Radiative Neutrino Masses

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But

- Why m_ν are so small?
- Why omit terms of the form $\overline{\nu_R^c} M \nu_R$ in the Lagrangian?

Effective Lagrangian Approach

If the all new particles are much heavier than m_Z their effect can be parametrized at low energies by an effective Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_i \left(\frac{C_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)} + \text{h.c.} \right)$$

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If $E \ll \Lambda$, effects of $\mathscr{O}_i^{(n)}$ suppressed by powers of E/Λ

Dominated by the lowest dimension operators.

Only a dimension 5 operator (Weinberg operator)

$$\mathscr{O}^{(5)} = (\overline{\tilde{L}_L}\Phi)(\tilde{\Phi}^\dagger L_L) \to -\frac{1}{2} v^2 \overline{\nu_L^c} \to (M_\nu)_{\alpha\beta} = C_{\alpha\beta}^{(5)} \frac{v^2}{\Lambda}$$

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If $C^{(5)} \sim 1$, to obtain $m_\nu < 1\,\text{eV}$ one needs $\Lambda > 10^{14}$ GeV

The See-Saw Models

Type I (fermion singlet ν_R as discussed)

$$C^{(5)} \approx Y_\nu Y_\nu^T, \qquad \Lambda = M$$

Type II (scalar triplet χ with $Y = 1$)

$$\mathscr{L}_\chi = -\left(\bar{\tilde{L}}_L Y_\chi \chi L_L - \mu \tilde{\Phi}^\dagger \chi^\dagger \Phi + \mathrm{h.c.}\right)$$

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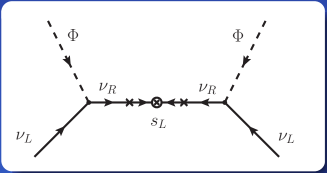
Type III (fermion triplet Σ with $Y=0$). Like Type I
Variation (Inverse see-saw): $3\nu_R$ and $3s_L$ fermion singlets



$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}, \quad \begin{array}{ccc} C^{(5)} & \approx & Y_\nu Y_\nu^T \frac{\mu}{M} \\ \Lambda & = & M \end{array}$$

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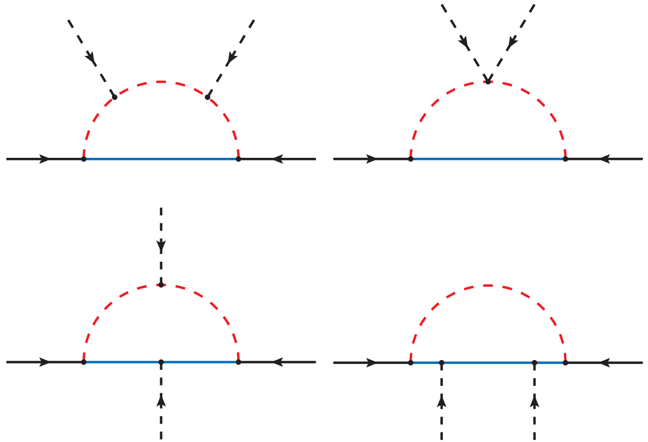
But, why should $C^{(5)} \ll 1$?
If there are no fields with the quantum numbers of the see-saw ν_R, χ, Σ masses cannot be generated at tree level
If LN is not conserved the Weinberg operator will be generated at one loop (or more).
Natural justification for $C^{(5)} \ll 1$

(Bonnet, Hirsch, Ota, Winter, '12)



Many possibilities

The Zee Model

Adds to the SM a scalar singlet h^+ and a new doublet Φ'
$h^+ \sim (1,1), \qquad \Phi' \sim (2, \frac{1}{2})$

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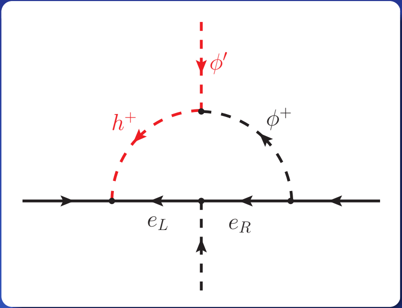

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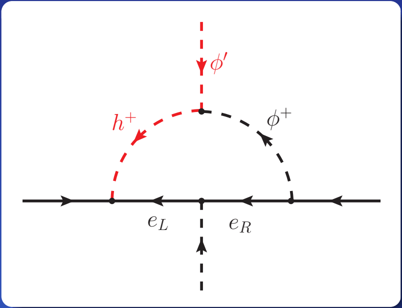

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- "Too predictive": excluded
- Type III 2HDM versions OK
  (Balaji, Grimus, Schwetz '01)
- $H \to \tau\mu$ linked to ν masses?
  (Herrero-Garcia, Rius, AS, '15,
  Herrero-Garcia, Wiren in preparation)
- Rich LFV phenomenology
  $(\mu \to e\gamma, \tau \to e\gamma, \dots)$

The Inert/Scotogenic Doublet

Add a fermion singlet s_R and scalar doublet η (Ma '06)

$$\mathscr{L}_Y = -\bar{L}_L Y_s \tilde{\eta} s_R - \frac{1}{2}\overline{s_R^c} M s_R - \lambda_5 \left(\Phi^\dagger \eta\right)^2 + \cdots + \text{h.c.}$$

Exact discrete symmetry: Weinberg operator at one loop.

