Lecture II : 0νββ-Decay

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U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

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

University of Massachusetts Amherst

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

NNPSS, Wright Laboratory
Yale 6/18-29/18

Lecture II Goals

- *Give a theoretical overview of $0\nu\beta\beta$ decay*
- *Connect $0\nu\beta\beta$ decay to the origin of matter*
- *Provide a framework for interpreting $0\nu\beta\beta$ decay results: the mechanisms*
- *Discuss the interplay with other experiments*
- *Invite questions !*

Lecture II Outline

I. *Overview*

II. *“Standard Mechanism” for $0\nu\beta\beta$-Decay*

III. *TeV Scale LNV*

IV. *Sub-weak scale LNV*

V. *Discussion questions*

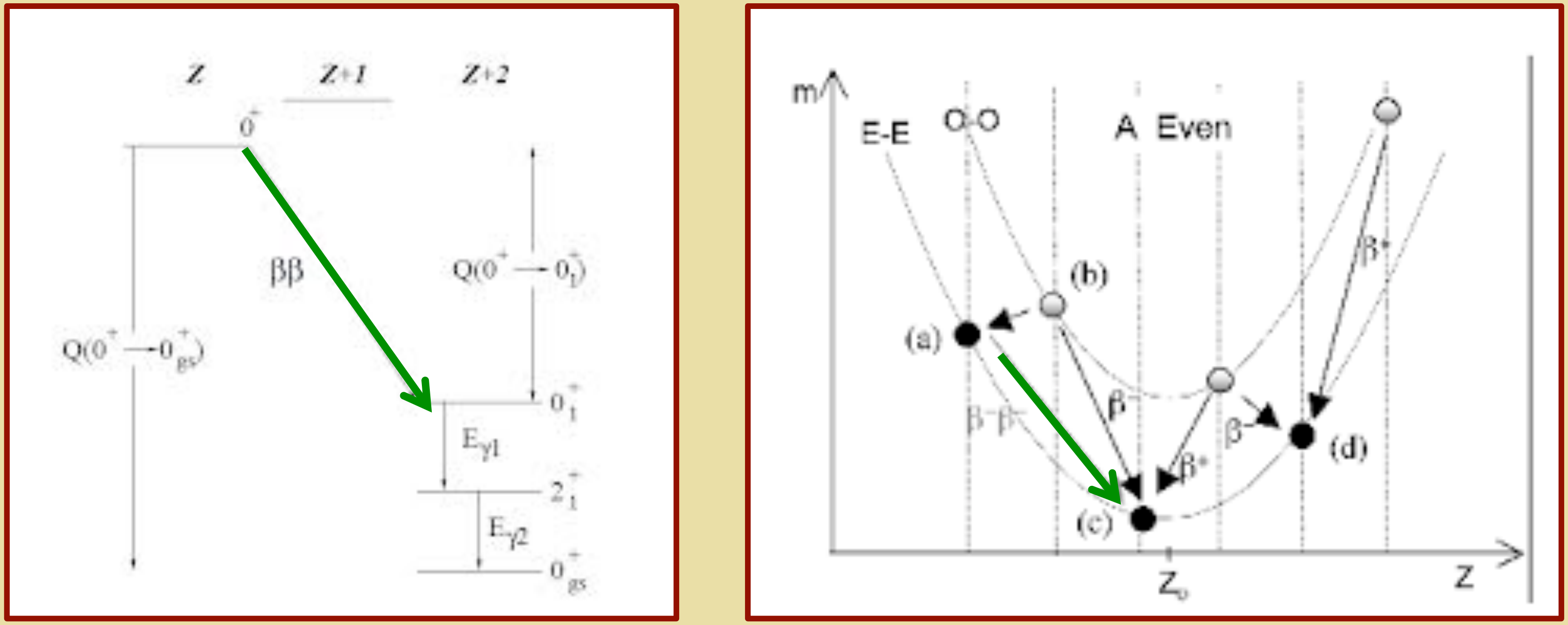
I. 0νββ-Decay Overview

What is Neutrinoless Double Beta Decay ?

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

Test of total lepton number conservation

Why Do Nuclei Double Beta Decay ?



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

Observed

What Questions Does It Address ?

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

What Questions Does It Address ?

- Is the neutrino its own antiparticle ?
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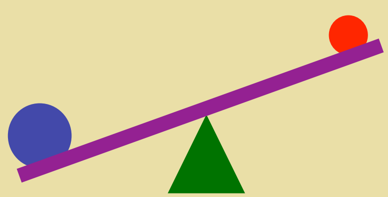
"See saw mechanism"



"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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0νββ-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

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If own antiparticle, can be emitted then absorbed during decay

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

What Questions Does It Address ?

- *Is the neutrino its own antiparticle ?*

Yes $\rightarrow$ "Majorana neutrino":

Theoretically favored explanation of the matter-antimatter asymmetry & small scale of neutrino masses

No $\rightarrow$ "Dirac neutrino":

Points to alternate origin of matter-antimatter asymmetry & some string theory underpinnings of neutrino masses

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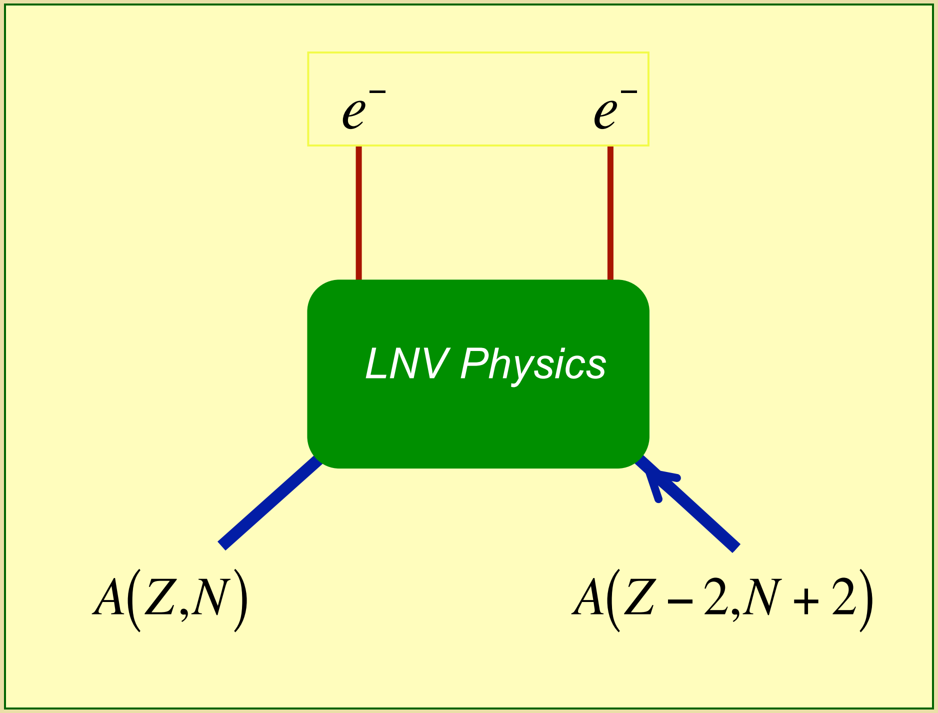

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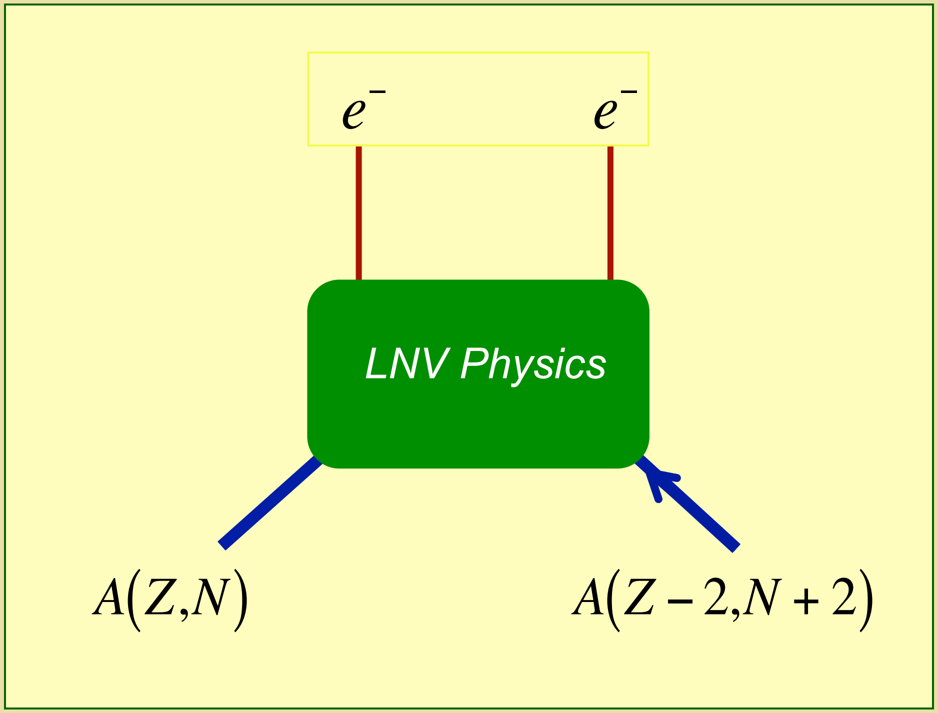
Impact of observation

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

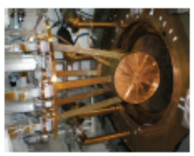


Ton Scale Experiments: Worldwide Quest

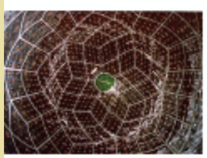
0νββ decay Experiments - Efforts Underway

CUORE

EXO200



KamLAND Zen



Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	**100 kg - ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	**~ ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA

SNO+

The U.S. Context

2015 NSAC Long Range Plan

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Why Is It So Challenging to Observe ?

- *The rate is exceptionally tiny*

$$\Gamma \sim (m_{eff})^2$$

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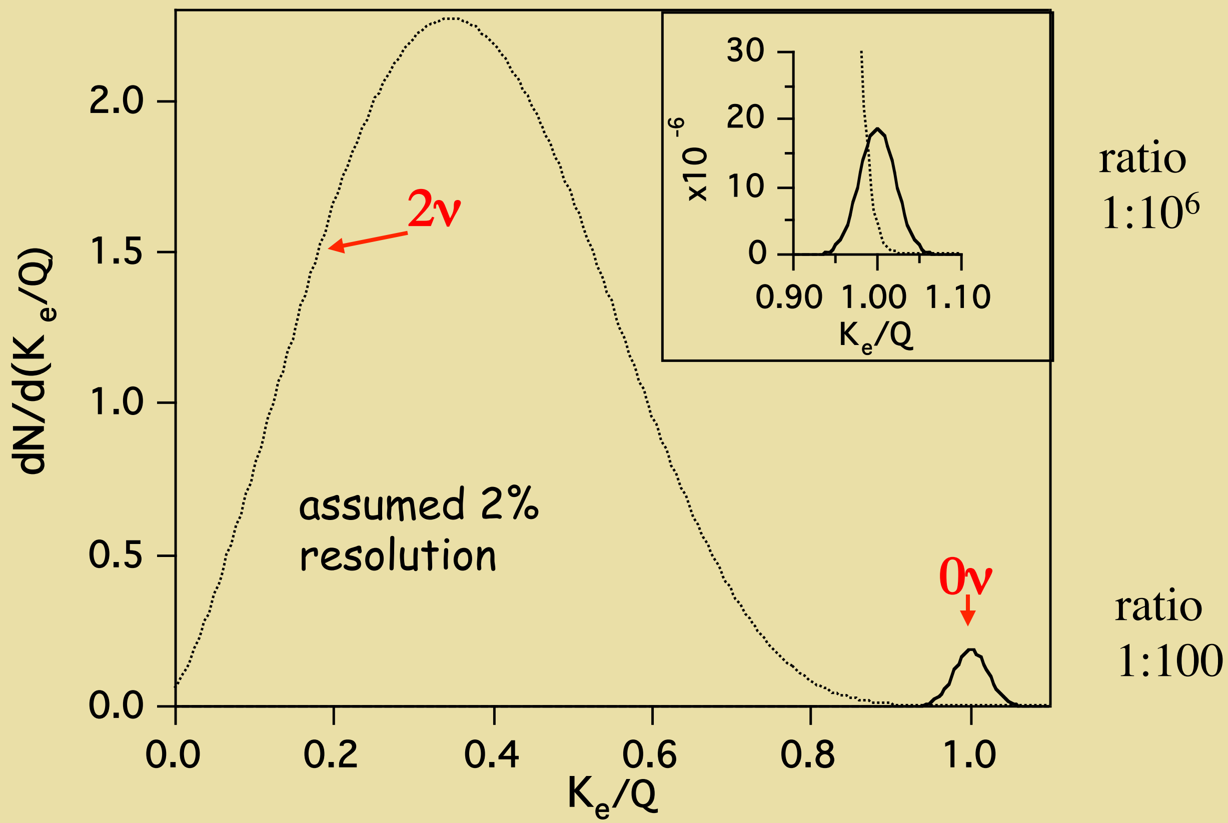

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Experimental details: See
D. Parno second lecture !

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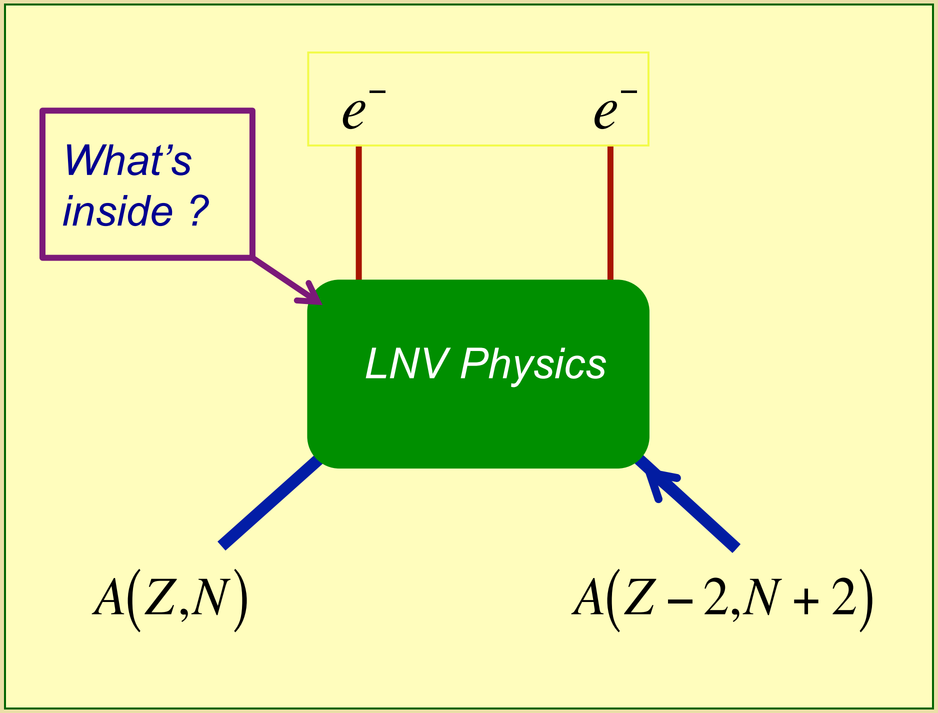
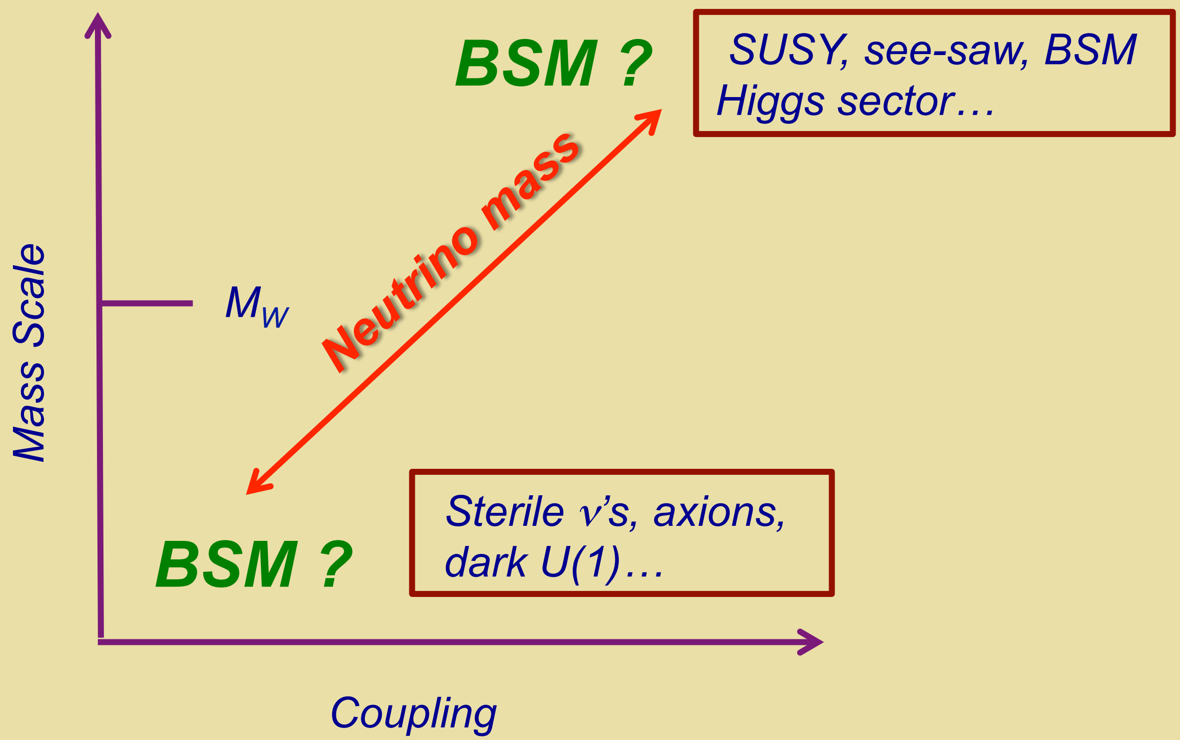


BSM Physics: Where Does it Live ?



