Searching for new physics with precision

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Reconnect: Remote Conference on New Concepts in Particle Theory

Outline

- Intro, 21st century log crisis/opportunity
- Case study, relaxion/scalar-portal, a few lessons
- Precision with isotope shifts, recent progress
- Searching for (scalar) time dependent backgrounds
- Conclusions

Intro

- Our current 21st century struggle:

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

- Motivates us to look for new paradigms new search strategies

- Accelerators - work \w what you have now (be lucky) & plan …

- Great news for precision front \w exponential progress

Intro, (potential) hints from theory

- Our current 21st century puzzle:

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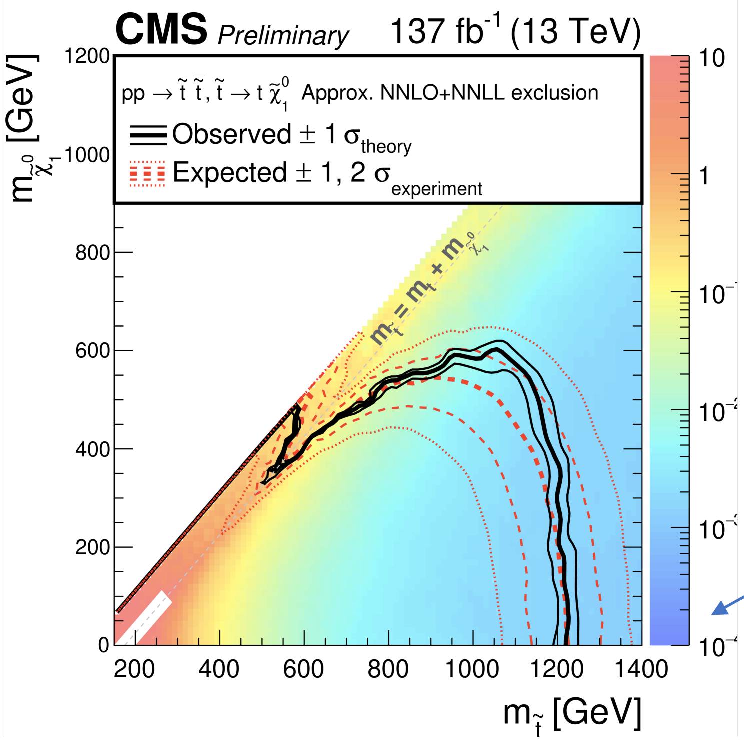
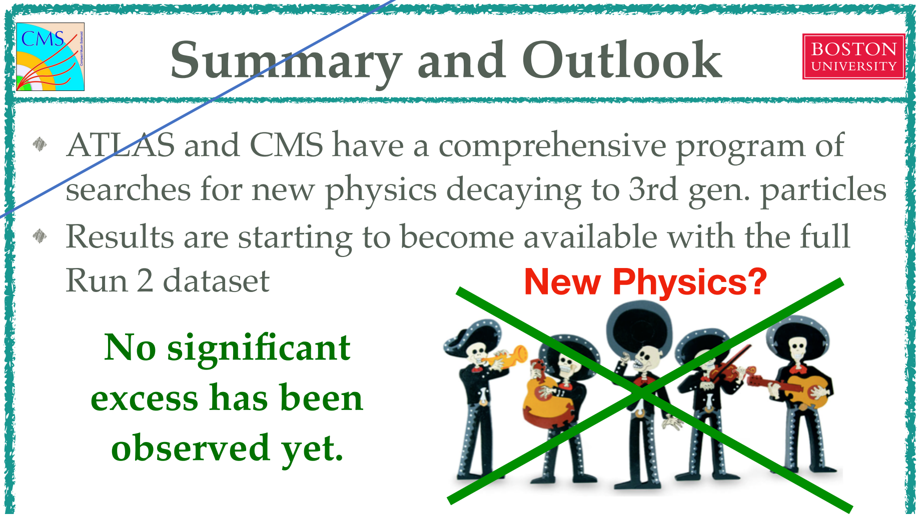
Conventional wisdom

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

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

  Graham, Kaplan & Rajendran (15)

  under some assumption allows for a concrete QFT realisation.

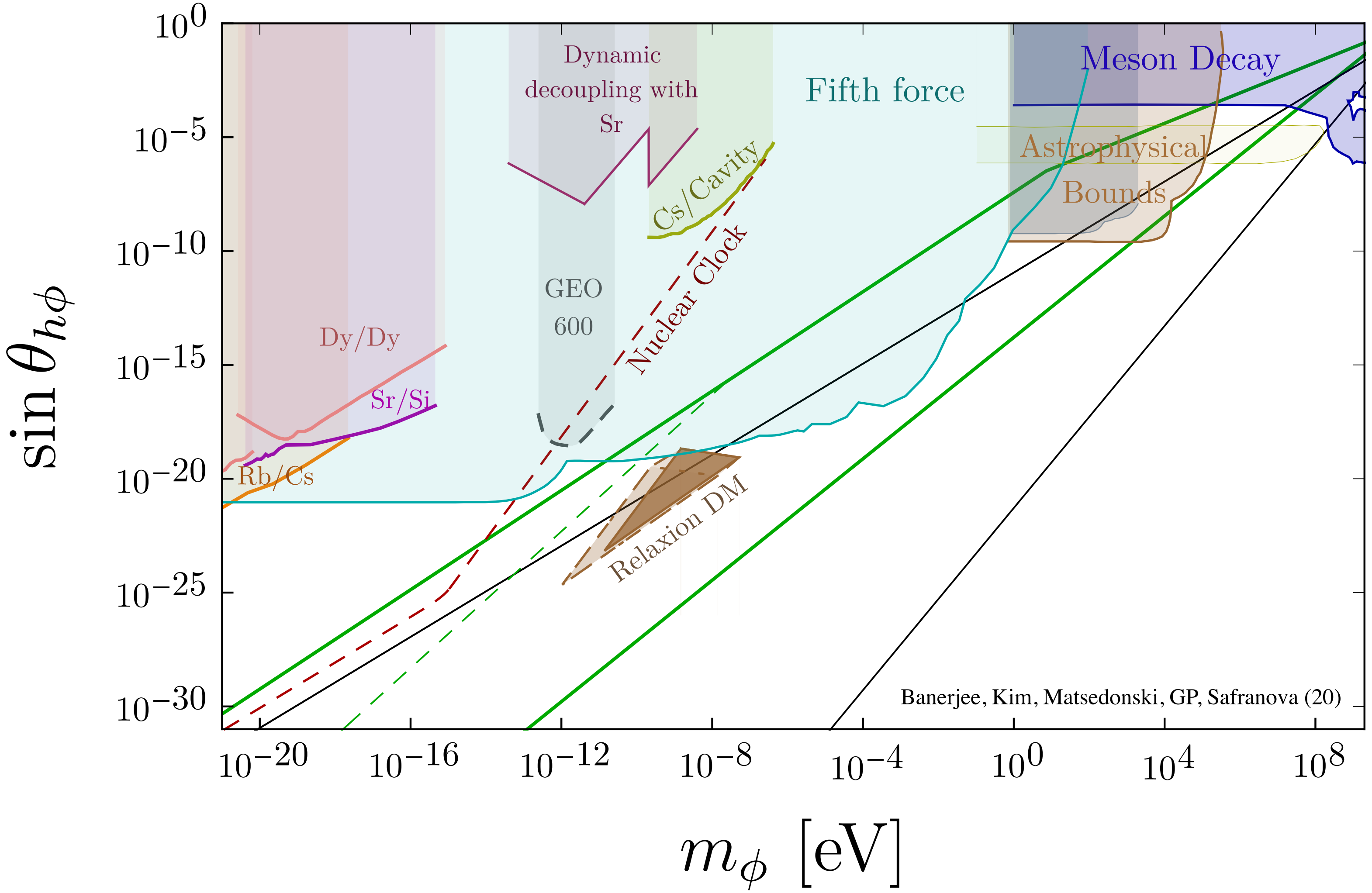
- Bottomline here: relaxion is axion-like-particle (ALP)-DM that (due to CP violation) can be described as scalar mixes \w the Higgs.

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

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

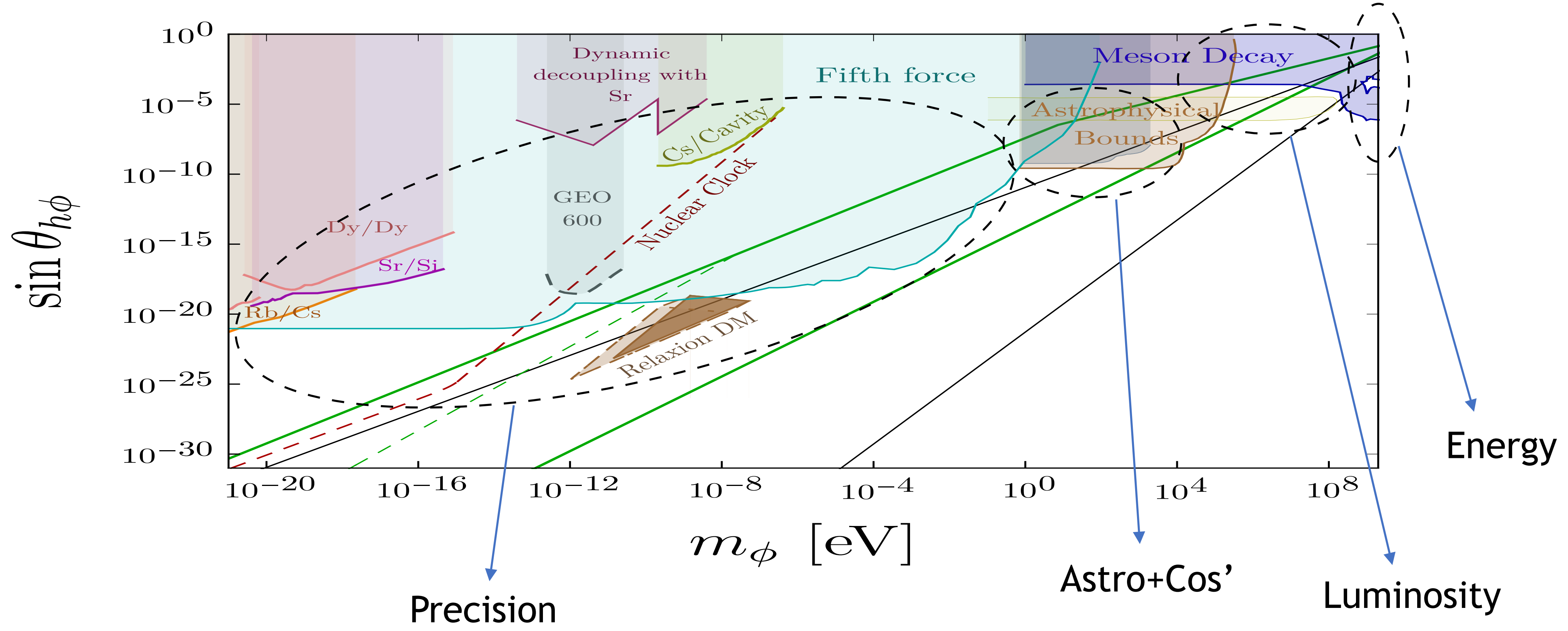
The relaxion (Higgs portal) parameter space & the *log crisis*

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



The log crisis, toy example, some lessons

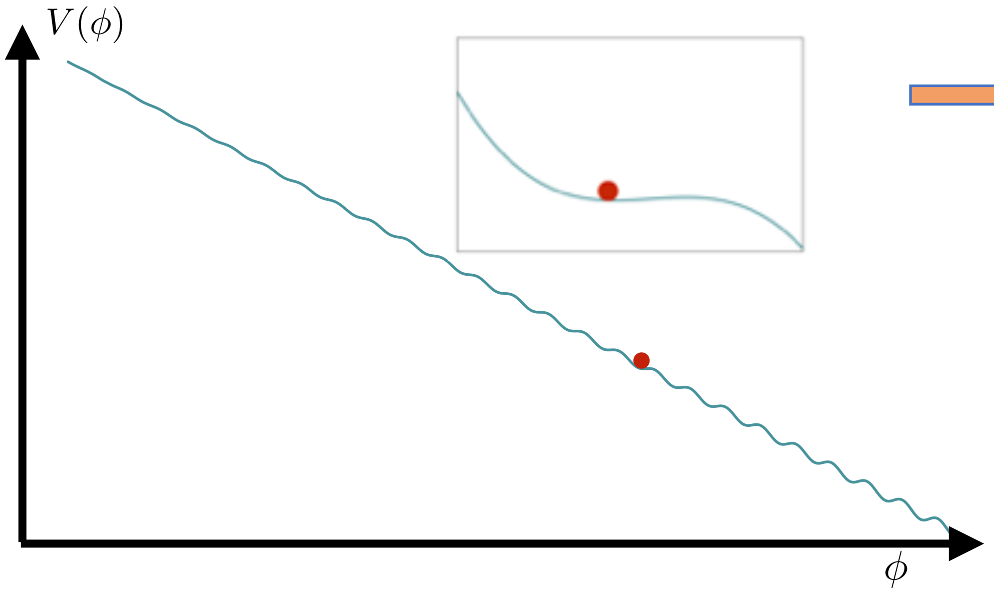
- Lesson 1 - finding NP requires diverse approach, searches across frontier
- Lesson 2 - experimentally, worth checking where many decades are covered:

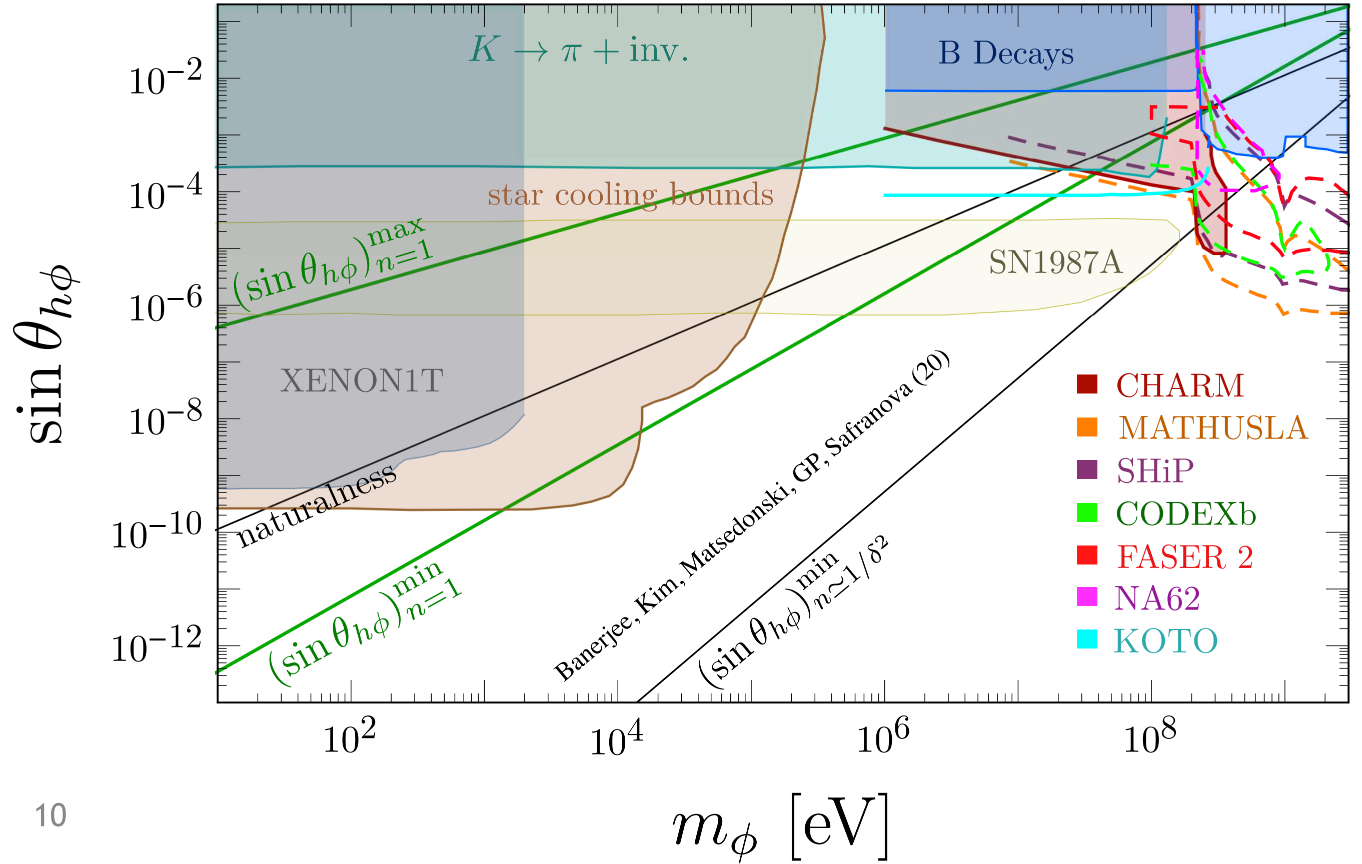


The log crisis, toy example, some lessons

- Lesson 1 - finding NP requires diverse approach, searches across frontiers
- Lesson 2 - experimentally, worth efforts where many decades are covered
- Lesson 3 - relaxion Higgs-portal interesting (un)natural region (relaxed-relaxion):

