Probing ultralight scalars through magnetised star observations and black hole superradiance

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Based on **2501.02286, 2503.02940**

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Light Dark World 2025

NS/Magnetar/SGR/GRB

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

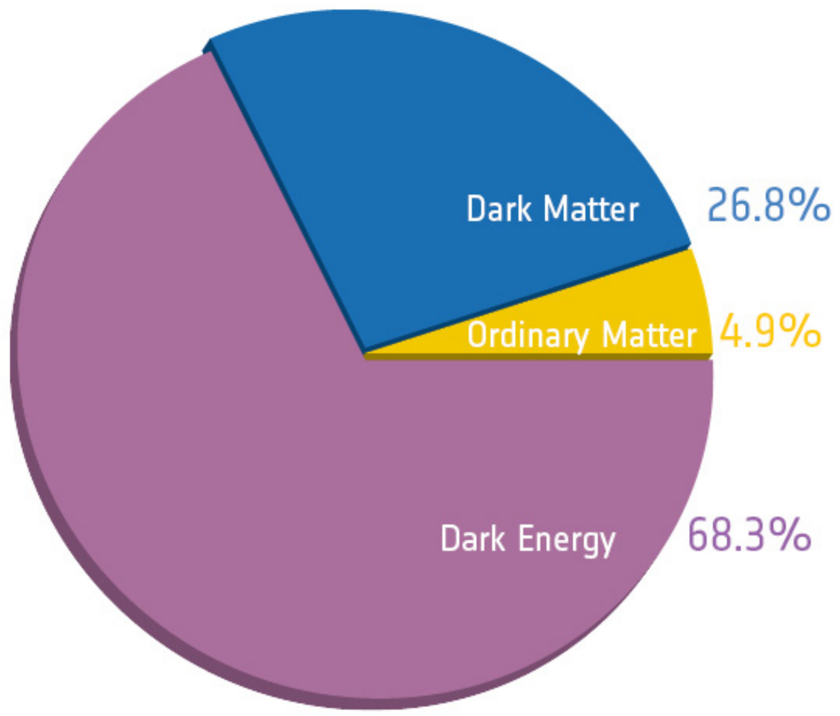
Input parameters:

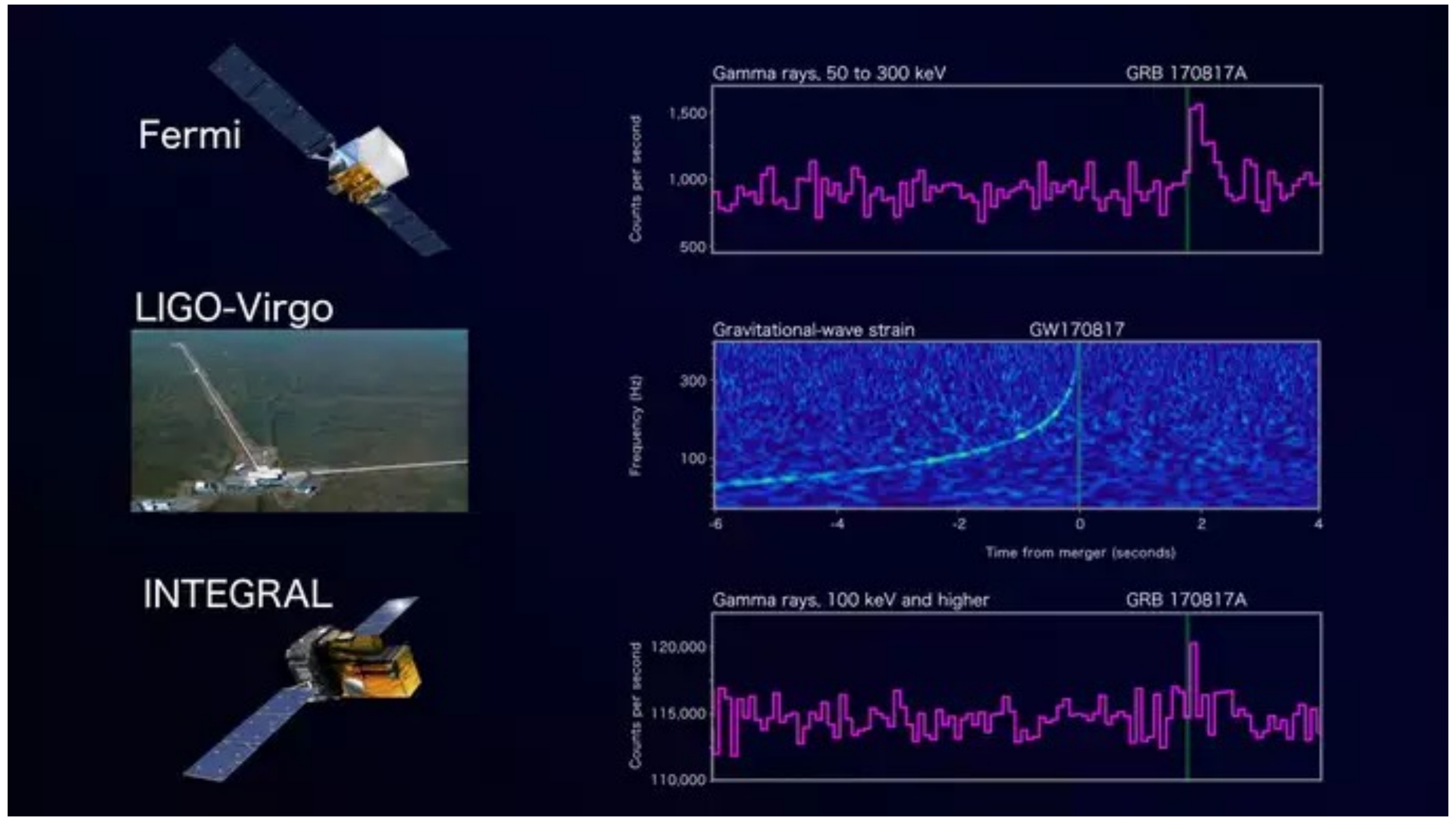
Constituents: neutrons, protons, electrons, muons, hyperons

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

Cosmic laboratories for exploring the mysteries of the universe

Study multi-messenger astronomy





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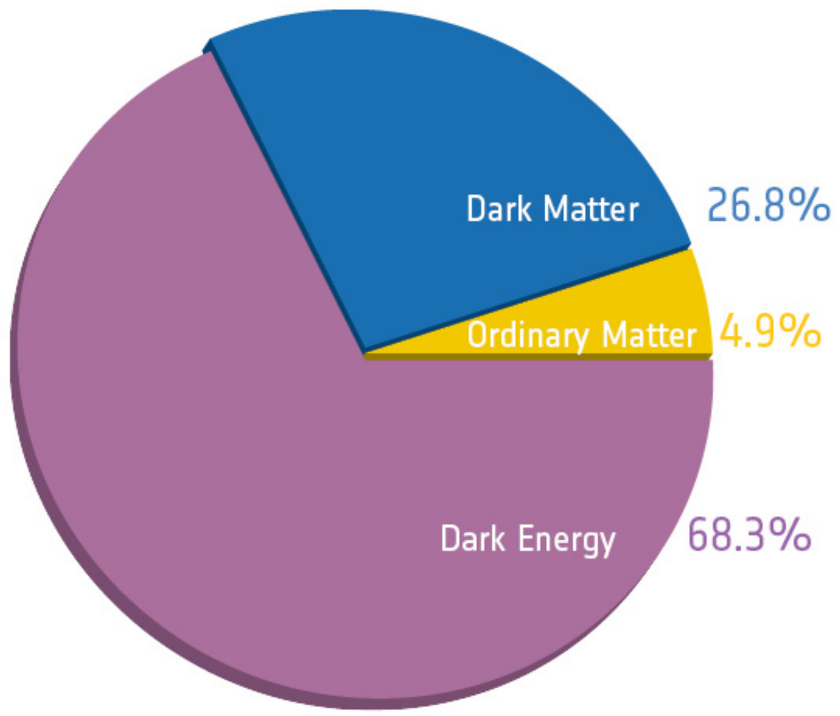

