$0\nu\beta\beta$ – Decay: Inter-frontier Implications

M.J. Ramsey-Musolf

- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst*
- *Caltech*

About MJRM:

Science

Family

Friends

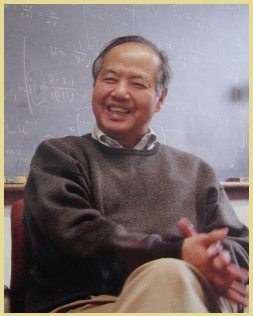
My pronouns: he/him/his
 # MeToo

DBD Workshop, Hawaii
December 2, 2023

Thanks !

- ***Alan Poon & DBD 23 Workshop organizers***
- ***Osaka University for making my participation possible***
- ***Emi Matsuda***
- ***Darrel Ramsey-Musolf***

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world famous source of original innovation

Founded 2016

Theory & Experiment

- Particle & Nuclear Physics
- Astronomy & Astrophysics
- Quantum Science
- Dark Matter & Neutrino
- Laboratory Astrophysics
- Topological Quantum Computation

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

https://tdli.sjtu.edu.cn/EN/

Goals for This Talk

- ***Encourage the community to adopt a broader framing for the scientific significance of the $0\nu\beta\beta$ decay "campaign"***

- ***Highlight the $0\nu\beta\beta$ decay inter-frontier connections***

Outline

I. Scientific Motivation

II. Inter-frontier Connections

III. High-scale LNV

IV. TeV-Scale LNV

V. GeV and Below-Scale LNV

VI. Conclusions

Time permitting

I. Scientific Motivation

Why pursue $0\nu\beta\beta$ - decay ?

- ***The conventional question:***

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

Why pursue $0\nu\beta\beta$ - decay ?

- ***The conventional question:***

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

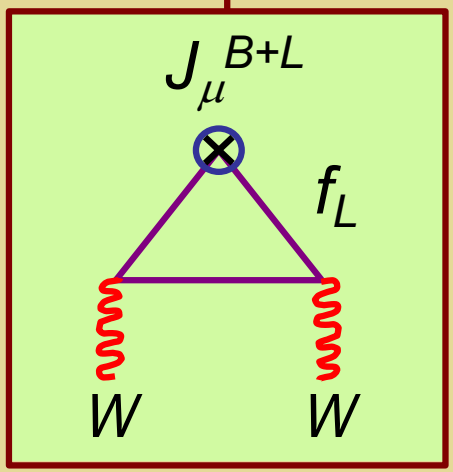
- ***The deeper questions:***

  - ***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

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



SM B+L Violation & Sphalerons

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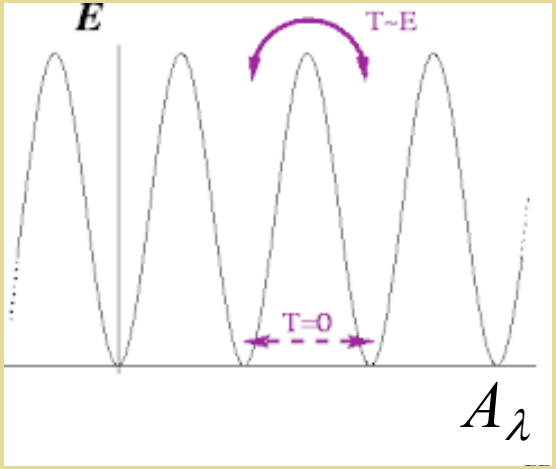

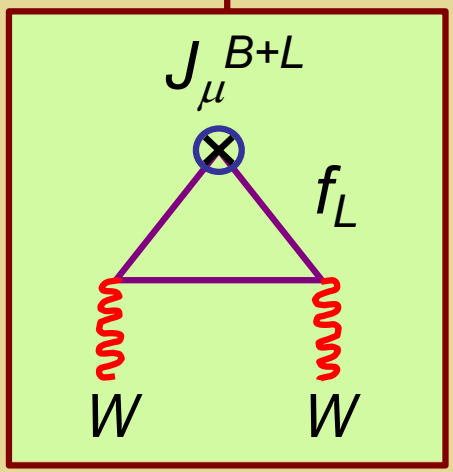

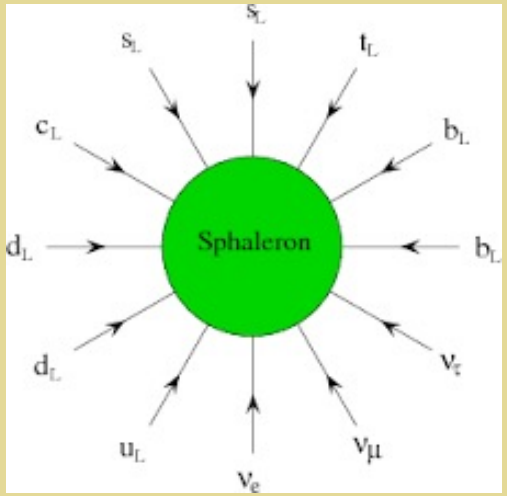

Sphaleron Configuration → Anomaly → $\Delta (B+L) \propto N_F$

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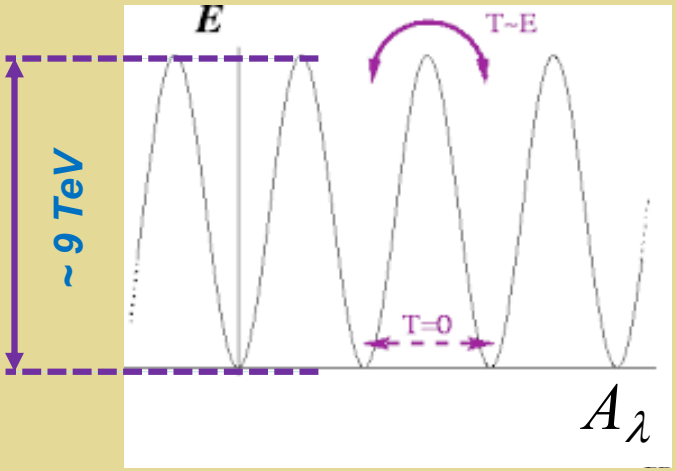

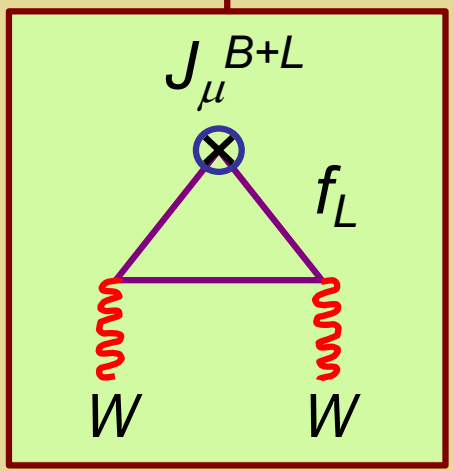

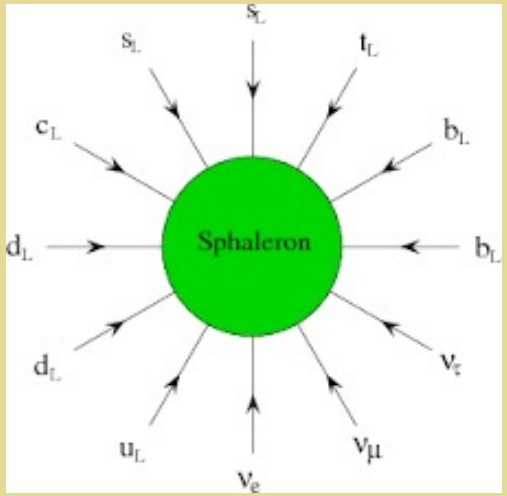

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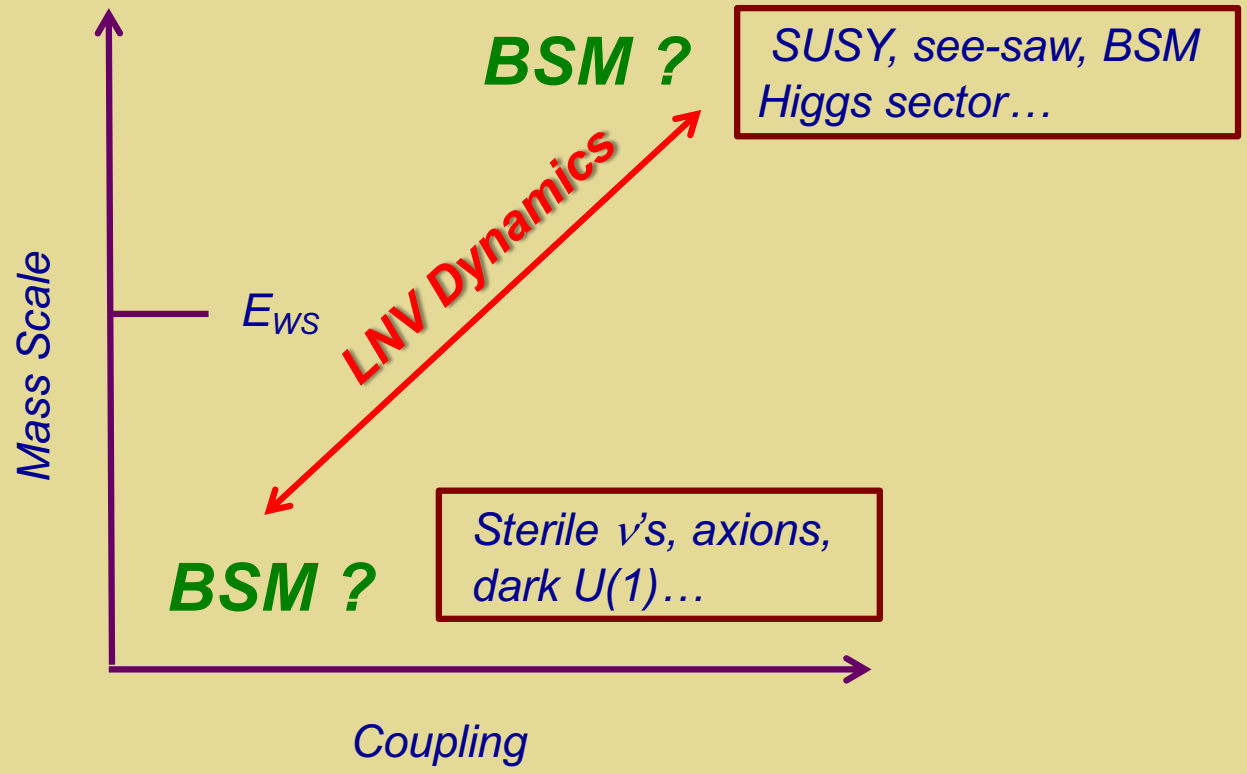
Lepton Number Violation

- *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***

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

Colliders

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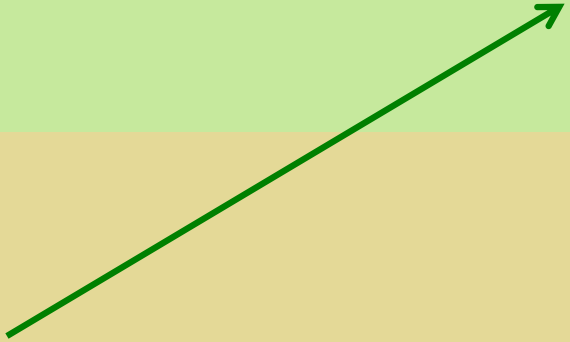
Lepton Number: ν Mass Term?

