VISHν: solving five SM shortcomings with a protected electroweak scale

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Variant-ax**I**on **S**eesaw **H**iggs **ν**-trino extensions to the Standard Model

AS, Volkas (2022)

The Standard Model is incomplete:

Key issues for BSM physics:

1. Small neutrino masses
2. Dark matter
3. Baryon asymmetry of the universe
4. No neutron EDM (strong *CP* problem)

Scale of BSM* physics?

1. $\sim m_{EW}$
2. $\gg m_{EW}$ (new heavy fundamental scale).

*non-gravitational!

RH neutrinos

- Small **active neutrino masses** from Type-I **seesaw** mechanism:

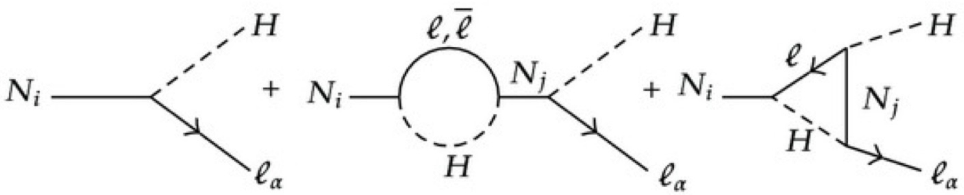
Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)
Mohapatra, Senjanovic 1980

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

- **BAU** from thermal **leptogenesis:**

$$M_1 \gtrsim 5 \times 10^8 \text{ GeV}$$

Davidson, Ibarra (2002)
Giudice + (2004)



(out of equilibrium)

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

- $\cancel{U(1)}_L$ and $M_i \sim \langle S \rangle \gg m_{EW}$.

Chikashige, Mohapatra, Peccei (1980)

... and an invisible axion

$$S = \frac{\sigma}{\sqrt{2}} e^{i\, a/v_S}$$

Identify seesaw scale with Peccei-Quinn scale:

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

- Impose global $U(1)_{PQ}$ which is spontaneously broken by vev of S (also breaks lepton number)

  $U(1)_L \subset U(1)_{PQ}$

  with a colour anomaly: $\partial_\mu J^\mu_{PQ} \supset \mathcal{N} \frac{g_3^2}{16\pi^2} G\tilde{G}$

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

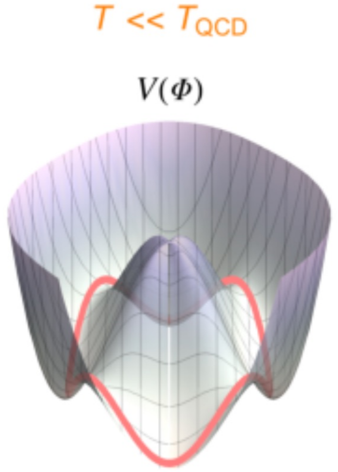
$$\mathcal{L}_\theta = \bar{\theta} \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu} \xrightarrow{\langle S \rangle \neq 0} \mathcal{L}_\theta = \left(\frac{a(x)}{f_a} + \bar{\theta} \right) \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu} \quad \text{and} \quad \langle a \rangle = -\bar{\theta} f_a$$

axion

$\bar{\theta} \lesssim 10^{-10}$

Abel+ (2020)

$\Longrightarrow$ **CP-invariant strong interactions.**



- **Dark matter:** DFSZ or KSVZ invisible axion

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

νDFSZ

- Global $U(1)_{PQ/L}$ broken by vev of complex scalar-singlet S.
- Three right-handed sterile neutrinos.
- Two Higgs electroweak doublets Φ_1, Φ_2 in Type II setup.

$$\langle S \rangle = \frac{v_S}{\sqrt{2}}, \quad \langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix} \qquad v_S \gg v_i$$

