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Some News on HNLs

11. 11. 2021

LLPX Workshop

Overview

- Pure type I seesaw: reinterpretation news
- Non-minimal models: pheno news
- Pure type I seesaw: leptogenesis news
- Non-minimal models: leptogenesis news

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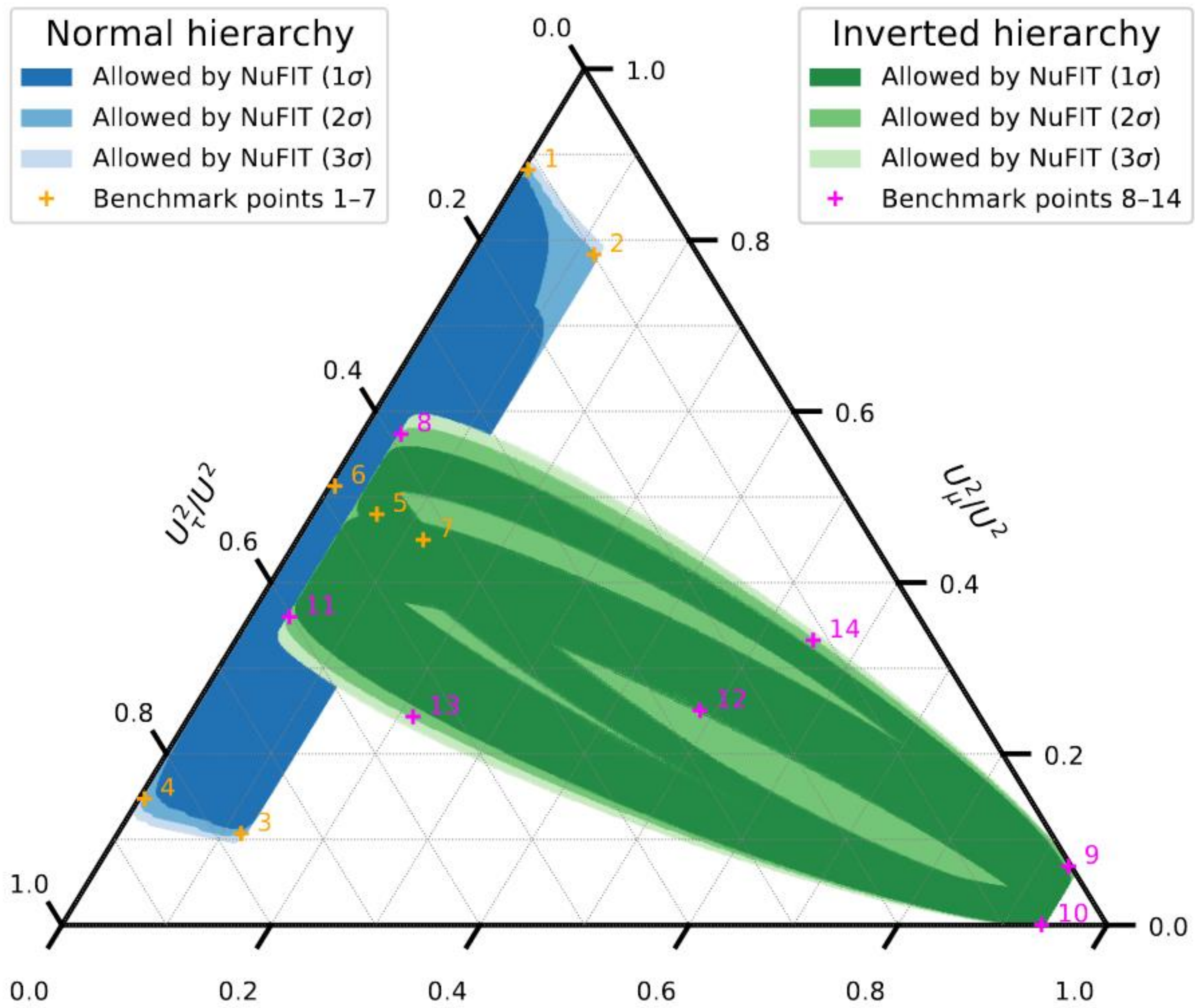
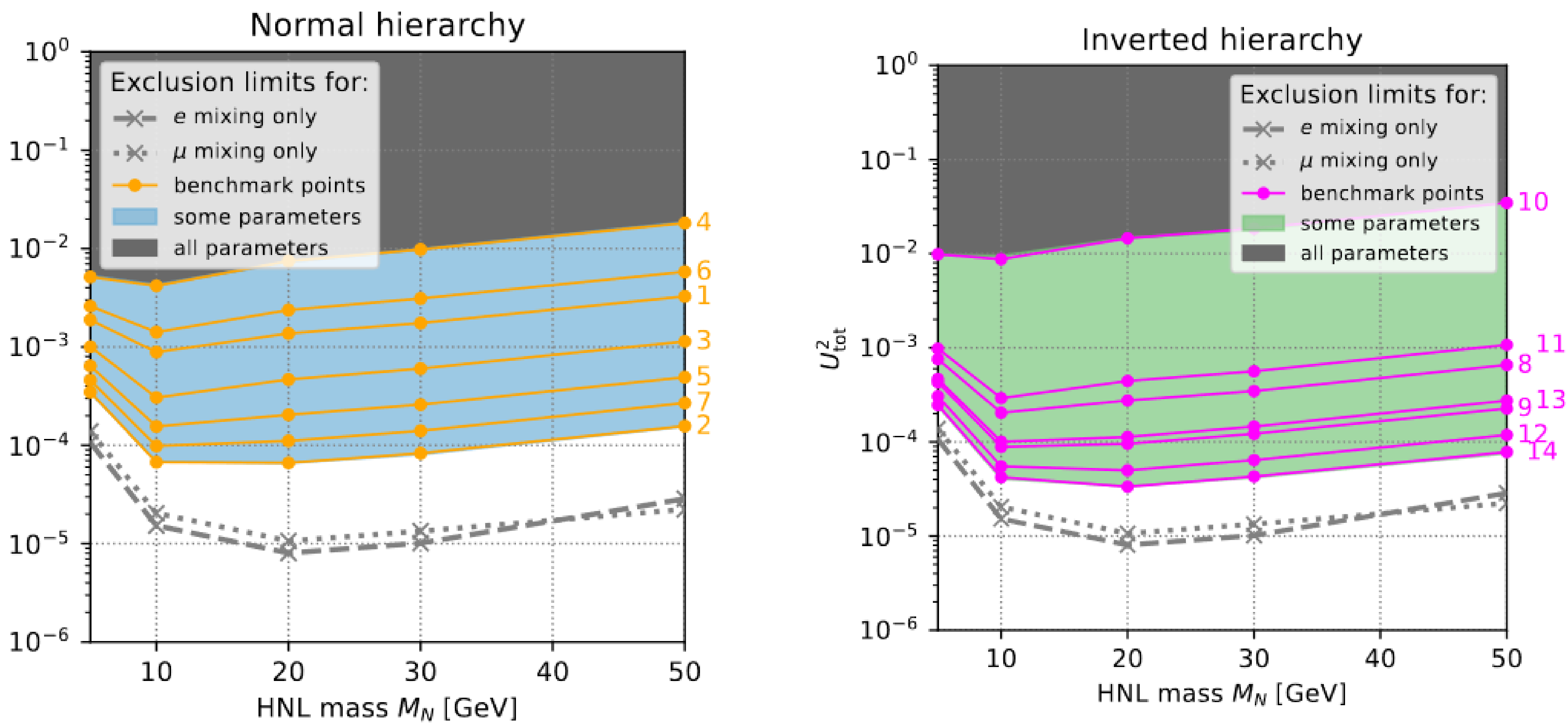
Constraints from ν-Oscillation Data in Model with 2 Heavy Neutrinos



Tastet et al 2107.12980

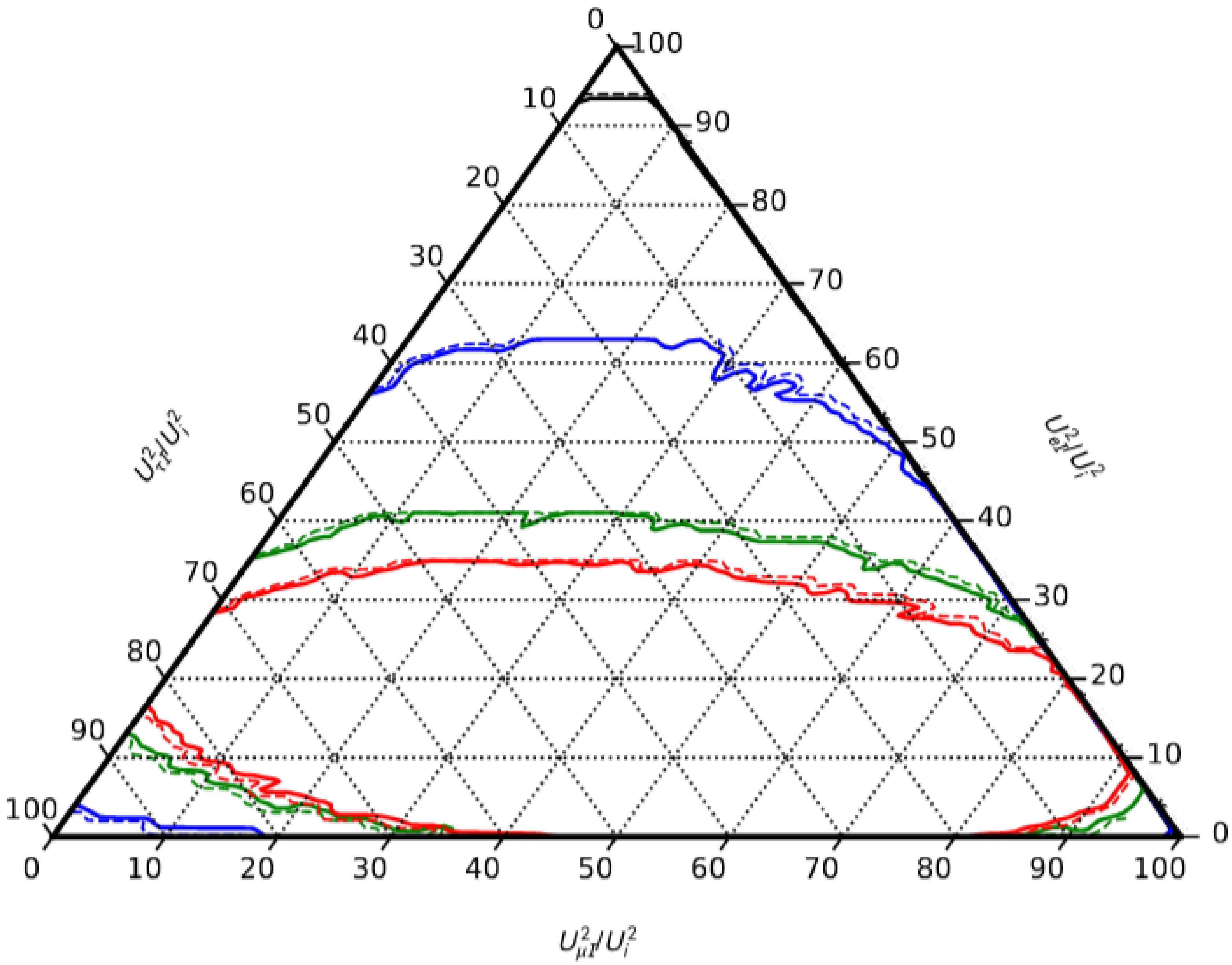
ATLAS Reinterpretation



Interpretation of ATLAS data (and others) depends on assumptions about "flavour mixing pattern"

Tastet et al 2107.12980

Constraints from ν-Oscillation Data in Model with 3 Heavy Neutrinos



normal ordering

$m_{lightest} < 10$ meV

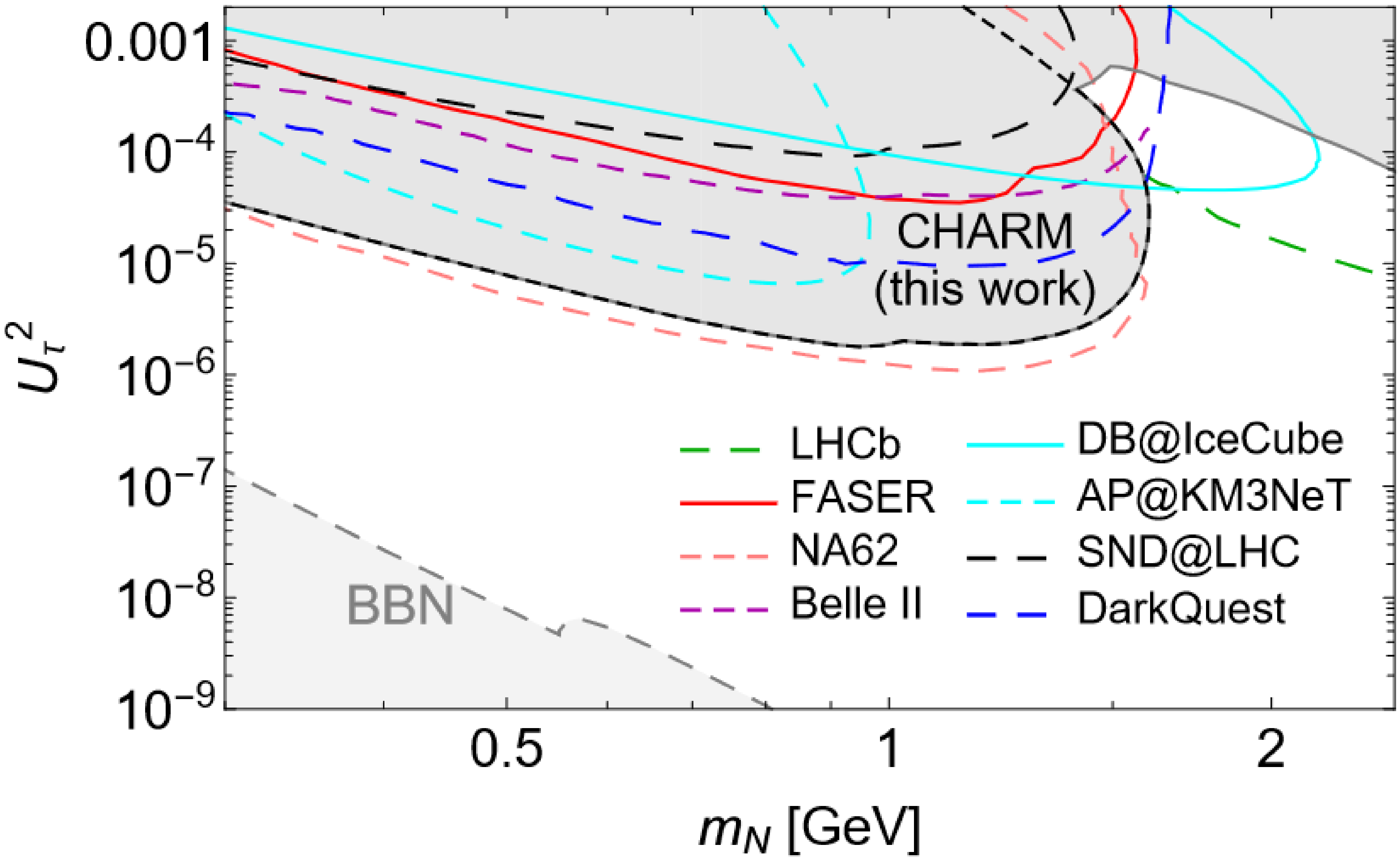
$m_{lightest} < 1$ meV

$m_{lightest} < 0.1$ meV

$m_{lightest} < 0.01$ meV

Chrzaszcz et al 1908.02302

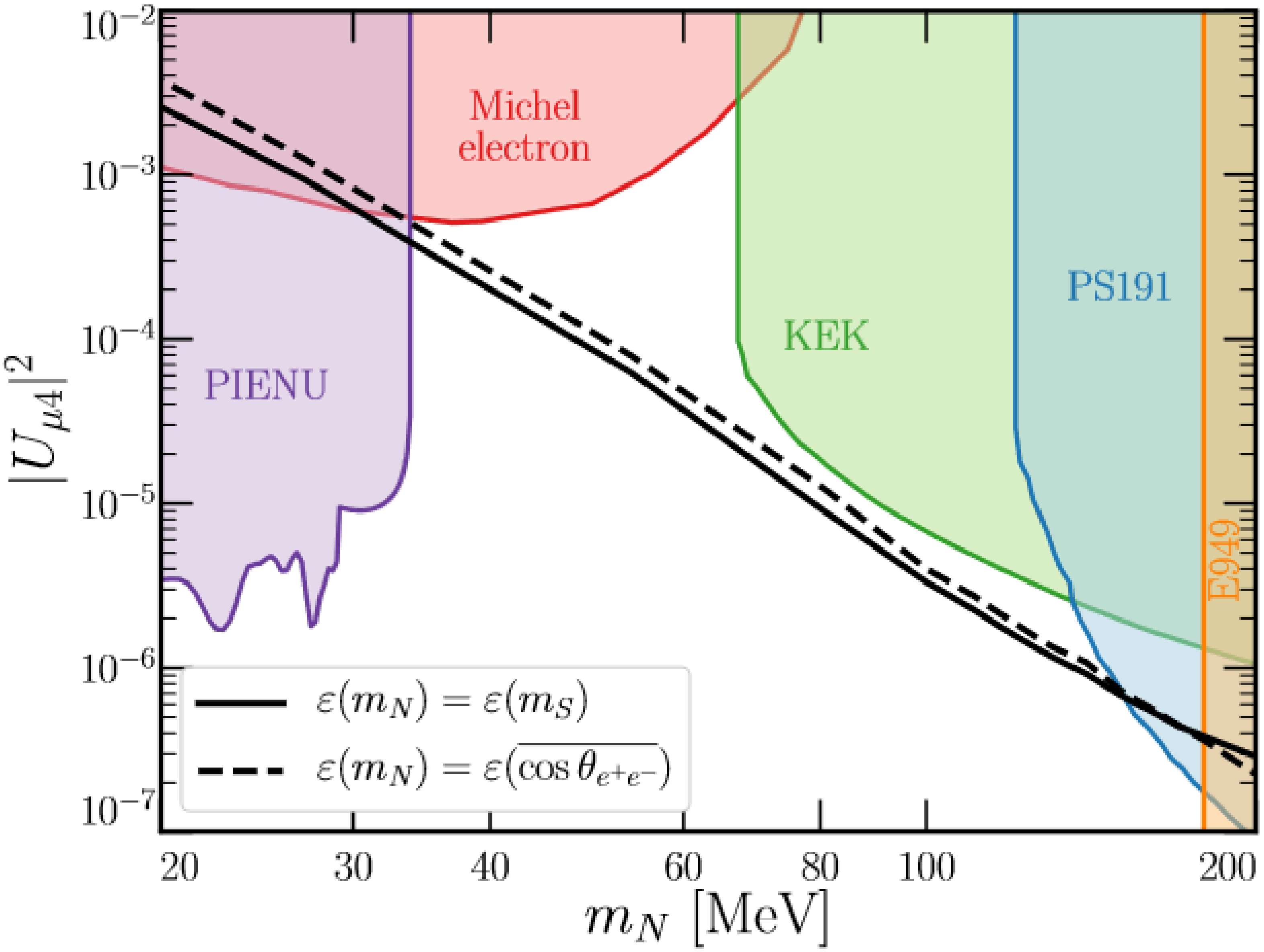
CHARM Reinterpretation



HNL decay through neutral current can produce electrons any muons even for pure τ mixing

Boiarska et al 2107.14685

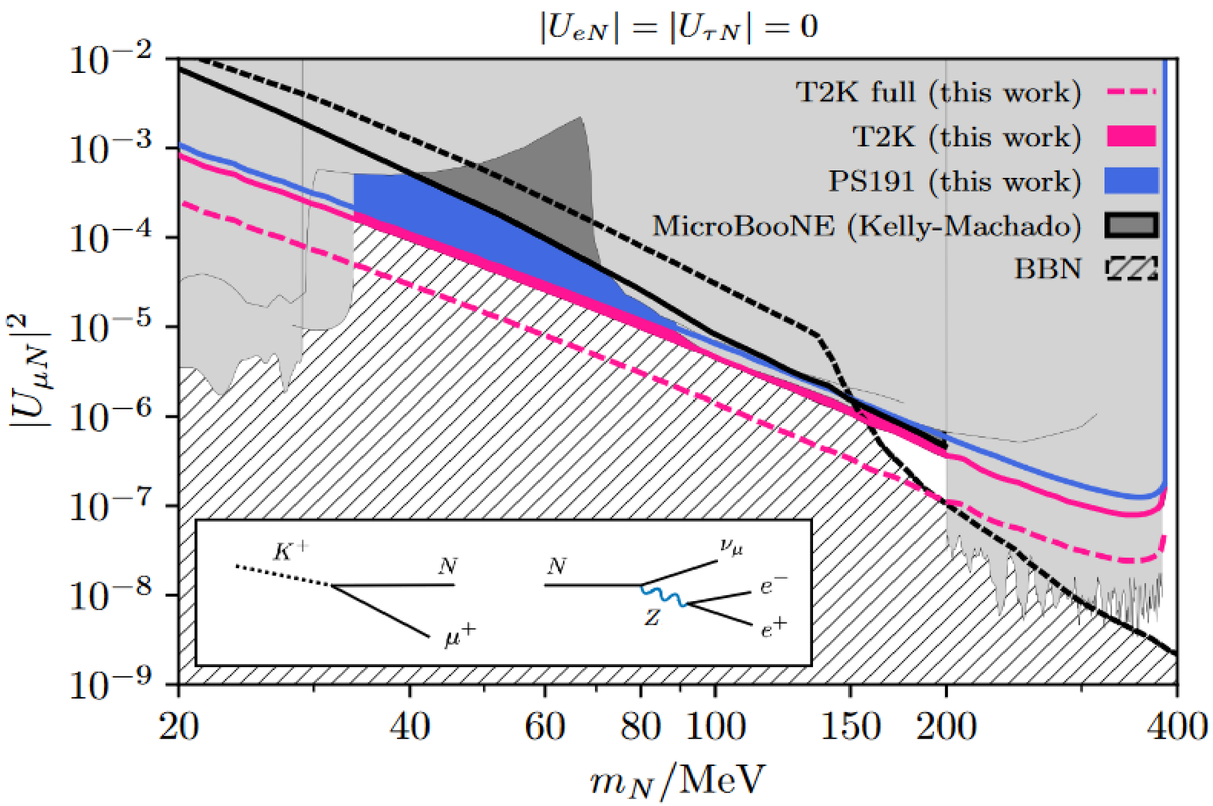
MicroBooNE Reinterpretation



Kelly/Machado 2106.06548

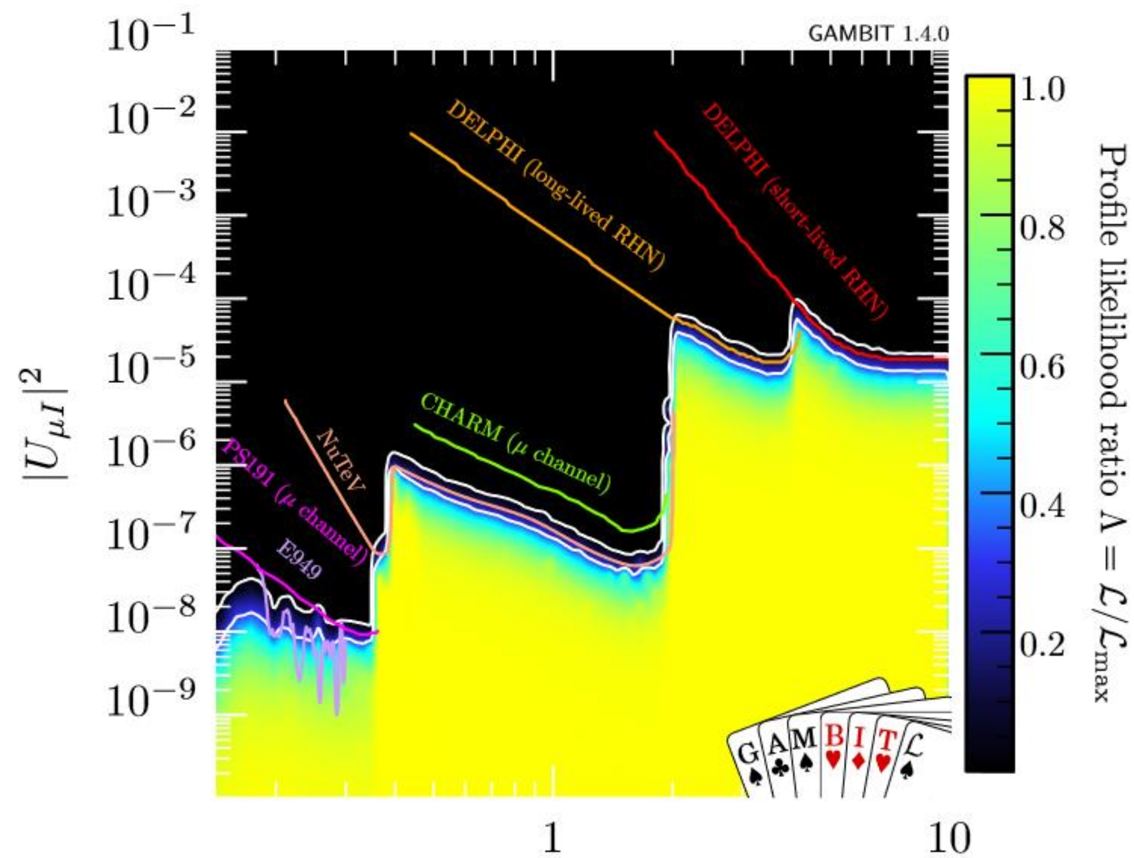
Authors re-interpret Higgs-portal scalar decay in terms of HNLs

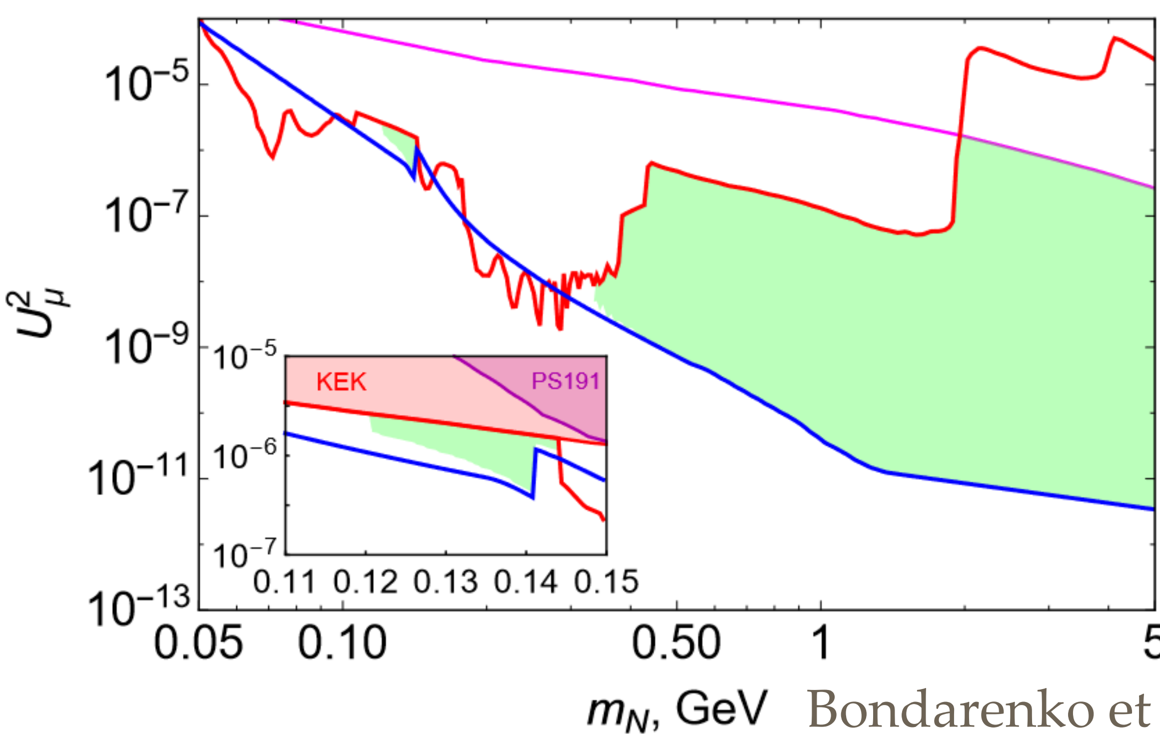
T2K Reinterpretation



Arguelles et al 2109.03831

- Authors claim to rule out HNLs below the kaon mass.
- **However**: Note that BBN bound depends on flavour mixing pattern!

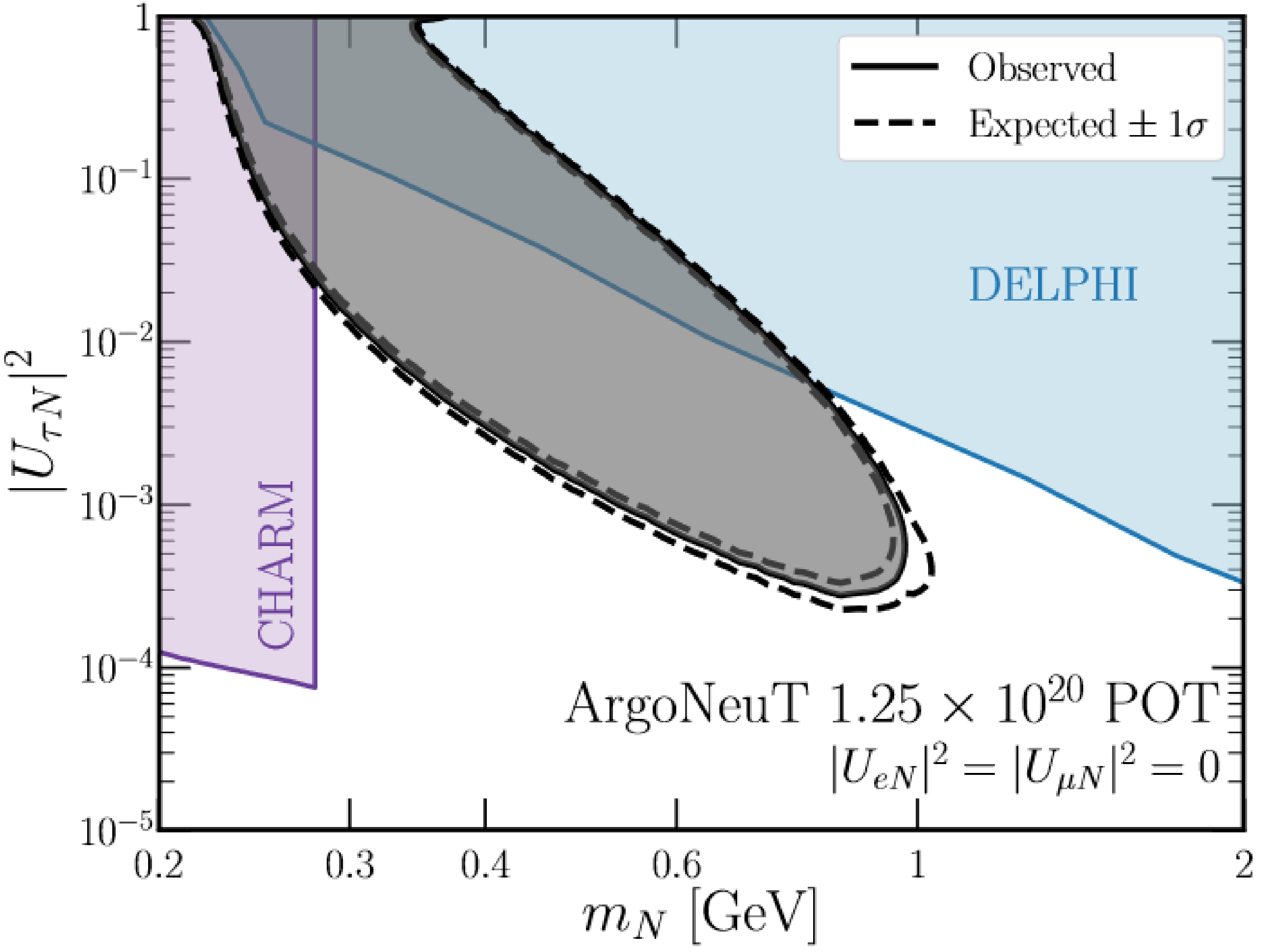




Bondarenko et al 2101.09255

Chrzaszcz et al 1908.02302

ArgoNeuT Reinterpretation



Acciarri et al 2106.13684

Overview

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- Pure type I seesaw: leptogenesis news
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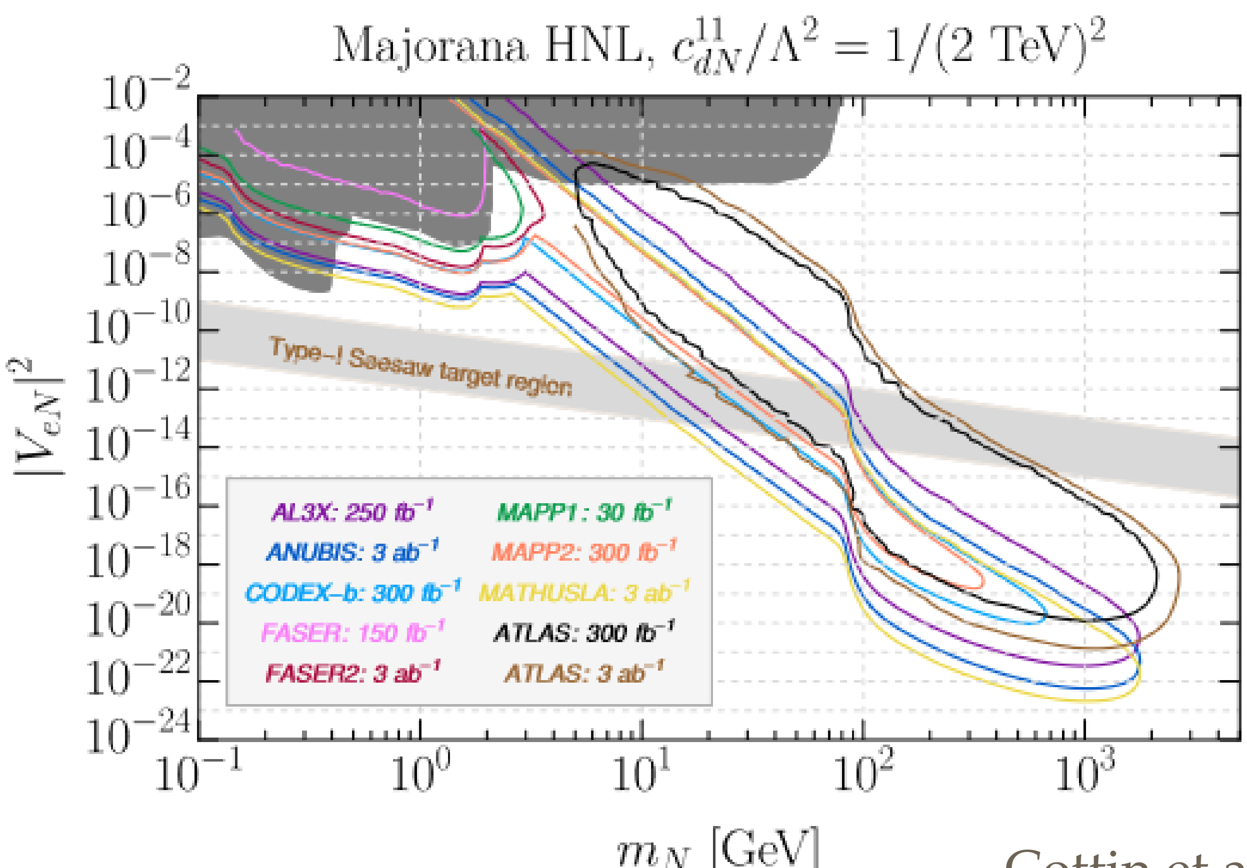
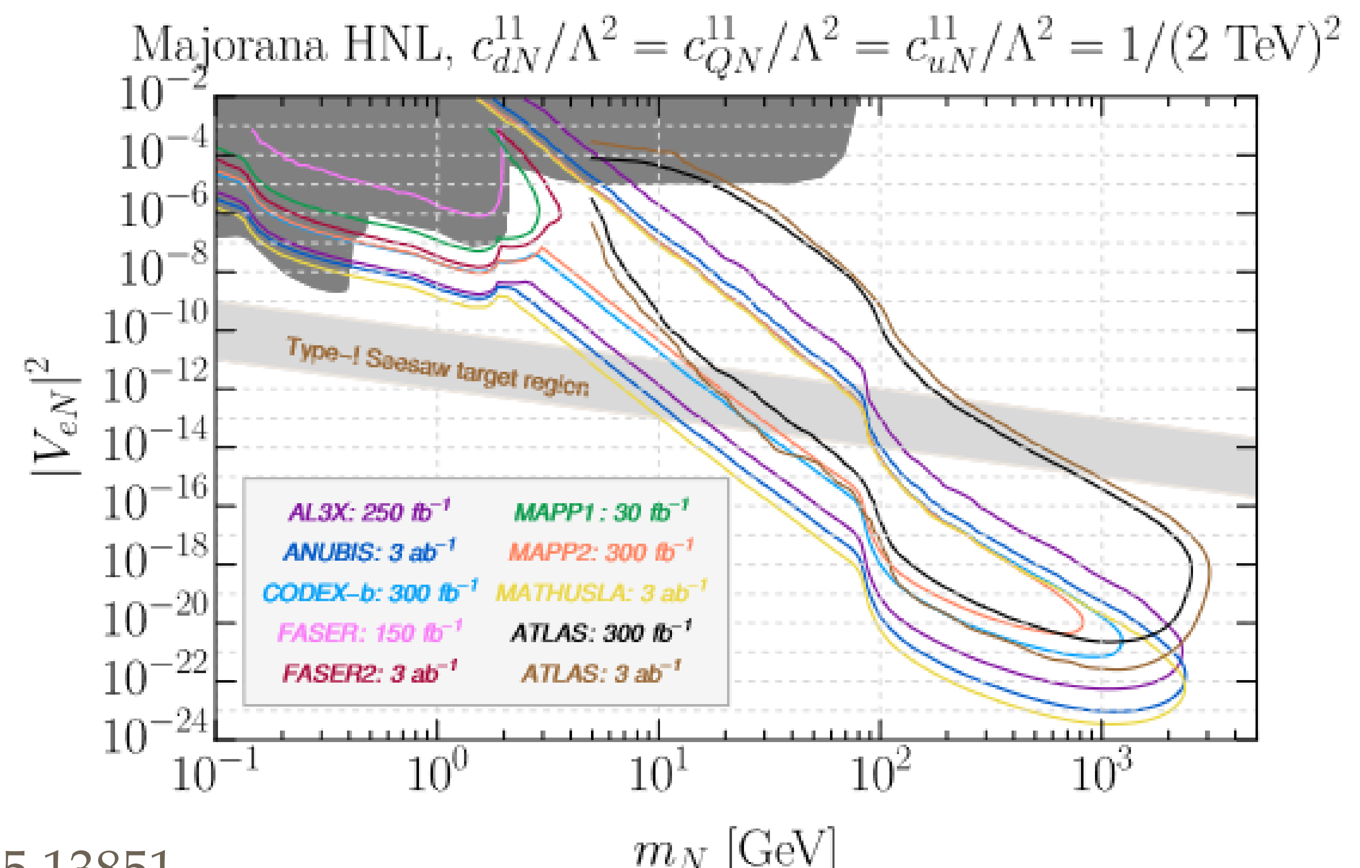
EFT Approach

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$	9	81

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\,\epsilon\,(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\,\epsilon\,(\overline{Q}N_R)$	54	162
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\,\epsilon\,(\overline{L}e_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)\,(\overline{N_R}L)$	54	162





Cottin et al 2105.13851

EFT Approach

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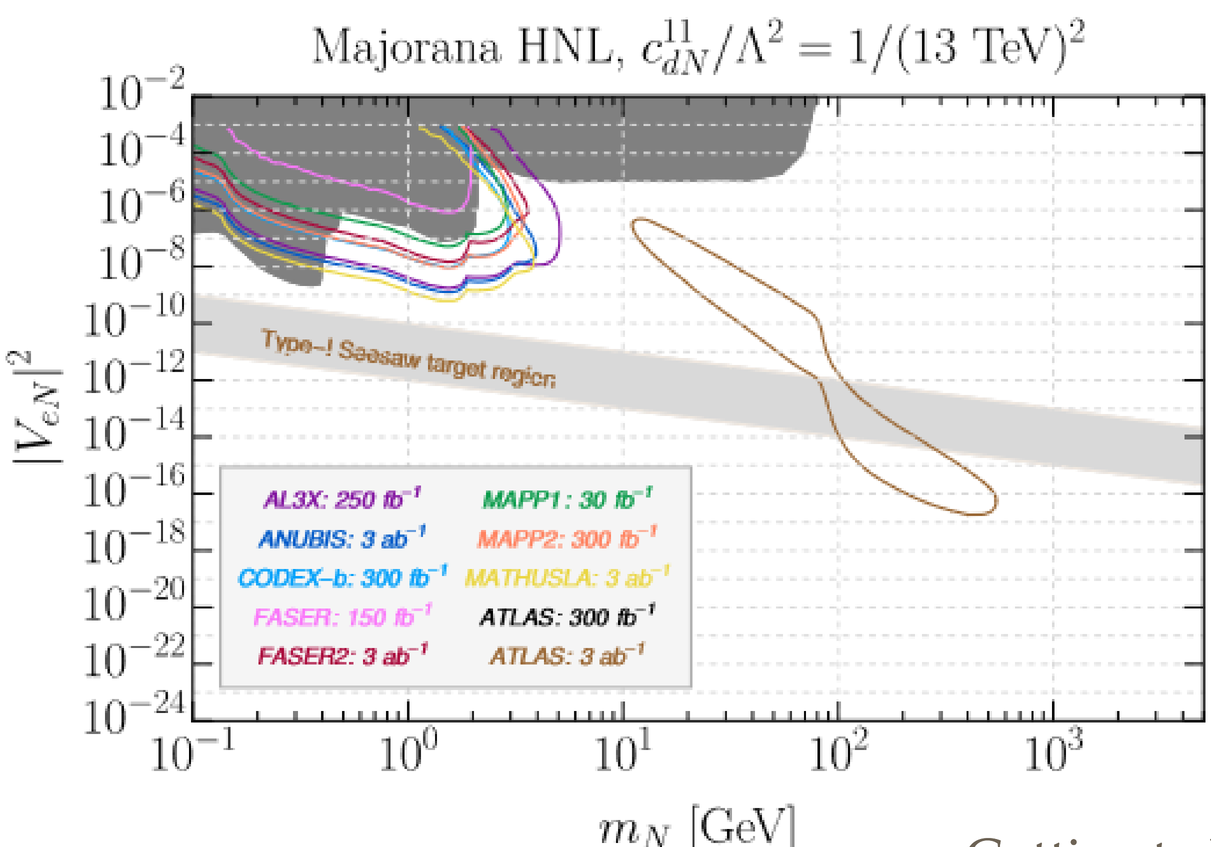

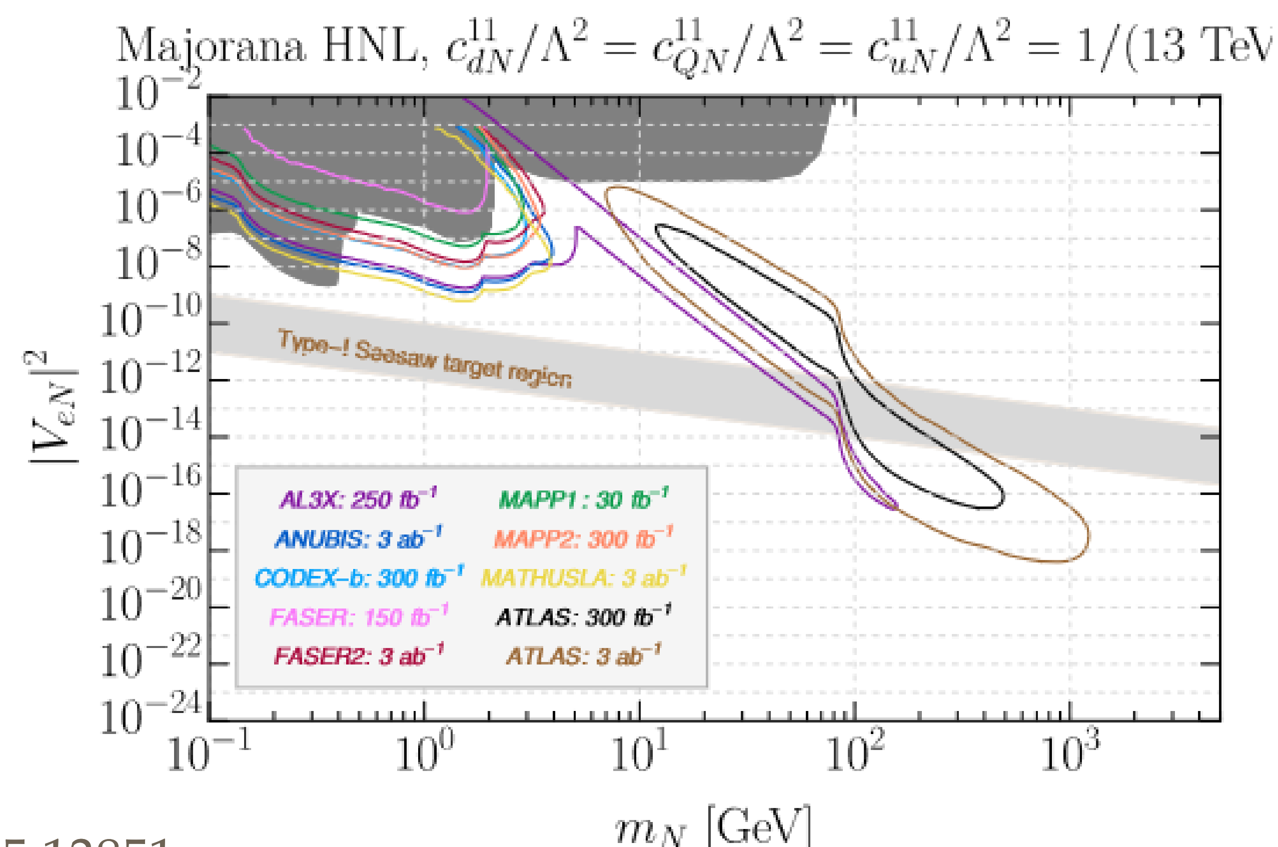

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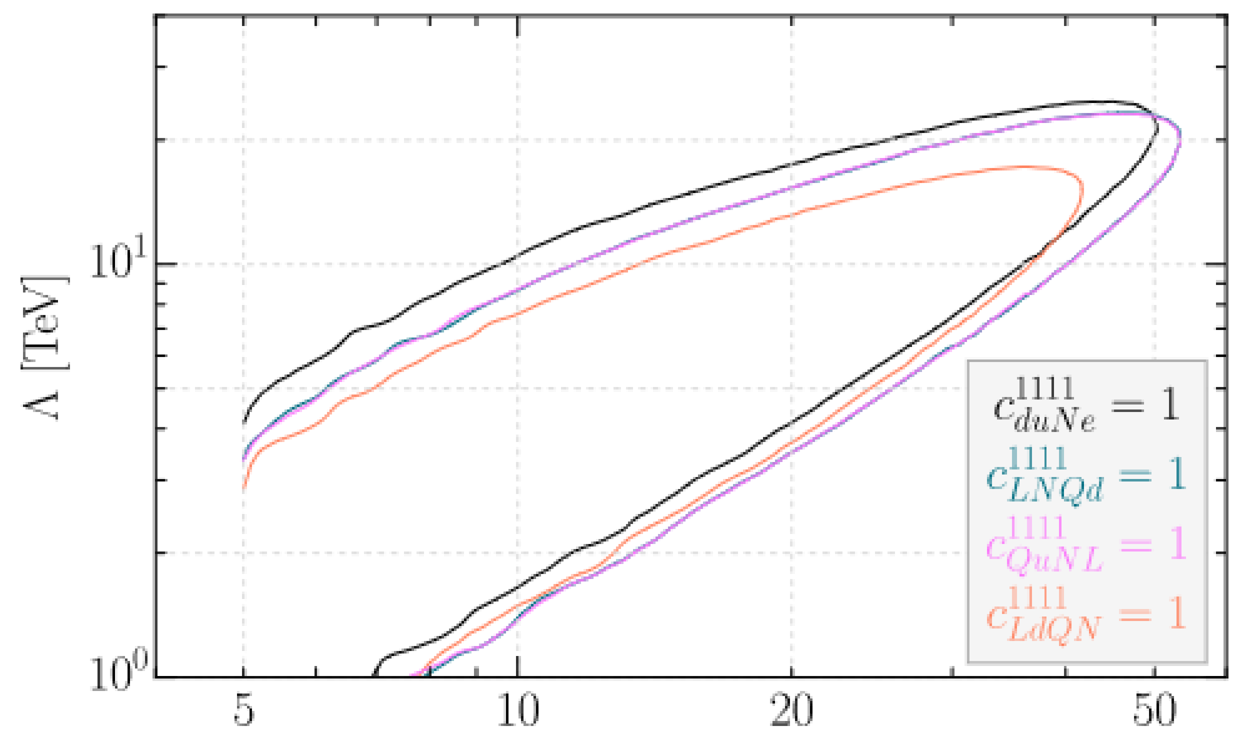
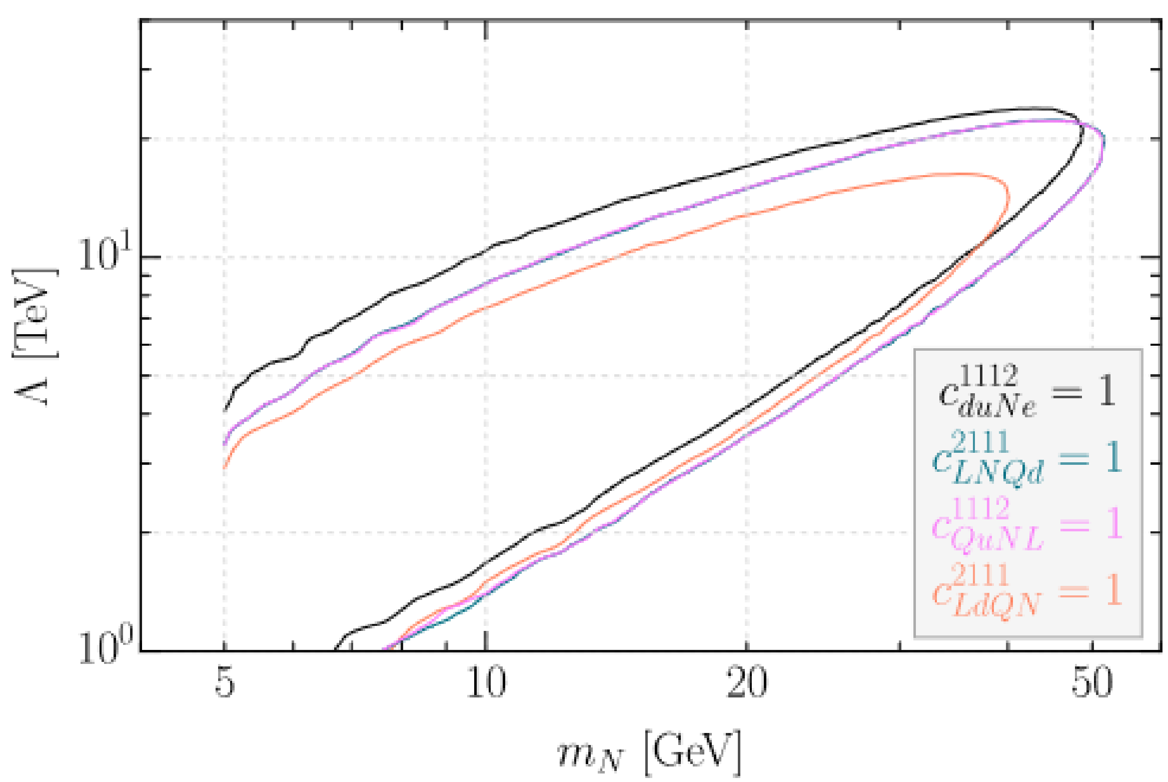
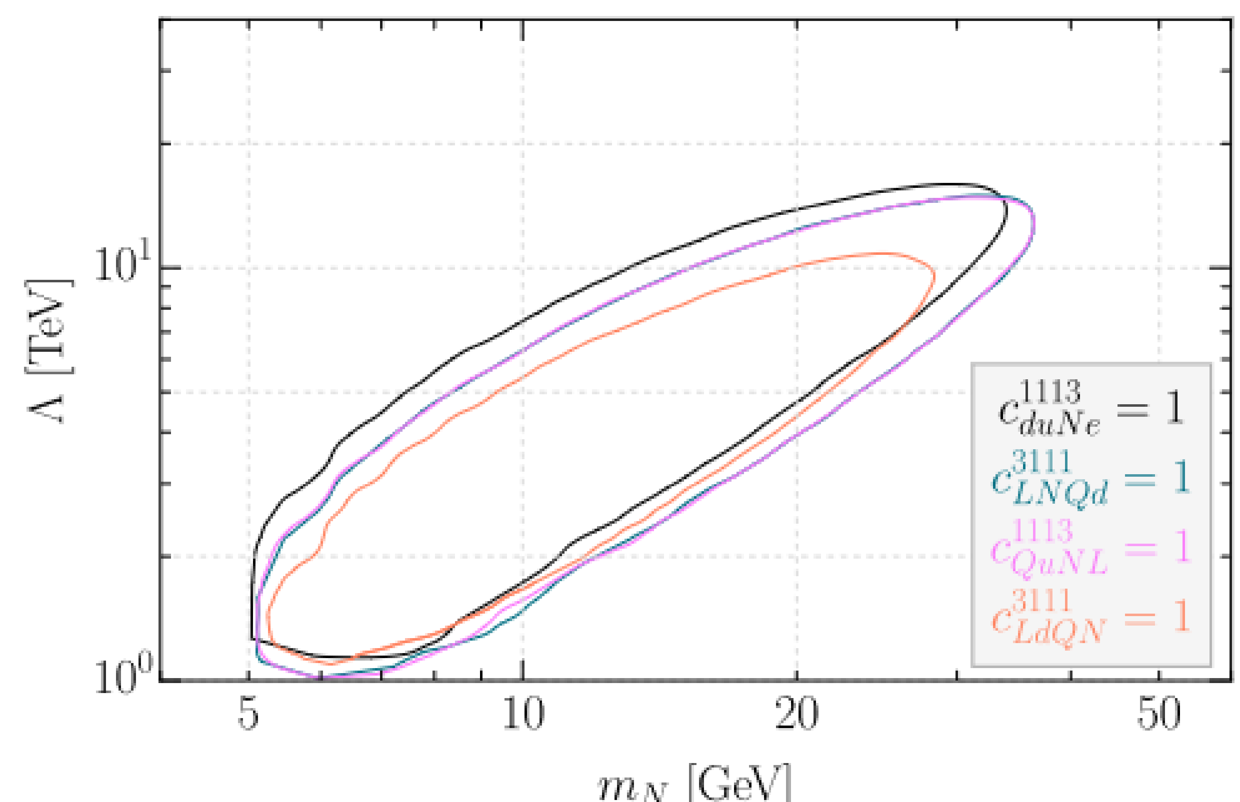
Plots from Beltran et al 2110.15096

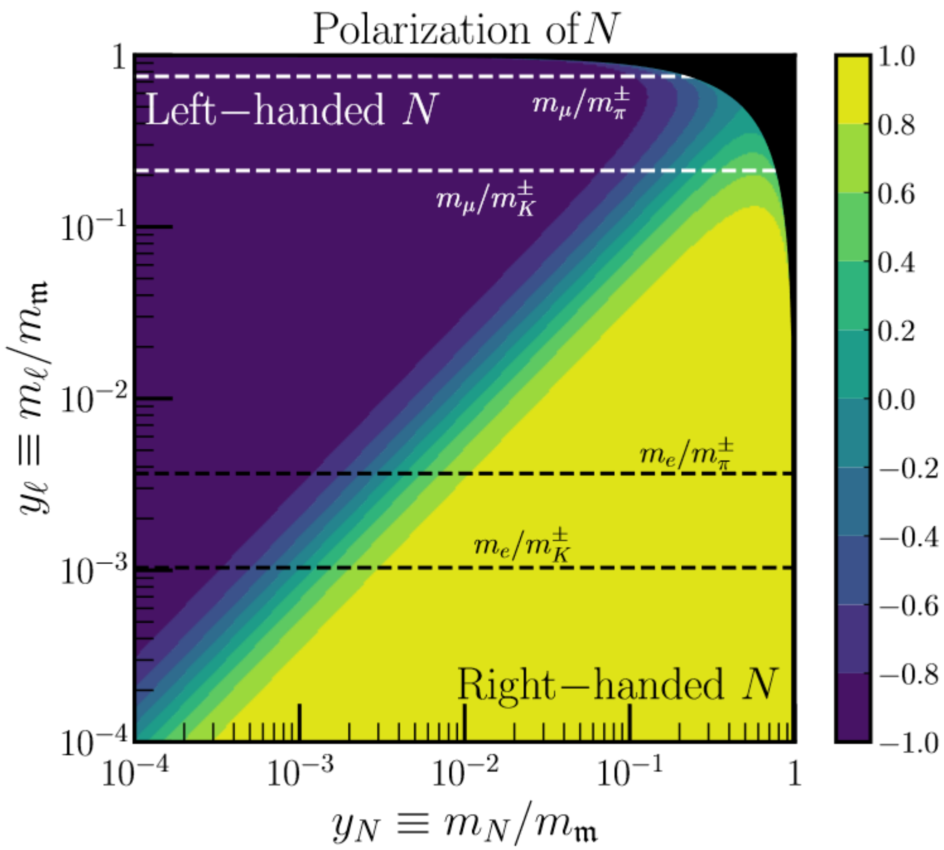
See also Julian Günther's talk and 2111.04403





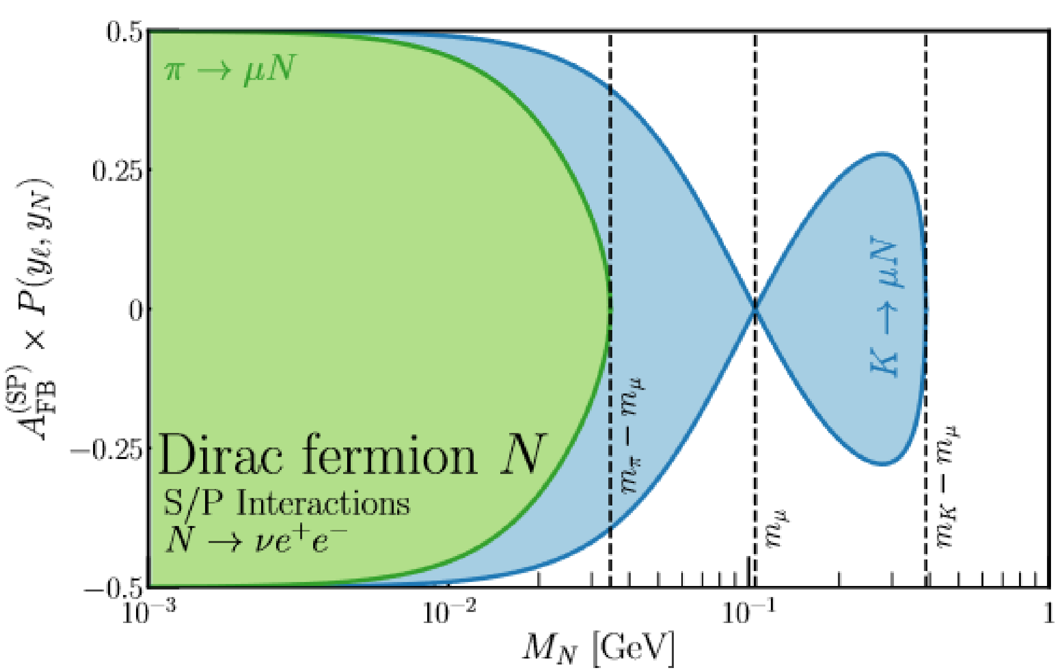


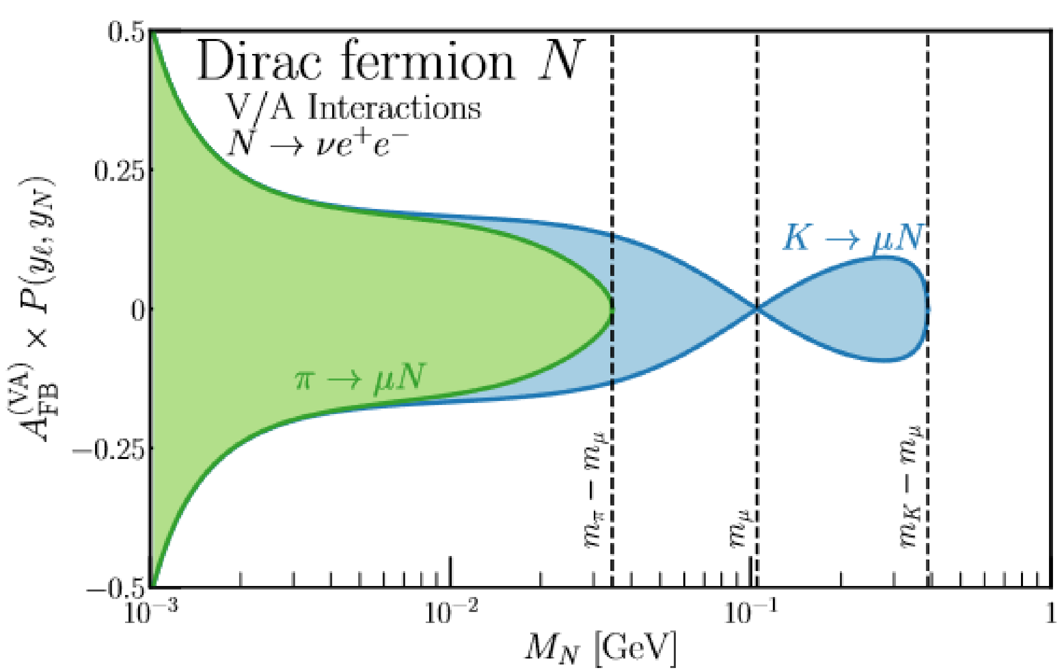
Dirac vs Majorana



- Polarisation of HNLs is related to their nature (Dirac/Majorana) and interactions
- This leads to forward-backward asymmetry in the decay

de Gouvea et al 2109.10358





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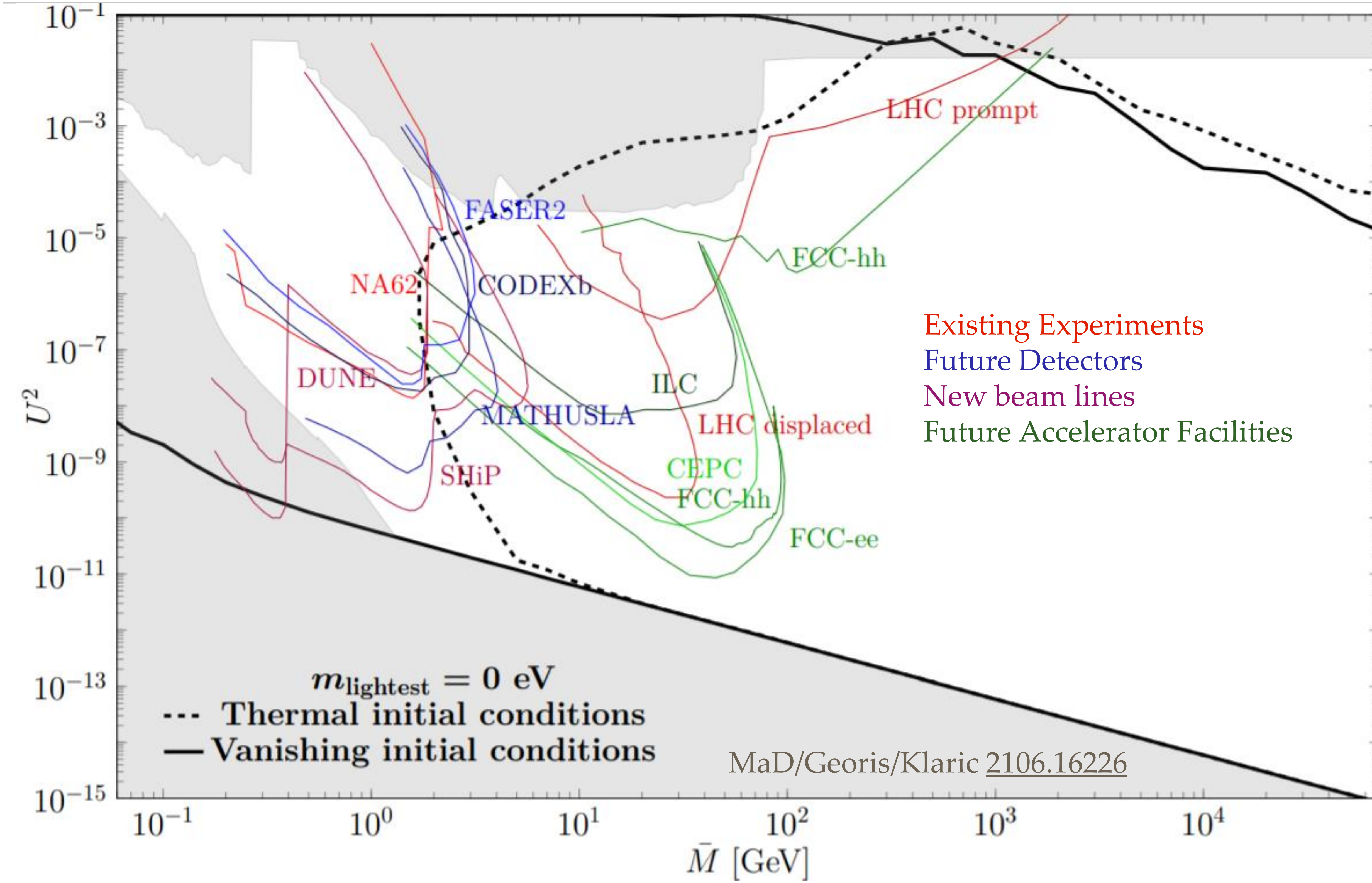
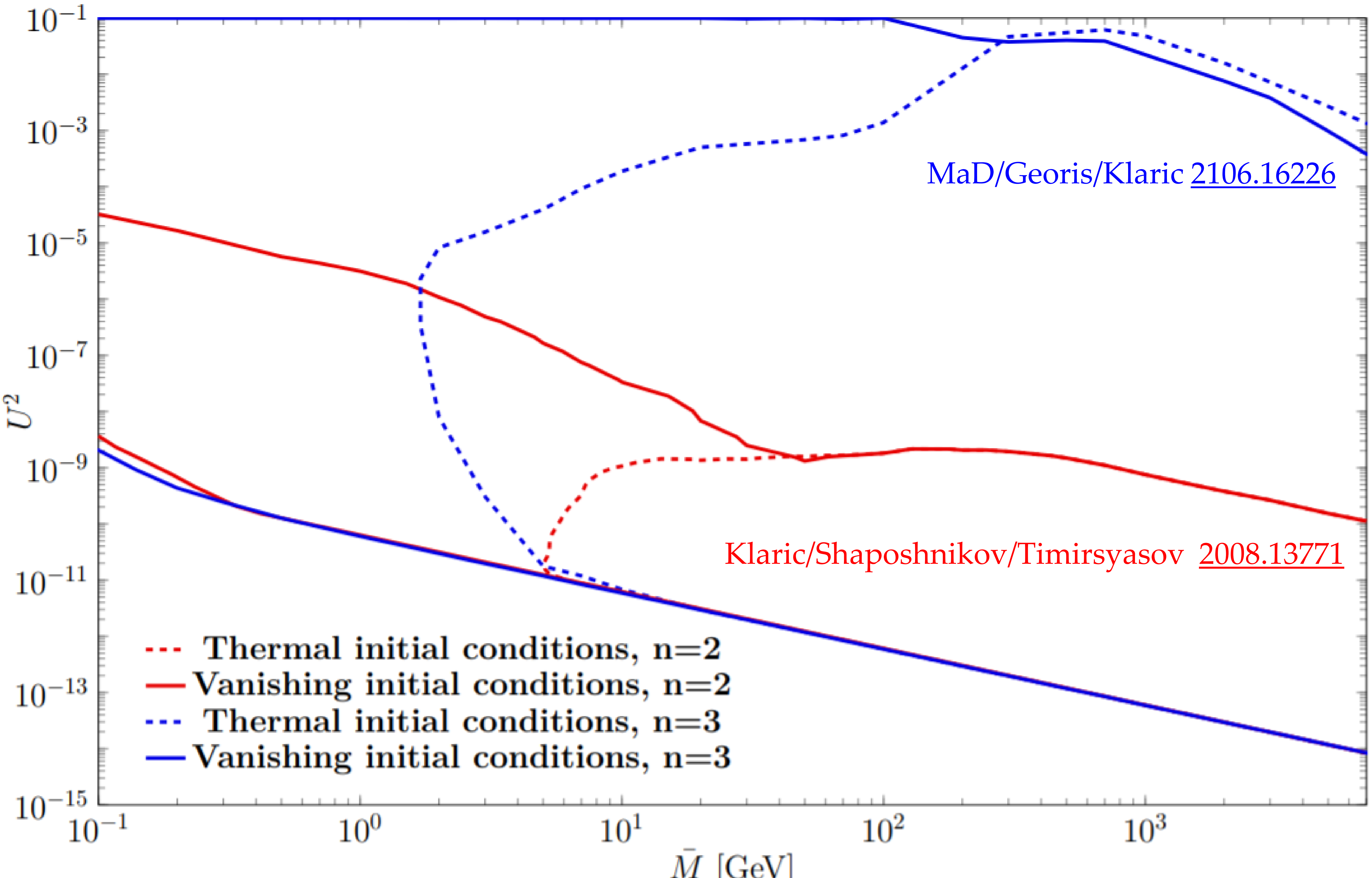
Leptogenesis with 3 HNLs



Leptogenesis with 3 HNLs vs 2 HNLs



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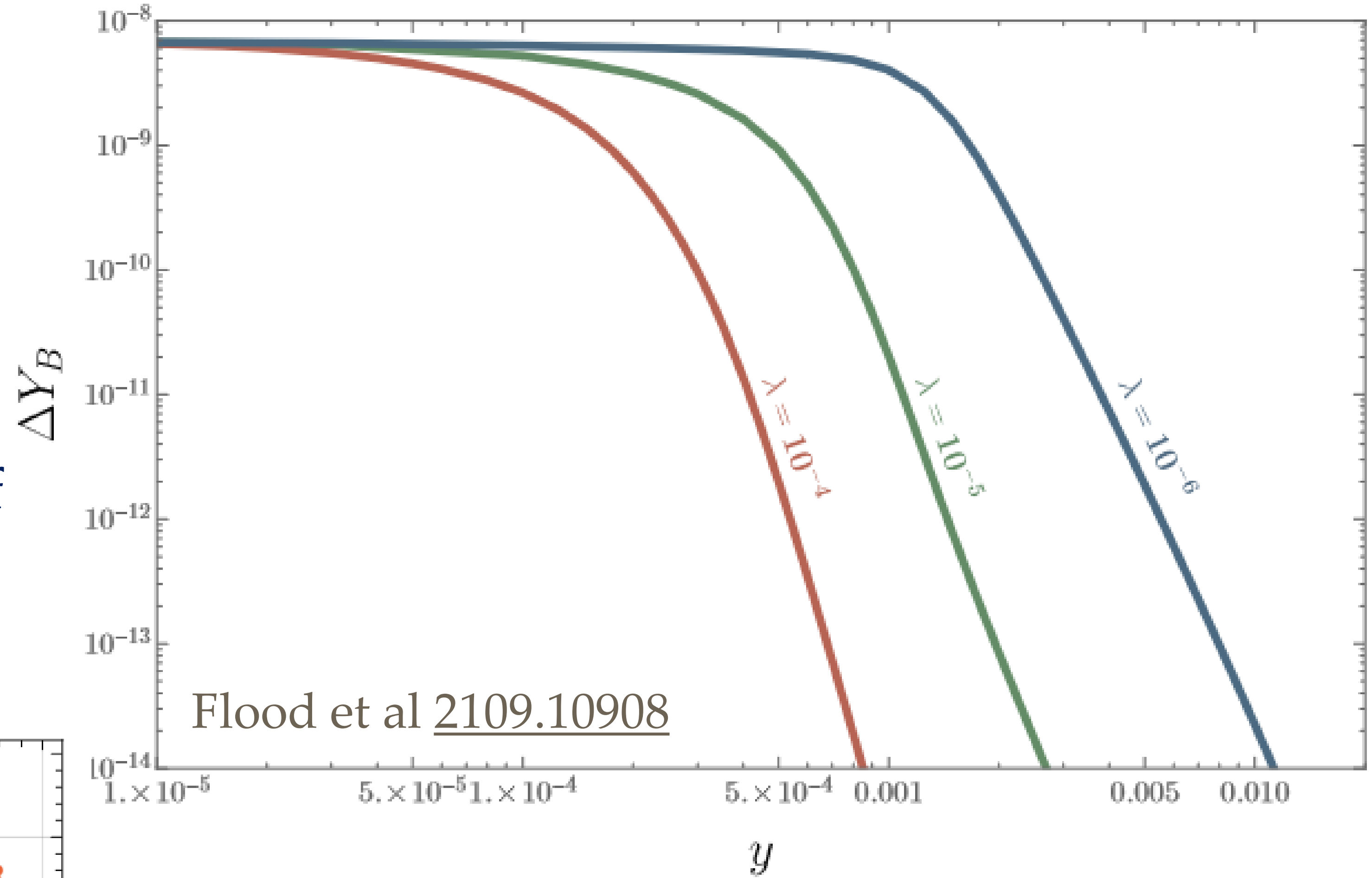
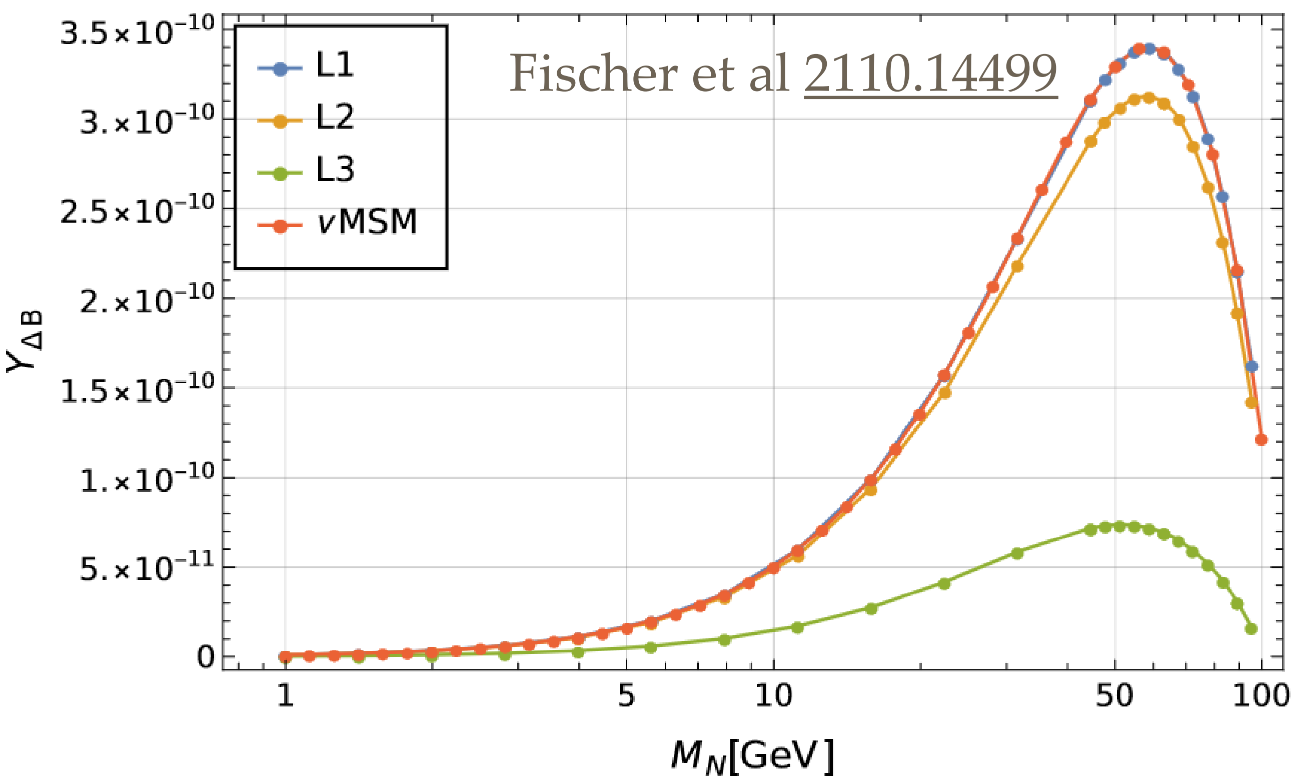
ARS Leptogenesis with extra Scalar

$$\mathcal{L}_\phi = -\frac{\lambda}{2}\phi^2|H|^2 - \frac{y_{IJ}}{2}\,\phi\overline{N_I^c}N_J - F_{\alpha I}\,\overline{L}_\alpha(\epsilon H^*)N_I + \text{h.c.}$$



- Equilibration of HNLs by new interactions suppresses efficiency of ARS mechanism ("freeze-in leptogenesis")

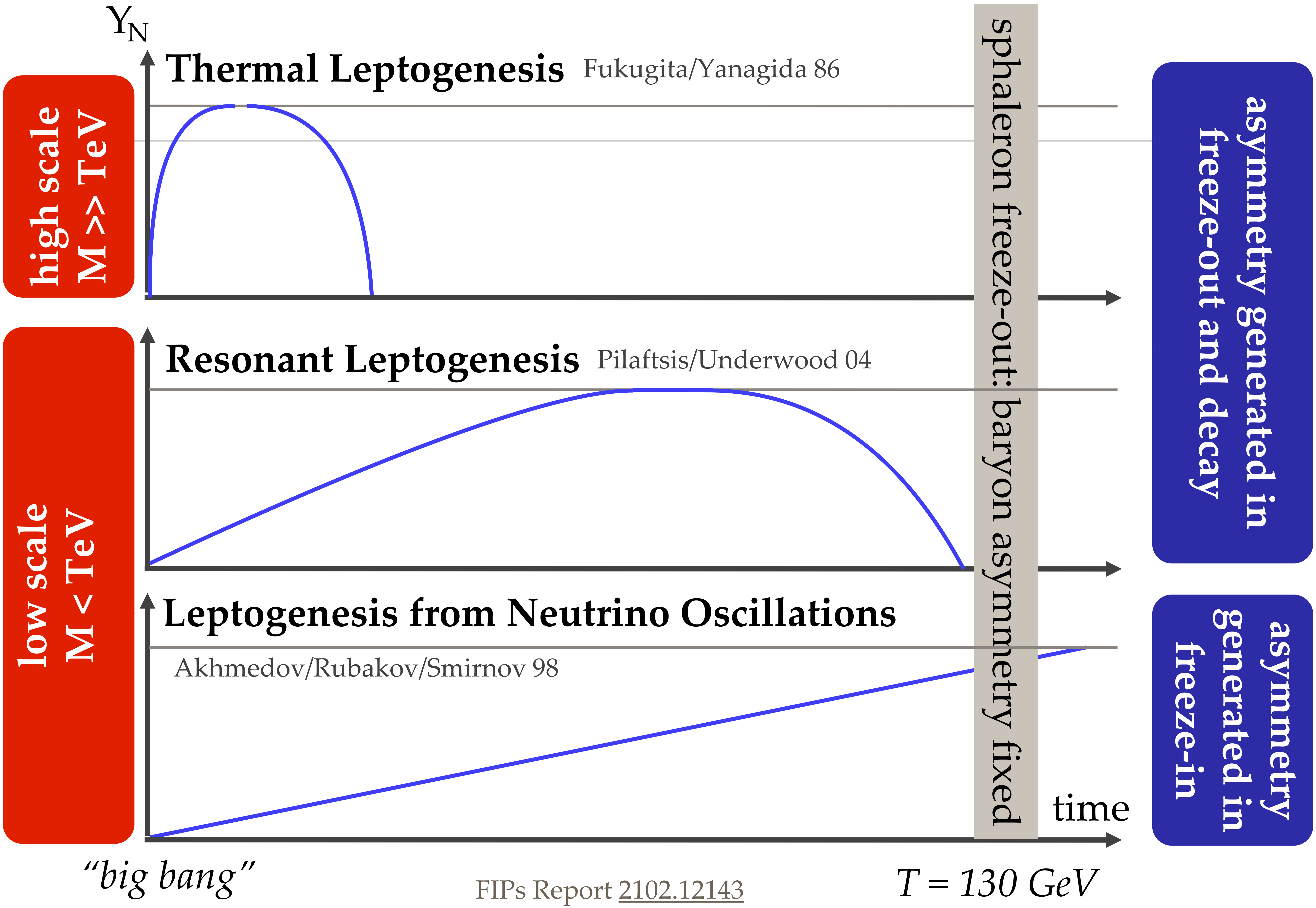


- But "freeze-out mechanism" works down to M~ 2 GeV (see previous slide), making low scale leptogenesis feasible in presence of new interactions!

Take Home Messages

- **Many re-interpretations** are being done – exciting!!!
- However: re-interpretations, cosmological bounds **strongly depend on "flavour mixing pattern"**
  (and therefore on ν-oscillation bounds, # HNL generations, lightest SM ν mass…)
- Exploration of **non-minimal models** is gaining momentum!
- **Leptogensis from HNL freeze-out** works for masses down to few GeV and mixings accessible to LHC, making it potentially testable in both minimal and non-minimal models!

Backup Slides



FIPs Report 2102.12143

B-L Symmetric Limit with 2 HNLs

- Mass basis at $T=0$ is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

spinor	$\bar{L}$-charge
$\nu_{Rs} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
$\nu_{Rw} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} - i\nu_{R2})$	-1

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) \end{pmatrix}$$

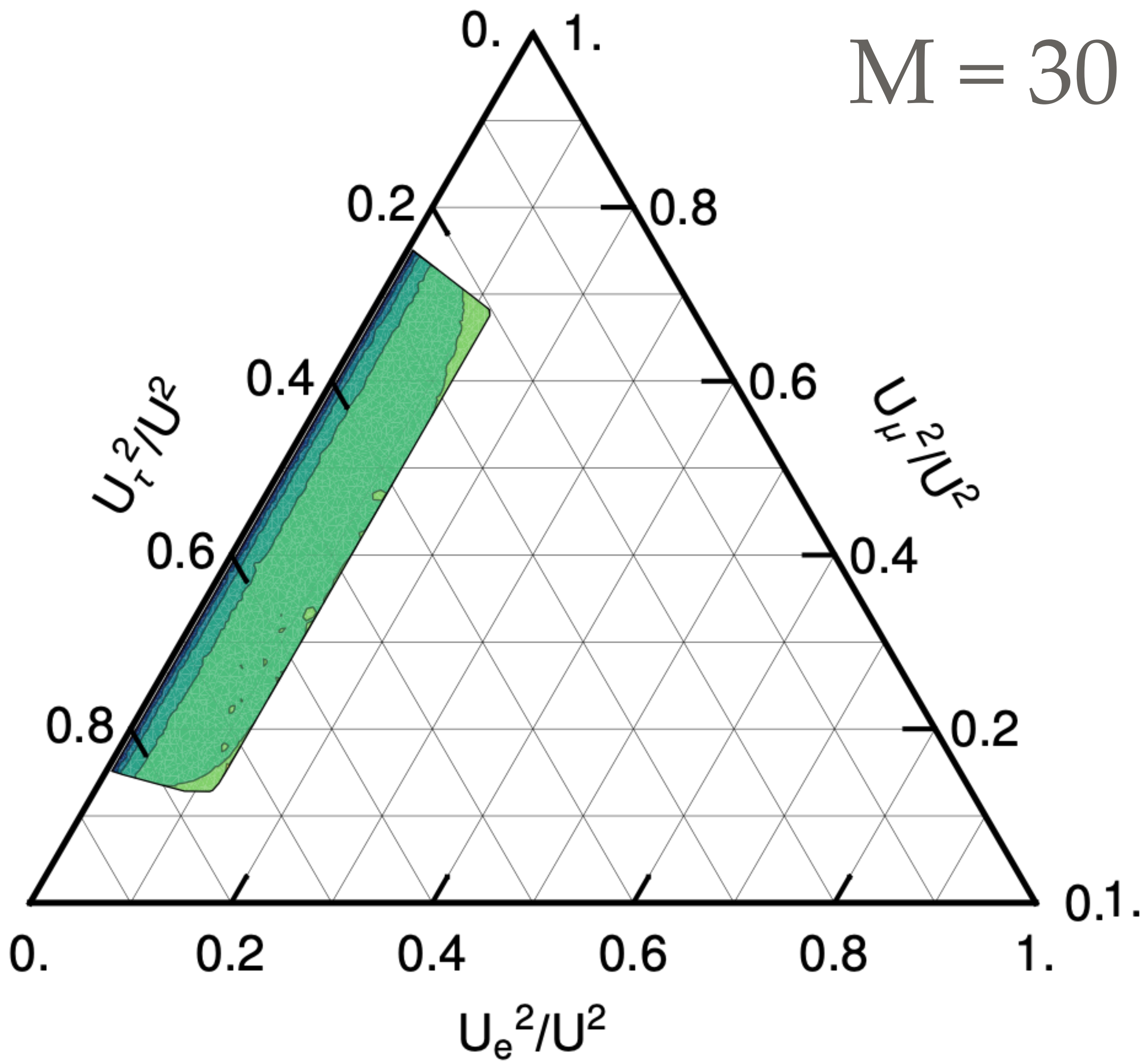
"mass basis"

ν oscillation data constrains strucrure in SM flavours

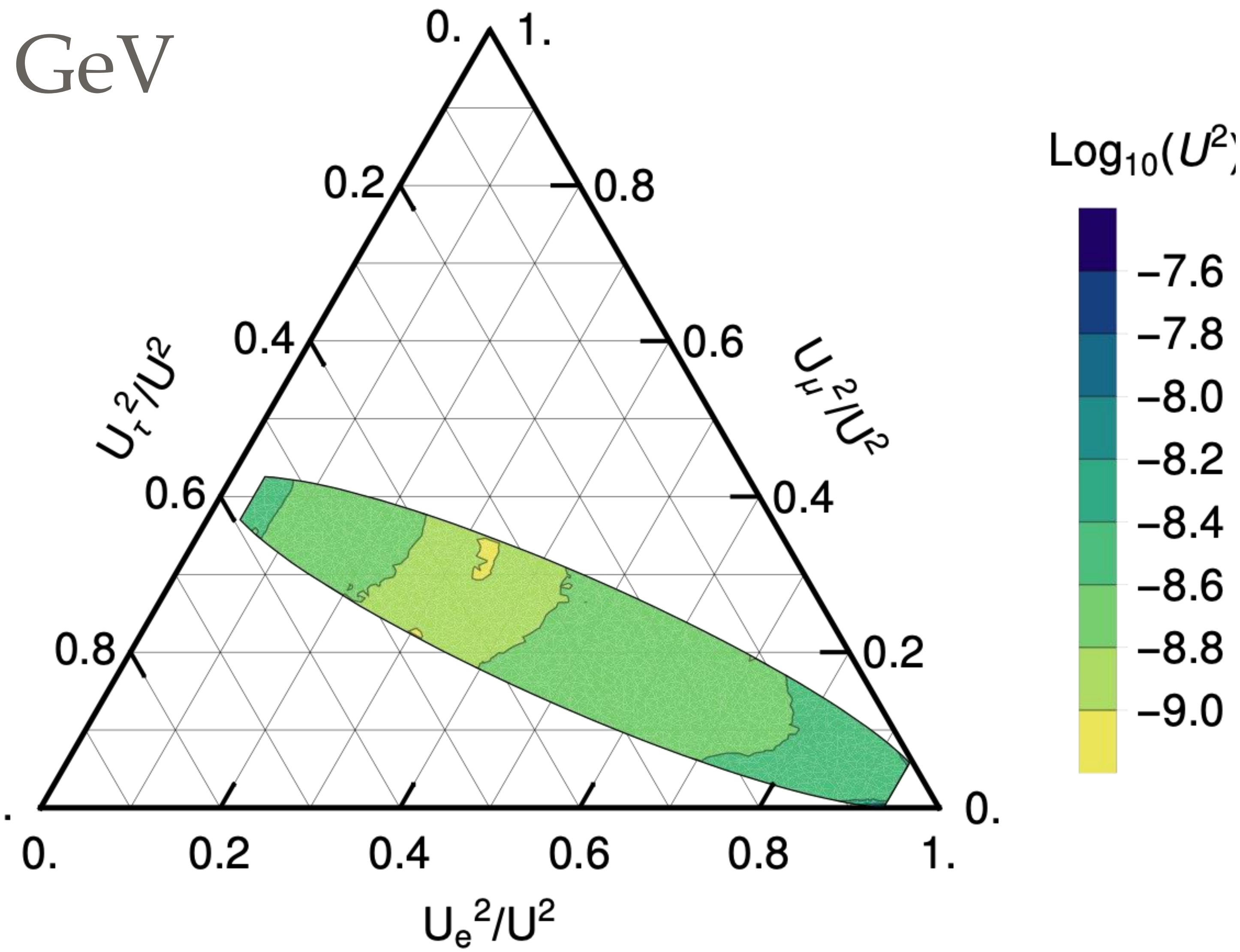
B-L **symmetry dictates structure in sterile flavours**

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos

M = 30 GeV



normal neutrino mass ordering



inverted neutrino mass ordering

Large U² require strong hierarchies in couplings to SM generations

plots from Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos

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"mass basis"

$$F \sim \begin{pmatrix} F_e & F_e\epsilon_e \\ F_\mu & F_\mu\epsilon_\mu \\ F_\tau & F_\tau\epsilon_\tau \end{pmatrix}$$

"interaction basis"

Quantitative Description

- Need to track three SM chemical potentials
- Track coherences for heavy neutrinos ("density matrix equations")

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\Gamma_\alpha]f_N(1-f_N) + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\tilde{\Gamma}_\alpha\,(\delta\bar{\rho}_N-\delta\rho_N)]\,,$$

$$i\frac{d\delta\rho_N}{dt} = -i\frac{d\rho_N^{eq}}{dt} + [H_N,\rho_N] - \frac{i}{2}\{\Gamma,\delta\rho_N\} - \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right],$$

$$i\frac{d\delta\bar{\rho}_N}{dt} = -i\frac{d\rho_N^{eq}}{dt} - [H_N,\bar{\rho}_N] - \frac{i}{2}\{\Gamma,\delta\bar{\rho}_N\} + \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right].$$

SM chemical potentials

Heavy neutrino density matrix

LNC rate ~ $F^2\,T$

LNV rate ~ $(M/T)^2\,F^2\,T$

Heavy neutrino effective Hamiltonian

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos

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$\nu_{Rs} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
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$$F = \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) \end{pmatrix}$$

"mass basis"

$$F \sim \begin{pmatrix} F_e & F_e\epsilon_e \\ F_\mu & F_\mu\epsilon_\mu \\ F_\tau & F_\tau\epsilon_\tau \end{pmatrix}$$

"interaction basis"

- For large U^2, ν_{Rs} comes into equilibrium quickly, deviation from equilibrium necessary for baryogenesis comes from ν_{Rs}
- For $T \sim M$ both states become "strongly" coupled (LNV rates)
- Only way to prevent washout: Have one SM flavour feebly coupled

Structure in sterile flavours enforces hierarchy in SM flavour!

B-L Symmetric Limit with 3 HNLs

charge assignment in Lagrangian

spinor	$\bar{L}$-charge
$\nu_{Rs} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
$\nu_{Rw} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} - i\nu_{R2})$	-1
ν_{R3}	0

approximately conserved charges in leptogenesis

spinors	$\widetilde{L}$-charge
$P_+ N_i, \quad \bar{N}_i P_+$	$+1$
$P_- N_i, \quad \bar{N}_i P_-$	-1

$$\psi_N = (\nu_{Rs} + \nu_{Rw}^c)$$

***B-L* violating parameters** $\mu, \ \epsilon, \ \epsilon'$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\psi_N}(\mathrm{i}\partial\!\!\!/ - \bar{M})\psi_N + \overline{\nu_{R3}}\mathrm{i}\partial\!\!\!/\nu_{R3} - F_a^*\overline{\psi_N}\phi^T\varepsilon^\dagger\ell_{La} - F_a\bar{\ell}_{La}\varepsilon\phi^*\psi_N$$
$$-\epsilon_a^* F_a^*\overline{\psi_N^c}\phi^T\varepsilon^\dagger\ell_{La} - \epsilon_a F_a\bar{\ell}_{La}\varepsilon\phi^*\psi_N^c - \epsilon_a' F_a\overline{\ell_{La}}\varepsilon\phi^*\nu_{R3} - \epsilon_a'^* F_a^*\overline{\nu_{R3}}\phi^T\varepsilon^\dagger\ell_{La}$$
$$-\mu\bar{M}\frac{1}{2}\left(\overline{\psi_N^c}\psi_N + \overline{\psi_N}\psi_N^c\right) - \mu'\bar{M}\overline{\nu_{R3}^c}\nu_{R3}\,,$$

Shaposhnikov 06
Kersten/Smirnov 07

B-L Symmetric Limit

charge assignment in Lagrangian

spinor	$\bar{L}$-charge
$\nu_{R\text{s}} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
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$P_+ N_i, \quad \bar{N}_i P_+$	$+1$
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$$M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

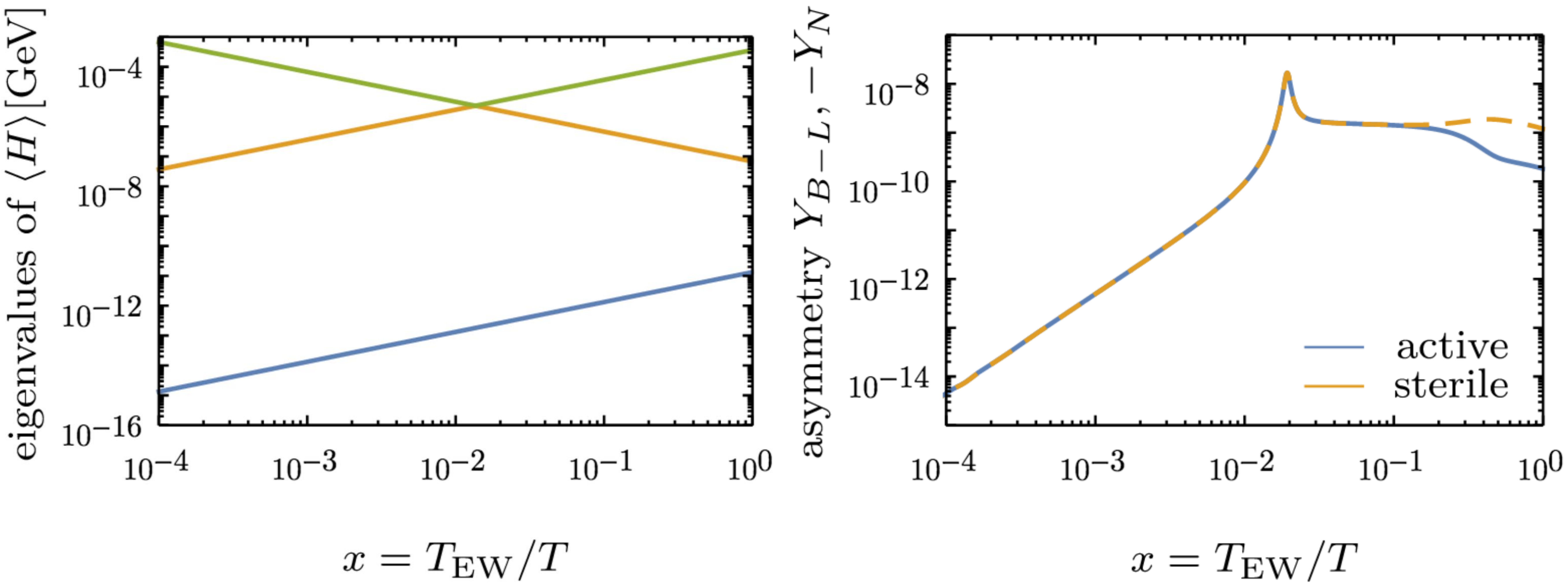
***B-L* violating parameters** $\mu, \ \epsilon, \ \epsilon'$

***B-L* symmetry dictates structure in sterile flavours**

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

ν oscillation data constrains strucrure in SM flavours

Dynamical Generation of Resonance



Abada et al 1810.12463

- level crossing between the quasiparticle dispersion relations in the plasma ("thermal masses") can dynamically generate a resonance
- Strong enhancement of the asymmetry with only moderate degeneracy in the vacuum masses

Maverick Heavy Neutrino

- Mass basis at *T=0* is the one where *M* is diagonal
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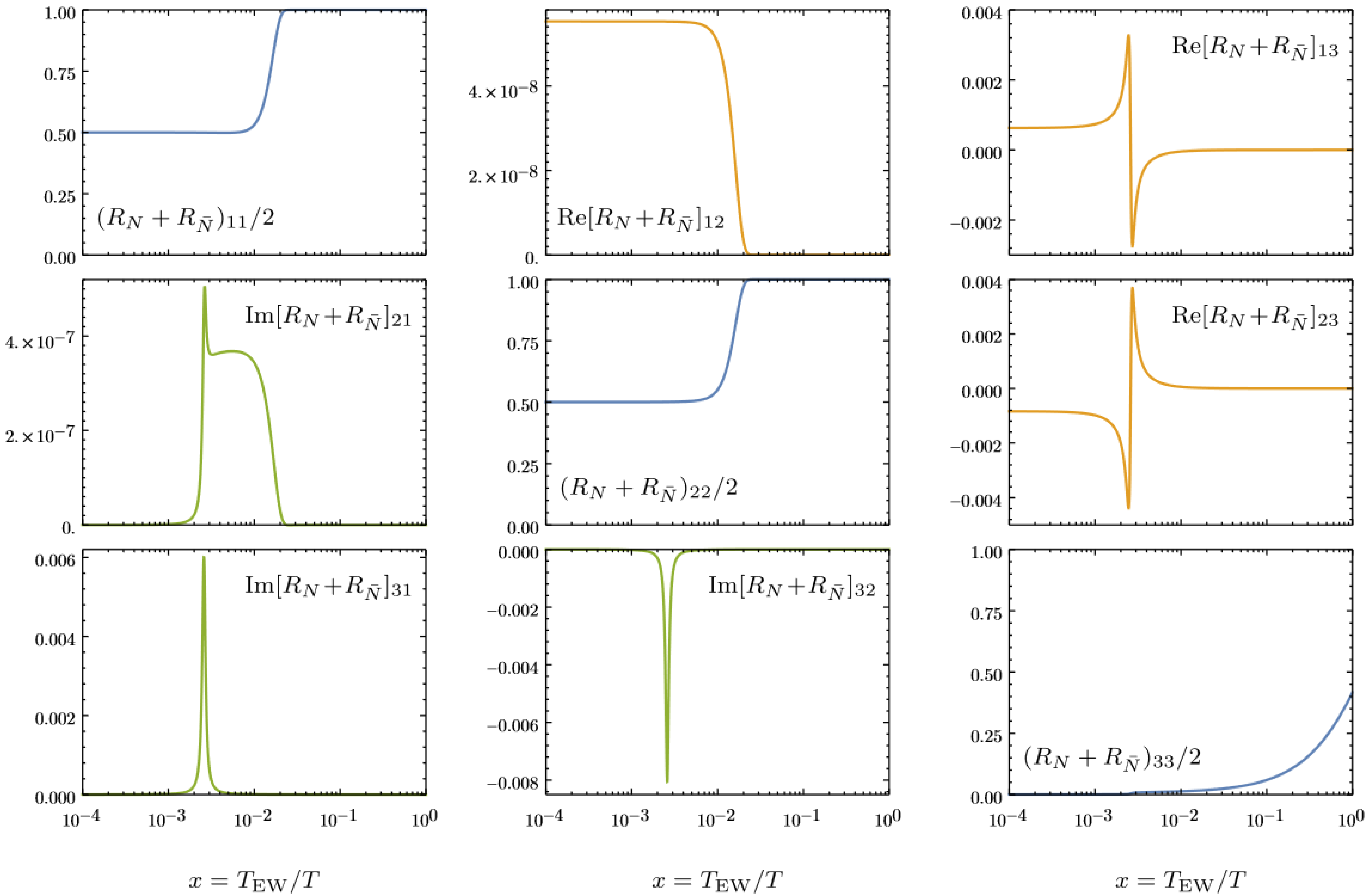
- Third state ν_{R3} is free of the constraints that relates ν_{R3} and ν_{Rw}
- It can maintain deviation from equilibrium even when LNV rates come into equilibrium
- Can avoid washout even for large couplings of pseudo-Dirac pair
- No need for a hierarchy in SM flavour couplings to prevent washout!

Maverick Heavy Neutrino



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