Non-Standard Contributions to $0\nu\beta\beta$ Decay: Implications for Cosmic & Energy Frontiers

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- *UMass Amherst*

My pronouns: he/him/his

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Tao Peng	*Former UW Madison PhD student*

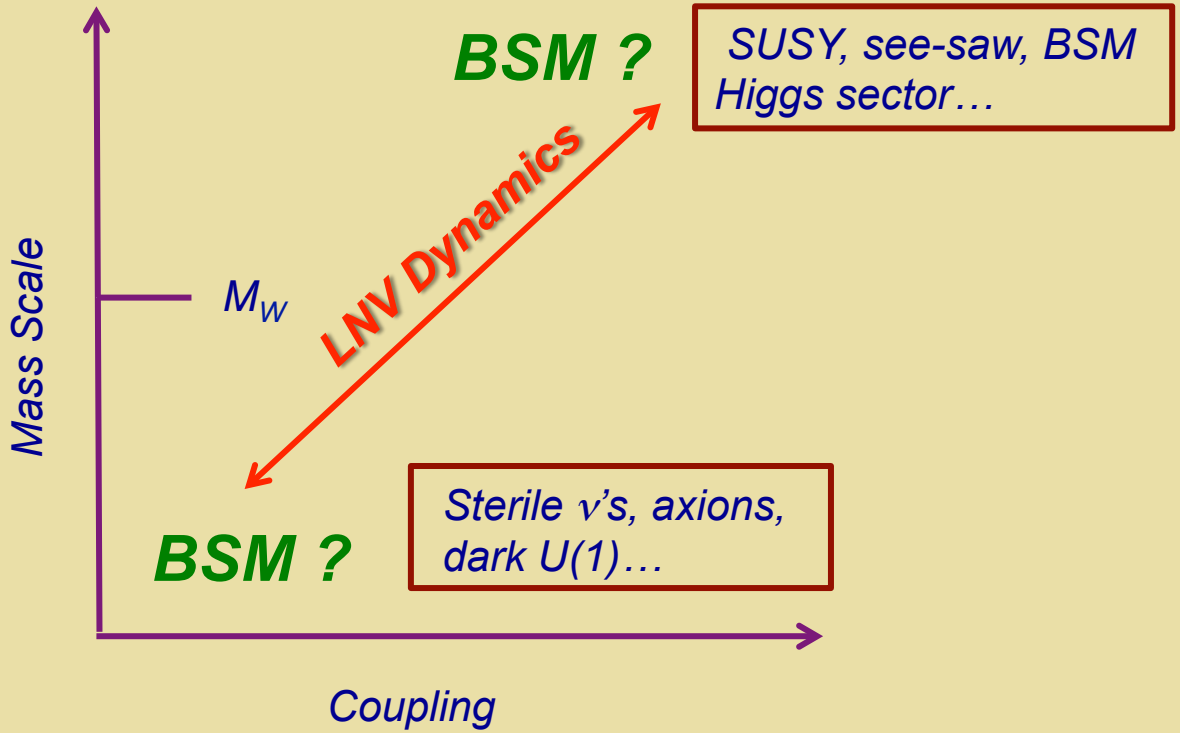
Snowmass $0\nu\beta\beta$ Decay WS
July 15, 2020

2007.NNNNN x 2
1508.04444

Thanks

V. Cirigliano, J. de Vries, M. Graesser, W. Haxton, G. Li, E. Mereghetti, G. Prezeau, P. Vogel...

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 ?

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*

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This talk

Questions

- *If TeV scale "non-standard" LNV physics contributes to $0\nu\beta\beta$ decay, what is the interplay with cosmology and collider physics?*
    - *Leptogenesis*
    - Σm_ν
    - *LHC & Beyond*
- *How do we reliably compute TeV scale contributions to to $0\nu\beta\beta$ decay ?*

Outline

I. LNV & Leptogenesis: Context

II. TeV Scale LNV: Leptogenesis-Colliders-$0\nu\beta\beta$ Decay

- Interlude: EFT for $0\nu\beta\beta$ Decay

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

Time permitting

I. LNV & Leptogenesis: Context

The "Standard" Picture: High-Scale LNV

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

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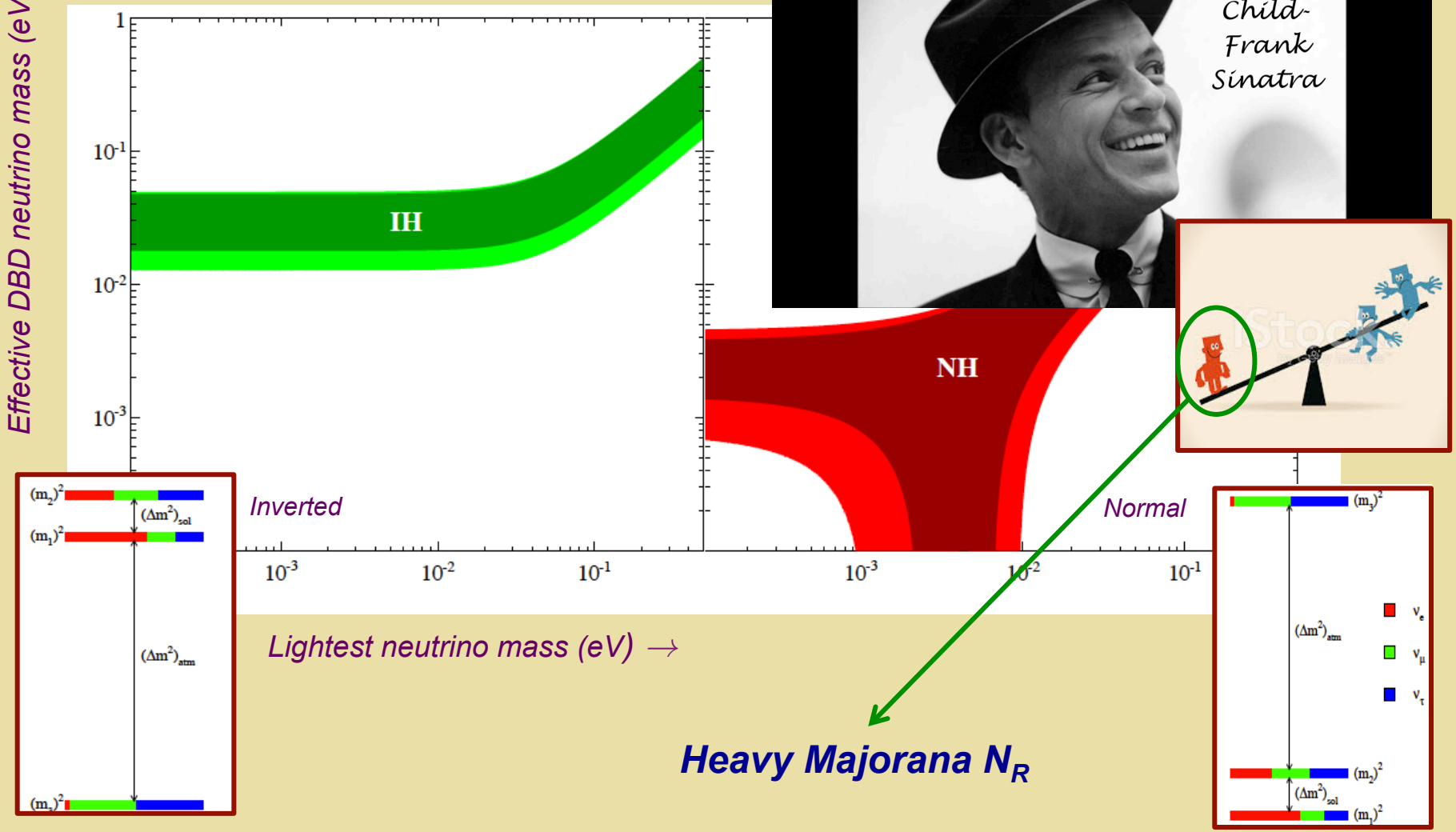
$0\nu\beta\beta$-Decay: "Poster Child" Mechanism

Three active light neutrinos



Heavy Majorana N_R

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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II. TeV Scale LNV: Leptogenesis-Colliders-$0\nu\beta\beta$ Decay

- *T. Peng, MJRM, P. Winslow 1508.04444*
- *J. Harz, MJRM, S. Shen, S. Urrutia-Quiroga 2007.NNNNN*

Implications

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

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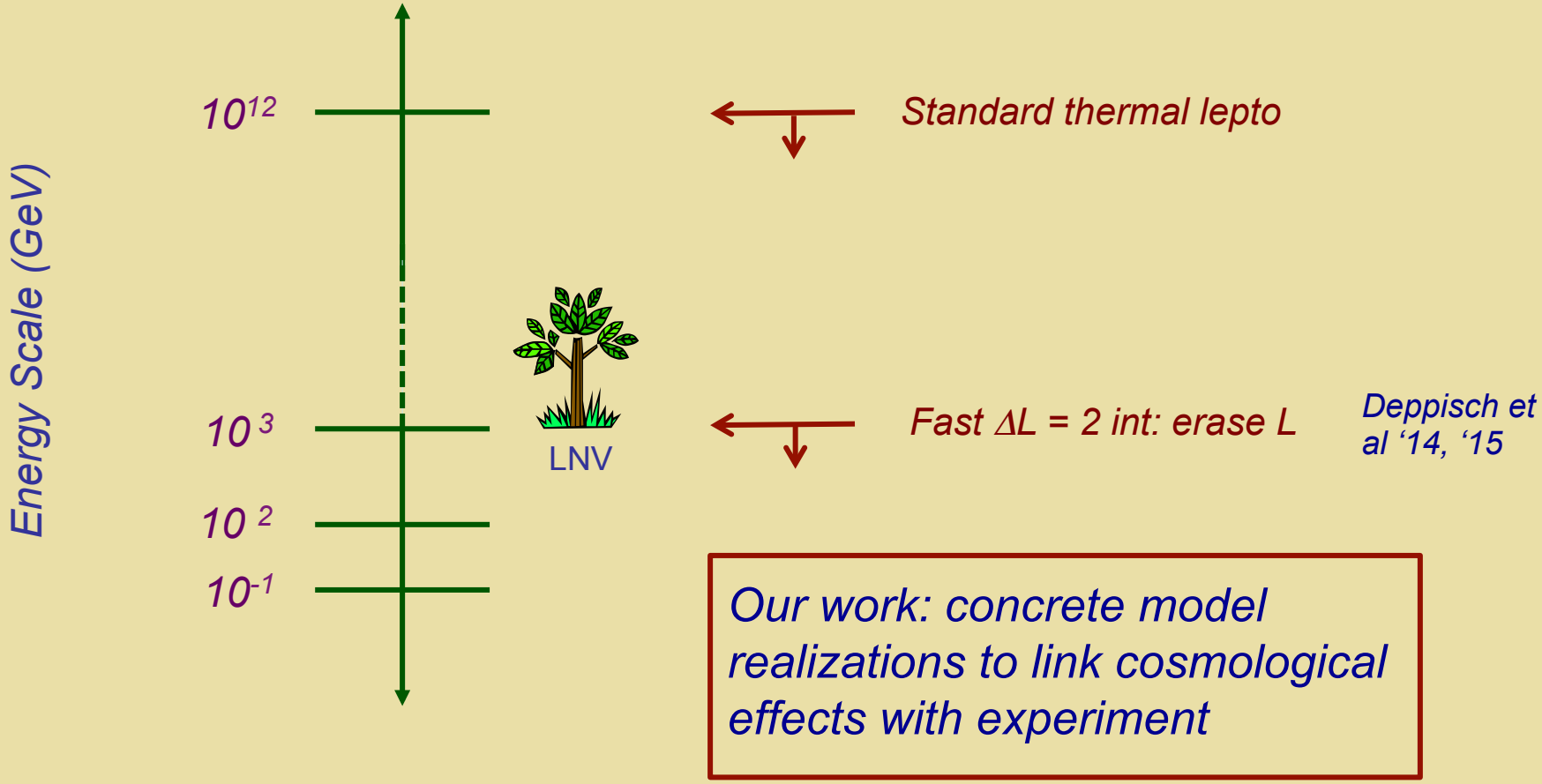
TeV LNV & Leptogenesis