Relaxion: barriers increase incrementally:
relaxion stops at shallow => small mass, large mixing





Intro, guidelines from experiments

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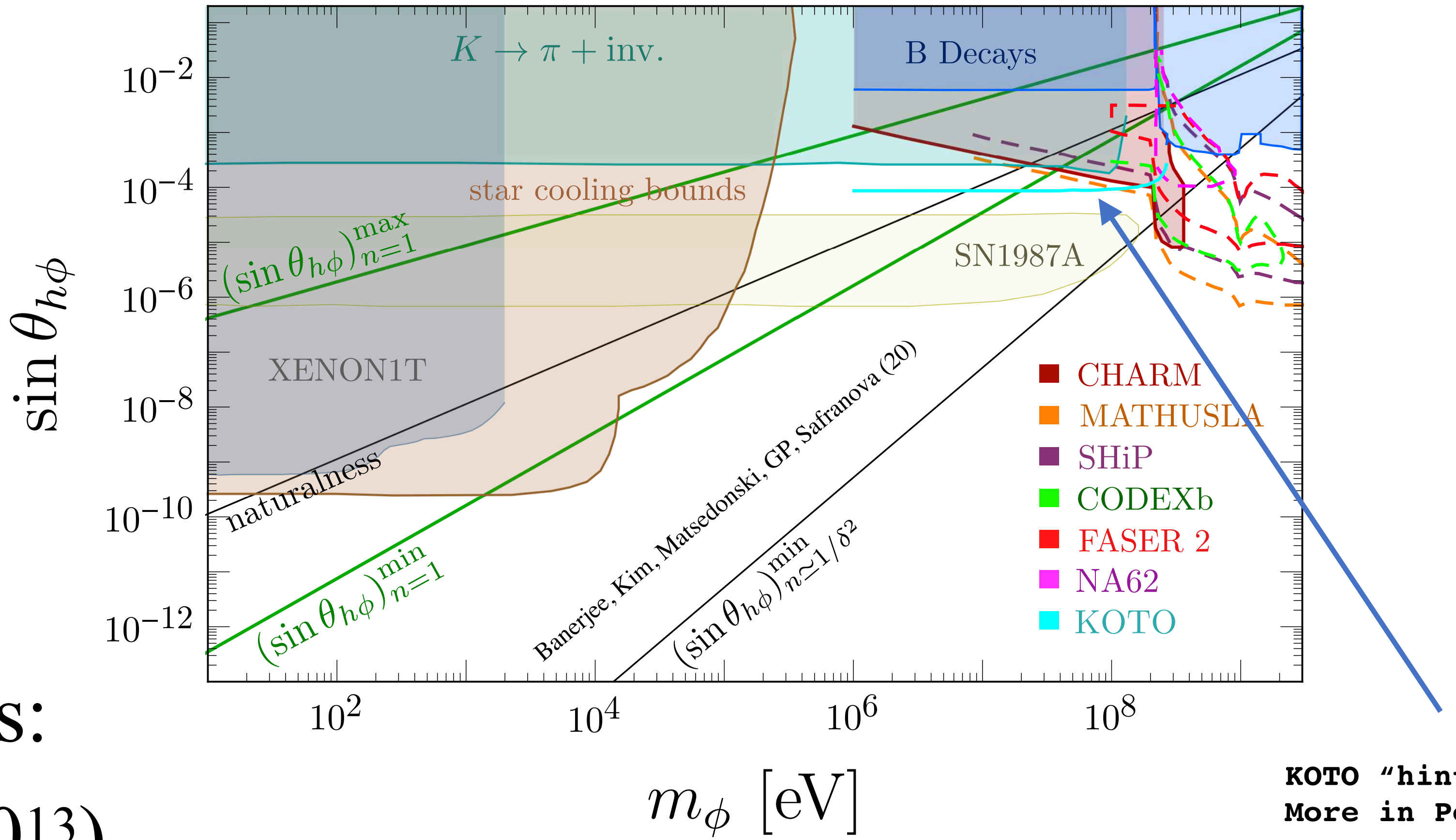
Luminosity & precision: the era of Kaon factories

CERN

J-PARC



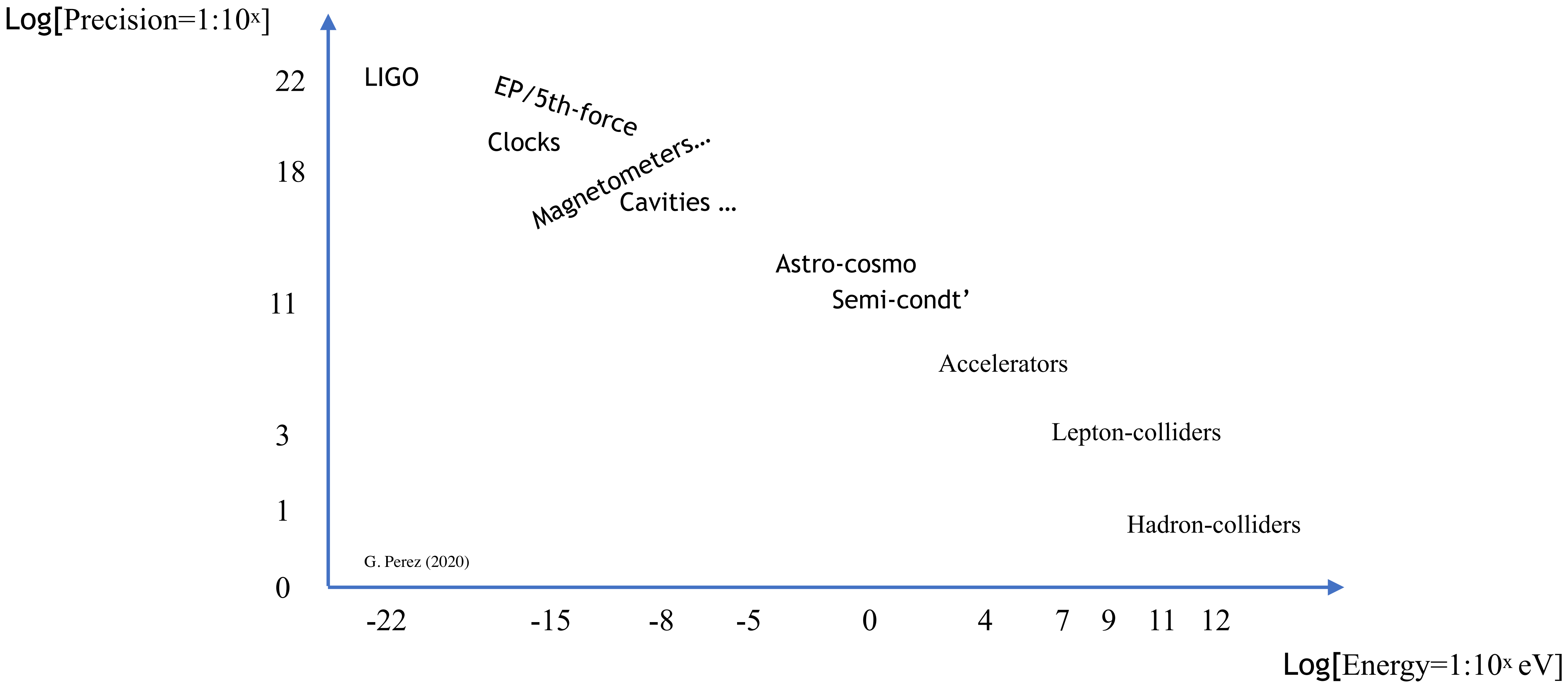
The Kaon factories:

\# of Kaon of O(10^{13})

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

KOTO "hint";
More in Pospelov's talk?

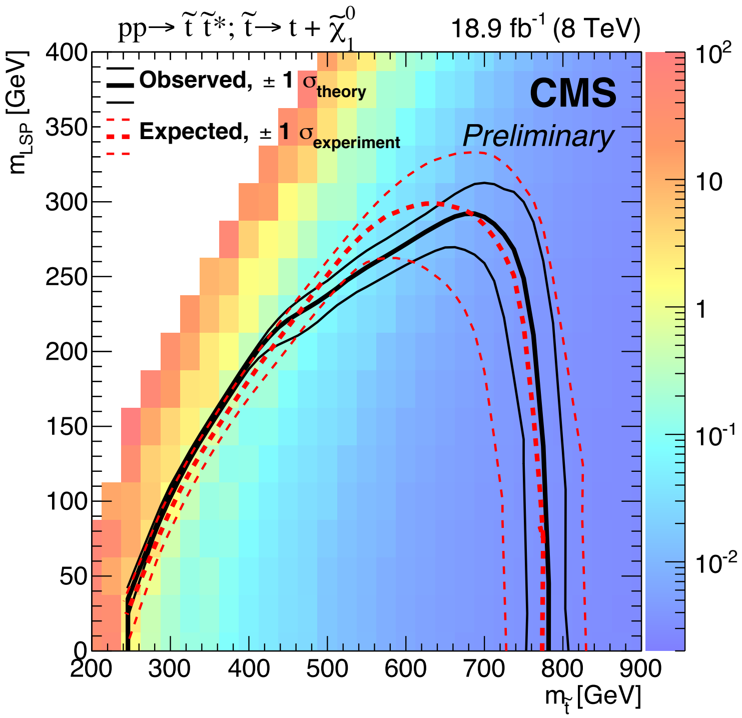
Sketch: precision vs. energy-reach currently



Energy frontier evolution of bound \w time

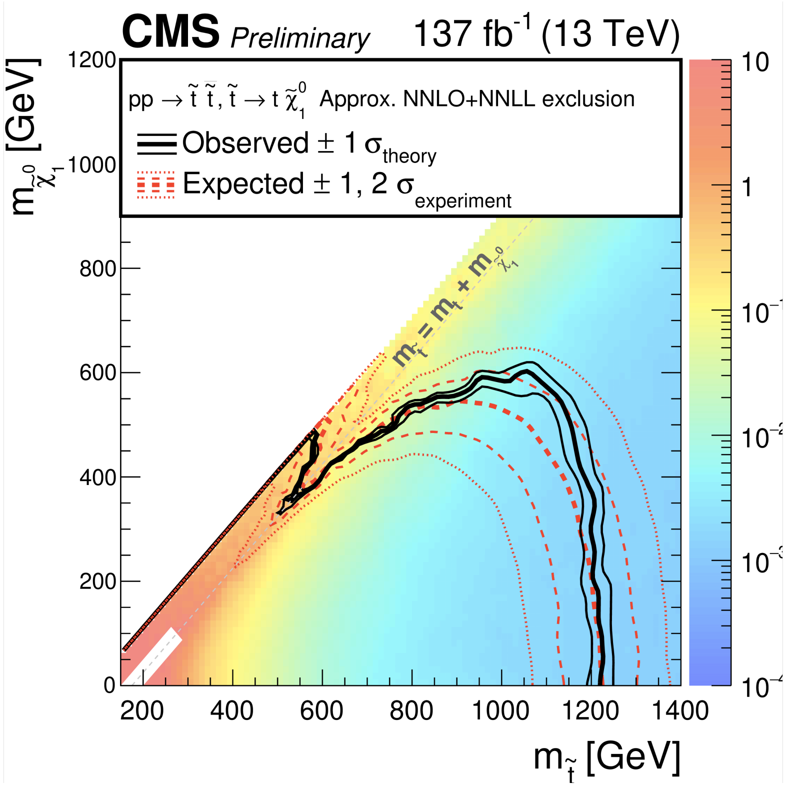
Bounds on stops-neutralino from 2015-2019

2015 : $\left(m_{\tilde{t}}\right)_{m_\chi=0} \gtrsim 0.8\,\mathrm{TeV}$



LHCP15: Ulmer, ATLAS & CMS

2019 : $\left(m_{\tilde{t}}\right)_{m_\chi=0} \gtrsim 1.2\,\mathrm{TeV}$



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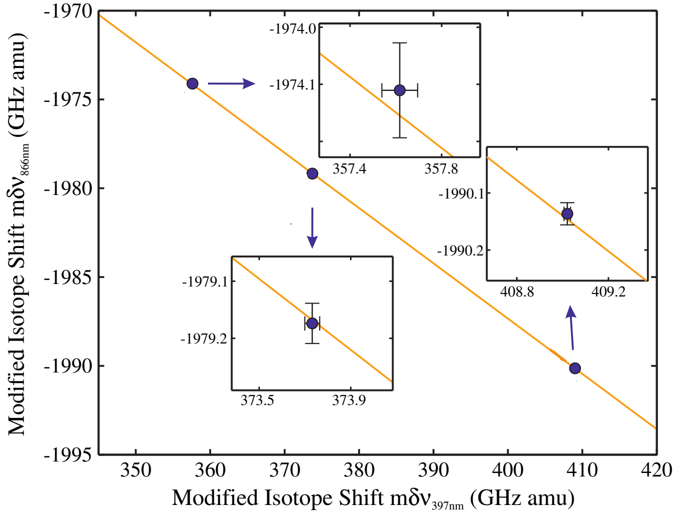
Recent ex. improving bounds by 10^3

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

Gebert et al. (PTB)



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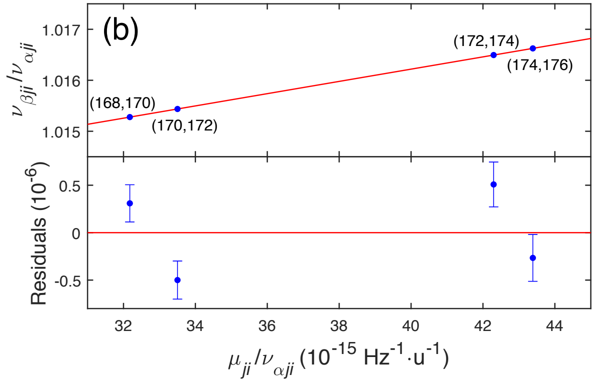

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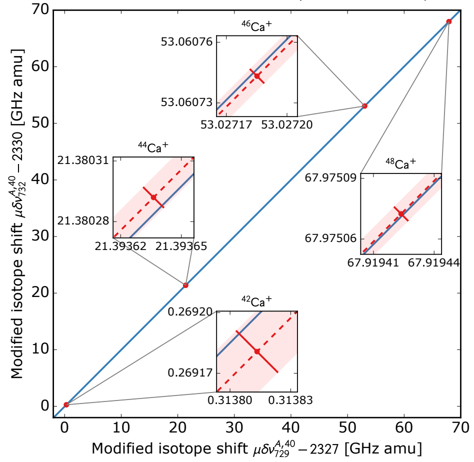

