DPC-SMF

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Dirac neutrino masses and axion + WIMP dark matter from Peccei Quinn symmetry

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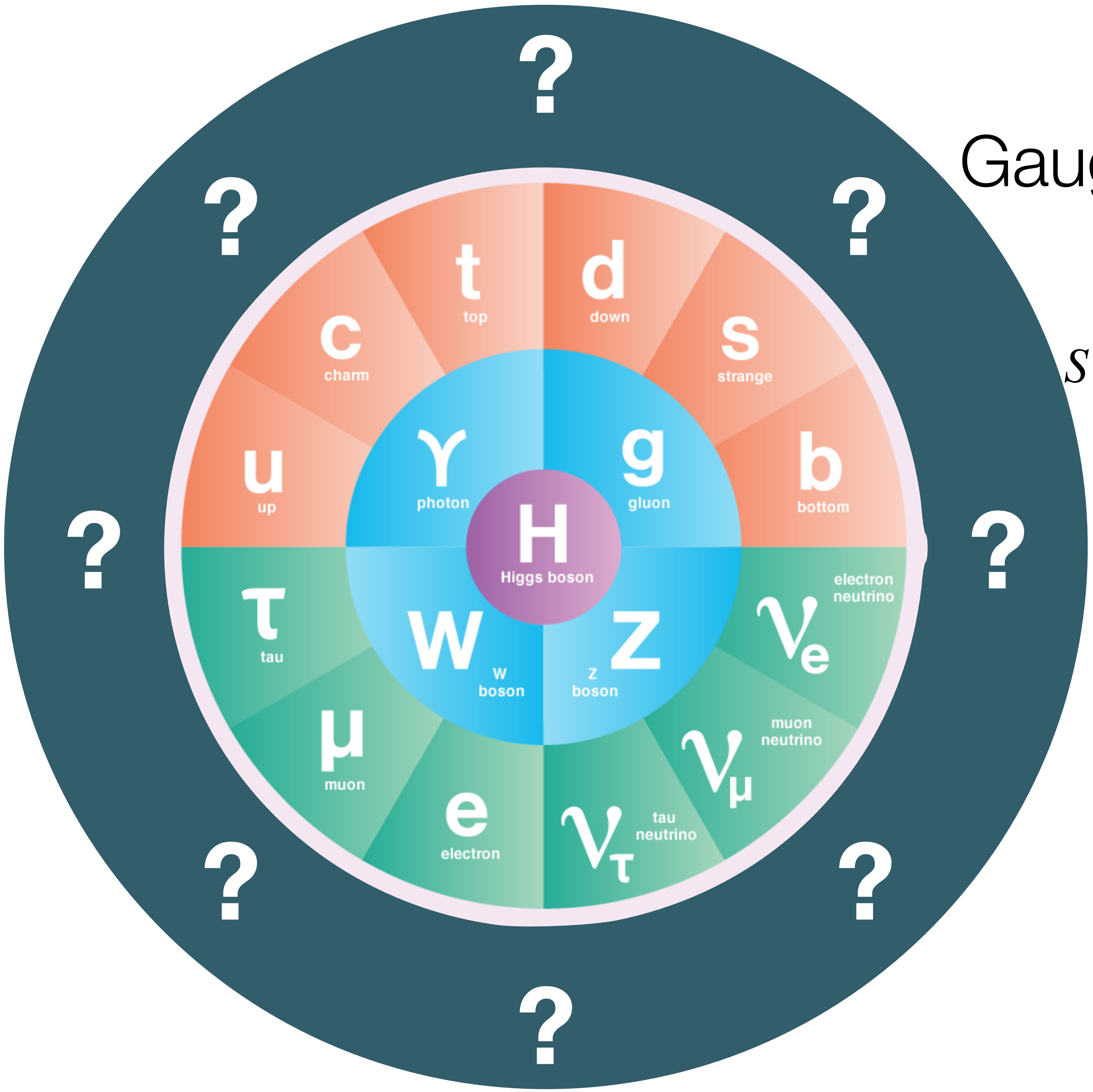
Outline

- Motivation (Neutrino masses, DM, strong CP problem)
- PQ solution to CP problem
- Models for neutrino masses
- PQ models for neutrino masses and WIMP DM

Standard Model



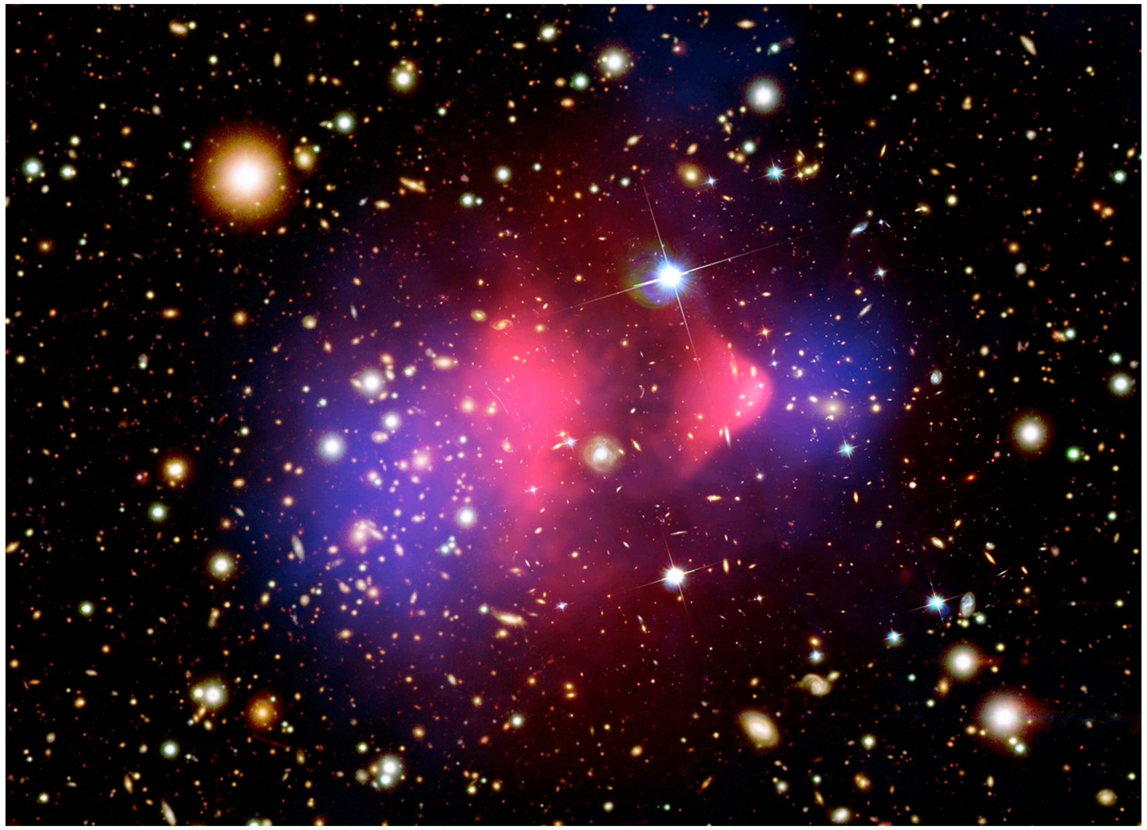
Gauge group + Pattern of SSB

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_Q$$

Yukawa couplings for fermion masses

Standard Model

Dark Matter



Neutral non-baryonic component of matter

~25% of matter-energy of the Universe today

- WIMPs ?
- Axion & ALPs ?
- MACHOs ?
- ...

