The search for the fundamental scale of gravity

Manuel Ettengruber

Institut de Physique Théorique

Many additional species one can lower the fundamental scale of gravity M_f via [Dvali 2007; Dvali, Redi 2007]:

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

One Argument: Imagine a quantum field theory with N bosons with mass Λ and an exact discrete symmetry $Z_2^N = Z_2^{(1)} \times Z_2^{(2)} \times \cdots \times Z_2^{(N)}$. The mass of the minimal black hole with maximum charge is

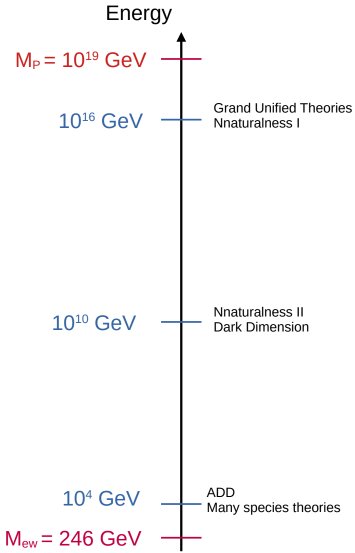
$$M_{BH} = N\Lambda \,. \tag{2}$$

As soon the temperature reaches Λ (with a mass $M_{BH}^\star \sim M_P^2/\Lambda$) it can start emitt such bosons again. Therefore the maximal number of emitted bosons is

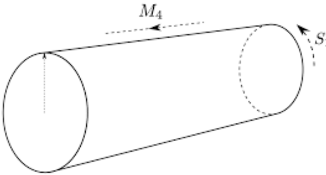
$$N \sim \frac{M_P^2}{\Lambda^2} \,. \tag{3}$$

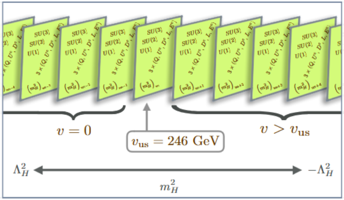
$$M_f = ??$$

Where could we expect M_f?

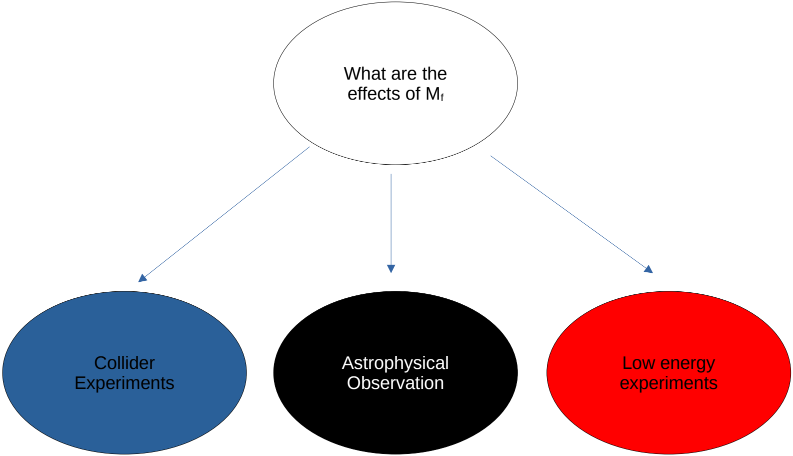


- Vacuum landscape models, $N = 10^3$ [*Arkani-Hamed, Raffaele Tito D'Agnolo, Hyung Do Kim 2020*].
- Large extra dimensions ADD model, $N = 10^{32}$ [*Arkani-Hamed, Dimopoulos, Dvali 1998*]. Dark Dimension, $N = 10^{16}$ [*Montero, Vafa, Valenzuela 2023*].
- Many copies theory , $N = 10^{32}$ [*Dvali, Redi 2008*].
- Nnaturalness, $N = 10^4$, $N = 10^{16}$ [*Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner 2017*].





