Theories of Neutrino Masses and EDMs

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CASE WESTERN RESERVE UNIVERSITY EST. 1826
think beyond the possible

Electric Dipole Moments: Experimental and Theoretical Horizons, Caltech, May 12-14, 2025

References

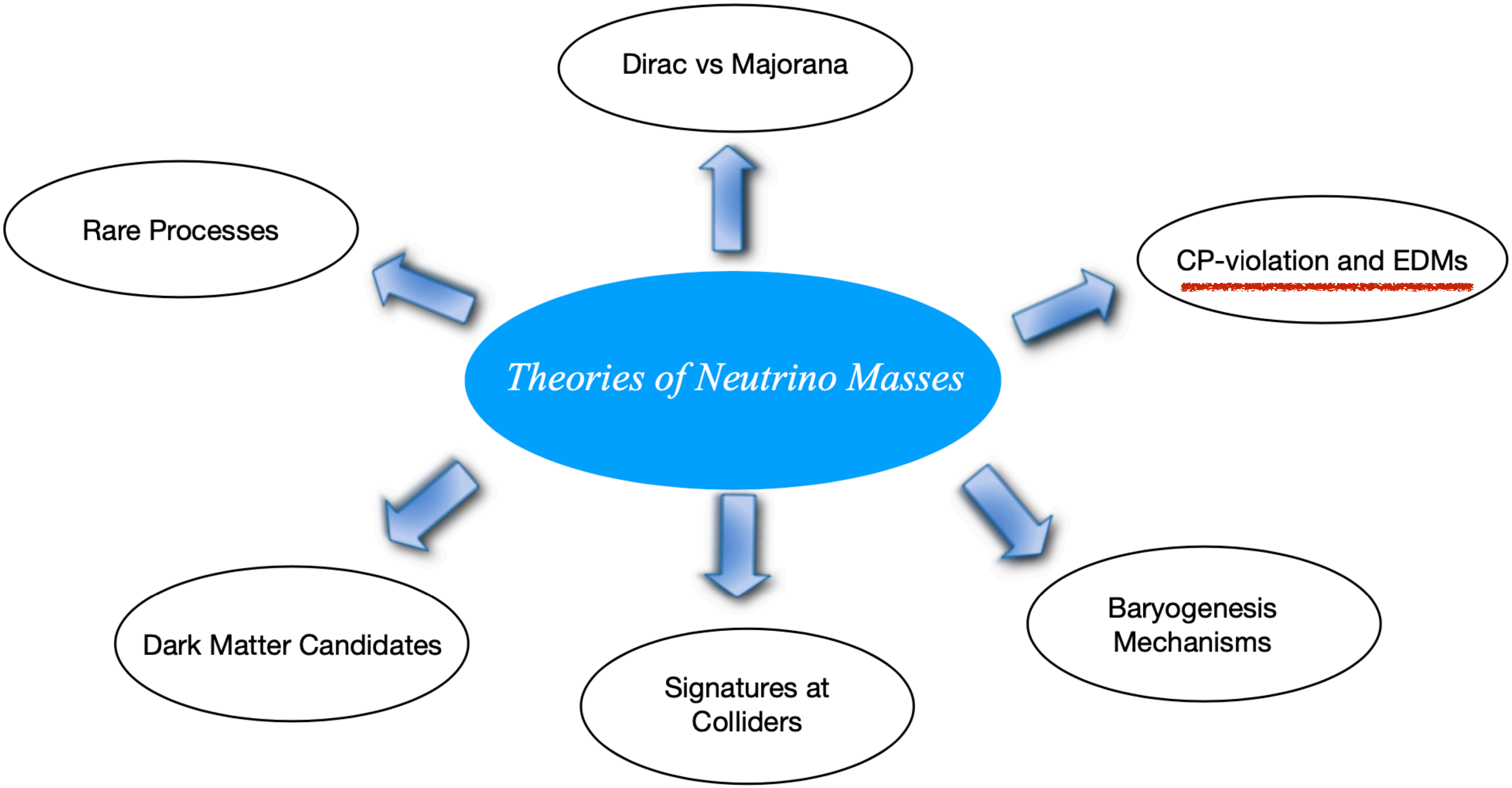
- H. Debnath, P. F. P., in progress

- H. Debnath, P. F. P., Physical Review D 111, 075020 (2025)

- P. F. P., Physical Review D 110, 035018 (2024)

- P. F. P., M. B. Wise (Caltech)

Main Goal


Theories of Neutrino Masses
Dirac vs Majorana
Rare Processes
CP-violation and EDMs
Dark Matter Candidates
Signatures at Colliders
Baryogenesis Mechanisms

Massive Neutrinos

- Majorana Fermions *(Lepton Number is broken by two units)*

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_M \nu_L$$

- Dirac Fermions *(Lepton Number is conserved or broken but not effective Majorana masses)*

$$\mathcal{L} \supset M_D \bar{\nu}_L \nu_R$$

Majorana Neutrino Masses

$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_\nu \nu_L$$

Mechanisms:

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Witten's Model

…

…

Theories:

- B-L
- Left-Right Symmetry
- Pati-Salam
- GUTs
- ….

- Majorana

$$-\mathcal{L} \supset y_\nu^D \, l_L^T C i\sigma_2 H (\nu^c)_L + \frac{1}{2} (\nu^c)_L^T C M_R (\nu^c)_L + h.c.$$

$$m_\nu \simeq M_\nu^D M_R^{-1} (M_\nu^D)^T \qquad (M_R >> M_\nu^D)$$

$$M_N \simeq M_R$$

$$M_\nu^D = y_\nu^D \frac{v}{\sqrt{2}}$$

if $M_\nu^D \sim 10^2$ GeV $\Rightarrow M_R \lesssim 10^{14-15}$ GeV

- Dirac

$$-\mathcal{L} \supset y_\nu^D \, \bar{l}_L i\sigma_2 H^* \nu_R + h.c.$$

$$M_\nu = y_\nu^D \frac{v}{\sqrt{2}} \qquad y_\nu^D \lesssim 10^{-12}$$

CPV and Neutrino Masses

Dirac

$$\mathcal{J}^{\mathrm{CP}}_{\mathrm{lepton}} = \mathrm{Tr}\left[(\mathbf{m}_\nu \mathbf{m}_\nu^\dagger)^*, \mathbf{m}_l \mathbf{m}_l^\dagger\right]^3 .$$

$$\mathcal{J}^{\mathrm{CP}}_{\mathrm{lepton}} = -\,6\,i\,({m_\mu}^2 - {m_e}^2)\,({m_\tau}^2 - {m_\mu}^2)\,({m_\tau}^2 - {m_e}^2)$$

$$\times\, \Delta m^2_{21}\, \Delta m^2_{31}\, \Delta m^2_{32}\, \mathcal{J}^{21}_{e\mu}$$

$$\begin{aligned} \mathcal{J}^{21}_{e\mu} &\equiv \mathrm{Im}\,[\,\mathbf{U}_{11}\mathbf{U}_{22}\mathbf{U}^*_{12}\mathbf{U}^*_{21}\,] \\ &= \frac{1}{8}\sin(2\,\theta_{12})\sin(2\,\theta_{13})\sin(2\,\theta_{23})\sin\delta\,, \end{aligned}$$

