Leptogenesis

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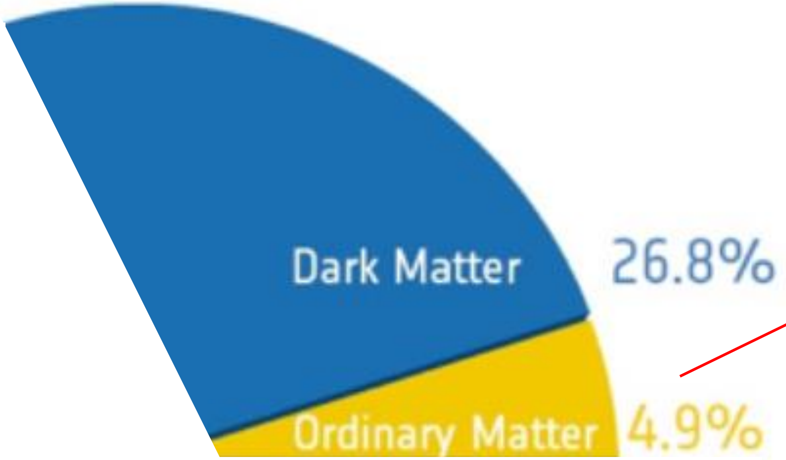
University of Rome Three

Given the broadness of the subject,

this will be an overview of some selected topics.

Apologizes if some interesting topics (and references) will not be covered.

Baryogenesis in a nutshell



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.02 - 6.18) \times 10^{-10}$$

Planck Collaboration, arXiv:1807.06209

Dynamical mechanism for the generation of the matter-antimatter asymmetry (BAU) in the primordial Universe

Necessary requirements →

A.D. Sakharov *Pisma Zh.Eksp.Teor.Fiz.* 5 (1967) 32-35, *JETP Lett.* 5 (1967) 24-27, *Sov.Phys.Usp.* 34 (1991) 5, 392-393

Violation of Baryon Number (B);

Violation of C and CP;

Departure from Thermal Equilibrium

The Standard Model cannot succesfully account for the BAU. We need to look for Physics beyond the Standard Model.

Baryogenesis

Direct Baryogenesis: mechanism which created dynamically a baryon-antibaryon asymmetry.

Leptogenesis: First dynamical generation of a lepton asymmetry. Conversion of the lepton asymmetry into a baryon asymmetry, e.g. by B-L Sphalerons.

$$\eta \leftrightarrow Y_{\Delta B} = A\, Y_{\Delta(B-L)}$$

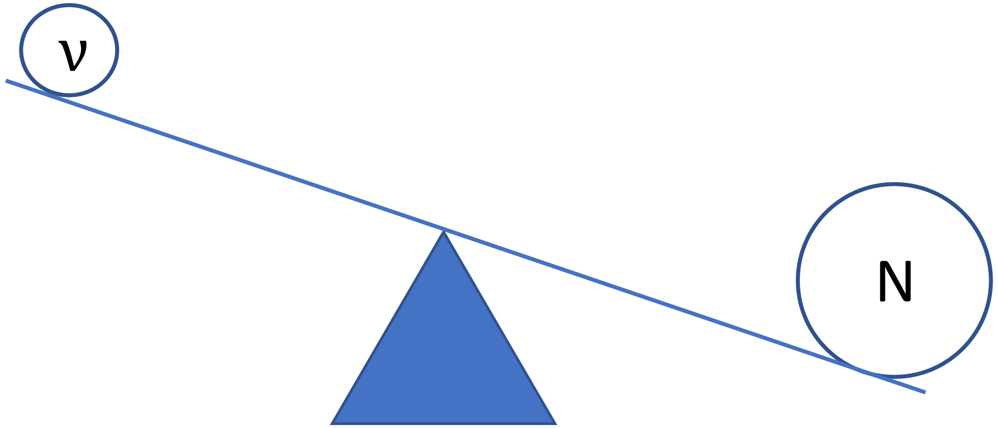
System of Boltzmann's equations

$$\begin{cases} \dfrac{dY_N}{dT} = \cdots \\ \dfrac{dY_{\Delta(B-L)}}{dT} = \cdots \end{cases}$$

Source: State(s) generating the asymmetry e.g. out-of-equilibrium decaying heavy neutrino

Details of the system depend on the specific model

Mechanism for generation of neutrino mass.



(Original idea from M. Fukugida and T. Yanagida Phys. Lett. B174 (1986) 45-47)

→ Leptogenesis

Connection with other observables ⟷ Experimental tests

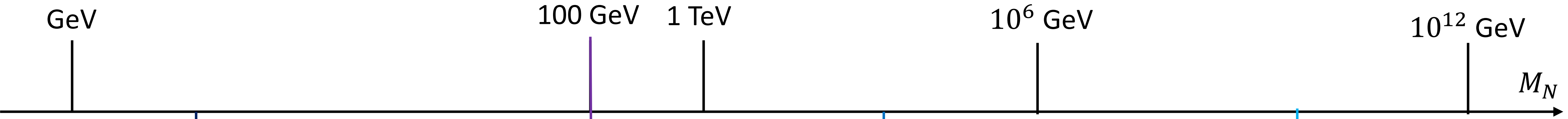
Leptogenesis requires violation of the lepton number (LNV)

e.g:
Neutrinoless Double-beta decay
Searches of extra neutrinos

Searches in Low energy experiments

LHC

Possible connection with low energy phases.
Lepton number violating processes



Leptogenesis from Oscillations (ARS)

Asaka, Eijima, Ishida, 1112.5565
Asaka, Shaposhinokov, 0505013
Akhmedov, Rubakov, Smirnov 9803255

Leptogenesis from LPV decay of the Higgs

T. Hambye and D. Teresi arXiv:1606.00017
Eijima, Shaposhnikov 1703.06085
Eijima, Shaposhnikov, Timiryasov 1808.10833

Resonant Leptogenesis

A. Pilaftis and T. E. J. Underwood Nucl. Phys. B692, 303 (2004)
A. Abada, H. Aissaoui, M. Losada 0406304

Thermal Leptogenesis

M. Fukugida and T. Yanagida Phys. Lett. B174 (1986) 45-47
W. Buchmuller, P. Di Bari, M. Plumacher arXiv:0401240
R. Barbiere, P. Creminelli, A. Strumia, N. Tetradis

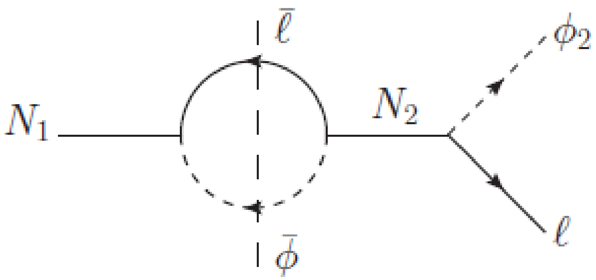
Case of study: interaction responsible of asymmetry generation associated to right-handed (sterile) neutrinos involved in the mass generation of active neutrinos.

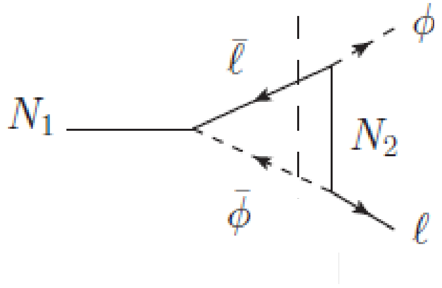
Examples of other possibilities (not exhaustive list):

L. Covi, E. Roulet, F. Vissani 9605319
S. Antush, S. F. King 0405093
L. Boubekeur, T. Hambye, G. Senjanovic 0404038
T. Hallgren, T. Konstandin, T. Ohlson 0710.2408
T. Hambye 1212.2888
T. Rink, W. Rodejohann, K. Schmitz 2006.03021
J. Harz et al; 2106.10838

$M_N > 100\ GeV$

Out-of-equilibrium (L-violating) decays of right-handed neutrinos produced in the Early Universe. CP-asymmetry generated by interference between tree level and loop diagrams.

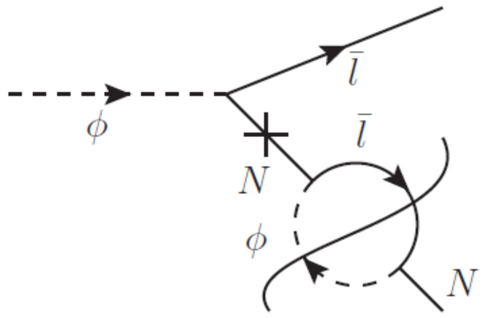




$M_N < 100\ GeV$

L-violating decays of the Higgs

Asymmetry generated by CP-violating oscillations of extra heavy neutrinos.



ARS Leptogenesis

A.Abada, G.A., V. Domcke, M. Lucente 1709.00415
G. Ghiglieri, M. Laine 1703.06087, 1811.09171
Hernandez, Kekic, Lopez-Pavon, Racker, Salvado 1606.06719
A. Abada, G.A., V. Domcke, M. Lucente 1507.06215
Canetti, Drewes, Fossard, Shaposhnikov 1208.4607
Asaka, Eijima, Ishida, 1112.5565
Asaka, Shaposhinokov, 0505013
Akhmedov, Rubakov, Smirnov 9803255

(Ahkmedov Rubakov Smirnov)

Converted into baryon asymmetry by Sphalerons

Right-handed neutrinos thermally produced in Early Universe with CP-violating oscillations.

Asymmetry converted into asymmetry between active flavors

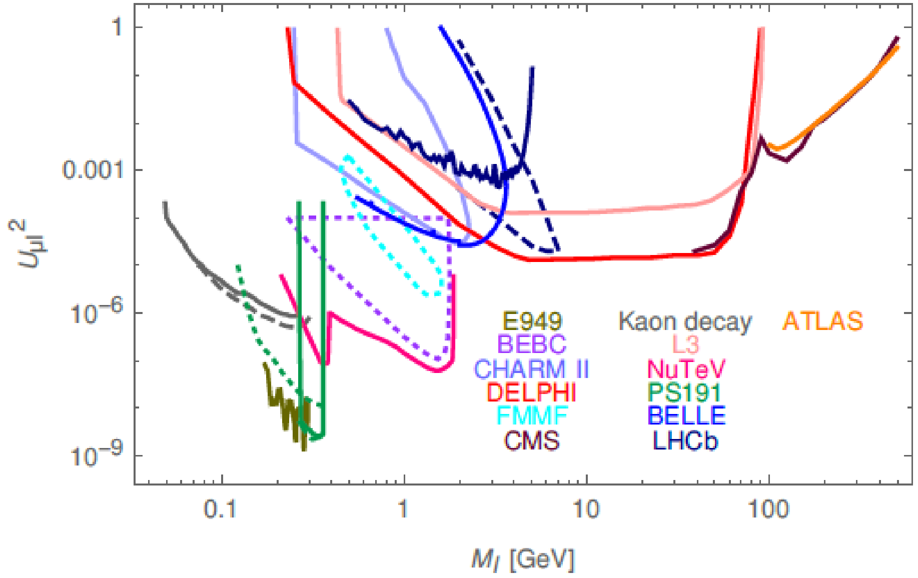
Asymmetry in the active sector acts as background potential and enhances the asymmetry in the RH sector

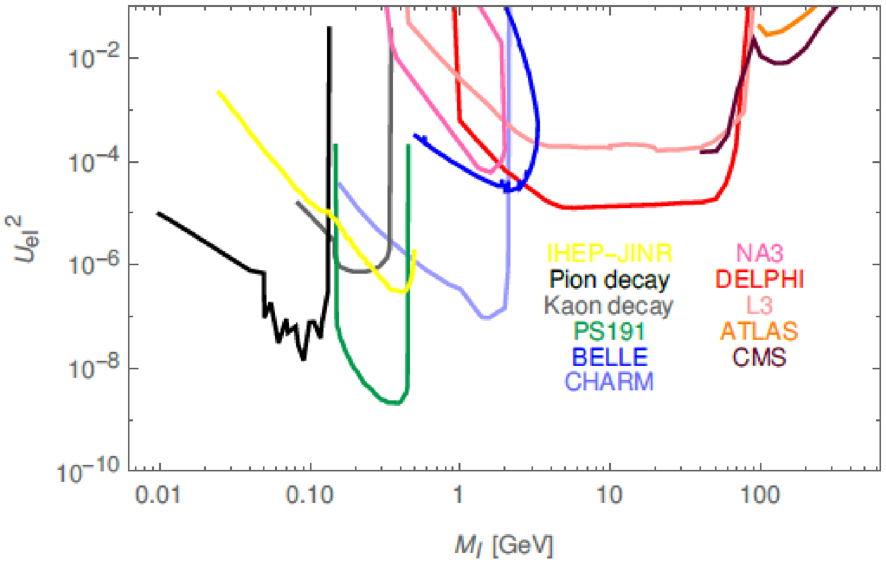
Limits on Light Extra Neutrinos

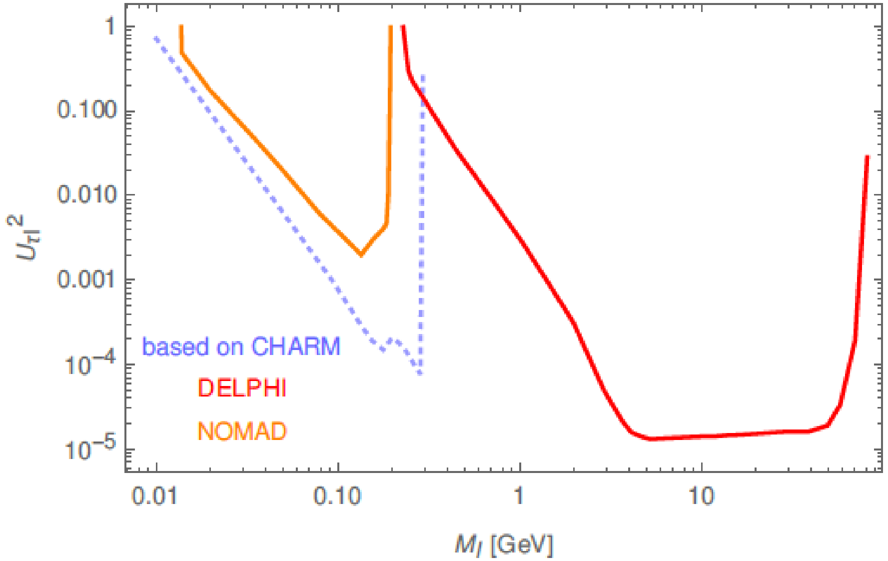
ARS Leptogenesis requires extra neutrinos to be at most as heavy as few tens of GeV.

Possibility of tests from low energy experiments.

A. Atre, T. Han, S. Pascoli, B. Zhang 0901.3589
E.J. Chun et al, arXiv:1711:02865
A. Abada, C. Hati, X. Marcano, A. M. Texeira, arXiv:1904.05367



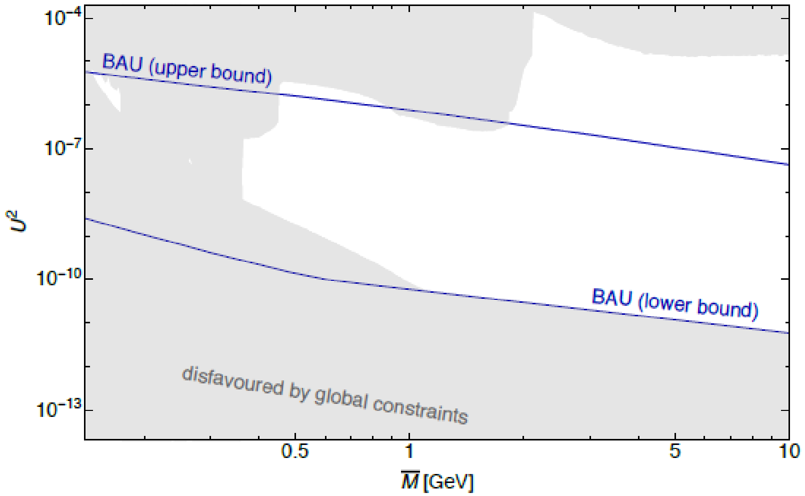




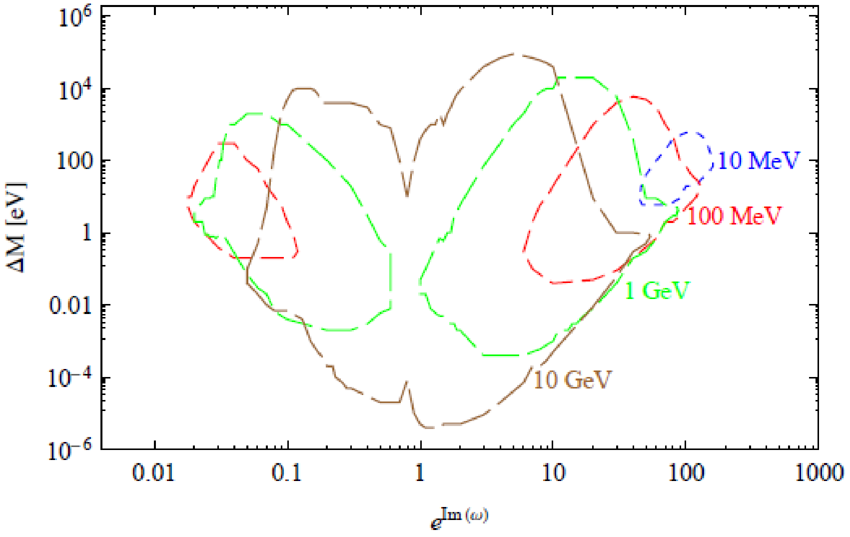
The minimal realization of the ARS mechanism requires a pair of almost mass degenerate heavy (as opposed to active neutrinos) neutrinos.

E.J. Chun et al, arXiv:1711.02865

M. Drewes, B. Garbrecht, D. Gueter, J. Klaric 1609.09609

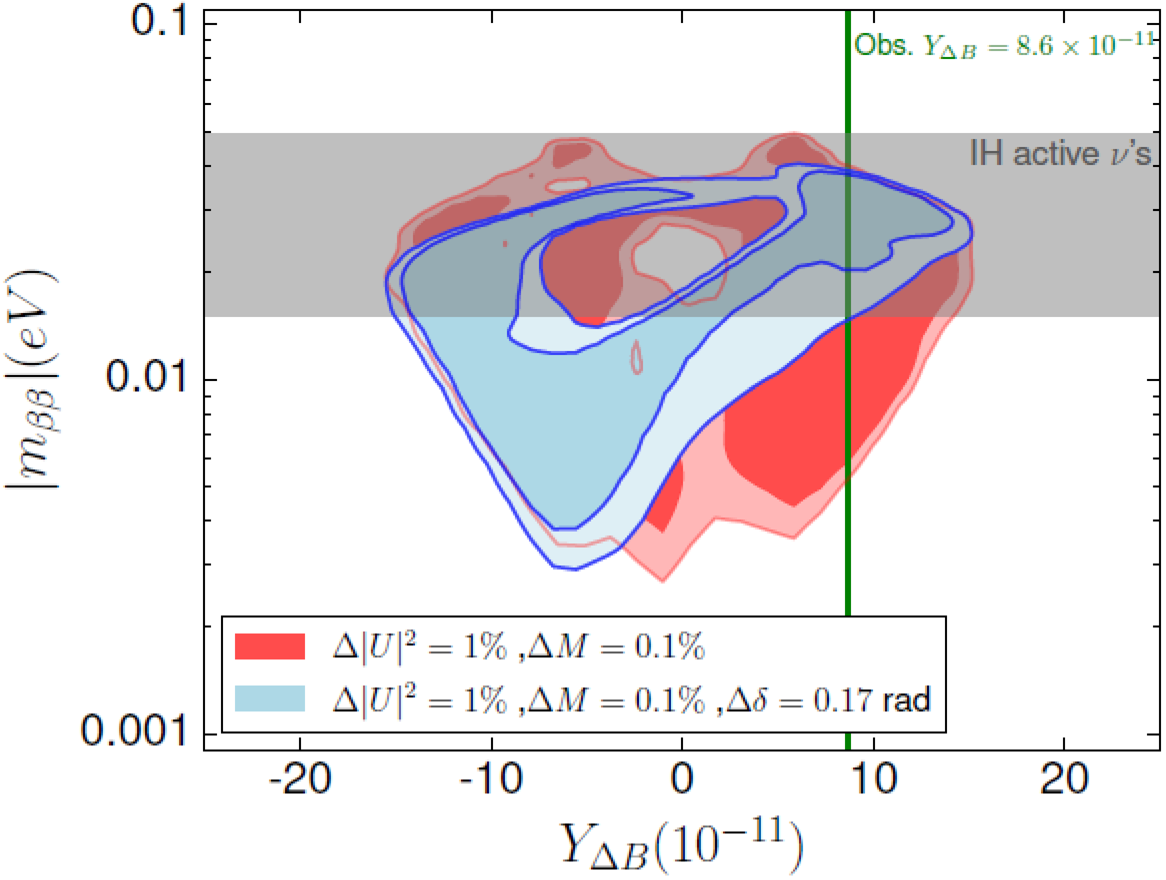


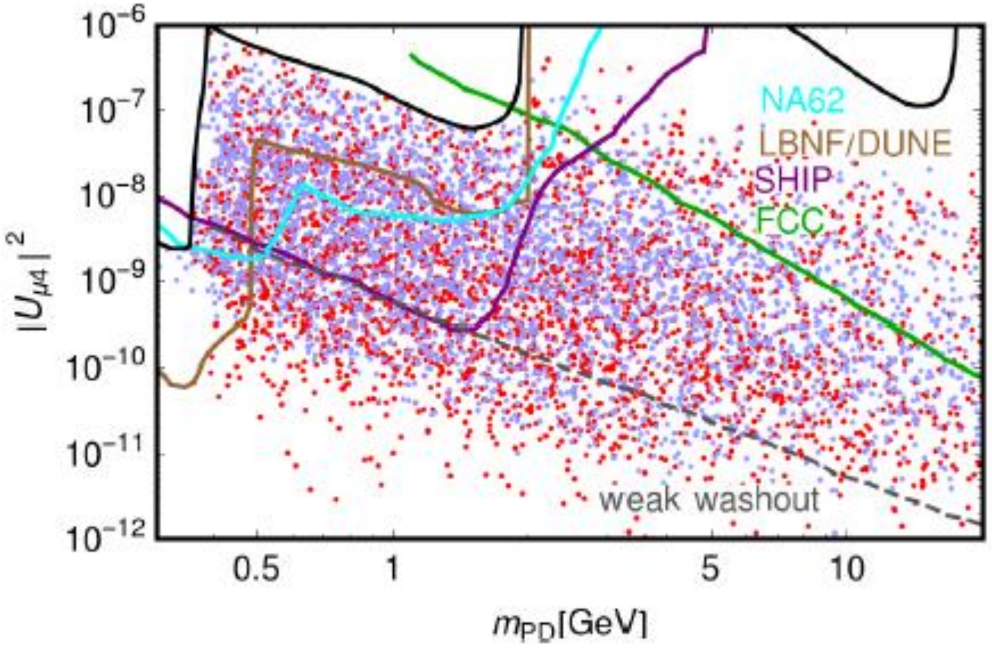
L. Canetti, M. Drewes, T. Frossard, M. Shaposhnikov 1208.4607



Type-I See-saw

P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker, J. Salvado 1606.06719





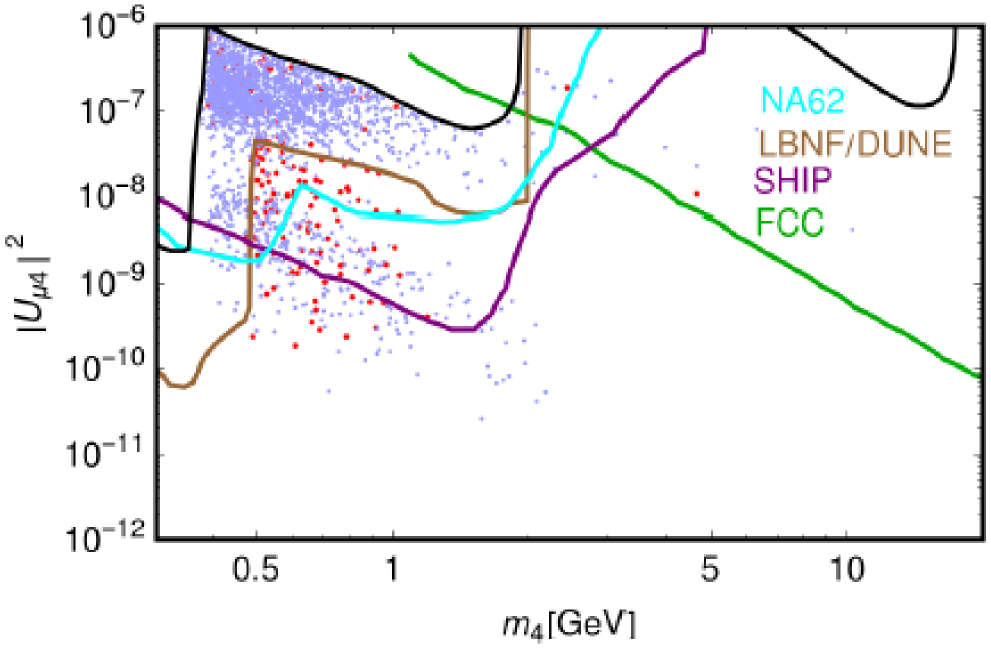
Linear+Inverse See-Saw

A. Abada, **G.A.**, V. Domcke, M. Lucente 1507.06215

In linear+inverse See-saw heavy neutrinos are pseudo-dirac

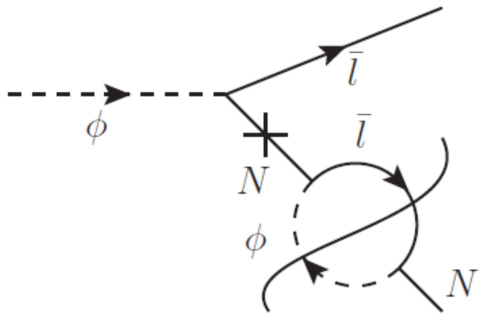
Inverse See-Saw

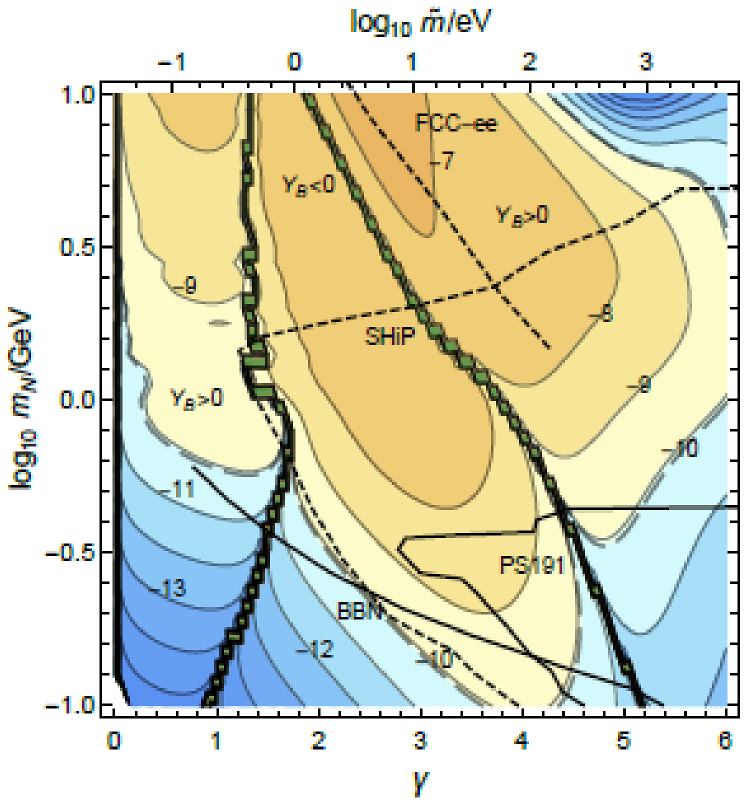
A. Abada**, G.A.**, V. Domcke, M. Lucente 1709.00415



Including LNV decays of the Higgs

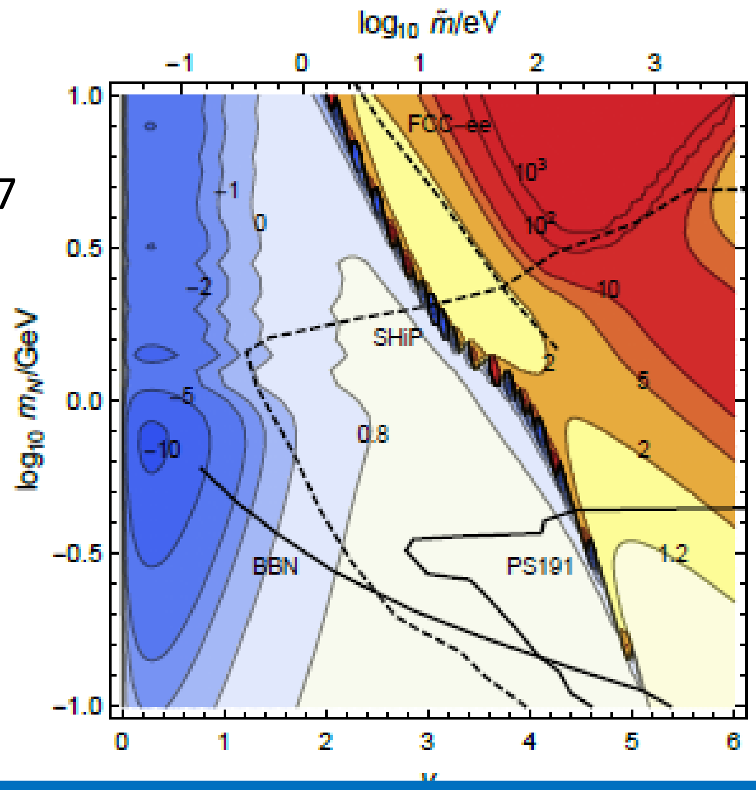
Leptogenesis from: Oscillations + LNV Decays





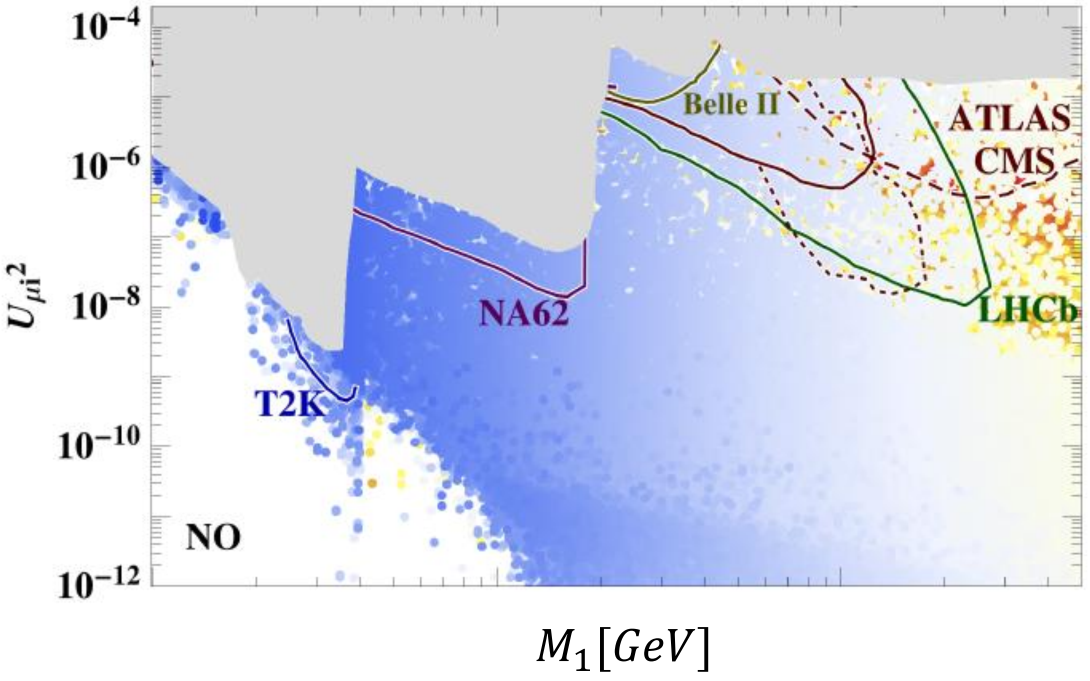
T. Hambye and D. Teresi arXiv:1606.00017

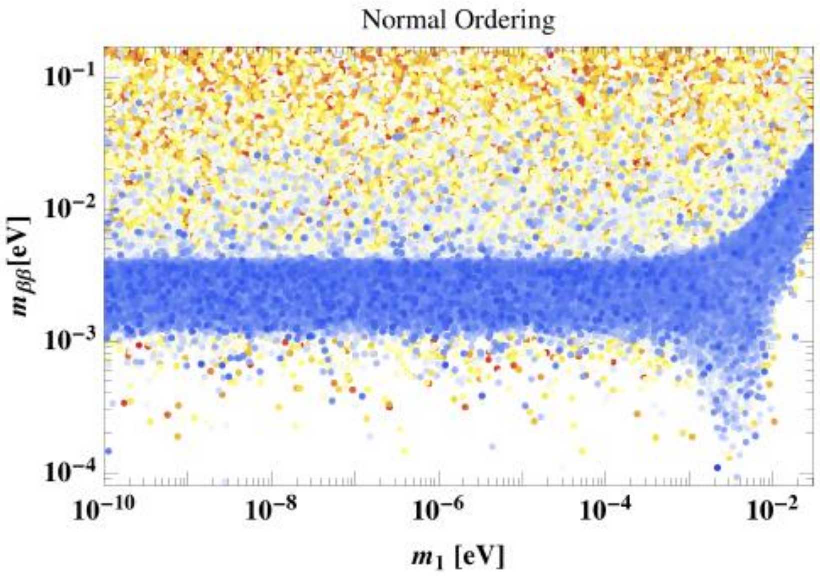
(See also
Eijima, Shaposhnikov 1703.06085
Eijima, Shaposhnikov, Timiryasov 1808.10833)

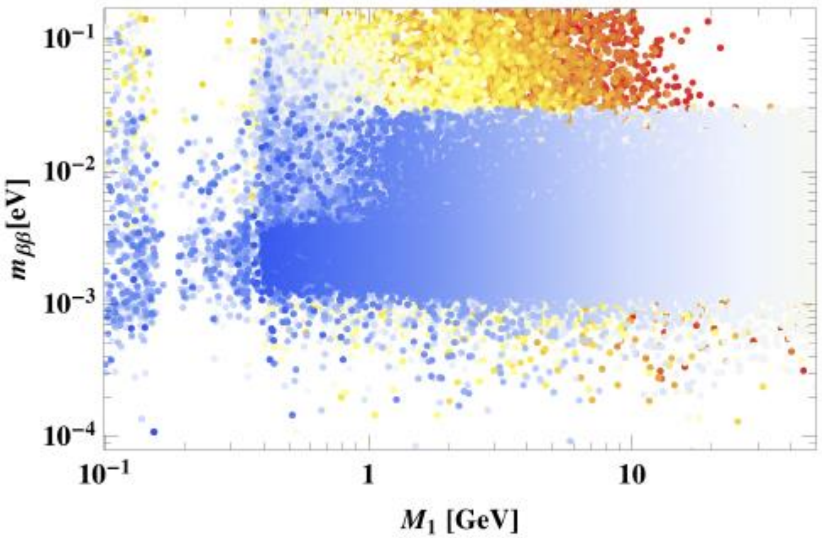


ARS Leptogenesis from 3 heavy neutrinos

Degeneracy removed for leptogenesis from 3 (or more) neutrinos.
(Drewes and Garbrecht, arXiv:1206.5537
P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Racker, N. Ruis 1508.03676)

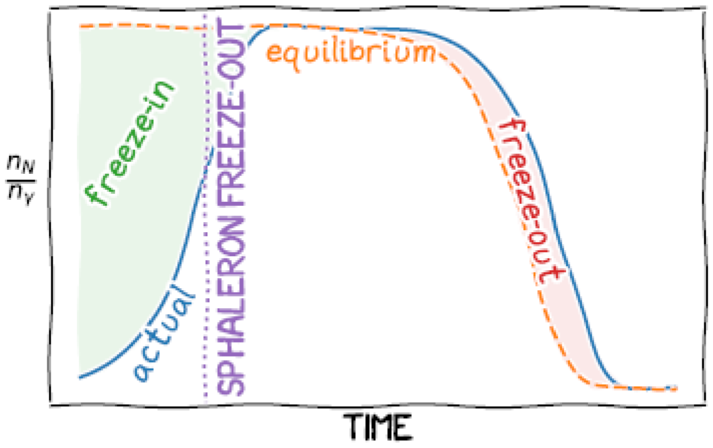


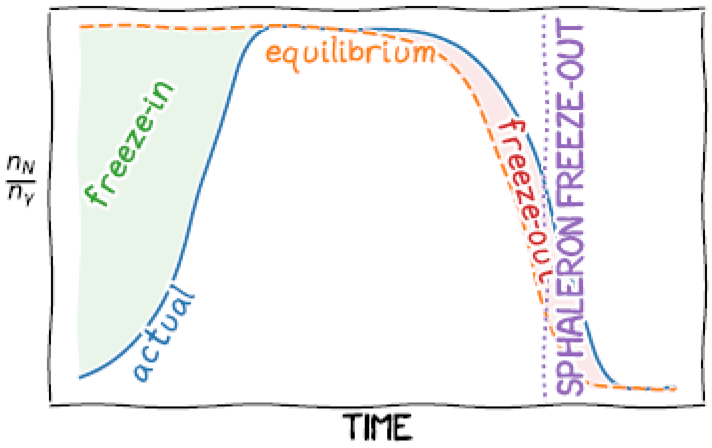


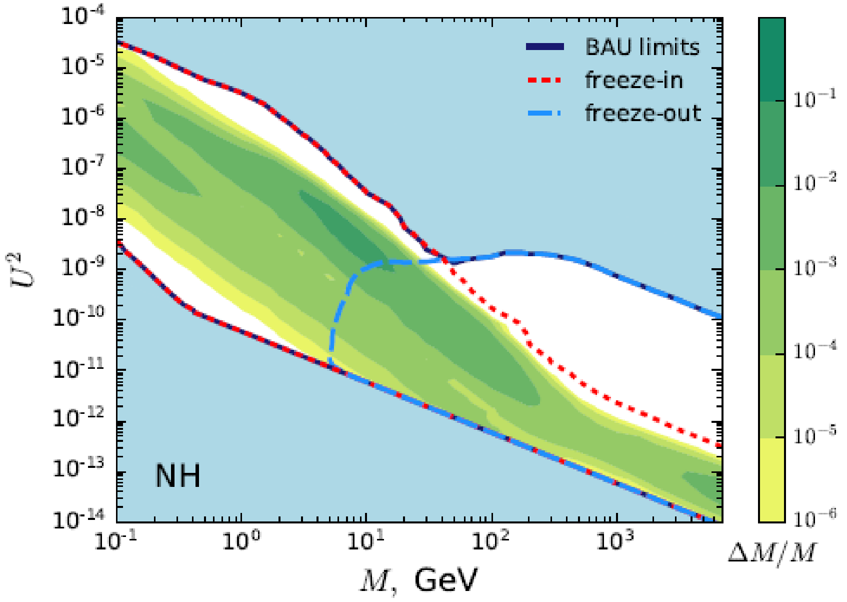


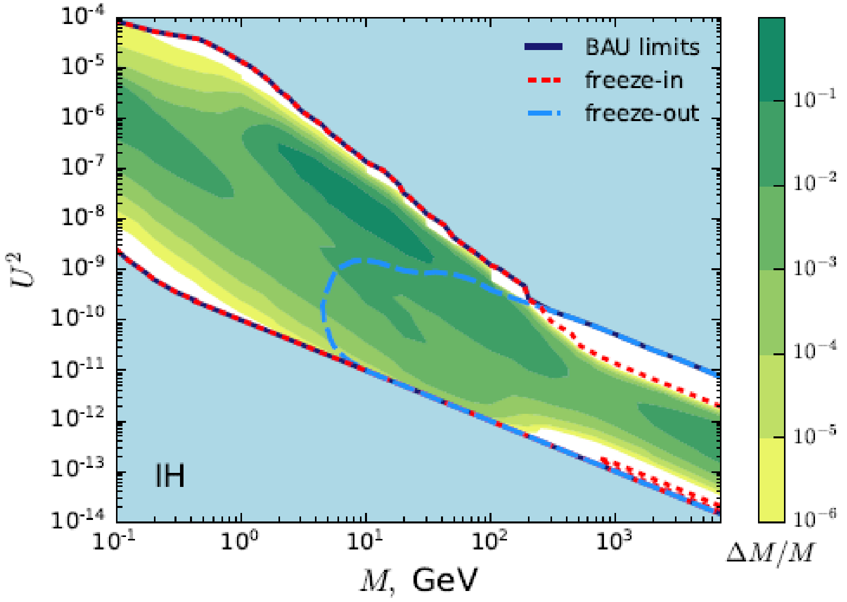
A. Abada, **G.A.**, V. Domcke, M. Drewes, J. Klaric, M. Lucente
arXiv: 1810.12463

Unifying leptogenesis from oscillations and resonant leptogenesis





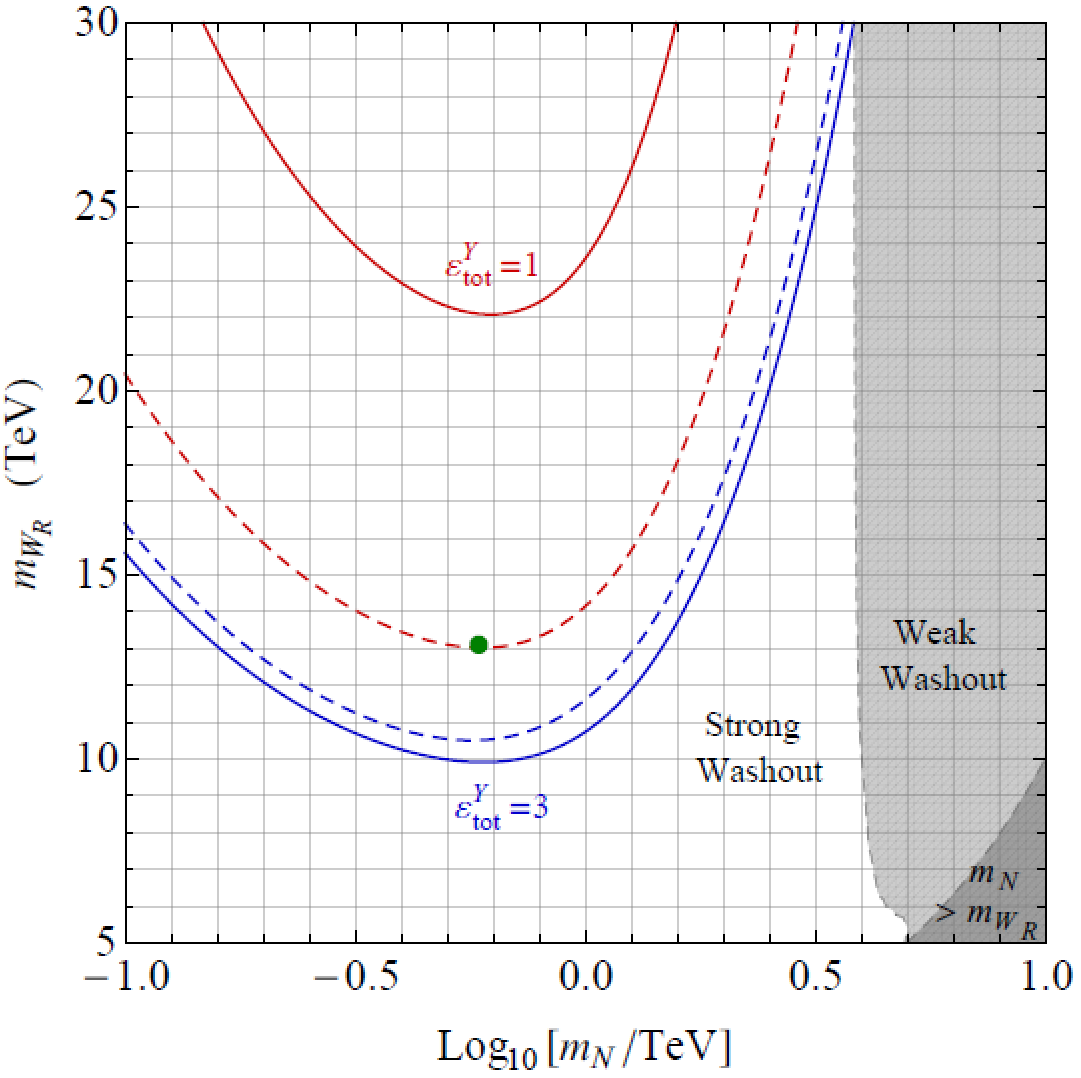




J. Klaric, M. Shaposhnikov, I. Timiryasov, arXiv:2103.16545

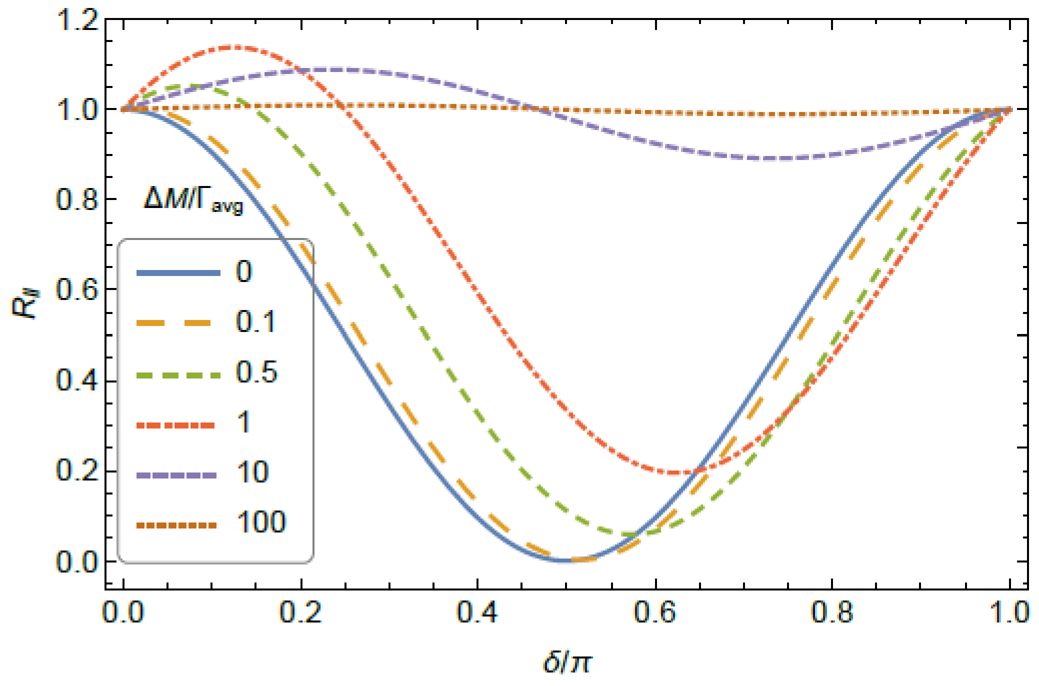
(Extension to three neutrino case, M. Drewes, Y. Georis, J. Klaric, 2106.16226)

TeV scale Leptogenesis in L-R model



See-saw based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

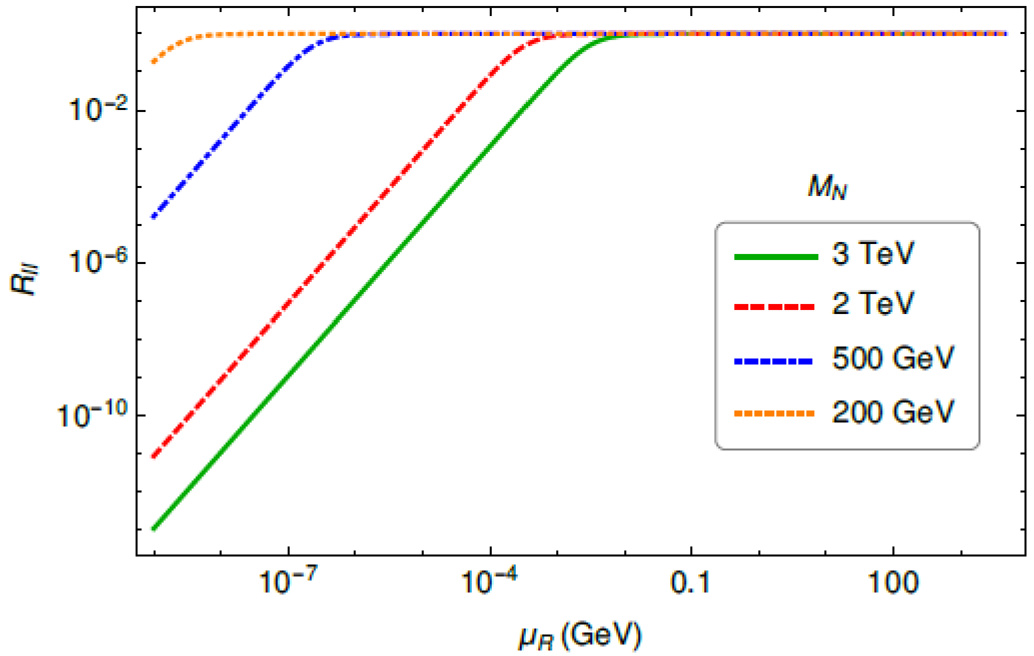
P.S. B. Dev, C. Lee, R. Mohapatra 1503.04970
(See also A. Abada, P. Hosteins, F. Josse-Michaux, S. Lavignac 0808.2058)



$$pp \to W_R^{\pm} \to N l^{\pm}$$

$$R_{ll} = \frac{Same\ Sign}{Opposite\ Sign}\ Dileptons$$

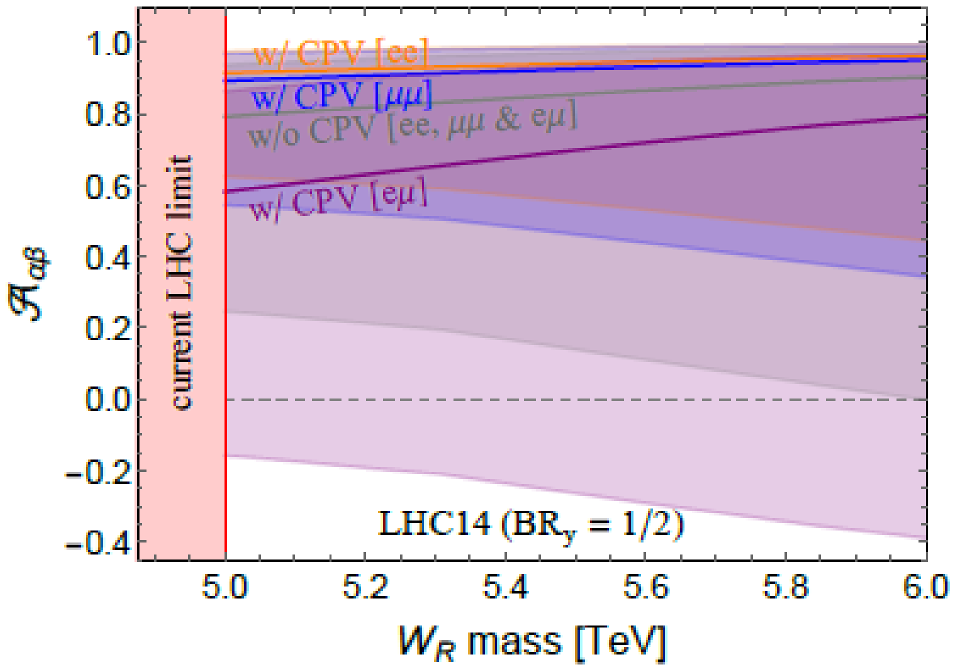
Inverse See-saw+Linear See-saw

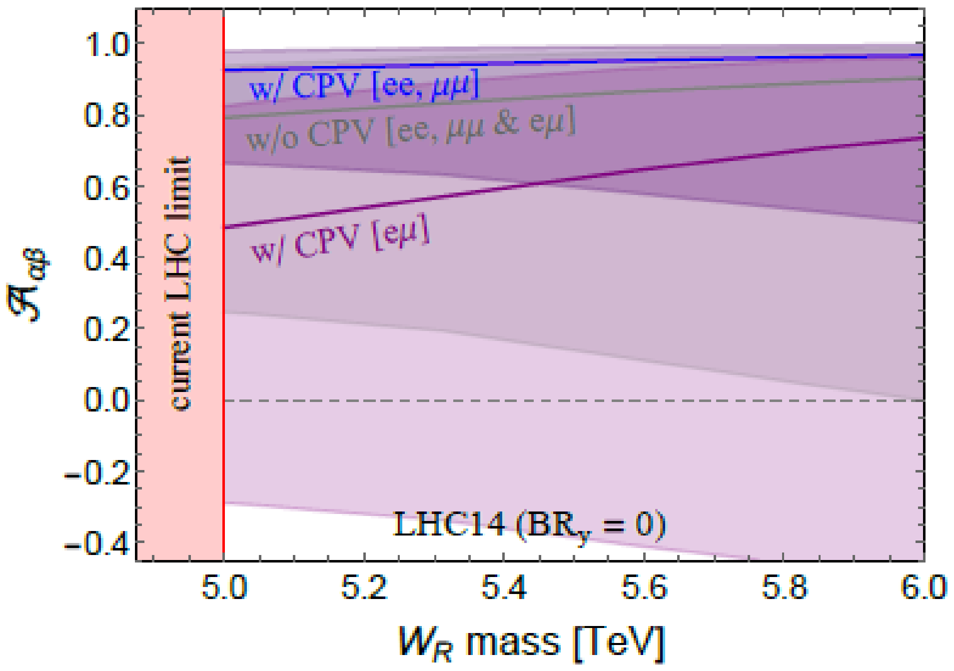


Type-I See-saw.

A. Das, P. S. B. Dev, R. Mohapatra, arXiv:1709.06553

Test mass degeneracy through charge asymmetries in W_R decays.



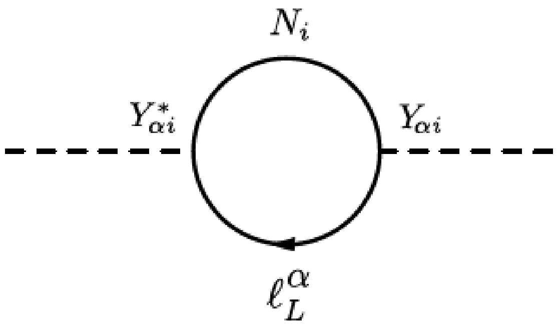


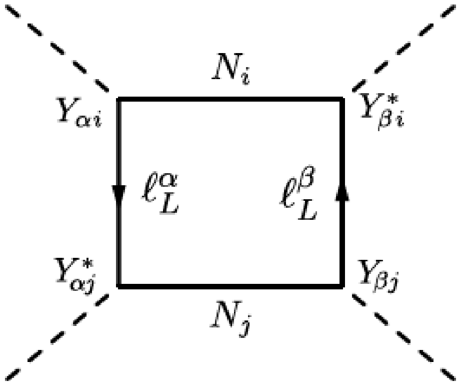
P.S.B. Dev, R. Mohapatra, Y. Zhang, 1904.04787

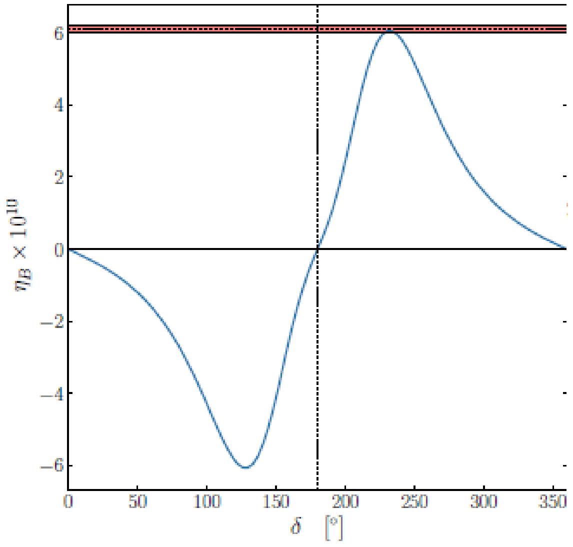
Leptogenesis and neutrino option

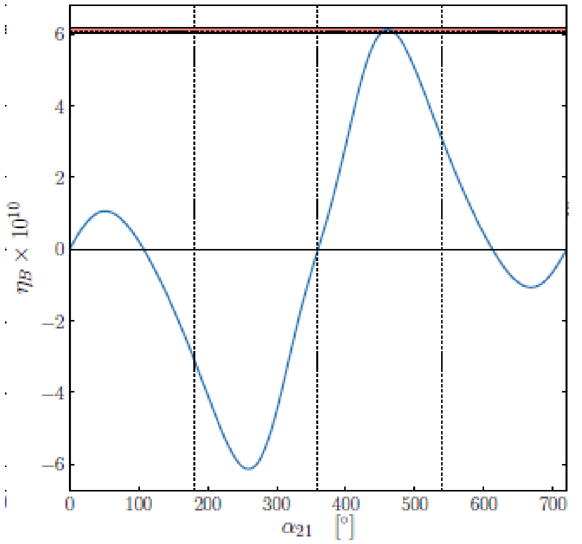
I.Brivio, K. Moffat, S. Pascoli, S.T. Petcov, J. Turner JHEP 10 (2019) 059
V. Brdar, J. Hembolt, S. Iwamoto, K. Schmitz, Phys. Rev. D100 (2019) 075029

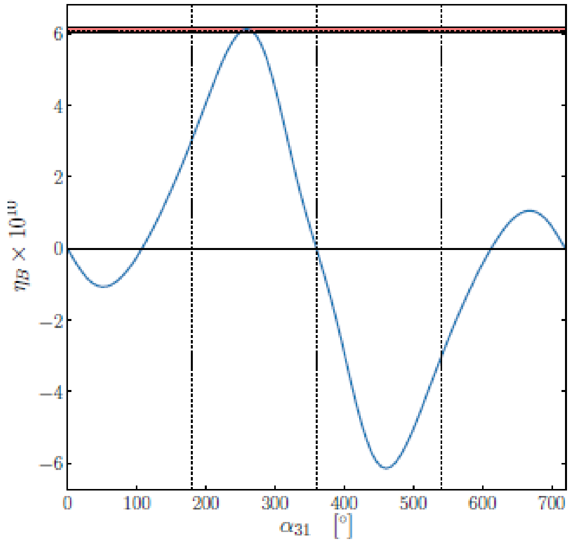
Interesting possibilitity: Right-handed neutrino can provide successfule leptogenesis and at the same time explain the generation of the EW scale and leptogenesis.







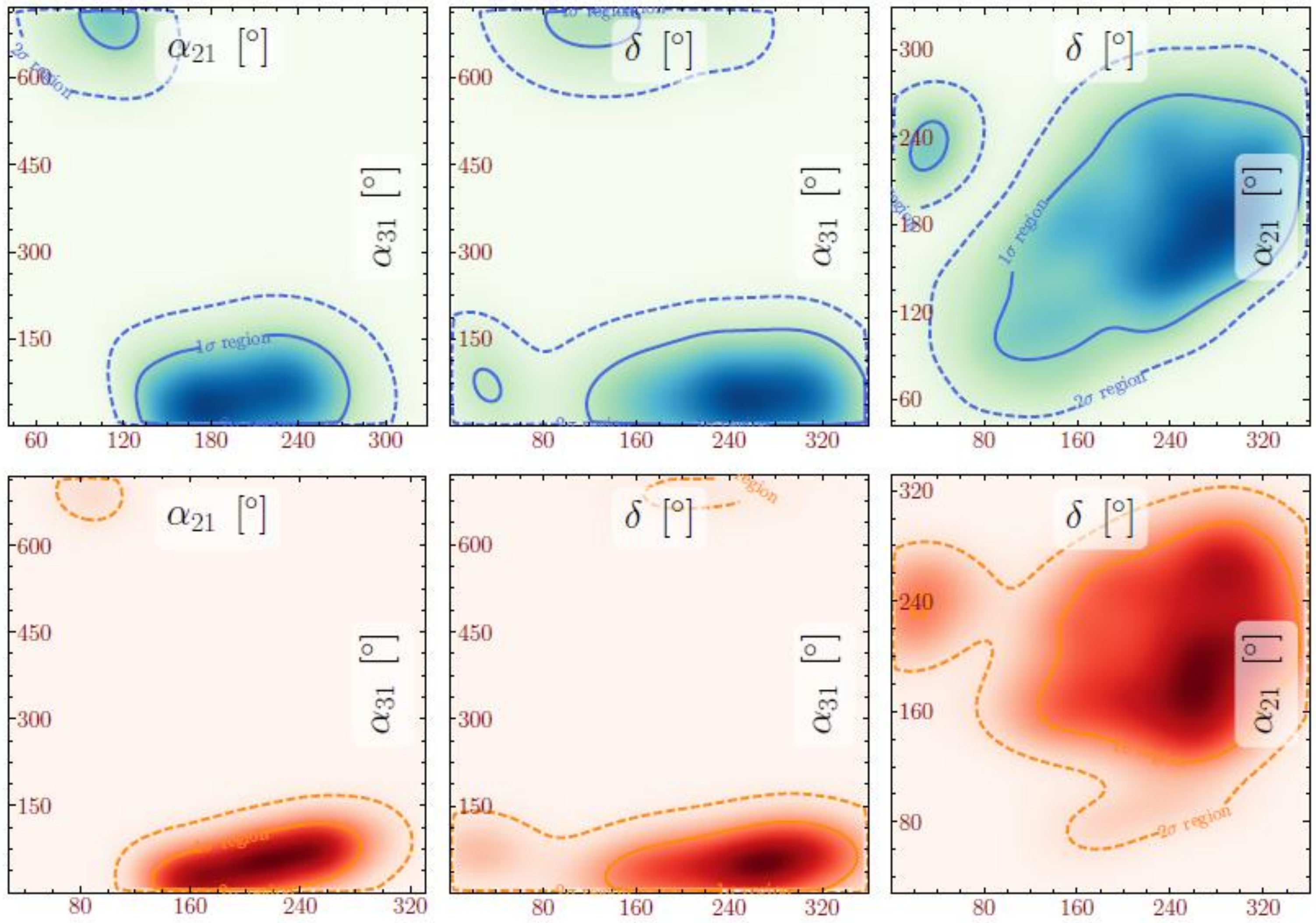




$$1.2 \times 10^6 < M \text{ (GeV)} < 8.8 \times 10^6 \quad \text{Normal Ordering,}$$
$$2.4 \times 10^6 < M \text{ (GeV)} < 7.4 \times 10^6 \quad \text{Inverted Ordering.}$$

Leptogenesis from phases of PMNS only

Finally an example of high energy See-saw.



$\longleftarrow \quad M_1 = 10^{10}\ GeV$

K. Moffat, S. Pascoli, S. Petcov, J. Turner JHEP 03 (2019) 034

Conclusions

Leptogenesis is a viable option to explain the generation of the baryon asymmetry of the Universe.

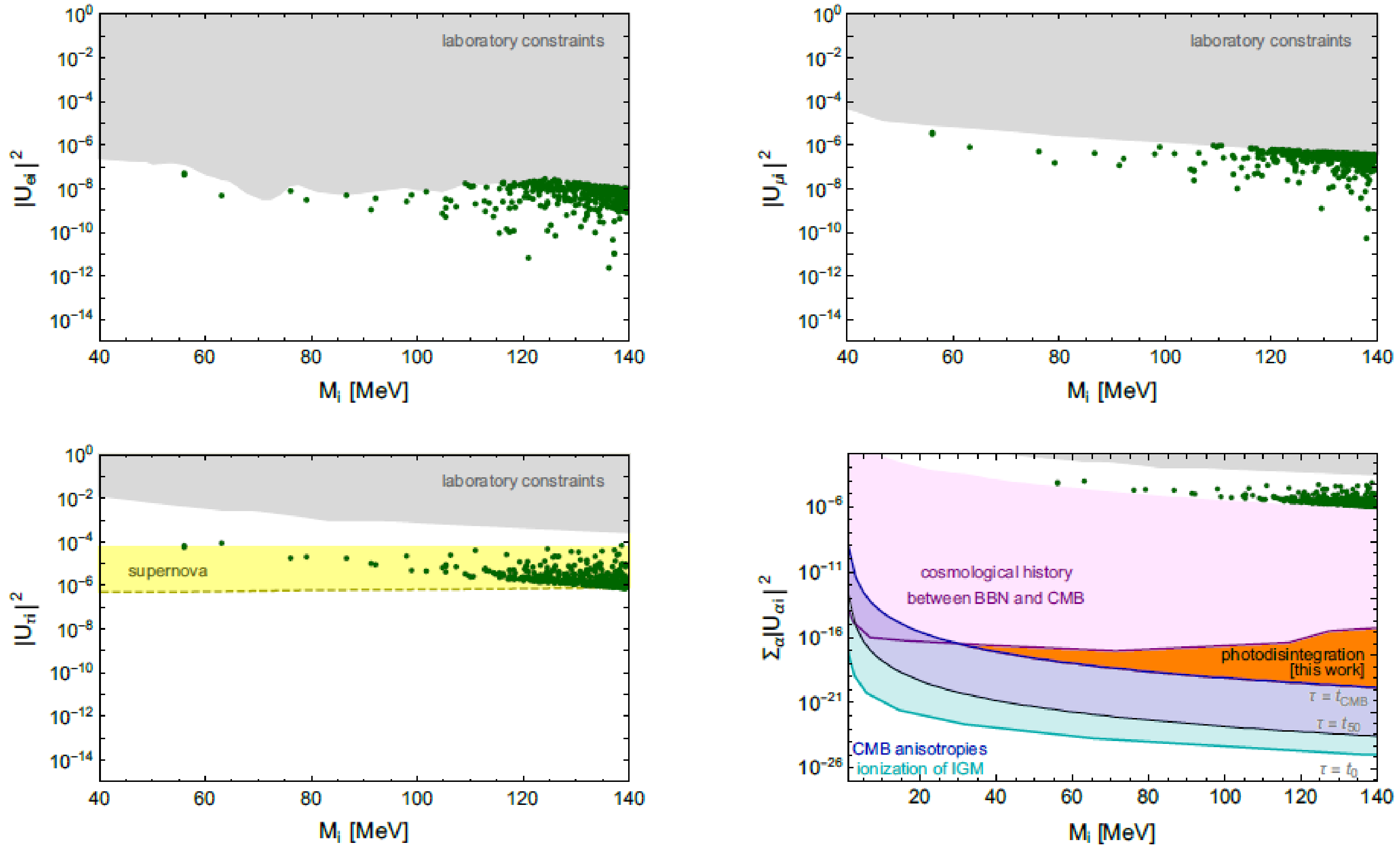
It can be related to the origin of neutrino masses and many low energy observables.

Successful leptogenesis can occur for a broad range of New Physics Scales. Very challenging scenario to probe as a whole.

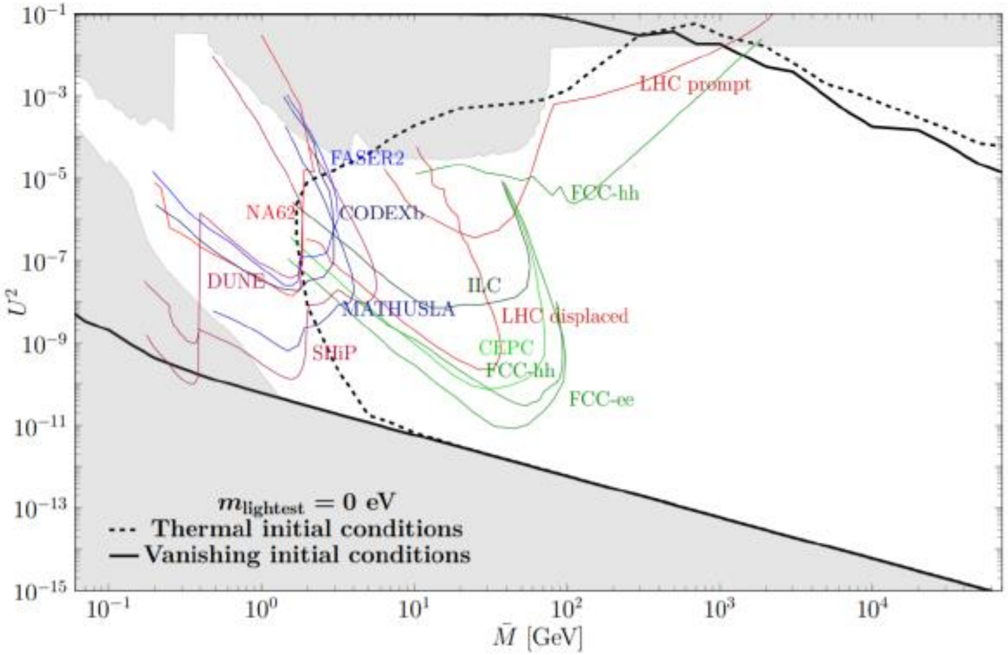
There are nevertheless interesting individual scenarios which can be tested at present and next future experimental facilities.

Back up

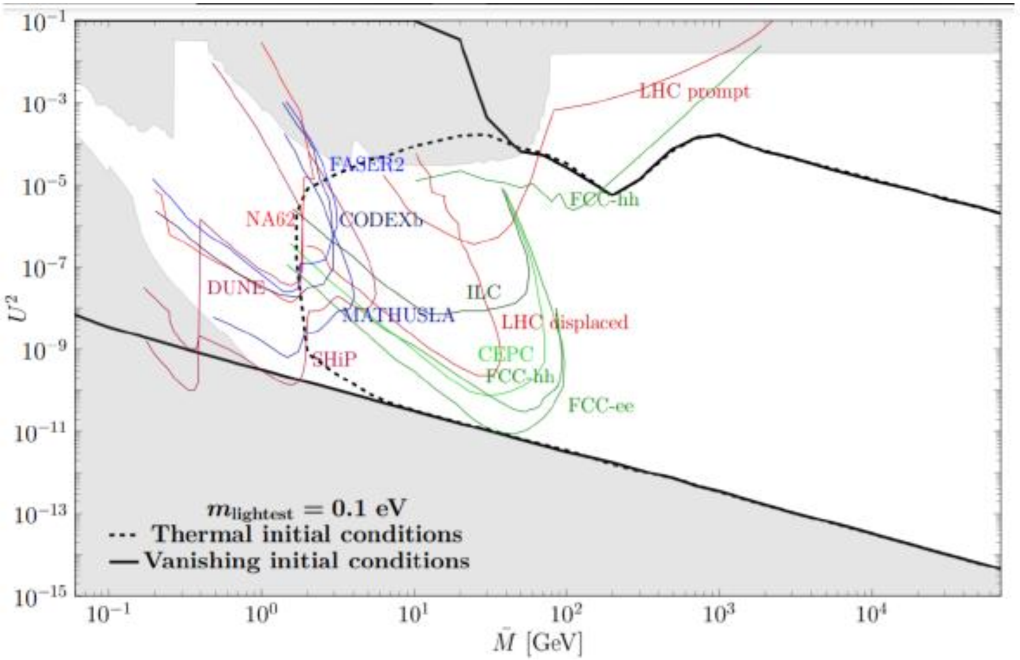
Leptogenesis from MeV scale see-saw

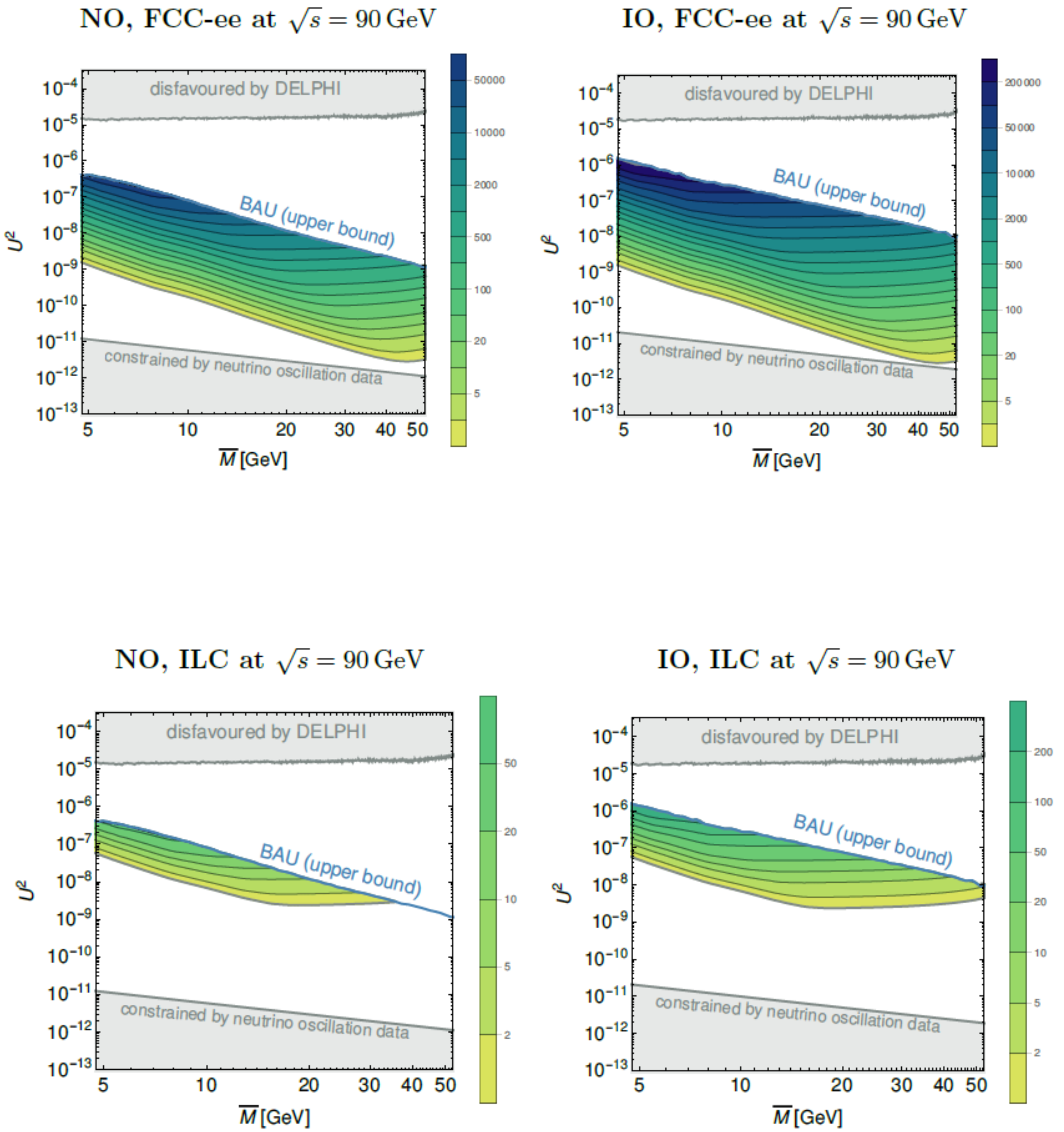


V. Domcke, M. Drewes, M. Hufnagel, M. Lucente ,JHEP 01 (2021) 200, arXiv:2009.11678



M. Drewes, Y. Georis, J. Klaric, 2106.16226





Number of expected events at future colliders

S. Antush, E. Cazzato, M. Drewes, O. Fisher, B. Gabrecht
JHEP 09 (2018) 124,
1710.03744