Testing the Seesaw Mechanism

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TU München

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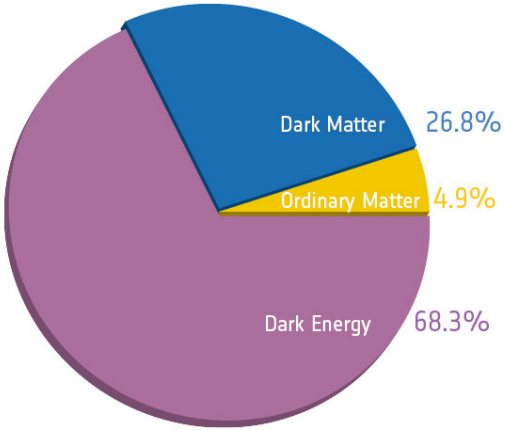
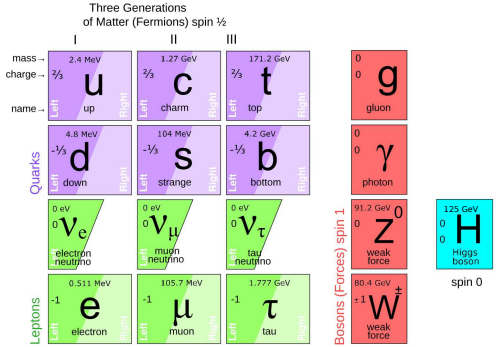
But what generates them?
And may the same new physics solve cosmological puzzles?

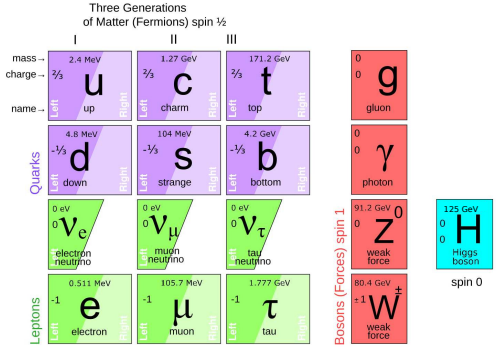


Neutrino masses: Seesaw mechanism



Neutrino masses: Seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \bar{\nu}_R F^\dagger L \tilde{H}^\dagger$$



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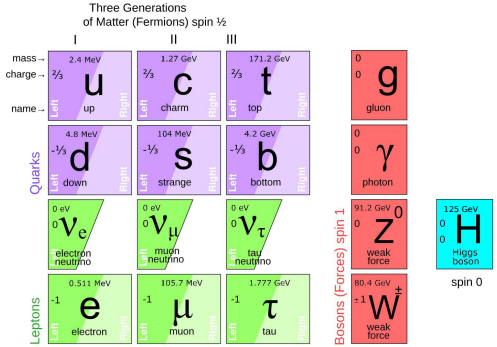

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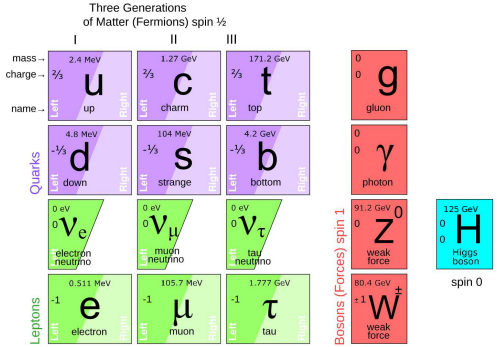
Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

$$\Rightarrow \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$



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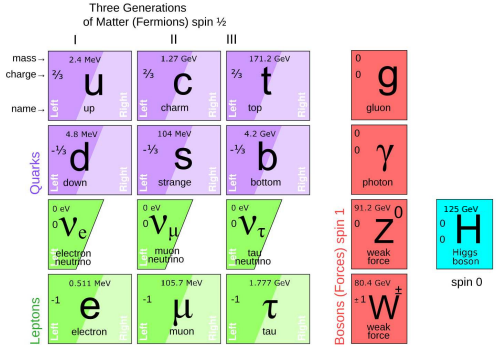
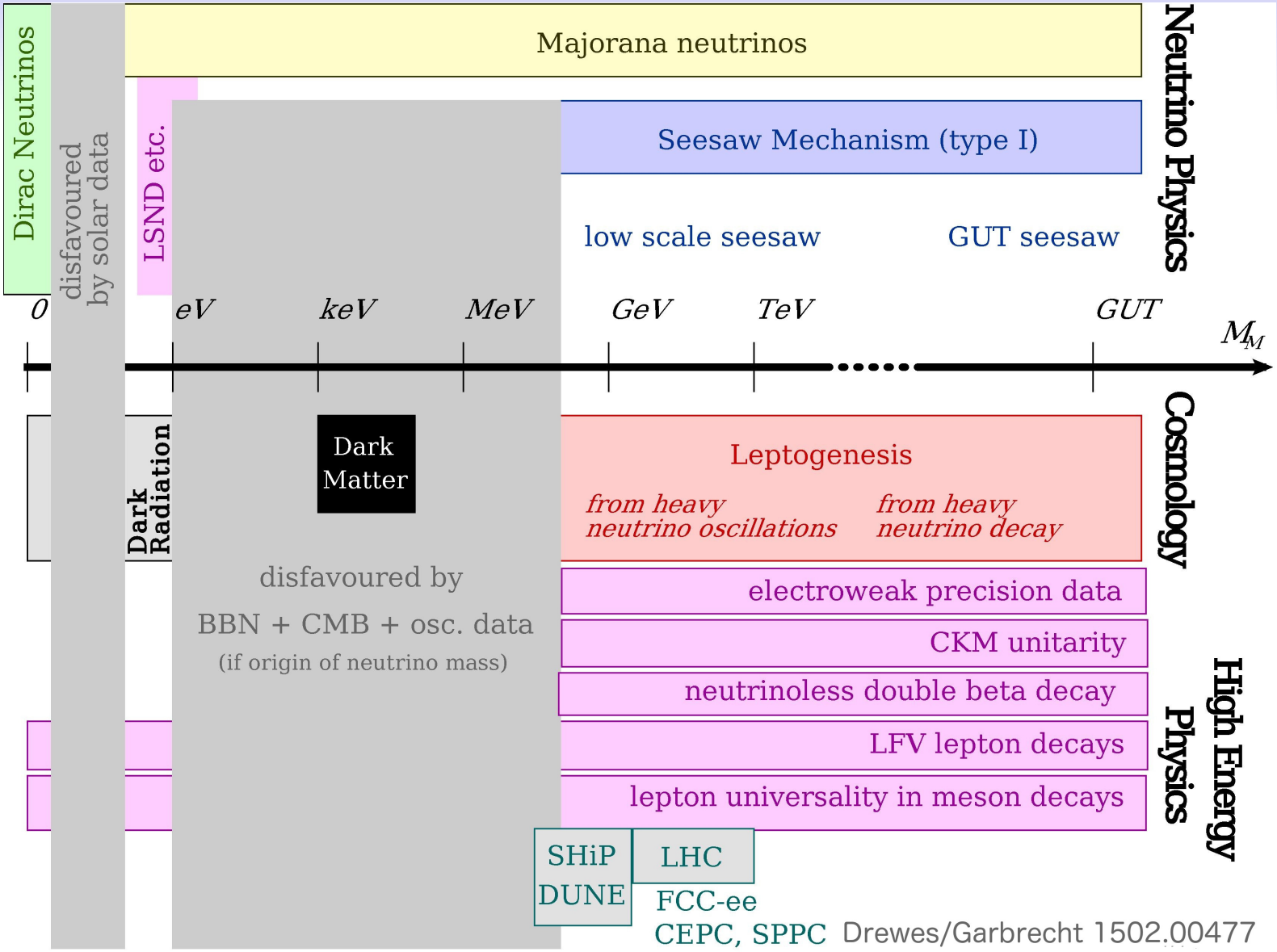


two sets of Majorana mass states with mixing $\theta = m_D M_M^{-1} = vFM_M^{-1}$

- three light neutrinos $\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - light masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N \simeq M_M}$
- Majorana masses M_M introduce new mass scale(s) M_I
- new heavy states only interact via small mixing $U_{aI}^2 = |\theta_{aI}|^2 \ll 1$


Dirac Neutrinos
disfavoured by solar data
Majorana neutrinos
LSND etc.
Seesaw Mechanism (type I)
low scale seesaw
GUT seesaw
Neutrino Physics
0
eV
keV
MeV
GeV
TeV
GUT
M_M
Dark Radiation
Dark Matter
Leptogenesis
from heavy neutrino oscillations
from heavy neutrino decay
Cosmology
disfavoured by
BBN + CMB + osc. data
(if origin of neutrino mass)
electroweak precision data
CKM unitarity
neutrinoless double beta decay
LFV lepton decays
lepton universality in meson decays
High Energy Physics
SHiP
DUNE
LHC
FCC-ee
CEPC, SPPC
Drewes/Garbrecht 1502.00477

Combining constraints on heavy neutrinos

Combined analyses:

Atre/Han/Pascoli/Zhang 0901.3589 collection of direct and indirect constraints

Asaka/Eijima/Ishida 1101.1382 + later work by Asaka et al indirect constraints

Ruchayskiy/Ivashko 1112.3319, 1202.2841 direct constraints, BBN

Abada, De Romeri, Teixeira, Vicente, Weiland (various works) indirect and direct constraints

Hernandez/Kekic/Lopez-Pavon 1406.2961 combined cosmological constraints

Antusch/Fischer 1407.6607 + later worksglobal fits of indirect constraints

Gorbunov/Timiryasov 1412.7751 indirect constraints

MaD/Garbrecht 1502.00477 combined analysis of direct, indirect and cosmological constraints

Fernandez-Martinez/Hernandez-Garcia/Lopez-Pavon/Lucente 1508.03051 indirect constraints at loop level

Gouvea/Kobach 1511.00683 global fits of direct and indirect constraints

Enrique Fernandez-Martinez/Hernandez-Garcia/Lopez-Pavon 1605.08774 global fits of indirect constraints

recent reviews:

Boyarsky/Ruchayskiy,/Shaposhnikov 0901.0011, Abazajian et al 1204.5379 , MaD 1303.6912,

Gninenko/Gorbunov/Shaposhnikov 1301.5516, Dev/Deppisch 1502.06541, [Adhikari et al 1602.04816]

Combining constraints

- **Indirect searches**
- **Direct searches**
- **Cosmology**: BBN

Combining constraints

- **Indirect searches**
  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality,
  - (apparent) violation of CKM unitarity
  - neutrinoless double β-decay
  - EW precision data
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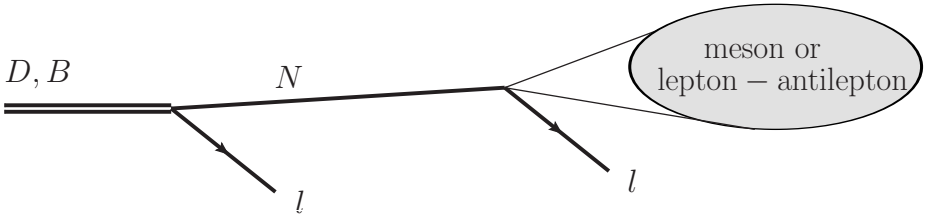
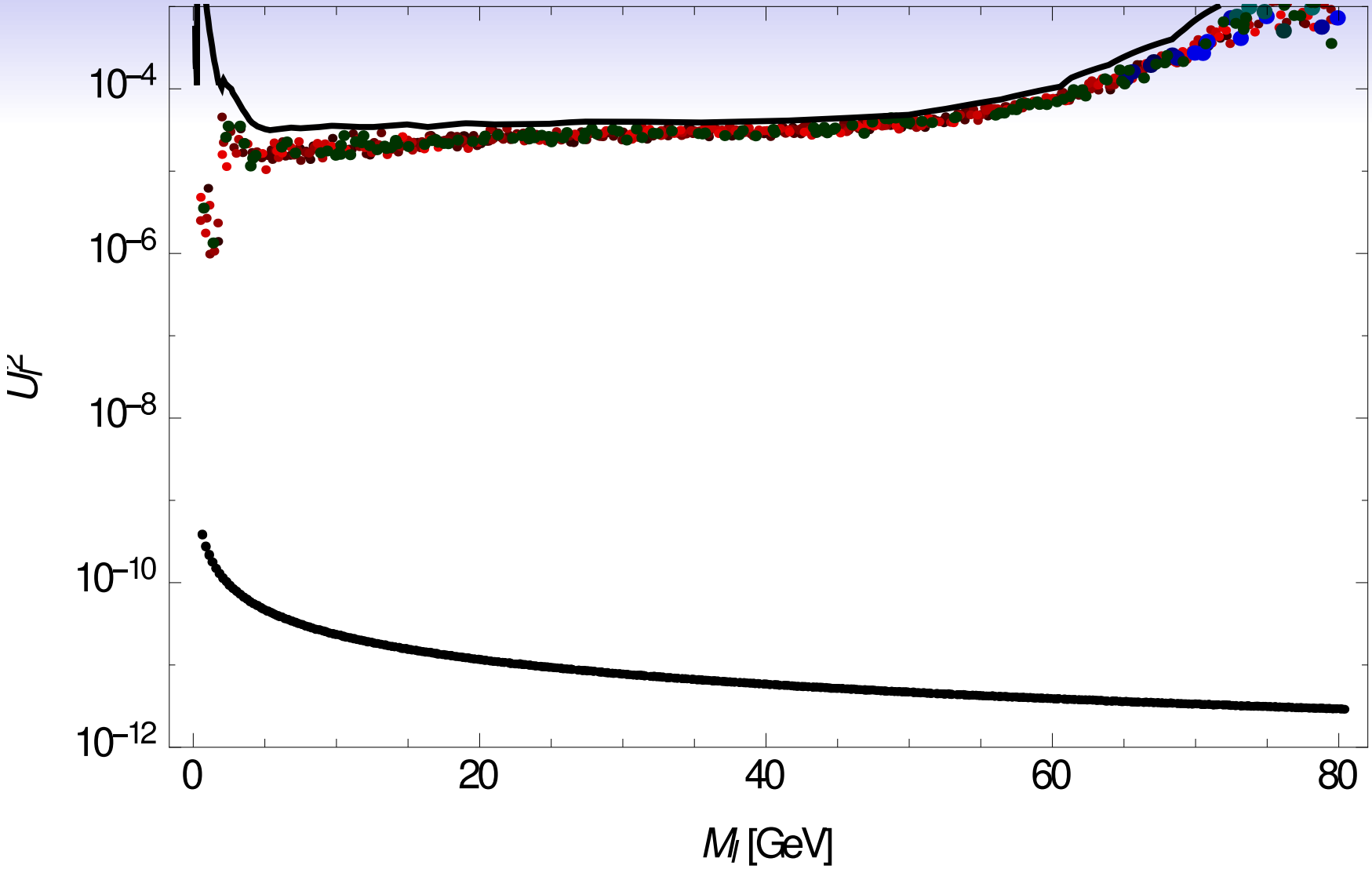
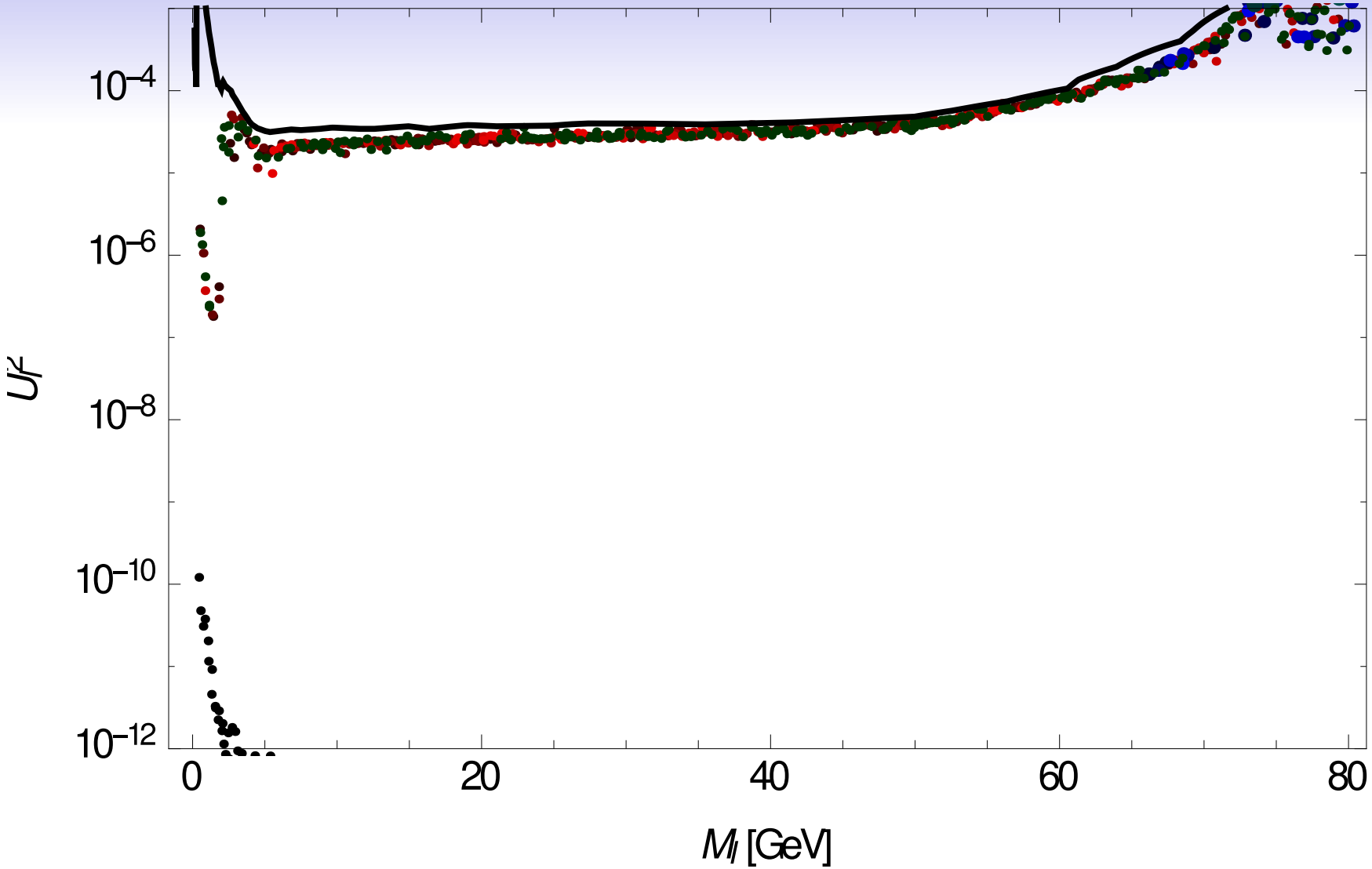
- **Direct searches**
  - LNV and LFV in gauge boson or meson decays



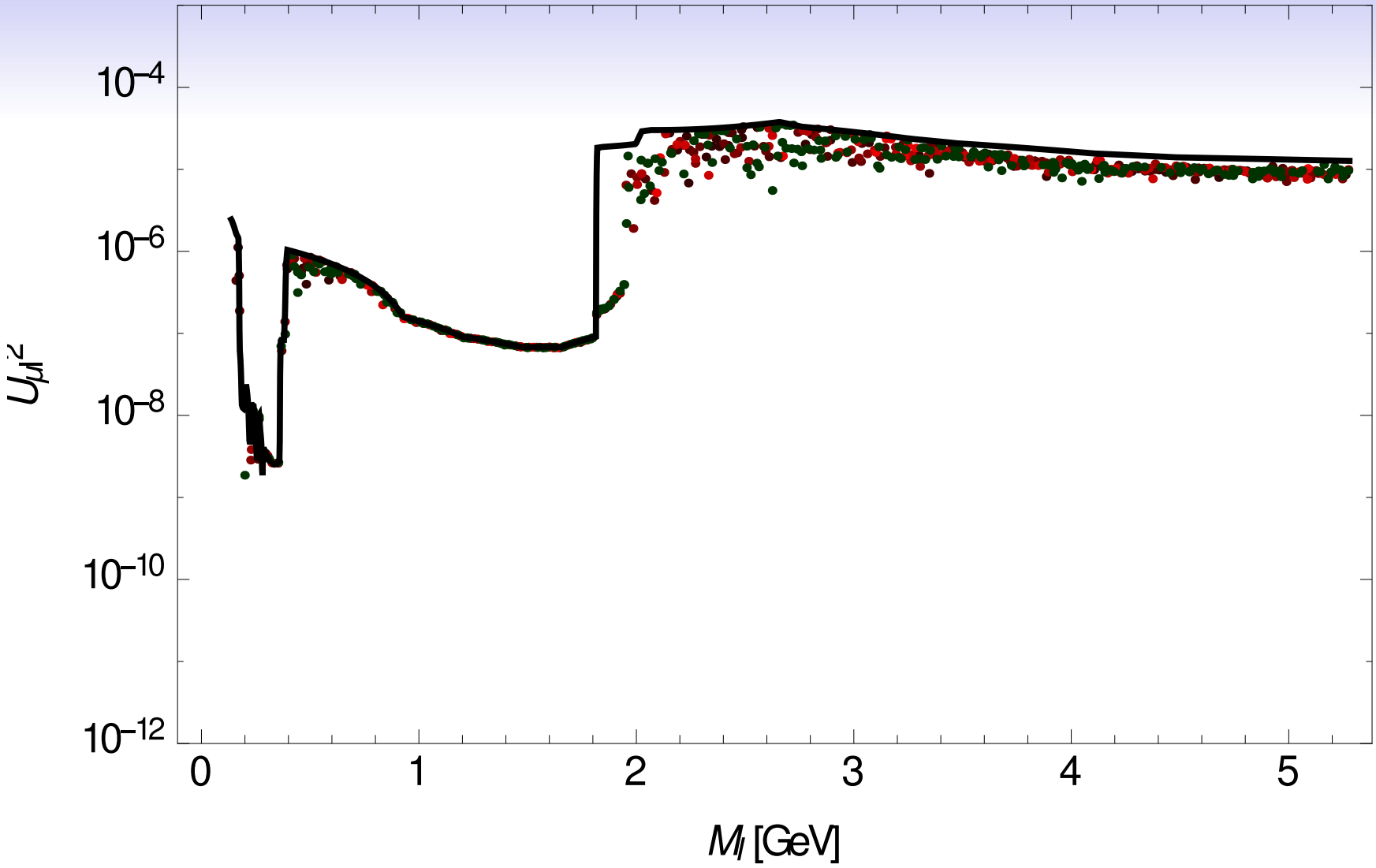
  - displaced vertices, peak searches, missing 4-momentum
  - SHiP see SHiP physics case paper 1504.04855
- **Cosmology**: BBN



inverted hierarchy, $m_{\text{lightest}} = 0.23$ eV, $n = 3$



inverted hierarchy, $m_{\text{lightest}} = 0$, $n = 3$



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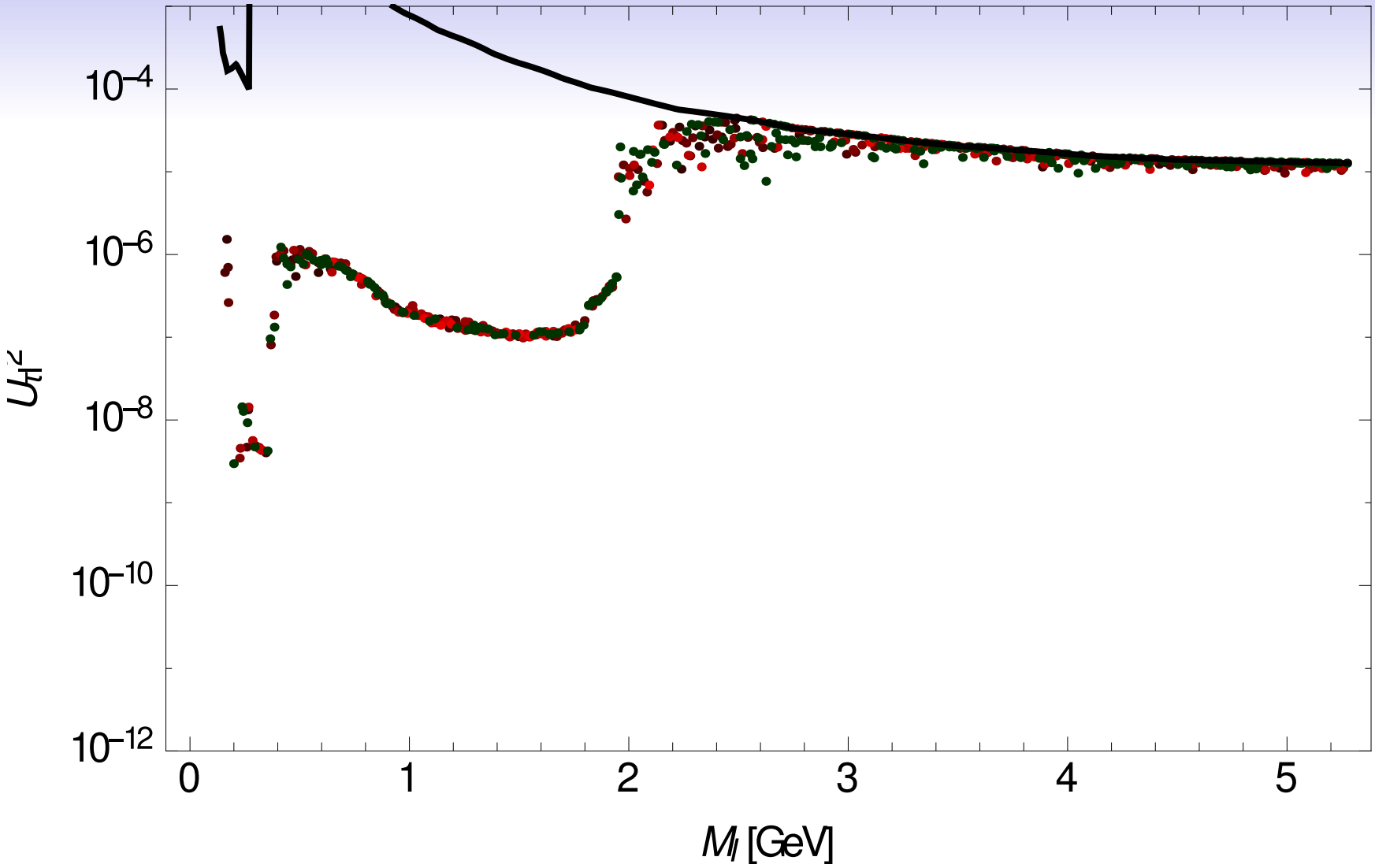

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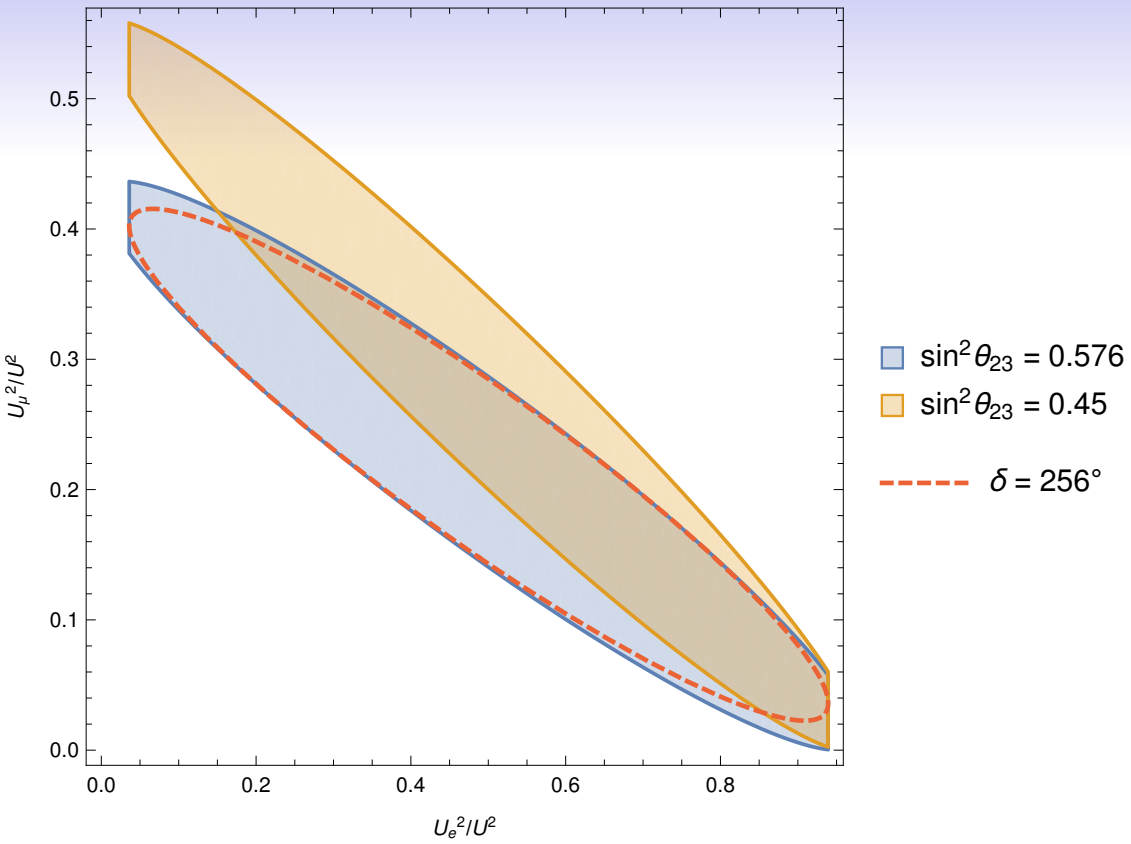


inverted hierarchy, $m_{\text{lightest}} = 0$, $n = 2$

A measurement of the Dirac phase will lead to rather precise predictions for the flavour mixing pattern!

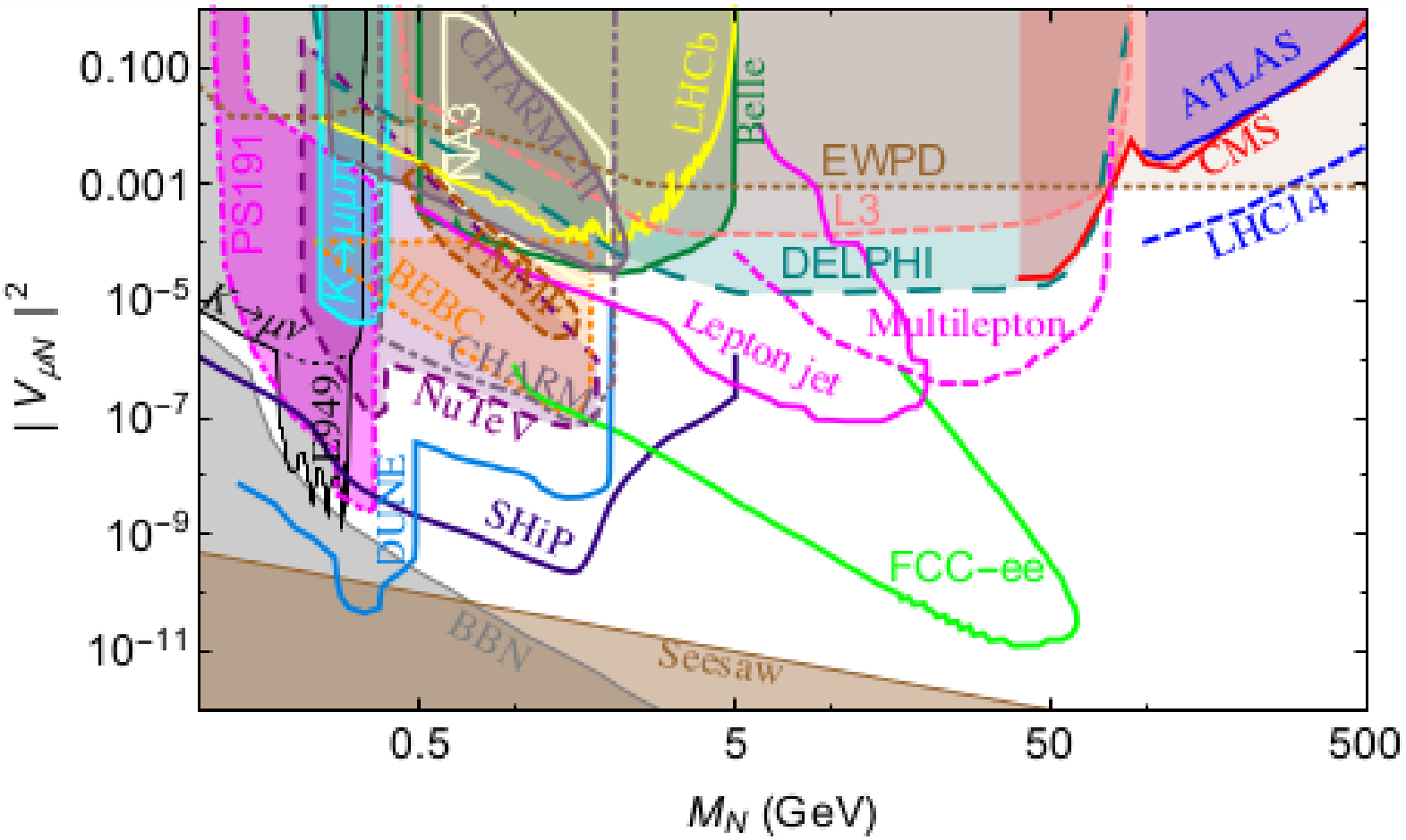
$\Rightarrow$ If a heavy neutral lepton discovered in experiment, we can decide if it is part of the seesaw mechanism

- **For U^2_{eI} and $U^2_{\mu I}$, the global constraints are only mildly stronger than the direct search bound alone.** But:
  - Not every combination of $U^2_{\alpha I}$ is allowed
  - This is a two dimensional projection of a twelve dimensional parameter space.
  - Large U^2_{eI} are only possible in very specific properties (approximate B-L conservation)

  $\Rightarrow$ Any external constraint could drastically change the picture (model building, cosmology...)

- **For $U^2_{\tau I}$ and $M_I < 2$ GeV, the combined constraints are much stronger than the direct search bound.**

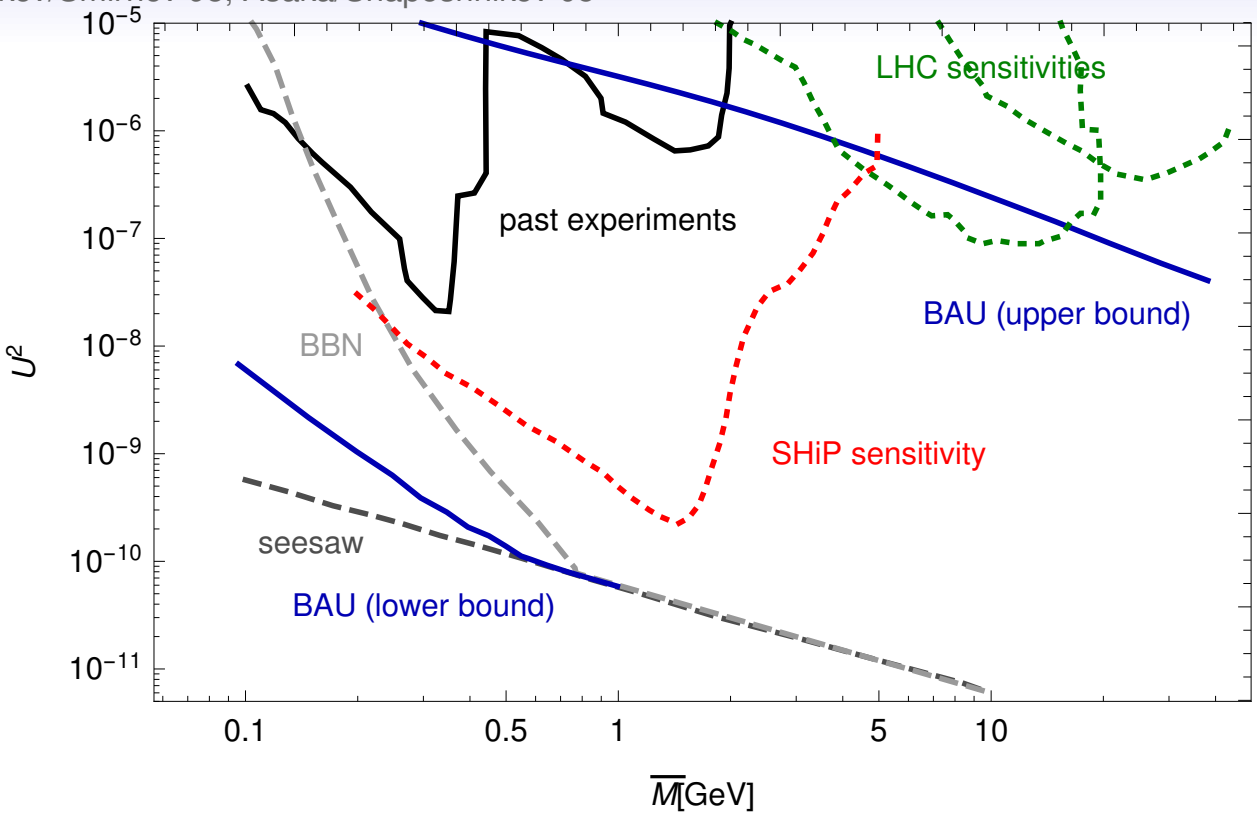
Future sensitivities



plot by Bhupal Dev

Leptogenesis with two heavy neutrinos

Akhmedov/Rubakov/Smirnov 98, Asaka/Shaposhnikov 05



plot: MaD/Garbrecht/Gueter/Klaric 1606.06690,sensitivities: Izaguirre/Shuve 1504.02470, Graverini et al 1503.08624

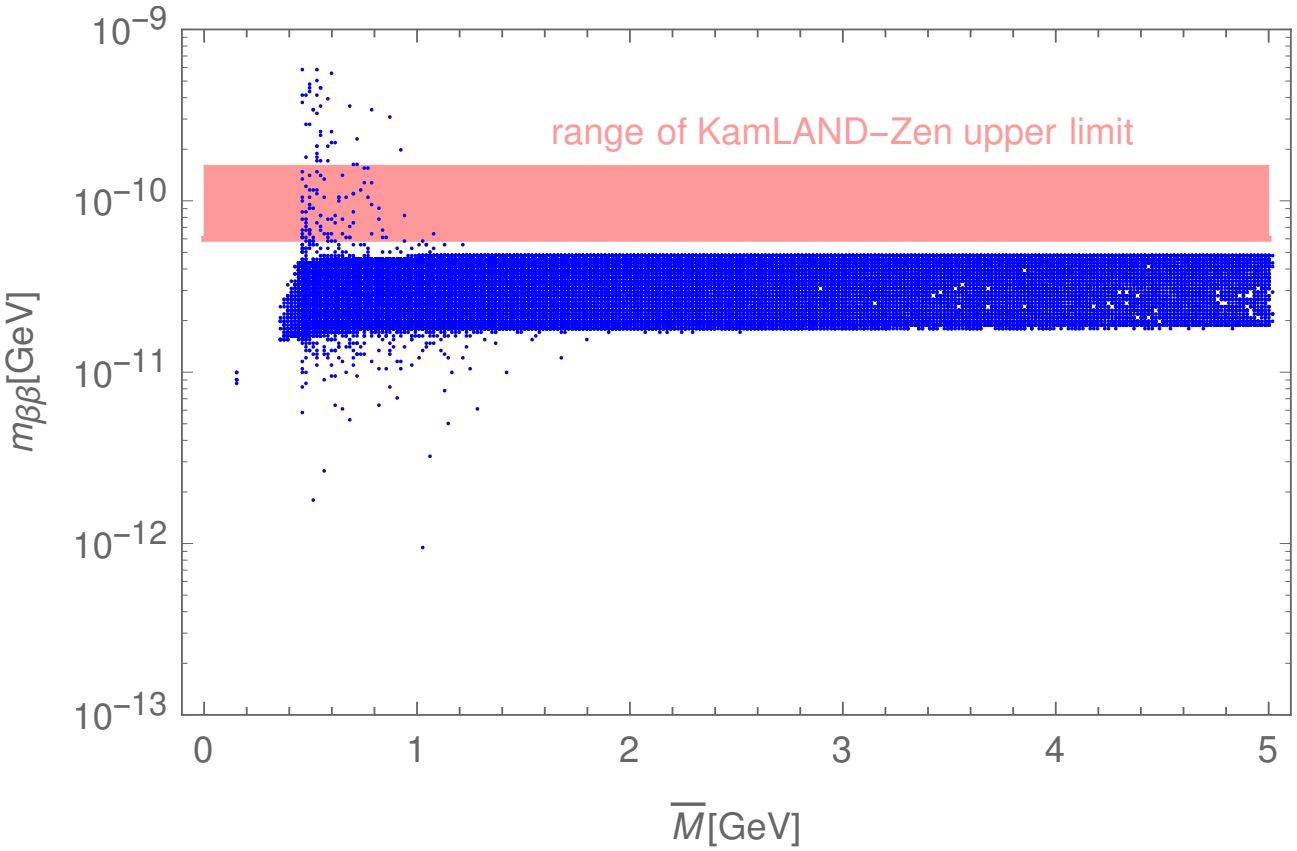
The common origin of matter and neutrino masses
can be discovered in the lab!

see also talks by Juraj Klaric and Jacobo Lopez-Pavon

as well as Canetti/MaD/Frossard/Shaposhnikov 1208.4607, Hernandez/Kekic/Lopez-Pavon/Salvado 1508.03676 and Abada/Arcadi/Domcke/Lucente 15

Indirect searches

Example: leptogenesis and neutrinoless double β-decay



plot from MaD/Eijima 1606.06221
see also Hernandez/Kekic/Lopez-Pavon/Racker/Salvado 1606.06719, Asaka/Eijima/Ishida 1606.06686

see also: talk by Jacobo Lopez-Pavon

Conclusions

- The seesaw mechanism (still) provides an elegant explanation for the observed neutrino masses.
- Any value of the seesaw scale between 100 MeV and the GUT scale is consistent with experiment at observation.
- However, for Majorana masses below the TeV scale,
  - strong constraints on the heavy neutrino properties can be imposed by combining various data sets and
  - many experiments can discover the heavy neutrinos (ATLAS, CMS, NA62, LHCb, BELLE II, SHiP, FCC-ee, CEPC...).
- The low scale seesaw also allows to address cosmological problems (leptogenesis, sterile neutrino Dark Matter, ...) within the experimentally accessible parameter space.
- The future? Stay tuned!
  - Not all existing data has been exploited
  - New data is coming
  - Theory studies need improvement