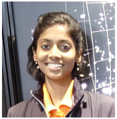

Observational constraints on the possibility that Sterile Neutrinos cause Anti-Gravity

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Exploring a New Idea

Theory :

Can acceleration of universe be due to repulsive gravity caused by sterile neutrinos ?

Motivation :

- More no. of stars formed late in the cosmic timeline $\Rightarrow$ more supernovae explosions ; stellar neutrinos produced copiously.
- Greater flux of sterile neutrinos ; if they cause repulsive gravity $\Rightarrow$ accelerated expansion in late-time universe.

The math :

- Introduced a negative gravitational constant $-G'$ ($G' > 0$) associated with sterile neutrinos.
- In the Einstein Field Equation, replace $\Lambda g_{\mu\nu}$ with $-G'$ and $(T_{\mu\nu})_{s\nu}$, the stress-energy tensor associated with sterile neutrinos.

Modified Einstein Field Equation :

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} - \frac{8\pi G'}{c^4} (T_{\mu\nu})_{s\nu}$$

Modified FLRW Equations :

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\left[\rho_m + \rho_r - \frac{G'}{G}\rho_{s\nu}\right] - \frac{kc^2}{a^2} \tag{1}$$

$$\frac{2\ddot{a}}{a} + \frac{\dot{a}^2 + kc^2}{a^2} = -\frac{8\pi G}{c^2}\left[p_m + p_r - \frac{G'}{G}p_{s\nu}\right] \tag{2}$$

Analyzing Repulsive Gravity due to Sterile Neutrinos

- Substituting eqn (1) in (2), we get the condition for late-time acceleration :

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho_m - \frac{G'}{G}\rho_{s\nu}\left(1 + \frac{1}{c^2}\right)\right]$$

- Rearranging (1), leads us to an important condition regarding the curvature k of the universe :

$$\boxed{H^2 = \frac{8\pi G}{3}\rho_m\left[1 - \frac{G'}{G}\frac{\rho_{s\nu}}{\rho_m}\right] - \frac{kc^2}{a^2} > 0} \implies \boxed{k = -1}$$

- For an accelerating universe, 1st term of RHS is negative.
- This implies 2nd term of RHS *has* to be negative i.e. $k = -1$, for LHS to remain positive.

Analyzing Repulsive Gravity due to Sterile Neutrinos

- We consider two cases, one of light sterile neutrinos and other of massive sterile neutrinos.
- Calculate radial distance, $r(z)$ for both cases.

(i)Very light (radiation-like) sterile neutrinos

$$r(z) = \sinh\left[\cosh^{-1}\left(\frac{1+\frac{K_0}{2}}{\sqrt{K_1+\frac{K_0^2}{4}}}\right) - \cosh^{-1}\left(\frac{\frac{1}{1+z}+\frac{K_0}{2}}{\sqrt{K_1+\frac{K_0^2}{4}}}\right)\right]$$

With,

$$K_0 = \frac{H_0^2 a_0^2 \Omega_{m,0}}{c^2} \text{and} \qquad K_1 = K_0 \frac{G'}{G}\frac{\Omega_{s\nu,0}}{\Omega_{m,0}}$$

Analyzing Repulsive Gravity due to Sterile Neutrinos

(ii)Massive sterile neutrinos

$$r(z) = \sinh\left[\frac{c}{a_0 H_0}\frac{1}{\sqrt{K_3}}\left(\ln\left|\frac{\sqrt{K_2(1+z)+K_3}-\sqrt{K_3}}{\sqrt{K_2(1+z)+K_3}+\sqrt{K_3}}\right| - \ln\left|\frac{\sqrt{K_2+K_3}-\sqrt{K_3}}{\sqrt{K_2+K_3}+\sqrt{K_3}}\right|\right)\right]$$

With,

$$K_2 = \Omega_{m,0} - \alpha \qquad \text{and} \qquad K_3 = \frac{c^2}{a_0^2 H_0^2}$$

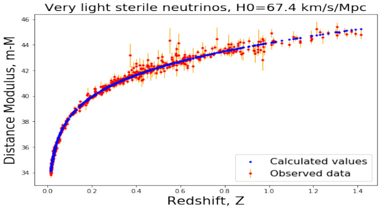
Results

- Using radial distance values, computed the distance modulus values :

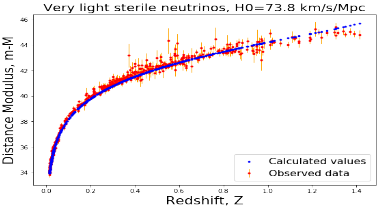
$$m - M = 5\log_{10}\left(\frac{d_L(z)}{10pc}\right)$$

- Used z from Type Ia Supernovae observed data (Supernova Cosmology Project, Suzuki et al., 2012).

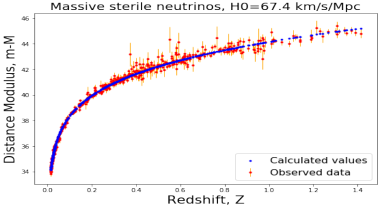
Plots & Figures



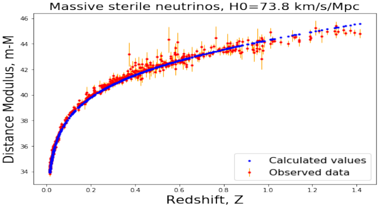
(a) Light Sterile Neutrinos,
$H_0 = 67.4, (G'/G)\Omega_{s\nu,0} = 0.1584$



(b) Light Sterile Neutrinos,
$H_0 = 73.8, (G'/G)\Omega_{s\nu,0} = 0.2759$



(a) Massive Sterile Neutrinos,
$H_0 = 67.4, (G'/G)\Omega_{s\nu,0} = 0.3579$



(b) Massive Sterile Neutrinos,
$H_0 = 73.8, (G'/G)\Omega_{s\nu,0} = 0.7238$

Results & Conclusions

- Plotted and compared calculated & observed values of $(m - M)$ vs. z, according to best fit of the free parameter $\frac{G'}{G}\Omega_{s\nu}$.
- Different combinations of H_0 and $\frac{G'}{G}\Omega_{s\nu}$ studied. Goodness of fit estimated using weighted least-squared minimization.
- Satisfactory fits even with recent findings of $H_0 \sim 74$ (Pesce et al., 2020).

H_0	Massive case, $\frac{G'}{G}\Omega_{s\nu}$	Light case, $\frac{G'}{G}\Omega_{s\nu}$
67.4	0.3579	0.1584
69.8	0.5243	0.2199
73	0.6904	0.2685
73.8	0.7238	0.2759