A Cocktail Model:
From Radiative ν Masses
to Dark Matter and Back

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In Collaboration with Michael Gustafsson & Maximiliano Rivera.

November 14th 2012

Neutrino Masses

- *Neutrino Oscillations*

Direct Experimental Evidence
of Massive Neutrinos

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 = 7.62^{+0.19}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| \equiv \left|m^2_3 - m^2_1\right| = 2.53^{+0.08}_{-0.1} \times 10^{-3}\,\mathrm{eV}^2$$

Neutrino Masses

- *Neutrino Oscillations* → Direct Experimental Evidence of Massive Neutrinos

$$\Delta m^2_{21} \equiv m_2^2 - m_1^2 = 7.62^{+0.19}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| \equiv \left|m_3^2 - m_1^2\right| = 2.53^{+0.08}_{-0.1} \times 10^{-3}\,\mathrm{eV}^2$$

- $m_\nu = 0$ *in the* SM

  - NO Right-Handed Neutrinos ✘ → **No Dirac Mass Term**
  - NO Lepton Number Violation ✘ → **No Majorana Mass Term**

- *Can Generate Majorana* m_ν *in* SM via Effective Operators

Lowest Order: Dim-5 (*Unique*) →

$$\overline{L_L^c}\,\tilde{\phi}^*\,\tilde{\phi}^\dagger L_L + \mathrm{h.c}$$

*S. Weinberg, Phys. Rev. Lett **43** (1979) 1566*

Neutrino Masses

If we add Right-Handed Neutrinos to the SM... ☑

Yukawa coupling for Neutrinos

$$\mathcal{L} \supset -\overline{L_L}\phi Y_l l_R - \overline{L_L}\tilde{\phi} Y_\nu \nu_R$$

(Dirac Mass Term)

Neutrino Masses

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(Dirac Mass Term)

However...

Neutrino Oscillation Data **+**

$$m_{\nu_e} \equiv \sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2} < 2\,\mathrm{eV}$$

Tritium β- Decay

➔ $m_\nu < \mathrm{eV}$

$$Y_\nu \sim 10^{-11} \ll Y_l$$

Why So Small?

Suggests Alternative Mechanism for Neutrino Mass Generation

“Natural” Neutrino Mass Generation

❶ See-Saw Mechanism:

Type I See-Saw

(Fermion Singlet)

Majorana Mass Term

$$\mathcal{L} \supset -\overline{L_L}\phi Y_l l_R - \overline{L_L}\tilde{\phi} Y_\nu \nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R$$

Lepton Number Breaking

Majorana Neutrino Mass Matrix

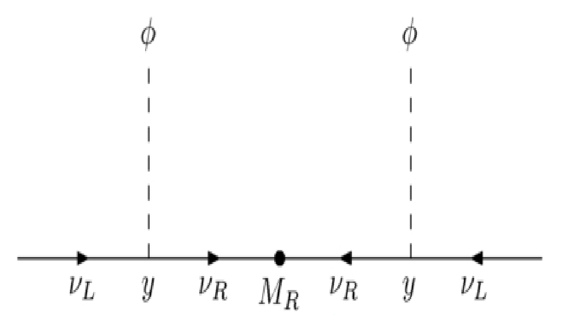
$$\begin{pmatrix} 0 & Y_\nu v \\ Y_\nu v & M_R \end{pmatrix} \longrightarrow \begin{pmatrix} \frac{(Y_\nu v)^2}{M_R} & 0 \\ 0 & M_R \end{pmatrix}$$

$$m_\nu \sim (Y_\nu v)^2/M_R$$

$$\Downarrow$$

$M_R \sim 10^{15}$ GeV → $Y_\nu \sim 1$

$M_R \sim$ TeV → $Y_\nu \sim 10^{-6}$



D = 5 Weinberg Operator Generated at Tree Level

“Natural” Neutrino Mass Generation

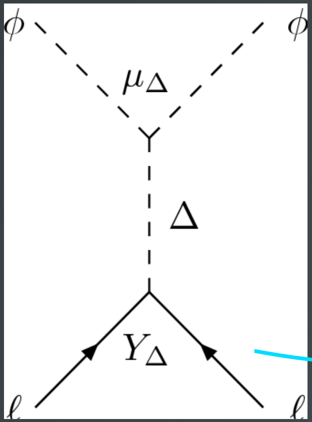
❶ See-Saw Mechanism:

Type II See-Saw

(Scalar Triplet)

$$\mathcal{L} \supset -\vec{\Delta}^\dagger M_\Delta^2 \vec{\Delta} + \overline{\tilde{L}_L} Y_\Delta (\vec{\sigma}\cdot\vec{\Delta}) L_L + \mu_\Delta \tilde{\phi}^\dagger (\vec{\sigma}\cdot\vec{\Delta})^\dagger \phi + \text{h.c.}$$

Lepton Number Breaking



D = 5 Weinberg Operator Generated at Tree Level

$$m_\nu \sim Y_\Delta \, \mu_\Delta \, (v/M_\Delta)^2$$

...Type III See-Saw

(Fermion Triplet)

Typically $M_R, M_\Delta \gg 100$ GeV in See-Saw models

“Natural” Neutrino Mass Generation

❷ Radiative Neutrino Masses:

(*Typically Involving Extended Scalar Sectors*)

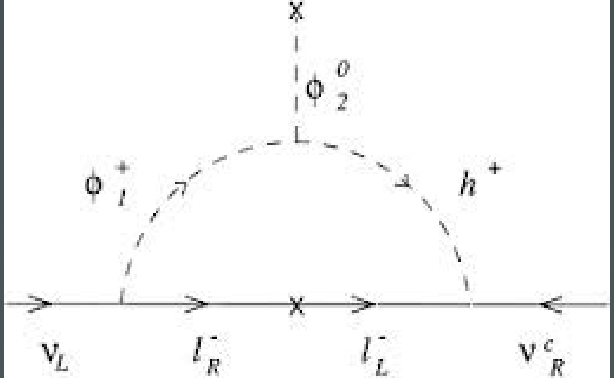
Zee Model

$$-\Delta\mathcal{L}_{\rm Zee} = \kappa_1\,\phi_1^T i\sigma_2\phi_2\,h^- + Y_{ab}\phi_1\overline{l_{L_a}}\,l_{R_b} + f_{ab}\,\overline{l^c_{L_a}}^{\,T} i\sigma_2 l_{L_b}\,h^+ + \text{h.c.}$$

