Making a Cocktail:

Neutrino masses, 0νββ-decay, dark matter and flavor mixing

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@Nordita, Stockholm, May 26th, 2014

Open Questions

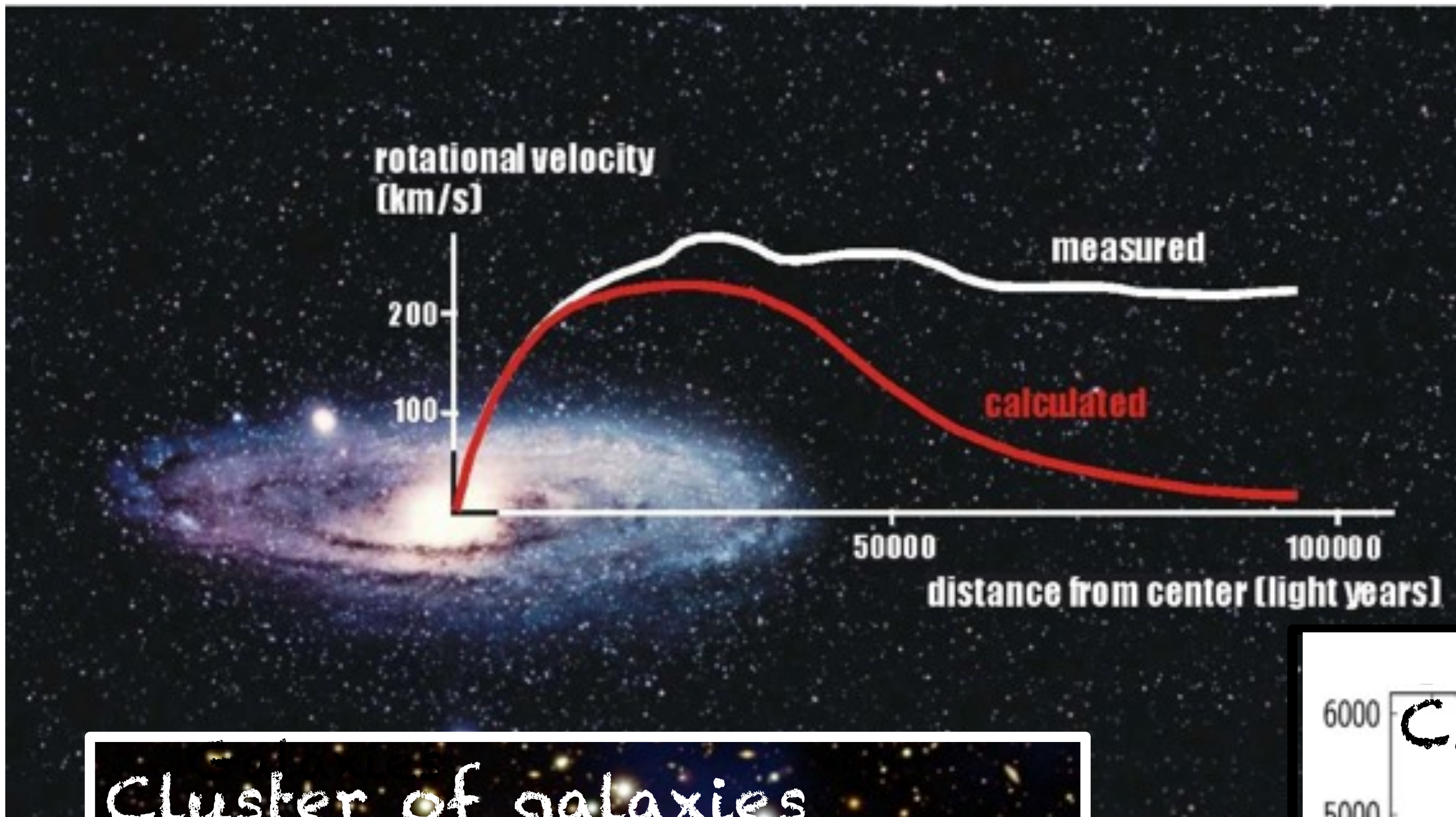
- Neutrinos
  - What mechanism gives masses to neutrinos?
  - Are neutrinos Dirac or Majorana particle?
  - What is the origin of flavor mixing structures?

- Dark Matter
  - What is the dark matter (particle)?
    - Few properties known, and many candidates

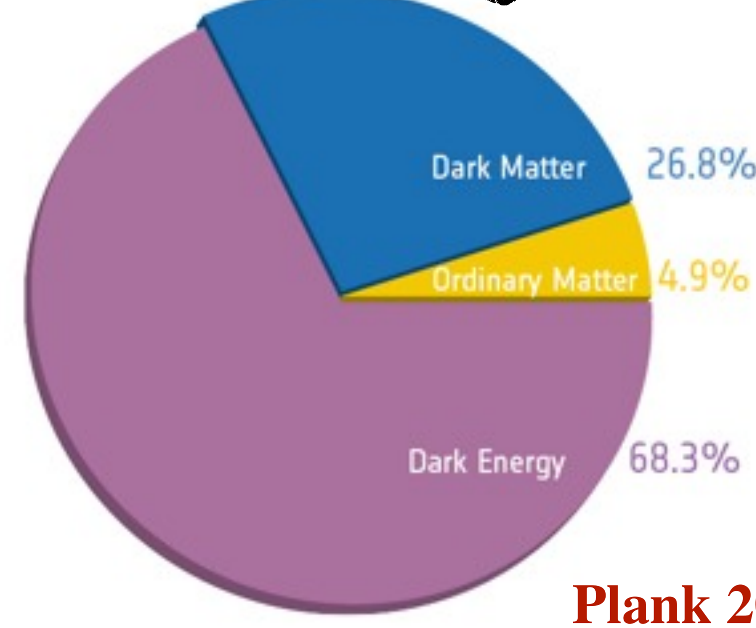
- Want to create a model that relates above questions and is within experimental reach

Dark Matter Evidences

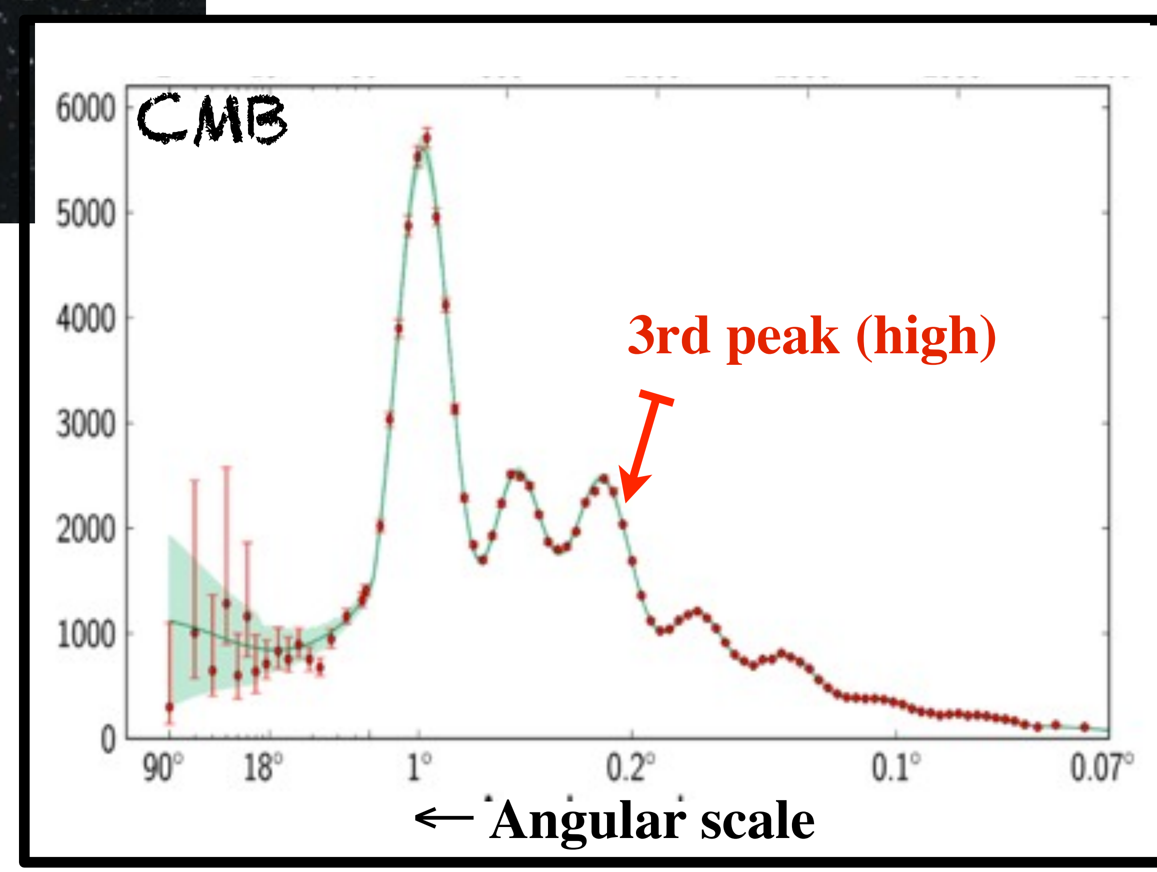
Galaxies



Universe budget



Plank 2014



New ‘Dark’ particle → Physics beyond the SM required

Neutrino Oscillations → Neutrino Masses

Flavor Eigenstates

$$\nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix}$$

$$j^{\rho}_{W,L} = 2\,\overline{\nu_L}\,\gamma^{\rho}\,\ell_L$$

Propagation

Oscillations

Mass Eigenstates

$$\mathbf{n} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathscr{L}^{M} = \frac{1}{2}\,\overline{\mathbf{n}}\,(i\partial\!\!\!/ - M)\,\mathbf{n}$$

$$\nu_L = U\,\mathbf{n}_l$$

PMNS matrix (Pontecorvo-Maki-Nakawa-Sakata)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

Mixing Angles: Atmospheric | reactor + CP phase δ_{13} | Solar | (2 Majorna phases)

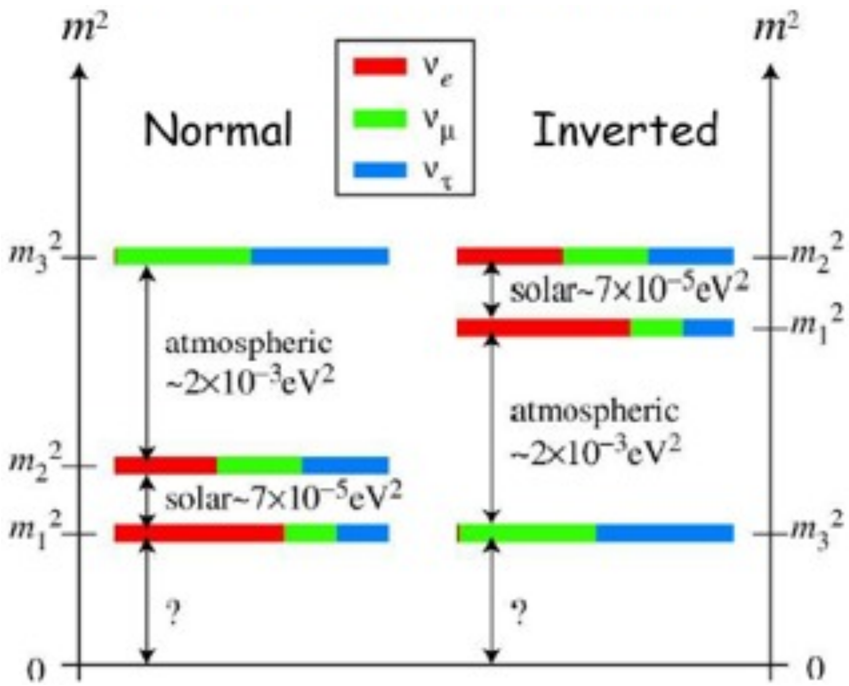
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

Osc. probability

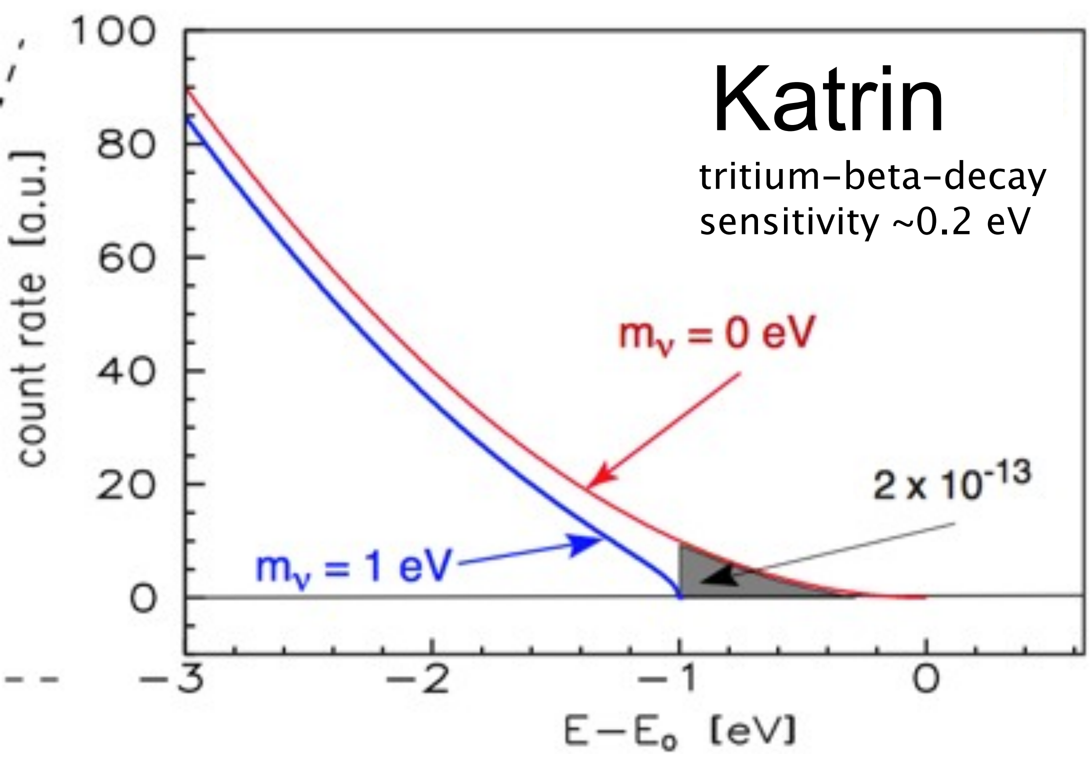
Propagation in vacuum

m_ν=0 in the SM → Physics beyond the SM required

Absolute Mass Scales



- Normal *or* Inverted mass ordering for the neutrinos?



