Frontiers in non-natural (but sensible) BSM

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Joint ICTP-SAIFR/MITP Summer School on Particle Physics

Outline

- Lecture 1: Perspective - The current paradoxalic state of particle physics, observations vs. predictions & 2-soft principles (naturalness & quality)
- Lecture 2: deviation from conventional naturalness, ex. - relaxion
- Lecture 3: the experimental frontier of unconventional naturalness - quantum sensors, precision tests

Lecture 1

Perspective - The current paradoxalic state of particle physics,
observations vs. 2-soft principles (naturalness & quality), anthropics …

Outline

- The current state of particle physics, observational problem vs. theoretical expectations
- Soft principles: (1) naturalness (2) quality (will come later)
- Anthropics: deviation from naturalness with cosmology, Weinberg's solution to the hierarchy problem
- The anthropic solution to the weak scale and its lack of robustness, the weakless universe
- Quality of theories, UV (in)sensitivity

The rules of the game for this lecture

♦ What is particle physics ? Understanding the microscopic (high-energy) nature, in region where we can't neglect *v*/*c* and $\hbar$ (can't include gravity):

$$\mathscr{L}^{\text{mic}}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

♦ This requires usage quantum field theory (QFT), it makes our lives more demanding but also more interesting

♦ *Shall try to use minimal exp' input, mainly focus on principles & theory (no anomalies)*

So what is our quest ?

$$\mathscr{L}^{\text{mic}}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

Regarding our current understanding:

Do we miss anything conceptually ?

Do we miss anything associated with observation ?

We are definitely missing stuff …

$$\mathscr{L}^{\text{mic}}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

ν-oscillation

baryogenesis

dark matter

$\Downarrow$

New forces and/or particle must exist!

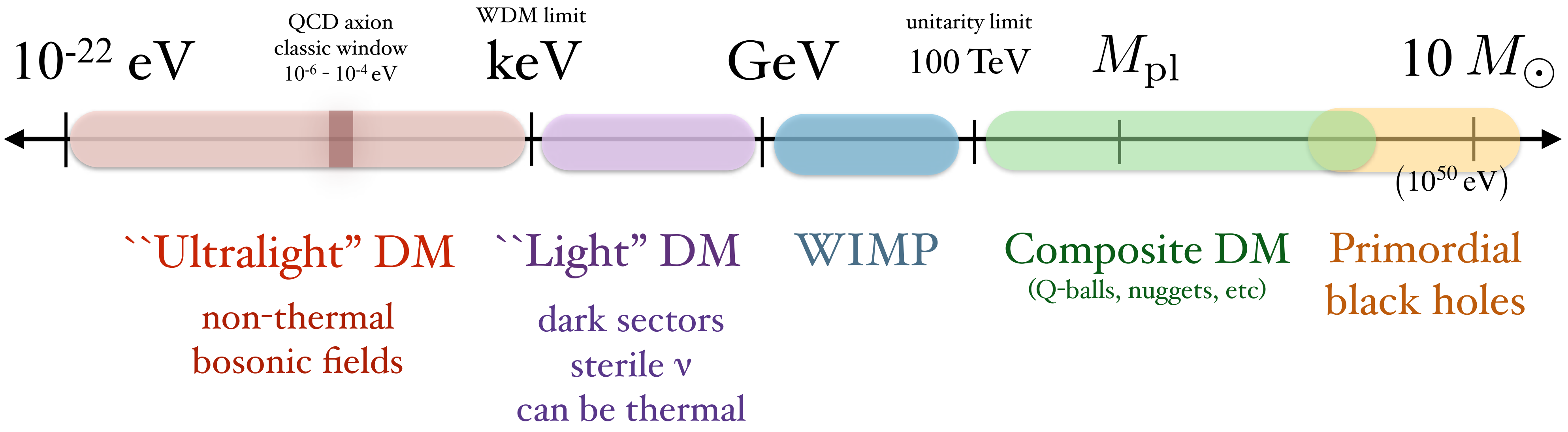
Our paradox: what exists can't be guaranteed, what guaranteed might barely exists

$$\mathscr{L}^{\text{mic}}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

New forces and/or particle must exist!

Sounds straightforward - let's find them

Searching for dark matter ??



This is crazily hard!
How can we cover all this range?
Is there any prefer region?
Not really unless you add some more theoretical guidance (speculations)

The paradoxalic state of particle physics

$$\mathscr{L}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

ν-oscillation

baryogenesis

dark matter

New forces and/or particle must exist

However, we have no idea regarding their energy scale !!

Homework: neutrino masses, $\mathscr{L}^{\nu}(N, L, H) = M_N NN + y_N HLN \quad (\langle H \rangle \sim 10^2\,\text{GeV})$

Works both with: $M_N \approx 10^{14}\,\text{GeV} \quad \& \quad y_N \approx 1$

$M_N = 0\,\text{GeV} \quad \& \quad y_N \approx 10^{-12}$

The paradoxalic state of particle physics

$$\mathscr{L}_{\text{Nature}} = \mathscr{L}_{\text{Forces}} + \mathscr{L}_{\text{Matter}} + \mathscr{L}_{\text{Int.}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{New}}$$

- ν-oscillation
- baryogenesis
- dark matter

New forces and/or particle must exist
However, we have no idea regarding their energy scale !!

To make progress we need (theoretical) guidance

Theoretical guidance, 2 “soft principles”

In order to prioritise where and how to search for new physics,
let us add more “soft principles”:

- Naturalness* [mainly involves scalars within Quantum Field Theories (QFT)]
- Quality of theory, sensitivity to “quantum gravity” (Planck-mass suppressed contributions)

* see lectures by Csaki from last week, here I’m only going to emphasise the minimal stuff to contrast with alternative solutions

1st principle, naturalness

In order to prioritise where and how to search for new physics,
let us add more soft principles:

- Naturalness [mainly involves scalars within Quantum Field Theories (QFT)]
- Quality of theory, sensitivity to “quantum gravity” (Planck-mass suppressed contributions)

The Higgs hierarchy & scale

- You have already heard last week about the Higgs and the naturalness problem, let's reiterate the argument in a way that would help us later

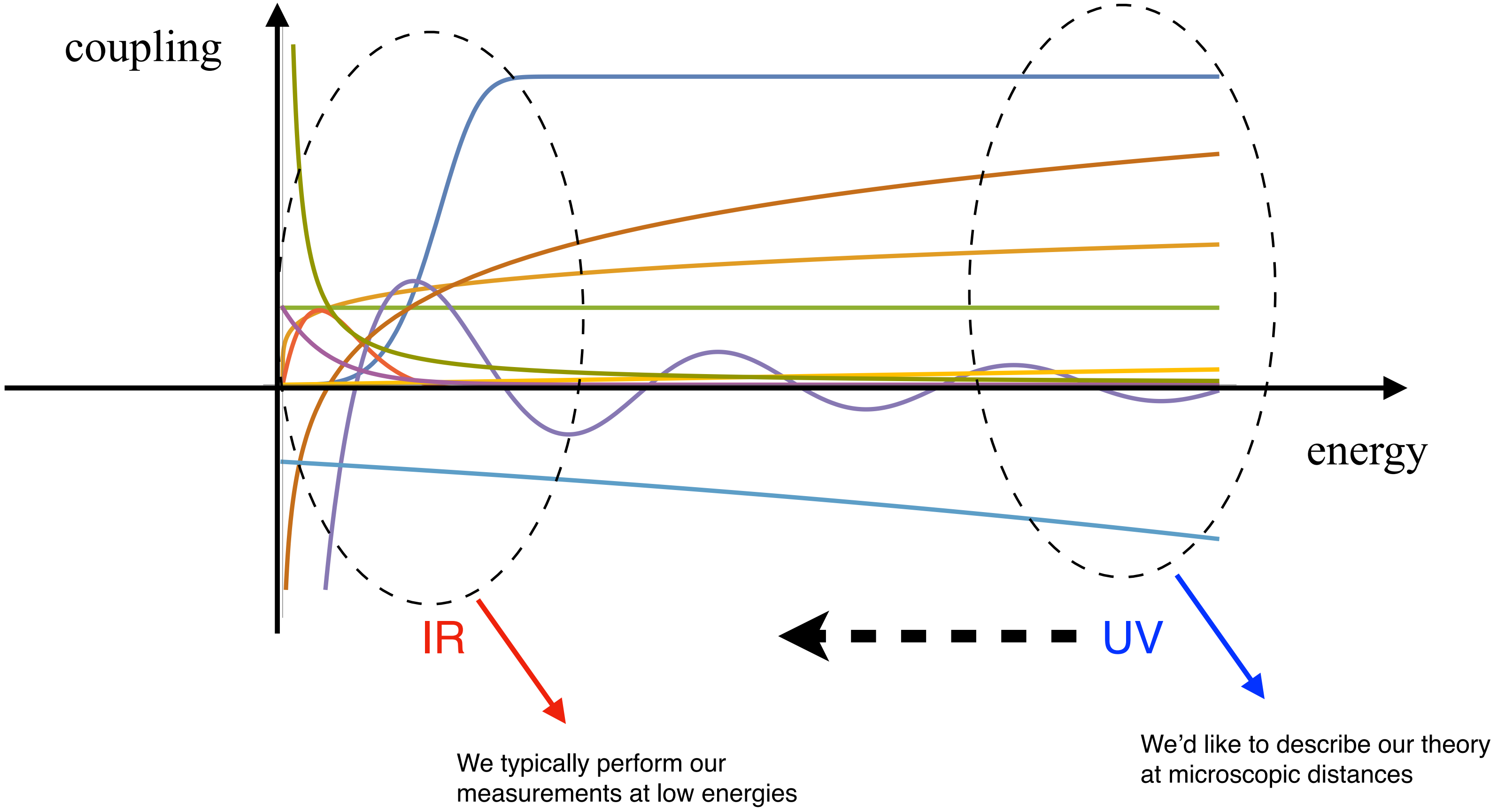
- Recall our task is to figure out: $\mathscr{L}^{\rm mic}_{\rm Nature} = \mathscr{L}_{\rm Forces} + \mathscr{L}_{\rm Matter} + \mathscr{L}_{\rm Int.} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm new}$

- $\mathscr{L}^{\rm mic}_{\rm Nature}$ consists of fields and coefficient, "constants of nature", that however in QFT <u>*depend on energy and on each other*</u>: $\mathscr{L}^{\nu} = M_N NN + y_N HLN + M_H^2 H^2$

For instance: $M_N = M_N(E)$ & $y_N = y_N(E)$ & $M_H^2 = M_H^2(E, M_N, y_N)$

QFT havoc (simplistic picture)

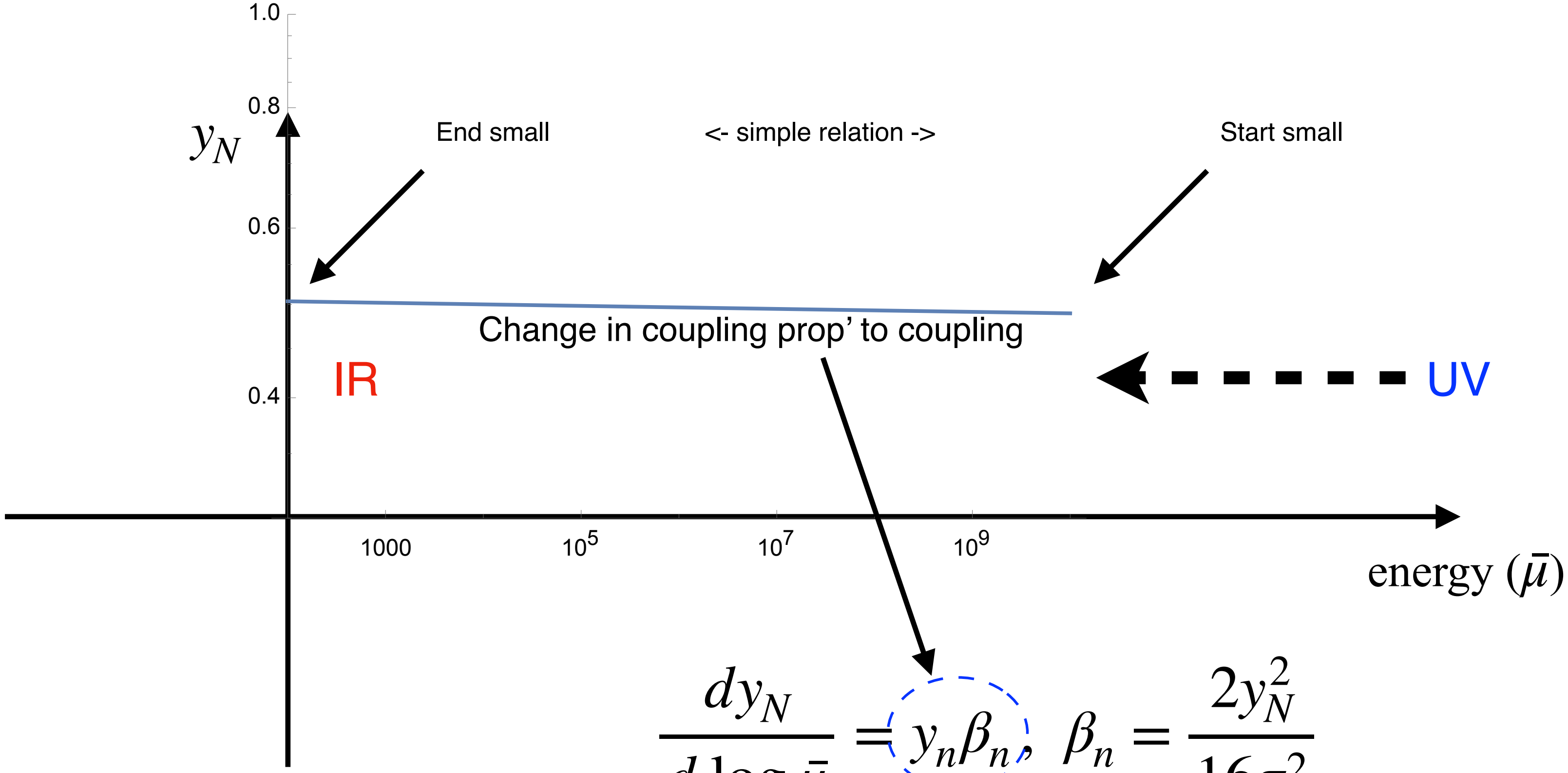
♦ If all couplings depend on energy and on each other, how can we even define our theory and seek for microscopic description ???



What’s the issue with unnatural light Higgs? Warmup ex.

♦ Best explained using observable effects looking at the energy dependence of the Higgs mass, however, as a warmup let’s just investigate a simple ***natural*** fermion mass model:

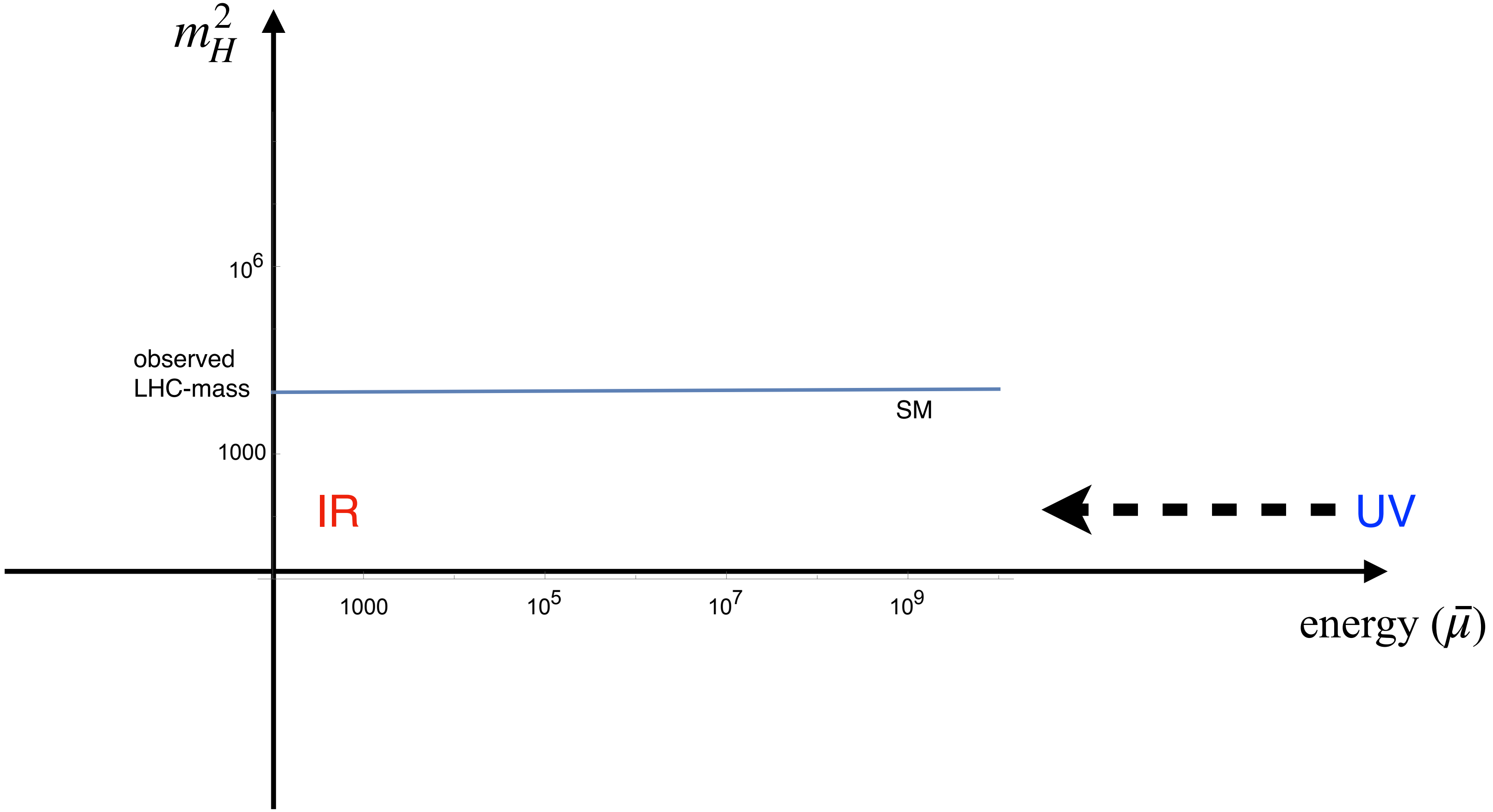
$$\mathscr{L}^{\nu}(N, L, H) = M_N NN + y_N HLN$$



$$\frac{dy_N}{d\log\bar{\mu}} = y_n\beta_n, \quad \beta_n = \frac{2y_N^2}{16\pi^2}$$

What's the issue with an unnatural light Higgs?

