Theories of Neutrino Masses and Dark Matter

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think beyond the possible

Phenomenology Before and After the Standard Model: a Symposium in honor of Vernon Barger
University of Wisconsin-Madison, June 5, 2025

I was a Postdoc and Dirac Fellow (2007-2011) at UW-Madison, a wonderful place !

PRL **102,** 181802 (2009) PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

Minimal Gauged $U(1)_{B-L}$ Model with Spontaneous R Parity Violation

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We study the minimal gauged $U(1)_{B-L}$ supersymmetric model and show that it provides an attractive theory for spontaneous R-parity violation. Both $U(1)_{B-L}$ and R parity are broken by the vacuum expectation value of the right-handed sneutrino (proportional to the soft supersymmetry masses), thereby linking the $B-L$ and soft SUSY scales. In this context we find a consistent mechanism for generating neutrino masses and a realistic mass spectrum, all
supersymmetry standard model. We discuss the most
the Z' gauge boson and R-parity violation.

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Three layers of neutrinos

Vernon Barger, Pavel Fileviez Pérez, Sogee Spinner

https://doi.org/10.1016/j.physletb.2011.01.015

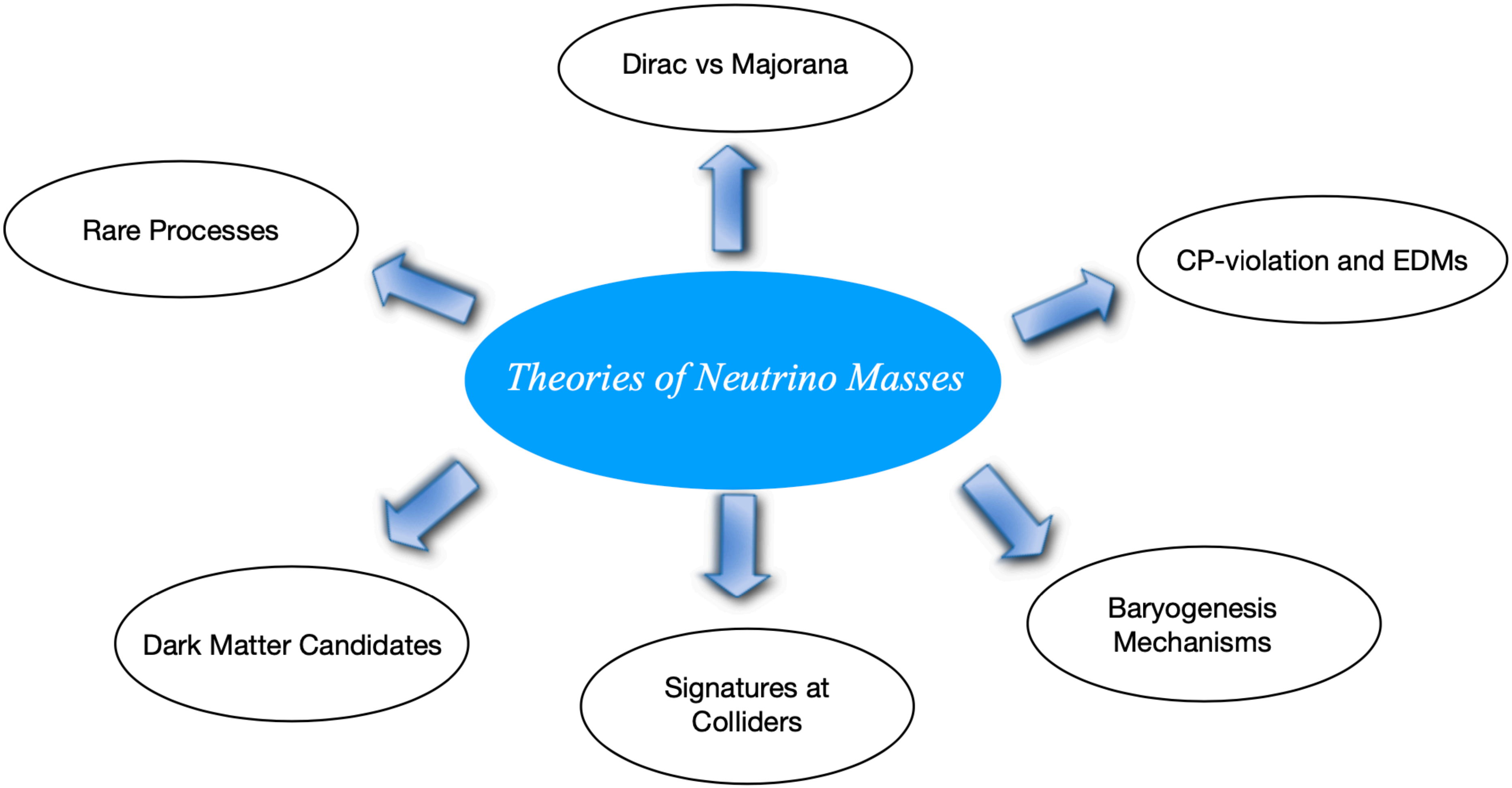
Abstract

In this Letter we point out that in a class of models for spontaneous R-parity breaking based on gauged $B-L$, the spectrum for neutrinos is quite peculiar. We find that those models generally predict three layers of neutrinos: one heavy sterile neutrino, two massive active neutrinos, and three nearly massless (one active and two sterile) neutrinos.

References

- P. F. P., Physical Review D 110, 035018 (2024)
- H. Debnath, P. F. P., Physical Review D 111, 075020 (2025)
- J. Butterworth, H. Debnath, J. Egan, P. F. P., arXiv:2505.06341
- P. F. P., M. B. Wise, PRL and Phys.Rev.D88, 057703

Main Goal



Dirac vs Majorana
Rare Processes
CP-violation and EDMs
Theories of Neutrino Masses
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
- ….

(Minkowski, Mohapatra, Senjanovic, Glashow, Yanagida, Gell-Mann, Ramond, Slansky)

Canonical Seesaw

$$-\mathcal{L}_\nu = Y_\nu \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \ \nu_R^T C \nu_R + h.c.$$

$$\Rightarrow \quad M_\nu = m_D M_R^{-1} m_D^T$$

if $m_D \sim 10^2 \ \text{GeV}$ $\Rightarrow$ $M_R \lesssim 10^{14-15} \ \text{GeV}$

(Seesaw Scale)

What is the Seesaw Scale ?

Neutrino Masses:

“Standard Paradigm”

Pati, Salam, 1974

Quark-Lepton Unification

$$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \supset SO(10)$$

$$\begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix}_L \qquad \begin{pmatrix} u_r & u_g & u_b & N \\ d_r & d_g & d_b & e \end{pmatrix}_R$$

$$M_\nu = m_D^\nu M_R^{-1} (m_D^\nu)^T \qquad m_D^\nu = m_U$$

$$M_R \lesssim 10^{14-15} \text{ GeV}$$

High Scale Seesaw

Low Scale Quark-Lepton Unification

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

$$F_{QL} = \begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix} \sim (\mathbf{4}, \mathbf{2}, 0),$$

$$F_u = \left(u_r^c \ \ u_g^c \ \ u_b^c \ \ \nu^c \right) \sim (\bar{\mathbf{4}}, \mathbf{1}, -1/2),$$

$$F_d = \left(d_r^c \ \ d_g^c \ \ d_b^c \ \ e^c \right) \sim (\bar{\mathbf{4}}, \mathbf{1}, 1/2).$$