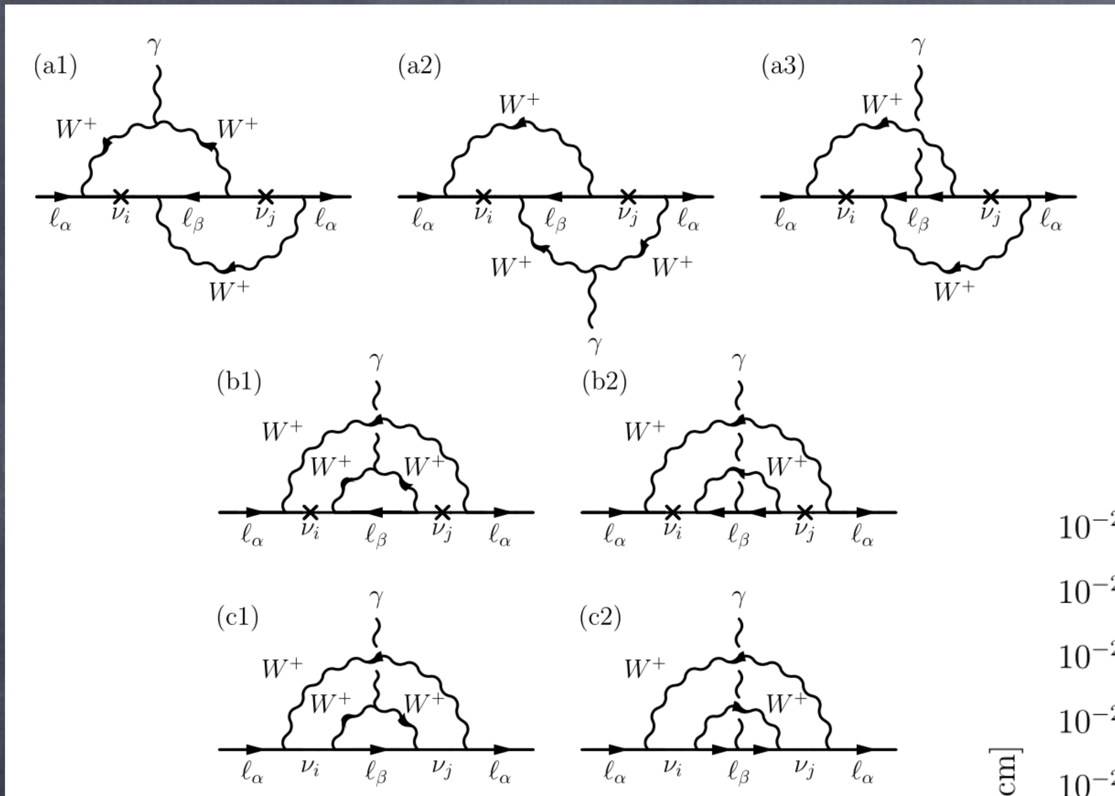
$U = V_{PMNS}$

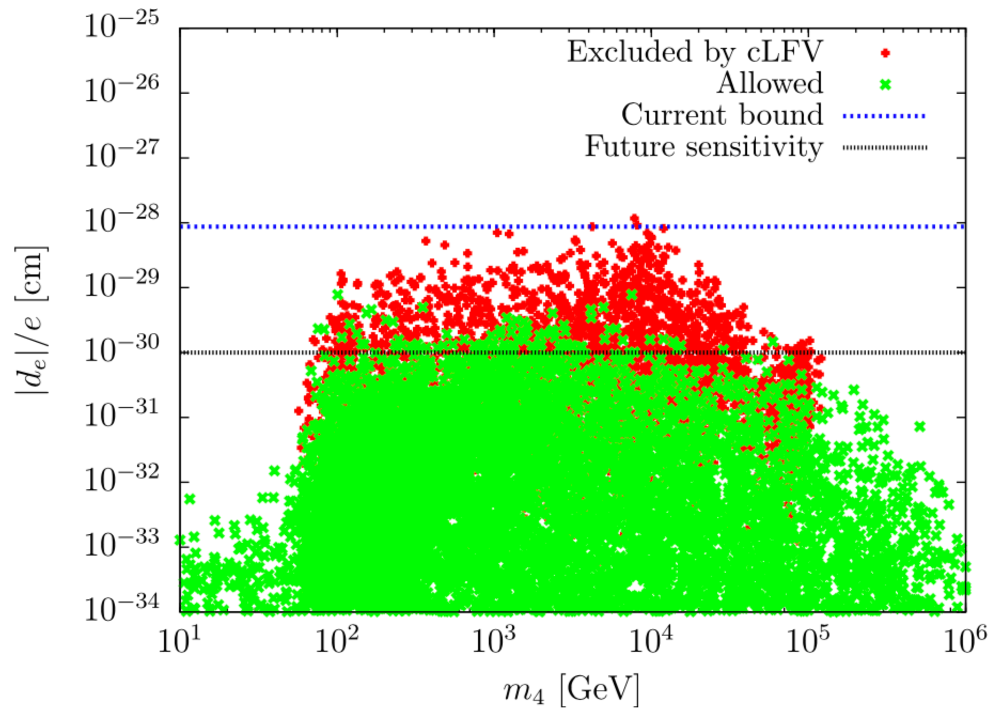
Majorana

$$\mathcal{J}^{\mathrm{CP}}_{\mathrm{Maj}} = \mathrm{Im}\ \mathrm{Tr}\big(\mathbf{m}_l \mathbf{m}_l^\dagger \mathbf{m}_\nu^* \mathbf{m}_\nu \mathbf{m}_\nu^* \mathbf{m}_l^T \mathbf{m}_l^* \mathbf{m}_\nu\big).$$

See Branco, Gonzalez Felipe, Joaquim

eEDM and Sterile neutrinos





CORRECT ?

Abada, Toma

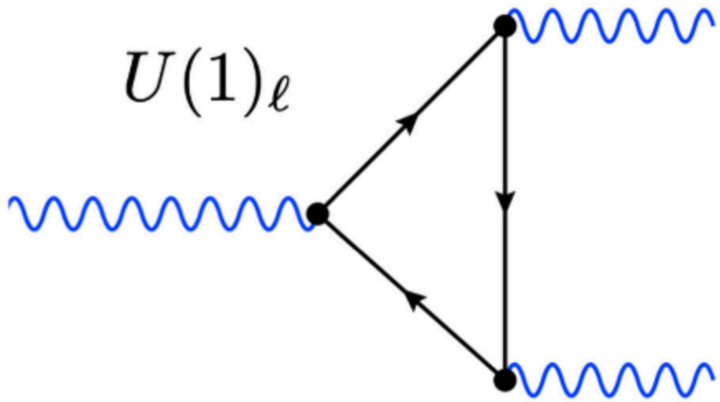
Theory of Neutrino Masses at the Low Scale