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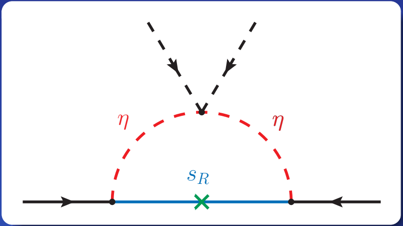

$$C^{(5)} \sim \frac{\lambda_5}{(4\pi)^2} Y_s Y_s^T \,, \quad \Lambda = M_h$$

- Charged particles could be seen in the LHC
- s_R or η's stable: good dark matter candidate

(Ma '06, Barbieri '06,
Lopez-Honorez, Nezri, Oliver, Tytgat '07)

The Zee-Babu Model

Add two scalar singlets h^+, k^{++} (Zee '86, Babu '88, Babu,Macesanu '03)
(Aristizabal,Hirsch '06, Nebot,Oliver,Palao,AS '08, Ohlsson,Schwetz,Zhang '09, Schmidt,Schwetz,Zhang '14)

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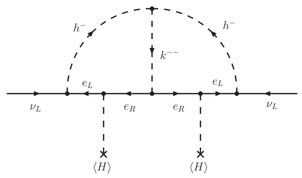

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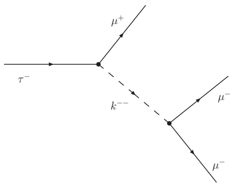
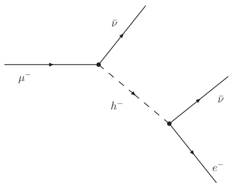
- Lightest ν is massless
- $f_{e\tau}/f_{\mu\tau}, f_{e\mu}/f_{\mu\tau}$ fixed from mixings

$\ell_a^- \to \ell_b^+ \ell_c^- \ell_d^-$: limits on g_{ab}



$\ell_a \to \ell_b \nu \bar{\nu}$: limits on f_{ab}



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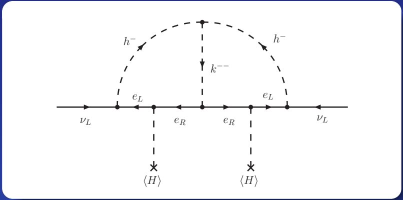

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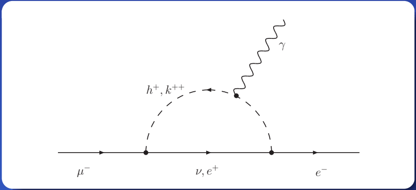
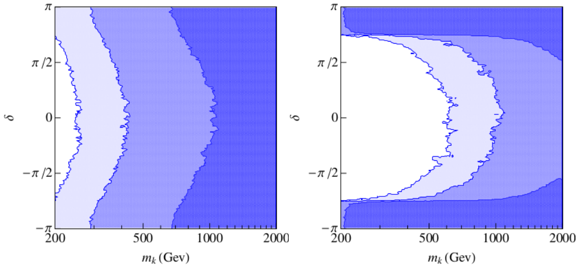
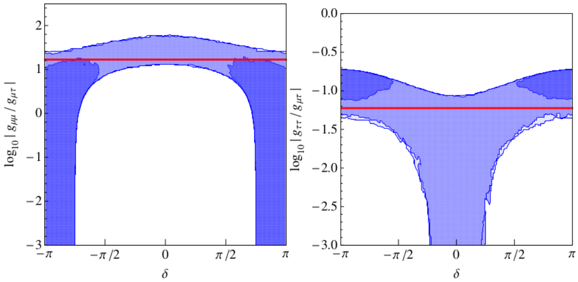
$\ell_a^- \to \ell_b^- \gamma$: bounds g_{ab} and f_{ab}



Constrained Parameter Space

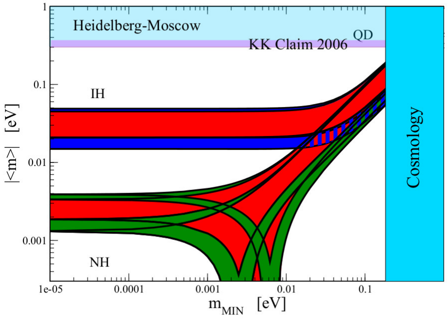
(Nebot,Oliver,Palao,AS ’08, Herrero-Garcia,Nebot,Rius,AS ’14)





m_ν Contribution to $0\nu\beta\beta$

Present:
$m_{\beta\beta} \lesssim 0.12$–$0.25\,\text{eV}$ (KamLAND-Zen, EXO-200, GERDA)
Future:
$m_{\beta\beta} \sim 0.01\,\text{eV}$ (KamLAND2-Zen,nEXO,GERDA2,CUORE,. . .)



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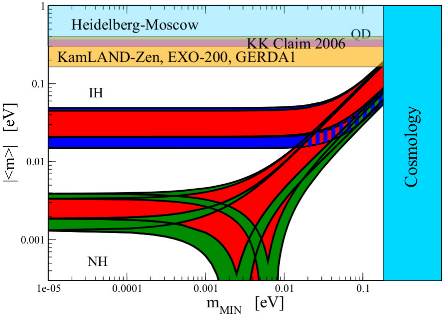

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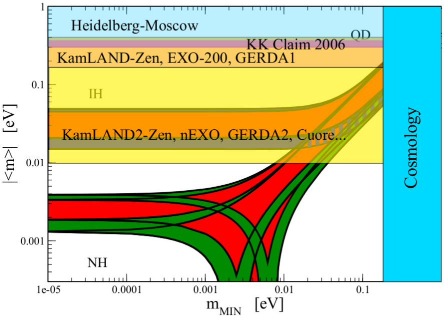

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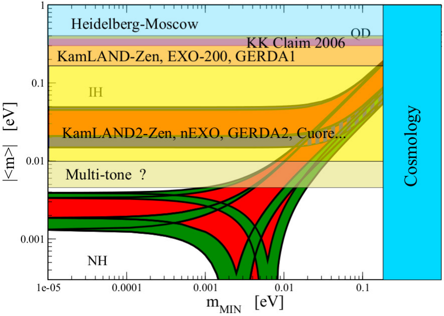
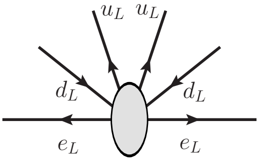


$0\nu\beta\beta$ Contribution to m_ν

$0\nu\beta\beta \Longrightarrow$ Majorana m_ν



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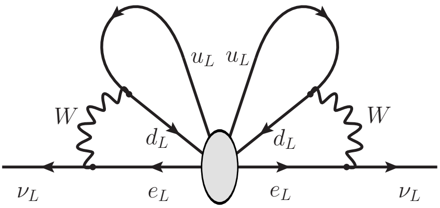

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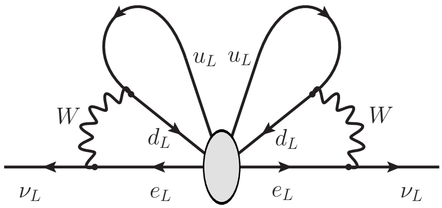

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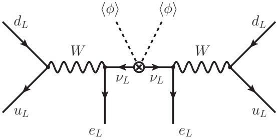
Fermion chirality

$$\text{Majorana}\,\nu: \quad \nu_L\nu_L\,, \qquad 0\nu\beta\beta: \begin{cases} e_Le_L \\ e_Le_R \\ e_Re_R \end{cases}$$

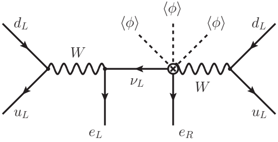
Operators Contributing to $0\nu2\beta$

(del Aguila, Aparici, Bhattacharya, AS, Wudka '12)



$$\mathcal{O}^{(5)} = \left(\overline{\tilde{L}_L}\phi\right)\left(\tilde{\phi}^\dagger L_L\right)$$

$$\mathcal{A}^{(5)}_{0\nu2\beta} \sim \frac{C^{(5)}_{ee}}{\Lambda p^2_{\text{eff}} v^2}$$



$$\mathcal{O}^{(7)} = \left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger \overline{e_{\text{R}}}\gamma^\mu \tilde{L}_L\right)$$

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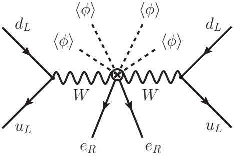


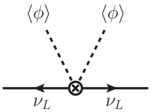
$$\mathcal{O}^{(9)} = \overline{e_{\text{R}}} e^c_{\text{R}} \left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger D^\mu \tilde{\phi}\right)$$

$$\mathcal{A}^{(9)}_{0\nu2\beta} \sim \frac{C^{(9)}_{ee}}{\Lambda^5}$$

Contribution to ν Masses

Neutrino masses

$\mathcal{O}^{(5)}$



$$(m_\nu)_{ab} \sim \frac{v^2}{\Lambda} C^{(5)}_{ab}$$

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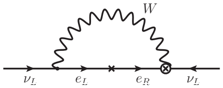

$$\frac{v}{16\pi^2\Lambda}\left(m_a C^{(7)}_{ab} + m_b C^{(7)}_{ba}\right)$$

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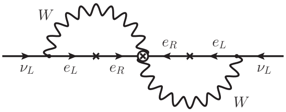

$$\frac{1}{(16\pi^2)^2\Lambda} m_a C^{(9)}_{ab} m_b$$

An Example of RR-type Model

3 new scalars $\chi \sim (3,1)$, $\kappa \sim (1,2)$,$\sigma \sim (1,0)$ and Z_2 symmetry

$$\mathscr{L} = g_{\alpha\beta}\, \overline{e^c_{\alpha\mathrm{R}}} e_{\beta\mathrm{R}}\, \kappa - \mu_\kappa\, \kappa \mathrm{Tr}\left\{\chi^\dagger \chi^\dagger\right\} - \lambda_6\, \sigma\, \phi^\dagger \chi \tilde{\phi} + \cdots$$

- No new fermions $\Longrightarrow$ No see-saw I-III
- No $\chi L_L L_L$ coupling (Z_2 symmetry) $\Longrightarrow$ No see-saw II

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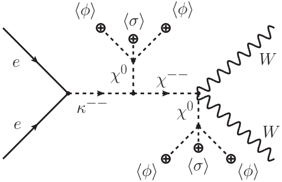
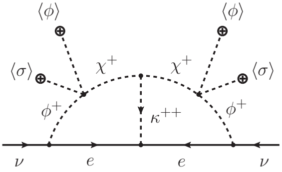
The $0\nu2\beta$ Operator



The neutrino mass



An Example of RR-type Model

3 new scalars $\chi \sim (3,1)$, $\kappa \sim (1,2)$,$\sigma \sim (1,0)$ and Z_2 symmetry

$$\mathscr{L} = g_{\alpha\beta}\, \overline{e^c_{\alpha\mathrm{R}}}\, e_{\beta\mathrm{R}}\, \kappa - \mu_\kappa\, \kappa \mathrm{Tr}\left\{\chi^\dagger \chi^\dagger\right\} - \lambda_6\, \sigma\, \phi^\dagger \chi \tilde{\phi} + \cdots$$

- No new fermions $\Longrightarrow$ No see-saw I-III
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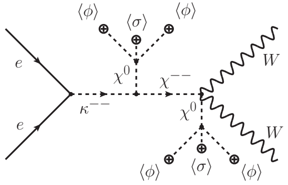

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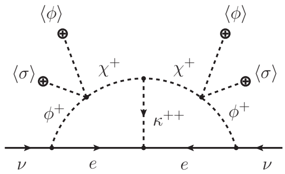


Variations (Gustafsson, No, Rivera, '13 and '14): If Z_2 exact

- $0\nu\beta\beta$ at one loop and m_ν at three loops
- Dark matter candidate

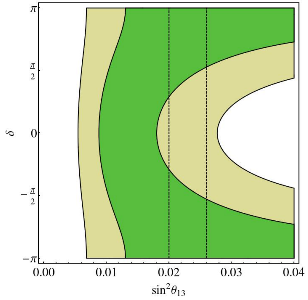
Constraints on the ν Mass Matrix

- Large $0\nu\beta\beta$: relatively large g_{ee} and small scalar masses
- $(M_\nu)_{ee}$ highly suppressed by the factor m_e^2
- $(M_\nu)_{e\mu}$ also suppressed because the $\mu \to 3e$ bound on $g_{e\mu}$

ν mass matrix highly constrained

$$|m_\nu| = \begin{pmatrix} < 10^{-4} & < 10^{-4} & \sim 0.01 \\ < 10^{-4} & \sim 0.01 & \sim 0.01 \\ \sim 0.01 & \sim 0.01 & \sim 0.01 \end{pmatrix} \text{eV}$$

- Only NH allowed
- Predicction for $m_{\text{light}} \sim 0.004\,\text{eV}$
- Prediction for $\sin^2\theta_{13}$



2012: $\sin^2\theta_{13} \sim 0.02 - 0.026$

Conclusions

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- New contributions to $0\nu2\beta$

Thanks for your attention

BACKUP SLIDES