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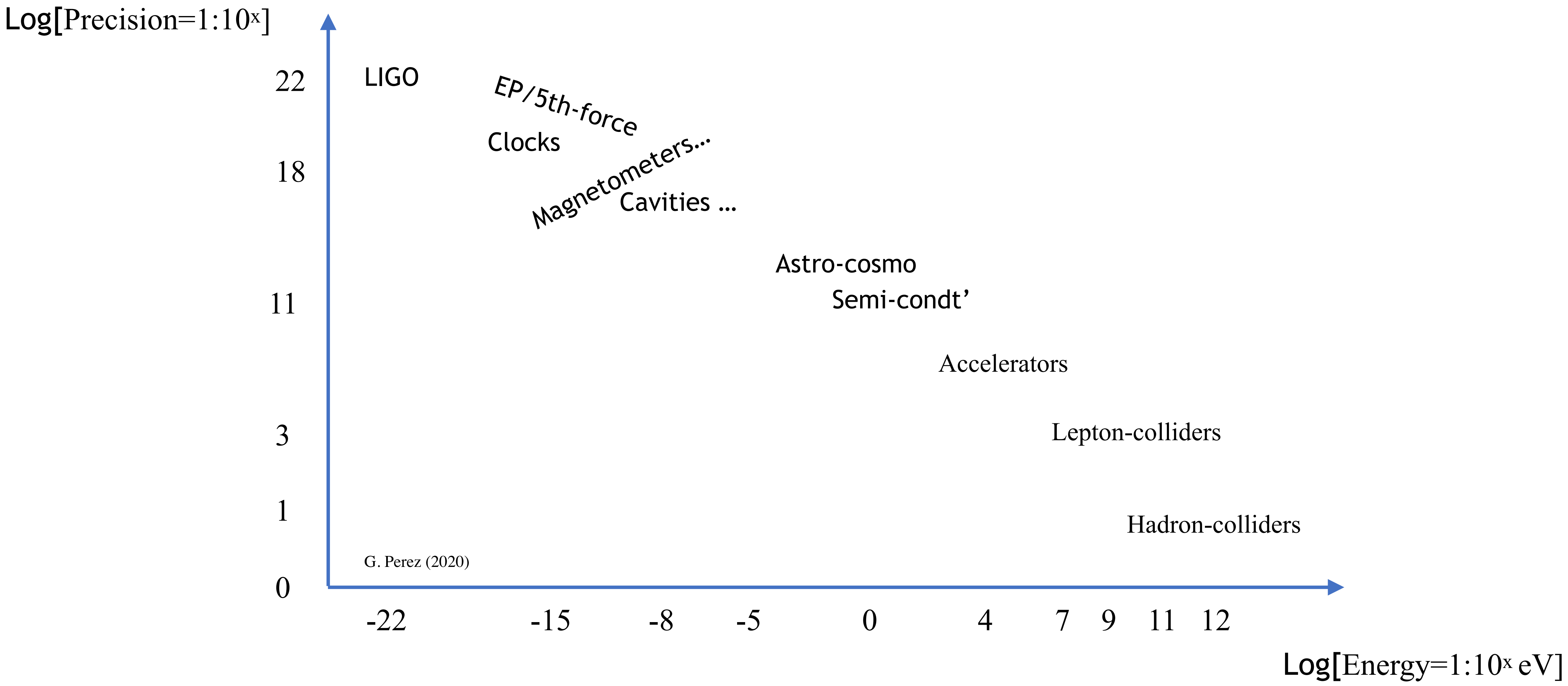
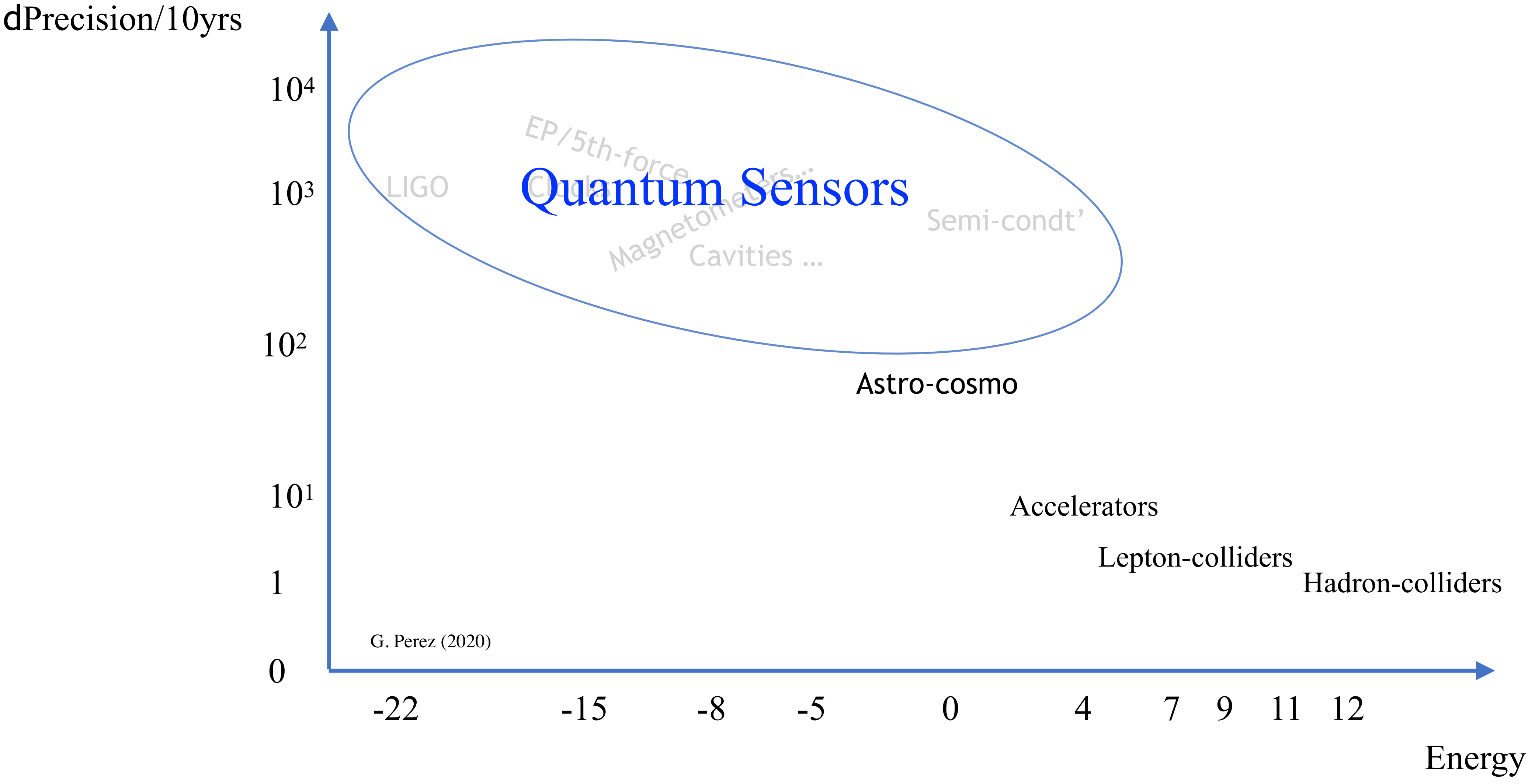


Progression: precision vs. energy-reach per 10/ys



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

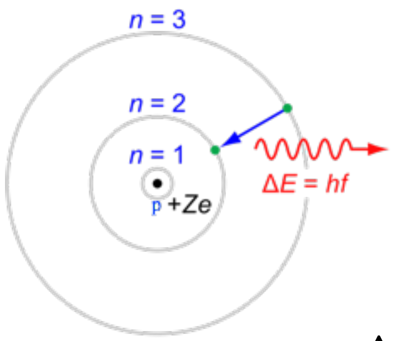
(i) virtual processes searching for atomic-range "Yukawa" force

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

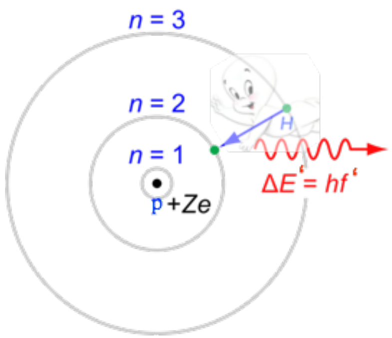
Hunting “heavy” relaxion with isotope shift spectroscopy

Basic concept: precision isotope shift spectroscopy

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



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



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

Delaunay, Ozeri, GP & Soreq (16)

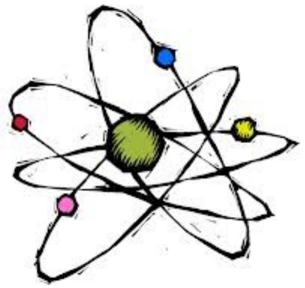
- We cannot switch on and off these light Higgs-like couplings.

- Use different isotopes to effectively compare force mass dependence.

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

King (1963)

Consider the following systems



$Ca^{(+)}, Sr^{(+)}, Yb^{(+)}$

1. At least two narrow electronic transitions (< 10 Hz possibility) with the same nucleus;

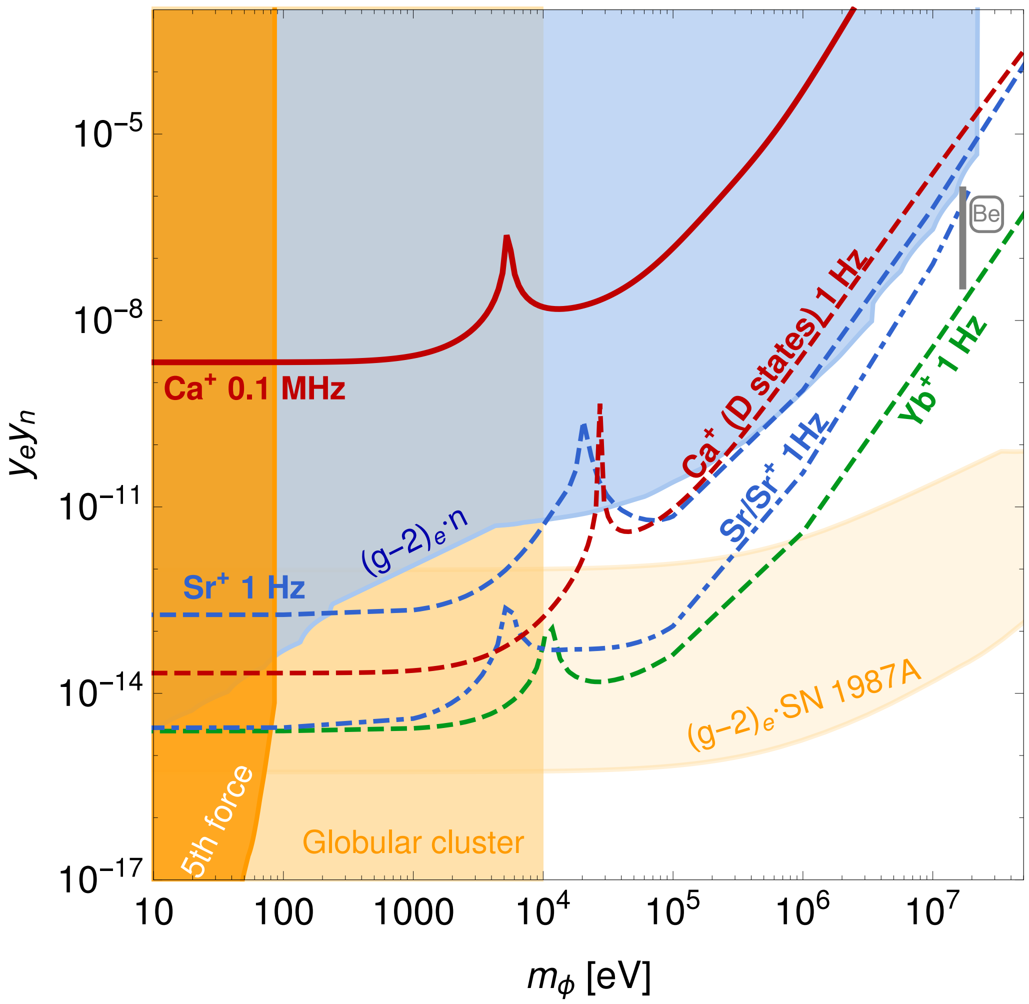
2. At least four stable (even) isotopes without nuclear spin for three independent IS comparisons.

3. Recent theory computation for above transitions => King-linearity-violation (KLV) O(1-10Hz) for non-hole states.

Flambaum, Geddes & Viatkina (18); Mikami, Tanaka & Yamamoto (17); Tanaka & Yamamoto (19)

Bounds & sensitivity

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, GP & Soreq (17)



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

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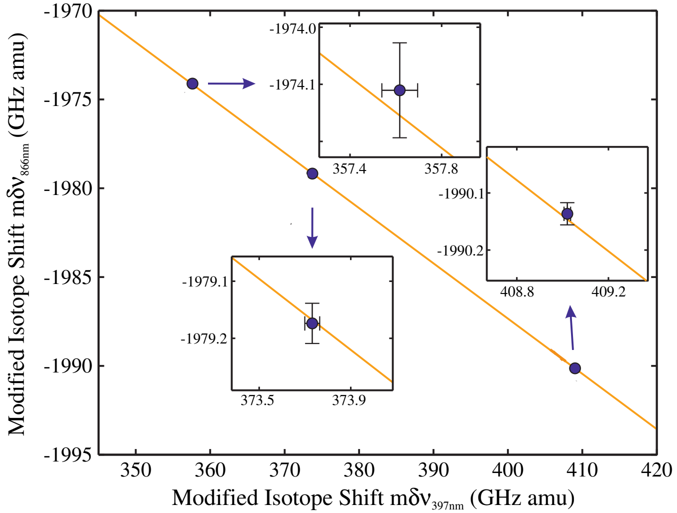


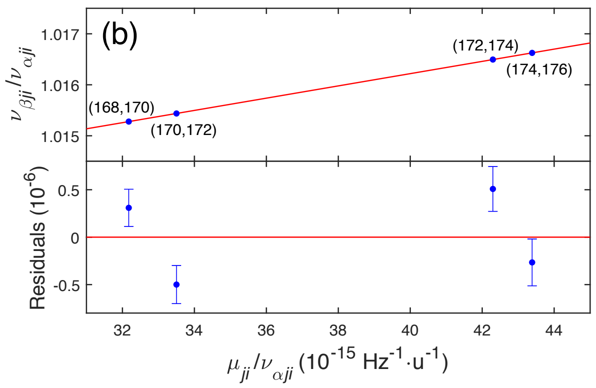
Ca$^+$ (A=40,42,44,48)

$D_{3/2} — P_{1/2}$

$S_{1/2} — D_{5/2}$

2020: Isotope shift @ 1:10^7

Counts et al. (MIT), 3sigmas

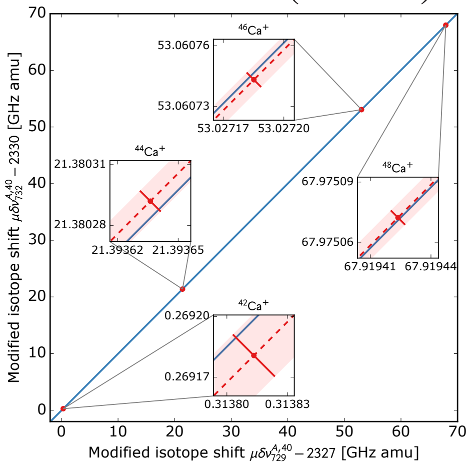


Yb$^+$ (A=168,70,72,74,76)

$S_{1/2} — D_{3/2}$

$S_{1/2} — D_{5/2}$

Solaro et al. (Aarhus)



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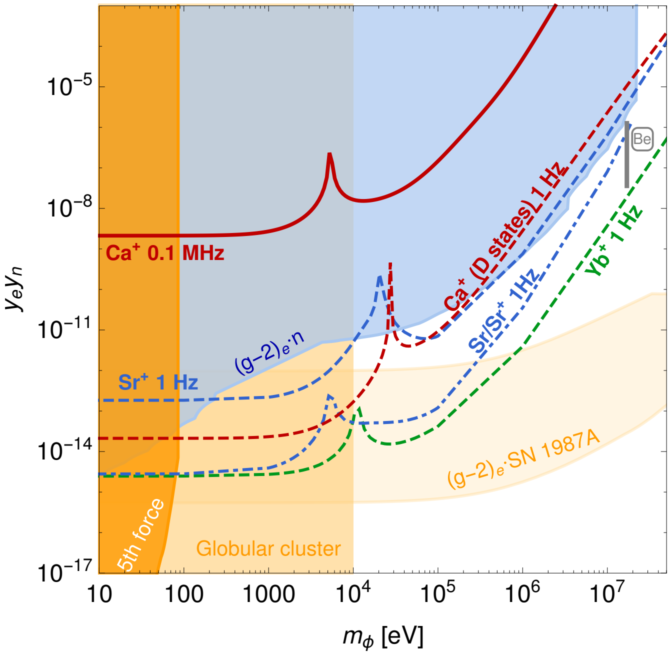