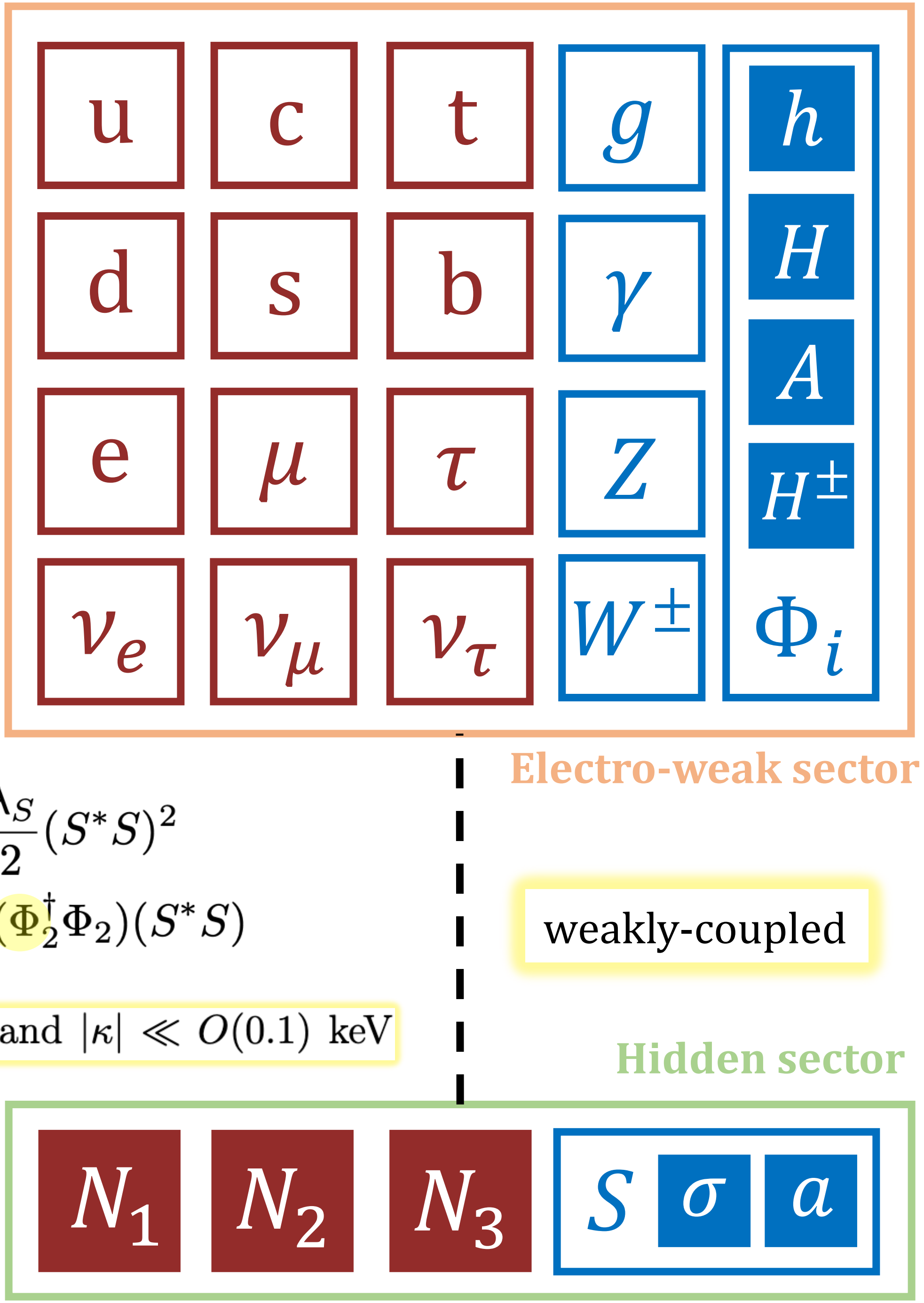
Can resolve four key issues for particle physics/cosmology.

Volkas, Davies, Joshi (1988)
Clarke, Foot, Volkas (2015)
Clarke, Volkas (2016)

$$V = M_{11}^2 \Phi_1^\dagger \Phi_1 + M_{22}^2 \Phi_2^\dagger \Phi_2 + M_{SS}^2 S^* S + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \frac{\lambda_S}{2} (S^* S)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_{1S} (\Phi_1^\dagger \Phi_1)(S^* S) + \lambda_{2S} (\Phi_2^\dagger \Phi_2)(S^* S)$$
$$+ \begin{cases} \kappa \Phi_1^\dagger \Phi_2 S \ + \text{h.c.} & [\text{VISH}\nu] \\ \epsilon \Phi_1^\dagger \Phi_2 S^2 + \text{h.c.} & [\nu\text{DFSZ}] \end{cases}$$

$|\lambda_{1S}| \lesssim 10^{-18}$, $|\lambda_{2S}| \lesssim 10^{-16}$ and $|\kappa| \ll O(0.1)$ keV

$$-\mathcal{L}_Y \supset y_\nu \overline{l_L} \tilde{\Phi}_2 \nu_R + \frac{1}{2} y_N \overline{(\nu_R)^c} S \nu_R + H.c.,$$



Theory aside (Poincaré protection):

Volkas, Davies, Joshi (1988)
Foot, Kobakhidze, McDonald, Volkas (2014)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i (\mathcal{L}_{\text{mix},i} + \mathcal{L}_i)$$

↓ Decoupling Limit

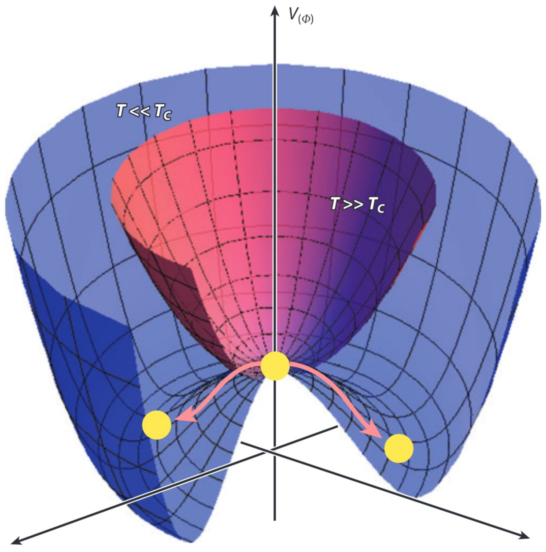
$$S = S_{SM} + S_i = \int d^4x \; \mathcal{L}_{SM} + \int d^4x' \; \mathcal{L}_i$$

