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Flavour effects in low scale leptogenesis and their experimental tests

24. 09. 2021

Physics of the flavourful Universe Workshop

Portoroz, Slovenia

Overview

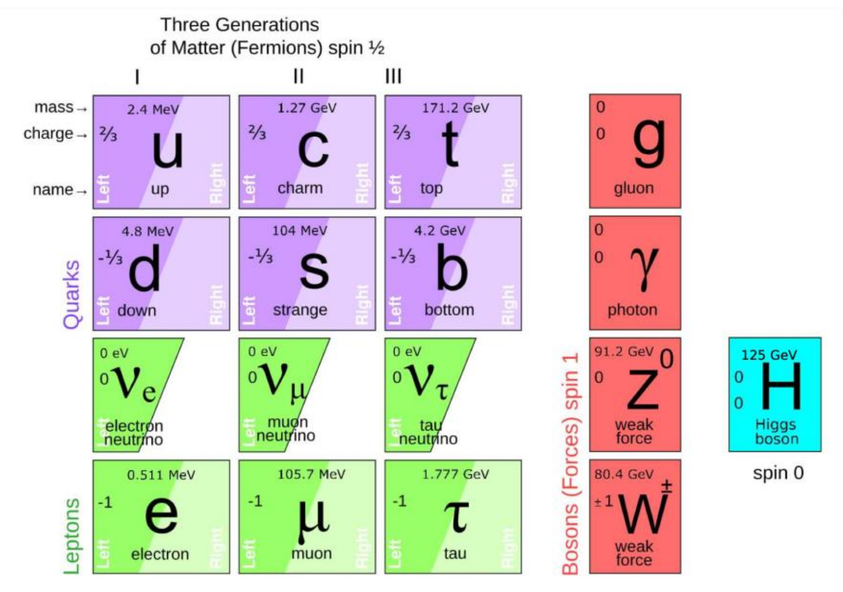
Low Scale Seesaw Predictions for Neutrino Yukawas

Leptogenesis Predictions for Neutrino Yukawas

Other tests: LNV and CPV

The Seesaw Model (type I)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$-\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$



three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

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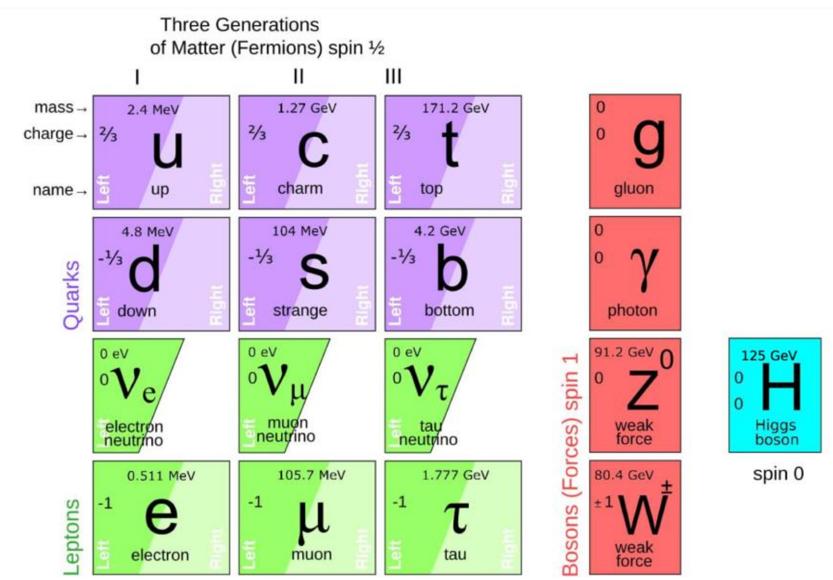

 # massive SM neutrinos ≤ #RH neutrino flavours

- minimal model with $m_{\text{lightest}} = 0$ has two RHN
- if all SM neutrinos are massive, three RHN flavours are needed

three light neutrinos mostly "active" SU(2) doublet

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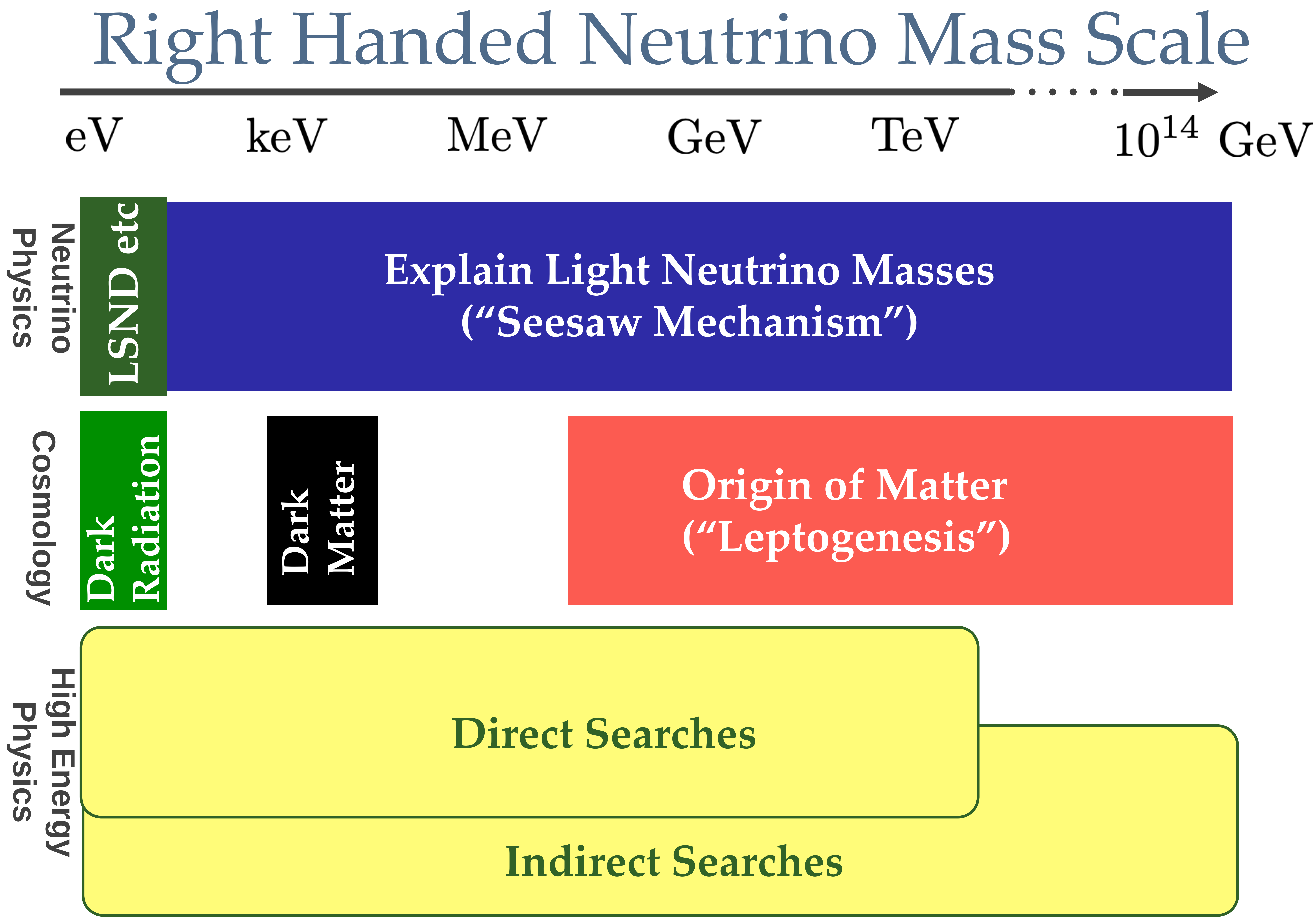
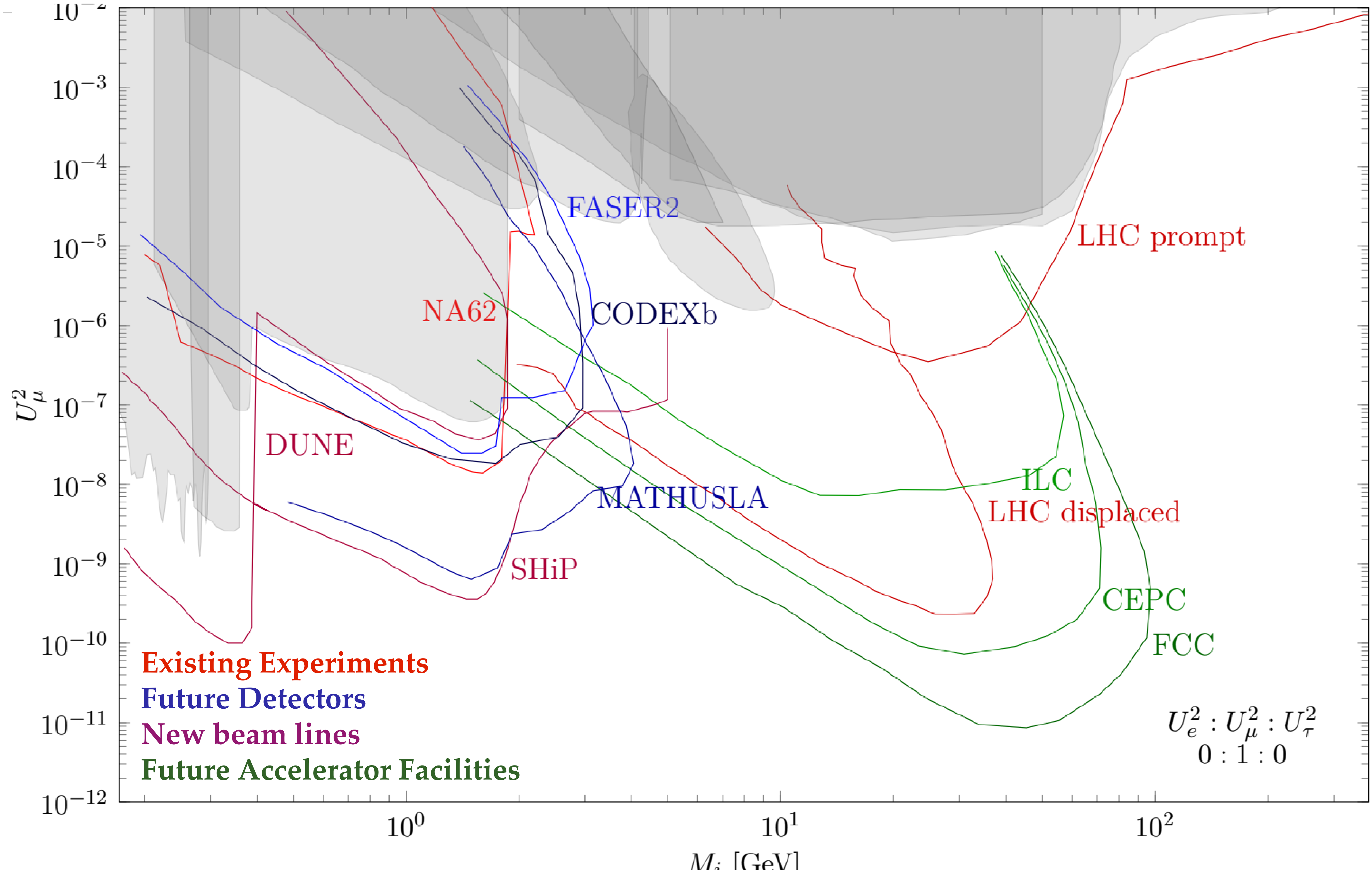
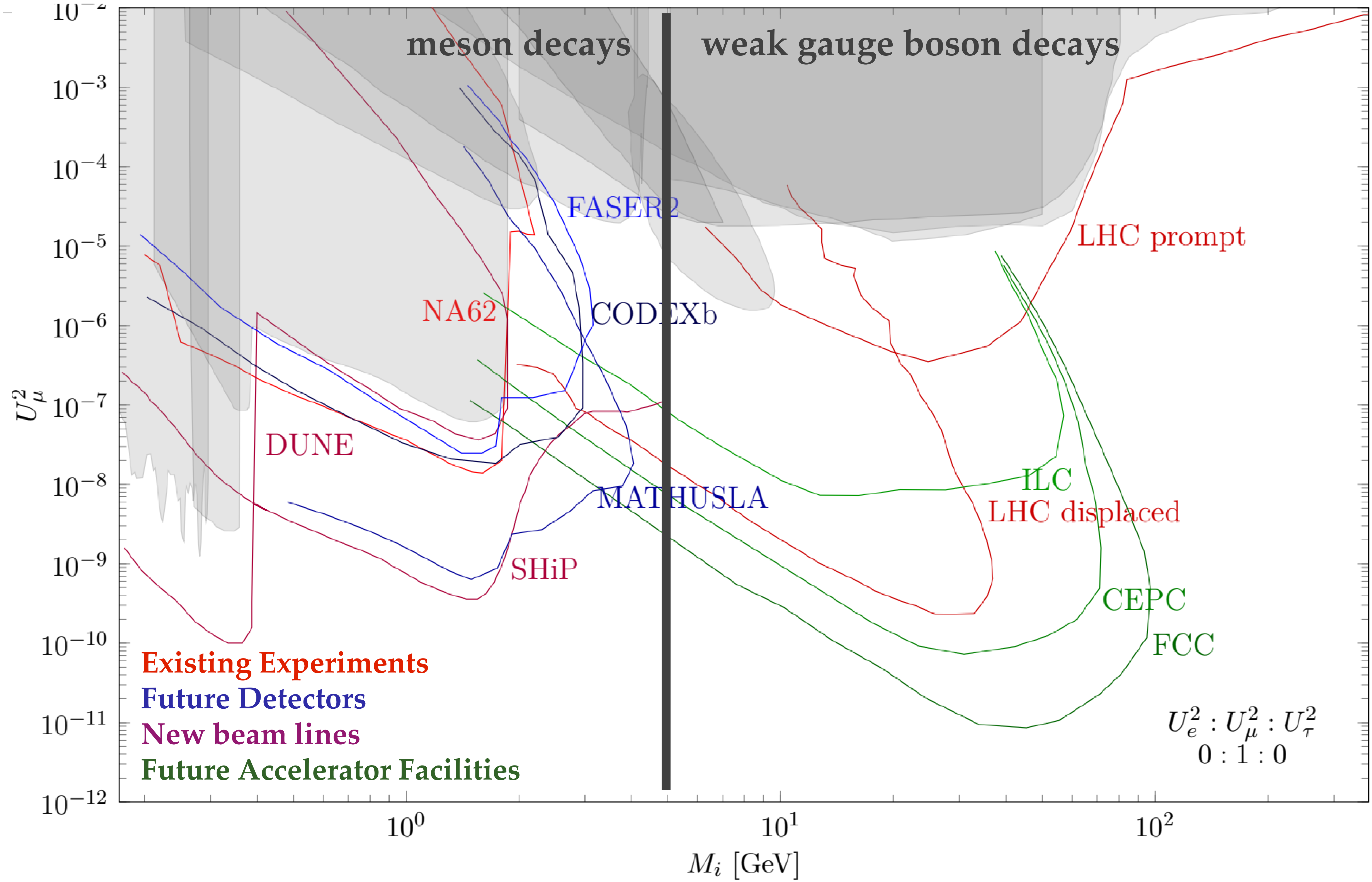

Right Handed Neutrino Mass Scale
eV
keV
MeV
GeV
TeV
10^{14} GeV
Neutrino Physics
LSND etc
Explain Light Neutrino Masses
("Seesaw Mechanism")
Cosmology
Dark Radiation
Dark Matter
Origin of Matter
("Leptogenesis")
High Energy Physics
Direct Searches
Indirect Searches

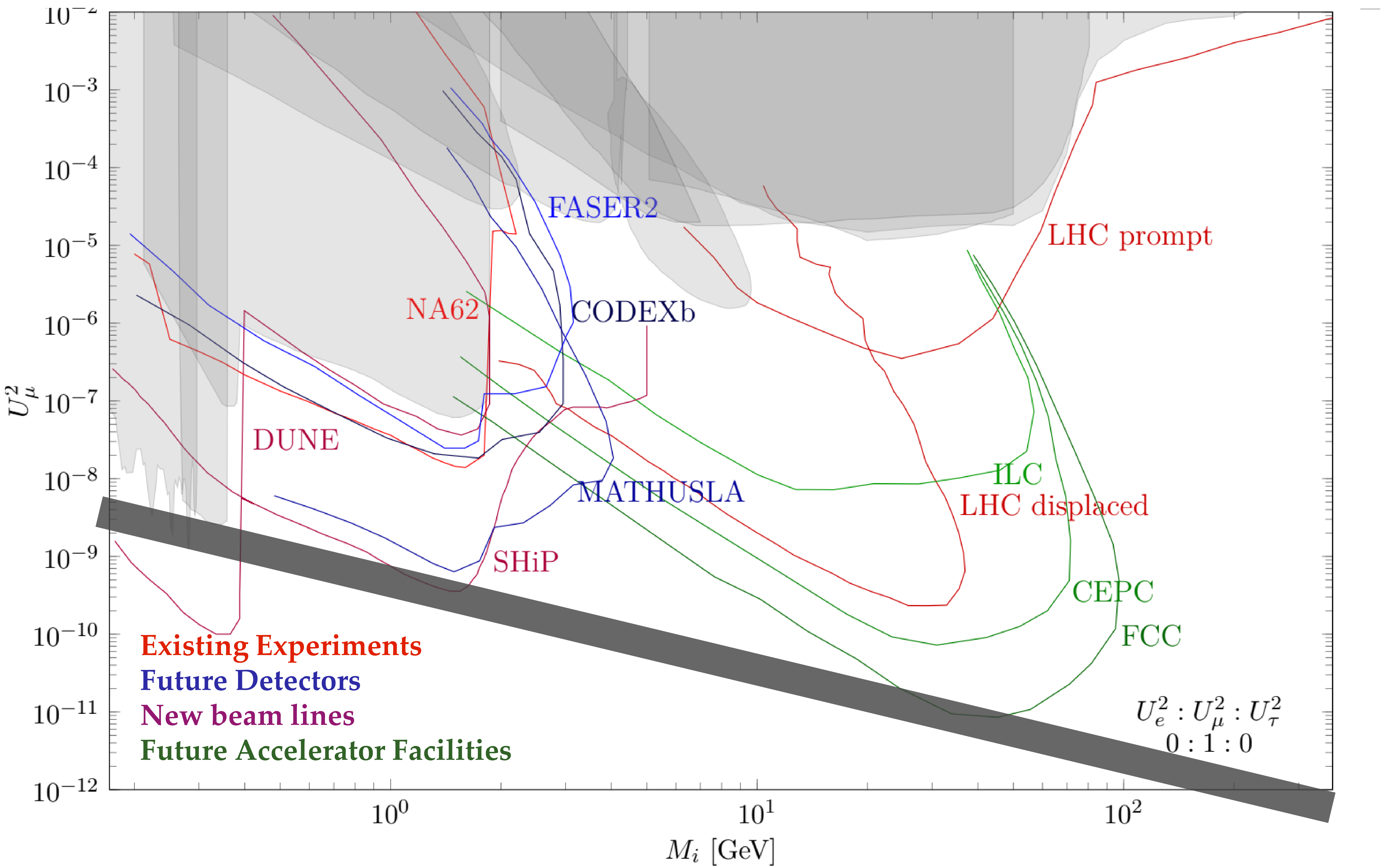
Heavy Neutrino Searches



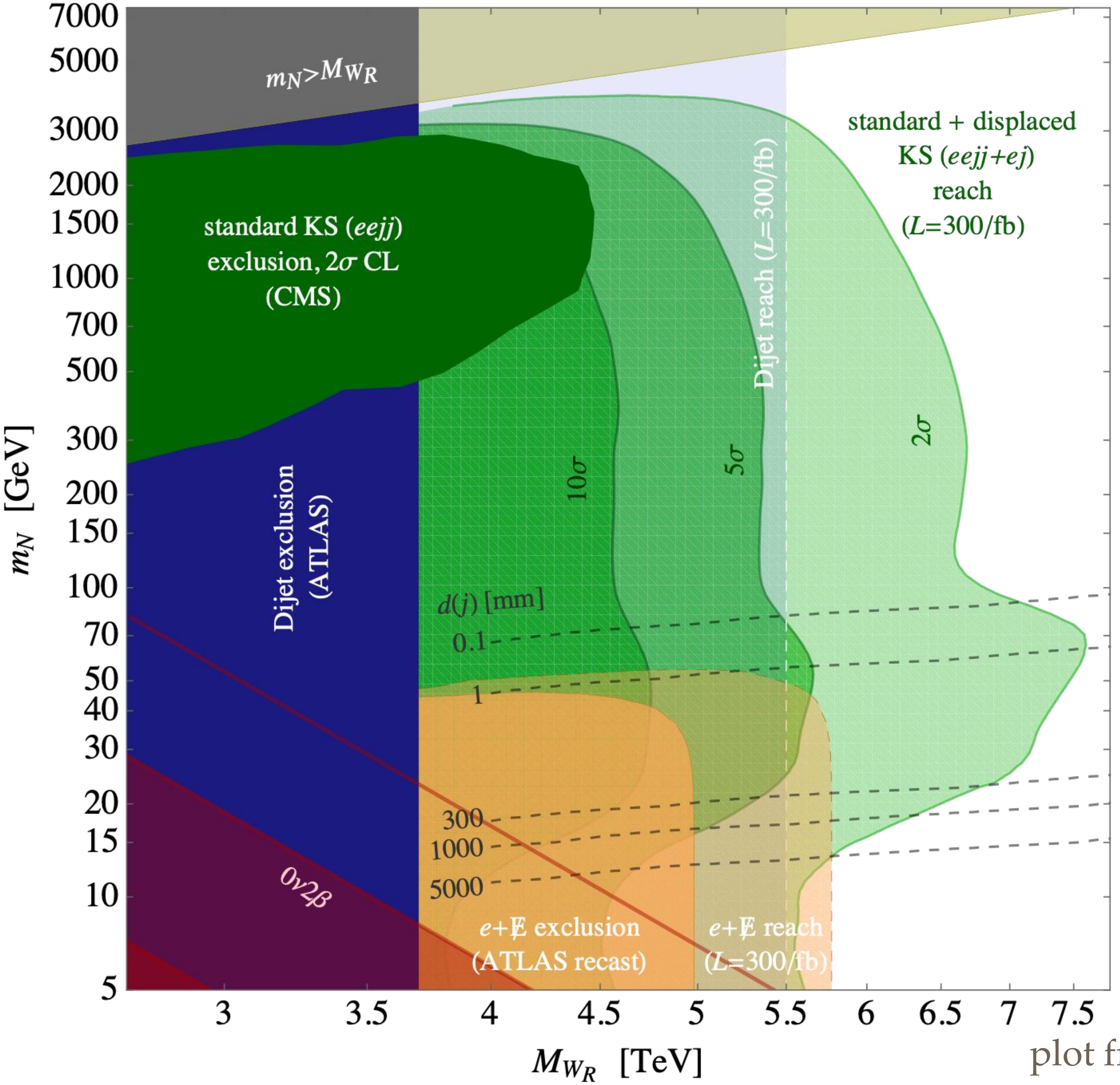
Heavy Neutrino Searches



$$m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T$$

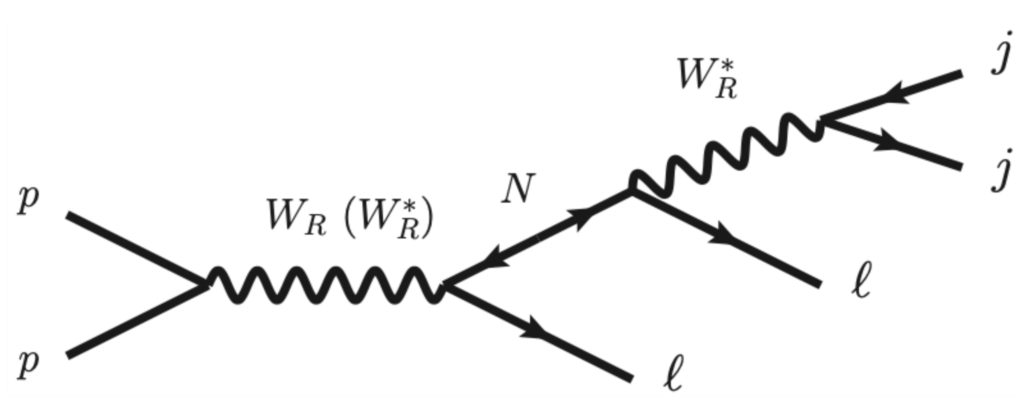


Non-minimal Scenarios



- discovery potential is much better in models with extra gauge interaction
- example: L-R symmetric model

Pati, Salam, Mohapatra, Senjanovic



Keung/Senjanovic 83

plot from Nemevšek/Nesti/Popara 1801.05813

B-L Symmetric Limit

charge assignment in Lagrangian

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

approximately conserved charges in leptogenesis

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

$$\psi_N = (\nu_{R\mathrm{s}} + \nu_{R\mathrm{w}}^c)$$

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

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

Shaposhnikov 06
Kersten/Smirnov 07

B-L Symmetric Limit

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$P_+ N_i, \quad \bar{N}_i P_+$	$+1$
$P_- N_i, \quad \bar{N}_i P_-$	-1

$$M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

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

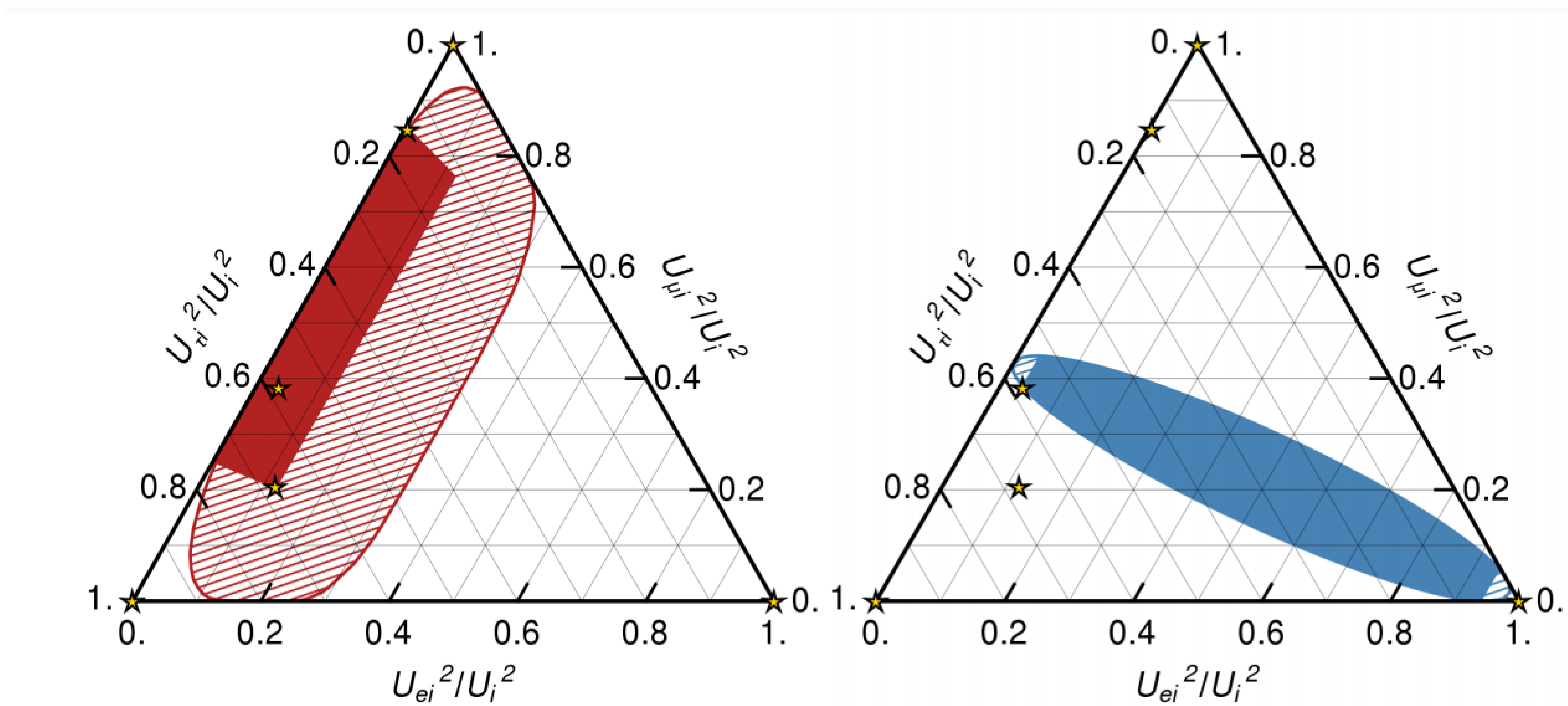
***B-L* symmetry dictates structure in sterile flavours**

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

ν oscillation data constrains strucrure in SM flavours

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

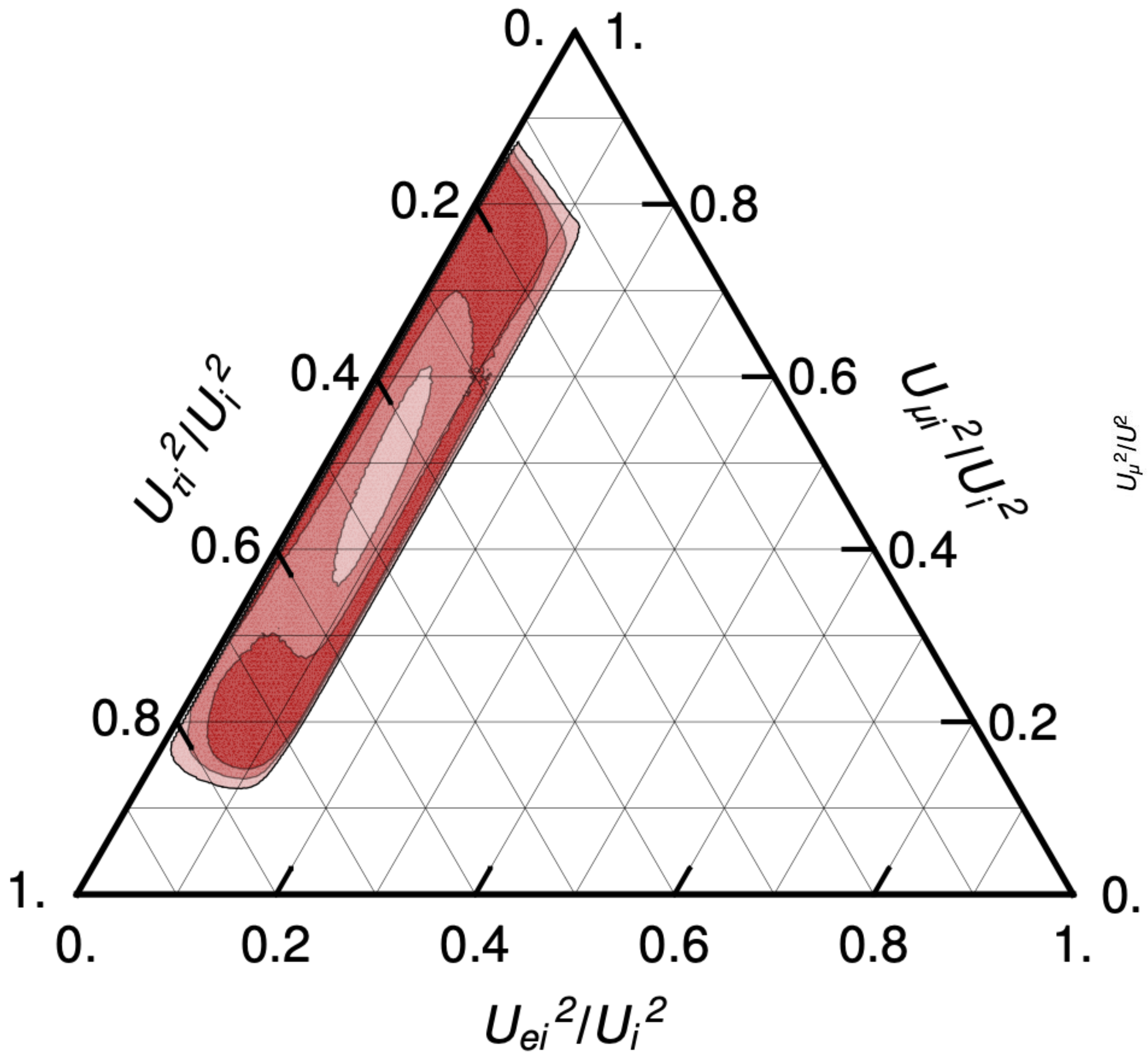
- This νMSM-like scenario is very predictive
- In particular, the flavour mixing pattern is strongly constrained: important for experimental sensitivity 1606.06719, 1609.09069, 1704.08721, 1801.04207



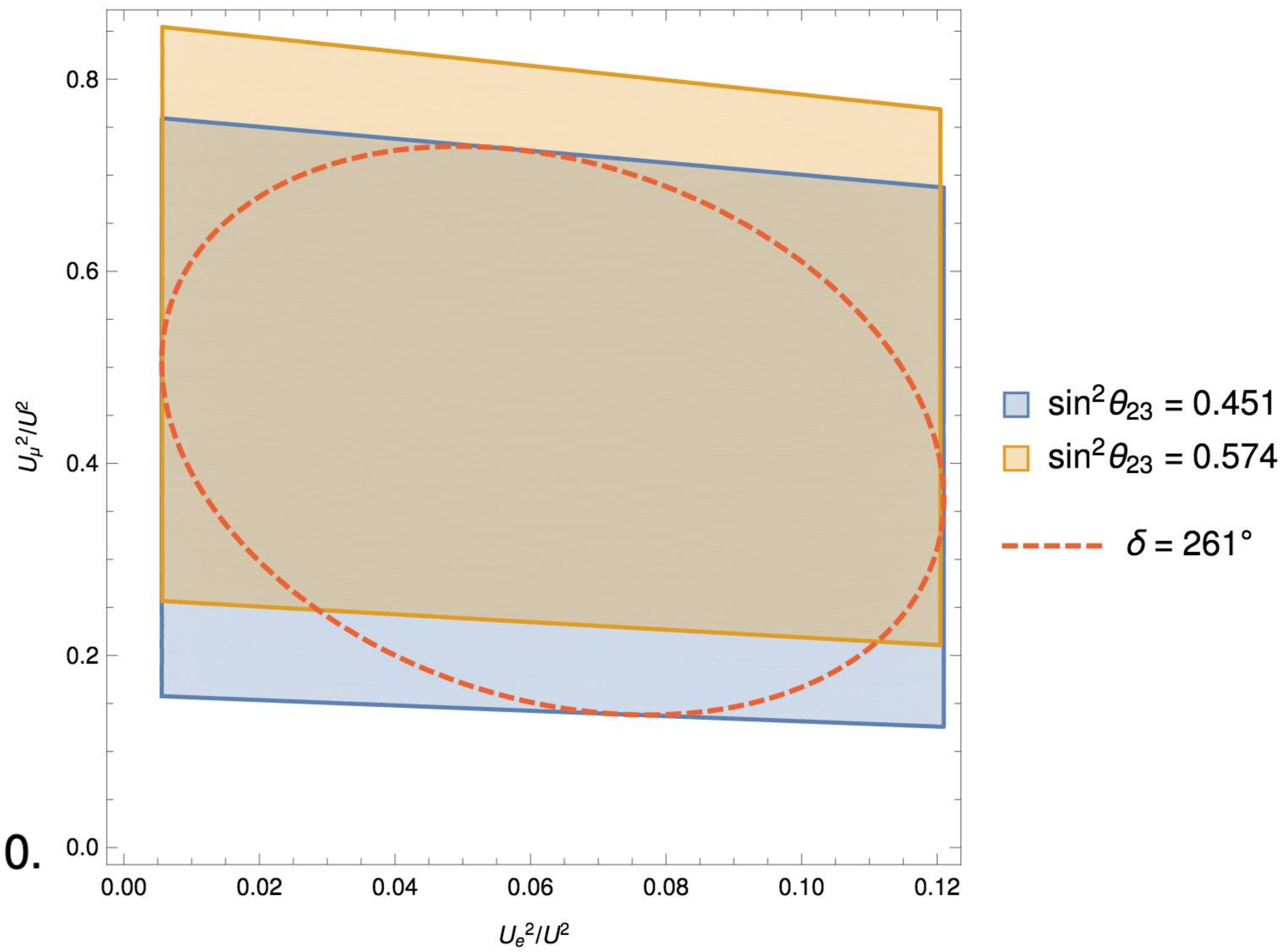
(a) Normal ordering. (b) Inverted ordering.

plot from 1801.04207

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



normal neutrino mass ordering



normal neutrino mass ordering

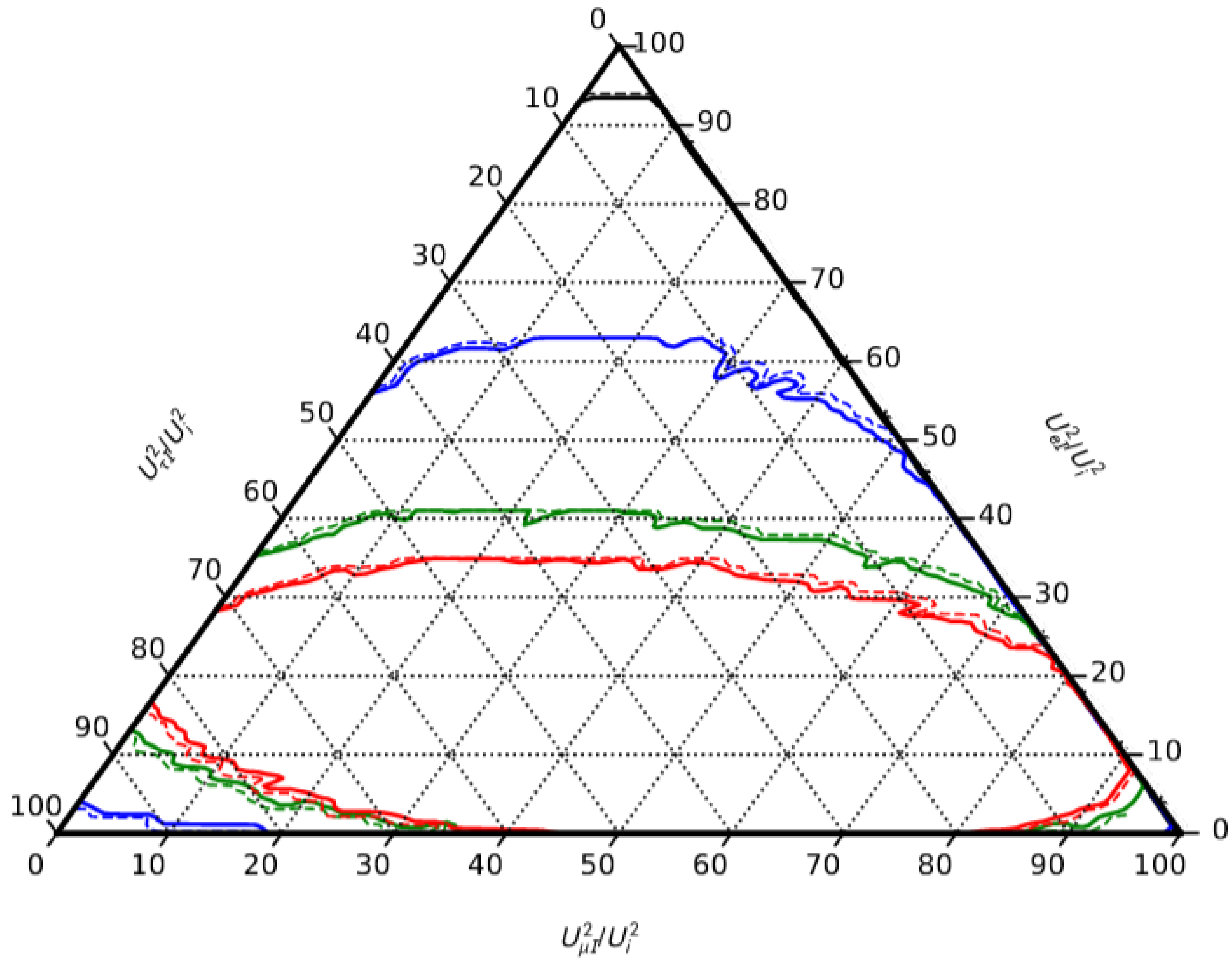
coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ

MaD/Hajer/Klaric/Lafranchi 1801.04207

can measure Majorana phase α!

MaD et al 1609.09069, Caputo et al 1611.05000

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



normal ordering

$m_{\text{lightest}} < 10$ meV

$m_{\text{lightest}} < 1$ meV

$m_{\text{lightest}} < 0.1$ meV

$m_{\text{lightest}} < 0.01$ meV

Chrzaszcz et al 1908.02302

Overview

Low Scale Seesaw Predictions for Neutrino Yukawas

Leptogenesis Predictions for Neutrino Yukawas

Other tests: LNV and CPV

Thermal Leptogenesis

Basic idea Fukugita/Yanagida

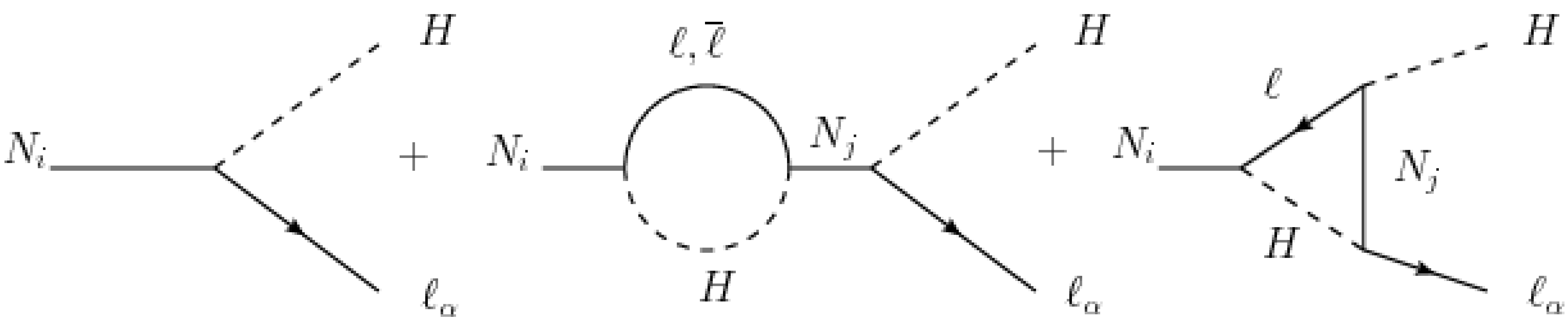
- *N* are around in the early universe
- *N* interactions are CP violating
- *N* may preferably decay into matter

CP violating parameter ϵ

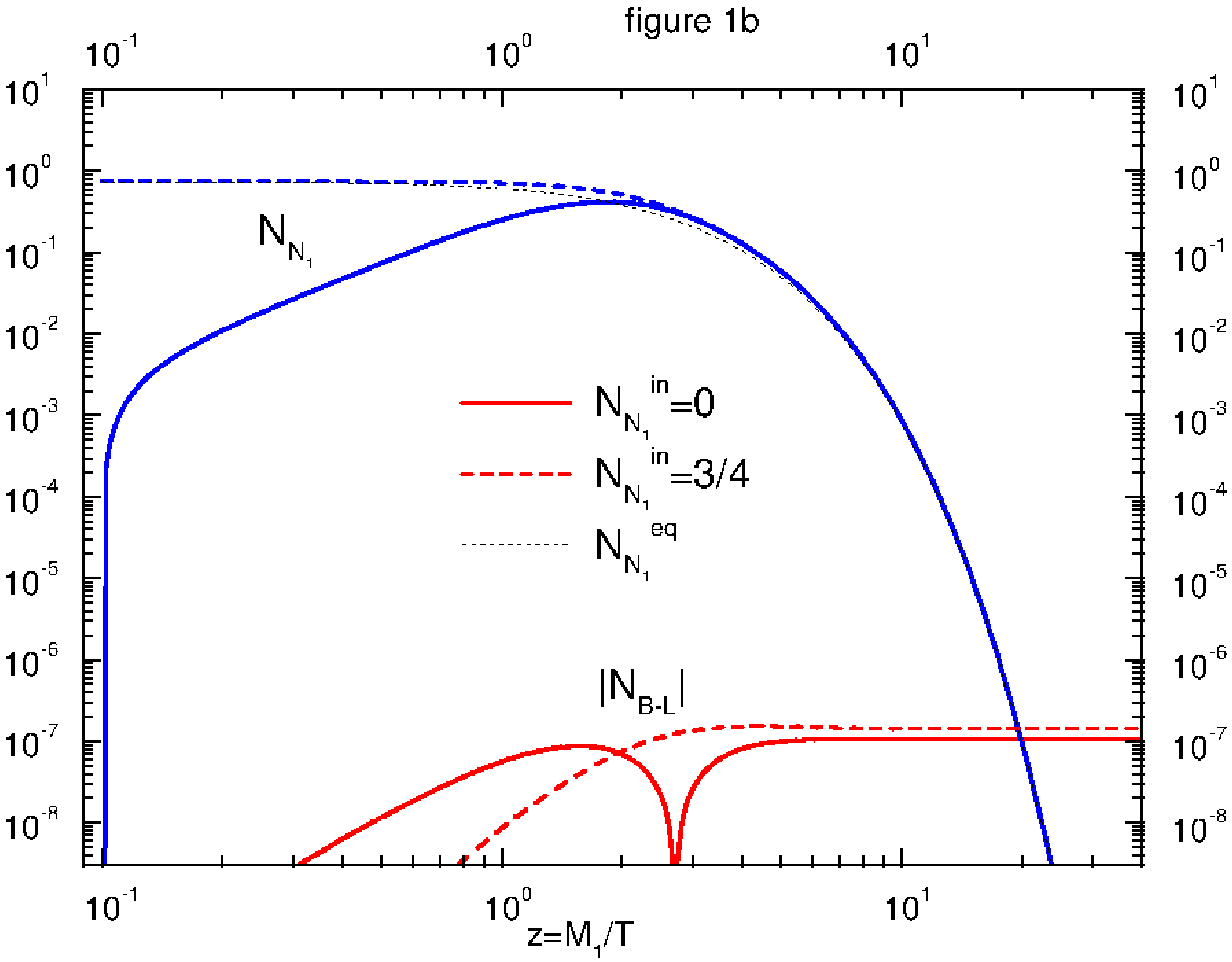
$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

final asymmetry

$$Y_{B-L} \propto \epsilon/g_*$$



Leptogenesis with sub-TeV *M*?



Buchmuller/Di Bari/Plumacher 0205349

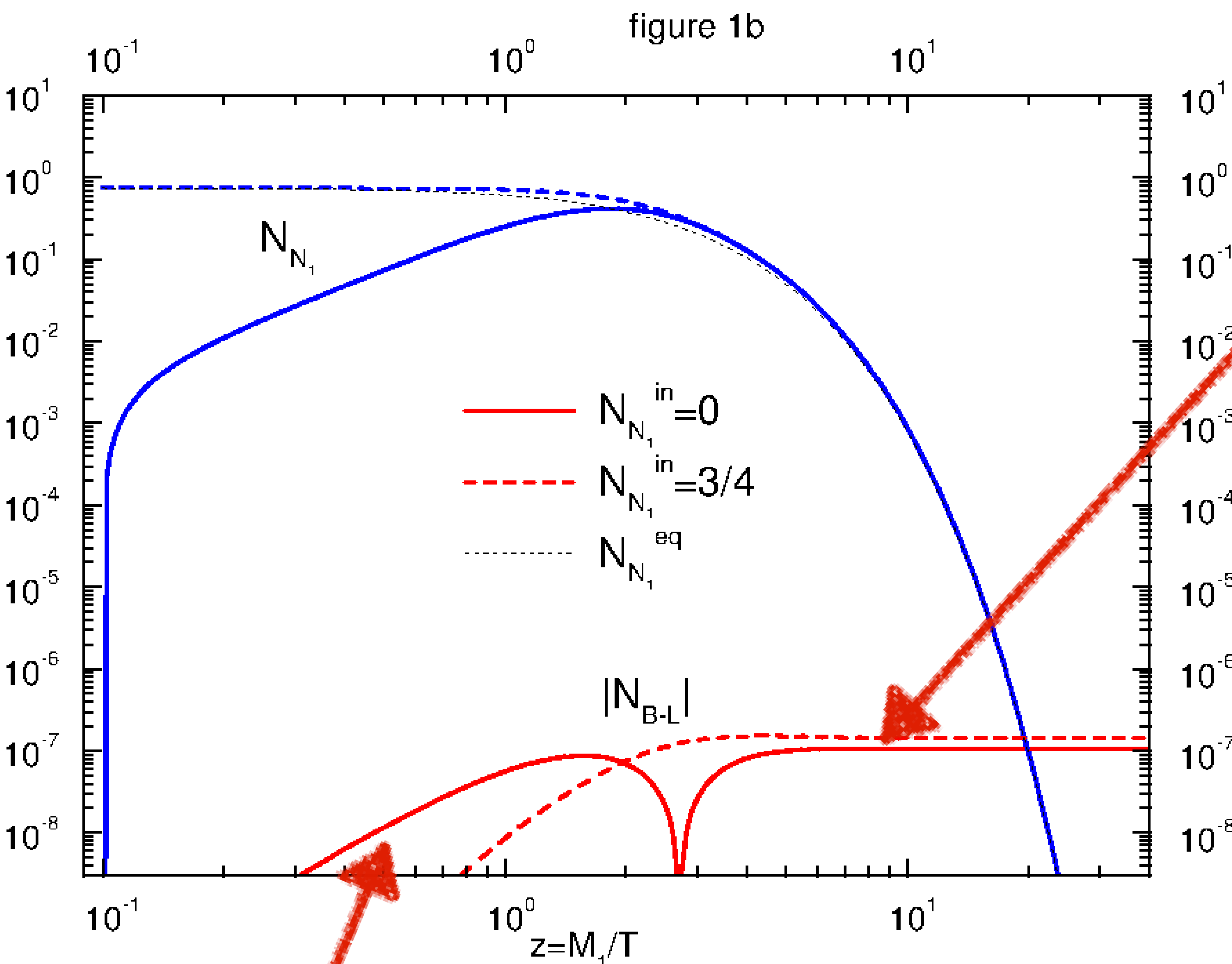
- In "vanilla leptogenesis" flavour plays no role, asymmetry is independent of PMNS phases
- M should be larger than 10^9GeV (Davidson/Ibarra 02)
- Flavour effects reduce lower bound on M a bit Abada/Davidson/Josse-Michaux/Losada/Riotto 06, Nardi/Nir/Roulet/Racker 06, Blanchet/Di Bari 07, Pascoli/Petcov/Riotto 07, De Simone/Riotto 07
- But how to go below TeV?

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

Leptogenesis with sub-TeV M?



asymmetry generated during N decay ("freeze-out scenario")

Sakharov's nonequilibrium condition can be fulfilled in two ways.

asymmetry generated during N production ("freeze-in scenario")

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

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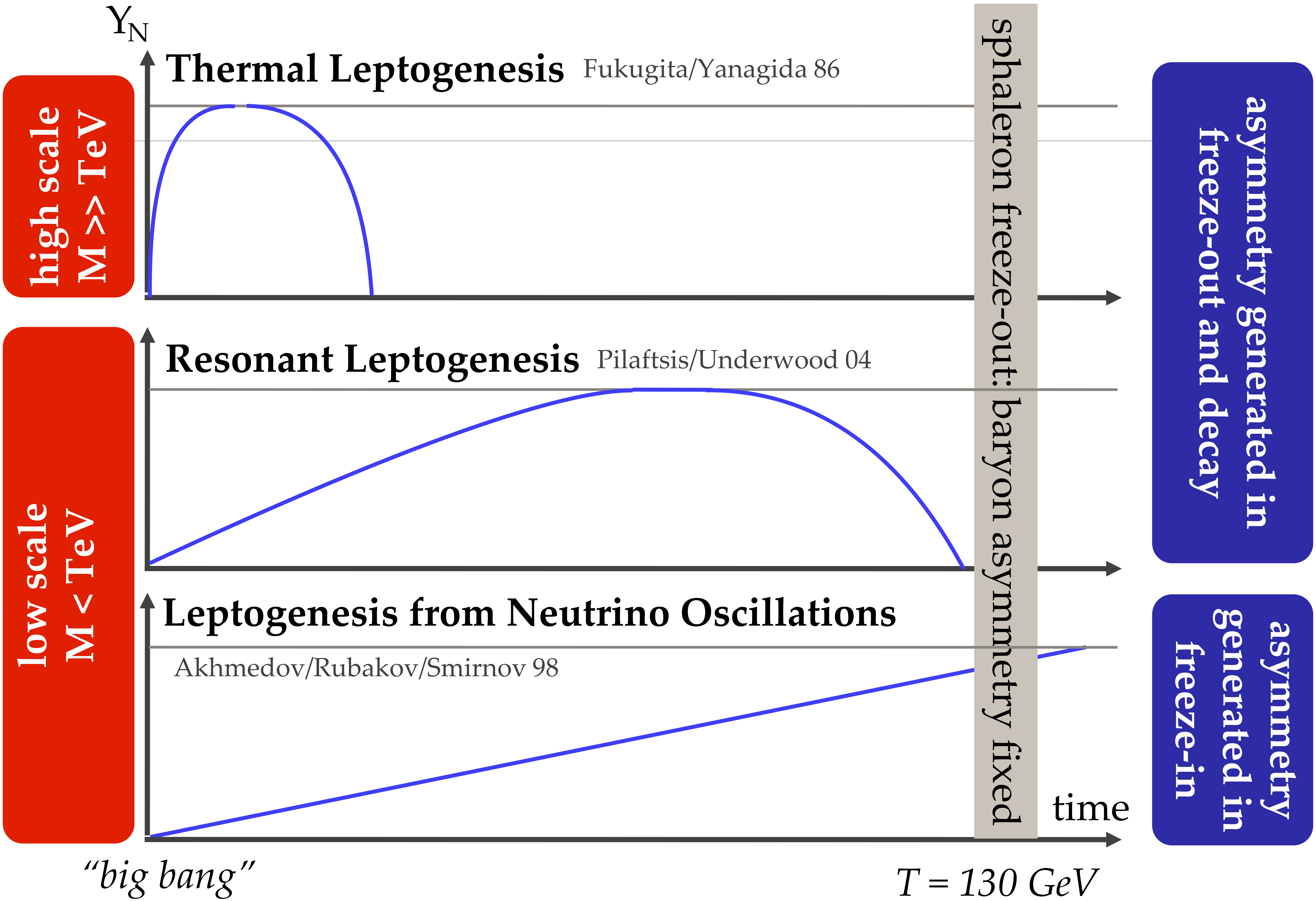


Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
low scale
M < TeV
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in
time
"big bang"
T = 130 GeV

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

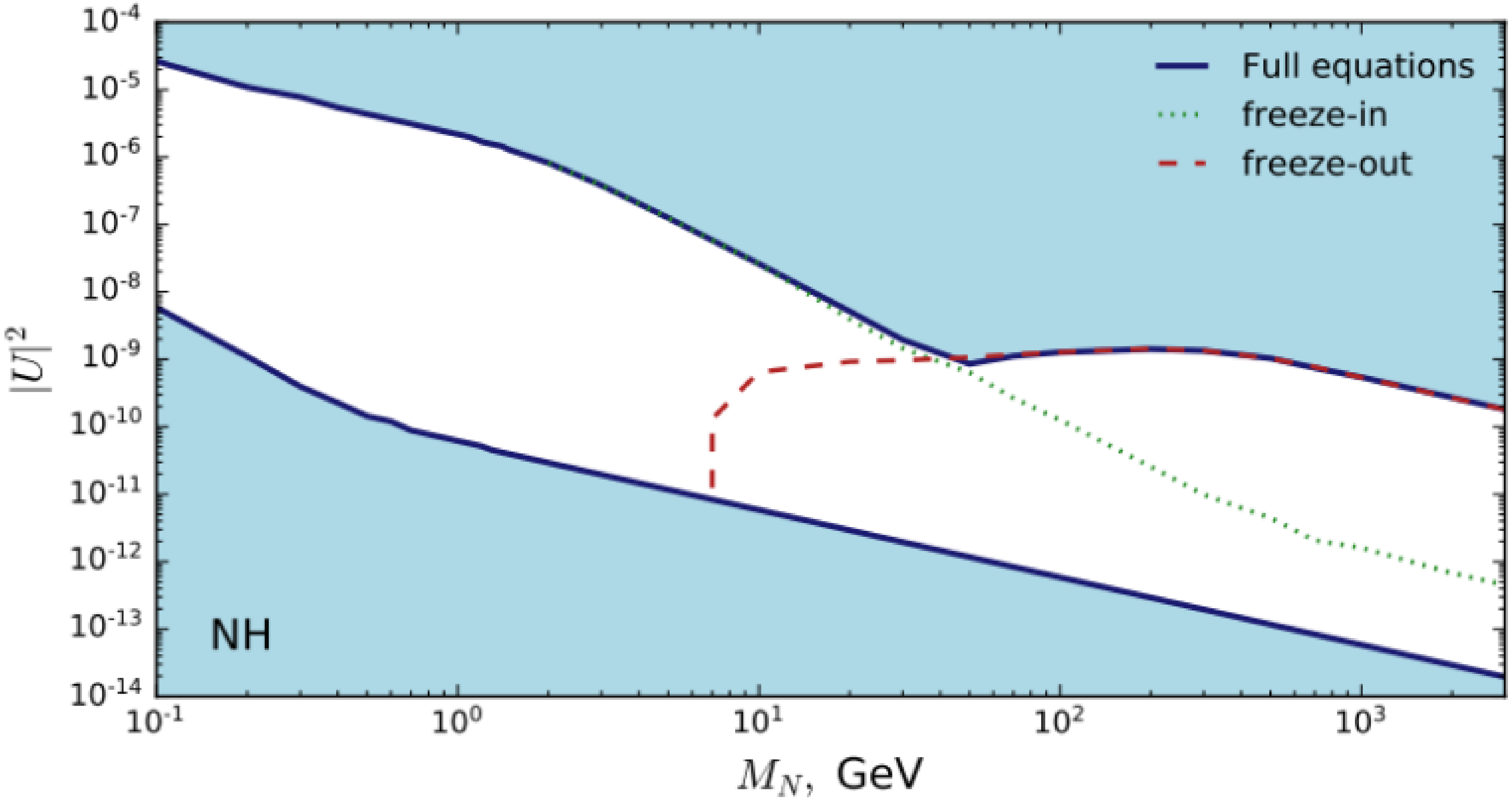
Heavy neutrino density matrix

LNC rate ~ $F^2\,T$

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

Heavy neutrino effective Hamiltonian

Leptogenesis with 2 RH Neutrinos

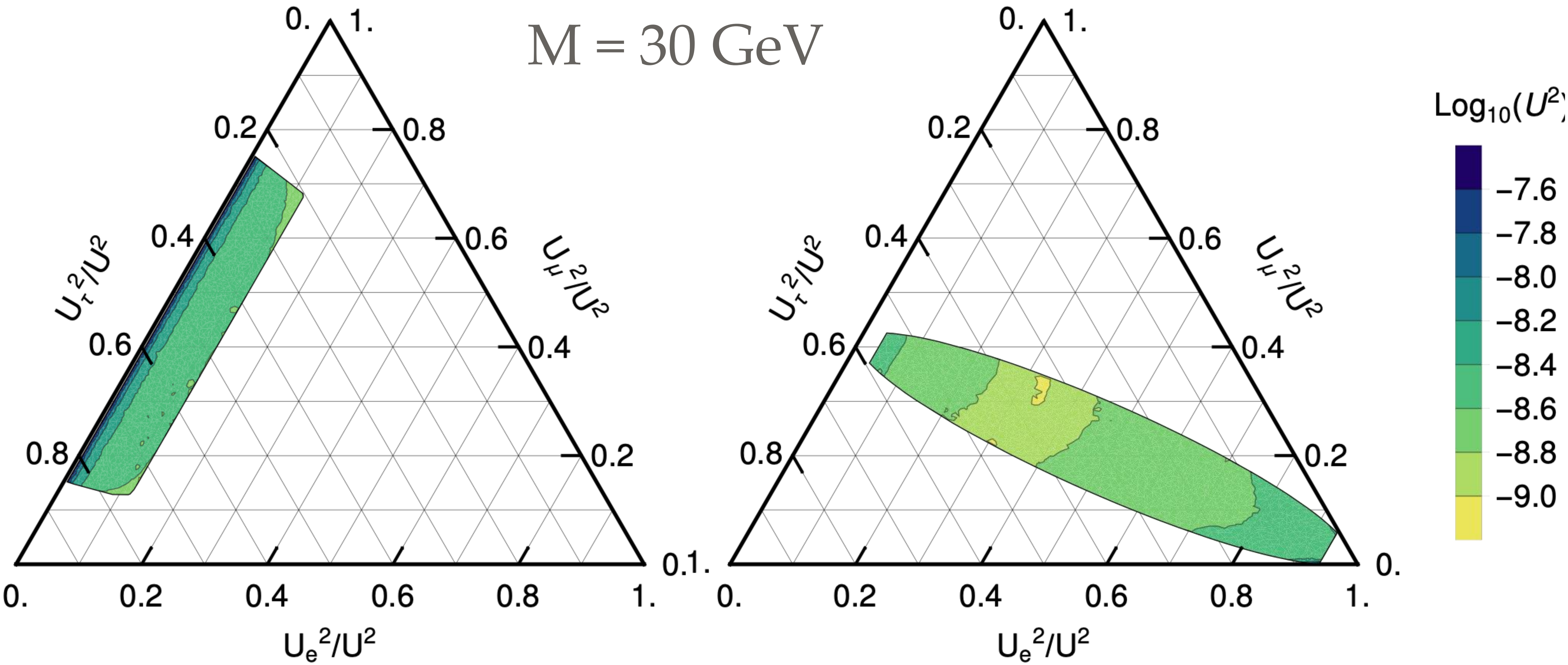


The region in which the freeze-out scenario ("resonant leptogenesis") and freeze-in scenario ("ARS leptogenesis") work overlap!

Klaric/Shaposhnikov/Timirsyasov 2008.13771

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

- 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
$\nu_{R\mathrm{s}} \equiv \frac{1}{\sqrt{2}}(\nu_{R1} + i\nu_{R2})$	$+1$
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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"

Constraints from Leptogenesis in Model with 2 Heavy Neutrinos

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"mass basis"

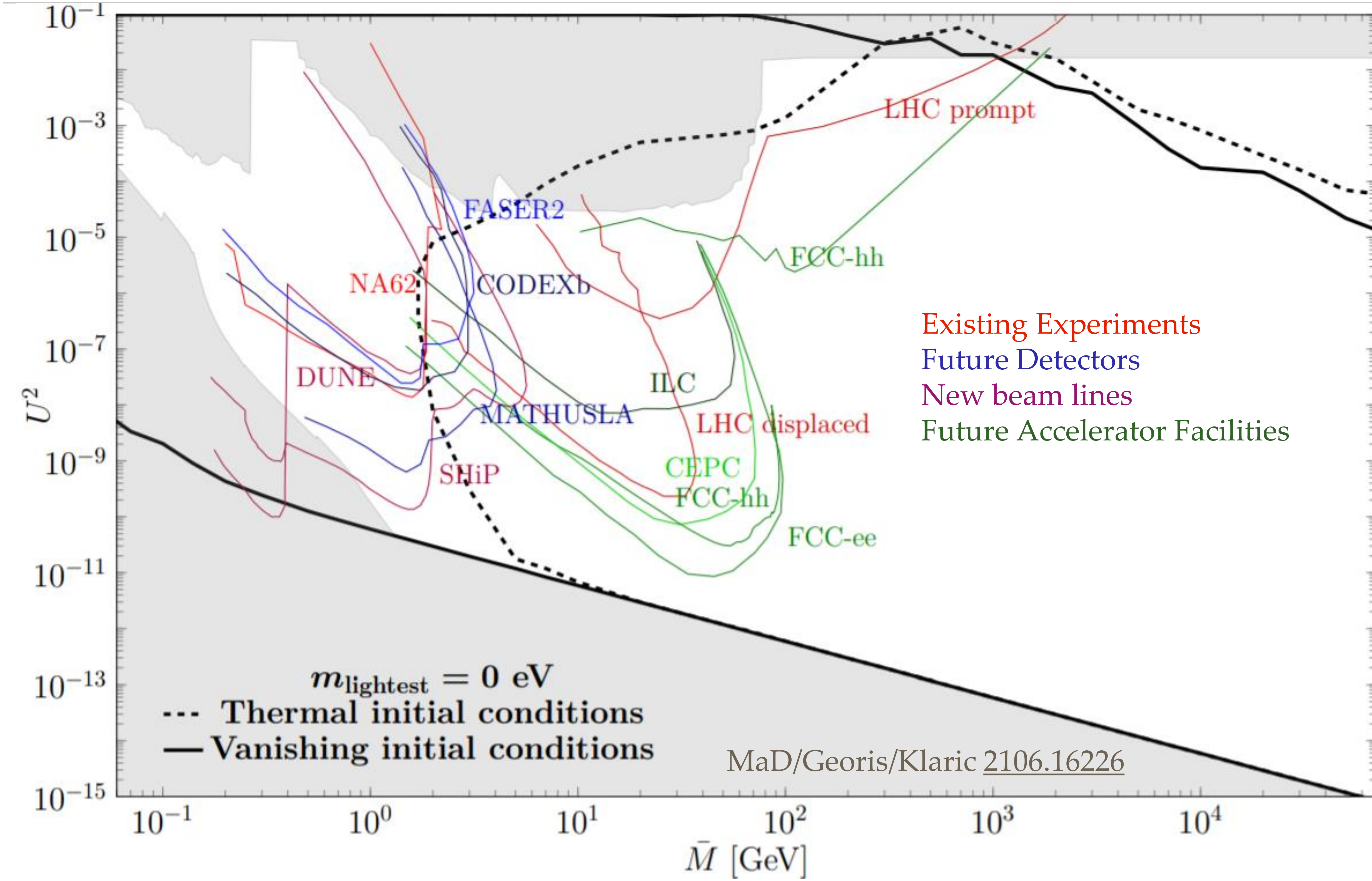
$$F \sim \begin{pmatrix} F_e & F_e\epsilon_e \\ F_\mu & F_\mu\epsilon_\mu \\ F_\tau & F_\tau\epsilon_\tau \end{pmatrix}$$

"interaction basis"

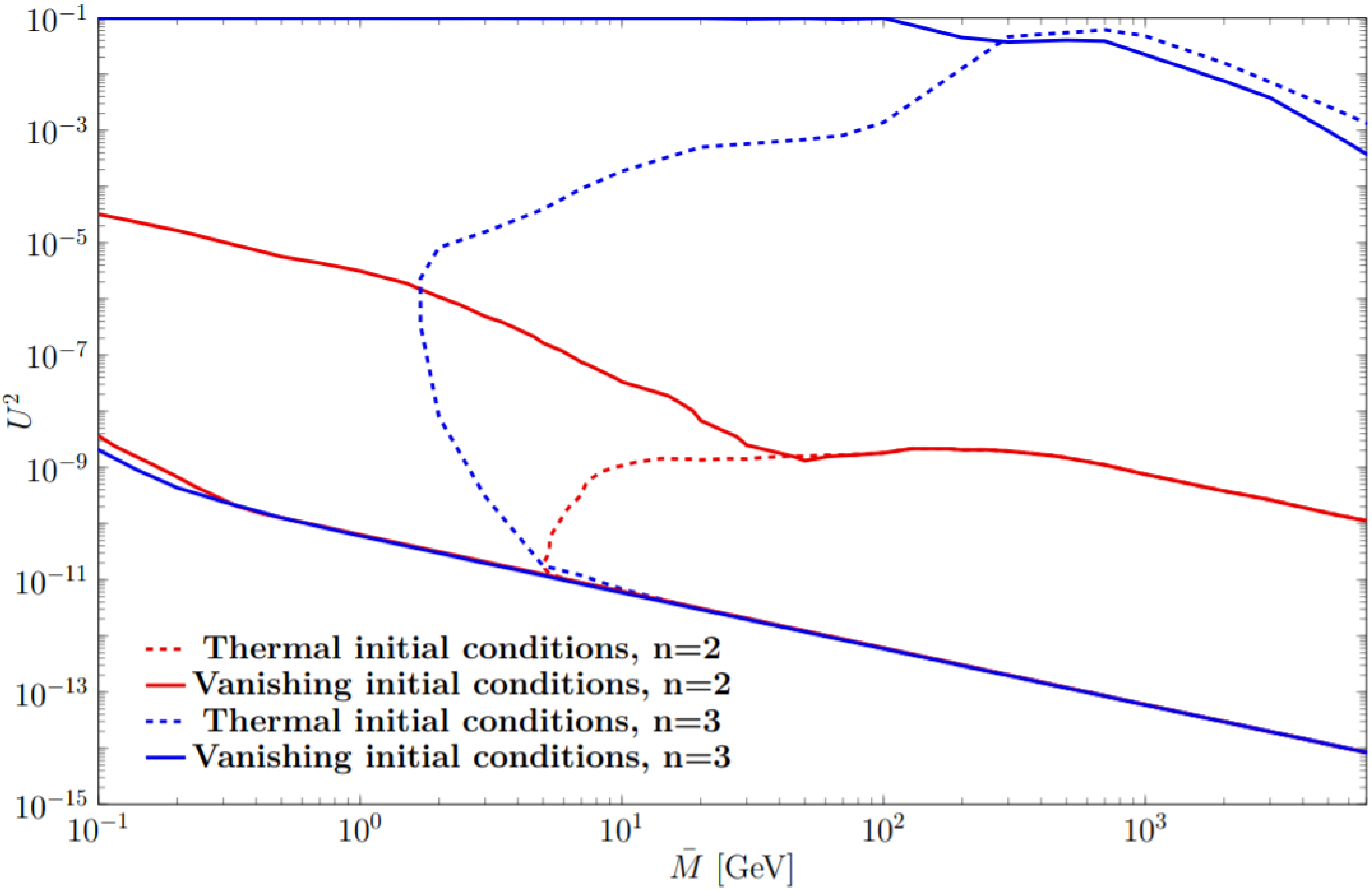
- For large U^2, ν_{Rs} comes into equilibrium quickly, deviation from equilibrium necessary for baryogenesis comes from ν_{Rs}
- For $T \sim M$ both states become "strongly" coupled (LNV rates)
- Only way to prevent washout: Have one SM flavour feebly coupled

Structure in sterile flavours enforces hierarchy in SM flavour!

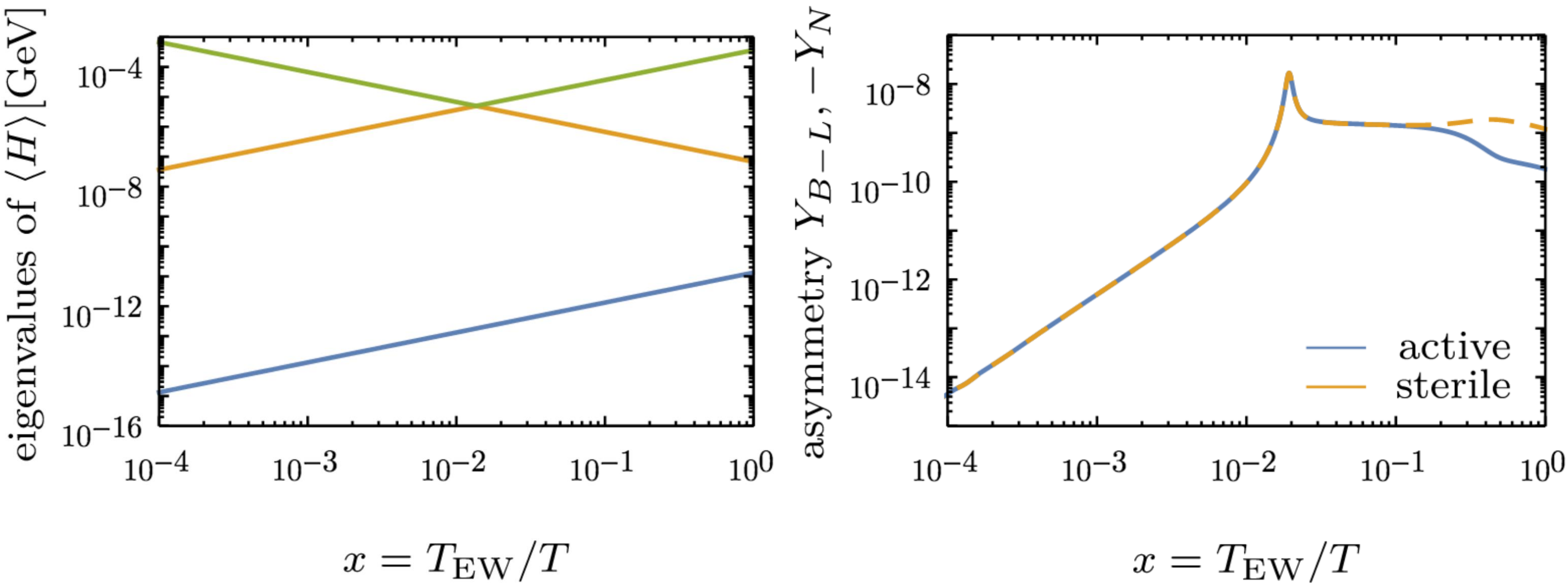
Leptogenesis with 3 RH Neutrinos



Leptogenesis with 3 RH Neutrinos



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

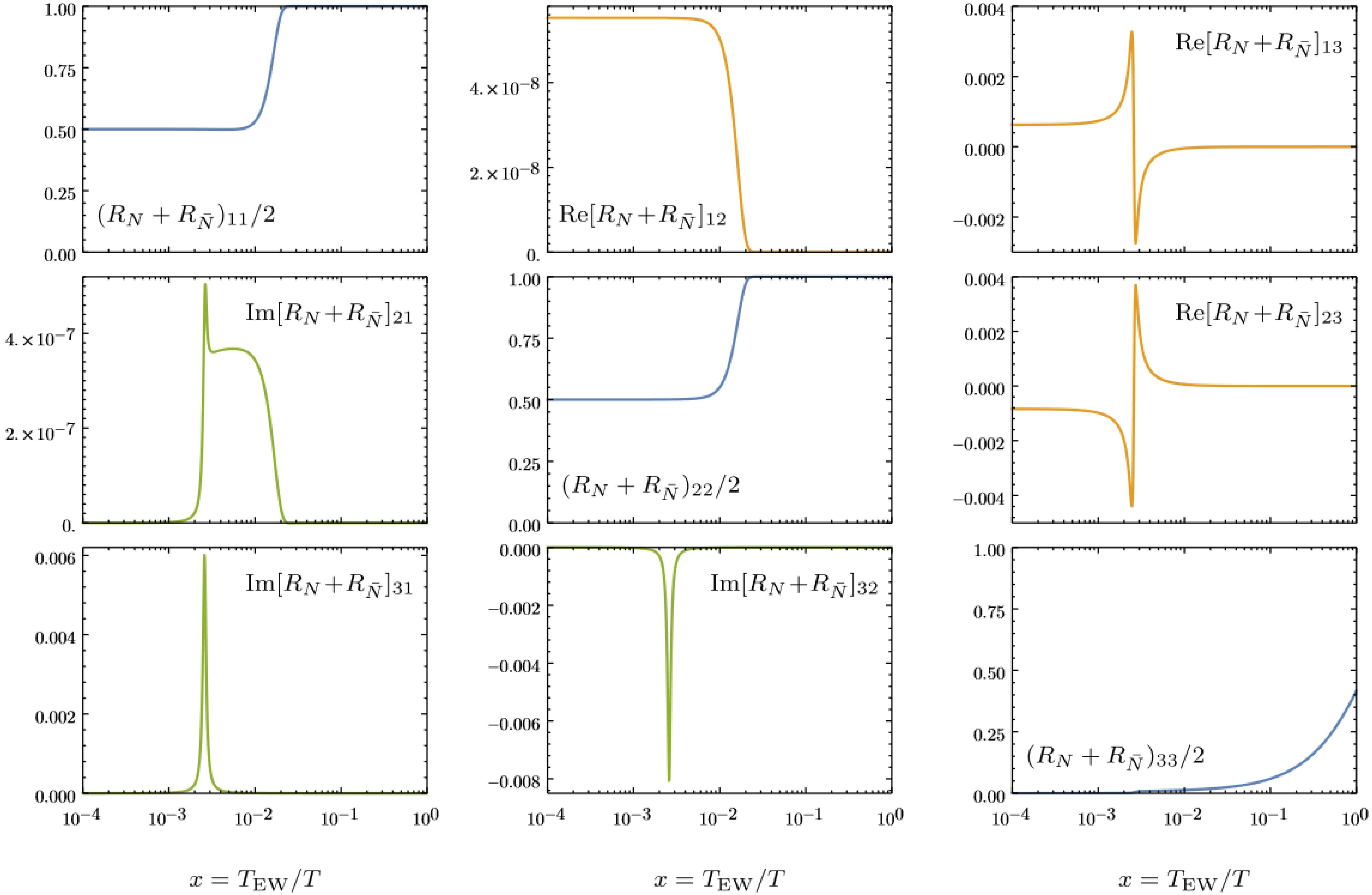
- Mass basis at $T=0$ is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

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
ν_{R3}	0

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

- 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



Abada et al 1810.12463

Overview

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Leptogenesis Predictions for Neutrino Yukawas

Other tests: LNV and CPV

What can we learn?

Dirac vs Majorana

- **LNV vs LFV decay rates** e.g. Anamiati / Hirsch / Nardi 1607.05641
- **Angular distribution** e.g. Arbelaez et al 1712.08704 , Balantekin/Gouvea/Kayser 1808.10518
- **Flavour mixing pattern** e.g. Dib / Kim / Wang / Zhang 1605.01123

CP properties

e.g. Cvetic / Dib / Kim / Saa 1503.01358

Mass spectrum

e.g. Antusch / Fischer 1709.03797

Test seesaw mechanism and leptogenesis

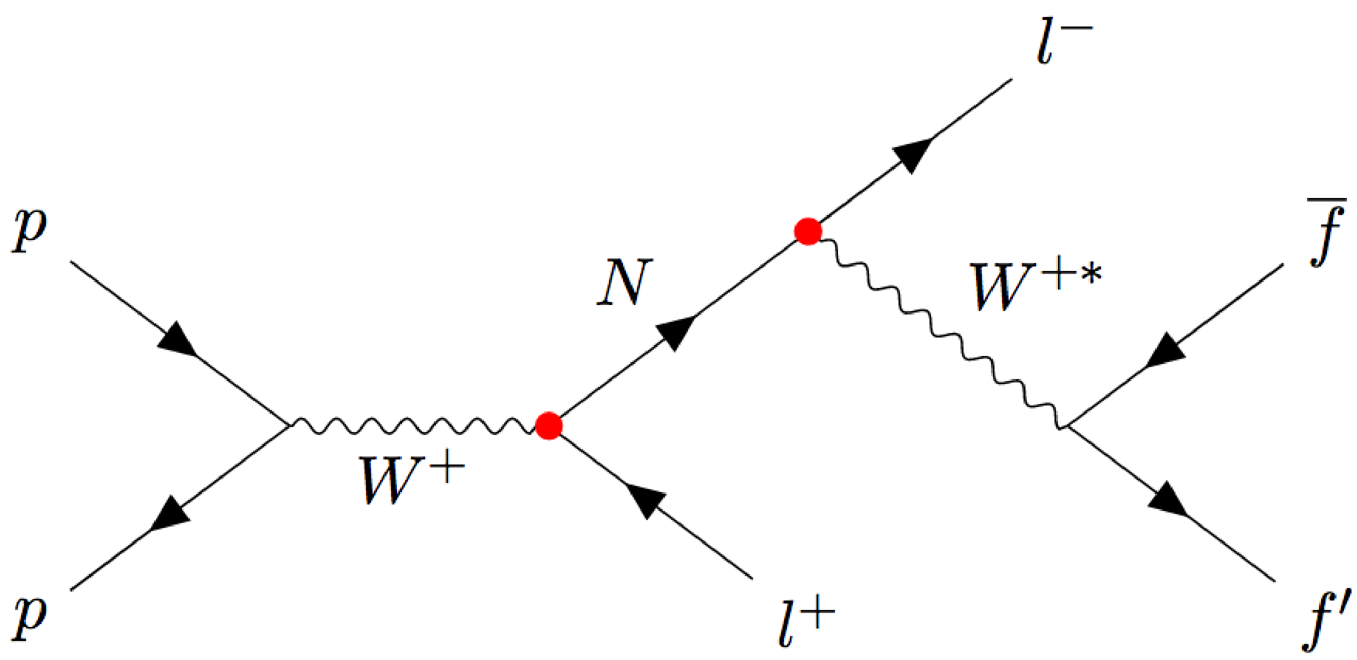
- **For 2 RHN all Lagrangian parameters can in principle be constrained**

Hernandez /Kekic / Lopez-Pavon / Racker / Savaldo 1606.06719,
MaD / Garbrecht / Gueter / Klaric 1609.09069
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Can LNV be observed?

B-L symmetry: destructive interference amongst contributions from different HNL flavours

But: B-L is broken to generate neutrino mass. Is this enough???



(a) Charged current decay

Can LNV be observed?

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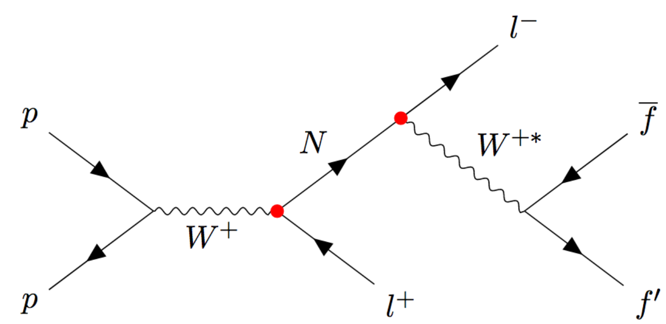

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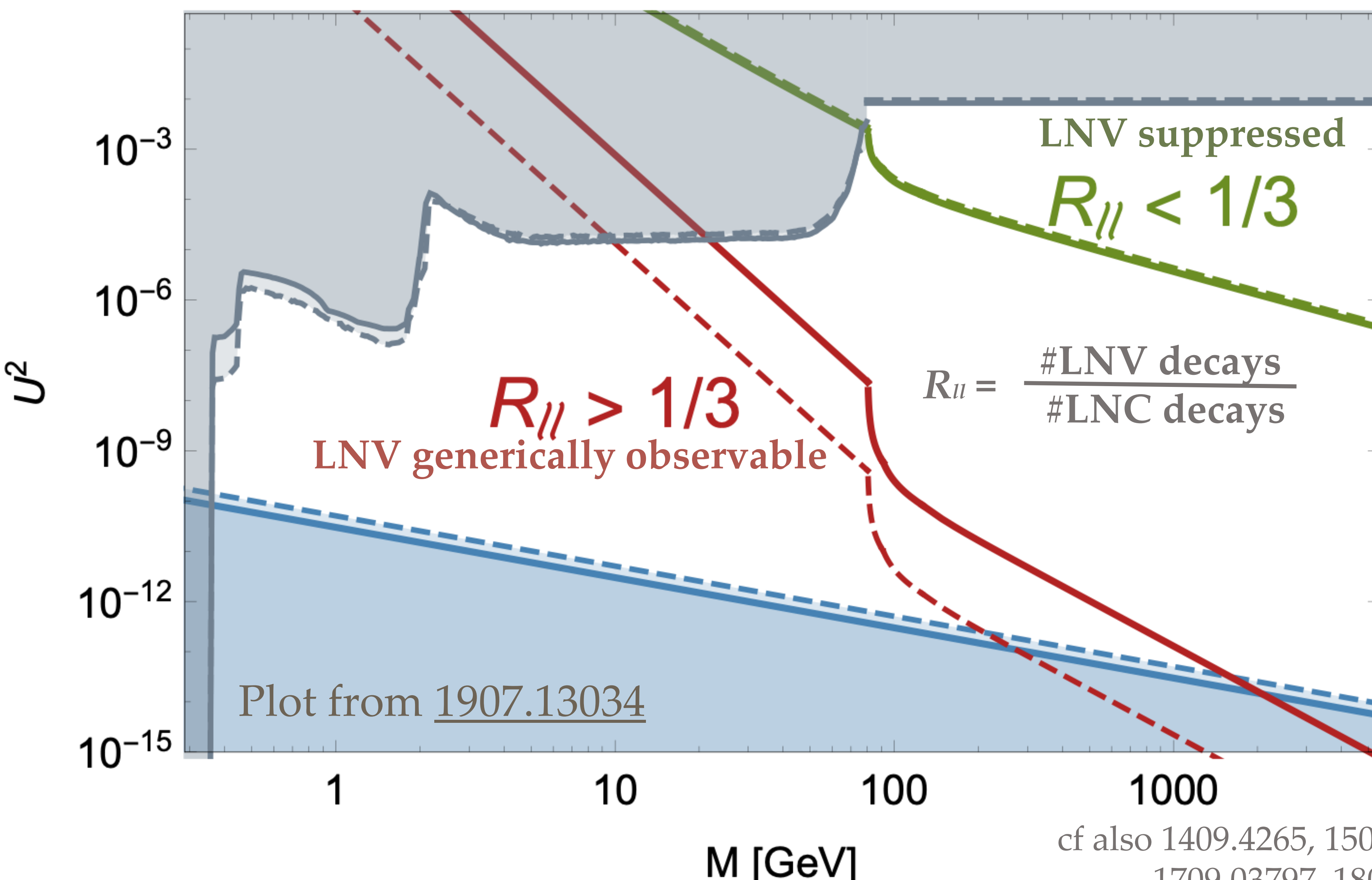
Is this enough???



HNL oscillations destroy coherence and make LNV observable!
Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M_{\rm phys}^2}{2\Gamma_N^2 + \Delta M_{\rm phys}^2}$$

Does neutrino osc. data allow for this without fine tuning? It depends
MaD/Klaric/Klose 1907.13034

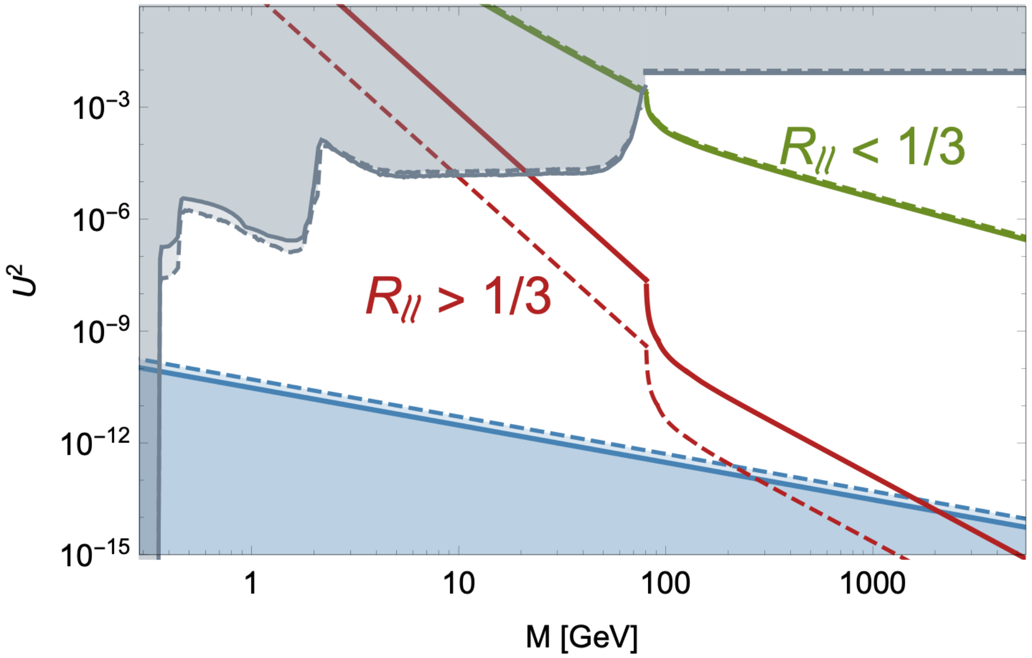
cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367

How to measure ΔM?

ratio of LNV to LNC decays
is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M_{\text{phys}}^2}{2\Gamma_N^2 + \Delta M_{\text{phys}}^2}$$

Anamiati et al 1607.05641



MaD/Klaric/Klose 1907.13034

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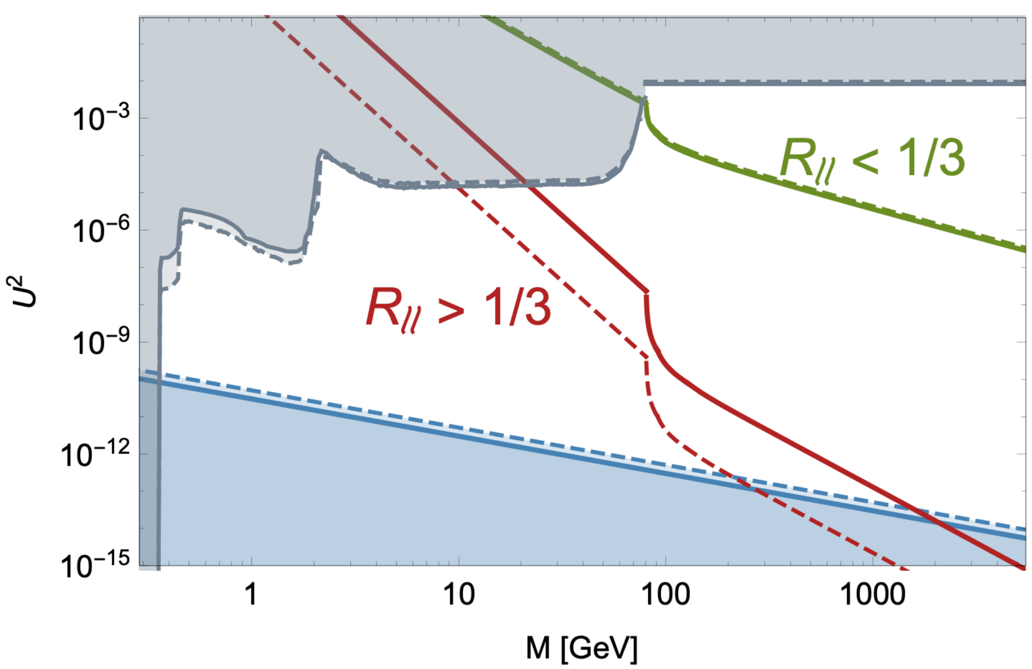
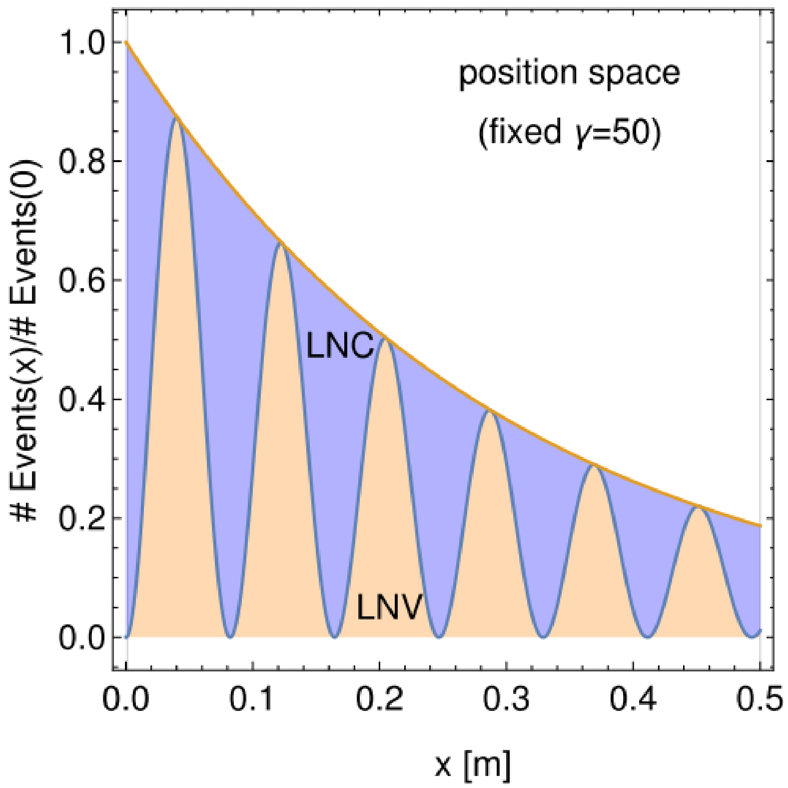
Anamiati et al 1607.05641

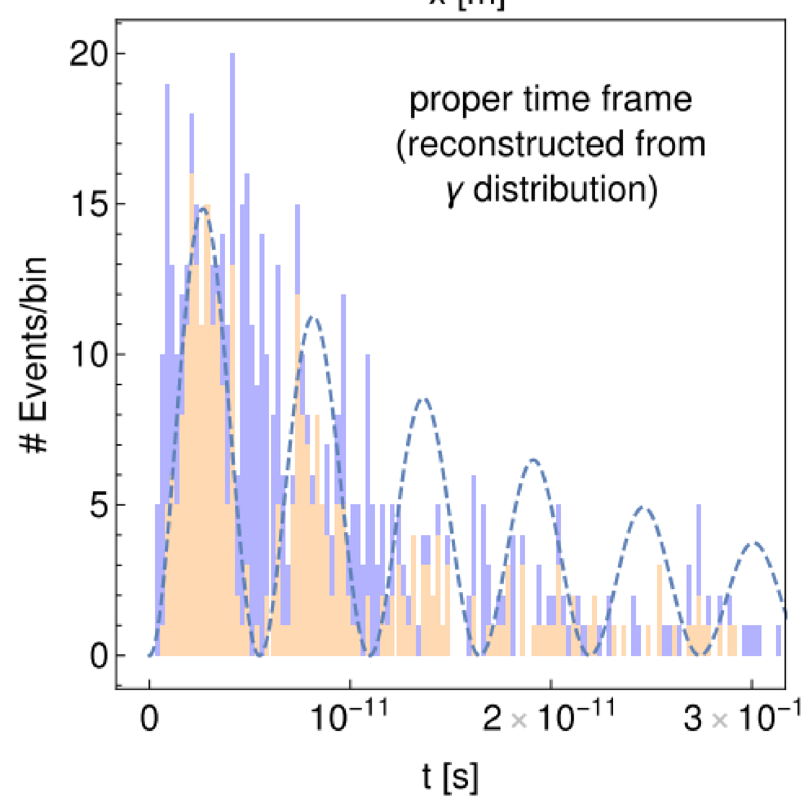


MaD/Klaric/Klose 1907.13034

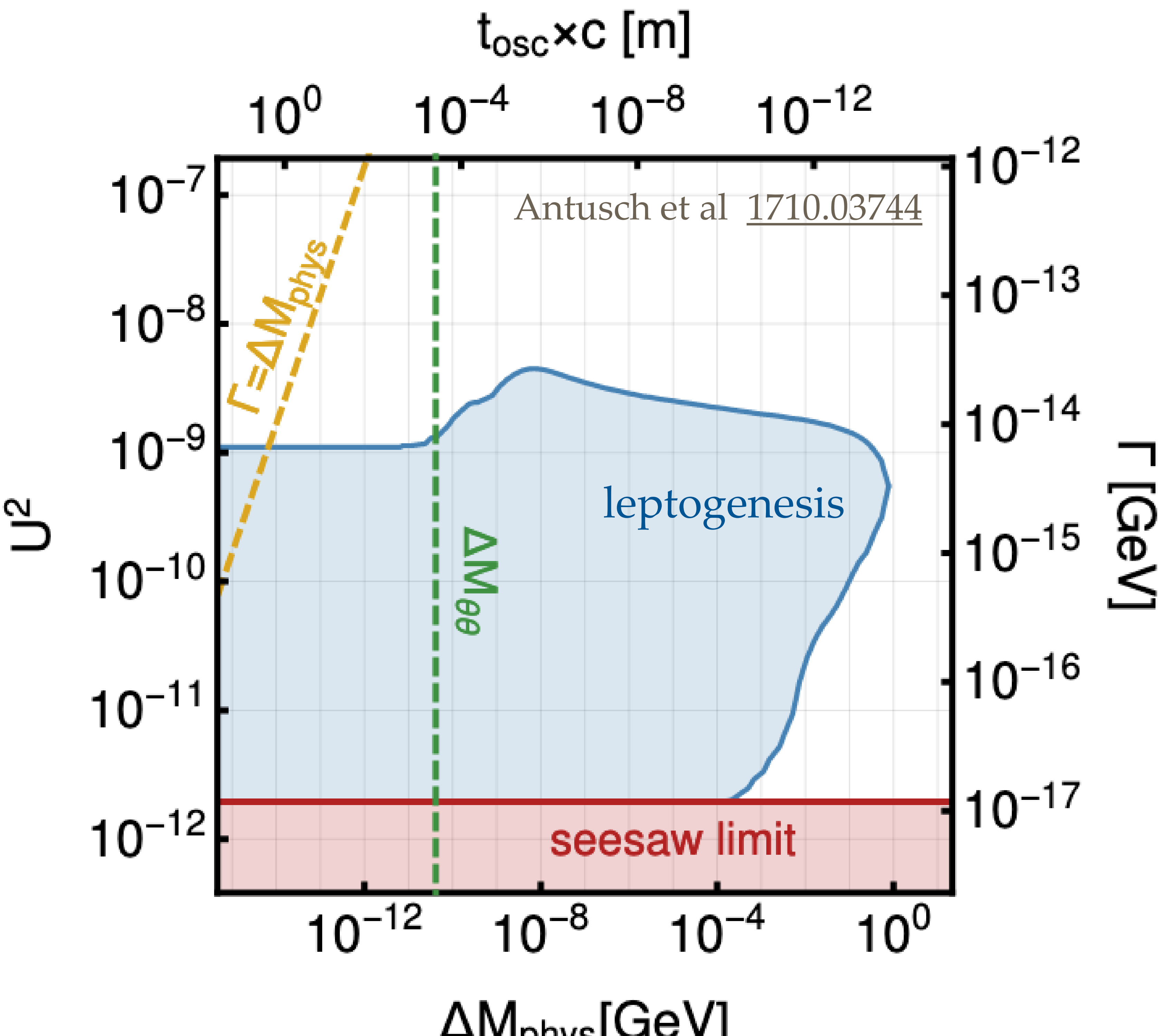
spatially resolving this ratio gives more information!

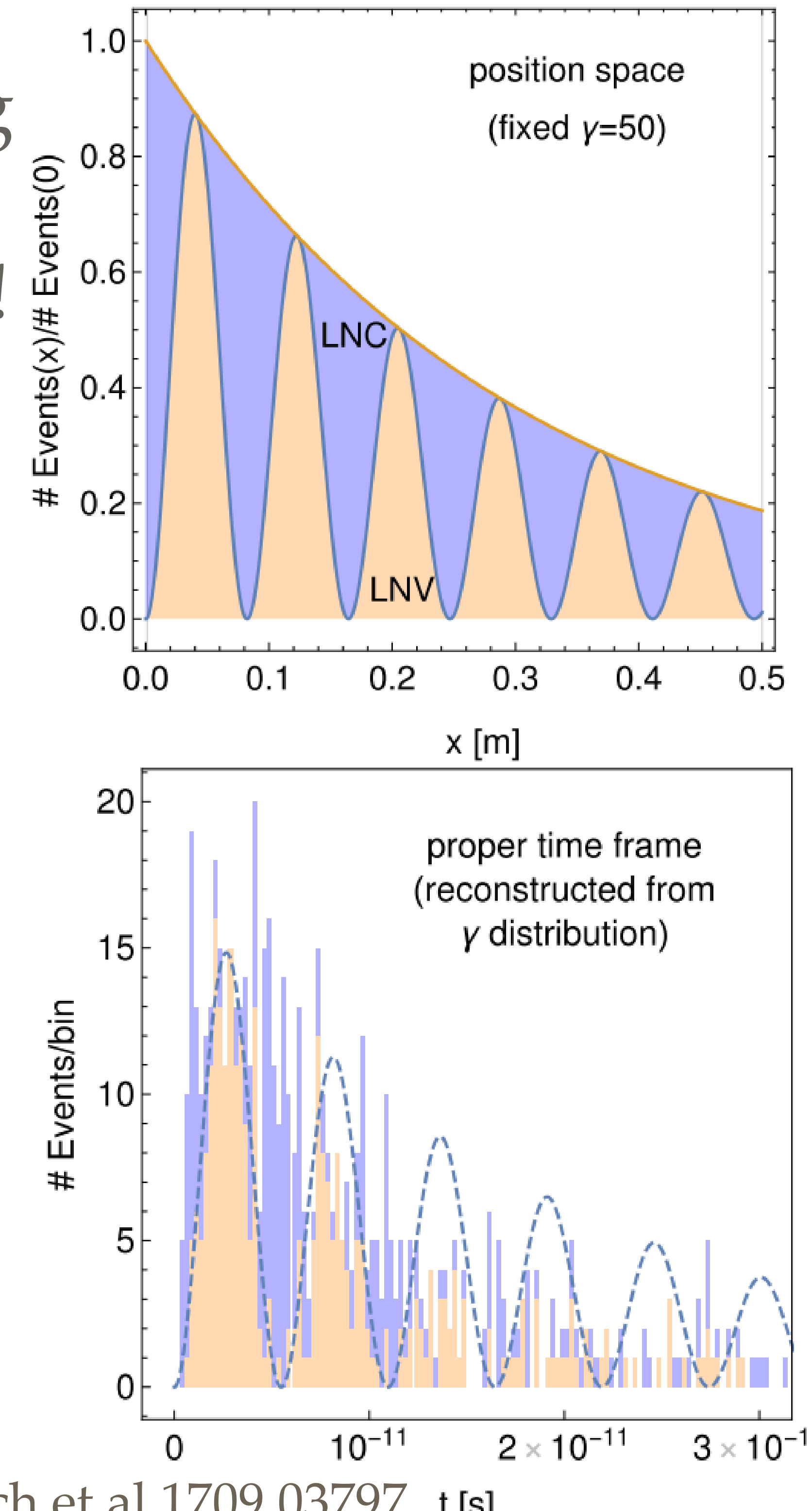
Antusch et al 1709.03797





How to measure ΔM?



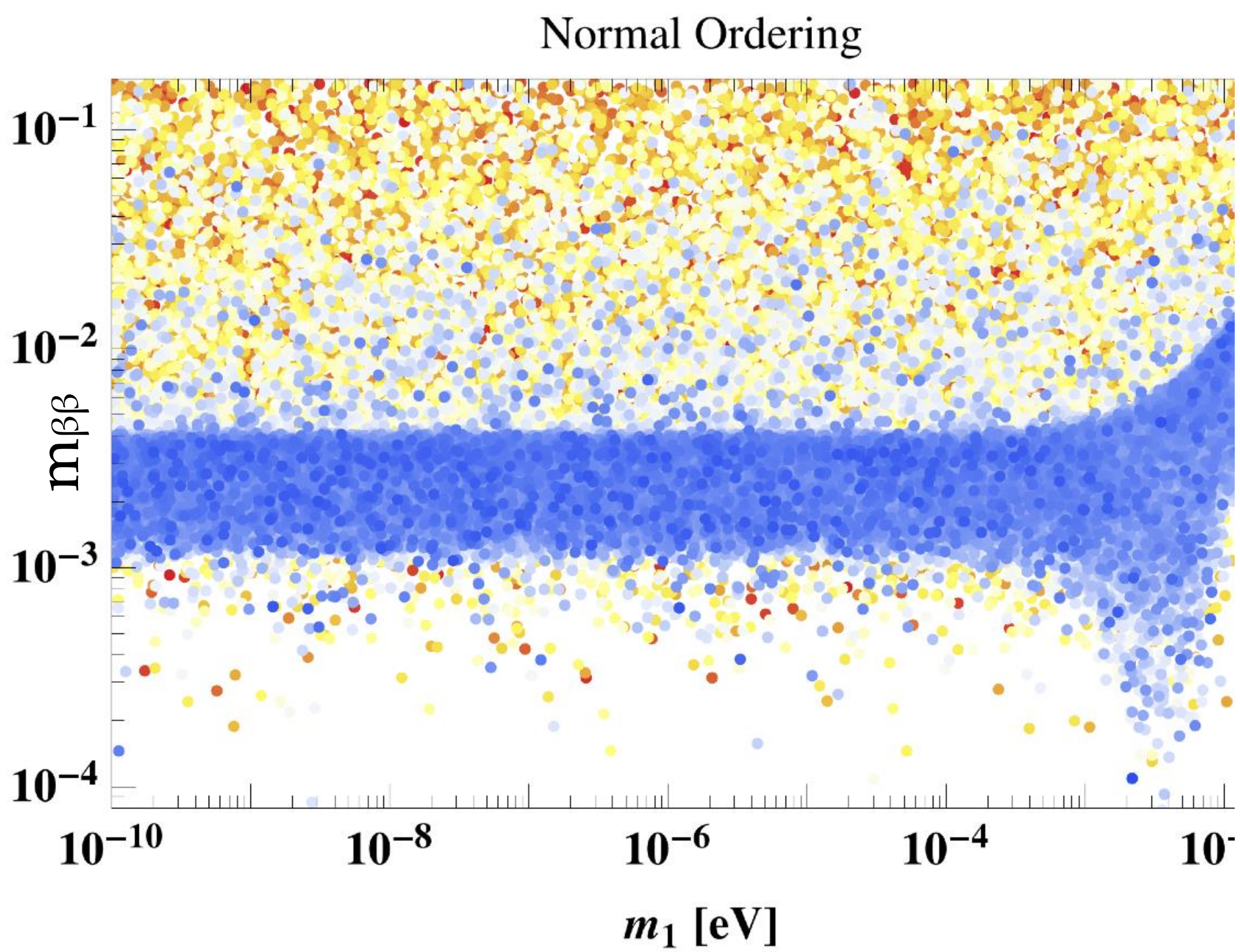


Antusch et al 1709.03797

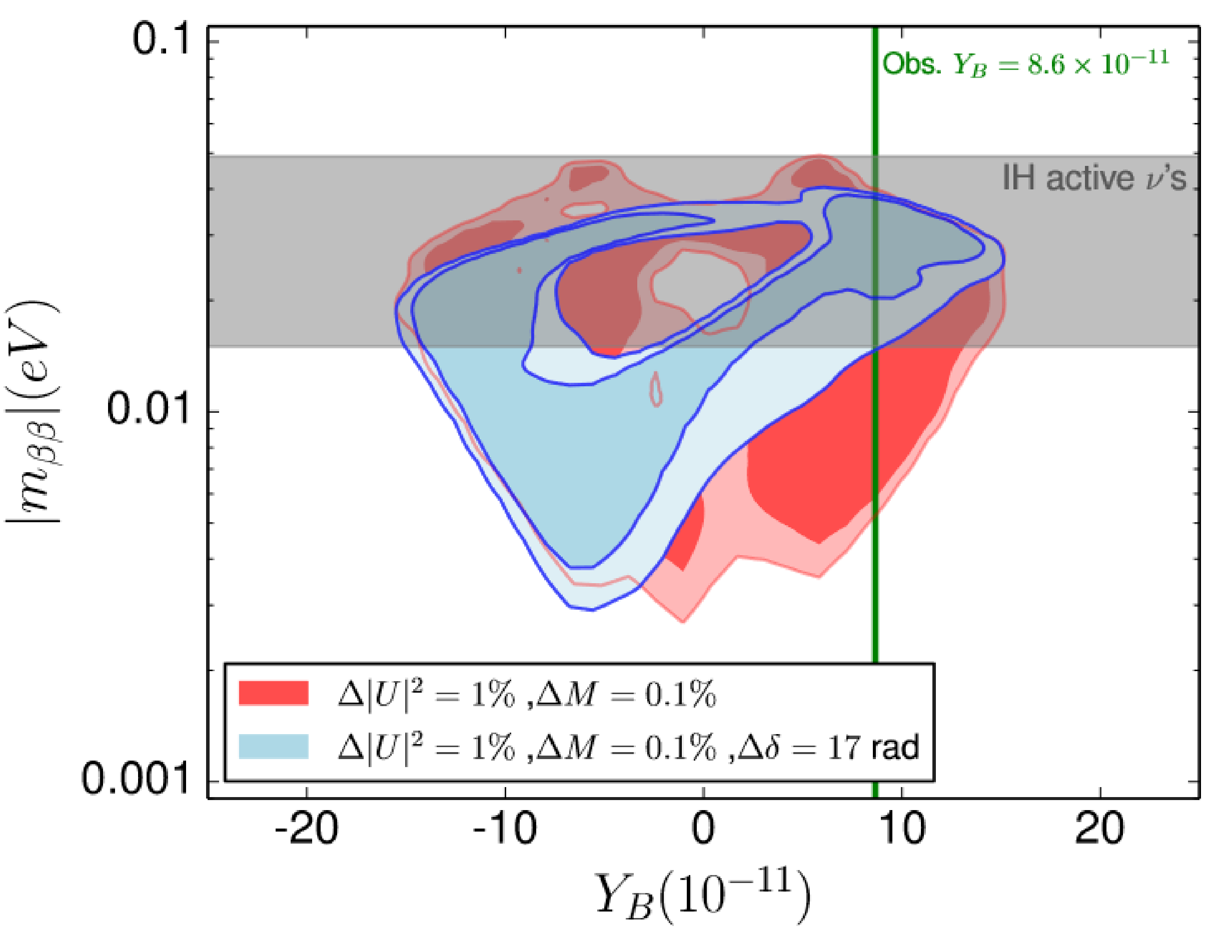
The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…
…even in the leptogenesis region
⇒ additional probe of phase in the sterile sector

Bezrukov 0505247
Blennow et al 1005.3240
Lopez Pavon et al 1209.5342
MaD/Eijima 1606.06221
Hernandez et al 1606.06719
Asaka et al 1606.06686
Abada et al 1810.12463



Abada et al 1810.12463



Hernandez et al 1606.06719

Summary

- Leptogenesis during freeze-out is possible for GeV Majorana masses M, for freeze-in even M in the MeV range is feasible
- With two RH neutrinos the model makes clear predictions for the flavour structure of the Yukawas that can be tested
- With three RH neutrinos the viable parameter space is several orders of magnitude larger, but the model is less predictive
- If heavy neutral leptons are discovered, the leptogenesis hypothesis can be tested by combining data from different "frontiers"

A Multi Frontier Problem!

Indirect probes at accelerators rare decays, EWPD, lepton universality)

new detectors (FASER, Codex-b, MATHUSLA, Al3X, ANUBIS

Collider searches for heavy neutrinos

X-ray searches: SRG/eROSITA, SRG/ART-XC, ATHNEA, XRISM, Lynx...

absolute neutrino mass searches (KATRIN ect.)

CMB and LSS : absolute neutrino mass

non-accelerator searches (TRISTAN...)

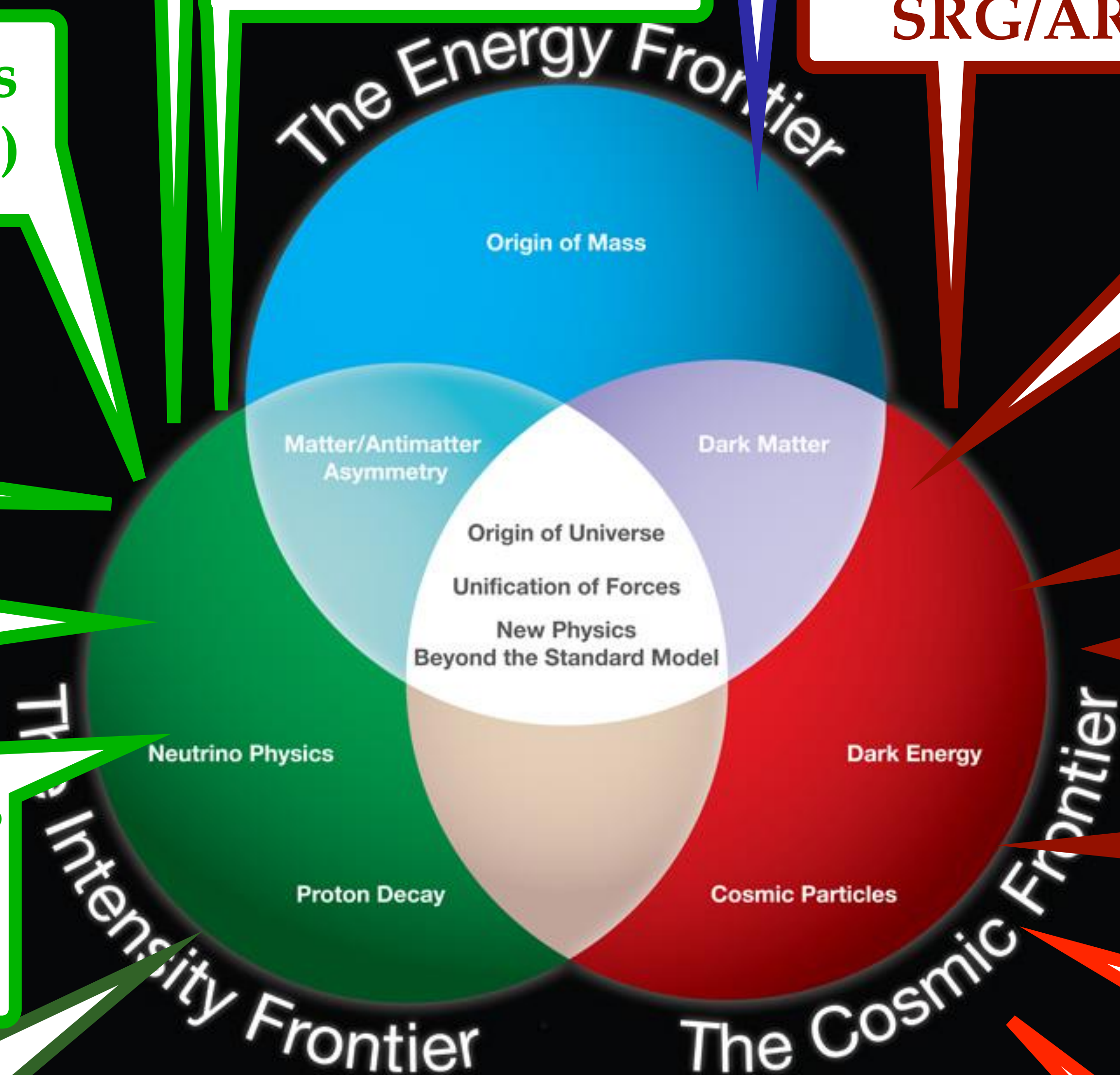
astrophysics: supernovae etc.

neutrinoless double β decay

Structure formation: simulation, observation

fixed target experiments (SHiP, NA62, DUNE, T2K..)

IGM temperature: WDM vs CDM



Theory: leptogenesis parameter region

neutrino oscillation experiments DUNE, Hyper-K

RF, NF, EF, CF, TF

Theory: Sterile neutrino DM production

Full Testability of the νMSM

In principle all parameters in the Lagrangian can be constrained experimentally… cf. Hernandez et al 1606.06719, MaD et al 1609.09069

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$ Casas/Ibarra 01

Full Testability of the νMSM

In principle all parameters in the Lagrangian can be constrained experimentally…

cf. Hernandez et al 1606.06719, MaD et al 1609.09069

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Casas/Ibarra 01

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM