TeV Scale LNV: Connecting $0\nu\beta\beta$ – Decay, Colliders & Cosmology

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- UMass Amherst
- Caltech

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
MeToo

SYSU Workshop,
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Outline

I. Scientific Context

II. High-scale LNV

III. TeV-Scale LNV

IV. GeV and Below-Scale LNV

Time permitting

V. Conclusions

I. Scientific Motivation

Scientific Questions

- *Does nature violate conservation of total lepton number at the classical (Lagrangian) level ?*
- *If so, what is the associated LNV mass scale ?*
- *What is the sensitivity of ton-scale $0\nu\beta\beta$-decay searches under various LNV scenarios ?*
- *What are the inter-frontier implications?*

Origin of m_ν

Cosmology:
- **BAU**
- **Σm_ν**

ν Pheno

HEP

Lepton Number: ν Mass Term?

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

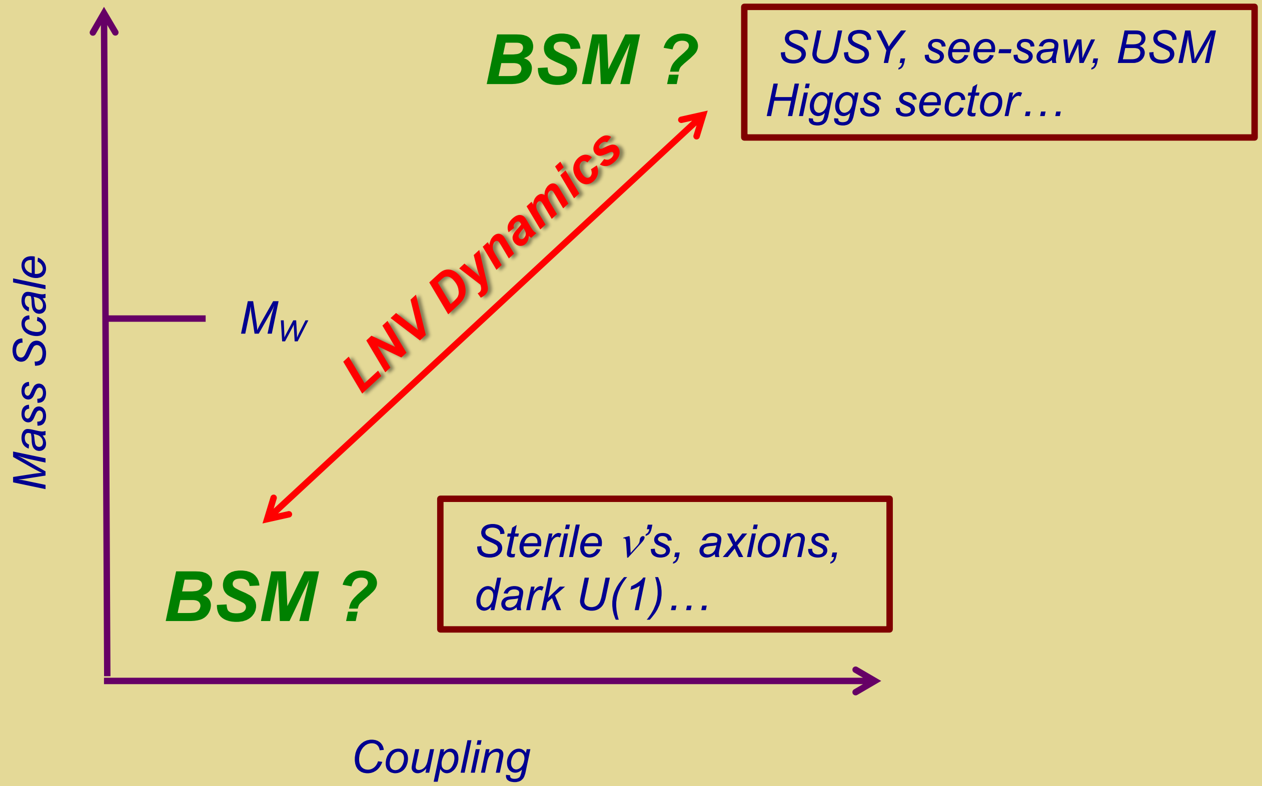
Dirac

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

Majorana

Mass scale for LNV dynamics ?

LNV Physics: Where Does it Live ?



Is the LNV scale (associated with m_ν) far above M_W ? Near M_W ? Well below M_W ?

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

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

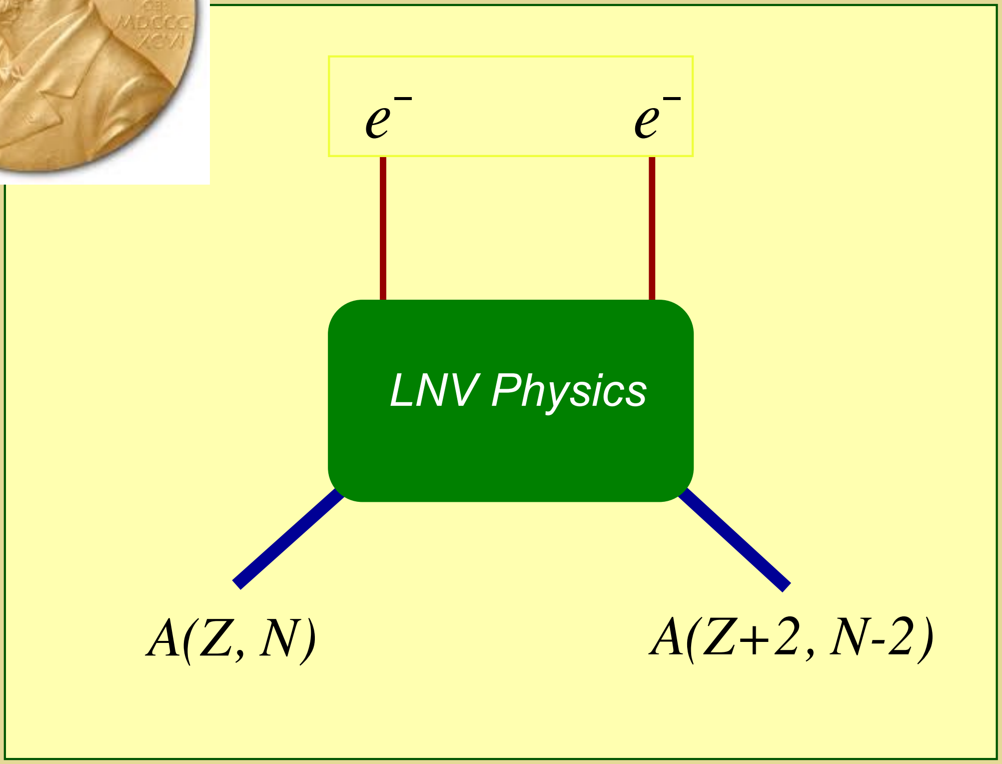
Dirac

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

Majorana

Impact of observation

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



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

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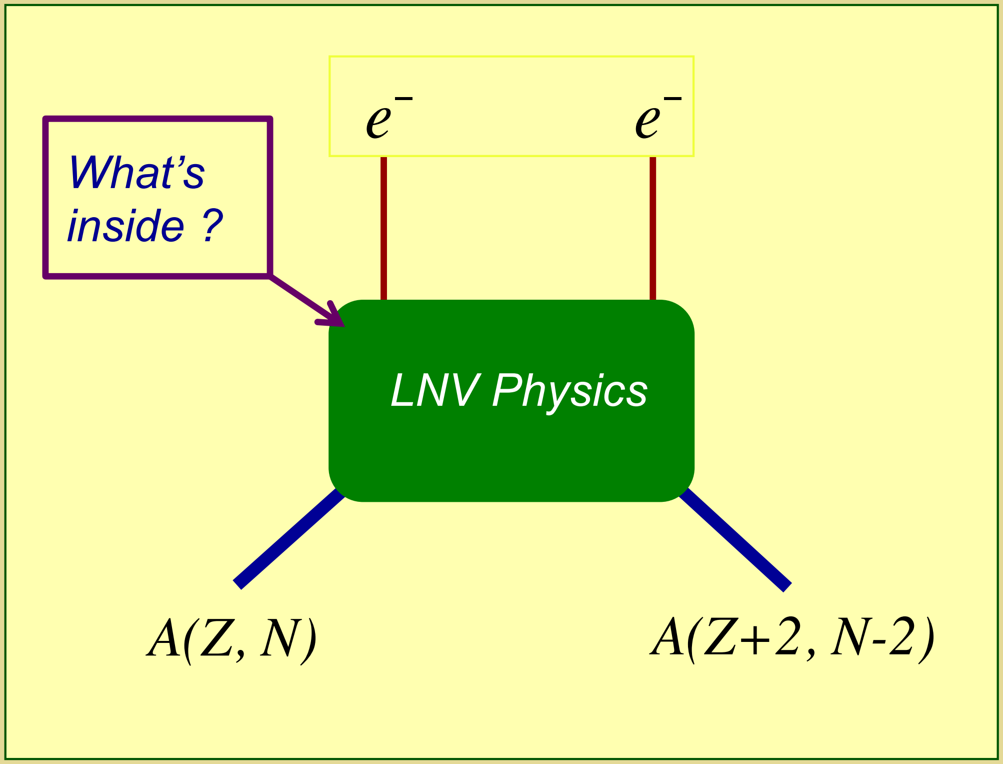
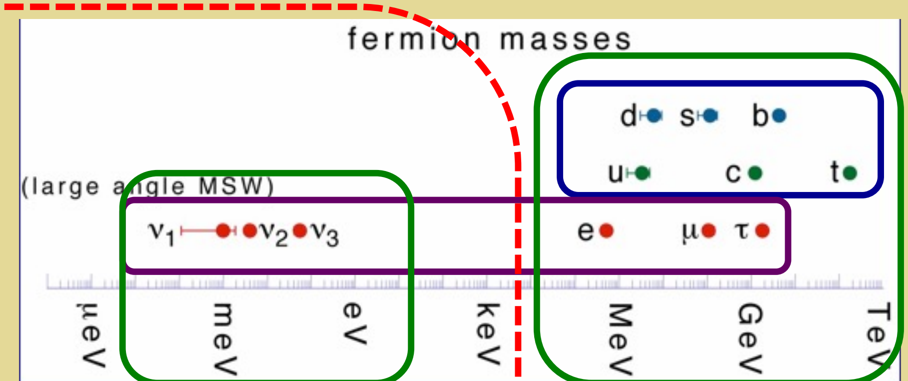


Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

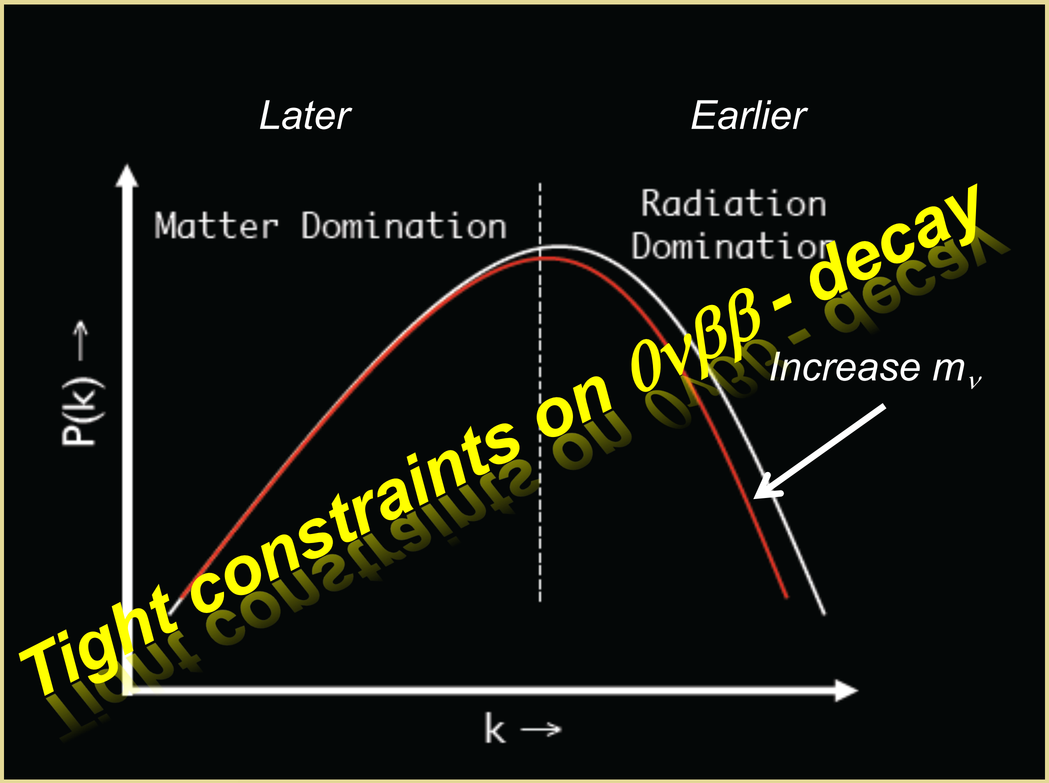
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

$0\nu\beta\beta$ Decay

Neutrino Mass & Cosmology

Matter Power Spectrum



$\Sigma\, m_\nu < 0.12$ eV

Palanque-Dalabrouille '15

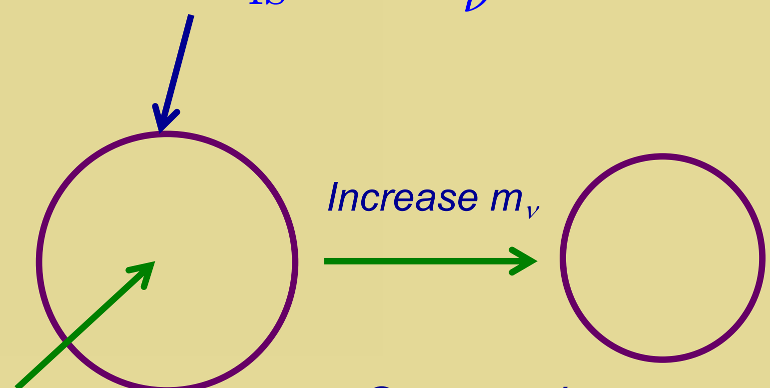
Neutrino Free Streaming

$\Omega_M = \Omega_\nu + \Omega_{DM} + \Omega_B$

$\delta\rho_\nu \longleftrightarrow \delta\rho_{DM}$

Free Streaming Scale

$$L_{\rm fs} \propto m_\nu^{-1/2}$$



$\delta\rho_\nu$ (power) suppressed for $L < L_{fs}$

Suppression moves to smaller scales → Larger k

BSM LNV: $0\nu\beta\beta$-Decay & Colliders

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

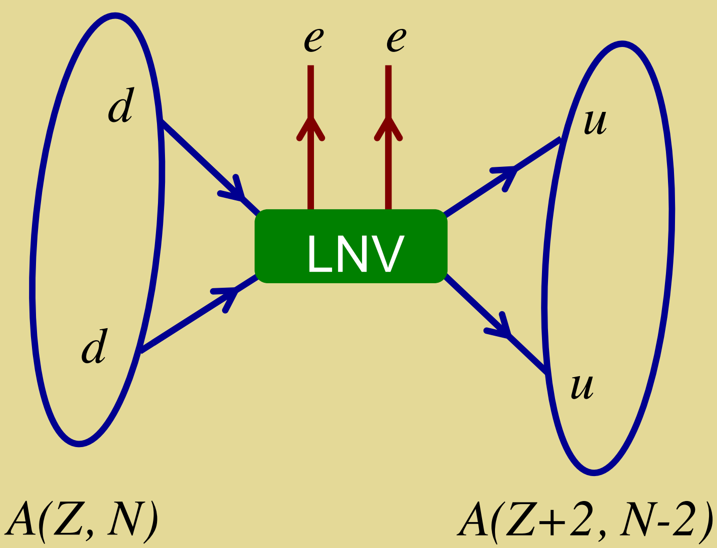
Dirac

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

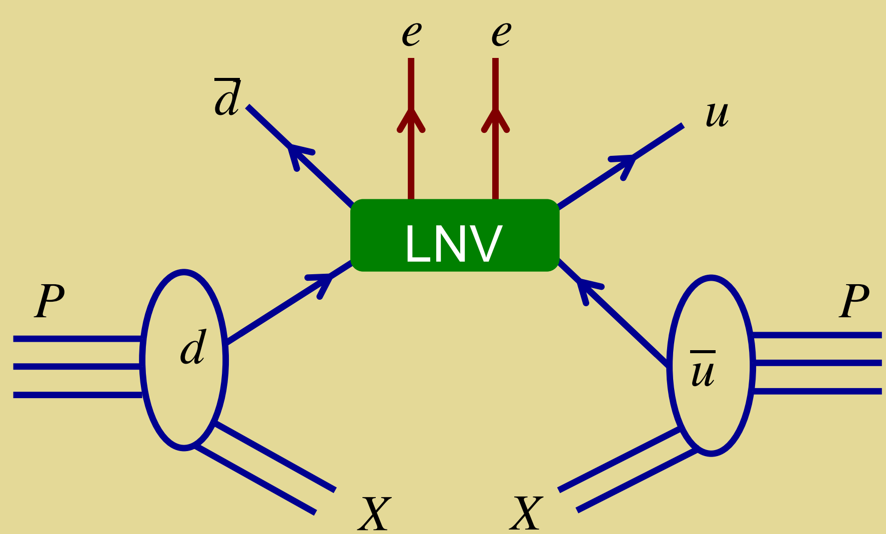
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



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 LNV*
- *> 3 light neutrinos*

II. High-Scale LNV

The “Standard Mechanism”

LNV Mass Scale & 0νββ-Decay

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

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
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$0\nu\beta\beta$-Decay: LNV? Mass Term?