$ISO(3,1) \otimes ISO(3,1) \otimes \ldots$

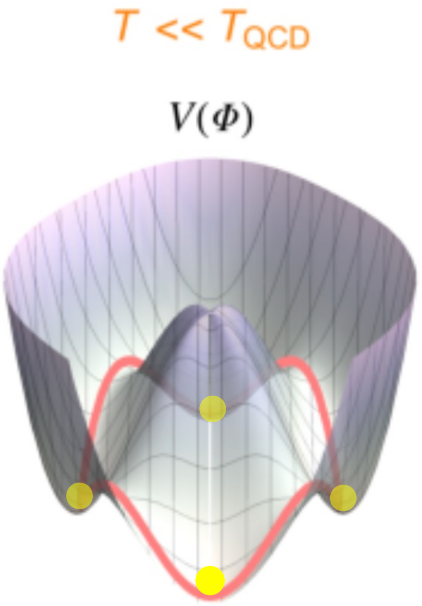
i.e. **technically natural**.

Cosmological challenge:

Domain wall problem



Kawasaki, Nakayama (2013)



Armengaud+ (2019)

- Post-inflation DFSZ axion models have a domain wall problem because $N_{DW} > 1$.
  - ➢ Stable string-domain-wall network forms around QCD phase transition.

VISHν extensions are variations of the νDFSZ which remove this problem.

- **Top-specific** PQ is well-motivated. Our implementation is:

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

$N_{DW} = 1$

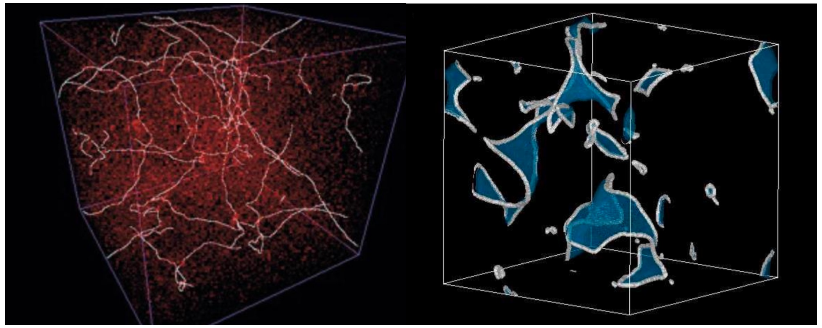
$$-\mathcal{L}_Y = \overline{q_L}^j y_{u1}^{j3} \widetilde{\Phi}_1 u_R^3 + \overline{q_L}^j y_{u2}^{ja} \widetilde{\Phi}_2 u_R^a + \overline{q_L}^j y_d^{jk} \Phi_2 d_R^k + \overline{l_L}^j y_e^{jk} \Phi_2 e_R^k + \overline{l_L}^j y_\nu^{jk} \widetilde{\Phi}_2 \nu_R^k + \frac{1}{2} \overline{(\nu_R)^c}^j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

✓ Large top mass from $v_1 \gg v_2$!

(small protected vev hierarchy req. for natural leptogenesis)

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

$\tan\beta \equiv v_2/v_1$


Hiramatsu+ (2012)

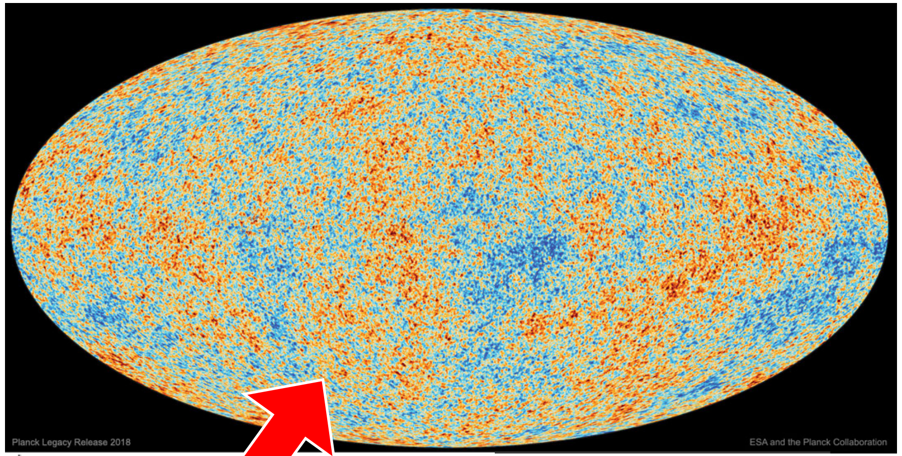
Cosmological frontier:

Inflation

$$ds^2 = -dt^2 + a^2(t)\left[\left(\frac{1}{1-kr^2}\right)dr^2 + r^2 d\Omega^2\right]$$

- Early period of accelerated scale-factor expansion
- Large-scale homogeneity, flatness w/o initial fine-tuning

Starobinsky (1980)
Guth (1981)



Scalar/tensor power spectra:

$$\Delta_s^2(k) = A_s(k_*)\left(\frac{k}{k_*}\right)^{n_s(k_*)-1} \qquad r \equiv \frac{\Delta_t^2(k)}{\Delta_s^2(k)}$$

BICEP/KECK 2021

$$A_s \sim 2.1 \times 10^{-9} \qquad n_s = 0.9649 \pm 0.0042$$

$k_* = 0.05\ \mathrm{Mpc}^{-1}$

PLANCK 2018

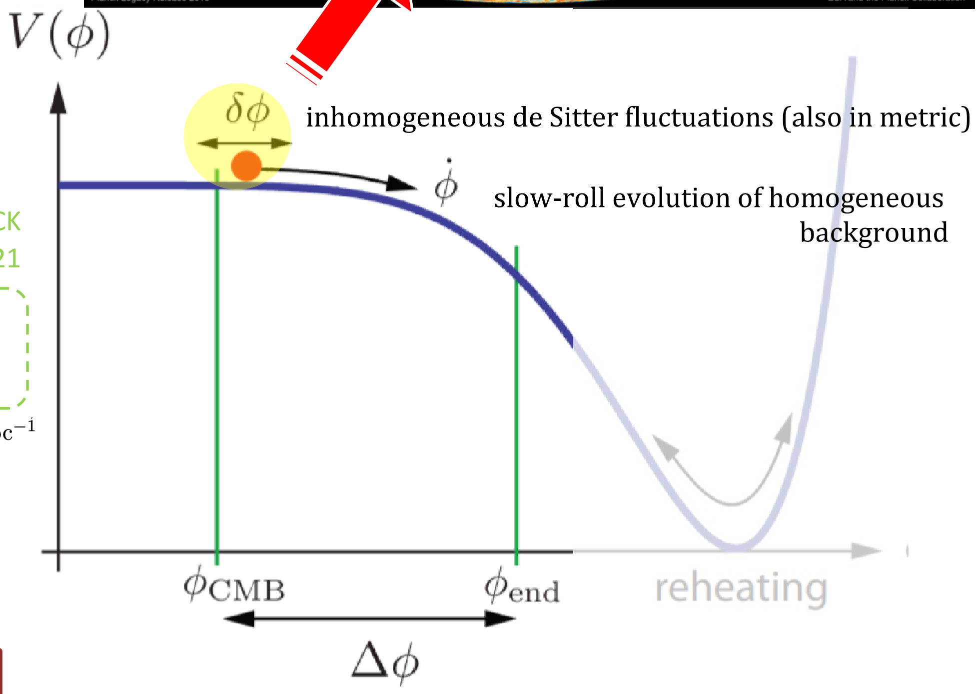
$$r < 0.036$$

$k_* = 0.05\ \mathrm{Mpc}^{-1}$

Slight scale-dependence in scalar spectrum

Suppression of primordial GW

$\Longrightarrow$ favour concave (flat) potentials.



Einstein Frame

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

- **Non-minimal couplings** of scalars to gravity generically arise in curved spacetime:

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

Jordan frame

- Weyl rescaling $g_{\mu\nu}^{\mathcal{J}} \to g_{\mu\nu}^{\mathcal{E}} = \Omega^2(\rho_1, \rho_2, \sigma) g_{\mu\nu}^{\mathcal{J}}$ where $\Omega^2 \equiv 1 + \frac{\xi_1 \rho_1^2 + \xi_2 \rho_2^2 + \xi_S \sigma^2}{M_P^2}$.

- Result $\frac{\mathcal{L}^{\mathcal{E}}}{\sqrt{-g^{\mathcal{E}}}} \supset \frac{M_P^2}{2} R^{\mathcal{E}} - \frac{1}{2} \mathcal{G}_{IJ}^{\mathcal{E}} \partial_\mu \varphi^I \partial^\mu \varphi^J - V^{\mathcal{E}}(\varphi^I)$ and **flattened** potential at large-field values:

$(\xi_1 \rho_1^2 + \xi_2 \rho_2^2 + \xi_S \sigma^2 \gg M_P^2)$.

Induced field-space metric

$$\mathcal{G}_{IJ}^{\mathcal{E}} = \frac{\delta_{IJ}}{\Omega^2} + \frac{3M_P^2}{2} \frac{\partial \log \Omega^2}{\partial \varphi^I} \frac{\partial \log \Omega^2}{\partial \varphi^J}.$$

Einstein frame

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

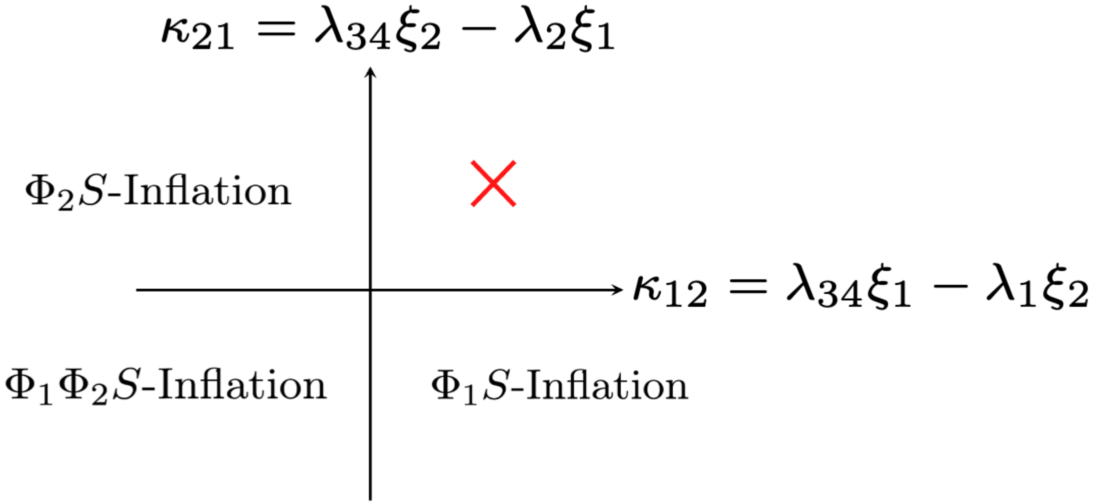
$(\lambda_{34} \equiv \lambda_3 + \lambda_4)$

Inflaton Valleys

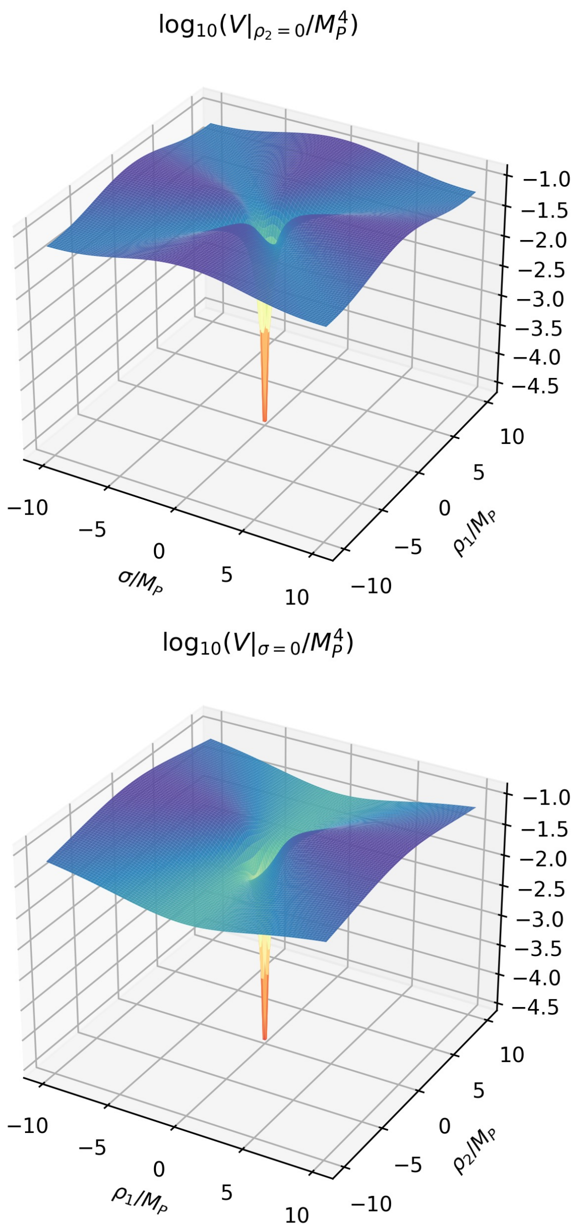
- **Effective single-field inflation along valleys** of the potential = attractors for general initial trajectories due to Hubble friction.
  - ➢ Negligible turn rate + suppressed multi-field effects*

*axion isocurvature fluctuations are an exception

- Classification of valley-structure in a general three-scalar problem leads to nine possibilities (parameter space in paper).
- Only three are generally satisfied in VISHυ models:



3D slices:



$\xi \gg 1$

$$V^{\mathcal{E}} \simeq \frac{M_P^4}{8}\frac{\lambda_{\text{eff}}}{\xi_{\text{eff}}^2}\left[1 - e^{-\frac{2}{\sqrt{6}}\frac{\chi_r}{M_P}}\right]^2$$

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

$A_s \sim 2.1 \times 10^{-9}$ [Planck, 2018]

- Large non-minimal couplings reproduce Starobinsky and Higgs inflation potential (excellent fit to CMB data).

$$\chi_r \equiv \sqrt{\frac{3}{2}} M_P \log(\Omega^2 - 1)$$

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

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

$\Phi_1\Phi_2 S$-Inf.

$$\frac{\lambda_S\lambda_i}{\lambda_S\xi_i^2 + \lambda_i\xi_S^2}$$

$\Phi_i S$-Inf.

- We compute the inflation observables in the slow-roll approximation.

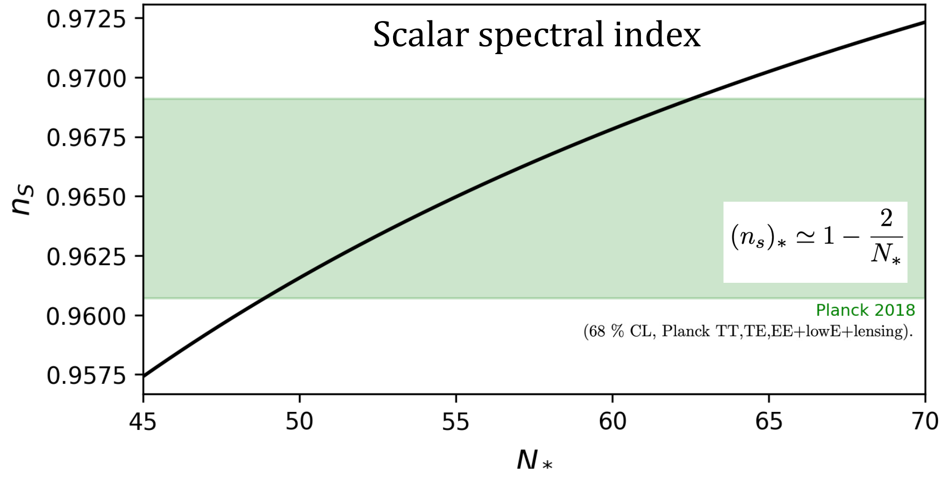
Not plotted: running in scalar spectral index in agreement with data for standard N_*

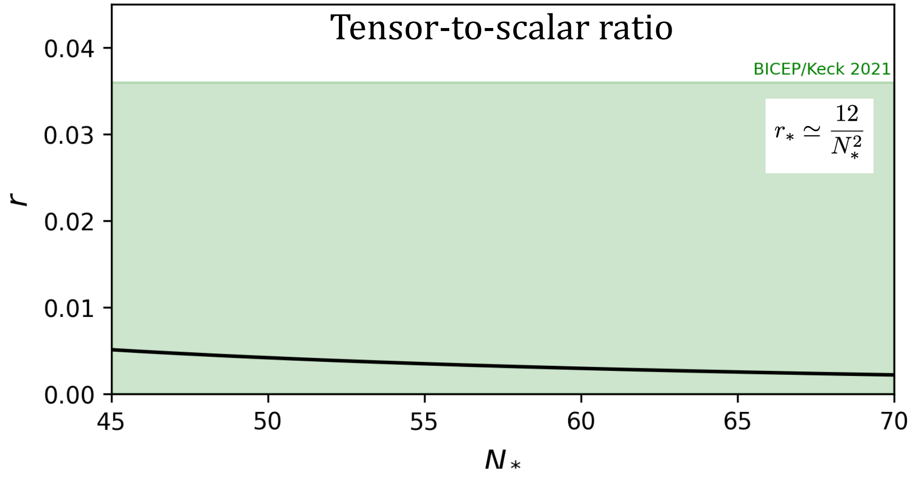
$$\alpha_s \equiv \frac{dn_s}{d\log k} = -0.0045 \pm 0.0067$$

(68 % CL, Planck TT,TE,EE+lowE+lensing).

$k_* = 0.05\ \text{Mpc}^{-1}$

[favoured region]





(**e-folds** between end of inflation and horizon exit of CMB pivot scale)

$\xi \lesssim 1$

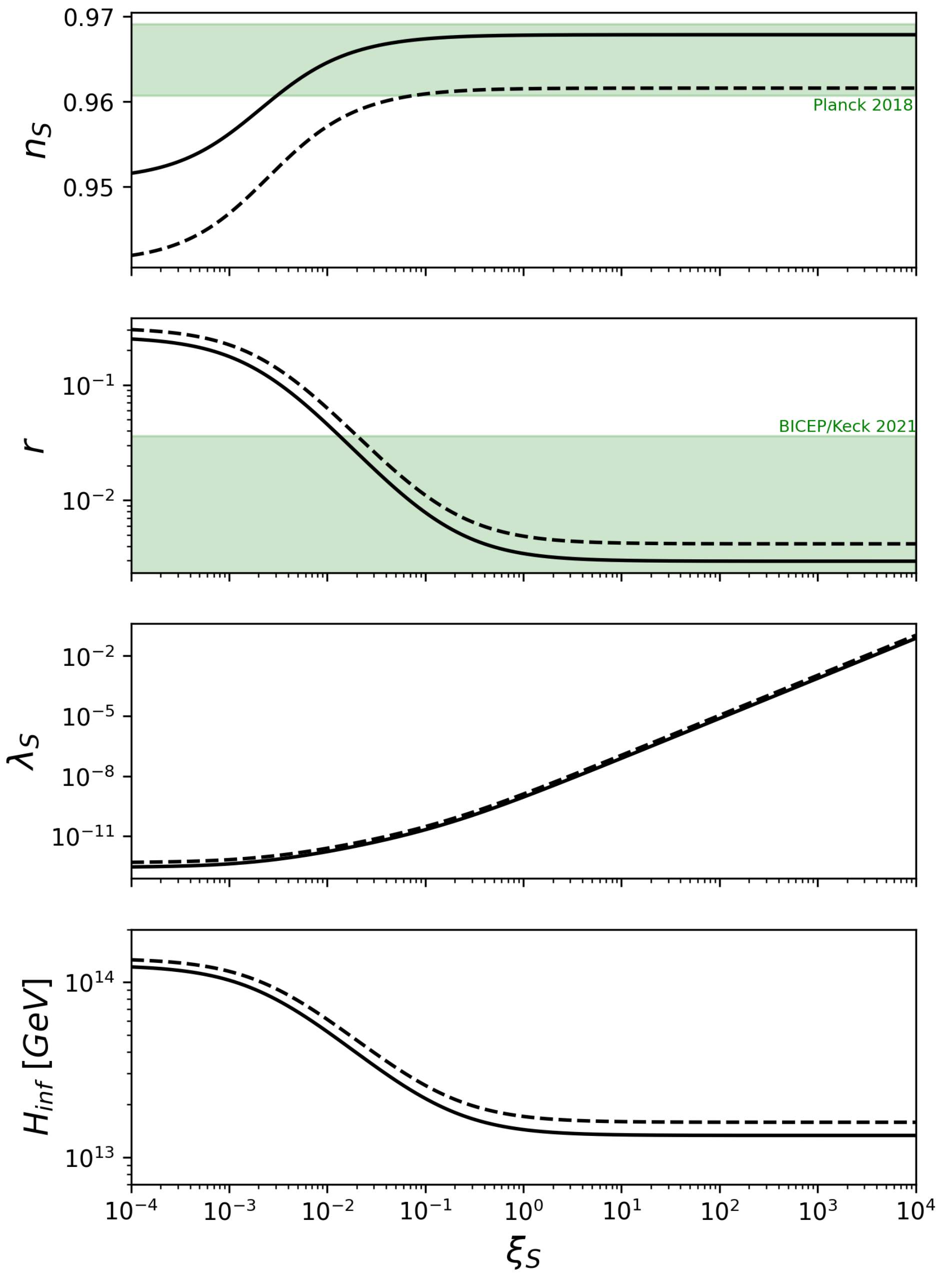
- Stability of the singlet direction ($\hat{\lambda}_S > 0$) can be preserved for viable inflaton self-couplings ($\lambda_S \gtrsim 10^{-11}$) provided $y_N^{\max} < 10^{-3}$.

$k = 1/16\pi^2$　　$\sigma_* \sim \mathcal{O}(10)M_P$

$$\hat{\lambda}_S(\sigma_*) \sim \lambda_S(\mu) - \mathcal{O}(k)\,(y_N^{\max})^4 \log(\sigma_*/\mu)$$

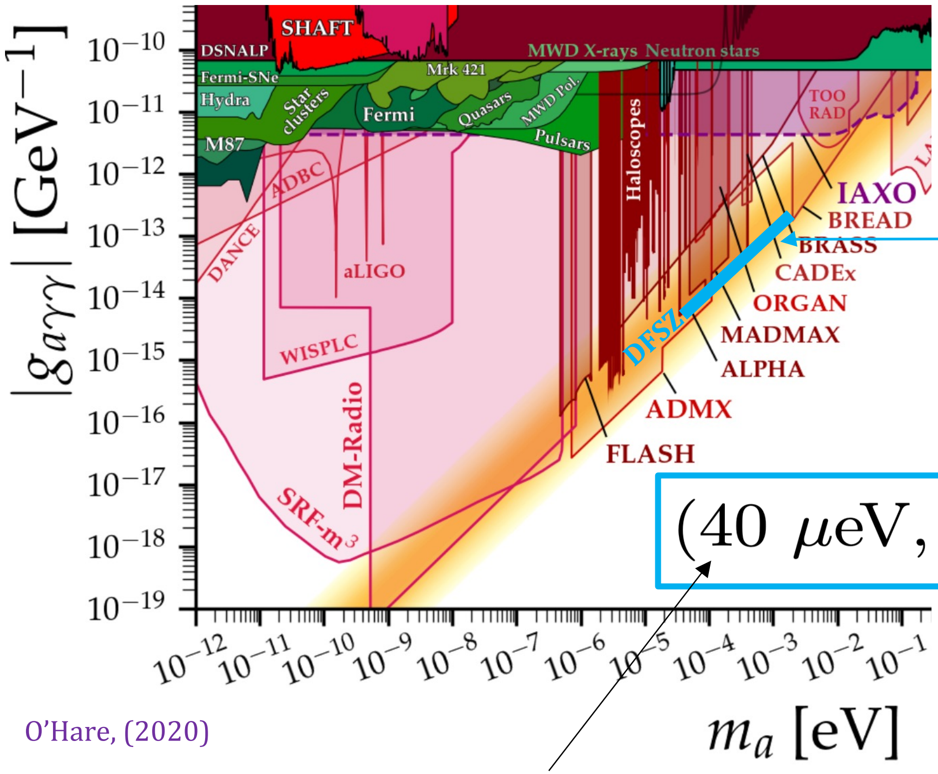
$\mu \sim m_\sigma$

- ➢ Smaller non-minimal couplings are viable ($\xi > 0.01$)
- ➢ $\xi \lesssim 1$ avoid possible unitarity issues
- Sufficient to analyse the singlet modulus direction (kinetic mixing an obstruction otherwise)



Some experimental prospects

Expect post-inflationary **axion** scenario accessible to haloscope projections:



O'Hare, (2020)

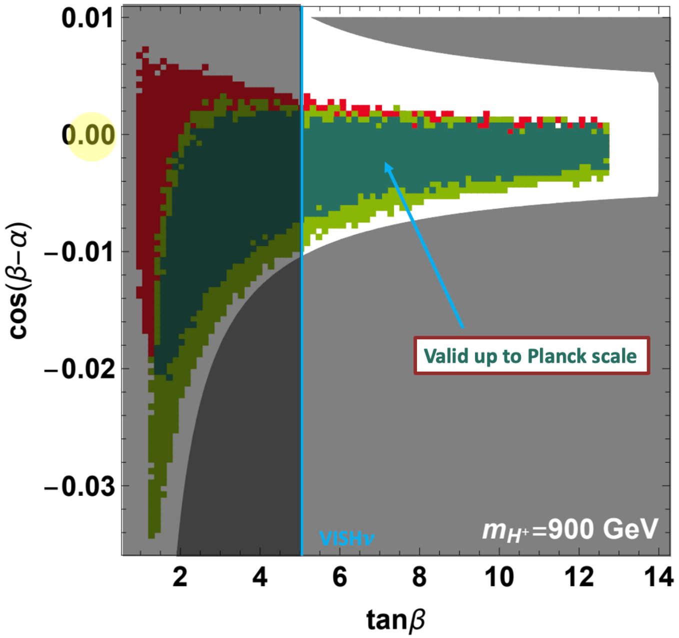
$$(40\ \mu\text{eV},\ \sim 2\ \text{meV})$$

Fixed by CDM density and unit domain wall number (subject to theoretical uncertainty in simulations)

DFSZ-like stellar cooling bound (RGB)

Colliders:

Oda, Shoji, Takahashi (2020)



Expect FCNC decays of top quark:

$$\mathcal{B}(t \to hc) < 0.073\ (0.051)\ \%,$$
$$\mathcal{B}(t \to hu) < 0.019\ (0.031)\ \%,$$

CMS, (2022)

$t-c$ mixing angle

$$a^2 \sin^2 \rho < 0.023$$

$$a = (\tan\beta + \cot\beta)\cos(\beta - \alpha)$$

Chiang+, (2018)

+ other processes, e.g. $cg \to tH$ or tA

Kodak, Modak, Hou, (2020)

Alignment preferred for high-scale validity and natural leptogenesis.

HL-LHC likely insensitive to predicted g_{hVV} deviations

Next generation of CMB experiments will decisively probe tensor-to-scalar ratio predictions: $r \gtrsim 0.01$

+ possible gravitational waves signatures from PQ phase transition

Ringwald, Saikawa, Tamarit, (2021)

Summary

- VISHν extensions are successful inflation models that meet particle physics objectives, solving five SM shortcomings:
  - ✓ Dark matter, active neutrino masses, BAU, strong *CP* and inflation (+ heavy top mass...)
- Accomplished *without* introducing naturalness issues to the SM (and *with* a detectable dark matter candidate).
  - ✓ Existence proof that weakly-coupled high-scale physics is a minimal + coordinated way of addressing these issues.
- Reheating outcomes under investigation.

Thank you for listening.