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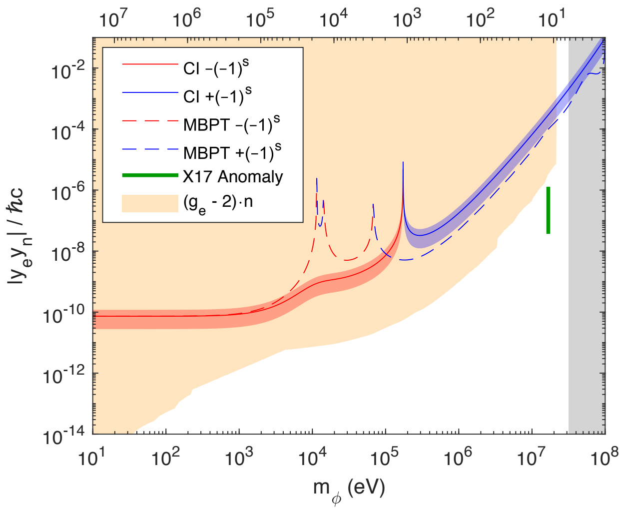

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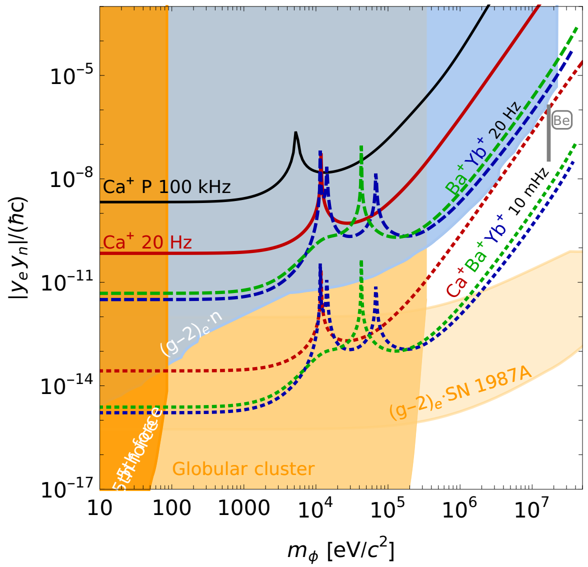
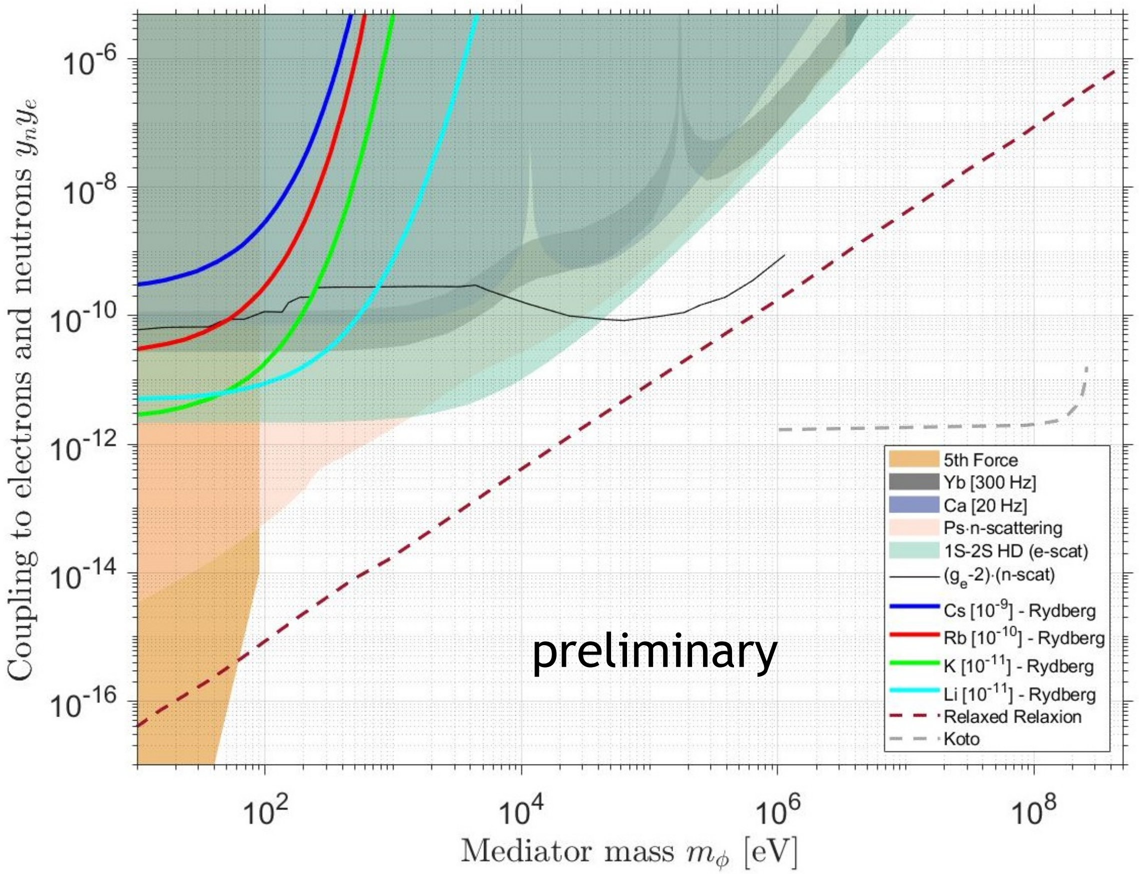


How robust is the $(g\text{-}2)_e$ bound? Can we reduce SM contamination?

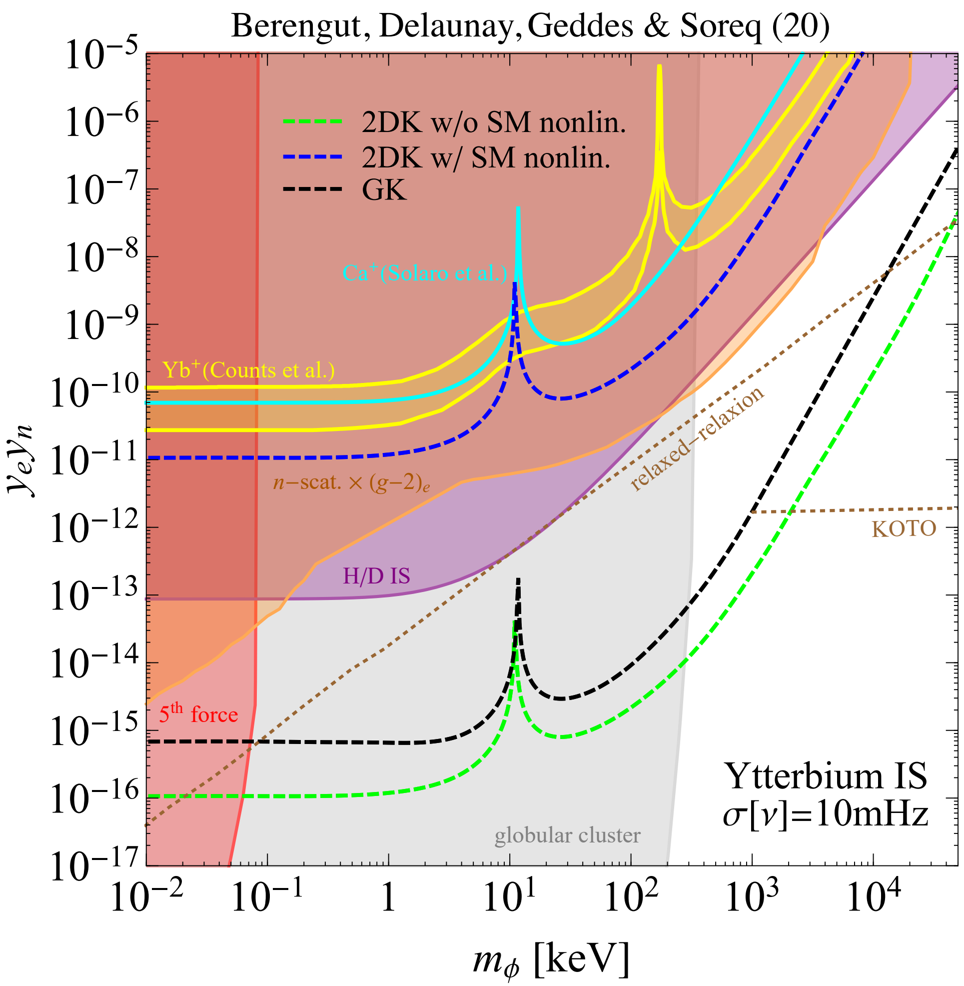
- The $(g\text{-}2)_e$ bound is model dep. & can be naturally suppressed (mirror sym.).
- Looking at (2-3) isotope shifts in “heavy" Rydberg transitions => reduce nuclear-impact.

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



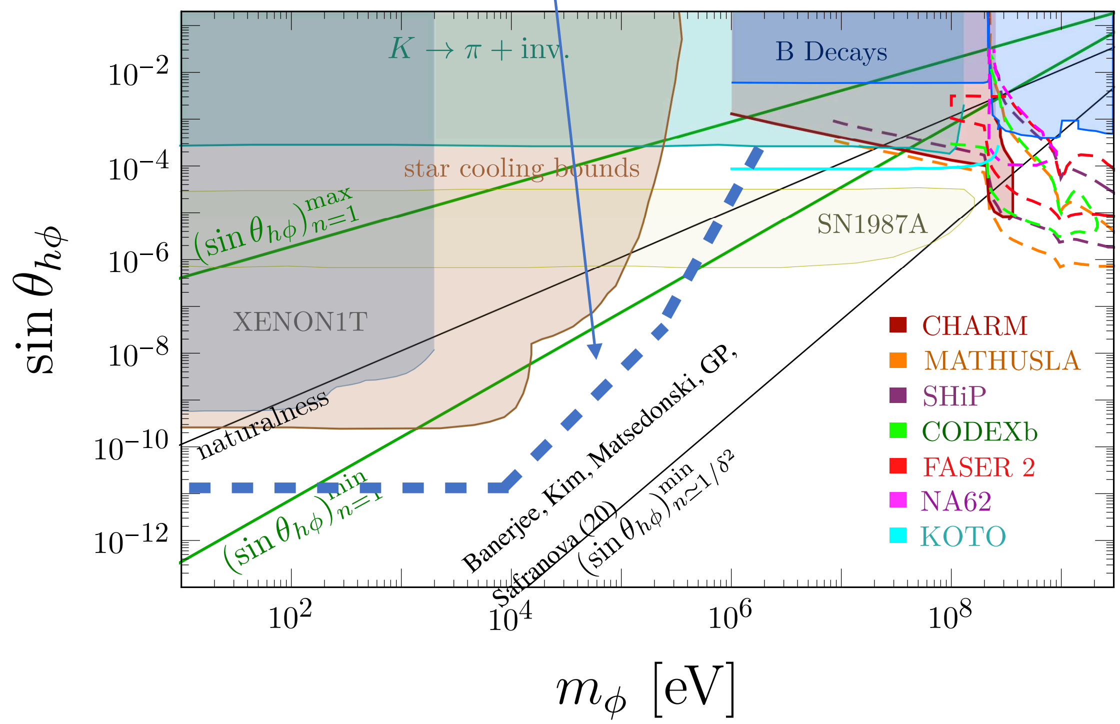
Duque-Mesa, Geller, Firstenberg, Fuchs, Ozeri, GP & Shpilman, in prep.

Projections, complementarity



KLV: (blue) or not (green) NL_{SM} and from the generalized King analysis (GK) adding the S → P transition (black). Existing NP bounds from IS in Yb^+ (the preferred 95 % CL NP interval) and Ca^+ (the upper bound) are shown in yellow and cyan solid lines. Also shown, 5th force searches, electron-neutron scattering, neutron-nucleus scattering, combined with the electron magnetic moment, hydrogen-deuterium (HD) IS, and globular cluster. The dotted lines indicate the relaxed-relaxion and a scalar that may explain the KOTO result.

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



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:

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

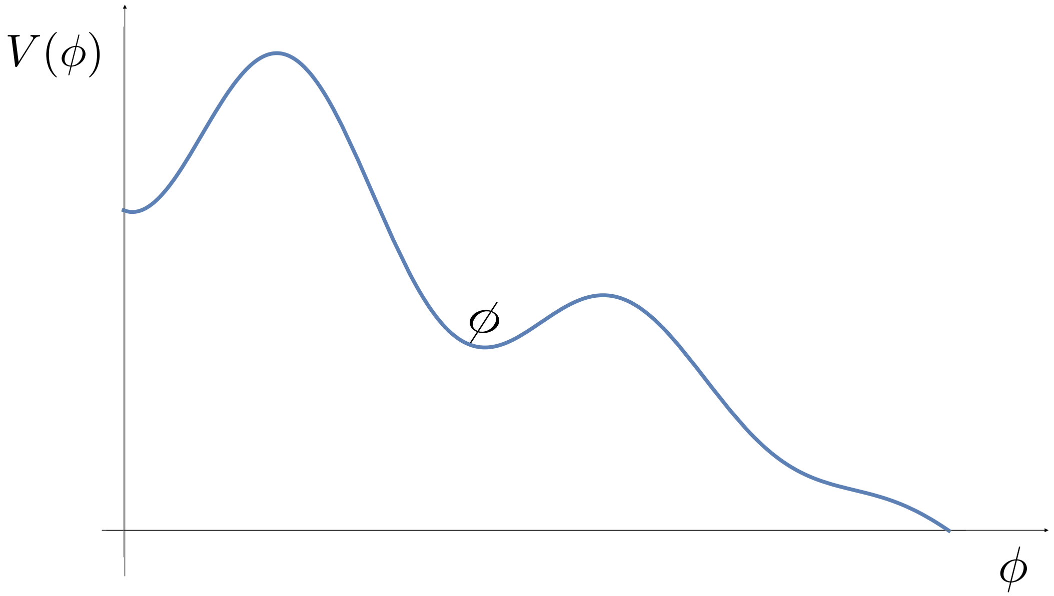
Relaxion/scalar light dark matter

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)

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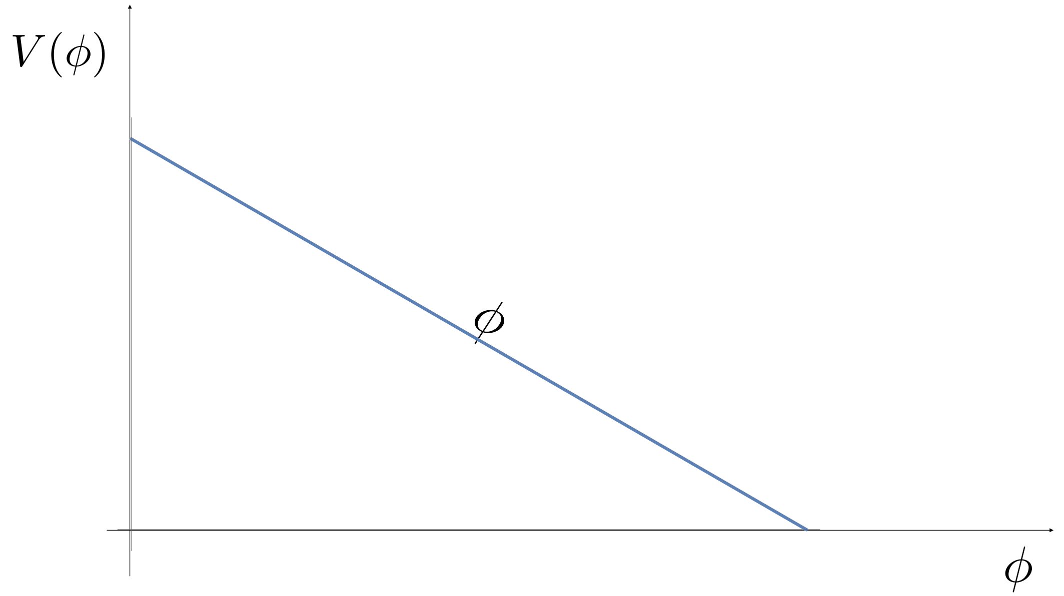
  After reheating the wiggles disappear (sym' restoration):