Lepton Number Breaking

Majorana Mass Matrix
for Left-Handed Neutrinos
Generated at 1-loop

A. Zee, Phys. Lett. B ***93*** *(1980) 389*



"Natural" Neutrino Mass Generation

❷ Radiative Neutrino Masses:

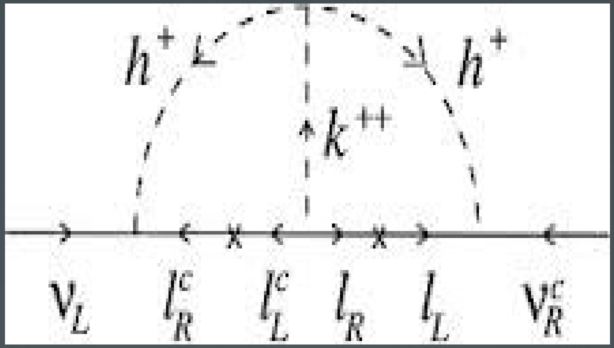
Babu Model

$$-\Delta\mathcal{L}_{\mathrm{Babu}} = \kappa_2\, h^- h^- k^{++} + C_{ab}\, \overline{l^c_{R_a}}\, l_{R_b}\, k^{++} + f_{ab}\, \overline{l^c_{L_a}}^{T} i\sigma_2 l_{L_b}\, h^+ + \mathrm{h.c.}$$

Lepton Number Breaking

Majorana Mass Matrix
for Left-Handed Neutrinos
Generated at 2-loops

K. S. Babu, Phys. Lett. B ***203*** *(1988) 132*



Both Zee and Babu Models Generate the D = 5 Weinberg Operator at Loop Level

“Natural” Neutrino Mass Generation

❷ Radiative Neutrino Masses:

Other Models... (inspired by Zee/Babu)

*C. S. Chen, C. Q. Geng & J. N. Ng, Phys. Rev. D **75** (2007) 053004*

*F. del Aguila, A. Aparici, A. Santamaria & J. Wudka, JHEP **1205** (2012) 133*

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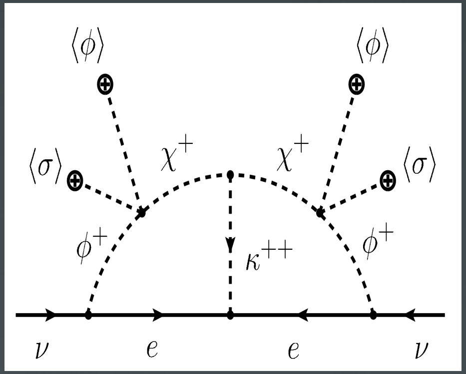
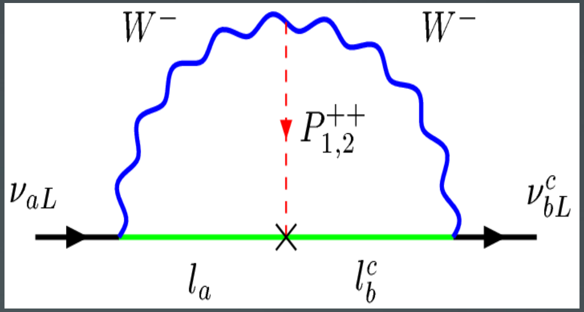




Very Rich Phenomenology:

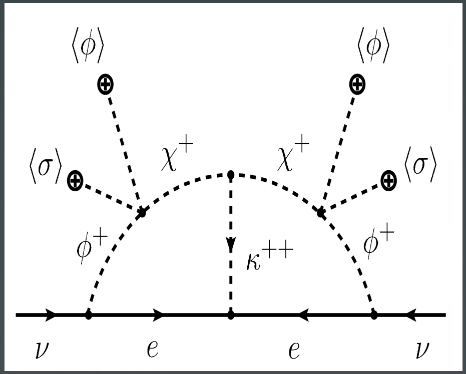
➔ ***Possible Collider Signatures at LHC & ILC***

- ➔ New Charged States
- ➔ Same Sign Di-Leptons
- ➔ LFV Processes
- ...

“Natural” Neutrino Mass Generation

❷ Radiative Neutrino Masses:

Other Models... (inspired by Zee/Babu)



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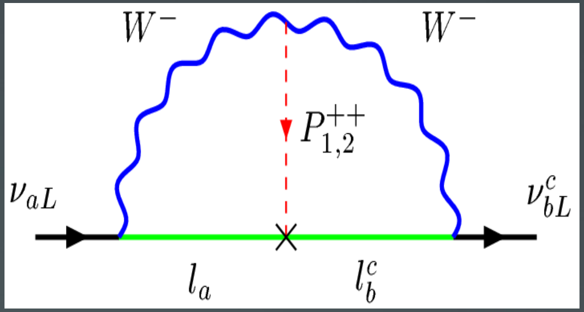
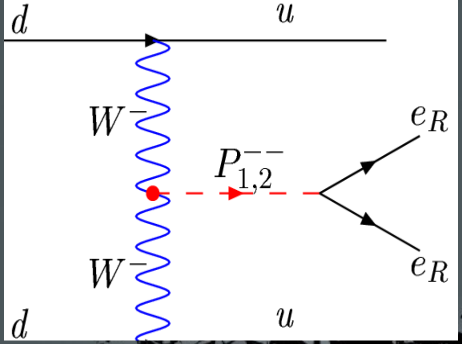


Very Rich Phenomenology:

