An extended scalar sector for the known physics beyond the SM

Scalars 2015 - Warsaw

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In collaboration with Stefano Bertolini, Helena Kolešová, Michal Malinský, Juan Carlos Vasquez

Beyond the Standard Model (SM)

- Experimental evidence for physics beyond the SM
  - Neutrino oscillations
  - Dark Matter
  - Baryon asymmetry
  - Gravity
  - …

- Theoretical issues of the SM
  - Strong CP
  - EW naturalness
  - Cosmological constant
  - Landau poles / triviality
  - …

Beyond the Standard Model (SM)

- Experimental evidence for physics beyond the SM
  - Neutrino oscillations
  - Dark Matter
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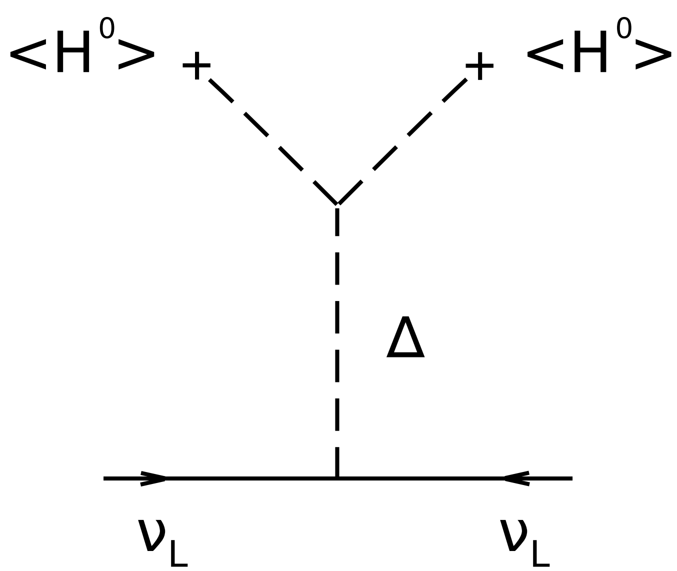
$\rightarrow$ A simple *scalar* extension of the SM may account for all these issues

- Theoretical issues of the SM
  - Strong CP
  - EW naturalness
  - Cosmological constant
  - Landau poles / triviality
  - …

Neutrino masses

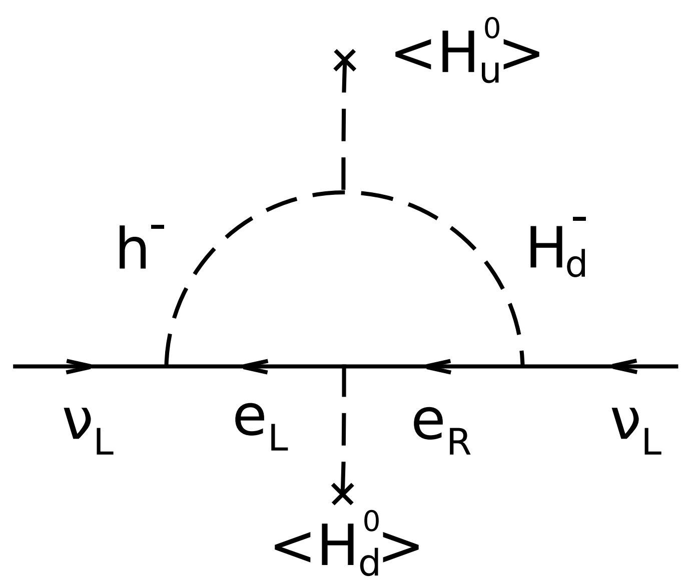
- Realizations of neutrino masses in *scalar* extensions of the SM

$(\ell\ell HH)/\Lambda$



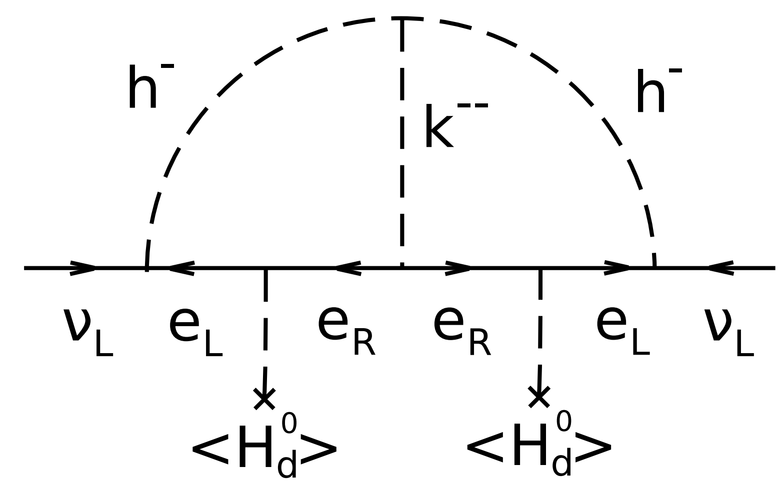
[Schechter, Valle (1980),
Cheng, Li (1980),
Lazarides, Shafi, Wetterich (1981),
Mohapatra, Senjanovic (1981)]

$(\ell\ell\ell e^c H)/\Lambda^3$



[Zee (1980), Wolfenstein (1980),
Balaji, Grimus, Schwetz (2001),
Babu, Julio (2014)]

$(\ell\ell\ell e^c \ell e^c)/\Lambda^5$



[Zee (1986), Babu (1988)]

⇨ See talk by Santamaria

Strong CP and the QCD Axion

- Two sources of CP violation in QCD

$$\mathcal{L}_{\rm QCD} = \sum_q \overline{\psi}_q \left(i\not{D} - m_q e^{i\theta_q}\right) \psi_q - \frac{1}{4} G^{\mu\nu}_a G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}$$

- No neutron EDM $\longrightarrow$ $\bar{\theta} = \theta - \text{Arg Det } M_q < 10^{-11}$

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- No neutron EDM $\longrightarrow$ $\bar{\theta} = \theta - \text{Arg Det } M_q < 10^{-11}$

- Spontaneously broken chiral (anomalous) global U(1)PQ [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

- axion: PGB of U(1)PQ $\quad a \to a + \delta\alpha \, v_{PQ}$

$$\mathcal{L}_{eff} = -\frac{1}{2} \partial_\mu a \partial^\mu a + \mathcal{L}(\partial_\mu a, \psi) + \left(\bar{\theta} + \xi \frac{a}{v_{PQ}} \right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - V_{eff}(a)$$

- The $\bar{\theta}$-term is *washed out* at the minimum by the axion

$$V_{eff} \sim \Lambda^4_{\rm QCD} \left[1 - \cos \left(\bar{\theta} + \xi \frac{a}{v_{PQ}} \right) \right] \longrightarrow \bar{\theta} = -\xi \frac{\langle a \rangle}{v_{PQ}}$$

DFSZ invisible axion

- Simplest implementation of the PQ mechanism for *scalar* extensions of the SM

[Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

DFSZ invisible axion

- Simplest implementation of the PQ mechanism for *scalar* extensions of the SM

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- Requires:

i) two Higgs doublets in order for $U(1)_{PQ}$ to be anomalous (Weinberg-Wilczek axion)

