Seesaw scale as a bridge to axions

In collaboration with J. T. Penedo (CFTP, Lisbon) and Y. Reyimuaji (XJU)

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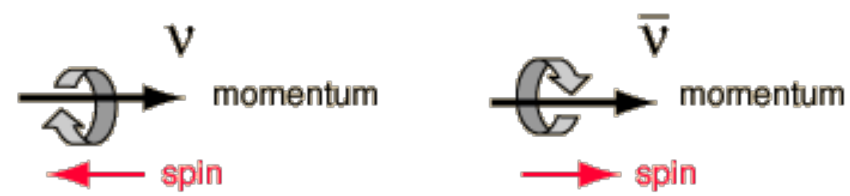
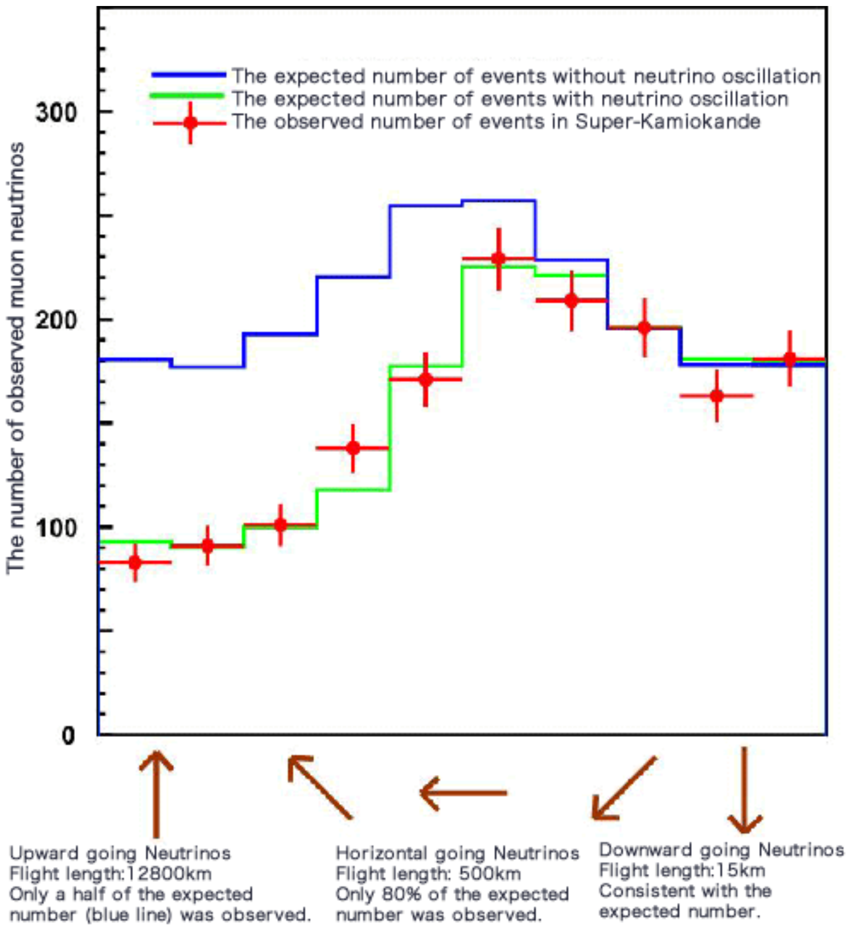
Neutrinos are massive

Neutrinos in the Standard Model:
massless, interact only weakly

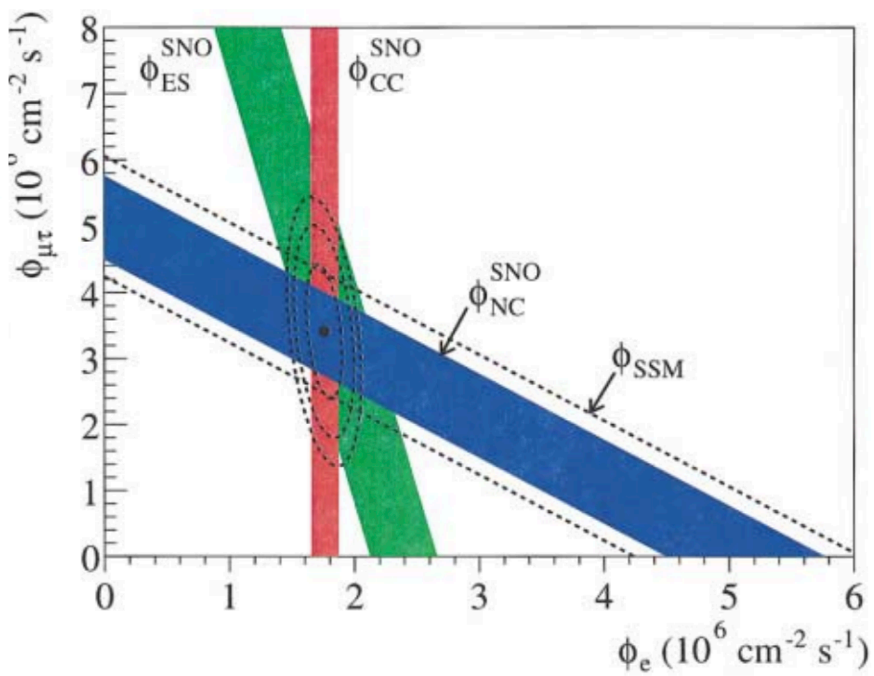


Neutrino
(left-handed)

Antineutrino
(right-handed)



http://www.hyper-k.org/



Phys.Rev.Lett. 89 (2002), 011301

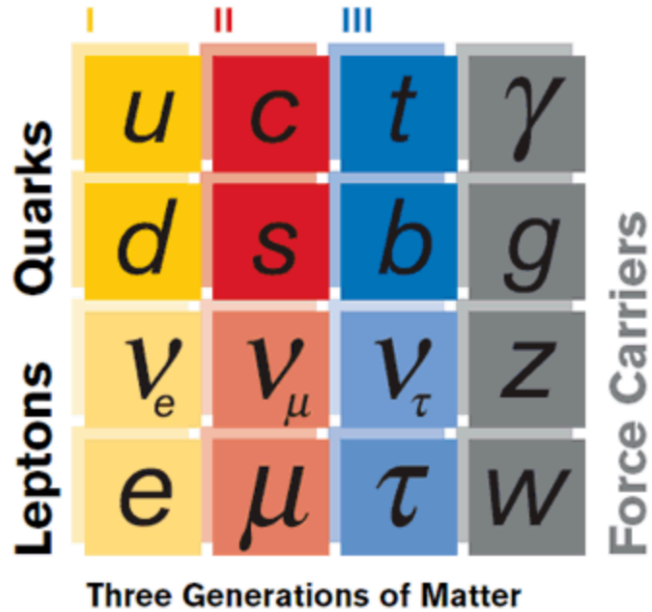
- Neutrinos have mass
- Mass eigenstates do not match flavor (weak) eigenstates
  → neutrino mixing

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Takaaki Kajita and Arthur B. McDonald shared the 2015 Nobel Prize in Physics,
“for the discovery of neutrino oscillations, which shows that neutrinos have mass”.

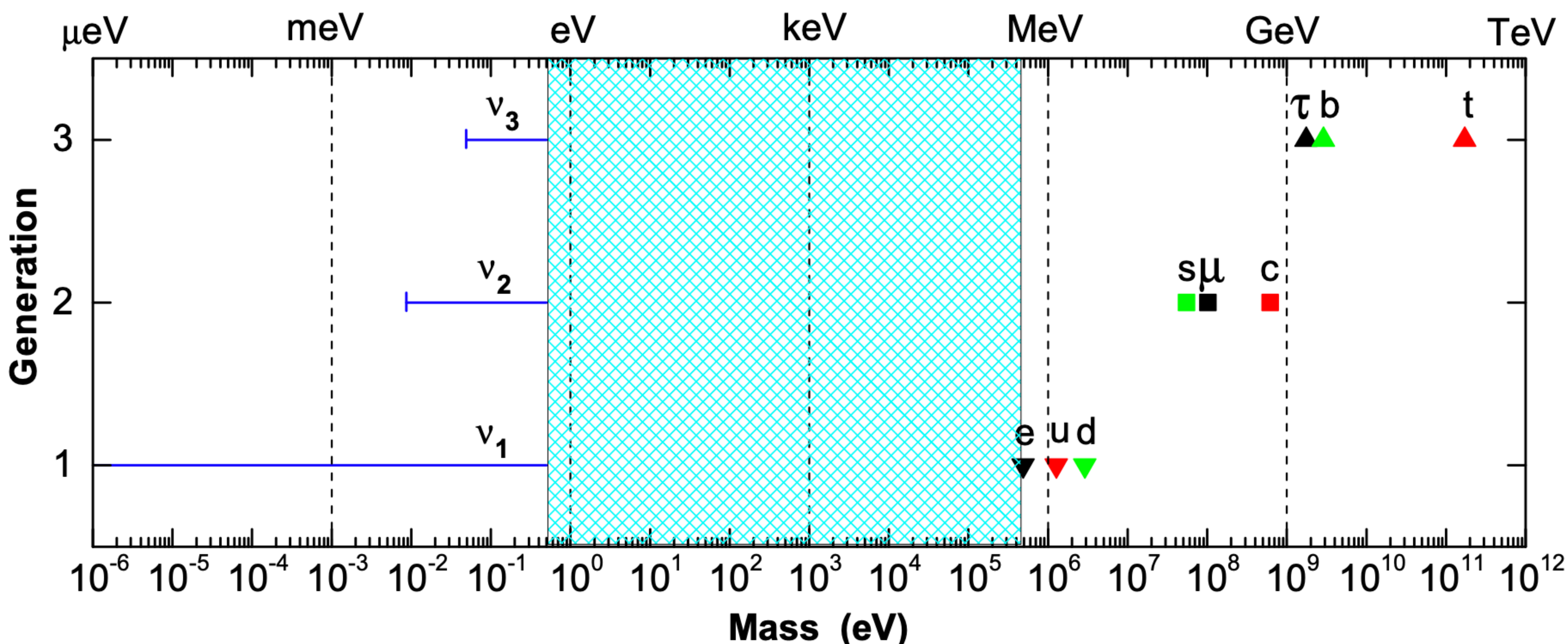
Solid beyond Standard Model physics

How massive are neutrinos?



Tritium decay (KATRIN) $m_{\nu_e} < 1.1 \text{ eV}$ 1909.06048

Cosmology $\sum m_\nu < 0.13 \text{ eV}$ 2105.13549



Xing, 2019

How massive are neutrinos?

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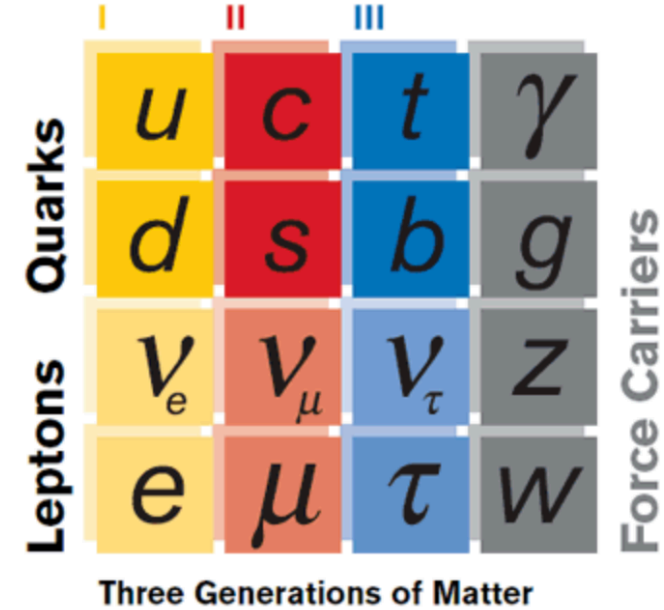
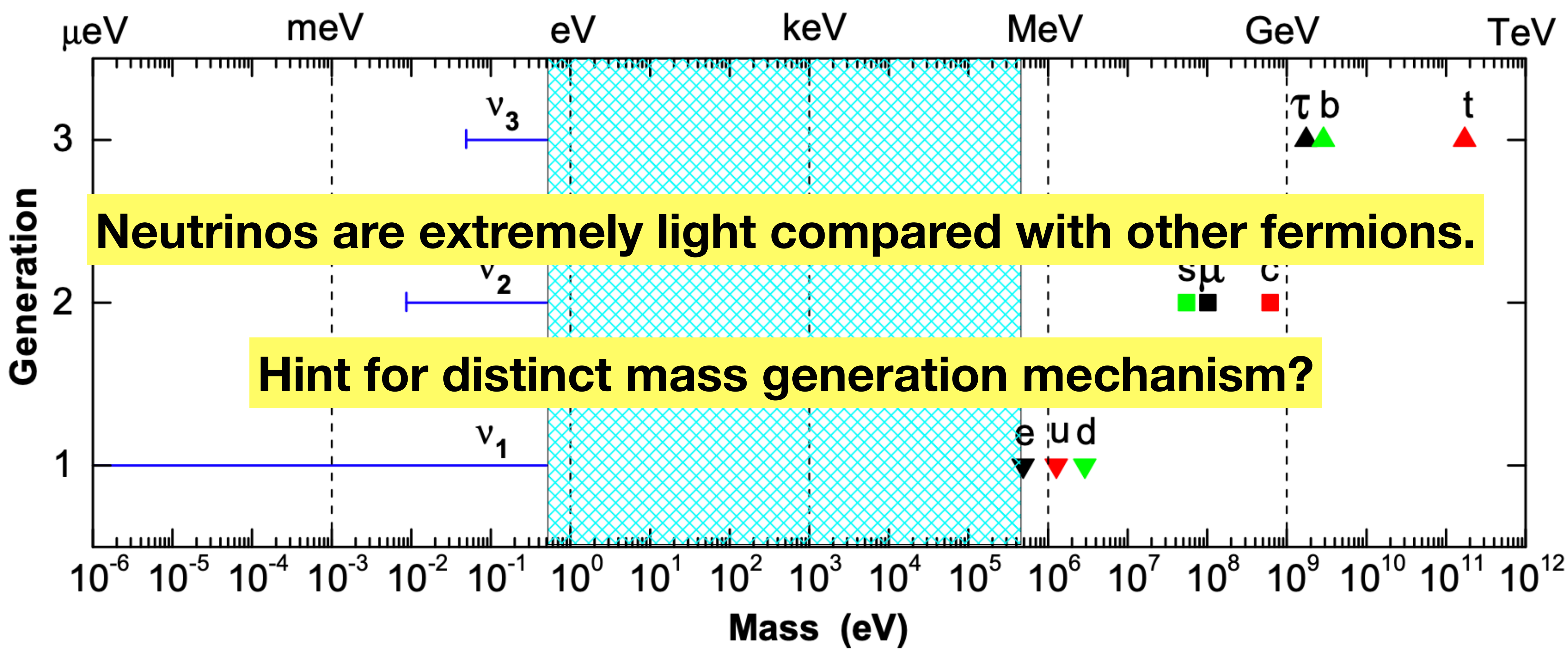




Neutrinos are extremely light compared with other fermions.

Hint for distinct mass generation mechanism?

Xing, 2019

Two key questions concerning massive neutrinos:

- The nature of massive neutrinos — Dirac/Majorana
- The mass generation mechanism — Explain the small mass

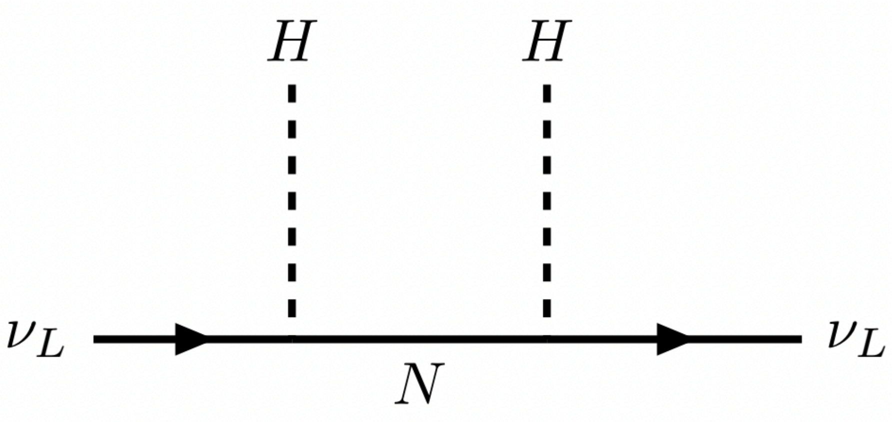
The seesaw mechanism

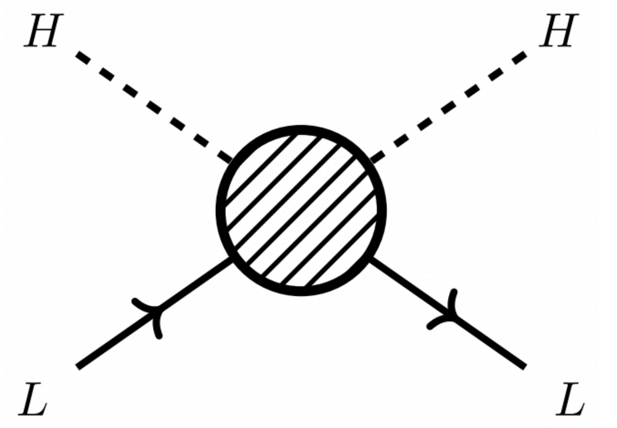
for Majorana neutrinos

Type-I seesaw

P. Minkowski,1977; T. Yanagida, ,1979;
J. Schechter and J. W. F. Valle, 1980, …

$$\mathscr{L} = - y_\nu \overline{L}\tilde{H}N - M_N \overline{N^c} N$$





in basis $(\nu_{\rm L}, N^{\rm c})$, full neutrino mass matrix $\begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^{\rm T} & M_N \end{pmatrix}$

Light neutrino mass matrix $M_\nu = - M_{\rm D} M_N^{-1} M_{\rm D}^{\rm T}$

$$M_{\rm D} \sim 10^2 \text{ GeV}, M_\nu \sim 0.1 \text{ eV} \to M_N \sim 10^{14} \text{ GeV}$$

The seesaw paradigm

for Majorana neutrinos

With only SM fields, **unique dimension 5 operator Lepton-number violating**

Tree-level, high-scale

S. Weinberg, 1980 $\frac{1}{\Lambda}\bar{L}^c \otimes \Phi \otimes \Phi \otimes L$

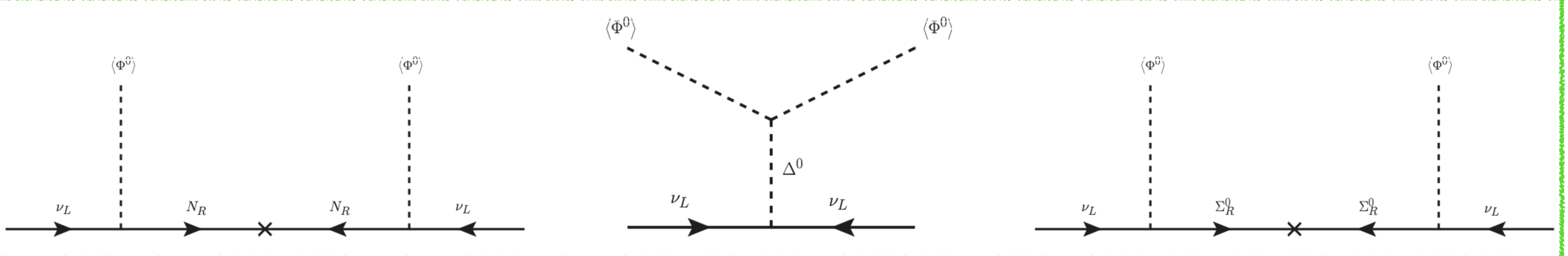
Consider different contracting,

$$\underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{1} \otimes \underbrace{\Phi \otimes L}_{1}}_{\text{Type I}}\ ,\quad \underbrace{\underbrace{\bar{L}^c \otimes L}_{3} \otimes \underbrace{\Phi \otimes \Phi}_{3}}_{\text{Type II}}\ ,\quad \underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{3} \otimes \underbrace{\Phi \otimes L}_{3}}_{\text{Type III}}$$

Chulia, Srivastava and Valle, 2018

Add new fields to make renormalizable operators

Tree-level realization of Weinberg operator



Type I, II, III Seesaw mechanism:
Neutrino mass suppressed by the heavy mediator mass

The Dirac seesaw mechanism

for Dirac neutrinos

- With only SM fields (except for ν_R),

$$y_\nu \bar{L}\Phi^c \nu_R \qquad \frac{1}{\Lambda^{2n}}\bar{L}\Phi^c\left(\Phi^\dagger\Phi\right)^n \nu_R, \quad n \in \{0,1,2,3,4...\}$$

- Introduce more BSM fields,

$$\frac{1}{\Lambda}\bar{L}\otimes X \otimes Y \otimes \nu_R$$

Analog of Weinberg operator

For e.g. X ~ singlet, Y ~ doublet $X = \chi \quad Y = \Phi$

$$\underbrace{\underbrace{\bar{L}\otimes\Phi^c}_{1}\otimes\underbrace{\chi\otimes\nu_R}_{1}}_{\text{Type I analogue}}, \quad \underbrace{\underbrace{\bar{L}\otimes\nu_R}_{2}\otimes\underbrace{\Phi^c\otimes\chi}_{2}}_{\text{Type II analogue}}, \quad \underbrace{\underbrace{\bar{L}\otimes\chi}_{2}\otimes\underbrace{\Phi^c\otimes\nu_R}_{2}}_{\text{Type III analogue}}$$

Chulia, Srivastava and Valle, 2018

The seesaw scale $\Lambda_{\rm ss}$

- For Majorana neutrinos,

From Weinberg operator $\frac{1}{\Lambda} \bar{L}^c \otimes \Phi \otimes \Phi \otimes L$

$m_\nu \sim \frac{y_\nu^2 v^2}{\Lambda}$, with $y_\nu \sim 0.1, v \sim 100~\text{GeV}, m_\nu \sim 0.1~\text{eV} \rightarrow \Lambda \sim 10^{12}~\text{GeV}$

- For Dirac neutrinos,

From the operator $\frac{1}{\Lambda} \bar{L} \otimes X \otimes Y \otimes \nu_R$

Hard to tell!

But a "natural" guess of $\langle X \rangle \sim \langle Y \rangle \sim \mathcal{O}_{\rm EW}$ leading to the same result.

$$10^8~\text{GeV} \lesssim \Lambda_{\rm SS} \lesssim 10^{14}~\text{GeV}$$

Lower limit determined by how much "fine-tuning" can tolerate

The axion decay constant

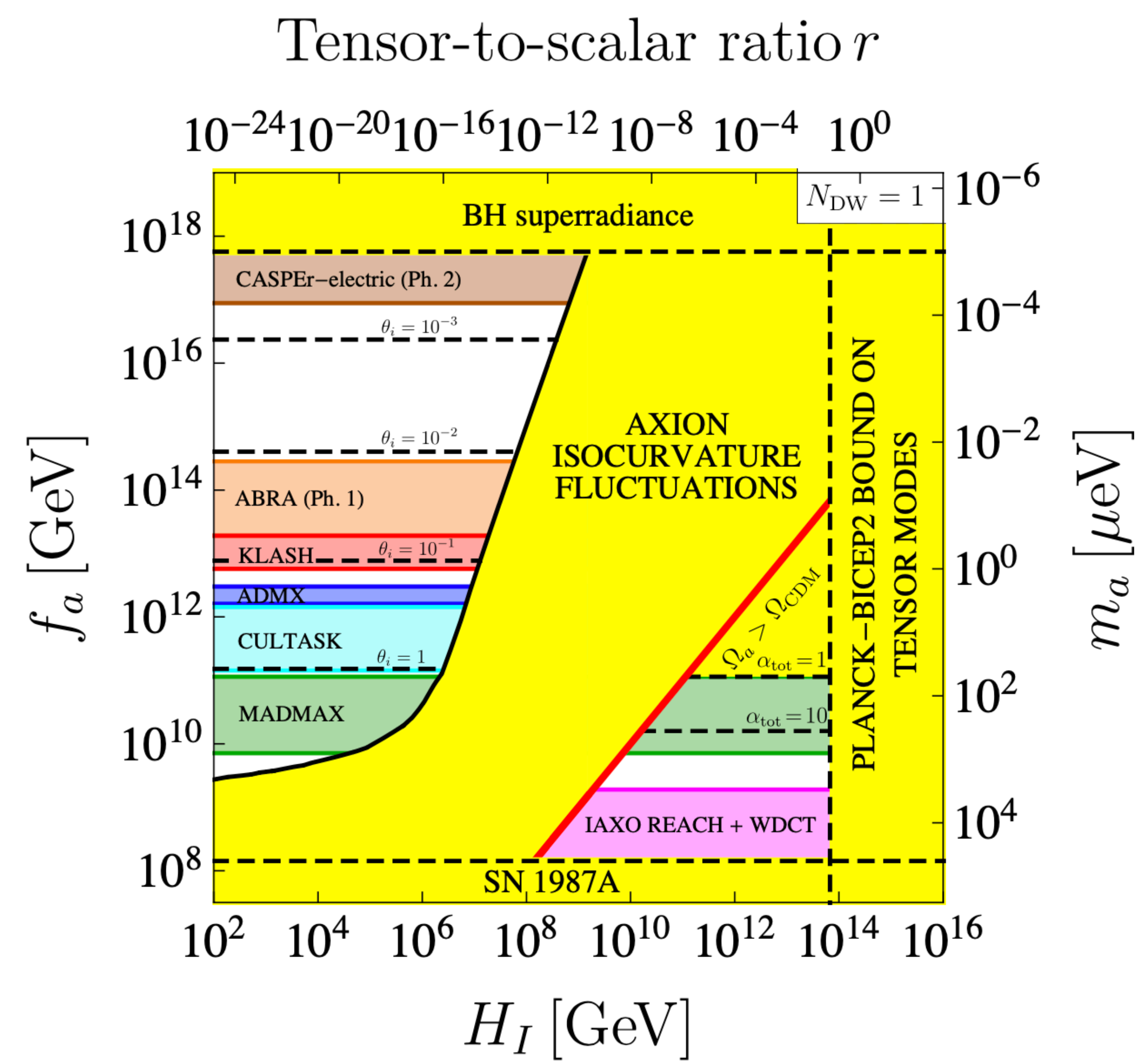
$$10^8 \text{ GeV} \lesssim f_a \lesssim 10^{17} \text{ GeV}$$

Recall that

$$10^8 \text{ GeV} \lesssim \Lambda_{SS} \lesssim 10^{14} \text{ GeV}$$

$$\Lambda_{SS} \sim f_a$$

Hint for connection?



Luzio, Giannotti, Nardi, Visinelli, 2020

Why does it matter?

- ✓ Small neutrino mass
- ✓ Leptogenesis

$\Lambda_{SS} \sim f_a$

- ✓ Strong CP problem
- ✓ Axion dark matter

Possibility to explain more by adding less to SM

Rich phenomenology:

- Dark matter
- Baryon asymmetry
- Interplay of the two sectors (ν and a)
- Enlarged scalar sector

$\Lambda_{SS} \sim f_a$: Majorana case

$$\mathscr{L} = -y_\nu \overline{L}\tilde{H}N - M_N \overline{N^c} N$$

$$\mathscr{L} = -y_\nu \overline{L}\tilde{H}N - \sigma \overline{N^c} N$$

PQ field

Dynamical origin of RHN mass
as Majoron model

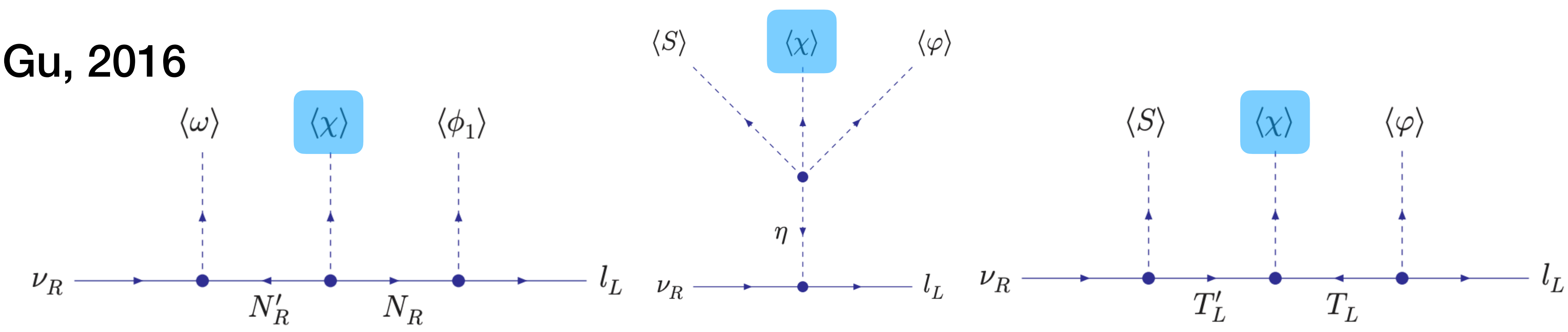
$$m_\nu \sim \frac{v^2}{f_a}$$

Kim, 1981; Langacker, Peccei and Yanagida, 1986; Shin, 1987;
Dias, Machado, Nishi, Ringwald and Vaudrevange, 2014;
Ballesteros, Redondo, Ringwald and Tamarit, 2016

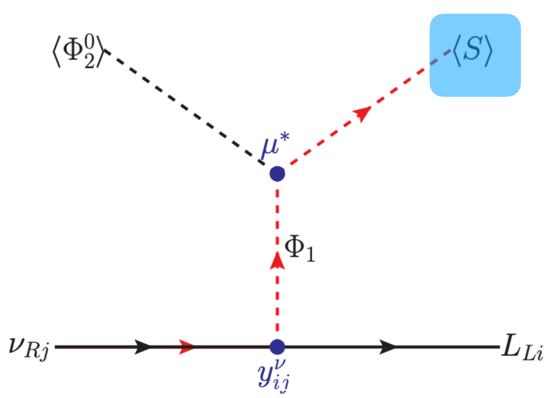
Dirac neutrino + axion

PQ field

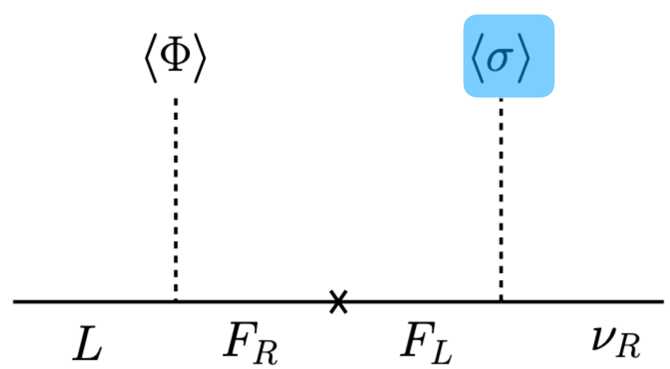
Gu, 2016



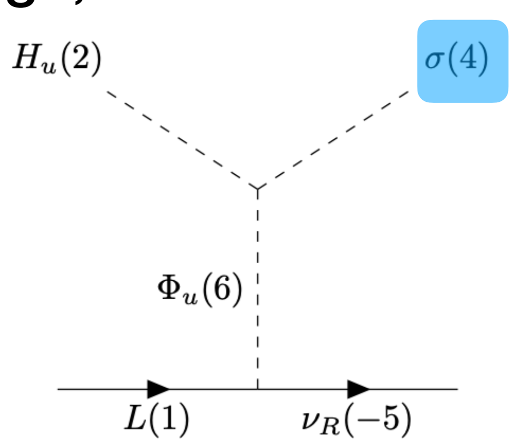
Baek, 2019



Peinado, Reig, Srivastava and Valle, 2020



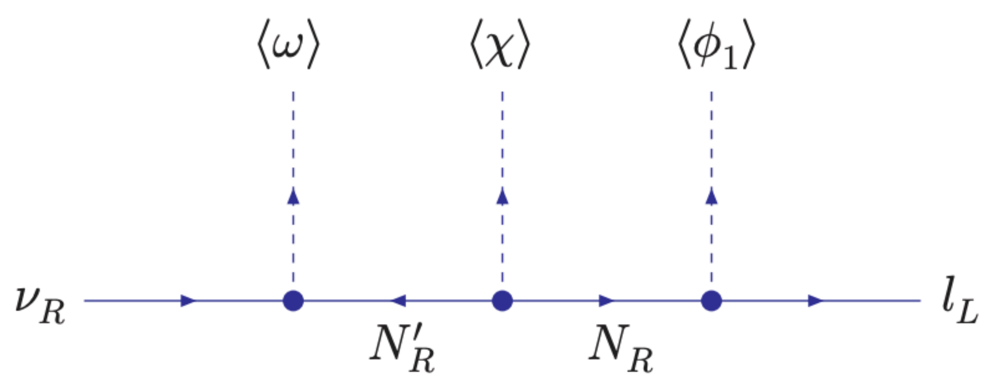
Vega, N. Nath and E. Peinado, 2020



And many loop-generated ν mass models...

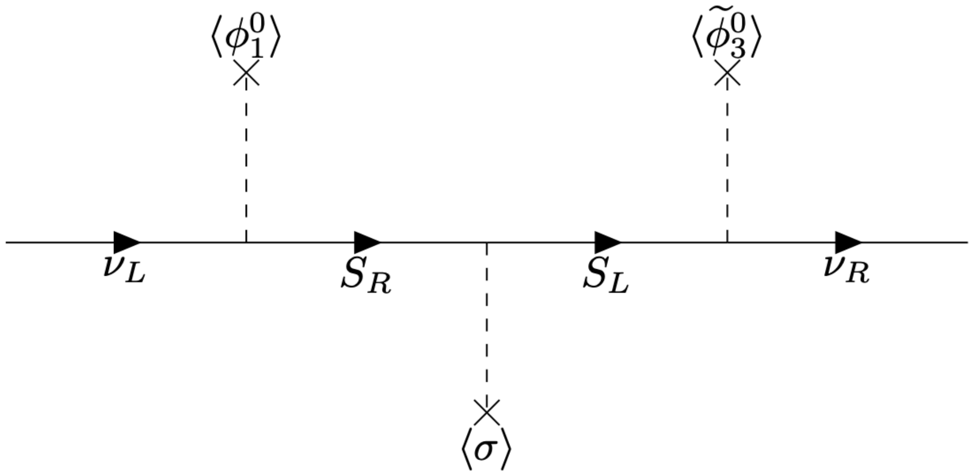
$\Lambda_{SS} \sim f_a$: Dirac case

Gu, 2016



DFSZ

Dias, Leite, Valle and Vaquera-Araujo, 2020



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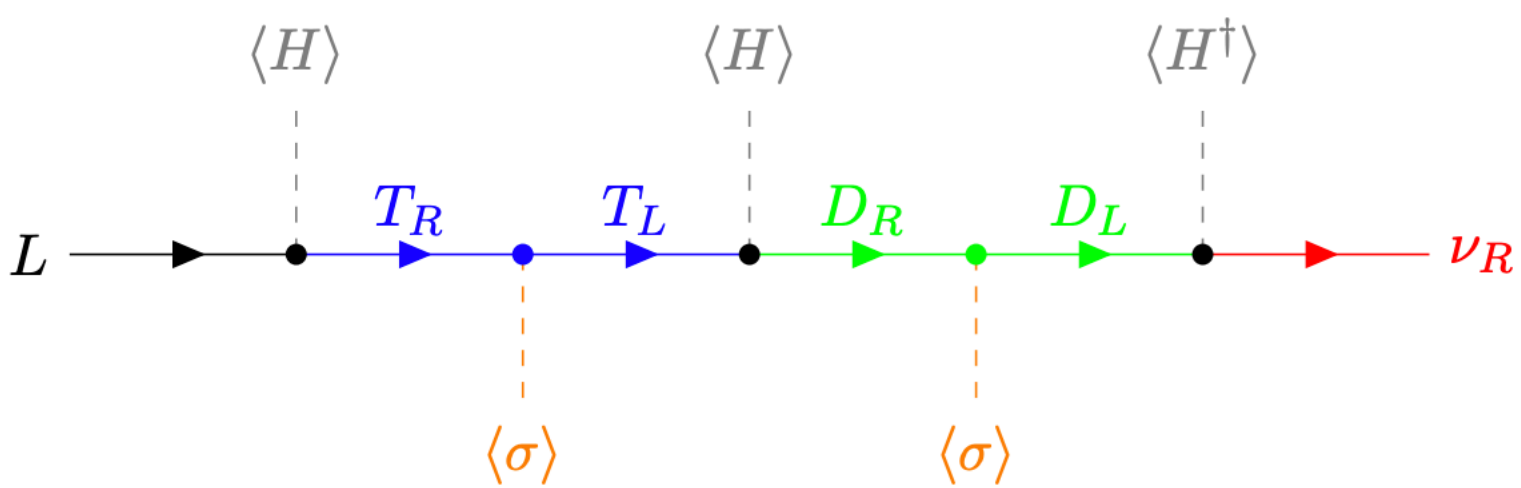
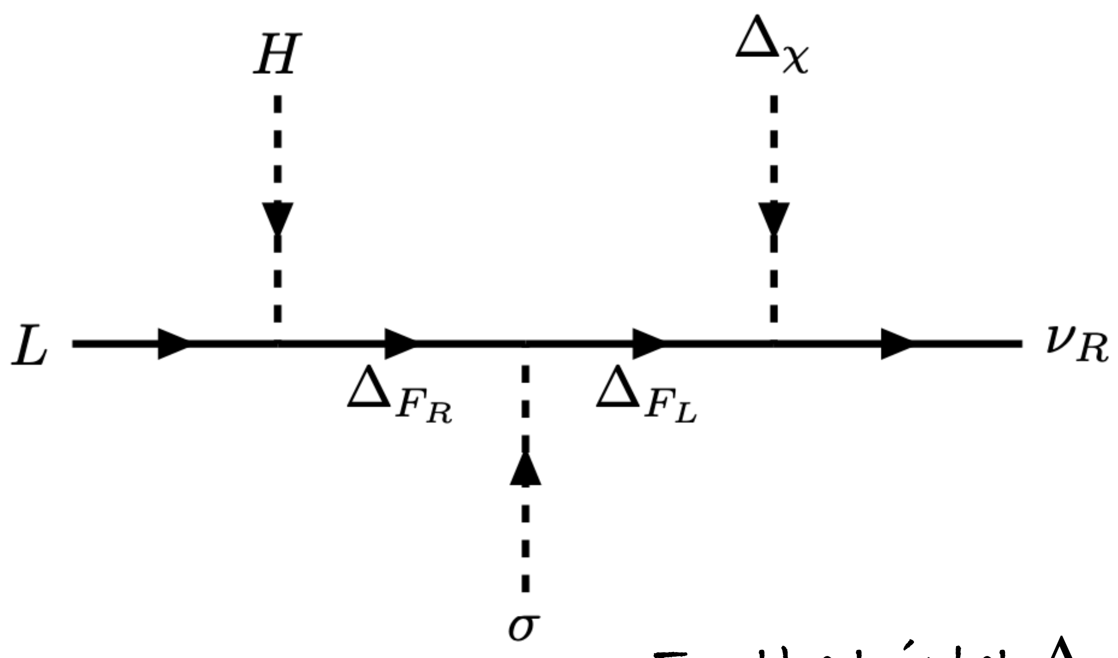
Berbig, 2022



$$m_\nu \simeq 0.05\,\text{eV} \cdot Y_{LT}Y_{TD}Y_{DR} \cdot \left(\frac{10^9\,\text{GeV}}{M_T}\right) \cdot \left(\frac{10^8\,\text{GeV}}{M_D}\right)$$

$\Lambda_{SS} \sim f_a$: Dirac case — Our construction

Extend SM minimally to get $\Lambda_{SS} \sim f_a$



Scalar $\Delta_\chi \sim \mathbf{1}, \mathbf{3}$ in SU(2)

Vector-like fermions $\Delta_{F_R}, \Delta_{F_L} \sim \mathbf{1}, \mathbf{3}$

PQ field: σ

For the triplet $\Delta_X, X = \chi, F_R, F_L$

$$m_\nu \sim \frac{v_\chi \, v}{v_\sigma}$$

sub-eV m_ν: $v_\chi / v_\sigma \sim 10^{-12}$

ρ: $v_\chi \sim 5.4$ GeV

Axion DM: $f_a \sim (10^9 - 10^{12})$ GeV

Yukawa $\sim \mathcal{O}(10^{-3} - 1)$

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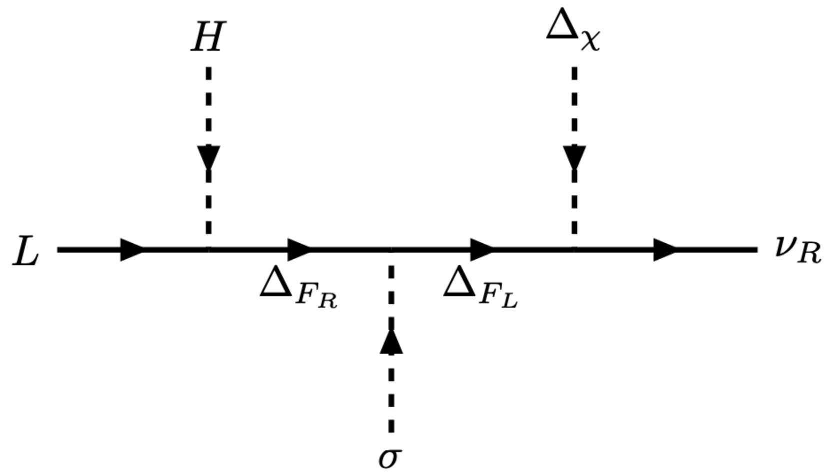
PQ symmetry enforces lepton number

Field	L	e_R	ν_R	Δ_{F_R}	Δ_{F_L}	Q_R	Q_L	H	σ	Δ_χ
$SU(3)_c$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{3}$
$U(1)_Y$	$-\frac{1}{2}$	-1	0	0	0	0	0	$\frac{1}{2}$	0	0
$U(1)_{\text{PQ}}$	α	α	$\alpha+1$	α	$\alpha+1$	$-\frac{1}{2}$	$\frac{1}{2}$	0	1	0



$\alpha \neq -1$ forbids $\overline{\nu_R}\nu_R^c$, $\overline{\nu_R}\nu_R^c\Delta_\chi^n$

$\alpha \neq k/2$ forbids $\overline{\nu_R}\nu_R^c(\sigma^{(*)})^n$, $(\sigma \to H, \Delta_\chi)$

No other symmetries besides PQ

PQ enforces Lepton number

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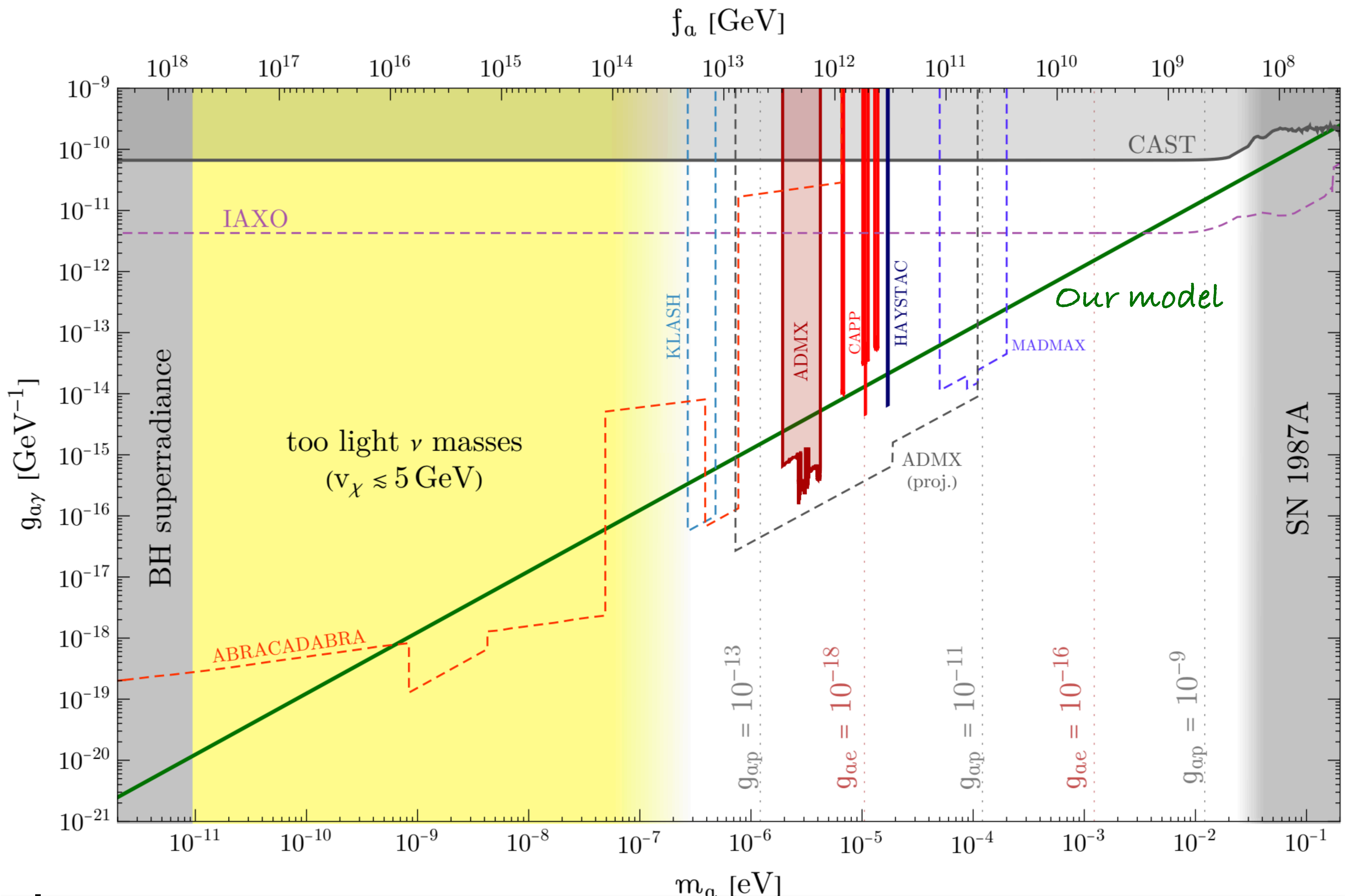
Axion in our model

Kim, 1979
Shifman, Vainshtein and Zakharov, 1980

Only σ is charged under PQ (among scalars)



- QCD axion in this model ~ KSVZ type

QCD anomaly coefficient

$$N = 1/2$$

EM anomaly coefficient

$$E = 4$$

- **In view of new CDF II result**

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + 4\frac{v_\chi^2}{v^2} \qquad \rho = \frac{(M_W^{\rm CDF})^2}{M_Z^2\cos^2\theta_W} \simeq \left(\frac{M_W^{\rm CDF}}{M_W^{\rm SM}}\right)^2 \rho_{\rm SM} \qquad v_\chi = 5.4~{\rm GeV}$$

The following Lagrangian is adding to the SM one

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \mathcal{L}_{\rm Yuk} - V(H, \Delta_\chi, \sigma) \;,$$

$$\mathcal{L}_{\rm kin} = |\partial_\mu \sigma|^2 + {\rm Tr}\, |D_\mu \Delta_\chi|^2 + \overline{\nu_R} i \partial\!\!\!/ \nu_R + \overline{Q} i D\!\!\!\!/ Q + \overline{\Delta_F} i D\!\!\!\!/ \Delta_F \;,$$

$$\mathcal{L}_{\rm Yuk} = Y_Q\, \overline{Q_L} Q_R \sigma + \overline{L} \tilde{H}\, Y_L\, \Delta_{F_R} + {\rm Tr}\left(\overline{\Delta_{F_L}}\, Y_F\, \Delta_{F_R}\right) \sigma + {\rm Tr}\left(\overline{\Delta_{F_L}} \Delta_\chi^*\right)\, Y_R\, \nu_R + {\rm H.c.} \;,$$

ν mass

The most general scalar potential is

$$V(H, \sigma, \Delta_\chi) = -\, \mu_H^2 H^\dagger H - \mu_\chi^2\, {\rm Tr}\left(\Delta_\chi^2\right) - \mu_\sigma^2 \sigma^* \sigma + \kappa H^\dagger \Delta_\chi H + \frac{\lambda}{2} (H^\dagger H)^2 + \frac{\lambda_\chi}{2}\, {\rm Tr}\left(\Delta_\chi^4\right) + \frac{\lambda_\sigma}{2} (\sigma^* \sigma)^2 + \frac{\lambda_a}{2} (H^\dagger H)\, {\rm Tr}\left(\Delta_\chi^2\right) + \frac{\lambda_b}{2} (H^\dagger H)(\sigma^* \sigma) + \frac{\lambda_c}{2} (\sigma^* \sigma)\, {\rm Tr}\left(\Delta_\chi^2\right)$$

Charged Higgs mass & mixing

With presence of both fermions and scalars, there is no a priori conclusion about their effect on stabilizing the vacuum → a detailed study is necessary!

Mass spectrum

$$M^2_{\text{CP-even}} = \begin{pmatrix} \lambda v^2 & \frac{1}{2}\lambda_a v v_\chi - \frac{1}{2}\kappa v & \frac{1}{2}\lambda_b v v_\sigma \\ \frac{1}{2}\lambda_a v v_\chi - \frac{1}{2}\kappa v & \frac{\kappa v^2}{4 v_\chi} + \frac{\lambda_\chi v_\chi^2}{2} & \frac{1}{2}\lambda_c v_\sigma v_\chi \\ \frac{1}{2}\lambda_b v v_\sigma & \frac{1}{2}\lambda_c v_\sigma v_\chi & \lambda_\sigma v_\sigma^2 \end{pmatrix}$$

Three CP-even mass eigenstates with masses $m_{H_1} \leq m_{H_2} \ll m_{H_3}$

Heavy spectrum: $m_{H_1} = m_H < m_{H_2}$

Light spectrum: $m_{H_1} < m_{H_2} = m_H$

$$M^2_{\text{charged}} = \begin{pmatrix} \kappa v_\chi & \frac{\kappa v}{2} \\ \frac{\kappa v}{2} & \frac{\kappa v^2}{4 v_\chi} \end{pmatrix} \qquad m^2_{H^\pm} = \frac{\kappa\left(v^2 + 4 v_\chi^2\right)}{4 v_\chi}$$

Vacuum stability constraints

Theoretical constraints:

perturbativity, unitarity, copositivity, global minimum

Experimental constraints:

Electroweak precision: ρ, S, T, U

Collider: LHC for charged Higgs, LEP for neutral Higgs

Viable parameter space

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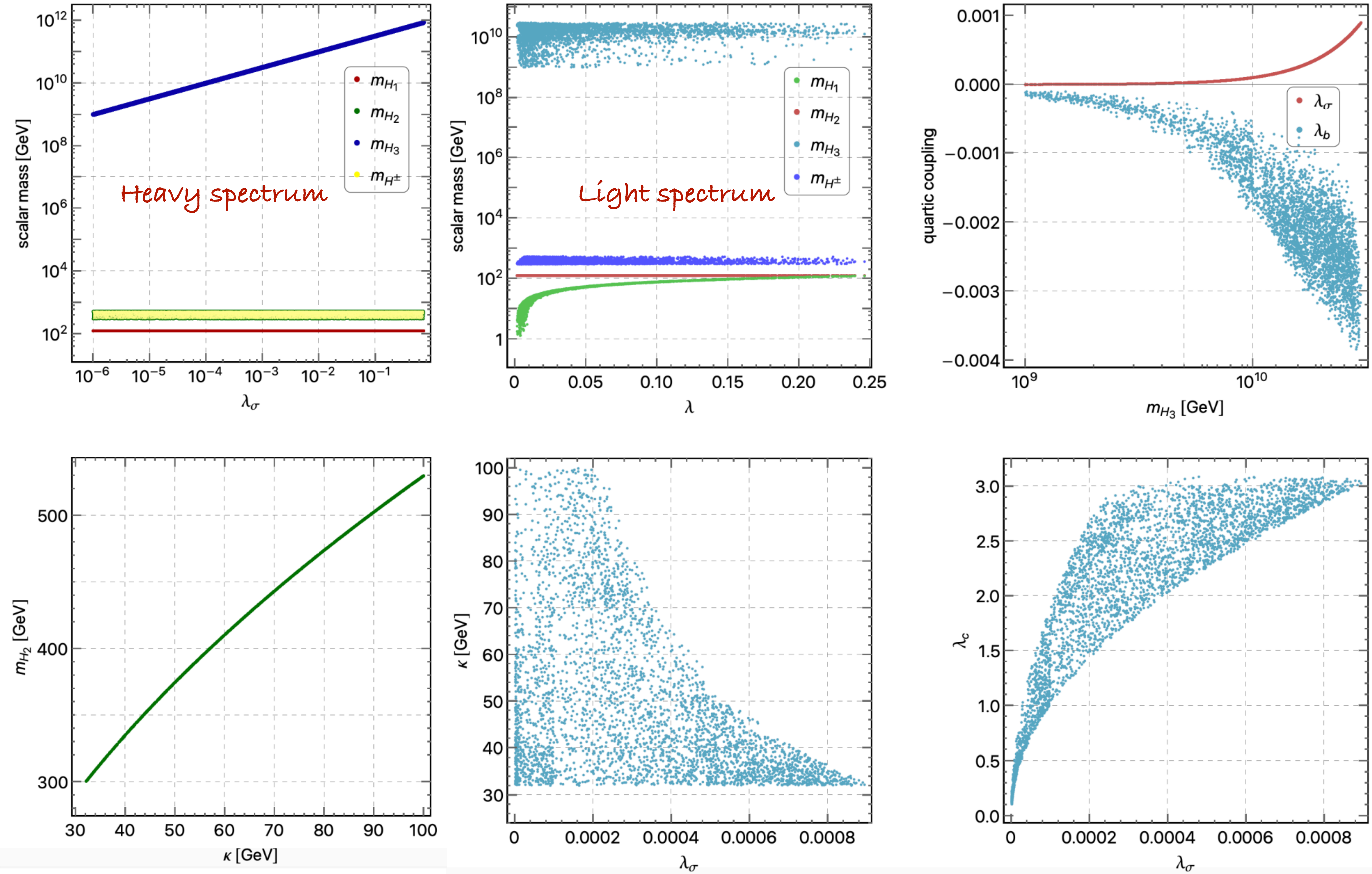

Summary

Build a model which features

- $\Lambda_{\rm SS} \sim f_a$ for Dirac neutrinos $\rightarrow 10^8 \text{ GeV} \lesssim f_a \lesssim 10^{14} \text{ GeV}$
- PQ enforces L number conservation
- $\Delta_\chi \rightarrow m_W$
- Desired vacuum (v, v_χ, v_σ) can be the global one (heavy spectrum)

It can be extended in many ways:

Flavors, singlet, Dirac leptogenesis, collider phenomenology, etc

Most importantly, $\Lambda_{\rm SS} \sim f_a$ is worth exploration!

Thank you for your attention!