- ➔ ***Large Lepton Flavour Violation***
- ➔ ***Large Neutrinoless Double β-Decay***



$0\nu\beta\beta$ Decay independent of m_ν

LFV and $0\nu\beta\beta$ Much More Supressed
in See-Saw Models (typically)

“Natural” Neutrino Mass Generation

Radiative Neutrino Mass Generation:

→ Attractive Alternative to See-Saw Mechanism

→ Very Rich (and Testable) Phenomenology

“Natural” Neutrino Mass Generation

Radiative Neutrino Mass Generation:

→ Attractive Alternative to See-Saw Mechanism

→ Very Rich (and Testable) Phenomenology

→ Possible Connection between Neutrino Masses & Dark Matter

Linking Neutrino Masses & WIMP Dark Matter

- *WIMP Dark Matter from BSM Extended Scalar Sectors*

Singlet Higgs-Portal DM

$$-\mathcal{L}_S \supset V(\phi) + \xi \left|\phi\right|^2 S^2$$

J. McDonald, Phys. Rev. D ***50*** *(1994) 3637*

C. P. Burgess, M. Pospelov & T. ter Veldhuis, Nucl. Phys. B ***619*** *(2001) 709*

...

Inert Doublet Model

$$-\mathcal{L}_D \supset V(\left|\phi_1\right|^2, \left|\phi_2\right|^2) + \lambda_4 \left|\phi_1^\dagger \phi_2\right|^2 + \lambda_5 \left(\phi_1^\dagger \phi_2\right)^2 + \text{h.c.}$$

E. Ma, Phys. Rev. D ***73*** *(2006) 077301*

R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D ***74*** *(2006) 015007*

L. Lopez-Honorez, E. Nezri, J. F. Oliver and M. Tytgat, JCAP ***1207*** *(2007) 028*

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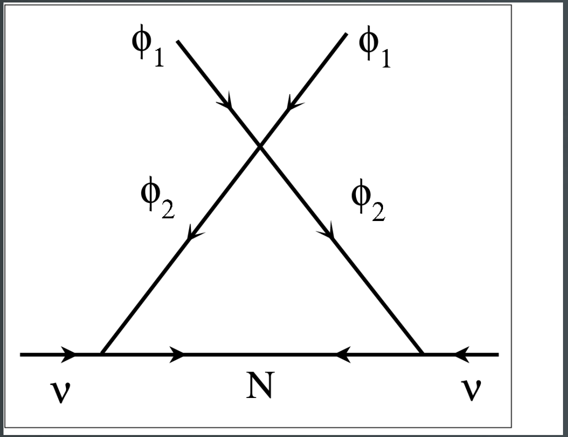
Linking Neutrino Masses & WIMP Dark Matter

- *WIMP Dark Matter from BSM Extended Scalar Sectors*
- *Small ν Masses May be Connected to Dark Matter Stability*

*E. Ma, Phys. Rev. D **73** (2006) 077301*

*L. Krauss, S. Nasri and M. Trodden, Phys. Rev. D **67** (2003) 085002*

$$-\mathcal{L} \supset V\left(|\phi_1|^2, |\phi_2|^2\right) + \lambda_4 \left|\phi_1^\dagger \phi_2\right|^2 + \lambda_5 \left(\phi_1^\dagger \phi_2\right)^2 + \frac{1}{2}\overline{\nu_R^c} M_R \nu_R$$
$$+ \overline{L_L}\phi_1 Y_l l_R + \xcancel{\overline{L_L}\tilde{\phi}_1 Y_\nu \nu_R} + \overline{L_L}\tilde{\phi}_2 Y_\nu \nu_R + \text{h.c.}$$



Radiative (1-loop) See-Saw

N (ν_R) or Neutral component of ϕ_2

Fermionic ⇩ Bosonic

DM candidate

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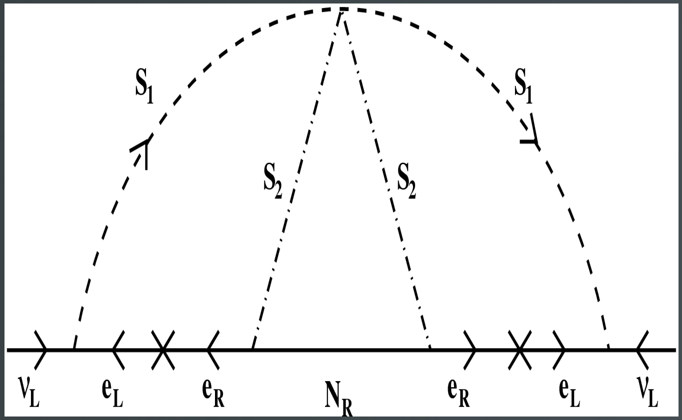
  *L. Krauss, S. Nasri and M. Trodden, Phys. Rev. D **67** (2003) 085002*

$$-\mathcal{L} \supset V(|S_1|^2, |S_2|^2) + \lambda_4 \left|S_1^+ S_2^-\right|^2 + \lambda_5 \left(S_1^+ S_2^-\right)^2$$
$$+ f_{ab}\, \overline{l^c_{L_a}}^T i\sigma_2 l_{L_b}\, S_1^+ + g_a \nu_R\, S_2^+ l_{R_a} + \frac{1}{2}\overline{\nu^c_R} M_R \nu_R + \text{h.c.}$$



3-loop Majorana Mass!

