Title: Neutron Stars as Laboratories for Physics Beyond the Standard Model

Speakers: Anirudh Prabhu

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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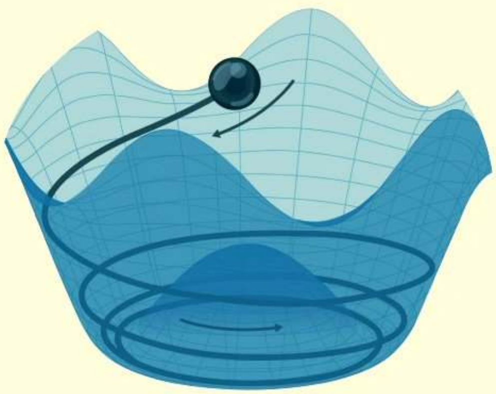
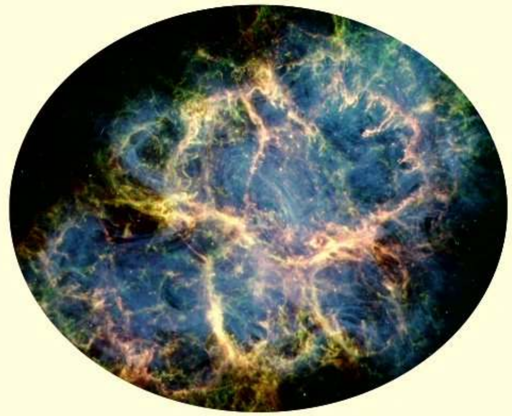
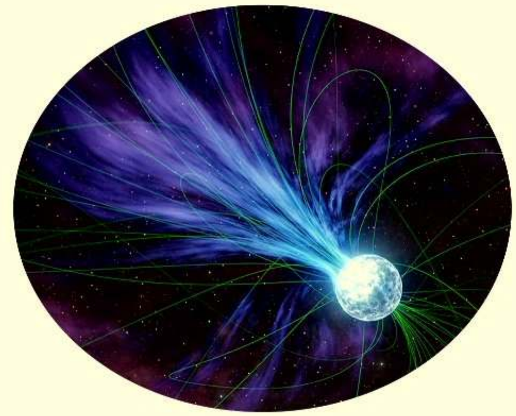
Abstract:

Compact objects like neutron stars and black holes host extreme conditions that cannot be replicated in terrestrial laboratories or even by the most ambitious future particle colliders. These conditions make them unparalleled natural laboratories for exploring new physics. Neutron stars stand out due to their incredibly strong electromagnetic fields, some of the most intense in the universe. This makes them ideal for testing the limits of electromagnetism and for probing physics beyond the Standard Model, including axions and dark photons, which are among the leading dark matter candidates. In this talk, I will highlight recent advancements in using pulsars to detect axions and discuss ongoing efforts to probe axions using magnetars, ultra-magnetic neutron stars that are the most magnetic objects in the Universe.

Neutron Stars as Laboratories for Physics Beyond the Standard Model







PRINCETON CENTER FOR THEORETICAL SCIENCE

Ani Prabhu, Princeton University

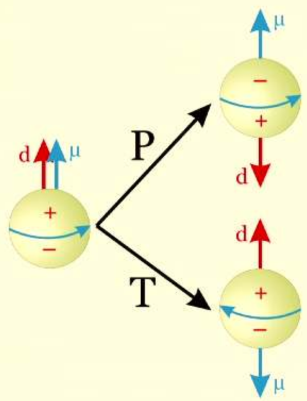
Perimeter Institute Cosmology Seminar

October 7, 2025

In collaboration with: Carlos Blanco, Alexander Y. Chen, Fábio Cruz, Mariia Khelashvili, Mariangela Lisanti, Dion Noordhuis, Sandip Roy, Ben Safdi, Christopher Thompson, Christoph Weniger, Sam Witte, Jonathan Zhang

Axions

$$\boxed{\text{Periodic pseudoscalar field: } a \cong a + 2\pi f_a}$$



Strong CP Problem
(Why is the neutron EDM so small?)

"The Most Underrated Puzzle In All Of Physics"
- **Forbes Magazine**

String Theory
(How can we reconcile quantum mechanics with gravity?)

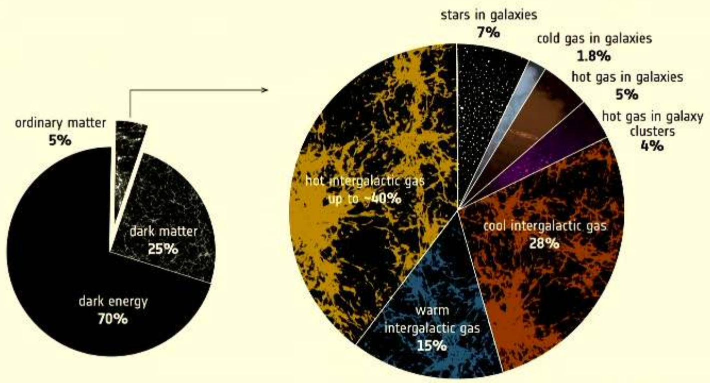


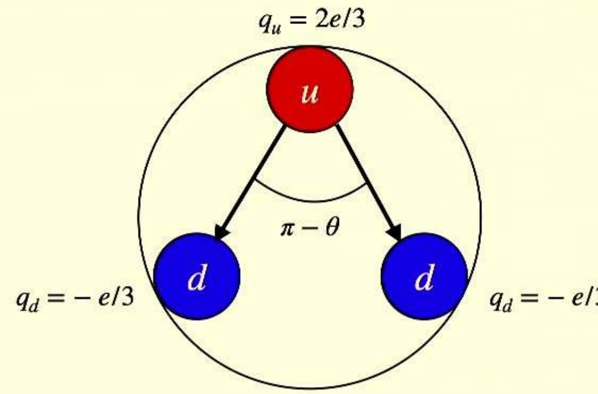
Image credit: ESA

Dark Matter
(What makes up ~80% of the matter in the Universe?)

Axion Introduction

Strong CP problem: Why is the neutron EDM $d_n \ll e \cdot r_n$?

$$\mathscr{L}_{QCD} \supset \frac{g_s^2}{32\pi^2}\theta_0 \; G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

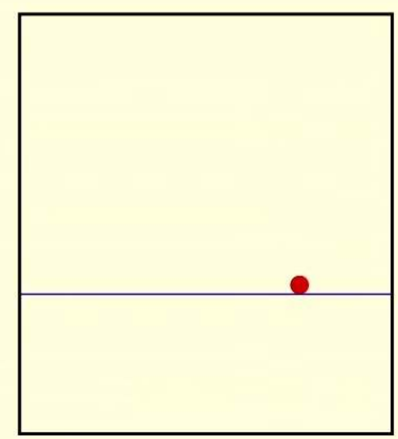


Theoretical Prediction: $d_n = 3 \times 10^{-16} \; (\theta_0 + \arg\det M_u M_d) \, e \cdot \mathrm{cm}$

Experimental Bound: $d_n \lesssim 10^{-26} \; e \cdot \mathrm{cm}$

Axion Solution: Promote $\theta \to a(x)$ (**QCD axion**), which obtains

$$V_{inst}(a) = \Lambda^4 \left[1 - \cos\left(\frac{a}{f_a} + \bar{\theta}\right)\right]$$



Peccei-Quinn Mechanism

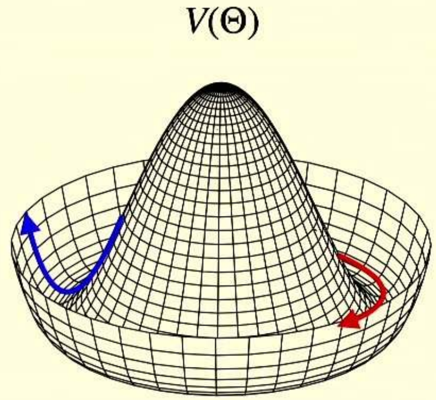
Peccei & Quinn (1977)
Weinberg & Wilczek (1978)

Promote θ to a dynamical field with a potential with minimum at CP-conserving value

Introduce global $U(1)$ (PQ) symmetry

SSB

$$\Theta = \left(\rho(x) + \langle\rho\rangle\right) e^{ia(x)/f_a}$$



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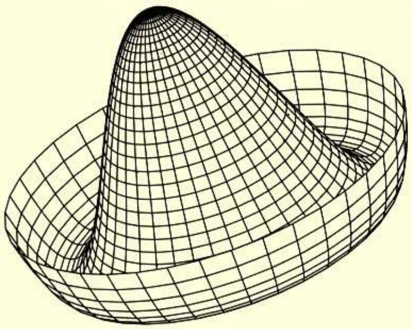
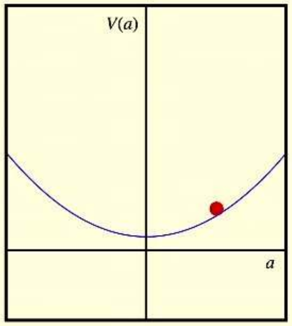
Instantons

$$V_{inst}(a) = \Lambda^4 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

$V(\Theta)$





Axions in String Theory

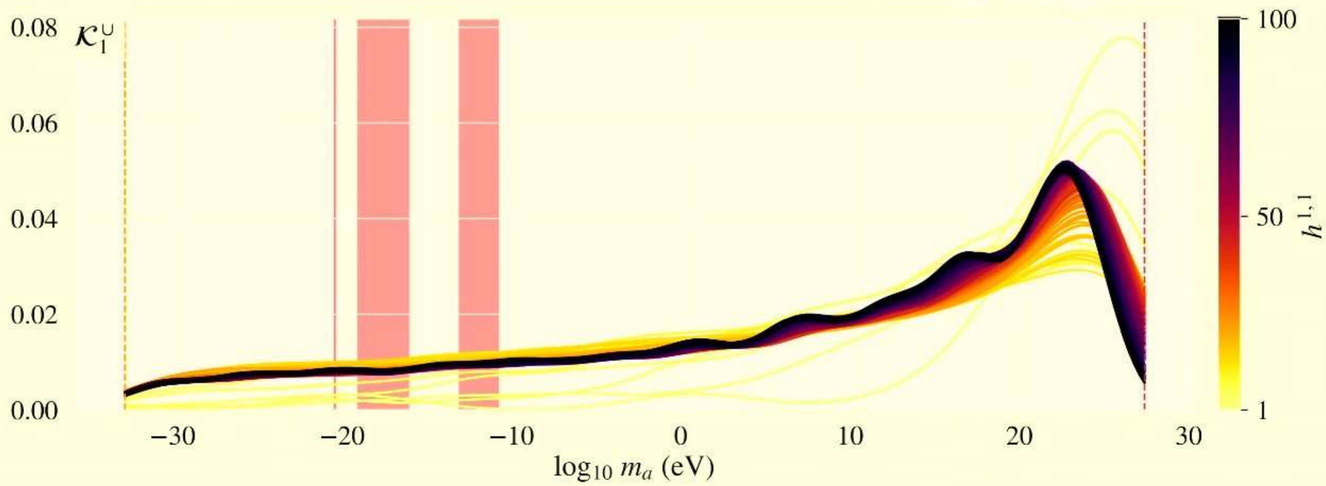
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2010)

p-forms (gauge fields) + Extra Dimensions + Topology = CP-odd scalars

B_{MN}(NS), C_p(Ramond-Ramond), …

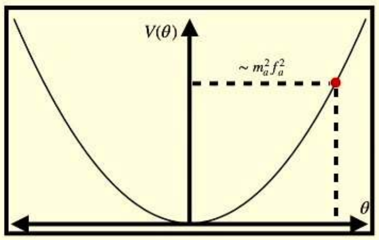
$M = 0,1,2,3,\underbrace{4,\ldots,D-1}_{\text{Compact Extra Dimensions}}$

