# Astrophysical searches of ultralight particles

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1) PRD 100 (2019)12, 123023 2) PRD 101 (2020)8, 083007

3) EPJC 81 (2021) 4, 286 4) JCAP 09 (2021)041

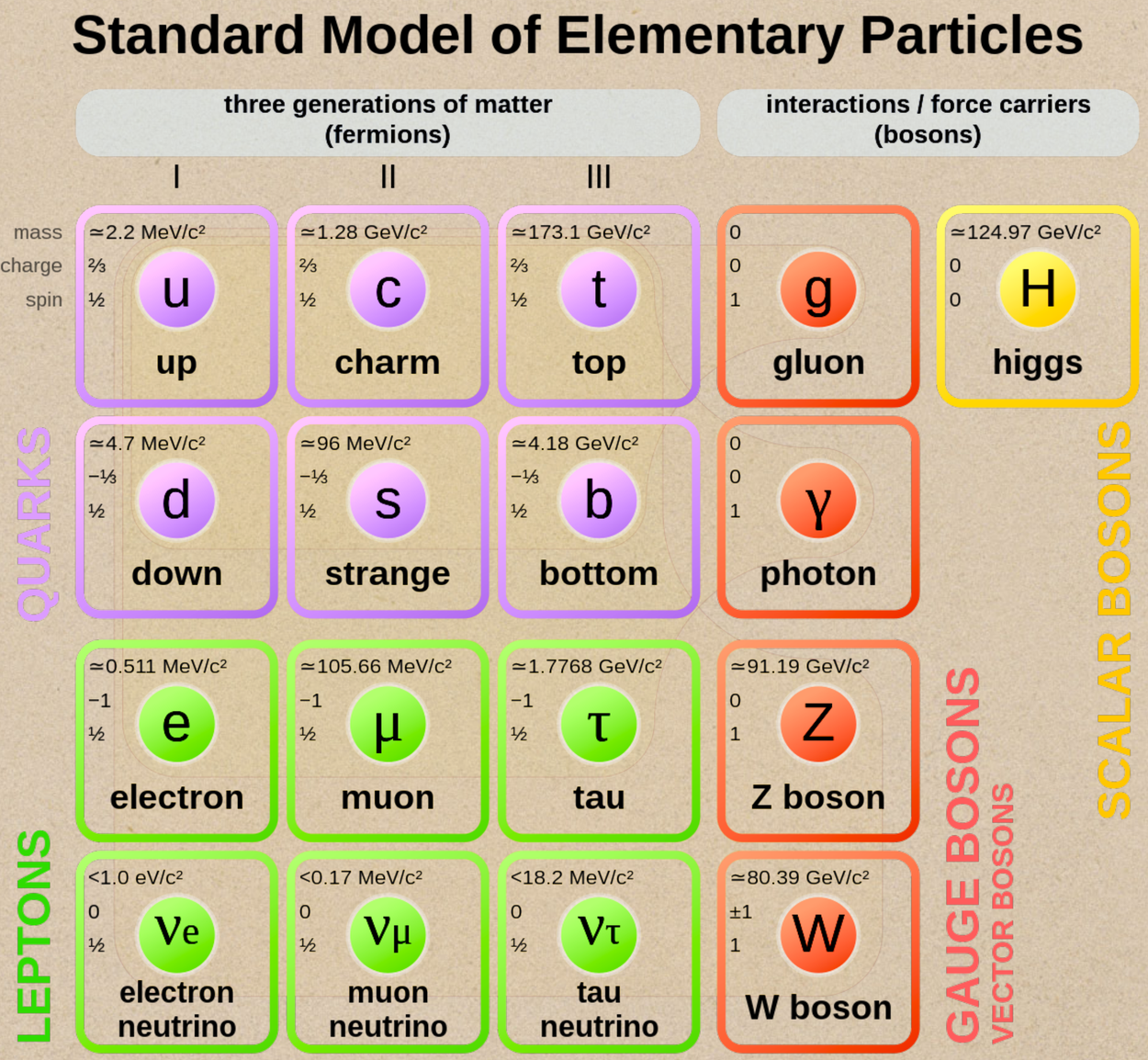
ICHEP 2022 BOLOGNA

ICHEP 2022, Bologna 08.07.2022

# Outline of the Talk

- Motivation
- Axions : A saviour of the strong CP problem, Dark Matter, and its Searches
  - Indirect evidence of gravitational waves
  - Gravitational light bending and Shapiro time delay
- Light Gauge Boson : Long Range Force, Dark Matter, and its Searches
  - Indirect evidence of gravitational waves
  - Perihelion precession of planets
- Summary and Conclusions

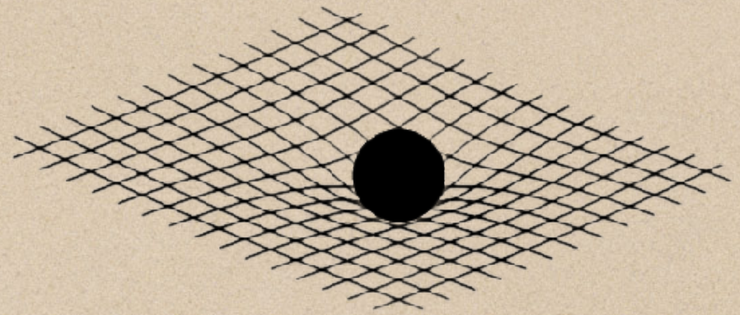
# Standard Model of Particle Physics and its Shortcomings




https://en.wikipedia.org/ wiki/ Standard_Model

- Neutrino mass
- Dark Matter
- Matter -Antimatter Asymmetry
- Strong CP Problem
- Hierarchy Problem
- Gravity etc.

# Einstein's General Relativity Theory and its Shortcomings



$$G_{\mu\nu}+\Lambda g_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$$

Curvature Tensor

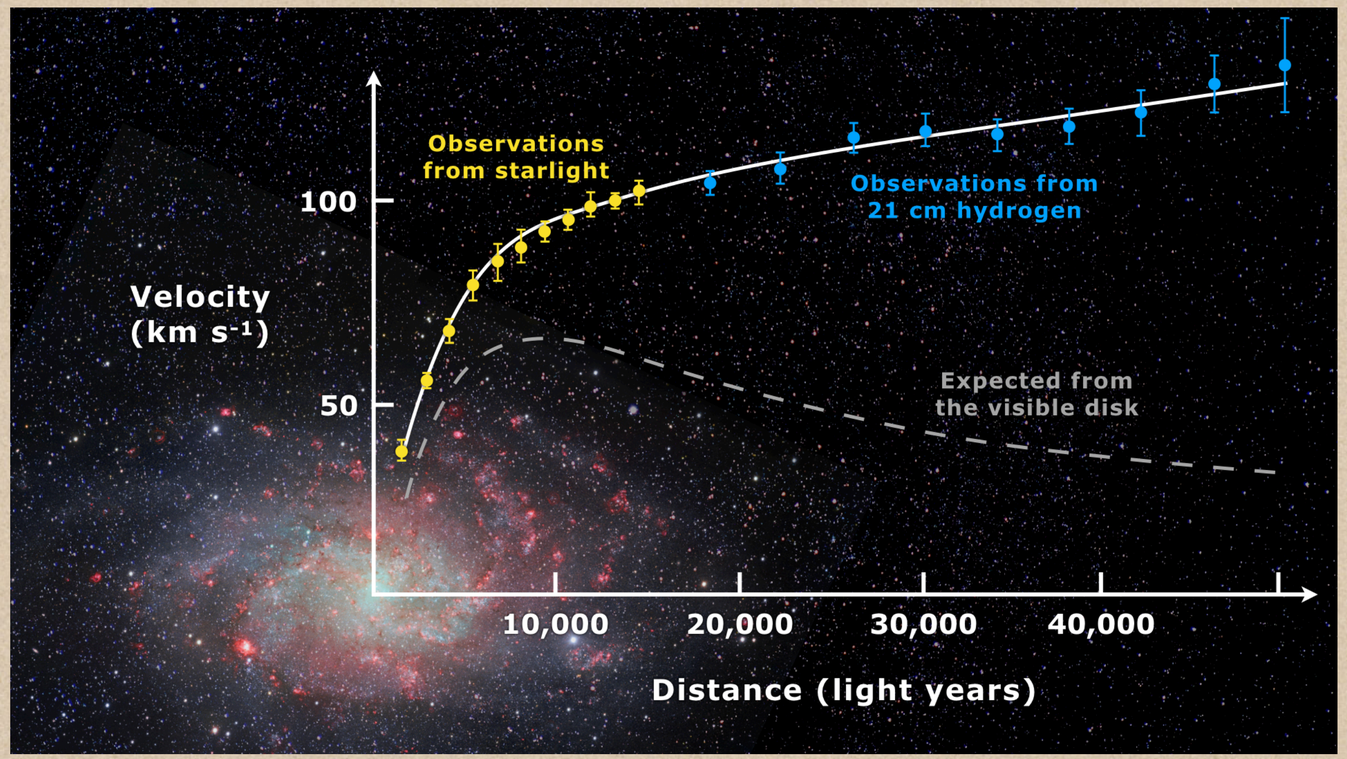
Cosmological Constant

Matter Energy Tensor

- Singularity Problem
- Dark Matter
- Dark Energy
- Classical Theory
- Massive Gravity
- Precision Measurements: Fifth Force

