— Outlook — Behind and Beyond the Standard Model

Axions++ 2023

LAPTH, Annecy, 28.09.2023

Ch!"*o*#*e Grojean e Grojean*

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Standard Model"

Disclaimer

- ‣ **Organisers**: would you be available to deliver the keynote talk for the axions++ workshop?
- Me: I feel a bit embraced since I'm certainly not an expert on axion physics, despite my interest in the subject. But if you are happy with a broader outlook look, I would certainly be happy to prepare one. Furthermore I won't be able to come to Annecy on the first days of workshop, so I might not be the ideal speaker for the closing talk.

— Starting from the beginning during the summer—

Axions for amateurs

 $\frac{d}{dt}$ n H Anson Hook

 $N_{\rm look}$ increasing are space in the Goldstone field $N_{\rm do}$ Global Symmetries to Axion Physics radial and Axions of complex scalar modes of the explicit calculation of the expli

Primer on Axion Physics

David J. E. Marsh^a

Felix Yu^{*}

TASI Lectures on the Strong CP Problem and Axions on
2308.160
2023

Matthew Reece

Standard Model … ereformations, a strong interactions, a struggle between two theoretical camps \bullet For weak and strong interactions, a strong interactions, a strong interactions, a struggle between two theoretical camps in the struggle between two three two three two terms in the struggle between two terms in the \mathbf{v}

- 1961 S. Glashow *SU*(2)⊗ *U*(1) weak mixing 1901.68 . Shashow $50(2)$ g $0(1)$ weak hiking
- 1967-68 S. Weinberg, A. Salam spontaneous symmetry breaking $1907-00$ B. Wennoeig, T. Balam spontaneous symmetry
- 1971. G. 't Hooft how to renormalise weak interaction $1971. \, \text{G}$. Gardin How to renormalise weak interaction
- 1973. Gargamelle Discovery of neutral weak currents
- $\frac{1072}{2}$ Orientaire Church and $\frac{1}{2}$ • 1973 Quantum Chromodynamics
- 1973 Quantum Chromodynamics (Lecture by F. A. Wilczek) …J/Psi, b, W, Z, top, Higgs discoveries