N (ν_R) is a DM candidate

Linking Neutrino Masses & WIMP Dark Matter

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→ ***Z_2 Symmetry (DM) Responsible for Small m_ν (<u>Loop Suppression</u>)***

→ ***In Both Models, <u>D = 5 Weinberg Operator</u> → Leading Contribution to m_ν***

Linking Neutrino Masses & WIMP Dark Matter

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→ ***Z_2 Symmetry (DM) Responsible for Small m_ν (Loop Suppression)***

→ ***In Both Models, D = 5 Weinberg Operator → Leading Contribution to m_ν***

→ ***ν_R as DM Candidate:***

- No Direct Detection Signal ☒
- Indirect Detection Signal ☑

Linking ν Masses to WIMP Dark Matter
May Influence DM Phenomenology

Neutrino Masses & WIMP Dark Matter

- *Naturally Small ν Masses from BSM Extended Scalar Sectors*

+

WIMP Dark Matter

(inspired by Zee/Babu)

→ ***Z_2 Symmetry (DM) Responsible for Small*** m_ν

→ ***Rich Phenomenology* (LFV, $0\nu\beta\beta$, Colliders...)**

→ ***Properties of Neutrino Sector Affected in Dramatic Way***

Neutrino Masses & WIMP Dark Matter

- *Naturally Small* **ν** *Masses from BSM Extended Scalar Sectors*

+

WIMP Dark Matter

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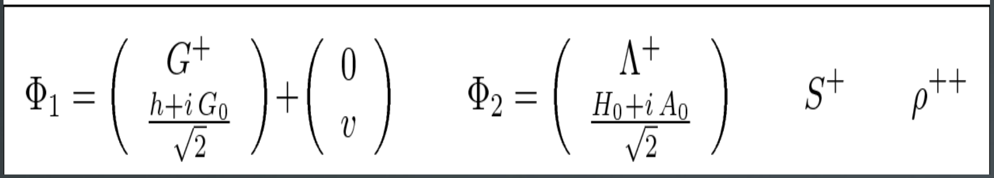

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+i\,G_0}{\sqrt{2}} \end{pmatrix} + \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+i\,A_0}{\sqrt{2}} \end{pmatrix} \qquad S^+ \qquad \rho^{++}$$

Neutrino Masses & WIMP Dark Matter

- *Naturally Small* **ν** *Masses from BSM Extended Scalar Sectors*

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WIMP Dark Matter

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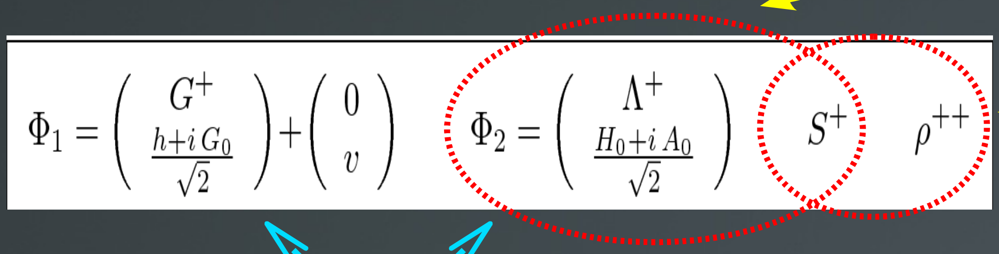

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Inert Doublet Model

Neutrino Masses & WIMP Dark Matter

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WIMP Dark Matter

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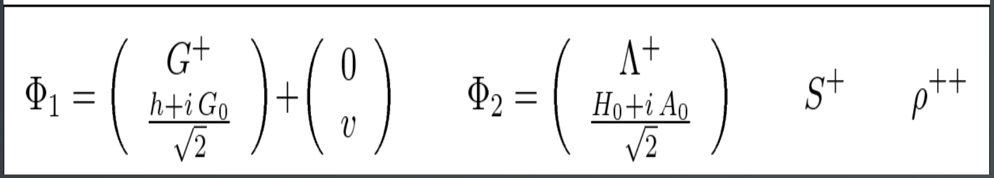

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Z_2	+	−	−	+

Neutrino Masses & WIMP Dark Matter

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WIMP Dark Matter

(inspired by Zee/Babu)

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG_0}{\sqrt{2}} \end{pmatrix} + \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+iA_0}{\sqrt{2}} \end{pmatrix} \qquad S^+ \qquad \rho^{++}$$

$$-\Delta\mathcal{L} = C_{ab}\,\overline{l^c_{R_a}}\,l_{R_b}\,\rho^{++} + V\left(|\Phi_1|^2, |\Phi_2|^2, |S|^2, |\rho|^2\right) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2$$
$$+\kappa_1\,\Phi_1^T i\sigma_2\Phi_2\,S^- + \lambda_{\rho S}\,\Phi_1^T i\sigma_2\Phi_2\,S^+\rho^{--} + \kappa_2\,S^-S^-\rho^{++} + \mathrm{h.c.}$$

For $\kappa_1 \neq 0$, S-Λ Mixing

$$\begin{aligned} \Lambda^+ &= c_\theta H_1^+ - s_\theta H_2^+ \\ S^+ &= s_\theta H_1^+ + c_\theta H_2^+ \end{aligned}$$

Neutrino Masses & WIMP Dark Matter

- *Naturally Small ν Masses from BSM Extended Scalar Sectors*

+

WIMP Dark Matter

(inspired by Zee/Babu)

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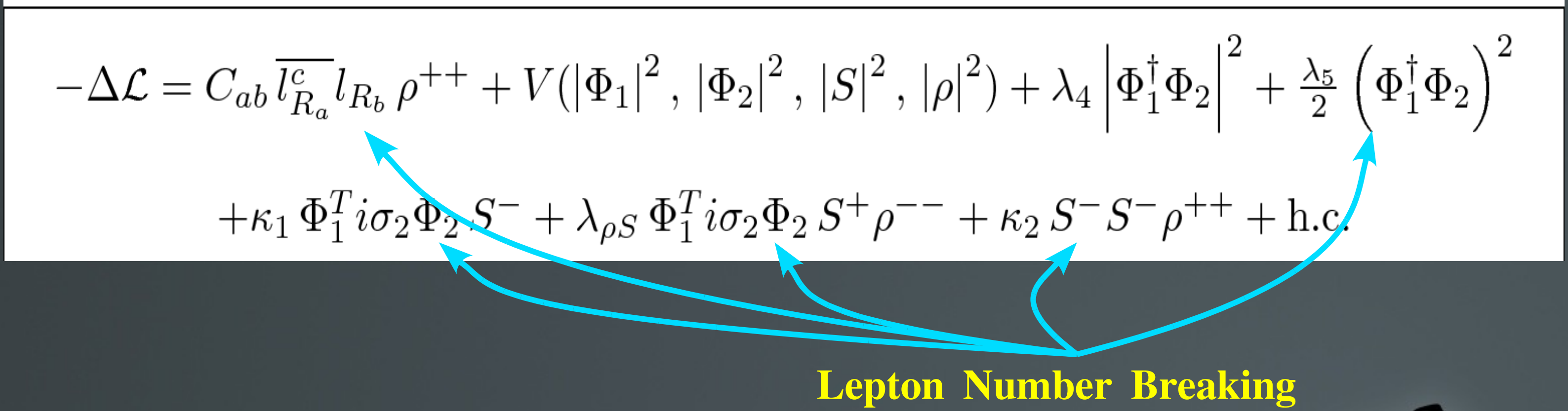