Standard Model

Strong CP problem

No observed effect of CP violating θ term of QCD

$$\mathscr{L} \supset \frac{\alpha_s}{8\pi} G\tilde{G}\theta_{SM}$$

leads to

$$d_n \sim 3 \times 10^{-16}\theta_{SM} \text{ e cm}$$

$$\theta_{SM} \leq 10^{-10}$$

PQ symmetry?

Standard Model

Neutrino masses?

KATRIN: $m_\nu \leq 1.1$ eV

Cosmology: $\sum m_\nu \leq 0.12$ eV

Why is $\frac{m_\nu}{EWBS} \leq 10^{-11}$?

Dirac or Majorana?

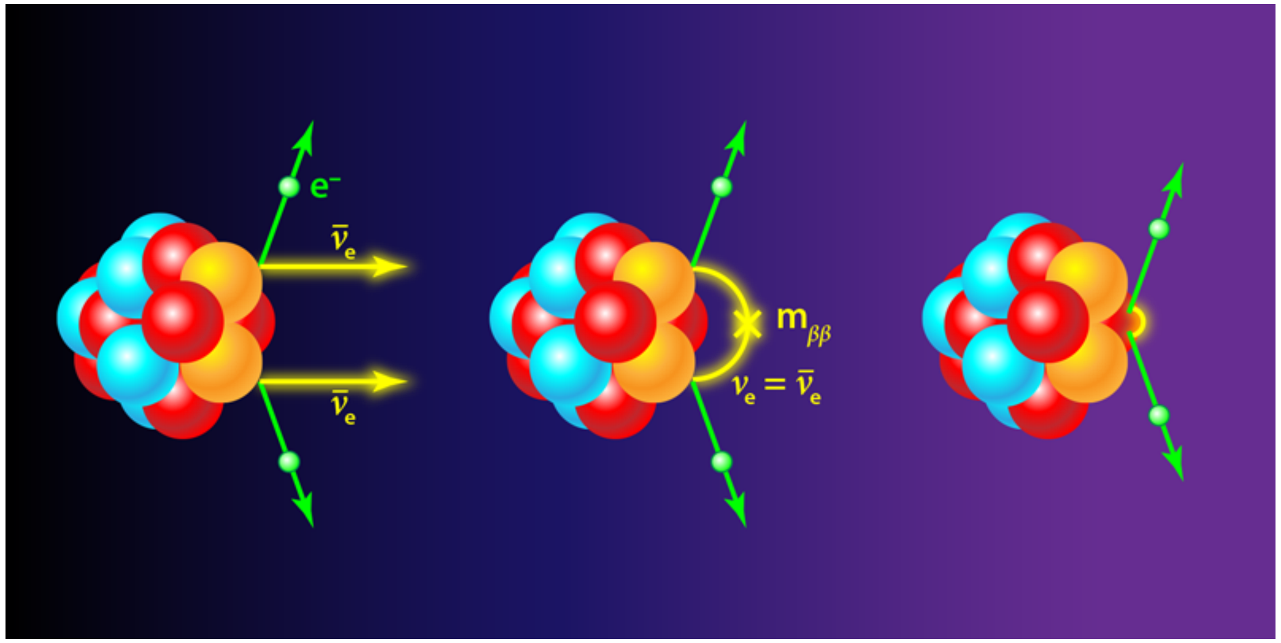
KamLAND-Zen $< m_{\beta\beta} > \leq 0.061 - 0.165$ eV

Is lepton number conserved?

Majorana v. Dirac masses

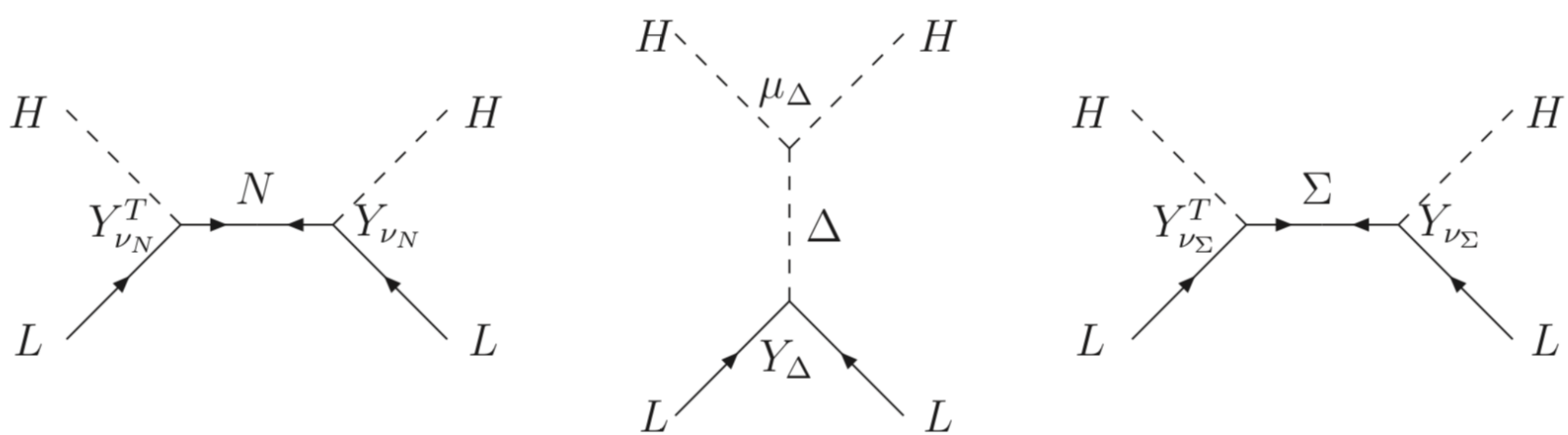
Lepton Number Violating terms: $m\nu^c\nu$