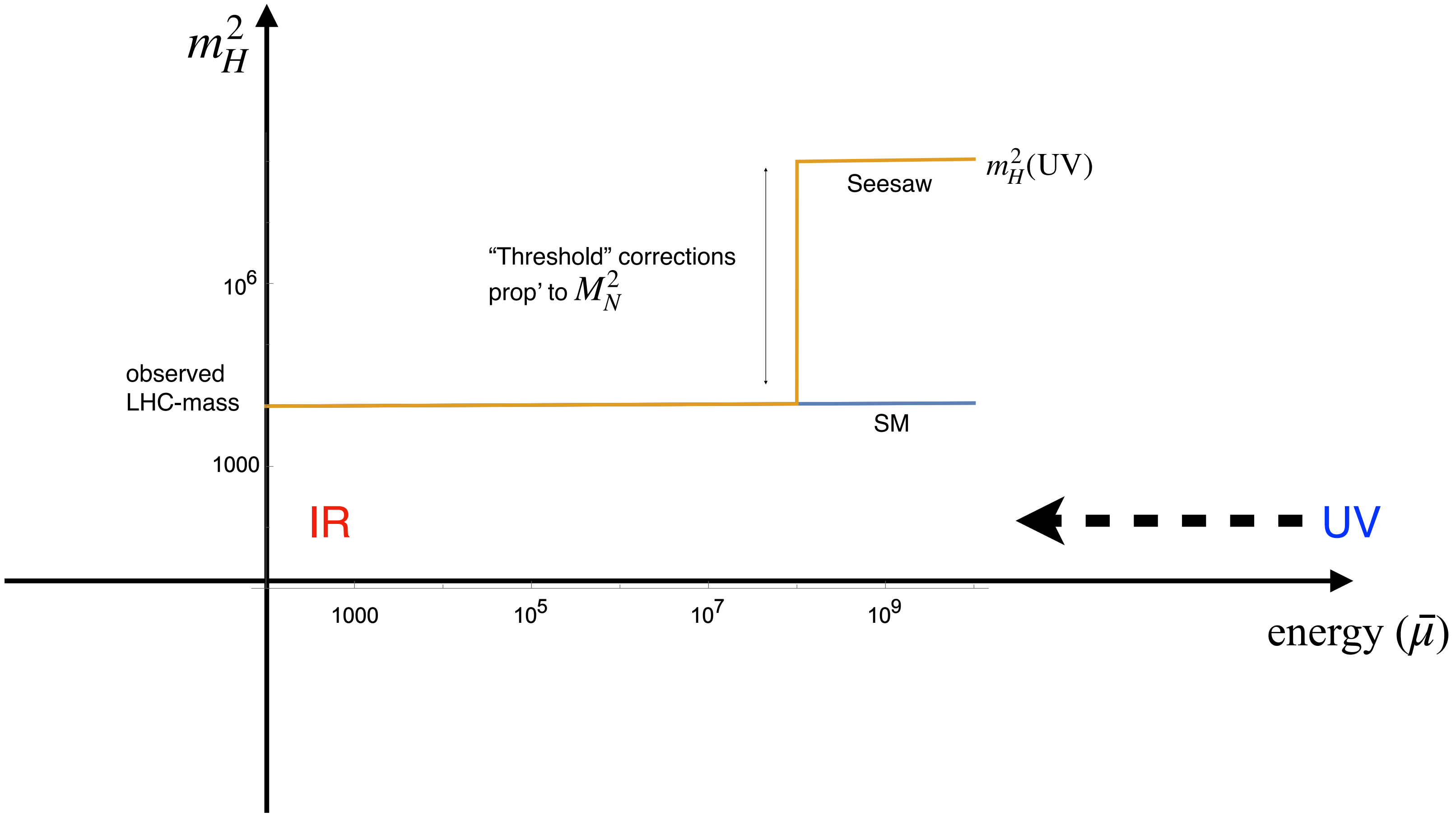
- First energy evolution of Higgs mass within the standard model (SM, boring):



$$\frac{dm_H^2}{d\ln\bar{\mu}^2} = \beta_m^{\rm SM} m_H^2, \qquad \beta_m^{\rm SM} = \frac{3}{4}\frac{4y_t^2 + 8\lambda - 3g^2 - g_Y^2}{(4\pi)^2}$$

Higgs mass evolution in Seesaw model, matching the SM

$$\mathscr{L}^{\nu} = M_N NN + y_N HLN + M_H^2 H^2$$

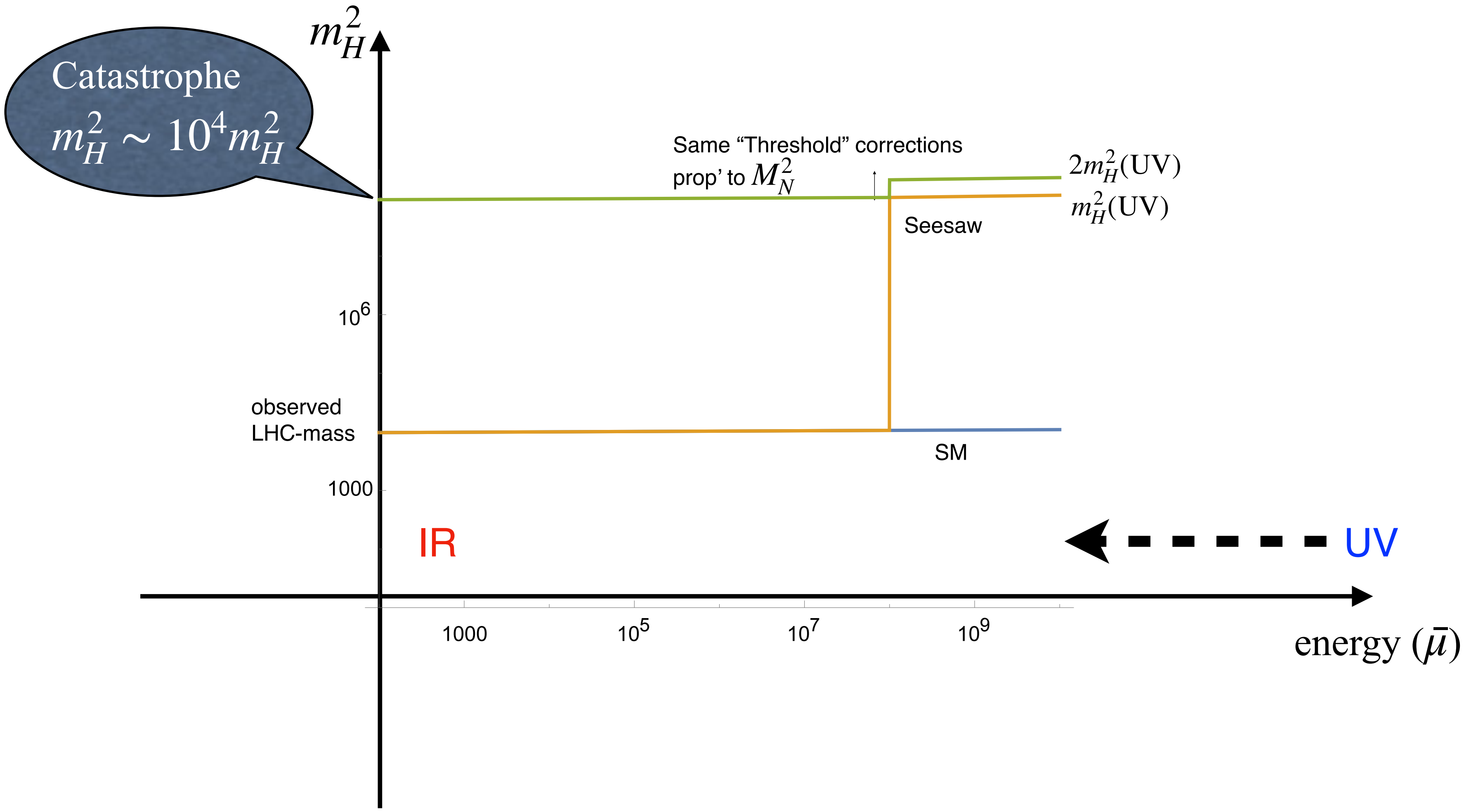


In the IR: $\dfrac{dm_H^2}{d\log\bar{\mu}} = m_H^2\beta_{\mathrm{SM}}$; in the UV a new term: $\dfrac{dm_H^2}{d\log\bar{\mu}} = \dfrac{2y_N^2}{16\pi^2}M_N^2$

While the Yukawa coupling is multiplicative normalised

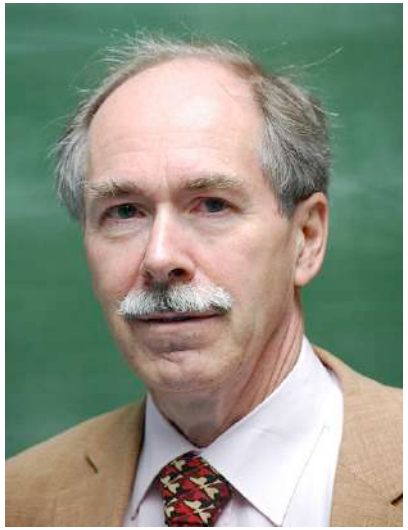
the Higgs is like a trash bin it’s additively normalised

What if we change the Higgs mass in the UV by x 2?



Organising principle, (technical) naturalness

♦ ’t Hooft proposed a principle to distinguish in QFT parameters that nicely behave (UV-insensitive), that we denote as technical natural parameters, and those that are unnatural



1999

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

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Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search program for models with improved naturalness and concentrate on the possibility that presently elementary fermions can be considered as composite. Chiral symmetry must then be responsible for the masslessness of these fermions. Thus we search for QCD-like models where chiral symmetry is not or only partly broken spontaneously. They are restricted by index relations that often cannot be satisfied by other than unphysical fractional indices. This difficulty made the author's own search unsuccessful so far. As a by-product we find yet another reason why in ordinary QCD chiral symmetry must be broken spontaneously.

III1. INTRODUCTION

The concept of causality requires that macroscopic phenomena follow from microscopic equations. Thus the properties of liquids and solids follow from the microscopic properties of molecules and atoms. One may either consider these microscopic properties to have been chosen at random by Nature, or attempt to deduce these from even more fundamental equations at still smaller length and time scales. In either case, it is unlikely that the microscopic equations contain various free parameters that are carefully adjusted by Nature to give cancelling effects such that the macroscopic systems have some special properties. This is a

Technical naturalness => Causality (UV=>IR)

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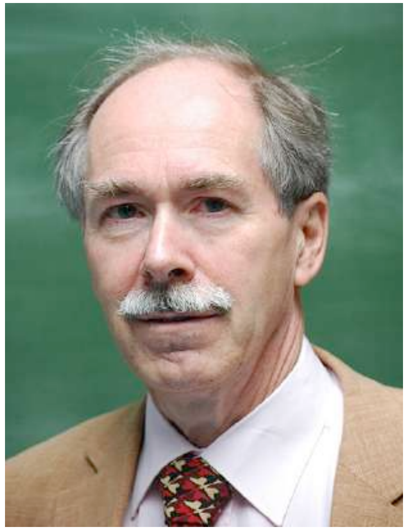


1999

Naturalness vs Scalars

♦ What are technically natural parameters?

Natural parameter: when taken to zero => theory admits a new symmetry

♦ Bottomline for the school:

In interacting theory, scalar mass is not a natural parameter

♦ Roughly, expect scalars to be, at least, as massive as the product of the heaviest particle that they coupled to and their coupling to it

♦ So how what is the SM fare on this front of naturalness?

Perspective, digression: SM & vs. naturalness

Technical natural parameters

Easy problems

Baryogenesis

Leptogenesis
EW-baryo'
Cold-baryo'
Inflation decay
RS phase trans'
...

Neutrino masses

EFT
Seesaw
Dirac neutrinos
Radiative masses
Infinite flavor models
...

Dark matter

BH
WIMP
MeV-GeV
Composite variety
Axion-like-particle
Asymmetric DM
...

Technical **un**natural parameters

Hard problems

Cosmological constant

Higgs mass

Strong CP ("7-loop" problem)

Conventional Naturalness vs the SM Higgs

♦ The conventional way to address the Higgs mass is to promote it to a technical natural parameter, we basically know 2 ways to do it (Csaki):

i. SUSY (chirality)
ii. Dimensional-transmutation/compositeness/technicolor/RS

Sounds good, but what about the cosmological constant (CC)?

$$\frac{\Lambda}{M_{\rm Pl}^4} \sim 10^{-120} \quad \Rightarrow$$

Requires subeV new physics that couples to everything
All conventional attempts failed!!

Weinberg's observation (1987)

(for more cosmological details, see lectures by Hubisz)

- Observers requires complexity (elements, galaxies, stars etc.)

- Requires time for evolution: > 10^5 years for DM to form halos and for Hydrogen molecules to form, > 10^9 yrs for galaxies

- Large CC does not allow it: $M_{\rm Pl}^2 H^2 = \Omega_M/(1+z)^3 + \Omega_{\rm rad}/(1+z)^4 + \Lambda$

  Matter and radiation decrease with time, CC is constant

  There's a finite time equal to that takes it to dominate $t_\Lambda \sim 10\,\mathrm{Gyr}\sqrt{\frac{10^{-12}\mathrm{eV}^4}{\Lambda}}$

Weinberg's anthropic argument

♦ Values of the CC of roughly 10^3 bigger => forbid the creation of galaxies, not to mention stars & planet etc => no conventional observers

♦ Now, suppose that there are many realisation of our universe, either because of eternal inflation or other more speculative ideas, and also that there is a mechanism allow to scan the value of the CC in each of them, then while all the others would either become empty quickly or crunch there will be a few with small CC that are long lived and allow for structure/complexity to form

Anthropic reasoning applied to the Higgs mass?

Agrawal, Barr, Donoghue & Seckel (98)

- What if during cosmology the Higgs VEV/mass is scanned?

$m_n - m_p = (m_d - m_u - 1.7)$ MeV$=(3(v/v_0) - 1.7)$ MeV,

and the Q value for neutron beta decay, $Q \equiv m_n - m_p - m_e$ is $(2.5(v/v_0) - 1.7)$ MeV

As v increases neutron becomes more unstable, $m_n - m_p$ increases, and the nuclear potential between nucleons gets weaker (since m_π is getting hevier).

For instance: the critical reaction for decay of the deuteron is $\boldsymbol{d} \rightarrow p + p + e- + \nu$ which occurs whenever $B\boldsymbol{d} < m_n - m_p - m_e \sim [2.5(v/v_0) - 1.7]$ MeV.
With $m_\pi \propto ((mu + md)f_\pi)1/2$ and $V(r) \sim e^{-m_\pi r}/r$ with $r \sim 1/m_\pi$
$B\boldsymbol{d}$ ~[2.2-6 delta v/v_0] MeV, so already at $v/v_0 \sim 1.5$ deuteron doesn't bind

Anthropic reasoning applied to the Higgs mass?

Agrawal, Barr, Donoghue & Seckel (98)

- What if during cosmology the Higgs VEV/mass is scanned?

  Estimate that for $v/v_0 \gtrsim 5$ there will be no stable nuclei resulting with inert proton universe

  For $v/v_0 \gtrsim 10^3$ Δ^{++} becomes the lighters state resulting with a Helium-like inert universe …

- Looks like we've found the best explanation for the lightness of the Higgs mass …

A universe \wo weak interaction

Harnik, Kribs & GP (06)

- What if the scan is such that the masses are kept fixed?

