Type-I Seesaw Mechanism and EW Vacuum Metastability (with Gravity!)

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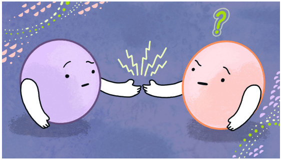
Neutrino masses : Type-I seesaw

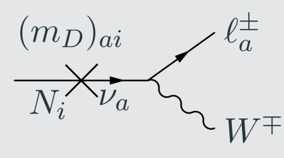
[Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

- Add SM-singlet heavy Majorana neutrinos.

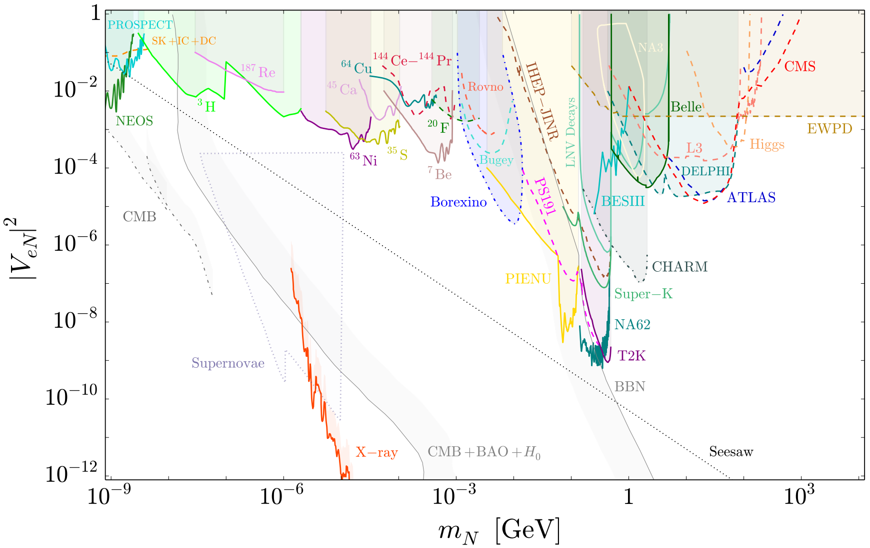
$$-\mathcal{L} \supset Y_l \bar{L}_l H l_R + Y_D \bar{L}_l \tilde{H} N + \frac{1}{2} \bar{N^c} M_N N + h.c.$$

- For small mixing, $m_\nu \simeq m_D\, M_N^{-1}\, m_D^T$, where $m_D = v_{ew}\, Y_D$.

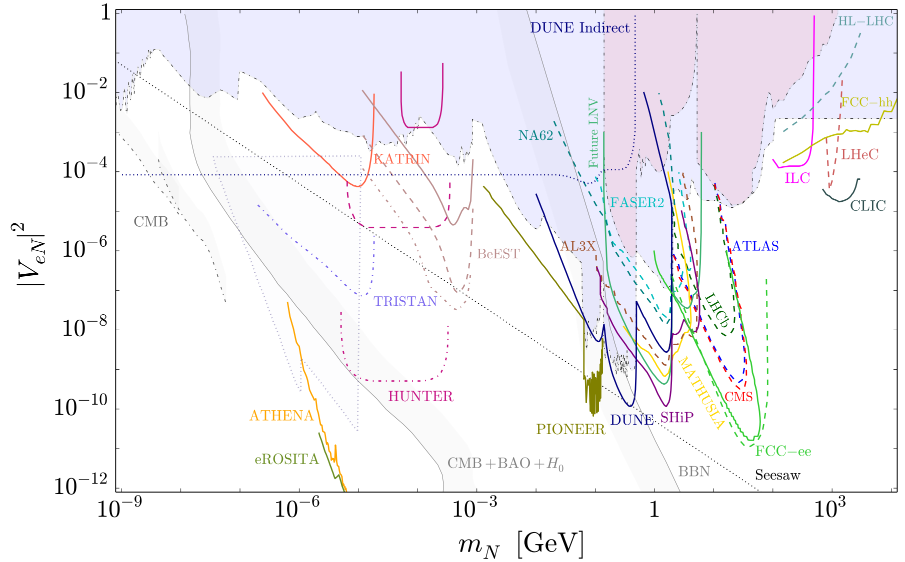




- It can connect neutrino mass mechanism and matter-antimatter asymmetry.



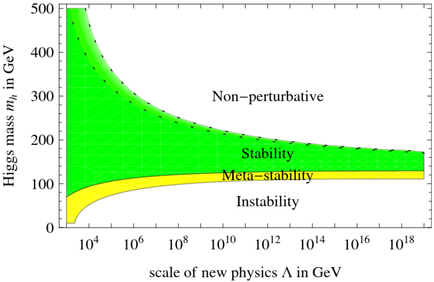
[Bolton, Deppisch, Dev (JHEP '20)][Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, Dev, Pilaftsis (NJP '15); de Gouvea, Kobach (PRD '16); Drewes, Garbrecht (NPB '17)]



[Bolton, Deppisch, Dev (JHEP '20)]

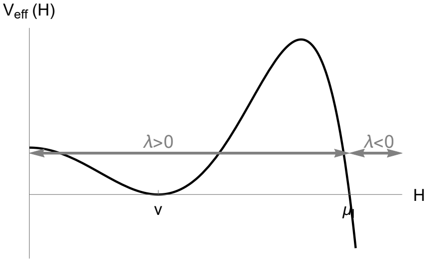
Beyond $M_N >$ TeV

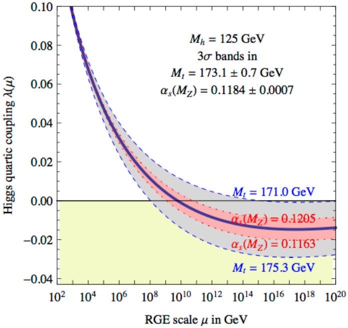
- From theoretical standpoint, naturalness criterion [Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya,Dev,Goswami,Khan,Rodejohann (PRD '17)] can help constrain.
- Other tool : (meta-)stability of the vacuum [Rodejohann,Zhang(JHEP'12); Khan,Goswami,Roy(PRD'14); Rose,Marzo,Urbano(JHEP'15); Lindner,Patel,Radovcic(PRD'16); Bambhaniya,Dev,Goswami,Khan,Rodejohann (PRD '17); Ipek,Plascencia,Turner(JHEP'18); Mandal,Srivastava,Valle(PRD'20)].
- Mass range for Higgs boson was constrained before its discovery. [Linder (ZPCF'86); Casas, Espinosa, Quiros (PLB'94); Isidori, RIdolfi, Strumia (NPB'01); ...]



- We constrain low-scale seesaw for M_N above TeV and high-scale seesaw above 10^9 GeV.

- Higgs potential develops a deeper minimum at 10^{11} GeV, making the SM vacuum metastable.[Isidori, Ridolfi, Strumia (Nucl.Phys '01)]





- Effective potential $V_{eff} \sim -m^2(H)H^2 + \lambda(H)H^4$,

$$\beta_\lambda = \frac{\mathrm{d}\lambda}{\mathrm{d}\log\mu} \sim (4\pi)^{-2}(\lambda^2 - y_t^4 + \dots)$$

makes λ run to negative values.

- Total decay rate is the integral over the contributions of all nucleated bubbles.

$$\frac{\Gamma}{V} = \int \frac{\mathrm{d}r}{r^5}\ \mathrm{e}^{-S_E}\ ,\ \text{where } S_E = \frac{8\pi^2}{3\left|\lambda\left(r^{-1}\right)\right|}.$$

- The integral over r can be performed analytically,

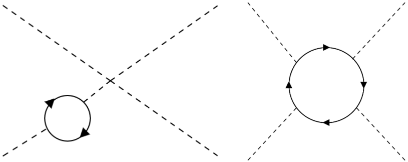
$$\frac{\Gamma}{V} \propto \mu_*^4 \mathrm{e}^{-\frac{8\pi^2}{3|\lambda(\mu_*)|}}\,,$$

where $\beta_\lambda(\mu_*) = 0$.

- Decay rate maximized $\rightarrow$ minimum euclidean action S_E $\rightarrow$ maximize $|\lambda|$

- RHNs contribution to the λ's beta function[1],

$$\Delta\beta_\lambda = \frac{1}{4\pi^2}(4\lambda \text{Tr}[\mathbf{Y_D^\dagger Y_D}] - 2\text{Tr}[\mathbf{Y_D^\dagger Y_D Y_D^\dagger Y_D}])$$



- RHNs effect on the y_t,

$$\Delta\beta_{y_t} = \frac{1}{4\pi^2} y_t \text{Tr}[\mathbf{Y_D^\dagger Y_D}]$$

- Drives λ to more negative values, increases the decay rate.
- Pushes μ_* towards large values, often **beyond the Planck scale**.
- Gravity cannot be neglected!

[1] [Pirogov,Zenin (EPJC'99); Casas,Espinosa,Ibarra,Navarro(NPB'00); Antusch,Kersten,Lindner,Ratz(PLB'02,NPB'03);]

- Higgs can interact with gravity in two ways[2]

$$S = \int \mathrm{d}^4 x \sqrt{-g} \, \left(\mathcal{L}_{\mathsf{SM}} + \frac{\xi}{2} R H^2 \right),$$

where R is the curvature scalar.

- ξ can be generated radiatively.
- Gravitational correction to euclidean action is

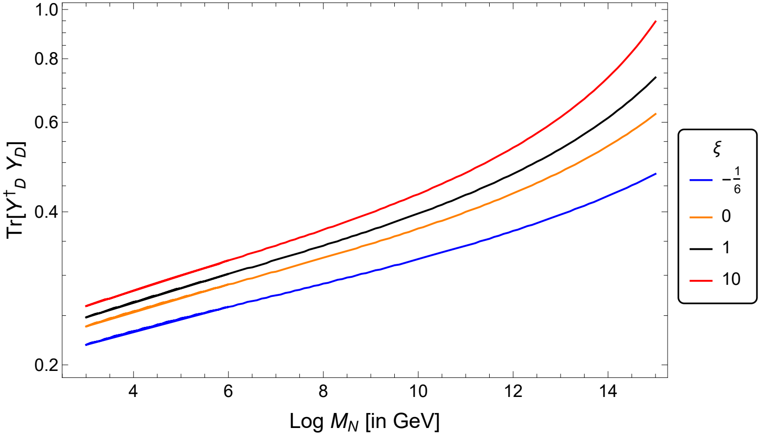
$$S_E^{\mathsf{grav}} \simeq \frac{8\pi^2}{3\left|\lambda\left(r^{-1}\right)\right|} + \frac{256\pi^3(1+6\xi)^2}{45\lambda^2\left(r^{-1}\right)} \frac{1}{\left(r M_{\mathsf{Pl}}\right)^2},$$

[2] [Isidori,Rychkov,Strumia,Tetradis(PRD'08); Salvio,Strumia,Tetradis,Urbano(JHEP'16)]

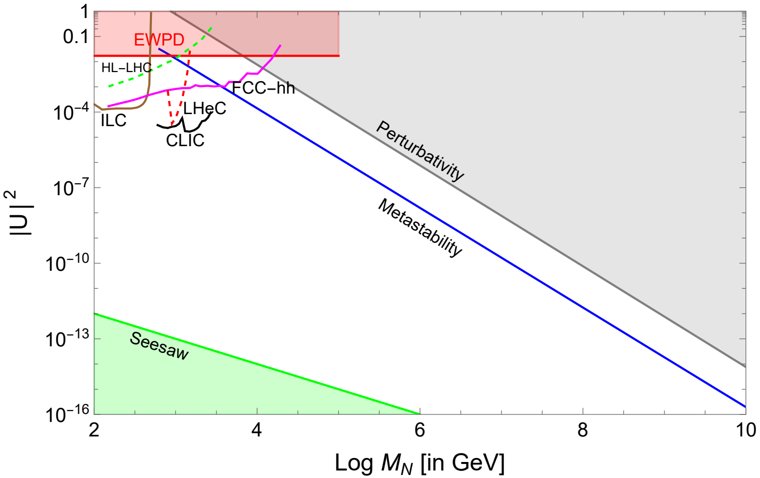
Type-I Low-Scale seesaw

- Lowering M_N below GUT scale leads to tiny mixing angles, in canonical seesaw.
- Lighter M_N and larger mixings $\rightarrow$ internal cancellation in the seesaw relation.
- Large mixing angles are possible with special textures for Y_D and M_N. [Pilaftsis (ZPC '92);; Gluza (APPB '02); de Gouvea '07; Kersten, Smirnov (PRD '07); Gavela, Hambye, Hernandez, Hernandez (JHEP '09); Ibarra, Molinaro, Petcov (JHEP '10); Deppisch, Pilaftsis (PRD '11); Adhikari, Raychaudhuri (PRD '11); Mitra, Senjanovic, Vissani (NPB '12); ; Dev, Lee, Mohapatra (PRD '13); Babu, Ghosh '17]
- Cancellations are stable under radiative corrections, if RHNs masses are degenerate. Kerston, Smirnov (Phys. Rev. D '07)
- RGE running using Tr$[Y_D^\dagger Y_D]^2 \sim$ Tr$[Y_D^\dagger Y_D Y_D^\dagger Y_D]$ and Casas-Ibarra parametrisation.

Results : Low-scale seesaw

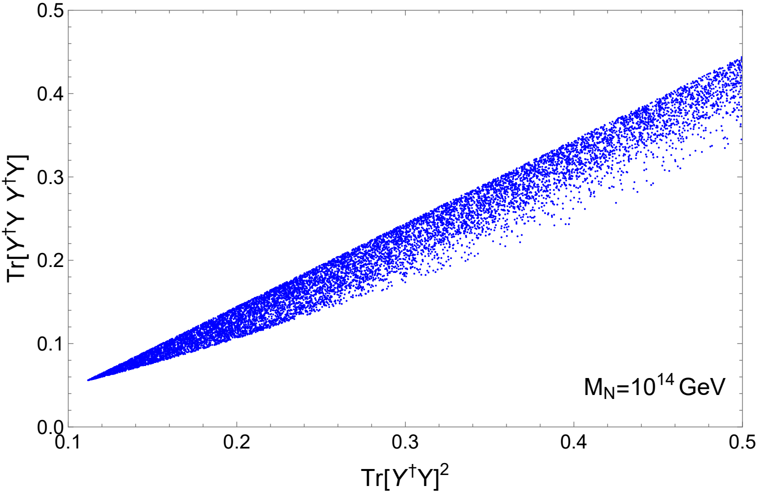


- Bounds on Tr$(Y_D^\dagger Y_D)$ are independent of 2 or 3 RHNs
- These bounds get relaxed for increasing ξ



- Bounds from metastability are the strongest above TeV scale.

Does always $T_2^2 \sim T_4$?



- Scan plot of T_2 vs. T_4 at $M_N = 10^{14}$ GeV.
- Whole matrix run necessary?

New Technique for RGE running

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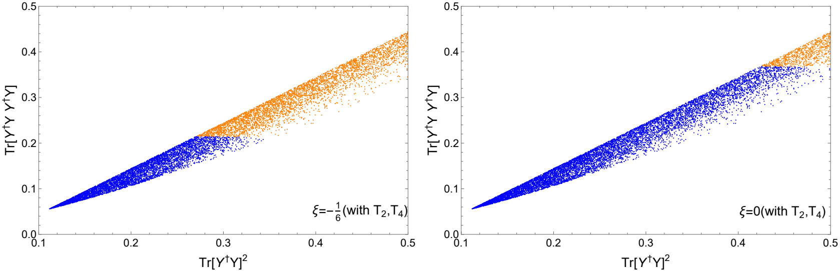
- RGE running with just β_{T_2} and β_{T_4} achieves accurate results!



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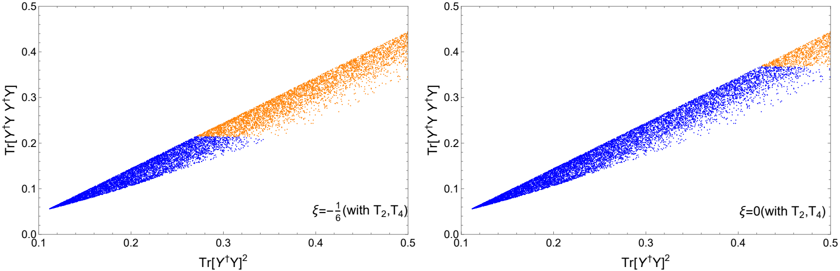


- **Metastability bound depends very strongly on T_4.**

High-scale seesaw

- Features heavy RHN mass scales near GUT scale.
- Can generate baryon asymmetry (η_B) without requiring finely tuned M_N
- Davidson-Ibarra Bound $< M_1 <$ Instanton Scale

  [Davidson, Ibarra '02; Buchmuller, Di Bari, Plümacher '02]
- Scan over the RHN mass ranges :

$$M_1 = \{10^9,\ 10^{15}\}\ \text{GeV}$$

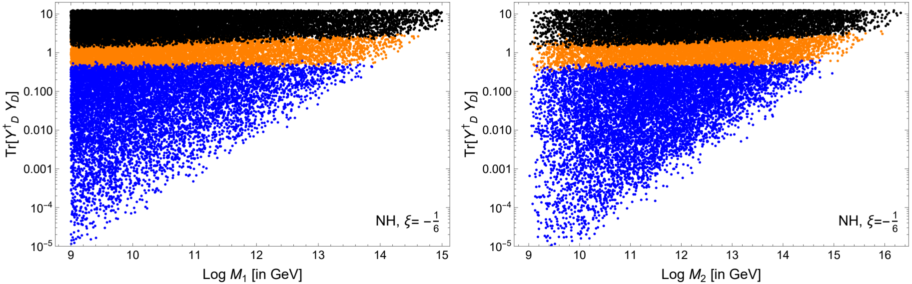
$$M_2 = \{M_1,\ 10^{19}\ \text{GeV}\}$$

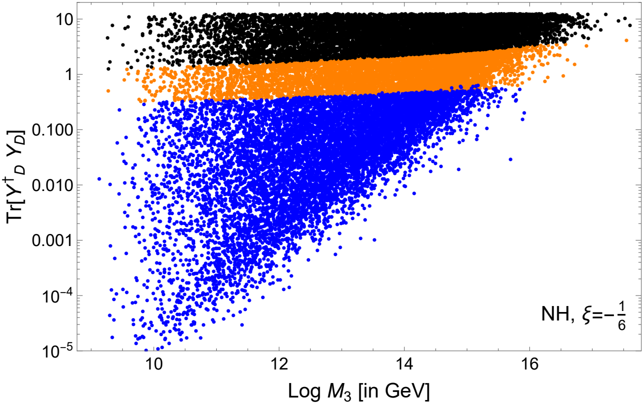
$$M_3 = \{M_2,\ 10^{19}\ \text{GeV}\}$$

$$R = R_{23}(z_1)R_{13}(z_2)R_{12}(z_3)$$

where $z_i\ (i = 1, 2, 3)$ are complex, $\text{Re}(z_i) \in [-\pi, \pi]$ and $\text{Im}(z_i) \in [-\pi, \pi]$.

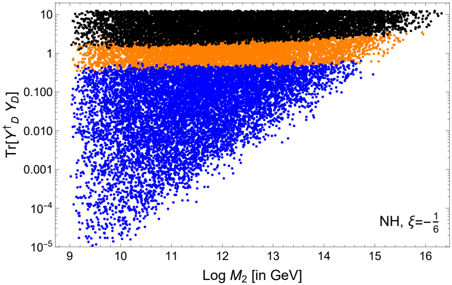
- NH and no gravity
- $(M_1)_{max} = 10^{13.9}$ GeV and $(M_2)_{max} = 10^{14.9}$ GeV
- $(T_2)_{max} = 0.63$

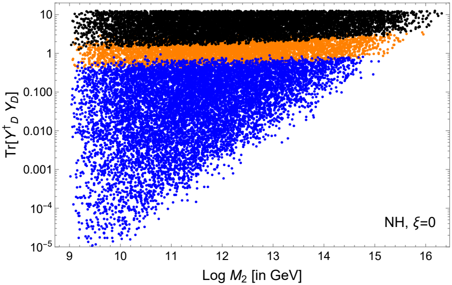




- NH and no gravity
- $(M_3)_{max} = 10^{15.9}$ GeV and $(T_2)_{max} = 0.63$

Results : High-scale seesaw (with gravity)





- $(T_2)_{max} = 0.63 \rightarrow 0.94$
- $(M_2)_{max} = 10^{14.9}$ GeV $\rightarrow 10^{15.1}$ GeV

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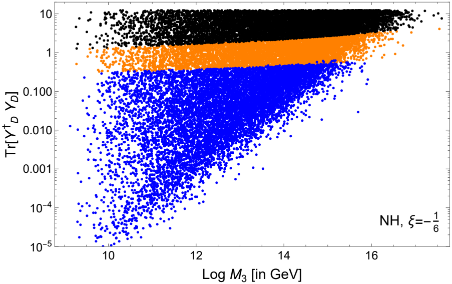

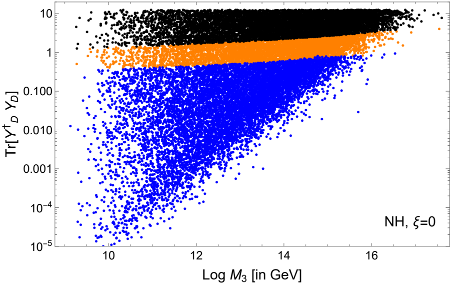

- $(T_2)_{max} = 0.63 \rightarrow 0.94$
- $(M_3)_{max} = 10^{15.9}$ GeV $\rightarrow 10^{16.5}$ GeV

Summary

- Studied the effect of Type-I seesaw (for $M_N > 1$ TeV) on EW vacuum metastability including gravity.
- Strong bounds on mixing $|U|^2$ in low-scale seesaw.
- Upper bound on allowed $M_{1,2,3}$ from metastability in high-scale seesaw.
- Effect of T_4 on running of quartic coupling $\rightarrow$ $T_2 - T_4$ method for RGE running.
- Gravity significantly stabilizes the potential and lowers the stringent bounds on Y_D.

Thank you!
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