Lecture II: Neutrino Mass Models in Context

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

ACFI NLDBD School
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Lecture II Goals

- *Provide broader BSM context for $0\nu\beta\beta$ decay*
- *Provide a simple overview of classes of neutrino mass models with example illustrations*
- *Discuss implications for the interpretation of $0\nu\beta\beta$ decay searches*
- *Invite questions !*

Lecture II Outline

I. The BSM Context

II. $0\nu\beta\beta$-decay: General Considerations

III. Neutrino Mass Models

IV. Implications for $0\nu\beta\beta$-decay

I. The BSM Context

Fundamental Questions

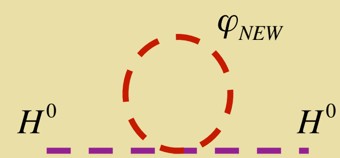
MUST *answer*

SHOULD *answer*

Fundamental Questions

MUST *answer*

SHOULD *answer*



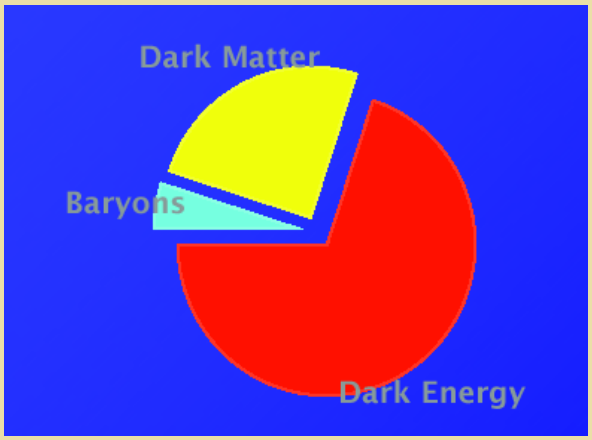
$\Delta m^2 \sim \lambda \Lambda^2$

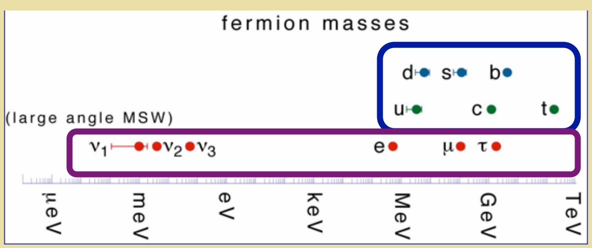
$\Lambda_{Cosmological}$

θ_{QCD} , *parity, unification...*

Fundamental Questions

MUST *answer*

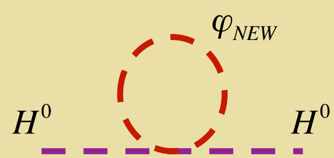




Origin of m_ν

flavor…

SHOULD *answer*



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$\Lambda_{Cosmological}$

θ_{QCD} *, parity, unification...*

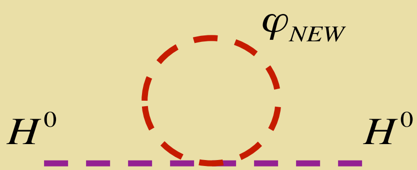
Naturalness Problem

Scalar Fields in Particle Physics

Scalar Fields in Particle Physics

Scalar fields are a simple

Scalar fields are theoretically problematic



$\Delta m^2 \sim \lambda \Lambda^2$

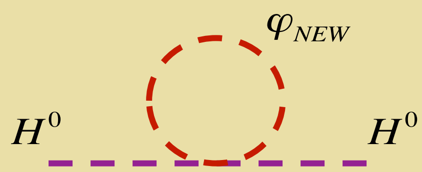
Discovery of a (probably) fundamental 125 GeV scalar :

Is it telling us anything about Λ ? Naturalness?

Scalar Fields in Particle Physics

Scalar fields are a simple

Scalar fields are theoretically problematic



$\Delta m^2 \sim \lambda \Lambda^2$

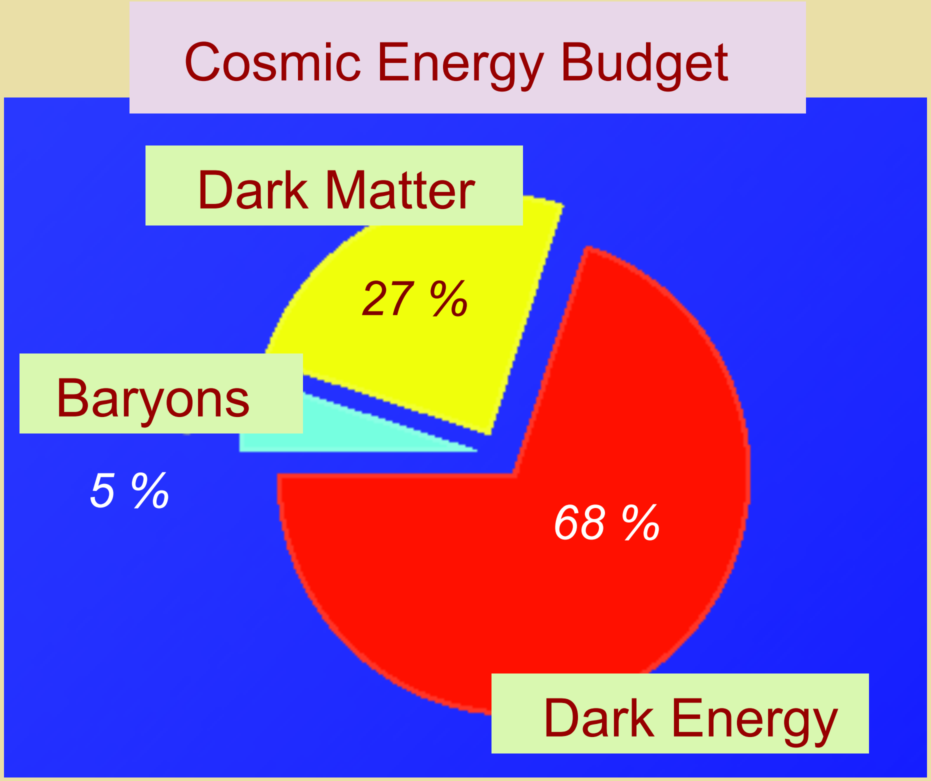
Discovery of a (probably) fundamental 125 GeV scalar :

$m_h^2 \sim \lambda v^2$ & $G_F \sim 1/v^2$: *what keeps G_F "large" ?*

LHC Implications

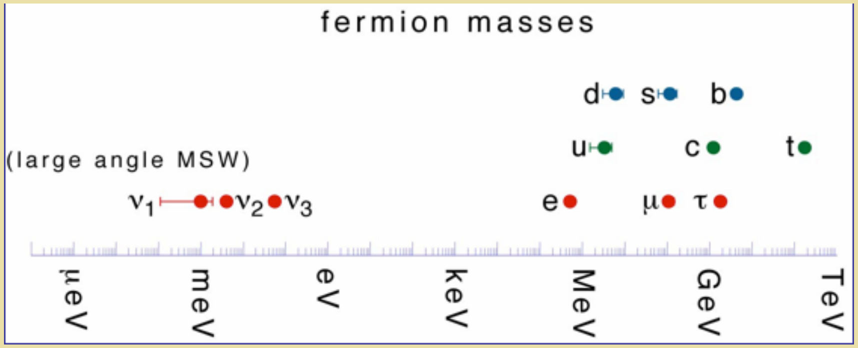
- *Weak scale BSM physics (e.g., SUSY) is there but challenging for the hadronic collider*
- *BSM physics is there but a bit heavy (some fine tuning)*
- *We are thinking about the problem incorrectly (cosmological constant???)*

The Origin of Matter



Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

Neutrino Masses



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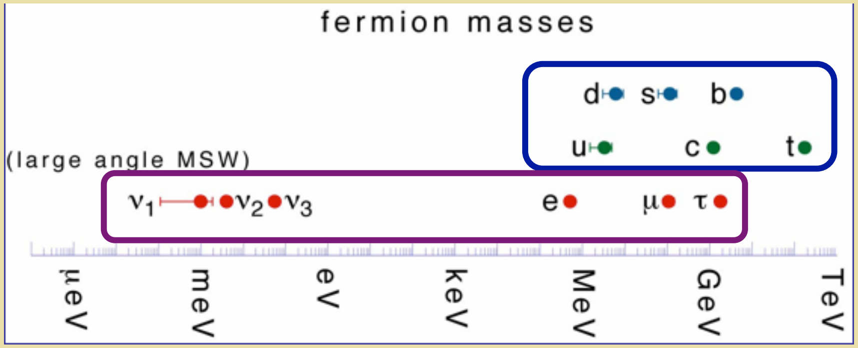
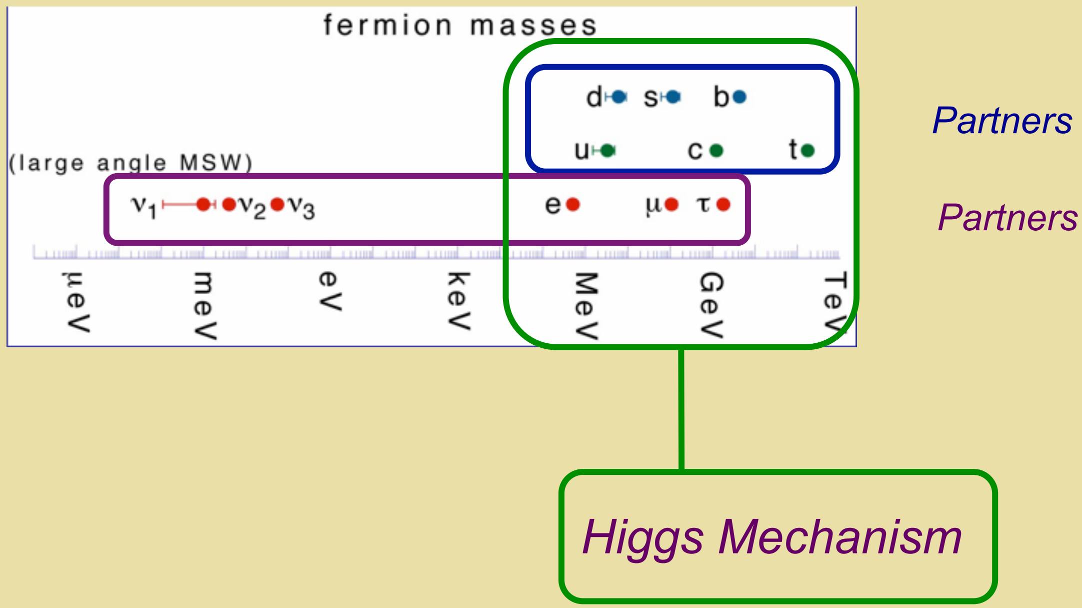


Partners

Partners

Neutrino Masses



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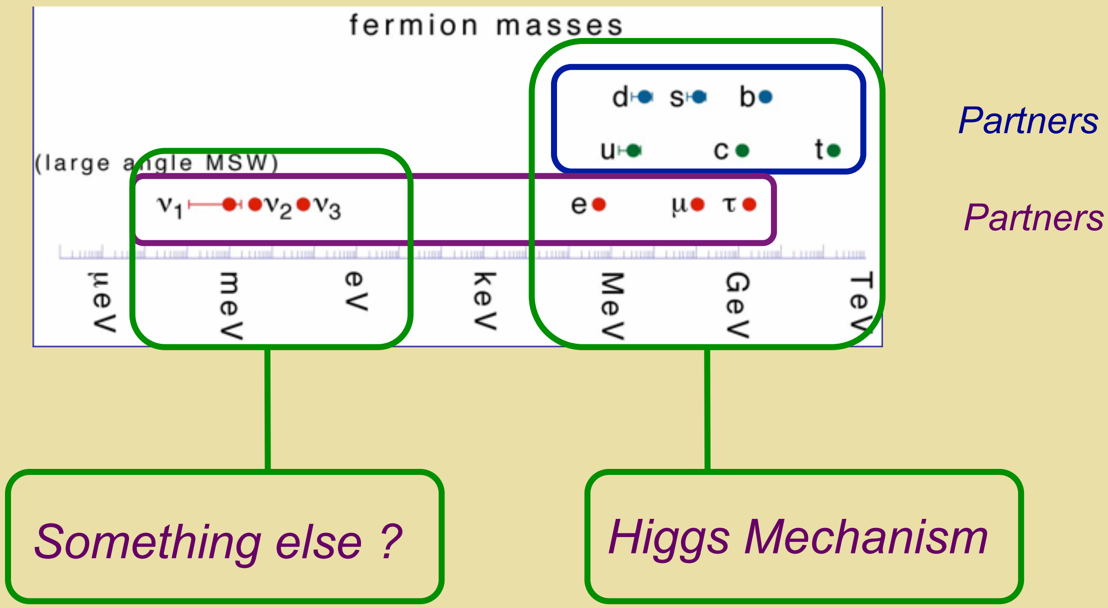

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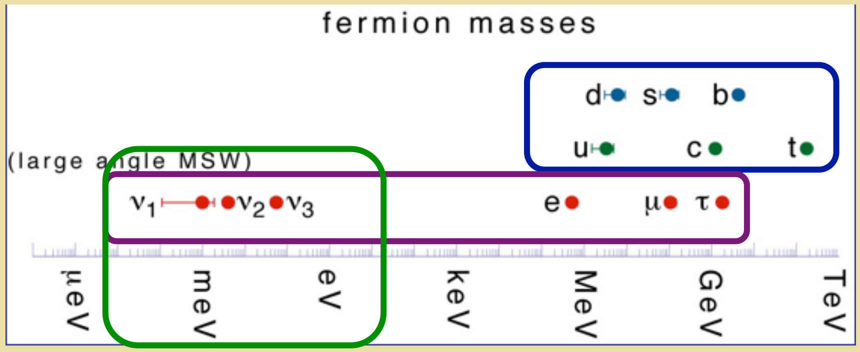
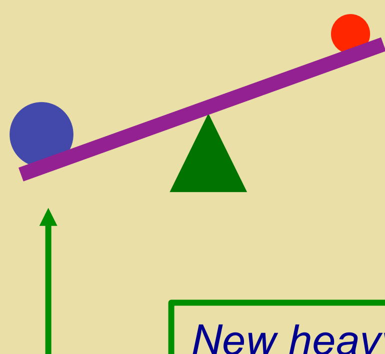


Partners

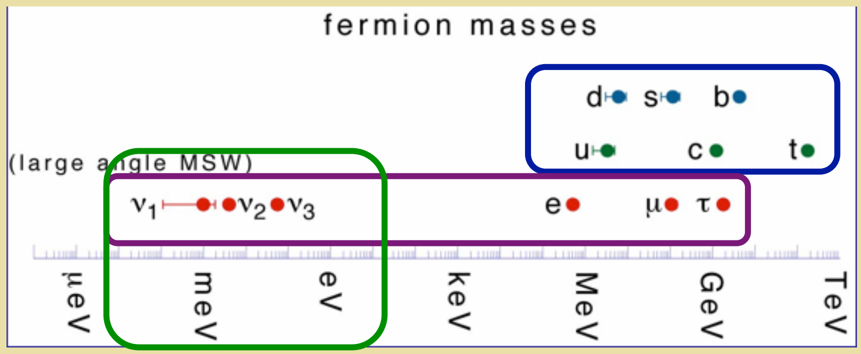
Partners

"See saw mechanism"



New heavy neutrino-like particle = its own anti-particle

Neutrino Masses



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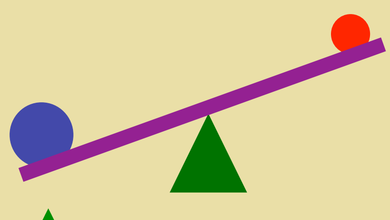

Physical state masses

$$m_1 \approx \frac{m_D^2}{M_N}$$ ~ *eV*

$$m_2 \approx M_N$$ ~ $10^{12} – 10^{15}$ *GeV*

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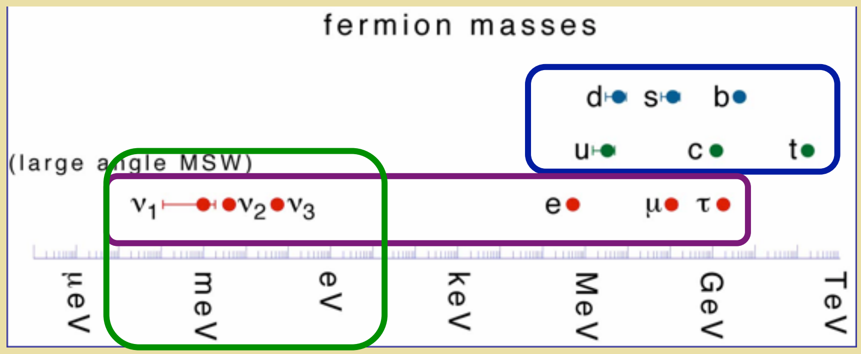
Neutrino Masses



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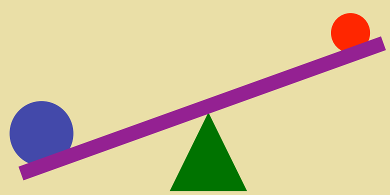
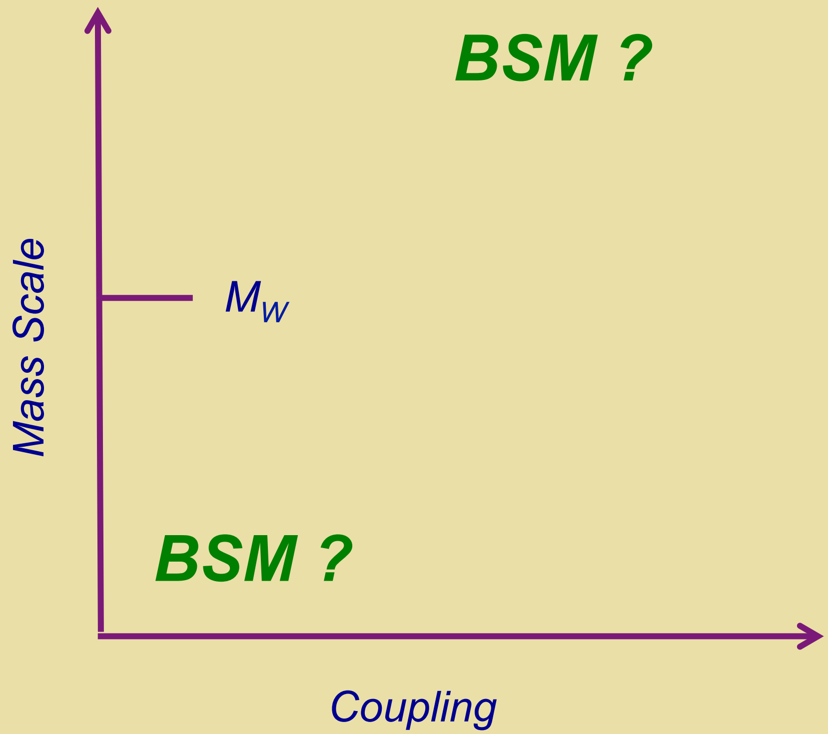


"Leptogenesis"

Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle = its own anti-particle

BSM Physics: Where Does it Live ?



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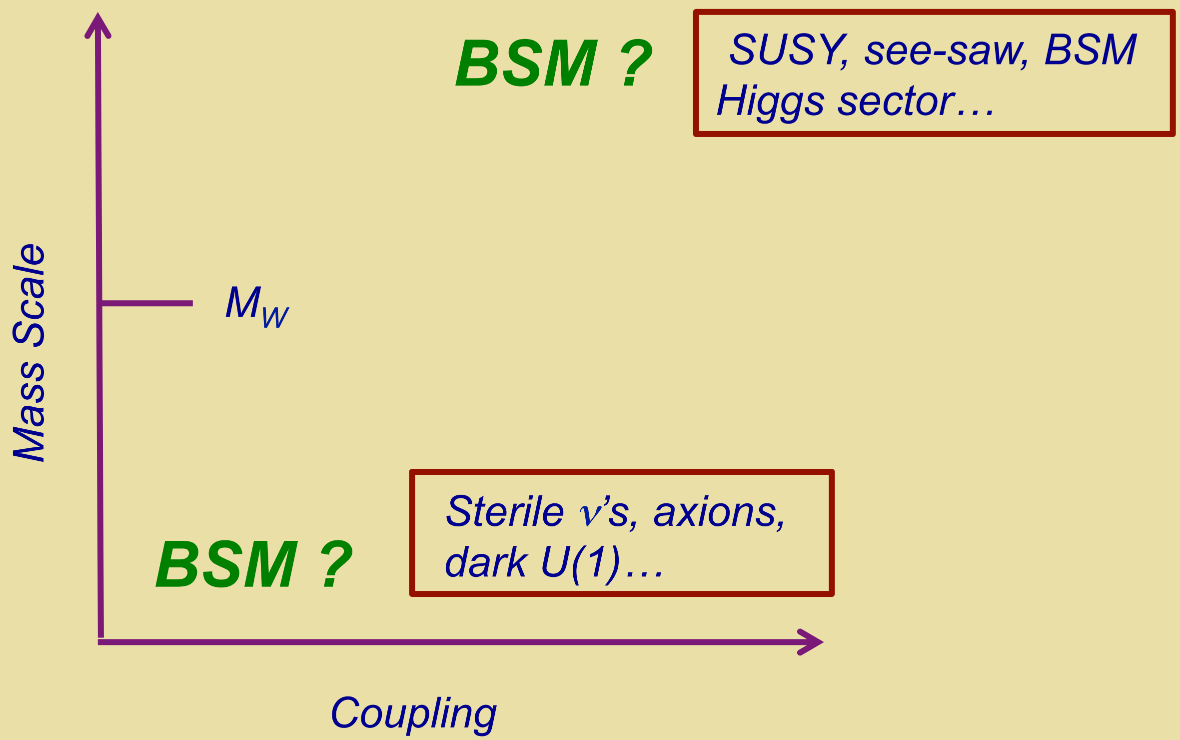

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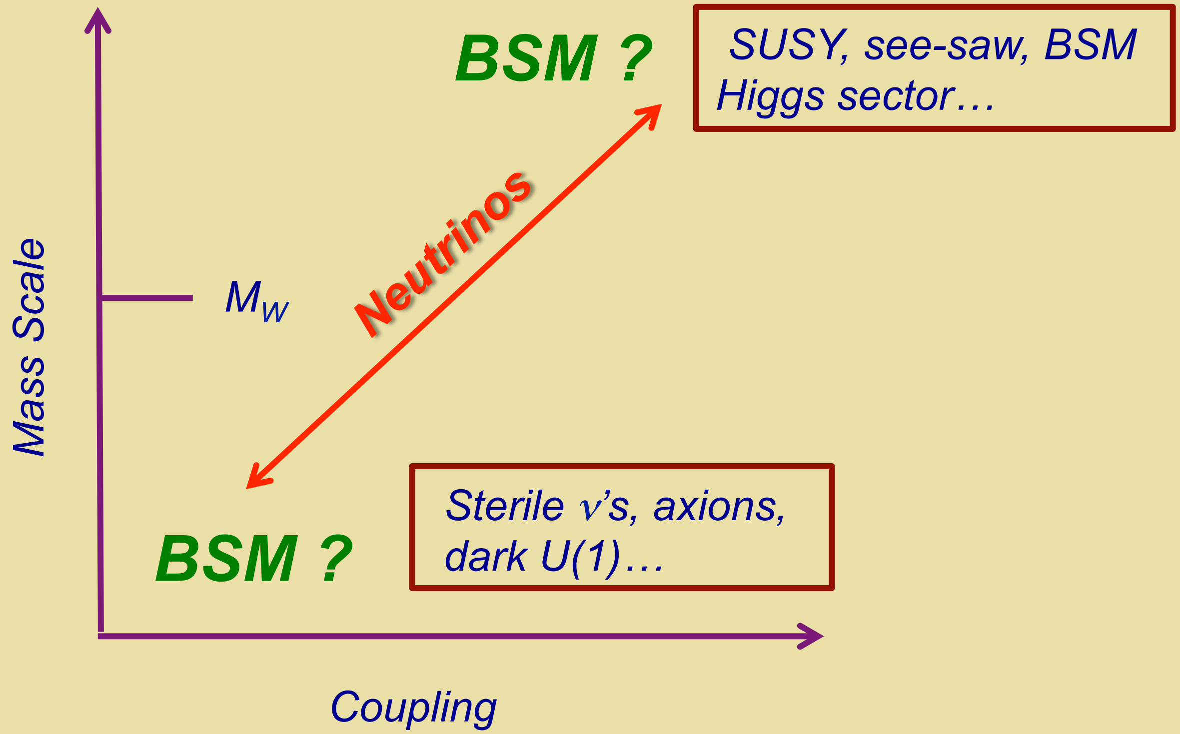

II. $0\nu\beta\beta$-Decay: General Considerations

What Questions Does It Address ?