P. F. P., M. B. Wise, Phys.Rev.D88, 057703

Neutrino Masses

$$-\mathcal{L} \supset Y_5 F_u \chi S + \frac{1}{2}\mu S S + \text{h.c.}\,,$$

$S \sim (1,1,0)$

$\chi \sim (4,1,1/2)$

$$\begin{pmatrix}\nu & \nu^c & S\end{pmatrix}\begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & M_\chi^D \\ 0 & (M_\chi^D)^T & \mu \end{pmatrix}\begin{pmatrix}\nu \\ \nu^c \\ S\end{pmatrix},$$

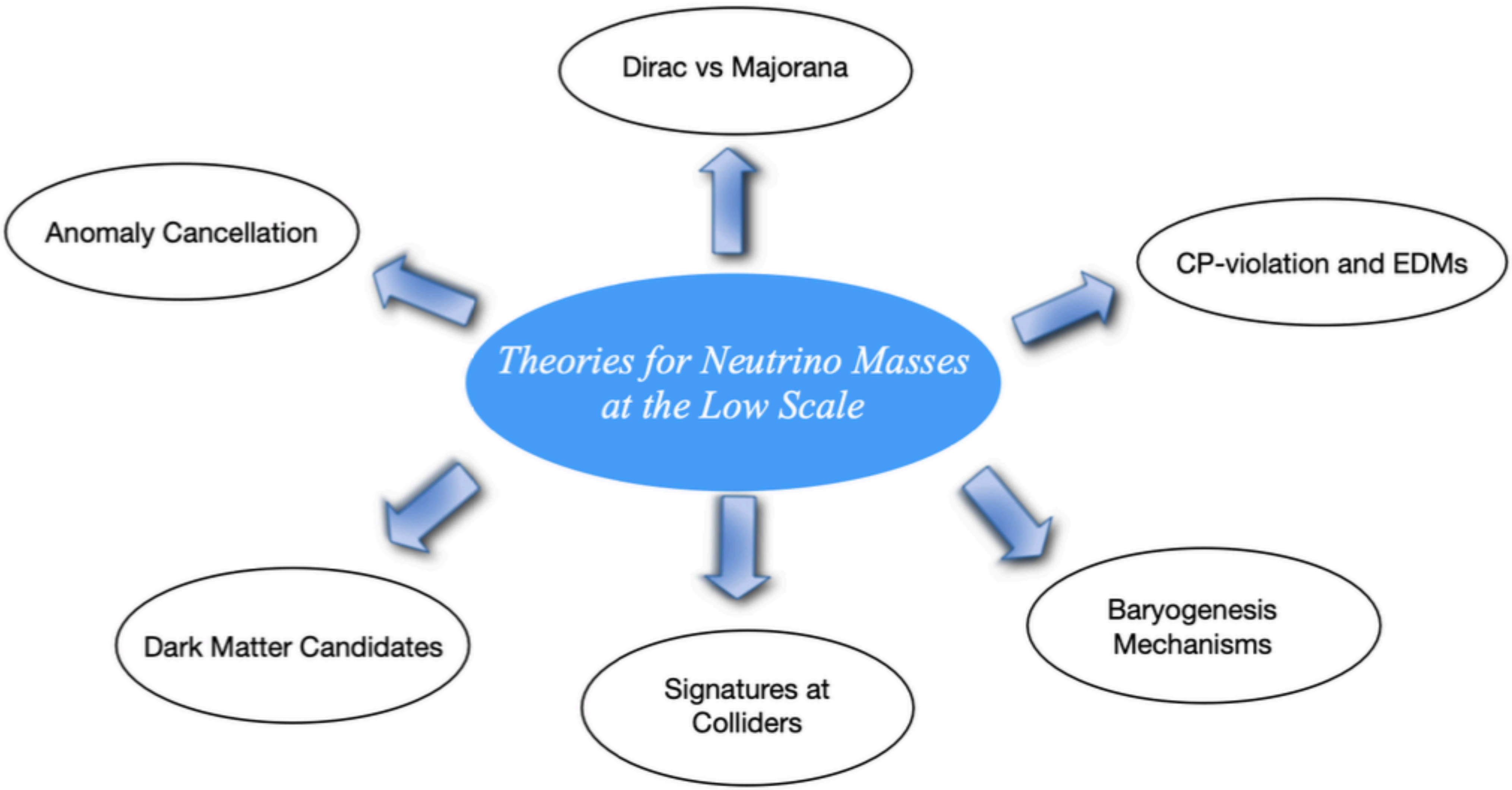
Inverse Seesaw

$$m_\nu \approx \mu \left(\frac{M_\nu^D}{M_\chi^D}\right)^2, \qquad M_\chi^D \gg M_\nu^D \gg \mu,$$

$$M_{QL} \geq 10^3 \ \text{TeV} \ (K_L^0 \to e^\pm \mu^\mp)$$

See also: 2308.07367, 2205.02235, 2203.07381, 2107.06895, 2104.11229

Main Goal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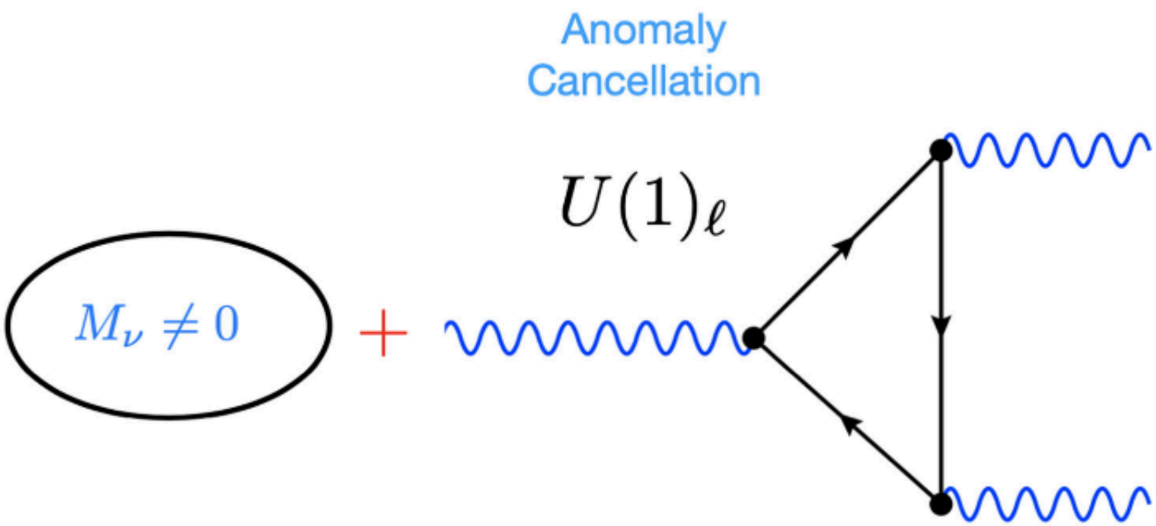
Theory of Neutrino Masses at the Low Scale

Lepton Number as Local Gauge Symmetry



DM

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

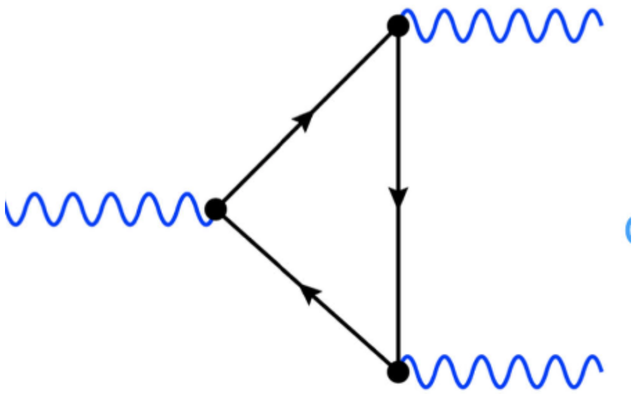
Low Scale Theory

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

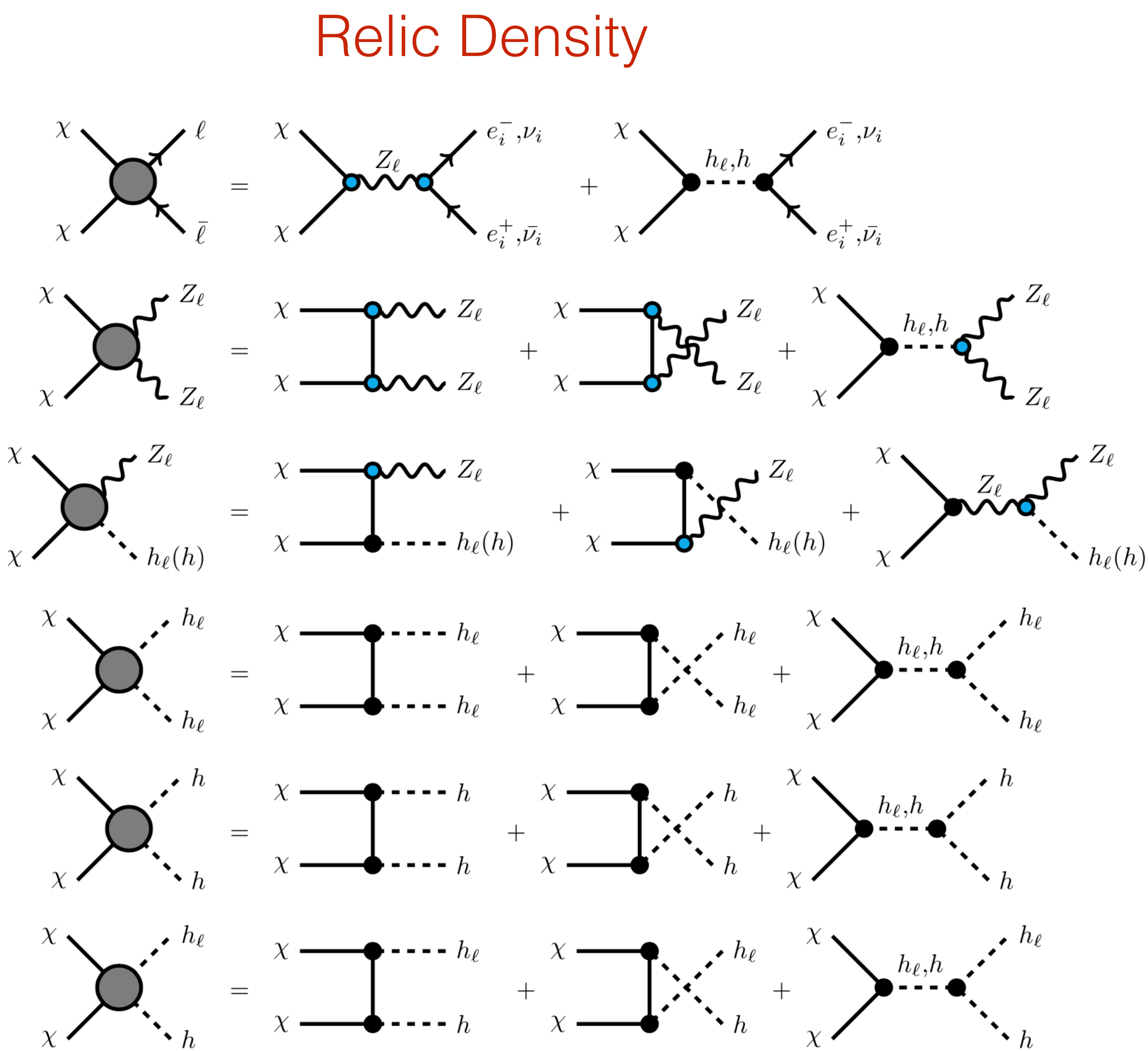
New Fermion Masses

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

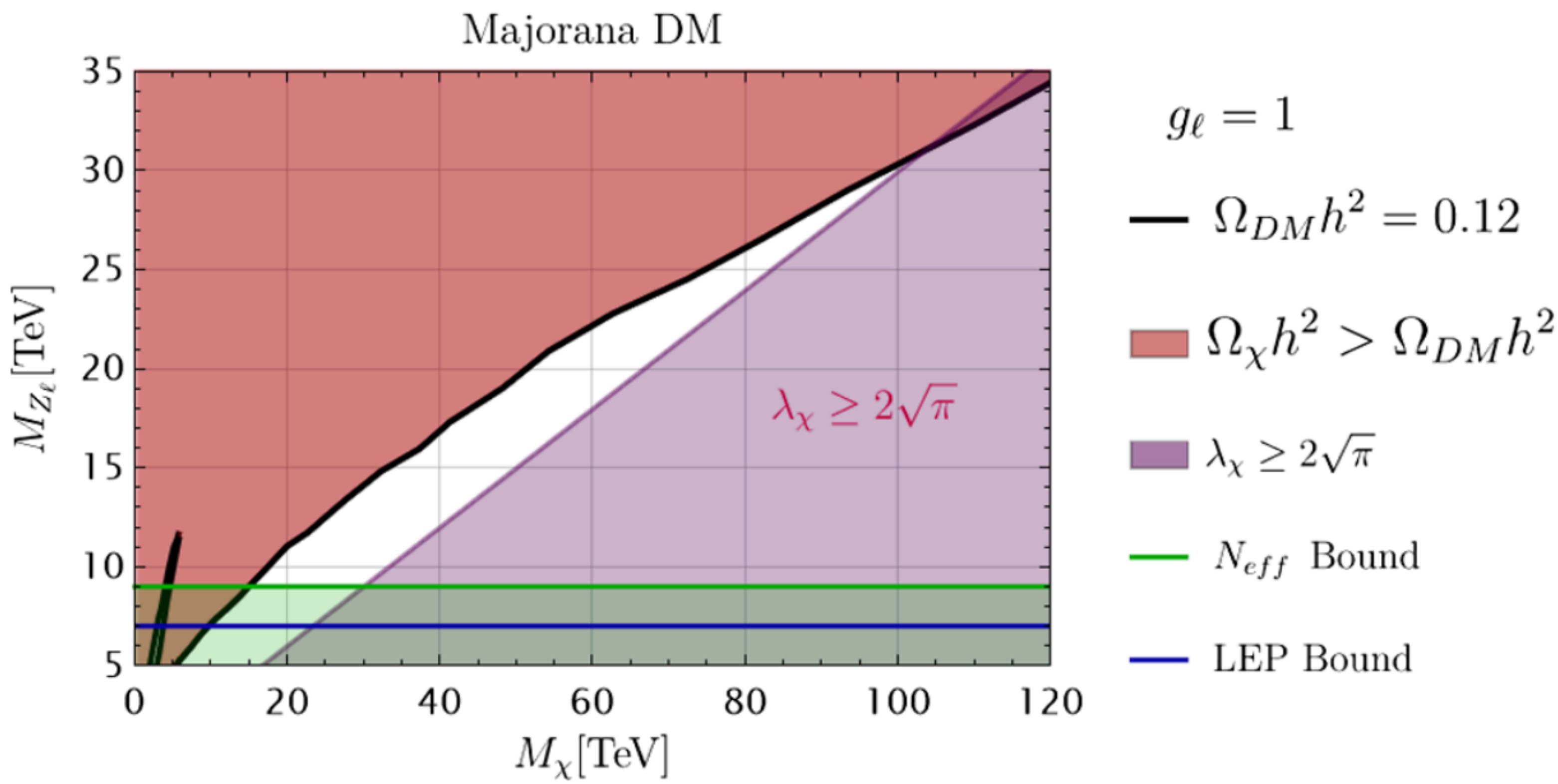
where $S \sim (\mathbf{1}, \mathbf{1}, 0, 3/2)$.

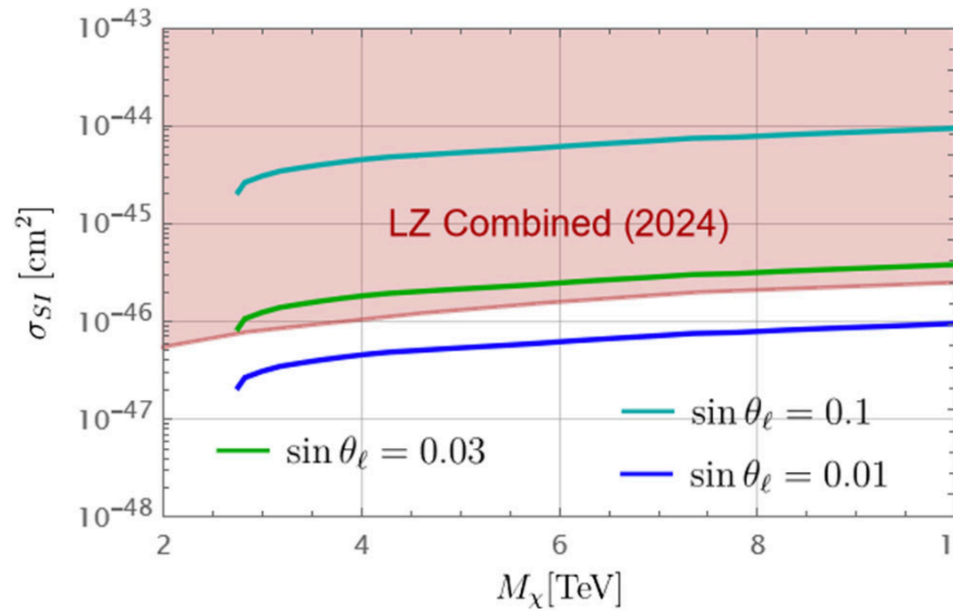
$$-\mathcal{L} \supset Y_\nu \overline{\ell}_L i\sigma_2 H^* \nu_R + y_e \overline{\ell}_L H e_R + \mathrm{H.c.}$$

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

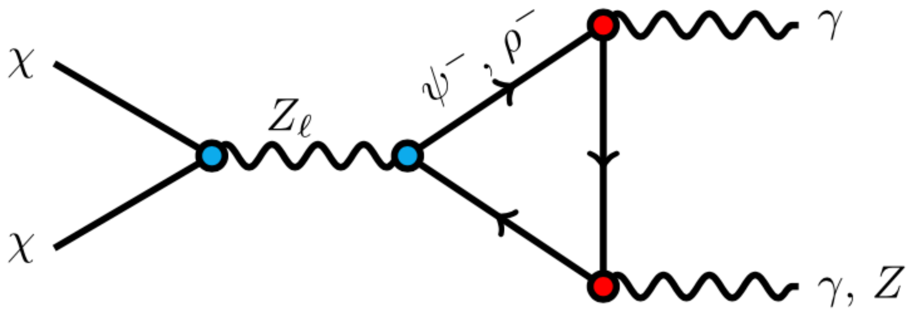


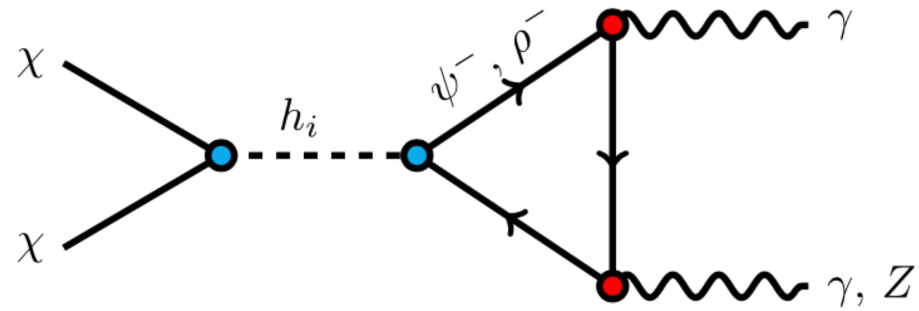
Relic Density
χ
ℓ
ℓ̄
=
Z_ℓ
e_i^-,ν_i
$e_i^+,\bar{\nu}_i$
+
h_ℓ,h
$h_\ell(h)$
h_ℓ
h

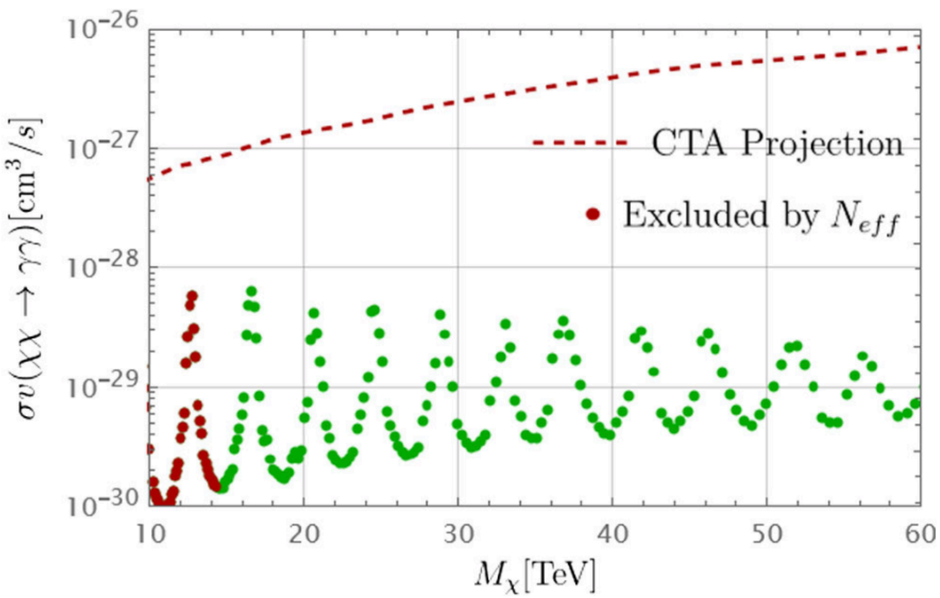

Majorana DM
M_{Z_ℓ}[TeV]
M_χ[TeV]
$\lambda_\chi \geq 2\sqrt{\pi}$
$g_\ell = 1$
$\Omega_{DM}h^2 = 0.12$
$\Omega_\chi h^2 > \Omega_{DM}h^2$
$\lambda_\chi \geq 2\sqrt{\pi}$
N_{eff} Bound
LEP Bound

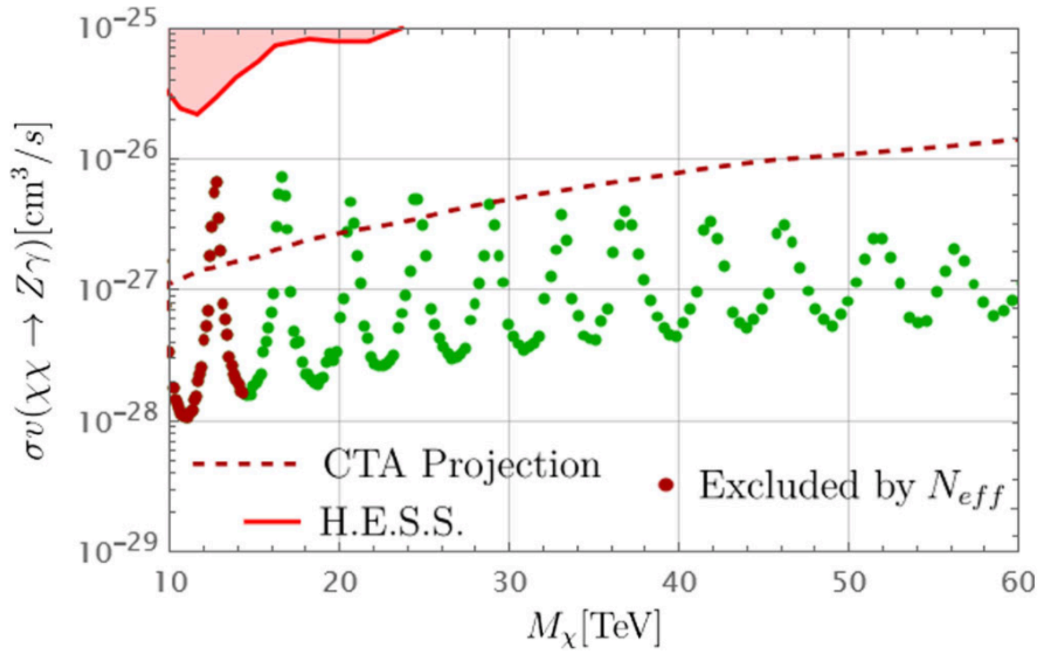

σ_{SI} [cm^2]
LZ Combined (2024)
$\sin\theta_\ell = 0.1$
$\sin\theta_\ell = 0.03$
$\sin\theta_\ell = 0.01$
M_χ[TeV]

Indirect Detection

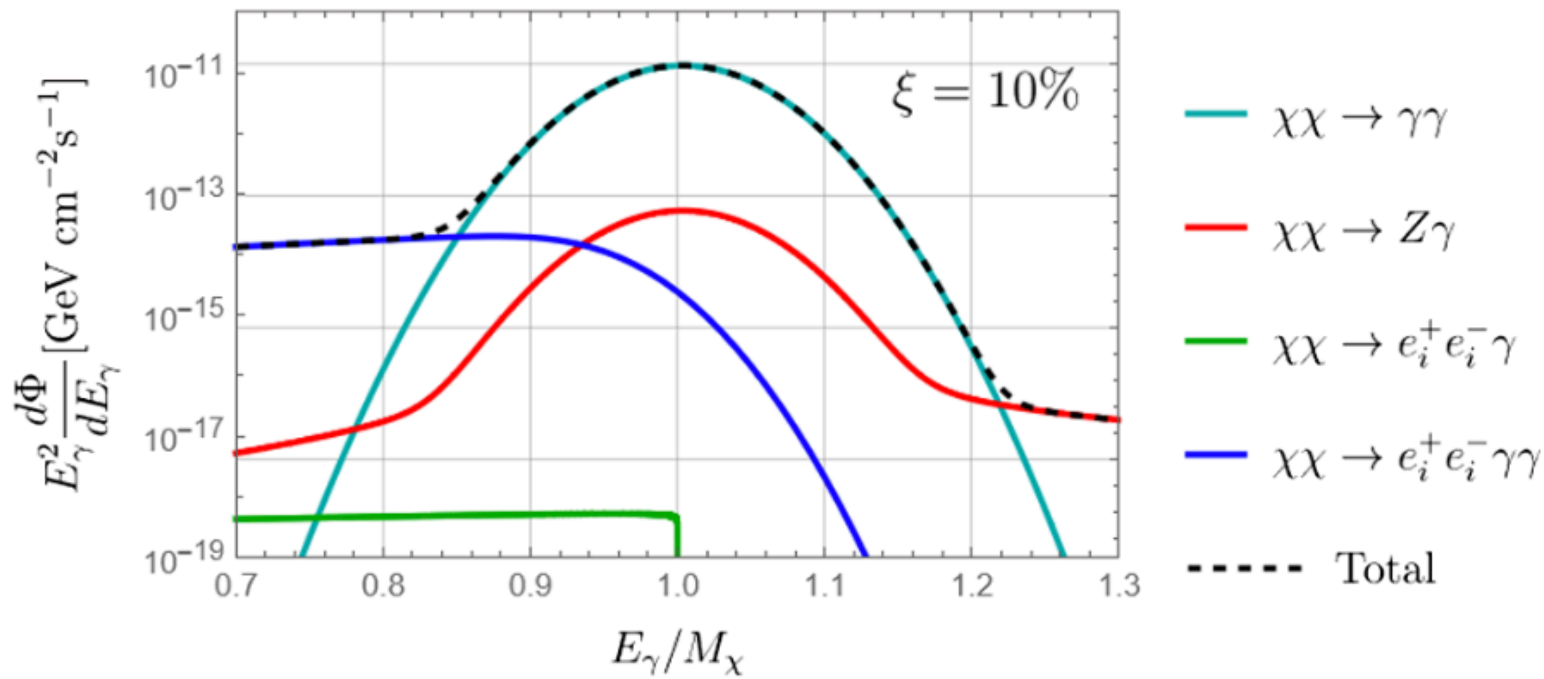






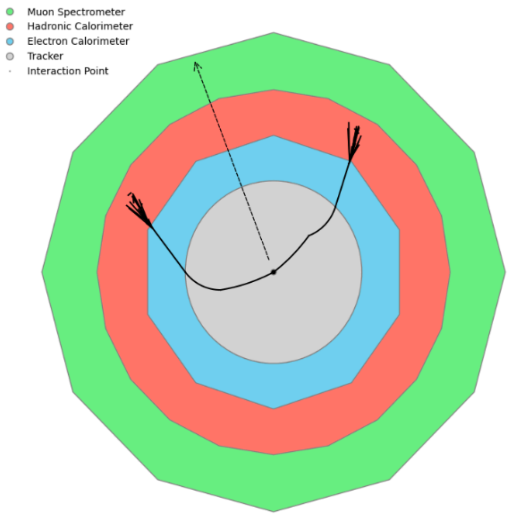


$$\frac{d\Phi_{\gamma\gamma}}{dE_\gamma} = \frac{n_\gamma}{8\pi M_\chi^2}\frac{d(\sigma v_{\rm rel}(\chi\chi \to \gamma\gamma))}{dE_\gamma}J_{\rm ann}$$
$$= \frac{n_\gamma(\sigma v_{\rm rel}(\chi\chi \to \gamma\gamma))}{8\pi M_\chi^2}\frac{dN_{\gamma\gamma}}{dE_\gamma}J_{\rm ann}.$$

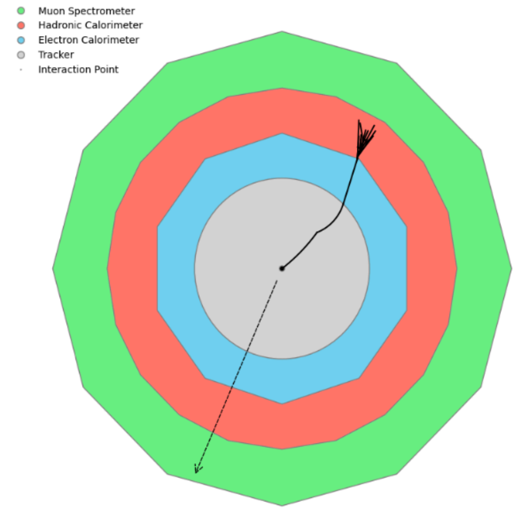


Collider Signatures

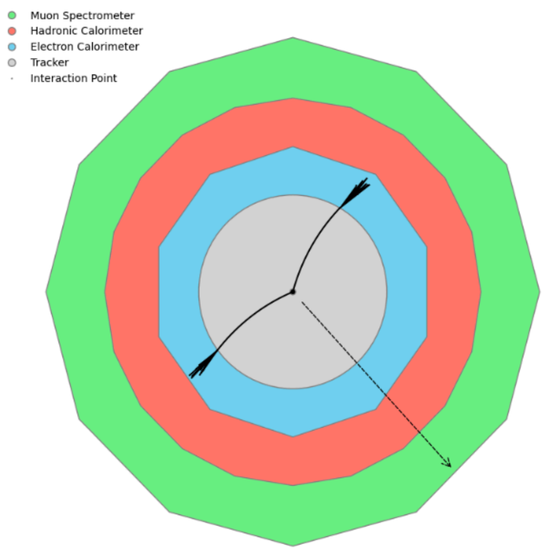
J. Butterworth, H. Debnath, J. Egan, P. F. P., arXiv:2505.06341



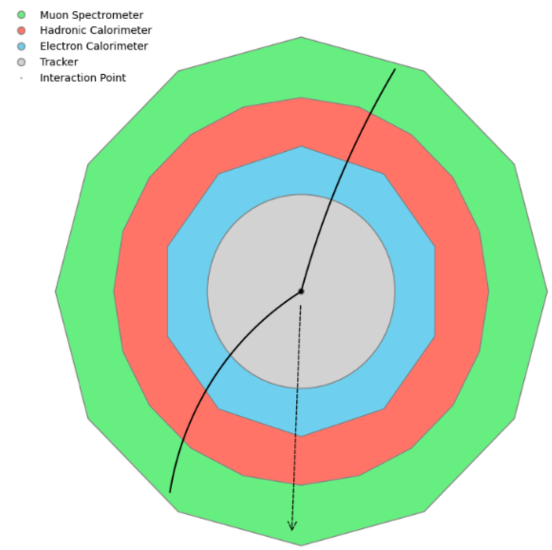
$$pp \to \rho^+\rho^- \to \rho^0\rho^0\pi^+\pi^-$$



$$pp \to \rho^\pm\rho^0 \to \rho^0\rho^0\pi^\pm$$

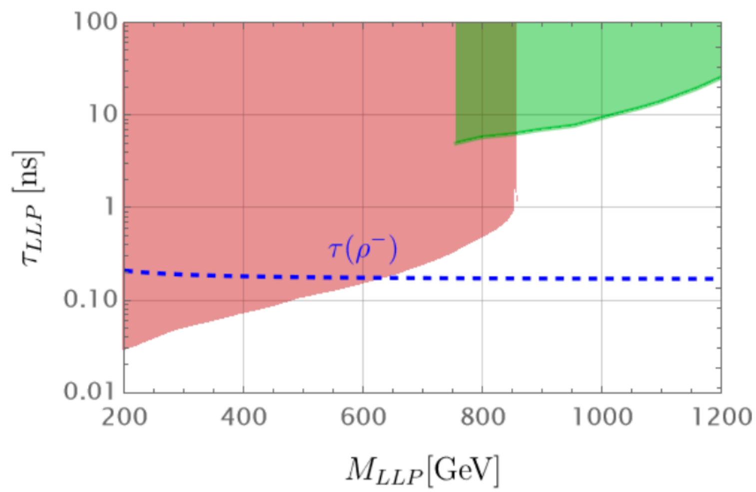


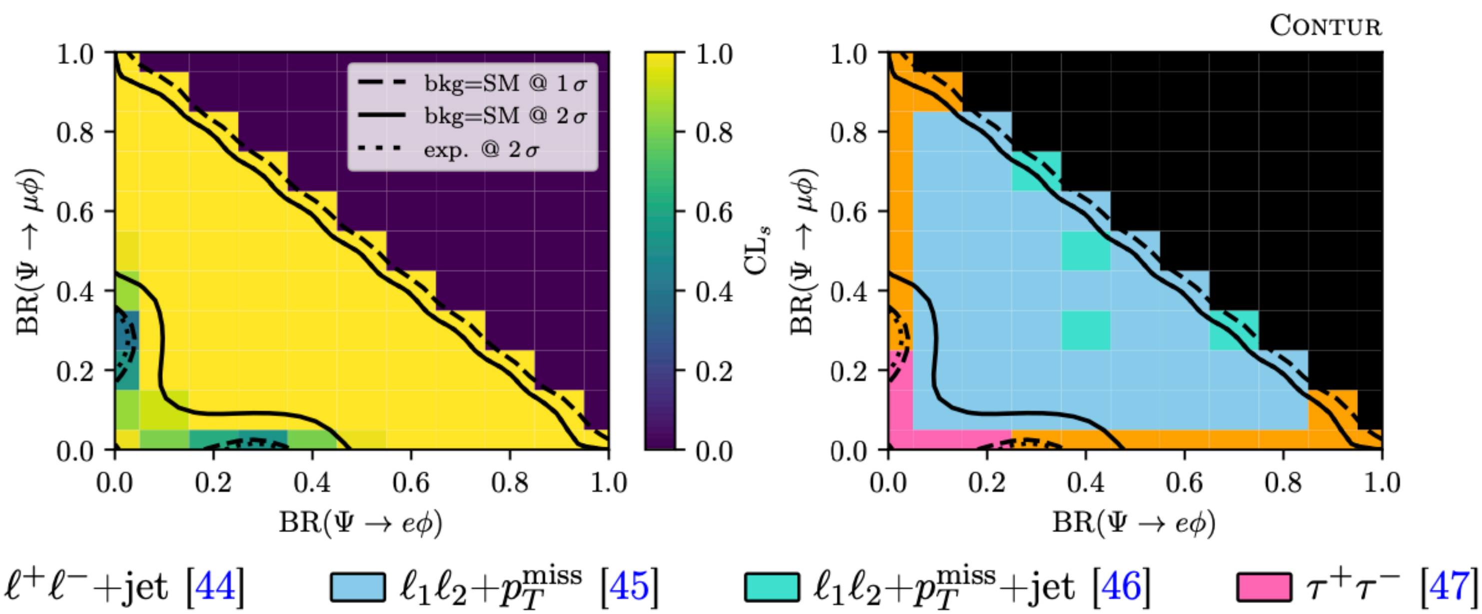
$$pp \to e^+e^-E_T^{miss}$$



$$pp \to \mu^+\mu^-E_T^{miss}$$

Collider Signatures





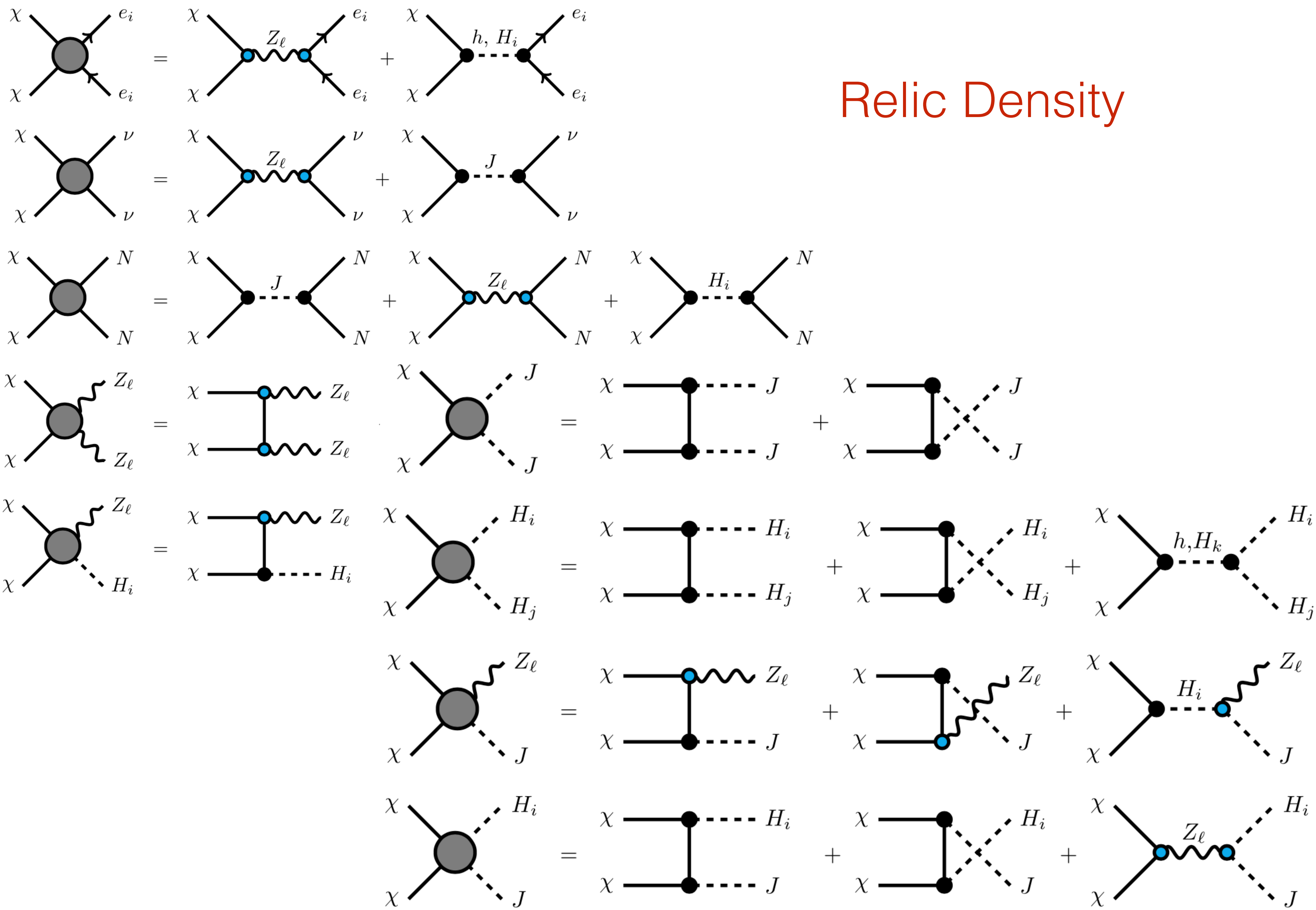
Majorana Neutrinos

$$-\mathcal{L} \supset Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + \lambda_R \nu_R^T C \nu_R \phi + \text{H.c.}$$

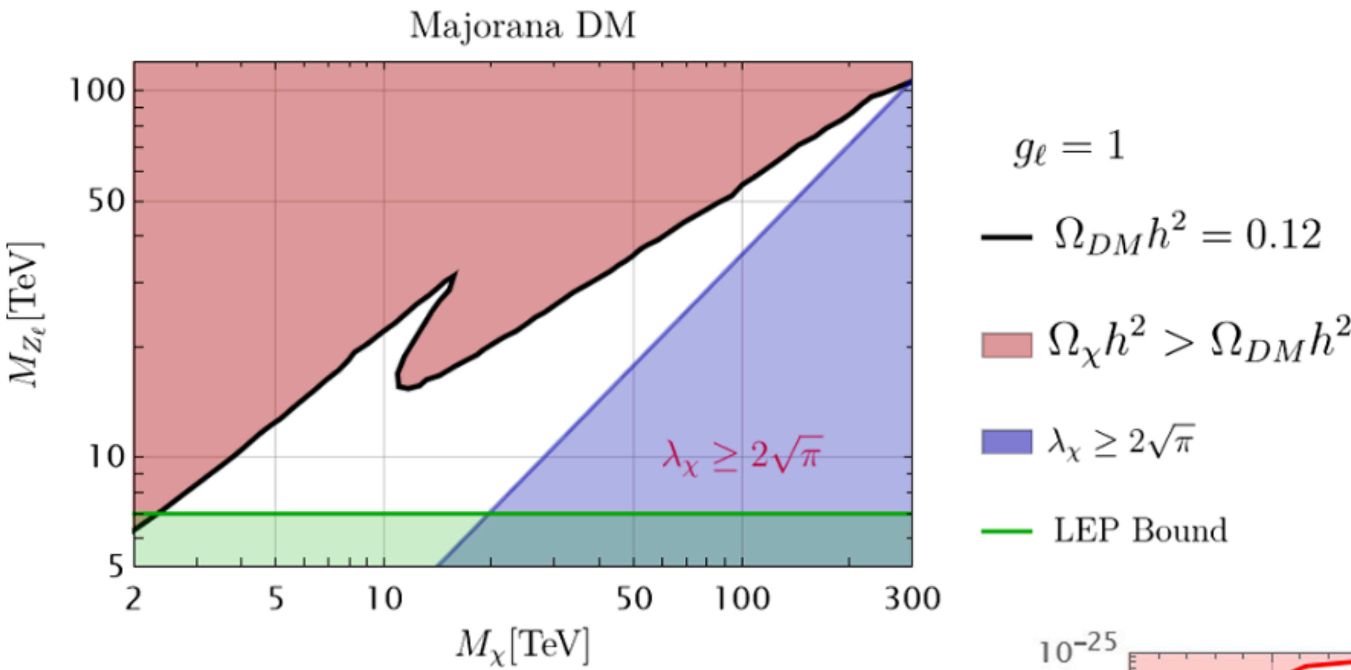
$$M_\nu = \frac{v_0^2}{2} Y_\nu M_N^{-1} Y_\nu^T,$$

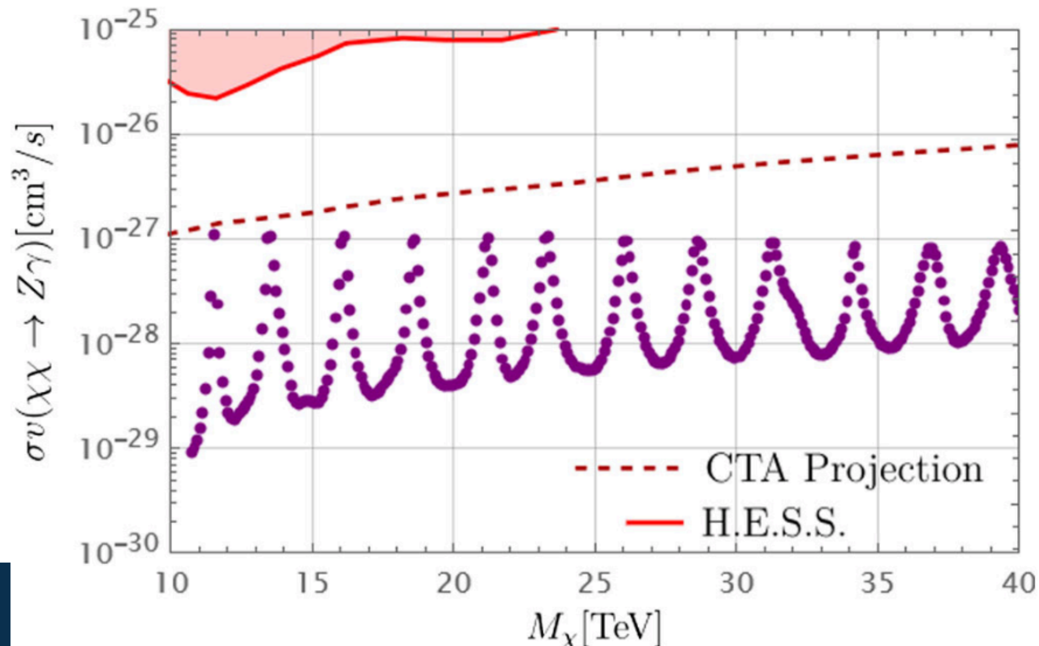
$$M_N = \sqrt{2}\lambda_R v_\phi = \frac{\lambda_R}{\sqrt{2}} \frac{M_{Z_\ell}}{g_\ell} \sin\beta.$$

Relic Density

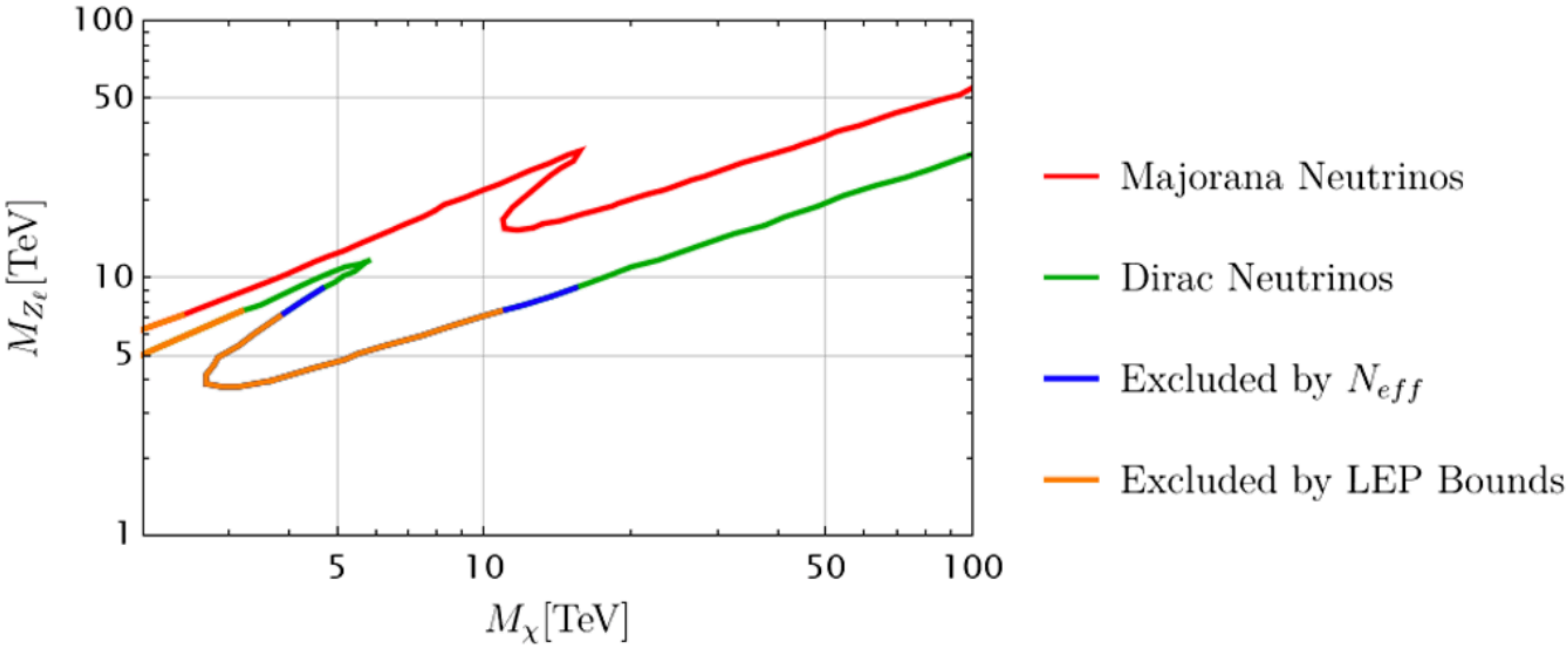


Majorana Neutrinos

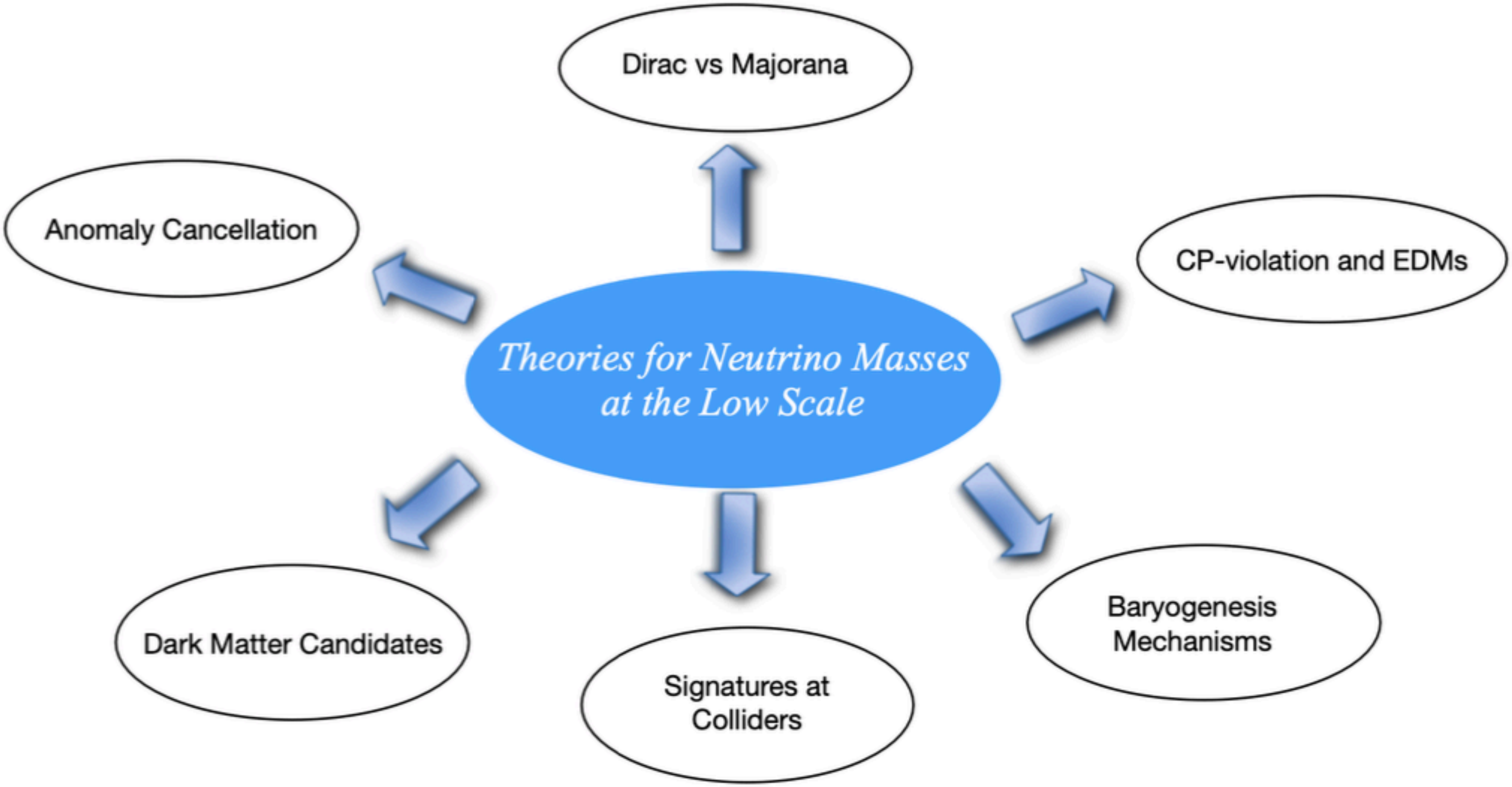




Symmetry Breaking Scale: Dirac vs. Majorana



Summary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