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Long-Lived HNLs: Guidelines from Theory and Cosmology

Bethe Forum LLP

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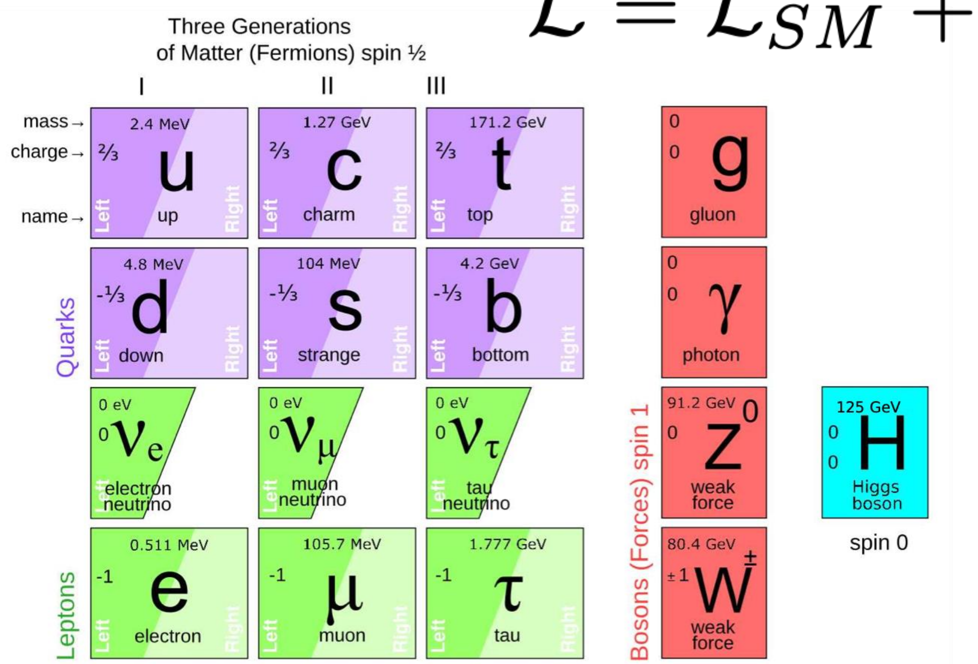
Bonn, Germany

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
$\nu \simeq U_\nu (\nu_L + \theta \nu_R^c)$
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

- Can simultaneously explain light neutrino masses ("seesaw mechanism") and matter-antimatter asymmetry of the universe ("leptogenesis")
- Heavy mass eigenstate N are type of heavy neutral lepton (HNL) that can be searched for at colliders

Name Game (my definitions)

A **Heavy Neutral Lepton (HNL)** is a fermion that is massive ("heavy"), has no colour charge ("lepton") and is electrically neutral ("neutral"). In principle it need not have any connection to neutrino masses or even mix with neutrinos (though such mixing generally occurs unless it is forbidden by some new symmetry).

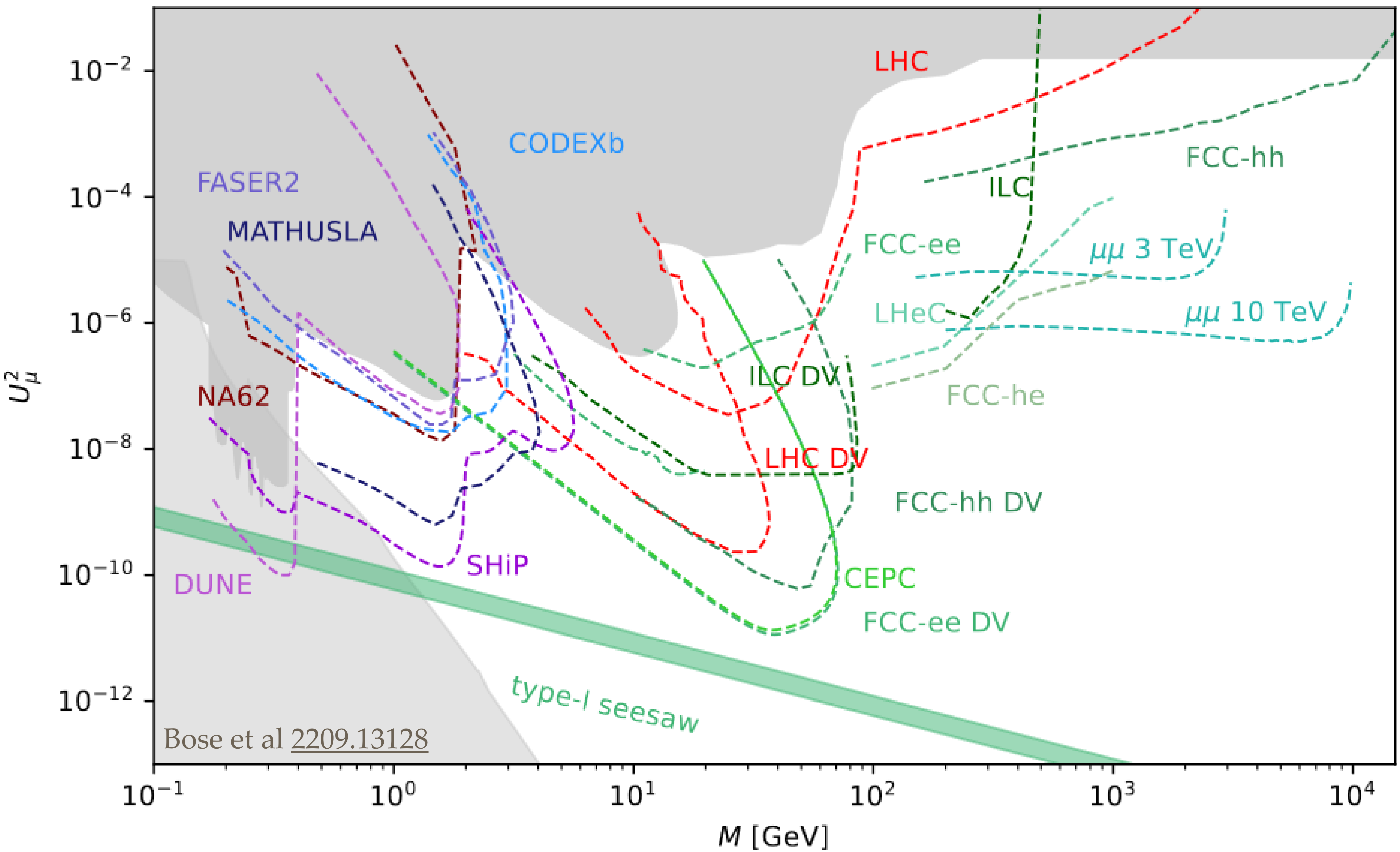
A **heavy neutrino** is a type of HNL that mixes with SM neutrinos. Typically "heavy" here either simply means "much heavier than SM neutrinos" or "heavy enough that the mass matters kinematically in accelerator-based experiments". It typically contributes to the light neutrino masses by this mixing, though this contribution may be negligible if the mixing is small, a symmetry supresses it, or a different mass mechanism dominates (e.g. type II in left-right symmetric model).

The term **right-handed neutrino** is often used to refer to the Weyl or Majorana spinors ν_R that couple to left-handed neutrinos and Higgs bosons. Since chirality is not conserved for massive particles, the term seems appropriate for the field, but not for a physical particle.

A **sterile neutrino** is a singlet fermion that mixes with SM neutrinos, which can be either light or heavy (some people use this term for any singlet fermion)

Why a Low Scale Seesaw?

Lamppost Approach?



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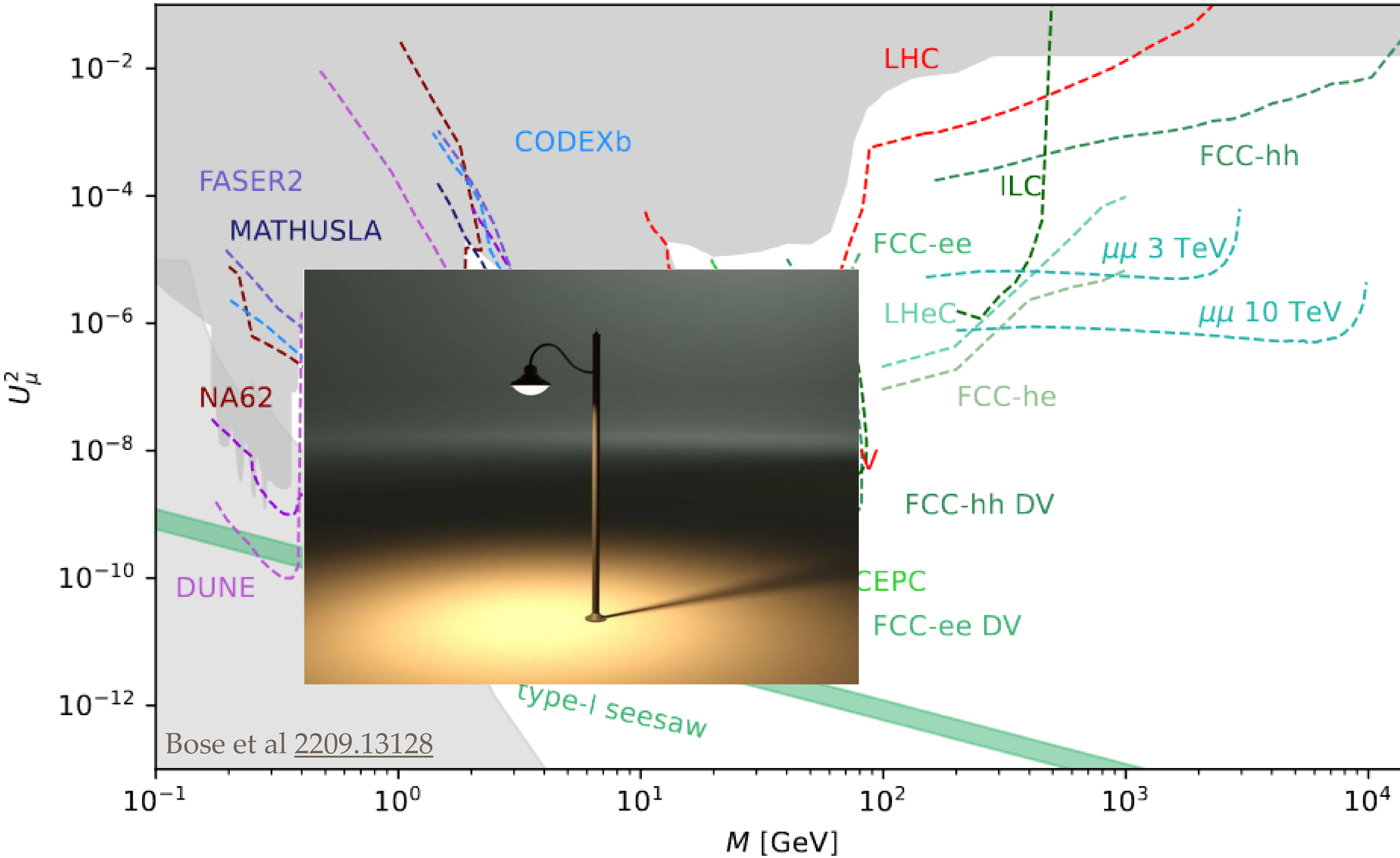
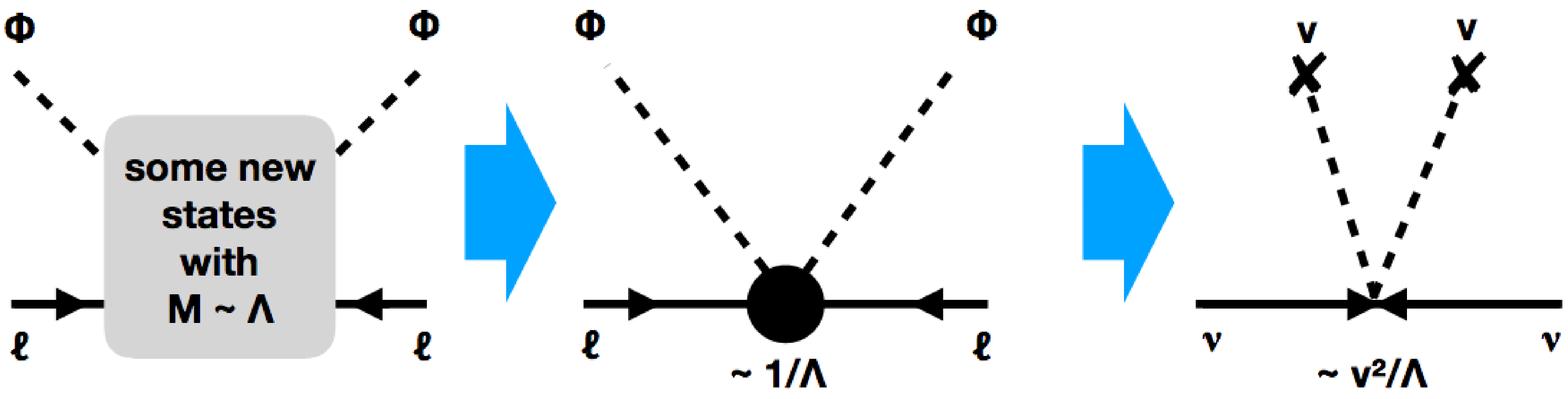


Why are the Neutrino masses small?



High Scale Seesaw: $\Lambda \gg v$

$$\frac{1}{2}\overline{\ell_L}\tilde{\Phi}c^{[5]}\Lambda^{-1}\tilde{\Phi}^T\ell_L^c \quad \xrightarrow{\Phi \to (0,v)^T} \quad \frac{1}{2}\overline{\nu_L}m_\nu\nu_L^c$$

with

$$m_\nu = -v^2 c^{[5]}\Lambda^{-1}$$

Why are the Neutrino masses small?

$$\frac{1}{2}\overline{\ell_L}\tilde{\Phi}c^{[5]}\Lambda^{-1}\tilde{\Phi}^T\ell_L^c + h.c. \qquad m_\nu = -v^2 c^{[5]}\Lambda^{-1}$$

a) Suppression by heavy scale (classic high scale seesaw mechanism)

- Smallness is result of $v/\Lambda \ll 1$
- Wilson coefficients $c_{[n]}$ can be O[1]
- Need no small numbers…
- …but contribute to hierarchy problem (unless SUSY or so added
- …can destabilises Higgs potential

b) Small numbers

- Smallness is result of small Wilson coefficients $c_{[n]}$
- Generally considered "tuned" unless smallness has a reason (breaking of symmetry by flavons, radiative breaking, gravitational origin…)

c) Protecting symmetry

- Ratio v/Λ and Wilson coefficients $c_{[n]}$ can both be O[1] if a flavour symmetry in m_v keeps the eigenvalues small
- Prime example: Approximate global $U(1)_{B-L}$, as in SM
- Low Λ and large couplings $c_{[n]}$ ideal for experimental searches!

section 5.1 in 2102.12143

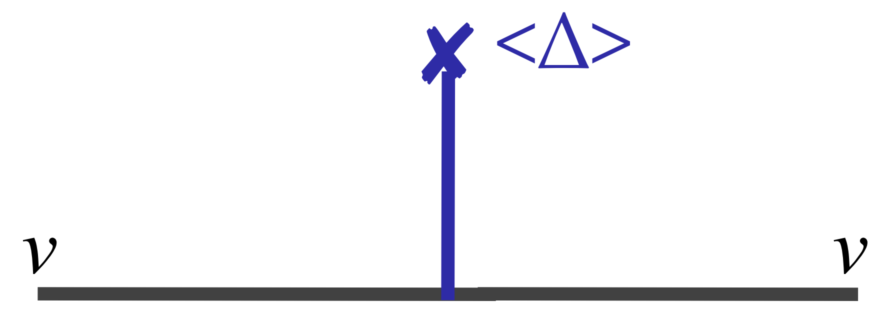
Tree Level Seesaw Mechanisms

- **Type I: right handed neutrino**

$$\overline{\ell_L} Y_{\rm I} \nu_R \tilde{\Phi}$$

- **Type II: scalar triplet Δ**

$$\overline{\ell_L^c} Y_{\rm II} {\rm i}\sigma_2 \Delta \ell_L$$



- **Type III: fermonic triplet Σ**

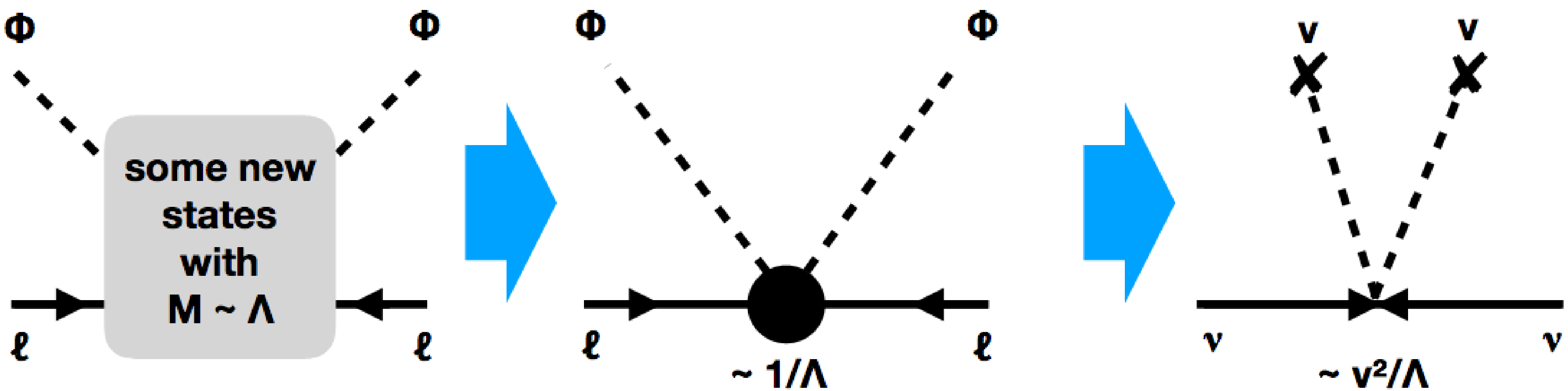
$$\overline{\ell_L} Y_{\rm III} \Sigma_L^c \tilde{\Phi}$$

$$m_\nu^{\rm I} = -v^2 Y_{\rm I} M_M^{-1} Y_{\rm I}^T \qquad \Lambda \sim (M_M)_{11} \qquad c_{ab}^{[5]} = (Y_{\rm I})_{a1}(Y_{\rm I})_{b1}$$

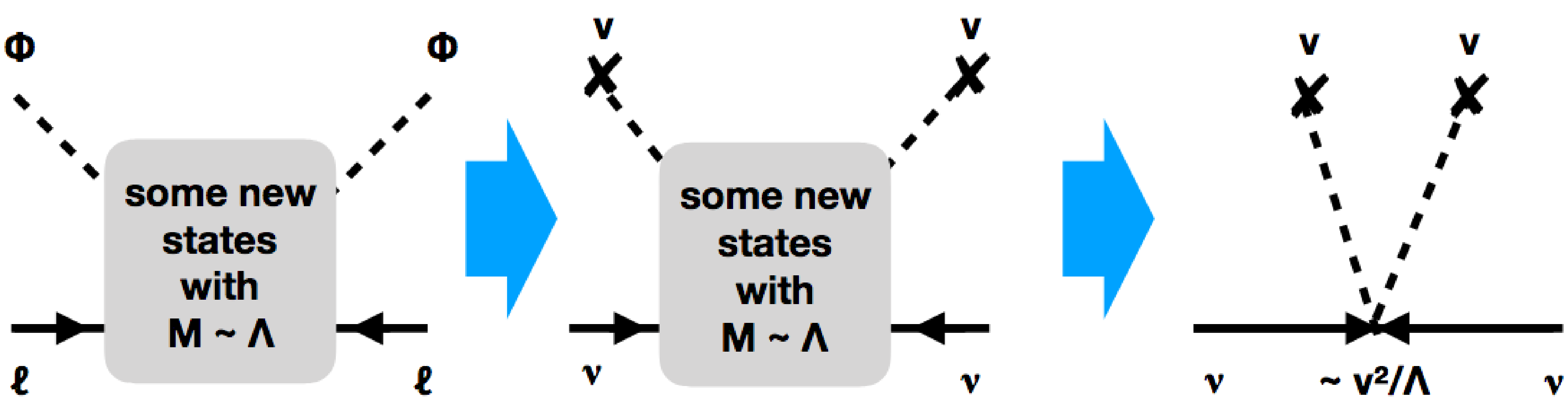
$$m_\nu^{\rm II} = -\sqrt{2} Y_{\rm II} v_\Delta \qquad \Lambda \sim M_\Delta \qquad c_{ab}^{[5]} = (Y_{\rm II})_{ab}\kappa / M_\Delta$$

$$m_\nu^{\rm III} = -\frac{1}{2} v^2 Y_{\rm III} M_\Sigma^{-1} Y_{\rm III}^T \qquad \Lambda \sim (M_\Sigma)_{11} \qquad 2c_{ab}^{[5]} = (Y_{\rm III})_{a1}(Y_{\rm III})_{b1}.$$

Low Scale and High Scale Seesaw Models

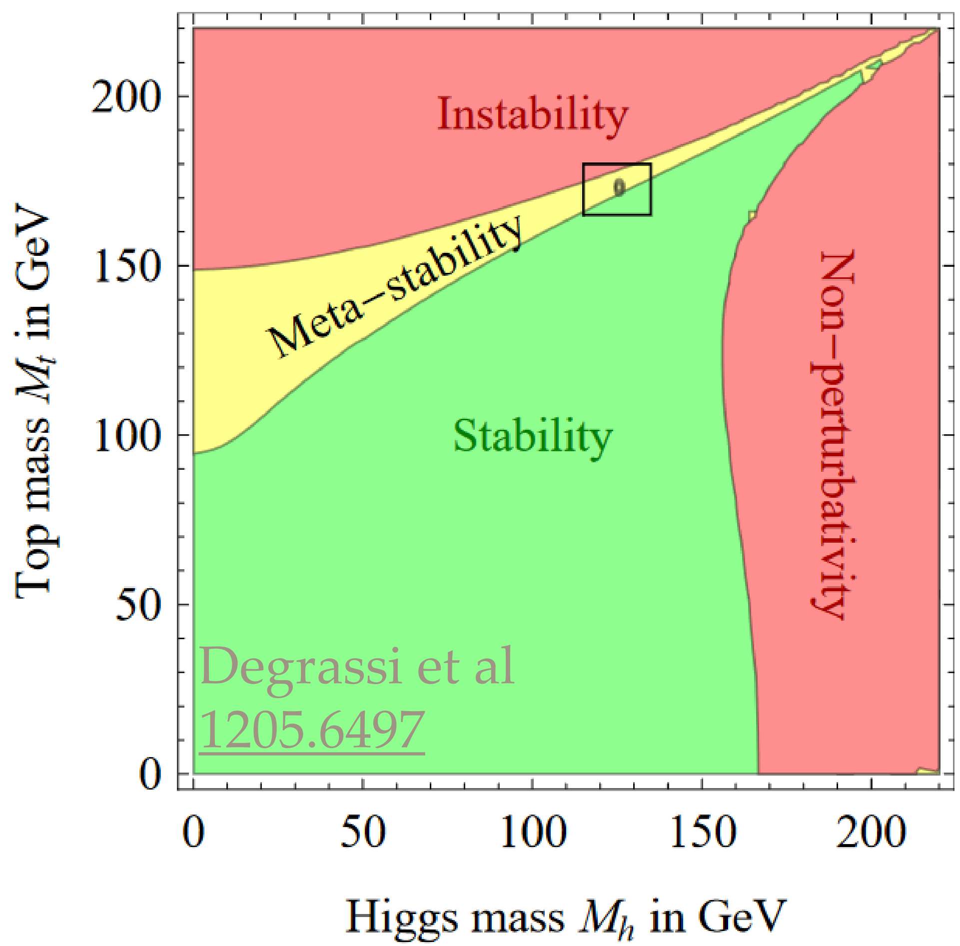


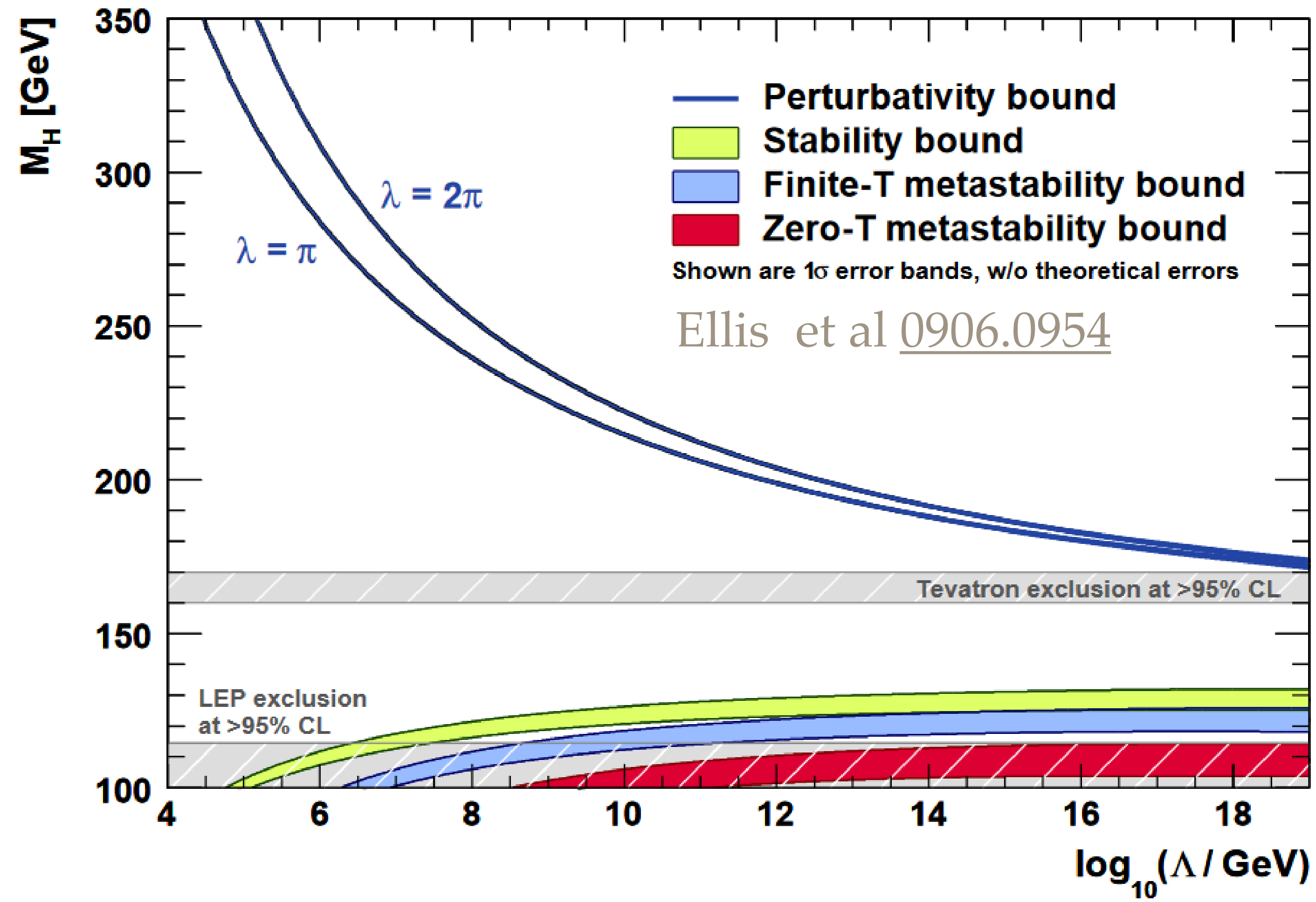
High Scale Seesaw: $\Lambda \gg v$



Low Scale Seesaw: $\Lambda \lesssim v$

Why should the seesaw scale be low?





- Apart from explaining data extremely well, the SM is also a fully consistent effective field theory up to the Planck scale
- Existence of new scales in between would spoil this and e.g. de-stabilise the vacuum (though this can of course in principle be fixed, as in SUSY)
- Together with current experimental bounds (e.g. flavour physics etc) this may be interpreted as indirect evidence for absence of a new scale!?!

e.g. Bezrukov et al 1205.2893

Symmetries in the Type I Model

Why are the Neutrino masses small?

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Minimal vs Non-minimal Scenarios

To classify models we distinguish

- Seesaw scale $\Lambda = M$
- Scale of all other new particles $\tilde{\Lambda} > M$

minimal = literally only add RH neutrinos

- generic EFT description of models with $M <$ TeV $\ll \tilde{\Lambda}$
- can even be UV complete in the sense $\tilde{\Lambda} = M_P$
- … or at least up to the scale of inflation e.g. Bezrukov et al 1205.2893

non-minimal = anything else (gauge extensions, extended scalar sector, RHN as "portal" to dark sector…) See talk by Martin Hirsch

- can use generic EFT description for models with $M <$ TeV $< \tilde{\Lambda}$
- need full dark sector description if $M, \tilde{\Lambda} <$ TeV
- Common gauge-extensions: Left-right symmetric model, gauged $U(1)_{B-L}$

I will assume $M < TeV \ll \tilde{\Lambda}$ throughout this talk

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B-L Symmetric Limit

- 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

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

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

Explains mass degeneracy favourable for leptogenesis

***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 structure in SM flavours

B-L Symmetry protected Scenarios

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- Technically natural seesaw with O[1] Yukawas and M < TeV
- Resonant enhancement in leptogenesis comes for free due to μ << 1
- Possible realisations:
  - **Inverse-seesaw-like** ε, ε′ << μ << 1 — Mohapatra 86, Mohapatra /Valle 86, …
  - **Linear-seesaw-like** μ << ε, ε′ << 1 — Akhmedov/Lindner/Schnapka/Valle 95
  - **νMSM-like** : ε, ε′, μ << 1 — Asaka/Shaposhnikov 05
  - **"mass communism"**: μ << 1 and M′ → M

section 5.1 in 2102.12143

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 to protect neutrino masses, but other than that no assumptions about flavour structure/texture

Symmetry-based approach:

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

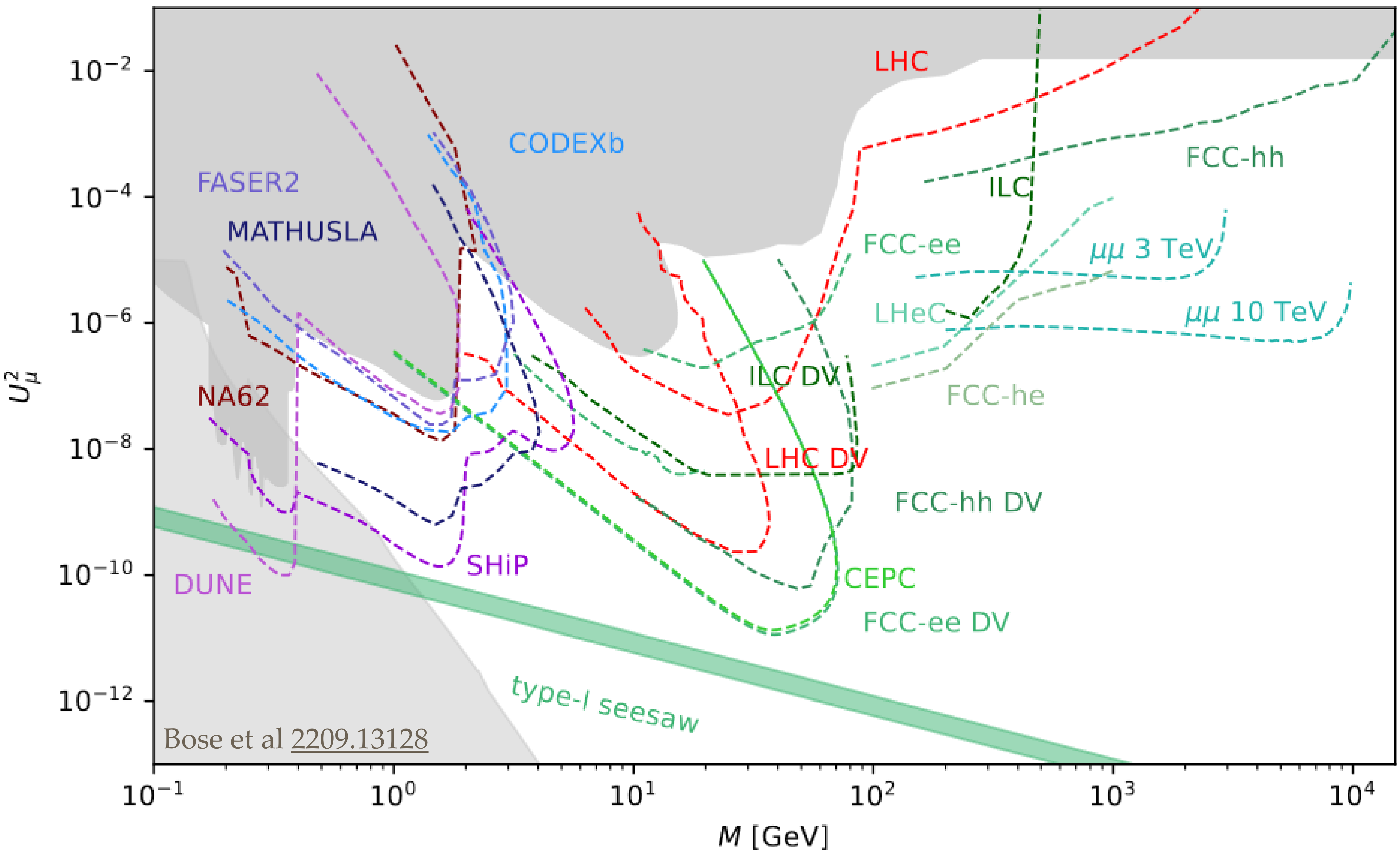
  See e.g. King 1701.04413, Xing 1909.09610,

- We consider groups $\Delta(3n^2)$ and $\Delta(6n^2)$ with CP symmetry Hagedorn et al 1408.7118
  - Model with three degenerate HNLs and six parameters M, y_1, y_2, y_3, θ_R, θ_L
  - Two parameters κ, λ break mass degeneracy
  - Discrete parameters describe implementation of symmetry group in three cases, namely (n,s), (n,s,t), (n,m,s)
- Symmetries reduce parameter space, make the model more testable

  MaD/Georis/Hagedorn/Klaric 2203.08538, 2xxx.xxxxx

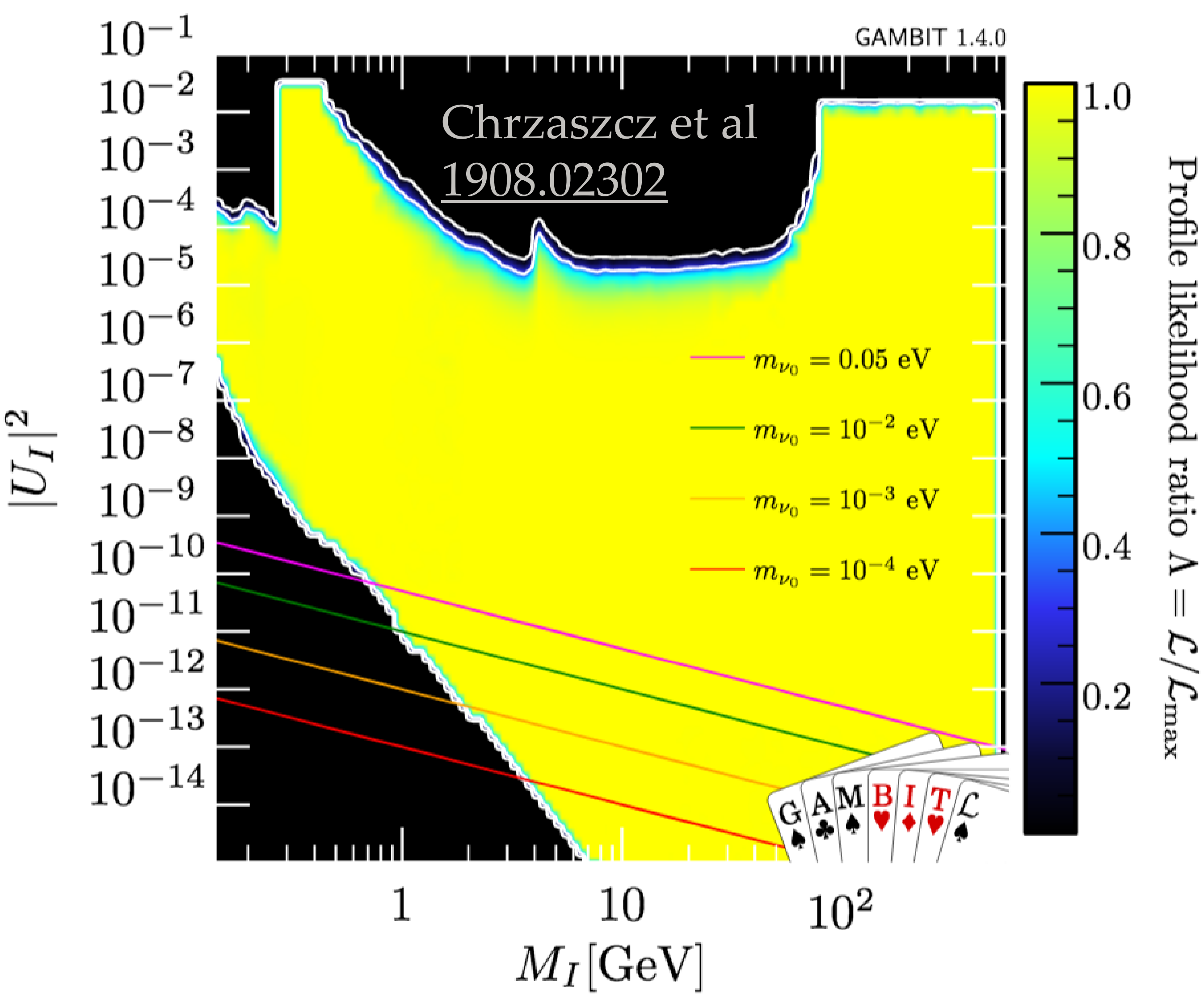
HNL Properties

Range of Mixings



Lower Limits on the Mixings

- The **Seesaw line** is indicates the lower bound on the mixing from the requirement to explain the light neutrino masses
- In general there is no lower bound on the mixing between individual flavours of light and heavy neutrinos



- For three HNLs is a lower bound on

$$U_i^2 = \sum_a U_{ai}^2 > \frac{m_{\text{lightest}}}{M_i}$$

MaD 1904.11959

- For 2 HNLs there are also lower bounds on

$$U_\alpha^2 = \sum_i U_{\alpha i}^2$$

MaD/Garbrecht/Gueter/Klaric 1609.09069

- For mass-degenerate HNLs

$$U^2 = \sum_i U_i^2 > \frac{\sum_i m_i}{M}$$

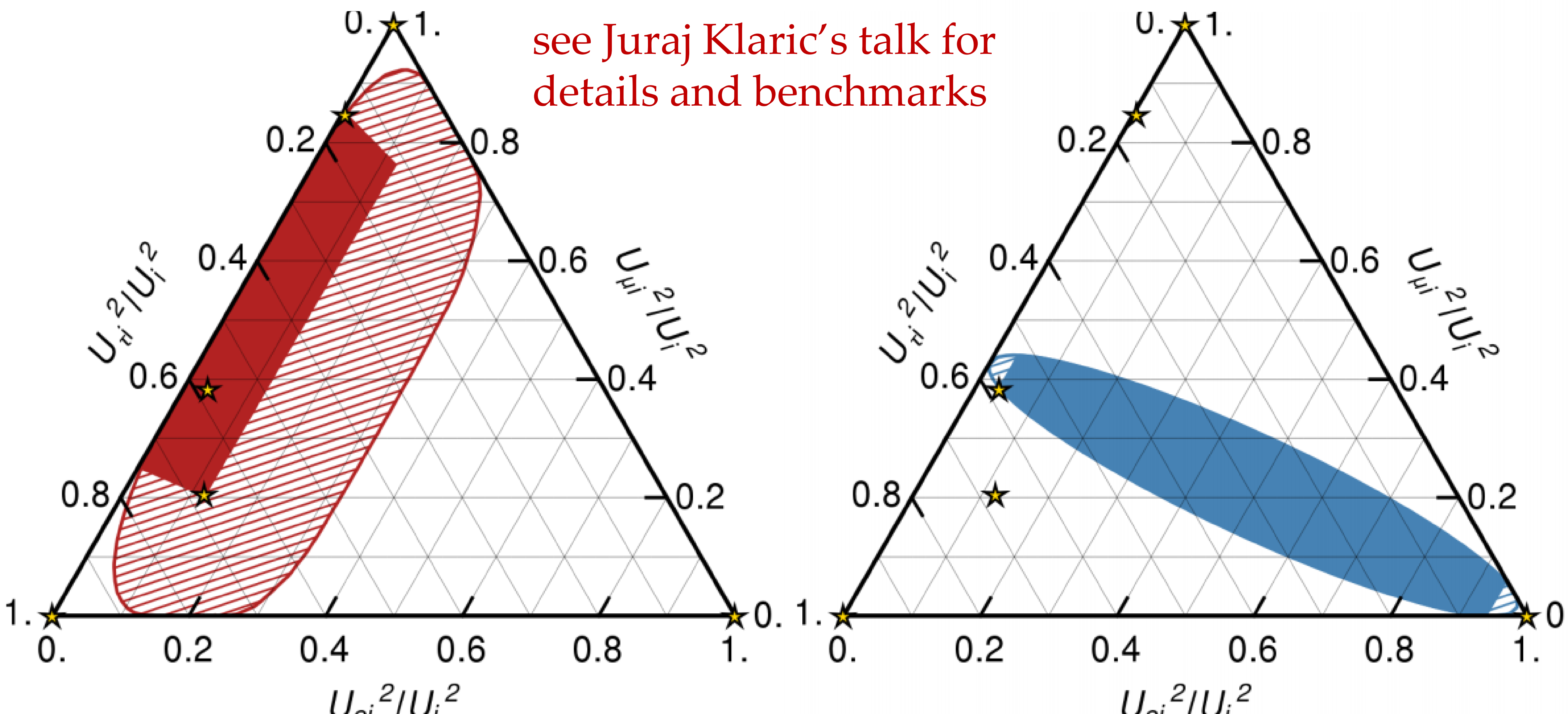
Varying lightest neutrino mass gives "seesaw band" used in Snowmass plots

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

- νMSM-like scenario: flavour mixing pattern is strongly constrained: important for experimental sensitivity 1606.06719, 1609.09069, 1704.08721, 1801.04207

$U_{\alpha i}^2 = |\theta_{\alpha i}|^2$ $U_\alpha^2 = \sum_i U_{\alpha i}^2$ $U_i^2 = \sum_\alpha U_{\alpha i}^2$

see Juraj Klaric's talk for details and benchmarks



plot from 1801.04207

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

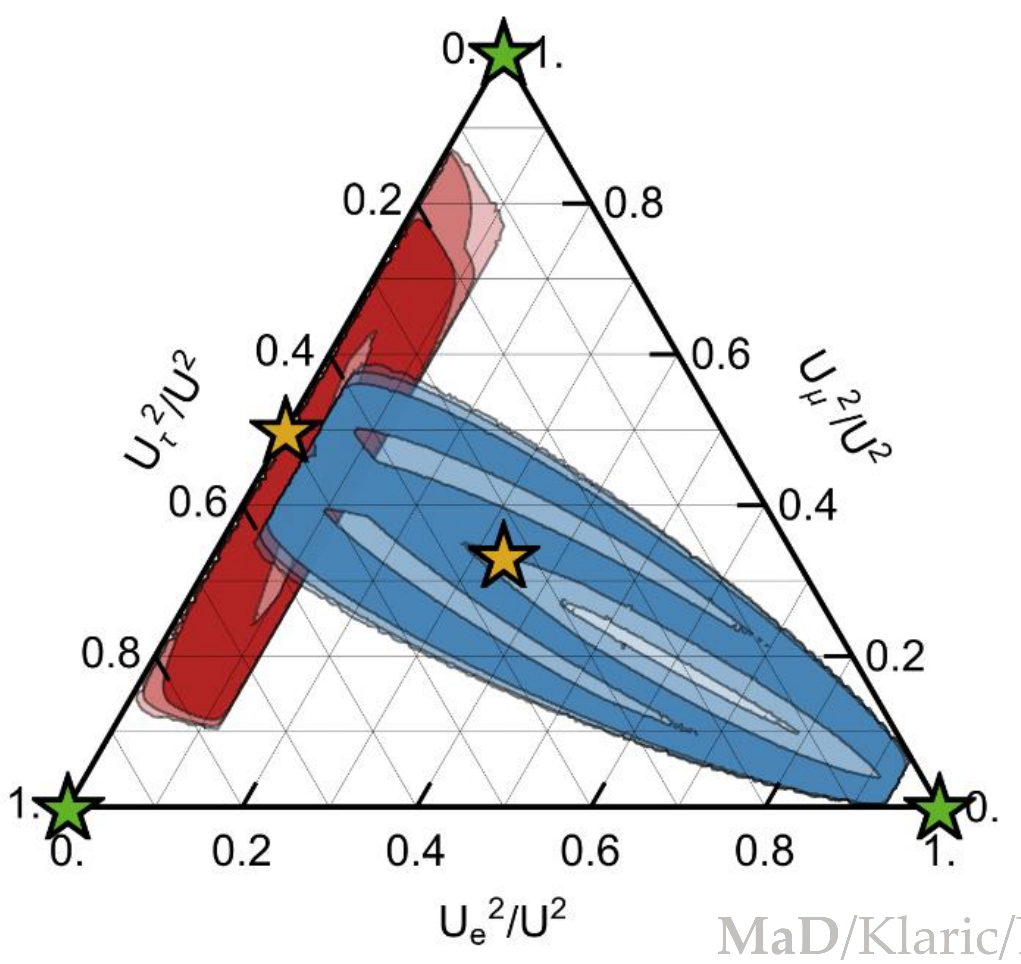
Majorana Phases

- Position in the triangle is basically given by parameters in PMNS

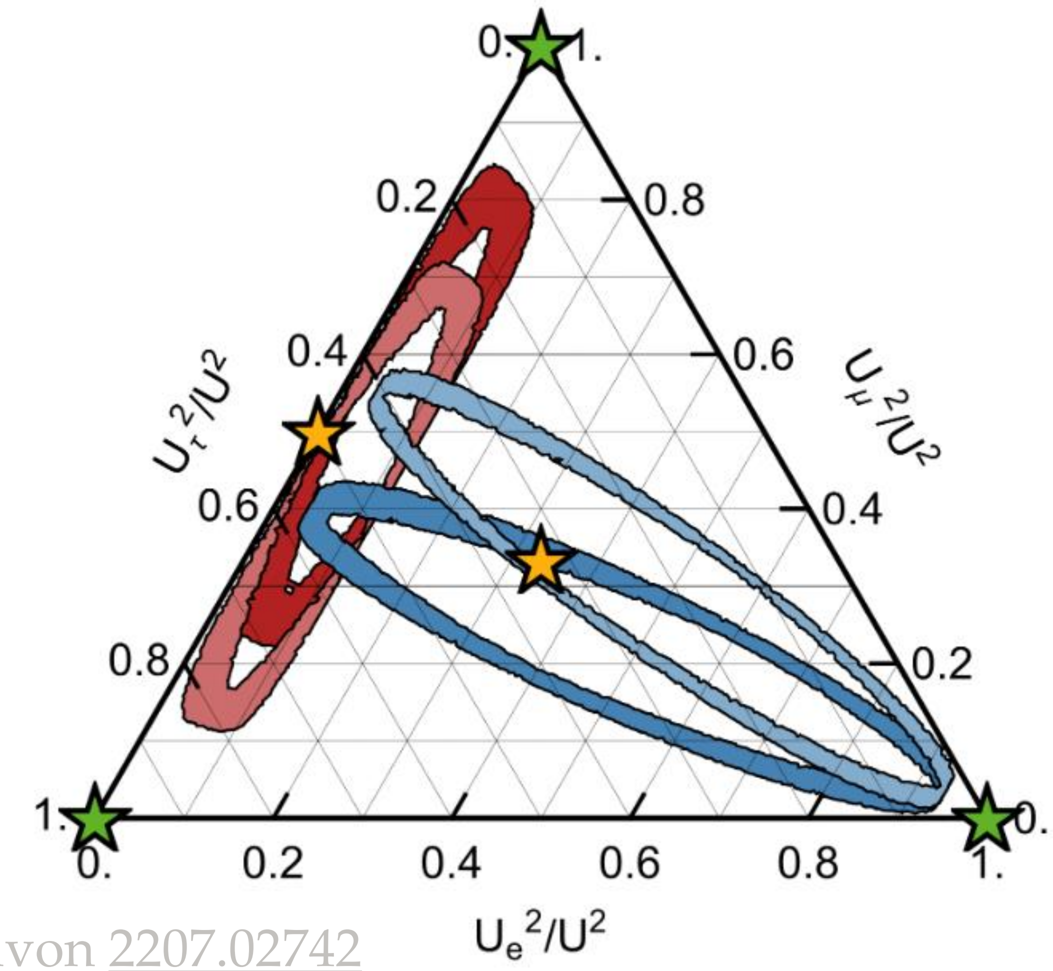
Hernandez et al 1606.06719 MaD et al 1609.09069

- After measuring Dirac phase at DUNE of HyperK, Majorana phase is only unknown
- Hence: branching ratios provide indirect probe of Majorana phase

MaD et al 1609.09069 Caputo et al 1611.05000



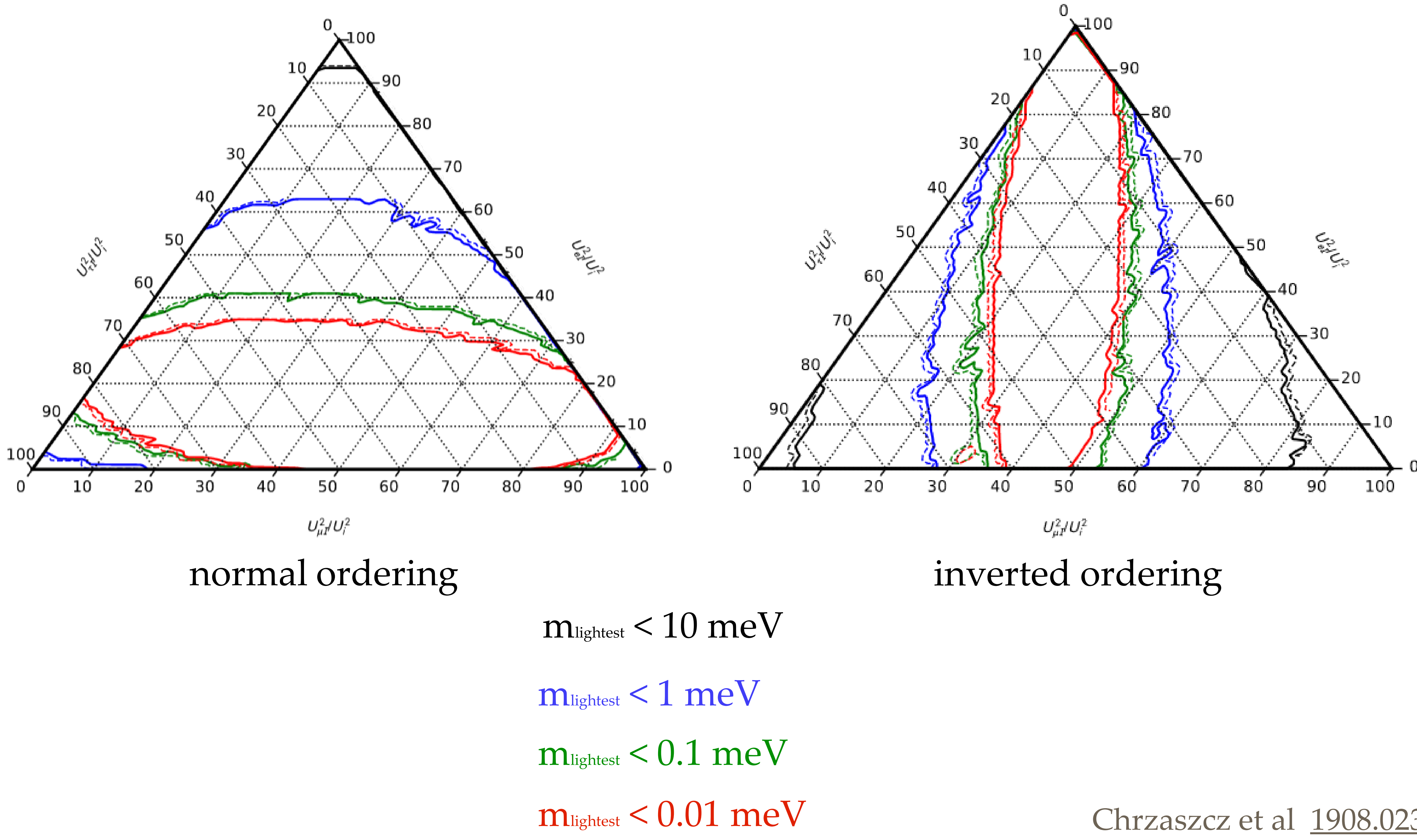
Current constraints



DUNE projection

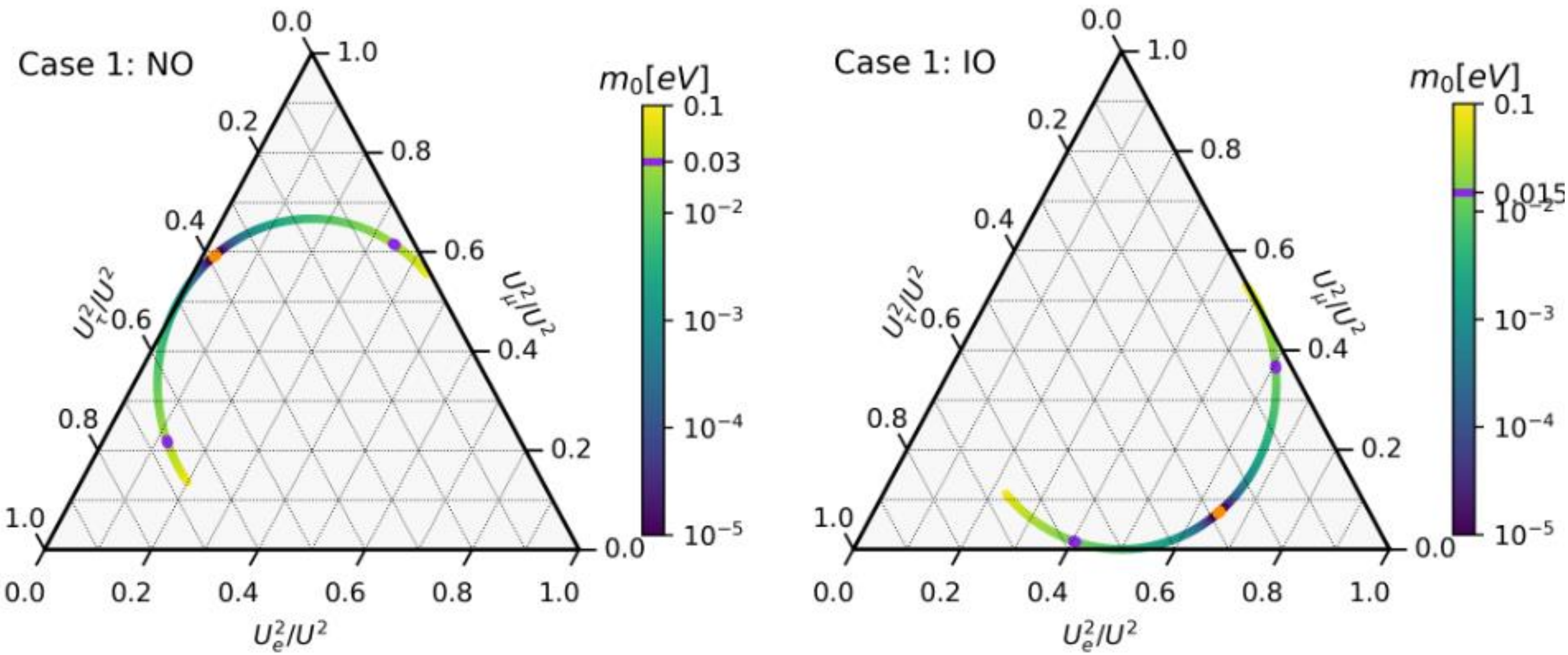
MaD/Klaric/Lopez-Pavon 2207.02742

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



Chrzaszcz et al 1908.02302

Flavour Mixing Pattern with Discrete Symmetries



MaD/Georis/Hagedorn/Klarix 2203.08538, 23xx.xxxxx

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

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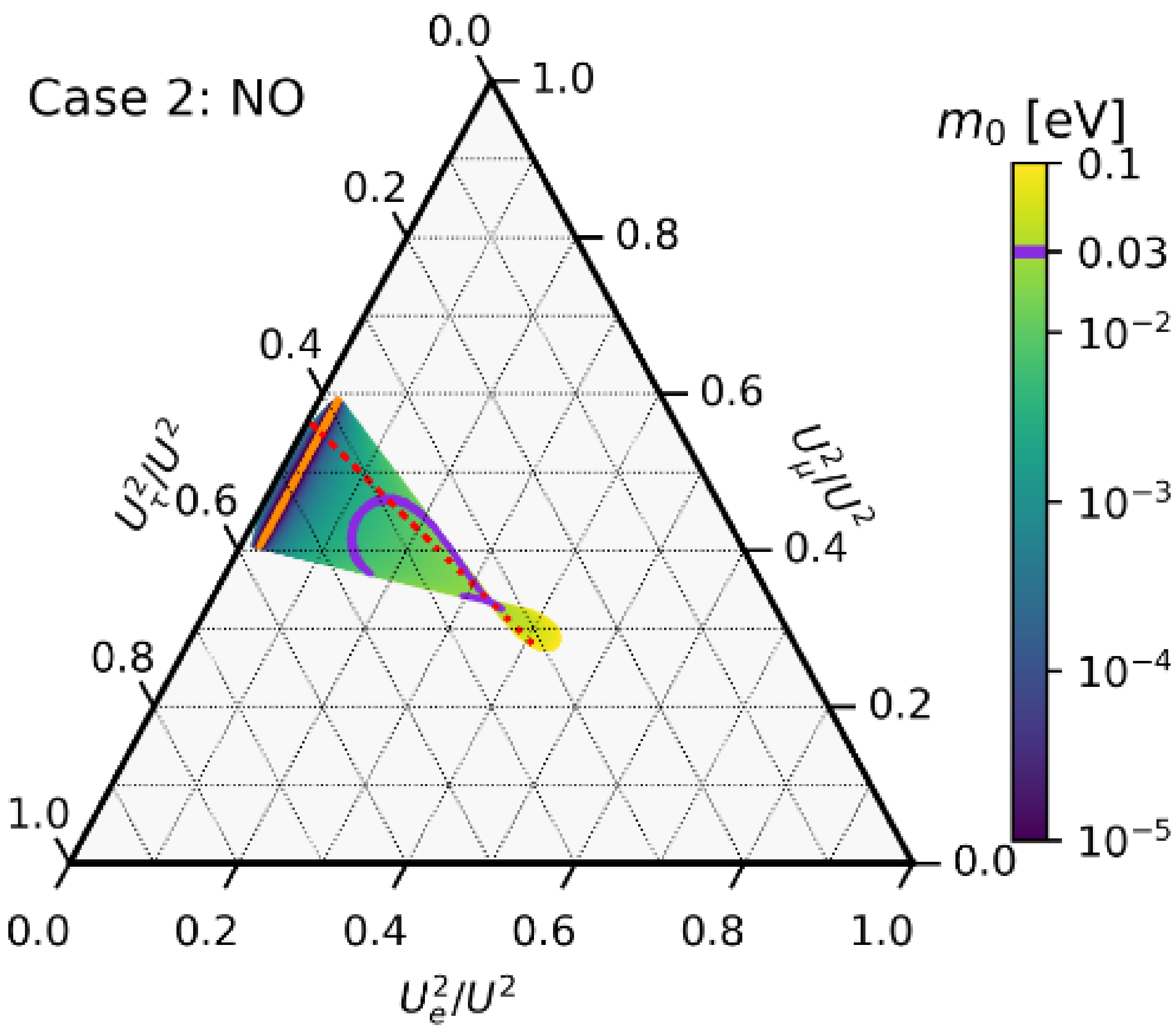

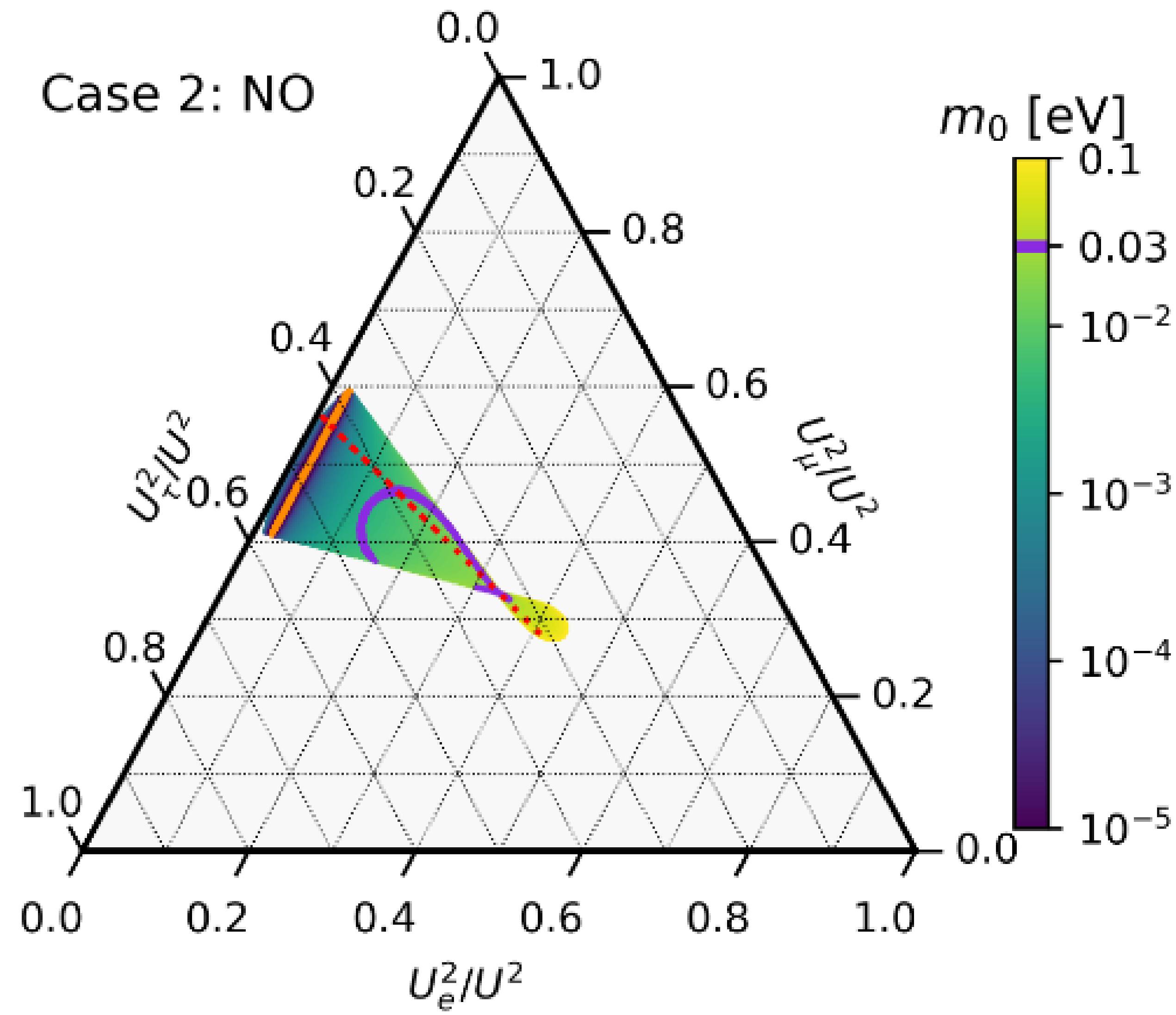

MaD/Georis/Hagedorn/Klarix 2203.08538, 23xx.xxxxx

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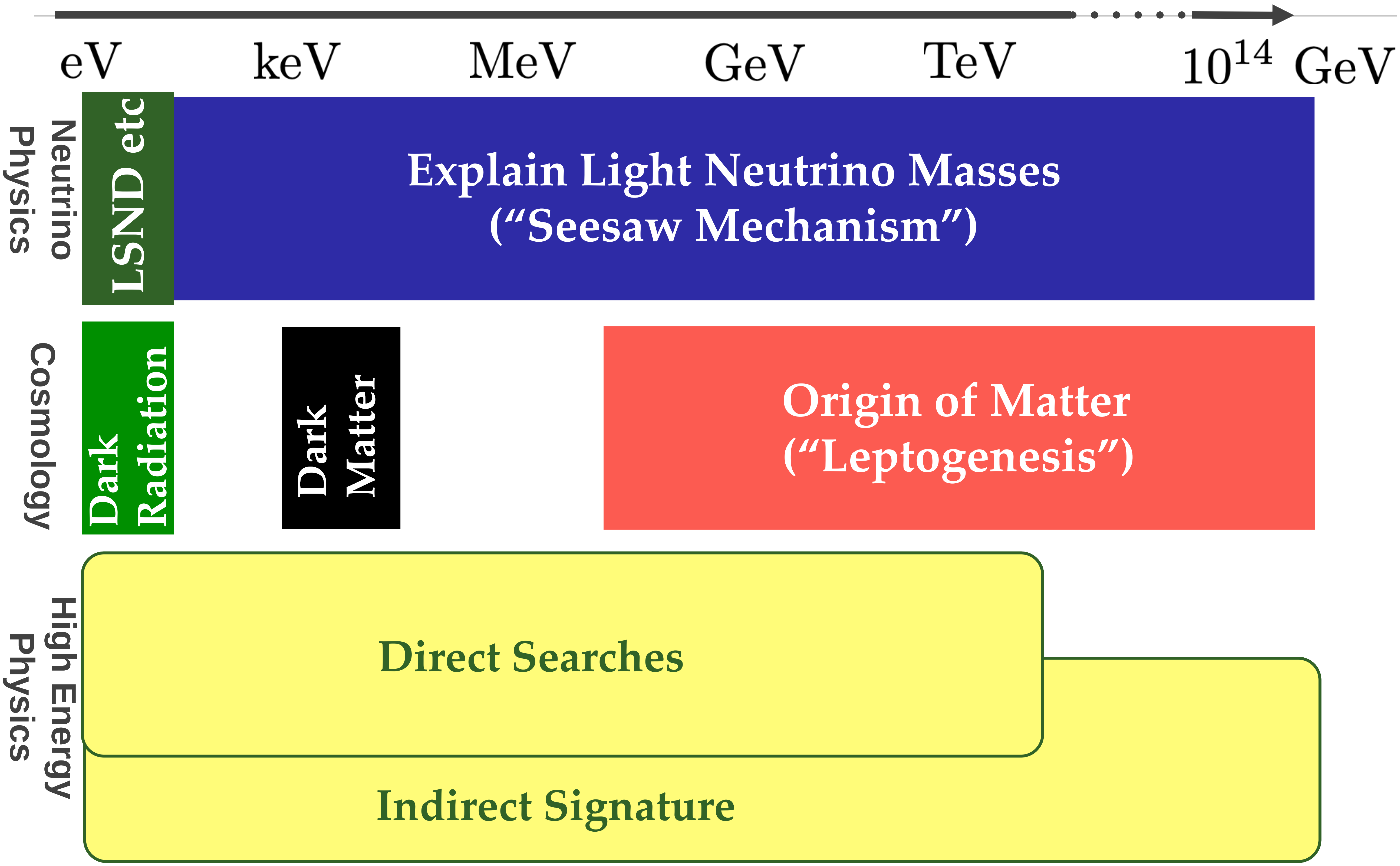
Low Scale Leptogenesis

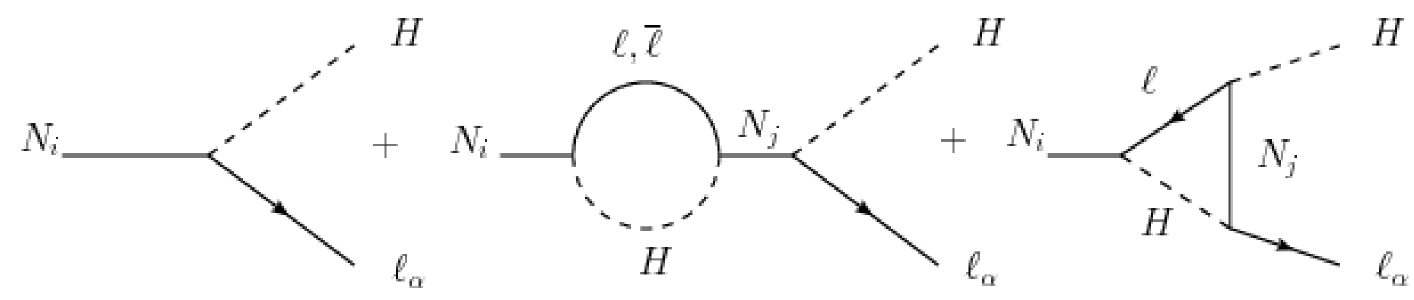
Heavy Neutrino Mass Scale



Leptogenesis as the Origin of Matter

Basic idea Fukugita/Yanagida 86

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

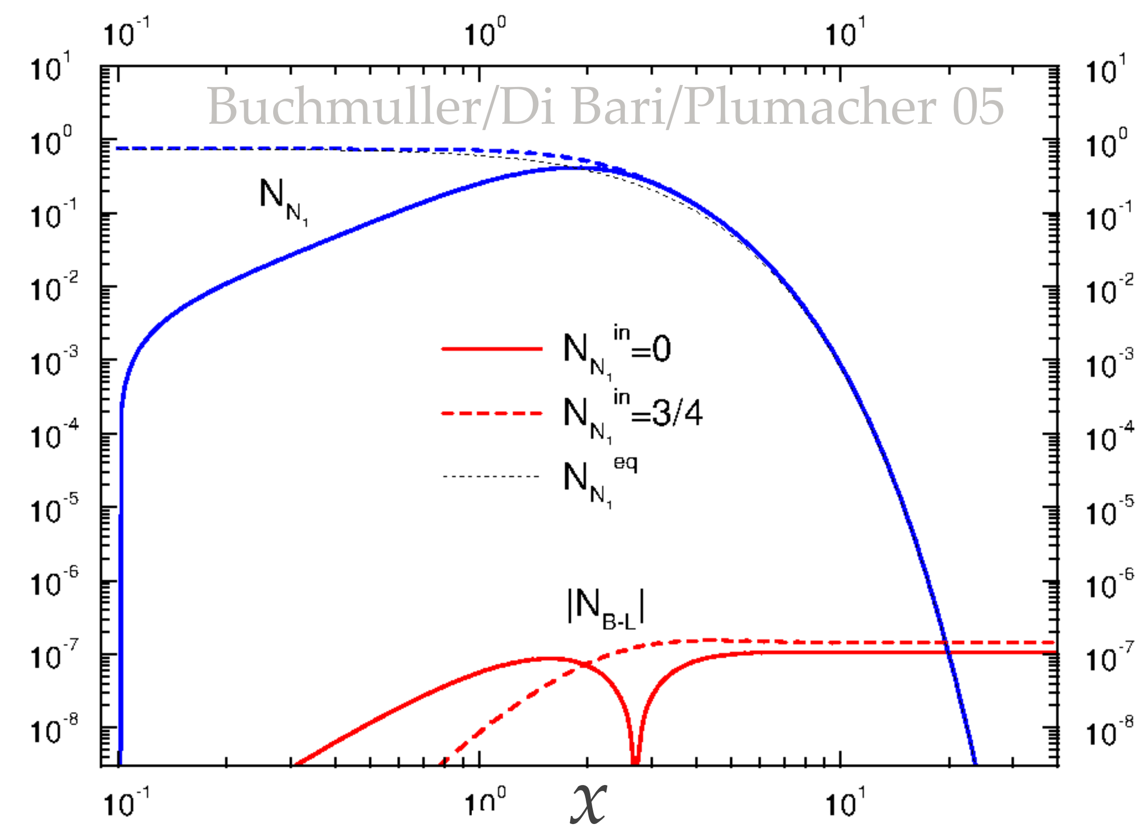


Quantitative description

- Conventionally described by semi-classical Boltzmann equations

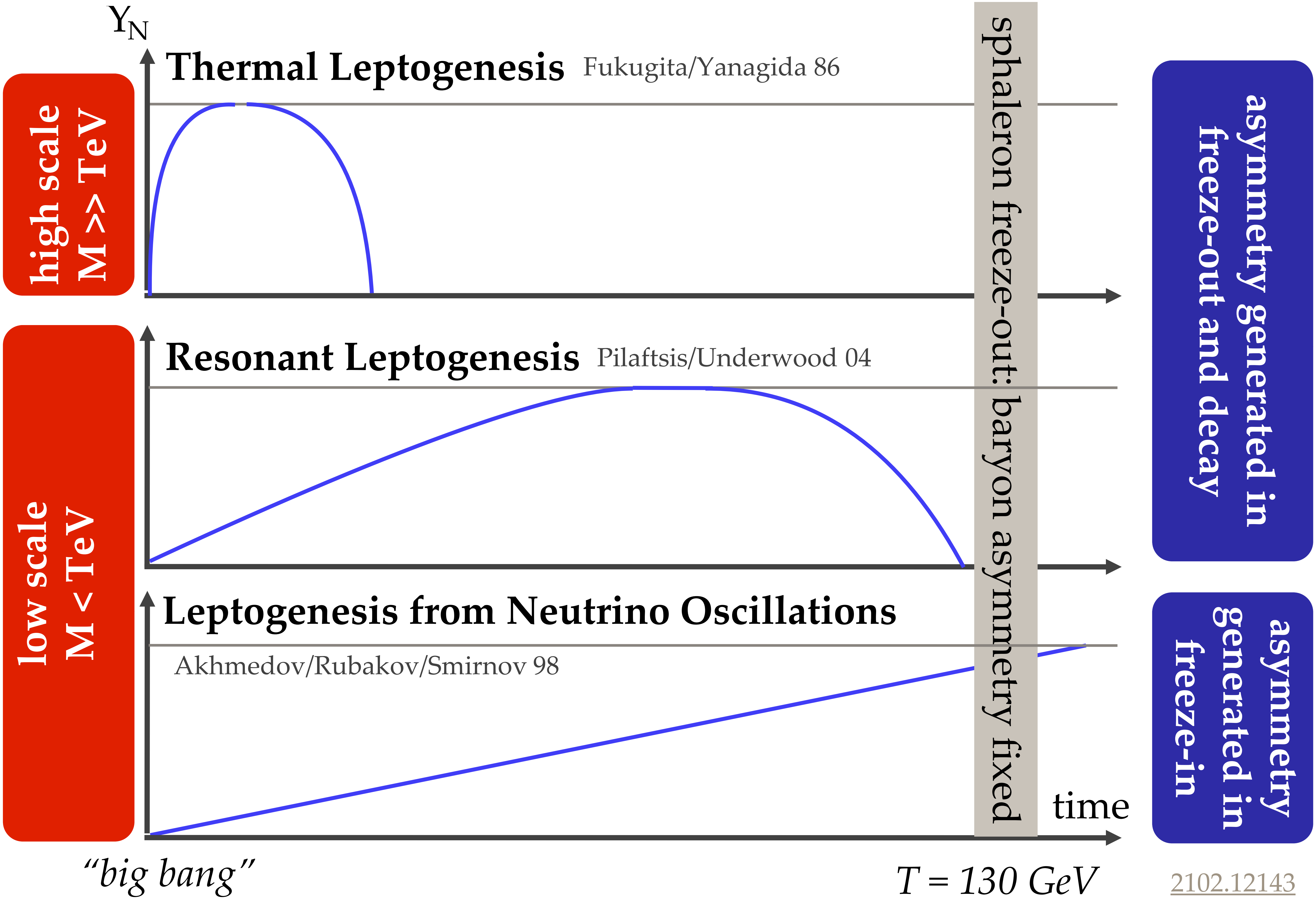
$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

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



- But: asymmetry arises from quantum interference in the plasma
- Low scale leptogenesis: asymmetry generated at M < T, flavour effects are crucial, thermal and quantum corrections can be large
  ⇒ derive quantum kinetic equations from first principles

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



2102.12143

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

Lepton Number Assignment

Symmetry in Lagrangian (protecting m_ν)

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

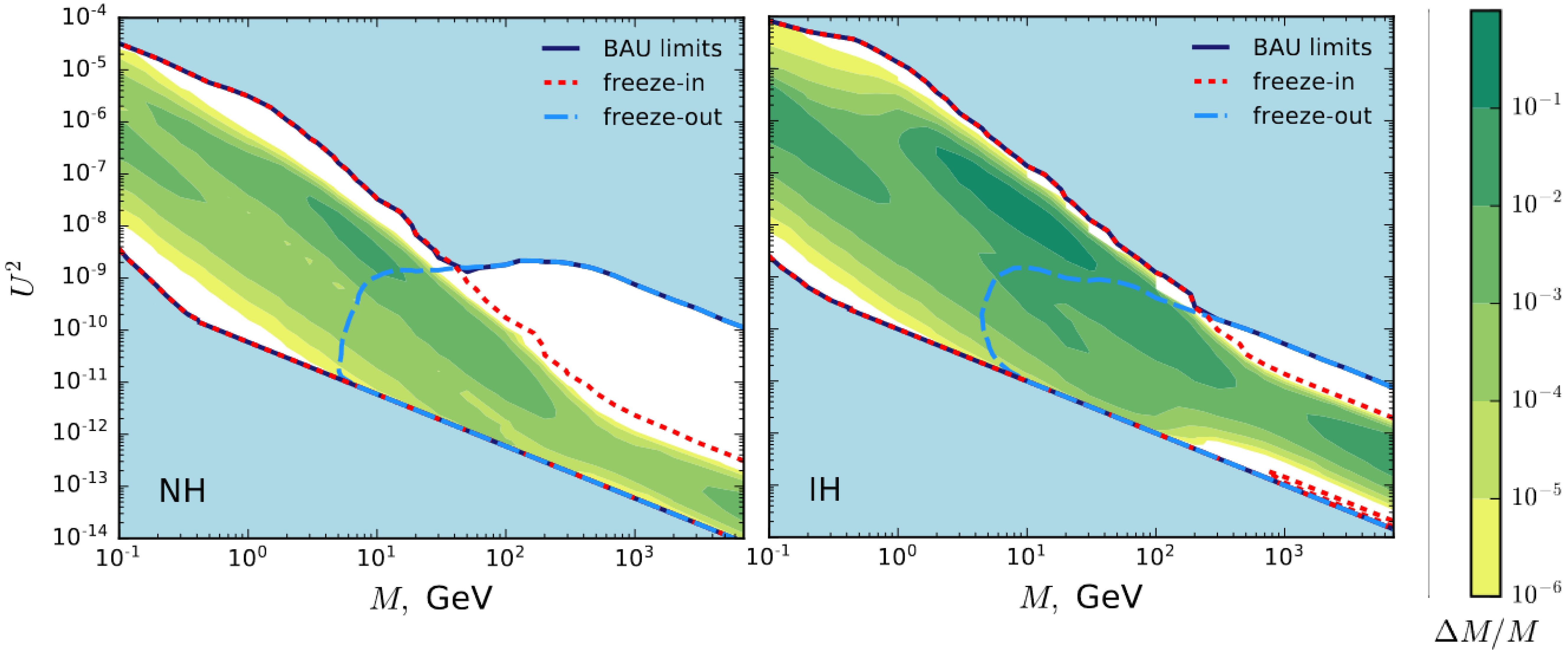
Approx. conserved for $M \ll T$

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

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

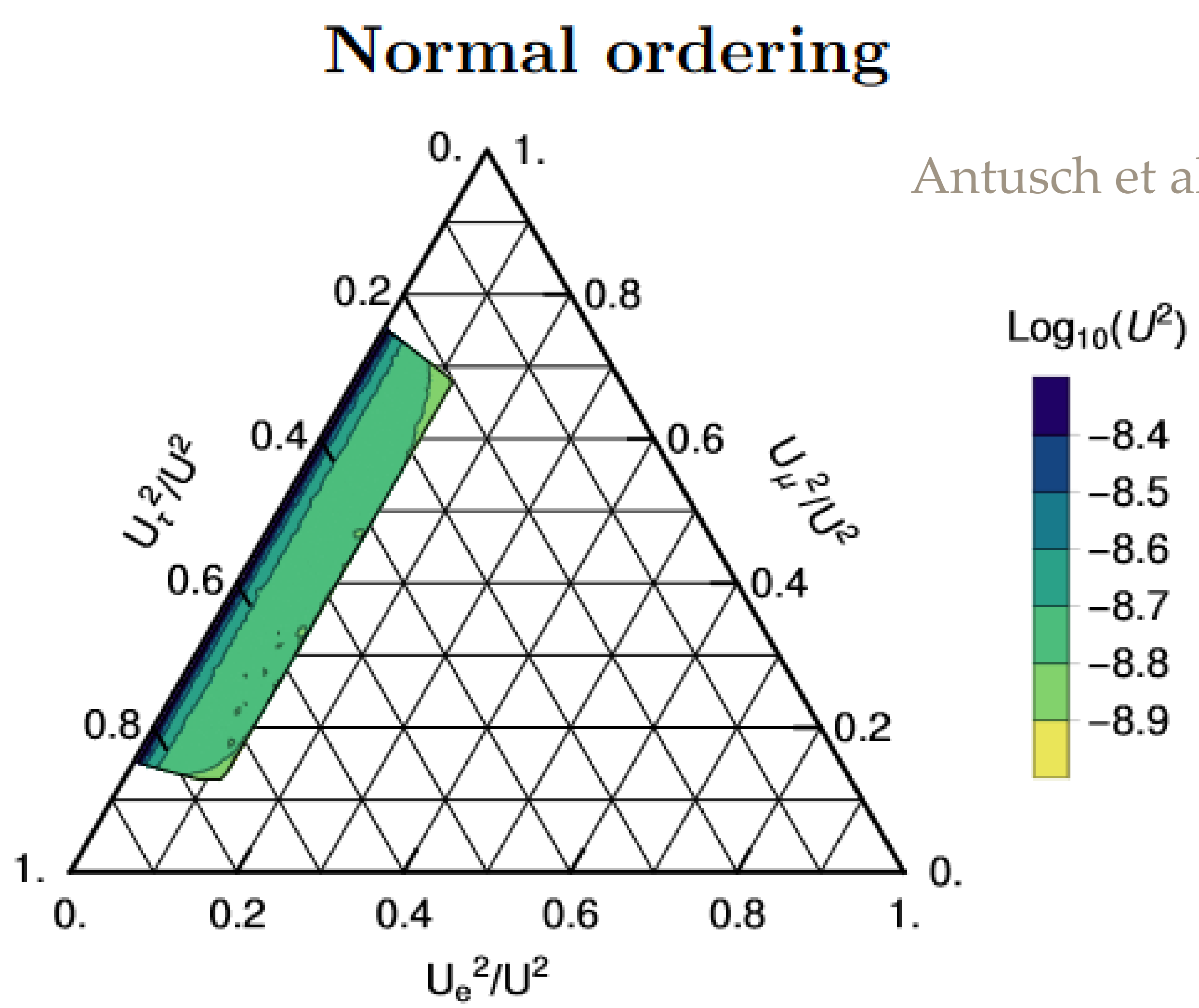
- The approximate lepton number that protects the light neutrino masses is strongly violated by HNL oscillations in the early universe
- HNL oscillations can also induce LNV in the detector, see Juraj Klaric's talk
- But another generalised lepton number (related to HNL helicities) in conserved for high temperatures ($T \gg M$)

Leptogenesis with 2 HNLs

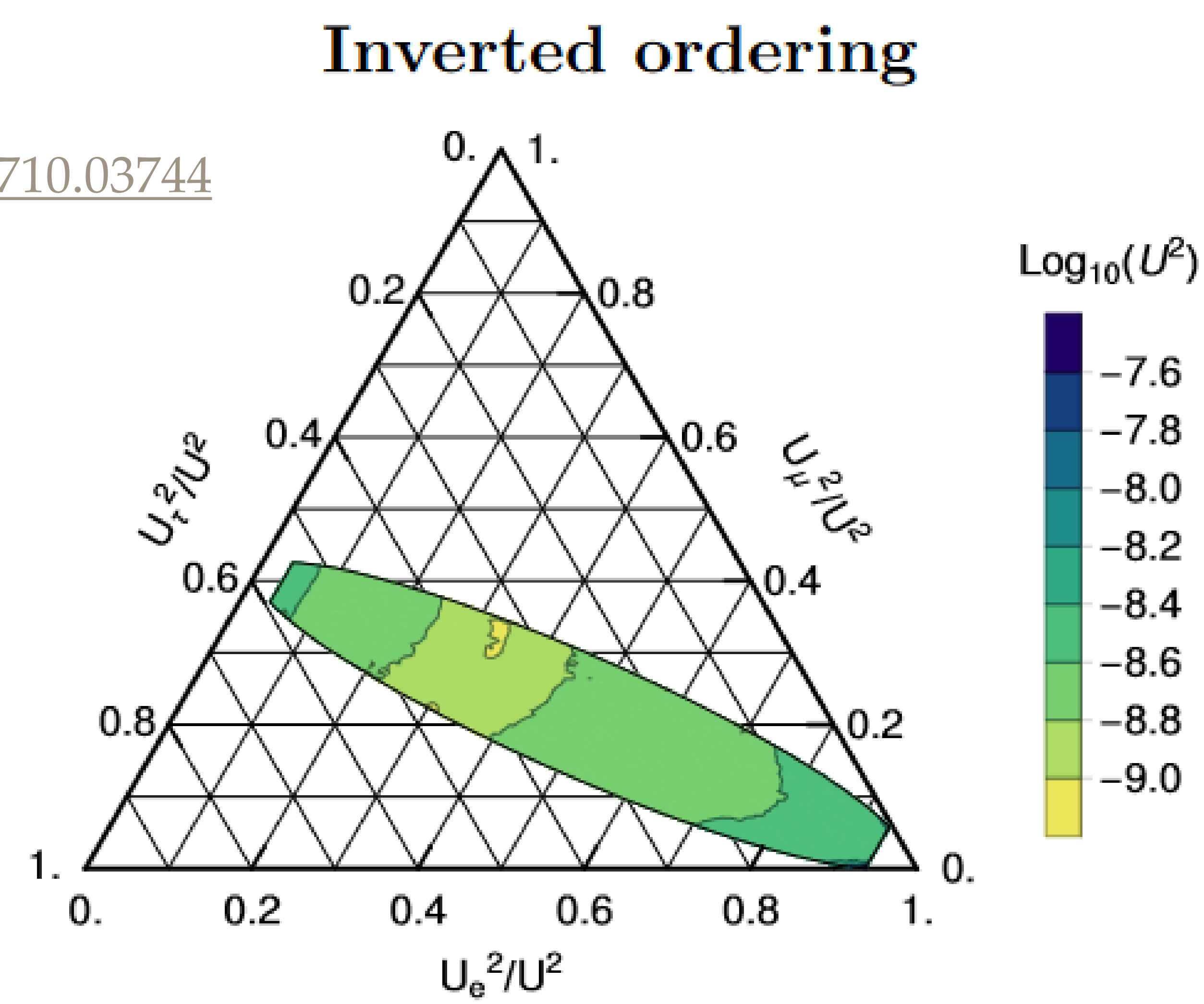


- Minimal # of HNL flavours consistent with ν-oscillations and leptogenesis is two
- This also effectively describes the seesaw mechanism and leptogenesis in the νMSM
- Leptogenesis requires mass degeneracy
- Leptogenesis region only accessible with LLP searches!

Leptogenesis with 2 HNLs

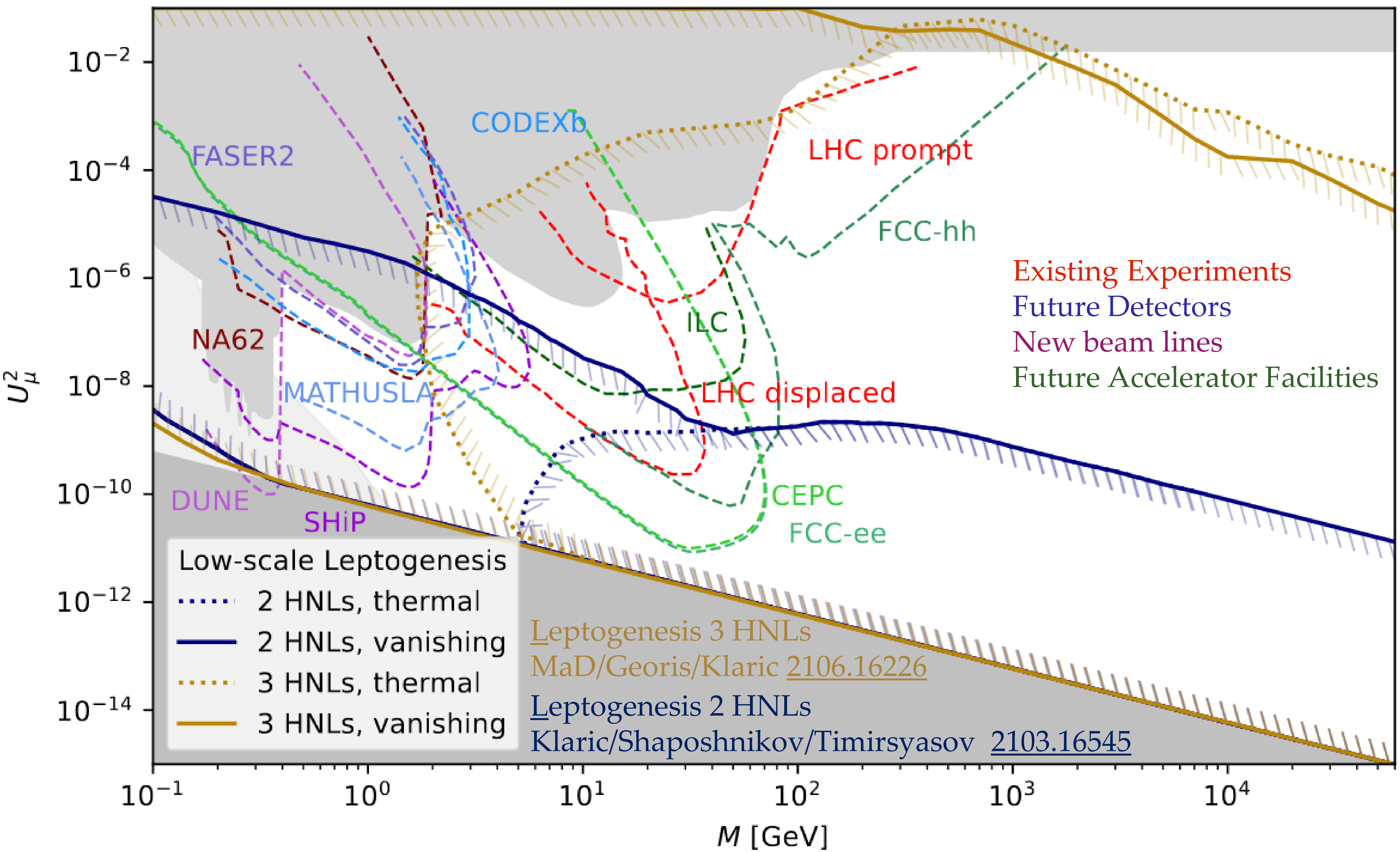


Antusch et al 1710.03744



- Requirement for leptogenesis imposes additional constraints on branching ratios Antusch et al 1710.03744
- Recently confirmed and refined in Hernandez et al 2207.01651

Leptogenesis Parameter Space



Leptogenesis: 2 vs 3 HNL Flavours

Two HNL flavours

- 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

Approx. conserved for $M << T$

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

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

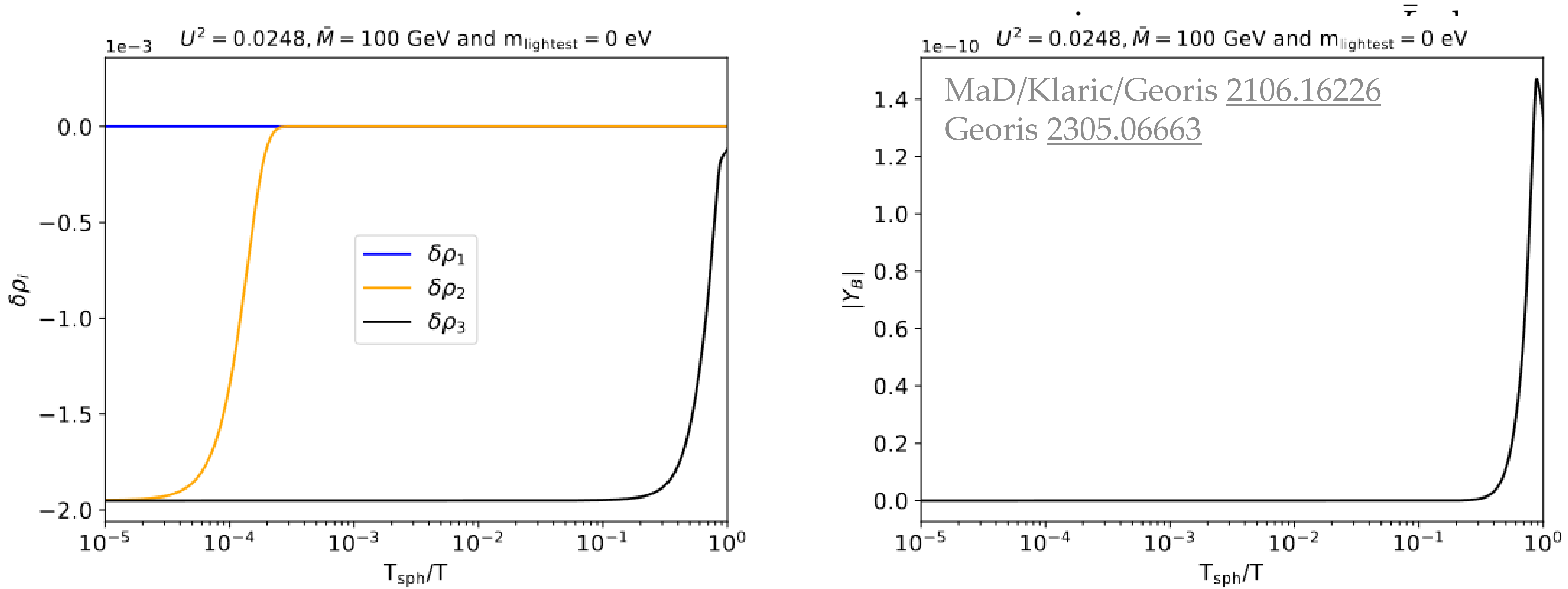
"interaction basis"

Three HNL flavours

- Third state ν_{R3} is free of constraints that relates ν_{Rs} and ν_{Rw}
- It can maintain deviation from equilibrium even when LNV rates come into equilibrium
- void washout even for large couplings of pseudo-Dirac pair
- No need for hierarchy in SM flavour couplings to prevent washout!

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

Maverick Heavy Neutrino



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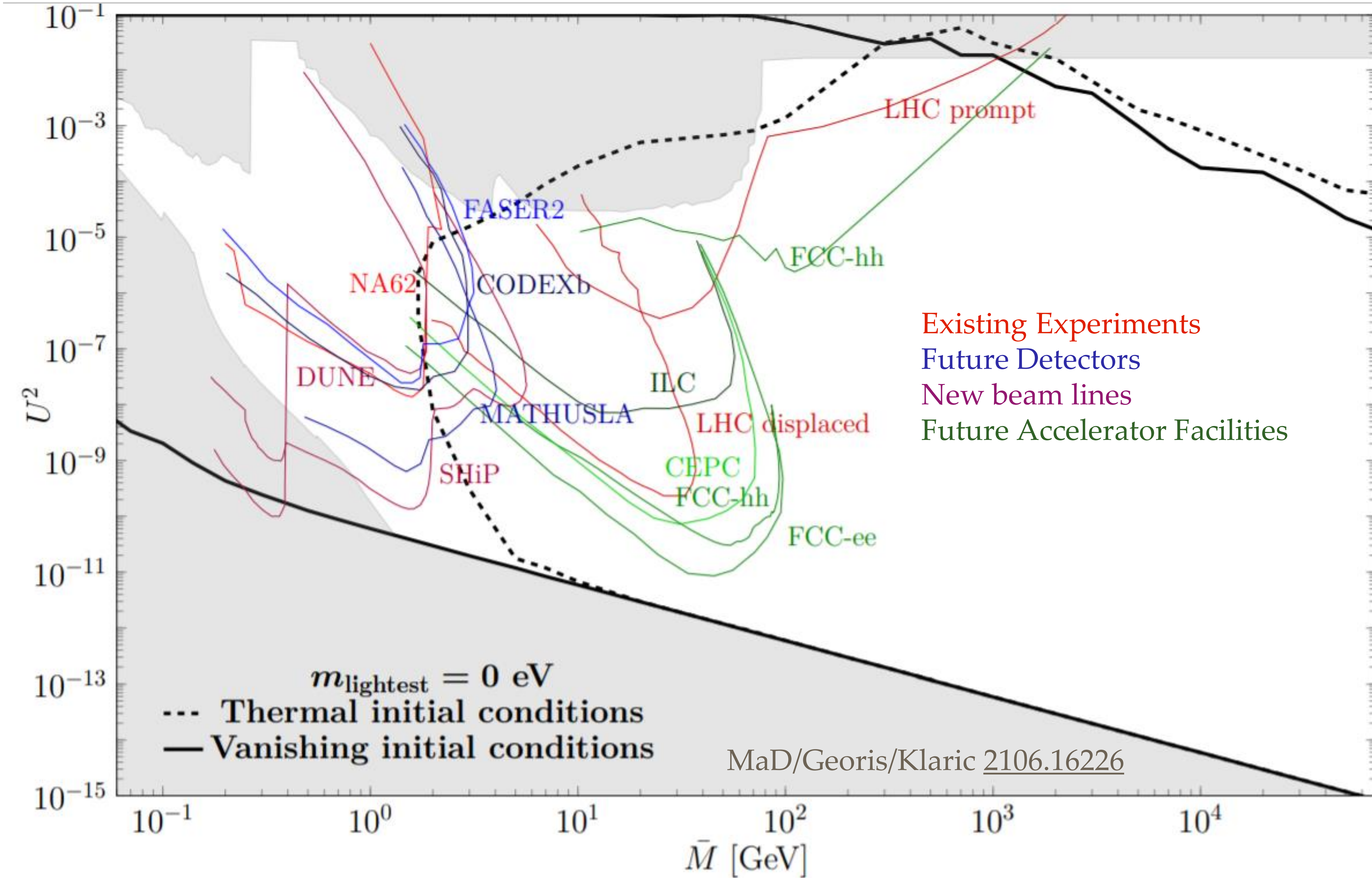
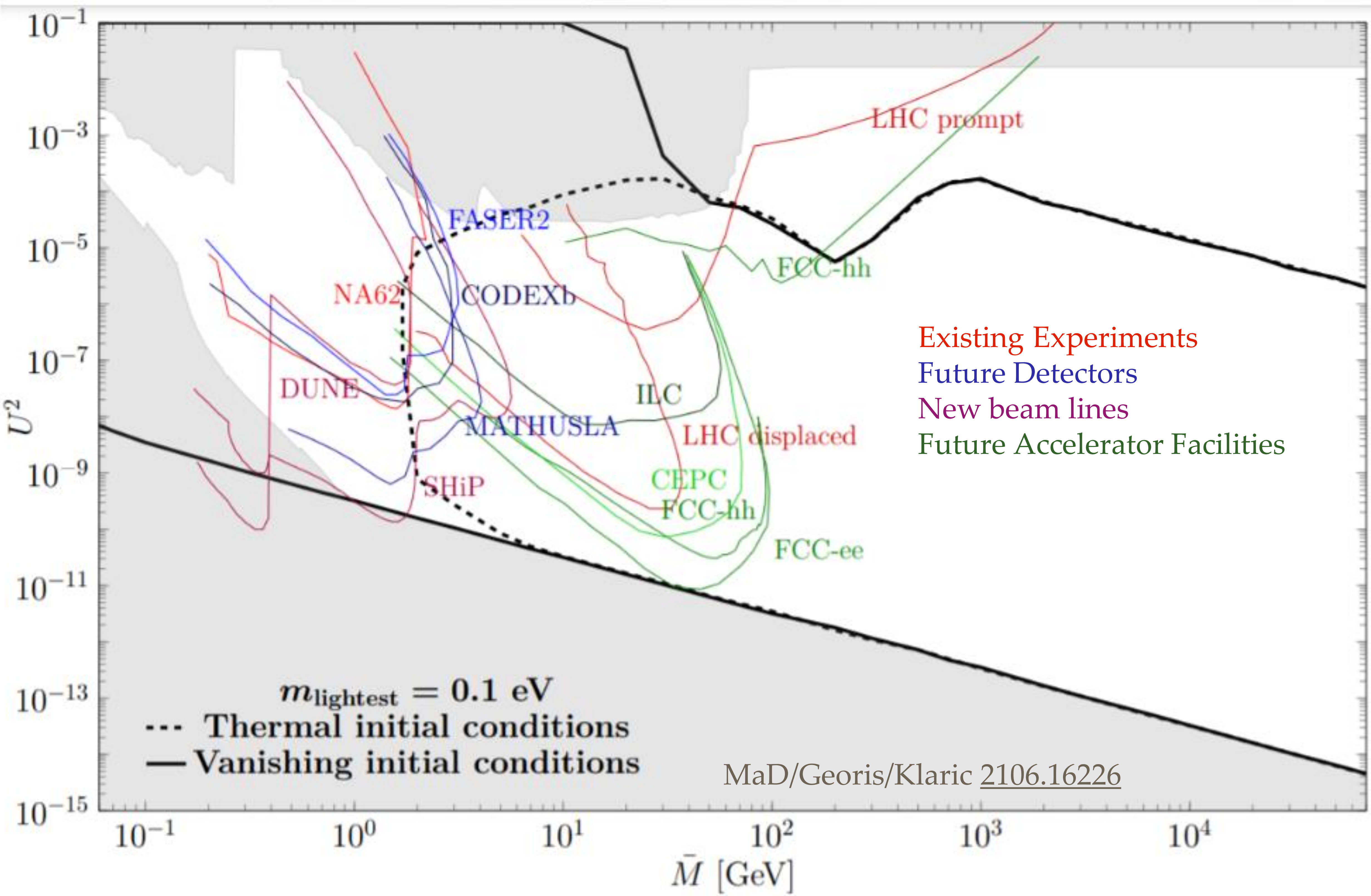
Leptogenesis with 3 RH Neutrinos

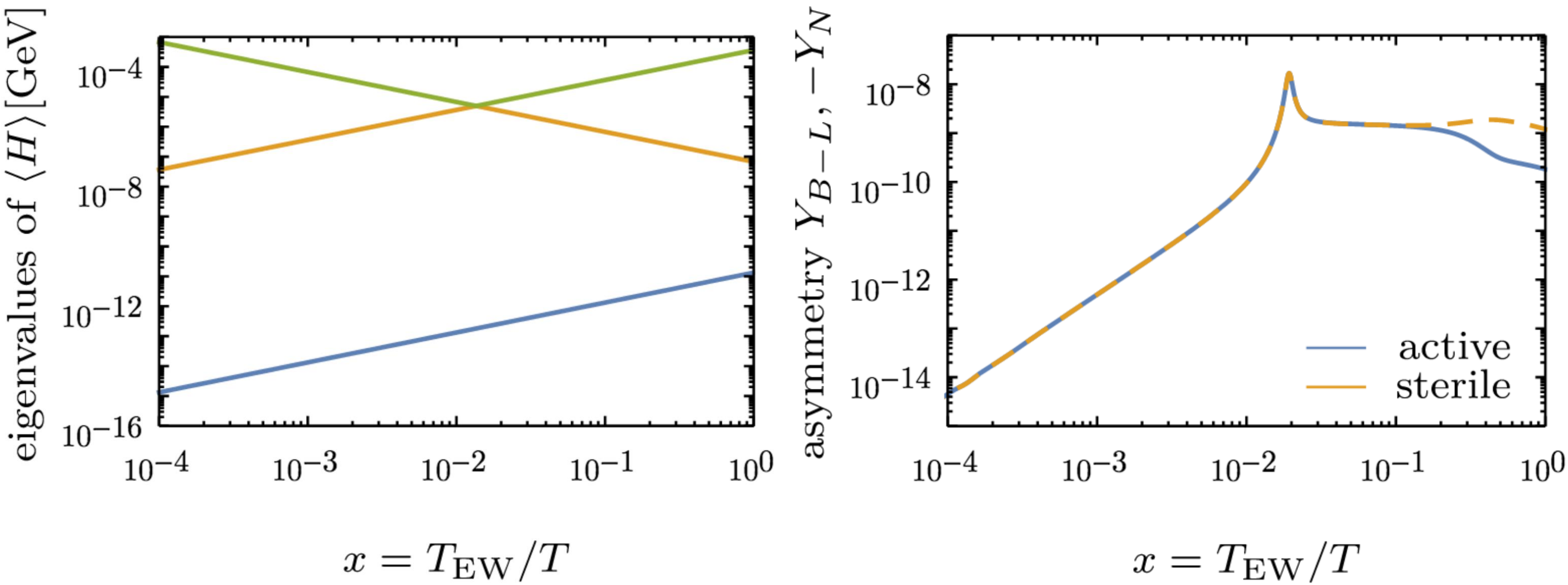


Leptogenesis with 3 RH Neutrinos



MaD/Georis/Klaric 2106.16226

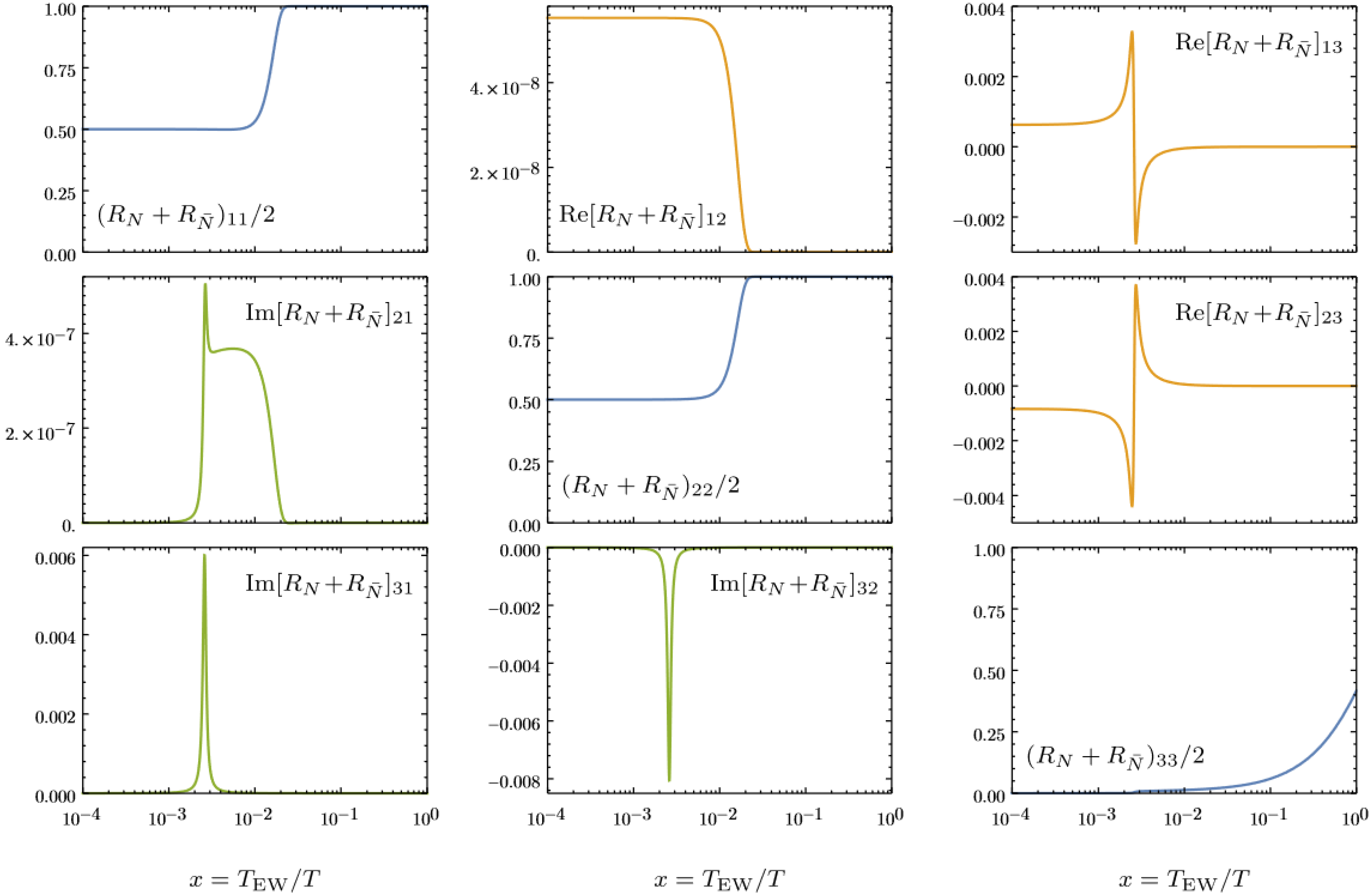
Dynamical Generation of Resonance



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

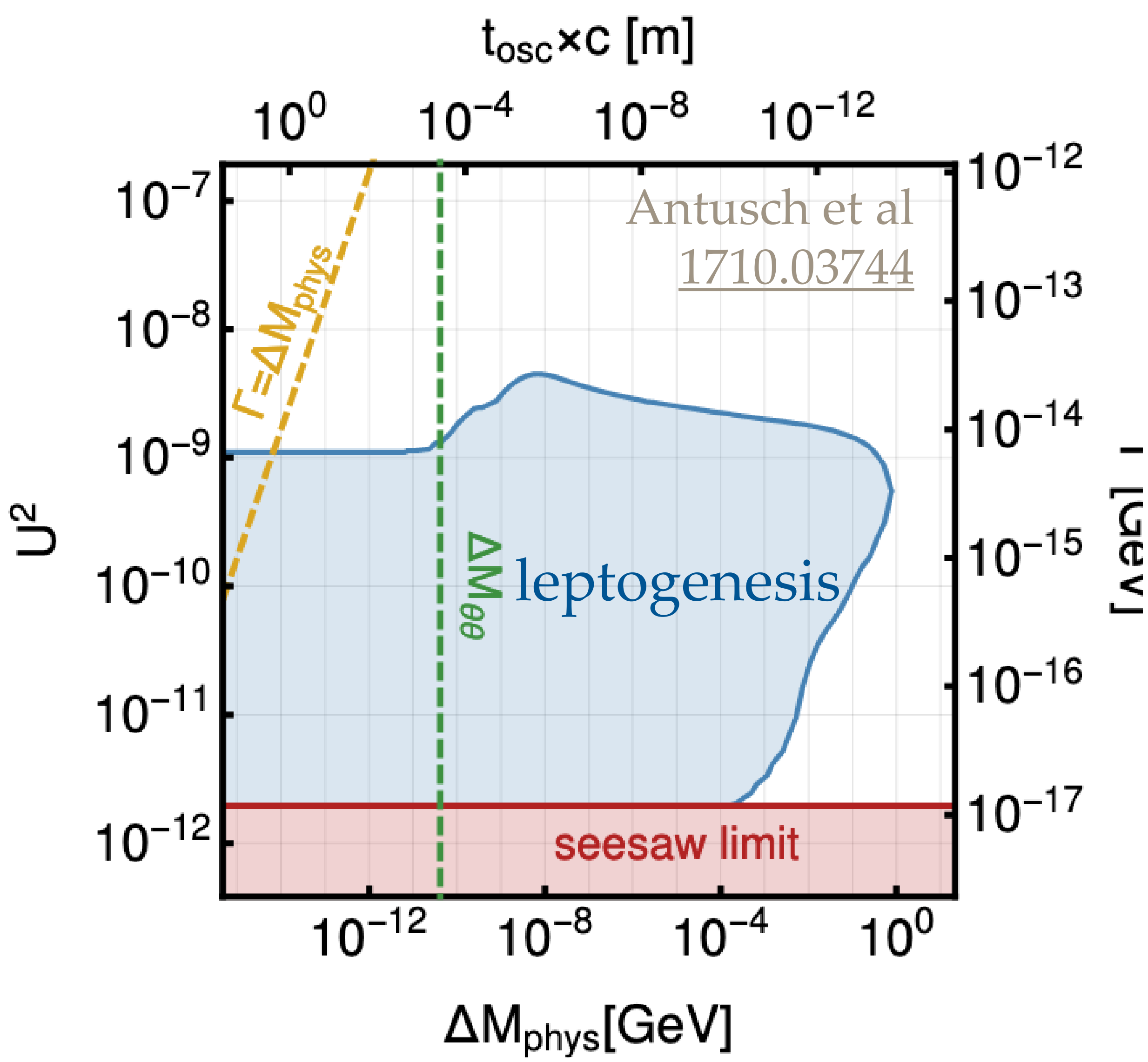
Full Density Matrix Evolution



Abada et al 1810.12463

Leptogenesis with Exactly Degenerate Majorana Masses: 2HNLs

- Leptogenesis is feasible even if Majorana mass in Lagrangian is a unit matrix



- Different contributions to thermal masses lead to misalignment between "mass basis" and "interaction basis"

$$H_N^{\rm vac} = \frac{\pi^2}{18\zeta(3)}\frac{a_{\rm R}}{T_{\rm ref}^3}\left({\rm Re}[M^\dagger M] + ih{\rm Im}[M^\dagger M]\right) ,$$
$$H_N^{\rm th} = \frac{a_{\rm R}}{T_{\rm ref}}\left(\mathfrak{h}_+^{\rm th}\Upsilon_{+h} + \mathfrak{h}_-^{\rm th}\Upsilon_{-h}\right) + \mathfrak{h}^{\rm EV}\frac{a_{\rm R}}{T_{\rm ref}}{\rm Re}[Y^*Y^t] ,$$
$$\Gamma_N = \frac{a_{\rm R}}{T_{\rm ref}}\left(\gamma_+\Upsilon_{+h} + \gamma_-\Upsilon_{-h}\right) ,$$
$$\tilde{\Gamma}_N^a = h\frac{a_{\rm R}}{T_{\rm ref}}\left(\tilde{\gamma}_+\Upsilon_{+h}^a - \tilde{\gamma}_-\Upsilon_{-h}^a\right) ,$$

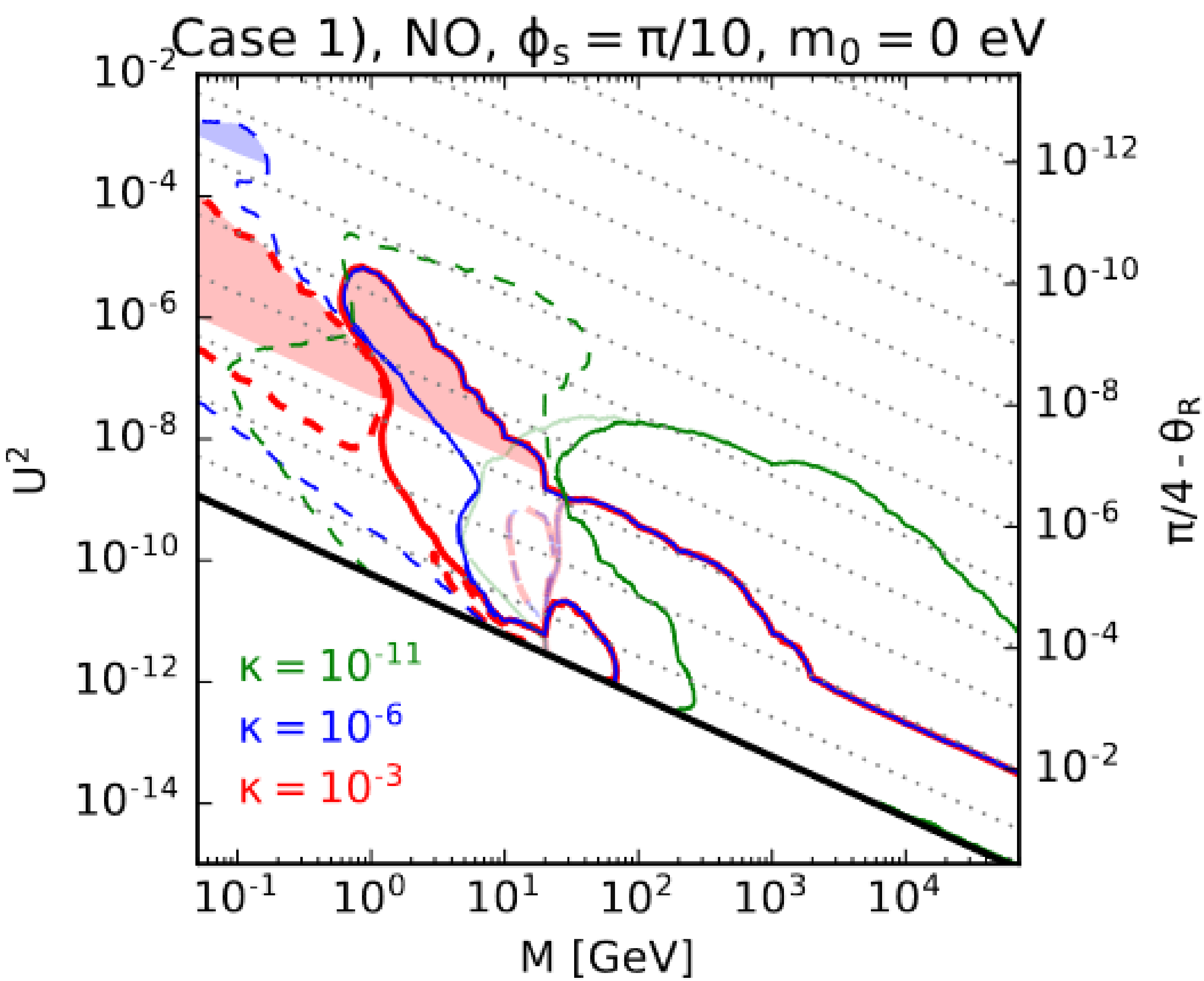
- Effect is only seen when using density matrix and including thermal corrections!

- Similar mechanism enables HNL oscillations in detector and observable LNV, see Juraj Klaric talk

$$M_N = M_M + \frac{1}{2}(\theta^\dagger\theta M_M + M_M^T\theta^T\theta^*)$$

MaD/Klaric/Klose 1907.13034

Leptogenesis with Discrete Symmetries



Plot from MaD/Georis/Hagedorn/Klaric 2203.08538

- 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

Flavour Invariants

- Density matrix equation

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

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

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

- Small Yukawas: solve perturbatively

$$\mathrm{Tr}\left[\tilde{\Gamma}_\alpha(\bar{\rho}_N-\rho_N)\right] \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\left[H_N,\Gamma\right]\right)$$

- Find CPV combinations

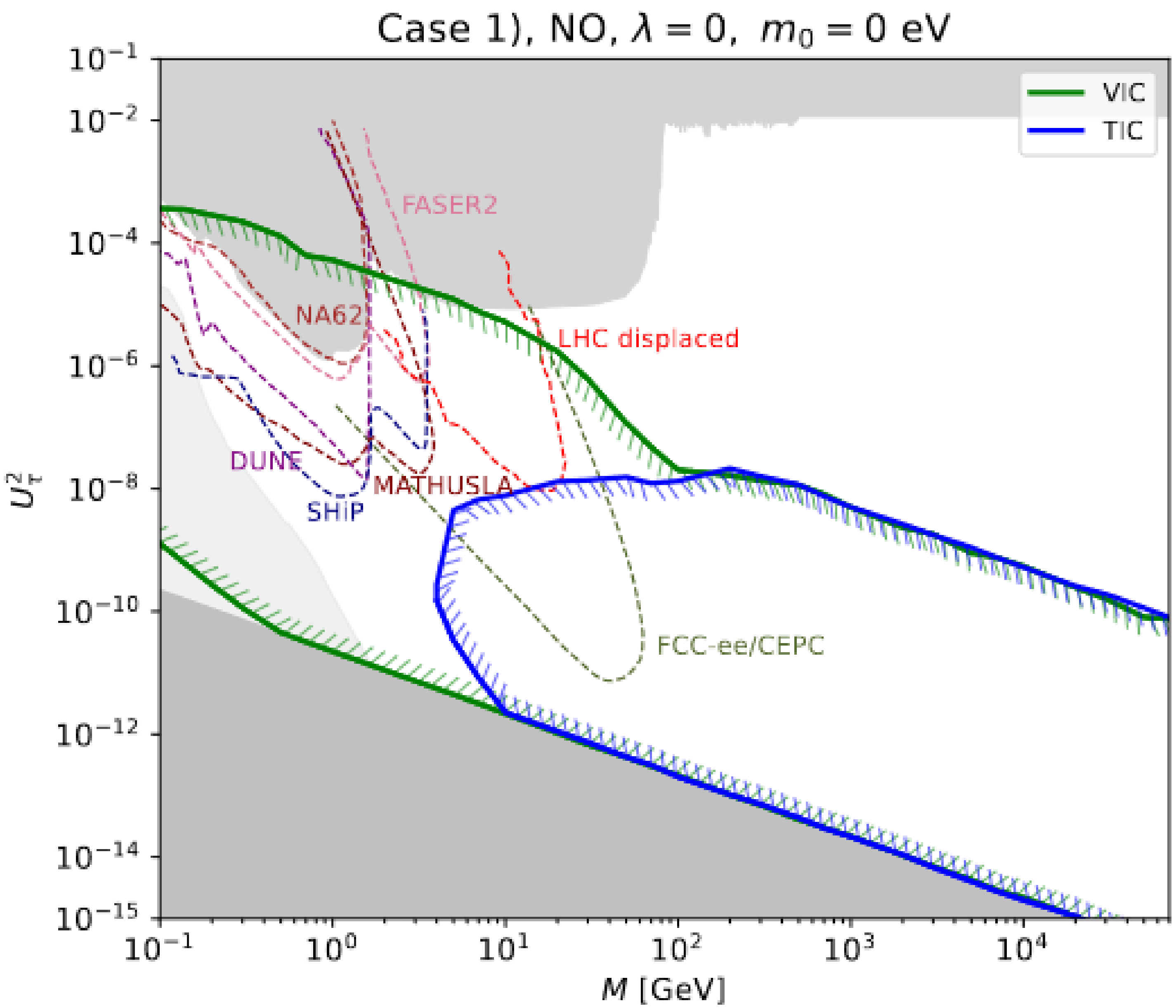
$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2,\hat{Y}_D^\dagger\hat{Y}_D\right]\hat{Y}_D^\dagger P_\alpha\hat{Y}_D\right), \qquad \text{LFV source}$$

$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2,\hat{Y}_D^\dagger\hat{Y}_D\right]\hat{Y}_D^T P_\alpha\hat{Y}_D^*\right), \qquad \text{LNV source}$$

$$C_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{Y}_D^T\hat{Y}_D^*,\hat{Y}_D^\dagger\hat{Y}_D\right]\hat{Y}_D^T P_\alpha\hat{Y}_D^*\right), \qquad \text{mass-degenerate source}$$

Antusch et al 1710.03744 MaD/Georis/HagedornKlaric 2203.08538

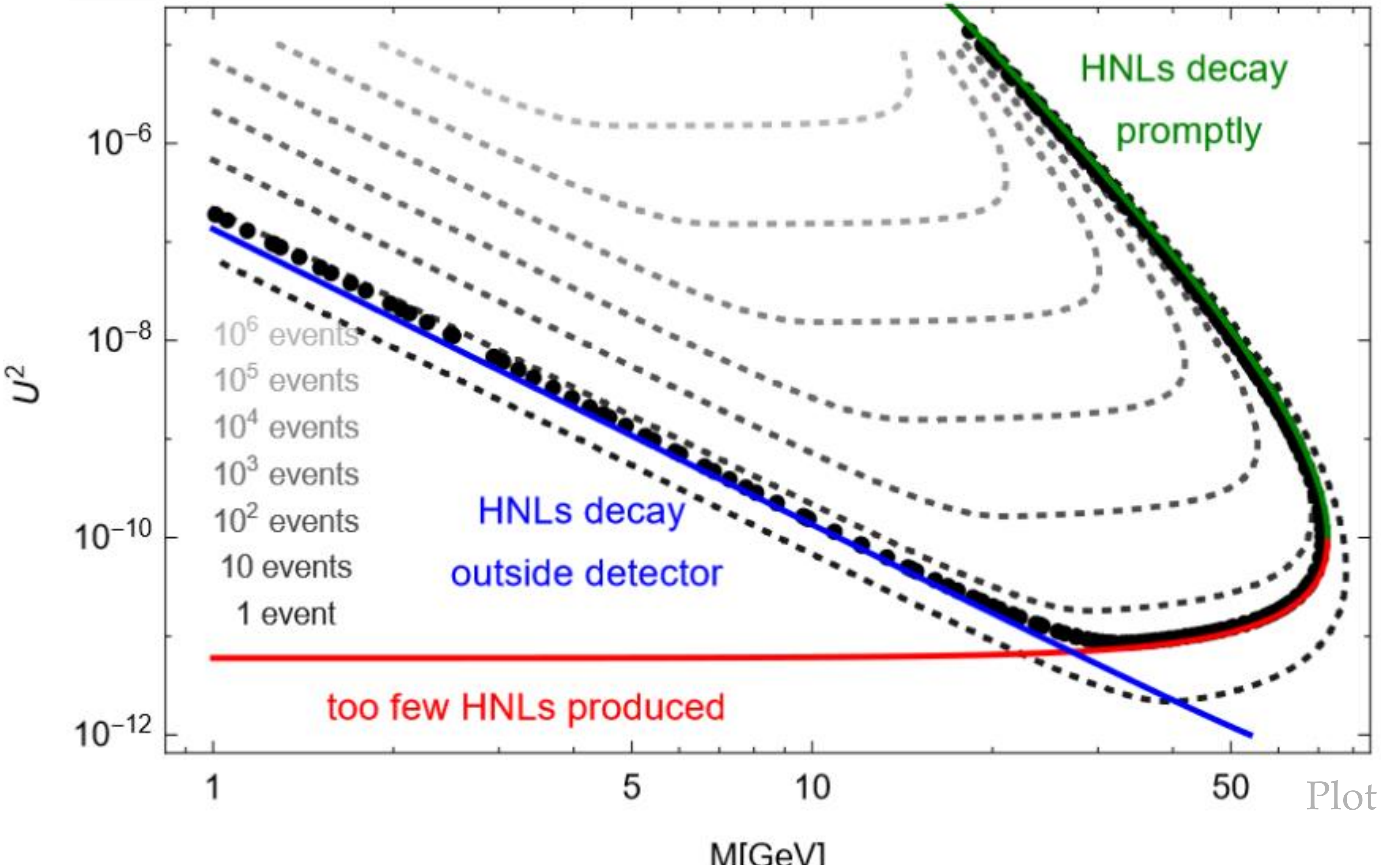
Leptogenesis Discrete Symmetries

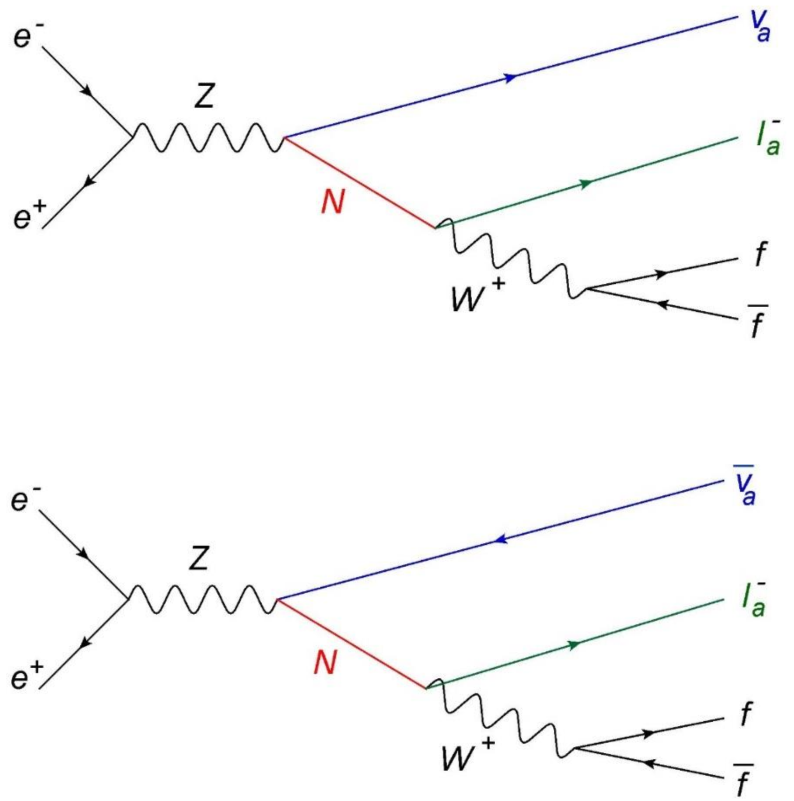


Plot from MaD/Georis/Hagedorn/Klaric 2xxx.xxxxx

- Generically mixing is near the "seesaw line" $U^2 \sim m_\nu/M$
- Can be enhanced in presence of enhanced residual symmetry
- Here unknown parameters have been marginalised
- Leptogenesis region in presence of these discrete symmetries can only be probed with LLP searches (even with three HNL flavours)
- Plot is for illustration, regions change for different residual symmetries

DV Vertex Searches during Z-pole Run





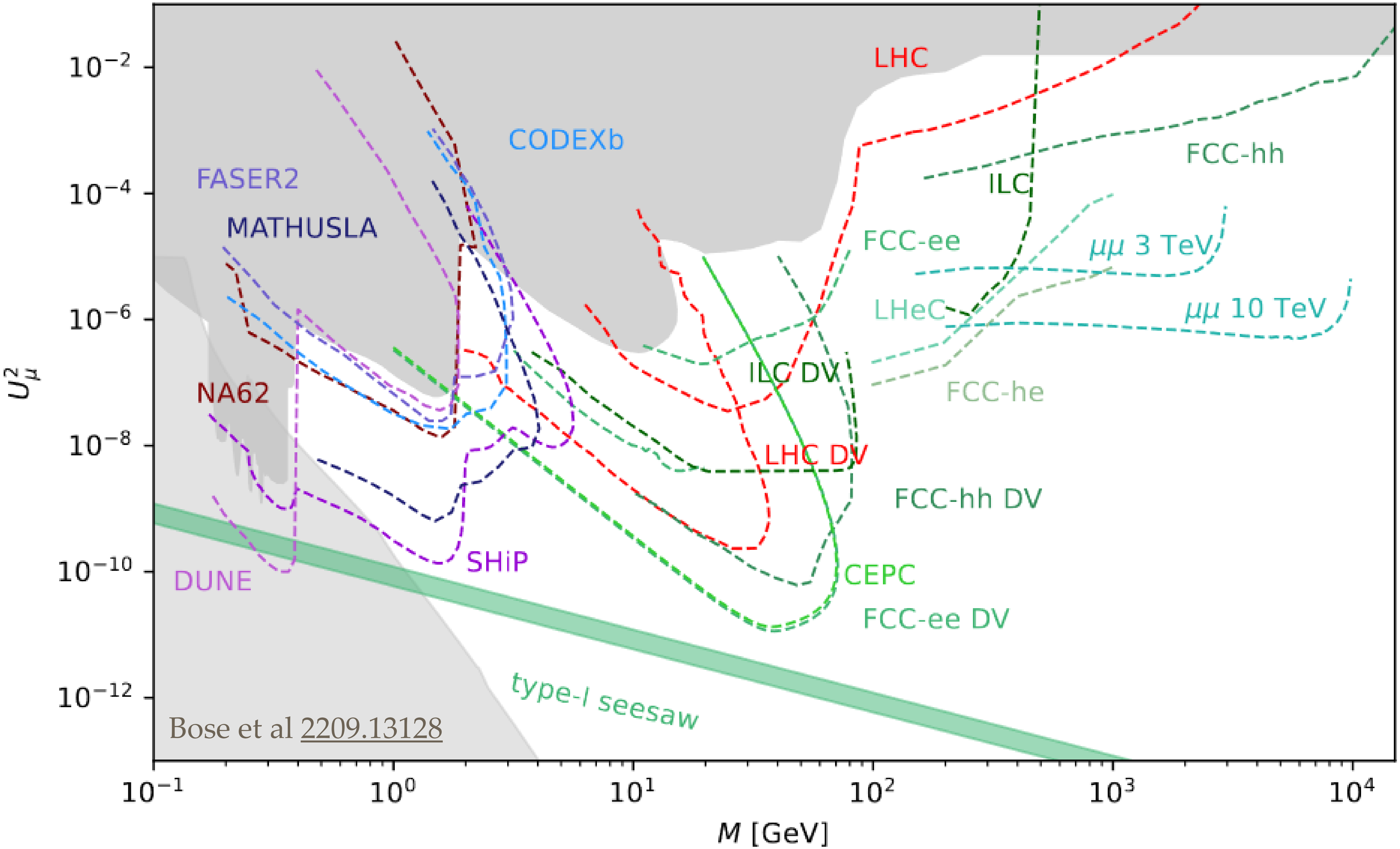
proposed in Blondel et al 1411.5230

Plot and estimates from MaD 2210.17110

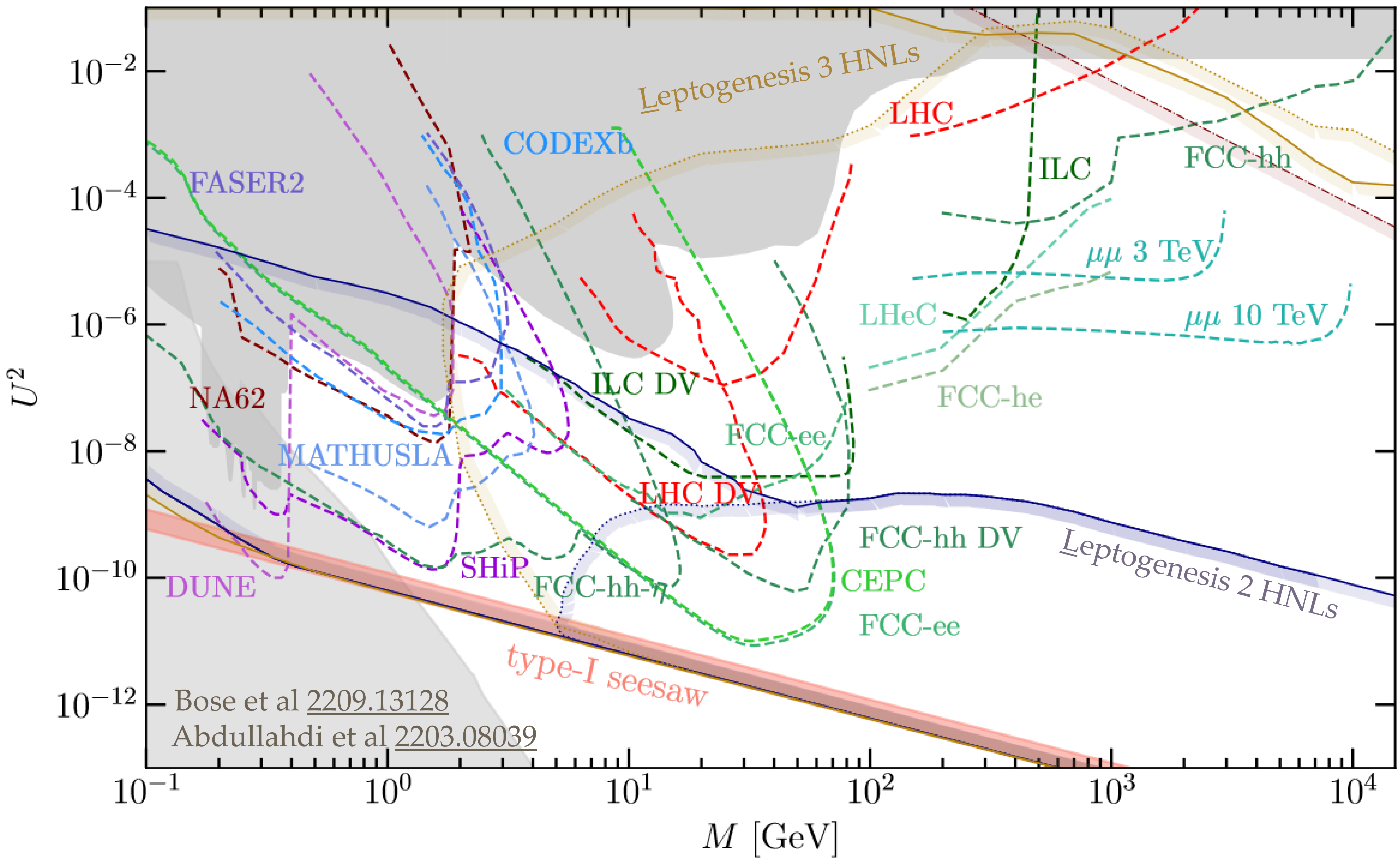
$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}} \left(\frac{M}{\rm GeV}\right)^{-6} \left(1 - (M/m_Z)^2\right) {\rm cm}.$$

$c_{\rm dec} = 1$ ($c_{\rm dec} = 1/2$) for Majorana (Dirac) HNL

Search Summary



Search Summary



A Multi Frontier Adventure!

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, …

absolute neutrino mass searches (KATRIN ect.)

CMB and LSS : absolute neutrino mass

non-accelerator searches (TRISTAN…)

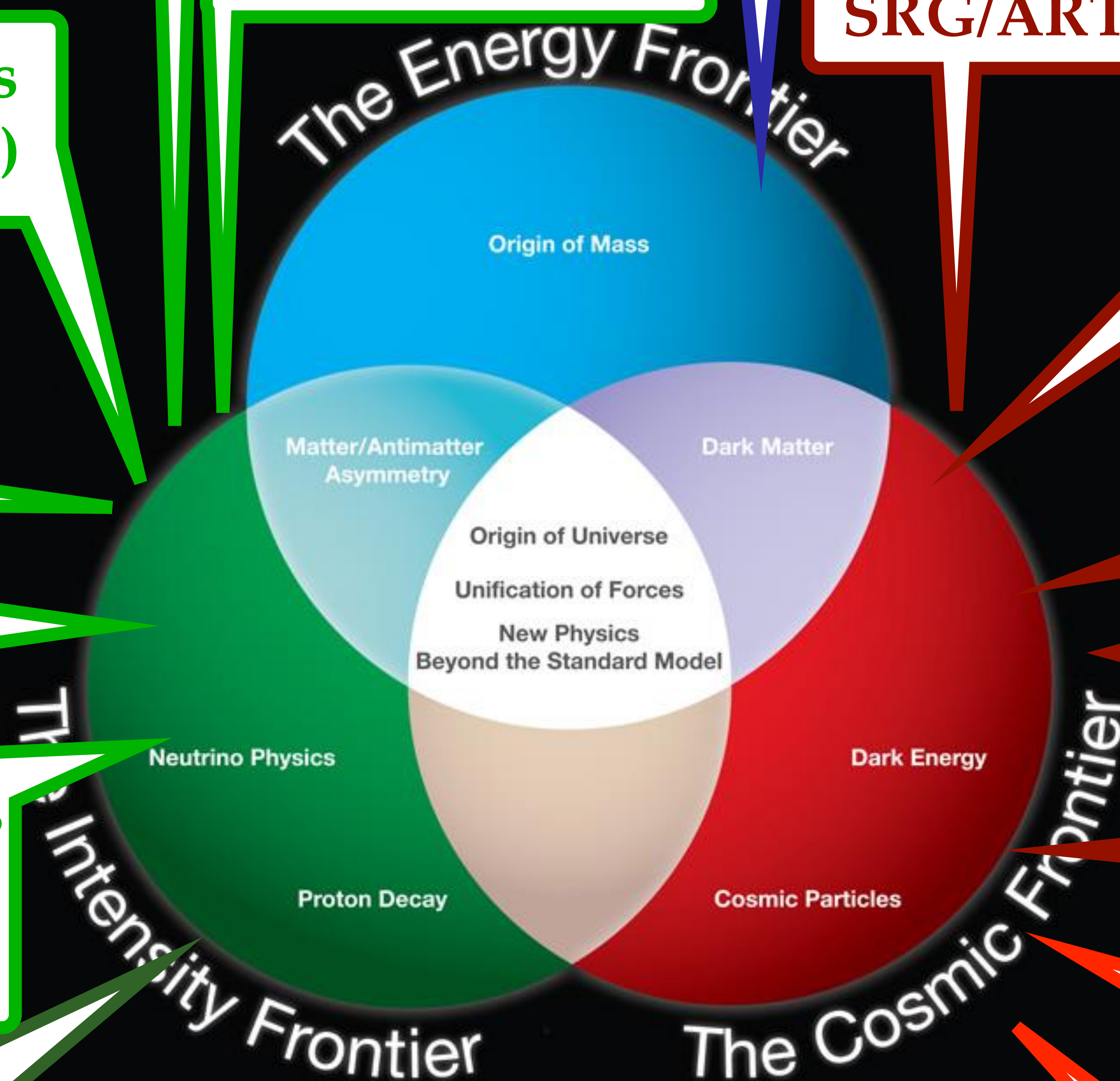
astrophysics: supernovae etc.

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

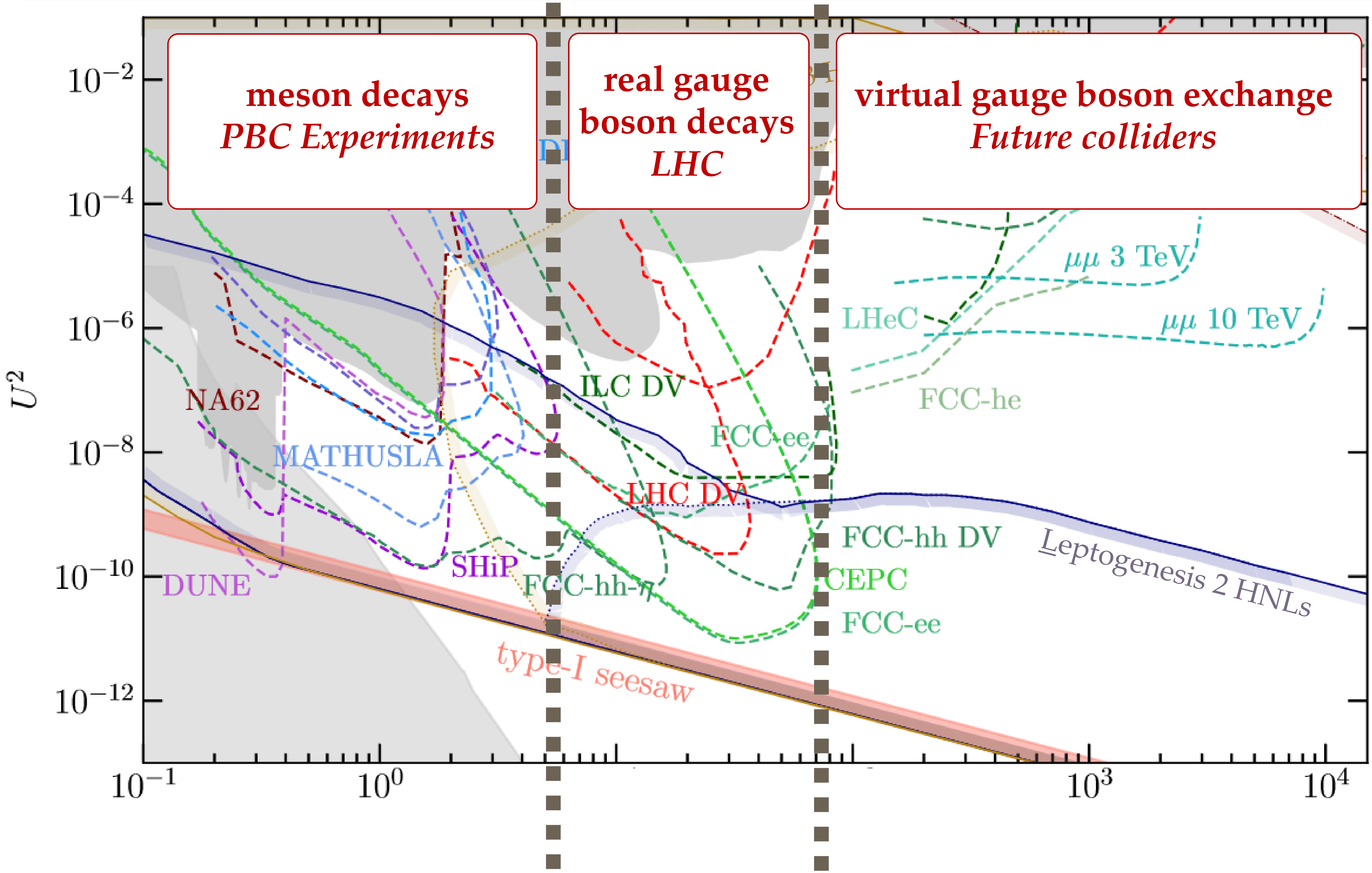
Theory: Sterile neutrino DM production

Summary

- Heavy neutrinos with collider accessible masses and couplings can simultaneously explain the light neutrino masses and origin of matter
- Can be realised in natural and UV complete models at the Fermi scale
- LLP searches can still explore orders of magnitude of uncharted terrain!
- Some interesting models can only be probed with LLP searches (νMSM, testable models with discrete symmetries discussed here, …)
- LLP searches can possibly see thousands of events at the LHC and millions at the FCC-ee, allowing to probe HNL properties in detail and test the origin of neutrino mass and matter in the universe!
- To be continued by Juraj Klaric…

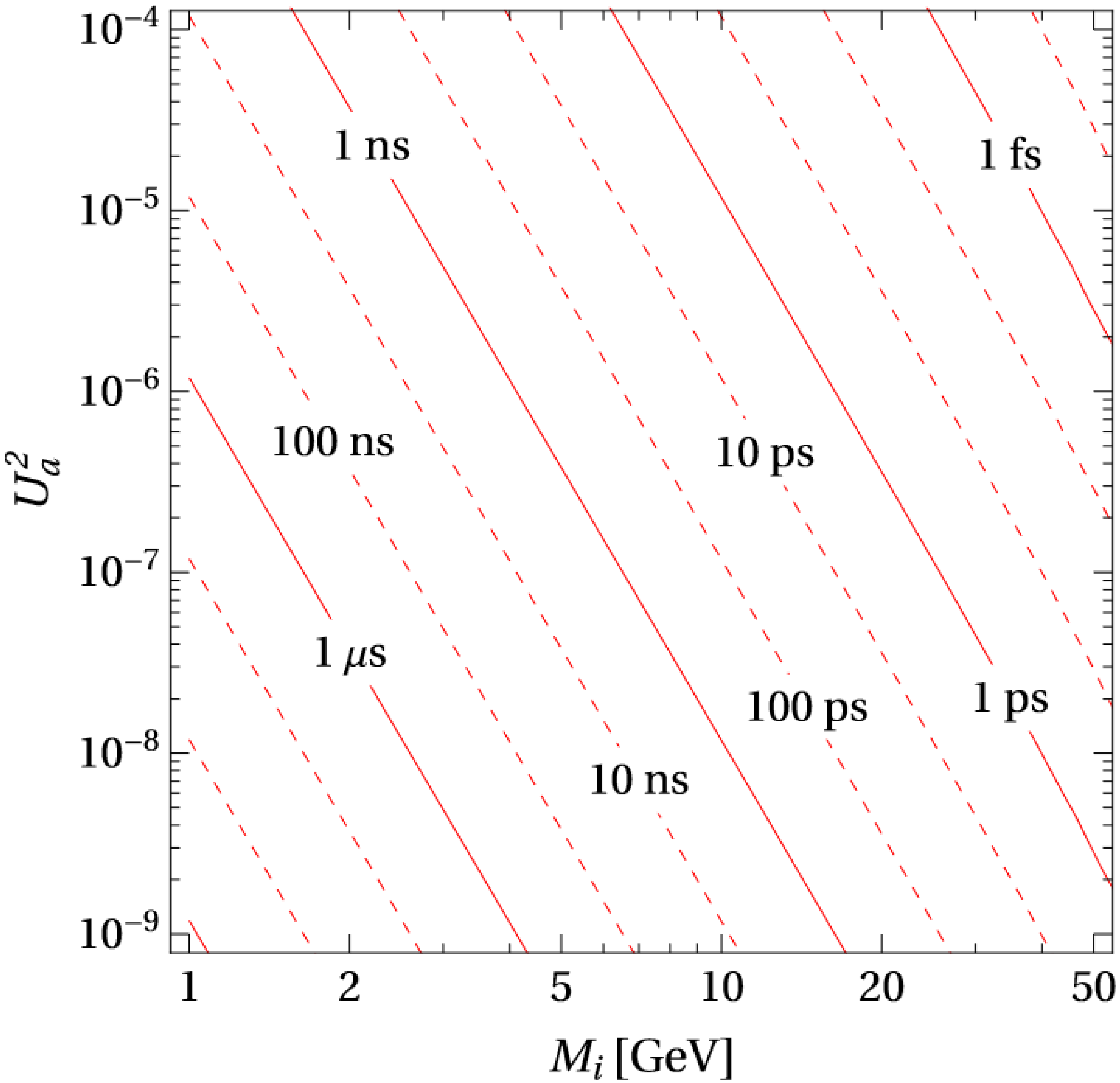
Backup Slides

HNL Production



HNL Lifetime and LNV

HNL Lifetime



- HNL decay width in rest frame scales as

$$\Gamma_N \sim U^2 M^5 G_F^2$$

- Decay length in lab frame

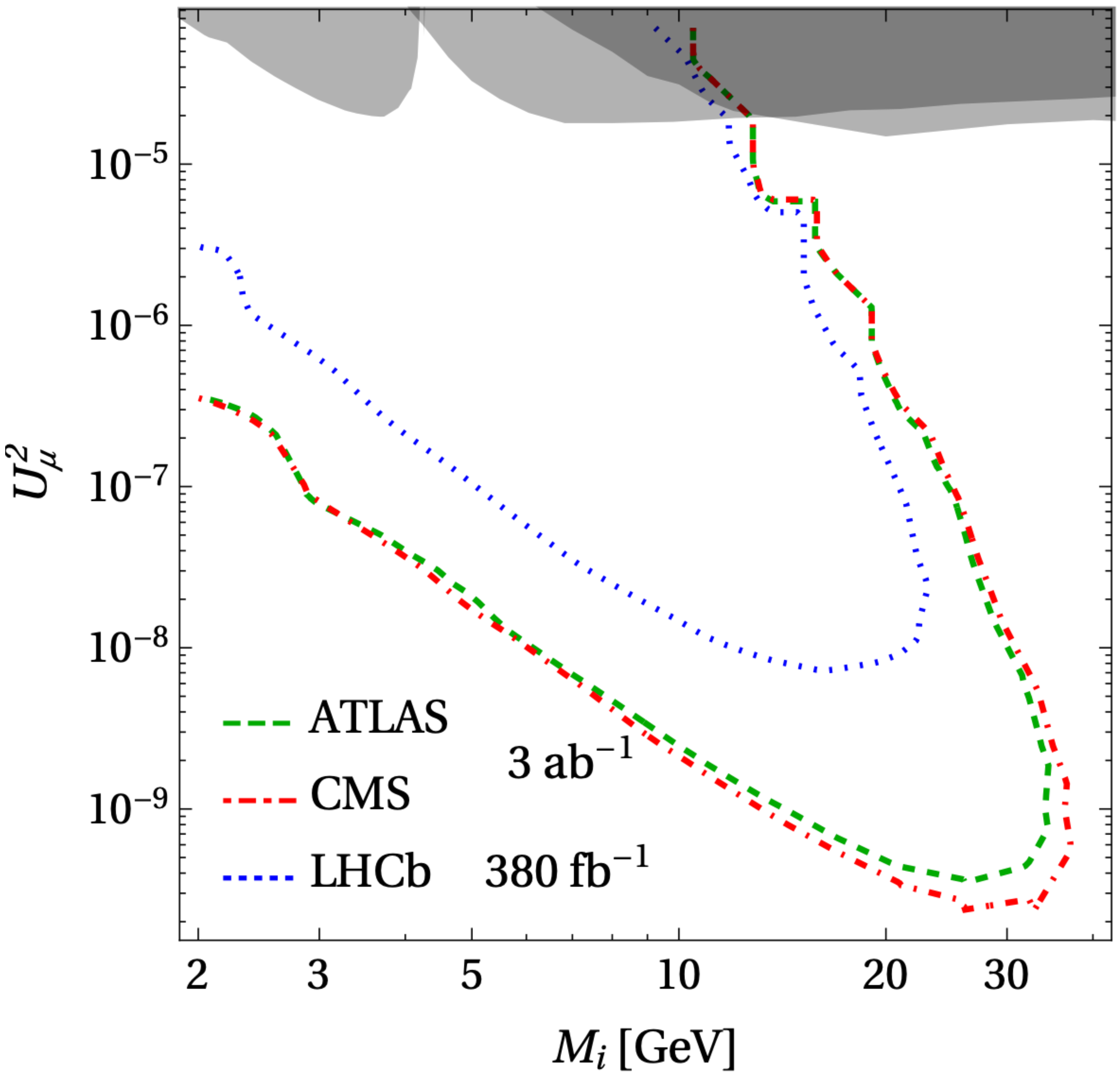
$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \sim \frac{\mathrm{p}}{U^2 M^6 G_F^2}$$

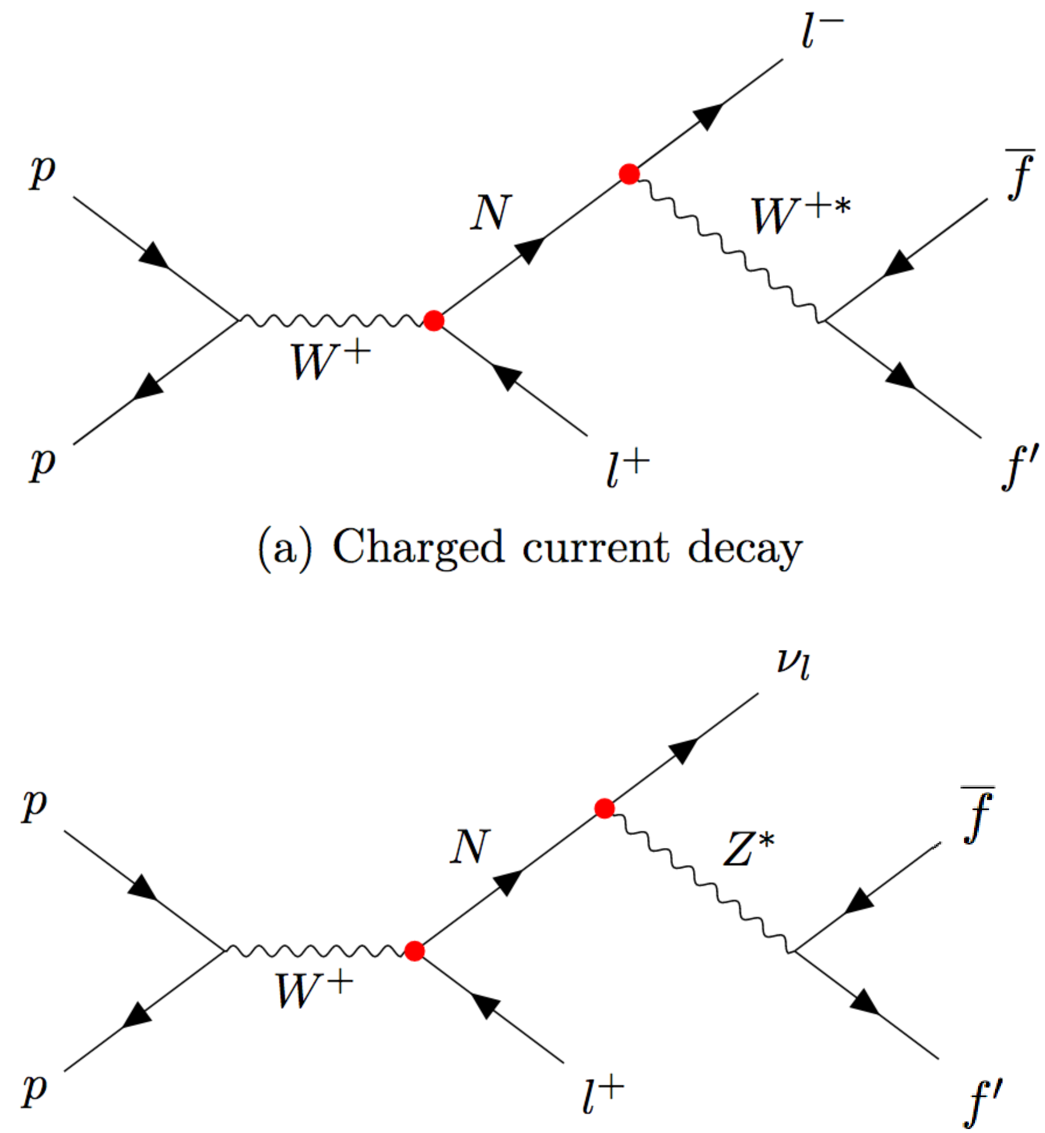
- For $M << m_W$

$$\lambda_N \simeq \frac{0.036}{U^2} \left(\frac{\mathrm{p}}{\mathrm{GeV}}\right) \left(\frac{M}{\mathrm{GeV}}\right)^{-6} \mathrm{cm}$$

- In regime where HNLs can be produced efficiently they are often long-lived

HL-LHC Displaced Vertex Search



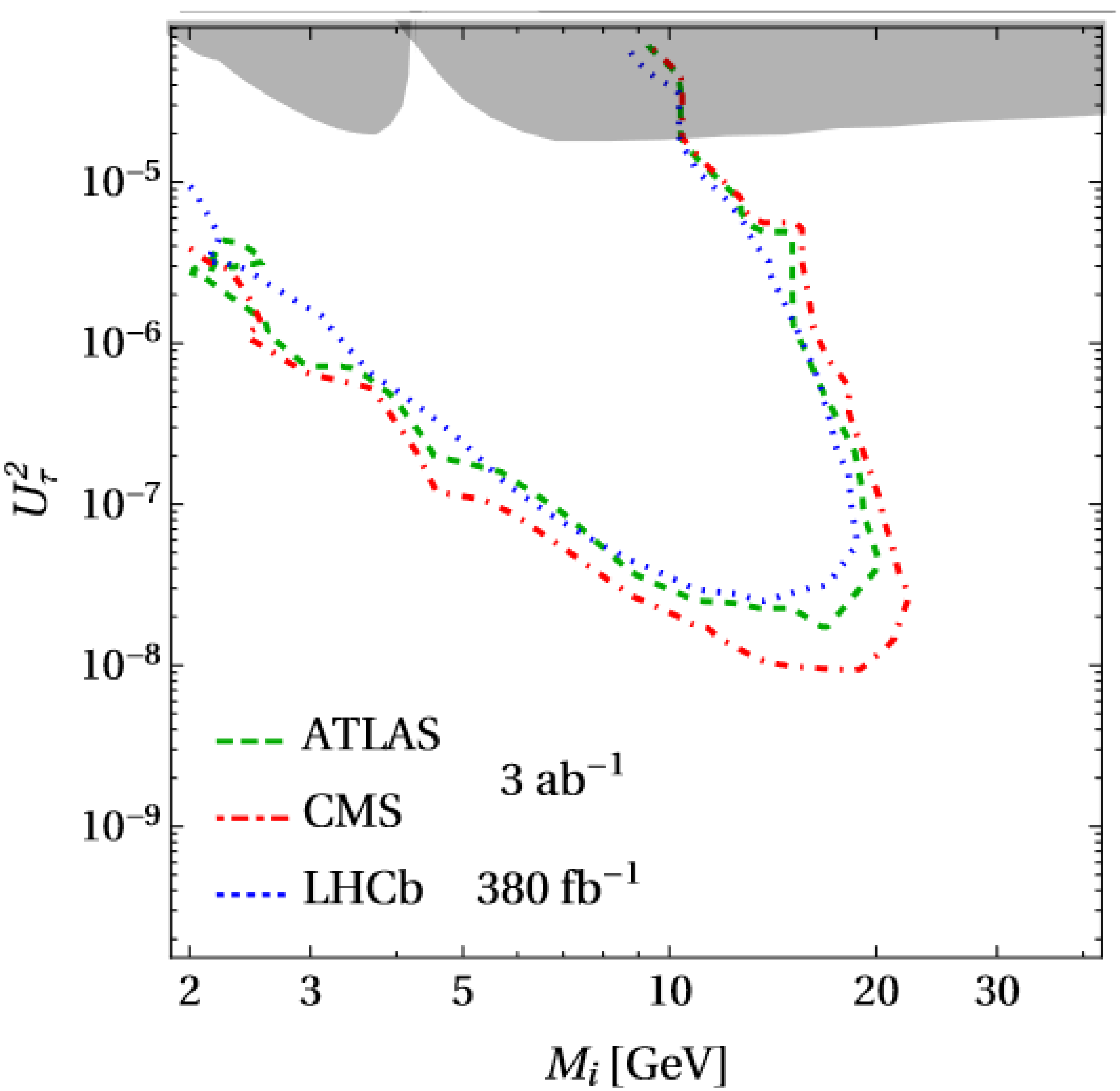


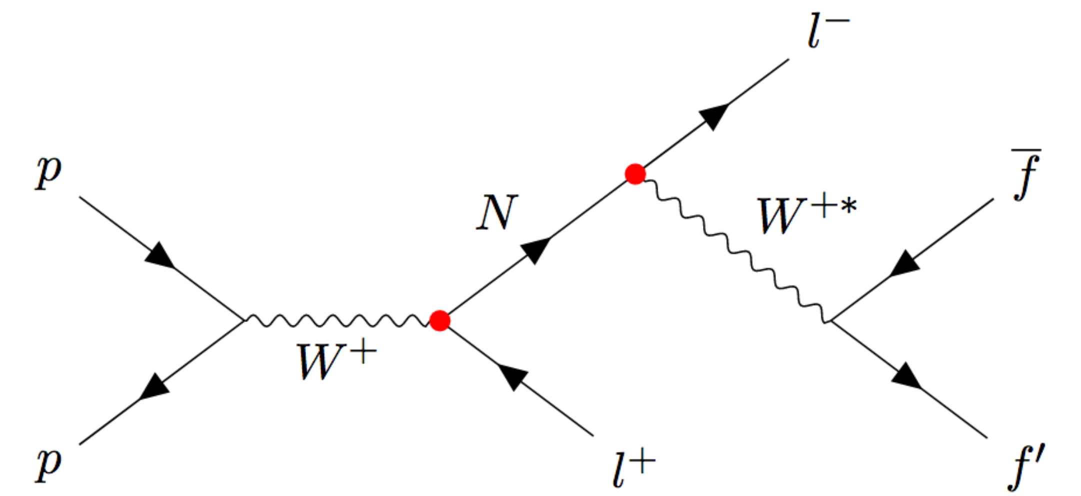
(a) Charged current decay

(b) Neutral current decay

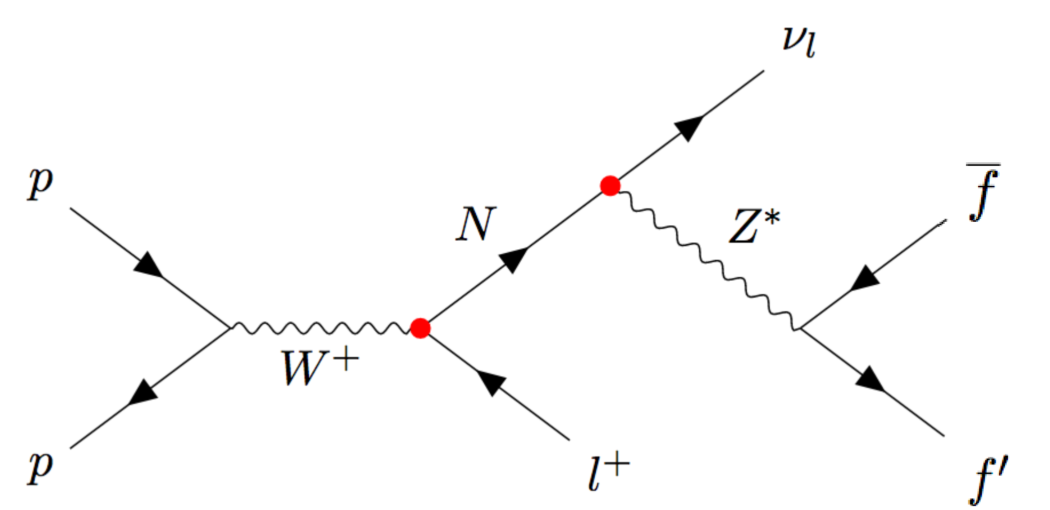
MaD/Hajer 1903.06100

HL-LHC Displaced Vertex Search





(a) Charged current decay

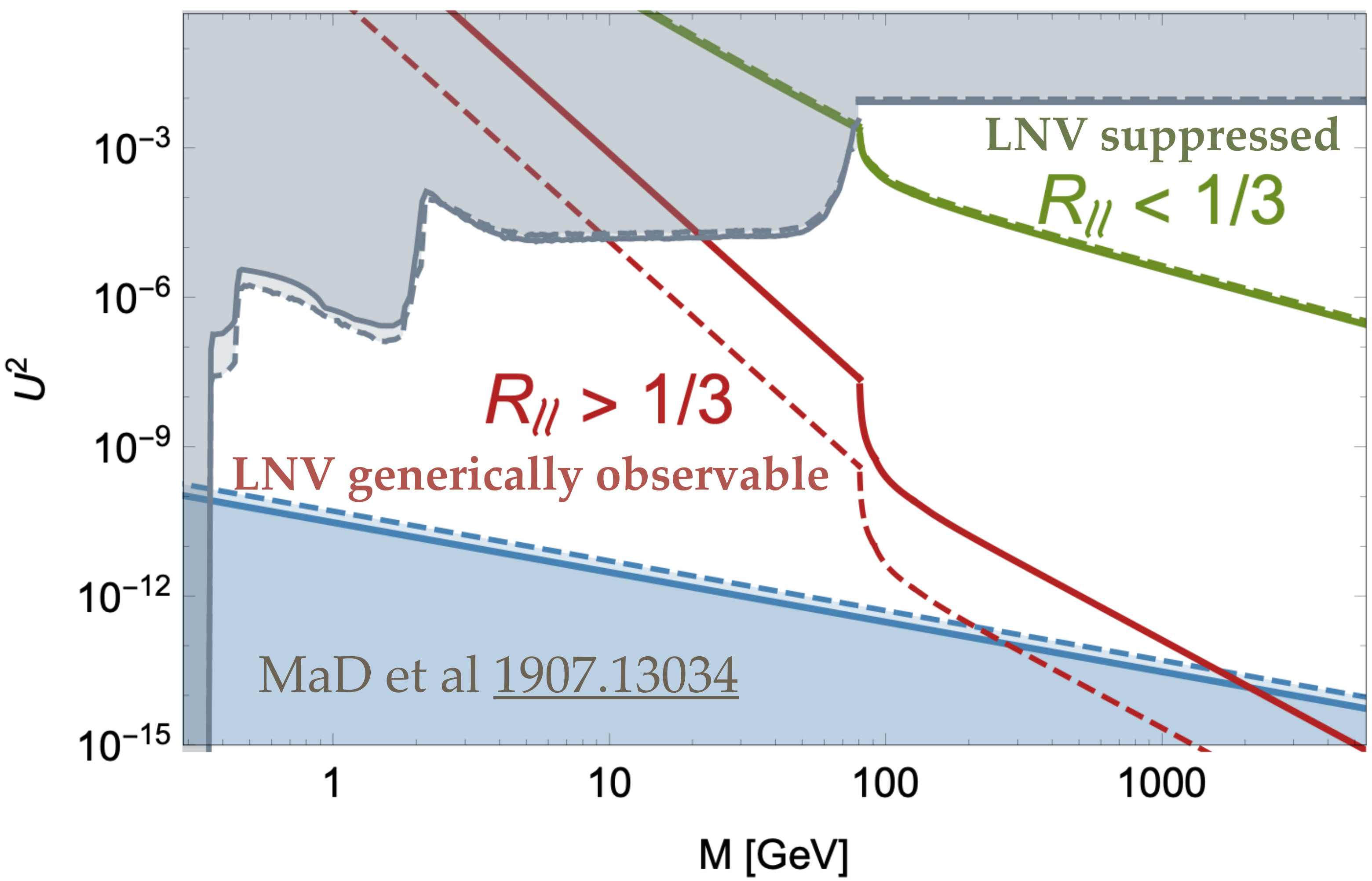


(b) Neutral current decay

MaD/Hajer 1903.06100

Majorana nature of HNLs: Can LNV decay be observed?

- Protecting symmetry parametrically suppresses LNV processes
- But symmetry must be broken to give masses to neutrinos
- Is this breaking enough?



- **Quasi-degenerate HNLs kinematically indistinguishable**
- **behave like one particle with non-integer R_{ll}!**

e.g. Anamiati et al 1607.05641

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

- suppression happens by destructive interference between exchange of different HNLs
- interference can be avoided if quantum coherence is lost between production and decay
- This happens if HNLs oscillate many times during their lifetime
- Hence, the relevant quantity is the ratio between their lifetime and oscillation frequency

Constraining R_{ll} from HNL Lifetime

- HNL production cross section is same for Dirac and Majorana:

$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\, \mathrm{BR}(Z \to \text{invisible}) \left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right)$$

- HNL decay length differs:
  Dirac: : $c_{dec} = 1/2$
  Majorana: $c_{dec} = 1$

$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}}\left(\frac{M}{\rm GeV}\right)^{-6}\left(1 - (M/m_Z)^2\right)\,\mathrm{cm}.$$

- HNL mass extracted from full 4-momentum reconstruction or from time-of-flight

➢ **Extract U_a^2 from total # decays , c_{dec} from # decays between displacement l_0, l_1**

- BUT: If you have two Majorana HNLs with similar masses that you cannot kinematically distinguish, you effectively see a twice larger U^2
- This factor 2 does not appear in their decay rate, so you would mistake them for a Dirac particle (since the extracted from decay law is half of the one extracted from the total number of HNLs
- We may introduce one more parameter $\sigma_N \sim U^2 c_{\rm prod}\sigma_\nu$
- To further complicate things: For sufficiently small mass splitting there can be interferences between the processes mediated by different HNLs

dichotomy of Dirac vs Majorana HNLs generally not sufficient to capture realistic models

HNL SM Weak Interactions

Common phenomenological description: "Single HNL Model"

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu\nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

- One flavour of HNLs *N*
- Couples to SM only through mixing θ_a with SM neutrinos, where a = e, μ, τ
- Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}.
- **R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) *N* decays; R_{ll} = 1 for Majorana *N* and R_{ll} = 0 for Dirac *N*.**

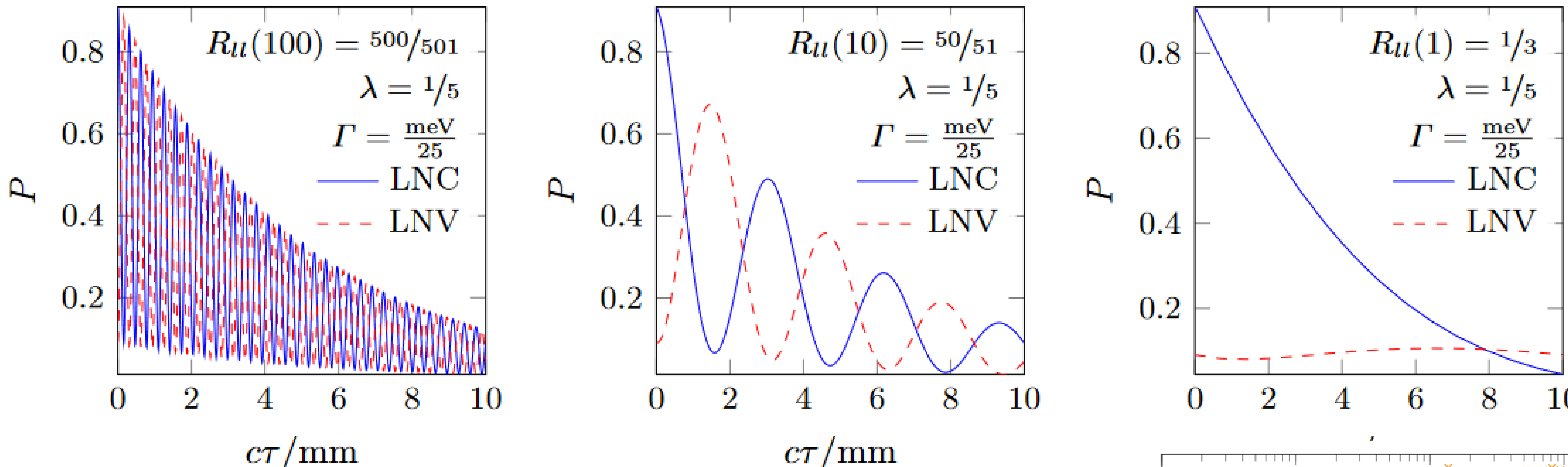
- This is not a realistic model of neutrino mass, but can effectively describe some phenomenological aspects of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}., with R_{ll} interpolating between 0 and 1.
- To be a bit more realistic one can introduce two more parameters c_{prod} and c_{dec}:

$$\sigma_N \sim U^2 c_{\text{prod}}\sigma_\nu \qquad\qquad \Gamma_N \simeq c_{\text{dec}}\frac{a}{96\pi^3}U^2M^5G_F^2$$

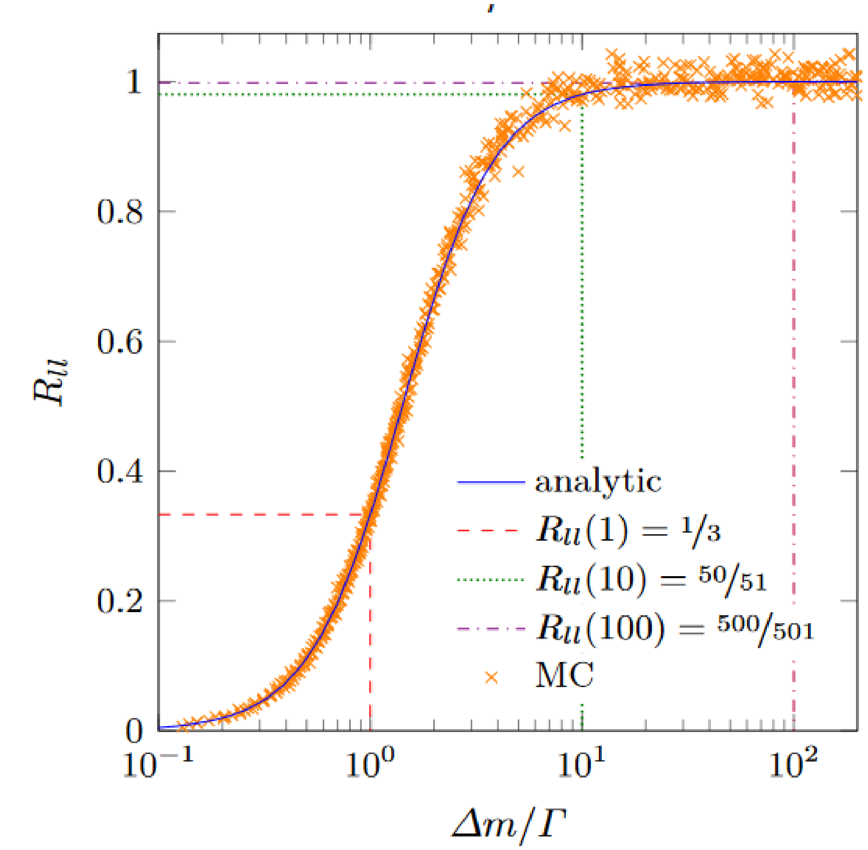
- Allows to effectively describe certain limits of realistic models

mass spectrum	c_{prod}	c_{dec}	R_{ll}	appearance
$\Delta M > \delta M_{\text{exp}} \gg \Gamma_N$	1	1	1	two Majorana HNLs with mixing U^2 each
$\delta M_{\text{exp}} > \Delta M \gg \Gamma_N$	2	1	1	one HNL, mixing $2U^2$, lifetime as Dirac, R_{ll} as Majorana
$\delta M_{\text{exp}} > \Gamma_N \gg \Delta M$	2	1	0	one Dirac HNL with mixing $2U^2$

Simulating Heavy Neutrino Oscillations



- Oscillations of pseudo-Dirac HNLs in the detector may be observed by studying R_{ll} as function of displacement
- Current framework of [MadGraph] and [HeavyN FeynRules] only allows to simulate single "Dirac" or "Majorana" HNL
- MadGraph patch to simulate oscillations has been published in Antusch/Hajer/Rosskopp 2210.10738



Complementarity and Testability

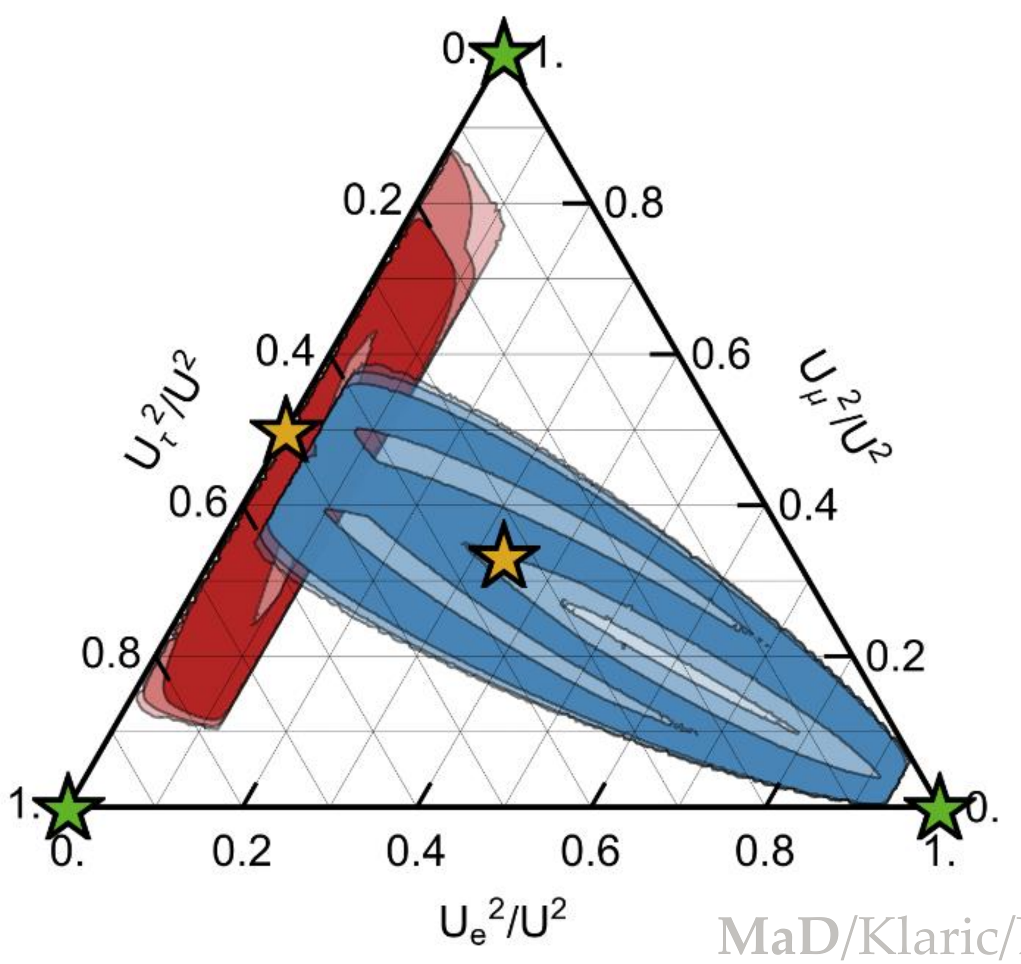
Majorana Phases

- Position in the triangle is basically given by parameters in PMNS

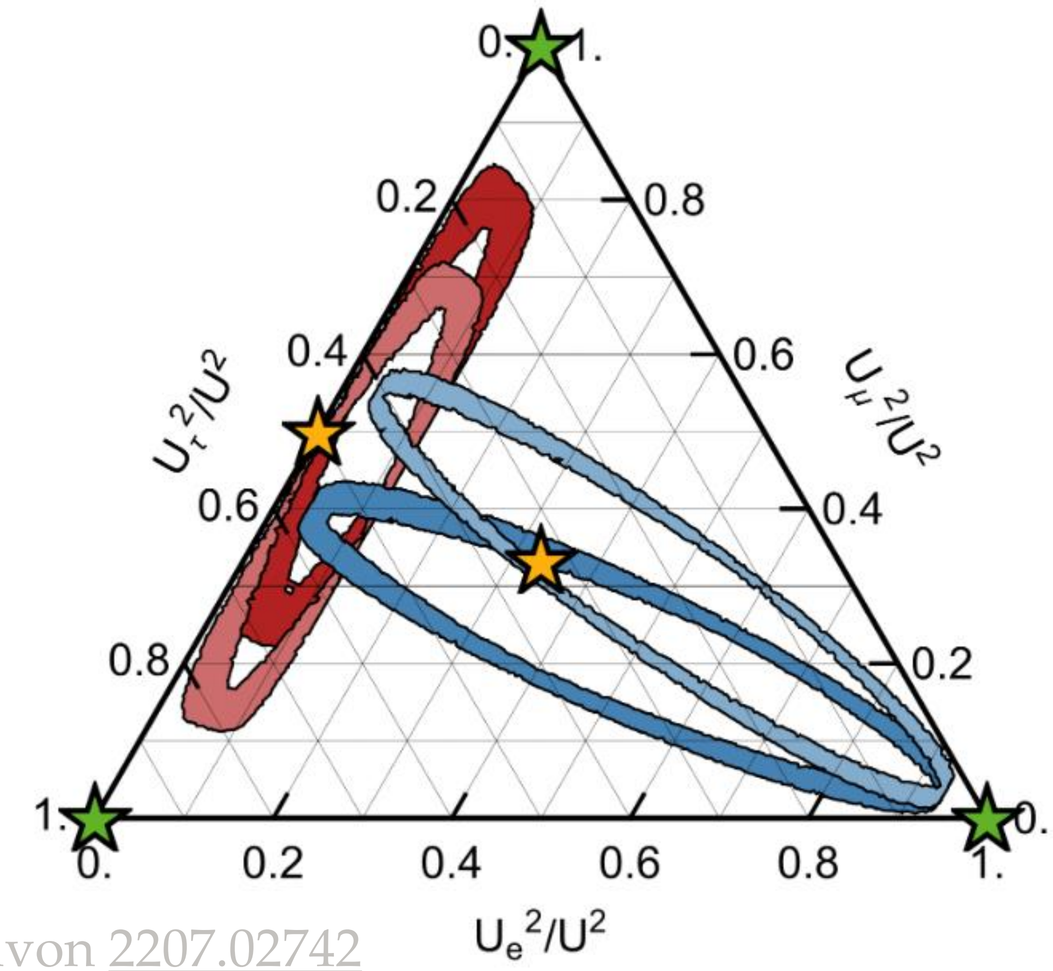
Hernandez et al 1606.06719 MaD et al 1609.09069

- After measuring Dirac phase at DUNE of HyperK, Majorana phase is only unknown
- Hence: branching ratios provide indirect probe of Majorana phase

MaD et al 1609.09069 Caputo et al 1611.05000



Current constraints

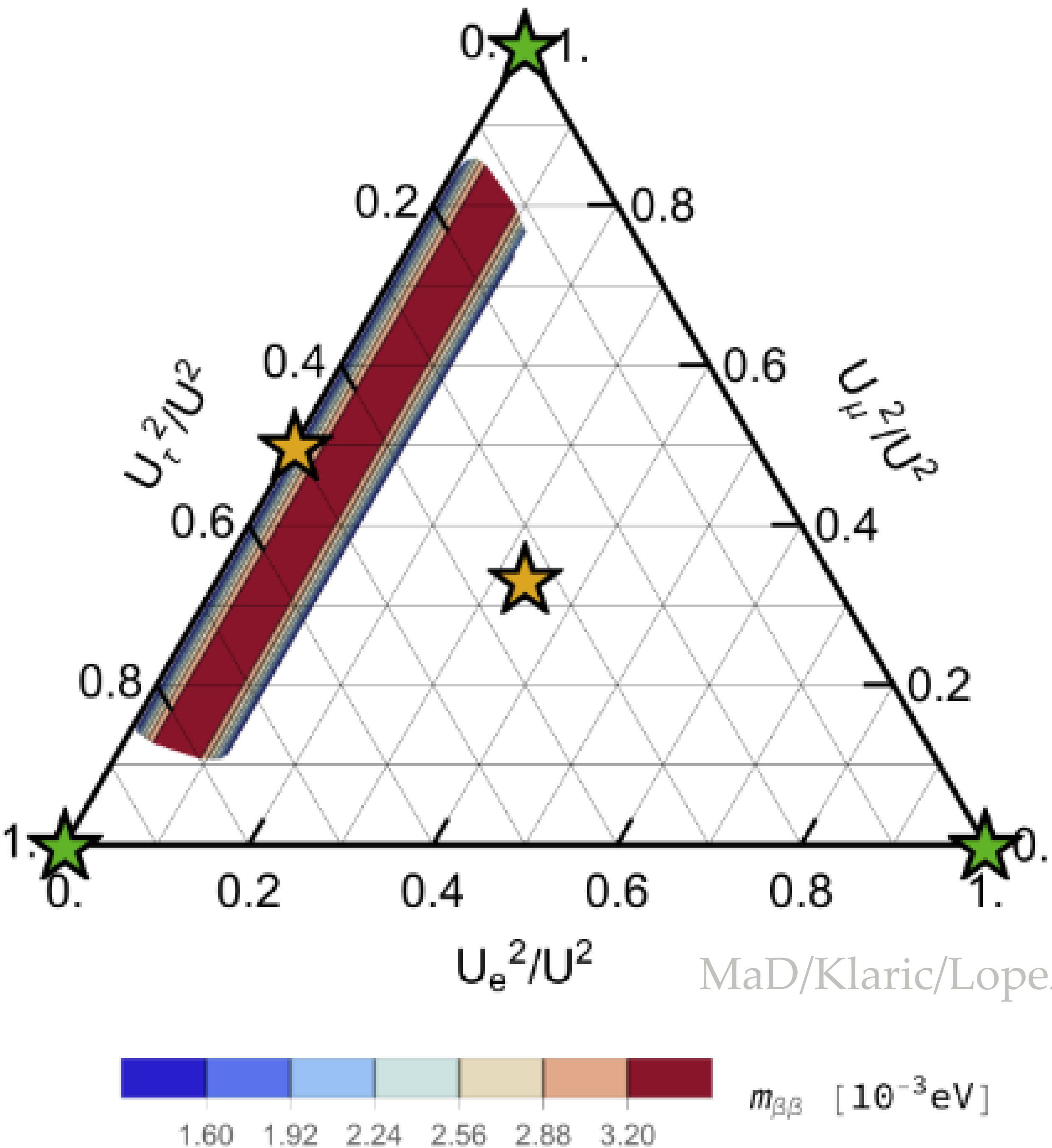


DUNE projection

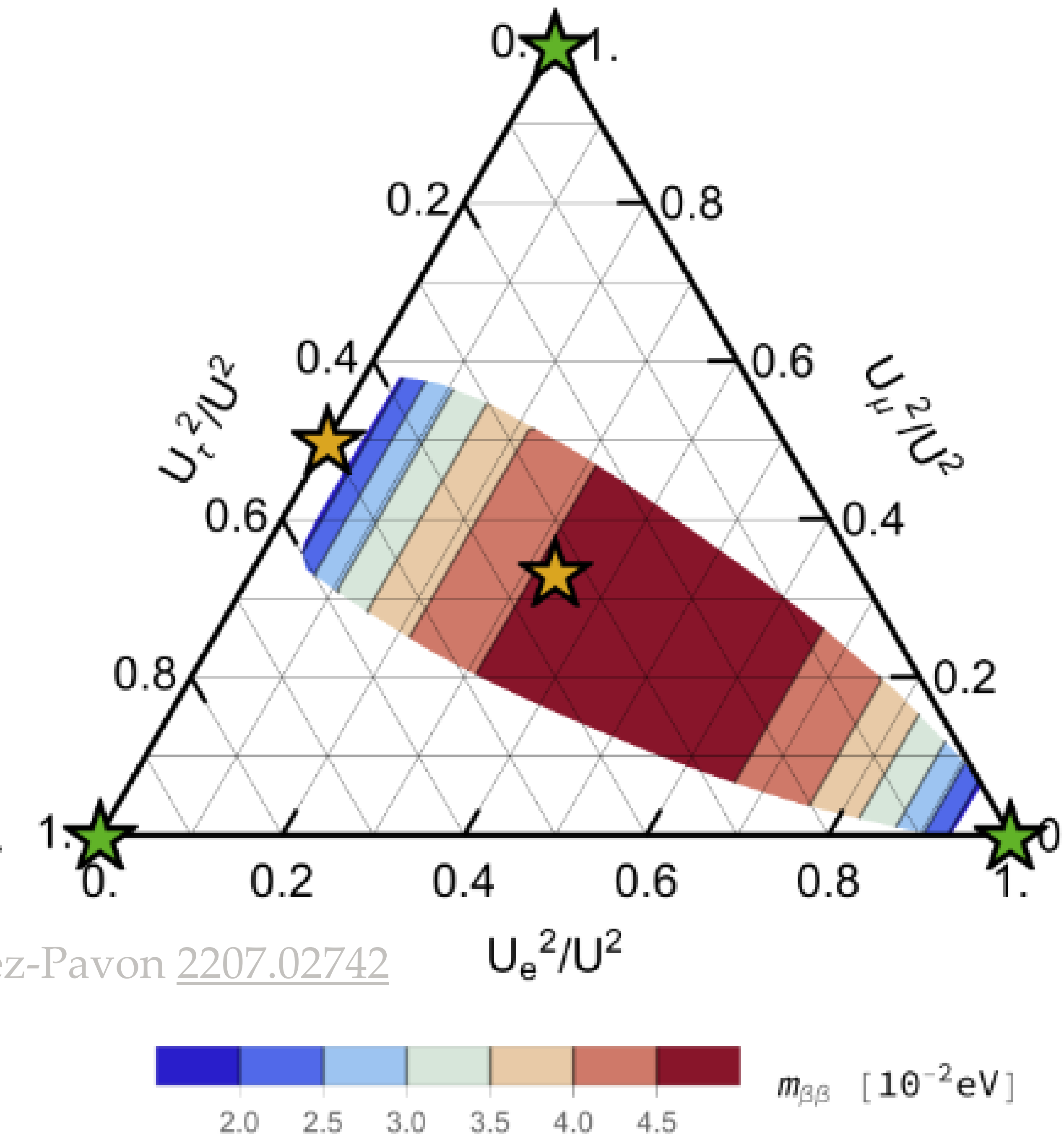
MaD/Klaric/Lopez-Pavon 2207.02742

Predictions for 0νββ Decay

normal ordering



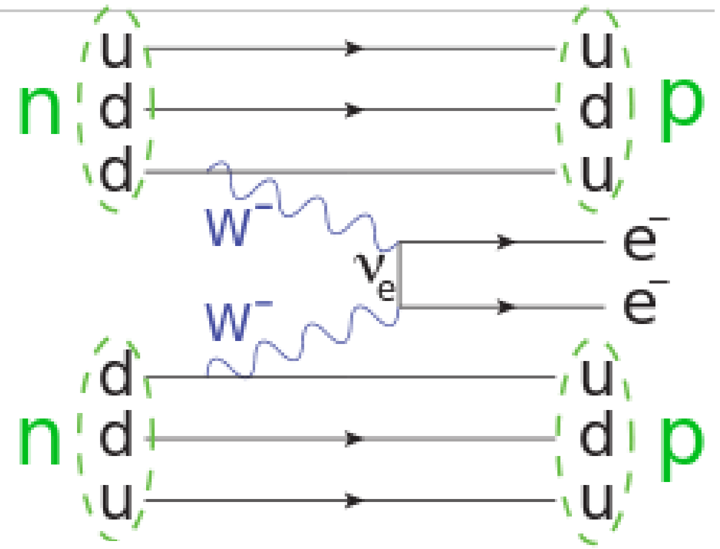
inverted ordering



MaD/Klaric/Lopez-Pavon 2207.02742

Heavy neutrinos in 0νββ Decay

- Heavy mass states also contribute to $m_{\beta\beta}$



$$m_{\beta\beta} = \left| \sum_i (U_\nu)^2_{ei} m_i + \sum_I \Theta^2_{eI} M_I f_A(M_I) \right|$$

$$= \left| [1 - f_A(\bar{M})] m^\nu_{\beta\beta} + \sum_I M_I \Theta^2_{eI} [f_A(M_I) - f_A(\bar{M})] \right|$$

suppression of standard contribution

new contribution from RH neutrinos

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

Parameter Spaces

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

Casas/Ibarra 01

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

Full Testability?

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

Casas/Ibarra 01

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

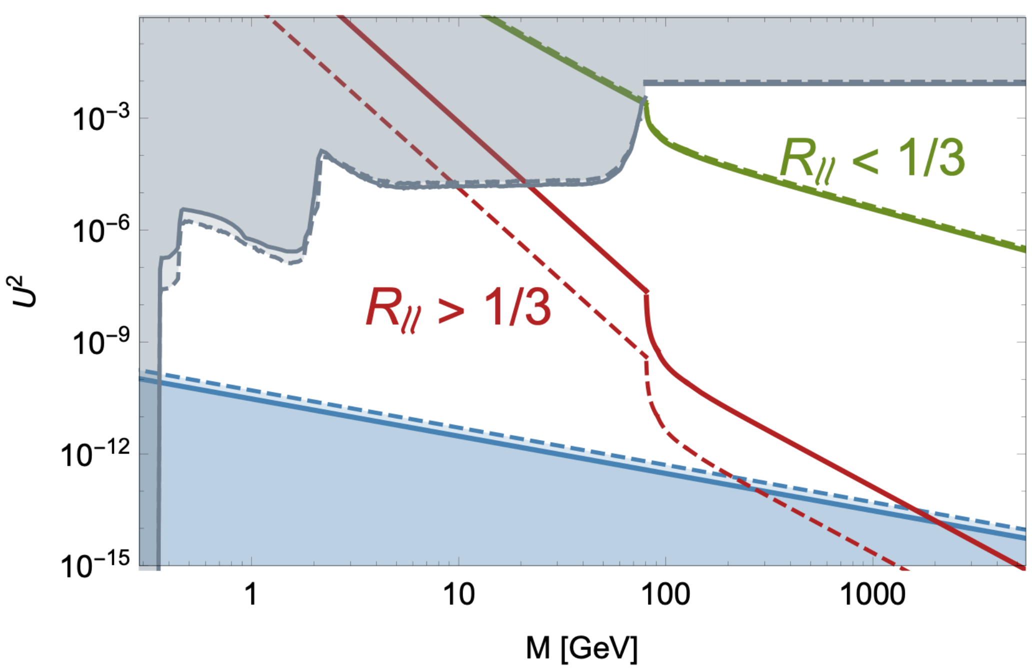
11 (6 free) parameters

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

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

Anamiati et al 1607.05641



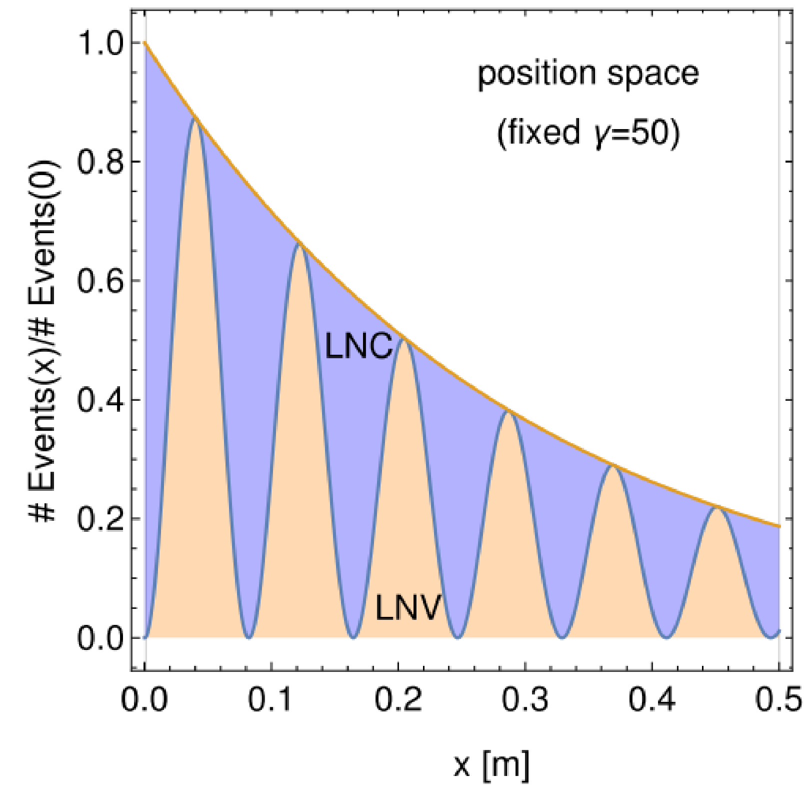
MaD/Klaric/Klose 1907.13034

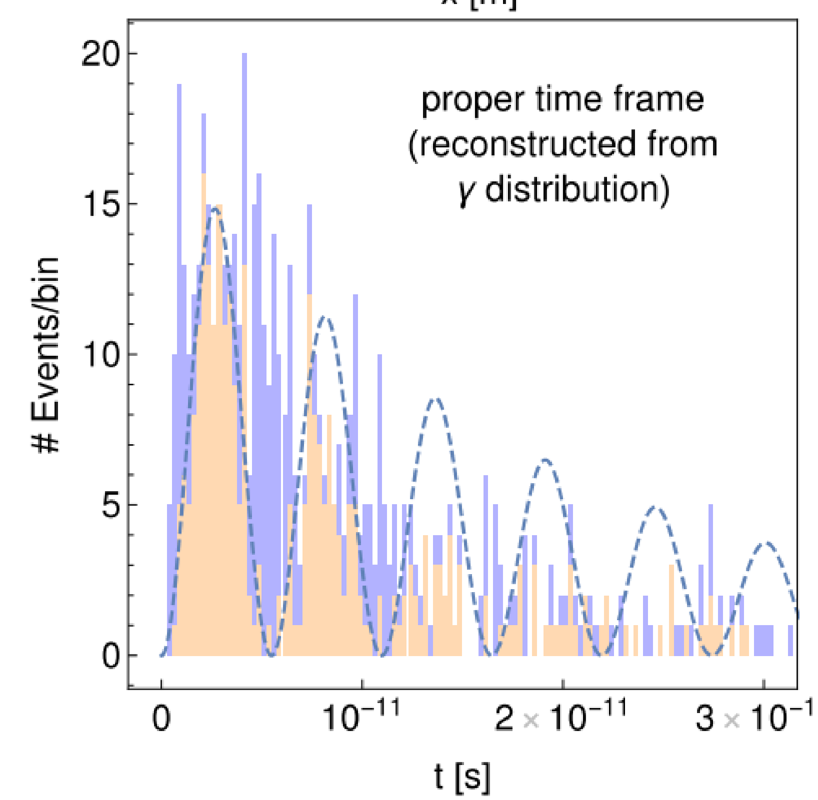
HNL oscillations may be resolved in LHC detectors

Antusch et al 1709.03797

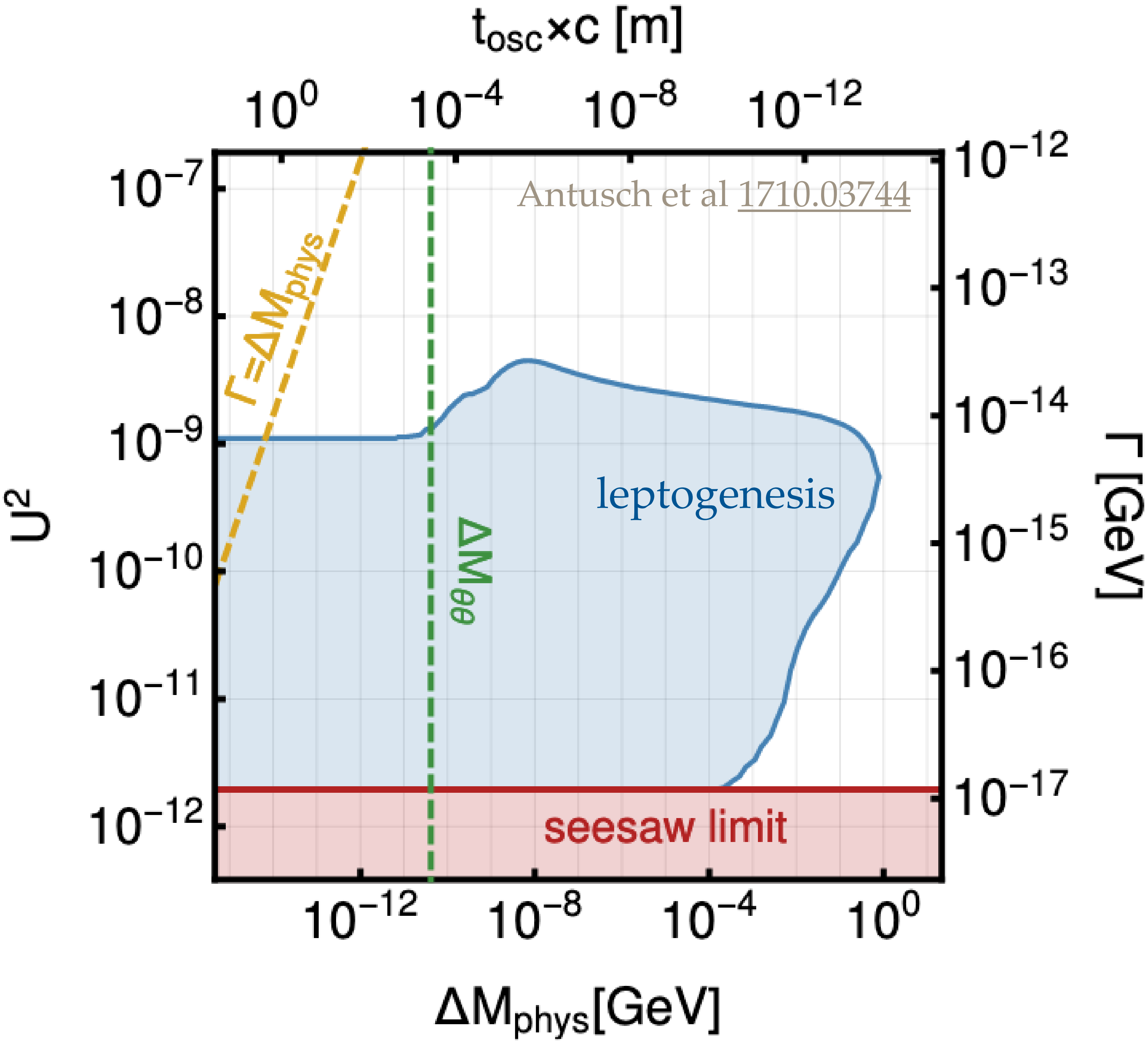
Measuring R_{ll} as a function of displacement helps testing leptogenesis!

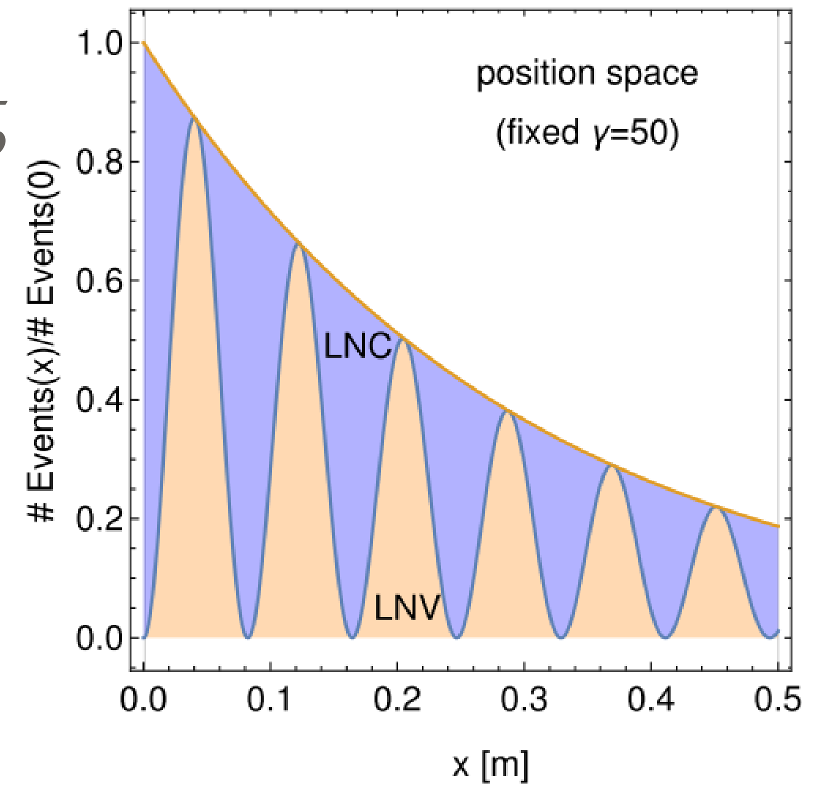
Antusch et al 1710.03744

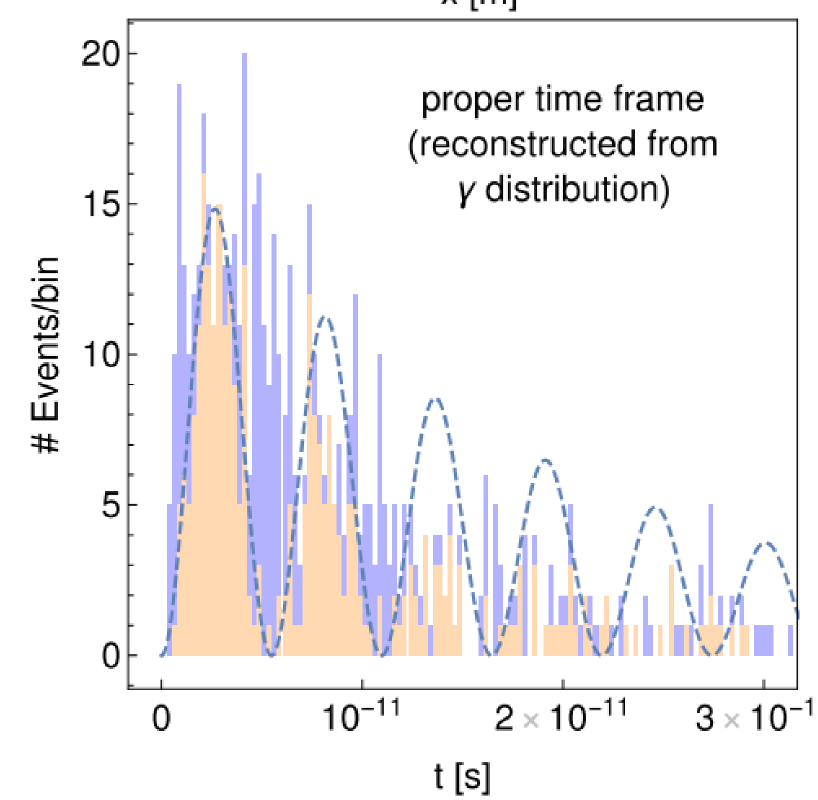




Testing Leptogenesis



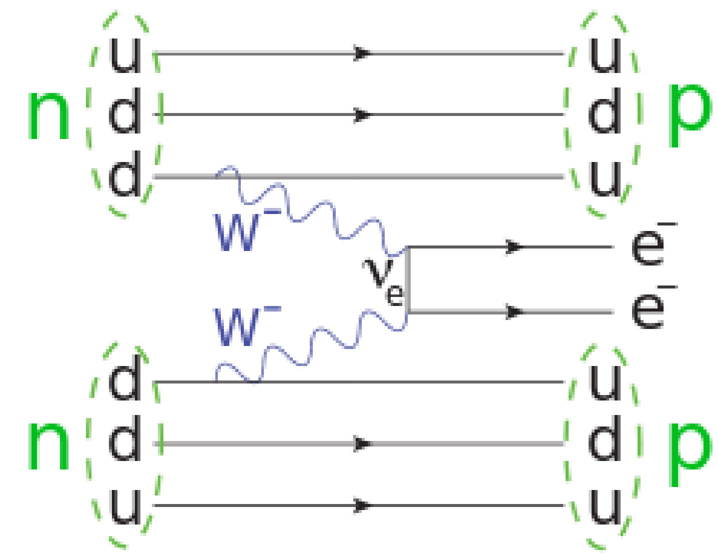




Heavy neutrinos in 0νββ Decay

- Heavy mass states also contribute to $m_{\beta\beta}$

$$m_{\beta\beta} = \left| \sum_i (U_\nu)^2_{ei} m_i + \sum_I \Theta^2_{eI} M_I f_A(M_I) \right|$$



- Example: Minimal model with 2 RH neutrinos

$$m_{\beta\beta} \simeq \Big| [1 - f_A(\bar{M})] m^\nu_{\beta\beta} + f_A^2(\bar{M}) \frac{\bar{M}^2}{\langle p^2 \rangle} \frac{\Delta M}{\bar{M}} |\Delta m_{\rm atm}| \sin^2\theta_{13} e^{2{\rm Im}\omega} e^{-2i({\rm Re}\omega + \delta)} \Big|$$

new contribution from RH neutrinos is sensitive to Reω

suppression of standard contribtion

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

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

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

- In the minimal model (νMSM-like) all parameters can in principle be constrained by experiment
  Hernandez et al 1606.06719 MaD et al 1609.09069
- This makes it a UV complete and testable model of neutrino masses and baryogenesis (and possibly a third HNL is DM)
- It is also a poster child example of cross frontier research