- Mainz experiment:

$$m_{\nu_e} < 2.3 \text{ eV}$$

Kraus *et al*.
Eur.Phys.J.C40:447-468,2005

- Cosmological constraints:

$$\sum m_\nu \lesssim 1 \text{ eV}$$

Planck

Building a Predictive Model

Building a Predictive Model

Ingredients:

1. Neutrino mass?

Generating a Neutrino Mass

$$\lambda_\nu \lesssim 10^{-12}$$

DIRAC MASS $\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \text{h.c.}$

EWSB $\rightarrow$ $-m_e \bar{e}_L e_R - m_D \bar{\nu}_L N_R + \text{h.c.}$

And Impose lepton no. conservation

but now nothing forbids breaking of lepton no

MAJORANA (→lepton number violation):

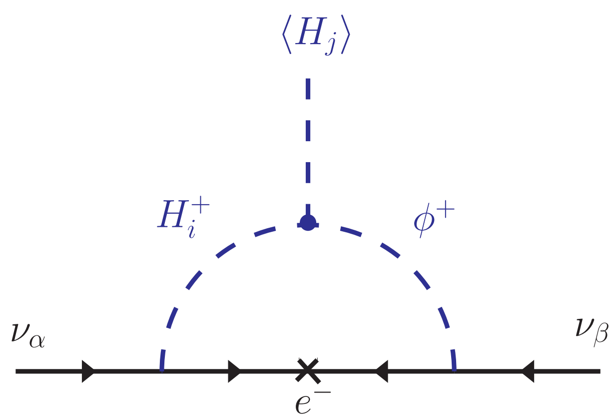
$$\mathcal{L} \supset -\lambda_l \bar{L_L} \phi l_R - \lambda_\nu \bar{L_L} \tilde{\phi} N_R - \frac{1}{2} M_R \bar{N}_R^c N_R + h.c.$$

Breaks lepton number, Δ=2

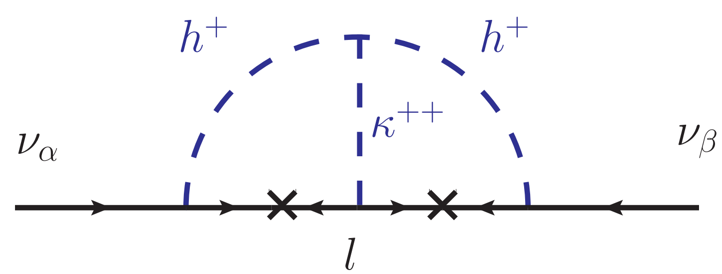
See-Saw Mechanism

RADIATIVELY

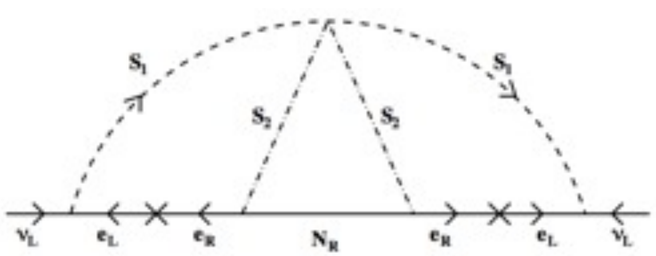
New states in loops



A. Zee, **Phys. Lett. B 93** (1980) 389
(L. Wolfenstein, **Nucl. Phys. B175**, 93(1980))

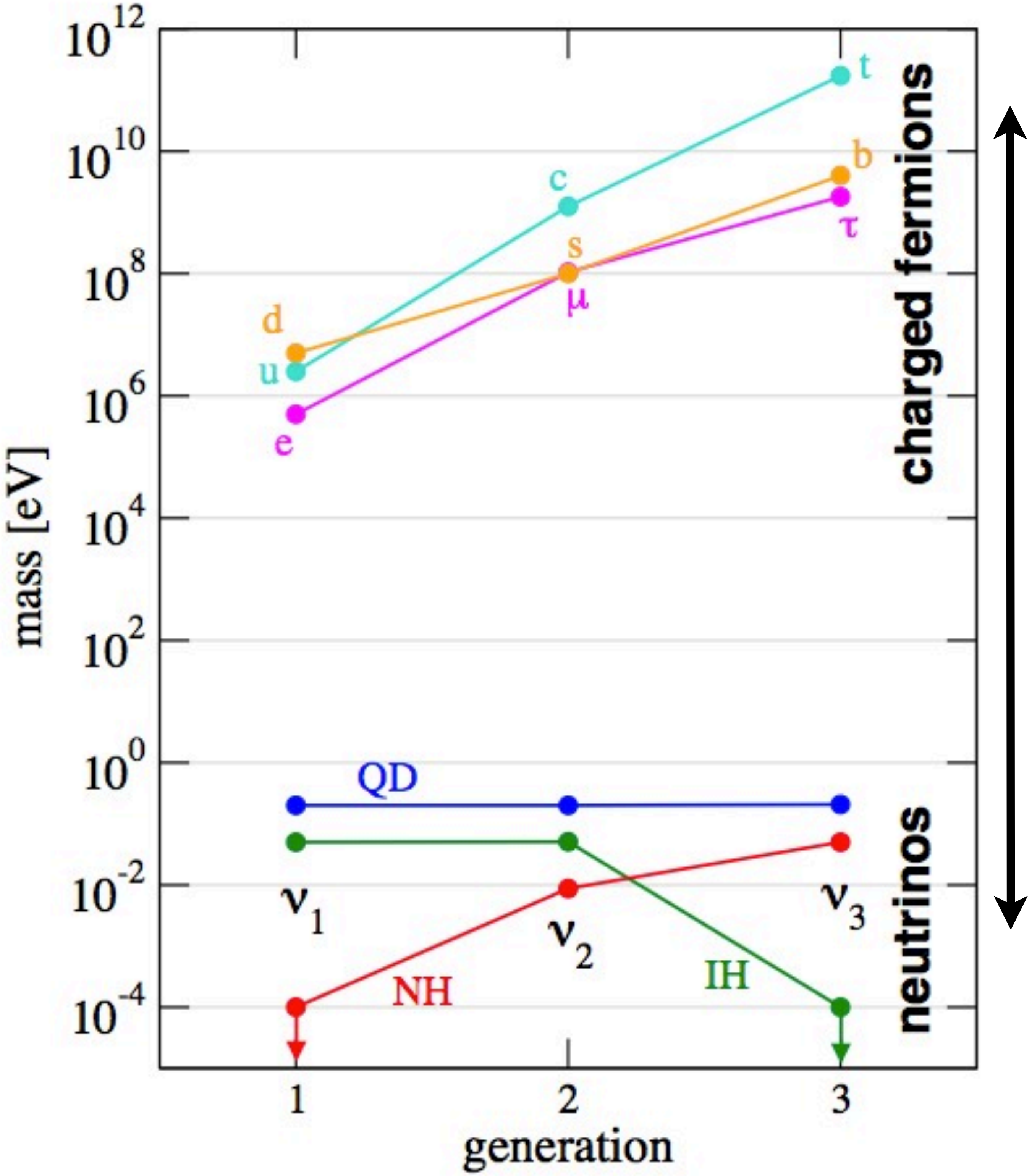


A. Zee, **Nucl. Physics. B 264** (1986) 99
K. S. Babu, **Phys. Lett. B 203** (1988) 132



L. M. Krauss, S. Nasri, M Trodden, **Phys.Rev. D67** (2003) 0850024

Mass hierarchy



- Neutrino masses tiny
  $m_\nu / vev \sim 10^{-13}$
- See-saw mechanism with couplings of ~1 gives: $m_D \sim M_{GUT} \sim 10^{16}$ GeV
- Electroweak scale (~*vev*) being loop suppressed?
  3-loops w/ gauge couplings:

$$(g^2/16\pi^2)^3 \sim 10^{-13}$$

Suggestive: a 3-loop suppression to naturally explains the hierarchy

Building a Predictive Model

Ingredients:

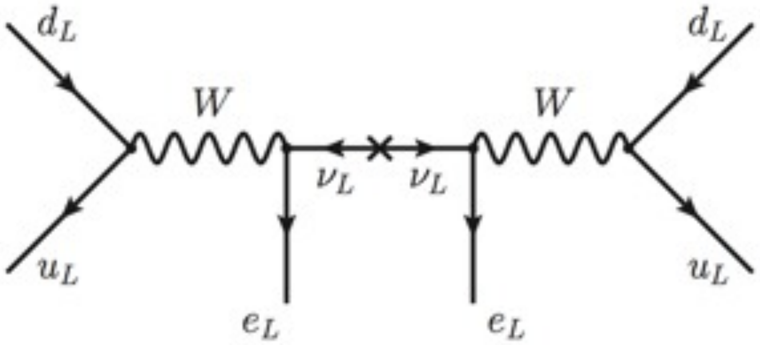
1. Neutrino mass radiatively (at 3-loops)
2. A large 0νββ-decay signal?

Majorana or Dirac?

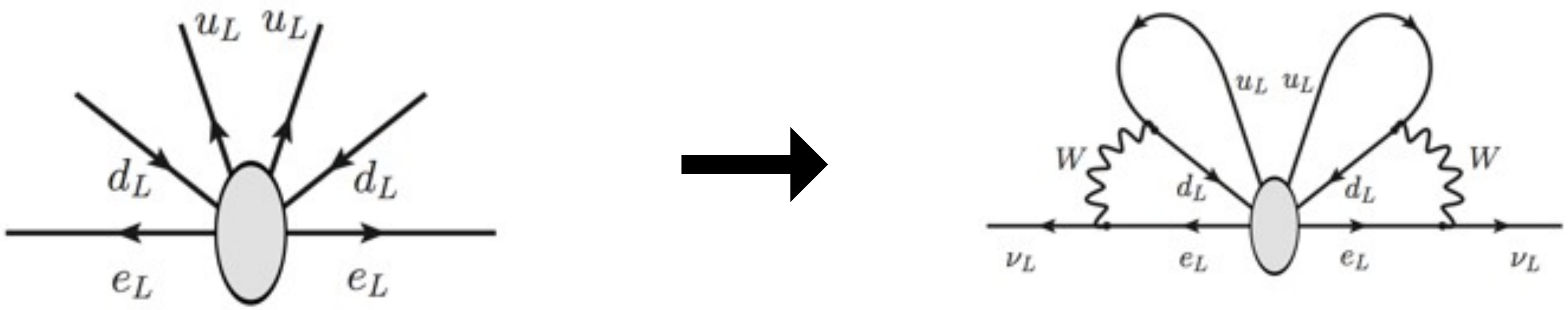
- Majorana neutrino → neutrinoless double-beta decay $0\nu\beta\beta$

2n → 2p + 2e⁻

(Does not exist in the SM)

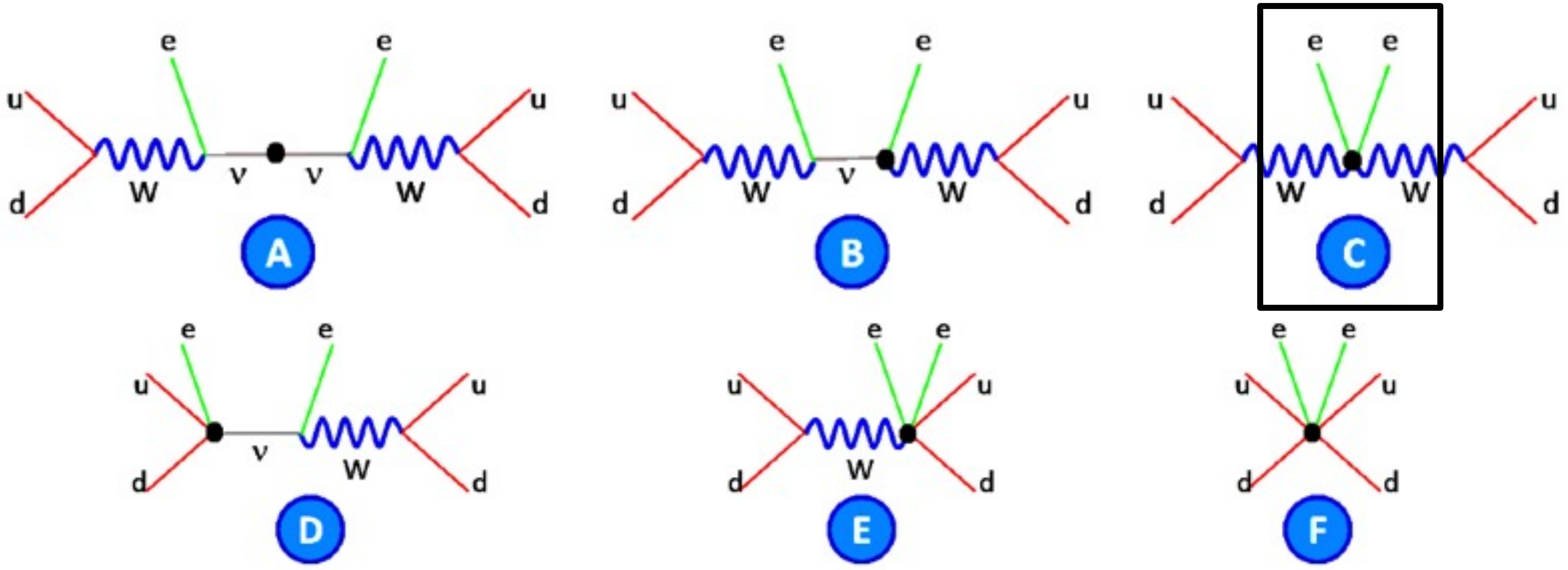


- Neutrinoless double-beta decay → Majorana neutrino mass (contribution)

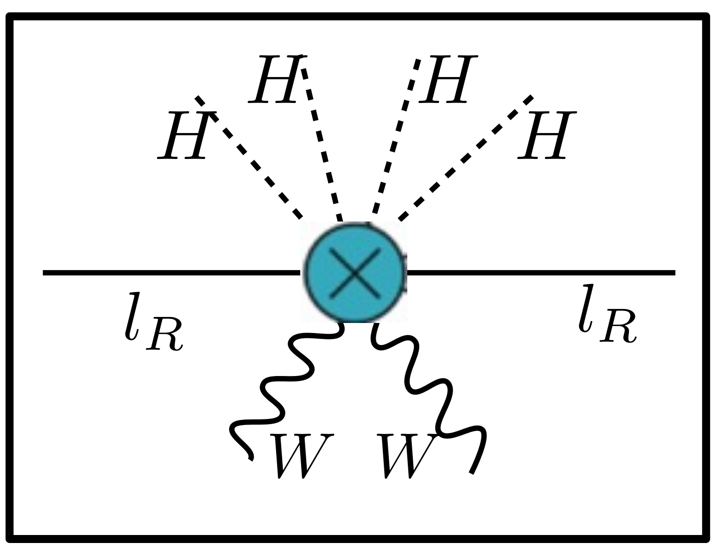


The exact connection depend on the underlying model

Effective operators for 0νββ



- If new physics does not couple directly to quarks
  → then we do not need to consider: **D-F**
- Remarkably, for **A-C** there are only 3 possible lowest-order gauge invariant LNV operators:



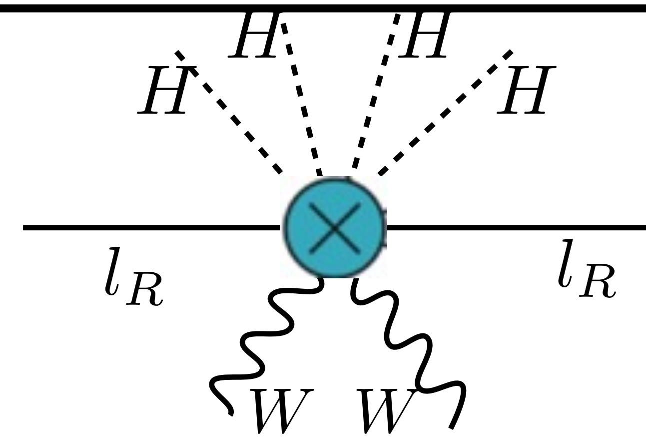
$$\mathcal{O}^{(5)} = (\overline{\tilde{\ell}_L}\phi)(\tilde{\phi}^\dagger \ell_L),$$ **LL**

$$\mathcal{O}^{(7)} = (\phi^\dagger D^\mu \tilde{\phi})(\phi^\dagger \overline{e_R}\gamma_\mu \tilde{\ell}_L),$$ **RL**

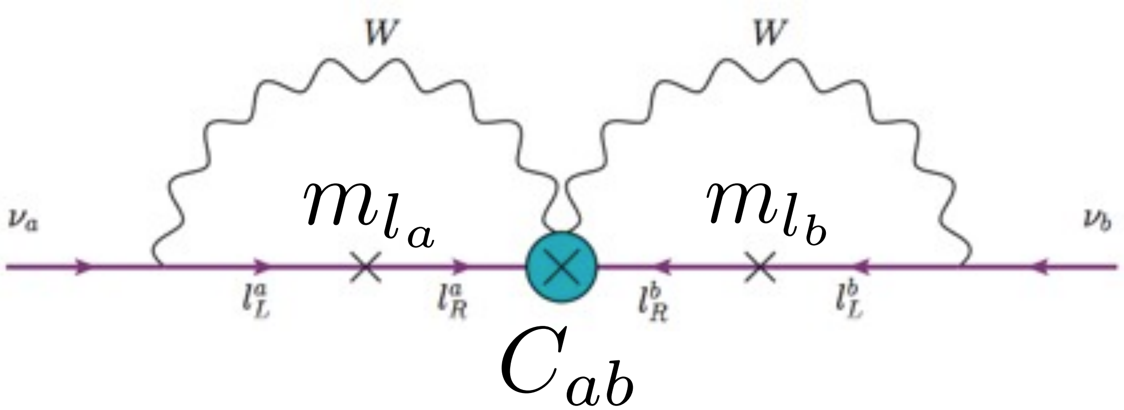
$$\mathcal{O}^{(9)} = \overline{e_R} e_R^c (\phi^\dagger D^\mu \tilde{\phi})(\phi^\dagger D_\mu \tilde{\phi})$$ **RR**

Steven Weinberg **Phys.Rev.Lett 43** (1979) 1566
F. del Aguila, A. Aparici, S. Bhattacharya, A. Santamaria and J. Wudka, **JHEP 1205** (2012) 133
F. del Aguila, A. Aparici, S. Bhattacharya, A. Santamaria and J. Wudka, **JHEP 1206** (2012) 146

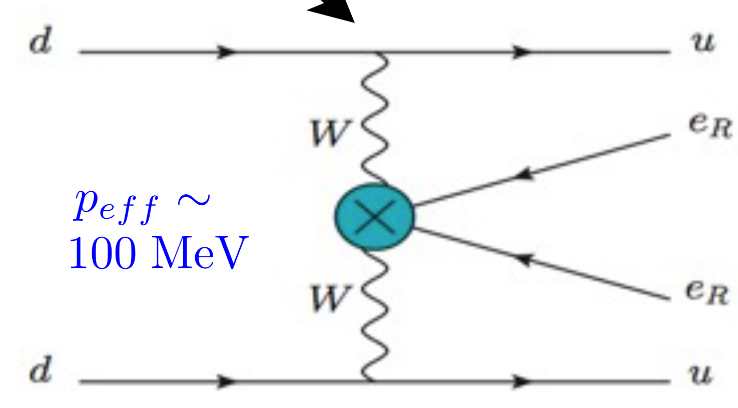
$$\mathcal{O}^{(9)}_{ab} = \bar{l}_{Ra} l^c_{Rb} (\phi^\dagger D_\mu \tilde{\phi})^2$$



Neutrino mass

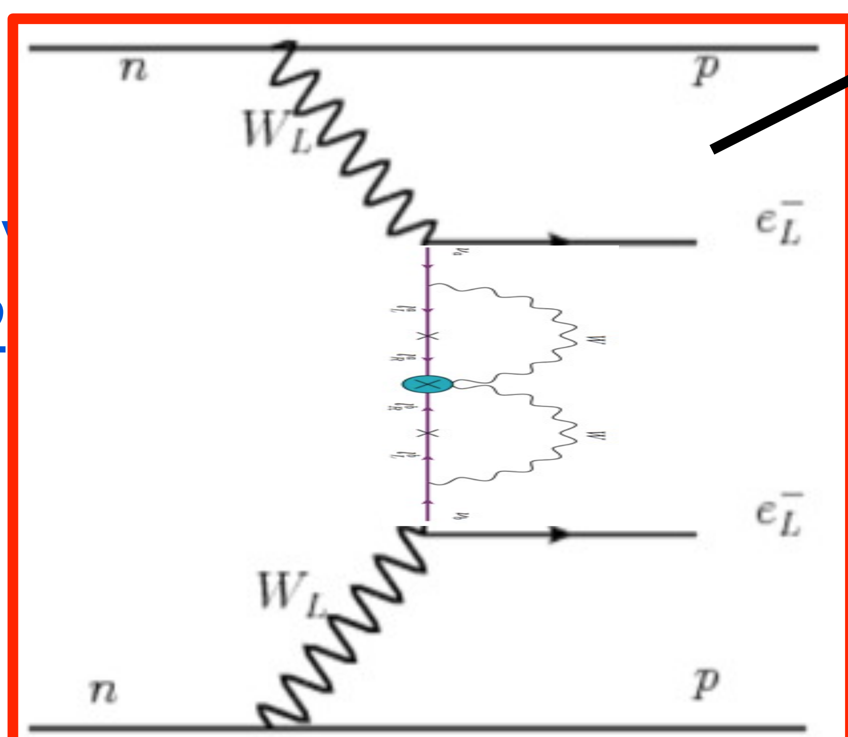


0νββ decay



$$m^\nu_{ab} \sim \left(\frac{1}{16\,\pi^2}\right)^2 C^{(9)}_{ab}\, \frac{m_{l_a} m_{l_b}}{\Lambda}$$

radiati
at 2



Short range $\mathcal{A}^{\rm SD}_{0\nu\beta\beta} \sim \dfrac{G_F^2 v^4 C^{(9)}_{ee}}{\Lambda^5}$

Long range $\mathcal{A}^{\nu}_{0\nu\beta\beta} \sim \dfrac{G_F^2}{p^2_{eff}} |m^\nu_{ee}|$

$$\frac{\mathcal{A}^{\rm SD}}{\mathcal{A}^\nu} \sim \left(16\pi^2 \frac{v^2}{\Lambda^2} \frac{p_{eff}}{m_e}\right)^2 \sim 10^9$$

Enhanced 0νββ:
2n → 2p + 2e⁻

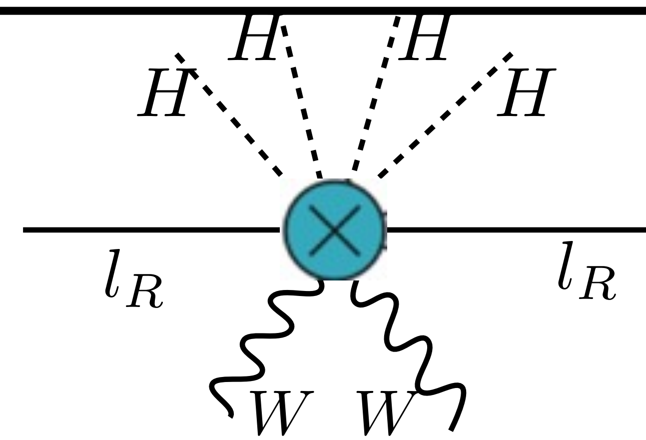
(if $\Lambda <$ 30 TeV)

Building a Predictive Model

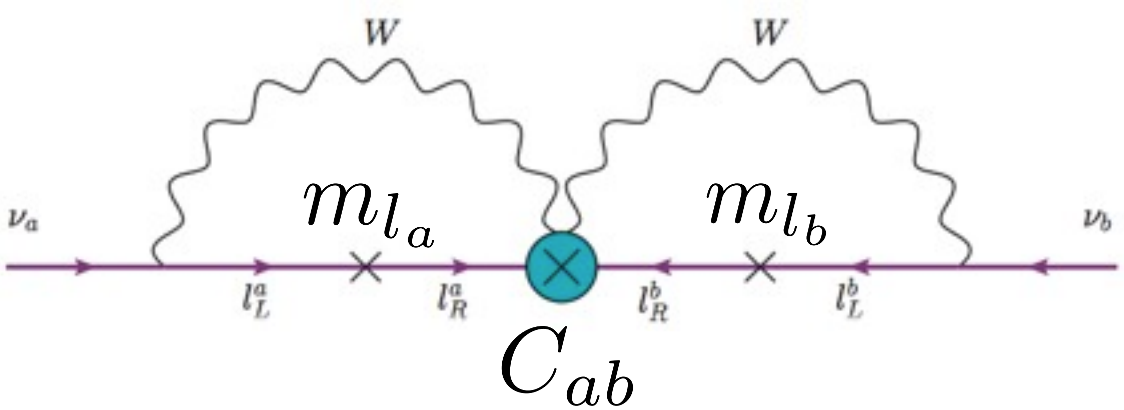
Ingredients:

1. Neutrino mass radiatively at 3-loops
2. A large $0\nu\beta\beta$-decay signal
3. Predictions for Flavor Mixing Structures and Neutrino Mass Hierarchy?

$$\mathcal{O}^{(9)}_{ab} = \bar{l}_{Ra} l^c_{Rb} (\phi^\dagger D_\mu \tilde{\phi})^2$$



Neutrino mass



$$m^\nu_{ab} \sim \left(\frac{1}{16\,\pi^2}\right)^2 C^{(9)}_{ab} \frac{m_{l_a} m_{l_b}}{\Lambda}$$

proportional to the charged lepton masses

radiative neutrino masses at 2-loops (or more)

for example

$$m_e^2 \ll m_\tau^2$$

$$m^\nu_{ab} = \begin{pmatrix} \sim 0 & \sim 0 & m_{e\tau} \\ \sim 0 & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

~Texture Zero

P. H. Frampton, S. L. Glashow and D. Marfatia, Phys. Lett. B 536 (2002) 79
W. Guo and Z. Xing, Phys. Rev. D 67 (2003) 053002
A. Merle and W. Rodejohann, Phys. Rev. D 73 (2006) 073012
S. Dev. S. Kumar, S. Verma and S. Gupta, Phys. Rev. D 76 (2007) 013002
H. Fritzsch. Z. Xing and S. Zhou, JHEP 1109 (2011) 083
P. O. Ludl, S. Morisi and E. Peinado, Nucl. Phys B 857 (2012) 411 ...

Mass Matrix Structure → Flavor Mixing Structure

$$m^\nu = U^T \, m^\nu_D \, U \qquad \text{with} \qquad m^\nu_D = \mathrm{Diag}\,(m_1, m_2, m_3)$$

PMNS matrix

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

flavor basis

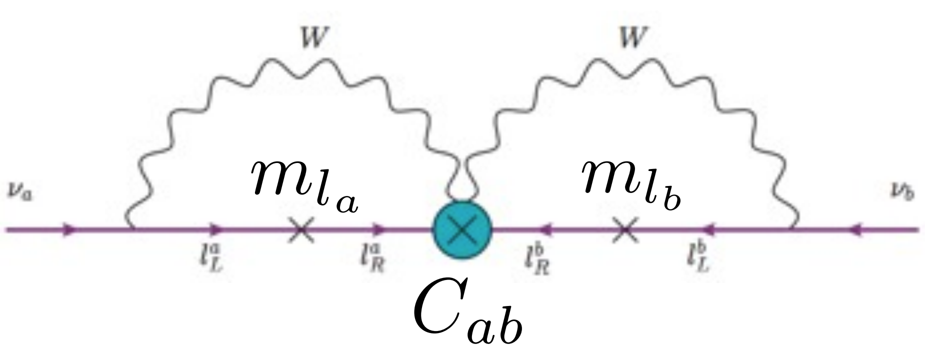
Neutrino osc. data		
	$s^2_{13} = 0.017 - 0.29$	$\Delta m^2_{21} \equiv m^2_2 - m^2_1 = 7.0 - 8.1 \times 10^{-5}\mathrm{eV}^2$
	$s^2_{23} = 0.37 - 0.66$	$\lvert\Delta m^2_{31}\rvert \equiv \lvert m^2_3 - m^2_1\rvert = 2.2 - 2.6 \times 10^{-3}\mathrm{eV}^2$
	$s^2_{12} = 0.27 - 0.35$	$\delta = 0 - 360^\circ, \quad \alpha_1, \alpha_2 = \text{unknown}$

$s_{ab} := \sin(\theta_{ab})$

Two of the matrix elements

$$m^\nu_{ee} \equiv c^2_{13}\left(m_1 c^2_{12} + e^{2i\alpha_1} m_2 s^2_{12}\right) + e^{2i\alpha_2} m_3 s^2_{13} = 0,$$

$$m^\nu_{e\mu} \equiv c_{13}\left[\left(e^{2i\alpha_1} m_2 - m_1\right) s_{12}c_{12}c_{23} + e^{i\delta} s_{23}s_{13}\left(e^{2i\alpha_2} m_3 - m_1 c^2_{12} - e^{2i\alpha_1} m_2 s^2_{12}\right)\right] = 0$$



$$m^{ab}_\nu = \begin{pmatrix} 0 & 0 & m_{e\tau} \\ 0 & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

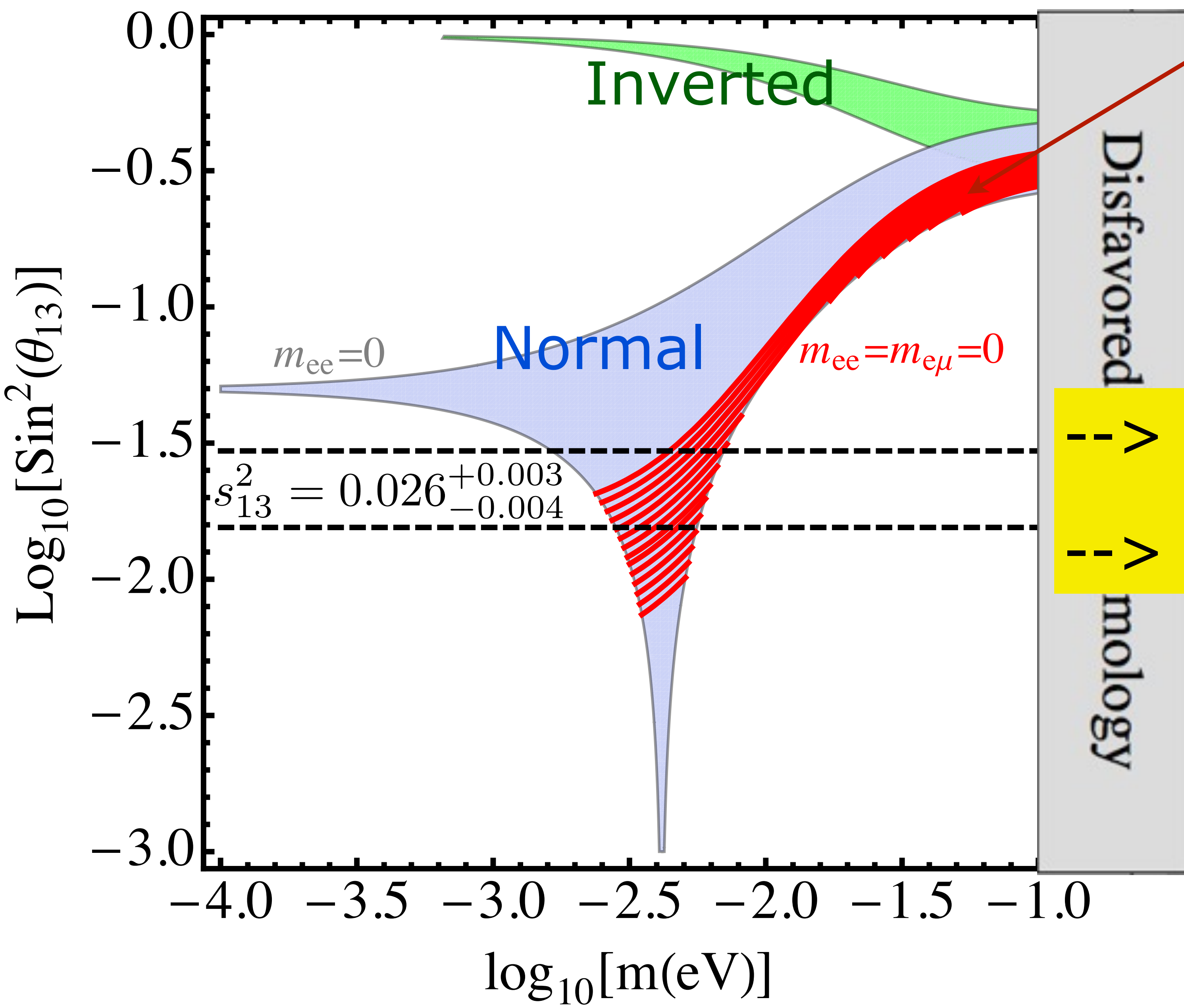
$m_{ee} = m_{e\mu} = 0$ →Flavor Mixing Structure

$$\cos\delta = -\frac{t_{23}^2(1-t_{12}^4)+t_{12}^2(1+t_{23}^2 t_{12}^2 - t_{13}^{-2})\frac{\Delta m_{21}^2}{\Delta m_{31}^2}}{2 s_{13} t_{12} t_{23}(1+t_{12}^2 - t_{12}^2 \frac{\Delta m_{21}^2}{\Delta m_{31}^2})}$$

$$m_1^2 = \frac{\Delta m_{31}^2 s_{13}^2 \left(s_{13}^2 + t_{12}^2 t_{23}^2 - 2 s_{13} t_{12} t_{23}\right)}{c_{13}^4 - s_{13}^2(s_{13}^2 + t_{12}^2 t_{23}^2 - 2 s_{13} t_{12} t_{23}\cos\delta)}$$

with unknown CP phase δ ->

$$|\cos\delta| \leq 1$$



--> Predict Normal Ordering

--> with m_ν ~ 0.005 eV

$m_{ee} = m_{e\mu} = 0$ →Flavor Mixing Structure

$$\cos\delta = -\frac{t_{23}^2(1-t_{12}^4)+t_{12}^2(1+t_{23}^2t_{12}^2-t_{13}^{-2})\frac{\Delta m_{21}^2}{\Delta m_{31}^2}}{2s_{13}t_{12}t_{23}(1+t_{12}^2-t_{12}^2\frac{\Delta m_{21}^2}{\Delta m_{31}^2})}$$

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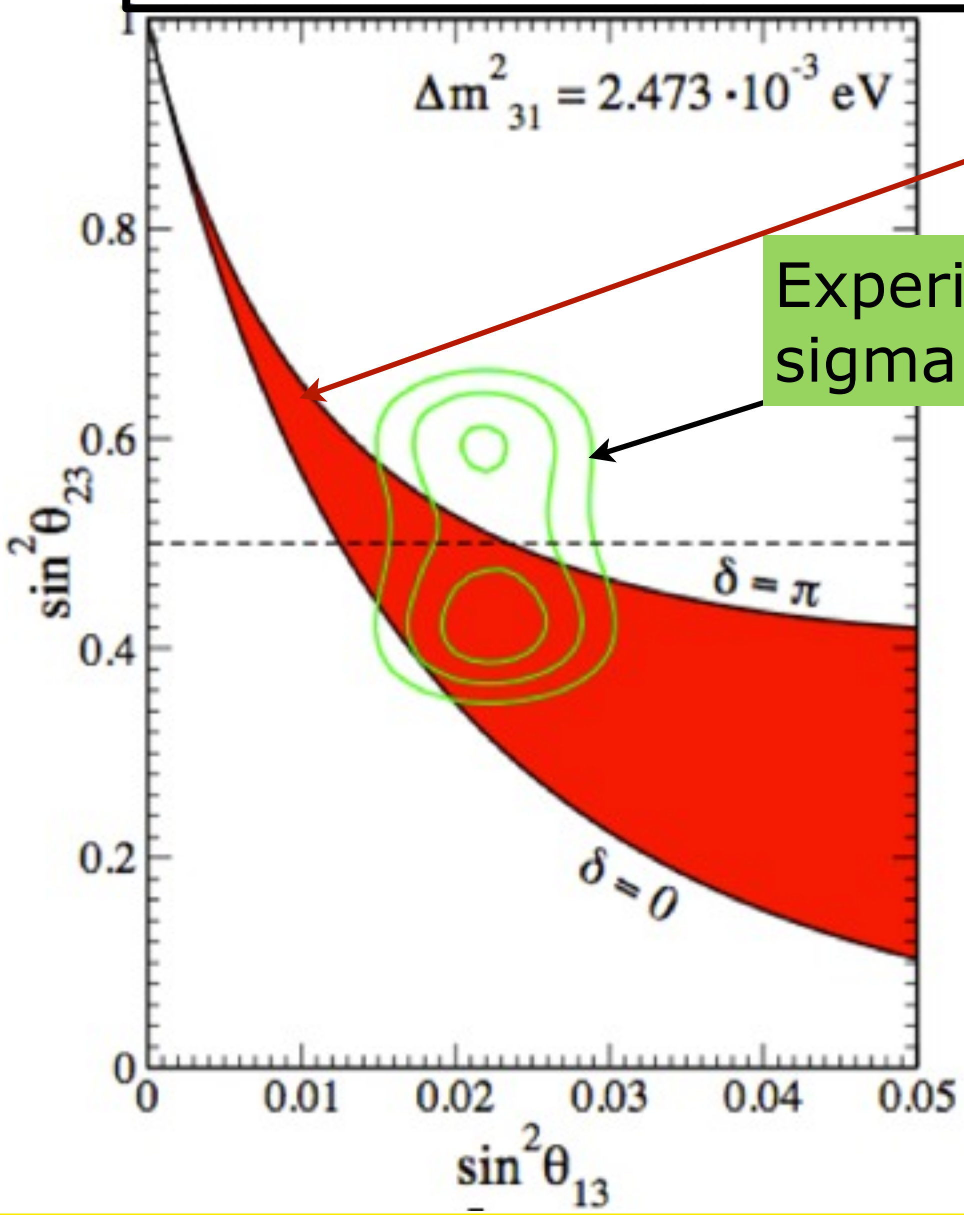
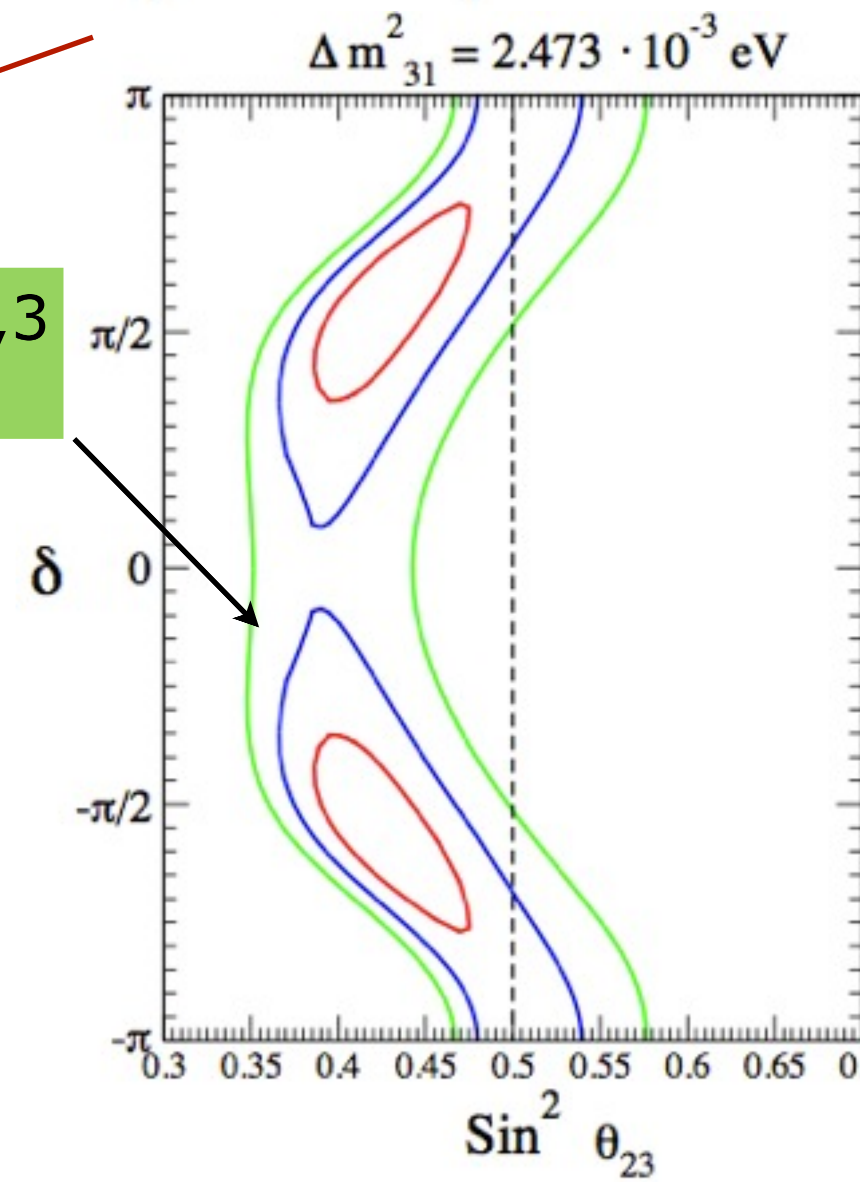


Experimental 1,2,3 sigma contours



--> Links the values of θ_{13} and octant of θ_{23}

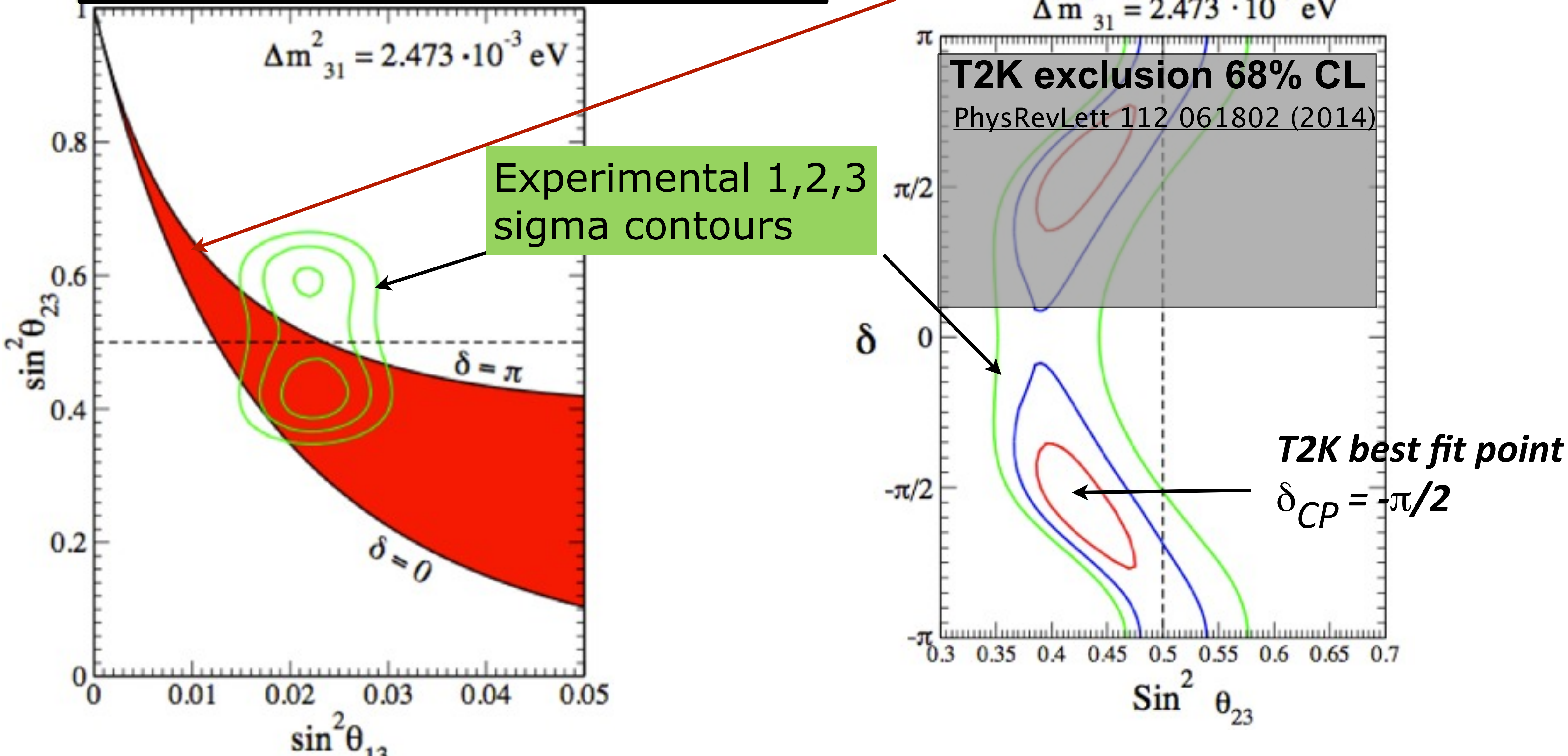
-->Predict δ if θ_{13} and θ_{23} are given

