Phenomenological implications of TeV scale gravity theories

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1. Introduction
2. Axions
3. Neutrinos
4. Neutrons
5. Conclusion

Introduction: TeV scale gravity theories

- Motivation: Solution to the Hierarchy Problem.
- Many additional species one can lower the fundamental scale of gravity M_f via [*Dvali 2007*]:

  $$M_f = \frac{M_P}{\sqrt{N}}. \tag{1}$$

  From this equation one can give an upper bound on the number of dark species $N < 10^{32}$.
- Models that implement this solution are the ADD model [*Arkani-Hamed, Dimopoulos, Dvali 1998*] and the many copies theory [*Dvali, Redi 2008*].

The need for many Axions in many copies theories

- All θ's that would be introduced by additional Yang-Mills groups have therefore to be set equal to zero due to consistency reasons with Quantum Gravity [*Dvali, Gomez 2014; Dvali, Gomez, Zell 2019; Dvali 2020; Dvali 2022*].
- For every additional θ a new axion has to be introduced. [*Dvali 2005; Dvali, Farrar 2008*]
- How does Axion phenomenology change due to the presence of many axions? Especially regarding many copies of the SM.

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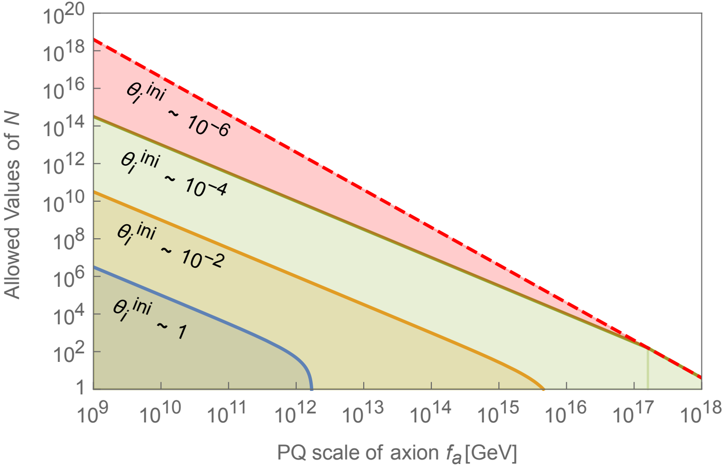
Misalignment Mechanism with Many Copies

- The equation of motion for every axion copy: $\ddot{a}_i + 3H(t)\dot{a}_i + m_a^2(T_i(t))a_i = 0$ (Damped Harmonic Oscillator) [M.E., Koutsangelas]
- Due to the reheating mechanism in many copies theories $T_1 \gg T_i$ [*Arkani-Hamed, Dimopoulos, Dvali, Kaloper 2000; Berezhiani, Comelli, Villante 2001; Dvali, Sawicki, Vikman 2005*]
- $$\frac{\Omega_{a_1}}{\Omega_{\mathrm{DM}}} \sim \left(\frac{f_a}{10^{12}}\right)^{\frac{7}{6}} \left(\frac{\theta_1^{\mathrm{ini}}}{1}\right)^2 , \tag{2}$$
  $$\frac{\Omega_{a_i}}{\Omega_{\mathrm{DM}}} \sim \left(\frac{f_a}{10^{12}}\right)^{\frac{3}{2}} \left(\frac{\theta_i^{\mathrm{ini}}}{1}\right)^2 . \tag{3}$$

Misaligment Mechanism with Many Copies



Kinetic Mixing with many Axions

- A minimal extension of the model is the kinetic mixing term: $\mathcal{L}_{\mathrm{mix}} = \epsilon \sum_{i \neq j} \partial_\mu a^i \partial^\mu a^j$.
- This results into the following kinetic part

$$\mathcal{L} \supset \begin{pmatrix} \partial_\mu a_1 \\ \vdots \\ \vdots \\ \partial_\mu a_N \end{pmatrix}^T \begin{pmatrix} 1 & \epsilon & \dots & \epsilon \\ \epsilon & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \epsilon \\ \epsilon & \dots & \epsilon & 1 \end{pmatrix} \begin{pmatrix} \partial_\mu a_1 \\ \vdots \\ \vdots \\ \partial_\mu a_N \end{pmatrix} . \quad (4)$$

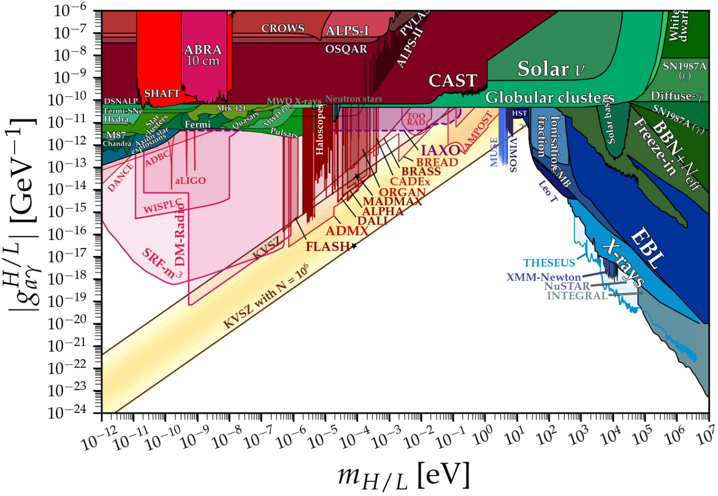
- After choosing a canonical kinetic basis one sees that two different physical axion states arise in such a model

Kinetic Mixing with many Axions

- One heavy state a_H with the mass $m_H = \frac{m_a}{\sqrt{1-\epsilon}}$ and all couplings get modified by the factor $f_H(N,\epsilon) = \sqrt{\frac{N-1}{N}} \frac{1}{\sqrt{1-\epsilon}}$.
- One lighter state a_L with the mass $m_L = \frac{m_a}{\sqrt{(1+(N-1)\epsilon}}$ and all couplings get modified by the factor $f_L(N,\epsilon) = \frac{1}{\sqrt{N}} \frac{1}{\sqrt{1+(N-1)\epsilon}}$.
- This gives a clear prediction about the mass ratio:

$$\frac{m_L}{m_H} = \sqrt{\frac{1-\epsilon}{1+(N-1)\epsilon}} \xrightarrow[\epsilon \to \frac{1}{N}]{} \frac{1}{\sqrt{2}}. \tag{5}$$

Kinetic Mixing with many Axions



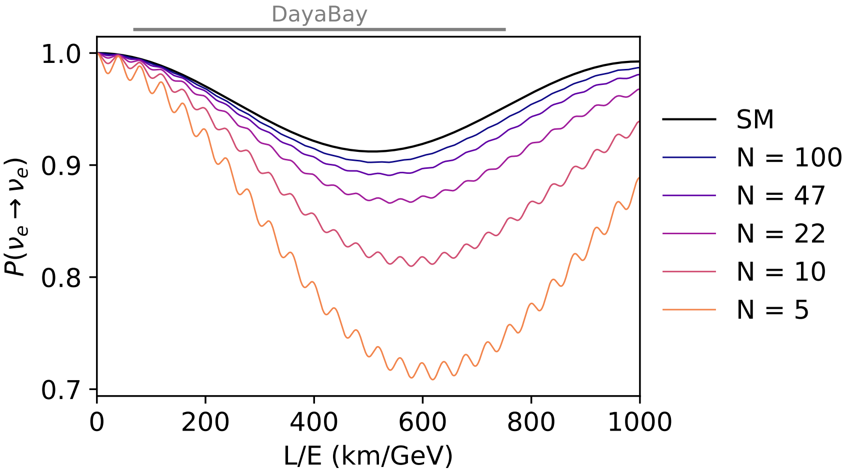
Neutrino masses in many species Theories

- In many species theories the neutrino masses get generated by introducing many light states (Infrared solution) instead of few heavy states (UV solution, Seesaw Mechanism). [*Dvali, Redi 2008*]
- The typical expression for flavor states in such theories looks like [*M.E. 2022*]:

$$\begin{aligned}|\nu_e\rangle = &\sqrt{\frac{N-1}{N}}\left(U_{e1}\,|m_1\rangle + U_{e2}\,|m_2\rangle + U_{e3}\,|m_3\rangle\right)\\ &+\frac{1}{\sqrt{N}}\left(U_{e1}\,|m_1^H\rangle + U_{e2}\,|m_2^H\rangle + U_{e3}\,|m_3^H\rangle\right).\end{aligned} \tag{6}$$

The masses $m_{1\dots 3}$ are the usual masses of SM neutrinos and the masses $m^H_{1\dots 3}$ are with them related via $m_i^H = \mu m_i$.

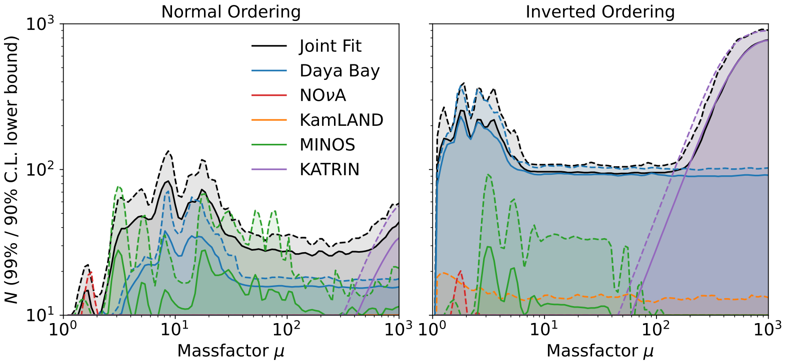
Neutrino Oscillations in many species Theories



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



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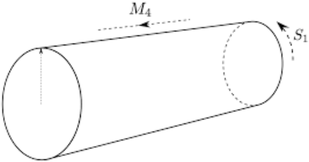
The ADD model

- Additional compactified extra dimensions

$$\mathcal{M} = \mathcal{M}_4 \times K_n \qquad (7)$$

- SM particles live on $\mathcal{M}_4$, particles uncharged under SM (e.g. graviton) live in $\mathcal{M}$.
- This lowers the fundamental scale of gravity via

$$M_f^{N+2} = \frac{M_P^2}{V_N} \qquad (8)$$



Neutron Mixing with KK states

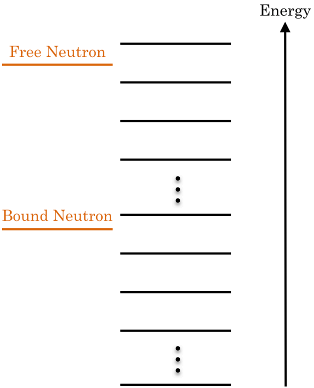
- Resulting mass matrix

$$M = \begin{pmatrix} m_n & \alpha & \alpha & \alpha \\ \alpha & 0 & 0 & 0 \\ \alpha & 0 & m_{\vec{k}} & 0 \\ \alpha & 0 & 0 & m_{\vec{k}'} \end{pmatrix}. \quad (9)$$

- Resulting neutron superposition and oscillation probability are

$$n = \frac{1}{\mathcal{N}}\left(n' + \sum_{\vec{k}} \frac{\alpha}{\Delta m_{\vec{k}}} \Psi'_{\vec{k}}\right) \quad (10)$$

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



Resulting bounds

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

$$\tau_n > 10^{30}\,\mathrm{y} \rightarrow \lambda_n = \frac{2Z\Lambda_{QCD}^6}{\Delta m M_*^{4+N} V_N} \leq \frac{1}{\tau_n}\,. \tag{11}$$

For different ADD scenarios, we get different bounds

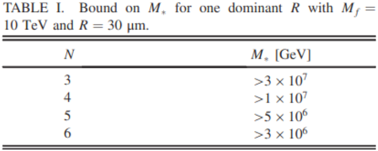


TABLE I. Bound on M_* for one dominant R with $M_f =$ 10 TeV and $R = 30$ μm.

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

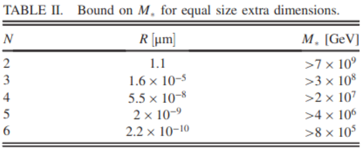


TABLE II. Bound on M_* for equal size extra dimensions.

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}	$>8 \times 10^5$

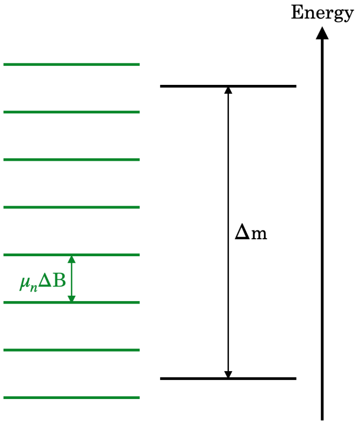
Resulting bounds

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

$$A \simeq \frac{\alpha^2}{|\epsilon - \Delta m|^2}\,. \tag{12}$$

Resulting bounds

- For experiments with a variable ϵ that are precise enough can lead to the regime $|\epsilon - \Delta m| \sim \Delta\epsilon$.
-
$$\alpha \lesssim 10^{-14}\mathrm{eV}, \tag{13}$$
$$0.8\mu\mathrm{m} < R < 10\mu\mathrm{m}. \tag{14}$$



Conclusion

- For every additional Yang-Mills group an additional axion is needed due to consistency reasons with Quantum Gravity with phenomenological consequences.
    - The upper bound on possible additional axions for SM copies in the most restrictive cosmological scenario can go up to $N \leq 10^6$.
    - Two axion states a_H and a_L with different masses and couplings.
    - Predicted ratio of masses $\frac{m_L}{m_H} = \sqrt{\frac{1-\epsilon}{1+(N-1)\epsilon}} \xrightarrow[\epsilon \to \frac{1}{N}]{} \frac{1}{\sqrt{2}}$.
- Neutrinos are suitable candidates to test the number of active species and the mass splitting with the additional neutrino states.

Conclusion

- Neutrino experiments are able to give lower bounds on the number of neutrino species. The first combined fit gives up to $N \geq 30$ for NO and $N \geq 100$ for IO (depending on μ).
- Neutrons are also able to test these models and we gave the first analysis with respect to the ADD model.
  - For $m_\Psi \ll m_n^{\mathrm{bounded}}$: neutron decays have to be heavily suppressed.
  - For $m_\Psi > m_n^{\mathrm{bounded}}$: Neutron Oscillation experiments probe the parameter space motivated by the Hierarchy Problem.