Lepton Number Violation: Inter-frontier Implications

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About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

νNN 2025 Lanzhou
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Key Themes for This Talk

- ***The discovery of beyond Standard Model lepton number violation could hold the key to explaining the origin of neutrino mass***
- ***The BSM LNV mass scale is unknown and could lie anywhere from the sub-eV scale to the conventional seesaw scale***
- ***While the search for $0\nu\beta\beta$-decay provides the most comprehensive probe of BSM LNV, identifying the mass scale and underlying dynamics requires input from a wide array of observations → the mystery of m_ν has exciting implications for research at the intensity, high energy, and cosmological/astrophysical frontiers***

Disclaimer

There is a vast array of important and interesting work on this topic → due to available time I'll focus on the work I'm most familiar with and apologize in advance to colleagues whose work I won't be able to discuss today

I. Context

Why Search for LNV ?

- *The conventional question:*
    - *What is the nature of the neutrino ?*

Why Search for LNV ?

- ***The conventional question:***

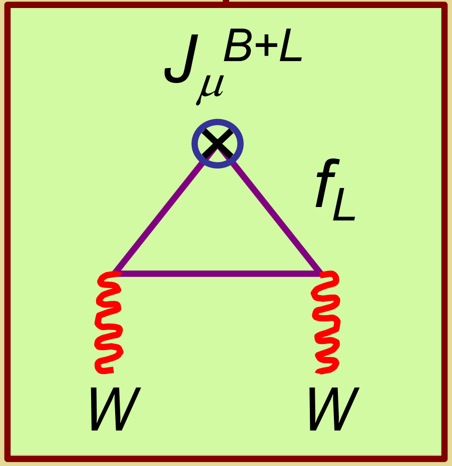
  - ***What is the nature of the neutrino ?***

- ***The deeper questions:***
  - ***Is there BSM lepton number violation ?***
  - ***If so, what is the LNV mass scale ?***
  - ***Does LNV undergird the generation of m_ν and the matter-antimatter asymmetry?***

SM: B+L Not Conserved

B+L Anomaly

$$\boxed{\partial^\mu J_\mu^{B+L} = \frac{2N_F}{32\pi^2} \times \left\{ g^2 W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right\}}$$



SM B+L Violation & Sphalerons

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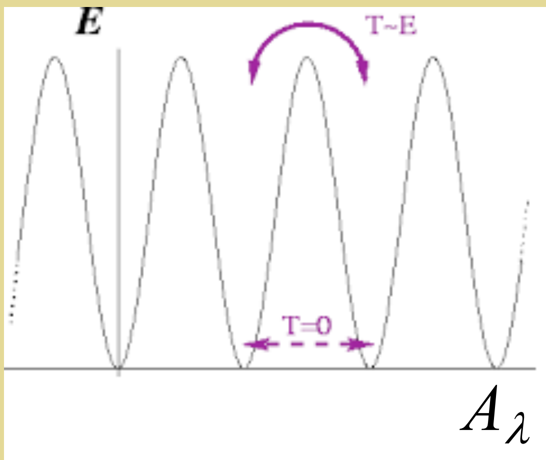

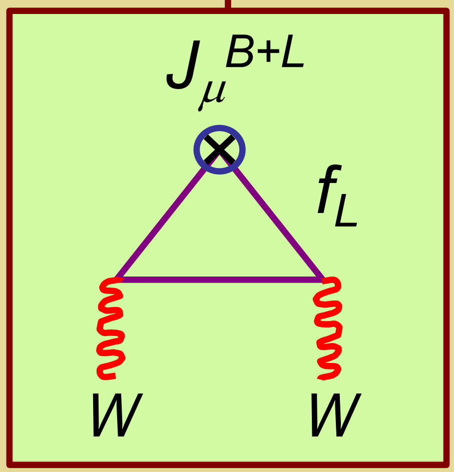

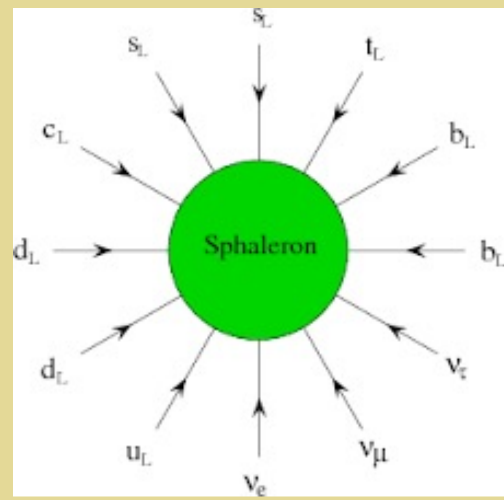

Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

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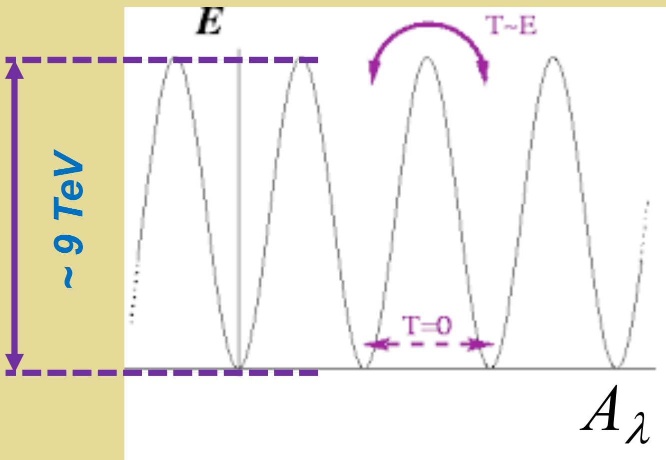
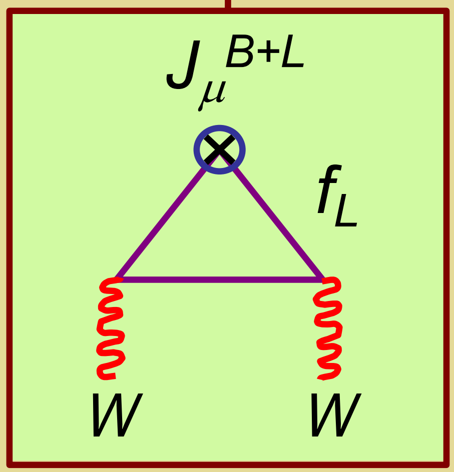
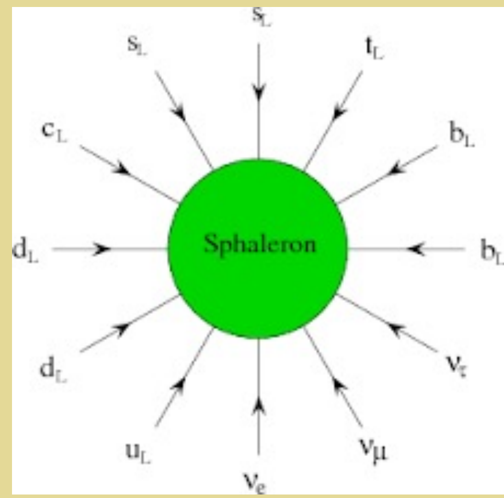






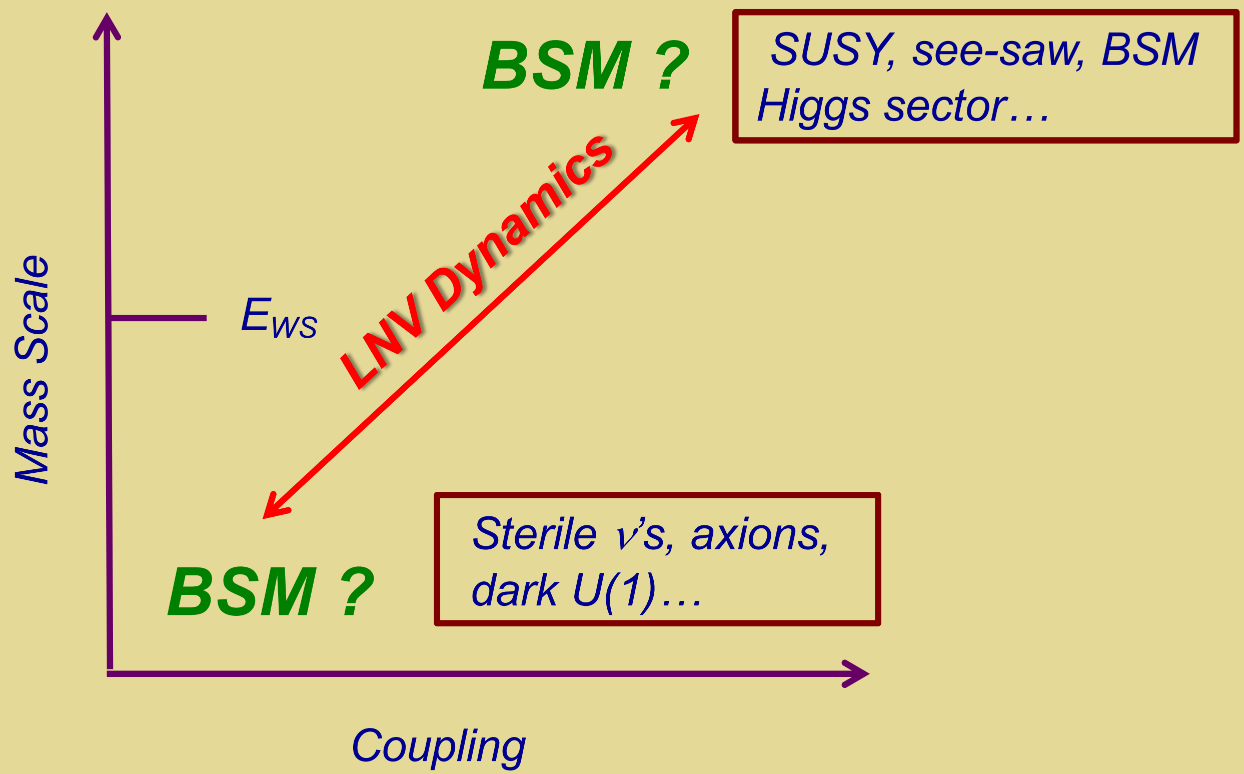
Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

Lepton Number Violation

- The "known" Standard Model LNV mass scale is ~ 10 TeV

- Are there additional LNV dynamics ? If so what is the associated mass scale ?

LNV Physics: Where Does it Live ?



Is the BSM LNV scale (associated with m_ν) far above E_{WS} ? Near E_{WS} ? Well below E_{WS} ?

BSM LNV: Questions

- *Are there additional sources of LNV 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**
- **$\Sigma\, m_\nu$**
- **Grav waves**

FSNN:
- **$0\nu\beta\beta$ decay**
- **μ_ν**
- **ν osc**
- **PV ee …**

Colliders

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Lepton Number: ν Mass Term?

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

Dirac

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

Majorana

Mass scale for LNV dynamics

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

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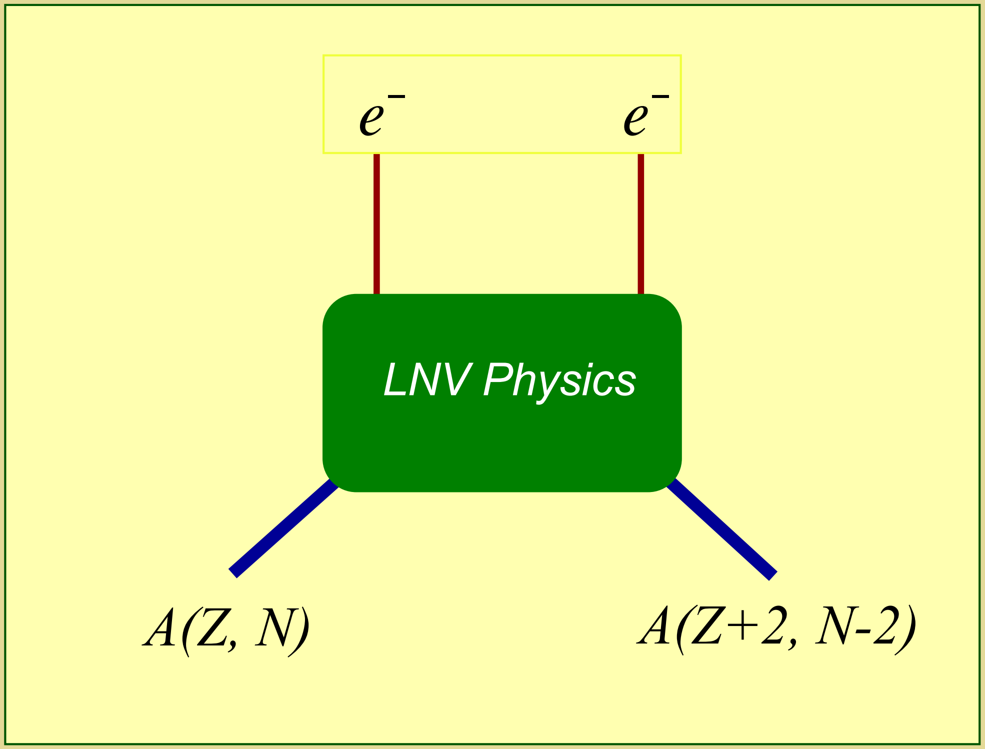

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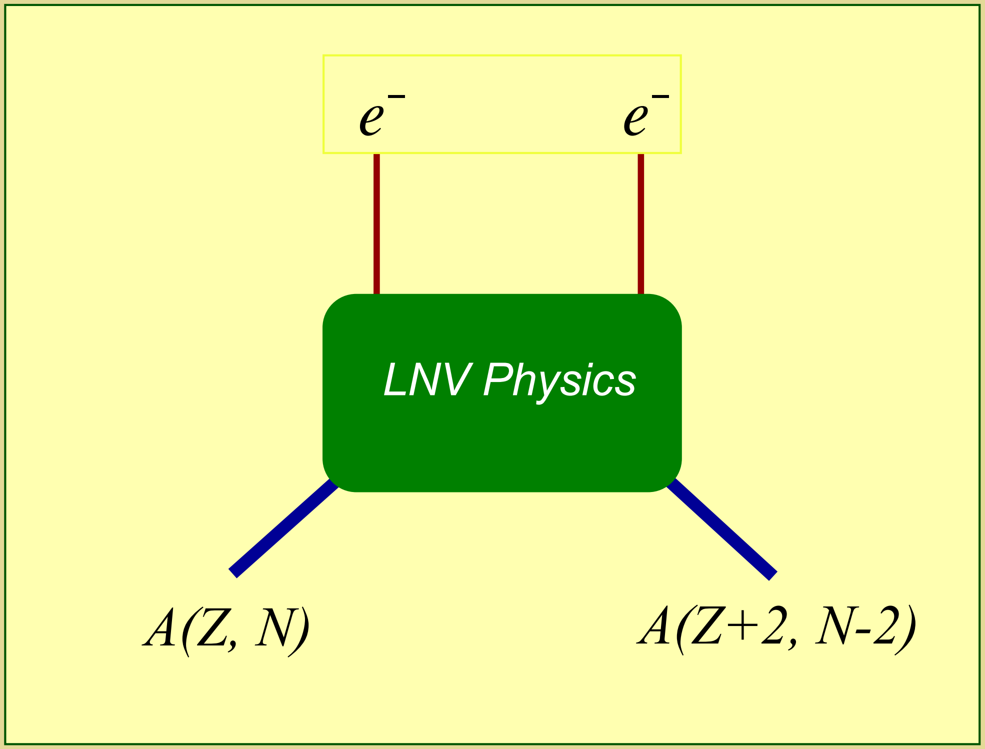
Impact of observation

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



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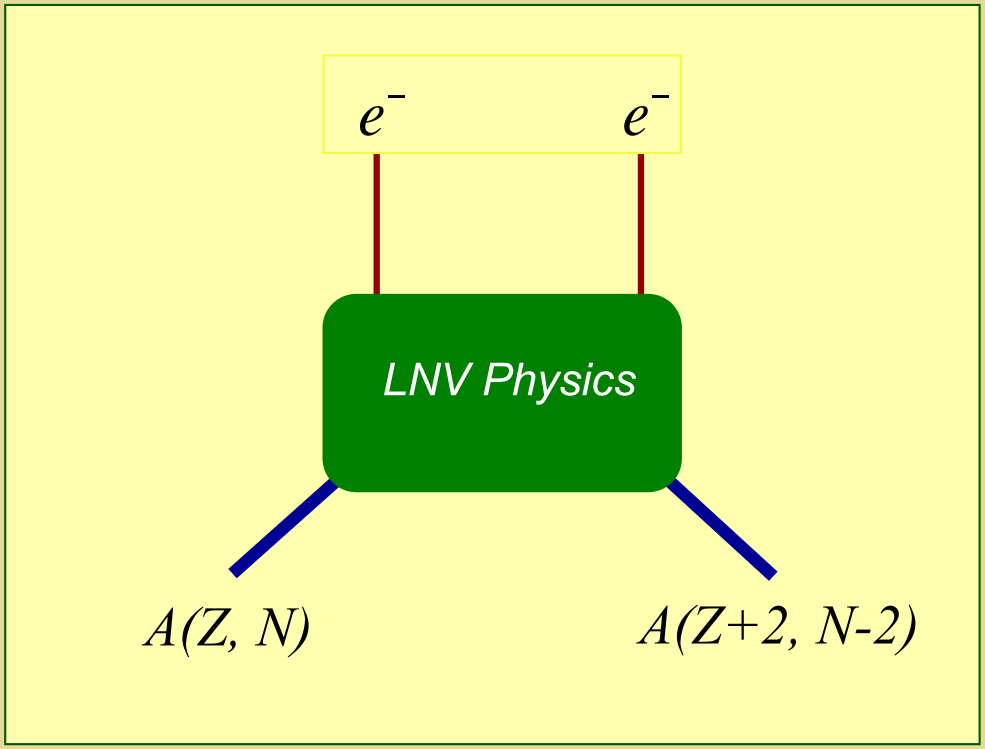

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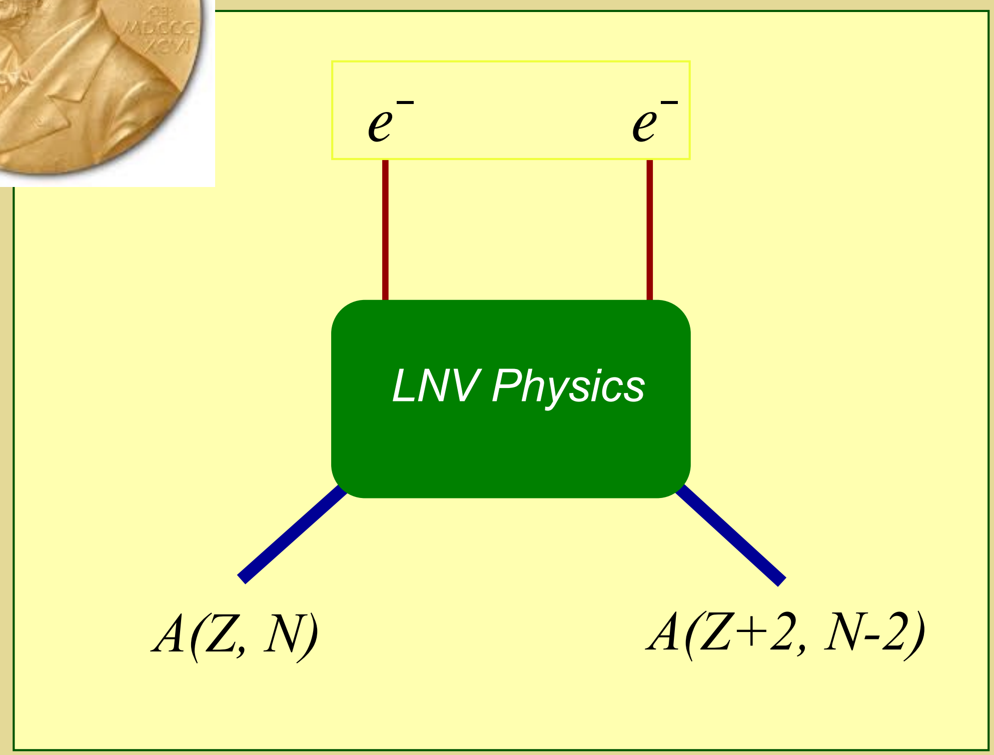

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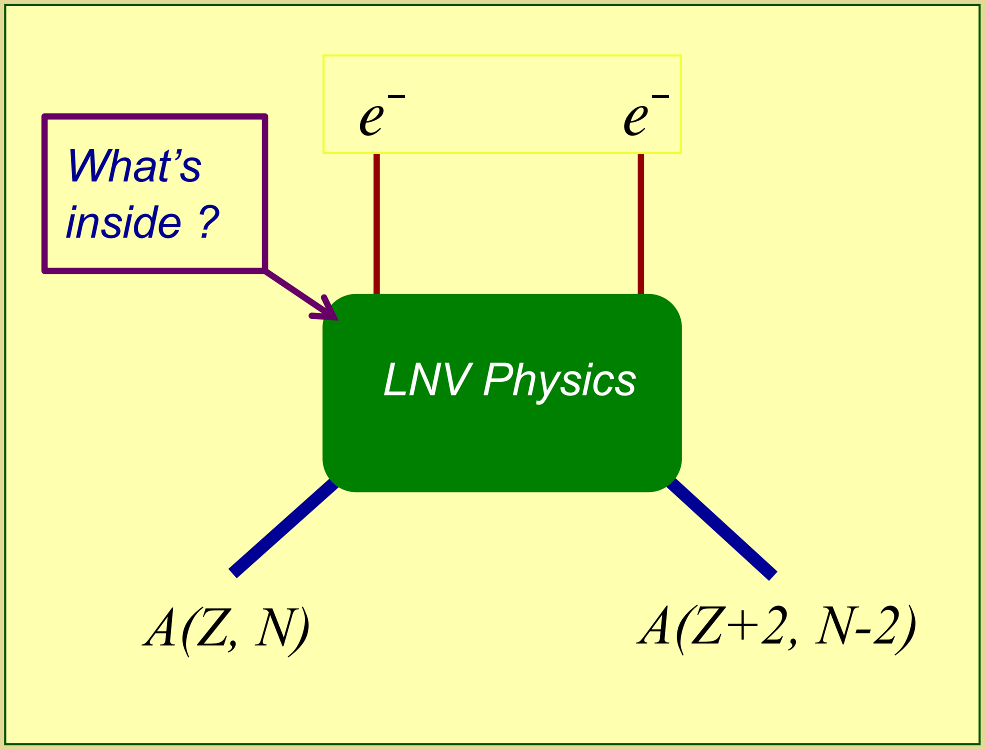

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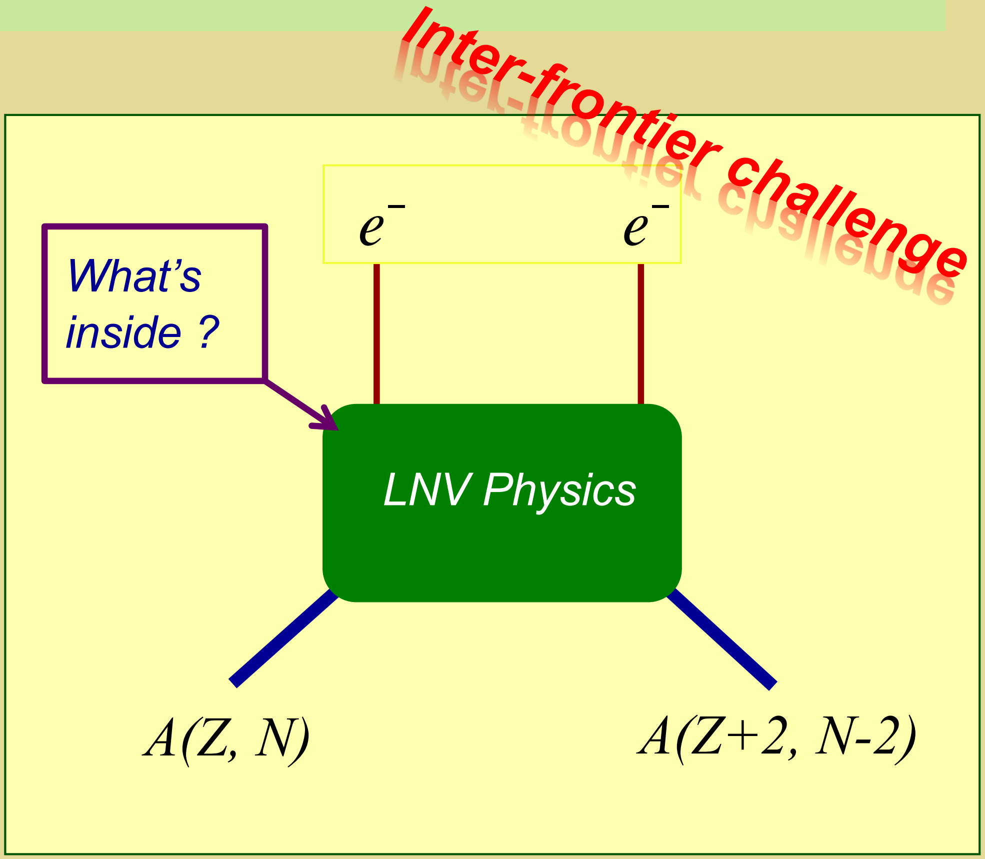
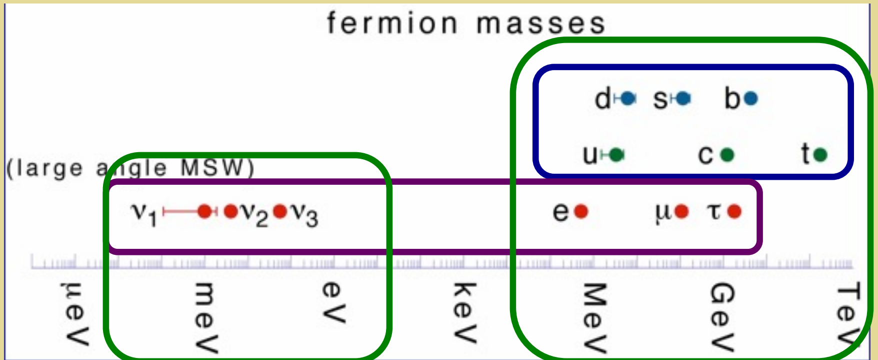


Fermion Masses & Baryon Asymmetry



Partners

Partners

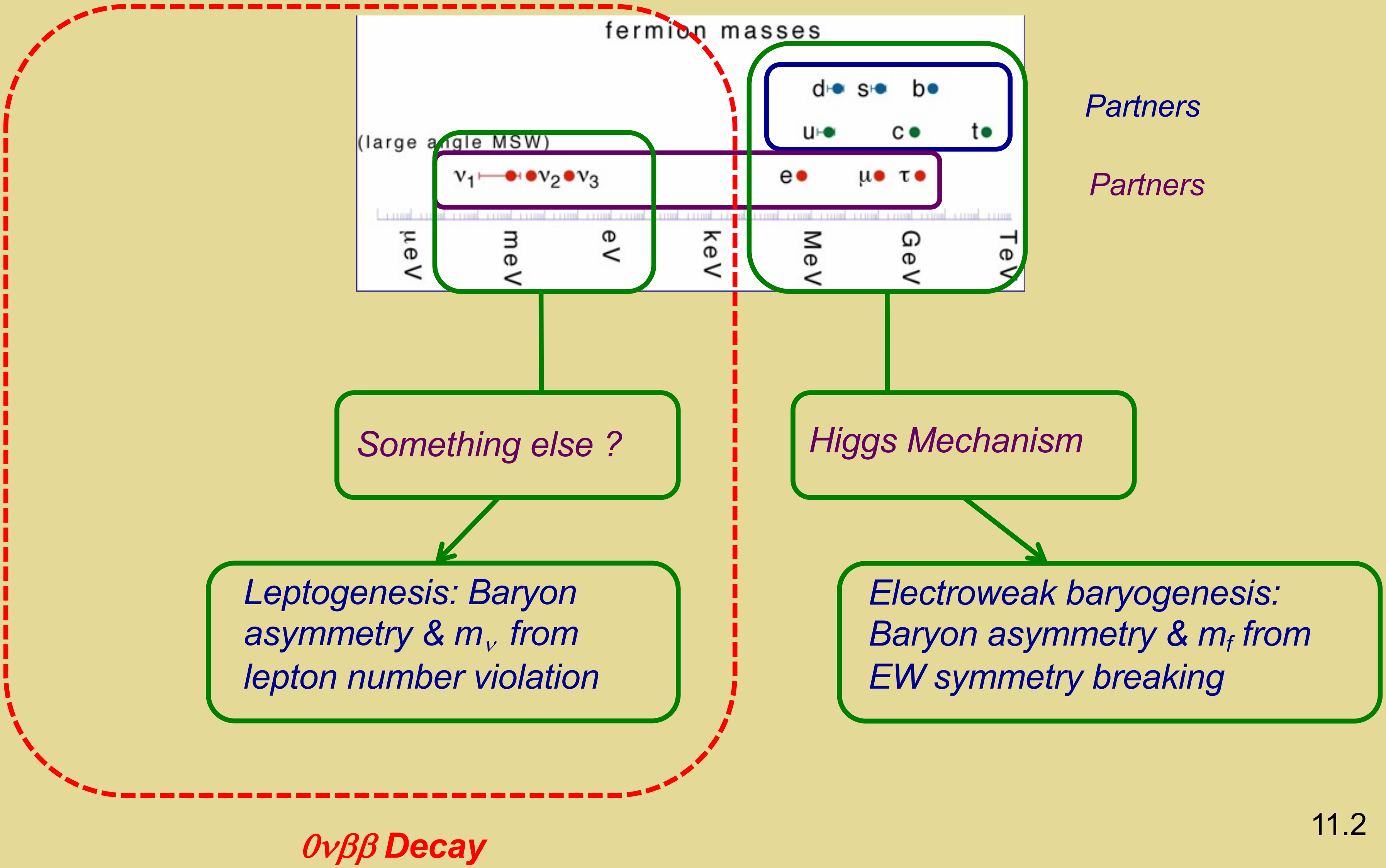
Something else ?

Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

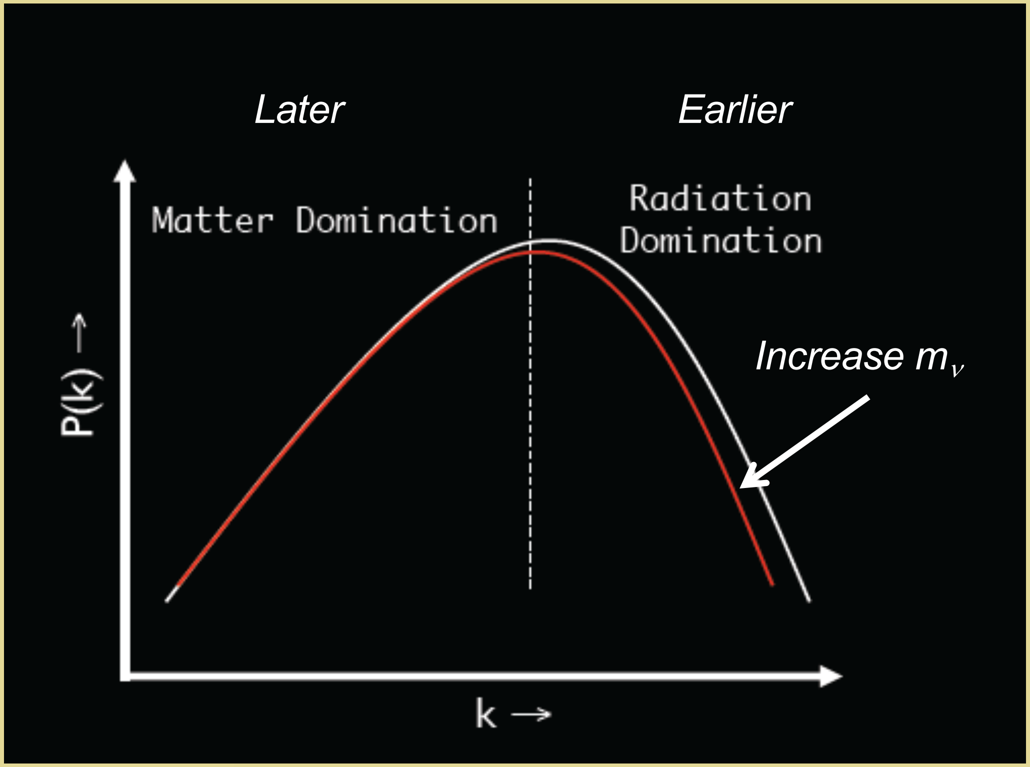
Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Fermion Masses & Baryon Asymmetry



Neutrino Mass & Cosmology

Matter Power Spectrum



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

Palanque-Dalabrouille '15

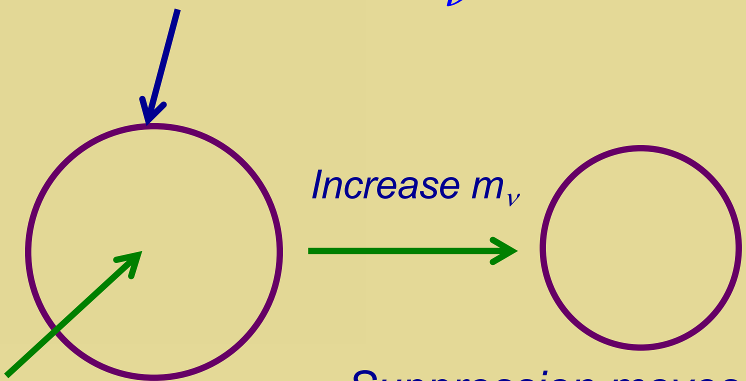
Neutrino Free Streaming

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

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

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

K. Abazajian ACFI neutrino mass workshop

Neutrino Mass & Cosmology

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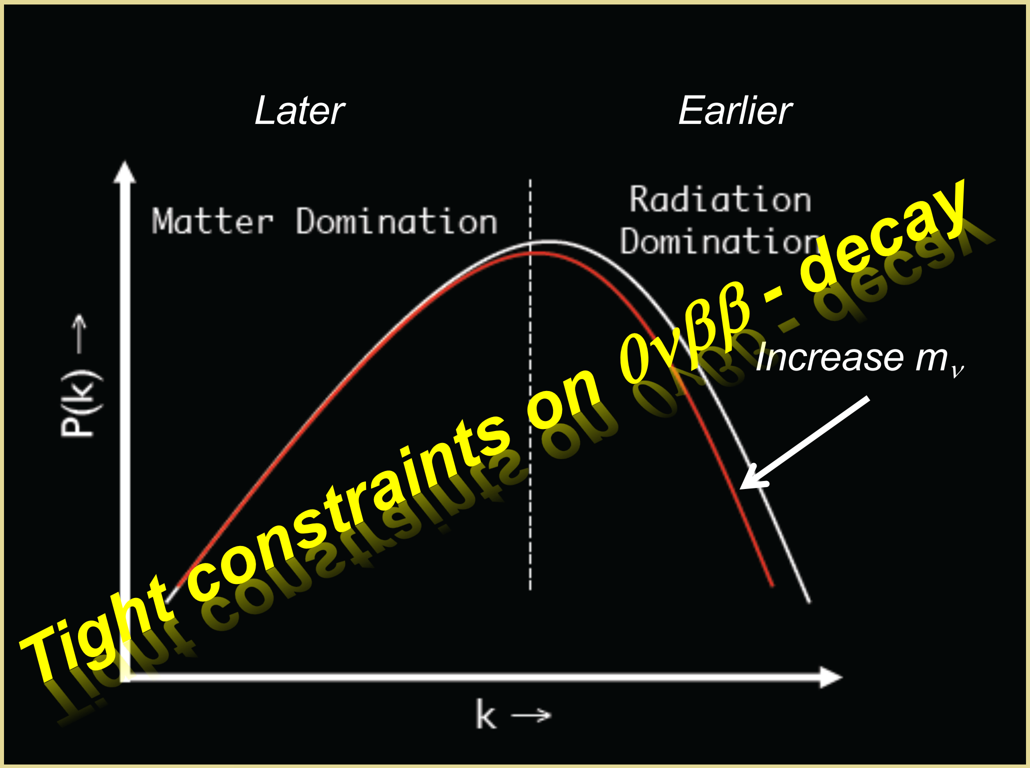

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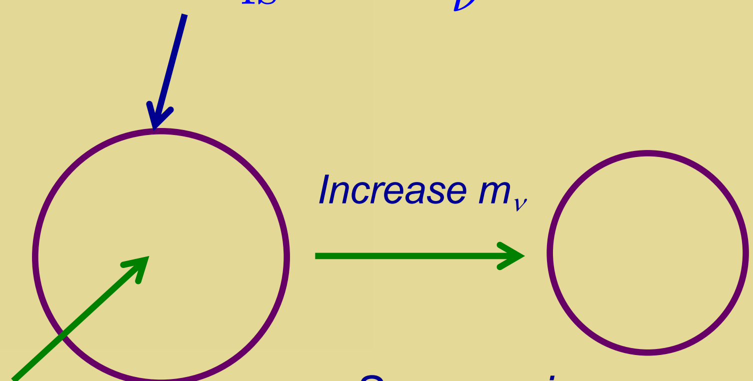

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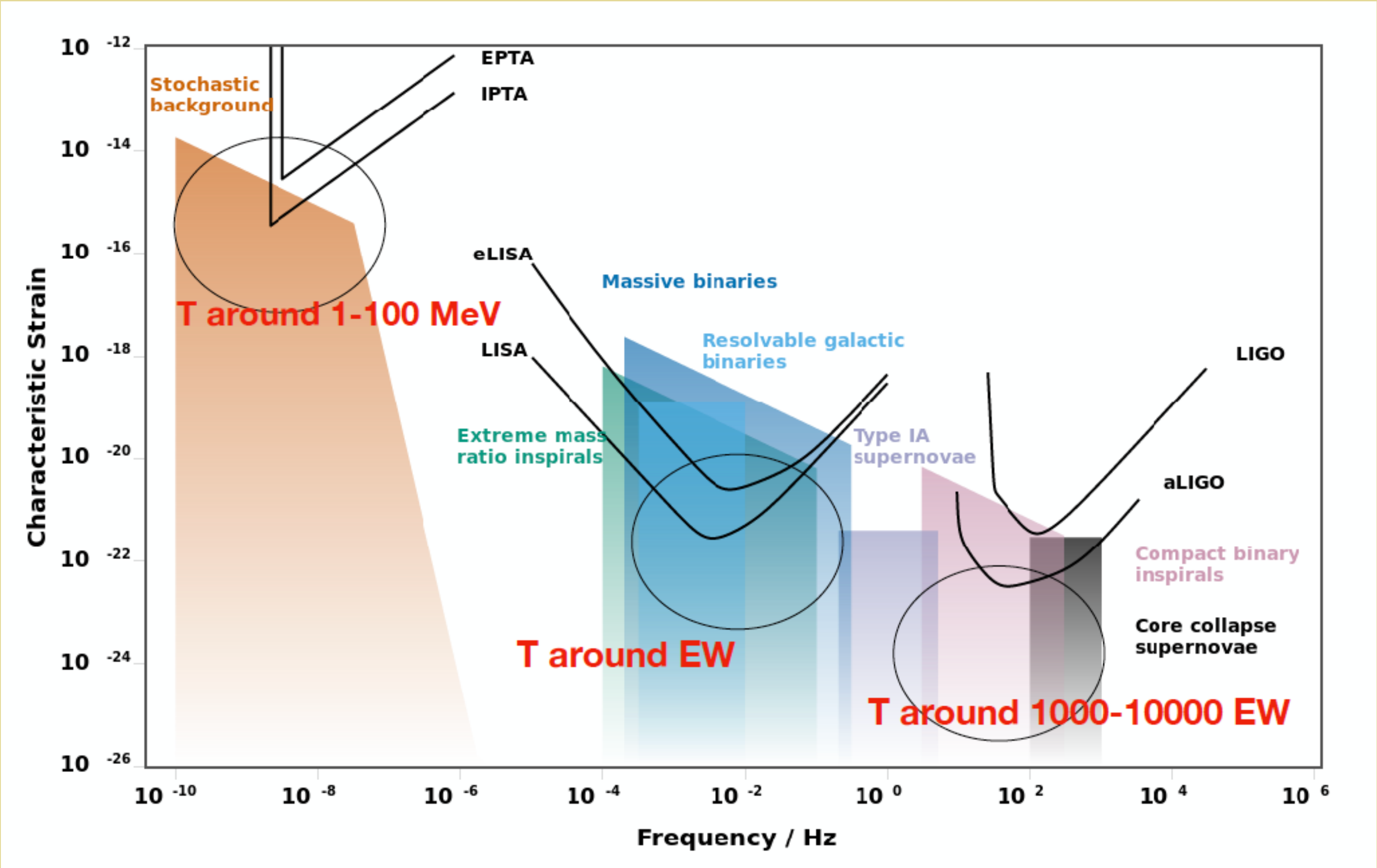
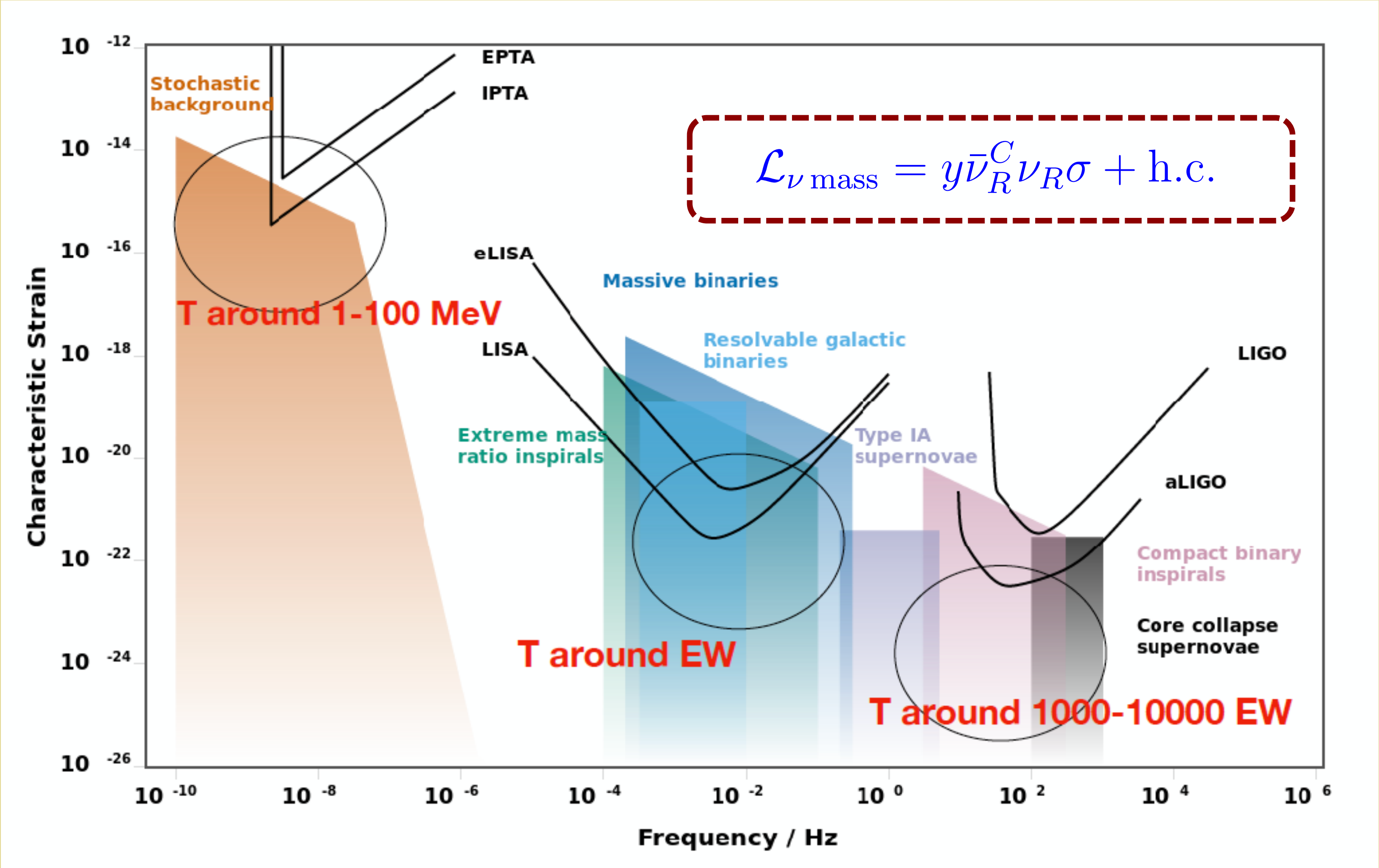
LNV Scalar Field & GW