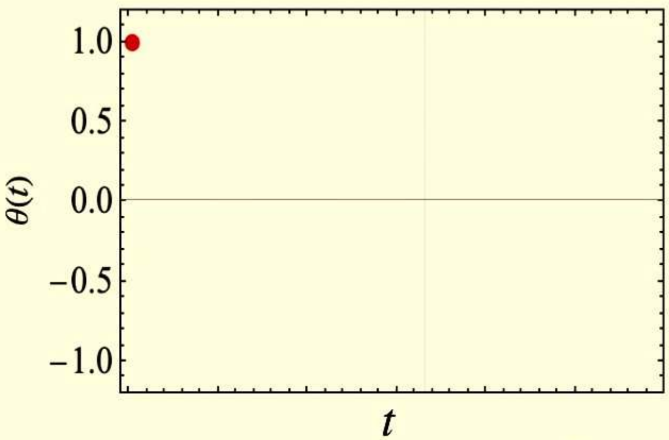
$$A_p = \sum_{i=1}^{b_p} a_i(x)\omega_{p,i}(y)$$



Axion Cosmology

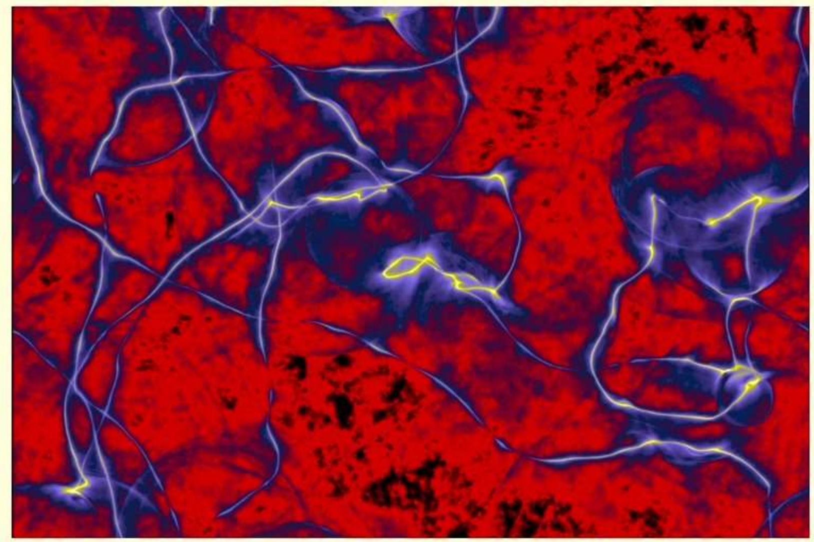
Scenario 1 (Pre-inflationary): $f_a > H_I$





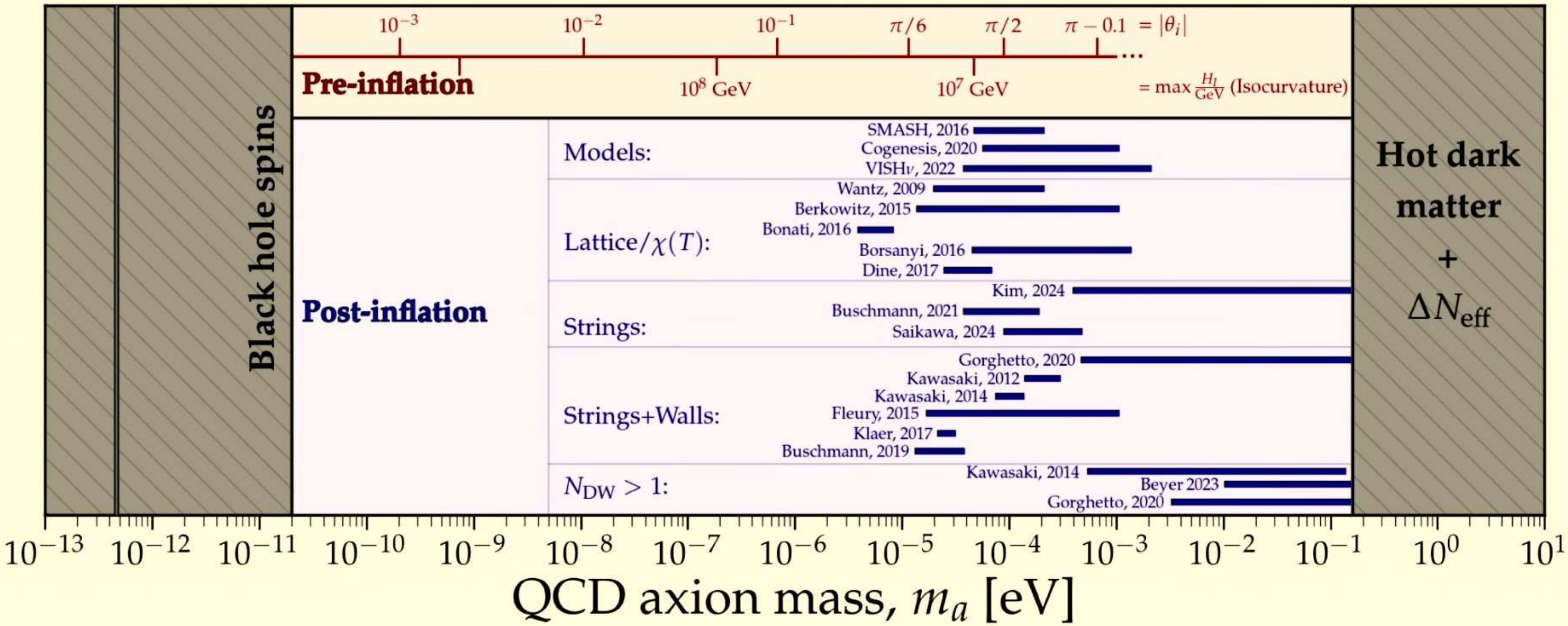
$$\rho_a = \frac{1}{2} m_a^2 \phi_i^2 \left(\frac{a_{\rm osc}}{a} \right)^3$$