Where to search for effects of M_f?



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

$$(HL)_i \lambda_{ij} \nu_{Rj} \ , \tag{4}$$

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

$$\lambda_{i,j} \leq 1/\sqrt{N} \ . \tag{5}$$

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

$$m_\nu \sim \frac{M_f}{M_P} v_{ew} \tag{6}$$

Infrared 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

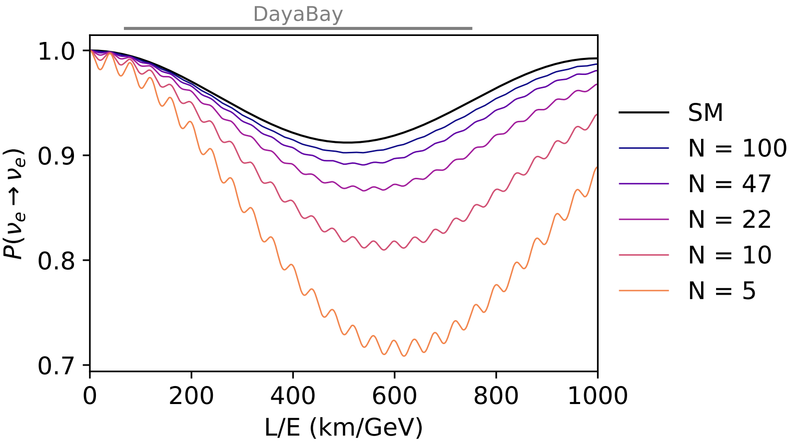
(Extra Dimensions, Many Species Theory, Nnaturalness) } **Many Mixing Partners**

- 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*]:

$$|\nu_e\rangle = \sqrt{\frac{N-1}{N}}\left(U_{e1}|m_1\rangle + U_{e2}|m_2\rangle + U_{e3}|m_3\rangle\right) + \frac{1}{\sqrt{N}}\left(U_{e1}|m_1^H\rangle + U_{e2}|m_2^H\rangle + U_{e3}|m_3^H\rangle\right). \quad (7)$$

The masses $m_{1\ldots3}$ are the usual masses of SM neutrinos and the masses $m^H_{1\ldots3}$ 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



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

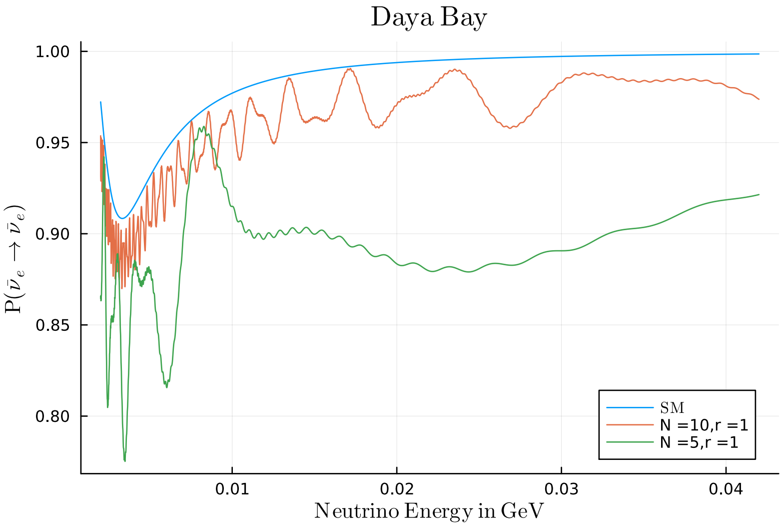
$$|\nu_1\rangle = |\nu_1\rangle_m + \frac{1}{N}\sum_{i=2}^{N-1}\frac{\sqrt{2i+r}\sqrt{r}}{2i}|\nu_i\rangle_m + \frac{1}{N}|\nu_N\rangle_m \tag{8}$$

- The scaling of the Δm^2_{i1} is

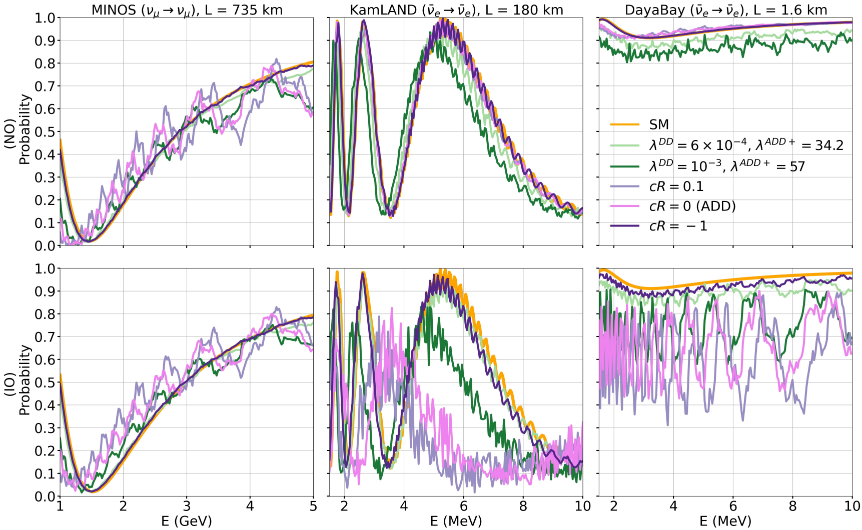
$$\Delta m^2_{i1} \propto 2i \quad \text{Dirac Case}\,, \tag{9}$$

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

Neutrino oscillations in Nnaturalness (Dirac case)



Neutrino oscillations in extra dimensional theories



- The species scale is a new scale in the physics of BH's.
- In the high mass limit the Einsteinian picture of a BH should hold. But for low mass BH's, M_f is the relevant scale.

$$M_f \ll M \ll \begin{cases} \sqrt{N} M_P & \text{(species)} \\ (M_P R) M_P & \text{(extra dimensions)} \end{cases} \tag{11}$$

[*Dvali 2008; Dvali, Pujolas 2008*]

- Within the intermediate regime the properties of a BH changes. [*Argyres, Dimopoulos, March-Russel 1998; Dvali 2008; Dvali, Pujolas 2008*]

$$r^{(\tilde{n})} = \frac{a_{\tilde{n}}}{M_f} \left(\frac{M}{M_f} \right)^{1/(1+\tilde{n})}, \tag{12}$$

$$T_H \propto \frac{1}{r^{(\tilde{n})}} \tag{13}$$

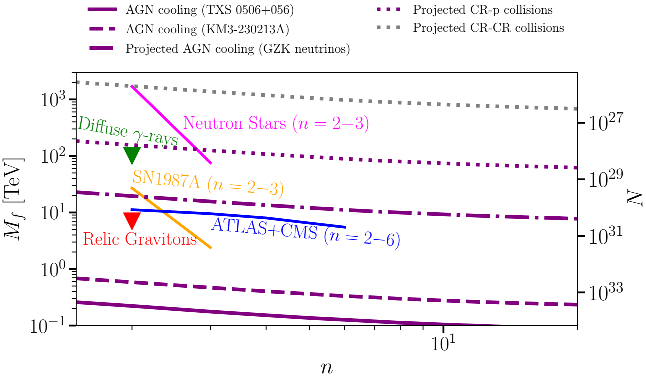
$$\frac{dM}{dt} = -\alpha \, T_H^2 \tag{14}$$

- In the environment of an active galactic nucleus (AGN) particles can get accelerated to energies up to $E \geq 10^8$ GeV.
- If such a high-energy particle interacts with an souround particle at rest or another cosmic ray black holes can be formed. (Classicalization for $\sqrt{s} \geq M_f$ [Dvali, Giudice, Gomez, Kehagias 2011; Dvali, Gomez, Isermann, Lüst 2015])
- The production cross-section for black holes is

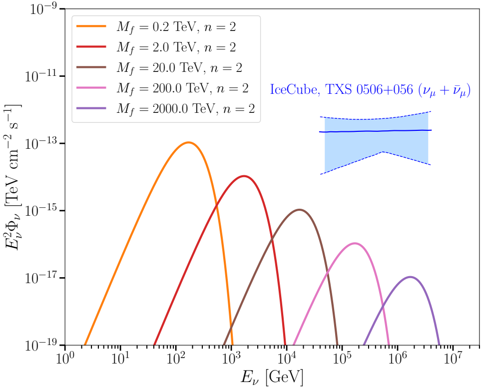
$$\sigma_0 = \pi r_s^2 \ . \tag{15}$$

- Therefore, AGN's can produce micro black holes and would populate their surrounding coronae [M.E., Herrera 2025].

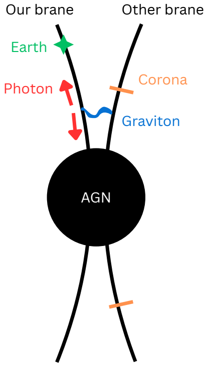
The BH production could cool the observed jets of AGN's more efficiently than SM processes. This can be used to give a bound on M_f.



One can search for the Hawking radiation of the micro black holes in the spectrum of the AGN corona.



Instead of BH's also bulk particles like gravitons can be produced. Within a braneworld such particles can reach us from another brane.

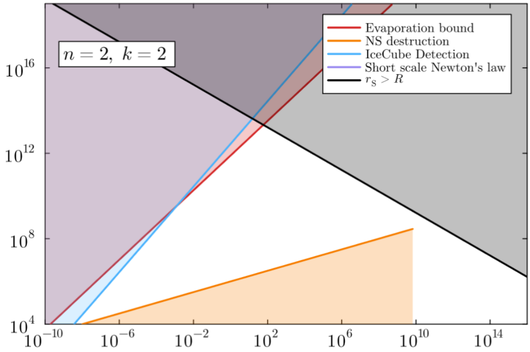


- Micro Black Holes are primordial black hole candidates with a mass range of $10^{-10}\mathrm{g} - 10^{21}\mathrm{g}$.
- Particularly fascinating extremely light BHs down to $M = 10^{14}\ \mathrm{GeV} \sim 10^{-10}\ \mathrm{g} \ll M_{\mathrm{P}} = 10^{-5}\ \mathrm{g}$, The resulting flux is $\phi_{\mathrm{BH}} = 1/\mathrm{hr}\ \mathrm{m}^2$, [M.E., Kühnel 2025].
- Such light black holes require a stabilization mechanism like the memory burden effect [*Dvali 2018*] that changes the evaporation behavior

$$\left.\frac{dM}{dt}\right|_{\mathrm{MB}} = \frac{1}{S^k}\left.\frac{dM}{dt}\right|_{SC}, \tag{16}$$

$$S_{\text{extra dim.}} = S^{(4)}\left(\frac{R}{r_S}\right)^{n/(n+1)} \sim S^{(4)}\left(\frac{M_P^{2n+2}}{M_f^{n+2}M^n}\right)^{1/(n+1)}, \tag{17}$$

A typical benchmark model is a large extra dimensional model with $n = 2$ and $M_\mathrm{f} = 10\ \mathrm{TeV}$. This leads to signals in experiments like IceCube [M.E., Kühnel 2026].



Conclusion

- Low scale gravity theories have plenty of observables in low energy experiments and distinctive signatures in astrophysical searches.
- The many mixing partners mechanism is a infrared solution to the neutrino mass problem.
- The predicted oscillatory behaviour of low scale gravity theories is very distinctive compared to other theories.
- Black Holes of all sizes have distinct neutrino signals experiments can search for.