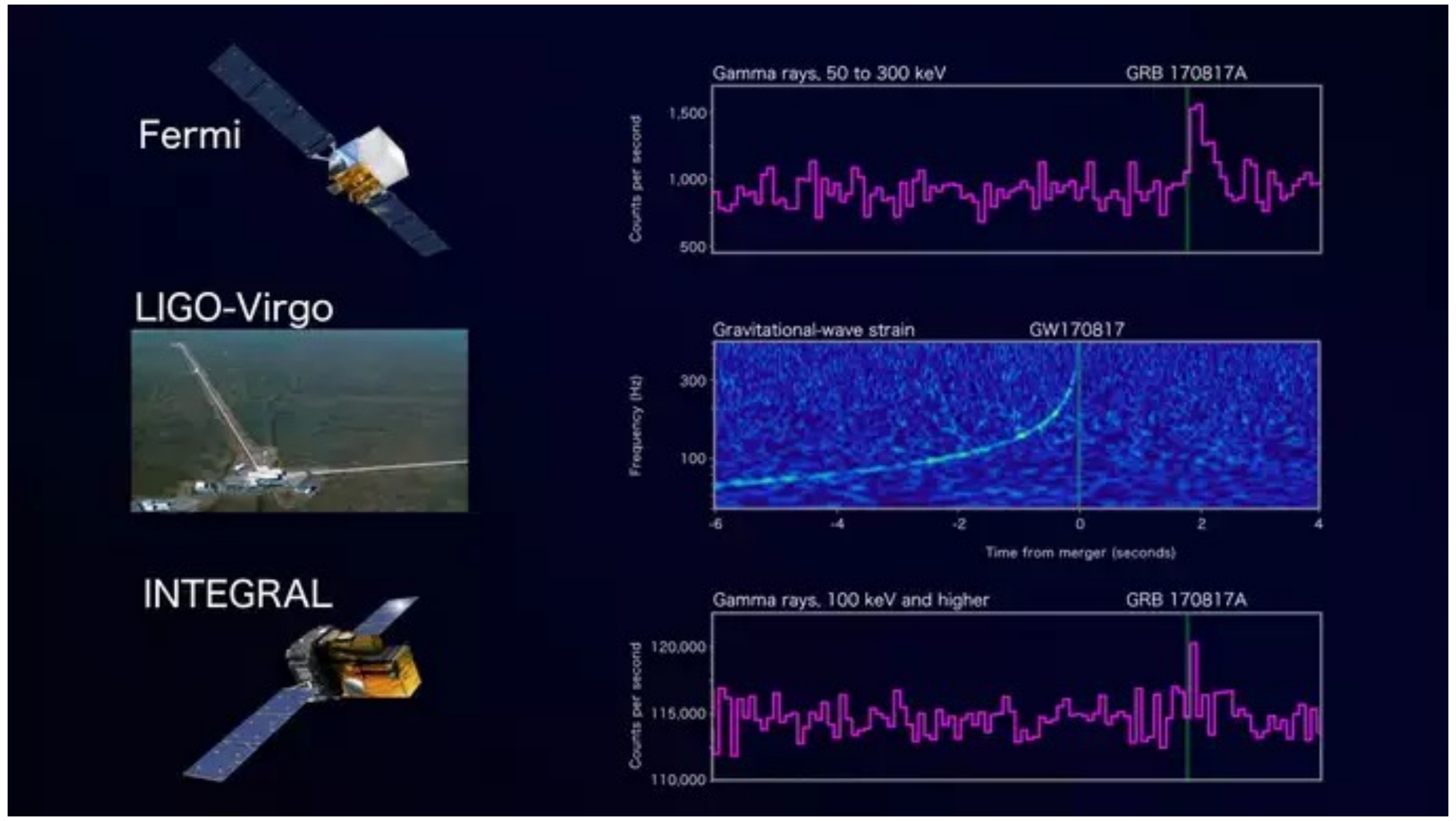

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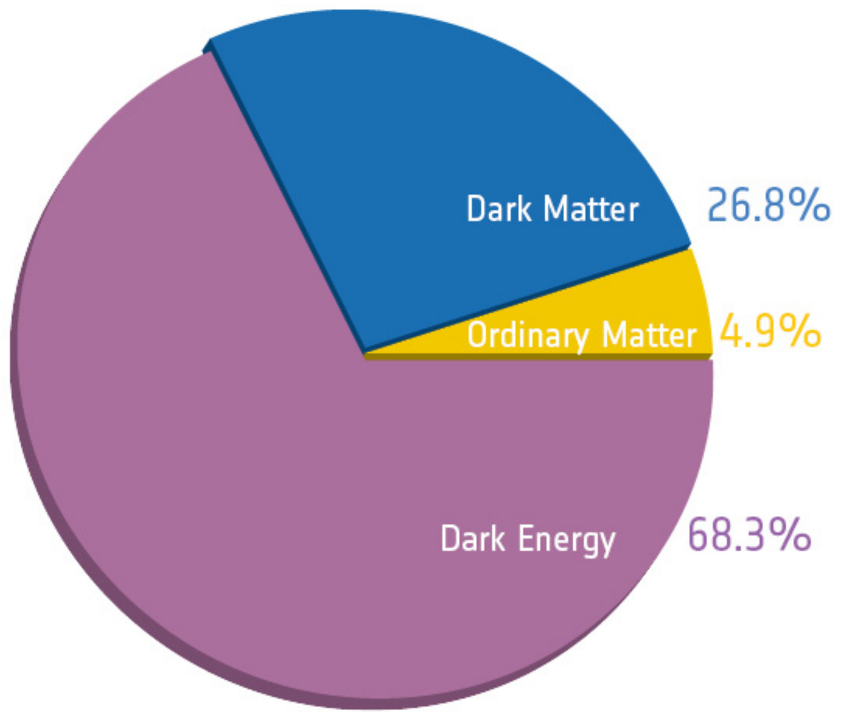

