Lepton Number Violation: Inter-frontier Implications

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About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

NuPhyR 2025 Zhuhai
November 30, 2025

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***

Outline

1. ***Context***
2. ***BSM LNV: Cosmology & Colliders***
3. ***BSM LNV: Precision Tests & Colliders***
4. ***Outlook***

I. Context

Why Search for LNV ?

- ***The conventional question:***

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

Why Search for LNV ?

- ***The conventional question:***

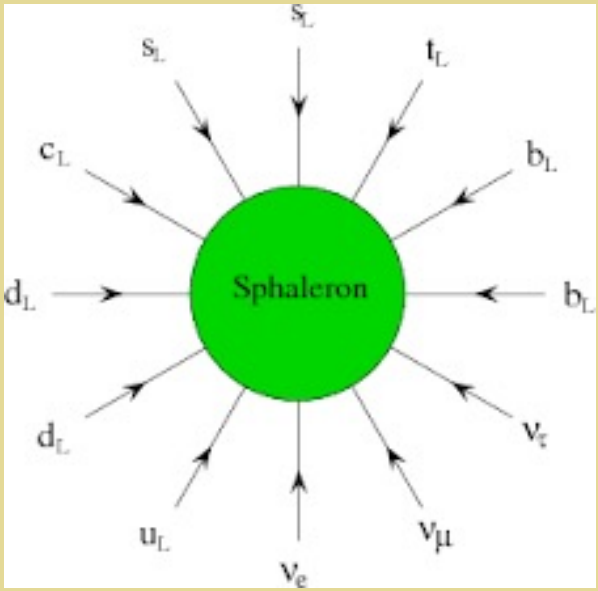
  - ***What is the nature of the neutrino ?***

- ***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 → Weak Sphaleron *



* Unstable gauge-Higgs field configuration

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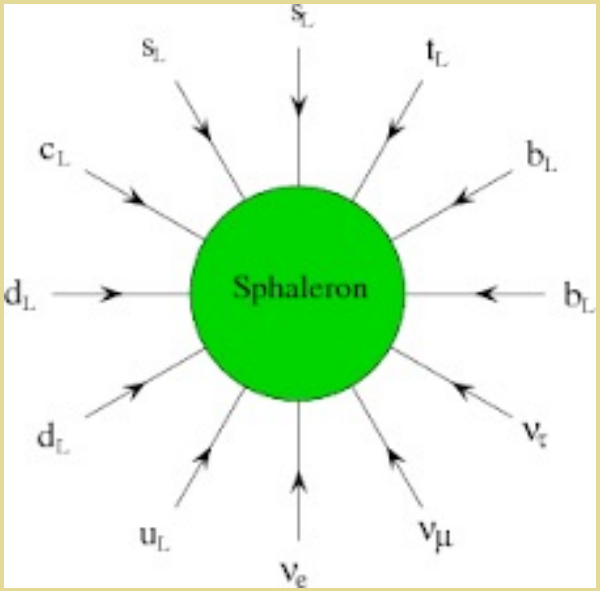

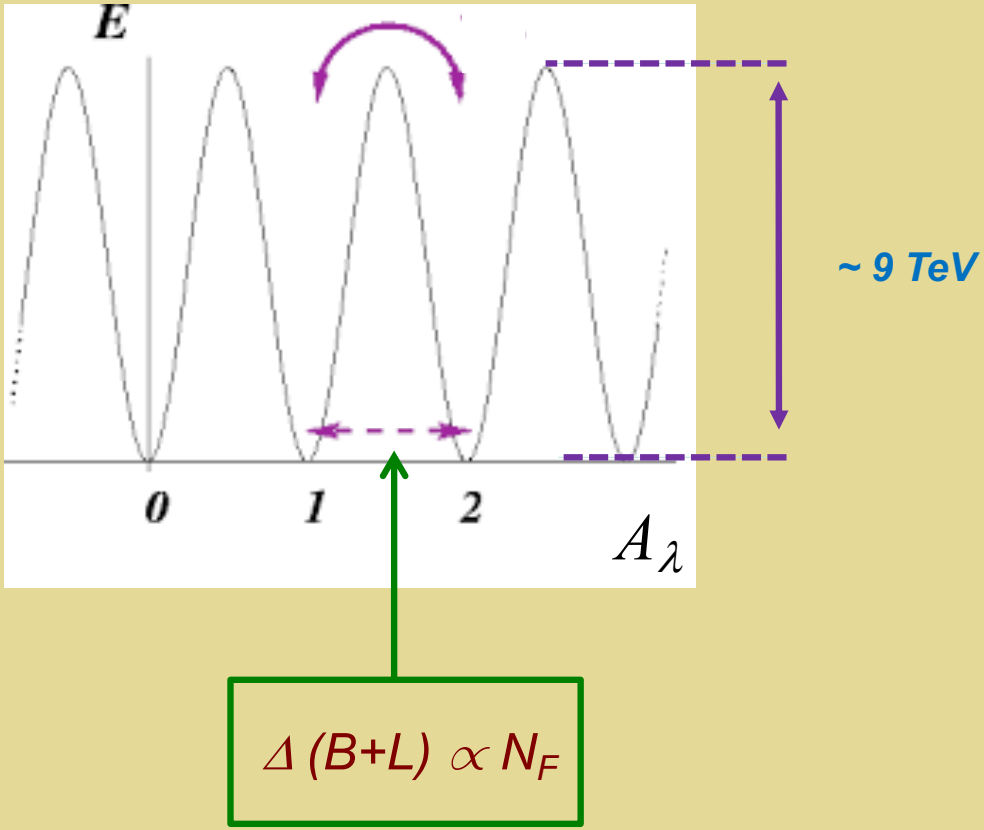

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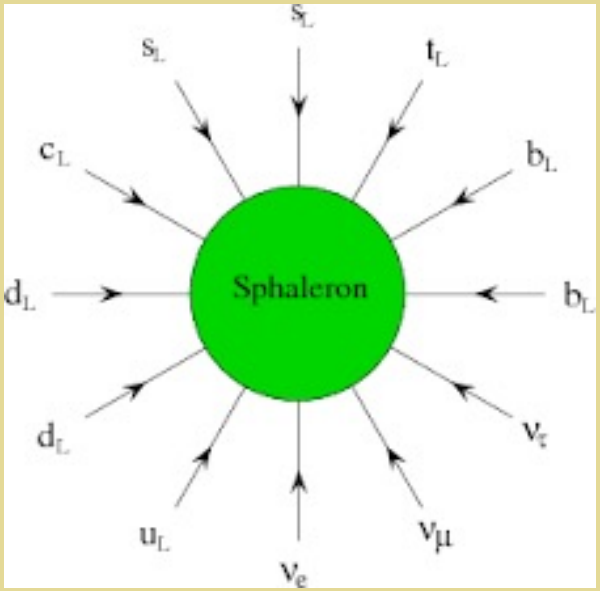
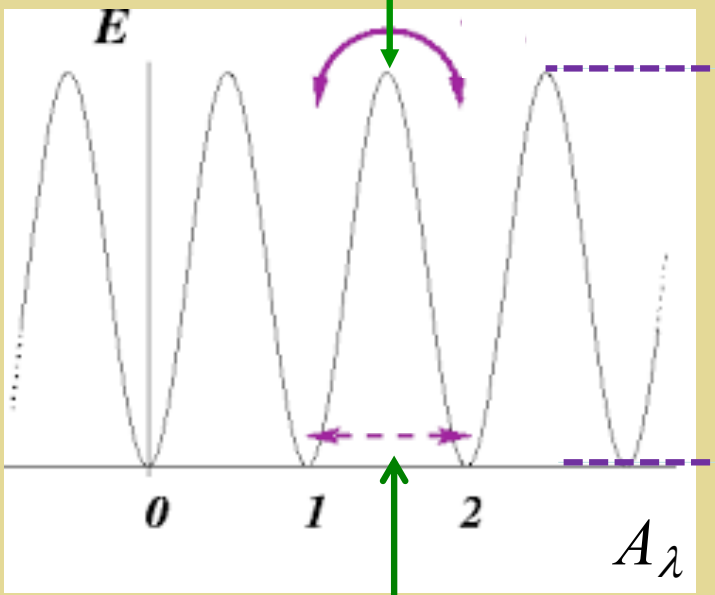




~ 9 TeV

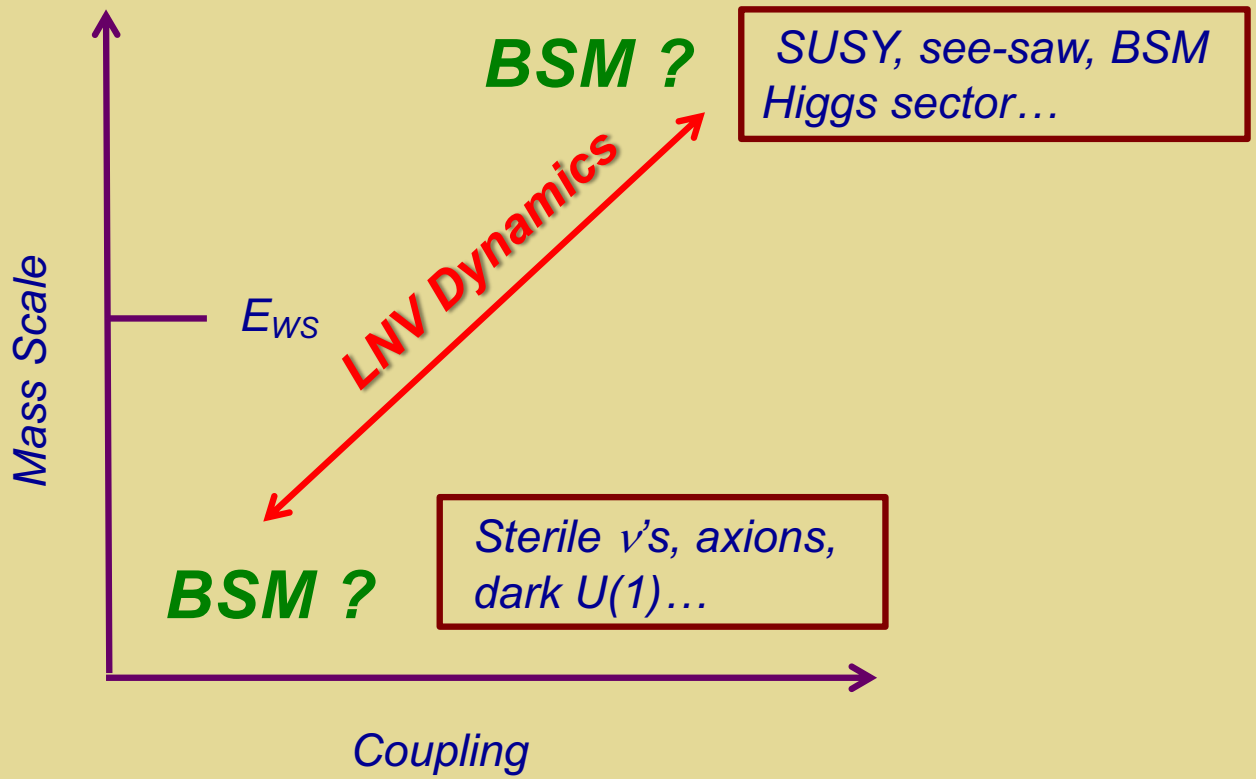
$\Delta (B+L) \propto N_F$

* Unstable gauge-Higgs field configuration

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***
- ***Σm_ν***
- ***Grav waves***
- ***Dark Matter***

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

Colliders

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Colliders

See Hao Ma talk

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

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

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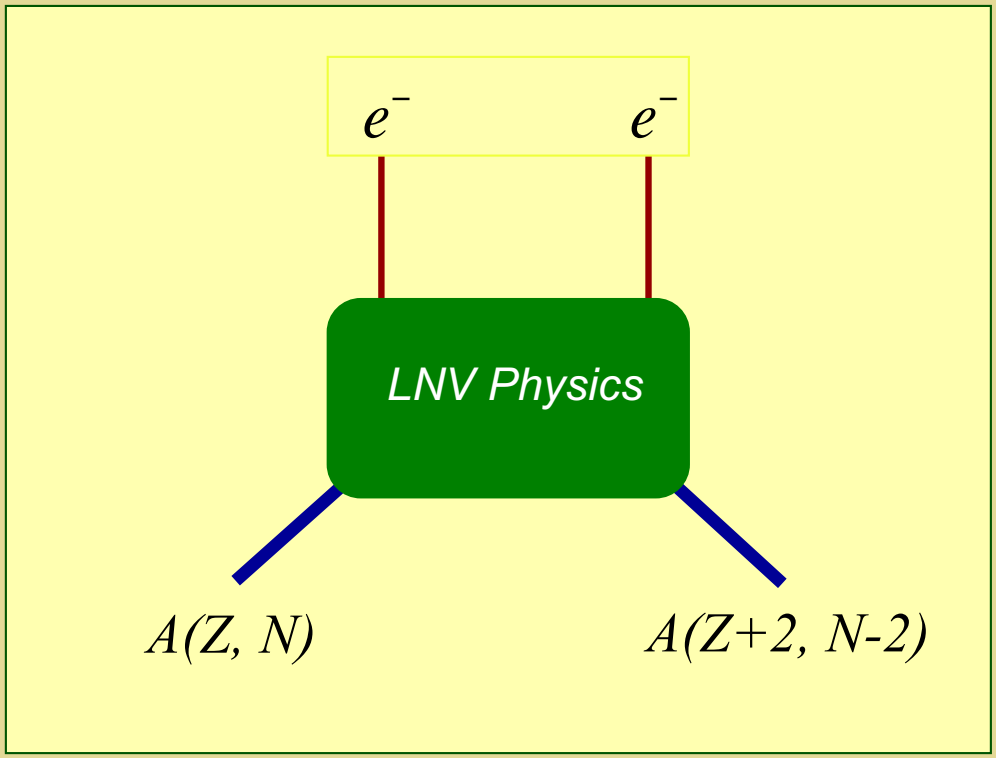

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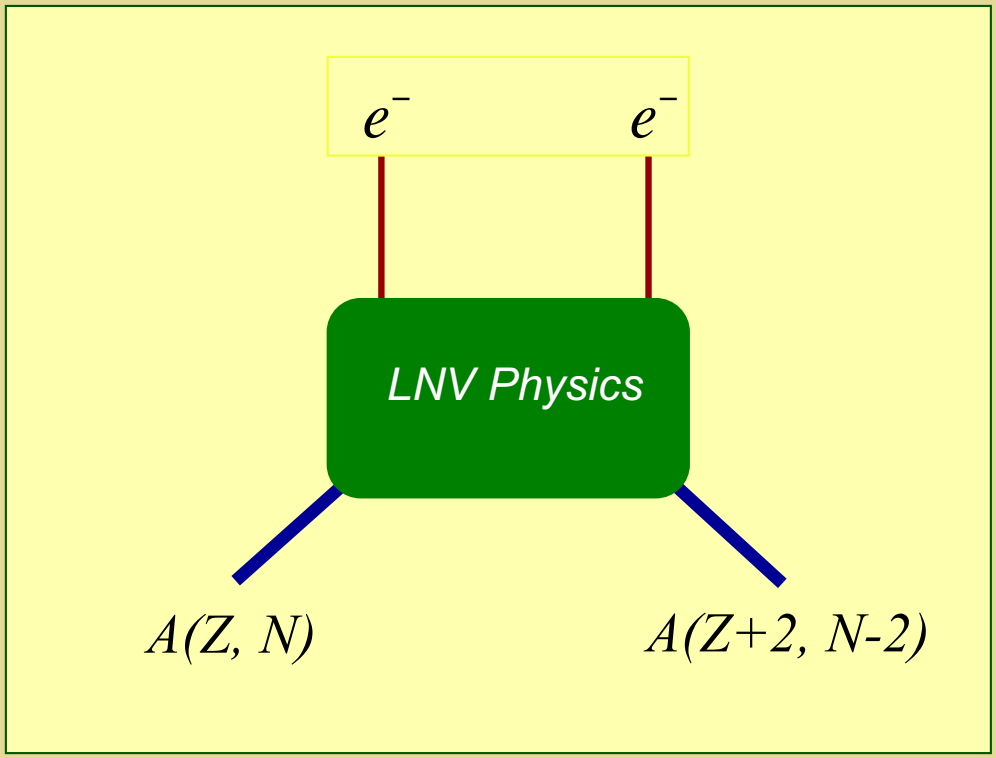
Impact of observation

- *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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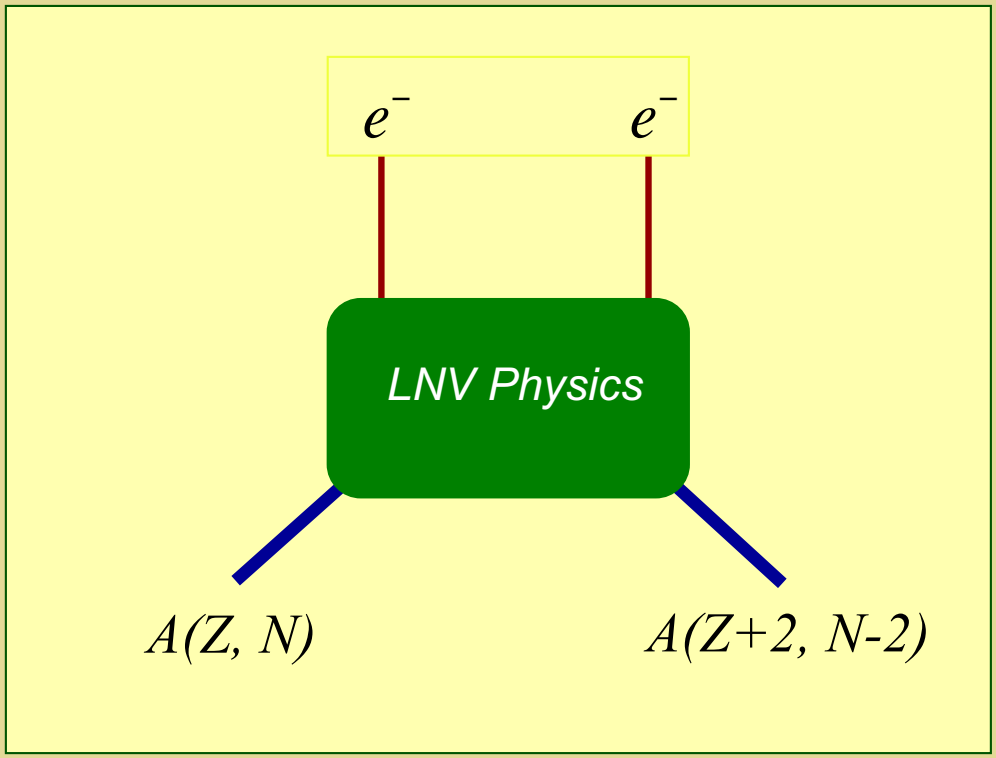

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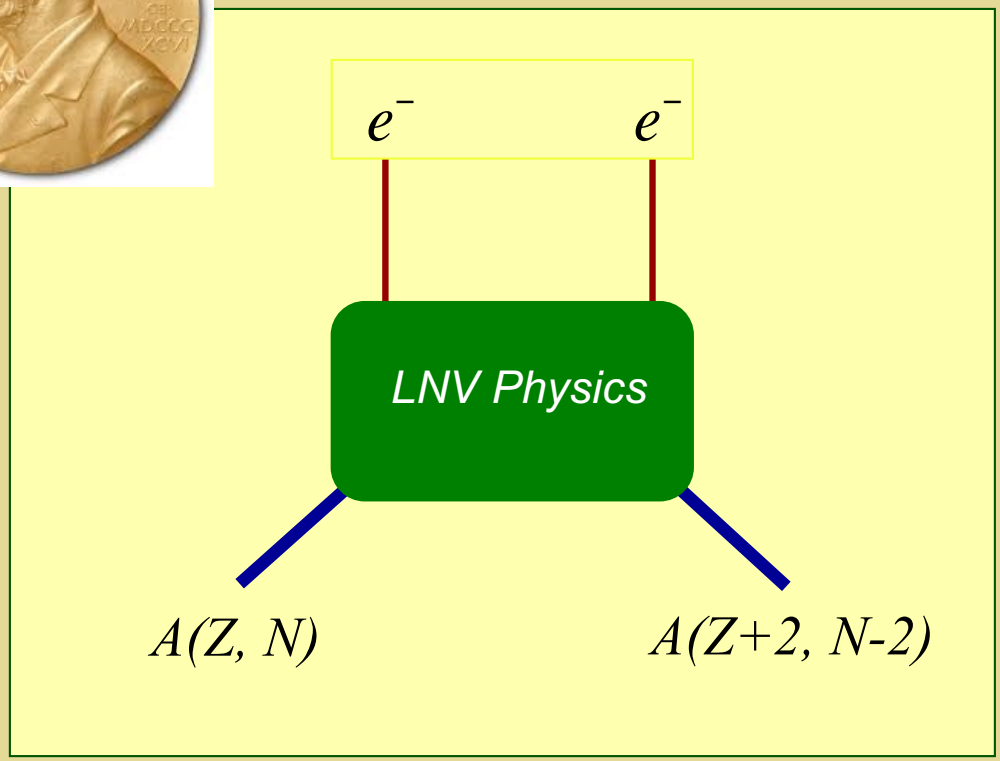

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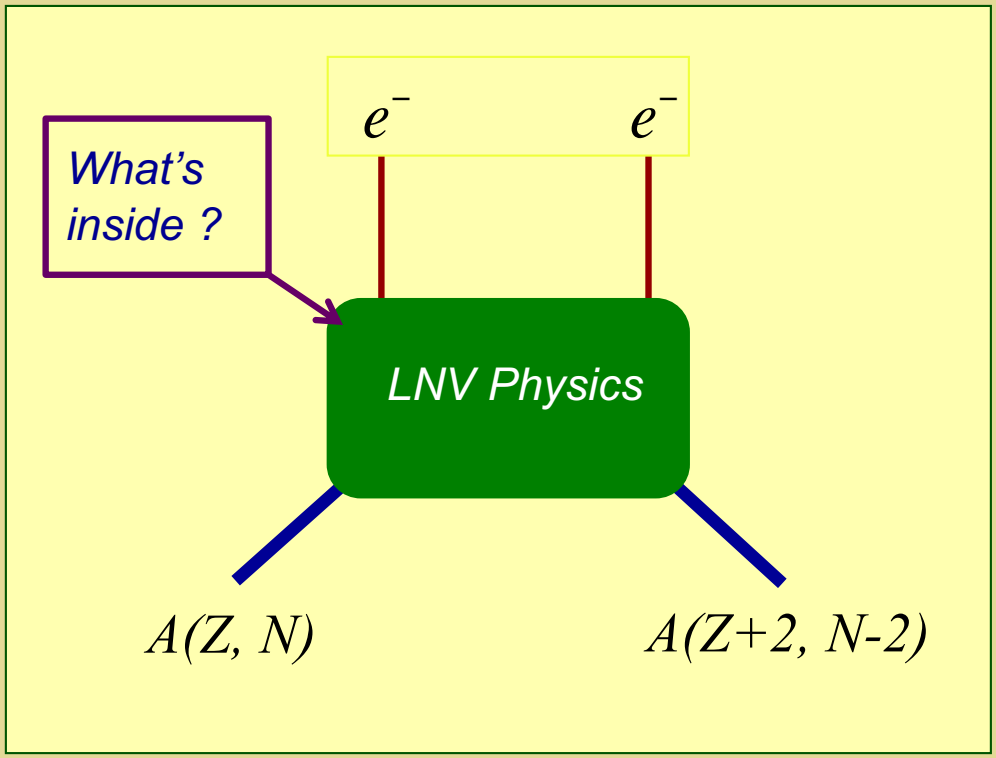

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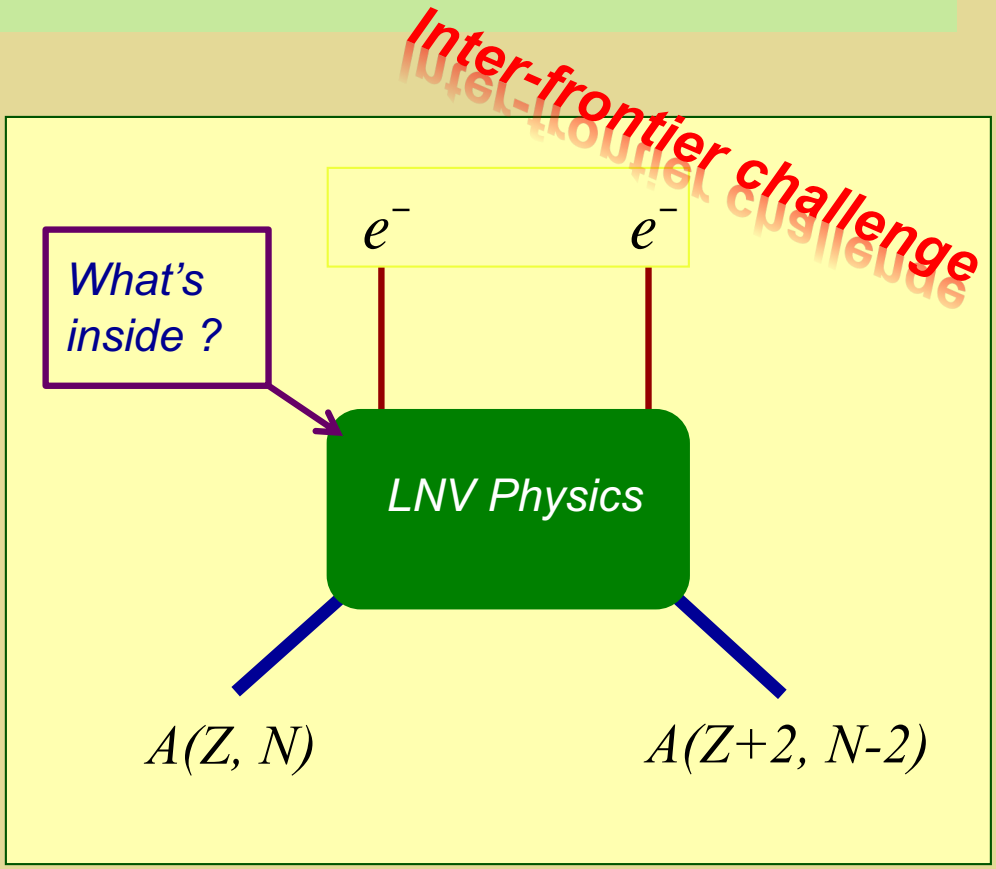

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **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*
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- *> 3 light neutrinos*

See talks by F. Deppisch, X-D Ma, J. Yao, Y. Li…

II. BSM LNV: Cosmology & Colliders

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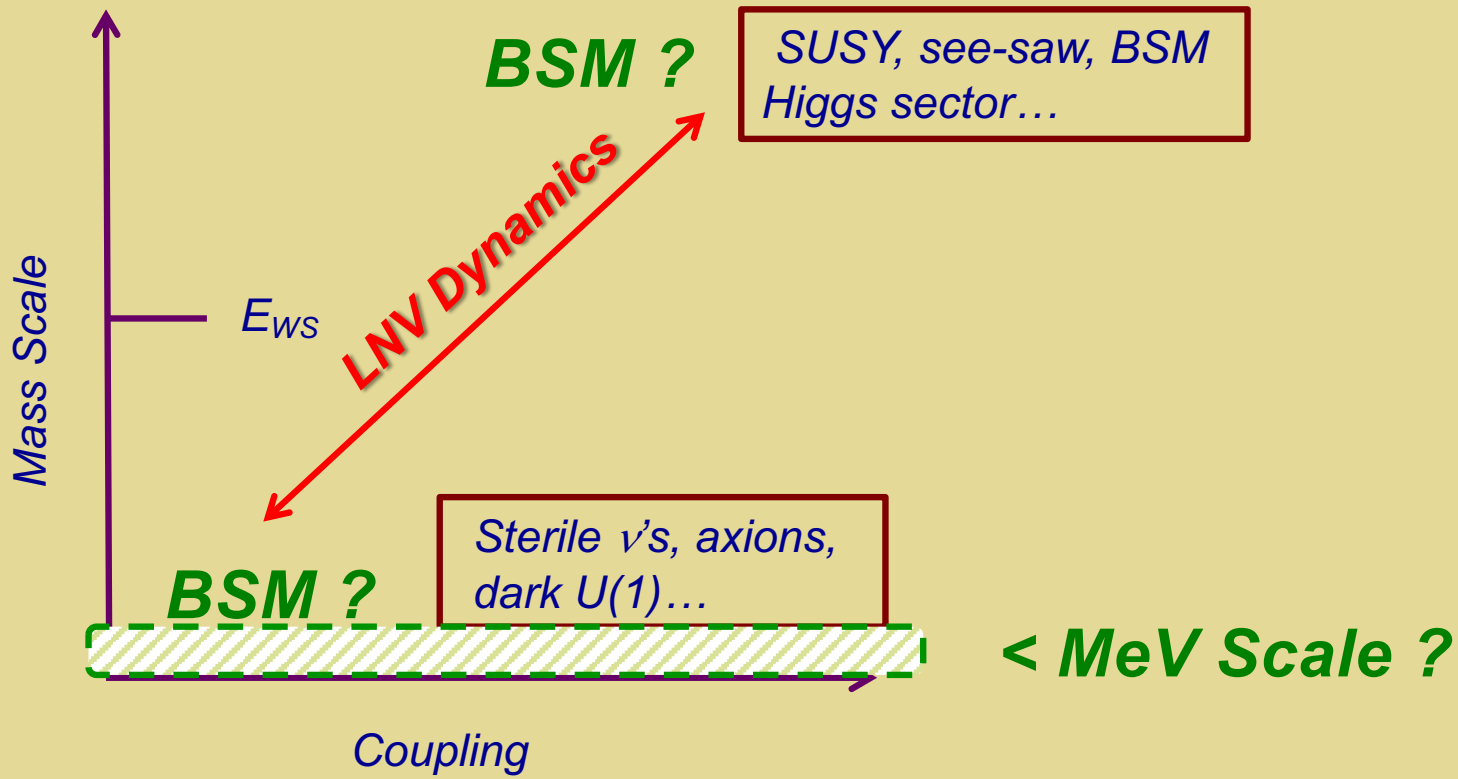