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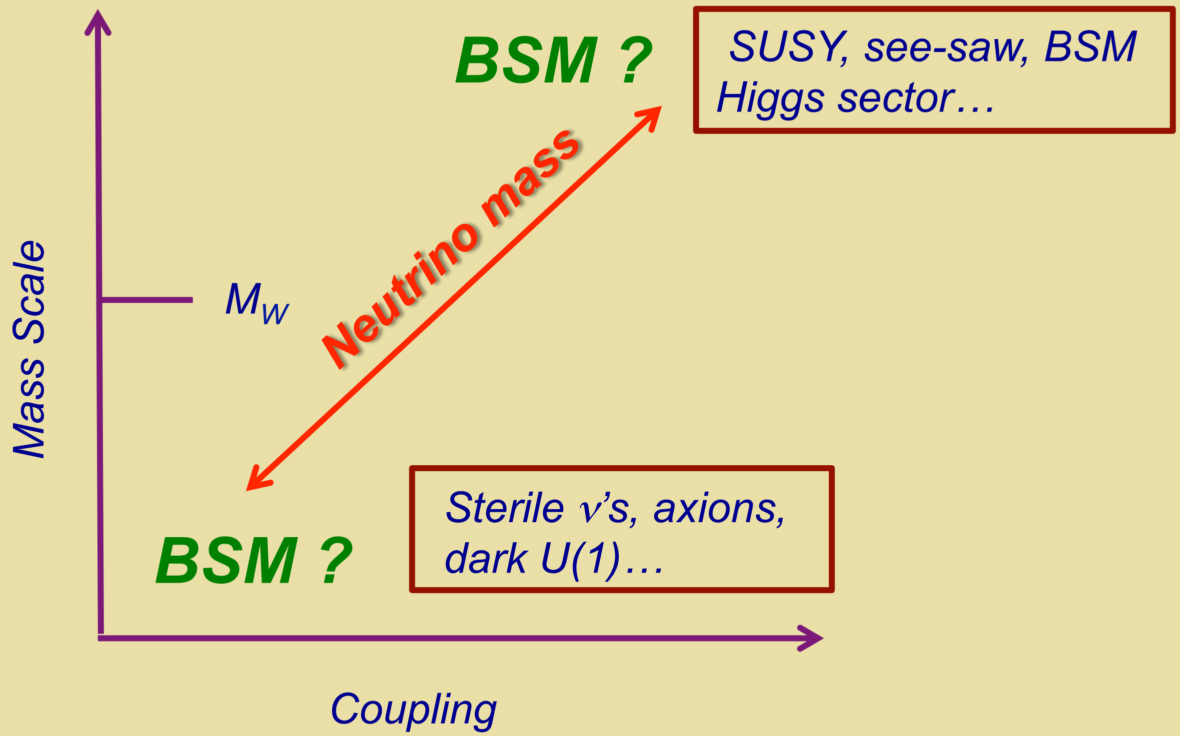

Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

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

$A(Z,N) \rightarrow$ **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*

II. The "Standard Mechanism"

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

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

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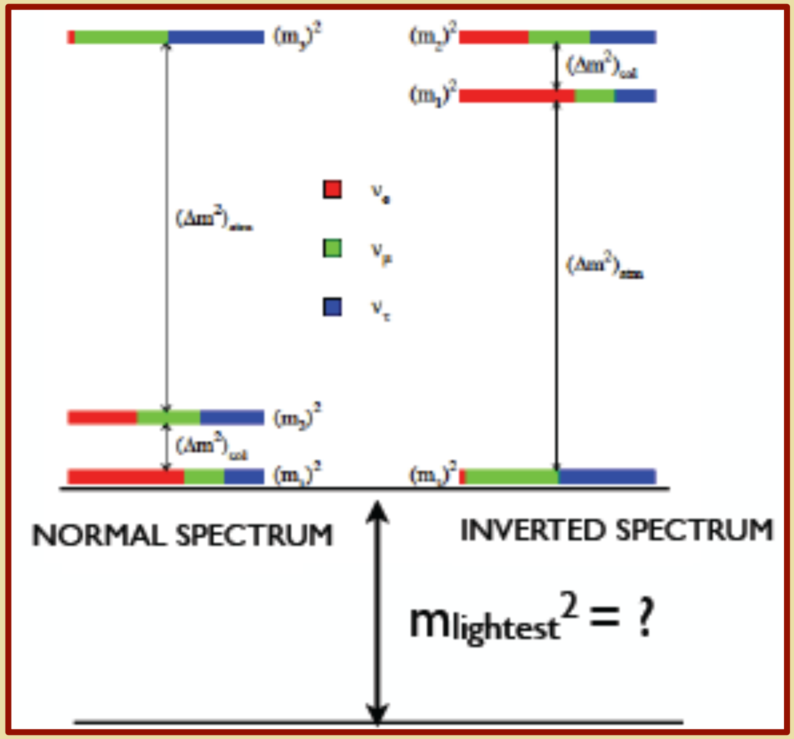
Three Light Neutrinos: What Do We Know ?

Neutrinos mix

$$\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \end{pmatrix} = U \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Physical neutrinos

e, μ, τ partners



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If own antiparticle, can be emitted then absorbed during decay

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

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

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

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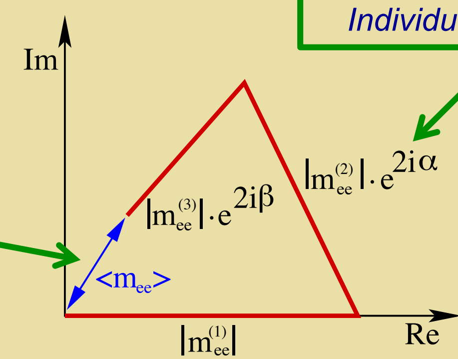
Individual contributions

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



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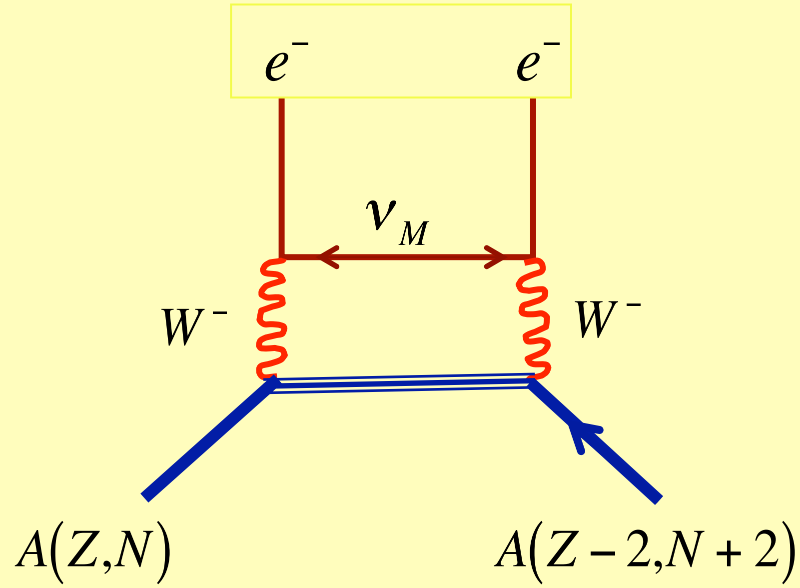
Majorana

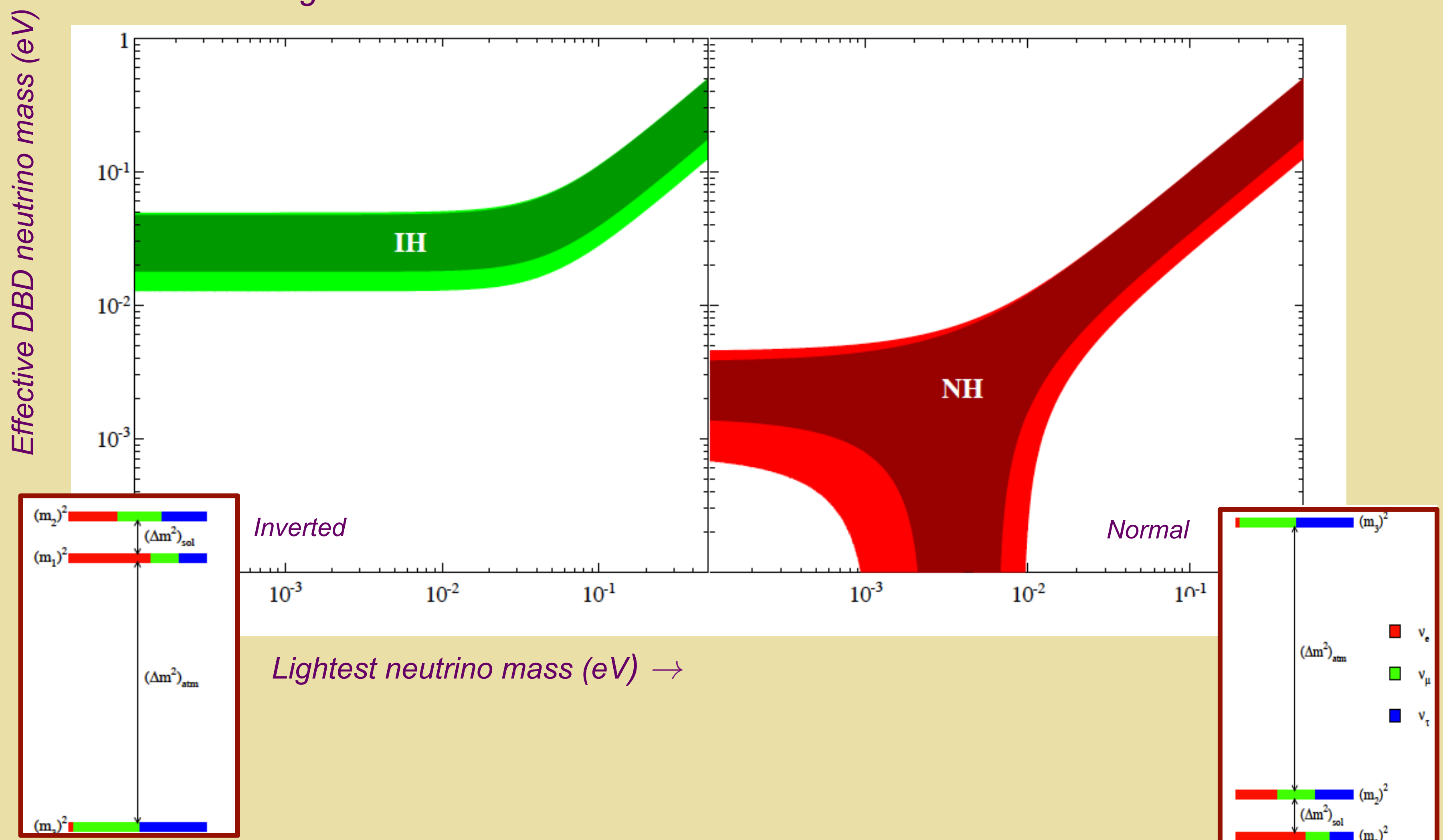
"Standard" Mechanism

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



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

Three active light neutrinos



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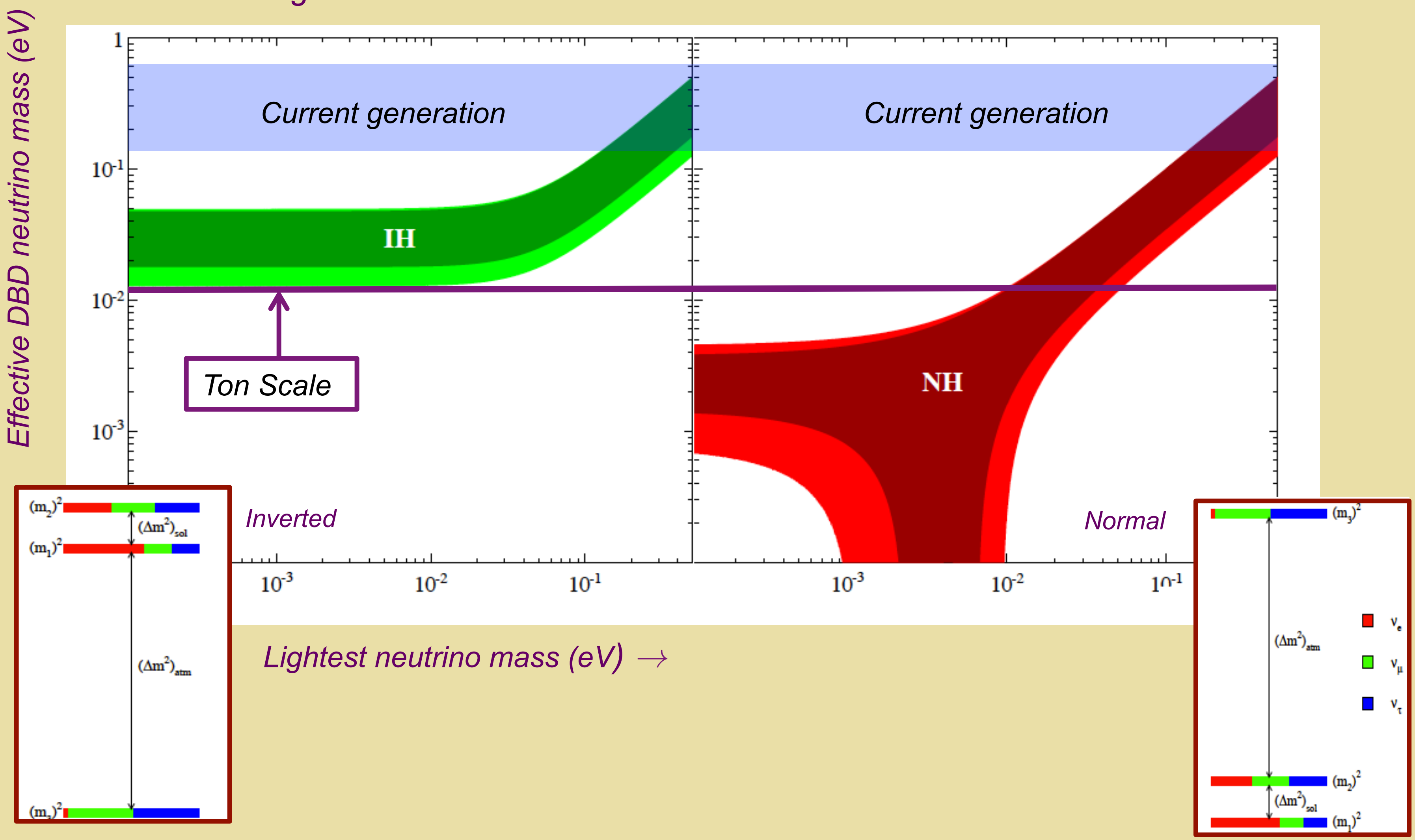
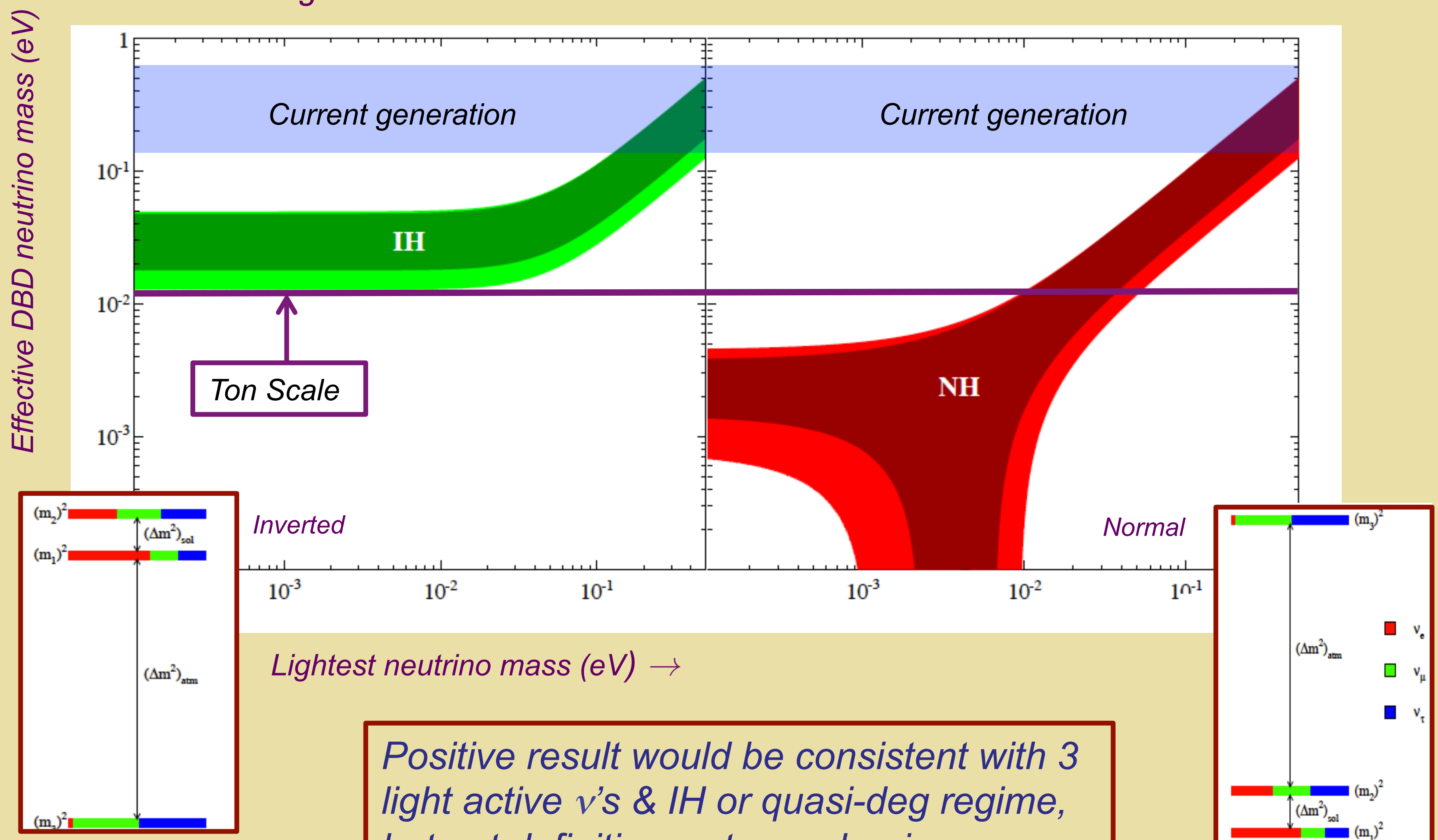


