Probing ultralight scalars through compact stars and precision test of gravity

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Based on **2501.02286, 2503.02940, 2412.09575**

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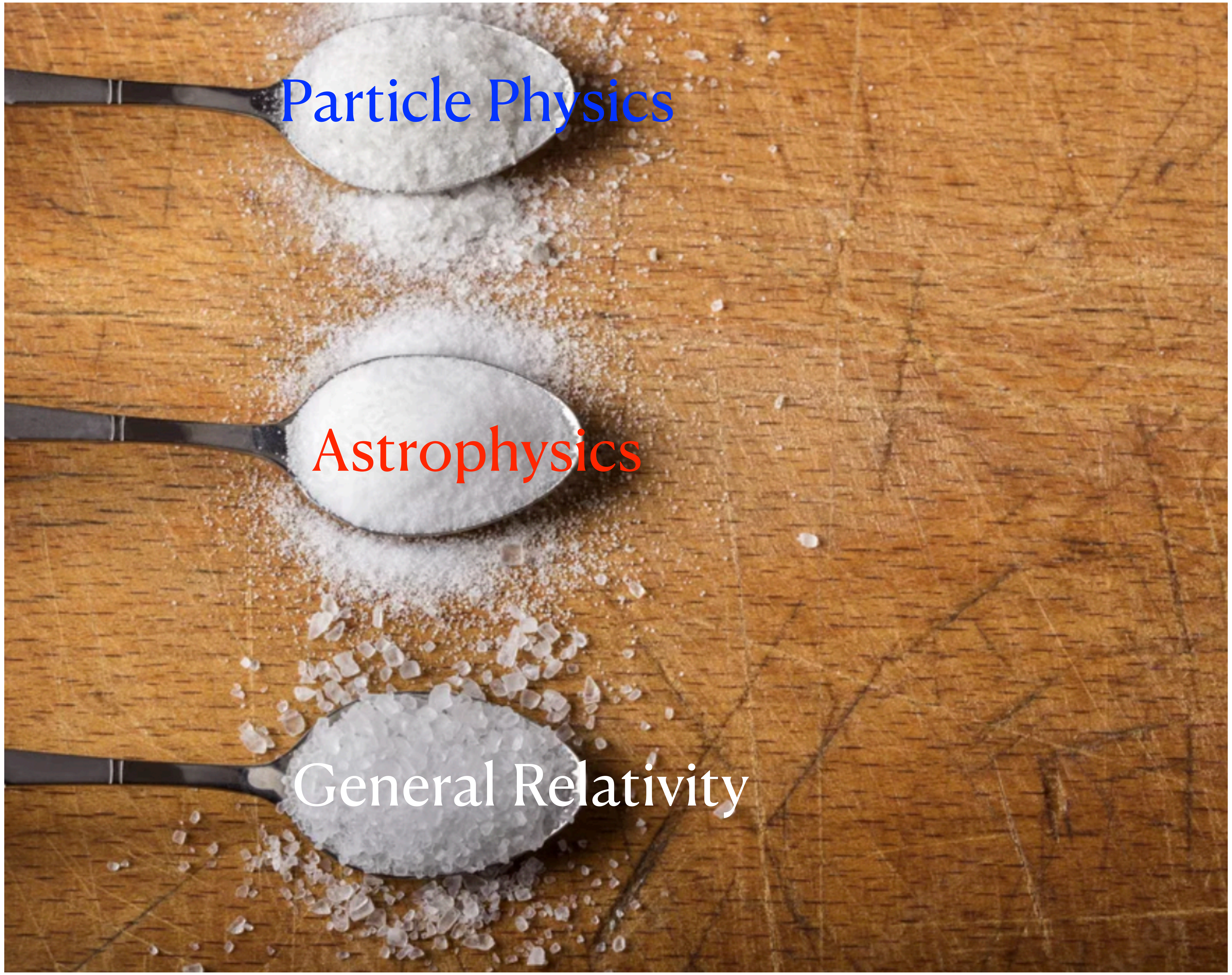
Istituto Nazionale di Fisica Nucleare

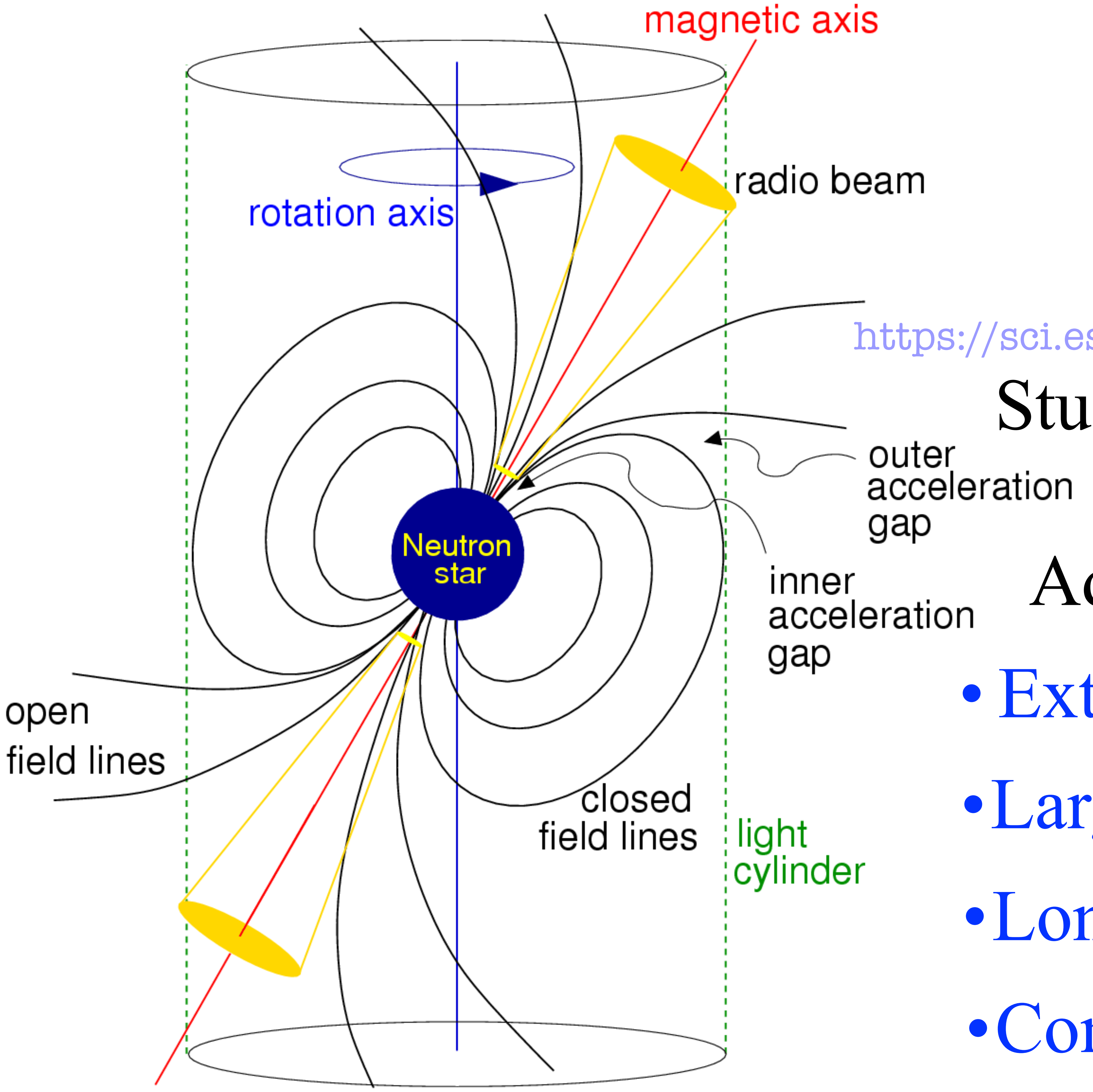
Requirements:



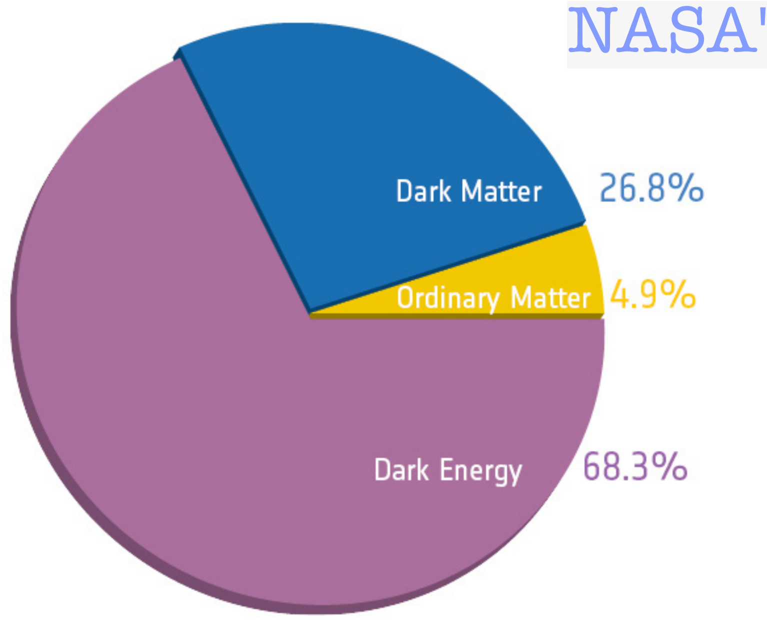
NS/Magnetar/SGR/GRB

Cosmic laboratories for exploring the mysteries of the universe

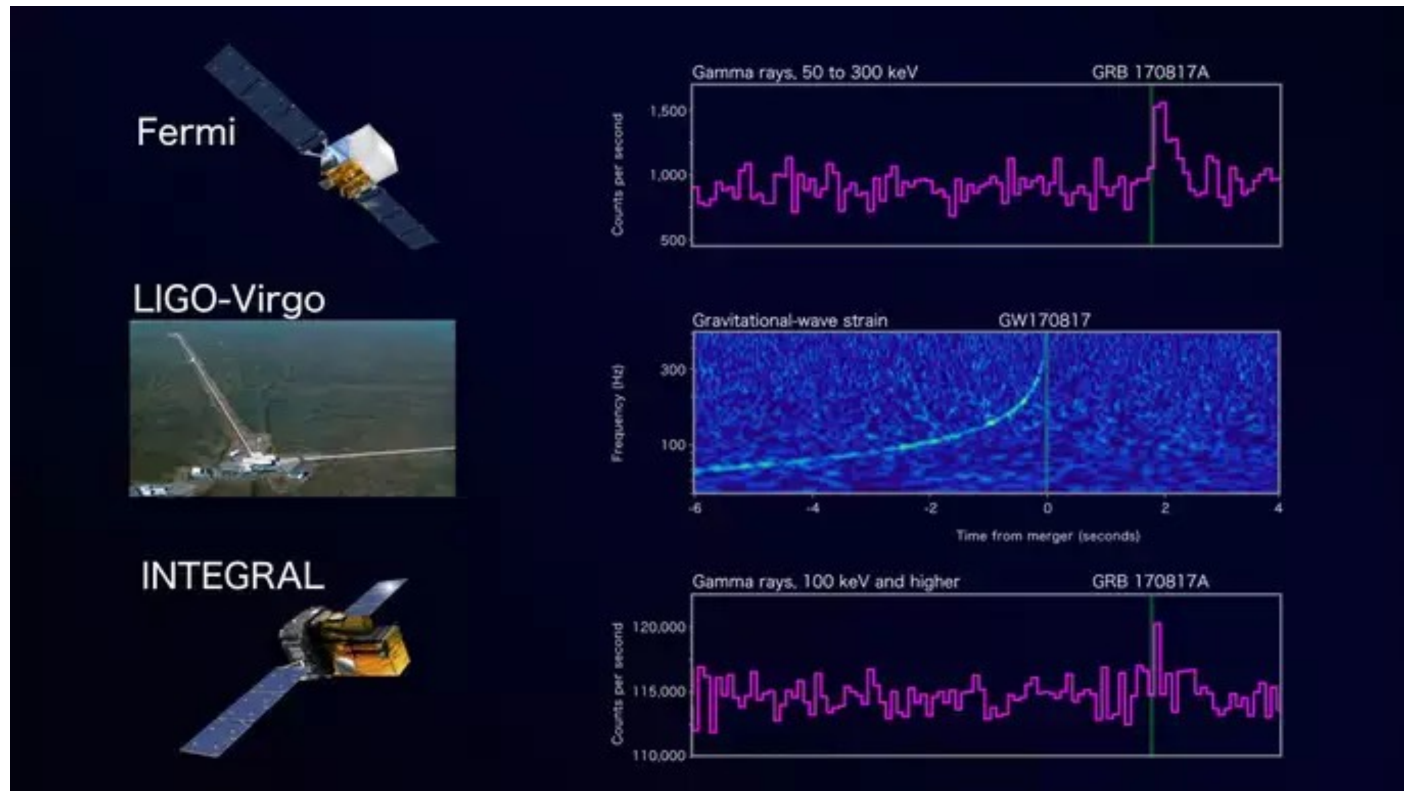
NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA



Lorimer and Kramer, 2005, Handbook of pulsar astronomy, Cambridge University Press



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



Study multi-messenger astronomy

Advantages over traditional laboratory-based experiments:

- Extreme environments that enhance interaction probabilities
- Large spatial volumes acting as effective detectors
- Long observation timescales
- Complementary approach to direct detection efforts

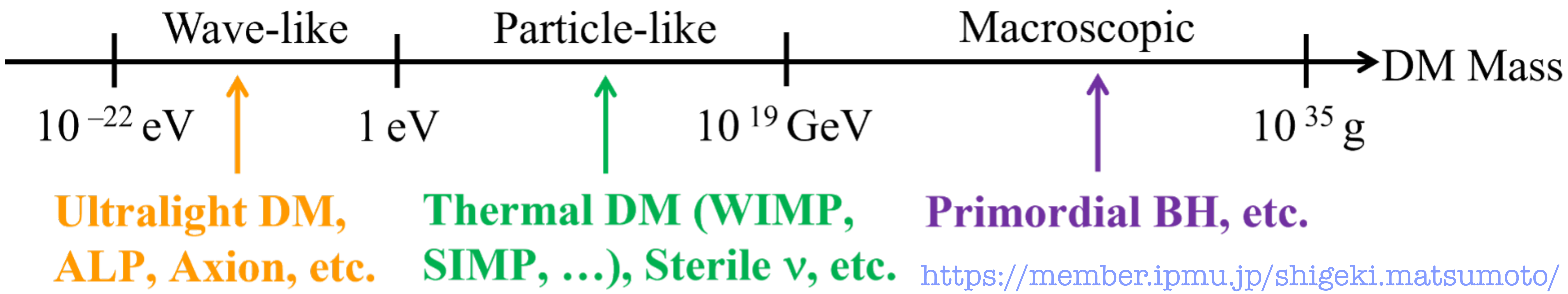
Input parameters:

Mass $\sim 1.4\ M_{\odot}$, **Radius** $\sim 10-20$ km , **Spin period** ~ 10 ms , **Mass density** $\sim 10^{14}$ g/cm^3 ,

Light cylinder radius $\sim 10^3$ km , **Constituents**: neutrons, protons, electrons, muons, hyperons

Surface magnetic field $\sim 10^{12}$ G, dipolar , **For magnetar, magnetic field** $\gtrsim \sim 10^{15}$ G

Ultralight scalars: A possible dark matter candidate



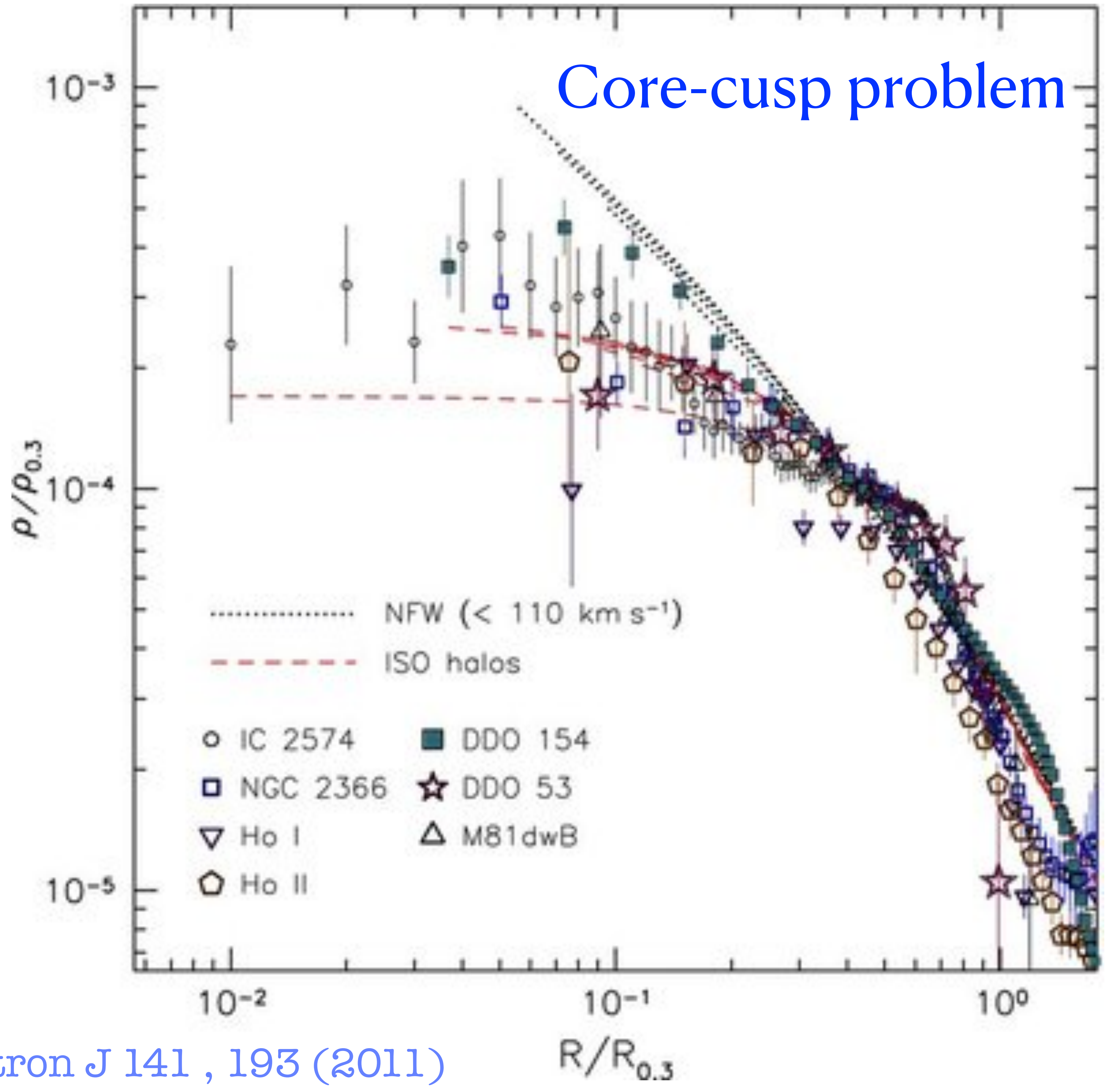
https://member.ipmu.jp/shigeki.matsumoto/

DM present at all scales

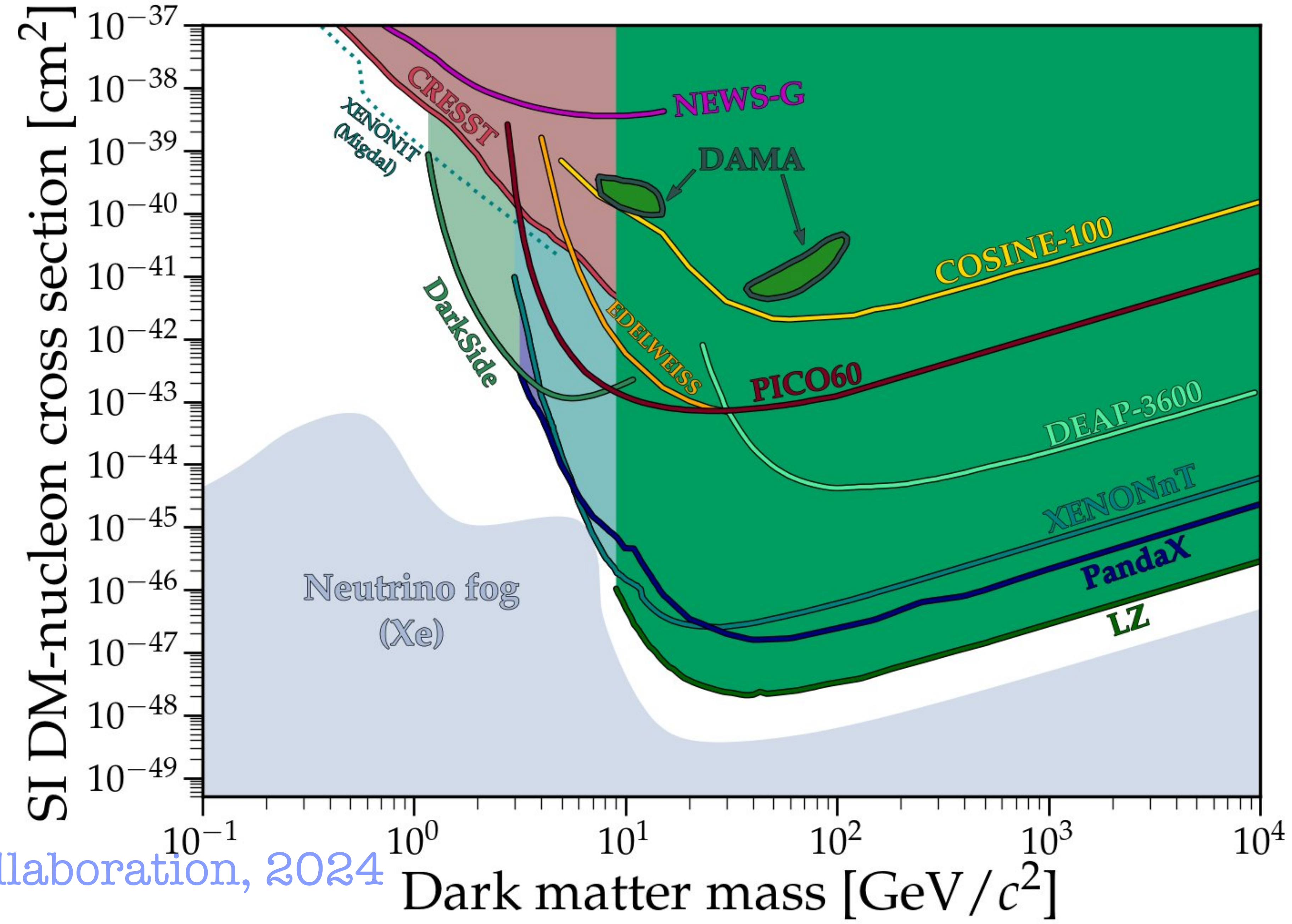
- Rotation curve
- Bullet clusters
- CMB
- Structure formation

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

$$\rho_\odot \sim 0.4\ \mathrm{GeV/cm^3},\ \mathrm{n_{DM}} \sim 10^{30}/\mathrm{cm}^3,\ \mathrm{m_{DM}} \sim 10^{-22}\ \mathrm{eV}$$



Astron J 141 , 193 (2011)



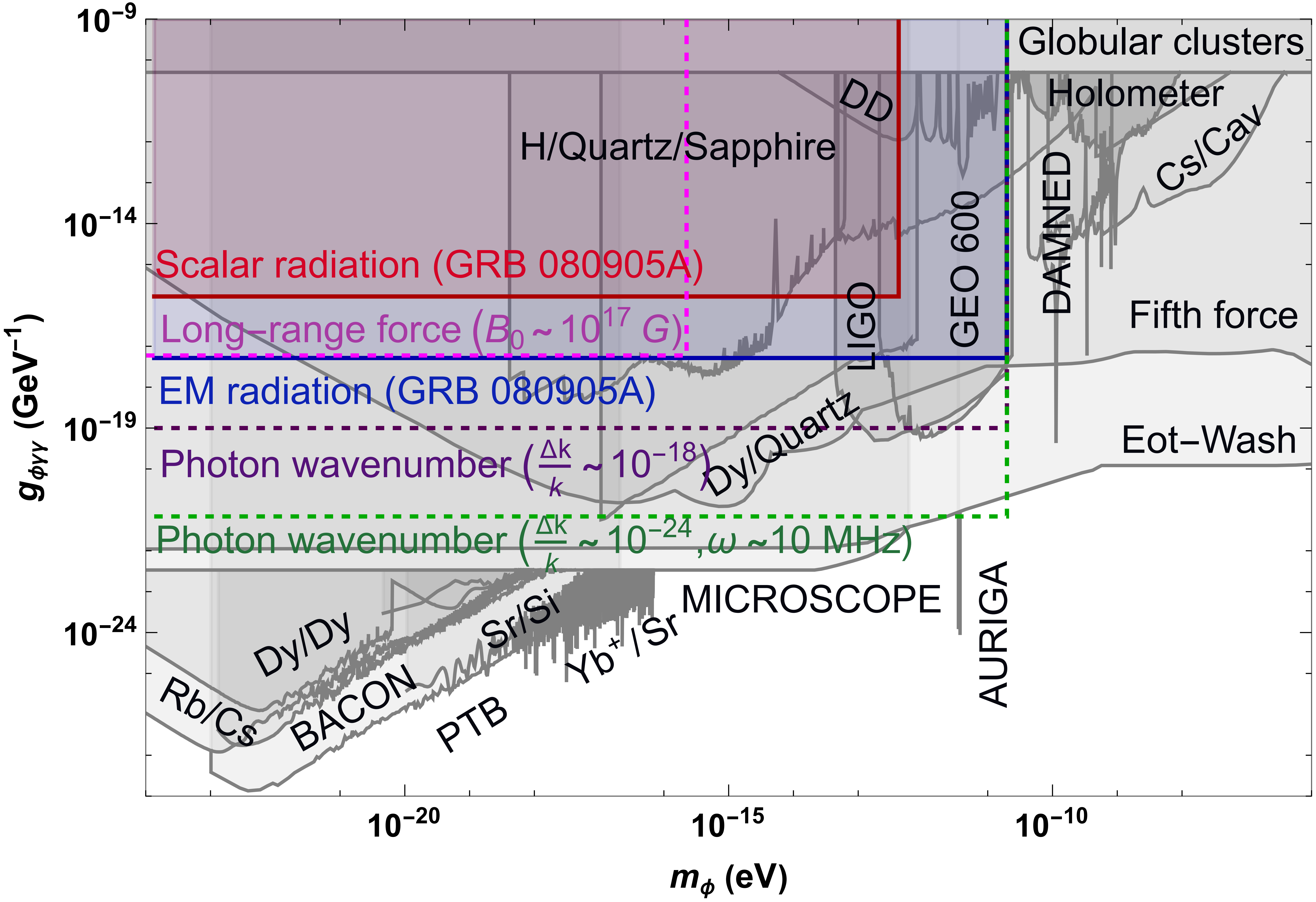
LZ collaboration, 2024

Direct detection constraints

Constraints on scalar-electromagnetic coupling from magnetzed stars

arXiv: 2501.02286

T.K.P., and Amol Dighe



Long-range scalar field outside a compact star

Aligned rotator model

The dipolar magnetic field outside of the star

$$\mathbf{B}^{\text{out}}_{(r>R)} = B_0 R^3 \left(\frac{\cos\theta}{r^3} \hat{r} + \frac{\sin\theta}{2r^3} \hat{\theta} \right)$$

The electric field outside the star

$$\mathbf{E}^{\text{out}}_{(r>R)} = -\frac{B_0 \Omega R^5}{r^4} \left[\left(1 - \frac{3}{2} \sin^2\theta \right) \hat{r} + \sin\theta \cos\theta \, \hat{\theta} \right]$$

Lagrangian for a CP even scalar field interacting with the EM fields

$$\mathscr{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} g_{\phi\gamma\gamma} \phi F_{\mu\nu} F^{\mu\nu}$$

$$\frac{1}{2} F_{\mu\nu} F^{\mu\nu} = \mathbf{B}^2 - \mathbf{E}^2$$

$$\mathbf{B}^2 - \mathbf{E}^2 = \frac{B_0^2 R^6}{4r^6} (3\cos^2\theta + 1) - \frac{B_0^2 \Omega^2 R^{10}}{4r^8} (5\cos^4\theta - 2\cos^2\theta + 1)$$

The equation of motion of the scalar field

$$\Box \phi = -g_{\phi\gamma\gamma} (\mathbf{B}^2 - \mathbf{E}^2)$$

Contd…

EOM of the scalar field in the Schwarzschild background

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[(r^2-2Mr)\frac{\partial}{\partial r}\phi(r,\theta)\right]+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta\frac{\partial}{\partial\theta}\phi(r,\theta)\right]=-\,g_{\phi\gamma\gamma}\frac{B_0^2R^6}{4r^6}(3\cos^2\theta+1)+$$
$$g_{\phi\gamma\gamma}\frac{B_0^2\Omega^2R^{10}}{4r^8}(5\cos^4\theta-2\cos^2\theta+1)$$

Soln.

$$\phi(r)\approx-\frac{g_{\phi\gamma\gamma}B_0^2\Omega^2R^{10}}{480M^5r}+\frac{g_{\phi\gamma\gamma}B_0^2R^6}{48M^3r}+\mathcal{O}\left(\frac{1}{r^2}\right)$$

For axions

$$a\sim\frac{\cos\theta}{r^2}\qquad l=1,\text{ dipole term}$$

The scalar field has a long-range behaviour

$$\phi(r)\approx\frac{Q_\phi^{\rm K}}{r}\qquad l=0\text{ monopole term}$$

For binary

The scalar charge

$$Q_\phi^{\rm K}=-\frac{g_{\phi\gamma\gamma}B_0^2\Omega^2R^{10}}{480M^5}+\frac{g_{\phi\gamma\gamma}B_0^2R^6}{48M^3}$$

$$F=\frac{Q_1^{\rm eff}Q_2^{\rm eff}}{r^2}$$

Scalar-induced EM fields from Maxwell's equations

Interaction of CP even scalar with EM fields modifies Maxwell's equations of EM fields in vacuum

Expanding the stress tensor in powers of $g_{\phi\gamma\gamma}$ $\quad F^{\mu\nu} = F^{\mu\nu}_{(0)} + F^{\mu\nu}_{\phi} + \mathcal{O}(g^2_{\phi\gamma\gamma})$

EOM: $\partial_\mu F^{\mu\nu}_\phi = -\, g_{\phi\gamma\gamma}(\partial_\mu \phi) F^{\mu\nu}_{(0)}$

$$\nabla \cdot \mathbf{E}_\phi = -\, g_{\phi\gamma\gamma}\, \mathbf{E}_{(0)} \cdot \nabla \phi$$

$$\nabla \times \mathbf{B}_\phi = \frac{\partial \mathbf{E}_\phi}{\partial t} - g_{\phi\gamma\gamma} \nabla \phi \times \mathbf{B}_{(0)} + g_{\phi\gamma\gamma} \left(\frac{\partial \phi}{\partial t} \right) \mathbf{E}_{(0)}$$

Bianchi identity $\quad \partial_\mu \tilde{F}^{\mu\nu}_\phi = 0$

$$\nabla \cdot \mathbf{B}_\phi = 0$$

$$\nabla \times \mathbf{E}_\phi = -\frac{\partial \mathbf{B}_\phi}{\partial t}$$

$$\Box\, \mathbf{B}_\phi = g_{\phi\gamma\gamma} \left(\nabla \phi \cdot \nabla \right) \mathbf{B}_{(0)}$$

$$\Box\, \mathbf{E}_\phi = g_{\phi\gamma\gamma} \left(\nabla \phi \cdot \nabla \right) \mathbf{E}_{(0)}$$

$$\mathbf{B}_\phi(r,\theta) \approx \frac{g_{\phi\gamma\gamma} Q^{\mathrm{K}}_\phi B_0 R^3}{12 M^2} \left(\frac{\cos\theta}{r^2} \right) \hat{r} + \frac{g_{\phi\gamma\gamma} Q^{\mathrm{K}}_\phi B_0 R^3 \pi}{64 M^3 r} \hat{\theta}$$

$$Q^{\mathrm{K}}_\phi = -\frac{g_{\phi\gamma\gamma} B_0^2 \Omega^2 R^{10}}{480 M^5} + \frac{g_{\phi\gamma\gamma} B_0^2 R^6}{48 M^3}$$

EM wave propagation in the background of long-range scalar field

Maxwell's equations for photon propagation modifies as

$$\nabla \cdot \mathbf{E} = -g_{\phi\gamma\gamma}\mathbf{E} \cdot \nabla\phi \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{\phi\gamma\gamma}\nabla\phi \times \mathbf{B} \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

The wave equation

$$\Box \mathbf{B} = g_{\phi\gamma\gamma}(\nabla\phi \cdot \nabla)\mathbf{B}$$

Choose the Eikonal ansatz

$$\mathbf{B}(x,t) = \mathscr{B}\, e^{iS(x,t)} \qquad \omega = -\partial S/\partial t, \qquad \mathbf{k} = \nabla S$$

The photon dispersion relation

Propagation is independent of photon polarisation, unlike axions

$$\omega^2 = k^2 - ig_{\phi\gamma\gamma}(\nabla\phi \cdot \mathbf{k})$$

The group velocity

$$v_g = \left(1 - \frac{m_\gamma^2}{4\omega^2}\right)^{\frac{1}{2}}$$

Scalar-induced photon mass

$$m_\gamma = |g_{\phi\gamma\gamma}\nabla\phi|$$

Contd…

The solution for the wavenumber

$$k = k_R + ik_I = \frac{\sqrt{4\omega^2 - m_\gamma^2}}{2} + \frac{im_\gamma}{2}$$

The scalar interaction modifies the redshift of the photon wavelength

$$\delta z = \frac{\lambda(r_2) - \lambda(r_1)}{\lambda(r_1)} \approx \frac{k_R(r_1) - k_R(r_2)}{k_R(r_2)} \approx \frac{m_\gamma^2}{8\omega^2} \approx \frac{g_{\phi\gamma\gamma}^4 B_0^4 R^8}{48^2 \times 8 M^6 \omega^2}$$

Benchmark values for GRB 080905A

$$\delta z = \frac{\Delta k}{k} \sim 10^{-4} \left(\frac{g_{\phi\gamma\gamma}}{10^{-15}\ \mathrm{GeV}^{-1}}\right)^4 \left(\frac{2.1\ \mathrm{GHz}}{\omega}\right)^2 \left(\frac{B_0}{3.93 \times 10^{16}\ \mathrm{G}}\right)^4 \left(\frac{R}{10\ \mathrm{km}}\right)^8 \left(\frac{1.4\ M_\odot}{M}\right)^6$$

$$\alpha = 2k_I = m_\gamma = \frac{1}{x} \ln\left(\frac{I_0}{I}\right) \quad \propto \quad \mathcal{O}(g_{\phi\gamma\gamma}^2)$$

Change in redshift is more pronounced for stars with larger magnetic fields, size and signal with lower frequencies

Scalar radiation from an isolated compact star

Previous discussion with static source ⟶ No radiation

$$\rho_\phi(\mathbf{r}, t) = g_{\phi\gamma\gamma}(\mathbf{B}^2 - \mathbf{E}^2)$$ Time-varying source charge density

For radiation, consider a skewed rotator model with time-oscillating EM fields of the star

$$\mathbf{B}^2 - \mathbf{E}^2 \approx -\frac{3}{2}\frac{B_0^2 R^6}{r^6}\cos\theta_m \sin\alpha \sin\theta \cos(\Omega t - \varphi)$$

In the far field and long wavelength approximation

$$\frac{dE}{dt} = \frac{1}{8\pi^2}\Omega k^3 \int dS_n |\mathbf{p}_\Omega \cdot \hat{\mathbf{n}}|^2$$

$$k^2 = \Omega^2 - m_\phi^2$$

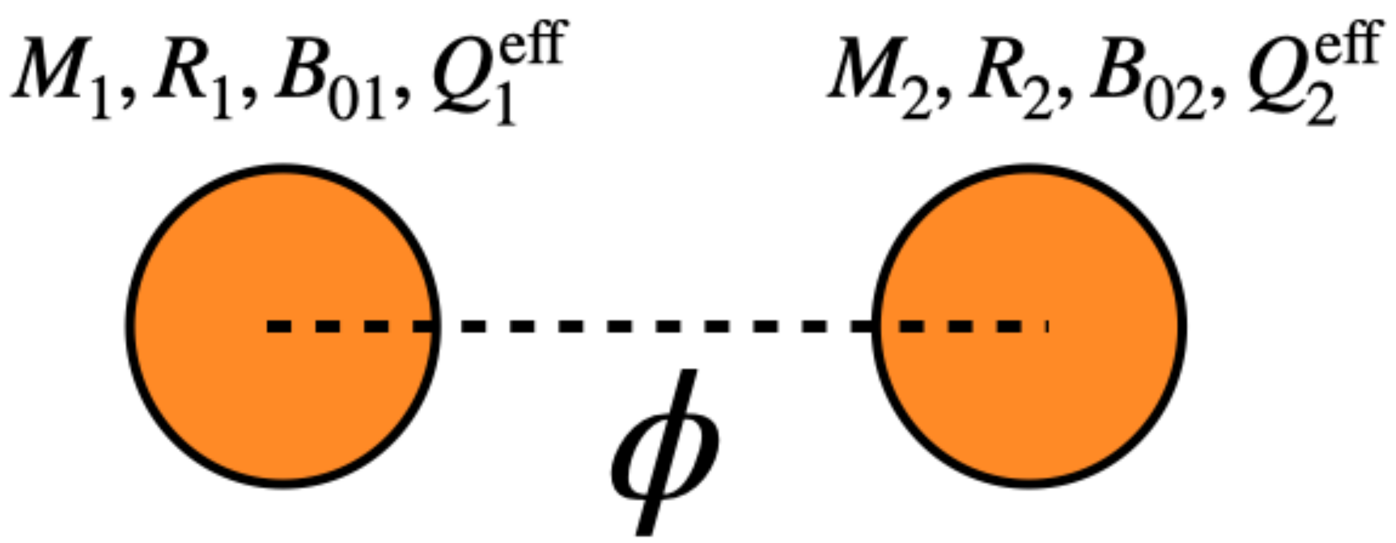
Time-averaged dipole moment

$$\mathbf{p}_\Omega = \frac{1}{P}\int_0^P dt e^{i\Omega t}\int \rho(\mathbf{r}, t)\, \mathbf{r}\, d^3 r$$

$$P = \frac{2\pi}{\Omega}$$

$$\frac{dE}{dt} \approx \frac{\pi}{48} g_{\phi\gamma\gamma}^2 B_0^4 R^8 \Omega^4 \sin^2(2\theta_m)\left(1 - \frac{m_\phi^2}{\Omega^2}\right)^{3/2}$$

Contributes to pulsar spin-down for $m_\phi < \Omega$



PSR J0737-3039

$$\eta = \frac{Q_1^{\mathrm{eff}} Q_2^{\mathrm{eff}}}{4\pi G M_1 M_2} \approx \frac{g_{\phi\gamma\gamma}^2 B_{01}^2 B_{02}^2 R_1^6 R_2^6}{(48)^2 \times 4\pi G^7 M_1^4 M_2^4}$$

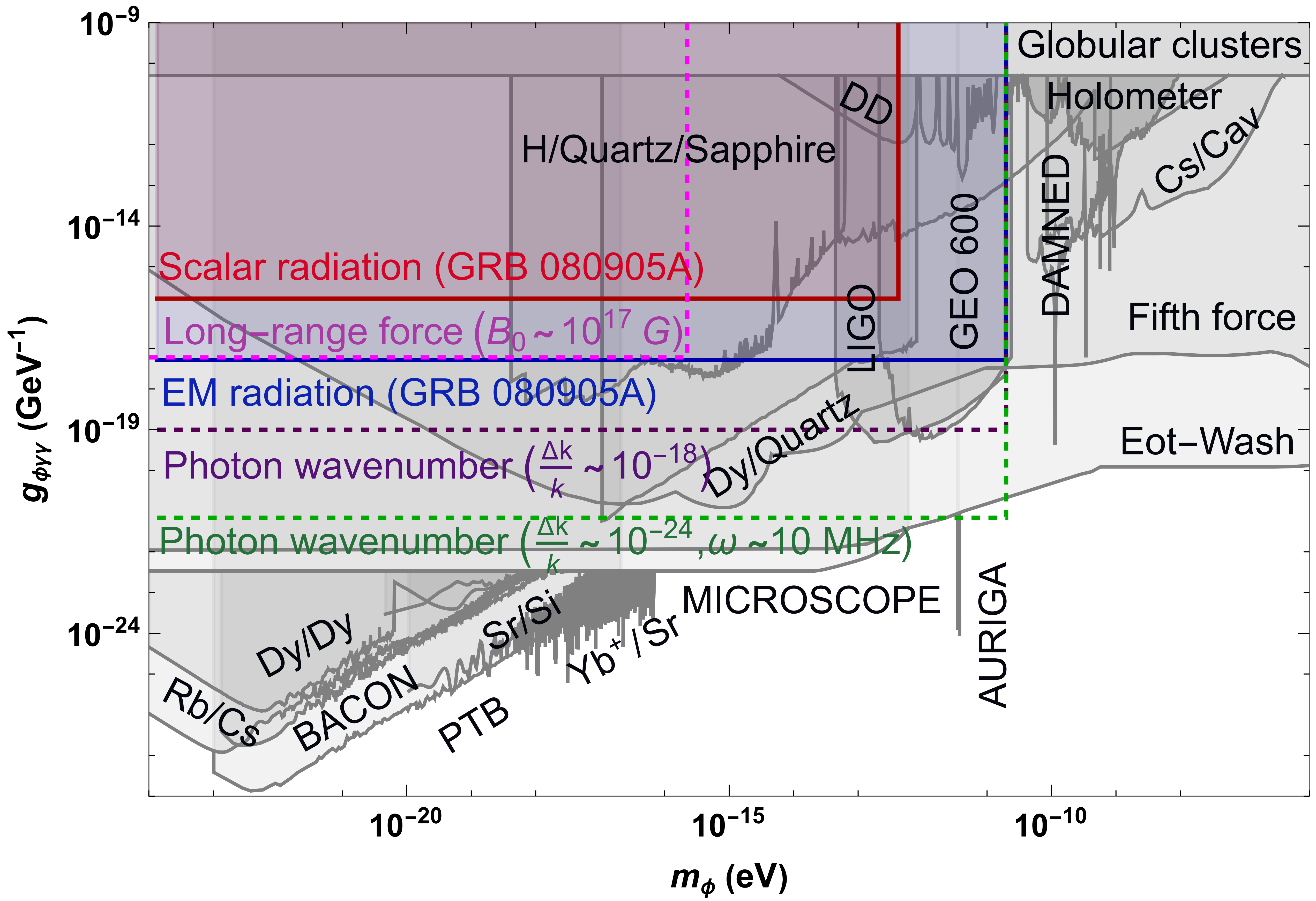
Magnetic dipole radiation

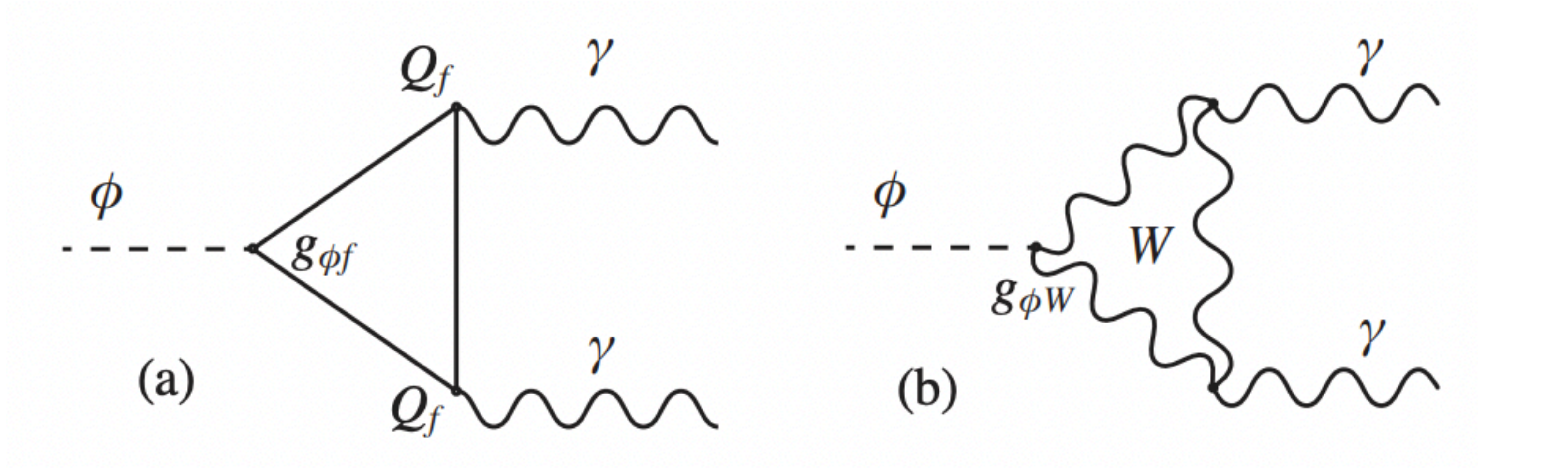
$$B_0 \sin\alpha = \left(\frac{3I}{8\pi^2 R^6}\right)^{\frac{1}{2}} (P\dot{P})^{\frac{1}{2}}$$

Look for NSs/magnetars with larger magnetic field, angular velocity, and size for better sensitivity

Results depend on magnetospheric model, EOS

Results are insensitive to the sign of $g_{\phi\gamma\gamma}$

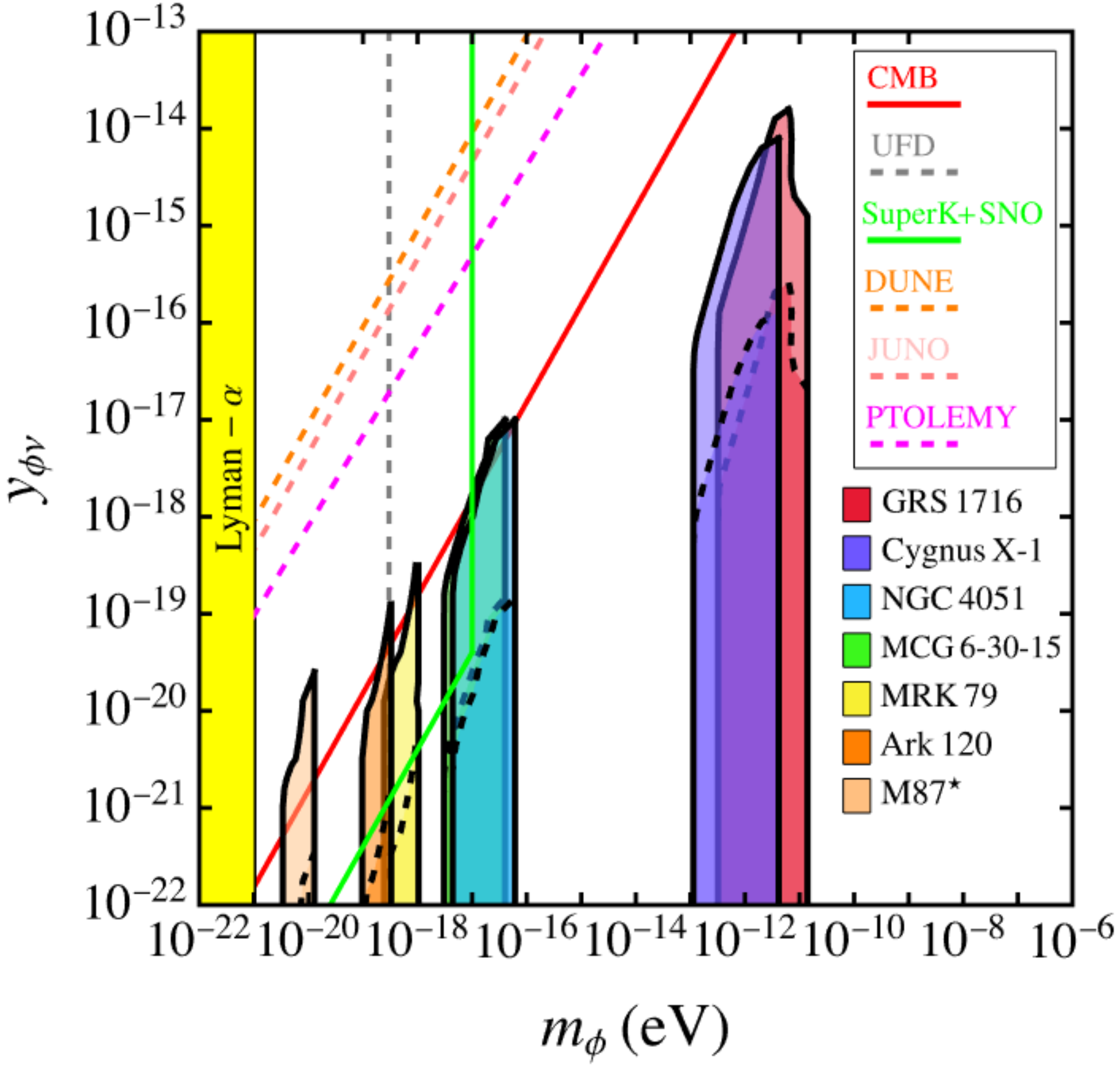




Effects of $C\nu B$ on BHSR

PRD 112, 016010 (2025)

Gaetano Lambiase, T.K.P., Luca Visinelli



BHSR driven by scalar fields

See talk by Francesca for the intro…

Excellent probe for ultralight scalars

$M_{ApBH} \approx (1 - 100)\ M_{\odot} \longrightarrow (10^{-11} - 10^{-13})$ eV

$M_{SMBH} \approx (10^6 - 10^9)\ M_{\odot} \longrightarrow (10^{-17} - 10^{-20})$ eV

Compton wavelength ~BH size

Need not be DM

Massive bosonic field (m_ϕ) forms a hydrogen-like bound state around a BH (M_{BH})

↓ Mass term acts as confining potential

Bound states grow via SR

↓ Occupation number amplified for

$$m\Omega_H > \omega$$

Forms macroscopic cloud

$$r_{cloud} \sim \frac{n^2}{\alpha^2} r_g$$

$$\alpha = r_g m_\phi = \frac{r_g}{\lambda_c}$$

Solve KG equation in Kerr metric

$$(\Box - m_\phi^2)\Phi = 0$$

$$\Phi \sim e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{nlm}(r)$$

Hydrogenic spectrum $\omega_{nlm} \simeq m_\phi\left(1 - \frac{\alpha^2}{2n^2}\right)$

Efficient growth for $\alpha \sim (0.1 - 0.3)$

Contd…

Imaginary part of angular frequency characterises instability mode

$$a_* \equiv a/r_g$$

$$r_+ = r_g(1 + \sqrt{1 - a_*^2})$$

$$\Omega_H = \frac{1}{2r_g}\frac{a_*}{1 + \sqrt{1 - a_*^2}}$$

$$\Gamma_{nlm} = 2m_\phi r_+ (m\Omega_H - m_\phi)\alpha^{4l+4}\mathcal{A}_{nl}\mathcal{X}_{nl}$$

$m\Omega_H > m_\phi$, amplitude of the wave shows exponential growth

The occupation number of particle increases $\dot{N}_{nlm} = \Gamma_{nlm} N_{nlm}$

$\tau_{\rm Sal} \approx 4.5 \times 10^7\ yr$ ApBH

The superradiant modes grow exponentially as long as $\tau_{SR} < \tau_{ch}$

$\tau_{\rm BH} = 10^9\ yr$ SMBH

SR condition ceases for $$N_{\max} = \frac{GM_{\rm BH}^2 \Delta a_*}{m} \approx \frac{10^{76}}{m}\left(\frac{M_{\rm BH}}{10\,M_\odot}\right)^2\left(\frac{\Delta a_*}{0.1}\right)$$

Energy extraction occurs at ergoregion: SR instability drains BH's angular momentum and energy, significant at $r \sim (\alpha m_\phi)^{-1}$

SR amplification can be suppressed by self-interaction of the scalar field

Observation of highly spinning BH excludes boson mass at $\sim r_g^{-1}$

Effects of $C\nu B$ around BH

Very low energy → $10^{-4} - 10^{-6}$ eV Difficult to detect

Decouple much earlier than photon→ can probe universe before CMB

At present epoch $T_\nu \sim 1.95\ K \sim 1.68 \times 10^{-4}$ eV

Standard cosmological model predicts $n_\nu \sim 336/\ \text{cm}^3$

Oscillation data gives two of the neutrino mass eigenstates are NR today

PTOLEMY can detect through inverse β decay of tritium

Affects CMB fluctuations→ indirect probe

Cosmic neutrinos and light scalar fields

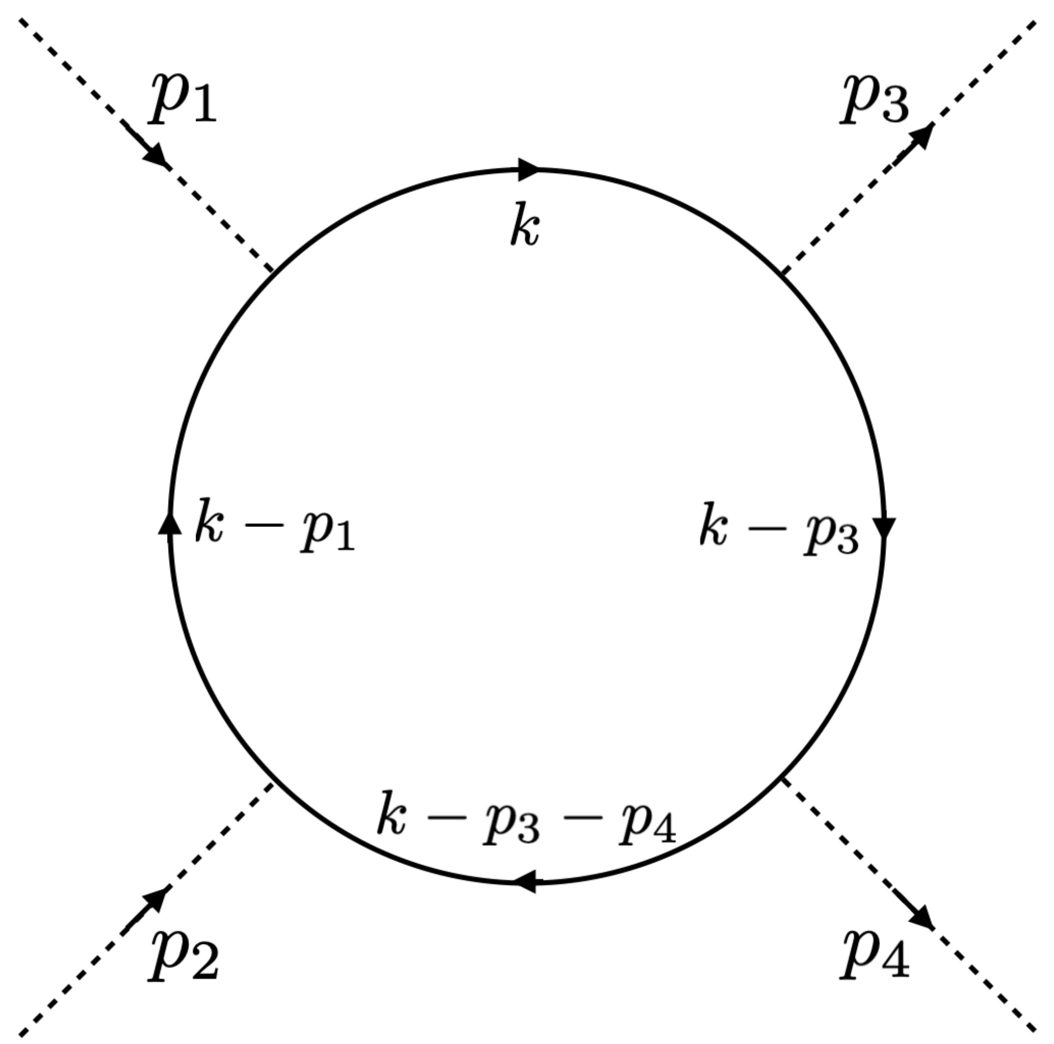
$$\mathscr{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - m_{\alpha\beta}\bar{\nu}_\alpha\nu_\beta - y_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$$

In a non-SUSY theory, radiative correction to the scalar potential from fermion loop generate effective quartic coupling even in the absence of tree level quartic coupling

The CW mechanism yields an effective potential $V_{\rm CW} \propto y_{\phi\nu}^4\phi^4 \ln\phi^2$

$$\lambda^{(0)} \sim \frac{y_{\phi\nu}^4}{16\pi^2}\ln\left(\frac{m_\phi^2}{m_\nu^2}\right)$$

In SUSY, quartic term cancel at zero temperature and radiative corrections to the scalar potential suppressed



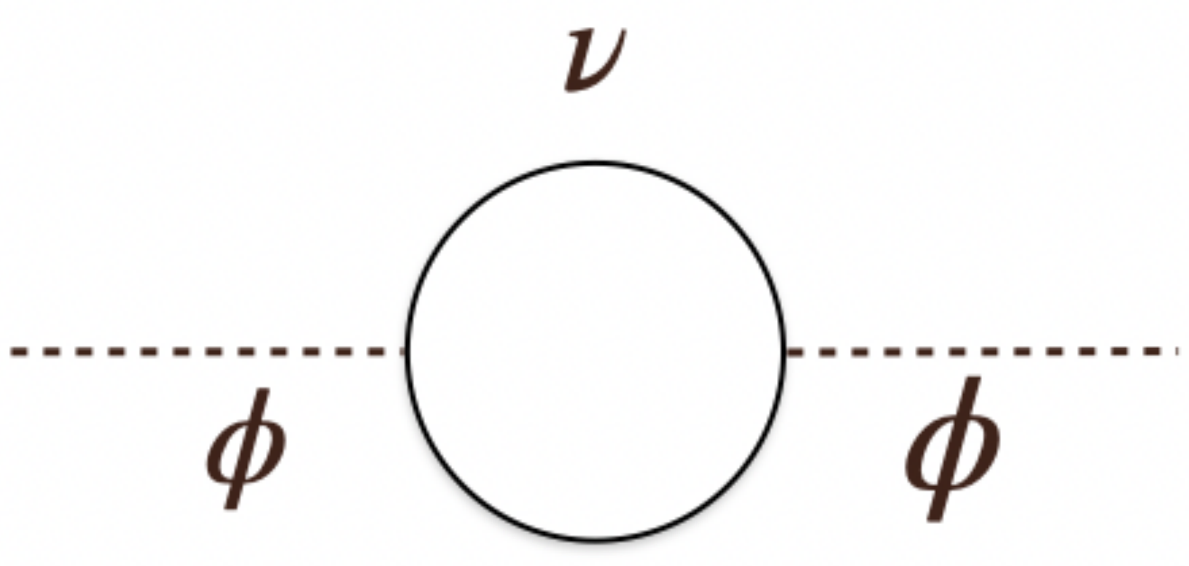
Thermal effects break SUSY: scalar fields acquire thermal mass and self-interaction through its Yukawa coupling to fermions

Contd…

Thermal correction from $C\nu B$ for $m_\phi \ll T_\nu,\, m_\nu$

The mass correction

$$\Delta m_\phi^2 = \frac{y_{\phi\nu}^2}{\pi^2} \int_{m_\nu}^{+\infty} \mathrm{d}\varepsilon \sqrt{\varepsilon^2 - m_\nu^2}\, f_\nu(\varepsilon)$$



For inverted hierarchy with $m_1 = m_2 = 50$ meV, $m_1 = 10$ meV

$$\Delta m_\phi^2 = 1.2 \times 10^{-10}\,\mathrm{eV}^2\, y_{\phi\nu}^2 \qquad m_{\phi,\mathrm{eff}}^2 = m_\phi^2 + \Delta m_\phi^2$$

Quartic Lagrangian is induced through loop that involves Yukawa coupling

$$\mathscr{L}_{\mathrm{int}} = \frac{1}{4!}\lambda\phi^4 \qquad \lambda = \lambda^{(0)} + \Delta\lambda^{(T)}$$

for $m_\nu \gg T_\nu$

$$\Delta\lambda^{(T)} \sim y_{\phi\nu}^4 \frac{n_{\nu,\mathrm{tot}}}{m_\nu^3}$$

Efficiency of the energy extraction is limited by the non-linear dynamics

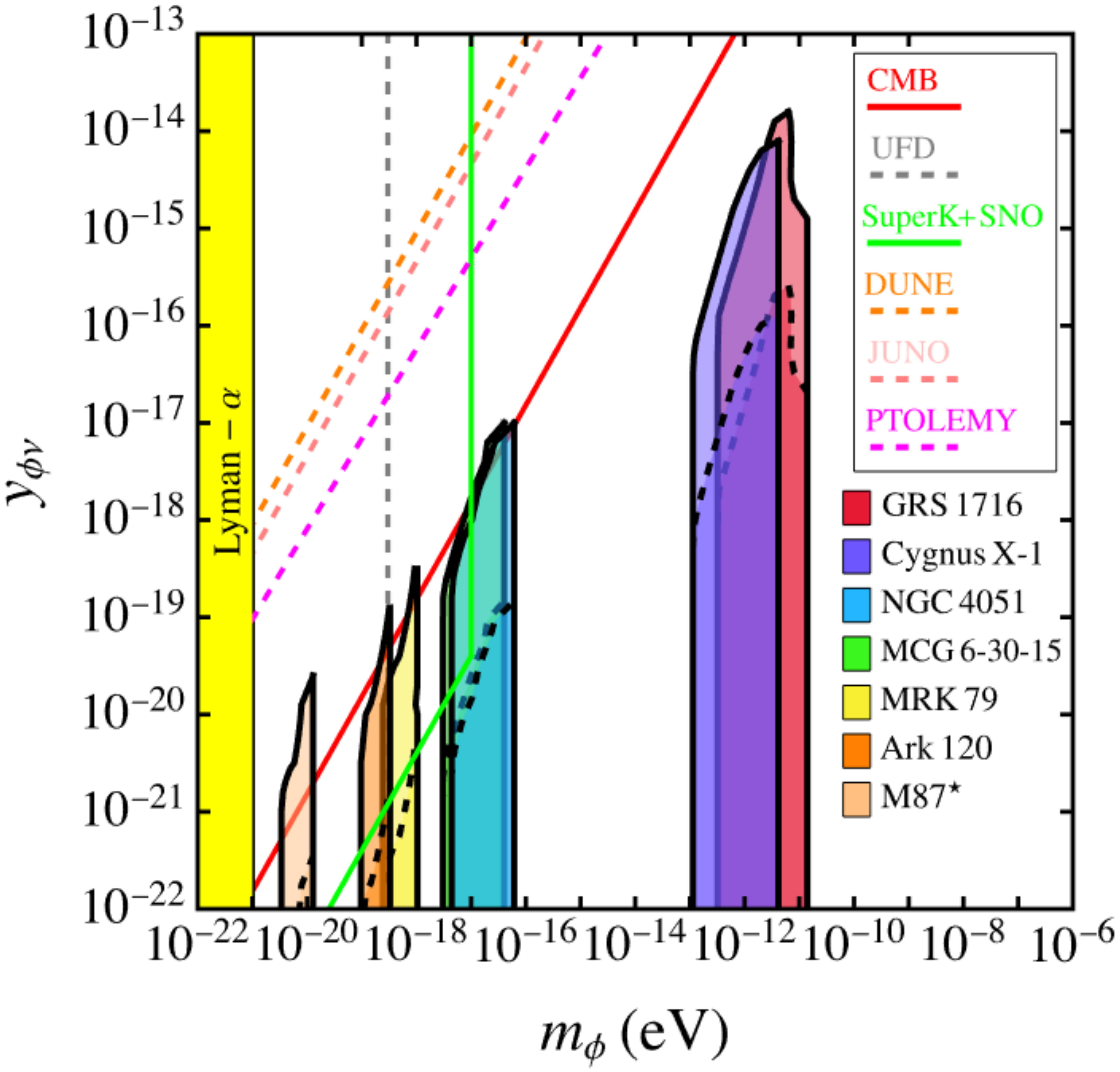
Perform least square fit based on maximum likelihood estimator, incorporates mass and spin of each BH

Vary scalar field mass and coupling, assuming Gaussian errors

Like neutrinos, electrons in the accretion disk of BH modify bosonic mass through thermal corrections

$$\Delta m_\phi^2 = 3 \times 10^{-10}\,\mathrm{eV}^2\, y_{\phi e}^2 \left(\frac{n_e}{10^{10}\,\mathrm{cm}^{-3}} \right)$$

Require dedicated spectral and timing analysis of X-ray obsevration

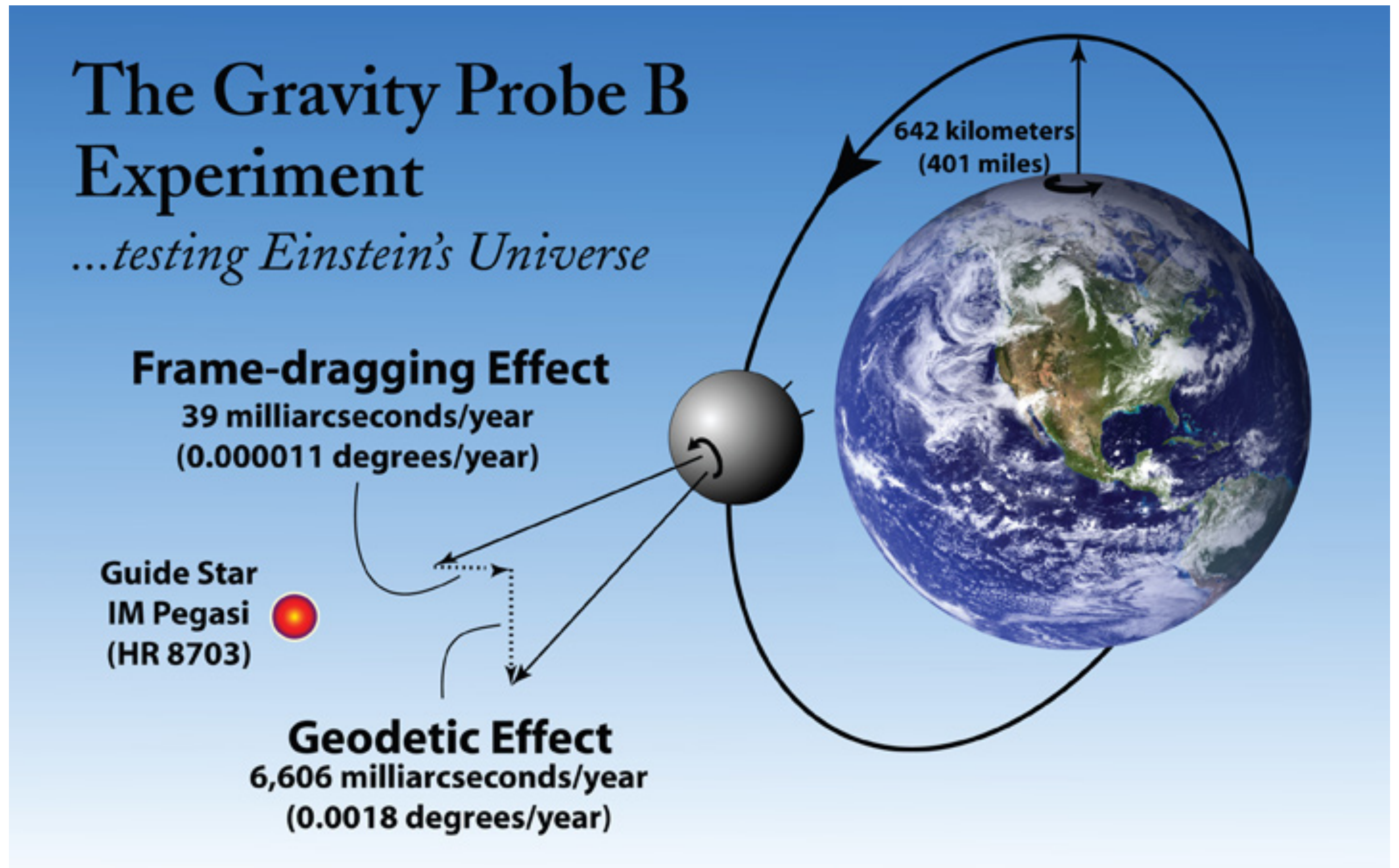


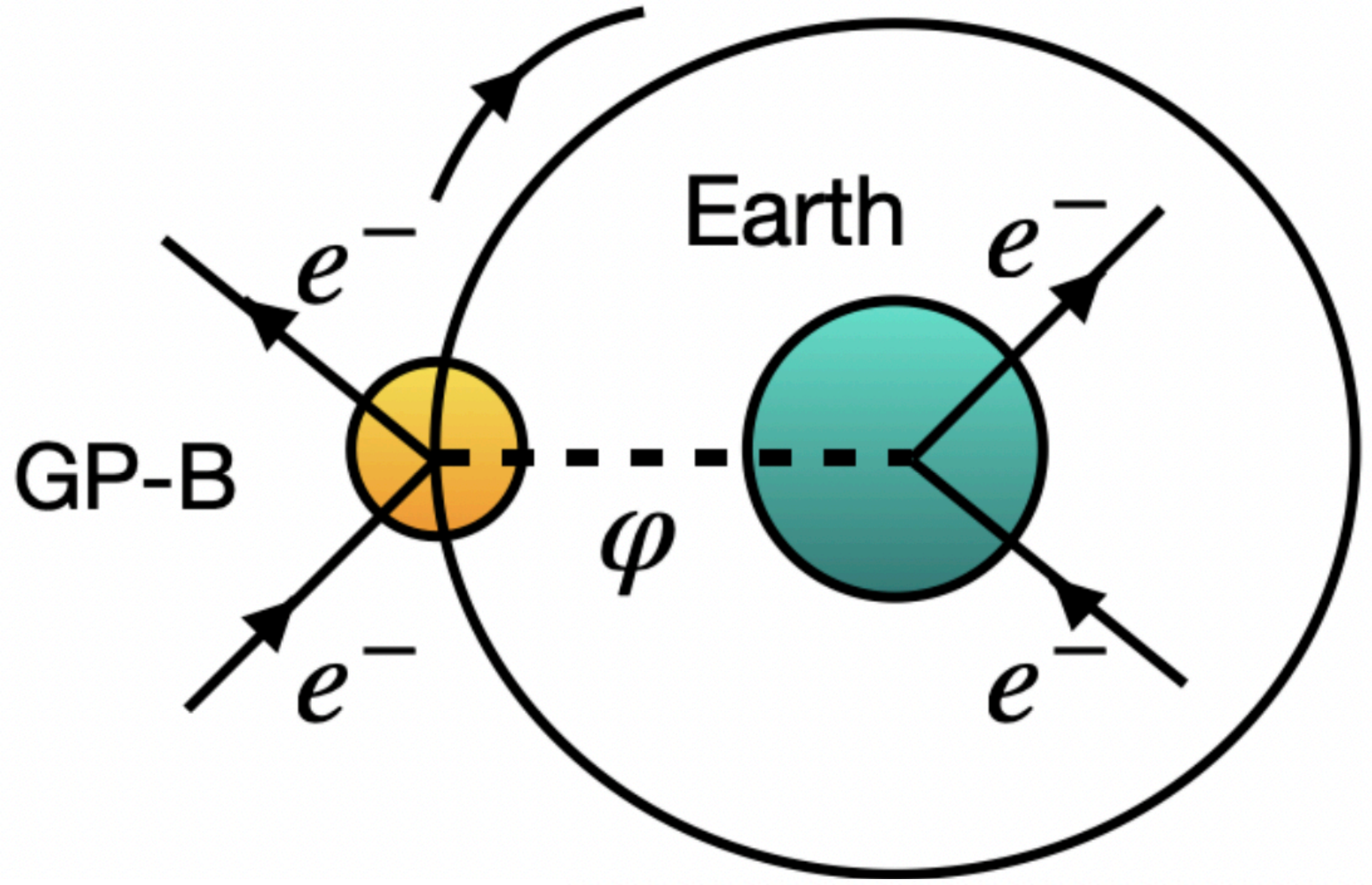
DSNB density is $\sim 10^{-11}$ cm^{-3}, does not affect our results

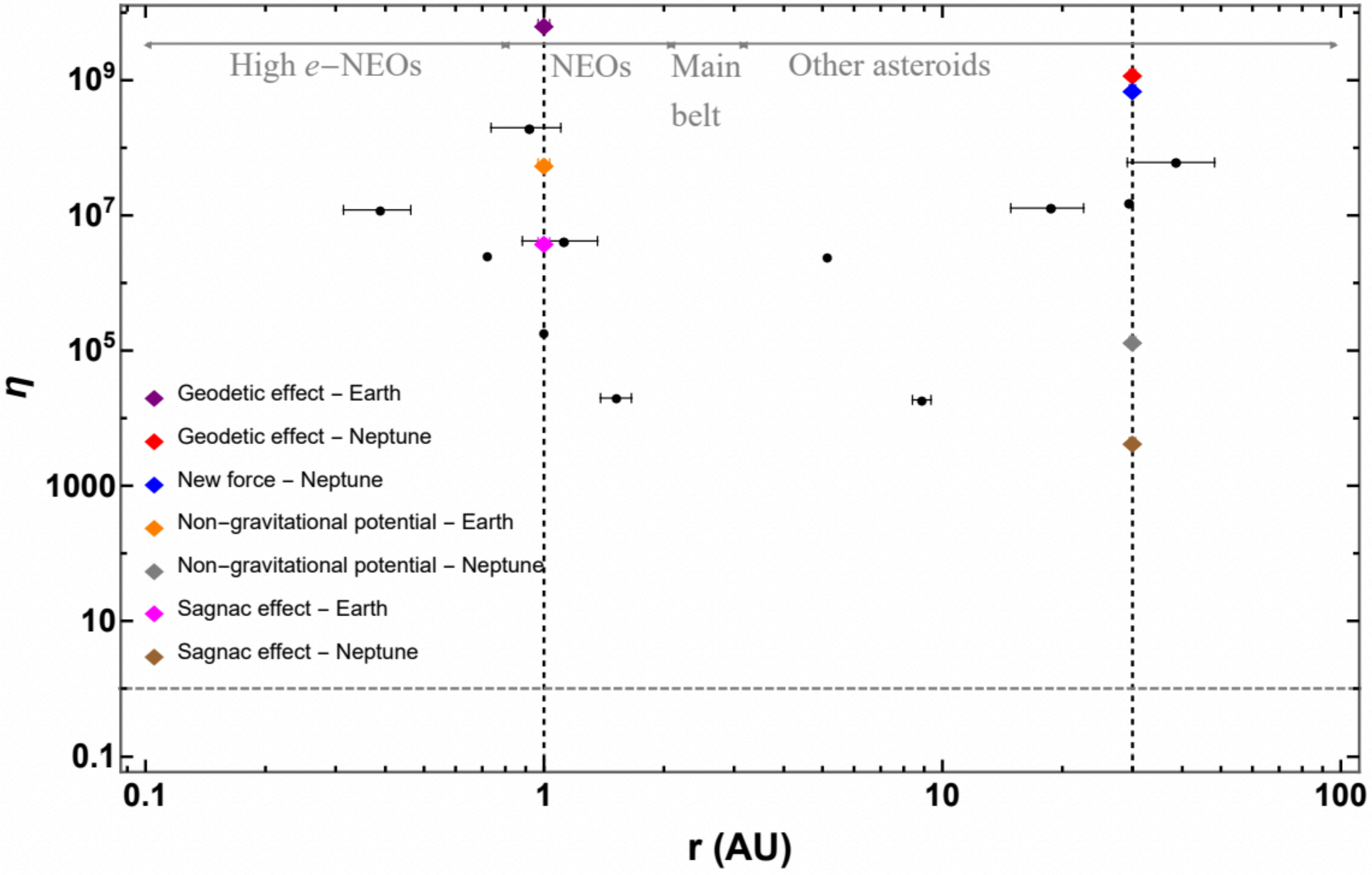
Constraints on ultralight scalars and DM density from geodetic effect

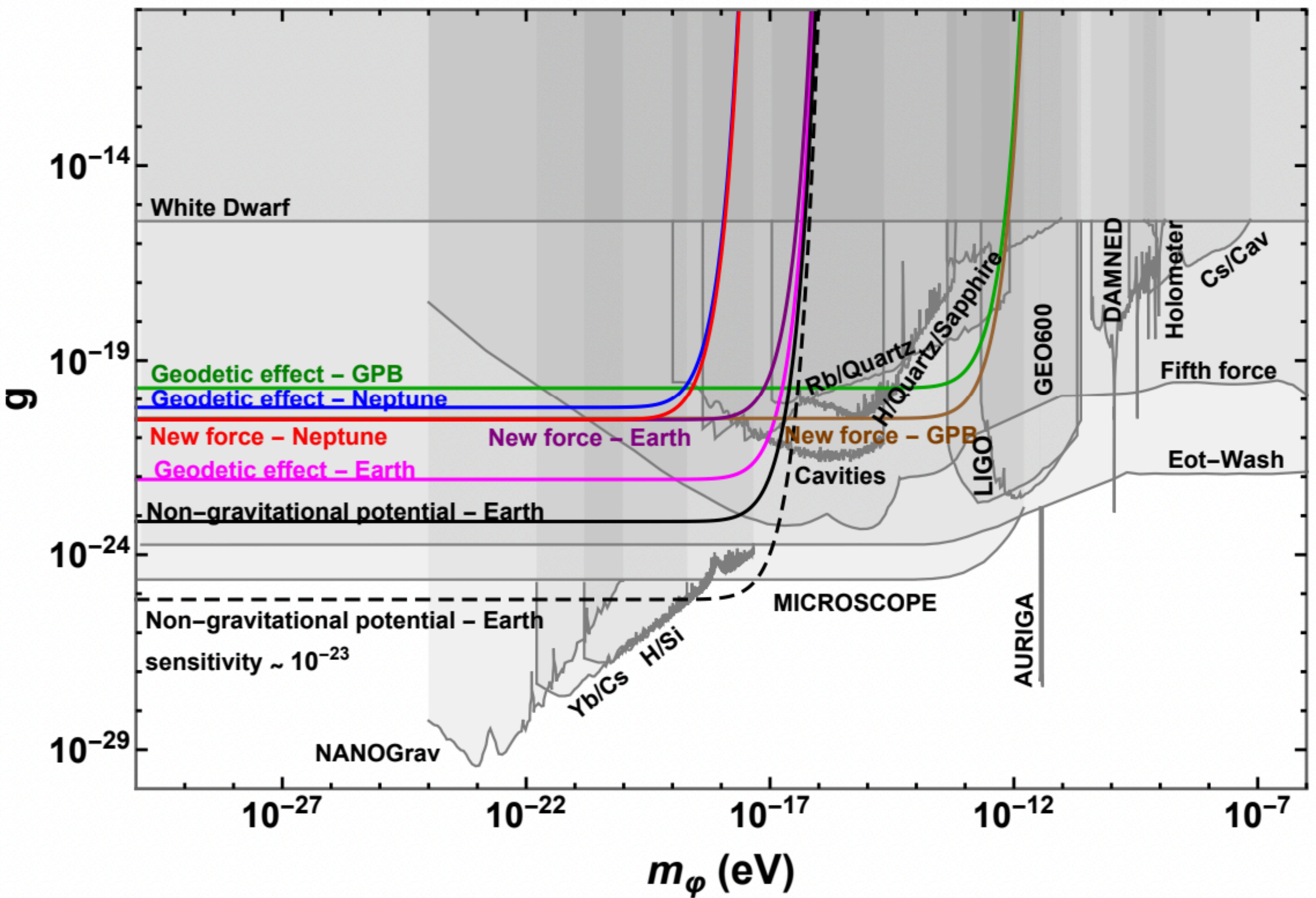
JCAP 03 (2025) 049

S.R.Aliberti, G.Lambiase, T.K.P









Thank You !