Standard Model and Beyond Concluding Remarks
 Concluding Remarks

• **The standard model is a wonderful achievement, but obviously incomplete**

BSM is turning 50

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 GUT (Pati-Salam '73, Georgi-Glashow '74)
 SUSY ('71) / MSSM ('77-'81)
o Technicolor ('79)
 Large extra dimension, aka ADD ('98)
 Warped extra dimension, aka RS ('99)
 Composite Higgs ('84-'03)
 Little Higgs ('01)
 Higgsless ('03)
o Relaxion ('15)
 …
```


Not a new story… many (failed?) attempts

If they had been successful, they would be part of the SM…

The LHC Legacy (so far)

SM confirmed to high accuracy up to energies of several TeV

- The remarkable and successful operation of the LHC
- (made possible thanks to technological advancements, accelerator performance, detector resolution, high-performance computing and data handling, as well as higher-order theoretical calculations)
	- … also changed the nature of the LHC itself:
	- ☺ it is not only an exploration machine but it also performs legacy precision measurements, ☺ a multi-messenger experiment on its own.

The LHC as a Precision Machine

The LHC is regularly surprising the community with its ability to deliver **precise measurements**

0.09% precision in Higgs mass determination

The LHC as a Precision Machine

The LHC is regularly surprising the community with its ability to deliver **precise measurements**

This potential for precision measurements relies on a firm **control of experimental systematic uncertainties**.

The systematic uncertainties for a hadron collider experiment depend on a careful evaluation of the **detector performance**, in the challenging pileup environment.

Detector simulations at future hadron collider like FCC-hh in presence of the O(1000) pileup are not reliable enough to make robust statements in the general context of precision studies.

We proved the ability to do precision measurements of the Higgs boson (for rare decays, ttH and self coupling) on the basis of conservative and believable assumptions. But to go beyond this needs a level of sophistication in the simulations, and in the understanding of physics backgrounds, that is not available today.

> We need at least the **HL-LHC** to validate assumptions on the control of backgrounds and systematic errors at **FCC-hh**.

What is the scale of New Physics?

Low Scale Wishes

 $\text{argdetY} \leq 10^{-10}$

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3} {\rm eV}\right)^4$

 $m_H^2 \approx M_{\rm NP}^2 \gg \left(125 \textrm{GeV}\right)^2$

compressed spectra district spectra in the spectra spectra \overline{a} **is the spectra sp** displaced vertices of the set of th 2. can push the frontiers of the unknown. **uncoloured new physics** We know for sure that New Physics exists. We need a broad, versatile and ambitious programme that \mathbf{N} **Relaxion** But no clear indication of the energy scale to probe. 1. will achieve legacy precision measurements, TWO FRONTIERS TO EXPLORE

SM has some structural deficiencies that call for new physics at low scale.

Future Circular Collider

a versatile machine able to perform exquisite measurements at the EW/Higgs/top threshold and to probe both the intensity and energy frontiers

 $CG - Axiomst +$ 9 /30

 $CG - Axiomst+$ 9 /30

Intensity Frontier: Why not → What for?

— multi-vacuua relaxion —

[Graham, Kaplan, Rajendran '15](http://arxiv.org/abs/1504.07551)

 $CG - Axiomst+$ 10 /30

$$
^{1O}/_{\rm 3O}
$$

Intensity Frontier: Why not → What for?

— multi-vacuua relaxion —

 $CG - Axiomst+$ 10 /30

$$
^{1O}/_{\rm 3O}
$$

Energy Frontier might not be the best place to look into

only BSM physics below Λ~107÷9GeV could be in the form of

(very) light and very weakly coupled axion-like scalar fields

$$
m_{\phi} \sim \left(\frac{g \Lambda^5}{f v^2}\right)^{1/2} \sim (10^{-20} - 10^2) \,\text{GeV}
$$

Phenomenological Signatures

oupon a diameter control below \blacksquare ◎ BBN constraints \circ decaying DM signs in γ -rays background ◎ ALPs ◎ superradiance

—interesting cosmology signatures—

اب
ا _◎ relaxion halo around earth/sun which nduc on naio around earth/surf which \parallel ◎ change of atom sizes

—interesting signatures @ Flavour— ◎ production of light scalars by B and K decays [Espinosa et al '15](http://arxiv.org/abs/1506.09217) Flacke et al '16 [Choi and Im '16](http://arxiv.org/abs/arXiv:1610.00680) [Flacke et al '16](http://arxiv.org/abs/arXiv:1610.02025)

Example 21 coupled as interesting atomic physics— \parallel

[Banerjee et al '19](https://inspirehep.net/literature/1721404)

A QFT rationale for light and weakly coupled degrees of freedom

with spectacular signatures across different scales

Phenomenological Signatures

Collider Searches for Light New Physics

- **• LLP searches with displaced vertices**
	- e.g. in twin Higgs models glueballs that mix with the Higgs and decay back to b-quarks

where we have defined ≠¹ © (*m^u* ⁺ *^md*)(*m*≠¹ *^u* ⁺ *^m*≠¹ *^d* ⁺ *^m*≠¹ *^s*), and *Ffi* is the pion decay *F*^{*⊥*} \rightarrow Colliders → short-lived ALPs MeV+ $Astro/Cosmo → long-lived ALPs$ $\overline{\text{colliders}} \rightarrow \text{short-lived ALPs MeV+}$

$$
^{12}/_{30}
$$

origin

non-perturbative

perturbative

non-perturbative?

pseudo Nambu-Goldstone bosons

Physics of Light Degrees of Freedom

light scalars are un-natural in QFT unless they are

How serious is the strong CP problem ? (sorry if trivial)

3 levels of formulating the strong CP problem, *assuming CP is respected by the UV*:

(who knows?)

(not if these are natural/protected and sequestered)

 (iii) $\bar{\theta} = \leq 10^{-10} \ll \theta_{\text{KM}}$, but $\bar{\theta} = \bar{\theta}_{\text{bare}} + \epsilon \theta_{\text{KM}} \ln(\Lambda_{\text{UV}}/M_W)$, is it a problem?

(ϵ appears in 7 loops and contains several other suppression factor) but in the MSSM, θ has 1-loop RG running from the gluino mass phase Should we be more cautious / more generic? [at least till we reach $\mathcal{O}(10^{-16})$ precision] \bigcirc

(i)
$$
\bar{\theta} = \theta - \arg \left[\det \left(Y_u Y_d \right) \right] \lesssim 10^{-10}
$$
, is it a problem?

 $CG - Axiomst+$ 14 /30

$$
(ii) \bar{\theta} = \lesssim 10^{-10} \ll \theta_{\text{KM}} = \arg \left\{ \det \left[Y_u Y_u^{\dagger}, Y_d Y_d^{\dagger} \right] \right\}, \text{ is it a problem?}
$$

 $CG - Axiomst+$ 15/30 in which the ALP field is initially frozen due to the strong Hubble friction, then it starts oscillating

, (3)

Axion Cosmology Axion Cosmology 10100 $\mathbf V$ f' (2*p*)³ ⇣ $\frac{1}{2}$ **Conventional misalignment**

Start with ALP lagrangian
\n
$$
\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_{\mu}\partial_{\nu}\partial_{\nu} - \nu(\phi) = \frac{1}{2}g^{\mu\nu}\partial_{\mu}\partial_{\nu}\partial_{\nu} - m^2(T)f^2\left[1 - \cos\left(\frac{\bf{a}}{f}\right)\right]
$$
\nDefine homogeneous zero-mode
\n
$$
\overline{a}(t) = f\Theta(t)
$$
\nNeglecting fluctuations, it satisfies $\overline{\Theta} + 3H\overline{\Theta} + m_a^2(T) \sin(\Theta) = 0$,
\nWith initial conditions:
\n
$$
\Theta(t_i) = \Theta_i, \underbrace{\bullet \overline{\Theta}(t_i) = 0}_{\bullet}, \underbrace{\bullet \overline{\Theta}(t_i) = 0}_{\bullet}, \underbrace{\bullet \overline{\Theta}(t_i) = 0}_{\bullet}, \underbrace{\bullet \overline{\Theta}(t_i) = 0}_{\bullet}
$$
\n
$$
\Rightarrow m_a \ll 3H \iff \rho_a \propto a^{0} \text{ (Frozen)}
$$
\n
$$
\Rightarrow m_a \gg 3H \iff \rho_a \propto a^{-3} \text{ (Oscillating)}
$$
\n
$$
\Rightarrow \text{standard misalignment mechanism}
$$
\nFor $\Theta_i \sim 1$ $\rho_{DM} \sim \rho_{osc} \left(\frac{a_{osc}}{a_0}\right)^3 \sim m_a^2 f_a^2 \left(\frac{T_0}{T_{osc}}\right)^3$

Axion Cosmology

Conventional misalignement makes too little DM for low f a .

 $CG - Axiomst+$

Axion Cosmology

\blacksquare radial/axion interplay to enlarge DM parameter space

With initial conditions:

energy such that it goes over many barriers before it got studies of the minimum stu $t_{\rm c}$ when the energy of the \sim $t_{\rm c}$ field falls below the height of the barrier: **2004.00629 [Co, Harigaya, Hall'19** [Co, Harigaya, Hall '19](https://indico.in2p3.fr/event/24773/contributions/110241/attachments/71086/100987/Servant_Planck2022.pdf)

I. Field frozen *^H* > *^m*e↵, ⁼ osc ⇢ / *^a*⁰

II. Field oscillation and rotation *^m*e↵ *^H* > osc > > *^f* ⇢ / *^a*³ or *^a*⁴

Delayed axion oscillations !

-> kinetic misalignment mechanism is that the ALP field has a very large initial kinetic method in its set of the ALP field has a very large initial kinetic method in its set of the ALP field has a very large initial kin

[G. Servant @ Planck'22](https://indico.in2p3.fr/event/24773/contributions/110241/attachments/71086/100987/Servant_Planck2022.pdf)

 \circledcirc

Servant

P

Planck'22

- density induced by instanton configurations in the dilute instanton gas approximation has a cosine [minium at θ =0 as expected]
	-

and in equipotically from into anal is deminated by ID (large instantanc) the ζ axion to this non-perturbatively generated vacuum potential, the axion field acquires QCD is asymptotically free: integral is dominated by IR (large instantons)

iotically free. integral is dominated by IR (large instantons)
The tiny axion mass is due to mixing $\frac{m_a}{a}$ $\frac{m_a}{\pi}$ $\frac{m_{\pi}}{m_u}$ $\frac{m_u}{m_d}$ $\mathbf{F}2 \longrightarrow 2\ \mathbf{F}2 \longrightarrow 2\ \mathbf{F}2$ $(m_u + m_d)$ with η' and pion:

 $CG - Axiomst+$ 18/30 Given the integral over the integral over integral once with an infrared with an infrared cutosal cutous phase concernsive in the Cherland concernsive concernsive in the Cherland concernsive concernsive concernsive concern \log_{10} induced by induced by instanton configurations in the direction gas approximation \log_{10} BVBI VINNIQ ADOUL AXION PHYSICS (MASS, COUPINGS TO SIVI...)
Dipole moment $\frac{1}{2}$ **If Nps** ≦ **Ninst all axions heavy** , we know (almost) everything about axion physics
Relation and axions heavy Once we know f_a, we know (almost) everything about axion physics (mass, couplings to SM...)

QCD axion *^L* ⁼ ¹ The only e↵ect on the previous computation is a new factor of *eⁱ* ⇥ (*n*+*n*) in Eq. (19), since the **How come the QCD axion mass is NOT ~ΛQCD**

QCD instantons generate the axion potential $(U(1)_{PQ} \times SU(3)_C²$ anomaly) hence axion physics is fully IR determined $\frac{d}{dt}$ the outlog perfective $\frac{d}{dt}$ (11/4) $\frac{d}{dt}$ CLI(2) 2 over need the sum over $\frac{d}{dt}$ m_0 in m_1 is m_2 in m_3 in m_4 in m_5 in m_6 QCD instantons generate the axion potential (U(1)_{PQ}xSU

GG˜ term integrates to a net topological winding number. Carrying this through, the sum over net **—> "Invisible axion"**

$$
C\;\frac{1}{g^8}\exp\left[-8\pi^2/g^2(\rho)\right]
$$

vacuum energy

yc

 $\frac{1}{2}$

\Rightarrow heavier axion (for fixed f_a)

\rightarrow also alleviates the axion quality problem

\Rightarrow lighter axion (for fixed f_a)

 $C_{\mathcal{G}_{\lambda}}$ (*Axions*++ $\int_{\mathcal{G}} \mathcal{H}_{\lambda}^{2} \hat{H}_{\lambda}^{2} d(\Lambda_{\mathcal{G}} R)^{\frac{1}{2}} \hat{R}^{2} \bar{\theta}^{-3} (\Lambda_{5} R)^{\frac{1}{2}(b_{0}-3)}$ (24) goal: introduce freedom in axion physics while still solving strong CP \hat{p}_{a} controlls, 0,25, a by the rounds to motion). **finagstawoochstee** the othroduction of the SM <u>Fernicions the *i*s and the strategy of the secondary of the secondary of the SM Yukawa couplings and the secondary of the SM Yukawa coupling of the SM Yukawa coupling and th</u> Excrements the T ↵*s*(*MP*) **box 1023 = 7 and including the factor (22), the factor (22), the factor (22), the factor (22), the factor (22)** ? fontvariowf eontqor3,0f25, 0.09.3tbp2500b2tt6tap.to bottom).
ineswfoonMain**ChiAMG@eredicaD**of**(d)DMMMG/SWGh**o**that small instan**t *A* Conservation may all the actings incorporating the concentration contribution of \mathcal{M}_P αs *The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f . The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no E* F ion for the boundary as ermions and popular $\alpha_s(m_Z)$ $=$ I fontvanious eo \pm t $(0$ r $3,0$ 125, \pm 10,3 \pm 0,2 $\frac{5}{6}$ 012) t (ta ψ , to bottom). $% \mathcal{L}$ gre Θ n). d \widehat{d} sthe d rtiene dephes e hitse theprotseitt δ nthof ald i ttion of the 5s ithudi $e \not\equiv$ o \emptyset .5s α . Westinel ∂ r $\tilde{\nu}$ Hebrai $\tilde{\varphi}$ pefo ψ dish α e(n)spienra i ho y ver χ rhi $_B$ q. $=$ masses and *N^f* the number of flavors. However since the fermion masses in the SM arise from a Higgs mechanism, the fermion legislation of the fermion legislation of the fermion diagram diagram diag)
Uttilhällen de de la en men mage hoscas antra eta de de antra normana $\frac{1}{2}$ s of $\frac{1}{2}$ and $\frac{1}{2}$ a \mathcal{H} y_s 295 *yt* थू# *yb* 4π $\frac{96.48}{47.27}$ $\frac{96.40}{10}$ \approx 10⁻²³¹⁶⁵ cading to $\frac{22}{22}$
 $\frac{1}{47.27}$ \approx 10⁻²³¹⁶⁵ cading to $\frac{22}{22}$ white a that was introduction when you are the SM introduction of the SM introduction of the international state Diguin mass long tion that an energy contribution can be under the unit of personal **a, A, A, A, A, A, A, A, A, A, A**
de la de la de la de la de la de $\left(\sqrt{\frac{2}{n}}\frac{a}{w}\frac{a}{b}\frac{f}{w}\frac{f}{d}\right)$ $\frac{1}{2}$ $\begin{array}{lllll}\n\frac{\sqrt{2}}{4} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4}$ $\frac{32.519}{100}$ $\frac{3}{100}$ $\frac{2}{10}$ $\frac{1}{100}$.]
ข้ .
R $\frac{n_d}{2}$ $\frac{1}{2}$ $\sqrt{\frac{\alpha}{\alpha_s(1)}}$ ↵*s*(1*/R*) ⇤5*^R*) $\frac{1}{2}$, $\frac{1}{2}$, masses and *N^f* the number of flavors. However since the fermion masses in the SM arise \mathcal{S} s from the ATM with \mathcal{G} on T and \mathcal{S} the Yukawa coupling and loop T and \mathcal{S} and T *^f* ⁼ *^u*4⇡ *d* 4π *yc* ∄ች *ys* % *yt* $\frac{1}{2}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{2}$ $\frac{1}{3}$ $\frac{1}{2}$ as well as in our 5D model. Thus the *yb* white attawation sthese they defind the most seed into the SM fermions the hvertin mass low-energy contribution can be underground from QCD chiral contribution can be underground from QCD chiral \mathbb{L} perturbation to be \mathbb{L} $\frac{1}{2}$ *a,QCD* ⁼ *^mum^d m*² ⇡*f* ² ⇡ axion mass low-energy contribution can be unambiguously determined from QCD chiral suppression is only proportional to the Yukawa couplings and loop factors, namely: suppression is only proportional to the Yukawa couplings and loop factors, namely: axion mass low-energy contribution can be unambiguously determined from QCD chiral $(p\hbar\omega_{\bm{y_b}} + m_d)^2$ $\frac{643\pi^{10}F}{f^2}$, $\frac{3648544F}{f^2}$ **Dime** 2*fC*[3] \bar{d} $\partial_{\rm M}^3$ (m_1^1 + m_2^2) $\frac{1}{1}$ *e* $\frac{1}{2}$ $\frac{2\pi}{2}$ $\frac{1182\pi}{\alpha_s(1)}$ $\frac{\Pi 22\pi\Pi E}{\alpha s(1/R)}$ $\frac{24}{\sqrt{25}}$ $\frac{24}{\sqrt{25}}$ $\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ ($\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ $\frac{24}{\sqrt{24}}$ α *numerical integration of (8) and no* ℓ ermion)s clibe spectrum proposed of ℓ experience the addition of the $h_{\text{eff}}(l_0, g_0) = 25$, 0.2 , $d_{\text{eff}}(l_0, g_0) = 0.52$, 0.000 , 0.000 , 0.000 , 0.000 , l_0 **Maarthestraigue végenitőon megségyűgytága a száz**bbe SM anise
1990-249 – Magyar Holley opera a százon a csapang törög a százon száz masses and number of the number of flavors. However the first of flavors. How the SM arise program a Higgs mechanism and the fermion of the fermion of the fermion of the closed $\mathcal{X} \to \mathcal{Y}$, \mathcal{Y} is \mathcal{Y} , \mathcal{Y} is \mathcal{Y} , the ingredients leading to the enhancement The Thing Chiange Leghlining Cauge C **f** $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\mathcal{A}\mathbf{\widetilde{g}}$ *yd* 4⇡ *yc* 4⇡ *ys* 4⇡ *yt* 獬 *yb* (新) $\frac{11}{10}$ **, (22) And All And All Act 1/2/20** $(\sqrt[q]{2}^{\prime}a$ of $\mathbb{Q}^{\prime}a$ *m*² *<u>MAY MYSERUSUSE LESSING</u>(LID) WILLERS)
MAIL CREATION COMPLETE VIOLTED 22019* where *m*⇡ ' 135 MeV, *f*⇡ ' 92 MeV, and *mu/m^d* ' 0*.*46. Using the result (10) with ²*fC*[3] ✓ ²⇡ ~ 2 (200⁻³) $\frac{1}{4}$ $\frac{1}{2}$ $\frac{$ nagamum ennan tement, in **enes strony coupeng einer as**
stanienis insteam pont einer stand texte strony aanderstelderden b *higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* masses and *NAS is the number of flavors of flavors* of the SM ferring. Higgin Langua dia Higgs mechanism and the fell of head of the Leading one of the ingredients leading to the enhancement Modes Rive 20th 5D model. Thu Miring Convolte $\frac{f(x)}{f}$ $4\overline{\pi}$ *yd* $A\pi$ *yc* $4\vec{x}$ *ys yt* $\tilde{\bar y}_b$ **where you are the source of the introduction of the internet of the internet feature. We are interested that t** α can be unambiguously determined from QCD chiral *^f* ² *,* (23) 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom).* 52 (m. 47) *for Jakes alguner (Tomres)*
1824 - Havdre Britan eskilar en bester alguner *The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* from a Higgs mechanism, the fermion legislation in an instanton value of the fermion of the federal began began ϵ G κ in ϵ and ϵ and ϵ the ingredients leading to the enhancements leading to the enhancement of the end $\frac{3\mu}{4} \frac{9\mu}{4} \frac{9\mu}{4} \frac{3}{4}$ where you are the settlement of the SM Yukawa couplings. axion can be una successive una determined from Quan be una *The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be considered and the constant of menhancement in the strong α . This is one of the ingre *,* (22) Leve one of the engregicity reading to the empleement **for a community of the community of the form (10)** With 23) $\lim_{k\to\infty} \frac{1}{4} \left(\lim_{k\to\infty} \frac{1}{k^2} \sum_{k=1}^{n} \frac{1}{k^2} \right)$ $\overline{\int C_{\epsilon} G_{\epsilon} \tau}$ **Instant**
E G I F T
L G I F T • color scalars extra-dimension der af 24. 256 as well, as in our 5D friddel. Thus the
The Museum GelGe highlight G.Gaugel Group De Elored
Buffer burthers Gell (3)CeB $m_a^2 f_a^2 = m_{\pi}^2 f_{\pi}^2$ [Dimopoulos++ '16](https://arxiv.org/abs/1606.03097) [Agrawal+ '17](https://arxiv.org/abs/1710.04213) [Hook '18](http://arxiv.org/abs/1802.10093) [Gavela++ '23](https://arxiv.org/abs/1606.03097)

QCD axion model building

 $\frac{1}{2}$

0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom).*

The solid lines are the exact results obtained from a numerical integration of (8) and no

*higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the*

*higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line.*

*The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .*

masses and *N^f* the number of flavors. However since the fermion masses in the SM arise

from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed

with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement

of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the

*The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the* $\overline{}$ **NEW EXPERIMENTAL FRONTIER**

suppression is only proportional to the Yukawa couplings and loop factors, namely:

0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom).*

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suppression is only proportional to the Yukawa couplings and loop factors, namely:

ys

yt

yb

Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) =

 \bigcup masses and *N^f* the number of flavors. However since the fermion masses in the SM arise from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement of *higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* axion searches through GW observation (see lecture by Valerie)

Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) = 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom).*

 $CG = \sqrt{\frac{1}{2\pi\sqrt{2}}\pi^2\ln 5 + \frac{1}{2\pi}\sqrt{\frac{2\pi}{\pi^2}}\sqrt{(\log R)^2\pi^2}}$ ($\sqrt{\log R}\sqrt[3]{\frac{1}{2}}$ $\sqrt[3]{\frac{1}{2}}$ $(\frac{6-1}{2\pi})$ (24) $\frac{1}{2}$ (*b*₀-3) $\frac{1}{2}$ (*b*₀-3) $\frac{1}{2}$ (*b*₀-3) $\frac{1}{2}$ (*b*₀-3) $\frac{1}{2}$ (*b*₀-3) $\frac{1}{2}$ 2*fC*[3] $\sqrt{2}G_0\sqrt{4\pi\omega n}$ 5++ $\sqrt{mR\pi a}(\sqrt{mR\pi^2})^{\frac{1}{2}(b_0-3)}$ (24) ²*fC*[3] ✓ ²⇡ ~ 2 (*n*_t π ^{*i*}) $\frac{1}{2}$ π (*n*_i) $\frac{1}{2}$ R^{2} π (*n*_i) $\frac{1}{2}$ π (*n*_i) *^f* ² *,* (23) *m*² $\overline{\int C_{\epsilon} G_{\epsilon} \tau}$

The solid lines are the exact results obtained from a numerical integration of (8) and no

*higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the*

*higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line.*

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from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed

with a Higgs loop Figure 2. This is one of the ingredients leading to the ingredients leading to the enhancement

QCD axion model building

 $\overline{}$. Change $\overline{}$ running such that small instantons can contribute that small instantons can contribute

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Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) = 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no*

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with a Higgs loop Figure 2.

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• change confining gauge group

QCD axion model building

WARNING

 $0 \times \infty$ can be finite. as
م masses and N_affermion masses in the since the flavors. However since the SM aris from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the suppression is only proportional to the Yukawa couplings and loop factors, namely: from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement of of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the suppression is only proportional to the Yukawa couplings and loop factors, namely: *higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line.* all you can be a we a masses and *N^f* the number of flavors. However since the fermion masses in the SM arise 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line.* Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) = 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* all (but one if we are lucky) these experiments won't find anything! Incarnation of Pascal's bet:

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Extra color scalars ← freezing as at the TeV scalars ← freezing as at the TeV scalars ← freezing as at the TeV
TeV scalars ← freezing as at the TeV scalars ← freezing as at the TeV scalars ← freezing as at the TeV scalars

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*m*² ⇡*f* ² ⇡

^f ² *,* (23)

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a,QCD ⁼ *^mum^d*

(*m^u* + *md*)²

axion mass low-energy contribution can be unambiguously determined from QCD chiral chiral chiral chiral chiral

*m*² ⇡*f* ² ⇡

^f ² *,* (23)

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f superra **Paramation Superradiance** is an
are the SM Yuperradiance is an (but [I won't talk a](https://arxiv.org/abs/1710.04213)[bout it today\)](http://arxiv.org/abs/1802.10093). axions are also a laborat *E* axions are a
How global sv *The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* masses and *N^f* the number of flavors. However since the fermion masses in the SM arise from a Higgs mechanism, the fermion diagram can be closed in an instanton legs in an instanton l with a Higgs loop \mathcal{F}_1 is one of the ingredients leading to the enhancements leading to the enhancement of axion mass in the 4D models of $[2, 2, 2]$, as well as well as α suppression is only proportional to the Yukawa couplings and loop factors, namely: axion mass low-energy contribution can be unambiguously determined from QCD chiral *The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* masses and *N^f* the number of flavors. However since the fermion masses in the SM arise with a Higgs loop \mathcal{L} is one of the ingredients leading to the enhancement of the enhancements leading to the enhancement of the end of the axions are also a laboratory of **Quantum Gravity**. axion mass low-energy contribution can be unambiguously determined from QCD chiral chiral chiral chiral chiral T **The solution obveice is a numerical integration** Axion physics is a playground to learn about non-perturbative QFT physics *higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* masses and *N^f* the number of flavors. However since the fermion masses in the SM arise with a Higgs loop \mathcal{A} is one of the ingredients leading to the enhancements leading to the enhancement of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the \mathbf{S} suppression is only proportional to the Yukawa coupling and loop \mathbf{S} \sim *,* (22) where *yu,d,c,s,t,b* are the SM Yukawa couplings. With the introduction of fermions the Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) = 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* How global symmetries are broken by gravitational effects? masses and **N** α the superradiance from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) = 0*.*118*), as a function of* 1*/R for various contours of* ✏ = (0*.*3*,* 0*.*25*,* 0*.*2) *(top to bottom). The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* end **Superradiance** is and **Superradiance** is and from a Higgs in an instanton legs in an instanton vacuum diagram can be closed in an instanton vacuum diagram c with a Higgs loop FIGURE?. This is one of the ingredients leading the ingredients leading to the enhancement of axion mass in the 4D moose models of [24, 25], as well as in our 5D model. Thus the *The solid lines are the exact results obtained from a numerical integration of (8) and no higher dimension terms (c*⁶ = 0*). The green dashed line represents the addition of the higher dimension term (11) with c*⁶ = 0*.*5 *and* ✏ = 0*.*52 (0*.*47) *for the upper (lower) line. The red line depicts the maximum enhancement in the strong coupling limit using ma,*5*^f .* masses and *N^f* the number of flavors. However since the fermion masses in the SM arise from a Higgs mechanism, the fermion legs in an instanton vacuum diagram can be closed with a Higgs loop Figure 2. of axion mass in the 4D models of $[24, 25]$ suppression is only proportional to the Yukawa couplings and loop factors, namely: *,* (22) where *yu,d,c,s,t,b* are the SM Yukawa couplings. With the introduction of fermions the • SU(3) ϵ in the first place, \sim also alleviates the axion quality problem \sim (confinement, anomaly, instantons...). But, relying on (approximate) global symmetries in the first place, Axion quality problem! **Superradiance** is another fascinating effect connecting axion and gravity

suppression is only proportional to the Yukawa couplings and loop factors, namely:

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Figure 3: *The axion mass ratio for the boundary fermions case (assuming* ↵*s*(*mZ*) =

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axion mass low-energy contribution can be unambiguously determined from QCD chiral

[Dimopoulos++ '16](https://arxiv.org/abs/1606.03097)

QCD axion model building

 \sim change \sim change \sim change \sim changes can contribute such that small instantons can contribute such that small instantons can contribute such that small instantons can contribute such a small instanton of \sim

Particle Physics & Quantum Gravity

Can the SM be embedded in a theory of quantum gravity at the Planck scale? Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**

This conjecture has potentially far-reaching implications for phenomenology.

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Landscape/Swampland Conjectures

1) No exact global symmetry [For a review, see Banks, Seiberg '10](http://arxiv.org/abs/arXiv:1011.5120)

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that: $M/M_P < g$. q

2) Gravity is the weakest force

[Arkani-Hamed, Motl, Nicolis, Vafa '06](http://arxiv.org/abs/hep-th/0601001)

Why? otherwise extremal charged BH cannot decay!

BH can decay iff $M_1 + M_2 < M$, i.e. $M_1 < M_2 = Q - q_2 = q_1$

Black-holes decay without memory of global charges

Swampland Conjectures

3) $M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel > cV(\phi_i)$ with c is O(1) for any field configuration

at least one of them is as small as \sim $(10^{-3} \,\text{eV})^4$ $\frac{(10-{\rm eV})}{(100\,{\rm GeV})^4} \sim 10^{-56}$

[Obied, Ooguri, Spodyneiko, Vafa '18](http://arxiv.org/abs/hep-th/0601001)

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden
- Quintessence: [Agrawal, Obied, Steinhart, Rafa '18](http://arxiv.org/abs/1806.09718)

 Higgs-quintessence coupling \Rightarrow 5th force signal

at least one of them is as small as $(10^{-3} \,\text{eV})^4$ $\frac{(10-{\rm eV})}{(200\, {\rm MeV})^4} \sim 10^{-44}$

$$
^{\kappa \phi /M_P} \left(V(H) + \Lambda_{cc}^4 \right)
$$

Swampland Conjectures

⇤⁴ + *V*⁰

 $\overline{\mathbf{a}}$ ⇤⁴ + *v*⁴ + *V*⁰ UV enforces interactions among IR degrees of freedom, ⇤⁴ @(*H* = *v,* = 0) *O* on IR EW⁴ ⇠ like anomaly conditions enforce constraints on IR physics. \sim \equiv But non-trivial interactions among seemingly decoupled sectors must exist: [Denef, Hebecker, Wrase '18](http://arxiv.org/abs/arXiv:1807.06581) *V* (*i*) like anomaly conditions enforce constraints on IR physics. Higgs-quintessence It is not that String Theory rules out the SM as we know it.

New Perspectives on BSM

1. The more rigorous the conjecture, the less powerful for BSM. 2. Assumptions are required, so you need new predictions.

@ Swamplandia '23 [N. Craig @ Swamplandia '23](https://eventos.uam.es/file_manager/getFile/145952.html)Craig $\overline{\mathbf{N}}$.

Two rules of thumb for applying SCs to BSM:

Festina Lente: Electron mass forbids $\rho_{\Lambda} \gtrsim 10^{-90} M_{\rm Pl}^4$ [Montero, Van Riet, Venken '19]

Your Idea Here

Your Idea Here

No Global Symmetries: Breaking of Chern-Weil symmetries favors highquality axions [Heidenreich, McNamara, Montero, Reece, Rudelius, Valenzuela '20]

New Perspectives on BSM

RdSC: Quark masses constrained by metastable vacua [March-Russell, Petrossian-Byrne '20]

Your Idea Here

Non-SUSY AdS Vacua, AdS distance conjecture:

Neutrino masses bounded by vacuum energy [Ibáñez, Martín-Lozano, Valenzuela '17; Gonzalo, Ibáñez, Valenzuela '21]

axion field redefinitions field redefinitions field redefinitions for $\frac{1}{2}$ $\$ (27 CP-even and 25 CP-odd couplings)

 $(27$ CP-even and 25 CP-odd couplings)

What is the nower counting of these new couplings? What are the conditions to recover a shift-symmetry? where a set of equations can be solved (we will review this approach in more details) and α **What is the power counting of these new couplings? What are the conditions to recover a shift-symmetry?**

Axion/ALP Power Counting **Axion/ALP=Goldstone boson → shift-symmetry** $\mathsf{AXION}/\mathsf{ALP}{=}\mathsf{Goldstone}\ \mathsf{D}{\mathsf{oson}}\ \to\ \mathsf{Shitt}\text{-}\mathsf{symmetry}$ shift-invariant couplings of an axion, and to \mathbf{z} and to \mathbf{z} the deviations from such conditions. The common and common and common is the first part of the first part of the should be able to the shock part o ϵ and ϵ interactions using the following the following ϵ $r_{\rm max} =$ can contain to all particles of the SM in all the SM in all the SM in all the Ways compatible with the SM in a Therefore, in a bottom-up approach, their couplings are essentially free parameters, up to $\bm{\mathsf{Axion/ALP=}Golds}$ constraint in $\bm{\mathsf{Axi}}$ shift-symmetry

$$
a \rightarrow a + \epsilon f \qquad \qquad \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial_{\mu} a) (\partial^{\mu} a) + \frac{\partial_{\mu} a}{f} \sum_{\psi \in \text{SM}} \bar{\psi} c_{\psi} \gamma^{\mu} \psi + \mathcal{O}\left(\frac{1}{f^2}\right)
$$

But shift-symmetry cannot be exact (PQ as approximate symmetry) Fracture and we couplings of all the tarter (sort) breaking of sime symmetry:
1 matrices in flavor space. The Lagrangian of Eq. (1.3) makes the axion shift symmetry shift symmetry shift symmetry shift symmetry shift symmetry shift symmetry symmetry symmetry symmetry symmetry symmetry symmetry symmetr What are the allowed couplings of an ALP after (soft) breaking of shift-symmetry? But shift-symmetry cannot be exact (PQ as approximate symmetry)

$$
\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} \left(\partial_{\mu} a \right) \left(\partial^{\mu} a \right) - \frac{a}{f} \left(\bar{Q} \tilde{Y}_{u} \tilde{H} u + \bar{Q} \tilde{Y}_{d} H d + \bar{L} \tilde{Y}_{e} H e + \text{h.c.} \right)
$$

 v_{as} for definition matrices hermitian matrices (26 CP-even and 13 CP-odd couplings) EFTs, with a focus on the breaking of axion shift-invariance due to the axion couplings to

$$
\frac{\tilde{Y}_e}{H}e + \text{h.c.}
$$

-
-
-

SM [56, 57] instead of scanning possible field redefinitions which absorb unphysical complex

\tilde{V} is $\tilde{V} = i(V e - e_{\tilde{V}} V)$

ALP Shift-Invariance Conditions T and T and T are shown is the first part of the \sim **ALP Shift-Invariance Conditions** $E_{\rm eff}$ shift-invariance due to the breaking of axion shift-invariance due to the axion coupling to the axion coupling to the axion shift-invariance due to the axion coupling to the axion coupling to the axion coupling t leading-order couplings of a light pseudoscalar *a* to SM fermions, namely rephasings can be again used to remove two phases3. Furthermore, there exists a freedom in the derivative basis, associated to the addition of the operator @*µaJµ*, for any conserved

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \left(\partial_{\mu} a \right) \left(\partial^{\mu} a \right) + \frac{\partial_{\mu} a}{f} \sum_{\psi \in \text{SM}} \bar{\psi} c_{\psi} \gamma^{\mu} \psi + \mathcal{O} \left(\frac{1}{f^2} \right) \qquad \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \left(\partial_{\mu} a \right) \left(\partial^{\mu} a \right) - \frac{a}{f} \left(\bar{Q} \tilde{Y}_{u} \tilde{H} u + \bar{Q} \tilde{Y}_{d} H d + \bar{L} \tilde{Y}_{e} H e + \text{h.c.} \right)
$$
\n
$$
\tilde{Y}_{u,d} = i \left(Y_{u,d} c_{u,d} - c_{Q} Y_{u,d} \right) , \qquad \tilde{Y}_{e} = i \left(Y_{e} c_{e} - c_{L} Y_{e} \right)
$$

Conversely what are the conditions on the couplings of Conversely, what are the conditions on the couplings of a pseudo-scalar to recover shift-invariance?

parameters of the breaking of the axion shift symmetry. $\frac{1}{10}$ conditions of FS to footed a similar for $\frac{1}{10}$ 13 conditions on Y's to recover a shift symmetry (1 CP-even and 12 CP-odd) symmetries in the lepton sector, one can remove one diagonal entry of either *cQ, c^u* and

–4–

ALP Shift Invariance *Ye, Y*˜*^e* 1 1 1 3 ¯3

The conditions for shift-symmetry can be written in an invariant way Table 2: Flavor transformation properties of the Yukawa matrices treated as spurions

In a flavor-invariant language, the constraints on *Y*˜*^e* read **• Lepton sector** For *x* = *u, d, e* and *n* = 0*,* 1*,* 2, these equations correspond to the diagonal constraints we

4 entangled conditions between up and down sectors \Rightarrow collective nature the constraints are non-degenerate. Instead, the r.h.s. of Eq. (2.3) is invariant the r.h.s. of Eq. (2.3) is i *Igled conditions* we continue continue that the continues of
Allegative continues of the continues of t

\n- \n**Quark sector**\n
$$
I_u^{(1)} = \text{Re Tr}\left(\tilde{Y}_u Y_u^\dagger\right), \qquad I_u^{(2)} = \text{Re Tr}\left(X_u \tilde{Y}_u Y_u^\dagger\right), \qquad I_u^{(3)} = \text{Re Tr}\left(X_u^2 \tilde{Y}_u Y_u^\dagger\right),
$$
\n
$$
I_d^{(1)} = \text{Re Tr}\left(\tilde{Y}_d Y_d^\dagger\right), \qquad I_d^{(2)} = \text{Re Tr}\left(X_d \tilde{Y}_d Y_d^\dagger\right), \qquad I_d^{(3)} = \text{Re Tr}\left(X_d^2 \tilde{Y}_d Y_d^\dagger\right),
$$
\n
$$
I_{ud}^{(1)} = \text{Re Tr}\left(X_d \tilde{Y}_u Y_u^\dagger + X_u \tilde{Y}_d Y_d^\dagger\right),
$$
\n
$$
I_{ud,ud}^{(2)} = \text{Re Tr}\left(X_u^2 \tilde{Y}_d Y_d^\dagger + \{X_u, X_d\} \tilde{Y}_u Y_u^\dagger\right),
$$
\n
$$
I_{ud,d}^{(3)} = \text{Re Tr}\left(X_d^2 \tilde{Y}_u Y_u^\dagger + \{X_u, X_d\} \tilde{Y}_d Y_d^\dagger\right),
$$
\n
$$
I_{ud}^{(4)} = \text{Im Tr}\left(\left[X_u, X_d\right]^2 \left(\left[X_d, \tilde{Y}_u Y_u^\dagger\right] - \left[X_u, \tilde{Y}_d Y_d^\dagger\right]\right)\right)
$$
\n
\n

one algebraic relation \Rightarrow only 10 independent invariants

13 flavour invariants all linear in Y's (note that CP ensures that 13 flavour invariants all linear in Y's (note that CP ensures that all but *I*⁽⁴⁾ vanish)

$X_x = Y_x Y_x^{\dagger}$ $\frac{1}{x}$ and $\frac{1}{x}$

Eventually, we consider the following set of flavor-invariants, linear in *Y*˜*u,d,e*, **• Quark sector**

$$
\operatorname{Re} \operatorname{Tr} \left(X_e^{0,1,2} \tilde{Y}_e Y_e^{\dagger} \right) = 0 \qquad \qquad \text{3 invariants}
$$

ALP Shift Invariance *Ye, Y*˜*^e* 1 1 1 3 ¯3

er 22, we also repeated the *X*^{*u*} These invariants define sum-rules \parallel invariant expression is important for our purpose, and function in the flavor \parallel \parallel They need to be tested to establish the ALP nature of a new light scalar. \parallel *^u*) *, I*(2) T hese invariants define sum-rules among ALP couplings to quarks and leptons. **• Quark sector** ⁴The r.h.s. of Eq. (2.8) is invariant under *^cQ,u,d* [→] *^cQ,u,d* ⁺ ↵**1**, so that only differences between the diagonal entries of *c^Q* can contribute. In Eq. (2.12), the invariance under *c^Q* → *c^Q* + ↵**1** is ensured by CKM unitarity. Here **1** corresponds to the only matrix which commutes with both *Y^u* and *Y^d* in the case where the quark masses and the CKM entries are non-degenerate. Instead, the r.h.s. of Eq. (2.3) is invariant *caldl,* \parallel

I \equiv

ud,u ⁼ Re Tr (*X*²

u Y˜ *^d^Y* †

^d + {*X*

u, Xd}*Y*˜

u Y † *^u*) *,*

(2.18)

between up and down sectors and down sectors are also between up and down sectors.

non-degenerate, we have *M^e* = diag (*me,i* ∈ **R**) in the flavor basis where *Y^e* is diagonal, which explains why

RG Invariance ˙ *I*(1) *^e* ⁼ ²*eI*(1) *^e* ⁺ ⁶*I*(2) *^e* ⁺ 2 Tr(*Xe*) (*I*(1) ˙ *I*(2) *^e* ⁼ ⁴*eI*(2) *^e* ⁺ ⁹*I*(3) *^e* ⁺ 2 Tr(*X*² nvariaı ˙ (2) (2) ′ *ud,u* = (4*^u* + 2*d*)*I ud,u* + 3*I ^u* − 6*I* DC Inuo 4.1 Renormalization group running above the electroweak scale scale scale $\overline{\Omega}$ \blacksquare *^u* ⁼ ⁴*uI*(2) *^u* ⁺ ⁹*I*(3) *^u* − 3*I ud,u* [−] 2 Tr(*X*² <u>unvariance</u>

The set of invariants is closed under RG ˙ *I* (2) *ud,u* = (4*^u* ˙ (2) *ud,d* = (4*^d* + 2*u*)*I* To verify the completeness of our set of invariants, we can calculate their RG evolution The set of invariants is closed. Using the components is the components of the components of the components of the components of the components. The complete the components of the compo J under $D C$ invariants y riants is closed under RG

- γ_e = $-\frac{15}{4} g_1^2 \frac{9}{4} g_2^2 + \text{Tr} \left(X_e + 3 (X_u + X_d) \right).$ $\frac{17}{2}$ $\frac{9}{2}$ $\frac{9}{2}$ $\frac{2}{2}$ $\frac{17}{2}$ $\frac{26}{2}$ $\frac{27}{2}$ $\frac{17}{2}$ $\gamma_u \equiv -\frac{17}{12}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2 + \text{Tr}(X_e + 3(X_u + X_d))$ $\alpha = \frac{5}{a^2} - \frac{9}{a^2} - \frac{9}{8a^2} + \text{Tr}(Y + 3(Y + Y))$ $\left(\frac{1}{u} \right)$, $\left(\frac{1}{u} \right)$, $\left(\frac{1}{u} \right)$, the Cayley-Hamilton theorem has the Cayley-Hamilton theorem has the $\frac{1}{u}$, the Cayley-Hamilton theorem has the $\frac{1}{u}$, the Cayley-Hamilton theorem has the Cayley-H $\gamma_e = -\frac{15}{4}g_1^2 - \frac{9}{4}g_2^2 + \text{Tr}(X_e + 3(X_u + X_d))$ $\gamma_d \equiv -\frac{5}{12}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2 + \text{Tr}(X_e + 3(X_u + X_d))$ $\gamma_u \equiv -\tfrac{17}{12} g_1^2 - \tfrac{9}{4} g_2^2 - 8 g_3^2 + \text{Tr}\big(X_e + 3(X_u + X_d)\big)$ *u d*(*<i>u I***^{***i***}** *I***^{***l***})** $= -\frac{16}{4}g_1^2 - \frac{9}{4}g_2^2 + 1r(X_e + 3(X_u + X_d))$ *ud* = 6 (*^u* + *^d* + where $\frac{u}{2}$ ⇒ $\frac{1}{2}$ = 177 $\frac{u}{2}$ = 177 $\frac{u}{2}$ = 177 $\frac{1}{2}$ = $8g_3^2 + \text{Tr}(X_e + 3(X_u + X_d))$. (4) *^u , I*(4) $-\frac{5}{12}q_1^2 - \frac{9}{4}q_2^2 - 8q_3^2 + \text{Tr}(X_e + 3(X_u + X_d))$
	-
	-

\overline{a} T_d ^o)($T_u^{(1)} + T_d^{(2)}$). Shiit-invariance conditions are closed under RG *u* + *I ^d* , $U_u^{(1)} + I_d^{(1)}$). Shift-invariance conditions are closed under RG as can be seen in Eq. (4.4). Therefore, the RG evolution will not only generate *I* riance conditions are closed under RG $T^{(1)}$, $T^{(1)}$ and $T^{(1)}$ and the full rank transfer matrix and the full rank transfer matrix $T^{(1)}$ and $T^{$ shift-invariance conditions are closed under RG and *I ^d* which evolve by themselves under RG flow

$$
I_{\mu}^{(1)} = 2\gamma_{\mu}I_{\mu}^{(2)} + 2\text{Tr}(X_{c})\left(I_{\mu}^{(1)} + 3(I_{\mu}^{(1)} - I_{\mu}^{(1)})\right), \qquad \gamma_{\mu} = -\frac{15}{4}g_{1}^{2} - \frac{9}{4}g_{2}^{2} + \text{Tr}(X_{e} + 3(X_{u} + X_{d}))
$$
\n
$$
I_{\mu}^{(2)} = 4\gamma_{\mu}I_{\mu}^{(2)} + 9I_{\mu}^{(3)} + 2\text{Tr}(X_{c}^{2})\left(I_{\mu}^{(1)} + 3(I_{\mu}^{(1)} - I_{\mu}^{(1)})\right), \qquad \gamma_{\mu} = -\frac{17}{12}g_{1}^{2} - \frac{9}{4}g_{2}^{2} - 8g_{3}^{2} + \text{Tr}(X_{e} + 3(X_{u} + X_{d}))
$$
\n
$$
I_{\mu}^{(1)} = 2\gamma_{\mu}I_{\mu}^{(1)} + 6I_{\mu}^{(2)} - 3\frac{1}{2}d_{\mu} - 2\text{Tr}(X_{u})\left(I_{\mu}^{(1)} + 3(I_{\mu}^{(1)} - I_{\mu}^{(1)})\right), \qquad \gamma_{\mu} = -\frac{17}{12}g_{1}^{2} - \frac{9}{4}g_{2}^{2} - 8g_{3}^{2} + \text{Tr}(X_{e} + 3(X_{u} + X_{d}))
$$
\n
$$
I_{\mu}^{(2)} = 4\gamma_{\mu}I_{\mu}^{(2)} + 9I_{\mu}^{(3)} - 3I_{\mu}^{(4)} - 2\text{Tr}(X_{u}^{3})\left(I_{\mu}^{(1)} + 3(I_{\mu}^{(1)} - I_{\mu}^{(1)})\right), \qquad \qquad \text{closed set except for:}
$$
\n
$$
I_{\mu}^{(2)} = 4\gamma_{\mu}I_{\mu}^{(2)} + 9I_{\mu}^{(3)} - 3I_{\mu}^{(4)} - 2\text{Tr}(X_{u}^{3})\left(I_{\mu}^{(1)} + 3(I_{\mu}^{(1)} - I_{\mu}^{(1)})\right), \qquad \qquad \qquad \qquad \text{closed set except for:}
$$
\

- $\{X_{d}X_{u} + \{X_{d}, X_{u}^{2}\}\}\tilde{Y}_{u}Y_{u}^{\dagger} + X_{u}^{3}\tilde{Y}_{d}Y_{d}^{\dagger}\}$ *u,d* in terms of invariants in the set, see App. A.2. \mathcal{I}_u = Re If $\left(\left(\Lambda_u \Lambda_d \Lambda_u + \left\{ \Lambda_d, \Lambda_u \right\} \right) \right) \mathcal{I}_u \mathcal{I}_u + \Lambda_u \mathcal{I}_d \mathcal{I}_d$ $\frac{\partial}{\partial t} Y_e Y_e$ if invariant axion. For details on the coupling invariant axion. For details on the coupling on the coupling on the coupling of $Y_e Y_e$ is a shift invariant axion. For details on the coupling of $Y_e Y_e$ is a $d_{\text{Tr}}((X, Y, Y + \mathcal{F} X, Y^2)) \tilde{V} V^{\dagger} + X^3 \tilde{V} V^{\dagger})$ We also want to highlight the form of the RGE of the CP even invariant *I* e^{τ}) is not independent from the invariant e $\mathbf{W}_u = \text{Re Tr} \left(\left(X_u X_d X_u + \{ X_d, X_u^2 \} \right) \tilde{Y}_u Y_u^\dagger + X_u^3 \tilde{Y}_d Y_d^\dagger \right)$ defined and can be defined and can be defined and can be defined and can be defined in the same way as a same way as α
- $T(t)$ $T(t)$) are actually inical compliations of our original set **¹** ((Tr*A*)³ [−] 3 Tr*A*² Tr*^A* ⁺ 2 Tr*A*3) (4.2) are actually linear combinations of our original set

$$
\begin{aligned}\n\begin{aligned}\n\begin{bmatrix}\n1 \\
\end{bmatrix}\n\end{aligned}\n\end{aligned}\n\begin{aligned}\n\begin{bmatrix}\n1 \\
\end{bmatrix} \\
\end{aligned}\n\end{aligned}
$$
\n
$$
\begin{aligned}\nI_{e}^{(4)} &= \text{Re Tr}\left(X_{e}^{3}\tilde{Y}_{e}Y_{e}^{\dagger}\right) \\
\begin{bmatrix}\nI_{u}^{(1)} \\
\end{bmatrix}, \\
\begin{bmatrix}\nI_{u}^{(1)} \\
\end{bmatrix} &= \text{Re Tr}\left((X_{u}X_{d}X_{u} + \{X_{d}, X_{u}^{2}\})\tilde{Y}_{u}Y_{u}^{\dagger} + X_{u}^{3}\tilde{Y}_{d}Y_{d}^{\dagger}\right) \\
\begin{bmatrix}\nI_{d}^{'}\n\end{bmatrix} &= I_{u}^{'}(u \leftrightarrow d)\n\end{aligned}
$$

are estually linear combinations of

^u ⁼ Re Tr ((*XuXdX^u* ⁺ {*Xd, X*² **u** *d d d due det der decept int* **into into into interval derivative intervals which are already in the set of an are already** *I***USEU SEI EAUEPITIUI.**
2 ∴ closed set except for:

for clarity, since both couplings will appear in the same relations when we match between is the basis independent condition for the shift-invariance to be maintained at the non-perturbative level
 By the basis independent condition for the Stillt invariance to be maintained at the

and to that of (1.3) the same term with *^C^g* [→] *^C*(*s*)

dimensional analysis, and with the origin of *Cg, C*(*s*) It can be shown again that this condition is **RG invariant**

an axion potential.

Shift-Invariance: Non-perturbative Condition ϴQCD again Tr (*X*2*Y Y*˜ †) [−] Tr *^X* Tr (*XY Y*˜ †) ⁺ ¹ Taking *^X* ⁼ *Y Y* †, we can use it in order to keep the flavor-invariant nature of the constraint -INV

$$
-\frac{C_g g_3^2}{16\pi^2}\frac{a}{f}\operatorname{Tr}\bigl(G_{\mu\nu}\tilde{G}^{\mu\nu}\bigr)
$$

 $-\frac{C_g g_3}{16\pi^2}\frac{a}{f}\text{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu})$ breaks shift-invariance non-perturbatively (instanton enects)
(in the operator basis where fermion couplings are derivative) $C_q q_3^2 a$ \sim \approx \approx \approx \approx \approx \approx \approx breaks shift-invariance non-perturbatively (instanton effects)

$$
I_g \equiv C_g + \operatorname{Im} \operatorname{Tr} \left(Y_u^{-1} \tilde{Y}_u + Y_d^{-1} \tilde{Y}_d \right) = 0
$$

$$
\mu \frac{dI_g}{d\mu} = 0
$$
 whenever shift-symmetry holds (*I_g=*I_i=*0 for i-*

 $\mu \frac{\partial}{\partial \mu}=0$ whenever shift-symmetry holds (/ $_{g}=$ / $_{i}=$ 0 for i: *P*
Prever s $\mathsf{hift-svmmetrv}\ \mathsf{holds}\ \mathsf{U}_a = \mathsf{I}_i = 0\ \mathsf{for}\ \mathsf{i} = 1 \dots 13\mathsf{d}$ $= 0$ whenever shift-symmetry holds (*I_g=I_i=0* for i=1…13)

Experimentalists haven't found (yet) what theorists told them they will find

Executive summary on status of BSM

There are rich opportunities for mind-boggling signatures @ colliders and beyond

BAD NEWS

GOOD NEWS