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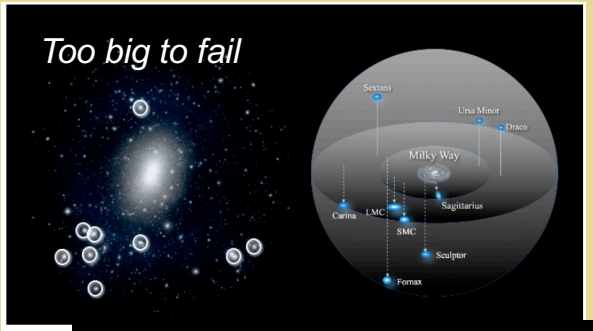
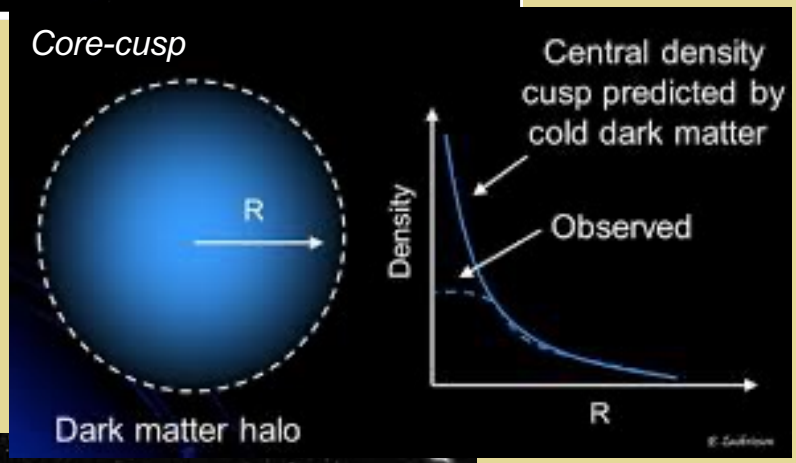
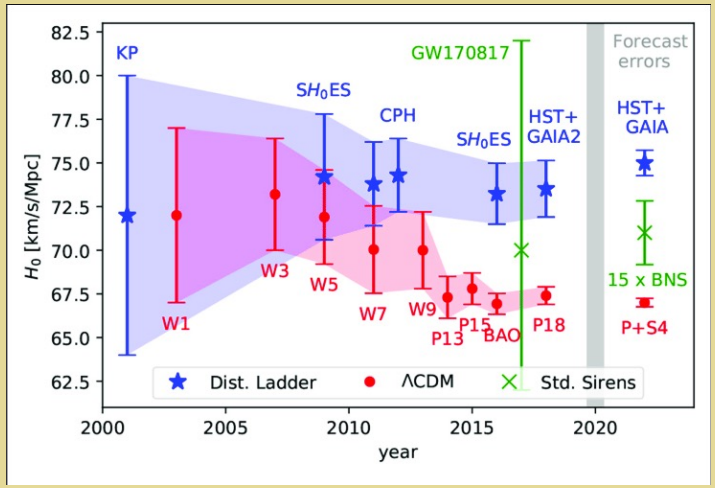
Colliders

Small Scale Problems & Hubble Tension







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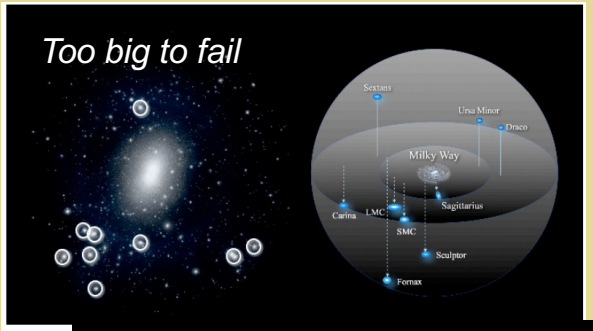

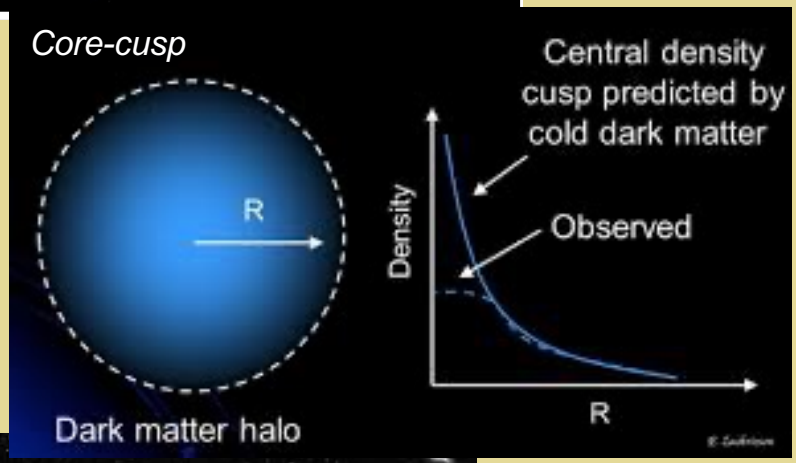

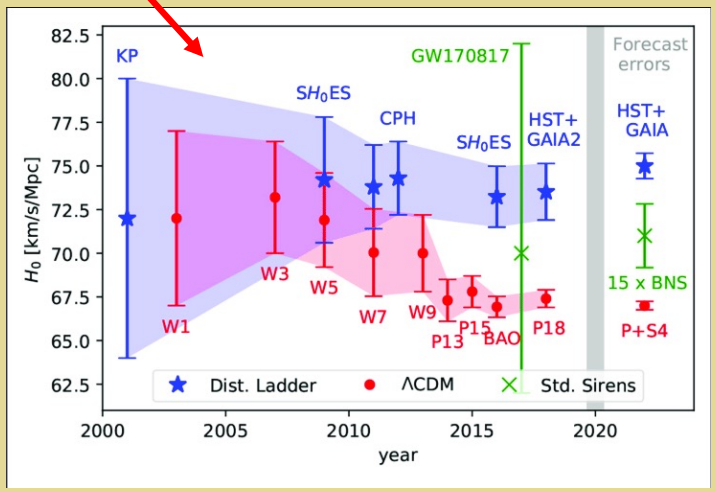

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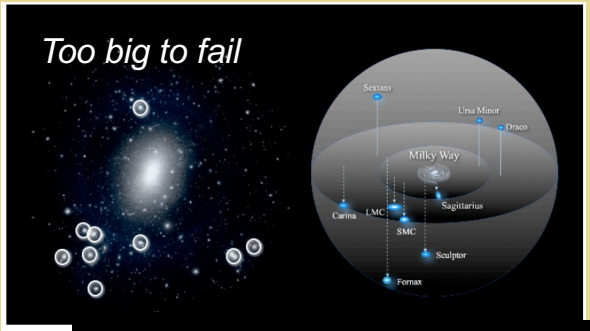

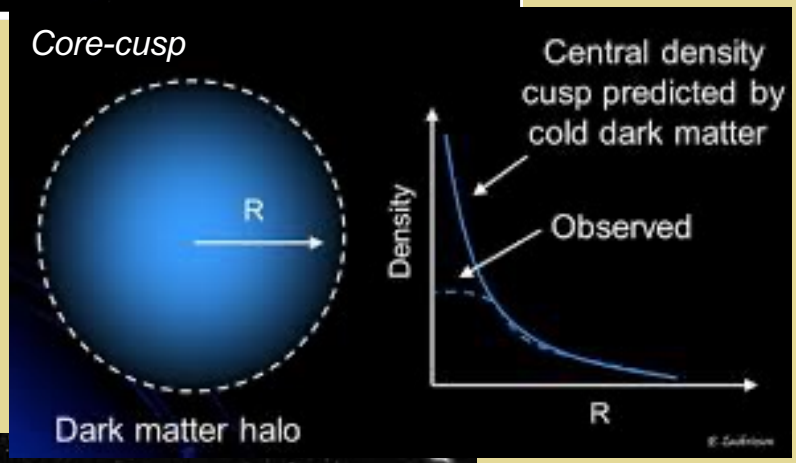

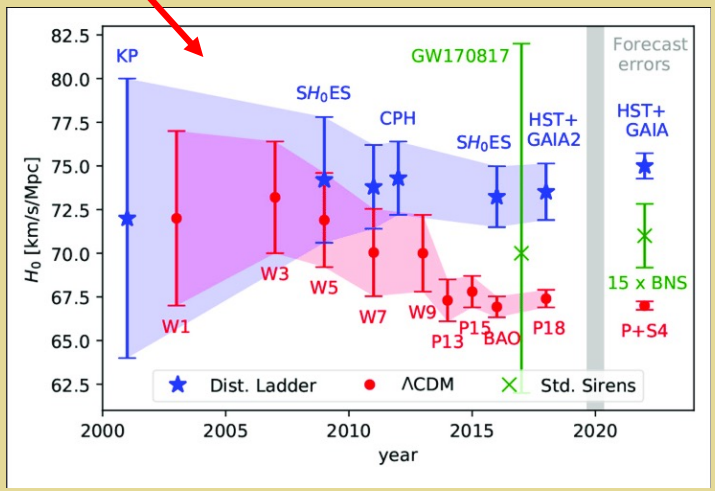

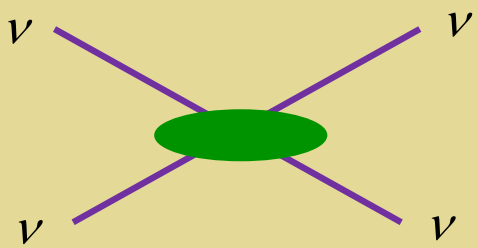

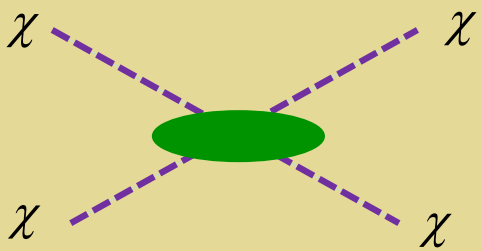

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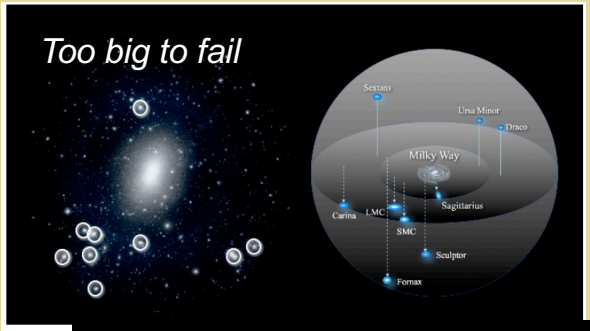
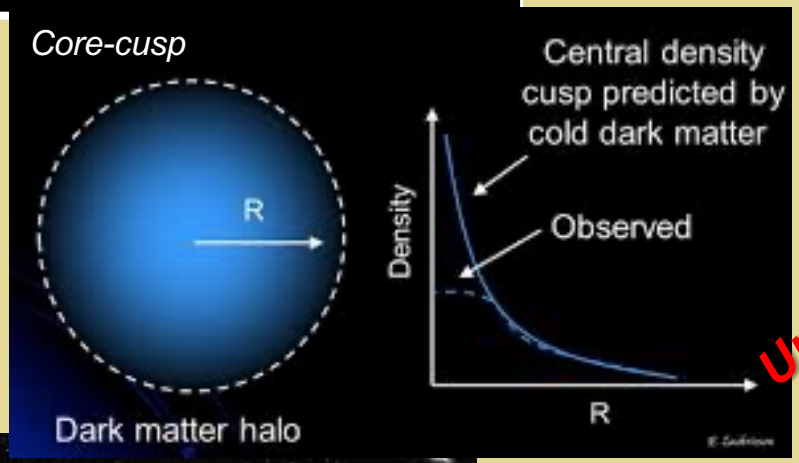
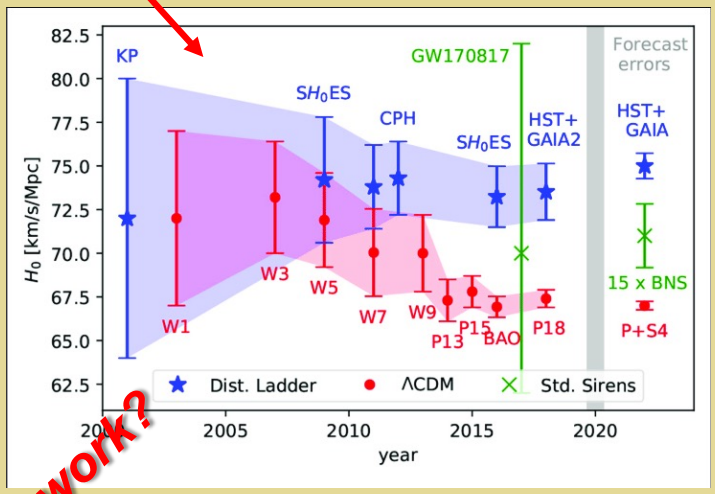
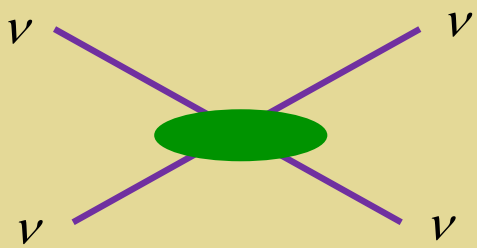
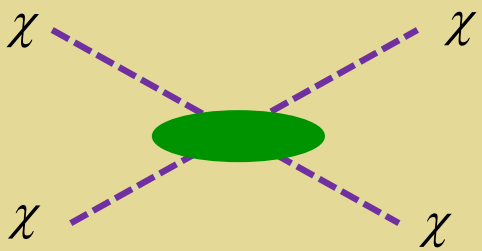






Unified framework?





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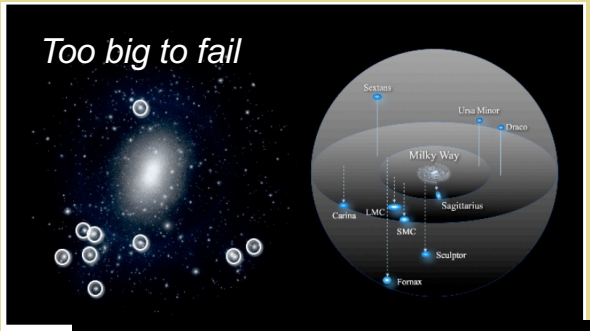
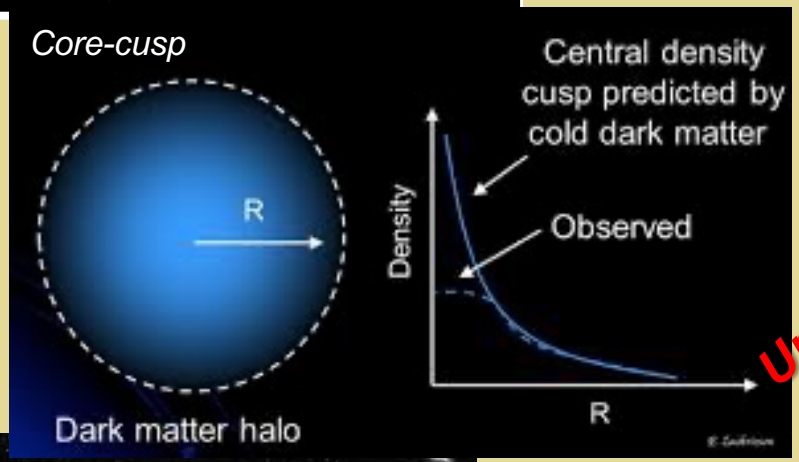
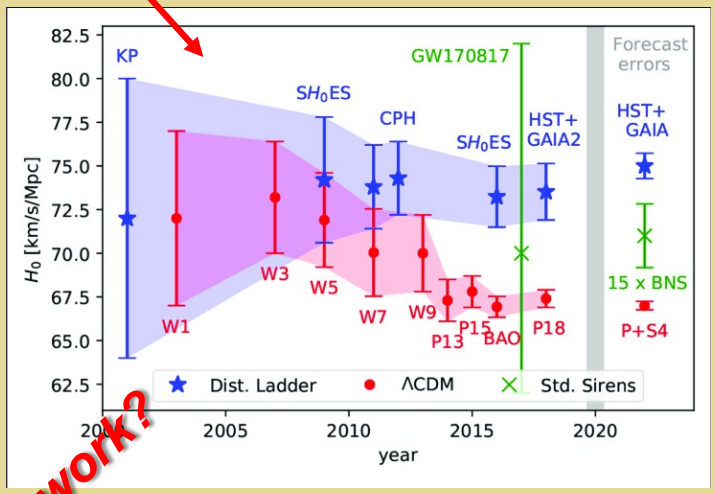
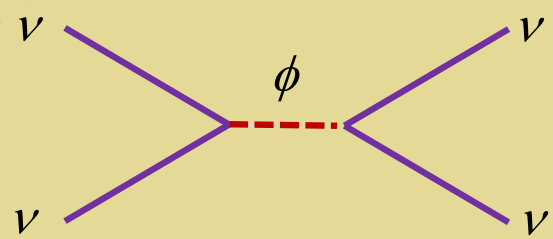
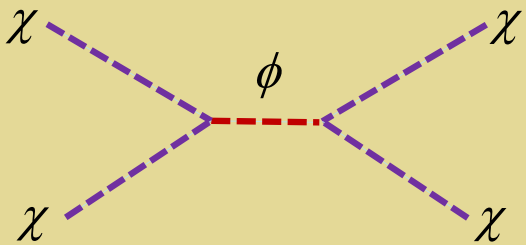






Unified framework?
Light mediator ?





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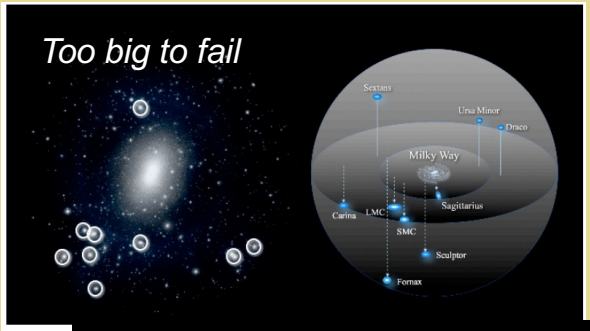

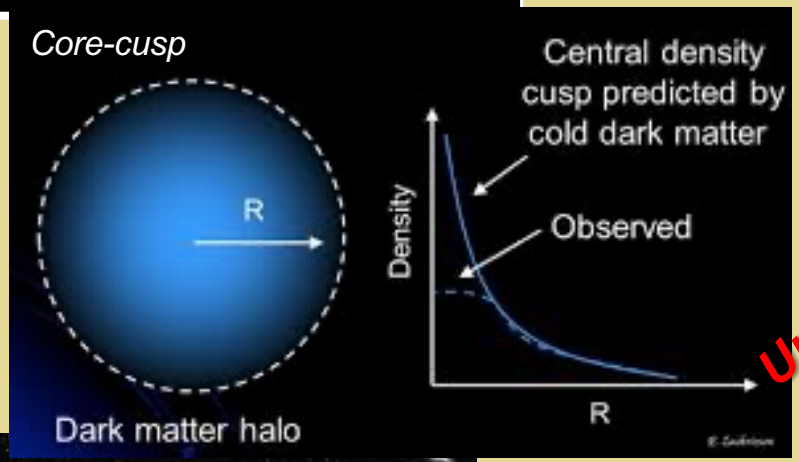

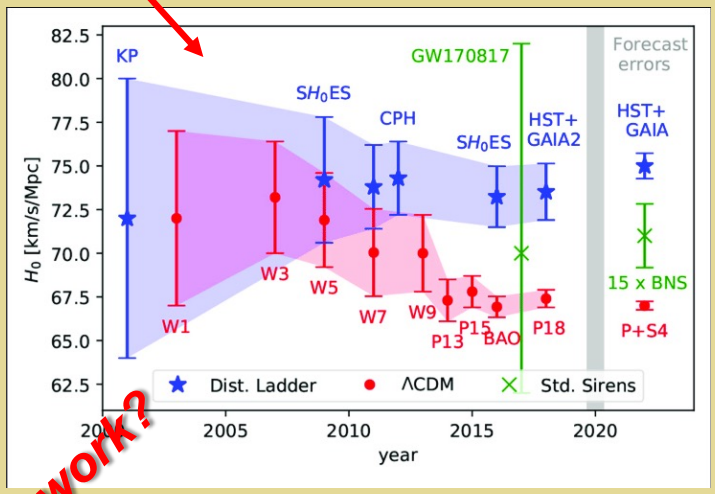

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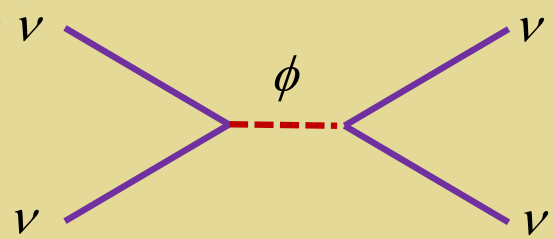
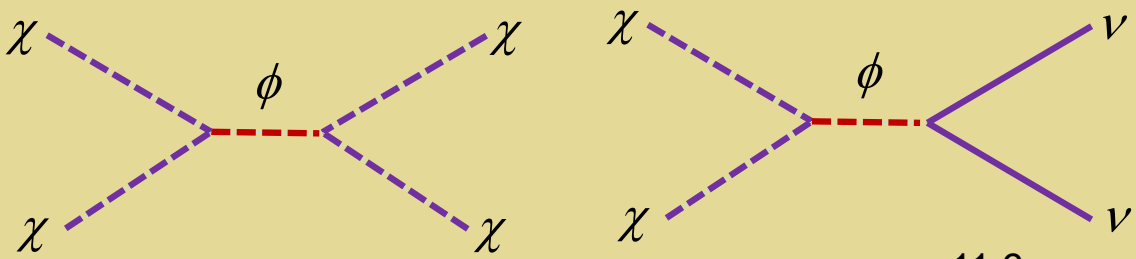
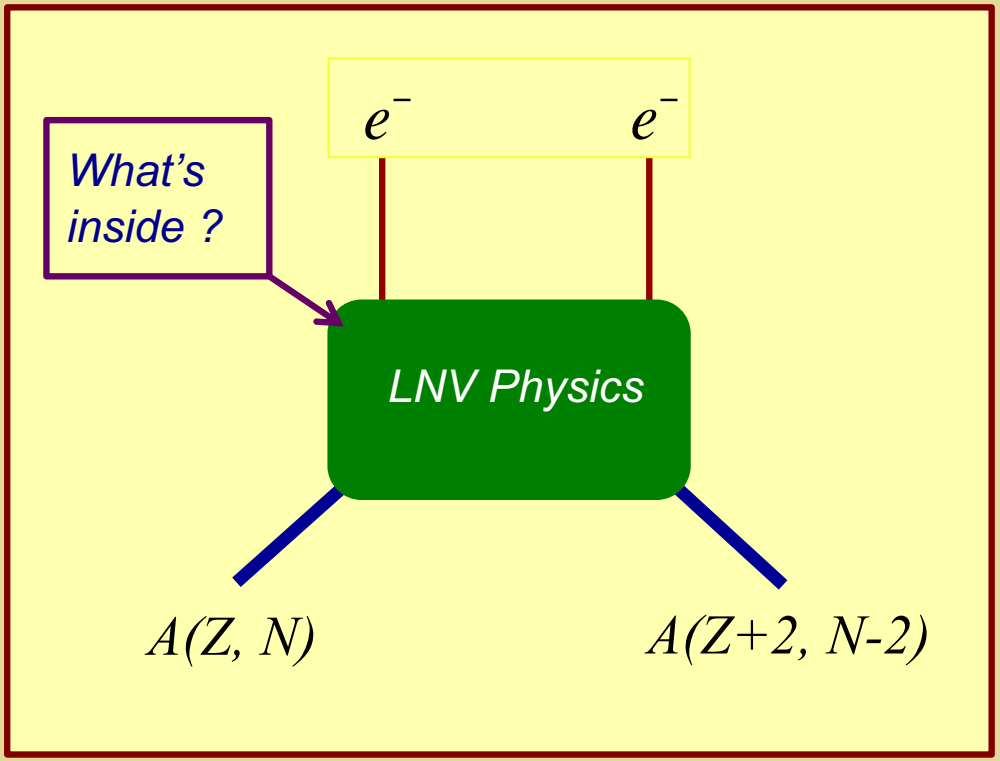




DM – ν interactions?

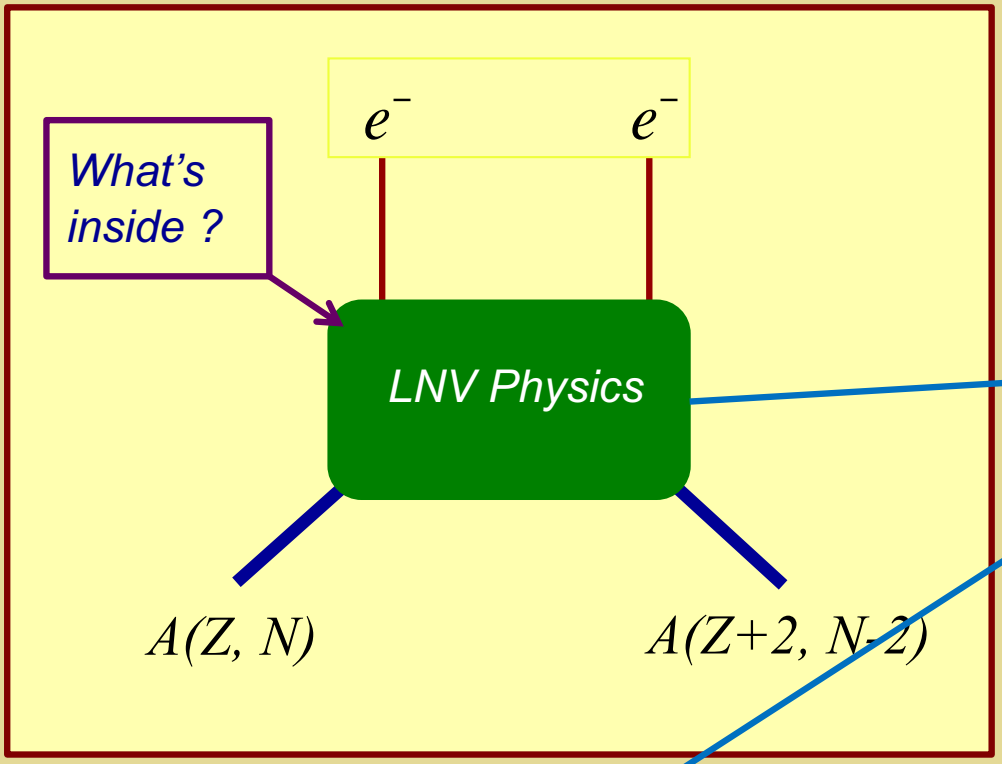
Light Mediator & $\beta\beta$ - Decay

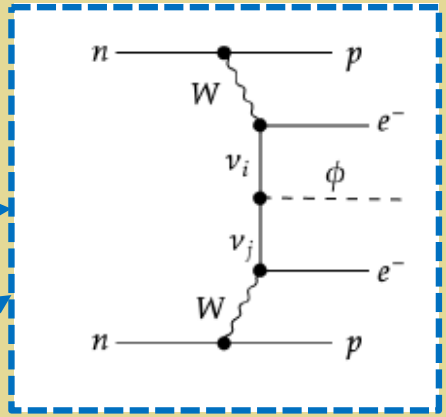


$$\mathcal{L} = g_{\nu\phi}\overline{\nu}P_R\nu^c\phi + g_{\chi\phi}\overline{\chi}\chi\phi + \text{h.c.}$$

LNV

Light Mediator & $\beta\beta$ - Decay





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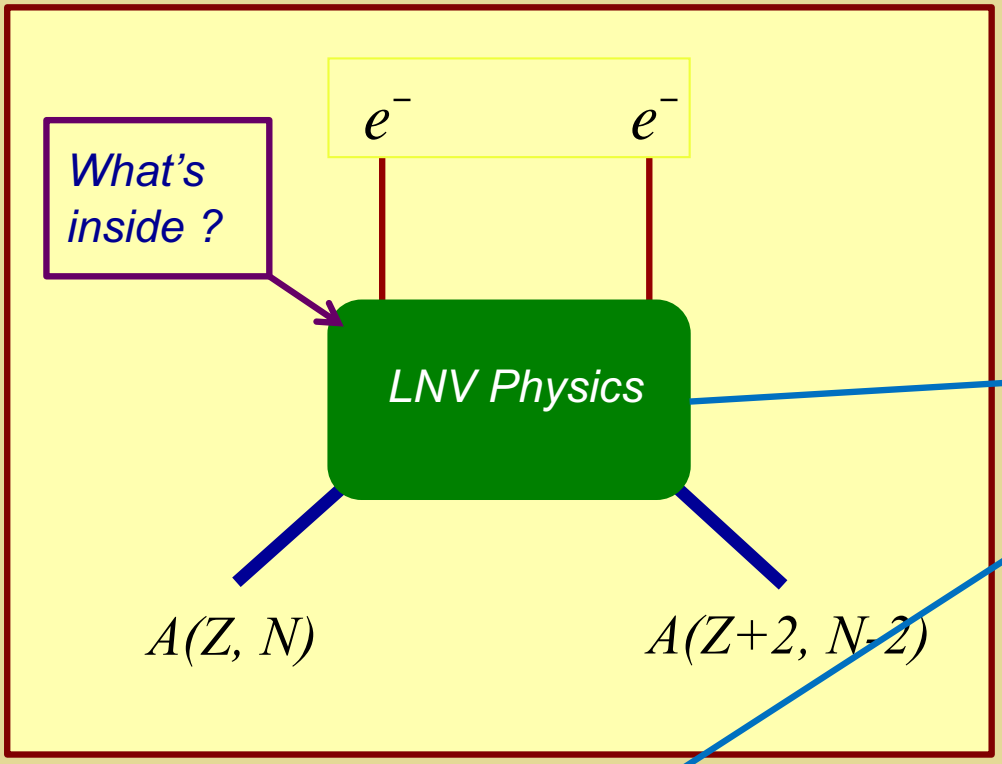

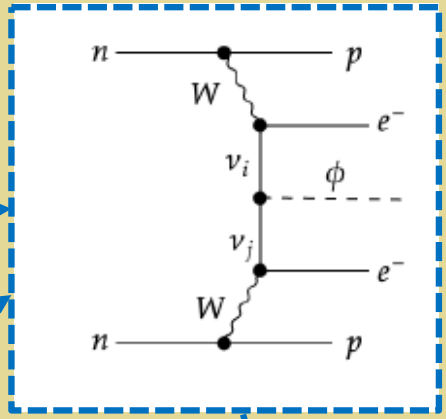

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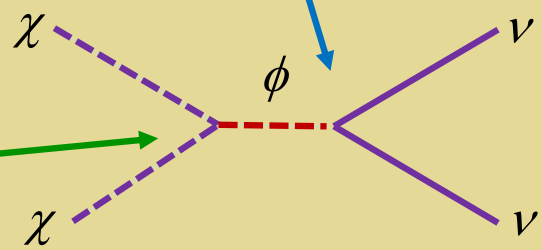
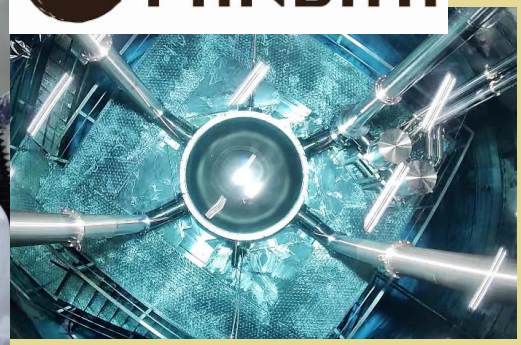


Light Mediator & $\beta\beta$ - Decay

PandaX 4T $\beta\beta$ - Decay

PandaX-4T is under operation at CJPL



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- **On-site installation in 2019, commissioning late 2020, first physics run late 2021**
- **Multi-purpose experiment, expected to run till 2025**
- **PandaX-20T upgrade under preparation**

See also Boudjema et al 2511.13606

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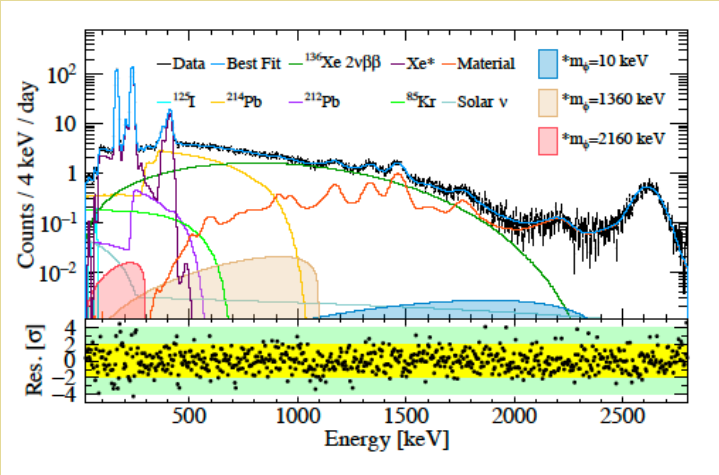
Light Mediator & $\beta\beta$ - Decay

$\beta\beta$ spectral distortion

PandaX 4T $\beta\beta$ - Decay



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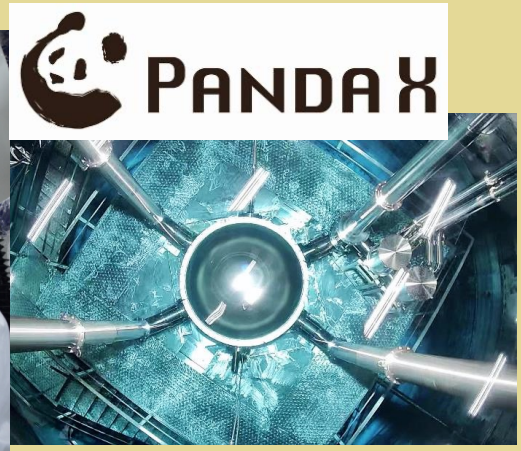

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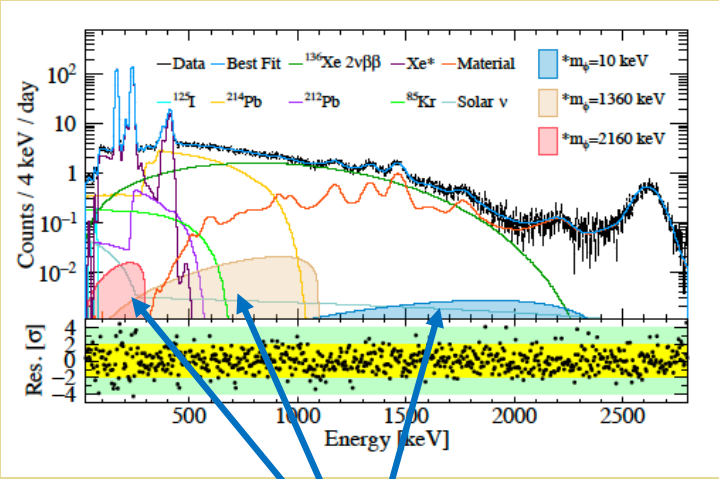

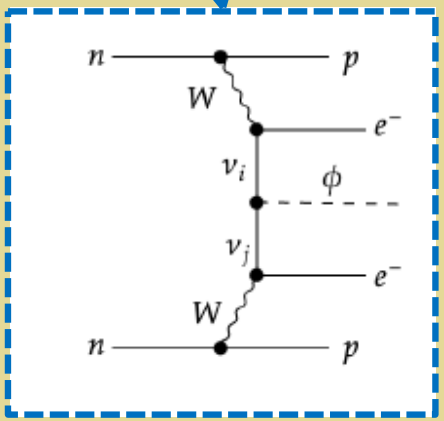

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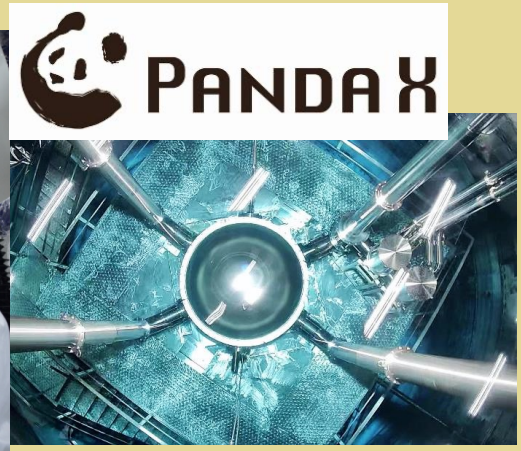

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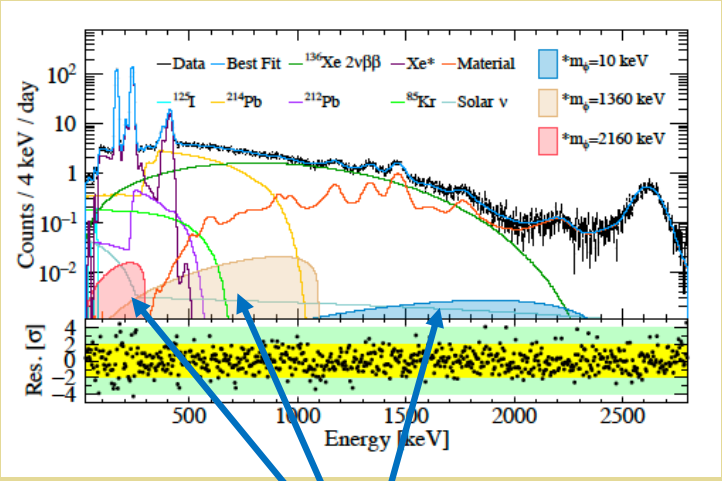
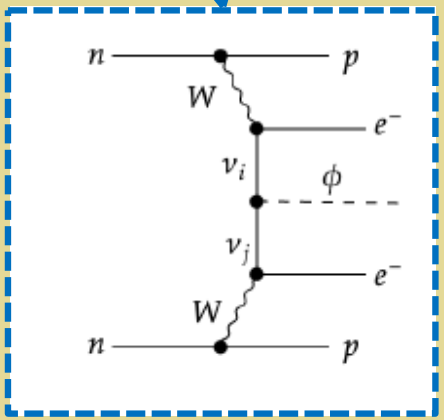
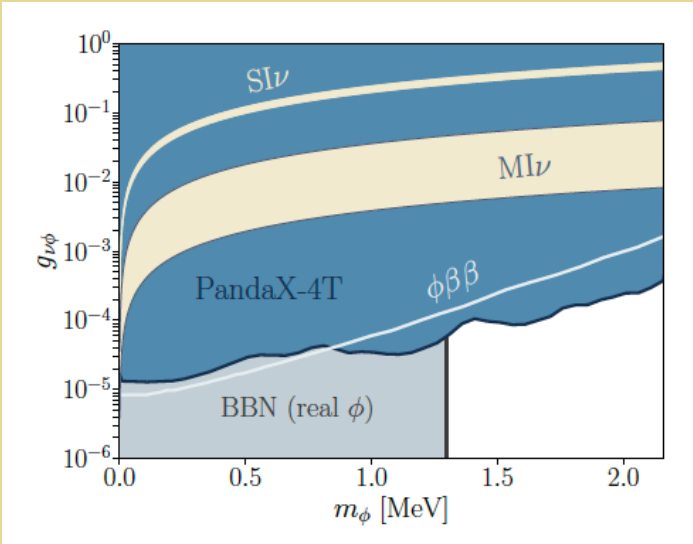




PandaX 4T & Hubble tension



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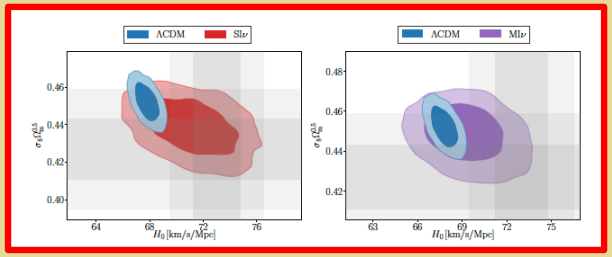
Light Mediator & $\beta\beta$ - Decay

1911.00543



PandaX 4T $\beta\beta$ - Decay

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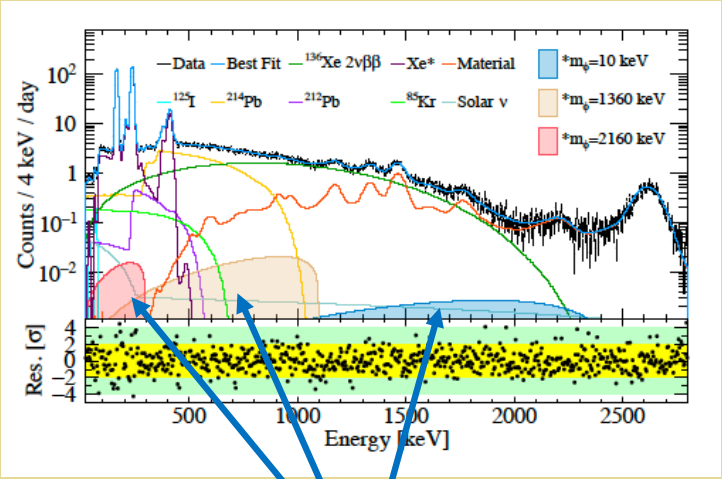

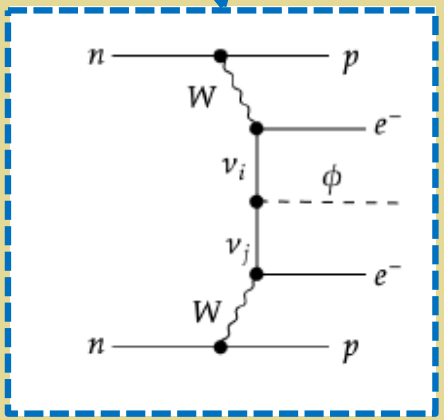

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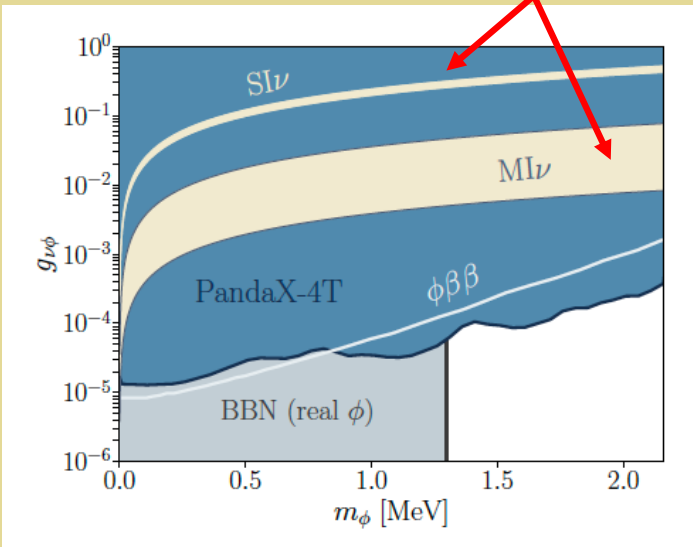

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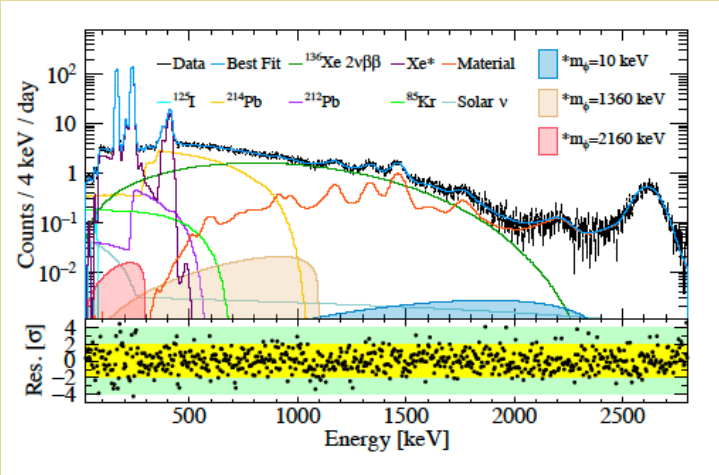
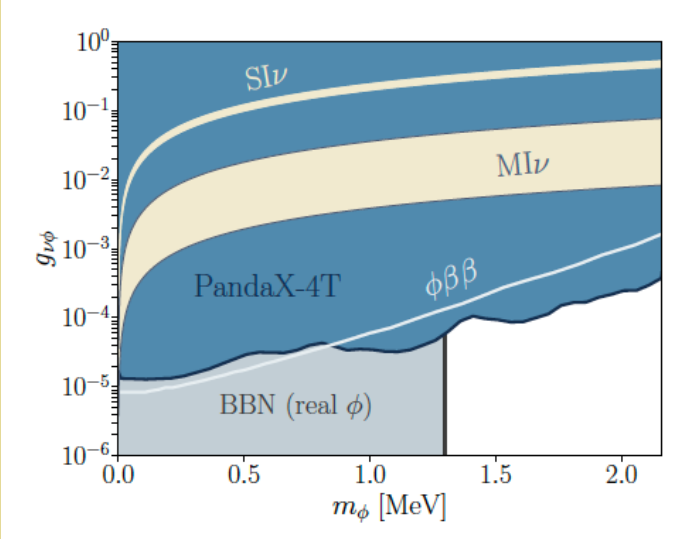
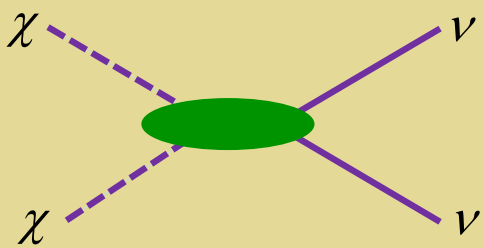




CMB & P(k)$_{matter}$

$$\sigma^{\rm el}_{\nu\chi} \lesssim 10^{-33}(m_\chi/{\rm MeV}){\rm cm}^2$$



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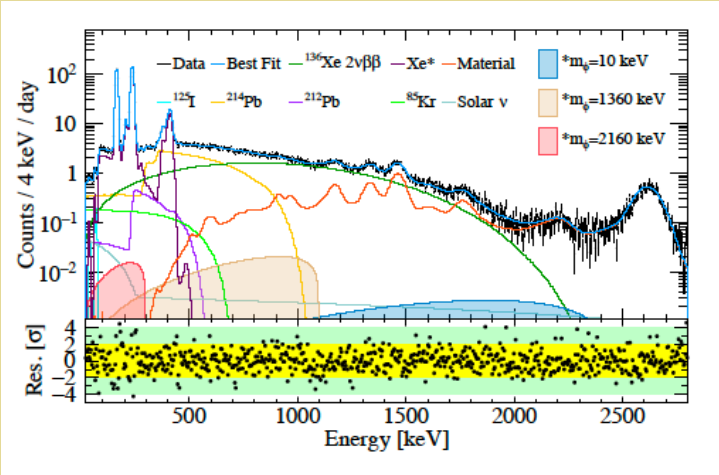

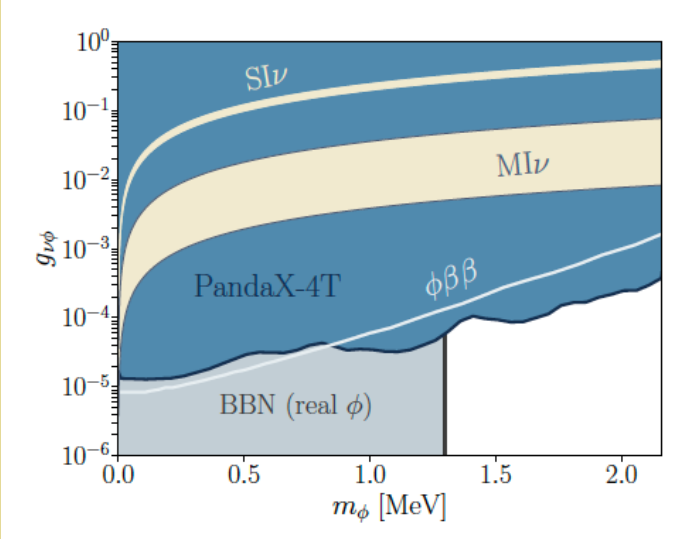

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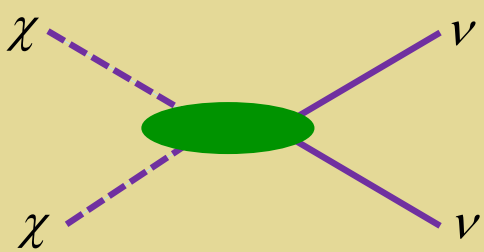

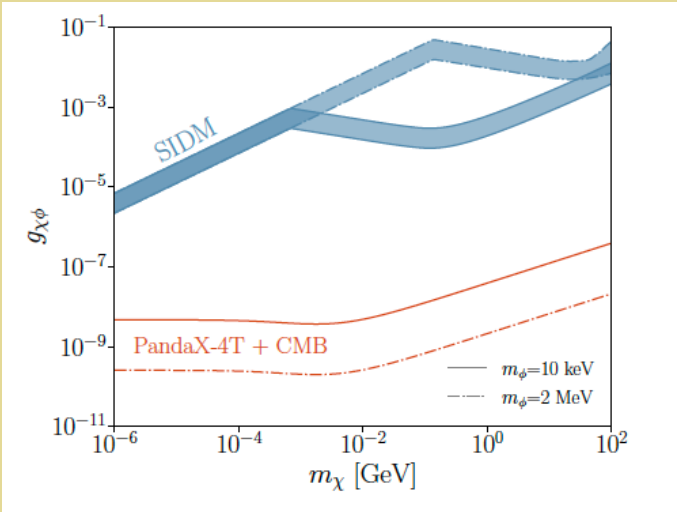

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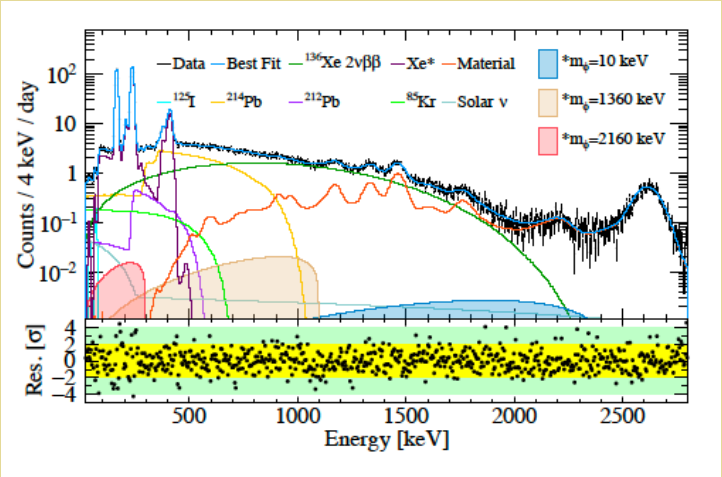

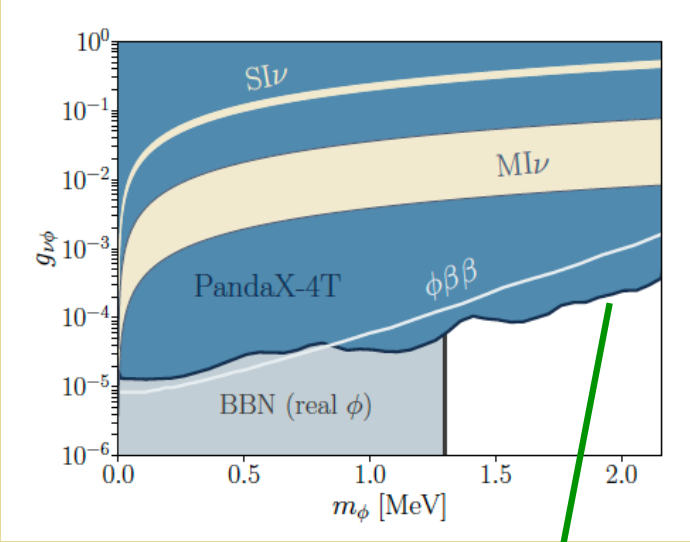

upper limit

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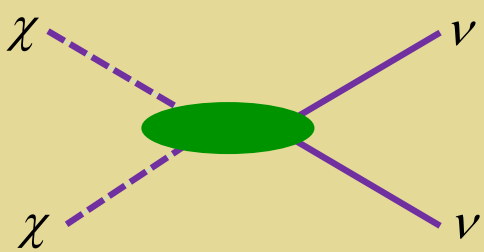

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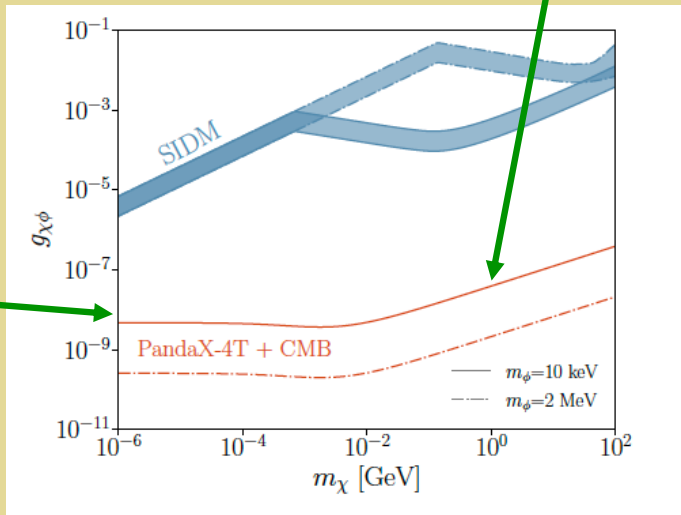
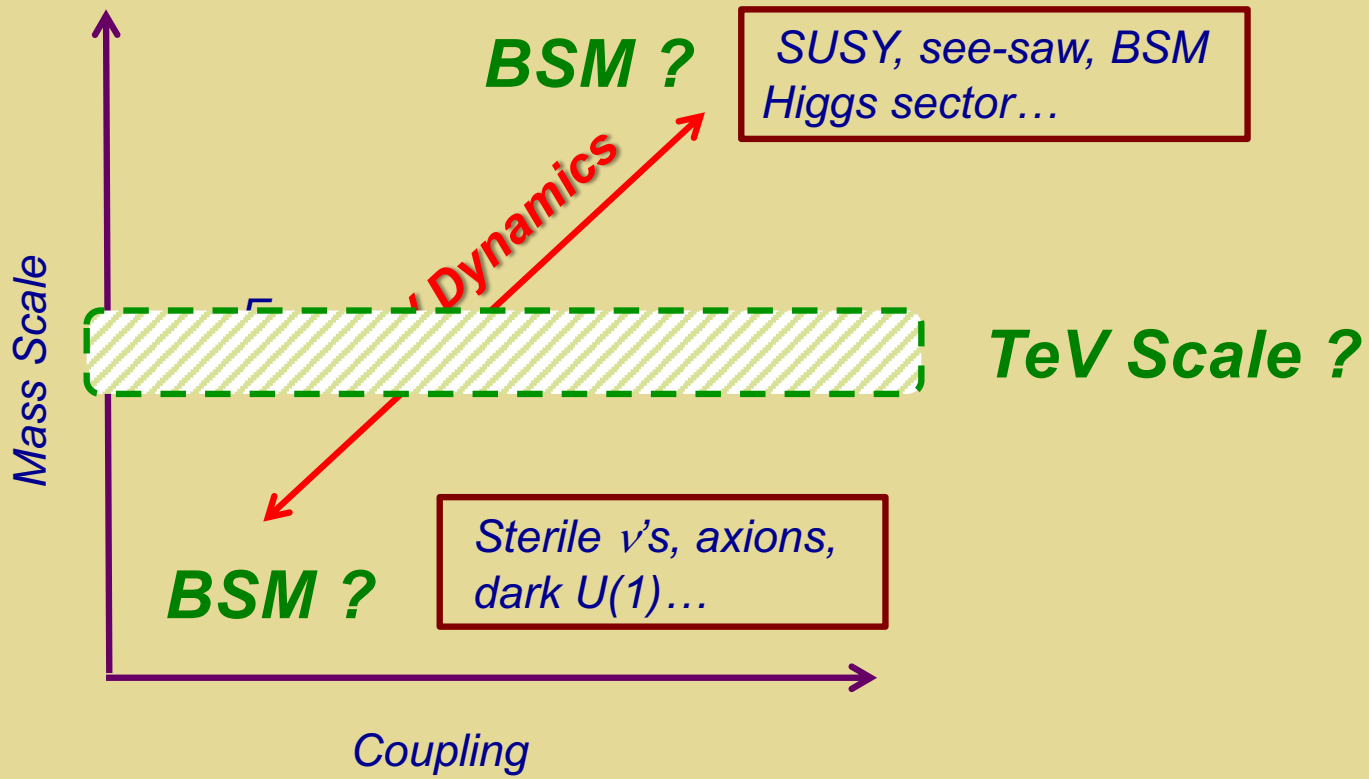


LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **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 with < MeV scale LNV*
- *> 3 light neutrinos*

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**
- **Σm_ν**
- **Grav waves**
- **Dark Matter**

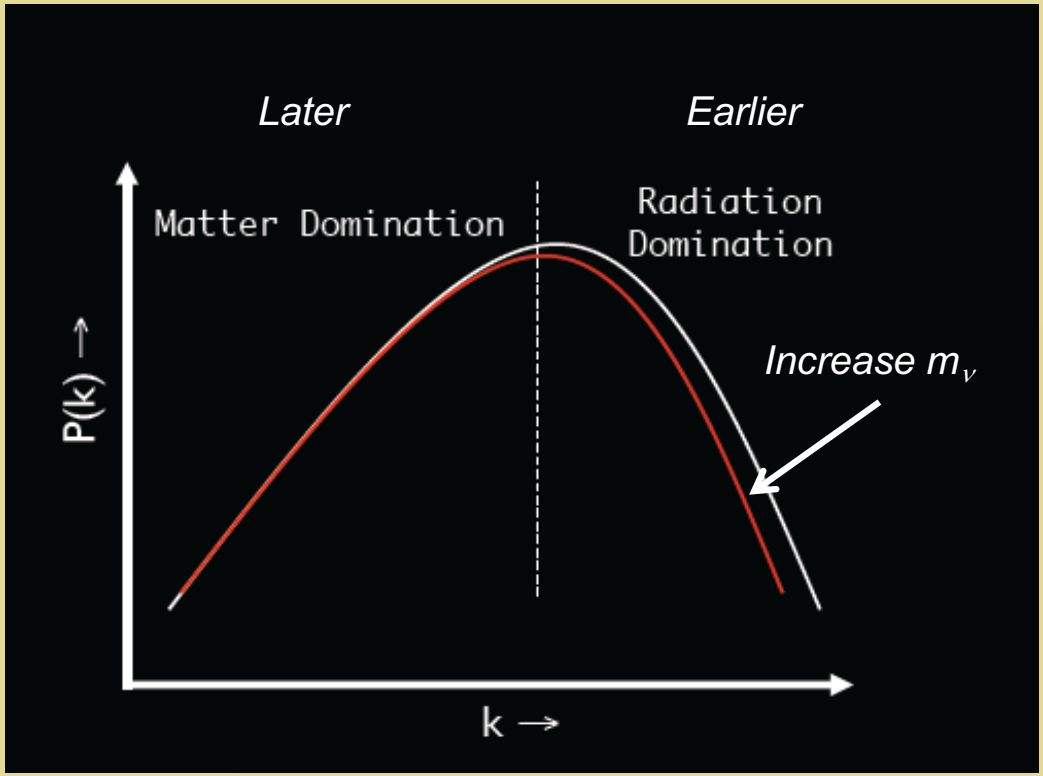
FSNN:
- **$0\nu\beta\beta$ decay**
- **μ_ν**
- **ν osc**
- **PV ee …**

Colliders

Neutrino Mass & Cosmology

See Junqing Xia talk

Matter Power Spectrum



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

Palanque-Dalabrouille '15

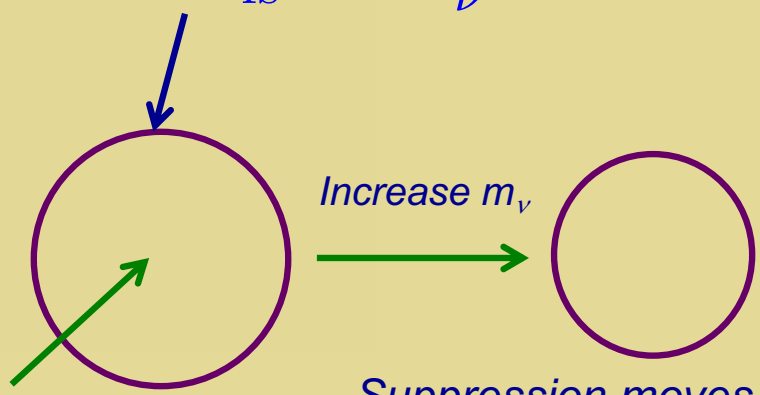
Neutrino Free Streaming

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

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

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

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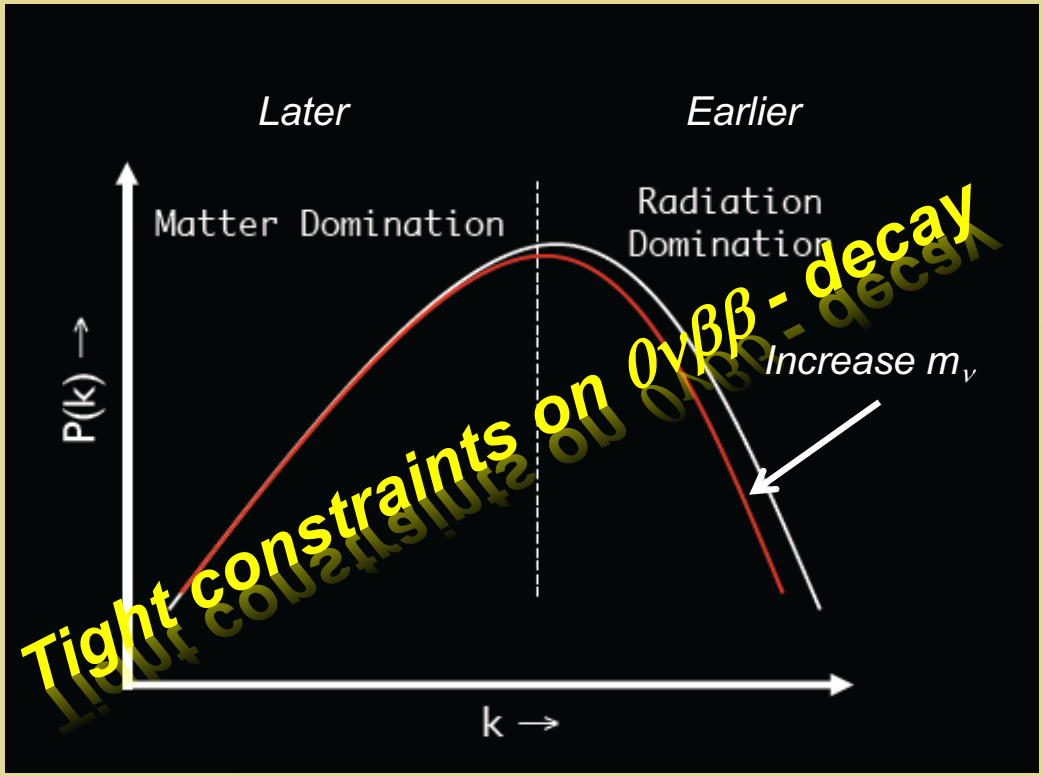
Matter Power Spectrum



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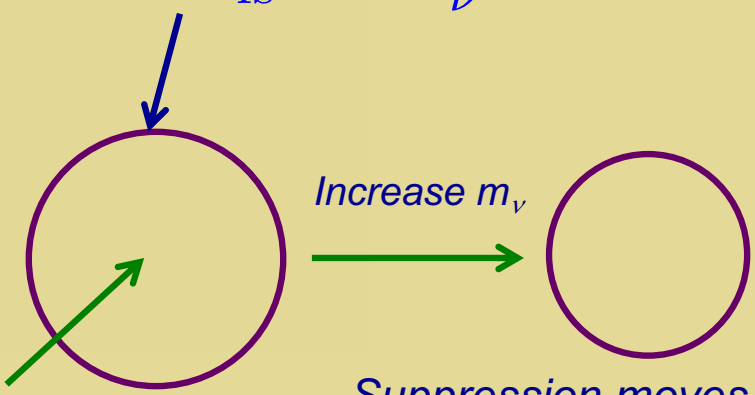

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The "Standard Mechanism"

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

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

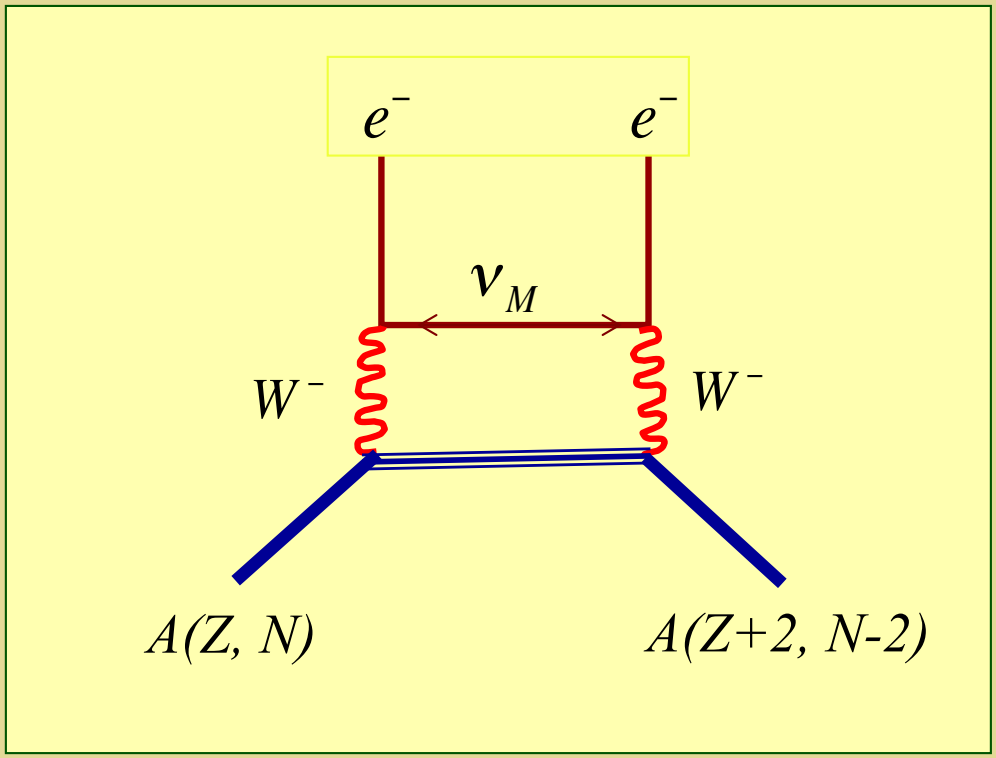
Dirac

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

Majorana

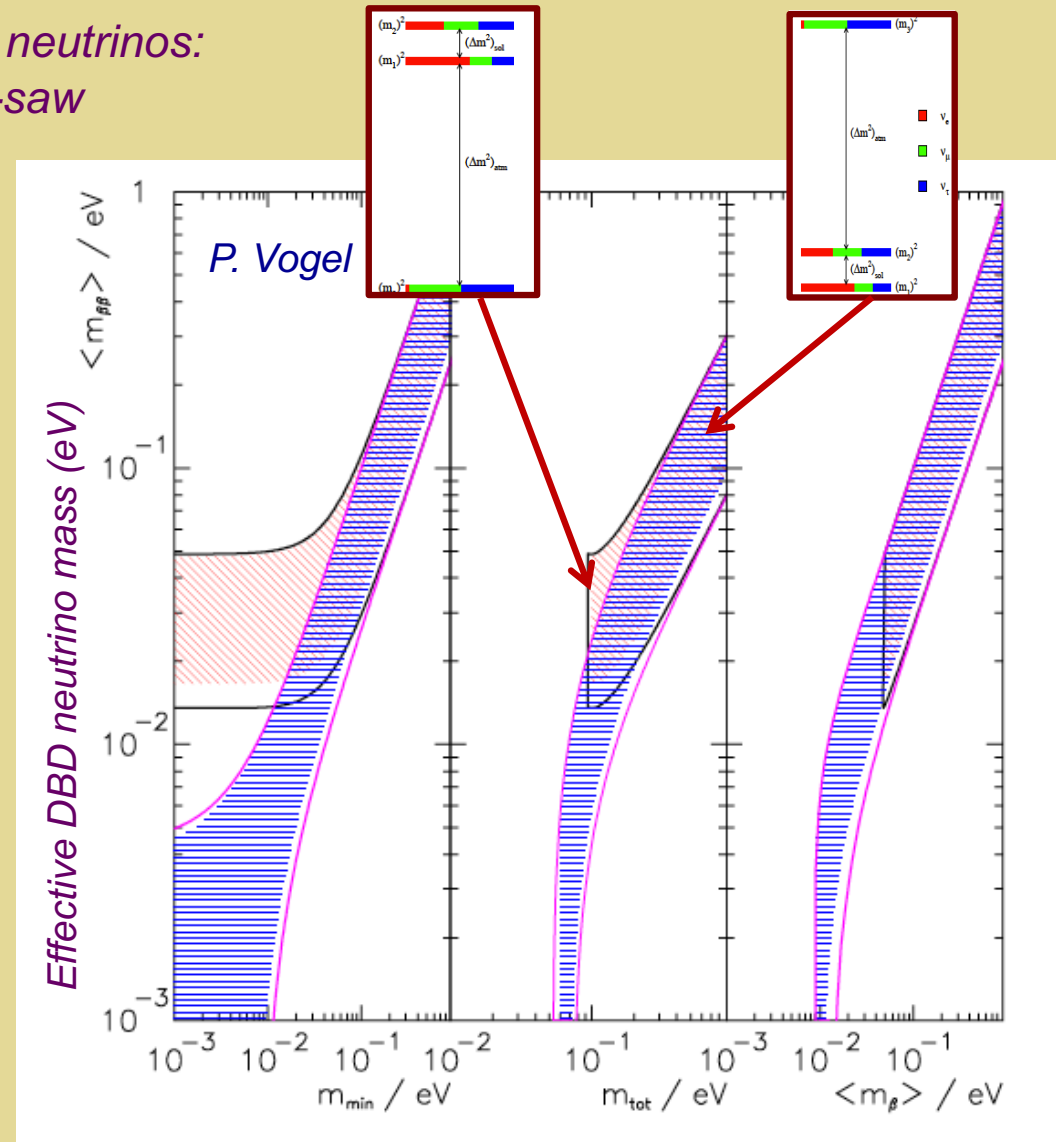
"Standard" Mechanism

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



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

Three active light neutrinos: conventional see-saw



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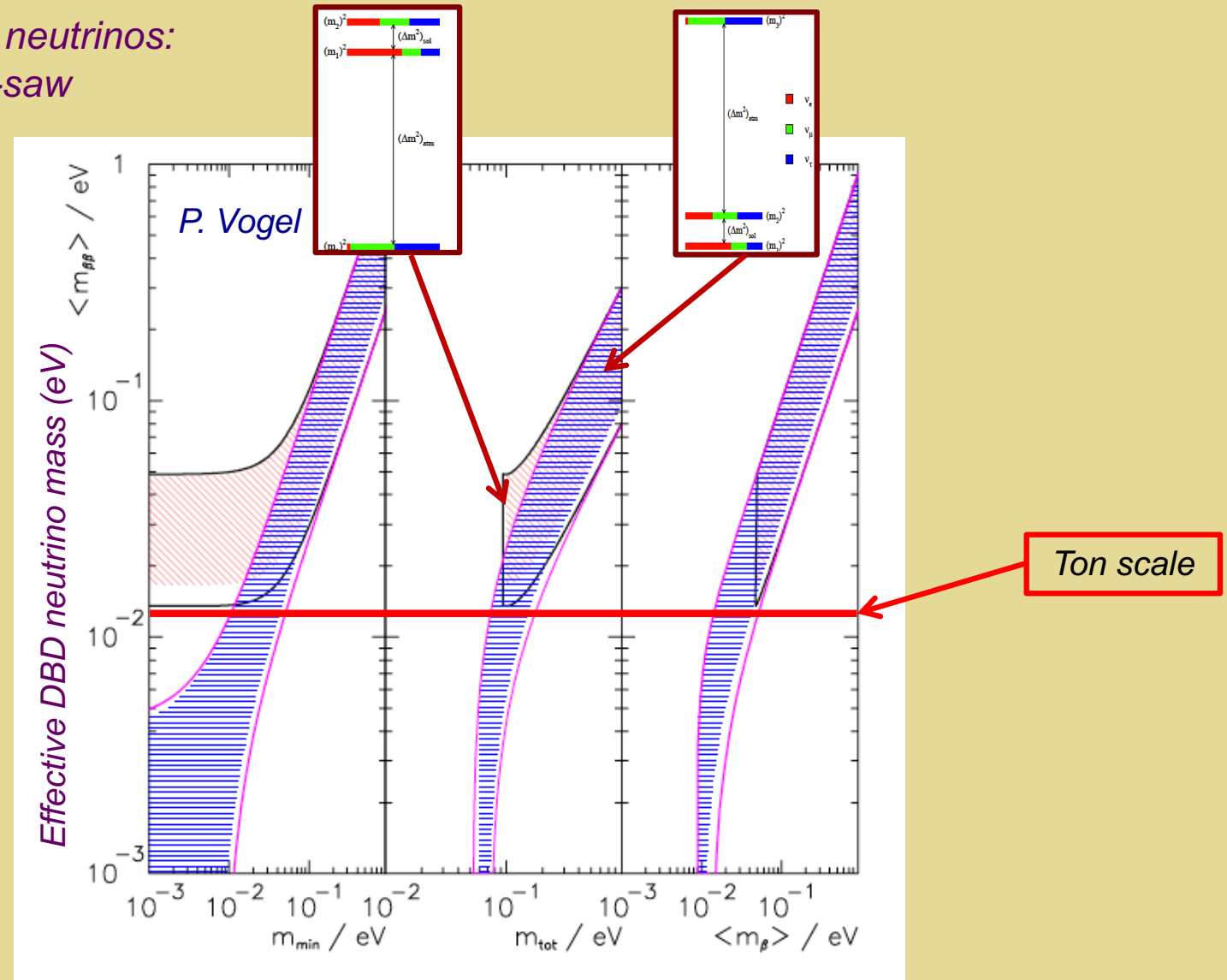

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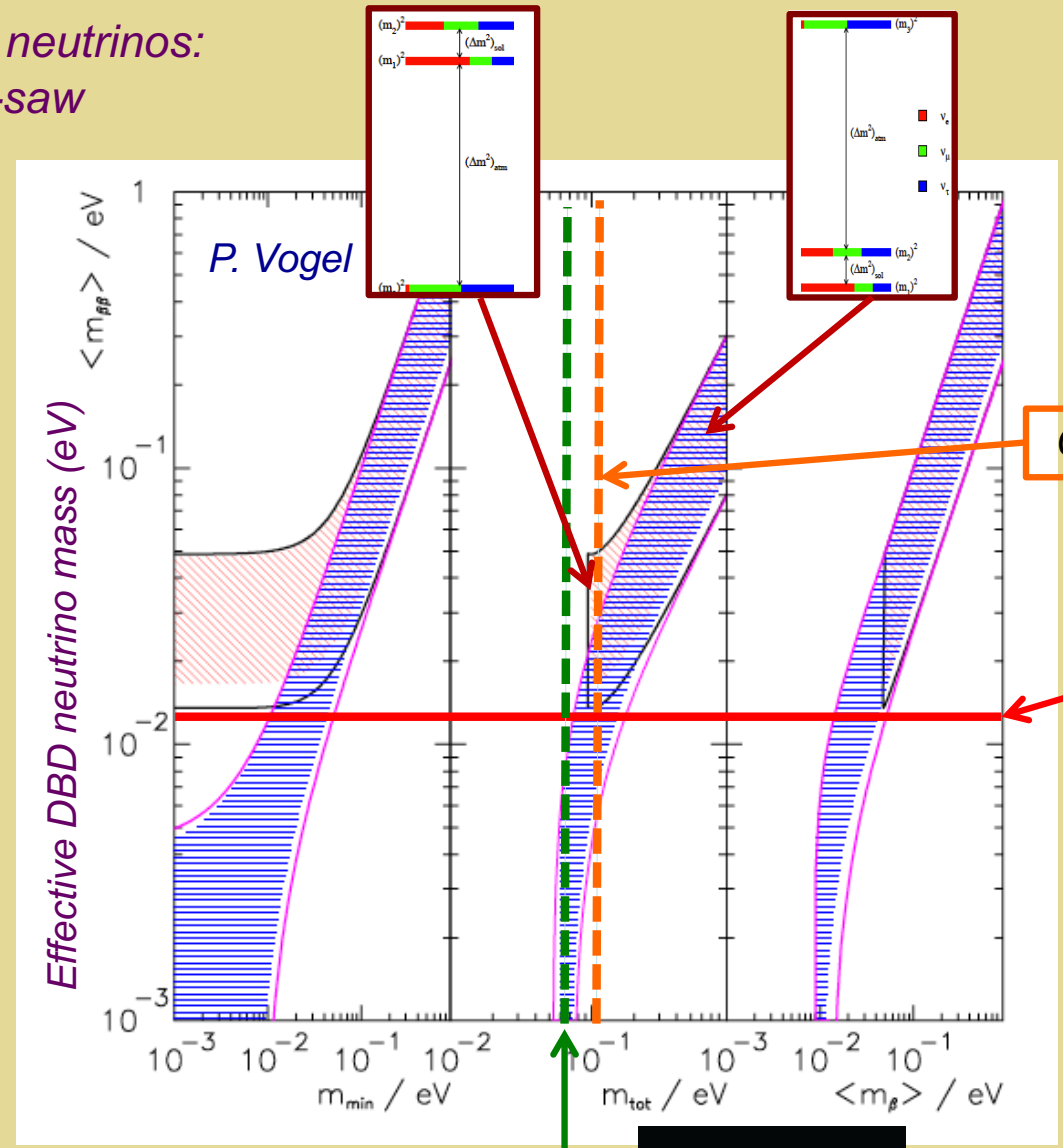
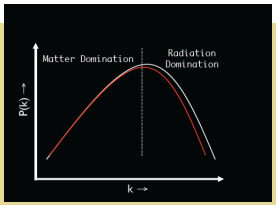


Cosmo current

Ton scale

Cosmo next gen



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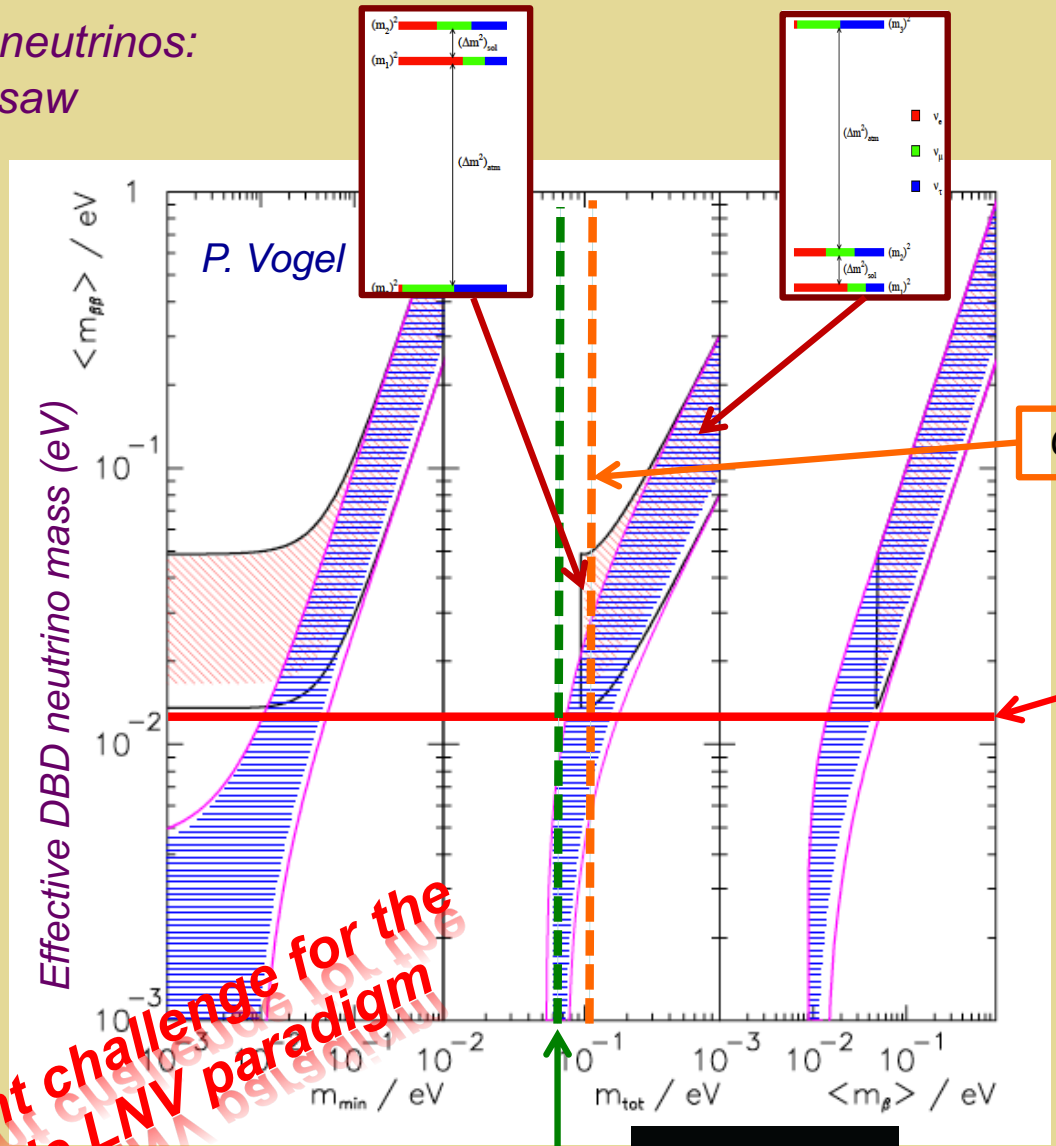
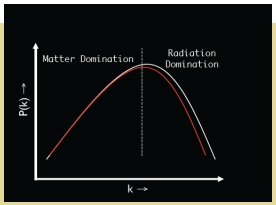


Cosmo current

Ton scale

Important challenge for the high scale LNV paradigm

Cosmo next gen



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

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

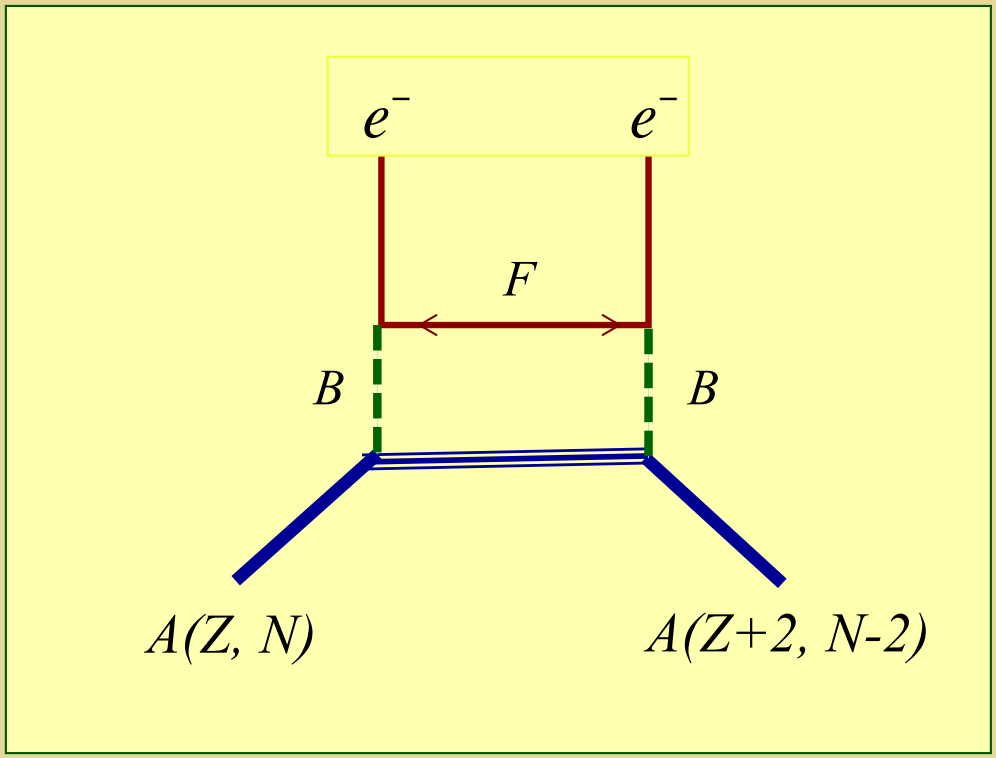
Dirac

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

Majorana

TeV LNV Mechanism

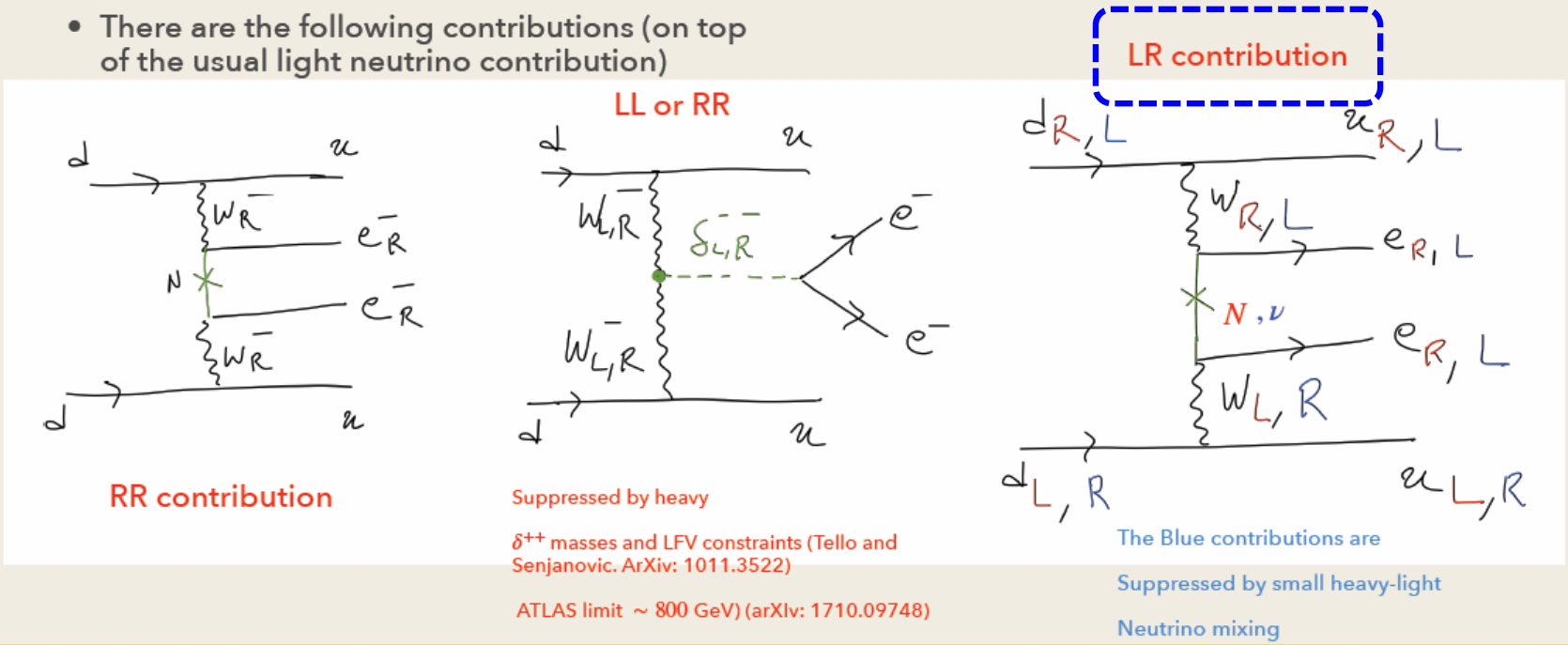
- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



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)



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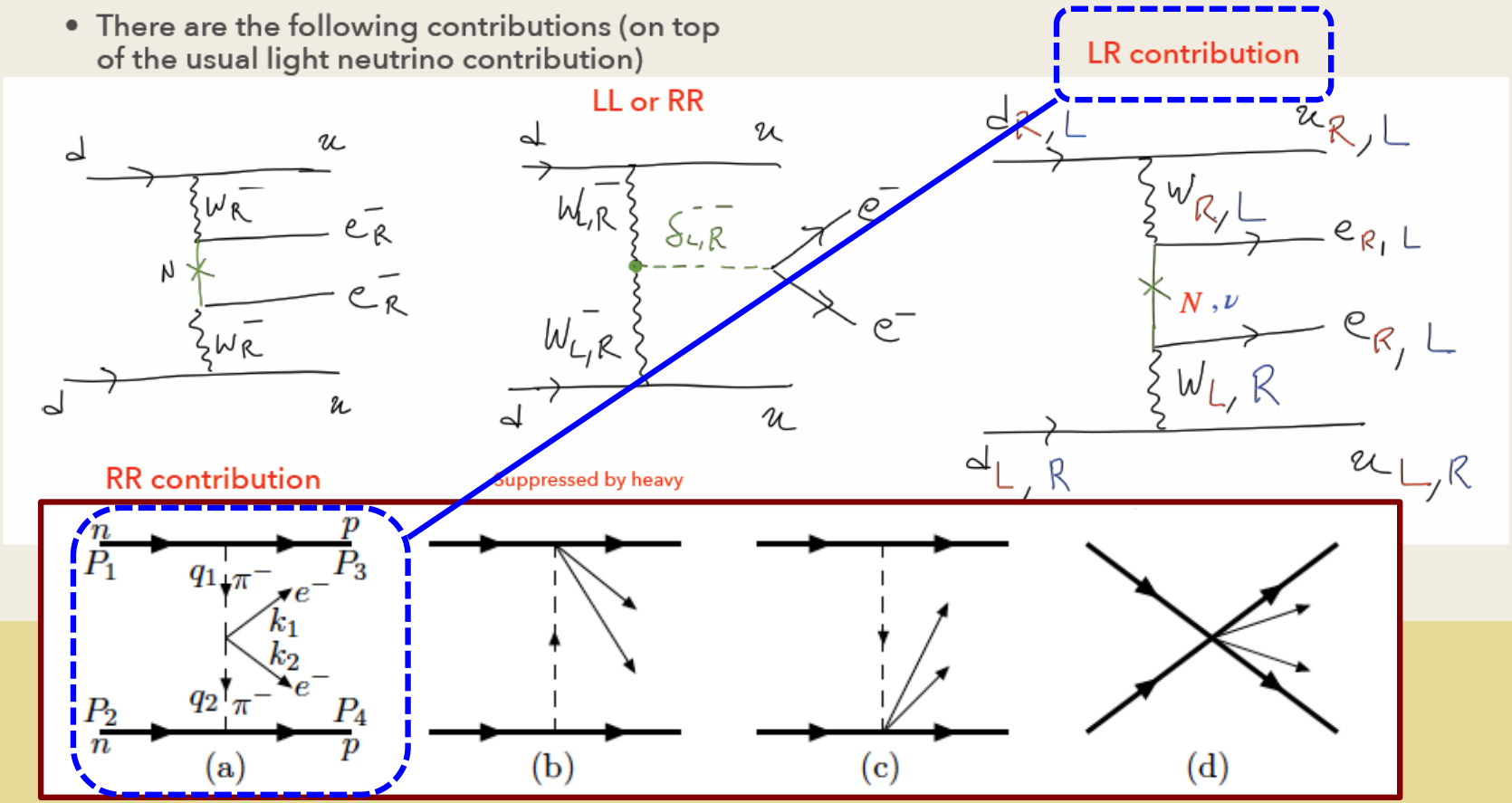

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Chiral EFT: Prezeau, R-M, Vogel hep-ph/0303025 ; Cirigliano et al 1806.02780

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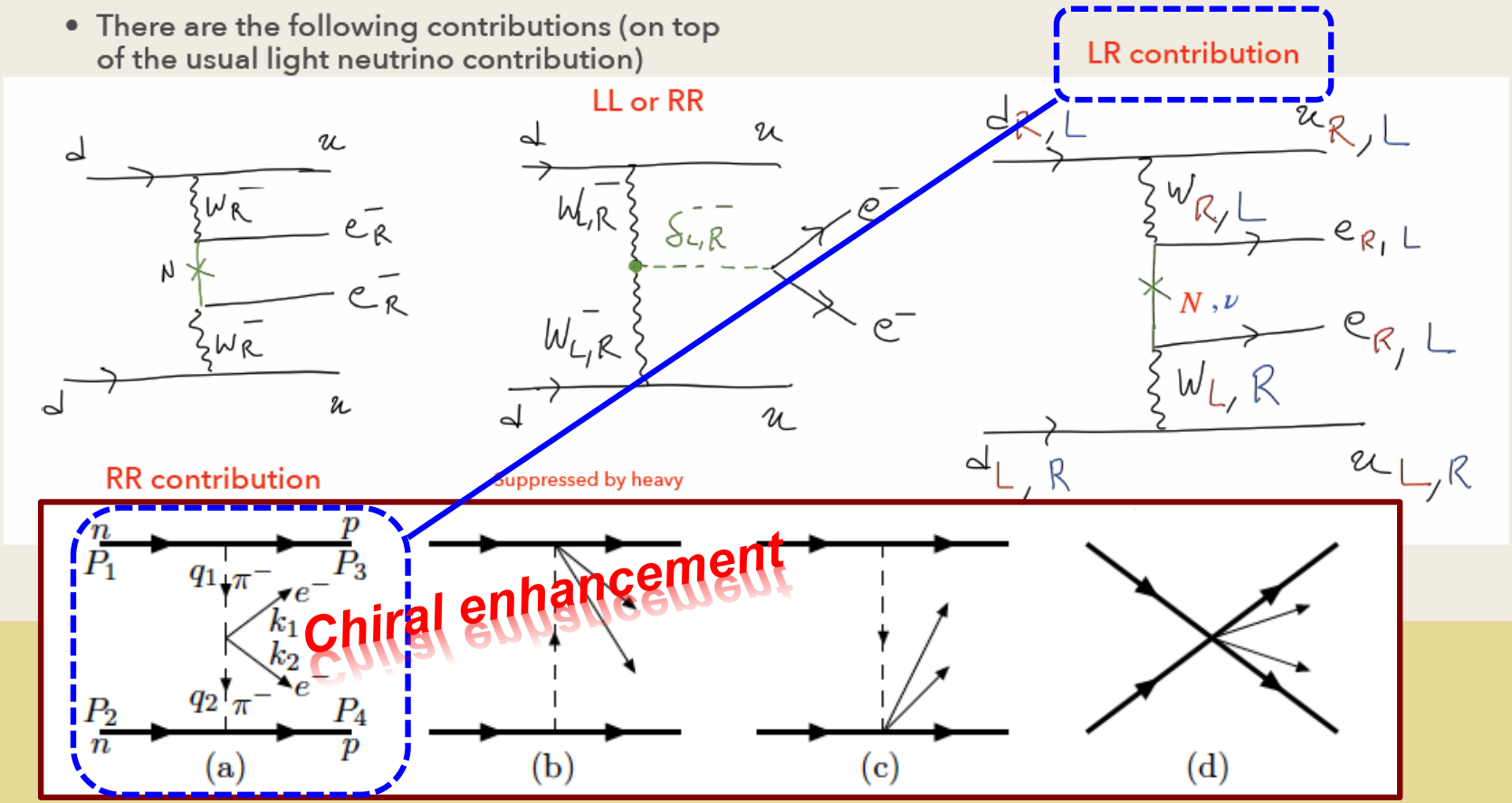

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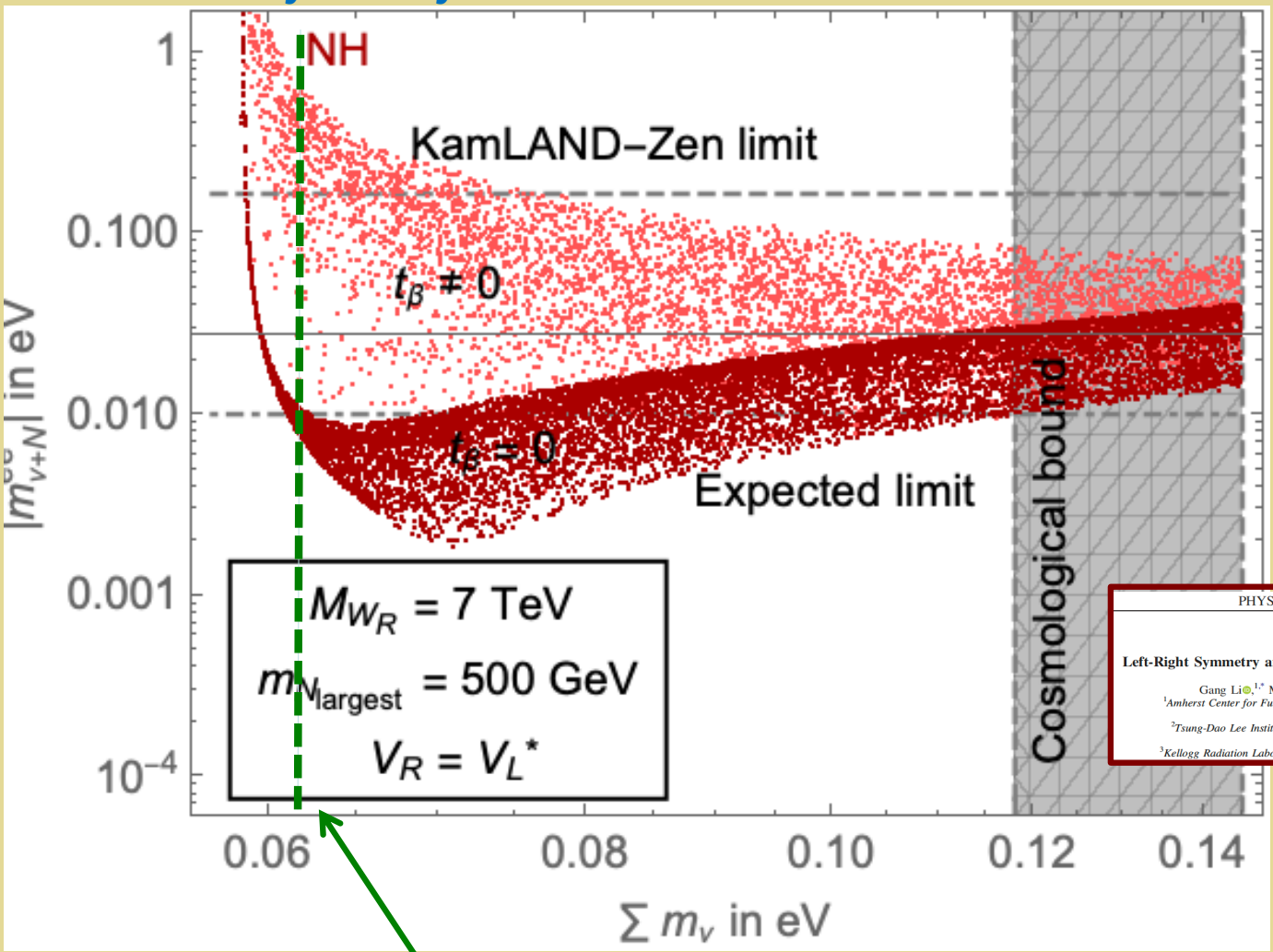
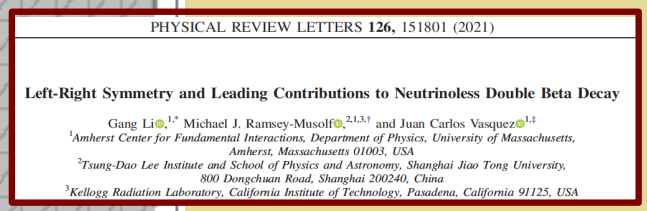
TeV-Scale LNV: $0\nu\beta\beta$-Decay & Σm_ν

Minimal LR Symmetry




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,‡]

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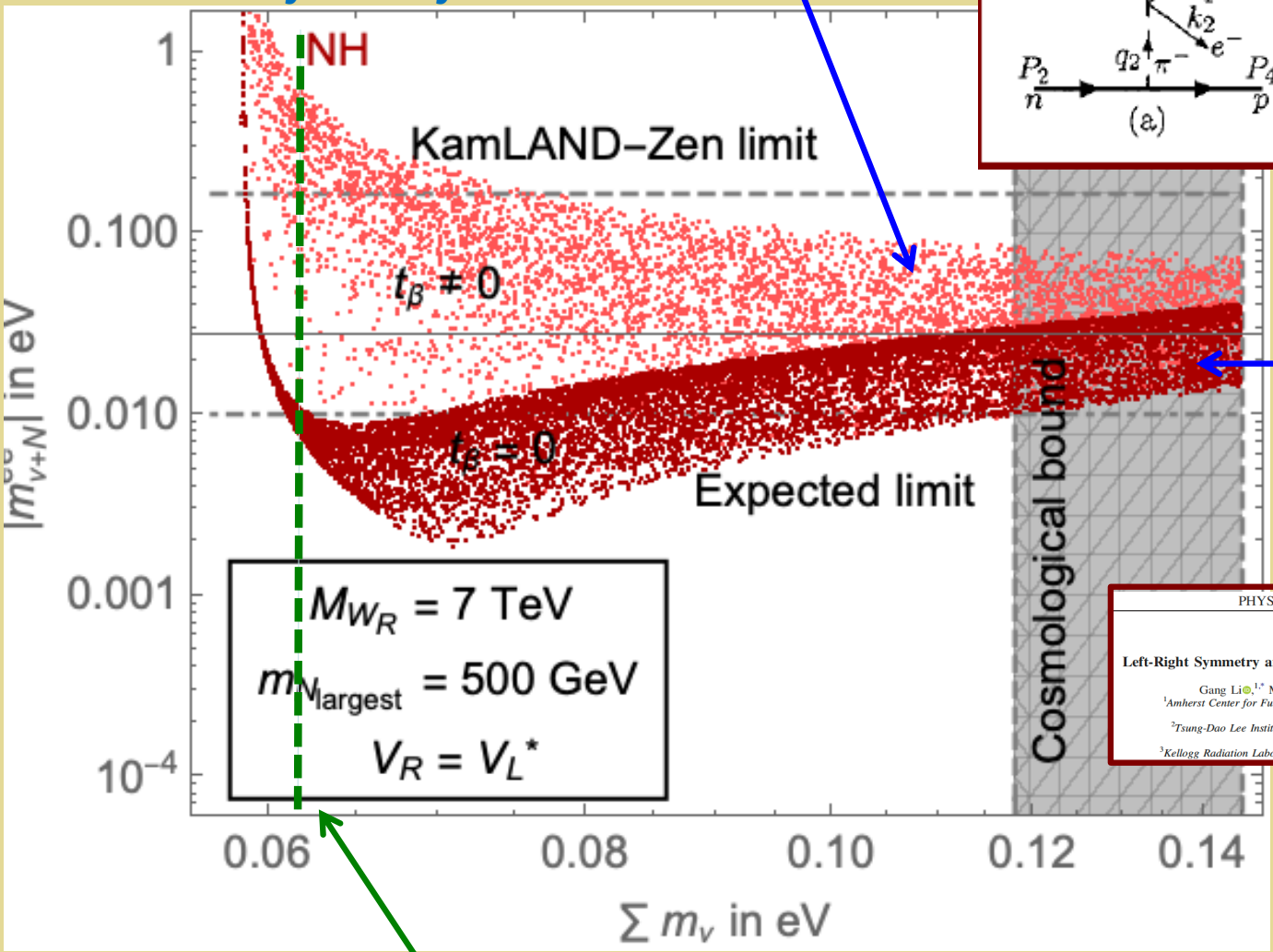
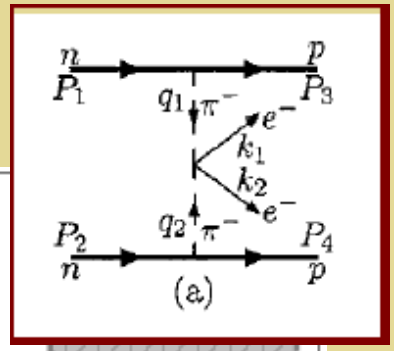
~ Cosmo next gen

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

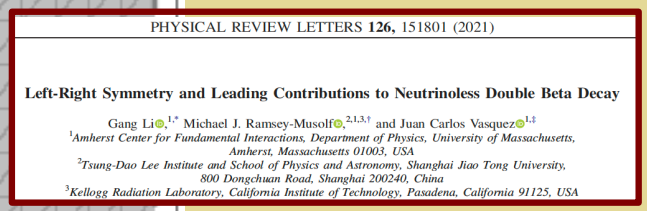
EFT: Long range

Minimal LR Symmetry





Short range only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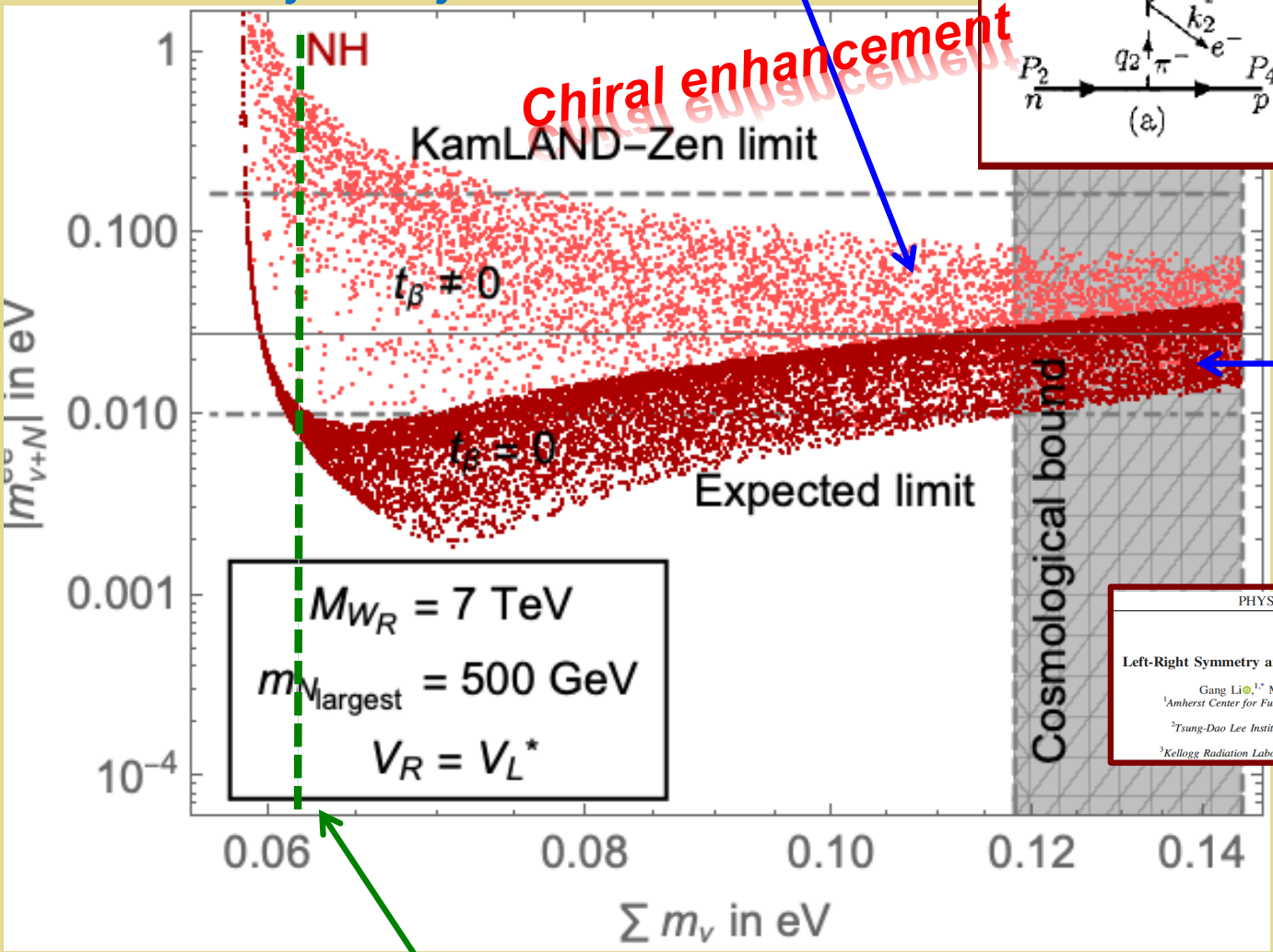
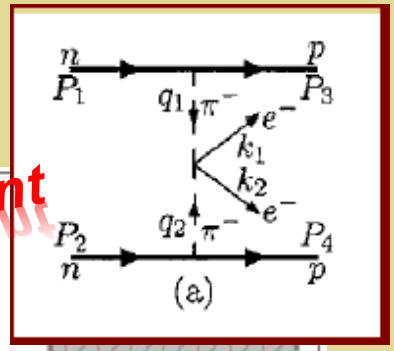
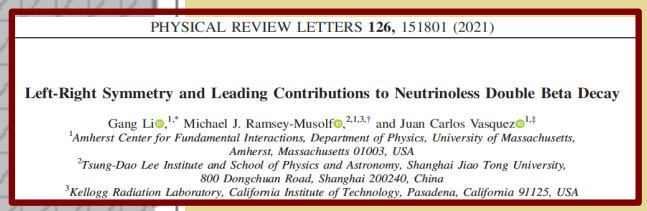




Chiral enhancement

Short range only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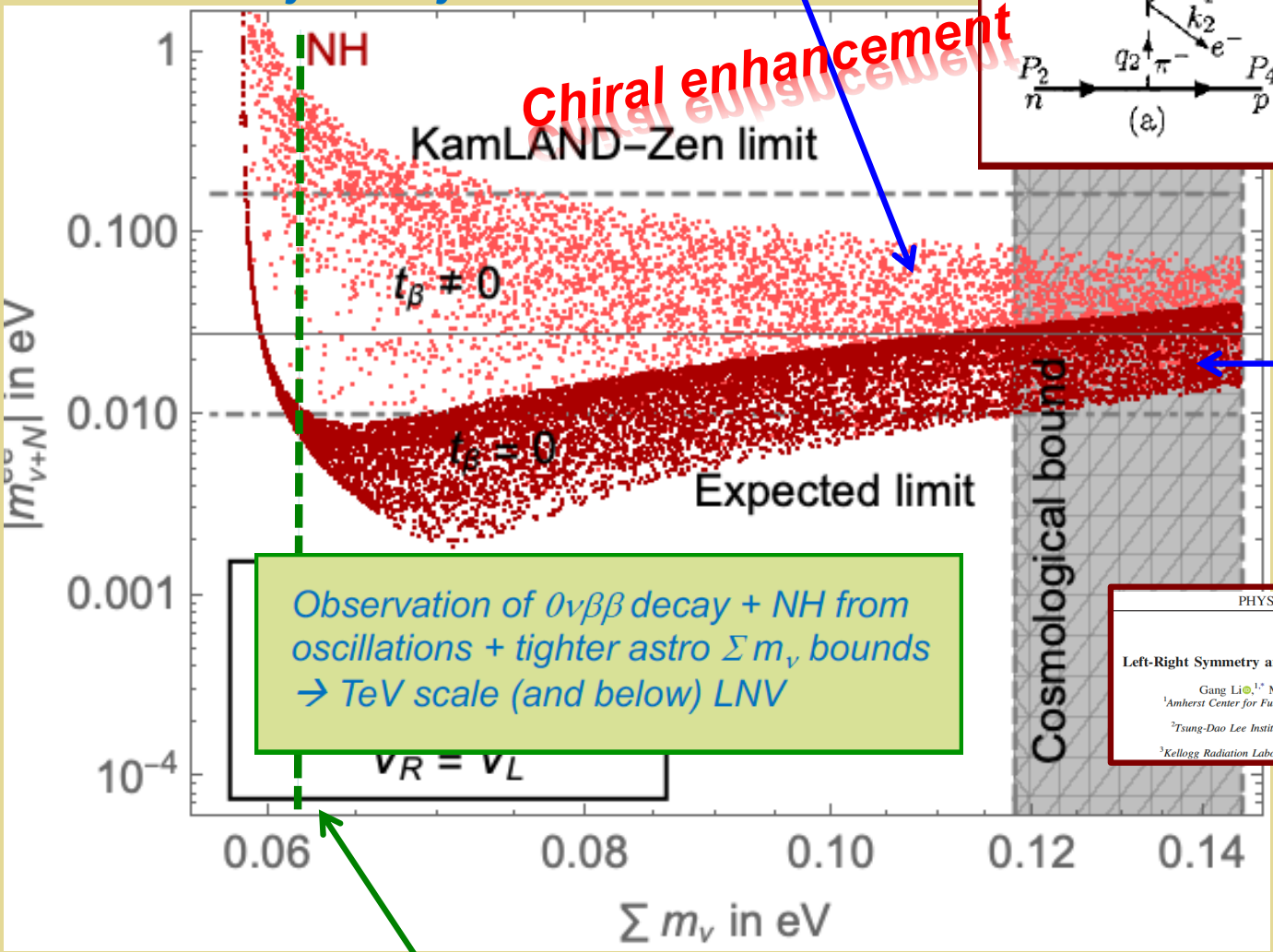
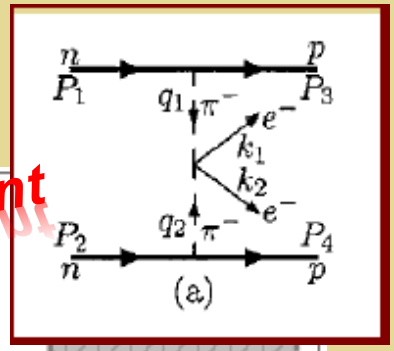
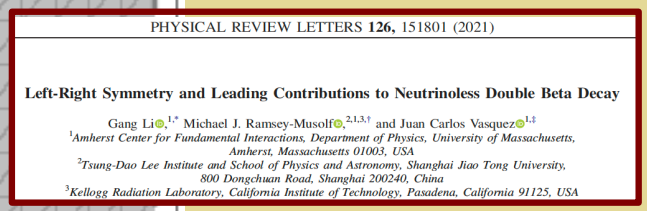




Short range only

Observation of $0\nu\beta\beta$ decay + NH from oscillations + tighter astro Σm_ν bounds → TeV scale (and below) LNV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~ Cosmo next gen

mLRSM W_L-W_R Mixing: LHC & $0\nu\beta\beta$ Decay

PHYSICAL REVIEW D **105**, 115021 (2022)

Unraveling the left-right mixing using $0\nu\beta\beta$ decay and collider probes

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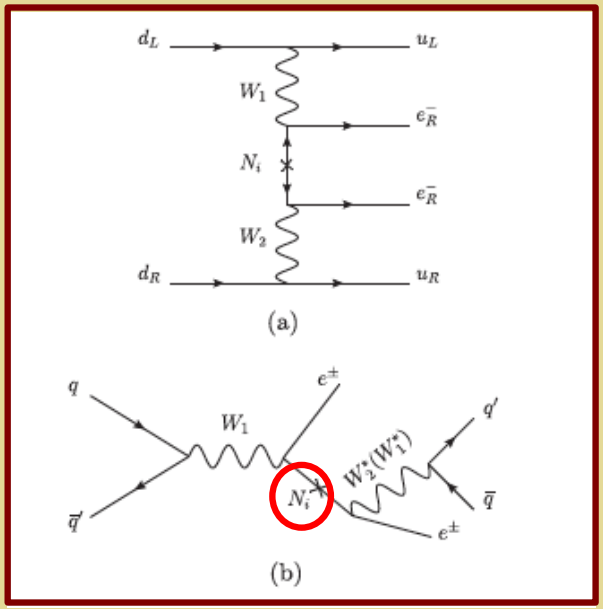

N_R : LLP

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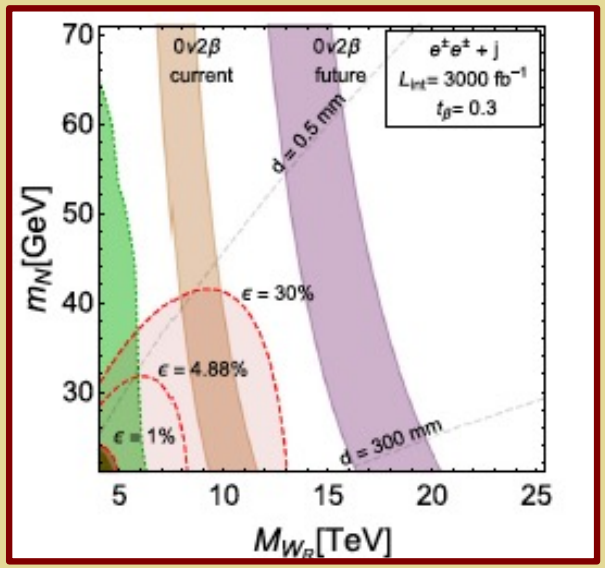

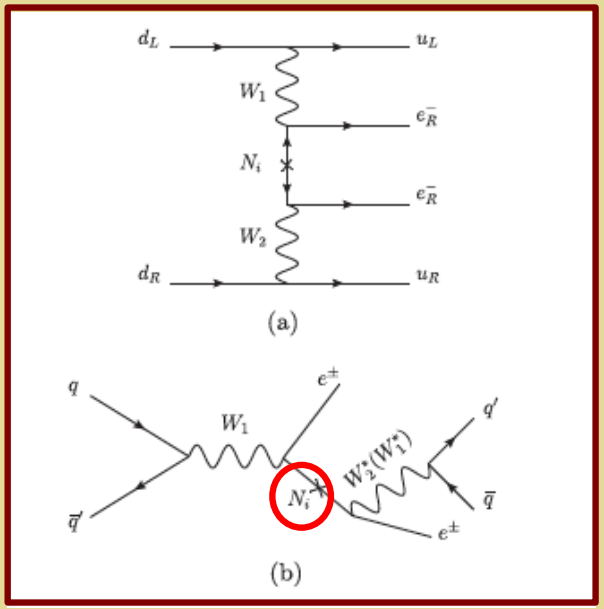

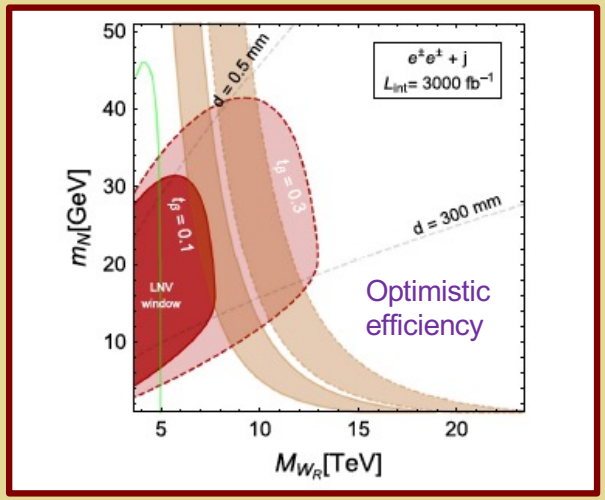

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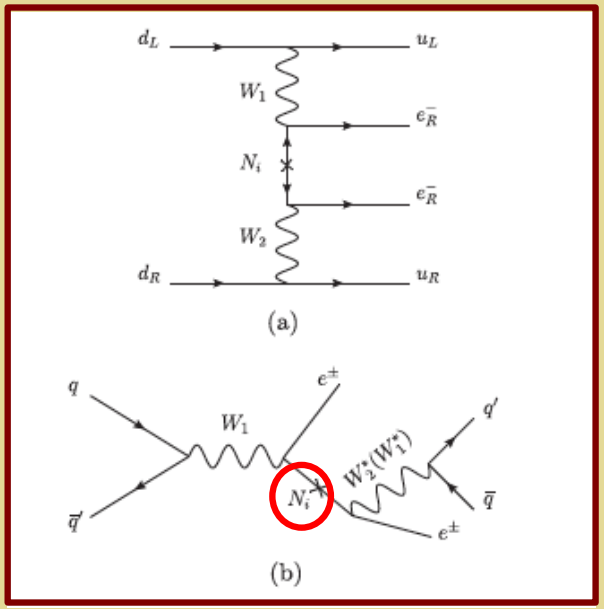

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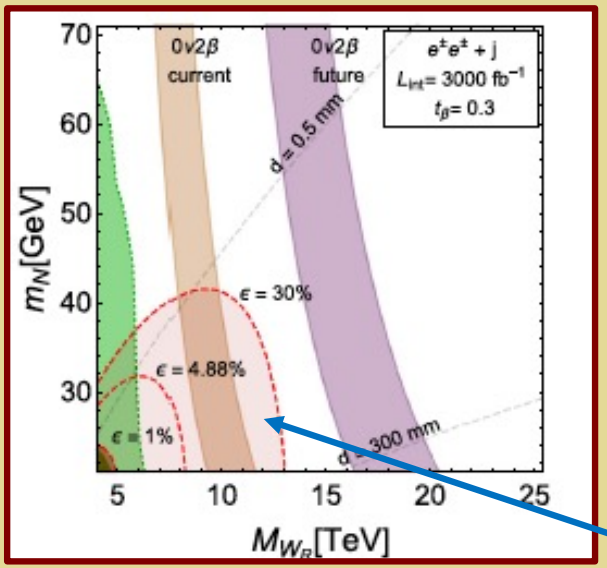
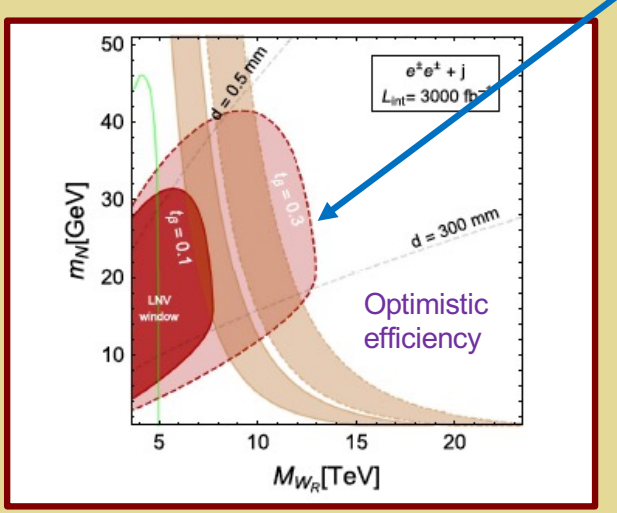


HL-LHC LLP



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

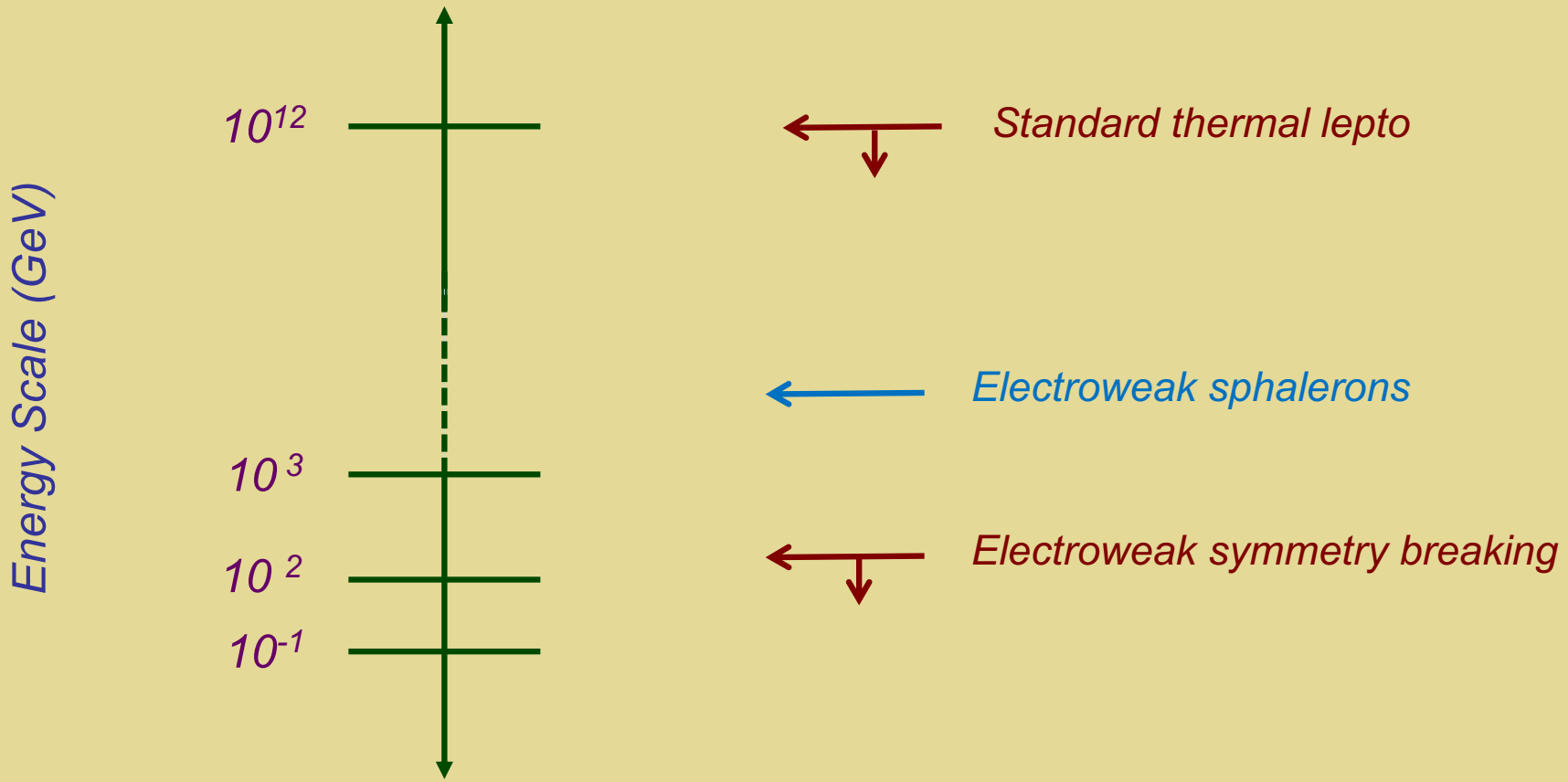
Cosmology:
- **BAU**
- **Σm_ν**
- **Grav waves**
- **Dark Matter**

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

Colliders

High Scale LNV & Leptogenesis

See Wei Chao & Wei Liu talks



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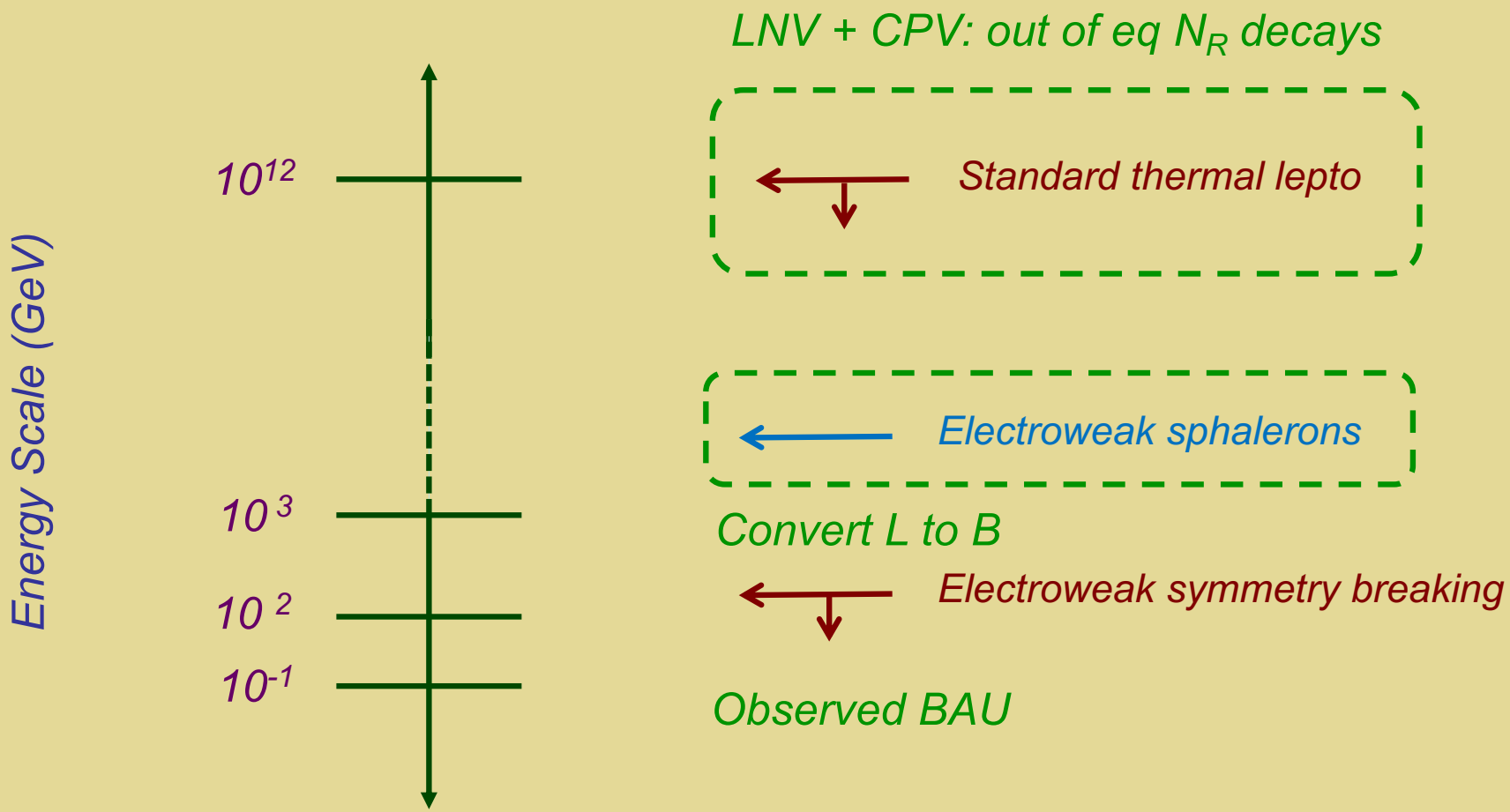

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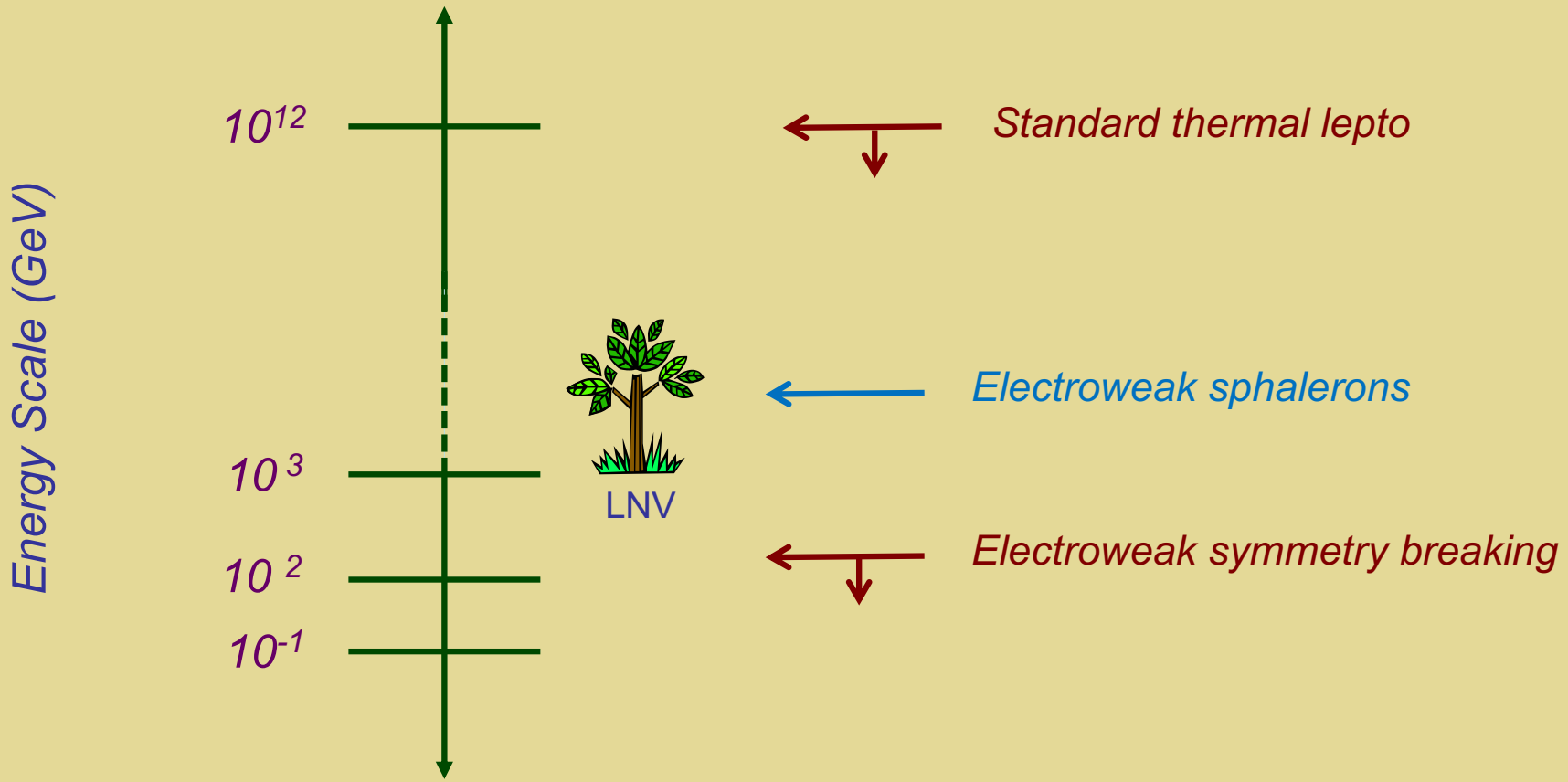
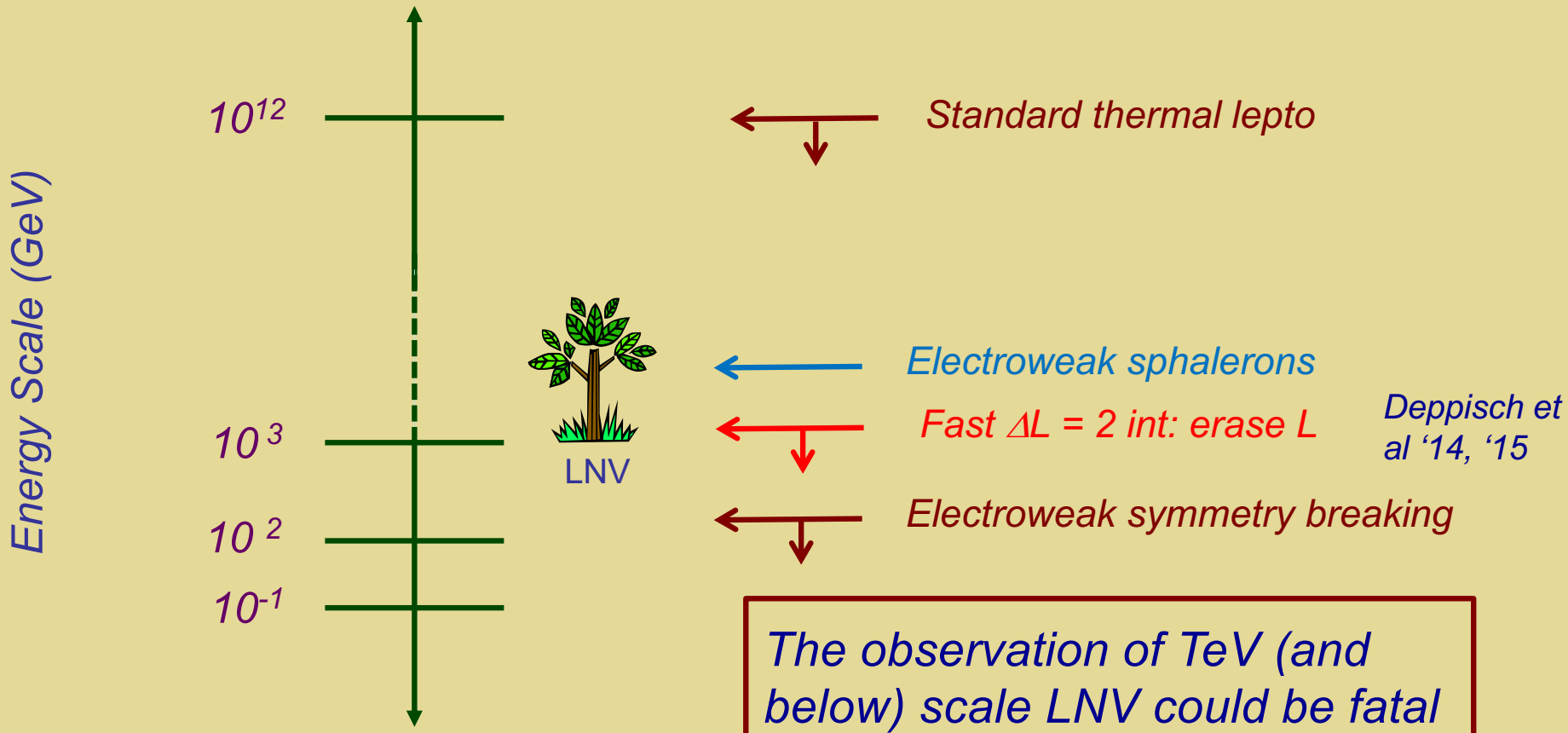
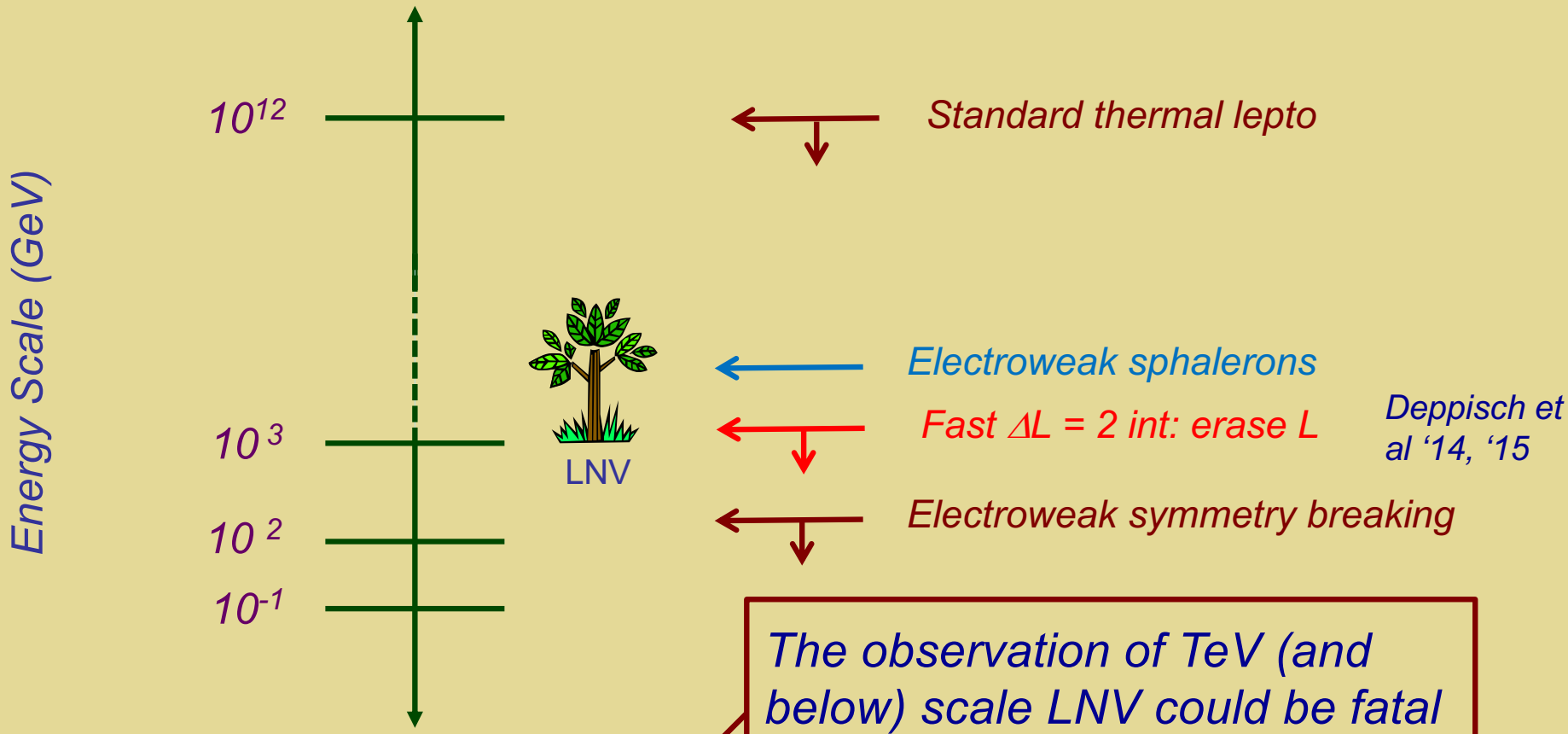


Low Scale LNV & Leptogenesis



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*

J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga 2106.10838

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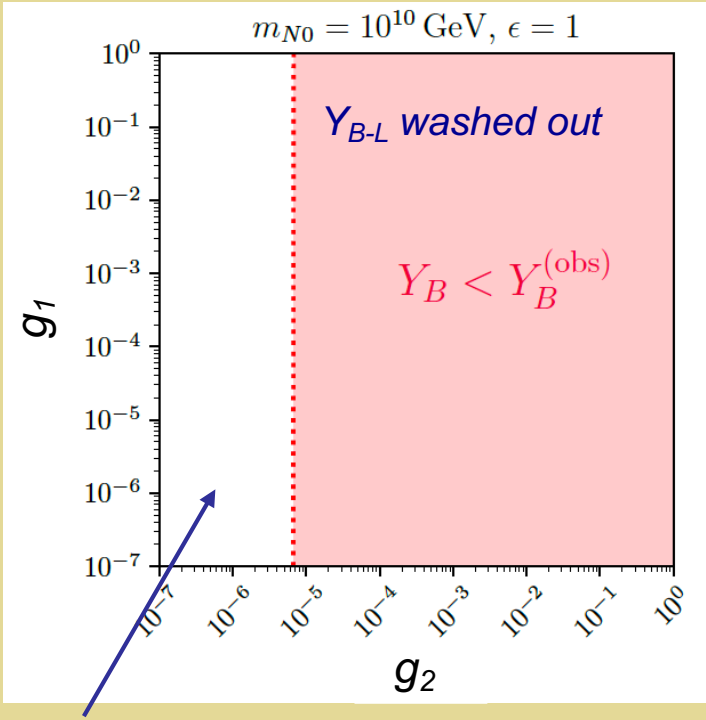

Y_{B-L} *survives*

J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga 2106.10838

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

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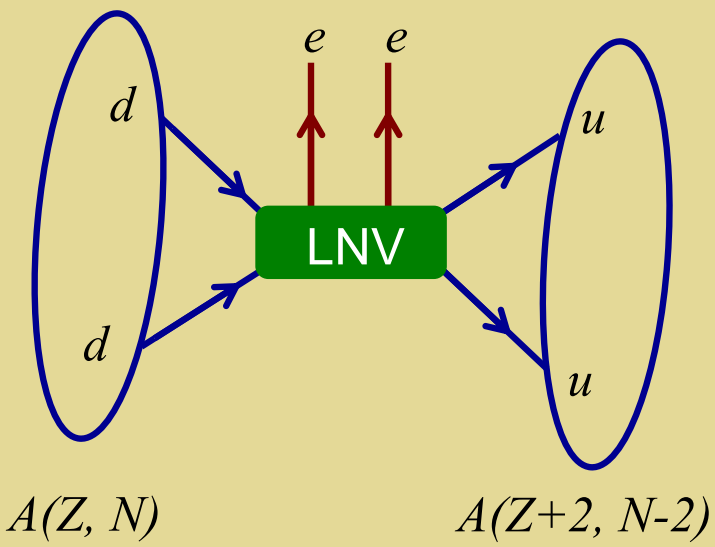
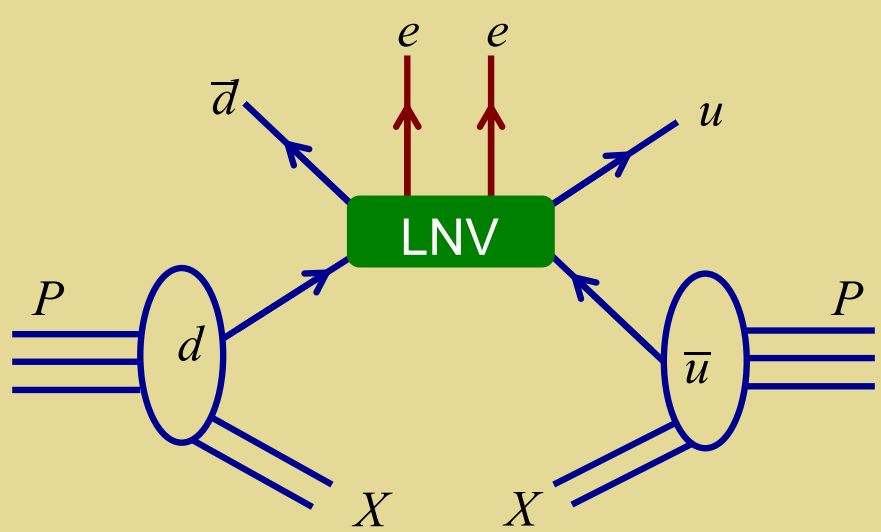
Majorana

$0\nu\beta\beta$-Decay



pp Collisions



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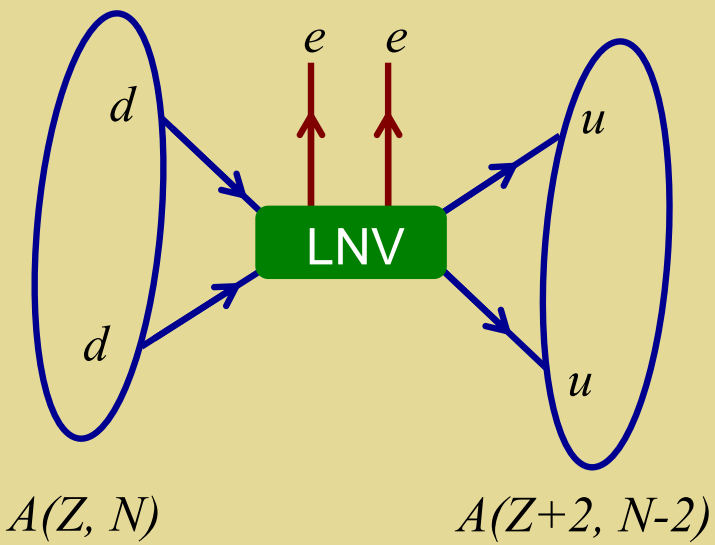
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}LHH^TL \;+\; {\rm h.c.}$$

Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



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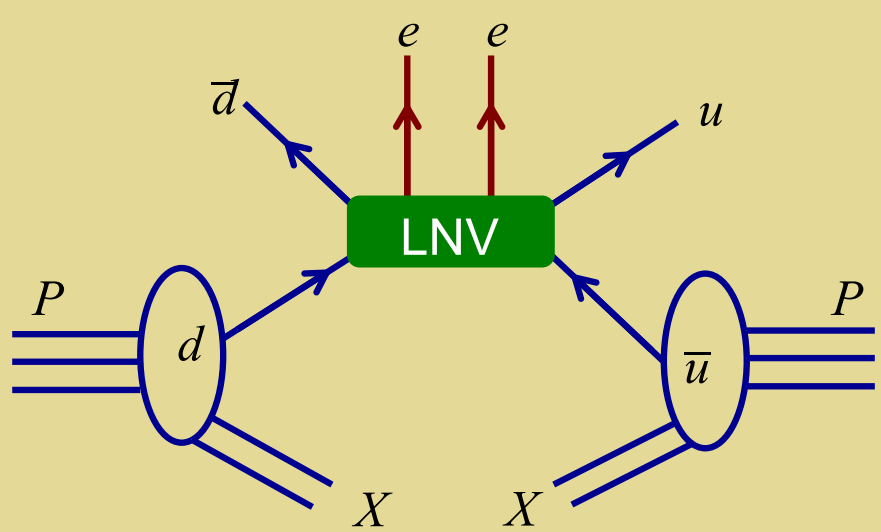

TeV-Scale LNV: lepto, $0\nu\beta\beta$-Decay & Colliders

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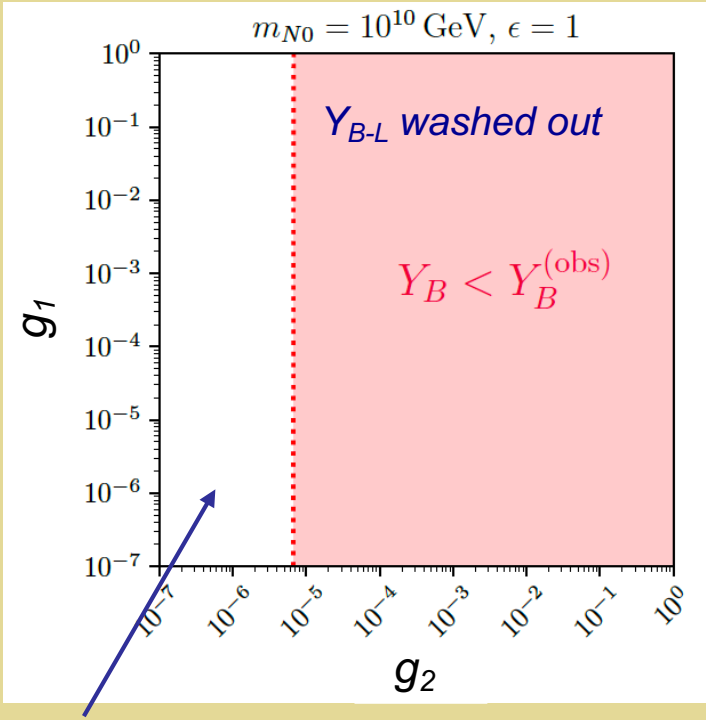
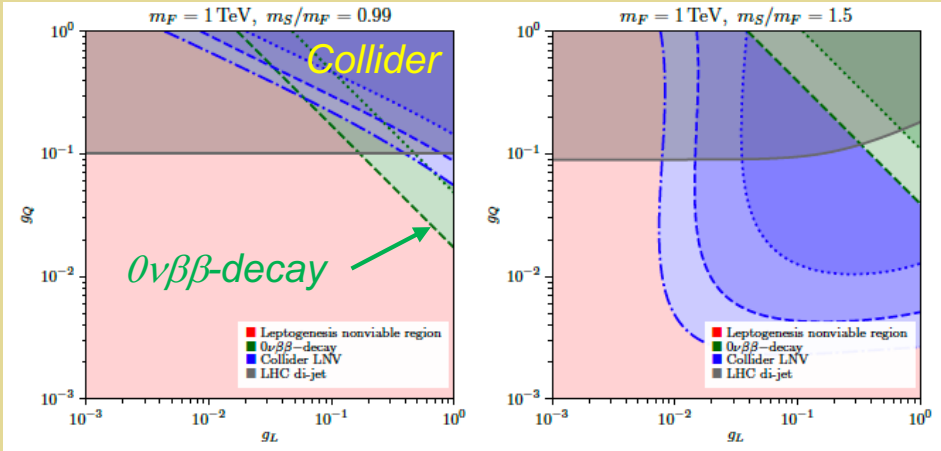




Comparing $0\nu\beta\beta$-decay, collider, & cosmo

Y_{B-L} survives

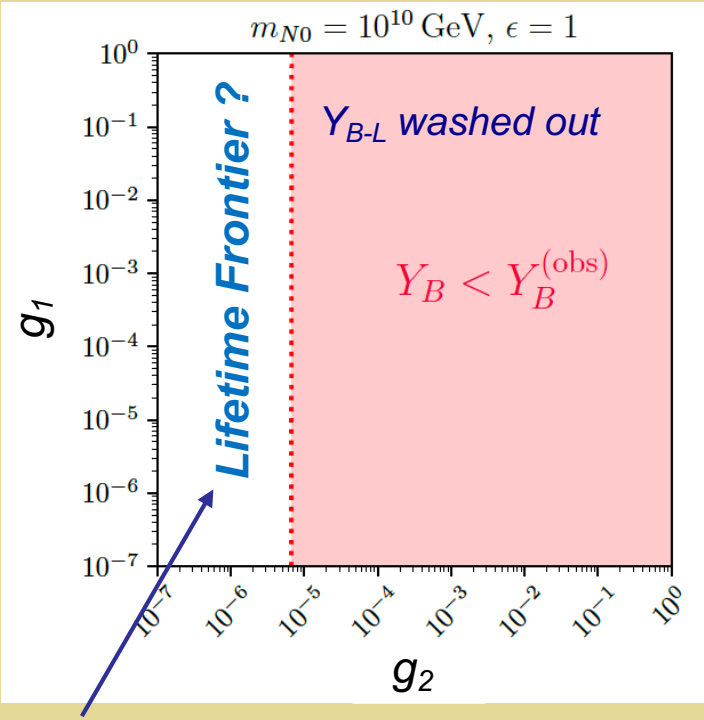
J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga 2106.10838

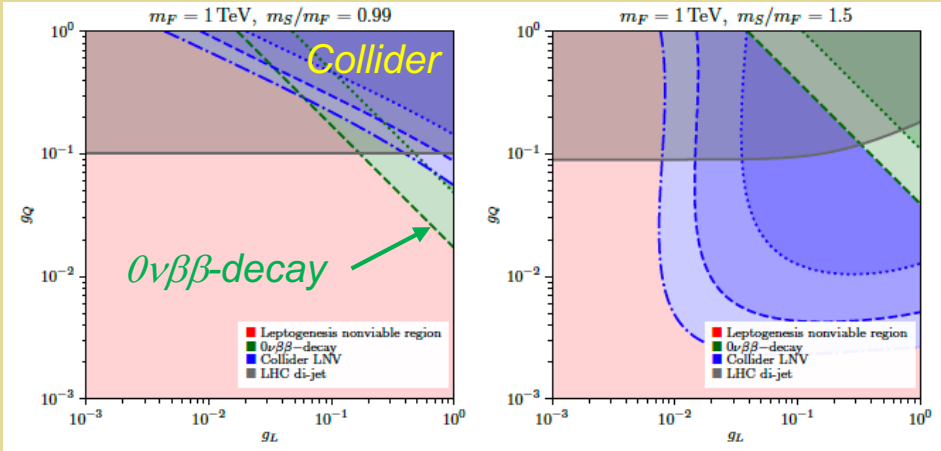
TeV-Scale LNV: lepto, $0\nu\beta\beta$-Decay & Colliders

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

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

S: (1, 2, ½)
F: (1, 0, 0) *Majorana*





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

Y_{B-L} survives

J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga 2106.10838

III. BSM LNV: Precision Tests & Colliders

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?*

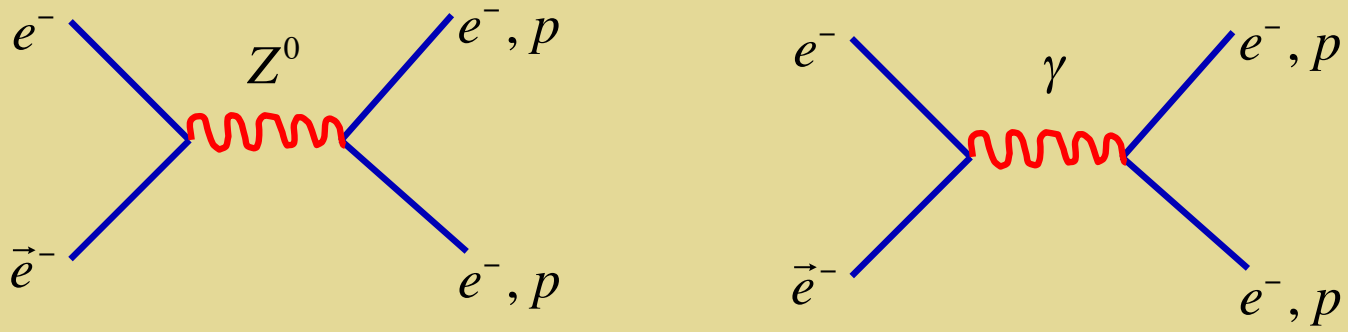
Origin of m_ν

Cosmology:
- ***BAU***
- ***Σm_ν***
- ***Grav waves***

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

Colliders

Parity-Violation & Weak Charges



Parity-Violating electron scattering

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

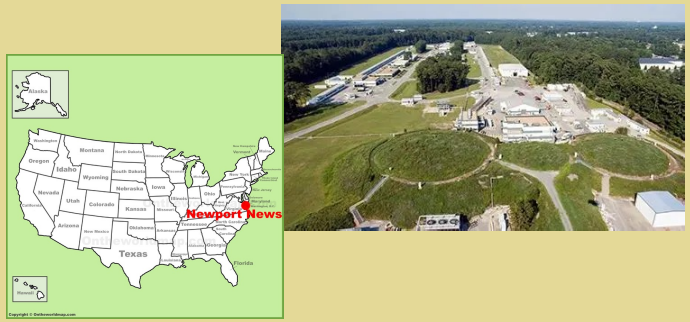
Atomic parity-violation

$$E_1^{PV} / \beta = i\, e\, \mathcal{M} \times 10^{-11}\, a_0\, (Q_W / N) / \beta$$

MOLLER Exp't at Jefferson Lab

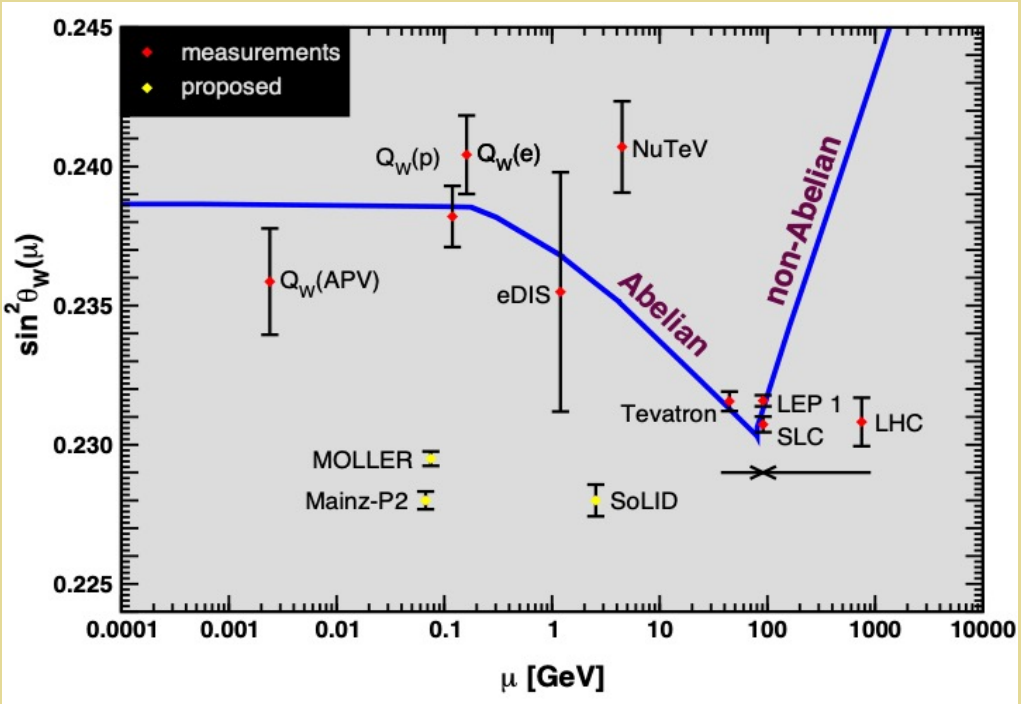
11 GeV, 65 μA 90% beam polarization

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb



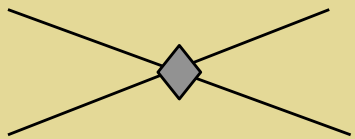
$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$ ⇒ ~ 0.1%



Search for new flavor diagonal neutral currents

A_{new}



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

MOLLER Reach

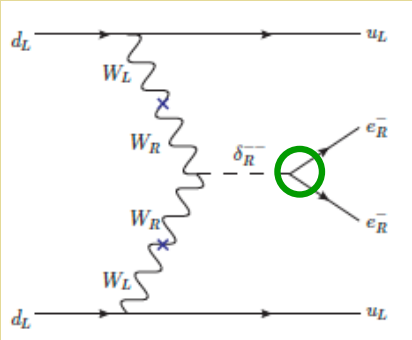
$$\Lambda^{ee}_{RR-LL} \sim 38\ \text{TeV}$$

Look for tiny but measurable deviations from precisely calculable prediction for SM processes

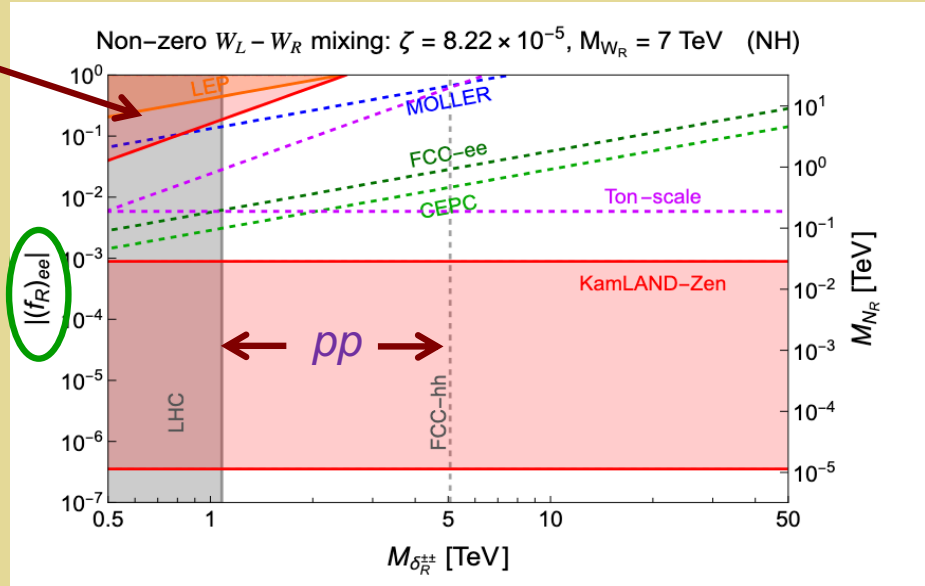
Thanks: K. Kumar

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; Dev, R-M, Zhang 1806.08499

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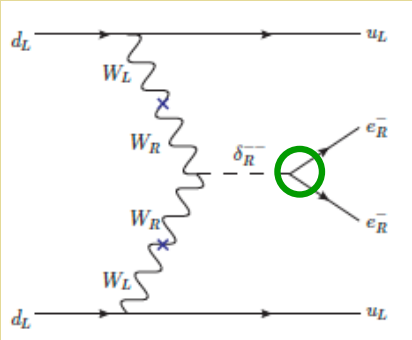

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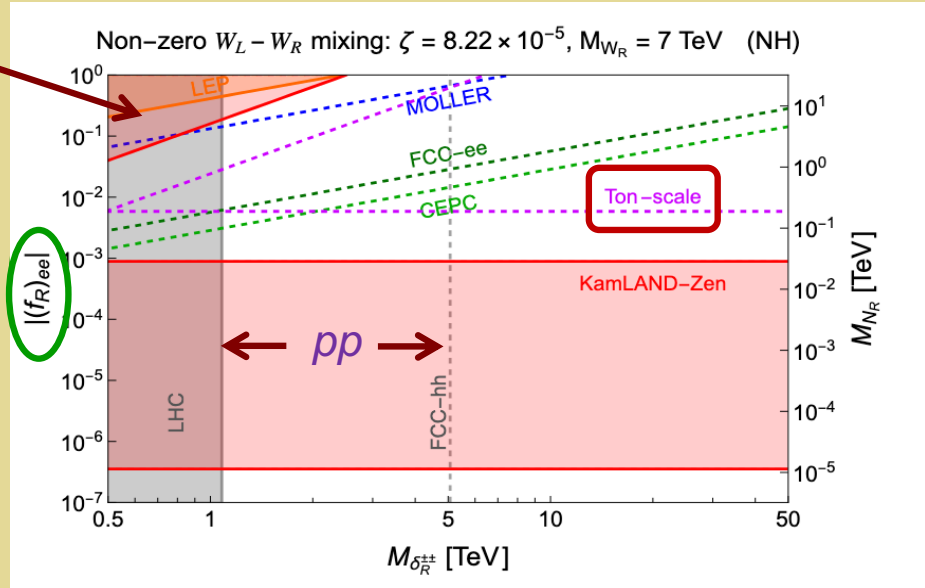

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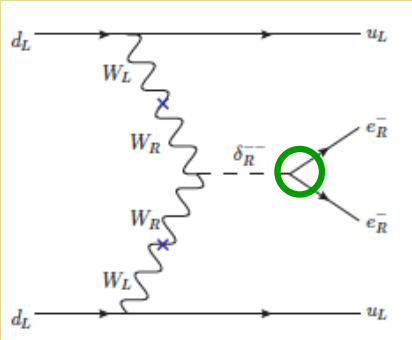

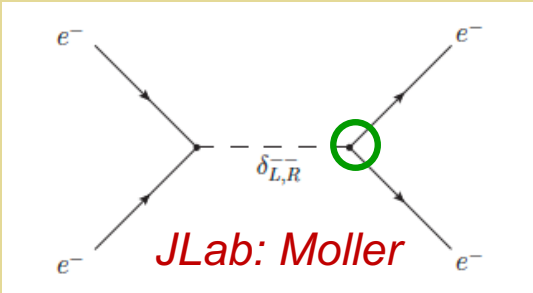

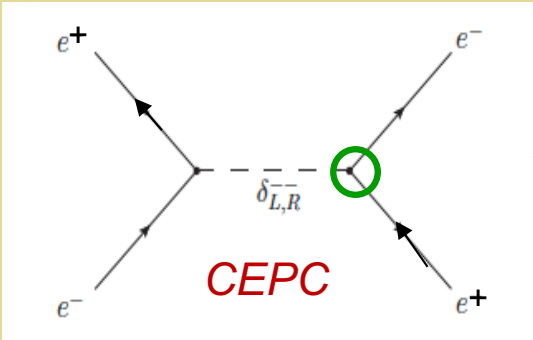

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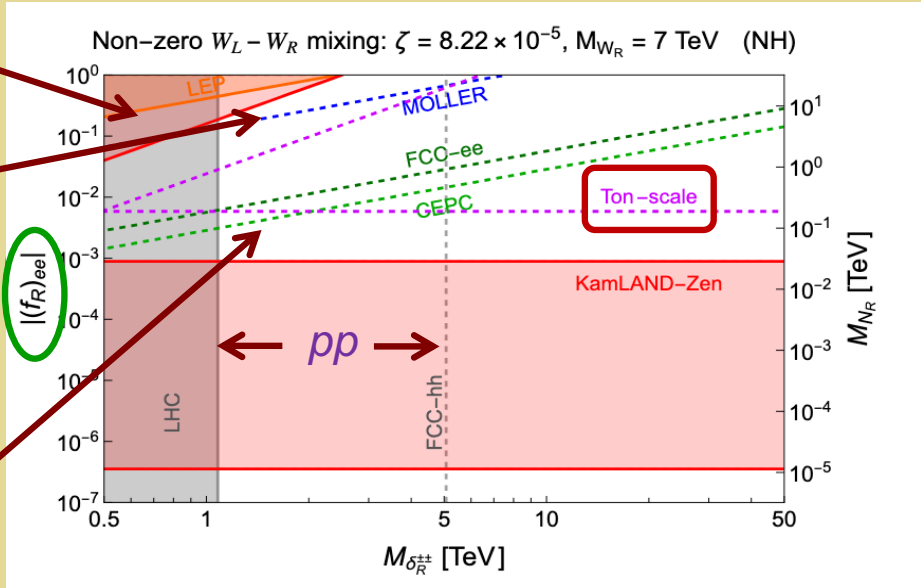


G. Li, MJRM, S. Urrutia-Quiroga, J.C. Vasquez 2408.06306; Dev, R-M, Zhang 1806.08499

IV. Outlook

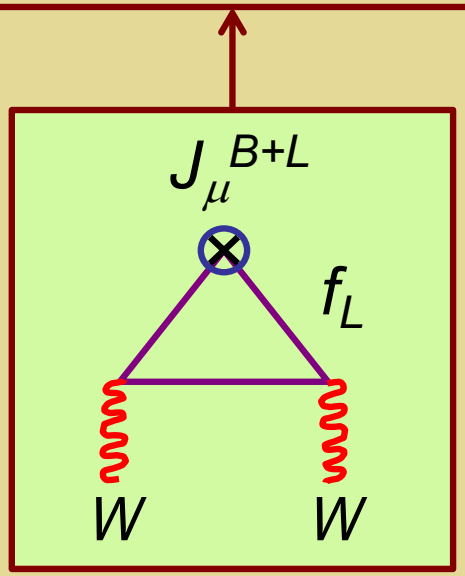
- ***The discovery of beyond Standard Model lepton number violation could hold the key to explaining the origin of neutrino mass***
- ***The BSM LNV mass scale is unknown and could lie anywhere from the sub-eV scale to the conventional seesaw scale***
- ***While the search for $0\nu\beta\beta$-decay 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

SM: B+L Not Conserved

B+L Anomaly

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



SM B+L Violation & Sphalerons

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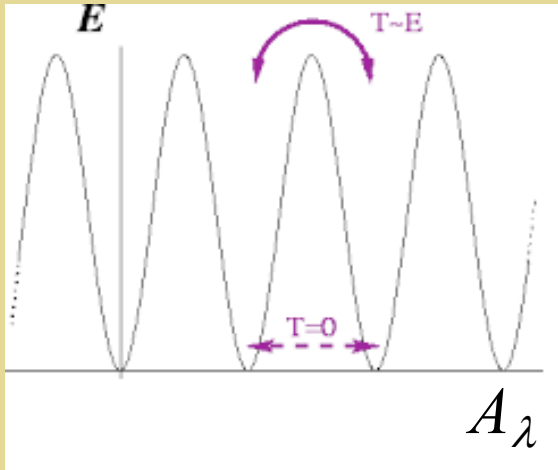

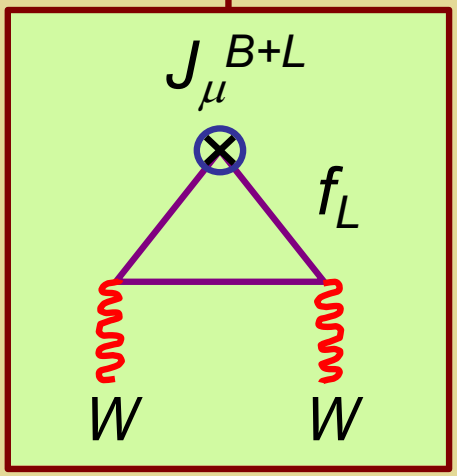

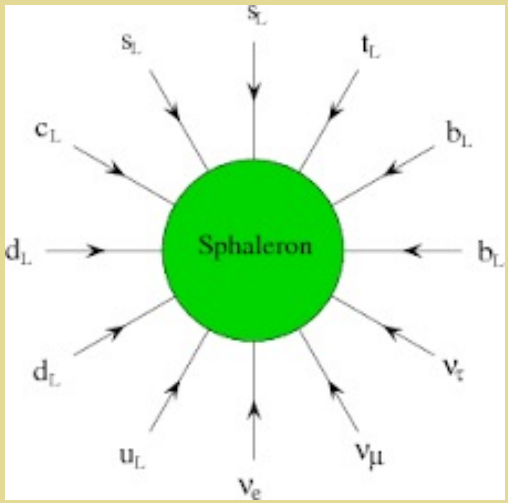

Sphaleron Configuration → Anomaly → Δ (B+L) $\propto N_F$

SM B+L Violation & Sphalerons

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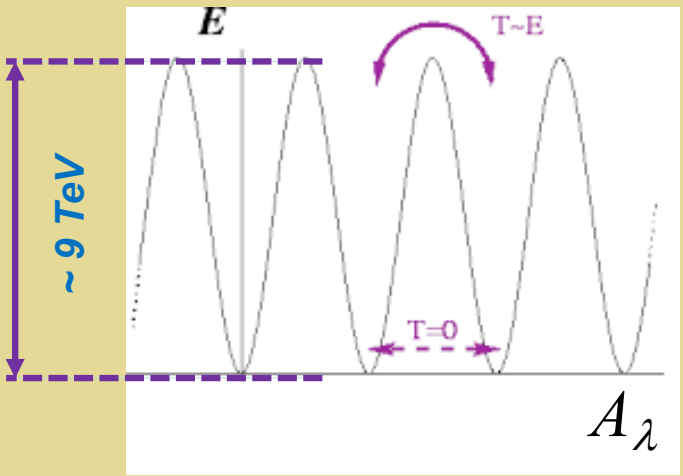
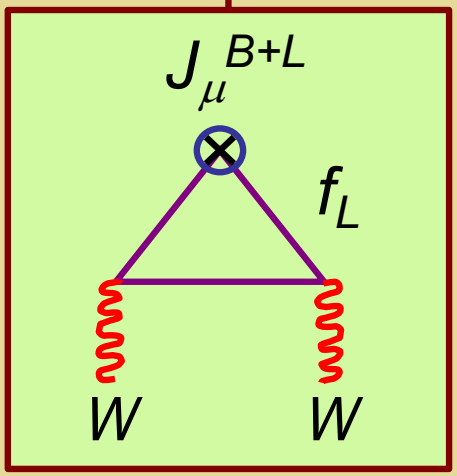
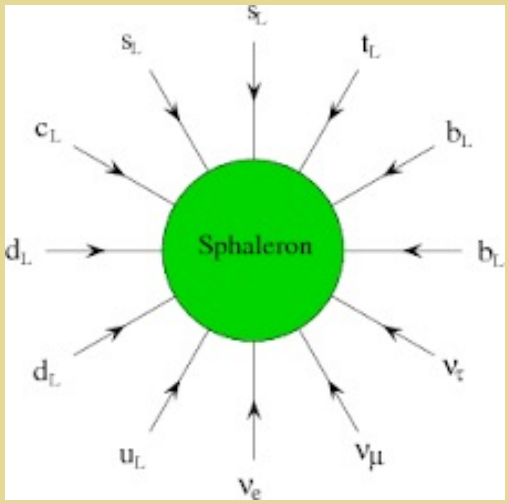


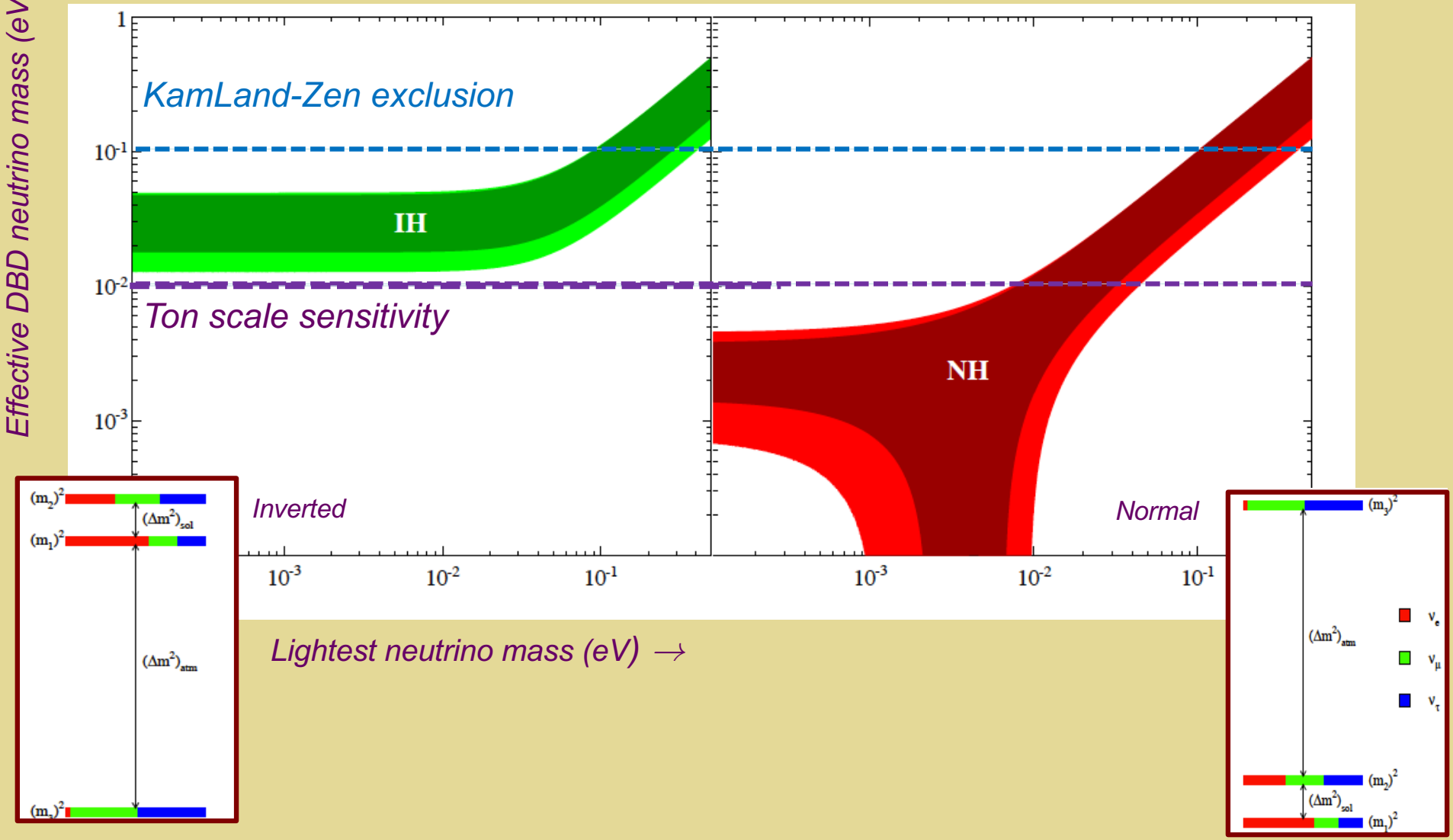




Sphaleron Configuration → Anomaly → Δ (B+L) $\propto N_F$

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

Three active light neutrinos



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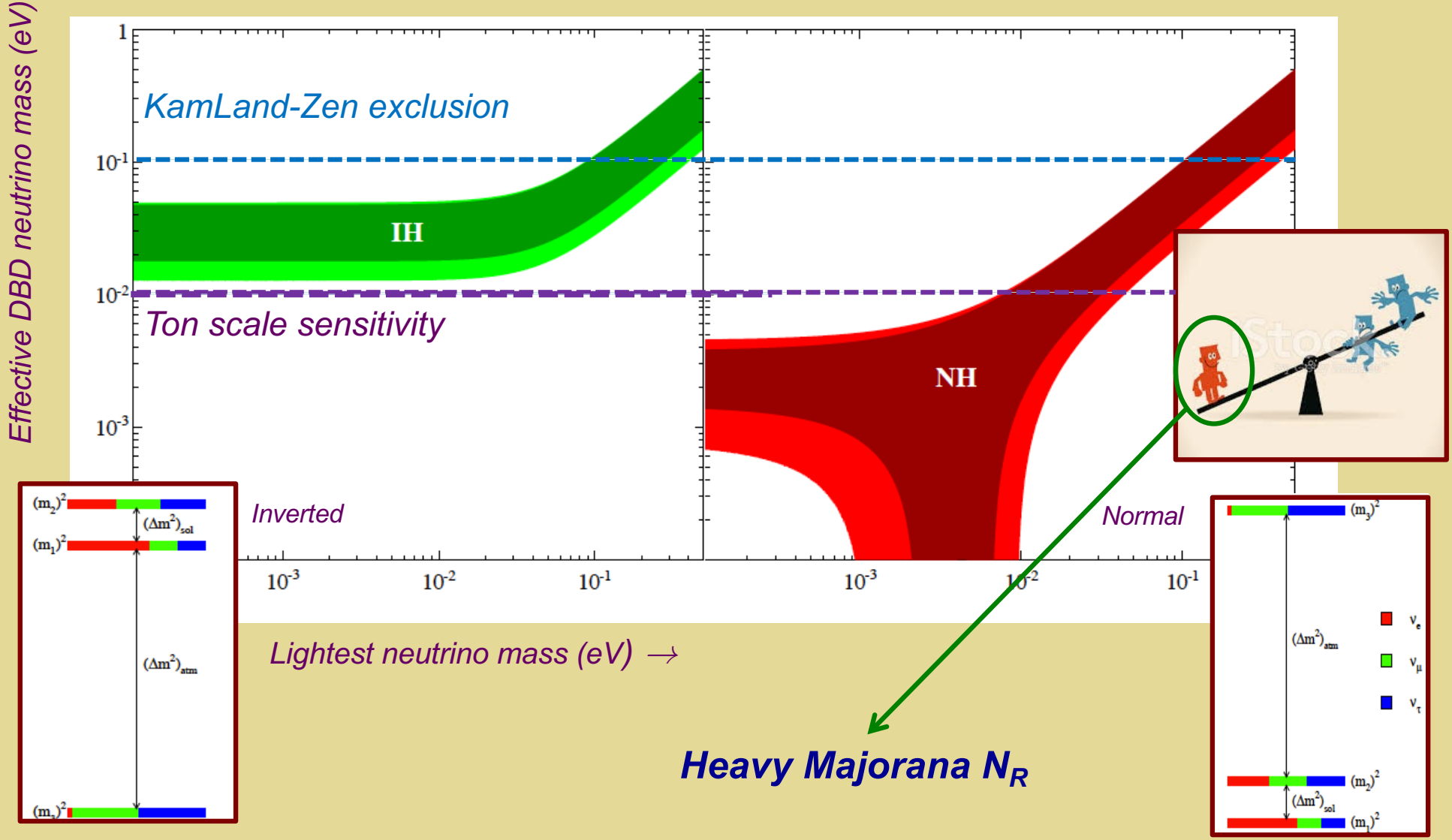
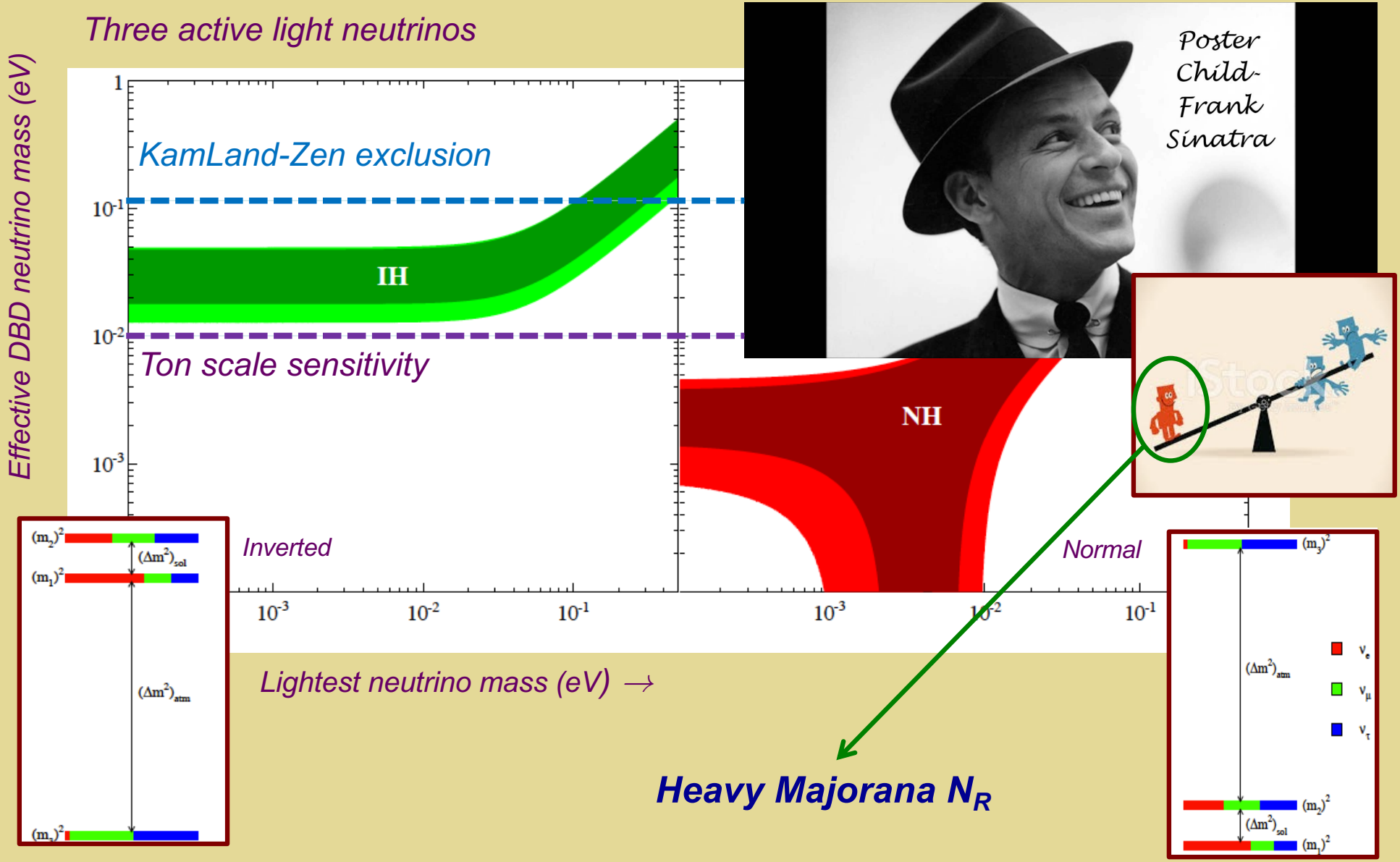


Heavy Majorana N_R

$0\nu\beta\beta$-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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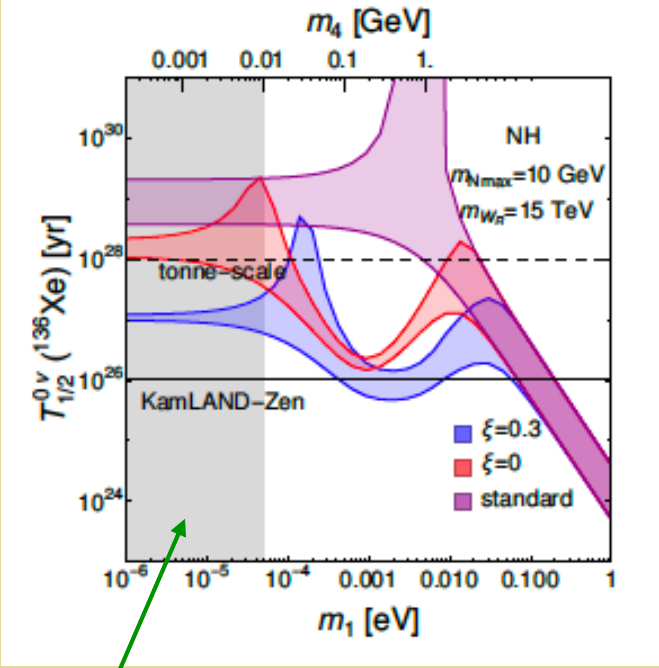
More Than 3 Light Neutrinos: MeV-GeV

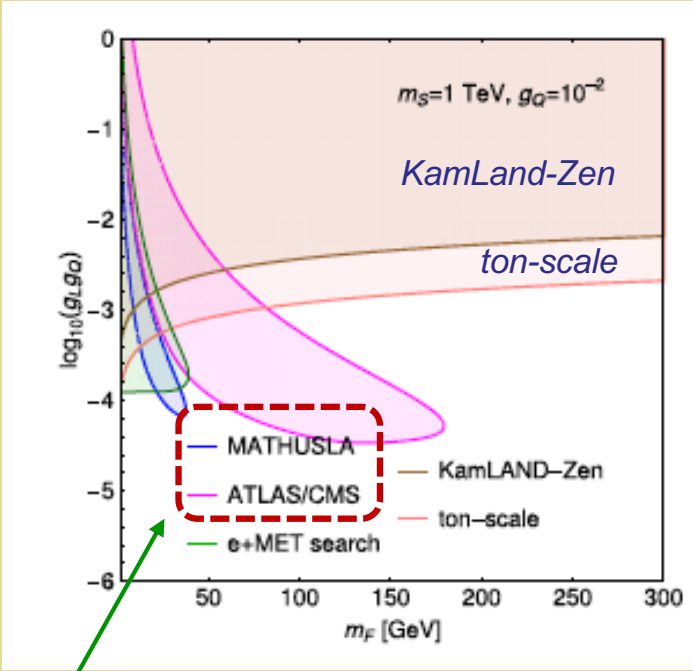
mLRSM



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

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

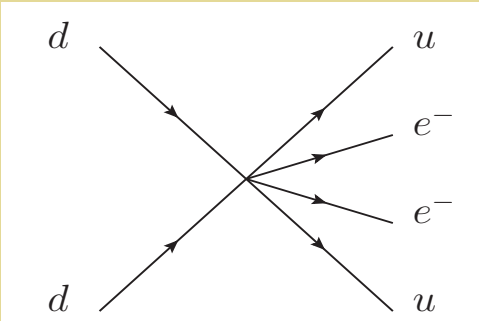
Dirac

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

Majorana

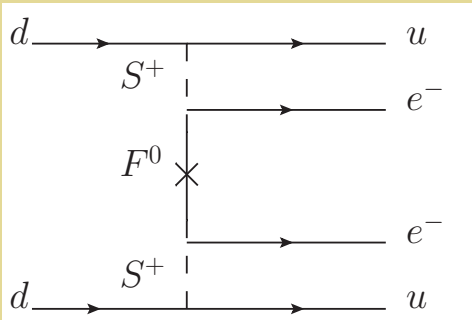
TeV Scale LNV

$0\nu\beta\beta$ - decay



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

LHC: pp → jj e^-e^-



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

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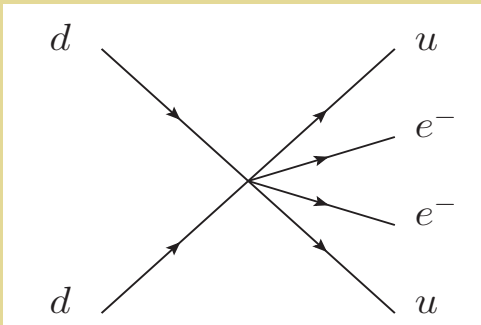
Majorana

EFT "Bridge"

$0\nu\beta\beta$ - decay



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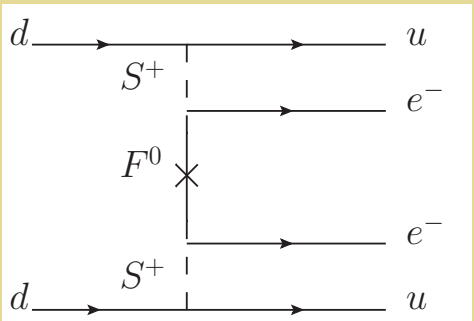


TeV Scale LNV

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.

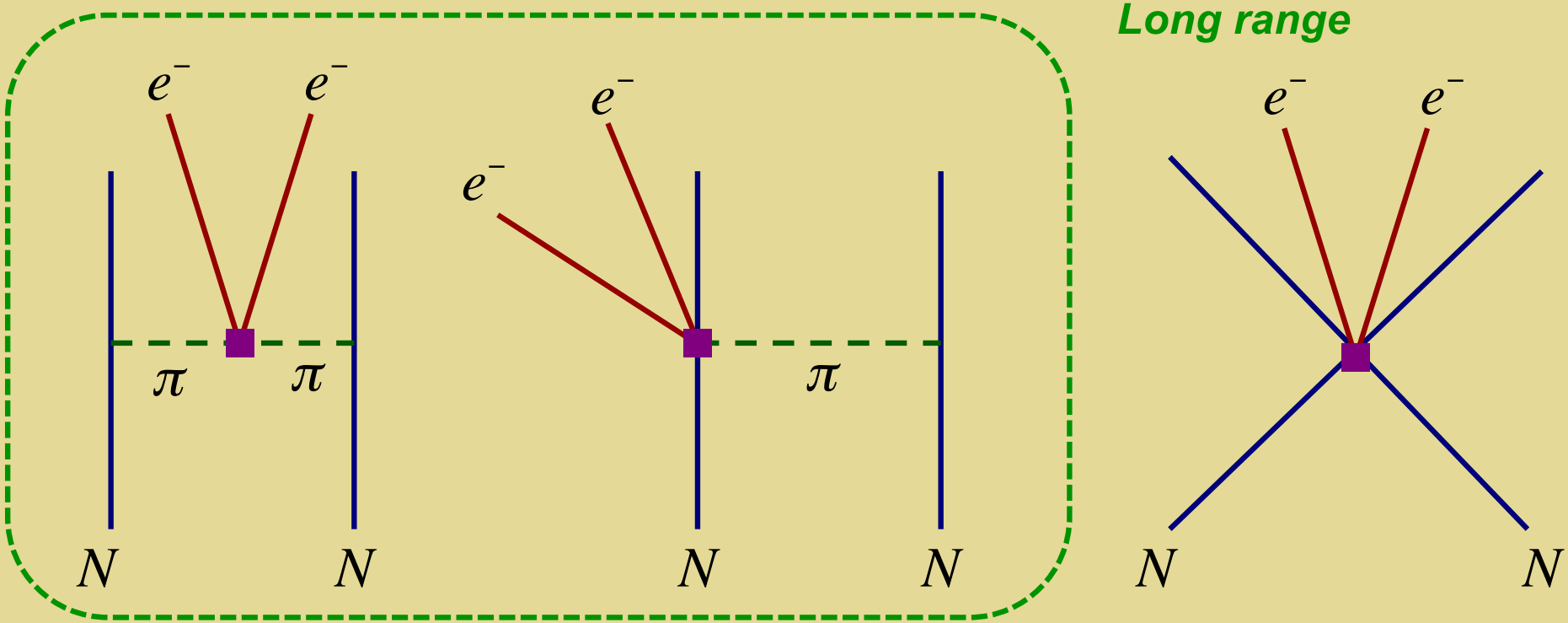
$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L\ \bar{q}_R \gamma_\mu \tau^b q_R$$

$0\nu\ \beta\beta$ - 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



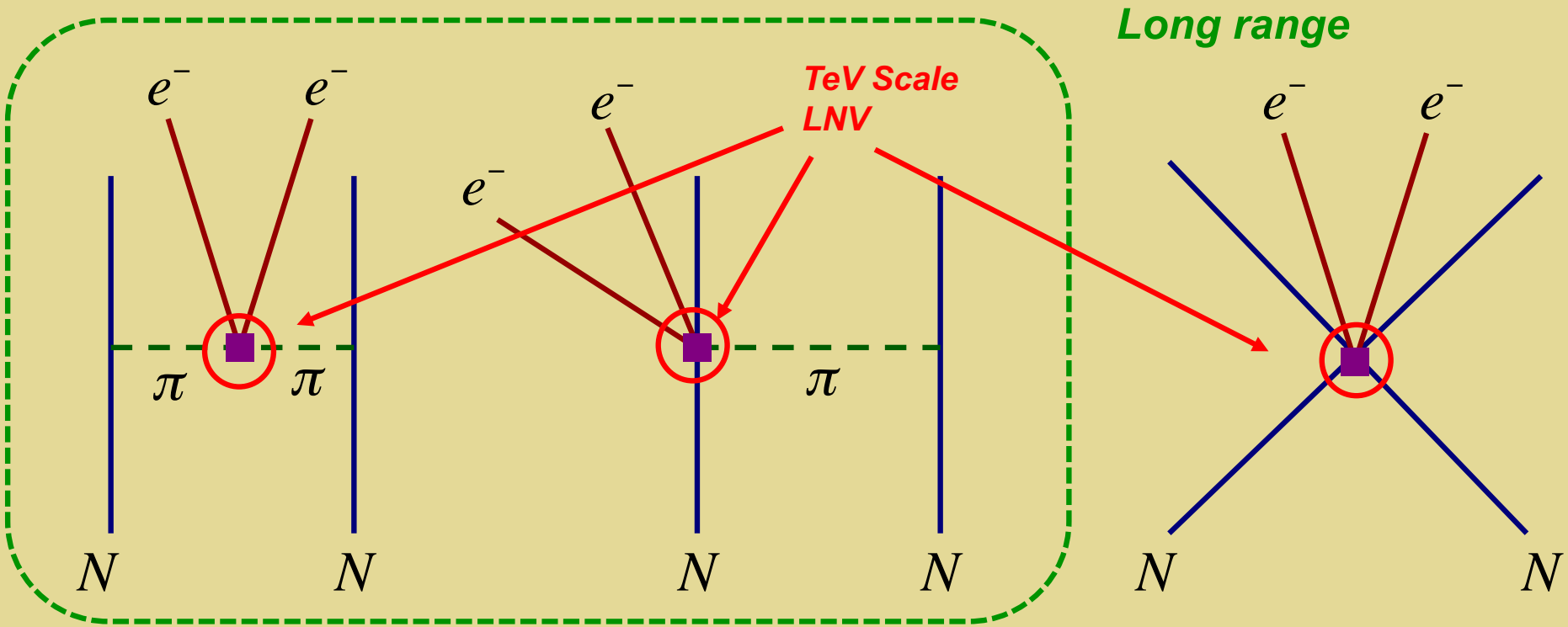
$K_{\pi\pi}\ p^{-2}$

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

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

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

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



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

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

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

Operator classification

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

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 → LEC's

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

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

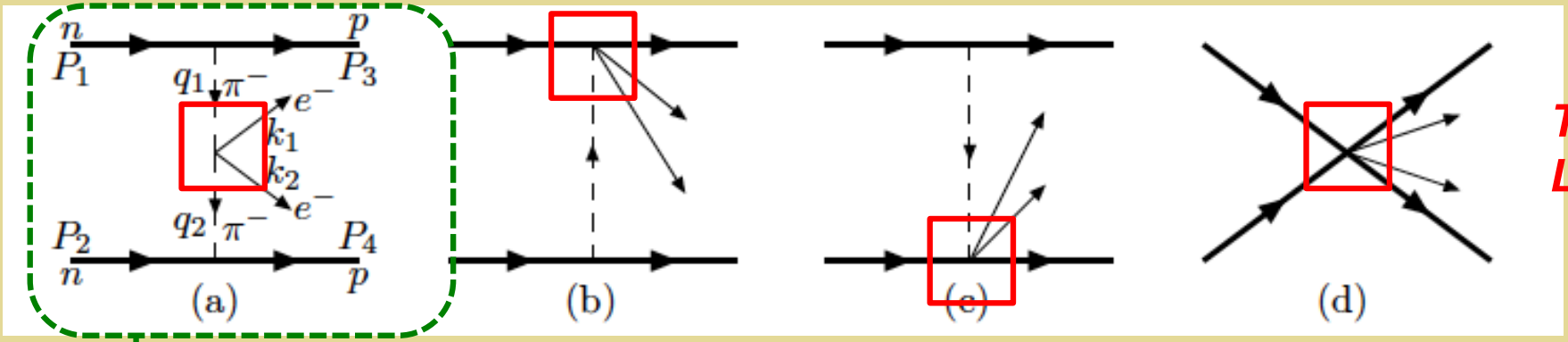
Dirac

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

Majorana

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

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



TeV LNV

Exploit Chiral Symmetry & EFT ideas

Following example:
LO + counterterm