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

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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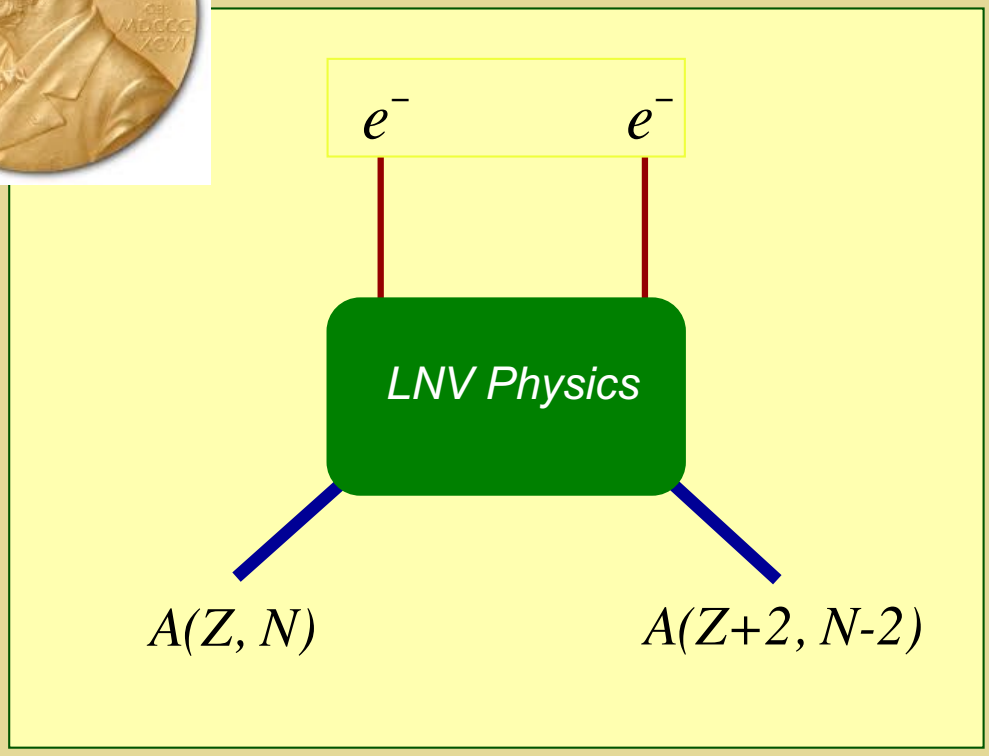
Impact of observation

- *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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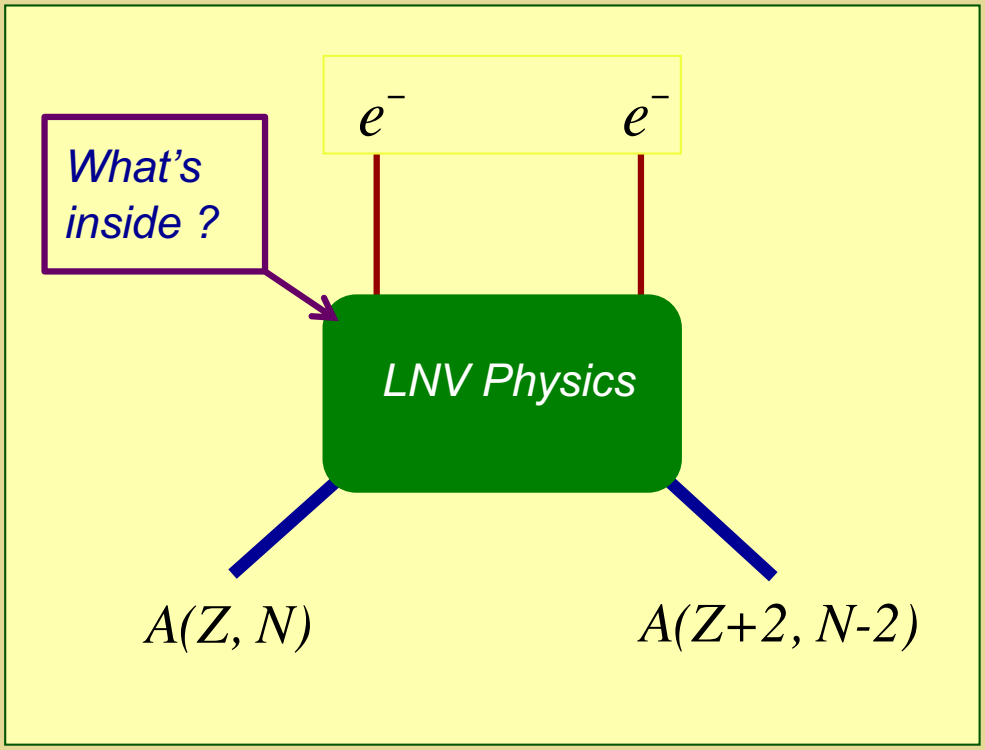

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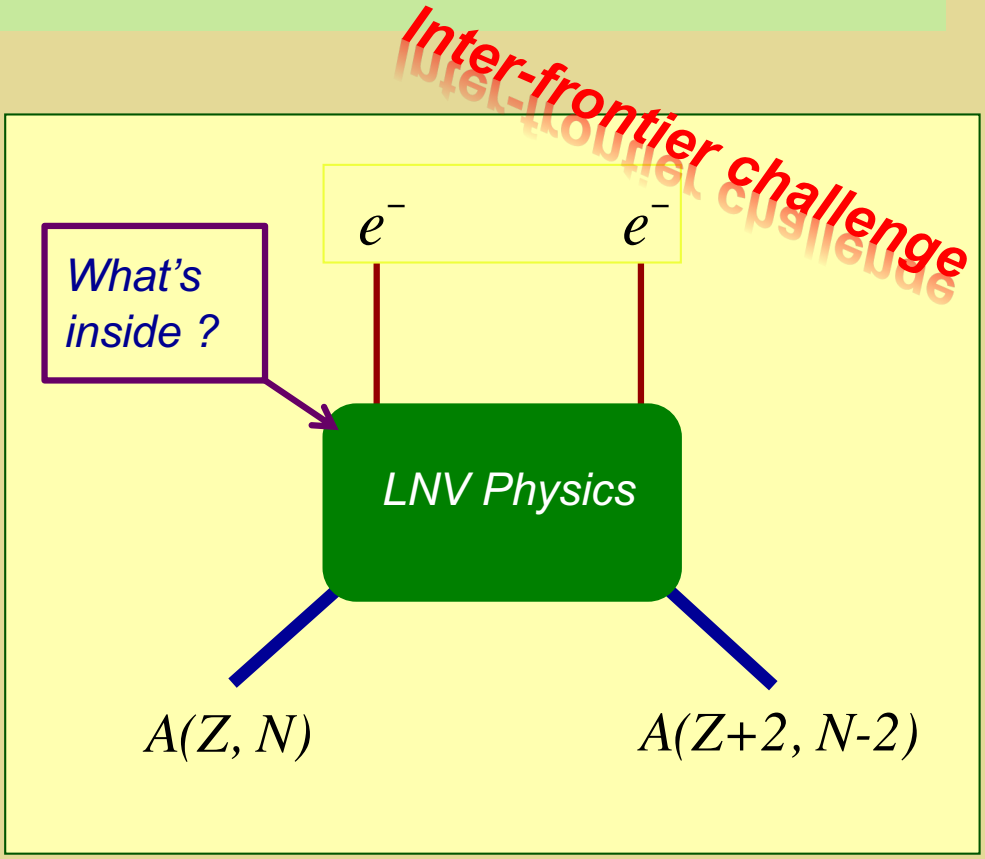
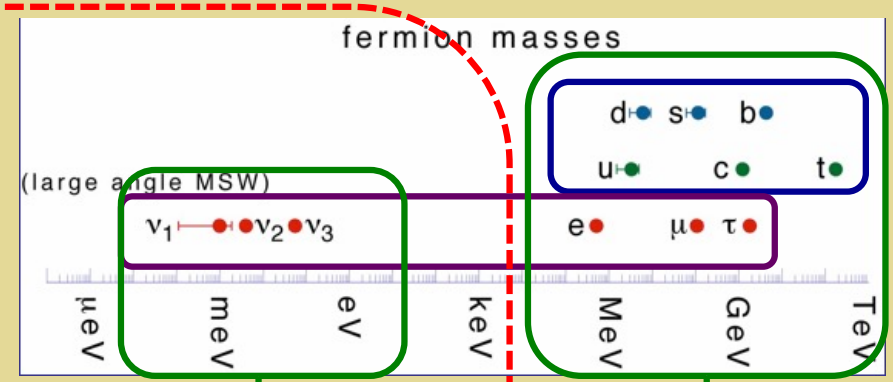


II. Inter-frontier Connections

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

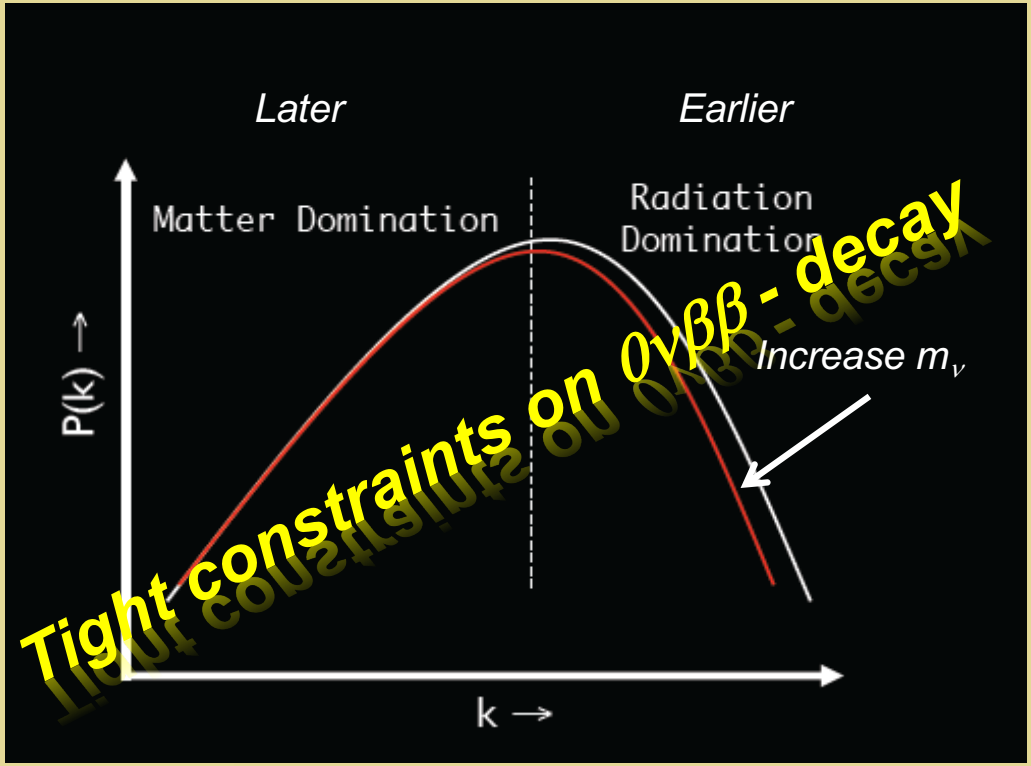
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