Scenario 2 (Post-inflationary): $f_a < H_I$



Credit: Malte Buschmann

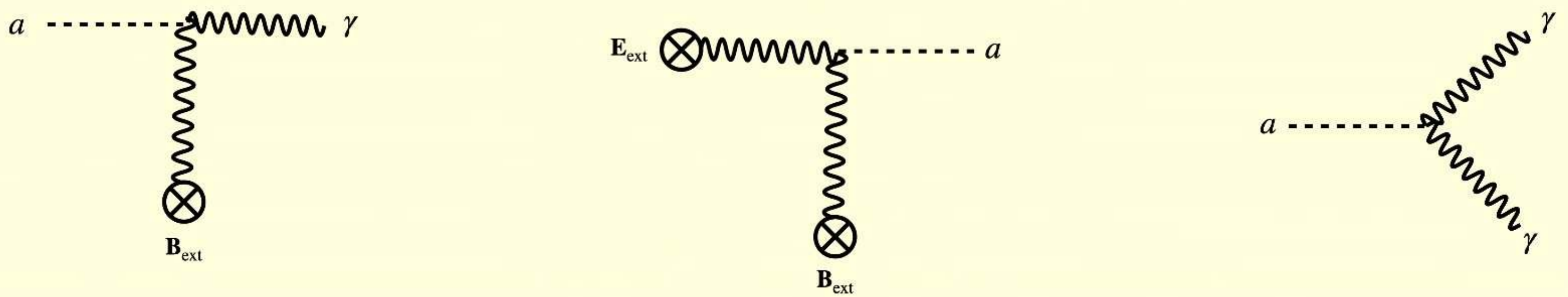
The Mass of QCD Axion Dark Matter



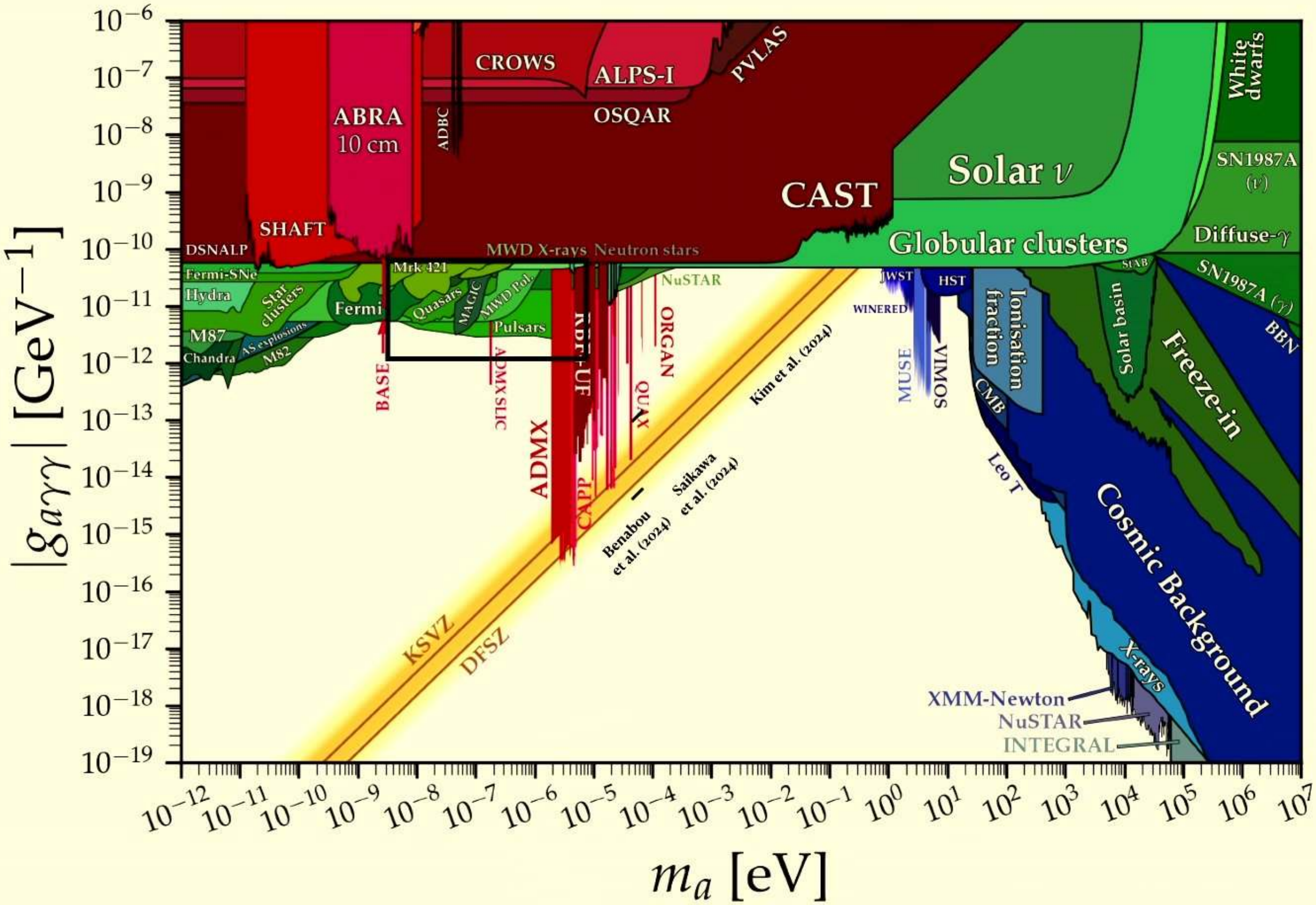
Axion Phenomenology Introduction

Axions couple to the SM through dim-5 operators that are suppressed by a scale f_a which represents the periodicity of the axion field $a(x) \to a(x) + 2\pi f_a$.

$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a(\mathbf{x}, t)\ F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f g_{aff} \bar{f}\gamma^\mu \gamma_5 f\ \partial_\mu a(\mathbf{x}, t)\ - \frac{i}{2} g_{aN\gamma} a \bar{\Psi}_N\ \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu} + \dots$$

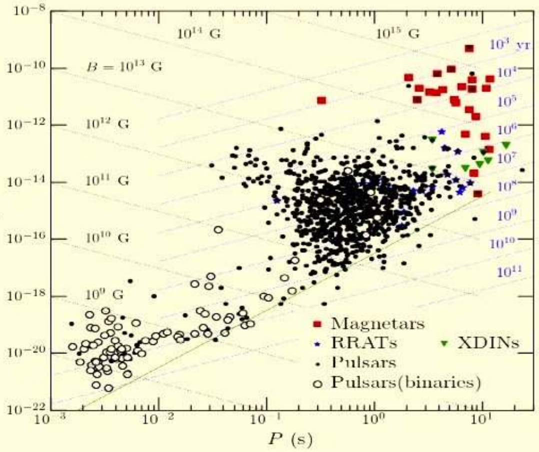


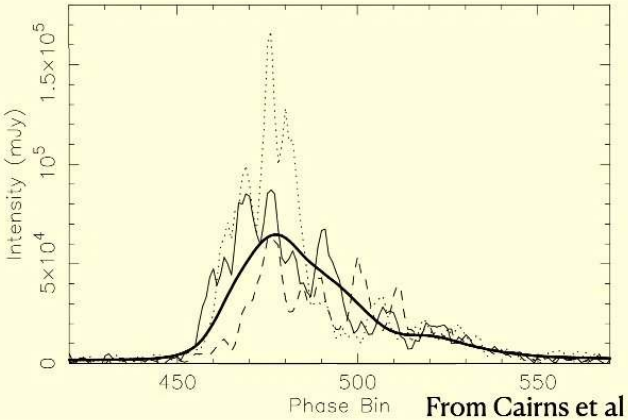
Axion-Photon Parameter Space



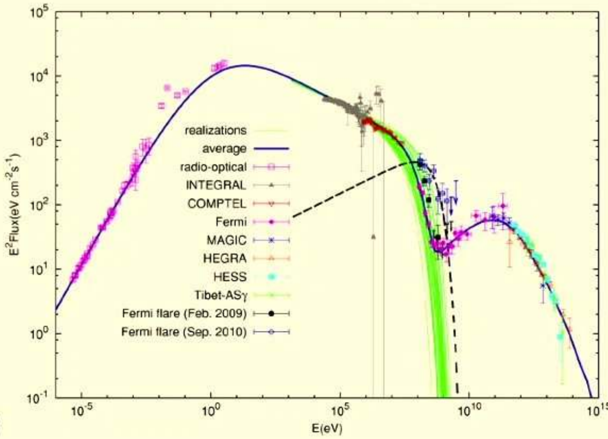
Pulsating **R**adio Sources: Rapidly-rotating Neutron Stars

- Neutron stars: $R_{\rm NS} \approx 10$ km, $M_{\rm NS} \approx 1.4\ M_\odot$, $v_{\rm esc} \approx 0.5c$.
- Density: $\rho \gtrsim \rho_{\rm nuc} \approx 0.15$ nucleons/fm^3.
- Spin periods ranging from ≈ 1.5 ms to 10 sec*.
- Highly stable (average) pulse profile.
- Magnetic fields ranging from $\approx 10^8$ Gauss to over 10^{15} Gauss*.
- Emission detected from radio to gamma rays



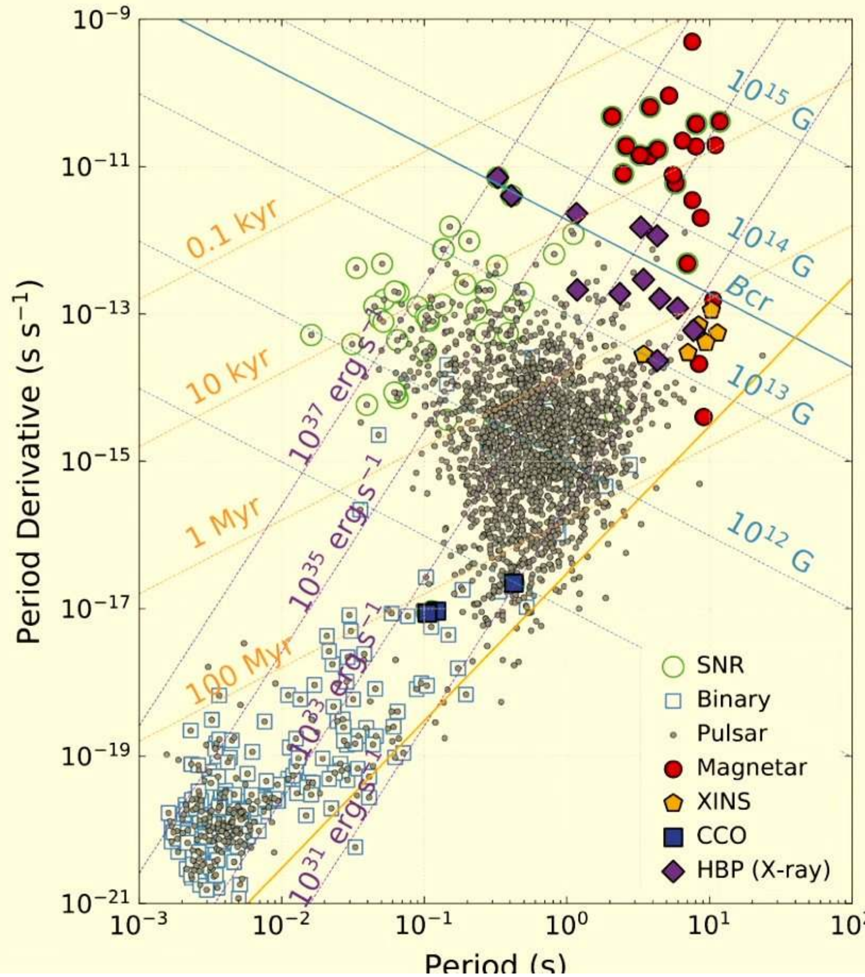


From Cairns et al (2001)



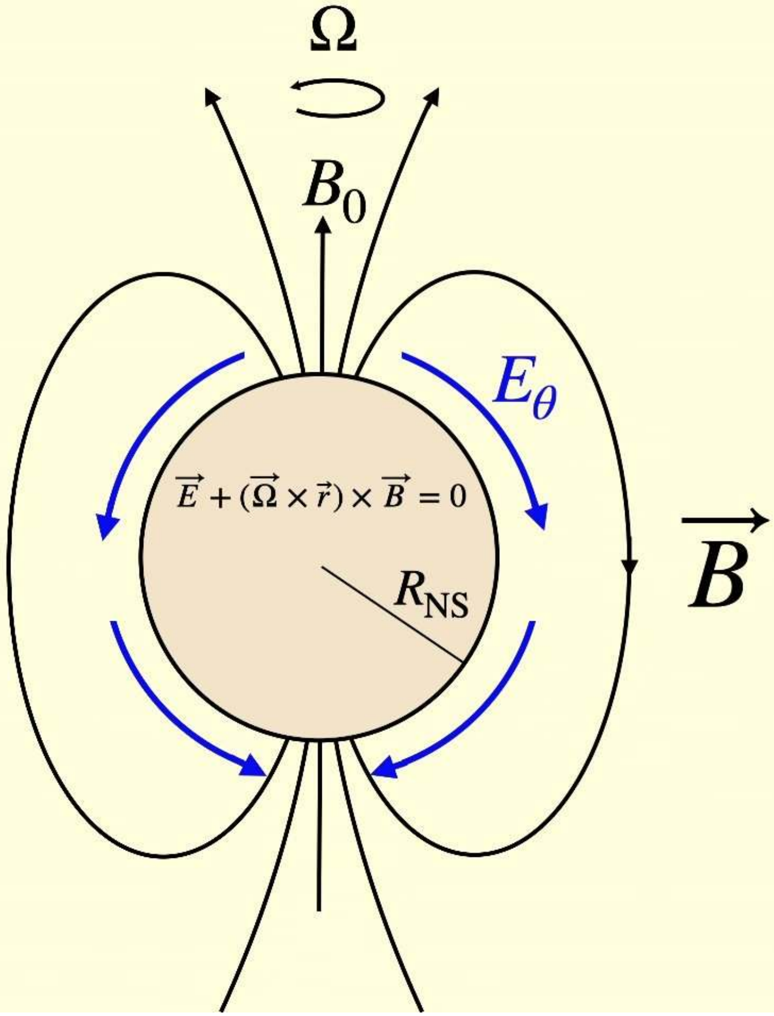
The Pulsar Zoo

- Canonical **radio pulsars**: middle-aged NSs magnetic fields $B \in [10^{11}, 10^{14}]$ Gauss and rotation periods $P \sim 1$ second.
- **Millisecond pulsars**: old NSs that have been spun up by accretion. Lower magnetic fields and high rotation frequency.
- **Magnetars**: young, ultra-magnetic ($B \gtrsim 10^{14}$ Gauss) NSs with rotation periods $P \sim 10$ seconds*.
- **Dead NSs**: Old, cold NSs that do not emit coherent radio emission.

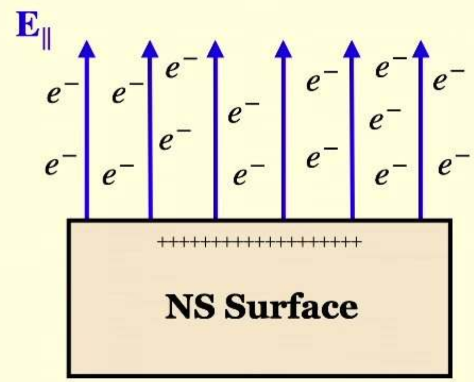


Pulsar Electrodynamics

Goldreich & Julian (1969)



$$\Phi_{\rm ext}(r,\theta) = -\frac{\Omega B_0 R_{\rm NS}^5}{3r^3} P_2(\cos\theta)$$



Pulsar Electrodynamics

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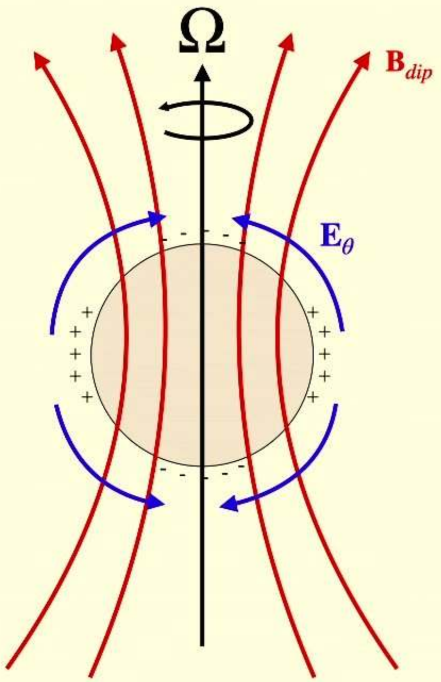
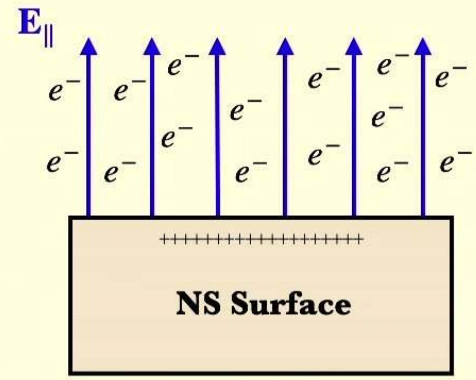


$$\mathbf{E}_{in} = -(\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B}_{in}$$

Vacuum Magnetosphere

$\Downarrow$ Laplace Equation

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



Force-free Magnetosphere

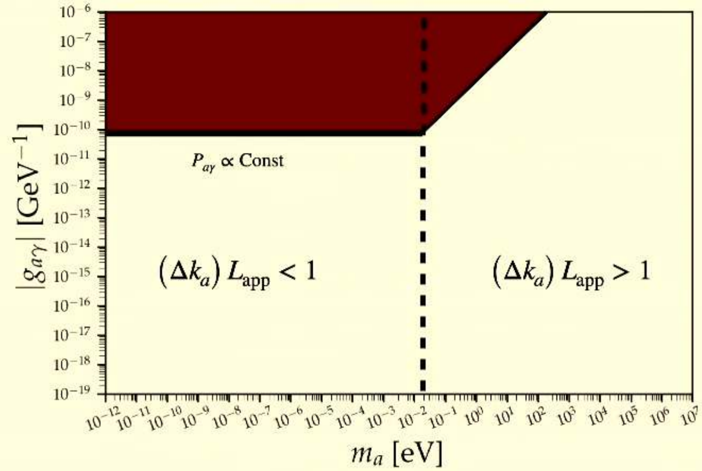
$$\boxed{\rho_{GJ} = \nabla \cdot \mathbf{E} = -\frac{2\mathbf{\Omega} \cdot \mathbf{B}}{1 - \Omega^2 r^2 \sin^2\theta}} \implies \mathbf{E} \cdot \mathbf{B} = 0$$

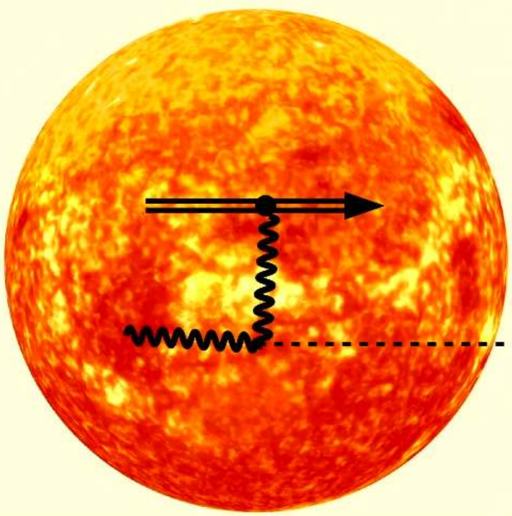
Axion-photon Mixing in Vacuum

Dimensional Analysis

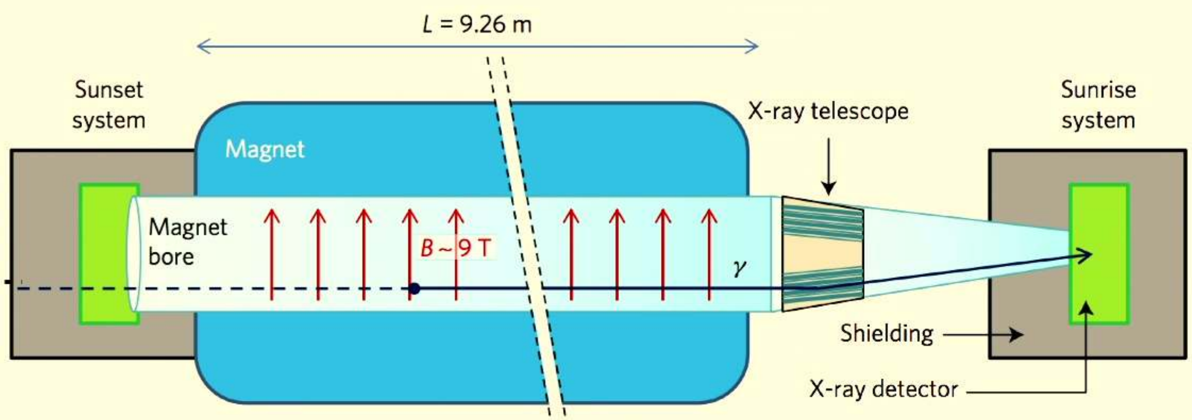
$$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 L^2, \quad L \simeq \min\left(L_{\rm app}, (\Delta k_a)^{-1}\right) \quad \Delta k_a = \frac{m_a^2}{2\omega_\gamma}$$

$\boxed{\text{Figure-of-merit: } BL}$

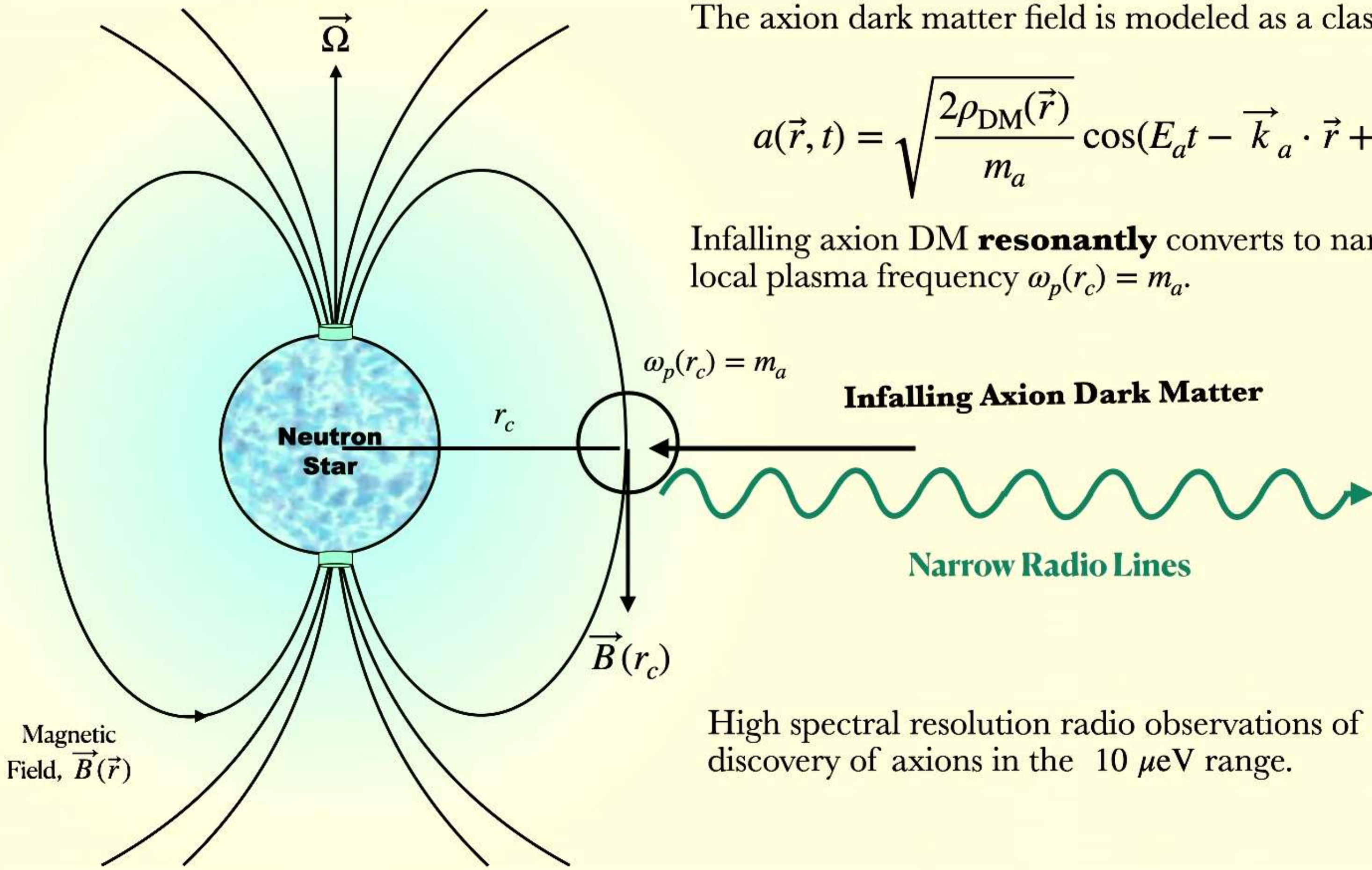




Solar Axions



Conversion of Axion Dark Matter



The axion dark matter field is modeled as a classical scalar field

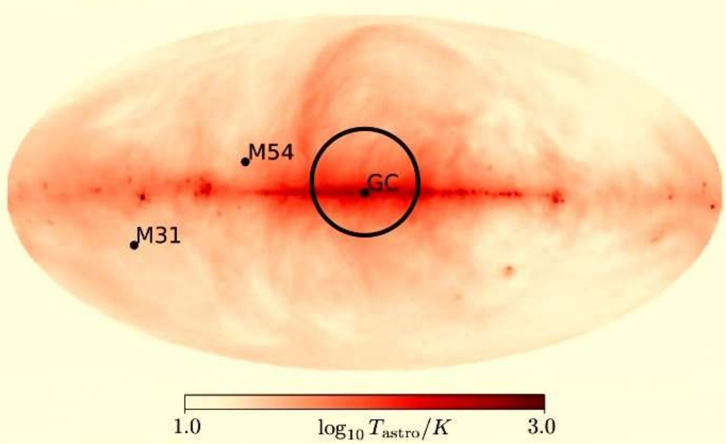
$$a(\vec{r}, t) = \sqrt{\frac{2\rho_{\mathrm{DM}}(\vec{r})}{m_a}} \cos(E_a t - \vec{k}_a \cdot \vec{r} + \varphi) \qquad \frac{\Delta E_a}{E_a} \sim \frac{\sigma_v^2}{2} \approx 10^{-6}$$

Infalling axion DM **resonantly** converts to narrow radio signals when the local plasma frequency $\omega_p(r_c) = m_a$.

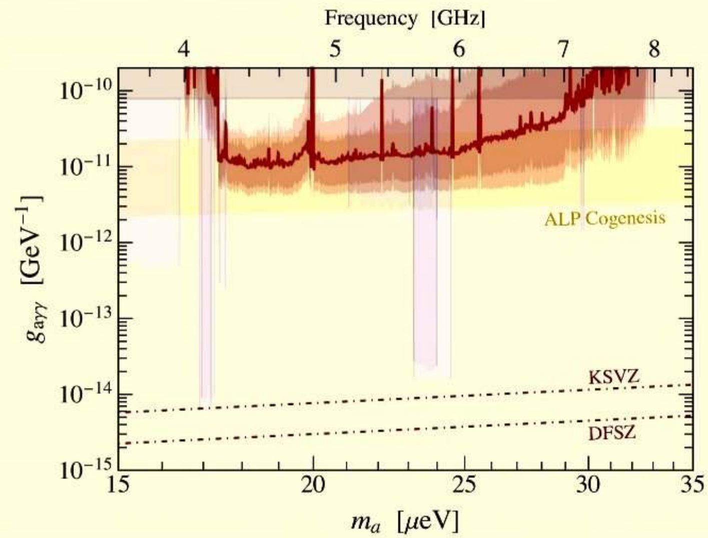
High spectral resolution radio observations of neutron stars can lead to discovery of axions in the $10\ \mu$eV range.

Search for Axion Lines from the GC

Foster et al. (2022)

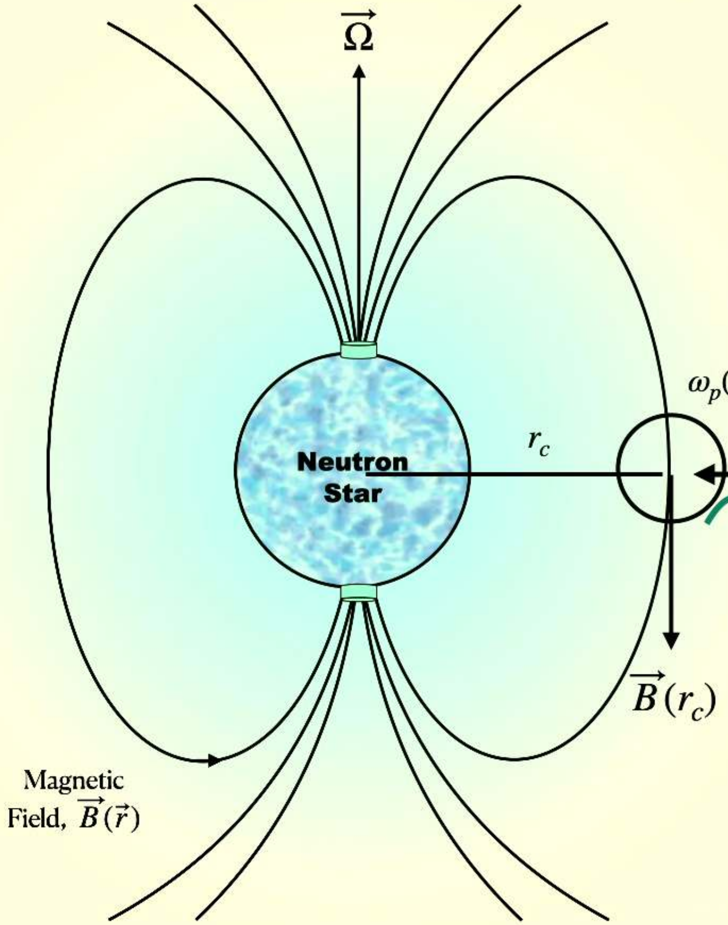


$\Longrightarrow$



Pushing to larger axion masses → Magnetars!

Conversion of Axion Dark Matter



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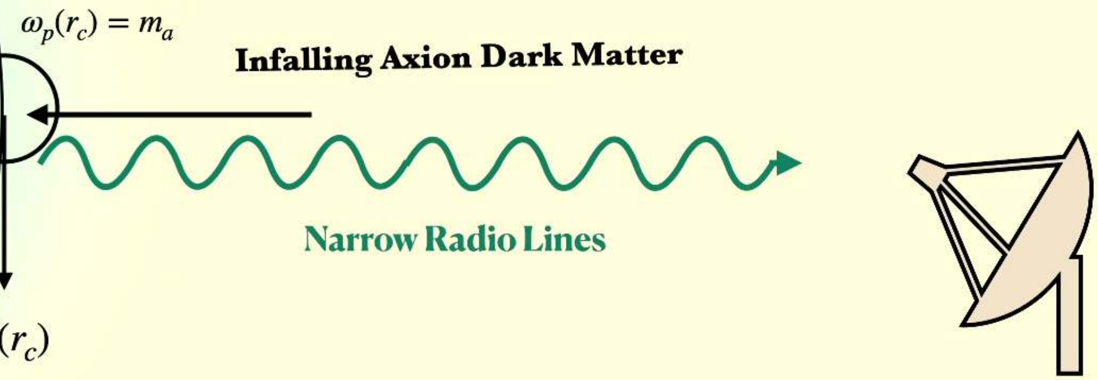

High spectral resolution radio observations of neutron stars can lead to discovery of axions in the $10\ \mu$eV range.

Conversion of Axion Dark Matter

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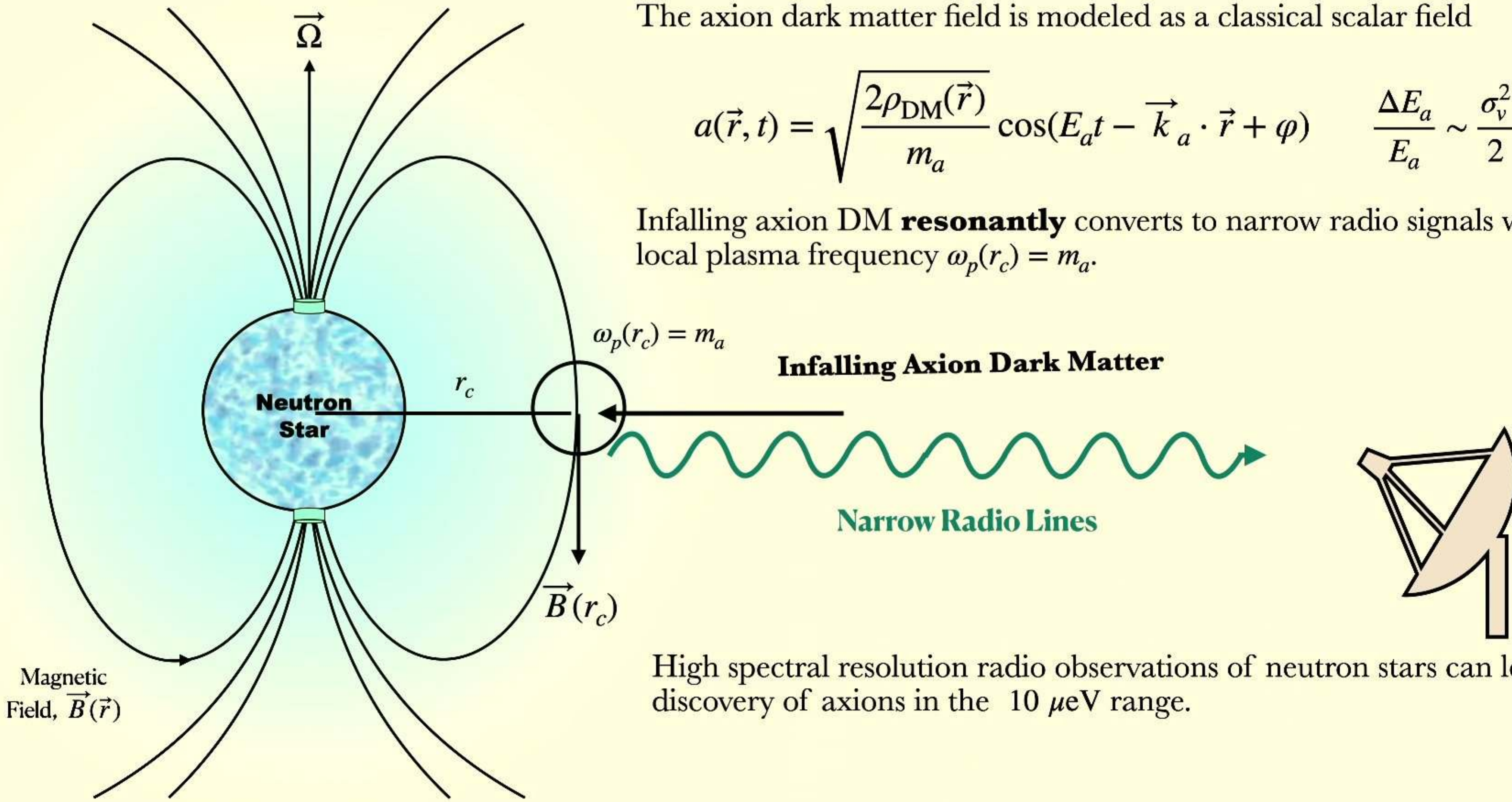
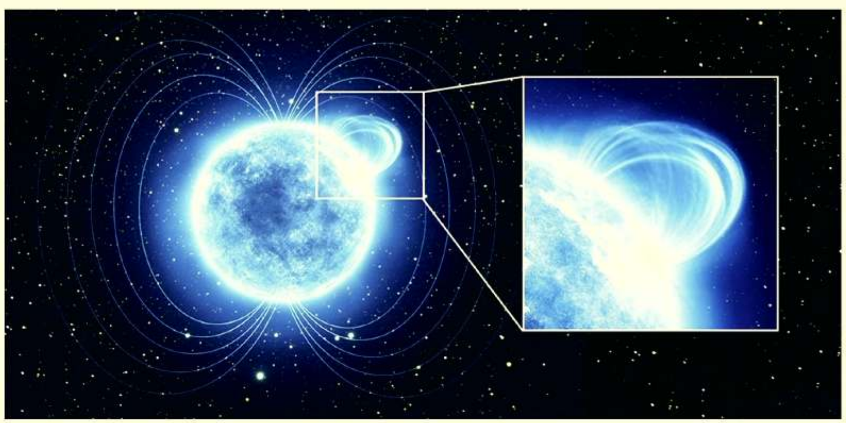


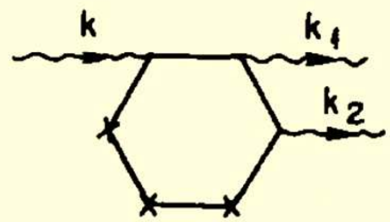
High spectral resolution radio observations of neutron stars can lead to discovery of axions in the 10 μeV range.

Magnetars $\neq$ High-B Pulsars!

Magnetar are ultra-magnetic neutron stars with $B \gtrsim 10^{14}$ G

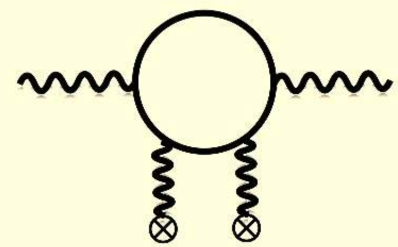
- In pulsars, magnetospheric "twist" ($\overrightarrow{\nabla} \times \overrightarrow{B}$) is localize to the open field lines (beam).
- Magnetar-strength fields can break the crust and inject twist all over the surface.
- Standard QED process modified in fields above $B \gtrsim m_e^2/e \approx 4 \times 10^{13}$ G.
- Numerous observational differences (e.g., hard X-ray emission, bursts/flares, FRBs)!





Photon Splitting

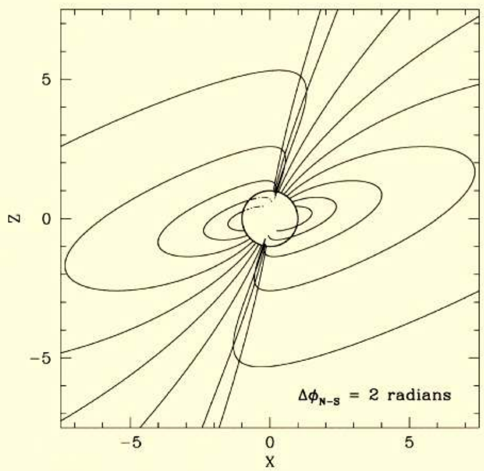
Adler (1971)



Vacuum Birefringence

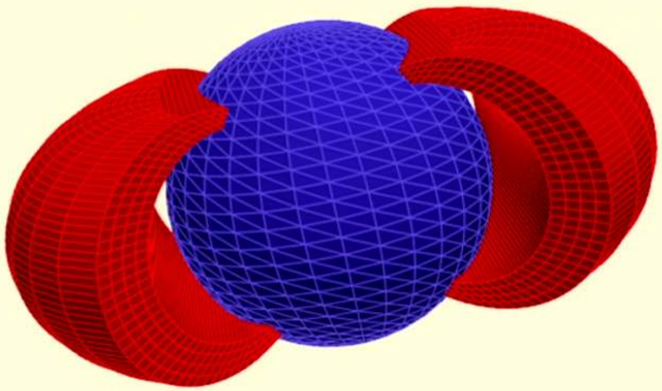
Magnetar Magnetosphere Models

Powerful magnetic field carry magnetic stress that can break the solid crust, driving **powerful currents** throughout the magnetosphere, deviating from Goldreich-Julian (1969)



Large-scale polar twist (J-bundle)

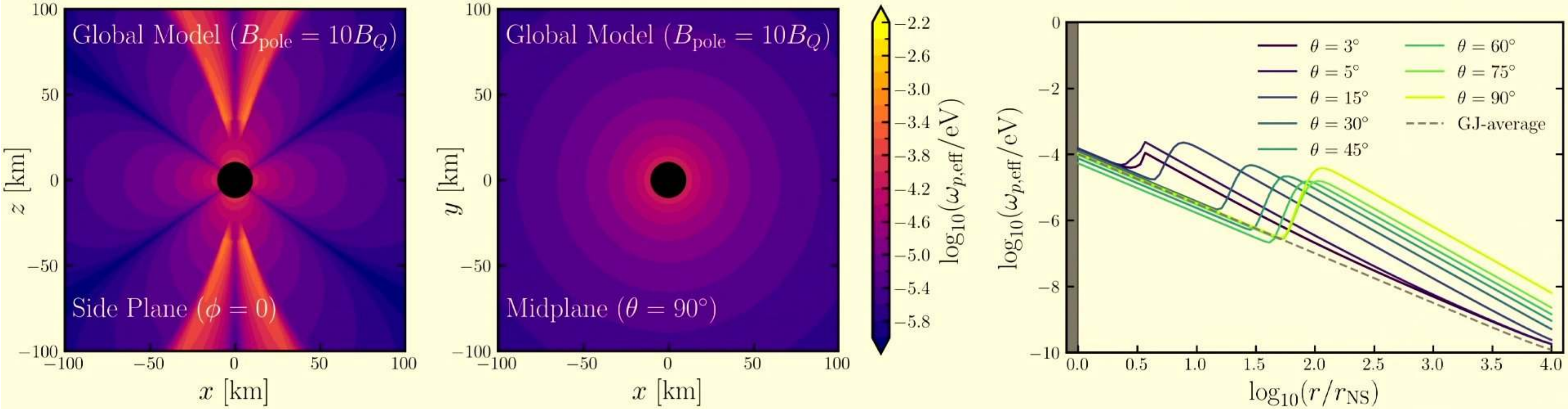
Thompson, Lyutikov, Kulkarni (2002), Beloborodov & Thompson (2007)
Beloborodov (2010), Beloborodov (2013a, b),



Small-scale twist zones (Collisional Models)

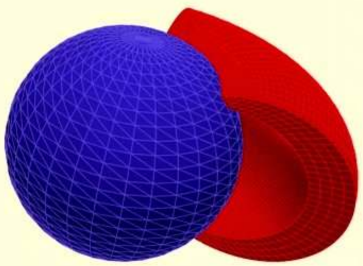
Thompson & Kostenko (2020), Zhang & Thompson (2024)
Thompson, Yang, & Ortiz (2017)

Anatomy of Quiescent Magnetosphere

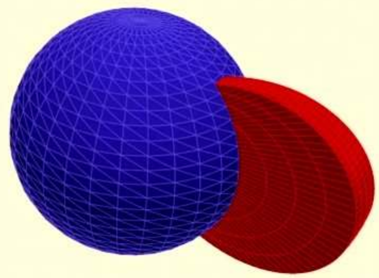


Small-scale "Shear Zones"

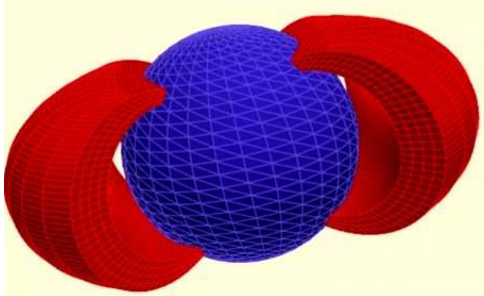
Magnetospheric twist resides in magnetic "shear zones" located all over the magnetar surface.



