Massive neutrinos and invisible axion minimally connected

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Beyond the SM

- Evidence/hints for physics beyond the SM
  - Neutrino oscillations
  - Dark Matter
  - Baryon asymmetry
  - EW vacuum instability
  - Gravity
  - …

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- Theoretical problems of the SM

- Strong CP	$\bar{\theta}\, G^{\mu\nu} \tilde{G}_{\mu\nu} \quad (D = 4)$	→	$\bar{\theta} \lesssim 10^{-11}$
- EW naturalness	$\Lambda^2\, H^\dagger H \quad (D = 2)$	→	$\Lambda \approx 100 \text{ GeV}$
- Cosmological constant	$\Lambda^4 \sqrt{g} \quad (D = 0)$	→	$\Lambda \approx 10^{-3} \text{ eV}$
- Landau poles			
- …			

Beyond the SM

- Evidence/hints for physics beyond the SM

  - Neutrino oscillations
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  - EW vacuum instability
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→ A simple scalar extension of the SM may account for all these issues

- Theoretical problems of the SM

  - Strong CP
  - EW naturalness
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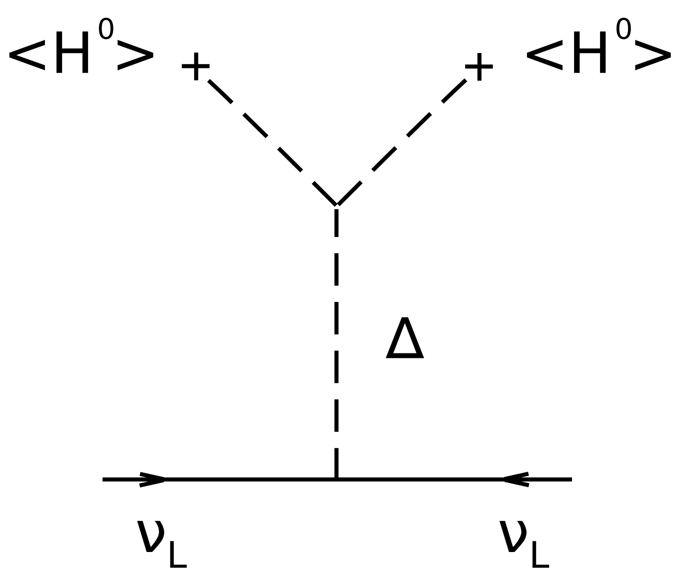
  - …

Axion + neutrino mass models

Neutrino masses

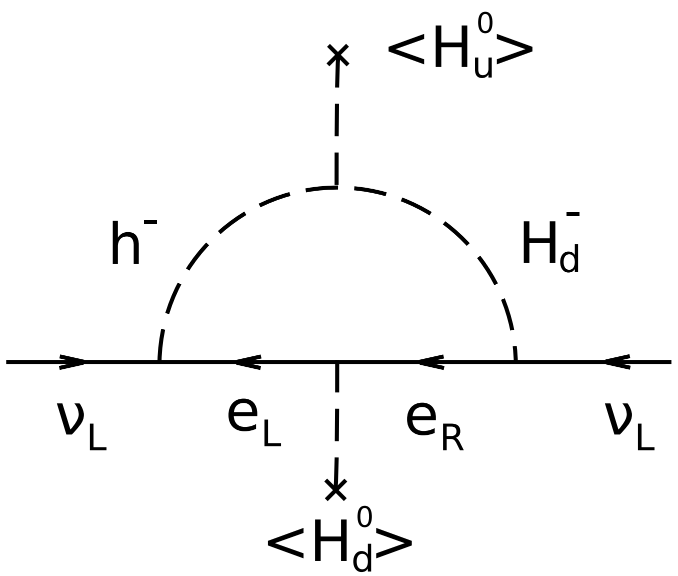
- Realizations of the Weinberg operator in scalar extensions of the SM

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



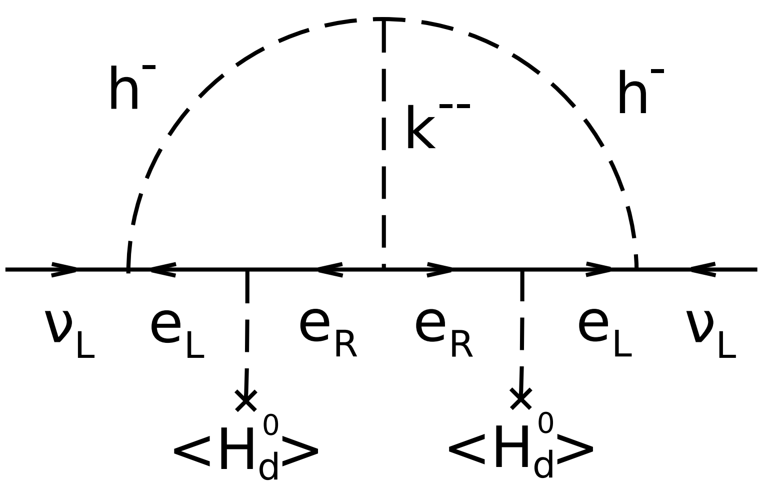
[Schechter, Valle (1980),
Cheng, Li (1980),
Lazarides, Shafi, Wetterich (1981),
Mohapatra, Senjanovic (1981)]

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



[Zee (1980), Wolfenstein (1980),
Babu, Julio (2014)]

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



[Zee (1986), Babu (1988)]

Peccei Quinn (PQ) mechanism

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

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

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \bar{\theta} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} + \xi \frac{a}{v_{PQ}} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2} \partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$$

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  - explicit breaking due to the anomaly

  - it generates an effective potential for the axion

$$V_{eff} \propto 1 - \cos\left(\bar{\theta} + \xi \frac{\langle a \rangle}{v_{PQ}}\right)$$

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$$V_{eff} \propto 1 - \cos\left(\bar{\theta} + \xi \frac{\langle a \rangle}{v_{PQ}}\right)$$

- The $\bar{\theta}$-term is dynamically cancelled at the minimum

$$\bar{\theta} = -\xi \frac{\langle a \rangle}{v_{PQ}}$$

DFSZ invisible axion

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

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

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- Requires:

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

$$\begin{cases} -\mathcal{L}_Y^{\text{quarks}} = Y_u \, \overline{q}_L u_R H_u + Y_d \, \overline{q}_L d_R H_d + \text{h.c.} \\ \mathcal{A} \propto X_{u_R} + X_{d_R} - 2X_{q_L} \end{cases}$$

$$H_u = H_d^* \quad \Longrightarrow \quad \mathcal{A} = 0$$

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

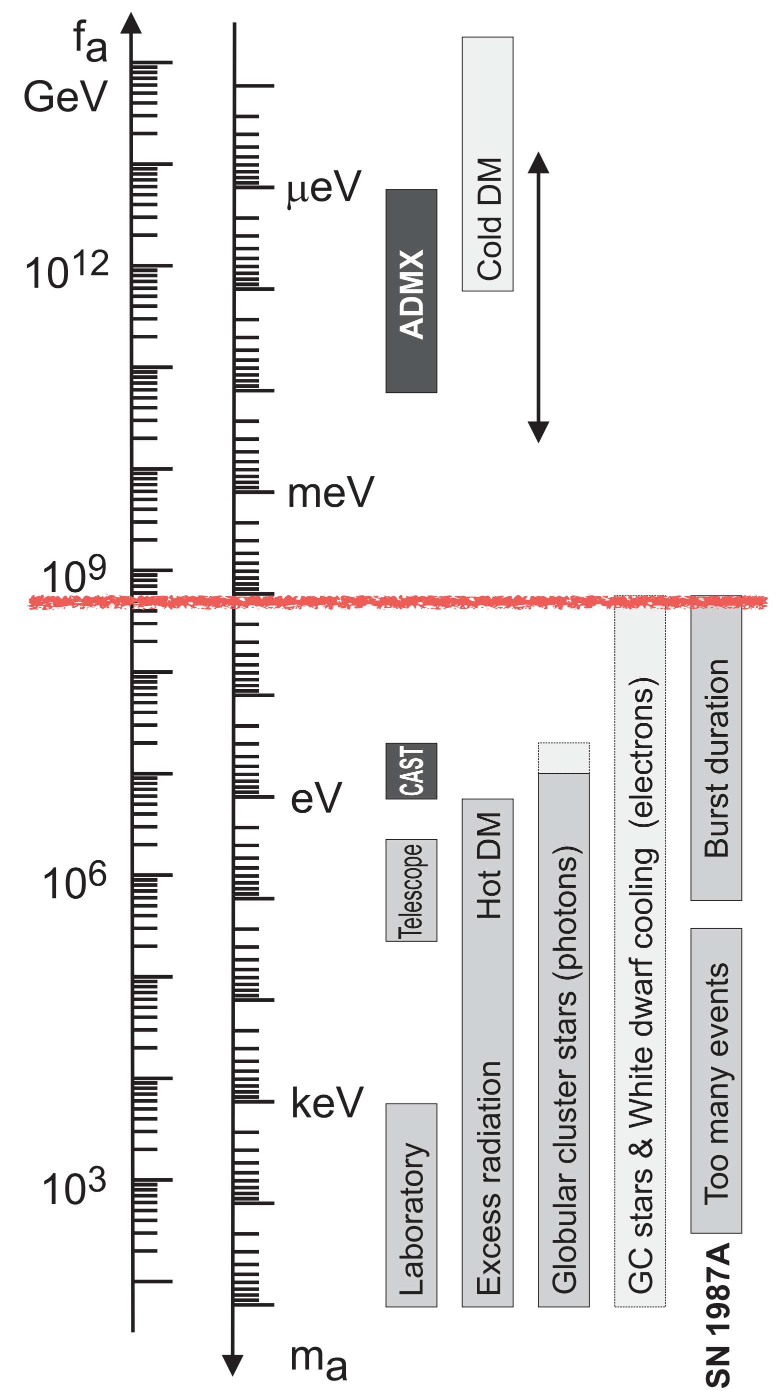
- a SM singlet which spontaneously break $U(1)_{PQ}$ at energies ≫ EW scale (invisible axion)

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

- axion mass $m_a \sim \frac{f_\pi m_\pi}{f_a}$ $(f_a = \sqrt{2} V_\sigma)$

- axion couplings $\sim 1/f_a$

DFSZ invisible axion



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Axionization of neutrino mass models

- The idea of connecting axions and neutrinos comes a long way (mostly Type-I seesaw)

  [For a (likely incomplete) list of refs.: Mohapatra, Senjanovic (1983), Shafi, Stecker (1984), Langacker, Peccei, Yanagida (1986), Shin (1987), He, Volkas (1988), Geng, Ng (1989), Berezhiani, Khlopov (1991), Bertolini, Santamaria (1991), Arason, Ramond, Wright (1991), Ma (2001), Dias, Pleitez (2006), Ma (2012), Chen, Tsai (2013), Park (2014), Dias, Machado, Nishi, Ringwald, Vaudrevange (2014), Salvio (2015)]

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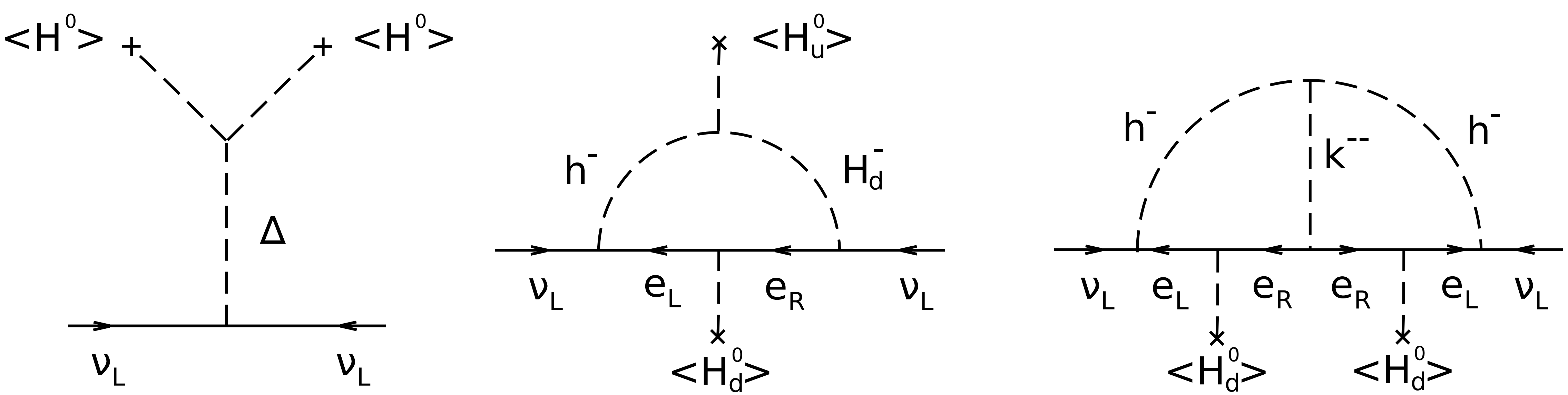
- Promote the trilinear mass parameters in the scalar potential to PQ spurions



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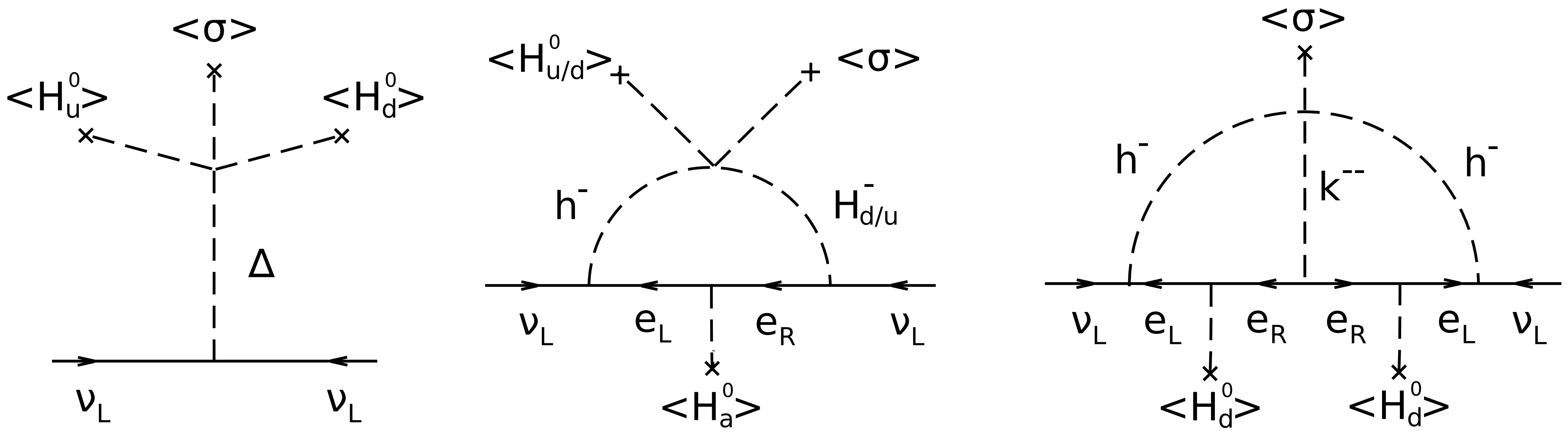

[Bertolini, DL, Kolesova, Malinsky (2014)]

- PQ symmetry 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

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

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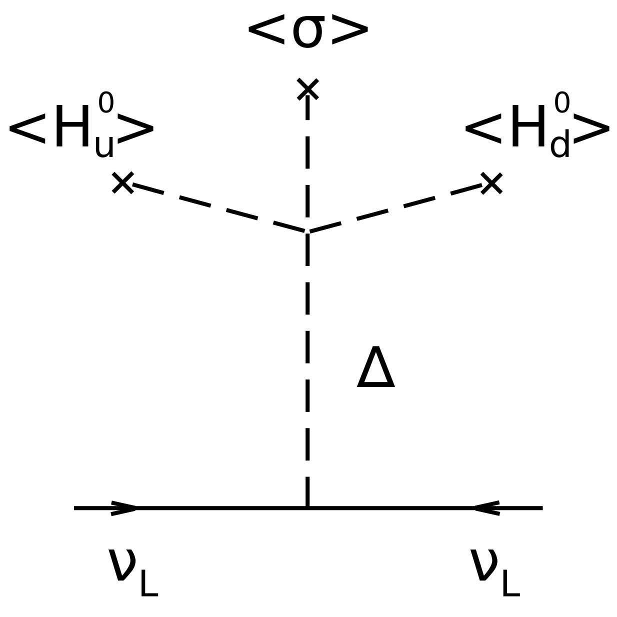
$$V_{\rm TII} = \text{moduli terms} + \left(\lambda_5 \sigma^2 \tilde{H}_u^\dagger H_d + \lambda_6 \sigma H_u^\dagger \mathbf{\Delta}^\dagger H_d + \text{h.c.}\right)$$

- We require the couplings
  - $\lambda_5\,\sigma^2 \tilde{H}_u^\dagger H_d$ to assign a non-vanishing PQ charge to sigma
  - $\lambda_6\,\sigma H_u^\dagger \mathbf{\Delta}^\dagger H_d$ to break L number (together with Y_Δ)

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



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$$

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

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

[Bertolini, Santamaria (1991)]

A closer look at the scalar potential

- Emerging symmetries in corners of parameter space

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

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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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$$

- 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 |\sigma|^2 + \lambda_3 |\sigma|^4 + \lambda_{13} |\sigma|^2 |H_u|^2 + \lambda_{23} |\sigma|^2 |H_d|^2 \\
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- $\text{All } \lambda \neq 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ}$
- $\lambda_6 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes U(1)_L$
- $\lambda_5 = 0 \quad \Longrightarrow \quad \widehat{U(1)}_{PQ} \otimes \widehat{U(1)}_L$ (Weinberg-Wilczek axion + Majoron)

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

A closer look at the scalar potential

- Emerging symmetries in corners of parameter space

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

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

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

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- Emerging symmetries in corners of parameter space

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

- by decoupling the singlet sector, the energy-momentum tensors are independently conserved*

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

*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)

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EW Naturalness*

- The hierarchy b/w PQ and EW scales is automatically achieved without fine-tunings for

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

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

  - This is readily verified by inspecting the fixed point structure of the RGEs

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

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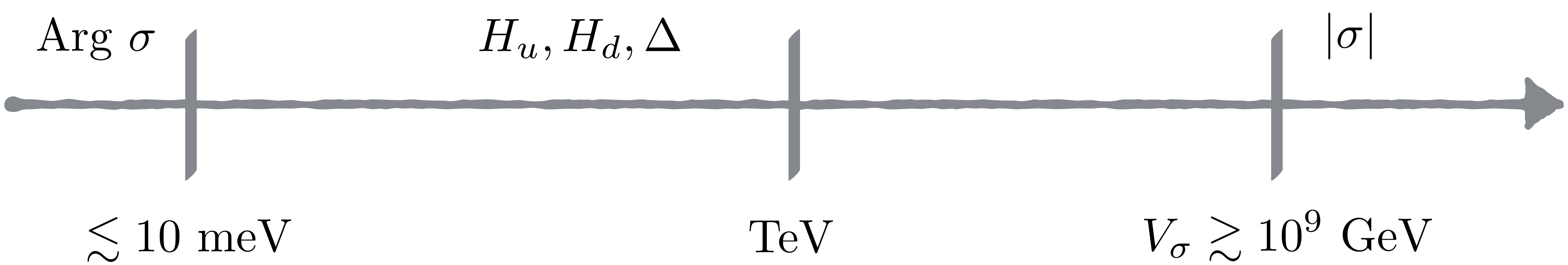
- For a fully natural model, an extended scalar sector is expected below the TeV scale



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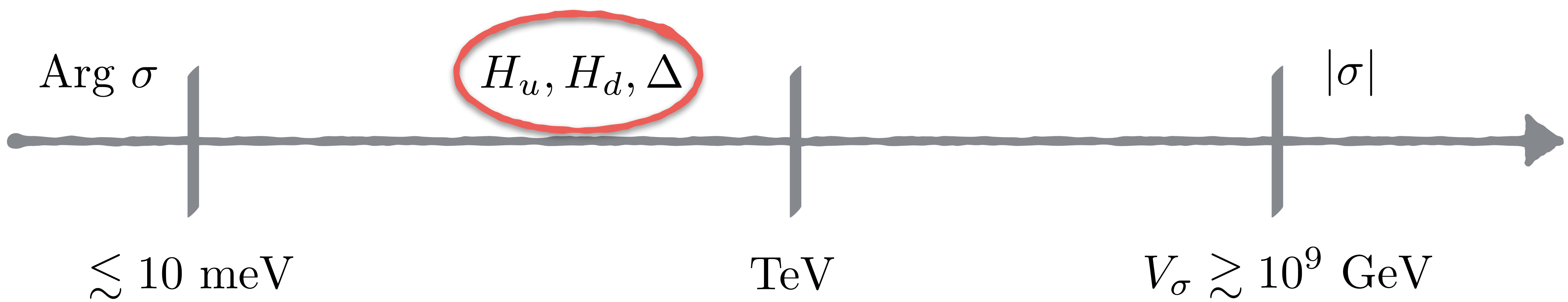

- LHC target !

*again, ignoring gravity

Gifts from light scalars

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

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

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

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

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

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

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- 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 simple framework interconnecting some of today's open issues in particle physics

DFSZ axion + neutrino mass models

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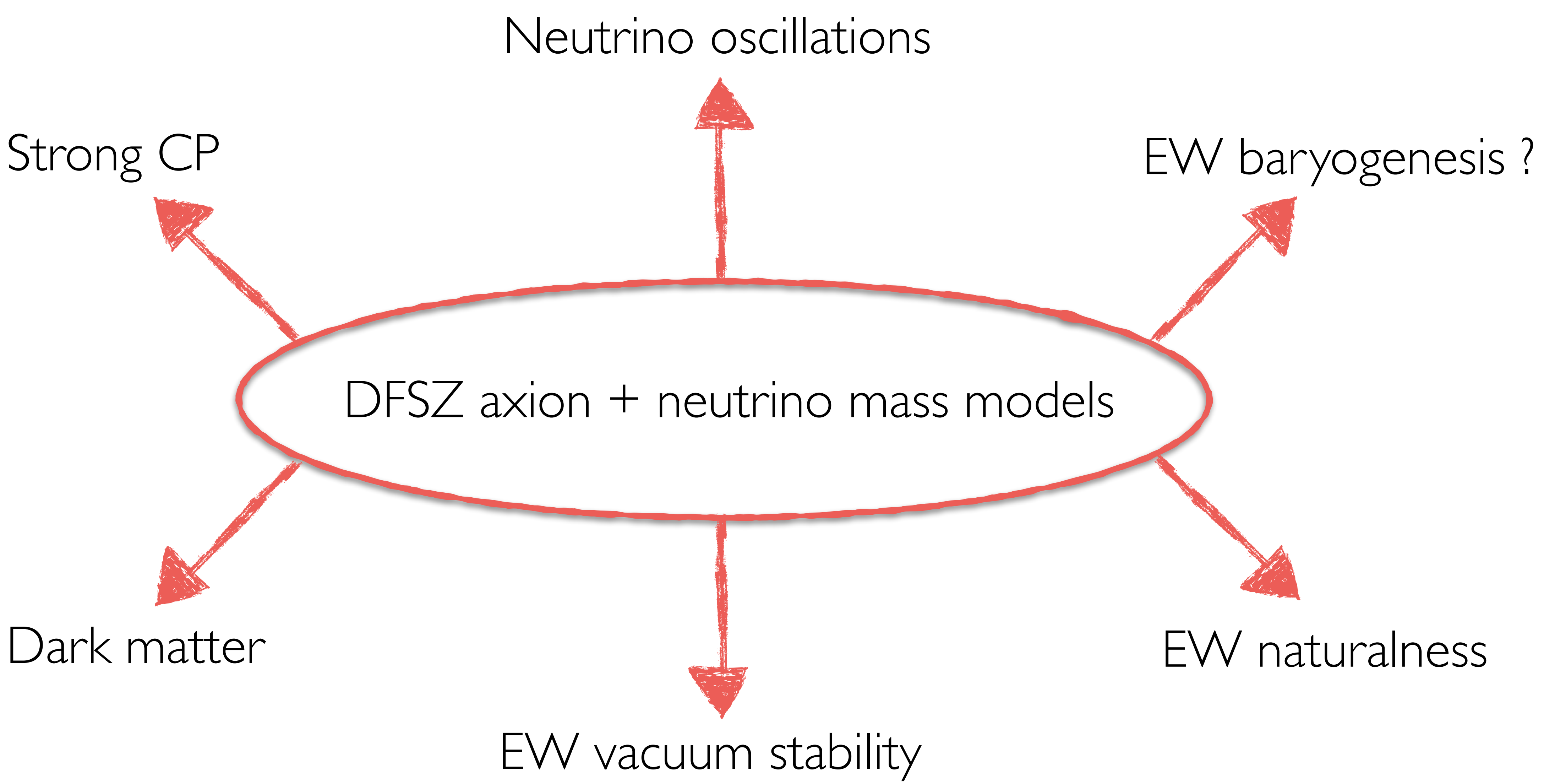
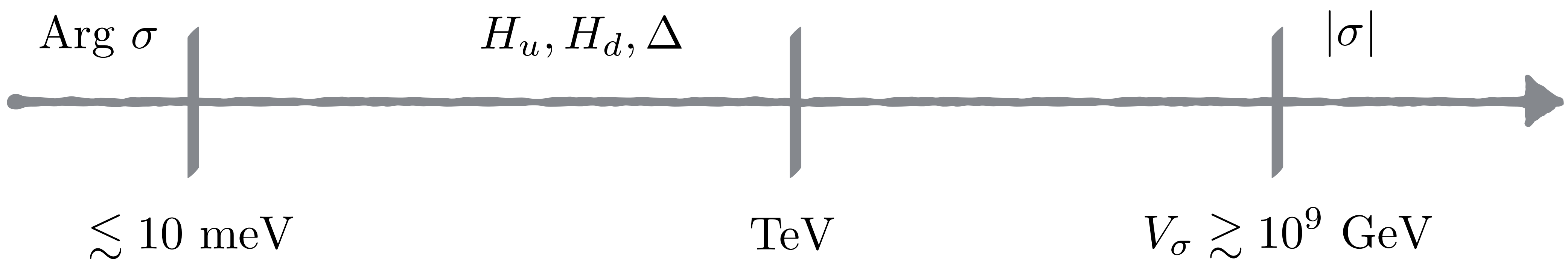


Backup slides

The extended scalar sector



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

- Neutral scalars $(h_u^0, h_d^0, \sigma^0, \delta^0)$ → SM-like Higgs + 2 neutral scalars + heavy singlet
- 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^{++}