Lepton Number as Local Gauge Symmetry

Anomaly
Cancellation

$U(1)_\ell$

$M_\nu \neq 0$ $+$



DM

$\Omega_{DM} h^2 \leq 0.12$

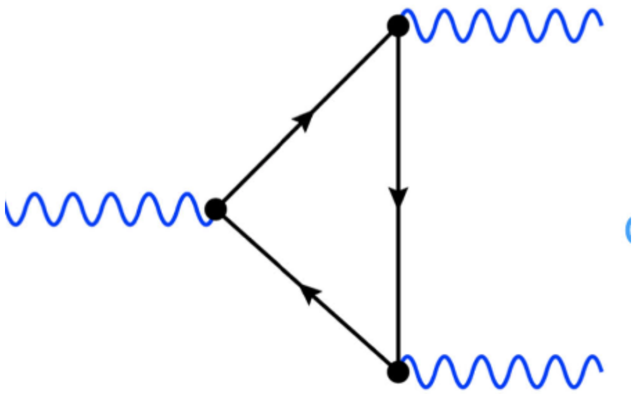
Low Scale Theory

Lepton Number as Local Gauge Symmetry

Anomaly Cancellation:

$$\ell_L \sim (\mathbf{2}, -1/2, 1) \quad \text{and} \quad e_R \sim (\mathbf{1}, -1, 1),$$

$$\mathcal{A}_1\left(SU(3)_C^2 U(1)_\ell\right) = 0,$$
$$\mathcal{A}_2\left(SU(2)_L^2 U(1)_\ell\right) = 3/2,$$
$$\mathcal{A}_3\left(U(1)_Y^2 U(1)_\ell\right) = -3/2,$$
$$\mathcal{A}_4\left(U(1)_Y U(1)_\ell^2\right) = 0,$$
$$\mathcal{A}_5\left(U(1)_\ell^3\right) = 3, \quad \text{and} \quad \mathcal{A}_6\left(U(1)_\ell\right) = 3.$$



Solutions:

- Minimal Model

P. F. P., Physical Review D 110, 035018 (2024)

- Four representations

P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

- Vector-like leptons

P. F. P., M. B. Wise, JHEP1108, 068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110, 231801

Minimal Model

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_\ell .$$

$$\Psi_L \sim (\mathbf{1}, \mathbf{1}, -1, 3/4), \qquad \Psi_R \sim (\mathbf{1}, \mathbf{1}, -1, -3/4),$$

$$\chi_L \sim (\mathbf{1}, \mathbf{1}, 0, 3/4), \quad \text{and} \quad \rho_L \sim (\mathbf{1}, \mathbf{3}, 0, -3/4).$$

$$\nu_R^i \sim (\mathbf{1}, \mathbf{1}, 0, 1),$$

Minimal number of fields to cancel all leptonic gauge anomalies

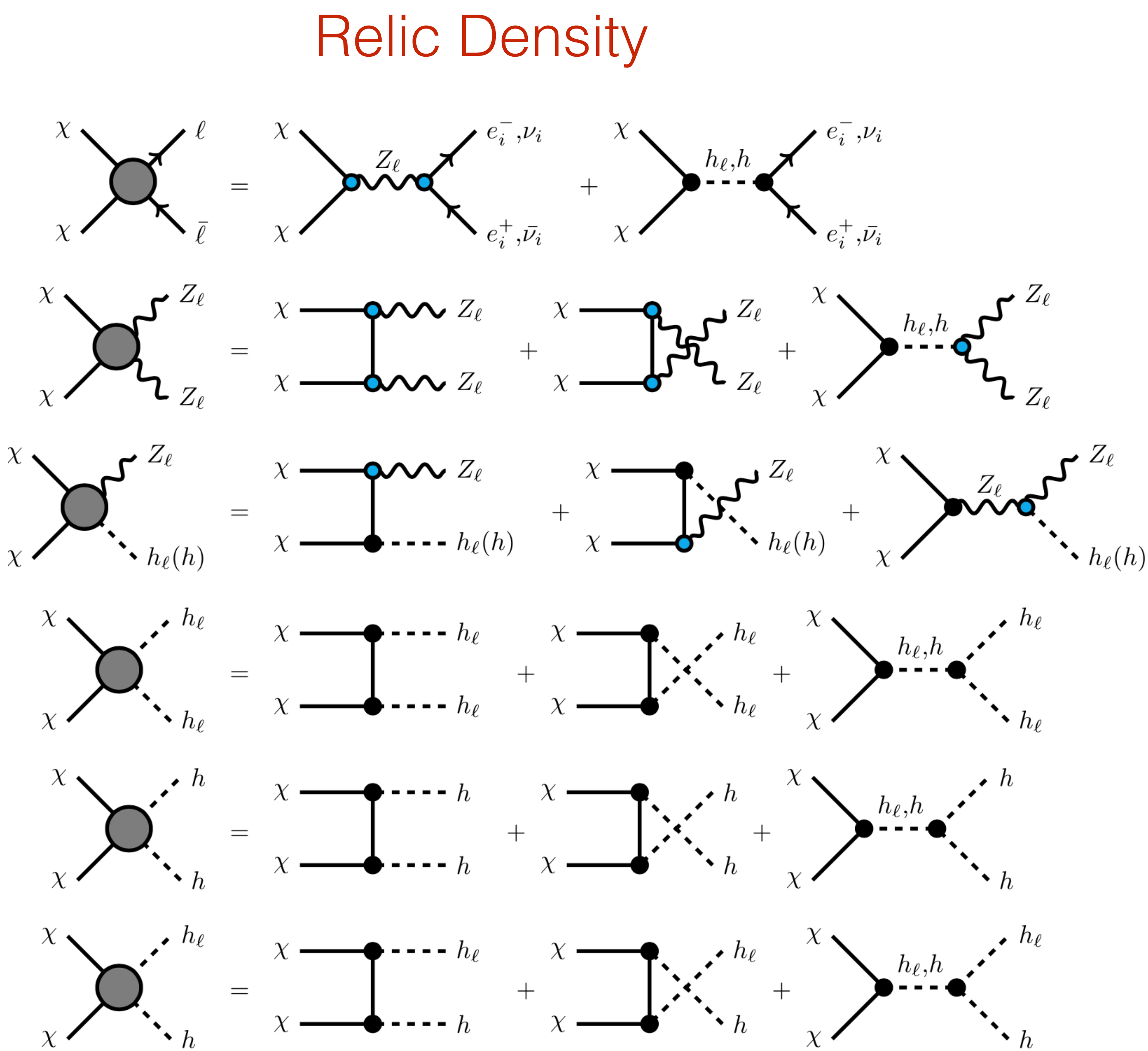
New Fermion Masses

$$-\mathcal{L} \supset \lambda_\rho \mathrm{Tr}(\rho_L^T C \rho_L) S + \lambda_\Psi \bar{\Psi}_L \Psi_R S + \lambda_\chi \chi_L^T C \chi_L S^* + \mathrm{H.c.},$$

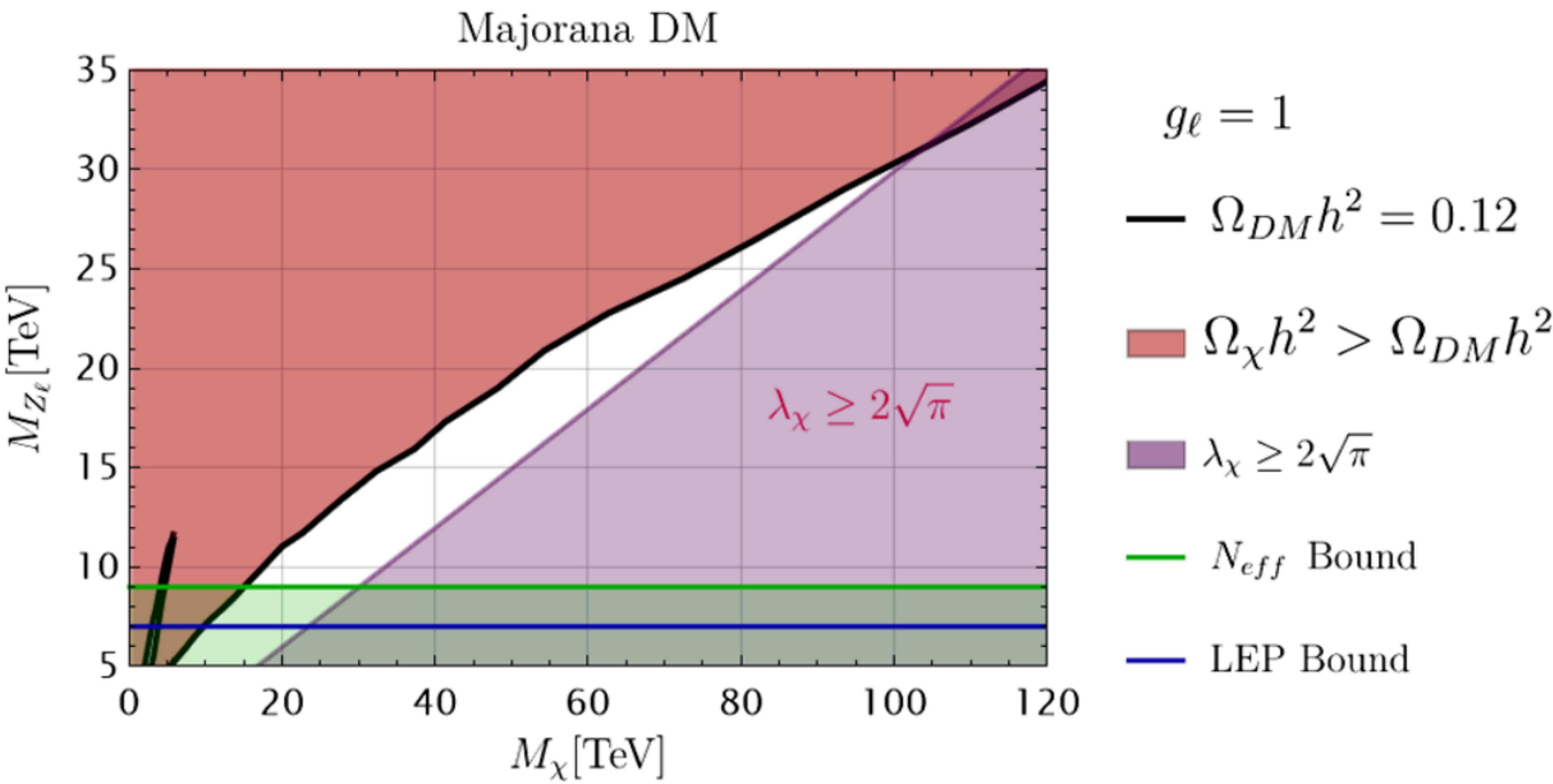
where $S \sim (\mathbf{1}, \mathbf{1}, 0, 3/2)$.

$$-\mathcal{L} \supset Y_\nu \overline{\ell}_L i\sigma_2 H^* \nu_R + y_e \overline{\ell}_L H e_R + \mathrm{H.c.}$$

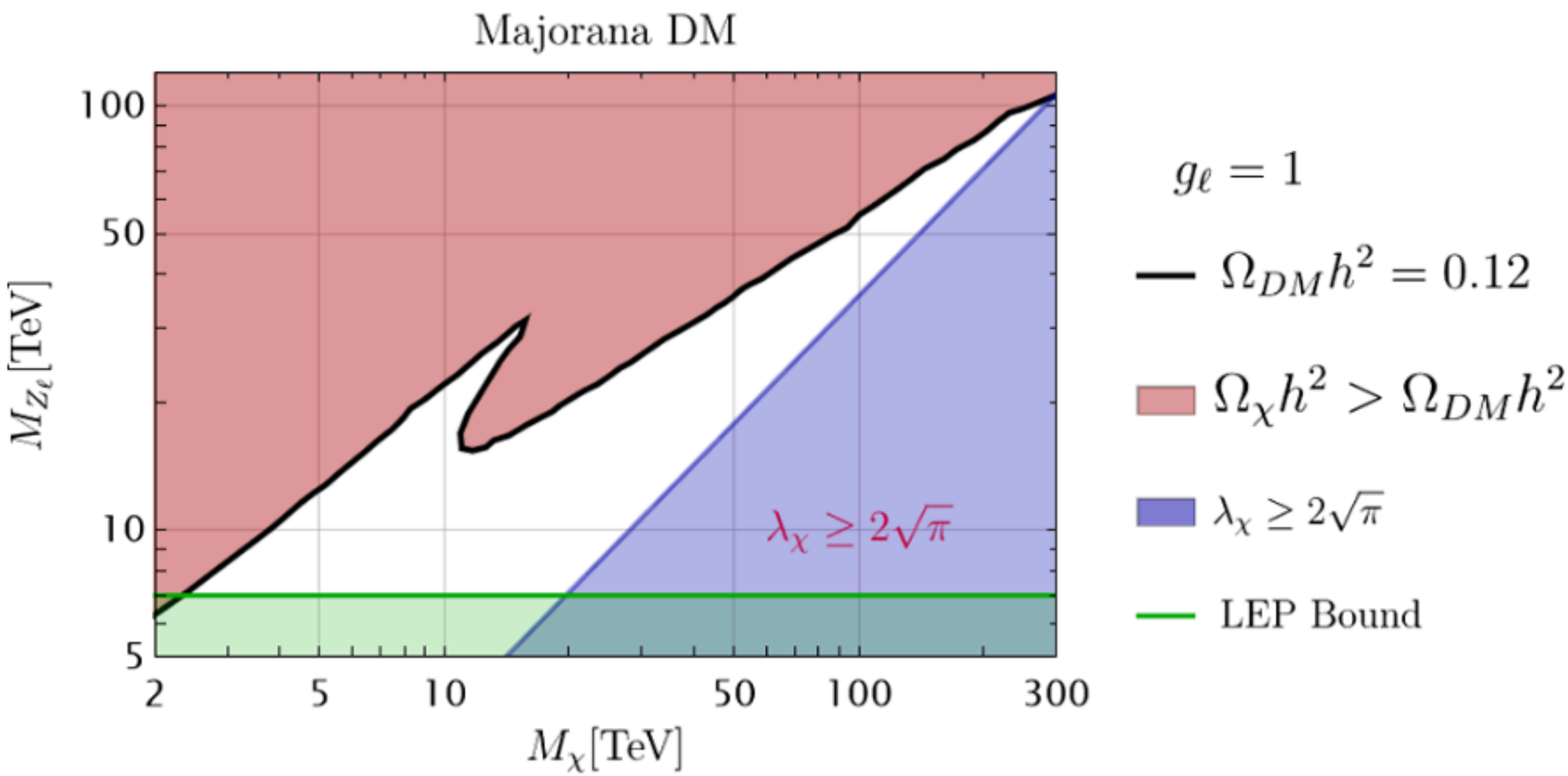
$$\mathcal{Z}_2: \Psi_L \to -\Psi_L, \quad \Psi_R \to -\Psi_R, \quad \rho_L \to -\rho_L, \quad \chi_L \to -\chi_L$$


Relic Density
χ
ℓ
$\bar{\ell}$
$=$
Z_ℓ
e_i^-, ν_i
$e_i^+, \bar{\nu_i}$
$+$
h_ℓ, h
$h_\ell(h)$
h_ℓ
h

Dirac Neutrinos



Majorana Neutrinos



CP-violation

$$Y_\nu \text{ and } y_e \text{ complex}$$

$$\rho_L \to e^{-i\theta_\rho/2}\rho_L, \chi_L \to e^{-i\theta_\chi/2}\chi_L,$$
$$\Psi_R \to e^{-i\theta_\Psi/2}\Psi_R, \Psi_L \to e^{i\theta_\Psi/2}\Psi_L$$

$$\lambda_\rho, \lambda_\Psi, \text{ and } \lambda_\chi \text{ are reals}$$

No CP-violation in the new sector !

The EDMs predictions the same as in the case of Dirac neutrinos

P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	1	3	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$-\frac{3}{2}$

P. F. P., S. Ohmer, H. H. Patel, Phys. Lett. B735, 283

$$-\mathcal{L} \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \Psi_L + y_4 \bar{\Psi}_R \Sigma_L H +$$

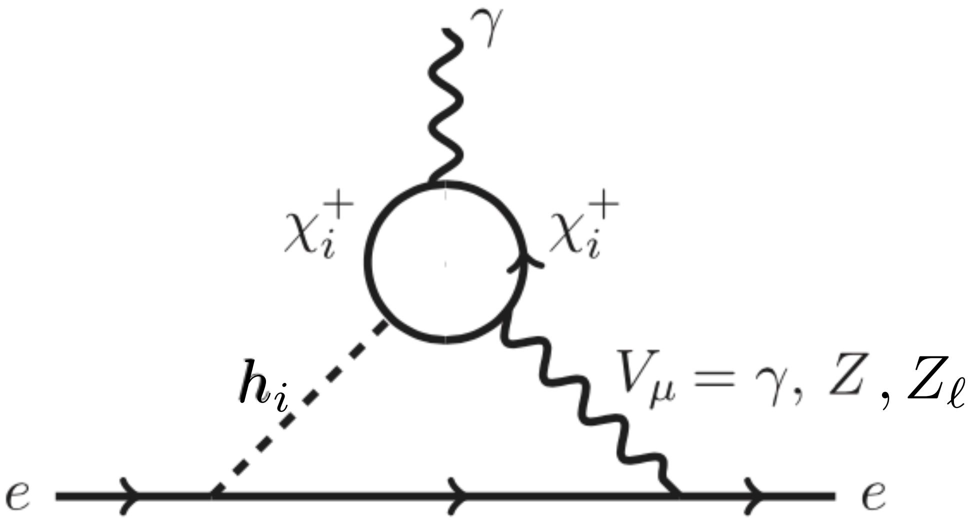
$$y_\Psi \bar{\Psi}_R \Psi_L S_\ell^* + \frac{y_\chi}{\sqrt{2}} \chi_L \chi_L S_\ell + y_\Sigma \mathrm{Tr}(\Sigma_\mathrm{L} \Sigma_\mathrm{L}) \mathrm{S}_\ell + \mathrm{h.c.}$$

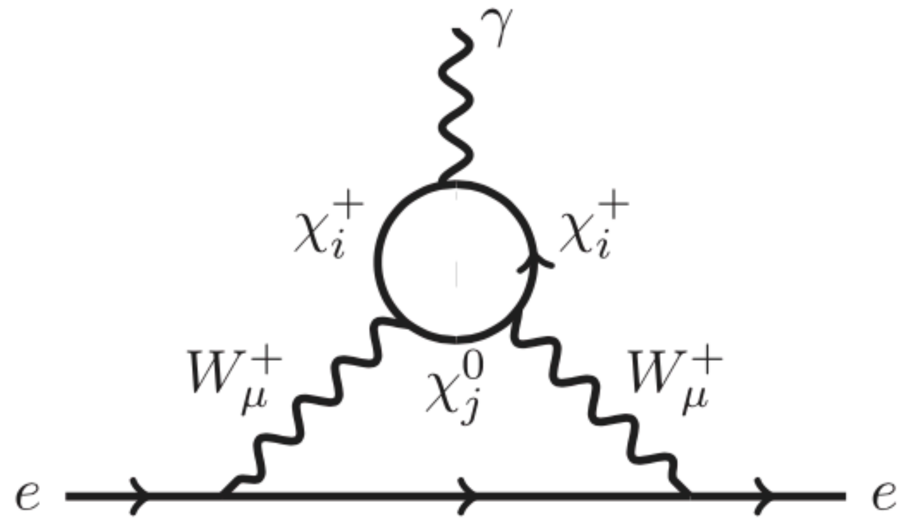
$$\begin{pmatrix} \Sigma_L^+ \\ \Psi_{1L}^+ \end{pmatrix} = V_L \begin{pmatrix} \chi_{1L}^+ \\ \chi_{2L}^+ \end{pmatrix}, \qquad \begin{pmatrix} \Sigma_R^+ \\ \Psi_{2R}^+ \end{pmatrix} = V_R \begin{pmatrix} \chi_{1R}^+ \\ \chi_{2R}^+ \end{pmatrix}.$$

There are 3 new CP-violating phases in this theory

In the charged sector we have: $\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi),$

e-EDMs



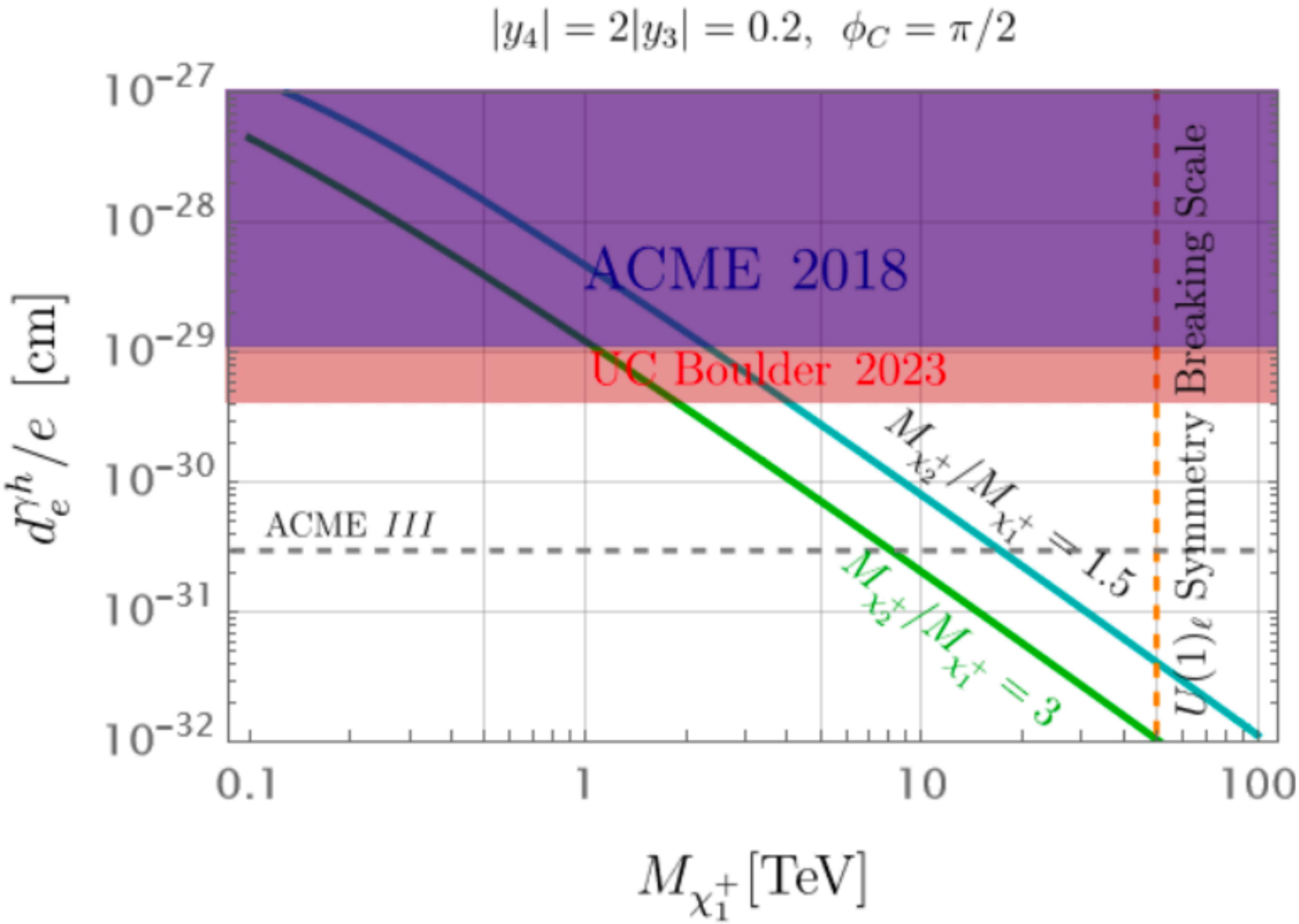


$$d_f^{\gamma h} = \frac{\alpha^2 \cos\theta_\ell Q_f}{4\pi^2 s_W} \frac{m_f}{m_h^2\, m_W} \sum_{i=1}^{2} M_{\chi_i^\pm} \mathrm{Im}[C_h^{ii}]\, I_{\gamma h}^i(M_{\chi_i^\pm}),$$

$$d_f^{hZ} = \frac{e\alpha\cos\theta_\ell}{32\pi^2 c_W s_W^2} \left(\frac{1}{2}T_3^f - s_W^2 Q_f\right) \frac{m_f}{m_h^2 m_W} \sum_{i,j=1}^{2} I_{hZ}^{ij}(M_{\chi_i^\pm}, M_{\chi_j^\pm}),$$

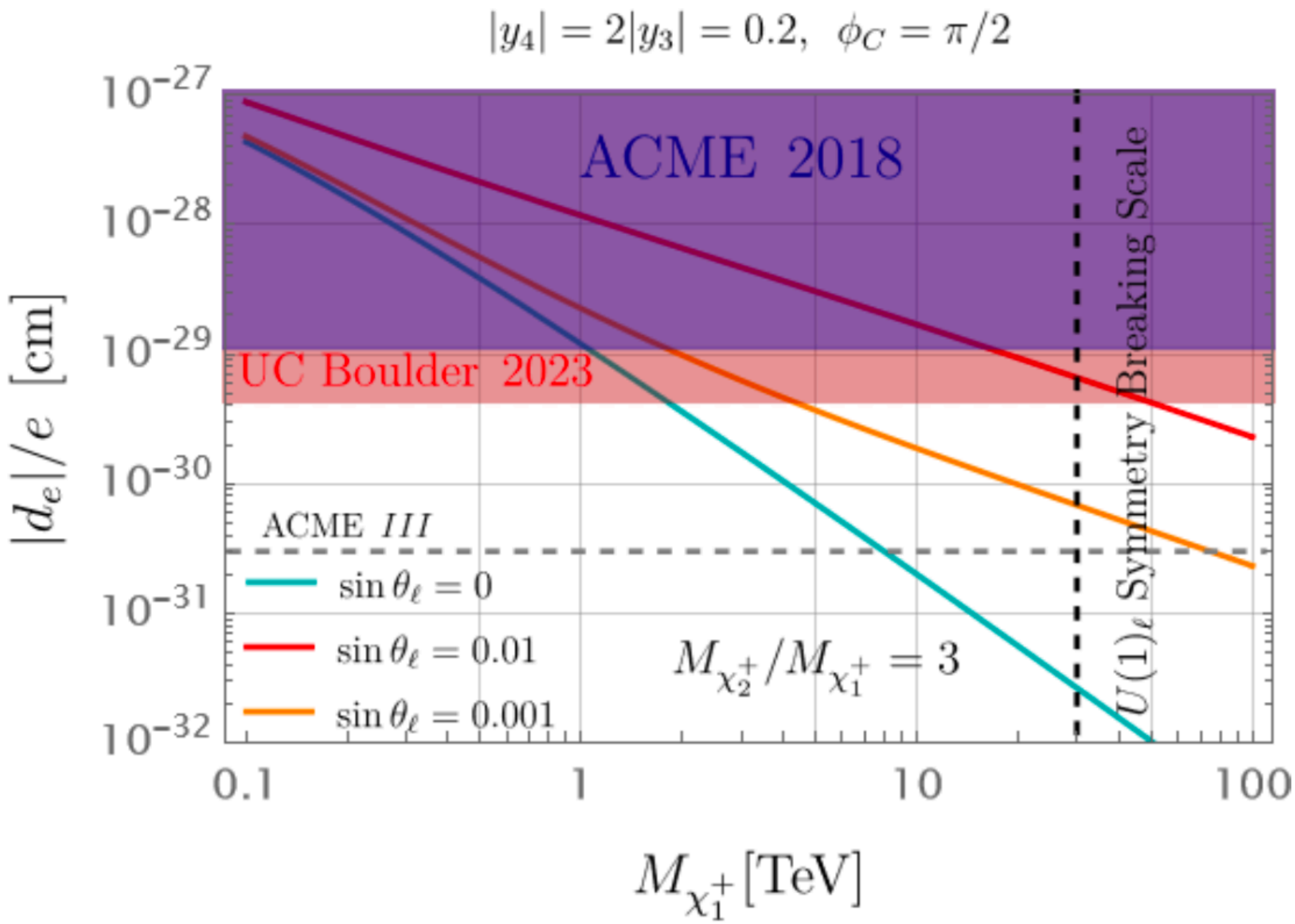
$$d_f^{hZ'} = \frac{g_\ell \alpha\cos\theta_\ell}{96\pi^2 s_W} \frac{m_f}{m_h^2 m_W} \sum_{i,j=1}^{2} I_{hZ'}^{ij}(M_{\chi_i^\pm}, M_{\chi_j^\pm}),$$

e-EDMs



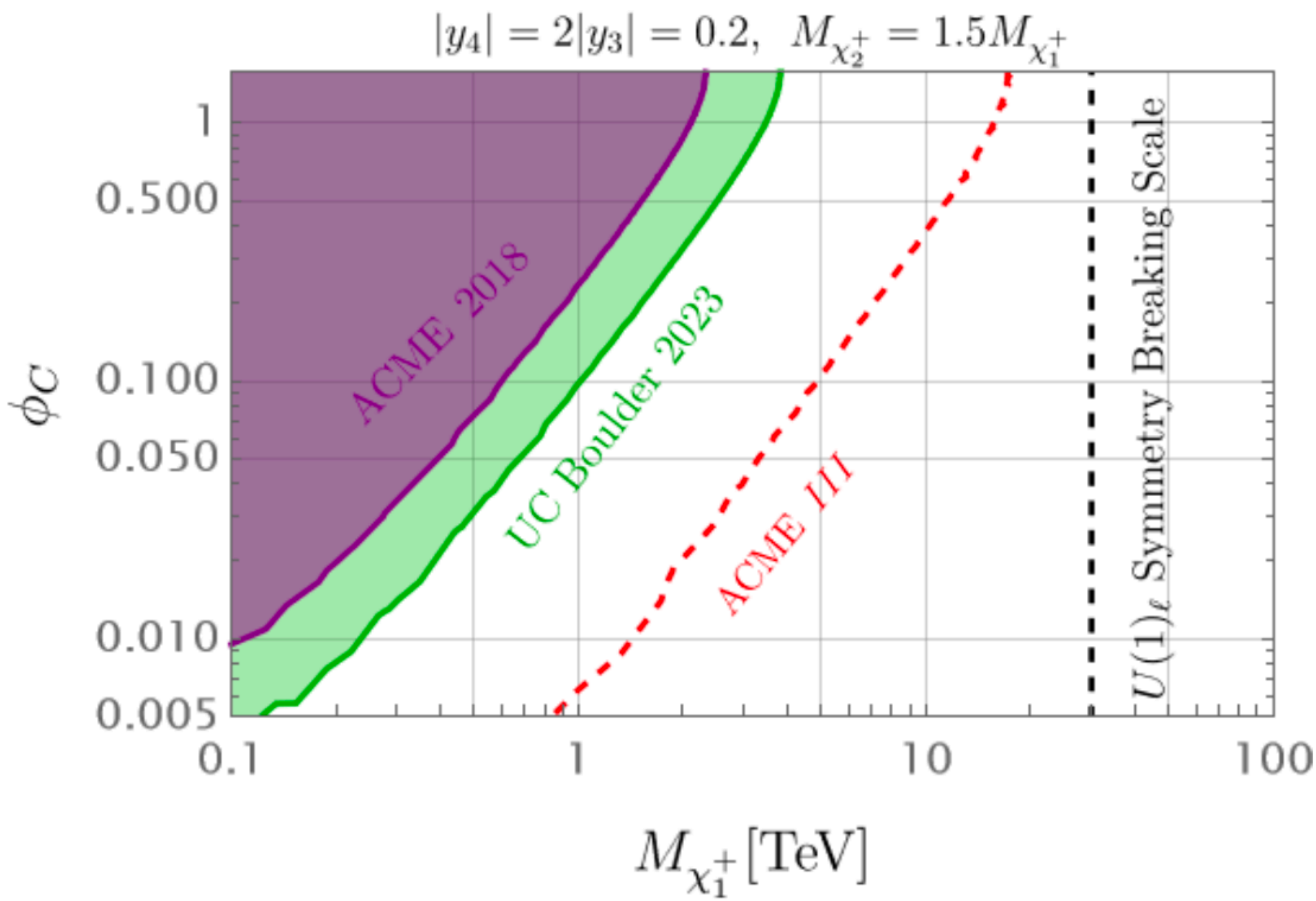
$|y_4| = 2|y_3| = 0.2, \;\; \phi_C = \pi/2$
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
$d_e^{\gamma h}/e$ [cm]
ACME 2018
UC Boulder 2023
ACME III
$M_{\chi_2^+}/M_{\chi_1^+} = 1.5$
$M_{\chi_2^+}/M_{\chi_1^+} = 3$
$U(1)_\ell$ Symmetry Breaking Scale
0.1
1
10
100
$M_{\chi_1^+}$ [TeV]

e-EDMs



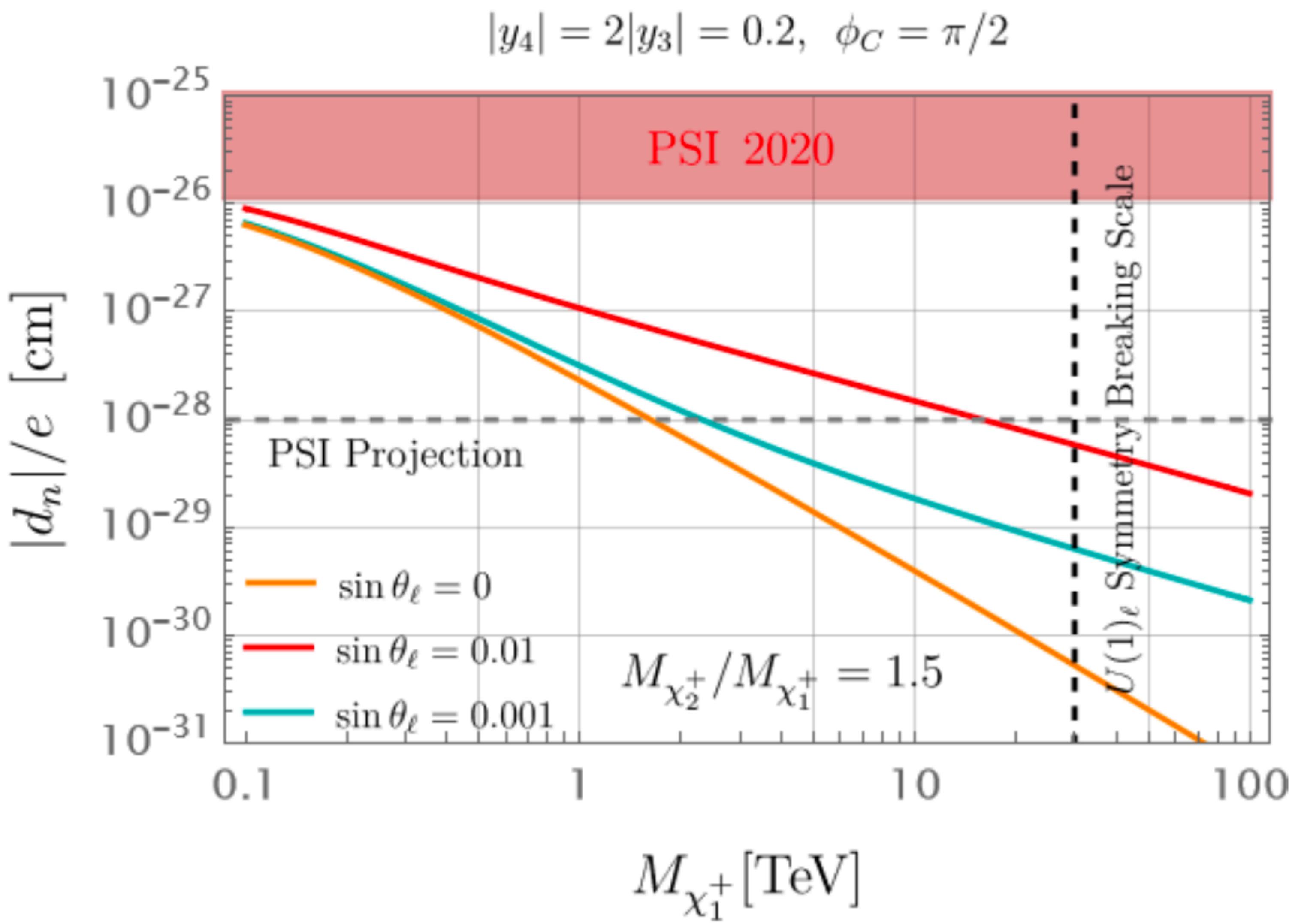
y_3=0.1, $y_4 = 0.2$,$M_{h_\ell} = 200$ GeV,$M_{\chi_2^+} = M_{Z_\ell} = 3M_{\chi_1^+}$ and $g_\ell = 1$.

e-EDMs

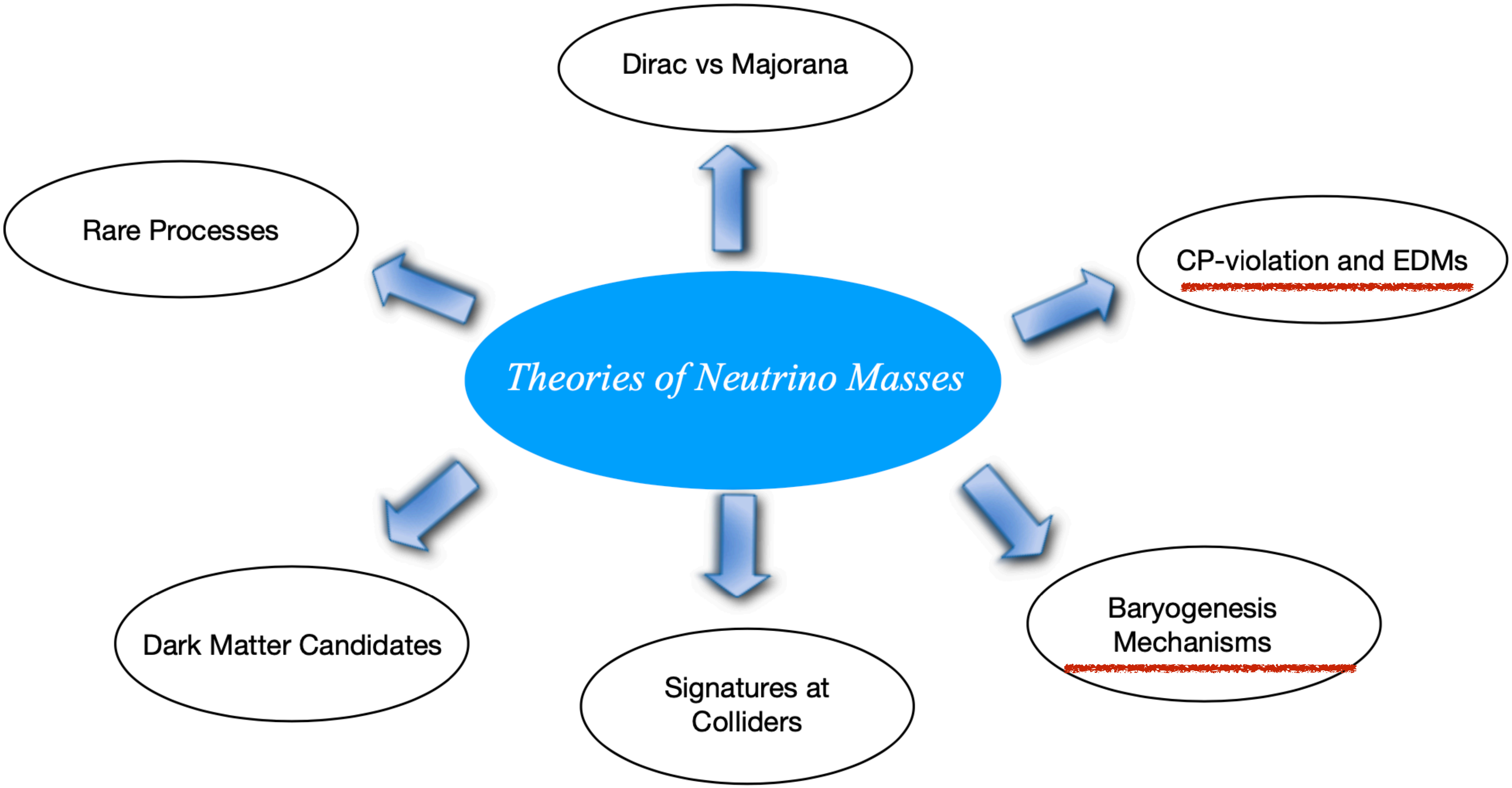


$|y_4| = 2|y_3| = 0.2, \quad M_{\chi_2^+} = 1.5 M_{\chi_1^+}$
ACME 2018
UC Boulder 2023
ACME III
$U(1)_\ell$ Symmetry Breaking Scale
ϕ_C
1
0.500
0.100
0.050
0.010
0.005
0.1
1
10
100
$M_{\chi_1^+}$ [TeV]

n-EDMs


$|y_4| = 2|y_3| = 0.2, \ \phi_C = \pi/2$
PSI 2020
PSI Projection
$U(1)_\ell$ Symmetry Breaking Scale
$\sin\theta_\ell = 0$
$\sin\theta_\ell = 0.01$
$\sin\theta_\ell = 0.001$
$M_{\chi_2^+}/M_{\chi_1^+} = 1.5$
$|d_n|/e$ [cm]
$M_{\chi_1^+}$ [TeV]
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
0.1
1
10
100

Main Goal



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