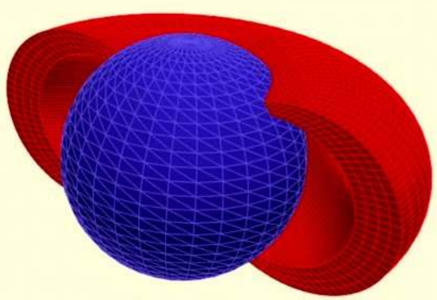
Quarter model



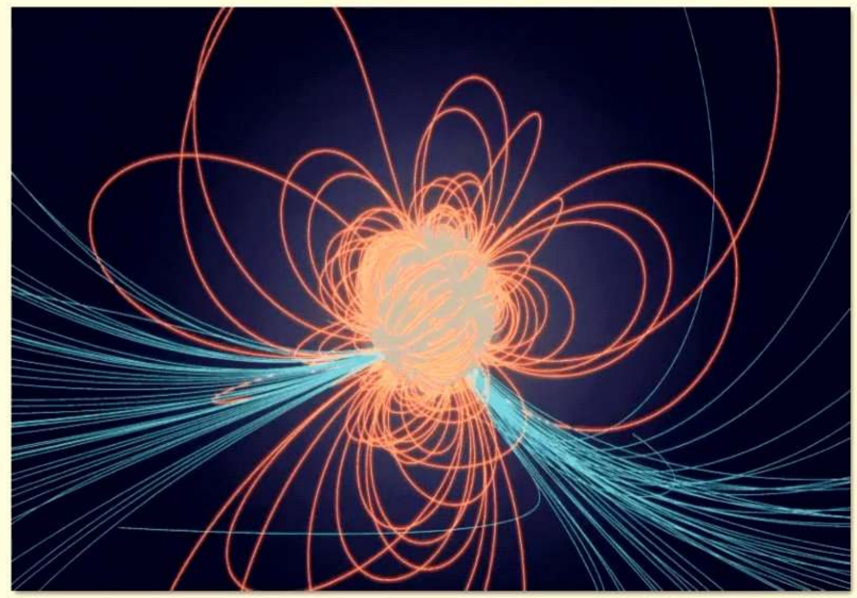
Wedge model



Double-quarter model

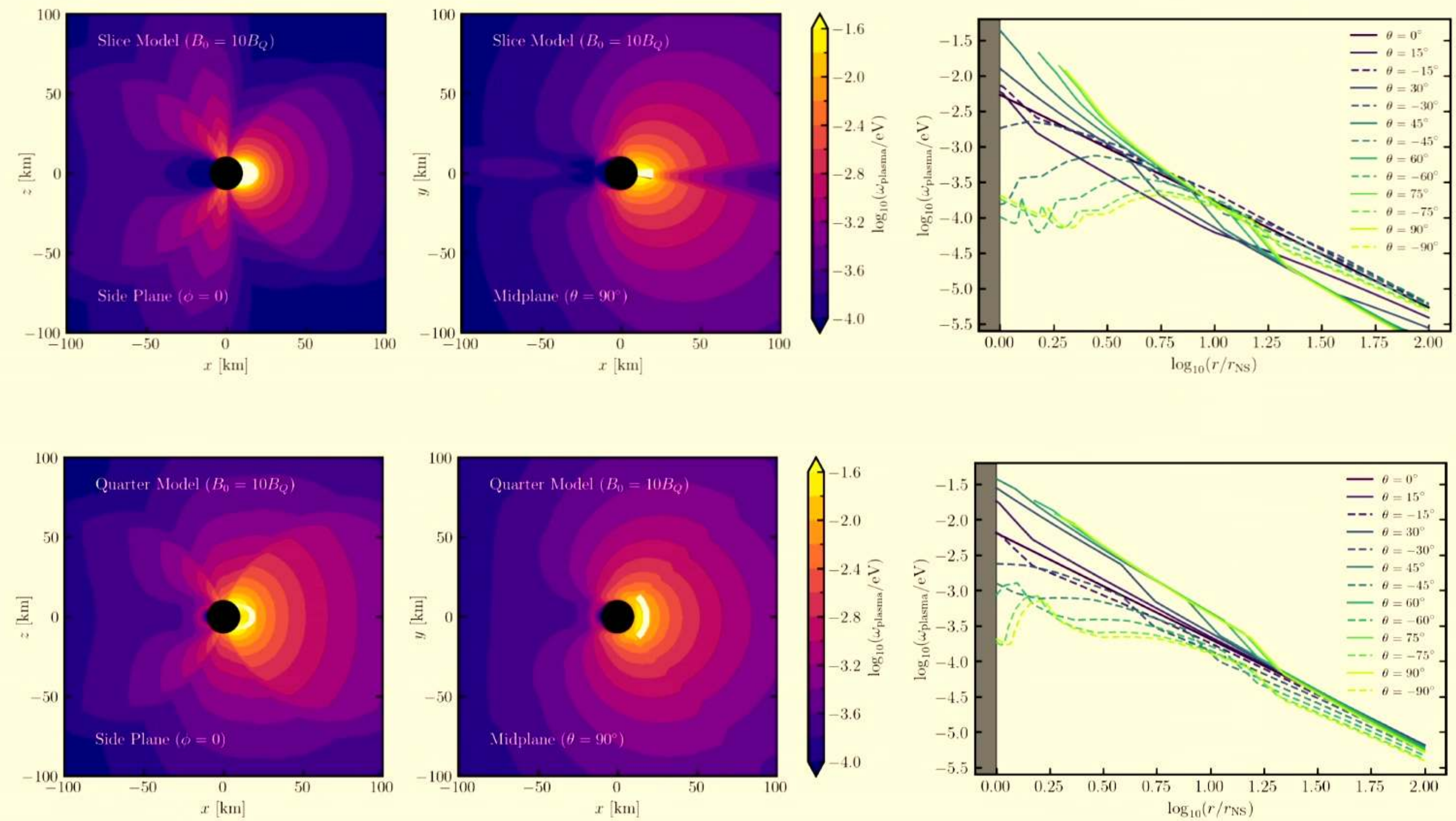


Half model



Connection to Global Magnetosphere

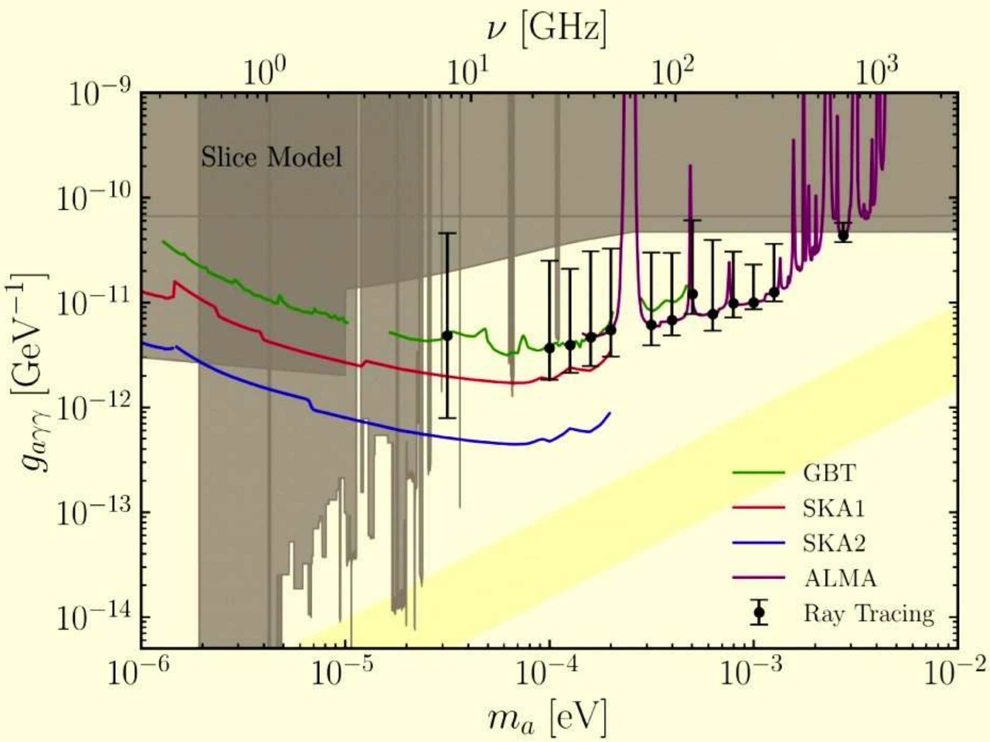
Zhang & Thompson (2024)



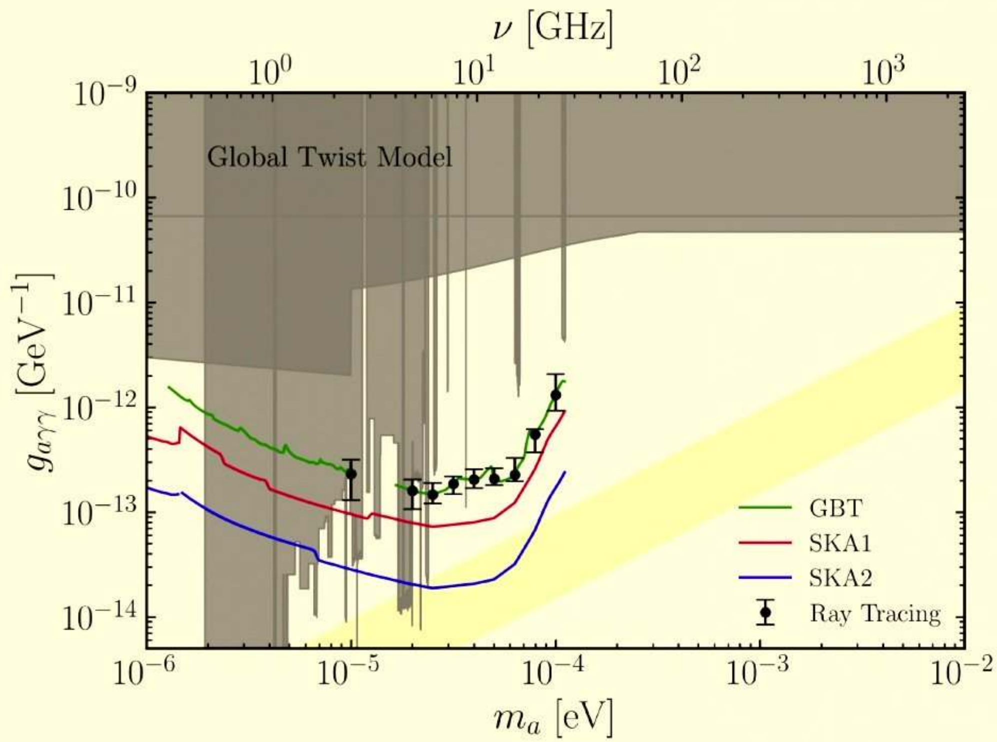
J1745-2900 Projection

Roy, **AP**, Thompson, Witte, Blanco, Zhang (2505.20450)