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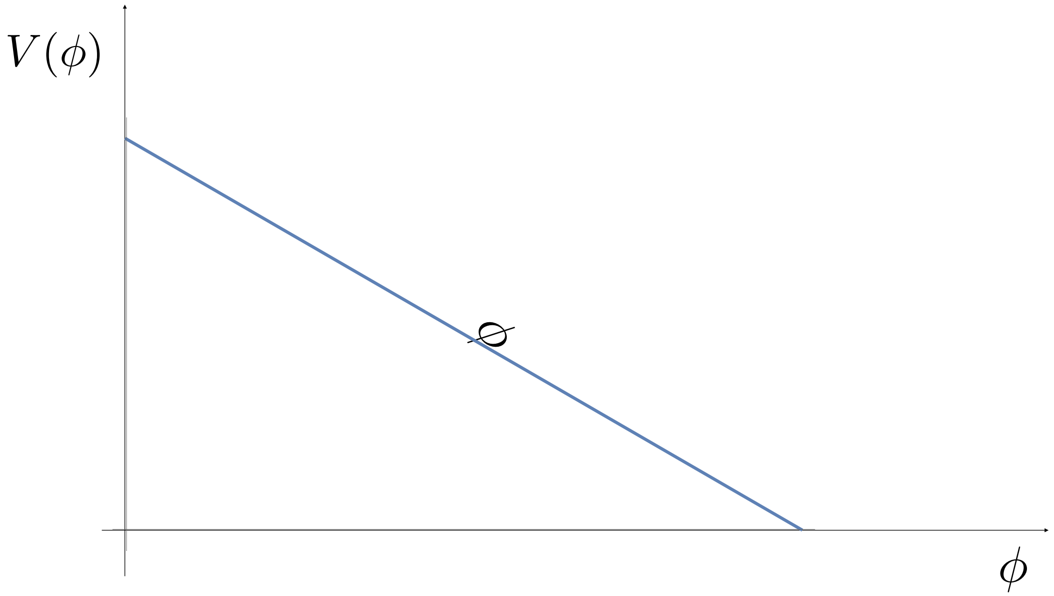
  After reheating the wiggles disappear: and the relaxion roles a bit.



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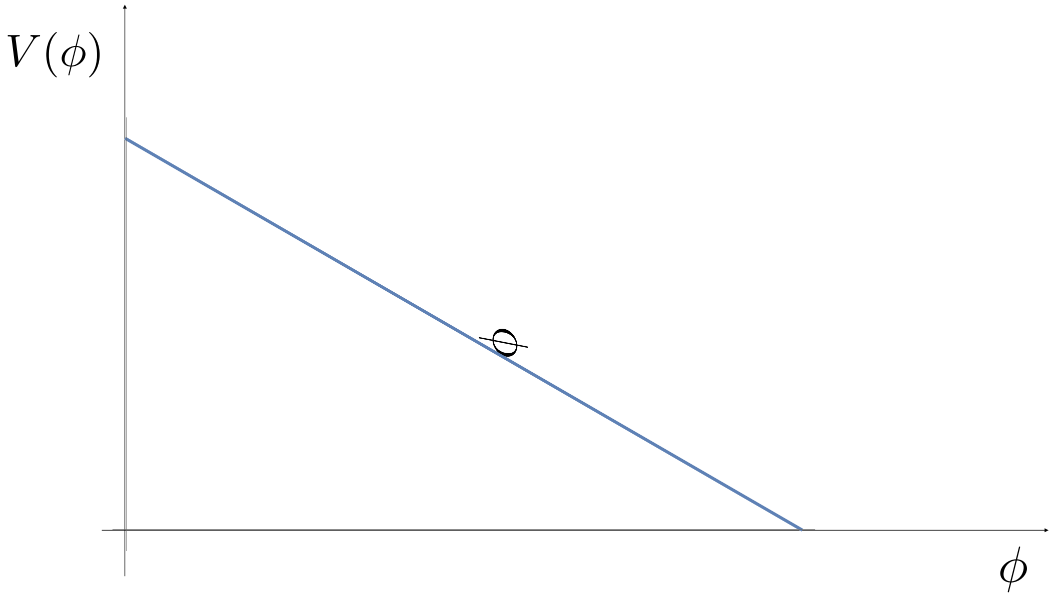

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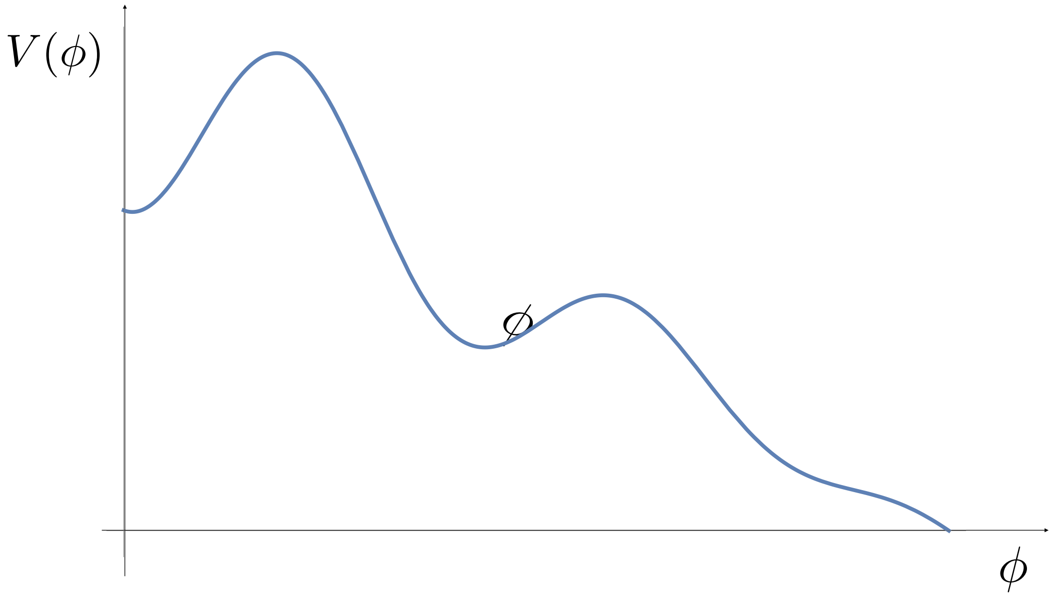
Now the relaxion not at the min' and start to oscillates = DM.



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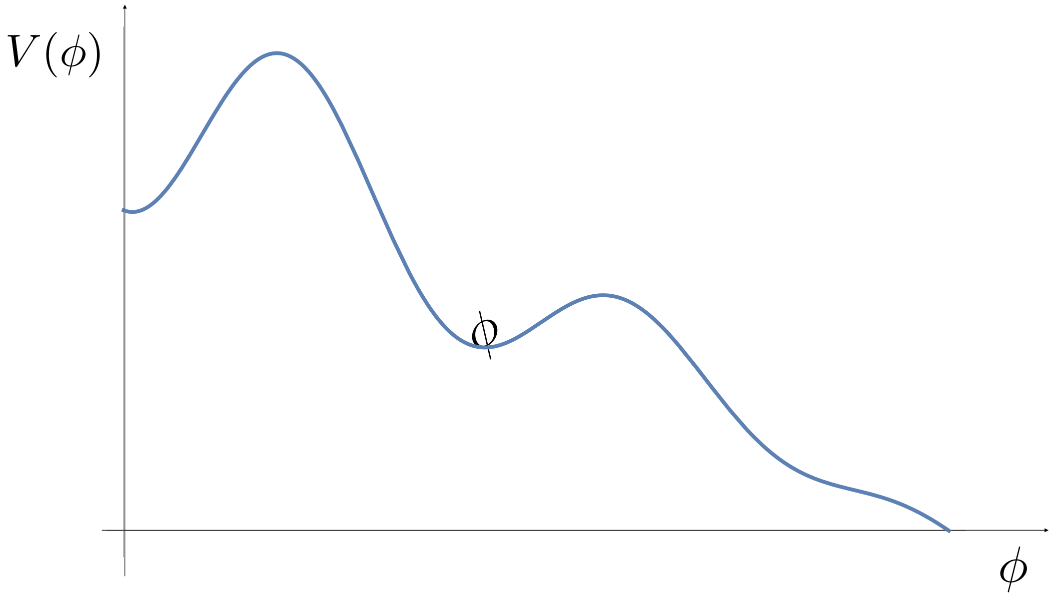

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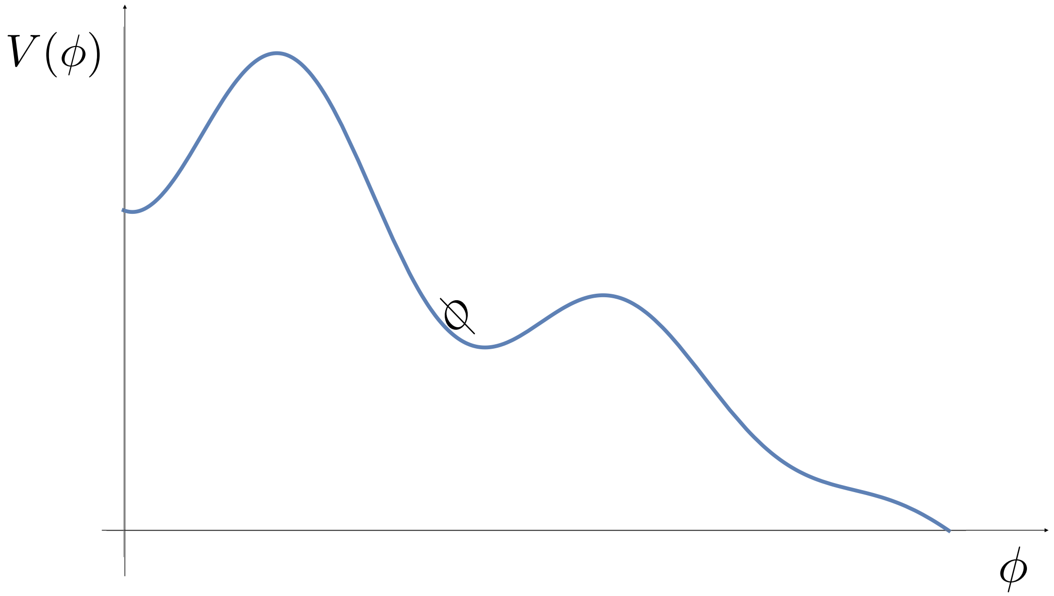

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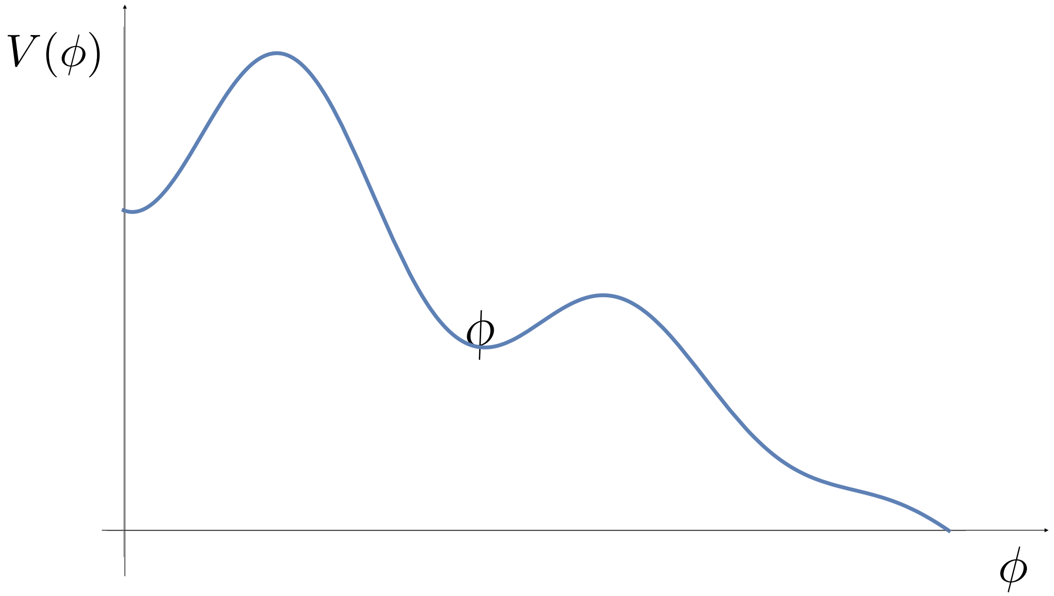

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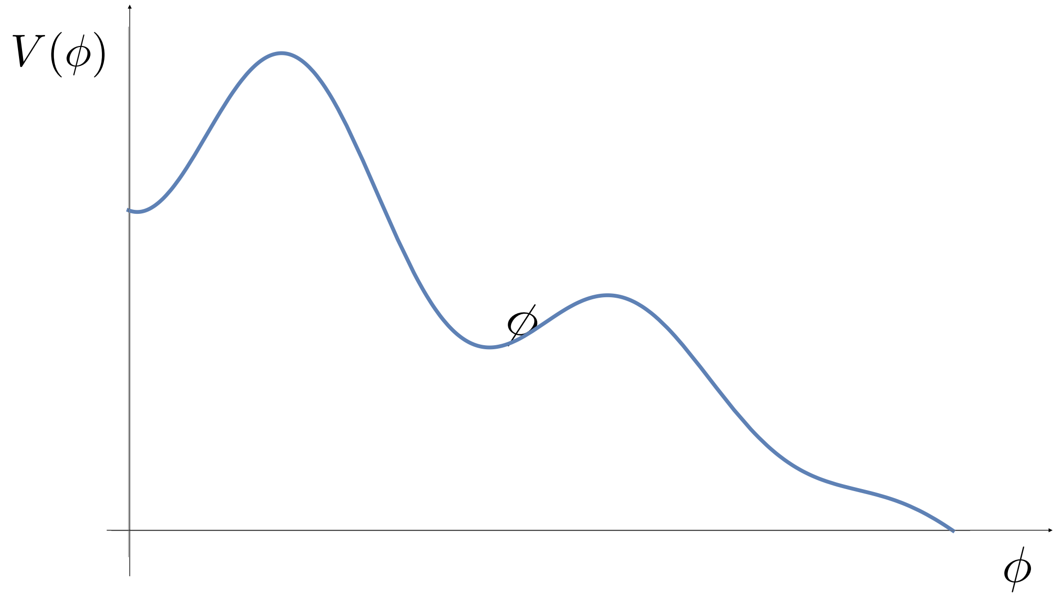
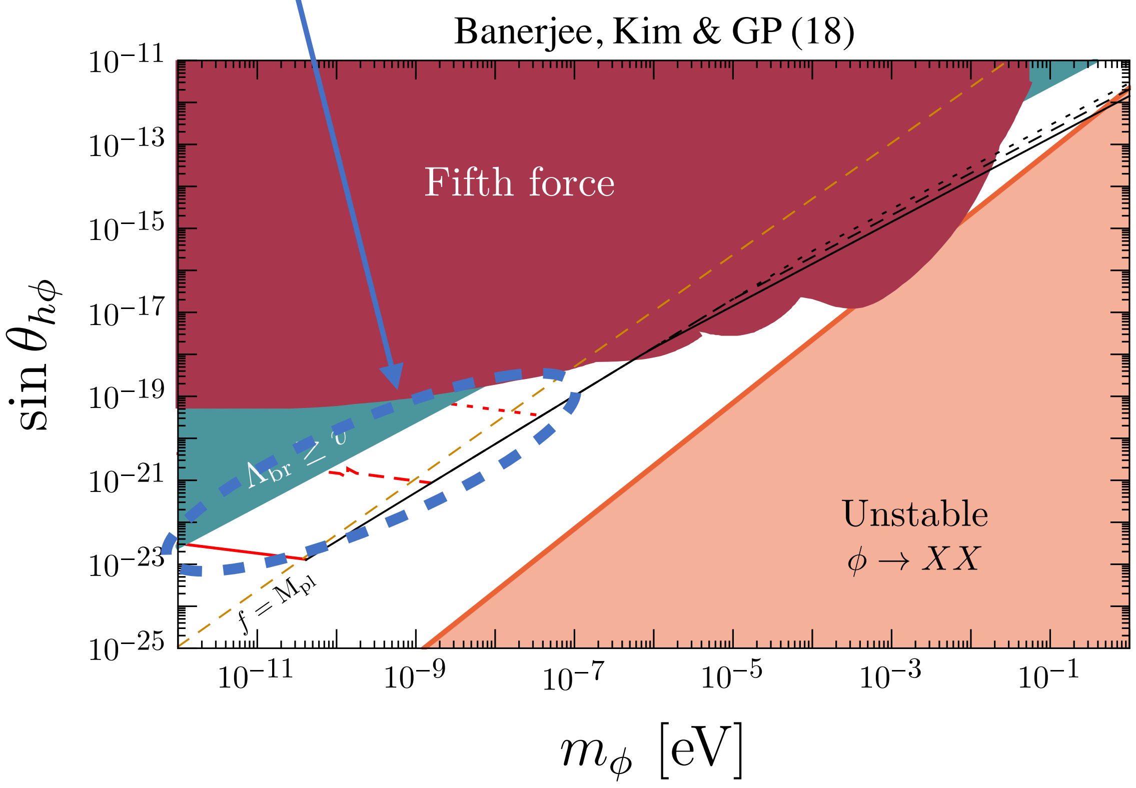


