

Astrophysical probes of ultralight particles: Pulsar spindown, birefringence, and superradiance

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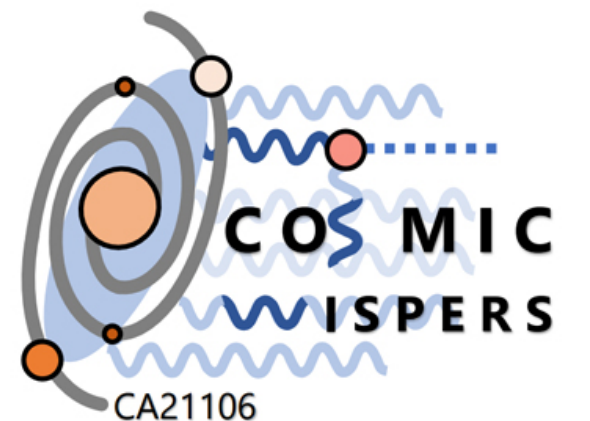
Based on **2501.02286, 2503.02940, 2602.03953, 2603.10189**

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BeyondWIMPs, Liverpool
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Outline

See Brax, Christine-Davis, TKP++ (Review article) 2603.03446

Cosmic WISPers, white paper 2603.03433

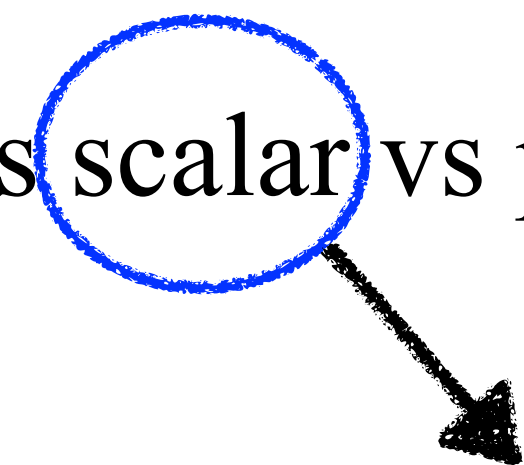
Astrophysical probes for ultralight DM:

Why should we look for ultralight DM?

Astrophysical probes: Pulsars/Magnetized stars, Black Holes

Why are they important?

A rigorous scalar vs pseudoscalar (axion) case:



Not too many astrophysical probes: Globular clusters

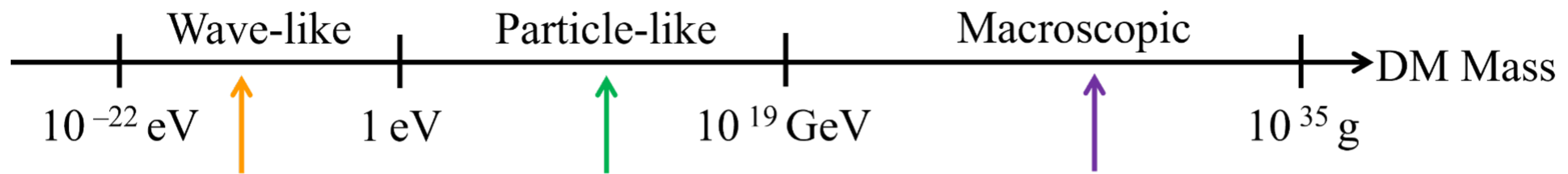
Environmental effects ($C\nu B$) on BH superradiance:

Bridging neutrino physics and BH physics

Novel constraints on scalar-neutrino coupling

Ultralight scalars: A possible dark matter candidate

DM present at all scales



Ultralight DM, ALP, Axion, etc.

Thermal DM (WIMP, SIMP, ...), Sterile ν , etc.

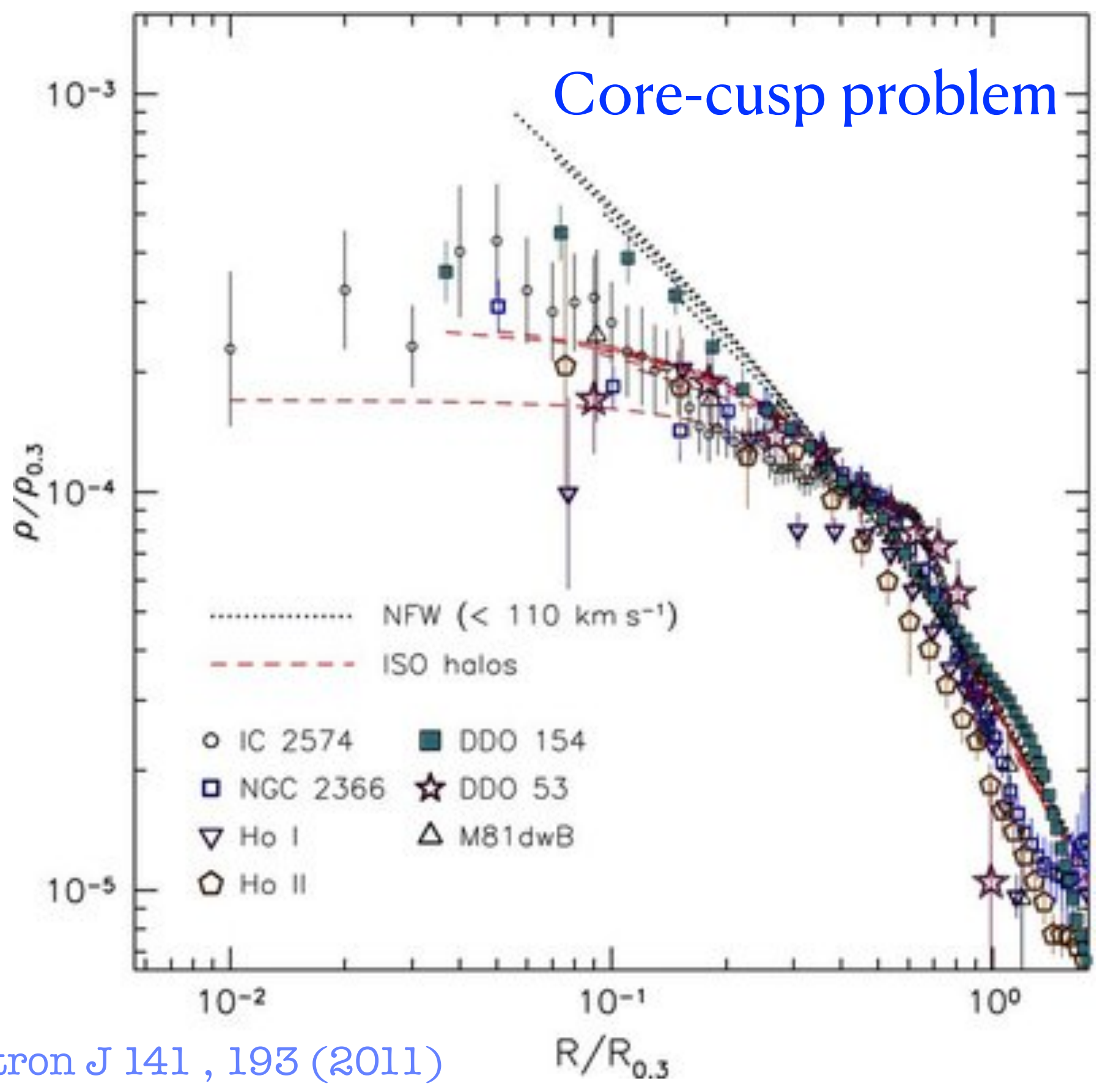
Primordial BH, etc.

- Rotation curve
- Bullet clusters
- CMB
- Structure formation

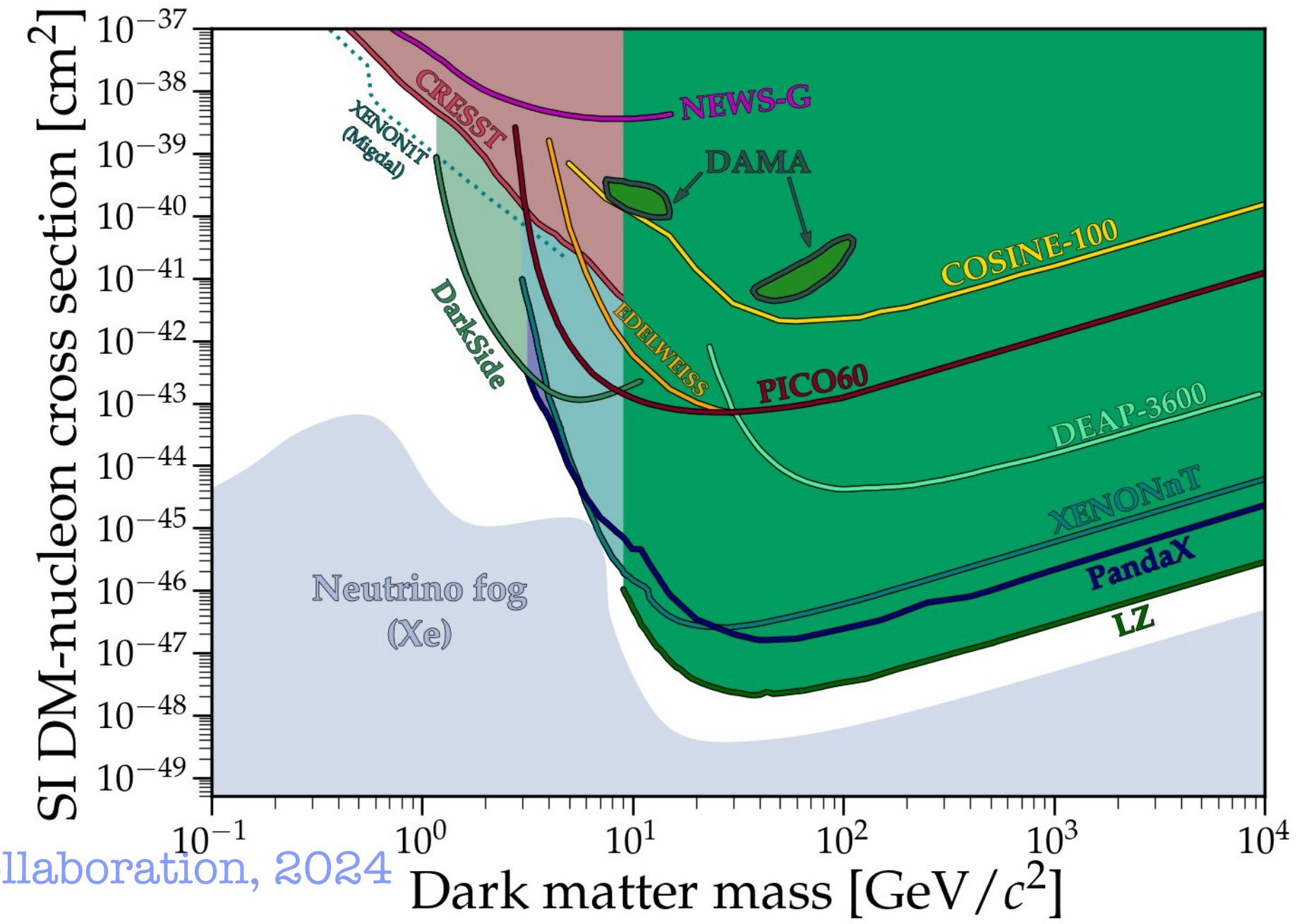
<https://member.ipmu.jp/shigeki.matsumoto/>

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

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



Astron J 141 , 193 (2011)

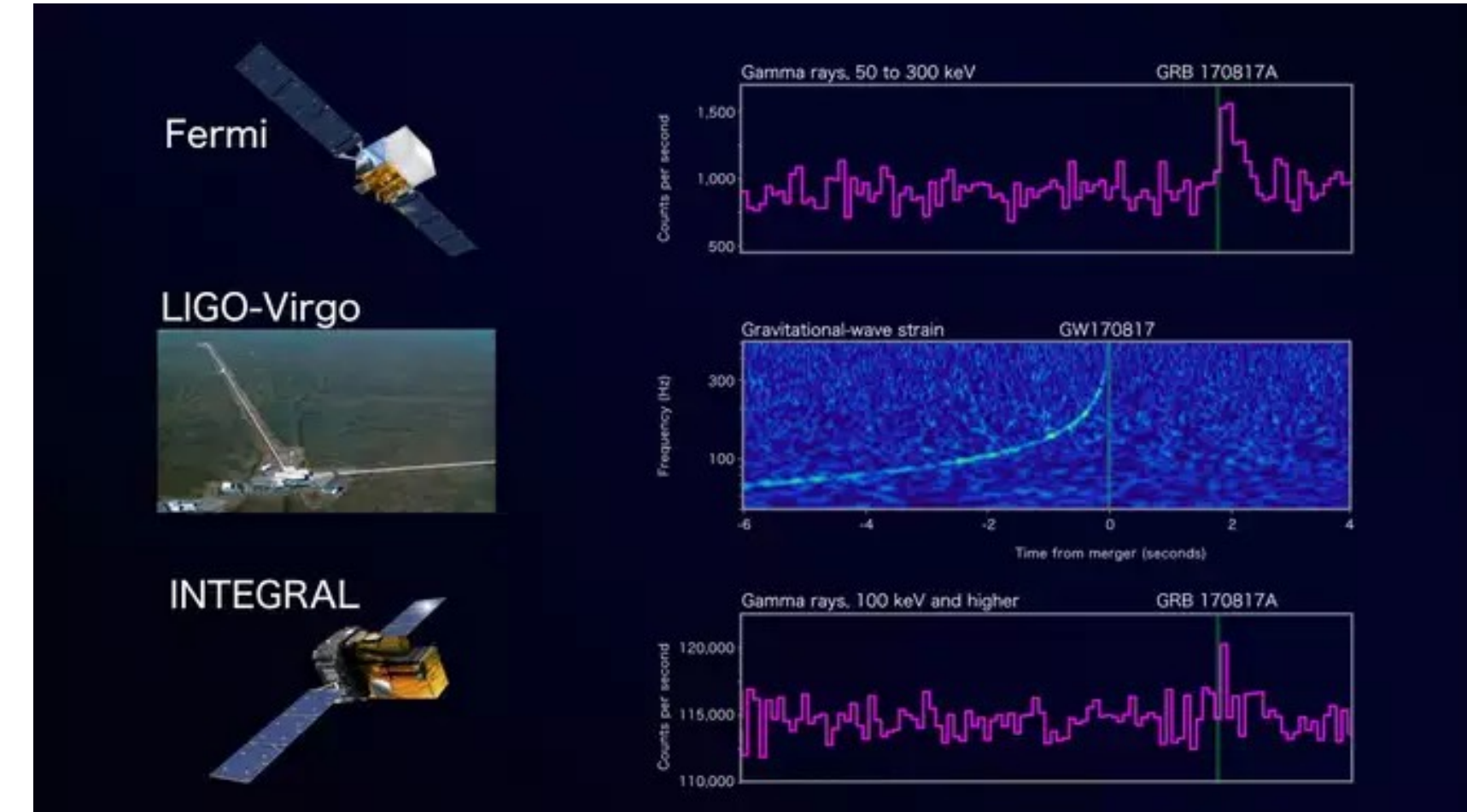
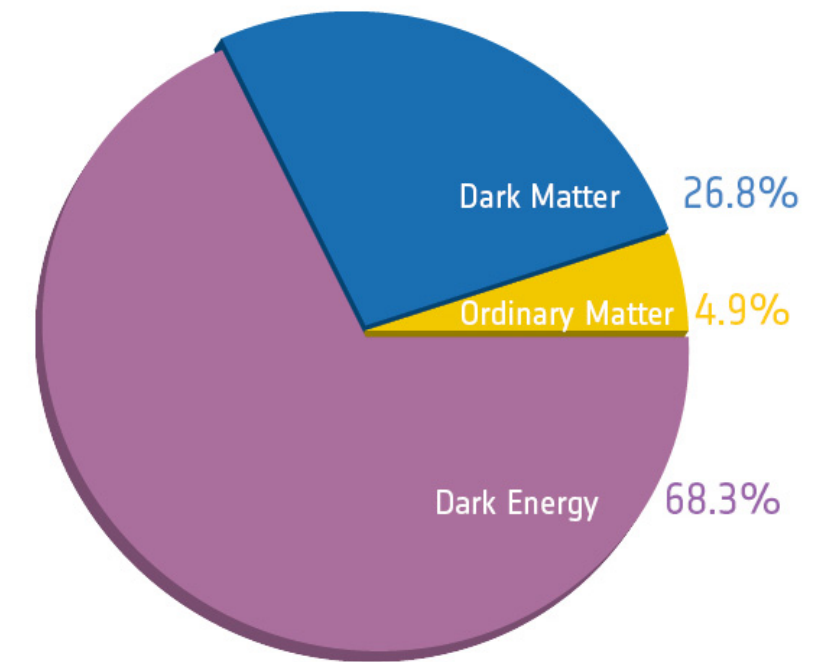
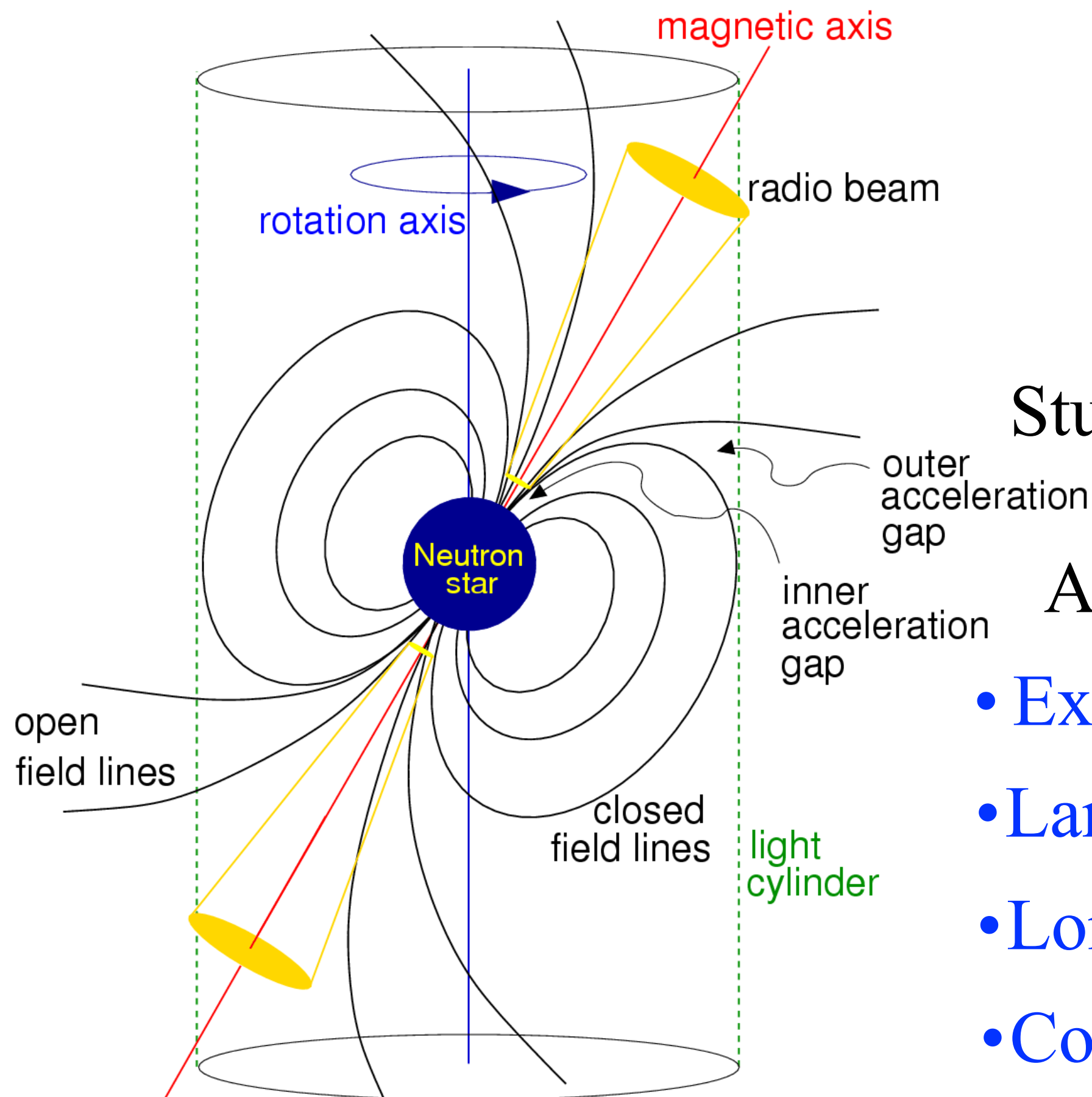


LZ collaboration, 2024

Direct detection constraints

NS/Magnetar/SGR/GRB

Cosmic laboratories for exploring the mysteries of the universe



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

Mass $\sim 1.4 M_{\odot}$, **Radius** $\sim 10 - 20$ km, **Spin period** ~ 10 ms, **Mass density** $\sim 10^{14}$ g/cm³,

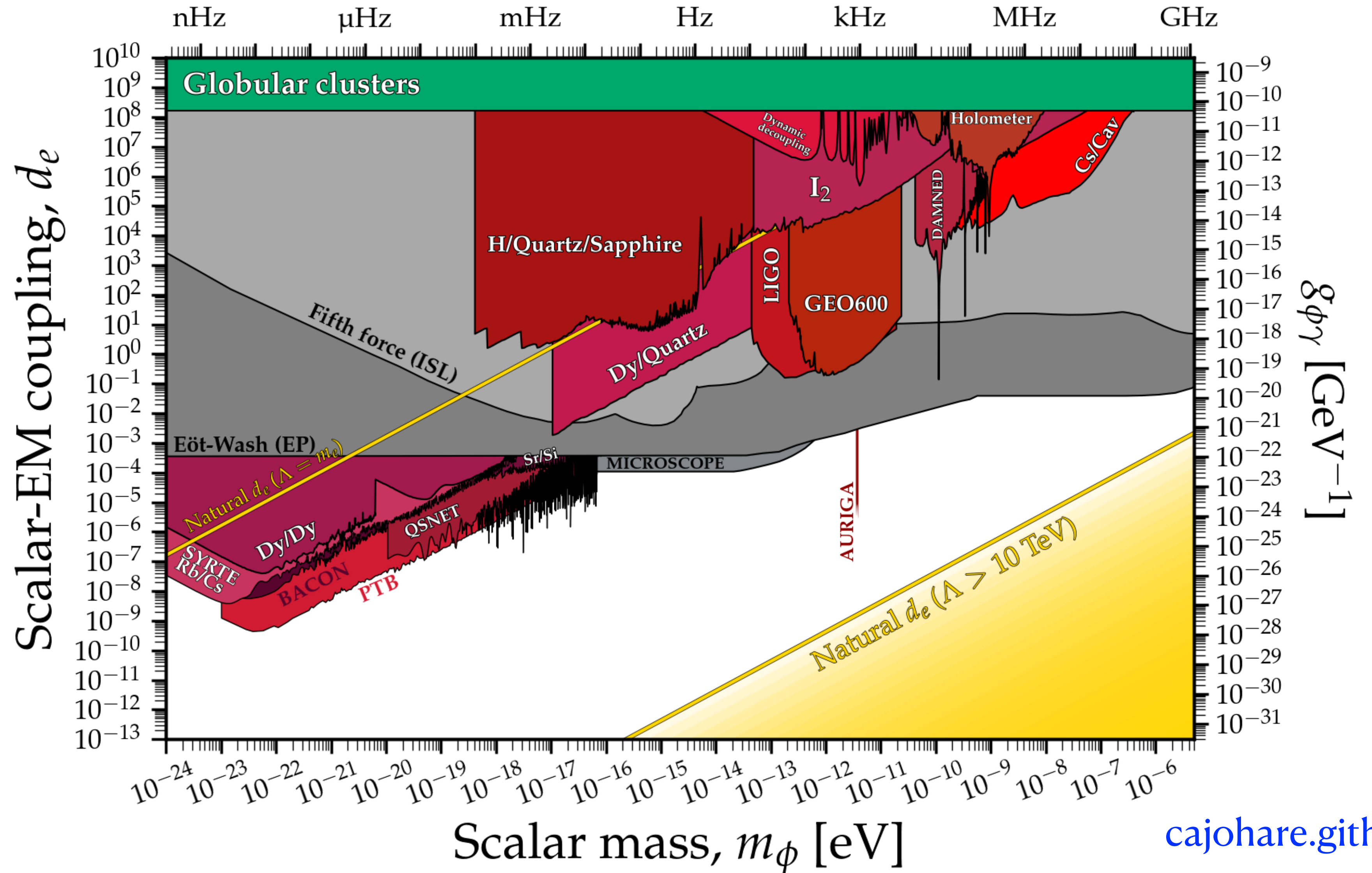
Light cylinder radius $\sim 10^3$ km, **Constituents**: neutrons, protons, electrons, muons, hyperons

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

Characteristics:

Pulsar Spindown and EM radiation effects: Constraints on the scalar-photon coupling

State of the Art:



Long-range time-independent scalar field outside a compact star

Aligned rotator model

The dipolar magnetic field outside of the star

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

The electric field outside the star

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

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

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

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

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

The equation of motion of the scalar field

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

Contd...

EOM of the scalar field

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

Soln.

$$\phi(r, \theta) \simeq \frac{Q_0^\phi}{r} + \frac{Q_2^\phi}{r^3} P_2(\cos \theta) + \frac{Q_4^\phi}{r^5} P_4(\cos \theta)$$

At the leading order

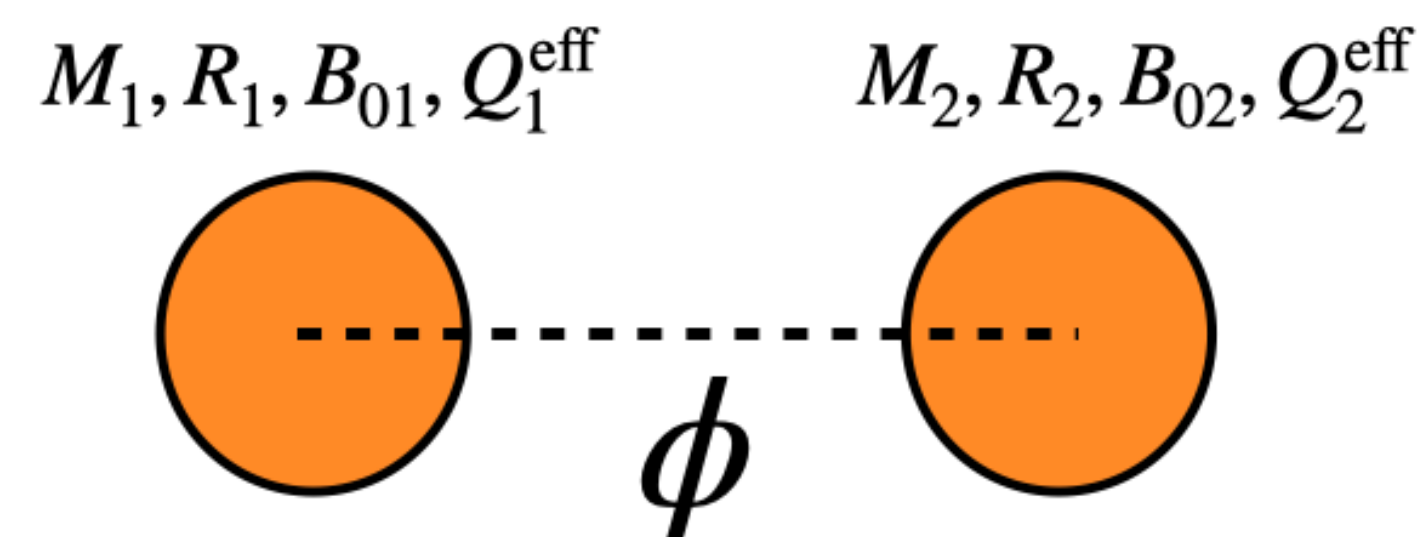
$$\phi(r) \simeq \frac{Q_0^\phi}{r} \quad l = 0 \text{ monopole term}$$

The scalar-induced charge

$$Q_0^\phi = g_{\phi\gamma\gamma} B_0^2 \left(\frac{R^3}{6} - \frac{\Omega^2 R^5}{15} \right)$$

For a scalar-mediated binary system

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



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

$$\text{EOM: } \partial_{\mu} F_{\phi}^{\mu\nu} = -g_{\phi\gamma\gamma} (\partial_{\mu} \phi) F_{(0)}^{\mu\nu}$$

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

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

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

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

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

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

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

$$B_{\phi}^r \simeq \frac{3}{10} g_{\phi\gamma\gamma} B_0 R^3 Q_{\phi}^{\text{eff}} \left(\frac{\cos \theta}{r^4} \right), \quad B_{\phi}^{\theta} \simeq \frac{3}{20} g_{\phi\gamma\gamma} B_0 R^3 Q_{\phi}^{\text{eff}} \left(\frac{\sin \theta}{r^4} \right)$$

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

Maxwell's equations for photon propagation modifies as

$$\left. \begin{aligned} \nabla \cdot \mathbf{E} &= -g_{\phi\gamma\gamma} \mathbf{E} \cdot \nabla \phi & \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{B} &= \frac{\partial \mathbf{E}}{\partial t} - g_{\phi\gamma\gamma} \nabla \phi \times \mathbf{B} & \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \end{aligned} \right\} \begin{aligned} &\text{The wave equation} \\ &\square \mathbf{B} = g_{\phi\gamma\gamma} (\nabla \phi \cdot \nabla) \mathbf{B} \end{aligned}$$

Choose the Eikonal ansatz

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

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

$$\delta z = \frac{\lambda(r_2) - \lambda(r_1)}{\lambda(r_1)} \approx \frac{k_R(r_1) - k_R(r_2)}{k_R(r_2)} \approx \frac{m_\gamma^2}{8\omega^2} \approx \frac{g_{\phi\gamma\gamma}^4 B_0^4 R^2}{288\omega^2}$$

Benchmark values for GRB 080905A

$$\delta z = \frac{\Delta k}{k} \simeq 10^{-4} \left(\frac{g_{\phi\gamma\gamma}}{2.8 \times 10^{-15} \text{ GeV}^{-1}} \right)^4 \left(\frac{2.1 \text{ GHz}}{\omega} \right)^2 \left(\frac{B_0}{3.93 \times 10^{16} \text{ G}} \right)^4 \left(\frac{R}{10 \text{ km}} \right)^2$$

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

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

Magnetic field outside the star

$$B_r = \frac{B_0 R^3}{r^3} (\cos \alpha \cos \theta + \sin \alpha \sin \theta \cos(\phi - \Omega t)),$$

$$B_\theta = \frac{B_0 R^3}{2r^3} (\cos \alpha \sin \theta - \sin \alpha \cos \theta \cos(\phi - \Omega t)),$$

$$B_\phi = \frac{B_0 R^3}{2r^3} \sin \alpha \sin(\phi - \Omega t),$$

Electric field outside the star

$$E_r = -\frac{B_0 \Omega R^5}{2r^4} \left[\cos \alpha (3 \cos^2 \theta - 1) + \frac{3}{2} \sin \alpha \cos(\phi - \Omega t) \sin 2\theta \right],$$

$$E_\theta = -\frac{B_0 R^3 \Omega}{2r^2} \left[\frac{R^2}{r^2} \cos \alpha \sin 2\theta + \sin \alpha \left(1 - \frac{R^2}{r^2} \cos 2\theta \right) \cos(\phi - \Omega t) \right],$$

$$E_\phi = \frac{B_0 R^3 \Omega}{2r^2} \sin \alpha \cos \theta \sin(\phi - \Omega t) \left(1 - \frac{R^2}{r^2} \right),$$

Solving the equation of motion

$$k_\Omega = \sqrt{\Omega^2 - m_\phi^2}, \quad k_{2\Omega} = \sqrt{4\Omega^2 - m_\phi^2}$$

Time-dependent scalar field profile at far zone

$$\begin{aligned} \varphi(t, r, \theta, \phi) \simeq & -\frac{g_{\phi\gamma\gamma} B_0^2 R^5}{40} k_\Omega^2 \frac{1}{r} \sin(2\alpha) \sin \theta \cos \theta \cos(k_\Omega r - \Omega t + \phi) + \\ & \frac{g_{\phi\gamma\gamma} B_0^2 R^5}{80} k_{2\Omega}^2 \frac{1}{r} \sin^2 \alpha \sin^2 \theta \cos(k_{2\Omega} r - 2\Omega t + 2\phi), \end{aligned}$$

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

$$\square \mathbf{B} \approx g_{\varphi\gamma\gamma}(\nabla\varphi \cdot \nabla)\mathbf{B} - g_{\varphi\gamma\gamma}\dot{\varphi}\dot{\mathbf{B}}$$

The group velocity

$$v_g \approx 1 - \frac{m_{\gamma k}^2}{8\omega^2} \approx 1 - \frac{g_{\varphi\gamma\gamma}^4 B_0^4 R^{10} \Omega^4}{51200\omega^2 r^4} \left(1 - \frac{m_\varphi^2}{\Omega^2}\right)^2 \sin^2(2\alpha) \sin^2(2\theta) \cos^2(k_\Omega r - \Omega t + \phi)$$

Redshift of the photon wavelength

$$\delta z(t) \approx \frac{g_{\varphi\gamma\gamma}^4 B_0^4 R^6 \Omega^4}{102400\omega^2} \left(1 - \frac{m_\varphi^2}{\Omega^2}\right)^2 \sin^2(2\alpha) \sin^2(2\theta) (1 + \cos(2k_\Omega R - 2\Omega t + 2\phi))$$

Scalar-induced time-dependent magnetic field

$$B_\varphi^r \simeq \frac{3}{2000} g_{\varphi\gamma\gamma}^2 B_0^3 R^8 \Omega^2 \left(1 - \frac{m_\varphi^2}{\Omega^2}\right) \sin(2\alpha) \frac{\cos\alpha}{r^4} \sin\theta \cos(\phi - \Omega t)$$

Scalar radiation from an isolated compact star

Previous discussion with static source \longrightarrow No radiation

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

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

$$\mathbf{B}^2 - \mathbf{E}^2 \approx -\frac{3}{2} \frac{B_0^2 R^6}{r^6} \left[\sin \alpha \cos \alpha \sin \theta \cos \theta \cos(\Omega t - \phi) + \frac{1}{2} \sin^2 \alpha \sin^2 \theta \cos^2(\Omega t - \phi) \right]$$

In the far field and long wavelength approximation

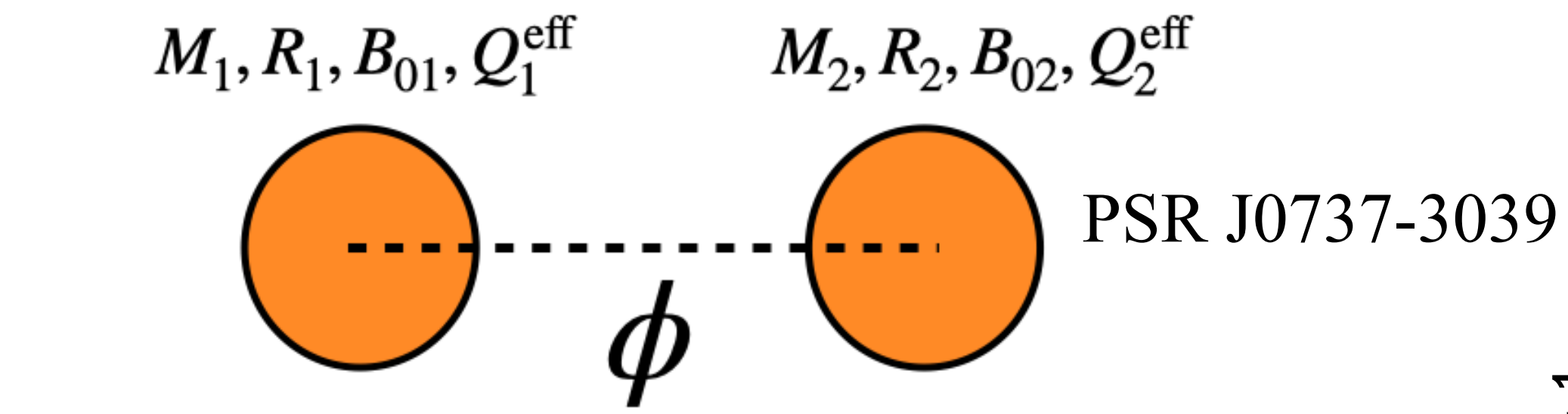
$$P_\omega = \int d\Omega r^2 \langle S_r \rangle = \frac{\omega k}{2} \sum_{lm} \left(\frac{k^l}{(2l+1)!!} \right)^2 |Q_{lm}(\omega)|^2 \quad k^2 = \Omega^2 - m_\phi^2$$

Multipole moments

$$Q_{lm}(\omega) = \int d^3 r' \rho_\omega(\mathbf{r}') r'^l Y_{l,m}^*(\hat{r}') \quad \text{Contributes to pulsar spin-down for } m_\phi < \Omega$$

$$P_\Omega \simeq \frac{1}{80} g_{\phi\gamma\gamma}^2 B_0^4 R^{10} \Omega^6 \left(1 - \frac{m_\phi^2}{\Omega^2} \right)^{5/2} \sin^2 2\alpha, \quad P_{2\Omega} \simeq \frac{1}{100} g_{\phi\gamma\gamma}^2 B_0^4 R^{10} \Omega^6 \left(1 - \frac{m_\phi^2}{4\Omega^2} \right)^{5/2} \sin^4 \alpha$$

Constraints from observations



$$\eta = \frac{Q_1^{\text{eff}} Q_2^{\text{eff}}}{GM_1 M_2} \simeq \frac{g_{\phi\gamma\gamma}^2 B_{01}^2 B_{02}^2 R_1^3 R_2^3}{36GM_1 M_2}$$

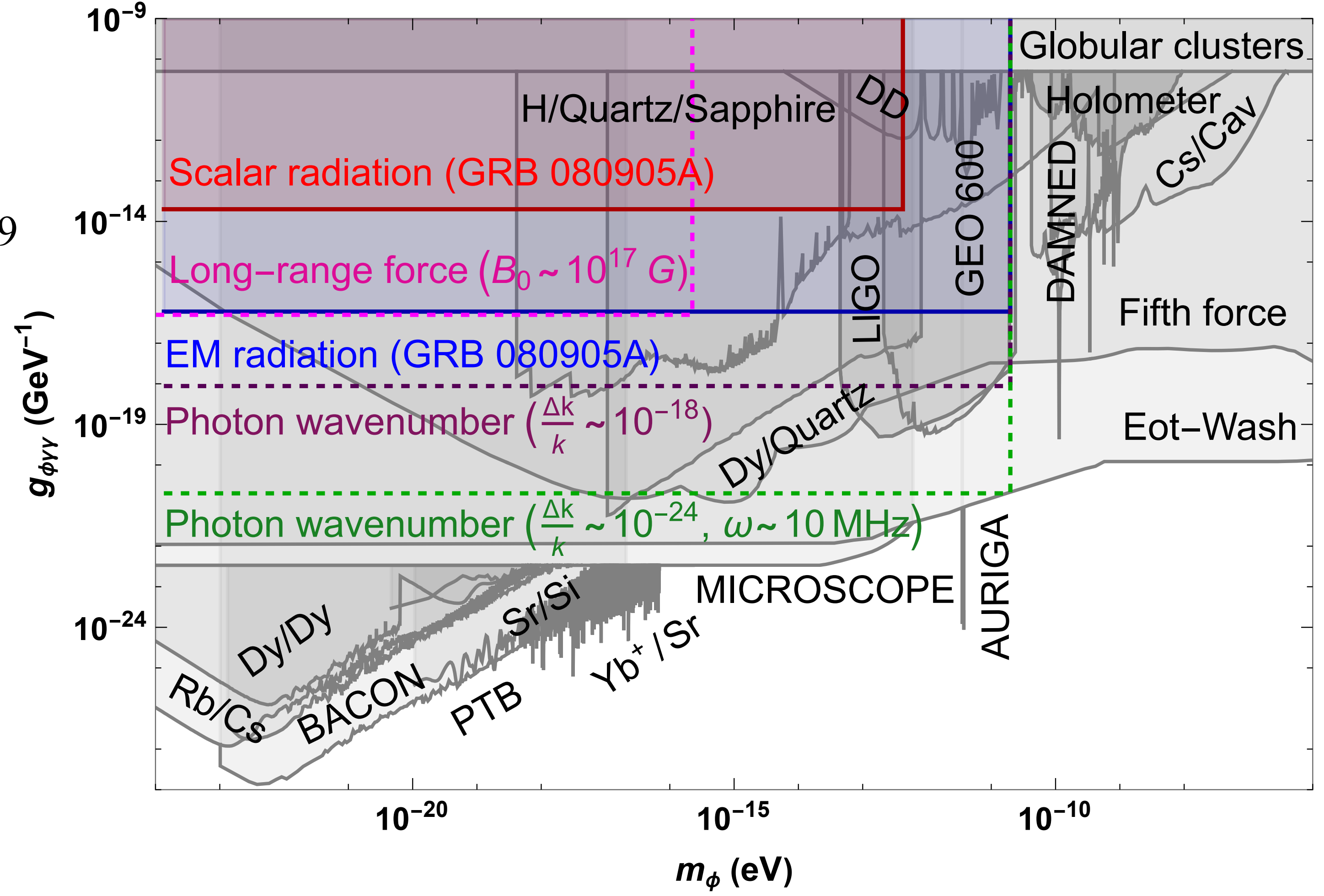
Loss of rotational energy

$$\frac{dE}{dt} = \frac{d}{dt} \left(\frac{I}{2} \Omega^2 \right) \approx I \Omega \dot{\Omega} = I \frac{(2\pi)^2}{P^3} \dot{P}$$

Magnetic dipole radiation

$$\frac{dE}{dt} = \frac{2}{3} (B_0 R^3 \sin \alpha)^2 \Omega^4 = \frac{2(2\pi)^4}{3} \left(\frac{B_0 R^3 \sin \alpha}{P^2} \right)^2$$

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



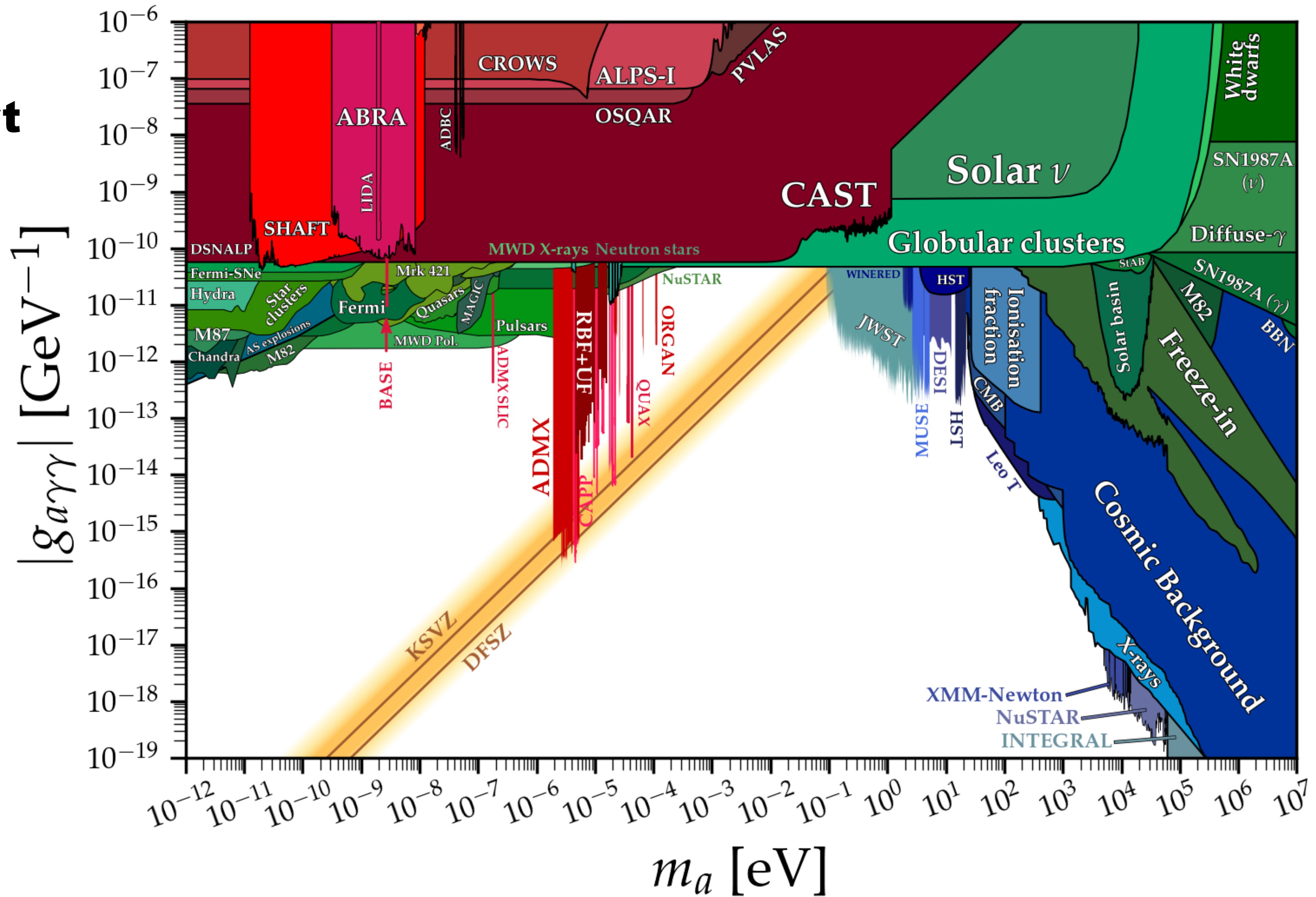
Look for NSs/magnetars with larger magnetic field, angular velocity, and size for better sensitivity

Results depend on magnetospheric model, EOS

Results do not need the scalar need to be the dark matter

Birefringence: Constraints on the axion-photon coupling

State of the Art



Long-range time-independent axion profile

Lagrangian for axion field interacting with the EM fields

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Equation of motion for the axion field

$$\nabla^2 a(r, \theta) = - g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$$

$$J(r, \theta) = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} = - g_{a\gamma\gamma} \frac{B_0^2 \Omega R^8}{r^7} \cos^3 \theta$$

Time-independent scalar field profile

$$a(r, \theta) \simeq \frac{g_{a\gamma\gamma} B_0^2 R^5 \Omega}{15 r^2} \cos \theta$$

Axion-mediated force between two stars would be suppressed

Time-dependent axion profile

Equation of motion for the axion field

$$(\square + m_a^2)a = g_{a\gamma\gamma} \frac{B_0^2 R^6 \Omega}{8r^5} \sin 2\alpha \sin \theta \cos(\phi - \Omega t)$$

Time dependent axion-field profile

$$a(t, \mathbf{r}) = - \frac{g_{a\gamma\gamma} B_0^2 R^5 k \Omega}{24r} \sin \theta \sin 2\alpha \sin(\phi - \Omega t + kr)$$

$$k = \sqrt{\Omega^2 - m_a^2}$$

The propagation of an EM wave through an axion field causes frequency and polarisation of photon to change: Frequency shift and Birefringence

EM wave propagation in the background of axion field

Maxwell's equations for photon propagation modifies as

$$\begin{aligned}\nabla \cdot \mathbf{E} &= -g_{a\gamma\gamma} \nabla a \cdot \mathbf{B}, \\ \nabla \times \mathbf{B} &= \frac{\partial \mathbf{E}}{\partial t} + g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \mathbf{B} \frac{\partial a}{\partial t} \right), \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t},\end{aligned}$$

EOM of the EM field

$$\begin{aligned}\square \mathbf{B} &= g_{a\gamma\gamma} \nabla \times [\dot{a} \mathbf{B} + \nabla a \times \mathbf{E}] \\ \square \mathbf{E} + \nabla(\nabla \cdot \mathbf{E}) &= -g_{a\gamma\gamma} \frac{d}{dt} [\dot{a} \mathbf{B} + \nabla a \times \mathbf{E}]\end{aligned}$$

Variation in photon frequency and wave-number

$$\Delta\omega = \mp \frac{g_{a\gamma\gamma}}{2} [\dot{a}(x_d, t_d) - \dot{a}(x_e, t_e)]$$

$$\Delta\kappa = \pm \frac{g_{a\gamma\gamma}}{2} [\nabla a(x_d, t_d) - \nabla a(x_e, t_e)]$$

Contd...

$$\frac{\Delta\omega}{\omega} \simeq 10^{-12} \left(\frac{g_{a\gamma\gamma}}{10^{-12} \text{ GeV}^{-1}} \right)^2 \left(\frac{B_0}{8.5 \times 10^{12} \text{ G}} \right)^2 \left(\frac{R}{14 \text{ km}} \right)^4 \left(\frac{\Omega}{(2\pi/33 \text{ ms})} \right)^3 \left(\frac{1 \text{ GHz}}{\omega} \right)$$

The axion-induced phase shift is too small to be observed

Let's look at the birefringence!

The photon dispersion relation modifies as

$$\kappa_r = \omega \pm \frac{g_{a\gamma\gamma}}{2} (\dot{a} + \partial_r a)$$

Phase shift between left- and right-circularly polarized modes

$$\Delta\psi = \int_{\text{path}} (k_r^+ - k_r^-) dr = \int_{l_e}^{l_d} g_{a\gamma\gamma} \frac{da}{dl} dl = g_{a\gamma\gamma} (a_o - a_e)$$

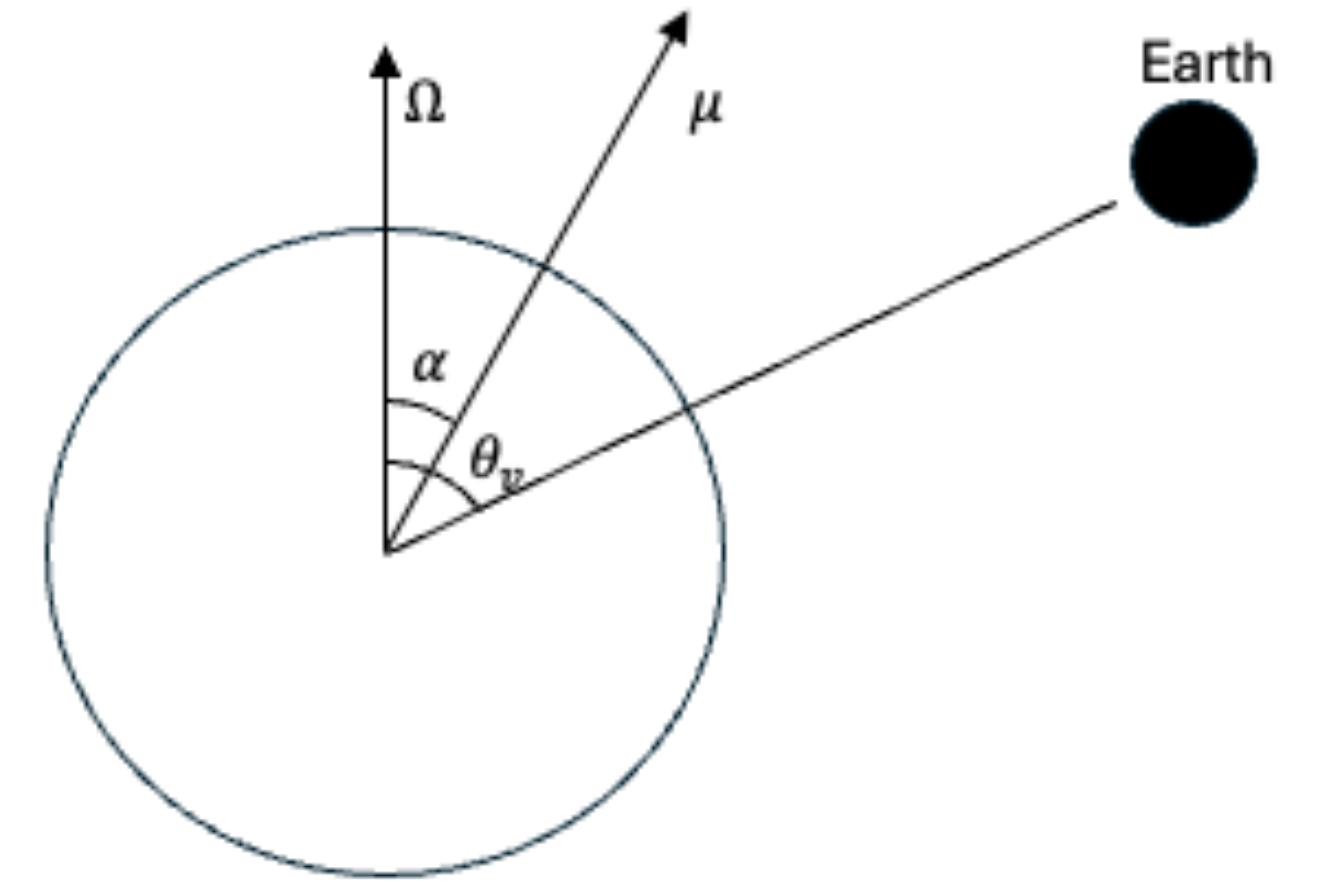
Axion-induces oscillatory birefringence signal in pulsar radiation

$$\Delta\psi = \frac{g_{a\gamma\gamma}^2 B_0^2 R^5 \Omega^2}{48 r_e} \left(1 - \frac{m_a^2}{\Omega^2} \right)^{1/2} \sin 2\alpha \sin \theta_e \sin(\phi_e - \Omega t_e + kr_e)$$

Constraints on axion-photon coupling from birefringence

The Stokes vector angular density is

$$d\mathbf{S}(\theta, \phi, \Omega t) = \frac{1}{2\pi} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} d\Omega = \frac{1}{2\pi} \begin{pmatrix} I \\ Ip \cos(2\psi + 2\Delta\psi(\theta, \phi, \Omega t)) \\ Ip \sin(2\psi + 2\Delta\psi(\theta, \phi, \Omega t)) \\ 0 \end{pmatrix} d\Omega.$$

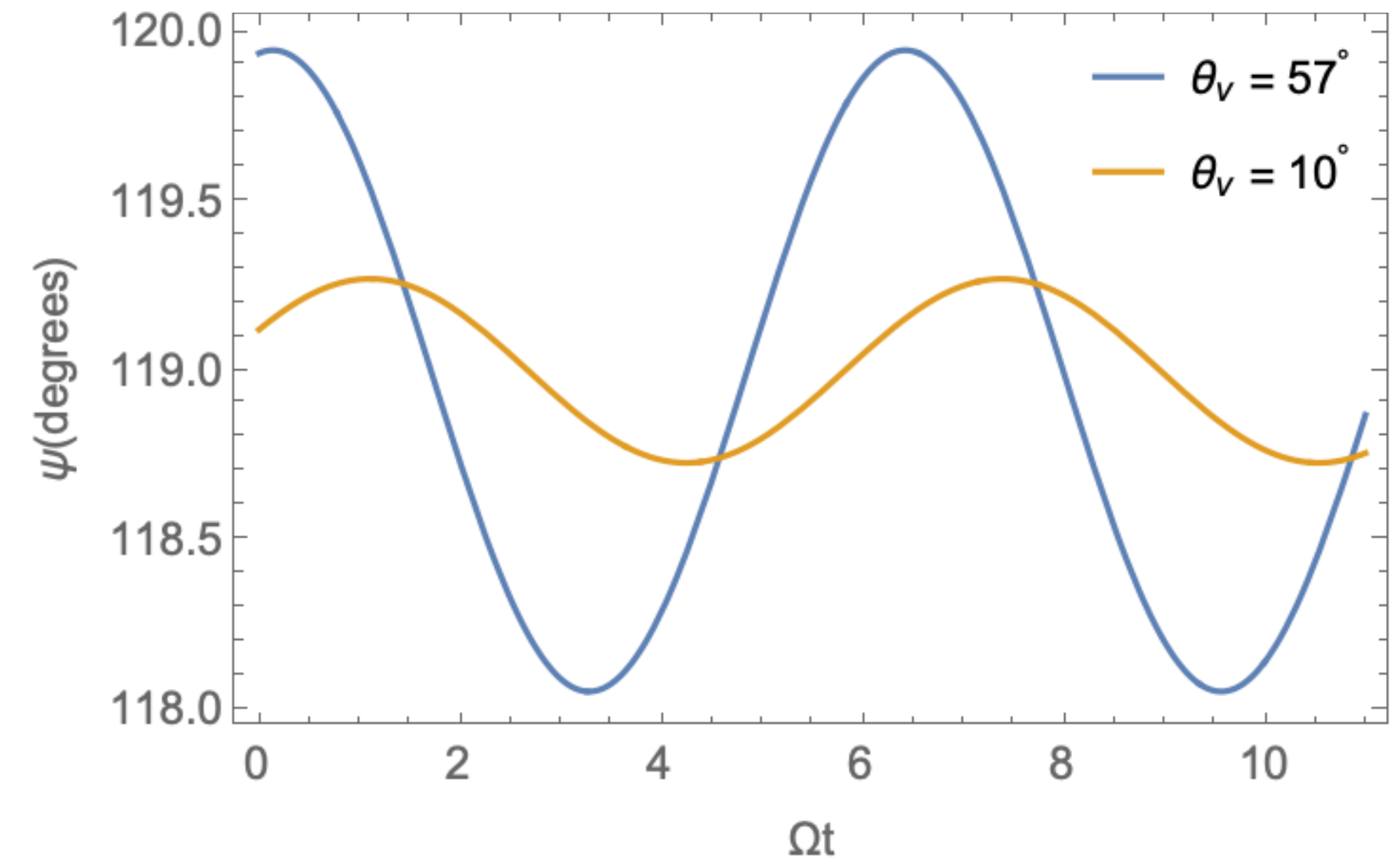


Integrate over the hemisphere of the pulsar facing the earth

$$\mathbf{S}_{\text{tot}}(\Omega t) = \int_{\phi=0}^{\frac{2\pi}{\sin(\theta_v)+1}} \int_{\theta=0}^{\theta=\theta_v+\pi/2} d\mathbf{S},$$

Linear polarization angle: $2\psi = \tan^{-1}(U/Q)$

Linear polarization degree: $p_{\text{lin}} = \sqrt{Q^2 + U^2}/I$



Crab pulsar: $g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-10} \text{ GeV}^{-1}$

Millisecond Magnetar: $g_{a\gamma\gamma} \sim 10^{-13} \text{ GeV}^{-1}$

The axion need not be the DM

Black Hole Superradiance: Constraints on the scalar-neutrino coupling

BHSR driven by scalar fields

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

Excellent probe
for ultralight scalars

Compton wavelength \sim BH size

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

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

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

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

Solve KG equation in Kerr metric

$$(\square - m_{\phi}^2)\Phi = 0$$

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

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

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

$$a_* \equiv a/r_g$$

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

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

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

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

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

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

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

SR condition ceases for

$$N_{\text{max}} = \frac{GM_{\text{BH}}^2 \Delta a_*}{m} \approx \frac{10^{76}}{m} \left(\frac{M_{\text{BH}}}{10 M_\odot} \right)^2 \left(\frac{\Delta a_*}{0.1} \right)$$

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

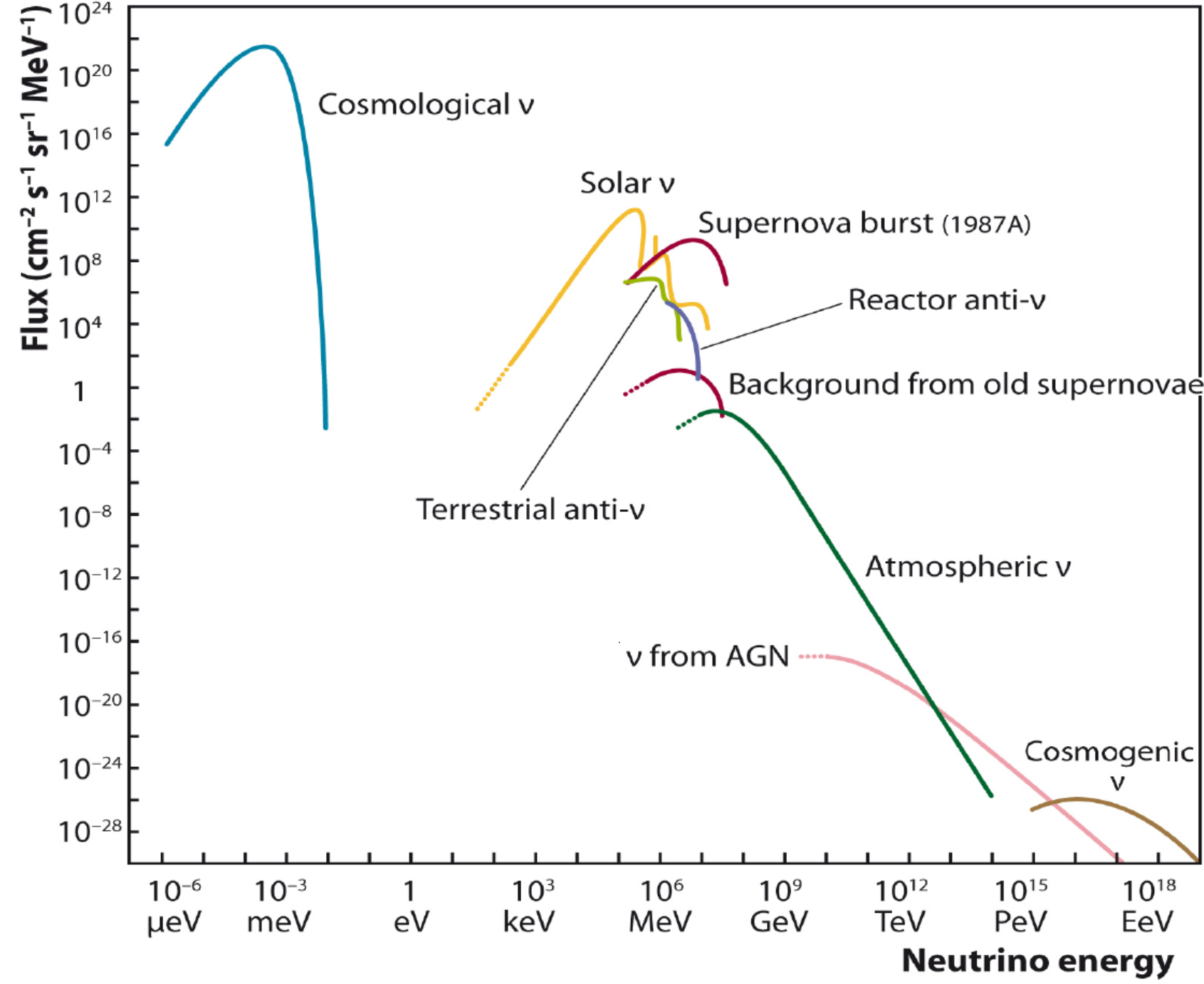
At present epoch $T_\nu \sim 1.95 K \sim 1.68 \times 10^{-4}$ eV

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

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

PTOLEMY can detect through inverse β decay of tritium

Affects CMB fluctuations \rightarrow indirect probe

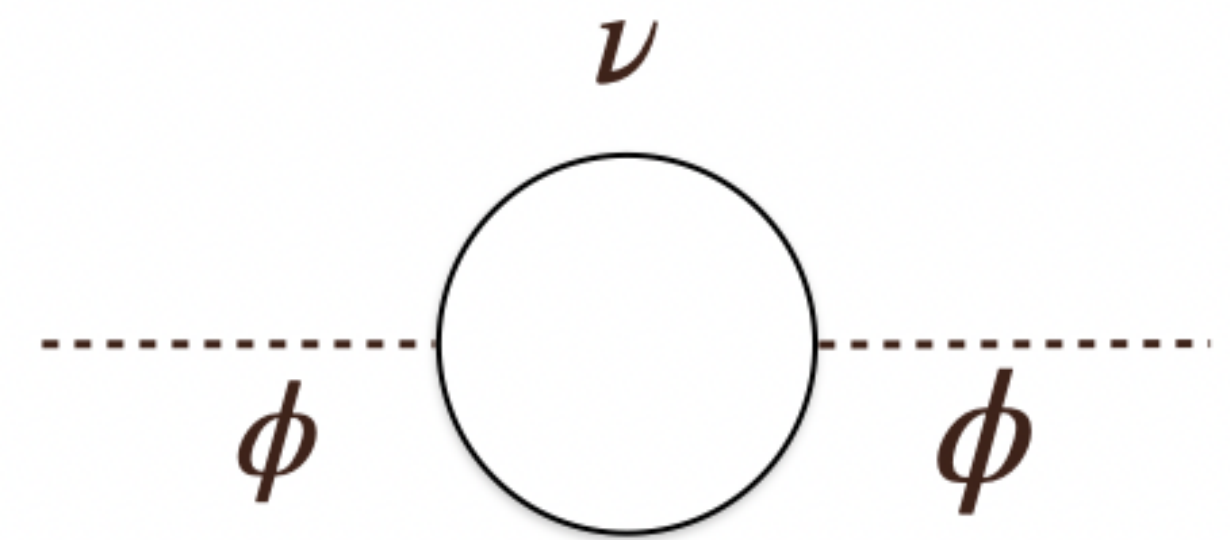


Cosmic neutrinos and light scalar fields

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

The mass correction

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



For inverted hierarchy with $m_1 = m_2 = 50$ meV, $m_3 = 10$ meV

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

Cosmic neutrinos and light scalar fields

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

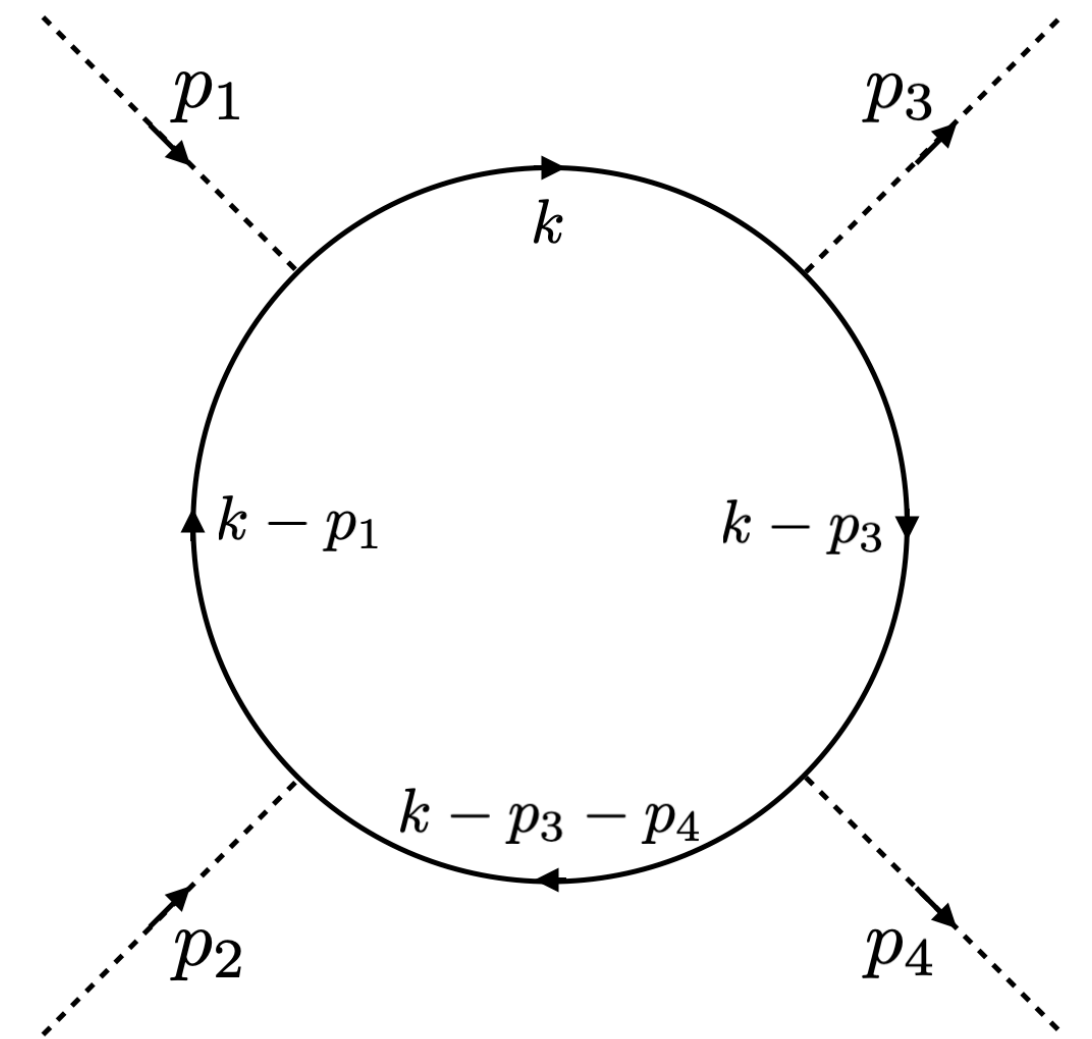
Quartic Lagrangian is induced through loop that involves Yukawa coupling

$$\mathcal{L}_{\text{int}} = \frac{1}{4!} \lambda \phi^4 \quad \lambda = \lambda^{(0)} + \Delta\lambda^{(T)}$$

$$m_\nu \gg T_\nu$$

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

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

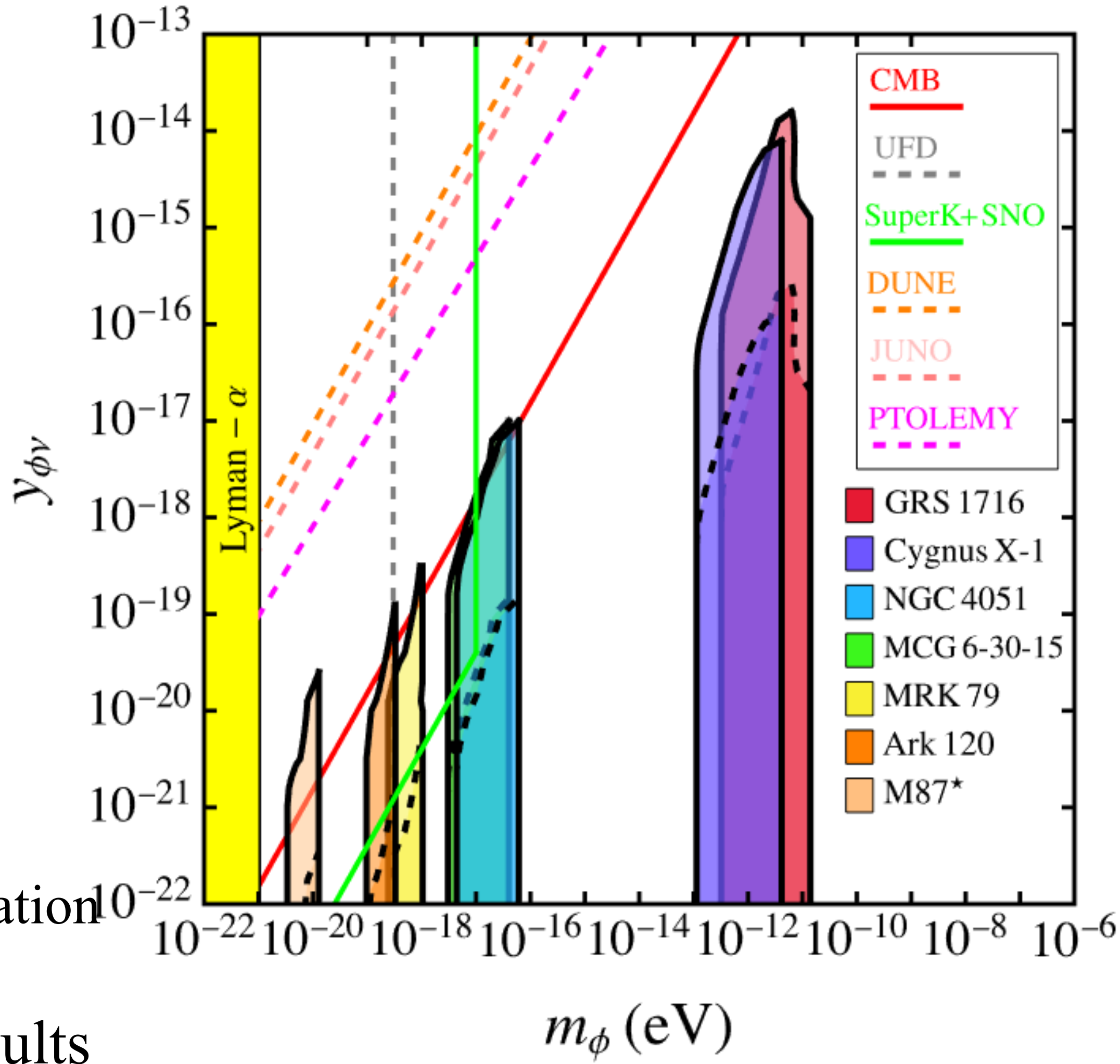
Like neutrinos, electrons in the accretion disk of BH modify bosonic mass through thermal corrections

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

Require dedicated spectral and timing analysis of X-ray observation

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

Gravitational clustering enhances neutrino density, $n_{spike} \sim r^{-3/2}$, weakens SR bound about one order of magnitude



Key takeaways/Future perspective

- ★ Look for neutron stars/magnetars with larger magnetic field, angular velocity, and size for better sensitivity on scalar electromagnetic and electrophilic coupling
- ★ Precision measurements (atomic clock, MeerKAT radio telescope) significantly improve our constraints
- ★ Results depend on magnetospheric model, EoS
- ★ Environmental (plasma) effects are important

Thank You...