Gravitational Origin for Neutrino Masses

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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” $\nu_R$, as heavy as $\sim 10^{14}$ GeV
    - $\nu_R$, uncharged under SM, largely inaccessible to experiments
    - Seesaw: Majorana $m_\nu \rightarrow$ rare $0\nu\beta\beta$ decay, yet to be observed
    - Alternatively, Dirac neutrino masses: very small Yukawa couplings $\lesssim 10^{-12}$
This Talk:

- Tiny $m_\nu$: 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 $M_{Pl} \approx 1.2 \times 10^{19}$ GeV
  - Transition between vacua with charge difference $\Delta Q$ 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 $\nu_R$ 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 $M_{Pl}$ 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:
  
  $$S \sim 2\pi/\alpha_G$$
  
  - $\alpha_G$ 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 $\Phi$
- $U(1)_g$ charges: $(Q_g(\Phi), Q_g(L), Q_g(\nu_R)) = (1, -2, -3)$
- We can then write down gravitational coupling, assuming $O(1)$ coefficient
  \[ O_5 \sim \frac{\Phi H^* \tilde{L} \nu_R}{M_{Pl}} \]
- To get $m_\nu \sim 0.1$ eV we then need $\langle \Phi \rangle = \phi_0 / \sqrt{2} \sim 10^7$ GeV with $\Phi = \frac{\phi + \phi_0}{\sqrt{2}} e^{i a / \phi_0}$
- Gravitational “instantons” generate potential for axion $a$

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

- Axion coupling to neutrinos
  \[ g_a a \tilde{\nu} \gamma_5 \nu = \frac{\langle H \rangle}{\sqrt{2} M_{Pl}} a \tilde{\nu} \gamma_5 \nu = \frac{m_\nu}{\phi_0} a \tilde{\nu} \gamma_5 \nu \]
- 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:

  \[
  \text{CMB and matter power spectra } \Rightarrow f \lesssim 0.038 \quad (95\% \ \text{CL})
  \]

  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 $T_{eq} \sim 1$ eV (radiation-matter equality)
  - Oscillation commences when $m_a$ is of order Hubble parameter

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

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 $a \rightarrow \nu \bar{\nu}$:
  \[ F_0^\nu \sim f \rho_{DM}/m_a \]
  - 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 $\phi_0$ (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 $U(1)$