Our work: concrete model realizations to link cosmological effects with experiment

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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

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

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Decay

Scattering

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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

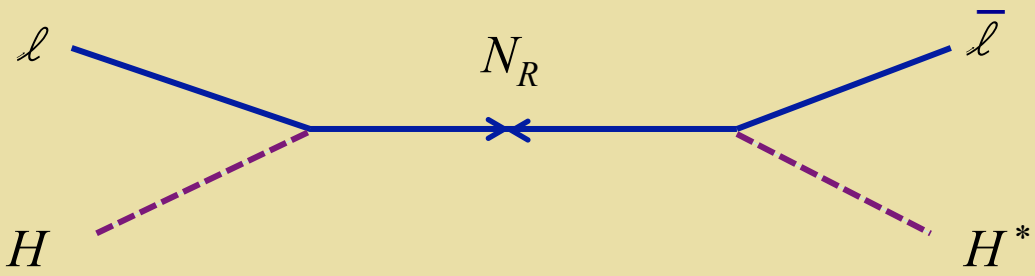
CPV Decay Asymmetry: source

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

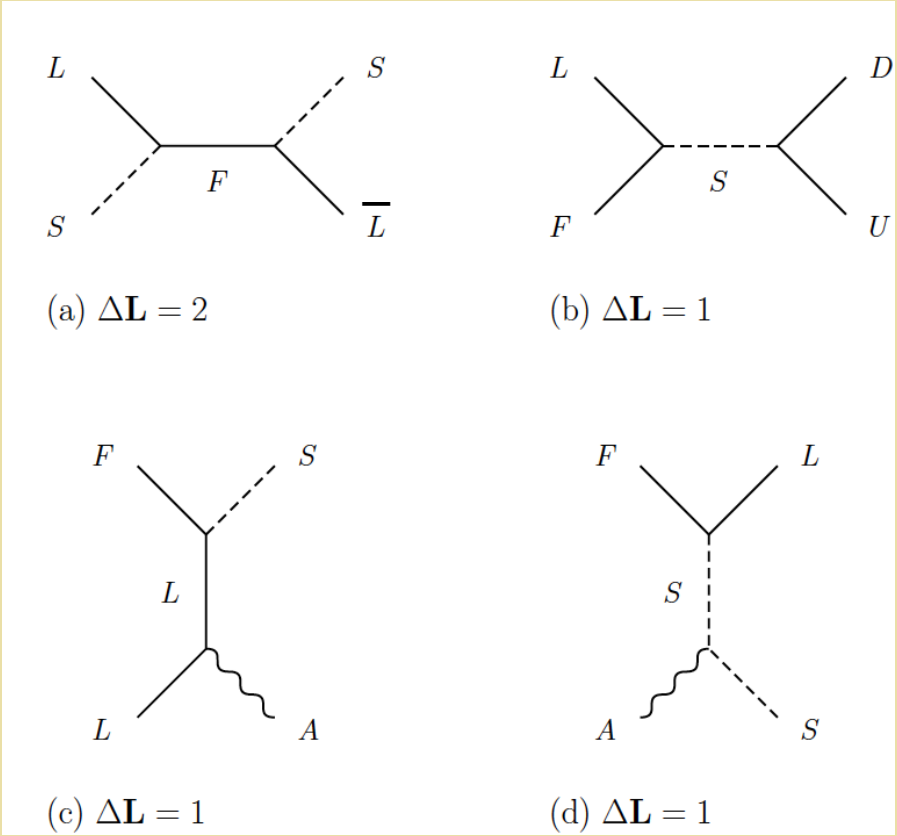
Simplified Models: Illustrative Case

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

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

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

Leptogenesis: Washout Processes



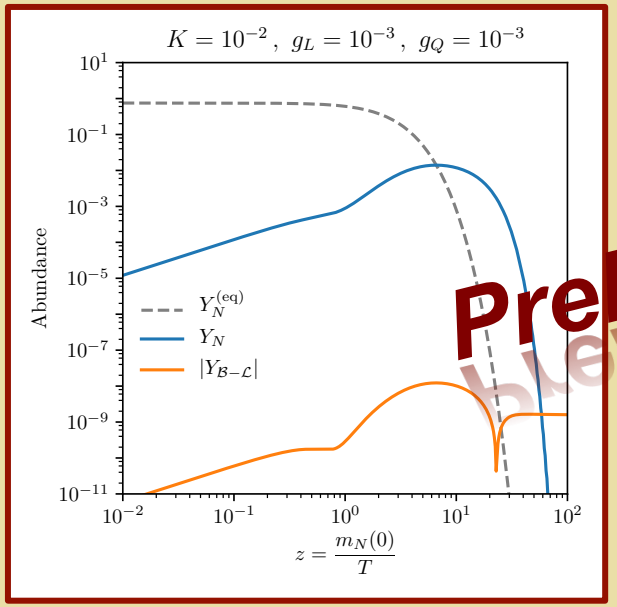
Thanks! S. Urrutia-Quiroga

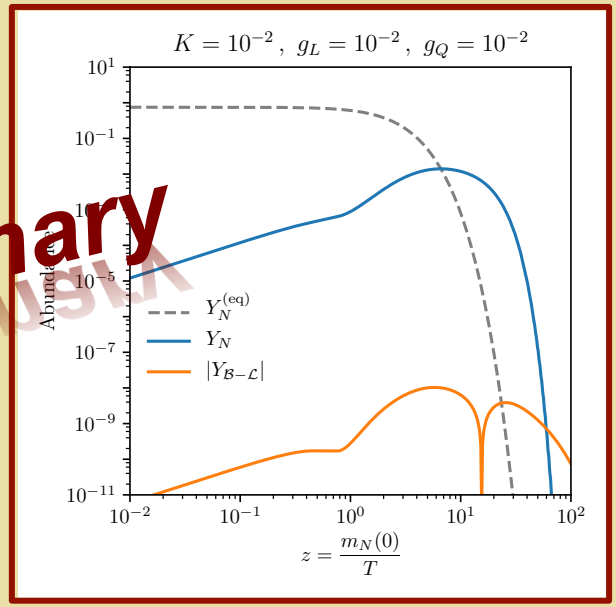
Neutrinos and the Origin of Matter

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

Washout processes

Example: weak washout, $m_N = 10^{10}$ TeV, $M_F = 1$ TeV, $M_S = 0.8$ TeV

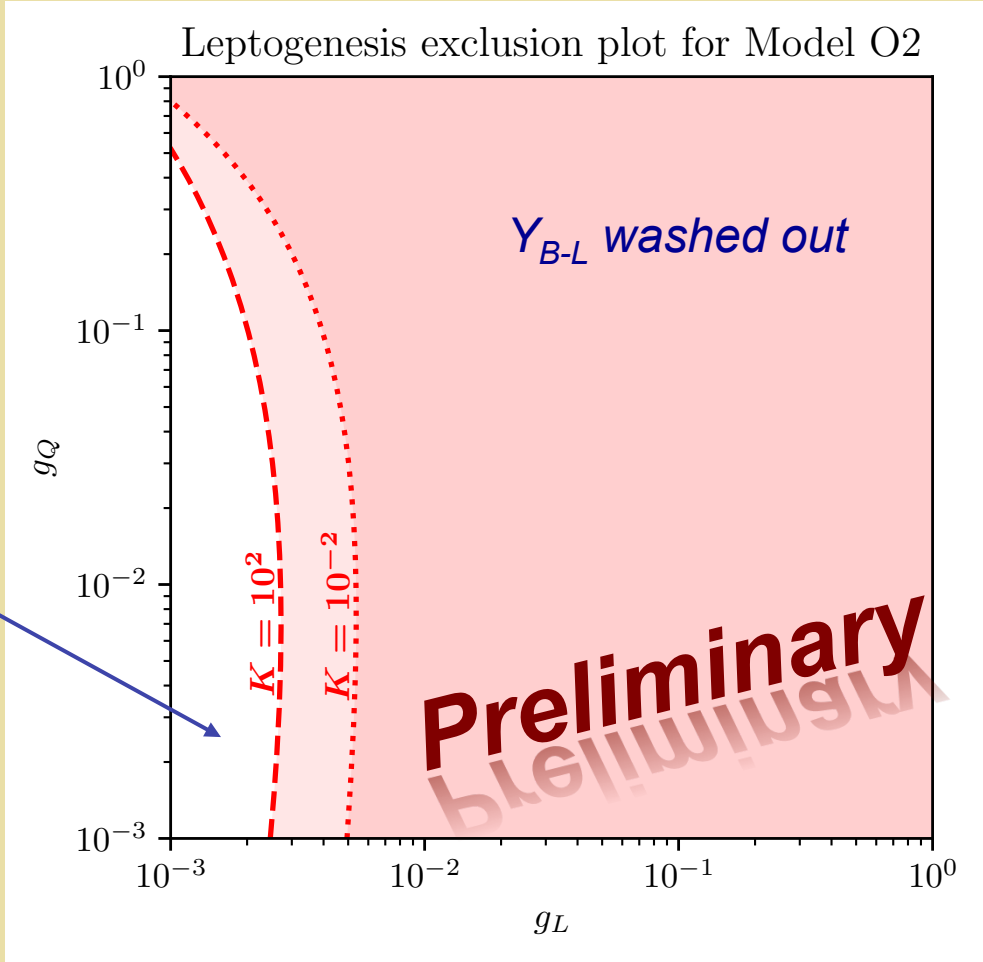




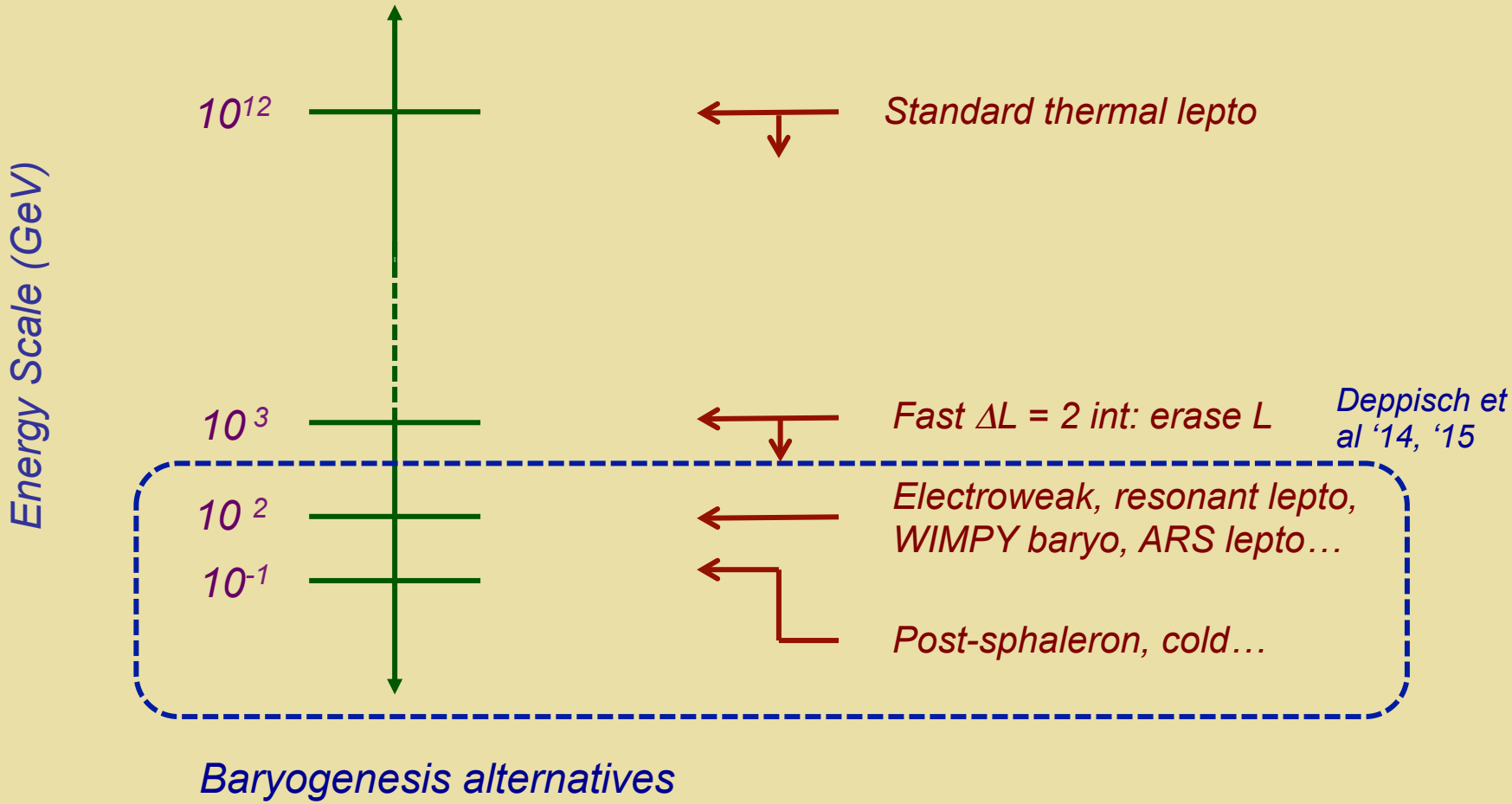
Preliminary

Thanks! S. Urrutia-Quiroga

Results: Leptogenesis



TeV LNV & Leptogenesis



Implications

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

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

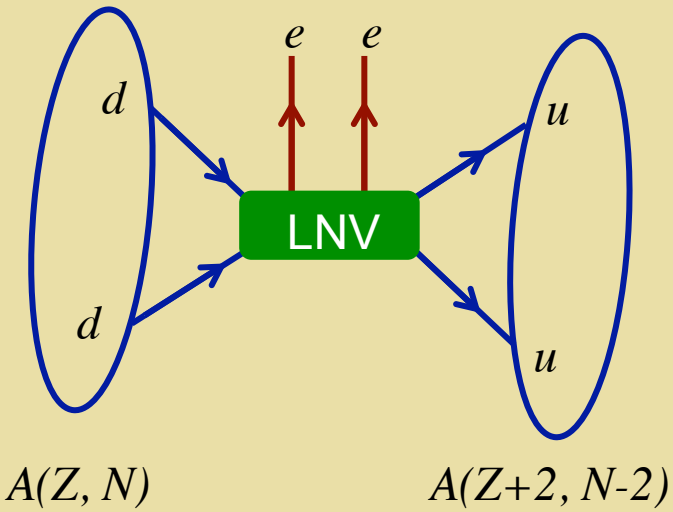
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

Dirac

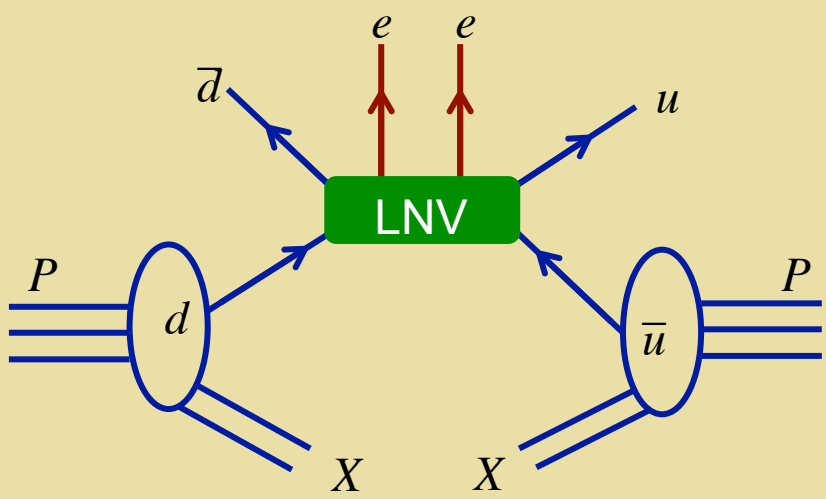
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \;+\; {\rm h.c.}$$

Majorana

$0\nu\beta\beta$-Decay



pp Collisions



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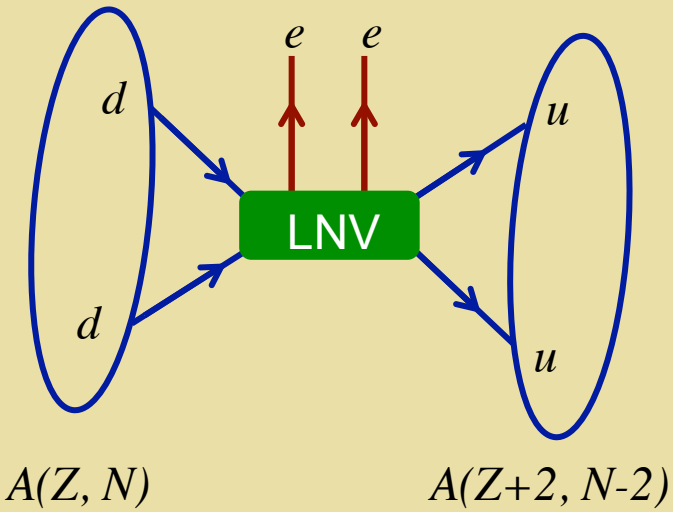
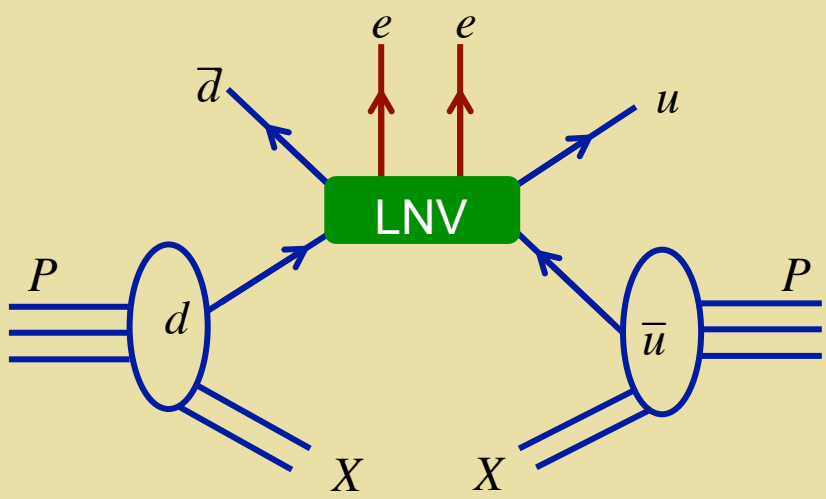
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



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

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

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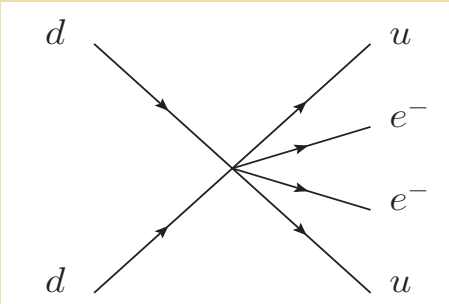
Majorana

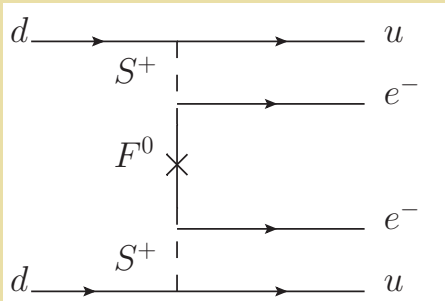
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

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



Simplified models

Interlude: 0ν ββ - decay in EFT

Operator classification

$$\mu = M_{WEAK}$$

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

e.g.

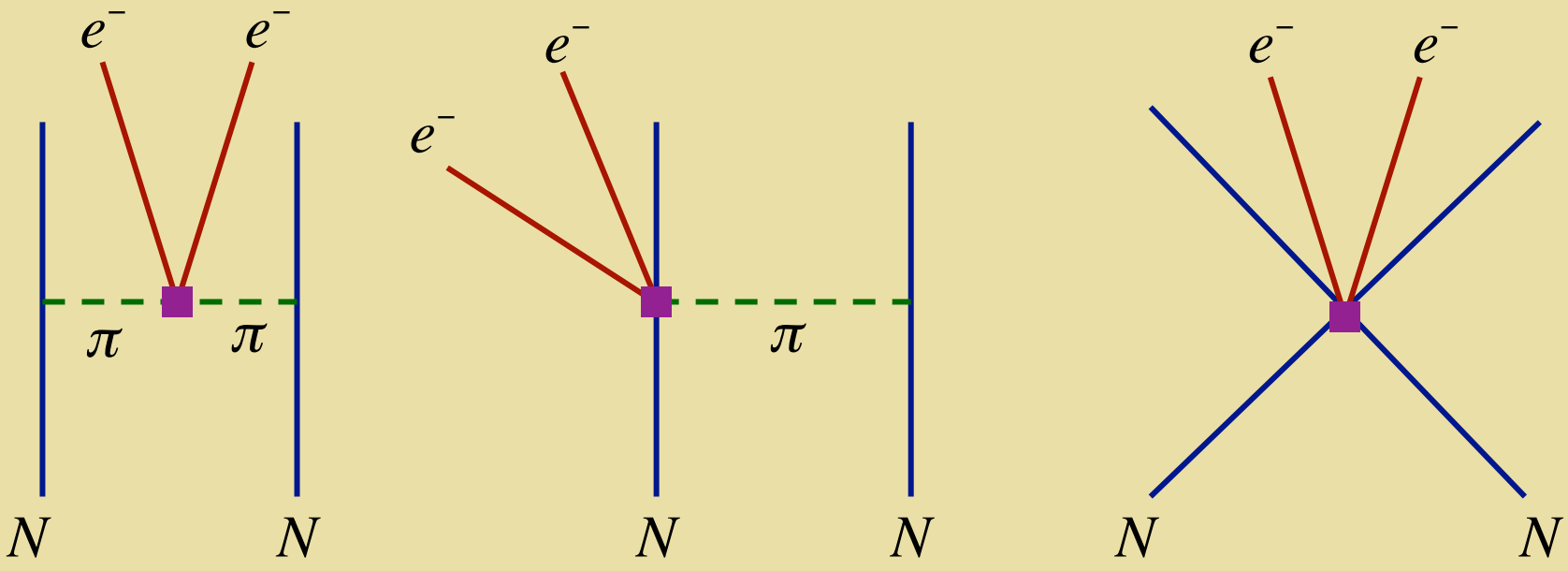
$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L \; \bar{q}_R \gamma_\mu \tau^b q_R$$

0ν ββ - decay: *a* = *b* = +

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

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

Interlude: $0\nu\ \beta\beta$ - decay in EFT

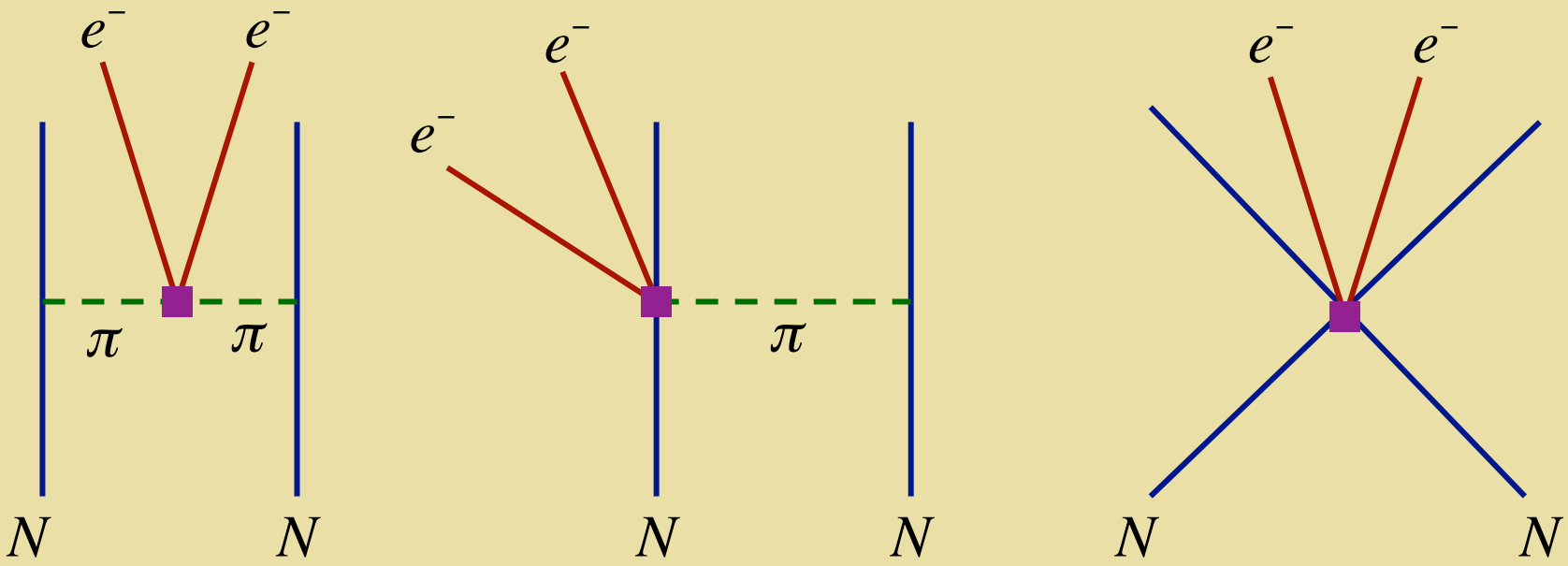


Tractable nuclear operators

Systematic operator classification

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

Interlude: $0\nu\ \beta\beta$ - decay in EFT



$K_{\pi\pi}\ p^{-2}$

$K_{\pi NN}\ p^{-1}$

$K_{NNNN}\ p^{0}$

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

Interlude: $0\nu\ \beta\beta$ - decay in EFT

Operator classification

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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

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

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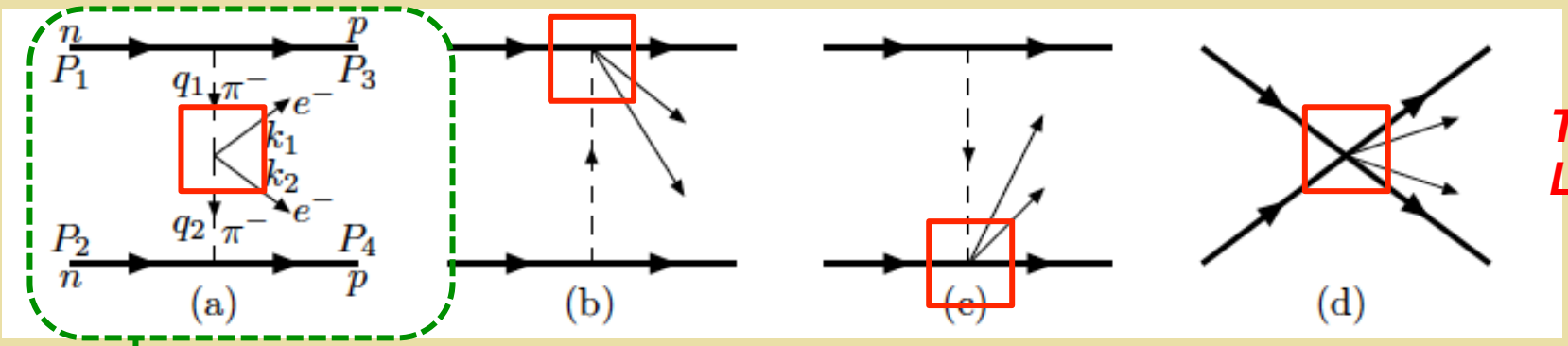
Majorana

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

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



TeV LNV

This model: LO + counterterm

Exploit Chiral Symmetry & EFT ideas

$0\nu\beta\beta$-Decay: Our Earlier Study

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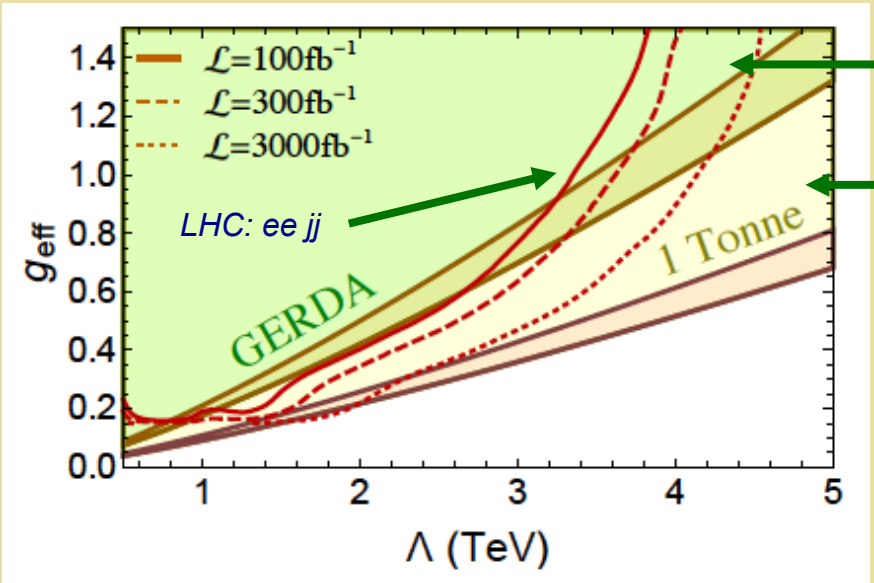
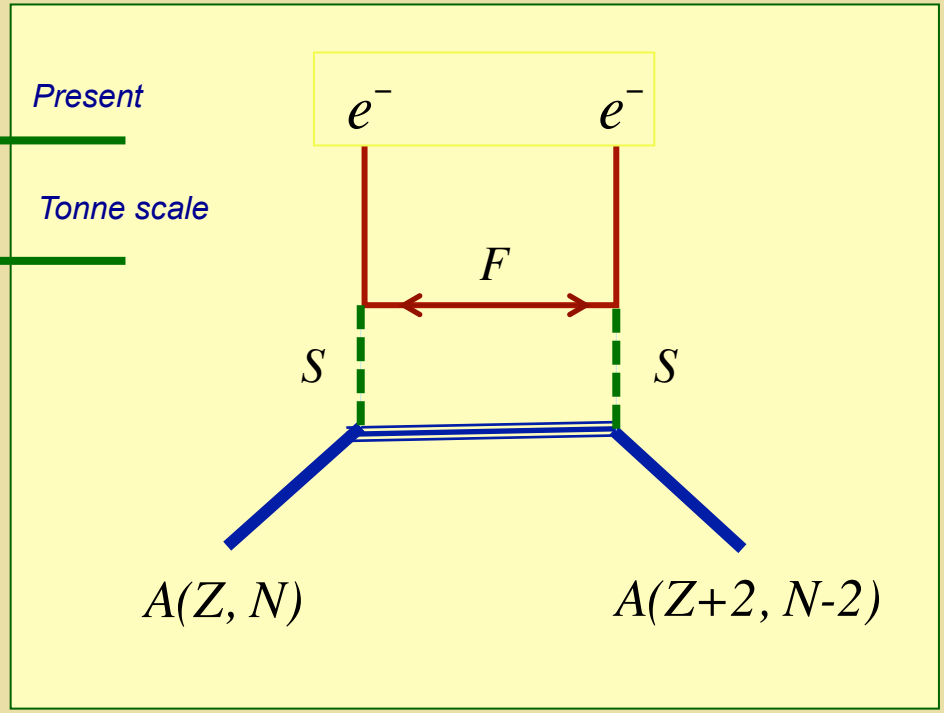
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

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

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Dirac

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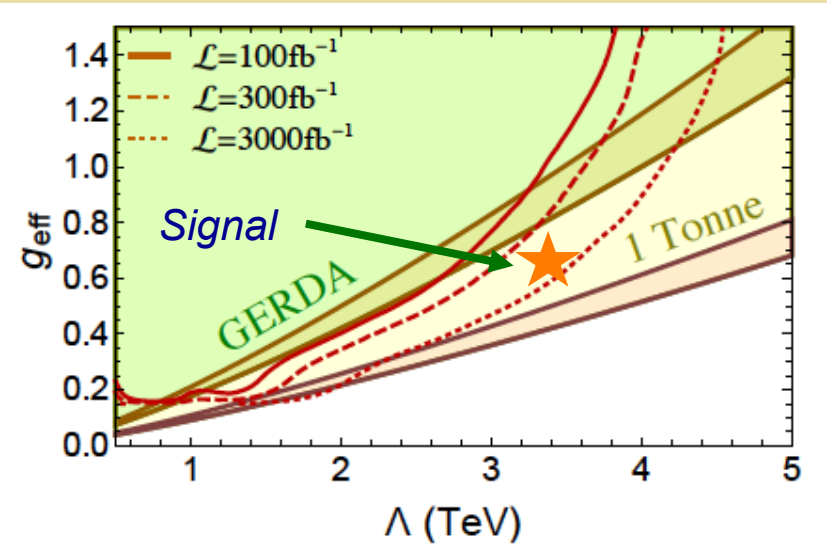
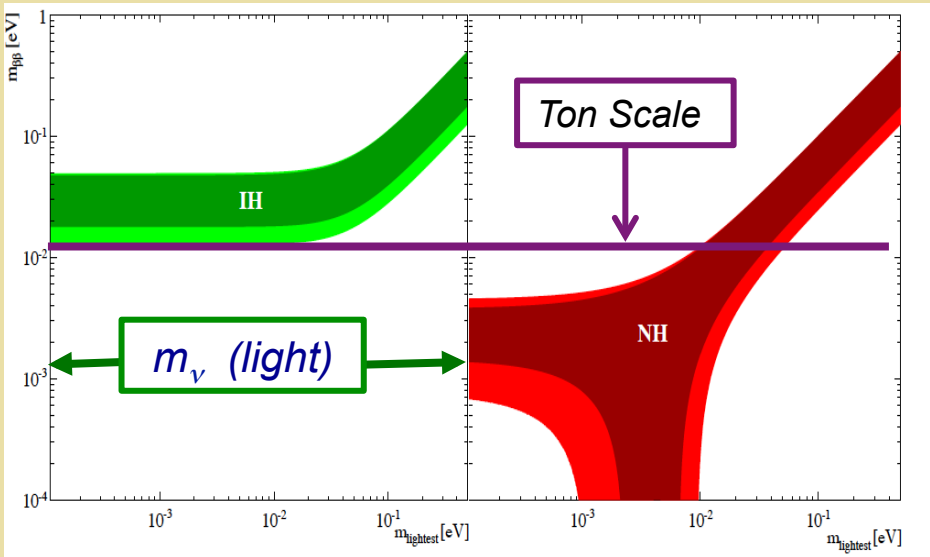
Majorana

Implications for m_ν:





A hypothetical scenario

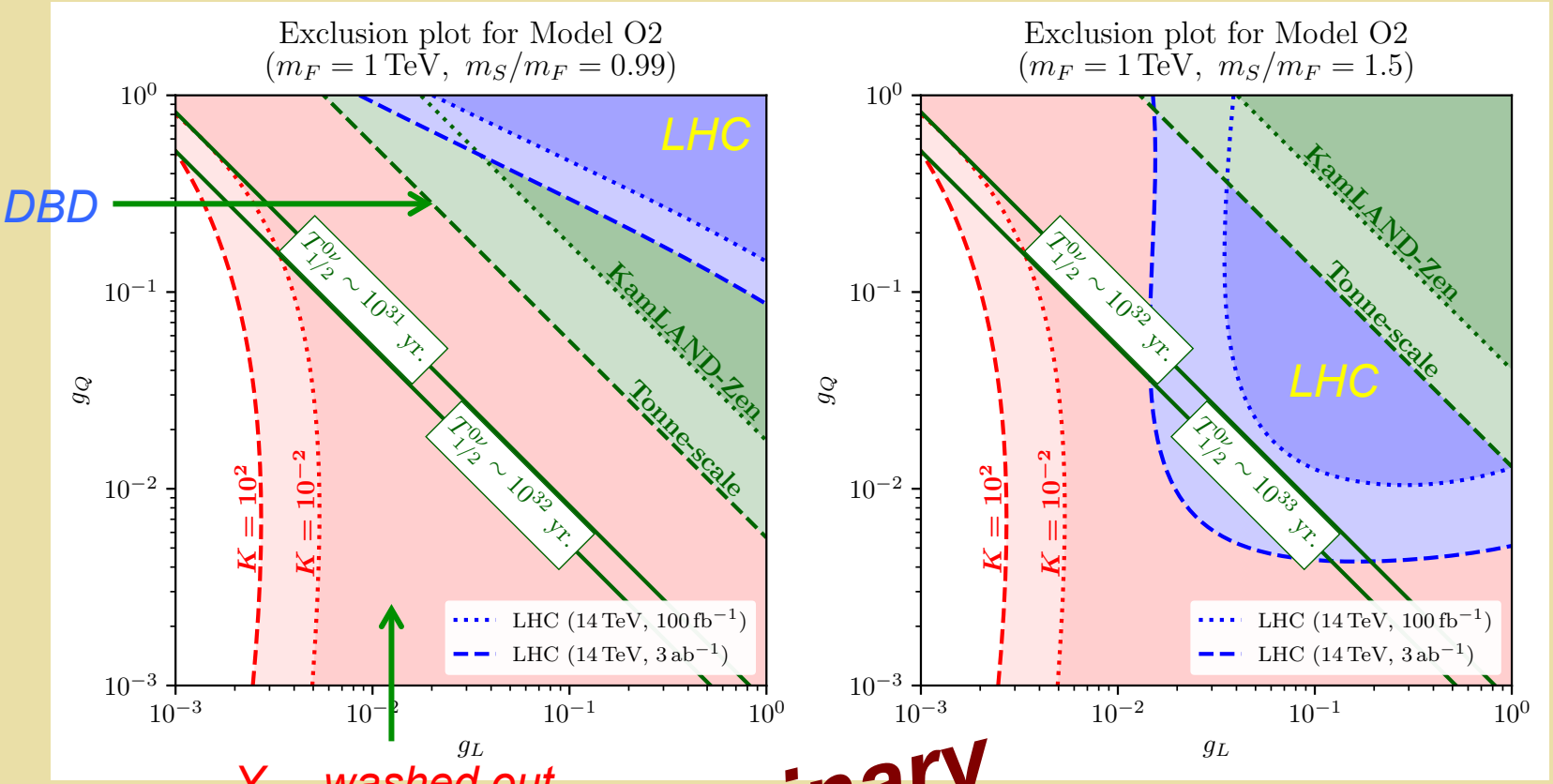
LHC Update: Signal & Background

	$g_L = 1.0\,,\ g_Q = 0.1$	$g_L = 0.1\,,\ g_Q = 1.0$
$\sigma(pp \to jje^+e^+)$ (pb)	9.701×10^{-3}	1.811×10^{-3}
$\sigma_{(b)}(pp \to S^+)$ (pb)	2.614×10^{-2}	2.614
$\mathrm{Br}(S^+ \to e^+F)$	9.494×10^{-1}	1.871×10^{-3}
$\mathrm{Br}(F \to e^+jj)$	0.5	0.5

(a) $\sqrt{s} = 14$ TeV, $m_F = 1$ TeV, and $m_S = 2$ TeV.

BKG type		σ before signal selection (pb)	σ after signal selection (pb)	σ after NN (pb)
Diboson	WW	3.28×10^{-3}	6.40×10^{-4}	6.87×10^{-5}
	WZ	2.59×10^{-2}	6.65×10^{-3}	2.10×10^{-4}
	ZZ	1.32×10^{-3}	5.62×10^{-4}	1.14×10^{-5}
Jet-fake	$W + 3j$	1.79×10^{-1}	4.34×10^{-2}	1.78×10^{-4}
	$t\bar{t}$	9.11×10^{-2}	2.64×10^{-2}	6.10×10^{-5}
Charge misidentification	$t\bar{t}$	3.33×10^{-2}	1.54×10^{-2}	4.45×10^{-4}
	Z/γ^*	2.54×10^{-1}	1.37×10^{-1}	4.89×10^{-3}
		5.88×10^{-1}	2.30×10^{-1}	5.86×10^{-3}

Results: $0\nu\beta\beta$ Decay & LHC



Thanks! S. Urrutia-Quiroga

The $0\nu\beta\beta$ / Leptogen / Collider Interplay

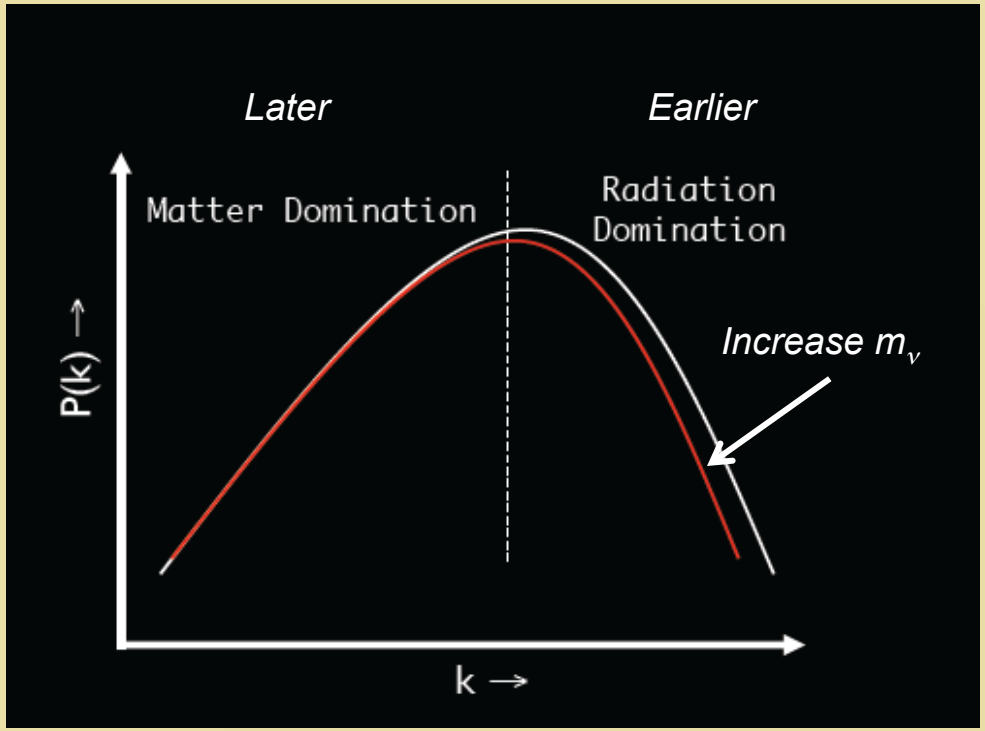
- ***The observation of TeV scale LNV through a combination of $0\nu\beta\beta$-decay and collider searches could preclude the viability of standard, thermal leptogenesis***
- ***The of $0\nu\beta\beta$-decay and collider searches provide complementary sensitivity (e.g., mass spectrum): discovery could occur in one or the other or both***
- ***Significantly enhanced $0\nu\beta\beta$-decay sensitivity and collider reach (100 TeV pp?) may be needed to reach the leptogenesis viable region***

III. TeV Scale LNV: $0\nu\beta\beta$−Decay & $\Sigma\, m_\nu$

- *G. Li, MJRM, J. C. Vasquez, 2007.NNNNN*

Neutrino Mass & Cosmology

Matter Power Spectrum



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

Palanque-Dalabrouille '15

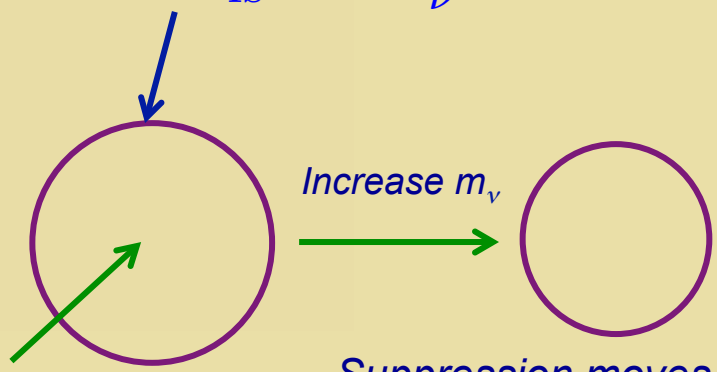
Neutrino Free Streaming

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

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

Free Streaming Scale

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

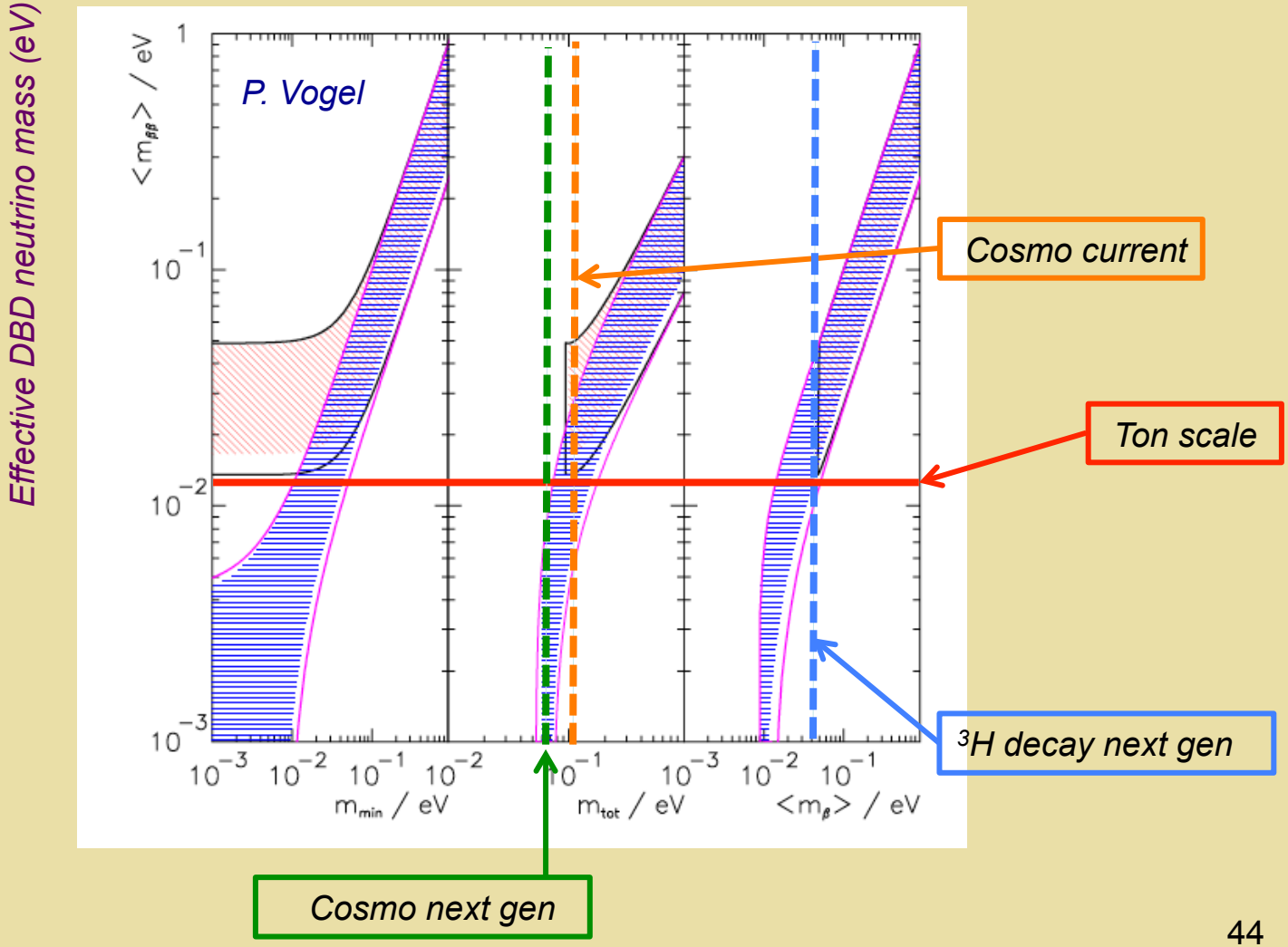


$\delta\rho_\nu$ *(power) suppressed for* $L < L_{fs}$

Suppression moves to smaller scales $\rightarrow$ *Larger k*

Implications for $0\nu\beta\beta$-Decay

Three active light neutrinos



TeV-Scale LNV Implications ?

Minimal Left-Right Symmetric Model

Minimal LR Symmetric Model

(J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2558 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975); G. Senjanovic, Nucl. Phys. B153, 334 (1979).
)

- Extends the SM gauge group

$$SU(3) \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times Z_2$$

- The mixing between the $W - W_R$ bosons give

$$\tan\xi = -\frac{v_1 v_2}{v_R^2} e^{-i\alpha} \simeq \left(\frac{M_W^2}{M_{W_R}^2}\right) \sin 2\beta e^{-i\alpha}, \quad \tan\beta \equiv v_2/v_1$$

v_1 and v_2 are the v.e.vs of the light and heavy doublets.

- $\tan\beta_{max} \sim 0.5$ from K and B meson systems (Bertolini, Nesti and Maiezza 2019. ArXiv: 1911.09472)

$$W_L^+ = \cos\xi W_{1\mu}^+ - \sin\xi e^{-i\alpha} W_{2\mu}^+ \text{ (SM } W \text{ boson)}$$

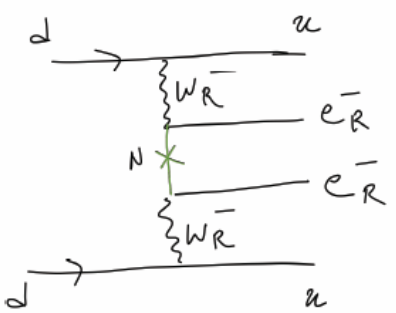
$$W_R^+ = \sin\xi e^{i\alpha} W_{1\mu}^+ + \cos\xi W_{2\mu}^+$$

Thanks! Juan Carlos Vasquez

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

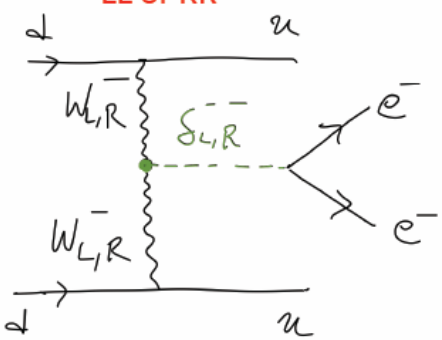
Long range chiral enhancement

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



RR contribution

LL or RR

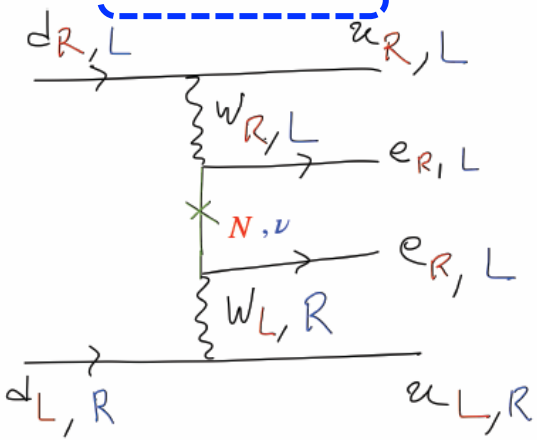


Suppressed by heavy

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

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

LR contribution



The Blue contributions are

Suppressed by small heavy-light

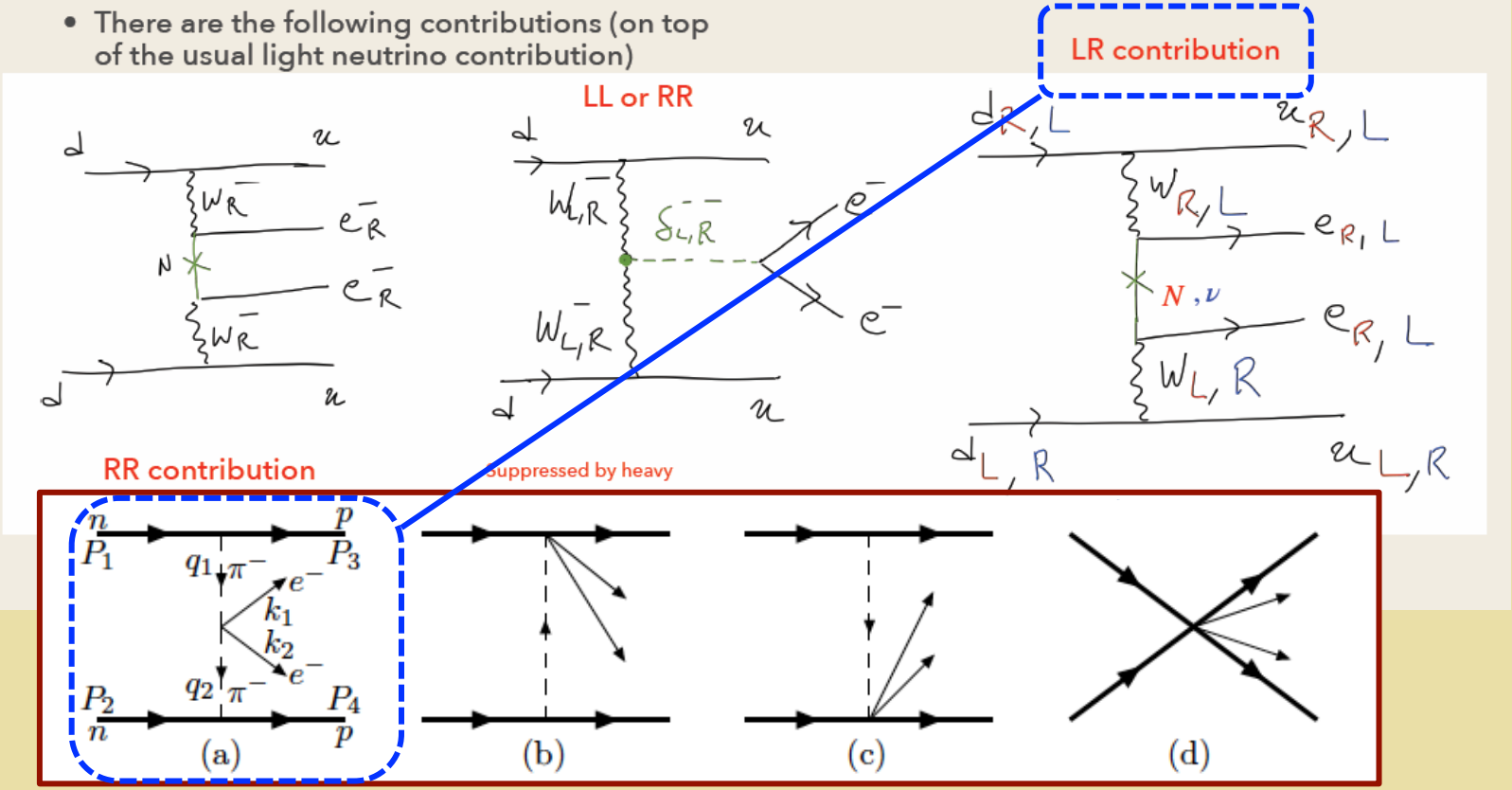
Neutrino mixing

Thanks! Juan Carlos Vasquez

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

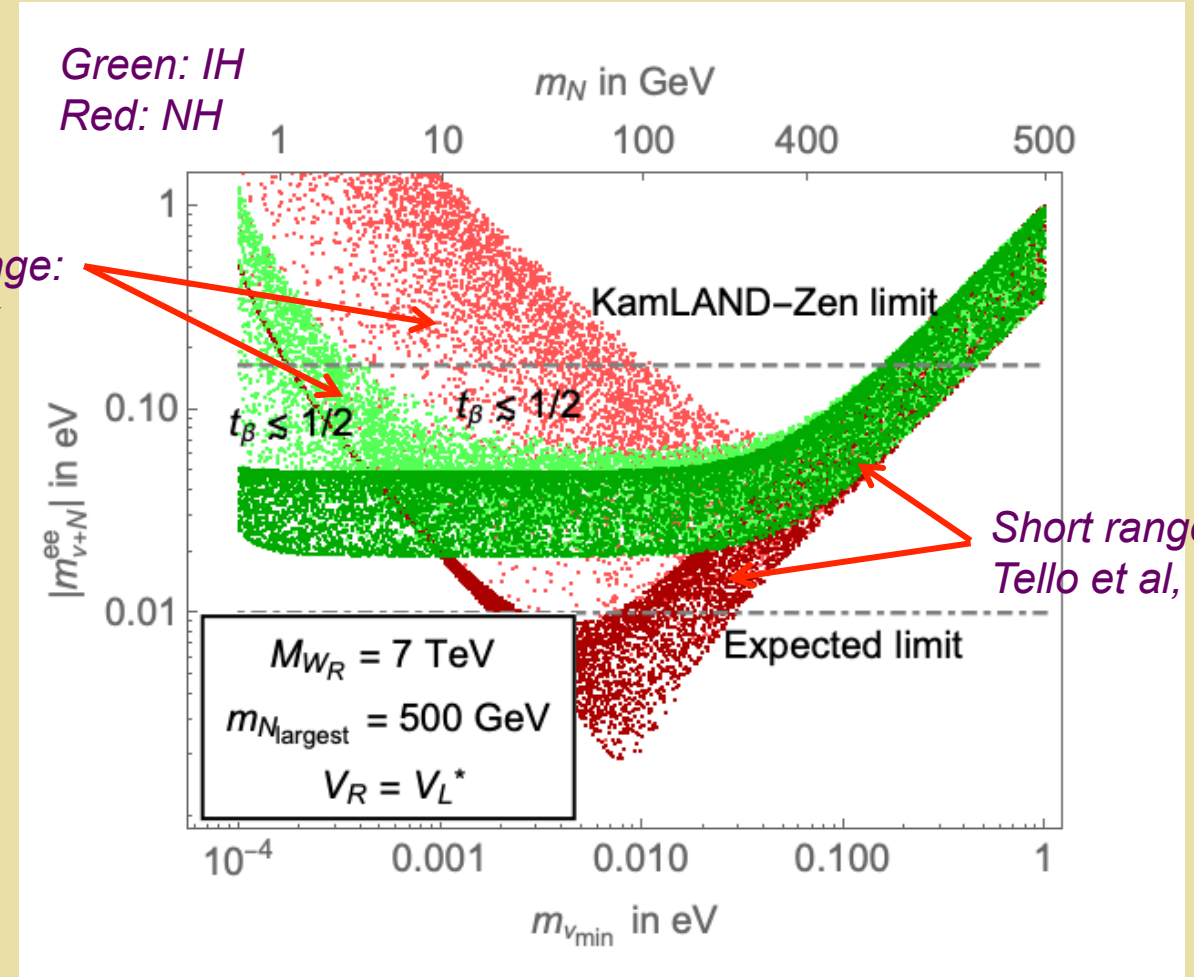
Long range chiral enhancement

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



Thanks! Juan Carlos Vasquez

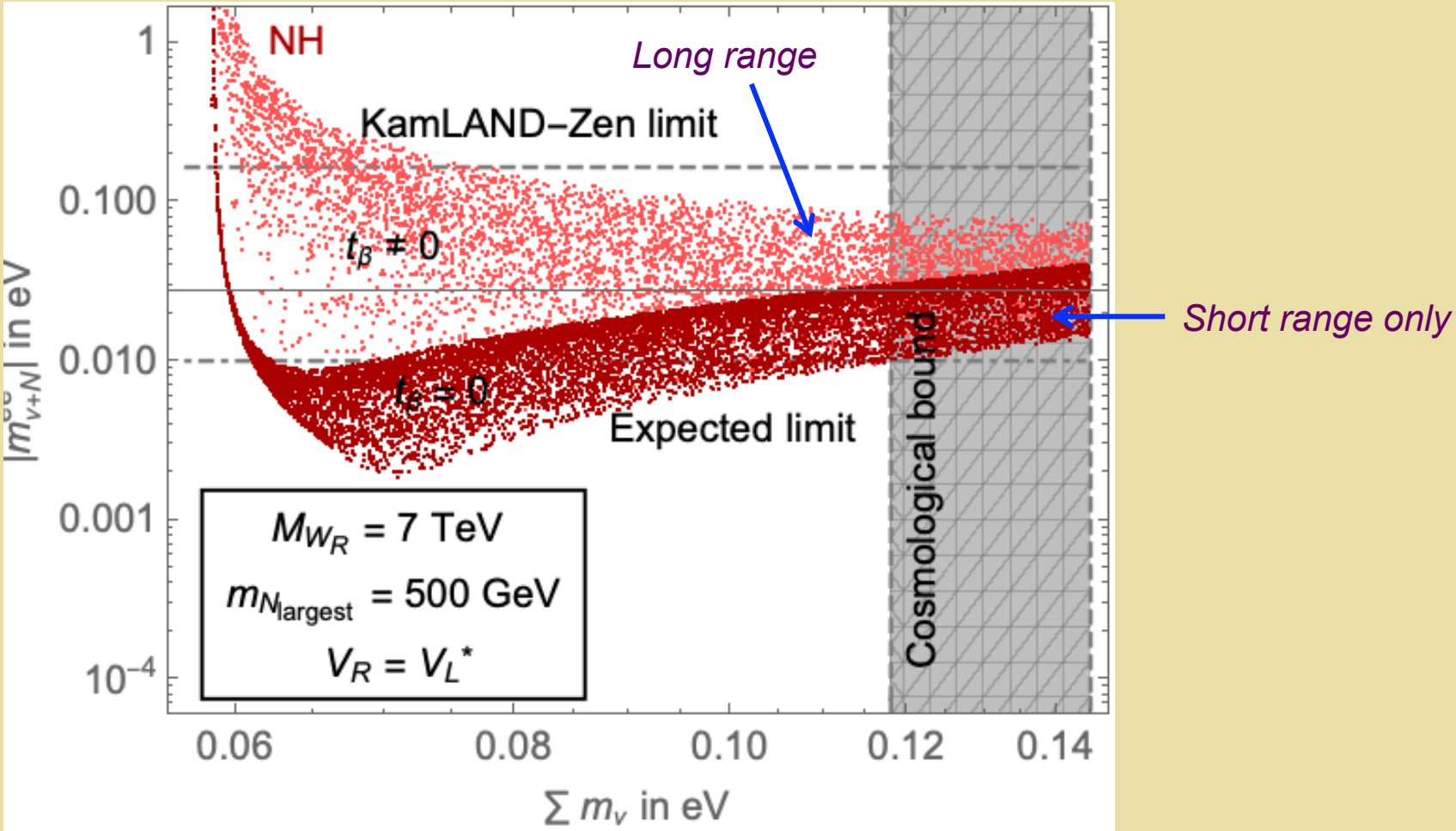
Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay



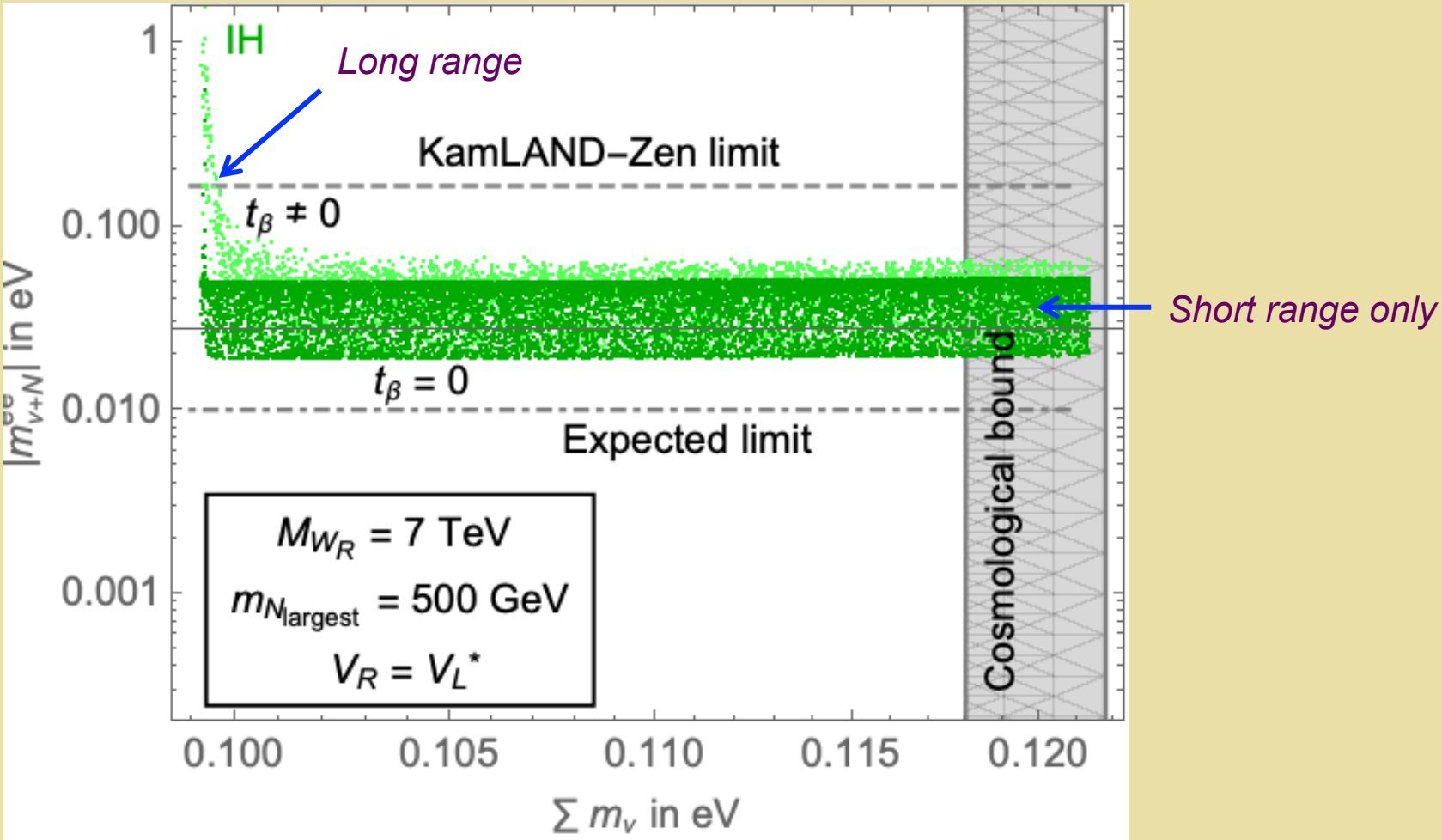
Long range: our work

Short range only: Tello et al, 1101.3522

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



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



V. 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

Lepton Number: ν Mass Term?

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

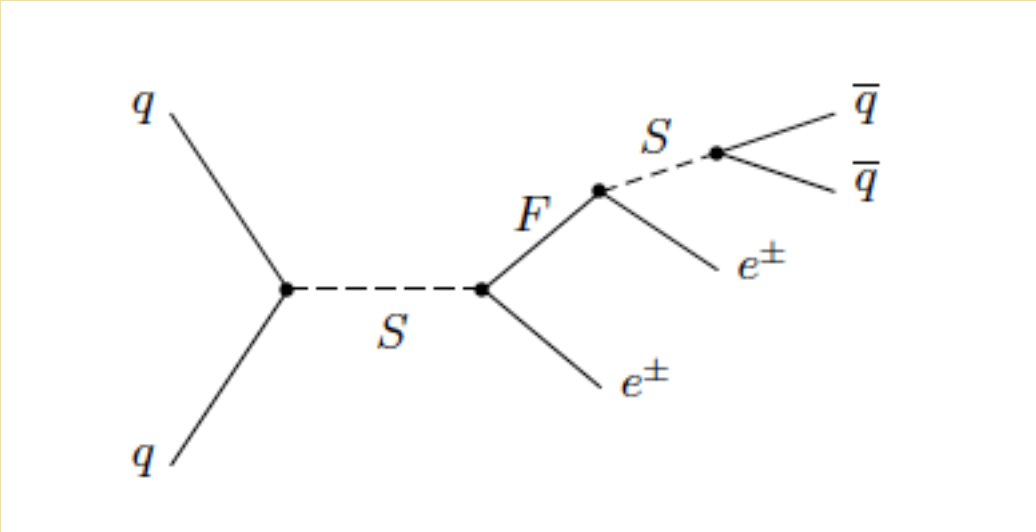
Dirac

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

Majorana

Mass scale for LNV dynamics ?

Results: LHC Cross Section



- *Largest σ for $m_S > m_F$*
- *Off-shell S suppression for $m_F > m_S$*

Thanks! S. Urrutia Quiroga

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

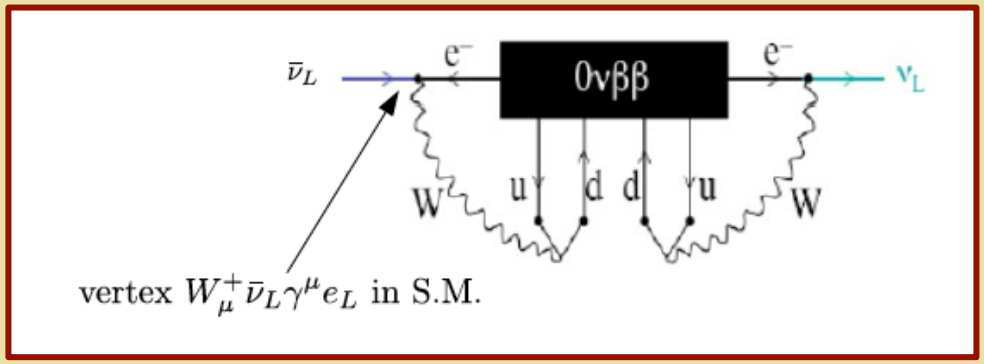
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \;+\; {\rm h.c.}$$

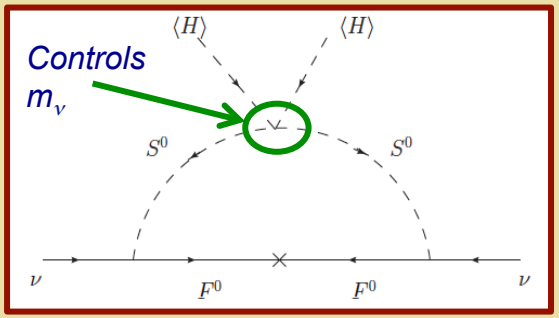
Dirac

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

Majorana

Implications for m_ν:





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

Simplified model: possible (larger) one loop Majorana mass