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$$+\kappa_1\,\Phi_1^T i\sigma_2\Phi_2\,S^- + \lambda_{\rho S}\,\Phi_1^T i\sigma_2\Phi_2\,S^+\rho^{--} + \kappa_2\,S^-S^-\rho^{++} + \text{h.c.}$$

Lepton Number Breaking

Need $C_{ab} \neq 0$, $\lambda_5 \neq 0$, ($\kappa_1 \neq 0$)

Need $\lambda_{\rho s}$ or $\kappa_2 \neq 0$

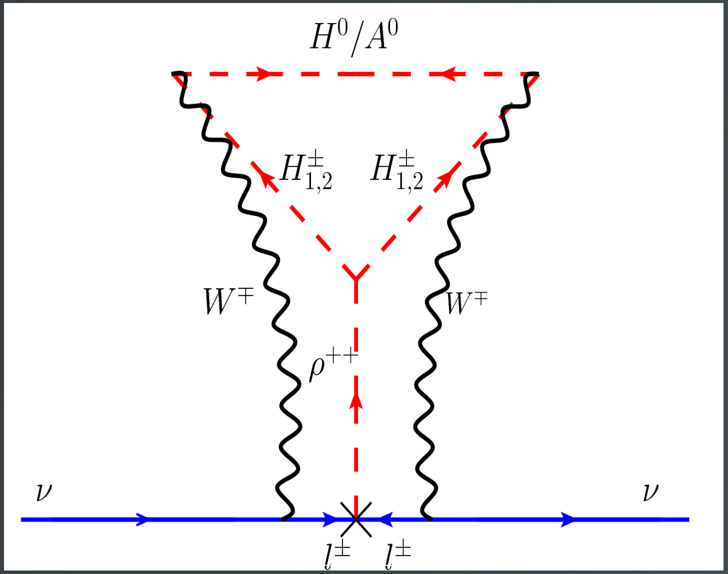
Neutrino Masses & WIMP Dark Matter

- *Naturally Small ν Masses from BSM Extended Scalar Sectors*

  \+

  WIMP Dark Matter

  (inspired by Zee/Babu)



ν Masses generated at 3-Loops via the "Cocktail Diagram"

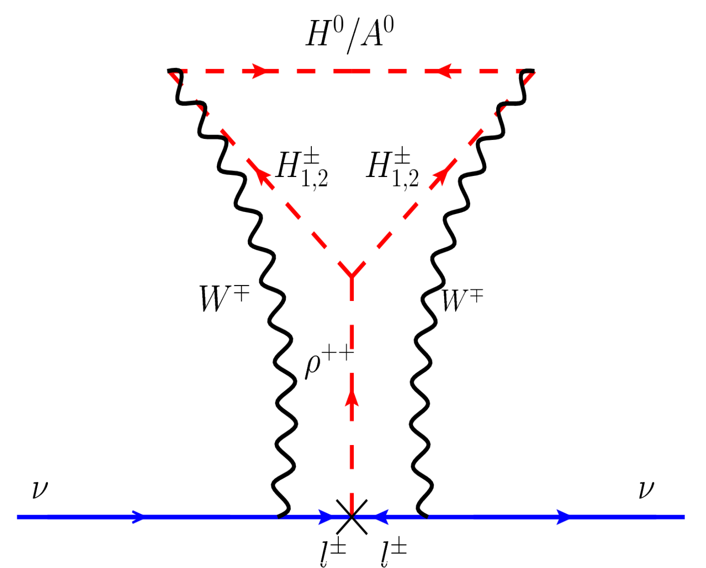
$$m_{\nu_{ab}} \simeq \frac{\mathrm{Sin}^2(2\,\theta)}{(16\,\pi^2)^3}\,\frac{m_{A_0}^2 - m_{H_0}^2}{m_{A_0}m_{H_0}}\left(\frac{m_{H_1}^2 - m_{H_2}^2}{m_{H_1}m_{H_2}}\right)^2\frac{(\kappa_2 + \lambda_{\rho S}v)}{m_\rho^2}\,m_{l_a}m_{l_b}\,C_{ab}$$

Neutrino Masses & WIMP Dark Matter

- *Naturally Small* ν *Masses from BSM Extended Scalar Sectors*

\+ (inspired by Zee/Babu)

WIMP Dark Matter



ν *Masses generated at 3-Loops via the "Cocktail Diagram"*

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→ ***Leading Contribution to*** m_ν ***from <u>D = 9 Operator</u> (D = 5 Operator Sub-Leading)***

WEINBERG OPERATOR
at 5-LOOPS

Neutrino Masses & WIMP Dark Matter

- *Naturally Small ν Masses from BSM Extended Scalar Sectors*

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WIMP Dark Matter

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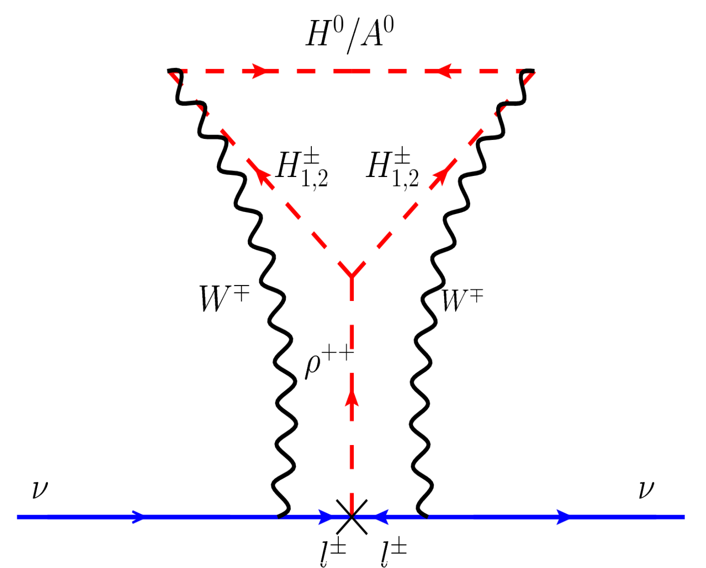

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"GIM" Mechanism: $m^2_{A0} - m^2_{H0} \sim \lambda_5$, $m^2_{H1} - m^2_{H2} \sim \kappa_1$

Experimental Constrains & Model Predictions

❶ ***Neutrino Masses & Mixings***

$$m_\nu = U^T\, m_\nu^D\, U$$

Experimental Constrains & Model Predictions

❶ *Neutrino Masses & Mixings*

$$m_\nu = U^T \, m_\nu^D \, U$$

$$U = \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} c_{13}c_{12} & -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} \\ c_{13}s_{12} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} \\ s_{13}e^{-i\delta} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix}$$

$$m_\nu^D = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

2 Majorana Phases **3 Mixing Angles, 1 CP Phase** **3 Neutrino Masses**

$s_{12} = \sin(\theta_{12})$, $s_{13} = \sin(\theta_{13})$, $s_{23} = \sin(\theta_{23})$

$c_{12} = \cos(\theta_{12})$, $c_{13} = \cos(\theta_{13})$, $c_{23} = \cos(\theta_{23})$

Experimental Constrains & Model Predictions

❶ *Neutrino Masses & Mixings*

$$m_\nu = U^T \, m_\nu^D \, U$$

$$U = \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} c_{13}c_{12} & -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} \\ c_{13}s_{12} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} \\ s_{13}e^{-i\delta} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix}$$

$$m_\nu^D = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

2 Majorana Phases **3 Mixing Angles, 1 CP Phase** **3 Neutrino Masses**

$s_{12} = \sin(\theta_{12})$, $s_{13} = \sin(\theta_{13})$, $s_{23} = \sin(\theta_{23})$

$c_{12} = \cos(\theta_{12})$, $c_{13} = \cos(\theta_{13})$, $c_{23} = \cos(\theta_{23})$

Global Fit to Neutrino Oscillation Data:

*D. V. Forero, M. Tortola and J. W. F. Valle, Phys. Rev. D **86** (2012) 073012*

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.62^{+0.19}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2 \qquad \left|\Delta m_{31}^2\right| \equiv \left|m_3^2 - m_1^2\right| = 2.53^{+0.08}_{-0.1} \times 10^{-3}\,\mathrm{eV}^2$$

$$s_{12}^2 = 0.320^{+0.015}_{-0.017} \qquad s_{23}^2 = 0.49^{+0.08}_{-0.05} \qquad s_{13}^2 = 0.026^{+0.003}_{-0.004}$$

m_1, α_1, α_2 Not Constrained

δ Beyond Exp. Sensitivity

"Large" θ_{13}

Experimental Constrains & Model Predictions

➊ *Neutrino Masses & Mixings*

"Cocktail Model" Prediction

$$m_{\nu_{ab}} \propto m_{l_a} m_{l_b} C_{ab} \simeq \begin{pmatrix} 0 & 0 & m_{e\tau} \\ 0 & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

Approximate ν Mass Texture

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→ ***Texture Predicts Normal Hierarchy***

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Approximate ν Mass Texture

→ ***Texture Imposes*** $Re(m_{ee}) \simeq 0, Im(m_{ee}) \simeq 0, Re(m_{e\mu}) \simeq 0, Im(m_{e\mu}) \simeq 0$

Prediction for $m_1, \alpha_1, \alpha_2, \delta$

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Approximate ν Mass Texture

→ ***Texture Imposes*** $Re(m_{ee}) \simeq 0, Im(m_{ee}) \simeq 0, Re(m_{e\mu}) \simeq 0, Im(m_{e\mu}) \simeq 0$

Solutions Only Exist for $0.014 < s^2_{13} < 0.023$ $(0.011 < s^2_{13} < 0.035)$

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Approximate ν Mass Texture

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Prediction for θ_{13}!!

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m_1, α_1, α_2 ***Not Constrained***