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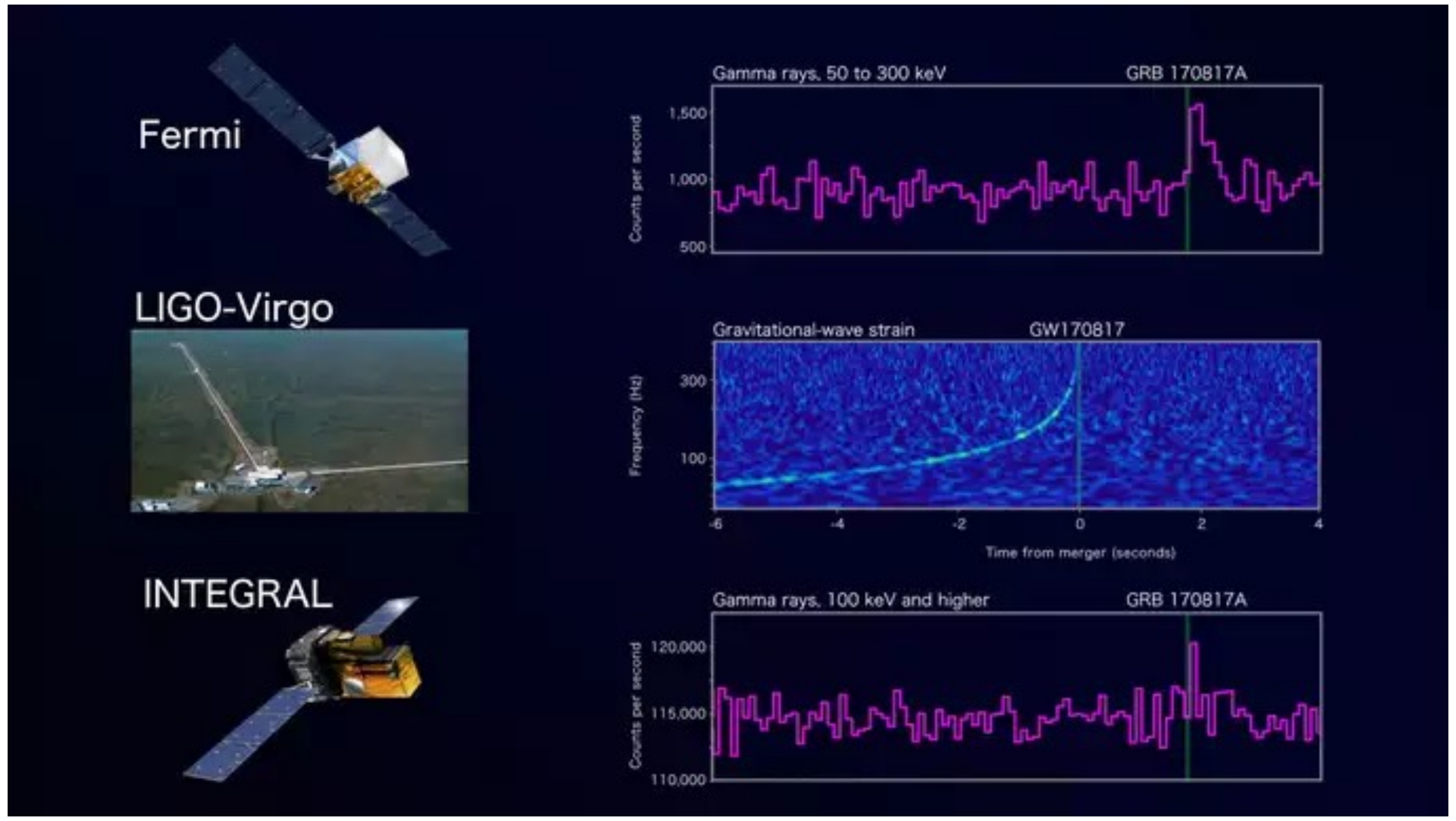

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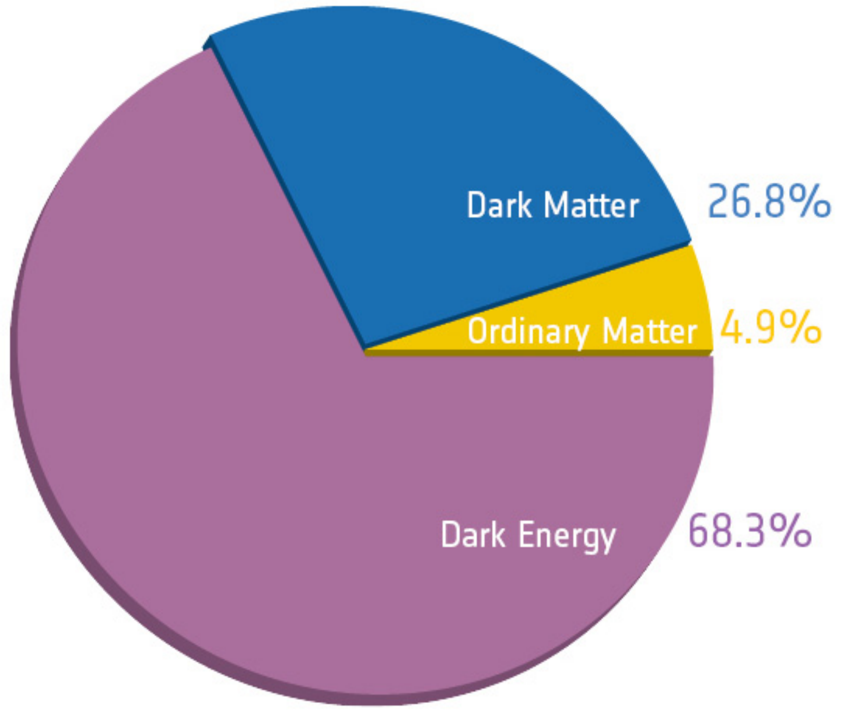

