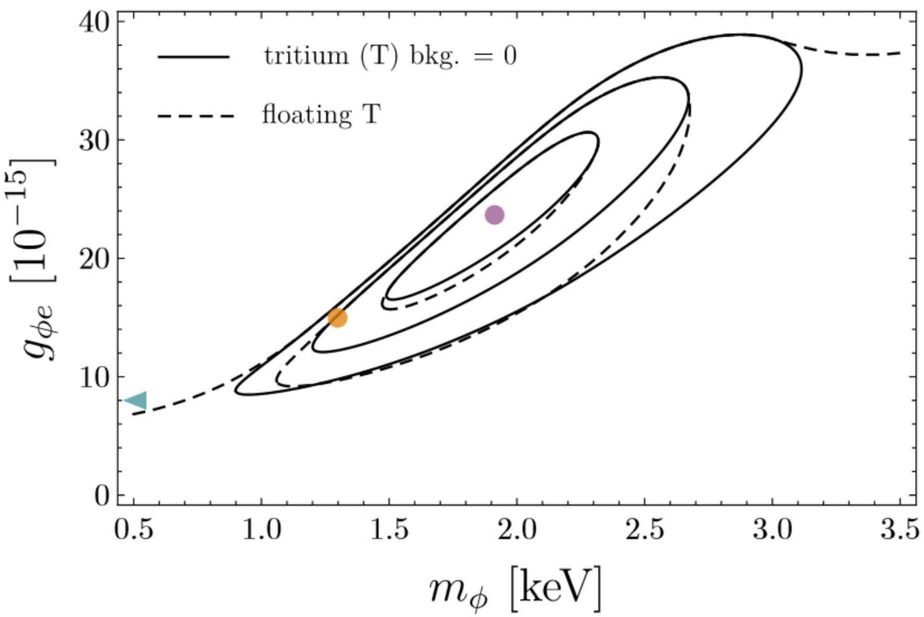
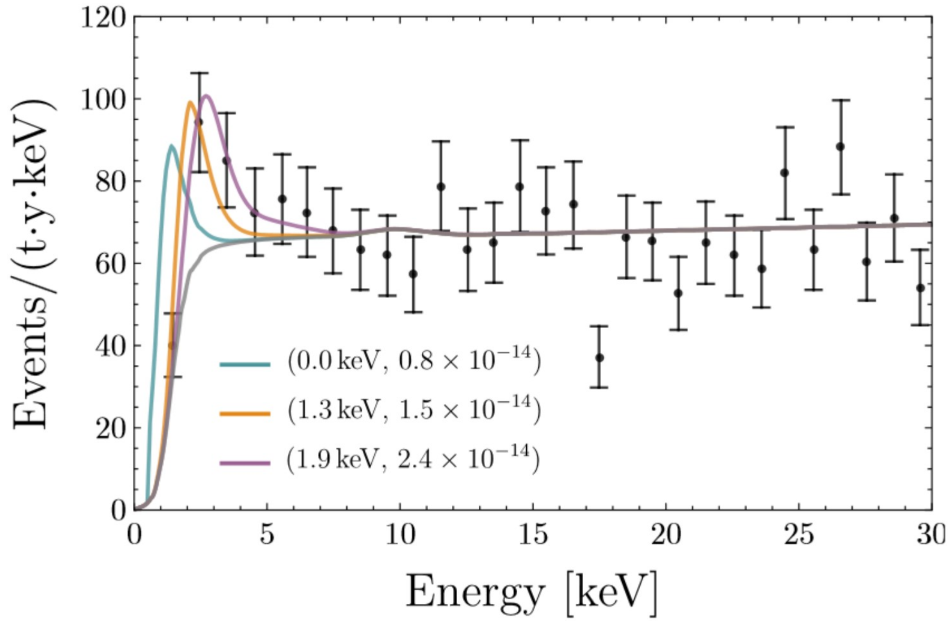


FIG. 4. A zoomed-in and re-binned version of Fig. 3 (top), where the data display an excess over the background model B_0. In the following sections, this excess is interpreted under solar axion, neutrino magnetic moment, and tritium hypotheses.

Fitting to scalar preliminary, S1

Budnik, Kim, Matsedonski, GP & Soreq (20)

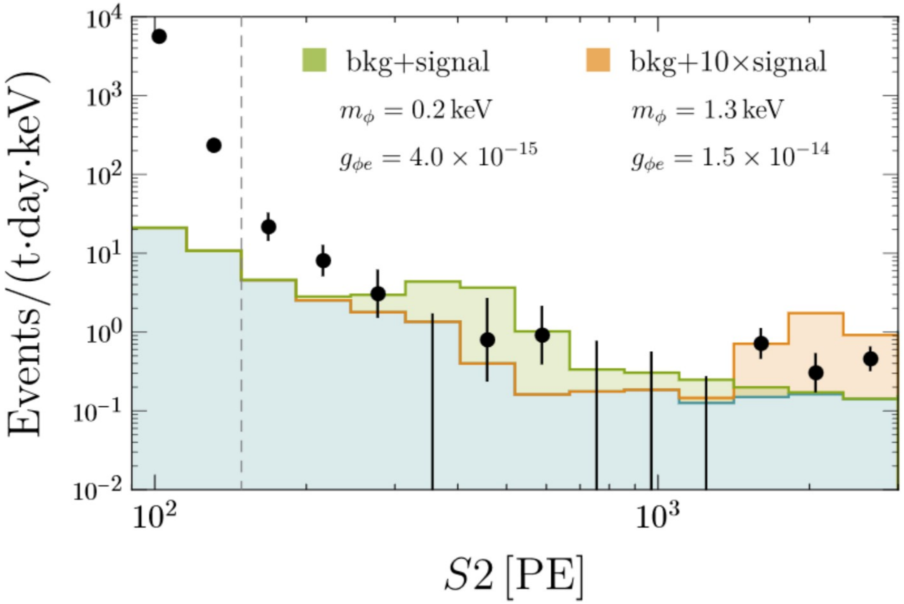


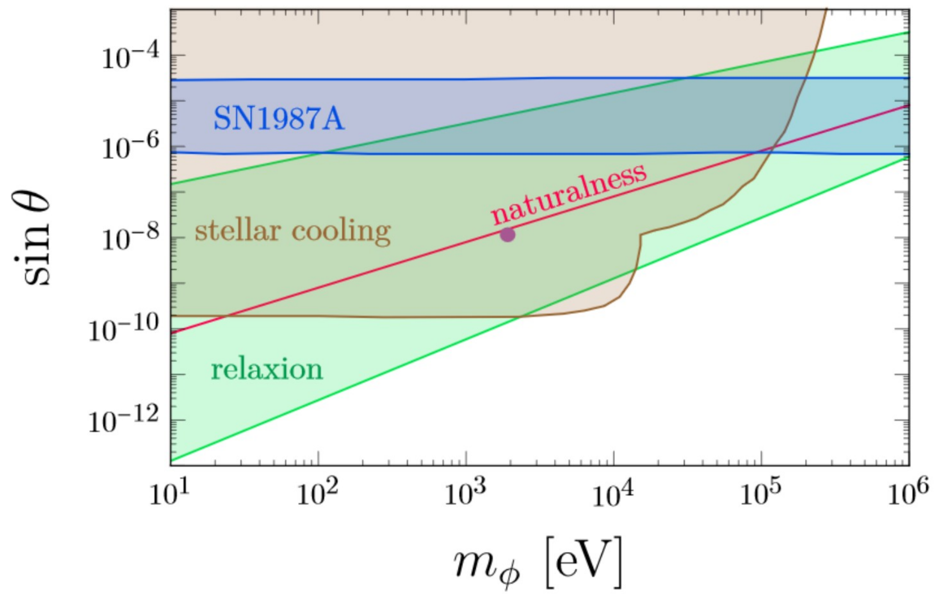


Left: showing the 1-2-3sigma CL with and without the BG. The three benchmark points with m_ϕ = (0, 1.3, 1.9) keV and $g_{\phi e}$ = (0.8, 1.5, 2.4) × 10^{-14}, are marked in green, orange and purple, respectively. The purple (BM_3) is the best fit point. Right: The signal+background is shown for the three benchmark point. The black points and gray line are data and background (without tritium) from XENON1T.

Fitting to scalar preliminary, S2; notice the background is not completely known!

Budnik, Kim, Matsedonski, GP & Soreq (20)

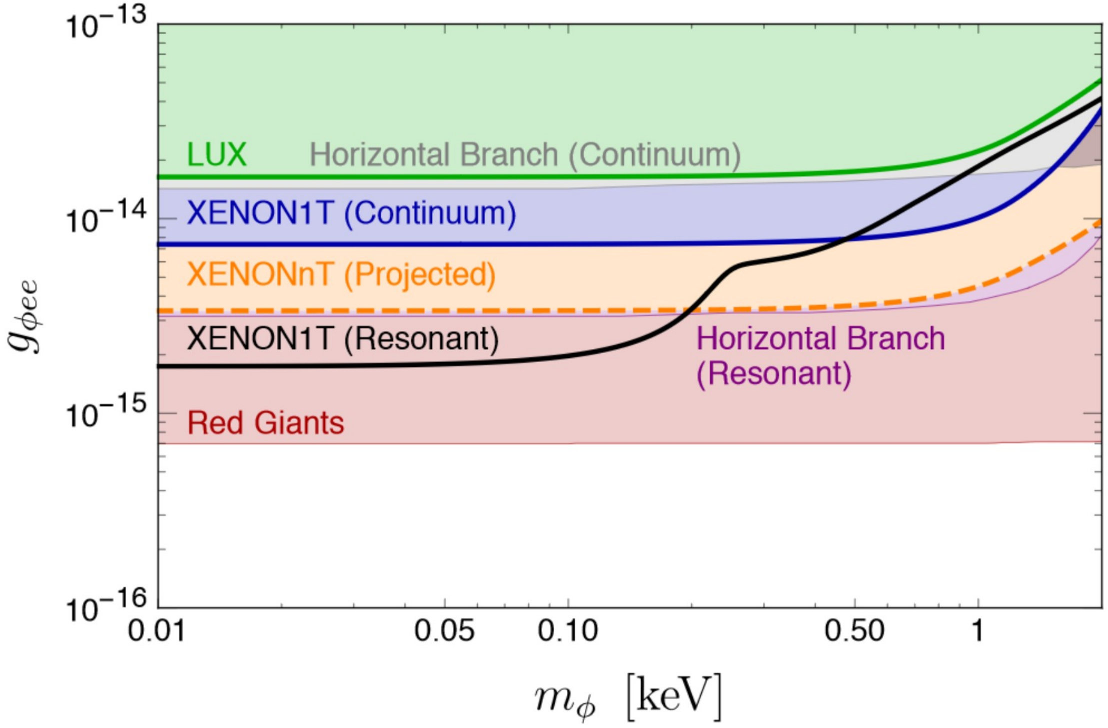




Strong tension with red-giant (RG) observation if the mass is keV
(can be avoided by adding largish couplings to photons).