So $\frac{y}{y_0}\frac{v}{v_0} = m_0 =$ fixed

- We can even try to take M_H & $v \to M_{\rm Pl} \;\Rightarrow$ weakless universe

One can go through the whole stages of the universe and see that with some amendments a universe similar to ours, with baryon, structure, chemistry, stars are formed

Weakless universe and flat direction

- The baryon/fermion asymmetry taken to be $\eta_b \sim 10^{-12}$ to create deuterium

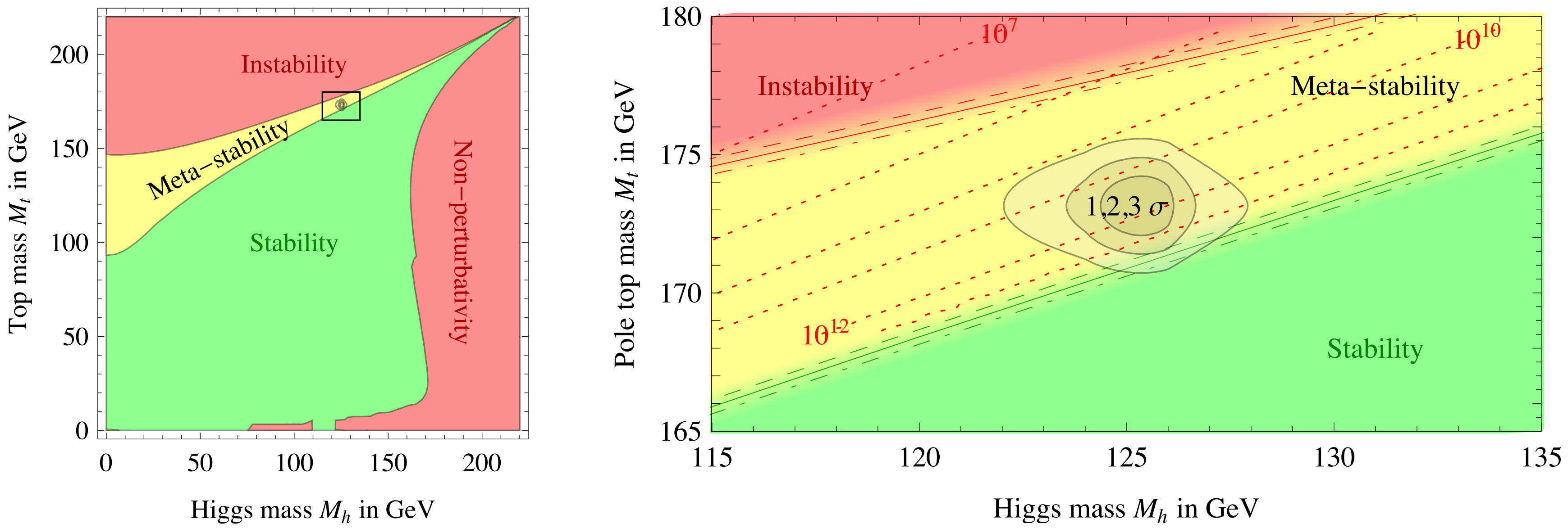
- From deuterium heavy element can be fused, and then star burn for long times

- How unlikely is this? Model Yukawa according to FN with scanning over VEV and charges suggests that it is very likely … Gedalia, Jenkins & GP (10)

- So it seems that the antropics argument for the Higgs mass is not-robust. Is there anything other lesson related to flavor on this front? Maybe …

The top-Higgs phase diagram & criticality

- Still notice a peculiar criticality associated with the top $\dfrac{d\lambda_H}{d\log\mu} \propto -|y_t|^4$

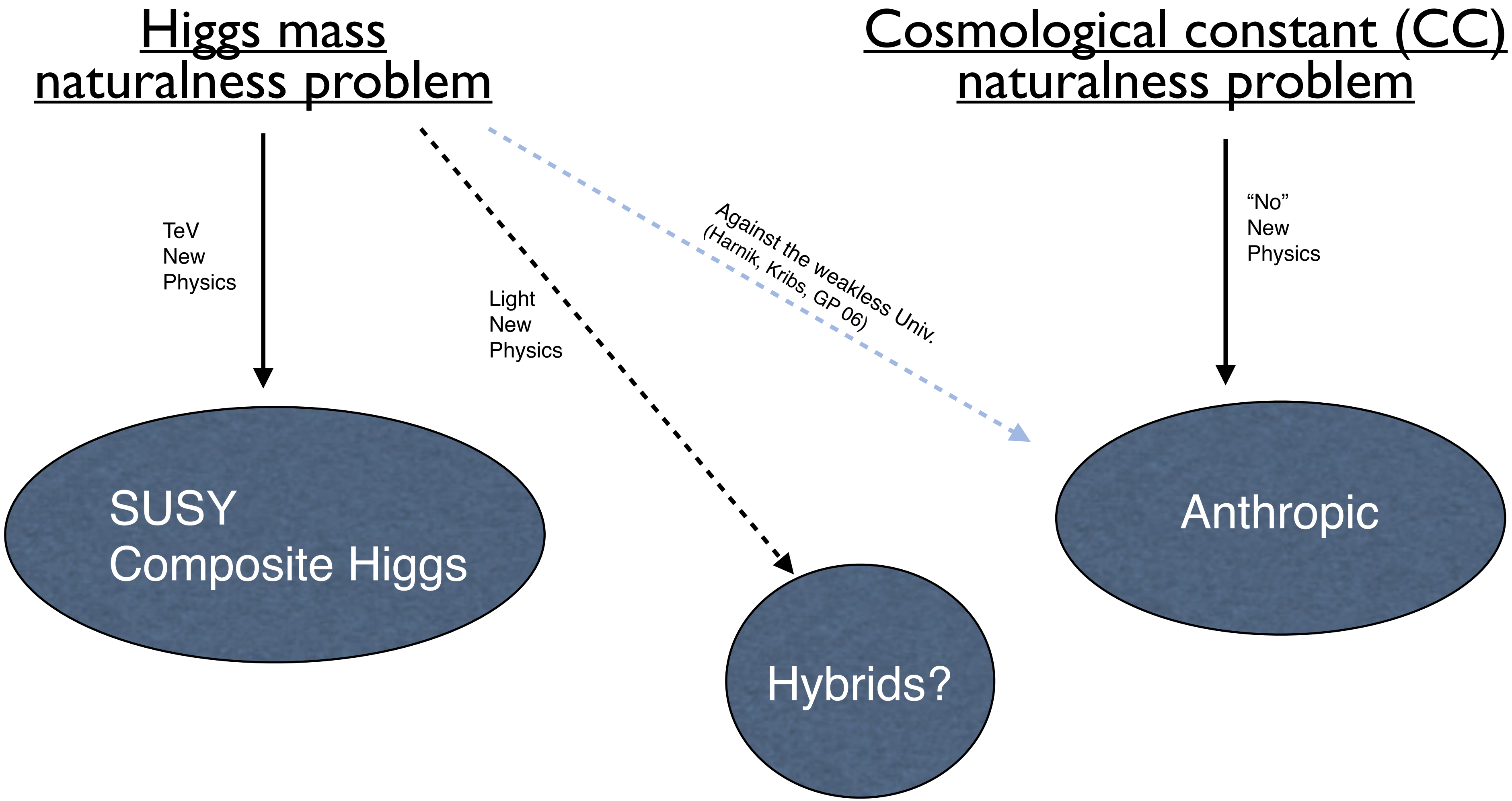


Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori & Strumia (12)

A raise of < 3% in top Yukawa => weakless universe

Is it coincidence or does it tells us something? (Hall et al., 2003 onwards)

Intermediate summary: Solution to the SM naturalness problems; Scales of new physics



Before go to discuss the second soft principle:
Let’s summarise the big picture
Observational vs. Conceptual cases for BSM

Perspective, digression: SM & beyond scoreboard

Technical natural parameters

Technical **un**natural parameters

Easy problems
No NP scale

Baryogenesis

Leptogenesis
EW-baryo'
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Neutrino masses

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Dark matter

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Composite variety
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Asymmetric DM
...

Hard problems
NP scale?

Cosmological constant

Higgs mass

Strong CP ("7-loop" problem)

Homework I

1. Is the theta term technically natural parameter?
2. Assuming the Planck scale as the cutoff of the SM, is the strong CP problem severe one?
3. By how many order of mag. will the EDM-neutron bound has to be improved such that the strong CP problem becomes significantly more serious? Why?

2nd principle, “quality”, blindness of gravity

In order to prioritise where and how to search for new physics, let us add more soft principles:

- Naturalness [mainly involves scalars within Quantum Field Theories (QFT)]
- Quality of theory, sensitivity to “quantum gravity” (Planck-mass suppressed contributions)

What to expect from the unknown

- We don't know much about quantum gravity so everything would be speculative
- In effective field theory approach (EFT) we can generically expect that the dynamics at around the Planck scale would connect different sectors of the SM and would not respect global symmetry
- For instance we should expect the presence of the operators for neutrino masses:

$$L^2H^2/M_{\rm Pl} \quad \Rightarrow \quad m_\nu \gtrsim 10^{-5}\,\mathrm{eV}, \quad \text{or,}$$

soft squark masses: $X^\dagger X \tilde{Q}^\dagger \tilde{Q}/M_{\rm Pl}^2 \quad \Rightarrow \quad m_{\rm squark} \gtrsim F_X/M_{\rm Pl}$ (F_X - SUSY breaking)

Planck suppression for ultralight spin 0 field

- In the following we shall discuss theories with ultra (pseudo) scalars (a) ϕ, how do such models fare with the above principle?

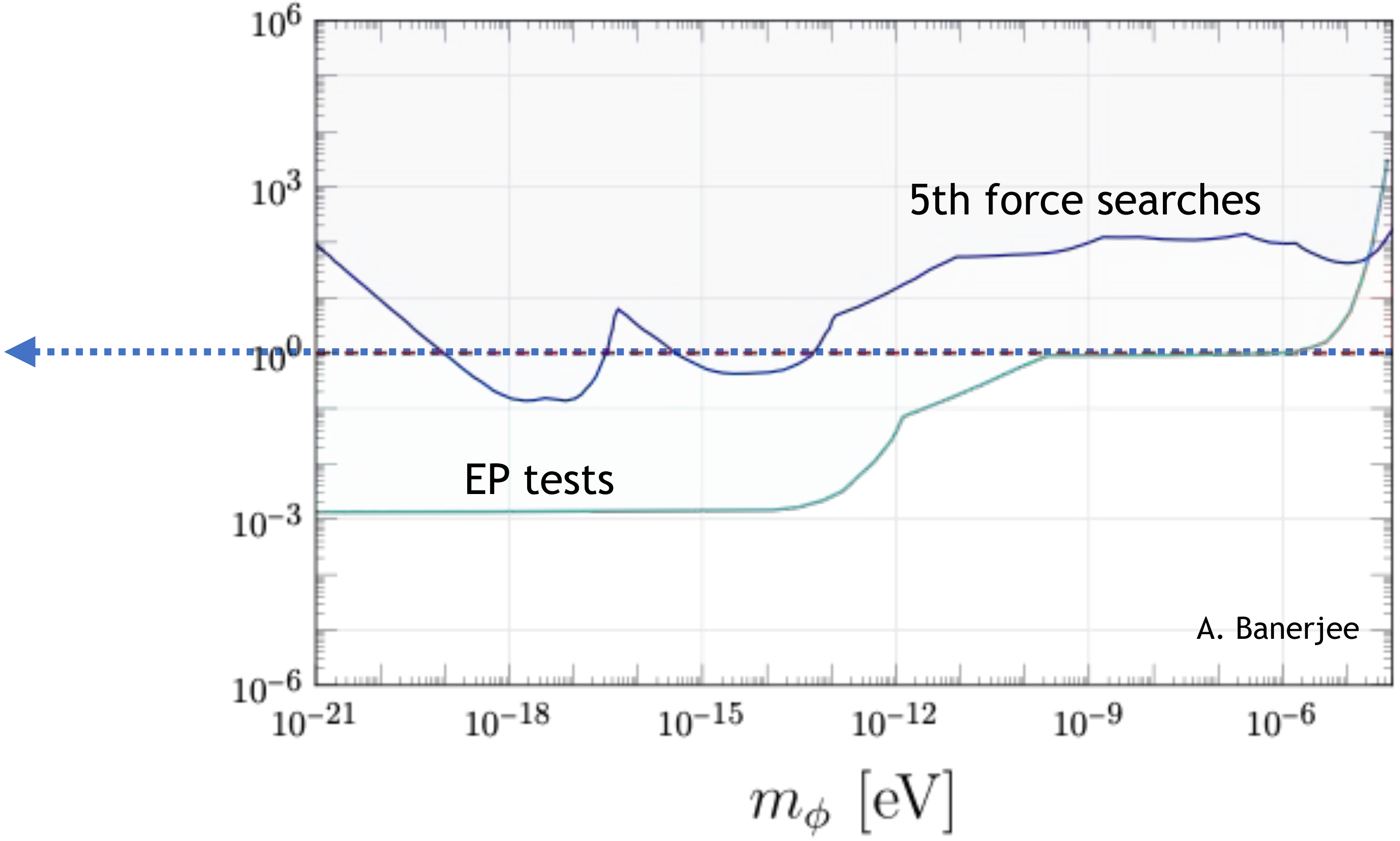
- Let's add some dimension 5 operators, and ask if current sensitivity reach the Planck scale: $\mathscr{L}_{\rm Pl} \in d_{m_e}\dfrac{\phi}{M_{\rm Pl}} m_e \bar{e}e + d_g \dfrac{\phi}{2gM_{\rm Pl}}\beta_g GG + \dfrac{a}{f}\bar{m}_e e\gamma^5 e + \dfrac{a}{32\pi^2 f}G\tilde{G}$

$$\beta_g = -\left(\tfrac{11}{3} - \tfrac{2}{3}N_f\right)\tfrac{g^3}{16\pi^2}$$

where we have assumed that gravity respects parity

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

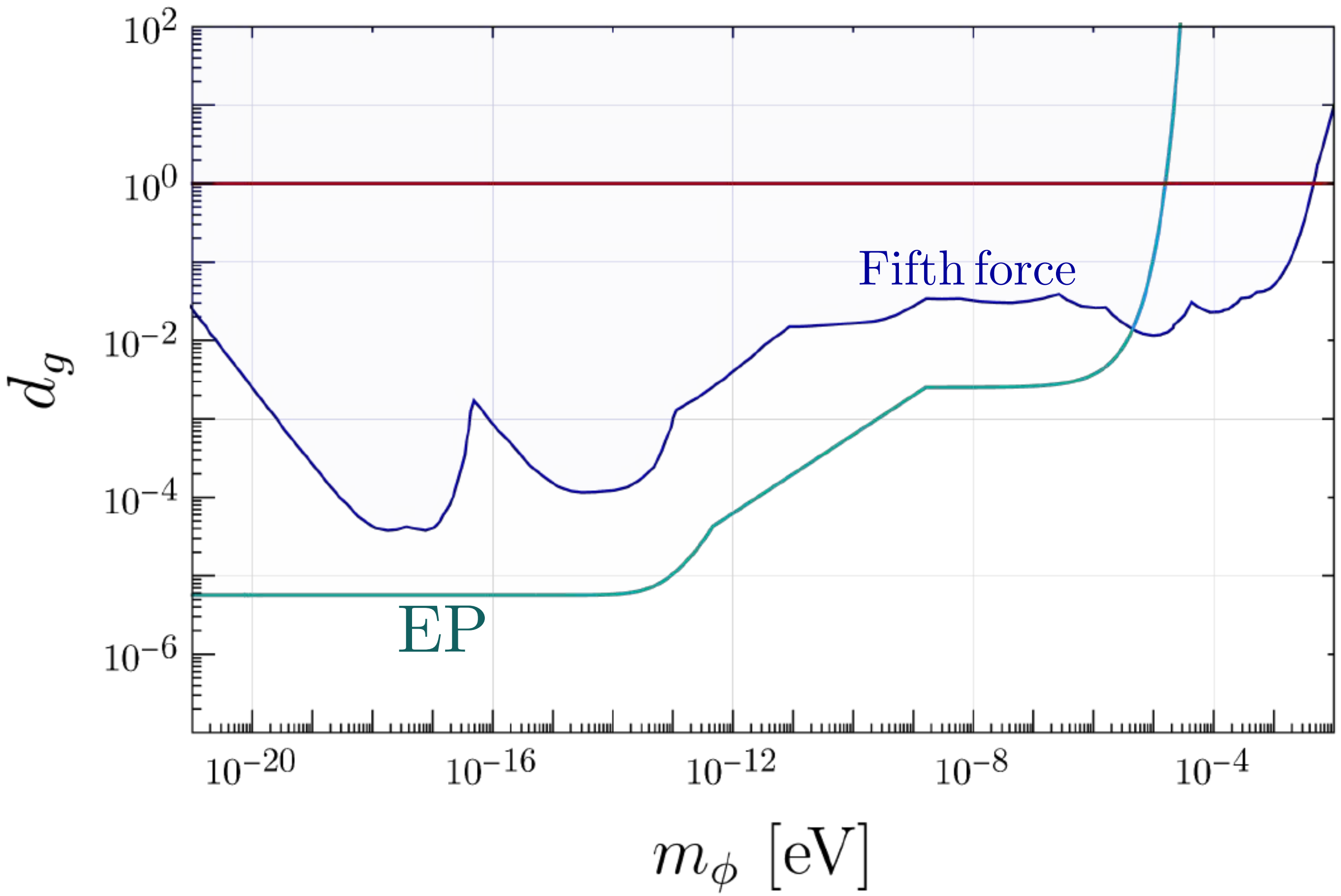
$$d_{m_e} \sim 1 \text{ or } g_e \sim \frac{m_e}{M_{\rm Pl}}$$



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

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

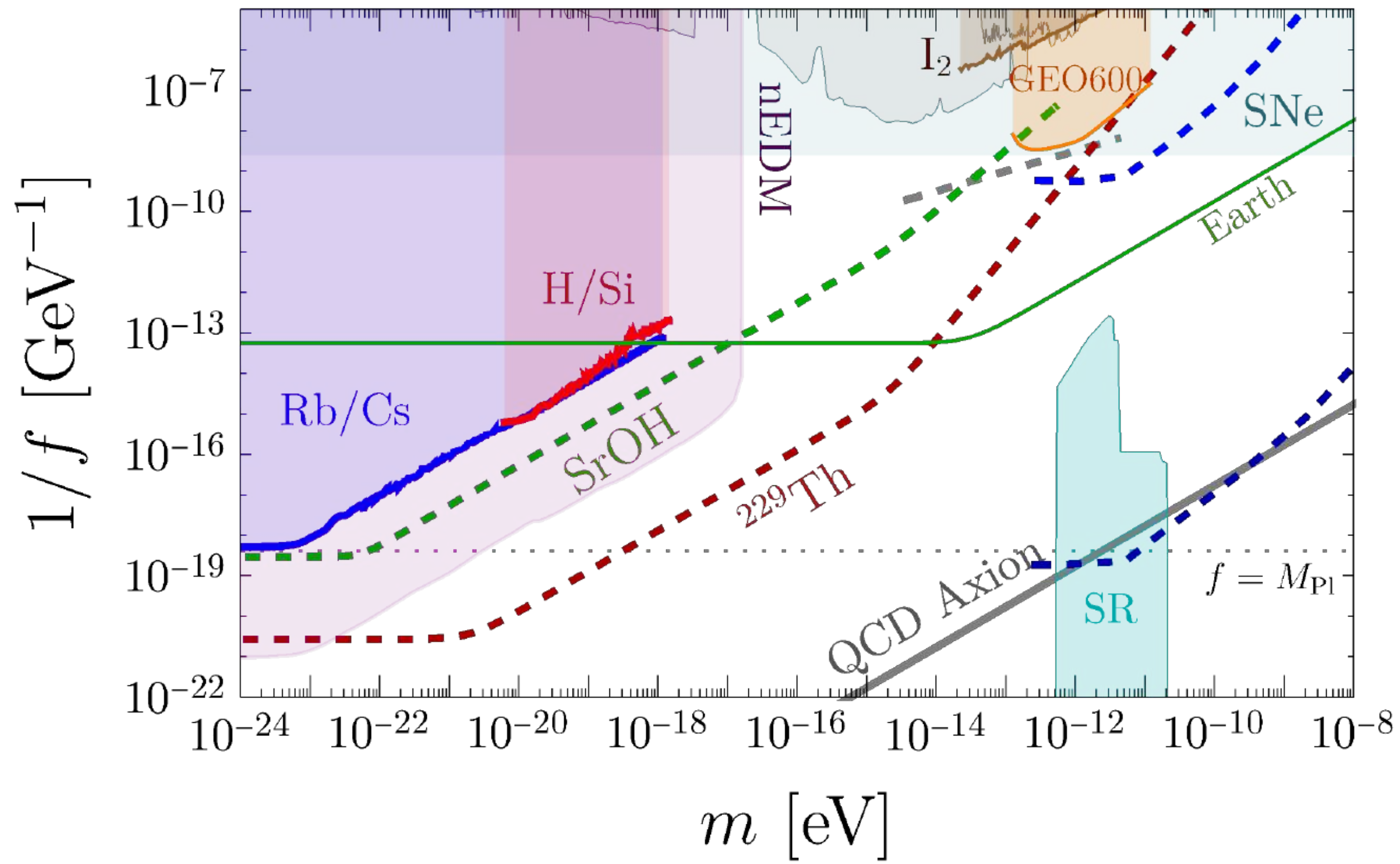
Quality problem, 5th force vs EP violation, gluon