Phase transition associated with spontaneous LNV → non-astrophysical GW source

LNV Scalar Field & GW



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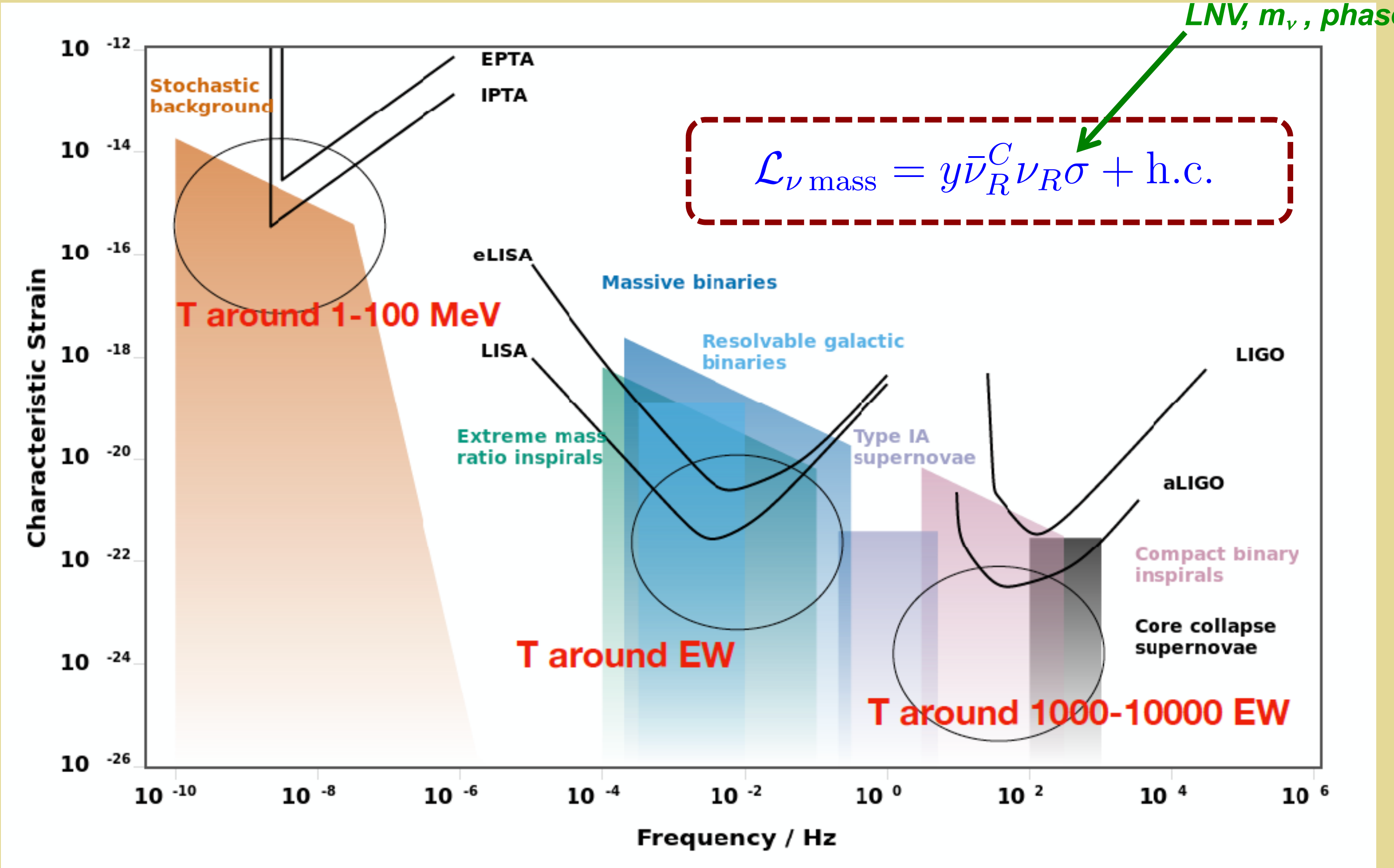
LNV Scalar Field & GW

σ VEV → spontaneous LNV, m_ν, phase transition



Phase transition associated with spontaneous LNV → non-astrophysical GW source

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

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Majorana

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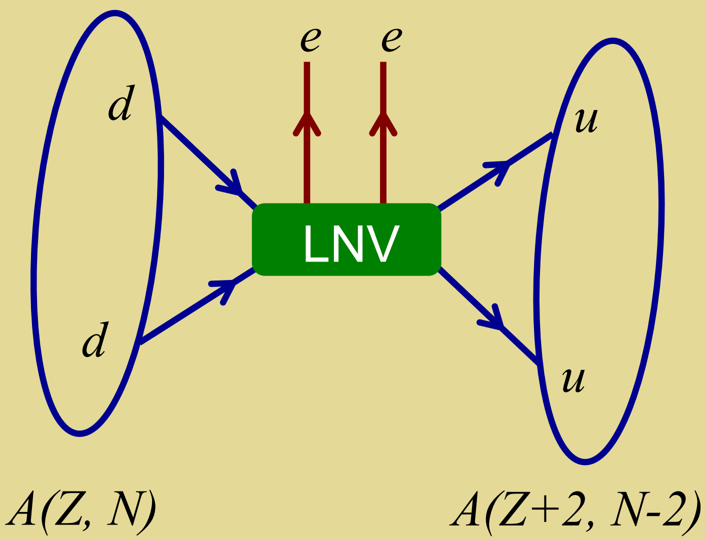
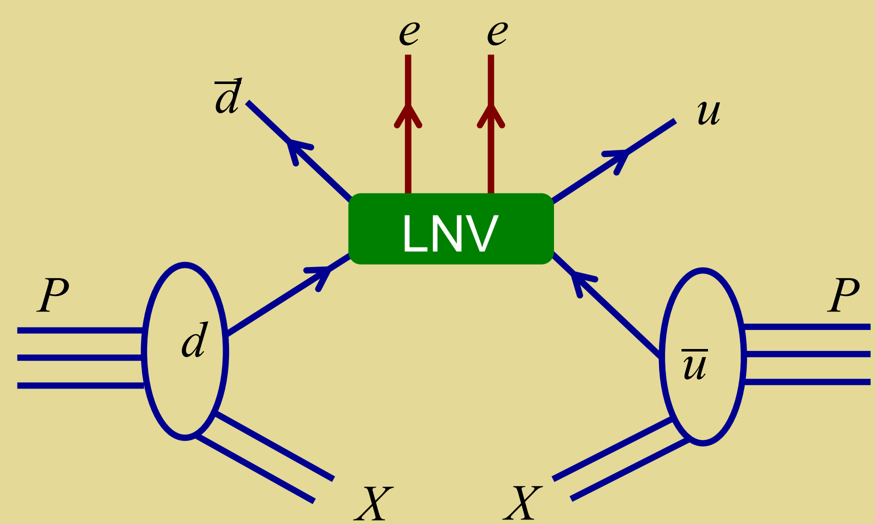


pp Collisions



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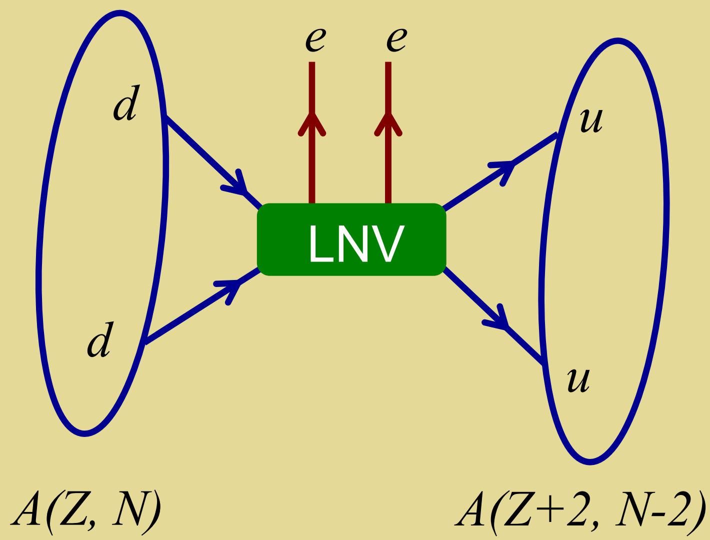
LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



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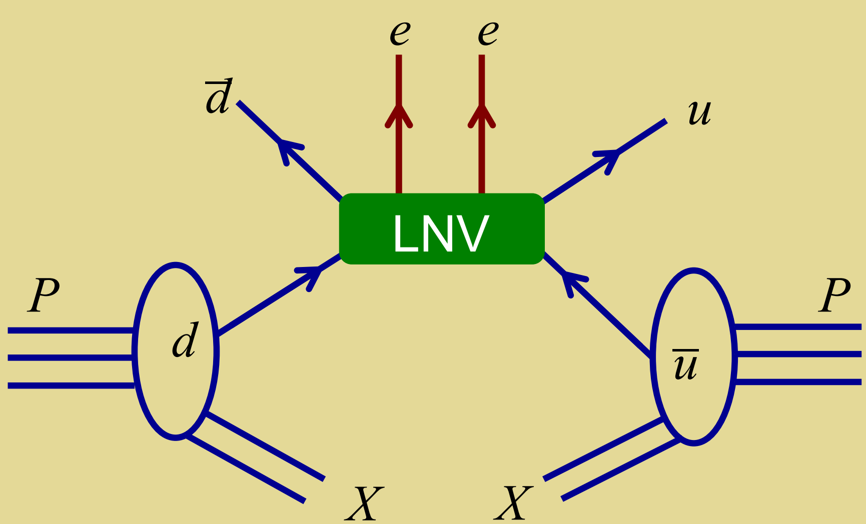

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ 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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How can we determine the underlying LNV physics?

II. Scenarios

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

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The "Standard Mechanism"

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

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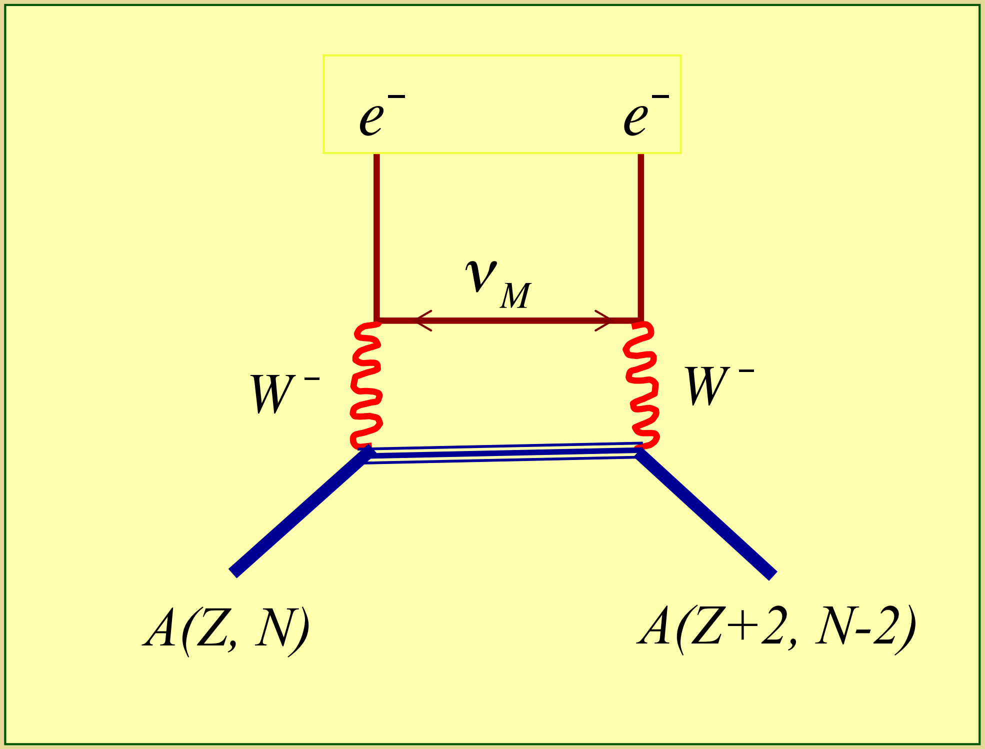
Majorana

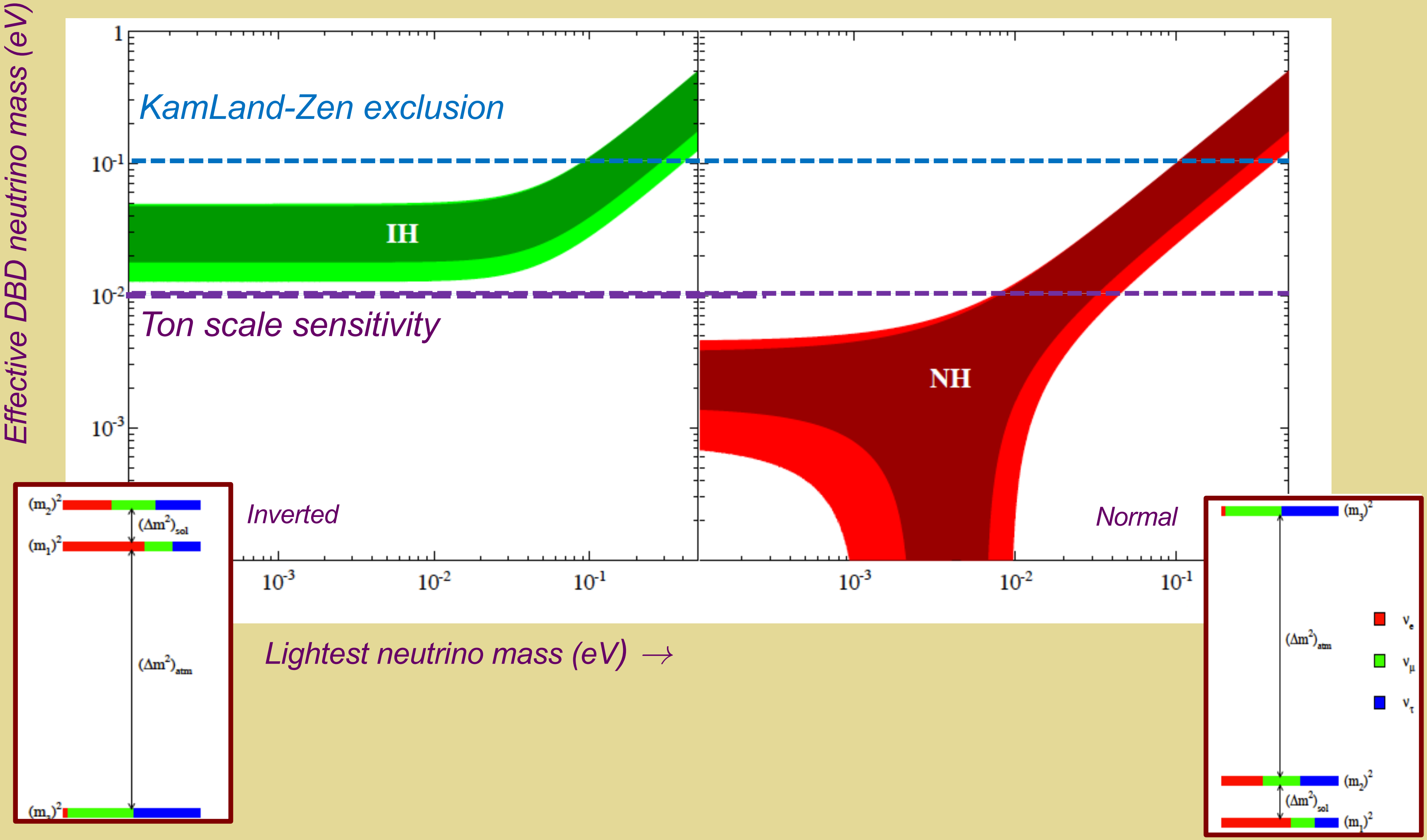
"Standard" Mechanism

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



$0\nu\beta\beta$-Decay: "Standard" Mechanism

Three active light neutrinos



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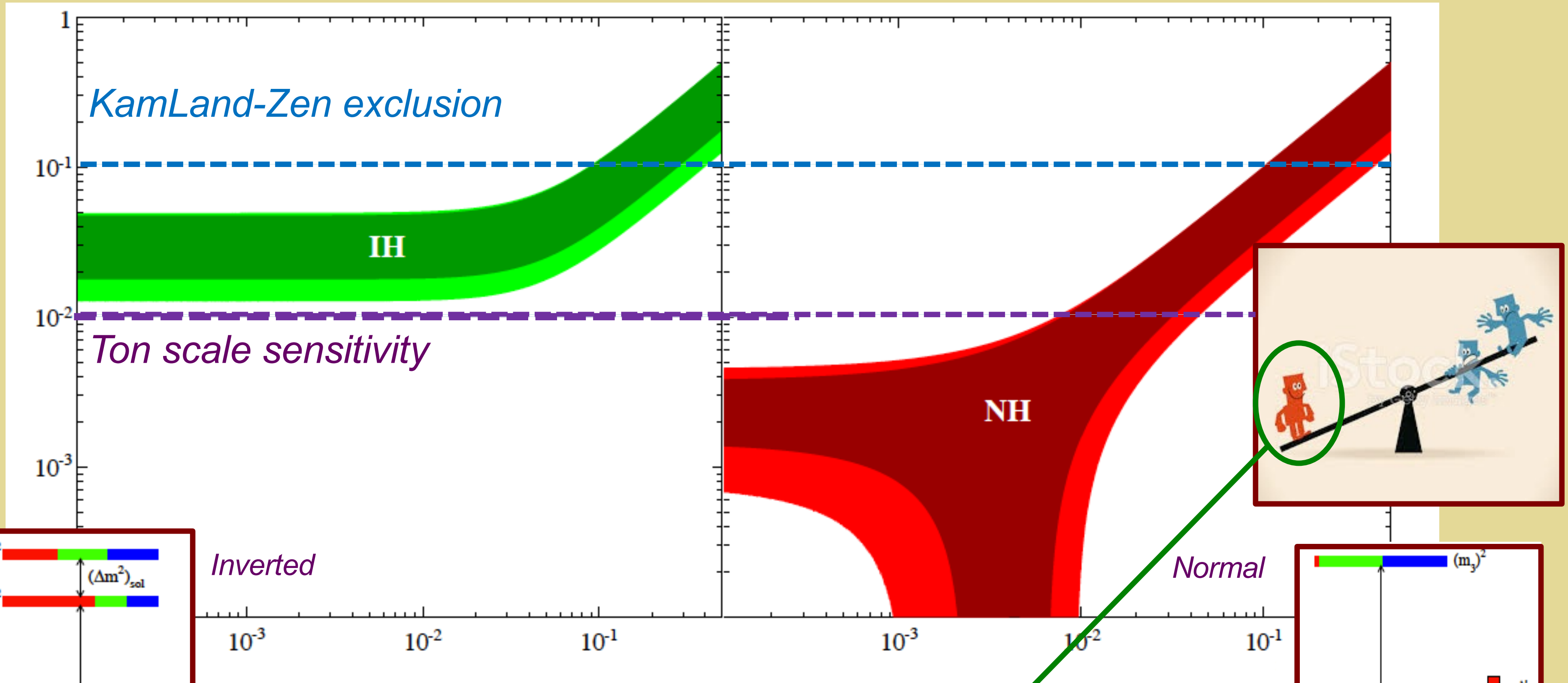
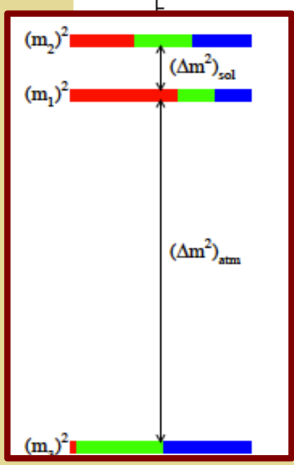
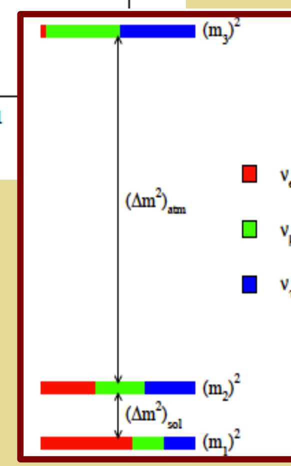
Effective DBD neutrino mass (eV)