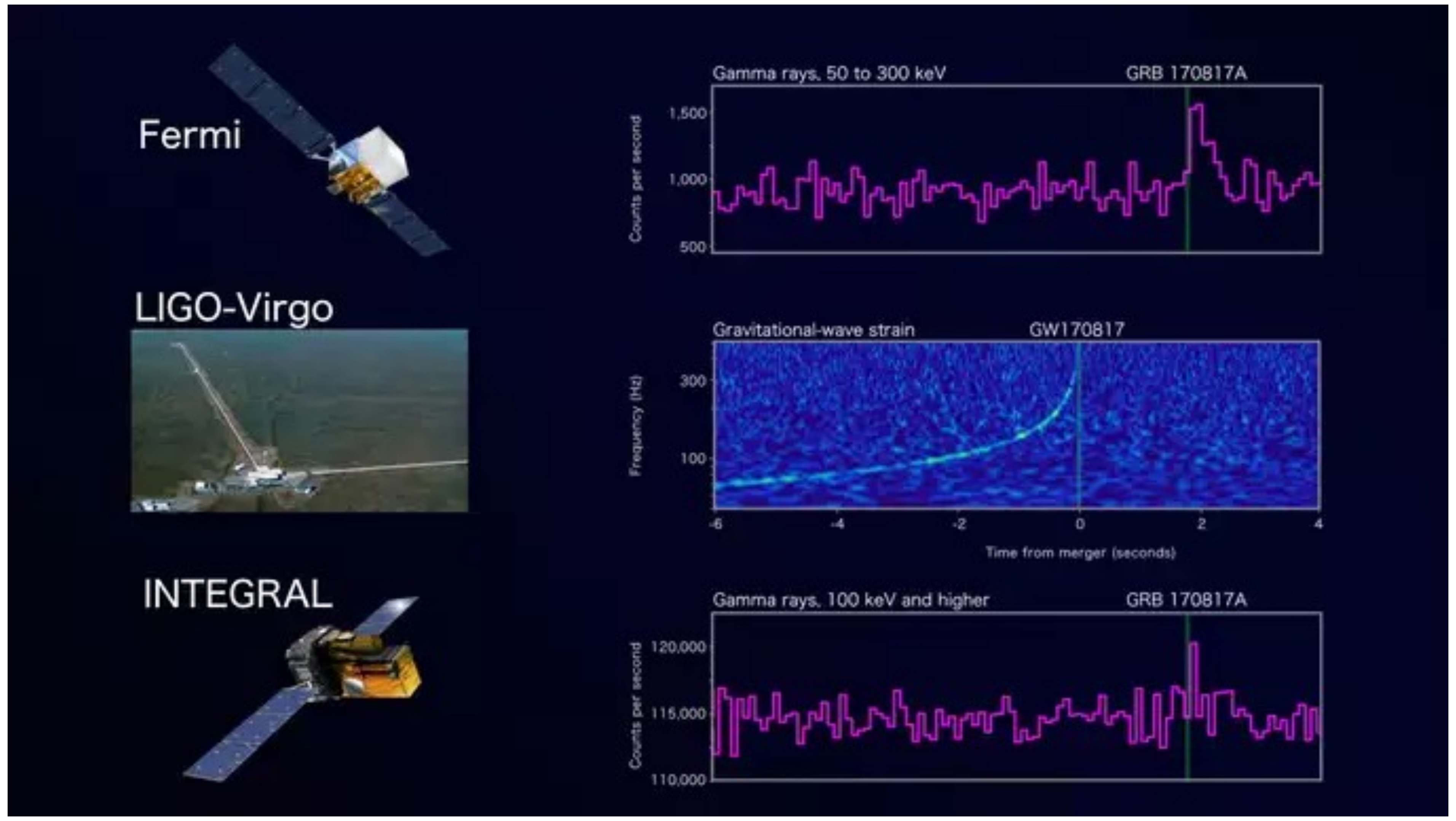

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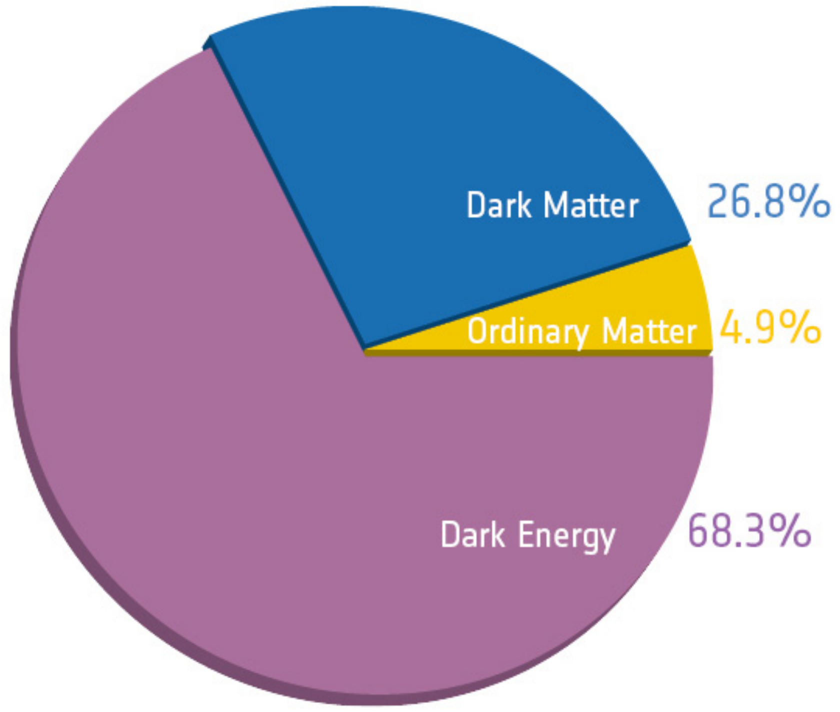
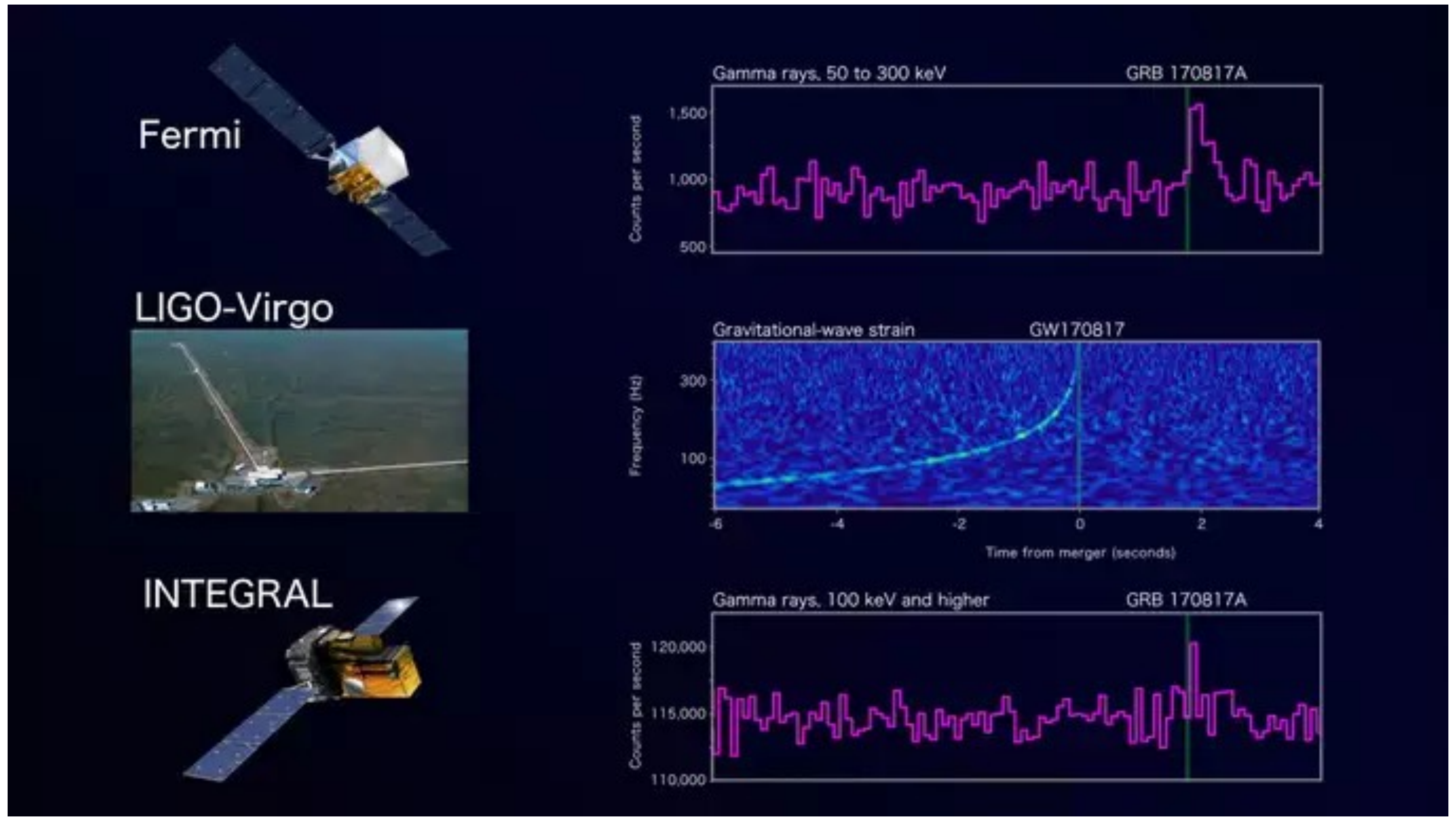
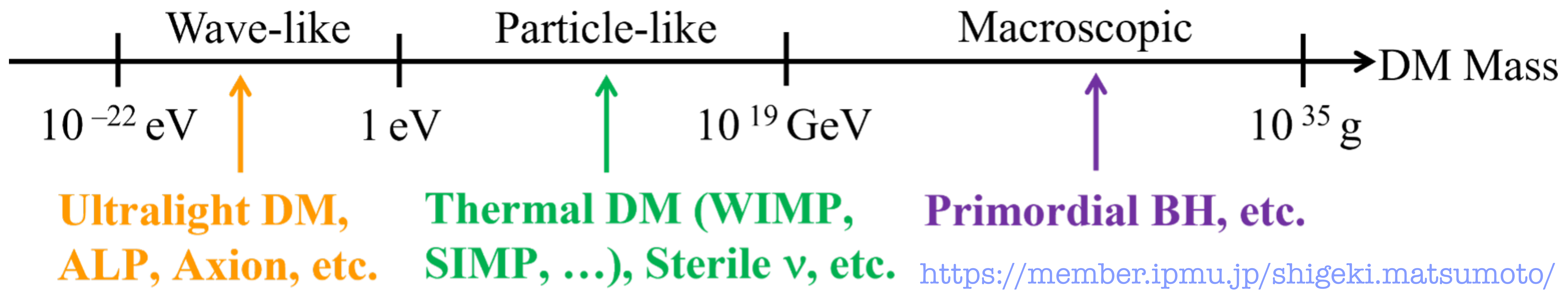




Advantages over traditional laboratory-based experiments:

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

Ultralight scalars: A possible dark matter candidate



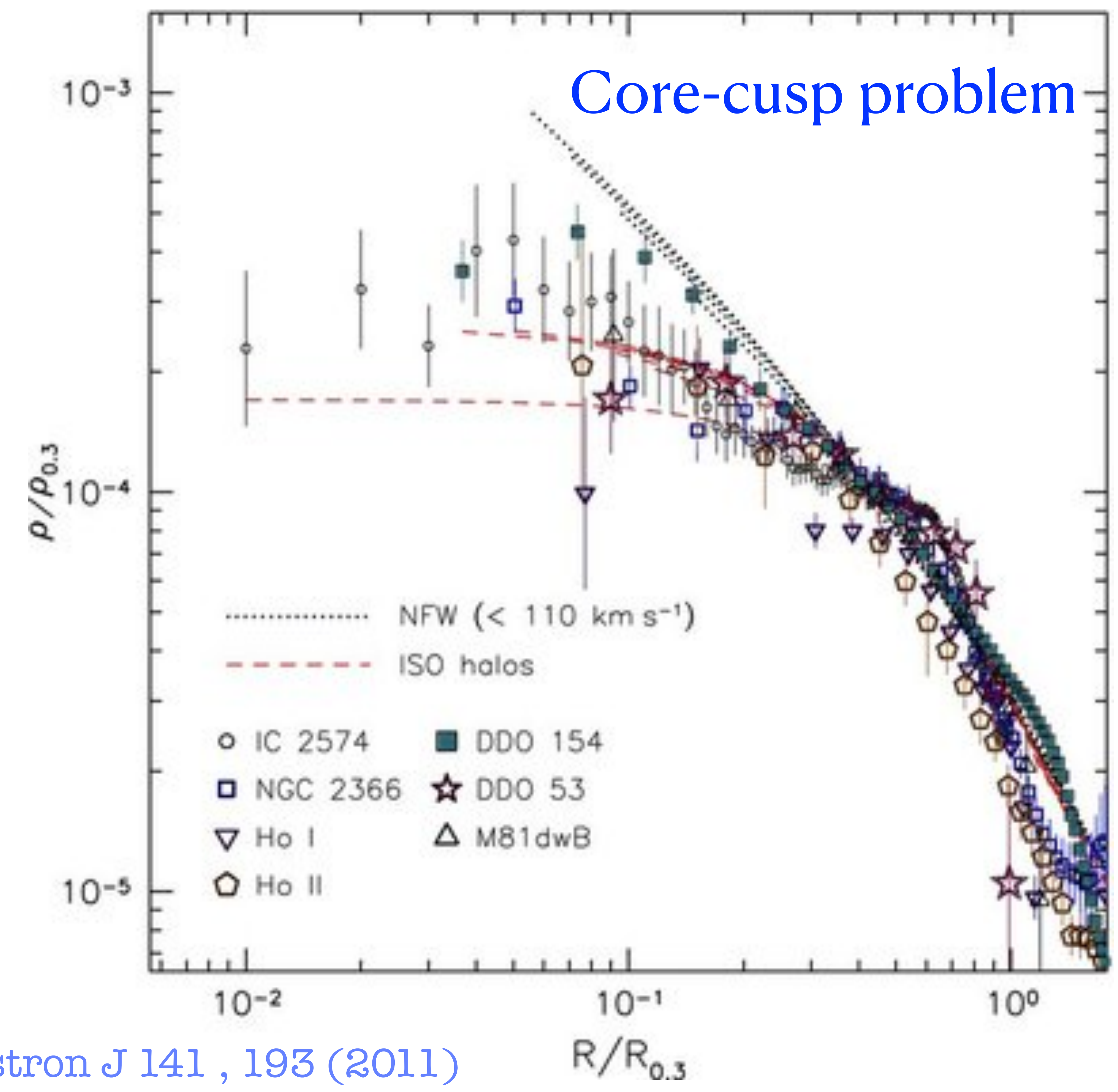
https://member.ipmu.jp/shigeki.matsumoto/

DM present at all scales

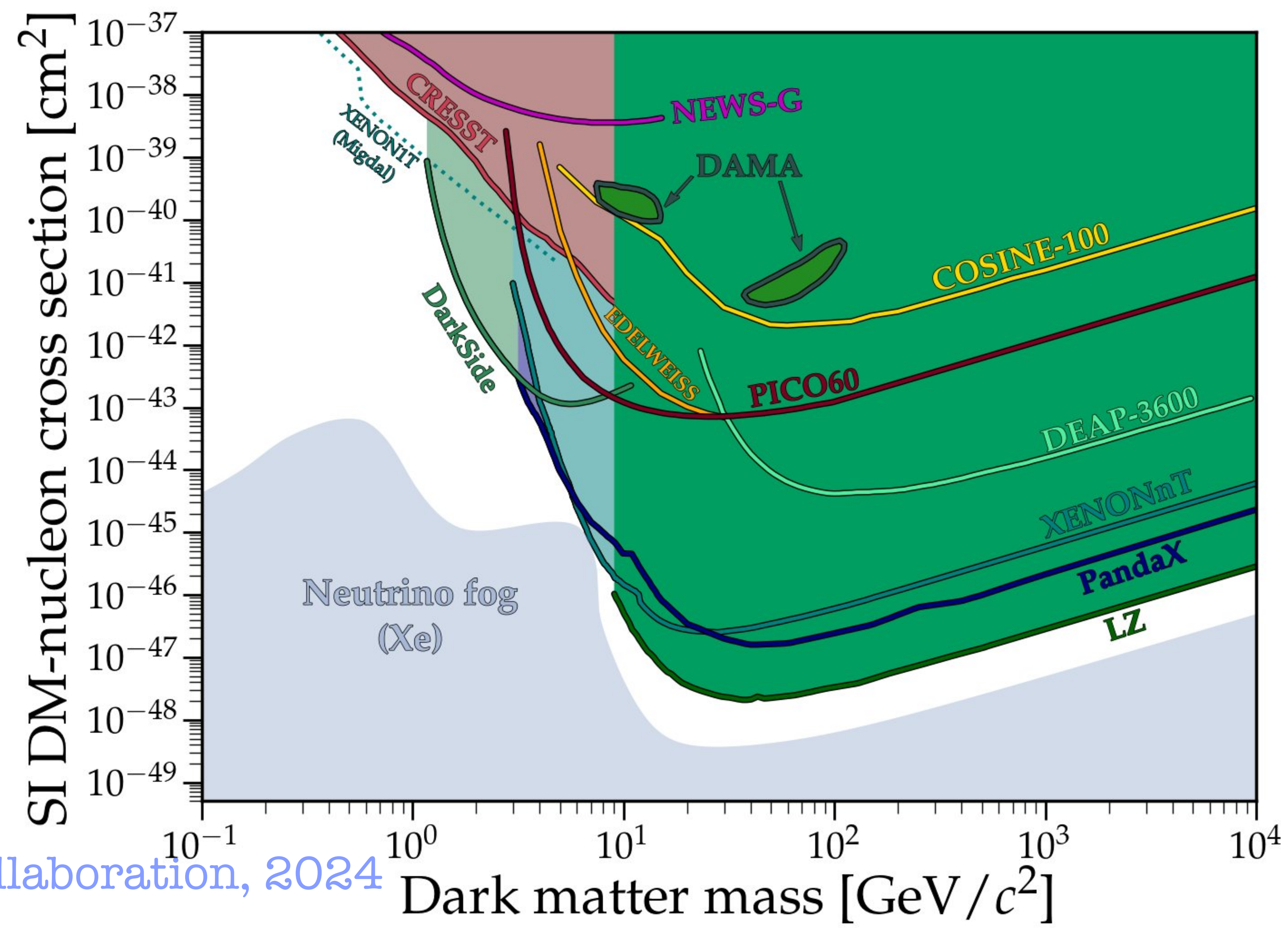
- Rotation curve
- Bullet clusters
- CMB
- Structure formation

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

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



Astron J 141 , 193 (2011)



LZ collaboration, 2024

Direct detection constraints

Scalar electromagnetic coupling

2501.02286

T.K.P., and Amol Dighe

Outline:

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Scalar interaction with the EM fields of the compact star/ Photon propagation through the scalar field → long-range field, Alters Maxwell's equation, photon dispersion relation, Photon wavenumber changes from point of emission to detection

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Scalar-mediated long-range force → Constraints from fifth force experiments

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Scalar-induced magnetic field alters surface magnetic field of the pulsar → Energy loss through magnetic dipole radiation

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- Scalar-mediated long-range force → Constraints from fifth force experiments

- Scalar-induced magnetic field alters surface magnetic field of the pulsar → Energy loss through magnetic dipole radiation

- Scalar radiation from the time-dependent source → Pulsar spin-down

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

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

Long-range scalar field outside a compact star

Aligned rotator model

For axions,

$$\mathscr{L} \supset g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \sim g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$

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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.

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

The scalar field has a long-range behaviour

$$\phi(r)\approx\frac{Q_\phi^{\mathrm{K}}}{r}$$

$l=0$ monopole term

The scalar charge

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

For binary

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

Contd…

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For axions

$$a\sim\frac{\cos\theta}{r^2}$$

$l=1$, dipole term

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For binary

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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 $g_{\phi\gamma\gamma}$ $\qquad F^{\mu\nu} = F^{\mu\nu}_{(0)} + F^{\mu\nu}_{\phi} + \mathcal{O}(g^2_{\phi\gamma\gamma})$

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

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

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

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

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

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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

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

The group velocity

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

Scalar-induced photon mass

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

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The photon dispersion relation

Propagation is independent of photon polarisation, unlike axions

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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

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

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

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

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

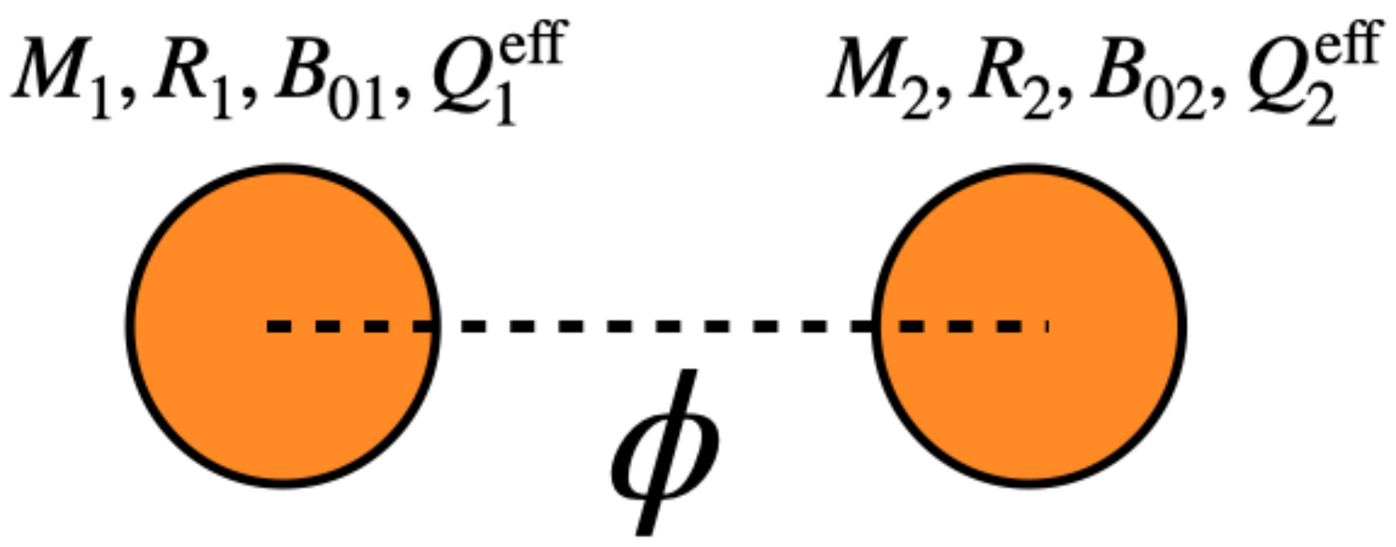
Time-averaged dipole moment

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

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

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

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

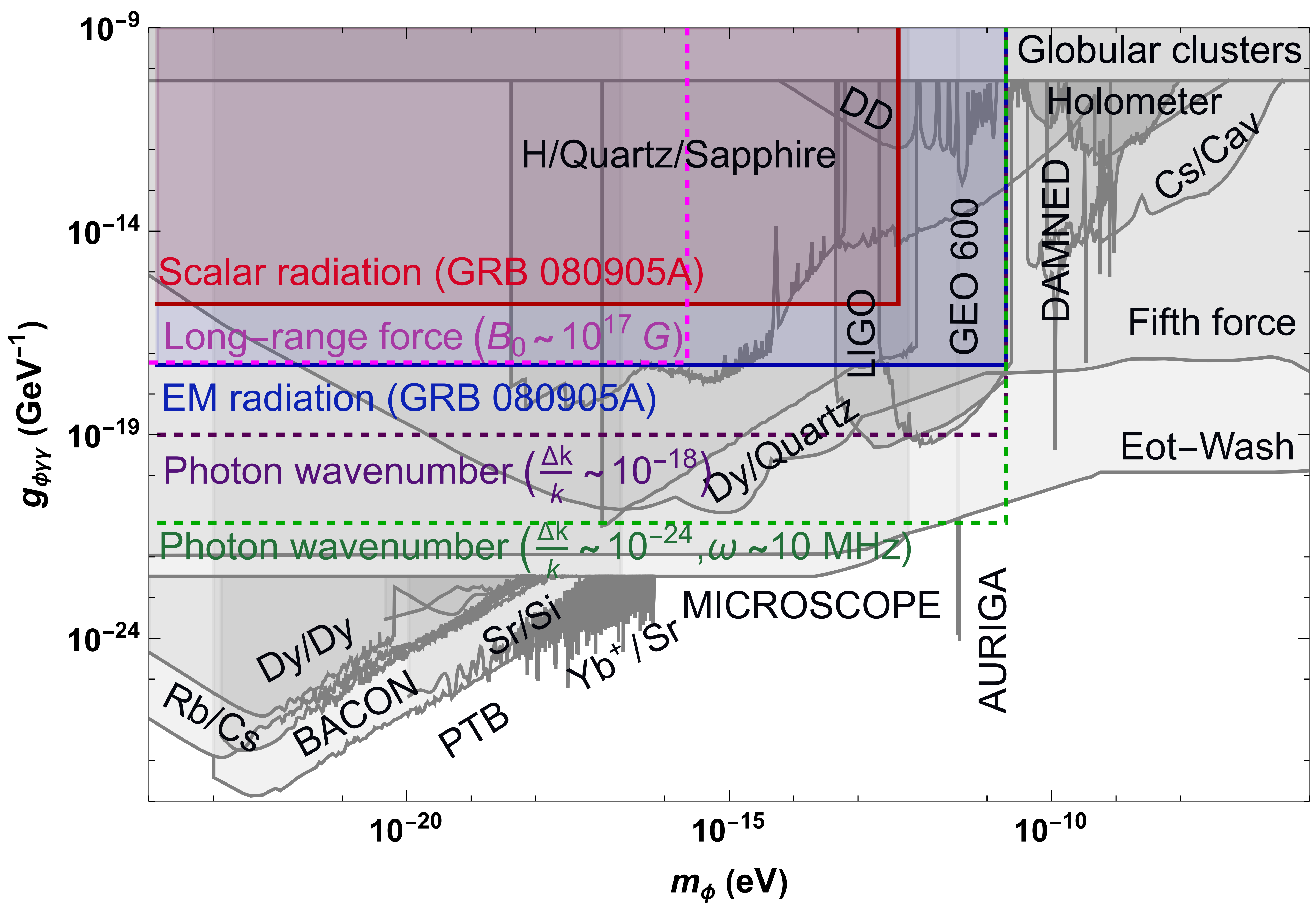


PSR J0737-3039

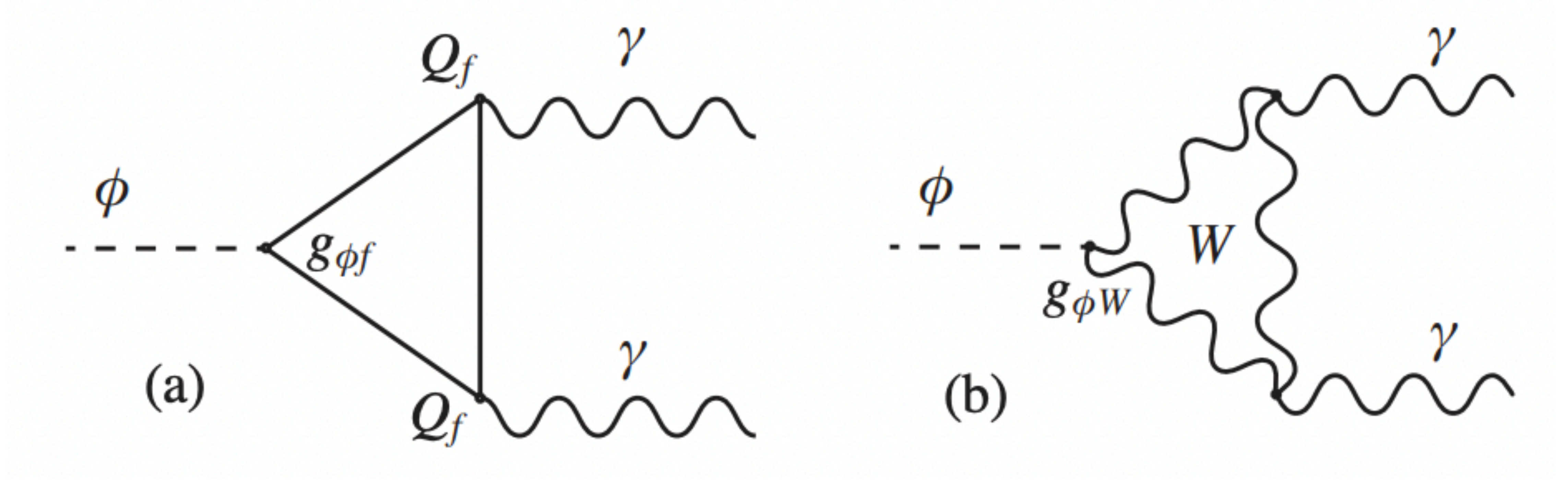
$$\eta = \frac{Q_1^{\rm eff} Q_2^{\rm eff}}{4\pi G M_1 M_2} \approx \frac{g_{\phi\gamma\gamma}^2 B_{01}^2 B_{02}^2 R_1^6 R_2^6}{(48)^2 \times 4\pi G^7 M_1^4 M_2^4}$$

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 $g_{\phi\gamma\gamma}$

Effect of $C\nu B$ on BH superradiance

PRD 112, 016010 (2025)

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

BHSR driven by scalar fields

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

Excellent probe for ultralight scalars

Compton wavelength ~BH size

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

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…

$$a_* \equiv a/r_g$$

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

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

Imaginary part of angular frequency characterises instability mode

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

$m\Omega_H > m_\phi$, 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

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

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

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 $\rightarrow 10^{-4} - 10^{-6}$ eV Difficult to detect

Decouple much earlier than photon $\rightarrow$ 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 $n_\nu \sim 336/\ \mathrm{cm}^3$

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

PTOLEMY can detect through inverse β decay of tritium

Affects CMB fluctuations $\rightarrow$ indirect probe

Cosmic neutrinos and light scalar fields

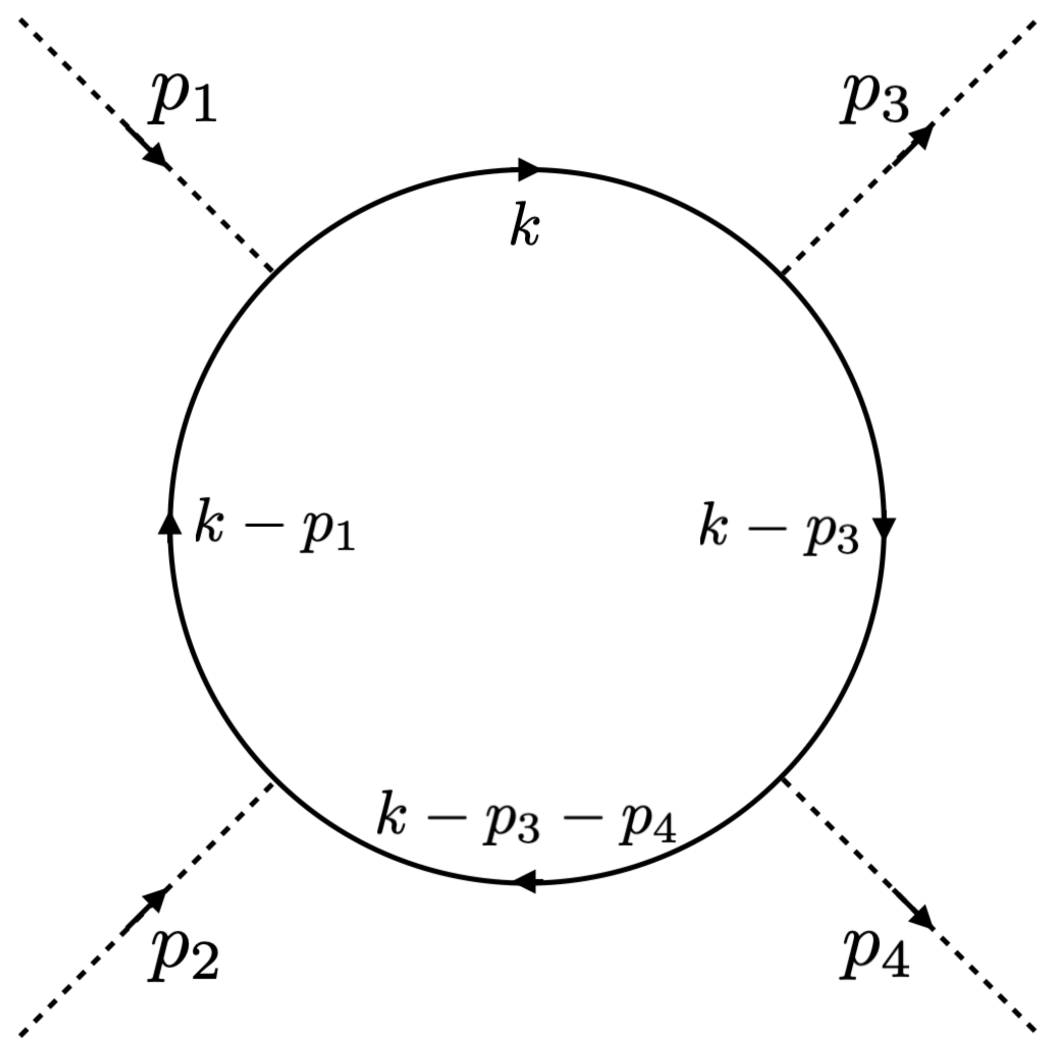
$$\mathscr{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - m_{\alpha\beta}\bar{\nu}_\alpha\nu_\beta - y_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta$$

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 $V_{\text{CW}} \propto y_{\phi\nu}^4\phi^4 \ln\phi^2$

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

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 $m_\nu \gg T_\nu$

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

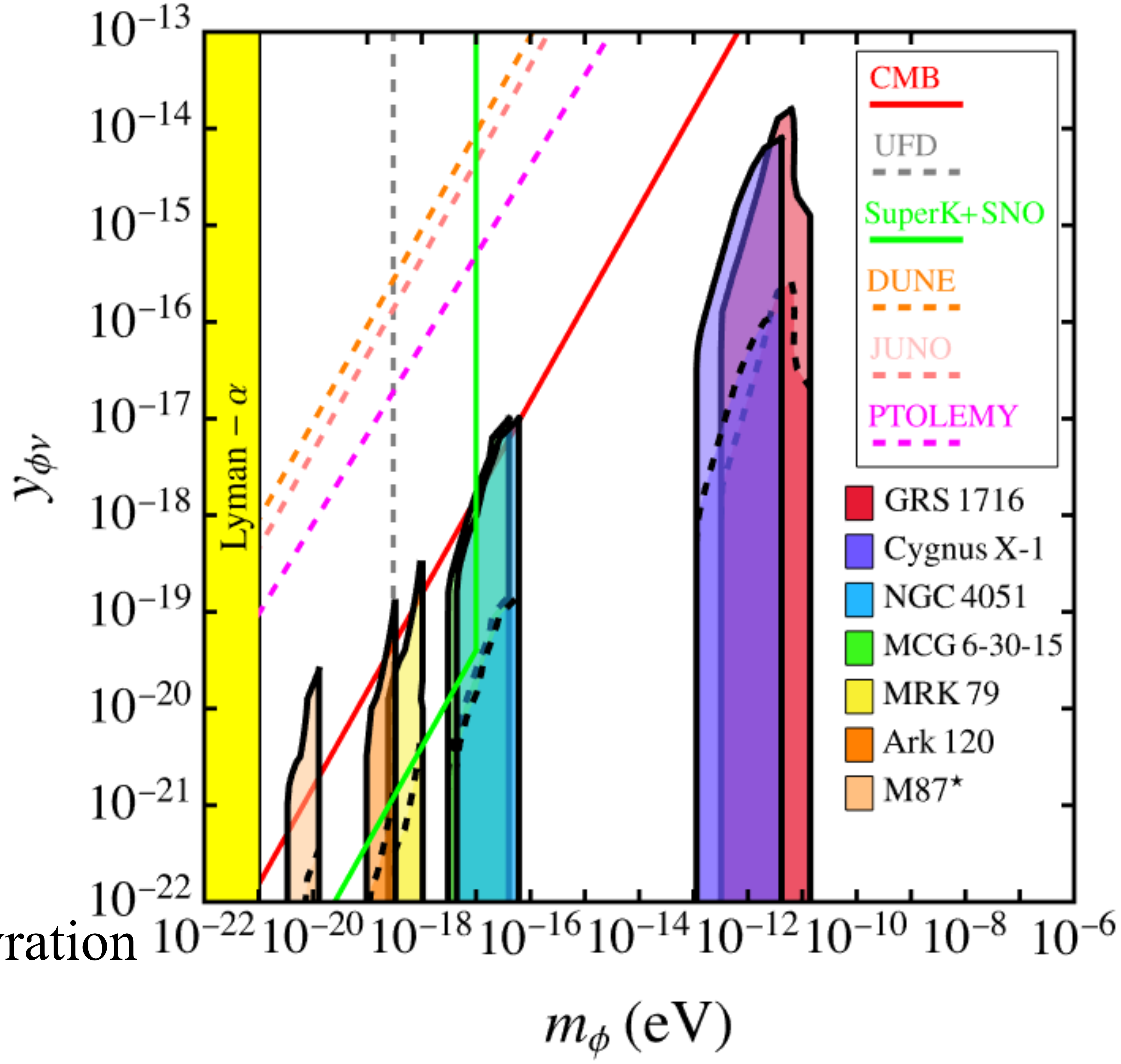
Efficiency of the energy extraction is limited by the non-linear dynamics

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

Summary

- Observation of the EM radiation from the highly magnetized star results strongest astrophysical bound on scalar-photon coupling till date

- Precision clock searches may result limits competitive with the Eot-Wash and MICROSCOPE fifth-force bounds

- Complementary bounds on the scalar-neutrino coupling from BH superradiance: exclude large parameter space

- No extra new physics parameters except coupling and mass

Thank You !