VISHν: flavour-variant DFSZ axion model for inflation, neutrino masses, dark matter and baryogenesis

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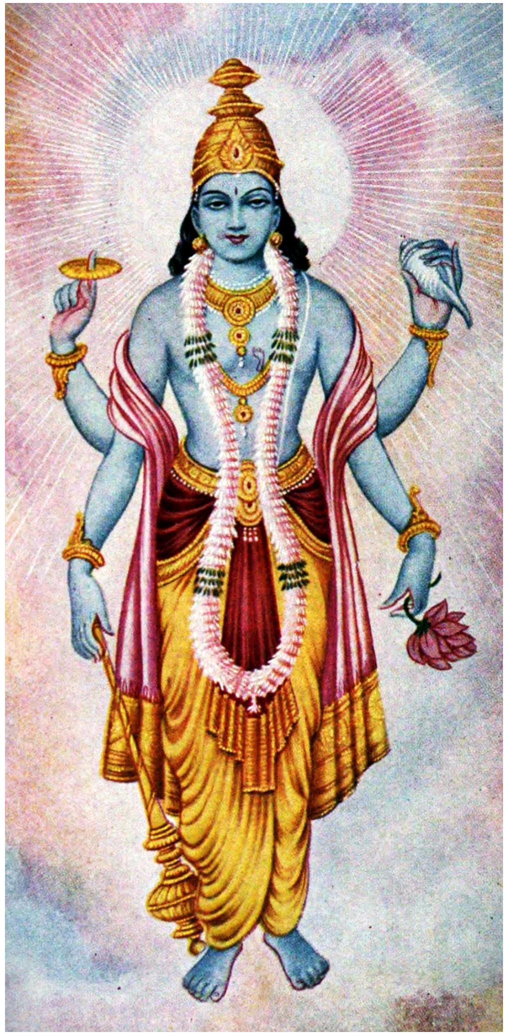

Image credit: Wikipedia

Hindu God of Preservation

"Vishnu is the supreme being who creates, protects and transforms the universe." – Wikipedia

Let's see if VISHν = Variant axIon Seesaw Higgs ν-trino lives up to its namesake …

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1. The strong CP problem
2. The invisible DFSZ axion and technical naturalness
3. The νDFSZ model: successes and cosmological challenges
4. VISHν: towards meeting the cosmological challenges
5. Closing remarks

RV, Davies, Joshi: Naturalness of the invisible axion model, PLB 215 (1988) 133
Clarke, Foot, RV: Natural leptogenesis and neutrino masses with two Higgs doublets, PRD 92 (2015) 033006
Clarke, RV: νDFSZ: Technically natural nonsupersymmetric model of neutrino masses, baryogenesis, the strong CP problem and dark matter, PRD 93 (2016) 035001
Sopov, RV: VISHν: a unified solution to five SM shortcomings with a protected electroweak scale, arXiv:2206.11598

Related to a KSVZ axion implementation (aka SMASH):
Salvio: PLB 743 (2015) 428; PRD 99 (2019) 015037
Ballesteros, Redondo, Ringwald, Tamarit: PRL 118 (2017) 071802; JCAP 08 (2017) 001; FASS 6 (2019) 55

1. The strong CP problem

QCD permits the term $\mathcal{L}_\theta = \bar{\theta}\frac{g^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$ that violates CP (and P) and induces an electric DM for the neutron.

Experimentally $\bar{\theta} \lesssim 10^{-10}$. The $\bar{\theta} \to 0$ limit is not technically natural, because weak interactions violate CP and P.

The strong CP problem is why is $\bar{\theta}$ so small? (Note: in the SM, $\bar{\theta}$ running is generated only at 7 loops …)

Ellis, Gaillard (1979)

In Peccei-Quinn axion models, a $U(1)_{PQ}$ that has a colour anomaly $\partial_\mu J^\mu_{\mathrm{PQ}} \propto G^{\mu\nu}\tilde{G}_{\mu\nu}$ is introduced, and the effective Lagrangian becomes $\mathcal{L}_\theta = \left(\frac{a(x)}{f_a} + \bar{\theta}\right)\frac{g^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$ where a(x) is the axion.

The axion potential is minimised when $\langle a \rangle = -\bar{\theta} f_a$ thus removing the CP-violating term.

Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)

2. The invisible DFSZ axion and technical naturalness

DFSZ axion model: Peccei-Quinn symmetry using only standard quarks but two Higgs doublets Φ_1 and Φ_2.
Axion made invisible by breaking PQ at high scale with gauge-singlet scalar S.

Zhitnitskii (1980) Dine, Fischler, Srednicki (1981)

Yukawa sector: $i\sigma_2\Phi_1^*$ couples to RH up-type and to Φ_2 RH down-type quarks (Type-II/Flipped 2HDM – flavour universal).

PQ charges:

q_L	u_R	d_R	Φ_1	Φ_2	S
0	$\cos^2\beta$	$\sin^2\beta$	$\cos^2\beta$	$-\sin^2\beta$	$\frac{1}{2}$ or 1

$\frac{1}{2}$: for $\Phi_1^\dagger\Phi_2 S^2$ term ← νDFSZ

1: for $\Phi_1^\dagger\Phi_2 S$ term ← VISHν

(Need cubic option as part of domain wall problem cure – see later)

$$\langle S\rangle = \frac{v_s}{\sqrt{2}} \qquad \langle\Phi_i^0\rangle = \frac{v_i}{\sqrt{2}} \qquad \tan\beta = \frac{v_1}{v_2}$$

Scalar potential:

$$V = M_{11}^2 \Phi_1^\dagger \Phi_1 + M_{22}^2 \Phi_2^\dagger \Phi_2 + M_{SS}^2 S^* S + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \frac{\lambda_S}{2}(S^* S)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_{1S}(\Phi_1^\dagger \Phi_1)(S^* S) + \lambda_{2S}(\Phi_2^\dagger \Phi_2)(S^* S)$$

$$+ \begin{cases} \kappa \Phi_1^\dagger \Phi_2 S \ + \text{h.c.} & [\text{VISH}\nu] \\ \epsilon \Phi_1^\dagger \Phi_2 S^2 + \text{h.c.} & [\nu\text{DFSZ}] \end{cases}$$

VEV hierarchy: PQ scale $\sim v_s \gg v_i \sim$ EW scale

How to generate this hierarchy at tree level?
What about radiative stability?

Potential minimisation:

$$M_{11}^2 = -\frac{1}{2} t_1 v_s^2 - \lambda_1 v_1^2 - \frac{1}{2}(\lambda_3 + \lambda_4) v_2^2$$

$$M_{22}^2 = -\frac{1}{2} t_2 v_s^2 - \lambda_2 v_2^2 - \frac{1}{2}(\lambda_3 + \lambda_4) v_1^2$$

$$M_{SS}^2 = -\frac{1}{2} t_1 v_1^2 - \frac{1}{2} t_2 v_2^2 - \lambda_S v_s^2$$

$$t_1 \equiv \epsilon \frac{v_2}{v_1} + \lambda_{1S}$$

$$t_2 \equiv \epsilon \frac{v_1}{v_2} + \lambda_{2S}$$

Generate hierarchy by $M_{SS} \gg M_{11,22}$

Need $t_{1,2} \lesssim \dfrac{v_{1,2}^2}{v_s^2}$

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Is this VEV hierarchy technically natural? Yes!

$$t_1 \equiv \epsilon \frac{v_2}{v_1} + \lambda_{1S}$$
$$t_2 \equiv \epsilon \frac{v_1}{v_2} + \lambda_{2S}$$

$t_{1,2} \lesssim \frac{v_{1,2}^2}{v_s^2} \ll 1$ achieved through $\epsilon,\ \lambda_{1S},\ \lambda_{2S} \ll 1$

In that limit, S decouples from all the SM fields: hidden sector.

$$S = \int d^4x\, \mathcal{L}_{\rm SM}(x) + \int d^4x' \mathcal{L}_{\rm S}(x')$$

Independent Poincaré transformations in SM and S sectors: Poincaré protection

RV, Davies, Joshi (1988) Georgi (private comm, 1988)
Foot, Kobakhidze, McDonald, RV (2014)

Note that $\epsilon = 0$ also enhances $U(1)_{PQ}$ to $U(1)'_{PQ} \times U(1)_S$.

Dangerous gravity effects?

Hidden sectors must interact with the SM sector through gravity.

Planck-suppressed effective operators?

Worst-case scenario: $a\frac{M_{SS}^2}{M_P^2}S^*S\Phi^\dagger\Phi \sim (10^{-16}\,a)\,S^*S\Phi^\dagger\Phi$ would be an issue for a > 0.01.

Even worse: generation of explicit PQ breaking terms? "Axion quality problem."

Kamionkowski, March-Russell (1992)
Barr, Seckel (1992)
Ghigna, Lusignoli, Roncadelli (1992)

These are generic issues for invisible axion models.

Direct effect on EW scale i.e. $\delta M_{ii}^2 \sim M_P^2$? Open problem?? Addition of PQ scale does not make it worse …

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3. The νDFSZ model: successes and cosmological challenges

Successes of DFSZ model: (i) solves the strong CP problem
(ii) provides axion DM candidate for PQ scale of $10^{10} - 10^{11}$ GeV

There is an obvious extension: identify PQ and type-I seesaw scales and (iii) explain ν masses

Langacker, Peccei, Yanagida (1986)
Shin (1987)

Then also: (iv) explain baryogenesis via type-I seesaw leptogenesis

Langacker, Peccei, Yanagida (1986)
Fukugita, Yanagida (1986)

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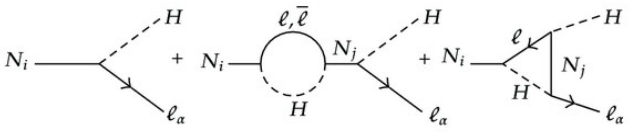
The νDFSZ model is a detailed incarnation of these ideas.

Clarke, RV (2016)

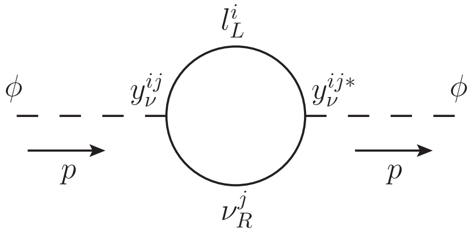
<u>Review of a problem with single Higgs-doublet leptogenesis</u>:

$$-\mathcal{L} \supset y_N \bar{\ell}_L \tilde{\Phi} \nu_R + \frac{1}{2} \bar{\nu}_R M_N \nu_R + h.c.$$



Seesaw formula: $m_\nu = \frac{v^2}{2} y_N M_N^{-1} y_N^T$

Vissani naturalness bound:



$$\delta\mu^2 \simeq \frac{1}{4\pi^2} \frac{1}{\langle\phi\rangle^2} m_\nu M_N^3 < 1 \text{ TeV}^2$$

$$\Rightarrow m_N < 3 \times 10^7 \text{ GeV}$$

Vissani (1998)
Clarke, Foot, RV (2015a)

Davidson-Ibarra bound: standard hierarchical, thermal leptogenesis requires $M_N > 5 \times 10^8 - 2 \times 10^9$ GeV

Davidson, Ibarra (2002)
Giudice+ (2004)

Tension between leptogenesis and naturalness

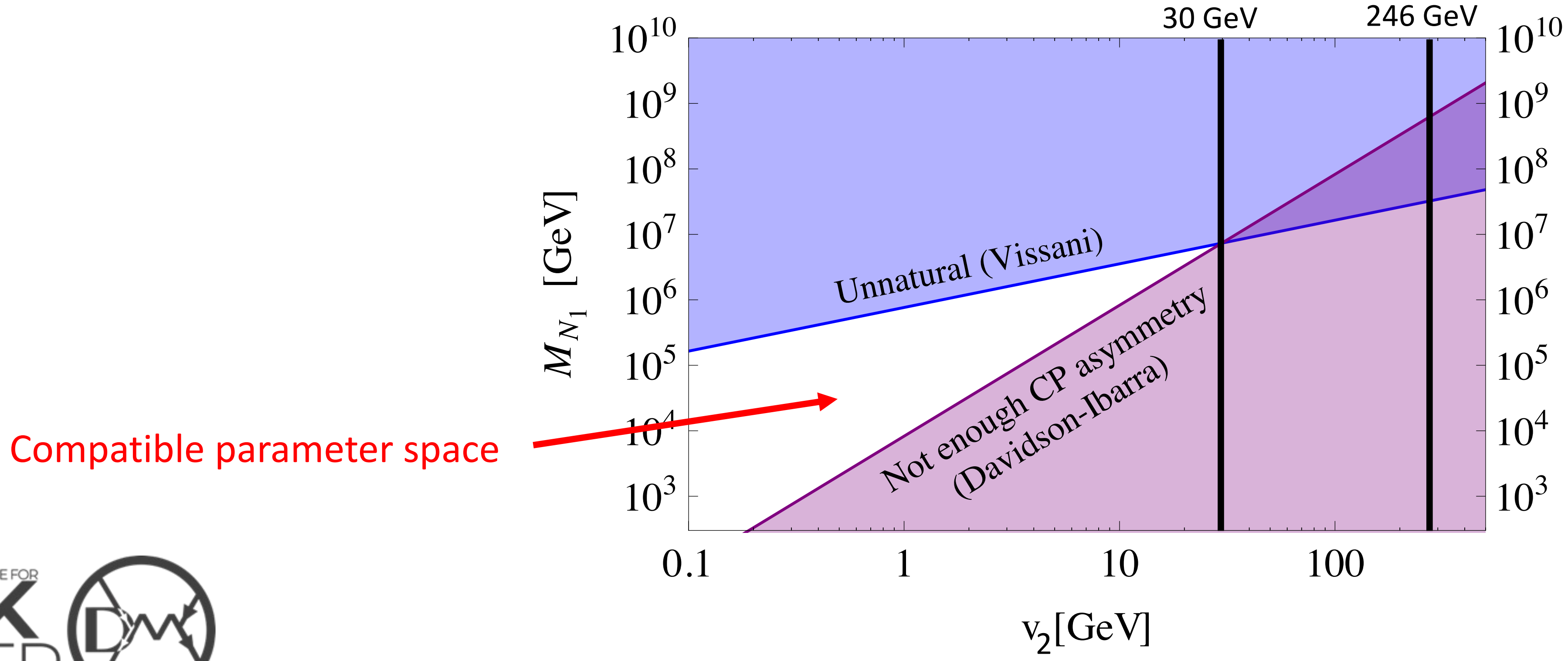
Two (non-susy) options: degenerate M_N, two Higgs doublets (our choice)

Now consider two Higgs doublets with Φ_2 coupling to the RH neutrino:

Clarke, Foot, RV (2015b)

Vissani bound: $M_{N_1} \lesssim 3 \times 10^7 \text{ GeV} \left(\frac{v_2}{246 \text{ GeV}}\right)^{\frac{2}{3}}$

DI bound: $M_{N_1} \gtrsim 5 \times 10^8 \text{ GeV} \left(\frac{v_2}{246 \text{ GeV}}\right)^{2}$



Now use that idea in the DFSZ context to get the νDFSZ:

Clarke, RV (2016)

Take the 2HDM, add three RH neutrinos and a complex scalar singlet S, impose Peccei-Quinn symmetry. Axion is the phase of S.

$$-\mathcal{L}_Y = y_u \bar{q}_L \tilde{\Phi}_1 u_R + y_d \bar{q}_L \Phi_2 d_R + y_e \bar{\ell}_L \Phi_J e_R + y_\nu \bar{\ell}_L \tilde{\Phi}_2 \nu_R + \frac{1}{2} y_N \overline{(\nu_R)^c} S \nu_R + h.c.$$

J=2 (1) is Type-II (Flipped) ν2HDM

generates $M_N < 3 \times 10^7$ GeV

EW scale ~ – $(88\ \text{GeV})^2$

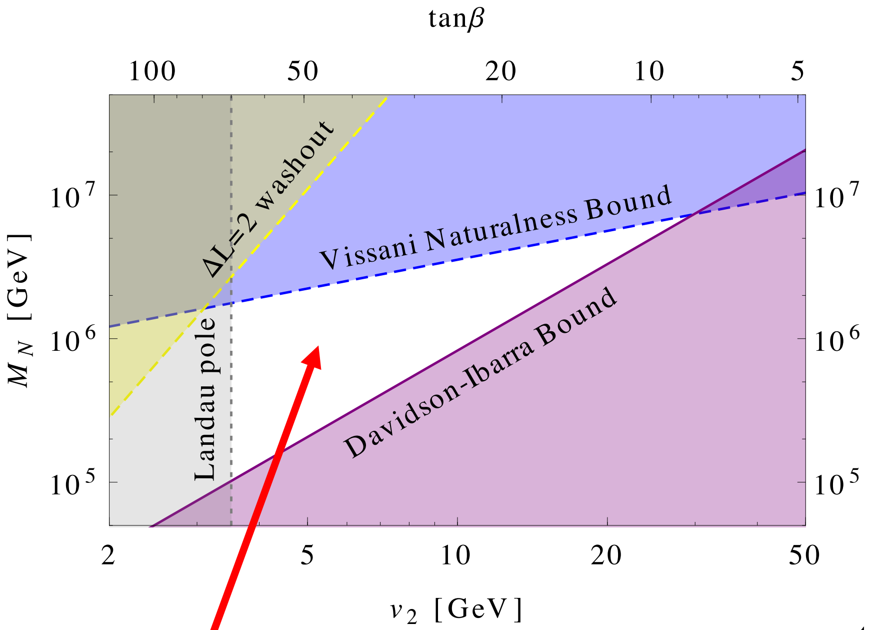
+$(10^3\ \text{GeV})^2$

PQ scale ~ –$(10^{11}\ \text{GeV})^2$

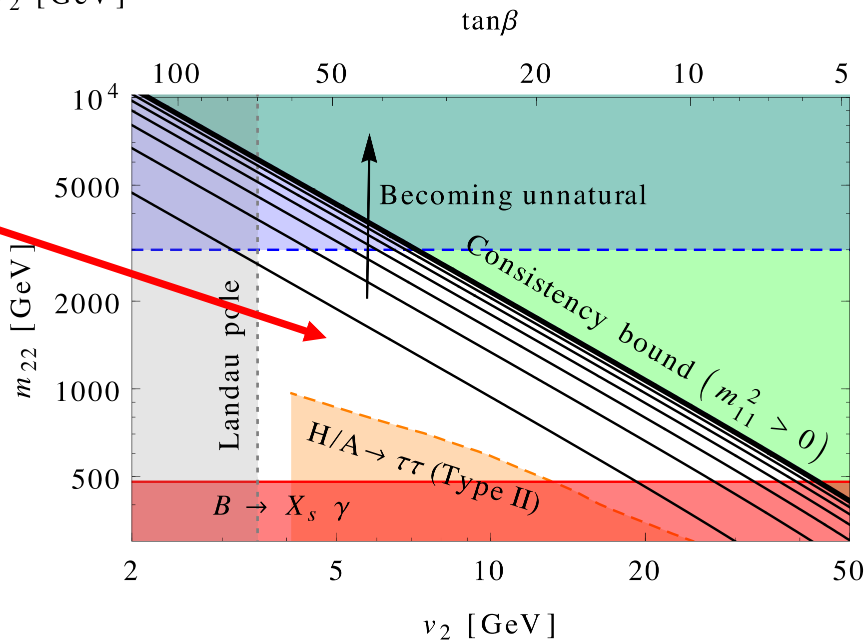
$$V = M_{11}^2 \Phi_1^\dagger \Phi_1 + M_{22}^2 \Phi_2^\dagger \Phi_2 + M_{SS}^2 S^* S + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \frac{\lambda_S}{2}(S^* S)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_{1S}(\Phi_1^\dagger \Phi_1)(S^* S) + \lambda_{2S}(\Phi_2^\dagger \Phi_2)(S^* S) + \epsilon \Phi_1^\dagger \Phi_2 S^2 + \text{h.c.}$$

tiny inter-sector couplings

induces linear term for Φ_2 and thus small v_2

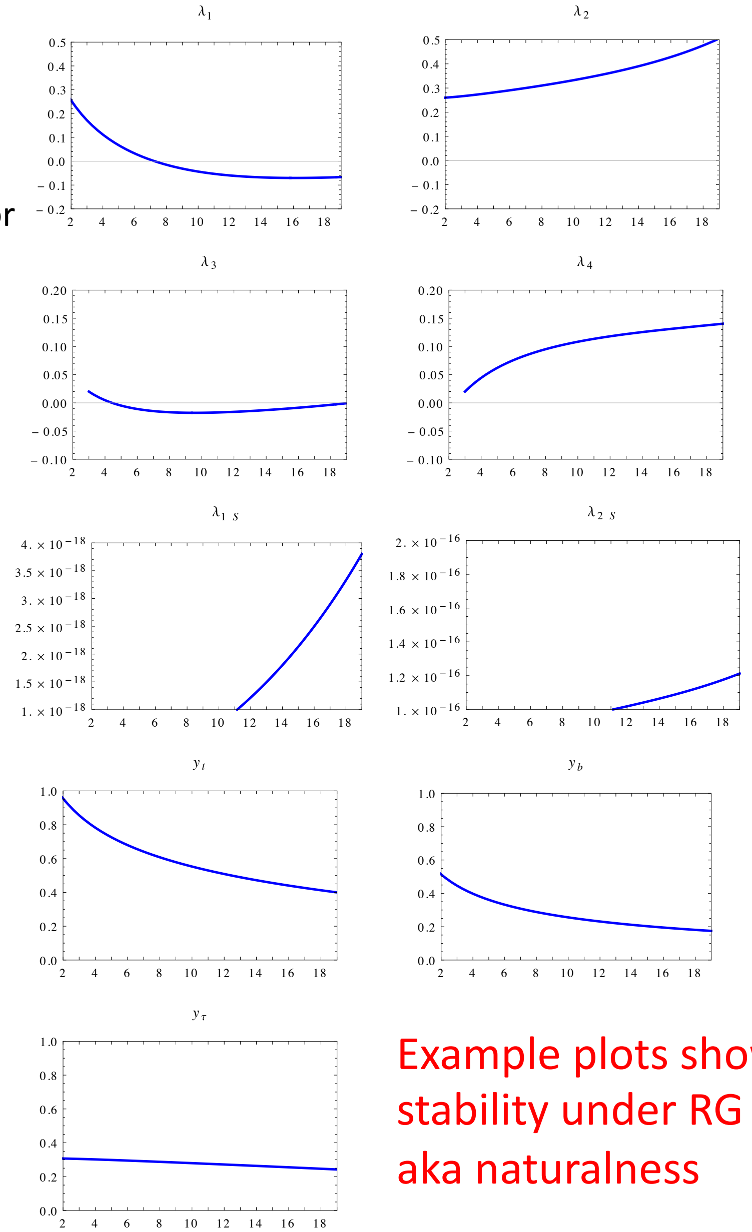


Acceptable regions



Concern about λ_1 going negative, driven by large top Yukawa. Examples shown are for tanβ=30. Ameliorated for smaller tanβ.

Oda, Shoji, Takahashi (2020)



Example plots showing stability under RG running aka naturalness νDFSZ successes: strong CP solution, DM, neutrino masses, non-fine-tuned leptogenesis.

νDFSZ challenges: cosmological history prior to leptogenesis (i) potential domain wall problem
(ii) viable inflation

VISHν is motivated by these challenges.

4. VISHν: towards meeting the cosmological challenges

Sopov, RV (2022)

The DFSZ domain wall problem:

Sikivie 1982

QCD instantons explicitly break $U(1)_{PQ}$ through the colour anomaly.

However, for standard DFSZ, there is an anomaly-free and hence not explicitly broken Z_6 subgroup.

Quark condensates spontaneously break this Z_6, producing cosmologically bad stable domain walls.

Elegant solution:

Make $U(1)_{PQ}$ flavour-dependent such that the colour anomaly fully breaks it.

Davidson, Vozmediano (1984a, 1984b)
Geng, Ng (1989, 1990)

There is a class of such theories. The "top-specific" model is a simple (interesting!) example that we adopt.

Peccei, Wu, Yanagida (1986)
Krauss, Wilczek (1986)

Chiang+ (2015, 2018)
Dolan, Hayat, Thamm, RV (in progress)

q_L	u_R^a	u_R^3	d_R	l_L	e_R	ν_R	Φ_1	Φ_2	S
0	$-\sin^2\beta$	$\cos^2\beta$	$\sin^2\beta$	$\frac{1}{2}-\cos^2\beta$	$\frac{3}{2}-2\cos^2\beta$	$-\frac{1}{2}$	$\cos^2\beta$	$-\sin^2\beta$	1

RH top has distinct PQ charge

Only Φ_1 couples to RH top

$$-\mathcal{L}_Y = \overline{q_L}^j y_{u1}^{j3} \tilde{\Phi}_1 u_R^3 + \overline{q_L}^j y_{u2}^{ja} \tilde{\Phi}_2 u_R^a + \overline{q_L}^j y_d^{jk} \Phi_2 d_R^k + \overline{l_L}^j y_e^{jk} \Phi_2 e_R^k + \overline{l_L}^j y_\nu^{jk} \tilde{\Phi}_2 \nu_R^k + \frac{1}{2} \overline{(\nu_R)^c}^j y_N^{jk} S \nu_R^k + \text{h.c.}$$

Collider signatures and constraints: $t \to hc$ and $t \to hu$

$cg \to tH$ or tA and $cg \to bH^+$

Chiang+ (2015, 2018)
Hou, Modak (2021)
Ghosh, Hou, Modak (2020)
Kohda, Modak, Hou (2018)

With $v_2 << v_1$, VISHν inherits the successes of νDFSZ.
And, get a nice explanation for why m_t >> other fermion masses!

Like SMASH, we explore variants of "Higgs inflation", through non-minimal couplings of scalar fields to gravity:

$$\frac{\mathcal{L}^{\mathcal{J}}}{\sqrt{-g^{\mathcal{J}}}} \supset \left(\frac{M_P^2}{2} + \xi_1 \Phi_1^\dagger \Phi_1 + \xi_2 \Phi_2^\dagger \Phi_2 + \xi_S S^\dagger S \right) R^{\mathcal{J}}$$

(J = Jordan frame)

Let $\Phi_1^0 = \frac{\rho_1}{\sqrt{2}} e^{i\vartheta_1/v_1}, \ \Phi_2^0 = \frac{\rho_2}{\sqrt{2}} e^{i\vartheta_2/v_2}, \ S = \frac{\sigma}{\sqrt{2}} e^{i\vartheta_S/v_S}$

Go to Einstein (E) frame: $g_{\mu\nu}^{\mathcal{J}} \to g_{\mu\nu}^{\mathcal{E}} = \Omega^2(\rho_1, \rho_2, \sigma) g_{\mu\nu}^{\mathcal{J}} \quad \text{where} \quad \Omega^2 \equiv 1 + \frac{\xi_1 \rho_1^2 + \xi_2 \rho_2^2 + \xi_S \sigma^2}{M_P^2}.$

Then: $\frac{\mathcal{L}^{\mathcal{E}}}{\sqrt{-g^{\mathcal{E}}}} \supset \frac{M_P^2}{2} R^{\mathcal{E}} - \frac{1}{2} \mathcal{G}_{IJ}^{\mathcal{E}} \partial_\mu \varphi^I \partial^\mu \varphi^J - V^{\mathcal{E}}(\varphi^I)$

$$V^{\mathcal{E}}(\varphi^I) = \Omega^{-4}(\varphi^I) V^{\mathcal{J}}(\varphi_I) \simeq \frac{M_P^4}{8} \frac{\lambda_i \rho_i^4 + 2\lambda_{34} \rho_1^2 \rho_2^2 + 2\lambda_{iS} \rho_i^2 \sigma^2 + \lambda_S \sigma^4}{(M_P^2 + \xi_i \rho_i^2 + \xi_S \sigma^2)^2}$$

$(\lambda_{34} \equiv \lambda_3 + \lambda_4)$

Potential is flat at large moduli: good for inflation

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Convenient to do a field redefinition: $\chi/M_P \equiv \sqrt{3/2}\log\Omega^2, \quad r_i/M_P \equiv \rho_i/\sigma$

to get: $V^{\mathcal{E}}(\varphi^I) \simeq [\Lambda(r_1, r_2)]^4 \left[1 - e^{-\frac{2}{\sqrt{6}}\frac{\chi}{M_P}}\right]^2$ χ is the inflaton

$$\Lambda^4(r_i) \simeq \frac{M_P^4}{8}\frac{\lambda_i r_i^4 + 2\lambda_{34} r_1^2 r_2^2 + 2\lambda_{iS} M_P^2 r_i^2 + \lambda_S M_P^4}{(\xi_i r_i^2 + \xi_S M_P^2)^2}$$

Work out the minima of Λ^4 in various parameter regimes to determine the inflaton trajectories in field space.

Get 7 possibilities for χ: $\rho_1, \ \rho_2, \ \rho_1 \& \rho_2$ Higgs doublet inflation driven by large ρ_1 or ρ_2 or combination.

$\rho_1 \& \sigma, \ \rho_2 \& \sigma, \ \rho_1 \& \rho_2 \& \sigma, \ \sigma$ S-Higgs or S inflation

Along each inflaton trajectory: $$V^{\mathcal{E}}(\chi) \simeq \frac{M_P^4}{8}\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2}\left[1 - e^{-\frac{2}{\sqrt{6}}\frac{\chi}{M_P}}\right]^2$$

$$\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} \simeq \frac{\lambda_S L}{\lambda_S(\lambda_2\xi_1^2 - 2\lambda_{34}\xi_1\xi_2 + \lambda_1\xi_2^2) + \xi_S^2 L}$$

$\Phi_1\Phi_2 S$ inflation

$$L \equiv \lambda_1\lambda_2 - \lambda_{34}^2$$

$$\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} \simeq \frac{\lambda_S\lambda_i}{\lambda_S\xi_i^2 + \lambda_i\xi_S^2}$$

$\Phi_i S$ inflation

$$\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} \simeq \frac{L}{\lambda_2\xi_1^2 - 2\lambda_{34}\xi_1\xi_2 + \lambda_1\xi_2^2}$$

$\Phi_1\Phi_2$ inflation

$$\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} = \frac{\lambda_{i,S}}{\xi_{i,S}^2}$$

Φ_i or S inflation

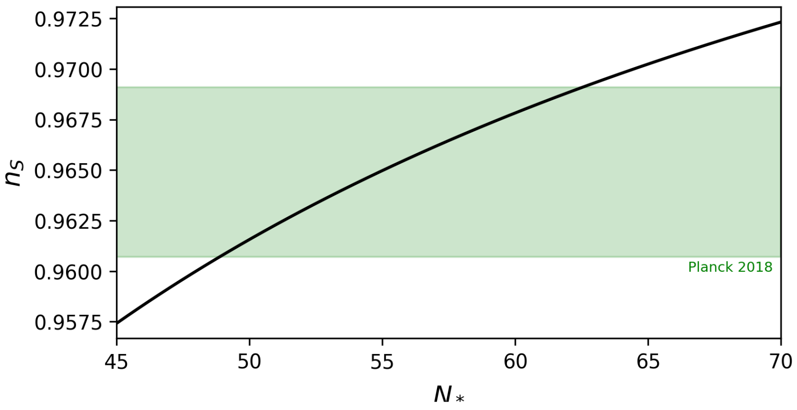
Fit to cosmological observables:

large ξ cases

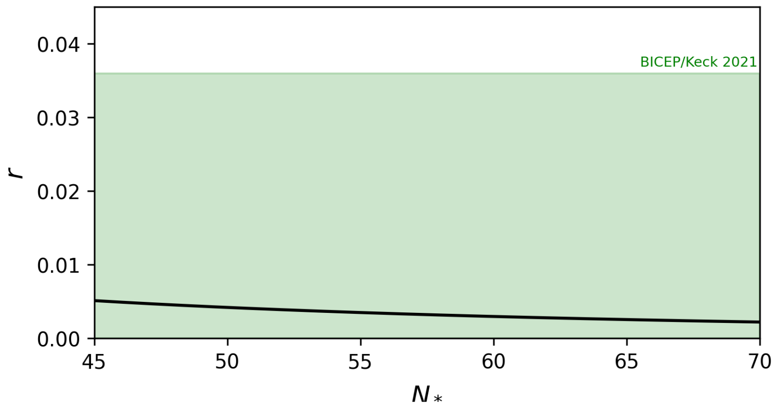
scalar amplitude

$$\frac{\lambda_{\rm eff}}{\xi_{\rm eff}^2} \sim 8.9 \times 10^{-10}$$

scalar spectral index



tensor-to-scalar ratio



number of e-folds

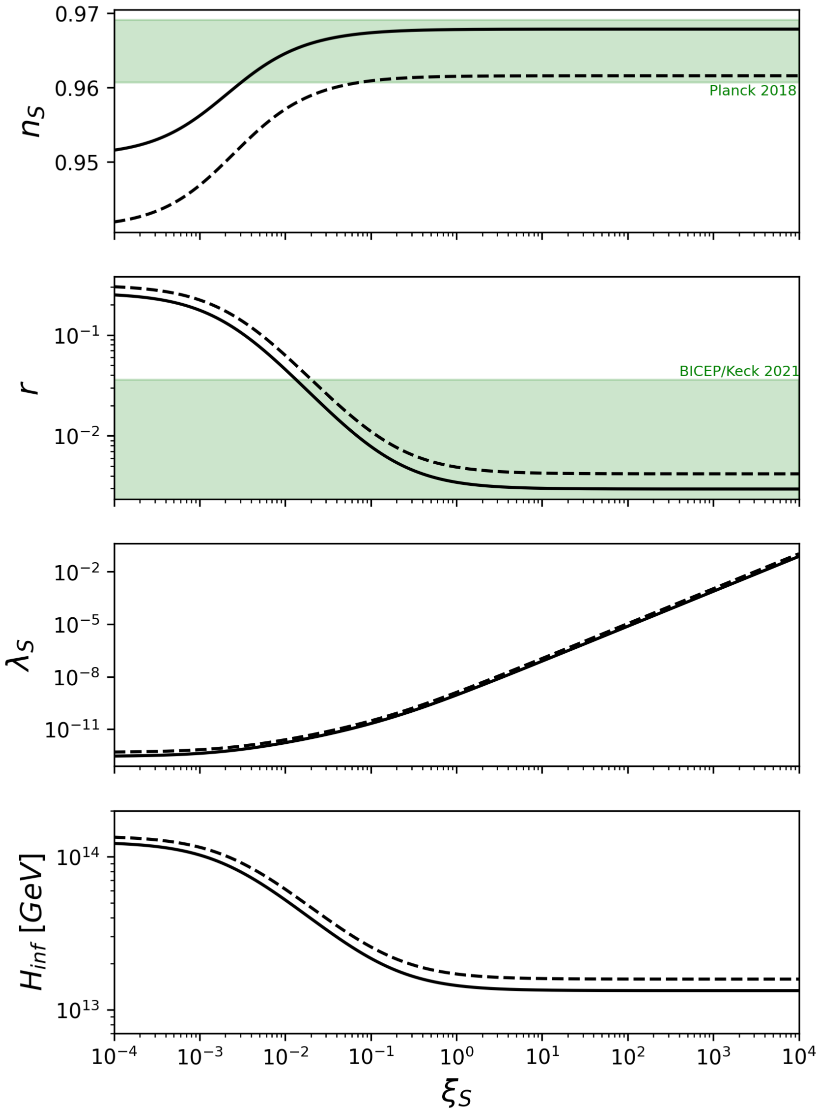
For Φ_i and $\Phi_1\Phi_2$ inflation, large ξ necessary to fit the scalar amplitude data – concerns about unitarity violation.

Small ξ possible for inflatons involving large S, since λ_S is free.

Good for avoiding possible unitarity problems.

General analysis complicated because of non-trivial 3x3 metric for the scalar kinetic terms. But $\xi_i << \xi_S < O(1)$ parameter space has approx. diagonal metric. $\xi_S >$ few x 10^{-2} is OK.

Small λ_S is also OK here – see paper for discussion.



(P)reheating analysis is yet to be performed.

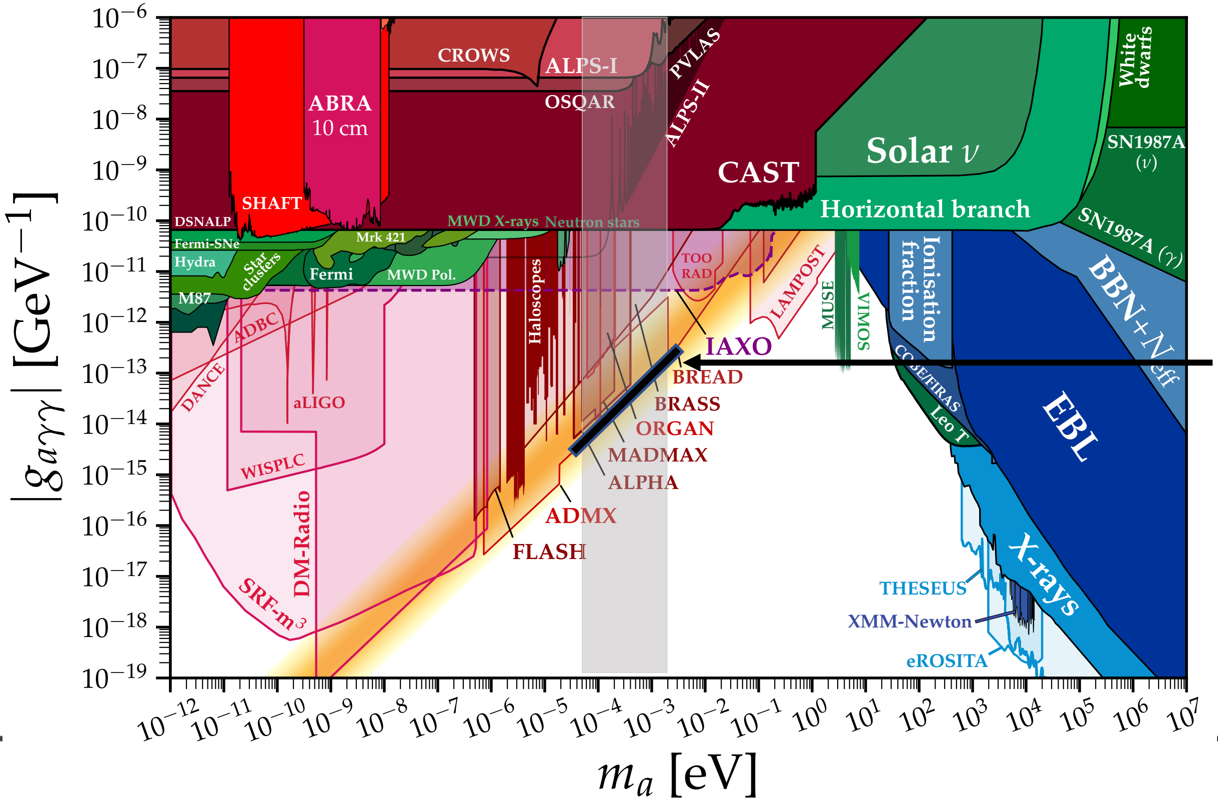
There should be reasonable scenarios where $U(1)_{PQ}$ is restored during either pre- or re-heating.

Then the axion DM abundance is driven by (i) the realignment mechanism, and
(ii) decaying axion-string and string-wall networks (uncertainties!).

To get DM density correct, need axion mass lower bound in the range: $m_A \sim (40 - 500)\ \mu\text{eV}$

There is an upper bound from stellar cooling constraints. $m_A \in (40\ \mu\text{eV},\ \sim 2\ \text{meV})$

Can be probed by a number of axion search experiments:



DFSZ region

Plot by Ciaran O'Hare

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5. Closing remarks

- VISHν and SMASH are interesting, economical models for solving 5 important problems.
- VISHν uses interesting PQ/flavour interplay to avoid domain wall problem (1980s!).
- VISHν has natural hierarchical thermal leptogenesis.
- VISHν has good rationale for why m_t >> other fermion masses.
- Higgs/S inflation works well.
- (P)reheating analysis is for future work.

Some worries:

- $\bar{\theta}$ stays small under radiative corrections in the SM (how wide is this class of theories?).
- Replacement of $<10^{-10}$ parameter with even smaller, but technically natural, parameters. Is technical naturalness a good enough justification?
- Quantum gravity effects? Never possible (for me) to be sure.

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