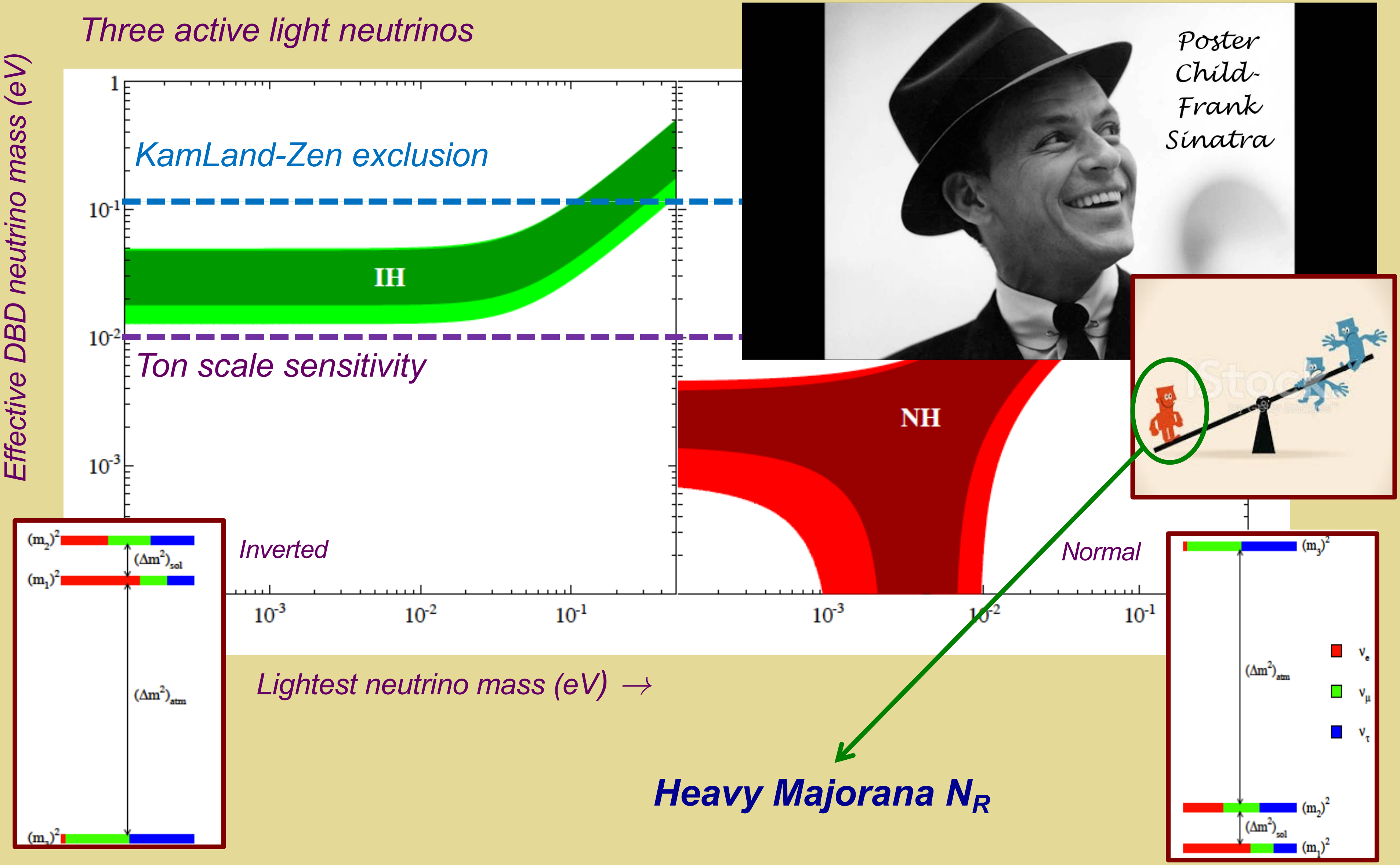


Lightest neutrino mass (eV) $\rightarrow$

Heavy Majorana N_R

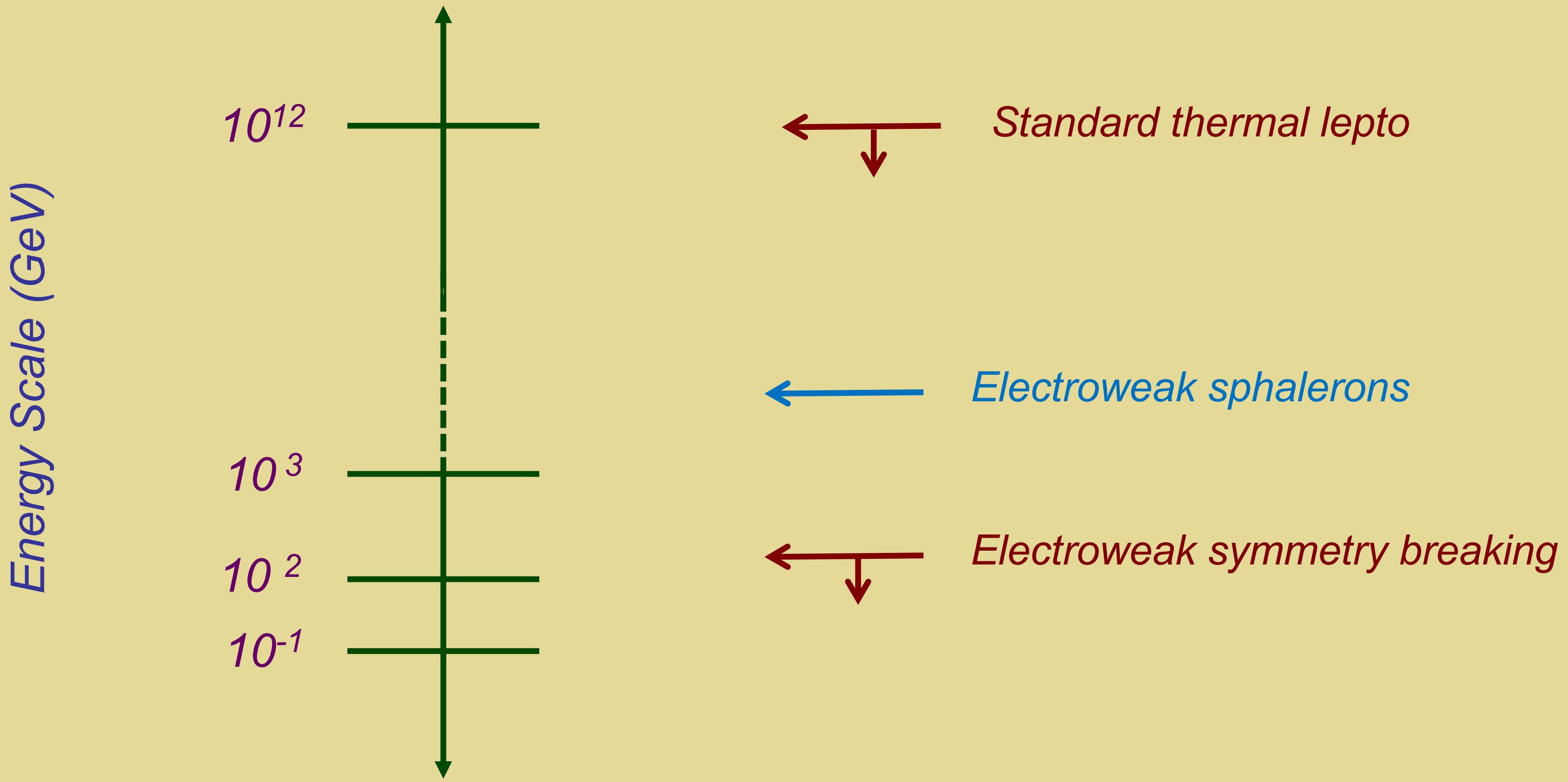
$0\nu\beta\beta$-Decay: "Poster Child" Mechanism

Three active light neutrinos



Heavy Majorana N_R

High Scale LNV & Leptogenesis



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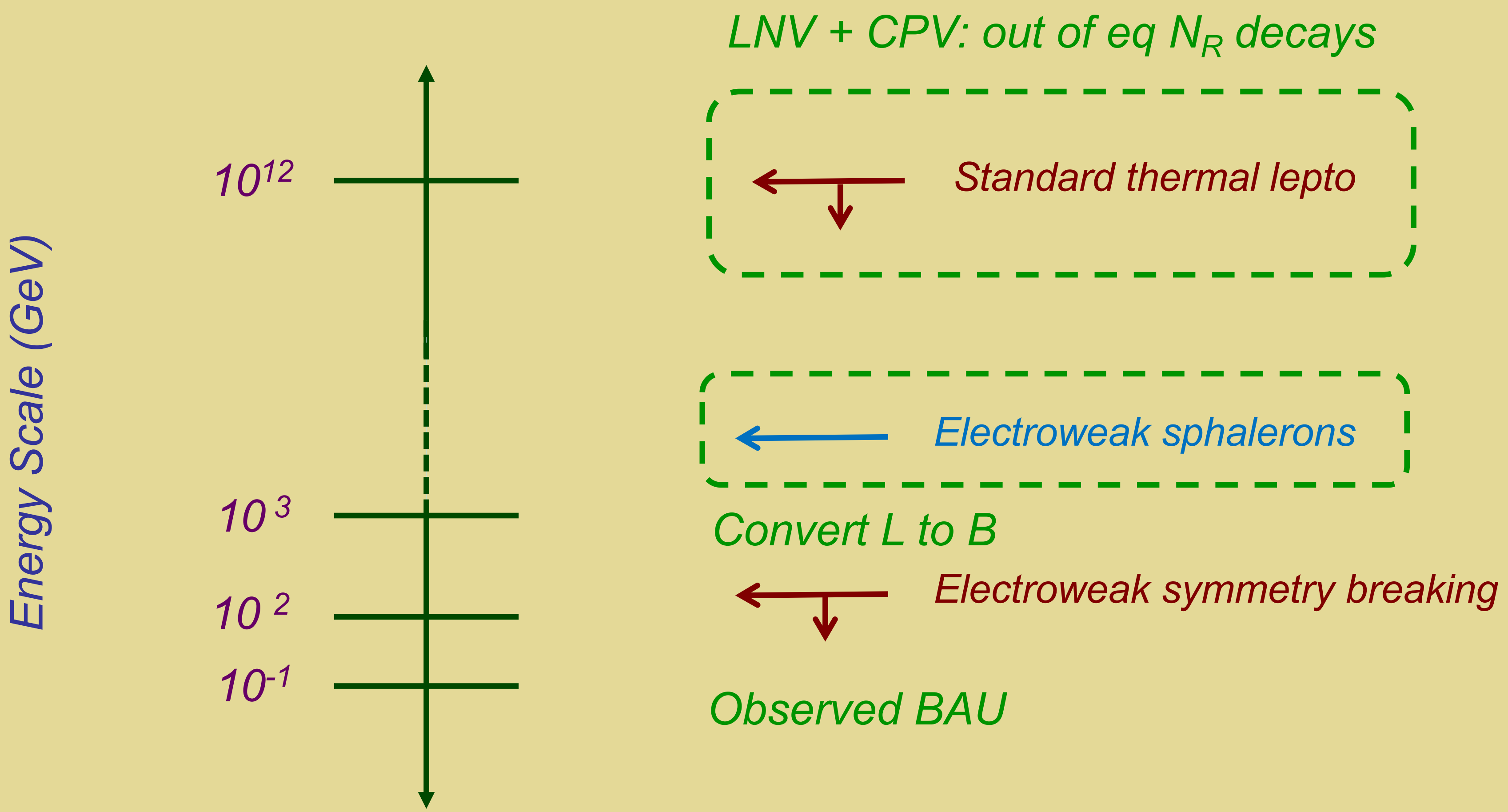
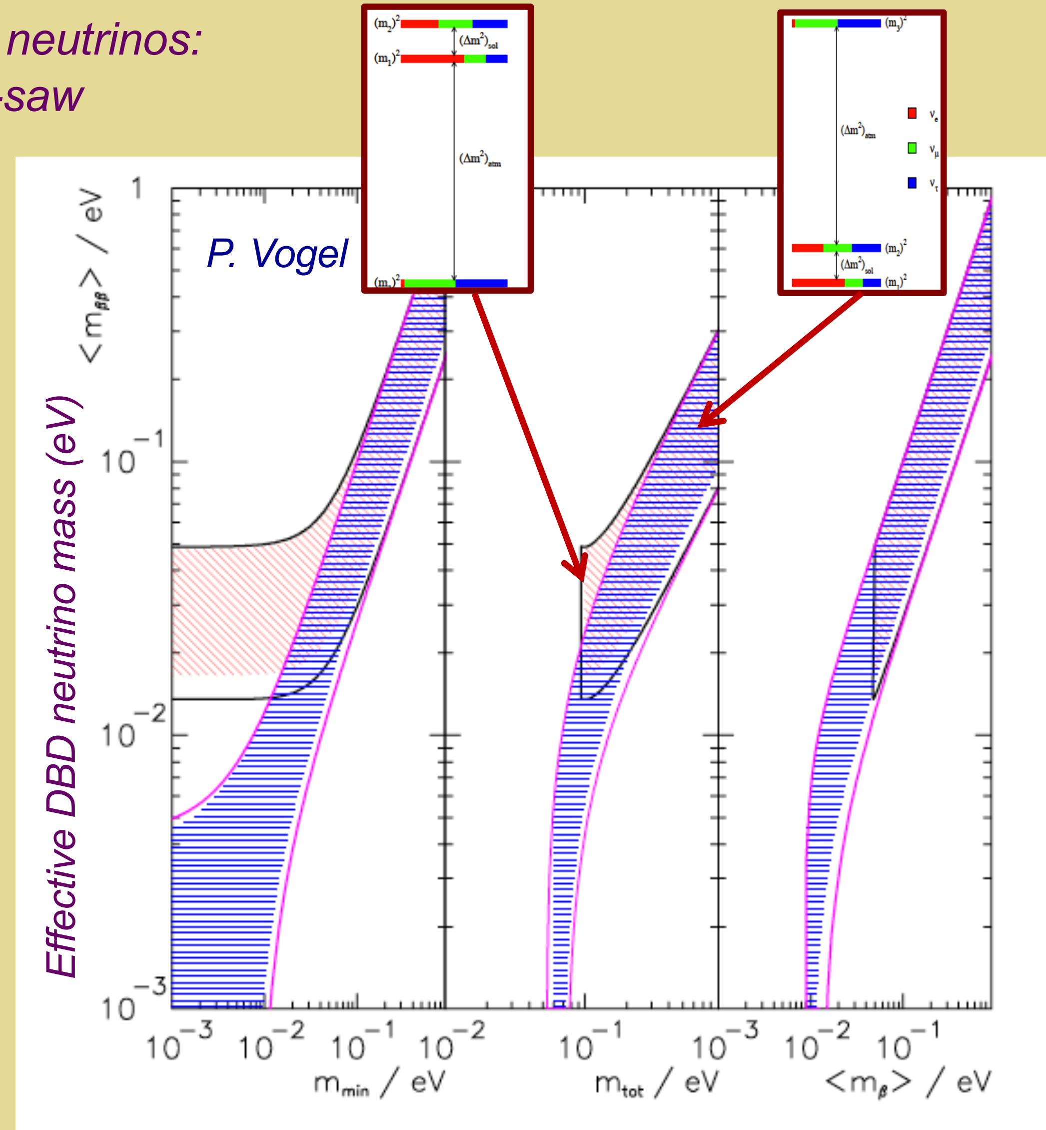


$\Sigma\, m_\nu$ from Cosmo: $0\nu\beta\beta$-Decay Implications

Three active light neutrinos:
conventional see-saw



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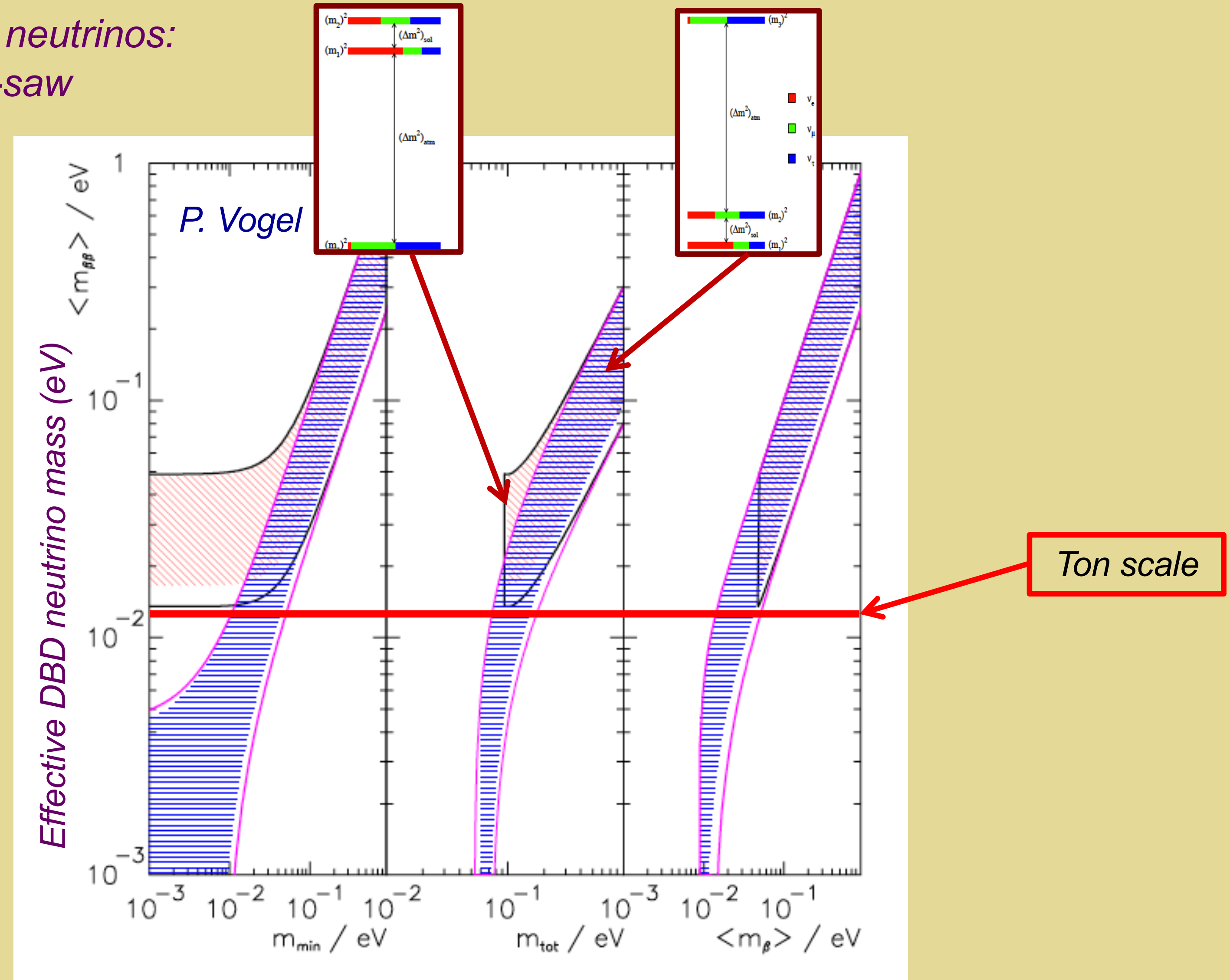

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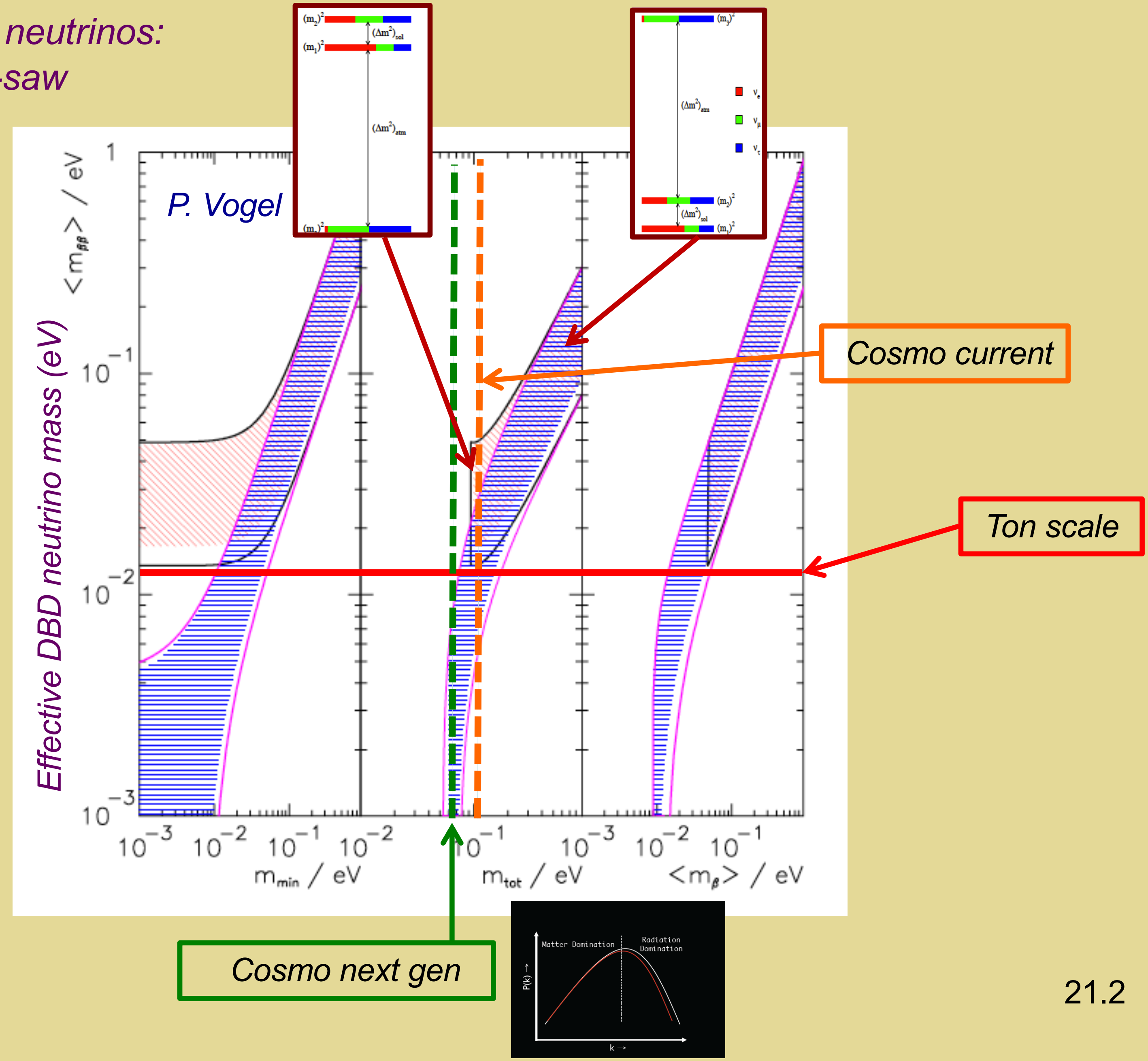

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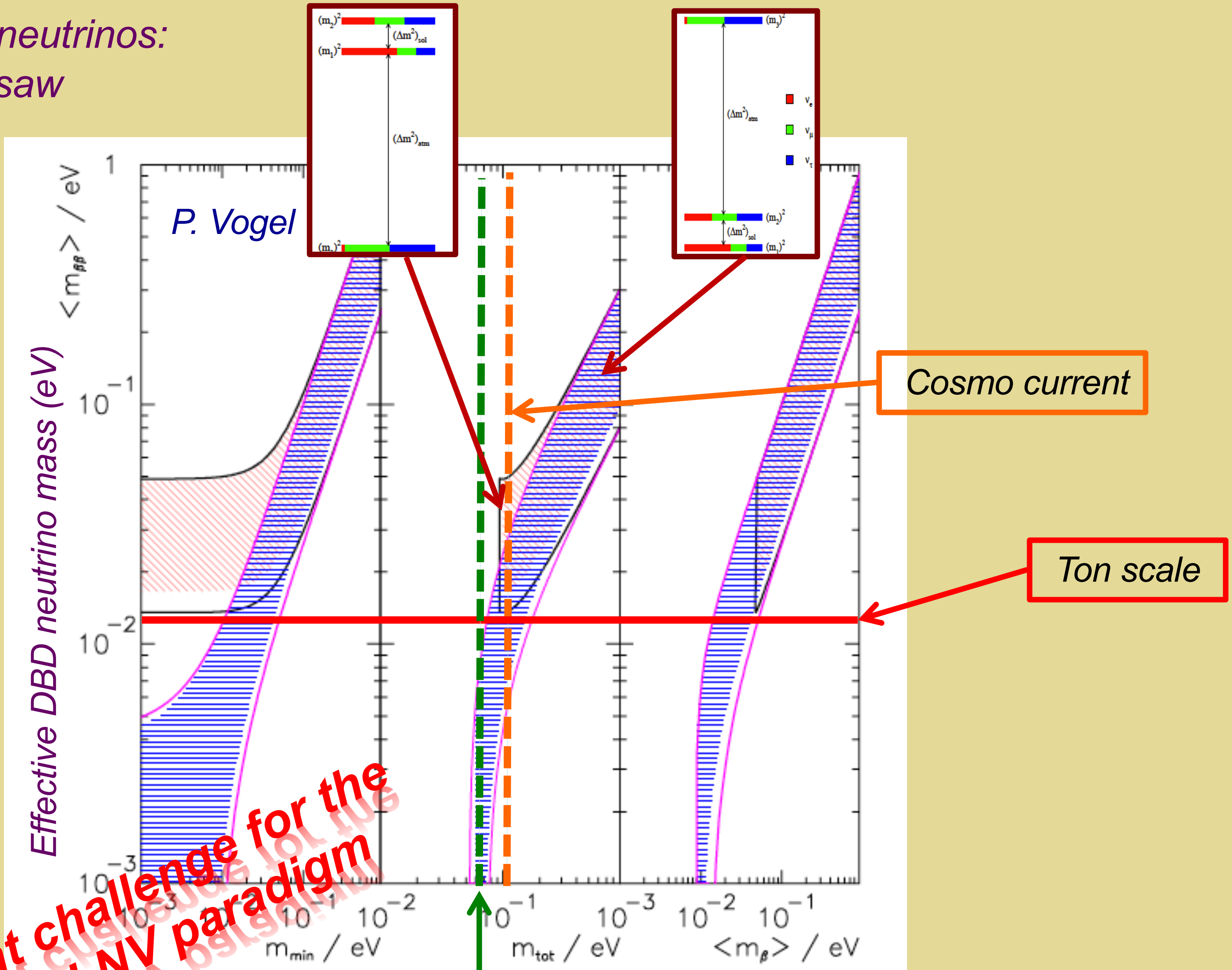

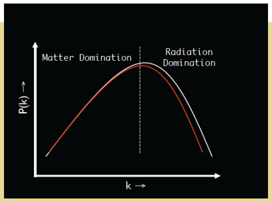

Important challenge for the high scale LNV paradigm

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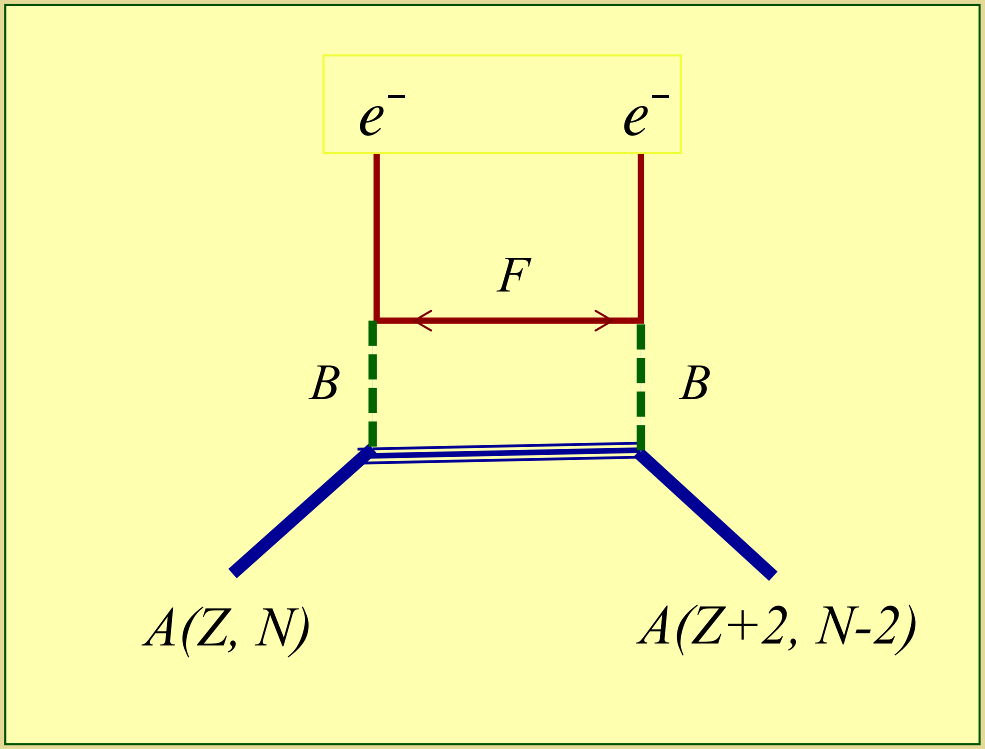
Majorana

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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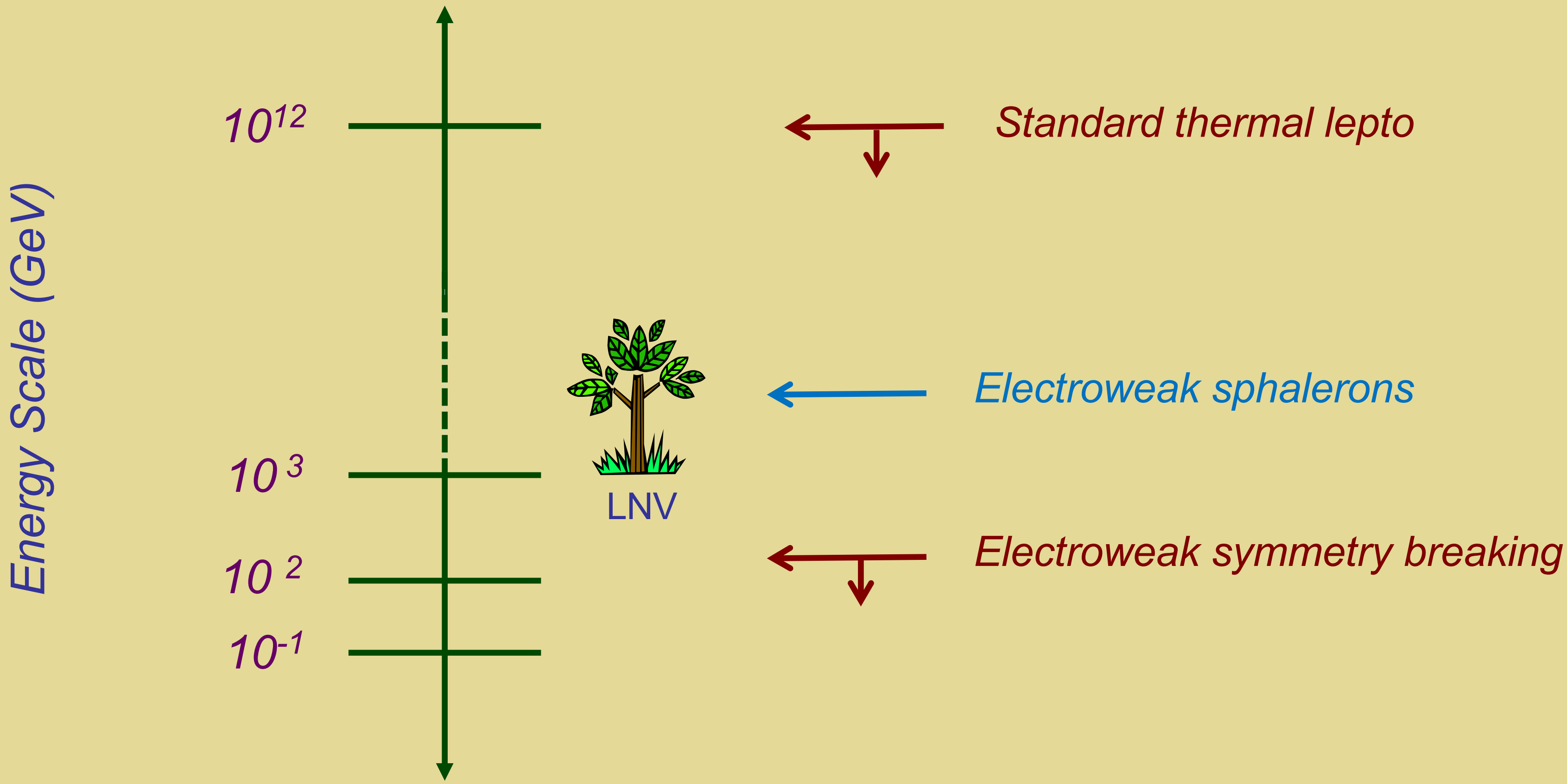
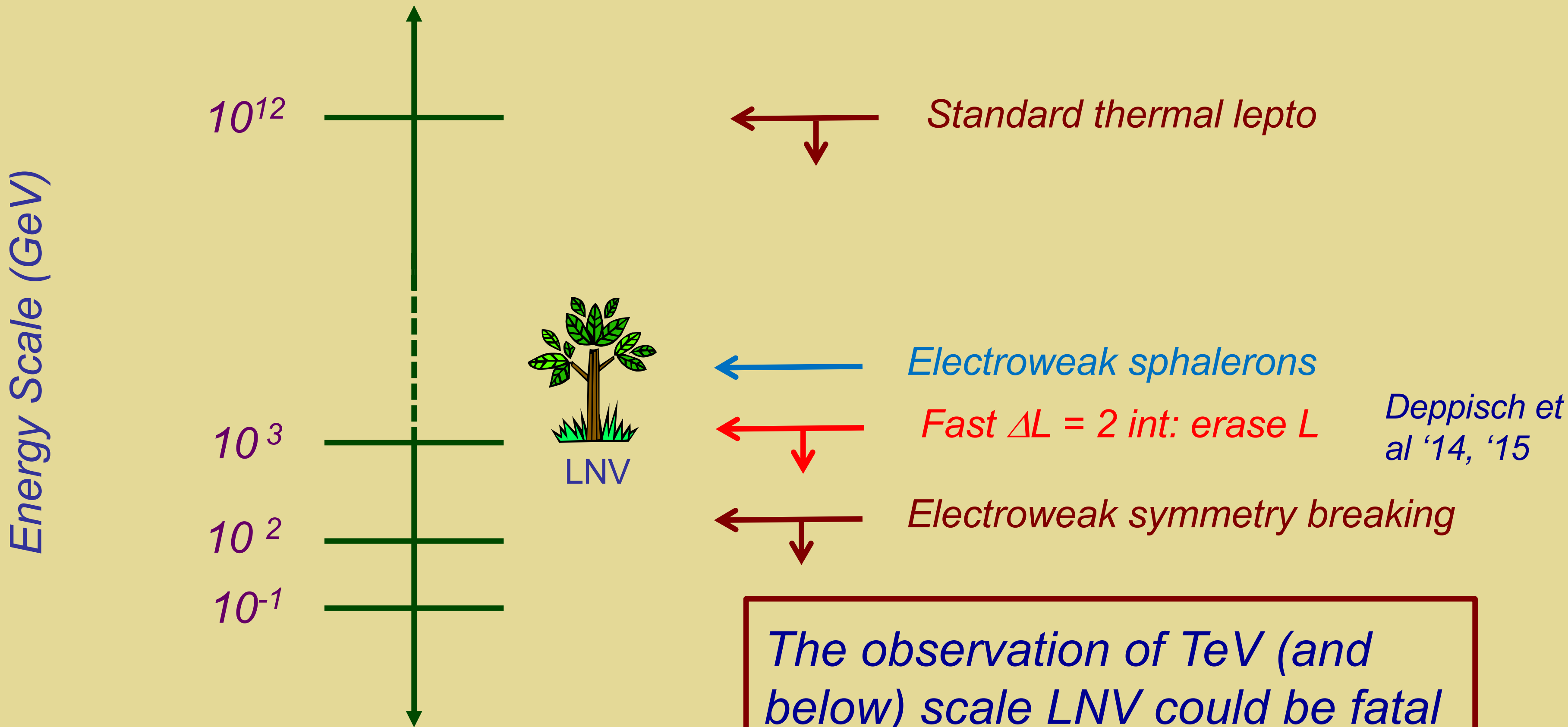
- **ν osc**
- **PV ee …**

Colliders

High Scale LNV & Leptogenesis

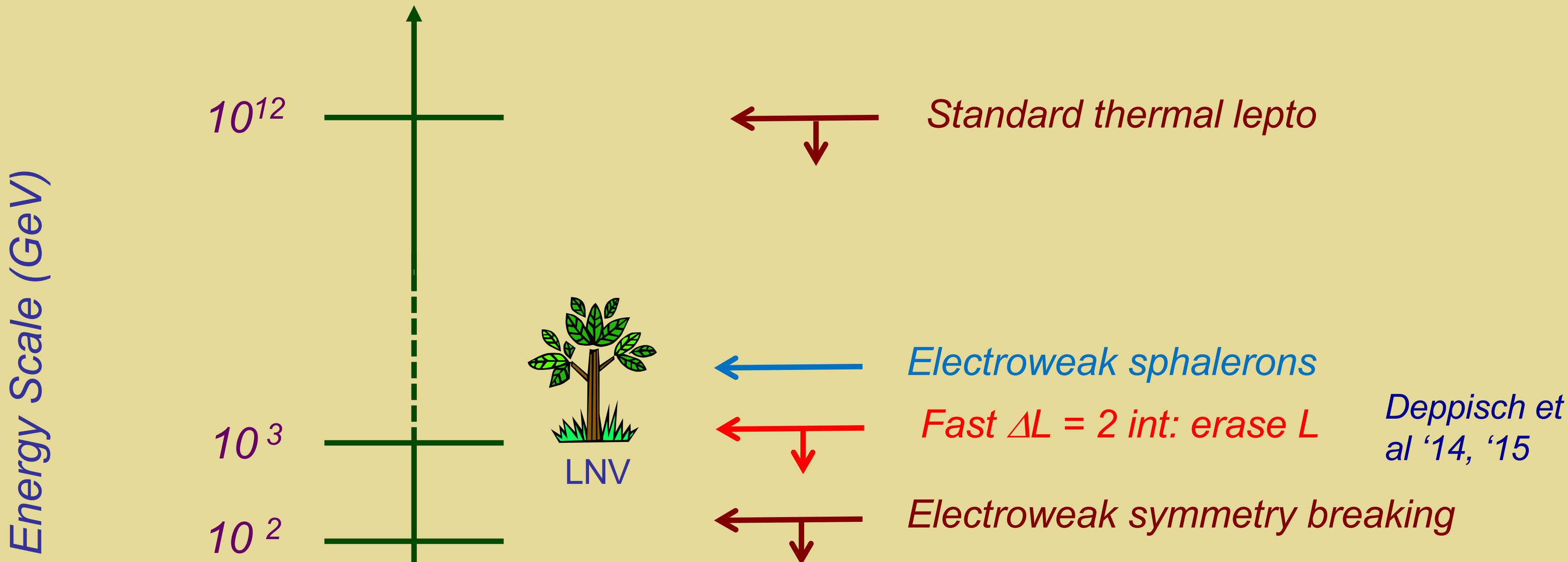


Low Scale LNV & Leptogenesis



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

Low Scale LNV & Leptogenesis



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

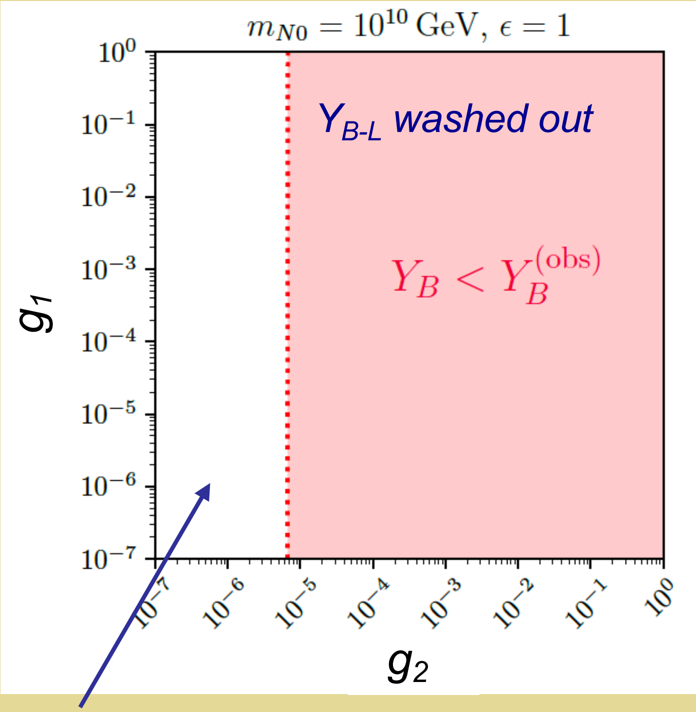
Other baryogenesis mechanisms needed

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)
F: (1, 0, 0) Majorana



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

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

BSM LNV: *0νββ*-Decay & pp Colliders

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

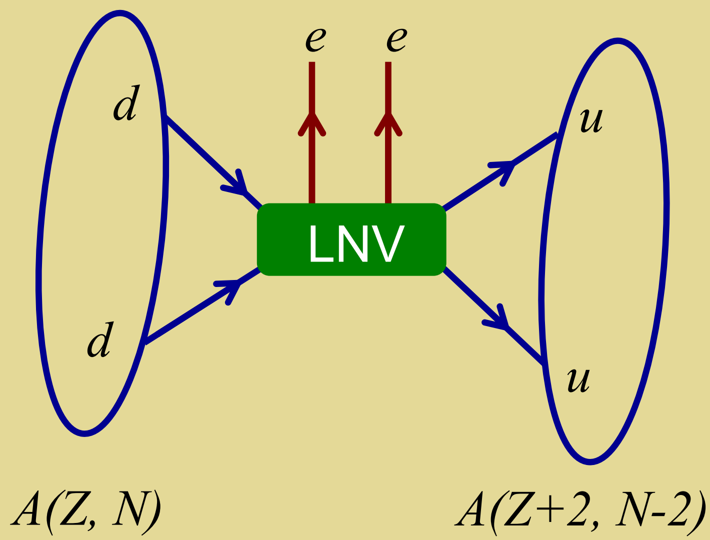
Dirac

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

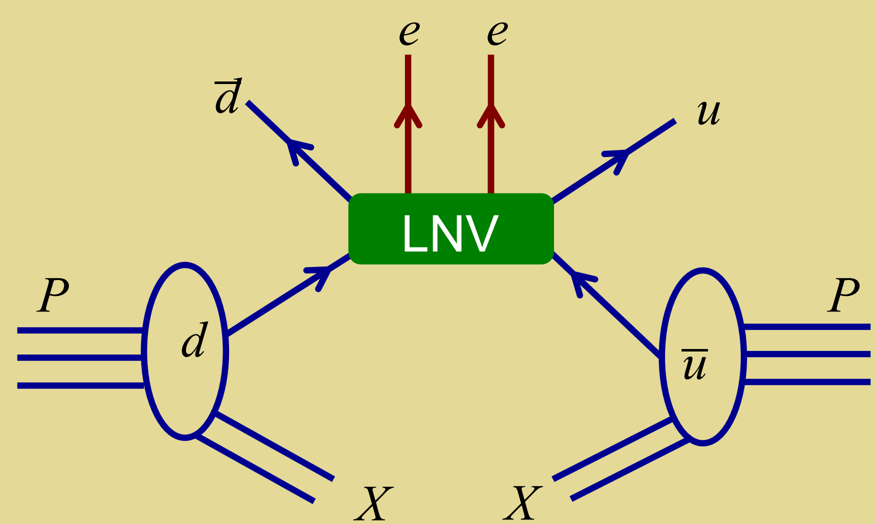
Majorana

LHC: SS Dilepton + Dijet

0νββ-Decay



pp Collisions



Numerous studies: another talk…

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

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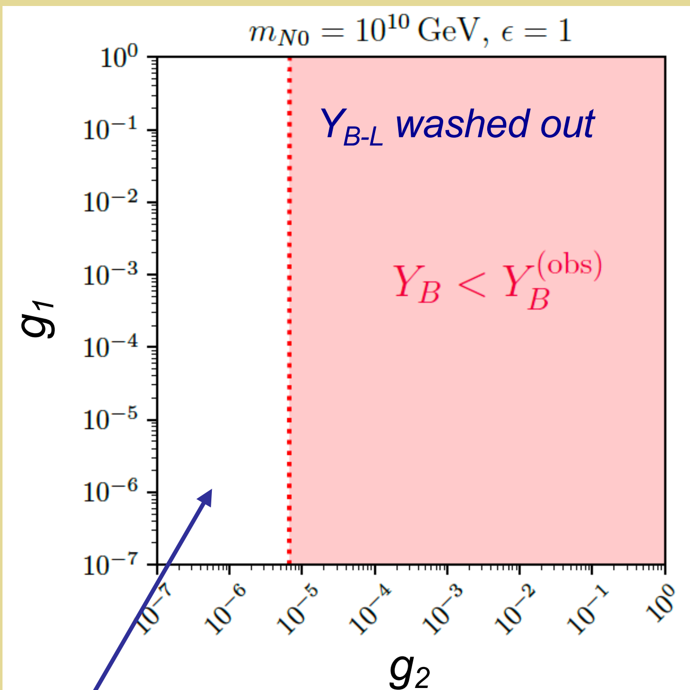

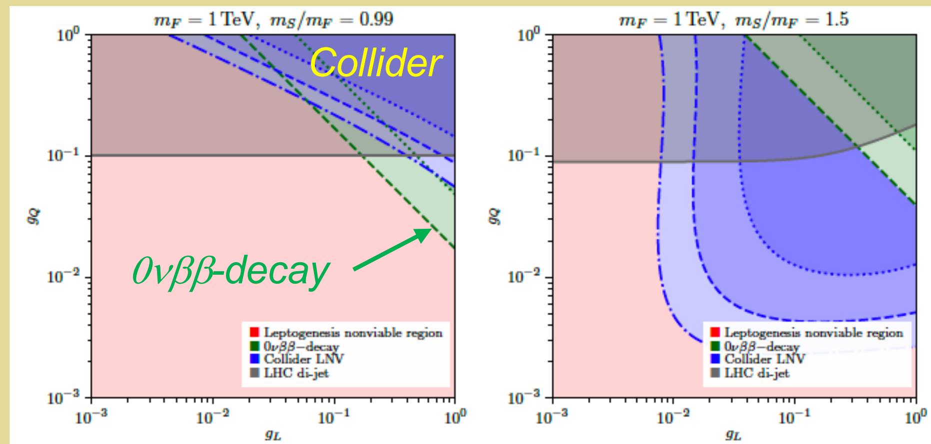

Comparing $0\nu\beta\beta$-decay, collider, & cosmo

Y_{B-L} survives

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

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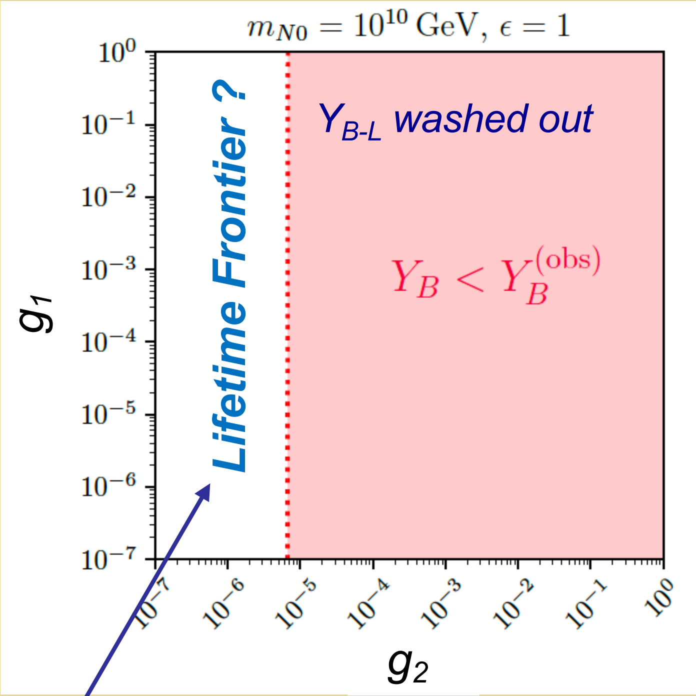

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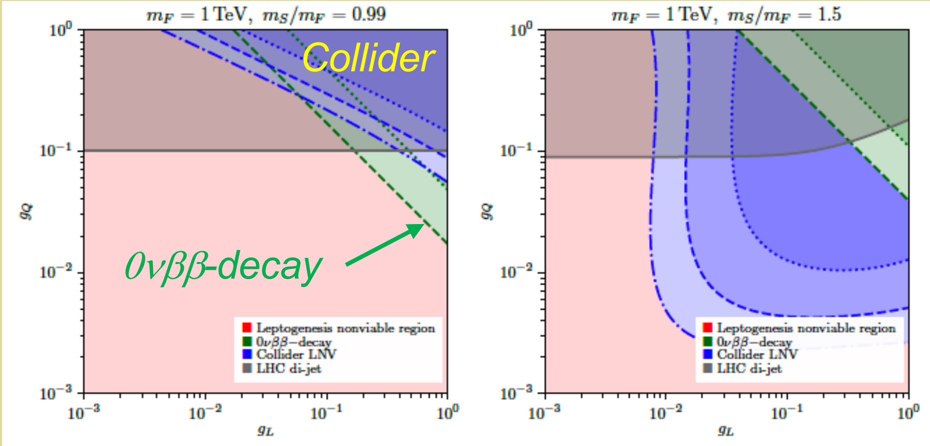

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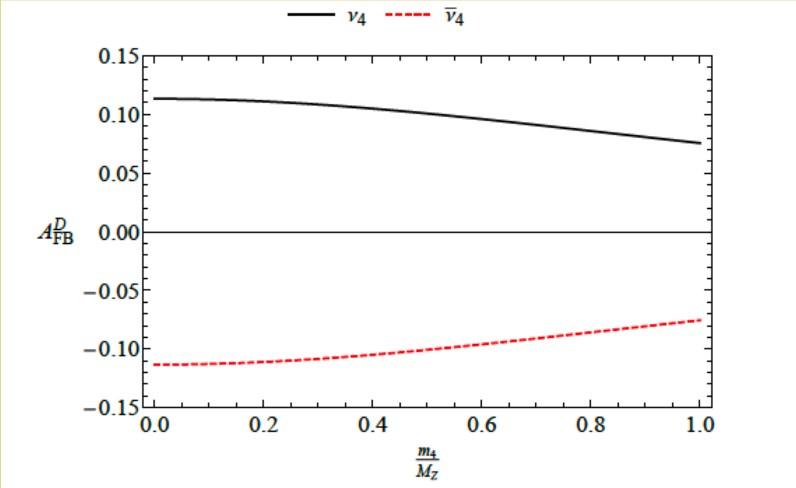
J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga '21

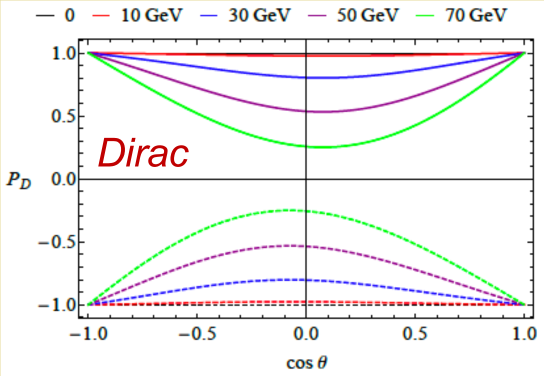
Lepton Collider Probes

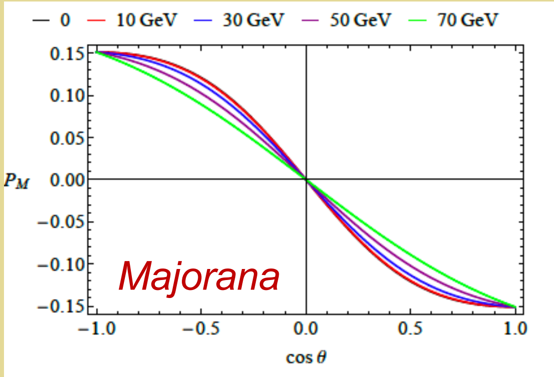
$e^+ e^- \rightarrow Z^0 \rightarrow N\ N$ **vs** $e^+ e^- \rightarrow Z^0 \rightarrow N\ \bar{N}$

Lepton FB Asymmetry



N Polarization





A_{FB} : vanish for Majorana N

M. Drewes 2210.17110 (mini-review)
Blondel, de Gouvea, Kayser 2105.06576

Lepton Collider Probes

$e^+ e^- \rightarrow Z^0 \rightarrow N N$ vs $e^+ e^- \rightarrow Z^0 \rightarrow N \bar{N}$

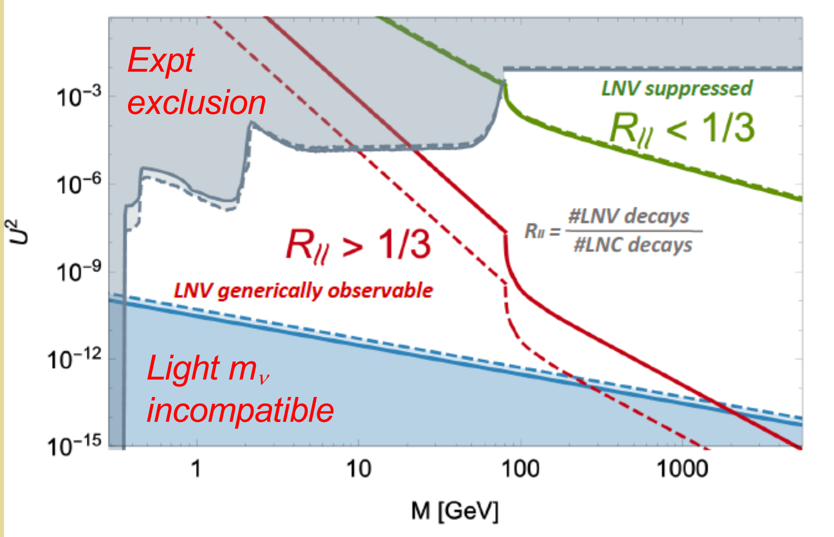
Displaced decays (LLPs)

$$N_{\rm obs} \simeq u_\beta^2 N_{\rm HNL\alpha} \left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right] \epsilon_{\alpha\beta},$$

$\lambda_N^{Majorana}$ = $2 \times \lambda_N^{Dirac}$

Active-HNL Mixing

LLP LNV Observability



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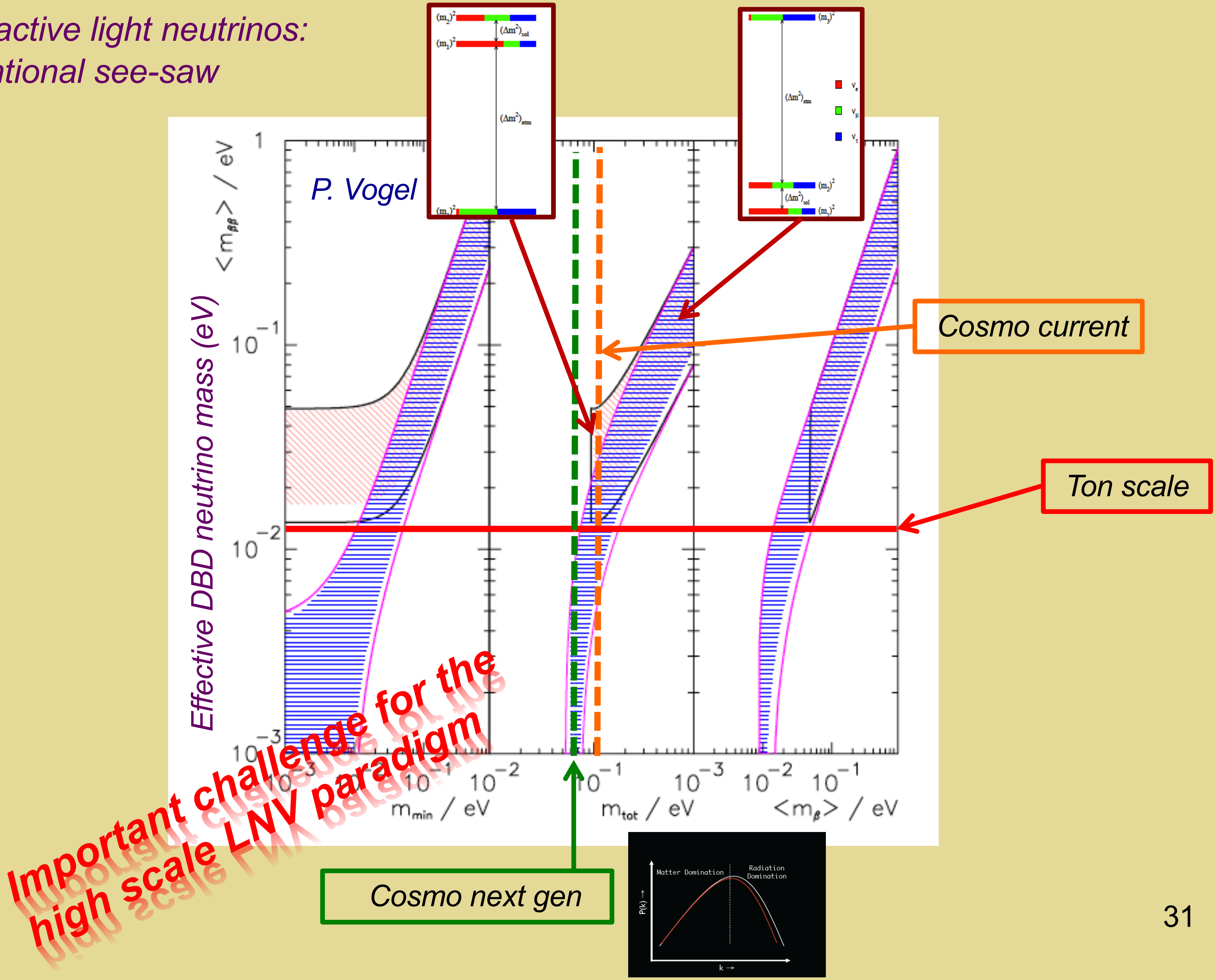
- $0\nu\beta\beta$ **decay**
- μ_ν
- ν **osc**
- **PV ee …**

Colliders

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

Three active light neutrinos: conventional see-saw

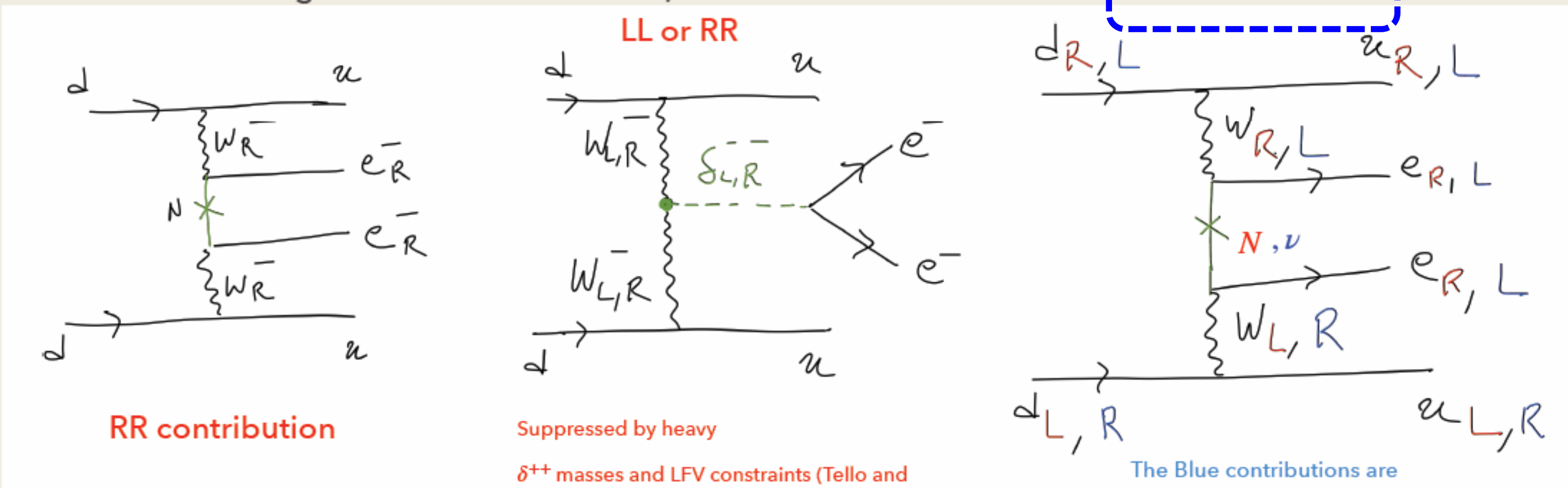


Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

Long range chiral enhancement

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

LR contribution



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

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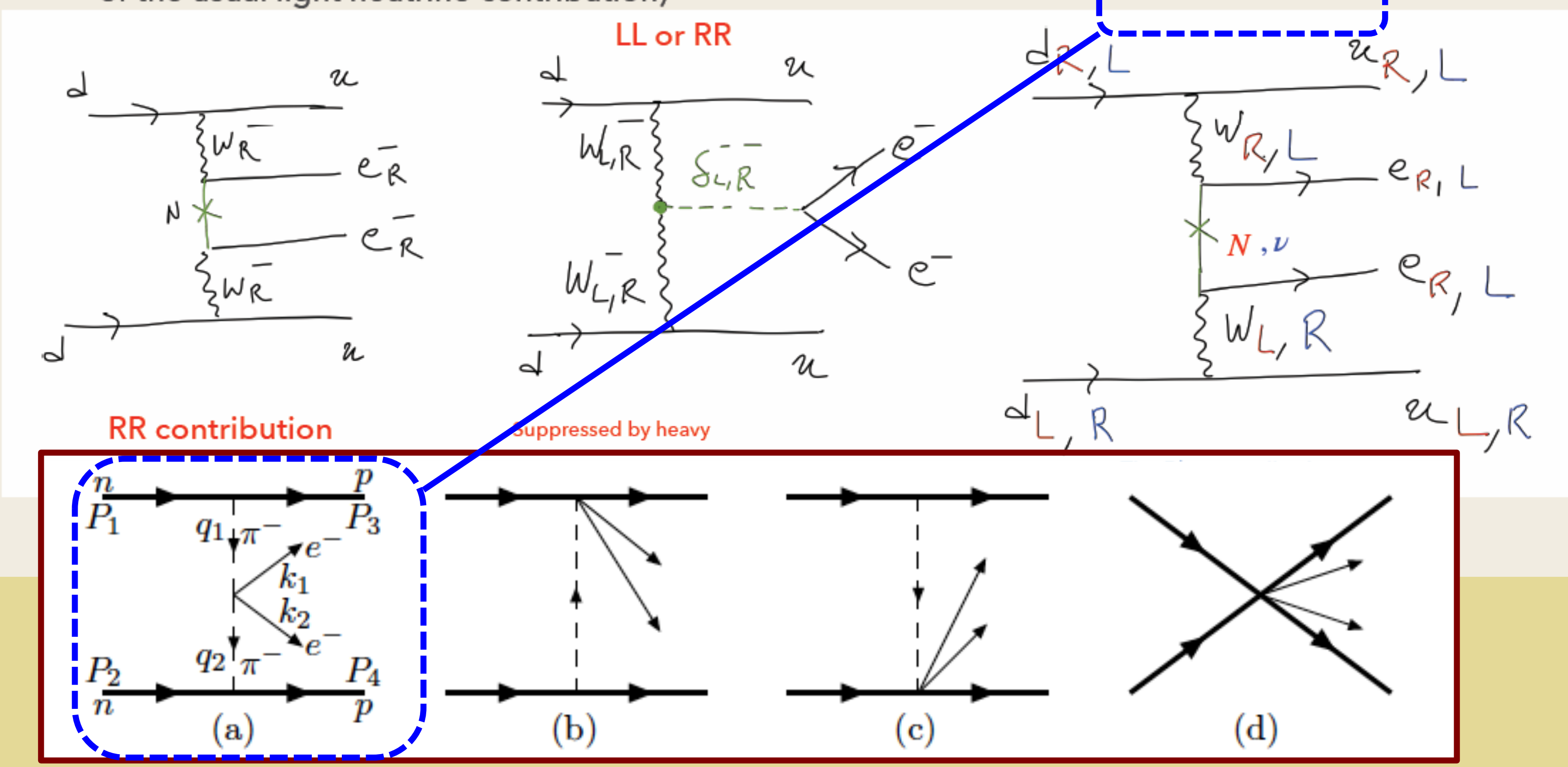
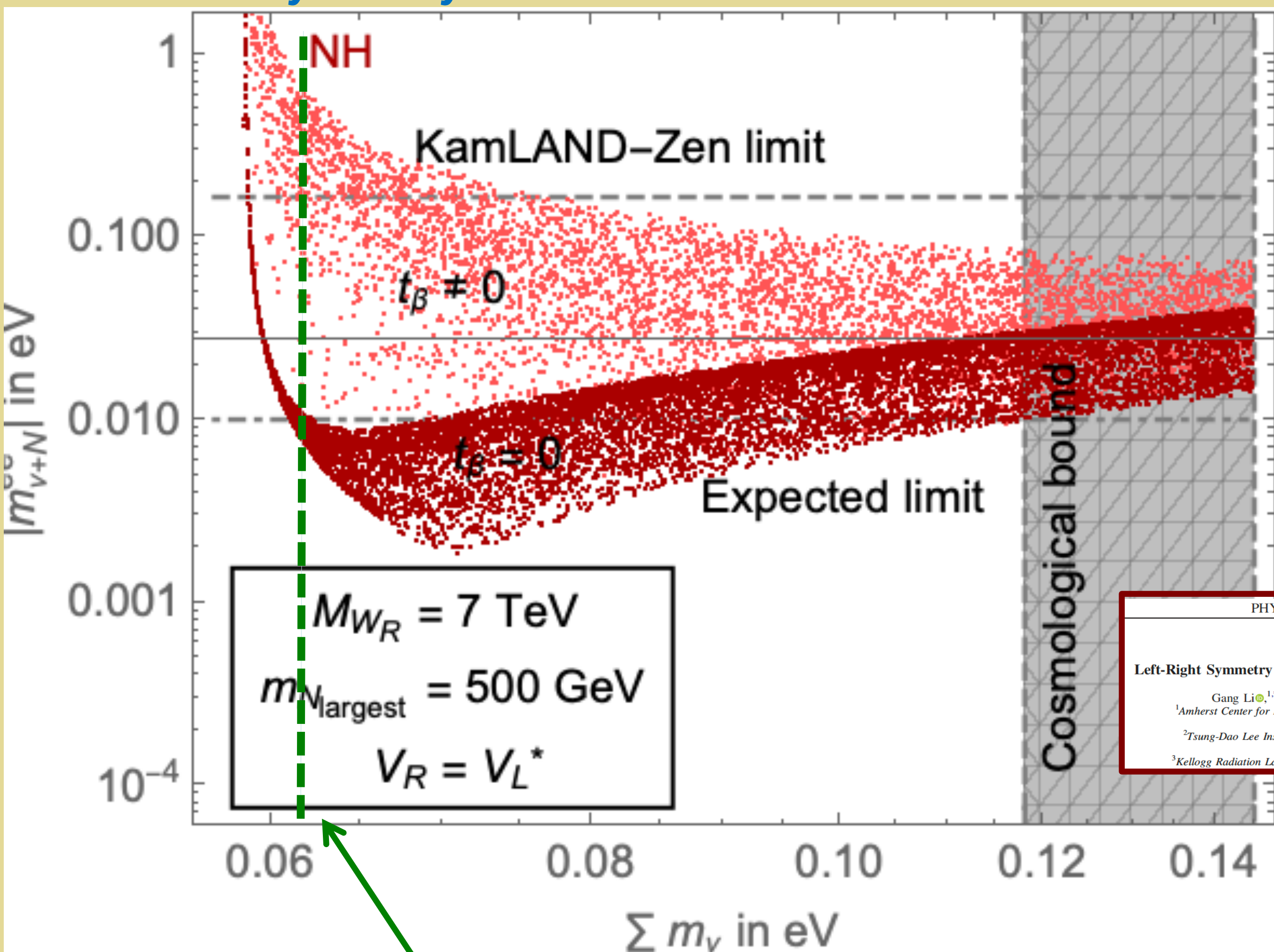


32.2

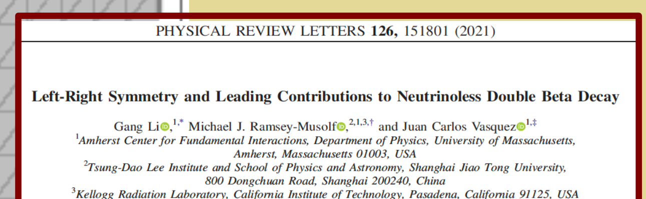
Thanks! Juan Carlos Vasquez

TeV-Scale LNV: $0\nu\beta\beta$-Decay & $\Sigma\, m_\nu$

Minimal LR Symmetry



~ Cosmo next gen



PHYSICAL REVIEW LETTERS **126,** 151801 (2021)

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

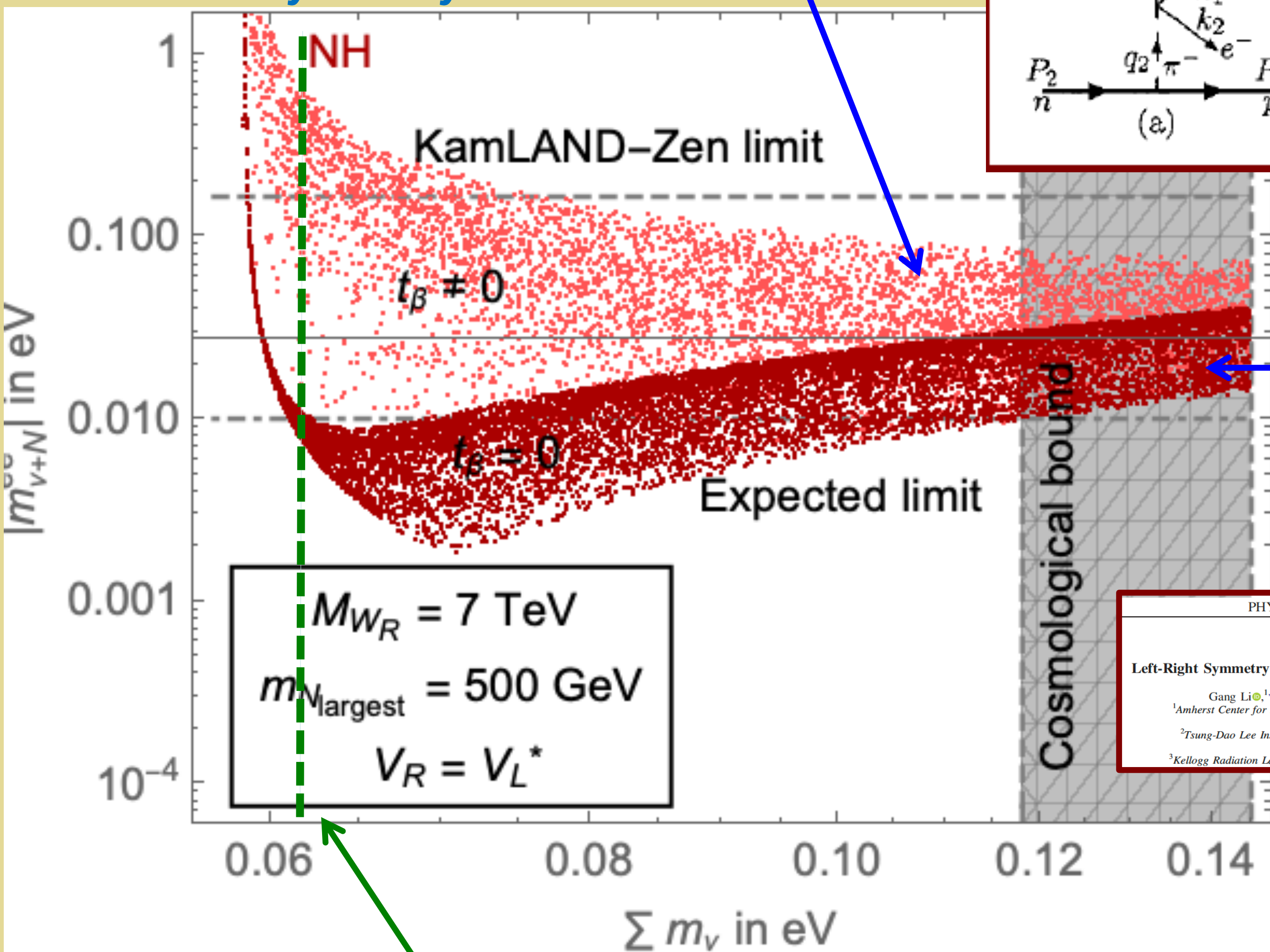
Gang Li,[1,*] Michael J. Ramsey-Musolf,[2,1,3,†] and Juan Carlos Vasquez[1,‡]

[1]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*

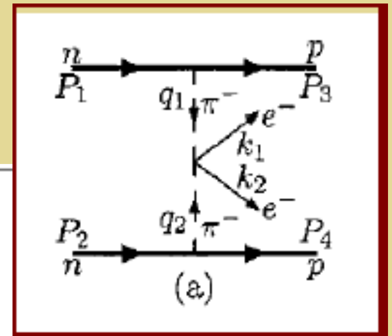
[2]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*

[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

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

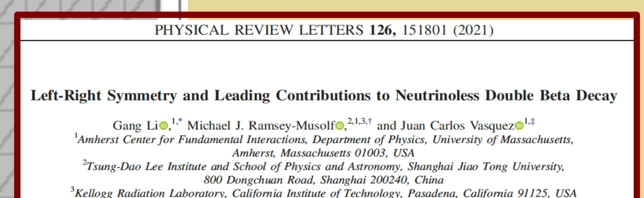


EFT: Long range



Short range only

~ Cosmo next gen



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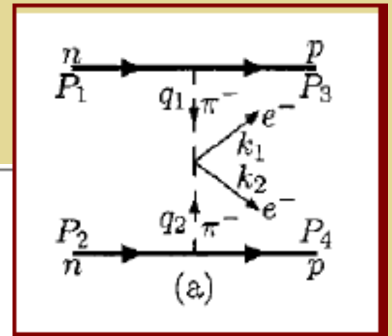

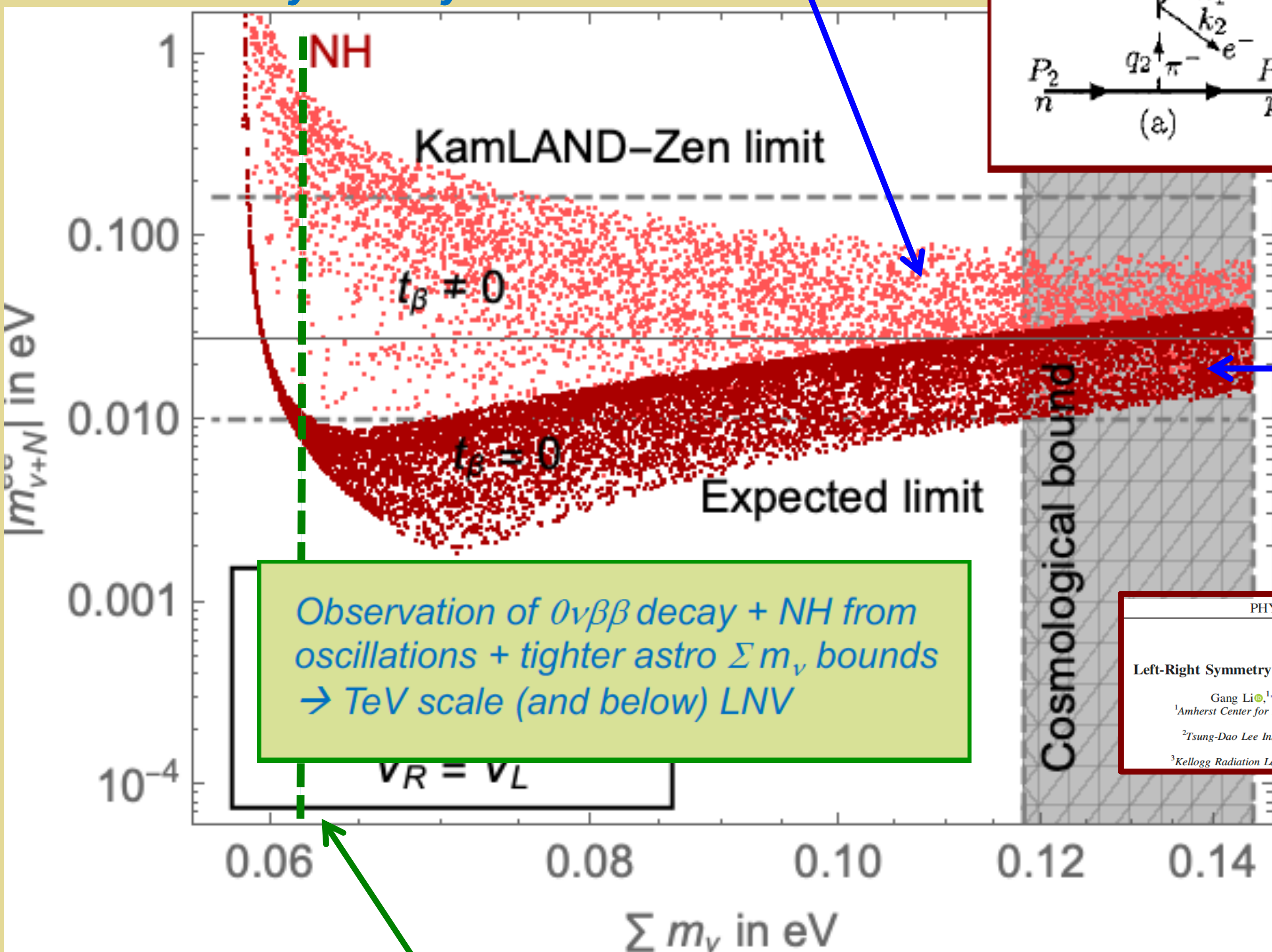

Short range only

Observation of $0\nu\beta\beta$ decay + NH from oscillations + tighter astro $\Sigma\, m_\nu$ bounds → TeV scale (and below) LNV

~ Cosmo next gen


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- **μ_ν**
- **ν osc**
- **PV ee …**

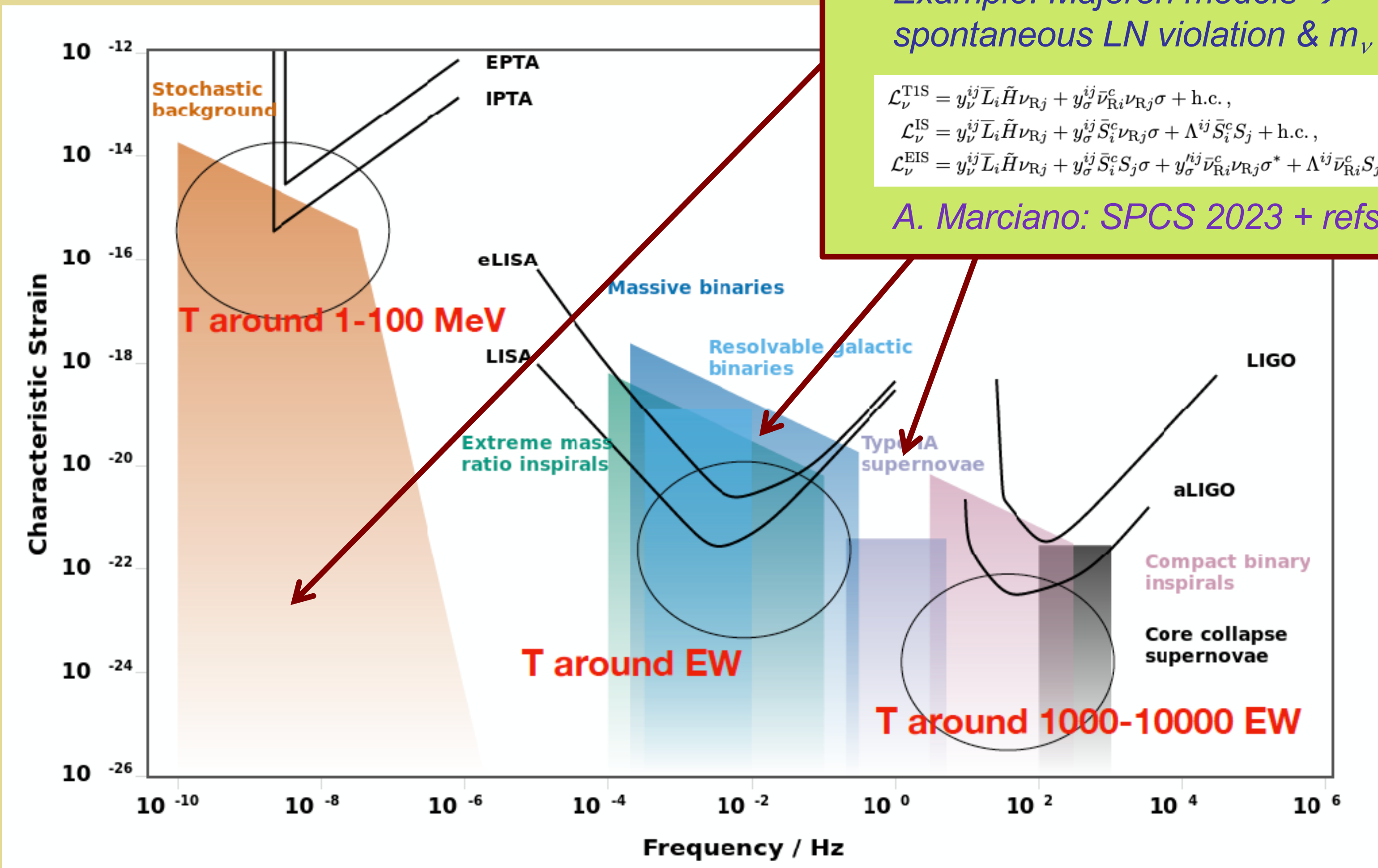
Colliders

LNV Scalar Field & GW

Example: Majoron models → spontaneous LN violation & m_ν

$$\mathcal{L}_\nu^{\rm T1S} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{\nu}^c_{{\rm R}i}\nu_{{\rm R}j}\sigma + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm IS} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}^c_i\nu_{{\rm R}j}\sigma + \Lambda^{ij}\bar{S}^c_i S_j + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}^c_i S_j\sigma + y_\sigma'^{ij}\bar{\nu}^c_{{\rm R}i}\nu_{{\rm R}j}\sigma^* + \Lambda^{ij}\bar{\nu}^c_{{\rm R}i}S_j + {\rm h.c.}$$

A. Marciano: SPCS 2023 + refs



Phase transition associated with spontaneous LNV → non-astrophysical GW source

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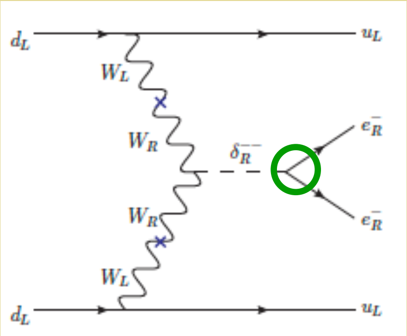
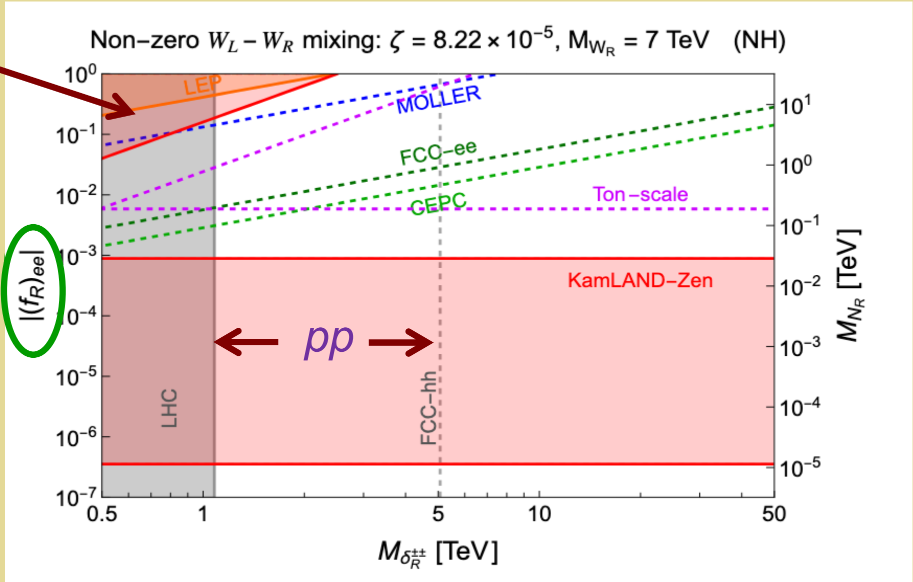
Colliders

LNV: Scalar Fields & m_ν

$0\nu\beta\beta$ Decay, PV $e^-e^- \rightarrow e^-e^-$, $e^+e^- \rightarrow e^+e^-$ & pp collisions