Relaxion/Higgs-portal & benchmarking

- 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))

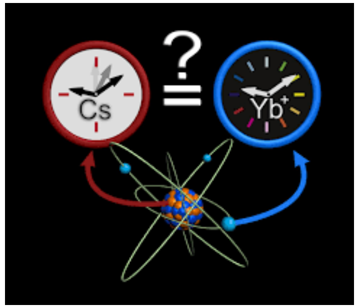


$$\mathcal{L} \supset \sin\theta_{h\phi}\frac{\phi}{v}\left[-m_f\bar{f}f + \frac{c_\gamma}{4\pi}FF + \frac{c_g}{4\pi}GG\right];$$

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

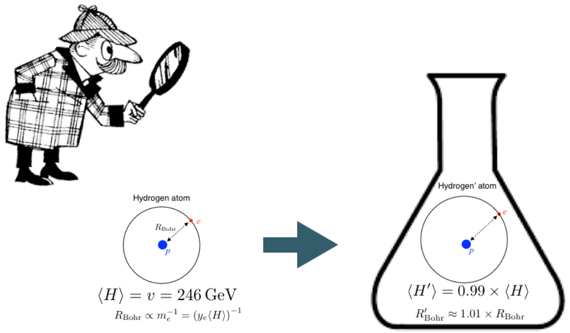
[see Safronova,Budker, DeMille, Kimball, Derevianko & Clark (18) for recent review]

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

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

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

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

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

Searching for a relaxion DM planet around us

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

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

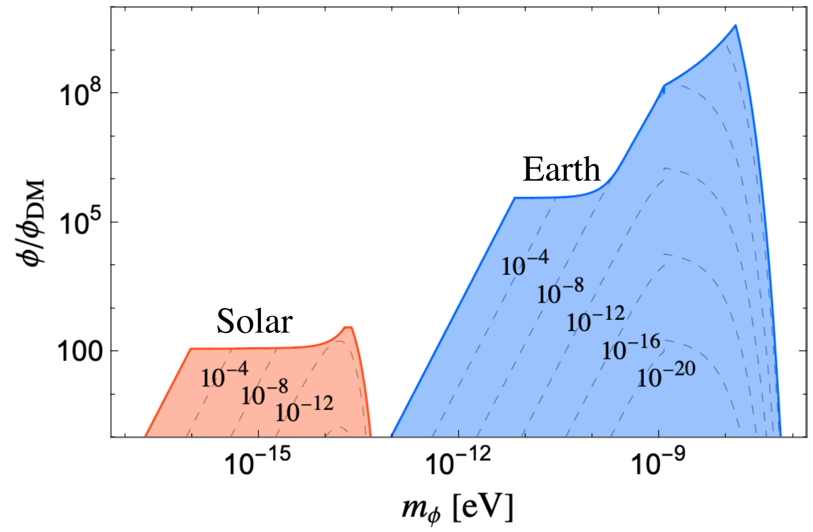
$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

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

Can obtain large density enhancement:

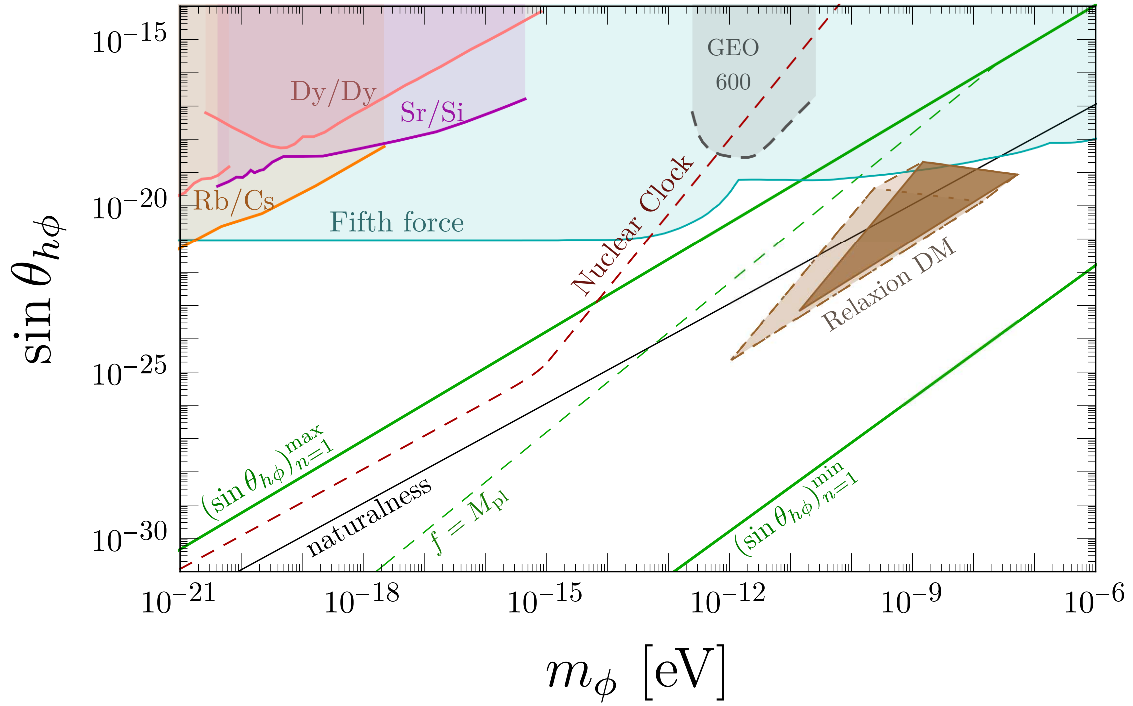
$$r \equiv \frac{\rho_{\rm star}}{\rho_{\rm loc-DM}} \sim \xi\,\frac{M_{\rm Earth}^4\, m_\phi^6}{M_{\rm Pl}^6\, \rho_{\rm loc-DM}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}}\right)^6$$

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

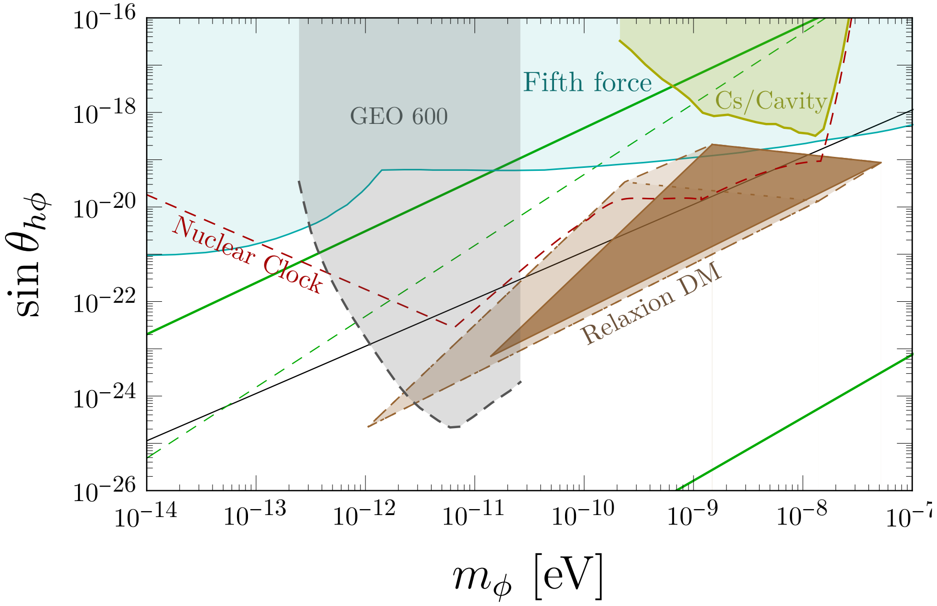


Enhancements in the axion halo scenario compared to the background DM case, in the field value for the Earth halo (blue) and solar halo (red) compared to the usual ALP DM case. Solid lines correspond to maximal halo mass M_* by gravitational constraints.

Ideal system, nuclear clock, current & near future bounds



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 -

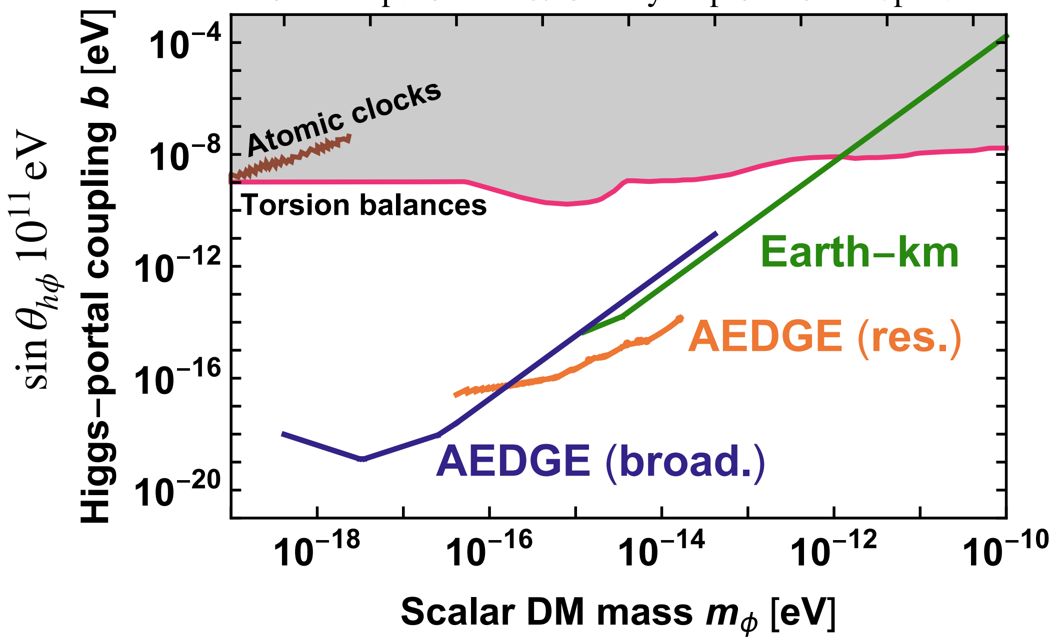
ELGAR, 1911.03701; MIGA, Sci. Rep. (18); MAGIS, 1711.02225; ZAIGA 1903.09288.

- 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)

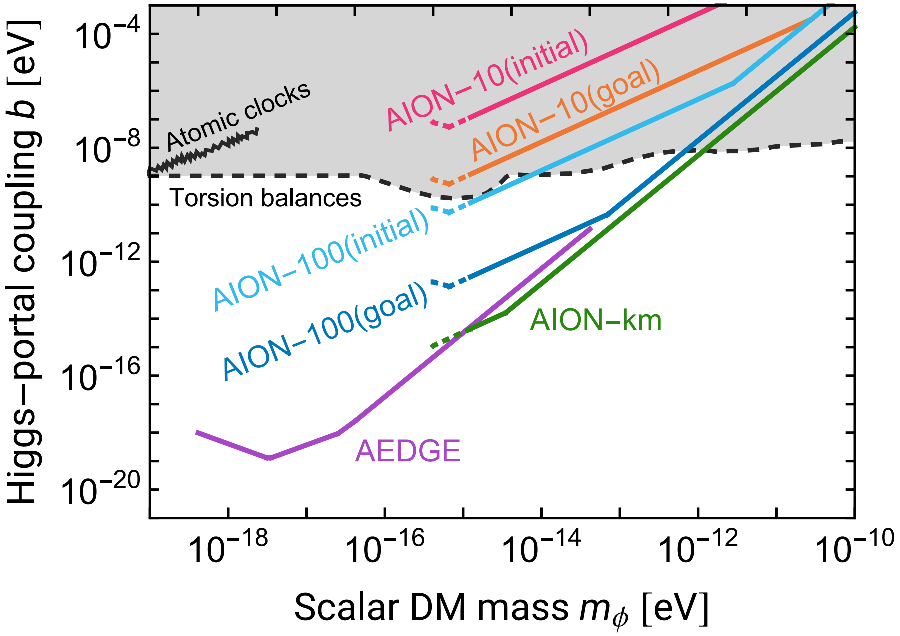
AEDGE (1908.00802)

Atomic Exp. for DM & Gravity Exploration in Space



AION (1911.11755)

An Atom Interferometer Observatory and Network



Conclusions

- Null-results + new theories => log crisis/opportunity (ex.: relaxion)

- Several Lessons: calls for experimental diversity, emphasises precision front.

- Discussed progress: i. isotope shifts; ii. scalar DM; iii. long-term projects

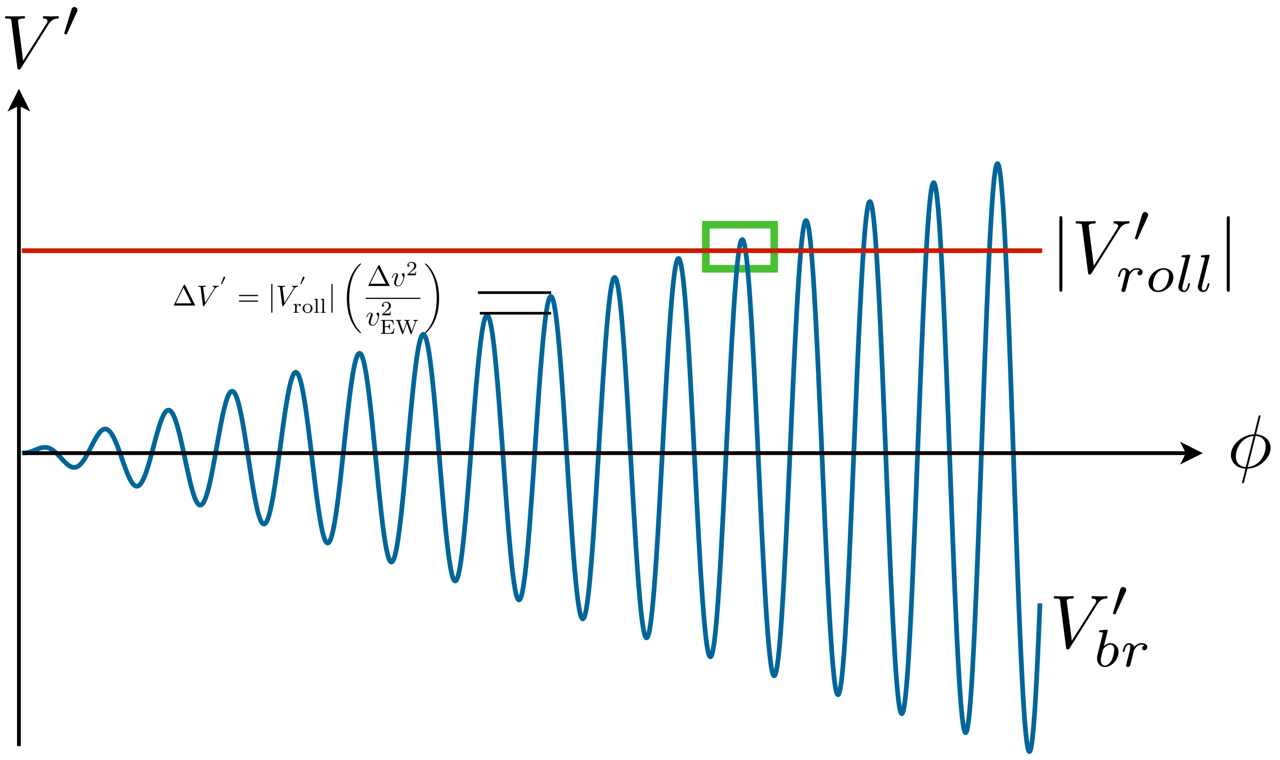
- Quantum sensors: exponential growth precision & innovation,

calls for *reconnection*, collaborative effort between AMO & particle physics.