Interpreting a Positive Result

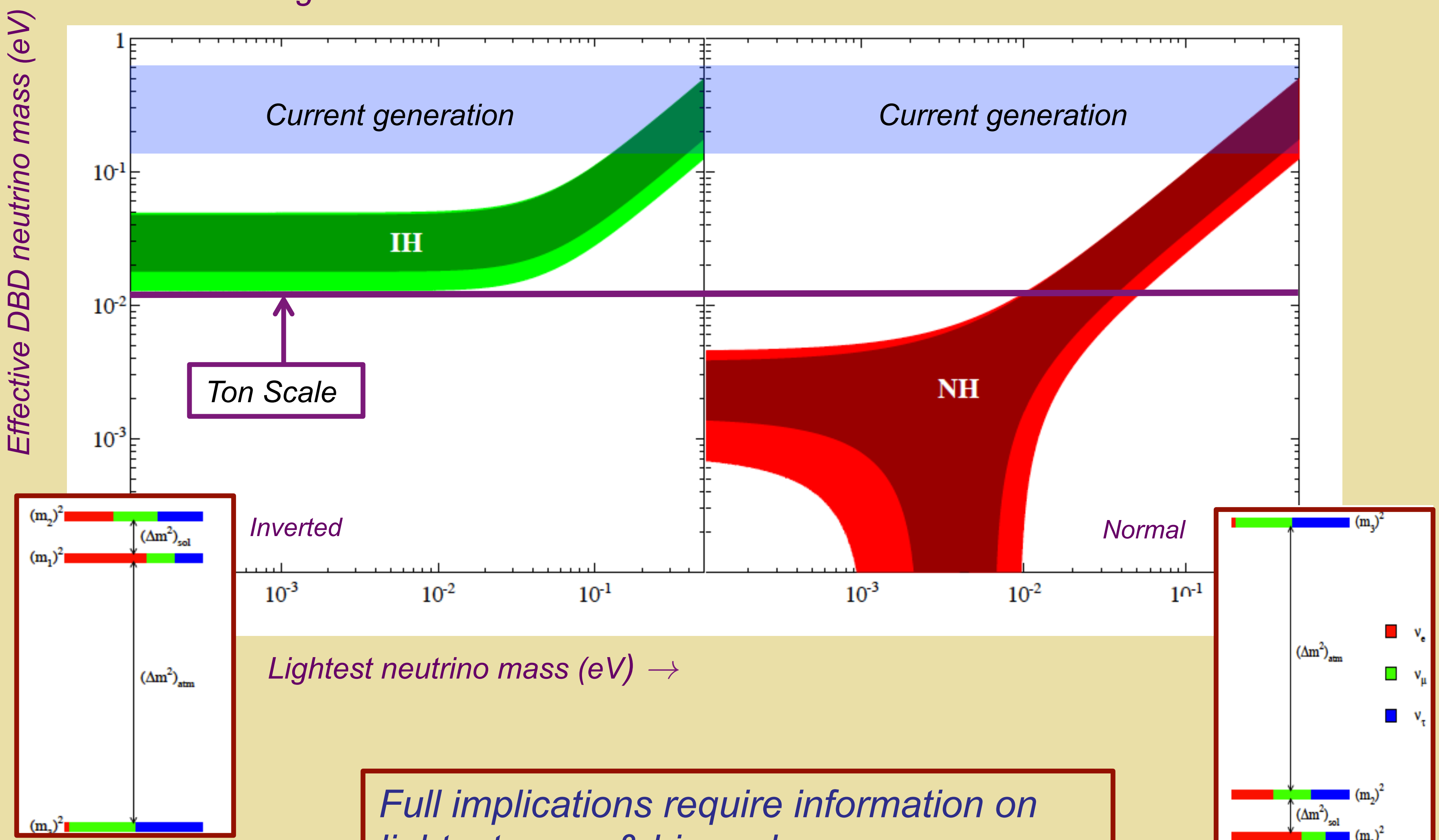
Three active light neutrinos



Positive result would be consistent with 3 light active ν's & IH or quasi-deg regime, but not definitive as to mechanism

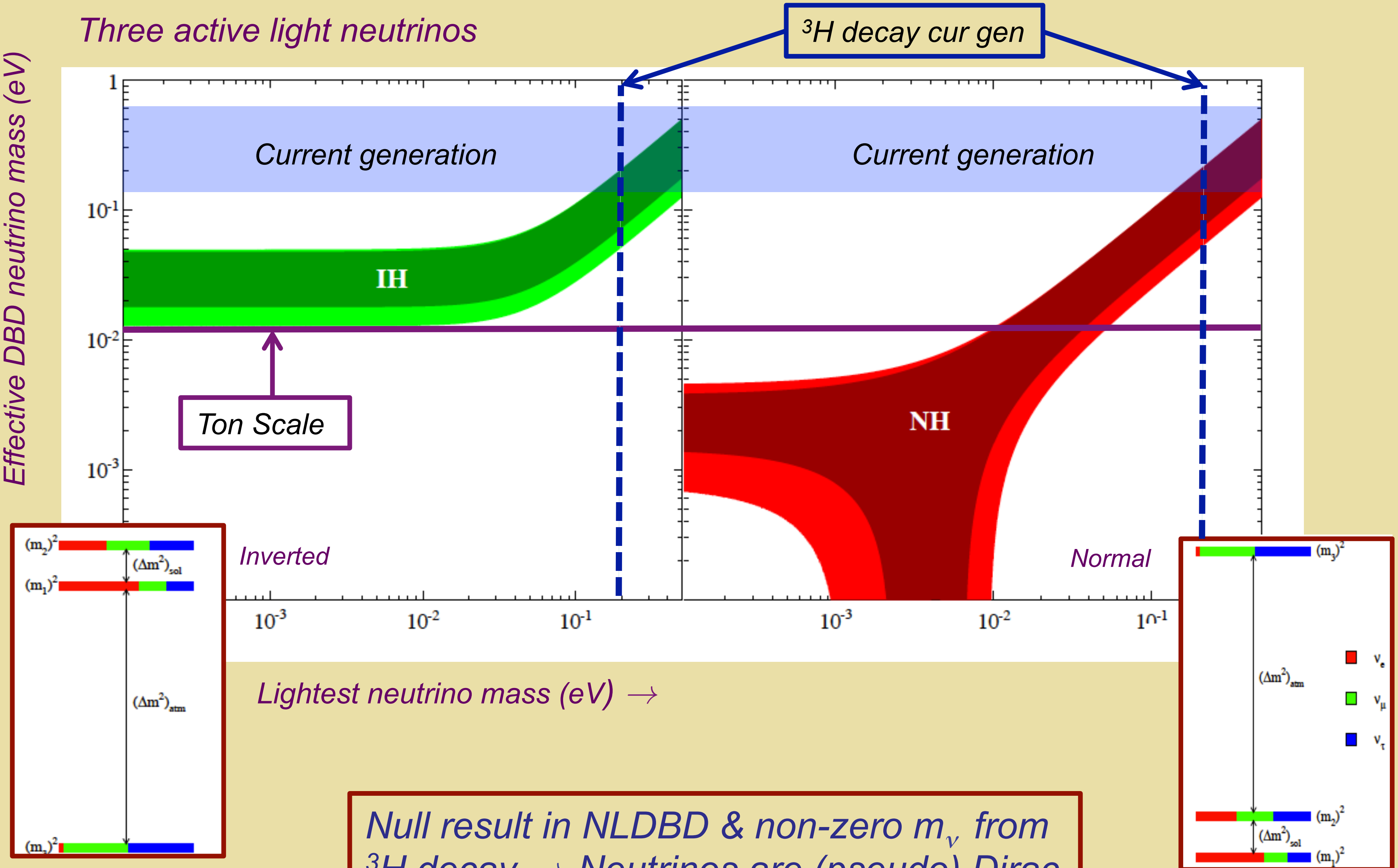
Interpreting a Null Result

Three active light neutrinos



Full implications require information on lightest mass & hierarchy

What Would a Null Result Imply ?



Null result in NLDBD & non-zero m_ν from ^3H decay → Neutrinos are (pseudo) Dirac

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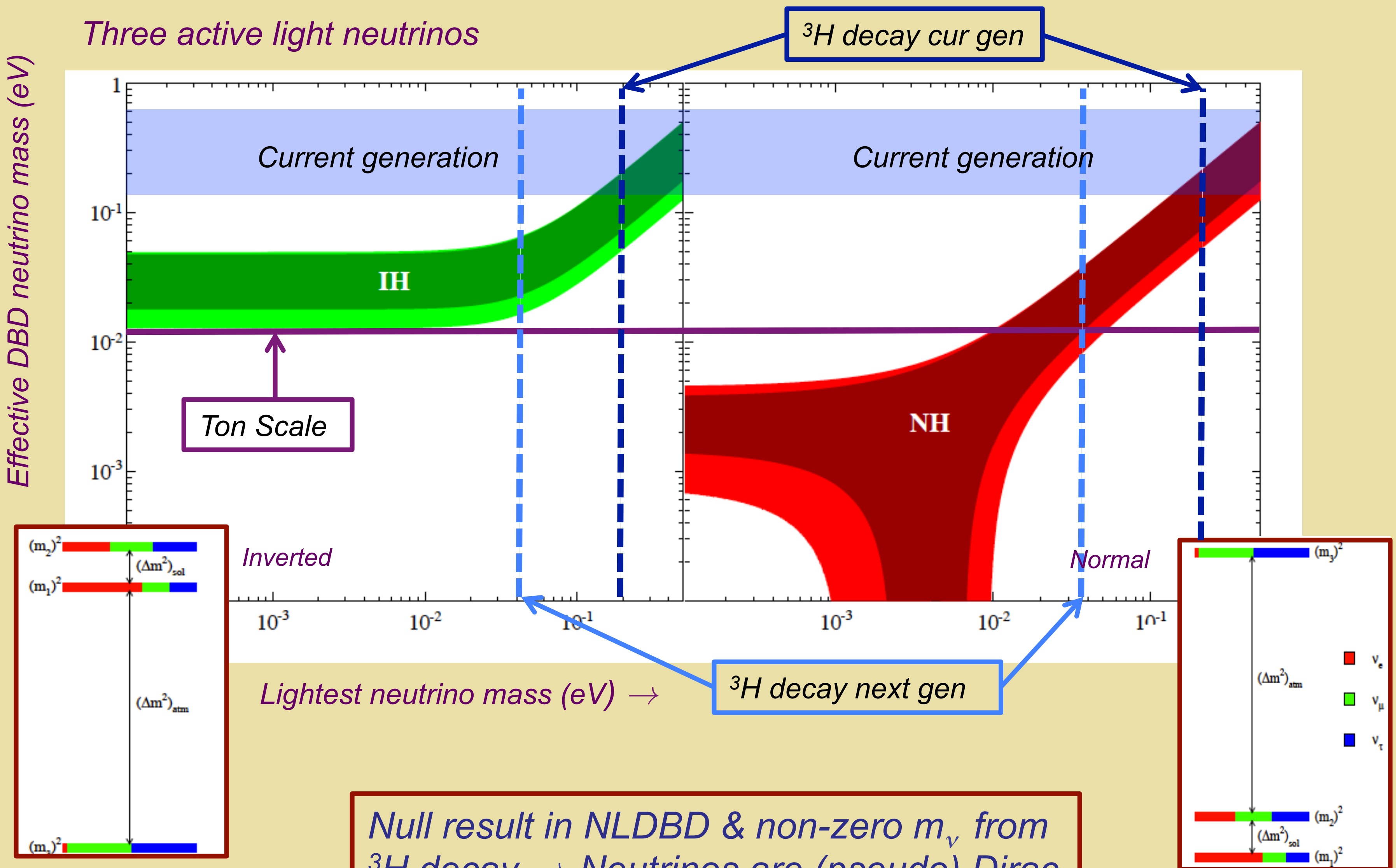

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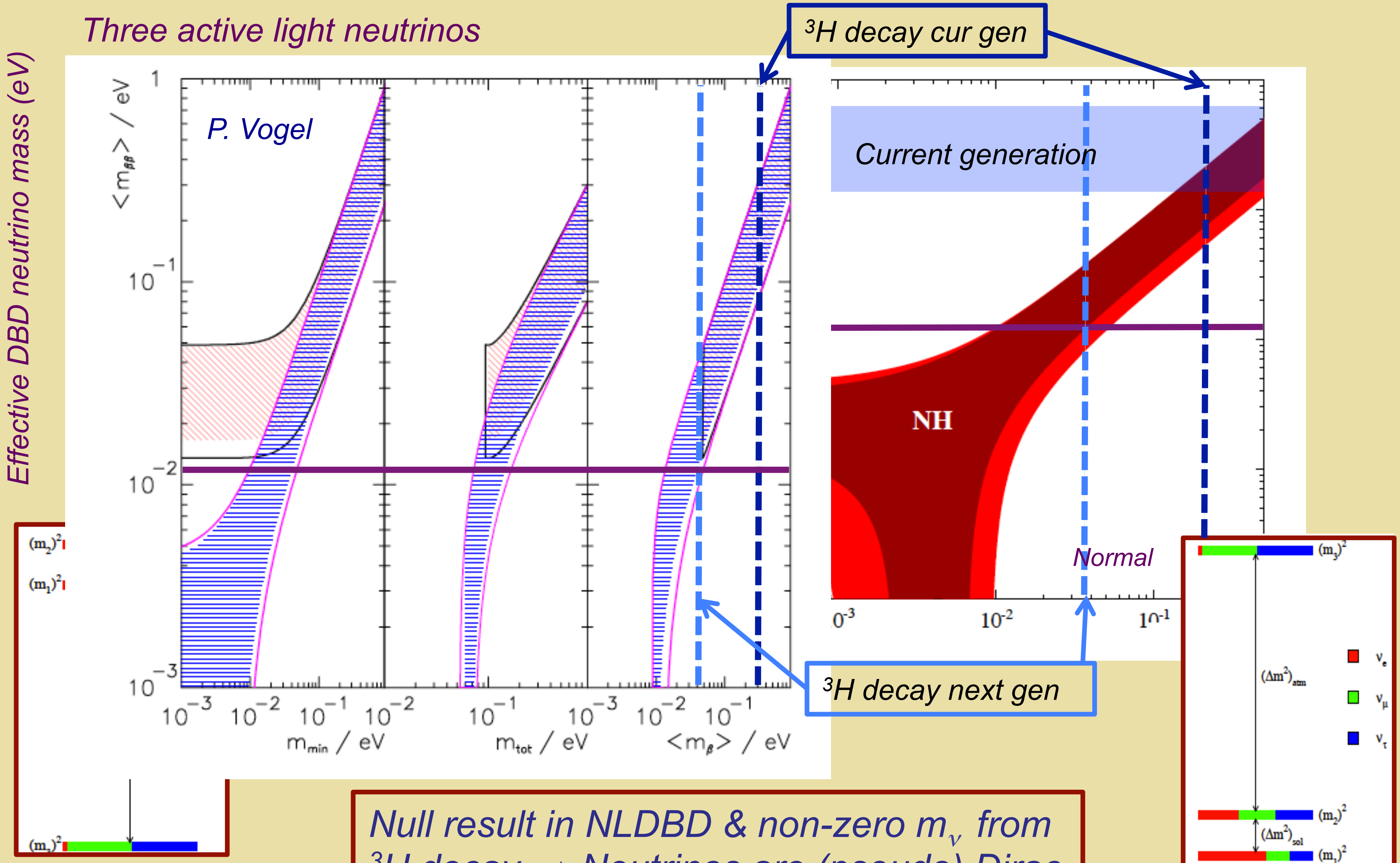

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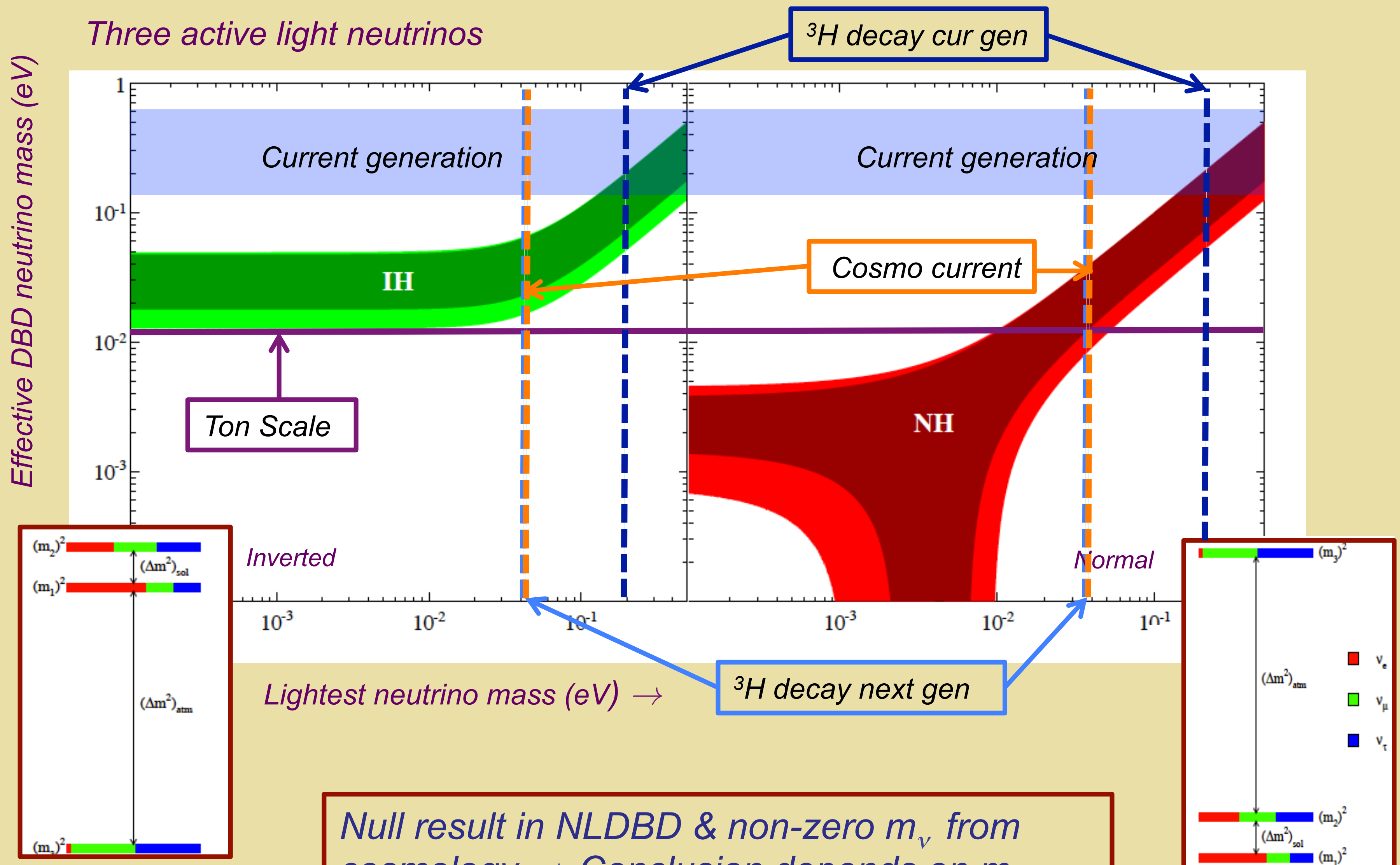

Null result in NLDBD & non-zero m_ν from cosmology → Conclusion depends on $m_{lightest}$ & hierarchy

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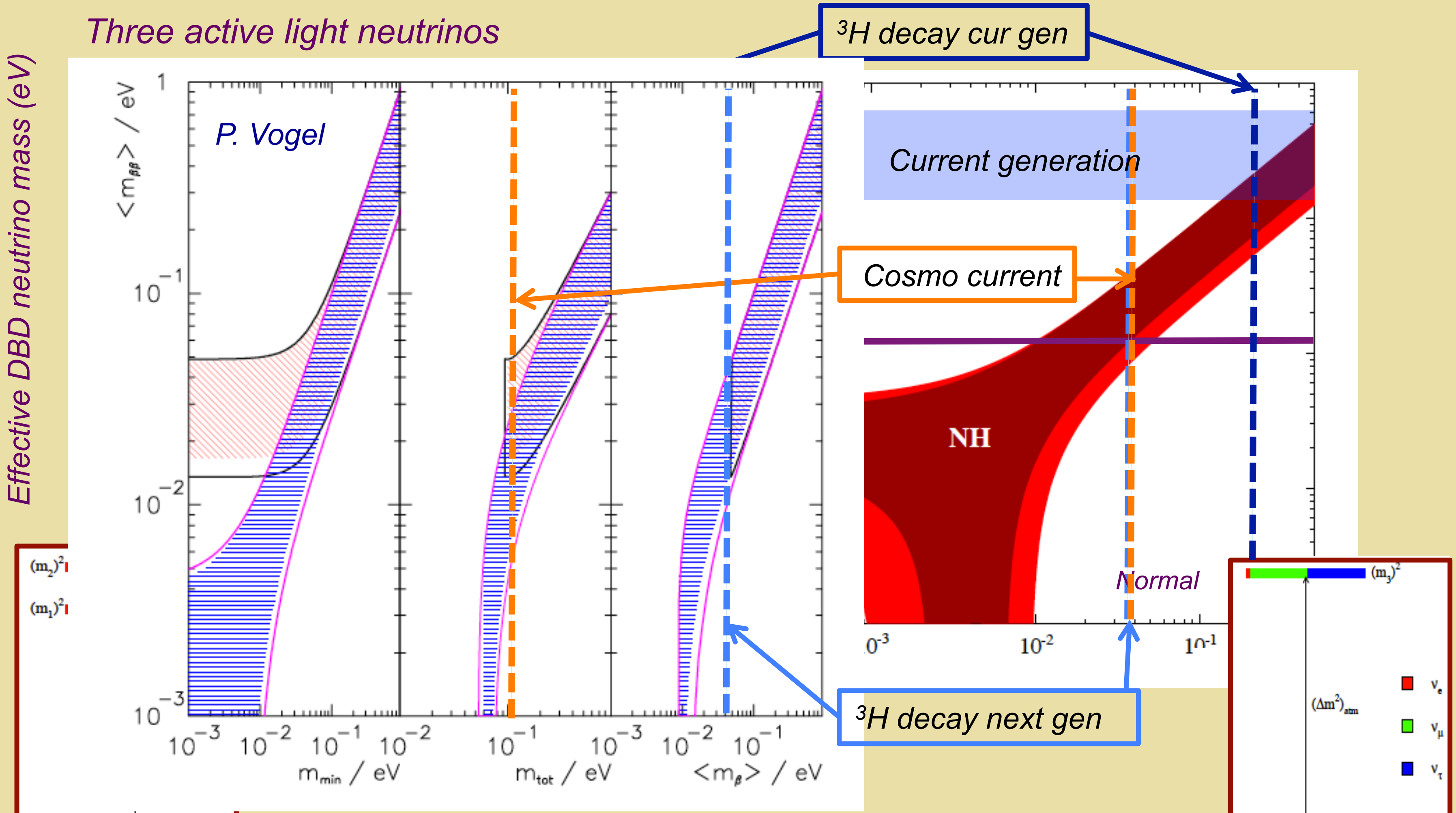

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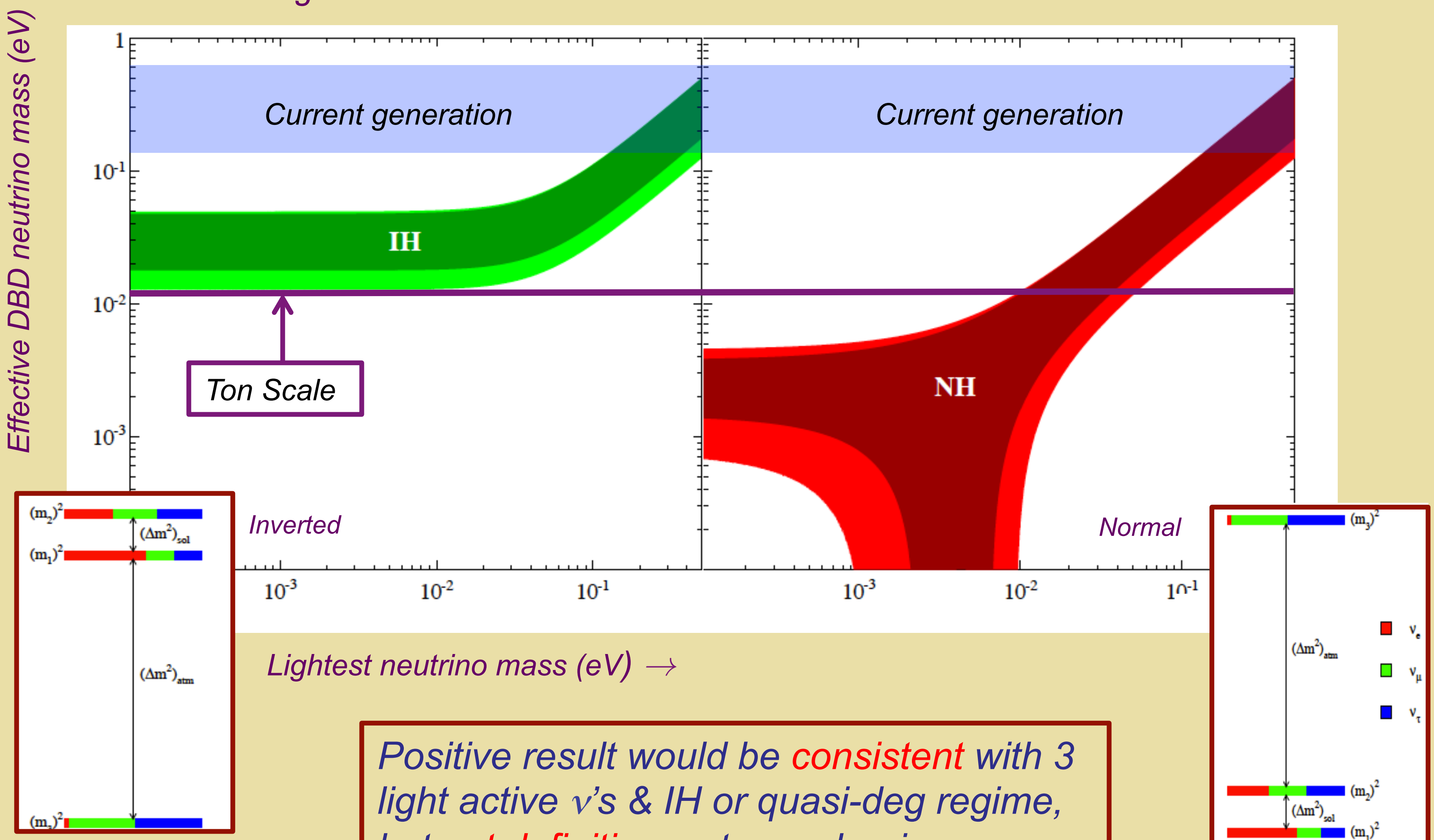
Interpreting a Positive Result

Three active light neutrinos



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$0\nu\beta\beta$-Decay: Nuclear Matrix Element

N_R

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

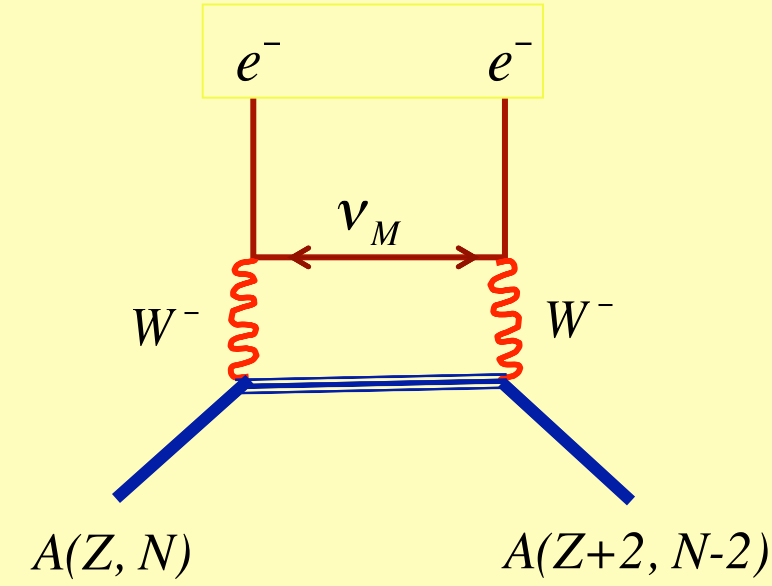
Dirac

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

Majorana

Light ν exchange

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



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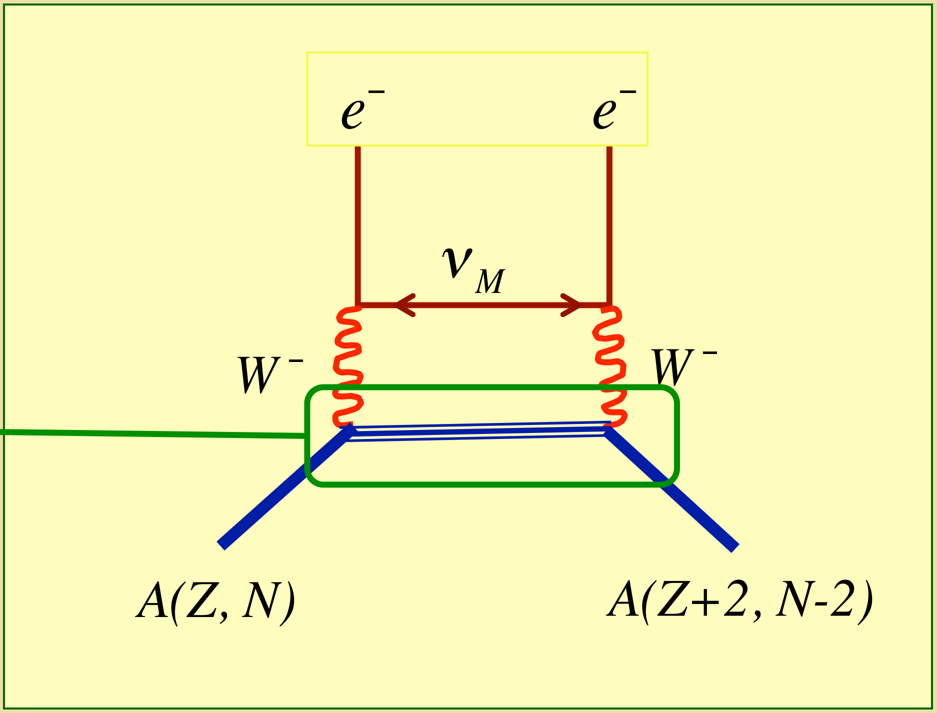

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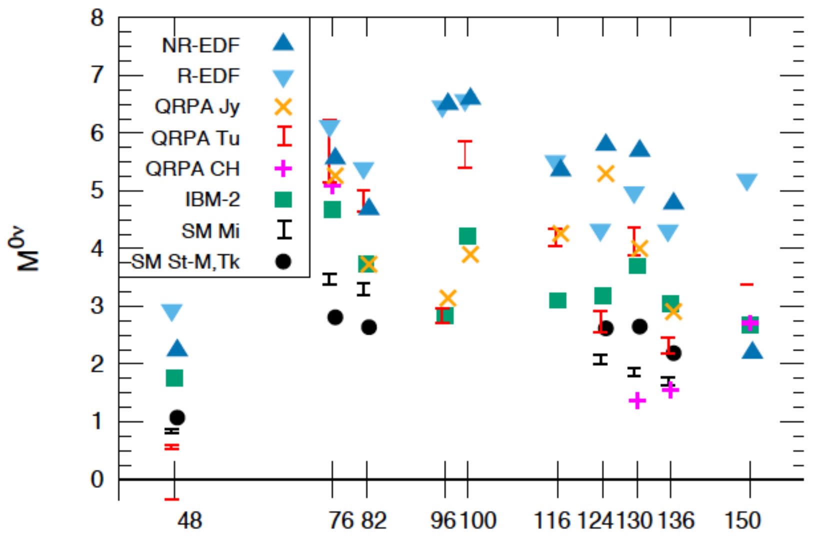

Figure from review by Engel and Menendez

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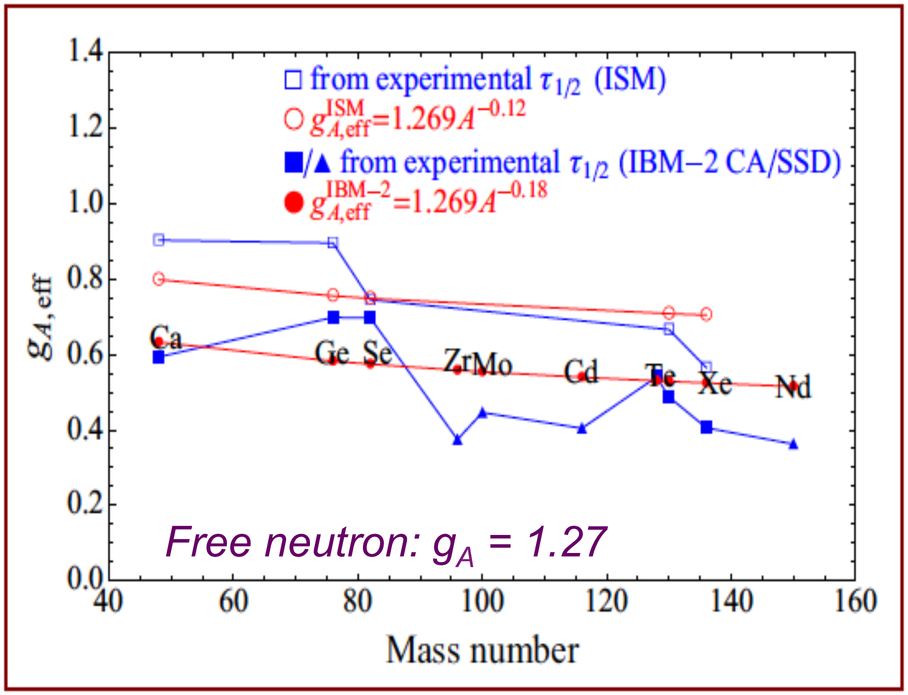
$M_{0\nu}$*: Quadratic dependence on* g_A



from F. Iachello

$0\nu\beta\beta$-Decay: Nuclear Matrix Element

Problem must be due to some combination of:

J. Engel

1. Truncation of model space.

   Should be fixable in ab-initio shell model, which compensates effects of truncation via effective operators.

2. Many-body weak currents.

   Size still not clear, particularly for $0\nu\beta\beta$ decay, where current is needed at finite momentum transfer q.

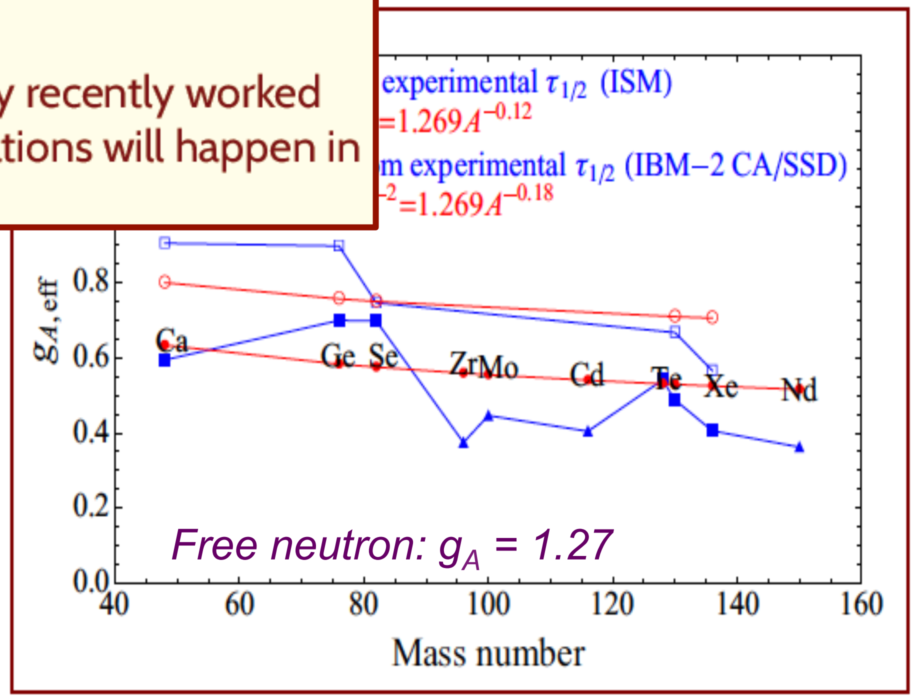
   Leading terms in chiral EFT for finite q only recently worked out. Careful fits and use in decay computations will happen in next year or two.

$$\bar{L}^c H H^T L \; + \; \text{h.c.}$$

ajorana

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

$M_{0\nu}$: Quadratic dependence on g_A



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III. TeV Scale LNV

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

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Two parameters: Effective coupling & effective heavy particle mass

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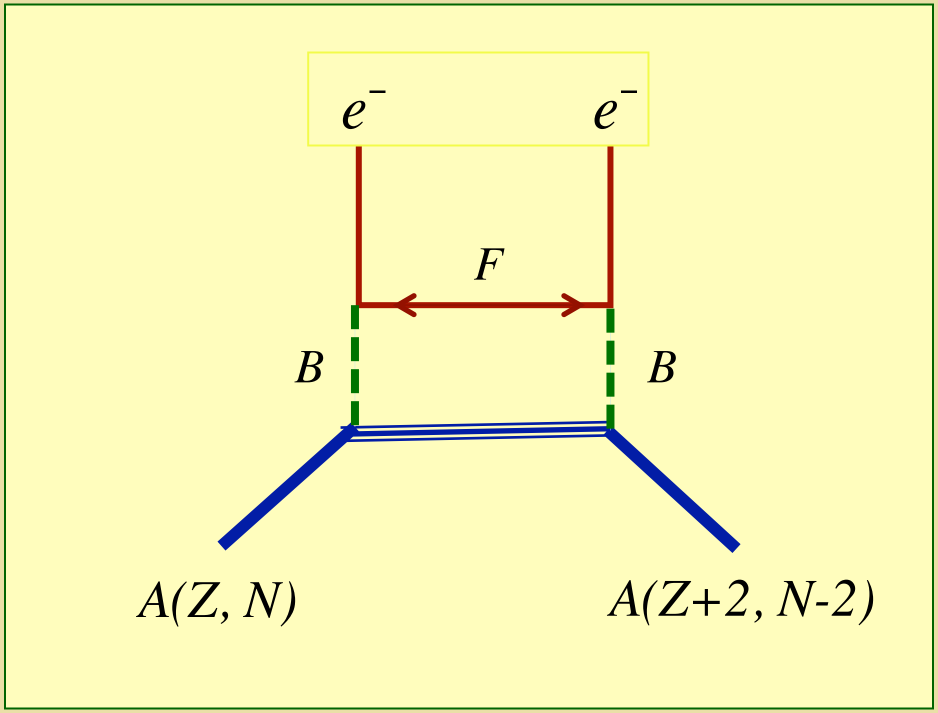
TeV LNV Mechanism

- *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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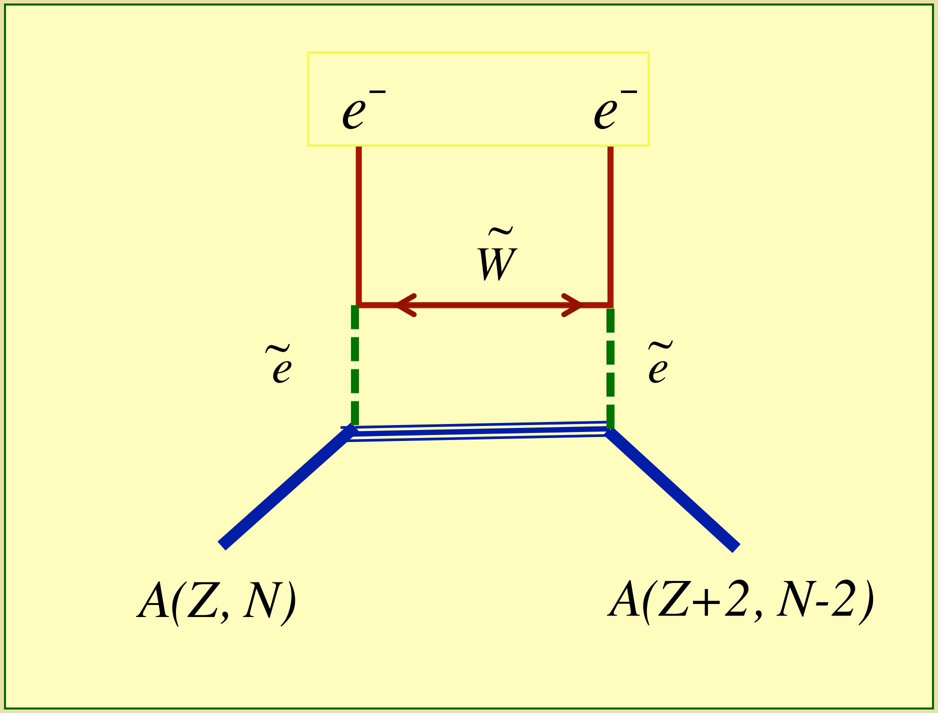


$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

Dirac

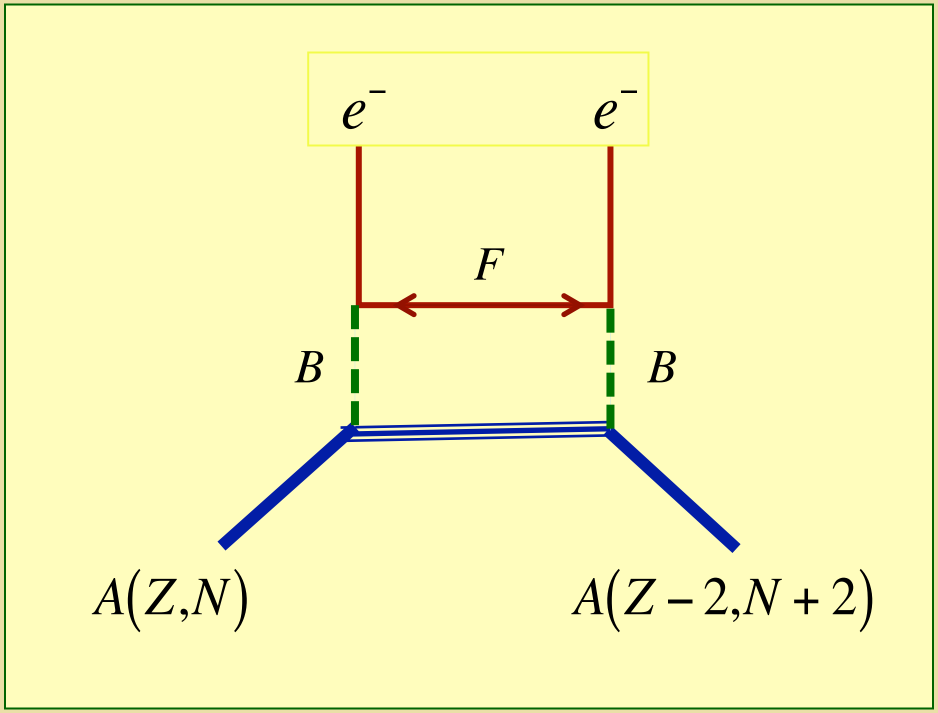
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

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



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Majorana

TeV LNV Mechanism

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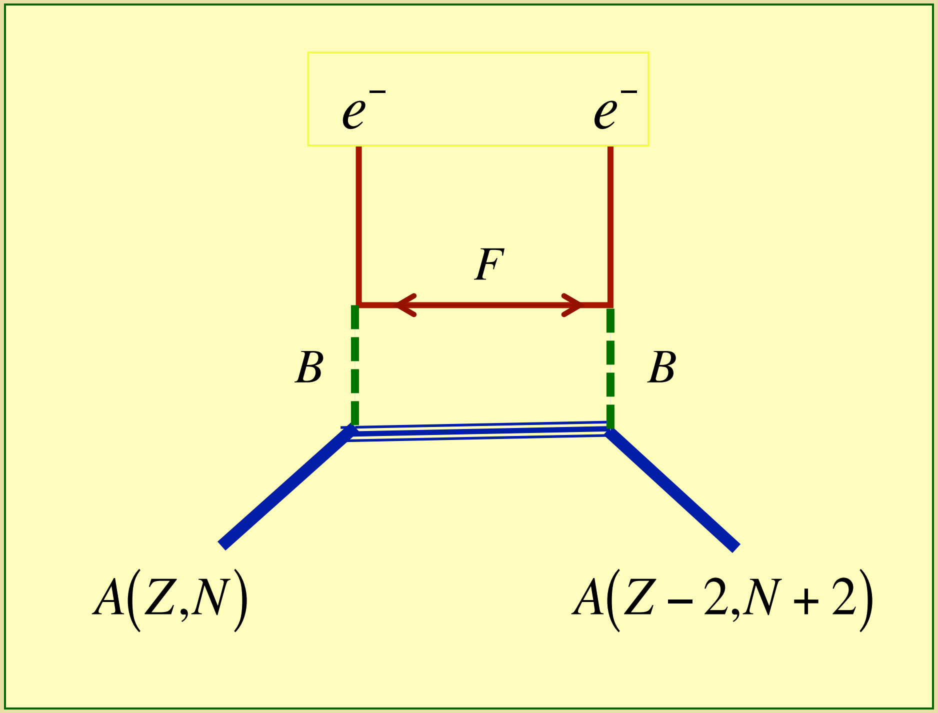
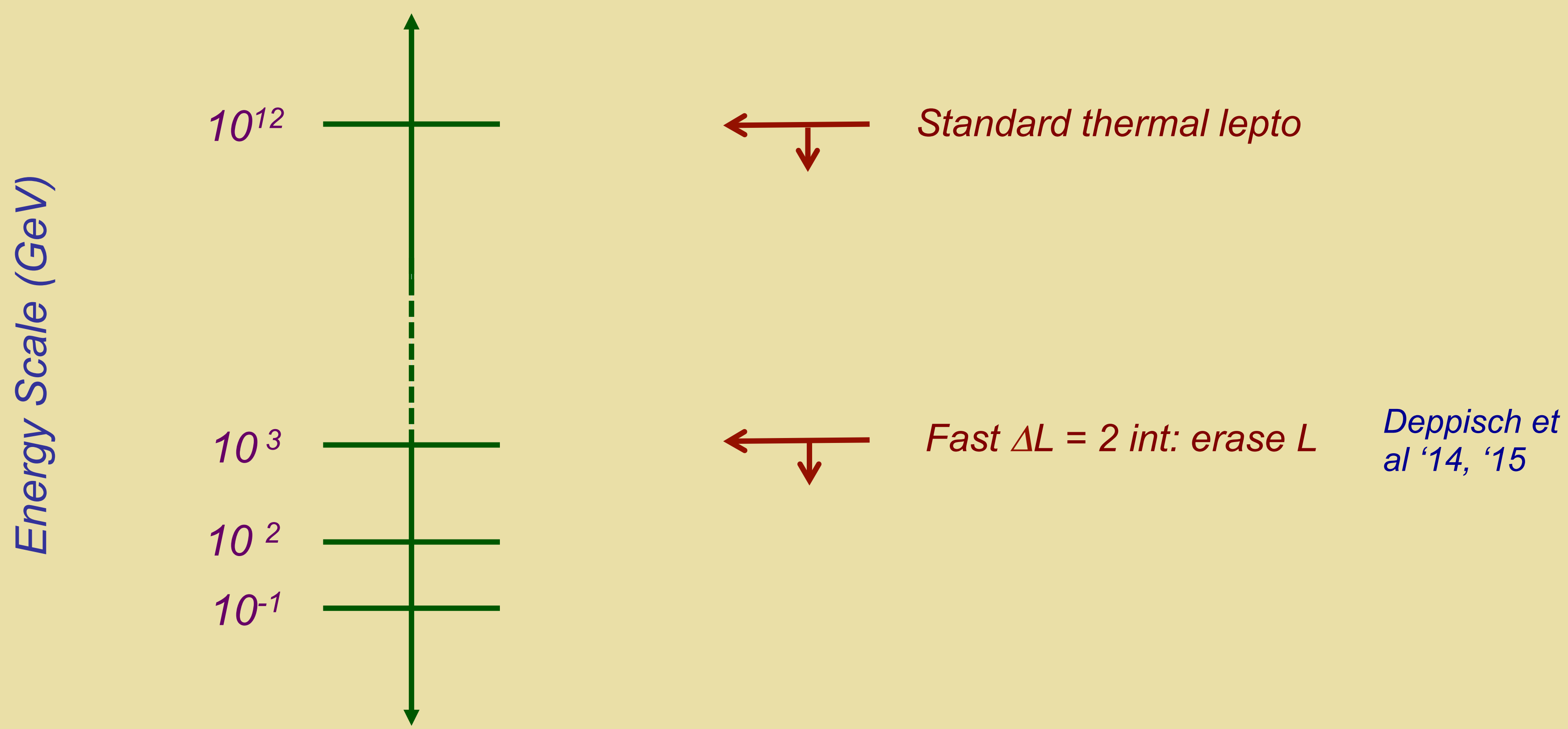
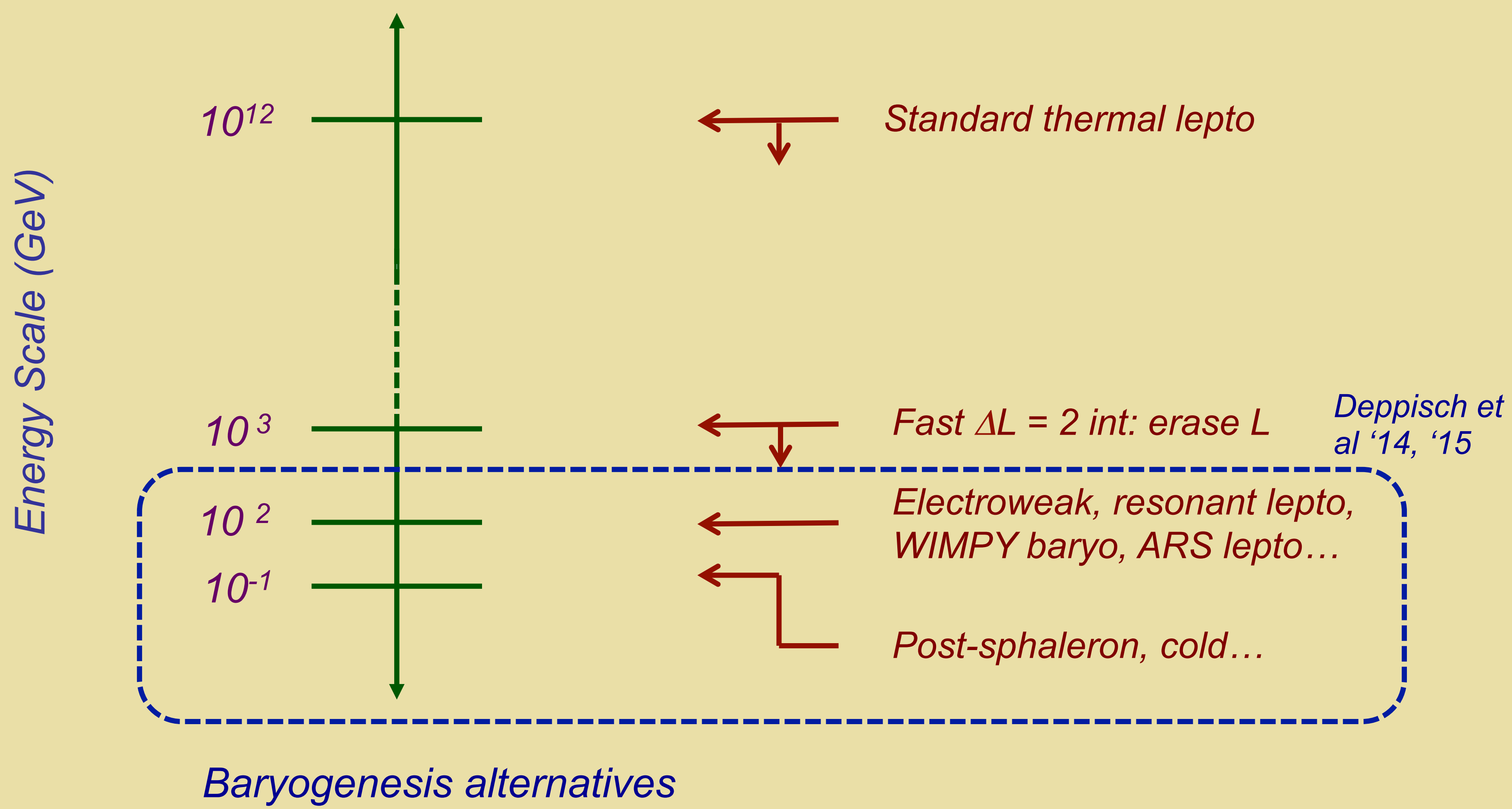
Implications



TeV LNV & Leptogenesis



TeV LNV & Leptogenesis



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

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

Dirac

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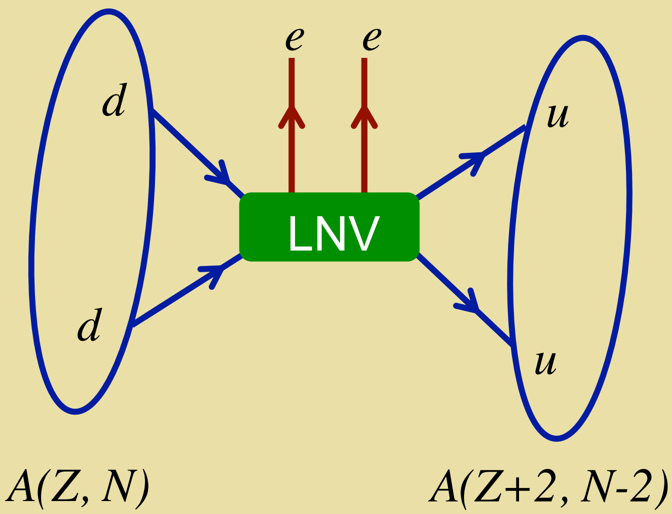
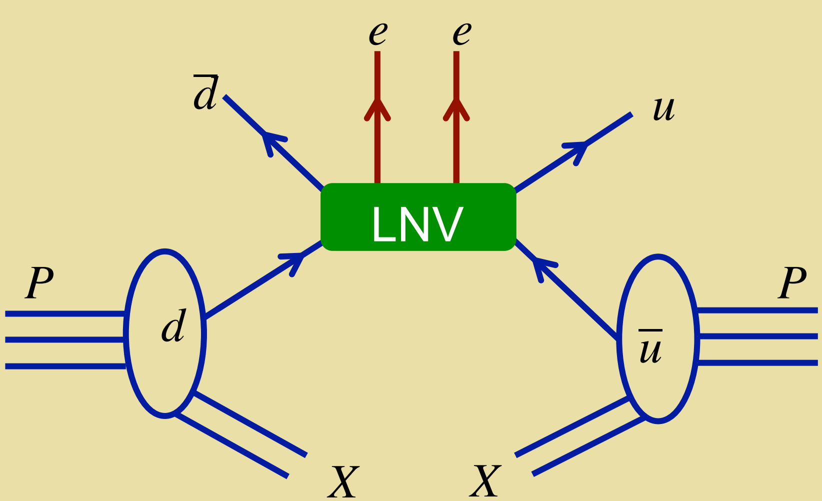
Majorana

$0\nu\beta\beta$-Decay



pp Collisions



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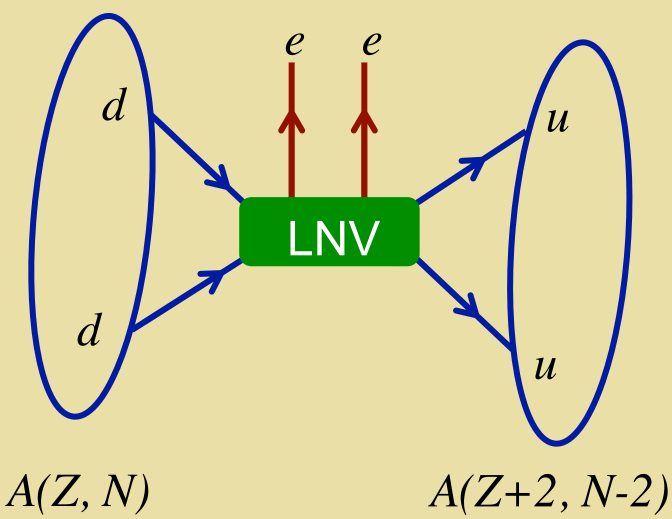
Dirac

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

Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



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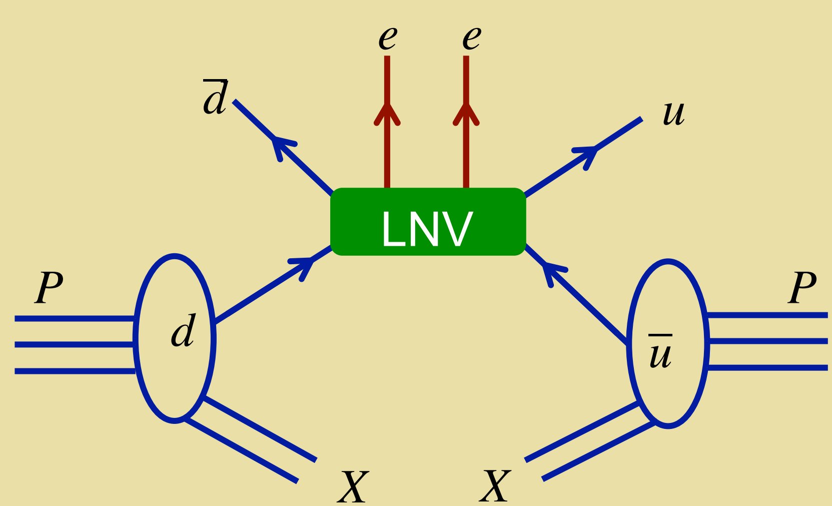

$0\nu\beta\beta$-Decay: TeV Scale LNV

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Dirac

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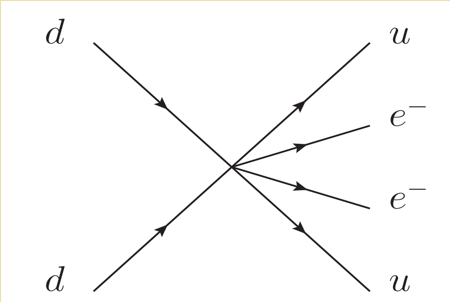
Majorana

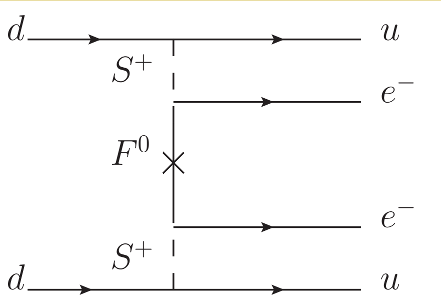
TeV Scale LNV

$0\nu\beta\beta$ - decay



Can it be discovered with combination of ***$0\nu\beta\beta$*** *& LHC searches ?*

LHC: pp $\rightarrow$ jj e^-e^-



Simplified models

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

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

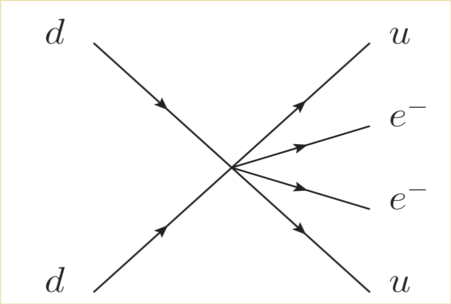
Dirac

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

Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay

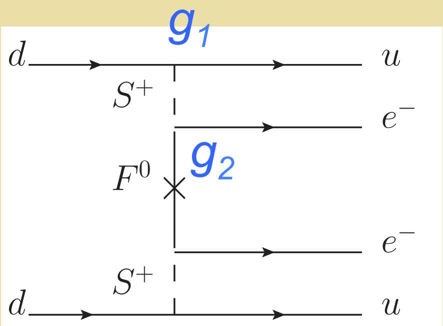


Effective operators:

$$\mathcal{L}^{\text{eff}}_{\text{LNV}} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + \text{h.c.}$$

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

LHC: pp $\rightarrow$ jj e⁻e⁻



$$g_{\text{eff}} = \sqrt{g_1 g_2}$$

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

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

Dirac

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

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

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

Scales as $1 / M^{10}$

0νββ-Decay: TeV Scale LNV

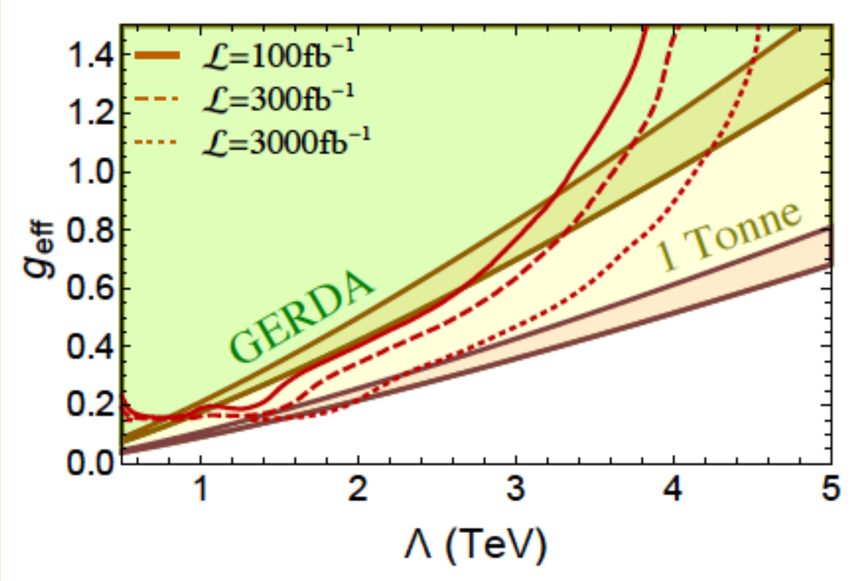
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

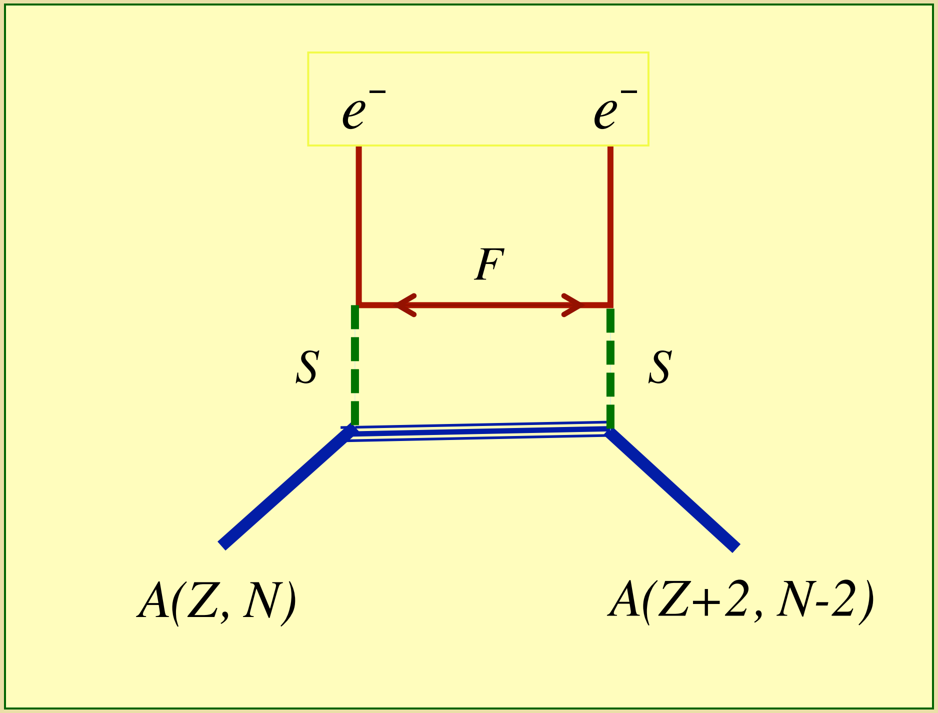
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



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

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

Dirac

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Majorana

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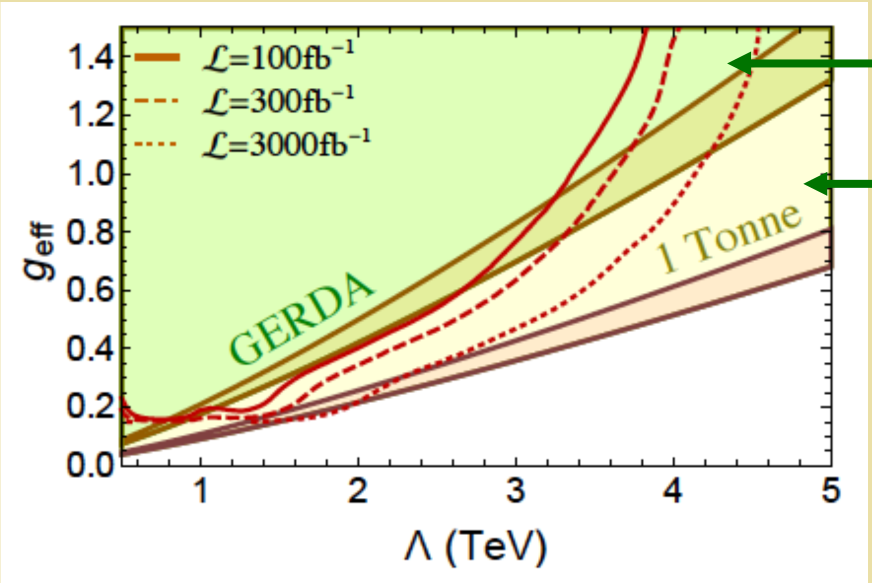

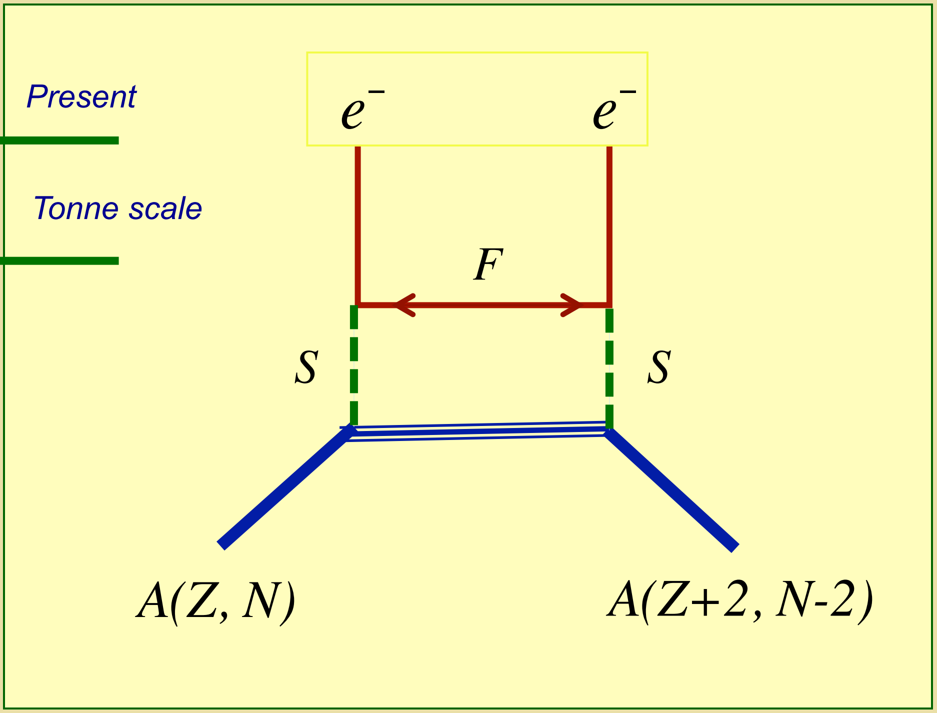

T. Peng, MRM, P. Winslow 1508.04444

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

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

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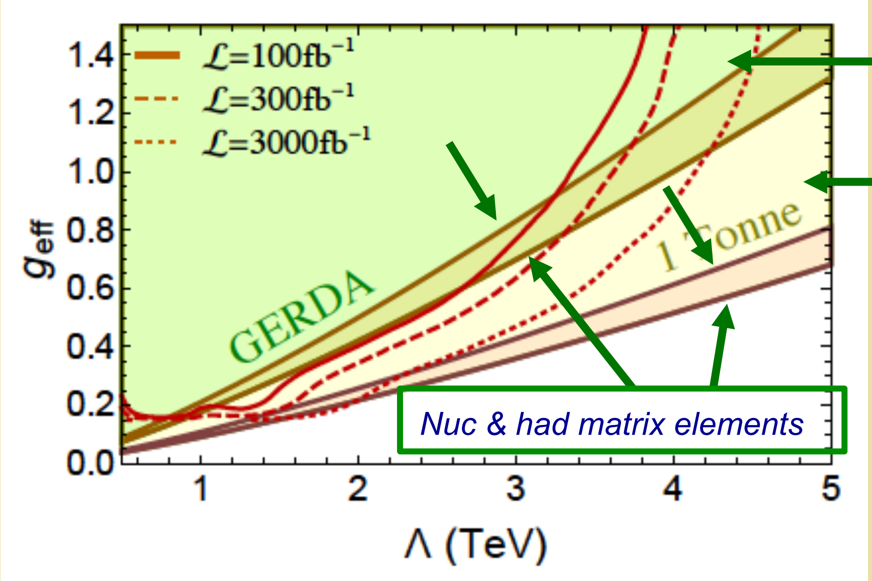
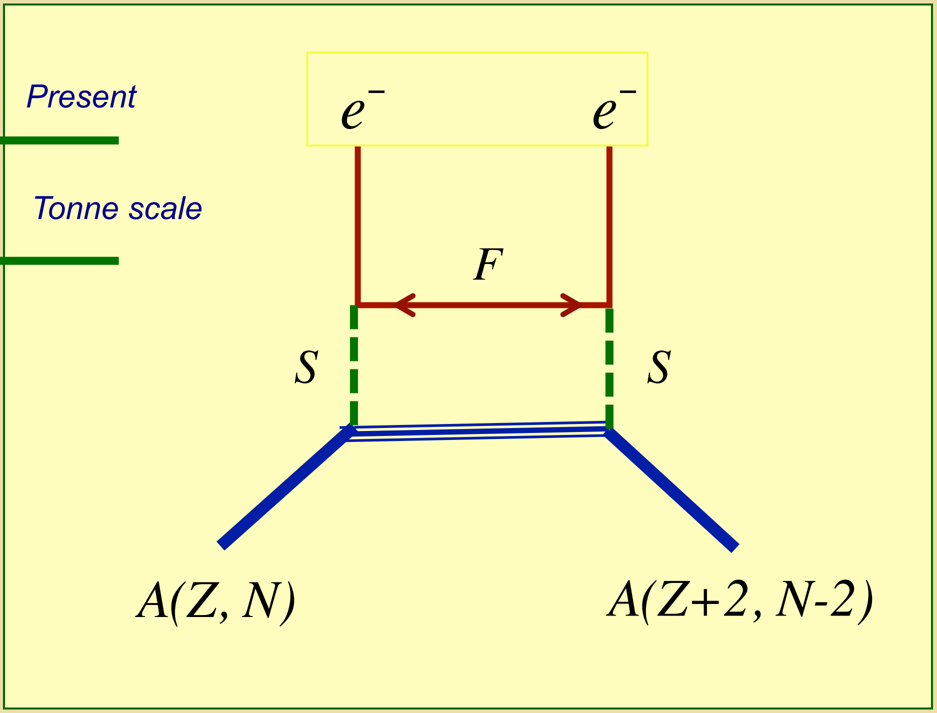
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

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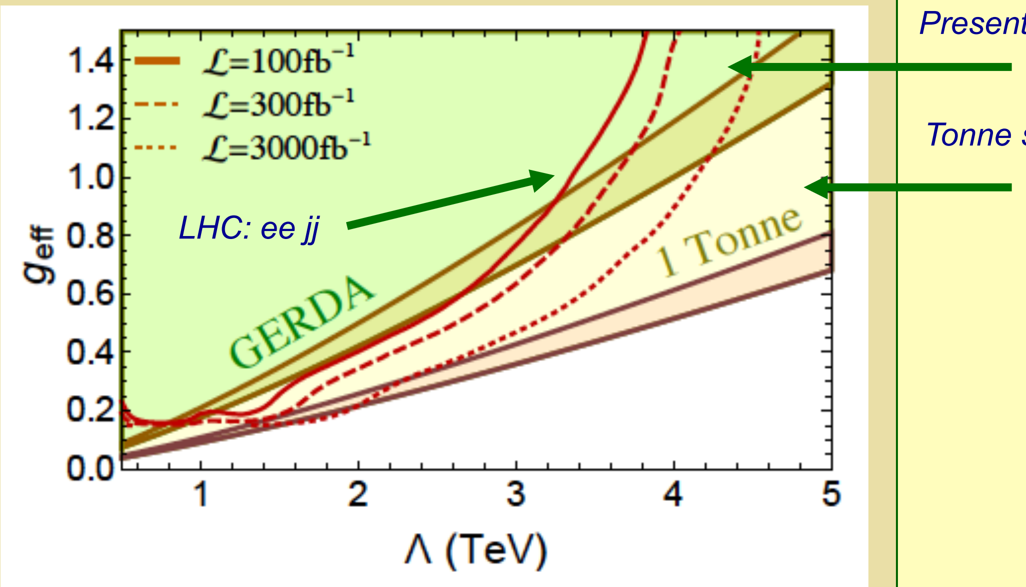
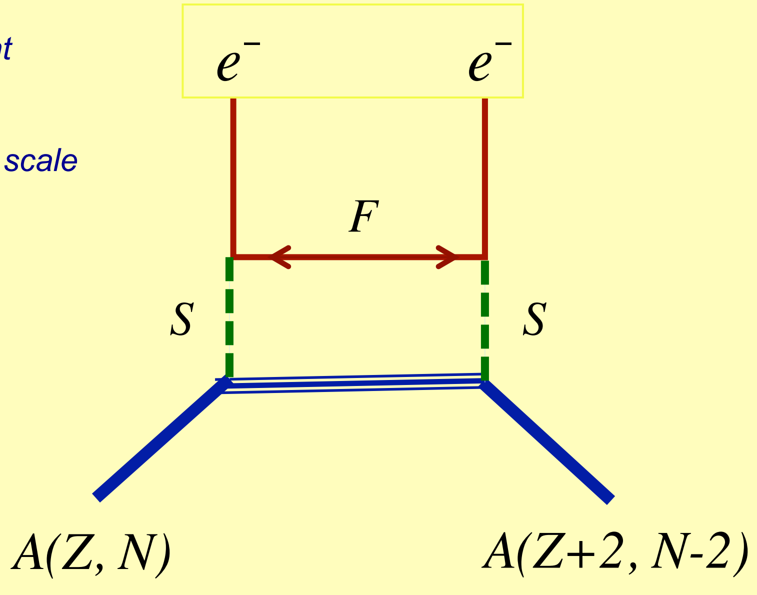
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

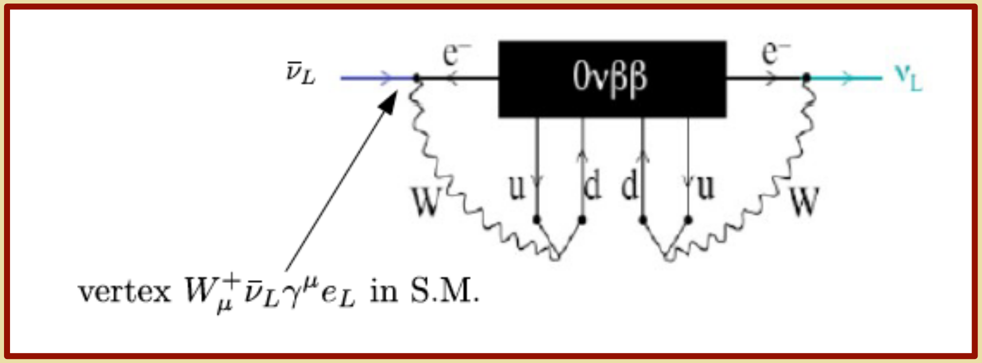
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

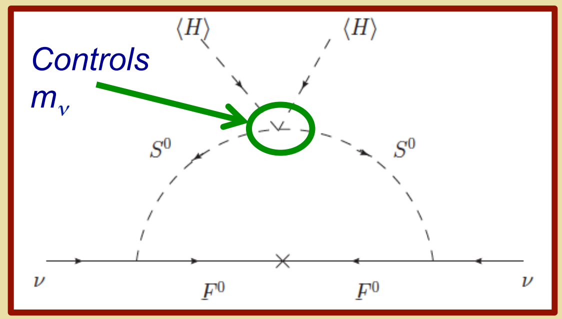
Dirac

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

Majorana

Implications for m_ν:





Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

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

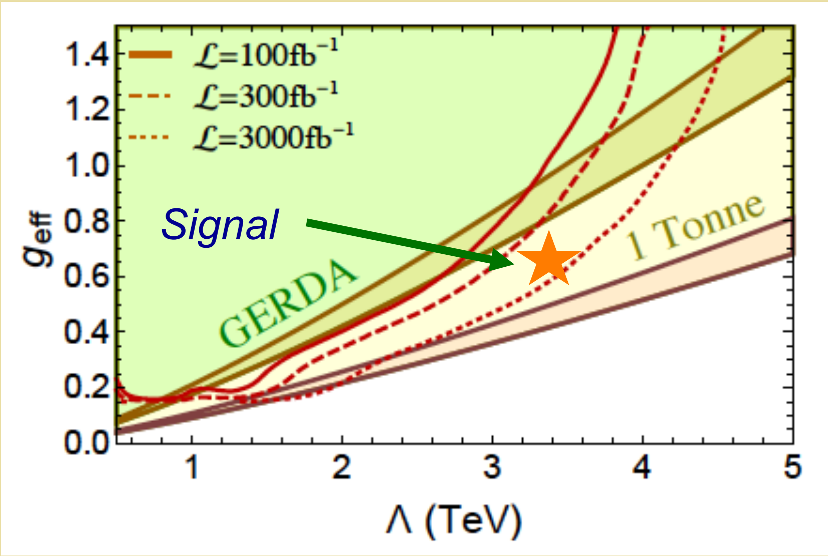
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

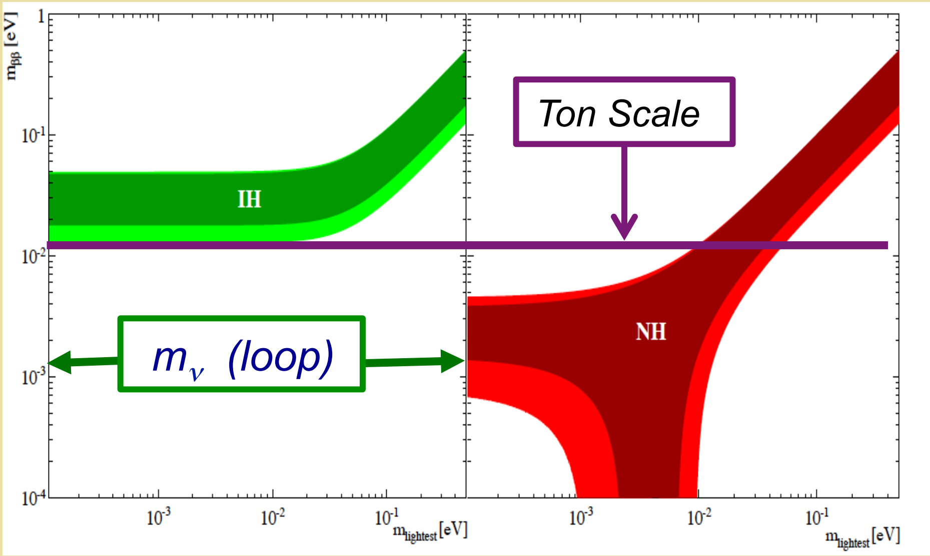
Dirac

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

Majorana

Implications for m_ν:

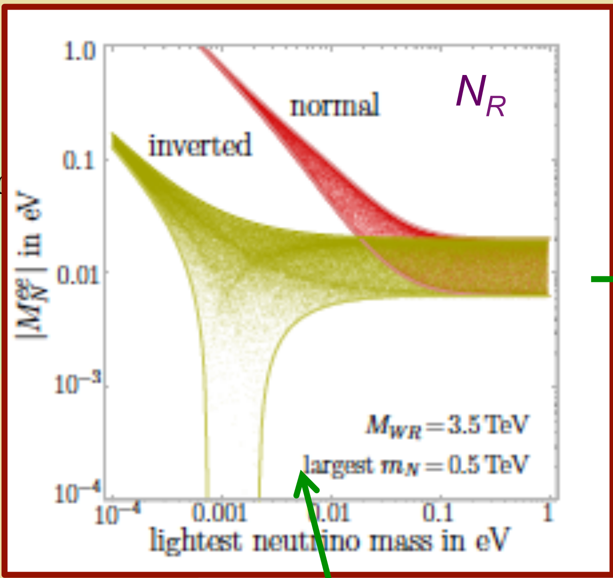


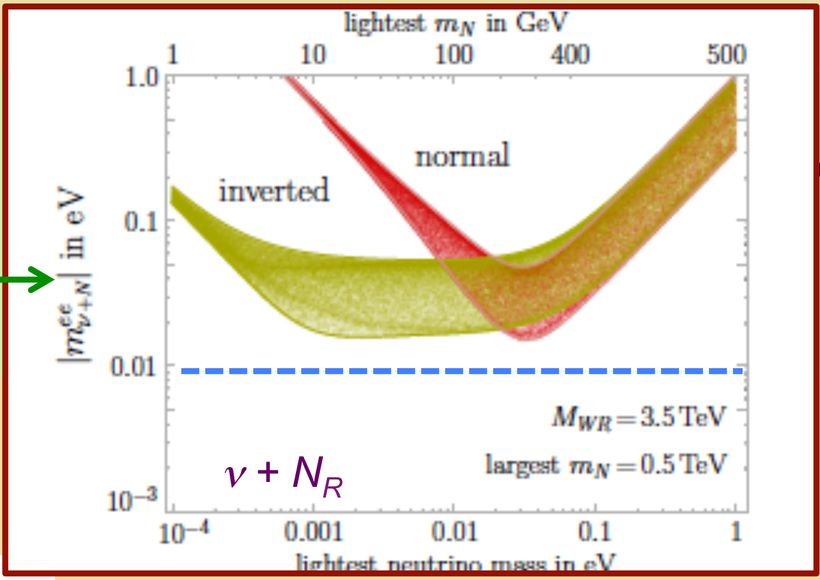


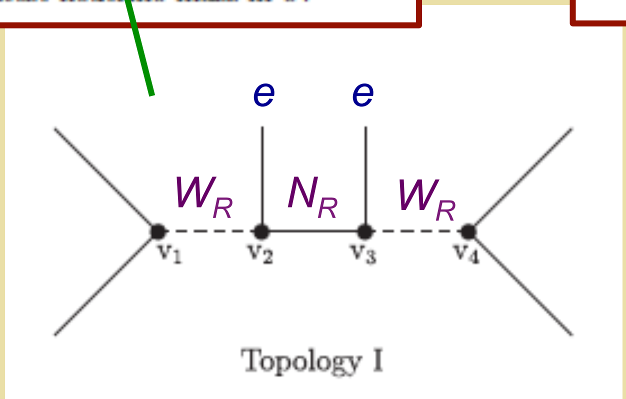
A hypothetical scenario

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

$\mathcal{L}_{\mathrm{n}}$ … c.







LRSM: Type I See-Saw

Mass: standard see-saw but TeV scale

Tello et al, 1011.3522

IV. Sub-Weak Scale LNV

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*

$0\nu\beta\beta$-Decay Sensitivity

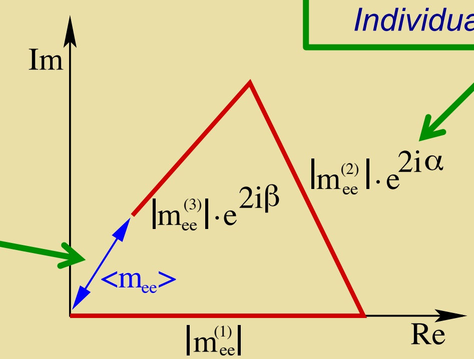
2ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^- \bar{\nu}\,\bar{\nu}$

If own antiparticle, can be emitted then absorbed during decay

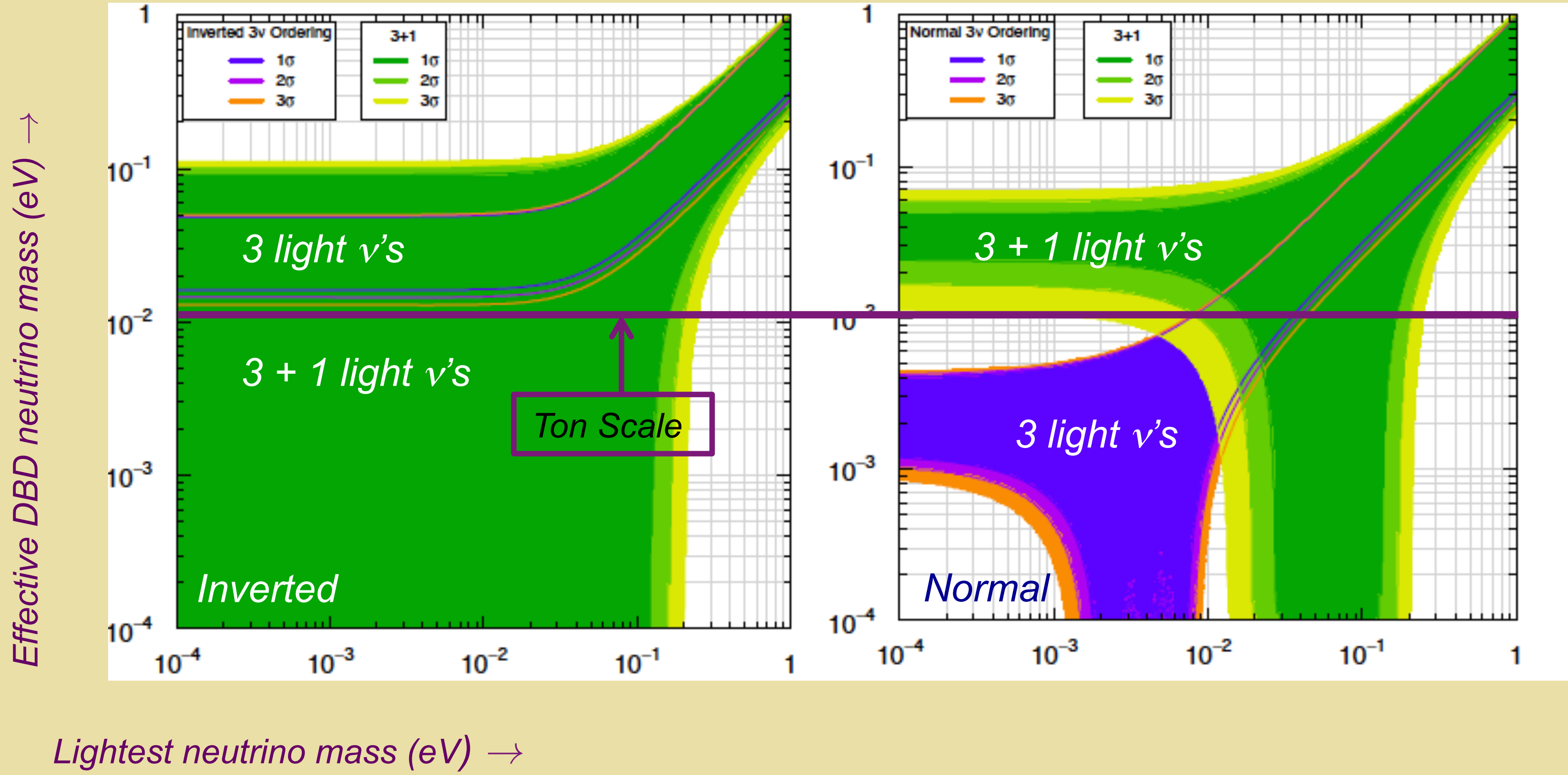
0ν DBD: $A(Z,N) \rightarrow A(Z+2, N-2) + e^- e^-$

Individual contributions

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



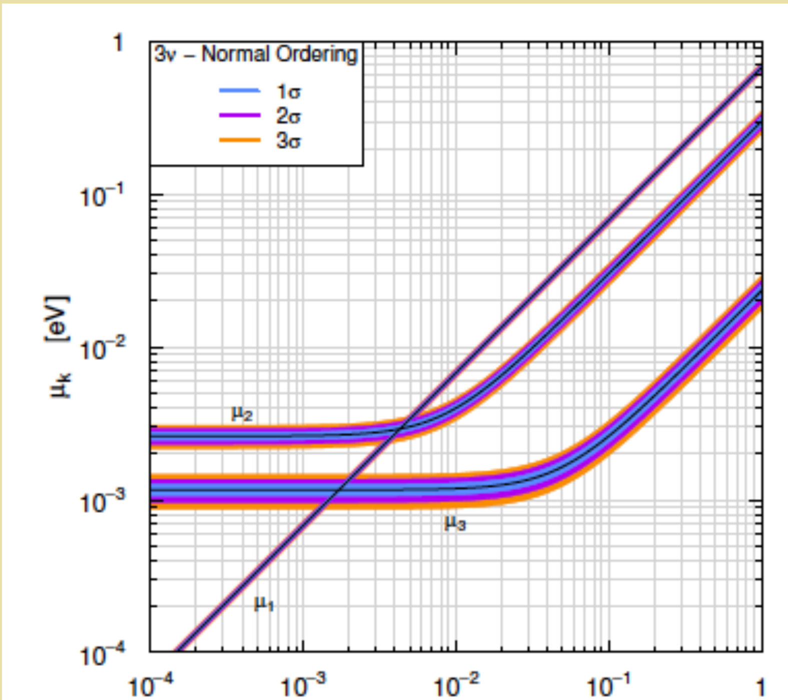
> 3 Light Neutrinos



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

Effective DBD neutrino mass (eV)

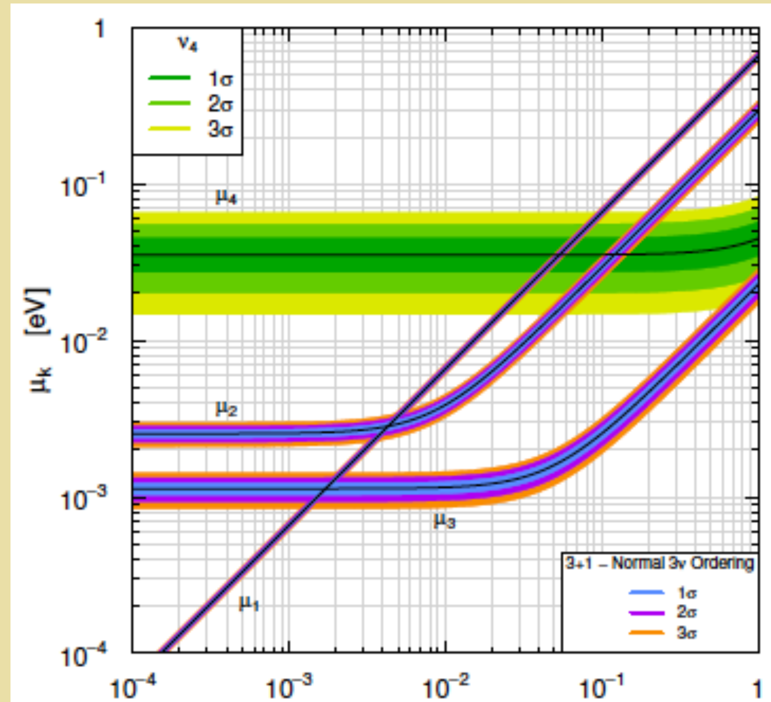
3 active light neutrinos



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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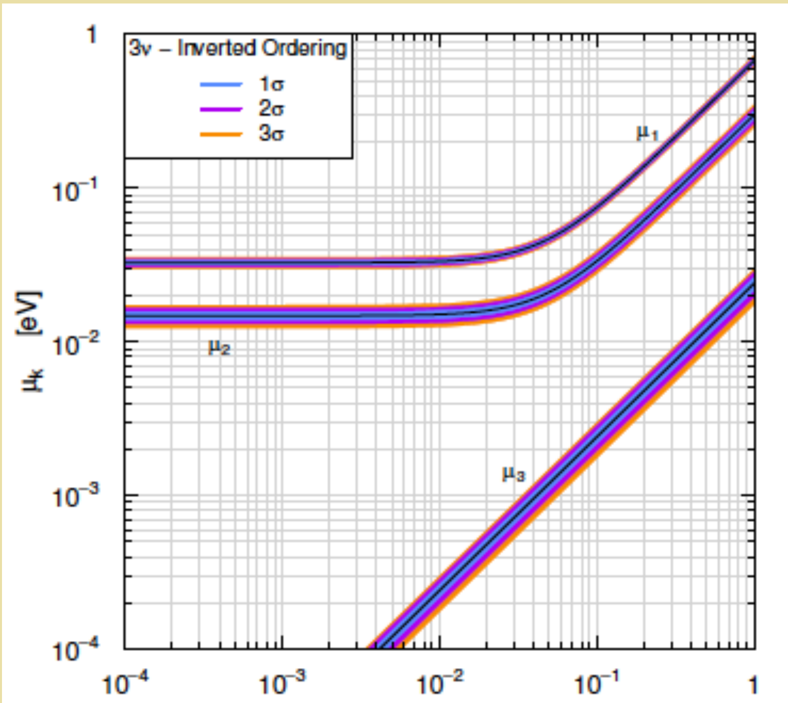
Giunti & Zavanin, JHEP07 (2015) 171

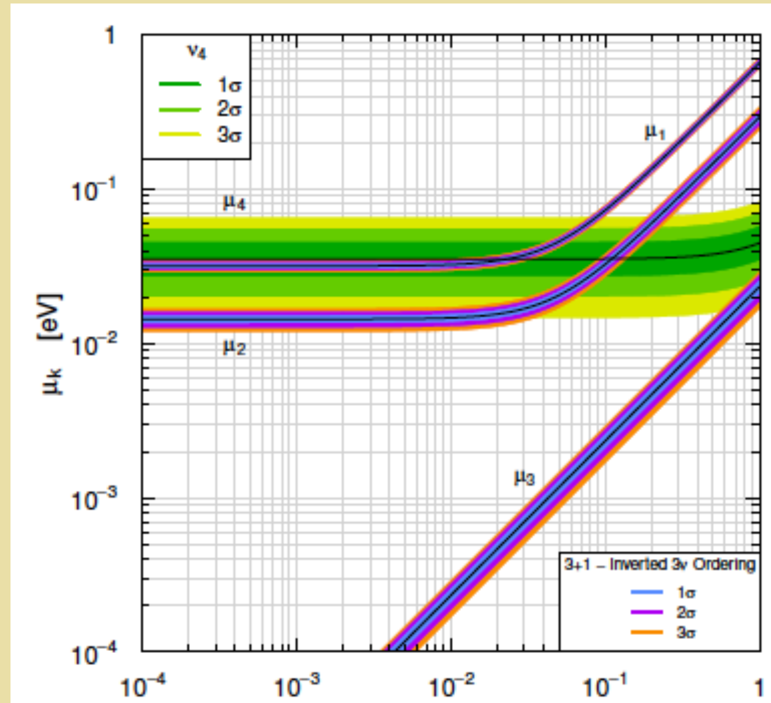
Sterile Neutrinos & $0\nu\beta\beta$−Decay

3 active light neutrinos

3+1 active light neutrinos

Effective DBD neutrino mass (eV)





Lightest neutrino mass (eV) $\rightarrow$

Lightest neutrino mass (eV) $\rightarrow$

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

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Giunti & Zavanin, JHEP07 (2015) 171

V. Discussion Questions

- *What is a sphaleron ?*
- *Is the CPV in V_{PMNS} the same as CPV for leptogenesis ?*
- *What is the conventional leptogenesis scale ?*
- *What is the Schecter-Valle (black box) theorem ?*