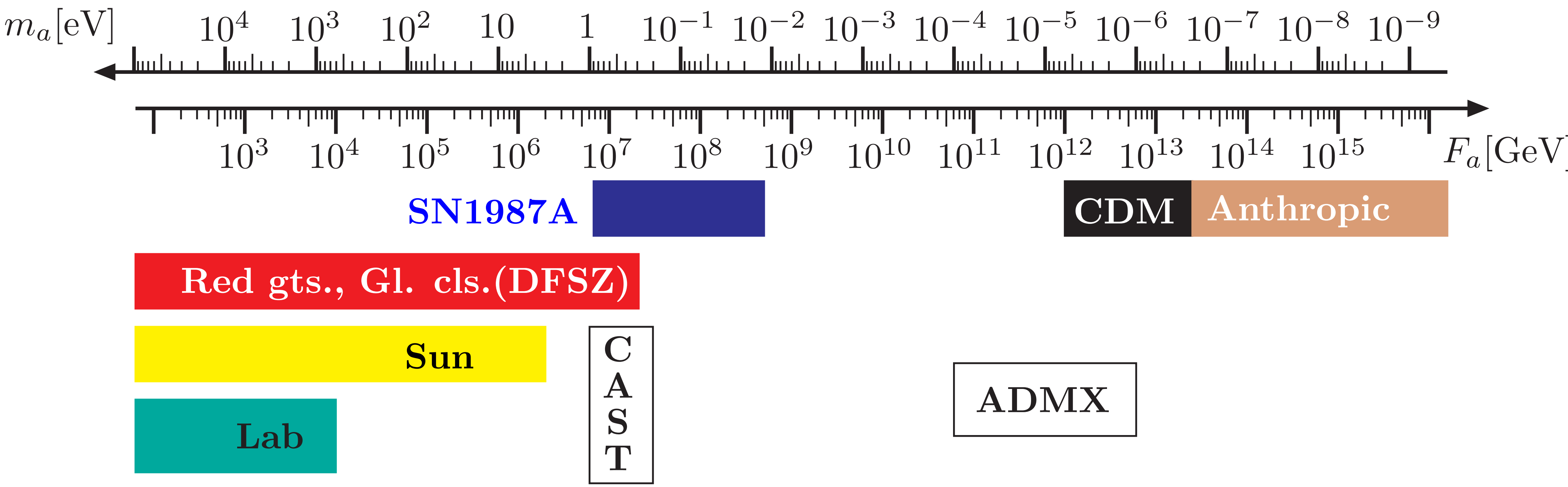
ii) a SM singlet which spontaneously break $U(1)_{PQ}$ at energies ≫ EW scale (invisible axion)

$$\langle \sigma \rangle \equiv V_\sigma \gg v_{u,d}$$

- axion mass $m_a \sim \dfrac{\Lambda^2_{\rm QCD}}{f_a}$ $(f_a = \sqrt{2} V_\sigma)$

- axion couplings $\sim 1/f_a$

DFSZ invisible axion



[Kim, Carosi (2009)]

- axion mass $m_a \sim \dfrac{\Lambda^2_{\text{QCD}}}{f_a}$ $\left(f_a = \sqrt{2} V_\sigma \right)$

- axion couplings $\sim 1/f_a$

"Axionization" of neutrino masses

- A (likely incomplete) list of refs. on the axion-neutrino connection

New fermions (mostly Type-I seesaw)

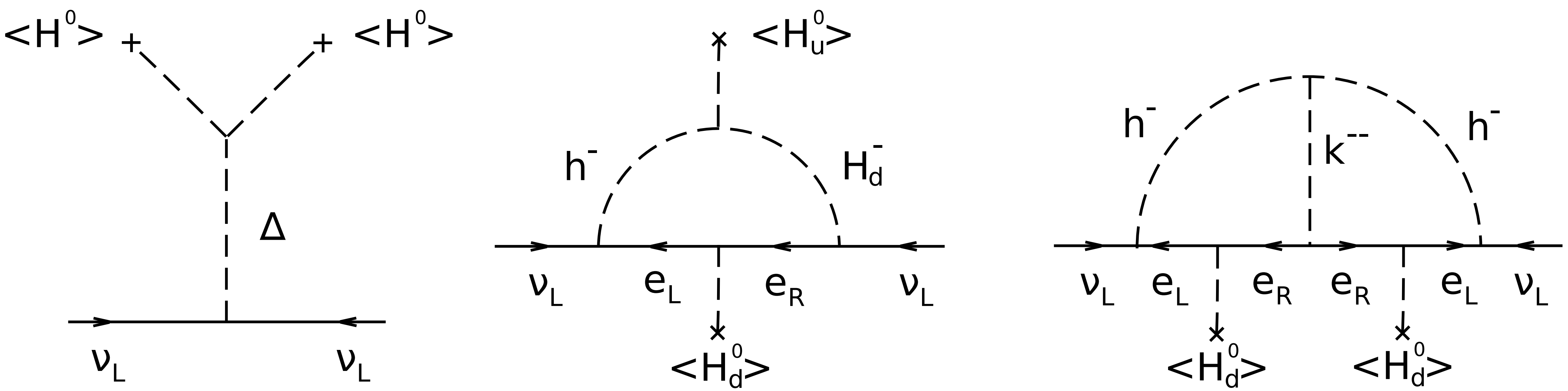
[Mohapatra, Senjanovic (1983),
Shafi, Stecker (1984),
Langacker, Peccei, Yanagida (1986),
Shin (1987),
He, Volkas (1988),
Geng, Ng (1989),
Berezhiani, Khlopov (1991),
Ma (2001),
Dias, Pleitez (2006),
Ma (2012),
Chen, Tsai (2013),
Park (2014),
Dias, Machado, Nishi, Ringwald, Vaudrevange (2014),
Salvio (2015),
Carvajal, Dias, Nishi, Sanchez-Vega (2015),
Clarke, Volkas (2015),
Ahn, Chun (2015)]

New *scalars* (Zee model)

[Bertolini, Santamaria (1991),
Arason, Ramond, Wright (1991)]

“Axionization” of neutrino masses

- A (likely incomplete) list of refs. on the axion-neutrino connection
- Promote the trilinear mass parameters in the scalar potential to PQ spurions



"Axionization" of neutrino masses

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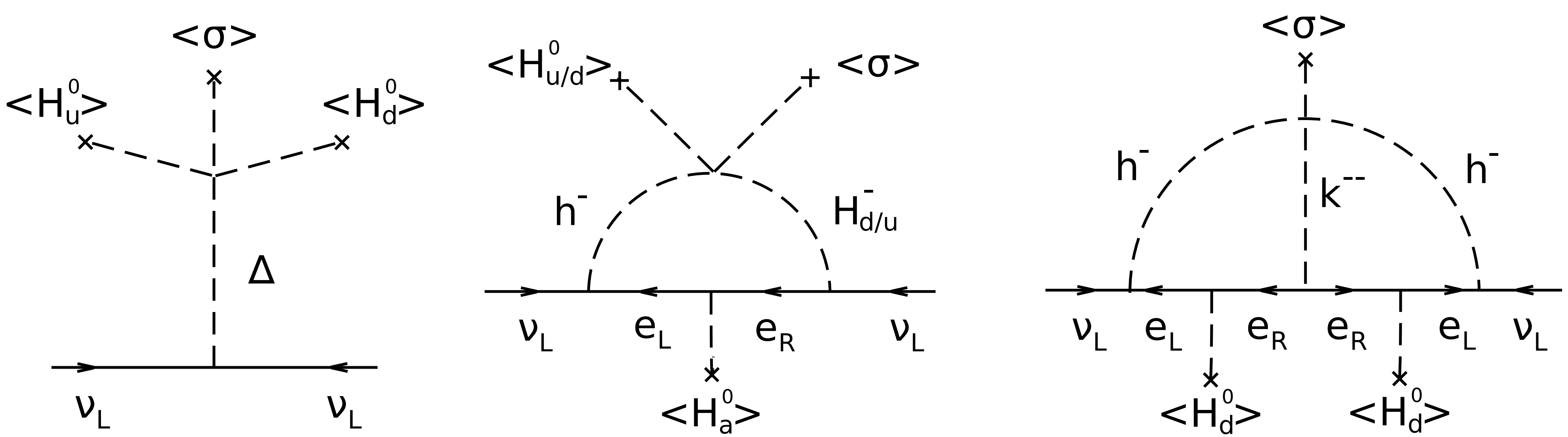

[Bertolini, DL, Kolesova, Malinsky (2014)]

→ PQ breaking triggers both neutrino masses and axion dynamics

PQ extended type-II seesaw

- Paradigmatic example: type-II seesaw

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
q_L	$\frac{1}{2}$	3	2	$+\frac{1}{6}$	0
u_R	$\frac{1}{2}$	3	1	$+\frac{2}{3}$	X_u
d_R	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	X_d
ℓ_L	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	X_ℓ
e_R	$\frac{1}{2}$	1	1	-1	X_e
H_u	0	1	2	$-\frac{1}{2}$	$-X_u$
H_d	0	1	2	$+\frac{1}{2}$	$-X_d$
Δ	0	1	3	$+1$	X_Δ
σ	0	1	1	0	X_σ

Extended scalar sector

PQ extended type-II seesaw

- Paradigmatic example: type-II seesaw

$$- \mathcal{L}_Y^{\rm TII} = Y_u \, \overline{q}_L u_R H_u + Y_d \, \overline{q}_L d_R H_d + Y_e \, \overline{\ell}_L e_R H_d + \tfrac{1}{2} Y_\Delta \, \ell_L^T C i \tau_2 \Delta \, \ell_L + \text{h.c.}$$

$$V_{\rm TII} = \text{moduli terms} + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \boldsymbol{\Delta}^\dagger H_d + \text{h.c.} \right)$$

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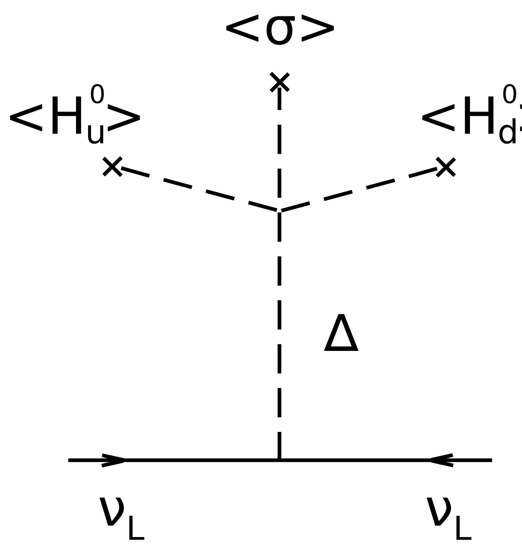
$$V_{\mathrm{TII}} = \text{moduli terms} + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \mathbf{\Delta}^\dagger H_d + \text{h.c.} \right)$$

- We require:
  - λ_5 to assign a non-vanishing PQ charge to sigma
  - λ_6 to break L number (together with Y_Δ)

$$M_\nu^{\mathrm{TII}} = Y_\Delta v_\Delta \approx - \frac{Y_\Delta \lambda_6 V_\sigma v_u v_d}{M_\Delta^2}$$



→ PQ charges fixed up to a normalization (as in DFSZ + tiny coupling axion-nu)

A closer look at the scalar potential

- Emerging symmetries in corners of parameter space

$$
\begin{aligned}
V_{\mathrm{TII}} = & -\mu_1^2 \left|H_u\right|^2 + \lambda_1 \left|H_u\right|^4 - \mu_2^2 \left|H_d\right|^2 + \lambda_2 \left|H_d\right|^4 + \lambda_{12} \left|H_u\right|^2 \left|H_d\right|^2 + \lambda_4 \left|H_u^\dagger H_d\right|^2 \\
& - \mu_3^2 \left|\sigma\right|^2 + \lambda_3 \left|\sigma\right|^4 + \lambda_{13} \left|\sigma\right|^2 \left|H_u\right|^2 + \lambda_{23} \left|\sigma\right|^2 \left|H_d\right|^2 \\
& + \mathrm{Tr}(\boldsymbol{\Delta}^\dagger \boldsymbol{\Delta}) \left[\mu_\Delta^2 + \lambda_{\Delta 1} \left|H_u\right|^2 + \lambda_{\Delta 2} \left|H_d\right|^2 + \lambda_{\Delta 3} \left|\sigma\right|^2 + \lambda_{\Delta 4} \mathrm{Tr}(\boldsymbol{\Delta}^\dagger \boldsymbol{\Delta})\right] \\
& + \lambda_7 H_u^\dagger \boldsymbol{\Delta} \boldsymbol{\Delta}^\dagger H_u + \lambda_8 H_d^\dagger \boldsymbol{\Delta} \boldsymbol{\Delta}^\dagger H_d + \lambda_9 \mathrm{Tr}(\boldsymbol{\Delta}^\dagger \boldsymbol{\Delta})^2 + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \boldsymbol{\Delta}^\dagger H_d + \mathrm{h.c.}\right)
\end{aligned}
$$

- All $\lambda \neq 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ}$ (“hat” stands for spontaneously broken)

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$$\begin{aligned}V_{\mathrm{TII}} = &-\mu_1^2 \left|H_u\right|^2 + \lambda_1 \left|H_u\right|^4 - \mu_2^2 \left|H_d\right|^2 + \lambda_2 \left|H_d\right|^4 + \lambda_{12} \left|H_u\right|^2 \left|H_d\right|^2 + \lambda_4 \left|H_u^\dagger H_d\right|^2 \\ &- \mu_3^2 \left|\sigma\right|^2 + \lambda_3 \left|\sigma\right|^4 + \lambda_{13} \left|\sigma\right|^2 \left|H_u\right|^2 + \lambda_{23} \left|\sigma\right|^2 \left|H_d\right|^2 \\ &+ \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta}) \left[\mu_\Delta^2 + \lambda_{\Delta 1} \left|H_u\right|^2 + \lambda_{\Delta 2} \left|H_d\right|^2 + \lambda_{\Delta 3} \left|\sigma\right|^2 + \lambda_{\Delta 4} \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta})\right] \\ &+ \lambda_7 H_u^\dagger \mathbf{\Delta} \mathbf{\Delta}^\dagger H_u + \lambda_8 H_d^\dagger \mathbf{\Delta} \mathbf{\Delta}^\dagger H_d + \lambda_9 \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta})^2 + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \mathbf{\Delta}^\dagger H_d + \mathrm{h.c.}\right)\end{aligned}$$

- All $\lambda \neq 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ}$
- $\lambda_6 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L$ (massless neutrino)

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& - \mu_3^2 \left|\sigma\right|^2 + \lambda_3 \left|\sigma\right|^4 + \lambda_{13} \left|\sigma\right|^2 \left|H_u\right|^2 + \lambda_{23} \left|\sigma\right|^2 \left|H_d\right|^2 \\
& + {\rm Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta}) \left[\mu_\Delta^2 + \lambda_{\Delta 1} \left|H_u\right|^2 + \lambda_{\Delta 2} \left|H_d\right|^2 + \lambda_{\Delta 3} \left|\sigma\right|^2 + \lambda_{\Delta 4} {\rm Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta})\right] \\
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- $\text{All } \lambda \neq 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ}$
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- $\lambda_5 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes \widehat{U(1)}_L$ (Weinberg-Wilczek axion + Majoron)

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- $\lambda_5, \lambda_6 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L \otimes \widehat{U(1)}_\sigma$

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- $\lambda_5, \lambda_6 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L \otimes \widehat{U(1)}_\sigma$
- $\lambda_5, \lambda_6, \lambda_{i3} = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L \otimes \widehat{U(1)}_\sigma \otimes \mathcal{G}_P^\sigma$ (extra Poincare' symmetry)

[Georgi (?), Volkas, Davies, Joshi (1988), Bertolini, Santamaria (1991), Foot, Kobakhidze, McDonald, Volkas (2014)]

A closer look at the scalar potential

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

- the energy-momentum tensors are independently conserved in the two sectors*

$$\partial_\mu T^{\mu\nu}_{/\sigma} = \partial_\mu T^{\mu\nu}_{\sigma} = 0$$

*the argument ignores gravity

- $\lambda_5, \lambda_6, \lambda_{i3} = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L \otimes \widehat{U(1)}_{\sigma} \otimes \mathcal{G}^{\sigma}_{P}$ (extra Poincare' symmetry)

[Georgi (?), Volkas, Davies, Joshi (1988), Bertolini, Santamaria (1991), Foot, Kobakhidze, McDonald, Volkas (2014)]

EW Naturalness*

- A stable hierarchy b/w PQ and EW is automatically achieved by decoupling the singlet

$$\lambda_{i3}, \lambda_5 \sim \mathcal{O}\left(\frac{v^2}{V_\sigma^2}\right) \quad \text{and} \quad \lambda_6 \sim \mathcal{O}\left(\frac{v_\Delta}{V_\sigma}\right)$$

$$V_{\text{mix}} \ni \lambda_{13} \left|\sigma\right|^2 \left|H_u\right|^2 + \lambda_{23} \left|\sigma\right|^2 \left|H_d\right|^2 + \lambda_{\Delta 3} \left|\sigma\right|^2 \text{Tr}(\boldsymbol{\Delta}^\dagger \boldsymbol{\Delta}) + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \boldsymbol{\Delta}^\dagger H_d + \text{h.c.}\right)$$

*again, ignoring gravity

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- The ultraweak limit $\lambda_{i3}, \lambda_5, \lambda_6 \ll 1$ is technically natural (extended Poincare' symmetry)

  - Verified by inspecting the fixed-point structure of the RGEs

$$\beta_{\lambda_{13}} \propto \lambda_{13}(\ldots) + \lambda_{23}(\ldots) + \lambda_{\Delta 3}(\ldots) + 8\lambda_5^2 + 3\lambda_6^2$$

$$\beta_{\lambda_{23}} \propto \lambda_{13}(\ldots) + \lambda_{23}(\ldots) + \lambda_{\Delta 3}(\ldots) + 8\lambda_5^2 + 3\lambda_6^2$$

$$\beta_{\lambda_{\Delta 3}} \propto \lambda_{13}(\ldots) + \lambda_{23}(\ldots) + \lambda_{\Delta 3}(\ldots) + 2\lambda_6^2$$

$$\beta_{\lambda_5} \propto \lambda_5(\ldots)$$

$$\beta_{\lambda_6} \propto \lambda_6(\ldots)$$

*again, ignoring gravity

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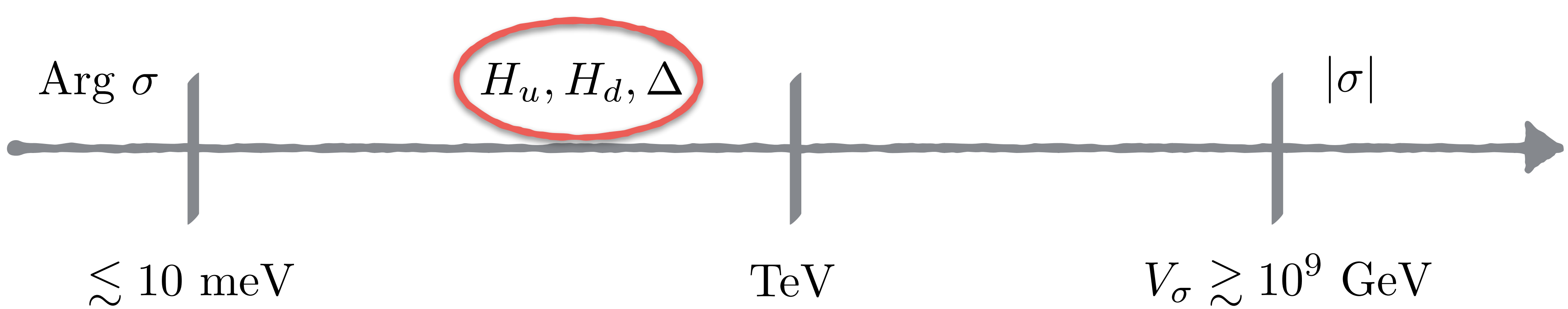
$$\lambda_{i3}, \lambda_5 \sim \mathcal{O}\left(\frac{v^2}{V_\sigma^2}\right) \quad \text{and} \quad \lambda_6 \sim \mathcal{O}\left(\frac{v_\Delta}{V_\sigma}\right)$$

- The ultraweak limit $\lambda_{i3}, \lambda_5, \lambda_6 \ll 1$ is technically natural (extended Poincare' symmetry)
- Non-singlet fields *cannot* be decoupled via ultraweak limit (2-loop gauge int.'s)

  - A "fully natural" model requires an extended scalar sector below the TeV scale



(classical) scale invariance

- PQ-EW hierarchy might arise radiatively à la Coleman-Weinberg [Allison, Hill, Ross (2014)] [Hill (2014)]

⇨ See talk by Lindner

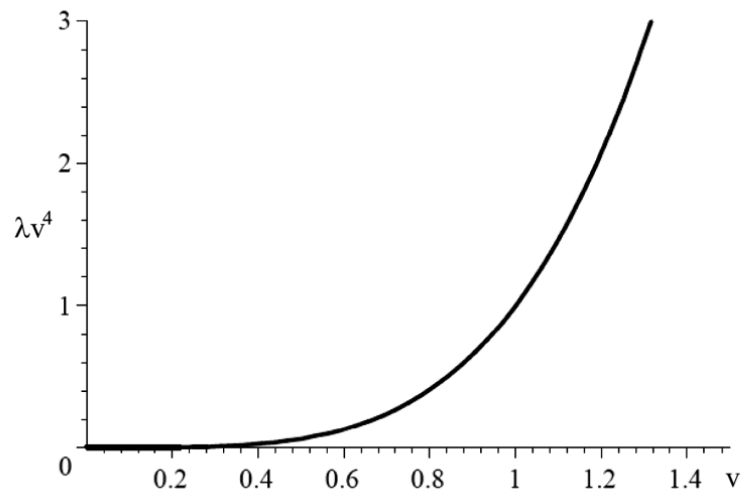


FIG. 1. Classical $\sim\lambda v^4$ potential.

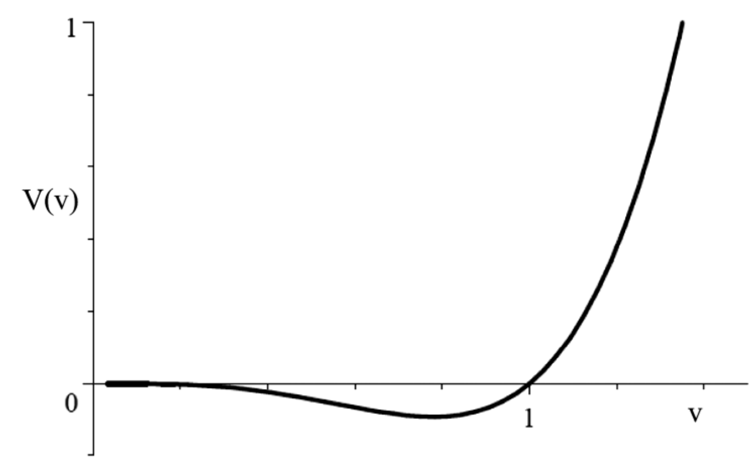


FIG. 3. Resulting CW potential, $\sim\beta v^4 \ln(v/M)$.

(classical) scale invariance

- PQ-EW hierarchy might arise radiatively à la Coleman-Weinberg [Allison, Hill, Ross (2014)]
- Absence of trilinear terms allows to implement the same idea in our setup

[Bertolini, DL, Kolesova, Malinsky, Vasquez (2015)]

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\begin{aligned}
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& - \mu_3^2 \left|\sigma\right|^2 + \lambda_3 \left|\sigma\right|^4 + \lambda_{13} \left|\sigma\right|^2 \left|H_u\right|^2 + \lambda_{23} \left|\sigma\right|^2 \left|H_d\right|^2 \\
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$$
\begin{aligned}
V_{\mathrm{TII}} = & -\cancel{\mu_1^2} |H_u|^2 + \lambda_1 |H_u|^4 - \cancel{\mu_2^2} |H_d|^2 + \lambda_2 |H_d|^4 + \lambda_{12} |H_u|^2 |H_d|^2 + \lambda_4 \left|H_u^\dagger H_d\right|^2 \\
& - \cancel{\mu_3^2} |\sigma|^2 + \lambda_3 |\sigma|^4 + \lambda_{13} |\sigma|^2 |H_u|^2 + \lambda_{23} |\sigma|^2 |H_d|^2 \\
& + \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta}) \left[\cancel{\mu_\Delta^2} + \lambda_{\Delta 1} |H_u|^2 + \lambda_{\Delta 2} |H_d|^2 + \lambda_{\Delta 3} |\sigma|^2 + \lambda_{\Delta 4} \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta}) \right] \\
& + \lambda_7 H_u^\dagger \mathbf{\Delta} \mathbf{\Delta}^\dagger H_u + \lambda_8 H_d^\dagger \mathbf{\Delta} \mathbf{\Delta}^\dagger H_d + \lambda_9 \mathrm{Tr}(\mathbf{\Delta}^\dagger \mathbf{\Delta})^2 + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \mathbf{\Delta}^\dagger H_d + \mathrm{h.c.} \right) \\
& + \frac{1}{64\pi^2} \mathrm{Tr}\, M^4(\sigma) \left(\log \frac{M^2(\sigma)}{\mu^2} - \frac{3}{2} \right)
\end{aligned}
$$

(classical) scale invariance

- PQ-EW hierarchy might arise radiatively à la Coleman-Weinberg [Allison, Hill, Ross (2014)]
- Absence of trilinear terms allows to implement the same idea in our setup

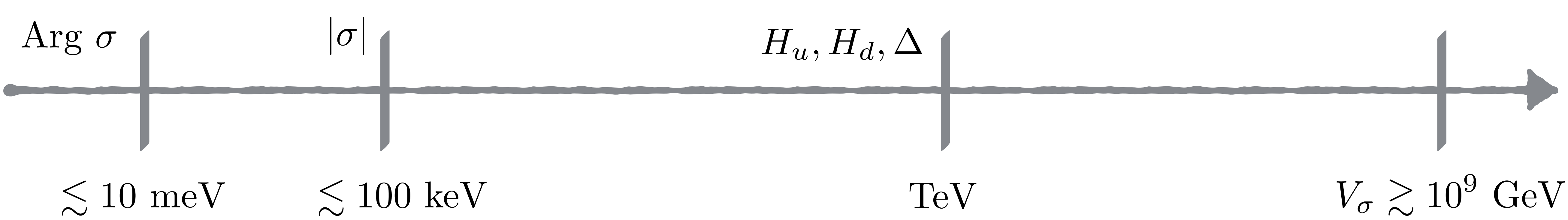
[Bertolini, DL, Kolesova, Malinsky, Vasquez (2015)]

- Requires: $\lambda_3 \sim (v/V_\sigma)^4 \ll \lambda_{i3,5} \sim (v/V_\sigma)^2$

- CW mechanism effective in the **σ** direction

- $|\sigma|$ behaves as a pseudo-dilaton

$$m_\sigma^2 = 2\beta_{\lambda_3} V_\sigma^2 \sim \frac{1}{16\pi^2}\left(\frac{v^2}{V_\sigma^2}\right)^2 v^2 \longrightarrow \text{scale anomaly}$$



Gifts from light scalars

- New extra scalars can easily improve the stability of the EW vacuum

$$V = V_{SM} + M_X^2 |X^2| + \lambda_{XH} |X|^2 |H|^2 + \dots$$

$$(4\pi)^2 \beta_{\lambda_H} = \left(12 y_t^2 - 3 g'^2 - 9 g^2\right) \lambda_H - 6 y_t^4 + \frac{3}{8} \left[2 g^4 + (g'^2 + g^2)^2\right] + 23 \lambda_H^2 + \frac{n_X}{2} \lambda_{XH}^2$$

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- EW baryogenesis [work in progress]

- Strong 1st order phase transition (enhanced cubic term in the Higgs background field)

$$\Delta V_{\rm eff}(\phi, T) \supset -\frac{n_X T}{12\pi} \left[\Pi_X(T) + M_X^2 + \frac{\lambda_{XH}}{2} \phi^2 \right]^{3/2}$$

Many known working examples: Inert doublet [Chowdhury, Nemevsek, Senjanovic, Zhang (2012)]
Type-II seesaw triplet [AbdusSalam, Chowdhury (2014)], …

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Type-II seesaw triplet [AbdusSalam, Chowdhury (2014)], …

- None of our tree-level minimal PQ-extended potentials violates CP

→ non-minimal PQ extended models ? [Geng, Jiang, Ng (1988), He, Volkas (1988)]

→ use $\bar{\theta}$-term ≠ 0 in the early universe ? [Servant (2014)]

Conclusions

- A *scalar* alternative to the ν_R-SM ?

DFSZ axion + type-II seesaw

Conclusions

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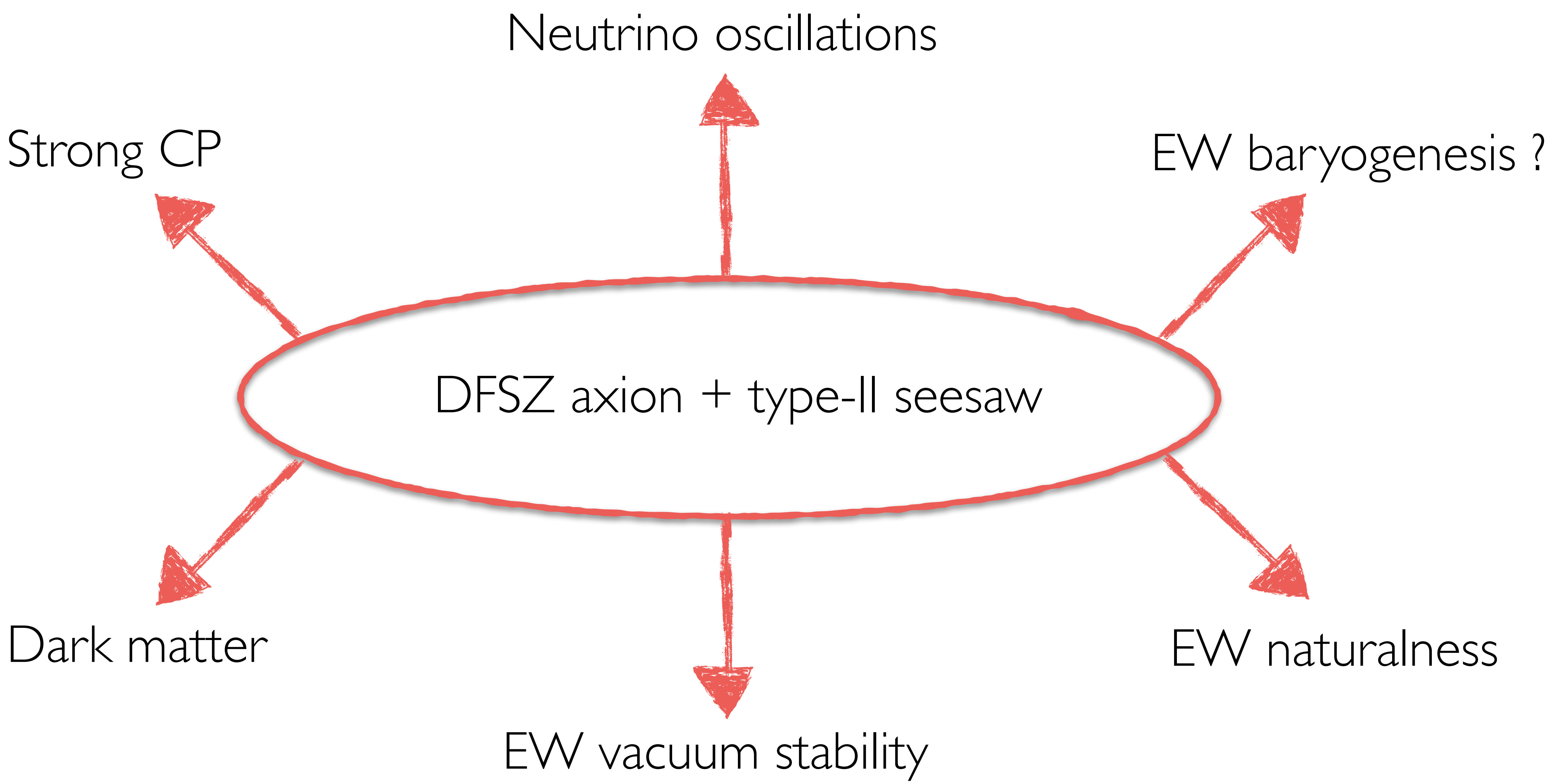


Backup slides

A threat to the PQ solution

- "Folk's theorem" about the non-existence of global symmetries in quantum gravity

  - global charges can be eaten by black holes, which may subsequently evaporate

[Bekenstein (1972), Zeldovich (1977)]

- Parametrizing explicit breaking by effective operators:

$$\mathcal{O}_{\cancel{\mathrm{PQ}}} = k \frac{\phi^n}{\Lambda^{n-4}} \qquad \xrightarrow{SSB} \qquad |k| \frac{f^n}{\Lambda^{n-4}} \cos(na + \arg k),$$

[Kamionkowski, March-Russell (1992), Kallosh, Linde, Linde, Susskind (1992), Holman et al. (1992)]

- for $\Lambda = m_{Pl}$ and $f = 10^9$ GeV :

$$\bar{\theta} \lesssim 10^{-10} \quad \longrightarrow \quad n \geq 10$$

Does the neutrino protect the axion ?

- Dual formulation of the axion allows to identify the source of gravitational breaking

[Kallosh, Linde, Linde, Susskind (1992), Dvali (2005)]

$$\partial_\mu J^\mu_{PQ} = G\tilde{G} + R\tilde{R}$$

- gravitational anomaly produces a non-zero $\bar{\theta}$

- For $m_\nu = 0$ there is a further chiral current ($J^\mu_L = \overline{\nu}_L \gamma^\mu \nu_L$) with a gravitational anomaly

$$\partial_\mu J^\mu_L = R\tilde{R}$$

[Dvali, Folkerts, Franca (2014)]

- if the axion couples to the current $J^\mu_{PQ} - J^\mu_L$ gravitational effects are absent

- Small neutrino mass disturbs the solution in a controlled way

$$m_\nu \lesssim 10^{-9} \frac{\Lambda^4_{\rm QCD}}{\Lambda^3_G} \longrightarrow \Lambda_G \lesssim 0.1 \text{ GeV}$$

Axion-neutrino coupling

- PQ charges fixed up to a normalization ($X_\sigma = 1$ and $x = \tan\beta \equiv v_u/v_d$)

$$X_u = \frac{2}{x^2+1} \qquad X_d = \frac{2x^2}{x^2+1} \qquad \boxed{X_\ell = \frac{x^2-3}{2(x^2+1)}} \qquad X_e = \frac{5x^2-3}{2(x^2+1)} \qquad X_\Delta = \frac{3-x^2}{x^2+1}$$

- With respect to DFSZ, an extra (tiny) coupling of the axion to neutrinos

$$\mathcal{L}_{a\nu\nu} = \frac{3-x^2}{2(x^2+1)} \frac{m_\nu}{f_a} a\bar{\nu} i\gamma_5 \nu$$

- Neutrinos might recouple (after EW decoupling) and leave an imprint in the CMB

[Hannestad, Raffelt (2005), …, Archidiacono Hannestad (2014)]

- Free-streaming requirement:

$$\Gamma_{\nu+\nu\to\nu+\nu} < H_{\rm dec} \quad \longrightarrow \quad (m_\nu/f_a)_{ii} < 10^{-7}$$

$$\Gamma_{\nu\to\nu'+a} < H_{\rm dec} \quad \longrightarrow \quad (m_\nu/f_a)_{ij} < 10^{-11}$$

The extended scalar sector

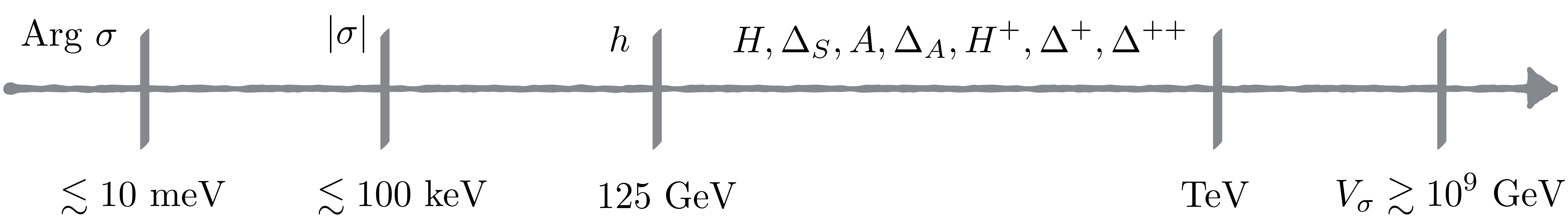
$$H_u = \begin{pmatrix} v_u + \frac{h_u^0 + i\eta_u^0}{\sqrt{2}} \\ h_u^- \end{pmatrix} \qquad H_d = \begin{pmatrix} h_d^+ \\ v_d + \frac{h_d^0 + i\eta_d^0}{\sqrt{2}} \end{pmatrix} \qquad \boldsymbol{\Delta} = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ v_\Delta + \frac{\delta^0 + i\eta_\delta^0}{\sqrt{2}} & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix} \qquad \sigma = V_\sigma + \frac{\sigma^0 + i\eta_\sigma^0}{\sqrt{2}}$$

- Neutral scalars $(h_u^0, h_d^0, \sigma^0, \delta^0)$: SM-like Higgs + 2 neutral scalars + pseudo-dilaton

- Neutral pseudo-scalars $(\eta_u^0, \eta_d^0, \eta_\sigma^0, \eta_\delta^0)$: Z0 GB + axion + 2 neutral pseudo-scalars

- Singly charged scalars (h_u^+, h_d^+, δ^+) : W GB + 2 singly charged scalars

- Doubly charged scalars δ^{++}



Higgs pheno and stability

- Effectively a 2HDM ($v_\Delta \ll v$) + extra constraints from PQ and classical scale invariance

- A benchmark point:

Quartic coupling	Electroweak-scale value
λ_1	0.15
$\lambda_2 = \lambda_{12} = \lambda_4$	0.08
$\lambda_7 = \lambda_8 = \lambda_9$	0.08
$\lambda_{\Delta 1} = \lambda_{\Delta 2} = \lambda_{\Delta 4}$	0.08
λ_5 / c_5	$3.0 \times 10^{-14} \left(\frac{10^9 \text{ GeV}}{V_\sigma} \right)^2$
λ_6 / c_6	$1.0 \times 10^{-9} \left(\frac{v_\Delta}{\text{GeV}} \right) \left(\frac{10^9 \text{ GeV}}{V_\sigma} \right)$
$\lambda_{13} (*)$	1.3×10^{-15}
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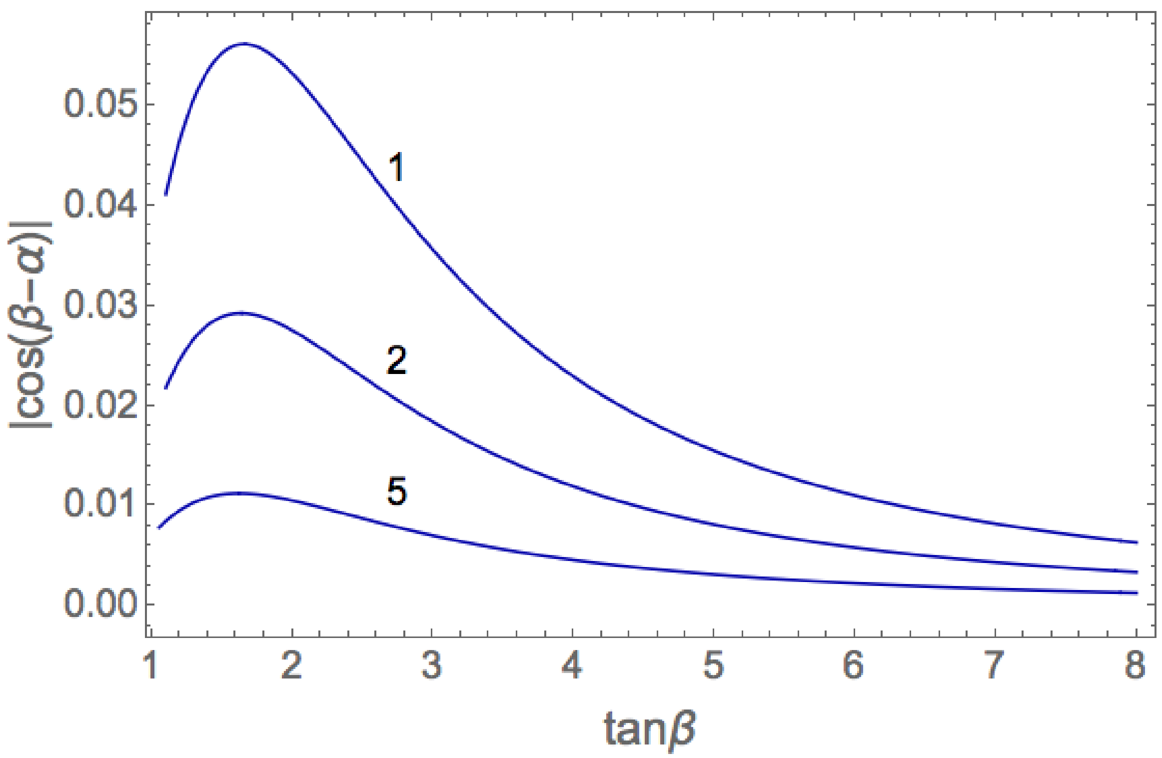
1) Satisfies Higgs data



$c_5 > 1$ gauges the degree of decoupling

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$\tan\beta$	c_5	m_h [GeV]	m_H [GeV]	m_A [GeV]	m_{H+} [GeV]
3.1	1.0	125	324	322	326
3.0	2.0	125	451	449	452
3.0	5.0	125	711	710	712

$\tan\beta$	$-c_6$	m_{Δ^0} [GeV]	m_{Δ^+} [GeV]	$m_{\Delta^{++}}$ [GeV]	m_σ [GeV]
	25	476	477	478	0.5×10^{-4}
3.0	50	674	674	675	0.9×10^{-4}
	75	825	826	826	1.3×10^{-4}

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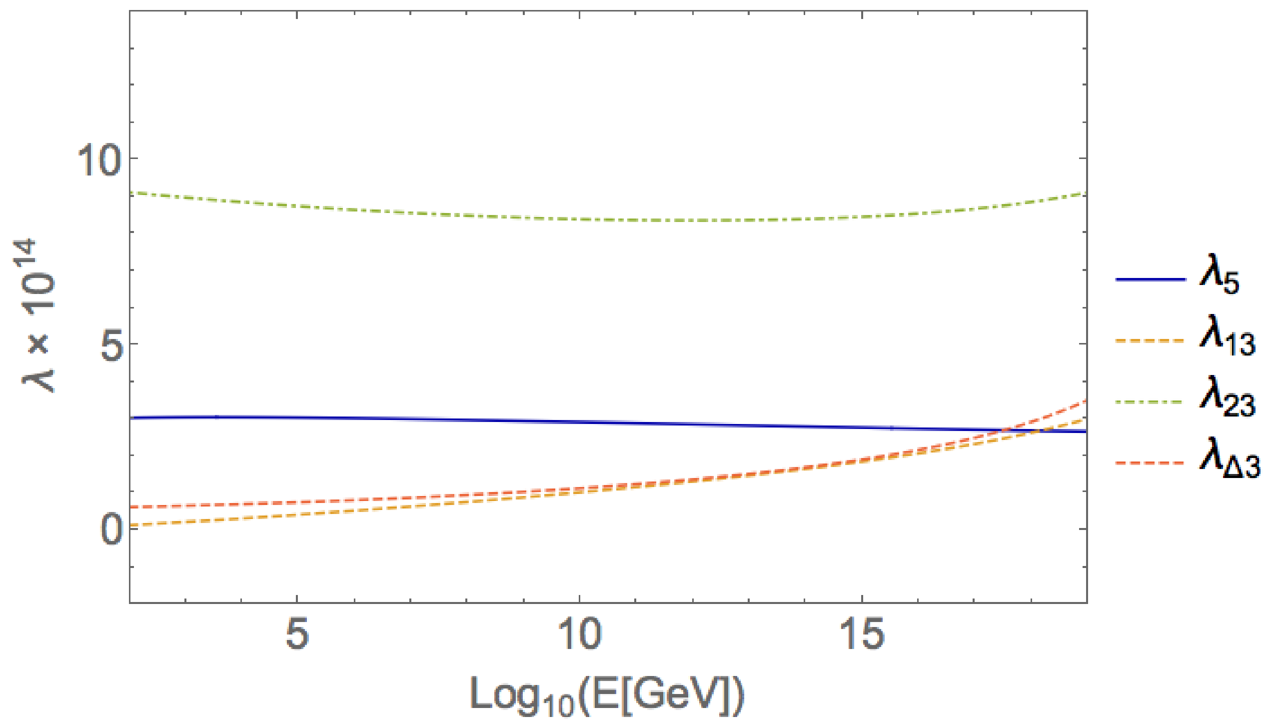

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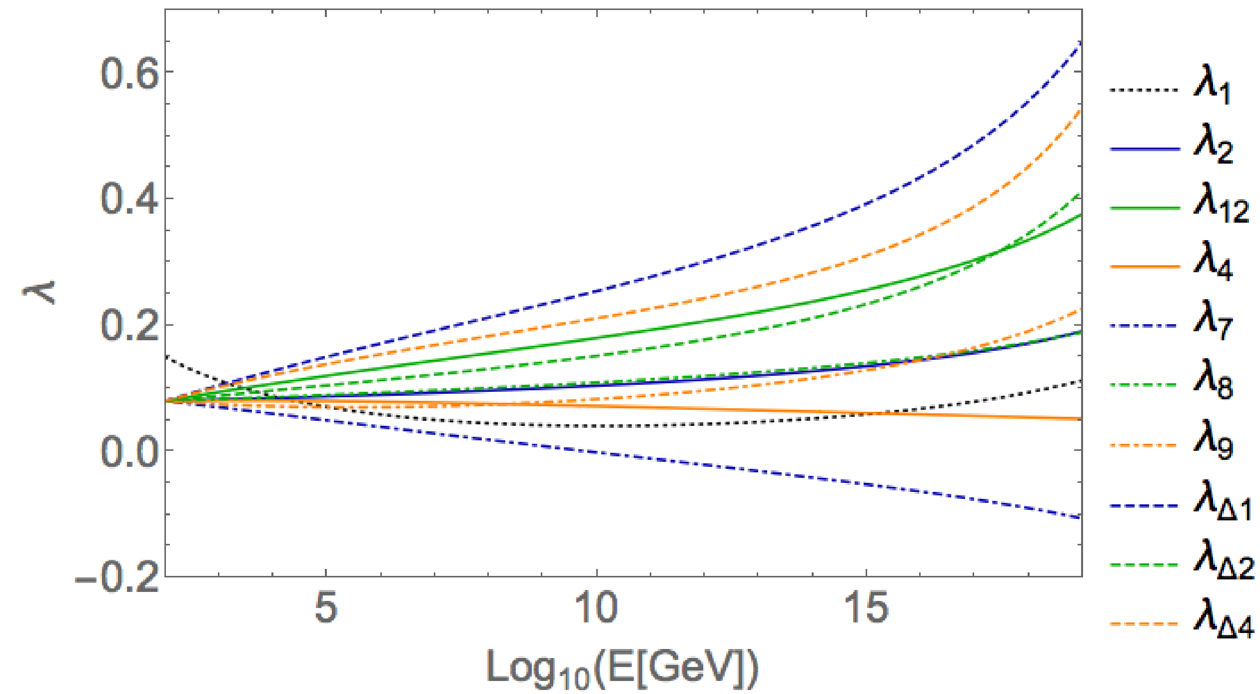
3) Radiative stability of ultraweak couplings

4) Vacuum stability and perturbativity



(classical) scale invariance

- PQ-EW hierarchy might arise radiatively à la Coleman-Weinberg [Allison, Hill, Ross (2014)] [Hill (2014)]

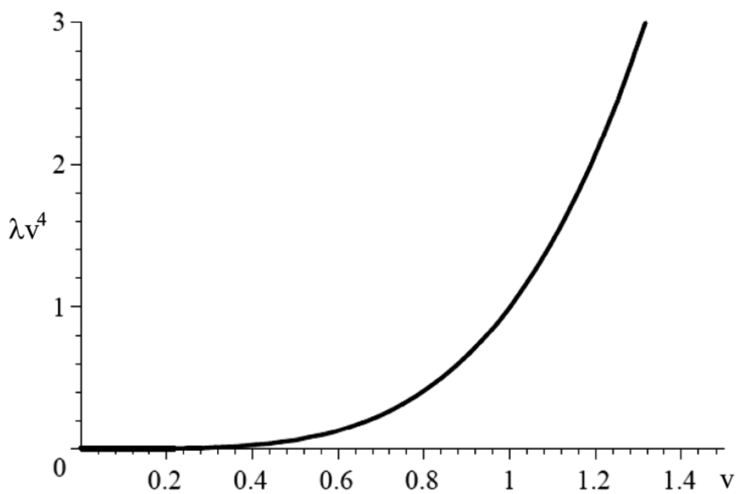


FIG. 1. Classical $\sim\lambda v^4$ potential.

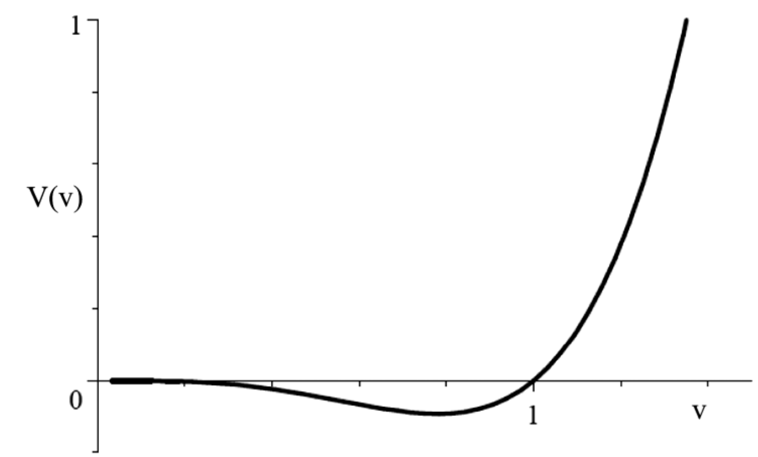


FIG. 3. Resulting CW potential, $\sim\beta v^4 \ln(v/M)$.

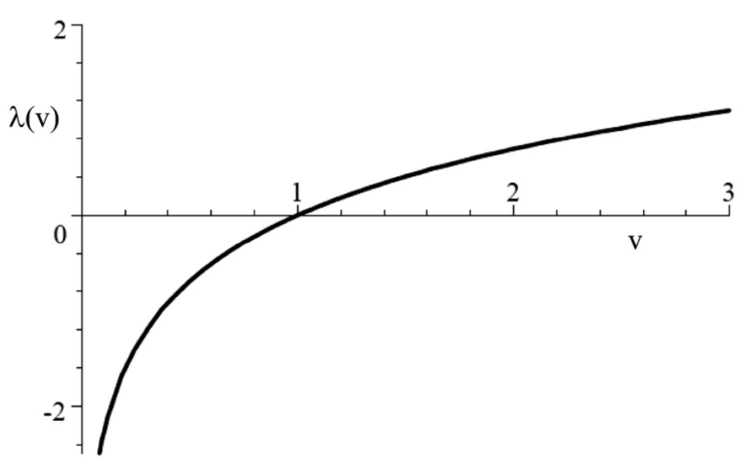


FIG. 2. Typical RG trajectory $\lambda \sim \beta \ln(v/M)$.

- local minimum $v_0 = M e^{-1/4}$
- extremal relationship $\beta(v_0) = -4\lambda(v_0)$