The Collider-Cosmology Interface II

M.J. Ramsey-Musolf

U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

HEP School, Lanzhou
8/1-8/18

Lecture II Goals

- *Explain how standard thermal leptogenesis works and its connection with the see saw mechanism for neutrino masses*
- *Illustrate the implementation of the Sakharov criteria*
- *Introduce the concept of sphalerons (anomalous symmetry breaking)*
- *Discuss how BSM searches at colliders may preclude standard thermal leptogenesis & provide clues about alternatives*
- *Invite questions !*

Lecture II Outline

I. Leptogenesis & the Seesaw Mechanism

II. Leptogenesis Overview

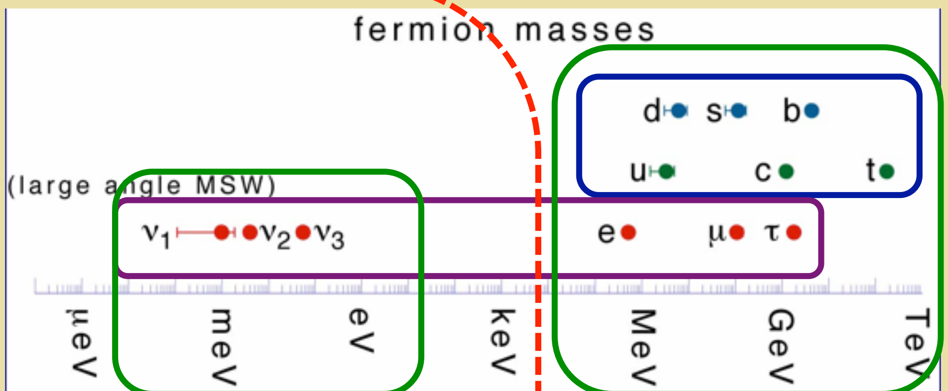
III. Leptogenesis & Colliders

Selected References

- *Mu-Chun Chen: 0703087*
- *Fukugita & Yanagida: Phys. Lett. B 174 (1986) 45*
- *Buchmuller, Di Bari, Plumacher: 0401240*
- *Buchmuller, Peccei, Yanagida: 0502169*
- *Luty: Phys. Rev. D45 (1992) 455*
- *Dev et al: 1711.02861*

I. Leptogenesis & the See Saw Mechanism

Neutrino Masses & Baryon Asymmetry



Partners

Partners

Something else ?

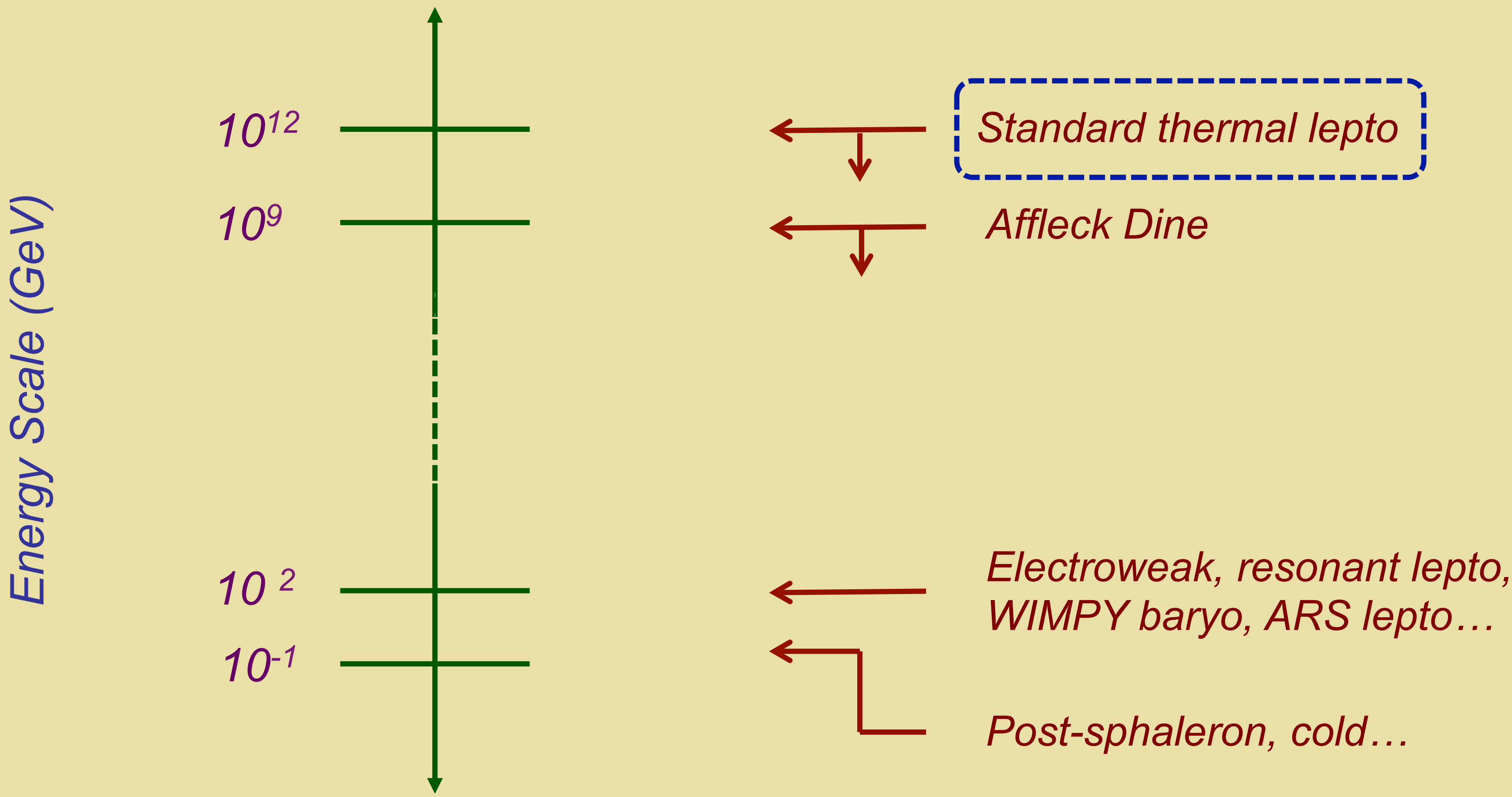
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This lecture

Baryogenesis Scenarios



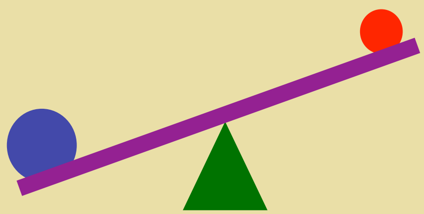
Seesaw Mechanism

- *Is the neutrino its own antiparticle ?*
- *Why is there more matter than antimatter ?*
- *Why are neutrino masses so small?*

Seesaw Mechanism

- *Is the neutrino its own antiparticle ?*
- *Why is there more matter than antimatter ?*
- *Why are neutrino masses so small?*

"See saw mechanism"



"Leptogenesis"

$$\nu = \overline{\nu}$$

Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle = its own anti-particle

Are Neutrinos = Antineutrinos ?

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

Dirac

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

Majorana

- ***Lepton number violating***
- ***Neutrino = antineutrino***

$\overline{L^C}\,L$: creates or destroys 2 leptons or anti-leptons

Type I See-Saw

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

Dirac

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

Majorana

One generation: SM + one N_R

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}N_R \ + \ \text{h.c.} + M_N \bar{N}_R^C N_R$$

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

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Eigenvalues

$$m_1 \approx \frac{m_D^2}{M_N}$$

$$m_2 \approx M_N$$

Type I See-Saw

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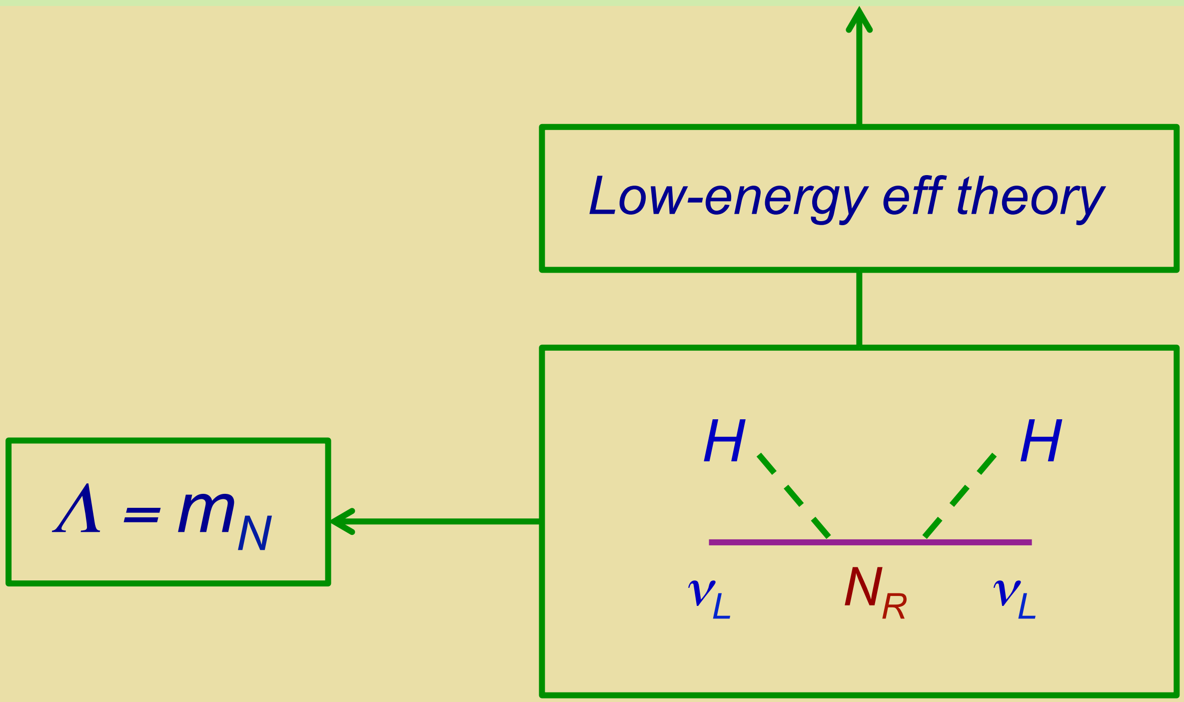
Majorana



Type I See-Saw

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Majorana

Seesaw scale:

$$m_1 = m_D \times \left(\frac{m_D}{M_N}\right)$$

Standard thermal leptogenesis

- *For $m_D \sim m_t \rightarrow M_N \sim 10^{16}$ GeV*
- *For $m_D \sim m_\tau \rightarrow M_N \sim 10^{12}$ GeV*
- *For $m_D \sim 0.1\, m_e \rightarrow M_N \sim 10^{3}$ GeV*

Take $m_1 \sim 10^{-3}$ eV

II. Leptogenesis Overview

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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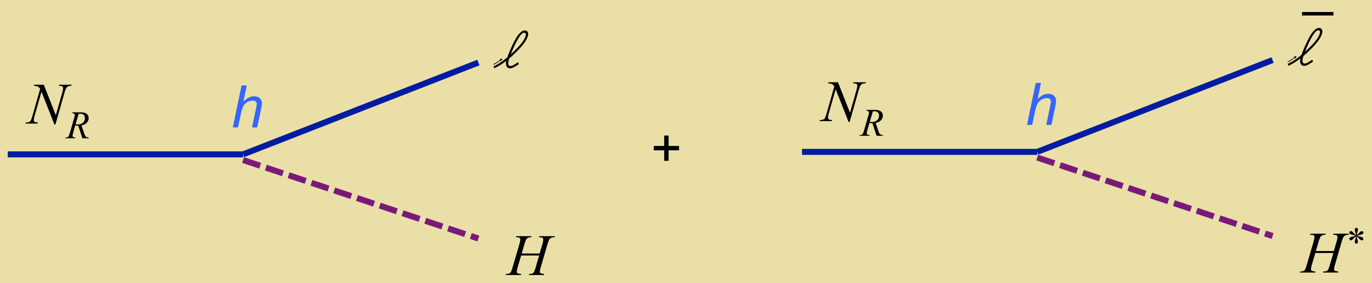


$$\Gamma_N \equiv \Gamma(N_R \to \ell H) + \Gamma(N_R \to \bar{\ell} H^*) = \frac{|h|^2}{8\pi} M_N$$

Hubble rate

$$H(T) \sim 1.66\, g_* \frac{T^2}{M_P}$$

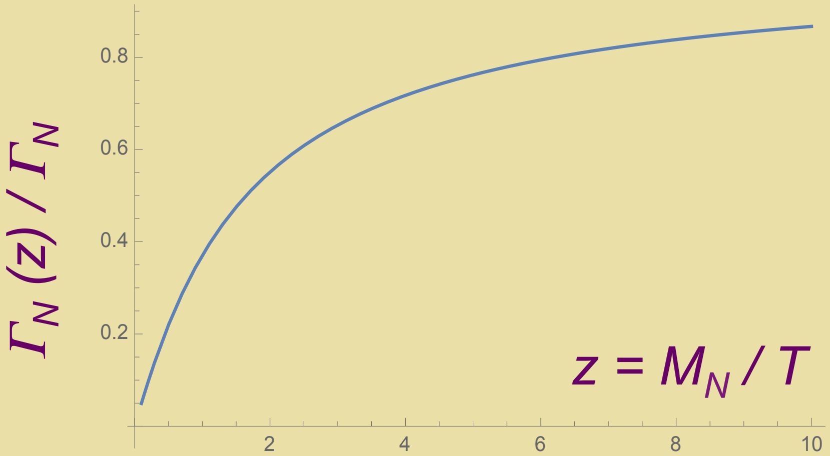
Neutrinos and the Origin of Matter

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

Simple estimation

$$\Gamma_N \lesssim H(T{=}M_N)$$

$$\Gamma_N(z) = \frac{K_1(z)}{K_2(z)}\,\Gamma_N$$



Neutrinos and the Origin of Matter

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

Simple estimation $\Gamma_N \lesssim H(T=M_N)$ ⇒

$$m_1 \approx m_*$$

$$m_1 \approx \frac{m_D^2}{M_N}$$

$$m_* = 8\pi * (1.66 g_*) \frac{v^2}{M_P}$$ ~ *few x* 10^{-3} *eV*

Neutrinos and the Origin of Matter

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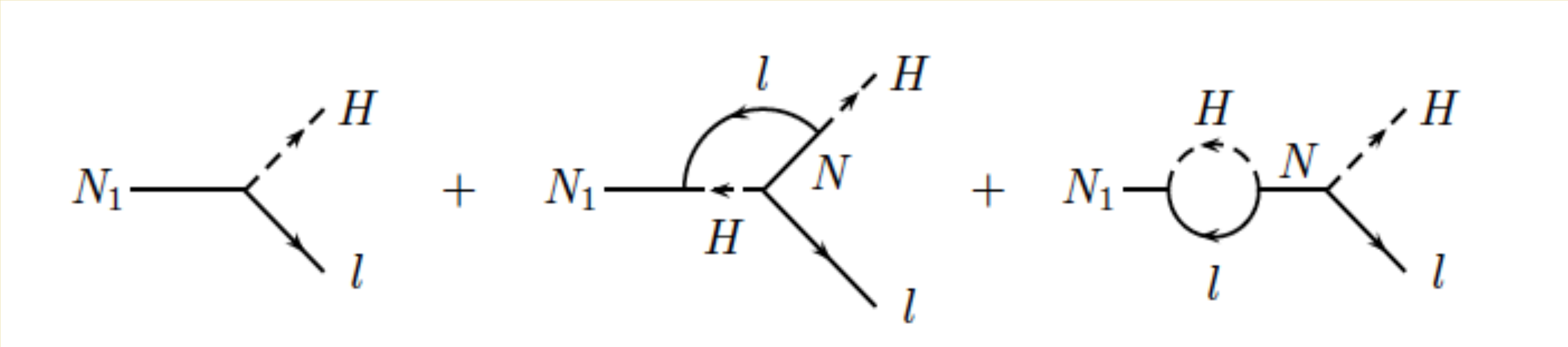
Neutrinos and the Origin of Matter

CPV Asymmetry

$$\varepsilon = \frac{\Gamma(N \to \ell H) - \Gamma(N \to \bar{\ell} H^*)}{\Gamma(N \to \ell H) + \Gamma(N \to \bar{\ell} H^*)}$$

Neutrinos and the Origin of Matter

CPV Asymmetry: Quantum Interference



Tree-level CPV X *One-loop "absoprtive part"*

$$\varepsilon_1 \simeq \frac{3}{16\pi} \frac{1}{(hh^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[\left(hh^\dagger\right)^2_{i1}\right] \frac{M_1}{M_i}$$

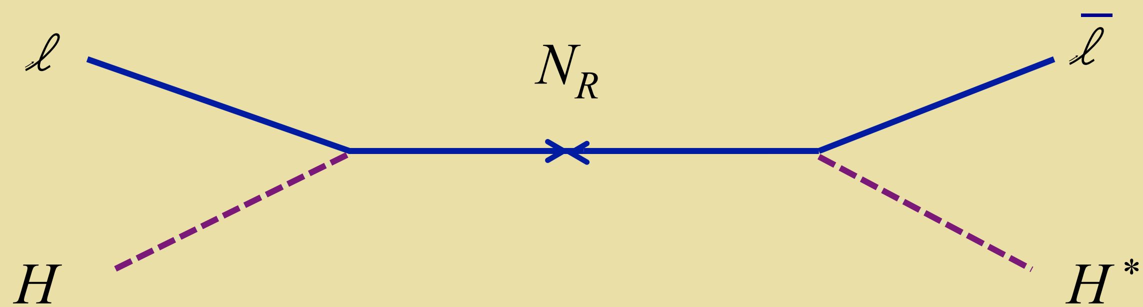
CPV phases but not same as ϕ_{PMNS}

Buchmuller, Peccei, Yanagida '05

Neutrinos and the Origin of Matter

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

Washout processes



$\Delta L = 2$

Converts leptons into anti-leptons

Boltzmann Equations: Heavy N_R

$$\frac{dY_N}{dz} = -(D+S)\left(Y_N - Y_N^{\mathrm{EQ}}\right) - A\left[Y_N^2 - \left(Y_N^{\mathrm{EQ}}\right)^2\right]$$

Decay (→ D) *Scattering* (→ S) *Annihilation* (→ A)

B-L Asymmetry

Lepton number

$$Y_L \equiv \frac{n_\ell - n_{\bar{\ell}}}{s}$$

$$Y_L \approx -Y_{B-L}$$

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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

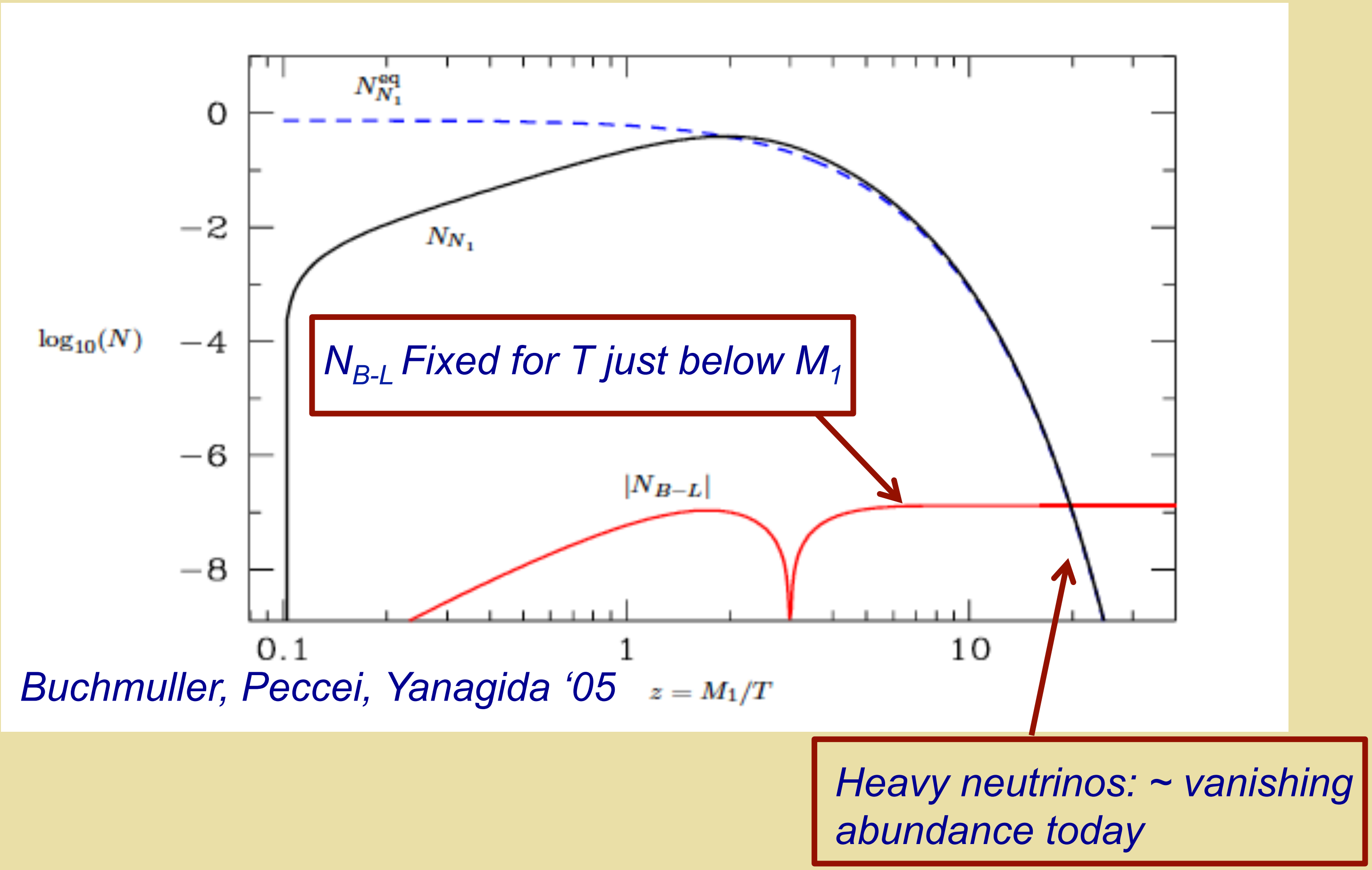
$$\frac{dY_{B-L}}{dz} = -\epsilon D\left(Y_N - Y_N^{\mathrm{EQ}}\right) - W\, Y_{B-L}$$

CPV Decay Asymmetry: source

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

Neutrinos and the Origin of Matter

Putting pieces together: B-L asymmetry



Buchmuller, Peccei, Yanagida '05

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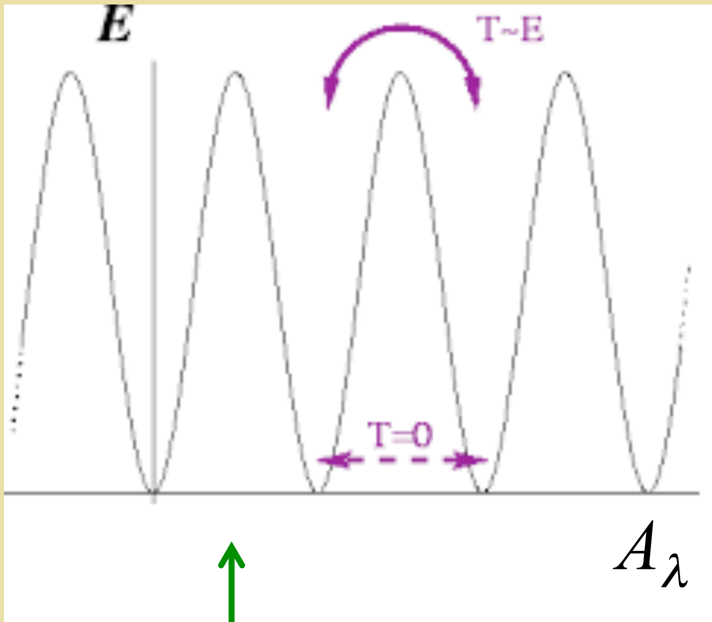
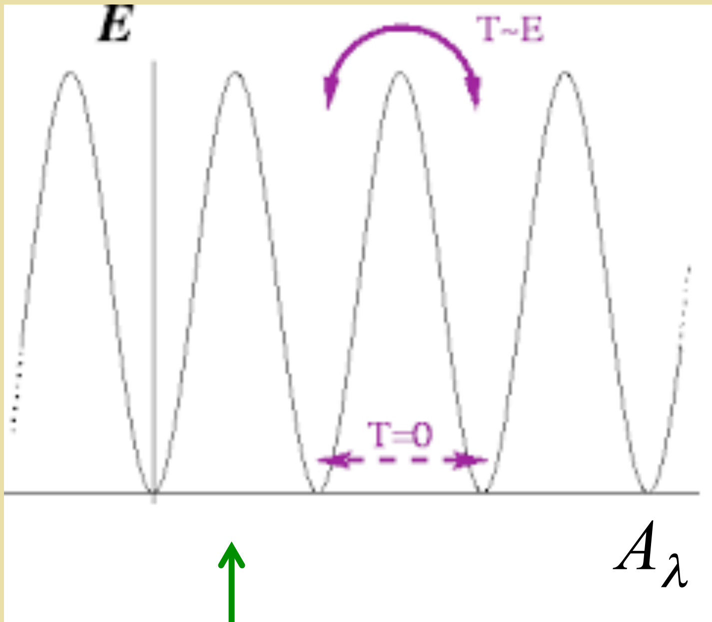
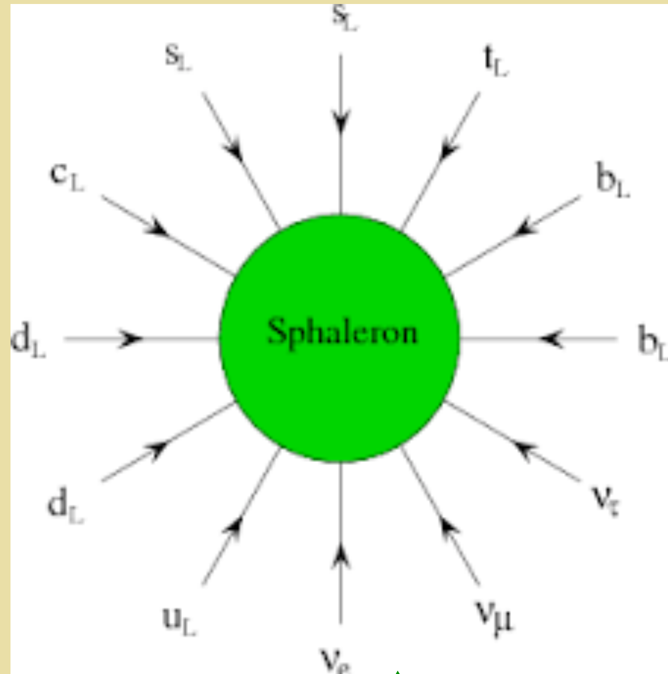
Electroweak Sphalerons



Sphaleron Configuration

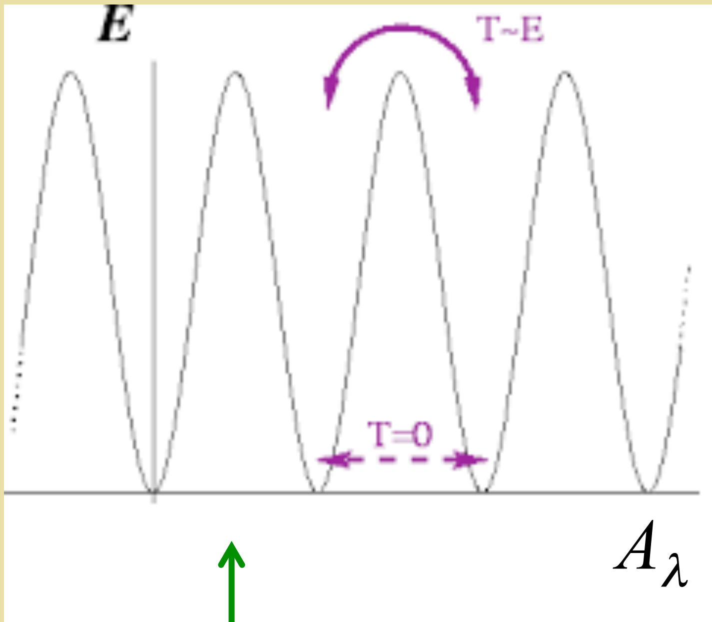
Electroweak Sphalerons

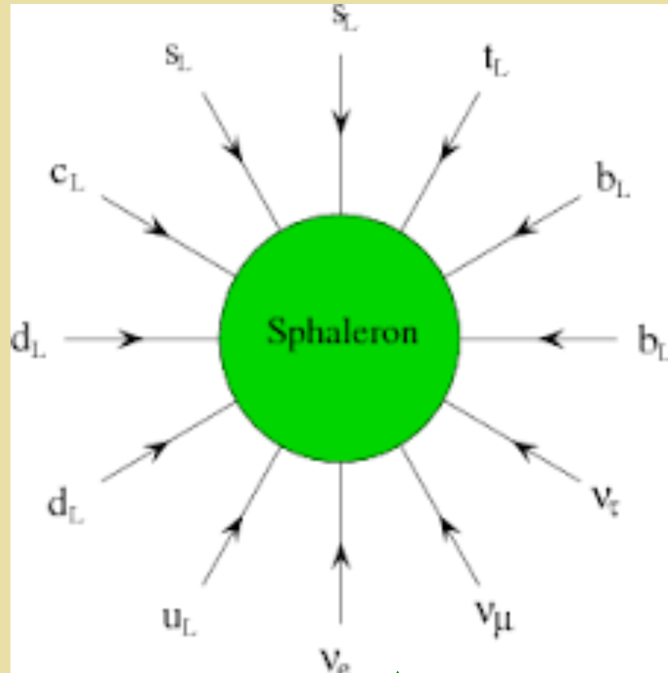




Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

Electroweak Sphalerons





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

EW sphalerons convert B-L asymmetry to Y_B

Baryon Asymmetry

Convert $Y_{B\text{-}L}$ to Y_B :

$$Y_B = C_S \, Y_{B-L}$$

$$C_S = \frac{8N_F + 4N_H}{22N_F + 13N_H}$$

St'd Model

$$= \frac{28}{79}$$

Davidson-Ibarra Bound

$$|\epsilon_1| \lesssim \frac{3}{8\pi} \frac{M_{N1} m_{\nu 3}}{\langle H^0 \rangle^2}$$

$M_{N1} \gtrsim 10^9$ GeV

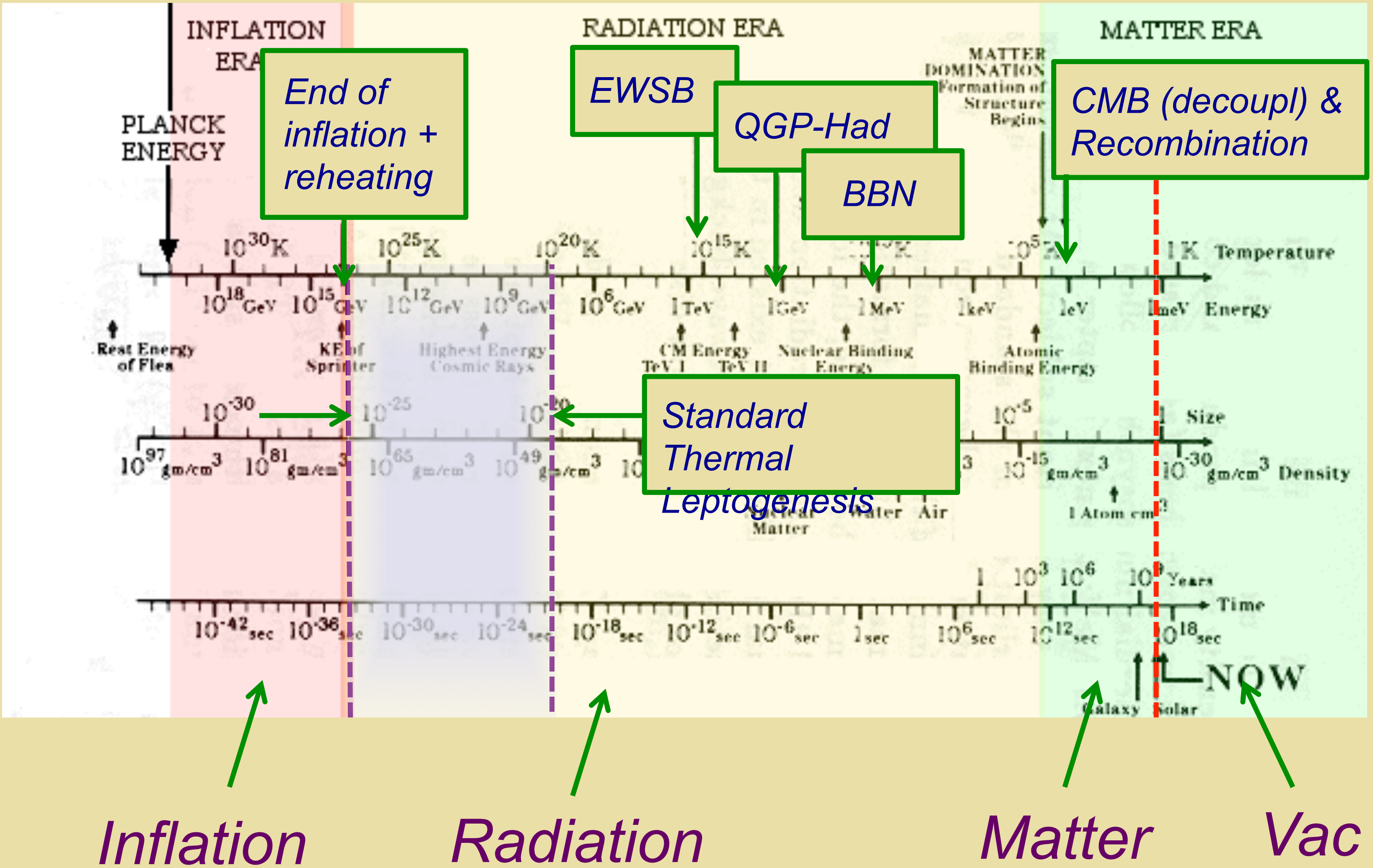
$$\frac{t_2}{t_1} = \left(\frac{T_1}{T_2}\right)^2$$

- $T \gtrsim 4 \times 10^{19}$ K
- $t \lesssim 6 \times 10^{-21}$ s

- $k\,T_{ROOM} \sim 1/40$ eV
- $T_{ROOM} \sim 300$ K

Davidson, Ibarra '02

Thermal History



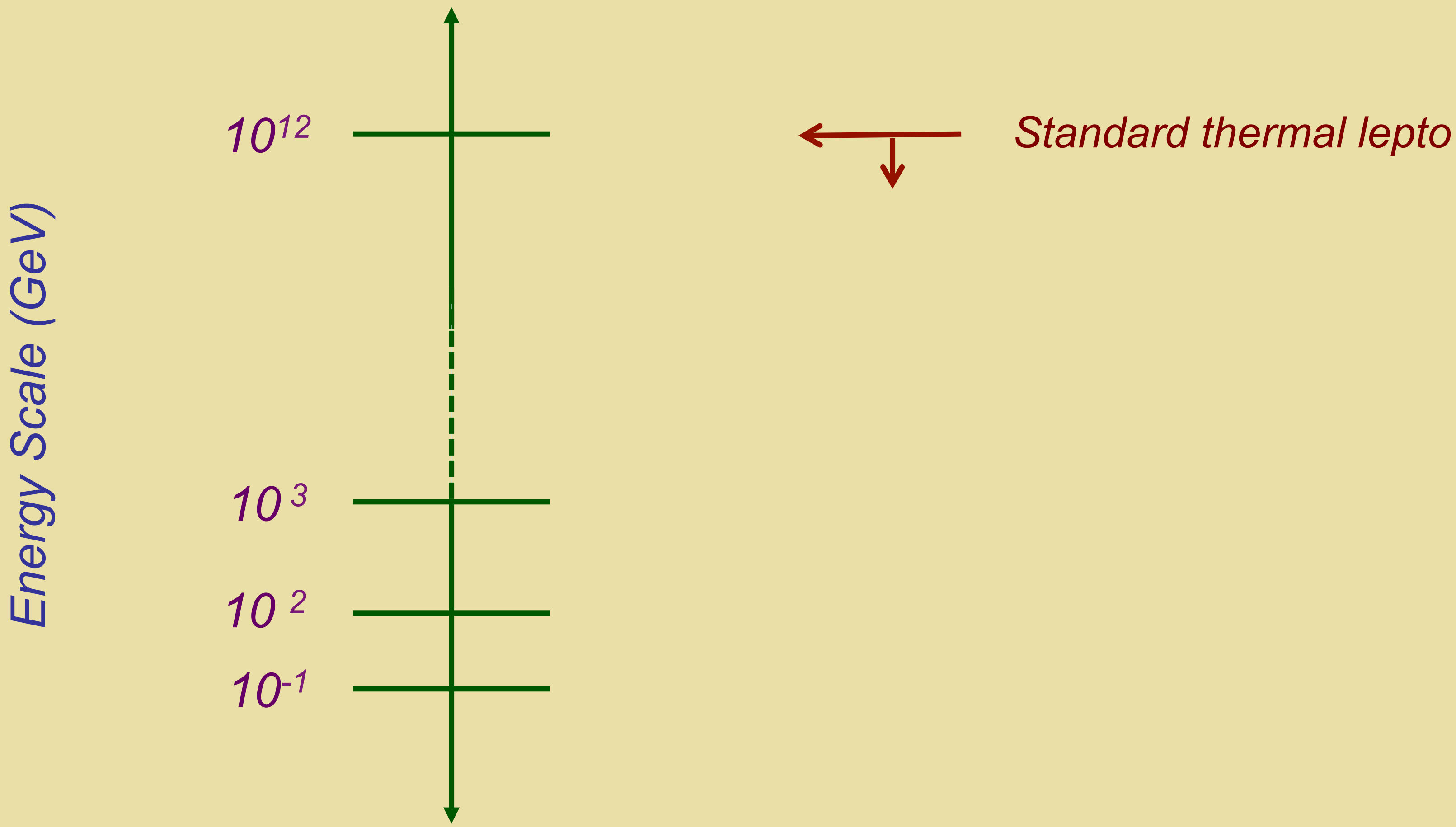
III. Leptogenesis & Colliders

Leptogenesis & Colliders

- *Discovery of TeV-scale LNV could rule out high scale leptogenesis*

- *Discovery of heavy neutral leptons (HNL) could point to low scale leptogenesis*

TeV LNV & Leptogenesis



Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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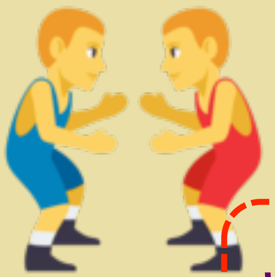
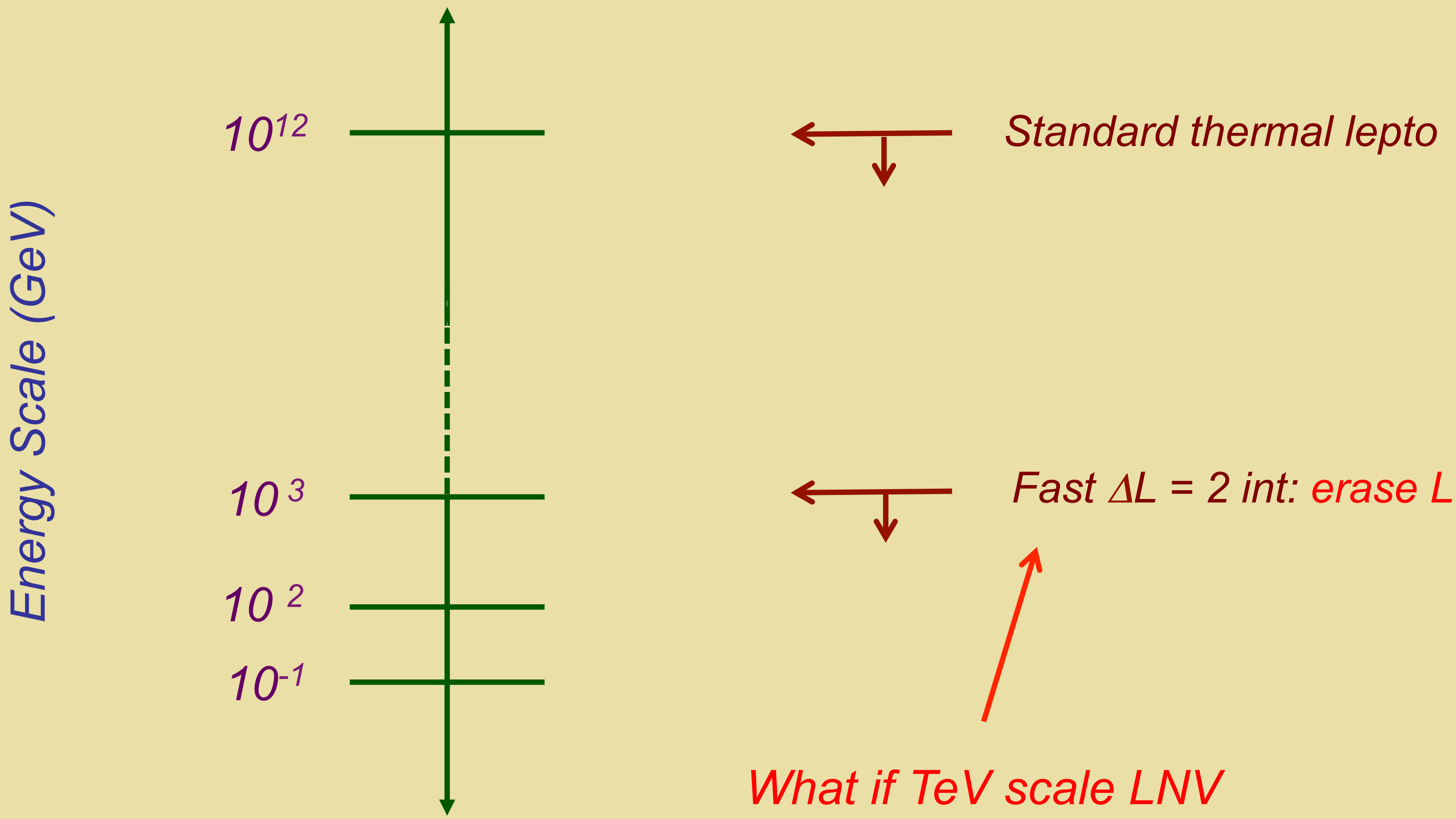


CPV Decay Asymmetry: source

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

TeV LNV & Leptogenesis



Deppisch et al '14, '15

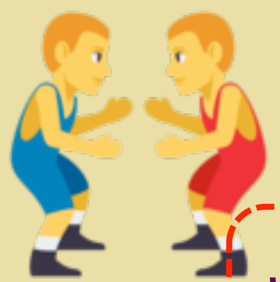
What if TeV scale LNV interactions exist ?

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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

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

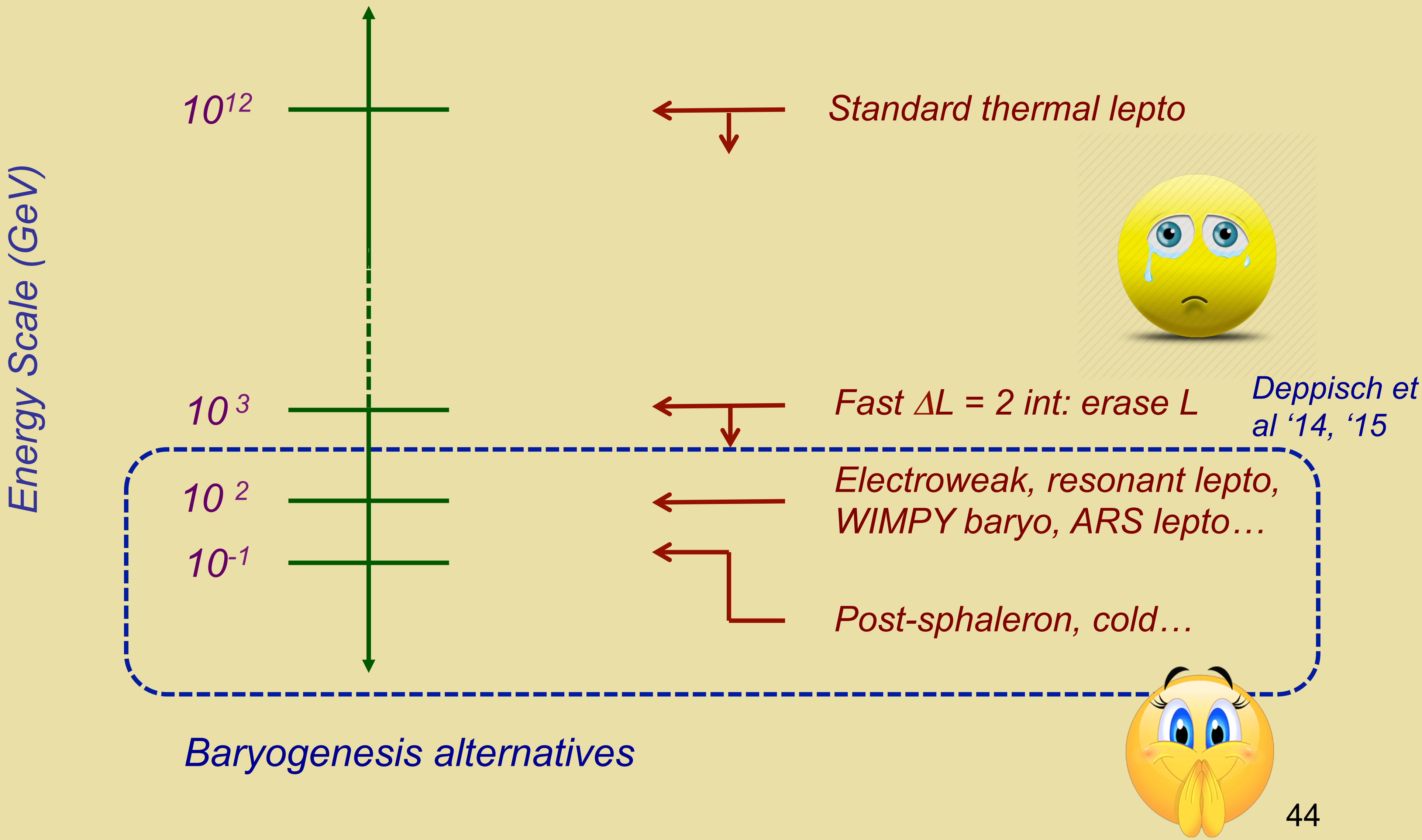


CPV Decay Asymmetry: source

TeV scale LNV can wipe out $Y_{B\text{-}L}$

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

TeV LNV & Leptogenesis



TeV Scale LNV: Models

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TeV Scale LNV: Models

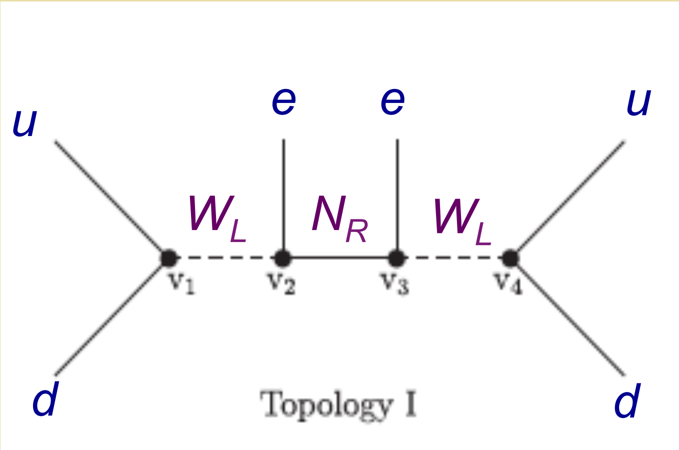
$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \mathrm{h.c.}$$

Dirac

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

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



νSM: Type I See-Saw

Mass: standard see-saw but TeV scale

TeV Scale LNV: Models

N_R

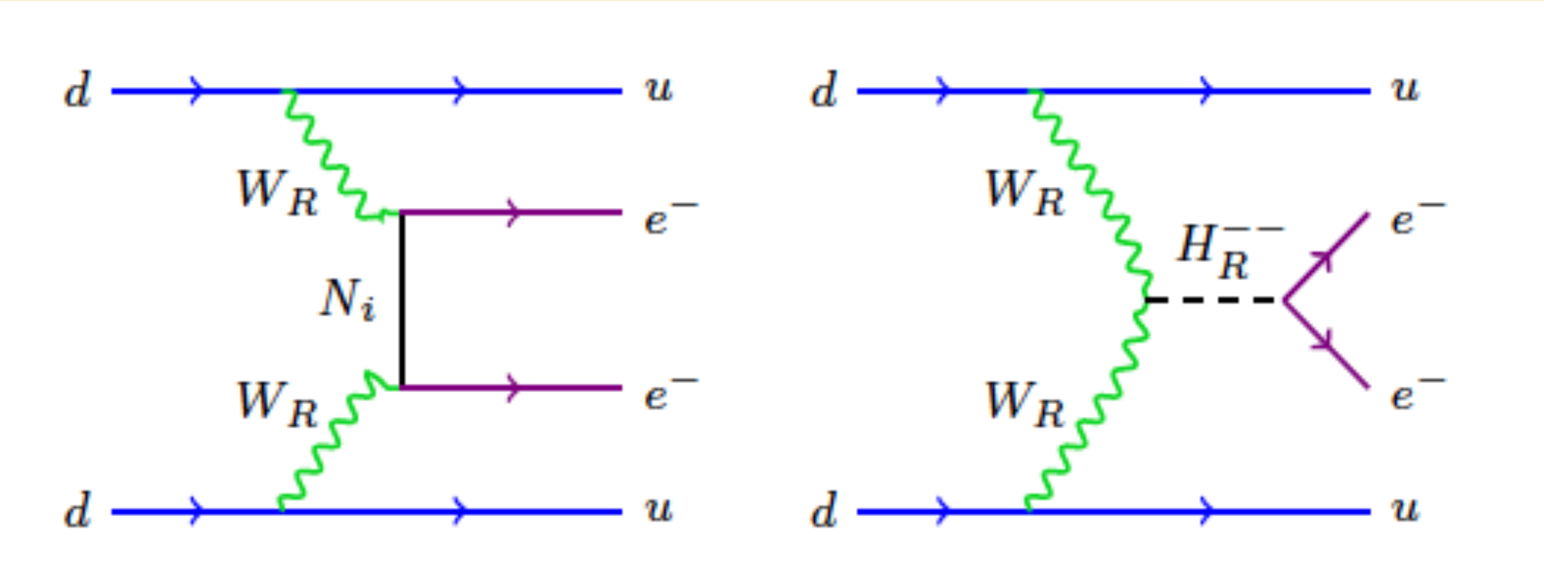
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

LRSM: Type I See-Saw **LRSM: Type II See-Saw**



TeV Scale LNV: Models

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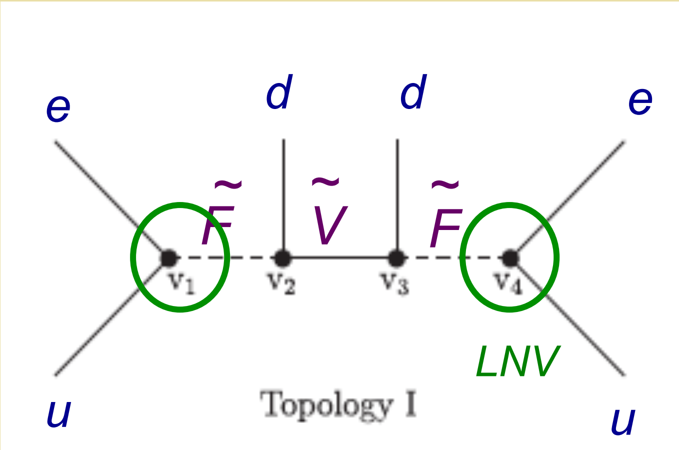


SUSY: R Parity-Violation

Sfermion $\tilde{q}$, $\tilde{l}$

Gaugino $\tilde{g}$, χ *Majorana*

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u,$$

TeV Scale LNV: Experimental Probes

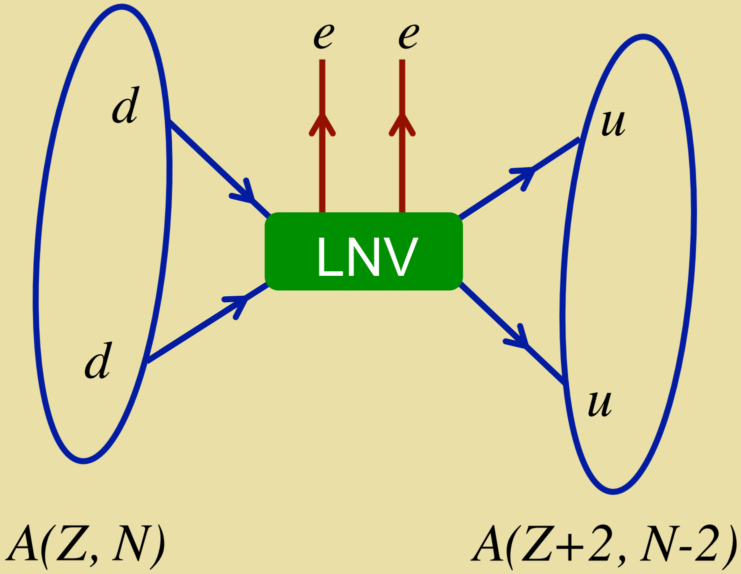
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

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

Majorana

$0\nu\beta\beta$-Decay

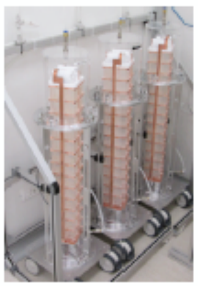


Low energy deep underground

Ton Scale Experiments: Worldwide Quest

0νββ decay Experiments - Efforts Underway

CUORE

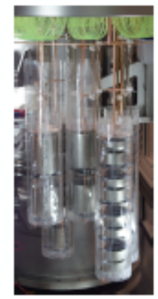


EXO200

KamLAND Zen

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	**100 kg - ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	**~ ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

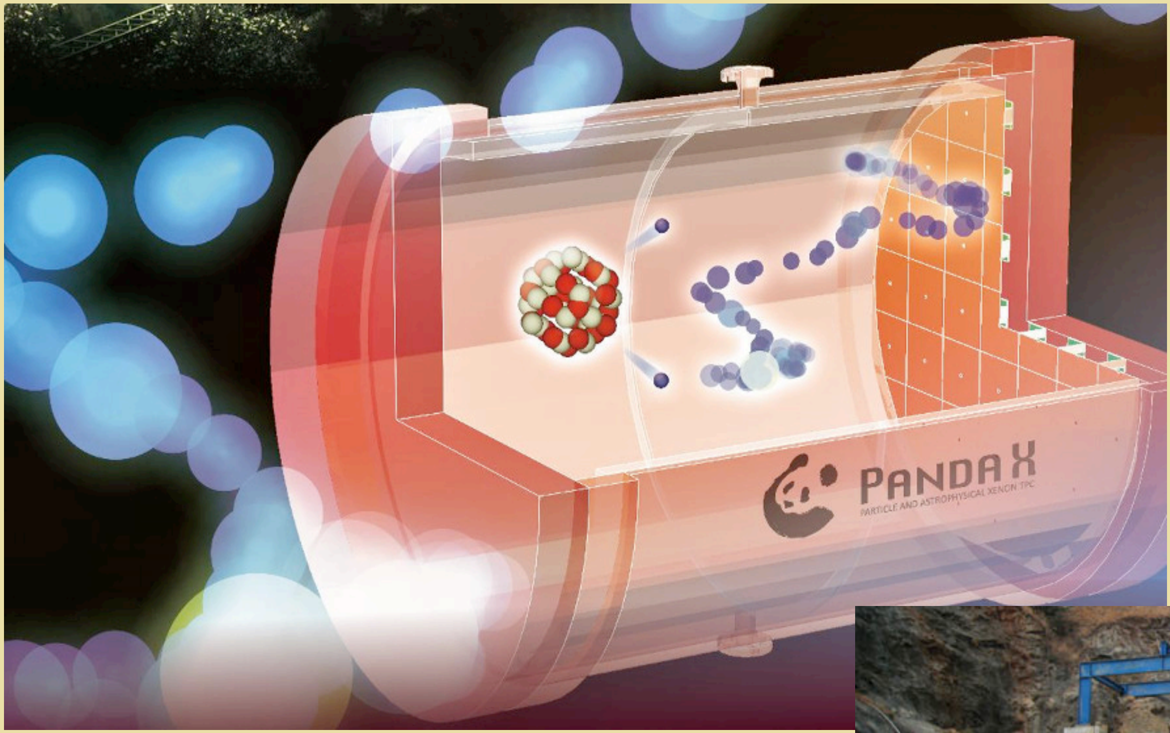
GERDA



MAJORANA

SNO+

The Chinese Context



PandaX III

TeV Scale LNV: Experimental Probes

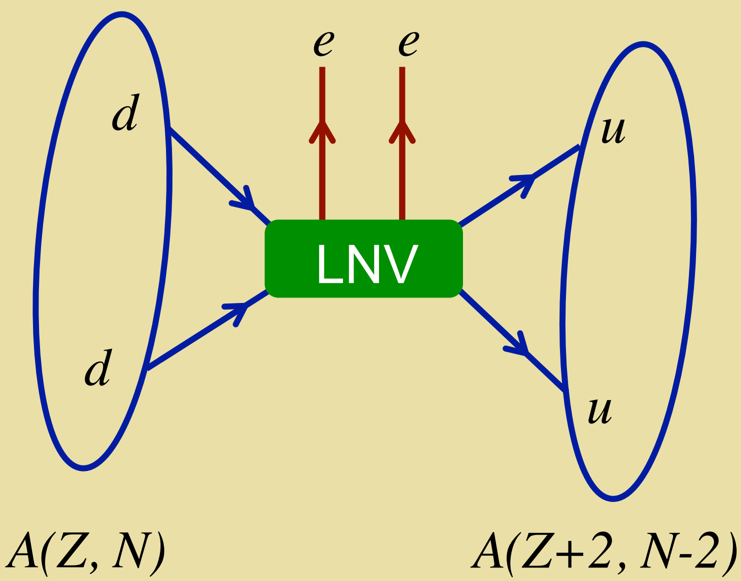
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

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

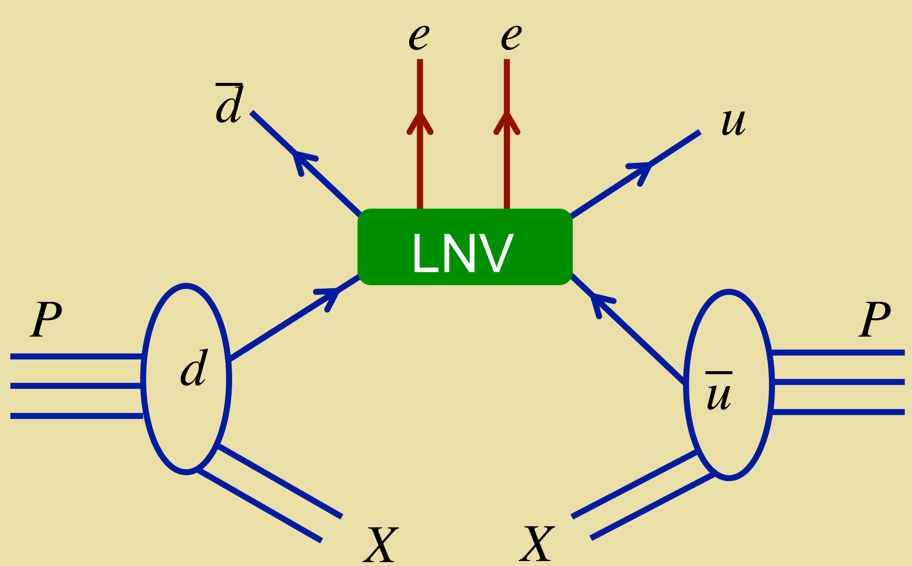
Majorana

0νββ-Decay



Low energy deep underground

pp Collisions



High energy

TeV Scale LNV: Experimental Probes

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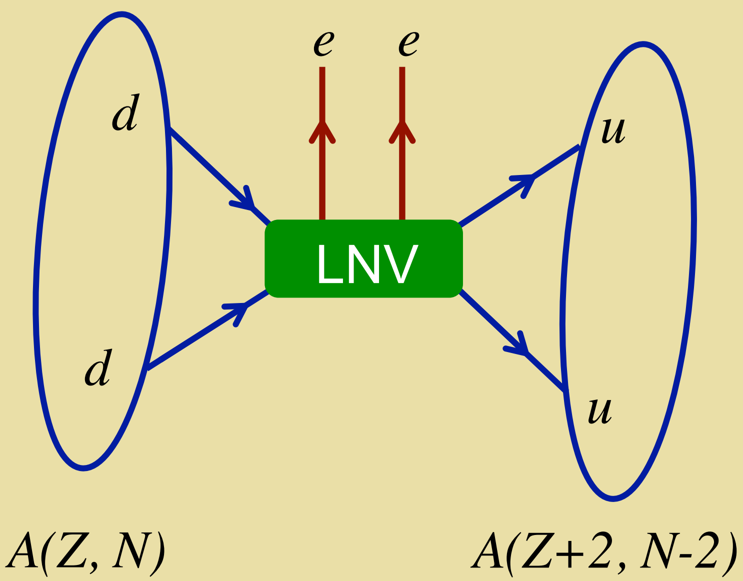
Majorana

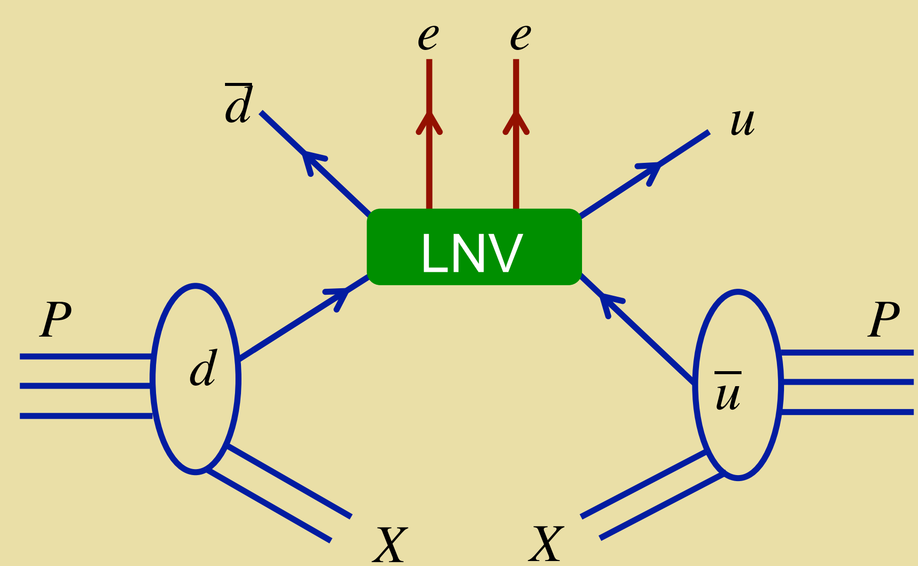
LHC: SS Dilepton + Dijet

0νββ-Decay



Low energy deep underground

pp Collisions



High energy

TeV Scale LNV: Experimental Probes

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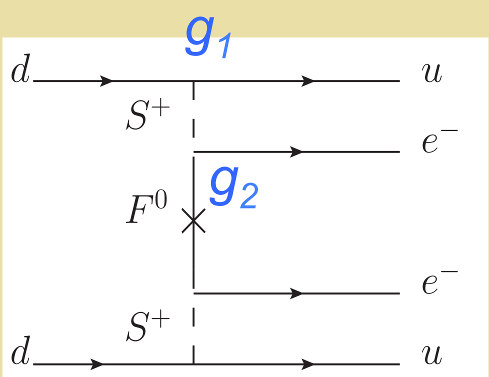
Dirac

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

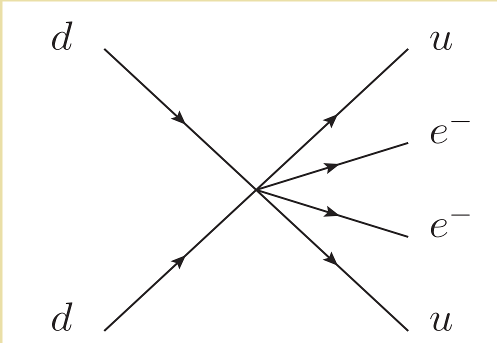
Majorana

LHC: pp $\rightarrow$ jj e⁻e⁻



TeV Scale LNV: "Simplified Models"

0νββ - decay



$$g_{\rm eff} = \sqrt{g_1 g_2}$$

TeV Scale LNV: Experimental Probes

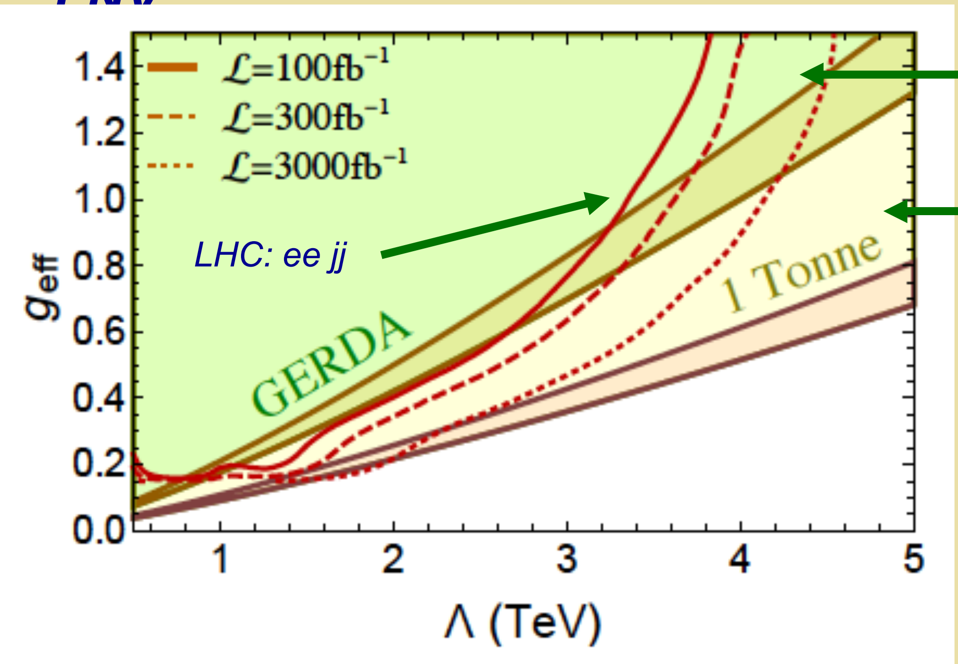
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R + \text{h.c.}$$

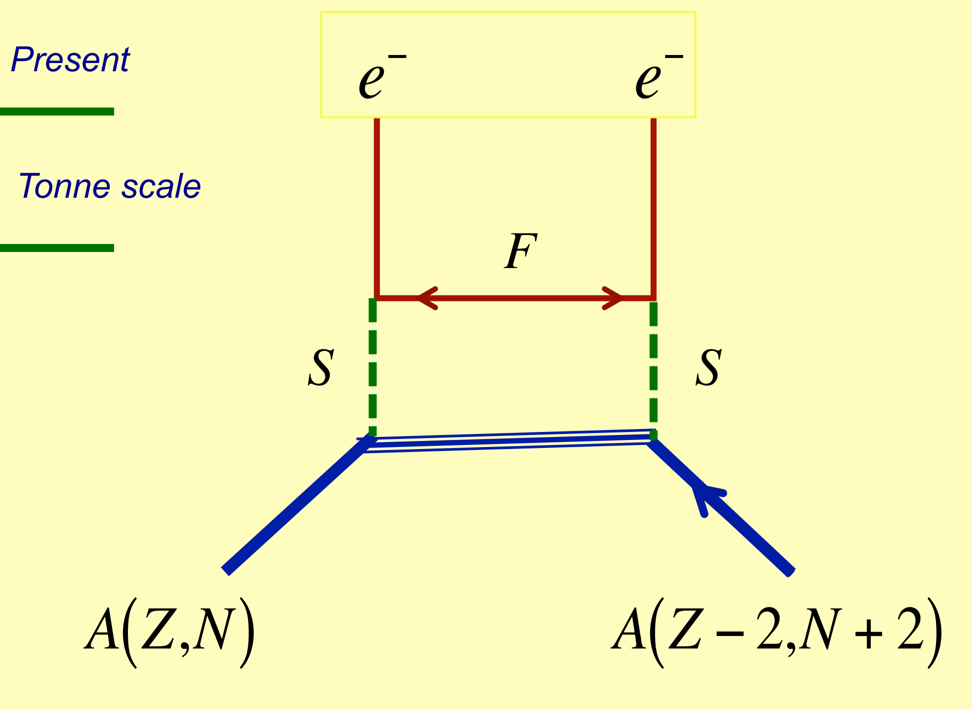
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





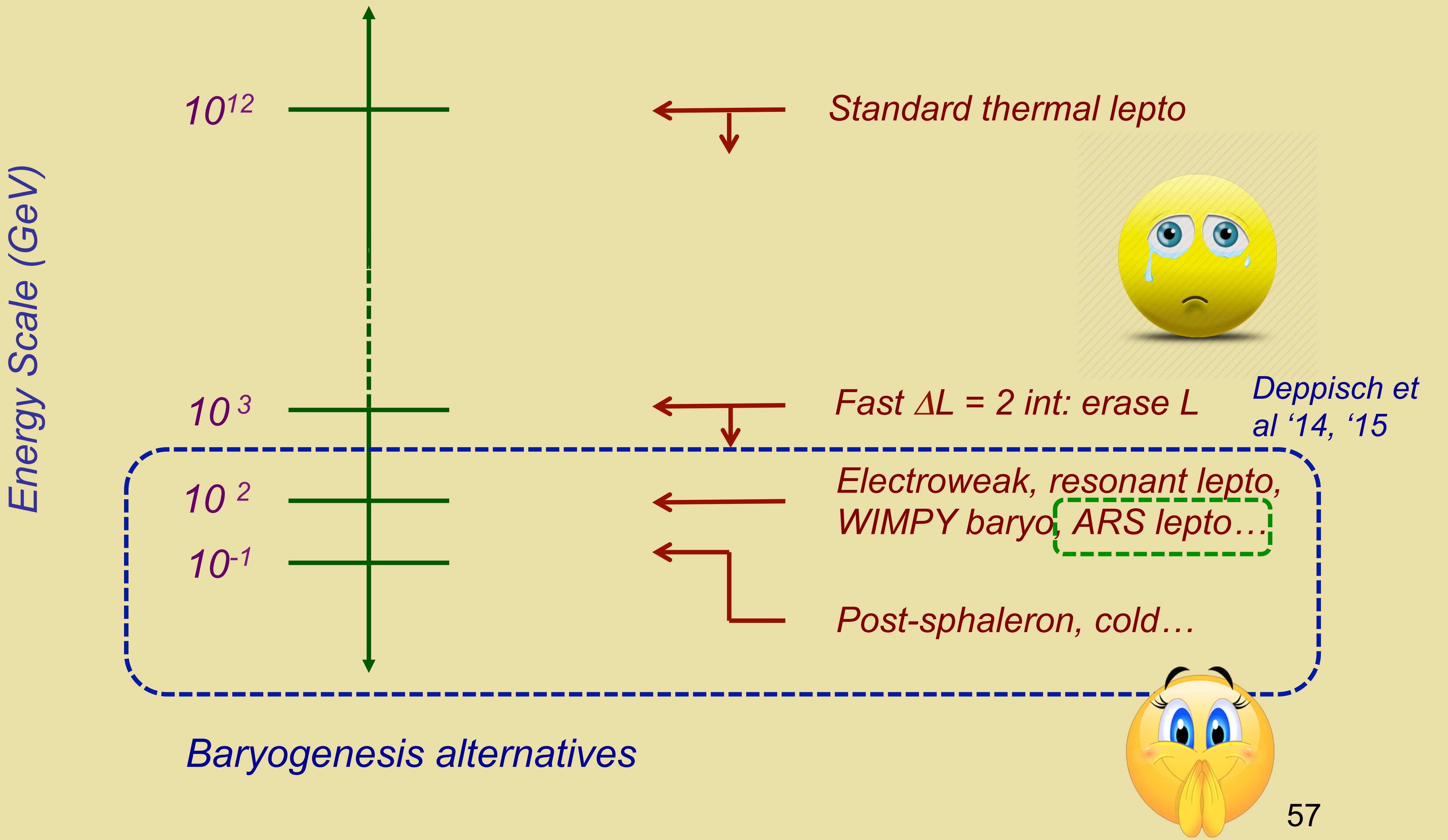
T. Peng, MRM, P. Winslow 1508.04444

Leptogenesis & Colliders

- *Discovery of TeV-scale LNV could rule out high scale leptogenesis*

- *Discovery of heavy neutral leptons (HNL) could point to low scale leptogenesis*

Low Scale Leptogenesis



Low Scale "ARS" Leptogenesis

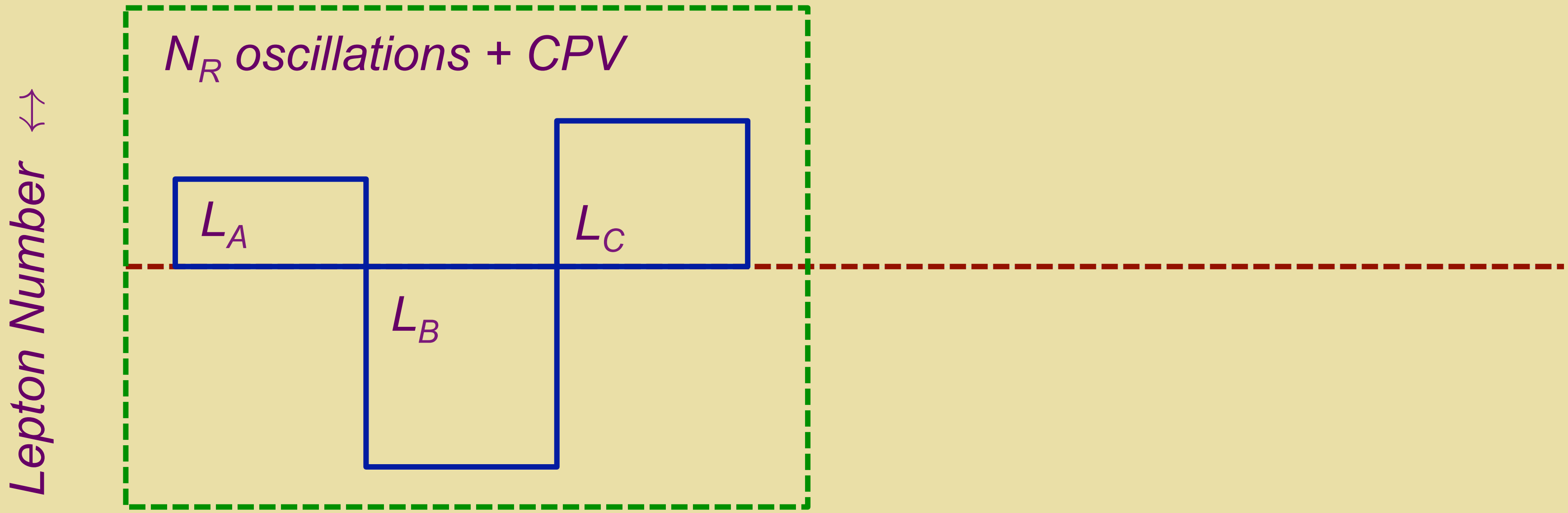
Leptogenesis from heavy neutrino oscillations

- *Right handed N_A , N_B , N_C oscillate*
- *Oscillations have a CPV component*
- *Each heavy flavor has non-zero L but $L_{TOT} = 0$*

Akhmedov, Rubakov, Smirnov '98

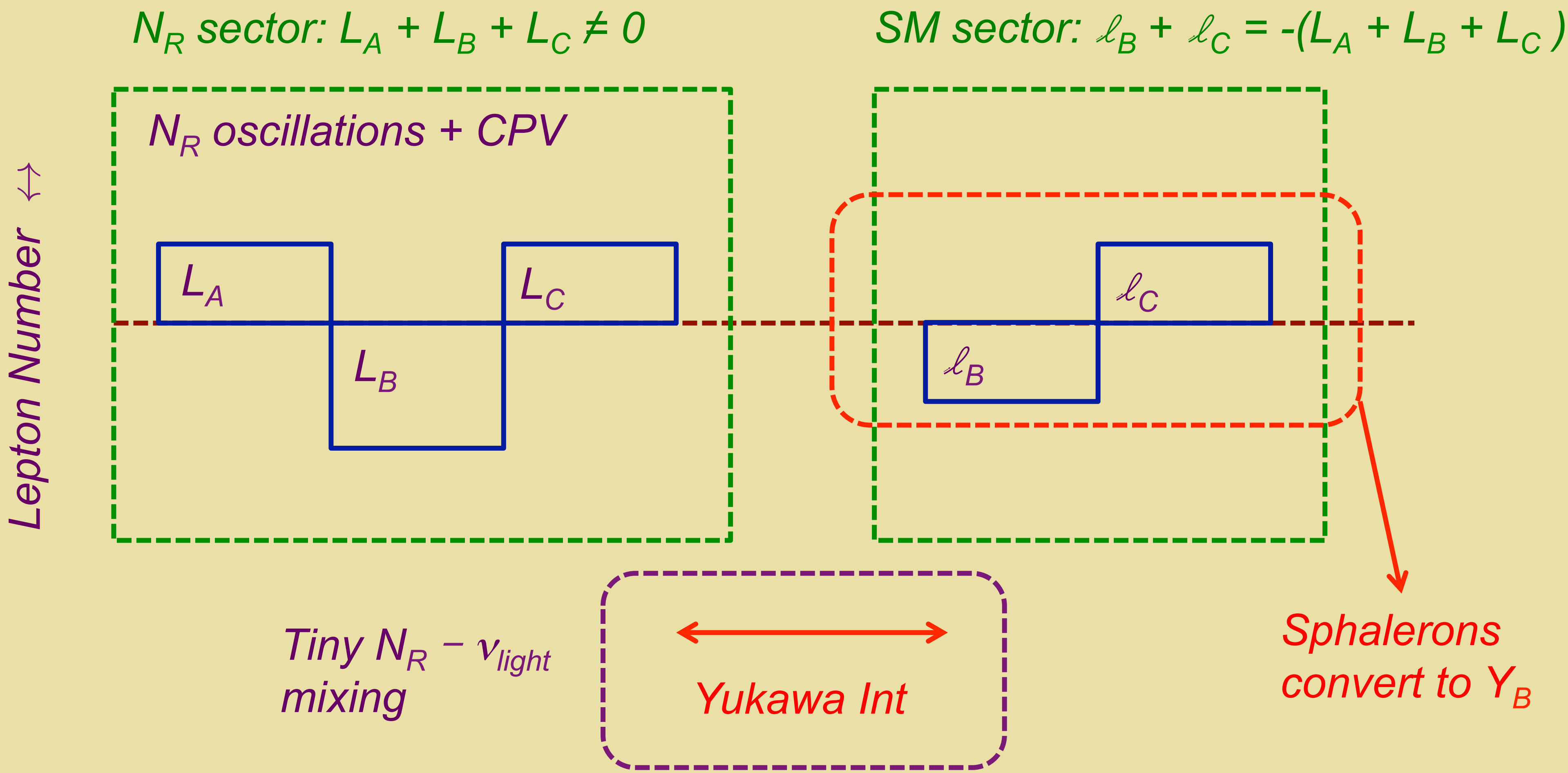
Low Scale "ARS" Leptogenesis

N_R sector: $L_A + L_B + L_C = 0$



Akhmedov, Rubakov, Smirnov '98

Low Scale "ARS" Leptogenesis



Akhmedov, Rubakov, Smirnov '98

RH Sterile Neutrinos

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

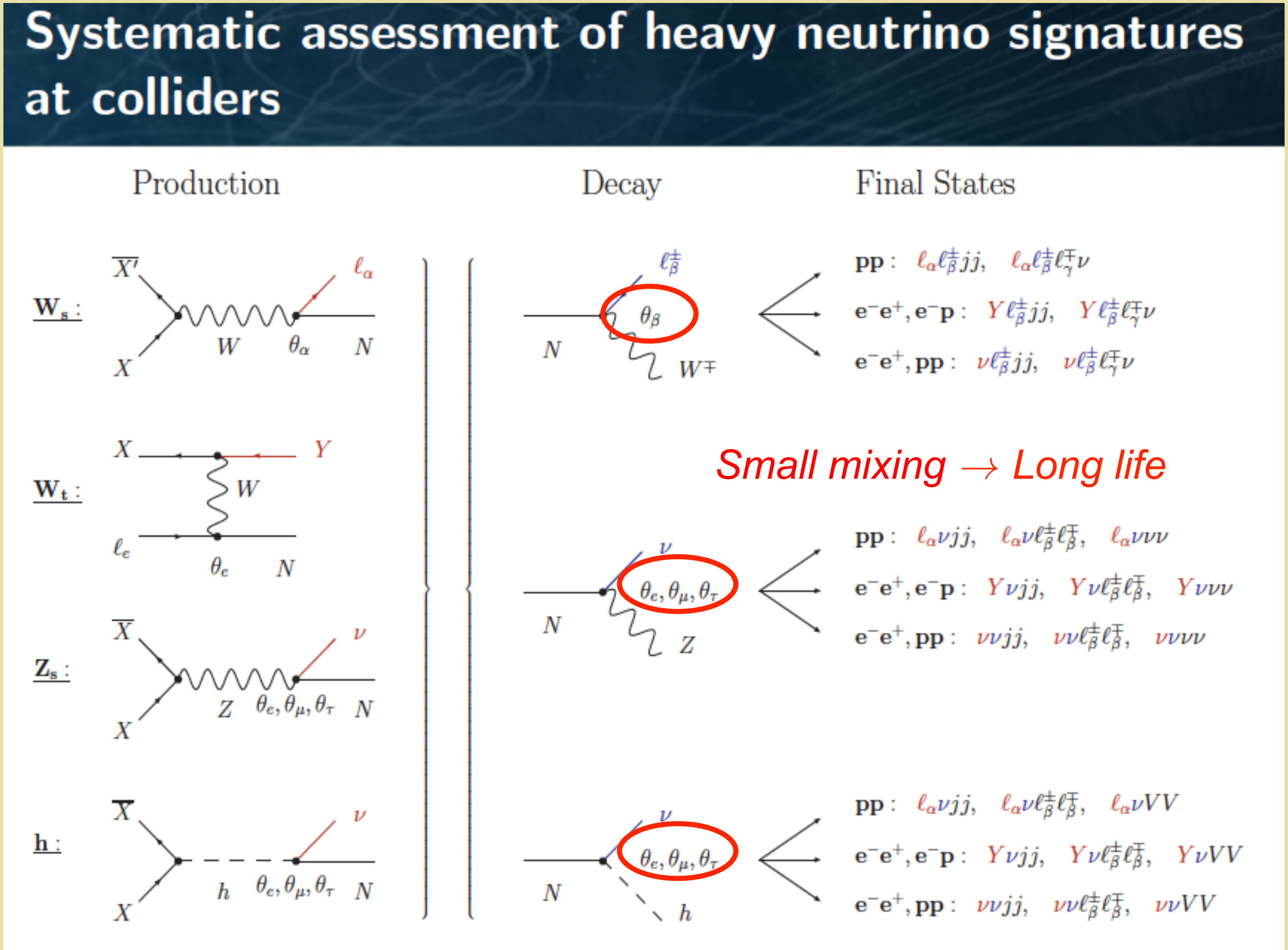
$$\begin{pmatrix} |\nu_\ell\rangle \\ |N_R\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{\ell N} & \sin\theta_{\ell N} \\ -\sin\theta_{\ell N} & \cos\theta_{\ell N} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Heavy neutrino

$$|\nu_2\rangle = \cos\theta_{\ell N}\ |N_R\rangle + \sin\theta_{\ell N}\ |\nu_\ell\rangle$$

"Sterile" *Small mixing* *St'd Model*

RH Sterile Neutrinos: Many Signatures



E. Cazzato

Long Lived Heavy Neutral Leptons

Lessons from τ_μ *:* $Y \rightarrow X^* \rightarrow SM$

Phase space (192 π^3 *~ 6000)*

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g_X^4} \left(\frac{M_X}{M_Y}\right)^4 \left(\frac{1\,\mathrm{TeV}}{M_Y}\right)$$

Muon decay:

- M_X *~ 80 GeV,* M_Y *~ 0.1 GeV &* g_X^4 *~ 0.004* $\rightarrow$ $c\tau$ *~ 660 m* *

** Additional ½ for half-life*

Long Lived Heavy Neutral Leptons

Lessons from τ_μ :

$Y \to X^* \to SM$

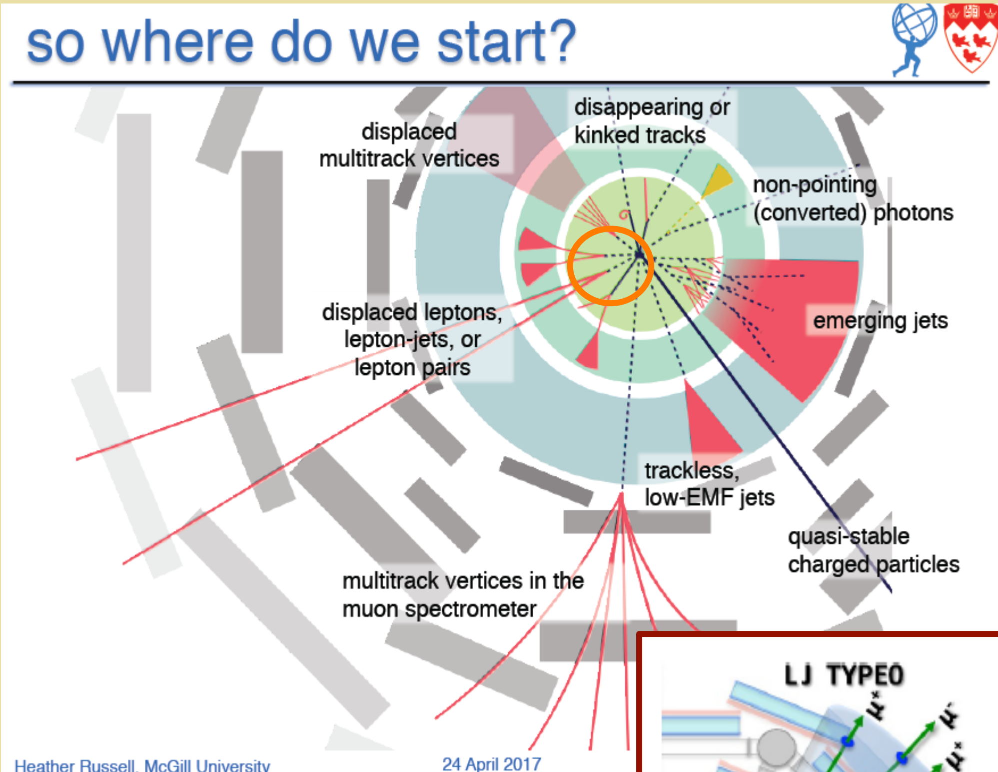
Phase space ($192\,\pi^3 \sim 6000$)

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g_X^4} \left(\frac{M_X}{M_Y}\right)^4 \left(\frac{1\,\mathrm{TeV}}{M_Y}\right)$$

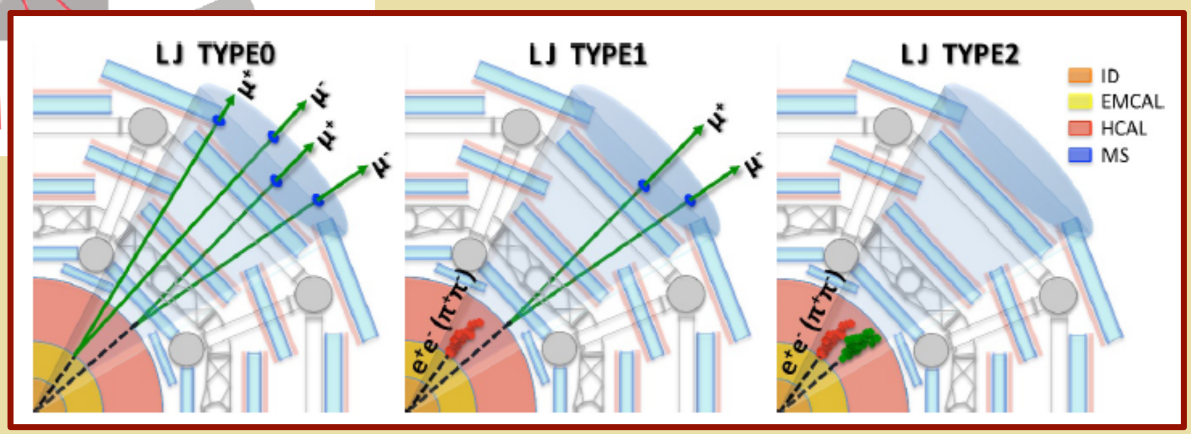
BSM Examples:

- $M_X \sim 100$ GeV, $M_Y \sim 10$ GeV , $g_X^4 \sim 10^{-7} \to$ $c\tau \sim 1$ cm N_R decay

Displaced Lepton Jets

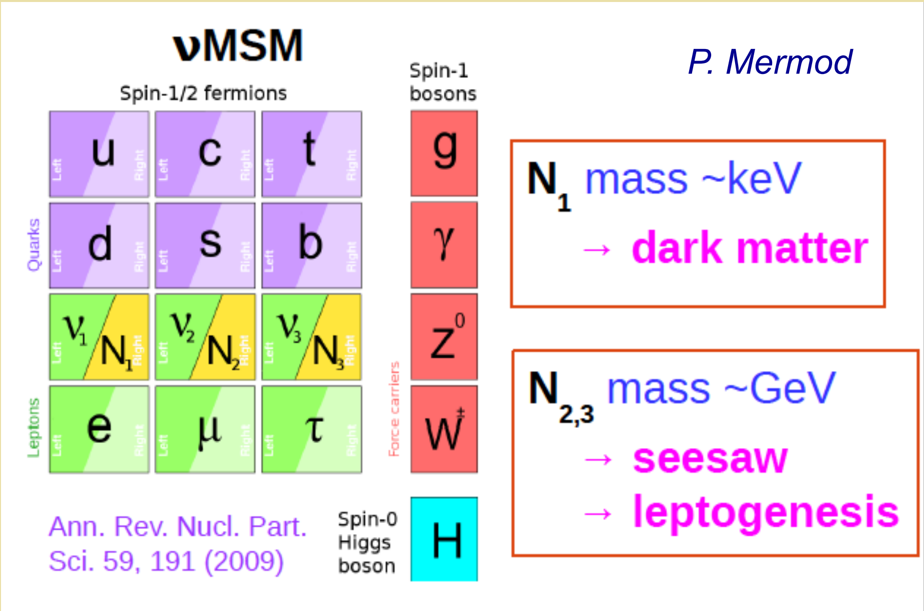


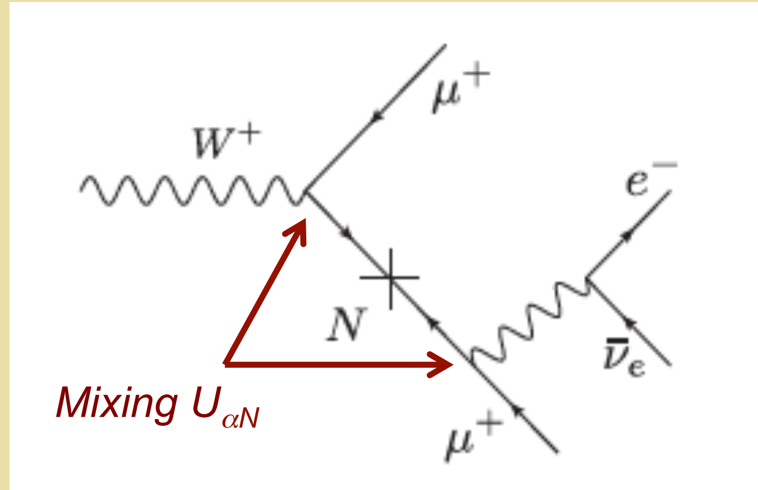
H. Russell, CERN LLP workshop, April 17

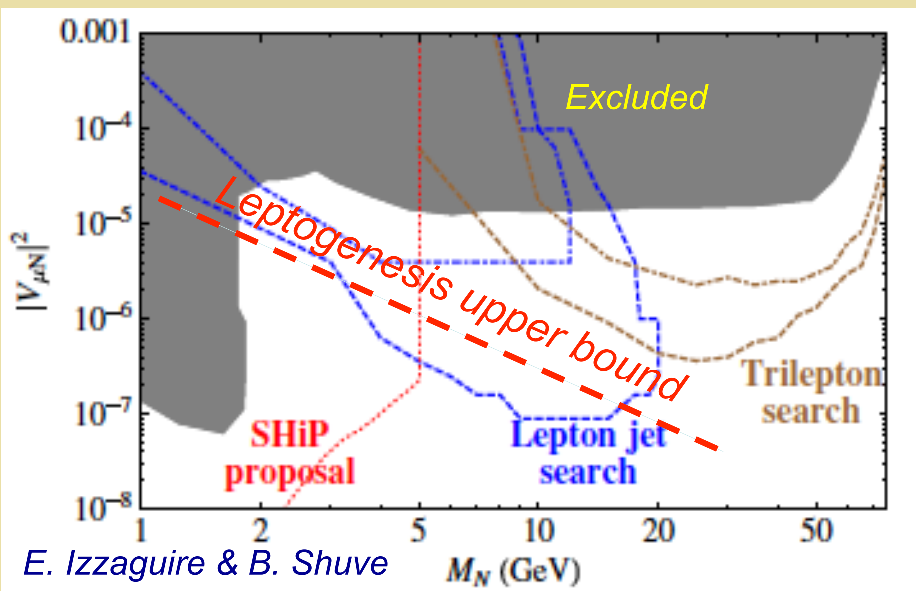


ATLAS JHEP11 (2014) 88

Solutions w/ LLP's: νSM



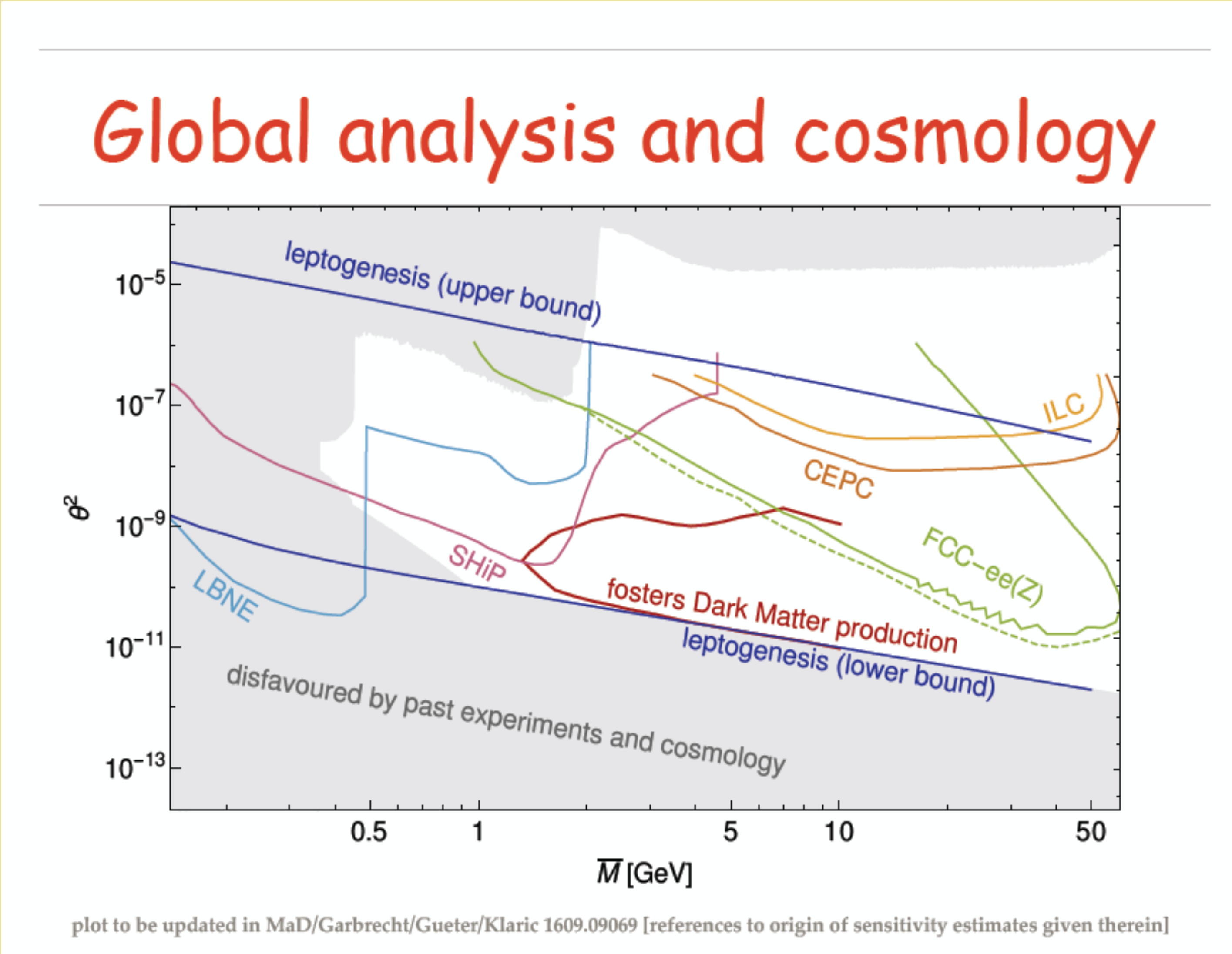




$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

- *Displaced LJ + μ*
- *3 resolved prompt leptons*

“ARS” Leptogenesis & Future Colliders

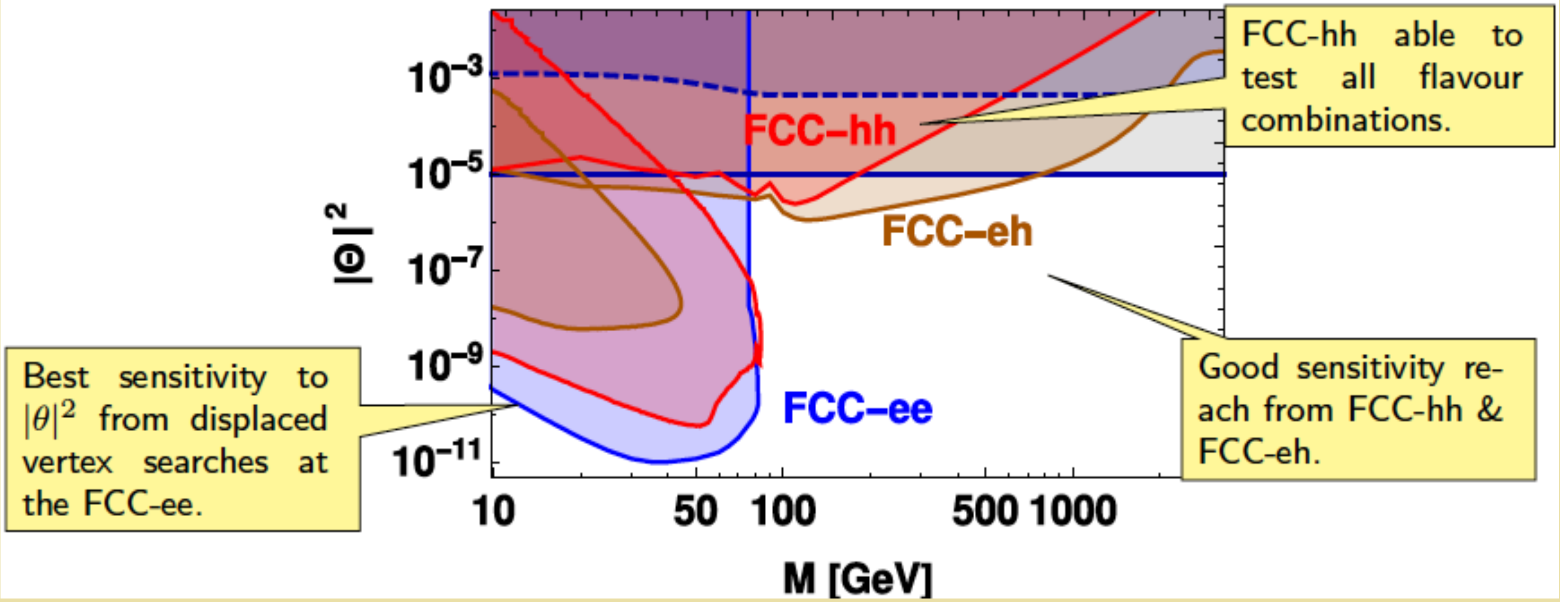


M. Drewes

RH Sterile Neutrinos: FCC & CEPC

Summary

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



E. Cazzato

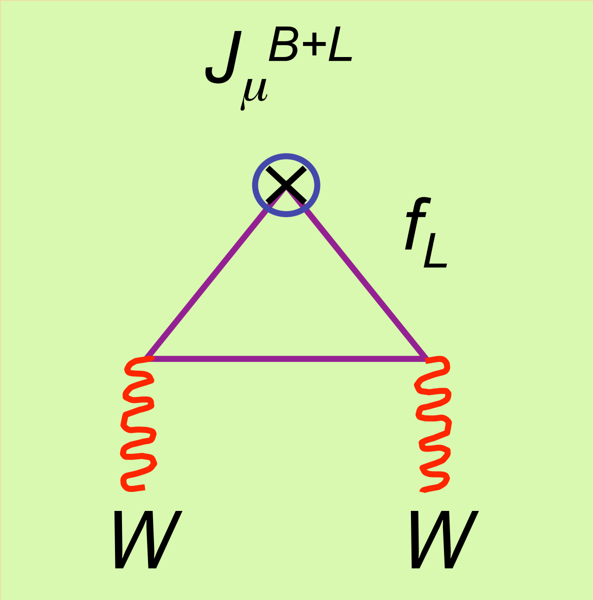
Lecture II Key Ideas

- *Seesaw mechanism to explain small m_ν*
- *Standard thermal leptogenesis: connecting seesaw mechanism to Y_B*
- *Anomalous symmetry breaking via EW sphalerons*
- *Low-scale leptogenesis alternatives: ARS leptogenesis (oscillations)*
- *Collider implications: observing TeV scale LNV & HNL's*

Back Up Slides

Electroweak Sphalerons

B+L Anomaly



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

Electroweak Sphalerons

Cherns Simons Number

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

$$N_{CS}(t) = \frac{g^3}{96\pi^2} \int d^3x \, \epsilon_{ijk} \; \epsilon_{abc} W_i^a W_j^b W_k^c$$

$$\Delta(B + L) = 2N_F \times \Delta N_{CS}$$

TeV Scale LNV ?

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

Dirac

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

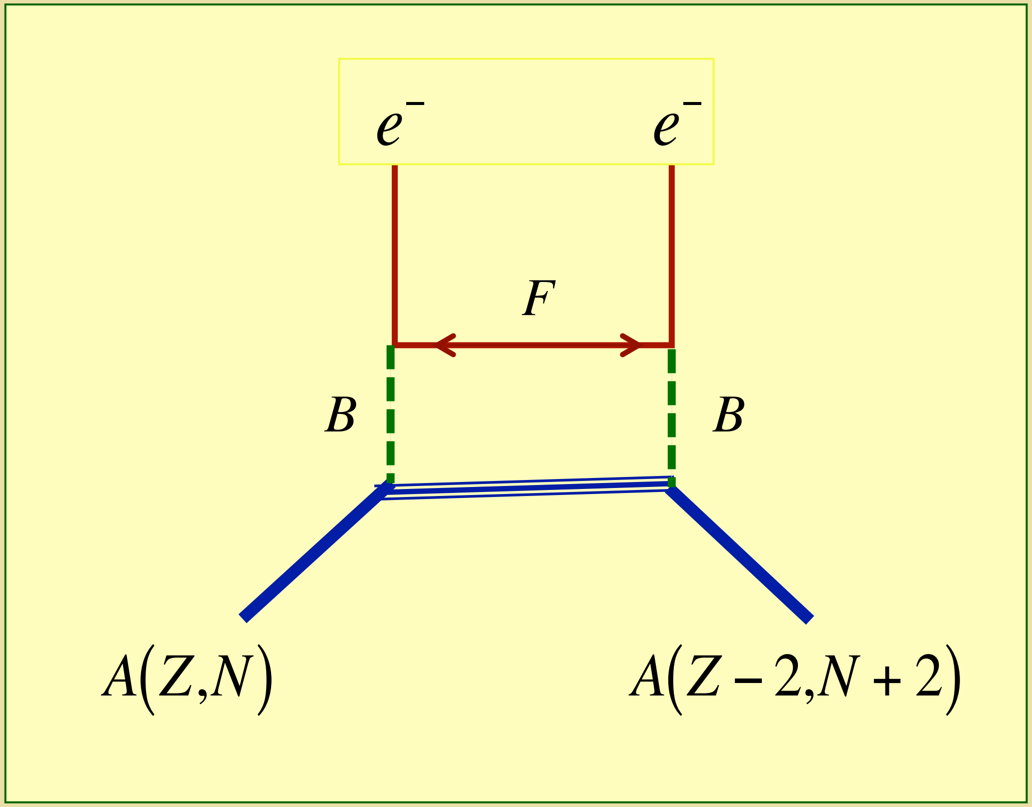
Majorana

TeV LNV Mechanism

$$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

O(1) for Λ ~ 1 TeV

Implications



TeV Scale LNV: Experimental Probes

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

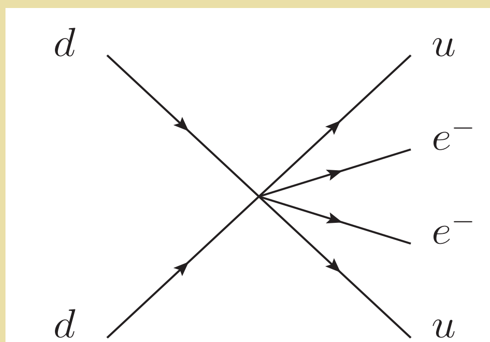
Dirac

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

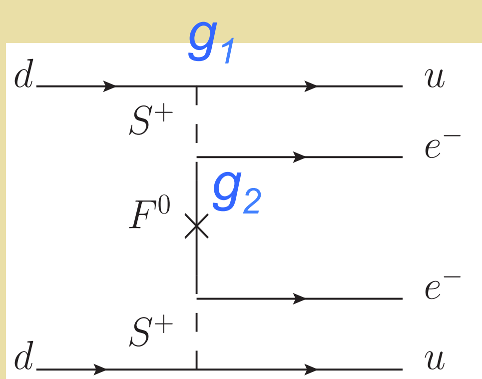
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



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



Effective operators:

$$\mathcal{L}^{\text{eff}}_{\text{LNV}} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + \text{h.c.}$$

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

$$g_{\text{eff}} = \sqrt{g_1 g_2}$$

TeV Scale LNV: Experimental Probes

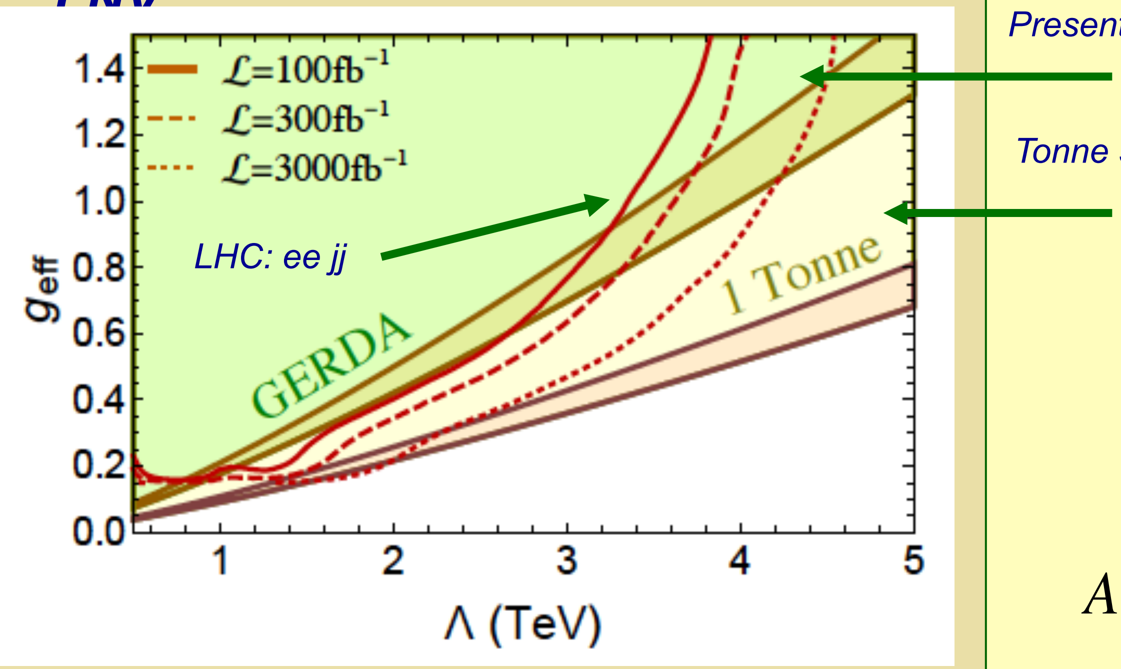
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

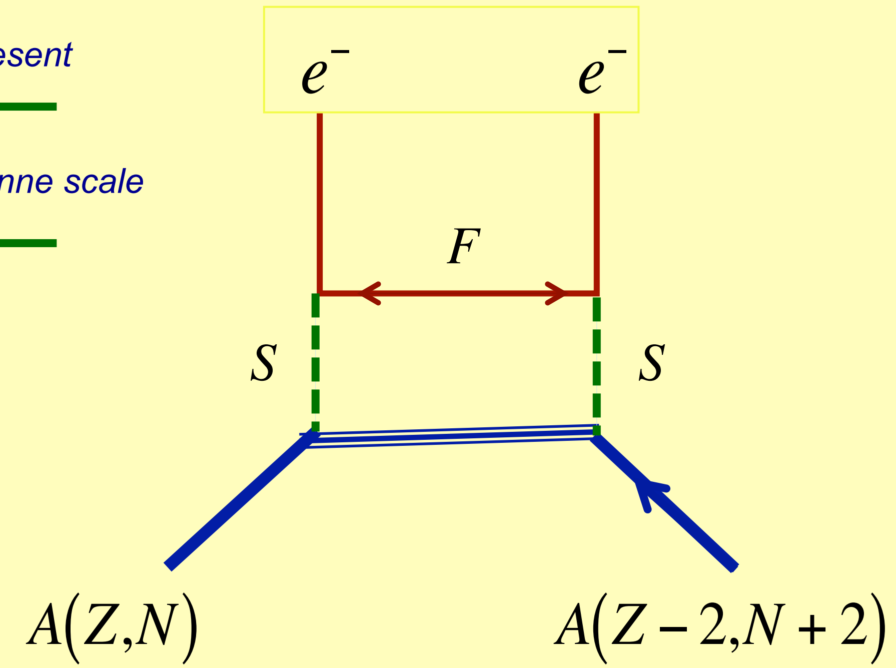
Dirac

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

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

TeV Scale LNV: Experimental Probes

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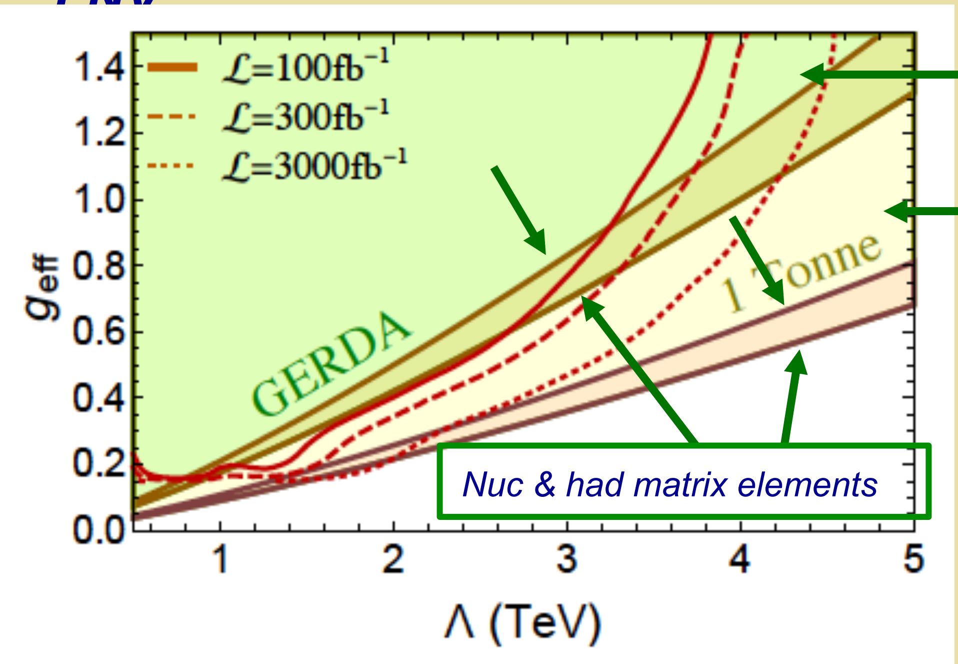
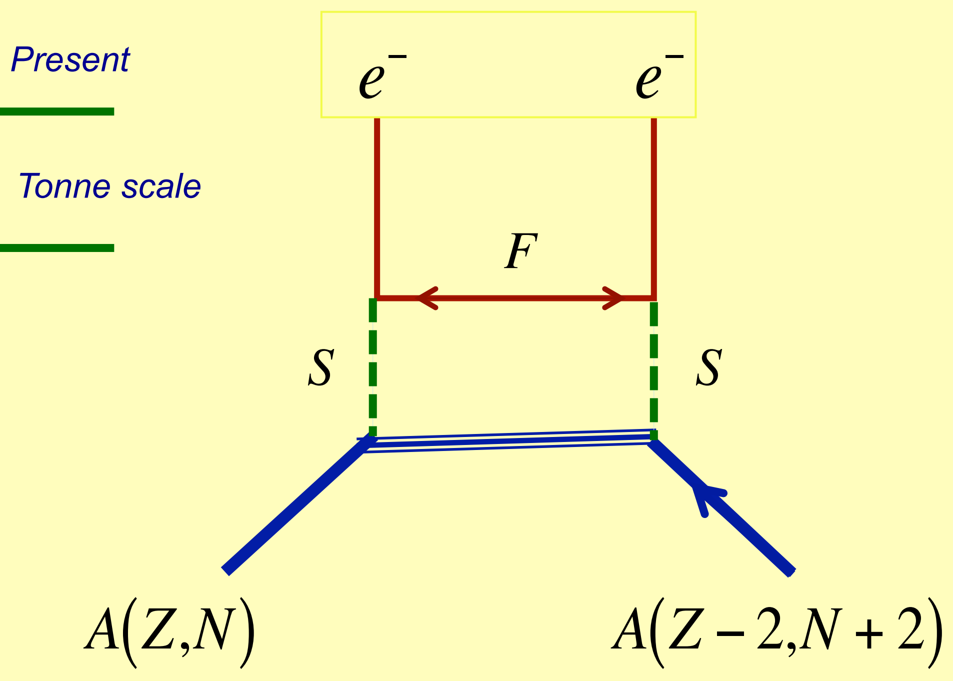




T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

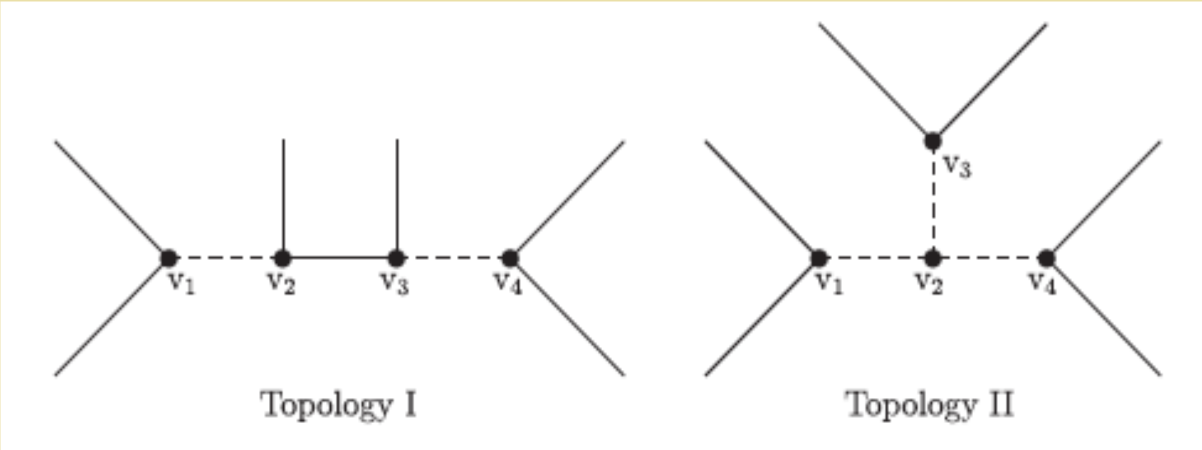
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

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

Majorana

General Classification: Helo et al, PRD 88.011901, 88.073011



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

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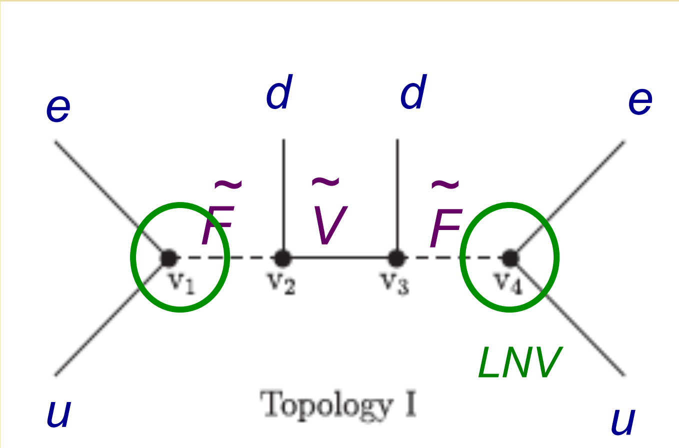
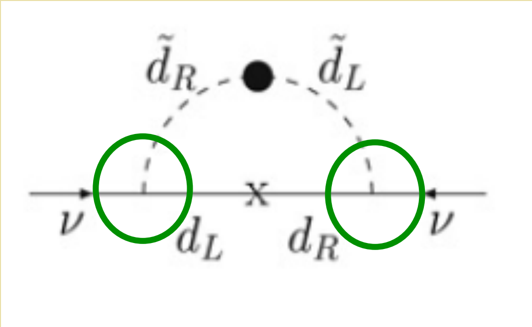


SUSY: R Parity-Violation



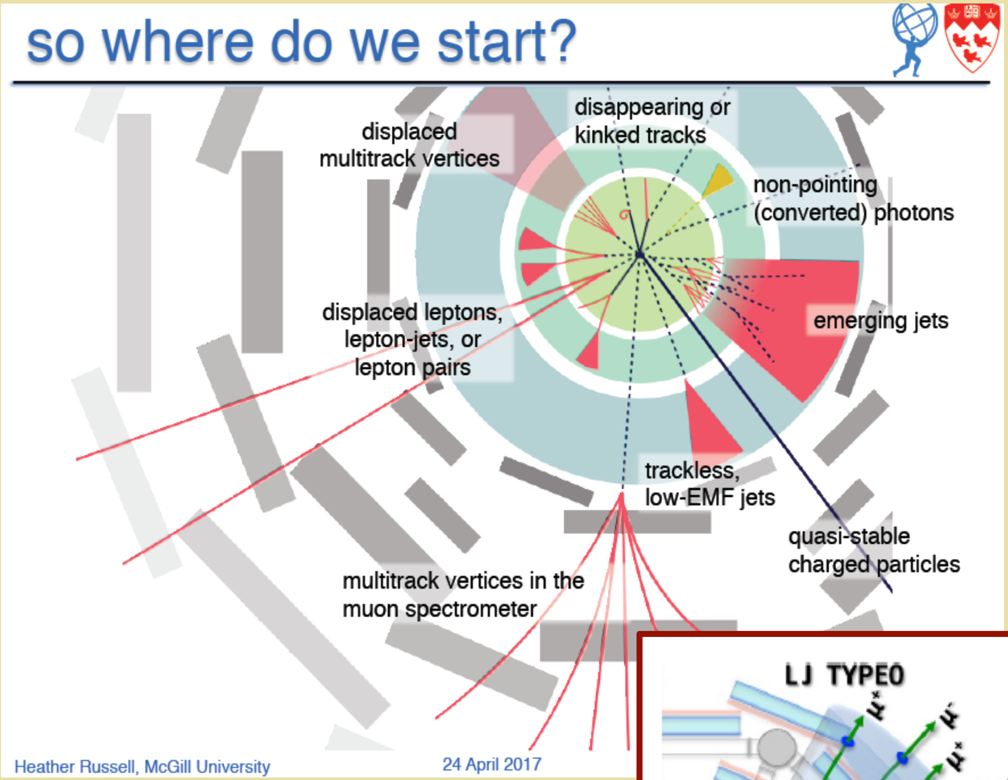
$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u,$$

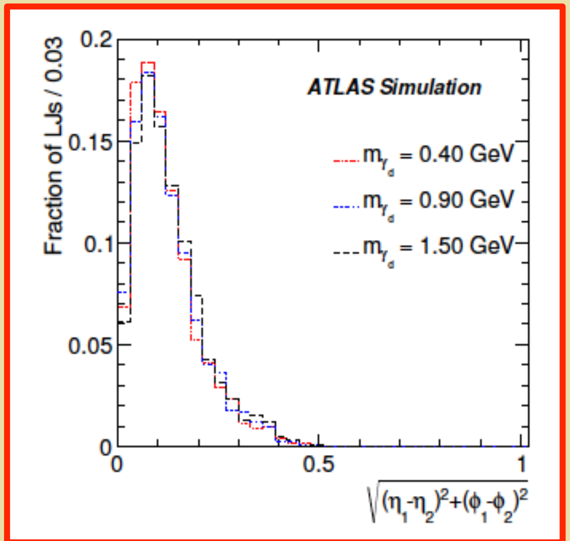
Low Scale "ARS" Leptogenesis

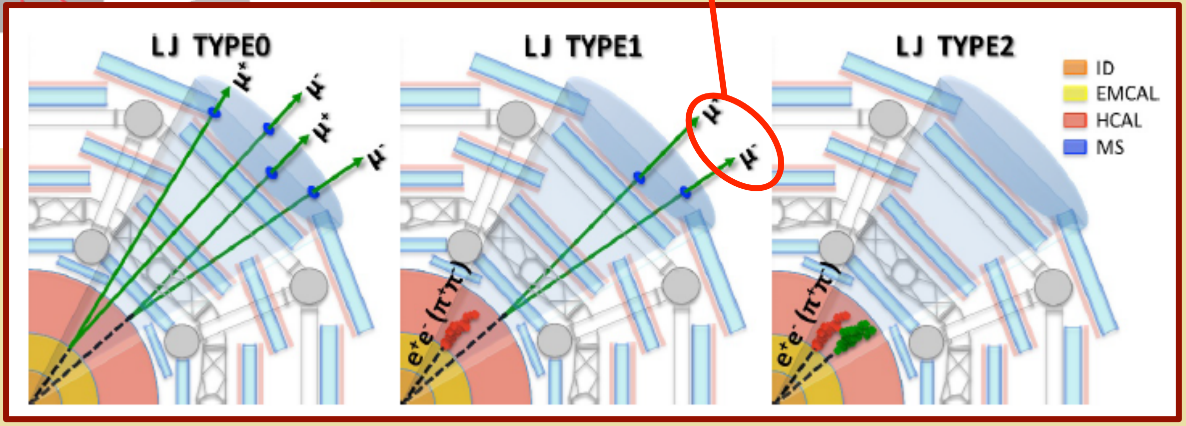
1. 3 Singlet RH neutrinos: N_A , N_B , N_C
2. $L^{TOT} = L^{SM} + L_A + L_B + L_C$
3. N_k oscillations + CPV $\rightarrow$ $L_A \neq 0$, $L_B \neq 0$, $L_C \neq 0$ but $L^{TOT} = 0$
4. Yukawa interactions: $L_k \Leftrightarrow H + \ell_k$ in equilibrium above T_{EW} for k=B,C but not for k=A
5. Lepton number for $\ell_{B,C}$ converted to n_B by EW sphalerons
6. Conditions 4 $\rightarrow$ M_{Nk} can be ~ O(GeV)

Akhmedov, Rubakov, Smirnov '98

Displaced Lepton Jets





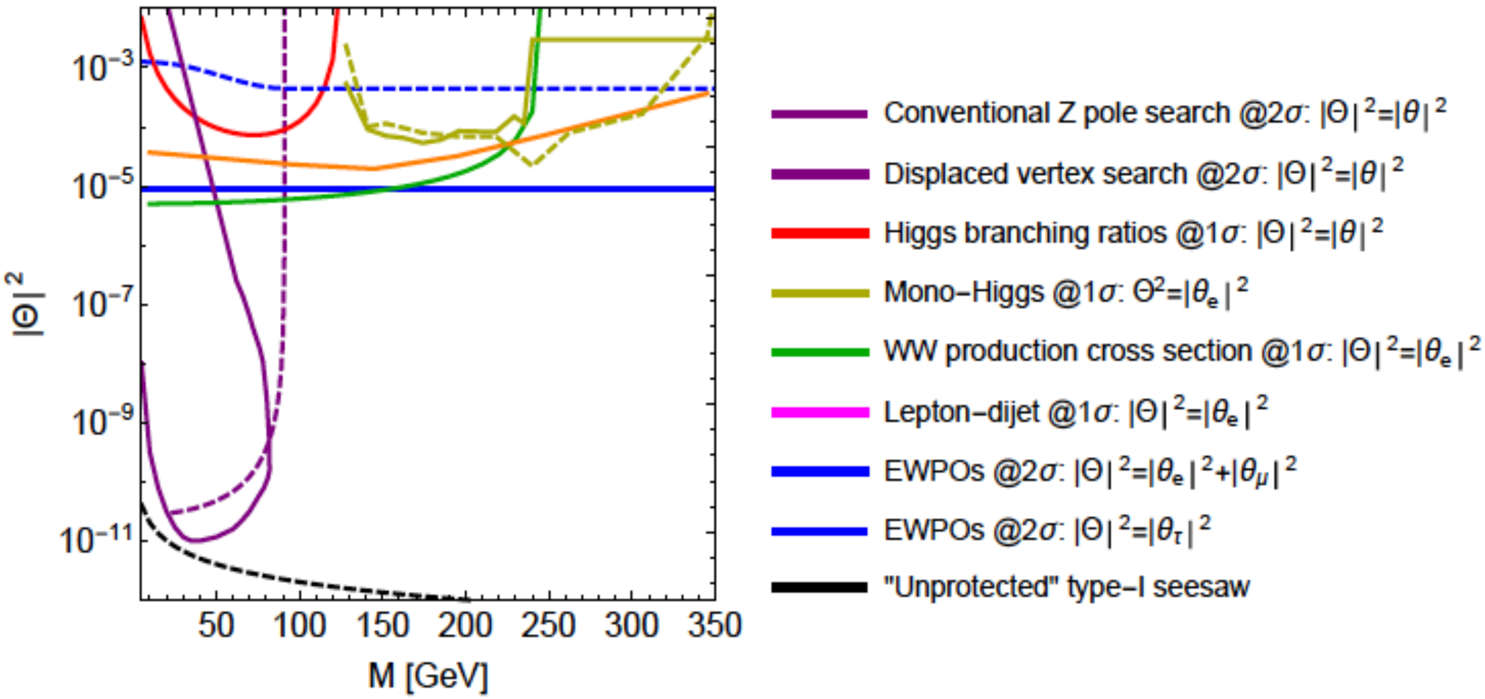


H. Russell, CERN LLP workshop, April 17

ATLAS JHEP11 (2014) 88

RH Sterile Neutrinos

Summary: FCC-ee sensitivities



- Displaced vertex searches test $|\theta|^2 \sim 10^{-11}$ for $M \leq m_W$.
- EWPOs test $|\theta|^2 \sim 10^{-5}$ up to $M \sim 60$ TeV with $\mathcal{O}(1)$ Yukawa couplings.

O. Fischer, ACFI '17 Workshop