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

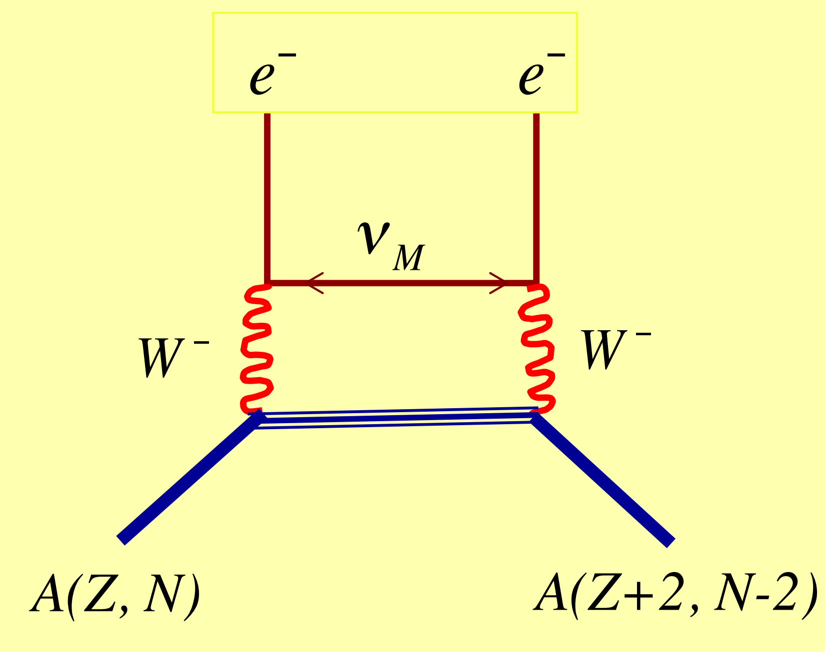
Dirac

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

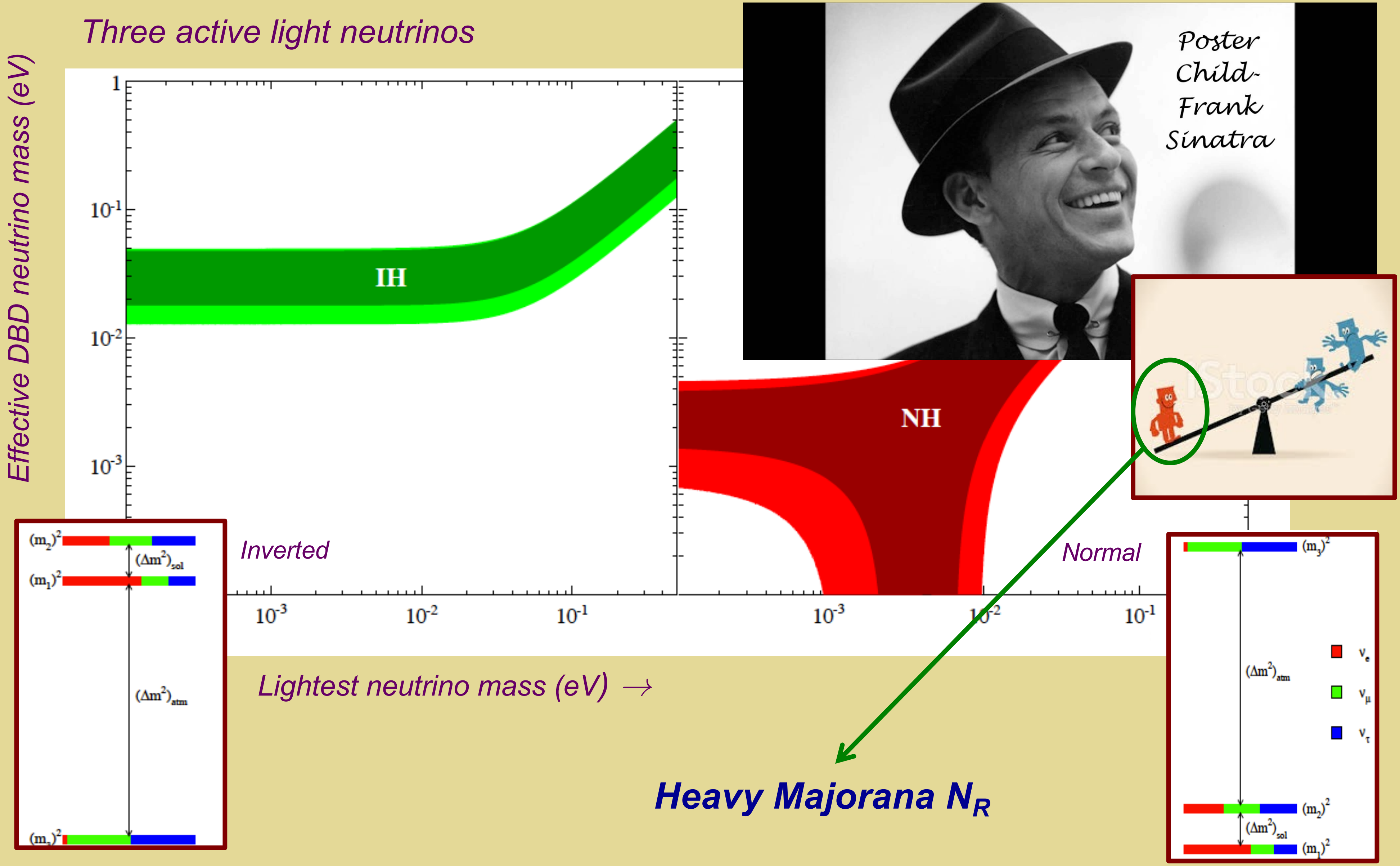
Majorana

"Standard" Mechanism

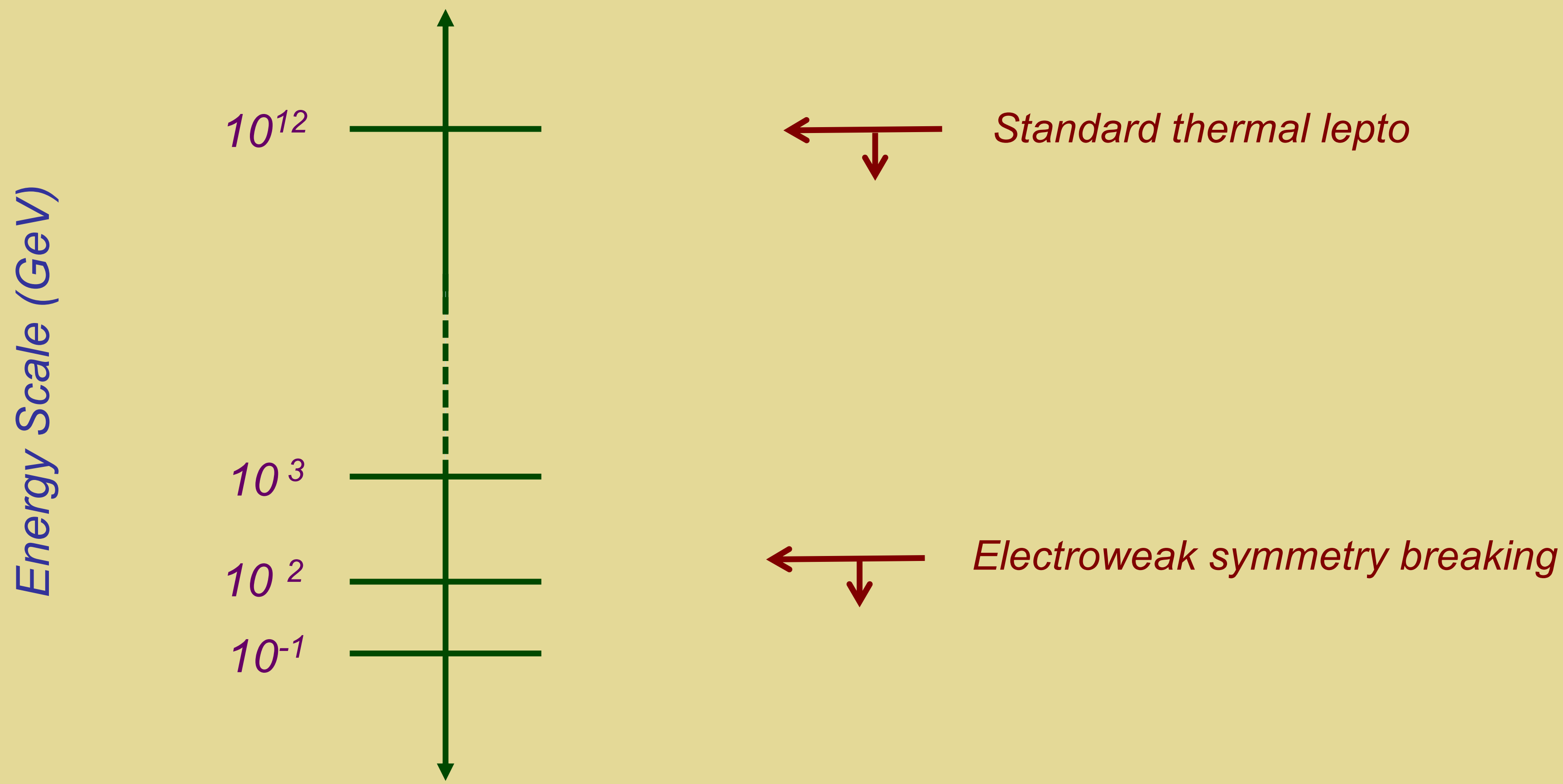
- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



