Testing Monopole-Dipole Interaction using Astrophysical Sources

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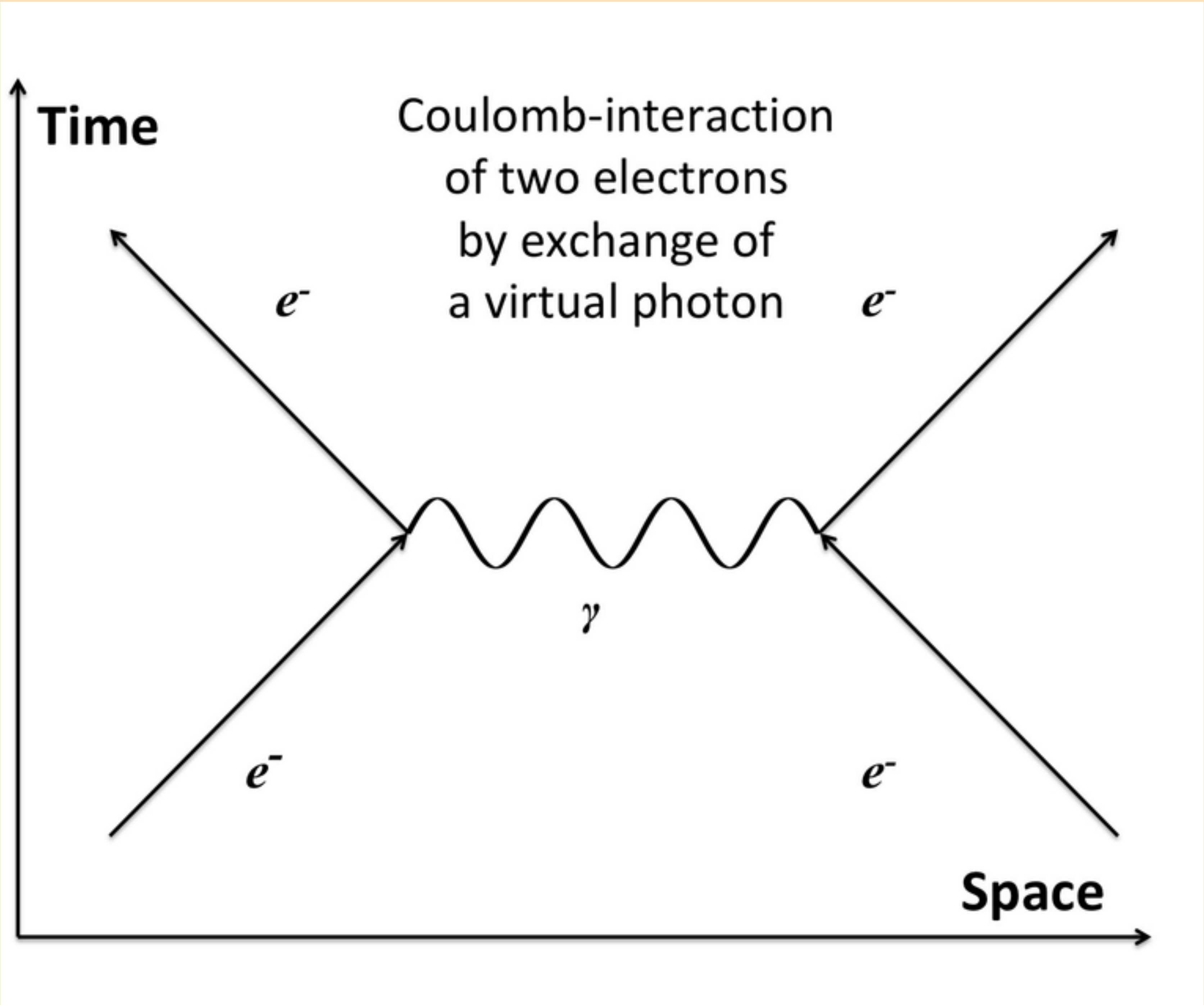
Introduction….

Potential from Interaction

$$\mathscr{L}_{int} = g\bar{\psi}\gamma^{\mu}\psi A_{\mu}$$



$$i\mathscr{M} = \left(\bar{u}_{s_1'}(p_1')(-i\,g_1)\gamma_{\mu}u_{s_1}(p_1)\right)\frac{-i}{q^2 - m_{\gamma}^2}\left(\bar{u}_{s_2'}(p_2')(-ig_2)\gamma^{\mu}u_{s_2}(p_2)\right)$$

NR Limit

$$u_s(p,m) = N\begin{pmatrix}\chi_s \\ \frac{\sigma\cdot\mathbf{p}}{\mathbf{2m}}\chi_s\end{pmatrix}$$

$$\bar{u}_{s_1'}(p_1')\gamma_{\mu}u_{s_1}(p_1) \rightarrow \chi_{s_1}^{\dagger}\chi_{s_1'} \rightarrow \delta_{s_1\,s_1'}$$

$$V(\mathbf{x}) = -\int\frac{d^3\mathbf{q}}{(2\pi)^3}e^{i\mathbf{q}\cdot\mathbf{x}}\,\mathscr{M} \quad \Longrightarrow \quad V(r) = \frac{g_1g_2}{4\pi\,r}e^{-m_{\gamma}r}$$

$$\text{Range} \sim \frac{1}{m_{\gamma}}$$

Axions and ALPs

- Standard model extensions are flooded with new particles like scalars, pseudo-scalars, bosons, fermions etc.

- Axions or Axion Like Particles (ALPs) are pseudo scalars which gain much attention for its ability to address several SM limitations.

- Axions and ALPs have same characteristics like low mass and weak couplings with SM particles.

Potential Due to Axion Exchange

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$$\mathcal{L}_{int} = g_s\left(\bar{\psi}_1\psi_1\right)a + g_p\left(i\,\bar{\psi}_2\gamma^5\psi_2\right)a$$

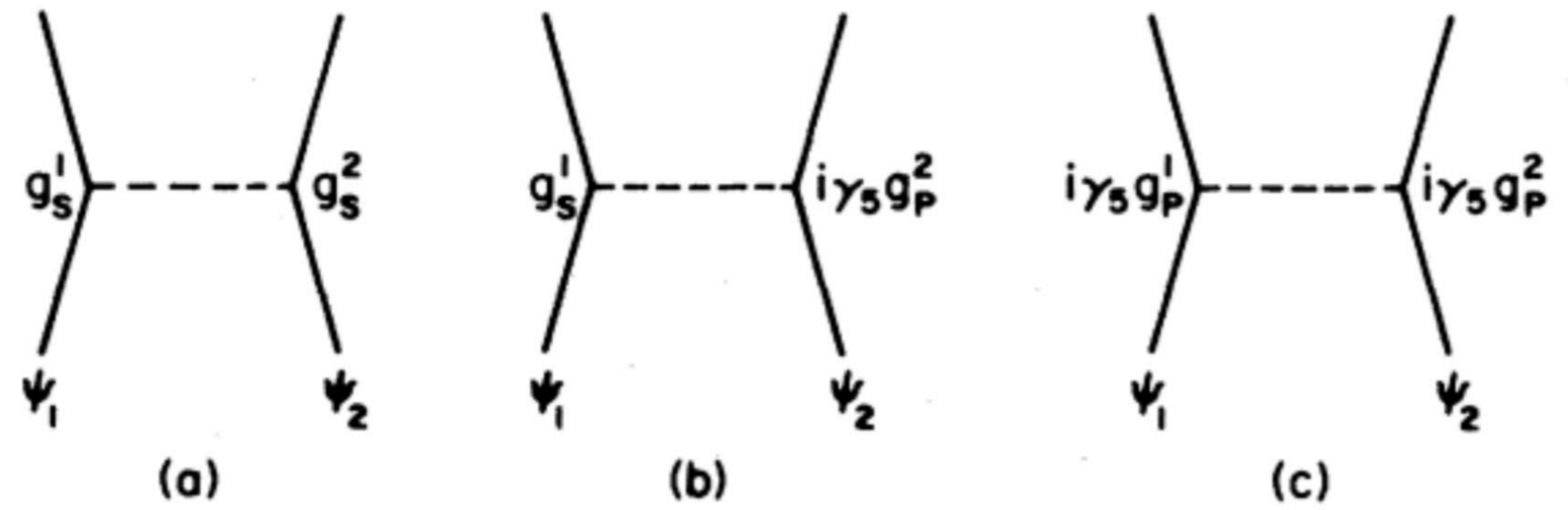

FIG. 1. Graphs for the potentials of Eqs. (4), (5), and (6). (a) (Monopole),[2] (b) monopole-dipole, (c) (dipole).[2]

$$V_{m-m} = -\frac{g_S^2}{4\pi}\frac{e^{-m_\phi r}}{r}$$

$$V_{d-d} = \frac{g_P^2}{4\pi m_{\psi_2}^2}\left(s_1\cdot\nabla\right)\left(s_2\cdot\nabla\right)\left(\frac{e^{-m_\phi r}}{r}\right)$$

P and T conserving

$$V_{m-d} = \frac{g_S\,g_P}{4\pi\,m_{\psi_2}}\left(s_2\cdot\hat{r}\right)\left(\frac{m_\phi}{r}+\frac{1}{r^2}\right)e^{-m_\phi r}$$

P and T violating

$$V_{m-d} = \frac{g_S\, g_P}{4\pi\, m_{\psi_2}} \left(s_2 \cdot \hat{r}\right) \left(\frac{m_\phi}{r} + \frac{1}{r^2}\right) e^{-m_\phi r}$$

- P and CP violating potential

- Need at least one polarised source to measure

- Only lab experiments available for the measurement of $g_S\, g_P$

- No Astrophysical bounds : as the sources are considered unpolarised

Cornering the axion with *CP*-violating interactions

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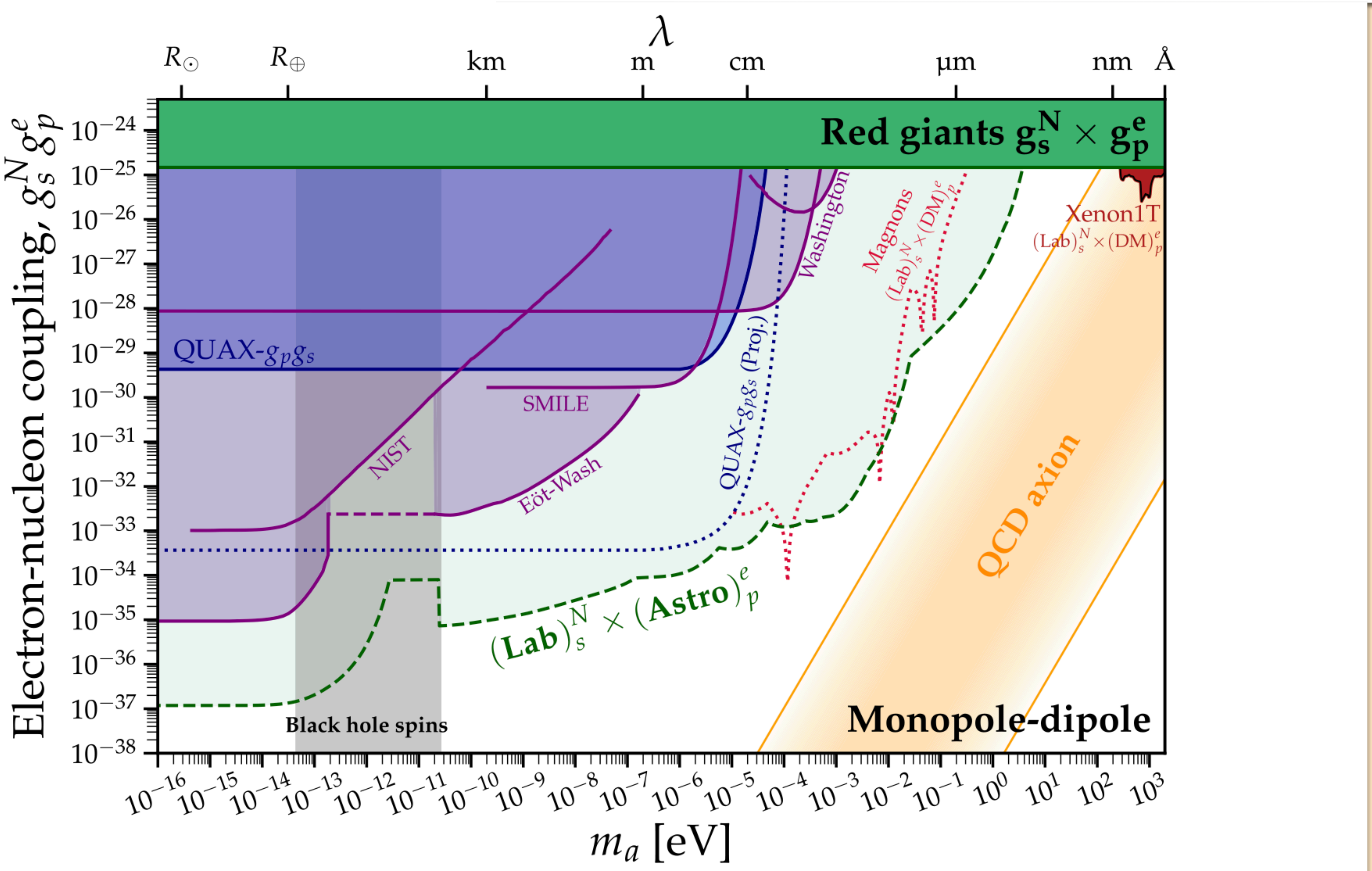

- Hybrid bounds
- g_S and g_P obtained from two different Observations

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Using the Earth as a Polarized Electron Source to Search for Long-Range Spin-Spin Interactions

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Spherically symmetric Earth models yield no net electron spin

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(Dated: November 14, 2024)

Terrestrial experiments that use electrons in Earth as a spin-polarized source have been demonstrated to provide strong bounds on exotic long-range spin-spin and spin-velocity interactions. These bounds constrain the coupling strength of many proposed ultralight bosonic dark-matter candidates. Recently, it was pointed out that a monopole-dipole coupling between the Sun and the spin-polarized electrons of Earth would result in a modification of the precession of the perihelion of Earth. Using an estimate for the net spin-polarization of Earth and experimental bounds on Earth's perihelion precession, interesting constraints were placed on the magnitude of this monopole-dipole coupling. Here we investigate the spin associated with Earth's electrons. We find that there are about 6×10^{41} spin-polarized electrons in the mantle and crust of Earth oriented anti-parallel to their local magnetic field. However, when integrated over any spherically-symmetric Earth model, we find that the vector sum of these spins is zero. In order to establish a lower bound on the magnitude of the net spin along Earth's rotation axis we have investigated three of the largest breakdowns of Earth's spherical symmetry: the large low shear-velocity provinces of the mantle, the crustal composition, and the oblate spheroid of Earth. From these investigations we conclude that there are at least 5×10^{38} spin-polarized electrons aligned anti-parallel to Earth's rotation axis. This analysis suggests that the bounds on the monopole-dipole coupling that were extracted from Earth's perihelion precession need to be relaxed by a factor of about 2000.

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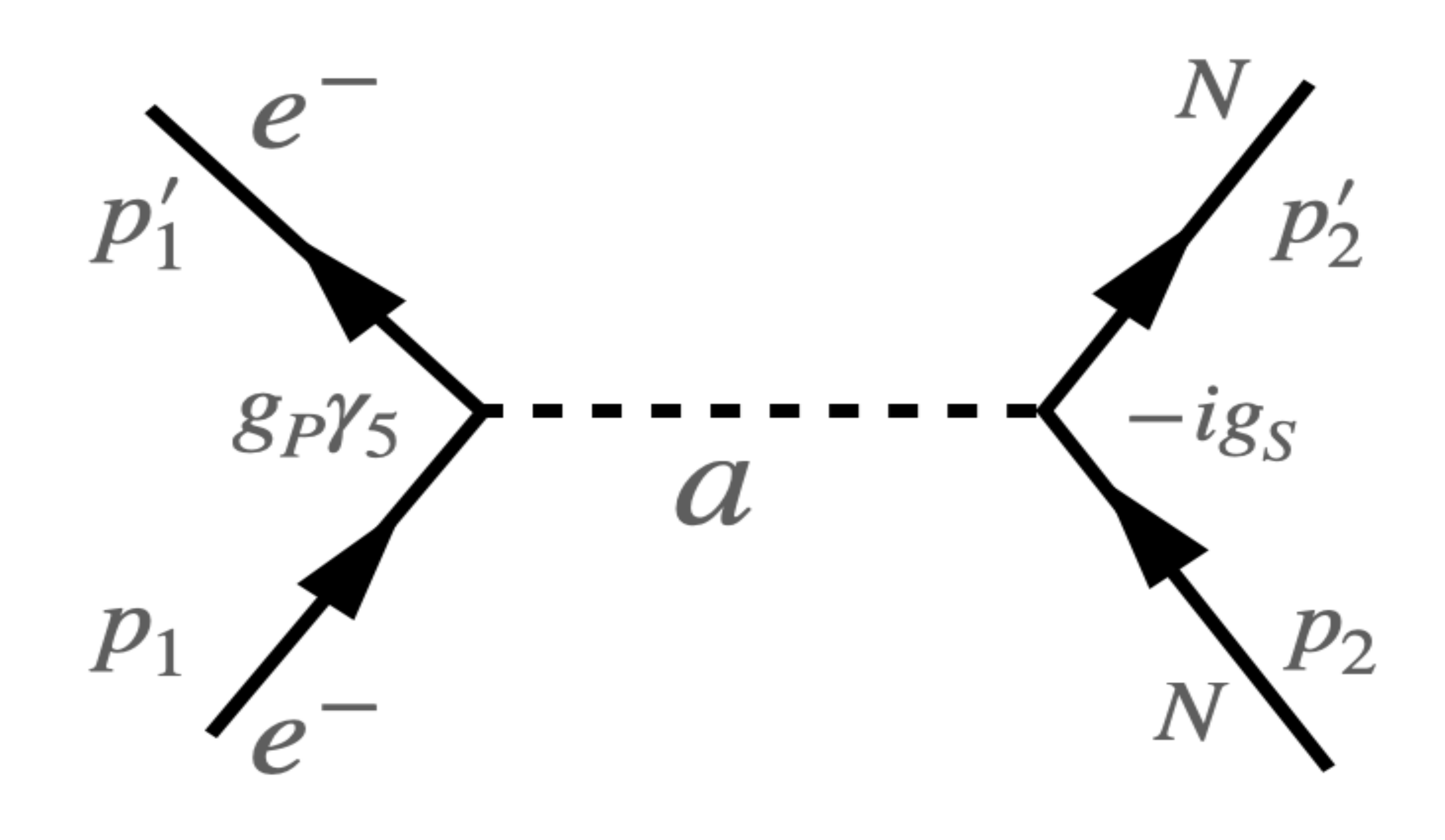
Earth as a spin polarised source ...



- Used the Earth as a spin polarised source
- There are almost 10^{42} electrons are polarised inside the Earth due its magnetic field antiparallel to its rotation axis
- When intergrated over a spherical volume, net spin is zero
- In reality, Earth is not a sphere (oblate spheroid)
- For a non-spherical Earth, at least $\sim 10^{39}$ electrons remain polarised antiparallel to the Earth's rotation axis

Perihelion precession due to the V_{m-d}

$$V_{\rm eff} = -GMu + \frac{L^2u^2}{2}(1-2GMu) - \frac{\beta m_a u}{M_P} e^{-\frac{m_a}{u}} - \frac{\beta u^2}{M_P} e^{-\frac{m_a}{u}} \qquad \beta = \frac{g_S g_P N_e N_n}{4\pi m_e}$$

$$\frac{d^2u}{d\phi^2} + u = \frac{GM}{L^2} + 3GMu^2 + \frac{2\beta u}{L^2 M_P} - \frac{\beta m_a^3}{3L^2 M_P u^2}$$

$$u(\phi) = \frac{GM}{L^2}\left(1 + \varepsilon\cos\left[(1-\alpha')\phi\right]\right)$$

$$\Delta\phi = 2\pi\alpha' = \frac{6\pi GM}{a(1-\varepsilon^2)} + \frac{g_S g_P N_e N_n}{2GMa(1-\varepsilon^2)M_P m_e} + \frac{g_S g_P N_e N_n\, a^2 m_a^3 (1-\varepsilon^2)}{6M_P GM(1+\varepsilon)m_e} + \mathcal{O}\left(\left(g_s g_p\right)^2, m_a^4\right)$$

Difference from GR:

$$\Delta\phi' = \frac{g_S g_P N_e N_n}{2GMa(1-\varepsilon^2)M_P m_e} + \frac{g_S g_P N_e N_n\, a^2 m_a^3 (1-\varepsilon^2)}{6M_P GM(1+\varepsilon)m_e} \lesssim 10^{-4}\text{arcsecond/century}$$

Light Bending due to V_{m-d}

$$V_{\text{eff}} = \frac{L^2u^2}{2}(1-2GMu) - \frac{\beta m_a u}{M_P} e^{-\frac{m_a}{u}} - \frac{\beta u^2}{M_P} e^{-\frac{m_a}{u}} \qquad \beta = \frac{g_S\, g_P\, N_e\, N_n}{4\,\pi\, m_e}$$

$$u(\phi) = \frac{\sin\phi}{b} + \frac{3GM}{2b^2}\left(1 + \frac{1}{3}\cos 2\phi\right) - \frac{\beta\phi\cos\phi}{M_P L^2 b} - \frac{\beta m_a^3 b^2}{3M_P L^2}\left[\cos\phi \ln|\csc\phi + \cot\phi| - 1\right].$$

$$\Delta\phi = \frac{\dfrac{4GM}{b^2} - \dfrac{2\beta m_a^3 b^2}{3M_P L^2}\ln 2}{\dfrac{1}{b} - \dfrac{\beta}{M_P L^2 b} + \dfrac{\beta m_a^3 b^2}{3M_P L^2}}$$

$$\Delta\phi' = \frac{\beta}{M_P L^2} \times \left(\frac{4GM}{b}\right) - \frac{\beta\, m_a^3\, b^3}{3M_p\, L^2} \times \left(\frac{4GM}{b}\right) - \frac{2\,\beta\, m_a^3\, b^3}{3M_p\, L^2}\ln 2 \lesssim 10^{-4}\text{arcsecond}$$

Shapiro Time Delay due to V_{m-d}

- Trajectory of light

$$\frac{E^2}{2} = \frac{E^2}{2\left(1-\frac{2GM}{r}\right)^2}\left(\frac{dr}{dt}\right)^2 + \frac{L^2}{2r^2}\left(1-\frac{2GM}{r}\right) - \frac{\beta m_a}{M_P r}e^{-m_a r} - \frac{\beta}{r^2 G M_P}e^{-m_a r}$$

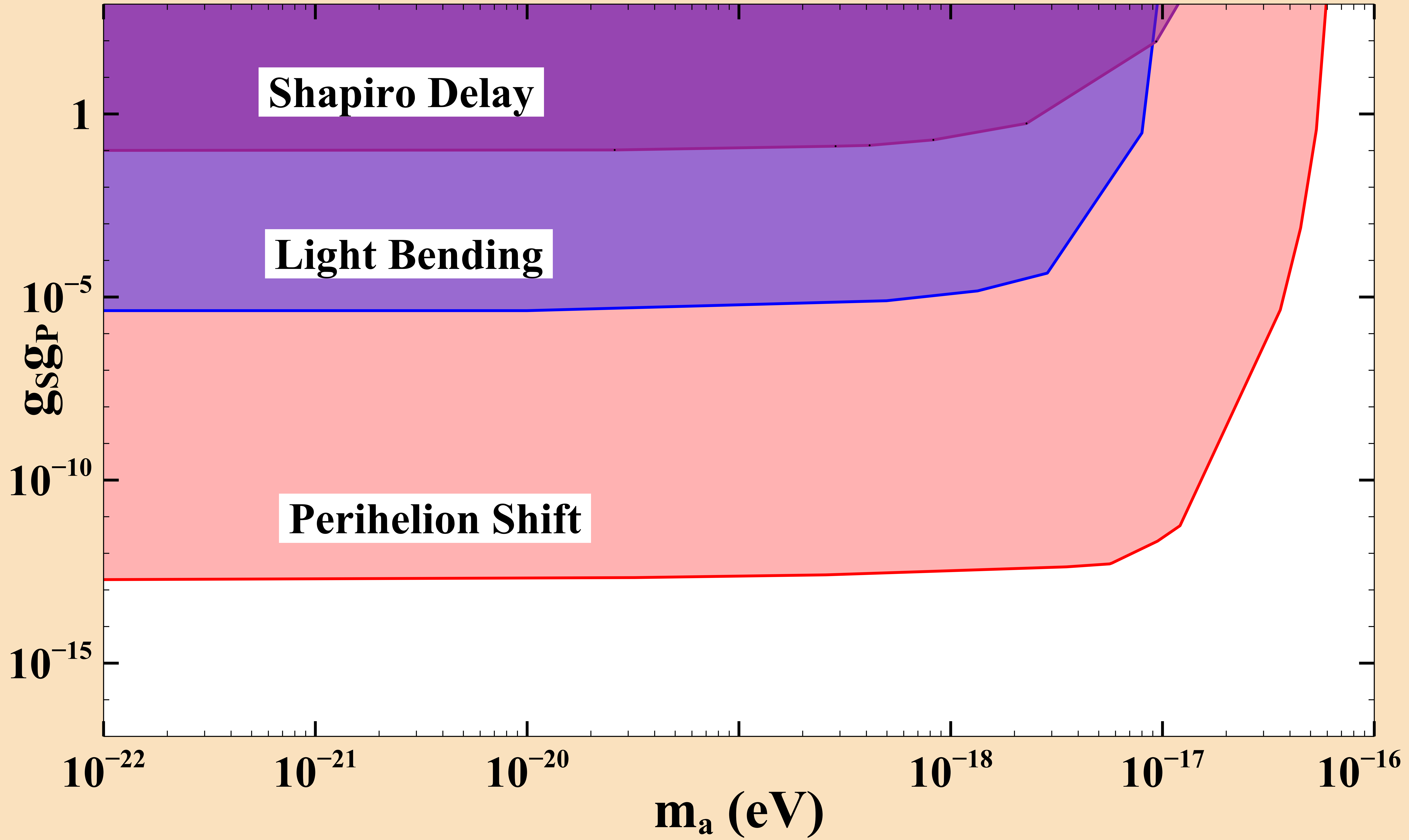
$$\eta = \frac{2\beta}{M_P r_0 E^2}\left(m_a + \frac{1}{r_0}\right)e^{-m_a r_0}$$

$$t = \int_{r_0}^{r}\frac{dt}{dr}dr = \int_{r_0}^{r} dr \frac{1}{\left(1-\frac{2GM}{r}\right)}\left[1 - \frac{r_0^2}{r^2}\frac{\left(1-\frac{2GM}{r}\right)}{\left(1-\frac{2GM}{r_0}\right)}(1+\eta) + \frac{2\beta}{M_P r E^2}\left(m_a + \frac{1}{r}\right)e^{-m_a r}\right]^{-\frac{1}{2}}$$

$$\Delta T = 4M\left[1 + \ln\left(\frac{4r_e r_v}{r_0^2}\right)\right] - \frac{4GM}{M_P E^2 r_0^2}\left(\frac{g_S g_P N_e N_n}{4\pi m_e}\right) + \frac{8GM}{M_P r_0 E^2}\left(m_a + \frac{1}{r_0}\right)e^{-m_a r_0}\left(\frac{g_S g_P N_e N_n}{4\pi m_e}\right)$$

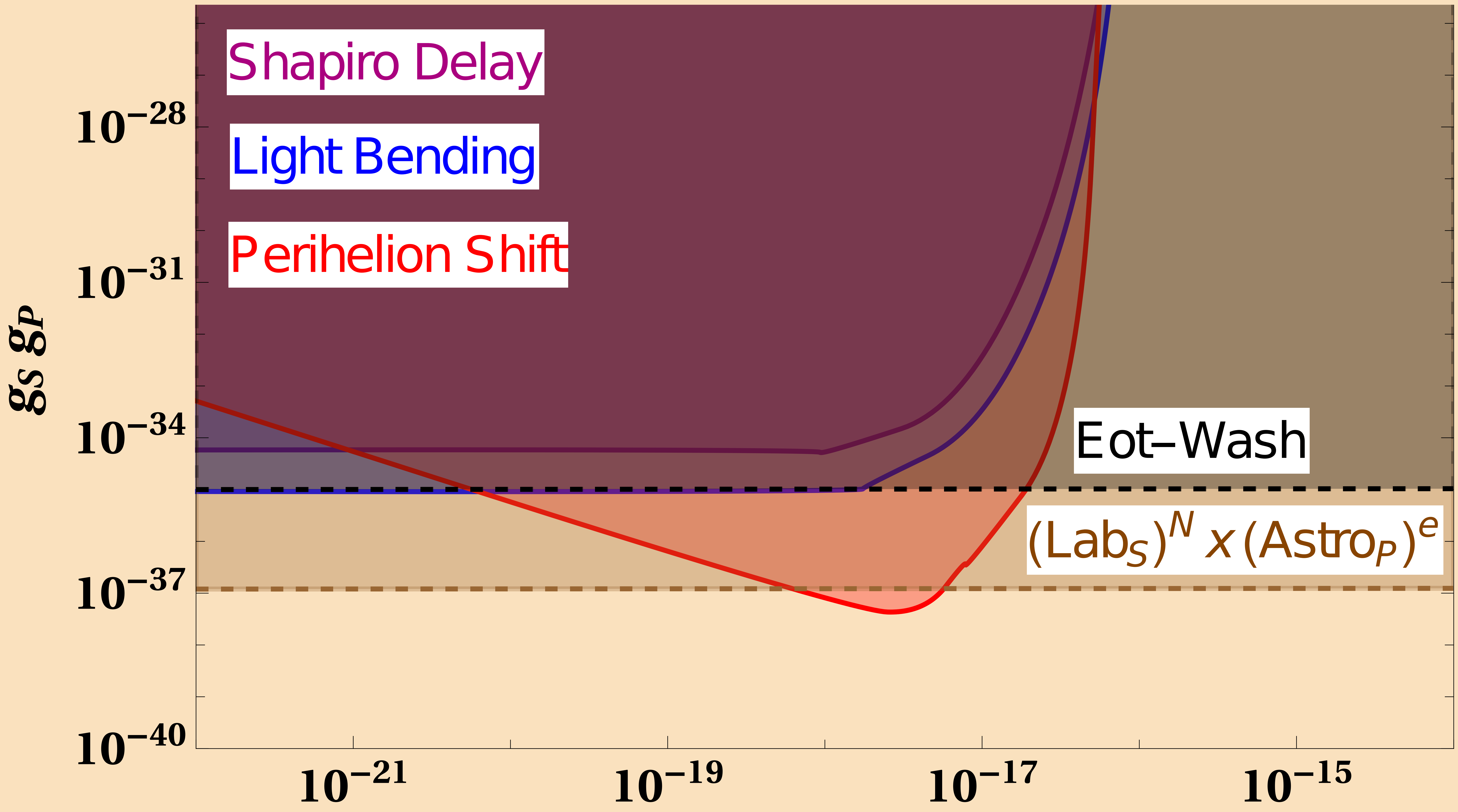
$$\Delta T' = \frac{8GM}{M_P r_0 E^2}\left(m_a + \frac{1}{r_0}\right)e^{-m_a r_0}\left(\frac{g_S g_P N_e N_n}{4\pi m_e}\right) - \frac{4GM}{M_P E^2 r_0^2}\left(\frac{g_S g_P N_e N_n}{4\pi m_e}\right) \lesssim 10^{-5} \text{ second}$$

RESULTS



Bounds on monopole-dipole interaction strength from single astrophysical observation

RESULTS



Bounds on monopole-dipole interaction strength from two different astrophysical observations

Conclusion

- It is the first attempt to study $g_S\, g_P$ from a single Astrophysical Observation

- Perihelion precession gives the strongest bound on $g_S\, g_P$ as

$$g_S\, g_P \lesssim 1.75 \times 10^{-13} \quad \text{for} \quad m_a \lesssim 10^{-18}\, eV$$

- In the case of hybrid bound, obtained $g_S\, g_P$ gives three order magnitude strong bound $\left(5.61 \times 10^{-38}\right)$ than the proposed Eöt-Wash experiment and one magnitude stronger than current hybrid bound.

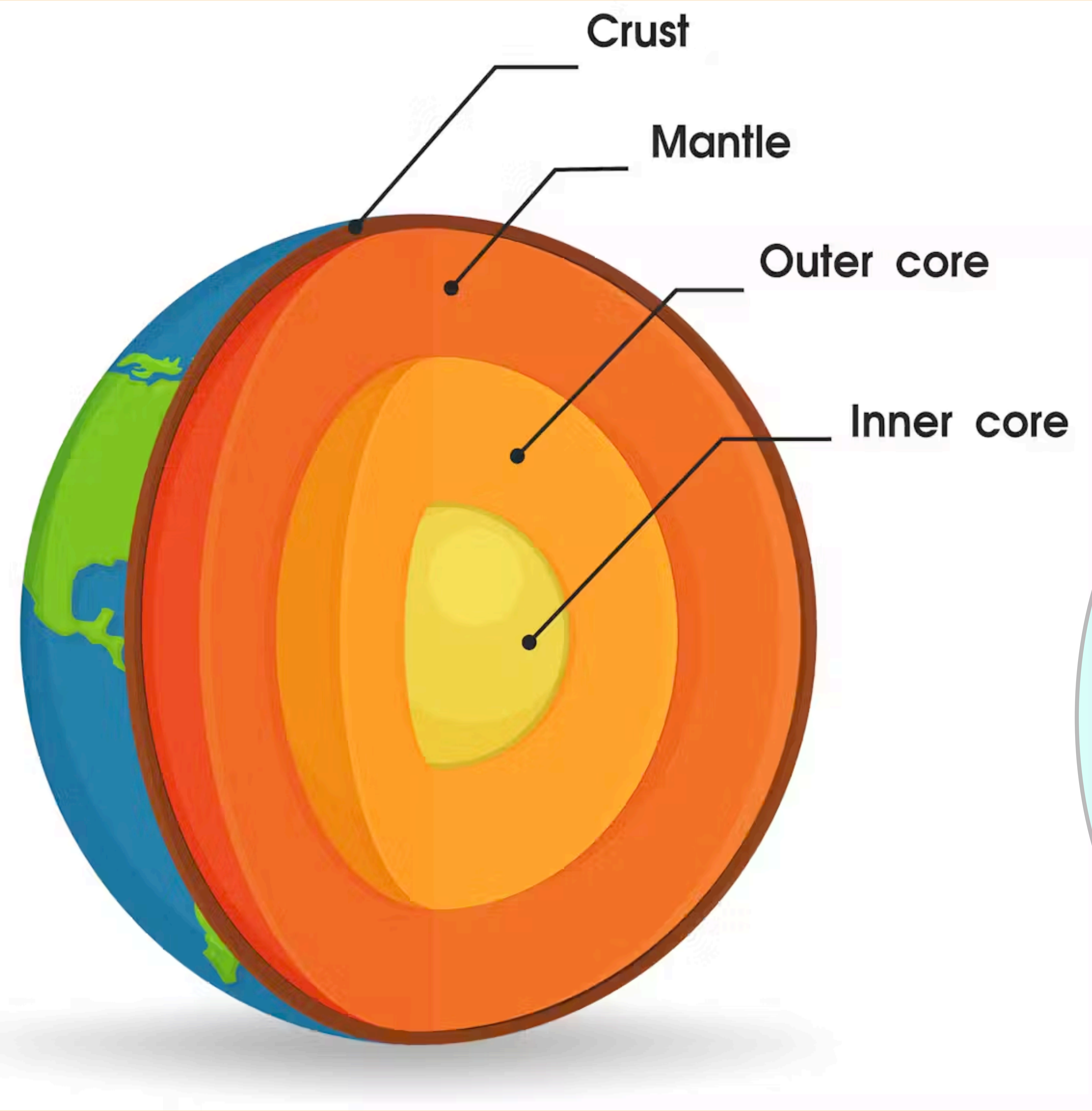
- Only order of magnitude calculations considered.

- The bounds can be significantly improved or relaxed by accurate incorporation of the number of polarized spins at each layer of Earth from geochemical and geological surveys.

THANK YOU 🙏

BACK UP SLIDES

Axions	ALPs
• Axions ⟼ proposed for "Strong CP Problem" (Absence of observable CP Violation in Strong Int.)	• ALPs arises in several BSM (String theories) to address DM,DE etc
• Low mass, $\mu eV \lesssim m_a \lesssim meV$	• Masses can vary over a wide range, model dependent
• $m_a \propto \frac{1}{f_a^2}$ $m_a \rightarrow$ Mass of axion , $f_a \rightarrow$ Symmetry breaking scale	• Mass and symmetry breaking scale is independent



Compositions:

Core:

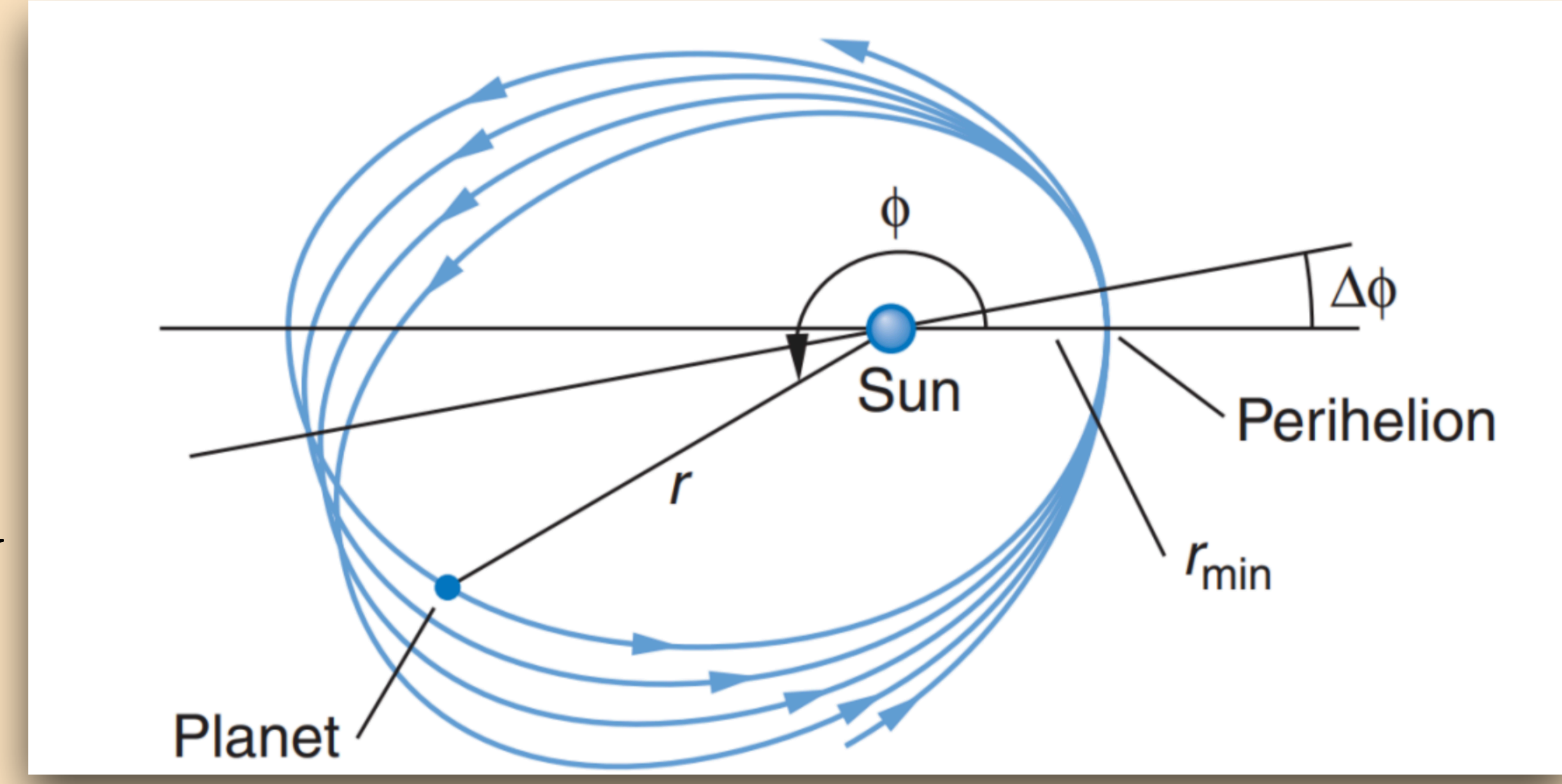
- Fe-Ni alloy
- No magnetization

- Fe with partially filled d shell in oxides and silicates
- Fe dominates the paramagnetism
- Other elements e.g. Al, Mg, Si

Mantle, crust:

Perihelion Precession of Earth

- A slight change in the perihelion position observed after it revolves around the Sun



- For Mercury, $\Delta\phi = 42.999$ arcs/century is observed which can't be explained by classical newtonian gravity

- The discrepancy can be explained by GR

$$M_P\left(\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau}\right) = 0$$

$$g_{\mu\nu} = \left\{1 - \frac{2GM}{r}, \left(1 - \frac{2GM}{r}\right)^{-1}, r^2, r^2 \sin^2\theta\right\}$$

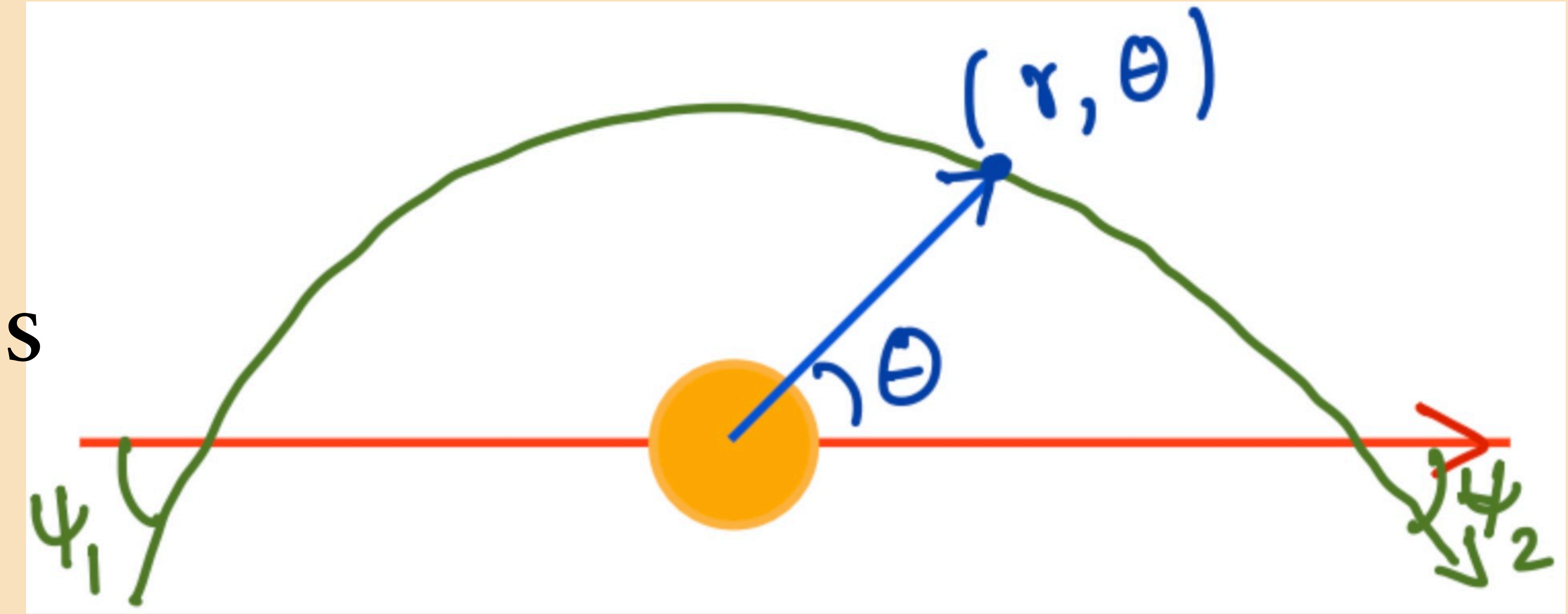
$$u(\phi) = \frac{GM}{L^2}\left(1 + \varepsilon \cos\left[(1-\alpha)\phi\right]\right)$$

$$\Delta\phi = 2\pi\alpha = \frac{6\pi GM}{a(1-\varepsilon^2)}$$

ε is eccentricity of the orbit

- $\Delta\phi \approx 43.03''/century$ is predicted by GR

Gravitational Light Bending



- massive objects distort the space time
- Increase gravitational potential due to the Mass
- Reduces speed of light and it bends

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0$$ (Null geodesic)

$$g_{\mu\nu}dx^\mu dx^\nu = 0$$ (Light-like)

$$\frac{1}{2}\left(\frac{dr}{d\lambda}\right)^2 + V_{eff} = E$$

$$V_{eff} = \frac{L^2}{2\,r^2}\left(1 - \frac{2GM}{r}\right)$$

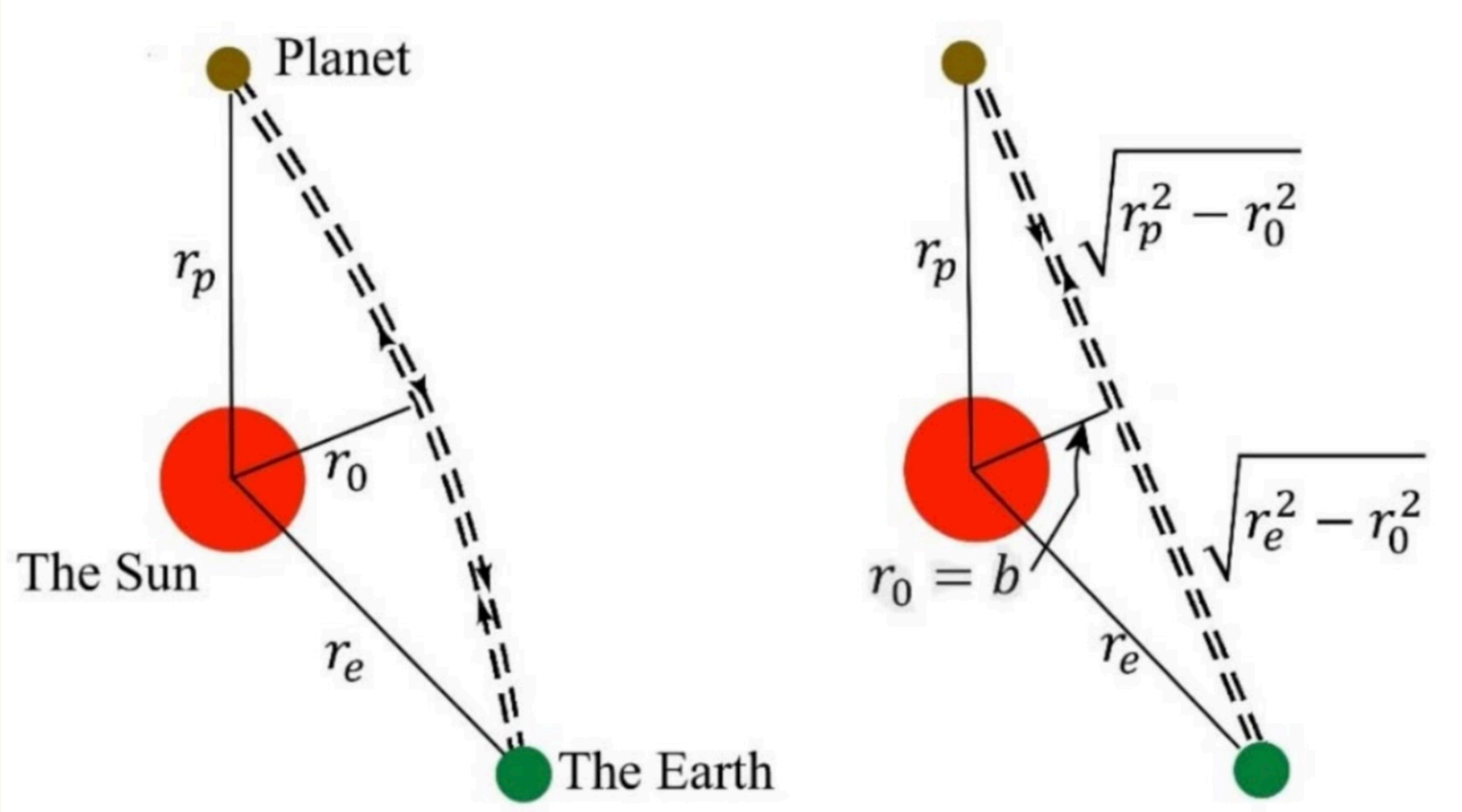
$$u(\theta) = \frac{\sin\theta}{b} + \frac{2GM}{b^2} - \frac{GM\sin^2\theta}{b^2}$$

$r \to -\infty, \quad \theta \approx -\psi_1$ and $\quad r \to +\infty, \quad \theta \approx \pi + \psi$

$$\Delta\phi = \psi_1 + \psi_2 = \frac{4GM}{b}$$

Shapiro Time Delay

$$t_N = \sqrt{r_p^2 - r_0^2} + \sqrt{r_e^2 - r_0^2}$$



- In GR, $g_{\mu\nu} dx^\mu dx^\nu = 0$

$$\left(\frac{dr}{dt}\right) = \sqrt{1 - \left(\frac{r_0}{r}\right)^2 \frac{1 - \frac{2GM}{r}}{1 - \frac{2GM}{r_0}}} \left(1 - \frac{2GM}{r}\right)$$

$$t = \int_r^{r_0} dr \left(1 - \frac{2GM}{r}\right)^{-1} \left[1 - \frac{r_0^2}{r^2} \frac{1 - \frac{2GM}{r}}{1 - \frac{2GM}{r_0}}\right]^{-1/2}$$

- $M \to 0, \quad t = t_{cl}$ and $M \neq 0, \quad t = t_{GR}$
- $\Delta t = t_{GR} - t_{cl} = 4GM\left(1 + \frac{r_e r_v}{r_0^2}\right)$

- $\Delta t_{me} \approx 200\,\mu s$
- $\Delta t_{th} \approx 246\,\mu s$

- For large m_a, $exp\left(-\frac{m_a L^2}{GM}\right)$ is multiplied to incorporate large mass suppression