Marco Drewes, Université catholique de Louvain

The Neutrino Portal at CEPC

21. 07. 2024

International Workshop on New Opportunities for Particle Physics 2024

IHEP, Beijing, China

Overview

- Symmetry-protected low scale seesaw
- Searches for HNLs
- Neutrino Mixing and HNL branching ratios
- Neutrino Masses and LNV
- Model Testability

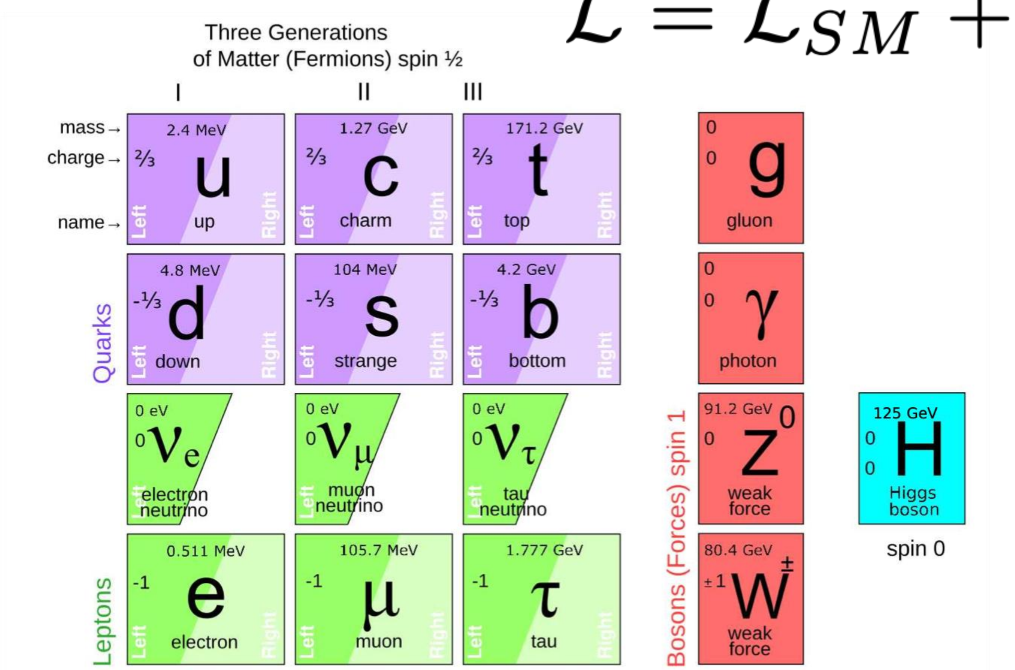
Biased towards type-I seesaw… for broader picture see e.g.

Deppisch/Dev/Pilaftsis et al 1502.06541

Cai/Han/Ruiz et al 1711.02180

Bhupal Dev's talk

The Seesaw Mechanism (type I)



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

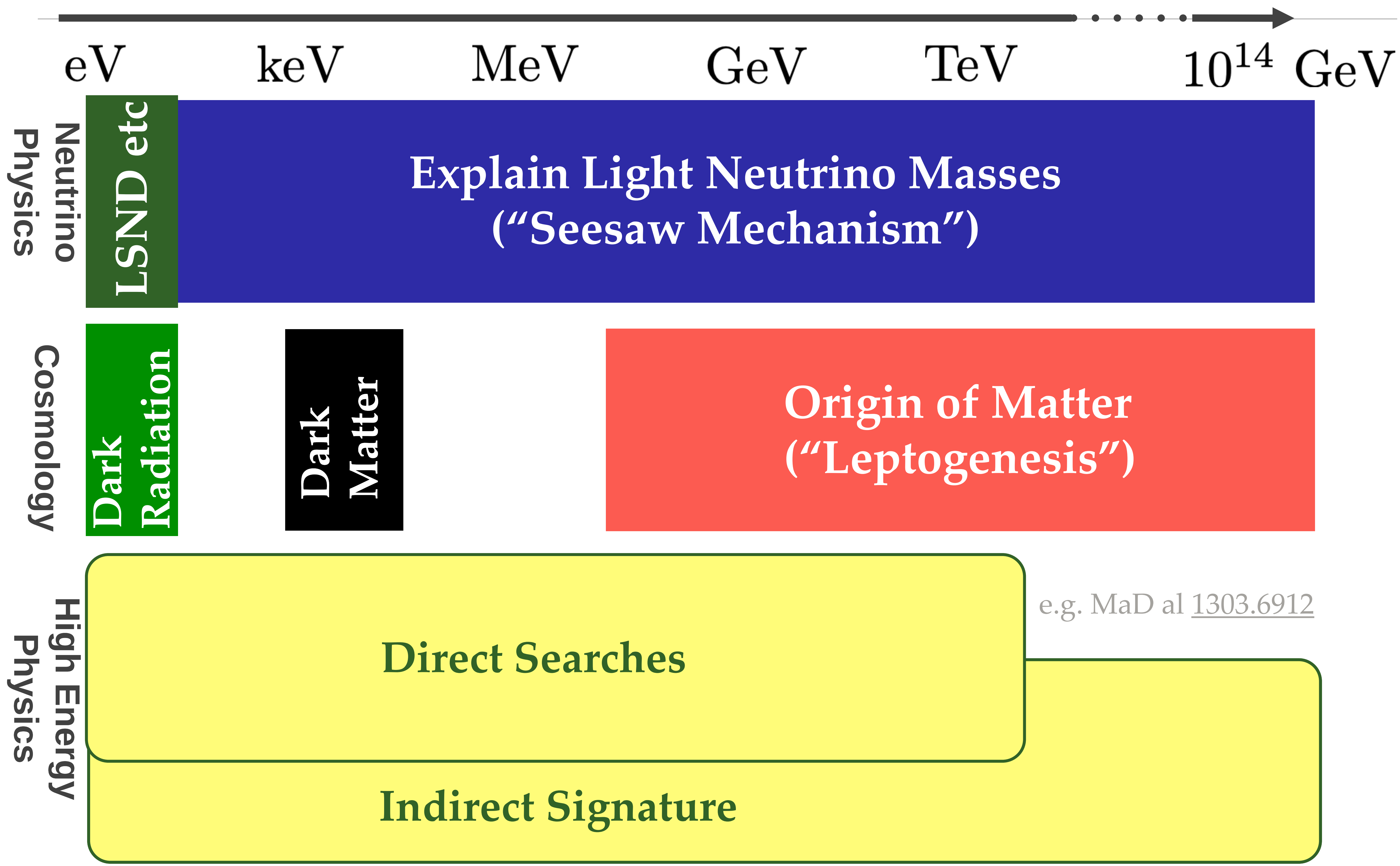
three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

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

Heavy Neutrino Mass Scale



Symmetry Protected Low Scale Seesaw

Why are the Neutrino masses small?

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

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

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

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

- 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

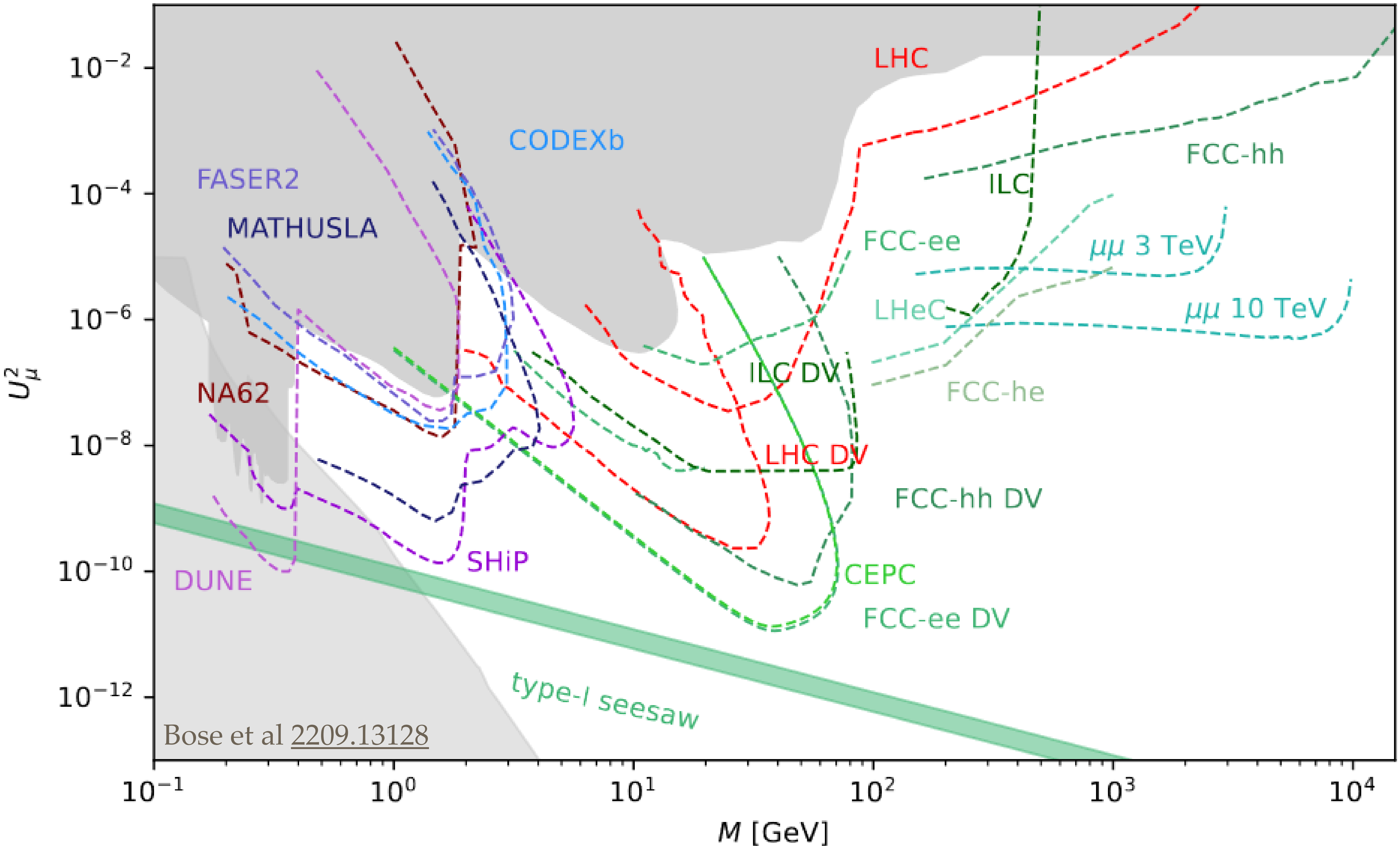
Searches for HNLs

The Search for Heavy Majorana Neutrinos #2

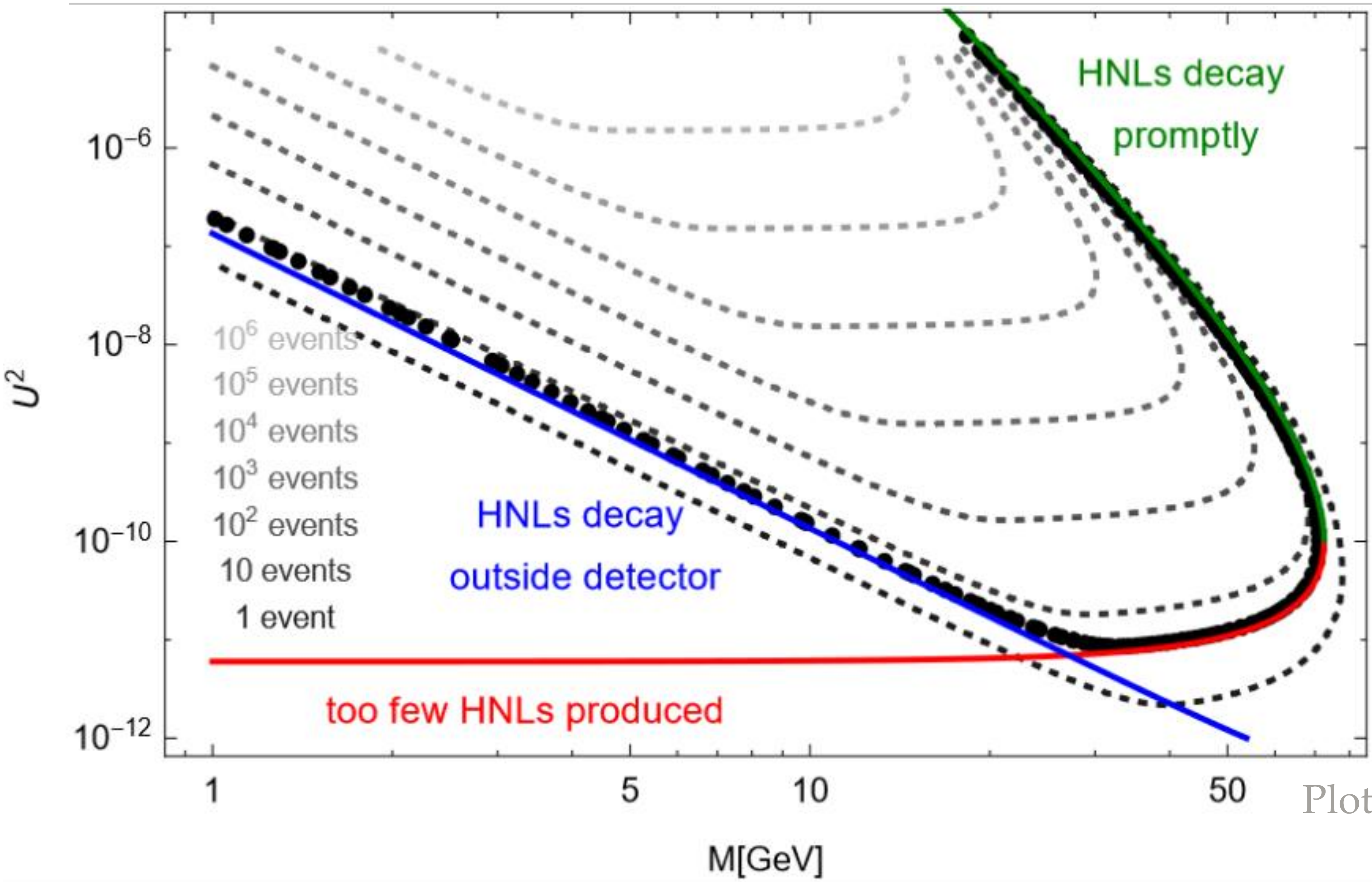
Anupama Atre (Santa Barbara, KITP and Fermilab), Tao Han (Tsinghua U., Beijing and Wisconsin U., Madison and Santa Barbara, KITP), Silvia Pascoli (Durham U. and Durham U., IPPP), Bin Zhang (Tsinghua U., Beijing) (Jan, 2009)

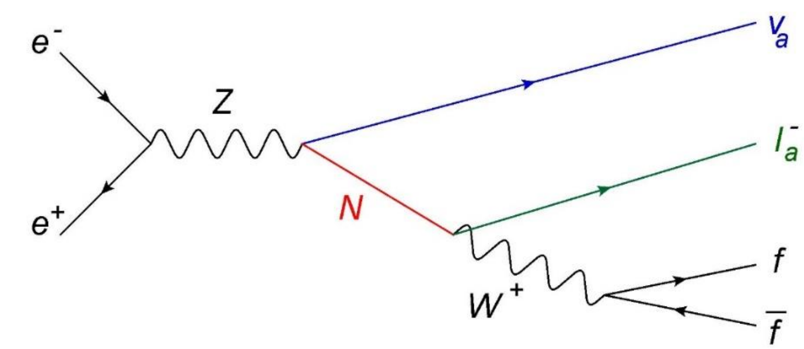
Published in: *JHEP* 05 (2009) 030 • e-Print: 0901.3589 [hep-ph]

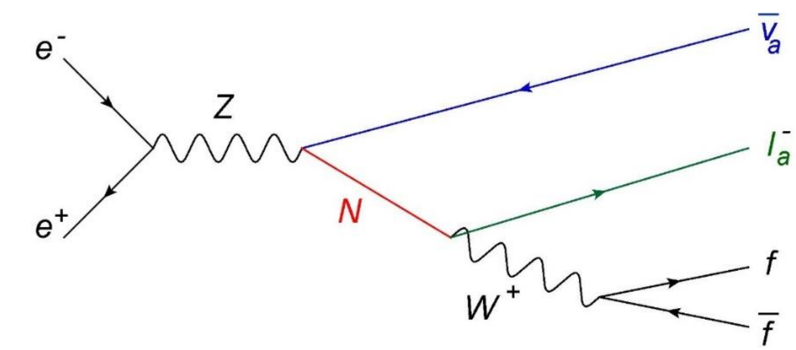
HNL Search Summary



DV Vertex Searches CEPC Z-pole Run







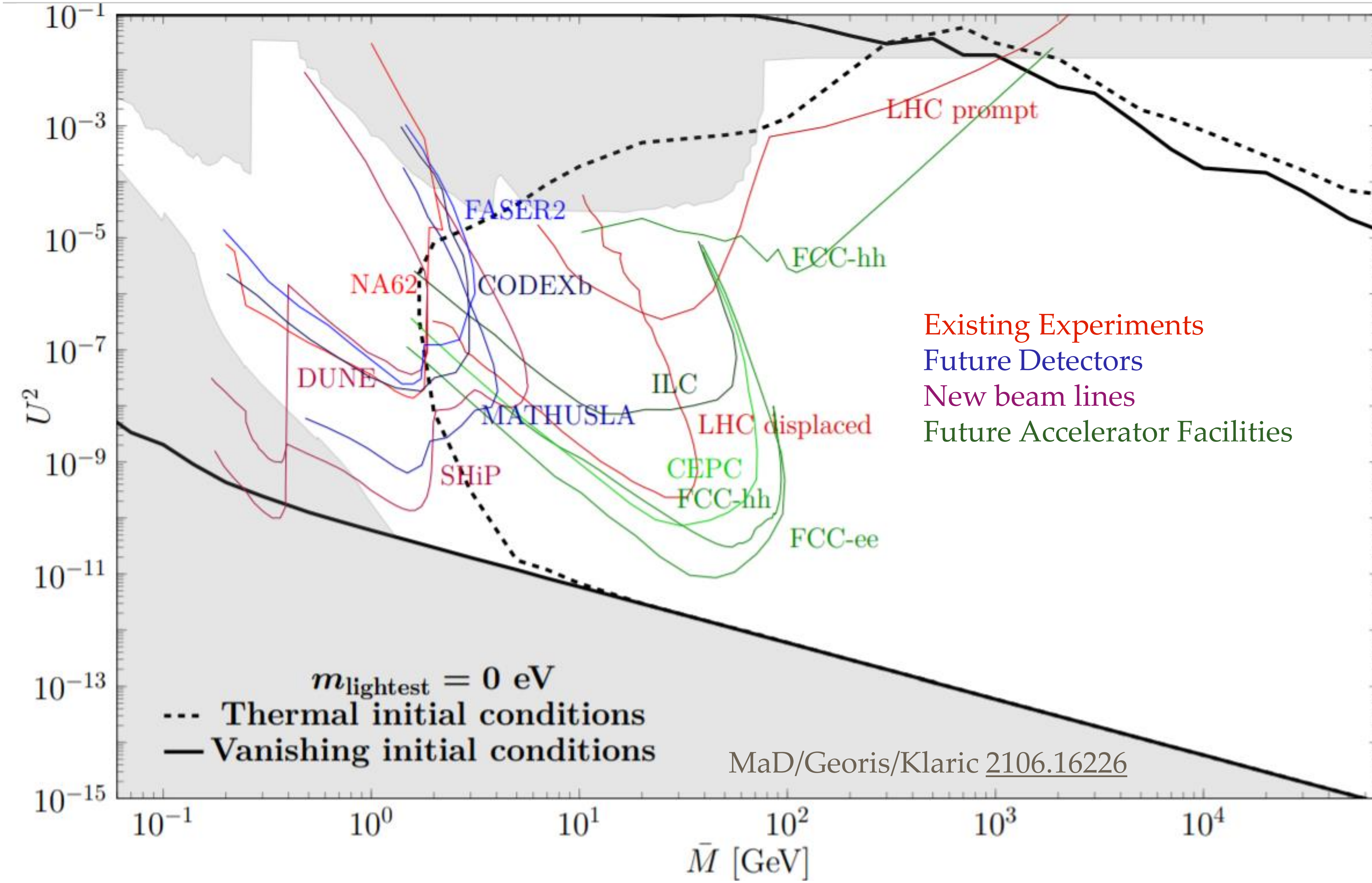
proposed in Blondel et al 1411.5230

Plot and estimates from MaD 2210.17110

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

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

HNL Searches vs Leptogenesis



MaD/Georis/Klaric 2106.16226

Neutrino Mixing:
HNL Branching Ratios

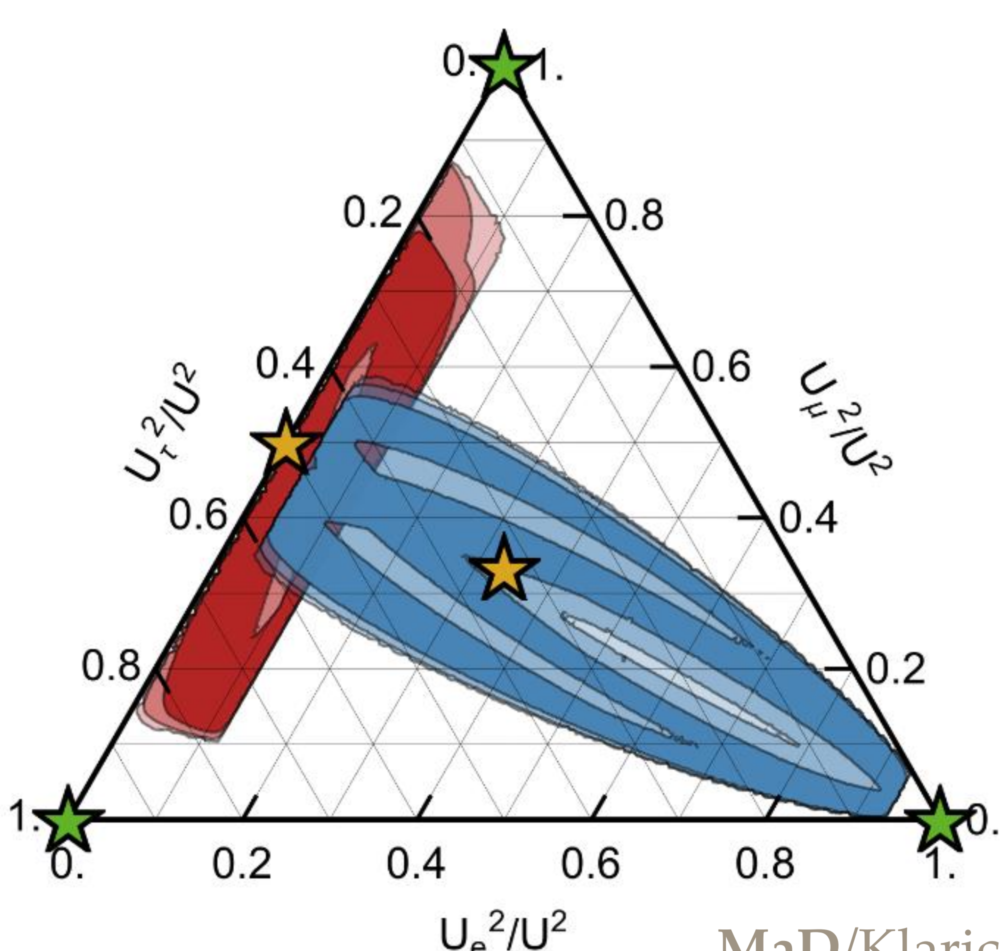
Branching Ratios with 2 HNLs

- Branching ratios of HNL decays given by parameters in PMNS

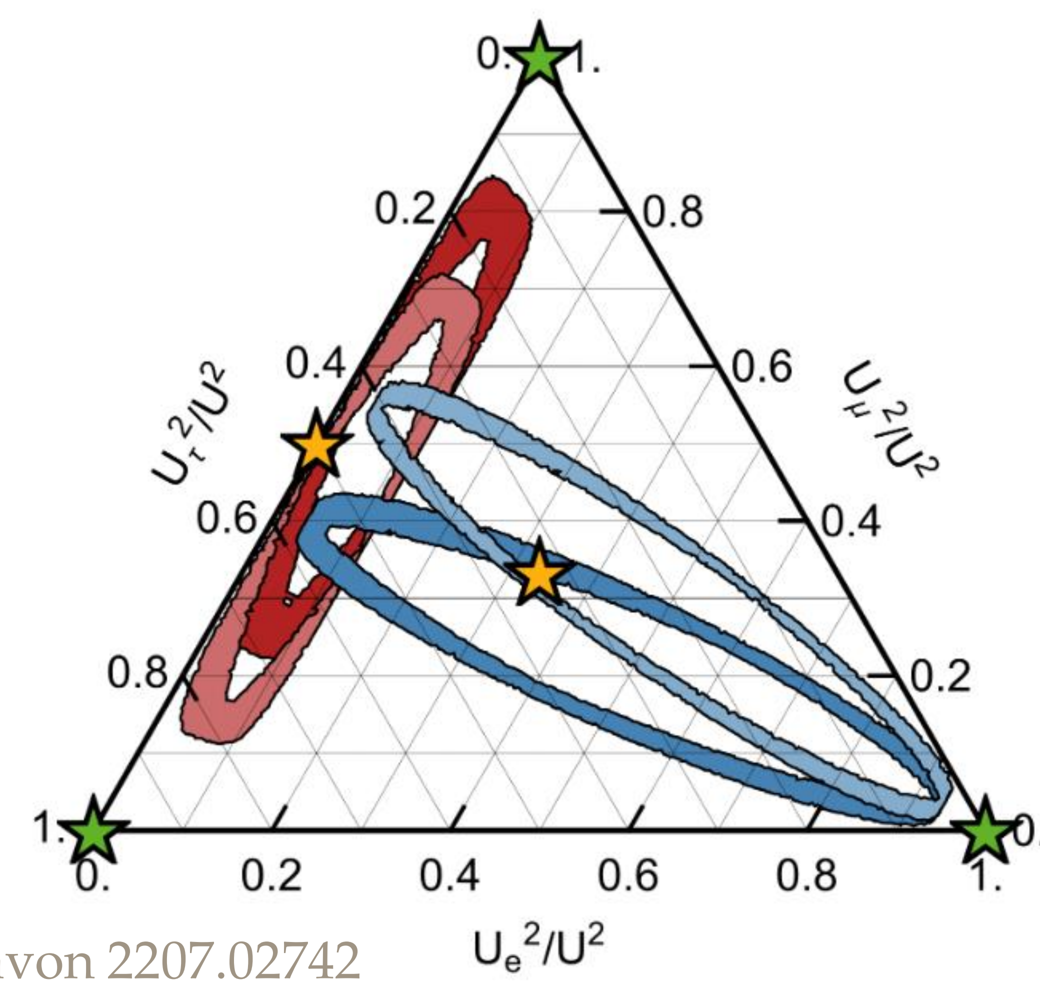
Hernandez et al 1606.06719 MaD et al 1609.09069

- 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



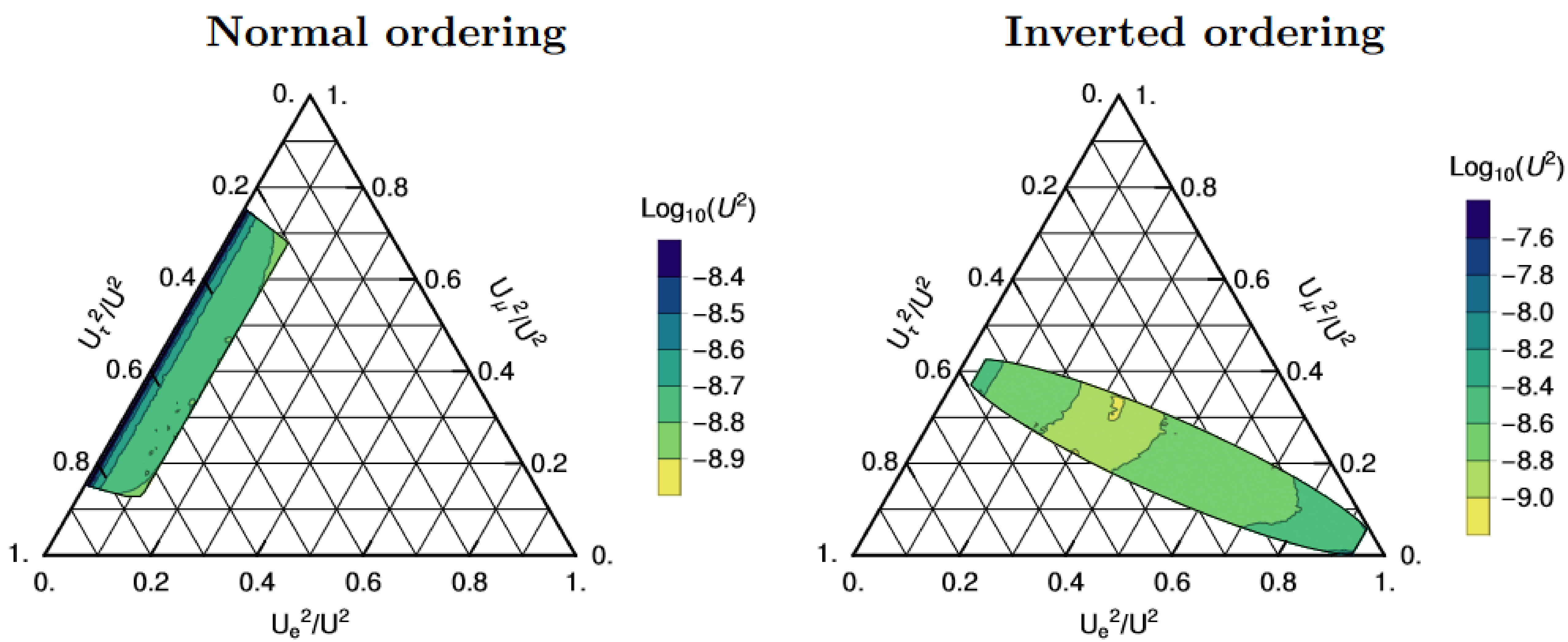
Current constraints



DUNE projection

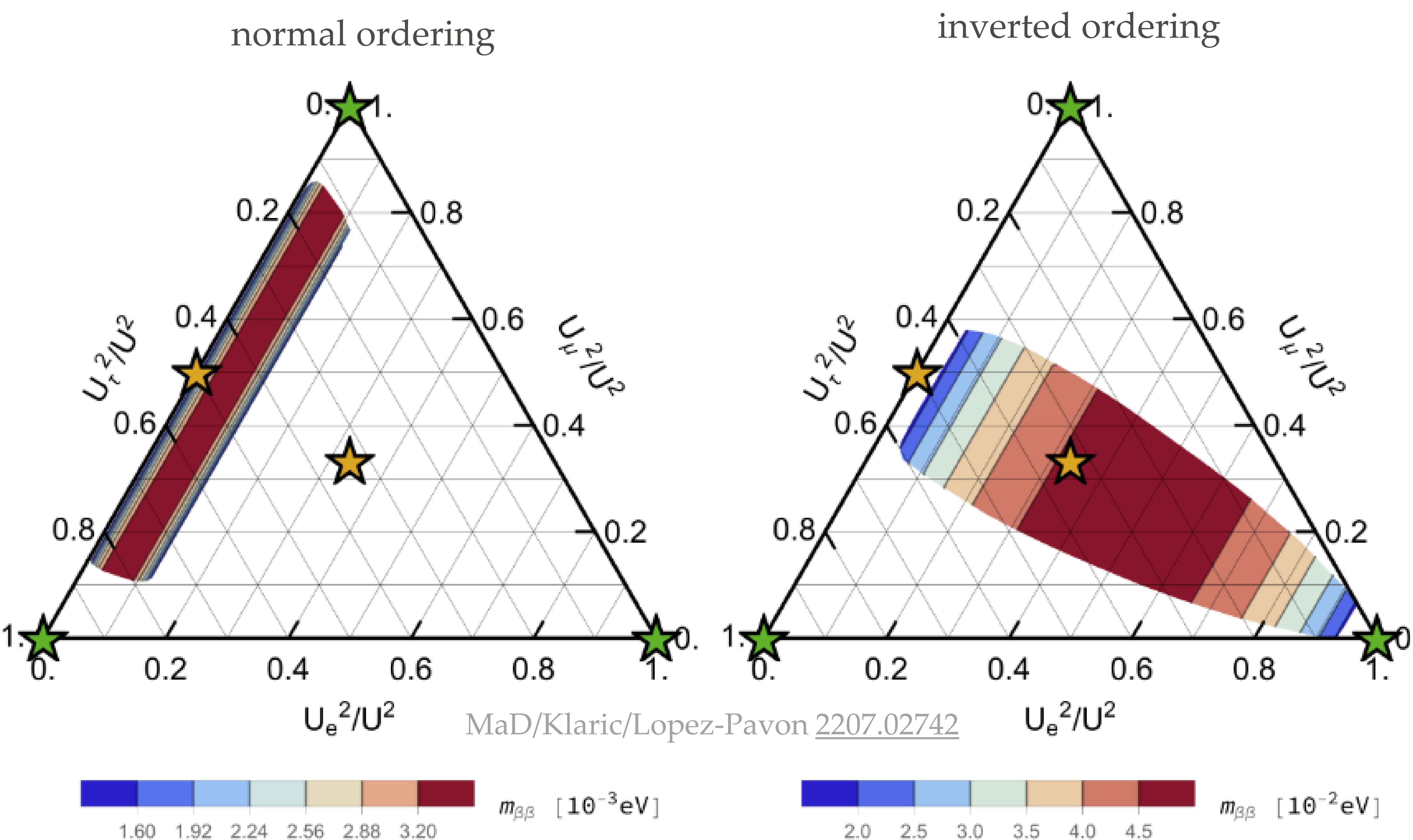
MaD/Klaric/Lopez-Pavon 2207.02742

Leptogenesis Flavour Predictions



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

Predictions for 0νββ Decay



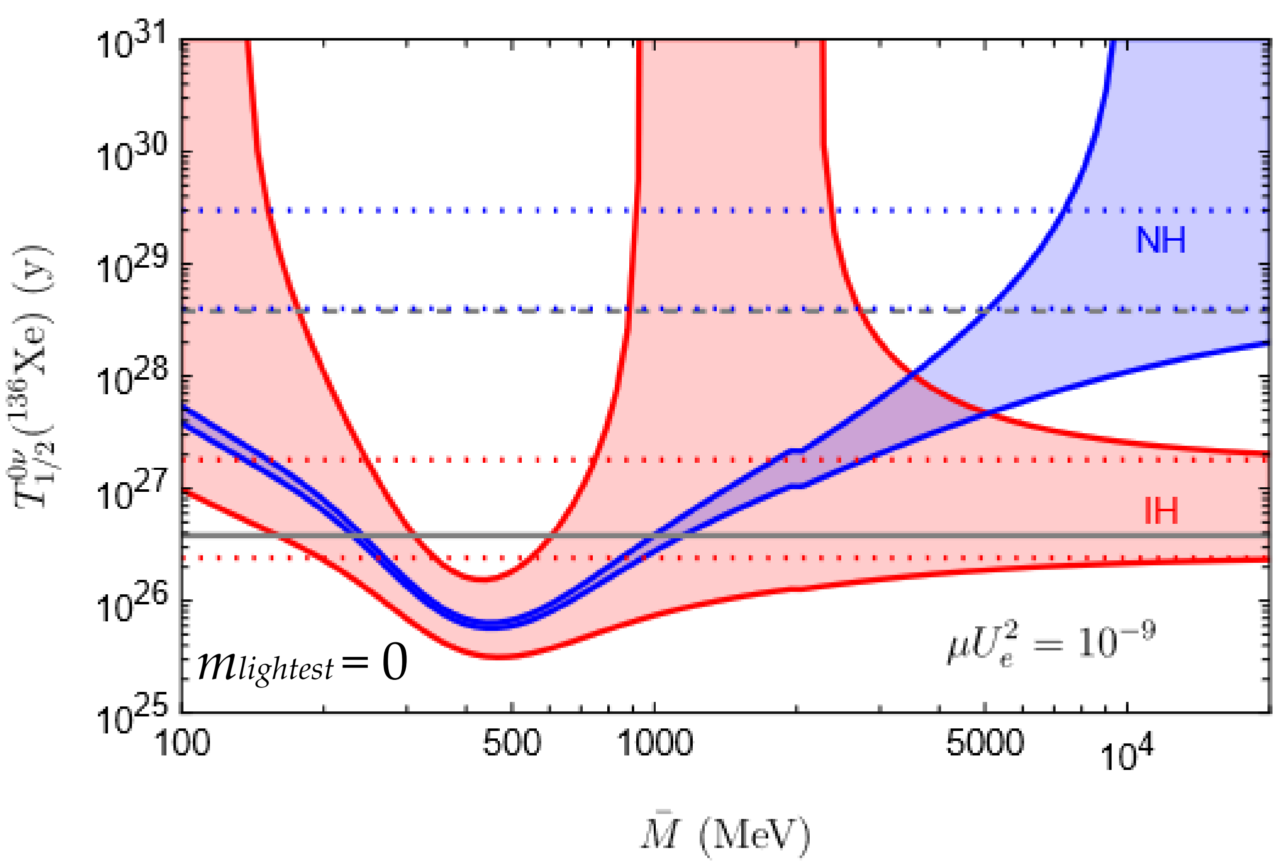
MaD/Klaric/Lopez-Pavon 2207.02742

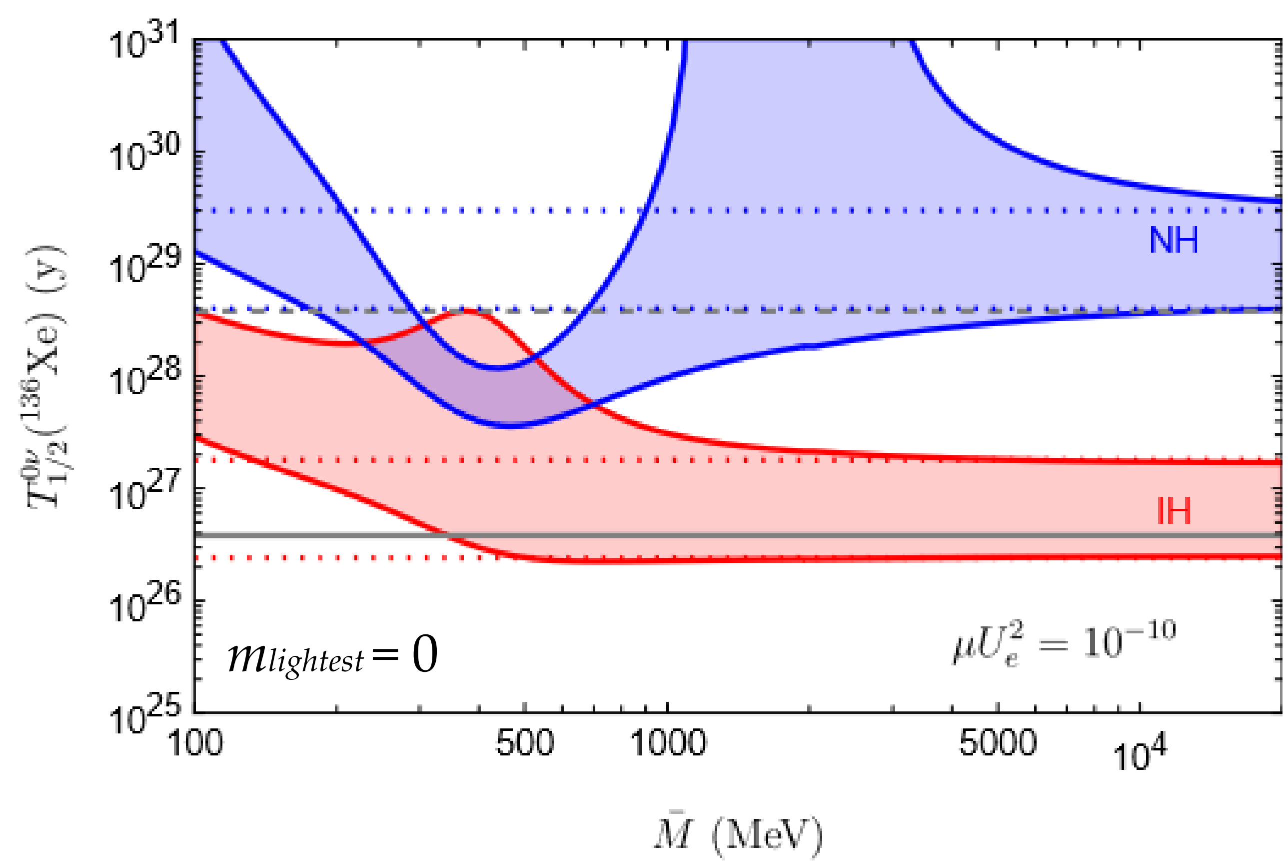
Predictions for 0νββ Decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} \to G_{01}\, g_A^4\, |\mathcal{A}(0)|^2 \frac{V_{ud}^4}{m_e^2} \left| \sum_{i=1}^{5} m_i \mathcal{U}_{ei}^2 \right|^2 \sim |(M_\nu)_{ee}|^2 = 0$$

$$\bar{m}_{\beta\beta} = m_{\beta\beta} \left[1 - \frac{\mathcal{A}(\bar{M})}{\mathcal{A}(0)}\right] - \frac{\bar{M}^2 \mu}{2} \frac{\mathcal{A}'(\bar{M})}{\mathcal{A}(0)} \left(\theta_{e4}^2 - \theta_{e5}^2\right)$$

de Vries et al 2407.10560



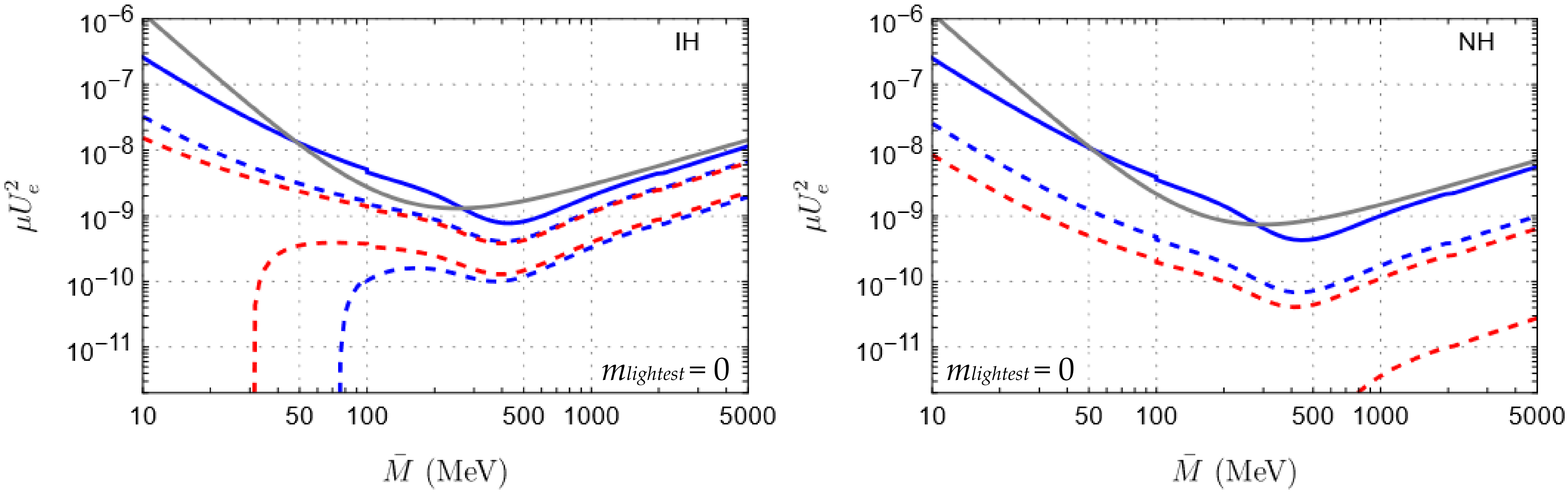


Predictions for 0νββ Decay

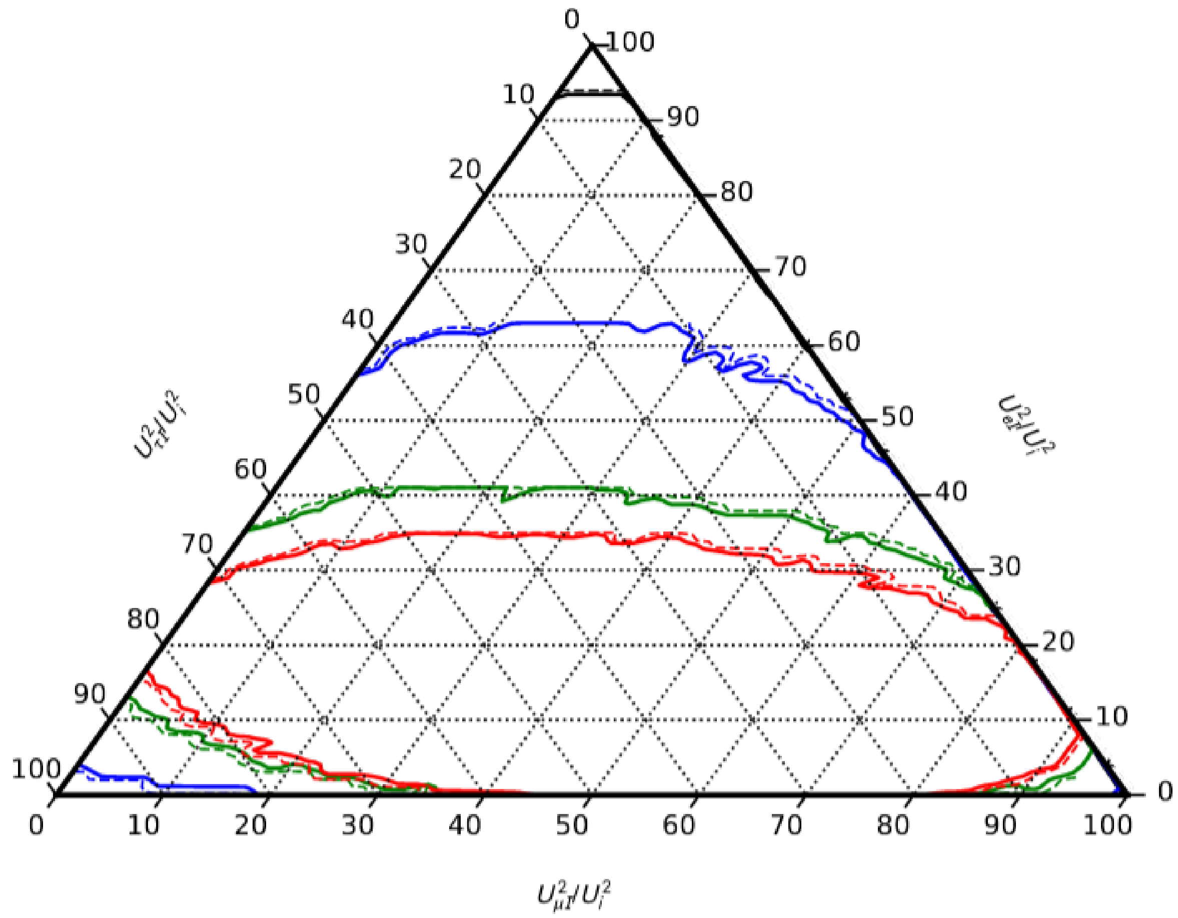
$$\left(T_{1/2}^{0\nu}\right)^{-1} \to G_{01}\, g_A^4\, |\mathcal{A}(0)|^2 \frac{V_{ud}^4}{m_e^2} \left| \sum_{i=1}^{5} m_i \mathcal{U}_{ei}^2 \right|^2 \sim |(M_\nu)_{ee}|^2 = 0$$

$$\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{\mathcal{A}(\bar{M})}{\mathcal{A}(0)}\right] - \frac{\bar{M}^2 \mu}{2} \frac{\mathcal{A}'(\bar{M})}{\mathcal{A}(0)} \left(\theta_{e4}^2 - \theta_{e5}^2\right)$$

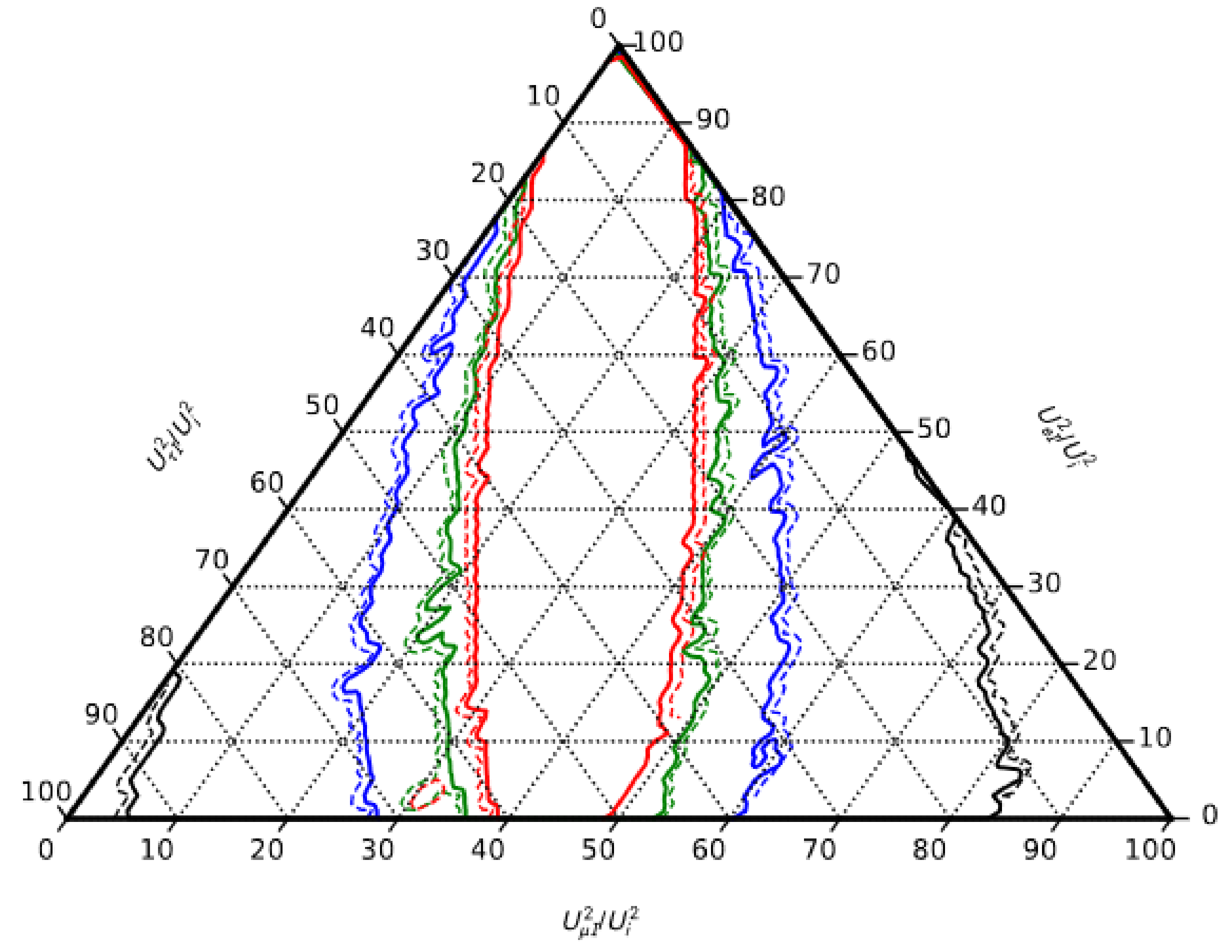
de Vries et al 2407.10560



Branching Ratios with 3 HNLs



normal ordering



inverted ordering

$m_{lightest} < 10$ meV

$m_{lightest} < 1$ meV

$m_{lightest} < 0.1$ meV

$m_{lightest} < 0.01$ meV

Chrzaszcz et al 1908.02302

Additional Global Symmetries

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

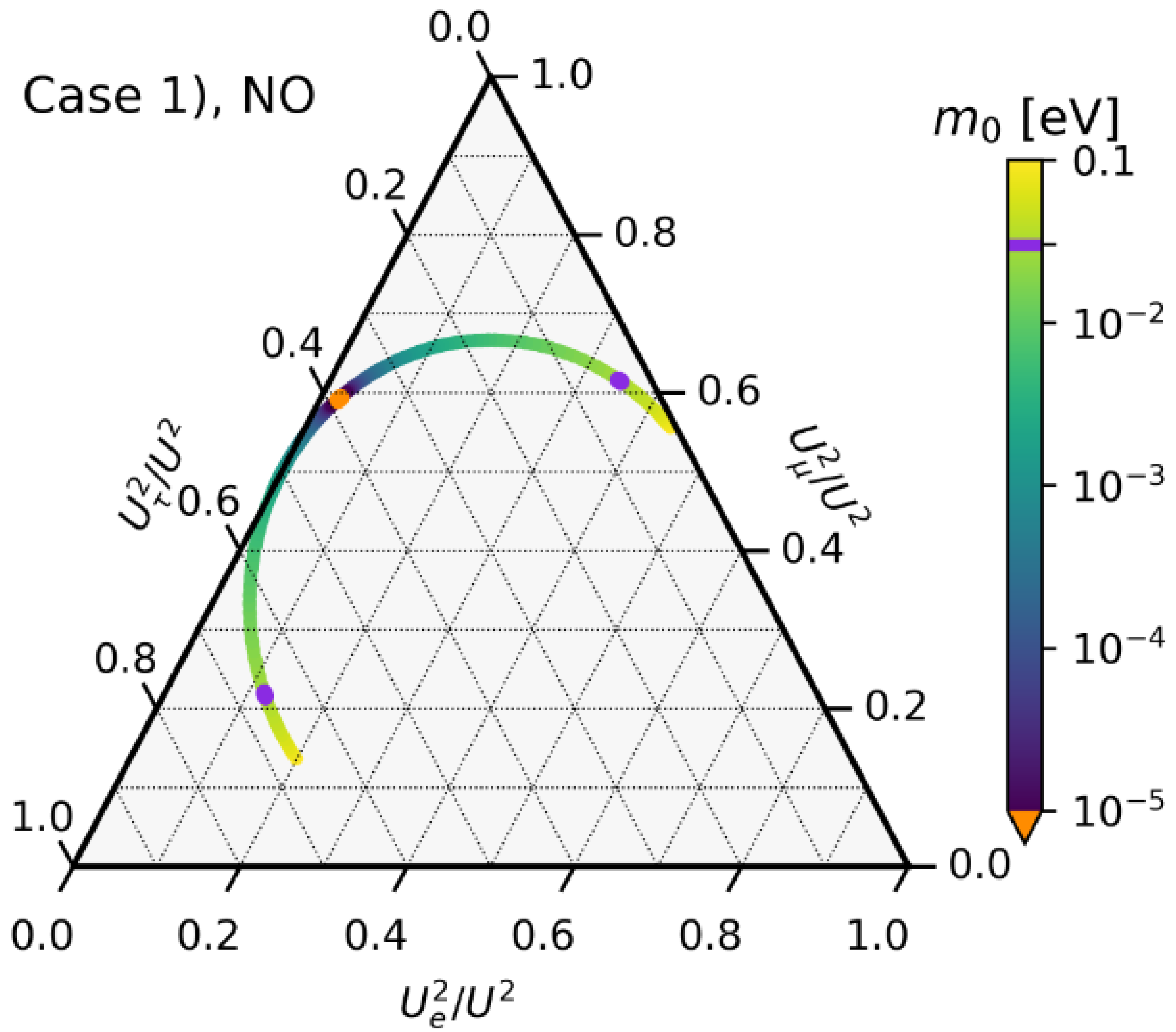
  See e.g. King 1701.04413, Xing 1909.09610

- 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

  Chauhan et al 2310.20681
  MaD/Georis/Hagedorn/Klaric 2203.08538, 2xxx.xxxxx

3 HNLs with Discrete Symmetries

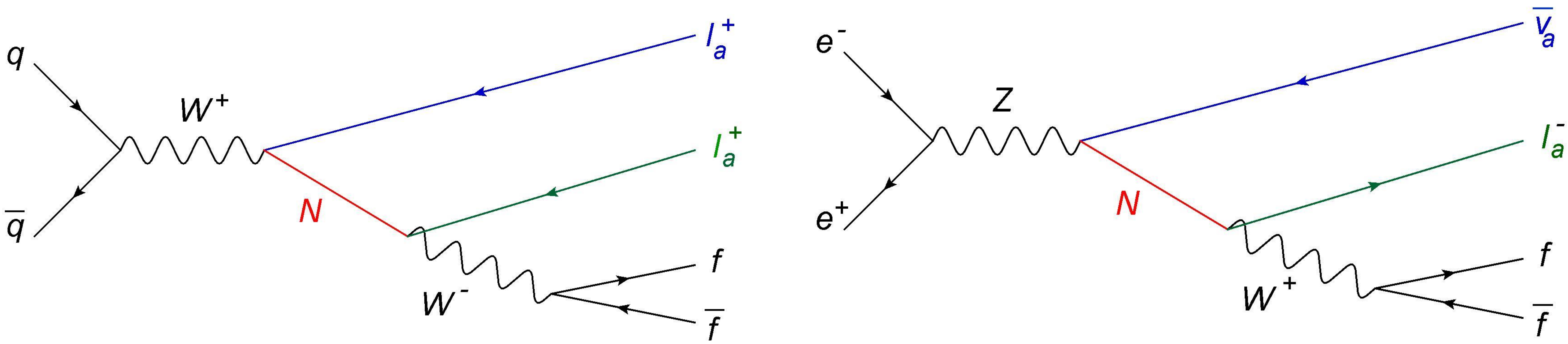


- With discrete flavour and CP symmetries: Mixing pattern very predictive
- Even more predictive if lightest neutrino mass is measured

Plot from Georis 2401.04840
Based on MaD/Georis/Hagedorn/Klaric 2203.08538

Neutrino Masses:
Lepton Number Violation

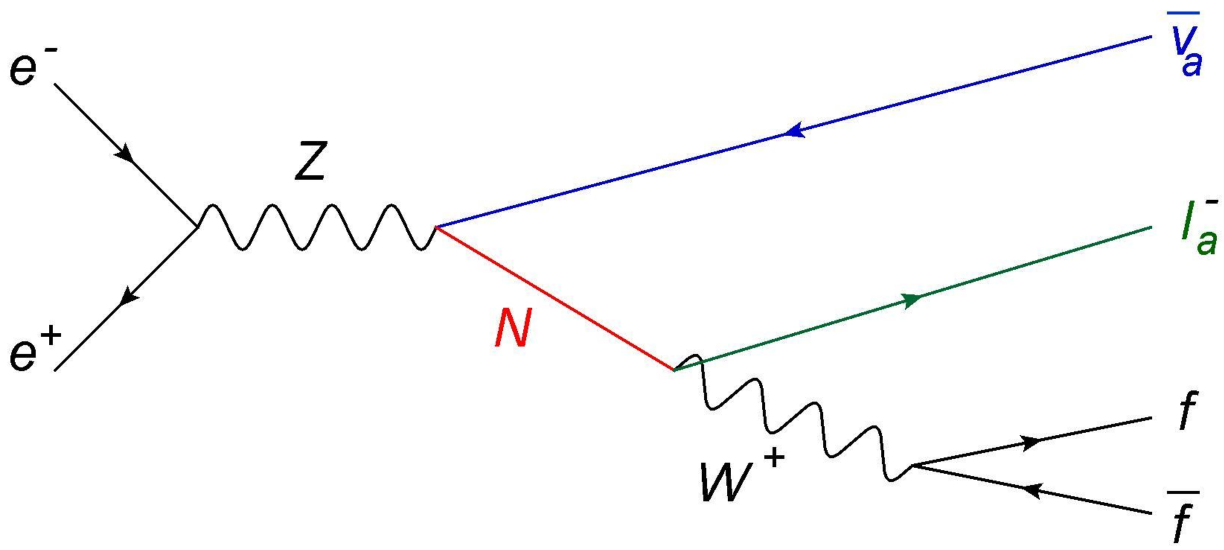
How to observe LNV?

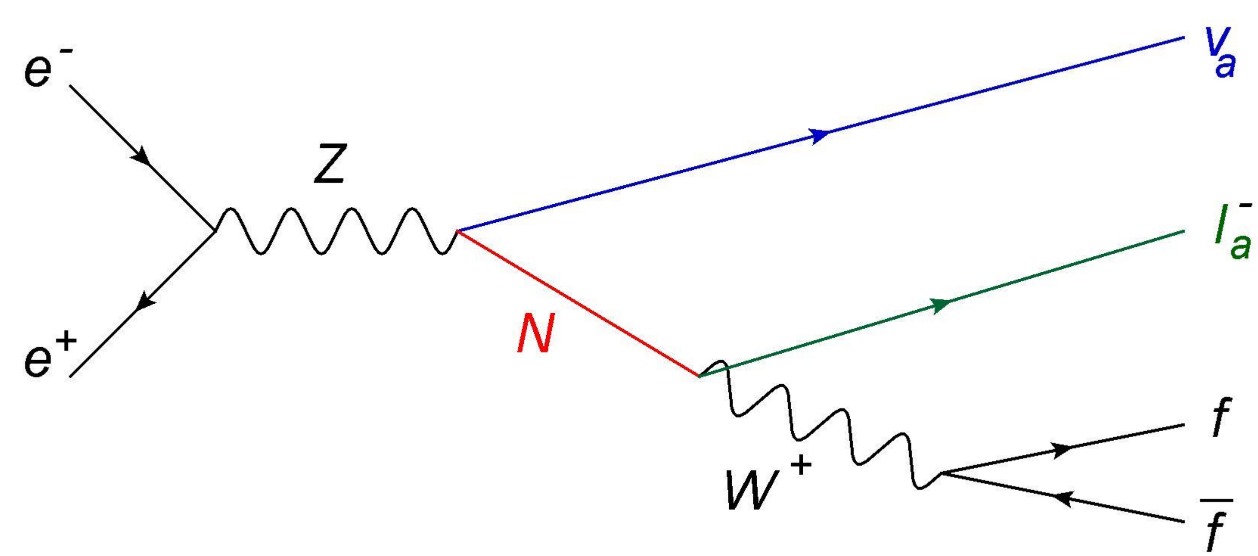


How to practically distinguish Dirac from Majorana *N*?

1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N

LNV at Lepton Colliders





Z-bosons are polarised due to P-violation of weak interaction:

$$g_R = 2\sin^2\theta_W \qquad g_L = (1 - 2\sin^2\theta_W) \qquad P_Z = \frac{(g_R^2 - g_L^2)}{(g_L^2 + g_R^2)} \simeq -0.15$$

- Chiral nature of weak interaction correlates charge, spin, and momenta of observable final state particles to spin of initial Z-boson

e.g. Blondel et al 2105.06576

- This correlation depends on whether HNLs are Dirac or Majorana

Observables:

- **Forward-backward asymmetry of charged leptons**: vanishes in Majorana case, is proportional to Z-polarisation in Dirac case
- **Energy distribution of charged leptons**: Dirac N and anti-N are highly polarised, while Majorana H are only mildly polarised, leading to different charged lepton spectra

Constraining LNV from HNL Lifetime

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

$$\sigma_N = U^2 \sigma_\nu \times [\text{phase space}]$$

- HNL decay length depends on availability of LNV channels

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

Dirac: : $c_{dec} = 1/2$,
Majorana: $c_{dec} = 1$

[note: dichotomy of Dirac vs Majorana HNLs generally not sufficient to capture realistic models, see below]

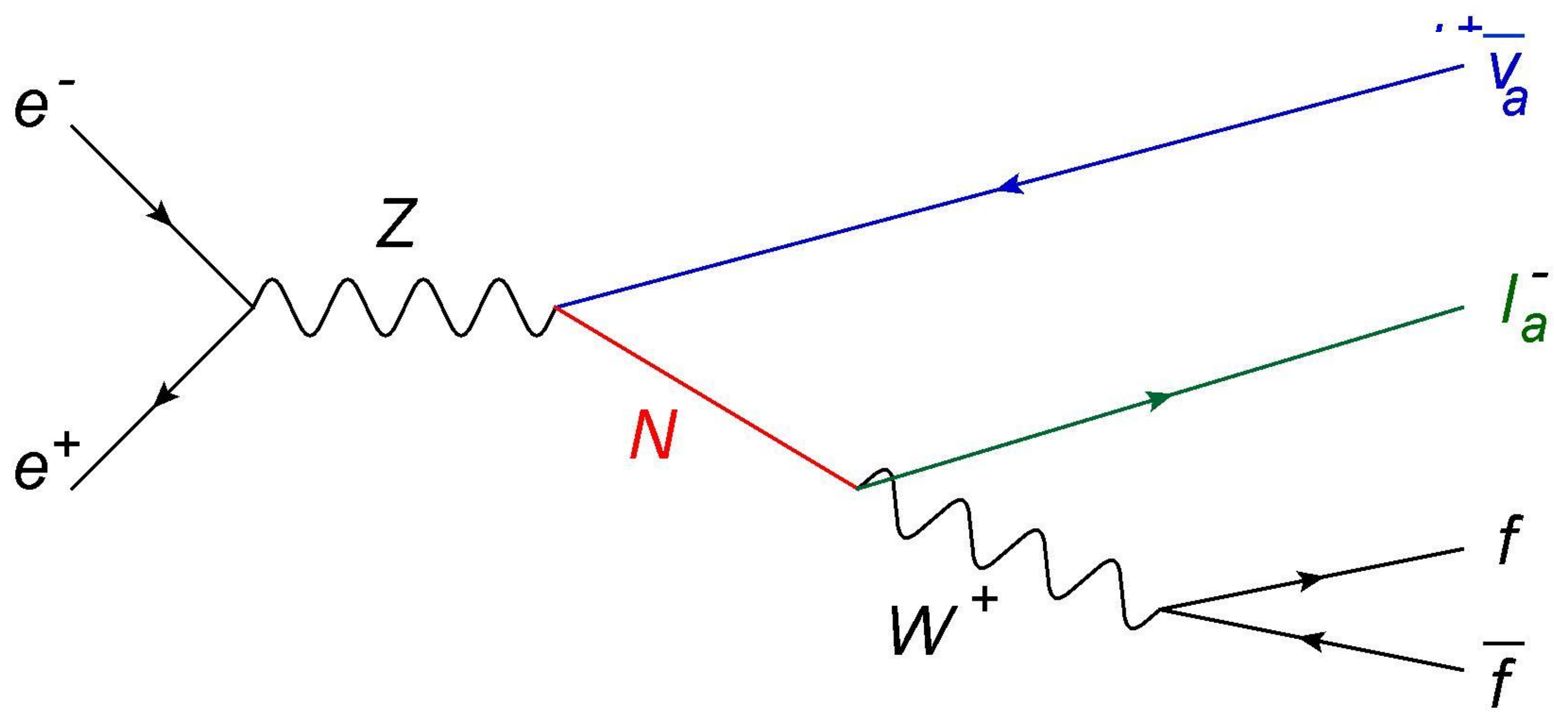
- HNL mass extracted from full 4-momentum reconstruction or from time-of-flight

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

Alimena et al 2203.05502
MaD 2210.17110

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 *Rll*!**

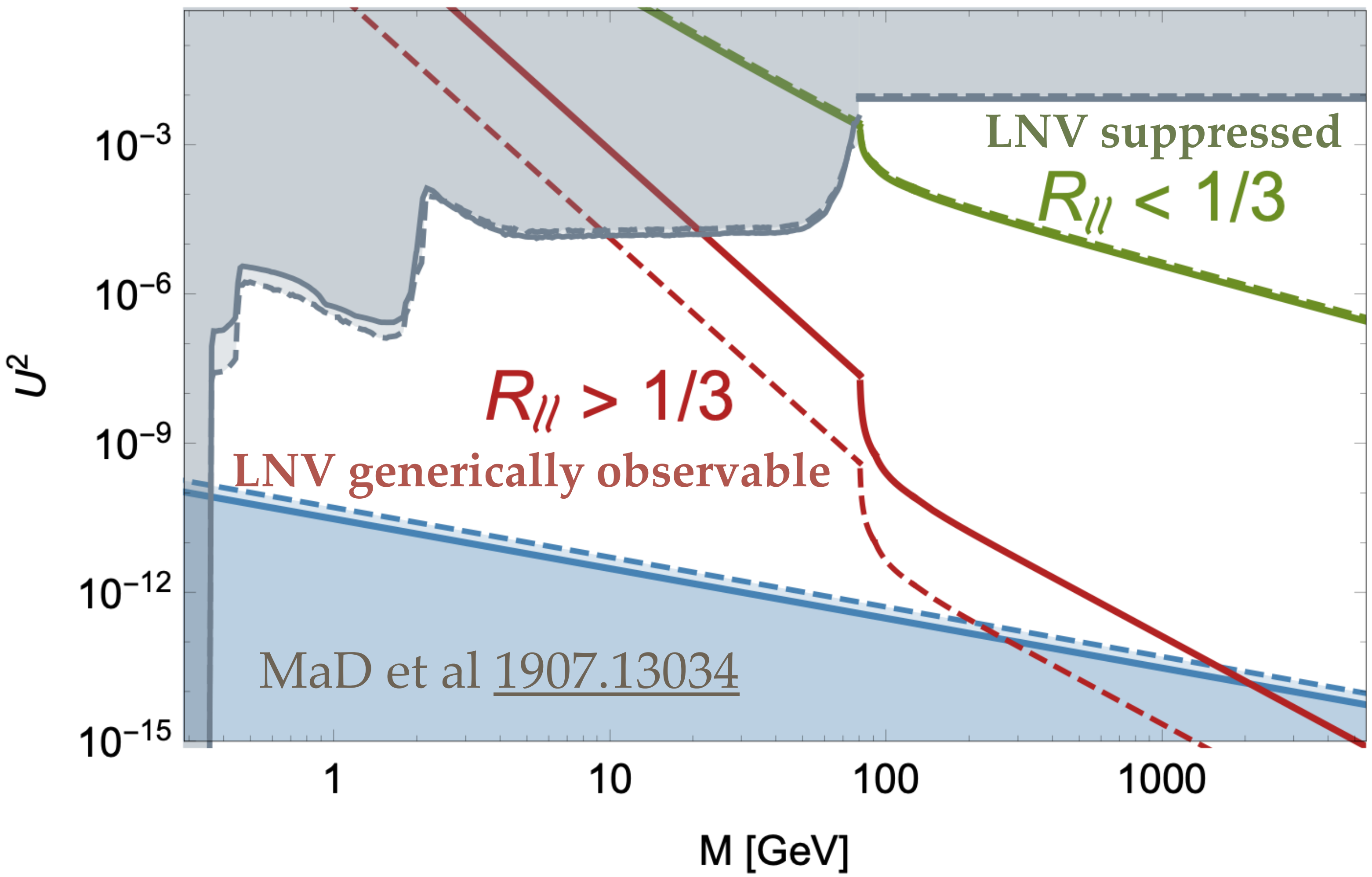
e.g. Deppisch et al 1502.06541

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

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

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?



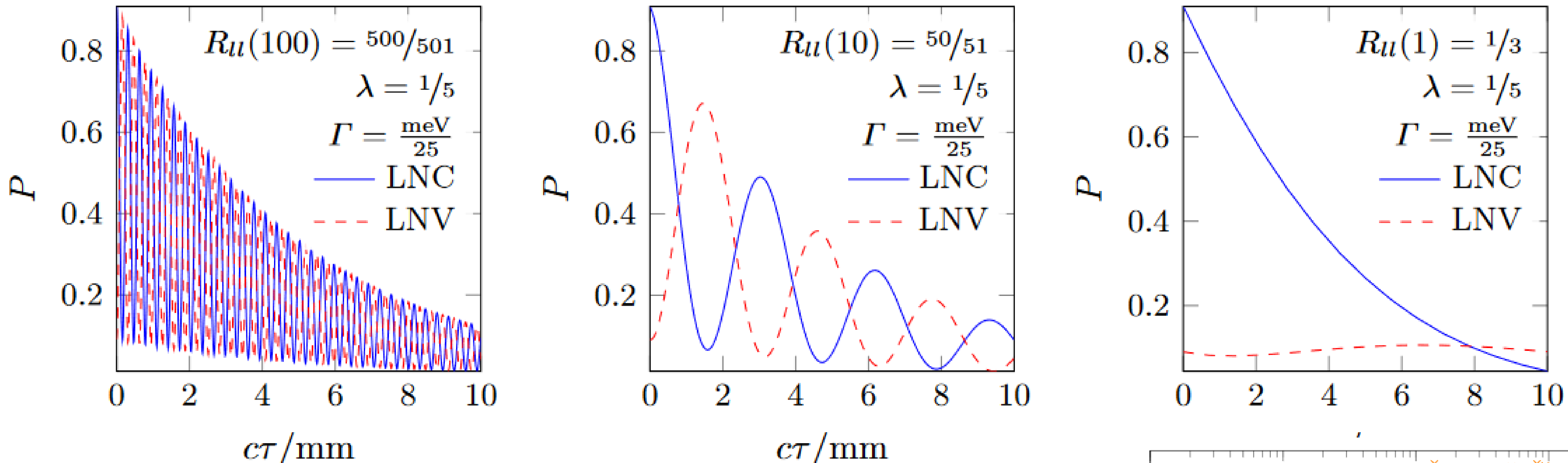
- **Quasi-degenerate HNLs kinematically indistinguishable**
- **behave like one particle with non-integer R_{ll}!**

e.g. Deppisch et al 1502.06541

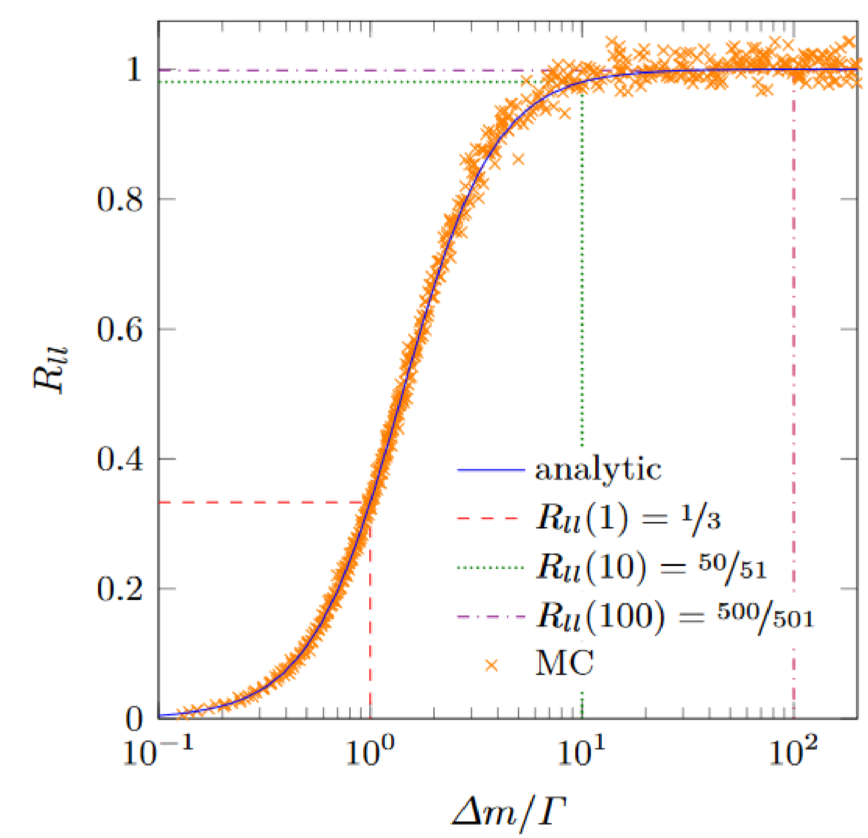
$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

- suppression happens by destructive interference between exchange of different HNLs
- interference can be avoided if quantum coherence is lost between production and decay
- relevant quantity is the ratio between their lifetime and oscillation frequency
- both related to light neutrino masses, can identify region where LNV is expected

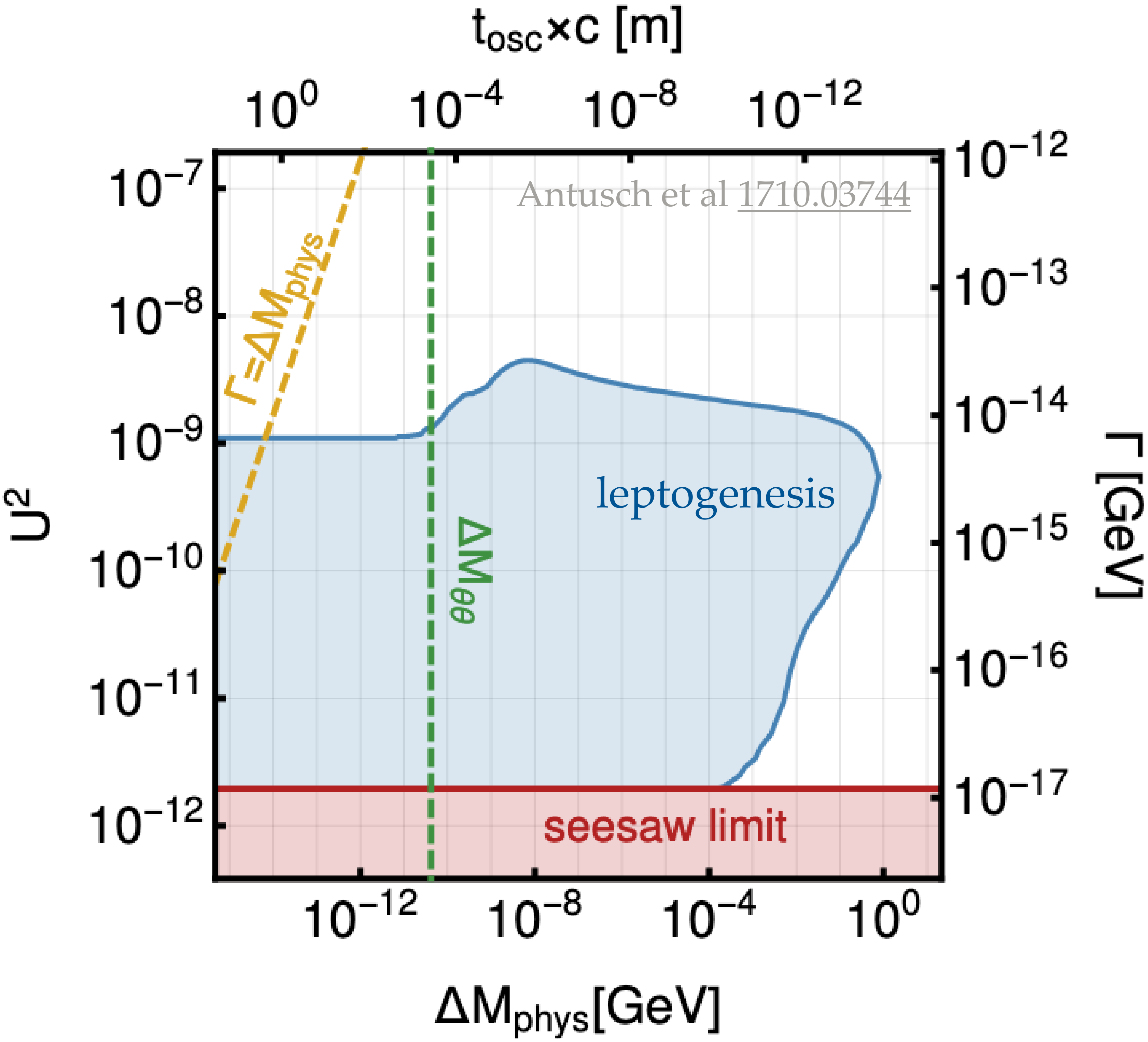
Simulating Heavy Neutrino Oscillations

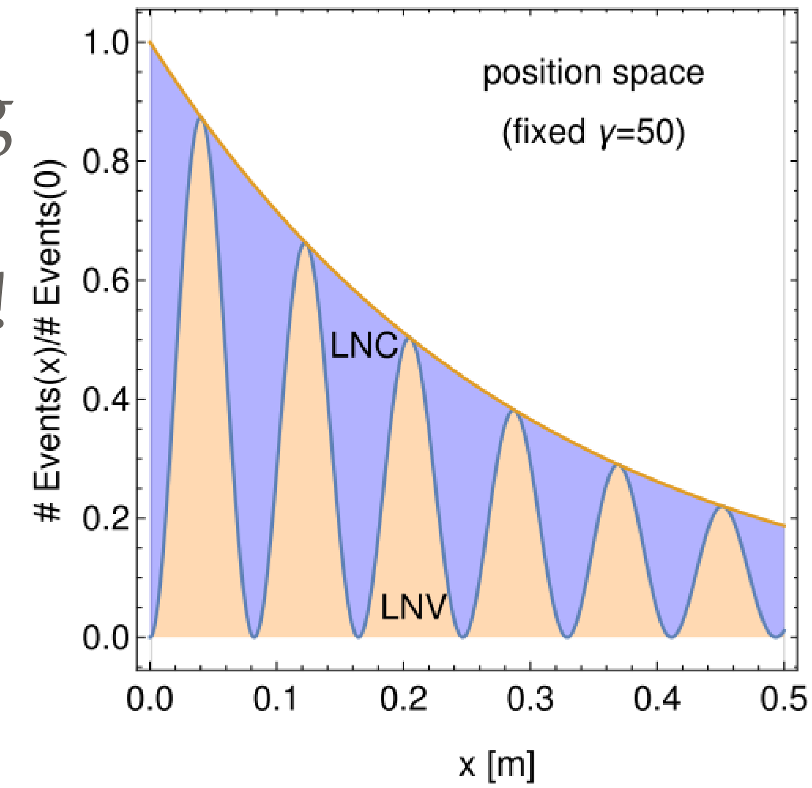


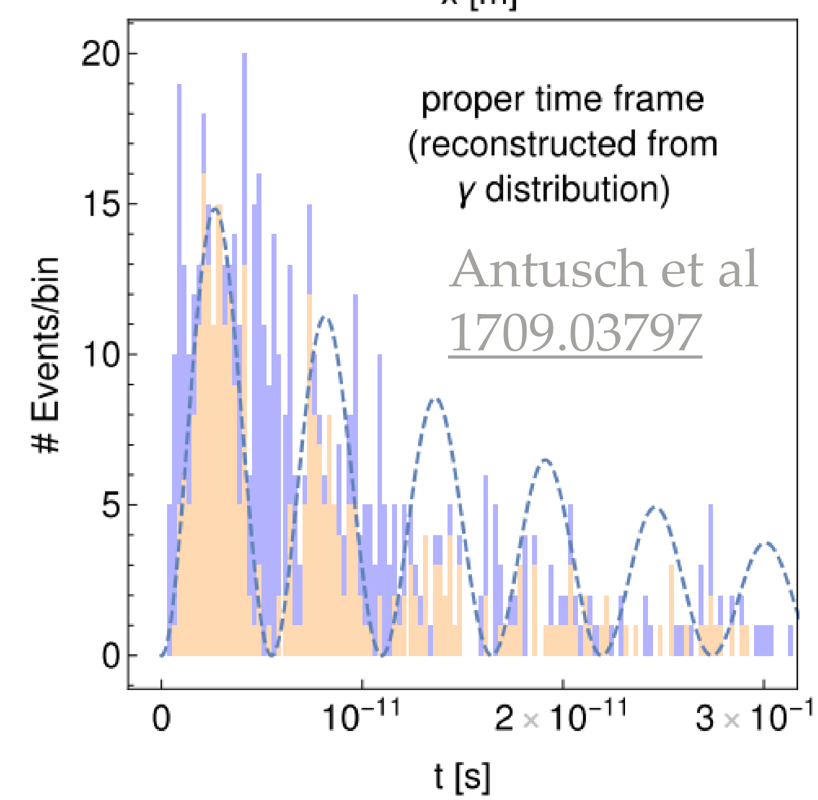
- Oscillations of pseudo-Dirac HNLs in the detector may be observed by studying R_{ll} as function of displacement
- Current framework of [MadGraph] with [HeavyN FeynRules] only allows to simulate single "Dirac" or "Majorana" HNL
- MadGraph patch to simulate oscillations has been published in Antusch/Hajer/Rosskopp 2210.10738
- Study specific to FCC-ee / CEPC in Antusch/Hajer/Oliviera 2308.07297



Testing Leptogenesis





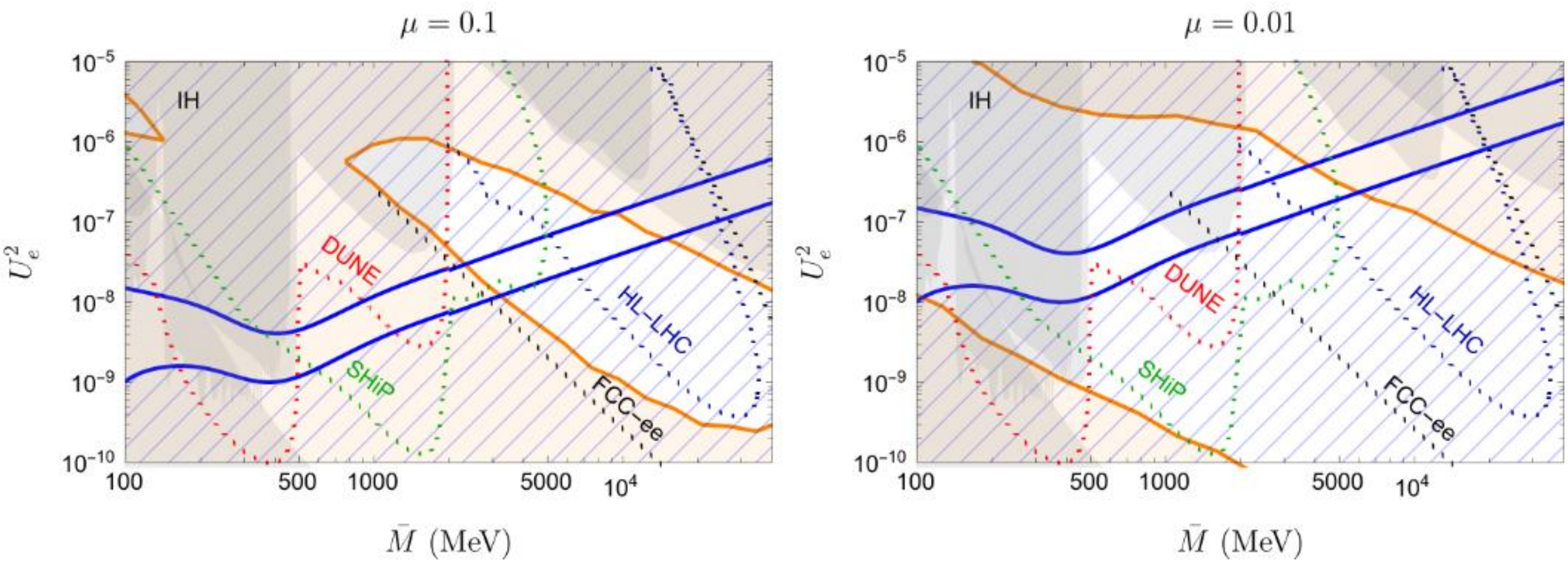


Leptogenesis and 0νββ Decay

$$\left(T^{0\nu}_{1/2}\right)^{-1} \to G_{01}\, g_A^4\, |\mathcal{A}(0)|^2 \frac{V_{ud}^4}{m_e^2} \left| \sum_{i=1}^{5} m_i \mathcal{U}_{ei}^2 \right|^2 \sim |(M_\nu)_{ee}|^2 = 0$$

$$\bar{m}_{\beta\beta} = m_{\beta\beta} \left[1 - \frac{\mathcal{A}(\bar{M})}{\mathcal{A}(0)} \right] - \frac{\bar{M}^2 \mu}{2} \frac{\mathcal{A}'(\bar{M})}{\mathcal{A}(0)} \left(\theta_{e4}^2 - \theta_{e5}^2\right)$$

de Vries et al 2407.10560



Model Testability

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 with 2 HNLs!

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

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

What about 3 HNLs?

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

Casas/Ibarra 01

Klarić Parametrisation

$\mathcal{R} = \mathrm{O}_\nu \mathrm{R}_\mathrm{C} \mathrm{O}_\mathrm{N}$ MaD/Georis/Klarić 2106.16226

$$\mathrm{O}_\nu = \begin{pmatrix} \mathrm{c}_{\nu 2} & 0 & \mathrm{s}_{\nu 2} \\ 0 & 1 & 0 \\ -\mathrm{s}_{\nu 2} & 0 & \mathrm{c}_{\nu 2} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_{\nu 1} & \mathrm{s}_{\nu 1} \\ 0 & -\mathrm{s}_{\nu 1} & \mathrm{c}_{\nu 1} \end{pmatrix}$$

$$\mathrm{O}_\mathrm{N} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_{\mathrm{N}1} & \mathrm{s}_{\mathrm{N}1} \\ 0 & -\mathrm{s}_{\mathrm{N}1} & \mathrm{c}_{\mathrm{N}1} \end{pmatrix} \cdot \begin{pmatrix} \mathrm{c}_{\mathrm{N}2} & 0 & \mathrm{s}_{\mathrm{N}2} \\ 0 & 1 & 0 \\ -\mathrm{s}_{\mathrm{N}2} & 0 & \mathrm{c}_{\mathrm{N}2} \end{pmatrix}$$

$$\mathrm{R}_\mathrm{C} = \begin{pmatrix} \cos(\omega + i\gamma) & \sin(\omega + i\gamma) & 0 \\ -\sin(\omega + i\gamma) & \cos(\omega + i\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Model Discrimination CEPC Z-pole Run

Parameter $\epsilon = e^{-2\gamma}$ quantifies ratio of $U^2_{\alpha i} \equiv |\Theta_{\alpha i}|^2$ to "seesaw floor" $U_0^2 \equiv \frac{\sum_i m_i}{\bar{M}}$

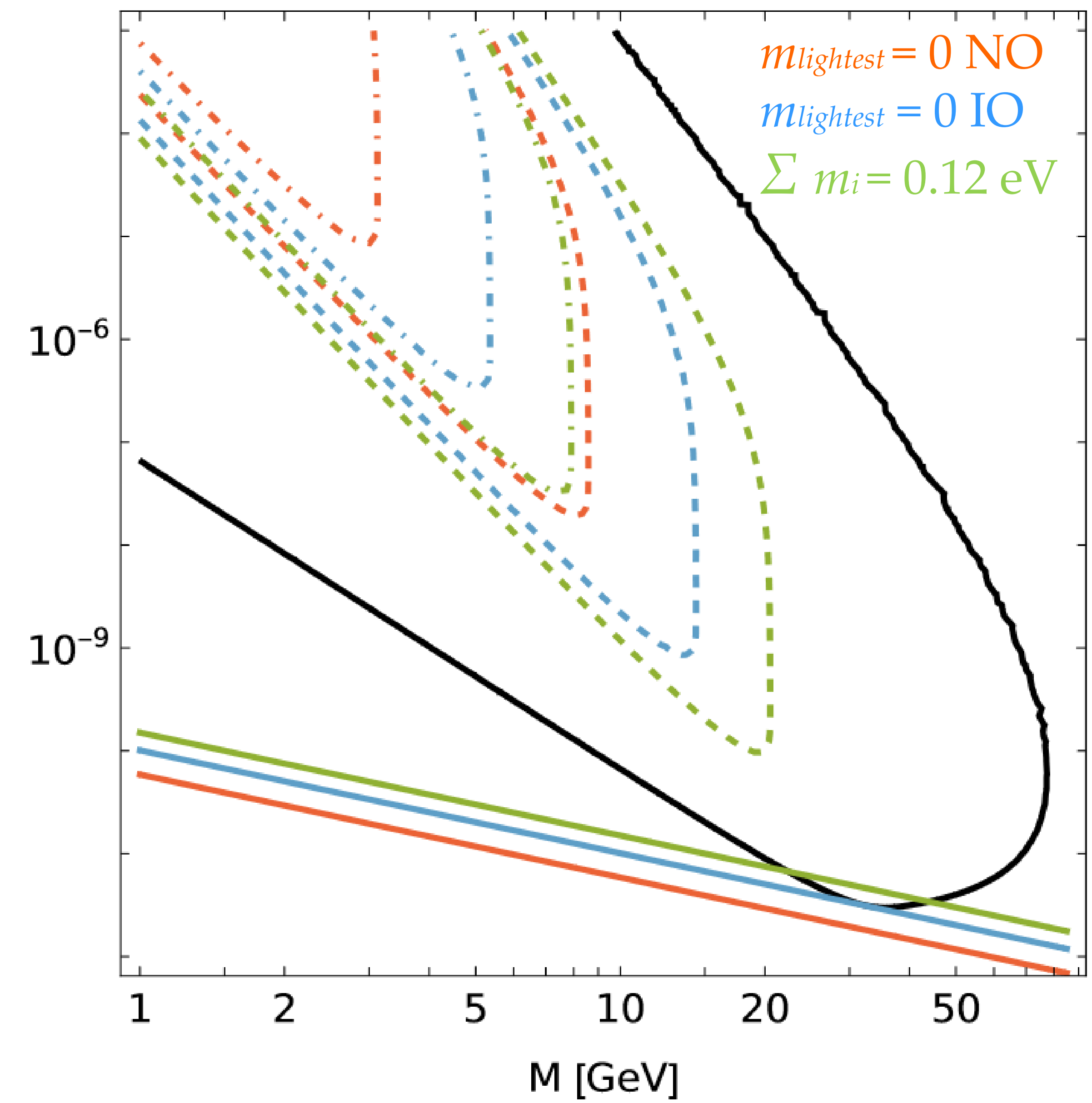
- Minimal model with 2 HNLs (νMSM-like): expansion of the only contains integer powers of ε.

$$U_{\alpha i} \propto 1/\epsilon \ , \ 1 \ , \ \epsilon$$

- Model with 3 HNLs contains half-integer powers

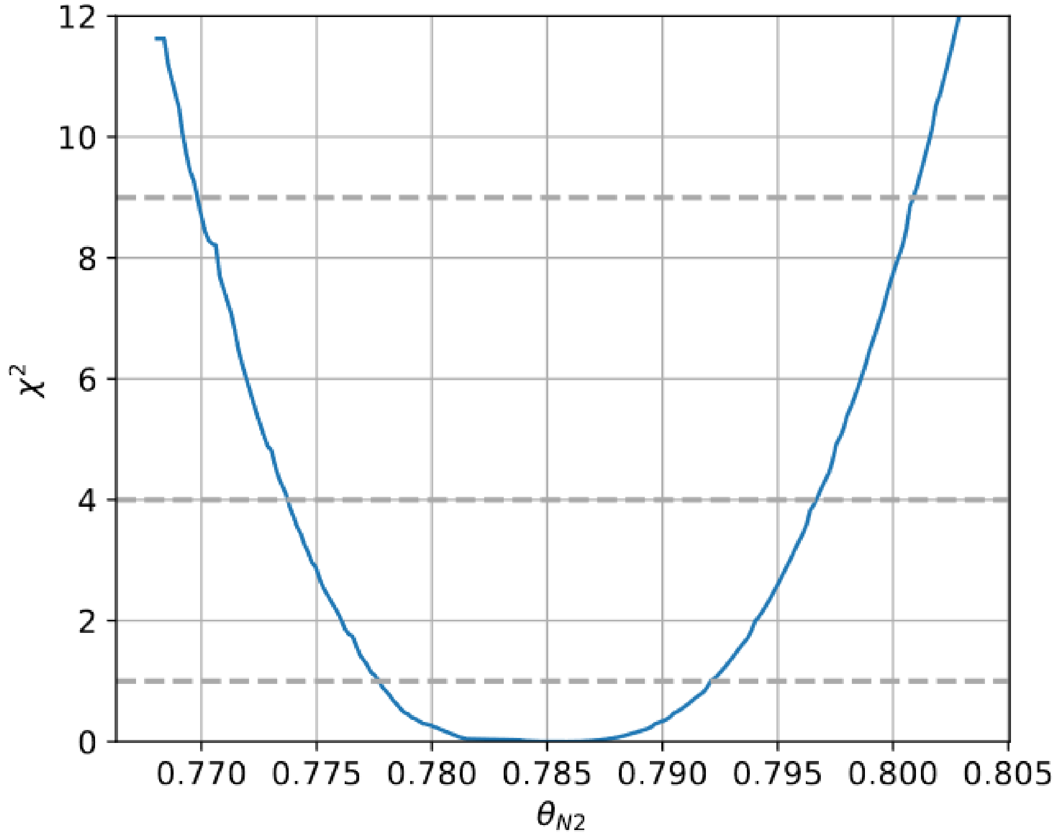
$$U_{\alpha i} \propto 1/\epsilon \ , \ 1/\sqrt{\epsilon} \ , \ 1 \ldots$$

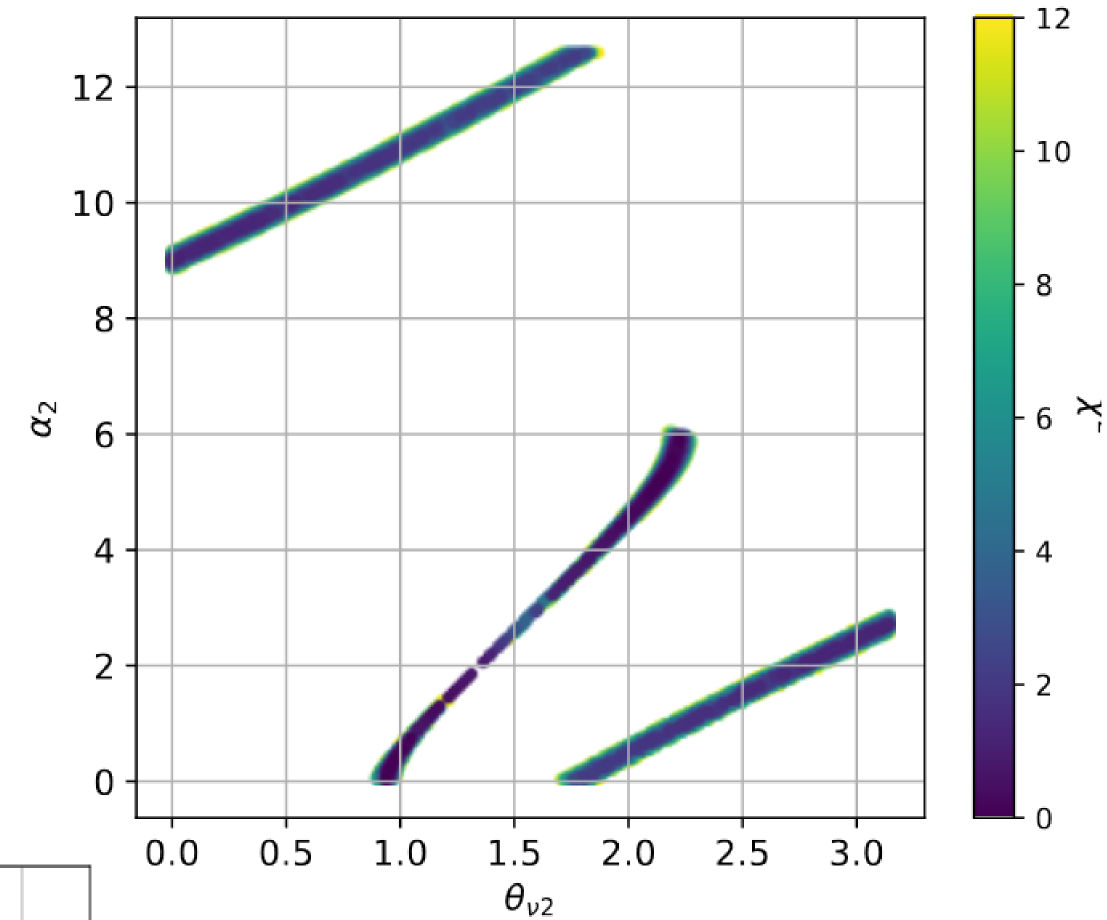
- CEPC or FCC-ee can detect different scaling of event rates within dashed lines

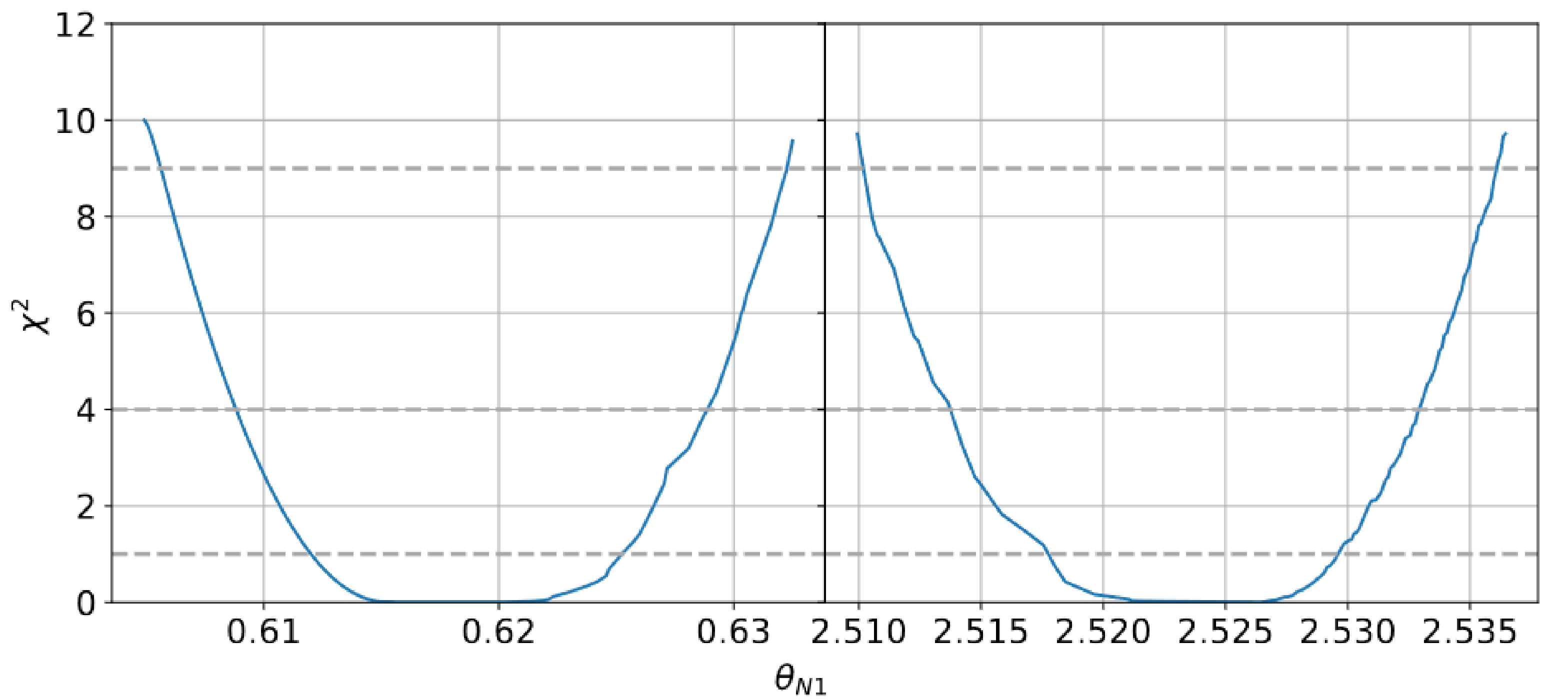


MaD/Georis/Klarić/Wendels 2407.13620

Parameter Inference CEPC Z-pole Run







MaD/Georis/Klarić/Wendels 2407.13620

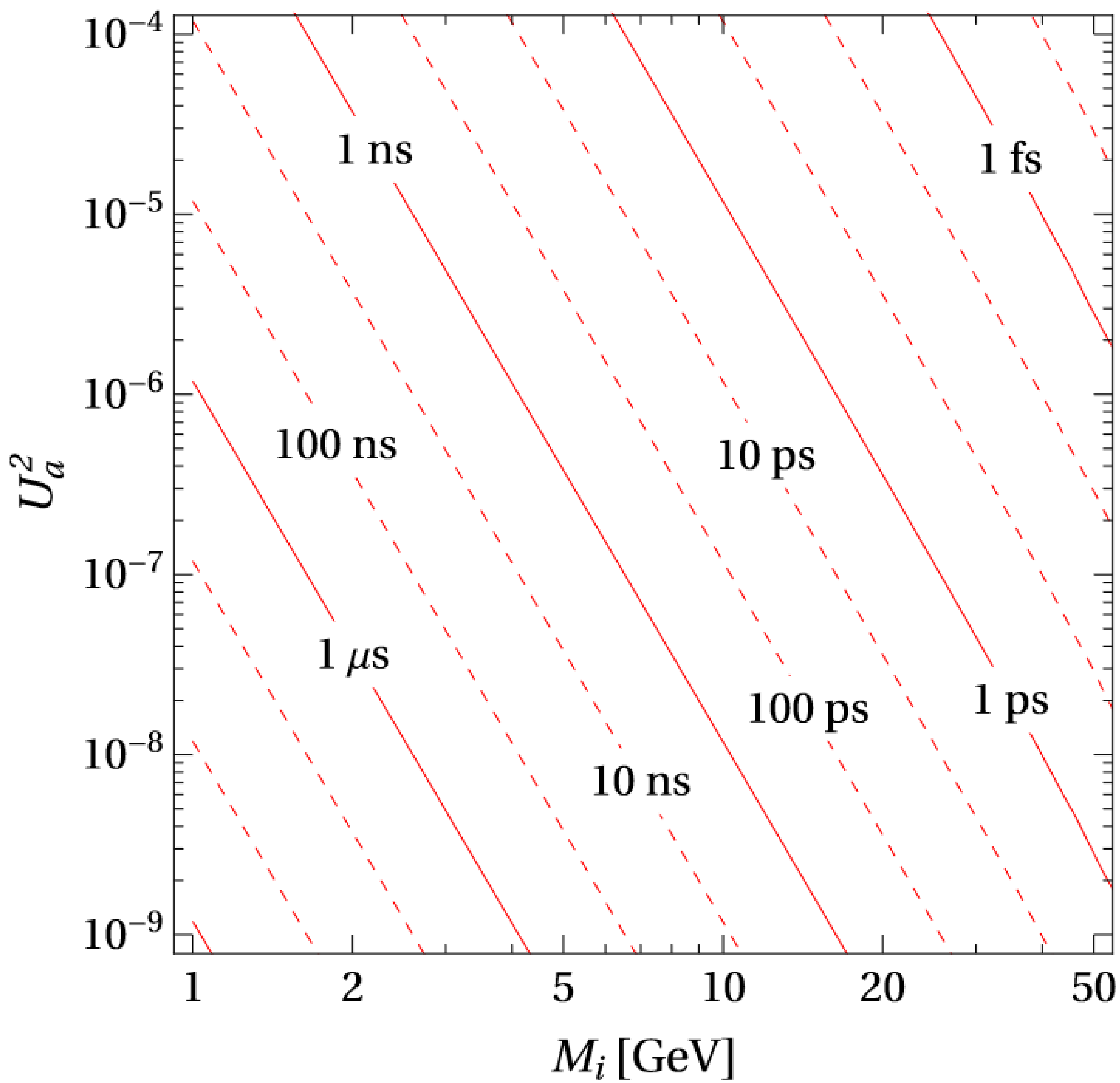
Summary

- 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 below the TeV scale.
- LLP searches can still explore orders of magnitude of uncharted terrain
- Using SM weak interaction alone: can potentially see thousands of events at the LHC and up to a million at CEPC…
- …sufficiently many to measure HNL branching ratios at %-level and to discover LNV, enabling tests underlying neutrino mass models
- Lepton colliders are discovery and precision machine in one, can probe connection to neutrino physics and cosmology!

Backup Slides

Long-lived HNL Searches

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 $M << m_W$

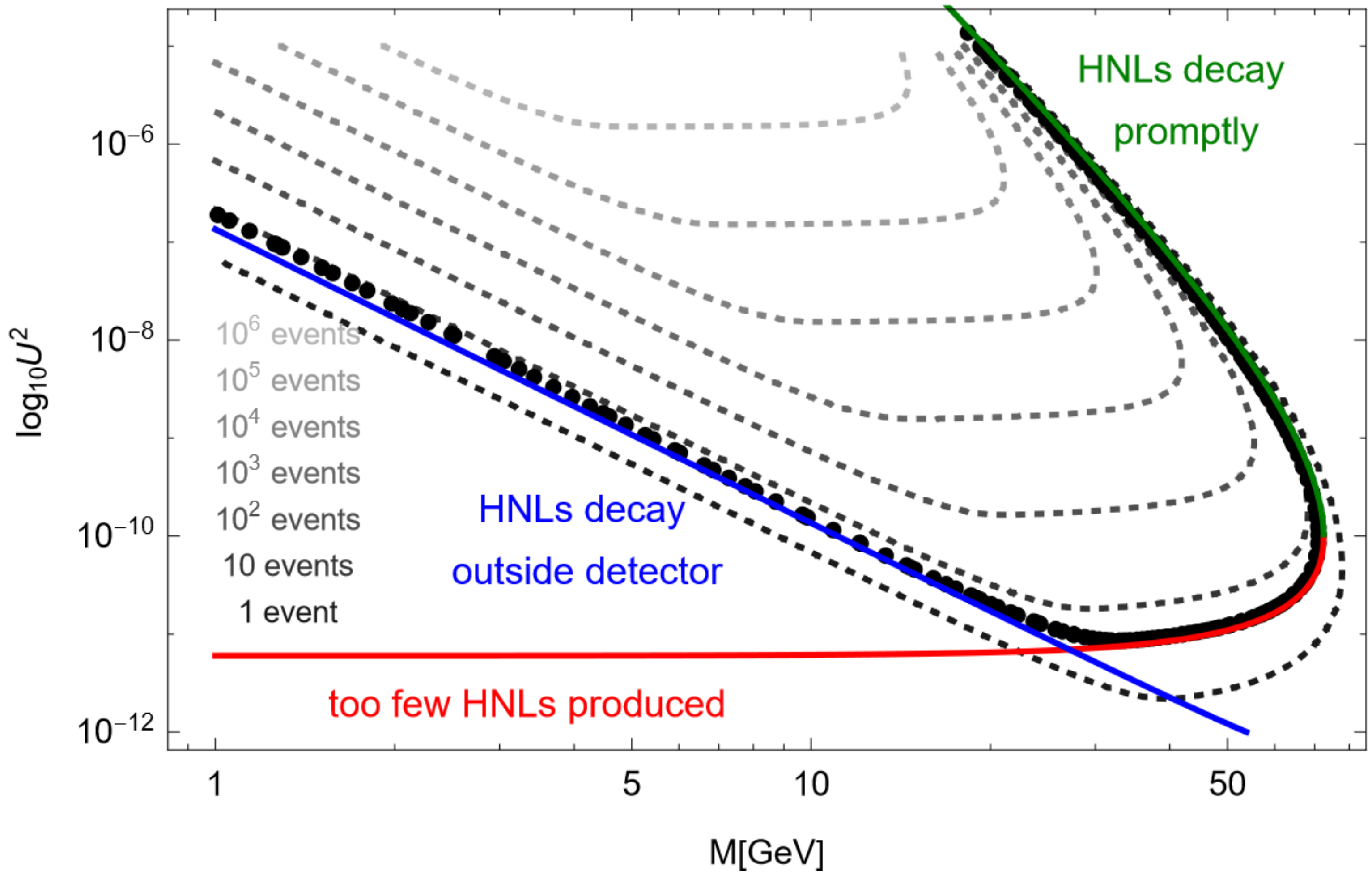
$$\lambda_N \simeq \frac{0.036}{U^2} \left(\frac{\mathrm{p}}{\mathrm{GeV}}\right) \left(\frac{M}{\mathrm{GeV}}\right)^{-6} \mathrm{cm}$$

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

Sensitivity Region

$$U^2_{\max} = \frac{W_{-1}\left(XY\right)}{X} \simeq \frac{\log\left(XY\right)}{X}$$

$$U^2_{\min} = \frac{W_0\left(XY\right)}{X} \simeq Y$$

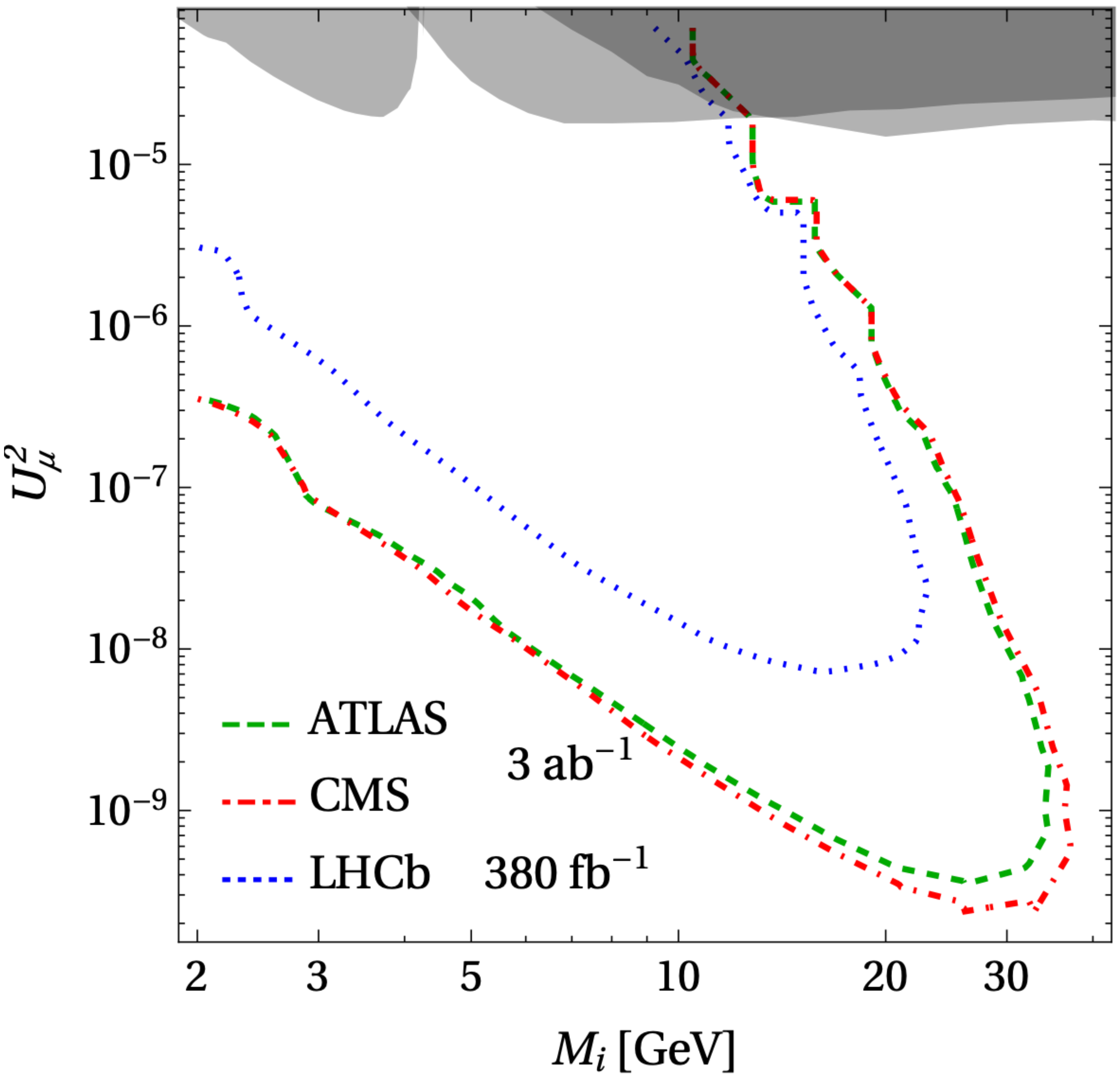


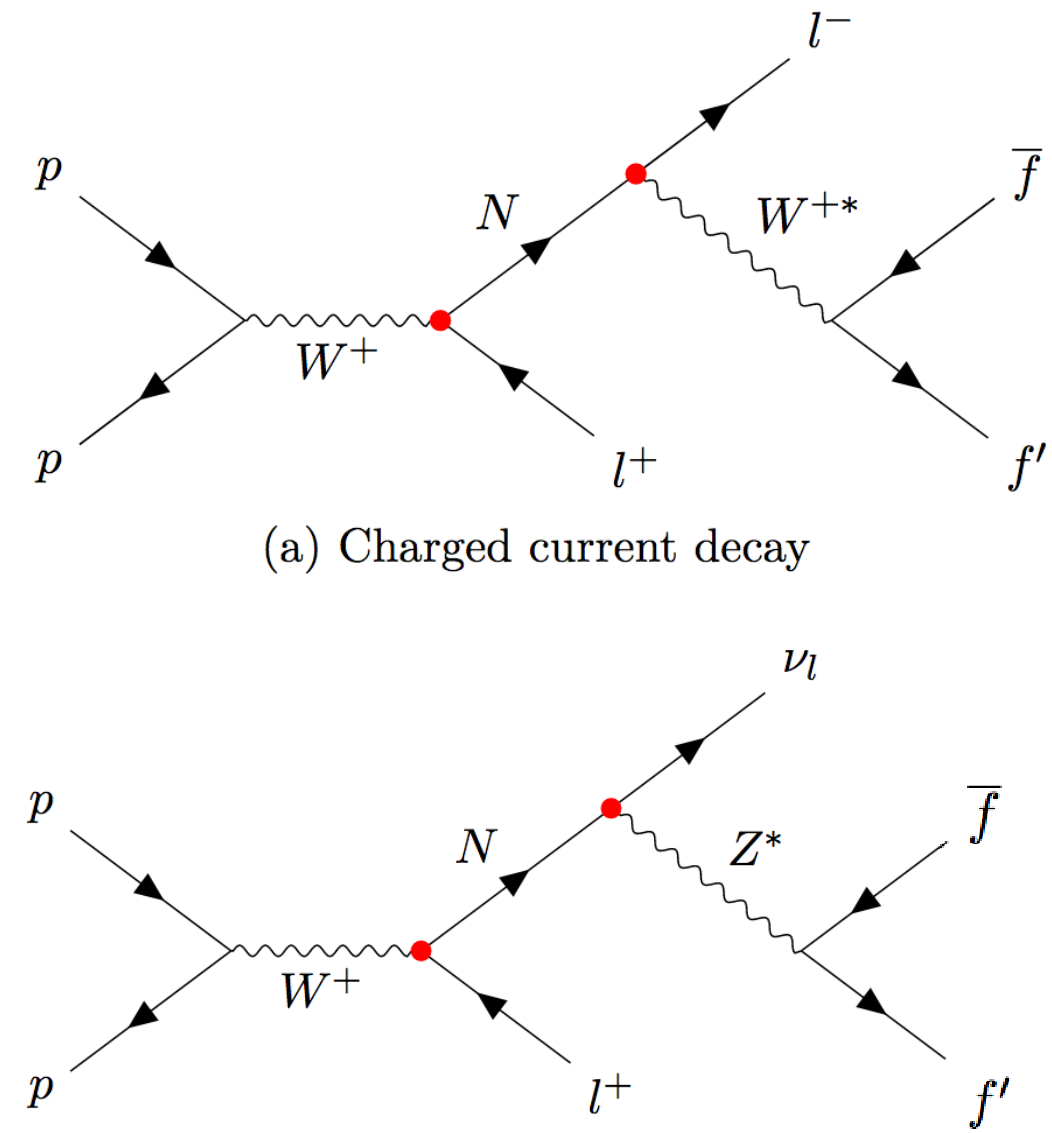
$$U^2_{\min} = \frac{2^{1/6}3^{1/3}8\pi^{3/2}(\mathrm{p}_N Y)^{1/2}}{(ac_{\mathrm{dec}})^{1/2}G_F M^3 d_{\mathrm{cyl}}^{1/3} l_{\mathrm{cyl}}^{1/6}} \simeq \sqrt{\frac{N_{\mathrm{obs}}}{\mathrm{u}_\alpha^2\mathrm{u}_\beta^2}}\frac{57}{G_F M^3}\sqrt{\mathrm{p}_N}d_{\mathrm{cyl}}^{-1/3}l_{\mathrm{cyl}}^{-1/6}\left(\epsilon_{\alpha\beta}N_Z N_{\mathrm{IP}}ac_{\mathrm{dec}}c_{\mathrm{prod}}\Pi\right)^{-1/2}$$

$$Y = \frac{U^2 N_{\mathrm{obs}}/\mathrm{u}_\beta^2}{\epsilon_{\alpha\beta}N_{\mathrm{HNL}\alpha}} = \frac{N_{\mathrm{obs}}/(\mathrm{u}_\alpha^2\mathrm{u}_\beta^2)}{2\epsilon_{\alpha\beta}\mathrm{B}_\alpha c_{\mathrm{prod}}N_{\mathrm{IP}}\Pi N_Z} \qquad X = \frac{l_0}{U_\beta^2\lambda_N} = -\frac{aG_F^2 l_0 M^6 c_{\mathrm{dec}}}{96\mathrm{p}_N\pi^3}$$

MaD 2210.17110

HL-LHC Displaced Vertex Search





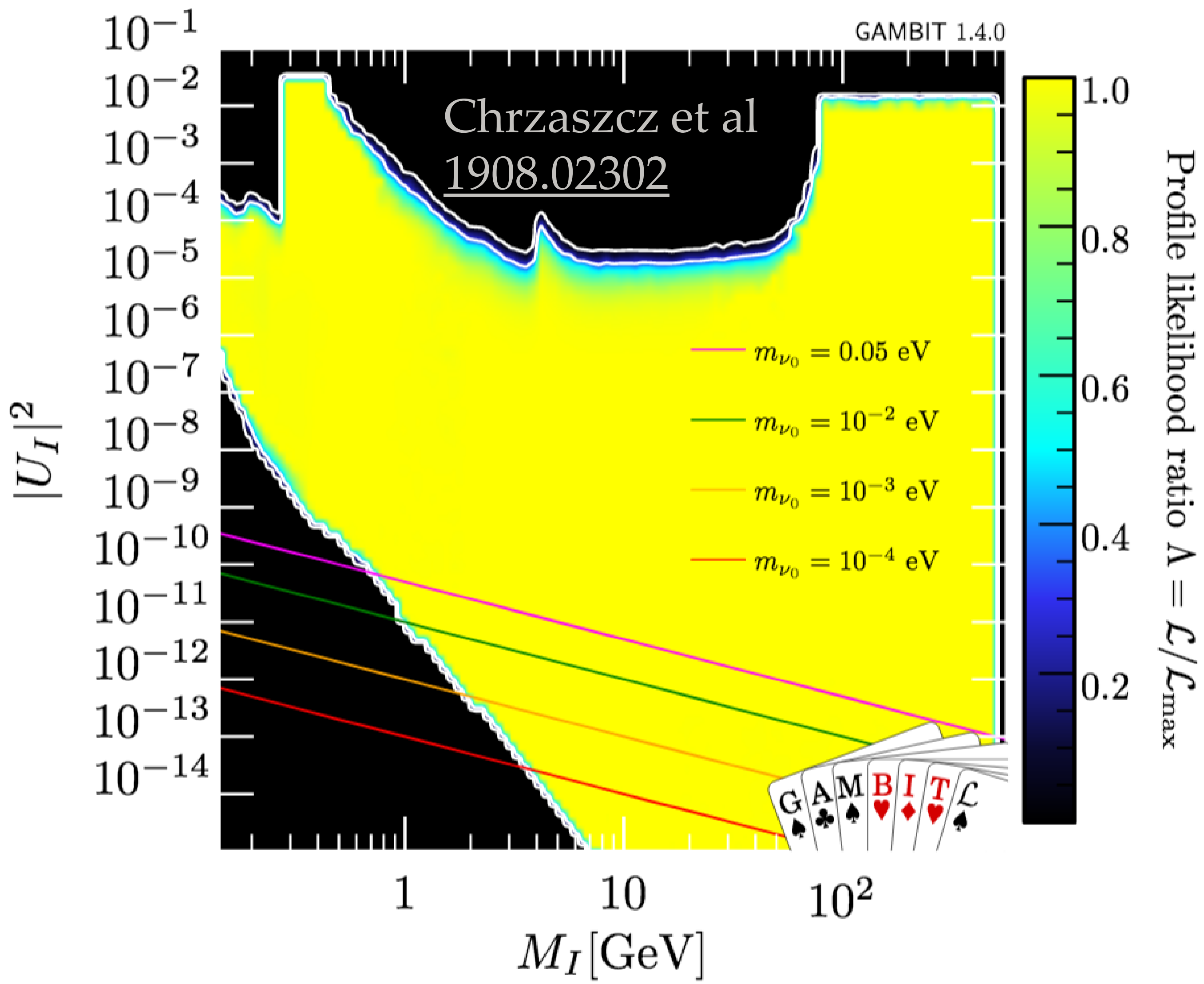
(a) Charged current decay

(b) Neutral current decay

MaD/Hajer 1903.06100

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

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

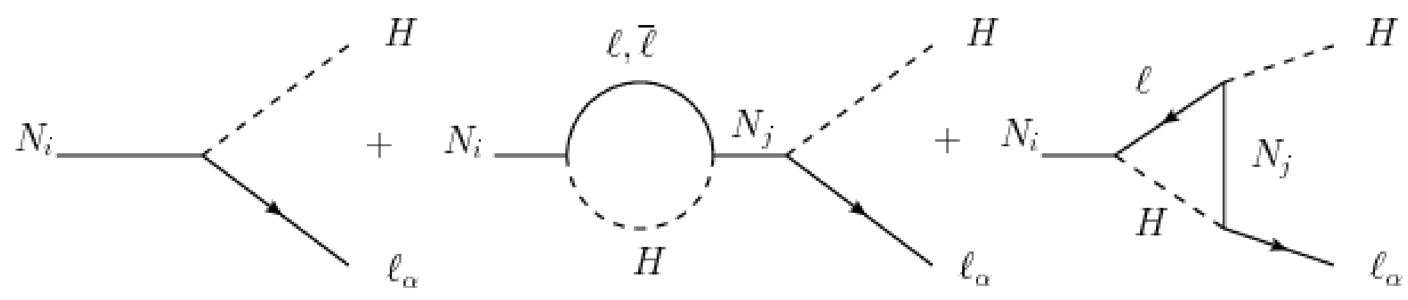
Varying lightest neutrino mass gives "seesaw band" used in Snowmass plots

Low Scale Leptogenesis

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

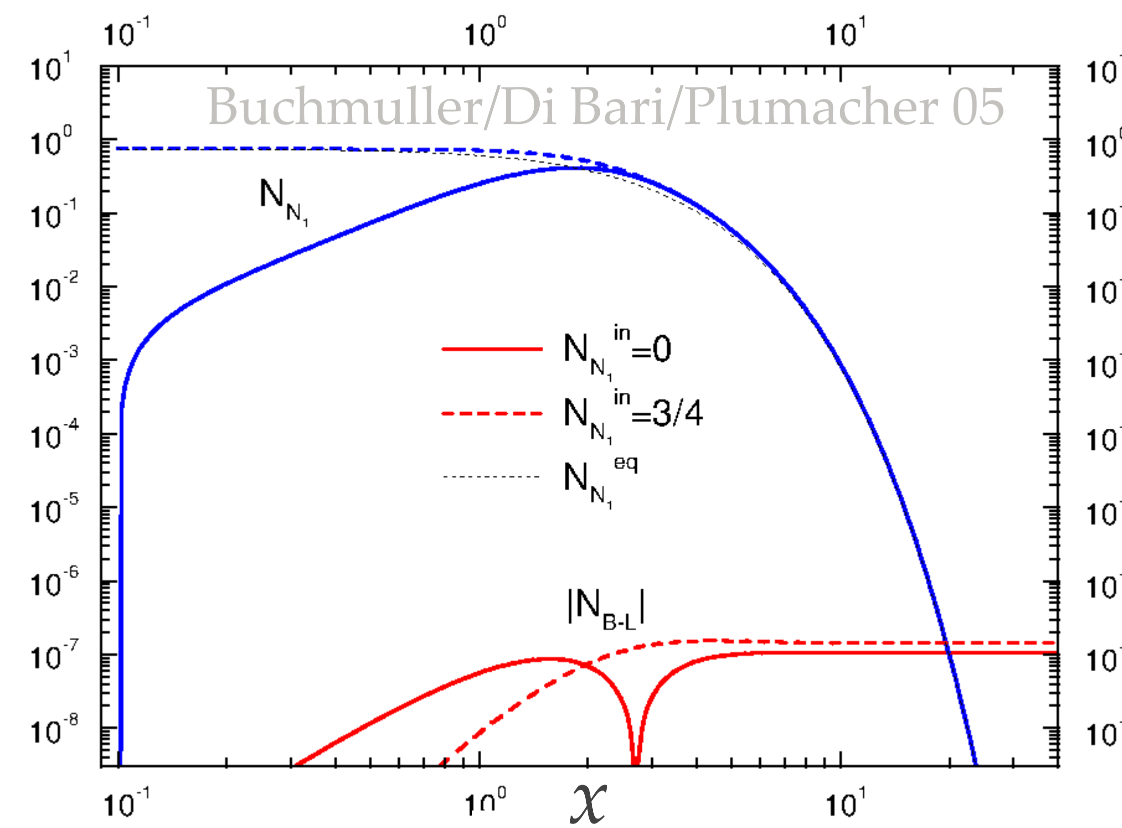


Quantitative description

- Conventionally described by semi-classical Boltzmann equations

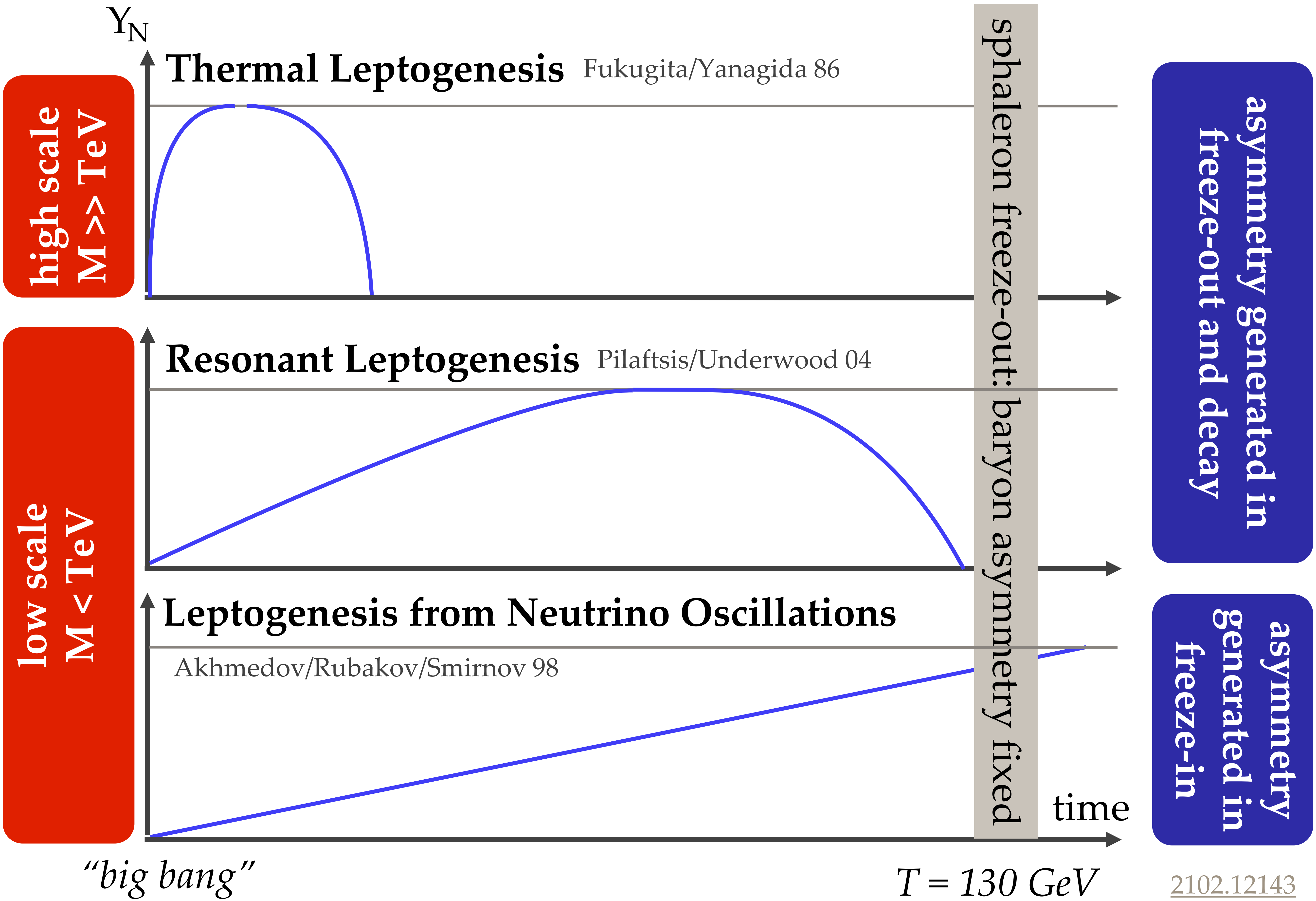
$$xH\frac{d\mathrm{Y}_N}{dx} = -\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) \qquad x = M/T$$

$$xH\frac{d\mathrm{Y}_{\mathrm{B-L}}}{dx} = \epsilon\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) - c_W\Gamma_N\mathrm{Y}_{\mathrm{B-L}}$$



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



Quantitative Description

- Need to track three SM chemical potentials

- Track coherences for heavy neutrinos ("density matrix equations")

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

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

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

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

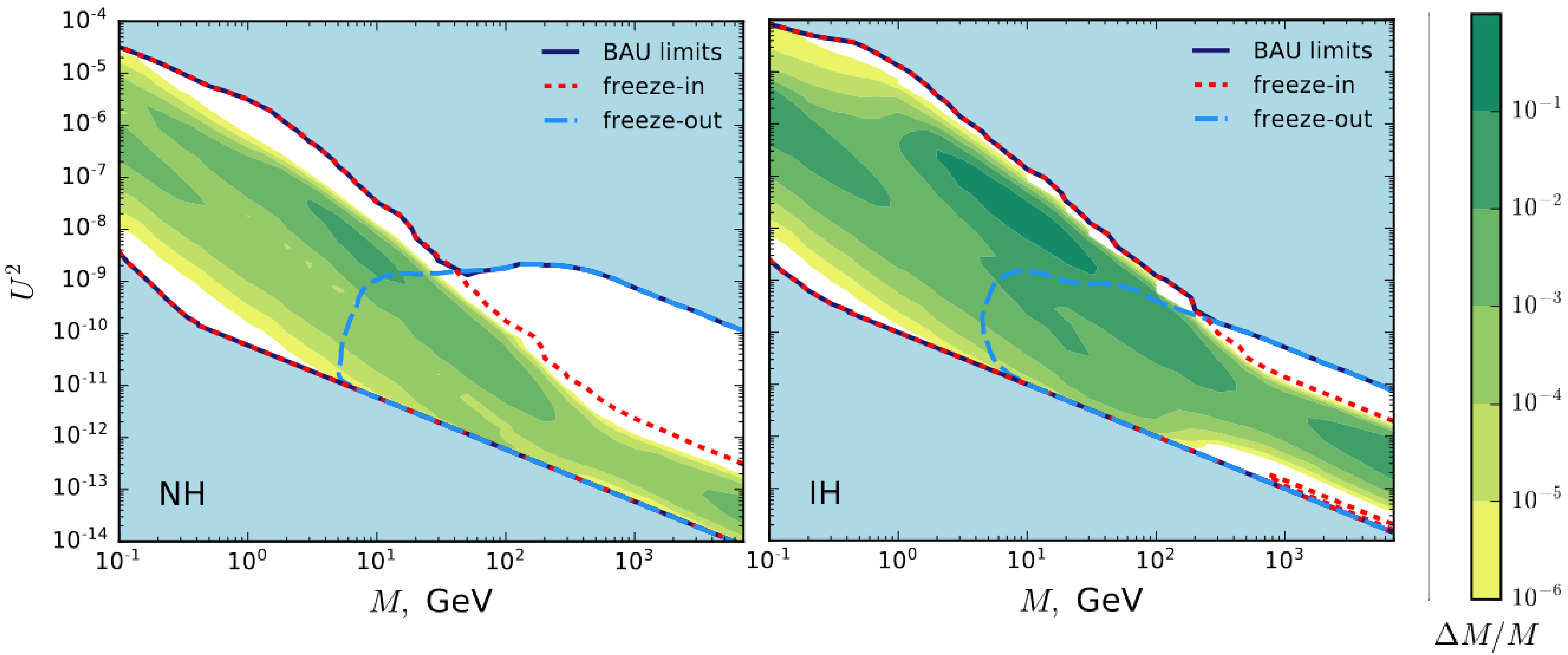
Approx. conserved for $M \ll T$

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
- But another generalised lepton number (related to HNL helicities) in conserved for high temperatures ($T \gg M$)

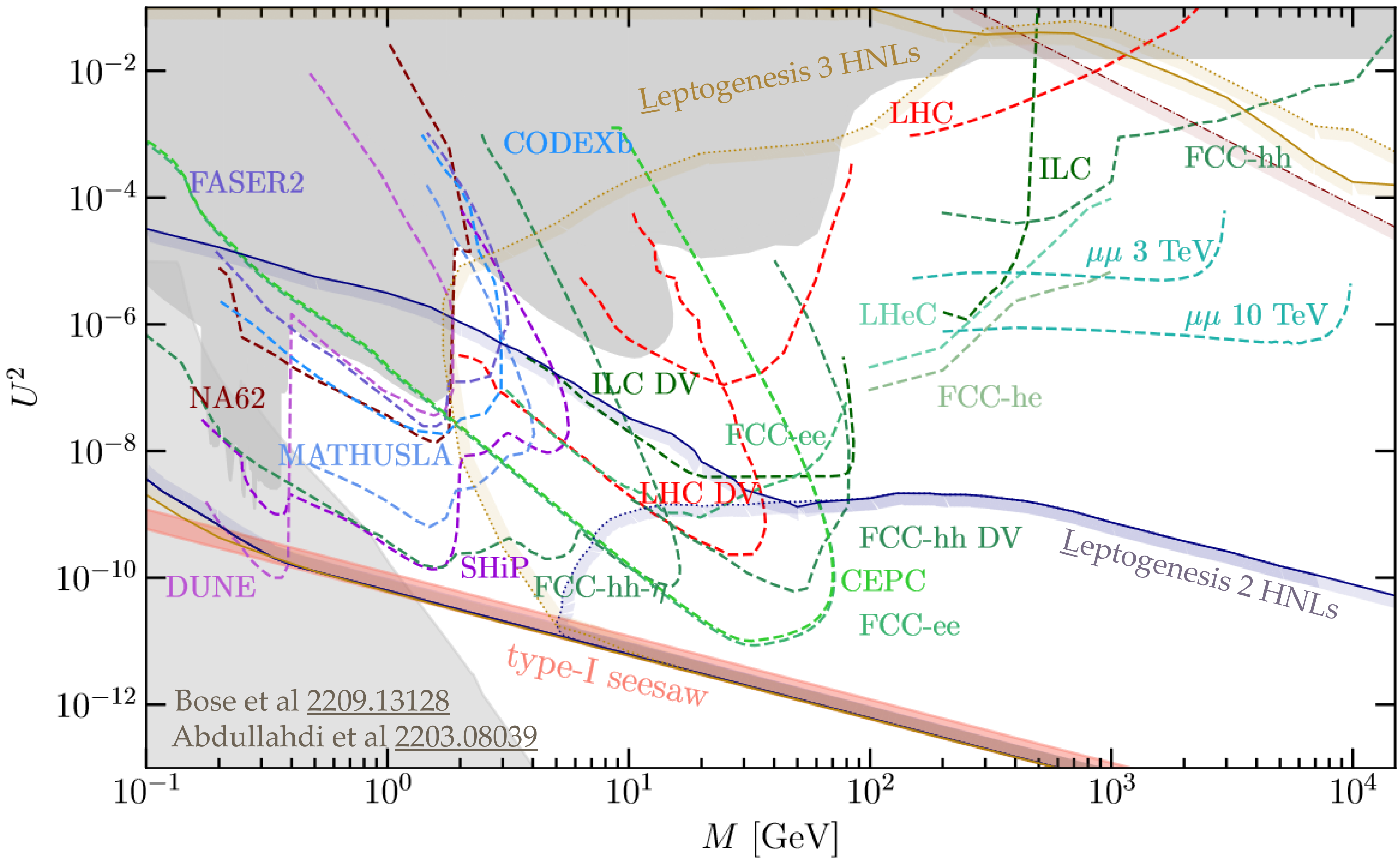
Leptogenesis with 2 HNLs



- 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!

Klaric/Shaposhnikov/Timiryasov 2103.16545

Leptogenesis: 2 vs 3 HNL Flavours



Leptogenesis with 2 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
$P_+N_i, \quad \bar{N}_iP_+$	$+1$
$P_-N_i, \quad \bar{N}_iP_-$	-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"

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

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

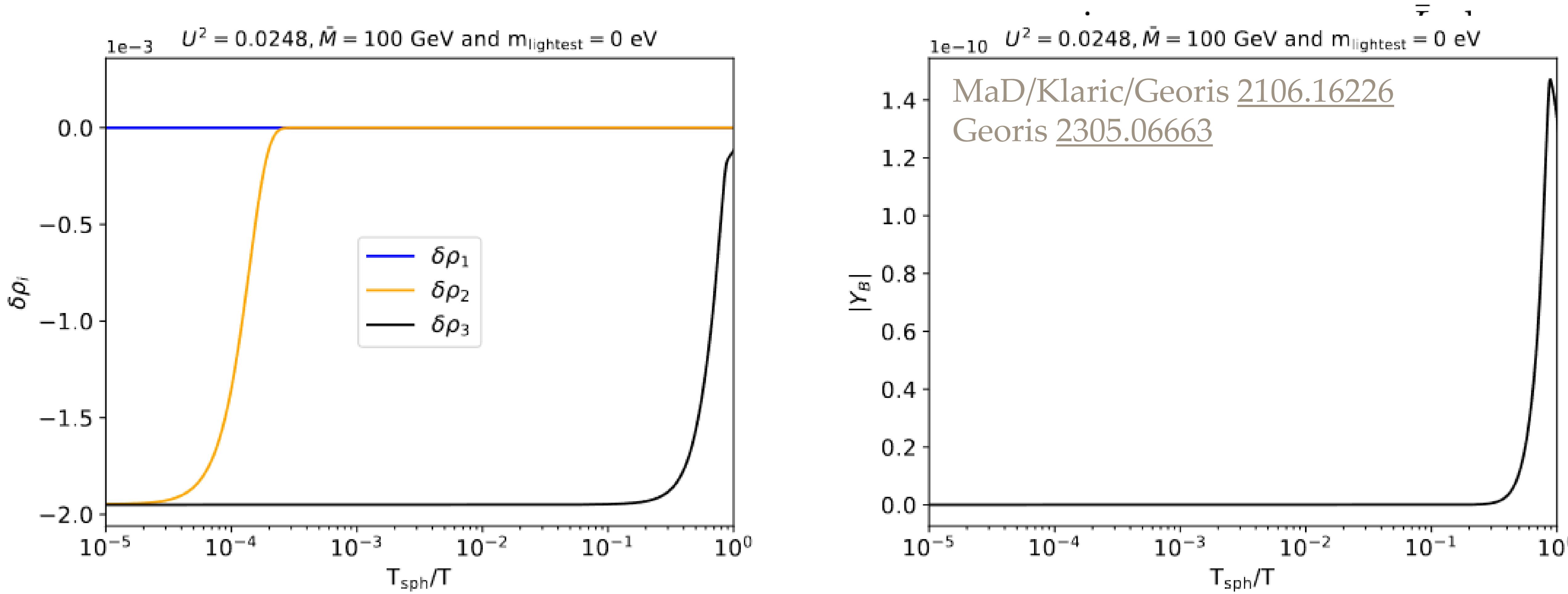
"interaction basis"

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!

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

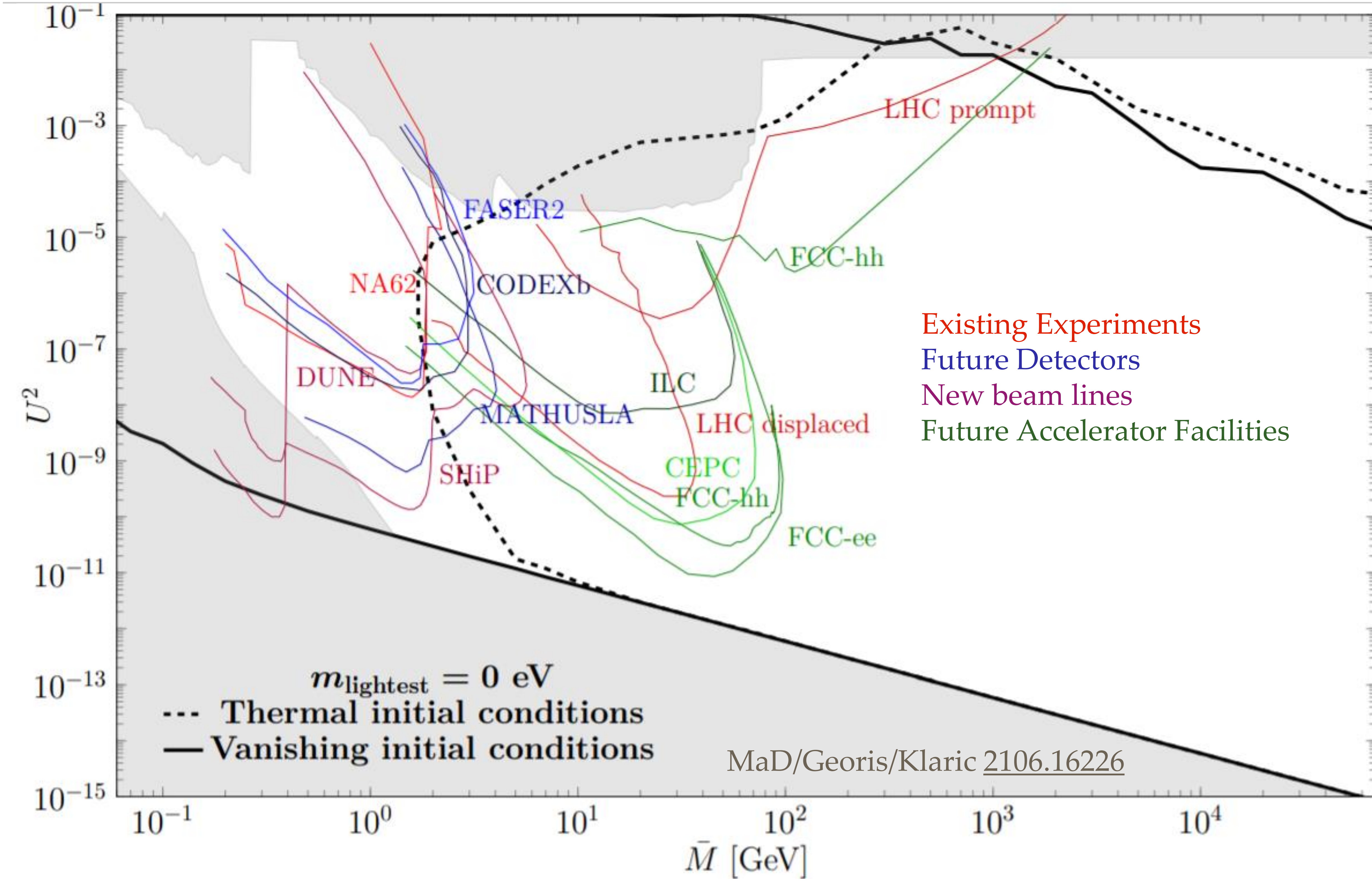
Maverick Heavy Neutrino



- 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!

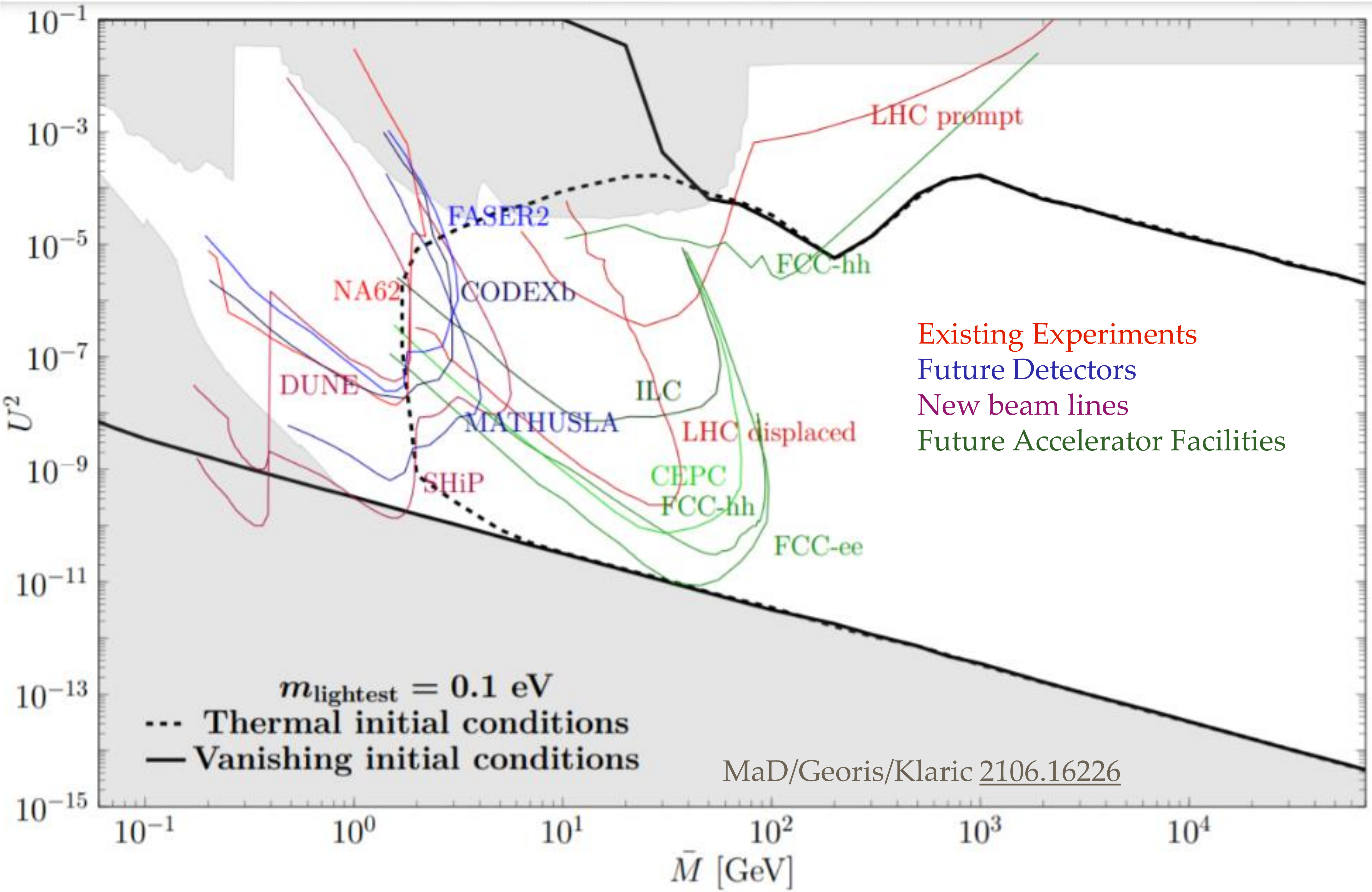
$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

Impact of the lightest SM Neutrino

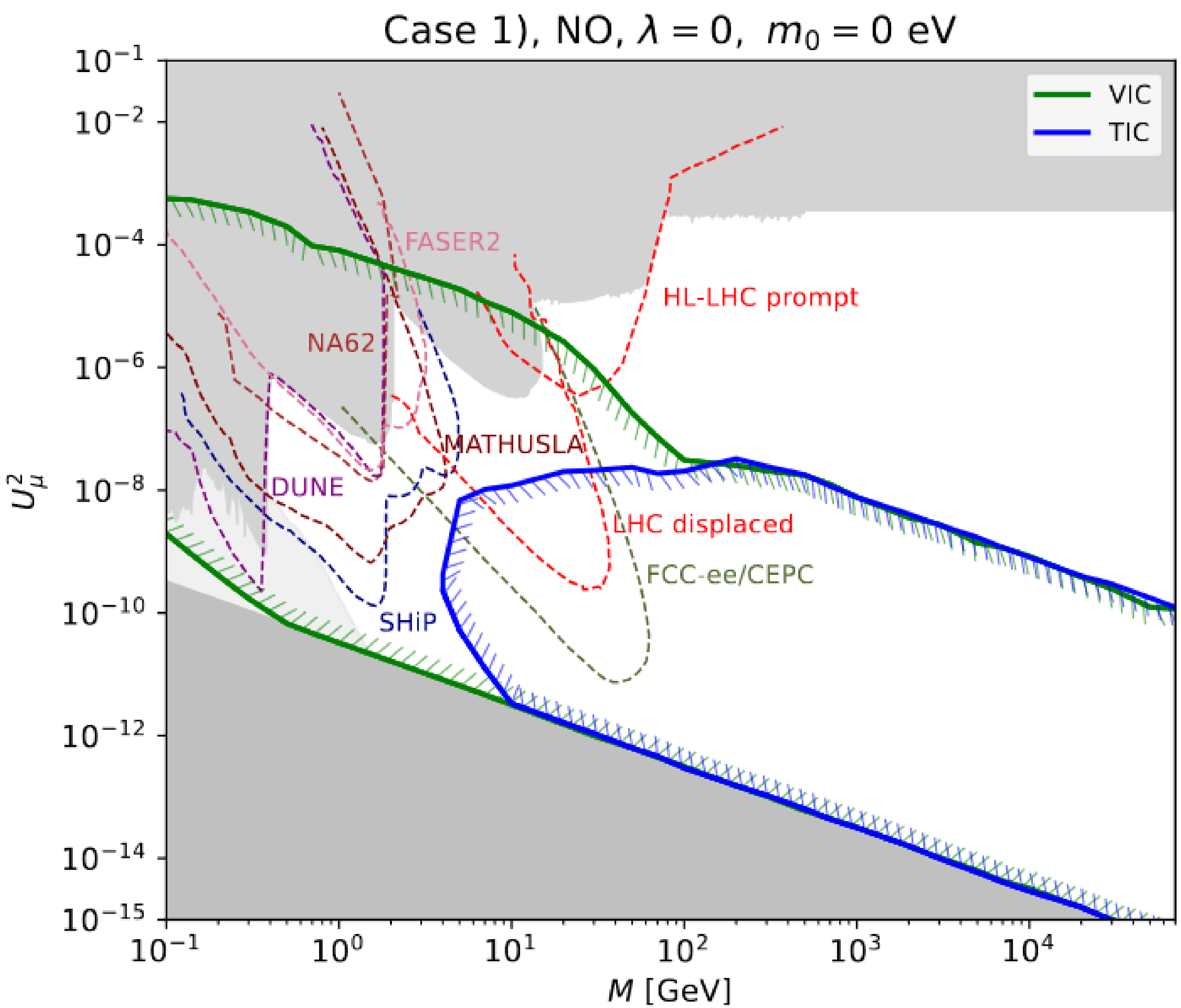


MaD/Georis/Klaric 2106.16226

Impact of the lightest SM Neutrino



Leptogenesis Discrete Symmetries



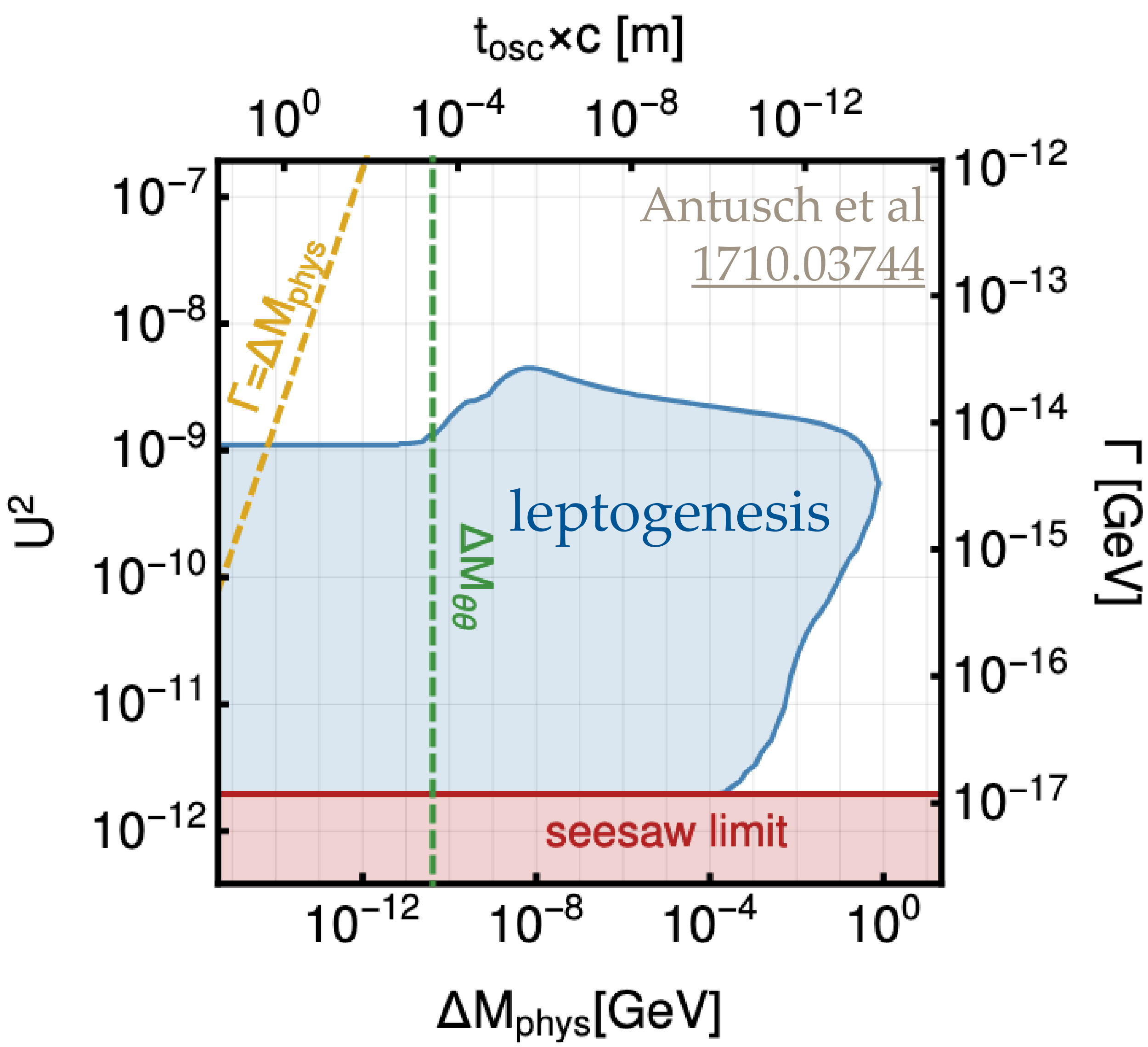
- Generically mixing is near the "seesaw line" $U^2 \sim m_\nu/M$
- Can be enhanced in presence of enhanced residual symmetry
- Here unknown parameters have been marginalised
- Leptogenesis region in presence of these discrete symmetries can only be probed with LLP searches (even with three HNL flavours)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

Plot from Georis 2401.04840
Based on MaD/Georis/Hagedorn/Klaric 2203.08538

Leptogenesis with exact Mass Degeneracy

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"

$$H_N^{\rm vac} = \frac{\pi^2}{18\zeta(3)}\frac{a_{\rm R}}{T_{\rm ref}^3}\left(\mathrm{Re}[M^\dagger M] + ih\mathrm{Im}[M^\dagger M]\right) ,$$

$$H_N^{\rm th} = \frac{a_{\rm R}}{T_{\rm ref}}\left(\mathfrak{h}_+^{\rm th}\Upsilon_{+h} + \mathfrak{h}_-^{\rm th}\Upsilon_{-h}\right) + \mathfrak{h}^{\rm EV}\frac{a_{\rm R}}{T_{\rm ref}}\mathrm{Re}[Y^*Y^t] ,$$

$$\Gamma_N = \frac{a_{\rm R}}{T_{\rm ref}}\left(\gamma_+\Upsilon_{+h} + \gamma_-\Upsilon_{-h}\right) ,$$

$$\tilde{\Gamma}_N^a = h\frac{a_{\rm R}}{T_{\rm ref}}\left(\tilde{\gamma}_+\Upsilon_{+h}^a - \tilde{\gamma}_-\Upsilon_{-h}^a\right) ,$$

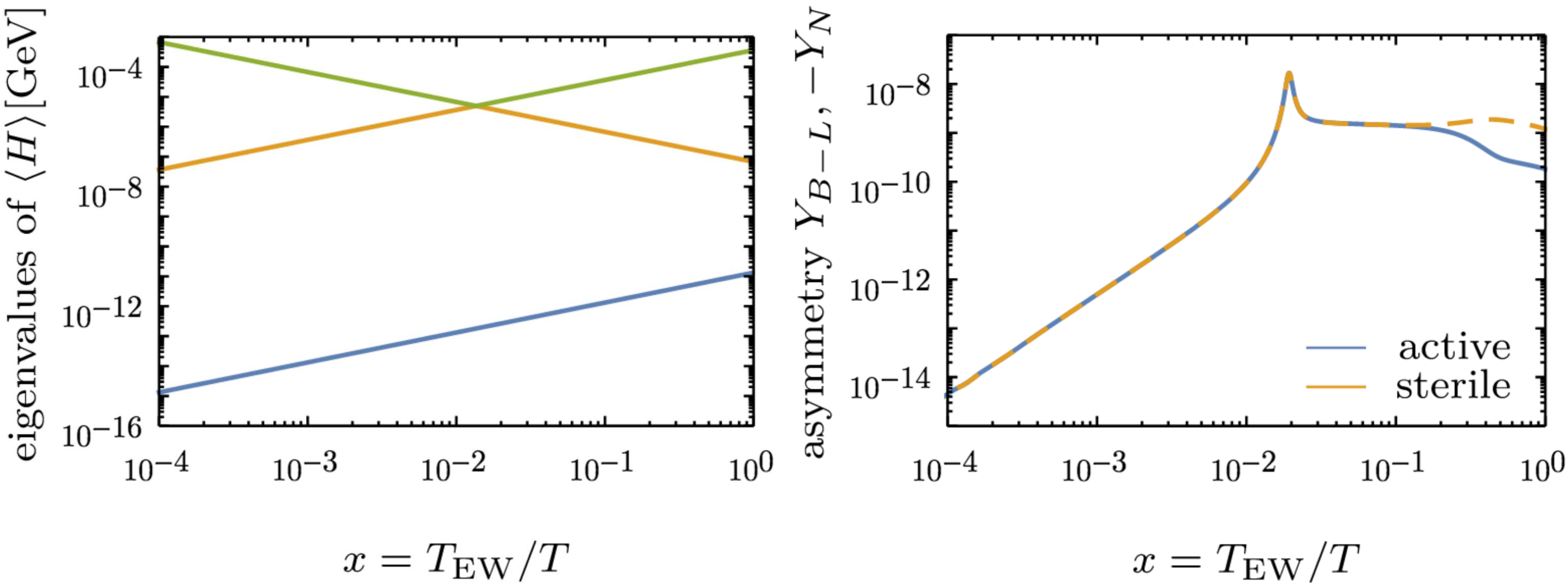
- Effect is only seen when using density matrix and including thermal corrections!

- Similar mechanism enables HNL oscillations in detector and observable LNV,

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

MaD/Klaric/Klose 1907.13034

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

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

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

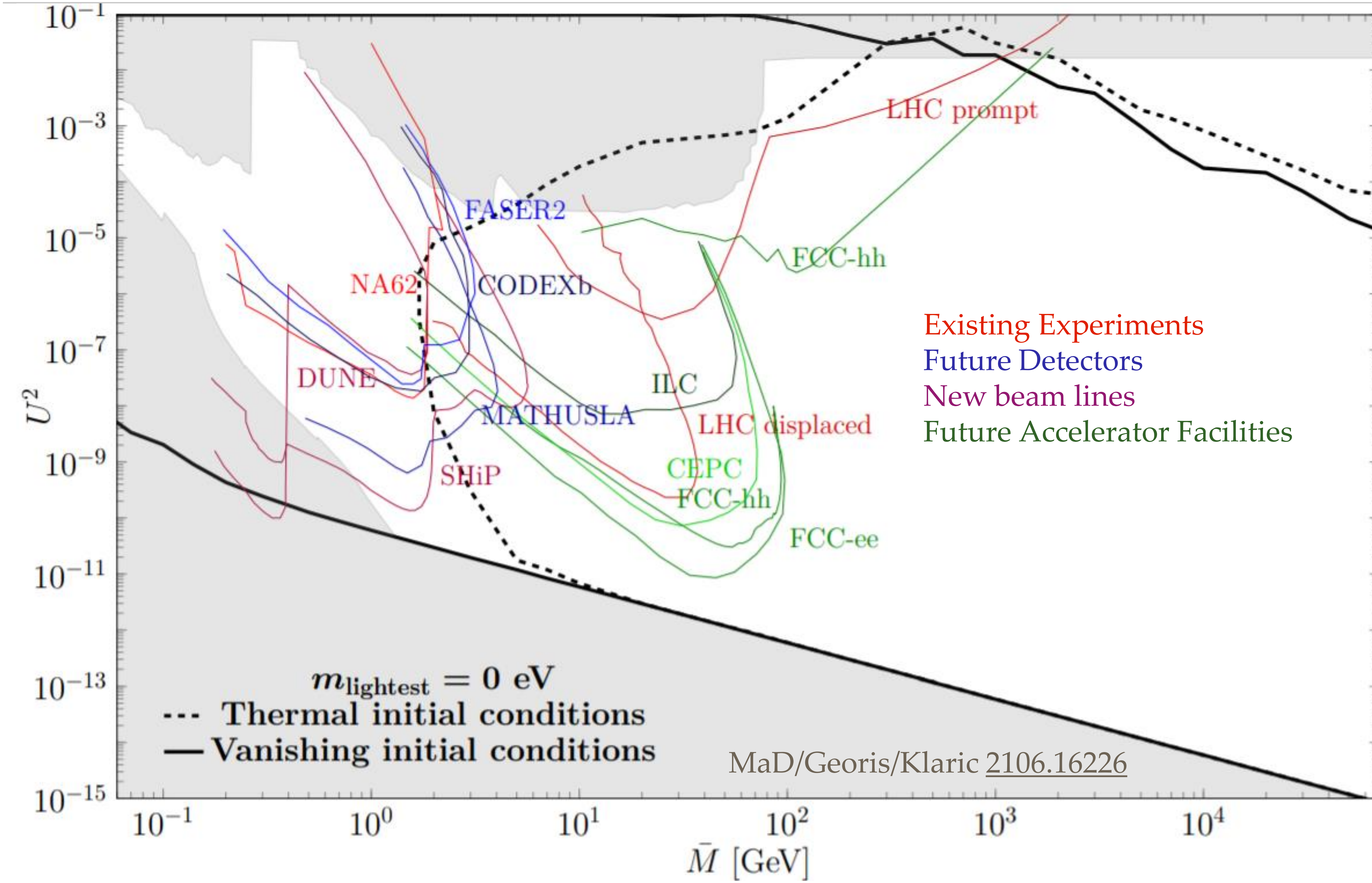
$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2,\hat{Y}_D^\dagger\,\hat{Y}_D\right]\,\hat{Y}_D^T\,P_\alpha\,\hat{Y}_D^*\right), \qquad \text{LNV source}$$

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

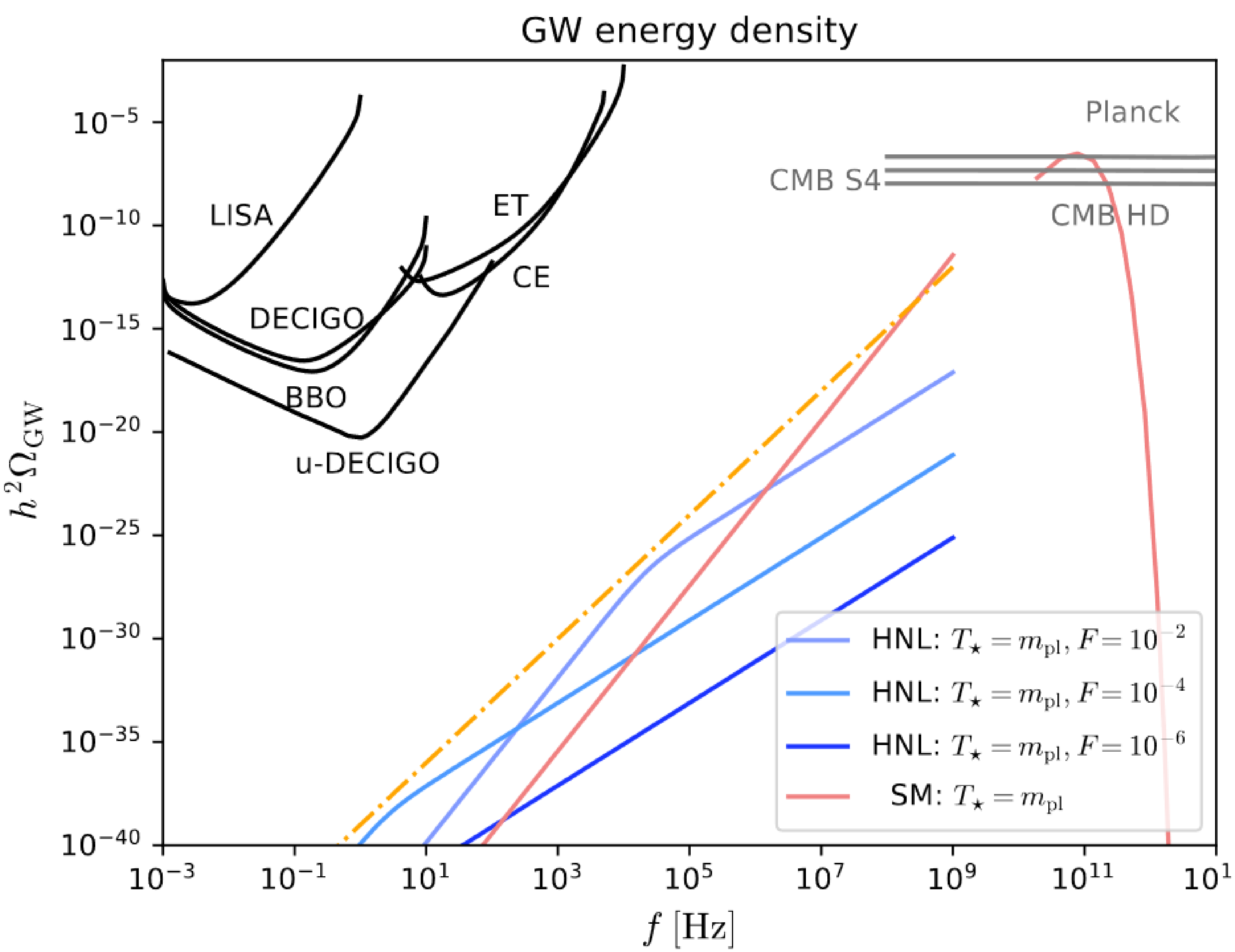
Antusch et al 1710.03744 MaD/Georis/HagedornKlaric 2203.08538

Leptogenesis Initial conditions

Leptogenesis with 3 HNLs



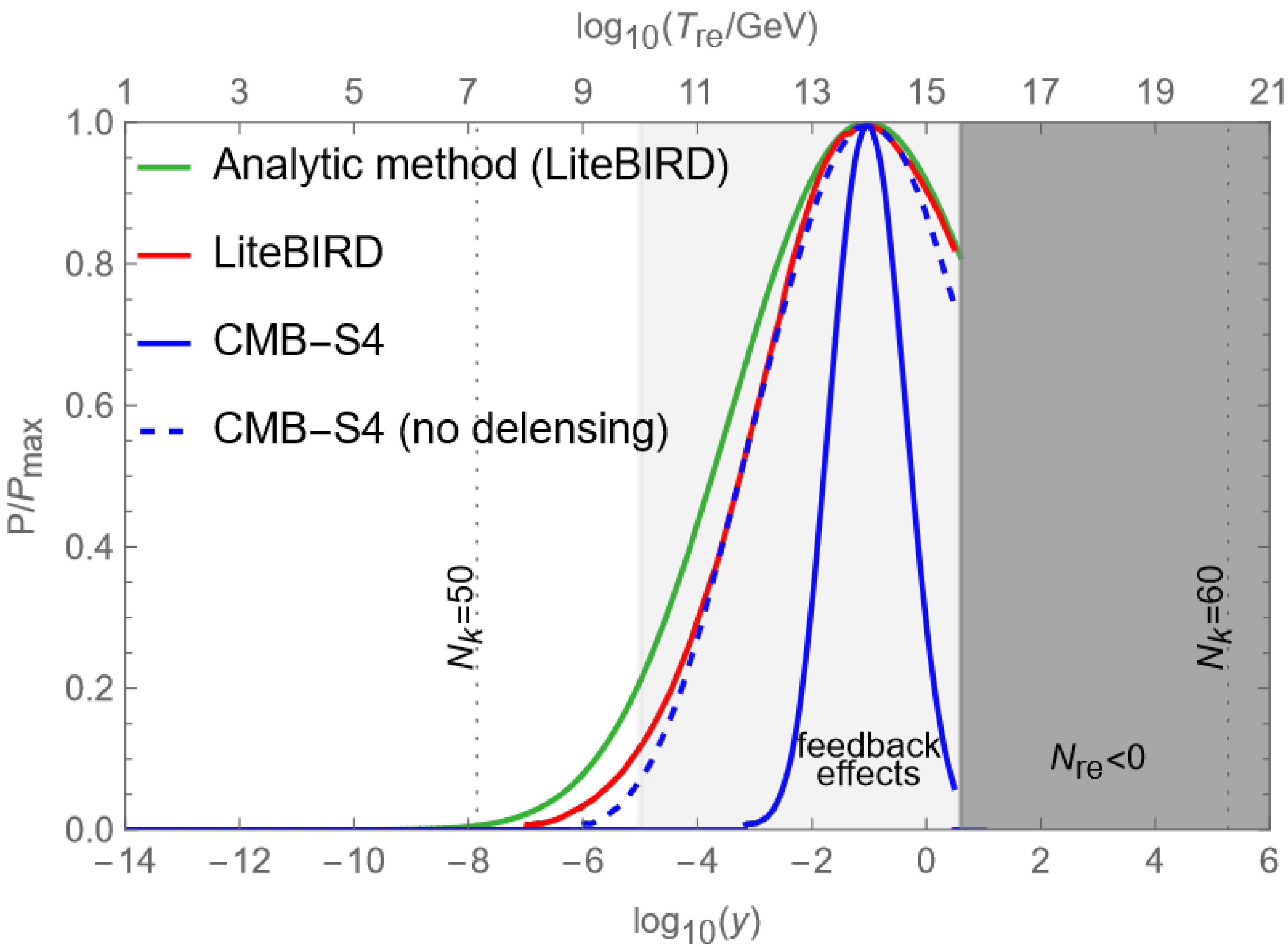
GW as a Probe of Reheating



- Primordial plasma emits thermal GWs (GW equivalent to CMB)
- Spectrum is sensitive to reheating temperature
- HNL contribution can exceed SM contribution… …but still too low for direct detection
- Indirect detection through *Neff* can be possible with CMB-S4

MaD/Georis/Klaric/Klose 2312.13855

Reheating Temperature from CMB



α -attractor T model (α-T)

$$\mathcal{V}(\varphi) = M^4 \tanh^{2n}\left(\frac{\varphi}{\sqrt{6\alpha}M_{pl}}\right)$$

MaD 1903.09599
MaD/Ming 2208.07609
MaD/Ming/Oldengott 2303.13503

- Next-generation CMB observatories can potentially measure the reheating temperature in a given model of inflation
- Further improvement possible with SKA and EUCLID