$0\nu\beta\beta$-Decay: "Poster Child" Mechanism

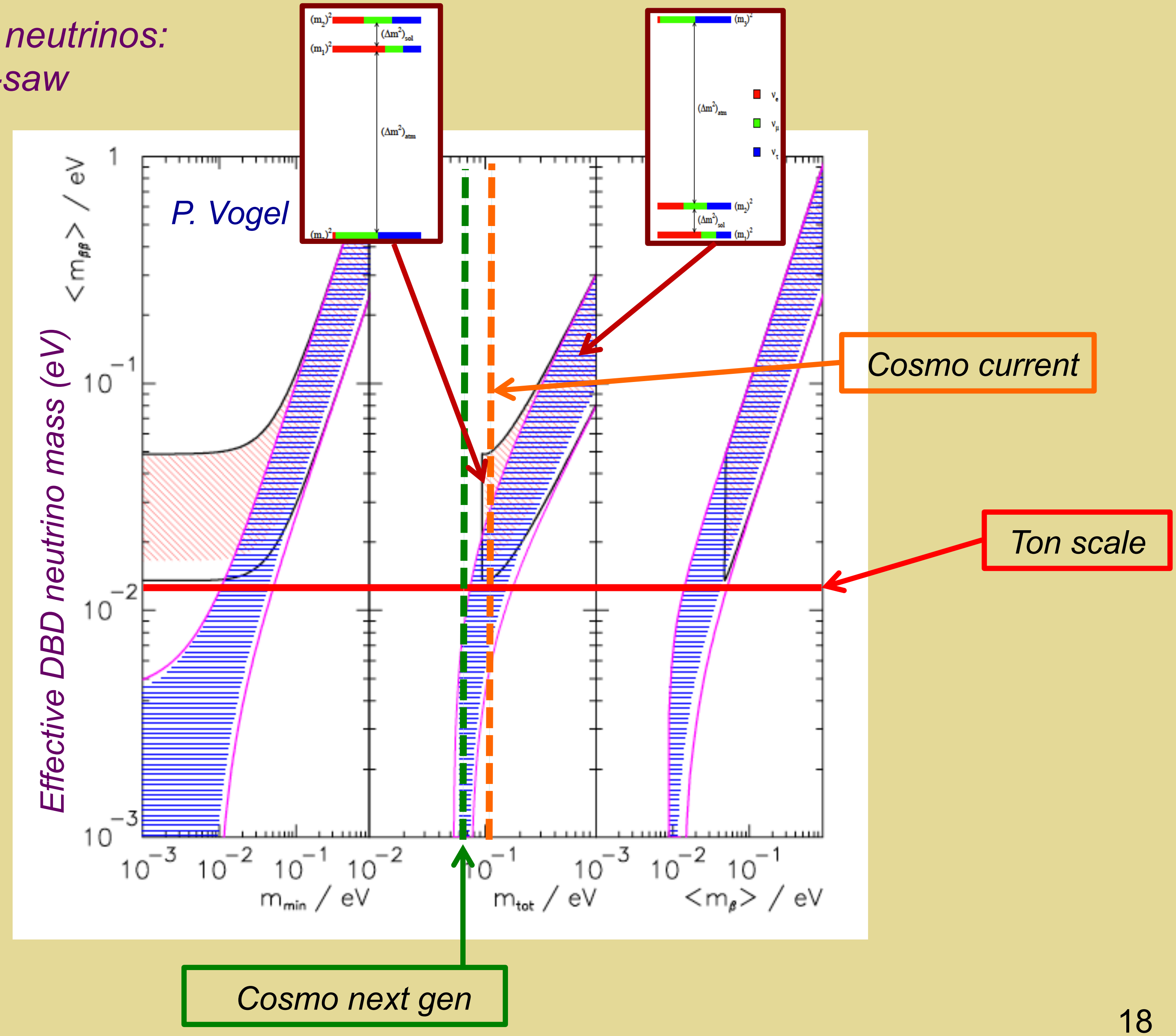


High Scale LNV & Leptogenesis



Σm_ν from Cosmo: $0\nu\beta\beta$-Decay Implications

Three active light neutrinos:
conventional see-saw



III. TeV-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 LNV
- > 3 light neutrinos

This talk

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

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

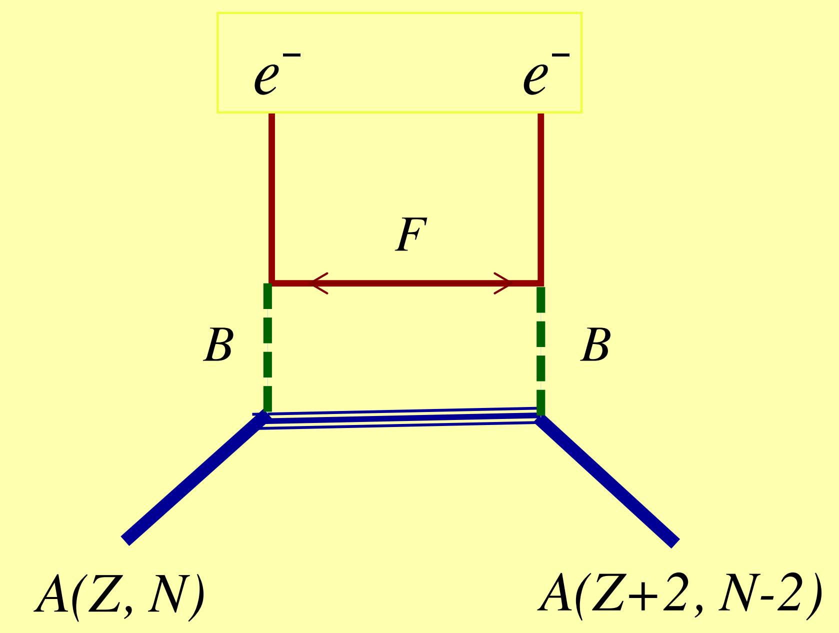
Dirac

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

Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *TeV 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*



Simplified Models: Illustrative Case

$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^a d^a S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$

S:	*(1, 2, ½)*	
F:	*(1, 0, 0)*	*Majorana*

Similar ingredients as in scotogenic neutrino mass models (but no Z_2 symmetry)

Implications

- *Nuclear Physics*
- *Leptogenesis*
- *Collider Searches*
- Σm_ν

TeV Scale LNV: EFT

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

Dirac

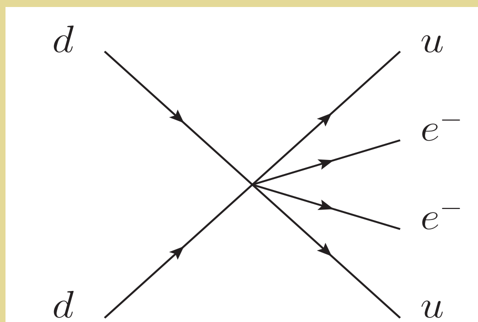
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

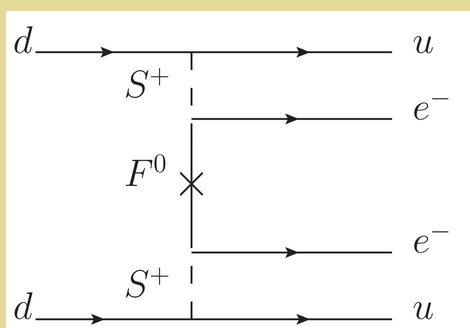
EFT "Bridge"

TeV Scale LNV

$0\nu\beta\beta$ - decay



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



Low-energy process → effective field theory with hadrons & leptons

High-energy process → "full theory" (simplified): keep TeV scale d.o.f. explicit

Low Energy: $0\nu\ \beta\beta$ - decay in EFT

d=9 effective operators

$$\mu = M_{WEAK}$$

$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{\beta\beta}} \sum_{j=1}^{14} C_j(\mu)\, \hat{O}_j^{++}\, \bar{e}\Gamma_j e^c \quad + \quad h.c.$$

e.g.