δ ***Beyond Exp. Sensitivity***

"Large" θ_{13}

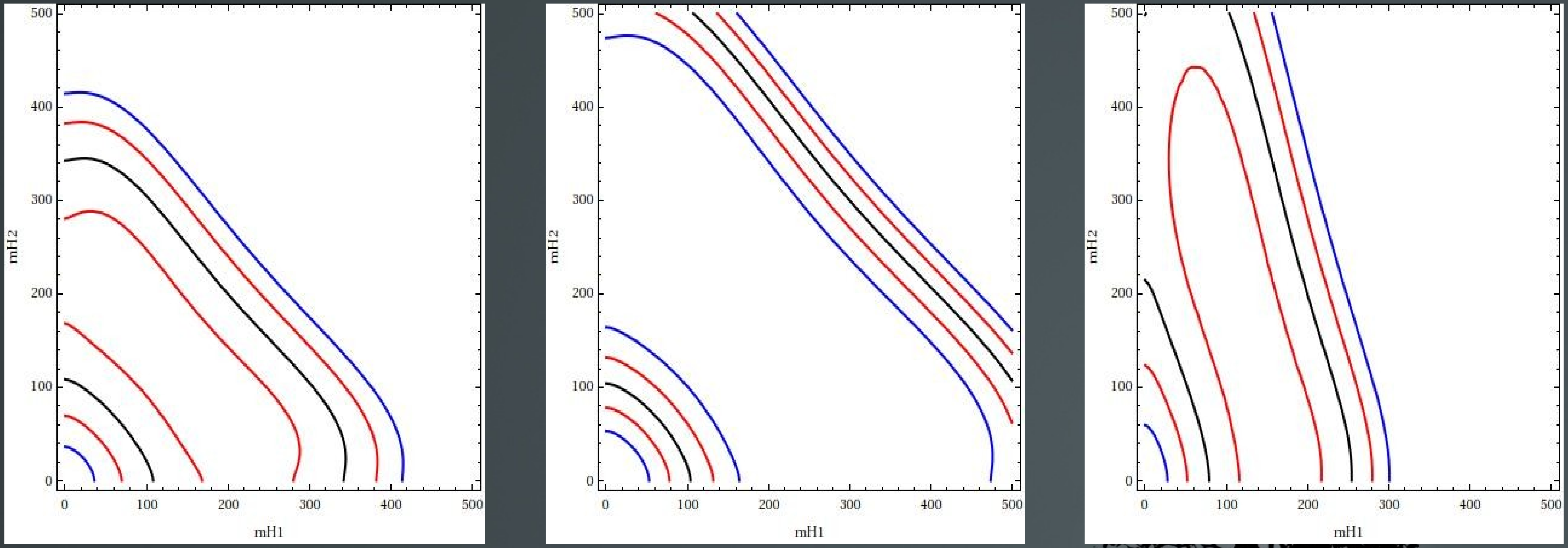
Experimental Constrains & Model Predictions

❷ *Electroweak Precision Constrains*

$H_0, A_0, H_1^+, H_2^+, \rho^{++}$ ***Contribute to EWPO*** **(S, T Parameters)**

$$\Delta T \sim \frac{1}{24\,\pi^2\,\alpha_{\rm EM} v^2}\left[(m_{H_1}^2 - m_{A_0}^2)(m_{H_1}^2 - m_{H_0}^2) + (m_{H_2}^2 - m_{A_0}^2)(m_{H_2}^2 - m_{H_0}^2)\right] + \Delta T_\rho$$

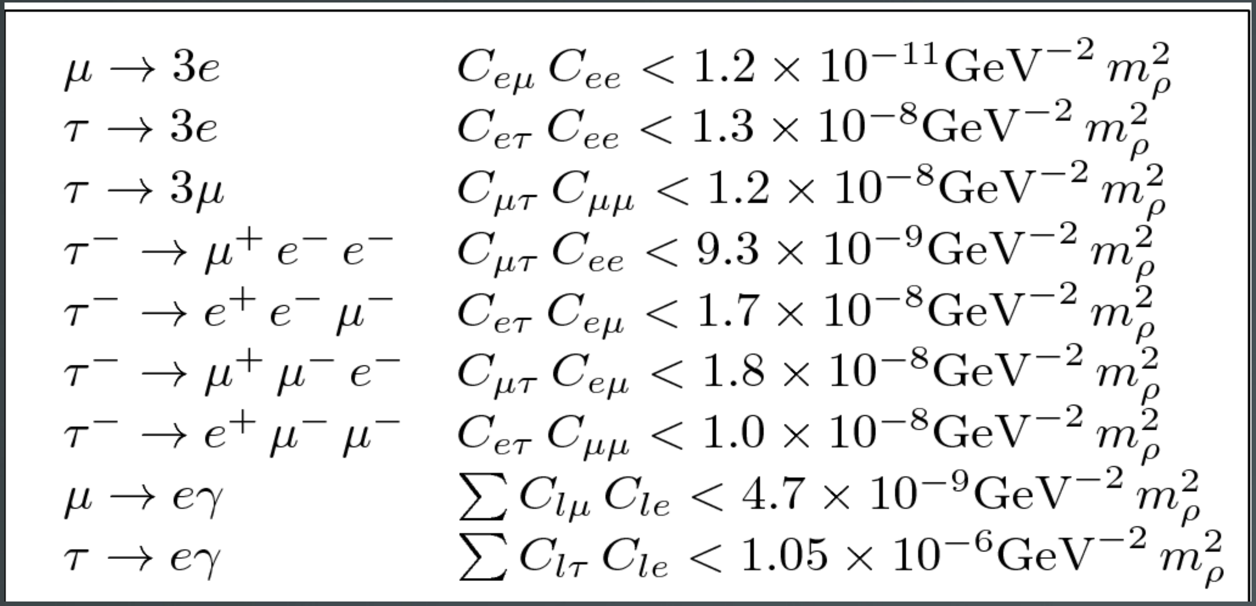
$m_{H_0} = m_{DM} = 65$ GeV, $m_\rho = 5$ TeV



$m_{A_0} = 200$ GeV, $\theta = \pi/4$ $m_{A_0} = 300$ GeV, $\theta = \pi/4$ $m_{A_0} = 200$ GeV, $\theta = \pi/6$

Experimental Constrains & Model Predictions

❸ *Lepton Flavour Violation Constrains*



$\mu \to 3e$	$C_{e\mu}\, C_{ee} < 1.2 \times 10^{-11} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau \to 3e$	$C_{e\tau}\, C_{ee} < 1.3 \times 10^{-8} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau \to 3\mu$	$C_{\mu\tau}\, C_{\mu\mu} < 1.2 \times 10^{-8} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau^- \to \mu^+ e^- e^-$	$C_{\mu\tau}\, C_{ee} < 9.3 \times 10^{-9} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau^- \to e^+ e^- \mu^-$	$C_{e\tau}\, C_{e\mu} < 1.7 \times 10^{-8} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau^- \to \mu^+ \mu^- e^-$	$C_{\mu\tau}\, C_{e\mu} < 1.8 \times 10^{-8} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau^- \to e^+ \mu^- \mu^-$	$C_{e\tau}\, C_{\mu\mu} < 1.0 \times 10^{-8} \mathrm{GeV}^{-2}\, m_\rho^2$
$\mu \to e\gamma$	$\sum C_{l\mu}\, C_{le} < 4.7 \times 10^{-9} \mathrm{GeV}^{-2}\, m_\rho^2$
$\tau \to e\gamma$	$\sum C_{l\tau}\, C_{le} < 1.05 \times 10^{-6} \mathrm{GeV}^{-2}\, m_\rho^2$

Most Stringent Constrains are on $m_{e\tau}$ and $m_{\mu\mu}$:

→ ❶ + ❸ *Set m^2_ρ > TeV, $m^2_{A0} - m^2_{H0} \sim V^2$, $m^2_{H1} - m^2_{H2} \sim V^2$ and $C_{e\tau} \sim 1$*

Need Heavy ρ^{++} & Large Mass Splittings

Experimental Constrains & Model Predictions

❹ *Collider Phenomenology*

→ ***Modification of*** $h \rightarrow \gamma\gamma$ ***Branching Ratio***

→ H_0, A_0, H_1^+, H_2^+ ***States Accesible at LHC***

Experimental Constrains & Model Predictions

❹ Collider Phenomenology

→ *Modification of* $h \to \gamma\gamma$ *Branching Ratio*

→ H_0, A_0, H_1^+, H_2^+ *States Accesible at LHC*

❺ Neutrinoless Double β-Decay

→ $m_{ee} \sim 0$, *But Still Potentially Large* $0\nu\beta\beta$!!

→ *Leading Contribution to* $0\nu\beta\beta$ *Independent of* m_ν

Experimental Constrains & Model Predictions

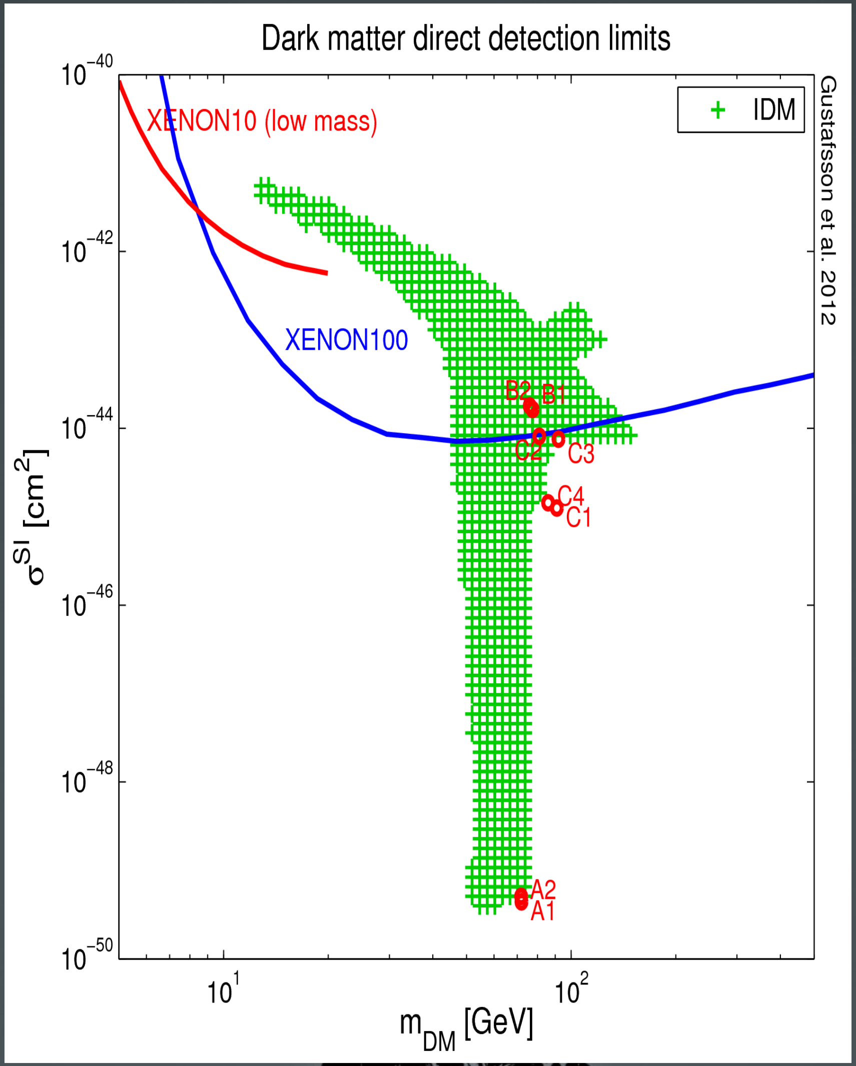
❻ *Dark Matter* (IDM)

→ ***Large Mass Splitting*** $m^2_{A_0} - m^2_{H_0}$

Disfavours Co-Annihilation

→ ***Direct Detection Bounds Impose*** m_{DM}

Close to Higgs Resonance or W Threshold



M. Gustafsson, S. Rydbeck, L. Lopez-Honorez and E. Lundstrom
Phys. Rev. D ***86*** *(2012) 075019*

Conclusions

Small ν Masses May be Connected to Dark Matter Stability

Properties of ν Sector and DM Sector Affected by this Connection:

→ ν_R ***as DM Candidate*** (Ma; Krauss, Nasri, Trodden)

NO Dark Matter Direct Detection Signal

→ ***Cocktail Model***

➔ ***Predicts Normal ν Mass Hierarchy & $0.011 < s^2_{13} < 0.035$***

➔ ***LFV Close to Current Experimental Limits***

➔ ***Collider Signatures at LHC & ILC (New charged States)***

➔ ***(Possibly) Large $0\nu\beta\beta$***

➔ ***DM Co-Annihilation Disfavoured ($m_{DM} \sim 60 - 65$ GeV?)***