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

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

Quality problem, bounds for QCD-axion-couplings (similar for electron)

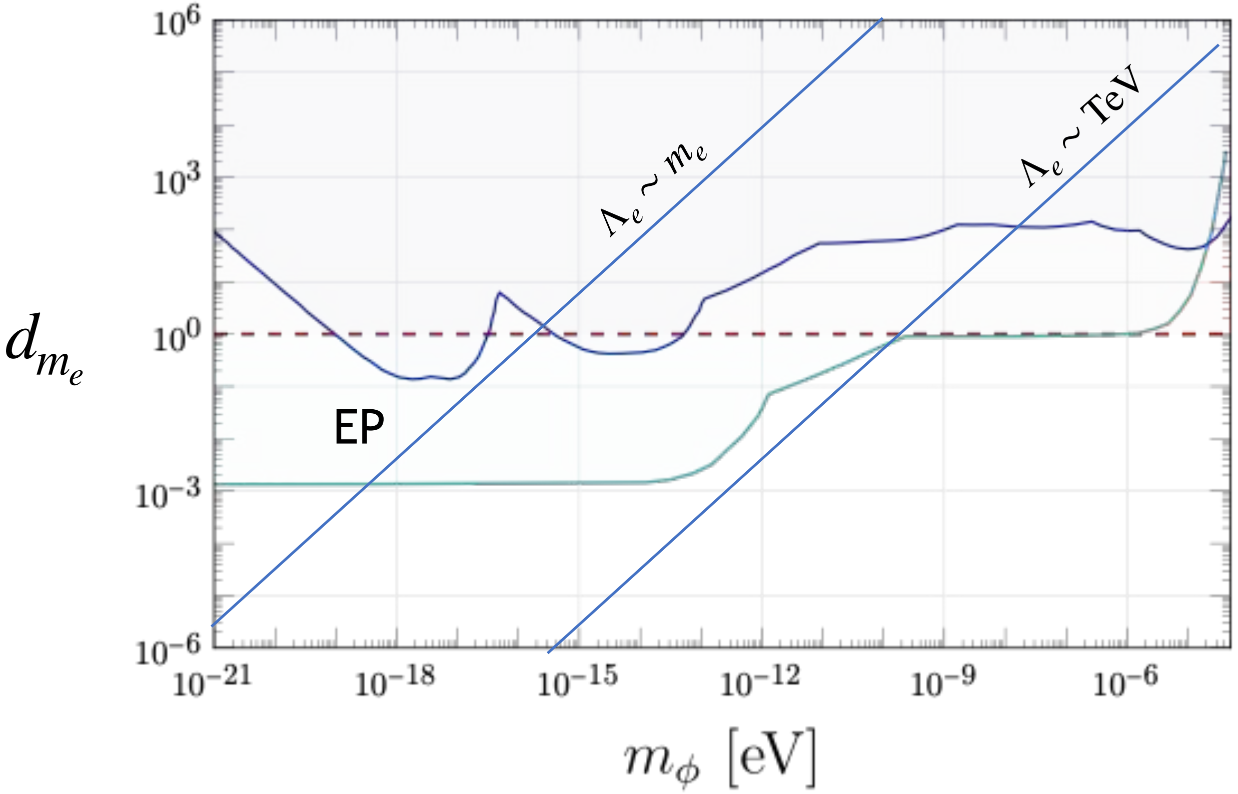


Seems like the bound are weaker, and so, for QCD axion-like models do not suffer neither from quality nor from naturalness, but that's naive, see more later …

ultralight spin 0 field & naturalness

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

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



Homework 2

Could you comment about the MNS mixing angles, not long ago we didn't know the value of θ_{13},
what would be the lower bound on its size?

Within the SM is there any precision measurement that lead to a tension with the idea that the SM is an EFT valid up to the Planck scale?

Repeat the naturalness analysis done for the electron coupling to the gluon coupling

To make sure that we're on the same page
Let's quickly go through the relevant part of the QCD axion story

For the full story see D'Agnolo' lectures

Outline

- Naive parameter space of QCD axion, the QCD line
- Quality argument
- How to go above the QCD line naturally & addressing the quality problem simultaneously

QCD low energy (2 gen ignoring eta')

At low energies: $$\mathcal{L} \supset \frac{\theta g_s^2}{32\pi^2} G\tilde{G} + qMq^c, \qquad M = \begin{pmatrix} , m_u & 0 \\ 0 & m_d \end{pmatrix}$$

	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_B$	$U(1)_A$
A_μ	adj				
q	$\square$	$\square$		1	1
q^c	$\bar{\square}$		$\bar{\square}$	-1	1
M		$\bar{\square}$	$\square$		-2

$$\langle qq^c \rangle \neq 0,$$ Breaks SU(2) L x R to diagonal

Chiral Goldstone action

$$U = e^{i\frac{\Pi^a}{\sqrt{2}f_\pi}\sigma^a},$$

	$SU(2)_L$	$SU(2)_R$	$U(1)_B$	$U(1)_A$
U	$\square$	$\overline{\square}$		2

$$U \propto qq^c$$

$$\mathcal{L} = f_\pi^2 \ \mathrm{Tr}\ \partial_\mu U \partial^\mu U^\dagger + a f_\pi^3 \ \mathrm{Tr}\ MU + h.c.,$$

Axial sym transformation

$$u \to e^{i\alpha} u, \qquad u^c \to e^{i\alpha} u^c,$$

$$\mathcal{L} \to \mathcal{L} + \alpha \frac{g^2}{16\pi^2} G\tilde{G}.$$

$$u \to e^{i\alpha} u, \qquad d \to e^{i\alpha} d, \qquad \theta \to \theta - 2\alpha.$$

$$U \to e^{i\alpha} U, \qquad M \to e^{-i\alpha} M.$$

Removing the GGdual coupling, phase freedom

$$U = e^{i\pi^a\tau^a/f_\pi} = \cos\frac{|\vec{\pi}|}{f_\pi} + i\frac{\pi^a}{|\vec{\pi}|}\tau^a \sin\frac{|\vec{\pi}|}{f_\pi}.$$

$$\begin{aligned} u &\to e^{i\phi_u}u \\ d &\to e^{i\phi_d}d, \end{aligned}$$

$$\phi_u + \phi_d = \theta.$$

$$U_0 = \begin{pmatrix} e^{i\phi_u} & 0 \\ 0 & e^{i\phi_d} \end{pmatrix}.$$

$$V = -B_0\mathrm{Tr}[(MU_0)U + (MU_0)^\dagger U^\dagger] = -B_0\left[4A\cos\frac{|\vec{\pi}|}{f_\pi} - 4D\frac{\pi^3}{|\vec{\pi}|}\sin\frac{|\vec{\pi}|}{f_\pi}\right].$$

$$D = \frac{1}{2}\mathrm{Tr}\left[\tau^3\begin{pmatrix} m_u\sin\phi_u & 0 \\ 0 & m_d\sin\phi_d \end{pmatrix}\right] = \frac{1}{2}(m_u\sin\phi_u - m_d\sin\phi_d) = 0$$

QCD parameter space

$$
\begin{aligned}
\sin\phi_u &= \frac{m_d \sin\theta}{[m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}} \\
\sin\phi_d &= \frac{m_u \sin\theta}{[m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}} \\
\cos\phi_u &= \frac{m_u + m_d \cos\theta}{[m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}} \\
\cos\phi_d &= \frac{m_d + m_u \cos\theta}{[m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}} .
\end{aligned}
$$

$$
A = \frac{1}{2}\mathrm{Tr}\begin{pmatrix} m_u \cos\phi_u & 0 \\ 0 & m_d \cos\phi_d \end{pmatrix} = \frac{1}{2}(m_u \cos\phi_u + m_d \cos\phi_d).
$$

QCD parameter space

$$m_\pi^2 = \frac{2B_0}{f_\pi^2}[m_u^2 + m_d^2 + 2m_u m_d \cos\theta]^{1/2}.$$

reduces to the well known $m_\pi^2 = \frac{2B_0}{f_\pi^2}(m_u + m_d)$.

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\frac{\overline{\theta}}{2}}.$$

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right)\frac{1}{32\pi^2}G\tilde{G}.$$

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a} + \frac{\overline{\theta}}{2}\right)}. \quad \sim -(m_\pi f_\pi)^2 \cos[a/f + \bar{\theta}]$$

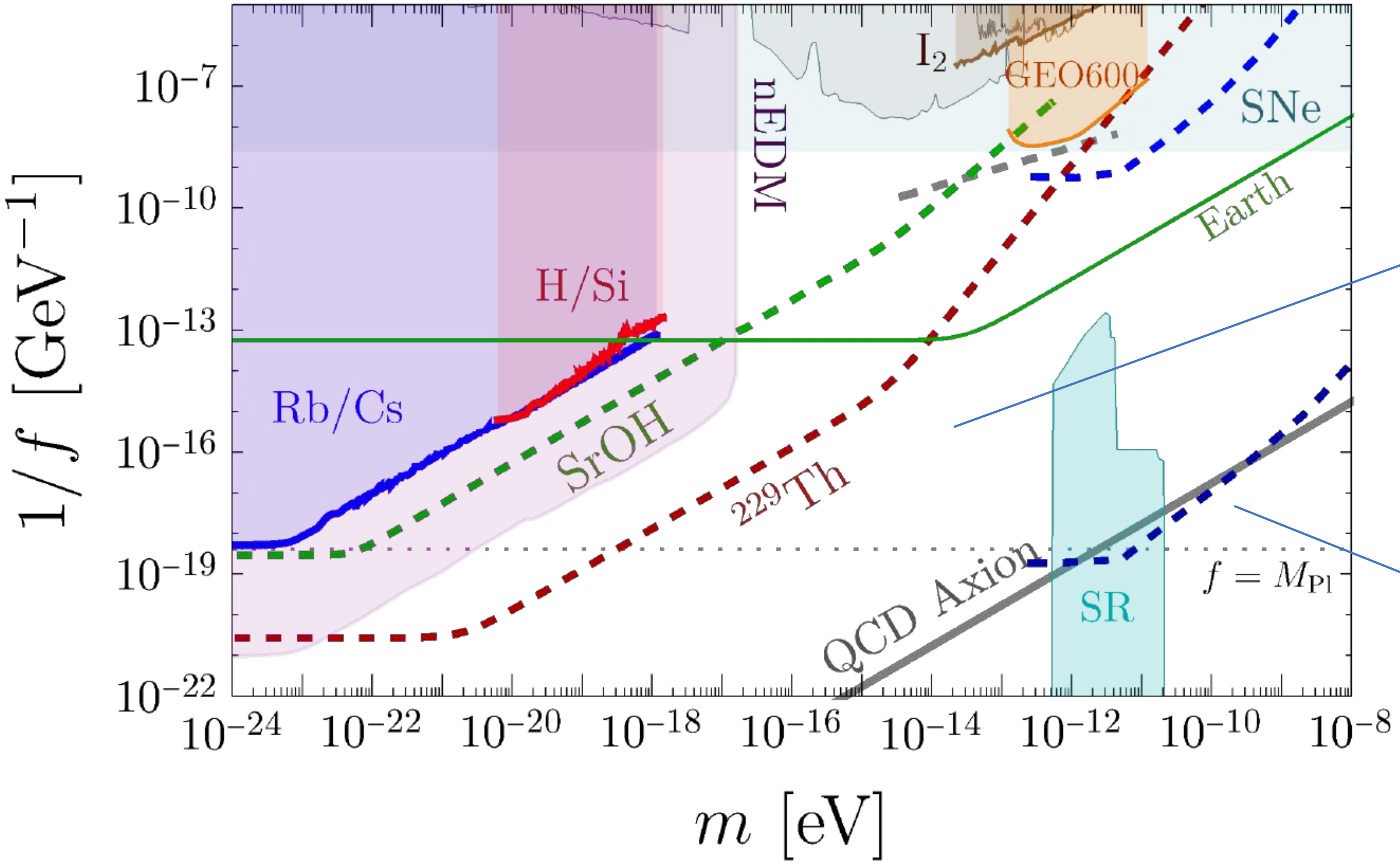
The QCD line

$$m_a \sim \frac{1}{f} \times \Lambda^2_{\rm QCD} \quad \text{or} \quad m_a \sim g_{\rm gluon} \times \Lambda^2_{\rm cutoff,\, shiftsym}$$

$$m_a \gtrsim g_{\rm gluon} \times \Lambda^2_{\rm cutoff,\, shiftsym} \quad \text{or} \quad 1/f \lesssim m_a/\Lambda^2_{\rm QCD}$$

It is not hard to go naturally below the QCD line but it is very hard to go above it.

The QCD line



Unnatural models

$1/f \gtrsim m_a/\Lambda^2_{\mathrm{QCD}}$

Natural models

$1/f \lesssim m_a/\Lambda^2_{\mathrm{QCD}}$

ALP/axion quality problem, 2nd look

Barr & Seckel; Kamionkowski & March-Russell (92); see also talk by Raffaele …

- Planck suppressed operators typically destroy the axion potential.

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

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

- Can be addressed if the axion has additional contribution to its mass (lowering *f*):

Rubakov (97); Berezhiani, Gianfagna & Giannotti (01); Hook (14);

Fukuda, Harigaya, Ibe & Yanagida (15); Alves & Weiner (17) …

- Can be addressed with a Z_n sym

Homework 3

Repeat the same analysis for general axion-like-particle (ALP), namely add higher dim’ operators, derive a naturalness bound, identify the level of quality required as a function of the ALP mass.

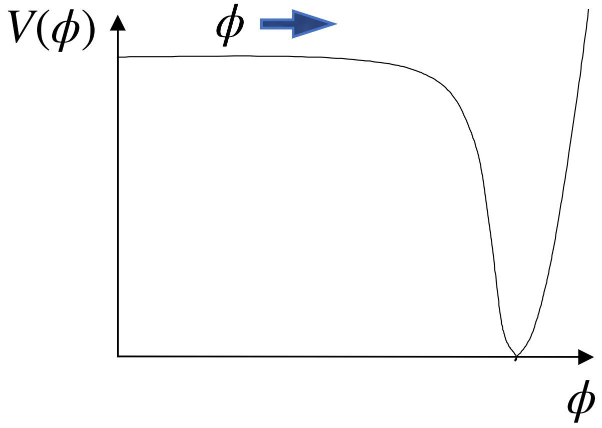
2nd part
Sensible unnatural models

To prepare our discussion on “unnatural” models,
let’s focus more on the anthropic solution & inflation

Bare minimal to understand field evolution during inflation

(for more cosmological details, see lectures by Hubisz)

♦ Standard inflation "classical" story- field slow rolling down flat potential for 60-e-folds ($\ddot{\phi} + 3H\dot{\phi} - V(\phi)' = 0$):



♦ However, this is in expanding background $H^2 \sim V(\phi_{\rm slow})/M_{\rm Pl}^2$ and so the field is subject to quantum fluctuation, can be literally thought as associated with evolution in fine temparature (Gibbons–Hawking) $T \sim H$.

♦ Therefore, in addition to the classical evolution the field is develop quantum spread around its classical value.

Stochastic field evolution

♦ The probability distribution of slow-rolling scalar field is describe by the Fokker-Planck equation: $\partial_\phi \left[\frac{1}{8\pi^2} \partial_\phi (H^3 P) + \frac{V' P}{3H} \right] = \partial_t P \,, \quad \int d\phi P(\phi, t) = 1 \,, \quad M_{\rm Pl} H \sim \sqrt{V(\phi)}$

diffusion drift

[FP obtained when $\dot{\phi} \approx aV' + f^{\rm stoc}(t)$ & $\langle f(t) f(t') \rangle \propto H^3 \delta(t - t')$ as quick check we can see weather
$\Delta\phi_{\rm QM} < \Delta\phi_{\rm clas} \quad \Leftrightarrow \quad H \lesssim \dot{\phi}/H \sim V'/3H^2$]

♦ The volume weighted version, $\langle e^{3Ht} \rangle$, of the Fokker-Planck equation:

$\partial_\phi \left[\frac{1}{8\pi^2} \partial_\phi (H^3 P_v) + \frac{V' P_v}{3H} \right] + 3HP_v = \partial_t P_v \,, \quad \int d\phi P_v(\phi, t) \neq 1$ gives advantage to uphill evolution

♦ Large Hubble implies non-classical evolution drives into critical points (max’ of potential)

Emphasised in: Csaki, D’Agnolo, Geller & Ismai (20)
Geller et al; Giudice McCullough & You (21)

Measure problem

♦ However, volume weighting is not gauge invariant, can’t define synchronous time gauge

see e.g. Bousso’s TASI lectures

♦ The conclusion might depends on which gauge is chosen

♦ More generally, why should we care about the volume? (different than complexity, it’s non-anthropic)

♦ The “only” safe way might be a measure which follows a single observer, say following a casual path, and typically it removes the volume enhancement, so the jury is still out (at least for me …)

Alternative to naturalness with cosmology

♦ There are many ideas related to this concept, most effort was related to Solving the CC problem (even pre-Weinberg), and I won’t attempt to cover them all

♦ What is interesting is that recently variety of ideas were introduced to account for the lightness of the Higgs using combination of multiverse/cosmological scanning of its mass

♦ I”ll just mention a few and then focus on the relaxion, because it is concrete can be understood via QFT & has interesting unnatural pheno’

Incomplete list on: Linking the Higgs naturalness to the CC or multiverse

- Linking the Higgs mass to the volume of the corresponding universe. Namely, constructing an extended inflation sector, such that the universe volume is an increasing function of inverse of the weak scale

  Inflating to the Weak Scale, Hochberg, Geller, Kuflik (19)
  Selfish Higgs, Giudice, Kehagias, Riotto;
  A Goldilocks Higgs, Kaloper, Westphal (19)
  See also "criticality" papers mentioned above

- Density of vacua is inversely proportional to the weak scale

  Cosmological attractors, Dvali (varoius)
  Small weak scale from small CC, Arvanitaki et al. (16)
  Weak scale as a trigger, Arkani-Hamed, Raffaele, Kim (20)

- NNaturalness, many copies of the SM with different Higgs mass, reheat dynamics is of low scale and only low EW scale is reheated (Arkani-Hamed et al. 16)

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  A Goldilocks...
  See also "c...

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  Small weak scal...
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- NNaturalness, many copies of the SM with different Higgs mass, reheat dynamics is of low scale and only low EW scale is reheated (Arkani-Hamed et al. 16)

Many of these involve light scalars
Some of them have generic scanning, but usually not
Some rely on measures, some factories the inflation from the Higgs, some not
Let's focus in the relaxion, for now decouple the inflaton from the relaxion dynamics

The relaxion mechanism

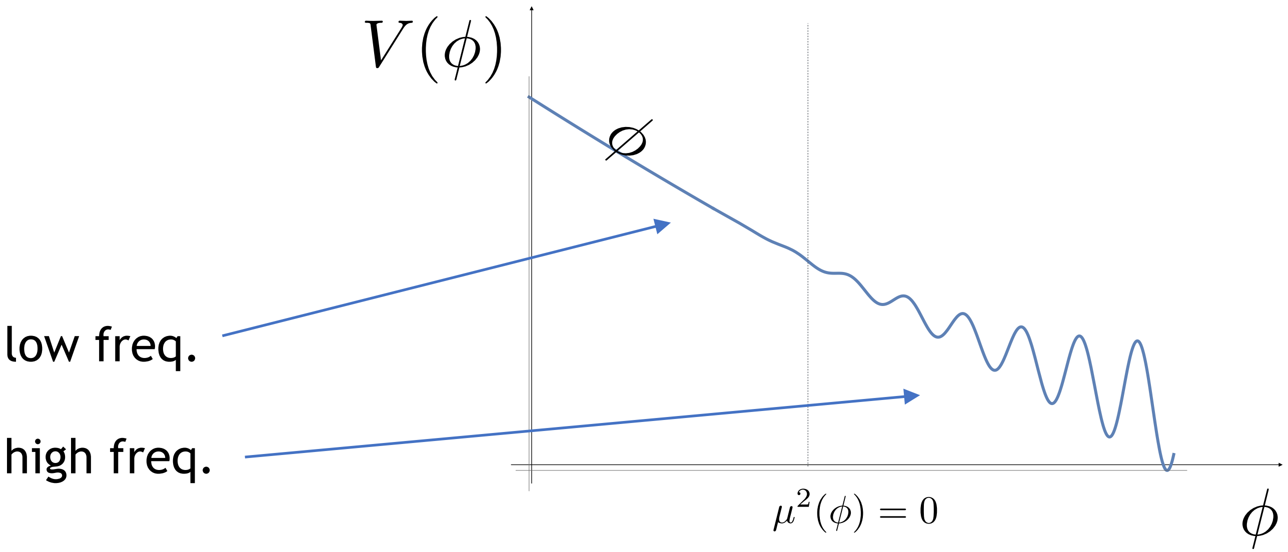
Graham, Kaplan & Rajendran (15)

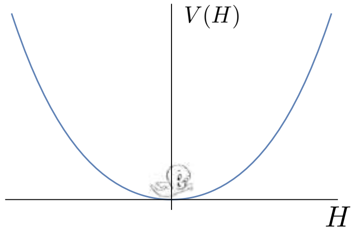
Relaxion mechanism (inflation based, slow rolling)

Graham, Kaplan & Rajendran (15)

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

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





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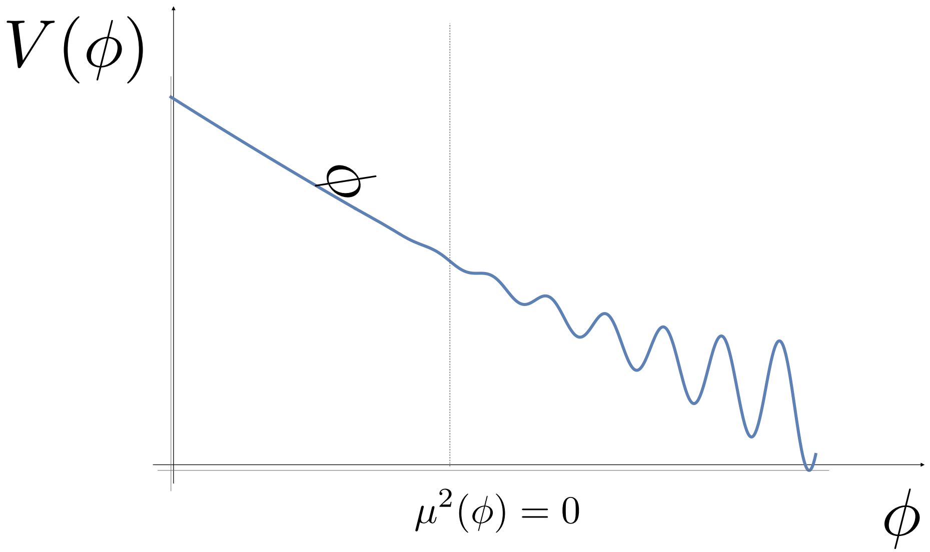

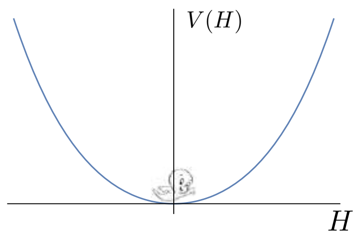

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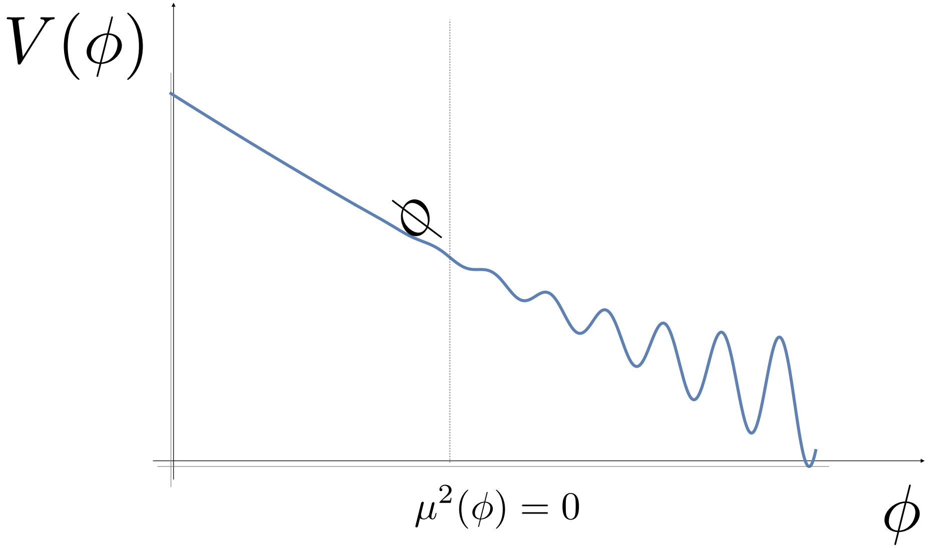

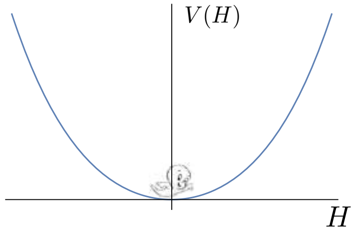

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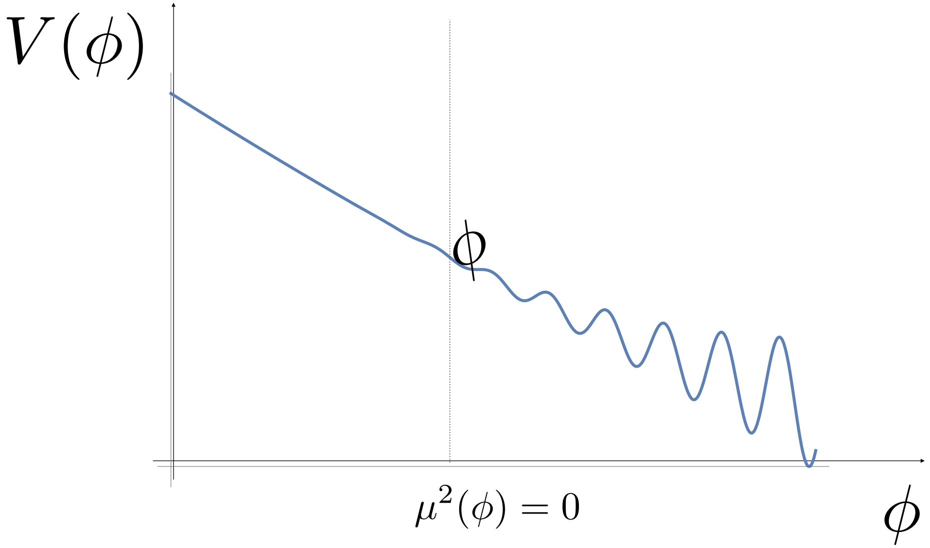

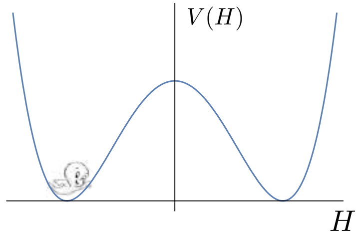

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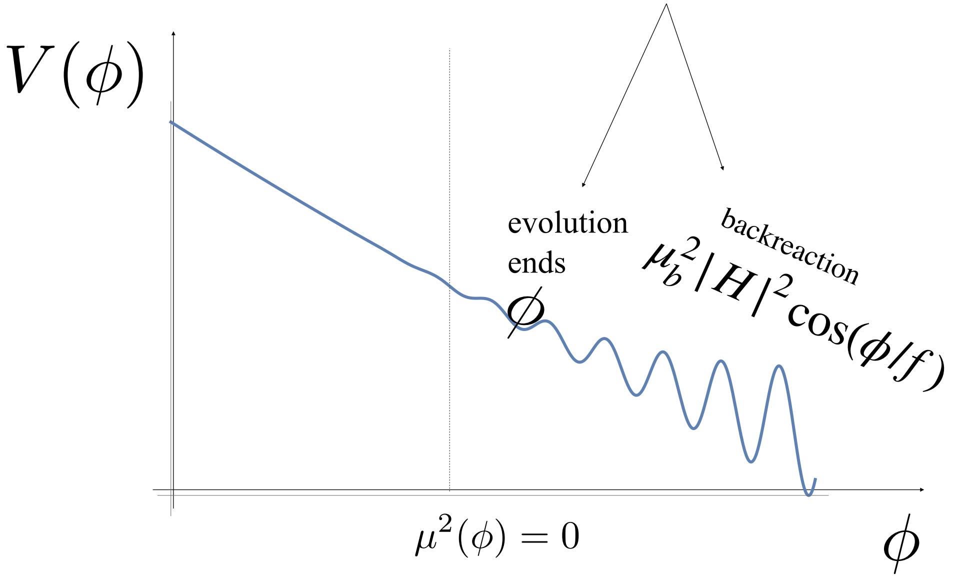
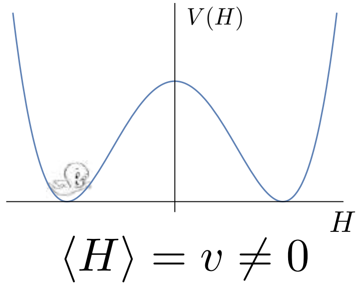




The basic relations & parametric dependence

- As the relaxion is an ALP, the potential must be a periodic function of it:

$$V(\phi)^{\rm rol} \sim M^4 \cos(\phi/F) \qquad\qquad \mu^2(\phi) = \Lambda^2 + M^2\cos(\phi/F) + m_{\rm back}^2 \cos(\phi/f + \alpha)$$

$$\text{with } \; f \ll F \;\&\; M \sim \Lambda \gg m_{\rm back}, v \quad \& \quad m_{\rm back} \lesssim v$$

Espinosa et al. (15)

- We start assuming $\phi \sim F$ and the stopping condition reads:

$$V'(\phi) = 0 \quad \Leftrightarrow \quad M^4/F = v^2 m_{\rm back}^2/f \quad \Rightarrow \quad v/\Lambda \lesssim (f/F)^{\frac{1}{4}}$$

Gupta, Komargodski, GP & Ubaldi (15)

- Require very big hierarchy between f and F

Clockwork

To have a cut-off of $10^4\ v$ we need $f/F = 10^{-16}$

Choi, Kim & Yun (14); Choi & Im; Kaplan & Rattazzi (15)

Clockwork model

Choi, Kim & Yun (14); Choi & Im; Kaplan & Rattazzi (15)

- The following linear sigma model:

$$V(\phi) = \sum_{j=0}^{N} \left(-m^2 \phi_j^\dagger \phi_j + \frac{\lambda}{4} |\phi_j^\dagger \phi_j|^2 \right) + \sum_{j=0}^{N-1} \left(\epsilon \phi_j^\dagger \phi_{j+1}^3 + h.c. \right)$$

In the $\epsilon \to 0$ limit have $U(1)^N \Rightarrow N$ Goldstones.

- However there is only one true Goldstone, upon the charge assignment:

$$Q = 1, 1/3, 1/9, \ldots 1/3^N$$

- Move to the non-linear sigma model:

$$\phi_j \to U_j \equiv f e^{i\pi_j/(\sqrt{2}f)}$$

Clockwork model at low energies

Choi, Kim & Yun (14); Choi & Im; Kaplan & Rattazzi (15)

- The following effective low energy non-linear sigma potential:

$$\begin{aligned}\mathcal{L}_{pNGB} &= f^2 \sum_{j=0}^{N} \partial_\mu U_j^\dagger \partial^\mu U_j + \left(\epsilon f^4 \sum_{j=0}^{N-1} U_j^\dagger U_{j+1}^3 + h.c. \right) + \cdots \\ &= \frac{1}{2} \sum_{j=0}^{N} \partial_\mu \pi_j \partial^\mu \pi_j + \epsilon f^4 \sum_{j=0}^{N-1} e^{i(3\pi_{j+1} - \pi_j)/(\sqrt{2} f)} + h.c. + \cdots\end{aligned}$$

- There is only one true Goldstone with the following profile:

$$\vec{a}_{(0)}^{T} = \mathcal{N} \left(1 \quad \tfrac{1}{3} \quad \tfrac{1}{9} \quad \ldots \quad \tfrac{1}{3^N} \right)$$

The 0-mode/exact Goldstone profile & breaking

Choi, Kim & Yun (14); Choi & Im; Kaplan & Rattazzi (15)

- Add small breaking on first and last sites:

$$\frac{\pi_0}{32\pi^2 f} G_0 \tilde{G}_0 + \frac{\pi_N}{32\pi^2 f} G_N \tilde{G}_N$$

$$\downarrow$$

$$\Lambda_N \cos\frac{\pi_N}{f} + \Lambda_0 \cos\frac{\pi_0}{f}$$

$$\downarrow$$

$$\Lambda_N \cos\frac{\pi}{3^N f_a} + \Lambda_0 \cos\frac{\pi}{f_a}$$

The 0-mode/exact Goldstone profile & breaking

Choi, Kim & Yun (14); Choi & Im; Kaplan & Rattazzi (15)

- Add small breaking on first and last sites:

$$\Lambda_N \cos\frac{\pi}{3^N f_a} + \Lambda_0 \cos\frac{\pi}{f_a}$$

$$f \equiv f_a \quad \& \quad F = 3^N f$$

To have a cut-off of $10^4\, v$ we need $f/F = 10^{-16}$ => 35 cites …

Homework 4

Derive a quality type argument for the clockwork model

A bit about the relaxion cosmology

Relaxion and cosmology

- Must not disturb inflation $H^2 > \Lambda^4/M_{\rm Mpl}^2$
- Dominated by classical evolution $H < \dot{\phi}/H \sim V'/H^2 \lesssim v^4/fH^2 \;\Rightarrow\; \Lambda < f < v^4/H^3$
- Combining the two $\Lambda \lesssim M^{\frac{3}{7}} v^{\frac{4}{7}} \sim 10^8\,\mathrm{GeV}$
- There is also an interesting relation between the cutoff and the number of e-folds

$$\Delta\phi \sim F \quad \Rightarrow \quad N_{\rm ef} \sim F/\dot{\phi} \times H \sim FH^2/V' \sim F^2H^2/\Lambda^4 \gtrsim F^2/M_{\rm Pl}^2$$

$$\sim (\Lambda/v)^8 f^2/M_{\rm Pl}^2 \gtrsim \Lambda^{10}/v^8 M_{\rm Pl}^2 \sim \left(\frac{\Lambda}{100\,\mathrm{TeV}}\right)^{10}$$