S2: Tension is lower for < 300eV

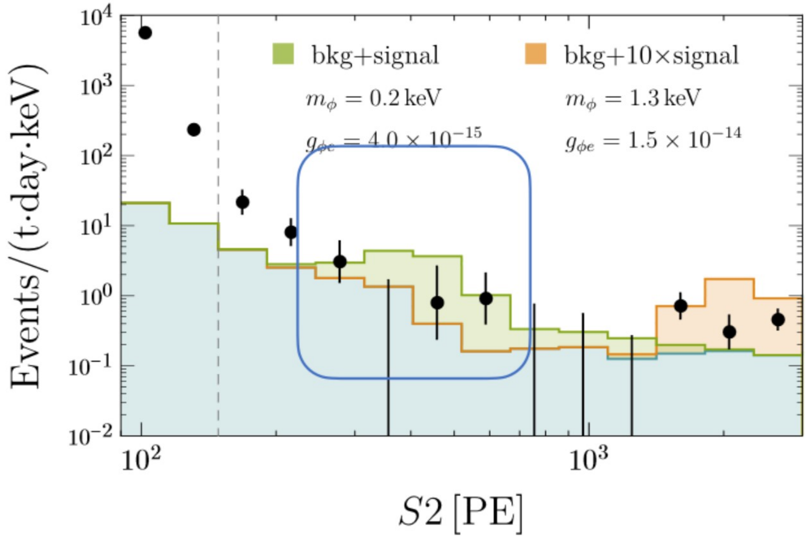
Budnik, Davidi, Kim, GP & Priel, 1909.02568



S2: Tension is lower for mass of 200 eV => relaxion = Chameleon

Budnik, Kim, Matsedonski, GP & Soreq (20).

See also: DeRocco, Graham & Rajendran; Bloch, et al (20)



$$\frac{\Delta\phi_{\mathrm{RG}}}{\Delta\phi_{\mathrm{mima}}} \sim \frac{g_{\phi pp}}{10^{-6}} \times \left(\frac{200\,\mathrm{eV}}{m_\phi}\right)^{\frac{8}{3}}_{\theta_{\min}}$$

For max. allowed natural coupling to protons inside the red giant the relation is destabilised for mass of order 200 eV.

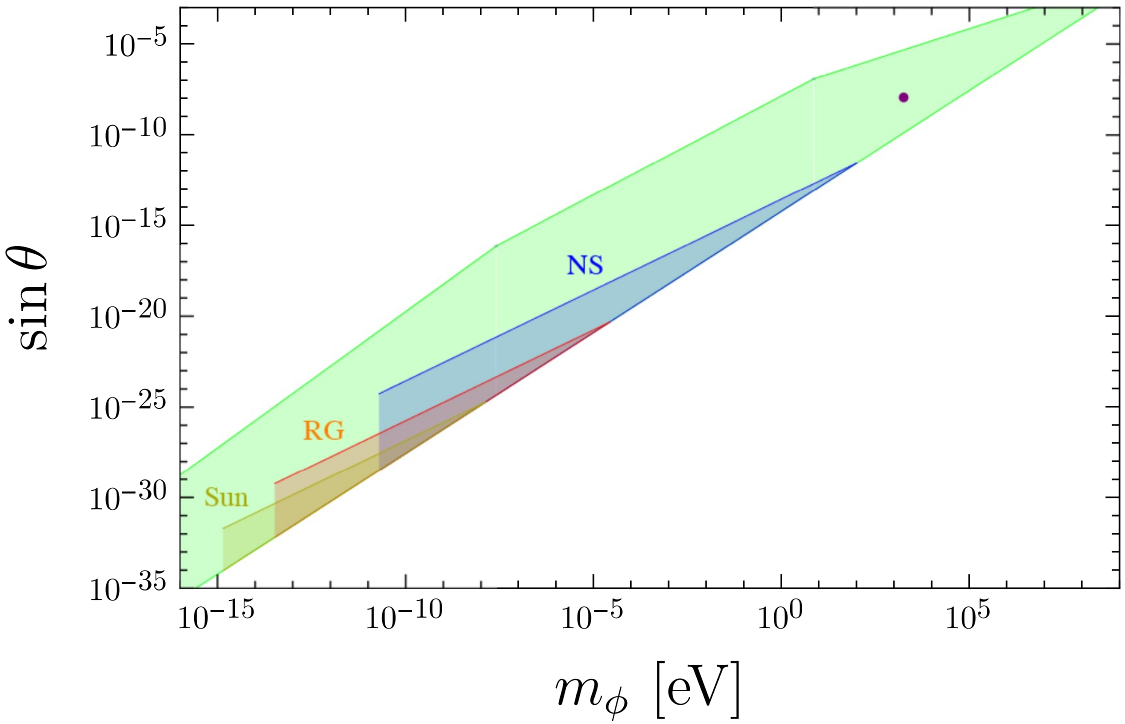
Catastrophic boundaries

For a sufficiently large shift the relaxion will start rolling towards the next minimum.
\Wo friction the relaxion won't stop triggering cosmological phase transition.

Budnik, Kim, Matsedonski, GP & Soreq (20).

See also: Hook & Huang (17)

Balkin, Serra, Springmann, & Weiler (20)



First minima para' space; mum (green) in terms of $\sin\theta$ and m_ϕ . Purple dot shows the best fit to XENON1T excess. The blue, red and yel- low regions show where the expanding bubbles are produced, resulting from neutron stars, RGs cores and the Sun core, respectively.

Precision Front

(i) virtual processes searching for atomic-range "Yukawa" force

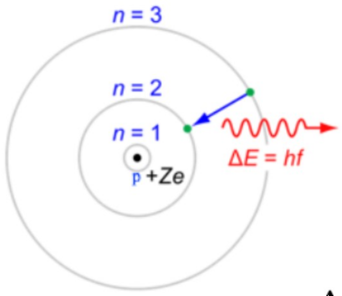
[(ii) time-depend. background if relaxion/scalar = ultra-light dark matter (DM)]

Recent progress:

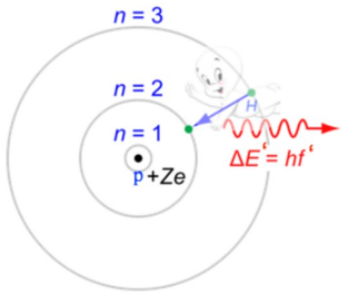
Hunting "heavy" scalar/relaxion with isotope shift spectroscopy

Basic concept: precision isotope shift spectroscopy

- New forces acts on electron & quarks leads to change of energy levels.



$$+ \quad \mathcal{L}_\phi = \phi\,(g_e \bar{e} e + g_q \bar{q} q) \quad \longrightarrow$$



$$\Delta\nu_h \sim 10^2\,\mathrm{kHz} \times \frac{g_e g_n}{10^{-10}} \times \left(\frac{1\mathrm{MeV}}{M_\phi}\right)^2 ,$$

Delaunay, Ozeri, GP & Soreq (16)

- We cannot switch on and off these light Higgs-like couplings.

- Use different isotopes to effectively compare force mass dependence.

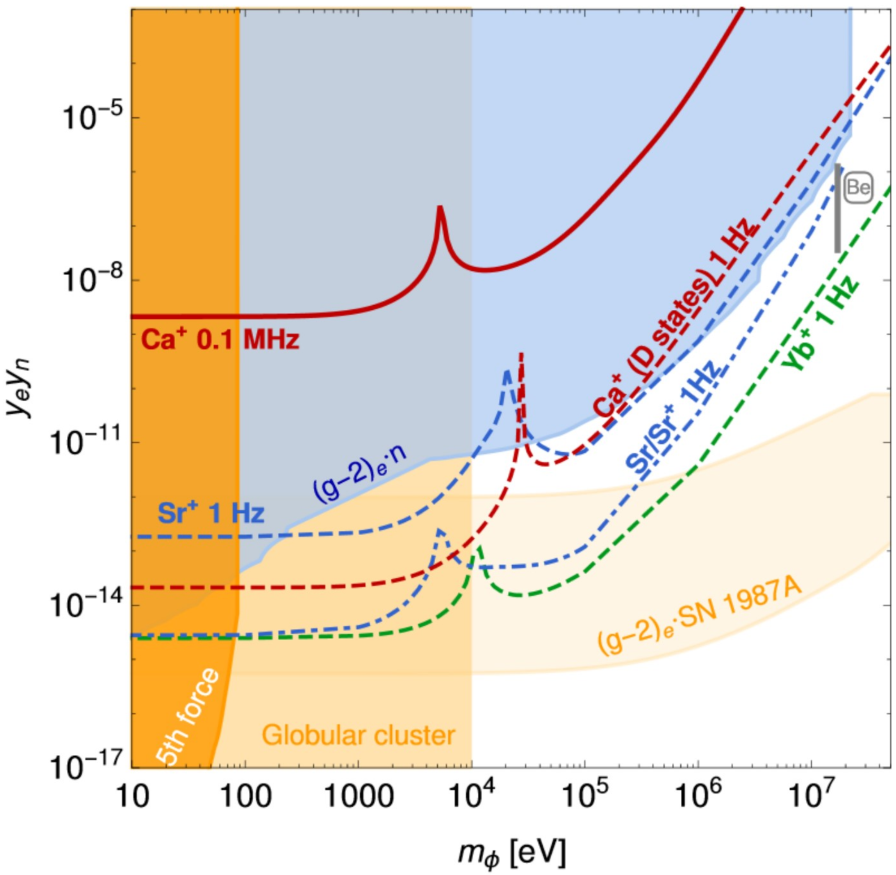
- Suppress nuclear effects via 2 transition comparison => King Linearity.

$$\left[\left(\nu_{ij}^{\alpha}\right)_{\mathrm{SM}} \simeq K^{\alpha}\mu_{ij} + F^{\alpha}\delta\langle r^2\rangle_{ij} \implies \bar{\nu}_{ij}^{\alpha} \propto \bar{\nu}_{ij}^{\alpha'}\right]$$

King (1963)

Bounds & sensitivity

Berengut, et al. (17)

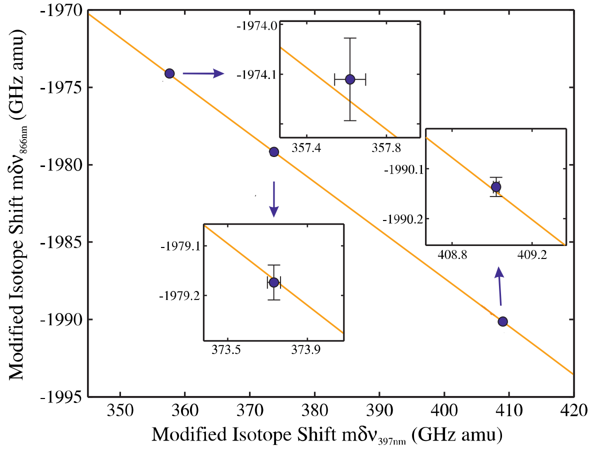


Recent ex. improving bounds by 10^3

Search for King-linearity-violation (KLV), from $O(100)$ kHz to $O(100)$.

2015: Isotope shift @ $1{:}10^4$

Gebert et al. (PTB)



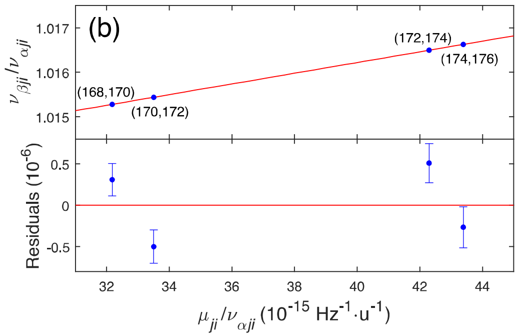
Ca⁺ (A=40,42,44,48)

$D_{3/2}$ — $P_{1/2}$

$S_{1/2}$ — $D_{5/2}$

2020: Isotope shift @ $1{:}10^7$

Counts et al. (MIT), 3sigmas

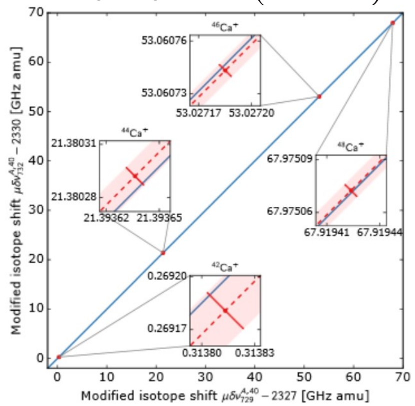


Yb⁺ (A=168,70,72,74,76)

$S_{1/2}$ — $D_{3/2}$

$S_{1/2}$ — $D_{5/2}$

Solaro et al. (Aarhus)



Ca⁺ (A=40,42,44,46,48)

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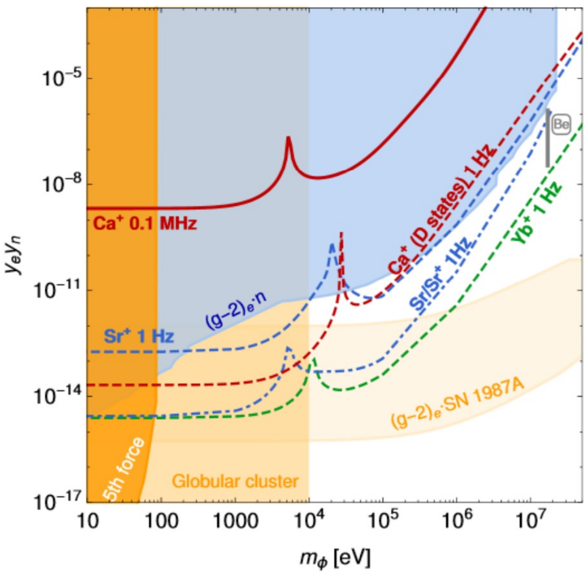
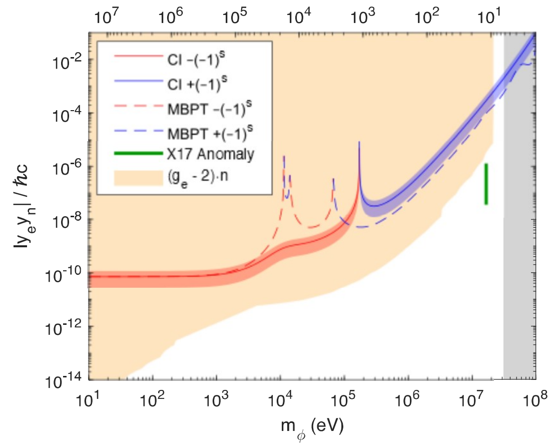
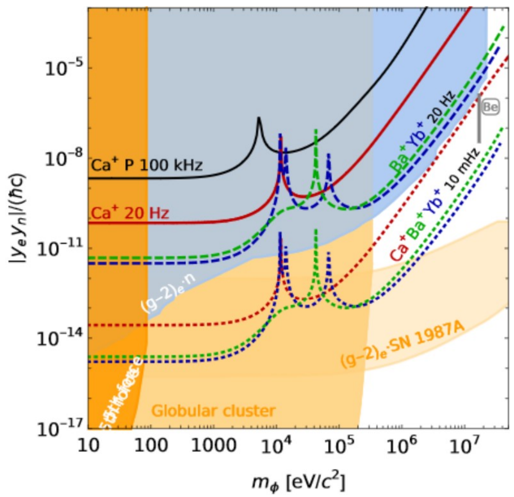


Counts et al. (MIT), 3sigmas



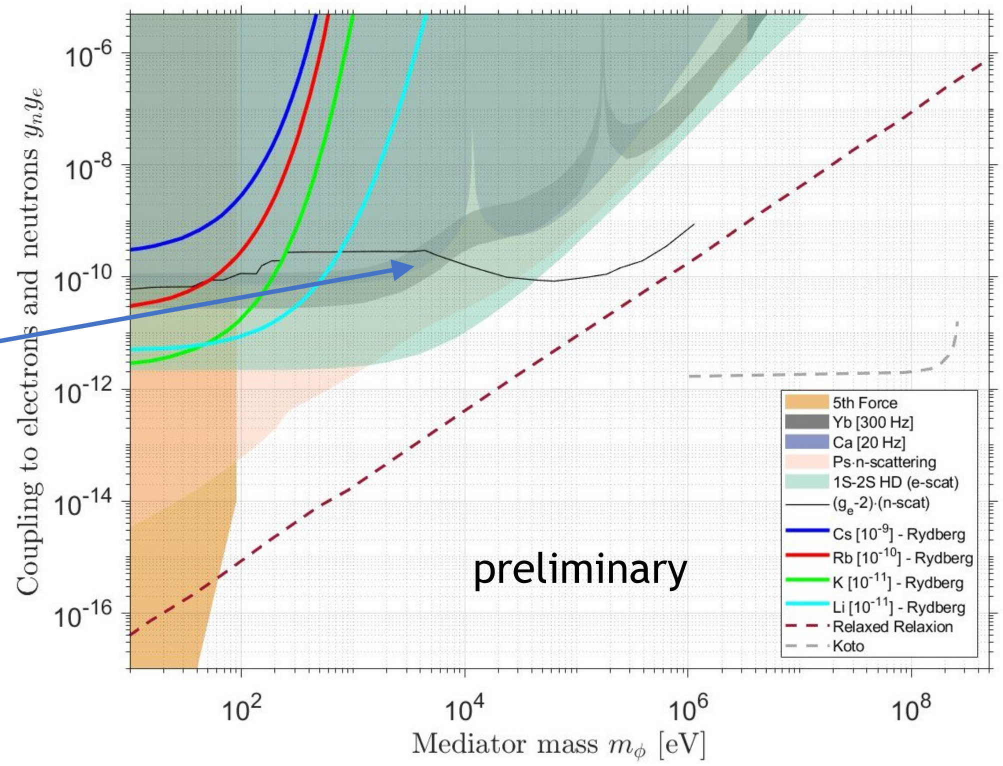
Solaro et al. (Aarhus)



How robust is the $(g\text{-}2)_e$ bound? Can we reduce SM contamination?

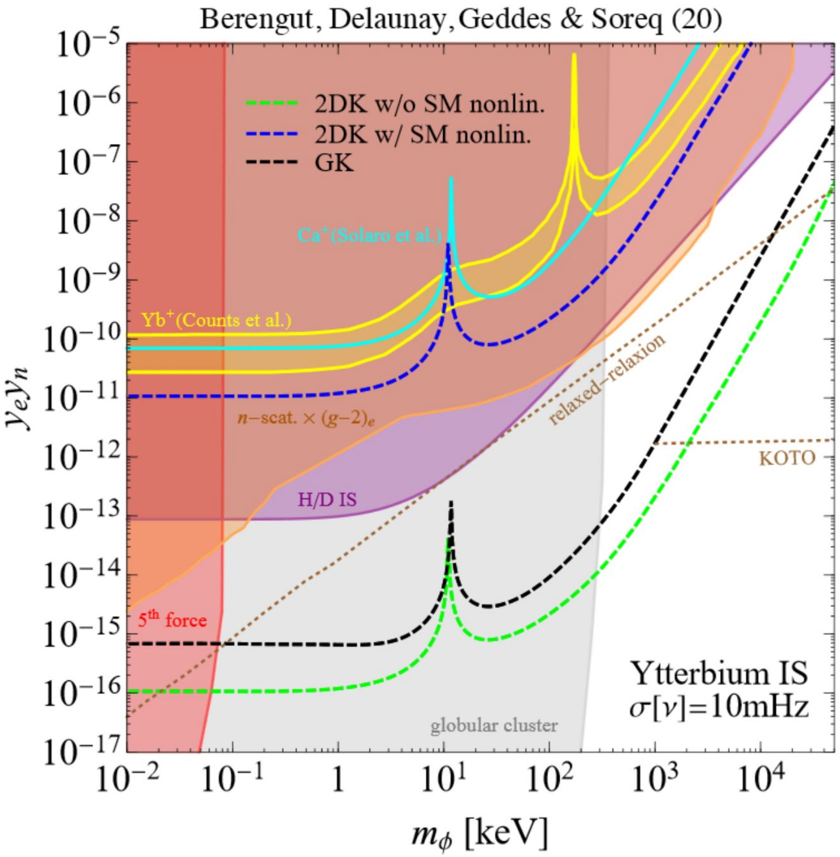
- The $(g\text{-}2)_e$ bound is model dep. & can be naturally suppressed (mirror sym.).
- Looking at (2-3) isotope shifts in “heavy" Rydberg transitions => reduce nuclear-impact.

See also: Jones, Potvliege & Spannowsky (19); Capolupo et al. (20)



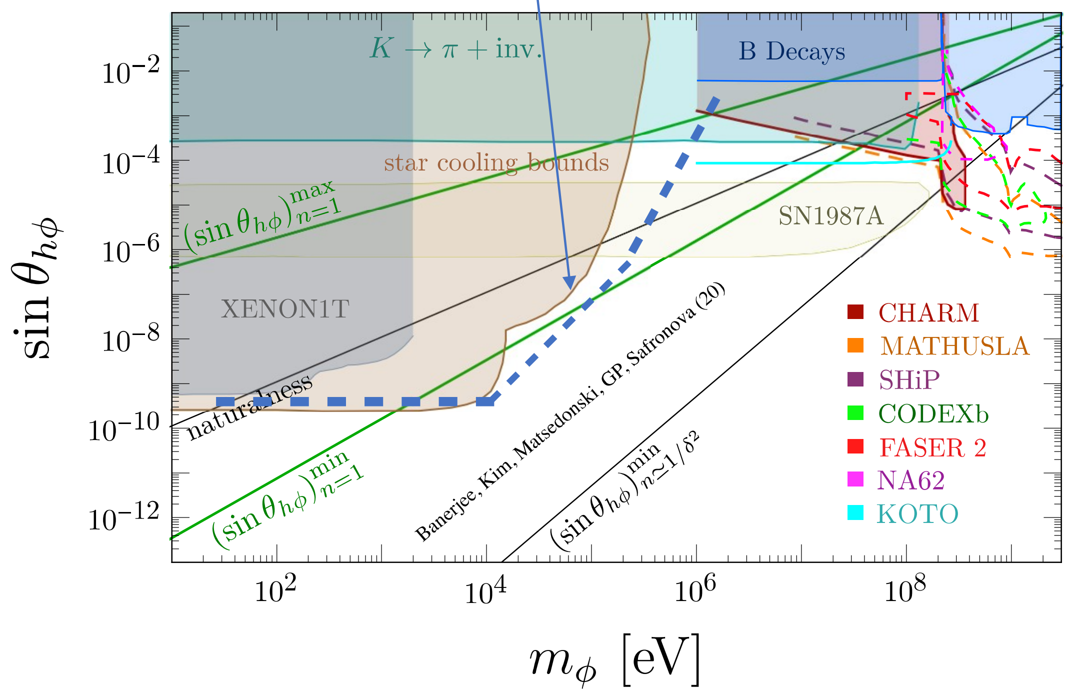
Duque-Mesa, Geller, Firstenberg, Fuchs, Ozeri, GP & Shpilman, in prep.

Projections, complementarity between precision & accelerators



2D KLV (2DK) analysis w (blue) \wo (green) NL_{SM} ; generalized King analysis (GK) adding the S → P transition (black). NP bounds in Yb^+ (95 % CL NP interval) + Ca^+ (upper bound) in yellow and cyan. 5th force searches, e-n scattering, neutron-nucleus scattering, \w $(g\text{-}2)_e$, hydrogen-deuterium (HD) IS & globular cluster. Dotted lines describes the relaxed-relaxion & the KOTO result.

Best case scenario: largest possible (non-SM) Yukawas & no non-linearity



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 + XENON provides 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.
- Potential new gravitational waves signal.

Hunting for ultra light scalar/relaxion DM

- 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)

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

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:

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

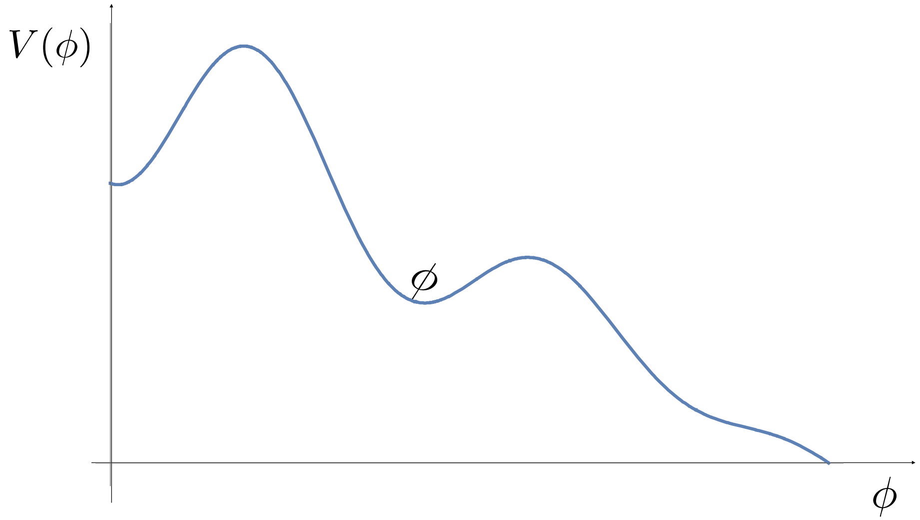
Relaxion/scalar light dark matter

Arvanitaki, Huang & Van Tilburg (15)
Banerjee, Kim & GP (18)

Concrete ex.: relaxion dark matter (DM)

Banerjee, Kim & GP (18)

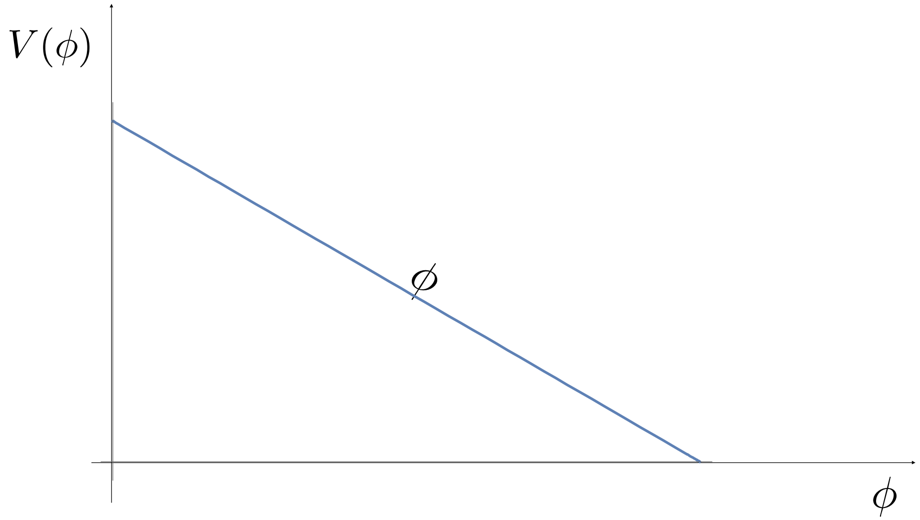
- Basic idea is similar to axion DM (but avoiding missalignment problem):



Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

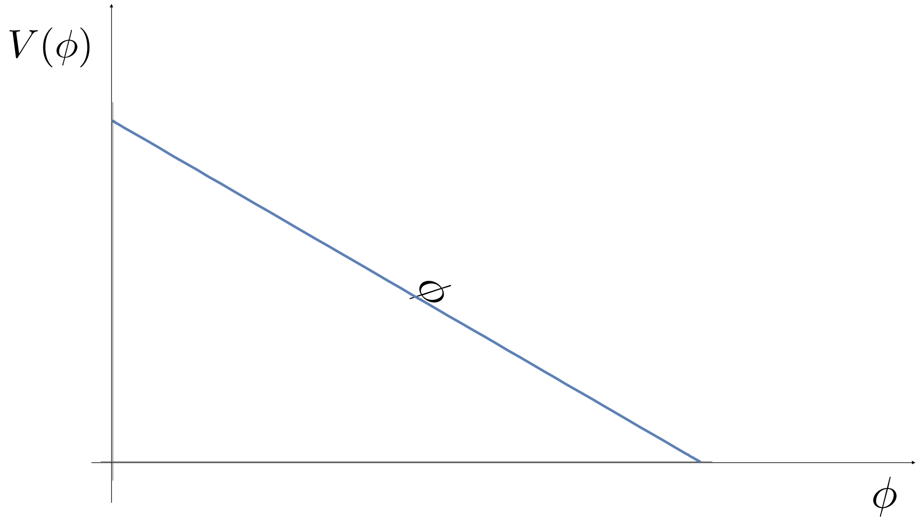
  After reheating the wiggles disappear (sym' restoration):



Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  After reheating the wiggles disappear: and the relaxion roles a bit.



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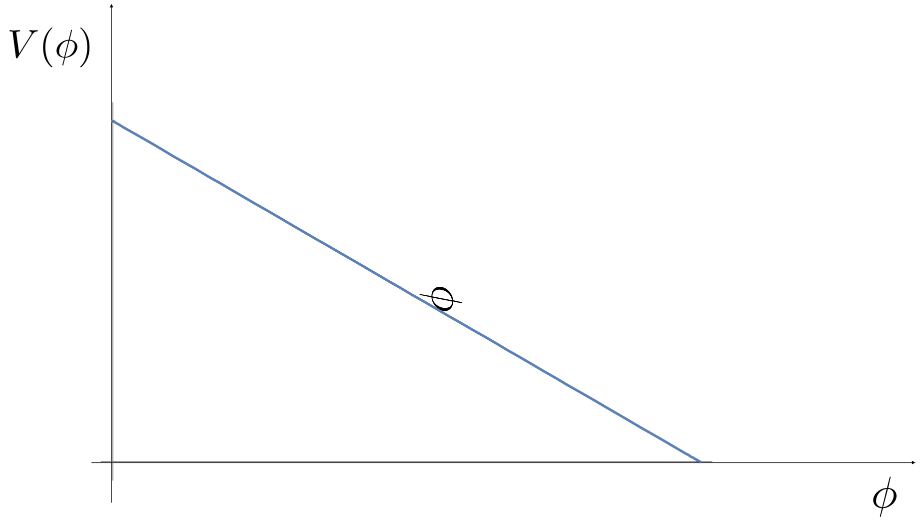
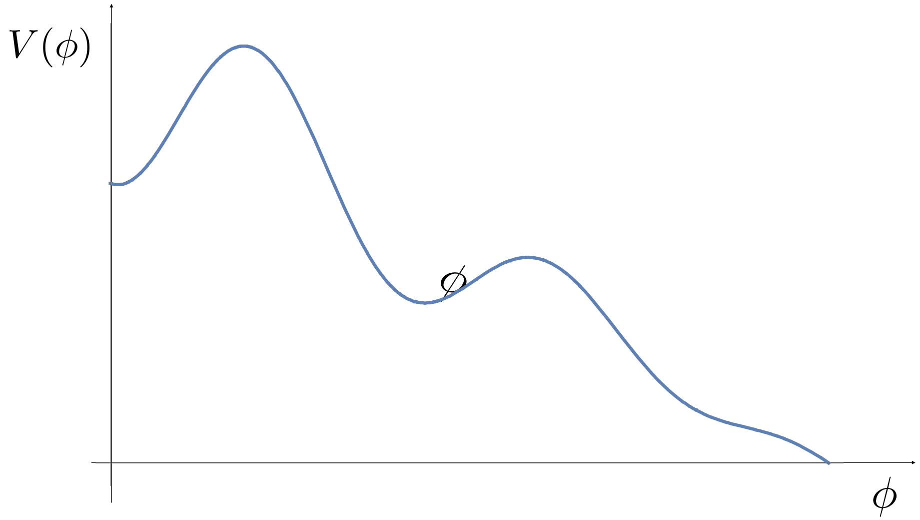


Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  Now the relaxion not at the min' and start to oscillates = DM.