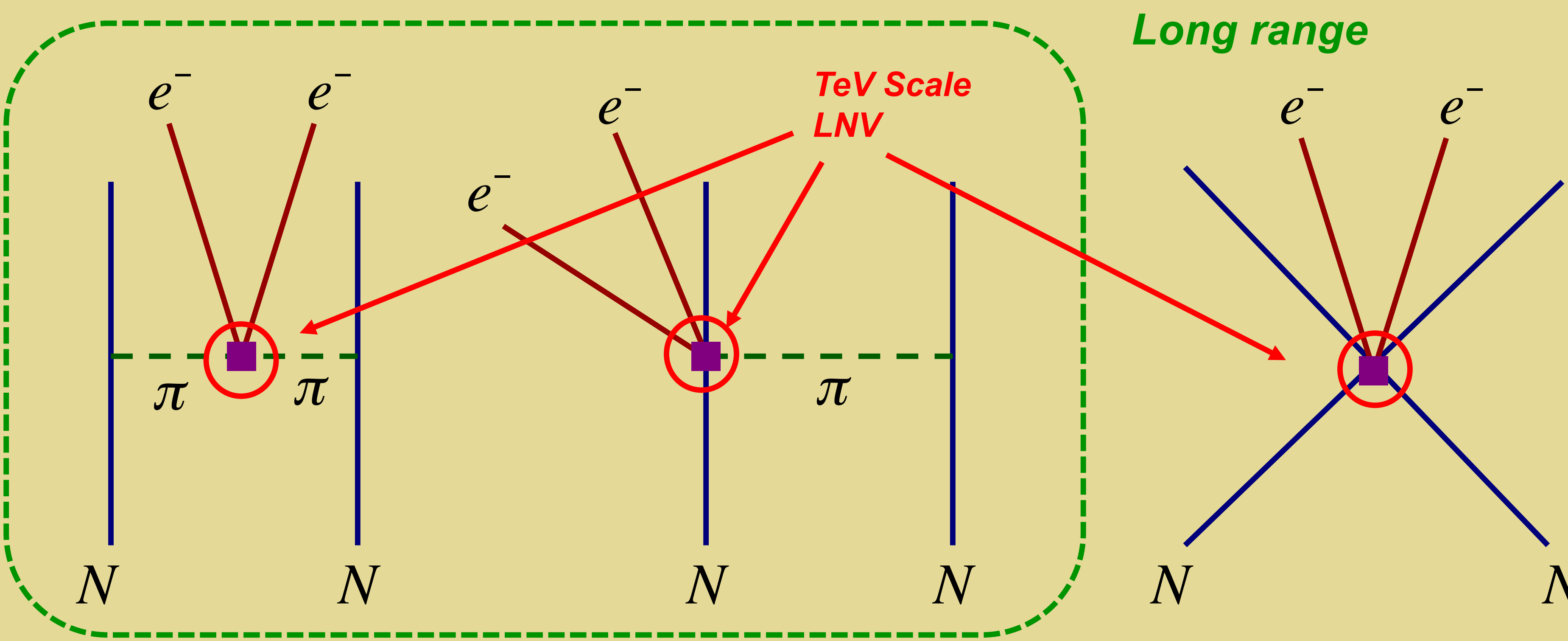
$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \boldsymbol{\tau}^a q_L\ \bar{q}_R \gamma_\mu \boldsymbol{\tau}^b q_R$$

$0\nu\ \beta\beta$ - decay: *a* = *b* = +

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

Chiral sym: map O_j onto $\mathcal{L}(\pi, N)$

Low Energy: $0\nu\ \beta\beta$ - decay in EFT



$K_{\pi\pi}\ p^{-2}$ $\qquad$ $K_{\pi NN}\ p^{-1}$ $\qquad$ $K_{NNNN}\ p^{0}$

$\mathcal{O}(p^{-2})$ for $\hat{O}^{++}_{1+}$ $\qquad$ $\mathcal{O}(p^{0})$ for $\hat{O}^{++}_{3+}$

Low Energy: $0\nu\ \beta\beta$ - decay in EFT

Operator classification

$$\mu = M_{WEAK}$$

$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{\beta\beta}} \sum_{j=1}^{14} C_j(\mu)\, \hat{O}_j^{++}\, \bar{e}\Gamma_j e^c \quad + \quad h.c.$$

Chiral sym: map O_j onto $\mathcal{L}(\pi, N)$

- Prezeau, MJRM, Vogel PRD 68 (2003) 034016 [hep-ph/0303205]
- M.J. Graesser, 1606.04549
- Cirigliano et al, 1806.02780
- …

EFT

- A. Nicholson et al, 1805.02634
- …

LQCD

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

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

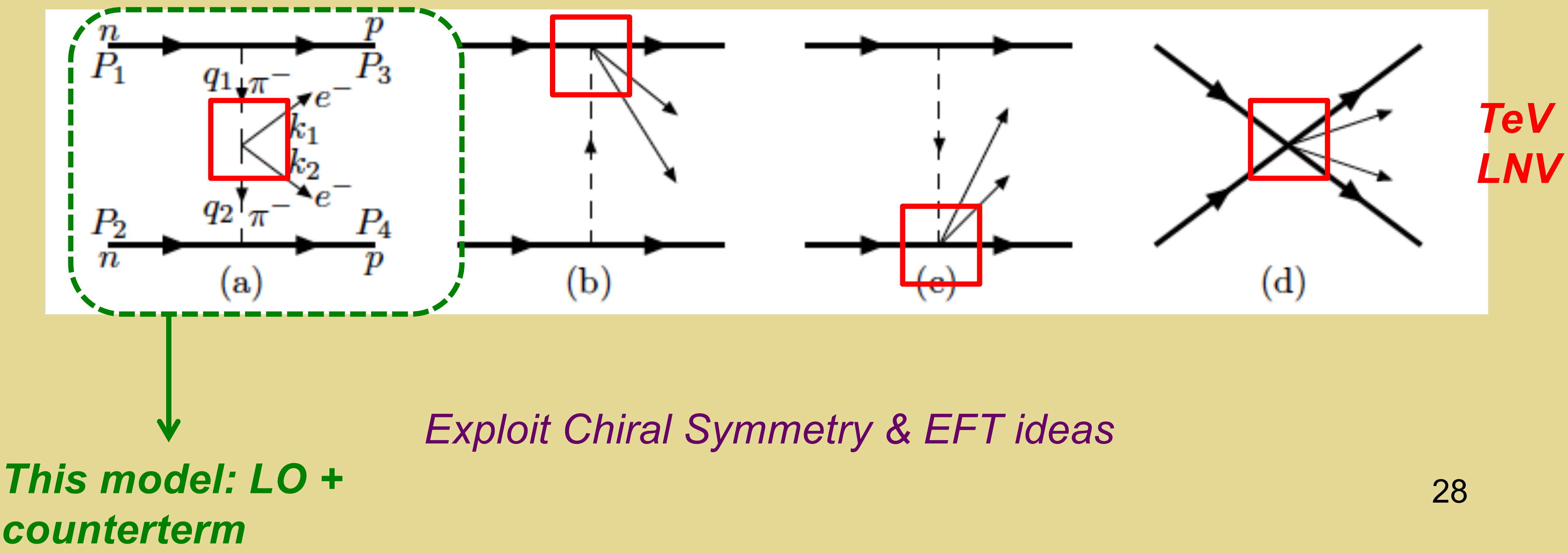
Dirac

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

Majorana

Low energy: *Nuclear Matrix Elements: Long Range Effects*

*Prezeau, R-M, Vogel '03 **

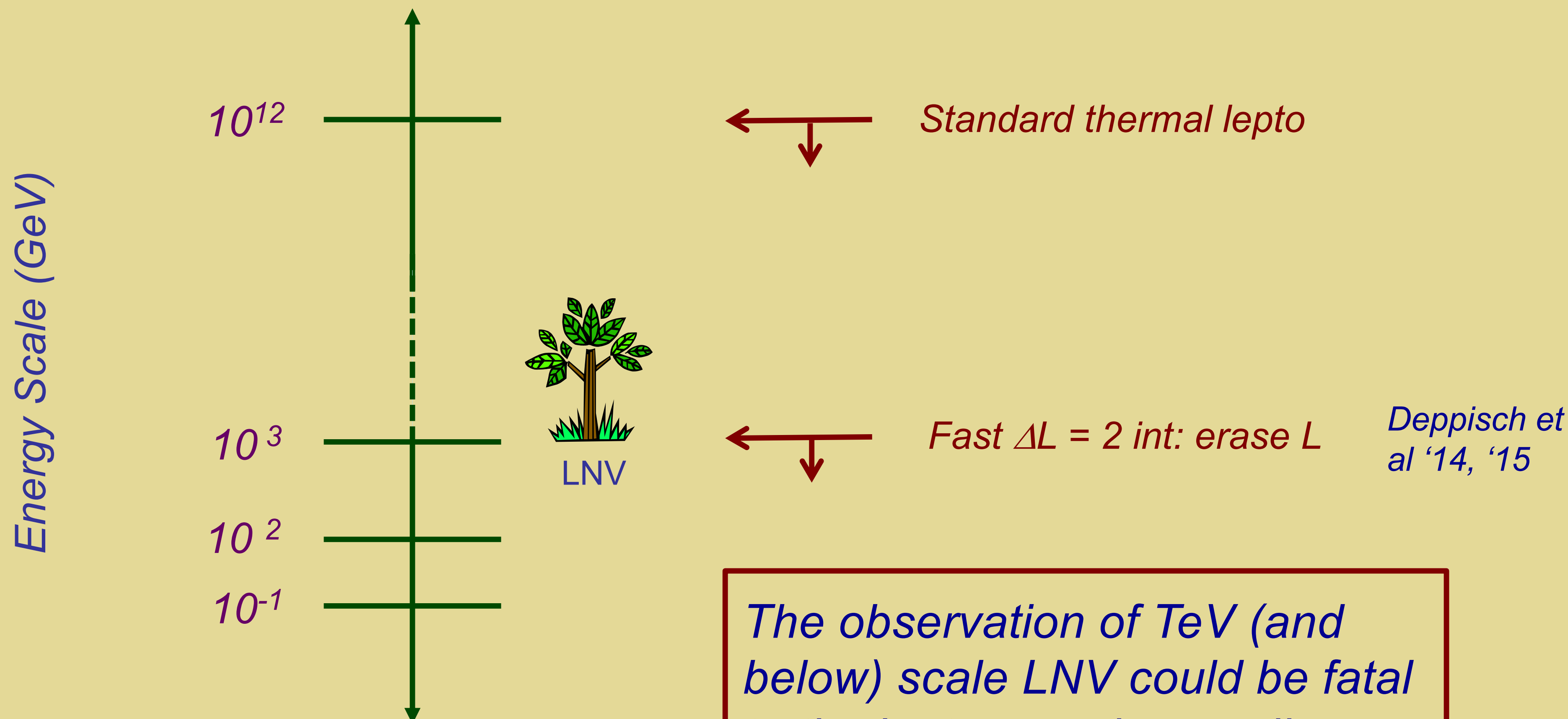


Exploit Chiral Symmetry & EFT ideas

Implications

- *Nuclear Physics*
- *Leptogenesis*
- *Collider Searches*
- Σm_ν

TeV LNV & Leptogenesis



The observation of TeV (and below) scale LNV could be fatal to the leptogenesis paradigm

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

$$\frac{dY_N}{dz} = -(D+S)\left(Y_N - Y_N^{\mathrm{EQ}}\right)$$

$$\frac{dY_{B-L}}{dz} = -\epsilon D\left(Y_N - Y_N^{\mathrm{EQ}}\right) - W\,Y_{B-L}$$

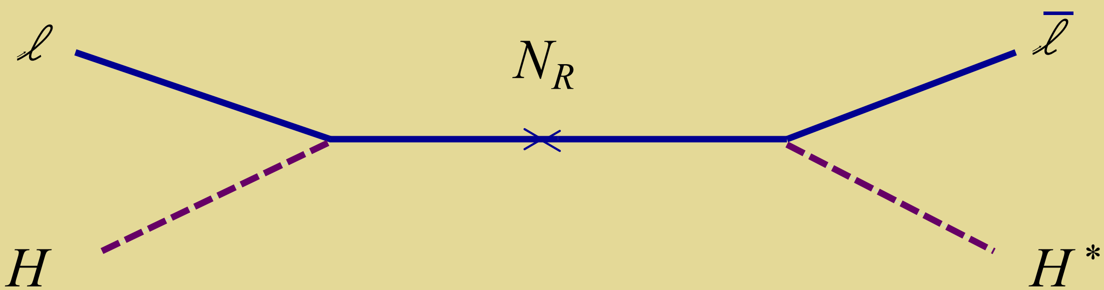
CPV Decay Asymmetry: source

Wash out: Inverse decays, ΔL = 1, 2 processes…

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Washout processes



$\Delta L = 2$

Converts leptons into anti-leptons

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Washout processes

$\Delta L = 2$

Converts leptons into anti-leptons

Leptogenesis & TeV Scale LNV: Example

The "O2 Model": similar ingredients as in scotogenic neutrino mass models (but no Z_2 symmetry)

$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^\alpha d^\alpha S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$

S:	*(1, 2, ½)*	
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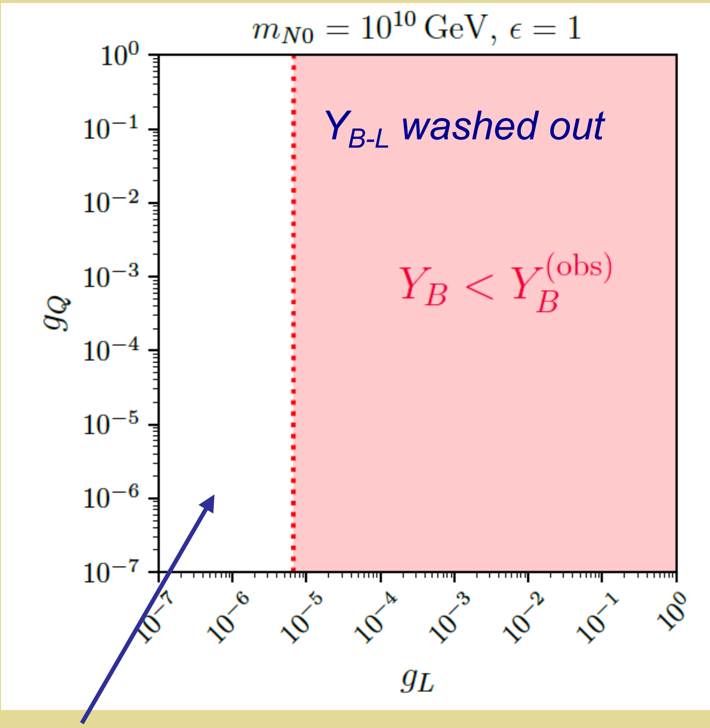

$Y_{B\text{-}L}$ survives

J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga '21

Implications

- *Nuclear Physics*
- *Leptogenesis*
- *Collider Searches*
- Σm_ν

TeV-Scale LNV: lepto, $0\nu\beta\beta$-Decay & Colliders

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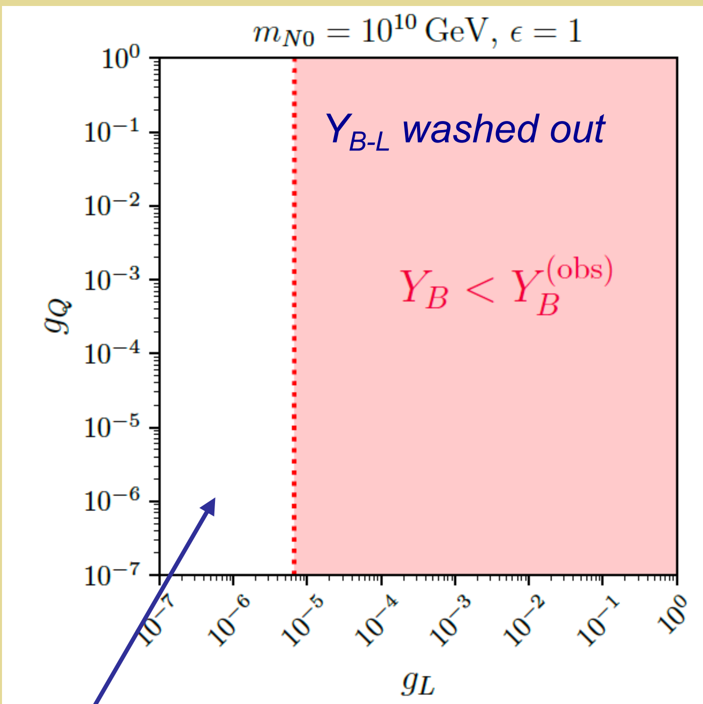

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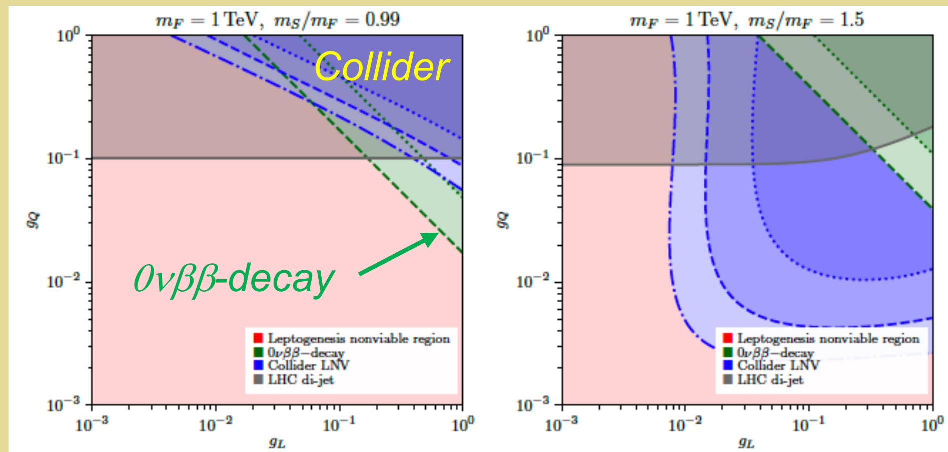


Comparing $0\nu\beta\beta$-decay, collider, & cosmo

J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga '21

Implications

- *Nuclear Physics*
- *Leptogenesis*
- *Collider Searches*
- Σm_ν

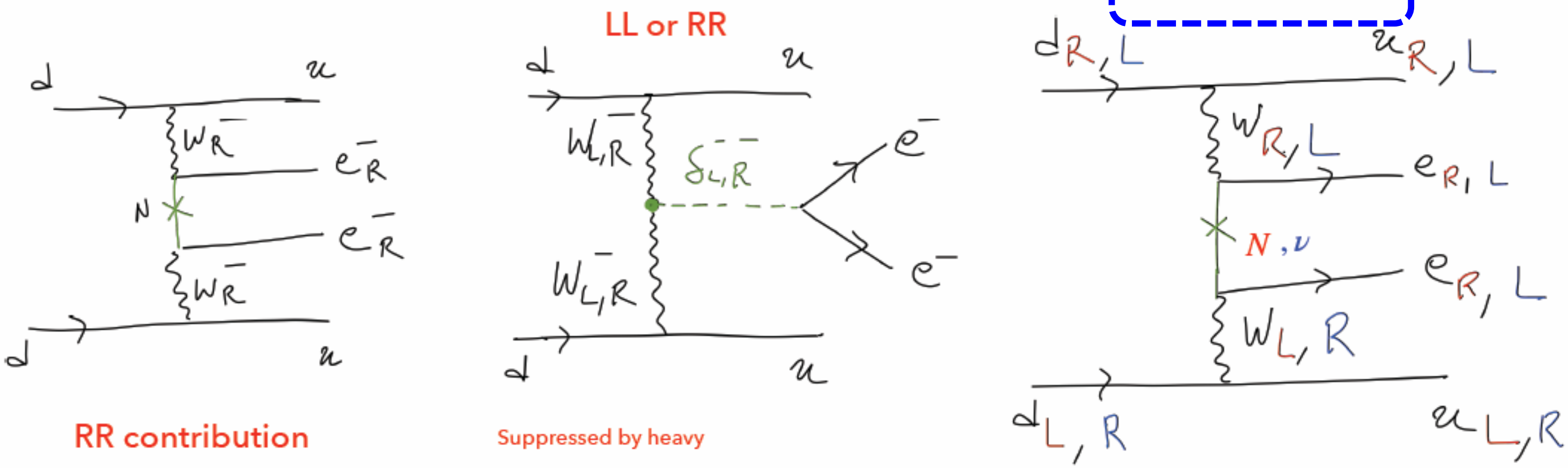
Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

Long range chiral enhancement

- There are the following contributions (on top of the usual light neutrino contribution)