Relaxion phenomenology

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

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

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

~ 1 ⇒ The relaxion is light and mixes with the Higgs

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

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

2 differences from generic Higgs portal

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

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

The relaxion parameter space

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

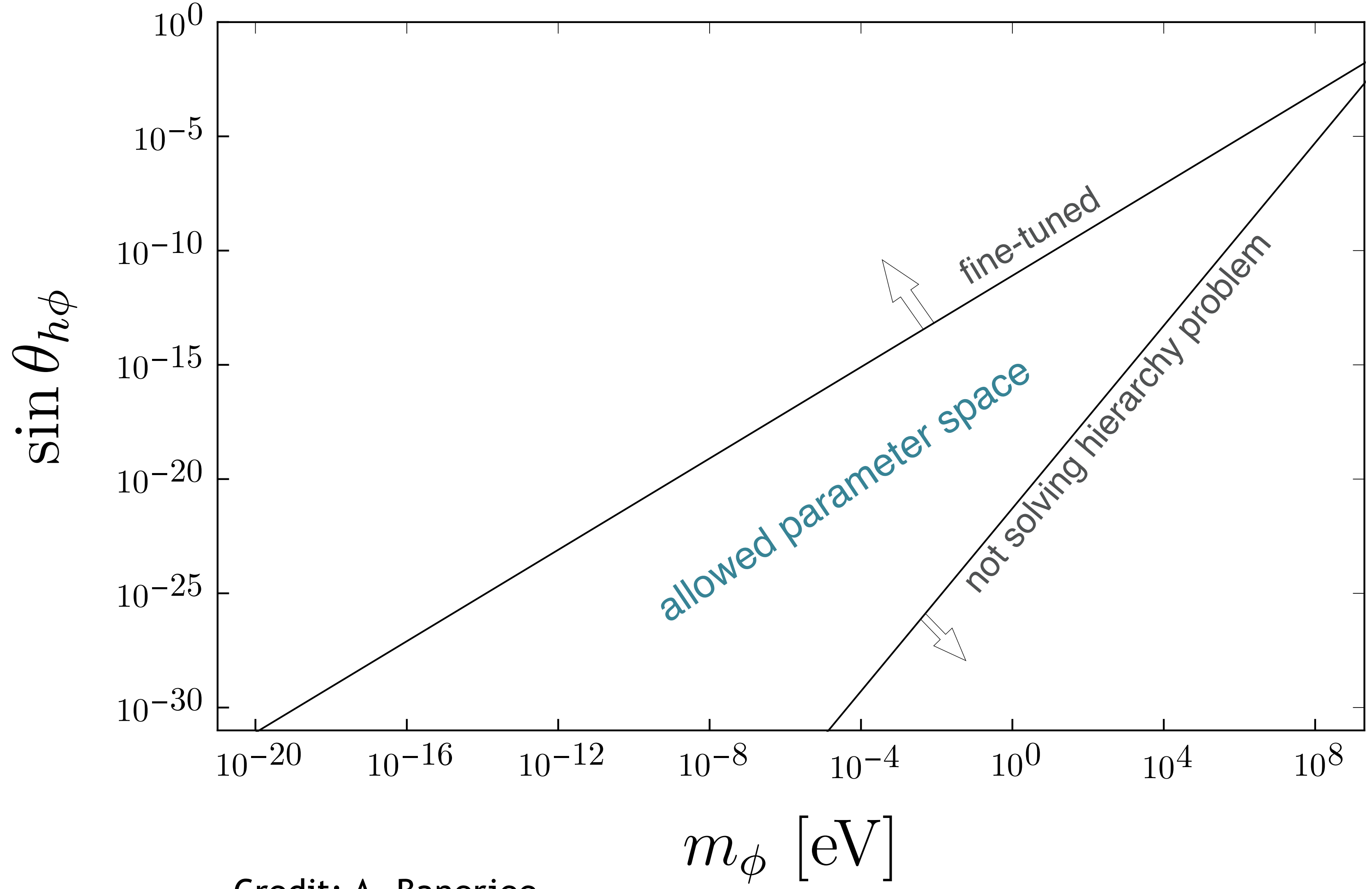
$$L_S \in m_S^2\, SS + \mu S H^\dagger H + \lambda S^2 H^\dagger H\,, \quad \text{with } S = \text{light scalar \& } H = \text{SM Higgs}\,.$$

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

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

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

The relaxion's naive parameter space

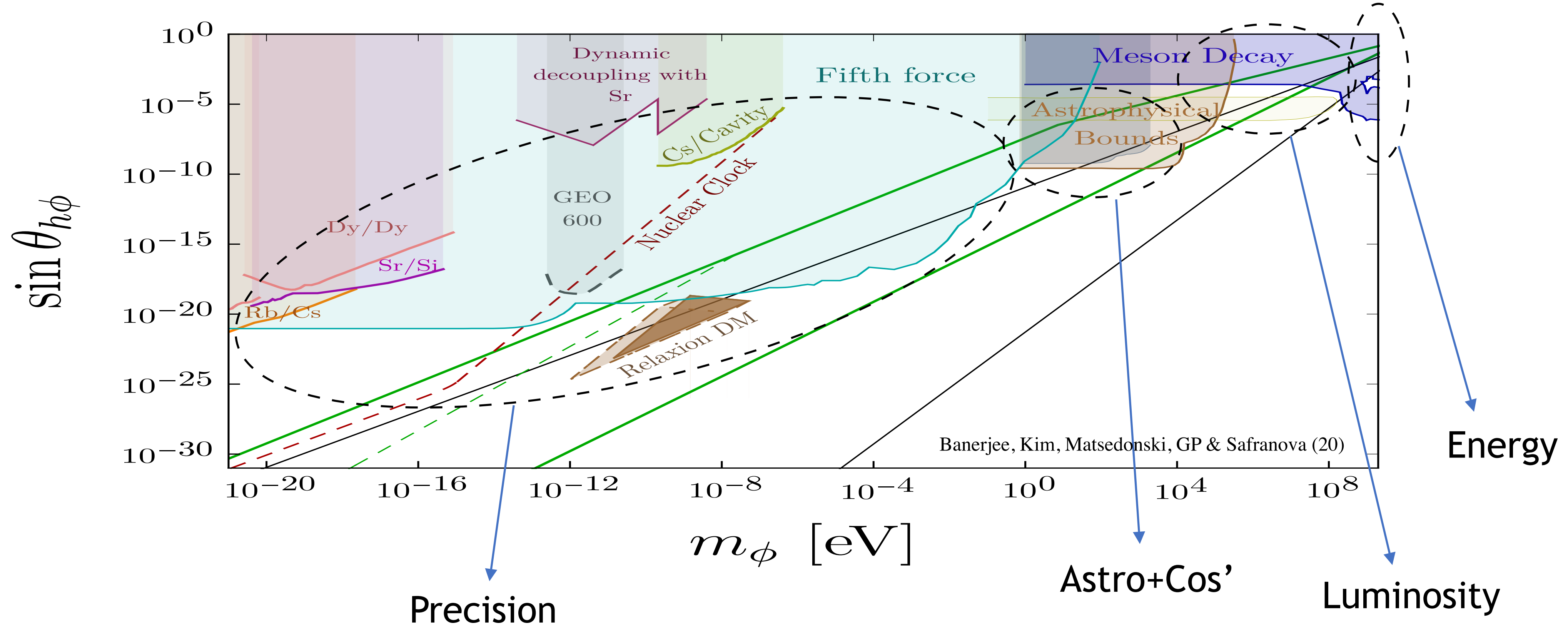


Credit: A. Banerjee

The log crisis

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

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



Less naive treatment, the relaxed relaxion

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

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

Resolution parameter

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

$$V_{\mathrm{br}} = -\mu_b^2|H|^2\cos\frac{\phi}{f}$$

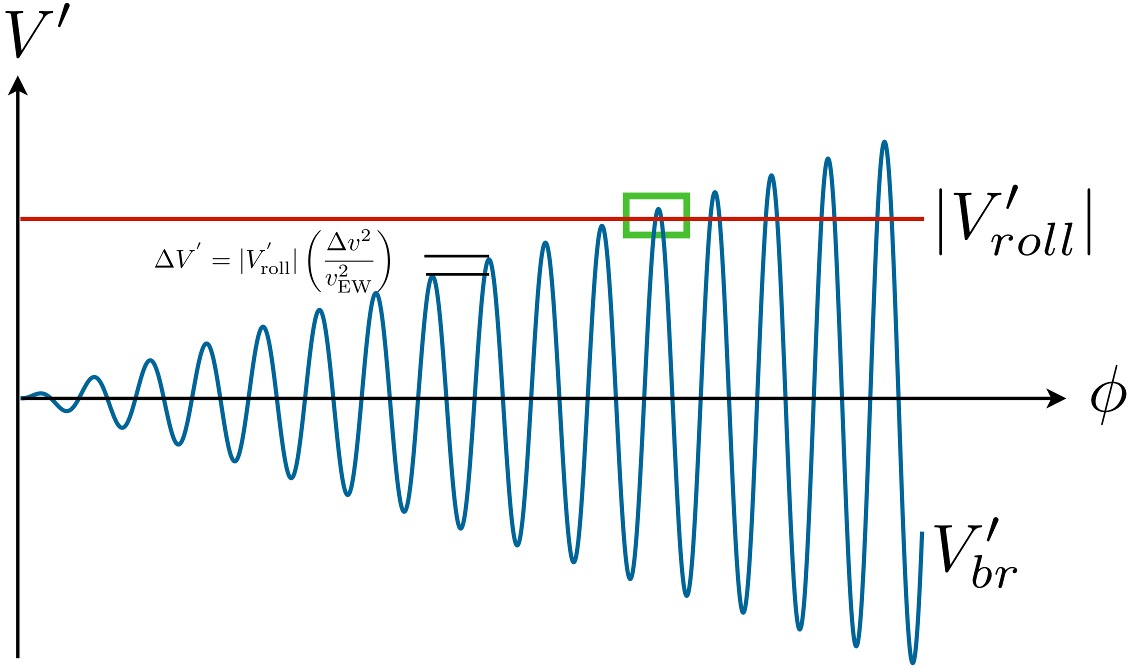
$\Rightarrow$ Potential height grows incrementally

Stopping condition, fine resolution

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

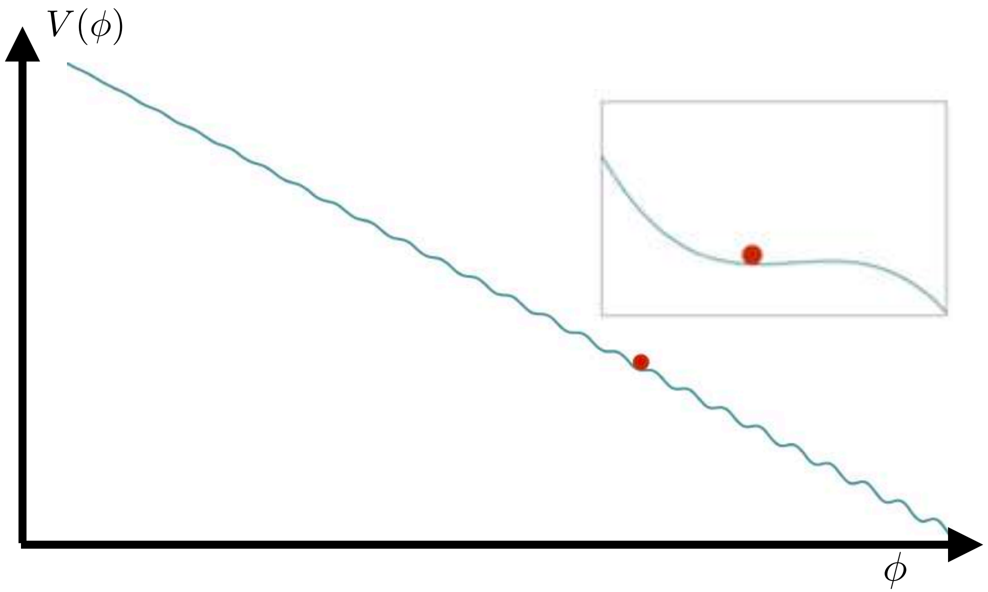
$$\boxed{V_\phi' = 0 \Rightarrow \sin\theta = \frac{v_{\rm EW}^2}{v^2(\phi)} + \frac{v_{\rm EW}^2}{\Lambda^2}} \quad \Rightarrow \quad \boxed{\frac{\phi_0}{f} \sim \frac{\pi}{2} \text{ upto resolution factors}}$$

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



Relaxion: barriers increase incrementally:

relaxion stops at shallow region => small mass

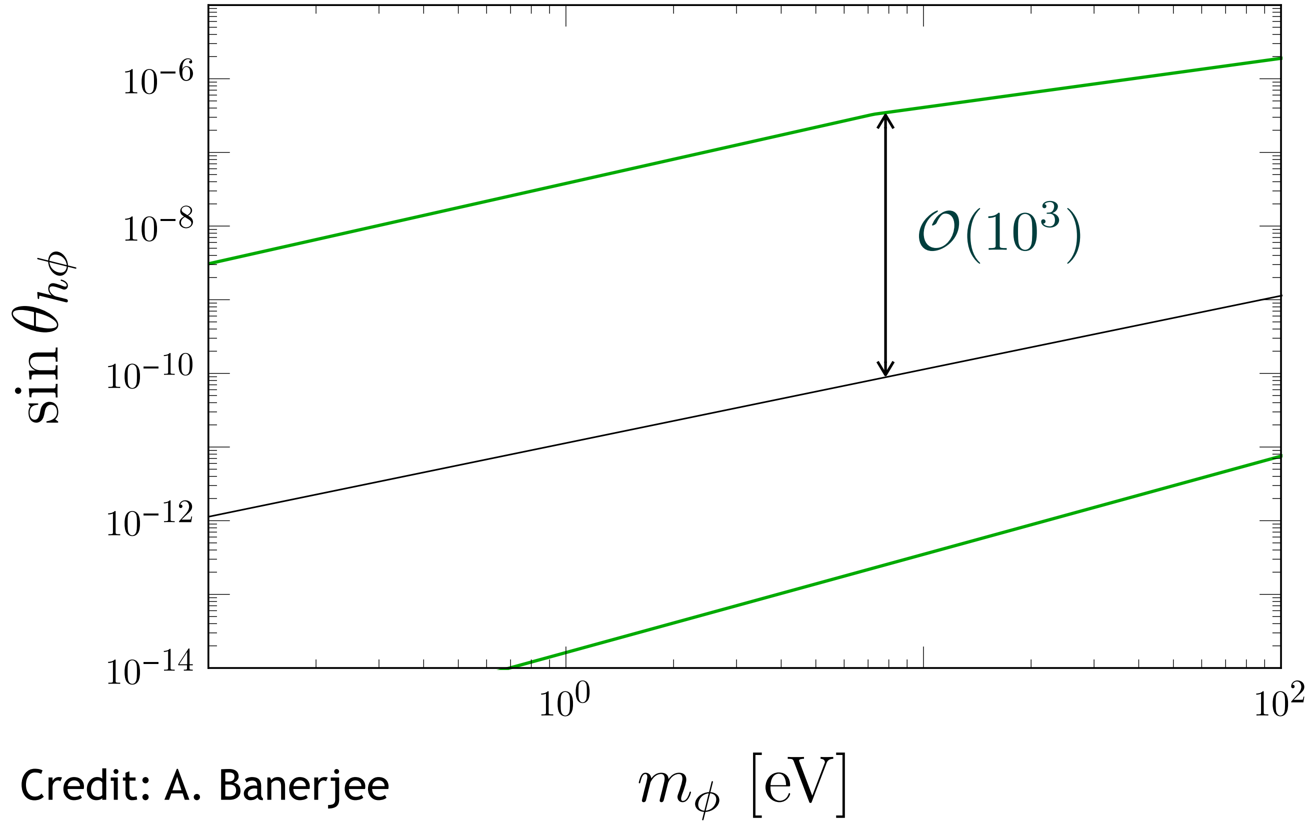


Credit: A. Banerjee

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

3 models of ultralight scalar DM
(not using the word string-theory)

1st model, just a free scalar

Simplest possible model, free massive scalar

- Most minimal model would be just a free massive scalar :

$$\mathscr{L} \in m_\phi^2 \phi^2 \, , \, \rho_{\rm Eq}^{\rm DM} \sim {\rm eV}^4 \sim m_\phi^2 \phi_{\rm Eq}^2 = m_\phi^2 \phi_{\rm init}^2 ({\rm eV}/T_{\rm osc})^3$$

$$T_{\rm os} \sim \sqrt{M_{\rm Pl} m_\phi} \implies \phi_{\rm init} \sim M_{\rm Pl} \left(\frac{10^{-27}\,{\rm eV}}{m_\phi} \right)^{\frac{1}{4}}$$

(can add a few more bounds, SR, isogurvature but still large parameter space, reasonable field excursion)

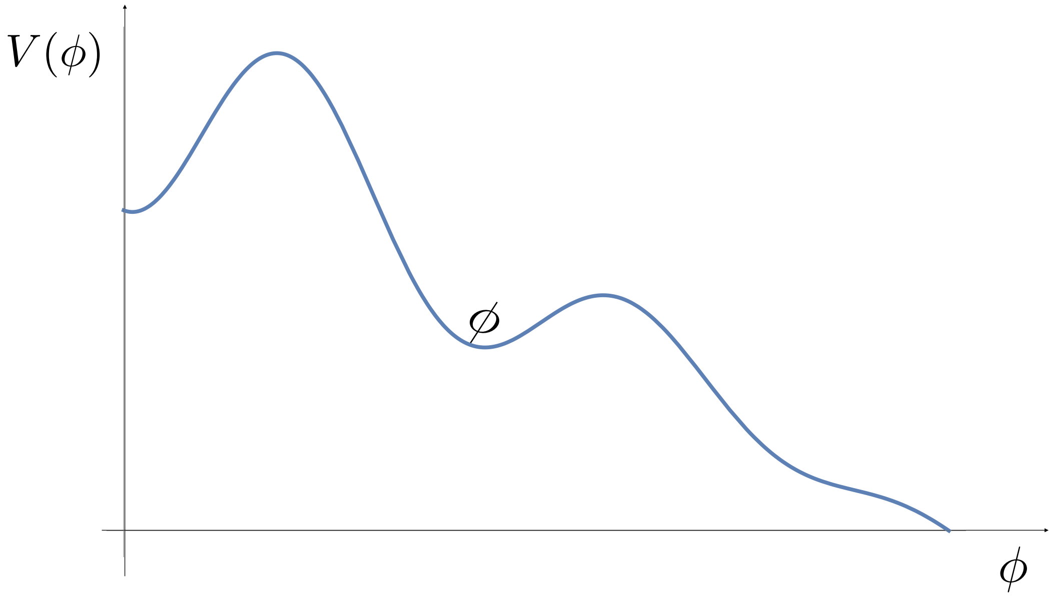
- Just remind you that if we add Planck suppressed operators then we did find bounds …

- Also, in the presence of these coupling if it's too light there will be naturalness issues …

The relaxion DM dynamical missalignment

Banerjee, Kim & GP (18)

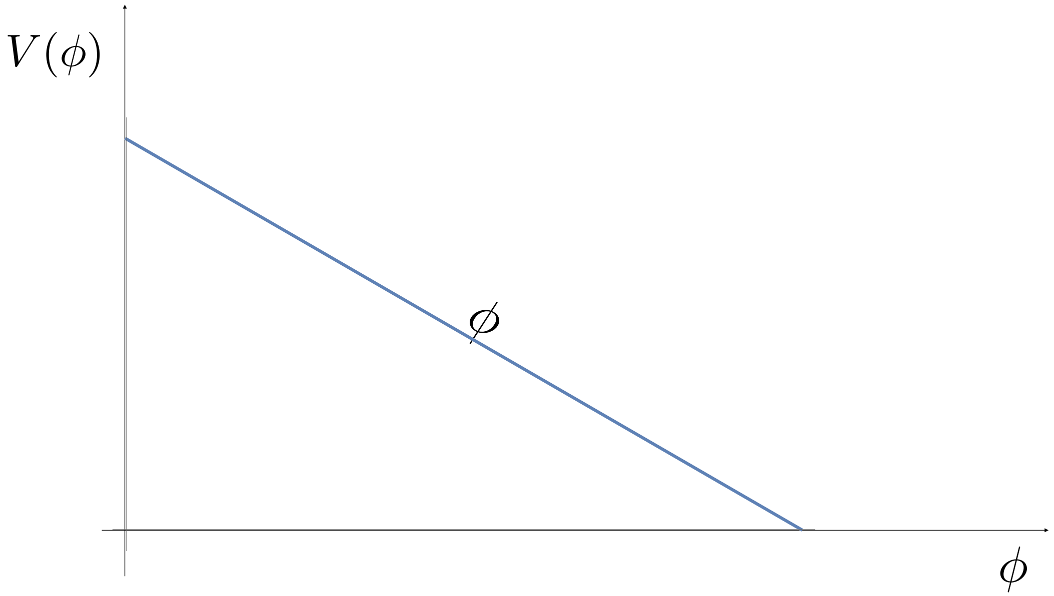
- Basic idea is similar to axion DM:



Concrete ex.: relaxion dark matter (DM)

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

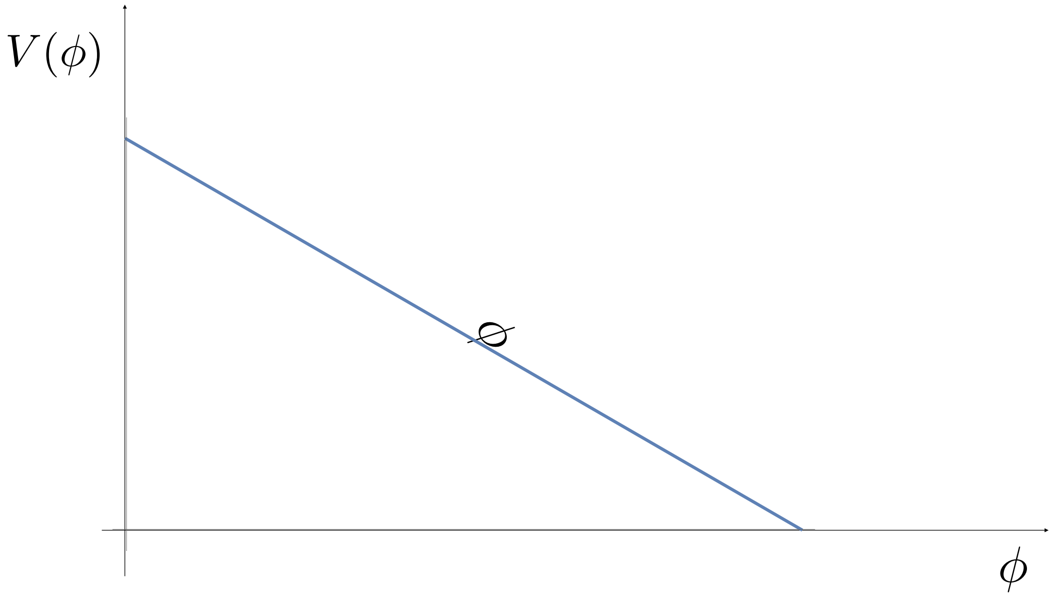
  After reheating the wiggles disappear (sym' restoration):



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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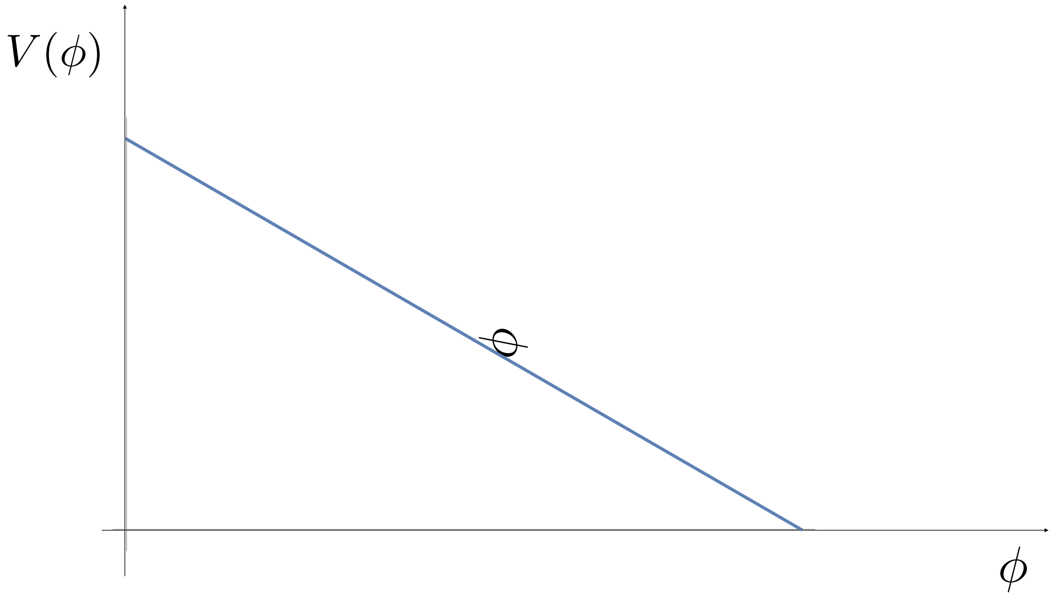
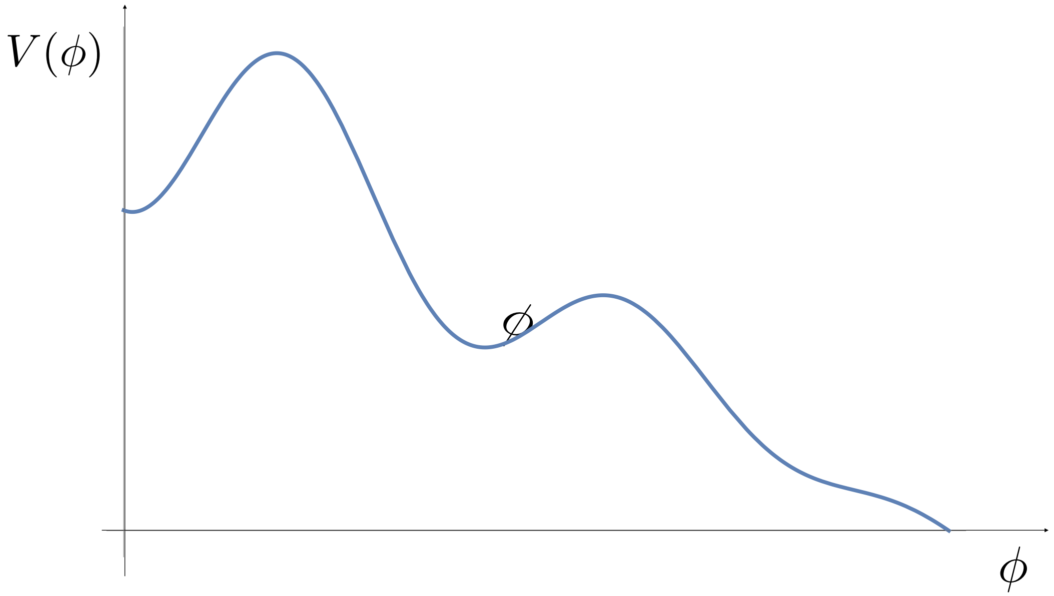


Concrete ex.: relaxion dark matter (DM)

When the universe cools the electroweak symmetry is broken, brings back the wiggles.
Now the relaxion not at the min', if trapped it starts to oscillates = DM



Concrete ex.: relaxion dark matter (DM)

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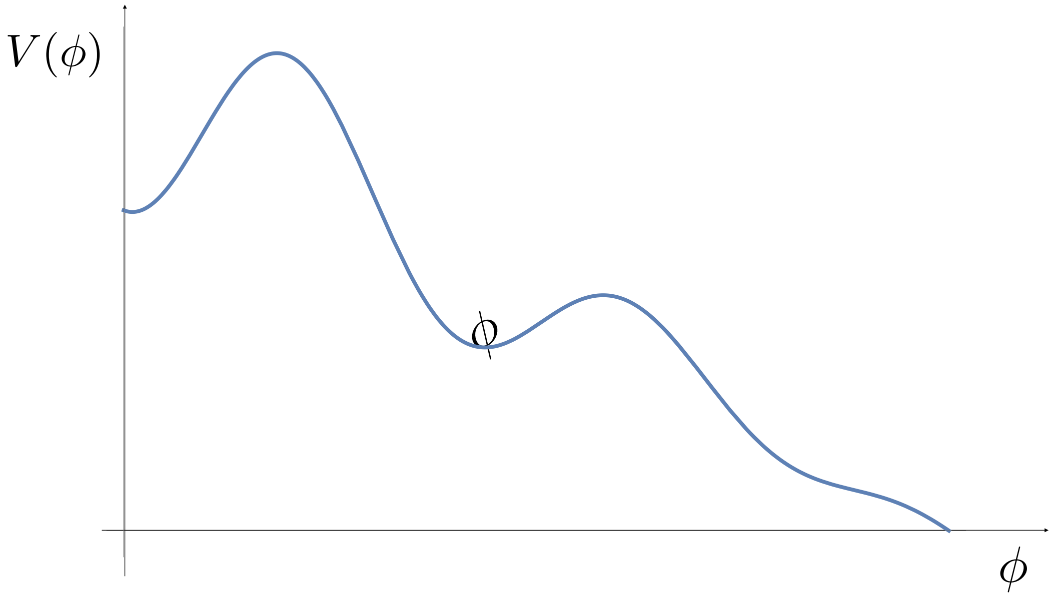

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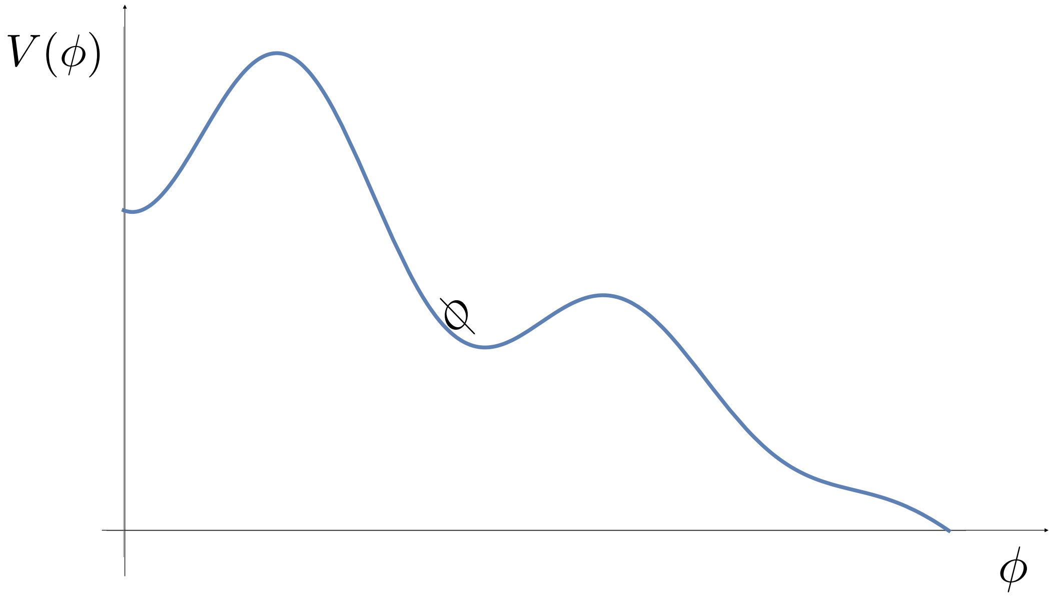

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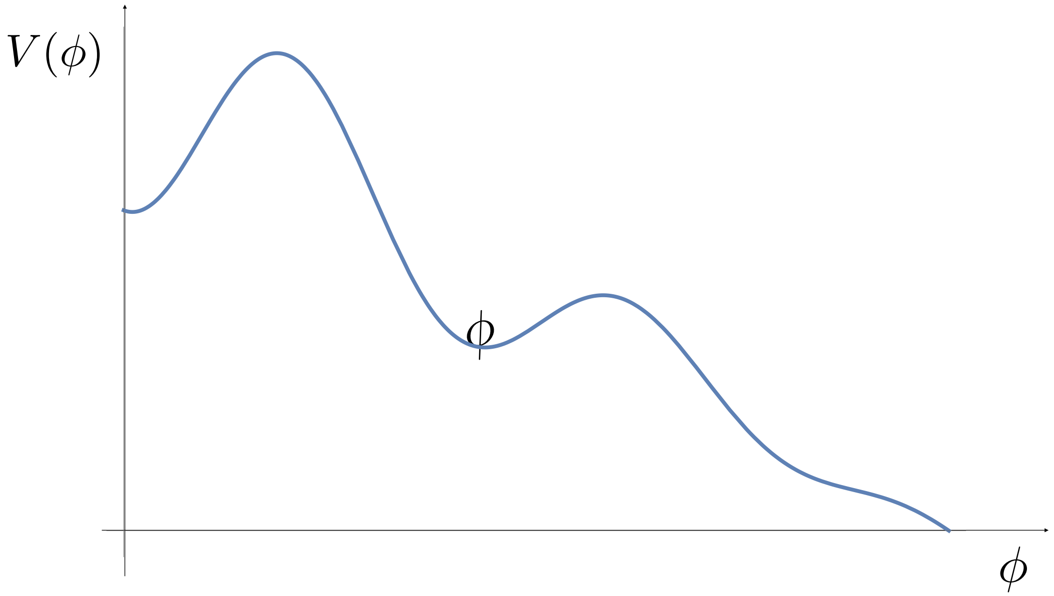
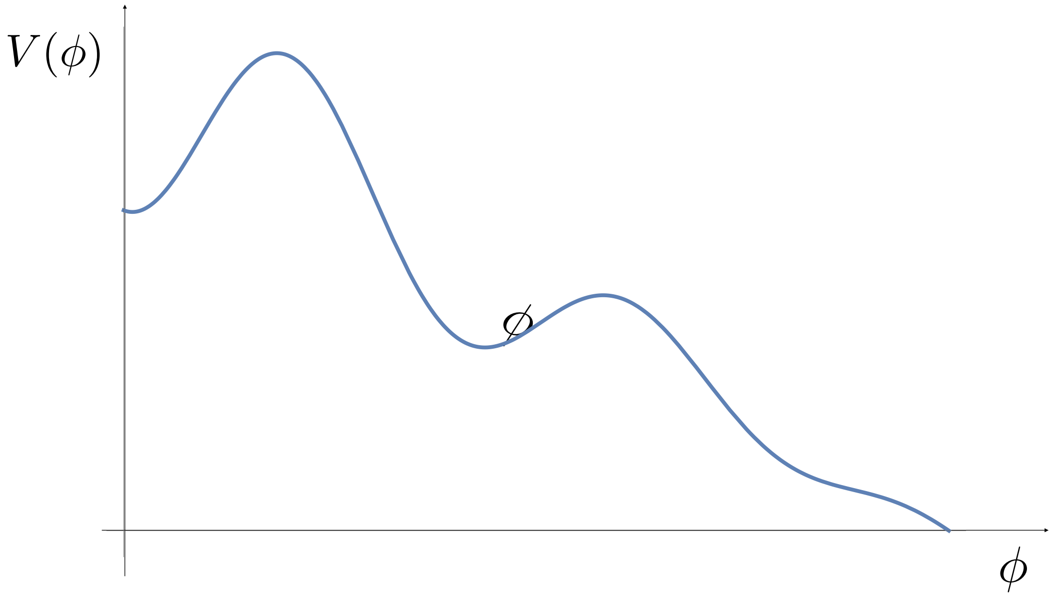


Concrete ex.: relaxion dark matter (DM)

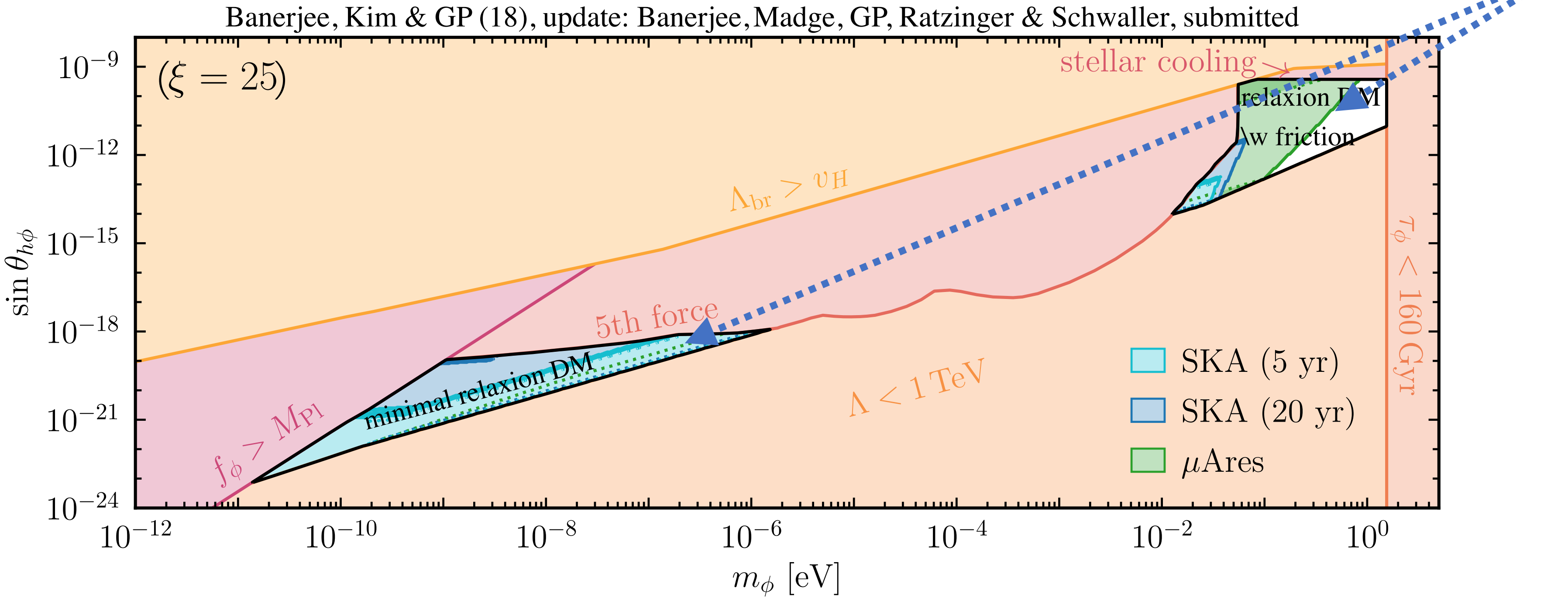
- Basic idea is similar to axion DM (but avoiding missalignment problem):

  Now the relaxion not at the min' & if it is trapped it starts to oscillates = DM.



relaxion DM+GW

DM window



The black solid line encompass the DM relaxion parameter space. The colored regions inside the viable DM space can be probed via GWs in μAres (green) or SKA (blue/turquoise). The light shading and solid lines indicate points that can be probed for a subrange of reappearance temperatures, whereas the darker shaded parts enclosed by dotted lines are accessible for all valid $T_{\rm ra}$.

3rd model, Dilation DM

It’s complicated and problematic,

and I won’t have time

and tabletop signals are similar to the others

3rd part
Precision frontier
How to search for ultralight scalar DM

Equivalence principle (EP) tests, prelim

- Consider the following effective action for scalar DM: $\mathscr{L}_\phi \in d_{m_e}\frac{\phi}{M_{\rm Pl}}m_e\bar{e}e + d_g\frac{\phi}{2gM_{\rm Pl}}\beta_g GG$
- The leading action in the non-relativistic limit, say, of the electron is

$$\mathscr{L}_e^{\rm NR} = m_e(\phi) + \frac{1}{2}m_e v^2 = m_e^0 + d_{m_e}\frac{\phi}{M_{\rm Pl}} \quad \Rightarrow \quad a = d_{m_e}\frac{\phi'}{M_{\rm Pl}}$$

- Inside an atom we can rewrite it as:

$$\mathscr{L}_{\rm atm}^{\rm NR} = M_{\rm Nuc}(\phi) + Nm_e(\phi) + B \;\Rightarrow\; M_{\rm atm}a = \phi'\left(\partial_\phi M_{\rm Nuc}(\phi) + N\partial_\phi m_e(\phi)\right) \;\Rightarrow\; a = \phi'\partial_\phi \ln M_{\rm atm} \equiv \sqrt{G_N}\phi'\alpha_{\rm atm}$$

which can be readily generalised to any system.

- For a test particle at distances such that $m_\phi R \ll 1$ and say $R \gtrsim R_{\rm Earth}$ have $\phi' \propto 1/R^2$ and the acceleration is given by $a = G_N M_{\rm test}\alpha_{\rm test}M_{\rm Earth}\alpha_{\rm Earth}/R^2$

Damour & Donoghue (10)

Equivalence principle (EP) tests

- We would compare two bodies, A and B, to search for a differential acceleration effect via the EotWash parameter $\frac{\delta a_{AB}}{a} = \alpha_{\mathrm{Earth}}(\alpha_A - \alpha_B)$

- Or if we switch on one coupling d_i it is useful to define the corresponding individual "diatonic charge" $d_i Q_i \equiv \alpha_i$

- The experiment test is very simple, let's search for masses smaller than the inverse size of the Earth then we can use two test bodies on a satellite that are free falling with the satellite and just track them. That's exactly what the Microscope mission is doing some 700km above earth

- After >5 yrs of running they've achieve precision of better than $\eta_{\mathrm{EP}} < 10^{-14}$, which can be translated to the following bounds on generic scalar models

Equivalence principle (EP) tests

- For variety of coupling it can be expressed as:

$$\text{EP bounds}: \quad \left(\frac{\delta a_{\text{test}}}{a}\right) < \eta_{\text{EP}} \sim 10^{-14} \quad \Leftrightarrow \quad \left(d_i^{(1)} d_j^{(1)}\right) \Delta Q_i^{\text{test}} Q_j^{\text{Earth}}$$

$$\vec{Q}^{\mathbf{a}} \approx F^{\mathbf{a}} \left(3\,10^{-4} - 4\,r_I + 8\,r_Z\,, 3\,10^{-4} - 3\,r_I\,, 0.9\,, 0.09 - \frac{0.04}{A^{1/3}} - 2 \times 10^6 r_I^2 - r_Z, 0.002\,r_I\right)$$

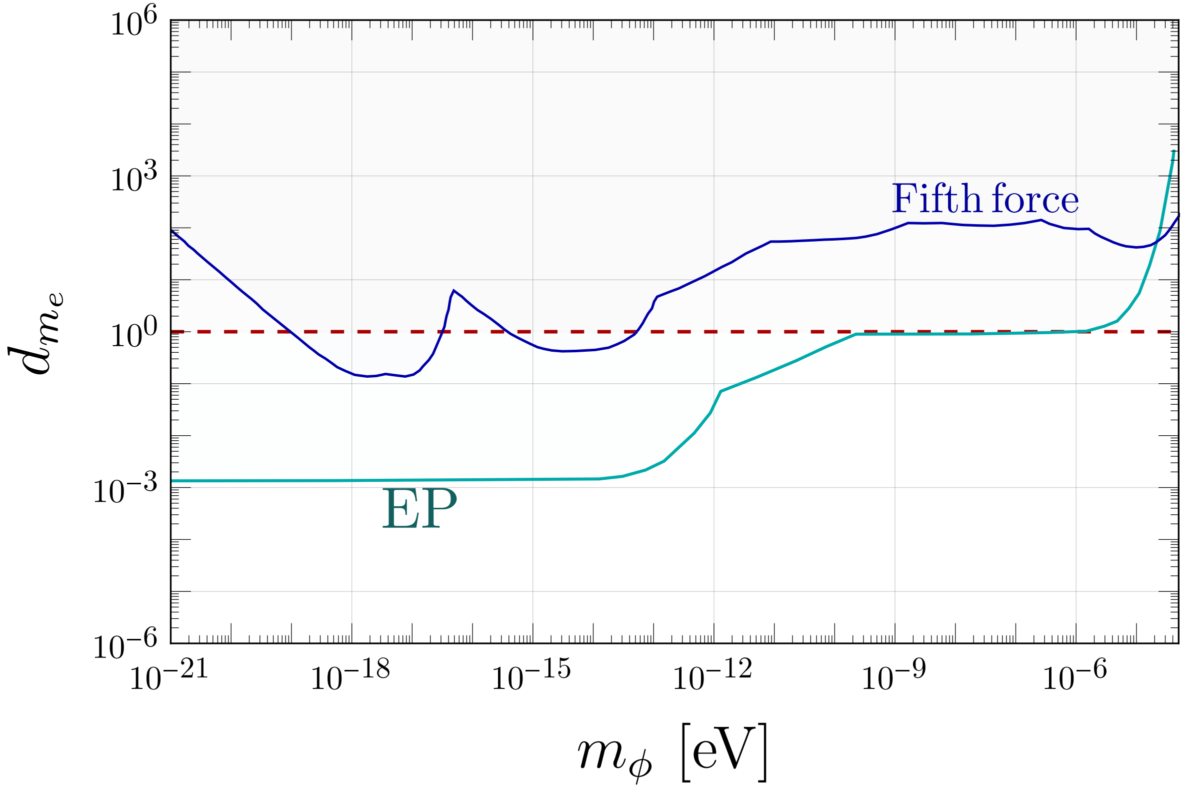
Where $\vec{X} \equiv X_{e,m_e,g,\hat{m},\delta m}$, with $\hat{m} \equiv (m_d + m_u)/2\,, \delta m \equiv (m_d - m_u)\,,\ 10^4\,r_{I;Z} \equiv 1 - 2Z/A; Z(Z-1)/A^{4/3}\,, \&\ F^{\mathbf{a}} = 931\,A^{\mathbf{a}}/(m^{\mathbf{a}}/\text{MeV})$ with $A^{\mathbf{a}}$ being the atomic number of the atom $\mathbf{a}$

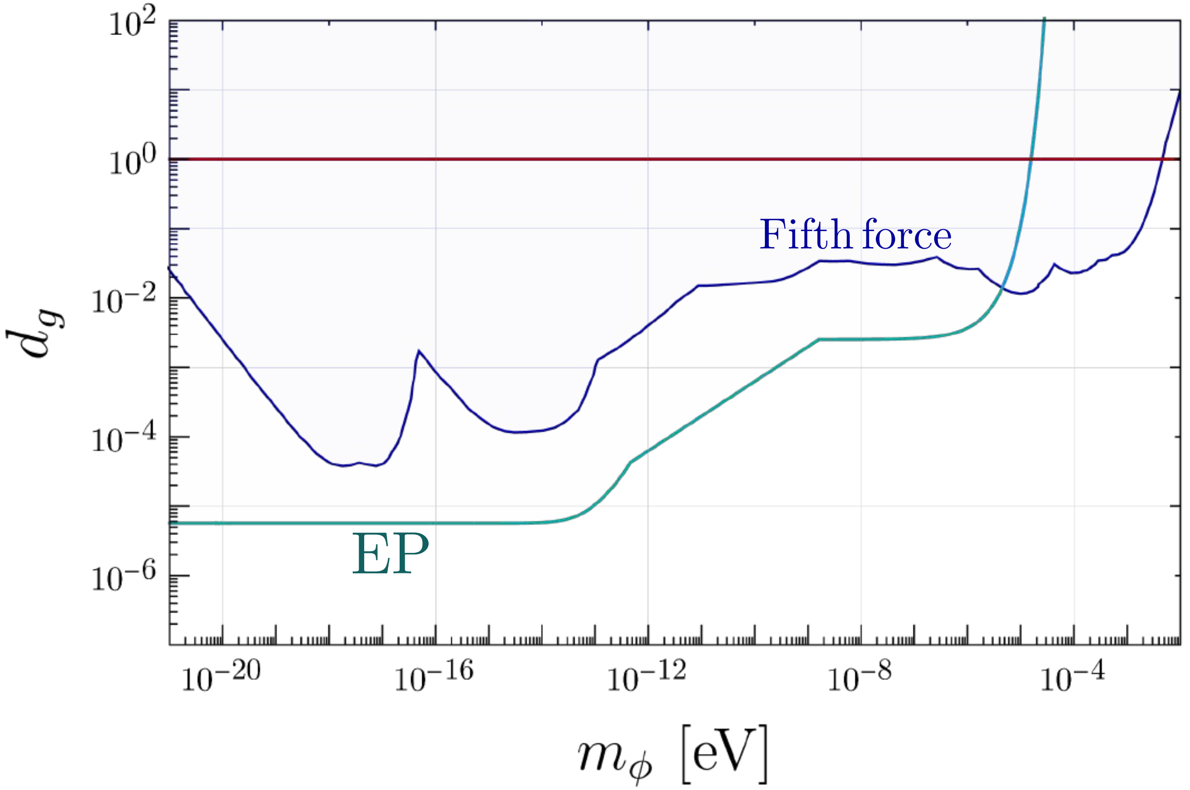
$$\Delta \vec{Q}^{\text{Mic}} \simeq 10^{-3}(-1.94\,, 0.03\,, 0.8\,,\ -2.61\,,\ -0.19)$$

Tretiak, et al.; Oswald, et al (22)

Equivalence principle (EP) tests

Banerjee, GP, Safronova, Savoray & Shalit (to appear)





Where one can find models that avoid the strongest EP bounds and for a pure dilaton the EP bound can be avoided

Tretiak, et al.; Oswald, et al (22)

Direct dark matter searches, sensitivity

- How do we search for ULDM directly?

Take for example the Lagrangian $\mathscr{L}_\phi \in d_{m_e}\frac{\phi}{M_{\rm Pl}}m_e\bar{e}e + d_g\frac{\phi}{2gM_{\rm Pl}}\beta_g GG$ and focus first about the electron coupling?

- The most sensitive way is with clocks, because $\phi \sim \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}\cos(m_\phi t)$ then the electron mass oscillates with time => energy levels oscillates with time: $E_n \sim m_e\alpha^2 1/2n^2$

- For instance: $\Delta E_{21} \sim m_e\alpha^2 1/2 \times 3/4 \times \left[1 + d_{m_e}\frac{\sqrt{2\rho_{\rm DM}}}{m_\phi M_{\rm Pl}}\left(\sim 10^{-15} \times \frac{d_{m_e}}{10^{-3}}\frac{10^{-15}\,{\rm eV}}{m_\phi}\right) \times \cos(m_\phi t)\right]$

Direct dark matter searches via clocks

- Which implies that clocks can win over EP for precision of roughly $1{:}10^{15}$ for about 1 Hz DM mass
- How the clock works: for this school it's just creating a state which is a superposition of the two states and thus oscillates with time and picking up the above phase: $\exp^{i\Delta E(m_e(t))t}$
- However, to see the effect you need to compare it to another system that would not have the above precise dependence …

Enhanced sensitivity

- The most robust coupling is to the gluons:

Mixing with the Higgs, dilaton and even QCD axion have coupling to the gluons

- How to be sensitive to the coupling to QCD?

- Could be via reduced mass, or via g-factor, magnetic moment-spin interactions-hyperfine or vibrational model in molecules, or the queen of all nuclear clock , ^{229}Th

- It is super sensitive because $E_{\text{nu}-\text{clock}} \sim E_{\text{nu}} - E_{\text{QED}} \sim 8\,\text{eV} \ll E_{\text{nu}} \sim \text{MeV}$

$$\frac{\Delta E}{E} = \frac{E_{\text{nu}}(t) - E_{\text{QED}}}{E_{\text{nu}-\text{clock}}} \Rightarrow \frac{\Delta E_{\text{nu}}(t)}{E_{\text{nu}-\text{clock}}} \sim \frac{E_{\text{nu}}}{E_{\text{nu}-\text{clock}}} \times d_g \frac{m_N}{M_{\text{Pl}}} \cos(m_\phi t) \sim 10^5 d_g \frac{m_N}{M_{\text{Pl}}} \cos(m_\phi t)$$

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

Kim & GP, last month

- Consider axion model \w $\left(\alpha_s/8\right)\left(a/f\right)\, G\tilde{G}$ coupling, usually searched by magnetometers
- However, spectrum depends on $\theta^2 = (a(t)/f)^2$: $m_\pi^2(\theta) = B\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos\theta}$

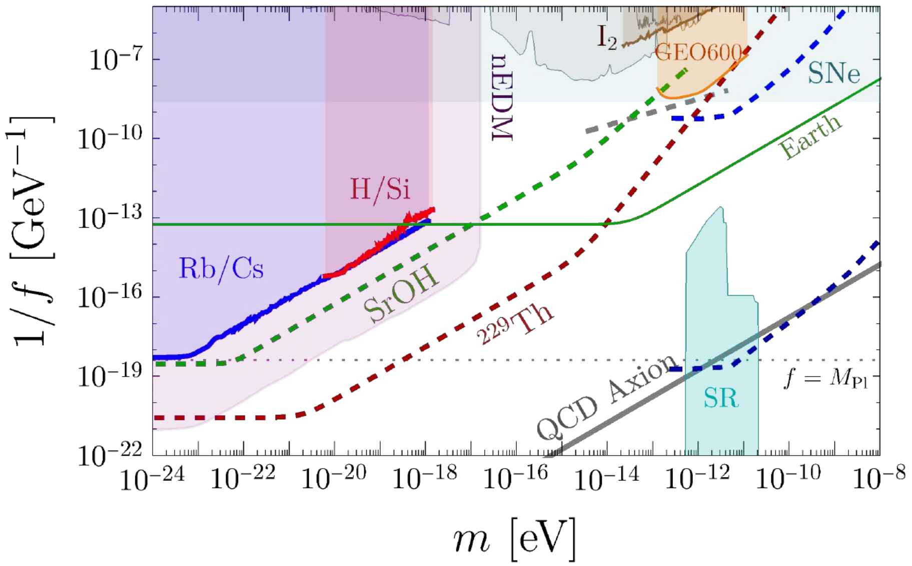
Brower, Chandrasekharanc, Negele & Wiese (03)

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

$$\frac{\delta m_\pi^2}{m_\pi^2} \approx \frac{1}{4}\theta^2$$

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

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



Summary

- Parodaxalic state of particle physics, observation vs vast predictive range
- 2 soft principles to assist, naturalness & quality
- Inspired by Weinberg solution to the CC: new approaches emerges to address the hierarchy problem, they are all questionable …
- New paradigms come with radically different pheno
- Exciting window is now opening because of technological boom of quantum science