$m_{ee} = m_{e\mu} = 0$ → Flavor Mixing Structure

$$\cos\delta = -\frac{t_{23}^2(1-t_{12}^4)+t_{12}^2(1+t_{23}^2 t_{12}^2 - t_{13}^{-2})\frac{\Delta m_{21}^2}{\Delta m_{31}^2}}{2 s_{13} t_{12} t_{23}(1+t_{12}^2 - t_{12}^2\frac{\Delta m_{21}^2}{\Delta m_{31}^2})}$$

with unknown CP phase δ ->

$$|\cos\delta| \leq 1$$



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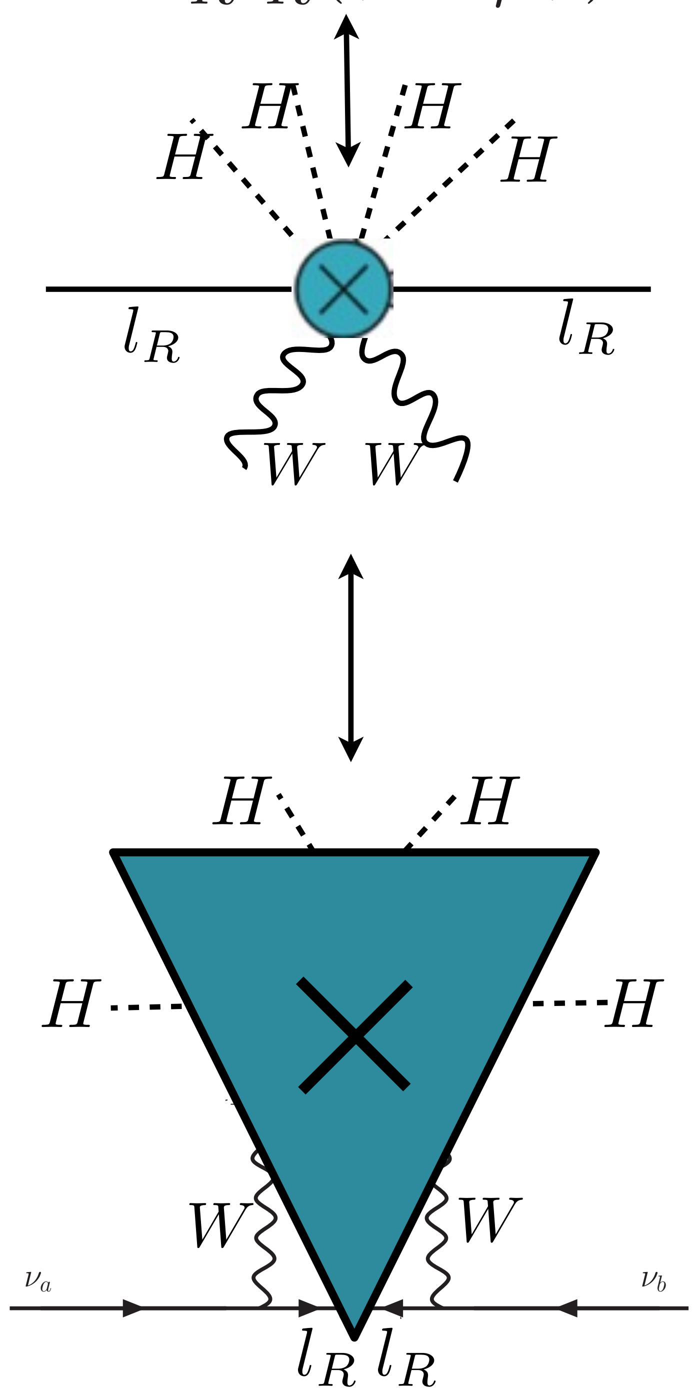
2. A large $0\nu\beta\beta$-decay signal
3. Predictions for Flavor Mixing Structures and Neutrino Mass Hierarchy
4. Dark Matter Candidate

Creating a Cocktail Model

Effective operator

$$\mathcal{O}^{(9)} = \bar{l}_R l_R^c (\phi^\dagger D_\mu \tilde{\phi})^2$$



❑ Concrete realization of ⊗ requires:

- lepton number violating interactions
- couplings to W-bosons and RH leptons
- New states at electroweak scale with *O*(1) couplings – so that a 1-loop realization give correct m_ν masses

❑ A possible realization:

- Add singlet ρ^{++} to couple to RH leptons
- Add singlet S^+ → m_ν at 2-loop (Zee/Babu) → avoided by imposing a Z_2 parity on S^+
- Add SU(2) scalar doublet ϕ_2 to mix with S^+ (Z_2 odd) and couple to W boson
- Unbroken Z_2 → new stable and EW interacting states → WIMP candidate?

↖ Ingredient no 4.

The Cocktail Model

The Field Content

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG_0}{\sqrt{2}} + v \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+i\,A_0}{\sqrt{2}} \end{pmatrix}, \quad S^+, \quad \rho^{++}$$

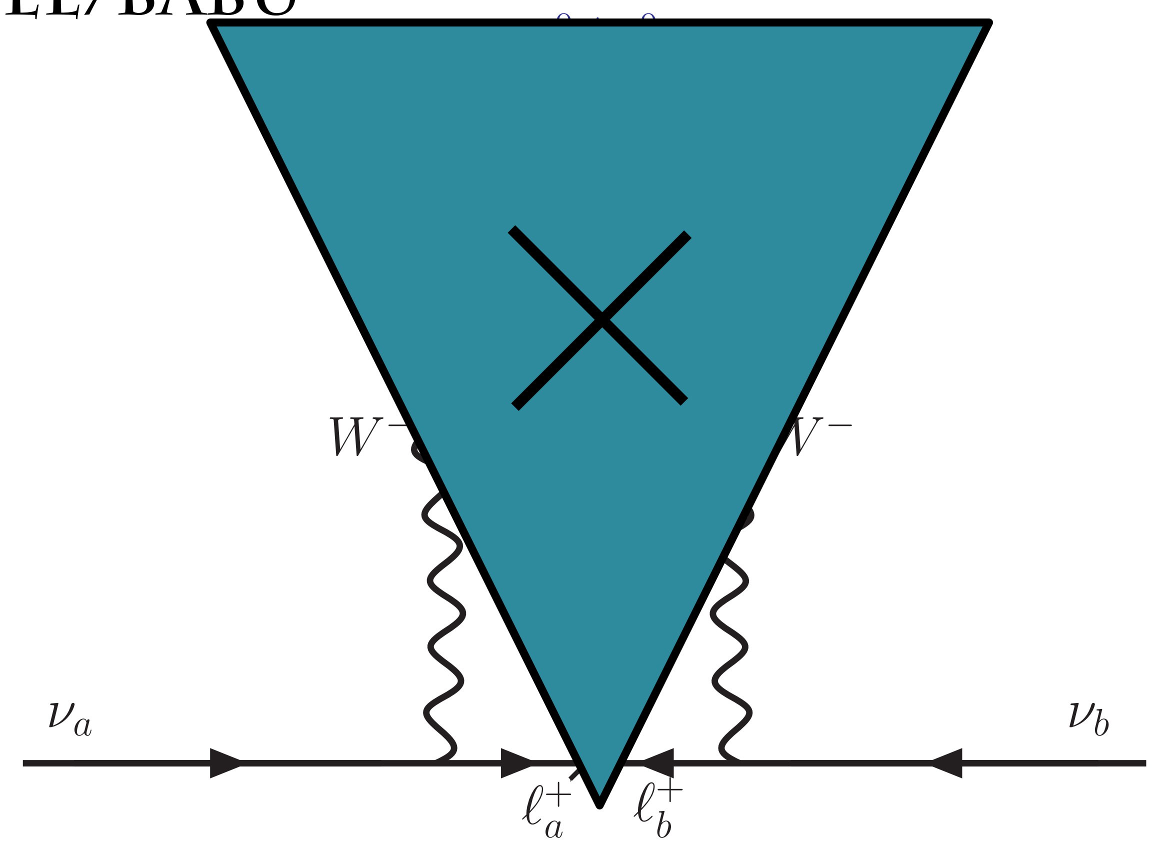
Z_2 parity: +   −   −   +

INERT DOUBLET MODEL & INSPIRED BY ZEE/BABU

The Lagrangian

$$-\Delta\mathcal{L} = C_{ab} l^{\bar{c}}_{R_a} l_{R_b} \rho^{++} + \kappa_1 \Phi_2^T i\sigma_2 \Phi_1 S^- + \kappa_2 \rho^{++} S^- S^- + \frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + \xi \Phi_2^T i\sigma_2 \Phi_1 S^+ \rho^{--} + h.c.$$

$$+\lambda_4 |\Phi_1^\dagger \Phi_2|^2 + V(|\Phi_1|^2, |\Phi_2|^2, |S|^2, |\rho|^2)$$



For $\kappa_1 \neq 0 \to S^+ - \Lambda^+$ mixing:

$$H_1^+ = s_\beta S^+ + c_\beta \Lambda^+$$

$$H_2^+ = c_\beta S^+ - s_\beta \Lambda^+$$

The Cocktail Model

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$$+\lambda_4 |\Phi_1^\dagger \Phi_2|^2 + V(|\Phi_1|^2, |\Phi_2|^2, |S|^2, |\rho|^2)$$

For $\kappa_1 \neq 0 \to S^+ - \Lambda^+$ mixing:

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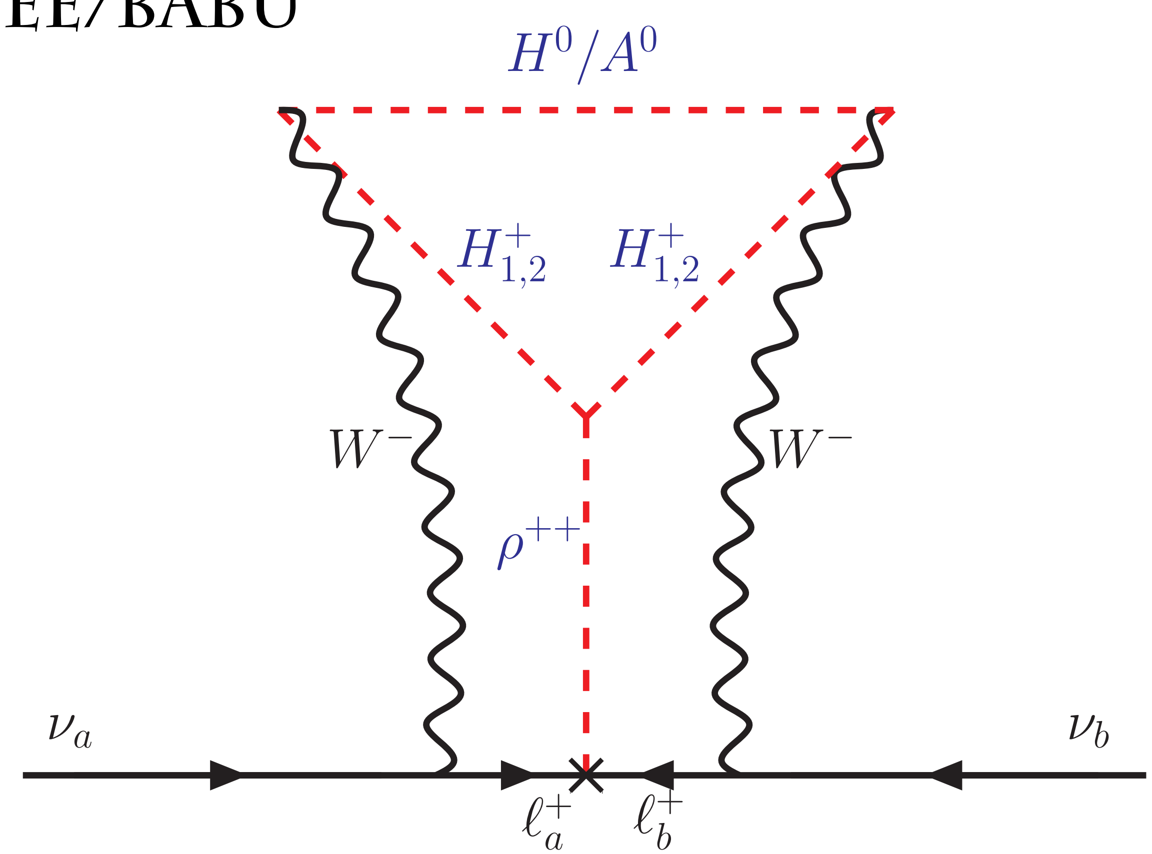


Neutrino mass at 3-loops

The Cocktail Model

The Field Content

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG_0}{\sqrt{2}} + v \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+i\,A_0}{\sqrt{2}} \end{pmatrix}, \quad S^+, \quad \rho^{++}$$

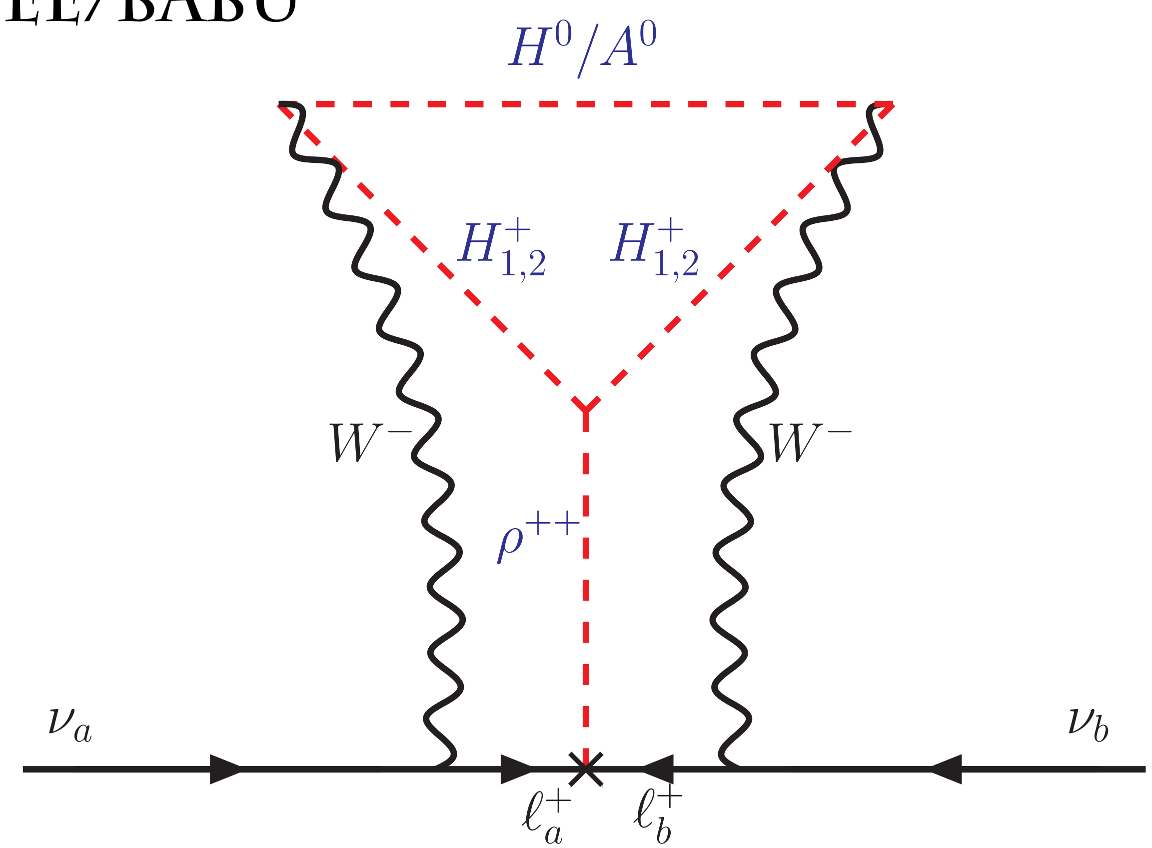
Z_2 parity: + − − +

INERT DOUBLET MODEL & INSPIRED BY ZEE/BABU

The Lagrangian

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

$$+\lambda_4 |\Phi_1^\dagger \Phi_2|^2 + V(|\Phi_1|^2, |\Phi_2|^2, |S|^2, |\rho|^2)$$



Lepton number violation:

$C_{ab}, \lambda_5, (\kappa_1) \neq 0$ and one of $\kappa_2, \xi \neq 0$
to break lepton number $+\lambda_{l_a} \overline{L_{L_a}} \phi_1\, l_{R_a}$

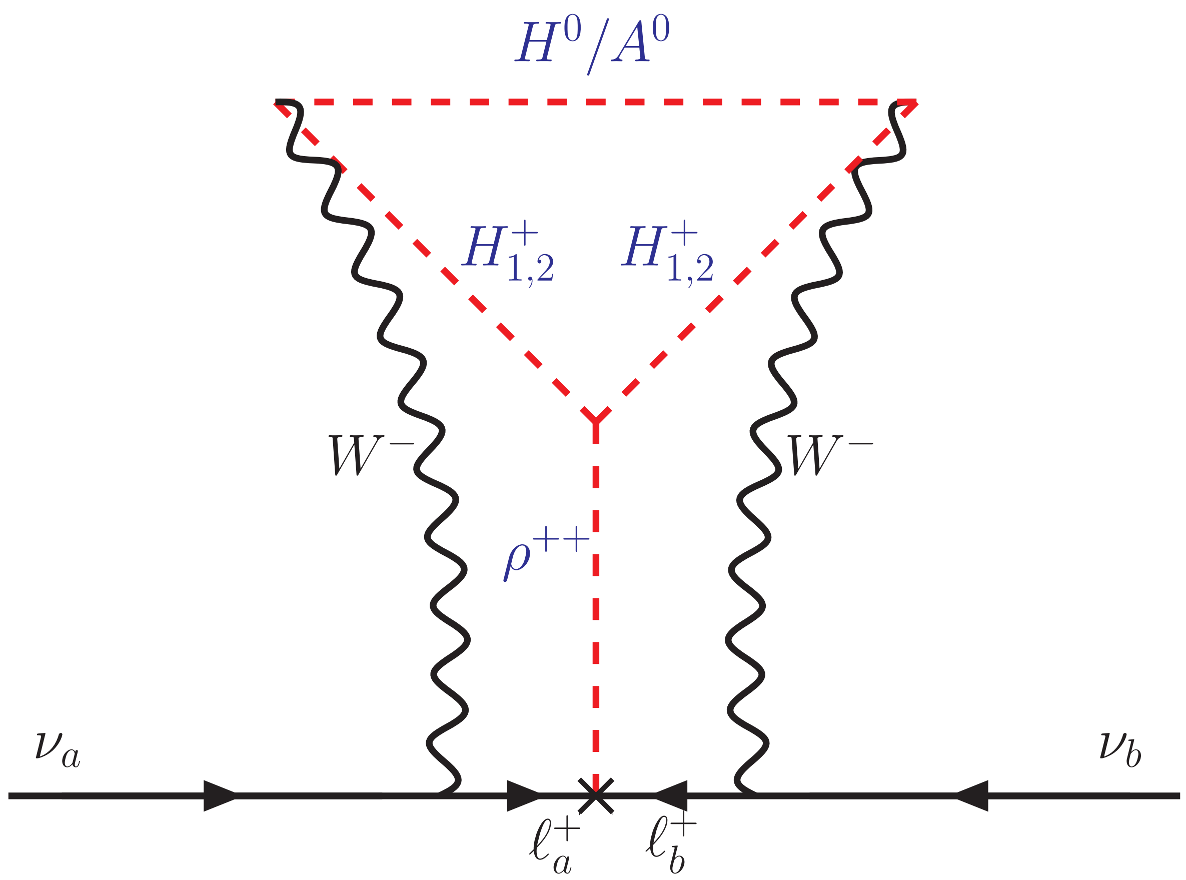
Neutrino mass at 3-loops

3-loop calculation

The loop mass is

Charged lepton masses

$$m^{\nu}_{ab} = C_{ab} m_a m_b \frac{s_{2\beta}}{(16\pi^2)^3} \times (A_1\, I_1 + A_2\, I_2)$$



$$A_1 = \frac{M_W^4}{2v^4} (\Delta m_+^2)^2 \Delta m_0^2 \left[\kappa_2 s_{2\beta} + \xi v\, c_{2\beta}\right]$$

$$A_2 = \frac{M_W^4}{2v^4} \Delta m_+^2 \Delta m_0^2\, \xi v$$

"GIM" mechanisms

$$\Delta m_0^2 = m_{A_0}^2 - m_{H_0}^2 \propto \lambda_5$$

$$\Delta m_+^2 = m_{H_2^+}^2 - m_{H_1^+}^2 \propto \kappa_1$$

$$I_1 = \int \frac{d^4k\, d^4q\, d^4l}{\pi^6} \frac{\mathcal{F}_2(k,q,l)}{D_{11}}$$

$$I_2 = \int \frac{d^4k\, d^4q\, d^4l}{\pi^6} \frac{\tilde{\mathcal{F}}_2(k,q,l)}{D_{10}}$$

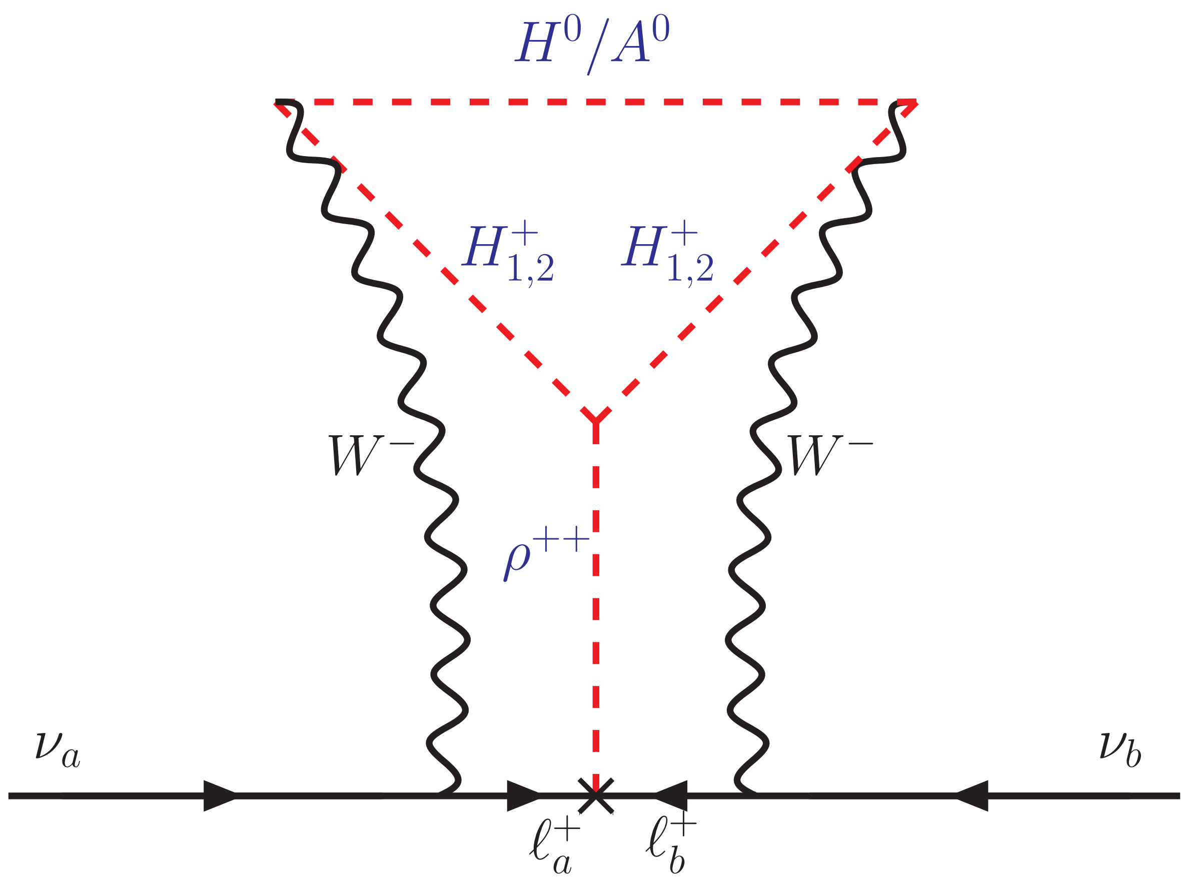
Partly Numerically evaluated (using SeCDec)

3-loop calculation

The loop mass is

Charged lepton masses

$$m^{\nu}_{ab} = C_{ab}\,\overline{m_a m_b}\,\frac{s_{2\beta}}{(16\pi^2)^3}$$
$$\times\left(A_1\, I_1 + A_2\, I_2\right)$$



$$A_1 = \frac{M_W^4}{2v^4}(\Delta m_+^2)^2\Delta m_0^2\left[\kappa_2 s_{2\beta} + \xi v\, c_{2\beta}\right]$$

$$A_2 = \frac{M_W^4}{2v^4}\,\underline{\Delta m_+^2}\,\underline{\Delta m_0^2}\,\xi v$$

$$I_1 = \int \frac{d^4k\, d^4q\, d^4l}{\pi^6}\,\frac{\mathcal{F}_2(k,q,l)}{D_{11}}$$

$$I_2 = \int \frac{d^4k\, d^4q\, d^4l}{\pi^6}\,\frac{\tilde{\mathcal{F}}_2(k,q,l)}{D_{10}}$$

$$I_1 \simeq \frac{1}{(1.88v)^8}\times\left(\frac{m_{H_0}}{70\text{ GeV}}\right)^{-0.03}\left(\frac{m_{A_0}}{475\text{ GeV}}\right)^{-0.4}\left(\frac{m_{H_1^+}}{90\text{ GeV}}\right)^{-0.2}\left(\frac{m_{H_2^+}}{850\text{ GeV}}\right)^{-2.0}\left(\frac{m_\rho}{2\text{ TeV}}\right)^{-1.5}\times\mathcal{I}_1,$$

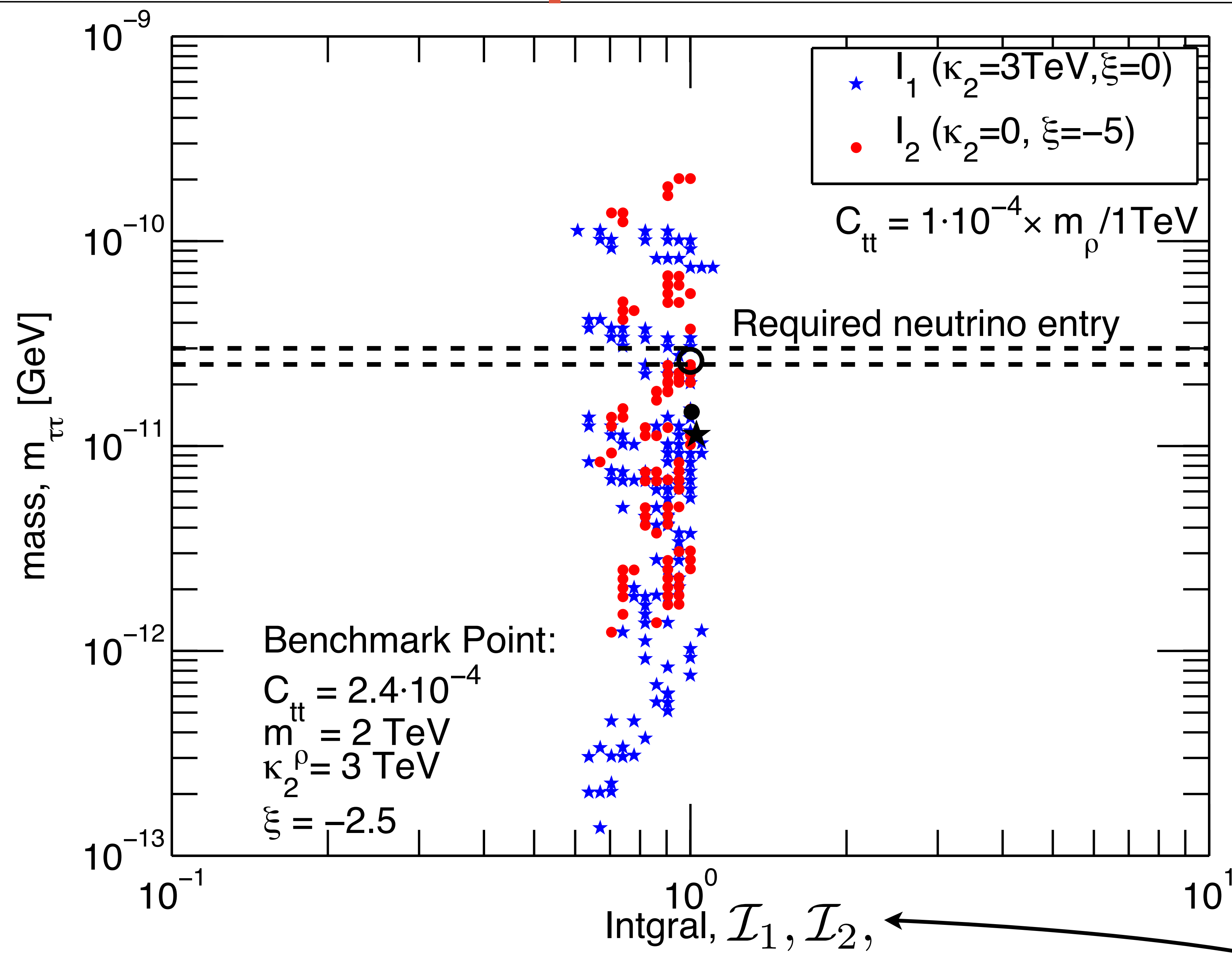
$$I_2 \simeq \frac{-1}{(0.95v)^6}\times\left(\frac{m_{H_0}}{70\text{ GeV}}\right)^{-0.03}\left(\frac{m_{A_0}}{475\text{ GeV}}\right)^{-0.4}\left(\frac{m_{H_1^+}}{90\text{ GeV}}\right)^{-0.04}\left(\frac{m_{H_2^+}}{850\text{ GeV}}\right)^{-0.6}\left(\frac{m_\rho}{2\text{ TeV}}\right)^{-0.9}\times\underline{\mathcal{I}_2}$$

empirical scaling

$\mathcal{O}(1)$

3-loop calculation

Neutrino mass



The calculation also done independently thanks to D. Huang, L. H. Tsai and C. Q. Geng

$$I_1 \simeq \frac{1}{(1.88v)^8} \times \left(\frac{m_{H_0}}{70\text{ GeV}}\right)^{-0.03} \left(\frac{m_{A_0}}{475\text{ GeV}}\right)^{-0.4} \left(\frac{m_{H_1^+}}{90\text{ GeV}}\right)^{-0.2} \left(\frac{m_{H_2^+}}{850\text{ GeV}}\right)^{-2.0} \left(\frac{m_\rho}{2\text{ TeV}}\right)^{-1.5} \times \mathcal{I}_1,$$

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empirical scaling

$\mathcal{O}(1)$

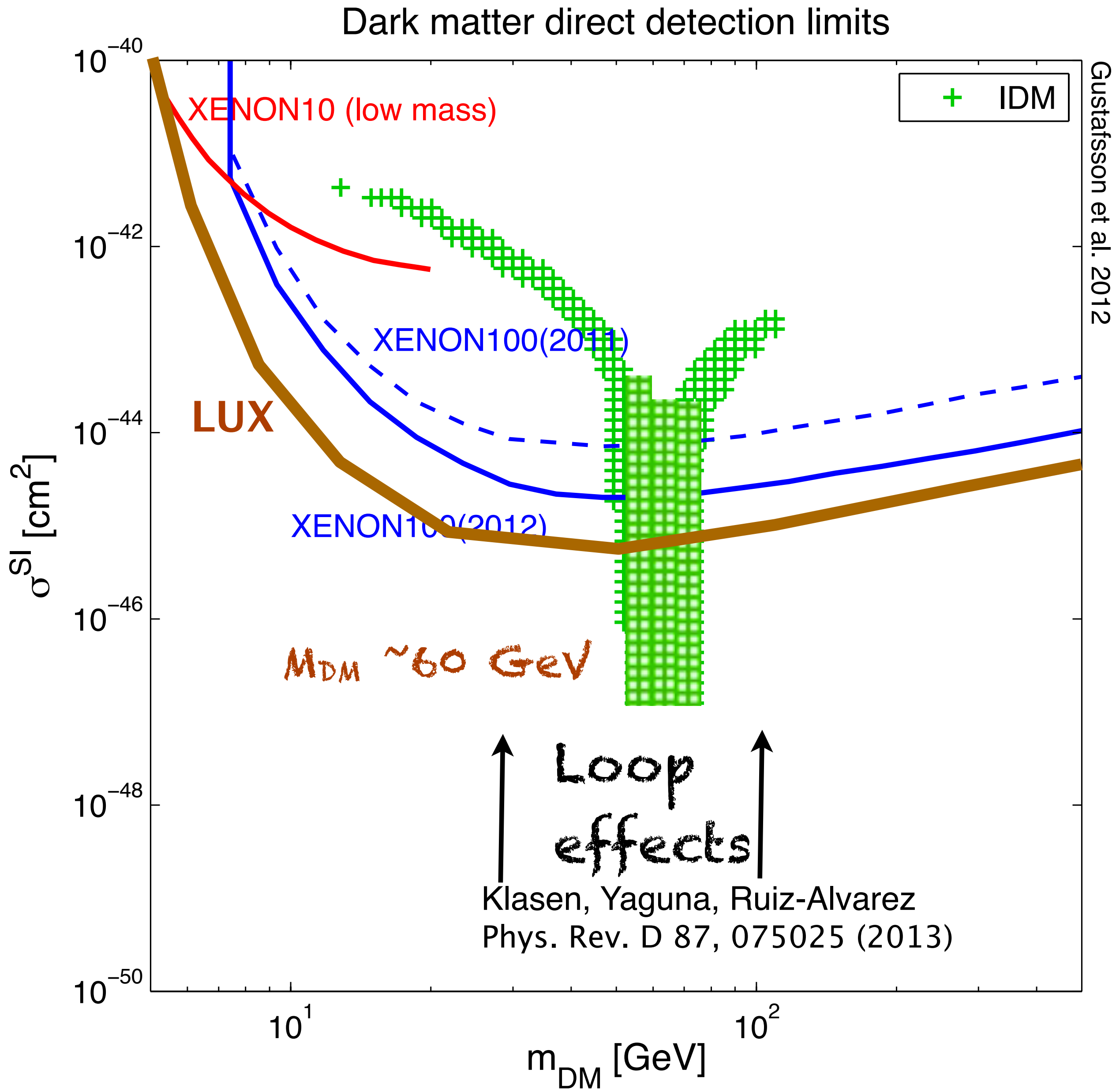
Its Dark Matter Candidate

Inert Doublet Model $\Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0 + i\,A_0}{\sqrt{2}} \end{pmatrix}$

H° (or A°) is good DM candidate

Thermal production at freeze-out

1. Higgs portal (resonance): ~60 GeV
2. Coannihilation with A°
   (gives too small m_ν)



MG, Rydbeck, Honorez, Lundström **Phys.Rev.D 86** (2012) 075019

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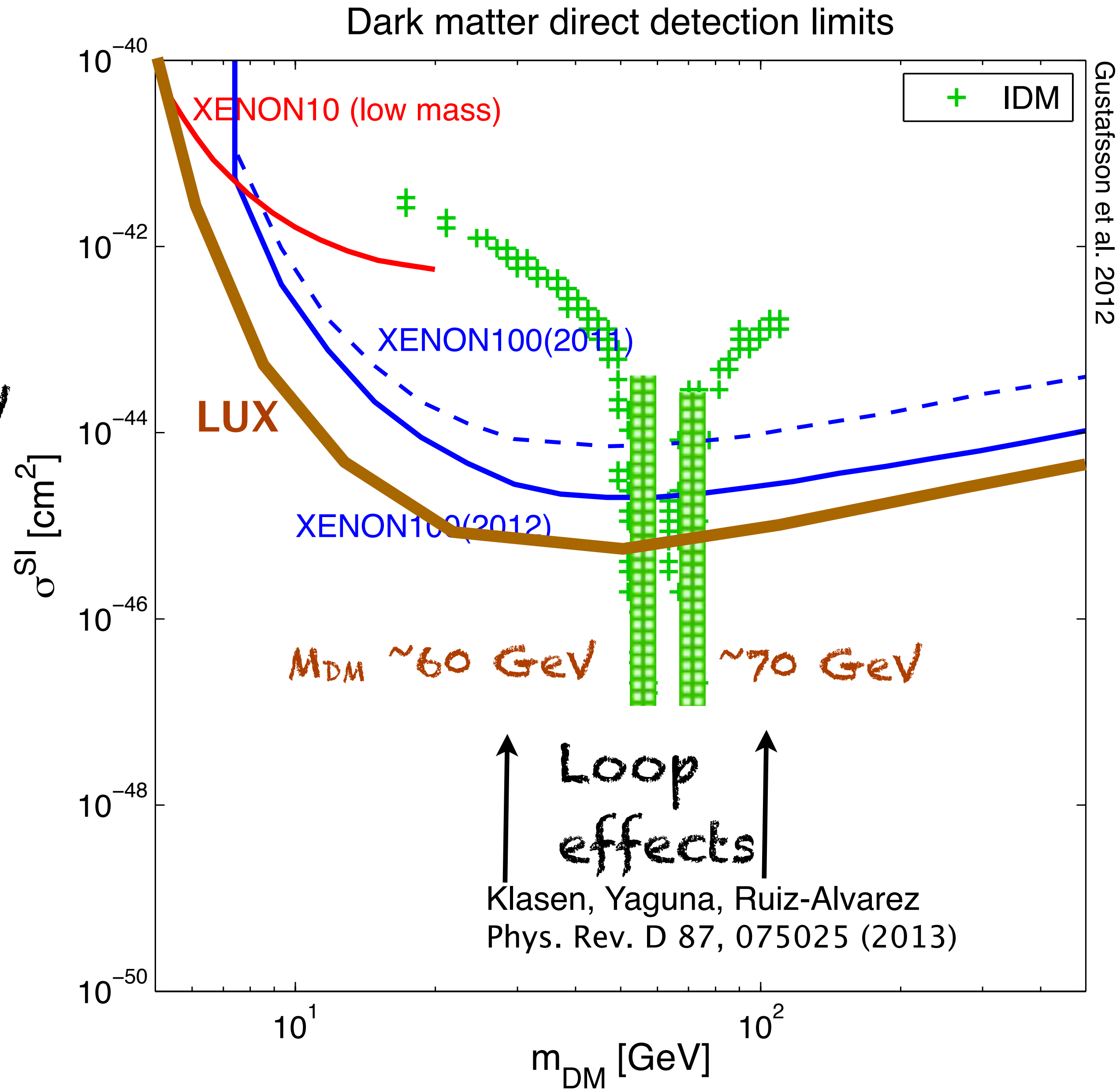


MG, Rydbeck, Honorez, Lundström **Phys.Rev.D 86** (2012) 075019

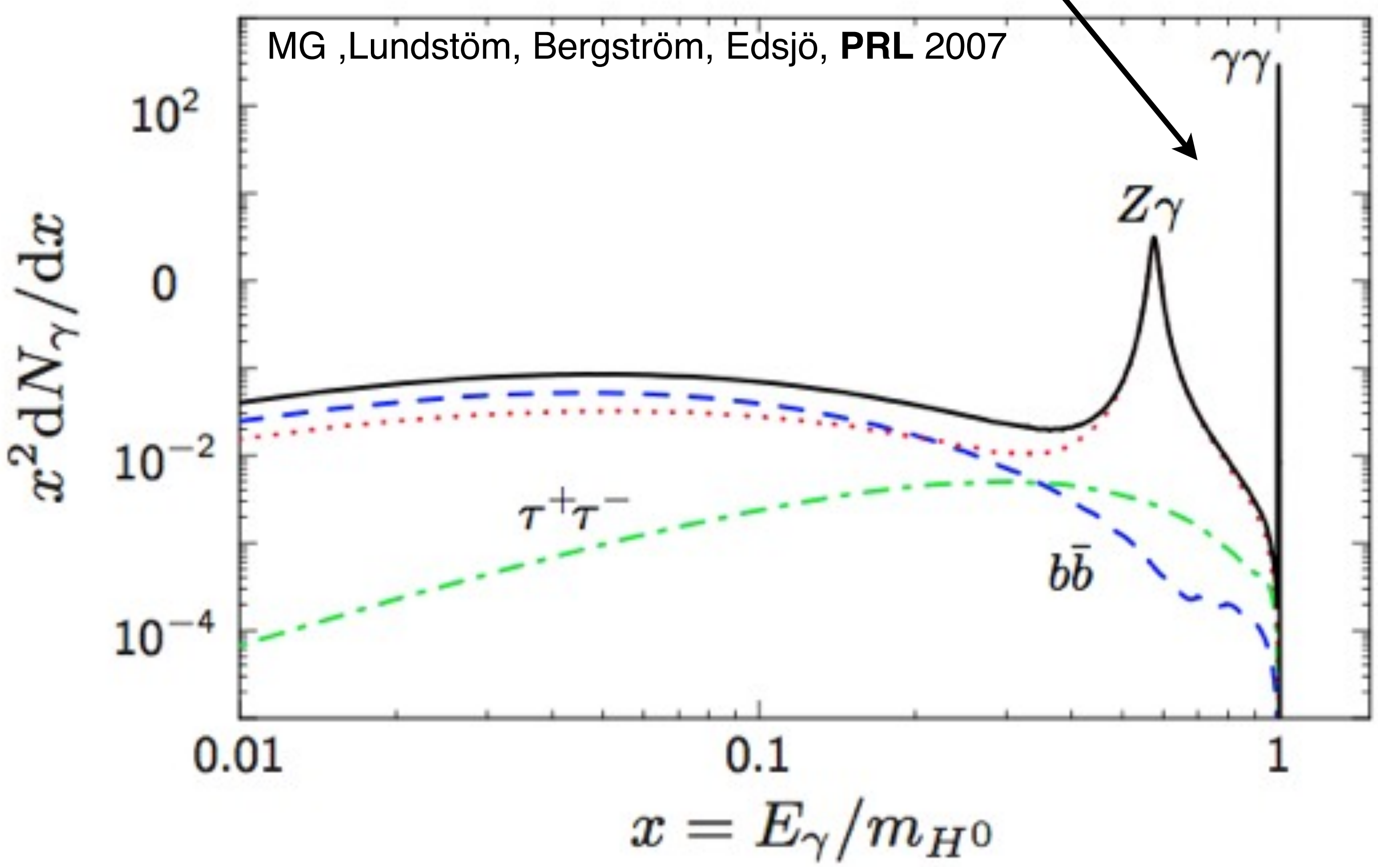
Its Dark Matter Candidate

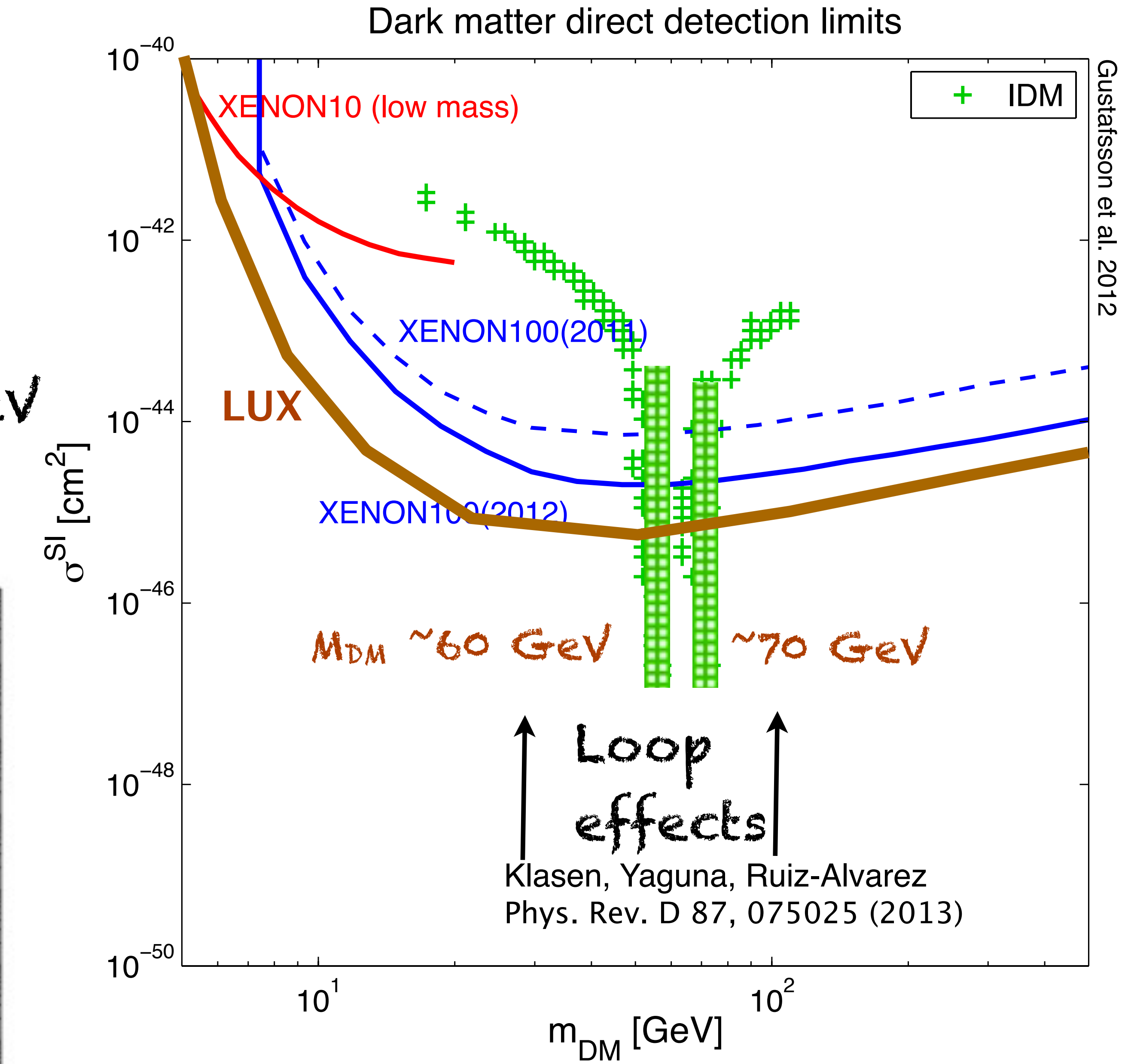
Inert Doublet Model $\Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0 + i A_0}{\sqrt{2}} \end{pmatrix}$

H^0 (or A^0) is good DM candidate

Thermal production at freeze-out

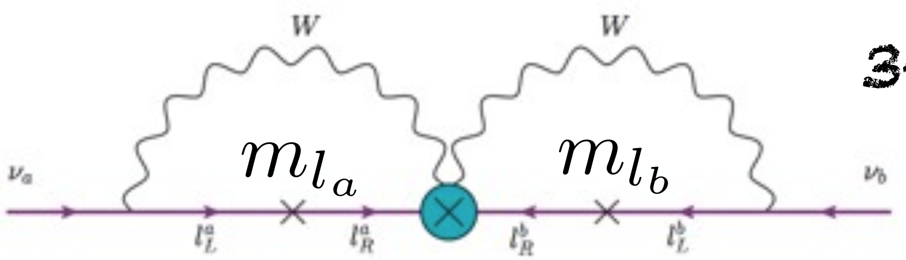
1. Higgs portal (resonance): ~60 GeV
2. Coannihilation with A^0 (gives too small m_ν)
3. H^0H^0 -> WW threshold effect: ~70 GeV (gives striking gamma-ray lines)





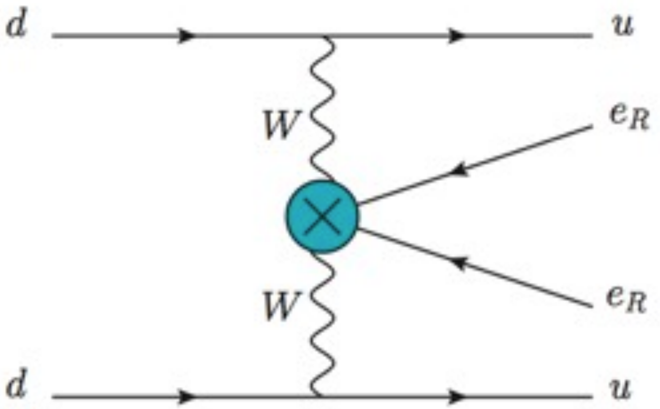
MG, Rydbeck, Honorez, Lundström **Phys.Rev.D 86** (2012) 075019

Neutrinoless Double Beta Decay

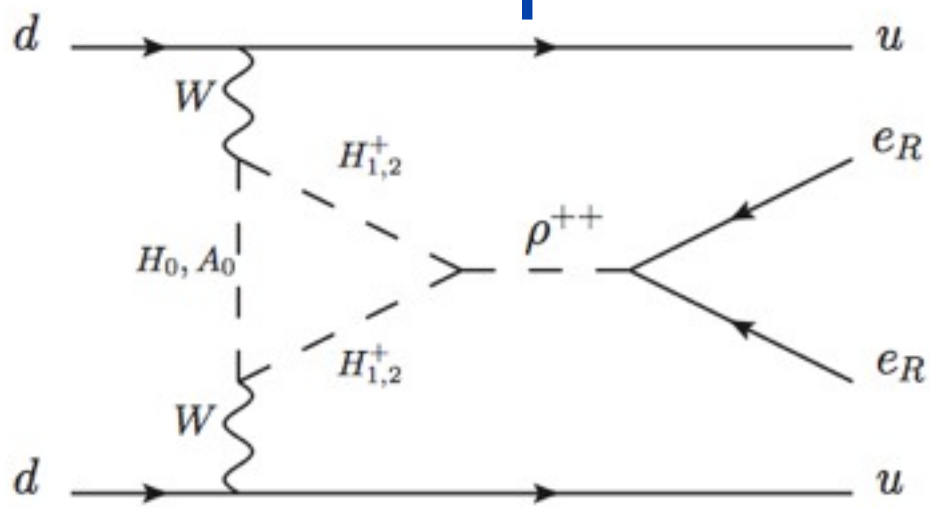


3-loop mass

...but 1-loop 0νββ



0νββ-decay fully dominated by the short range force



With a 0νββ-decay rate:

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1}_{SD} \simeq G_{01}\,|\epsilon_3|^2\,|\mathcal{M}^{\rm SD}|^2 .$$

Phase-space factor

Nuclear Matrix element

$$\epsilon_3 \equiv -2\,m_p\,\mathcal{A}^{\rm SD}_{0\nu\beta\beta}$$

$$\epsilon_3^{\rm loop} \simeq 1.2\times 10^{-5}\;|C_{ee}|$$

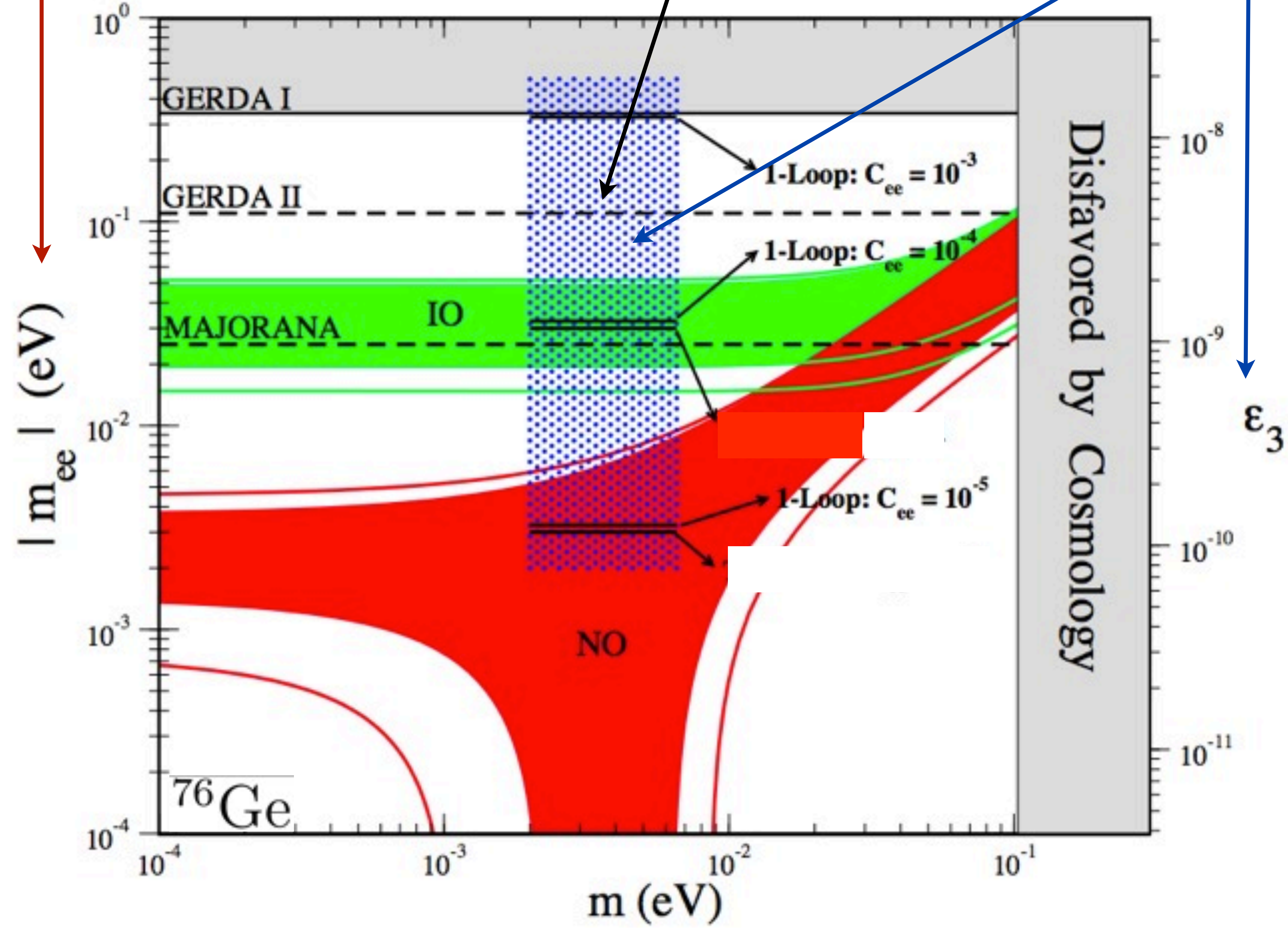
(In the Cocktail model)

0νββ Decay Bounds

neutrino exchange

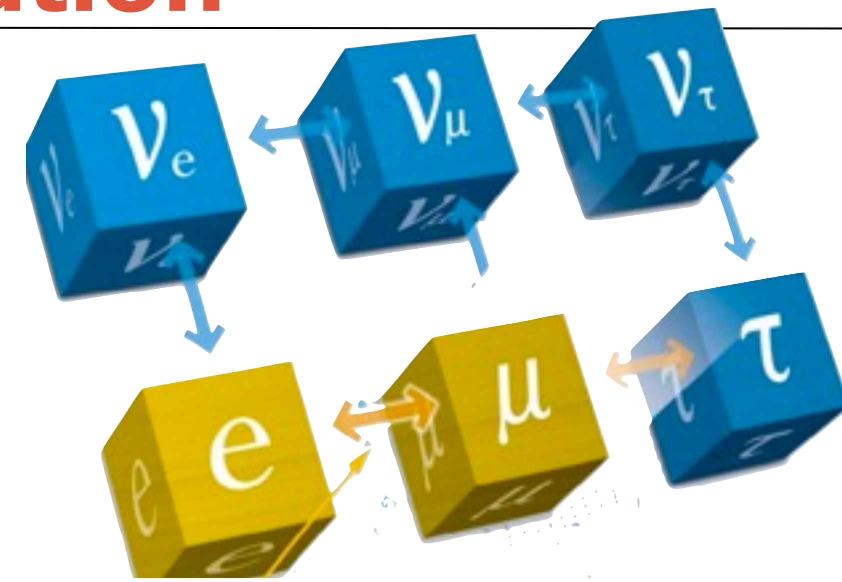
Cocktail model predictions

Short range force



0νββ-decay puts the strongest exp. constraint on the Yukawa coupling C_{ee}

Lepton Flavor Violation



Stringent bounds from rare flavor-violating processes

$\mu^- \to 3e$:	$\lvert C_{e\mu} C_{ee} \rvert$	$<$	$2.3 \times 10^{-5}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to 3e$:	$\lvert C_{e\tau} C_{ee} \rvert$	$<$	$9.0 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to 3\mu$:	$\lvert C_{\mu\tau} C_{\mu\mu} \rvert$	$<$	$8.1 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to \mu^+ e^- e^-$:	$\lvert C_{\mu\tau} C_{ee} \rvert$	$<$	$6.8 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to \mu^+ e^- \mu^-$:	$\lvert C_{\mu\tau} C_{e\mu} \rvert$	$<$	$6.5 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to e^+ e^- \mu^-$:	$\lvert C_{e\tau} C_{e\mu} \rvert$	$<$	$5.2 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\tau^- \to e^+ \mu^- \mu^-$:	$\lvert C_{e\tau} C_{\mu\mu} \rvert$	$<$	$7.1 \times 10^{-3}\ (m_\rho/\mathrm{TeV})^2$
$\mu^+ \to e^+ \gamma$:	$\lvert \sum_l C_{l\mu} C^*_{le} \rvert$	$<$	$3.2 \times 10^{-4}\ (m_\rho/\mathrm{TeV})^2.$

Nebot, Oliver, Palao and Santamaria, Phys. Rev. D 77 (2008) 093013
J. Adam et al. [MEG Collaboration], arXiv:1303.0754.
K. Hatasaka et al. [Belle Collaboration], Phys.Lett.B 687 (2010)

Constraints are of this form on the Yukawa C_{ab}:

$$\frac{|C_{ab} C_{xy}|}{(m_\rho/\mathrm{TeV})^2} \lesssim 10^{-4}$$

Recall that the neutrino mass matrix was of a similar form

$$m^\nu_{ab} \propto \frac{C_{ab}}{m_\rho/\mathrm{TeV}} \sim \sqrt{\frac{C_{ab} C_{xy}}{(m_\rho/\mathrm{TeV})^2}}$$

→ LFV limits impose strong upper bounds on m^ν_{ab}

→ LFV process predicted close to current bounds

Summary & Conclusions

- Electroweak Scale Physics Responsible for Neutrino Masses is Appealing: Very Rich Phenomenology (& testable)

- Neutrino Mass Suppression can be Linked to DM Stability in Models of Radiative Neutrino Mass Generation

- Neutrino Mass Generation via the Operator $\bar{l}_R l^c_R (\phi^\dagger D_\mu \tilde{\phi})^2$ Leads to Signatures in Neutrino Mixings & *0νββ*-decay

- The "Cocktail model" is a Concrete BSM Realization that Contains these (and other) Testable Ingredients