LR contribution

LL or RR



RR contribution

Suppressed by heavy

δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

The Blue contributions are

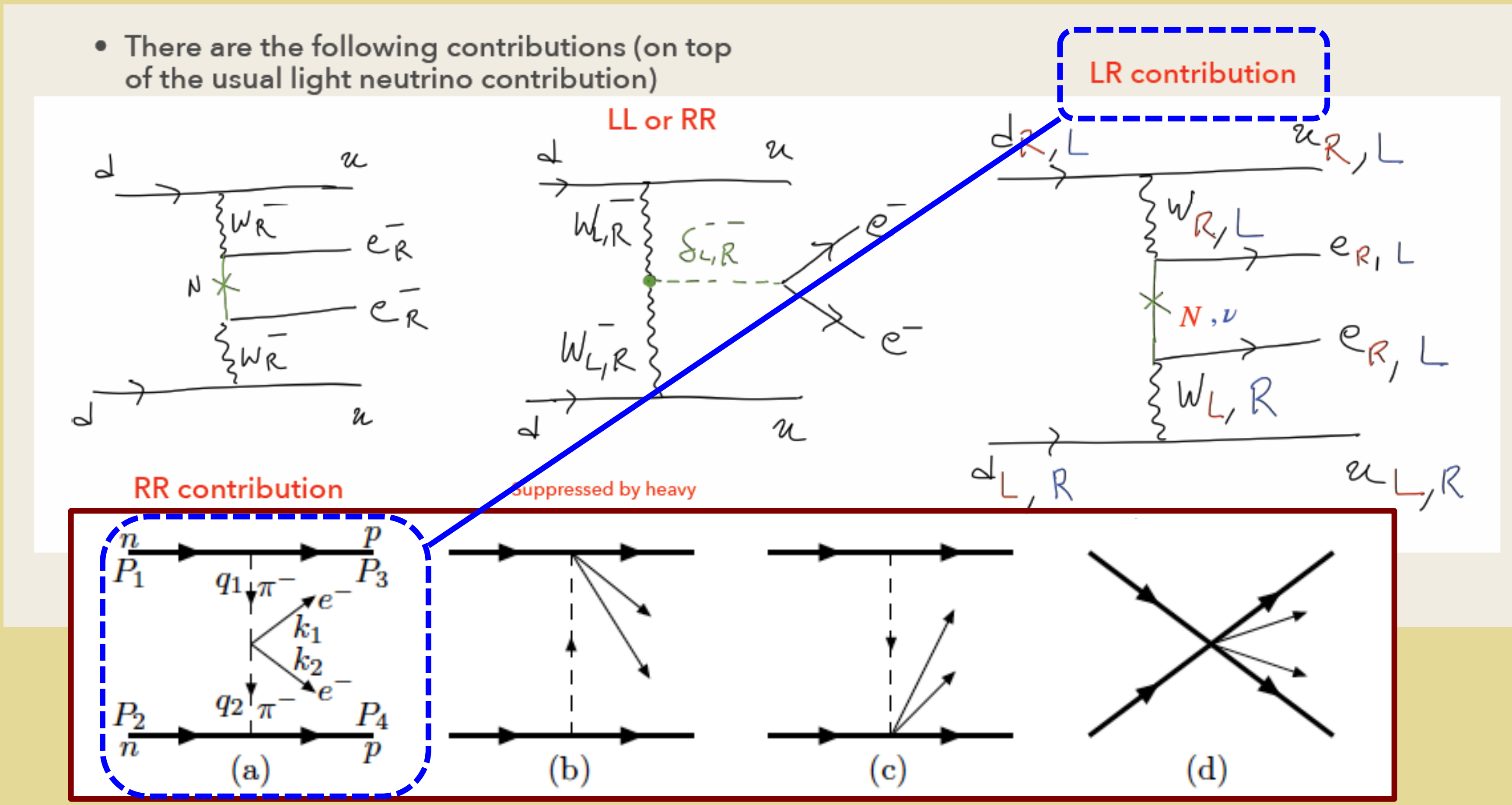
Suppressed by small heavy-light

Neutrino mixing

Thanks! Juan Carlos Vasquez

Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

Long range chiral enhancement



Thanks! Juan Carlos Vasquez

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

EFT: Long range

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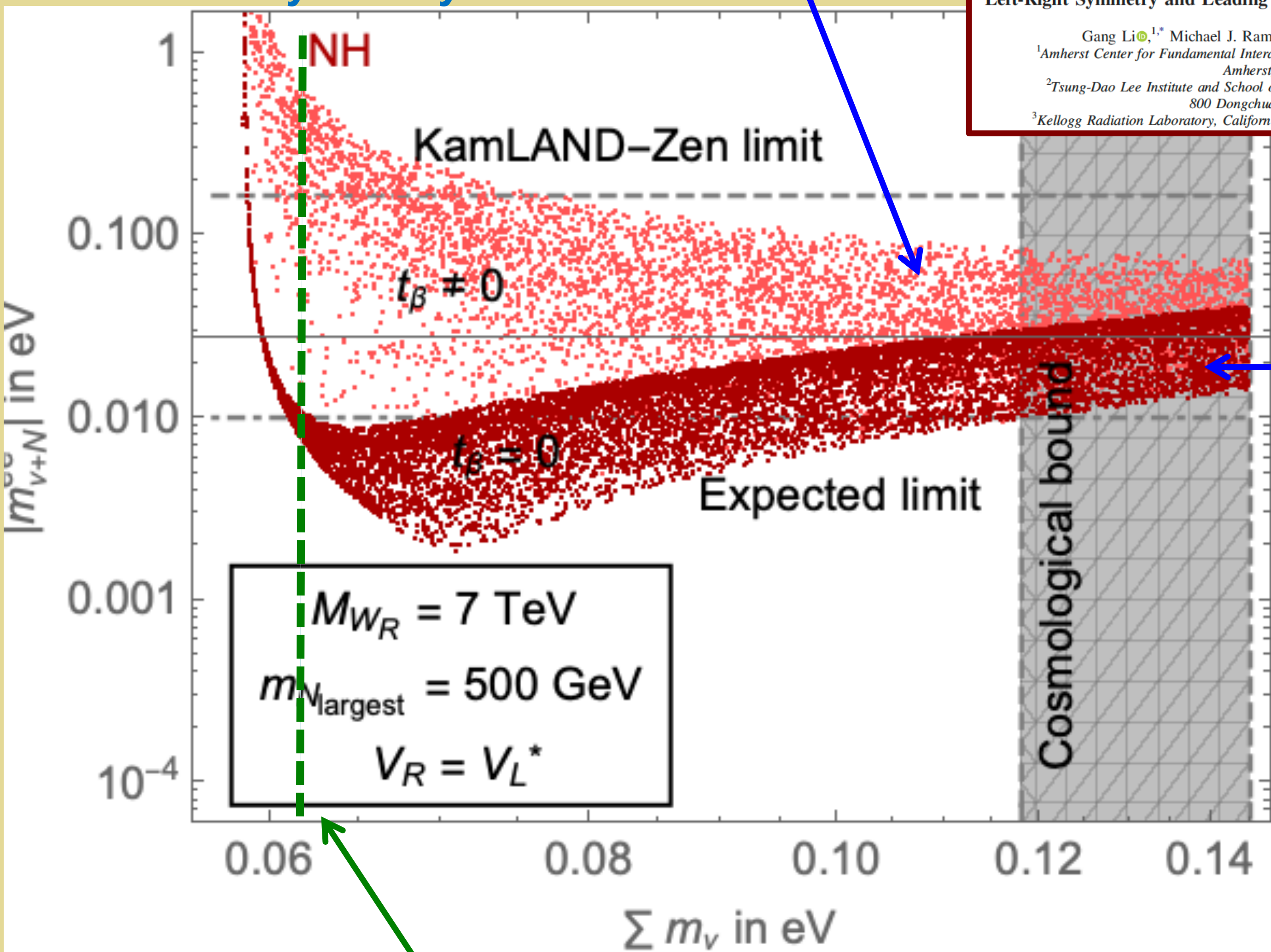
Left-Right Symmetry and Leading Contributions to Neutrinoless Double Beta Decay

Gang Li,[1,*] Michael J. Ramsey-Musolf,[2,1,3,†] and Juan Carlos Vasquez[1,‡]
[1]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[2]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*
[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

Minimal LR Symmetry



Short range only

~ Cosmo next gen

Observation of $0\nu\beta\beta$-decay in advent of more stringent Σm_ν bounds → TeV scale (or below) LNV

IV. GeV- and Below-Scale LNV

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

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

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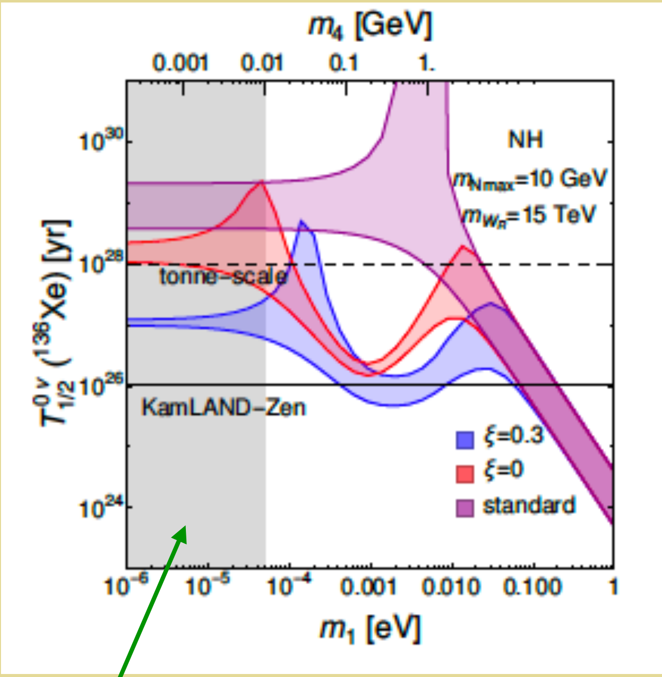
More Than 3 Light Neutrinos: MeV-GeV

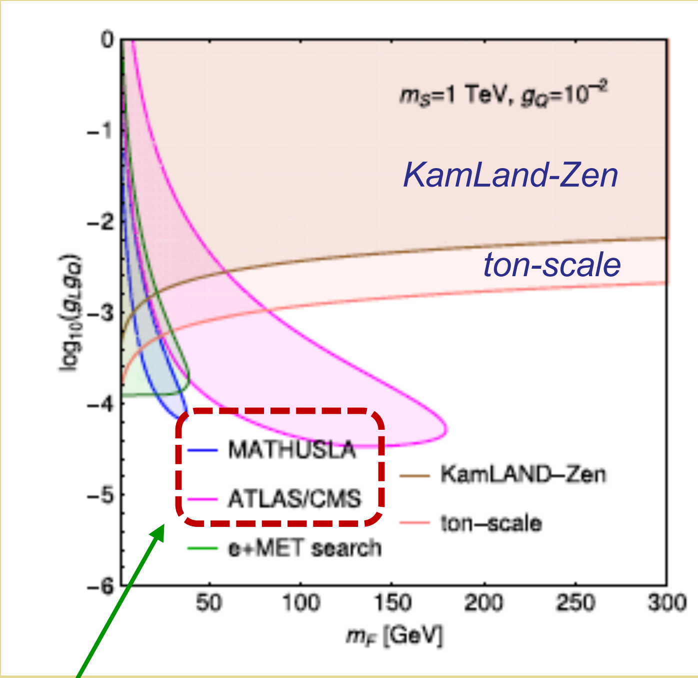
mLRSM



Current Σm_ν exclusion

J. De Vries, G. Li, MJRM, J. C. Vasquez '22

Simplified Model



LHC long-lived particle searches

G. Li, MJRM, S. Su, J.C. Vasquez '22

V. Conclusions & Outlook

- ***The observation of $0\nu\beta\beta$ –decay would imply the existence of BSM LNV that could hold the keys to answering fundamental questions: origin of m_ν & matter antimatter asymmetry.***

- ***If BSM LNV exists, we don't know the associated mass scale***

- ***Ton-scale $0\nu\beta\beta$ –decay searches provide a powerful probe of LNV at all scales, with broader implications for our understanding of physics at the cosmic and high energy frontiers***

V. Conclusions & Outlook

- ***The observation of TeV scale LNV would have profound implications for our understanding of the origin of m_ν & the connection to the cosmic baryon asymmetry***
- ***There exists a rich interplay between $0\nu\beta\beta$, collider searches, and m_ν information from cosmology***
- ***Exciting opportunities ahead for exploring model realizations, related phenomenology, and hadronic/nuclear theory***

谢谢

Back Up Slides

Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay