Marco Drewes, Université catholique de Louvain

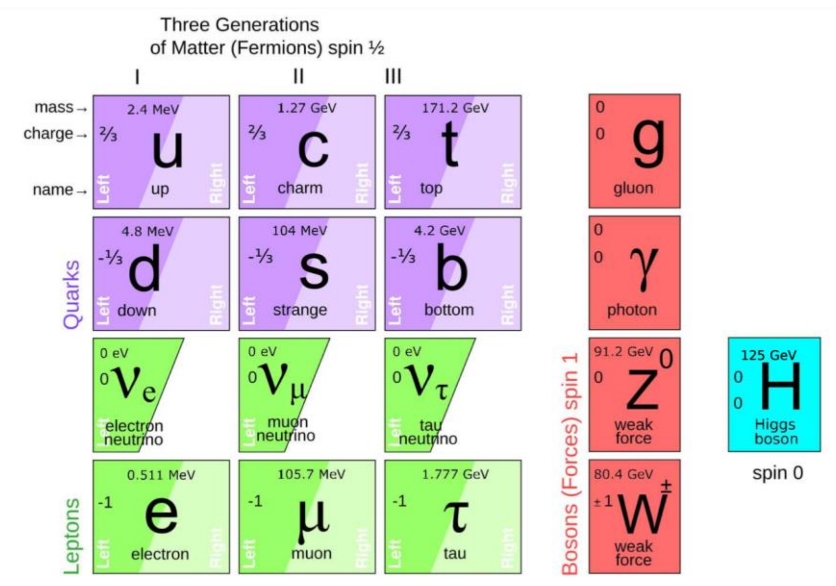
Testable scenarios of leptogenesis

15. 06. 2022

Online Workshop
"Physics of the Early Universe"

The Seesaw Mechanism (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
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$ known light neutrinos
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

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

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

Overview

Testable Leptogenesis Scenarios

- **mechanisms**
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

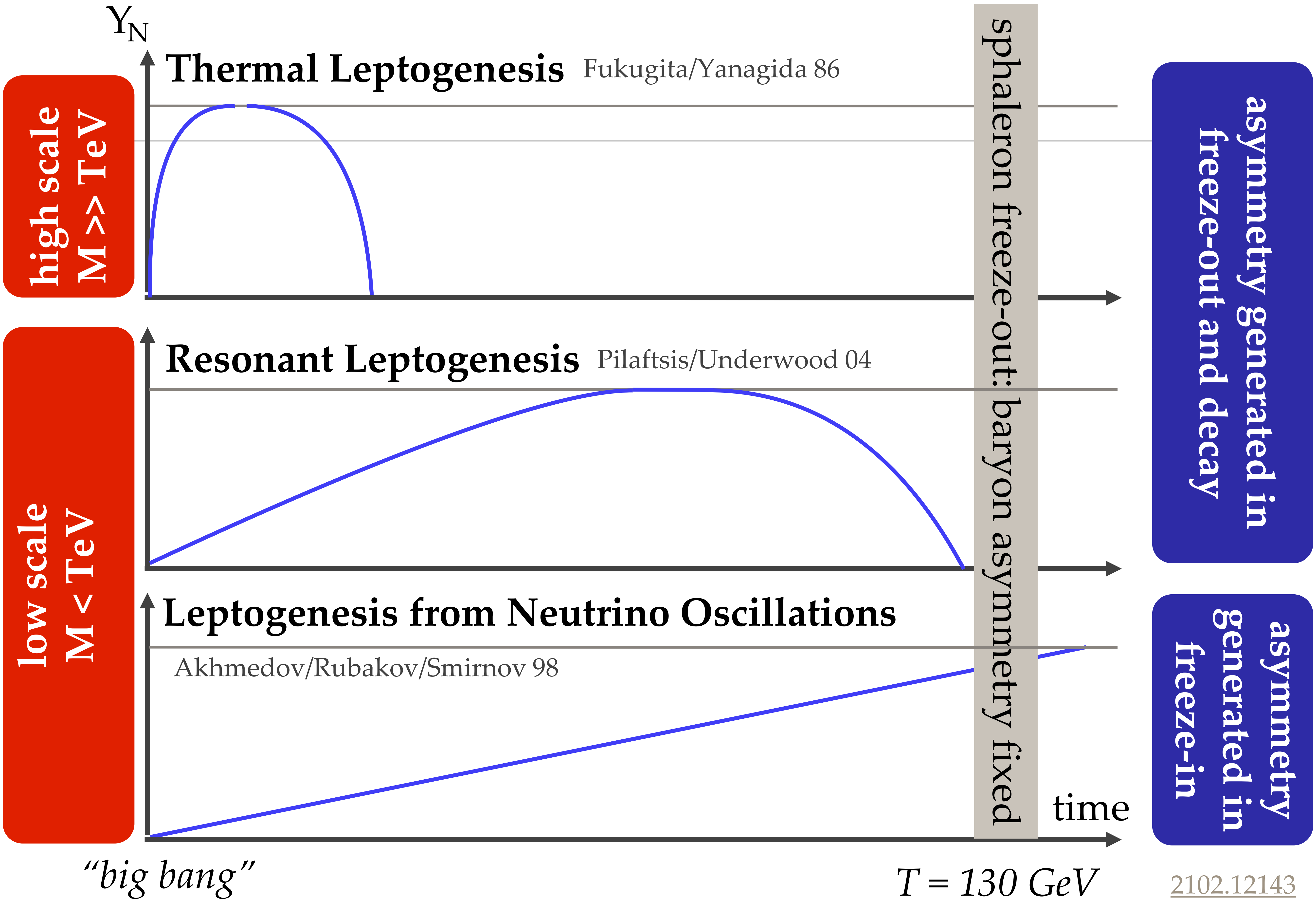
Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

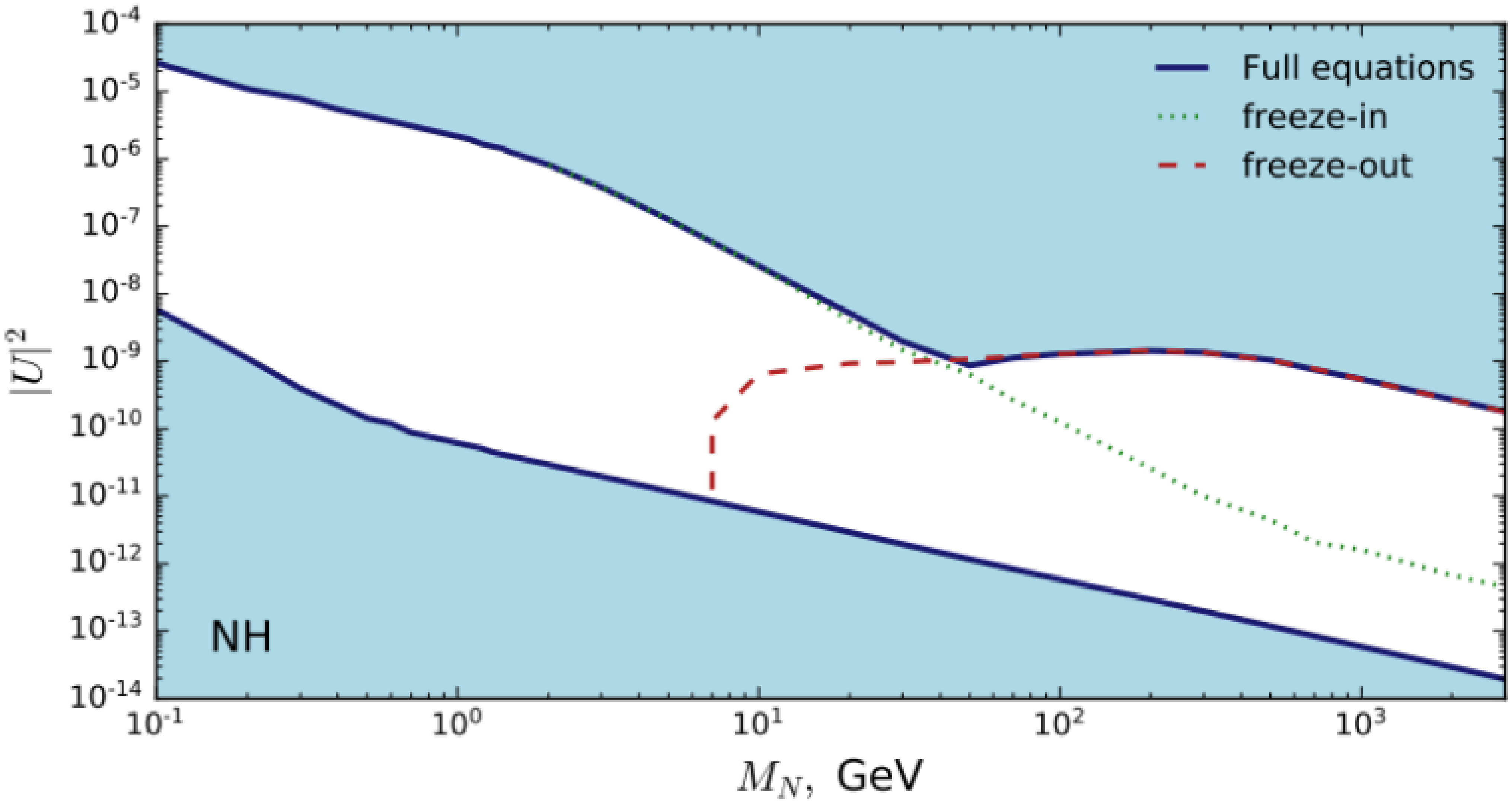
- proving Majorana nature
- resolving the heavy neutrino mass spectrum

Complementarity and testability



Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
low scale
M < TeV
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in
time
"big bang"
T = 130 GeV
2102.12143

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

Quantitative Description

- Low scale leptogenesis involves many effects not captured by simple Boltzmann equation (coherent oscillations, quantum statistics, screening by the plasma, …)
- Significant progress has been made towards a quantitative description

See e.g. Biondini et al 1711.02864, Garbrecht 1812.02651 [talk by Bjorn Garbrecht]

Overview

Testable Leptogenesis Scenarios

- mechanisms
- **models**

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

- proving Majorana nature
- resolving the heavy neutrino mass spectrum

Complementarity and testability

Global Symmetries

Agnostic approach:

- Treat Yukawa matrices F and Majorana mass M as free parameters, allowing all values that are not excluded experimentally
- Sizeable couplings require approximate B-L symmetry

Symmetry-based approach:

- UV-completions can motivate specific structures in F and M

  See e.g. King 1701.04413, Xing 1909.09610,

- Symmetries reduce parameter space, make the model more testable

B-L Symmetry protected Scenarios

- ν-masses naively scale $m_\nu \sim \theta^2 M$, implying tiny $U^2 = |\theta|^2 \sim m_\nu/M$
- production cross section at colliders scales as $\sigma_N \sim \theta^2 \sigma_\nu$
- Small ν-masses reconciled with sizeable couplings if protected by generalised B-L symmetry, broken by small parameters ε, ε′, μ

Shaposhnikov 06, Kersten/Smirnov 07

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}, \quad M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

- Resembles pheno of "inverse seesaw" Mohapatra 86, Mohapatra /Valle 86, …
- Technically natural seesaw with O[1] Yukawas and M < TeV
- Resonant enhancement in leptogenesis comes for free due to μ << 1
- Two possible realisations:
  - **νMSM-like** : ε, ε′, μ → 0 Asaka/Shaposhnikov 05
  - **"mass communism"**: μ → 0 and M′ → M

Parameter Spaces

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass

complex angle(s) ω

HNL-masses

2 Heavy Neutrinos (νMSM)

- 2 RHN masses
- 1 *complex* ($\times 2$) angle
- **2 light neutrino masses**
- **3 PMNS angles**
- 1 CP phase δ
- 1 Majorana phase α

11 (6 free) parameters

3 Heavy Neutrinos

- 3 RHN masses
- 3 *complex* ($\times 2$) angles
- **$2 + 1$ light neutrino masses**
- **3 PMNS angles**
- 1 CP phase δ
- 2 Majorana phases $\alpha_{1,2}$

18 (13 free) parameters

Global Symmetries

Agnostic approach:

- Treat Yukawa matrices F and Majorana mass M as free parameters, allowing all values that are not excluded experimentally
- Sizeable couplings require approximate B-L symmetry

Symmetry-based approach:

- UV-completions can motivate specific structures in F and M

  See e.g. King 1701.04413, Xing 1909.09610,

- Symmetries reduce parameter space, make the model more testable

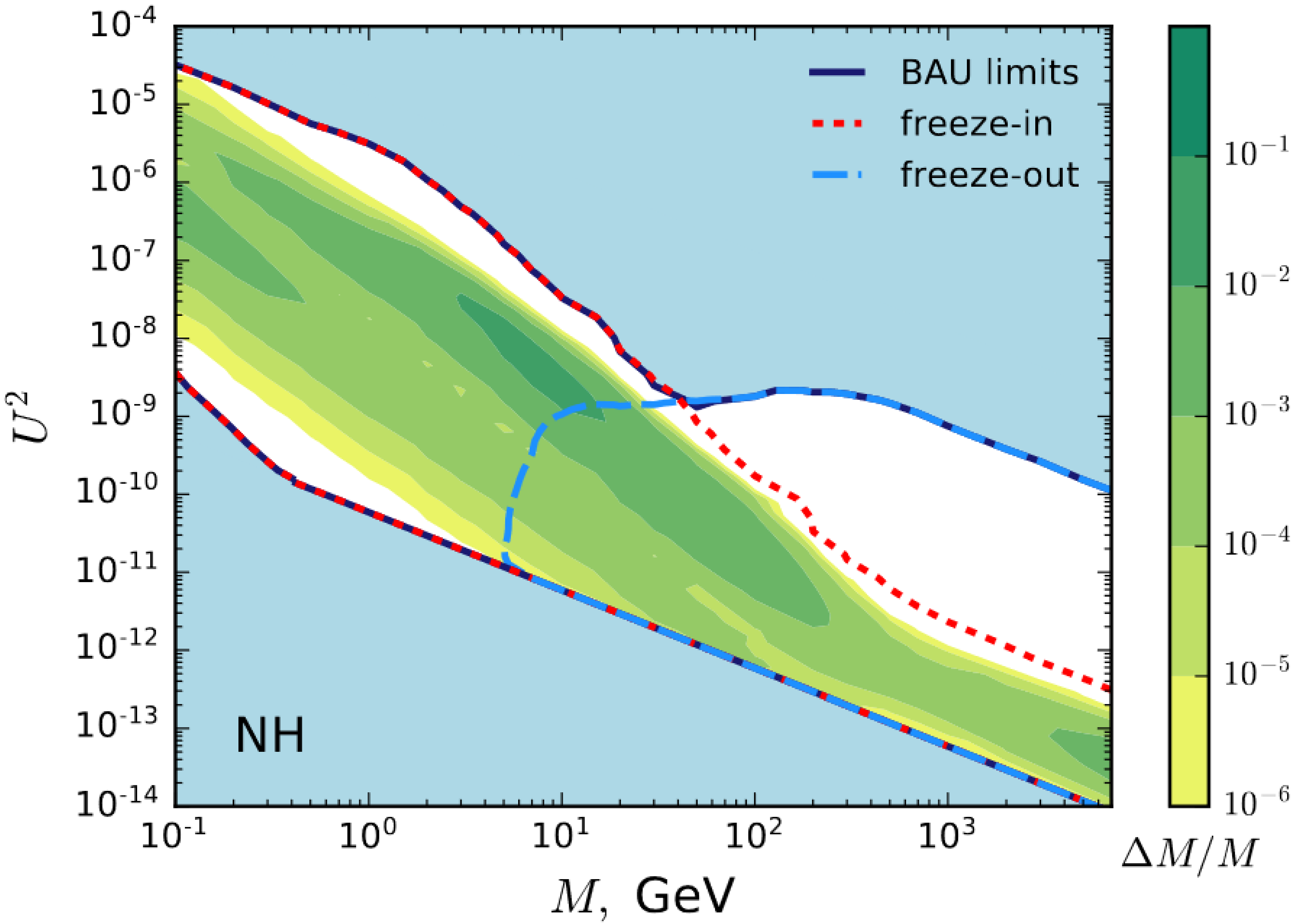
Benchmark Scenarios

1) B-L protected type I seesaw in νMSM limit.

- Obtained in limit ε, ε′, μ → 0
- Comprises two mass-degenerate HNLs (seesaw + leptogenesis) and one almost decoupled HNL (DM candidate)
- Leptogenesis, seesaw and collider pheno as in model with two HNLs
- Lightest SM neutrino is (almost) massless

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}, \quad M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

Leptogenesis in the νMSM



Klaric/Shaposhnikov/Timirsyasov 2103.16545

Benchmark Scenarios

1) B-L protected type I seesaw in νMSM limit.

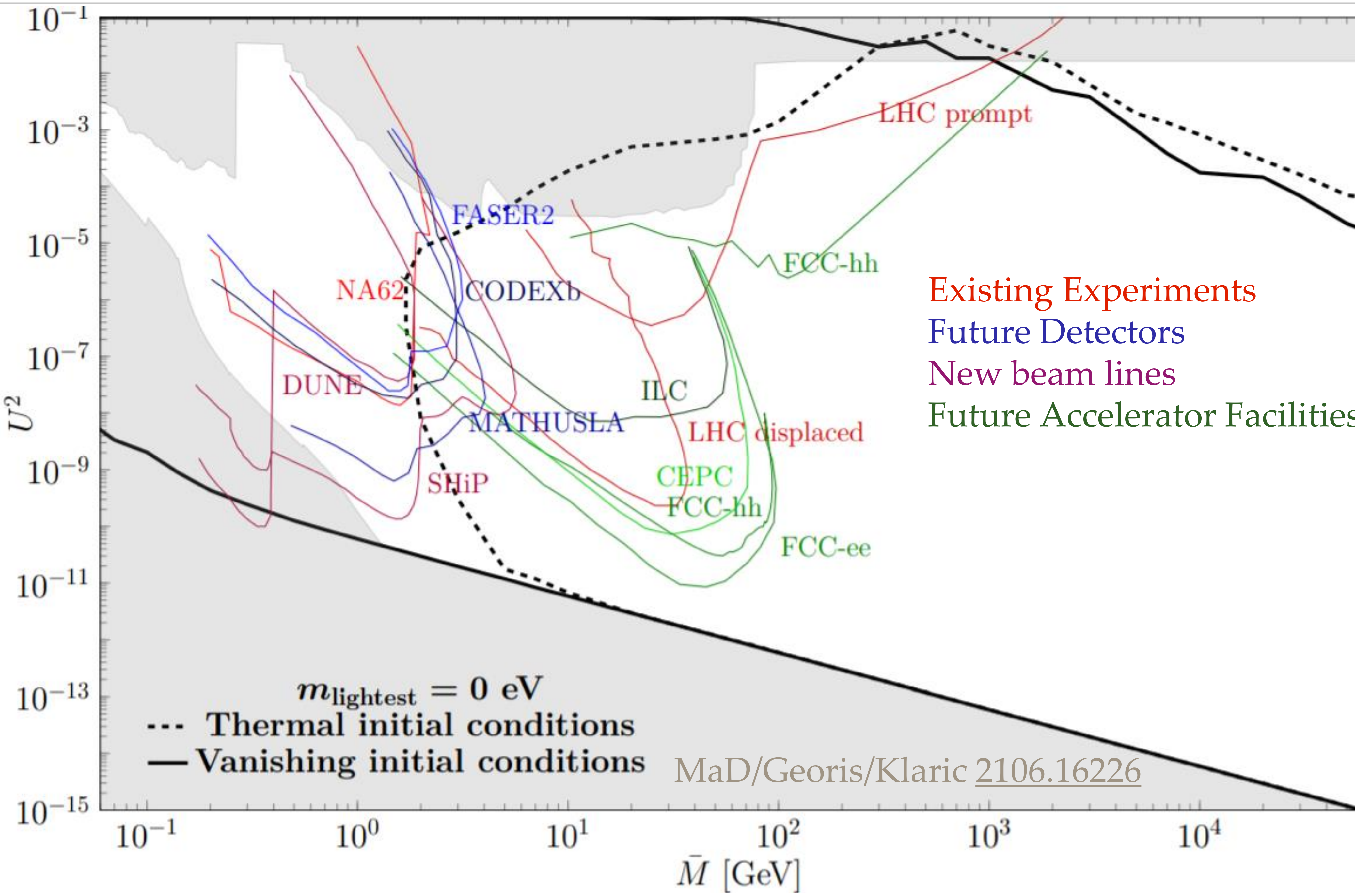
- Obtained in limit ε, ε′, μ → 0
- Comprises two mass-degenerate HNLs (seesaw + leptogenesis) and one almost decoupled HNL (DM candidate)
- Leptogenesis, seesaw and collider pheno as in model with two HNLs
- Lightest SM neutrino is (almost) massless

2) B-L protected type I seesaw in "mass communist" limit.

- Obtained in limit μ → 0 and M′ → M
- Comprises three mass-degenerate HNLs (seesaw + leptogenesis)
- Lightest SM neutrino can be massive or massless

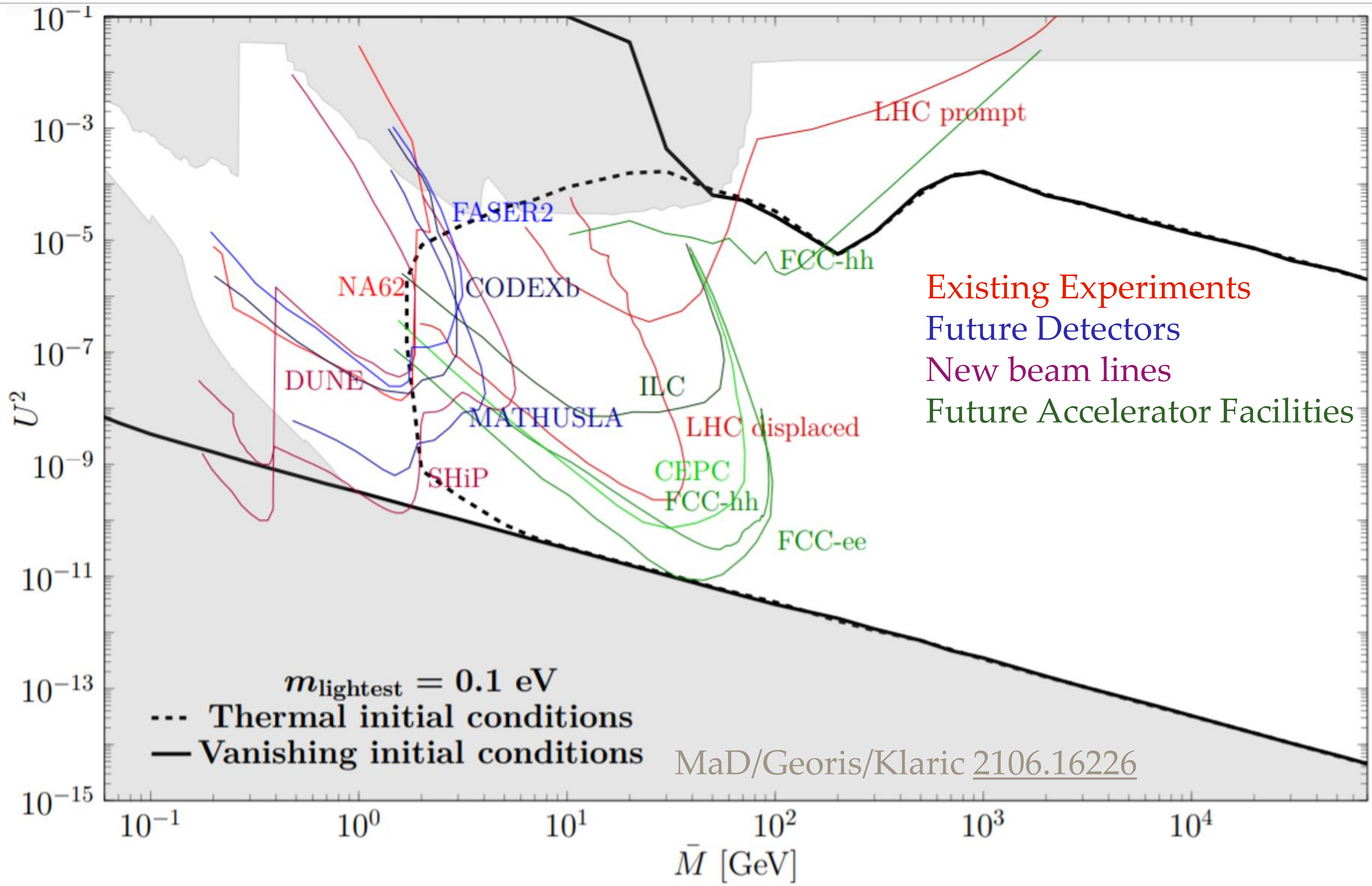
$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}, \quad M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

Leptogenesis with three HNLs



Largest U^2 possible when all HNLs have quasi-degenerate masses ("mass communism")

Leptogenesis with three HNLs



Largest U^2 possible when all HNLs have quasi-degenerate masses ("mass communism")

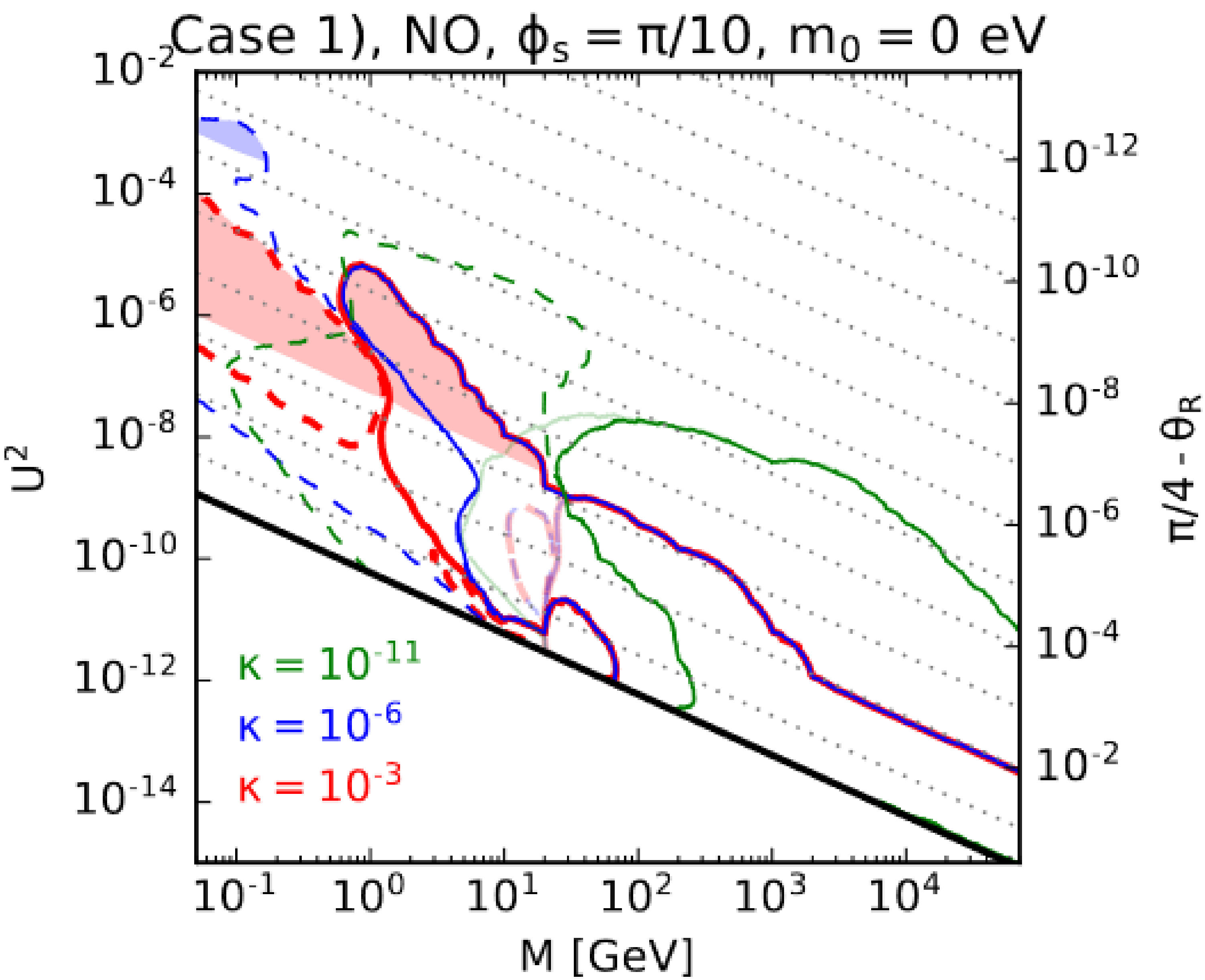
Benchmark Scenarios

1) **B-L protected type I seesaw in νMSM limit.**
   - Obtained in limit $\varepsilon, \varepsilon', \mu \to 0$
   - Comprises two mass-degenerate HNLs (seesaw + leptogenesis) and one almost decoupled HNL (DM candidate)
   - Leptogenesis, seesaw and collider pheno as in model with two HNLs
   - Lightest SM neutrino is (almost) massless

2) **B-L protected type I seesaw in "mass communist" limit.**
   - Obtained in limit $\mu \to 0$ and $M' \to M$
   - Comprises three mass-degenerate HNLs (seesaw + leptogenesis)
   - Lightest SM neutrino can be massive or massless

3) **Type I seesaw with discrete $\Delta(6n^2)$ flavour symmetry.**
   - Can be realised with different residual symmetries, known as cases 1), 2), 3.a) and 3.b.1) Hagedorn/Meroni/Molinaro 1408.7118,
   - Comprises three mass-degenerate HNLs
   - For fixed *n* and residual symmetries and given HNL mass(es), there are only five free parameters in the Yukawa matrix *F*
   - Lightest SM neutrino can be massive or massless

Leptogenesis Discrete Symmetries



Plot from MaD/Georis/Hagedorn/Klaric 2203.08538

(cf. also Chauhan/Dev 2112.09710)

- Generically mixing is near the "seesaw line" $U^2 \sim m\nu/M$
- Can be enhanced in presence of enhanced residual symmetry
- κ indicates splitting of Majorana mass eigenvalues
- Solid (dashed) curves give baryon asymmetry of correct magnitude and correct (wrong) sign
- Plot is for illustration, regions change for different residual symmetries

Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- **falsification through indirect signatures**
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

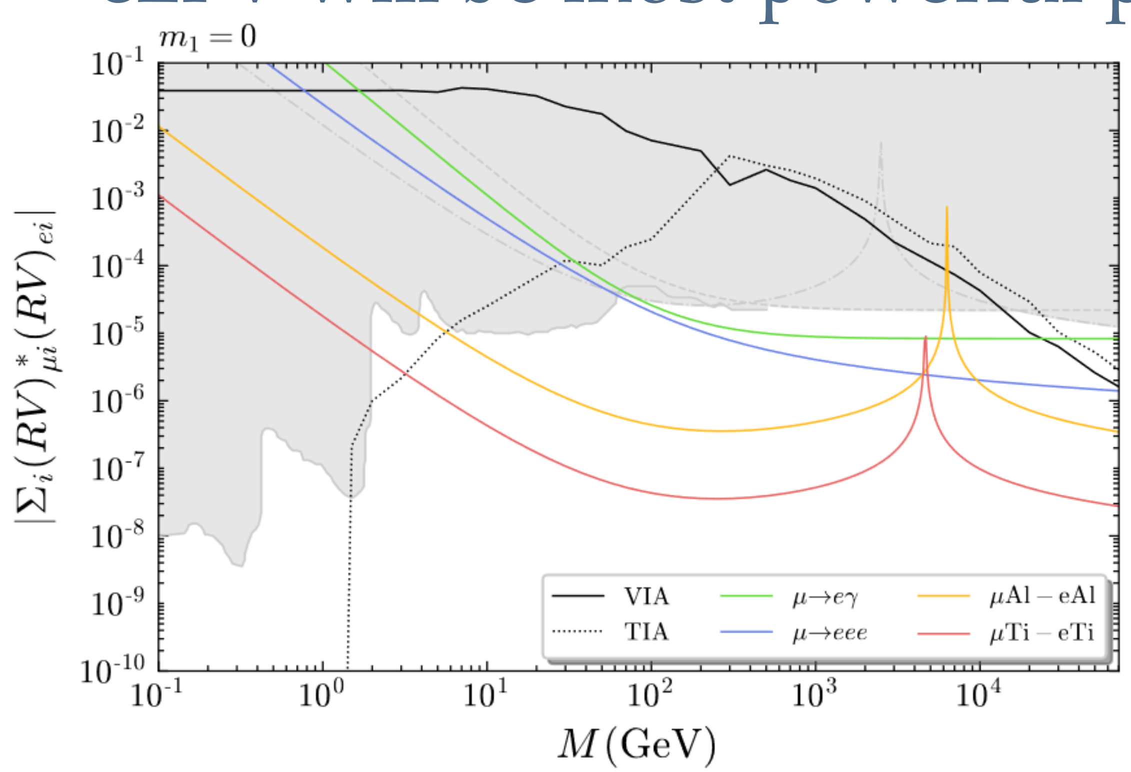
- proving Majorana nature
- resolving the heavy neutrino mass spectrum

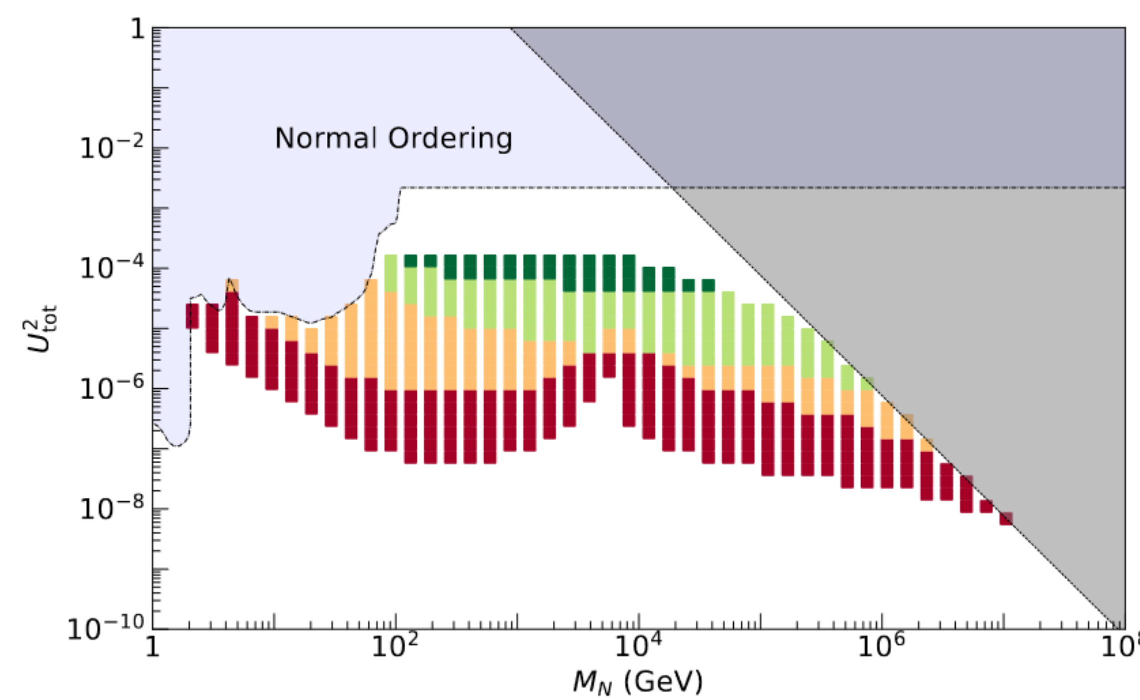
Complementarity and testability

Indirect Probes

- A large number of indirect observables is sensitive to RH neutrinos
  - Includes ν-oscillation data, 0νββ decay, EWPD, cLFV, lepton universality…
  - A (probably incomplete) list can e.g. be found in Chrzaszcz et al 1908.02302
- 0νββ decay is unique probe of LNV
  - Expected in various models e.g. Rodejohann 1106.1334
  - Can help to probe leptogenesis MaD/Eijima 1606.06221, Hernandez et al 1606.06719, Asaka et al 1606.06686
  - Promising experimental program (LEGEND, …)

- cLFV will be most powerful probe Granelli et al 2206.04342, Calderon et al 2206.04540





Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- **discovering heavy neutrinos**

Mixing parameters

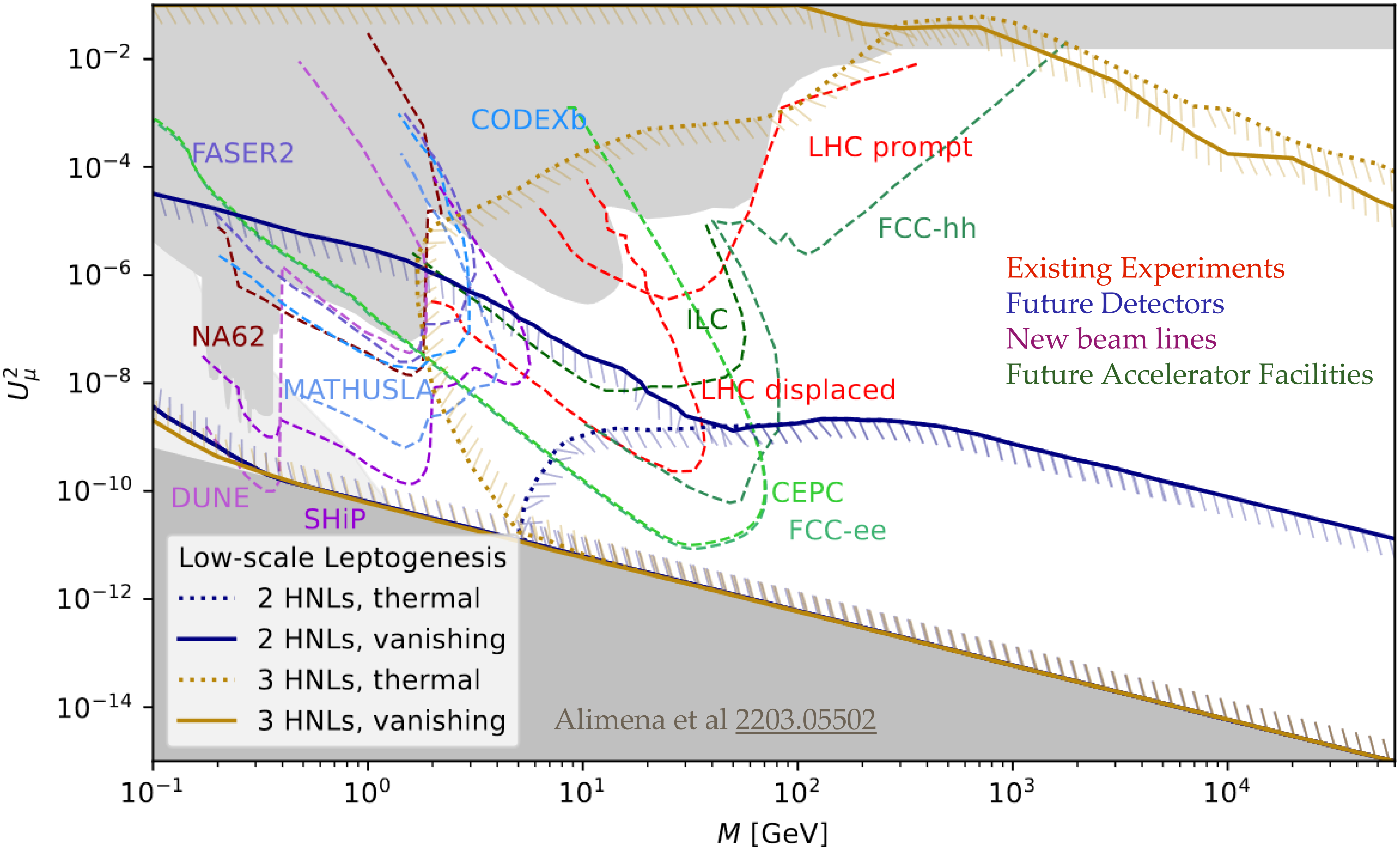
- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

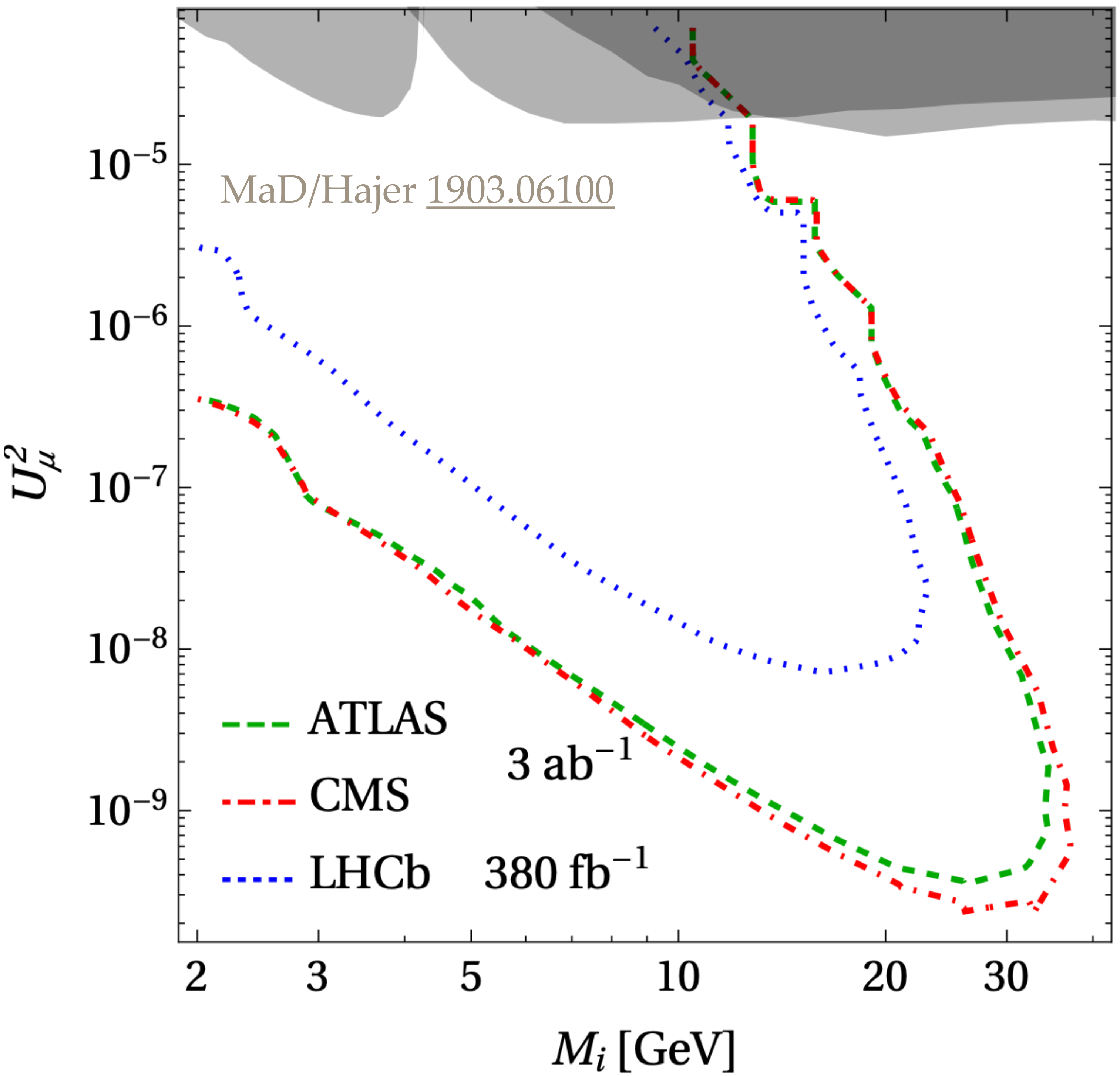
- proving Majorana nature
- resolving the heavy neutrino mass spectrum

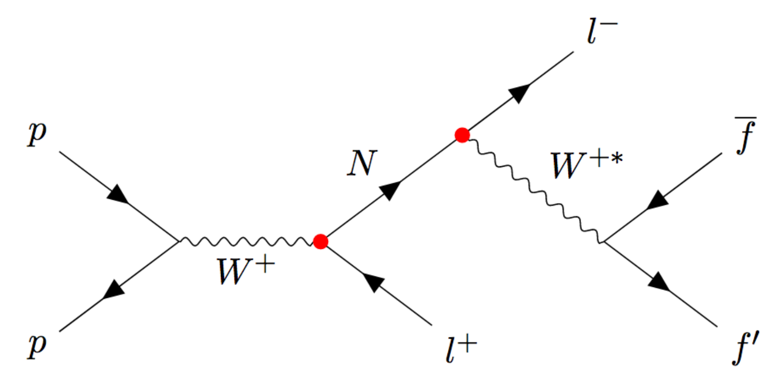
Complementarity and testability

Some HNL Searches

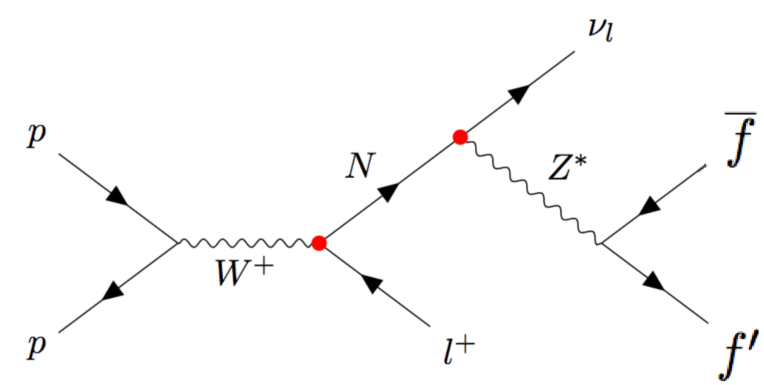


HL-LHC Displaced Vertex Search





(a) Charged current decay



(b) Neutral current decay

- Many authors studied such processes

e.g. Helo et al 1312.2900, Izaguirre/Shuve 1504.02470, Gago et al 1505.05880, Dib/Kim 1509.05981, Cottin et al 1806.05191, Abada et al 1807.10024, Boiarska et al 1902.04535, Liu et al 1904.01020 , Dib et al 1903.04905 , Cvetic et al 1805.00070, 1905.03097, …

- Sensitivity can be increased with new instrumentation FIPs report 2102.12143

What can we learn?

Dirac vs Majorana

- **LNV vs LFV decay rates** e.g. Ibarra et al 1007.2378, Anamiati et al 1605.01123
- **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
- **Lifetime** e.g. Alimena et al 2203.05502

CP properties

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

Mass spectrum

e.g. Antusch / Fischer 1709.03797 e.g. Tastet / Timiryasov 1912.05520

Test seesaw mechanism and leptogenesis

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

Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- **constraints from Neutrino oscillation data**
- constraints from leptogenesis

Majorana mass

- proving Majorana nature
- resolving the heavy neutrino mass spectrum

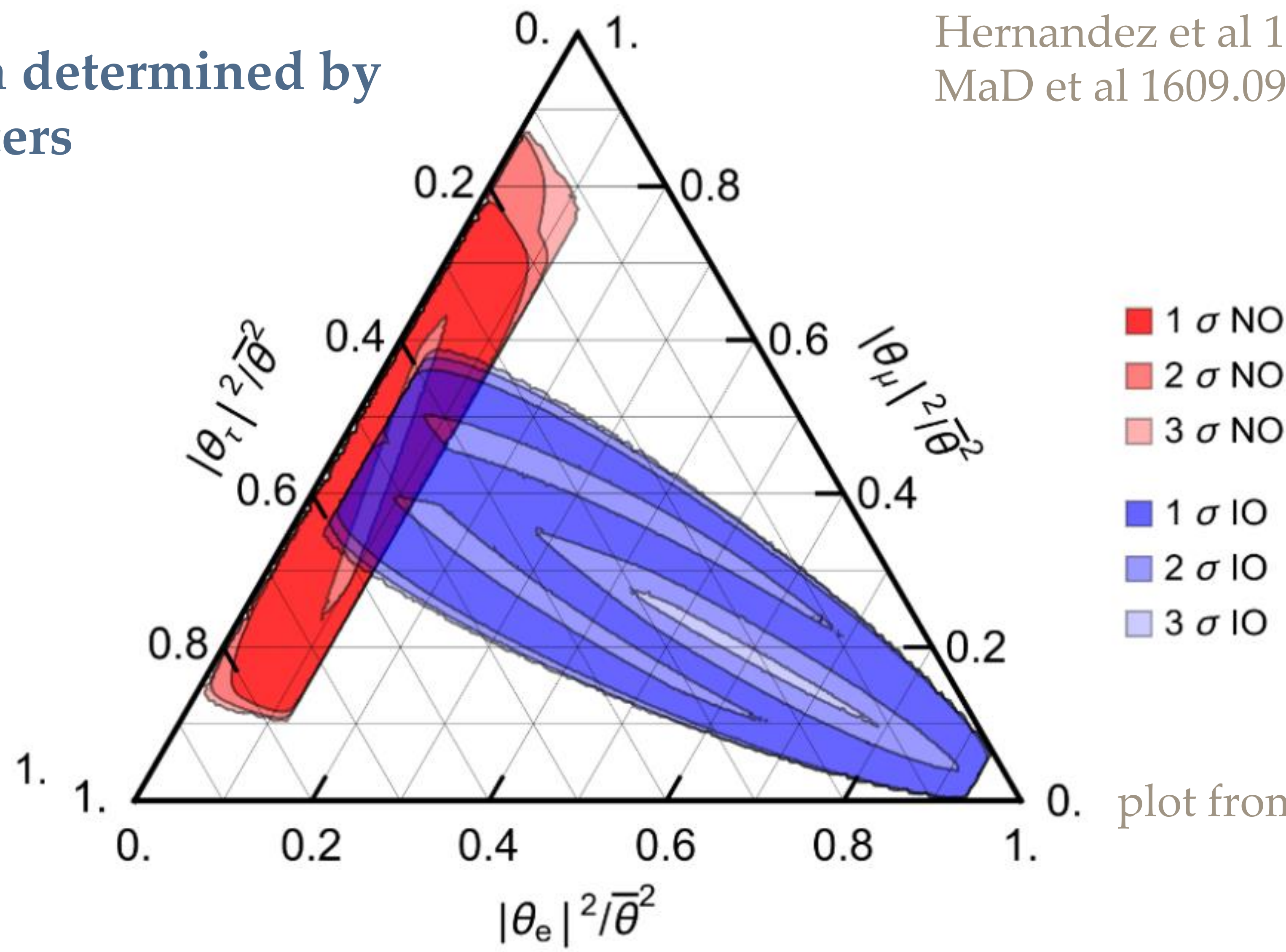
Complementarity and testability

Flavour Mixing Pattern from ν-Oscillation Data in the νMSM

- If RH neutrinos generate light neutrino masses, requirement to reproduce neutrino oscillation data constrains their properties
- In particular: relative size of mixings with individual SM flavours
- Determines branching ratio in their decays into SM flavours

Allowed region determined by PMNS parameters

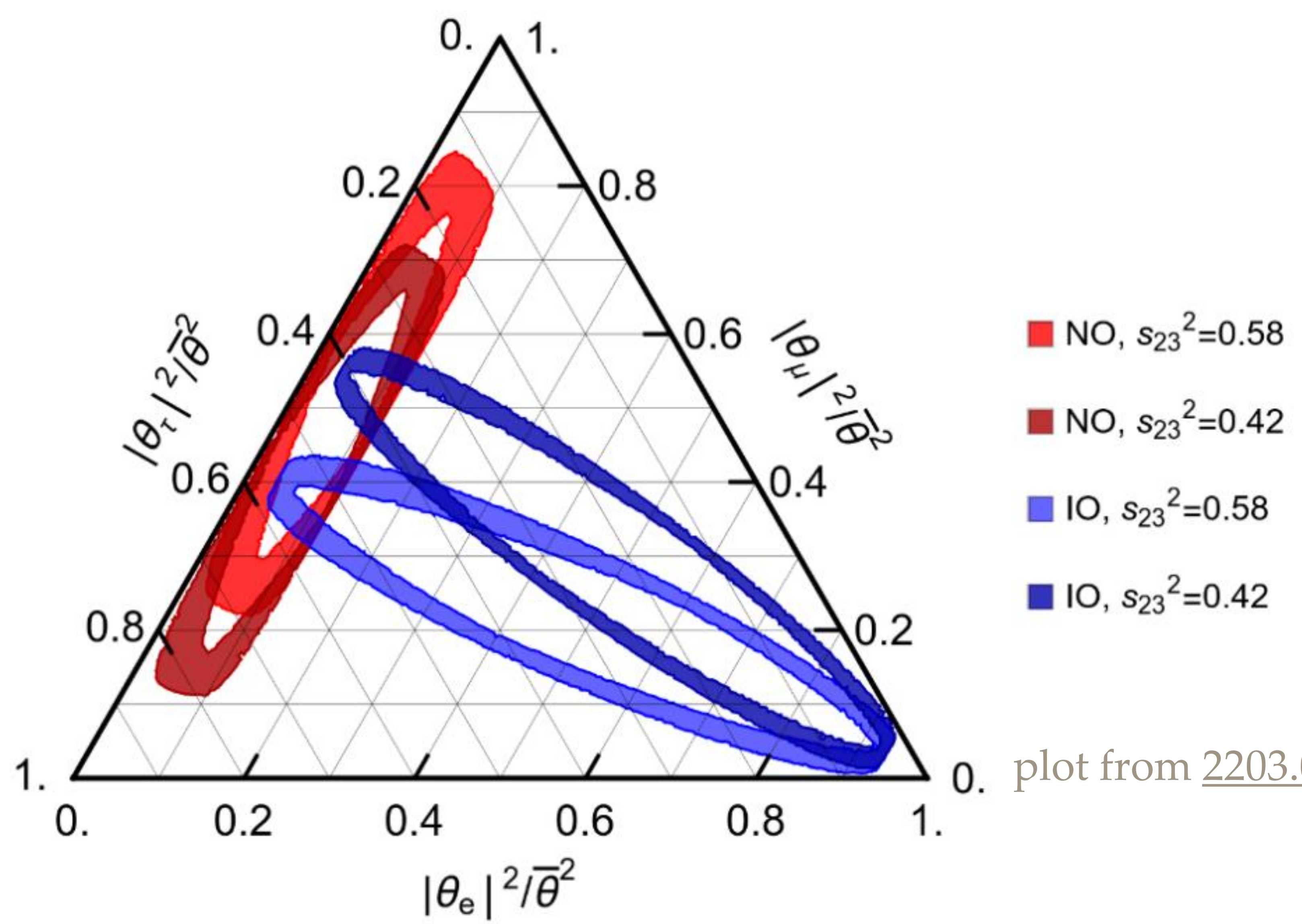
Hernandez et al 1606.06719, MaD et al 1609.09069, 1801.04207



plot from 2203.08039

Forecast with DUNE

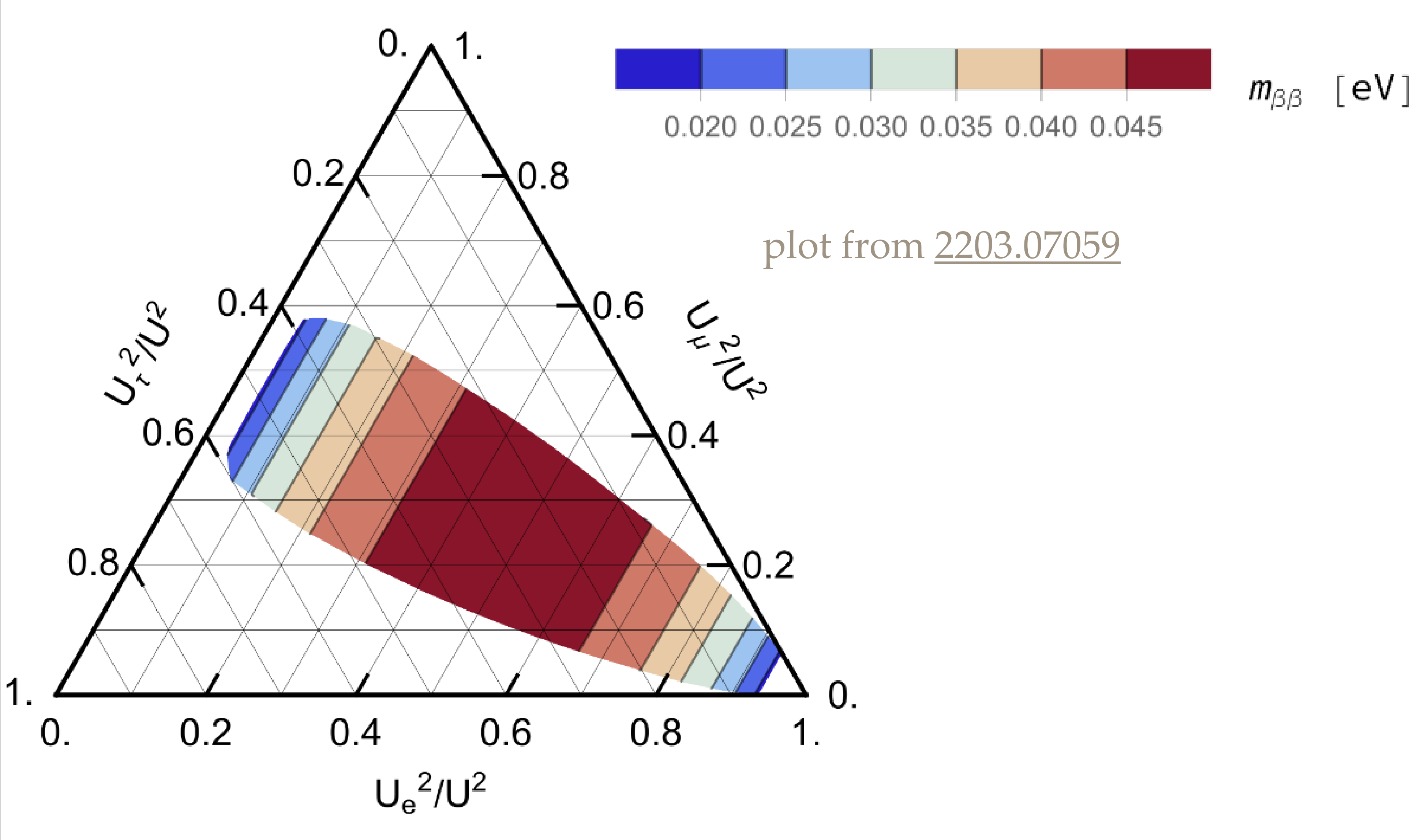
- The allowed region is determined by PMNS parameters
- Will improve a lot with DUNE, HyperK etc…
- can access Majorana phase α! MaD et al 1609.09069 Caputo et al 1611.05000



plot from 2203.08039

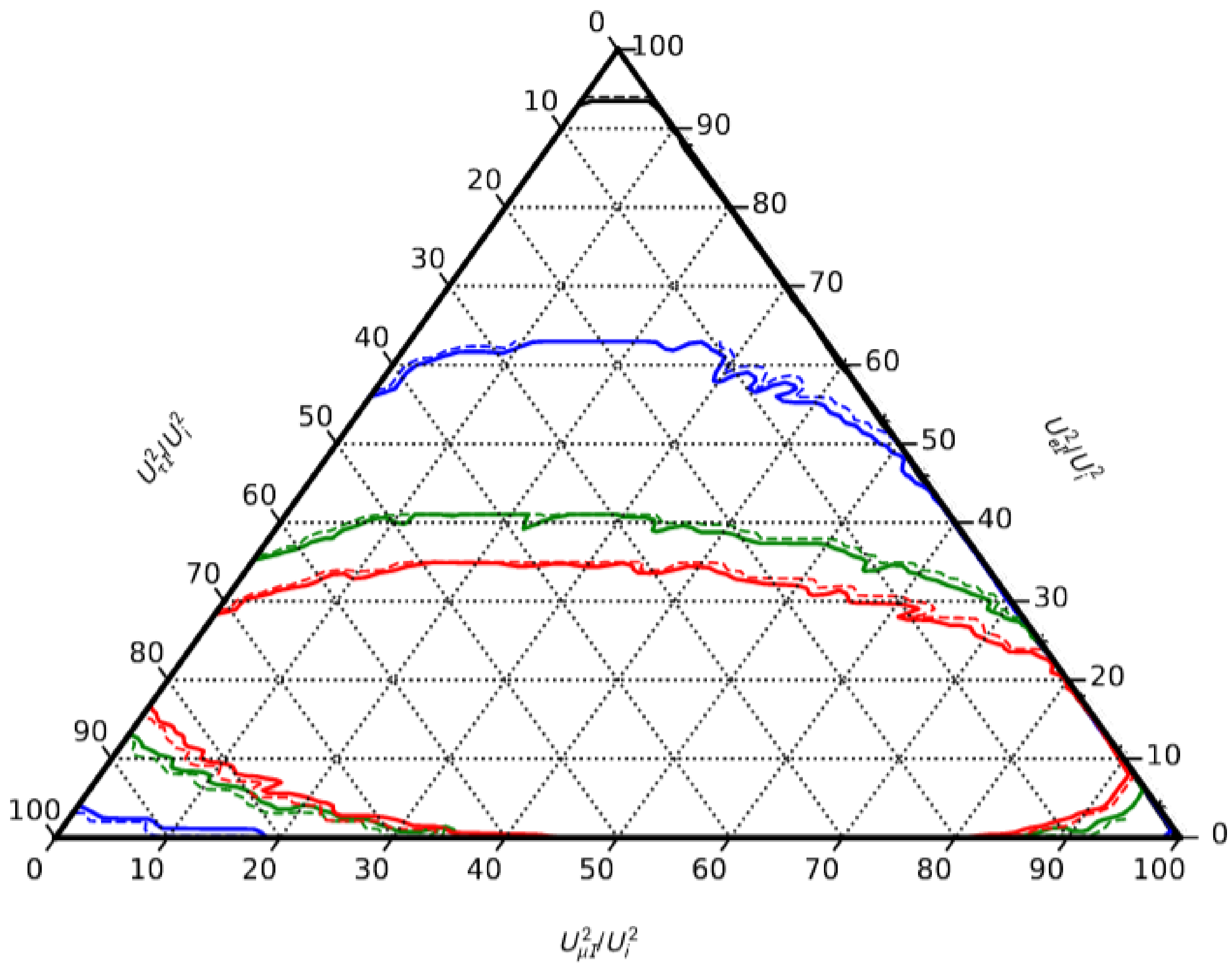
Connection to Neutrinoless Double β Decay

- Knowledge pf PMNS parameters permits to predict $0\nu\beta\beta$ decay
- If RH neutrino play a role: sensitivity to phase in RH neutrino sector Hernandez et al 1606.06719, MaD/Eijima 1606.06221



plot from 2203.07059

Flavour Mixing Pattern with 3 Heavy Neutrinos



$m_{lightest}$ < 10 meV

$m_{lightest}$ < 1 meV

$m_{lightest}$ < 0.1 meV

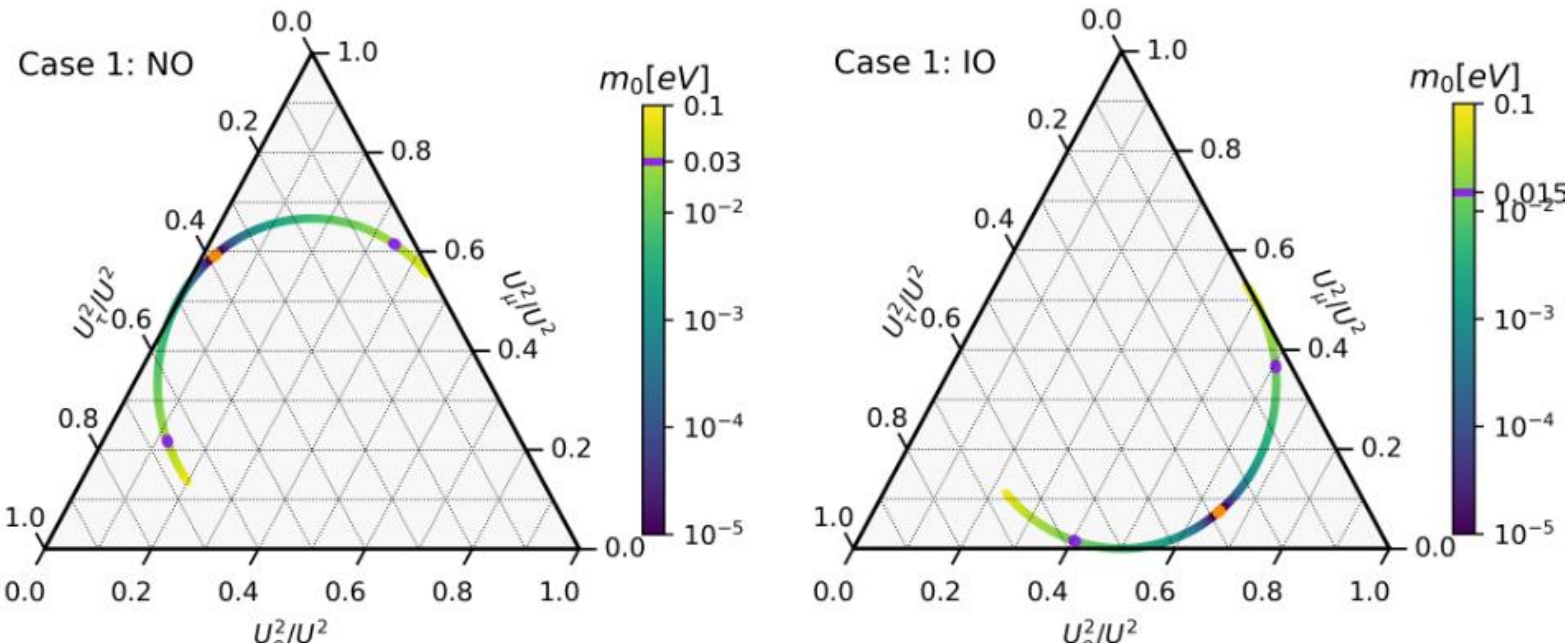
$m_{lightest}$ < 0.01 meV

normal ordering

Chrzaszcz et al 1908.02302

- For three HNLs the allowed flavour mixing pattern depends on the lightest neutrino mass

Flavour Mixing Pattern with Discrete Symmetries



MaD/Georis/Hagedorn/Klarix 22xx.xxxxx

- With discrete flavour and CP symmetries: Mixing pattern very predictive

Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- **constraints from leptogenesis**

Majorana mass

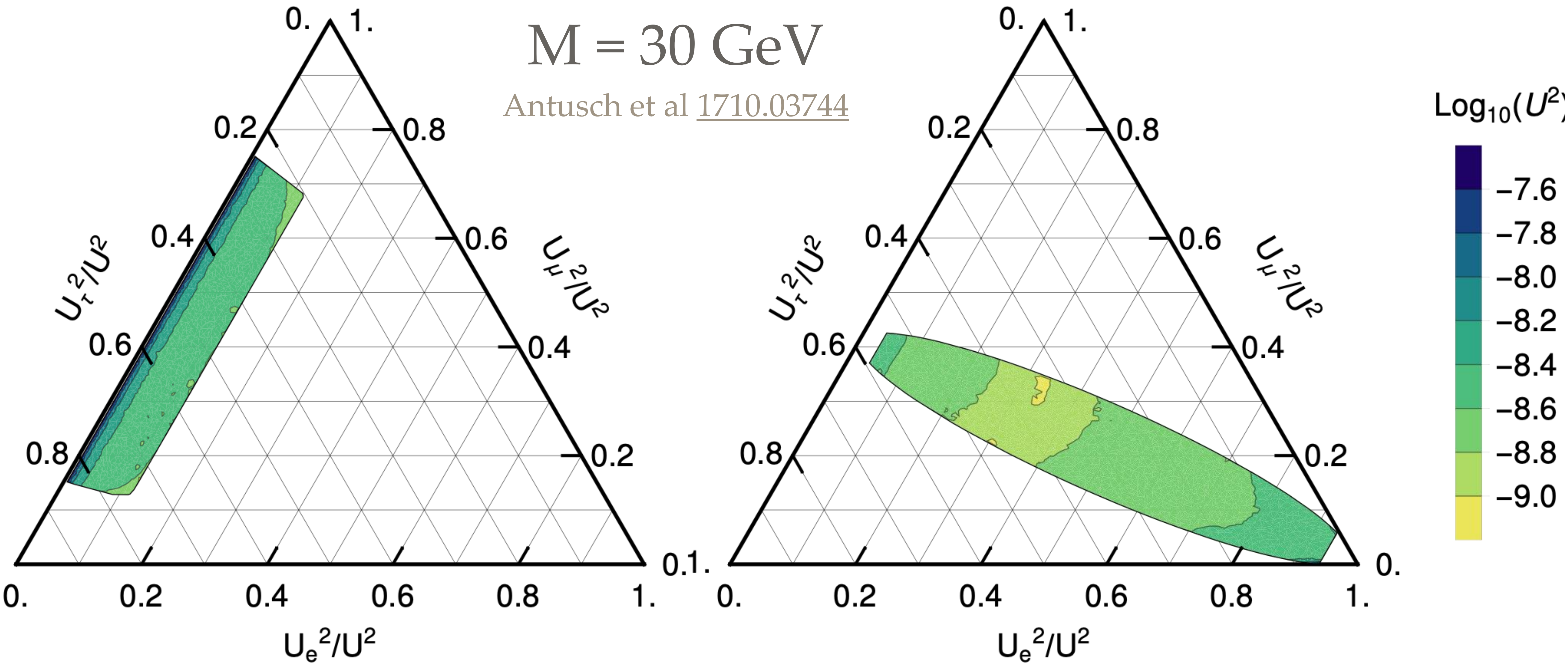
- proving Majorana nature
- resolving the heavy neutrino mass spectrum

Complementarity and testability

Constraints from Leptogenesis: νMSM

M = 30 GeV

Antusch et al 1710.03744



normal neutrino mass ordering **inverted neutrino mass ordering**

- Two HNLs: Large U^2 require strong hierarchies amongst couplings to SM generations… leptogenesis predicts flavor mixing pattern
- Three HNLs: no similar predictivity… let's understand the difference!

B-L Symmetric Limit with 2 HNLs

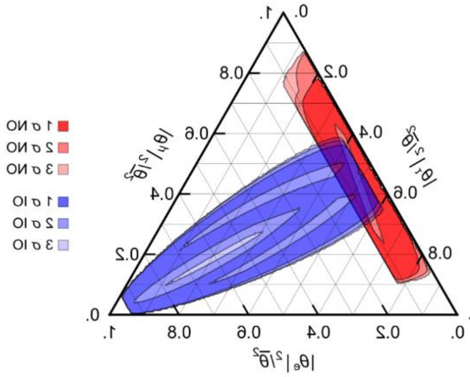
- Mass basis at $T=0$ is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

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 structure in SM flavours



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

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

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

"interaction basis"

Constraints from Leptogenesis in Model with 2 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

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

"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_{Rw}
- 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

- 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

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

ν oscillation data constrains strucrure in SM flavours

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

Leptogenesis with "Mass Communism"

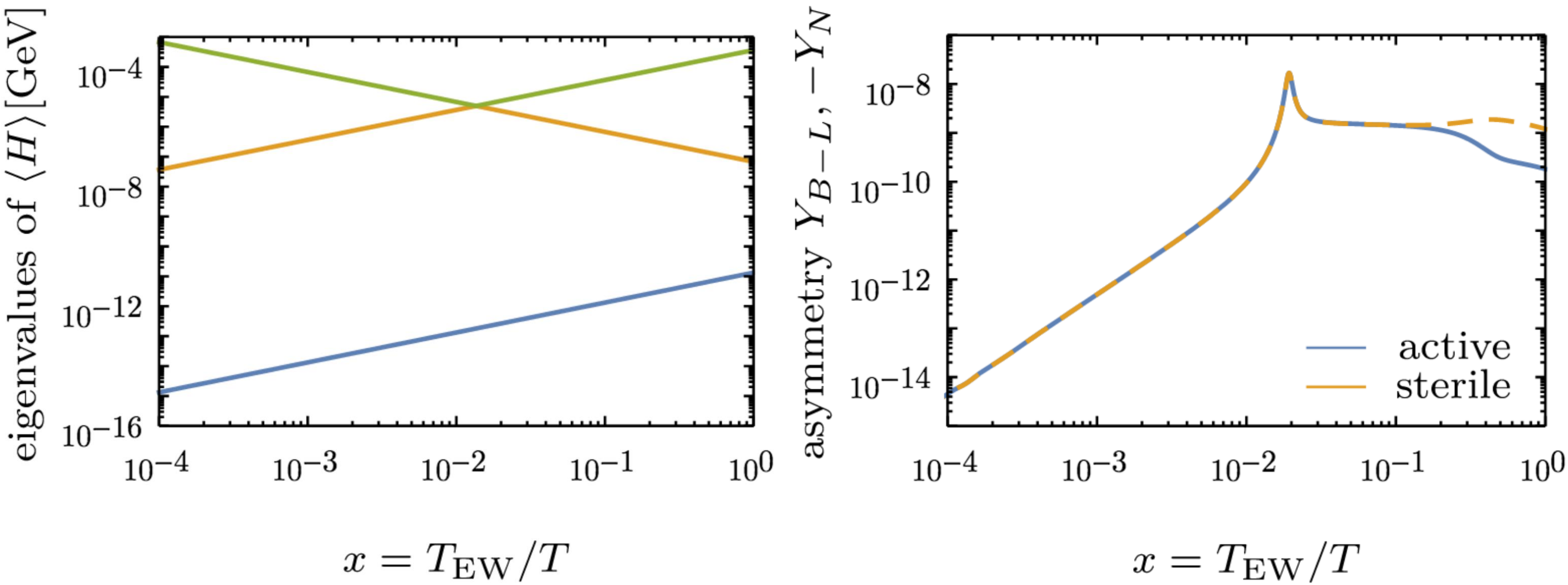
- Mass basis at $T=0$ is the one where M is diagonal
- B-L limit: ν_{Rs} and ν_{Rw} define "interaction basis"
- $T >> M$: thermal masses dominate, interaction basis is mass basis

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!

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, similar to MSW resonance in the sun

Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

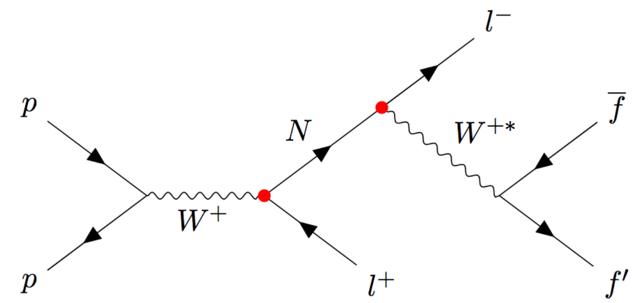
Majorana mass

- **proving Majorana nature**
- resolving the heavy neutrino mass spectrum

Complementarity and testability

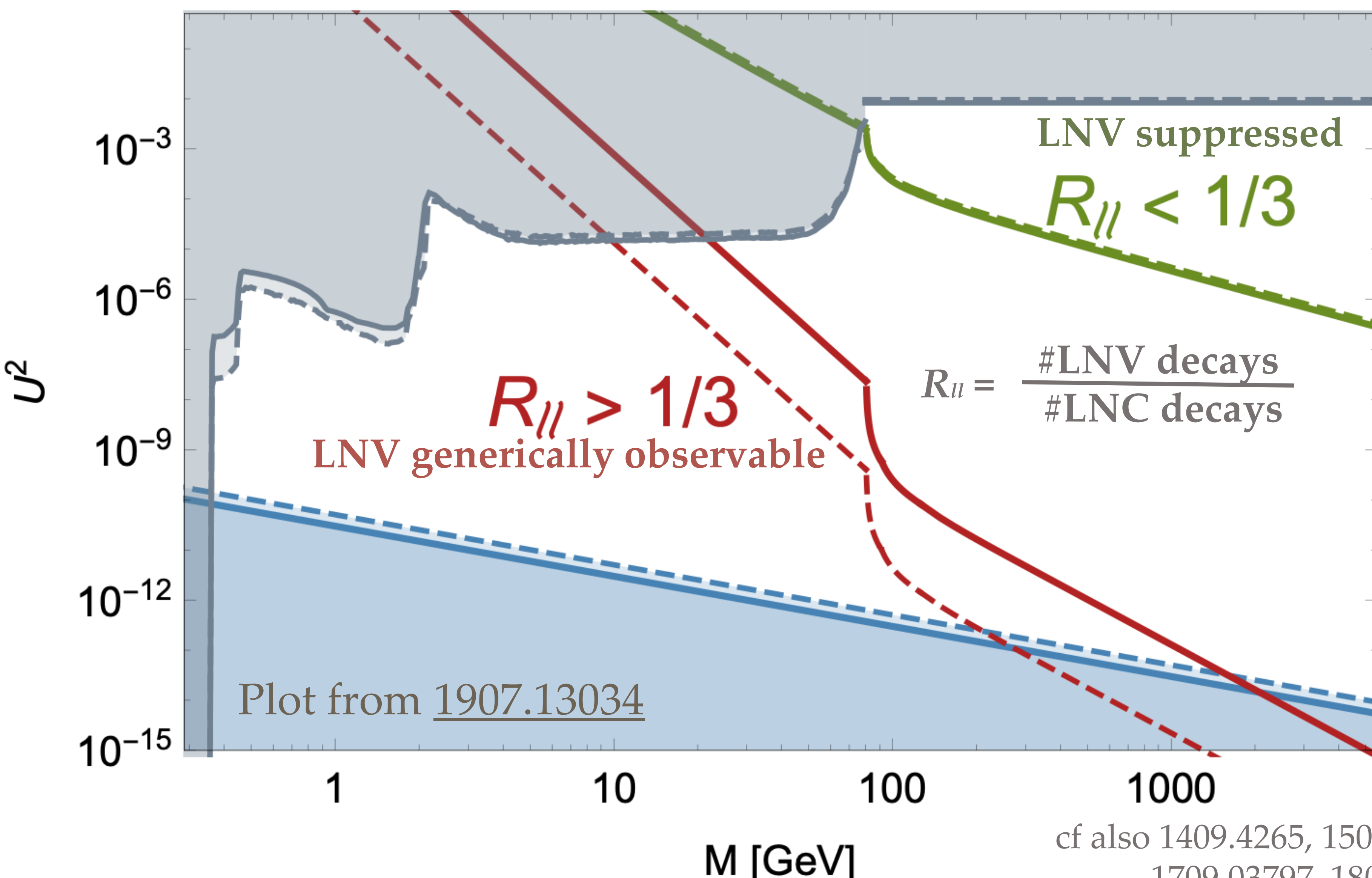
Majorana nature of HNLs: Can LNV decay be observed?

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



(a) Charged current decay

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



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

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

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

Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

- proving Majorana nature
- **resolving the heavy neutrino mass spectrum**

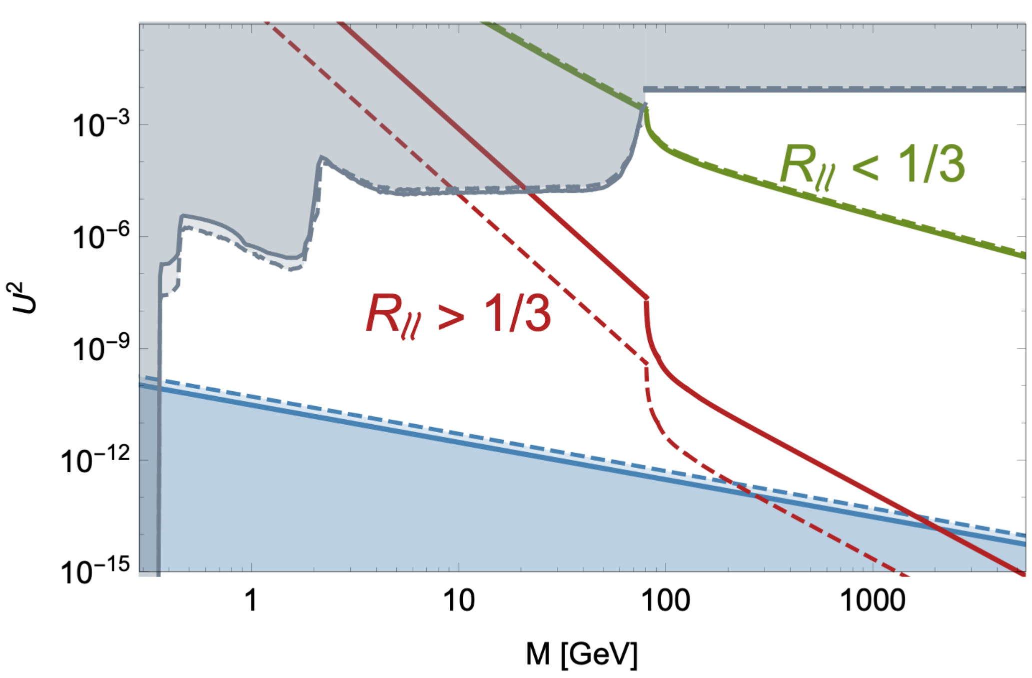
Complementarity and testability

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

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

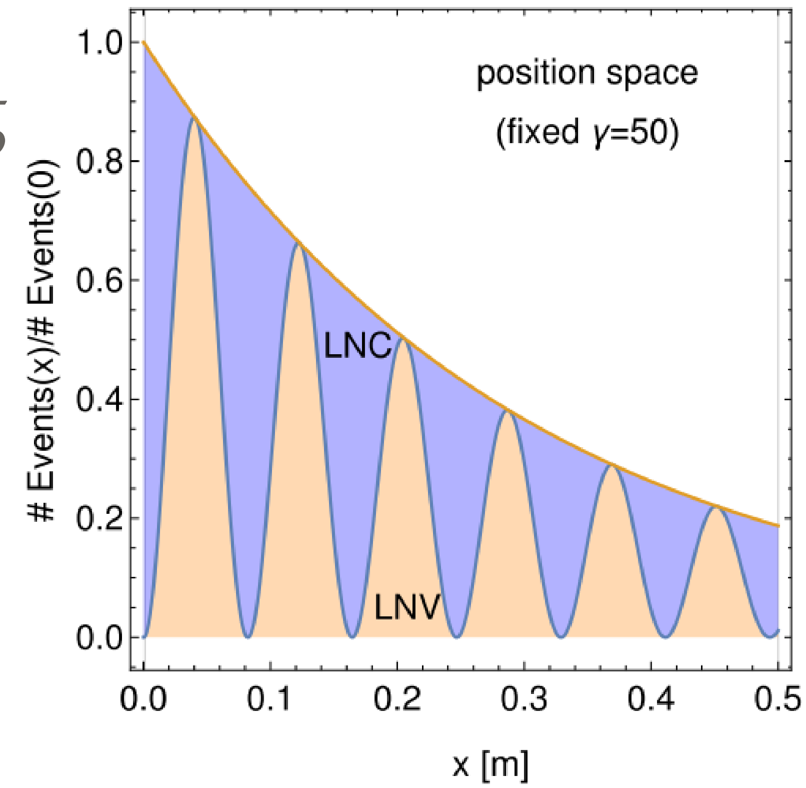
Anamiati et al 1607.05641

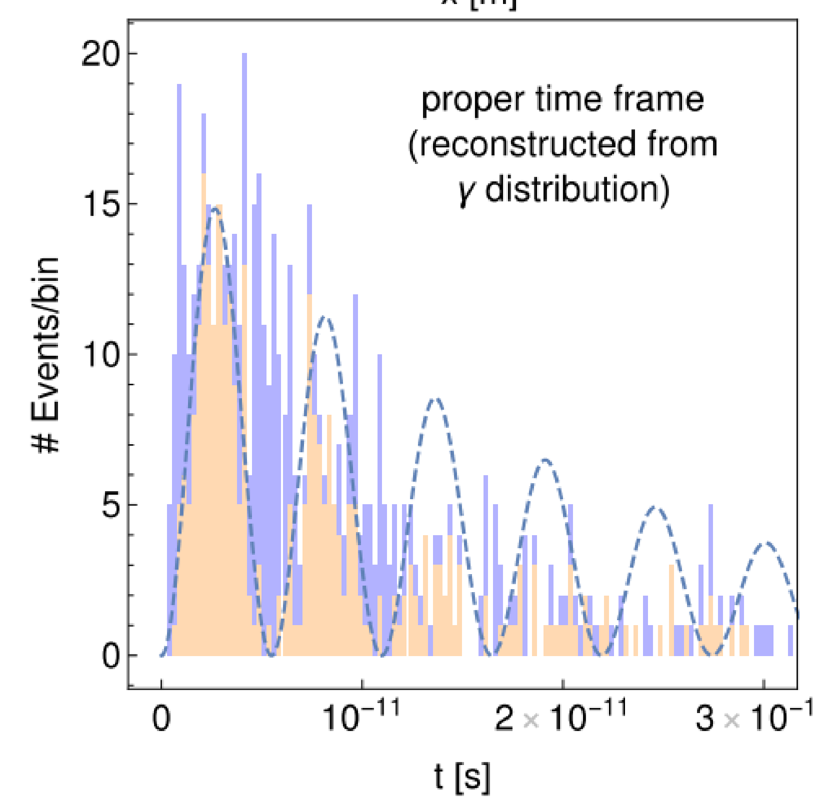


MaD/Klaric/Klose 1907.13034

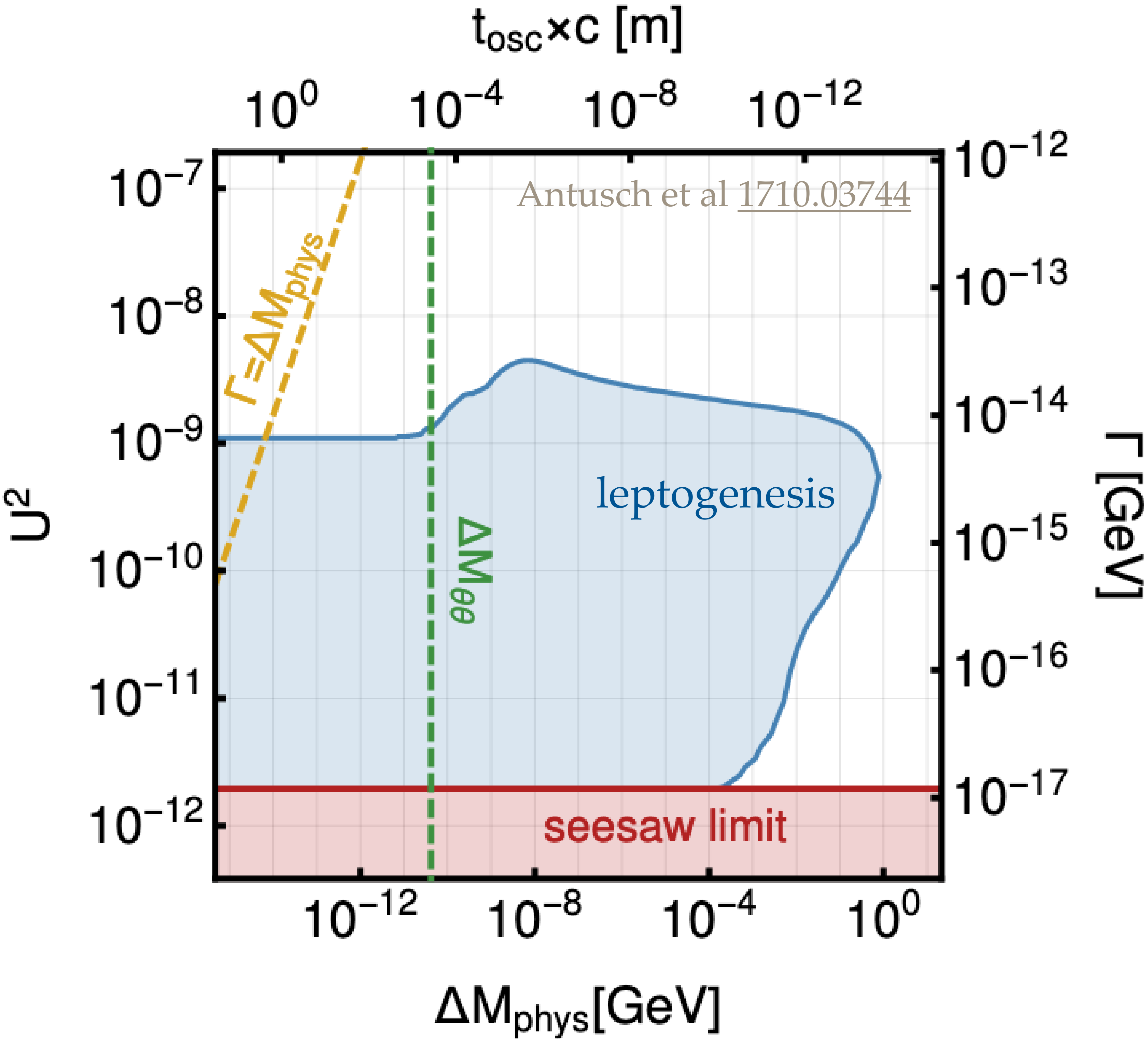
spatially resolving this ratio gives more information!

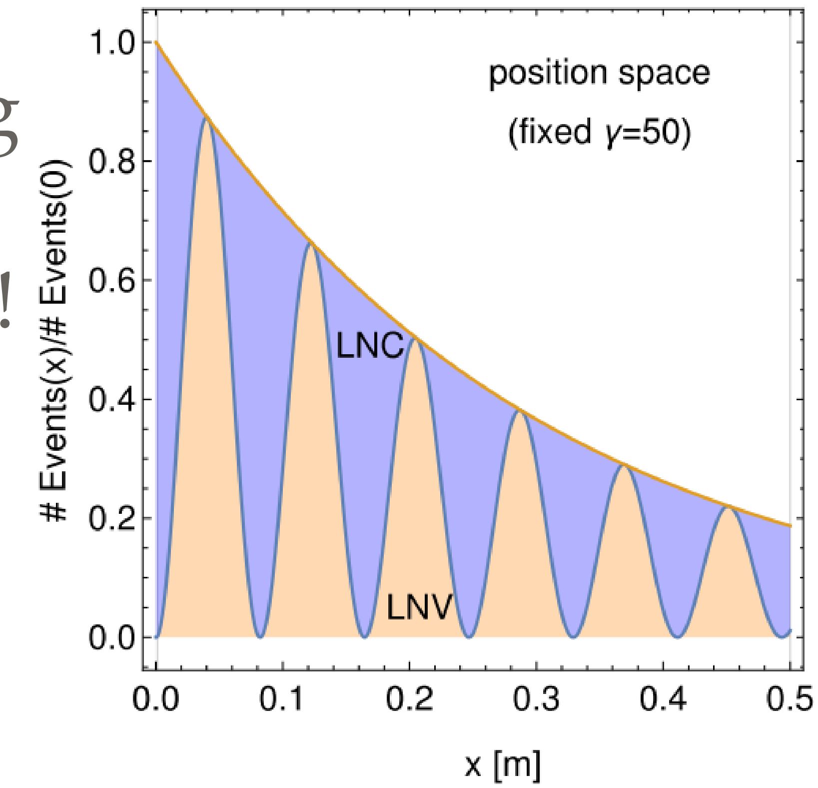
Antusch et al 1709.03797

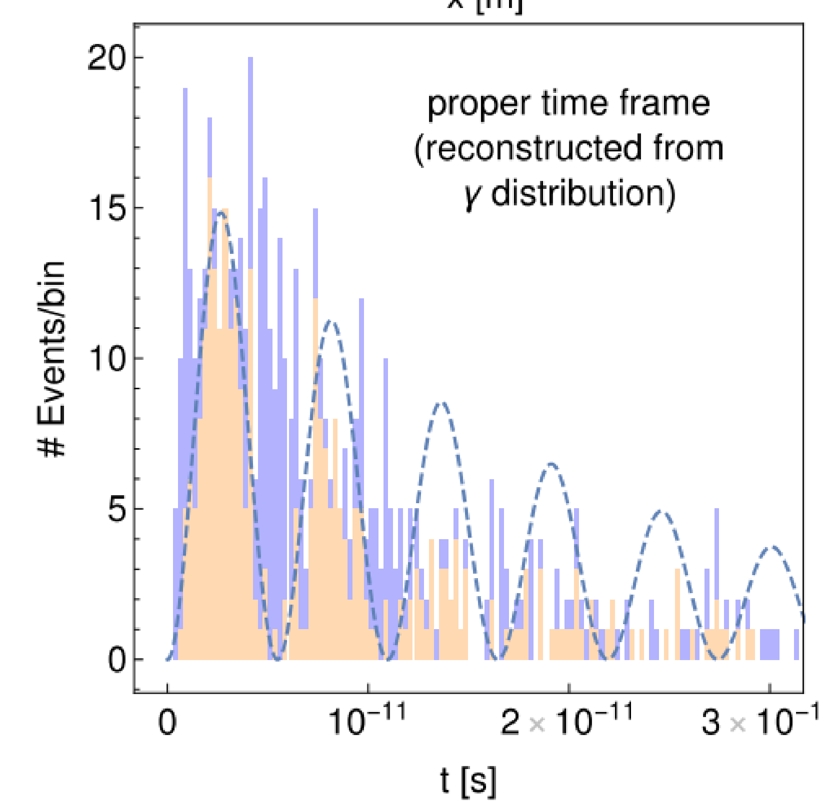




How to measure ΔM?







Overview

Testable Leptogenesis Scenarios

- mechanisms
- models

Probes of leptogenesis

- falsification through indirect signatures
- discovering heavy neutrinos

Mixing parameters

- constraints from Neutrino oscillation data
- constraints from leptogenesis

Majorana mass

- proving Majorana nature
- resolving the heavy neutrino mass spectrum

Complementarity and testability

Full Testability

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass

complex angle(s) ω

HNL-masses

Kinematics, LNV

Kinematics, LNV/LNC decays

relative *N1* and *N2* couplings, 0νββ decay

overall *Ni* coupling

DUNE, NOνA, T2K, HyperK…

M, Δ*M*, Reω, Imω, δ, *α*
six nknown parameters

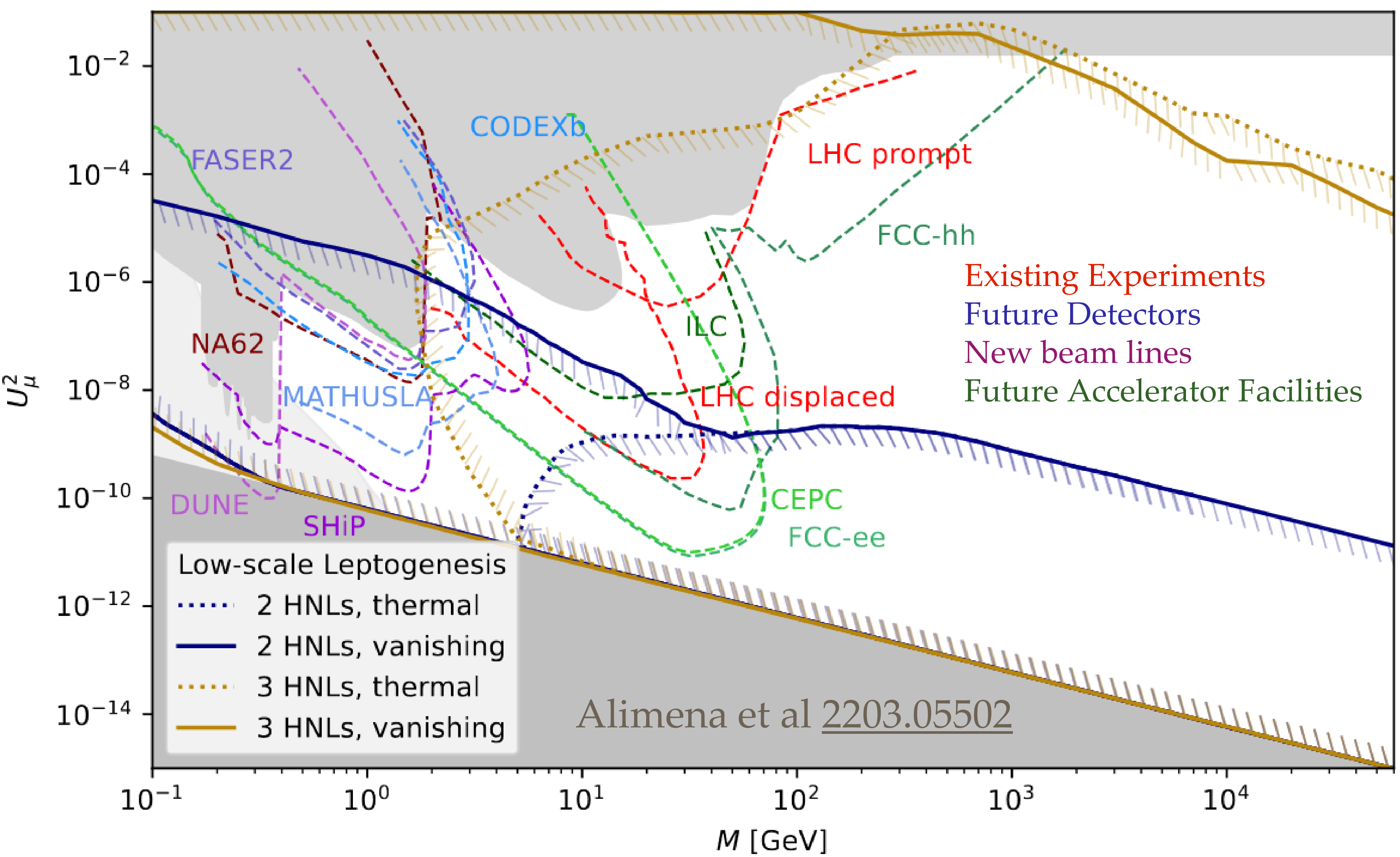
Ni flavour mixing pattern

For 2 HNLs in principle all model parameters can be constrained, making this a fully testable model of leptogenesis and neutrino mass!

Hernandez et al 1606.06719, MaD et al 1609.09069 , Antusch et al 1710.03744

Summary

- **Leptogenesis in type I seesaw based scenarios is possible for almost any Majorana mass roughly above the pion mass**
- **Various experiments can find the heavy neutrinos and study their properties** (mass, lifetime, flavour mixing pattern, CPV, LNV, …)
- **Complementarity of energy, intensity and cosmic frontiers clue to testability**



- Minimal model with two heavy neutrinos fully testable
- Model with three heavy neutrinos has higher chance of discovery, but more parameters…
- …but adding flavour and CP symmetries increases predictivity

Testability through complementarity - 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

absolute neutrino mass searches (KATRIN ect.)

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

CMB and LSS : absolute neutrino mass

non-accelerator searches (TRISTAN…)

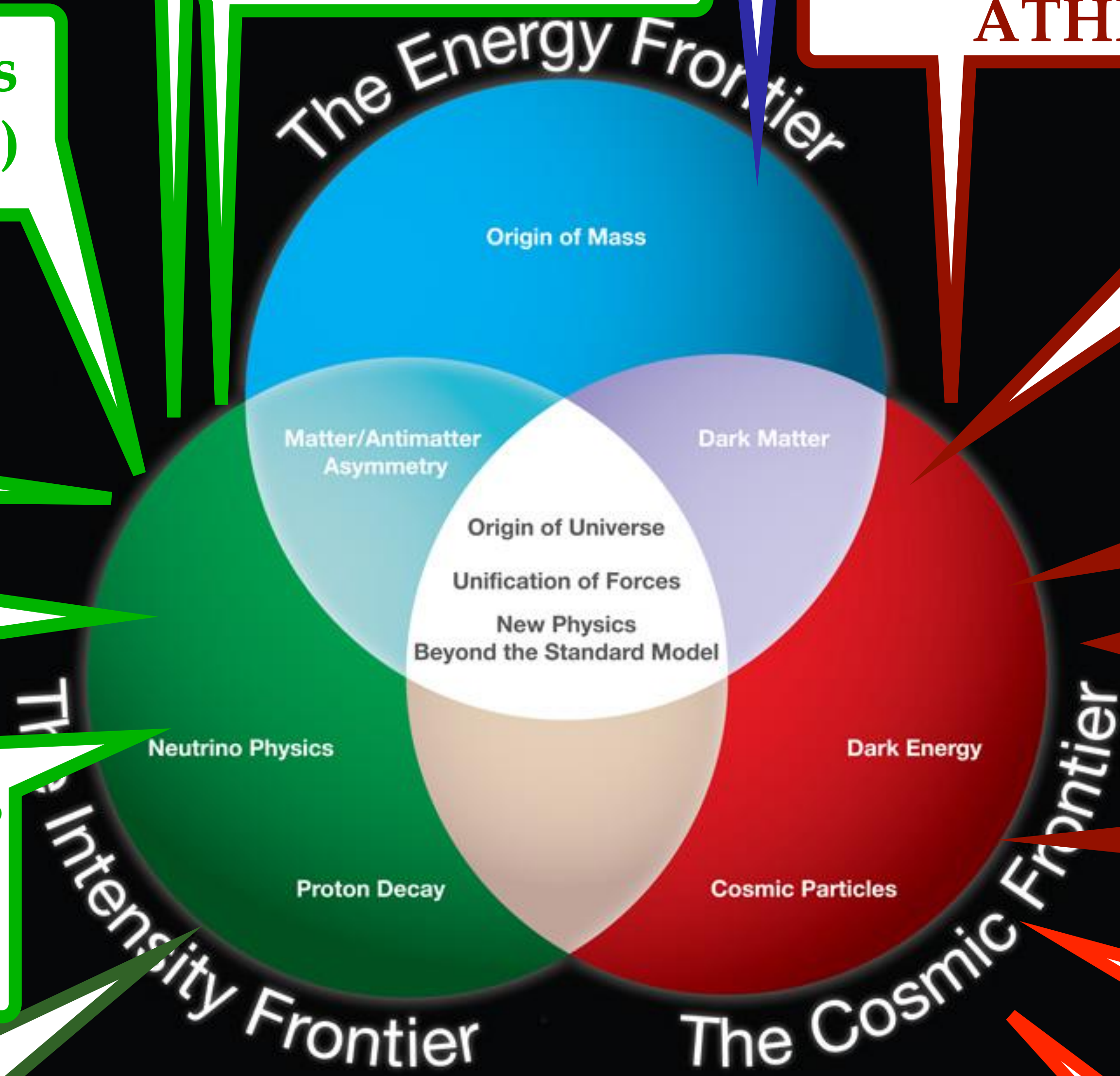
astrophysics: supernovae etc.

neutrinoless double β decay

Structure formation: simulation, observation

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

IGM temperature: WDM vs CDM



Theory: leptogenesis parameter region

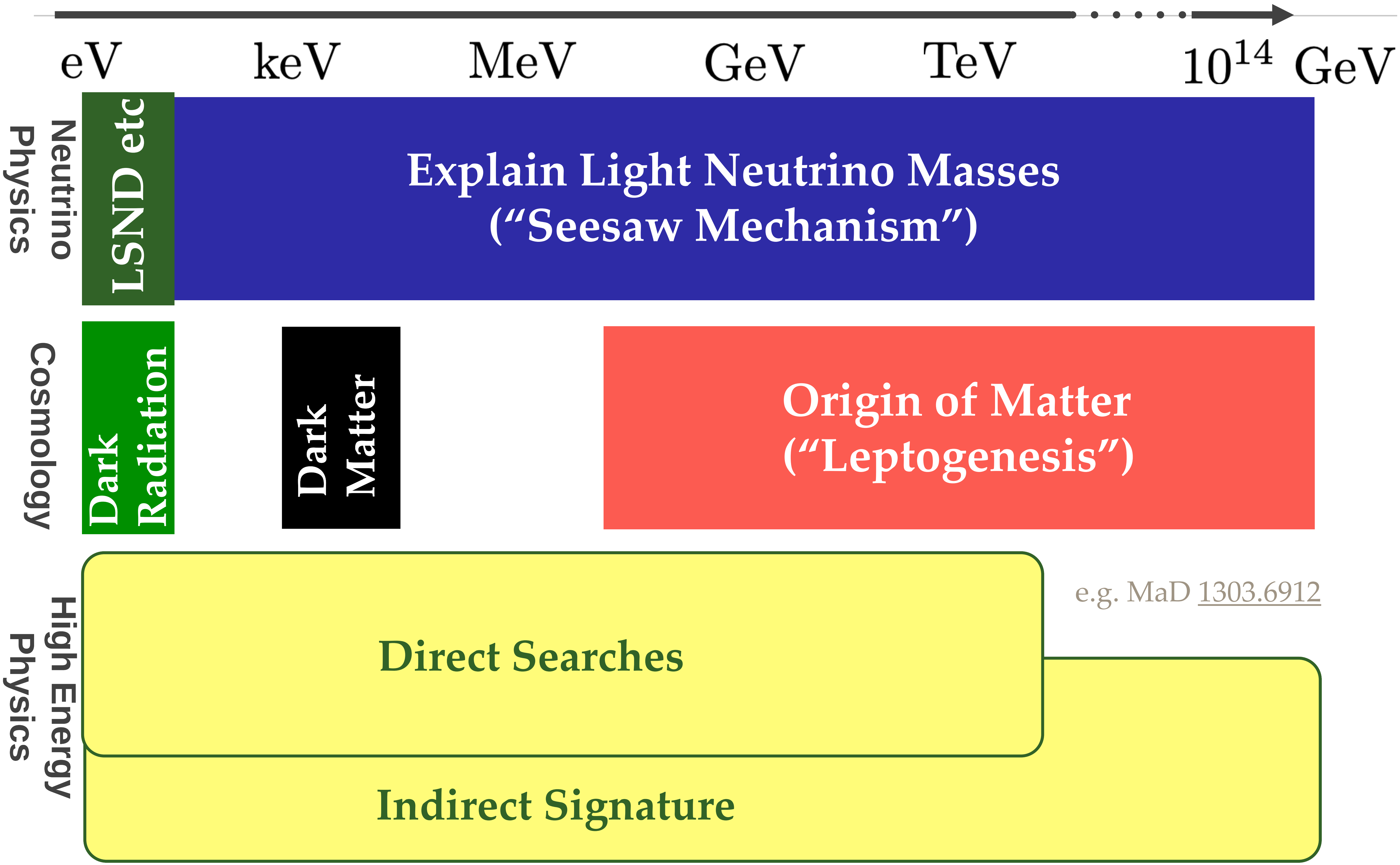
neutrino oscillation experiments DUNE, Hyper-K

RF, NF, EF, CF, TF

Theory: Sterile neutrino DM production

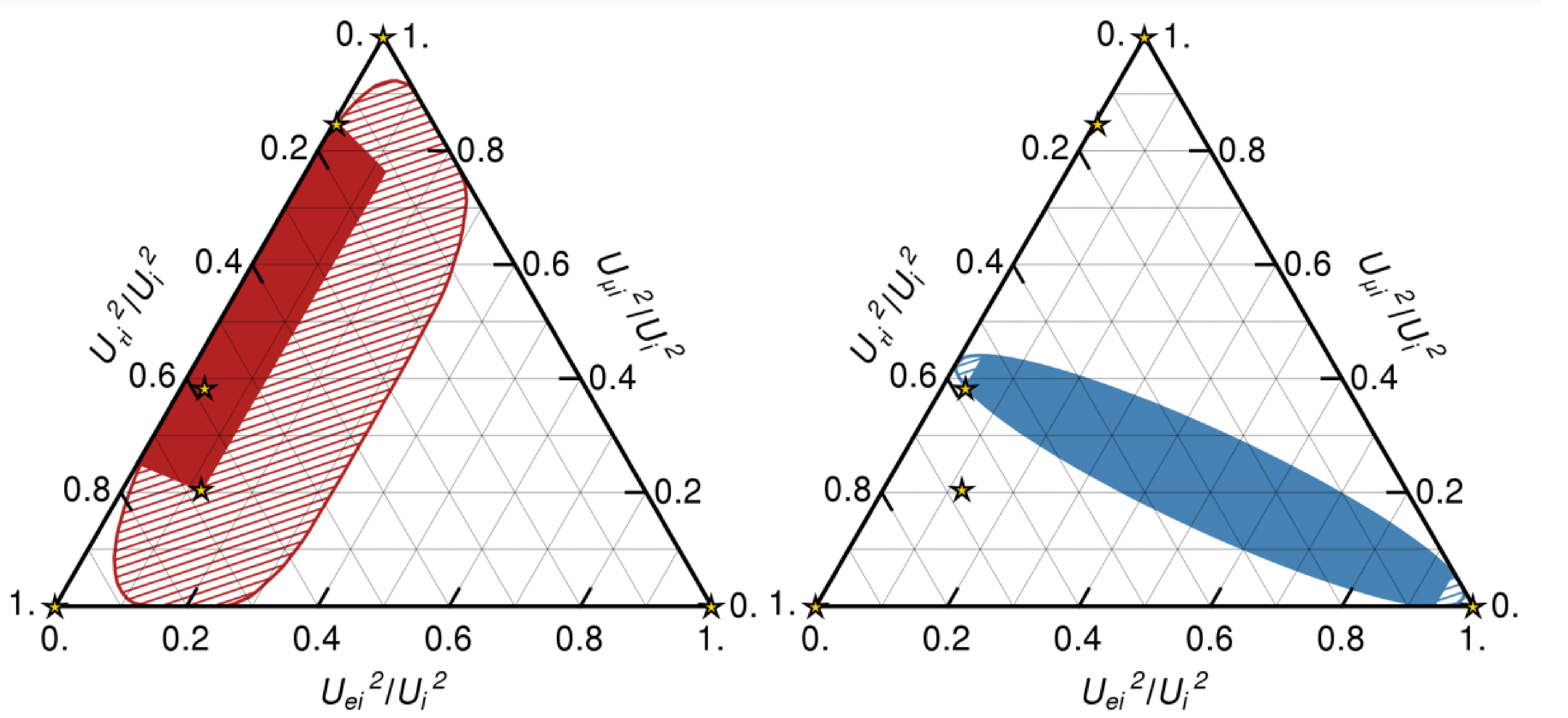
Backup Slides

Heavy Neutrino Mass Scale



Most Minimal Scenario (2HNL)

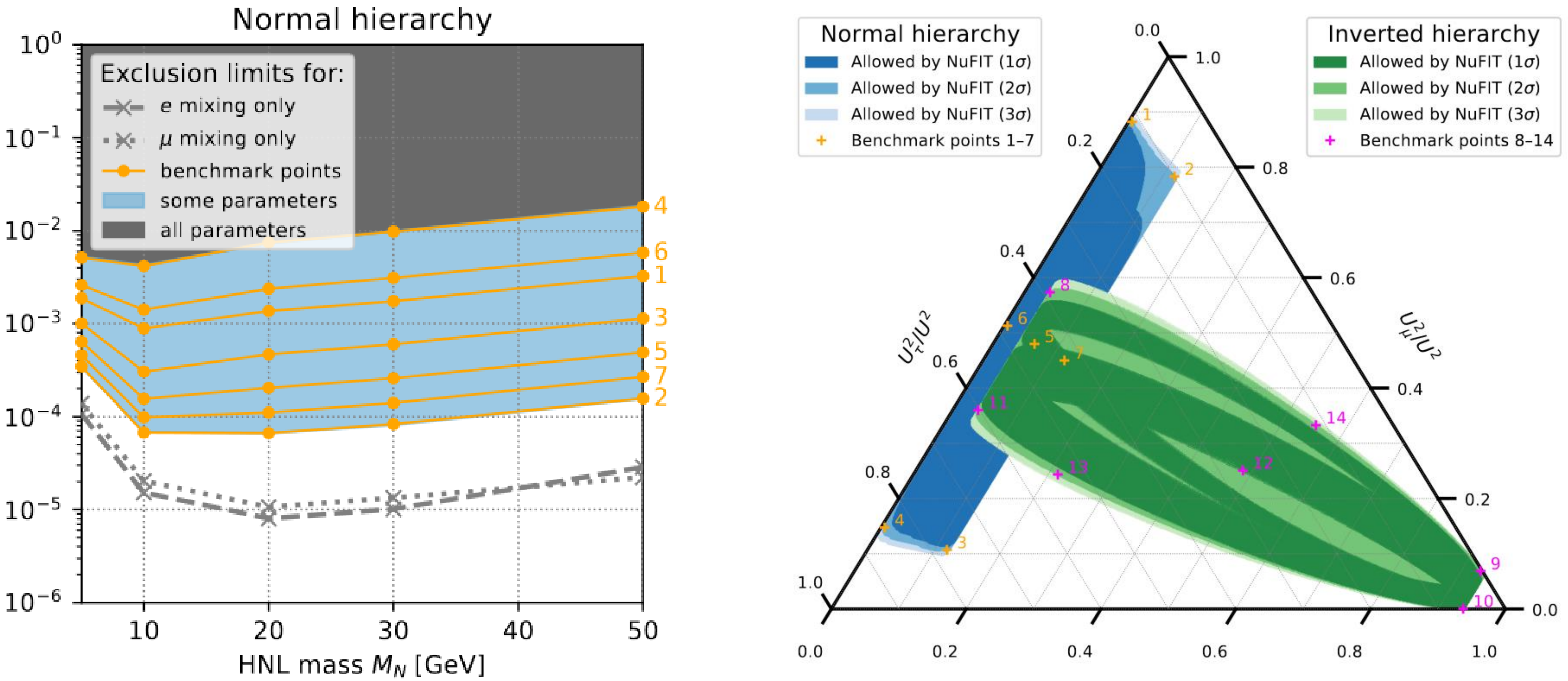
- This minimal scenario is very predictive
- In particular, the flavour mixing pattern is strongly constrained: important for experimental sensitivity



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

plot from 1801.04207

ATLAS Reinterpretation



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

Tastet et al 2107.12980

Global Symmetries

Agnostic approach:

- Treat Yukawa matrices F and Majorana mass M as free parameters, allowing all values that are not excluded experimentally
- Some theoretical consistency requirements can be applied:
  - **Technical naturalness**: demand radiative corrections small
  - **Perturbativity**: Keep entries of F small enough that perturbation theory applies
  - **Seesaw approximation**: Keep θ small enough for seesaw expansion to hold
  - **Perturbative unitarity**: HNL width smaller than HNL mass
- Requires approximate B-L symmetry Shaposhnikov 06, Kersten/Smirnov 07

Symmetry-based approach:

- UV-completions can motivate specific structures in F and M

  See e.g. King 1701.04413, Xing 1909.09610,
- Symmetries reduce parameter space, make the model more testable

B-L Charge Assignment

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 helicity charges during leptogenesis

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

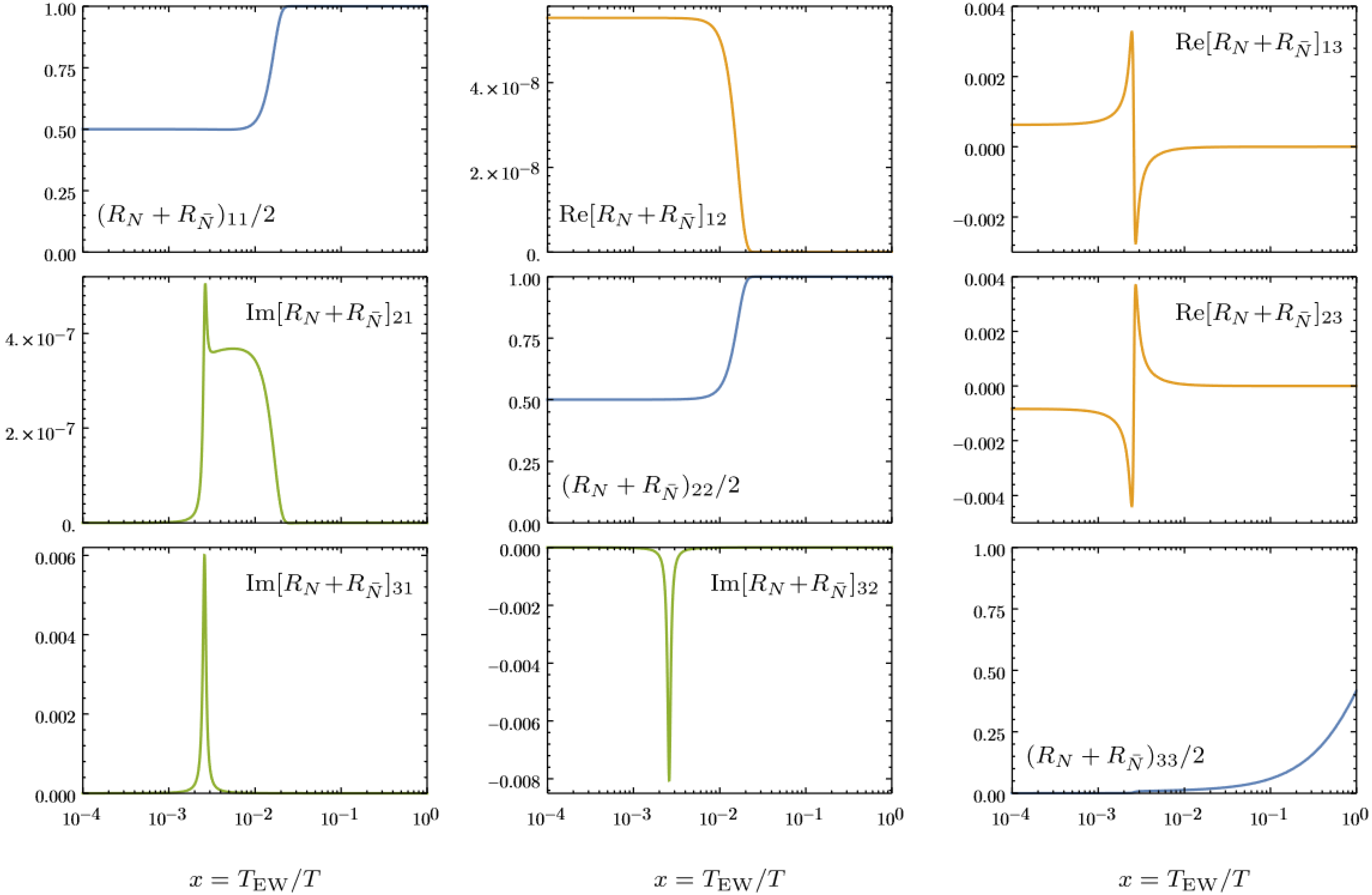
$$\psi_N = \quad (\nu_{R\mathrm{s}} + \nu_{R\mathrm{w}}^c)$$

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

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

Shaposhnikov 06
Kersten/Smirnov 07

HNL Density Matrix Evolution

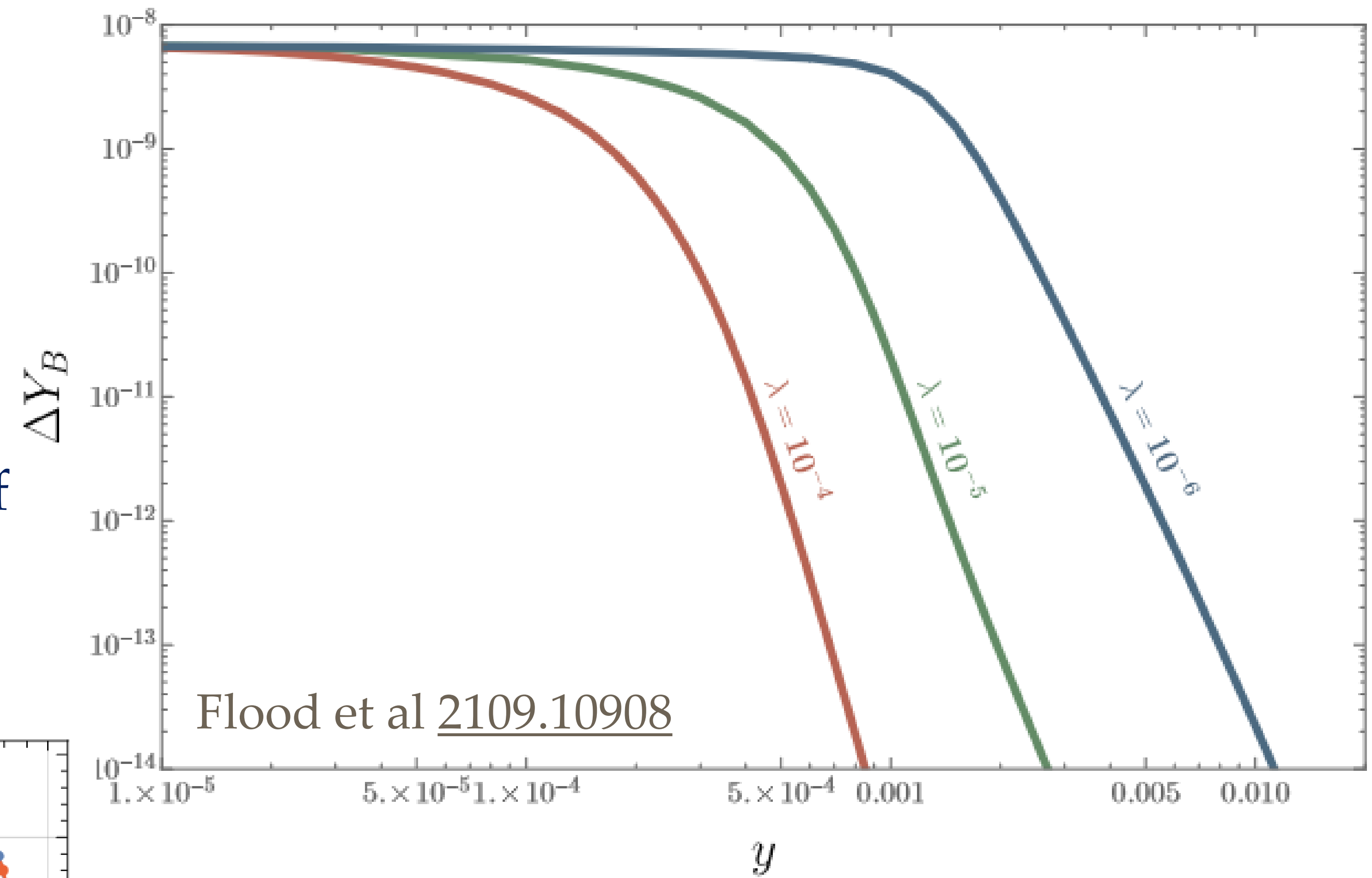


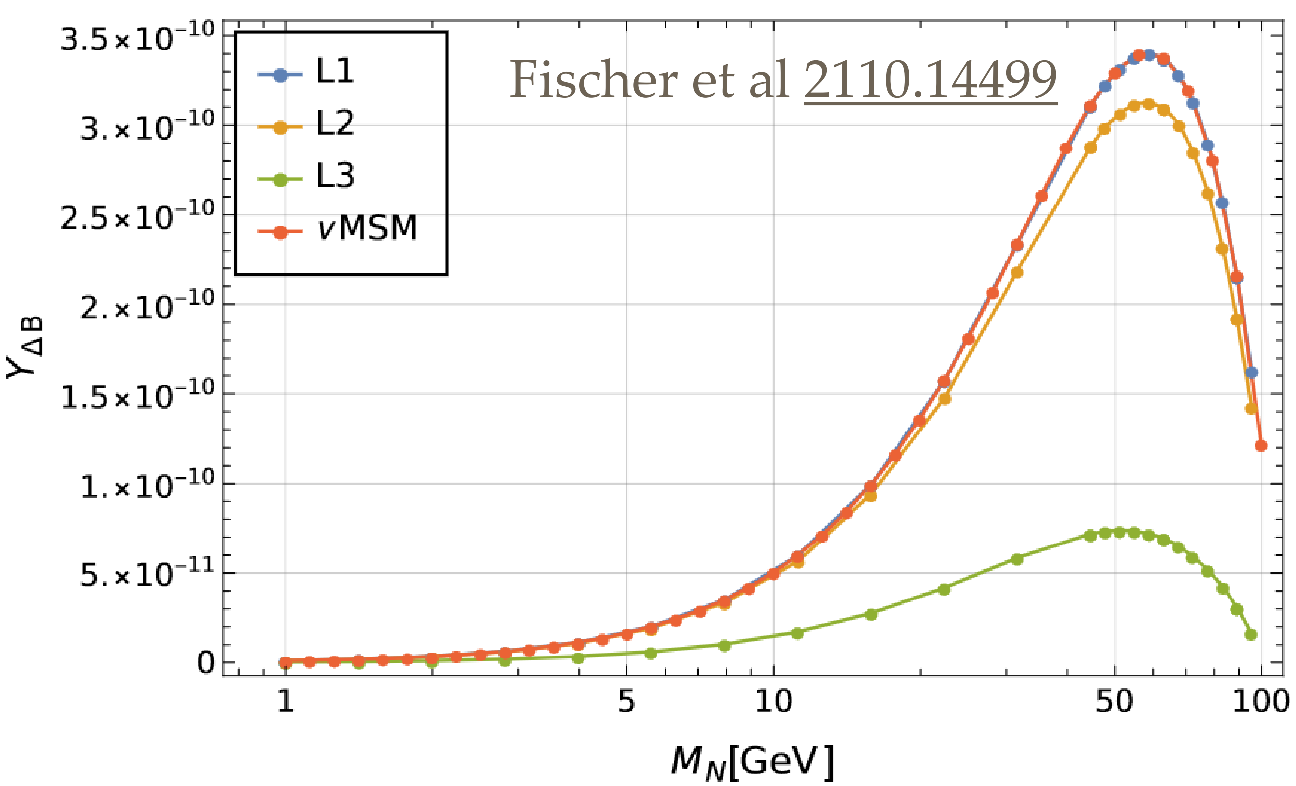
Abada et al 1810.12463

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")



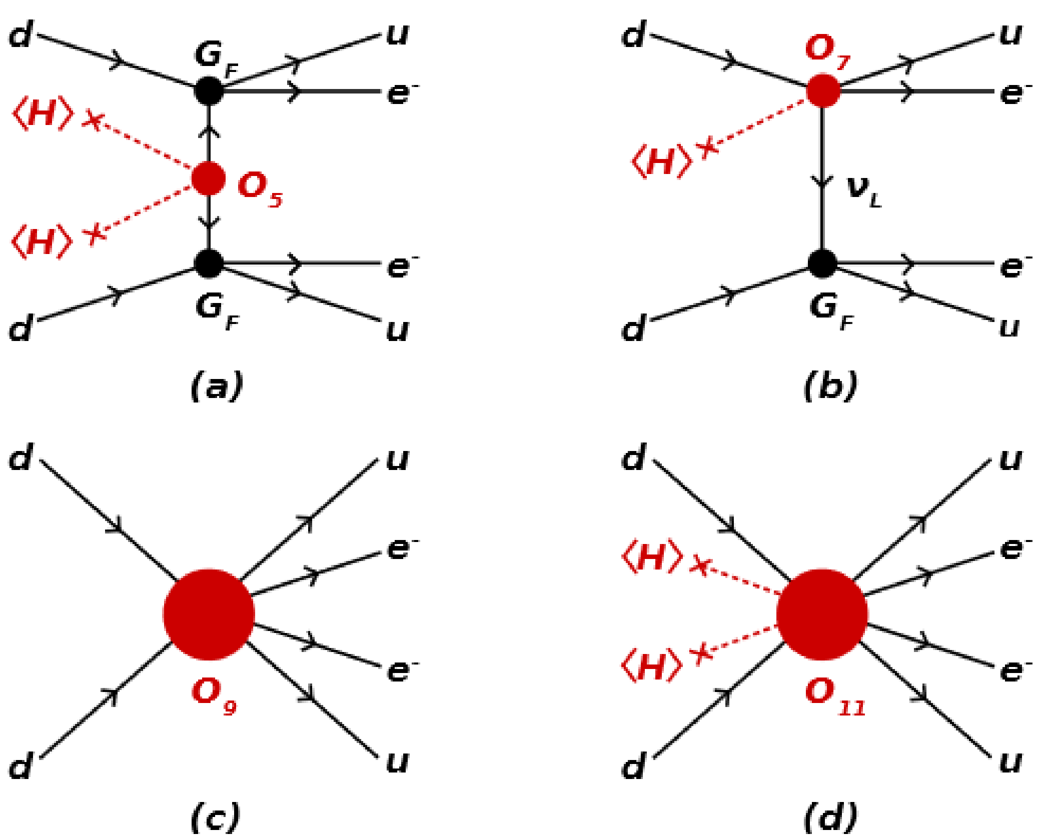


- But "freeze-out mechanism" works down to M~ 2 GeV (see previous slide), making low scale leptogenesis feasible in presence of new interactions!

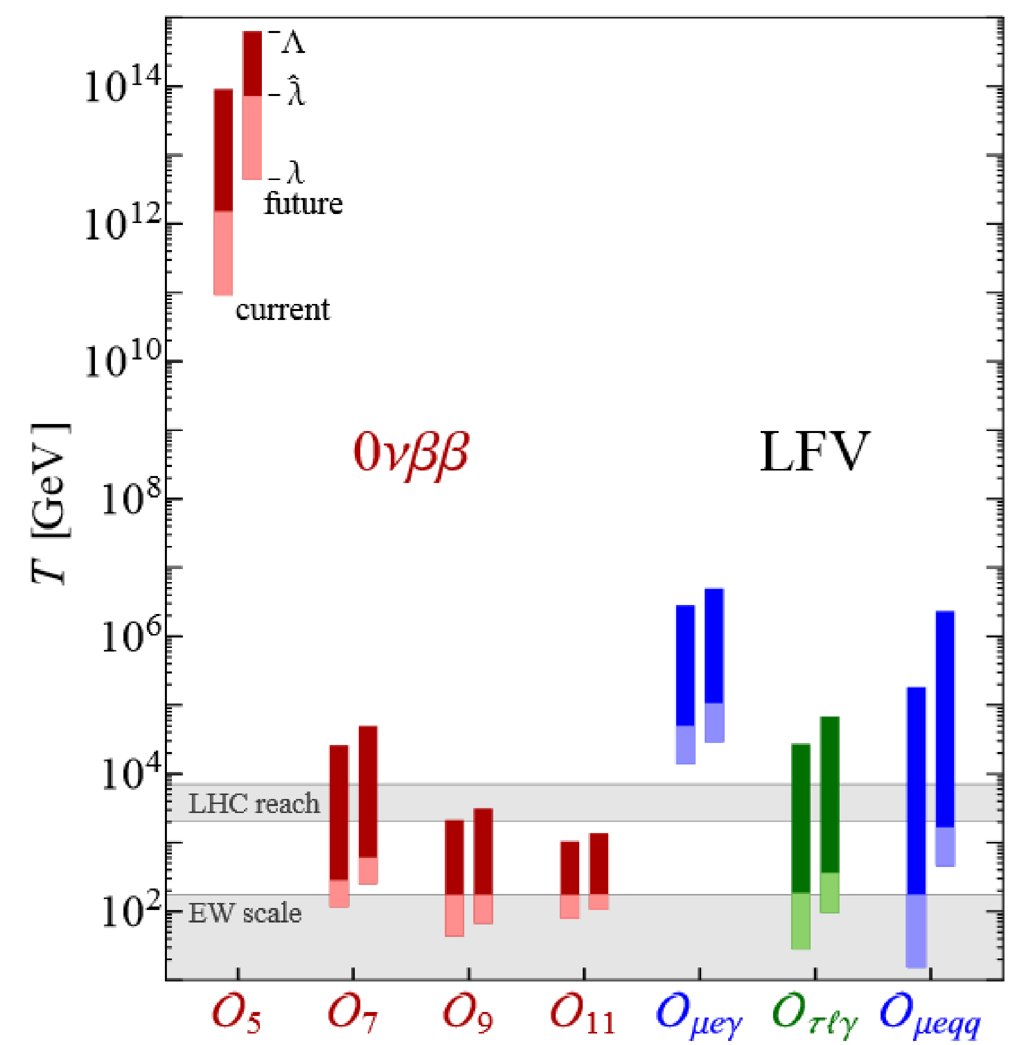
Falsifying High Scale Leptogenesis

- LNV at the TeV scale would wash out L generated at high scale
- electroweak sphalerons above ~130 GeV imply B also washed out
- discovery of low scale LNV can rule out high scale leptogenesis!

Deppisch/Harz 1312.4447

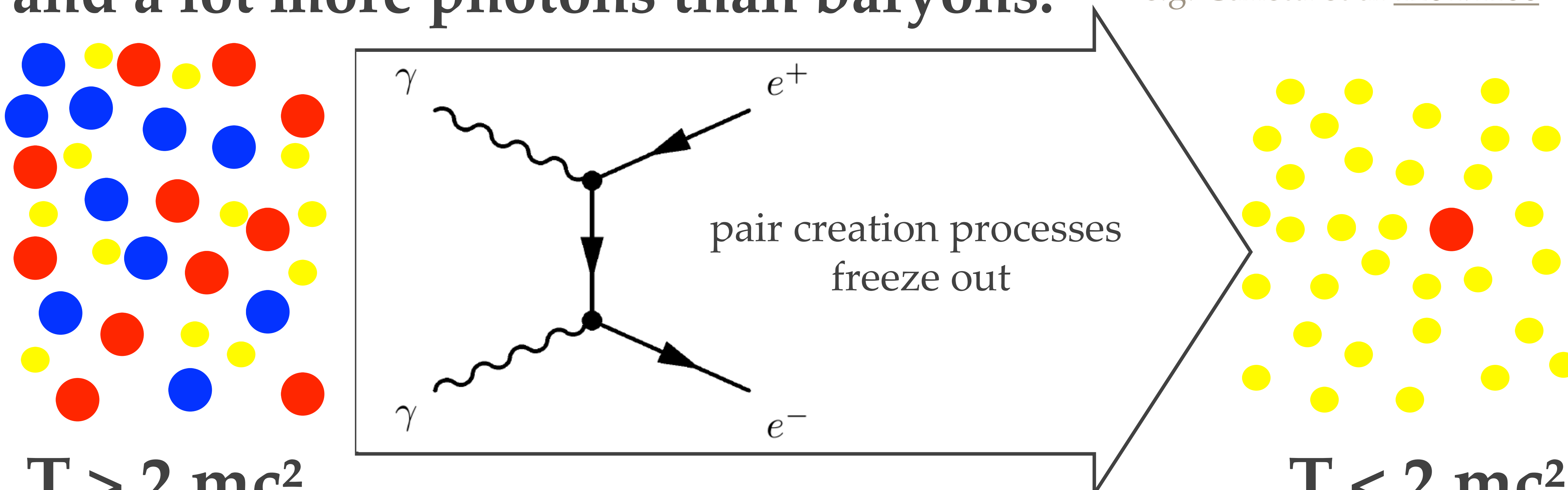


Deppisch et al 1503.04825, 1711.10432



Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons. e.g. Canetti et al 1204.4186



$T > 2\ mc^2$ **$T < 2\ mc^2$**

CMB constraint on baryon-to-photon ratio η:

$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:

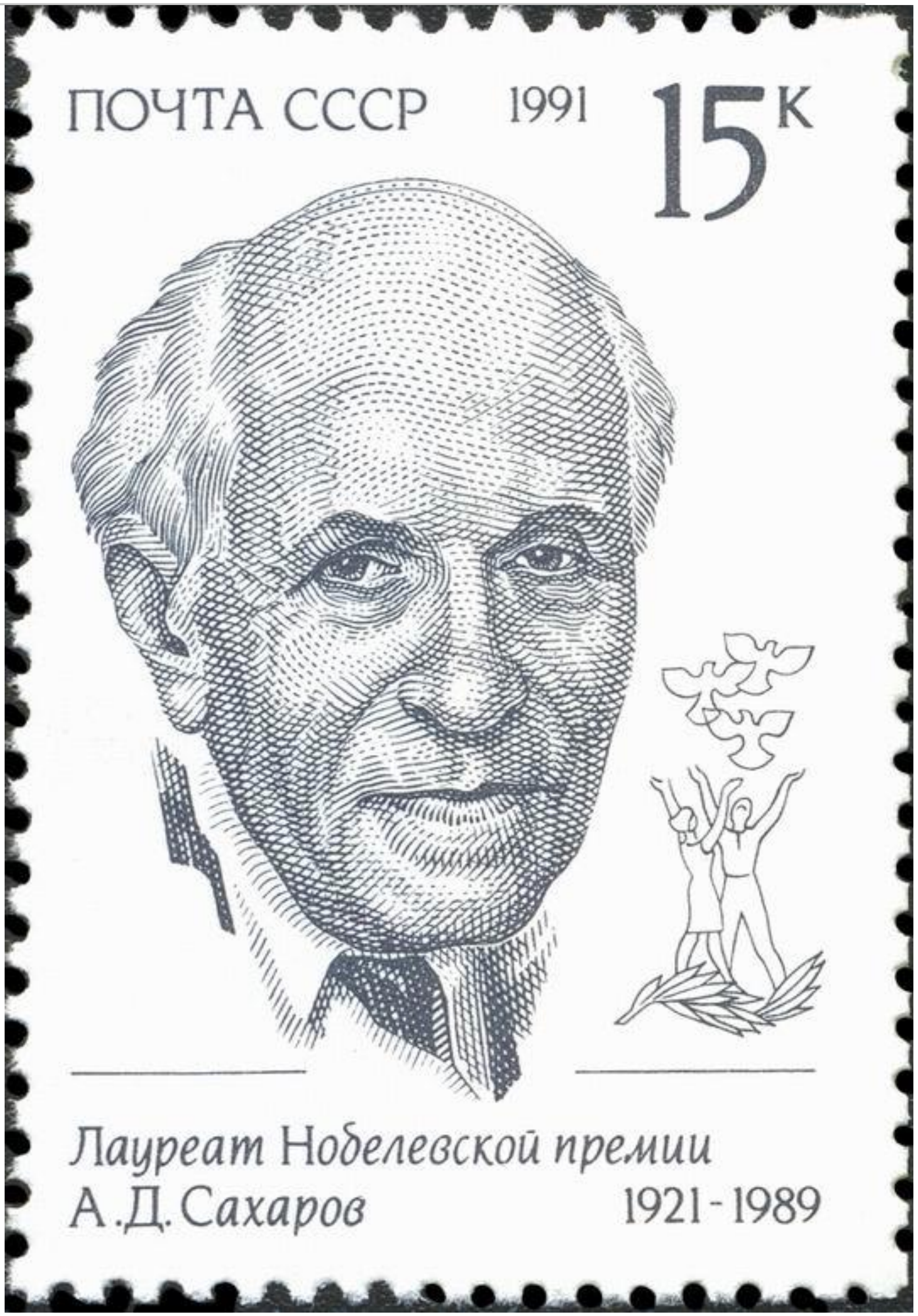
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



Thermal Leptogenesis

Basic idea

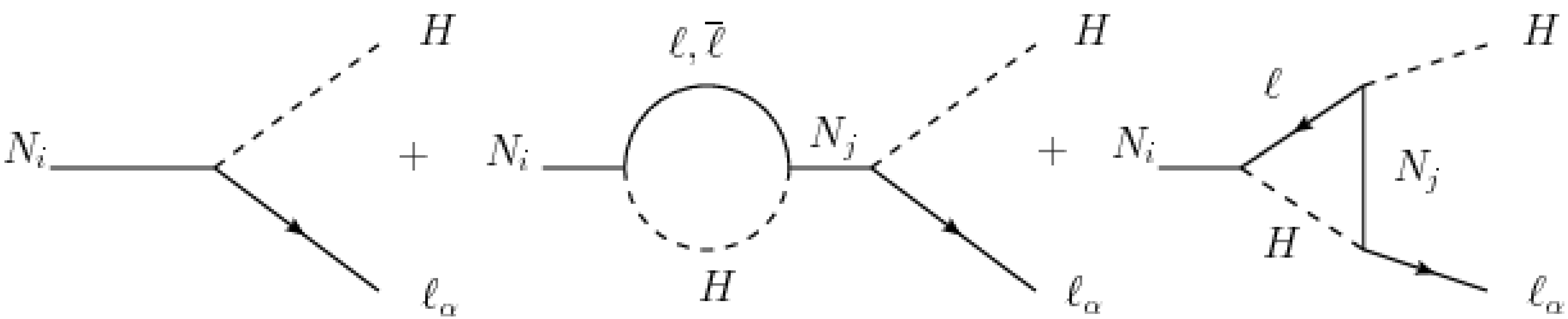
- ***N*** **are around in the early universe**
- ***N*** **interactions are CP violating**
- ***N*** **may preferably decay into matter**

CP violating parameter ϵ

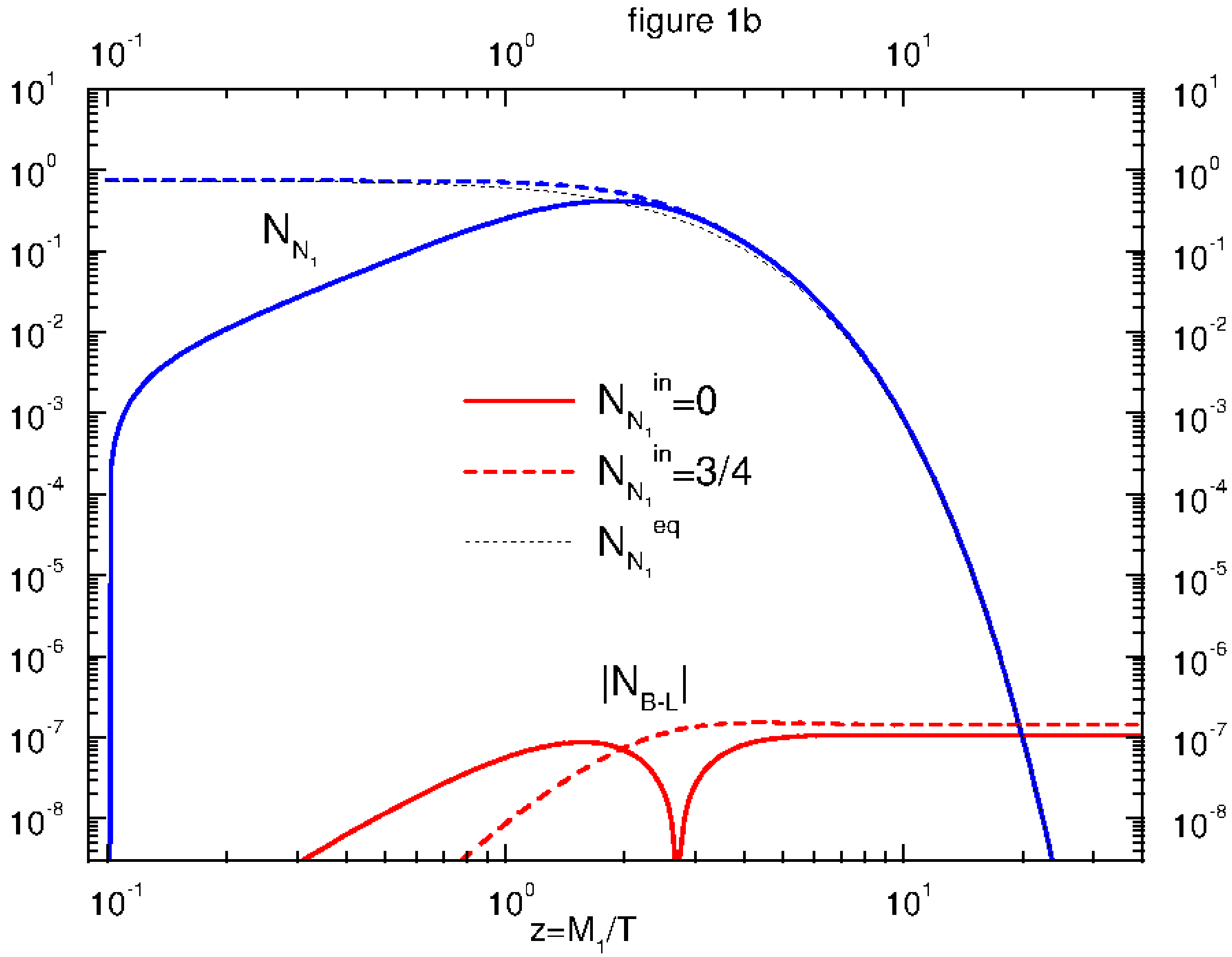
$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

final asymmetry

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



Boltzmann Equations



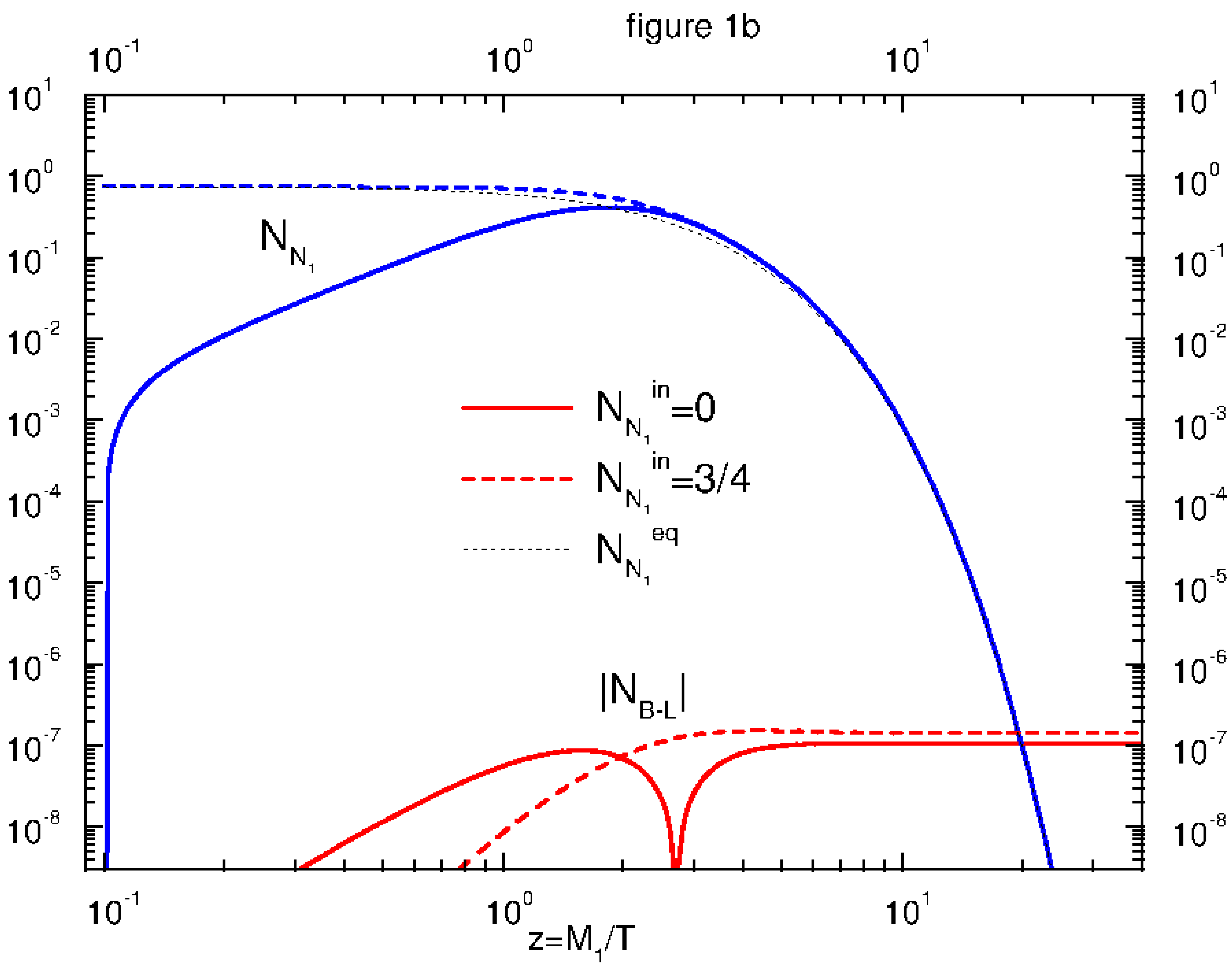
Buchmuller/Di Bari/Plumacher 0205349

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

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

"source" "washout"

Boltzmann Equations



Buchmuller/Di Bari/Plumacher 0205349

"Vanilla leptogenesis" requires $M > 10^9$ GeV Davidson/Ibarra 0202239

Flavour effects can reduce this by few orders e.g. Dev et al 1711.02861

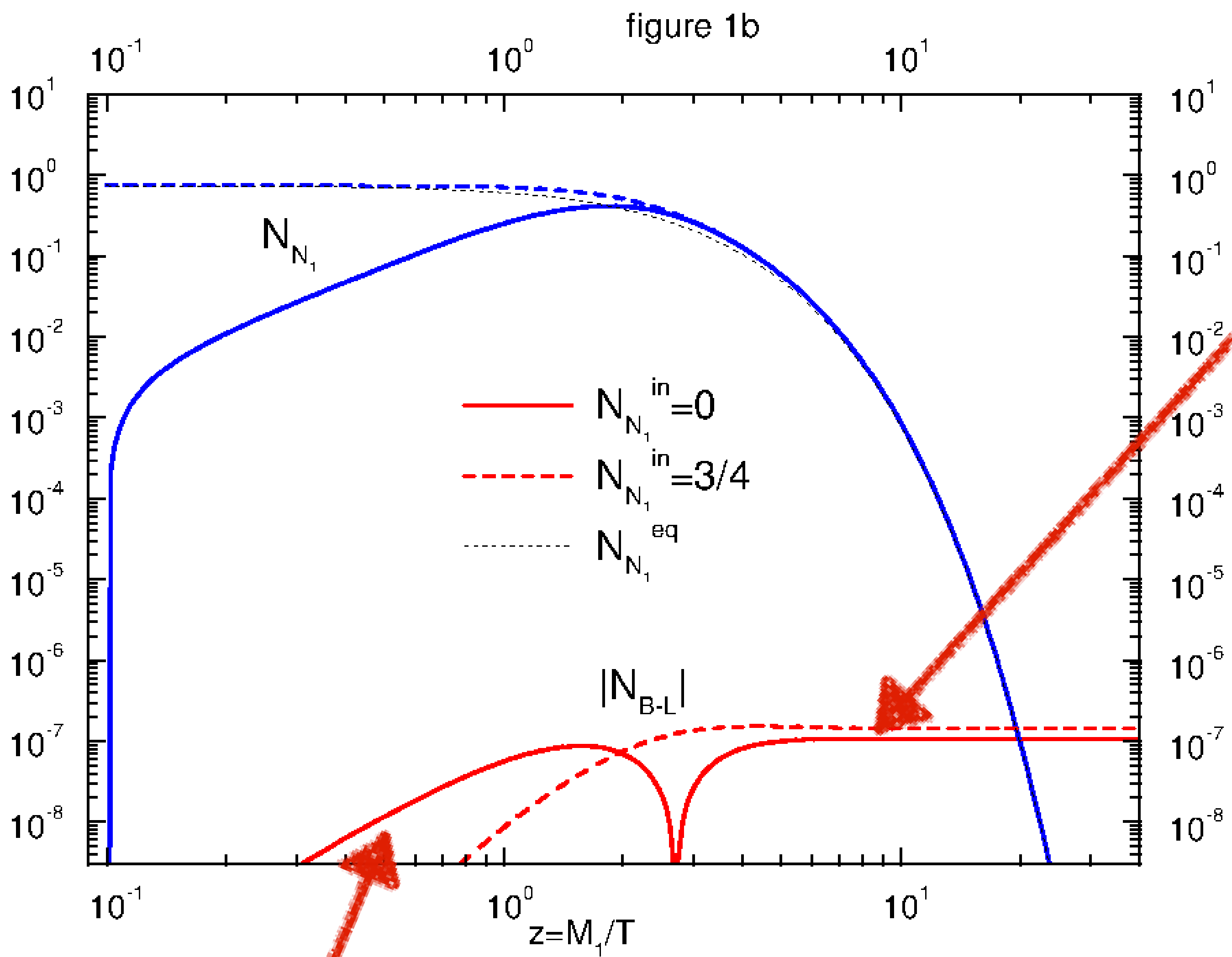
Resonant enhancement by $\Gamma / \Delta M$ permits $M <$ TeV e.g. Dev et al 1711.02863

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

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

"source" "washout"

Leptogenesis with small 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")

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

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

"source" "washout"

Quantitative Description

- Low scale leptogenesis involves many effects not captured by simple Boltzmann equation (coherent oscillations, quantum statistics, screening by the plasma, …)
- Significant progress has been made towards a quantitative description

See e.g. Biondini et al 1711.02864, Garbrecht 1812.02651 [talk by Bjorn Garbrecht]

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

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

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

Quantitative Description

- Low scale leptogenesis involves many effects not captured by simple Boltzmann equation (coherent oscillations, quantum statistics, screening by the plasma, …)
- Significant progress has been made towards a quantitative description

See e.g. Biondini et al 1711.02864, Garbrecht 1812.02651 [talk by Bjorn Garbrecht]

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

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

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

SM chemical potentials

Heavy neutrino density matrix

LNC rate ~ $F^2\,T$

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

Heavy neutrino effective Hamiltonian