Probing Beyond standard model physics from gravitational waves and other astrophysical experiments

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Outline

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3. Vector gauge boson radiation from compact binary systems in a gauged $L_\mu - L_\tau$ scenario
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6. Constraints on axionic fuzzy dark matter from light bending and Shapiro time delay
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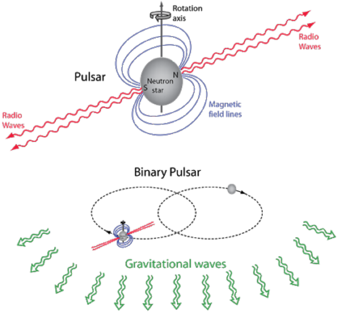
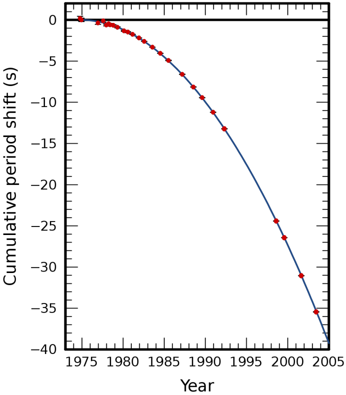
Indirect detection of Gravitational Wave





- Hulse and Taylor (1993): Orbital period loss of binary system (first indirect evidence of GW)
- GW150914: Merger of two steller mass black holes (first direct evidence of GW)

Quadrupole formula for GW radiation

$$P = \frac{G}{5c^5}\left(\frac{d^3 Q_{ij}}{dt^3}\frac{d^3 Q_{ij}}{dt^3} - \frac{1}{3}\frac{d^3 Q_{ii}}{dt^3}\frac{d^3 Q_{jj}}{dt^3}\right)$$

Peters and Mathews (1963):

The energy loss for arbitrary eccentricity of Keplerian orbit

$$\frac{dE}{dt} = \frac{32G}{5}\Omega^6\left(\frac{m_1 m_2}{m_1 + m_2}\right)^2 D^4(1-e^2)^{-7/2}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

The orbital period loss

$$\dot{P}_b = 6\pi G^{-\frac{3}{2}}(m_1 m_2)^{-1}(m_1 + m_2)^{-\frac{1}{2}} D^{\frac{5}{2}}\left(\frac{dE}{dt}\right)$$

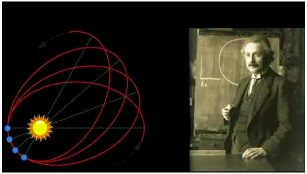
Hulse Taylor Binary System:

$$\dot{P}_{b\,GR} = (-2.40263 \pm 0.00005) \times 10^{-12} ss^{-1}$$

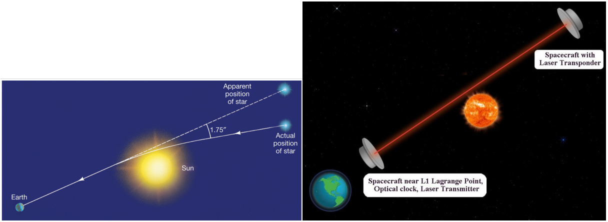
$$\dot{P}_{b\,observed} = -2.423(1) \times 10^{-12} ss^{-1}$$

Matches in good agreement with the GR prediction.→ Indirect evidence of GW.

However there is less than 1% uncertainty.

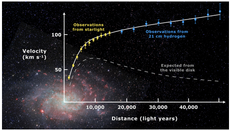


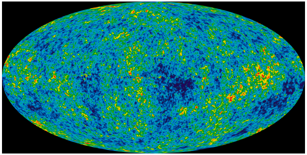
Perihelion precession of Mercury: Test of Einstein's GR Theory → Uncertainty in the measurement from the GR theory $\mathcal{O}(10^{-3})$

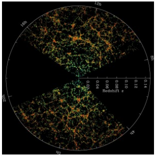


Gravitational light bending and Shapiro delay: Test of Einstein's GR Theory → Uncertainties in the measurement from the GR theory are $\mathcal{O}(10^{-4})$ and $\mathcal{O}(10^{-5})$ respectively.

Dark Matter: Why do we need it?







- Standard cold dark matter (WIMP)→ Strong constraint from direct detection.
- small scale structure problem.
- other possible dark matter models.

Fuzzy dark matter(Hu et.al,Phys.Rev.Lett. 85 (2000) 1158-1161, L.Hui et al, Phys. Rev. D 95, 043541 (2017)).
Candidates→ Ultralight scalars, vectors, pseudoscalars (ALPs)

Axions → PNGB → Solves strong CP problem

$$V = \Lambda^4 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$

Mass of axion

$$m_a = \frac{\Lambda^2}{f_a}$$

The equation of motion of axion for zero modes

$$\ddot{a_k} + 3H\dot{a_k} + m_a^2 a_k = 0$$

At late time $a \propto T^{\frac{3}{2}} \cos(m_a t)$ → redshifts like CDM.

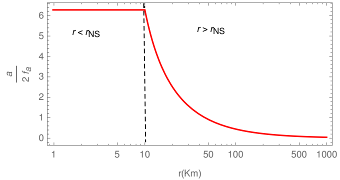
$$\Omega_{DM} \sim 0.1\left(\frac{a_0}{10^{17} GeV}\right)^2 \left(\frac{m_a}{10^{-22} eV}\right)^{\frac{1}{2}}$$

Constraints on ultralight axions from compact binary systems(Subhendra Mohanty, Soumya Jana, T.K.P), Phys.Rev.D 101 (2020) 8, 083007.

$$\omega=\left[\frac{G(m_1+m_2)}{D^3}\right]^{\frac{1}{2}}\sim 10^{-19}\mathrm{eV},\ \ \mathrm{a}=-\frac{\mathrm{q_{eff}}}{2\mathrm{GM}}\ln\left(1-\frac{2\mathrm{GM}}{\mathrm{r}}\right),\ \ \mathrm{q_{eff}}=-\frac{8\pi\mathrm{GMf_a}}{\ln\left(1-\frac{2\mathrm{GM}}{\mathrm{r_{NS}}}\right)}$$

$$\frac{dE}{dt}=-\frac{32}{5}G\mu^2D^4\omega^6(1-e^2)^{-\frac{7}{2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)-\frac{\omega^4p^2}{24\pi}\frac{(1+e^2/2)}{(1-e^2)^{\frac{5}{2}}}$$

$$\Omega_{DM}\sim 0.1\left(\frac{a_0}{10^{17}GeV}\right)^2\left(\frac{m_a}{10^{-22}eV}\right)^{\frac{1}{2}}$$



If ALPs are FDM, they do not couple with quarks.

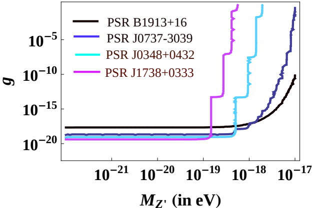
Compact binary system	f_a (GeV)	α
PSR J0348+0432	$\lesssim 1.66\times10^{11}$	$\lesssim 5.73\times10^{-10}$
PSR J0737-3039	$\lesssim 9.76\times10^{16}$	$\lesssim 9.21\times10^{-3}$
PSR J1738+0333	$\lesssim 2.03\times10^{11}$	$\lesssim 8.59\times10^{-10}$
PSR B1913+16	$\lesssim 2.12\times10^{17}$	$\lesssim 3.4\times10^{-2}$

Vector gauge boson radiation from compact binary systems in a gauged $L_\mu - L_\tau$ scenario(Subhendra Mohanty, Soumya Jana, T.K.P), Phys.Rev.D 100 (2019) 12, 123023.

$$N_\mu \approx 10^{55} (\mathrm{R.Garani, J.Heeck; 2019}).$$

$$\frac{dE}{dt} = \frac{g^2}{6\pi} a^2 M^2 \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \Omega^4 \sum_{n>n_0} 2n^2 \left[J_n'^2(ne) + \frac{(1-e^2)}{e^2} J_n^2(ne)\right] \left(1 - \frac{n_0^2}{n^2}\right)^{\frac{1}{2}} \left(1 + \frac{1}{2}\frac{n_0^2}{n^2}\right).$$

Compact binary system	g(fifth force)	g(orbital period decay)
PSR B1913+16	$\leq 4.99 \times 10^{-17}$	$\leq 2.21 \times 10^{-18}$
PSR J0737-3039	$\leq 4.58 \times 10^{-17}$	$\leq 2.17 \times 10^{-19}$
PSR J0348+0432	–	$\leq 9.02 \times 10^{-20}$
PSR J1738+0333	–	$\leq 4.24 \times 10^{-20}$

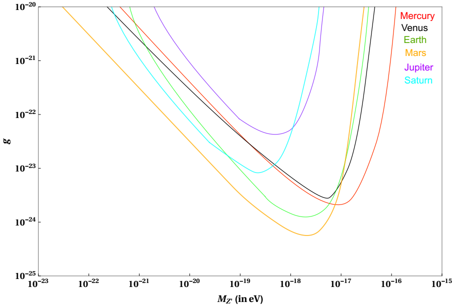


Constraints on long range force from perihelion precession of planets in a gauged $L_e - L_{\mu,\tau}$ scenario(Subhendra Mohnaty, Soumya Jana, T.K.P), Eur.Phys.J.C 81 (2021) 4, 286.

$$M_{Z'} \ll \frac{1}{a} \sim \mathcal{O}(10^{-19}\mathrm{eV}), \quad \frac{\mathrm{d}^2\mathrm{u}}{\mathrm{d}\phi^2} + \mathrm{u} = \frac{\mathrm{M}}{\mathrm{L}^2} + 3\mathrm{M}\mathrm{u}^2 + \frac{\mathrm{g}^2\mathrm{N}_1\mathrm{N}_2}{4\pi\mathrm{L}^2\mathrm{M}_\mathrm{p}}\mathrm{e}^{-\frac{\mathrm{M}_{\mathrm{Z}'}}{\mathrm{u}}} + \frac{\mathrm{g}^2\mathrm{N}_1\mathrm{N}_2\mathrm{E}\mathrm{M}_{\mathrm{Z}'}}{4\pi\mathrm{L}^2\mathrm{M}_\mathrm{p}\mathrm{u}}\mathrm{e}^{-\frac{\mathrm{M}_{\mathrm{Z}'}}{\mathrm{u}}}$$

$$\Delta\phi = \frac{6\pi GM}{a(1-e^2)} + \frac{g^2 N_1 N_2 |E| M_{Z'}^2 a^2 (1-e^2)}{4M_p(GM + \frac{g^2 N_1 N_2}{4\pi M_p})(1+e)}$$

$$\frac{g^2 N_1 N_2 |E| M_{Z'}^2 a^2 (1-e^2)}{4M_p(GM + \frac{g^2 N_1 N_2 |E|}{4\pi M_p})(1+e)} \left(\frac{\mathrm{century}}{T}\right) < 3.0 \times 10^{-3} \mathrm{arcsecond/century}$$



Probing the angle of birefringence due to long range axion hair from pulsars(Subhendra Mohanty, T.K.P), Phys.Rev.D 102 (2020) 8, 083029

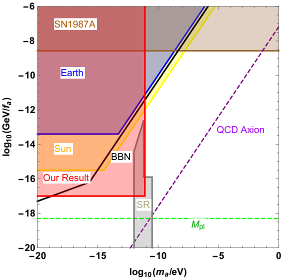
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \nabla_\mu\nabla^\mu\mathbf{B} = -g_{a\gamma\gamma}(\nabla a)\times\frac{\partial\mathbf{B}}{\partial t}$$

$$\omega^2\left(1-\frac{2GM}{r}\right)^{-1} - k_r^2\left(1-\frac{2GM}{r}\right) = \pm g_{a\gamma\gamma}(\partial_r a)\omega$$

$$\Delta\phi = -\frac{c\alpha_{em}}{2\pi f_a}\frac{q_a e^{-m_a R}}{R}\left[1+\frac{GM}{R}\{1-m_aR\ln(m_aR)+m_aRe^{2m_aR}E_i(-2m_aR)\}\right]$$

$$q_a = 4\pi f_a R e^{m_a R}\left[1+\frac{GM}{R}\{1-m_aR\ln(m_aR)+m_aRe^{2m_aR}E_i(-2m_aR)\}\right]^{-1}$$

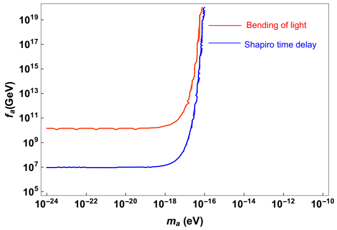
$$\Delta\theta = -c\alpha_{em} = 0.42^\circ$$



Constraints on axionic fuzzy dark matter from light bending and Shapiro time delay(T.K.P), arXiv:2104.09772

$$\Delta\phi_{axions} = \frac{\frac{4M}{b^2} + \frac{q_1 q_2}{2\pi M_p L^2}(1 - 0.347 m_a^2 b^2)}{\frac{1}{b} + \frac{q_1 q_2 m_a^2 b^2}{8\pi M_p L^2}} - \frac{4M}{b}$$

$$\Delta T_{axions} = \Bigg[4M\Big[\ln\Big(\frac{4 r_e r_v}{r_0^2}\Big) + 1\Big] + 2b_0 c_0(-1 + c_0 M)(r_e + r_v) + \frac{b_0 c_0^2}{2}(r_e^2 + r_v^2) + 2b_0 - 4c_0 M b_0 + 2a_0(r_e + r_v) + \frac{b_0}{24}(48 + 36 c_0^2 r_0^2)[Ei(-c_0 r_e) + Ei(-c_0 r_v)]\Bigg] - 4M\Big[\ln\Big(\frac{4 r_e r_v}{r_0^2}\Big) + 1\Big]$$



If ALPs are FDM, they do not couple with quarks.

Experiments	axion decay constant (f_a)	α
Light bending	$\lesssim 1.58 \times 10^{10}\mathrm{GeV}$	$\lesssim 10^{-2}$
Shapiro time delay	$\lesssim 9.85 \times 10^{6}\mathrm{GeV}$	$\lesssim 4.12 \times 10^{-9}$

Discussions

- The precision measurements of GW and other astrophysical experiments demands a possibility of radiation of light particles like axions, gauge bosons etc.

- One can probe $U(1)_{L_i - L_j}$ from those above experiments.

- Physics of those light particles is interesting as it can be a possible dark matter candidate.

Thank You!