***0νββ* Decay**

Neutrino Mass & Cosmology

Matter Power Spectrum



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

Palanque-Dalabrouille '15

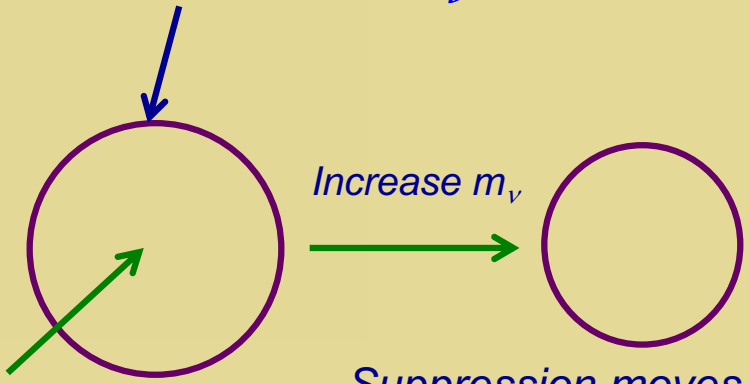
Neutrino Free Streaming

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

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

Free Streaming Scale

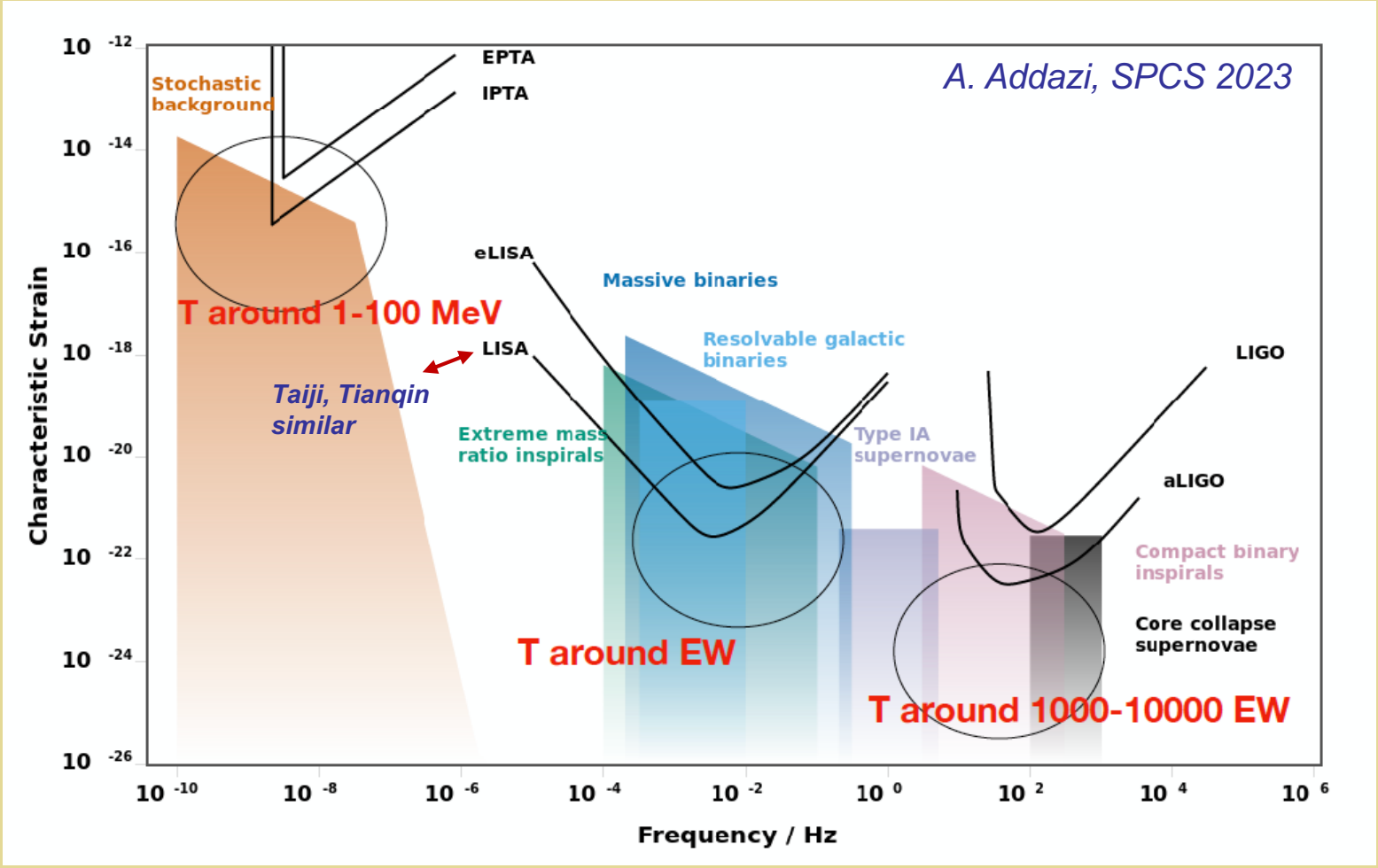
$$L_{\rm fs} \propto m_\nu^{-1/2}$$



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

Suppression moves to smaller scales → Larger k

Gravitational Waves



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

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

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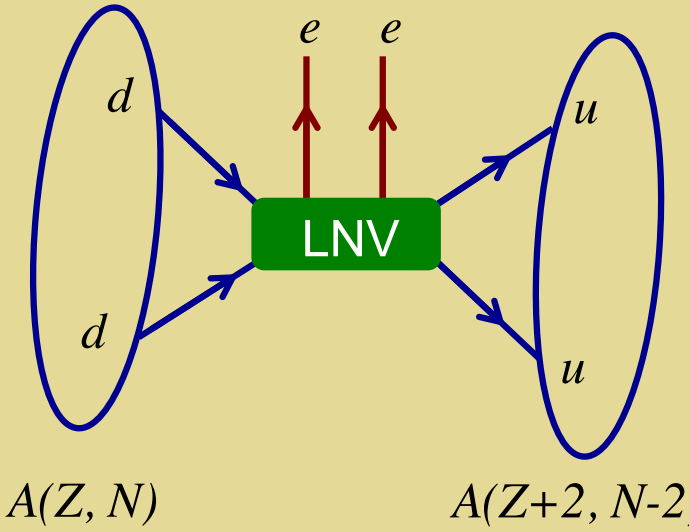
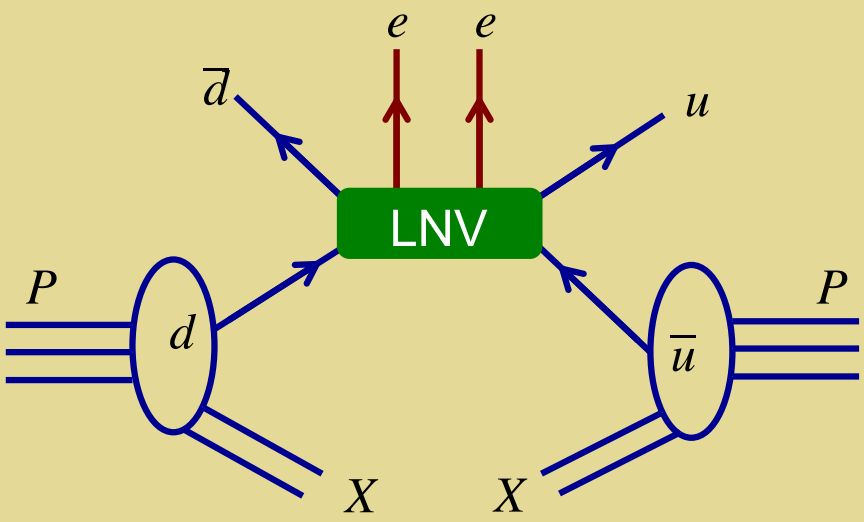
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



Nuc Phys: $0\nu\beta\beta$-Decay & LNV Mass Scale

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

III. High-Scale LNV

The "Standard Mechanism"

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

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

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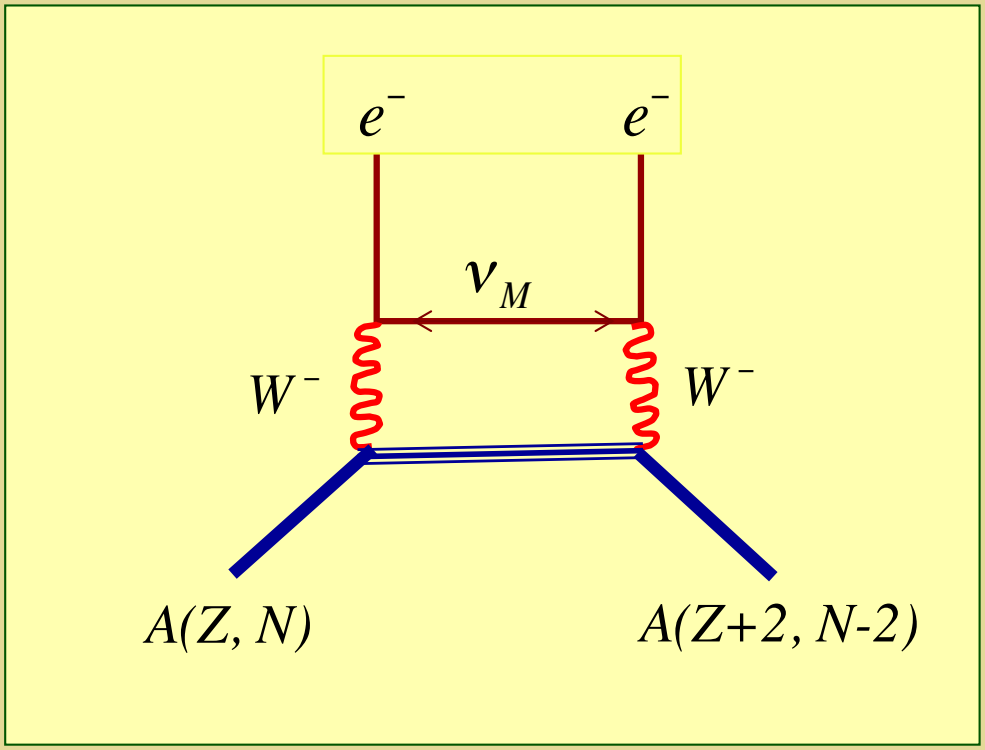
Majorana

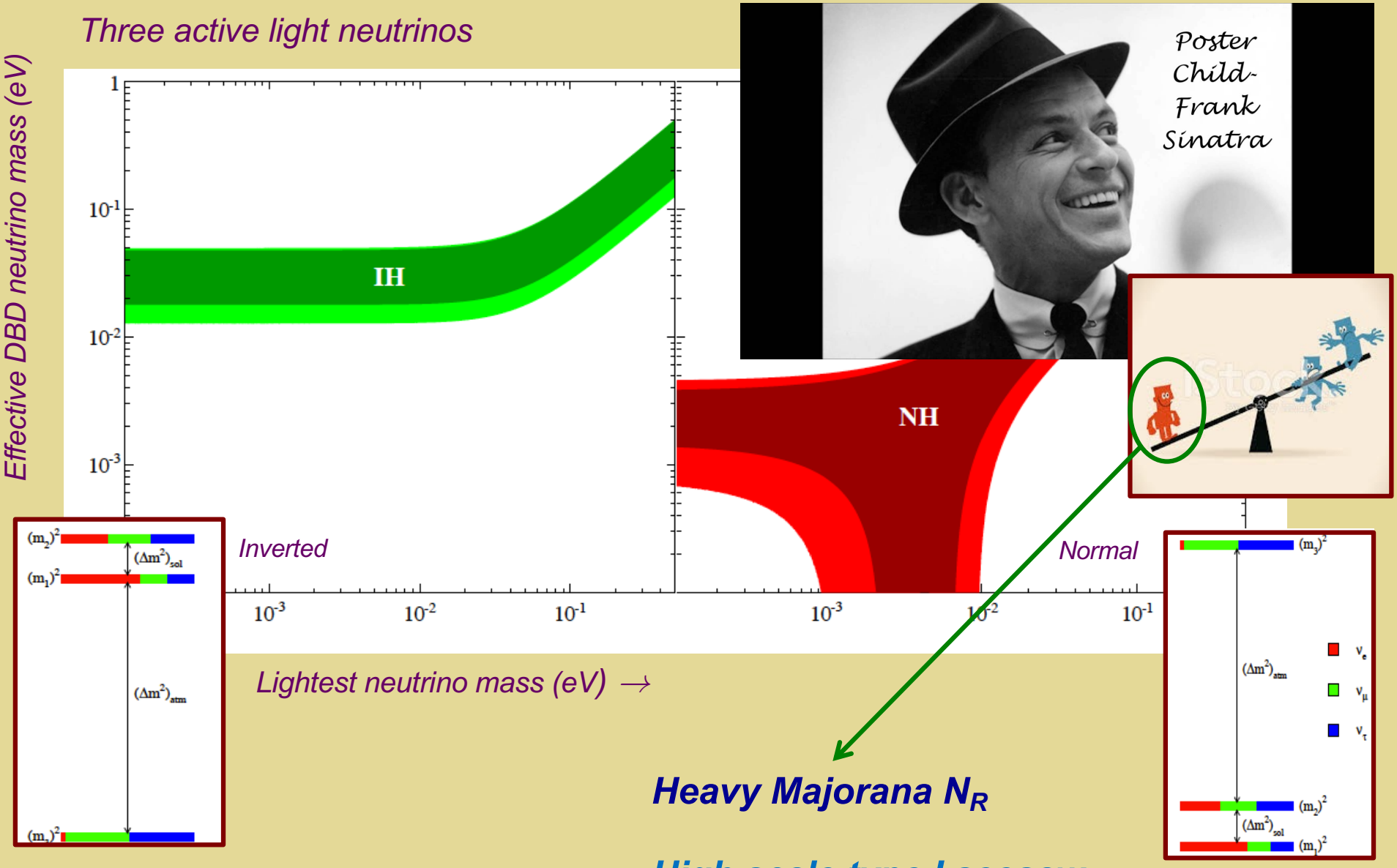
"Standard" Mechanism

- *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: "Poster Child" Mechanism

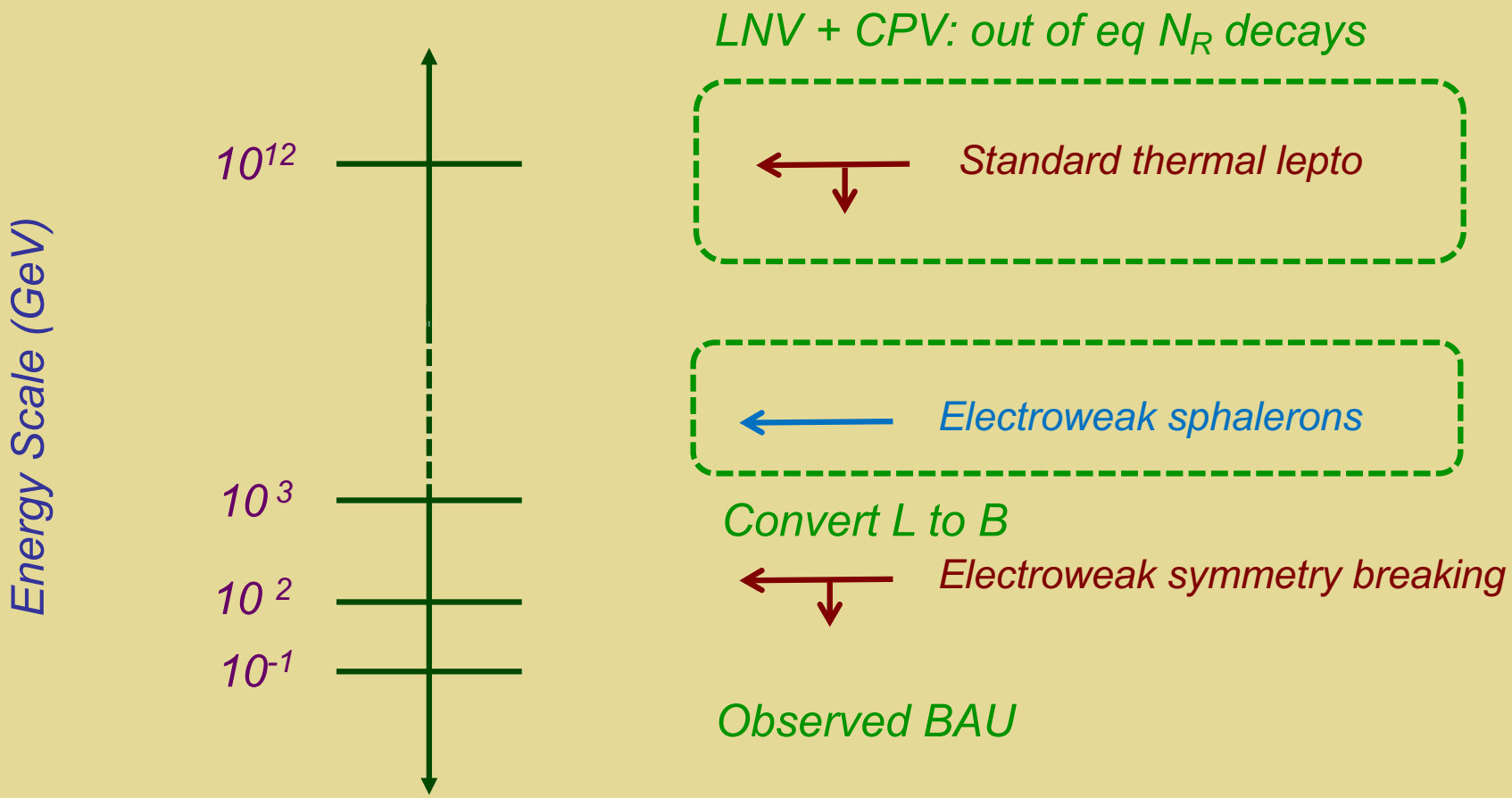
Three active light neutrinos



Heavy Majorana N_R

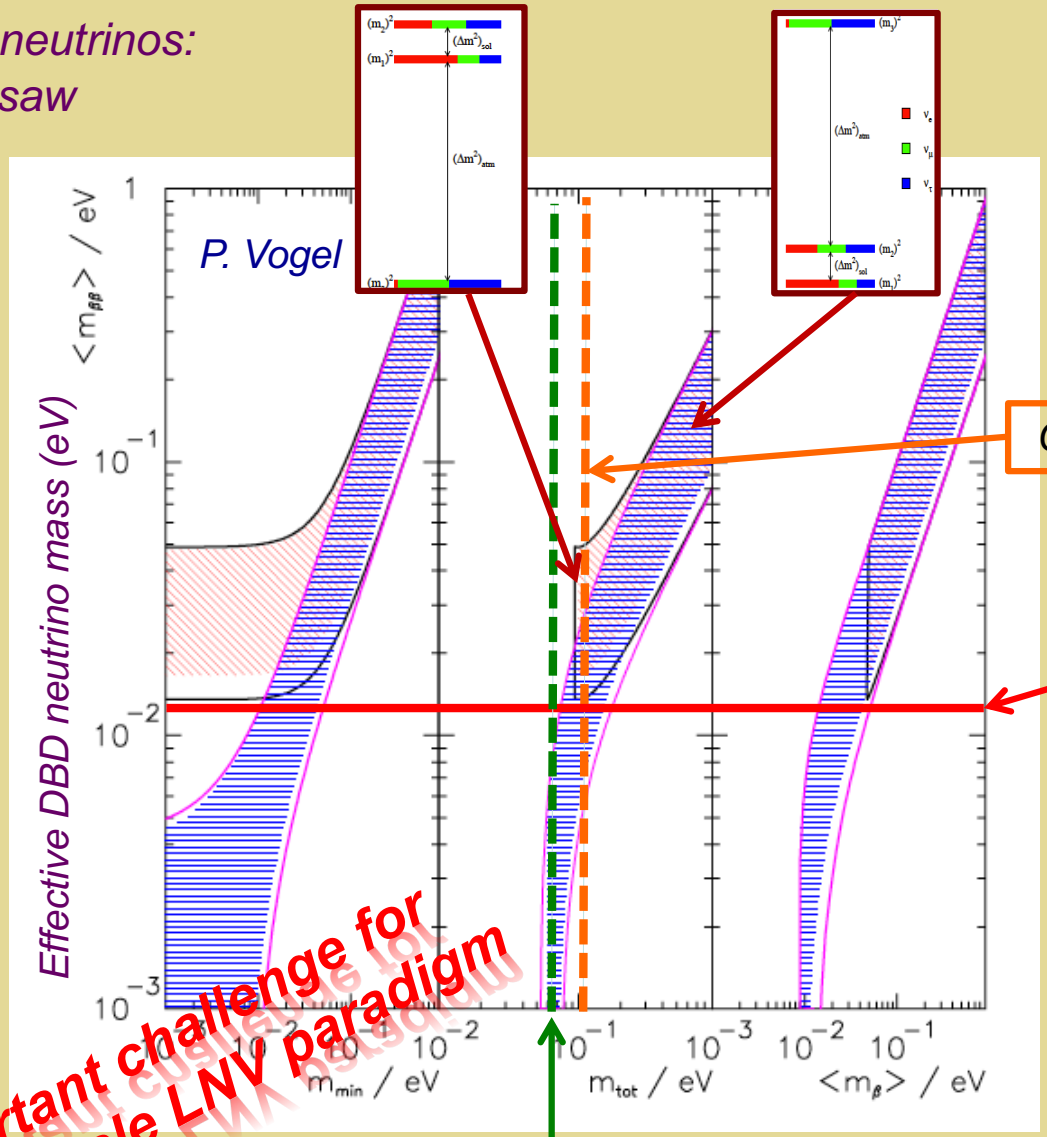
High scale type I seesaw

High Scale LNV & Leptogenesis



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

Three active light neutrinos: conventional see-saw



IV. TeV-Scale LNV

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

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This talk

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Origin of m_ν

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Colliders

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

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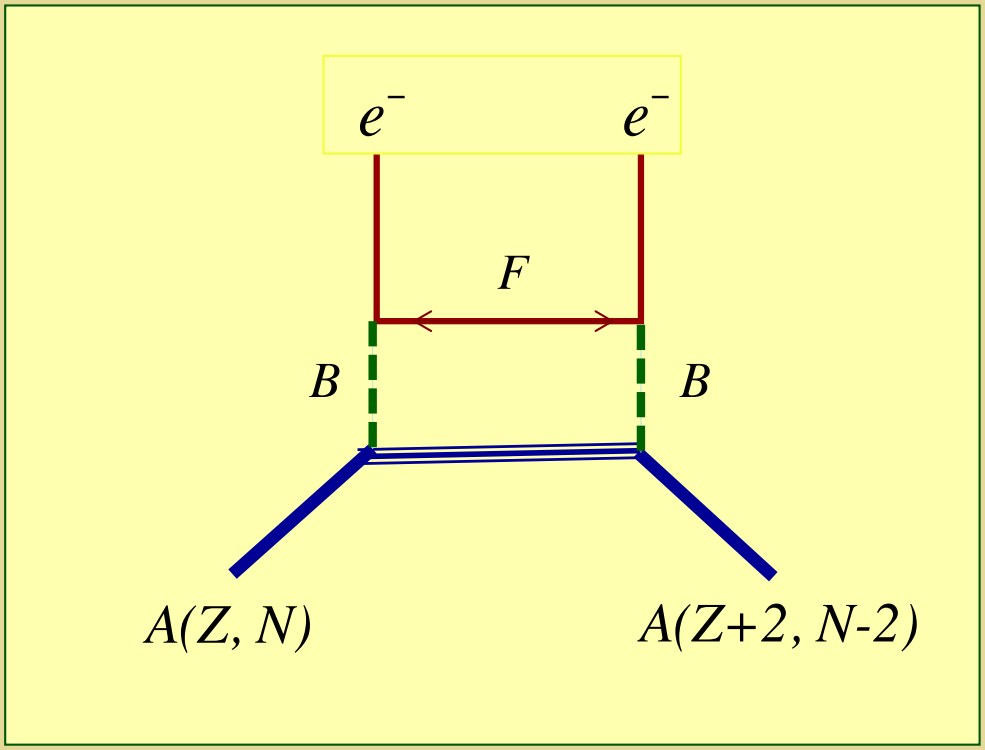
Majorana

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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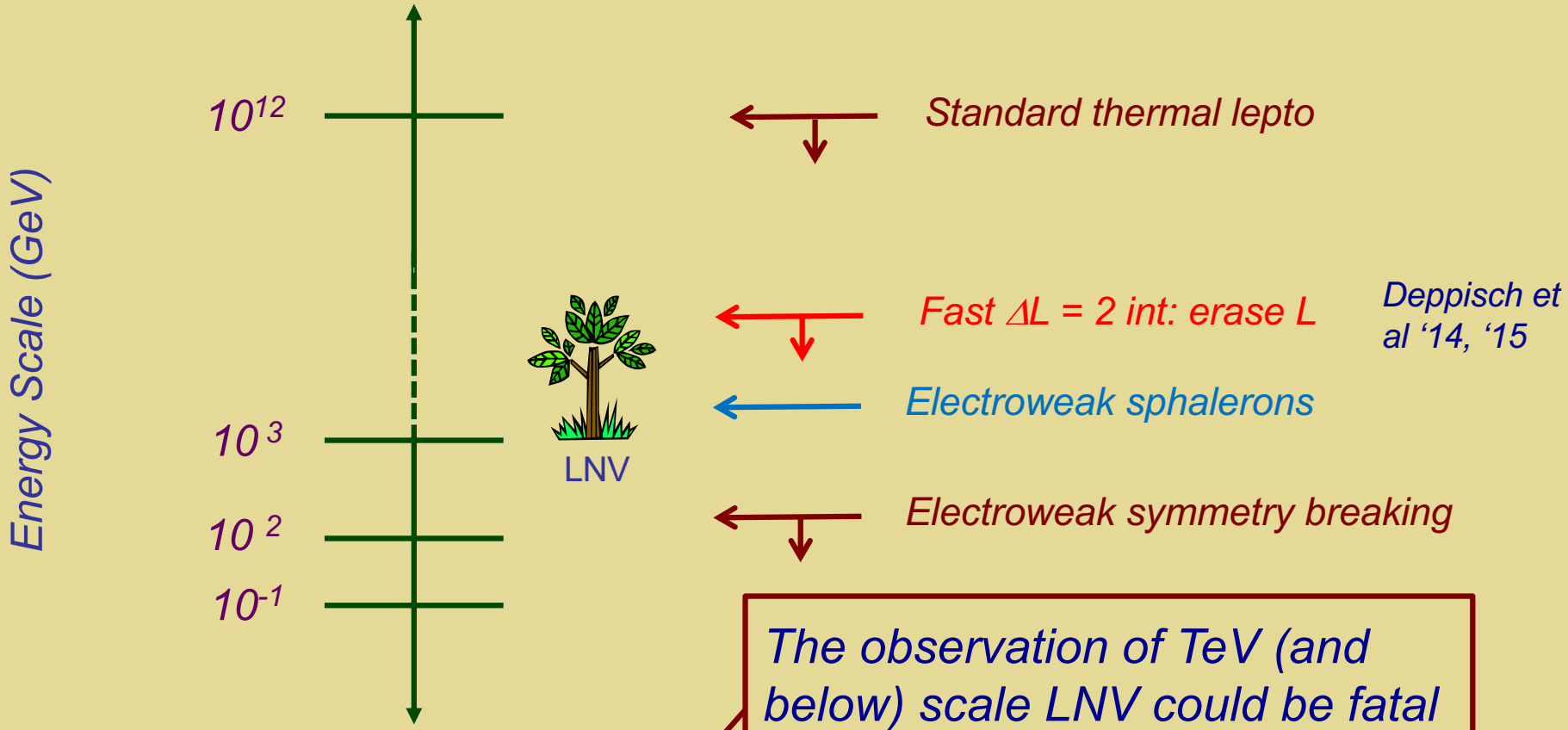
Low Scale LNV & Leptogenesis



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

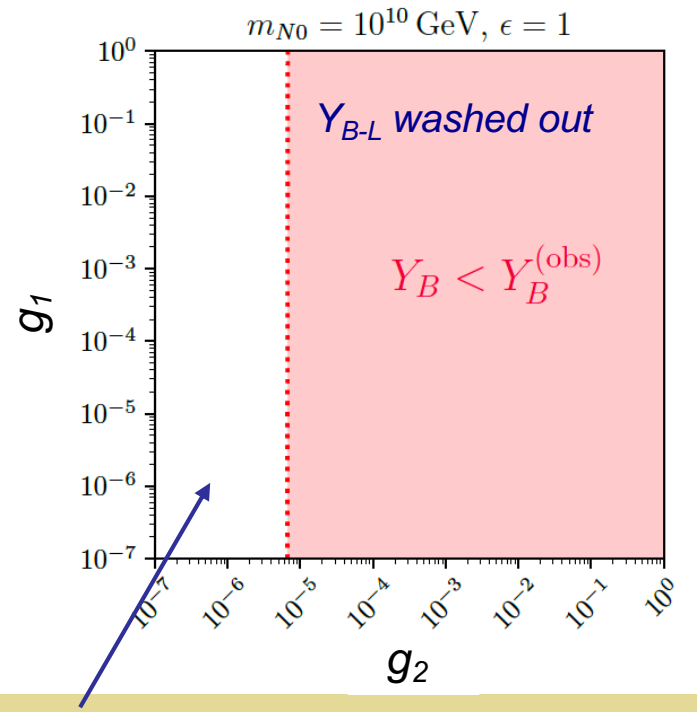
Other baryogenesis mechanisms needed

Leptogenesis & TeV Scale LNV: Example

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

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

S: (1, 2, ½)
F: (1, 0, 0) Majorana



Y_{B-L} survives

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

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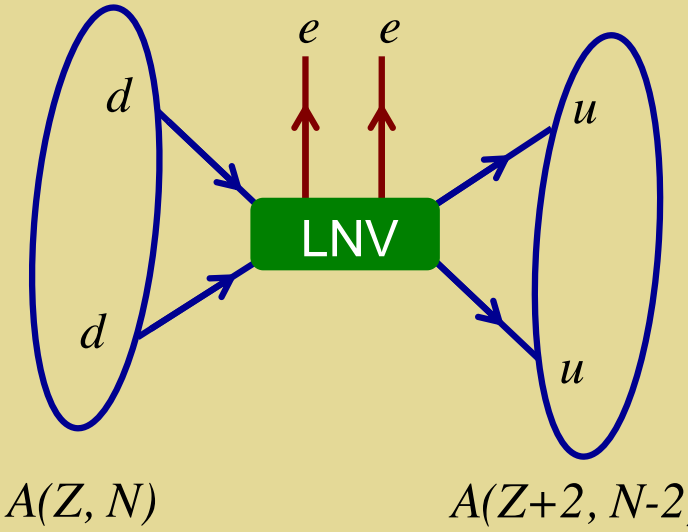

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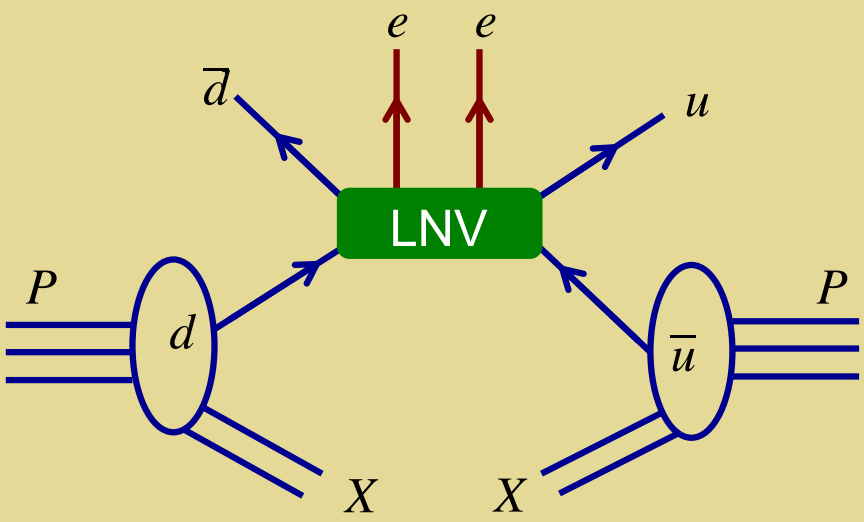

TeV-Scale LNV: lepto, $0\nu\beta\beta$-Decay & Colliders

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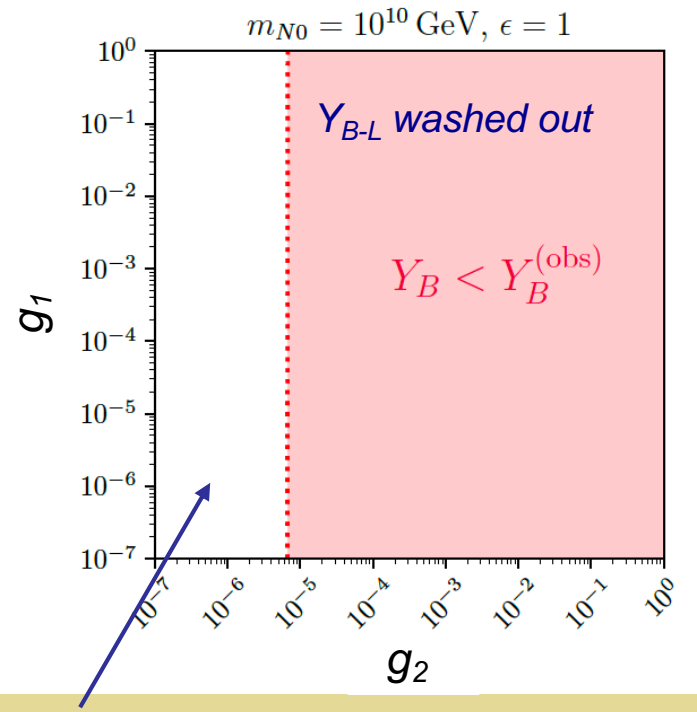

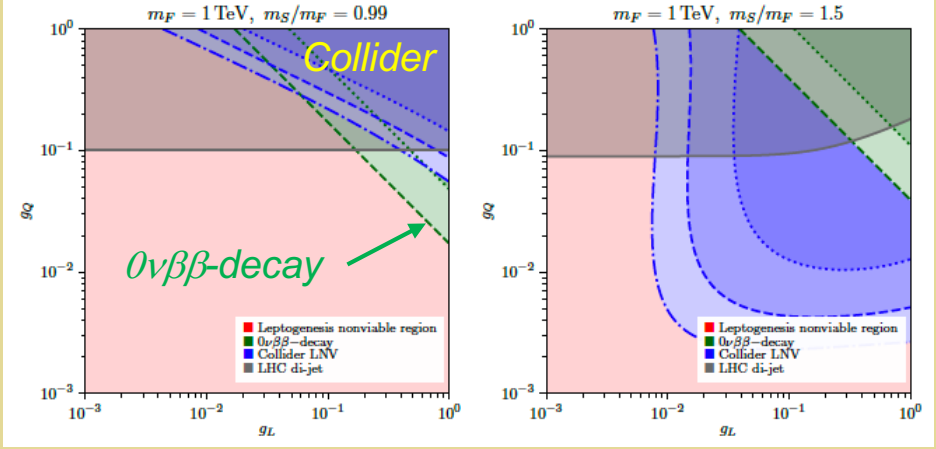

Comparing $0\nu\beta\beta$-decay, collider, & cosmo

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

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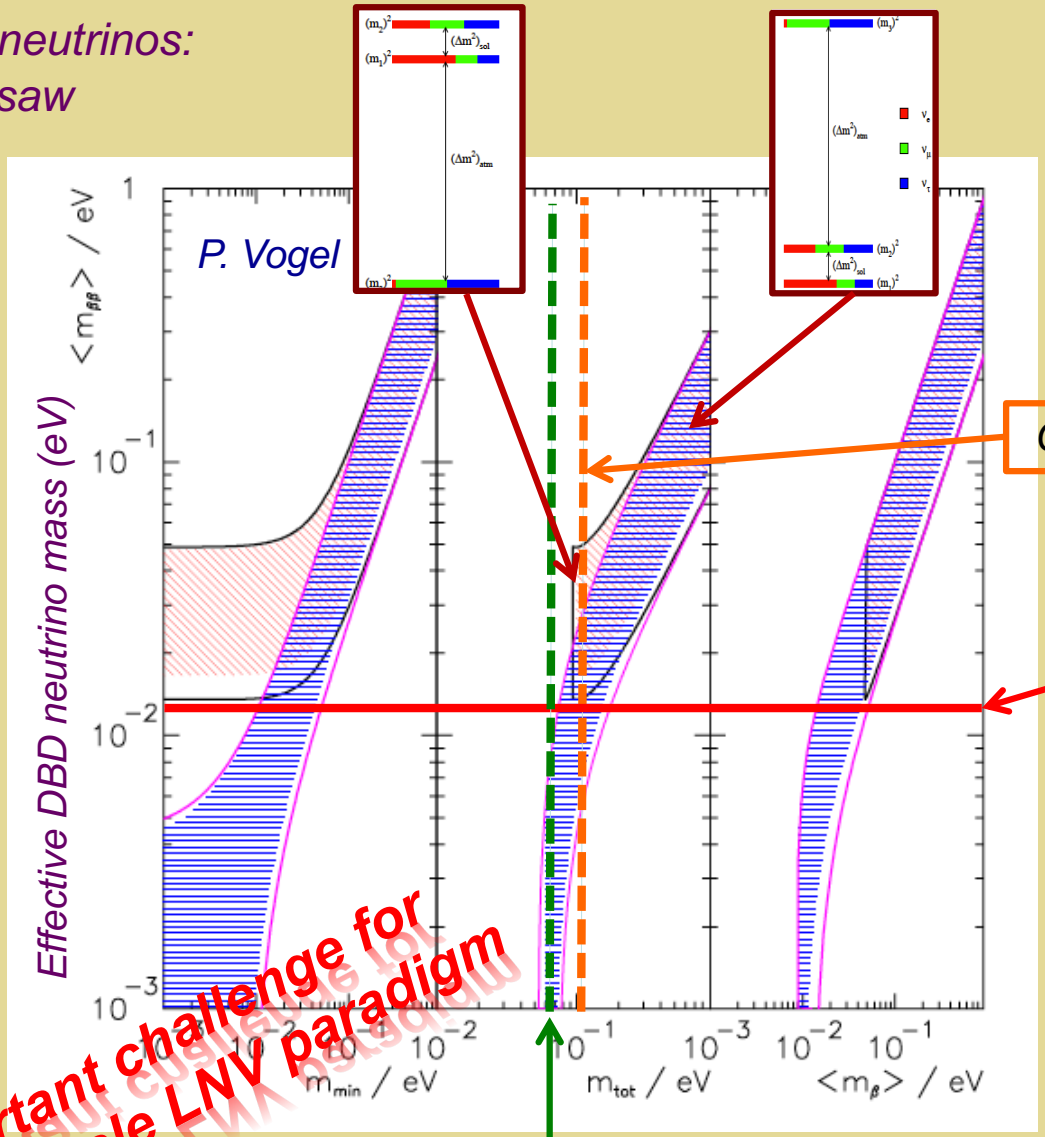
Σm_ν from Cosmo: $0\nu\beta\beta$-Decay Implications

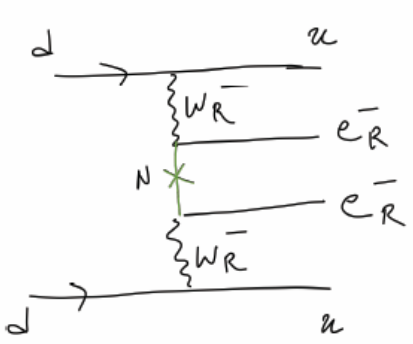
Three active light neutrinos: conventional see-saw



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

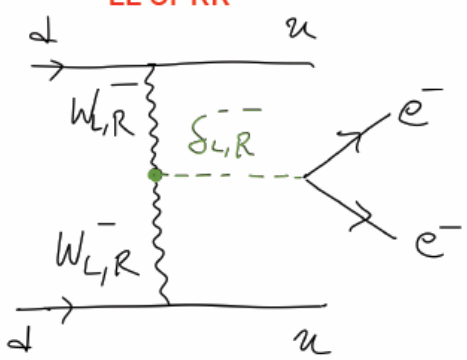
Long range chiral enhancement

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



RR contribution

LL or RR

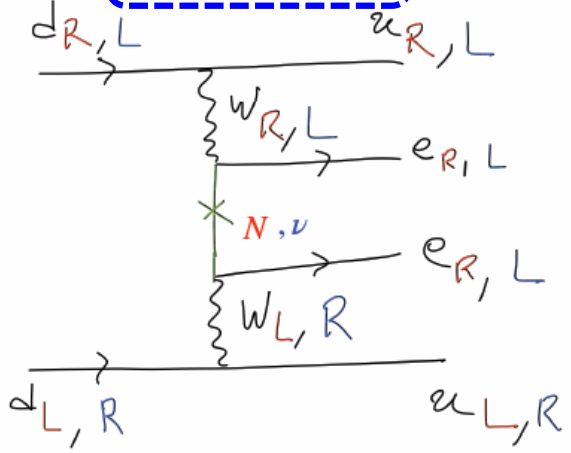


Suppressed by heavy

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

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

LR contribution



The Blue contributions are

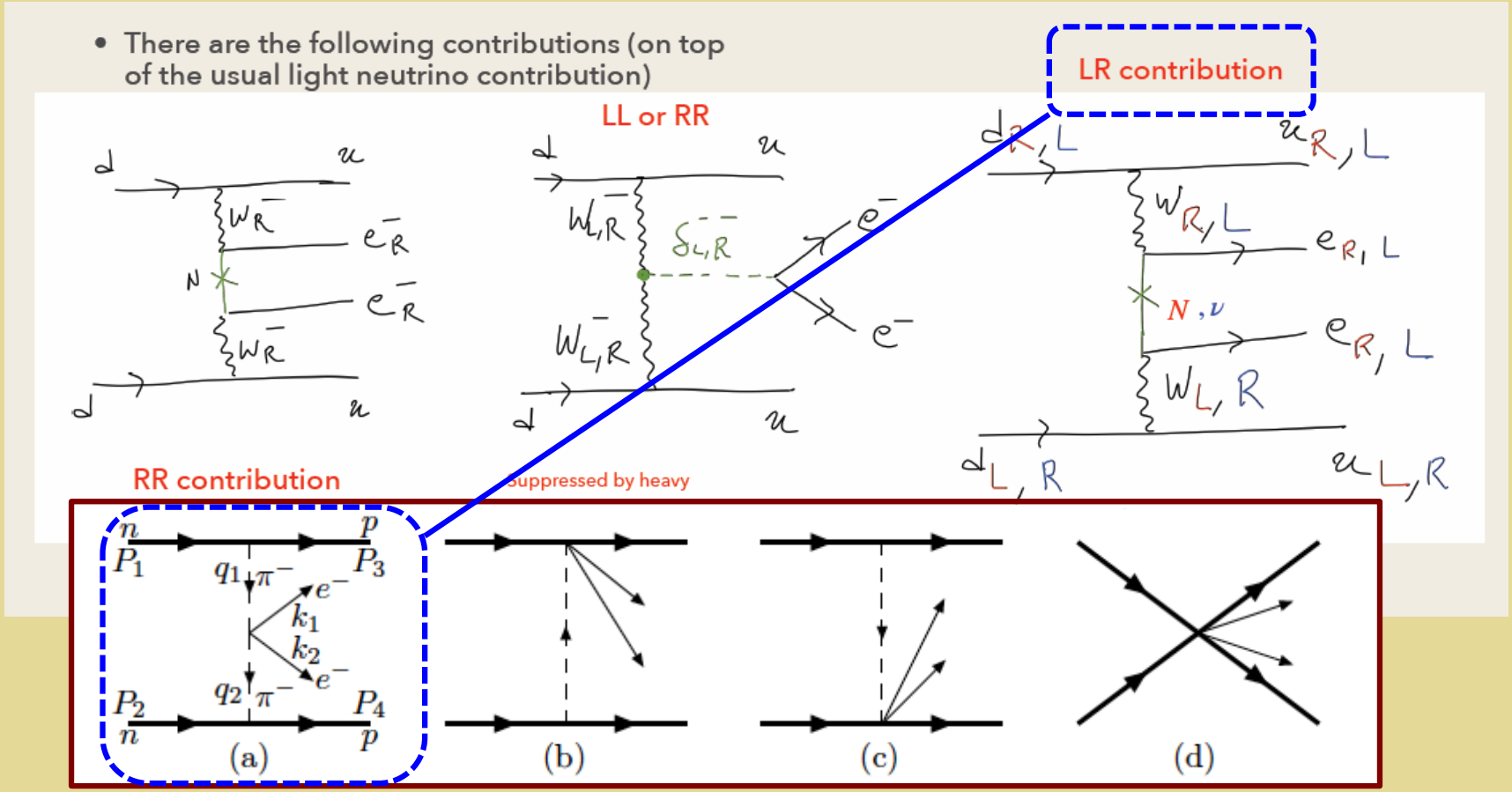
Suppressed by small heavy-light

Neutrino mixing

Thanks! Juan Carlos Vasquez

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

Long range chiral enhancement

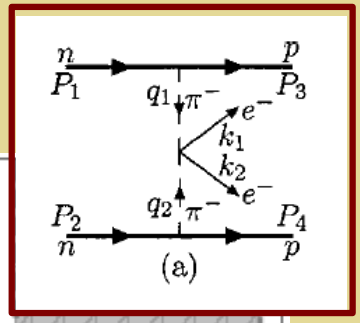


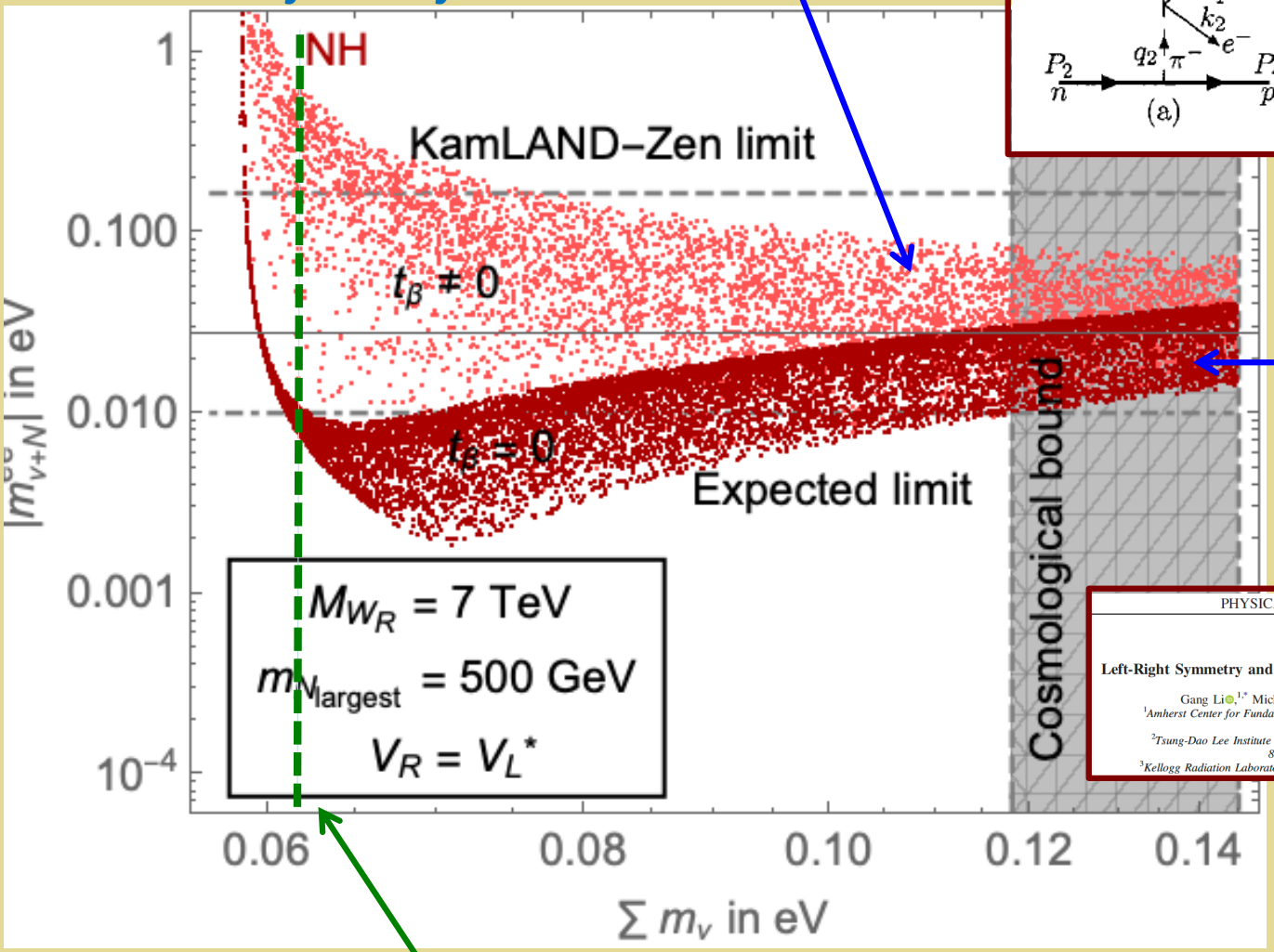
Thanks! Juan Carlos Vasquez

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

EFT: Long range

Minimal LR Symmetry





Short range only

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*

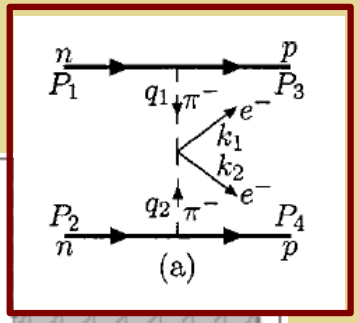
[2]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*

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

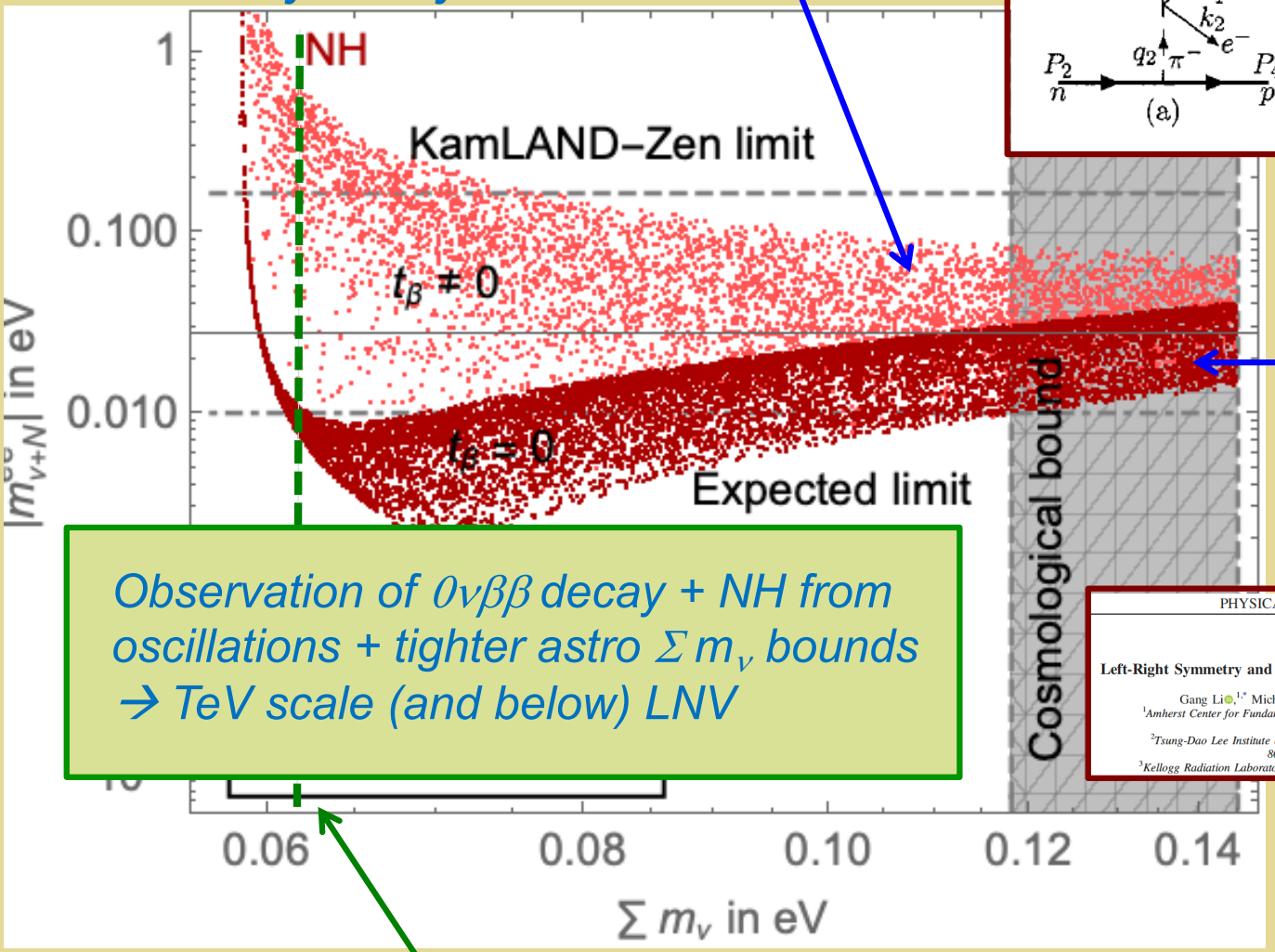
~ Cosmo next gen

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

EFT: Long range



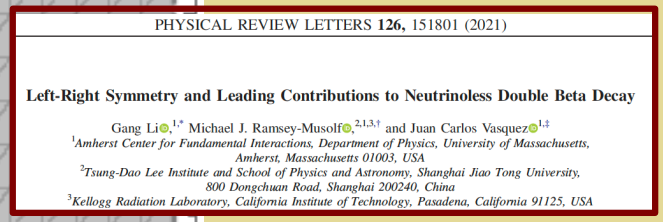
Minimal LR Symmetry



Short range only

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

~ Cosmo next gen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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?*

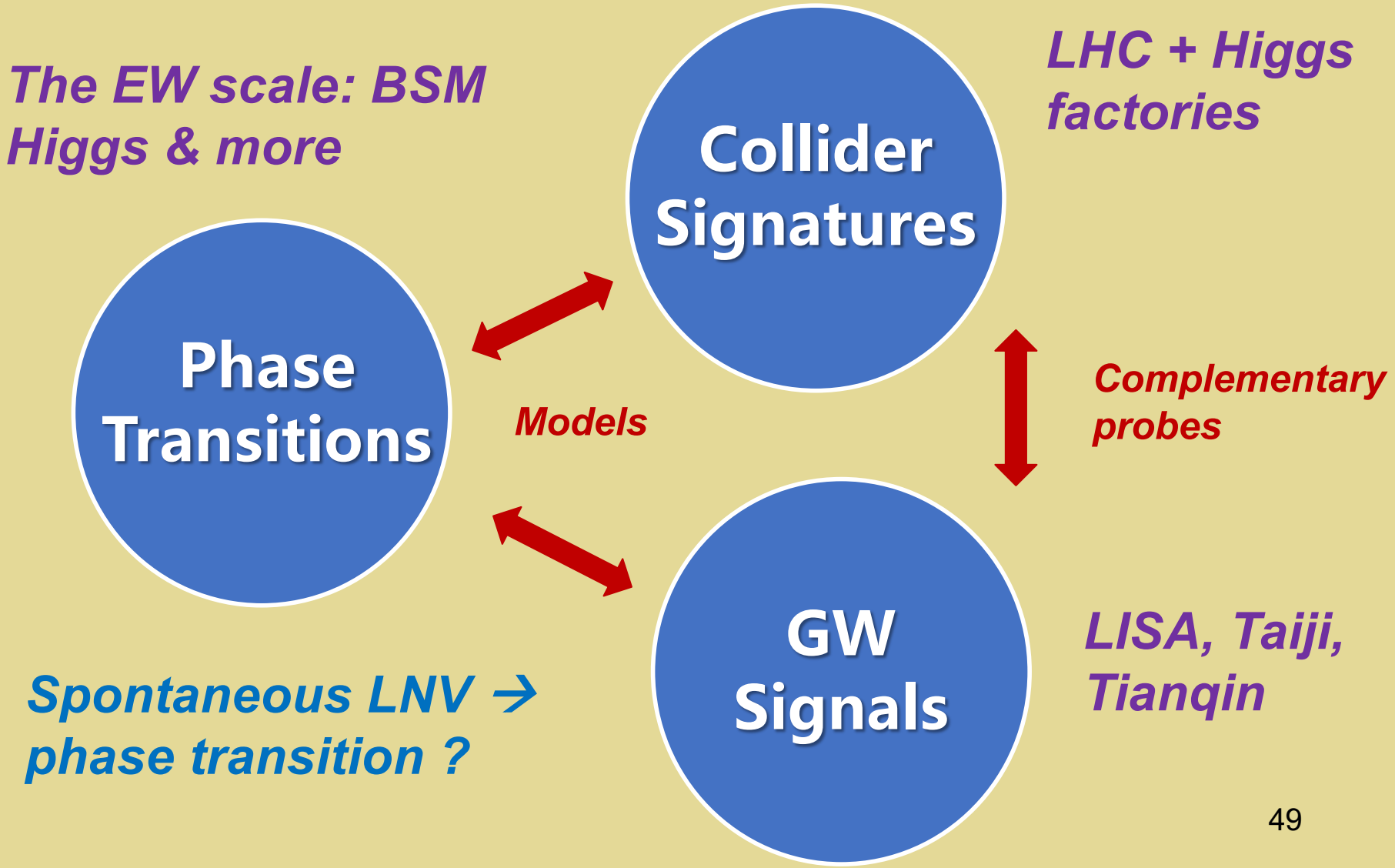
Origin of m_ν

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

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

Colliders

Spontaneous LNV: Higgs, GW, Collider

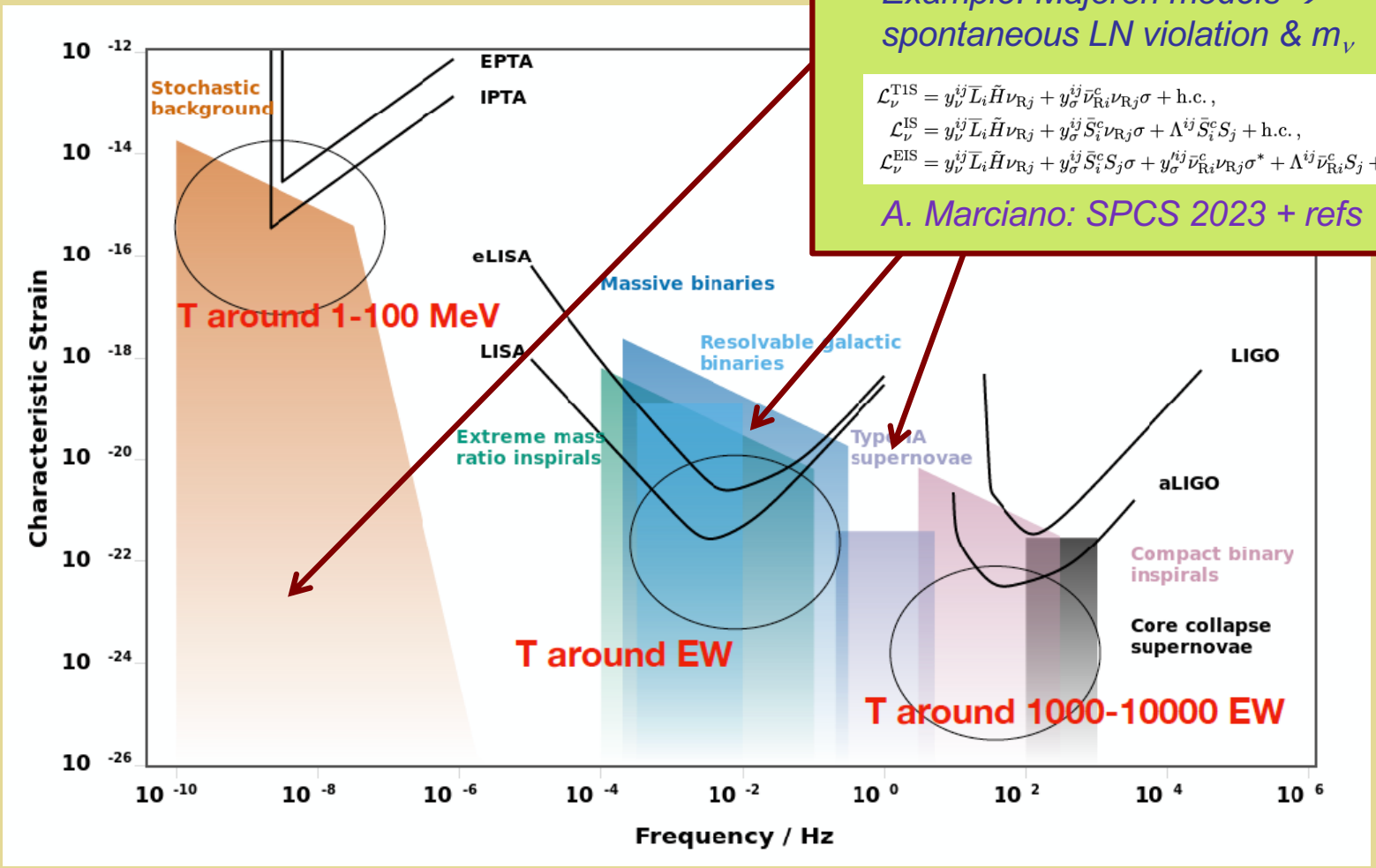


LNV Scalar Field & GW

Example: Majoron models → spontaneous LN violation & m_ν

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

A. Marciano: SPCS 2023 + refs



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

LNV Scalar Field & GW

Example: Majoron models → spontaneous LN violation & m_ν

$$\mathcal{L}_\nu^{\rm T1S} = y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{\nu}_{{\rm R}i}^c\nu_{{\rm R}j}\sigma + {\rm h.c.}\,,$$
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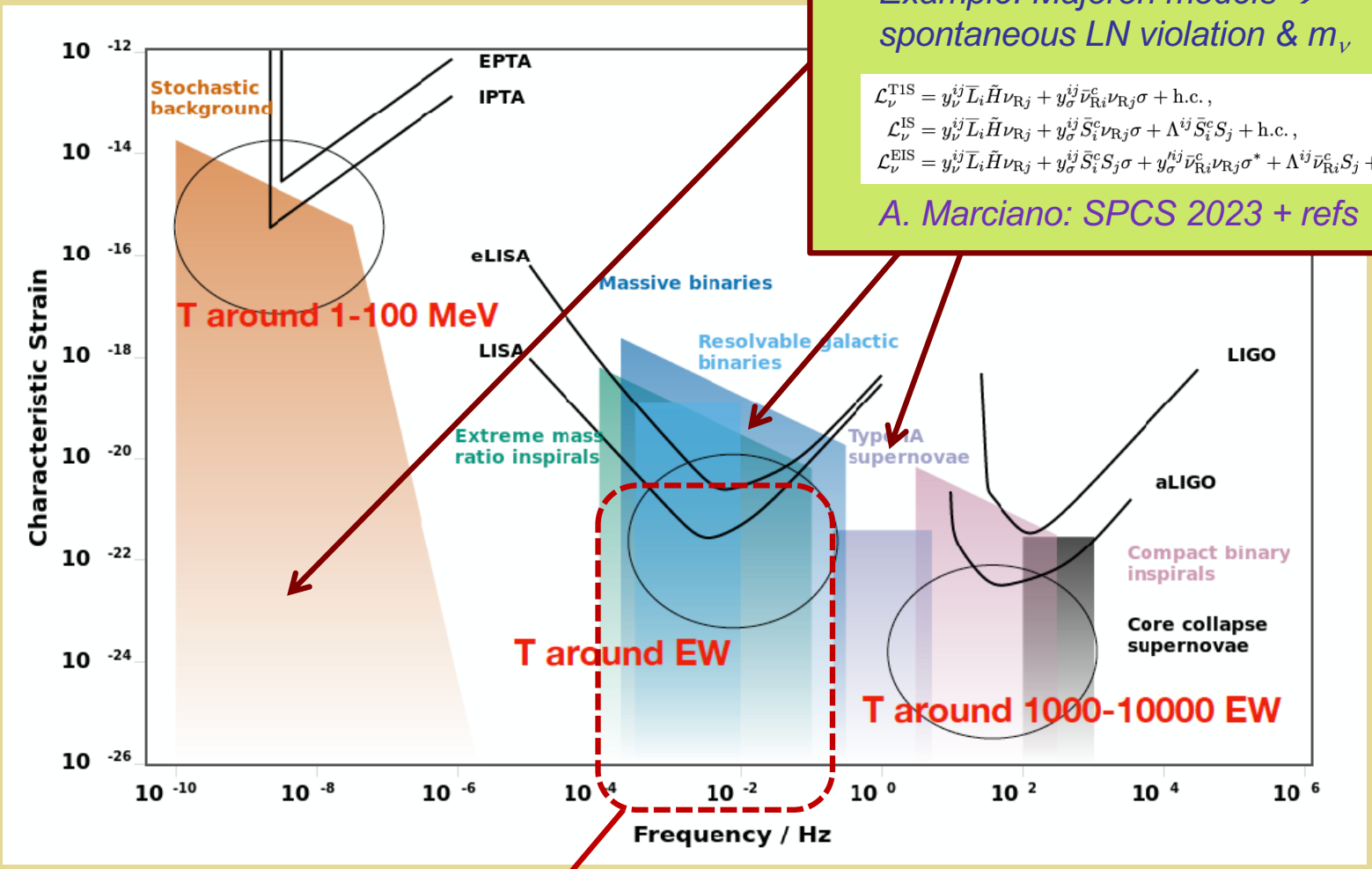
A. Marciano: SPCS 2023 + refs