- *Is the neutrino its own antiparticle ?*
- *Why is there more matter than antimatter ?*
- *Why are neutrino masses so small?*

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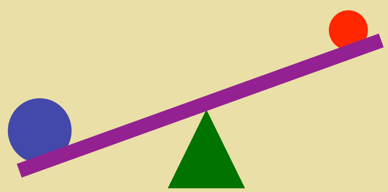

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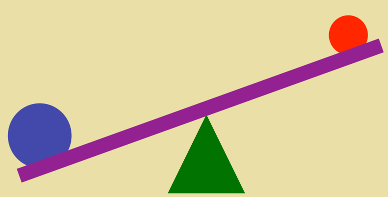

"Leptogenesis"

$\nu = \bar{\nu}$

Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle = its own anti-particle

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*
- *Majorana neutrinos can decay to particles and antiparticles*
- *Rates can be slightly different (CP violation)*

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \bar{\ell} H^*)$$

- *Resulting excess of leptons over anti-leptons partially converted into excess of quarks over anti-quarks by Standard Model sphalerons*

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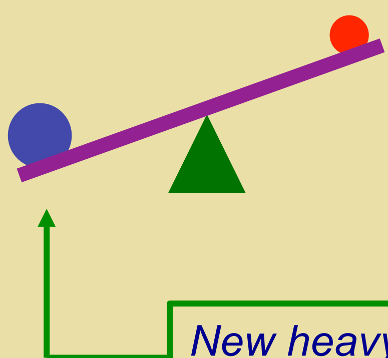

New heavy neutrino-like particle = its own anti-particle

Physical state masses

$$m_1 \approx \frac{m_D^2}{M_N}$$ ~ eV

$$m_2 \approx M_N$$ ~ 10^{12} – 10^{15} GeV

III. Neutrino Mass Models

- *Type I see-saw* — *"νSM", "νMSSM"*
- *Type II see-saw* — *LRSM*
- *Type III see-saw* — *GUTs*
- *Inverse see-saw* — *LRSM*
- *Radiative* — *MSSM*

+ combinations & many other examples

$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Neutrino Mass Models

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$0\nu\beta\beta$-Decay: Type I See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

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Majorana

One generation: SM + one N_R

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}N_R \; + \; \text{h.c.} + M_N \bar{N}_R^C N_R$$

⬇

$$\mathcal{L}_{\rm mass} = \left(\bar{\nu}_L \;\; \bar{N}_R^C \right) \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

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Lepton number violating

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$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}N_R \ + \ \text{h.c.} + M_N \bar{N}_R^C N_R$$

$\Downarrow$

Eigenvalues

$$\mathcal{L}_{\rm mass} = \left(\bar{\nu}_L \ \ \bar{N}_R^C \right) \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

$$m_1 \approx \frac{m_D^2}{M_N}$$

$$m_2 \approx M_N$$

$0\nu\beta\beta$-Decay: Type I See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

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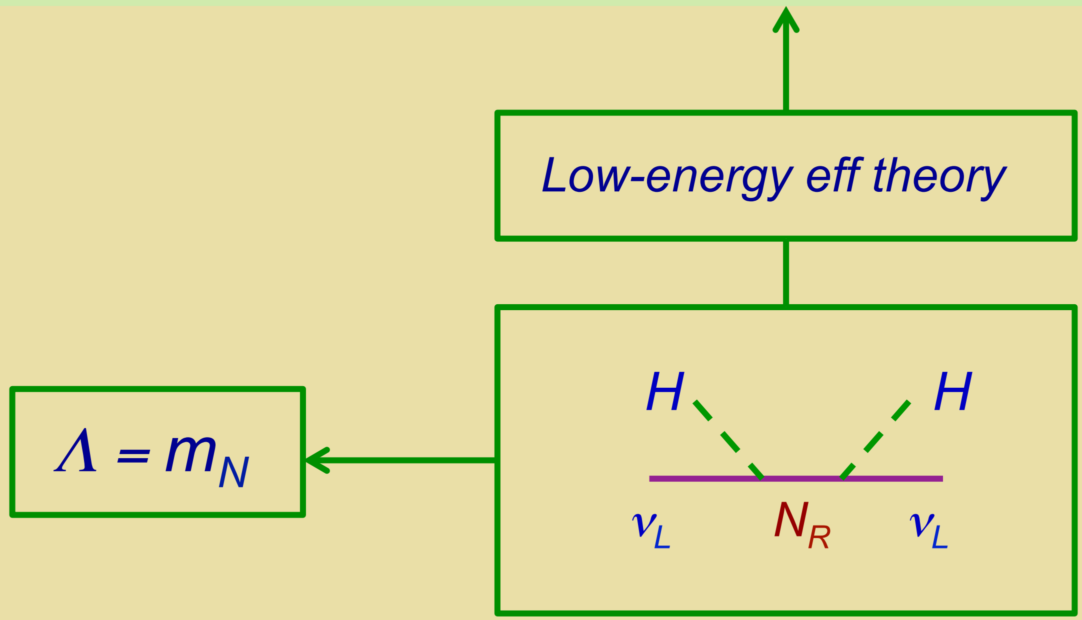
Majorana



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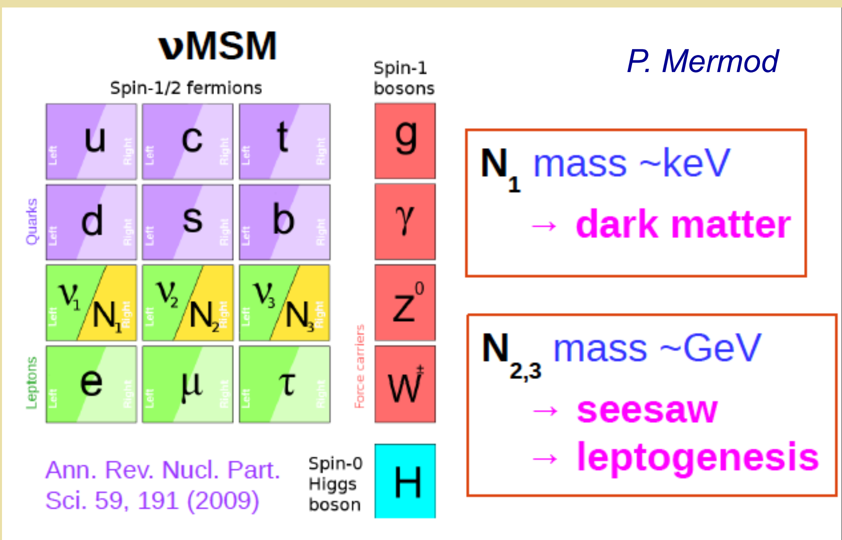
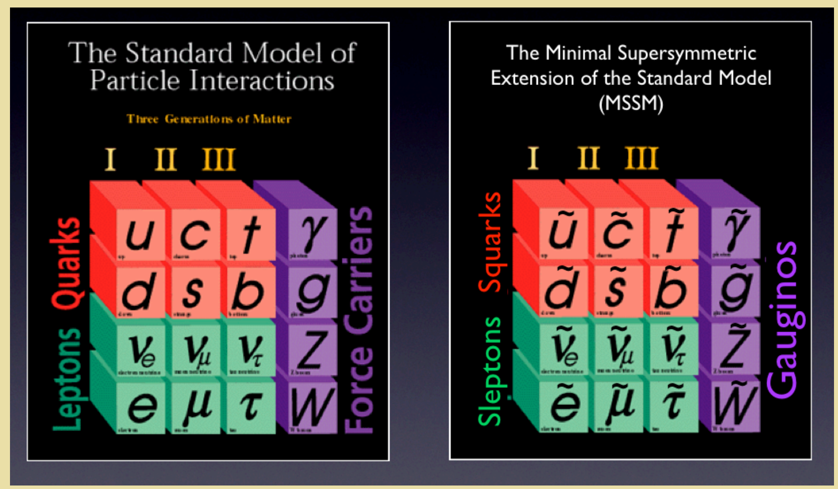
Majorana

"ν MSM"



"ν MSSM"



$$+ \quad \left(N_R, \; \tilde{N}_R \right)$$

Neutrino Mass Models

• *Type I see-saw*	*"νSM", "νMSSM"*
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+ combinations & many other examples

$0\nu\beta\beta$-Decay: Type II See-Saw

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Introduce "Complex Triplet": Δ_L ~ (1, 3, 2)

$$\Delta_L = \begin{pmatrix} \Delta^+\sqrt{2} & \Delta^+ \\ \Delta^0 & -\Delta^+\sqrt{2} \end{pmatrix}$$

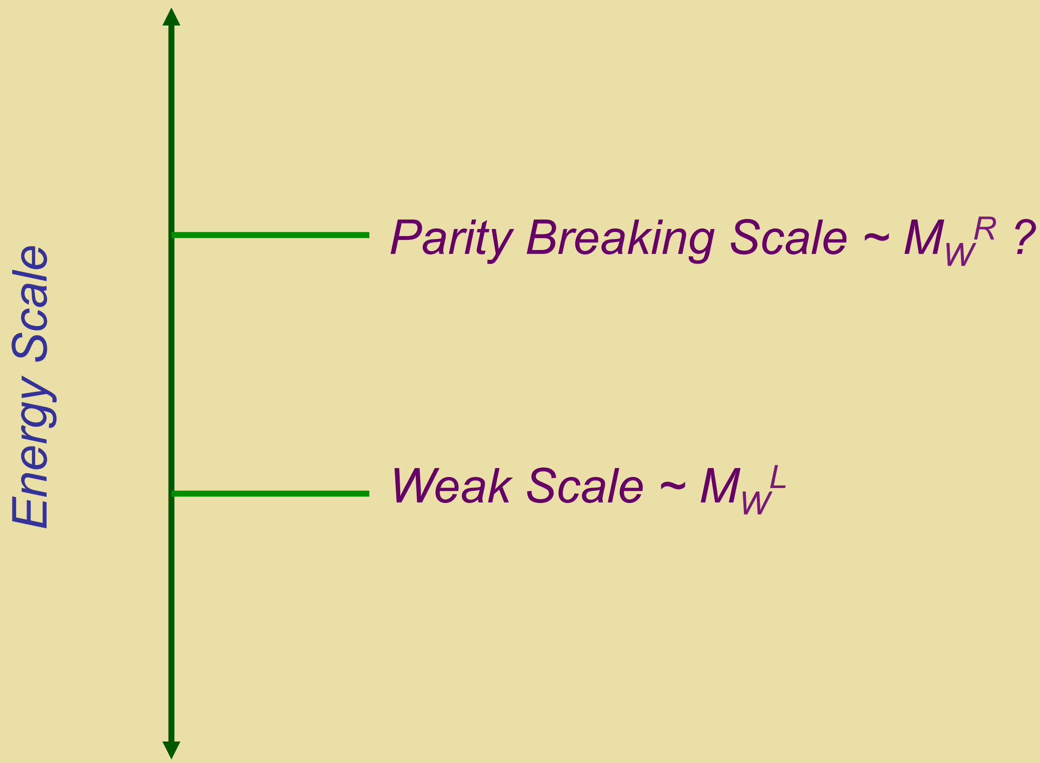
Δ^0 vev $\rightarrow$ Majorana m_ν

$$\mathcal{L} = \frac{g}{2}h_{ij}\left[\bar{L}^{C_i}\varepsilon\Delta_L L^j\right] + \text{h.c.}$$

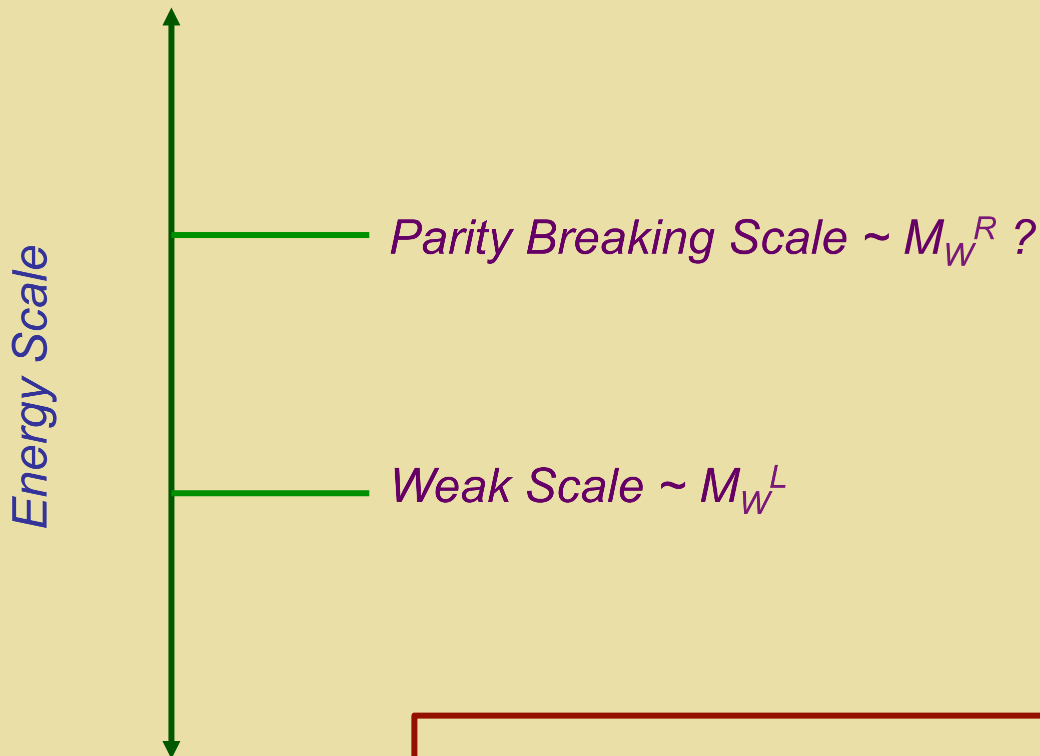
Lepton number violating

Left-Right Symmetric Model

BSM Mass Scale

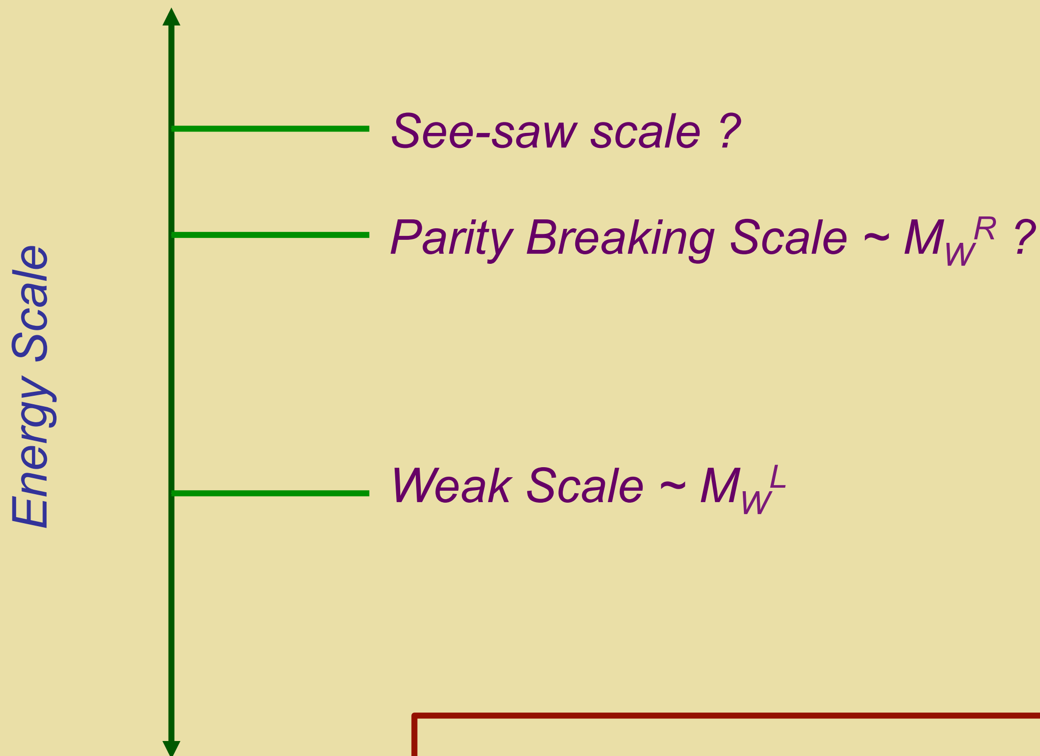


Left-Right Symmetric Model



$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Left-Right Symmetric Model



$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Left-Right Symmetric Model

Gauge boson mass eigenstates

$$W_1^+ = \cos\xi\, W_L^+ + \sin\xi\, e^{-i\alpha}\, W_R^+$$
$$W_2^+ = -\sin\xi\, e^{i\alpha}\, W_L^+ + \cos\xi\, W_R^+$$

CKM Matrices for LH & RH sectors: quarks

$$\begin{aligned} u_{Li}^I &= (S_u)_{ij}\, u_{Lj}^{\text{mass}} \\ u_{Ri}^I &= (T_u)_{ij}\, u_{Rj}^{\text{mass}} \\ d_{Li}^I &= (S_d)_{ij}\, d_{Lj}^{\text{mass}} \\ d_{Ri}^I &= (T_d)_{ij}\, d_{Rj}^{\text{mass}} \end{aligned}$$

→

$$V_{\text{CKM}}^L = S_u^\dagger S_d$$
$$V_{\text{CKM}}^R = T_u^\dagger T_d$$

Left-Right Symmetric Model

Gauge boson mass eigenstates

$$W_1^+ = \cos\xi\, W_L^+ + \sin\xi\, e^{-i\alpha}\, W_R^+$$
$$W_2^+ = -\sin\xi\, e^{i\alpha}\, W_L^+ + \cos\xi\, W_R^+$$

PMNS Matrices for LH & RH sectors: leptons

$$\begin{aligned}
\nu^I_{Li} &= (S_\nu)_{ij}\, \nu^{\rm diag}_{Lj} \\
N^I_{Ri} &= (T_N)_{ij}\, N^{\rm diag}_{Rj} \\
\ell^I_{Li} &= (S_\ell)_{ij}\, \ell^{\rm diag}_{Lj} \\
\ell^I_{Ri} &= (T_\ell)_{ij}\, \ell^{\rm diag}_{Rj}
\end{aligned}$$

→

$$V^L_{\rm PMNS} = S_\nu^\dagger S_\ell$$

Left-Right Symmetric Model

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$

Type I see-saw *Type II see-saw*

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} + m_L \bar{\nu}_L^C \nu_L$$

$$m_N \sim g h_R \left\langle \Delta_R^0 \right\rangle$$

$$m_L \sim g h_L \left\langle \Delta_L^0 \right\rangle$$

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+ combinations & many other examples

$0\nu\beta\beta$-Decay: Type III See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Introduce "Fermionic Triplet": $\Delta_L \sim (1, 3, 0)$

$$-\mathcal{L}_\nu^{III} = Y_\nu \, \ell_L \, \rho_L \, H + M_\rho \, \text{Tr} \, \rho_L^2 + \text{h.c.}$$

Like Type I but $N_R \rightarrow \rho_L$

See P. Fileviez Perez, 1501.01886

Neutrino Mass Models

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$0\nu\beta\beta$-Decay: Inverse See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Introduce "singlet" Majorana neutrino

$$\mathcal{L}_{\rm mass} = \left(\bar{\nu}_L \ \ \bar{N}_R \ \ \bar{N}_S^C \right) \begin{pmatrix} 0 & m_D^L & 0 \\ m_D^L & 0 & M_D^R \\ 0 & M_D^R & \mu \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \\ N_S \end{pmatrix}$$

Singlet Majorana mass

$$m_\nu \sim m_D^L \left(M_D^R\right)^{-1} \mu \left(M_D^R\right)^{-1} m_D^L$$

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$0\nu\beta\beta$-Decay: Type II See-Saw

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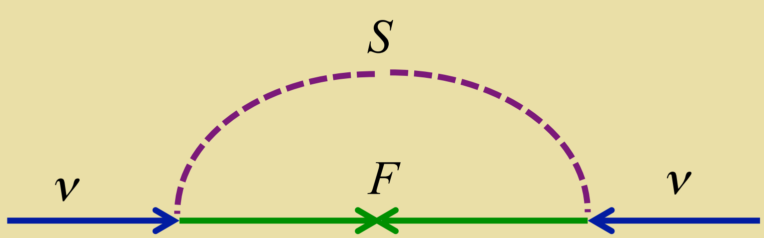
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Introduce new scalars (S) & Majorana fermions (F): "mediators"



Attach Higgs lines as appropriate to get Weinberg operator

Recent mini-review: H. Sugiyama, 1505.01738

$0\nu\beta\beta$-Decay: Type II See-Saw

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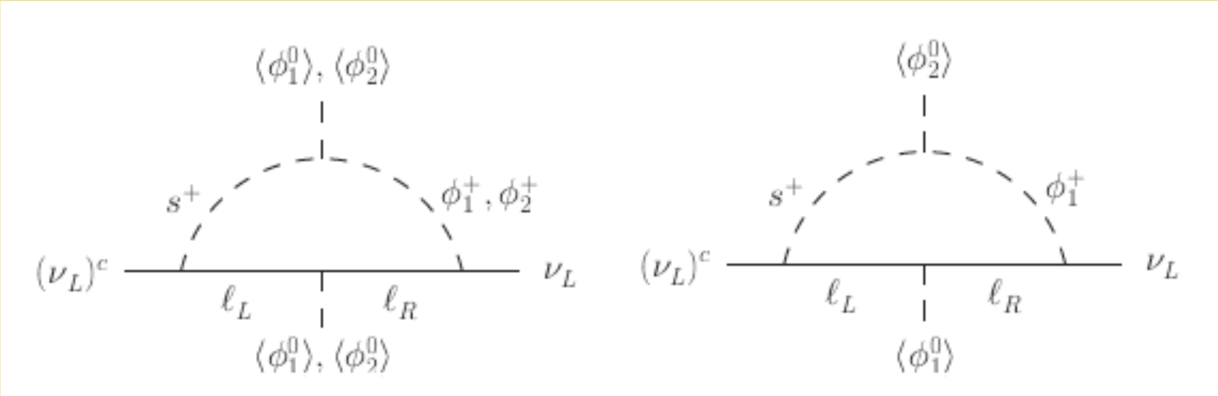
Majorana

Introduce new scalars (S) & Majorana fermions (F): "mediators"



"Zee Model"

Recent mini-review: H. Sugiyama, 1505.01738

0νββ-Decay: Type II See-Saw

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

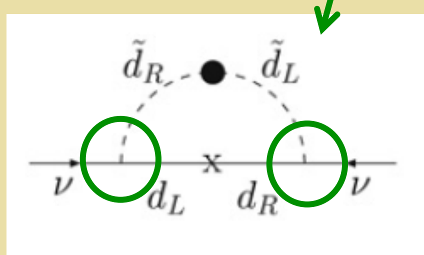
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

SUSY with "R parity" violation $P_R = (-1)^{2S+3(B-L)}$

"Superpotential"

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$



IV. Implications for $0\nu\beta\beta$-Decay

0νββ-Decay: LNV? Mass Term?

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

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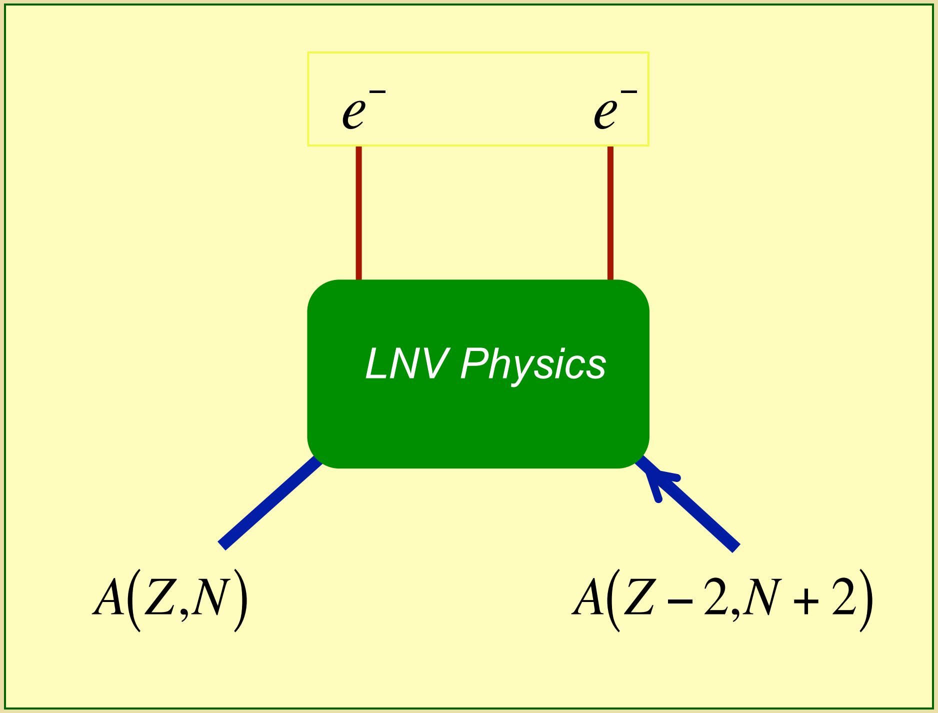
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



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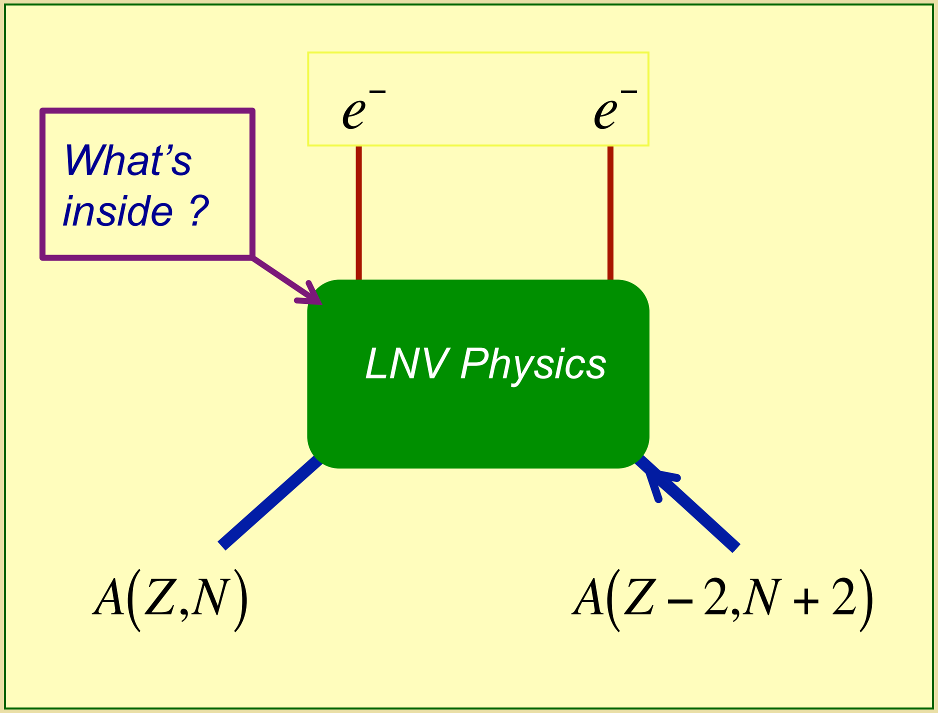
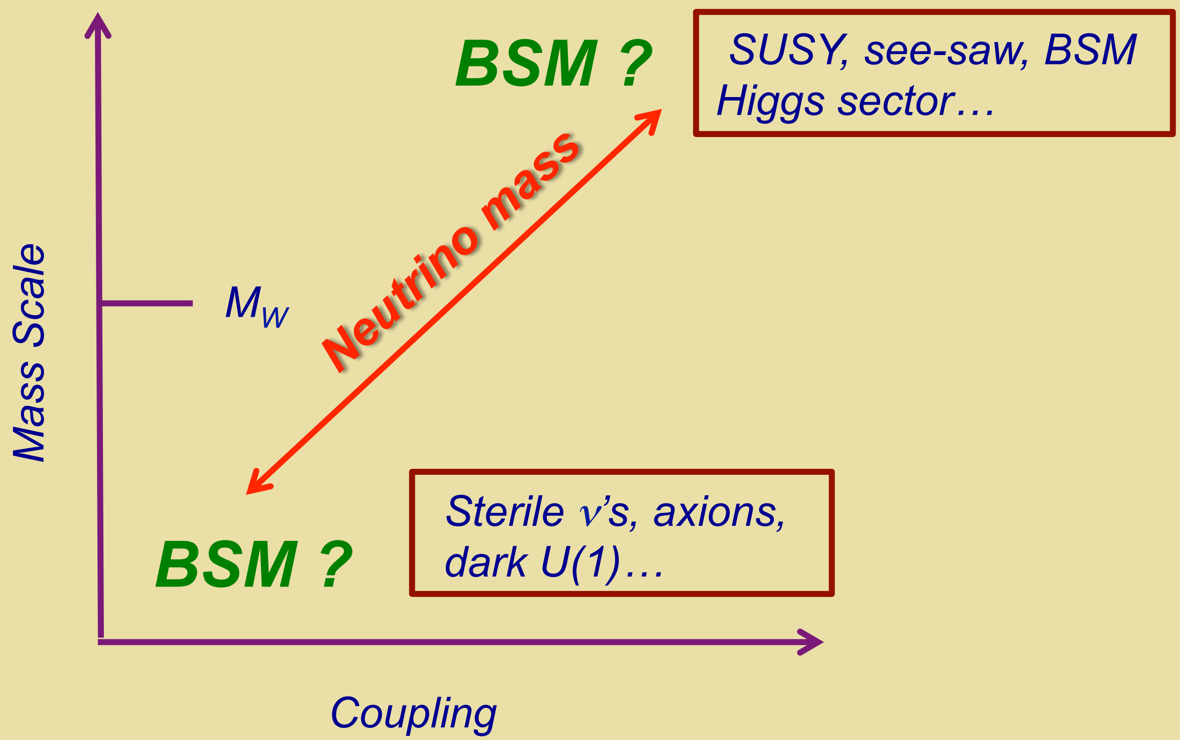


BSM Physics: Where Does it Live ?



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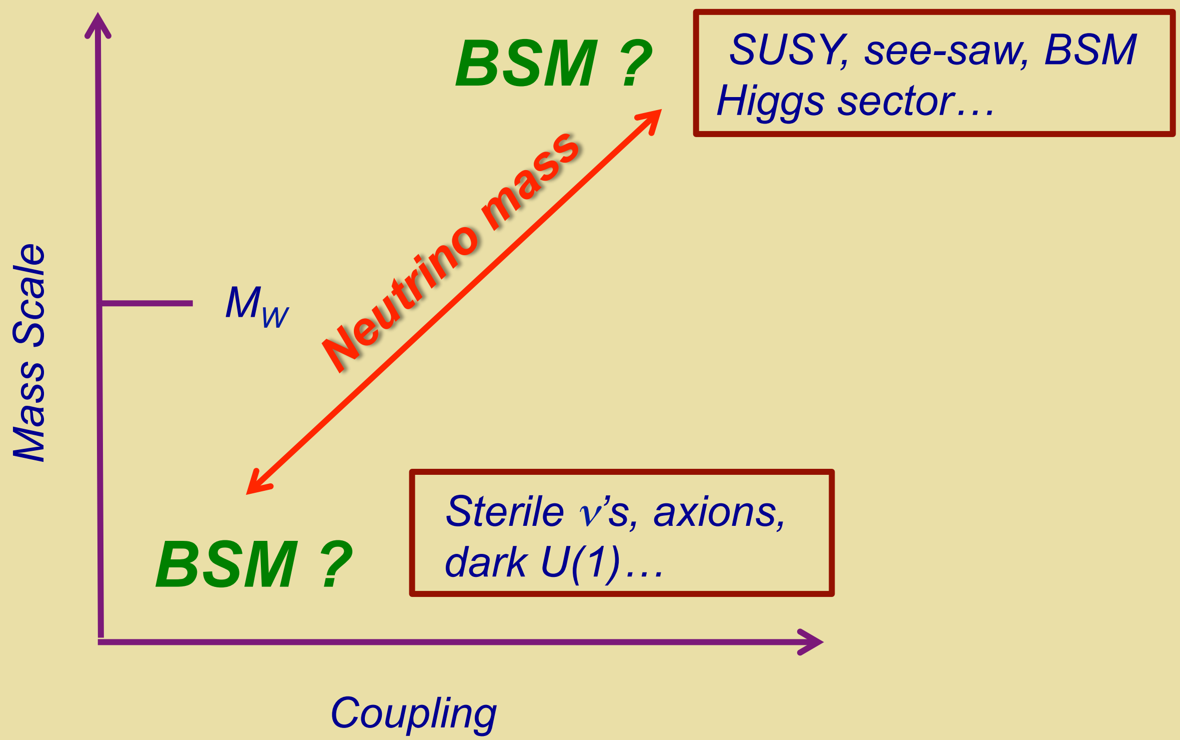

Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **Underlying Physics** $\rightarrow A(Z+2, N-2) + e^- e^-$

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

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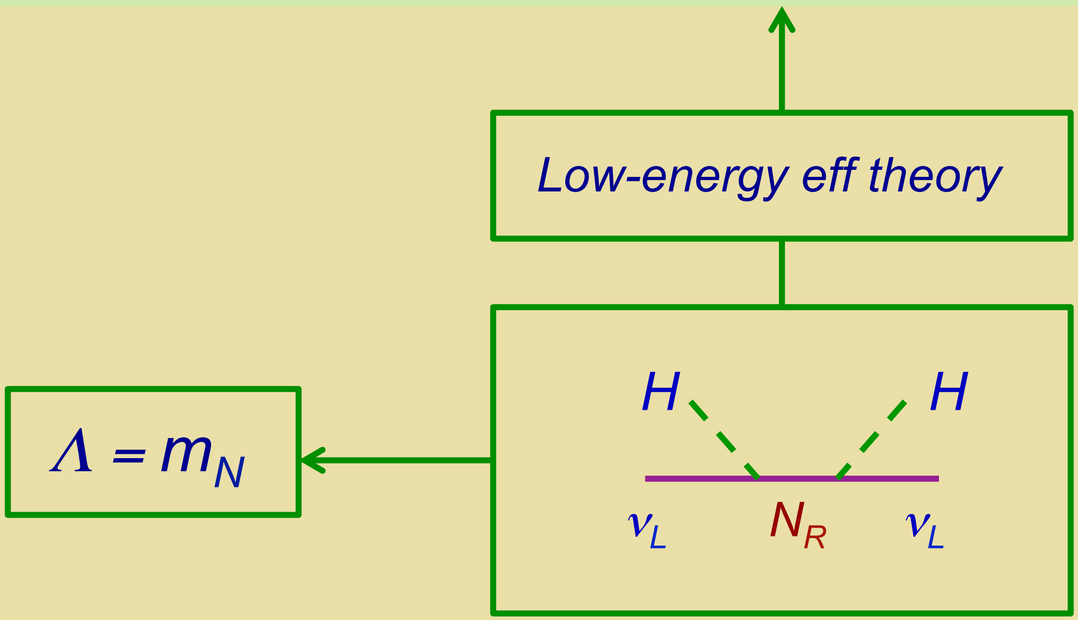
Majorana



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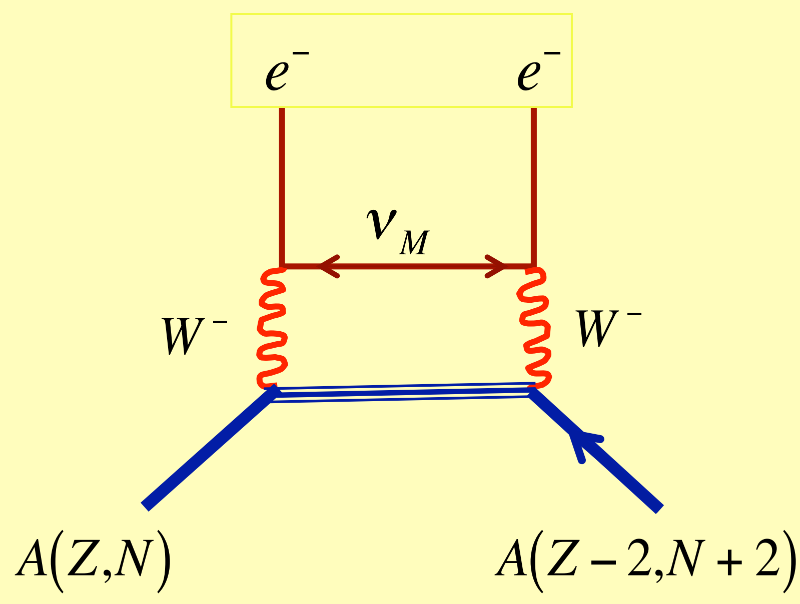
Majorana

"Standard" Mechanism

- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



Three Light Neutrinos: What Do We Know ?

2ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^- \overline{\nu}\,\overline{\nu}$

If own antiparticle, can be emitted then absorbed during decay

0ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^-$

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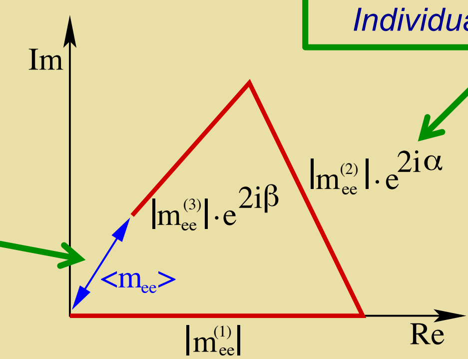
0ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^-$

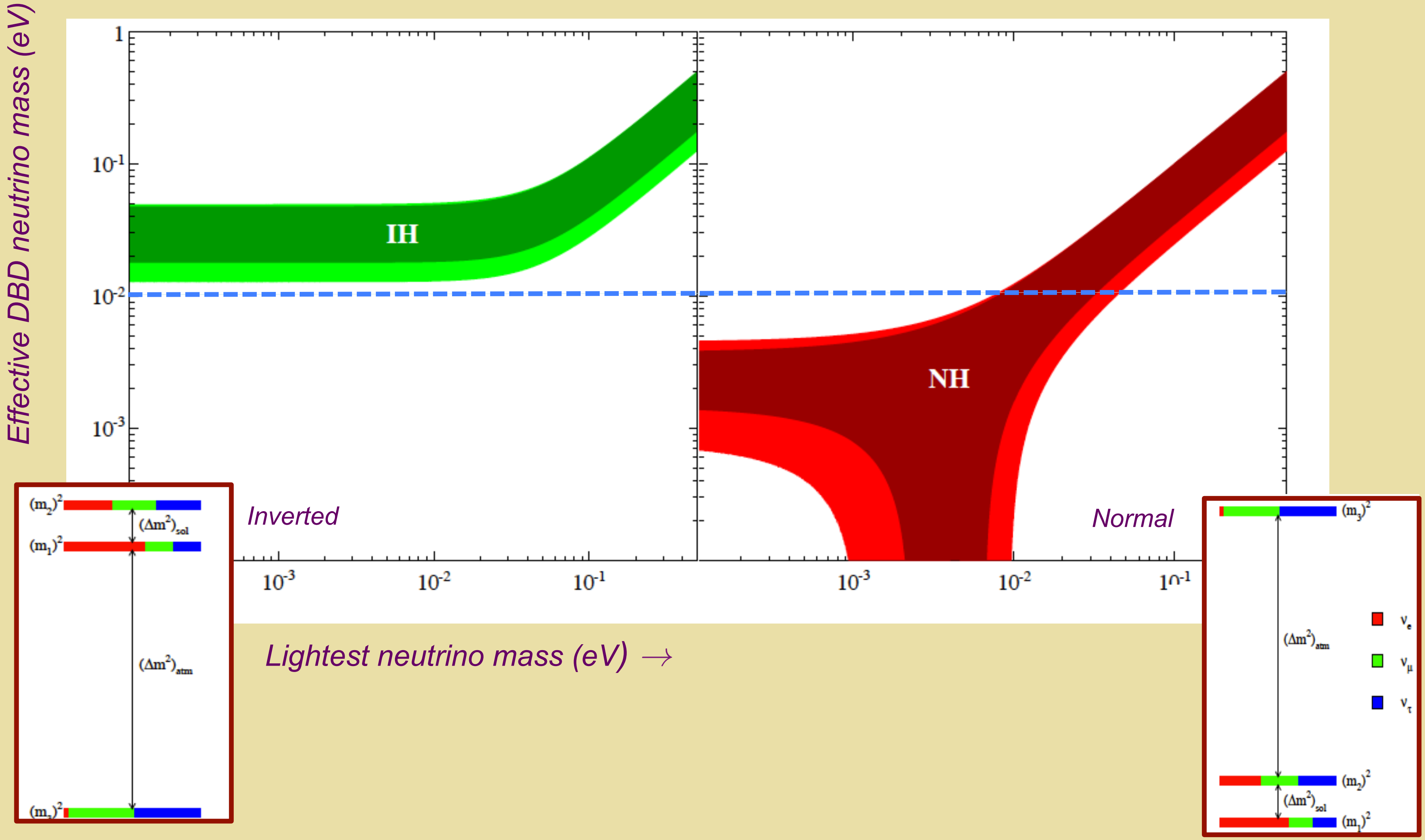
All three light neutrinos participate →
Rate governed by an effective mass

Individual contributions



Why Might A "Ton-Scale" Exp't See It?

Three active light neutrinos



LNV Mass Scale & $0\nu\beta\beta$-Decay

A(Z,N) $\rightarrow$ **Underlying Physics** *$\rightarrow$ A(Z+2, N-2) + $e^- e^-$*

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

Two parameters: Effective coupling & effective heavy particle mass

$0\nu\beta\beta$-Decay: LNV? Mass Term?

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Dirac

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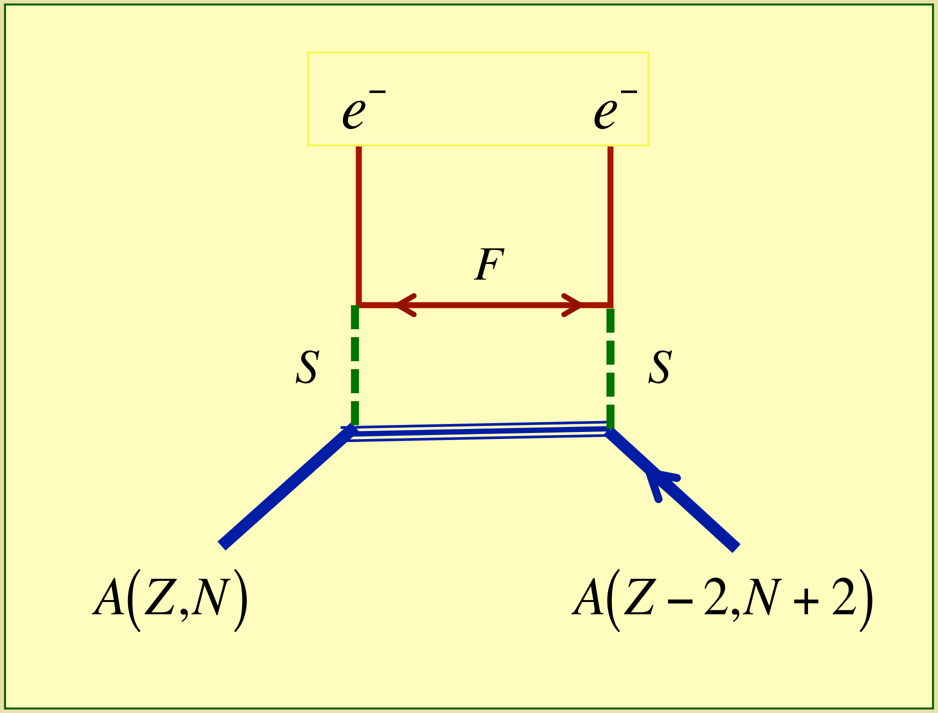
Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



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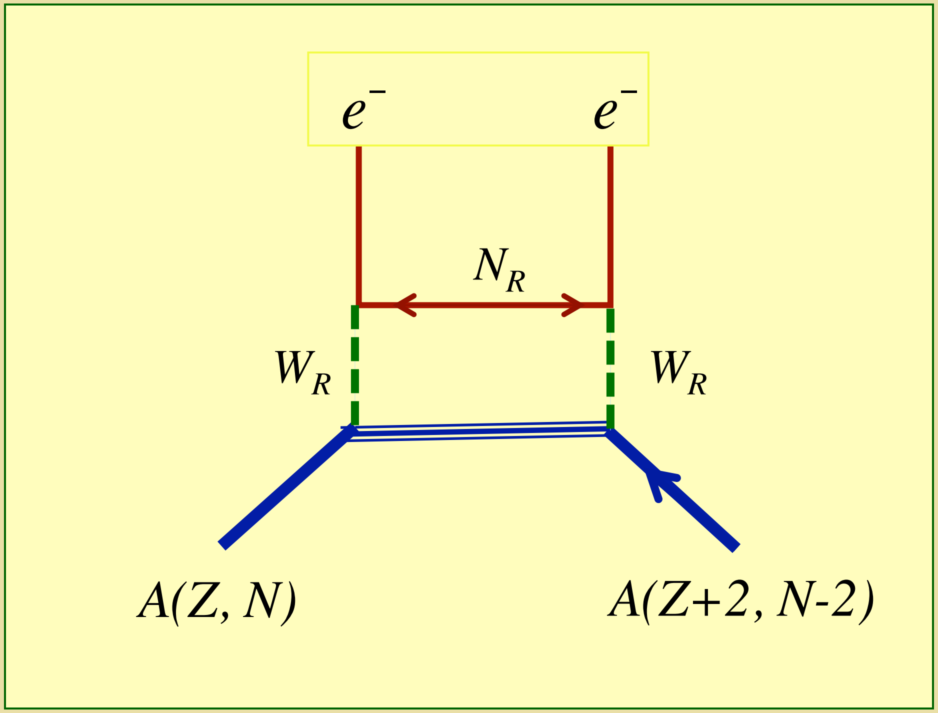

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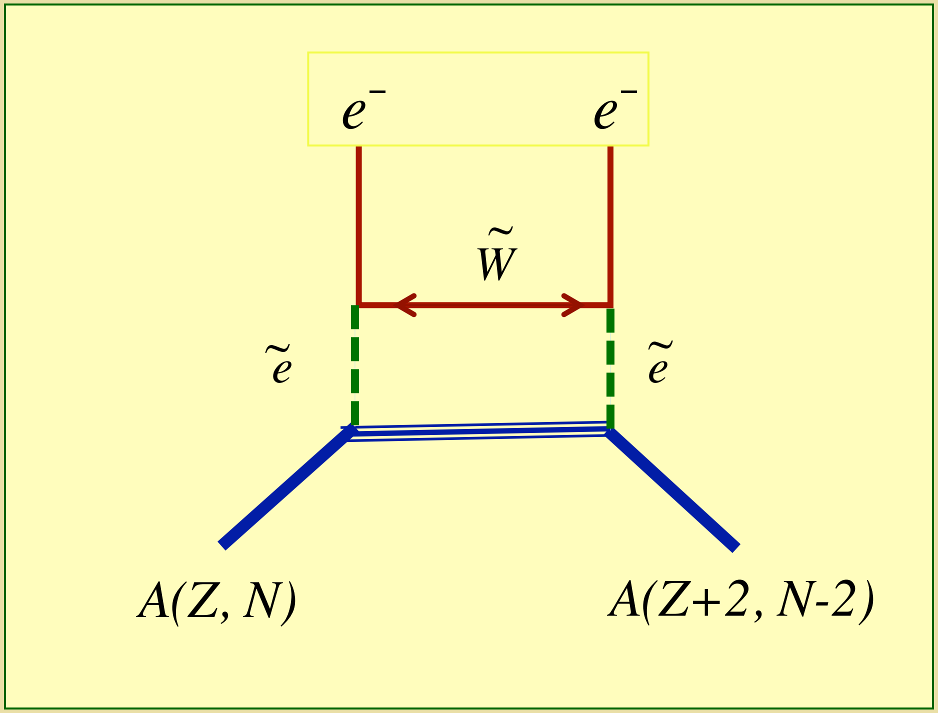

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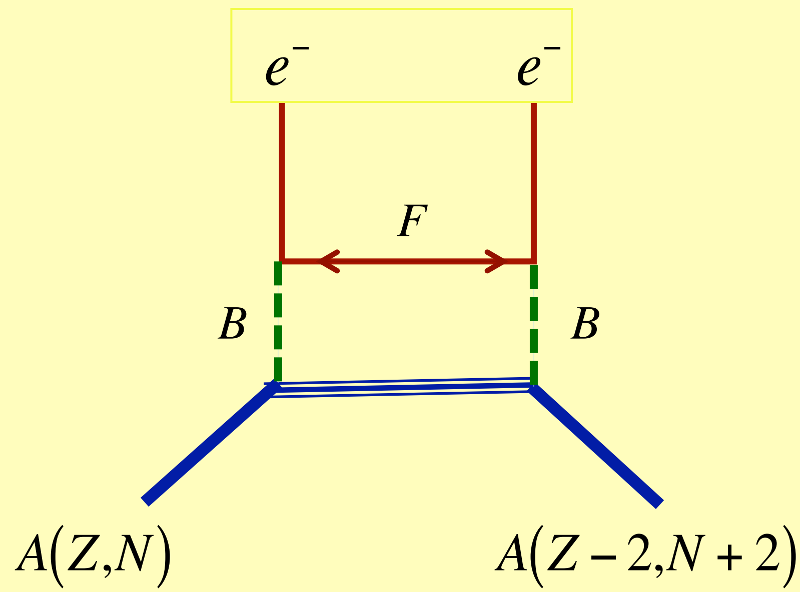
Majorana

TeV LNV Mechanism

$$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

O(1) for Λ ~ 1 TeV



$0\nu\beta\beta$-Decay: TeV Scale LNV

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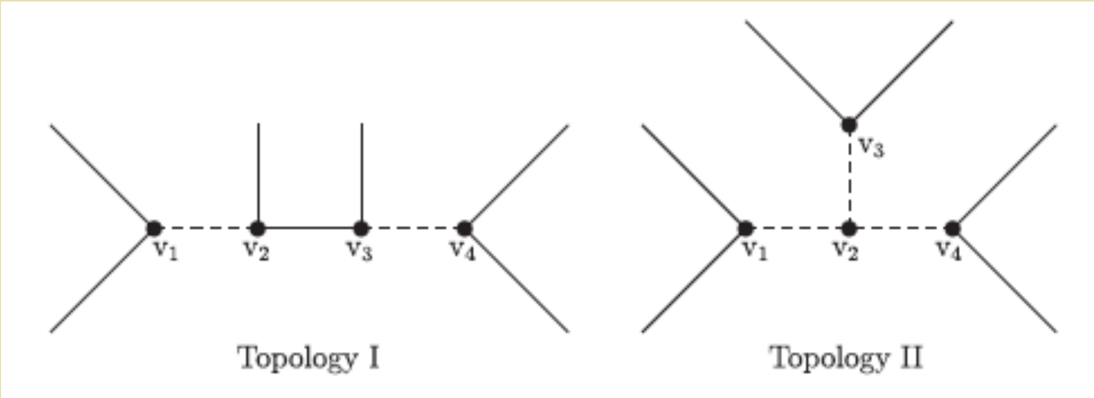
Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



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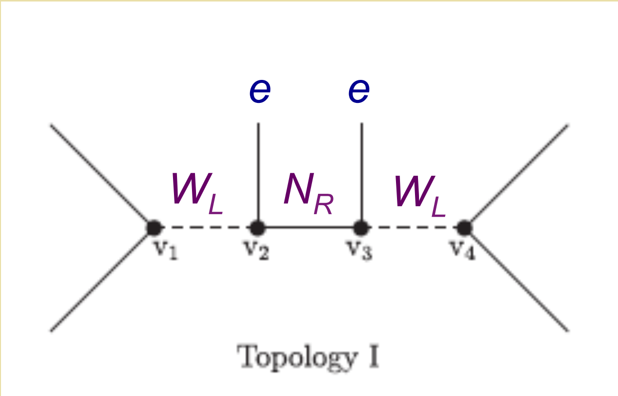

νSM: Type I See-Saw

Mass: standard see-saw but TeV scale

$0\nu\beta\beta$-Decay: TeV Scale LNV

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Majorana

Light + heavy Majorana ν contributions: Single heavy flavor

$$U_{e1}^2 \frac{m_1}{p^2} + V_{e1}^2 \frac{M_1}{p^2 - M_1^2}$$

$$U_{e1}^2 \frac{m_1}{p^2} \times \frac{M_1^2}{M_1^2 - p^2}$$

Type I see-saw: $M_{11} = 0$

$$U_{e1}^2 m_1 + V_{e1}^2 M_1 = 0$$

Mitra et al, 2012

Since $p^2 < 0 \rightarrow$ Amplitude reduction !

0νββ-Decay: TeV Scale LNV

N_R

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Dirac

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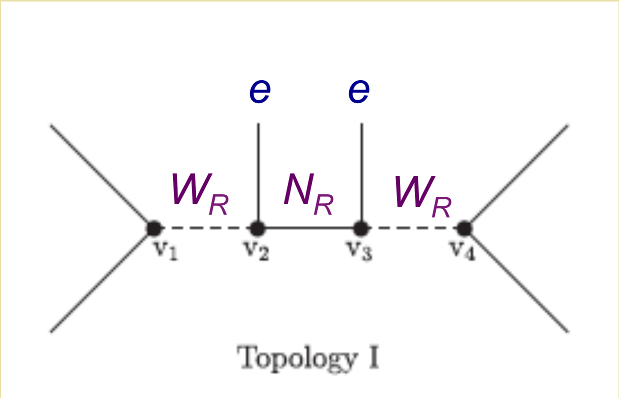
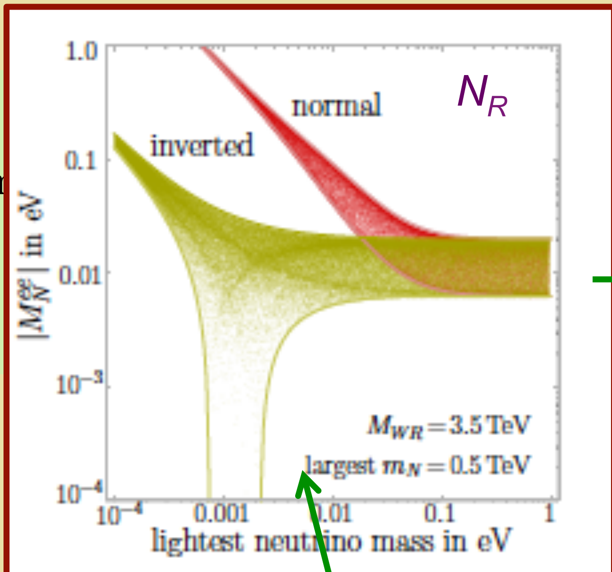
Majorana

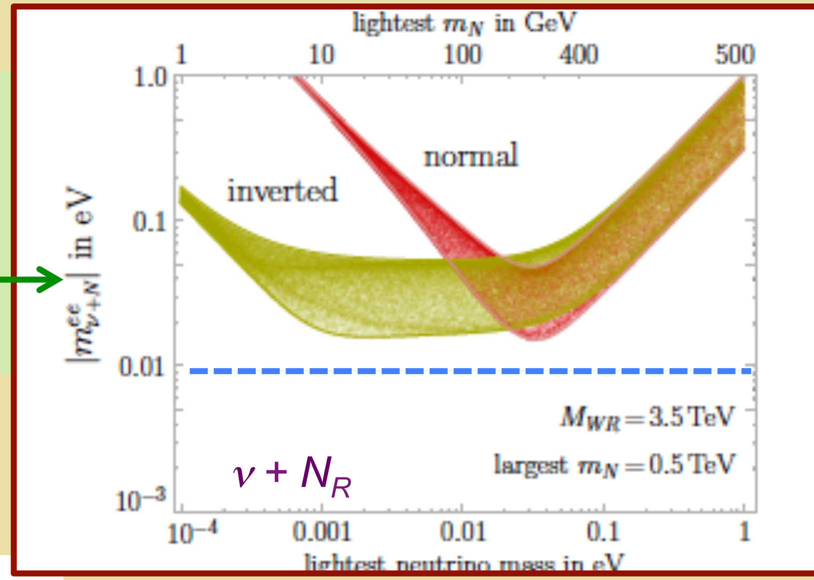


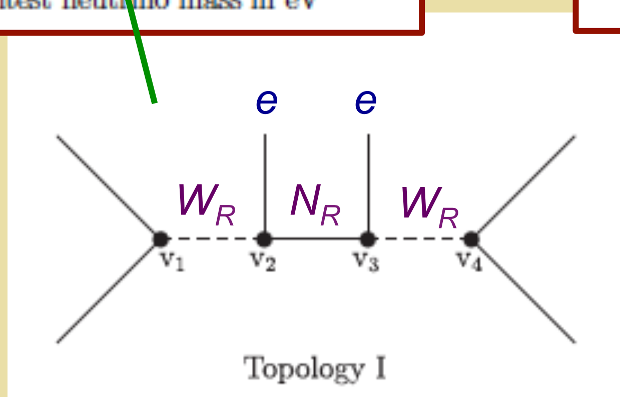
LRSM: Type I See-Saw

Mass: standard see-saw but TeV scale

$0\nu\beta\beta$-Decay: TeV Scale LNV







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Mass: standard see-saw but TeV scale

Tello et al, 1011.3522

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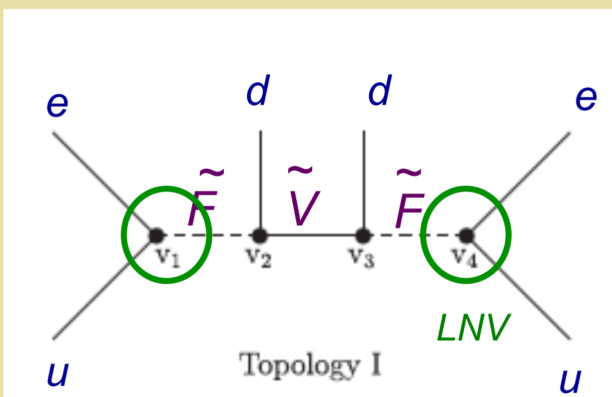

SUSY: R Parity-Violation

Sfermion $\tilde{q}$, $\tilde{l}$

Gaugino $\tilde{g}$, χ *Majorana*

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u,$$

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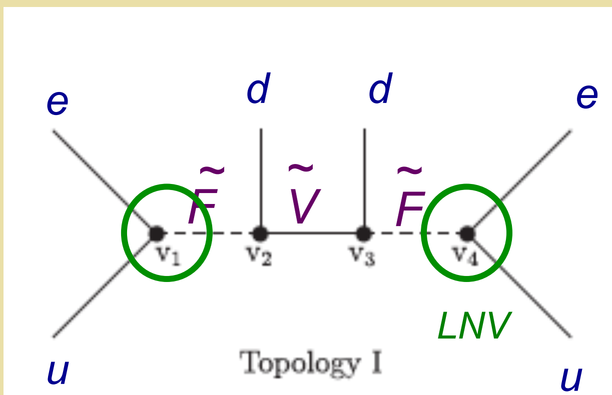

SUSY: R Parity-Violation

$$\lambda'_{111} \le 2 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\,\text{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\,\text{GeV}}\right)^{1/2}$$

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \boxed{\lambda'_{ijk} L_i Q_j \bar{d}_k} + \mu'_i L_i H_u,$$

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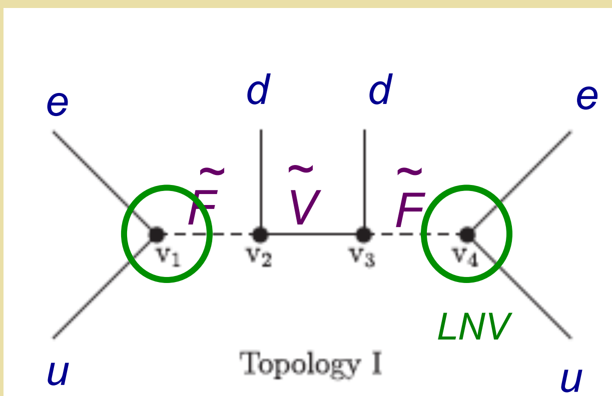

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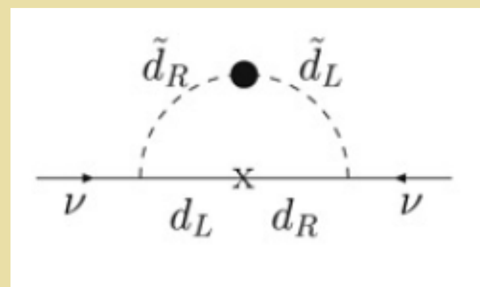

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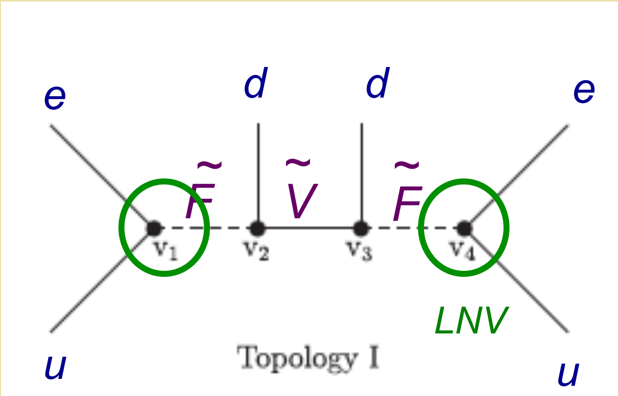

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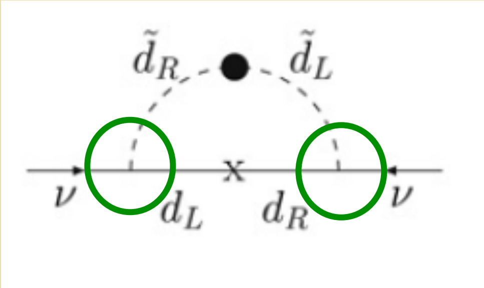

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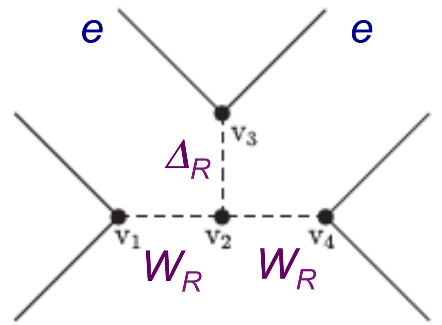
Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011

LRSM: Type II See-Saw

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j\right] + (L \leftrightarrow R) + {\rm h.c.}$$



Topology II

$0\nu\beta\beta$-Decay: TeV Scale LNV

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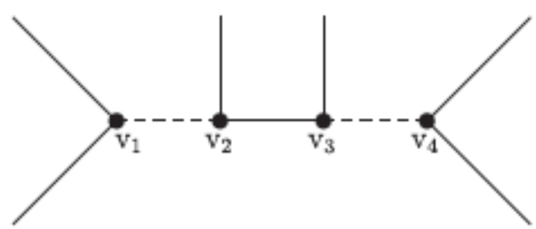
Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



Topology I

Scalar Leptoquarks

Mass: like RPV SUSY (loop)

NLDBD: need Majorana fermion

$$\mathcal{L}_{F=0} = h^L_{1/2}\overline{u}_R \ell_L S^L_{1/2} + h^R_{1/2}\overline{q}_L \epsilon e_R S^R_{1/2} + \tilde{h}^L_{1/2}\overline{d}_R \ell_L \tilde{S}^L_{1/2}$$

LNV Mass Scale & $0\nu\beta\beta$-Decay

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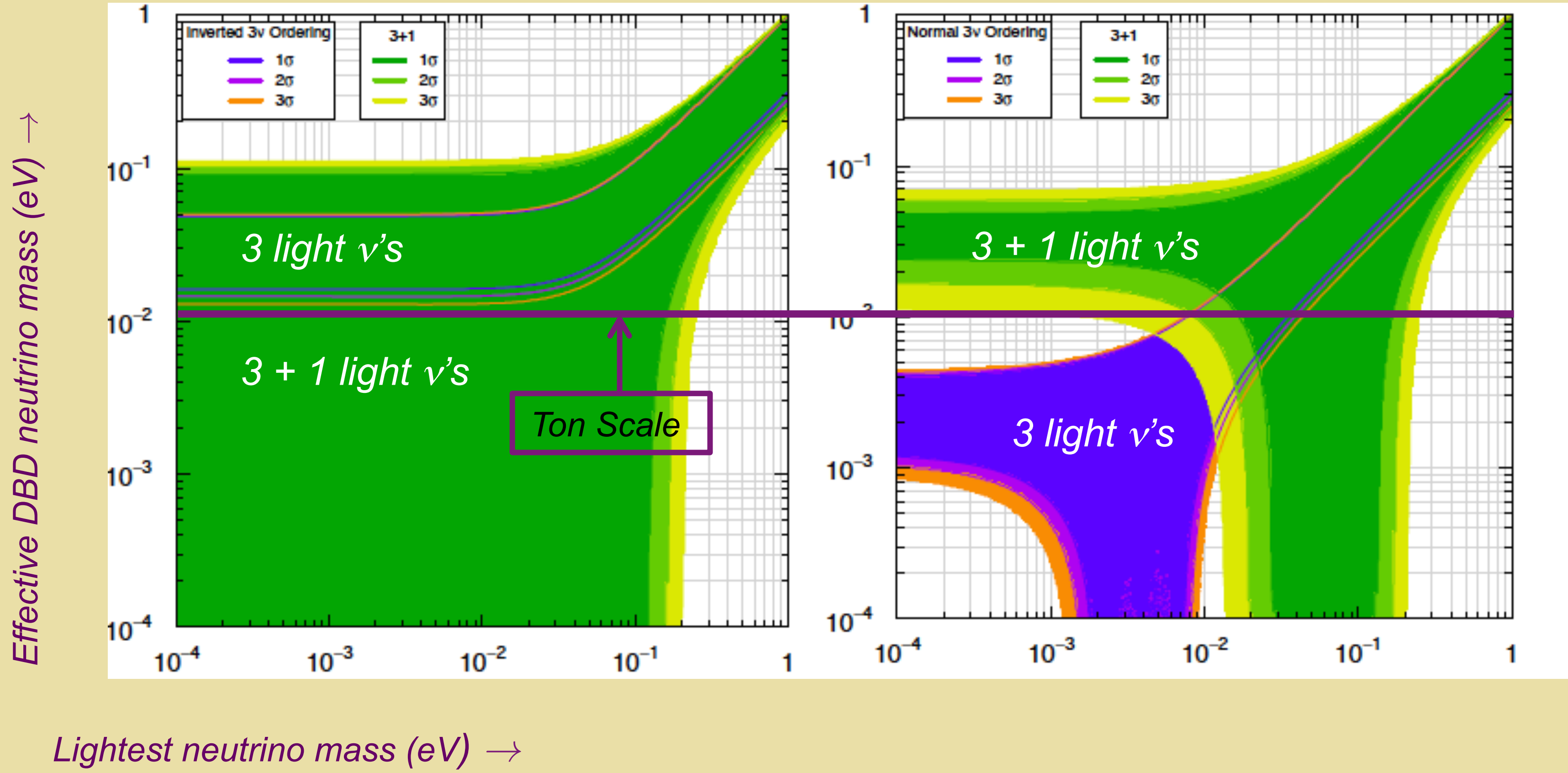
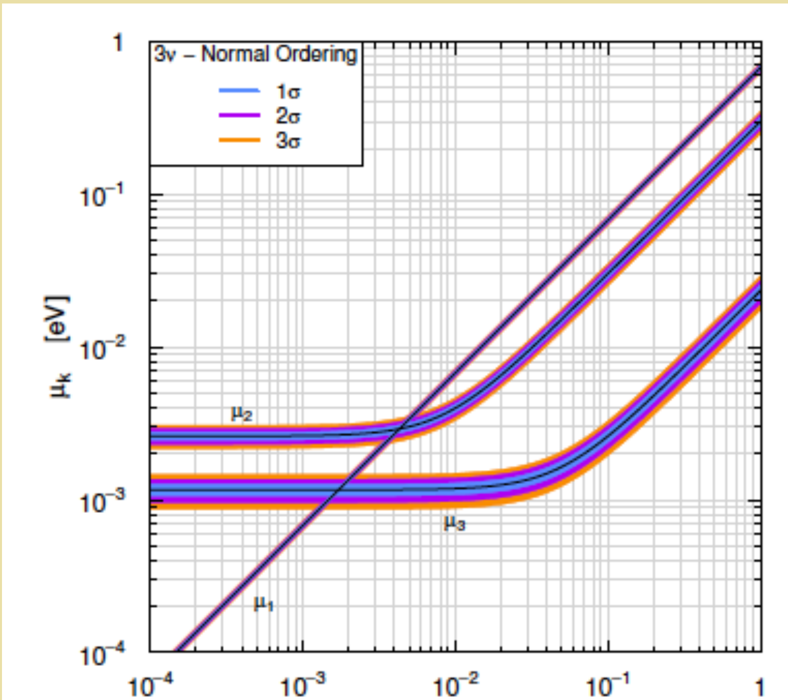


Sterile Neutrinos & $0\nu\beta\beta$−Decay

Effective DBD neutrino mass (eV)

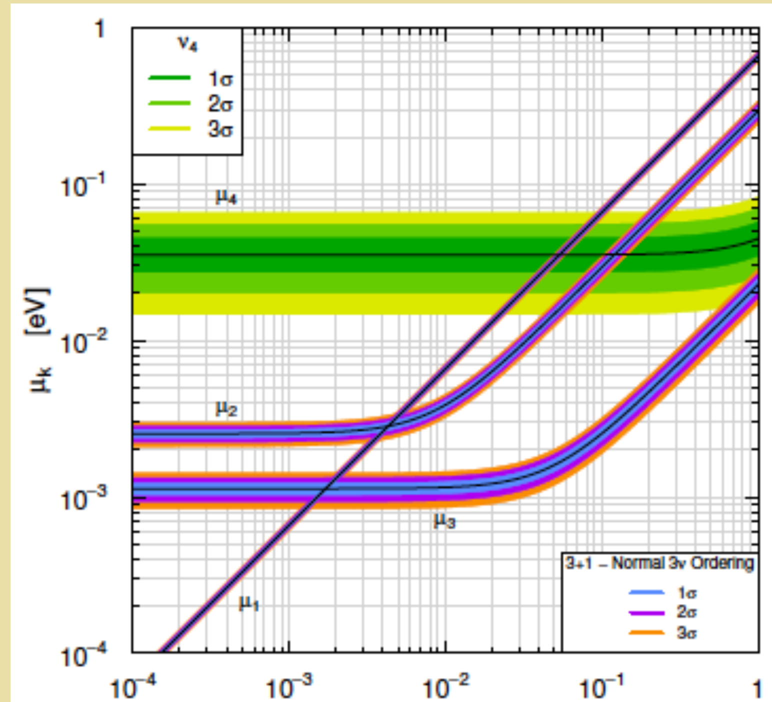
3 active light neutrinos



Lightest neutrino mass (eV) →

$$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3}\right|$$

3+1 active light neutrinos



Lightest neutrino mass (eV) →

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Giunti & Zavanin, JHEP07 (2015) 171

Sterile Neutrinos & $0\nu\beta\beta$−Decay

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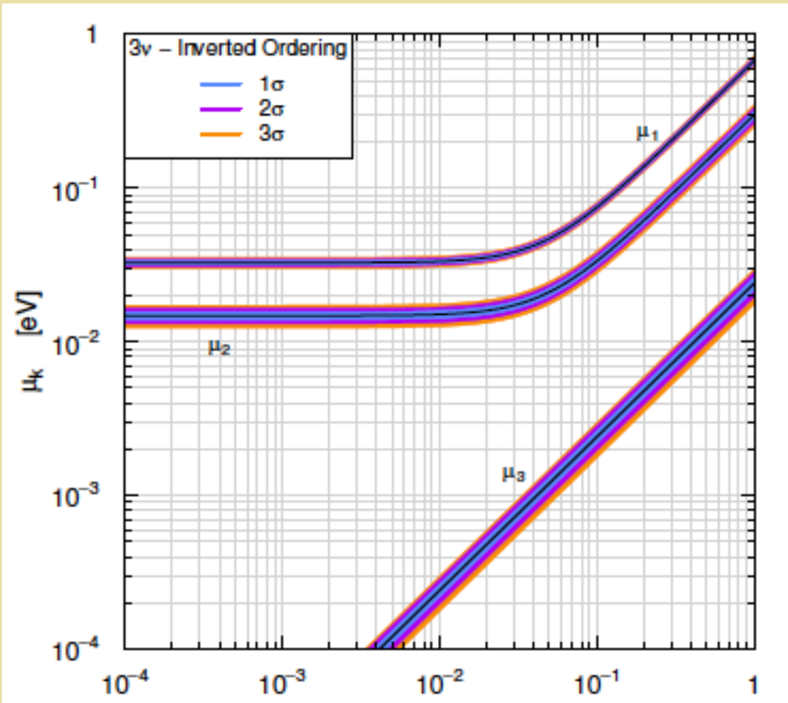
Effective DBD neutrino mass (eV)



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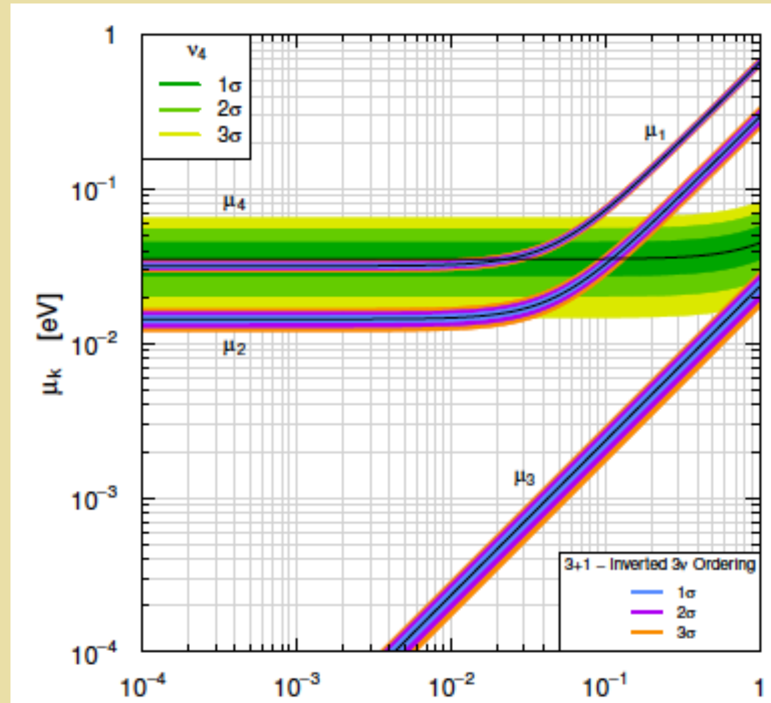

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Giunti & Zavanin, JHEP07 (2015) 171

$0\nu\beta\beta$-Decay: Rate & Mass Dependence

N_R

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Dirac

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Majorana

Light ν exchange

$$\frac{1}{T_{1/2}} \ = \ G^{0\nu}(E,Z)\ |M_{0\nu}|\ |\langle m_{\beta\beta}\rangle|^2$$

Quadratic dependence on $m_{\beta\beta}$

Heavy particle exchange

$$\frac{1}{T_{1/2}} = G_{01}\left(\frac{\text{TeV}}{m_e}\right)^2\left(\frac{\Lambda_H}{\text{TeV}}\right)^4\left(\frac{1}{18}\right)\left(\frac{v}{\text{TeV}}\right)^8 \times\left(\frac{1}{g_A\cos\theta_C}\right)^4|M_0|^2\left[\frac{C_{\text{eff}}^2}{(\Lambda/\text{TeV})^{10}}\right],$$

Scales as $1 / M^{10}$

Lecture II Summary

- *Origin of neutrino mass is a key open problem in fundamental interaction physics*
- *There exist a wide array of well-motivated models that address it with sensitivities to a variety of BSM mass scales*
- *These scenarios may also address other key open problems, such as the origin of the matter-antimatter asymmetry*
- *The corresponding implications for $0\nu\beta\beta$-decay are rich and go well beyond the simplest "standard mechanism" expectations*