Neutrino physics in extended theories of gravity

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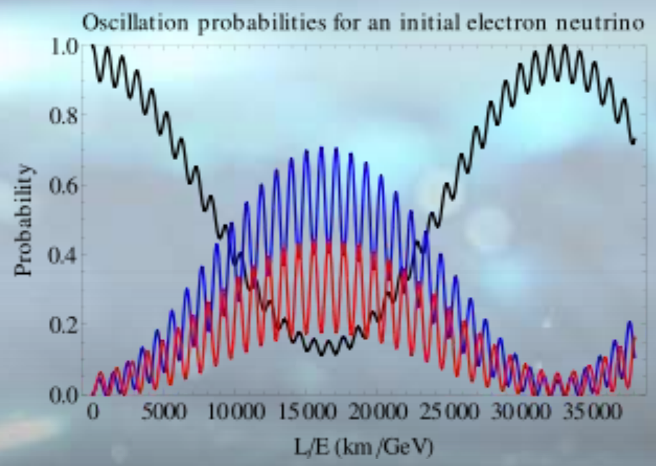
Based on the work:
L. Buoninfante, G.G. Luciano, L.P. and L. Smaldone, Phys. Rev. D ***101****, 024016 (2020), arXiv: 1906.03131 [gr.qc]*



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$$U(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\mathcal{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

This formalism perfectly describes ultra-relativistic neutrinos propagating on a flat background

… but what happens when neutrino oscillations occur in curved spacetime?

S.M. Bilenky and B. Pontecorvo, Phys. Rep. ***41****, 225 (1978)*

Assuming to work within the weak-field limit

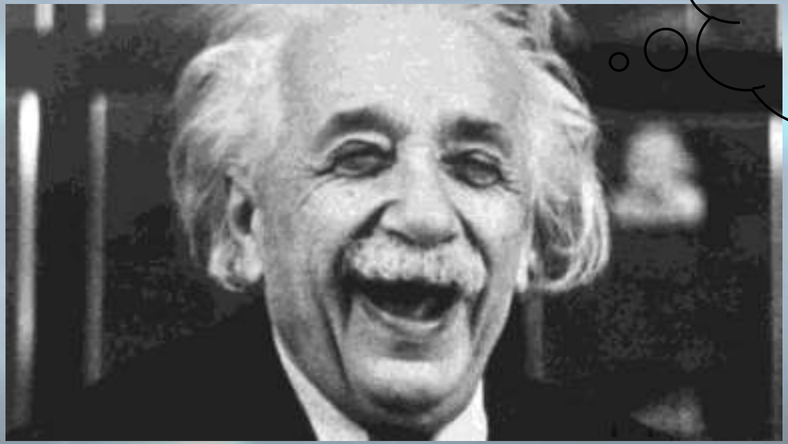
$$|\nu_i\rangle \to \exp\left[i\int_{\lambda_i}^{\lambda_f} P_\mu \frac{dx^\mu_{null}}{d\lambda}d\lambda\right]|\nu_i\rangle \quad \longrightarrow \quad \mathcal{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\varphi_{21}}{2}\right)$$

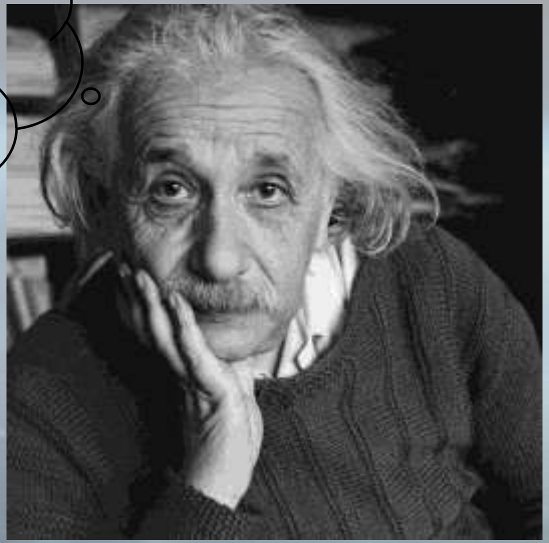
$$\varphi_{21} = \varphi_0 + \varphi_{GR}$$

where the first contribution is the one already analyzed in the flat background, whereas, starting from the Schwarzschild solution

$$\varphi_{GR} = \frac{\Delta m^2 L_p}{2E_\ell}\left[\frac{GM}{r_f} - \frac{GM}{L_p}\ln\left(\frac{r_f}{r_i}\right)\right]$$

*C.Y. Cardall and G.M. Fuller, Phys. Rev. D **55**, 7960 (1997)*
*N. Fornengo, C.Giunti, C.W. Kim and J. Song, Phys. Rev. D **56**, 1895 (1997)*





… but what if GR is not the end of the story?

Extended models of gravity can solve several issues related to GR in the quantum realm

$$\mathcal{L} = \frac{\sqrt{-g}}{2\kappa^2}\left\{\mathcal{R} + \frac{1}{2}\left[\mathcal{R}\mathcal{F}_1(\Box)\mathcal{R} + \mathcal{R}_{\mu\nu}\mathcal{F}_2(\Box)\mathcal{R}^{\mu\nu} + \mathcal{R}_{\mu\nu\rho\sigma}\mathcal{F}_3(\Box)\mathcal{R}^{\mu\nu\rho\sigma}\right]\right\}$$

T. Biswas, E. Gerwick, T. Koivisto and A. Mazumdar, Phys. Rev. Lett. ***108****, 031101 (2012)*

Always working in the weak-field limit, it is possible to show that

$$ds^2 = (1 + 2\phi)dt^2 - (1 - 2\psi)d\mathbf{r}^2$$

$\phi \rightarrow \phi_{GR} + \phi_Q$ $\qquad$ $\psi \rightarrow \phi_{GR} + \psi_Q$

The oscillation phase is then given by

$$\varphi_{21} = \varphi_0 + \varphi_{GR} + \varphi_Q \longrightarrow \varphi_Q = \frac{\Delta m^2 L_p}{2E_\ell}\left[\frac{1}{L_p}\int_{r_i}^{r_f} \phi_Q(r)\, dr - \phi_Q(r_f)\right]$$

Physics entails a restriction on the free parameters of extended models of gravity

$$\left|\frac{\varphi_Q}{\varphi_0}\right| \lesssim \left|\frac{\varphi_{GR}}{\varphi_0}\right| < 1$$

What happens from the viewpoint of an observer at infinity?

$$\varphi_{21} = \frac{\Delta m^2}{2E} \int_{r_i}^{r_f} [1 + \phi(r) - \psi(r)]\, dr$$

$$\eta = \frac{\phi - \psi}{\phi}$$

$$\varphi_{21} = \frac{\Delta m^2}{2E} \int_{r_i}^{r_f} [1 + \phi(r)\, \eta(r)]\, dr$$

Nordtvedt parameter (SEP quantifier)

$\eta \neq 0$ → SEP violation gives rise to phenomenologically observable effects!

K. Nordtvedt, Scholarpedia, 9 (9):32141

Thank you for your kind attention!