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

BSM LNV: Questions

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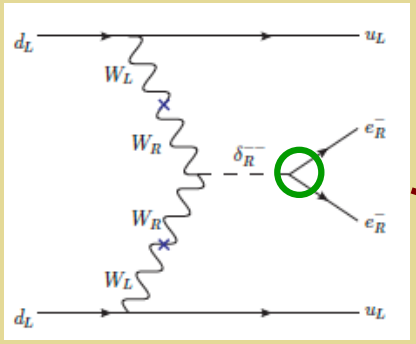
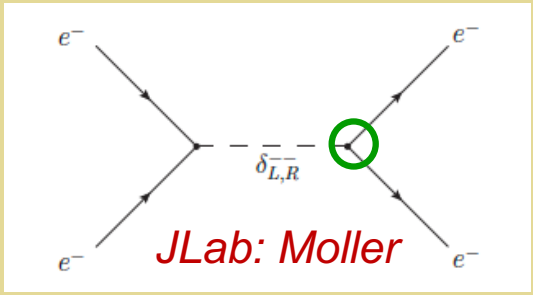
- ***$0\nu\beta\beta$ decay***
- ***μ_ν***
- ***ν osc***
- ***PV ee …***

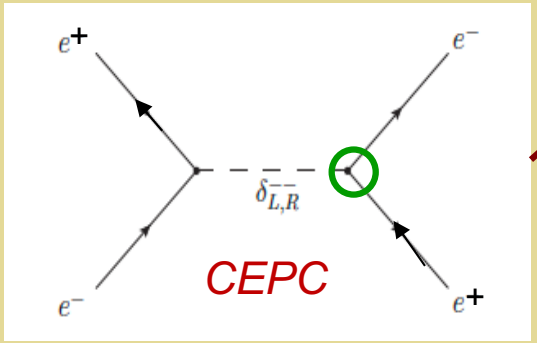
Colliders

LNV: Scalar Fields & m_ν

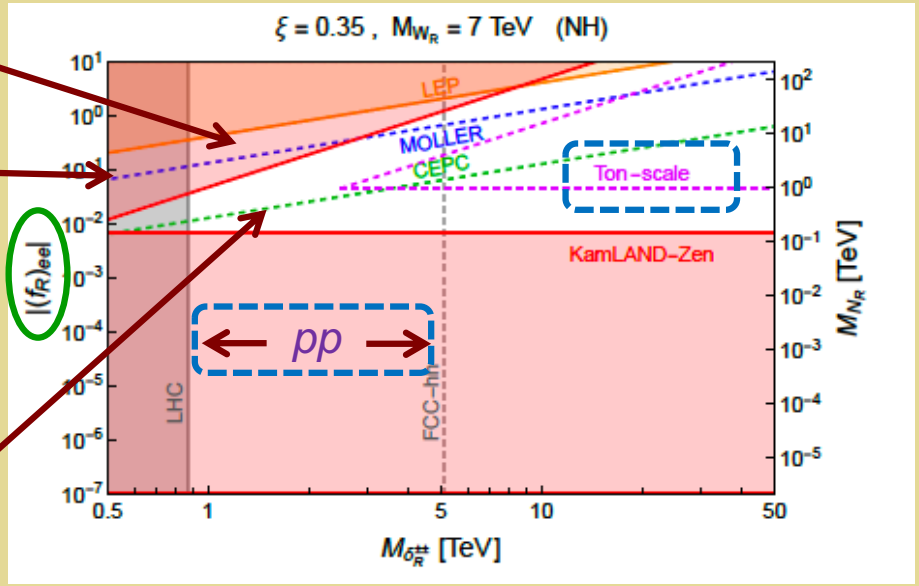
$0\nu\beta\beta$ Decay, PV $e^-e^- \rightarrow e^-e^-$, $e^+e^- \rightarrow e^+e^-$ & pp collisions







mLRSM type II Seesaw: δ^{--}



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

V. GeV- and Below-Scale LNV

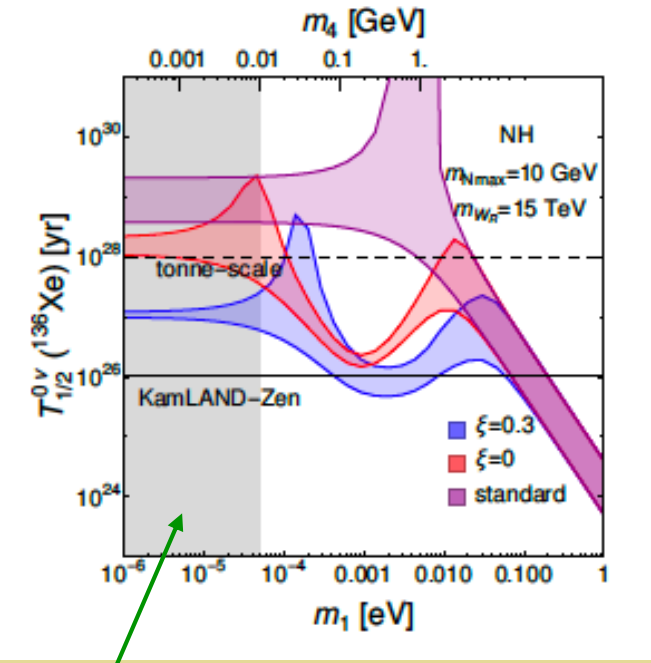
LNV Mass Scale & $0\nu\beta\beta$-Decay

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

- *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*

More Than 3 Light Neutrinos: MeV-GeV

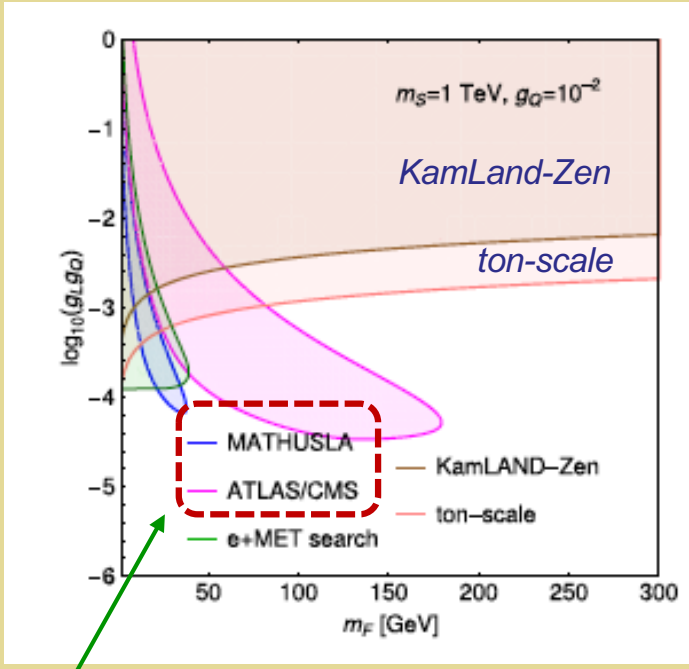
mLRSM



Current Σm_ν exclusion

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

Simplified Model



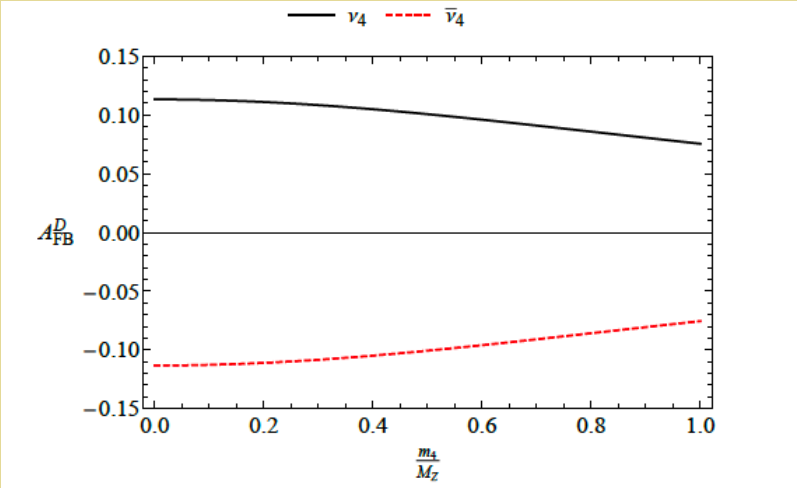
LHC long-lived particle searches

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

Lepton Collider Probes

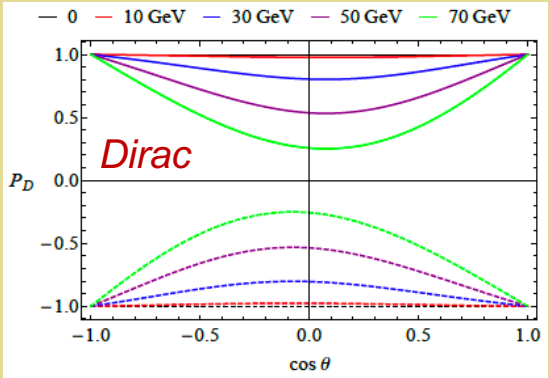
$e^+ e^- \rightarrow Z^0 \rightarrow N\,N$ vs $e^+ e^- \rightarrow Z^0 \rightarrow N\,\bar{N}$

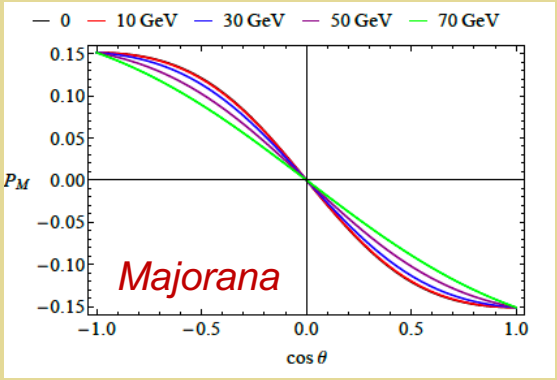
Lepton FB Asymmetry



A_{FB} : vanish for Majorana N

N Polarization





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

VI. Conclusions

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

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

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


谢谢

Back Up Slides

Neutrino Oscillation Fits

NuFIT: 2111.03086 *3 active light neutrinos*

	NuFIT 1.0	NuFIT 2.0	NuFIT 3.0	NuFIT 4.0	NuFIT 5.1
θ_{12}	15%	14%	14%	14%	14%
θ_{13}	30%	15%	11%	8.9%	9.0%
θ_{23}	43%	32%	32%	27%	27%
Δm^2_{21}	14%	14%	14%	16%	16%
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]
$\delta_{\rm CP}$	100%	100%	100%	100% [92%]	100% [83%]
$\Delta\chi^2_{\rm IO\text{-}NO}$	$\pm$0.5	$-$0.97	+0.83	+4.7 [+9.3]	+2.6 [+7.0]

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