Infrared Neutrino Mass Models and how to test them

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Introduction: Neutrino Mass Models

- Seesaw Mechanisms
  - Seesaw I (right-handed singlet)
  - Seesaw II (scalar triplet)
  - Seesaw III (fermion triplet)
  - Inverse Seesaw (right-handed singlet, left-handed singlet)
- Radiative Neutrino Mass models
- Scotogenic model
- Gravitational Anomaly Mass Generation
- Extra Dimensions
- Many Species Theory
- Nnaturalness

Introduction: Neutrino Mass Models

Ultraviolet models (UV)

- Seesaw Mechanisms
- Radiative Neutrino Mass models
- Scotogenic model

Infrared models (IR)

- Gravitational Anomaly Mass Generation
- Extra Dimensions
- Many Species Theory
- Nnaturalness

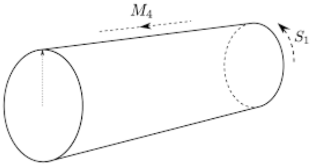
(Extra Dimensions, Many Species Theory, Nnaturalness) } **Many Mixing Partners**

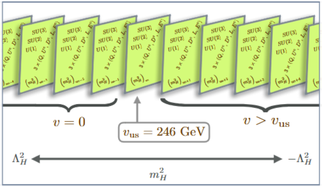
Introduction: Hierarchy Problem and IR models

- Many additional species one can lower the fundamental scale of gravity M_f via [*Dvali 2007*]:

$$M_f = \frac{M_P}{\sqrt{N}}. \qquad (1)$$

- Large extra dimensions ADD model, $N = 10^{32}$ [*Arkani-Hamed, Dimopoulos, Dvali 1998*].
- Many copies theory , $N = 10^{32}$ [*Dvali, Redi 2008*].
- Nnaturalness, $N = 10^4$, $N = 10^{16}$ [*Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner 2017*].





Neutrino masses in IR models

- In IR models the SM neutrinos mix with many mixing partners. This can be seen from the Dirac operator

$$(HL)_i \lambda_{ij} \nu_{Rj} \ , \tag{2}$$

where the subscripts i, j run over the additional mixing partners [*Arkani-Hamed, Dimopoulos, Dvali, March-Russel 1998; Dvali, Redi 2008, M.E. 2022*].

- The Yukawa coupling $\lambda_{i,j}$ follows the perturbative constraint

$$\lambda_{i,j} \leq 1/\sqrt{N} \ . \tag{3}$$

- Together with the species constraint (1) it leads to a neutrino mass of:

$$m_\nu \sim \frac{M_f}{M_P} v_{ew} \tag{4}$$

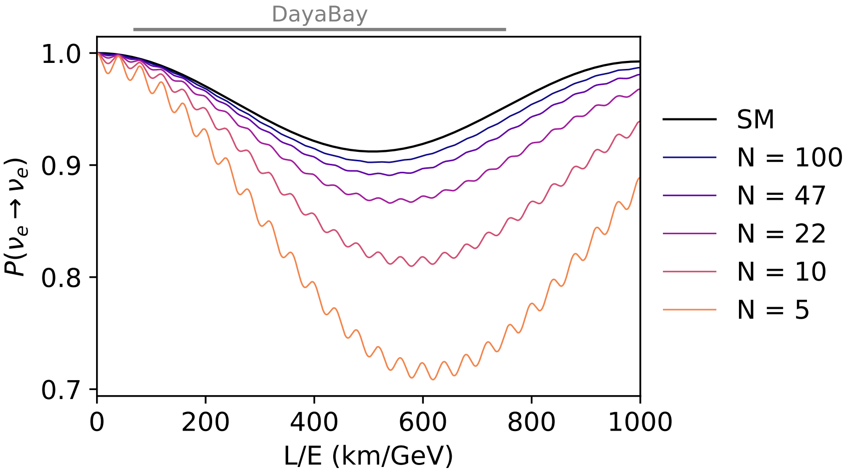
Neutrino masses in many species Theories

- In many species theories the existence of many additional SM dark copies is assumed. [*Dvali, Redi 2008*]
- The typical expression for flavor states in such theories looks like [*M.E. 2022*]:

$$|\nu_e\rangle = \sqrt{\frac{N-1}{N}}\left(U_{e1}|m_1\rangle + U_{e2}|m_2\rangle + U_{e3}|m_3\rangle\right) + \frac{1}{\sqrt{N}}\left(U_{e1}|m_1^H\rangle + U_{e2}|m_2^H\rangle + U_{e3}|m_3^H\rangle\right). \quad (5)$$

The masses $m_{1\dots3}$ are the usual masses of SM neutrinos and the masses $m^H_{1\dots3}$ are with them related via $m_i^H = \mu m_i$. The massfactor μ can range from 1 to 100 depending on the exact geometry in the species space.

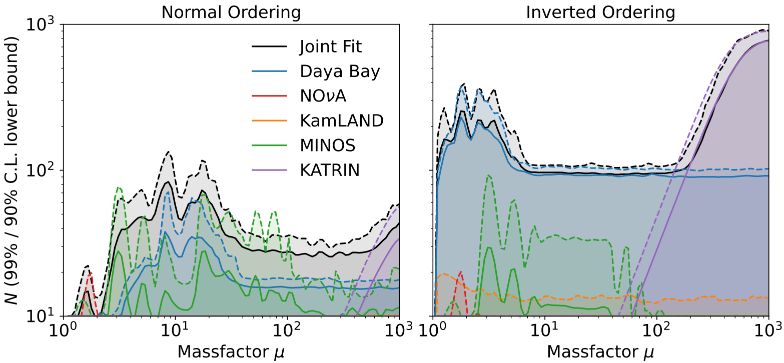
Neutrino Oscillations in many species Theories



Testing the Model by Neutrino Experiments

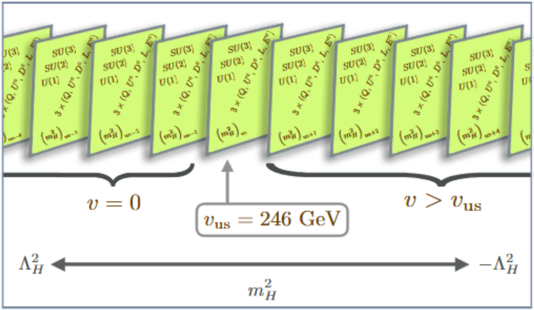
- The attempt is to make a combined neutrino fit with several different neutrino oscillation experiments to give a first bound on the parameters N and μ. [*M.E., Alan Zander, Philipp Eller 2024*]
- Different type of neutrino experiments (accelerator, reactor, atmospheric,...) can probe different scopes of the masssplitting.
- We have analyzed the datasets of DayaBay, Kamland, Minos, NOνA, Katrin with a likelihood ratio test statistic.

First Combined Fit Result



Neutrino masses in Nnaturalness

In Nnaturalness the hierarchy problem is solved by a cosmological selection mechanism that chooses the the smallest negative higgs mass parameter out of an interval $m_H = [-\Lambda_H^2, \Lambda_H^2]$, where Λ_H stands for the scale of Higgs stabilizing physics. [*Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner 2017*].



Neutrino masses in Nnaturalness

- The resulting VEV for the additional higgsed sectors is

$$v_i = \Lambda_H \sqrt{\frac{2i}{\lambda N} + \frac{r}{\lambda N}}\,, \tag{6}$$

and r ranges from 0 to 1 and quantifies the ammount of tuning.

- The neutrino mass could be either induced by the Dirac operator (2).
- Or through reheaton, S, exchange could a Weinberg operator be induced of the form

$$\frac{1}{m_S}(\bar{L}^c i\sigma_2 H)_i \lambda_{ij} (H i\sigma_2 L)_j\,. \tag{7}$$

Neutrino masses in Nnaturalness

- The resulting expression of a neutrino of our sector is [*M.E. 2025*]

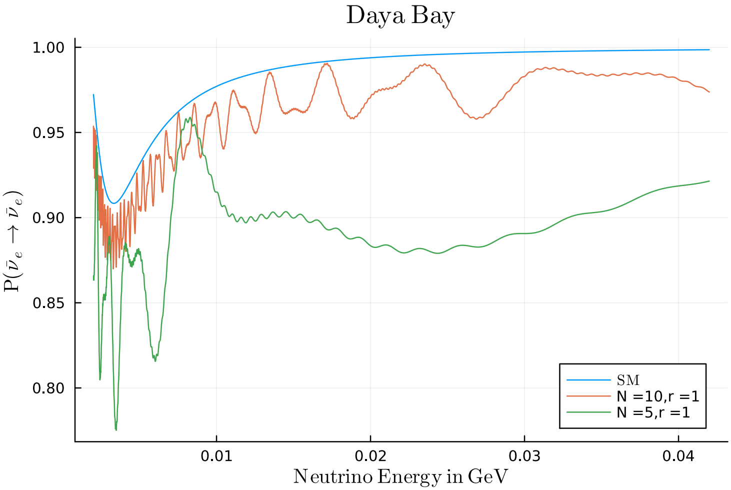
$$|\nu_1\rangle = |\nu_1\rangle_m + \frac{1}{N}\sum_{i=2}^{N-1}\frac{\sqrt{2i+r}\sqrt{r}}{2i}|\nu_i\rangle_m + \frac{1}{N}|\nu_N\rangle_m \qquad (8)$$

- The scaling of the Δm_{i1}^2 is

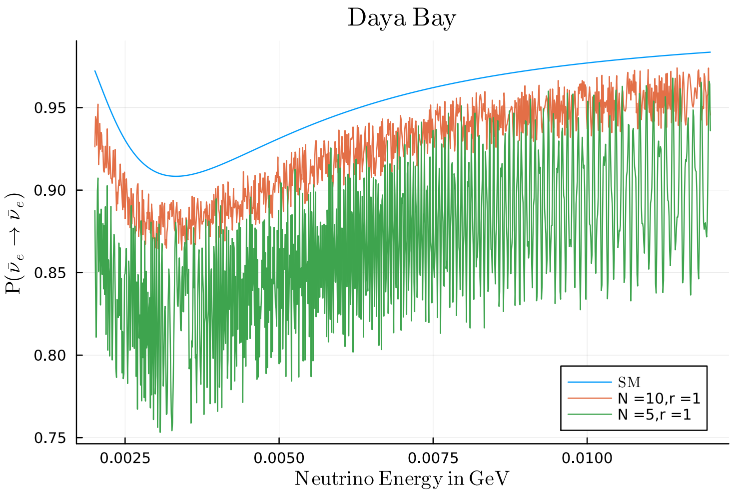
$$\Delta m_{i1}^2 \propto 2i \quad \text{Dirac Case}\,, \qquad (9)$$

$$\Delta m_{i1}^2 \propto (i^2 - ir) \quad \text{Majorana Case}\,. \qquad (10)$$

Neutrino oscillations in Nnaturalness (Dirac case)



Neutrino oscillations in Nnaturalness (Majorana case)

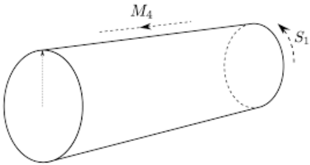


The ADD model

- Additionally to neutrinos also neutrons can be used to test such theories [*Dvali, M.E., Stuhlfauth 2023*]
- Additional compactified extra dimensions

$$\mathcal{M} = \mathcal{M}_4 \times K_n \qquad (11)$$

- SM particles live on $\mathcal{M}_4$, particles uncharged under SM (e.g. graviton) live in $\mathcal{M}$.



Kaluza-Klein Tower

Particles that can propagate into the compactified extra dimensions form a Kaluza Klein mass tower

$$m_{\vec{k}} = \sqrt{\frac{k_1^2}{R_1^2} + \cdots + \frac{k_N^2}{R_N^2}}\,. \tag{12}$$

Neutron mixing with a bulk particle Ψ can lead to the following effective Lagrangian

$$\mathcal{L} = \bar{n}\partial n - m_n \bar{n} n + \sum_k \left(\bar{\Psi}_k \partial \Psi_k - m_k \bar{\Psi}_k \Psi_k \right) + \alpha \sum_k \bar{n} \Psi_k + h.c., \tag{13}$$

with

$$\alpha \equiv \frac{\Lambda^3_{\mathrm{QCD}}}{M_*^{2+N/2}\sqrt{V_N}} \lesssim 10^{-24}\mathrm{GeV}\,. \tag{14}$$

Neutron Mixing with KK states

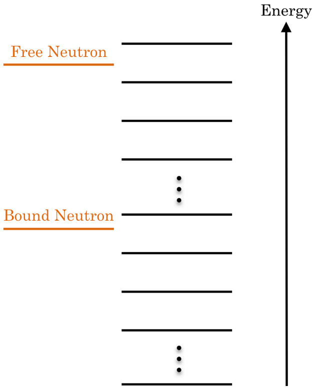
- Resulting mass matrix

$$M = \begin{pmatrix} m_n & \alpha & \alpha & \alpha \\ \alpha & 0 & 0 & 0 \\ \alpha & 0 & m_{\vec{k}} & 0 \\ \alpha & 0 & 0 & m_{\vec{k}'} \end{pmatrix} . \quad (15)$$

- Resulting neutron superposition and oscillation probability are

$$n = \frac{1}{\mathcal{N}}\left(n' + \sum_{\vec{k}} \frac{\alpha}{\Delta m_{\vec{k}}} \Psi'_{\vec{k}}\right) \quad (16)$$

$$P_{\rm surv}(t) = \frac{1}{\mathcal{N}^4}\left|1 + \sum_{\vec{k}} \frac{\alpha^2}{\Delta m^2_{\vec{k}}} \exp\left(\phi_{\vec{k}}\right)\right|^2 .$$



Resulting bounds

The strongest bound on this model comes from the bounded neutron lifetime

$$\tau_n > 10^{30}\,\mathrm{y} \rightarrow \lambda_n = \frac{2Z\Lambda_{QCD}^6}{\Delta m M_*^{4+N} V_N} \leq \frac{1}{\tau_n}\,. \tag{17}$$

For different ADD scenarios, we get different bounds

TABLE I. Bound on M_* for one dominant R with $M_f = 10$ TeV and $R = 30$ μm.

N	M_* [GeV]
3	$>3 \times 10^7$
4	$>1 \times 10^7$
5	$>5 \times 10^6$
6	$>3 \times 10^6$

TABLE II. Bound on M_* for equal size extra dimensions.

N	R [μm]	M_* [GeV]
2	1.1	$>7 \times 10^9$
3	1.6×10^{-5}	$>3 \times 10^8$
4	5.5×10^{-8}	$>2 \times 10^7$
5	2×10^{-9}	$>4 \times 10^6$
6	2.2×10^{-10}	$>8 \times 10^5$

Resulting bounds

- If Ψ is massive with: $m_n^{\mathrm{bounded}} \ll m_\Psi$, the previous bounds are evaded.
- Neutron oscillation experiments can also test the KK tower of the neutron. The oscillation amplitude is

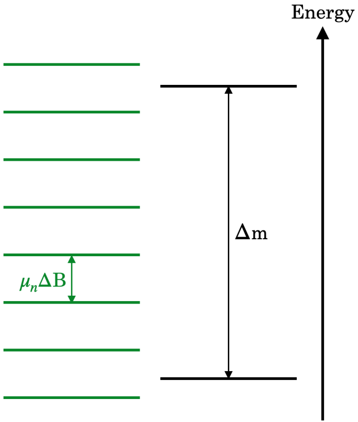
$$A \simeq \frac{\alpha^2}{|\epsilon - \Delta m|^2}\,, \tag{18}$$

- For experiments in the regime $|\epsilon - \Delta m| \sim \Delta m$

$$\frac{10\mathrm{TeV}}{M_f}\left(\frac{M_f}{M_*}\right)^{2+N/2}\frac{R^2}{R_{max}^2} \lesssim \frac{1}{3}\,. \tag{19}$$

Resulting bounds

- For experiments with a variable ϵ that are precise enough can lead to the regime $|\epsilon - \Delta m| \sim \Delta\epsilon$.
- $$\alpha \lesssim 10^{-14}\mathrm{eV}, \quad (20)$$
  $$0.8\mu\mathrm{m} < R < 10\mu\mathrm{m}. \quad (21)$$



Many additional signatures

- ADD and many species models predict Quantum Gravity effects at LHC.
- ADD and Nnaturalness predict a tower of additional light neutrino states that could influence neutrino mass maesurements like KATRIN [*Basto-Gonzalez, Esmaili, Peres 2013, M.E. 2025*].
- A tower of light neutrino states influencing neutrinoless double beta decay experiments [*M.E. 2025*].
- Axion physics could get influenced by many species and Nnaturalness model [*M.E., Koutsangelas 2023*]
- ...

Conclusion

- IR neutrino mass models are motivated by the hierarchy problem.
- IR neutrino mass models offer an alternative to explain the smallness of neutrino mass.
- They are highly predictive with a limited set of BSM parameters.
- They have a smoking gun signature in the mass distribution of the additional neutrino states.
- Several different types of neutrino experiments are suited to search for their signatures.
- Many additional signatures in other low energy experiments.