Axion Production in Pulsar Magnetosphere Gaps

Ani Prabhu (Stanford University)
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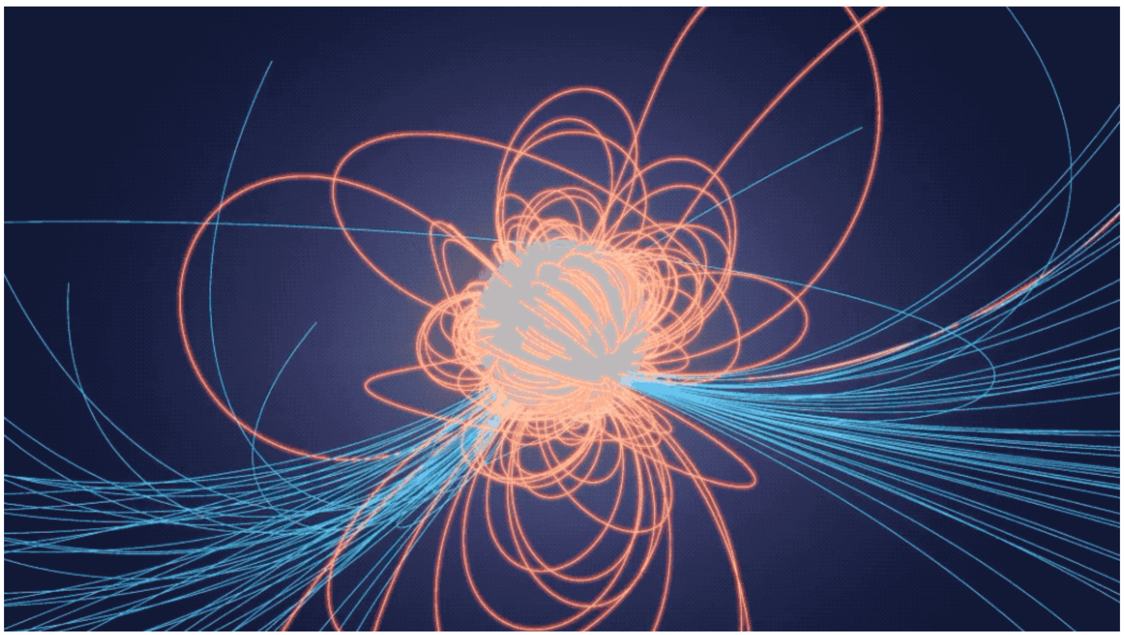
Stanford University

Based on:
arXiv 2104.14569
(Accepted for publication in PRD)

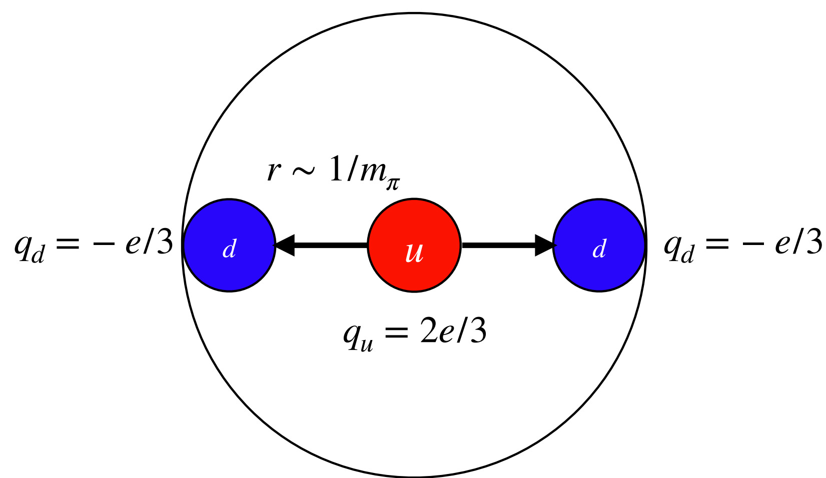
Ongoing:
Alexander Y. Chen
Fábio Cruz
Sam Witte
Dion Noordhuis
Tom Edwards
Christoph Weniger



Credit: NICER (2019)

Strong-*CP* and Axions

Classically: $\vec{d}_n = \sum_f q_f \vec{r}_f \sim \frac{e}{m_\pi}\sqrt{1+\cos\theta} \approx 10^{-13}\sqrt{1+\cos\theta}\ e\cdot\mathrm{cm}$



$\vec{d}_{n,exp} \lesssim 10^{-26}\ e\cdot\mathrm{cm}$

$\theta \lesssim 10^{-13}$

Quantum: $\mathscr{L}_{\mathrm{QCD}} \supset \frac{\theta g_s^2}{32\pi^2}\mathrm{Tr}\ G_{\mu\nu}\tilde{G}^{\mu\nu} \implies d_n \simeq 2\times 10^{-16}\ e\cdot\mathrm{cm}\left(\theta + \arg\det M_u M_d\right)$

$\theta + \arg\det M_u M_d \lesssim 10^{-10}$

PQ Mechanism

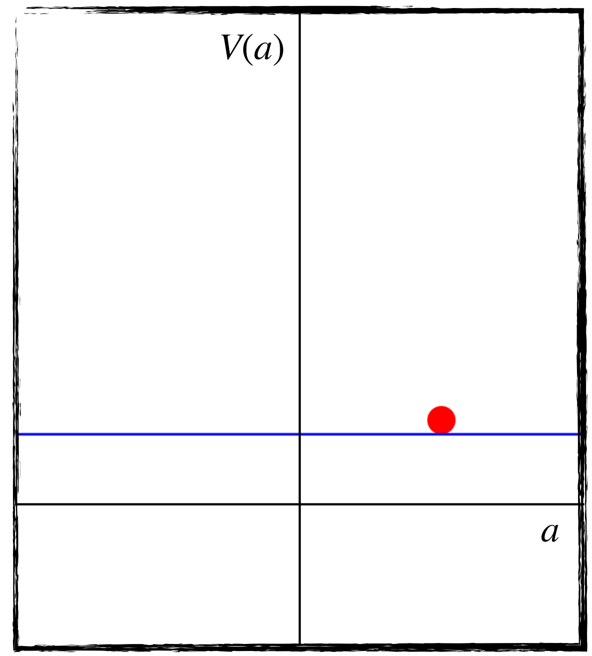
Peccei & Quinn (1977)

PQ Mechanism: $\theta \rightarrow \frac{a(x)}{f_a}$

$$V_{chiral}(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a(x)}{f_a} + \arg\det M_u M_d\right)}$$

$$V_{inst}(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a(x)}{f_a} + \arg\det M_u M_d\right)\right]$$

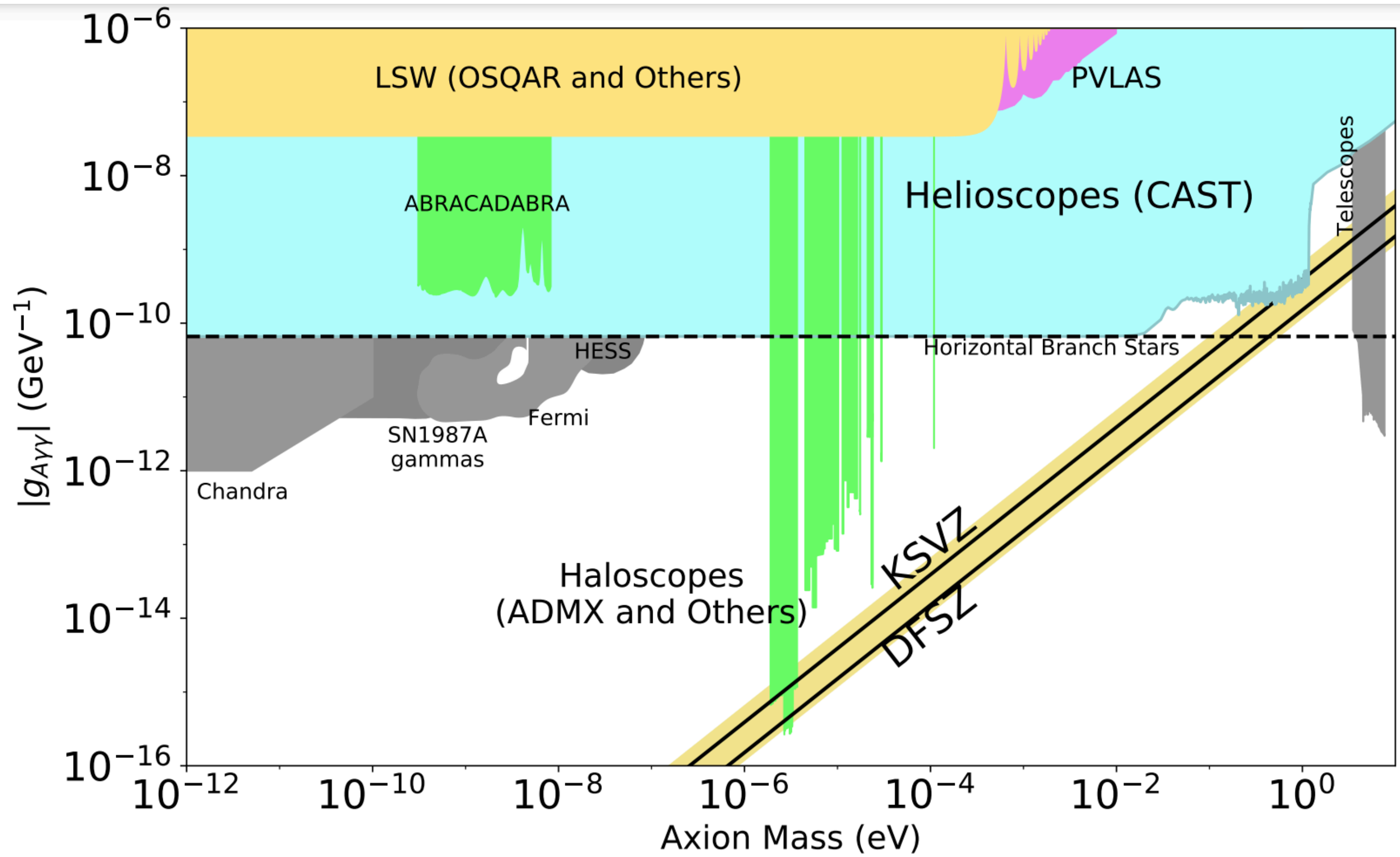
Potential dynamically relaxes axion to *CP* conserving value.



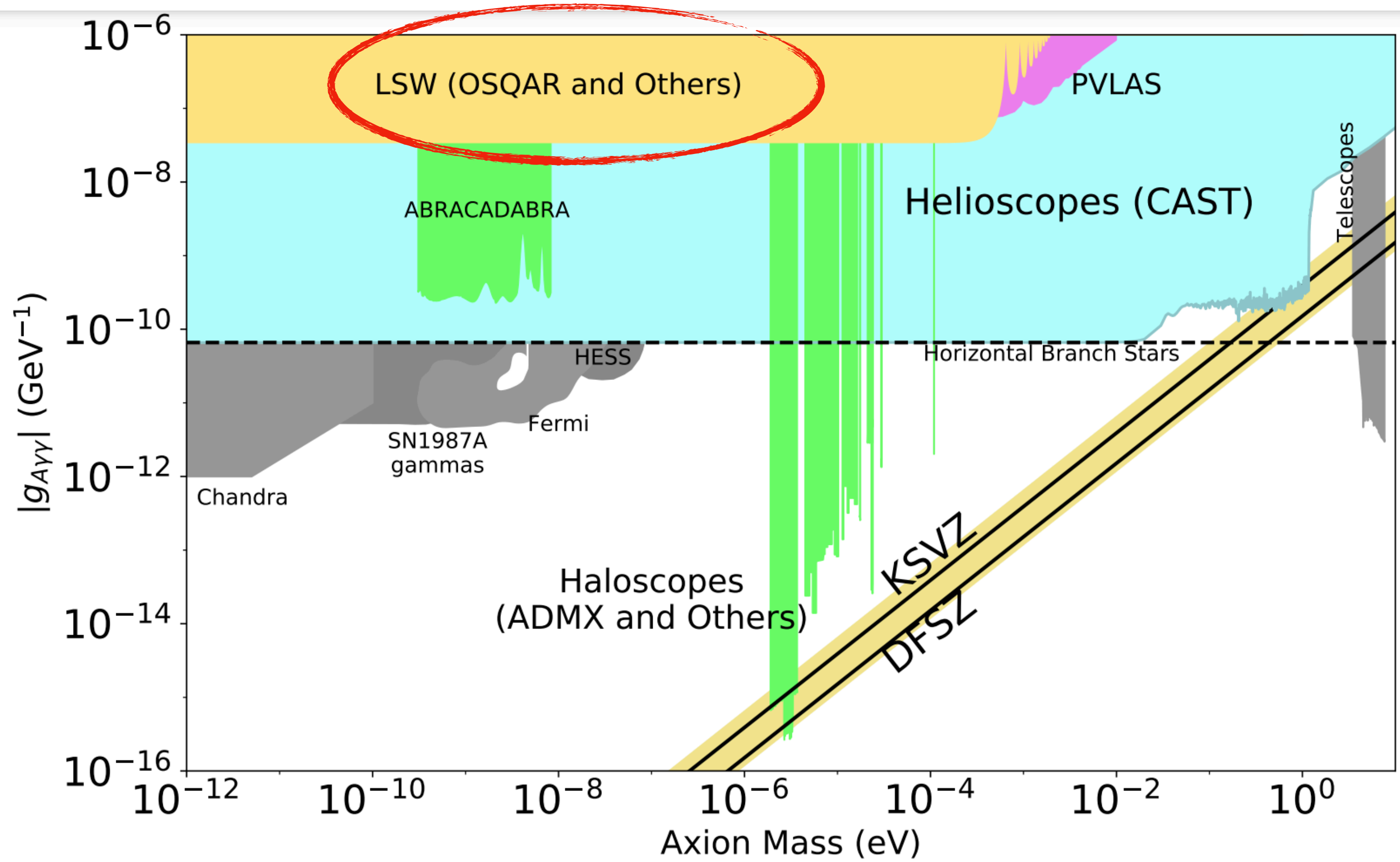
- Plenitude of "axion-like" particles are predicted in string theory with couplings to the SM.

$$\mathscr{L}_{a+SM} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f \frac{C_{a\bar{f}f}}{2f_a}\partial_\mu a \bar{\psi}\gamma_\mu\gamma_5\psi + \cdots$$

Axion-Photon Parameter Space

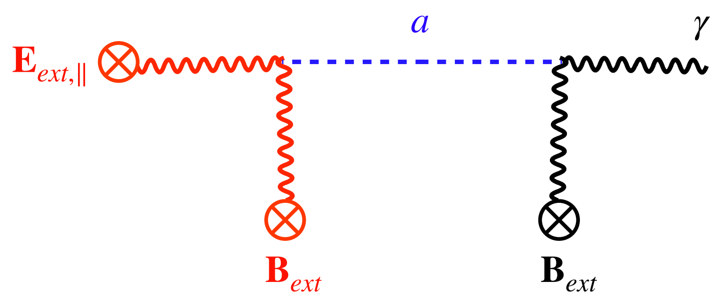


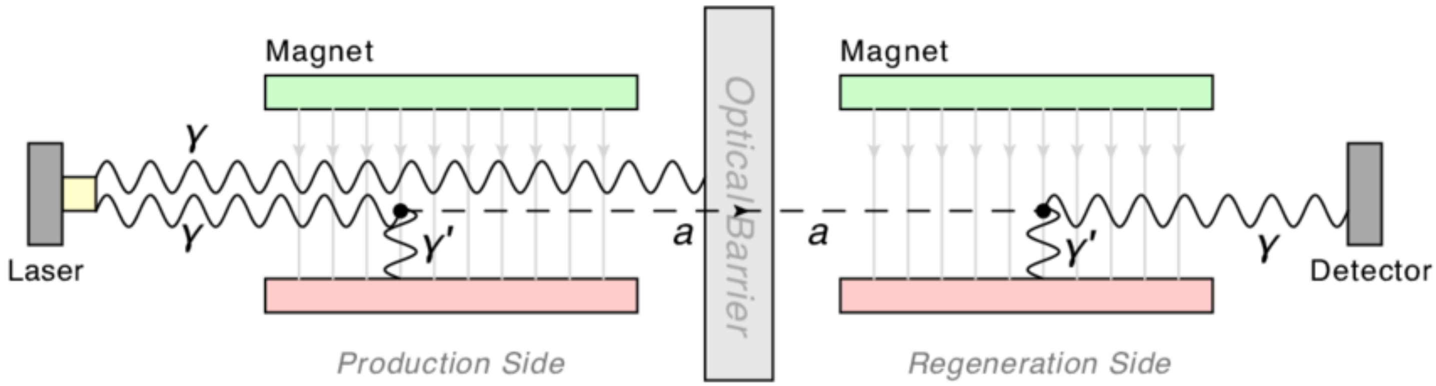
Axion-Photon Parameter Space



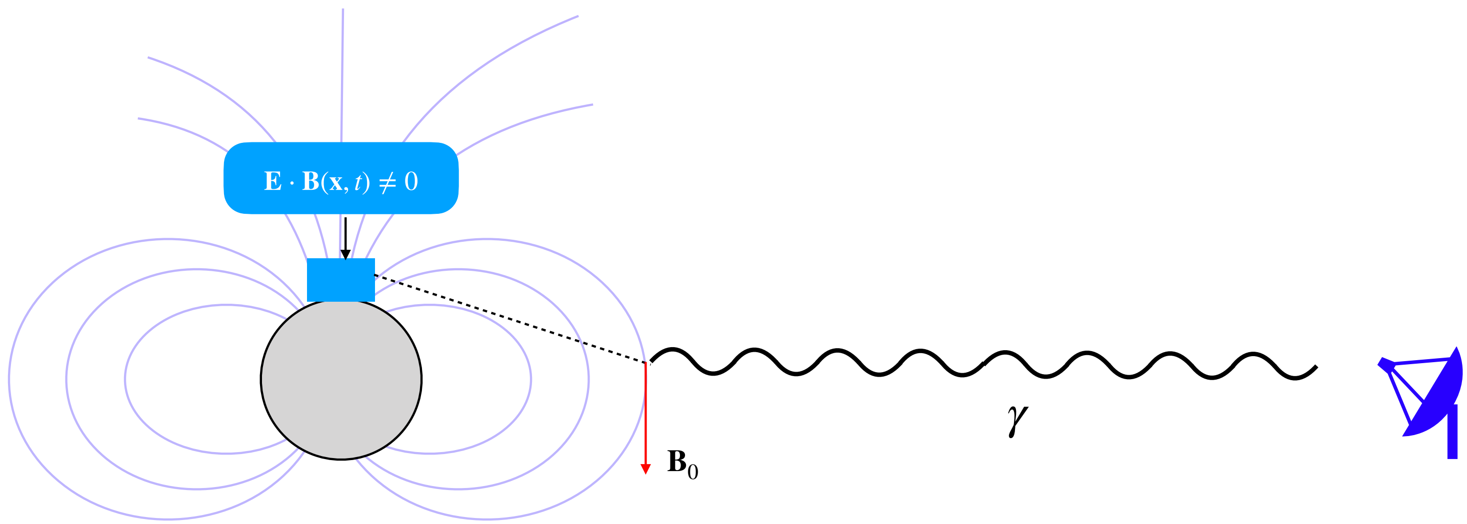
Light Shining through Walls

$$\mathscr{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = -g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})_{ext}\, a$$





Executive Summary



Pulsar Basics

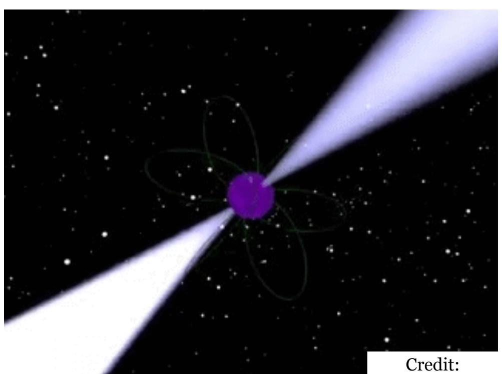
Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.



Credit: Michael Kramer

Rotating Neutron Stars

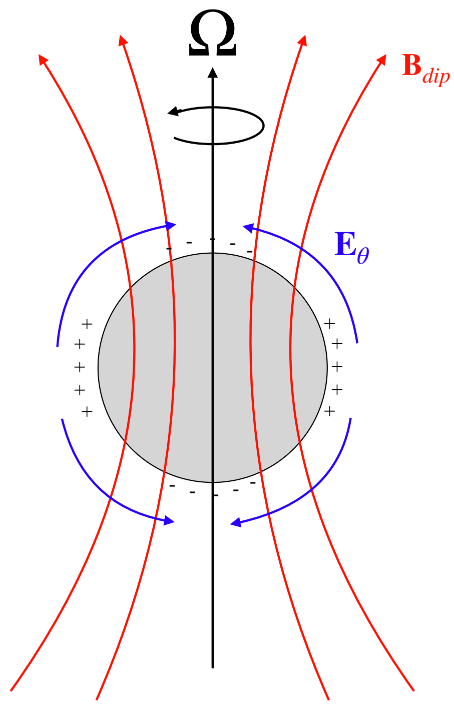
Large magnetic fields	Extremely stable periods	Neutron star
$(10^8\ \mathrm{G} - 10^{16}\ \mathrm{G})$	$\lvert \dot{P}/P \rvert \sim 10^{-16}$ Hz	$GM_{ns}/R_{ns} \sim 0.2$

↓ ↓ ↓

Pulsars are excellent laboratories for tests of new physics

a la Goldreich & Julian

Goldreich & Julian (1969)

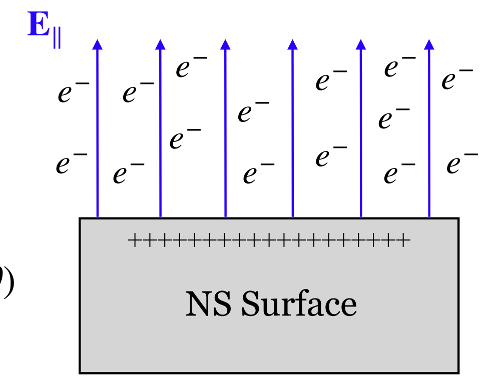


$$\mathbf{E}_{in} = -(\boldsymbol{\Omega} \times \mathbf{r}) \times \mathbf{B}_{in}$$

Vacuum Magnetosphere

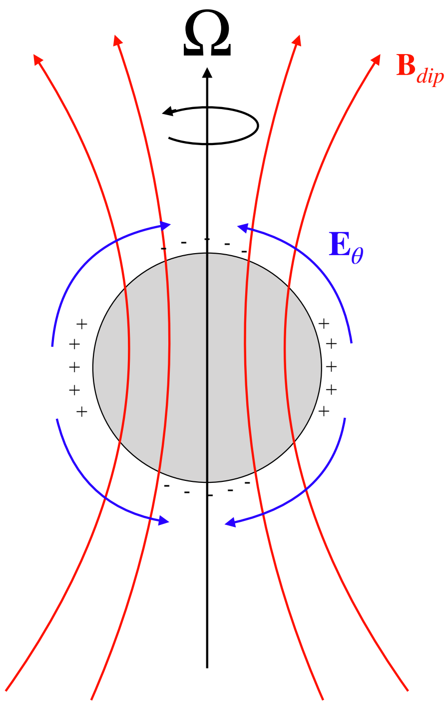
$$\Downarrow$$

$$\Phi_{\rm ext}(r,\theta) = -\frac{\Omega B_s R^5}{3r^3} P_2(\cos\theta)$$



a la Goldreich & Julian

Goldreich & Julian (1969)



$$\mathbf{E}_{in} = -(\boldsymbol{\Omega} \times \mathbf{r}) \times \mathbf{B}_{in}$$

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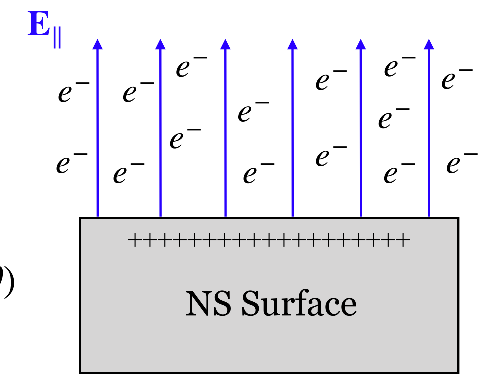


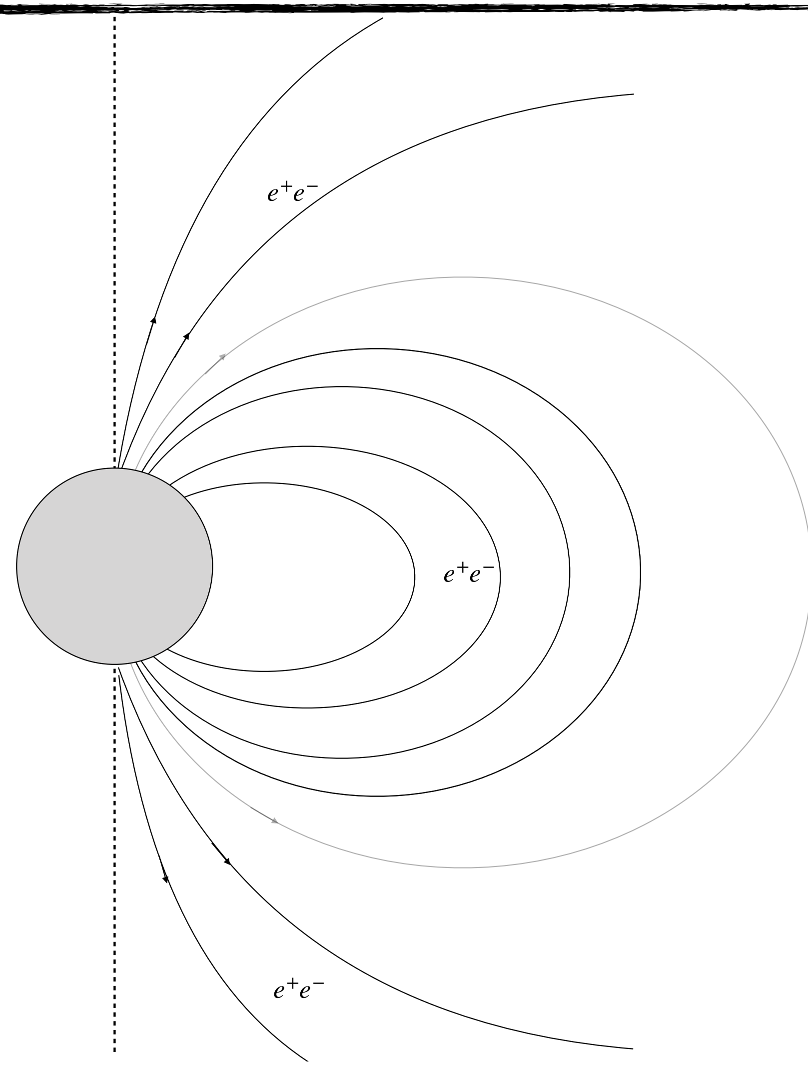
Force-Free Magnetosphere

Charges flow freely
along magnetic field lines:

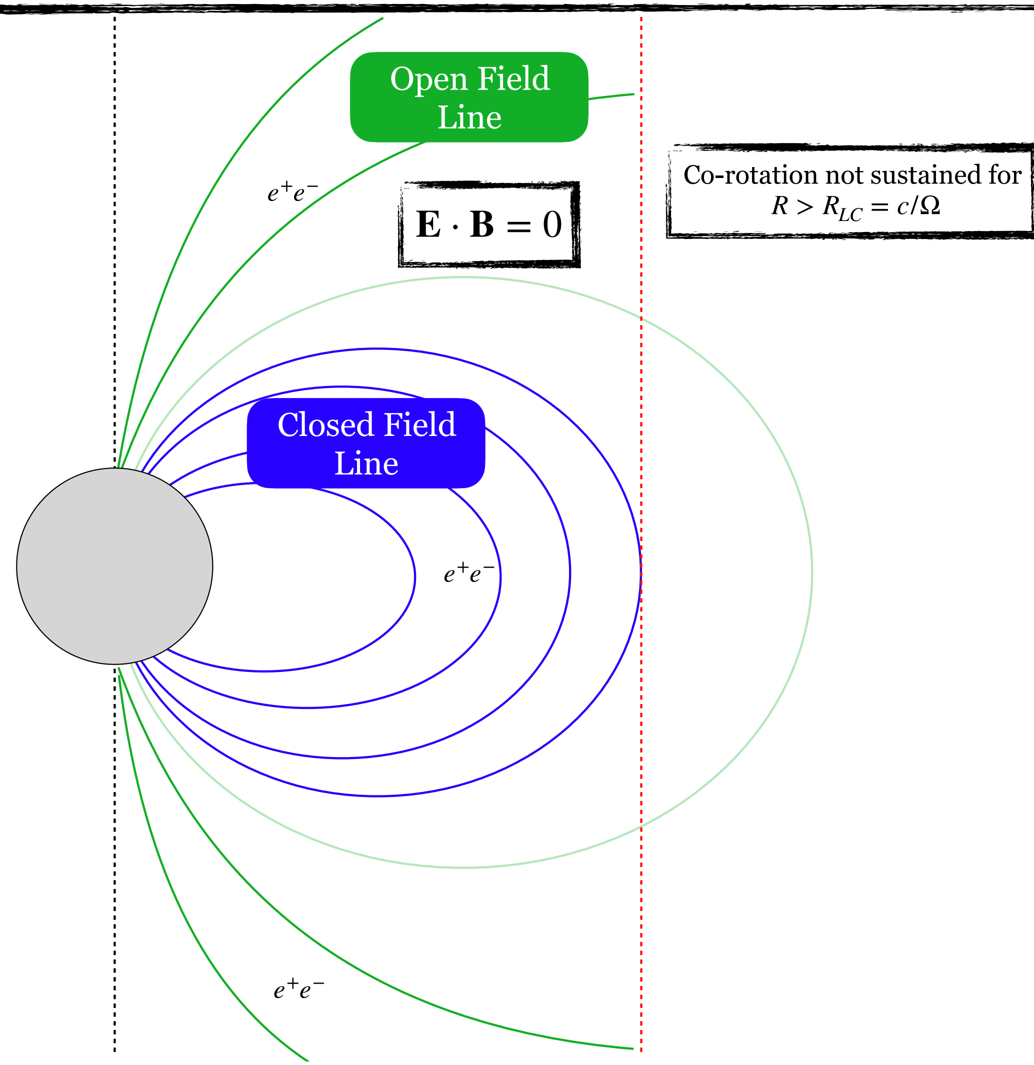
$$\Delta\Phi \Longleftrightarrow \mathbf{E}\cdot\mathbf{B} = 0^*$$

$$\rho_{GJ} = \nabla\cdot\mathbf{E} = -\frac{2\boldsymbol{\Omega}\cdot\mathbf{B}}{1-\Omega^2 r^2 \sin^2\theta}$$

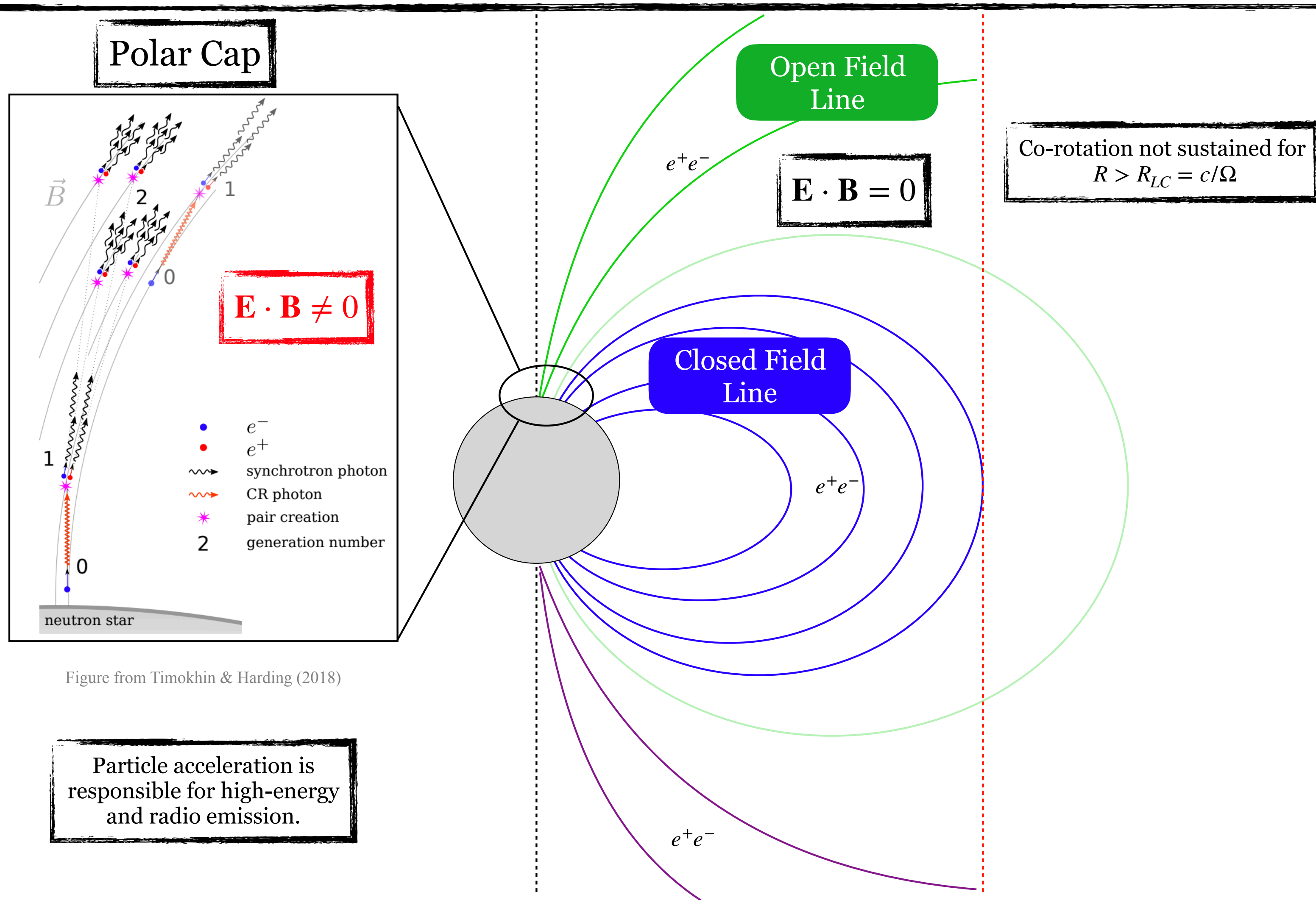
Constructing the Magnetosphere



Magnetosphere Dynamics



Magnetosphere Dynamics

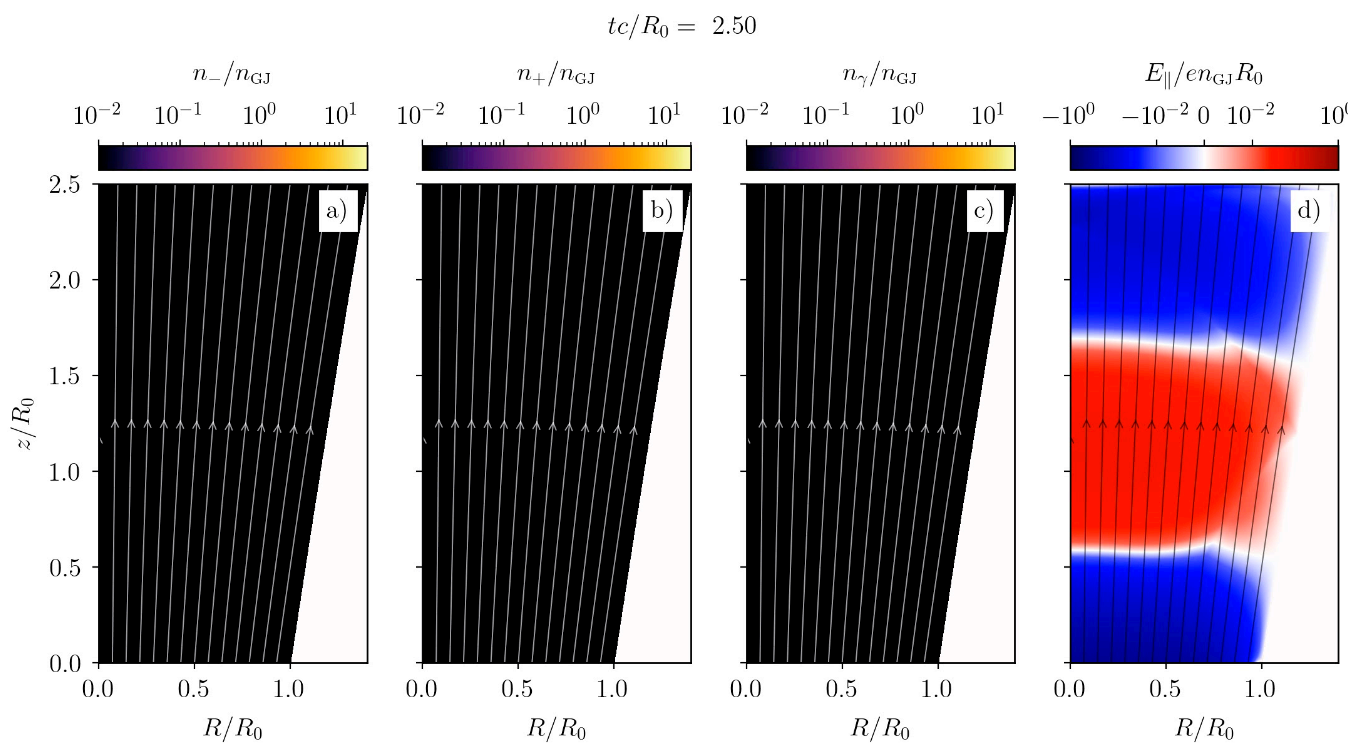


2D PIC Simulations [arXiv:2108.11702]

Coherent emission from QED cascades in pulsar polar caps

Fábio Cruz [1], Thomas Grismayer [1], Alexander Y. Chen [2], Anatoly Spitkovsky [3] and Luis O. Silva [1]

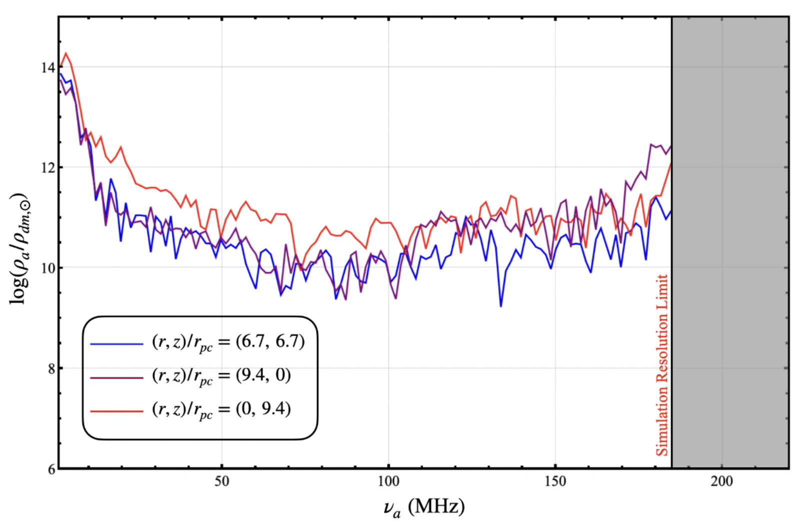
[1] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
[2] JILA, University of Colorado Boulder, 440 UCB, Boulder, CO 80309, USA
[3] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

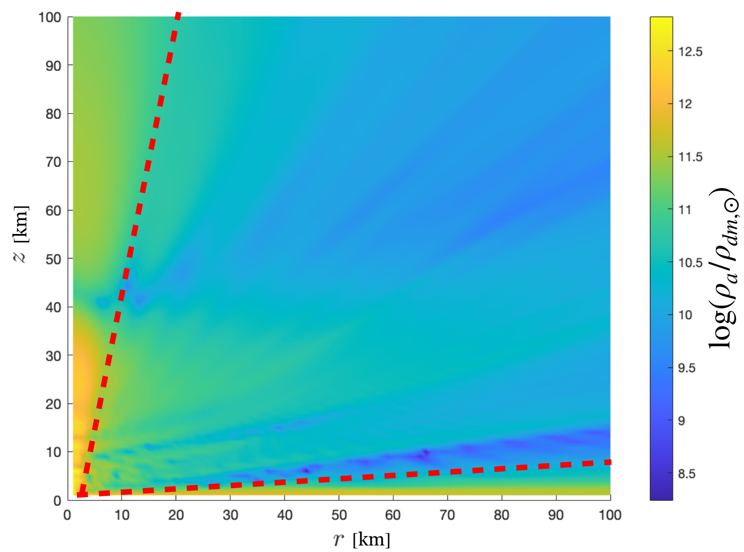


Axion Spectrum from Simulations

$$\left(\Box + m_a^2\right) a(x) = j(x) \equiv -\, g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}(x) \implies \boxed{\frac{dP}{d^3\mathbf{k}} = \frac{1}{2T}\left|\tilde{j}(\omega_{\mathbf{k}}, \mathbf{k})\right|^2, \quad \tilde{j}(k) = \int d^4x\; e^{ik\cdot x}\, j(x)}$$

$m_a = 10^{-10}$ eV, $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}



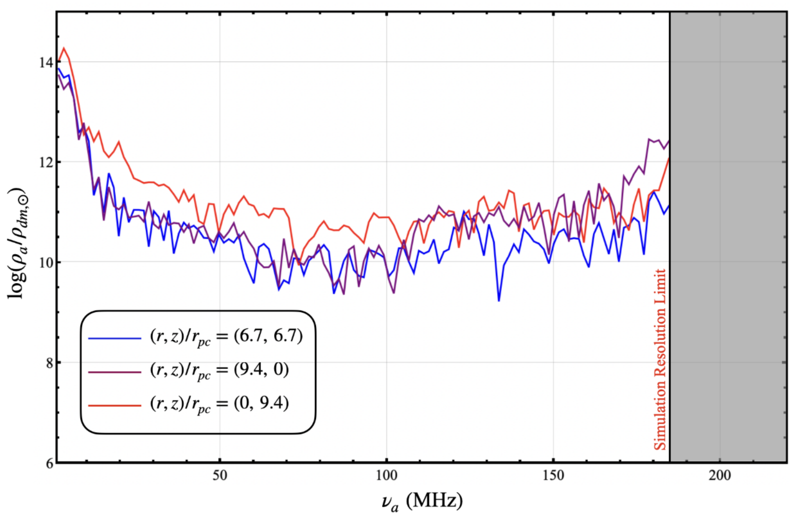


Gap-Sourced Axion Population

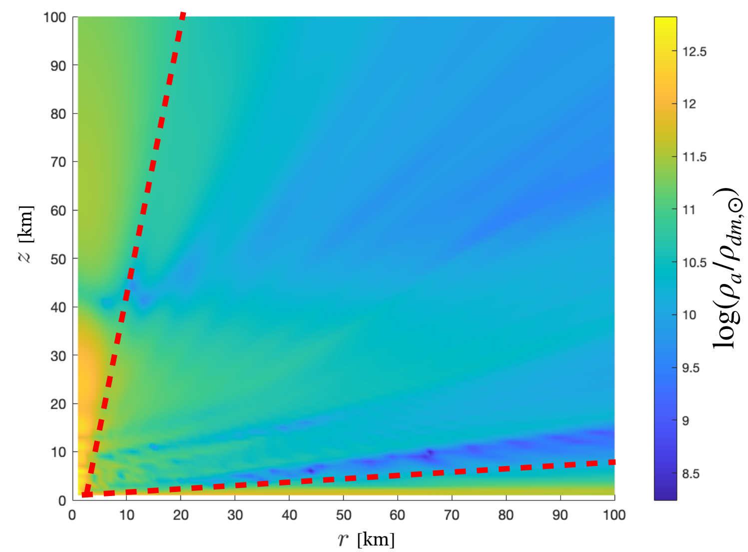
$$\left(\Box + m_a^2\right) a(x) = j(x) \equiv -\, g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}(x) \implies \boxed{\frac{dP}{d^3\mathbf{k}} = \frac{1}{2T}\left|\tilde{j}(\omega_{\mathbf{k}},\mathbf{k})\right|^2, \quad \tilde{j}(k) = \int d^4x\, e^{ik\cdot x}\, j(x)}$$

$m_a = 10^{-10}$ eV, $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}

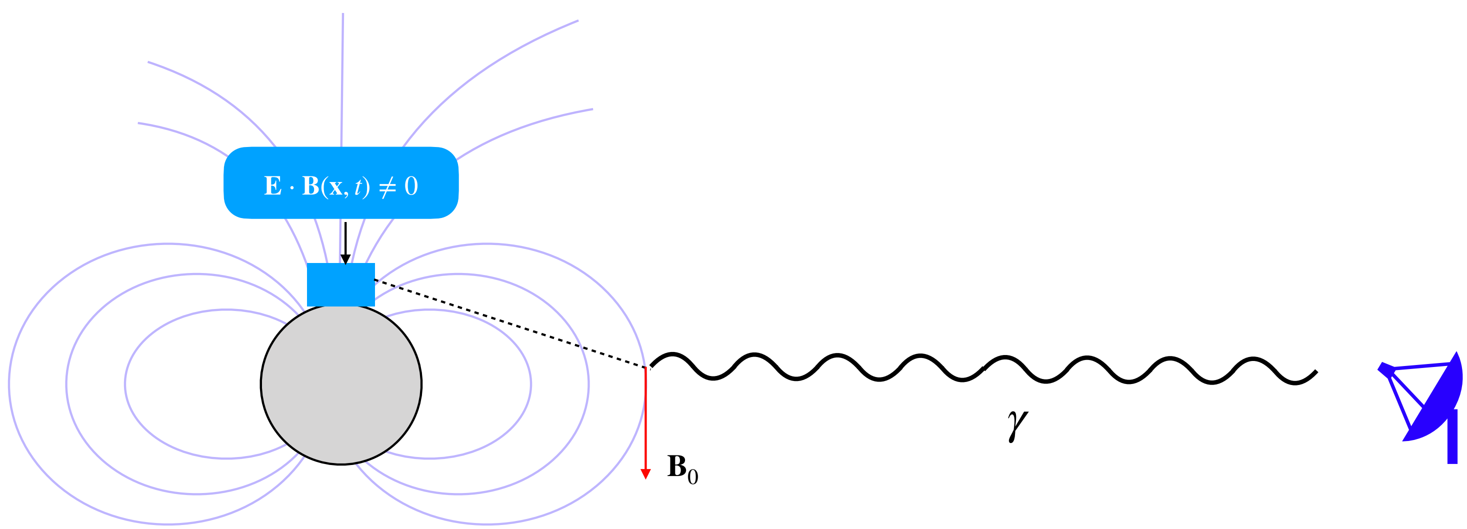
Orders of magnitude denser than DM near NS!



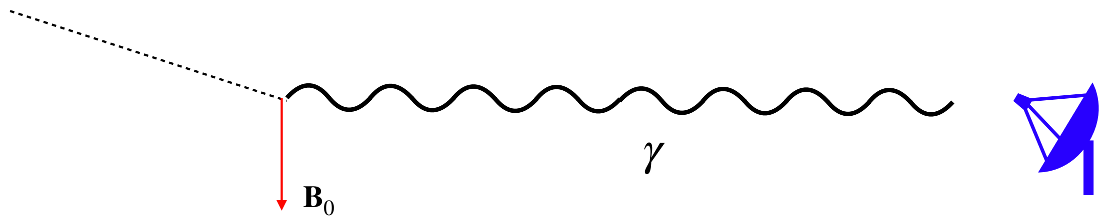
$\theta = 0$, $\theta = \pi/2$
Beaming



Executive Summary



Executive Summary



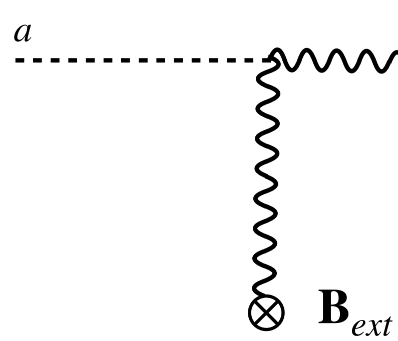
Hook et al. (2018), Safdi et al. (2019), Leroy et al. (2019),
Battye et al. (2020), Fortin & Sinha (2018, 2019, 2021), Witte et al. (2021)

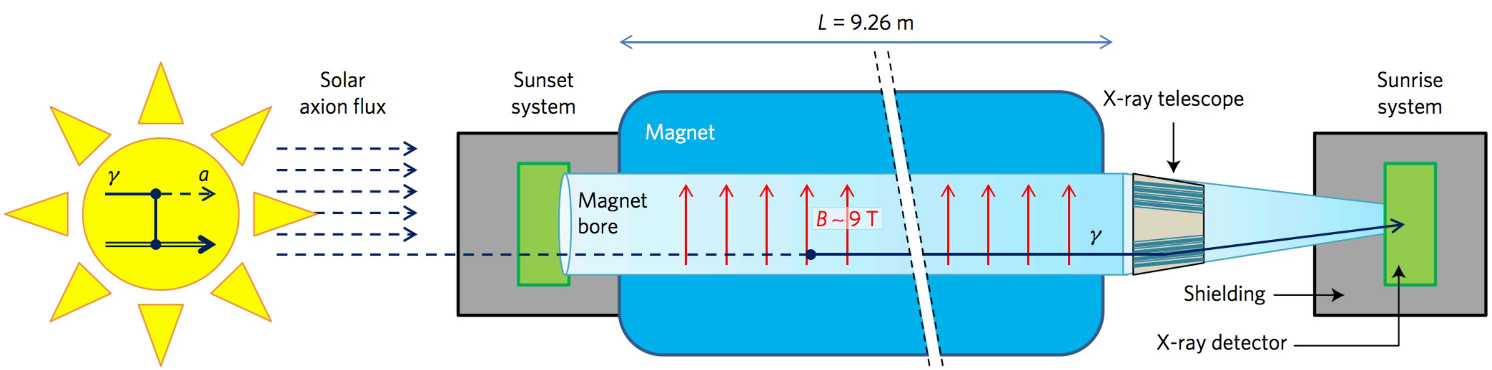
Axion-Photon Conversion

Uniform Magnetic Field

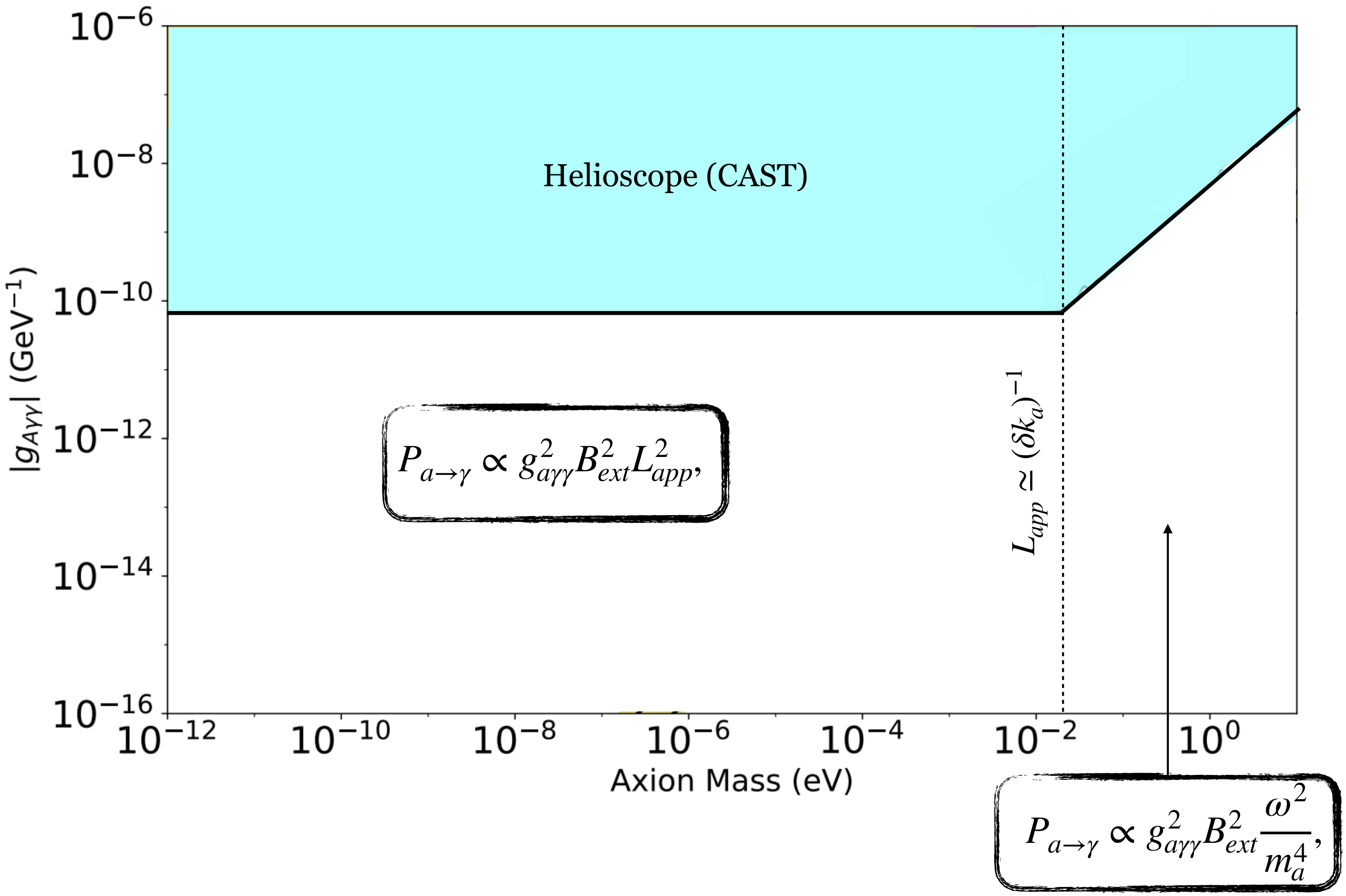
$$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 L^2, \qquad L \sim \min\left(L_{app},\, (\delta k_a)^{-1}\right)$$

$$\delta k_a = m_a^2/2\omega$$

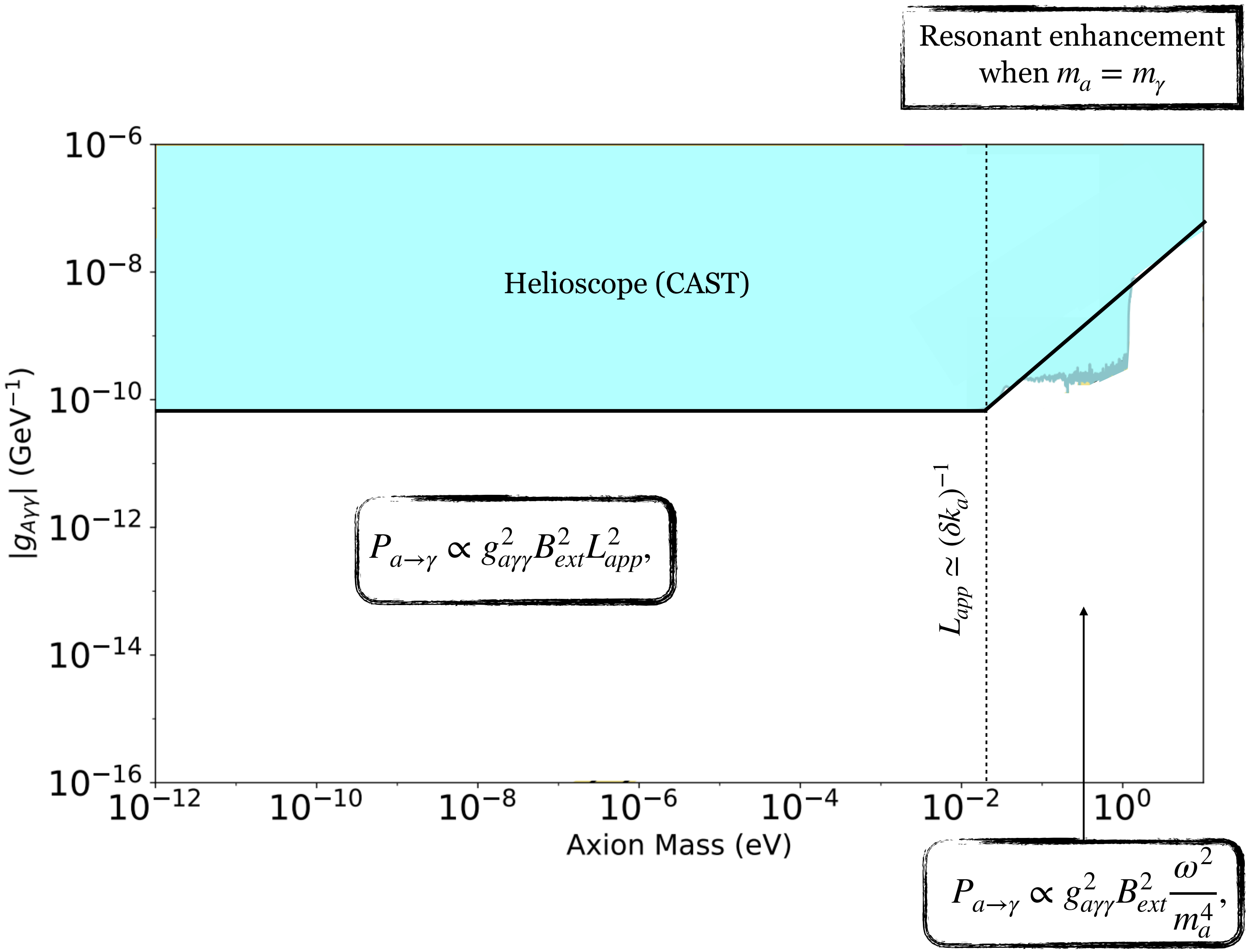




Credit: CAST Collaboration



Helioscope (CAST)
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 L_{app}^2,$
$L_{app} \simeq (\delta k_a)^{-1}$
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 \frac{\omega^2}{m_a^4},$
$|g_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}



Resonant enhancement
when $m_a = m_\gamma$
Helioscope (CAST)
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 L_{app}^2,$
$L_{app} \simeq (\delta k_a)^{-1}$
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 \frac{\omega^2}{m_a^4},$
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10^{-6}
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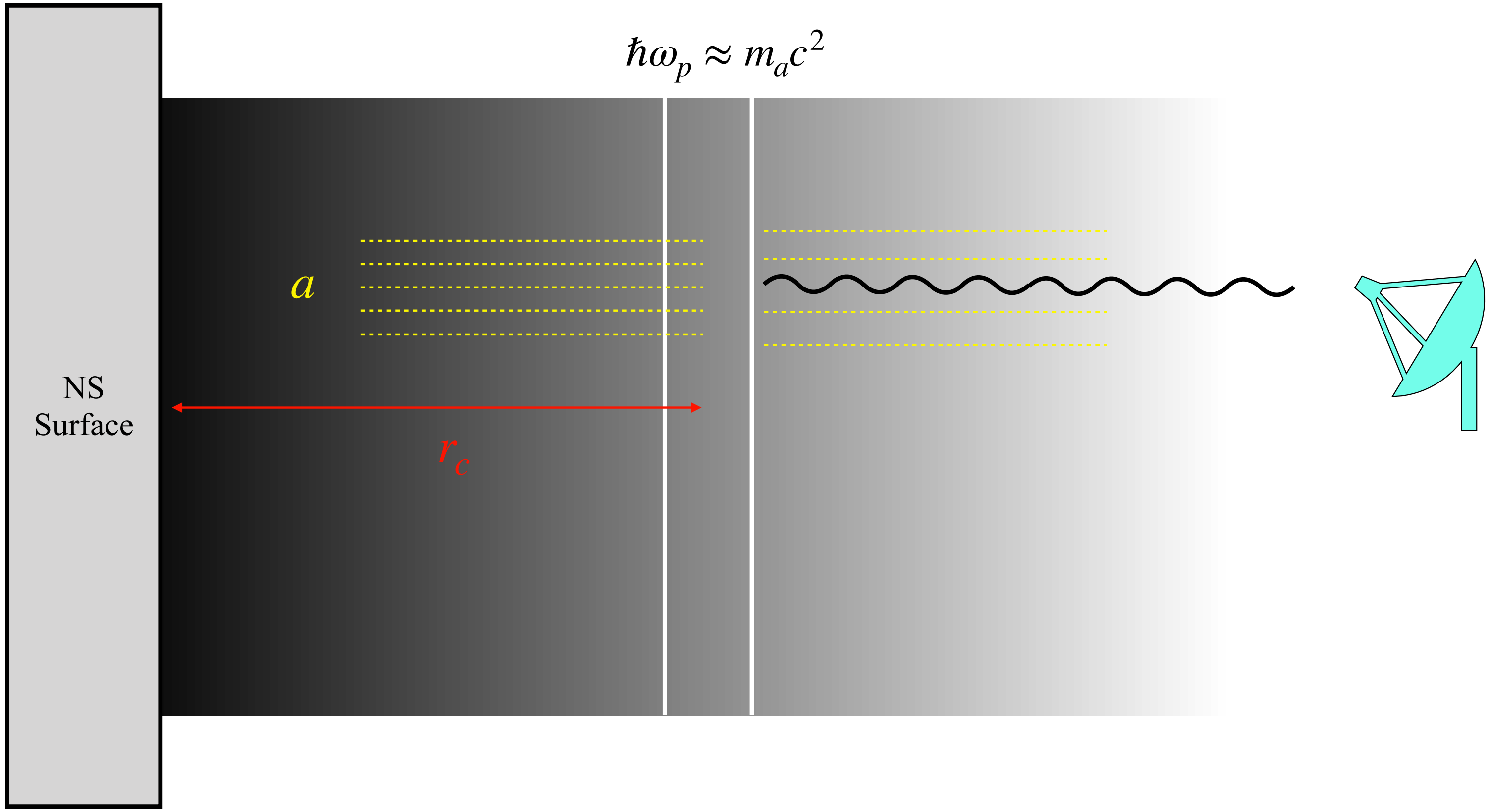
10^{-14}
10^{-16}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

Pulsar Plasma

Raffelt & Stodolsky (1988)
Hook, Kahn, Safdi, Sun (2018)

Pulsar magnetosphere gives the photon a spatially-varying mass



Neutron Star Targets: Magnificent Seven

Magnificent Seven

- ☑ High magnetic fields ($10^{13} – 10^{14}$ G).
- ☑ Very nearby to Earth (120-500 pc).
- ☑ Undetected pulsed radio emission ($\lesssim 10\ \mu$Jy).

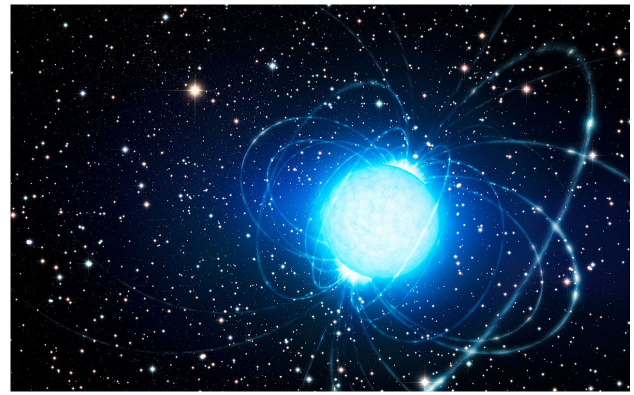
Minimum detectable frequency $\approx$ 70 MHz (FAST), $\approx$ 50 MHz (SKA1-Low)

Pulsar	B_s (10^{13} G)	P (sec)	Distance (pc)
RX J0420.0–5022	1.0	3.45	~ 345
RX J0720.4–3125	2.4	8.39	360^{+170}_{-90}
RX J0806.4–4123	2.5	11.37	240^{+10}_{-5}
1RXS J1308.8+2127	3.4	10.31	76 – 380
RX J1605.3+3249	~7.4	3.39	$\lesssim 410$
RX J1856.5–3754	1.5	7.06	123 ± 13
1RXS J2143.0+0654	2.0	9.43	$\gtrsim 250$

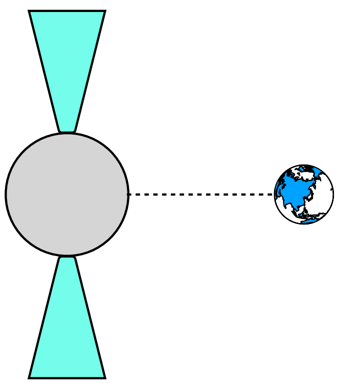
Neutron Star Targets: Magnetars

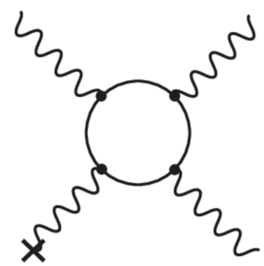
Magnetars

- ✅ Very high magnetic fields ($\gtrsim 10^{14}$ G).
- ❎ Very nearby to Earth (120-500 pc).
- ✅ Undetected pulsed radio emission ($\lesssim$ mJy).
- ❓ Gap formation?



Reason for absence of radio emission crucial to understanding e^+e^- production and axion production!





Noise and Backgrounds

$$S_{\min} = \frac{\text{SEFD}}{\sqrt{n_{\text{pol}} \Delta\nu_{\text{rec}} T_{\text{int}}}}$$

$$\text{SEFD}(\nu) = \frac{2(T_R(\nu) + T_a(\nu) + T_{ns}(\nu) + \cdots)}{A_{eff}}$$

$$A_{eff} = A_0\sqrt{N(N-1)}$$

(Interferometer)

$$A_{eff} = \eta A_{phys}$$

(Single-dish)

Noise and Backgrounds

$$S_{\min} = \frac{\mathrm{SEFD}}{\sqrt{n_{\mathrm{pol}} \Delta\nu_{\mathrm{rec}} T_{\mathrm{int}}}}$$

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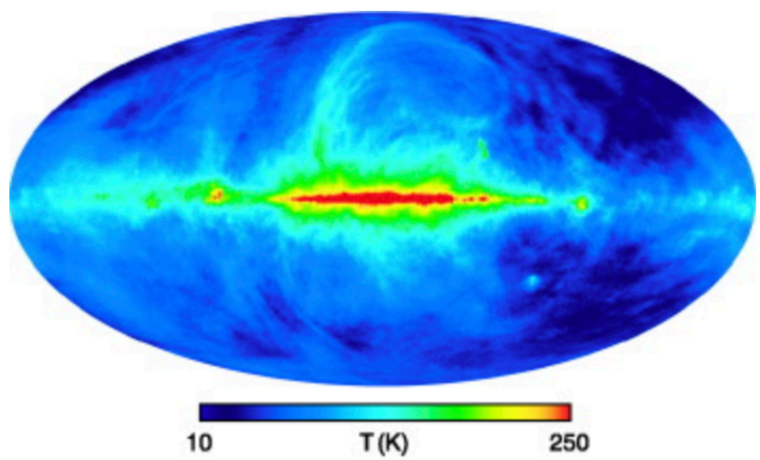
(Single-dish)

Galactic Synchrotron Emission

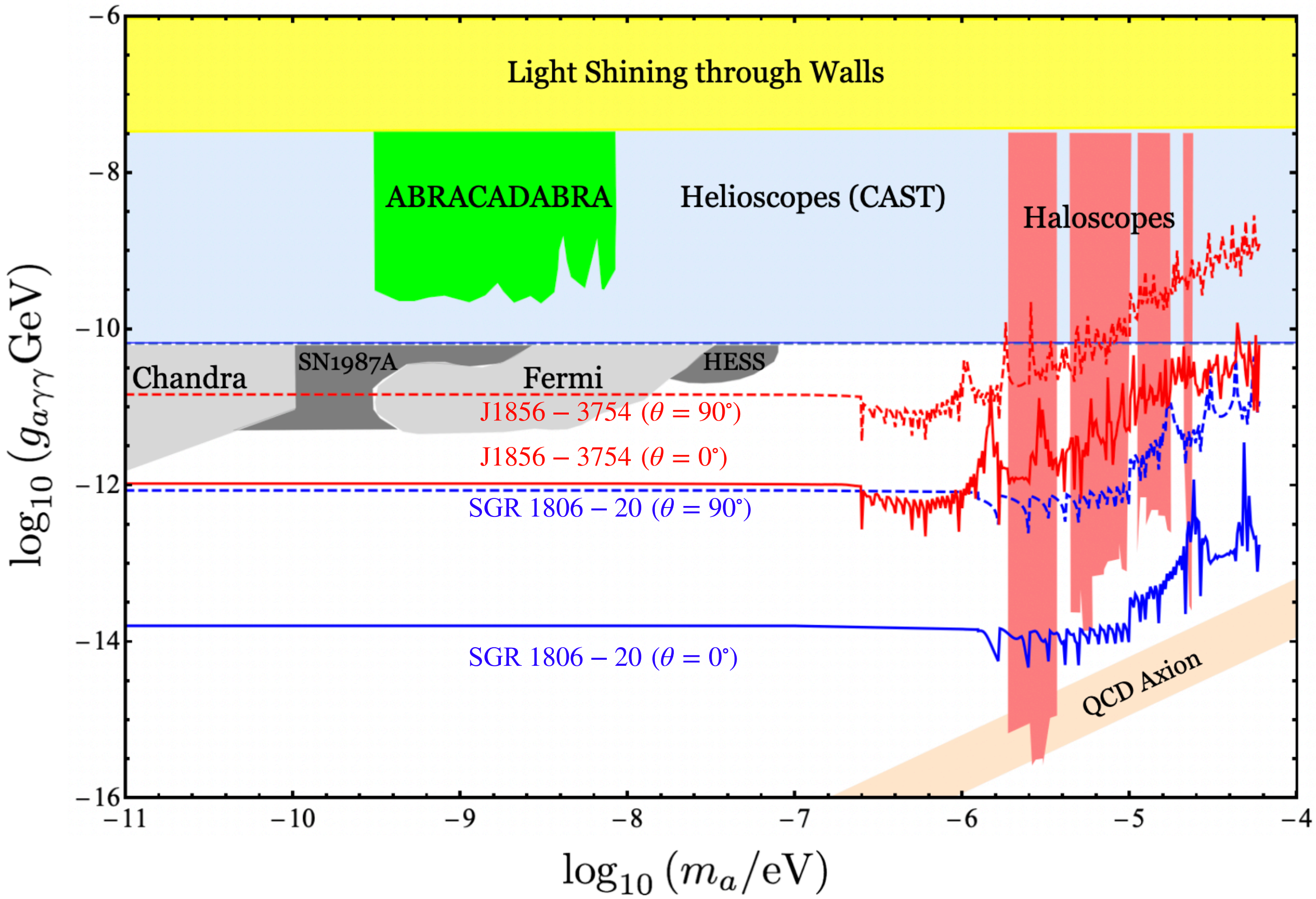
$$T_{\mathrm{a}} = (24.1 \pm 2.1)\ \mathrm{K} \left(\frac{\nu}{310\ \mathrm{MHz}}\right)^{-2.599\pm0.036}$$

ARCADE2 (2011)



Haslam et al (1982)

Sensitivity



Conclusions & Future Directions

- Axions are efficiently produced in particle acceleration gaps ($\mathbf{E} \cdot \mathbf{B} \neq 0$) in pulsar magnetospheres.
- Axions can resonantly convert to photons in the pulsar magnetosphere $\Longrightarrow$ broadband radio signals.
- Dedicated observation with FAST or SKA sensitive to $g_{a\gamma\gamma}$ orders of magnitude lower than astrophysical constraints.
- More sophisticated axion conversion computation including ray-tracing, plasma effects, signal time-dependence.
- Axion production in additional magnetosphere gaps (slot gap, outer gap, current sheet), other astrophysical settings (BHs?).
- Understand gap dynamics and pair production in magnetars.

Thank you!