Gravitational Origin for Neutrino Masses

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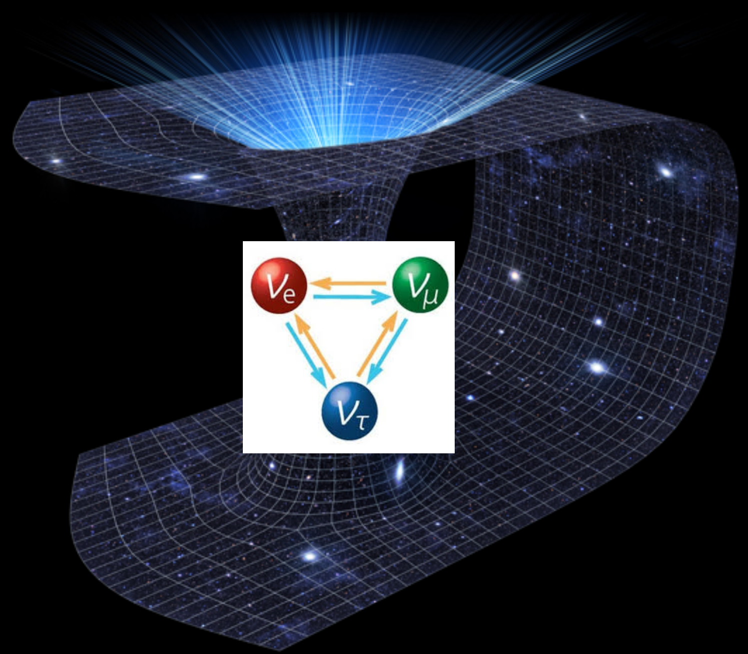

Based on: H.D., 2003.04908 [hep-ph]

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Introduction:

- Open fundamental questions unexplained in Standard Model (SM):

  – Neutrino masses, $m_\nu \lesssim 0.1$ eV, implied by neutrino flavor oscillation

  – Dark matter (DM)

- DM: only gravitational evidence, many possibilities at present

- Neutrino masses: a few ideas

- One interesting idea is seesaw mechanism

  – Ultra heavy "right-handed neutrinos" ν_R, as heavy as $\sim 10^{14}$ GeV

  – ν_R, uncharged under SM, largely inaccessible to experiments

  – Seesaw: Majorana $m_\nu \to$ rare $0\nu\beta\beta$ decay, yet to be observed

  – Alternatively, Dirac neutrino masses: very small Yukawa couplings $\lesssim 10^{-12}$

This Talk:

- Tiny m_ν: zero by global symmetry $U(1)_g$
  - Spontaneously broken, but only gravitationally mediated
- Quantum gravity expected to violate global symmetries explicitly
  - Black holes destroy global charges
  - Wormholes transport global charges "elsewhere"
  - More generally "gravitational instantons" corresponding to action S
  - Axion from spontaneous breaken $U(1)_g$ gets mass from gravitational instantons
- Right-handed neutrinos, possibly from entirely different sector
  - All fields could be coupled through gravitational interactions
- Organizing principles:
  - $U(1)_g$ preserving operators possibly suppressed by powers of $M_{\mathrm{Pl}} \approx 1.2 \times 10^{19}$ GeV
  - Transition between vacua with charge difference ΔQ suppressed by $\propto e^{-\Delta Q\, S}$

Abbott, Wise, 1989; Kalosh, Linde, Linde, Susskind, 1995

Caveats & Comments:

- Definite models require knowledge of quantum gravity
- Qualitative inferences from string theory, semi-classical treatments
- Our work has some elements in common with:

– Froggatt-Nielsen models of quark masses (1979)

– Majoron models, to explain ν_R masses with a broken global symmetry $\to$ axion

Chikashige, Mohapatra, 1981

- Gravitational global symmetry breaking has been considered in Majoron models

– Often only powers of $M_{\rm Pl}$ considered *E.g. Rothstein, Babu, Seckel, 1993*

– We require suppression by $e^{-\Delta Q\, S}$, and possible Planck suppression

- Arguments based on typical string constructions yield:

$$S \sim 2\pi/\alpha_G$$

– α_G of order grand unified gauge coupling

– We take: $1/30 \lesssim \alpha_G \lesssim 1/20 \;\; \Rightarrow \;\; e^{-S} \sim 10^{-82} - 10^{-55}$

Hui, Ostriker, Tremaine, Witten, 2016

A Minimal Model:

- To generate Dirac masses, introduce scalar Φ
- $U(1)_g$ charges: $(Q_g(\Phi), Q_g(L), Q_g(\nu_R)) = (1, -2, -3)$
- We can then write down gravitational coupling, assuming $\mathcal{O}(1)$ coefficient

$$O_5 \sim \frac{\Phi H^* \bar{L} \nu_R}{M_{\rm Pl}}$$

- To get $m_\nu \sim 0.1$ eV we then need $\langle \Phi \rangle = \phi_0/\sqrt{2} \sim 10^7$ GeV with $\Phi = \frac{\phi + \phi_0}{\sqrt{2}}\, e^{ia/\phi_0}$
- Gravitational "instantons" generate potential for axion a

$$V_a \sim -e^{-S} M_{\rm Pl}^4 \cos\frac{a}{\phi_0} \;\Rightarrow\; m_a^2 \sim e^{-S}\frac{M_{\rm Pl}^4}{\phi_0^2} \;\Rightarrow\; \boxed{10^{-10}\ \text{GeV} \lesssim m_a \lesssim 3\times 10^{3}\ \text{GeV}}$$

- Axion coupling to neutrinos

$$g_a\, a\, \bar{\nu}\gamma_5\nu = \frac{\langle H\rangle}{\sqrt{2} M_{\rm Pl}}\, a\, \bar{\nu}\gamma_5\nu = \frac{m_\nu}{\phi_0}\, a\, \bar{\nu}\gamma_5\nu$$

- Axion lifetime

$$\tau = \frac{8\pi}{g_a^2\, m_a} \sim 10^{13}\ \text{s} \left(\frac{20\ \text{MeV}}{m_a}\right)\left(\frac{10^{-17}}{g_a}\right)^2$$

$t_{CMB} \sim 10^{13}$ s

Cosmological Constraints:

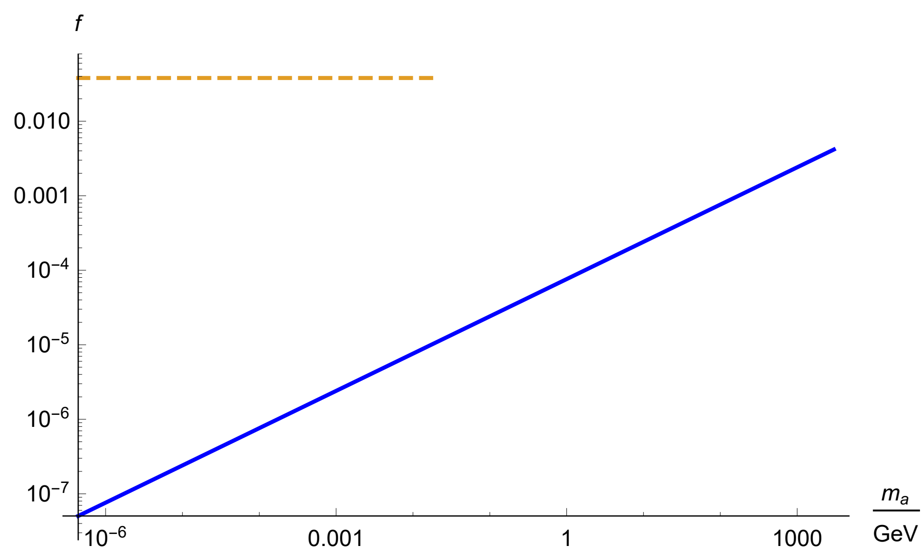
- If fraction of DM f with lifetime $t_{CMB} \lesssim \tau \lesssim H_0^{-1}$ decays into dark radiation:

$$\text{CMB and matter power spectra} \Rightarrow f \lesssim 0.038 \qquad (95\%\ \text{CL})$$

Poulin, Serpico, Lesgourgues, 2016

- Axion initial energy density $\sim m_a^2 a_i^2$; a_i initial amplitude of oscillations
- Fraction f of DM in unstable axion by $T_{\text{eq}} \sim 1$ eV (radiation-matter equality)
  – Oscillation commences when m_a is of order Hubble parameter

$$f \sim a_i^2 \left(\frac{g_*}{M_{\text{Pl}}^2}\right)^{3/4} \left(\frac{\sqrt{m_a}}{T_{\text{eq}}}\right)$$



Values above dashed line excluded (95% C.L.); $a_i = \phi_0$ and $m_a \gtrsim 20$ MeV corresponds to $t \lesssim t_{CMB}$

- Neutrino flux from $a \to \nu\bar{\nu}$:

$$F_0^\nu \sim f\,\rho_{DM}/m_a$$

– For $\tau \gtrsim t_{CMB}$ (i.e. $m_a \lesssim 20$ MeV) $\Rightarrow F_0^\nu \gtrsim 20$ cm^{-2} s^{-1}.

- Typical neutrino energy

$$E_0^\nu \sim \frac{m_a}{2}\left(\frac{\tau}{t_U}\right)^{2/3}$$

– For $m_a \lesssim 20$ MeV $\Rightarrow E_0^\nu \lesssim 10$ keV (challenging to detect)

- CMB and local measurements of present Hubble parameter disagree

– Potentially at $\gtrsim 4\sigma$ Riess, Casertano, Yuan, Macri, Scolnic, 2019

– Perhaps systematic effects, but could be new physics

- A decaying DM component could help address the tension

E.g., Berezhiani, Dolgov, Tkachev, 2015

– Minimal model example:

  - $f \ll 1$ [larger ϕ_0 (smaller dim-5 coefficient) can enhance f]
  - Requires another, sufficiently stable, DM component

- Expanded models (with more global symmetries) could have broader phenomenology and more accessible signals H.D., 2003.04908.

Concluding Remarks

- Small neutrino masses may be due to a global $U(1)$ symmetry and weak gravitational (Planck-suppressed) coupling

- Global symmetries are generically expected to be broken by non-perturbative gravitational processes: microscopic black holes, wormholes, instantons, . . .

- Possible that "right-handed neutrinos" separate from SM sector

  – However, gravity mediates interactions among all types of fields

  – Violation of global symmetry with suppressed instanton amplitude

- Generic feature: axions

  – Gravitational instantons expected to generate axion mass

- Axions decaying into neutrinos a typical expectation

- Could leave an imprint on cosmology (possibly address Hubble tension)

- Extensions: could invoke more than one global $U(1)$