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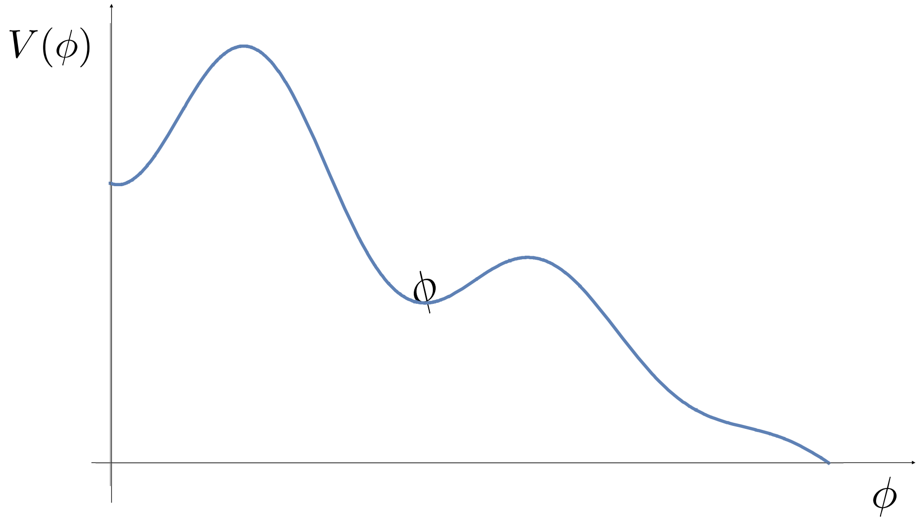

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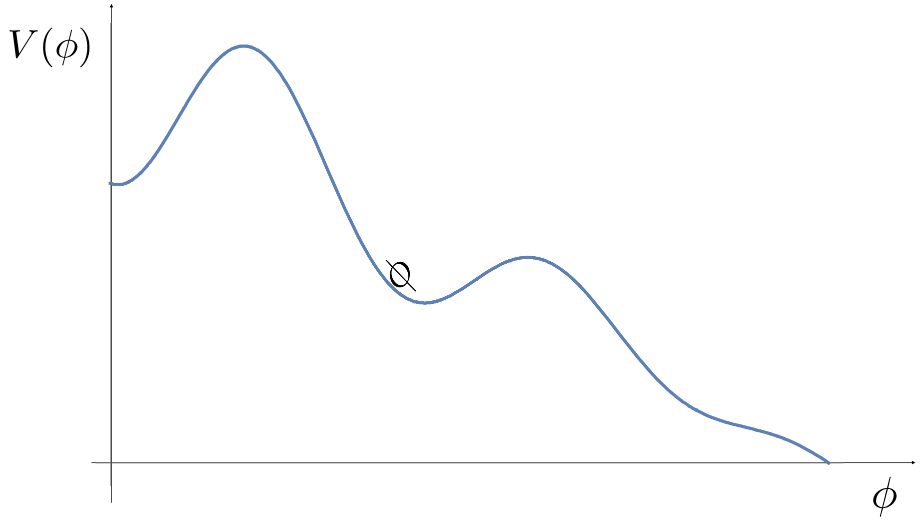

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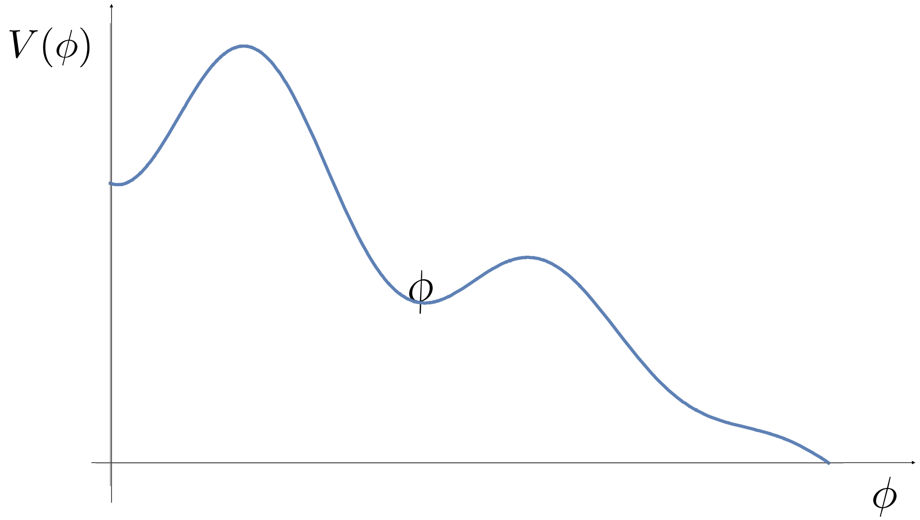

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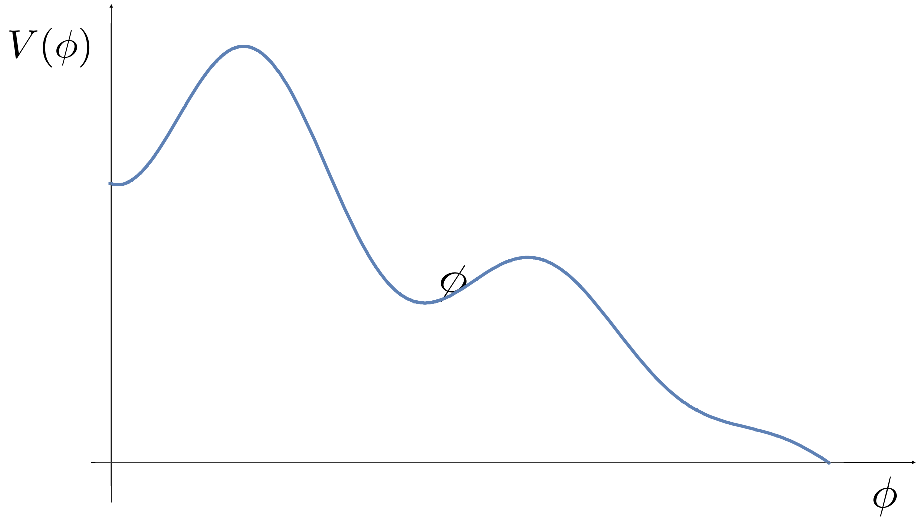
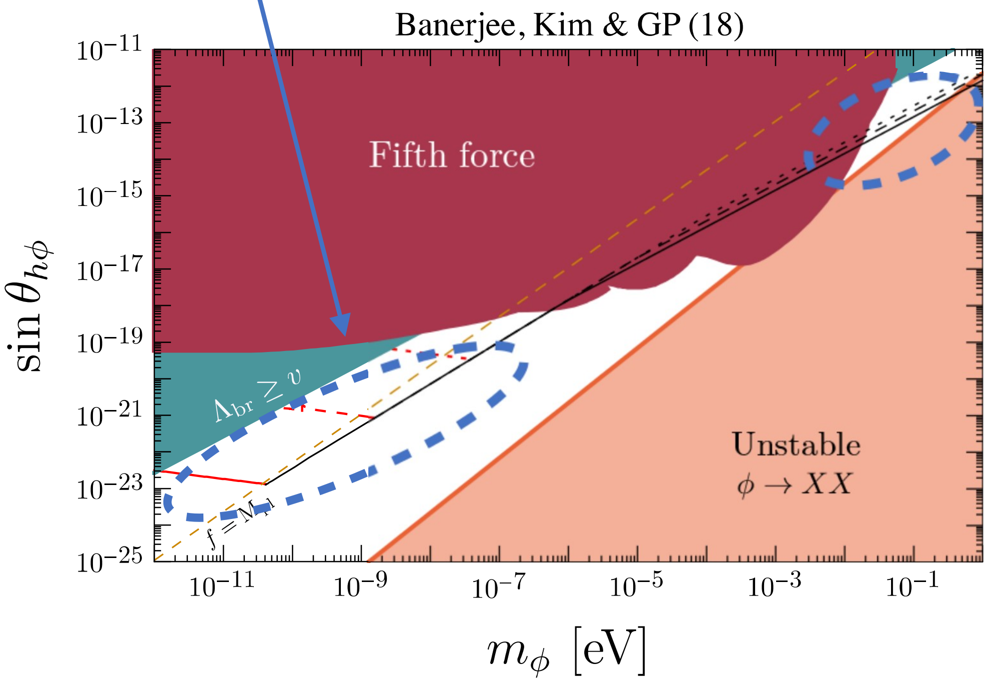


Relaxion/Higgs-portal & benchmarking

- Relaxion DM: a concrete realisation of the idea, via its Higgs mixing. Interesting that preferred region has oscillating frequency in the (blind-spot) kHz-MHz:

(requires alternative exp approaches, eg: Stadnik & Flambaum (14); Grote & Stadnik; Antypas et al.; Aharony et al. (19))

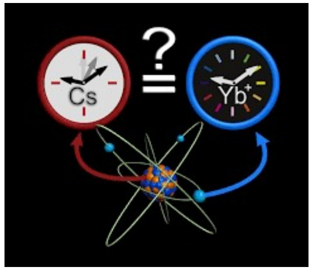


$$\mathcal{L} \supset \sin\theta_{h\phi}\frac{\phi}{v}\left[-m_f\bar{f}f + \frac{c_\gamma}{4\pi}FF + \frac{c_g}{4\pi}GG\right];$$

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

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)

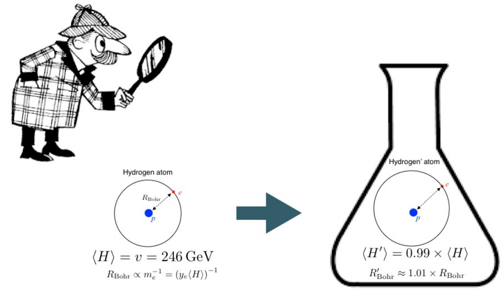
Fractional change of the frequency ratio: $\dfrac{\Delta\left(f_A/f_B\right)}{f_A/f_B}$

[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:



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

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

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

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

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

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

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 - $\phi \sim \sqrt{\rho}_{\mathrm{DM}} / m_\phi$

Extreme - $\phi \sim \sqrt{\rho}_{\mathrm{halo}} / m_\phi$

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:

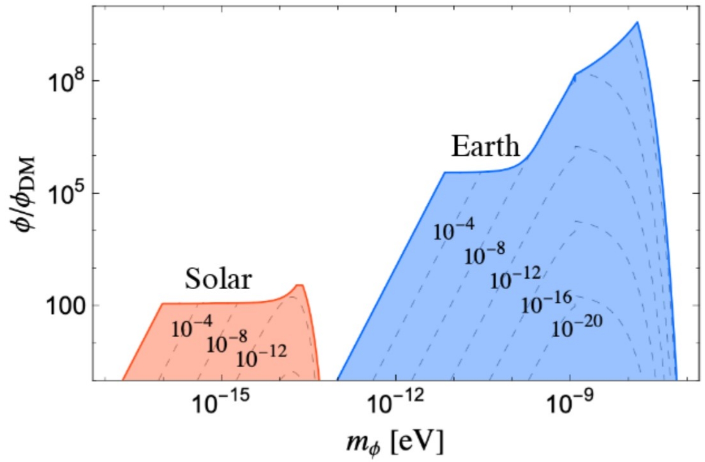
$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

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

Can obtain large density enhancement:

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

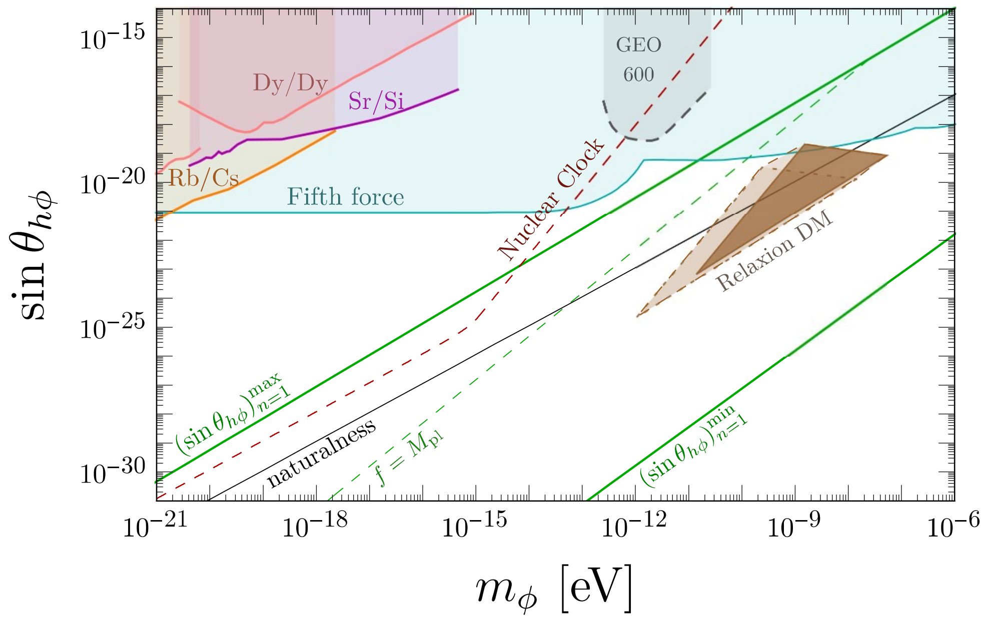
$$\xi \equiv M_{\rm star}/M_{\rm Earth}$$



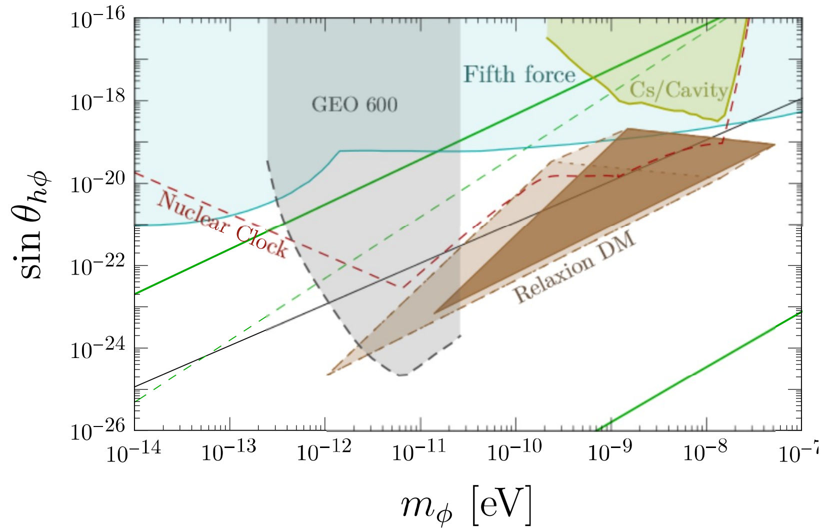
Enhancements in the axion halo scenario compared to the background DM case, in the field value for the Earth halo (blue) and solar halo (red) compared to the usual ALP DM case. Solid lines correspond to maximal halo mass M. by gravitational constraints.

Ideal system, nuclear clock, current & near future bounds

Banerjee, Kim, Matsedonski, GP & Safranova (20)



Best case “crazy“ scenario: largest possible DM density as allowed by indirect bounds.



Further in to the future

- Recent large scale Earth-based & space-based atom-interferometer were proposed/initiated -

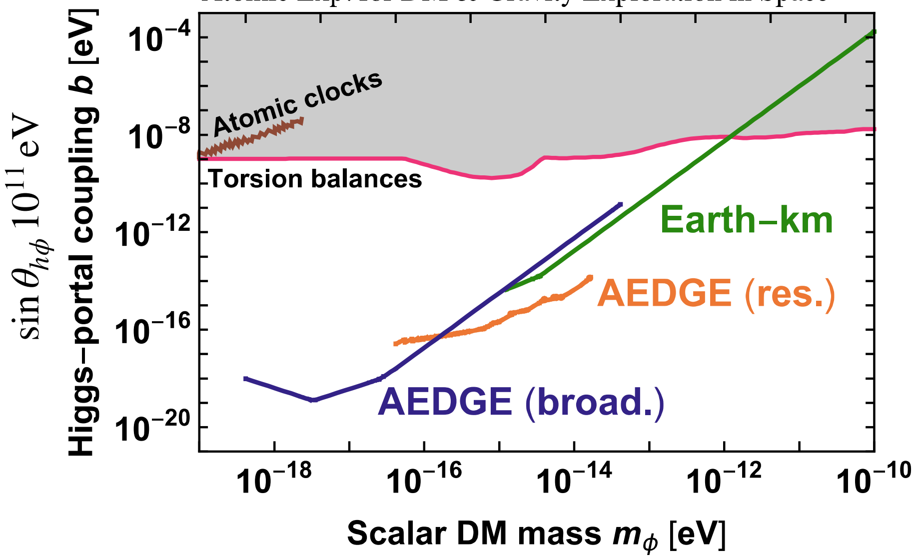
ELGAR, 1911.03701; MIGA, Sci. Rep. (18); MAGIS, 1711.02225; ZAIGA 1903.09288.

- Can potentially probe very large region, for intermediate DM masses (albeit slowly oscillating), for ex.:

Relevant th.: Graham, Hogan, Kasevich & Rajendran (13); Arvanitaki, Graham, Hogan, Rajendran, & Van Tilburg (18); Grote & Stadnik (19)

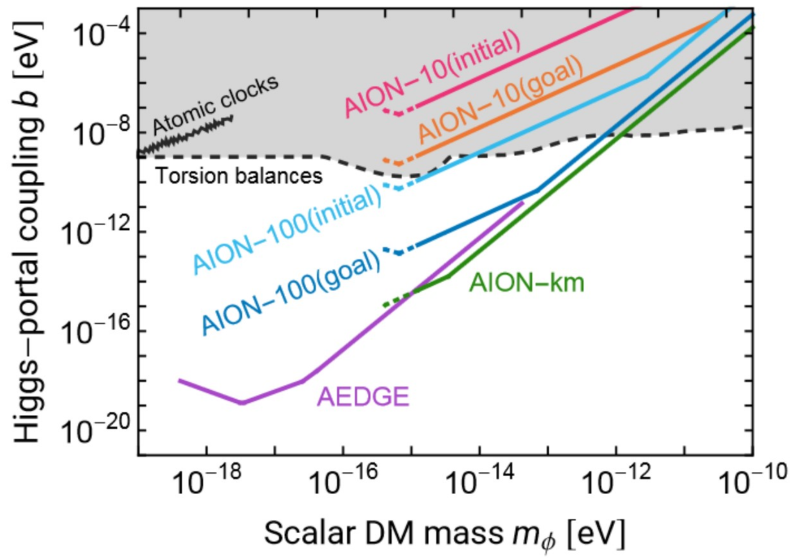
AEDGE (1908.00802)

Atomic Exp. for DM & Gravity Exploration in Space



AION (1911.11755)

An Atom Interferometer Observatory and Network



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.

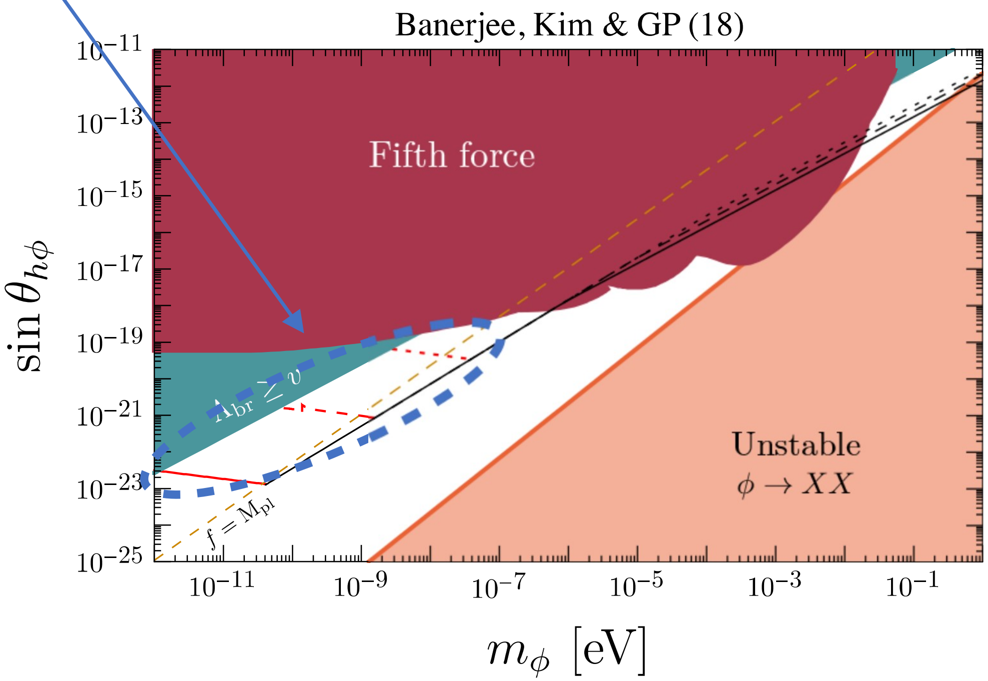
Antypas, Budker, Flambaum, Kozlov, GP & Ye (19)

- 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:

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

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:

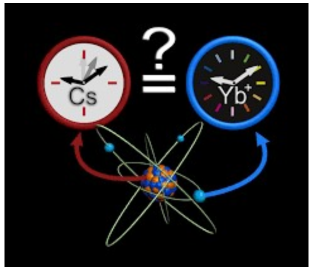


$$\mathcal{L} \supset \sin\theta_{h\phi}\frac{\phi}{v}\left[-m_f \bar{f} f + \frac{c_\gamma}{4\pi} FF + \frac{c_g}{4\pi} GG\right];$$

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: $\frac{\Delta\left(f_A/f_B\right)}{f_A/f_B}$

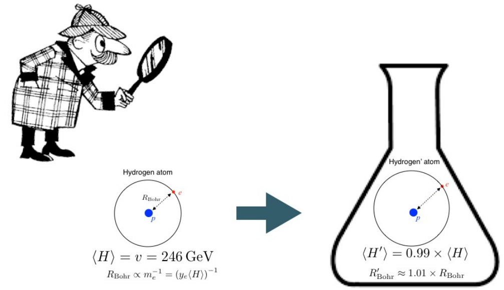
[see Safronova,Budker, DeMille, Kimball, Derevianko & Clark (18) for recent review]

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

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: $\tau_{\mathrm{DM}} \sim 1\mathrm{s} \times \dfrac{10^{-15}\mathrm{eV}}{m_{\mathrm{DM}}}$

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

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

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

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

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

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

  The sensitivity will be give by $\sin\theta_{h\phi}^{\text{bound}} \propto 1/m_{\phi}^{2}$. 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 - $\phi \sim \sqrt{\rho}_{\mathrm{DM}}/m_\phi$

Extreme - $\phi \sim \sqrt{\rho}_{\mathrm{halo}}/m_\phi$

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:

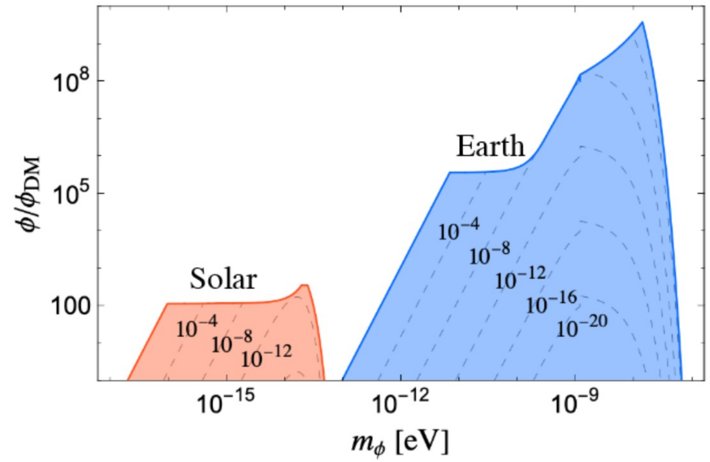
$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

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

Can obtain large density enhancement:

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

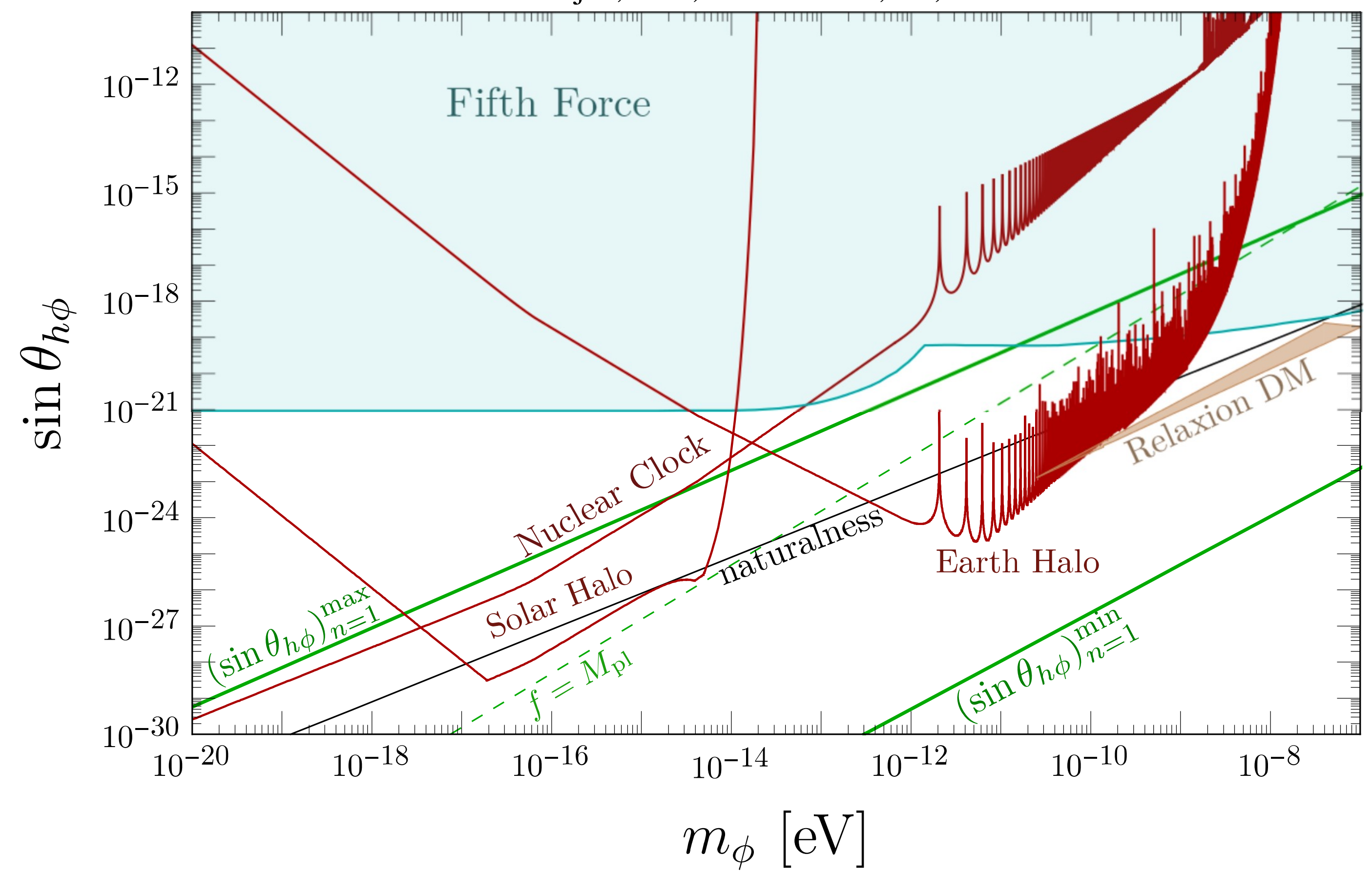
$$\xi \equiv M_{\rm star}/M_{\rm Earth}$$



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.

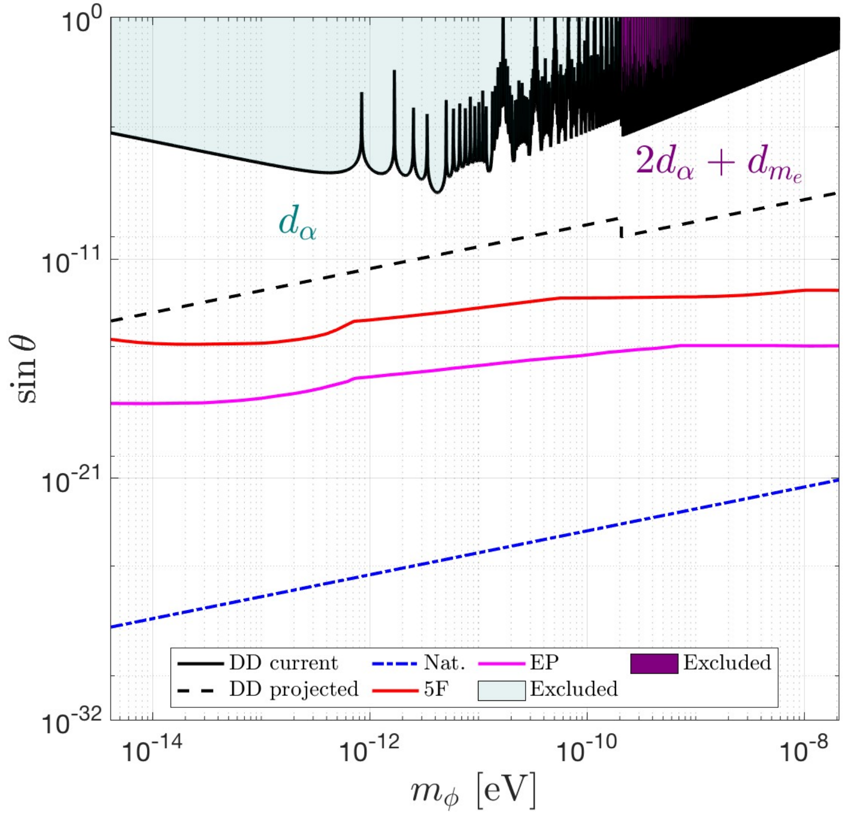
Ideal system, nuclear clock

Prelim: Banerjee, Kim, Matsedonski, GP, Safranova



Beyond 1Hz DM mass \w dynamical decoupling

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

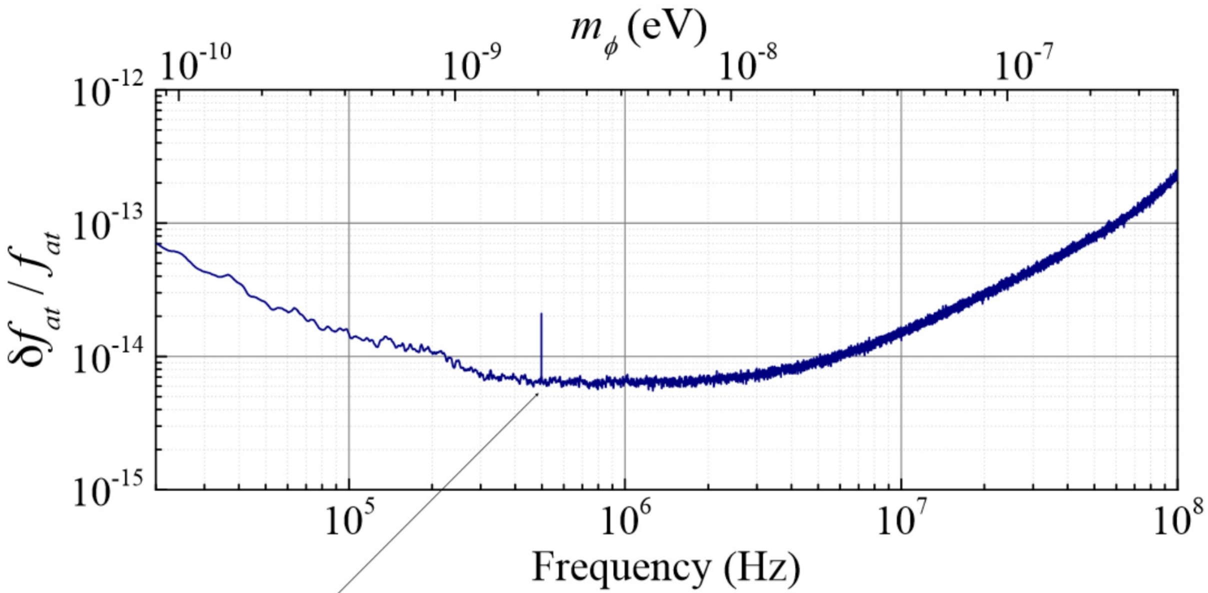


The bounds on the mixing angle of a relaxion DM: Black – current and projected bounds from DD experiments at 95% CL. Red – Bounds from fifth force experiments. Magenta – EP-tests bounds. Dash-dotted – Bounds from Naturalness.

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)



3rd laser harmonics.

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.

$\Downarrow$

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

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

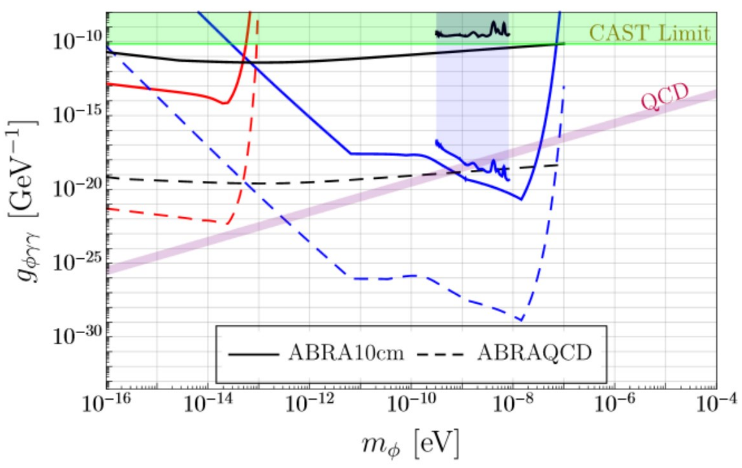
$\left(\mathcal{L} \supset g_{\phi NN}\partial_\mu\phi\bar{N}\gamma^\mu\gamma_5 N - \frac{i}{2} g_d\, \phi\, \bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu} + ...,\right)$

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

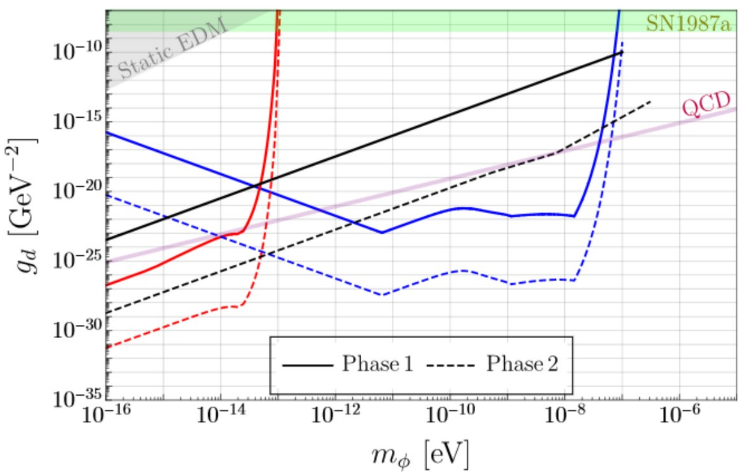
- In the case of axion-halo the “wind” is replaced by density gradient which is orientation-dependent => new type of signature.

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).

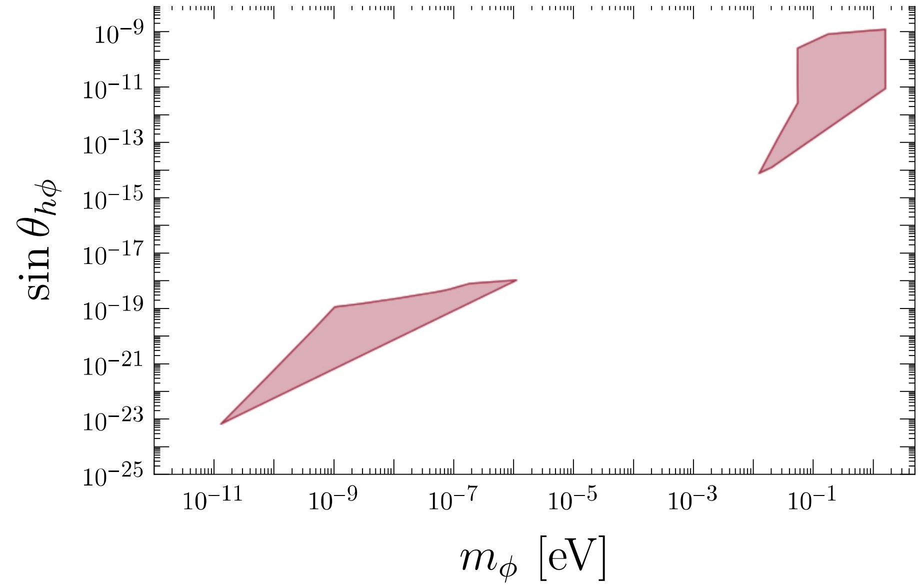
Conclusions

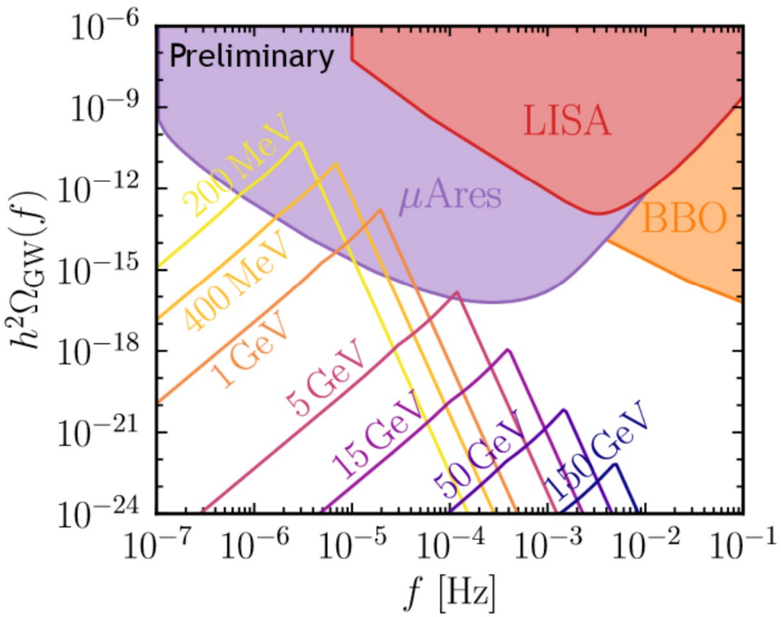
- Higgs physics has been always our beacon for new physics.
- Null-results + new theories (ex.: relaxion) => log crisis/opportunity, calls for experimental diversity.
- Accelerators provided a unique opportunity to search for (relaxed) relaxion.
- Ultra-light relaxion DM => Higgs VEV oscillating => exciting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

DM relaxion gravitational waves

Banerjee, Kim, Madge, GP, Ratzinger & Schwaller in preparation

Preliminary: the DM favoured region





Gravitational wave spectra for a relaxion mass of $m_\phi = 1$eV and a cutoff scale of $\Lambda = 1$TeV. The decay con- stant f_ϕ is set to the value for which the relaxion accounts for the full dark matter relic abundance, whereas the cou- pling r_X to the dark photon field is set to the minimal value for which the relaxion remains in its original minimum. The colored lines correspond to different values of the reappear- ance temperature T_{ra}, while the colored regions indicate the prospective detection reach of μAres (purple), LISA (red), and BBO or other LISA successors (orange).