LRSM type II Seesaw: δ^{--}



G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez 2408.06306

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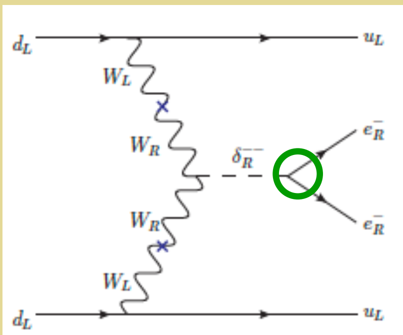

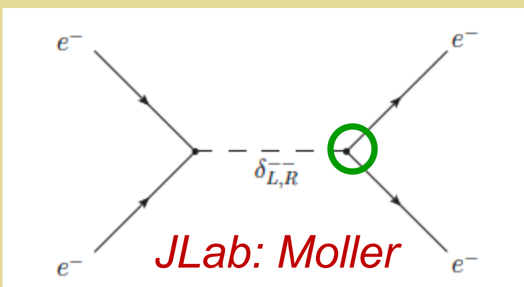

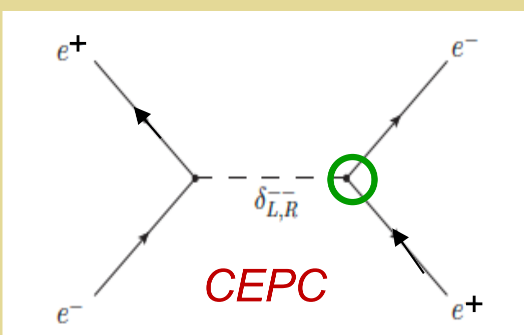

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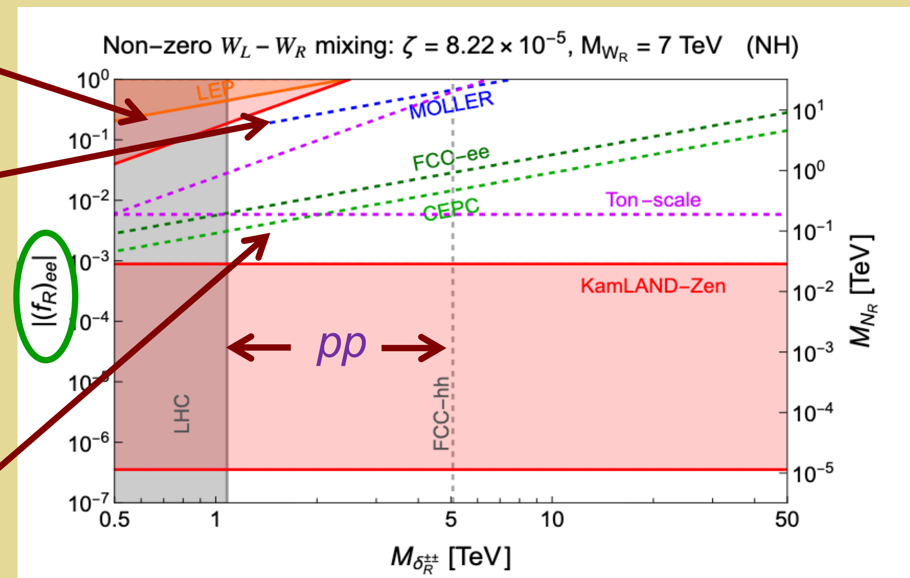


G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez
2408.06306

Outlook

- *The discovery of beyond Standard Model lepton number violation could hold the key to explaining the origin of neutrino mass*
- *The BSM LNV mass scale is unknown and could lie anywhere from the sub-eV scale to the conventional seesaw scale*
- *While the search for $0\nu\beta\beta$-decay provides the most comprehensive probe of BSM LNV, identifying the mass scale and underlying dynamics requires input from a wide array of observations → the mystery of m_ν has exciting implications for research at the intensity, high energy, and cosmological/astrophysical frontiers*

Back Up Slides

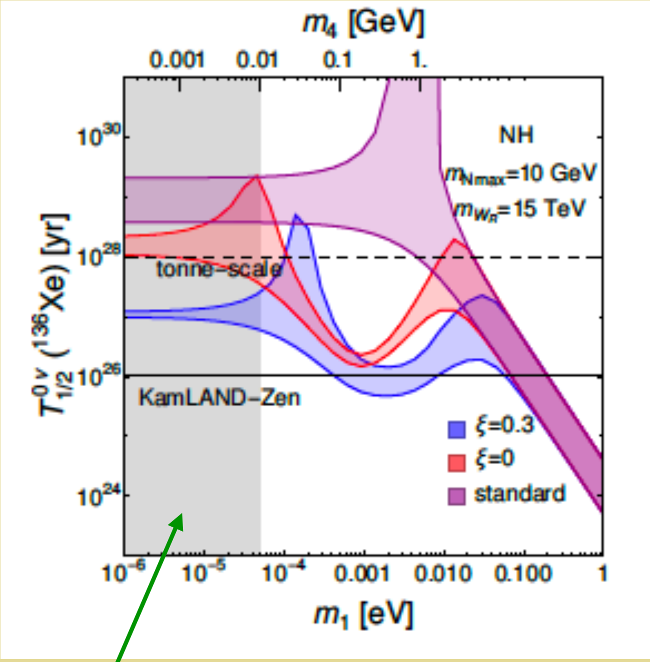
LNV Mass Scale & $0\nu\beta\beta$-Decay

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

- 3 light neutrinos only: source of neutrino mass at the very high see-saw
- 3 light neutrinos with TeV scale LNV
- > 3 light neutrinos

More Than 3 Light Neutrinos: MeV-GeV

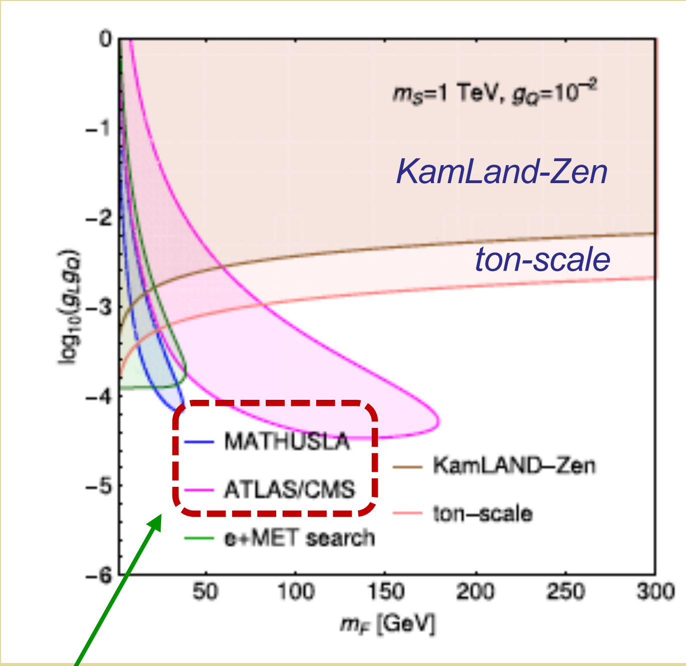
mLRSM



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

TeV Scale LNV: EFT

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Dirac

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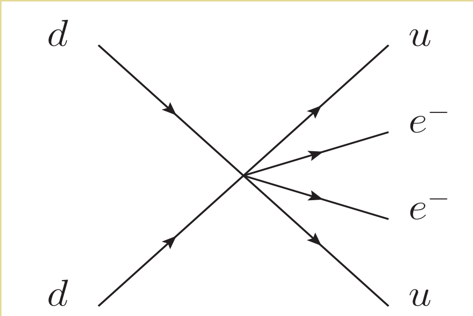
Majorana

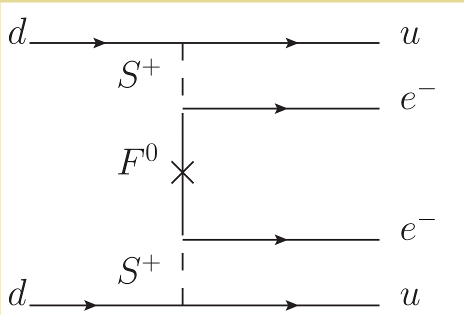
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

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



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

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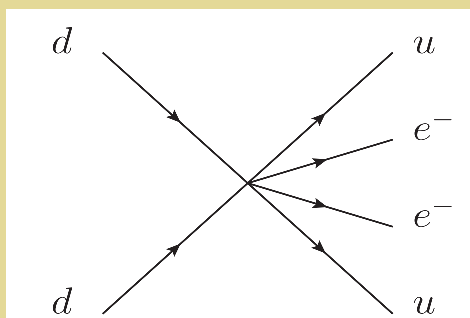
Majorana

EFT "Bridge"

TeV Scale LNV

$0\nu\beta\beta$ - decay



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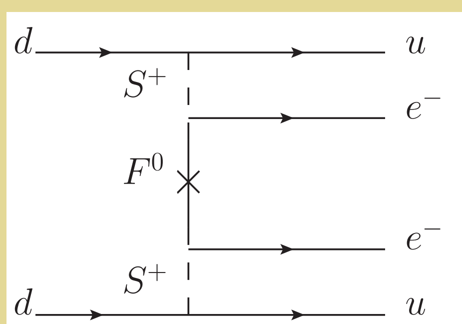


High-energy process → "full theory" (simplified): keep TeV scale d.o.f. explicit

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

d=9 effective operators

$$\mu = M_{WEAK}$$

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

e.g.

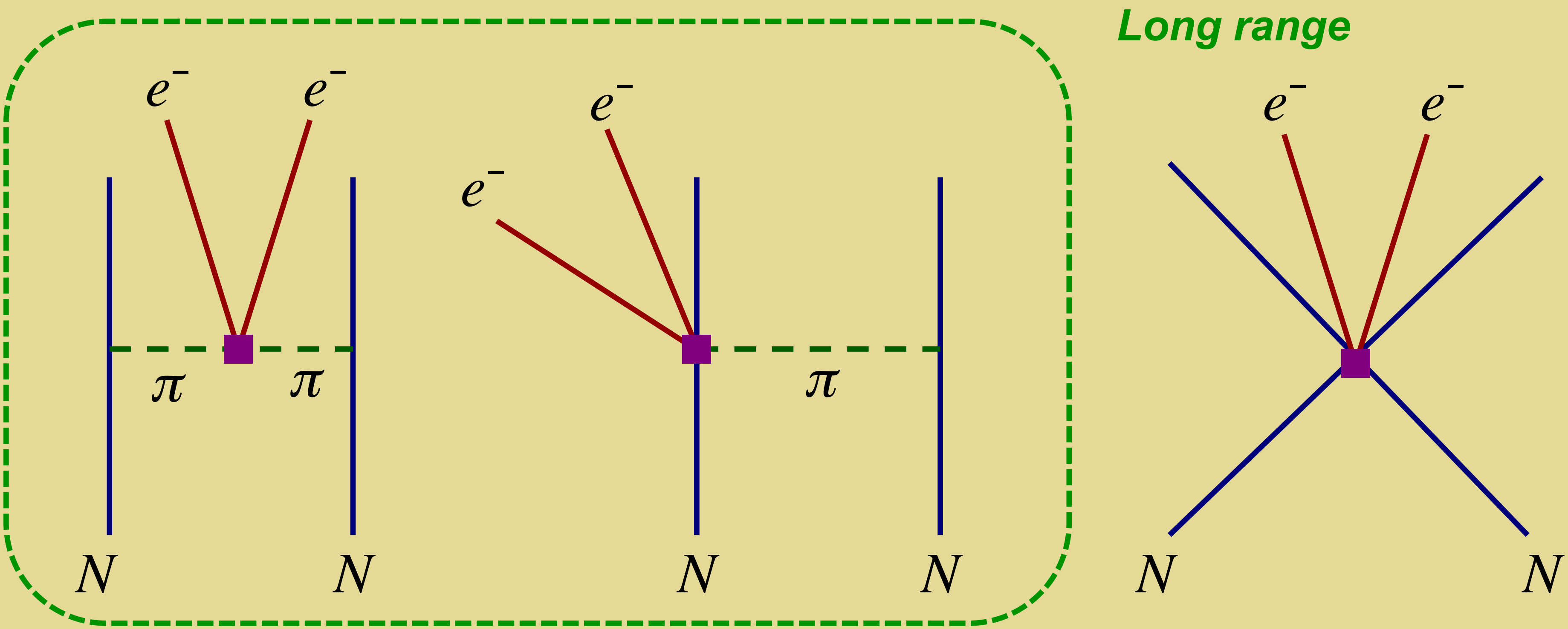
$$\hat{O}_{1+}^{ab} = \overline{q}_L \gamma^\mu \tau^a q_L\ \overline{q}_R \gamma_\mu \tau^b q_R$$

$0\nu\ \beta\beta$ - 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



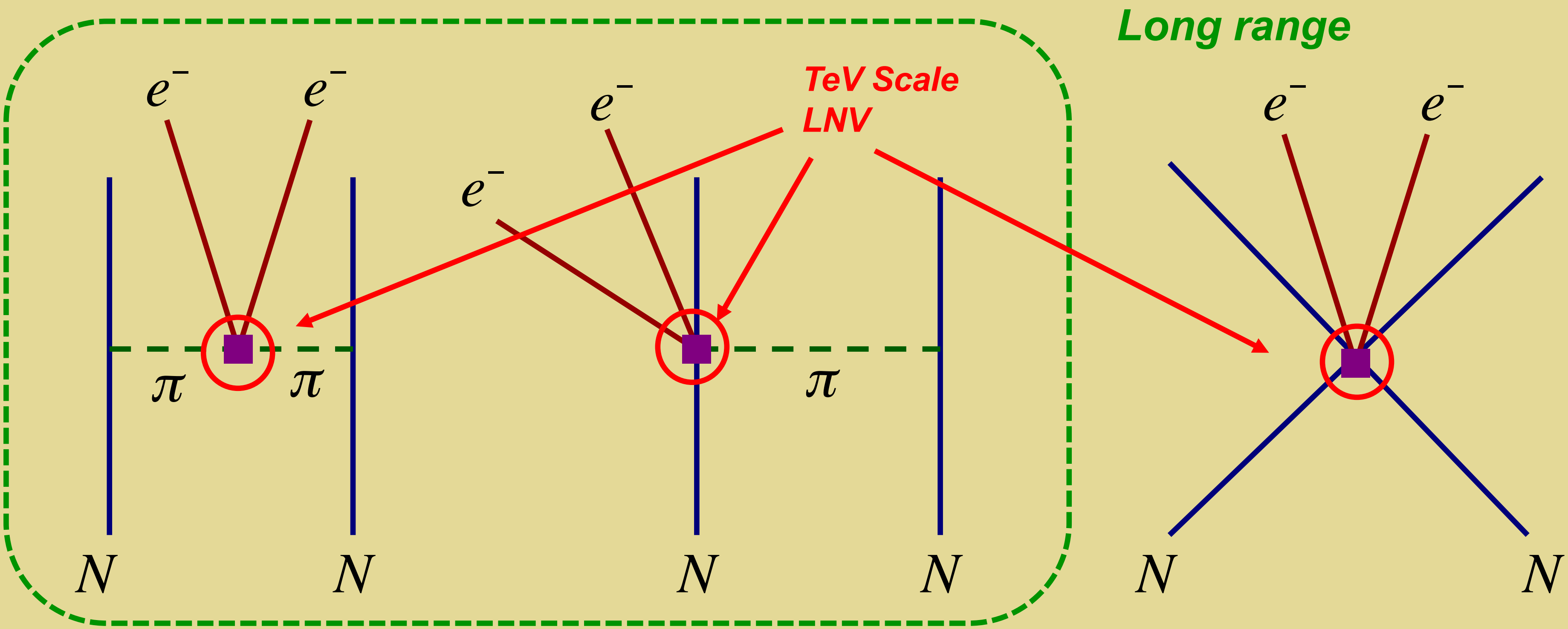
$K_{\pi\pi}\ p^{-2}$

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

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

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

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



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

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

B7

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

Operator classification

$$\mu = M_{WEAK}$$

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

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 → LEC's

0νββ-Decay: TeV Scale LNV

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

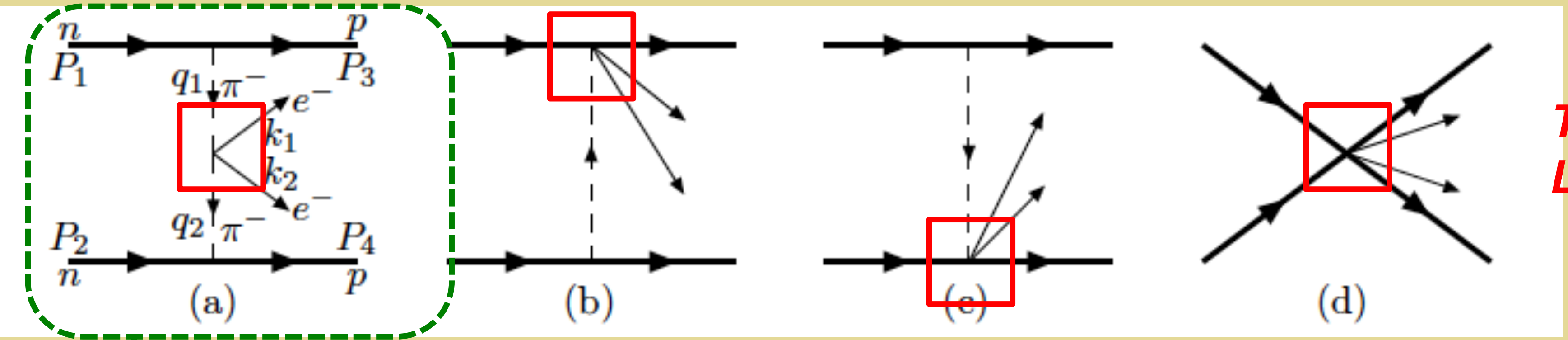
Dirac

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

Majorana

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

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

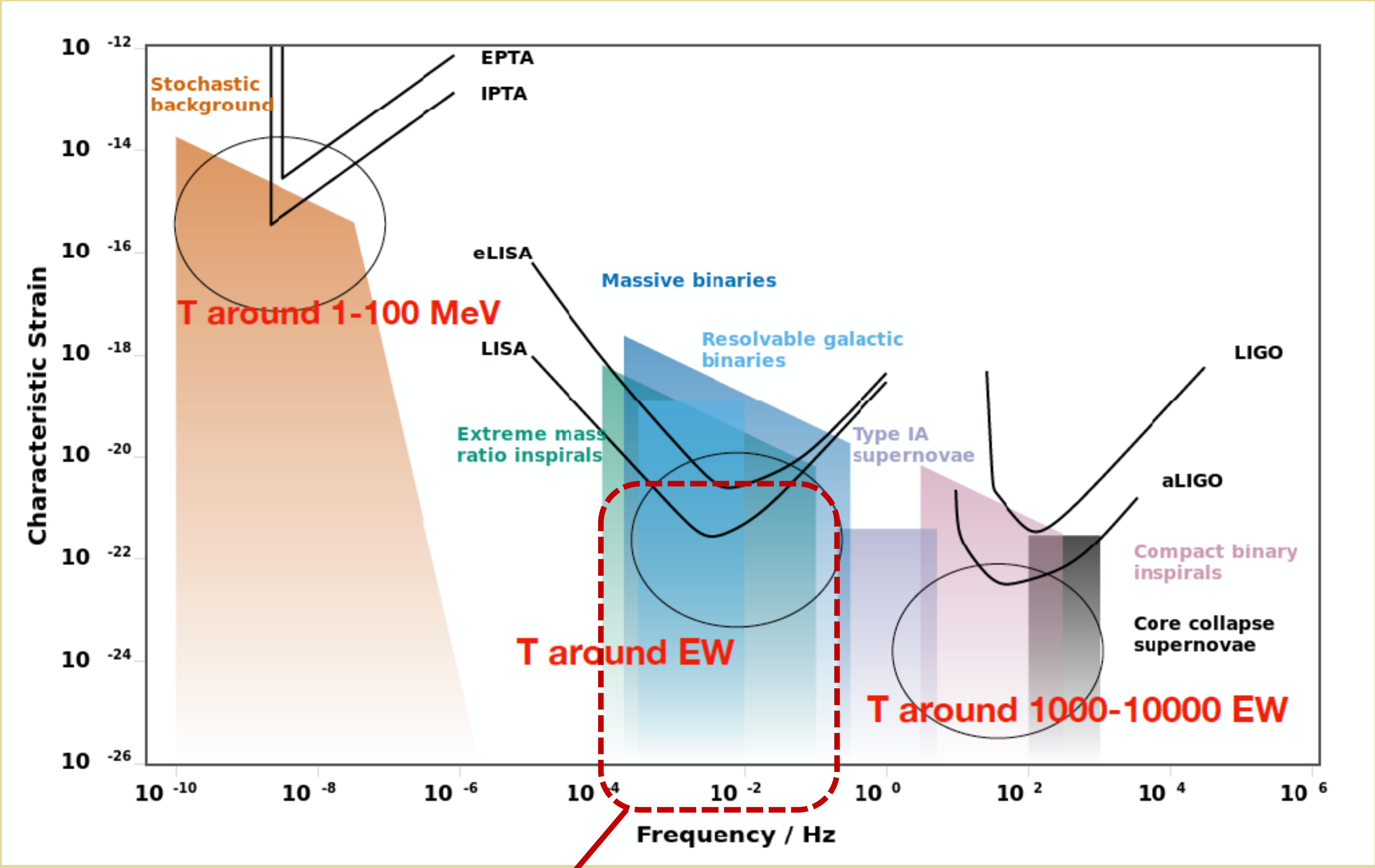


TeV LNV

Exploit Chiral Symmetry & EFT ideas

Following example:
LO + counterterm

Gravitational Waves



EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales