

Probing the relaxed relaxation with luminosity & S1 and S2

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Zooming in on Axions in the Early Universe

Outline

- Intro, 21st century log crisis/opportunity
- Case study, relaxed-relaxion, a few lessons
- (Luminosity on Earth)
- Solar luminosity & Xenon
- [Precision]
- 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

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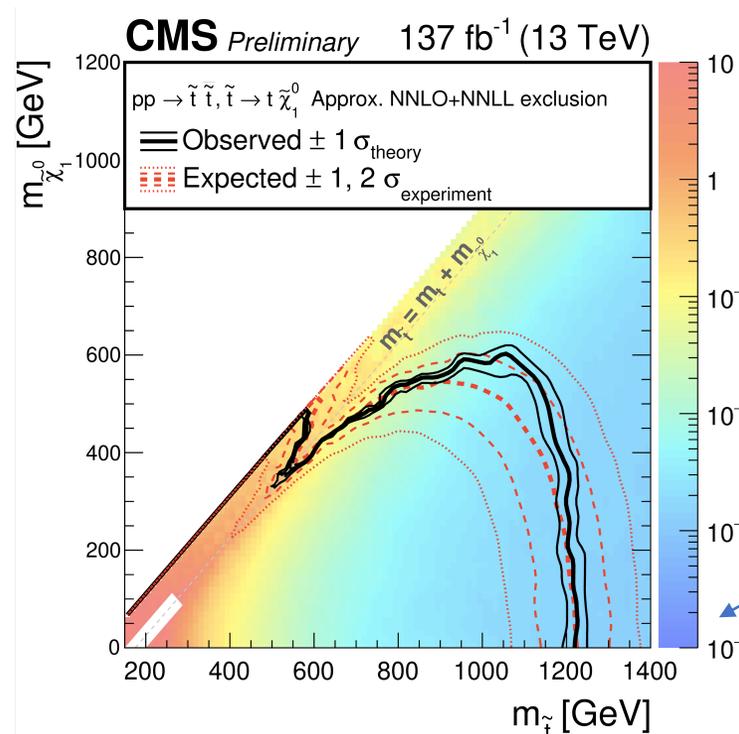
- Motivates us to look for new search strategies

Conventional wisdom

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

Sym' based solution to Naturalness \Leftrightarrow TeV NP (still the most compelling)

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



Summary and Outlook

- ATLAS and CMS have a comprehensive program of searches for new physics decaying to 3rd gen. particles
- Results are starting to become available with the full Run 2 dataset

No significant excess has been observed yet.

New Physics?

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.

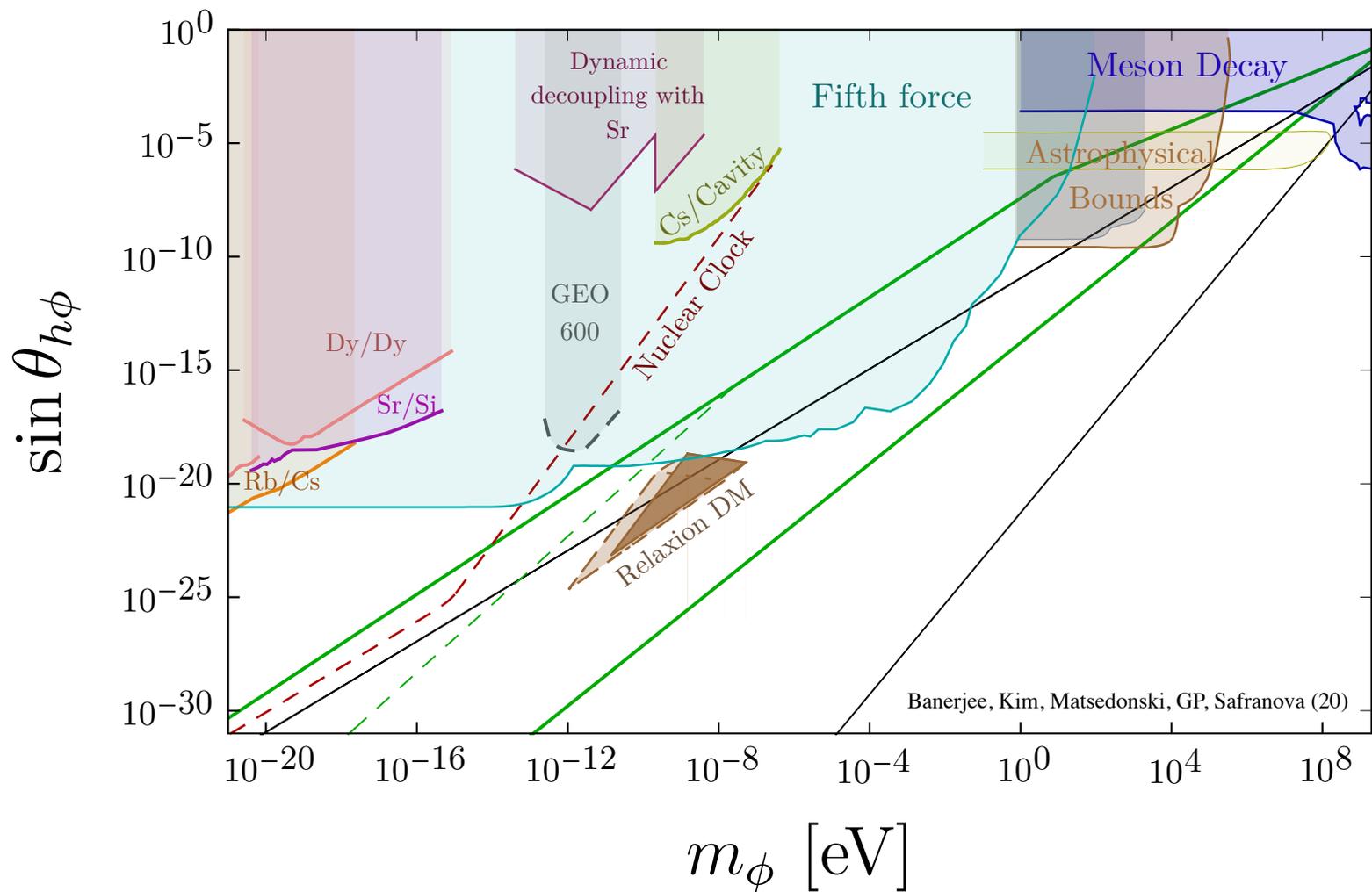
- Bottomline here: relaxion is axion-like-particle (ALP)-DM that (due to CP violation) can be described as scalar mixes w the Higgs but with weird (shallow) potential.

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

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

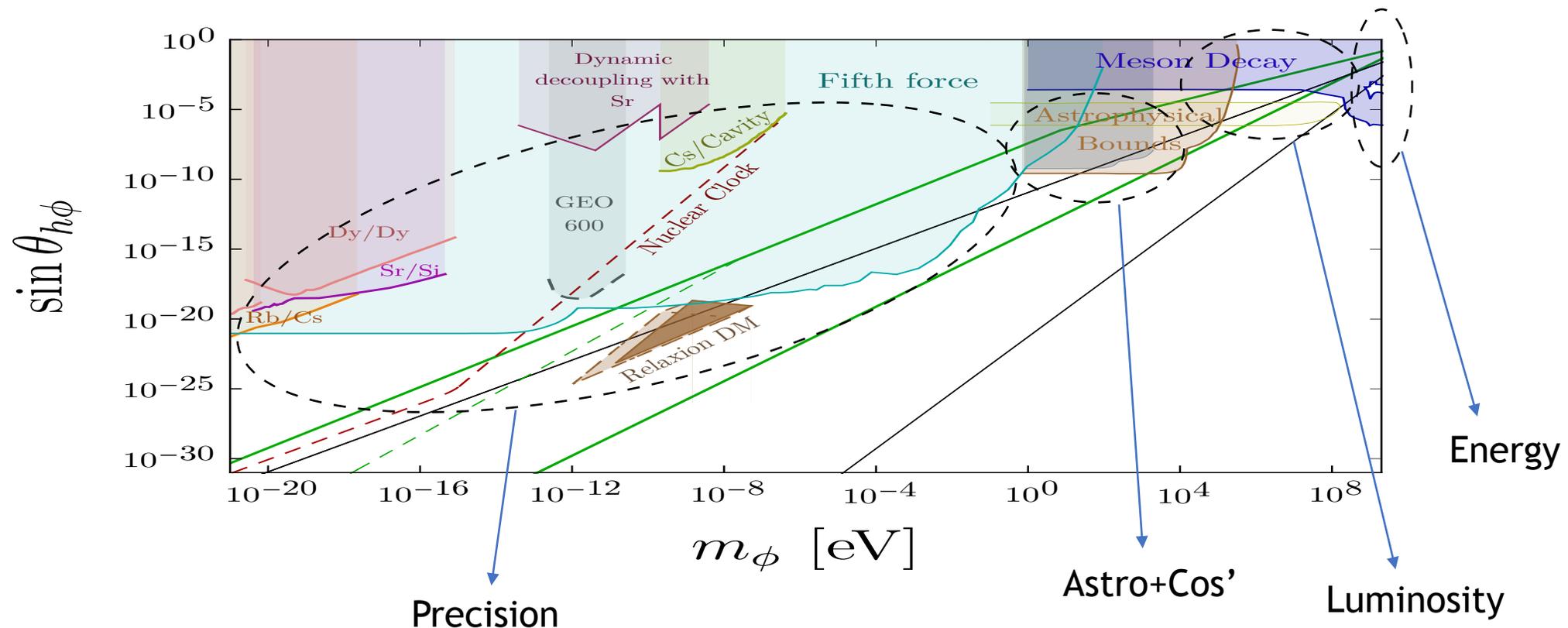
The relaxion (Higgs portal) parameter space & the *log crisis*

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



The log crisis, toy example, some PBC lessons

- Lesson 1 - finding NP requires diverse approach, searches across frontier
- Lesson 2 - experimentally, worth checking where many decades are covered:

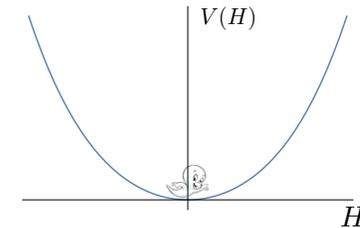
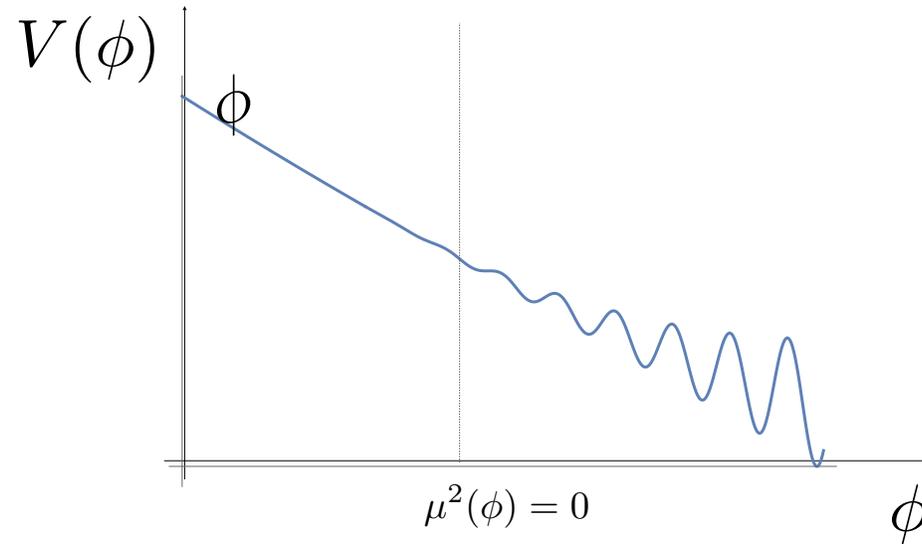


Relaxion mechanism (inflation based)

Graham, Kaplan & Rajendran (15)

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

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

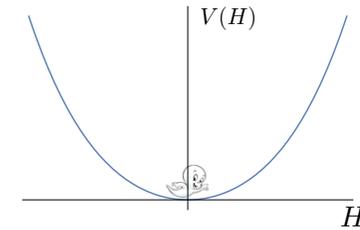
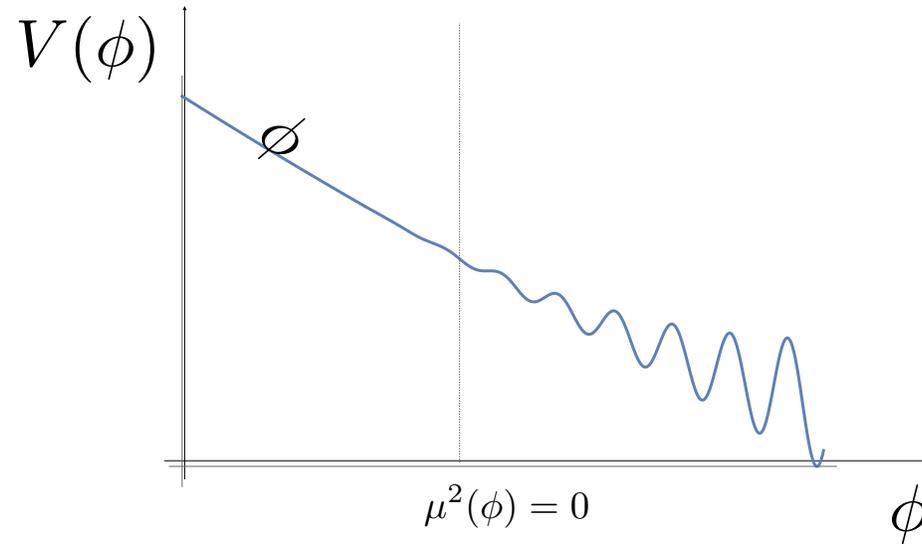


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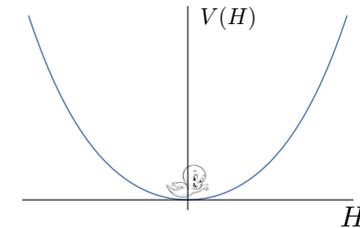
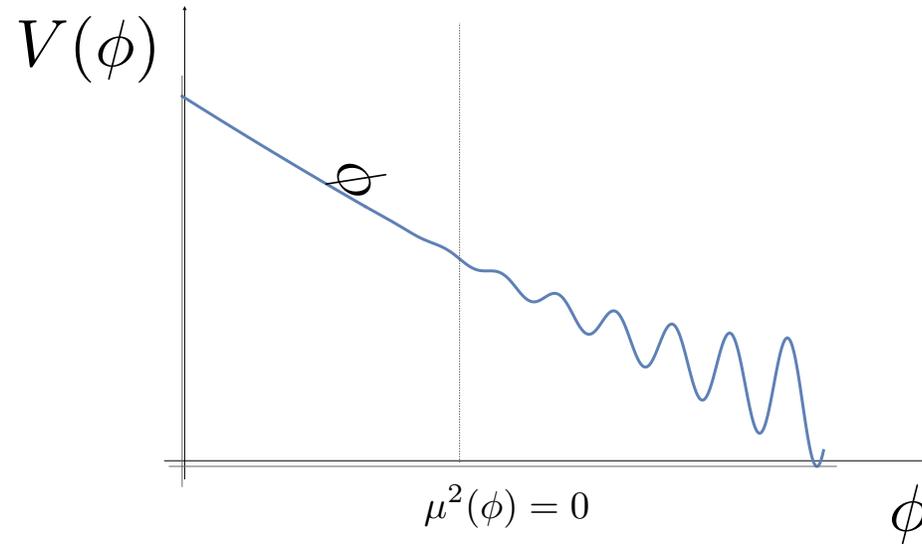


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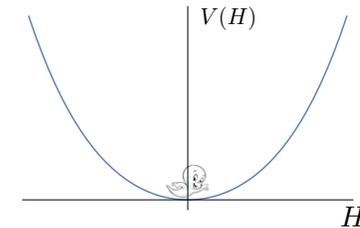
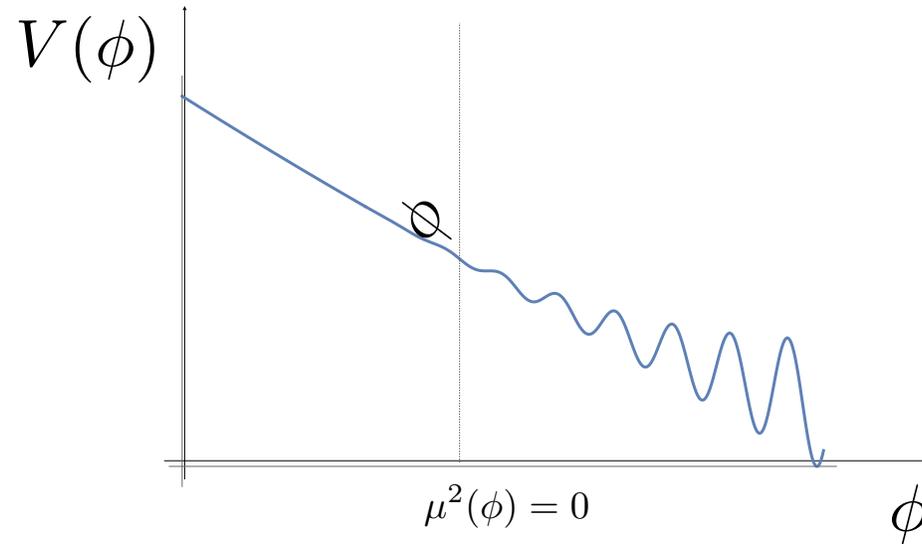


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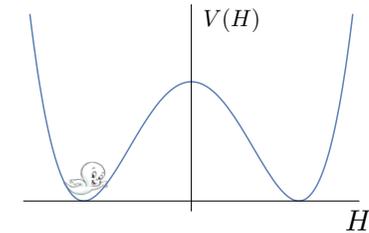
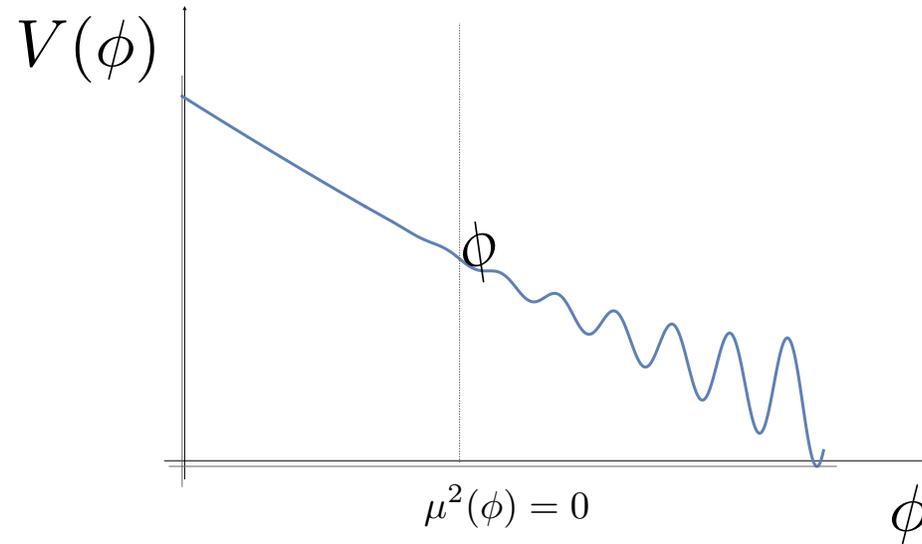


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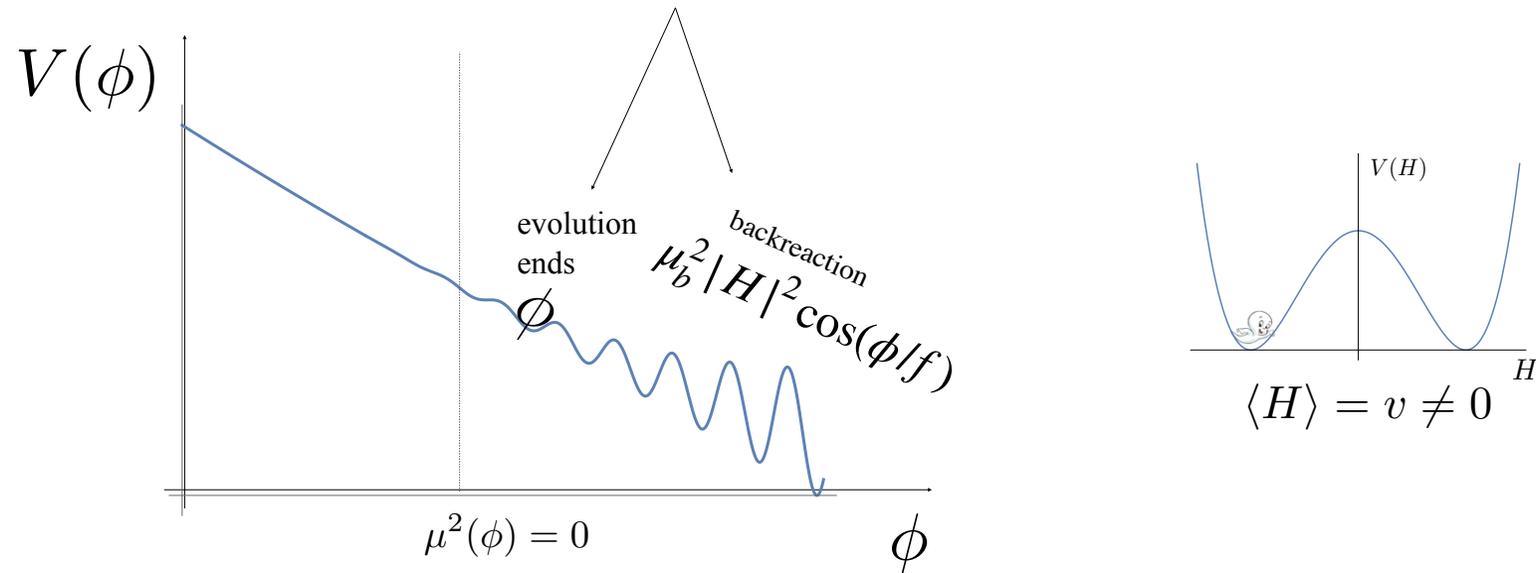


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The relaxion parameter space

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

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

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

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

Banerjee, Kim, Matsedonski, GP & Safranov (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)

$$m_\phi^2 \sim \partial_\phi^2 V_{br}(\phi, h) \sim \frac{\mu_b^2 v_{EW}^2}{f^2} \cos \frac{\phi_0}{f} \sim 1$$

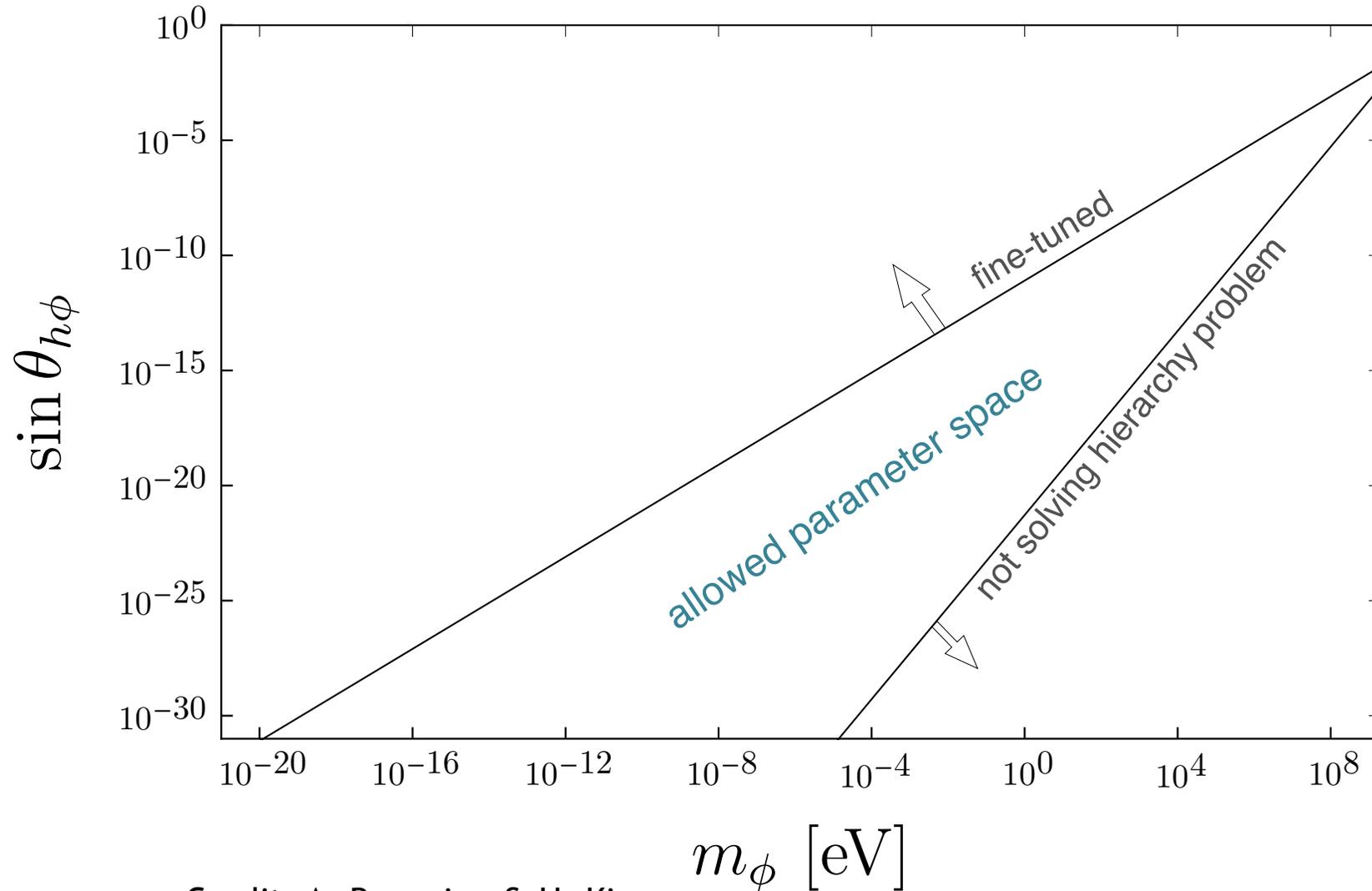
$$\sin \theta_{h\phi} \sim \partial_\phi \partial_h V_{br}(\phi, h) / v_{EW}^2 \sim \frac{\mu_b^2}{f v_{EW}} \sin \frac{\phi_0}{f}$$

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

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

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

The relaxion's naive parameter space



Credit: A. Banerjee & H. Kim

Less naive treatment

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

Relaxion stopping point determines the EW scale $\frac{\Lambda^4}{f_{\text{eff}}} \sim \frac{\mu_b^2 v_{\text{EW}}^2}{f}$

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

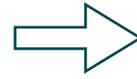
Resolution parameter 

$$V_{\text{br}} = -\mu_b^2 |H|^2 \cos \frac{\phi}{f} \quad \Rightarrow \quad \text{Potential height grows incrementally}$$

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

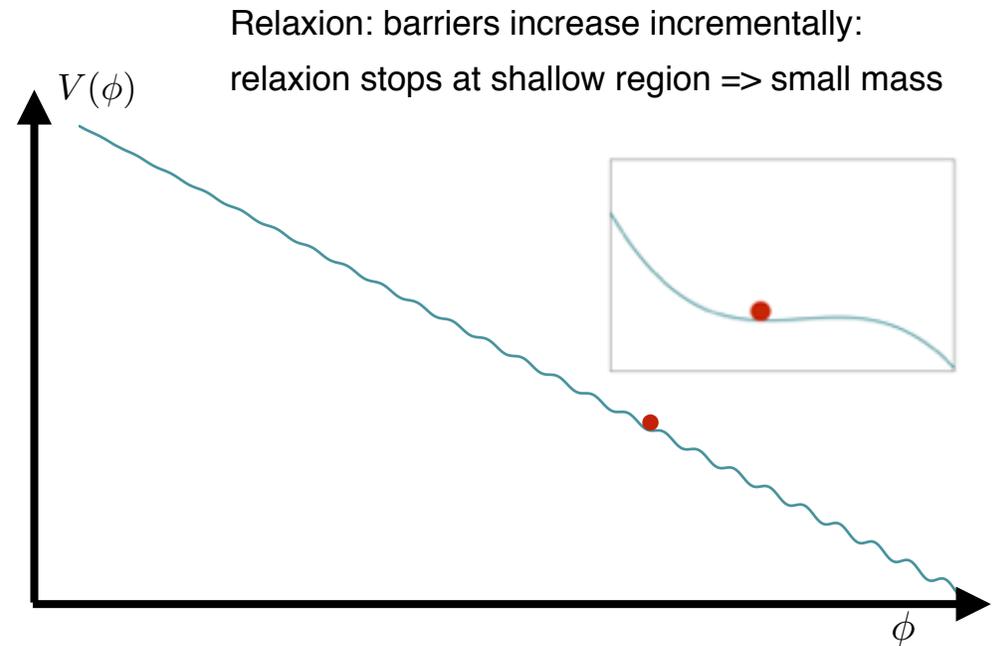
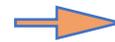
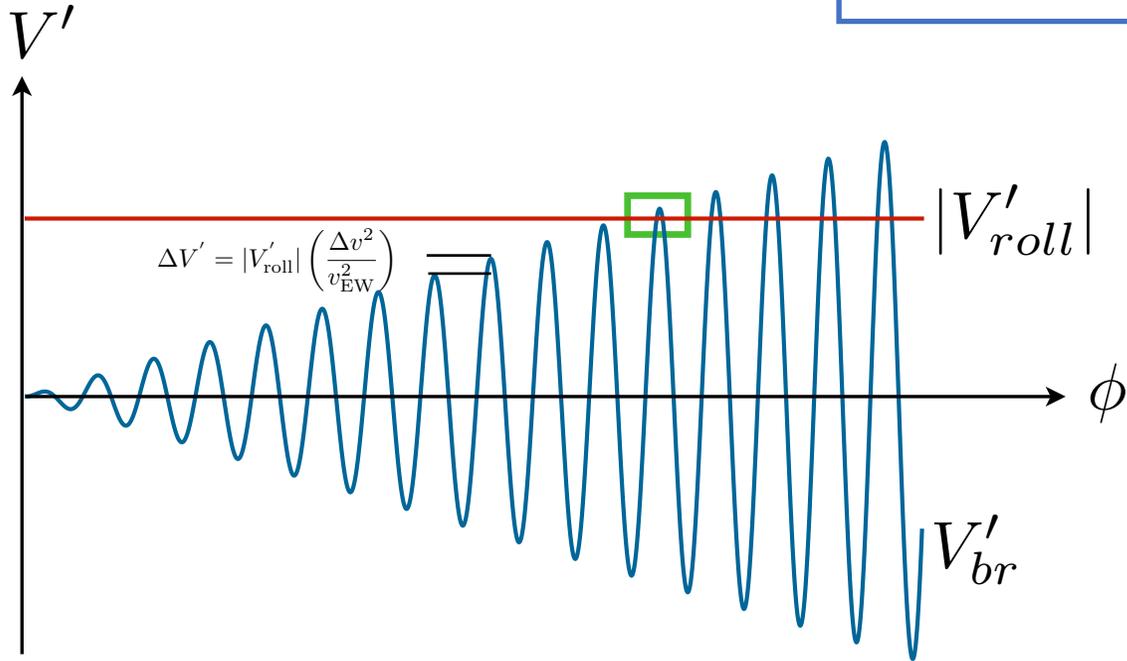
Banerjee, Kim, Matsedonski, GP, Safranov (20)

$$V'_\phi = 0 \Rightarrow \sin \theta = \frac{v_{EW}^2}{v^2(\phi)} + \frac{v_{EW}^2}{\Lambda^2}$$



$$\frac{\phi_0}{f} \sim \frac{\pi}{2} \text{ upto resolution factors}$$

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

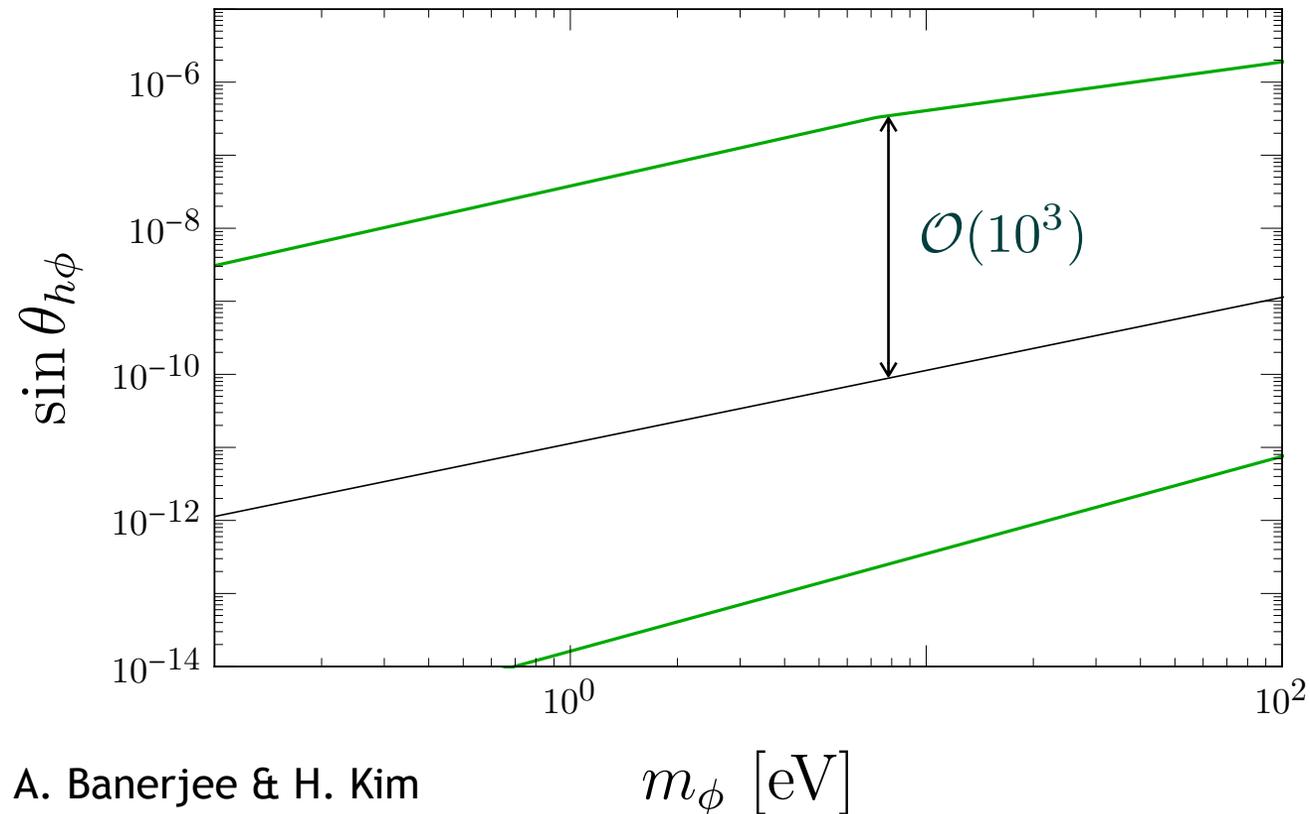


Credit: A. Banerjee & H. Kim

Relaxed mass => natural violation of naturalness bound

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

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



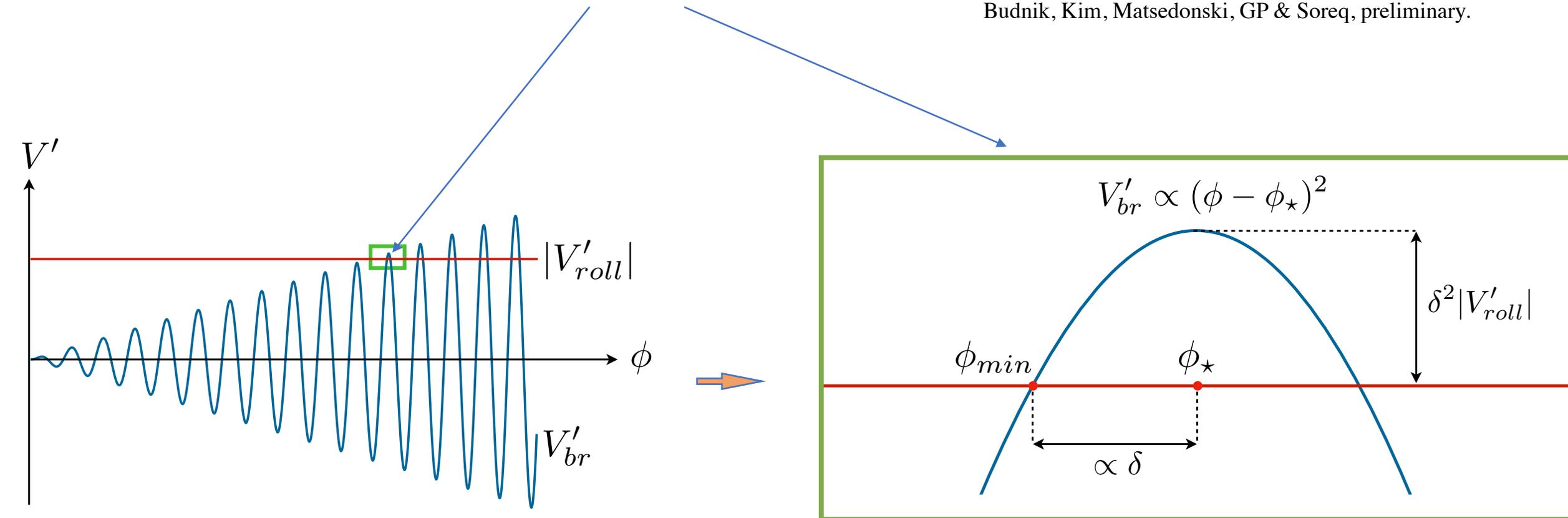
Credit: A. Banerjee & H. Kim

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

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

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

Budnik, Kim, Matsedonski, GP & Soreq, preliminary.



Credit: A. Banerjee & H. Kim

Intro, new search strategies

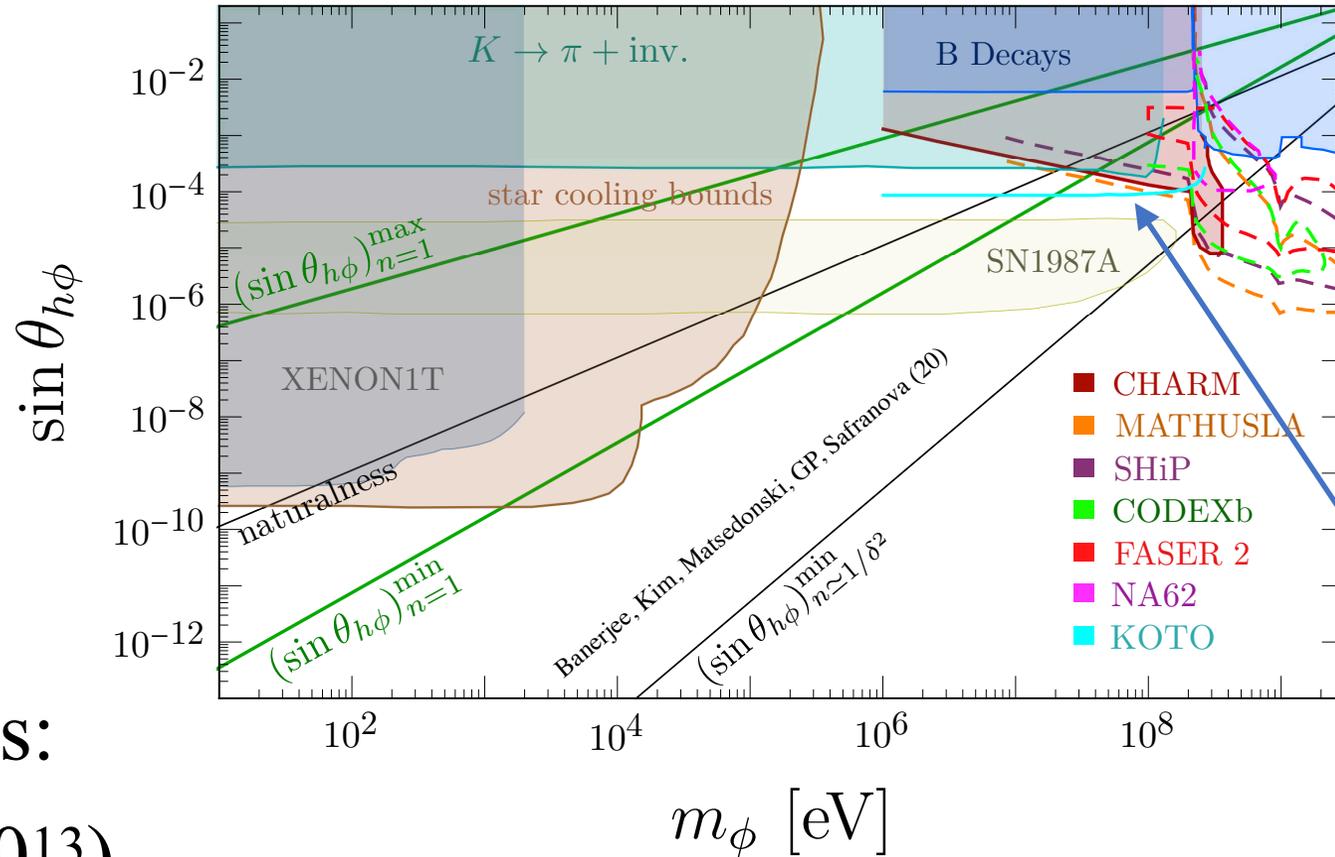
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Luminosity & precision: the era of Kaon factories



The Kaon factories:

of Kaon of $O(10^{13})$

aiming for BR of $O(10^{-11})$ soon (factor 10^{2-3})!

KOTO "hint"

Preliminary: Searching for a solar relaxion/scalar

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

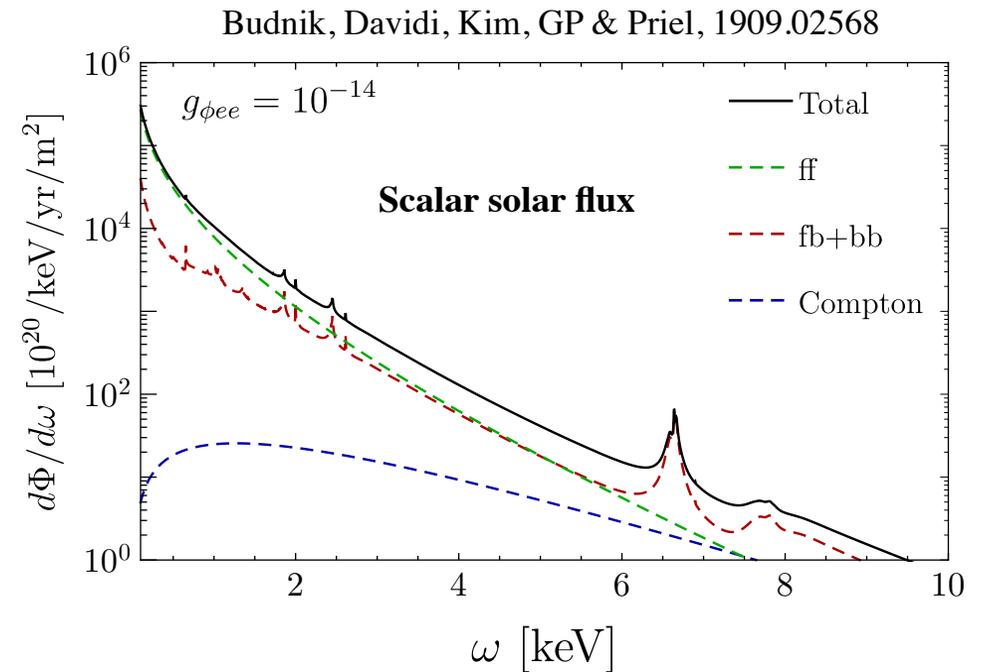
Budnik, Kim, Matsedonski, GP & Soreq, *preliminary*.

Everything discussed next is work in progress; you should take it with a grain of salt, we also have a discussion regarding our Xsec calculation \w Redigolo & Volansky.

However, at least some of the results are interesting in essential way and thus possibly interesting regardless.

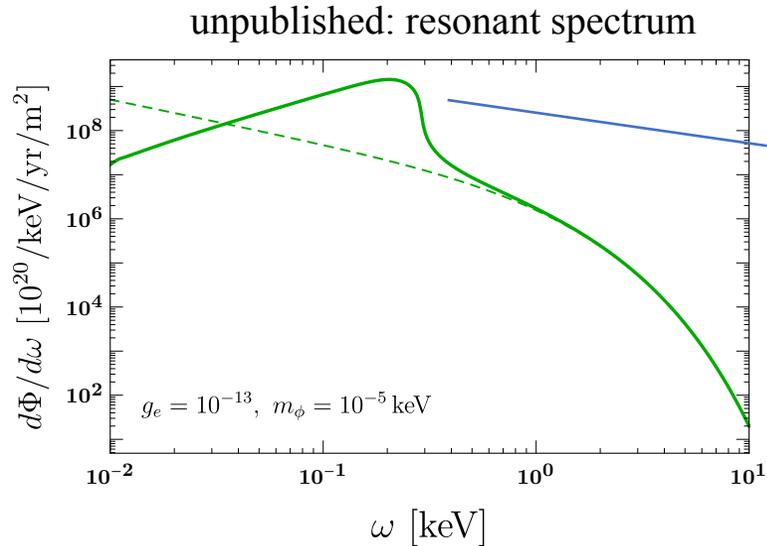
Prehistory: Searching for solar relaxion/scalar via dark matter detectors

- We computed the relaxion production in the solar core. (via Bremsstrahlung & resonant processes)
- This flux can be absorbed by liquid xenon dark matter (DM) detectors.
- Used XENON (19) & LUX (17) to constrain the relaxion-electron couplings ($g_{\phi ee}$):

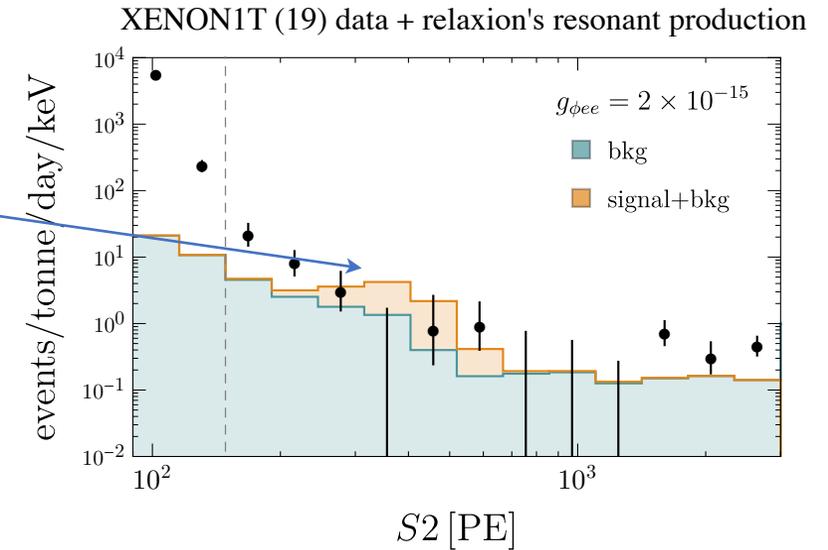


The coupling to electrons is chosen to be $g_{\phi ee} = 10^{-14}$, and scalar taken to be massless. Green dashed line is Bremsstrahlung flux from electrons interacting with hydrogen and helium ions, red dashed line is the flux due to recombination and transitions of bounded electrons in heavier elements,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



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



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

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

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

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].

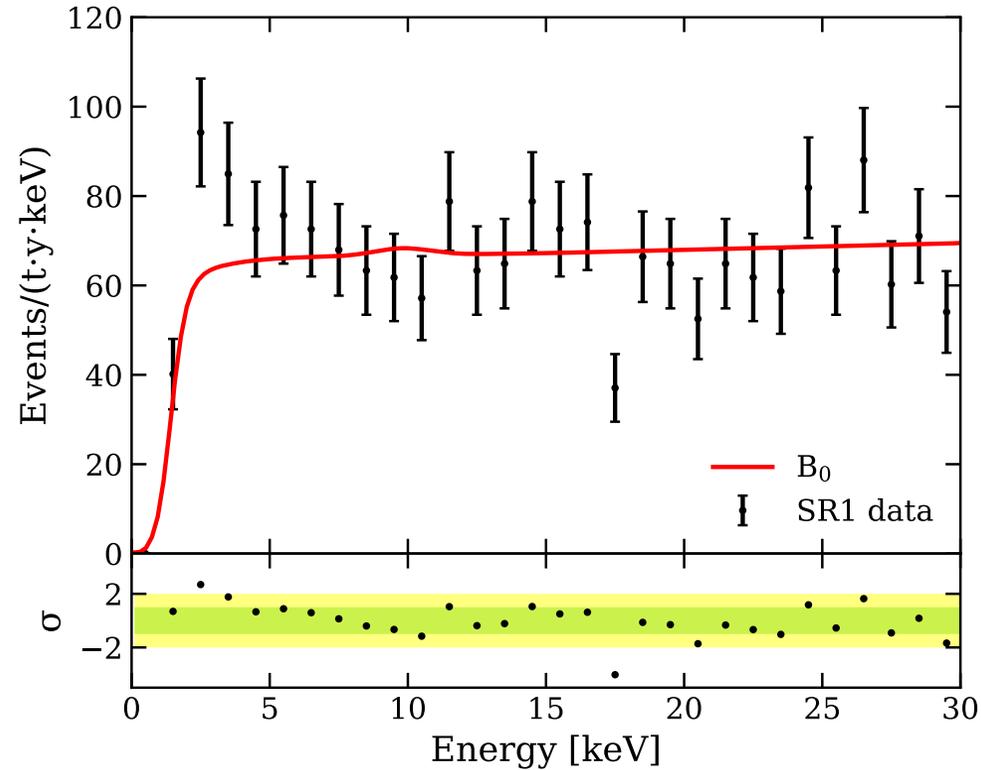
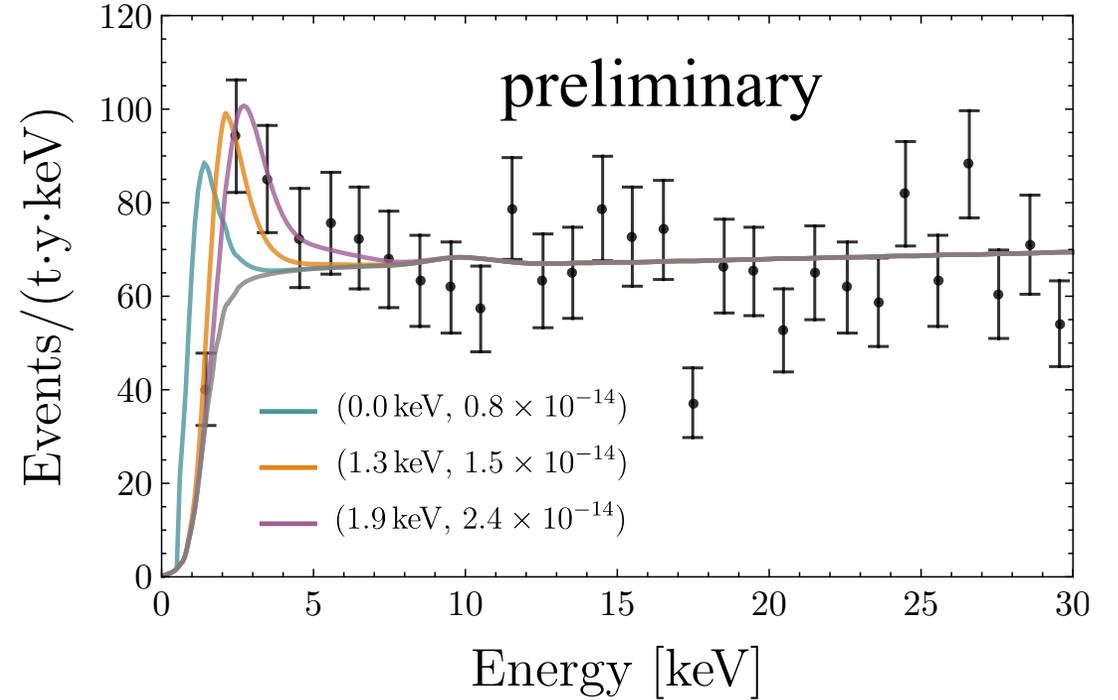
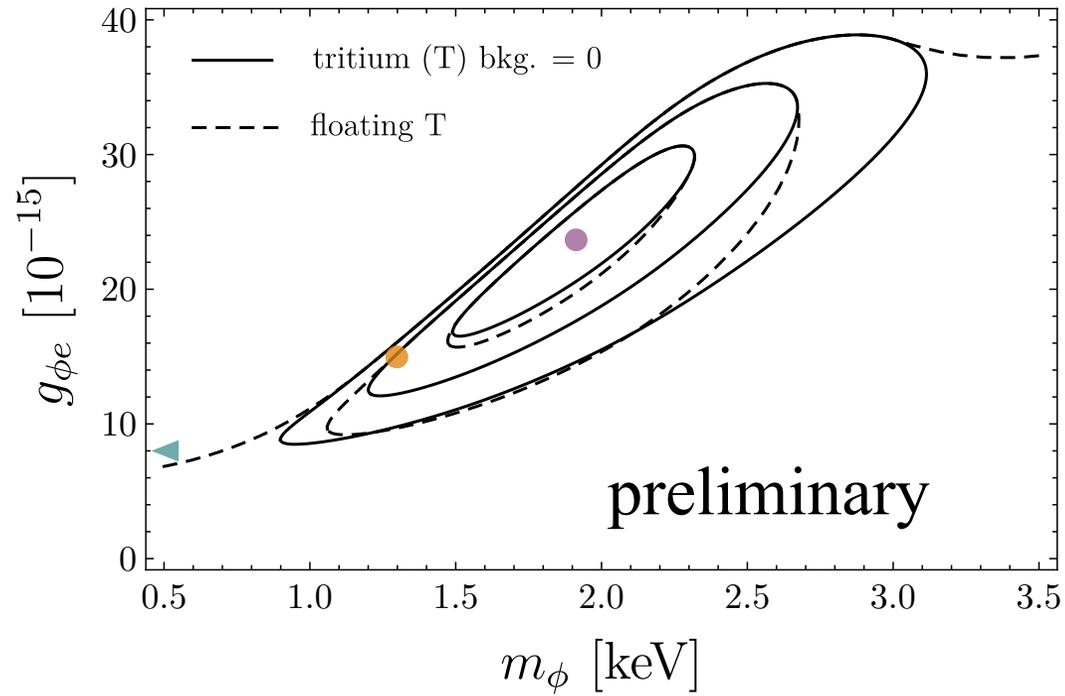


FIG. 4. A zoomed-in and re-binned version of Fig. 3 (top), where the data display an excess over the background model B_0 . In the following sections, this excess is interpreted under solar axion, neutrino magnetic moment, and tritium hypotheses.

Fitting to scalar preliminary, S1

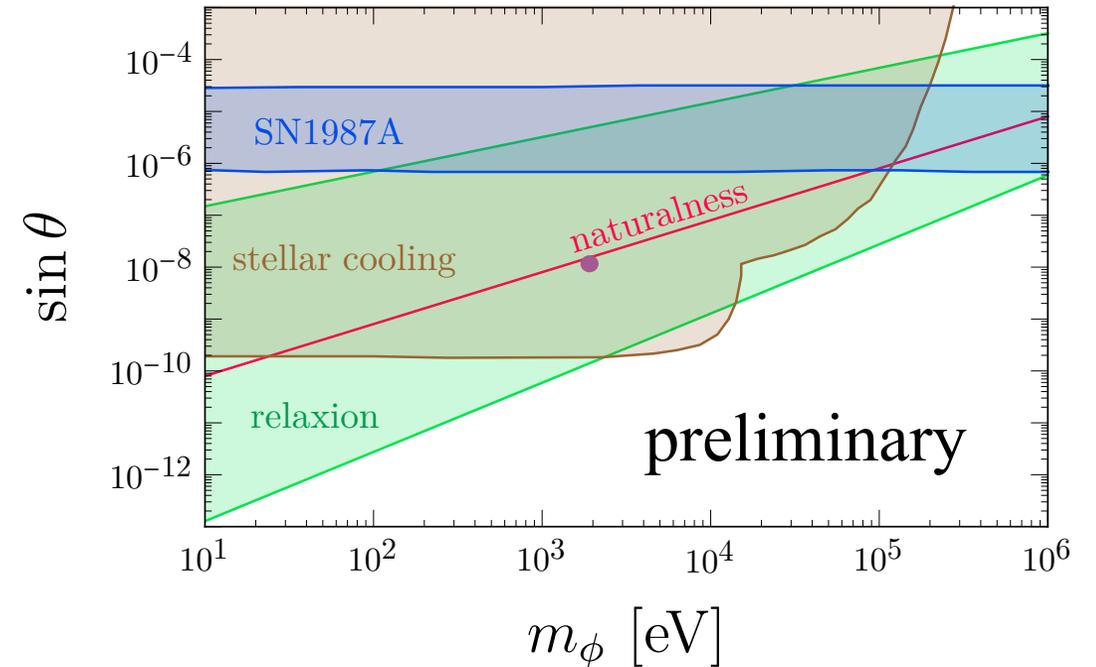
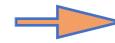
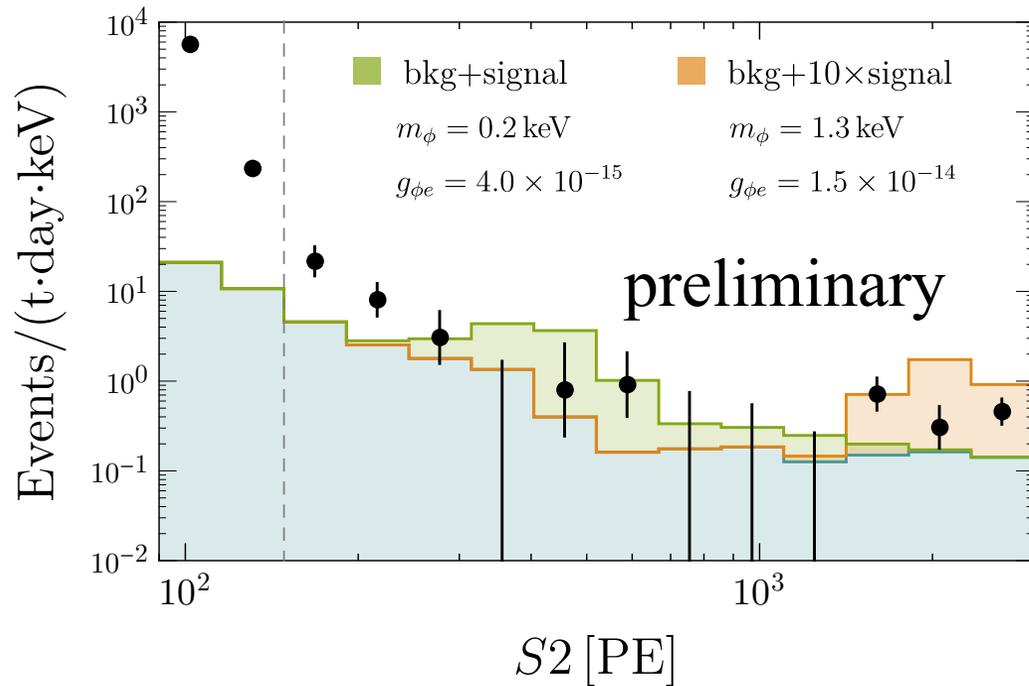
Budnik, Kim, Matsedonski, GP & Soreq, *in prep.*



Left: showing the 1-2-3sigma CL with and without the BG. The three benchmark points with $m_{\phi} = (0, 1.3, 1.9)$ keV and $g_{\phi e} = (0.8, 1.5, 2.4) \times 10^{-14}$, are marked in green, orange and purple, respectively. The purple (BM₃) 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.

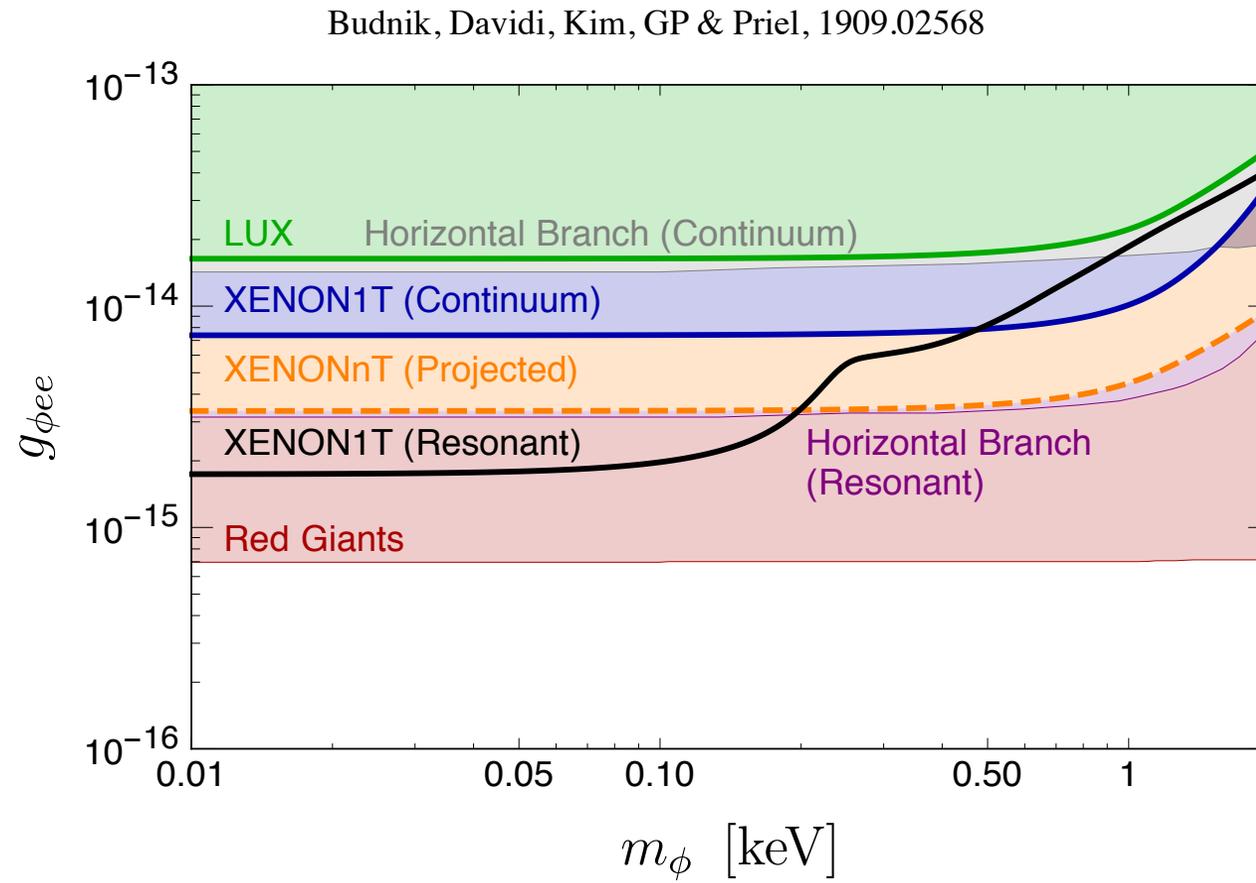
Fitting to scalar preliminary, S2; notice the background is not completely known!

Budnik, Kim, Matsedonski, GP & Soreq, *in prep.*



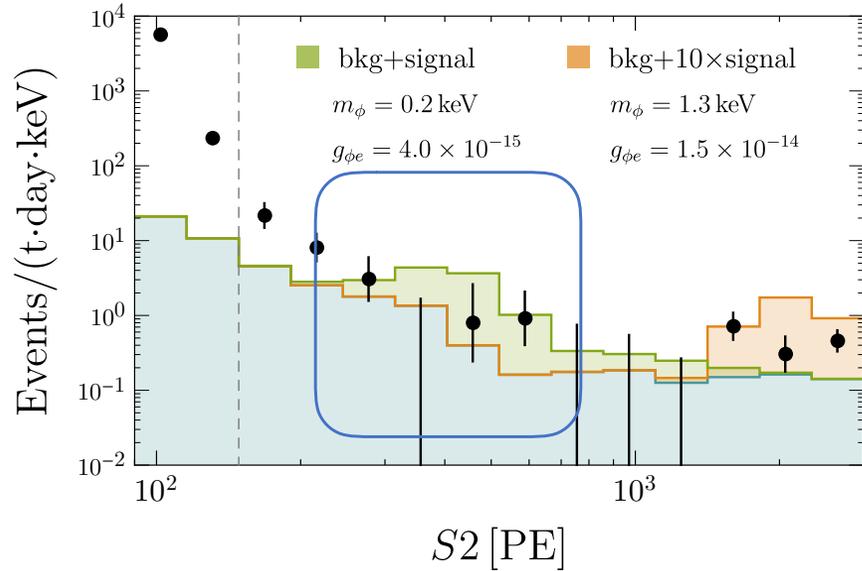
Strong tension with RG if the mass is keV.

S2: Tension is lower for $< 300\text{eV}$



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

Budnik, Kim, Matsedonski, GP & Soreq, *in prep.*



$$\begin{aligned} \frac{\delta\phi_{\text{RG}}}{\Delta\phi} &\simeq \frac{g_{\phi nn}}{\sin\theta} \frac{n_{\text{RG}}}{m_{\phi}^{4/3} v^{5/3}} \\ &\simeq 10^2 g_{\phi nn} \left(\frac{10^{-10}}{\sin\theta} \right) \left(\frac{2 \text{ keV}}{m_{\phi}} \right)^{4/3} \\ &\simeq 10^2 g_{\phi nn} \left(\frac{2 \text{ keV}}{m_{\phi}} \right)^{8/3} \quad \text{for } \theta = \theta_{\text{min}}, \end{aligned}$$

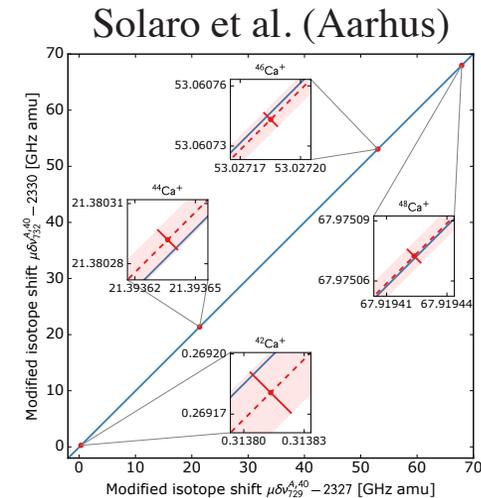
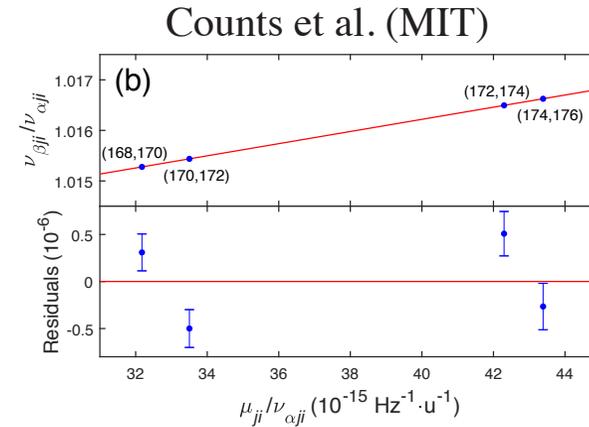
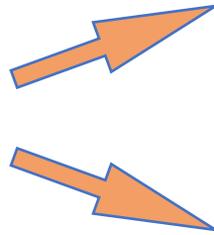
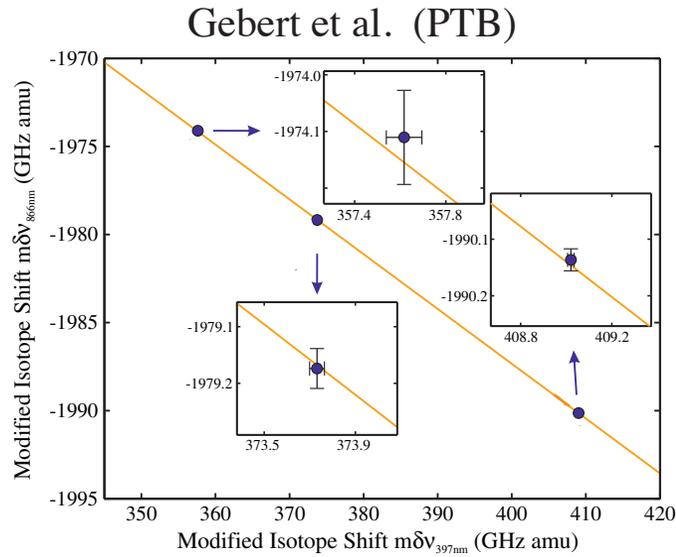
For max. allowed natural coupling to protons inside the red giant the relation is destabilised for mass of order 200 eV.

Recent ex. improving bounds by 10^3

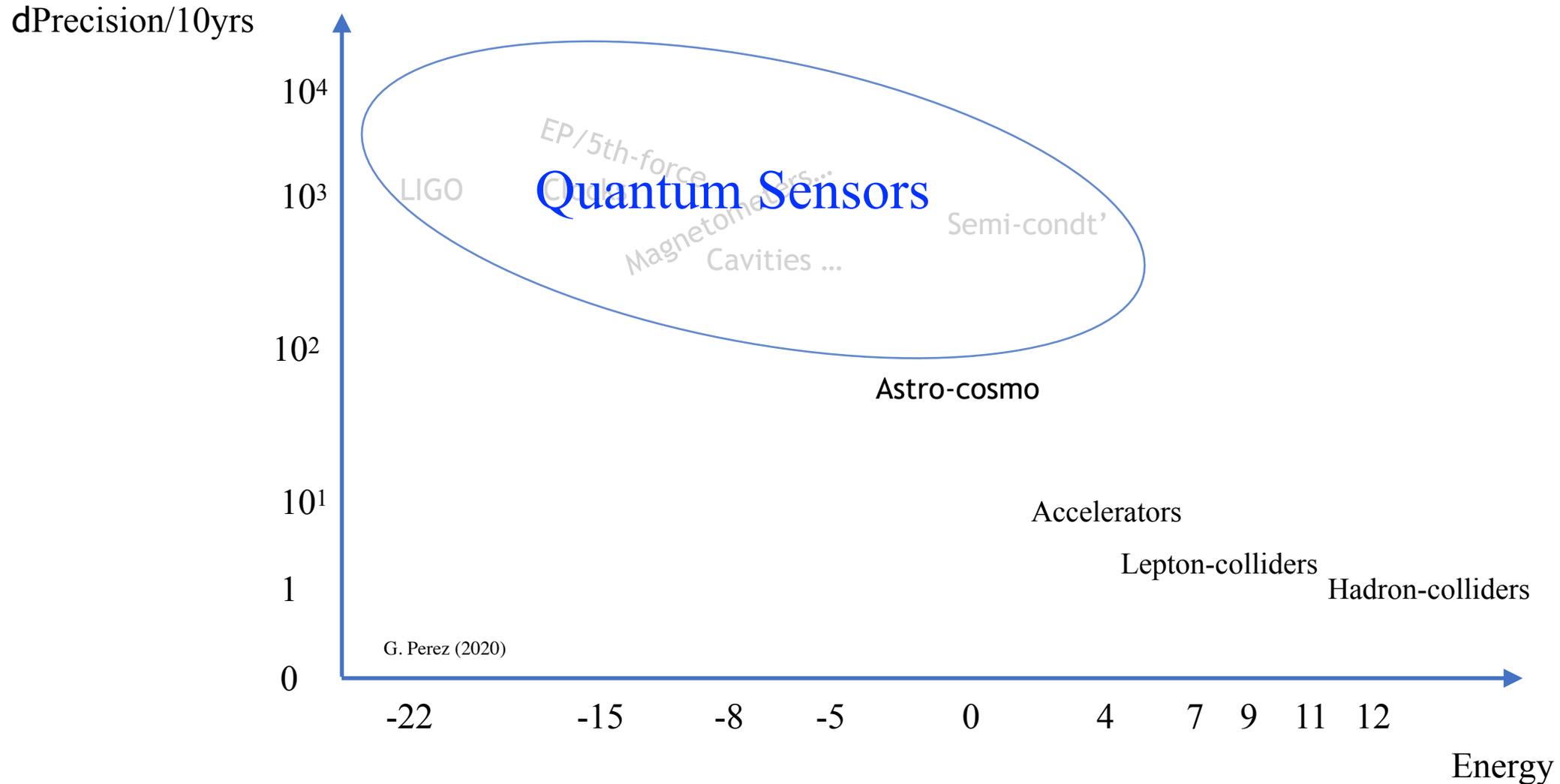
Search for King-linearity-violation (KLV), from $O(100)$ kHz to $O(100)$.

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

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



Progression: precision vs. energy-reach per 10/ys



G. Perez (2020)

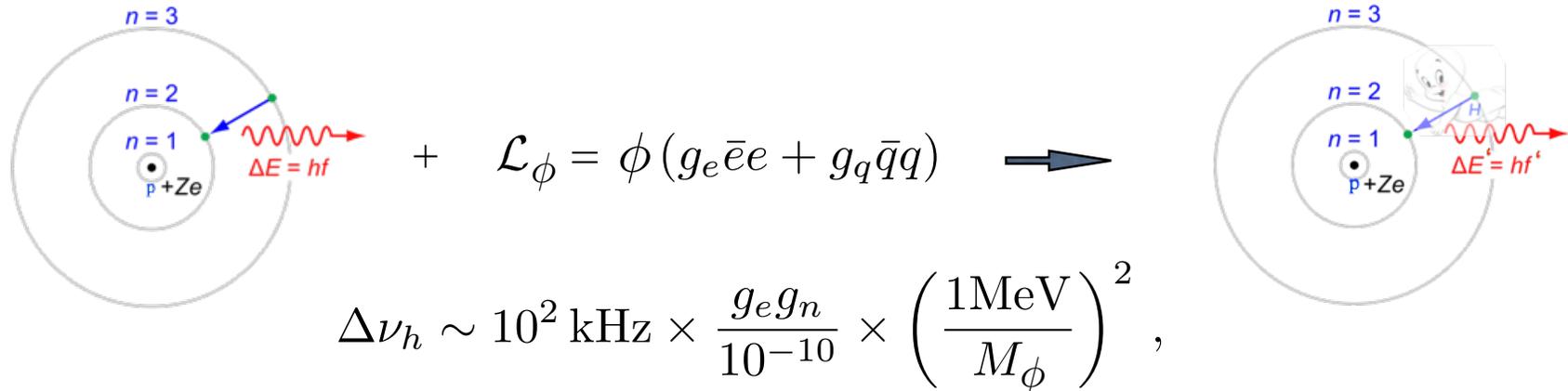
Motivation to hunt & compare sensitivity to broad class of scalar-new-physics in:

- (i) virtual processes searching for atomic-range “Yukawa” force
- (ii) time-depend. background if relaxion/scalar = ultra-light dark matter (DM)

Hunting “heavy” relaxation with isotope shift spectroscopy

Basic concept: precision isotope shift spectroscopy

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

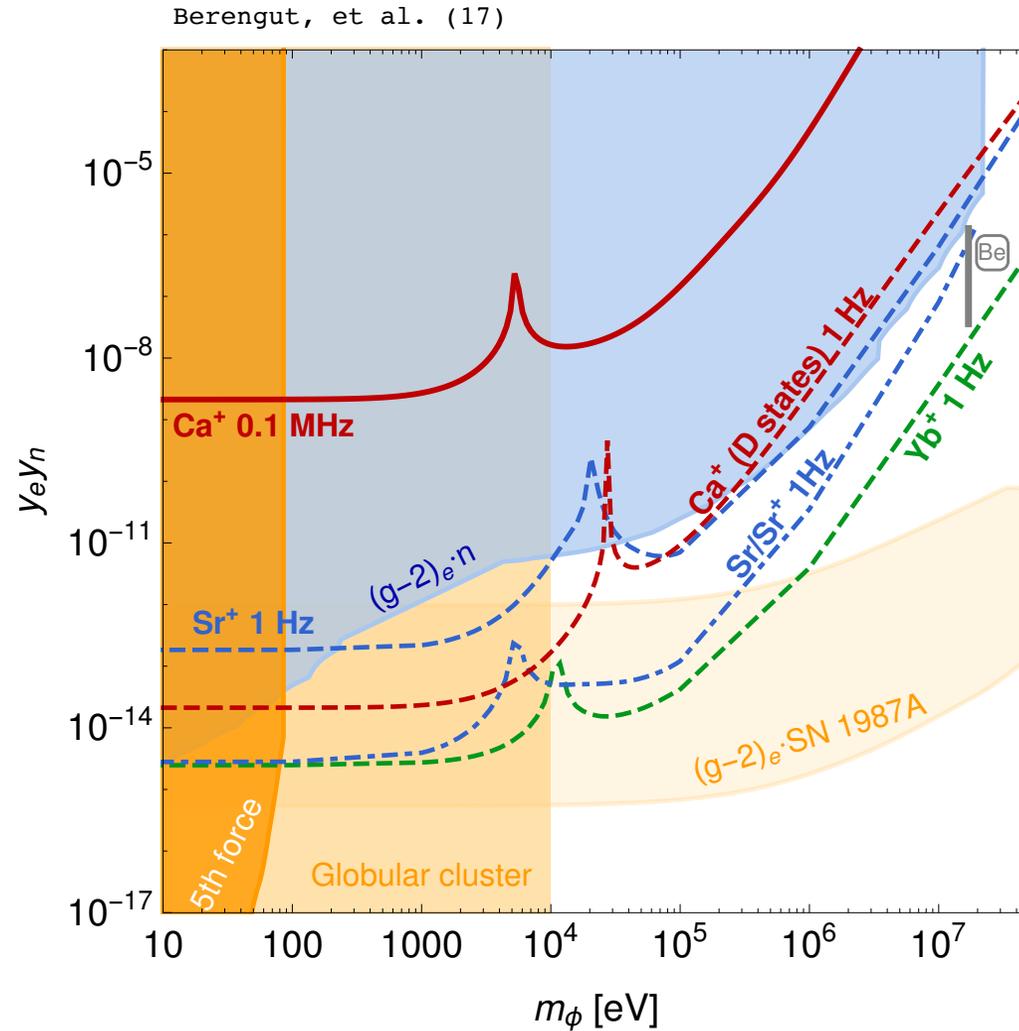


Delaunay, Ozeri, GP & Soreq (16)

- ◆ 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**.

$$\left[\left(\nu_{ij}^\alpha \right)_{\text{SM}} \simeq K^\alpha \mu_{ij} + F^\alpha \delta \langle r^2 \rangle_{ij} \implies \bar{\nu}_{ij}^\alpha \propto \bar{\nu}_{ij}^{\alpha'} \right] \quad \text{King (1963)}$$

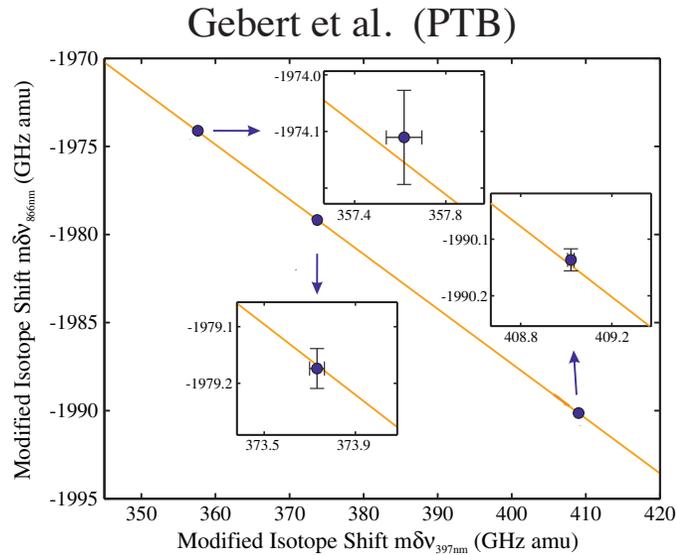
Bounds & sensitivity



Recent ex. improving bounds by 10^3

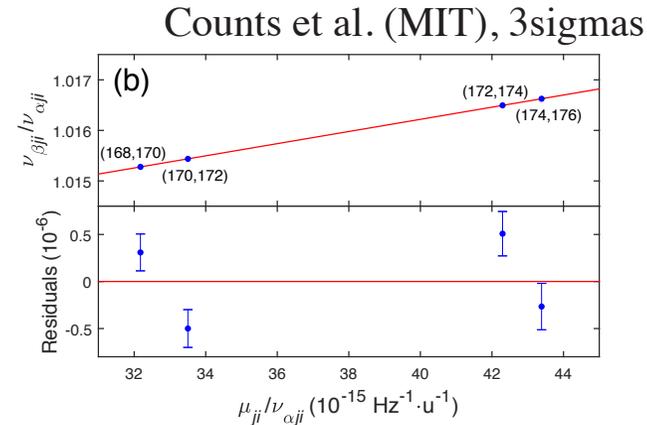
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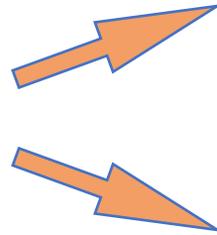


Ca^+ ($A=40,42,44,48$)
 $D_{3/2} - P_{1/2}$
 $S_{1/2} - D_{5/2}$

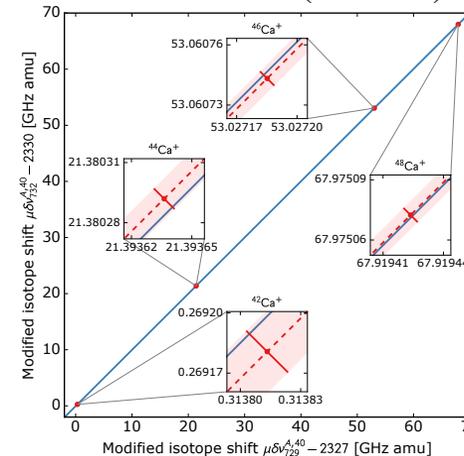
2020: Isotope shift @ $1:10^7$



Yb^+ ($A=168,70,72,74,76$)
 $S_{1/2} - D_{3/2}$
 $S_{1/2} - D_{5/2}$



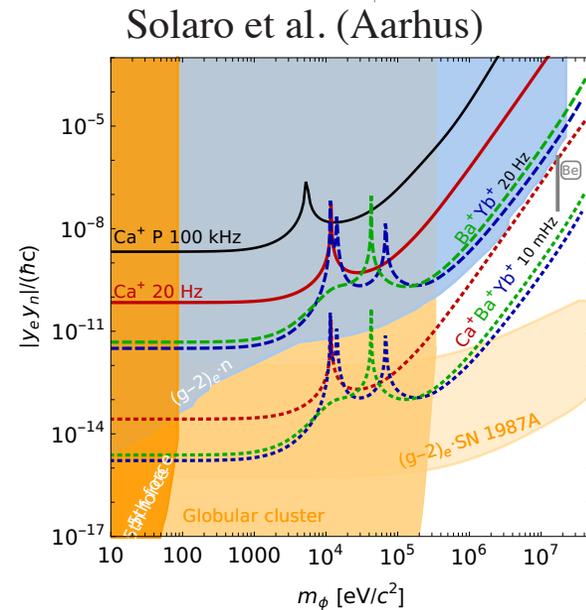
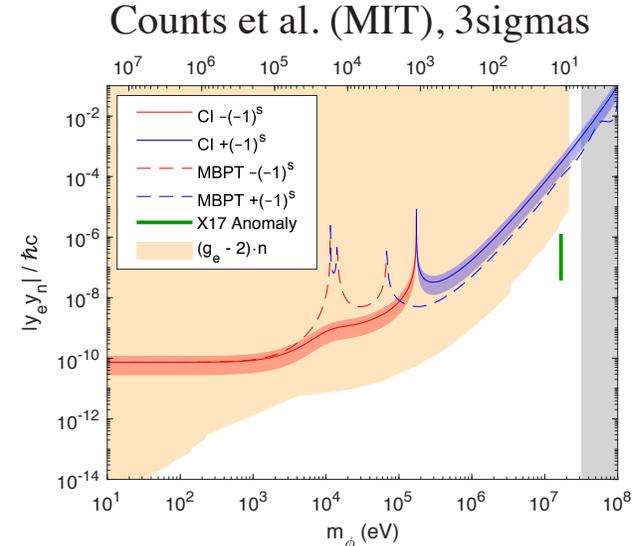
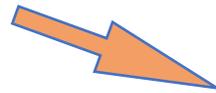
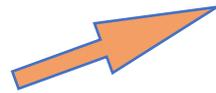
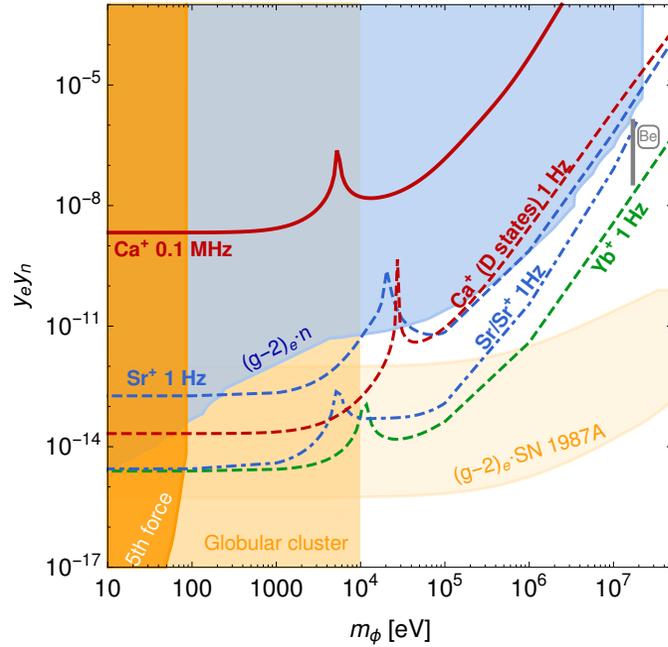
Solaro et al. (Aarhus)



Ca^+ ($A=40,42,44,46,48$)
 $D_{3/2} - D_{5/2}$
 $S_{1/2} - D_{5/2}$

Recent ex. improving bounds by 10^3

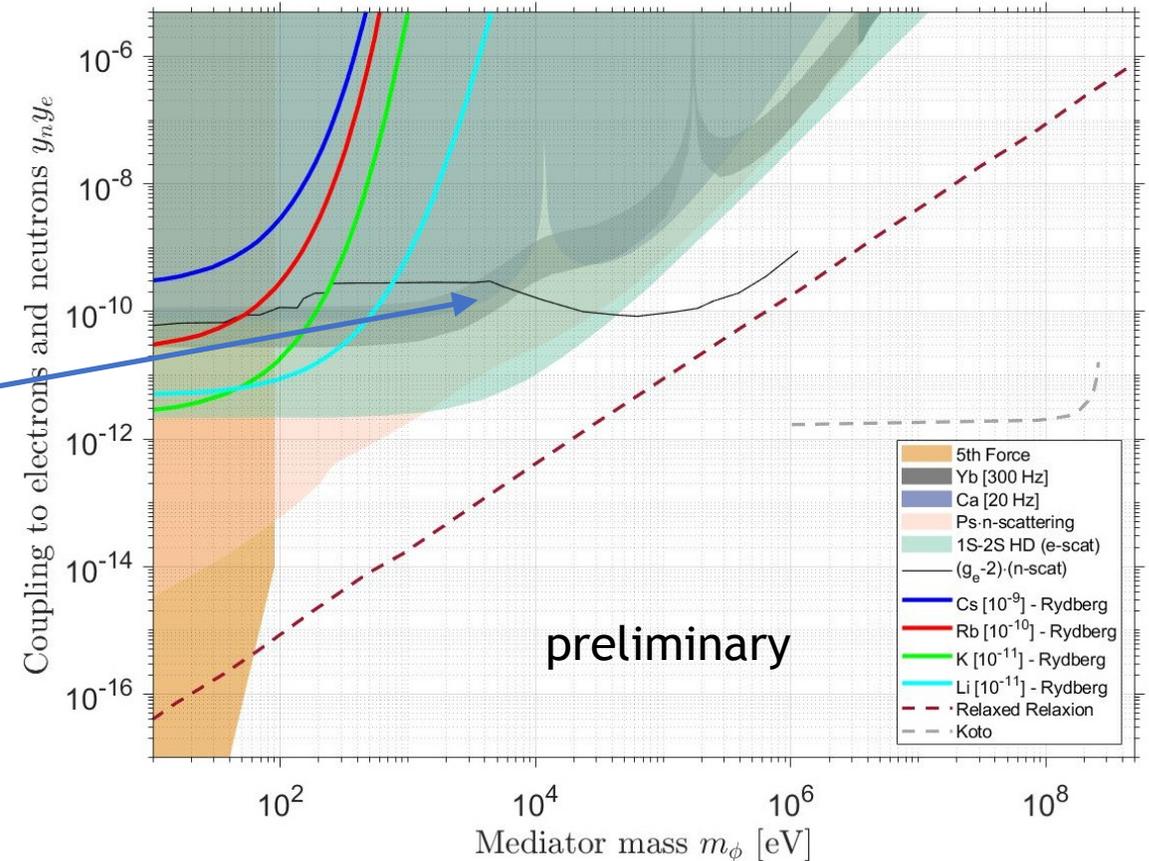
Search for King-linearity-violation (KLV), from $O(100)$ kHz to $O(100)$.



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

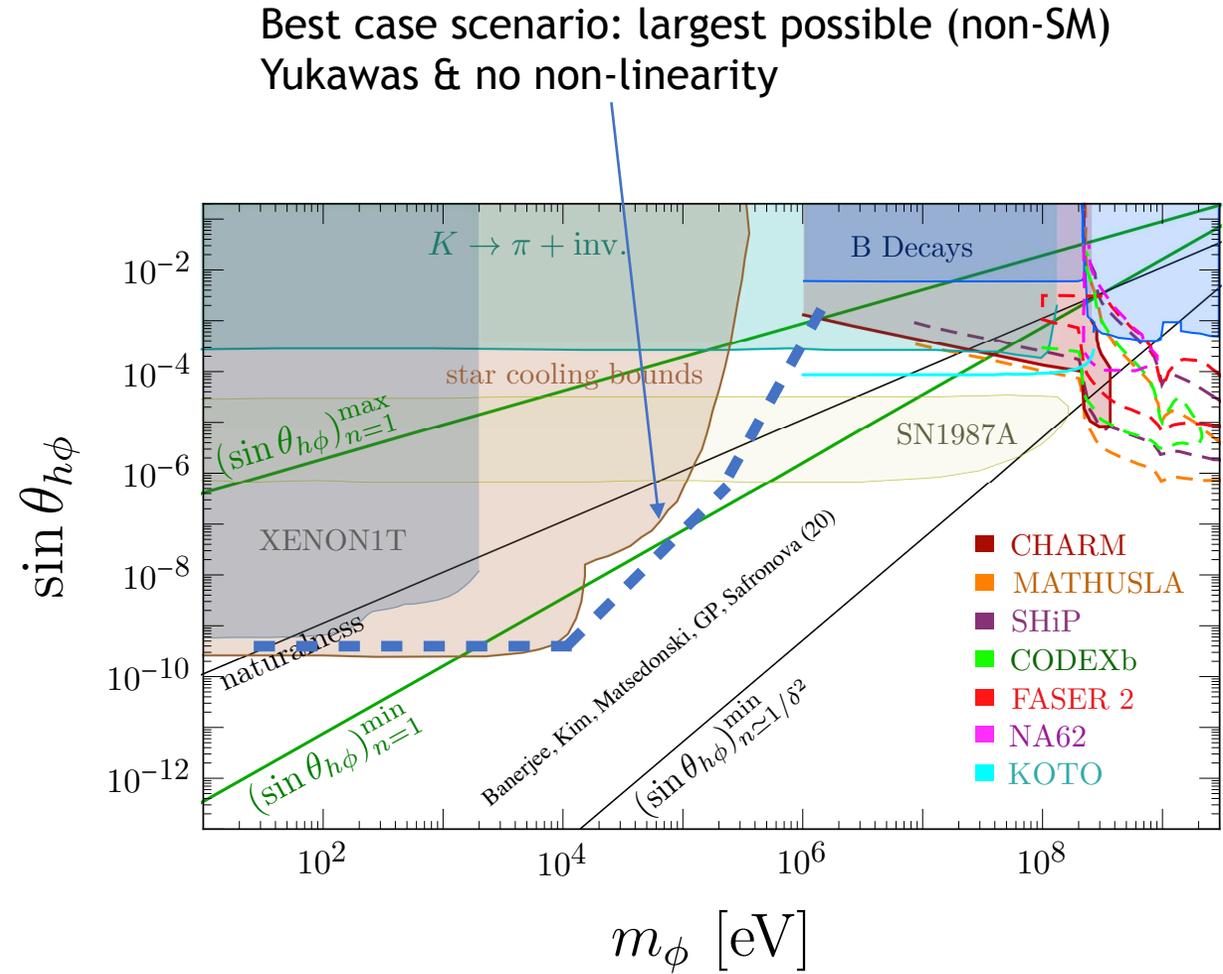
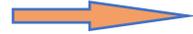
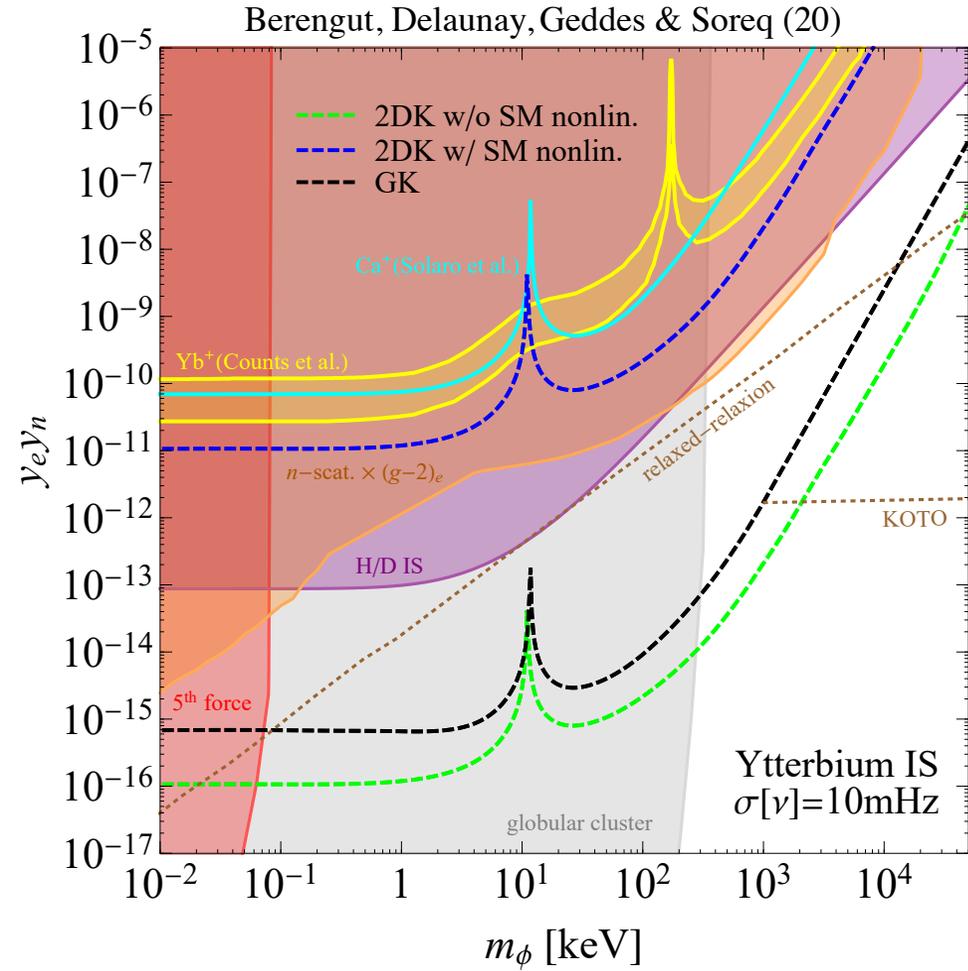
- The $(g-2)_e$ bound is model dep. & can be naturally suppressed (mirror sym.).
- Looking at (2-3) isotope shifts in “heavy” Rydberg transitions => reduce nuclear-impact.

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 $S \rightarrow P$ 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, \wo $(g-2)_e$, hydrogen-deuterium (HD) IS & globular cluster. Dotted lines describes the relaxed-relaxion & the KOTO result.

Conclusions

- Null-results + new theories \Rightarrow log crisis/opportunity (ex.: relaxion)
- Several Lessons: calls for experimental diversity, PBC emphasises.
- Briefly: i. Kaon factories; ii. Solar vs. XENON; iii. isotope shifts ...
- Future look at S2 could be very interesting.
- Relaxion Chameleon effects could be relevant to other systems.

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;
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Scalar DM & oscillating of constants

- Generically, time-varying scalar \Rightarrow 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 \Leftrightarrow scalar background is the only object that oscillates \Rightarrow can go beyond LO.

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- 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:

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

Relaxion/scalar light dark matter

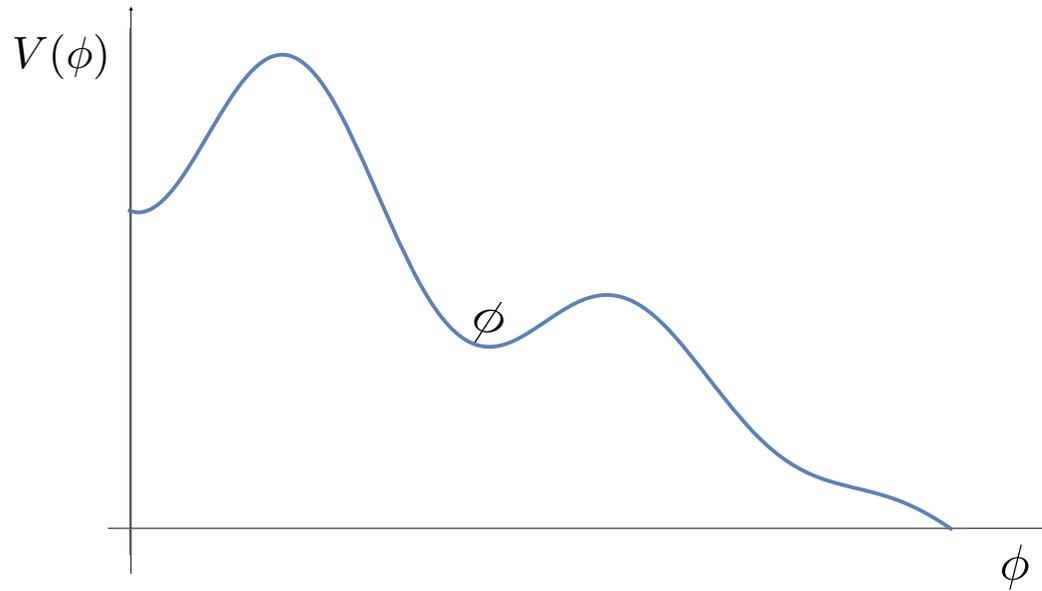
Arvanitaki, Huang & Van Tilburg (15)

Banerjee, Kim & GP (18)

Concrete ex.: relaxion dark matter (DM)

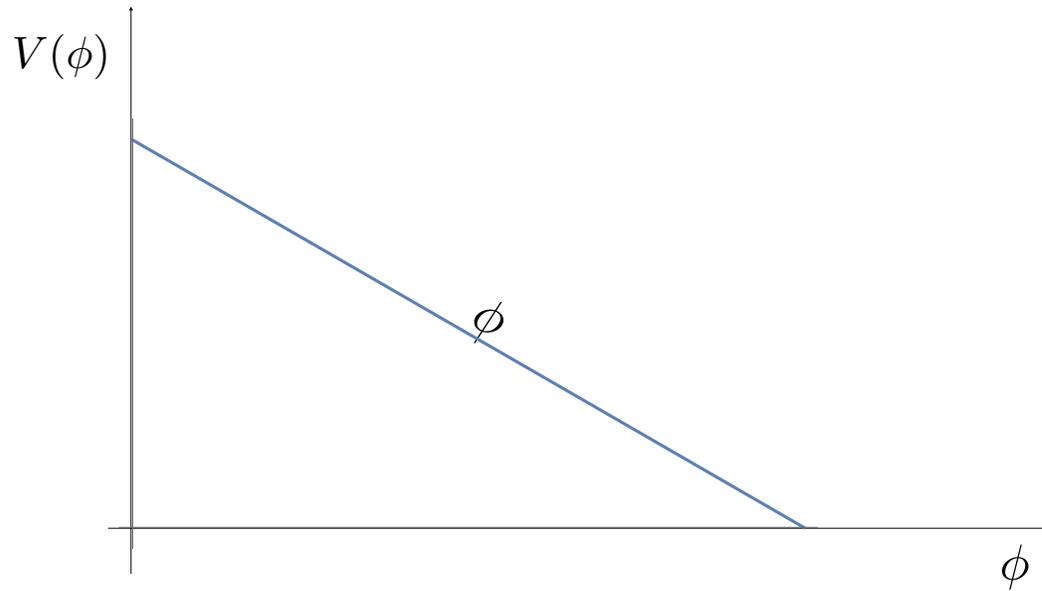
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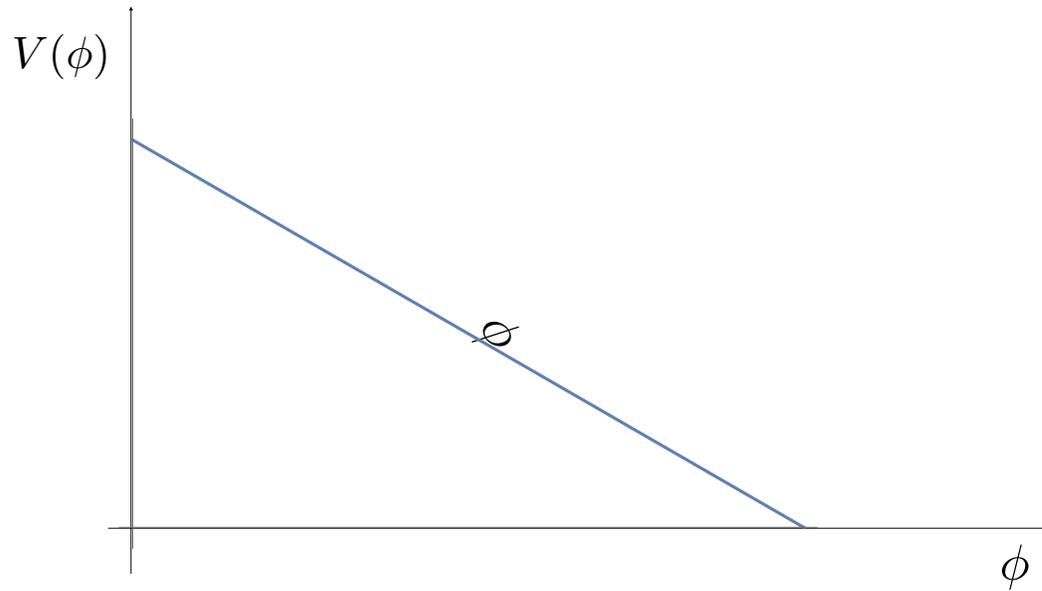
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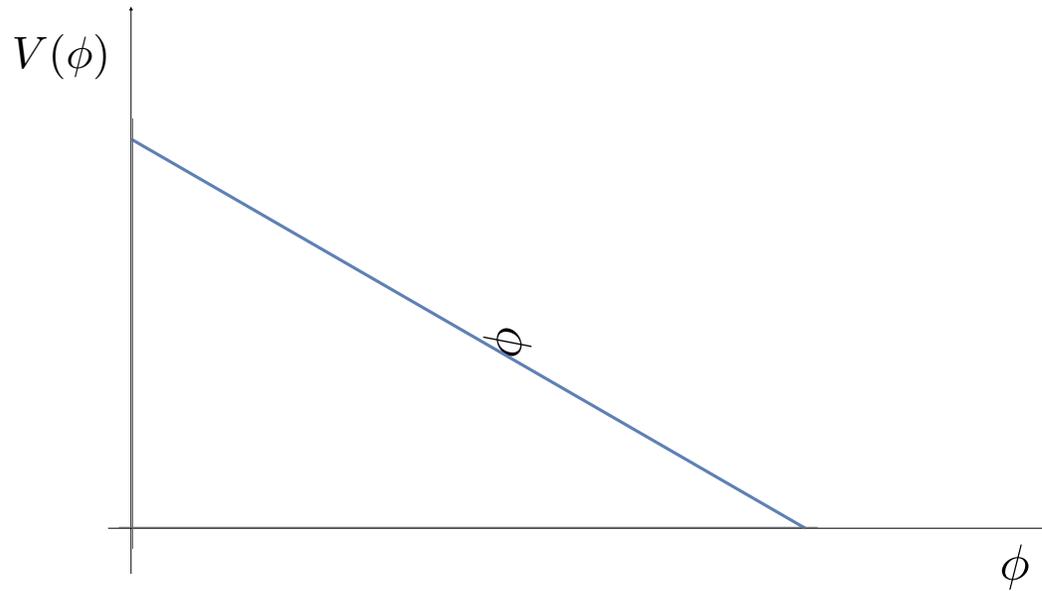
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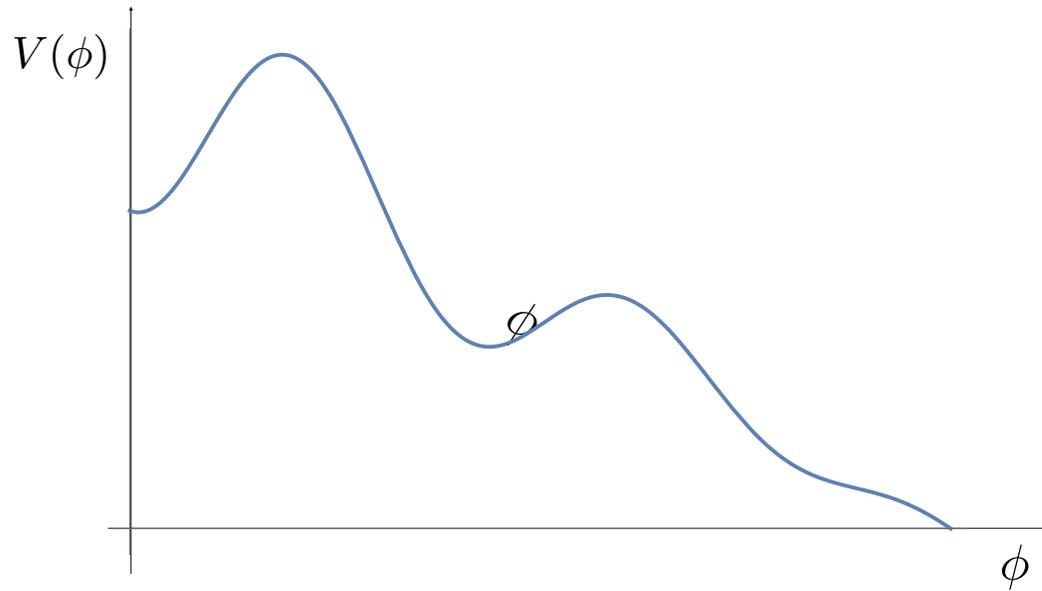
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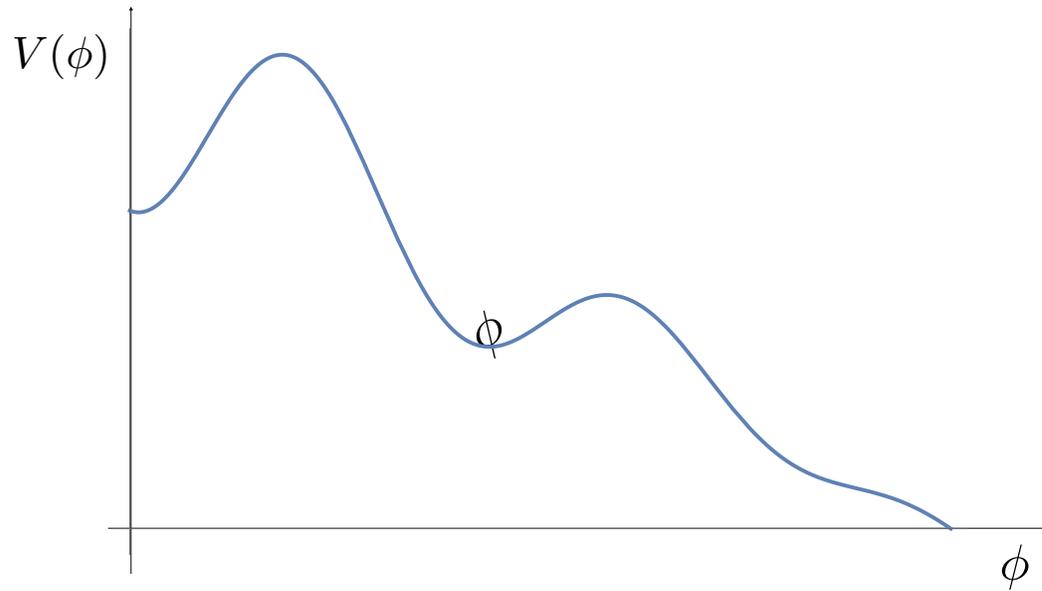
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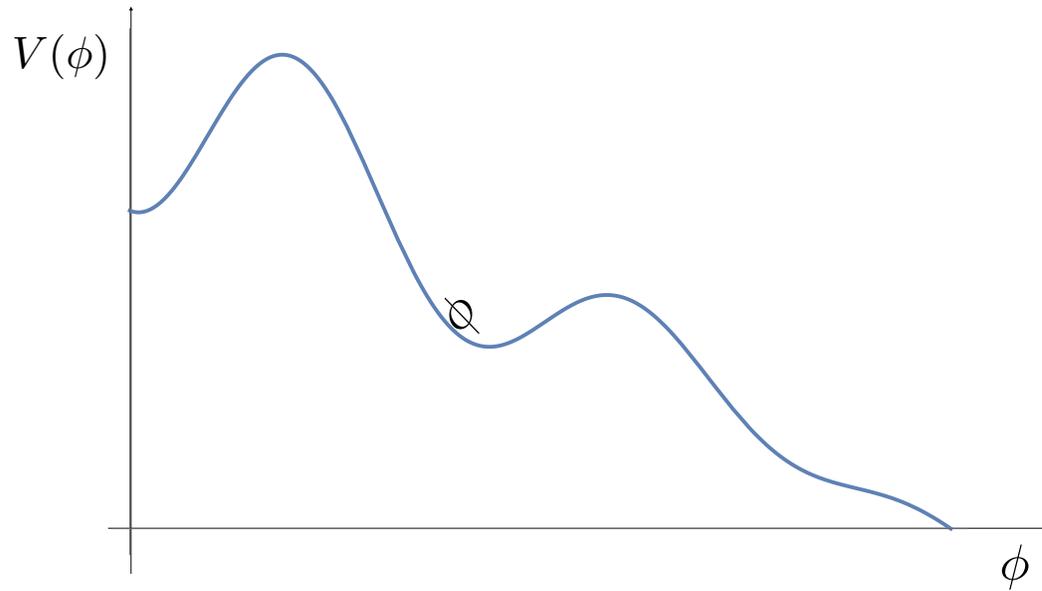
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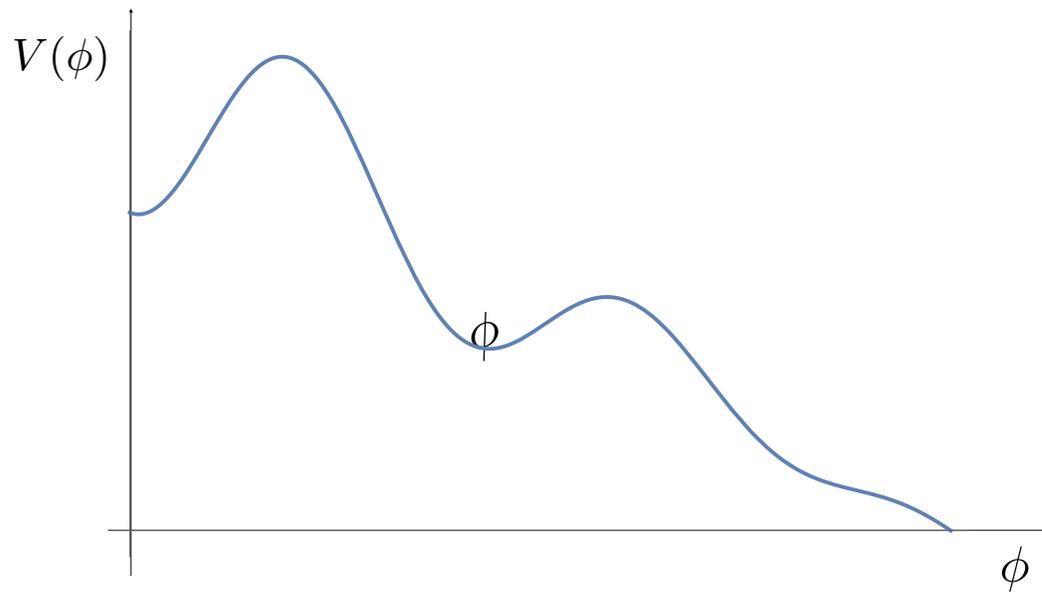
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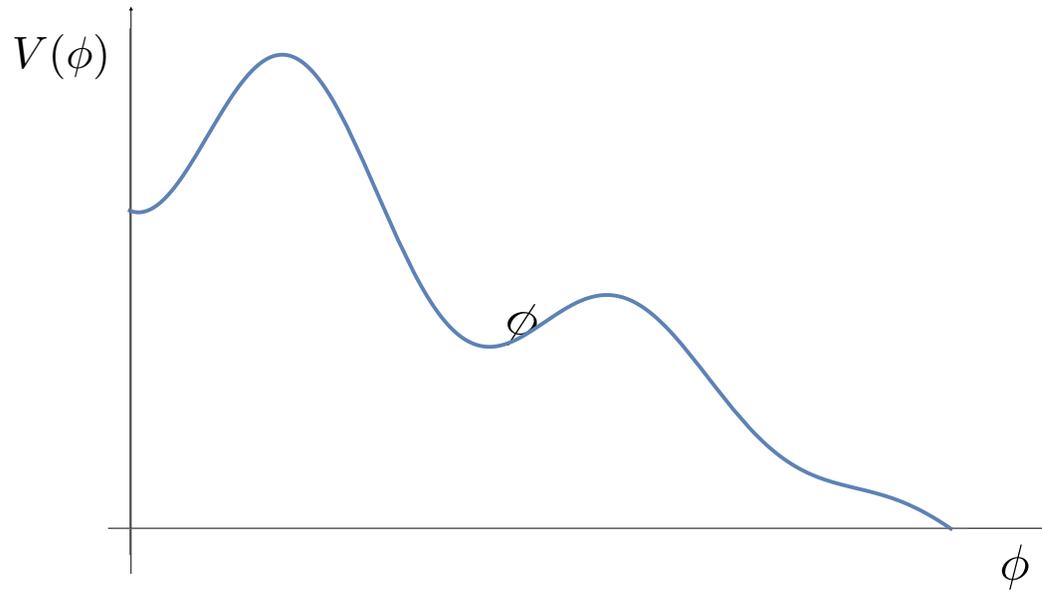
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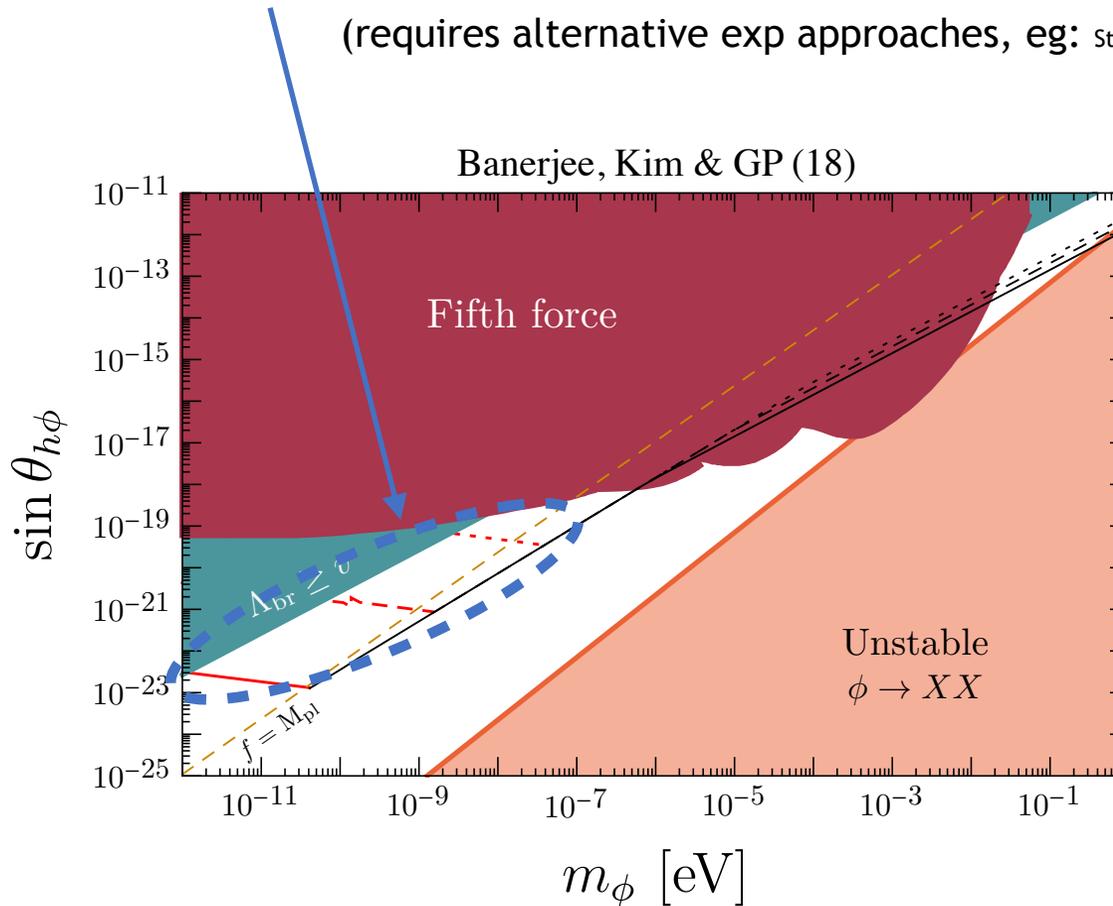
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Relaxion/Higgs-portal & benchmarking

- 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:

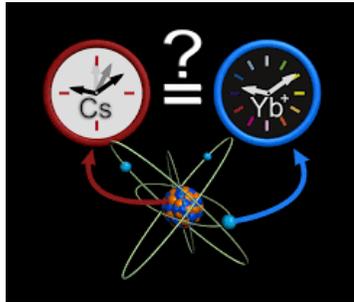
(requires alternative exp approaches, eg: Stadnik & Flambaum (14); Grote & Stadnik; Antypas et al.; Aharony et al. (19))



$$\mathcal{L} \supset \sin \theta_{h\phi} \frac{\phi}{v} \left[-m_f \bar{f} f + \frac{c_\gamma}{4\pi} FF + \frac{c_g}{4\pi} GG \right]; \quad \text{for instance: } \frac{\delta m_e}{m_e} \sim y_e \sin \theta_{\phi h} \frac{\sqrt{\rho_{\text{DM}}}}{m_e m_\phi} \sin(m_\phi t)$$

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: $\delta E_{1,2} \equiv \nu_{1,2} = f_{1,2}(\alpha^{\xi_{\alpha}^{1,2}}, \alpha_s^{\xi_{\alpha_s}^{1,2}}, m_e^{\xi_{m_e}^{1,2}}, m_q^{\xi_{m_q}^{1,2}})$



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

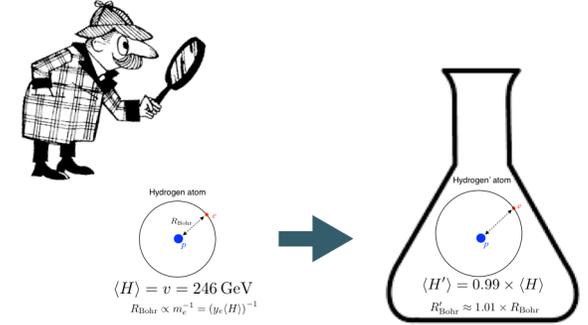
[see Safronova, Budker, DeMille, Kimball, Derevianko & Clark (18) for recent review]

$$R_{\infty} \propto \alpha^2 (m_e + O(m_e/m_A)) , R_{\text{Bohr}}^{-1} \propto \alpha(m_e + \dots) , \dots$$

Relaxion oscillating DM, scales

- Relaxion-Higgs mixing \Rightarrow 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)

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

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

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- The sensitivity will be give by:

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

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

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.):

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

Flambaum (06); Berengut & Flambaum (10)

where m_q is the light quark mass, and Λ_{QCD} is the QCD scale

What about the size of the scalar DM amplitude itself ?

- The effects are linear with the scalar amplitude:

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- This is astro stuff, there are considerable uncertainties.
- We consider 2 options:

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

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

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:

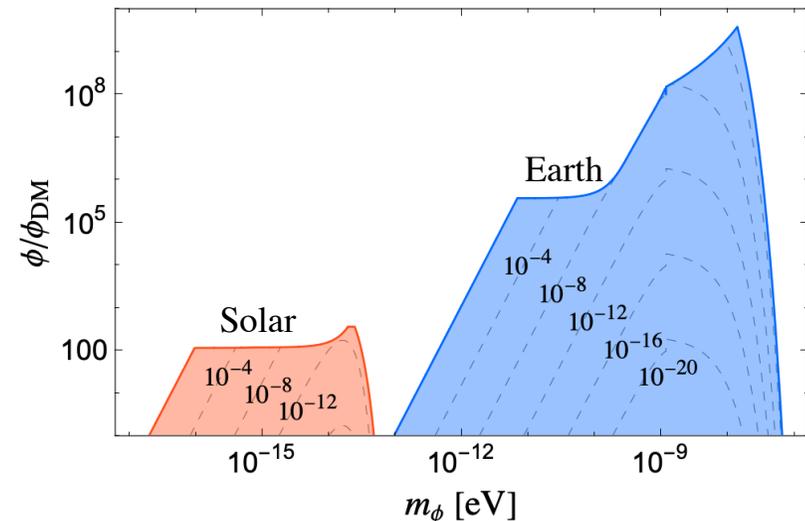
$$R_{\text{star}} \approx \frac{M_{\text{Pl}}^2}{m_\phi^2} \frac{1}{M_{\text{Earth}}} \quad (M_* \ll M_{\text{Earth}}).$$

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

Can obtain large density enhancement:

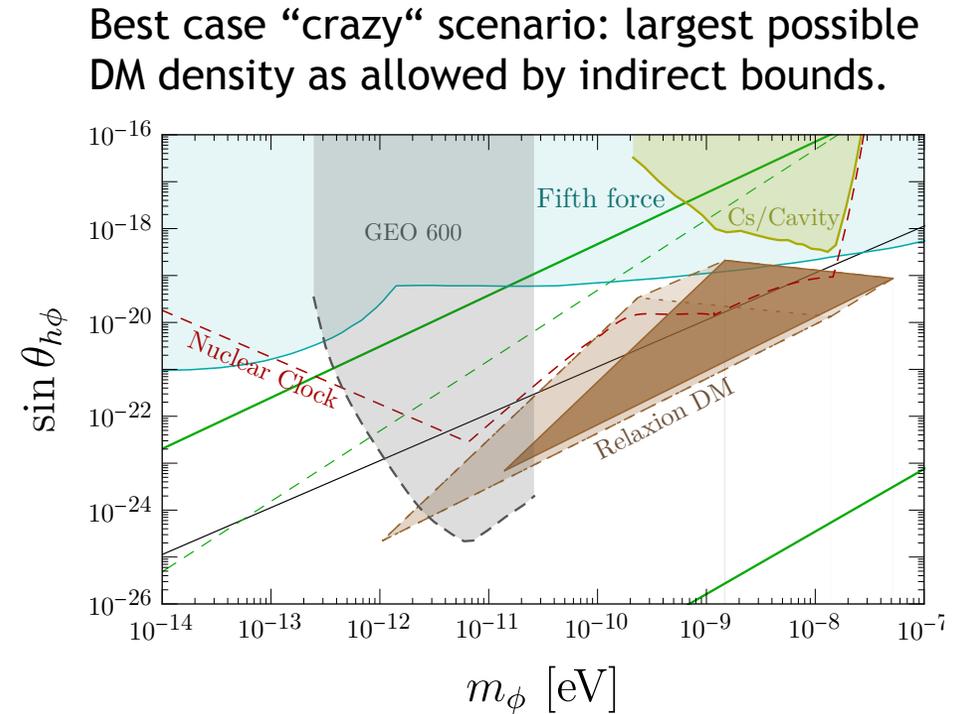
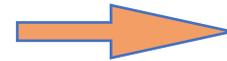
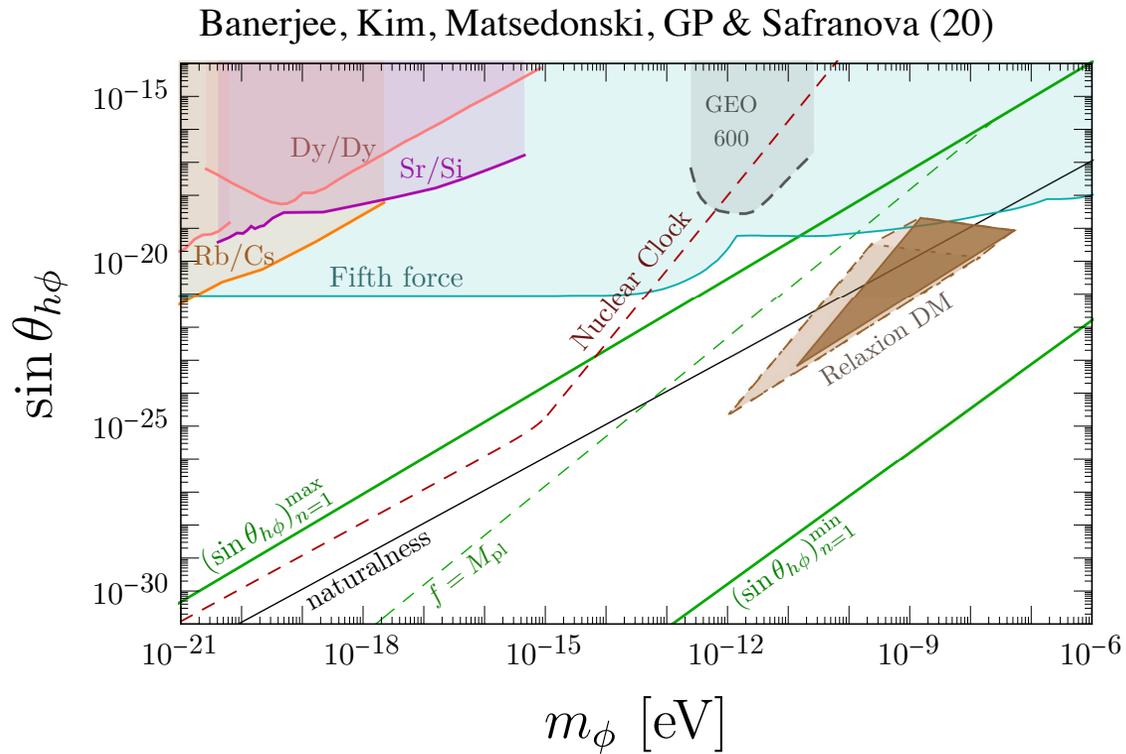
$$r \equiv \frac{\rho_{\text{star}}}{\rho_{\text{loc-DM}}} \sim \xi \frac{M_{\text{Earth}}^4 m_\phi^6}{M_{\text{Pl}}^6 \rho_{\text{loc-DM}}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}} \right)^6$$

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



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



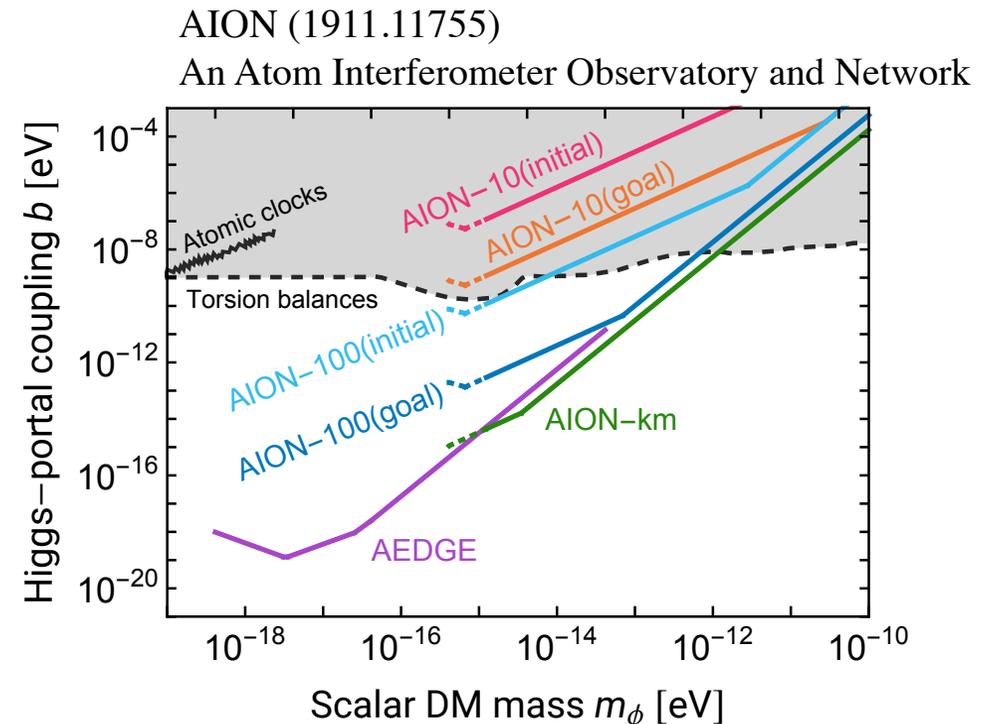
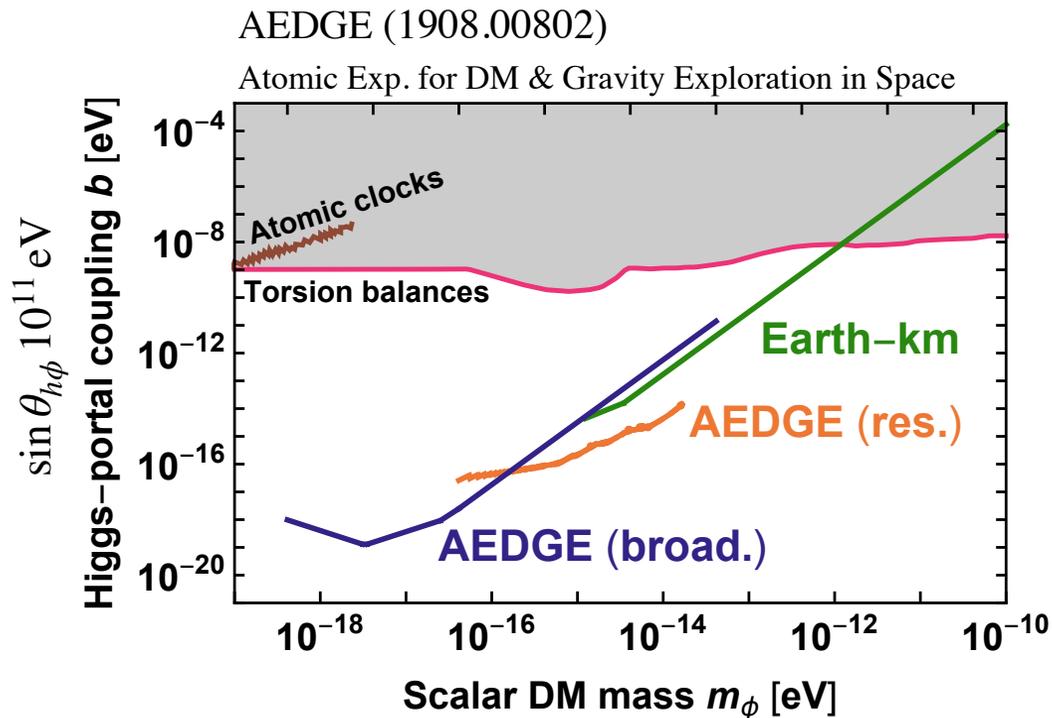
Further in to the future

- 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.:

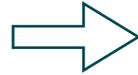
Relevant th.: Graham, Hogan, Kasevich & Rajendran (13); Arvanitaki, Graham, Hogan, Rajendran, & Van Tilburg (18); Grote & Stadnik (19)



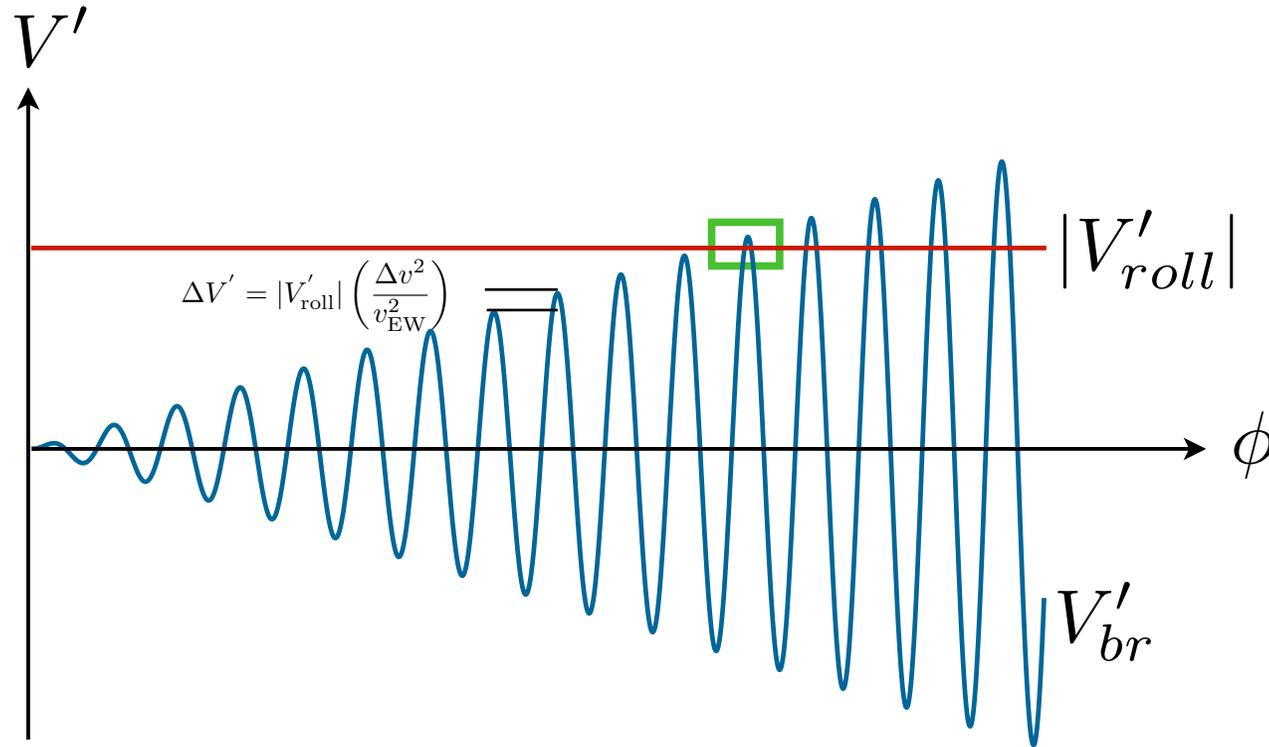
THE STOPPING POINT

Relaxion stops when

$$V'_\phi = 0 \Rightarrow \sin \theta = \frac{v_{\text{EW}}^2}{v^2(\phi)} + \frac{v_{\text{EW}}^2}{\Lambda^2}$$

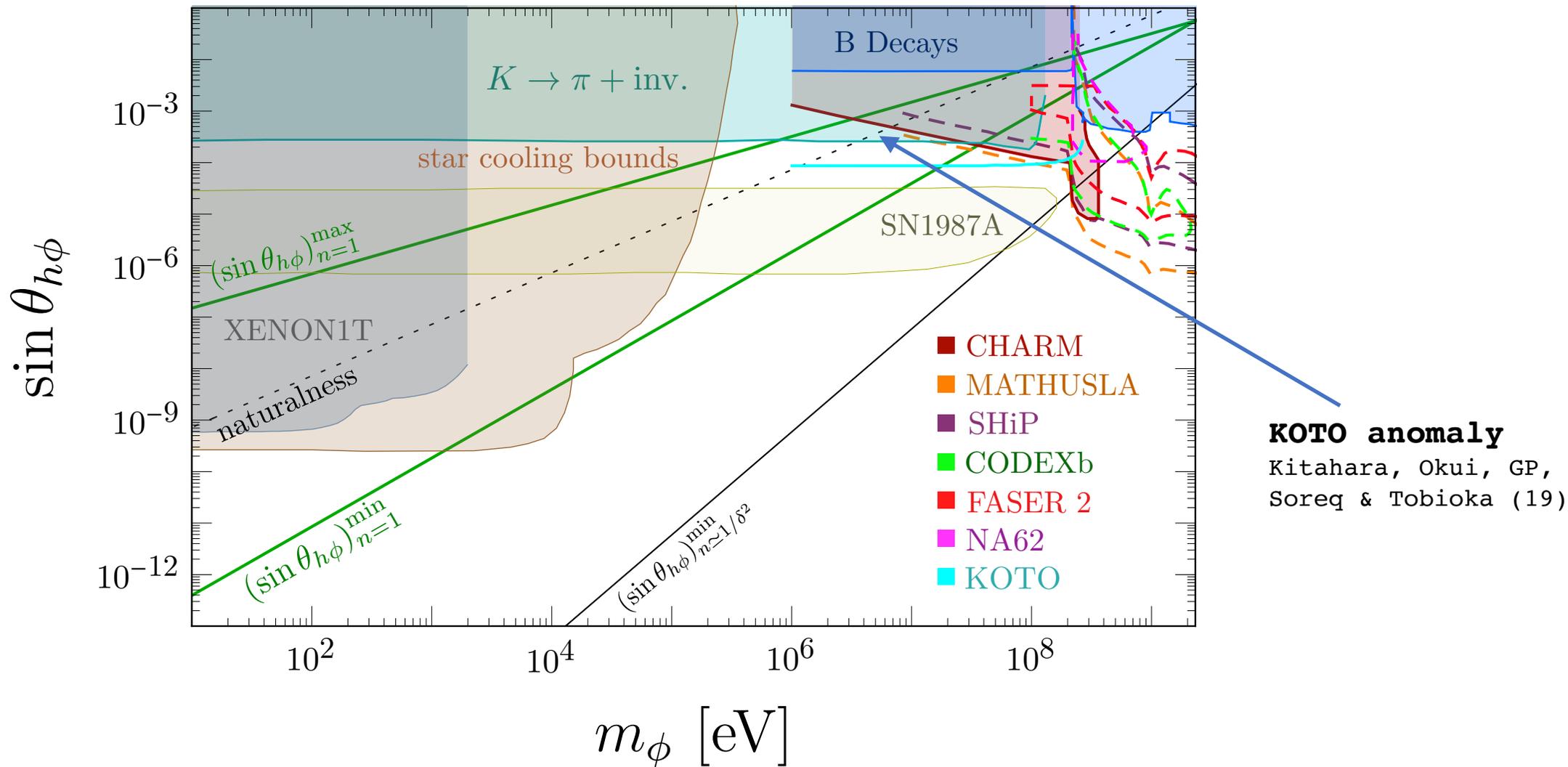


$$\frac{\phi_0}{f} \sim \frac{\pi}{2} \text{ upto resolution factors}$$



Overview: accelerator probes of relaxion

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).

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- Generically, time-varying scalar \Rightarrow variations of fundamental constants.

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

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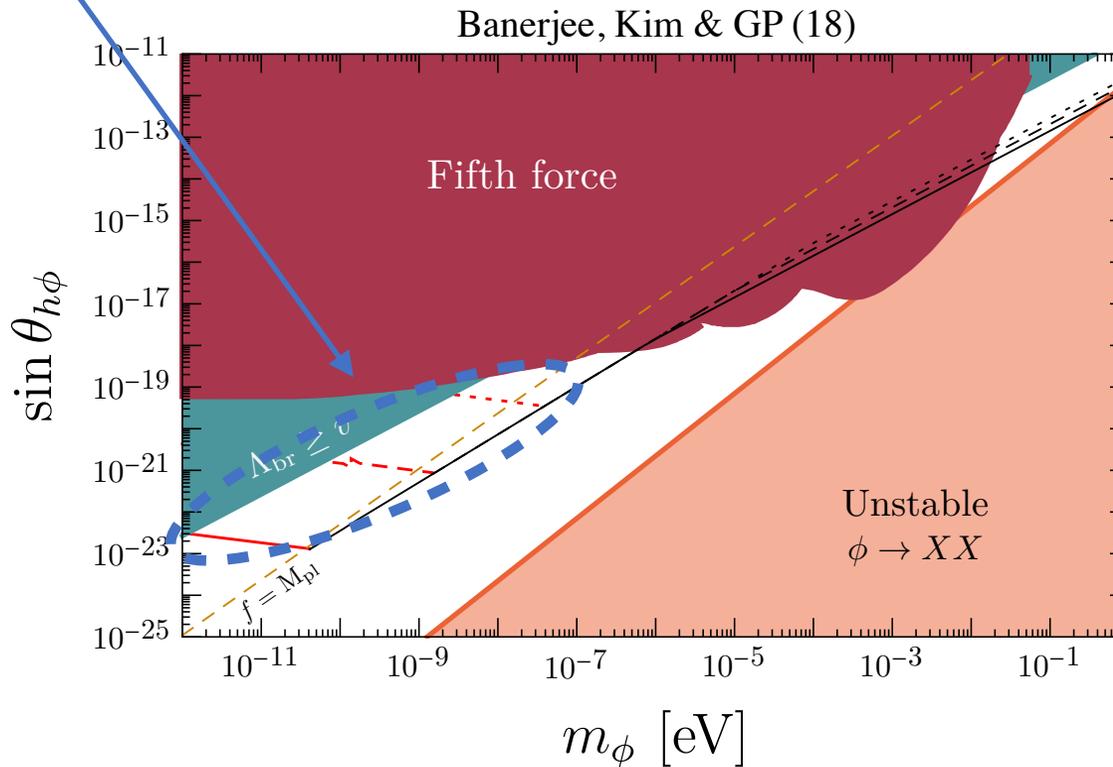
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Relaxion/Higgs-portal & benchmarking

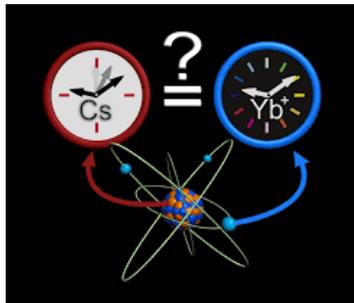
- The relaxion DM provides us with a concrete & simple realisation of the idea (via dynamical misalignment, see yesterday's talk), via it is Higgs mixing:



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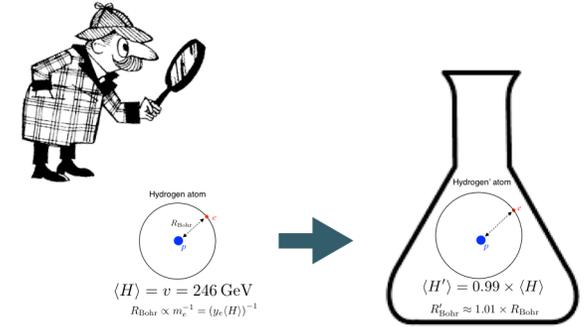
[see Safronova, Budker, DeMille, Kimball, Derevianko & Clark (18) for recent review]

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Blog, Nat. Ast., Eby (20)

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

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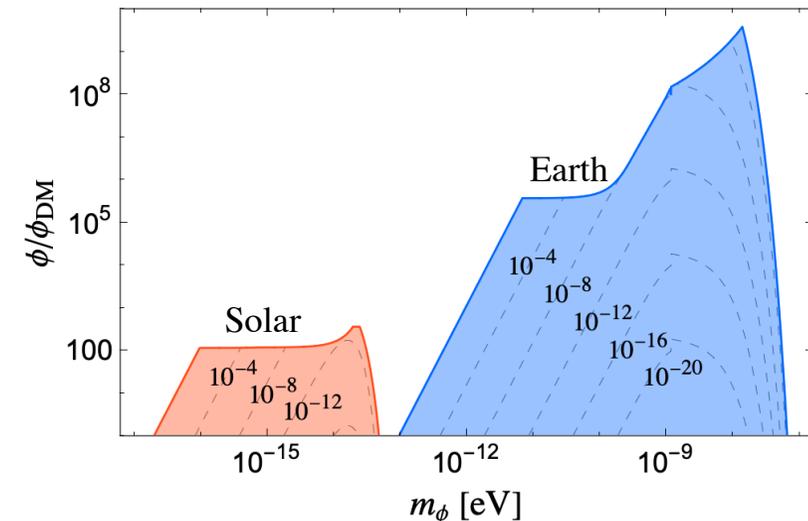
$$R_{\text{star}} \approx \frac{M_{\text{Pl}}^2}{m_\phi^2} \frac{1}{M_{\text{Earth}}} \quad (M_* \ll M_{\text{Earth}}).$$

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

Can obtain large density enhancement:

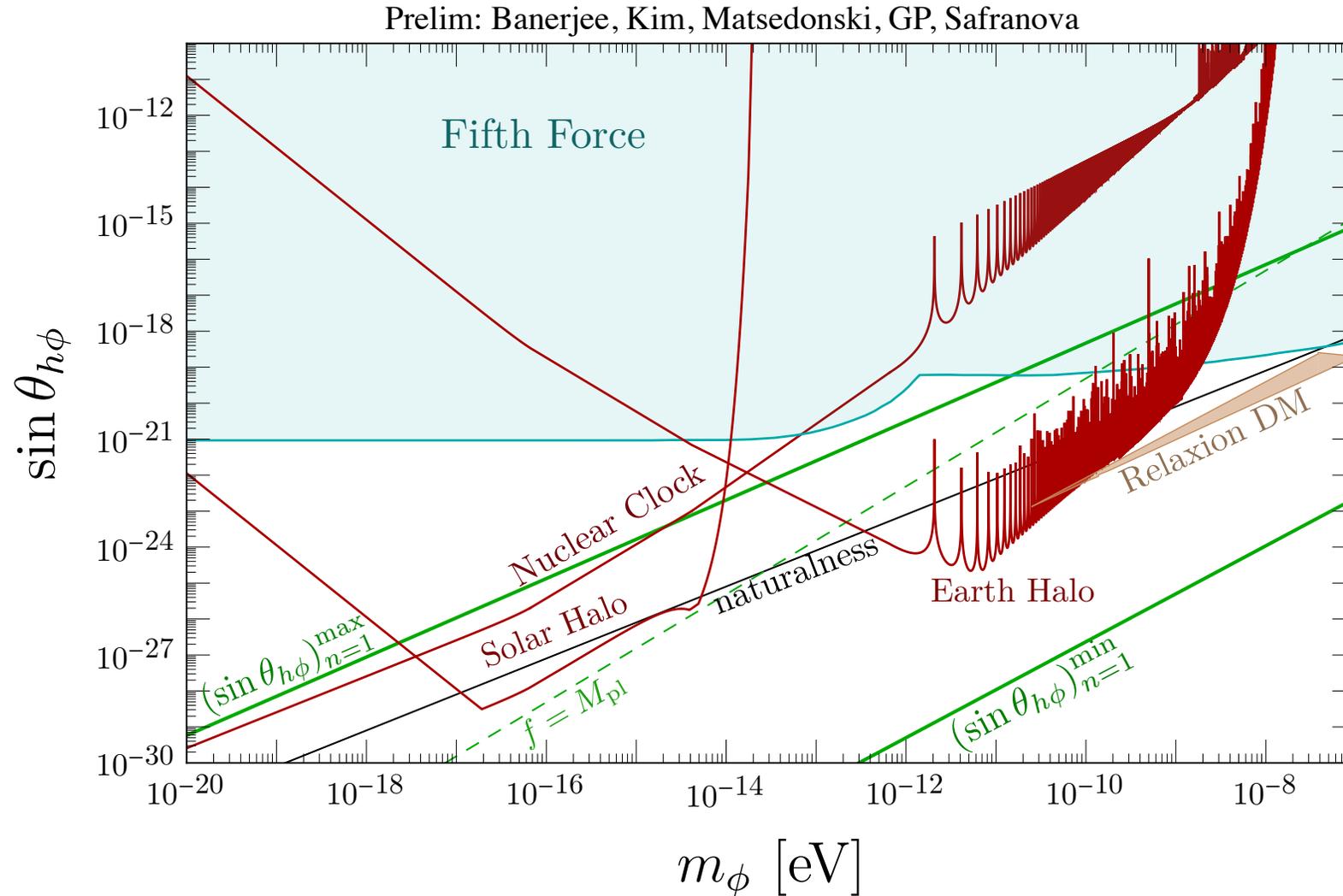
$$r \equiv \frac{\rho_{\text{star}}}{\rho_{\text{loc-DM}}} \sim \xi \frac{M_{\text{Earth}}^4 m_\phi^6}{M_{\text{Pl}}^6 \rho_{\text{loc-DM}}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}} \right)^6$$

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



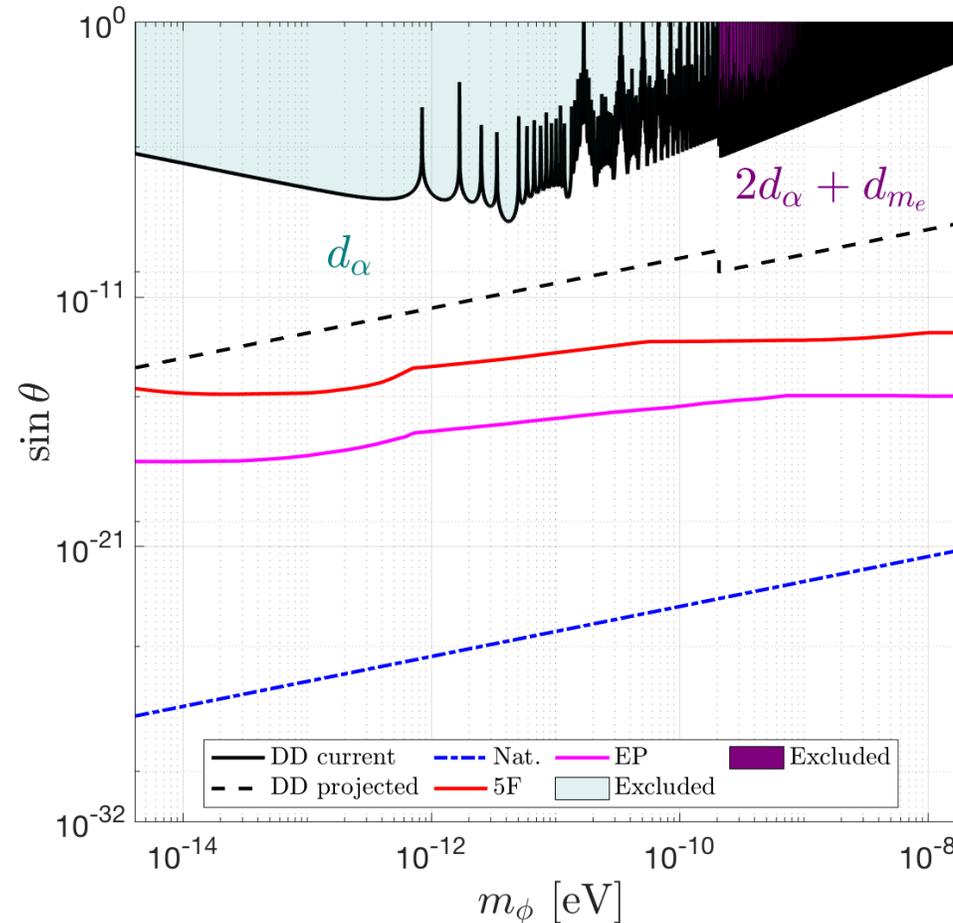
Enhancements in the axion halo scenario compared to the background DM case, in the field value for the Earth halo (blue) and solar halo (red) compared to the usual ALP DM case. Solid lines correspond to maximal halo mass M , by gravitational constraints.

Ideal system, nuclear clock



Beyond 1 Hz DM mass \w dynamical decoupling

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

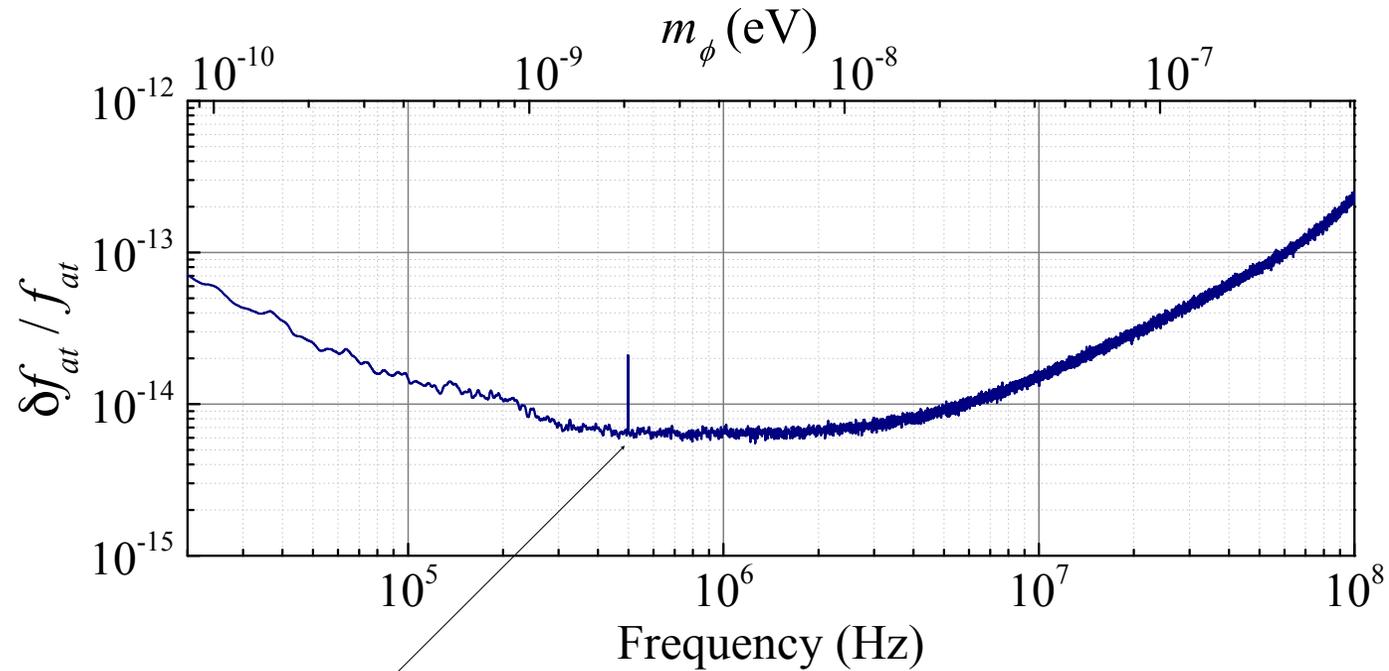


The bounds on the mixing angle of a relaxion DM: Black – current and projected bounds from DD experiments at 95% CL. Red – Bounds from fifth force experiments. Magenta – EP-tests bounds. Dash-dotted – Bounds from Naturalness.

Beyond 1 Hz 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.

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) $\left(\mathcal{L} \supset -\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$

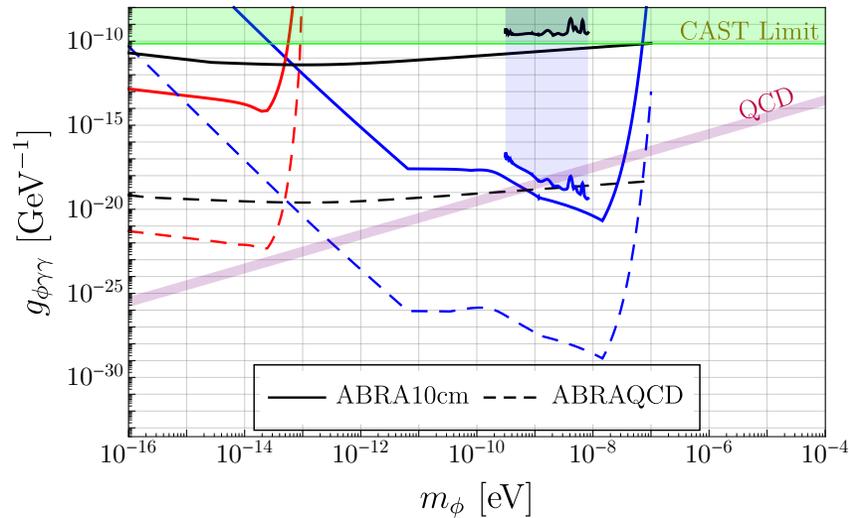
CASPEr(Wind) $H \simeq -[(d_a/I)\vec{I} \cdot \vec{E} + (\mu_n/I)\vec{I} \cdot \vec{B}_\phi] \cos(m_\phi t)$. $\vec{d}_a = g_{ad} \phi \vec{I}$, $\vec{B}_\phi = g_{\phi NN} \gamma_n^{-1} \nabla\phi$. $\left(\mathcal{L} \supset g_{\phi NN} \partial_\mu \phi \vec{N} \gamma^\mu \gamma_5 N - \frac{i}{2} g_d \phi \vec{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + \dots \right)$

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

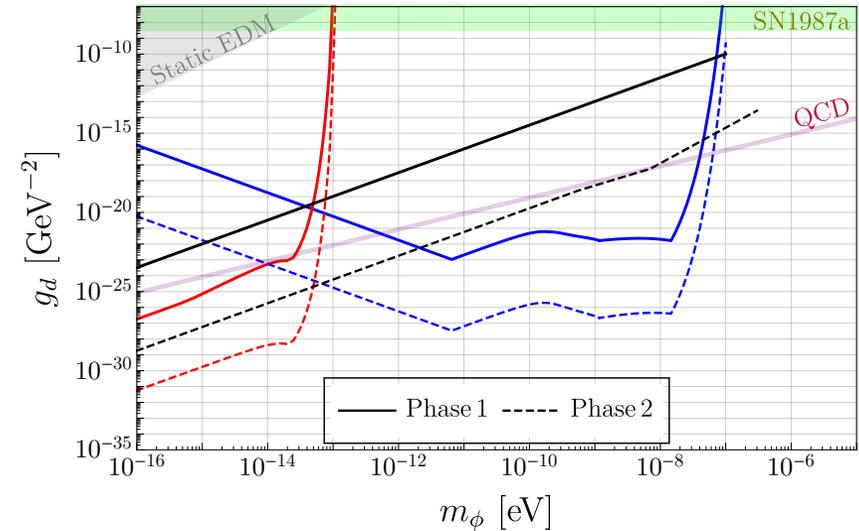
- In the case of axion-halo the “wind” is replaced by density gradient which is orientation-dependent => new type of signature.

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 sensitivity 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 background 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) \Rightarrow log crisis/opportunity, calls for experimental diversity.
- Accelerators provided a unique opportunity to search for (relaxed) relaxion.
- Ultra-light relaxion DM \Rightarrow Higgs VEV oscillating \Rightarrow exciting signals ...
- Signals are correlated with axion-searches which is a unique property.