# Dark Matter: Why do we need it?

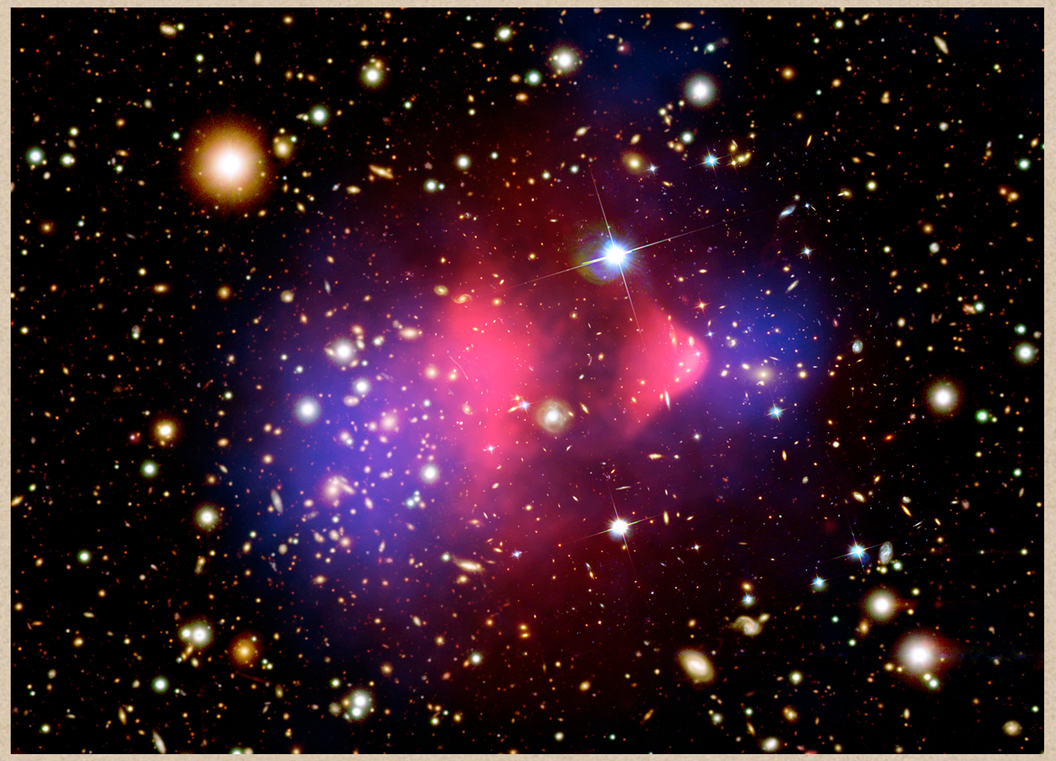
## Galactic Scale:




Galactic Rotation Curve of a Spiral Galaxy

https://en. wikipedia.org/wiki/Galaxy_rotation_curve

## Cluster Scale:

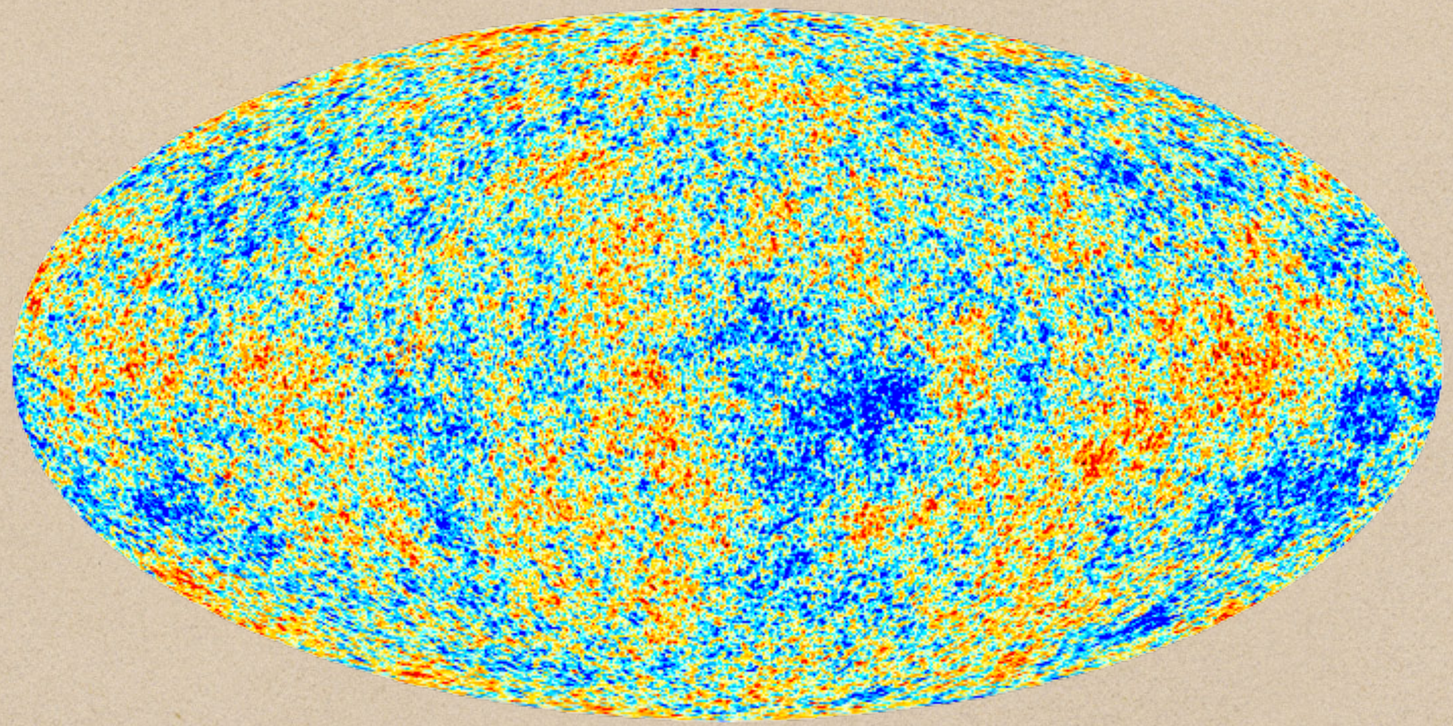


X-ray Map of Bullet Cluster

https://www.esa.int/ESA_ Multimedia/Images/2007/07/The_Bullet_Cluster2

Contd...

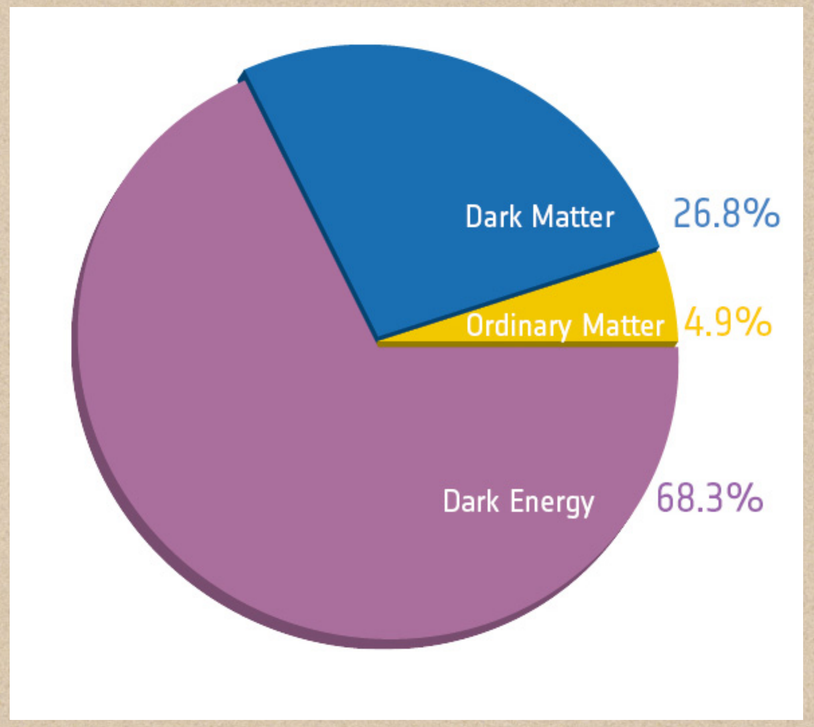
## Cosmological Scale:



CMB Map of the Universe

https://en.wikipedia.org/wiki/Cosmic_microwave_background

## Cosmic Pie:



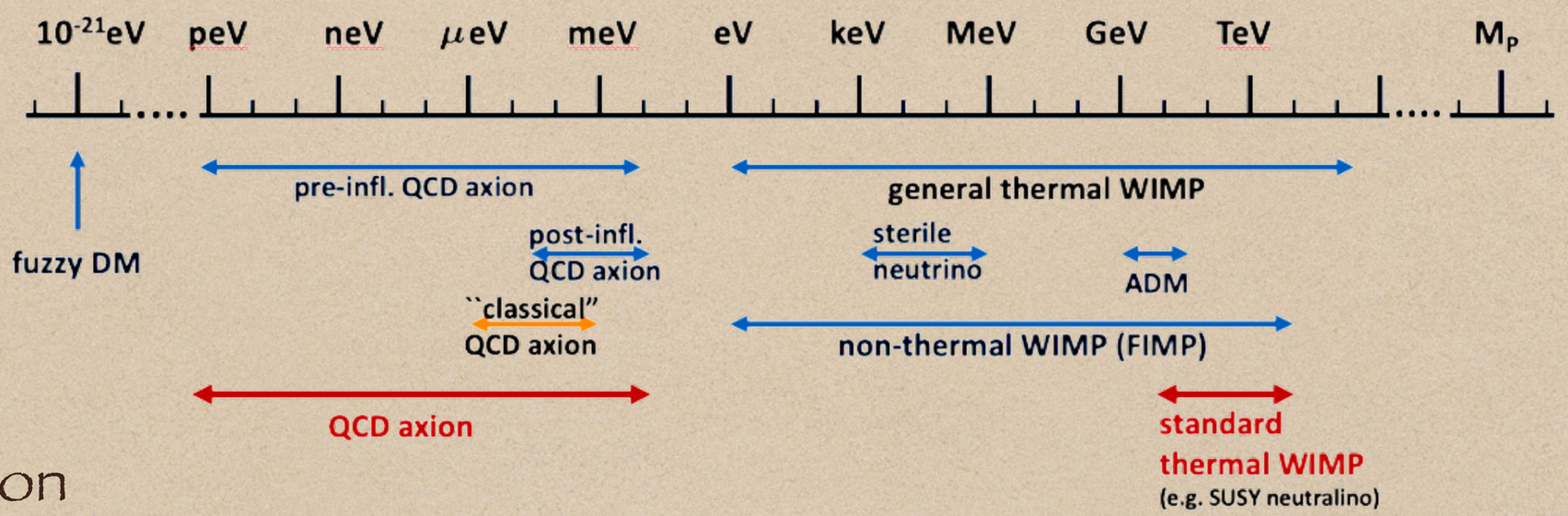

Present Energy density of the Universe

https://sci.esa.int/web/ planck/-/51557-planck-new-cosmic-recipe

Contd…

# Properties of Dark Matter

- Massive
- Non-relativistic
- Non-baryonic
- Non-luminous
- Only Gravitational Interaction




https://i.stack.imgur.com/CwcUo.png

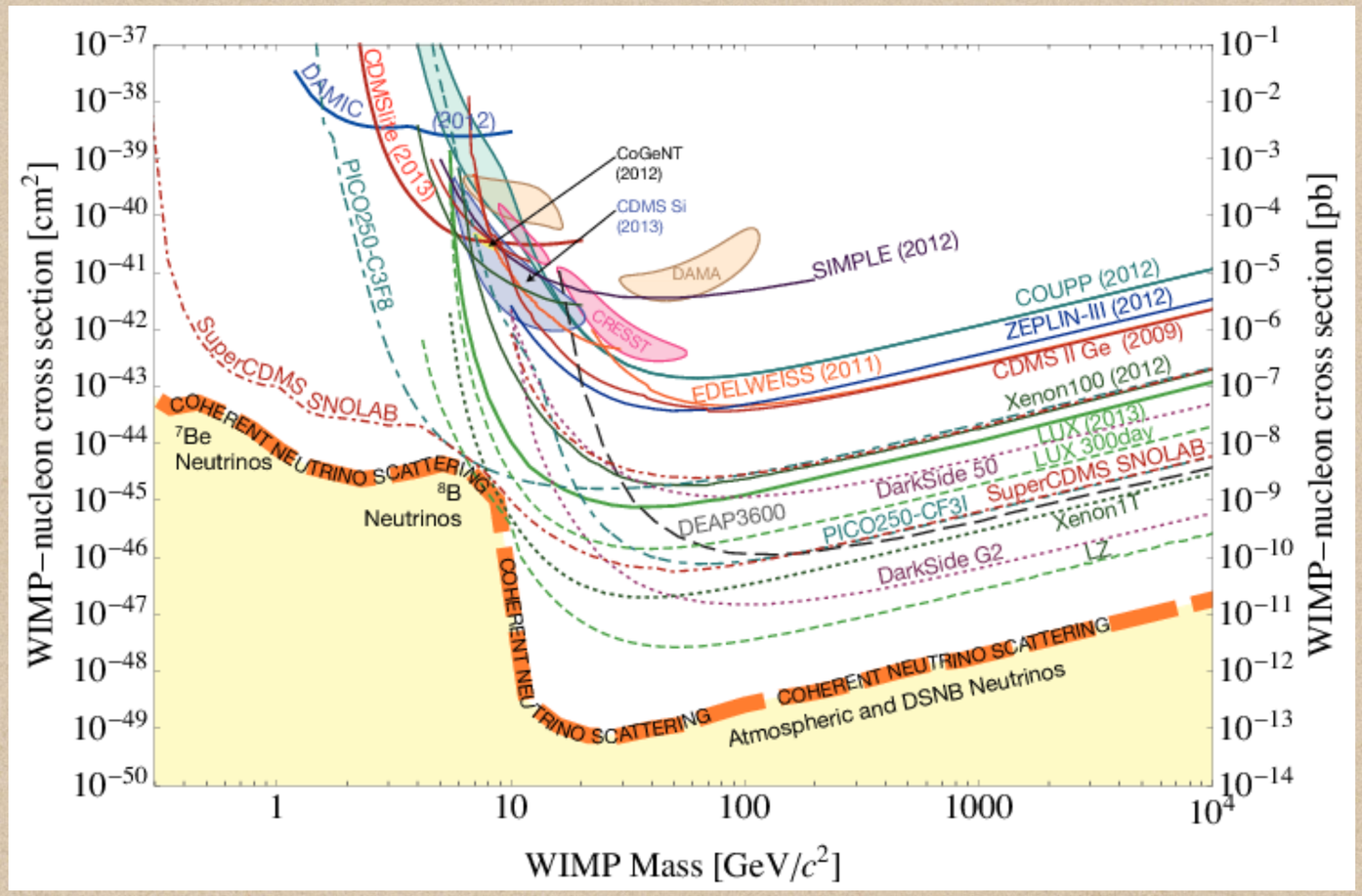
DM Models: WIMP, FIMP, SIMP, FDM, etc.

DM Candidates:

Axion, gauge bosons, sterile neutrino, graviton, primordial black hole, etc.

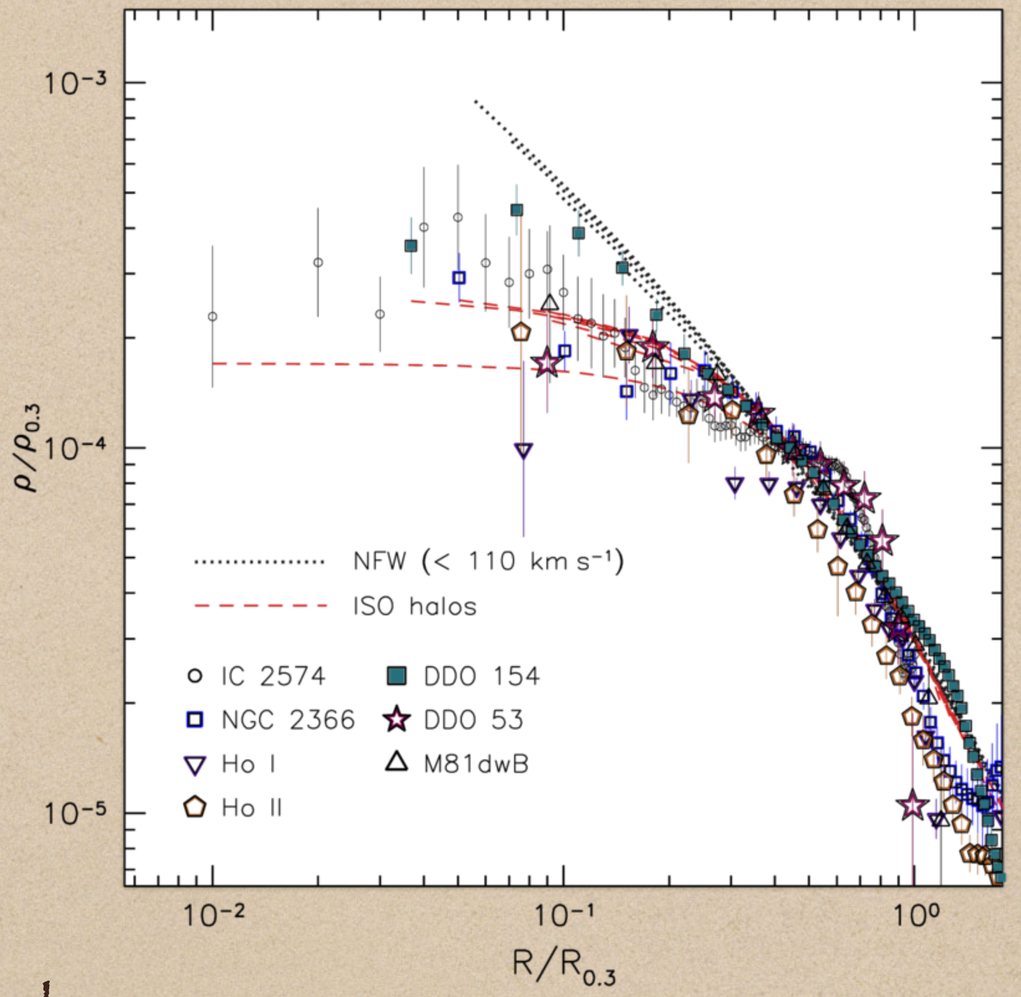
# Problems with WIMPs

- Strong Constraints from Direct Detections:




Phys. Dark. Univ 4 (92-97) 2014

- Small Scale Structure Problems:




Astron J 141 , 193 (2011)

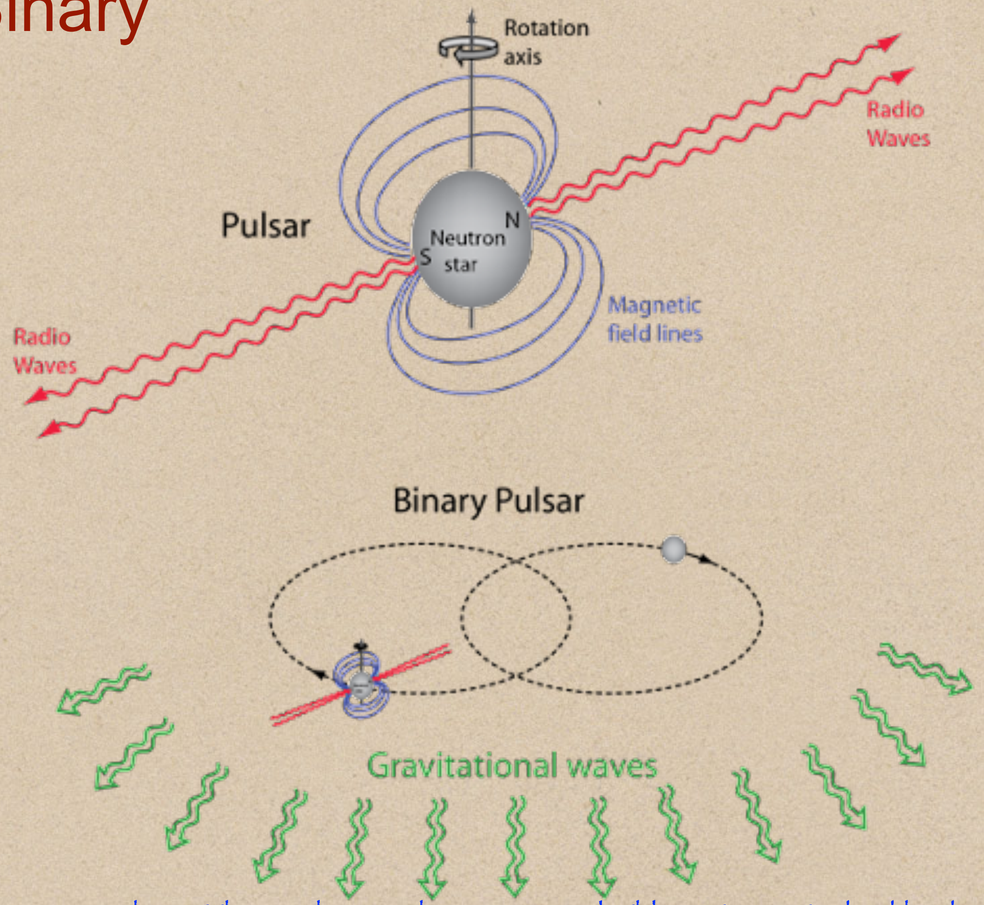
Motivation for studying FDM: Axions, light gauge bosons

# Astrophysical observations to probe ultralight particles

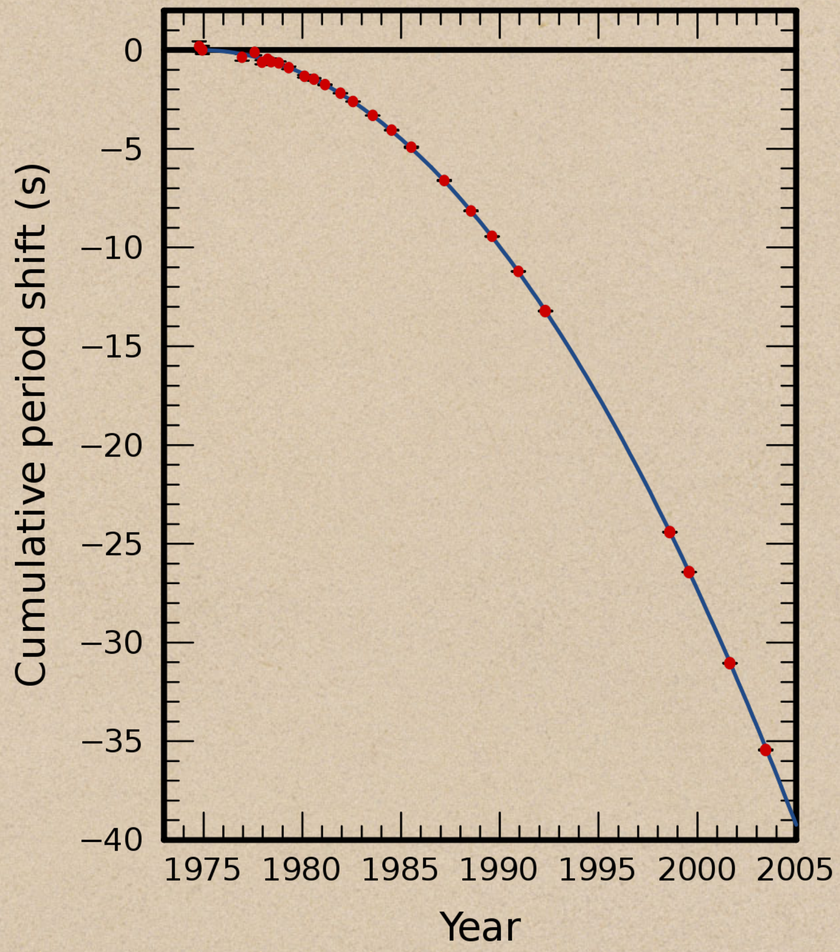
- Orbital period loss of binary systems
- Gravitational light bending
- Shapiro time delay
- Perihelion precession of planets

# Indirect Detection of gravitational Waves

## Hulse -Taylor Binary




http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/pulsrel.html




https://en.wikipedia.org/wiki/Hulse%E2%80%93Taylor_binary

## Detection

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

# Quadrupole formula for GW radiation

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

Peters and Mathews (1963)

The energy loss of a Keplerian orbit for arbitrary eccentricity

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

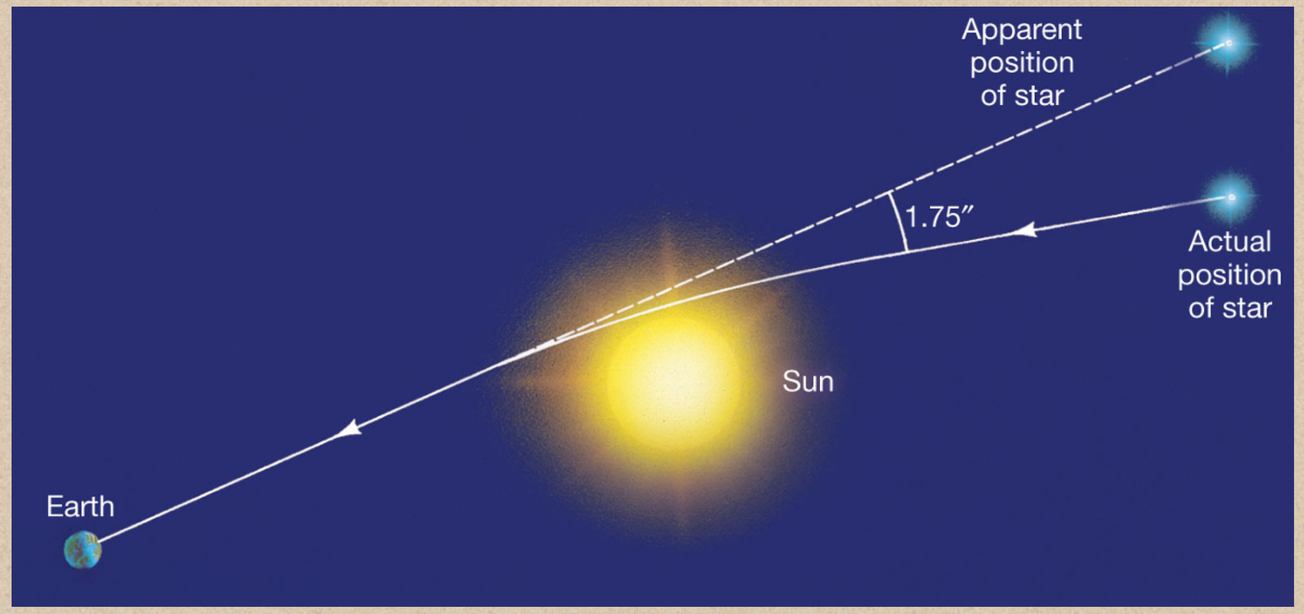
The orbital period loss

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

In good agreement with the GR prediction ⟶ Indirect evidence of GW

However < 1% uncertainty in the measurement

# Gravitational light bending

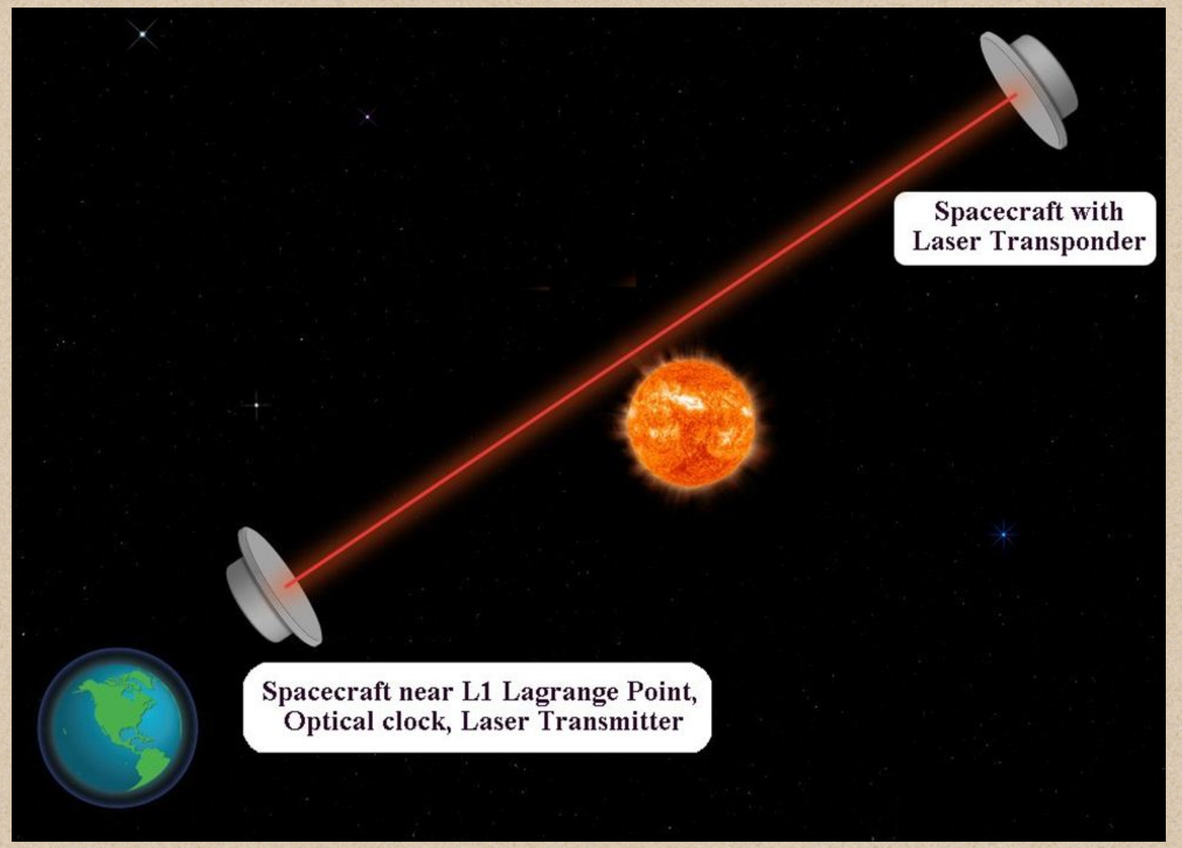



Test of Einstein's GR theory → Uncertainty

In the measurement $\mathcal{O}(10^{-4})$

https://towardsdatascience.com/einsteins-gravity-theory-and-the-bending-of-light-by-the-sun-1e796626dc19

# Shapiro time delay

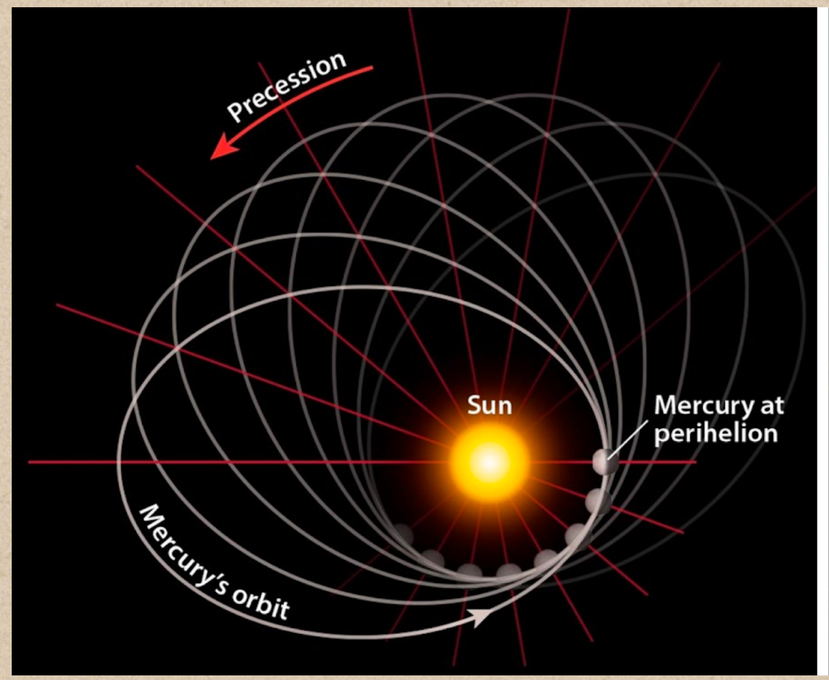


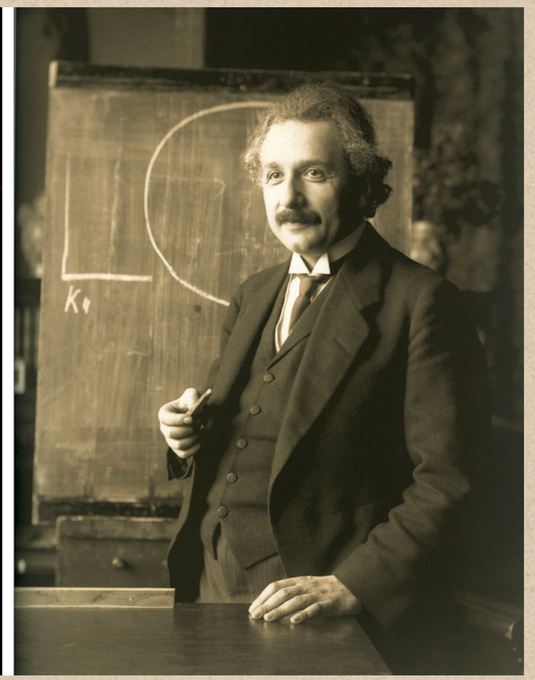

Test of Einstein's GR theory → Uncertainty

in the measurement $\mathcal{O}(10^{-5})$

https://physicsforme.com/2011/06/14/optical-clock-and-drag-free-requirements-for-a-shapiro-time-delay-mission/

# Perihelion Precession of planets



https://www.astronomicalreturns.com/2020/05/the-mystery-of-mercurys-missing.html

Test of Einstein's GR theory ⟶ Uncertainty in the measurement : $\mathcal{O}(10^{-3})$

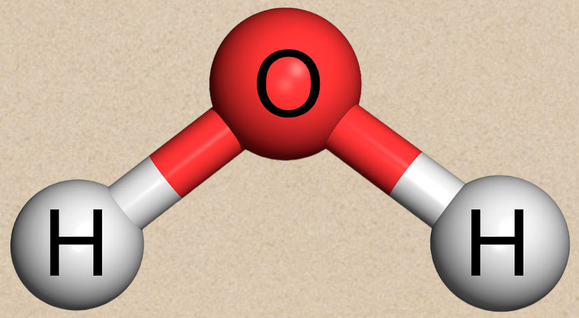
# Axion

# A Saviour of the Strong CP Problem, Dark Matter, and its Searches

# Axion : Motivation

## Strong CP Problem:

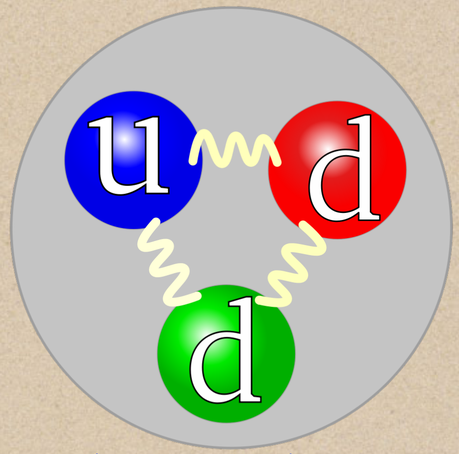
- Axion was introduced
- Stringent probe of strong CP violation: neutron electric dipole moment




https://www.alamy.com/stock-photo-water-molecule-11863066.html

The Strong CP Problem

10.1103/ Phys. Rev. D 92.092003




https://energywavetheory.com/subatomic-particles/neutron/

Estimate: $d_{H_2O} \sim 10^{-8} e\,.\,cm$

Data: $d_{H_2O} \sim 0.5 \times 10^{-8} e\,.\,cm$

Estimate: $d_n \sim 10^{-16} e\,.\,cm$

Data: $d_n < 3 \times 10^{-26} e\,.\,cm$

Contd...

QCD: The theory of strong interaction

$$\mathscr{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{j=1}^{n} [\bar{q}_j i\gamma^\mu D_\mu q_j - (m_j q^\dagger_{Lj} q_{Rj} + h.c)] + \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\tilde{G}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}$$

The last term violates the discrete symmetries CP, T, and P

Contd...

- $\theta$ term must be present if none of the quark mass vanishes

- QCD depends on $\theta$ through the combination of parameters

$$\bar{\theta} = \theta + arg(det(M))$$

- For a non vanishing $\bar{\theta}$, the induced neutron electric dipole moment is

$$d_n \simeq 5 \times 10^{-16} \bar{\theta} e \, . \, cm$$

S. Profumo, An introduction to particle Dark matter

- A general/natural $\bar{\theta} \sim \mathcal{O}(1)$ badly violates current experimental constraints

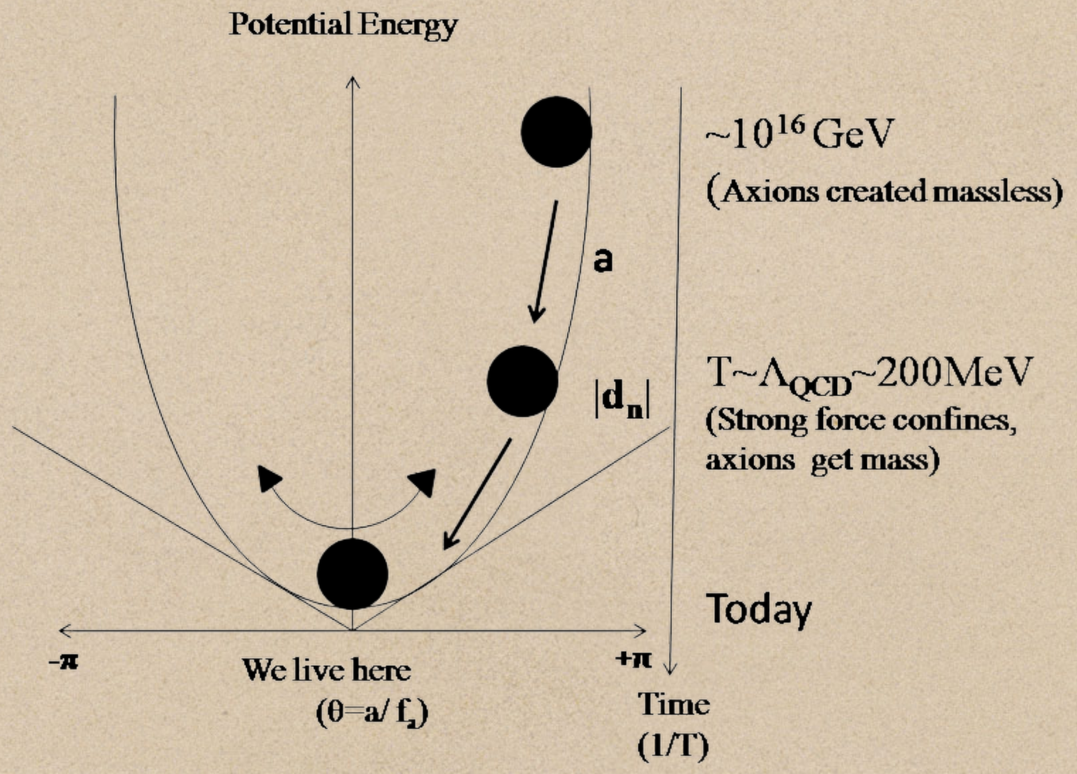
$$d_n < 3 \times 10^{-26} e \, . \, cm$$

10.1103/Phys. Rev. D 92.092003 ⟶ by ten order of magnitude small.

why nature choose such small value of $\bar{\theta}$: The strong CP problem

# Peccei-Quinn Solution (1977)

- $\bar{\theta}$ is a dynamical field driven to zero by its own classical potential
- Spontaneous breaking of $U(1)_{PQ}$ quasi symmetry at a scale $f_a$
- Explicit symmetry breaking at $\Lambda_{QCD}$ due to non perturbative QCD effects
- Pseudo Nambu goldstone boson appears which is called QCD axions



# Field evolution of axionic field

At the beginning of the universe, the axion field evolves with the potential

The action

$$S = \int d^4x\sqrt{-g}\,\mathcal{L} = \int d^4x\sqrt{-g}\left(\frac{f_a^2}{2}(\partial_\mu\theta)(\partial^\mu\theta) - V(\theta)\right)$$

$$= \int d^4x\sqrt{-g}\left(\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - V\left(\frac{a}{f_a}\right)\right)$$

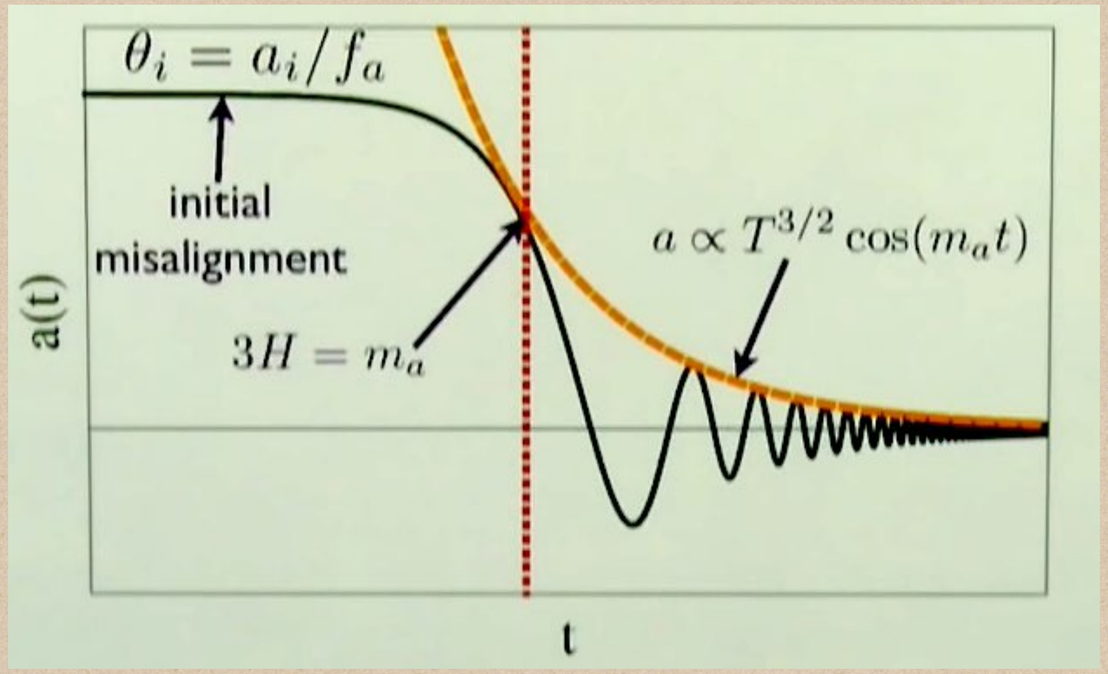
The potential

$$V\left(\frac{a}{f_a}\right) = m_a^2 f_a^2\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

E.O.M

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

Contd...




So at the late time the axion field redshifts like a cold dark matter

$$\Omega_{DM} \sim 0.12\left(\frac{a_0}{10^{17}GeV}\right)^2\left(\frac{m_a}{10^{-22}eV}\right)^{\frac{1}{2}}$$

L. Hui et al, Phys. Rev. D 95,043541

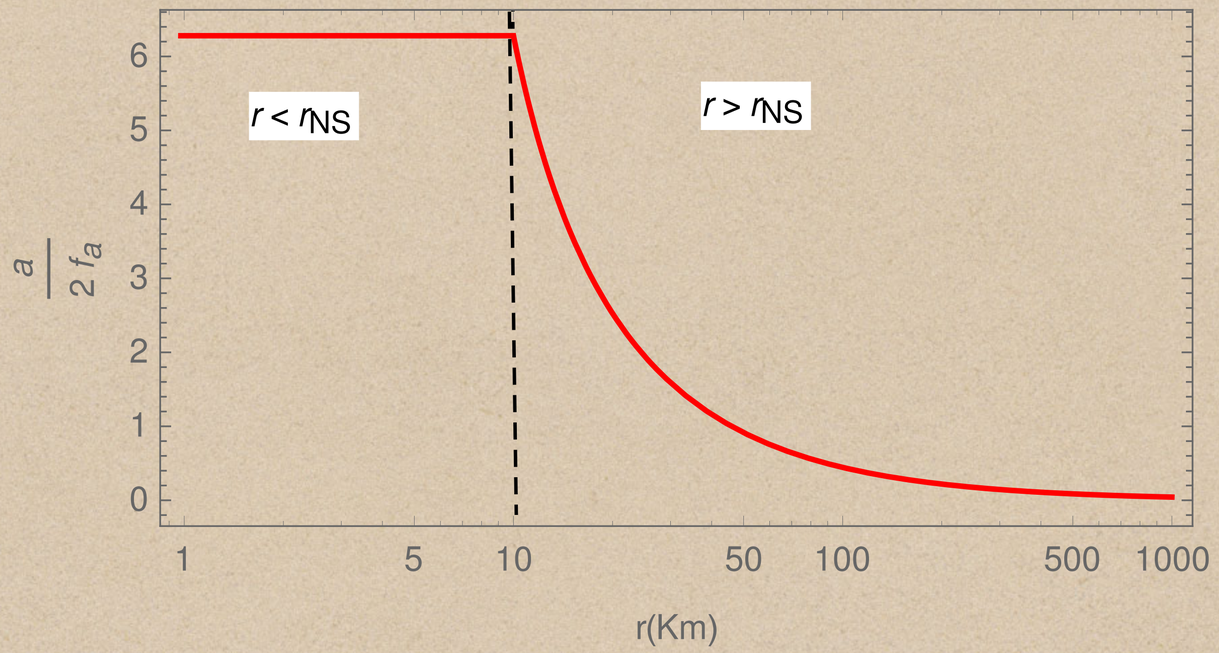
de Broglie wavelength ~ size of a dwarf galaxy ⟶ Fuzzy (wave ) dark matter

$$\frac{\lambda}{2\pi} = \frac{\hbar}{m_a v} = 1.92\text{kpc}\left(\frac{10^{-22}\text{eV}}{\text{m}_\text{a}}\right)\left(\frac{10\text{km/s}}{\text{v}}\right)$$

# Constraints on ultralight axions from compact binary systems

Subhendra Mohanty, Soumya Jana, and T.K.P,

Phys.Rev.D 101 (2020) 8, 083007




JHEP 06 (2018) 036

FDM

$$\omega = \left[\frac{G(m_1+m_2)}{D^3}\right]^{\frac{1}{2}} \sim 10^{-19}\text{eV}$$

$$a = -\frac{q_{eff}}{2GM}\ln\left(1-\frac{2GM}{r}\right)$$

$$q_{eff} = -\frac{8\pi GMf_a}{\ln\left(1-\frac{2GM}{r_{NS}}\right)}$$

## Axionic fifth force

$$F_5 = \frac{q_1 q_2}{4\pi D^2}\ , \quad \omega^2 = \frac{G(m_1+m_2)}{D^3}(1+\alpha)$$

Contd…

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

GR

Axion dipole radiation

The dipole moment $p = q_1 r_1 - q_2 r_2 = q_1 \frac{\mu D}{m_1} - q_2 \frac{\mu D}{m_2}$

$$p = 8\pi G f_a \mu D \left[ \frac{1}{\ln\left(1 - \frac{2Gm_2}{r_{NS}}\right)} - \frac{1}{\ln\left(1 - \frac{2Gm_1}{r_{NS}}\right)} \right]$$

Contd...

$$\omega > m_a \longrightarrow m_a < 10^{-19}\text{eV}$$

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

Stronger bound from NS-WD binary

If ALPs are FDM, they do not couple with quarks

# Constraints on axionic fuzzy dark matter from light bending and Shapiro time delay T. K. P JCAP 09(2021)041

## Light bending

The effective potential in presence of long range axion mediated Yukawa potential

$$V_{eff} = \frac{L^2}{2}\left(\frac{du}{d\phi}\right)^2 + \frac{L^2u^2}{2}(1-2Mu) - \frac{q_1q_2u}{4\pi M_p}e^{-\frac{m_a}{u}}$$

Trajectory of light

$$0 = \frac{d^2u}{d\phi^2} + u - 3Mu^2 - \frac{q_1q_2}{4\pi M_pL^2}e^{-\frac{m_a}{u}} - \frac{q_1q_2m_a}{4\pi M_pL^2u}e^{-\frac{m_a}{u}}$$

Total light bending due to axion field

$$\Delta\phi_{axions} = \frac{\frac{4M}{b^2} + \frac{q_1q_2}{2\pi M_pL^2}(1-0.347m_a^2b^2)}{\frac{1}{b} + \frac{q_1q_2m_a^2b^2}{8\pi M_pL^2}} - \frac{4M}{b}$$

GR: $\Delta\phi = \frac{4M}{b} = \frac{4GM}{R_\odot c^2} = 1.75\text{arcsec}$

Contd...

## Shapiro time delay

Trajectory of light

$$\frac{E^2}{2} = \frac{\dot{r}^2}{2} + \frac{L^2}{2r^2}\left(1 - \frac{2M}{r}\right) - \frac{q_1 q_2}{4\pi M_p r} e^{-m_a r}$$

Time delay due to GR and axion mediated fifth force

$$\Delta T = T_2 - T_1 = 4M\left[\ln\left(\frac{4r_e r_v}{r_0^2}\right) + 1\right] + 2b_0 c_0(-1 + c_0 M)(r_e + r_v) + \frac{b_0 c_0^2}{2}(r_e^2 + r_v^2) + 2b_0 -$$

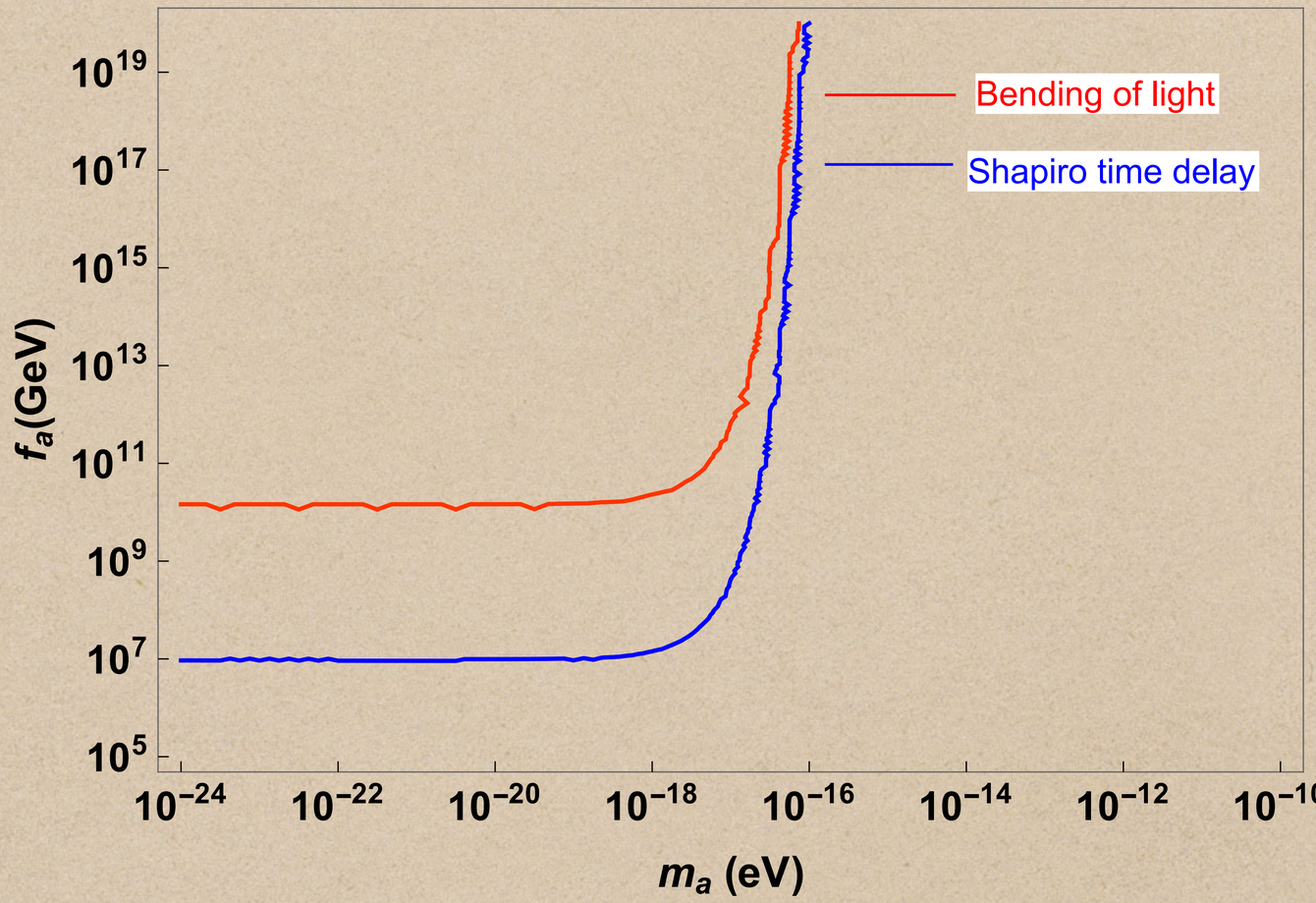
$$4c_0 M b_0 + 2a_0(r_e + r_v) + \frac{b_0}{24}(48 + 36c_0^2 r_0^2)[Ei(-c_0 r_e) + Ei(-c_0 r_v)]$$

$$a_0 = \frac{q_1 q_2 e^{-m_a r_0}}{4\pi M_p E^2 r_0} \quad , b_0 = \frac{q_1 q_2}{4\pi M_p E^2} \quad , c_0 = m_a$$

GR: $\Delta T = \dfrac{4GM}{c^3}\left[\ln\left(\dfrac{4r_e r_v}{r_0^2}\right) + 1\right] = 2 \times 10^{-4}\text{sec}$

Contd...

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




If ALPs are FDM, they do not couple with quarks

# Summary

- The NS-WD binaries put stronger bound on axion decay constant as $f_a \lesssim 10^{11}\mathrm{GeV}$, for axion mass $m_a \lesssim 10^{-19}\mathrm{eV}$, which suggest if ALPs are FDM, they do not couple with quarks.

- The Shapiro time delay gives the stronger bound on $f_a \lesssim 10^{7}\mathrm{GeV}$ for axions of mass $m_a \lesssim 10^{-18}\mathrm{eV}$

# CHAPTER 3

# Light Gauge Boson

## Long Range Force, Dark Matter, and its Searches

# Vector gauge boson radiation from compact binary systems in a gauged $L_\mu - L_\tau$ scenario

Subhendra Mohanty, Soumya Jana, and T. K. P Phys. Rev. D 100 (2019) 12, 123023

$L_\mu - L_\tau \rightarrow$ Long range force

Muon content in NS

$$N_\mu \approx 10^{55}$$

R. Garani, J. Heeck,
Phys. Rev. D 100, 035039 (2019)

$$\mathscr{L} \supset g' Z'_\mu (\bar{\mu}\gamma^\mu \mu - \bar{\tau}\gamma^\mu \tau + \bar{\nu}_\mu \gamma^\mu L \nu_\mu - \bar{\nu}_\tau \gamma^\mu L \nu_\tau)$$

Contd...

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

Charge to mass asymmetry

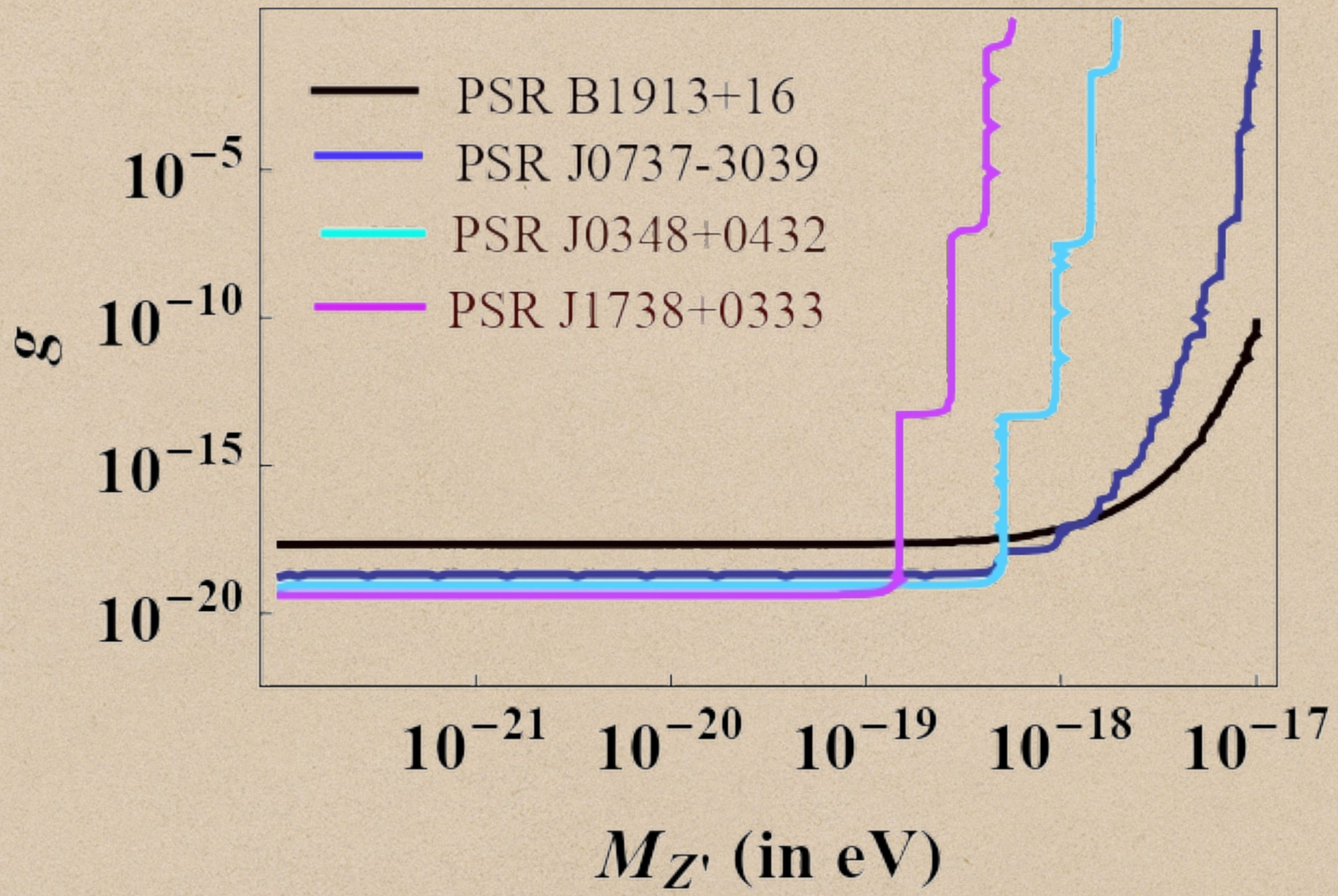
From fifth force constraint

$$\frac{g^2 Q_1 Q_2}{4\pi G m_1 m_2} \leq 1$$

$$M_{Z'} \lesssim 10^{-19}\text{eV}$$

| 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 | ... | $\leq 4.24 \times 10^{-20}$ |

Contd...




Ultralight vector dark matter

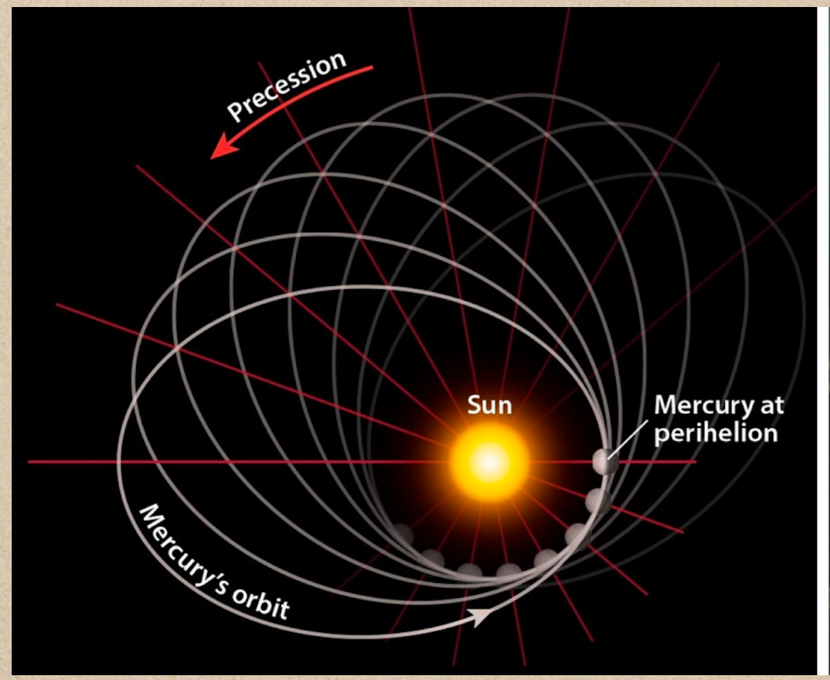
# Constraints on long range force from perihelion precession of planets in a gauged $L_e - L_{\mu,\tau}$ scenario

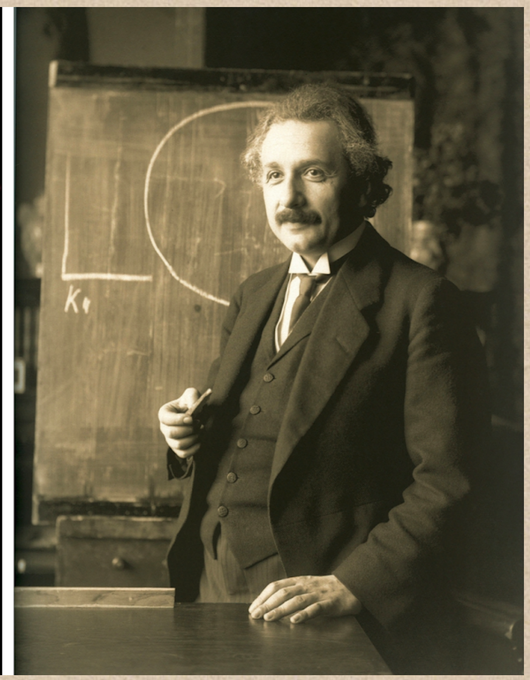
Subhendra Mohanty, Soumya Jana, and T. K. P Eur. Phys. J. C 81 (2021) 4, 286

## Perihelion Precession of planets

$L_e - L_{\mu,\tau} \rightarrow$ Long range force

Presence of electrons in the celestial objects



https://www.astronomicalreturns.com/2020/05/the-mystery-of-mercurys-missing.html

Test of Einstein's GR theory ⟶ Uncertainty in the measurement : $\mathcal{O}(10^{-3})$

Contd...

Ultralight gauge boson mass

$$M_{Z'} \ll \frac{1}{a} \sim \mathcal{O}(10^{-19}\text{eV})$$

Perihelion precession of planets in presence of long range $L_e - L_{\mu,\tau}$ Yukawa potential

E. O. M

$$\frac{d^2u}{d\phi^2} + u = \frac{M}{L^2} + 3Mu^2 + \frac{g^2N_1N_2}{4\pi L^2M_p}e^{-\frac{M_{Z'}}{u}} + \frac{g^2N_1N_2EM_{Z'}}{4\pi L^2M_pu}e^{-\frac{M_{Z'}}{u}}$$

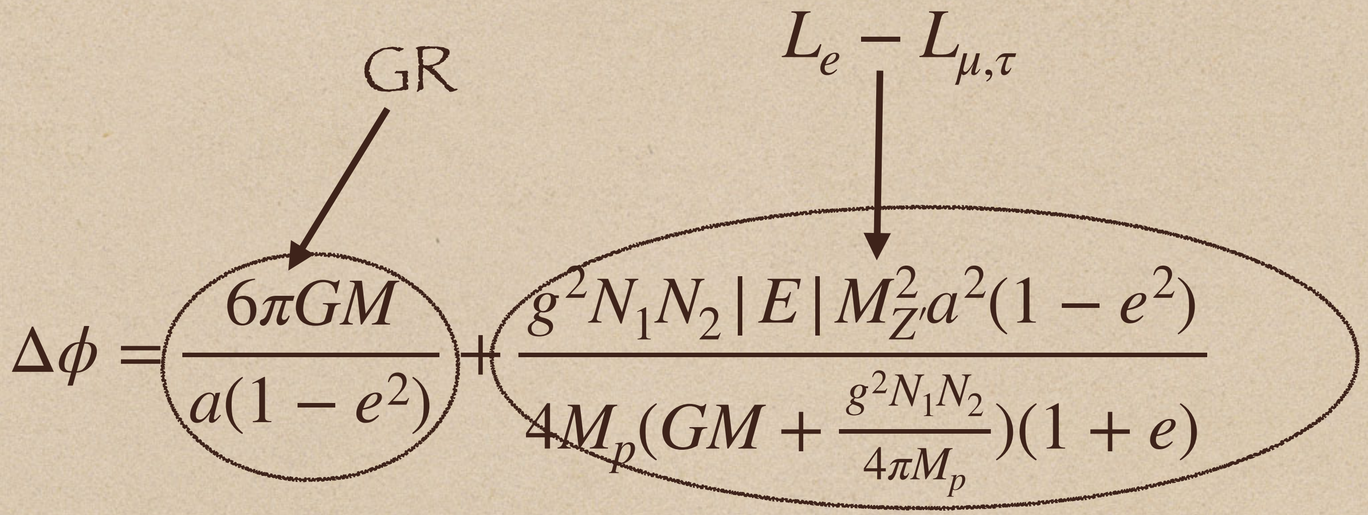
Newtonian term

GR

$L_e - L_{\mu,\tau}$

Contd…

The perihelion shift

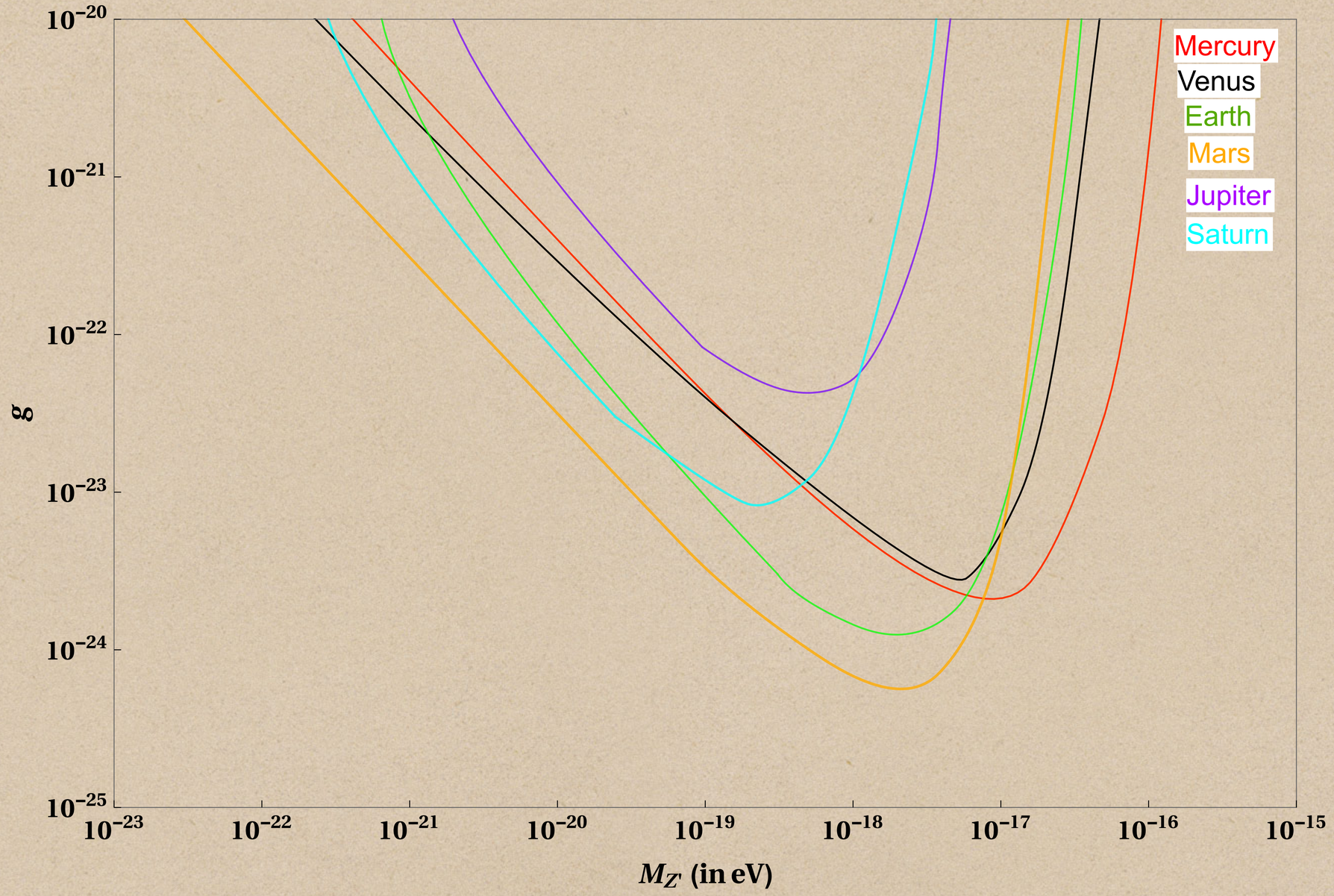



For Mercury

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

Contd...

Ultralight vector dark matter




→ Planet Mars gives the stronger bound

# Summary

- The radiation of ultralight vector gauge bosons can contribute to the orbital period loss of binary systems which can be a good candidate of dark matter. Their signature can also be looked in GW waveforms

- The ultralight vector particles can also contribute to the perihelion precession of planets within the permissible limits

- $L_i - L_j$ type of particle physics models can be probed by planetary motions and compact stars

# Thank You !

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