lead to processes $\Delta L = 2$



Majorana v. Dirac masses

SM symmetries allow Weinberg d=5 op: $L^c \tilde{H} \tilde{H} L$

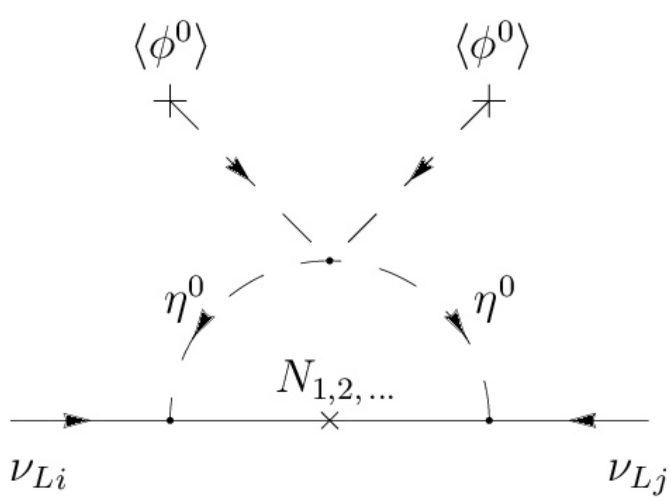


3 ways to generate op. at tree level

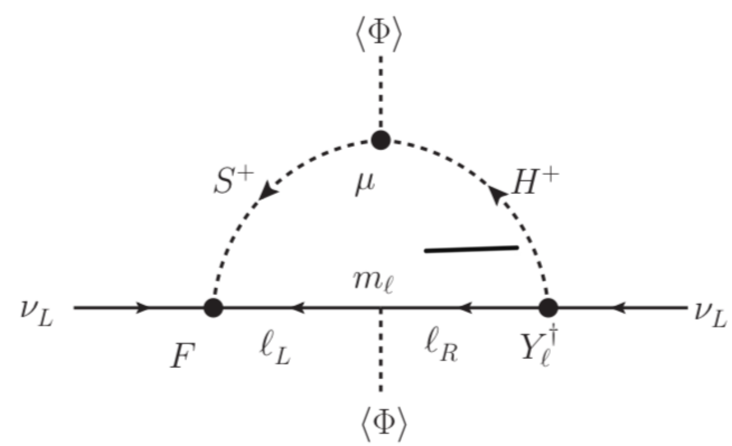
$$m_\nu \sim \frac{v_{EW}^2}{\Lambda}$$

Majorana v. Dirac masses

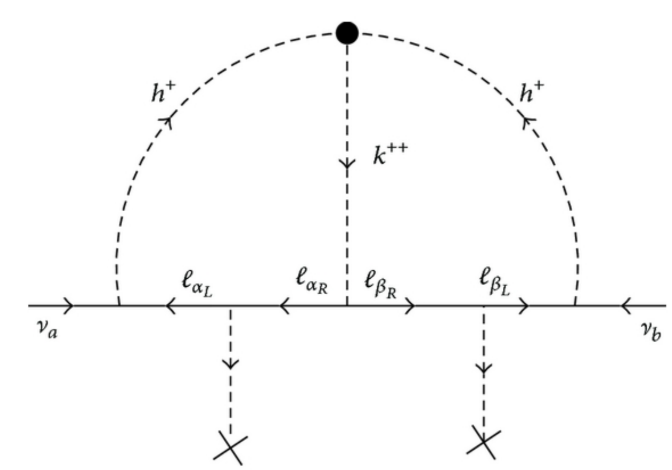
At loop level many completions are possible



Scotogenic



Zee



Zee-Babu

Additional symmetries forbid tree level masses → DM

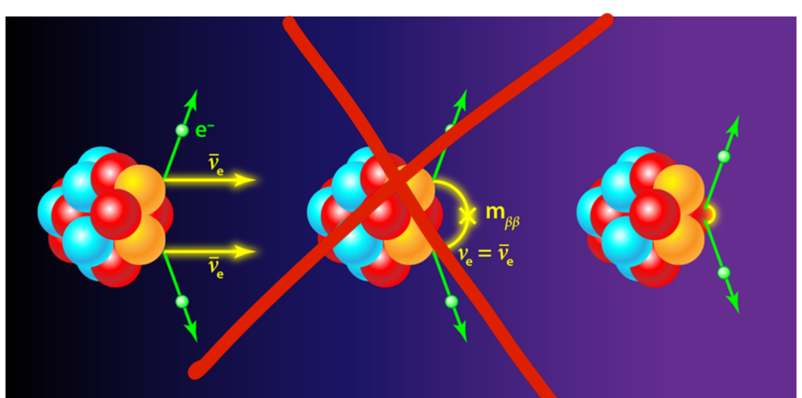
Majorana v. Dirac masses

$$L^c \tilde{H} \tilde{H} L$$

Forbidden by symmetry

$$L H \nu_R \checkmark$$

Lepton Number Conservation



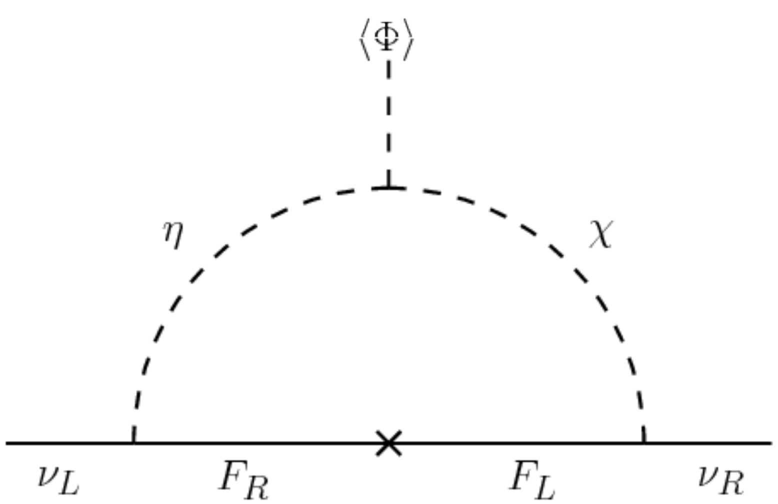
Abelian or non-Abelian symmetries

(e.g. Aranda, Bonilla, Morisi, Peinado, Valle (2014))

Majorana v. Dirac masses

Smallness explained by loop suppression, higher order operators

$$LH\nu_R$$



$$\frac{\mathscr{C}}{\Lambda^n} LH\nu_R(\phi \cdots)$$

Dirac d=4 Scotogenic

(or both...)

Peccei-Quinn symmetry for ν masses

PQ symmetry - $U(1)_{PQ}$ - absorbs θ and solves strong CP

→ new pNGB is predicted - the axion

→ new energy scale - PQ breaking scale f_a

$U(1)_{PQ}$ →

- PQWW: Axion inside $SU(2)_L$ doublet $v_{EW} << v_{PQ}$
- KSVZ: Heavy vector-like quarks
- DFSZ: Axion couples to H_u, H_d

Peccei-Quinn symmetry for ν masses

DFSZ models:

H_u, H_d and a SM singlet σ charged under PQ

$\mathscr{L} \supset \kappa H_u H_d \sigma$ or $\mathscr{L} \supset \lambda H_u H_d \sigma^2$

H_u, H_d give masses to fermions:

$$\mathscr{L} \supset Y\bar{Q}H_u u_r + Y\bar{Q}H_d d_r + Y\bar{L}H_d e_r$$

Peccei-Quinn symmetry for ν masses

For ν masses traditional mechanisms are possible:

INVISIBLE AXIONS AND LIGHT NEUTRINOS — ARE THEY CONNECTED?

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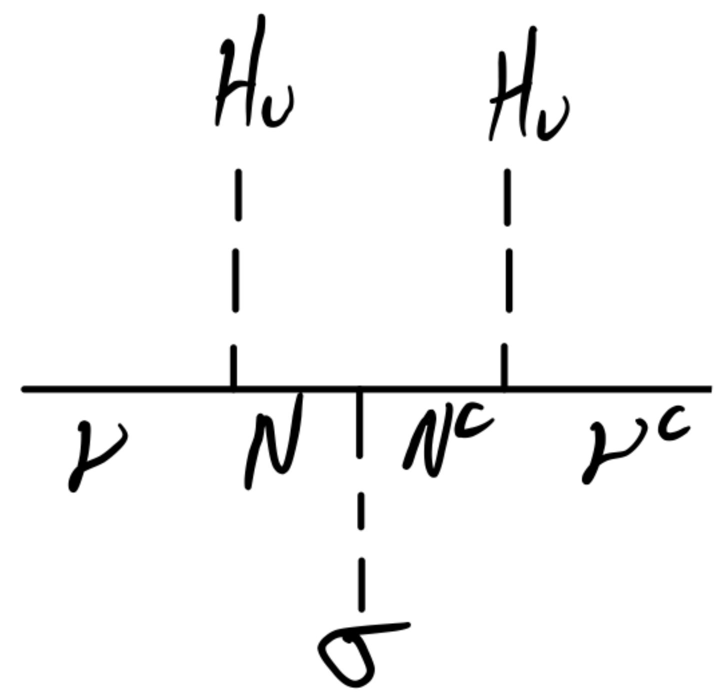


$$\frac{L^c H_u H_u L \sigma}{\Lambda^2}$$

Peccei-Quinn symmetry for ν masses

PQ charge assignment may forbid Majorana terms:

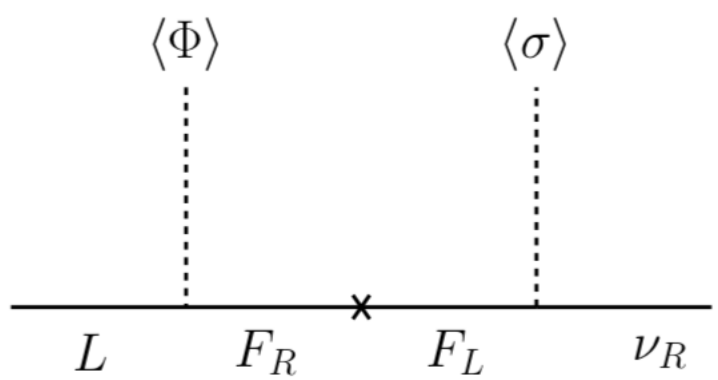
Fields/Symmetry	Q_i	u_i^c	d_i^c	L_i	l_i^c	H_u	H_d	σ
$SU(2)_L \times U(1)_Y$	(2,1/6)	(1,-2/3)	(1,1/3)	(2,-1/2)	(1,1)	(2,-1/2)	(2,1/2)	(0,0)
$U(1)_{PQ}$	1	1	1	1	1	2	2	4

Operator PQ charge

$$\mathcal{L}_{dim\ 5} \sim \begin{cases} \frac{LL\tilde{H}_u\tilde{H}_u}{\Lambda_{UV}} & 1+1+(-4)=-2 \\ \frac{LL\tilde{H}_u H_d}{\Lambda_{UV}} & 1+1+(0)=+2 \\ \frac{LLH_dH_d}{\Lambda_{UV}} & 1+1+(4)=+6 \end{cases}$$

$$\begin{array}{llll} \sigma^n & (4n); & (\sigma^*)^n & (-4n); \\ (H_uH_d)^n & (4n); & (H_uH_d)^{*n} & (-4n); \\ (H_u^\dagger H_u)^n & (0); & (H_d^\dagger H_d)^n & (0). \end{array}$$

Peinado, Reig, Srivastava, Valle (2019)



Exotic ν_R charge :

$$\nu_R \sim -5$$

$$LH_u\nu_R\sigma \checkmark$$

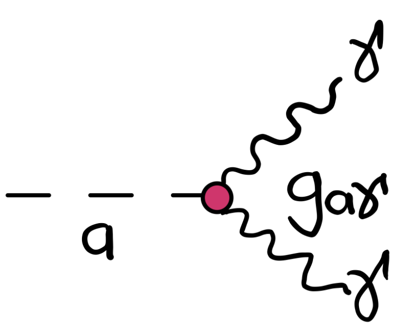
$$m_\nu \sim \frac{v_{EW} f_a}{\Lambda}$$

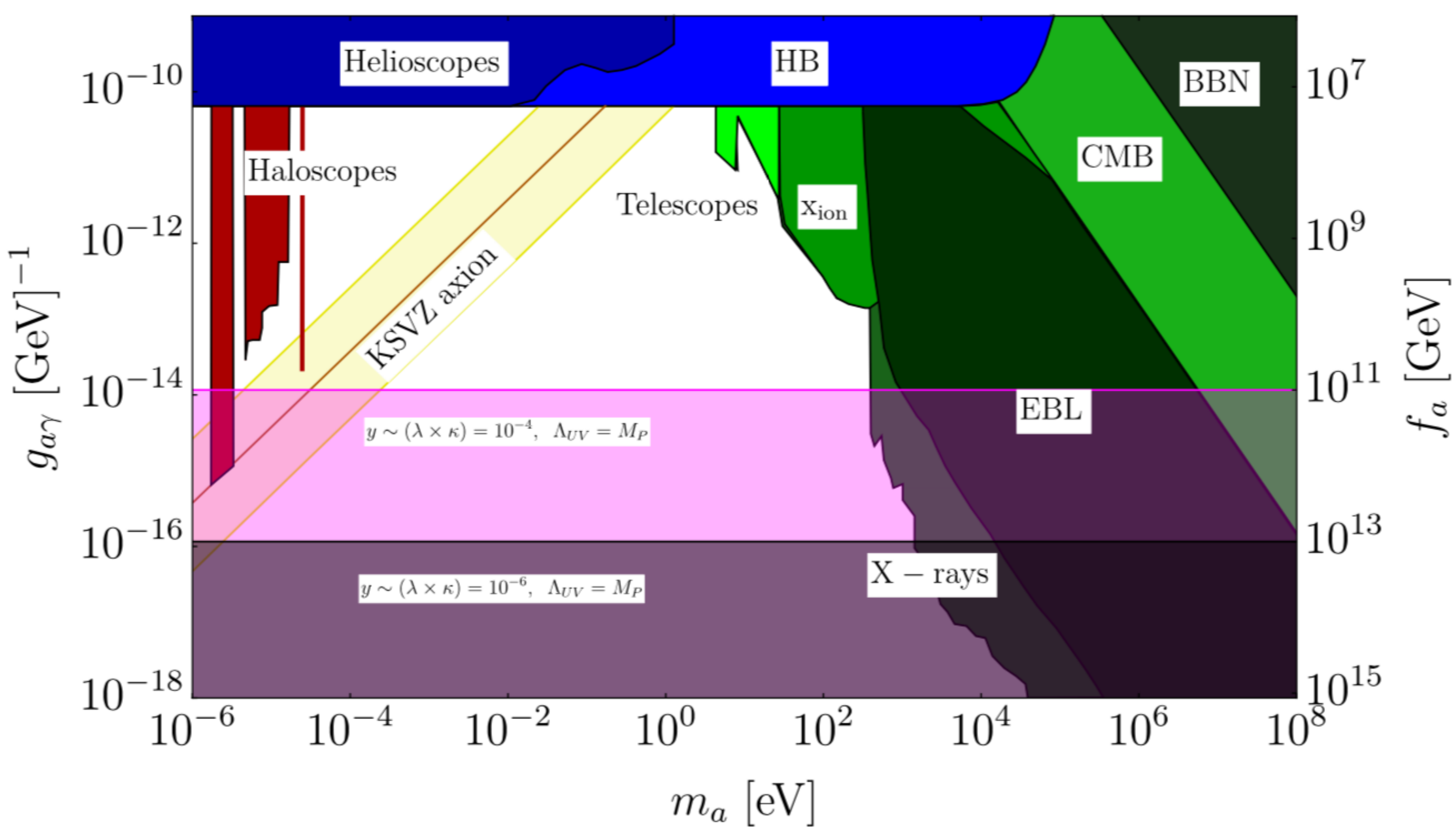
Peinado, Reig, Srivastava, Valle (2019)

$$m_\nu \sim \frac{v_{EW} f_a}{\Lambda}$$

$$\Lambda \sim M_{Pl}$$

f_a bounded by above by neutrino mass bounds (KATRIN)





Relaxing the UV scale:

de la Vega, Nath, Peinado(2020)

arXiv: 2001.01846

Nucl. Phys. B 957 (2020)

Case I : Type-II Dirac Seesaw

Symmetry/Fields	L_i	ν_{Ri}	H_u	H_d	σ	Φ_u
$SU(2)_L \times U(1)_Y$	(2, -1/2)	(1, 1)	(2, -1/2)	(2, 1/2)	(0, 0)	(2, -1/2)
$U(1)_{PQ}$	1	-5	2	2	4	6

Operator	PQ charge
$\frac{LL\tilde{H}_u\tilde{H}_u}{\Lambda_{UV}}$	$1+1+(-4)=-2$
$\frac{LL\tilde{H}_u H_d}{\Lambda_{UV}}$	$1+1+(0)=+2$
$\frac{LLH_dH_d}{\Lambda_{UV}}$	$1+1+(4)=+6$
$\frac{LL\tilde{\Phi}_u\tilde{\Phi}_u}{\Lambda_{UV}}$	$1+1+(-12)=-10$
$\frac{LL\tilde{H}_u\tilde{\Phi}_u}{\Lambda_{UV}}$	$1+1+(-8)=-6$
$\frac{LLH_d\tilde{\Phi}_u}{\Lambda_{UV}}$	$1+1+(-4)=-2\,.$

$\mathcal{L}_{dim\ 5} \sim$ (the operators above)

$$
\begin{array}{llll}
\sigma^n & (4n); & (\sigma^*)^n & (-4n); \\
(H_uH_d)^n & (4n); & (H_uH_d)^{*n} & (-4n); \\
(H_u^\dagger H_u)^n & (0); & (H_d^\dagger H_d)^n & (0); \\
(H_u^\dagger \Phi_u)^n & (4n); & (H_u^\dagger \Phi_u)^{*n} & (-4n); \\
(H_d\Phi_u)^n & (8n); & (H_d\Phi_u)^{*n} & (-8n); \\
(\Phi_u^\dagger \Phi_u)^n & (0); & &
\end{array}
$$

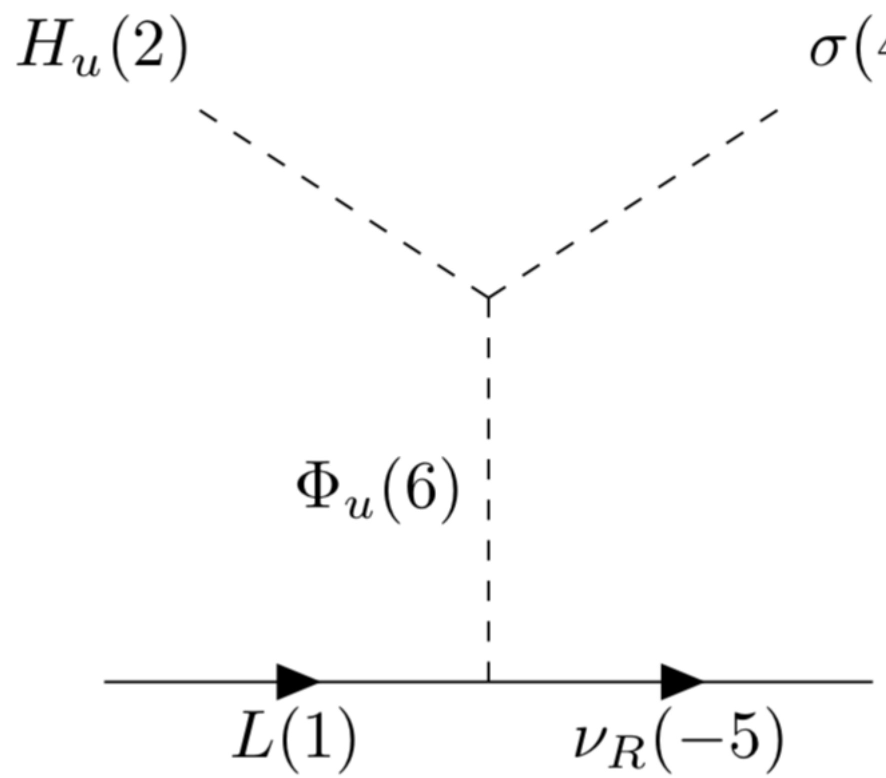
~~$L^c\tilde{H}\tilde{H}L$~~

~~$L^c\tilde{H}\tilde{\Phi}L$~~

~~$L^c\tilde{\Phi}\tilde{\Phi}L$~~

Case I : Type-II Dirac Seesaw

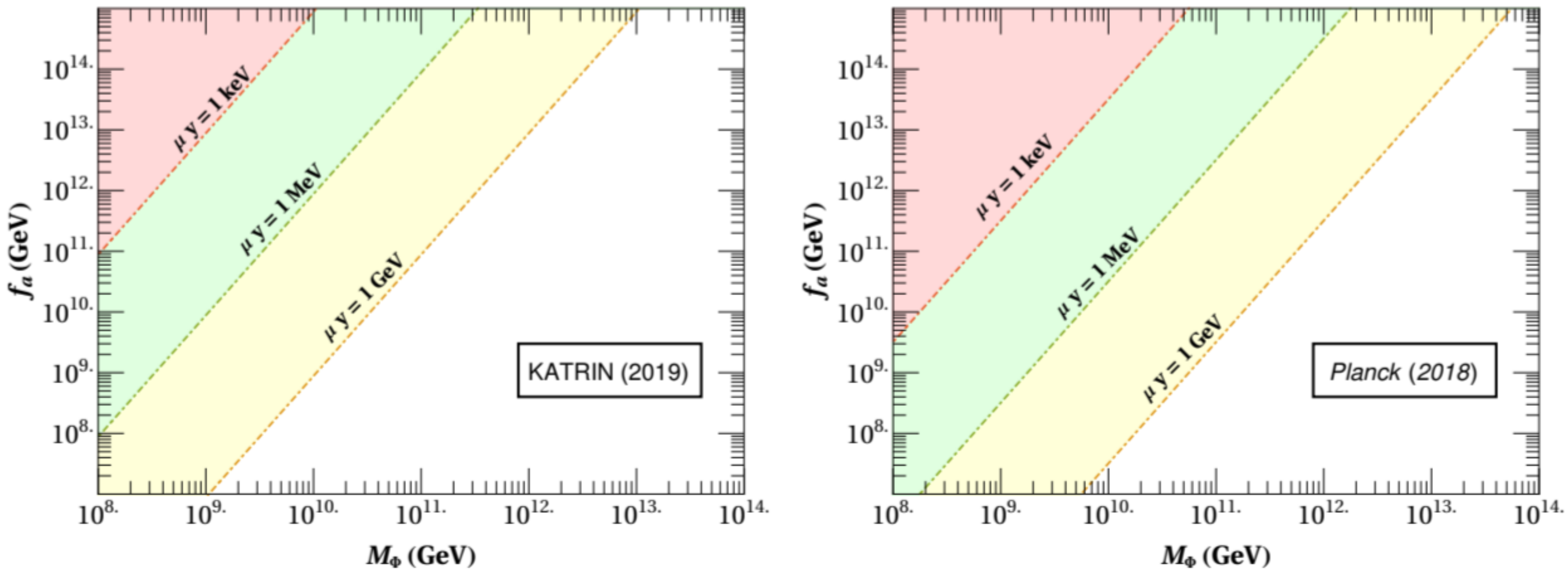
$LH_u\nu_R\sigma$ ✓



$$\mathcal{L}_Y \supset y^{\nu}_{ij}\overline{\nu}_{Li}\Phi_u\nu_{Rj} + \mu H_u\Phi_u^{\dagger}\sigma + h.c.$$

$$(m_\nu)_{ij} = y^{\nu}_{ij}\frac{\mu v_u f_a}{M^2_{\Phi_u}} \sim y^{\nu}_{ij} v_u \sin\theta$$

Case I : Type-II Dirac Seesaw



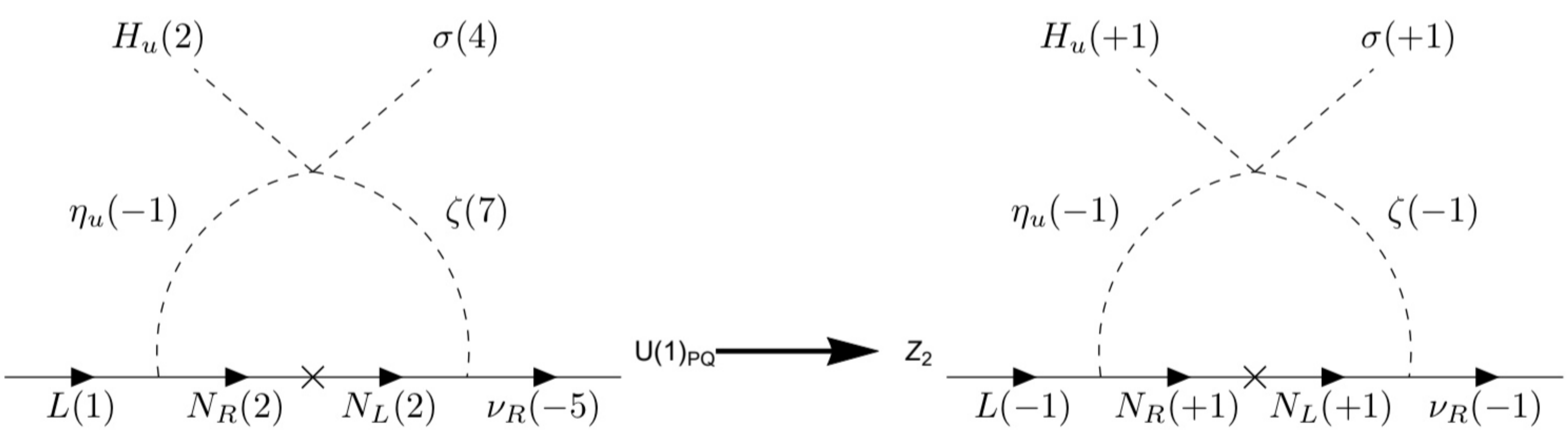
Case II : Dirac Scotogenic-like loop

Symmetry/Fields	L_i	ν_{Ri}	H_u	H_d	N_R	N_L	σ	η_u	ζ
$SU(2)_L \times U(1)_Y$	(2, -1/2)	(1, 1)	(2, -1/2)	(2, 1/2)	(1, 0)	(1, 0)	(1, 0)	(2, -1/2)	(1, 0)
$U(1)_{PQ}$	1	-5	2	2	2	2	4	-1	7
Z_2^{PQ}	-1	-1	+1	+1	+1	+1	+1	-1	-1

$$\mathcal{L}_Y \supset y^{\nu}_{ij}\overline{L}_i\eta_u N_{Rj} + M_{jk}\overline{N}_{Rj}N_{Lk} + y^{\nu\prime}_{ki}\overline{N}_{Lk}\nu_{Ri}\zeta + h.c.$$

$$V \supset \lambda_1 H_u \eta_u^\dagger \zeta^* \sigma$$

$$< \eta_u > = 0 = < \zeta >$$



Case II : Dirac Scotogenic-like loop

Scalar mixings
2 blocks:
(H_u, H_d, σ)
(η_u, ζ)

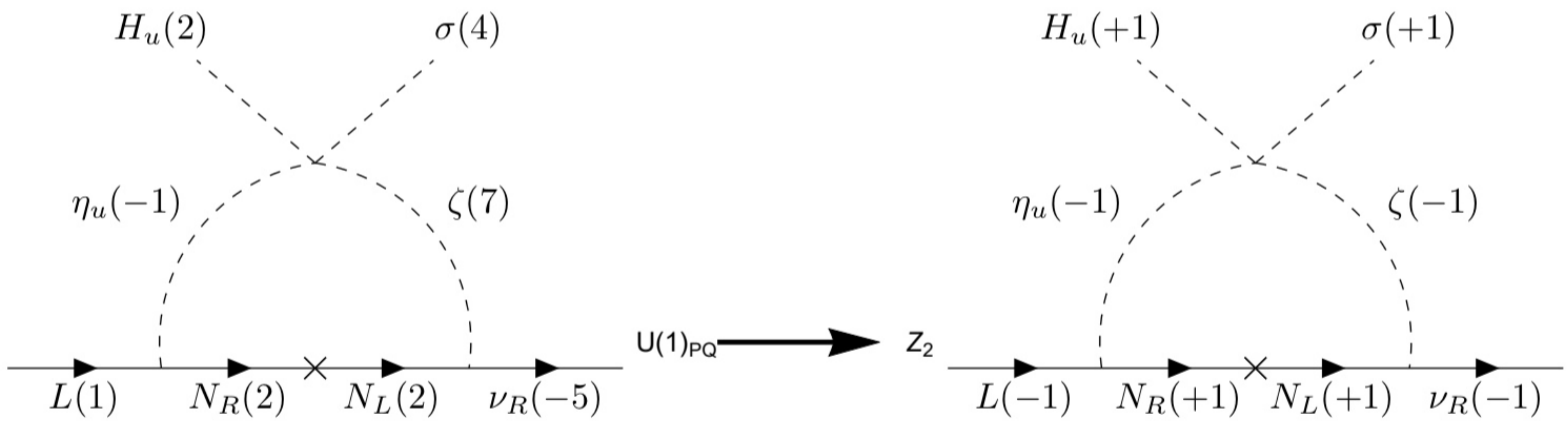
Spectrum:

(EW,PQ)

(1 TeV, PQ)

$$\sin 2\theta_X \sim \frac{\lambda_1 v_u f_a}{m^2_{S_{X_2}} - m^2_{S_{X_1}}}$$

Case II : Dirac Scotogenic-like loop



$$m_\nu^{ij} = \frac{1}{64\pi^2} \sum_{X=R,I} \frac{\lambda_1 v_u f_a}{m^2_{S_{X_2}} - m^2_{S_{X_1}}} \sum_k y^{ik} y'^{kj} m_{N_k} \left[F\left(\frac{m^2_{S_{X_2}}}{m^2_{N_i}} \right) - F\left(\frac{m^2_{S_{X_1}}}{m^2_{N_i}} \right) \right]$$

$$F(x) = x \log(x)/(x-1)$$

Case II : Dirac Scotogenic-like loop

Light N

$$m_\nu^{ij} \sim 1\mathrm{eV}\left(\frac{\lambda_1}{10^{-7}}\right)\left(\frac{v_u}{10^2\mathrm{GeV}}\right)\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)\left(\frac{y}{10^{-7}}\right)\left(\frac{y'}{0.82}\right)\left(\frac{m_{N_k}}{130\mathrm{GeV}}\right)\left(\frac{(280\mathrm{GeV})^2}{m_S^2}\right)$$

Light scalar

$$m_\nu^{ij} \sim \frac{\lambda_1 v_u f_a}{32\pi^2}\sum_k \frac{y^{ik}y'^{kj}}{m_{N_K}}\left[\log\left(\frac{m_{N_k}^2}{m_S^2}\right)-1\right]$$

Case II : Dirac Scotogenic-like loop

WIMP stability:

Z_2 + Lorentz

N must decay to an uneven number of fermions

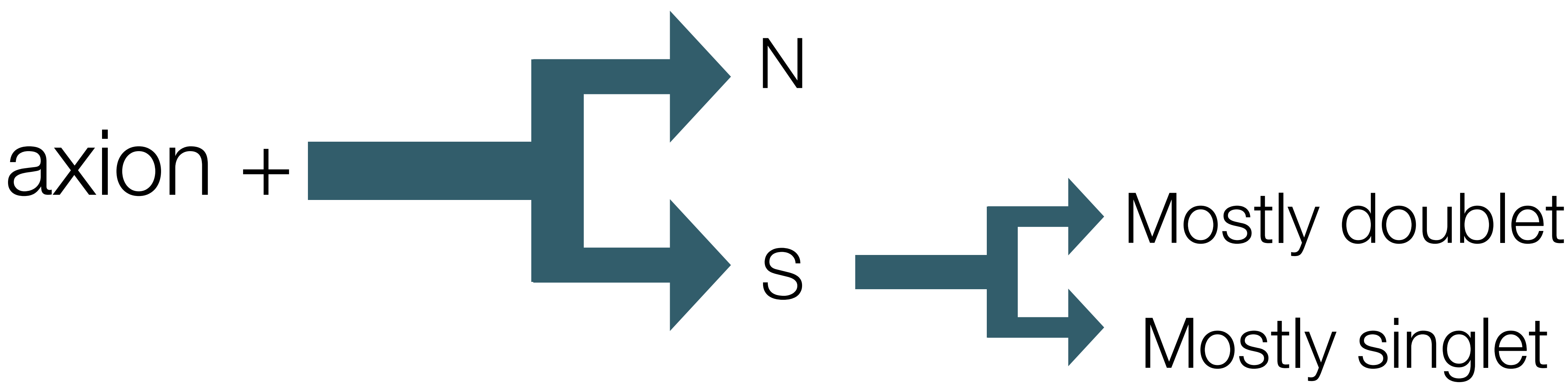
$(-1)^{2n-1} = -1$, but N has even charge !

S must decay to an even number of fermions

$(-1)^{2n} = 1$, but S has odd charge !

Case II : Dirac Scotogenic-like loop

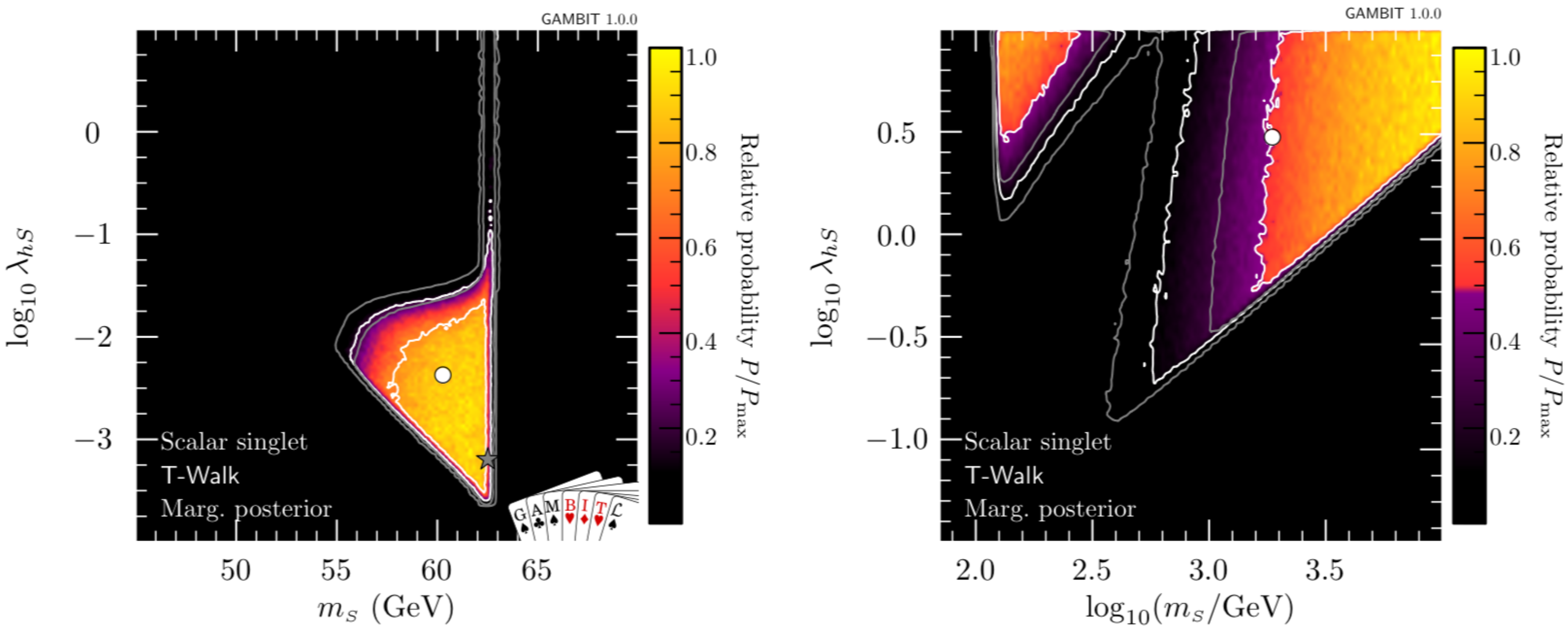
2 DM components: axion + lightest particle inside loop



Case II : Dirac Scotogenic-like loop

Scalar case:

Mostly singlet: Inert Singlet - like pheno



GAMBIT collaboration (2018)

Case

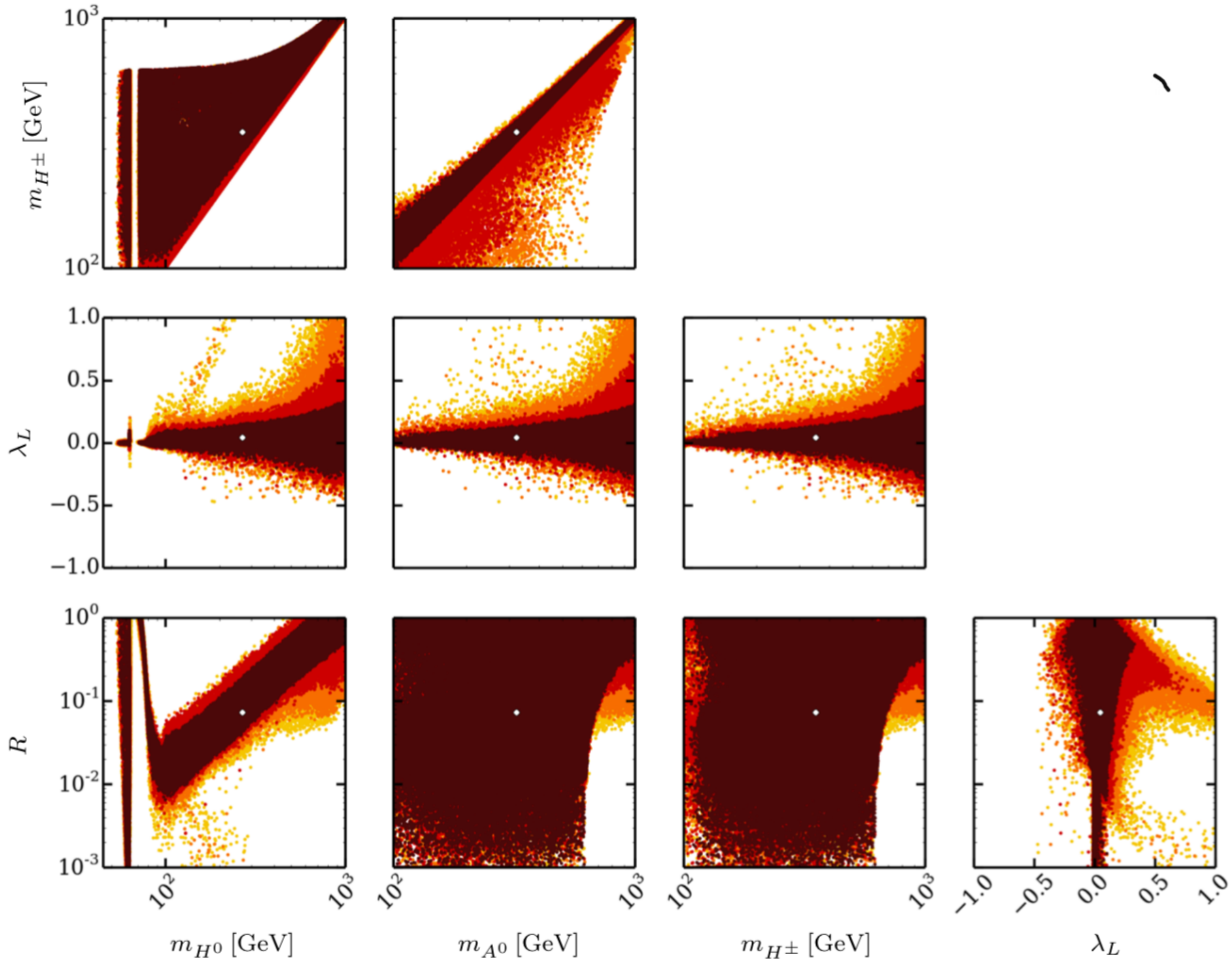


Figure 1: Global fit results for the IDM free parameters m_{H^0}, m_A^0, $m_H^\pm$, λ_L and the DM fraction R. The brown, red, orange and yellow points lie within 1-, 2-, 3- and 4σ away from the best-fit point (denoted by a white dot), respectively. Here we take into account the log-likelihood contributions from all observables described in section 3, except the GCE spectrum and unconfirmed dwarfs.

Eiteneuer, Goudelis, Heisig (2017)

Case II : Dirac Scotogenic-like loop

Fermion case:

Relic density and LFV processes dictated by Yukawas

Large yukawas for efficient annihilation

Small yukawas to avoid saturation of LFV limits

Case II : Dirac Scotogenic-like loop

Fermion case:

New coupling: N - ν_R - ζ

NN- $\nu_R \nu_R$ channel: saturation of N_{eff}?

Conclusions:

- PQ symmetry can provide a framework for neutrinos and DM
- PQ symmetry -> neutrino diracness?
- PQ symmetry -> multicomponent DM?
- Axion pheno <-> Neutrino pheno <-> DM pheno