Gravitational Interactions and Neutrino Masses

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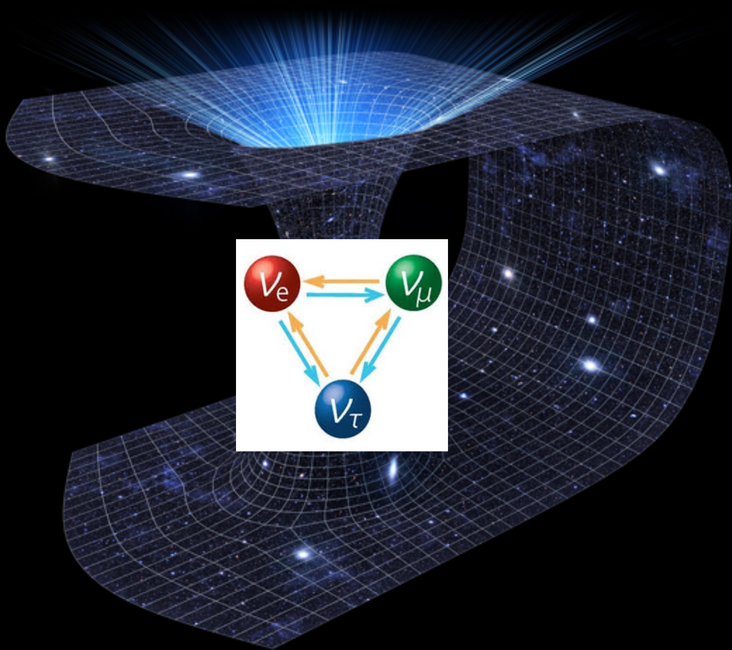

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Introduction:

- 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 to SM

- 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 spontaneously broken $U(1)_g$ 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
- The scenario 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 $\rightarrow$ 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: $(Q_g(\Phi), Q_g(L), Q_g(\nu_R)) = (1, -2, -3)$
- $U(1)_g$ preserving gravitational coupling, $\mathcal{O}(1)$ 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

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

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

Cosmological Constraints:

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

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

Poulin, Serpico, Lesgourgues, 2016

- Axion initial energy density $\sim m_a^2 a_i^2/2$; 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 $m_a/3$ is approximately equal to Hubble parameter

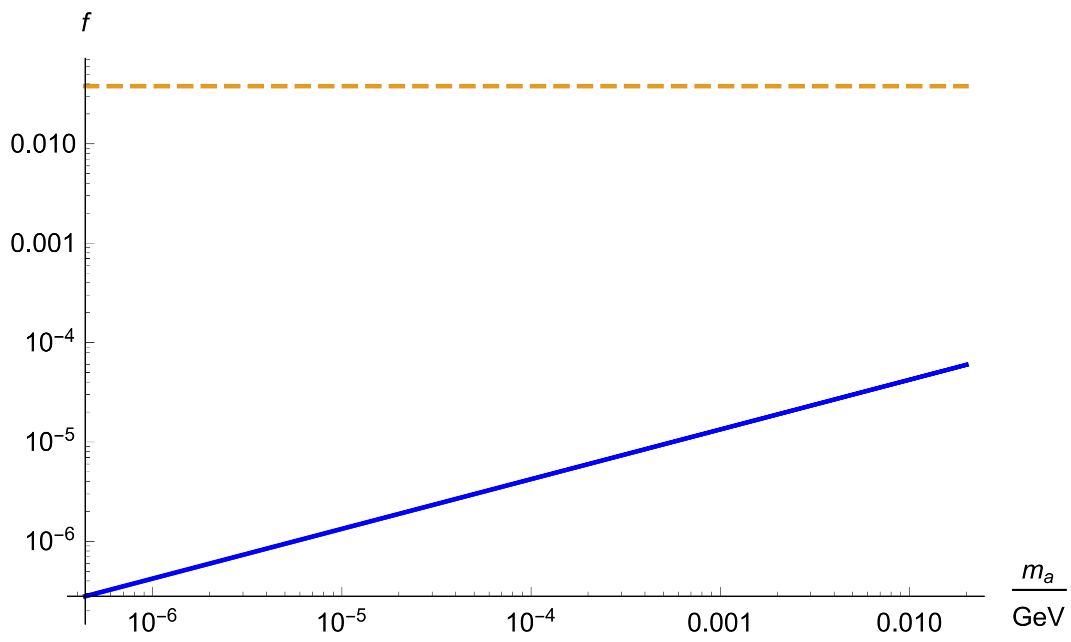
$$f \approx \frac{a_i^2}{2} \left(\frac{9 c_* \, g_*}{\bar{M}_{\text{P}}^2} \right)^{3/4} \left(\frac{\sqrt{m_a}}{T_{\text{eq}}} \right)$$

$\mathcal{H} = (c_* \, g_*)^{1/2} T^2 / \bar{M}_{\text{P}}$ and $c_* \equiv (2\pi)^3/90$

Caution: For sufficiently large m_a, requiring $m_a \approx 3\mathcal{H}$ would correspond to $T \gg \langle \Phi_0 \rangle$ $\rightarrow$ symmetry $U(1)_g$ is typically unbroken $\rightarrow$ No axion.

Representative range: $m_a \in [10^{-3}, 20]$ MeV

- Corresponds to the onset of axion oscillation, $T \lesssim 10^8$ GeV (for $\langle \Phi_0 \rangle \sim 10^7$ GeV)
- Assume $a_i = \phi_0$ and $g_* \sim 100$
- $m_a \gtrsim 20$ MeV corresponds to $\tau \lesssim t_{CMB}$



Values above dashed line excluded (95% C.L.)

- 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) $\Rightarrow F_0^\nu \gtrsim 100$ 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:

– Requires another, sufficiently stable, DM component

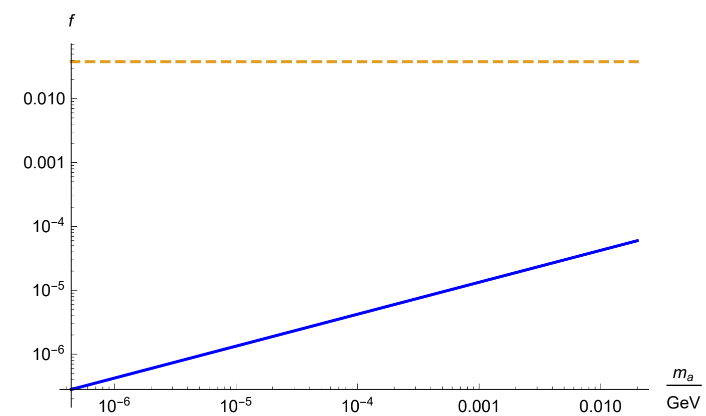
– Fraction $f \ll 1$ for $m_a \in [10^{-3}, 20]$ MeV

– For $m_a \gtrsim 20$ MeV oscillation will begin at $T \sim \langle \Phi_0 \rangle$, once $U(1)_g$ is broken

– The initial energy density (assuming "generic" $a_i \sim \phi_0$) will scale as m_a^2

– Hence $f(m_a \gtrsim 20\text{MeV}) \sim m_a^2 f(m_a \approx 20\text{MeV})$

$$m_a \sim 2 \text{ GeV, corresponding to } \tau \sim 0.01 t_{CMB} \Rightarrow f \sim 1$$



- Expanded models:

– With more global symmetries

– Broader phenomenology, potentially more accessible signals

– Could have two axions: one very long-lived DM and the other with $\tau \lesssim t_U$

H.D., 2003.04908

Possible Extension

- $U(1) \times U(1)'$ (multitude of such symmetries in string theory)
- New scalar Φ' to break $U(1)'$
- Assume $S = S'$ for simplicity (a wide range)
- Charge assignments:

$$(Q_g(\Phi), Q_g(\Phi'), Q_g(L), Q_g(\nu_R)) = \overbrace{(1, 0, q+1, q)}^{U(1)} \text{ and } \overbrace{(0, 1, 0, -1)}^{U(1)'}$$

- Can write down:

$$O_6 \sim \frac{\Phi\Phi' H^* \bar{L} \nu_R}{\bar{M}_{\mathrm{P}}^2}$$

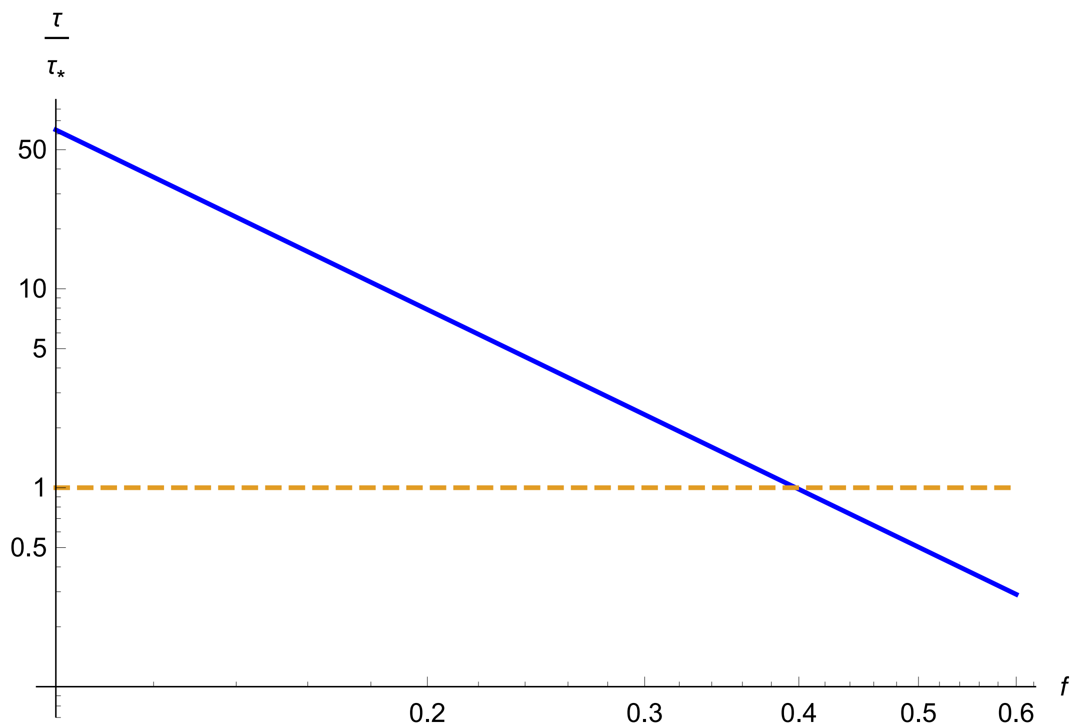
$$\Rightarrow \frac{\langle\Phi\rangle\langle\Phi'\rangle}{\bar{M}_{\mathrm{P}}^2} \sim 10^{-12} \quad \text{(effective Yuakawa coupling)}$$

- Example possibility: $\phi_0 = 10^9$ GeV and $\phi_0' = 10^{17}$ GeV
- Axion masses:

$$10^{-12} \text{ GeV} \lesssim m_a \lesssim 30 \text{ GeV}$$

$$10^{-20} \text{ GeV} \lesssim m_{a'} \lesssim 3 \times 10^{-7} \text{ GeV}$$

- Bound on f can be written as $\tau > f\, 2.0 \times 10^{18}$ s, for $\tau \gtrsim t_U$



Exclusion below dashed line (95% C.L., for $\tau \gtrsim t_U$); $a_i = \phi_0 = 10^9$ GeV and $\tau_* = f\, 2.0 \times 10^{18}$ s

- Axion a has $\tau \sim t_U$ due to $a \to \bar{\nu}\nu$
- Assume spherical distribution of DM around the Earth, radius D
- Flux F of neutrinos at Earth

$$F \approx \frac{D\, f \rho}{m\, \tau},$$

For: $\rho \approx 0.3$ GeV cm^{-3}, $D \sim 0.5$ kpc, $m_a \sim 5$ MeV, $a_i = \phi_0$, we find $f \sim 0.3$ and $\tau \sim 4 \times 10^{17}$ s

Flux of $\bar{\nu}, \nu$ with energy $E_\nu \sim 2.5$ MeV: $F \sim 10^5$ cm $^{-2}$ s^{-1} (mixture of flavors)

- "Geo-neutrino" flux observed by KamLAND and Boerxino

KamLAND Collaboration, 2005; Borexino Collaboration, 2010

KamLAND: $\bar{\nu}_e$ is $3.4^{+0.8}_{-0.8} \times 10^6$ cm^{-2}s^{-1} KamLAND Collaboration, 2013

Similar results from Borexino Collaboration, 2019

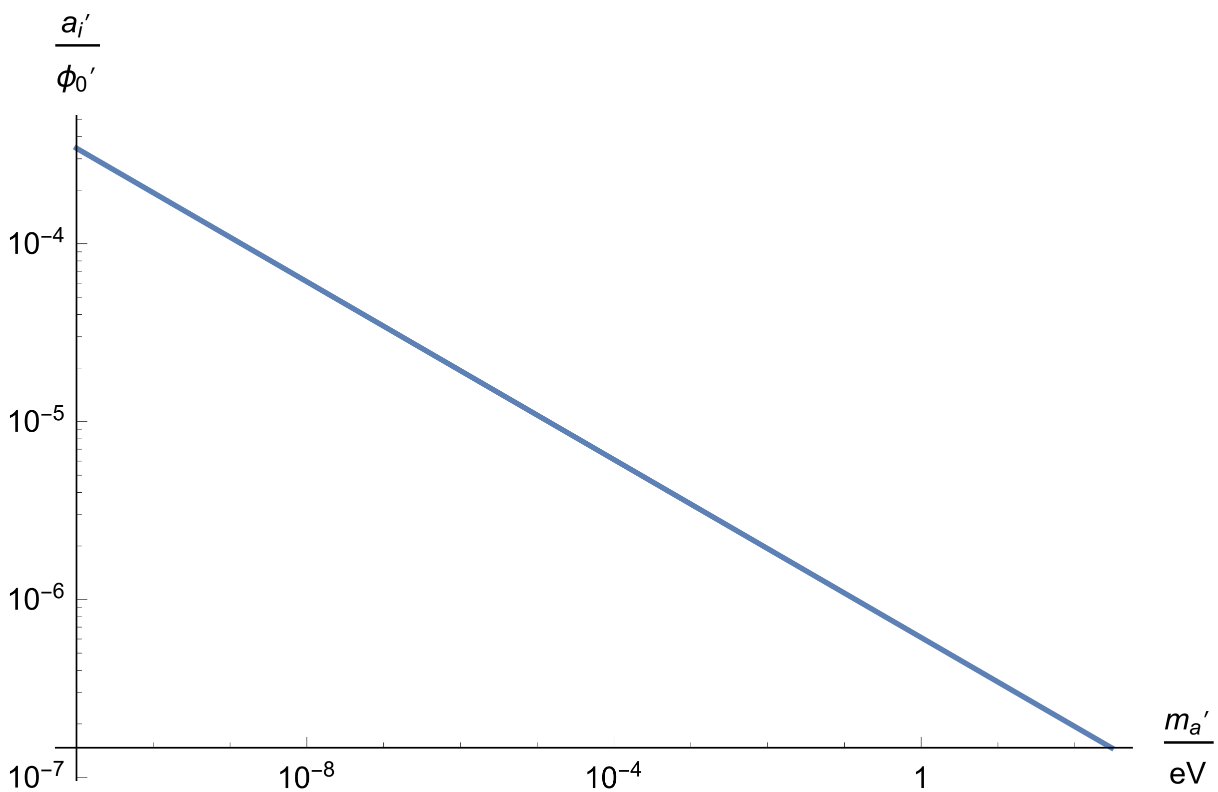
See also Garcia-Cely, Heeck, 2017

Perhaps better measurements and geological models can constrain the scenario

- Axion a' could be DM ($\tau' \gg t_U$)
- For $f = 1$, initial amplitude $< \phi'_0$ over the range considered
- Near $m_{a'} \sim 10^{-11}$ eV DM may be probed by gravitational wave measurements

– Copious production by spinning black holes

Arvanitaki et al., 2009; Arvanitaki, Baryakhtar, Huang, 2014



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 suppressed by 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 $U(1)$