THE STOPPING POINT

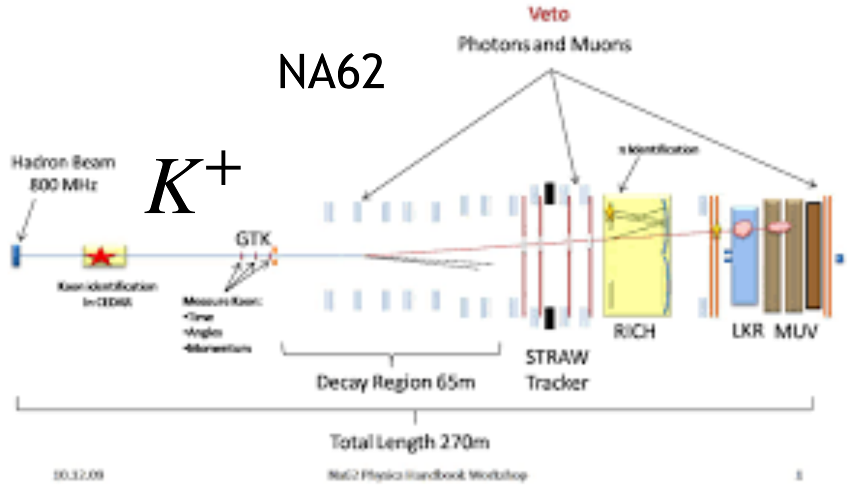
Relaxion stops when

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

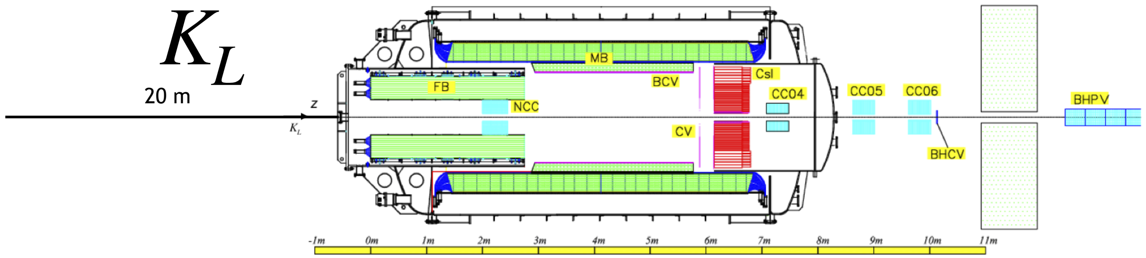


Brief look: Kaon factories NA62 & KOTO

NA62



KOTO



	NA62	KOTO
POT	10^{19} (400 GeV)	$10^{19\text{-}20}$ (30 GeV)
# Kaons	10^{13}	10^{13}
K-Energy	40 GeV	1.5 GeV
Length	300 m	30 m
Decay region	150 m	3-4 m

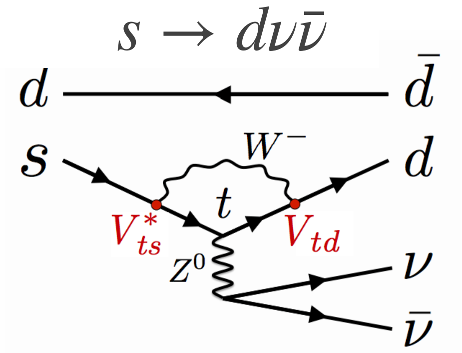
(Charm~ 10^{18})

Before data: NA62 & KOTO, the SM story

- ★ Both are searching to super-rare events:

$$\text{NA62}: \quad K^+ \to \pi^+ \nu\bar{\nu} \qquad \text{KOTO}: \quad K_L \to \pi^0 \nu\bar{\nu}$$

- ★ Suppression result of Loop (+GIM) + CKM:



$$\text{SM}: \text{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.4 \pm 1.0) \times 10^{-11}, \quad \text{BR}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.4 \pm 0.6) \times 10^{-11}$$

$K^+ \to \pi^+\nu\bar{\nu}$ vs. $K_L \to \pi^0\nu\bar{\nu}$ SM & Beyond

★ The Grossman-Nir (GN) bound (97):

In the SM, $K_L \longrightarrow \pi^0 vv$ and $K^+ \longrightarrow \pi^+ vv$ decays go through the same operator, $(s \longrightarrow dvv)$.

The $K_L \longrightarrow \pi^0 vv$ and $K^+ \longrightarrow \pi^+ vv$ matrix elements related through isospin -

$$\mathrm{BR}\left(K_L \to \pi^0\nu\bar{\nu}\right) \leq 4.3\,\mathrm{BR}\left(K^+ \to \pi^+\nu\bar{\nu}\right) \ .$$

★ The relation may hold in cases NP, say in 2 body, or heavy particles:

$$\Gamma\left(K_L \to \pi^0 a\right) \leq \Gamma\left(K_S \to \pi^0 a\right) \ . \quad [a = \text{axion like particle (ALP)}]$$

Leutwyler and M. A. Shifman (90)

NA62 & KOTO, data

$\left\{\mathrm{SM}:\mathrm{BR}\left(K^+\to\pi^+\nu\bar{\nu}\right)=(8.4\pm1.0)\times10^{-11},\ \mathrm{BR}\left(K_L\to\pi^0\nu\bar{\nu}\right)=(3.4\pm0.6)\times10^{-11}\right\}$

★ NA62 (2019) prelim' result is consistent \w expectation:

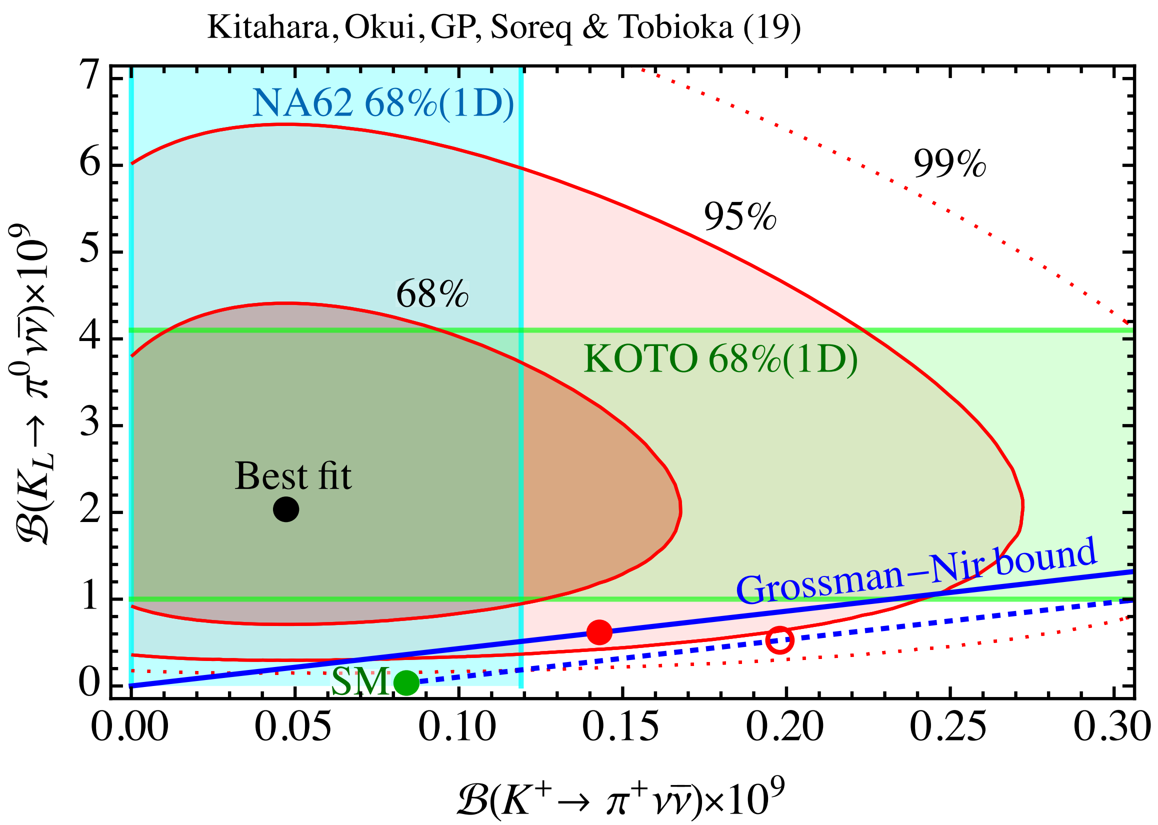
$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu})_{\mathrm{NA62}}=0.47^{+0.72}_{-0.47}(<2.44)\times10^{-10}\,,$$

★ KOTO (2019) prelim' analysis reveals 2-3 events \w BG << 0.5

$$\mathcal{B}(K_L\to\pi^0\nu\bar{\nu})_{\mathrm{KOTO}}=2.1^{+2.0\,(+4.1)}_{-1.1\,(-1.7)}\times10^{-9}\,,$$

KOTO is currently intensely investigating their BG estimation.

Are the two results compatible @ face value (v1)?



- GN: $\sim 2\sigma$ with SM interference; $\sim 3\sigma$ without interference.
- Can easily accommodated \w EFT:

Are the two results compatible @ face value (v1)?

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

- Can easily accommodated \w EFT: $\mathcal{L}_{\rm eff} = \sum_{i=S,A,D} C_i^{\nu\nu} \mathcal{O}_i^{\nu\nu}$

$$\mathcal{O}_D^{\nu\nu} = \left(\bar{d}^2 d^1\right)_{V+A} \left(\bar{L}L\right)_{V-A}$$

$$\mathcal{O}_{S,A}^{\nu\nu} = \left[\bar{Q}^2 \left(\mathbf{1}_2, \sigma^i\right) Q^1\right]_{V-A} \left[\bar{L} \left(\mathbf{1}_2, \sigma^i\right) L\right]_{V-A}$$

where Q/L is a quark/lepton doublet, d is the down-type quark singlet.

$$C_{S,D}^{\nu\nu} - C_A^{\nu\nu} \approx \begin{cases} \mathrm{i}/(110\,\mathrm{TeV})^2, & \text{KOTO} \\ \mathrm{e}^{-\mathrm{i}\frac{3}{4}\pi}/(150\,\mathrm{TeV})^2, & \text{KOTO \& NA62} \end{cases}$$

The two results compatible "experimentally" (v2)

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

★ Koto & NA62: different parameters & structure => account for significant differences:

(i) consider 2 body decay $K \to \pi X$, \w X stable => can't accommodate results:

With $m_X < m_{\pi^0}$, $K_L \to \pi^0 X$ & $K_L \to \pi^0 \nu\nu$ have same KOTO acceptance => BR~ 10^{-9} explain the data.

However this is in conflict with the generalised GN bound: $\mathcal{B}(K_L \to \pi^0 X) \lesssim 4.3\,\mathcal{B}(K^+ \to \pi^+ X)$.

Leutwyler and M. A. Shifman (90)

As seen above, in 3 sigma tension & BTW prefers that X would be a scalar.

The two results compatible "experimentally" (v2)

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

- Koto & NA62: different parameters & structure => account for significant differences:

(i) consider 2 body decay $K \to \pi X$, \w X stable => can't accommodate results.

(ii) If $K \to \pi X(\gamma\gamma)$, \w X being long lived (~ 1-10% ns) => accommodate results, why?

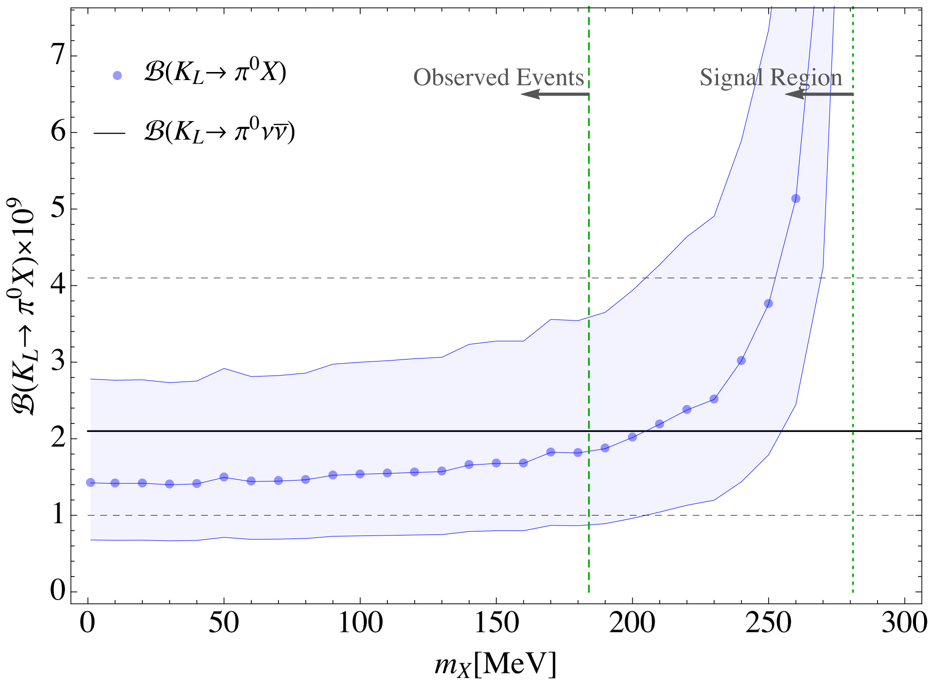
The dependence of X-lifetime of $K_L \to \pi^0 X$ differs from $K^+ \to \pi^+ X$ due to boost and size:

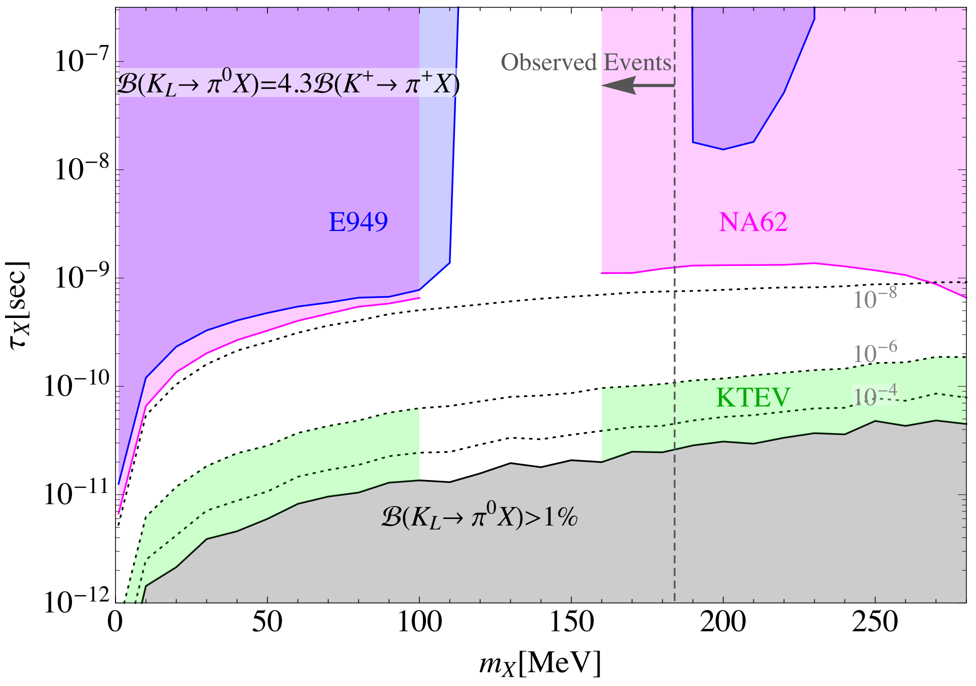
$$\mathcal{B}(K \to \pi X; \text{detector}) = \mathcal{B}(K \to \pi X) e^{-\frac{L}{p}\frac{m_X}{c\tau_X}},$$

with $\left(\frac{L}{E}\right)_{\text{KOTO}} \sim 2 \; < \; \left(\frac{L}{E}\right)_{\text{NA62}} \sim 4$ & 2-photon searches @ NA62 suffer from BGs…

The two results compatible “experimentally” (v2)

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





Left, BR to accommodate KOTO: dotted blue (solid gray) line correspond to the central value of $K_L \to \pi^0 X$ ($\pi^0 \nu\bar{\nu}$) interpretation, with blue shaded band (dashed horizontal lines) for two-sided 68% confidence interval. An uncertainty of Monte Carlo statistics is less than 10% thus omitted here. The dashed (dotted) vertical line corresponds to m_X = 180(280)MeV, and its left-hand side is compatible with the observed events (the signal region). Right: the new particle has finite lifetime considering the GN bound and $K^+ \to \pi^+ \nu\bar{\nu}$ search, and the allowed parameter space for two body decay $K_L \to \pi^0 X$ in mass and lifetime of X is shown. The $K^+ \to \pi^+ X$ bound is translated to K_L bound assuming a saturation of the GN bound. The purple(blue) shaded region is constrained by NA62 at 95% CL(E949 at 90% CL). Too short lifetime leads to $B(K_L \to \pi^0 X) > 1\%$, which is inconsistent with untagged K_L branching ratio. The $B(K_L \to \pi^0 X) = 10^{-4}$, 10^{-6} and 10^{-8} are indicated on the plot. The green shaded region is constrained from KTEV search for $K_L \to \pi^0 \gamma\gamma$ assuming $B(X \to \gamma\gamma) = 1$.

The two results compatible theoretically (v3)

Gori, GP & Tobioka (20); inspired by a talk of Pospelov.

R. Ziegler, J. Zupan, and R. Zwicky; Y. Liao, H.-L. Wang, C.-Y. Yao, and J. Zhang, M. Hostert, K. Kaneta, M Pospelov (20)

★ Koto & NA62 differ by isospin, KOTO's initial state is neutral:

Suppose 2-body neutral final state $K_L \to \sigma\chi, [\chi = Im(\phi), \sigma = Re(\phi)]$ is allowed by a model;

it would then dominates the charged 3-body final state $K^+ \to \pi^+\phi^2$ decay mode.

★ A working model based on approx' strange flavor sym.:

Add a light scalar, ϕ, it carries a half strange (or 2nd gen. doublet) flavor charge (in mass basis):

$$y_1 H\bar{Q}_1 s\phi^2/\Lambda^2 \ \text{ and/or } \ y_2 H\bar{Q}_2 d\phi^2/\Lambda^2 + h.c.\,, \quad \& \quad \frac{\chi}{\Lambda_\chi} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \text{(for the decay)}$$

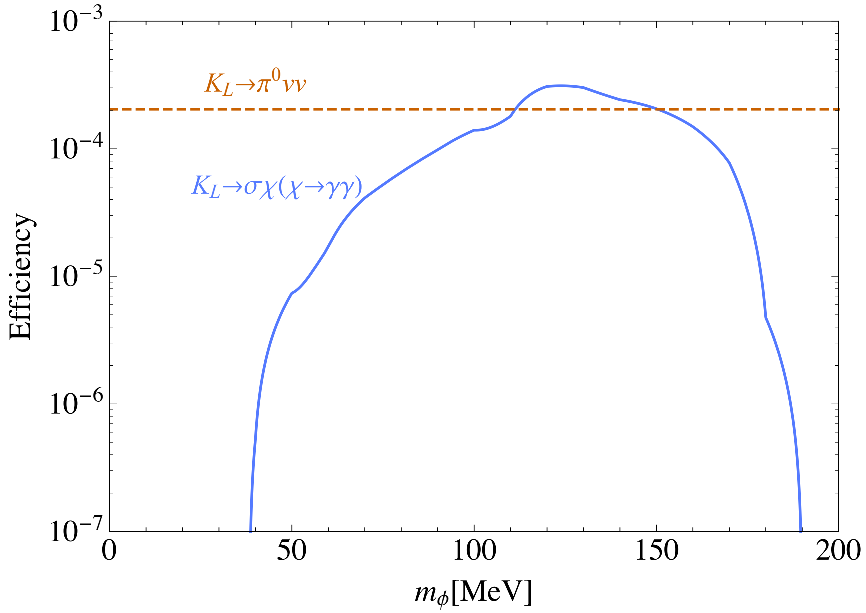
Leading to: $\Gamma(K_L \to \chi\sigma) \sim M_K \left|\frac{y_{1,2}v}{\Lambda^2}\right|^2 \times F_\pi^2$ followed by: $\chi \to \gamma\gamma$, σ being stable.

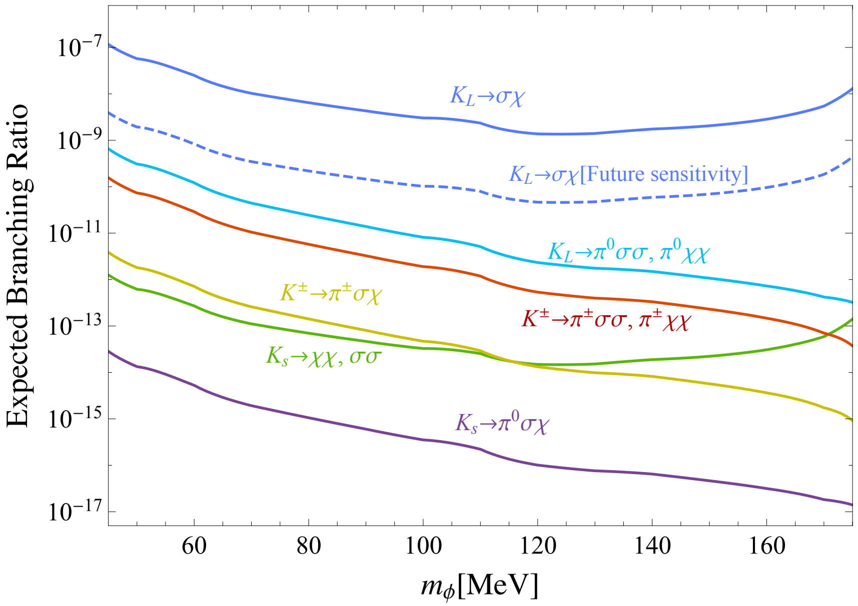
The two results compatible theoretically (v3)

- Koto & NA62 differ by isospin, KOTO's initial state is neutral:

  Suppose 2-body neutral final state $K_L \to \sigma\chi, [\chi = Im(\phi), \sigma = Re(\phi)]$ is allowed by a model;

  it would then dominates the charged 3-body final state $K^+ \to \pi^+\phi^2$ decay mode.

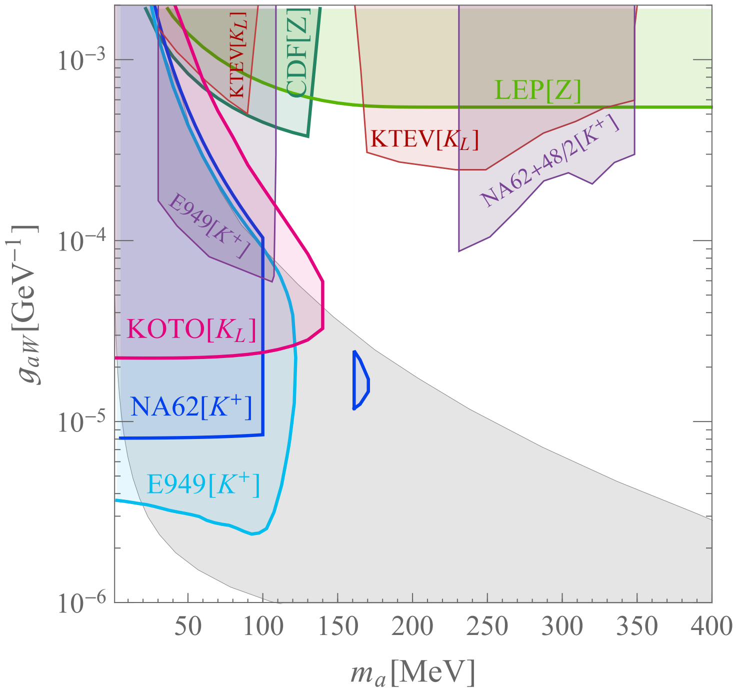


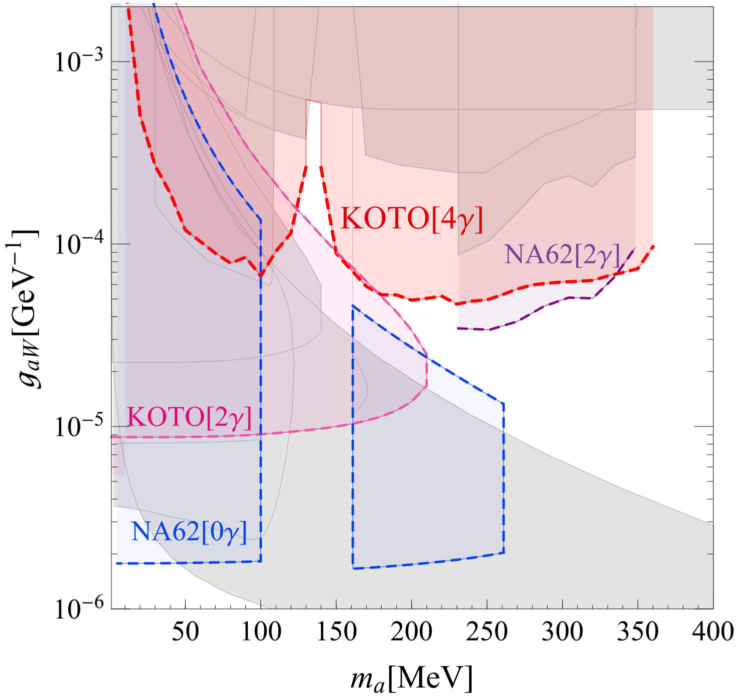


Gori, GP & Tobioka (20)

(different than NA62) KOTO has good sensitivity to $\pi^0(\gamma\gamma)X(\gamma\gamma)$

See paper for more details : Gori, GP & Tobioka (20)

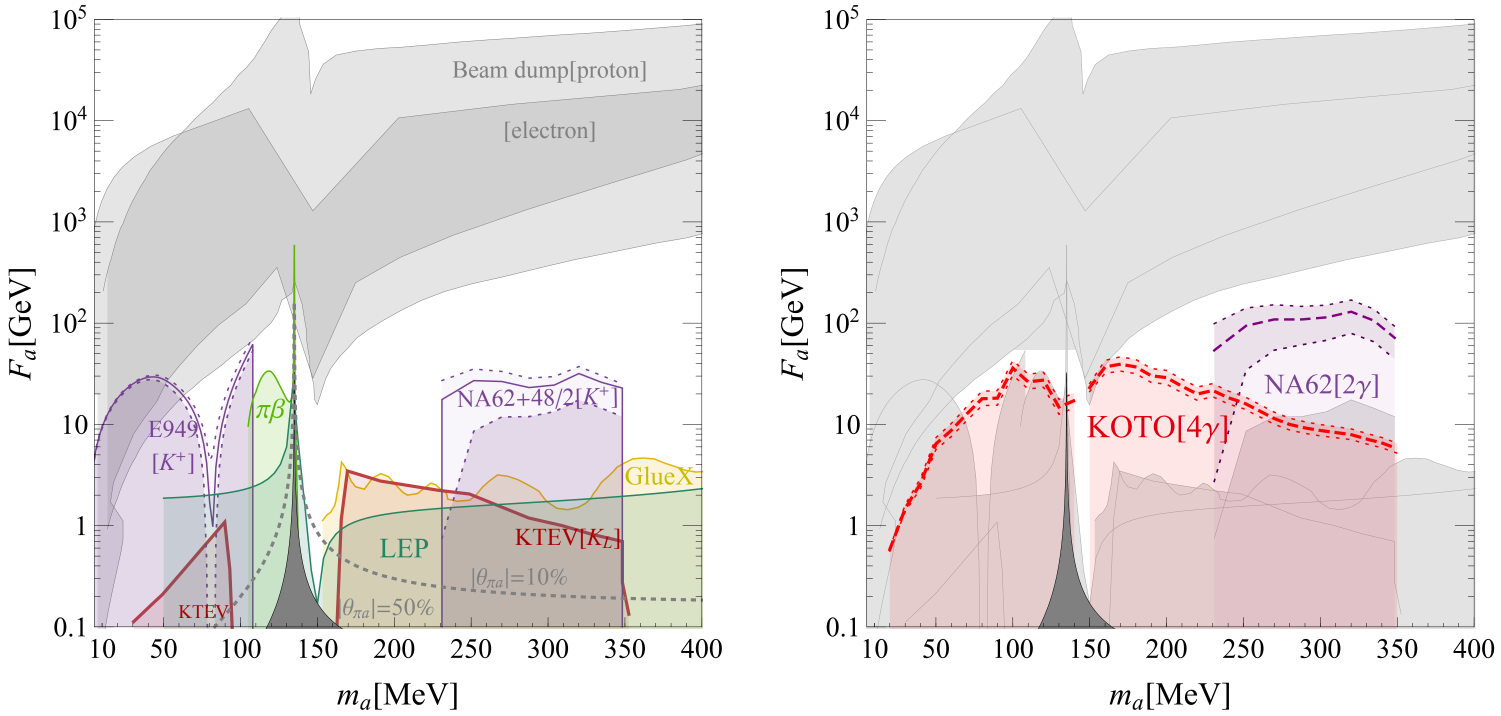




Left panel: Present bounds on the parameter space of the $SU(2)$ coupled-ALPs, as a function of the ALP mass, m_a, and of its couplings with $SU(2)$ gauge bosons, g_{aW}. Right panel: Present and future bounds on the parameter space. In gray, we present the present bound (as shown in the left panel); in red and magenta, and in purple and blue, we present the future bounds at KOTO (4γ and 2γ + invisible signatures), and at NA62 ($\pi^+ + 2\gamma$ and π^+ + invisible signatures).

(different than NA62) KOTO has good sensitivity to $\pi^0(\gamma\gamma)X(\gamma\gamma)$

See paper for more details : Gori, GP & Tobioka (20)



. Left panel: Present bounds on the parameter space of the $G\tilde{G}$ coupled-ALP benchmark, as a function of the ALP mass, m_a, and of its decay constant, F_a. Right panel: Present and future bounds on the parameter space. In gray, we present the present bound (as shown in the left panel); in red and purple we present the future bounds at KOTO (4γ proposed search), and at NA62 ($\pi^+ + 2\gamma$ signature), respectively. The bands for the Kaon experiments (E949, NA62, KOTO) show the uncertainties from the quark mass values.