$B_0 \approx 2 \times 10^{14}$ G, $P = 3.76$ s, $D_{GC} \approx 0.1$ pc



Quarter Model

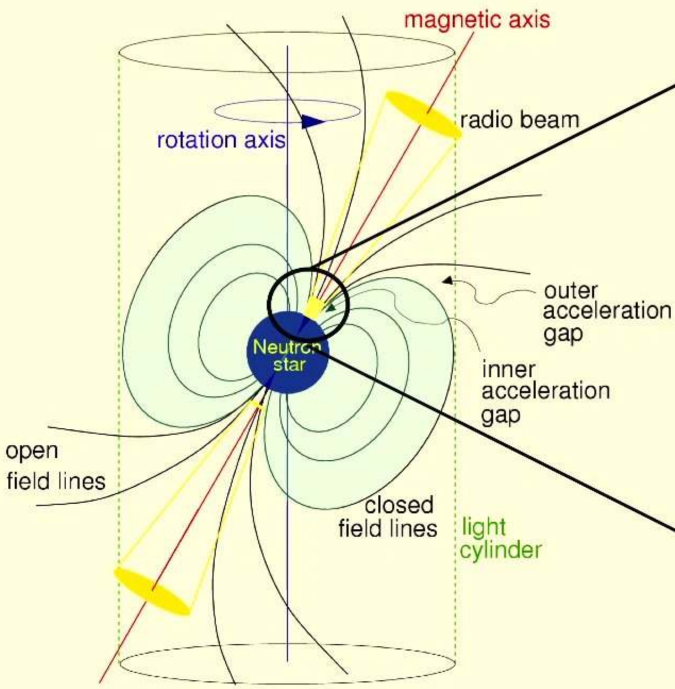


J-bundle Model

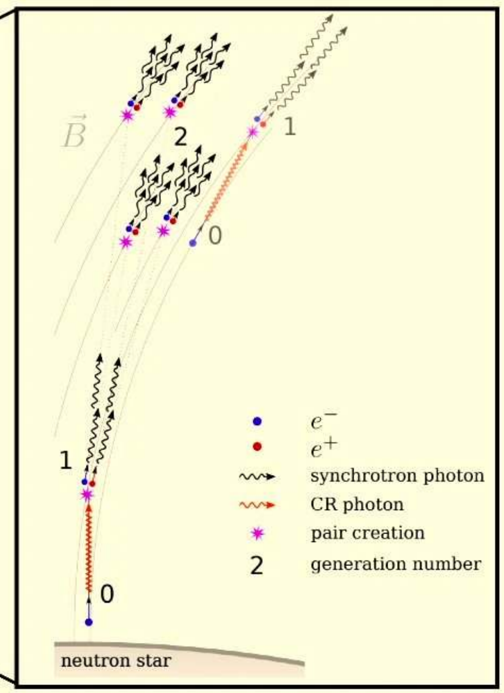
Polar Cap Microphysics

Rotation generates $E \cdot B$ $\Longrightarrow$ $E \cdot B$ screened in $e^{\pm}$ magnetosphere $\Longrightarrow$ $E \cdot B$ screening breaks down in "vacuum gaps" $\Longrightarrow$ Dynamical $E \cdot B$ produces axions

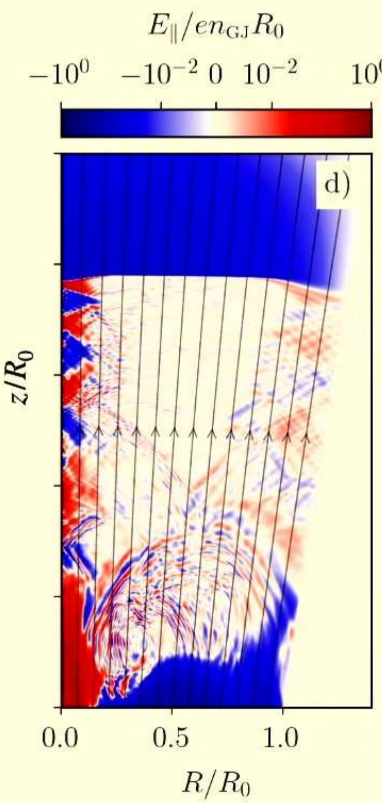
$$(\Box + m_a^2)\, a(\vec{x}, t) = g_{a\gamma\gamma}(\mathbf{E} \cdot \mathbf{B})(\mathbf{x}, t)$$



Dynamical screening



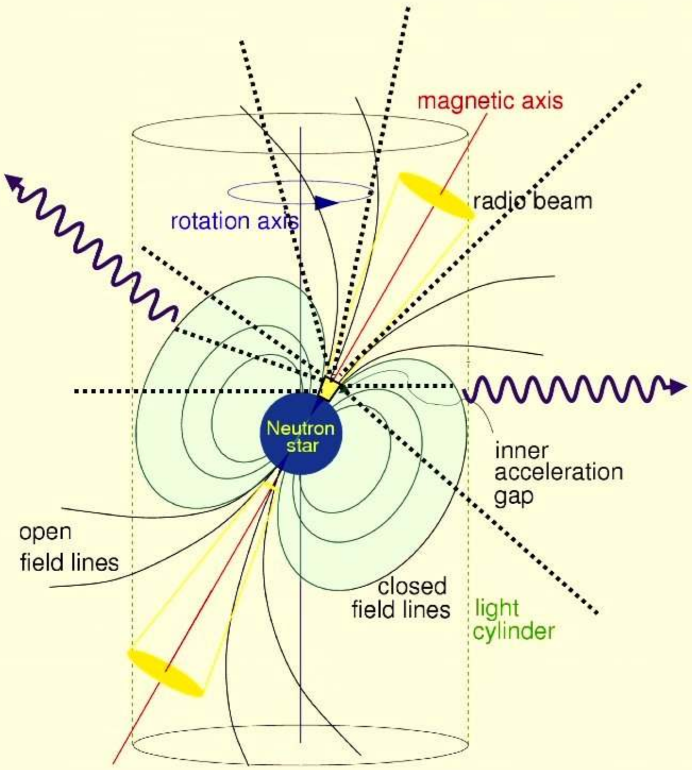
Plasma PIC $\Longrightarrow$

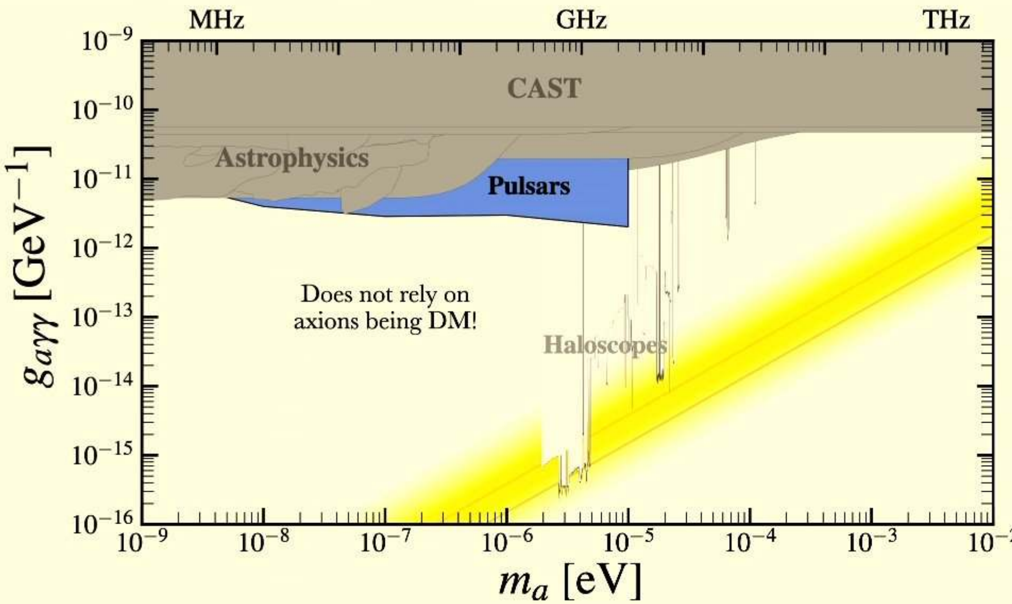


Broadband Radio Emission

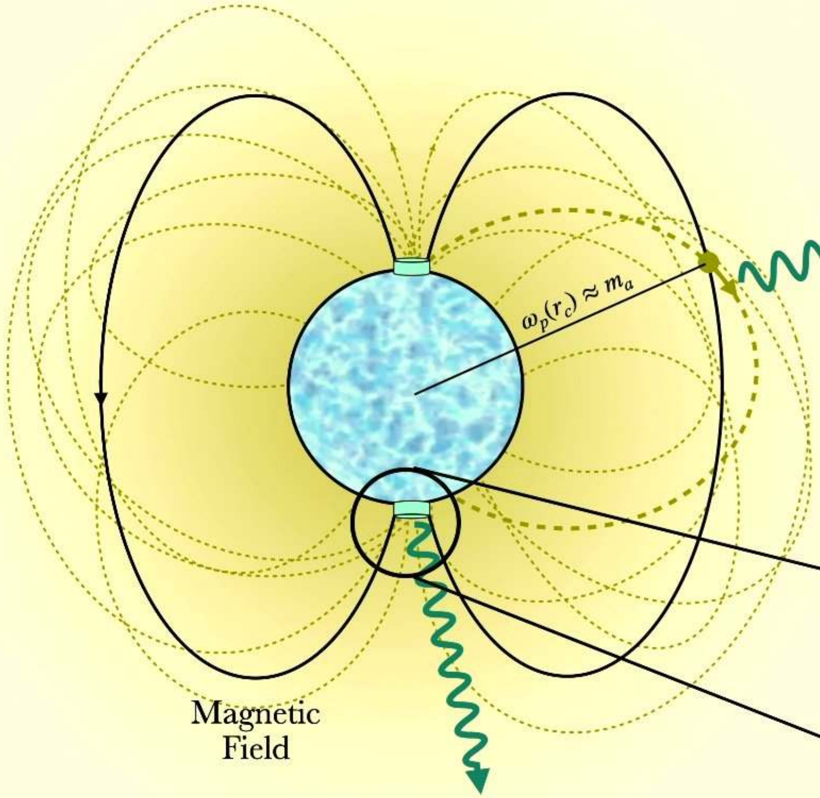
Noordhuis, **AP**, Witte, Chen, Cruz, Weniger, *PRL* **131**, 111004 (2023)

Relativistic gap-produced axions
convert to broadband radio emission





Observational Consequences



Radio Line

Kinematic Endpoint + Radio Line

Noordhuis, **AP**, Weniger, Witte
(2307.11811, PRX)

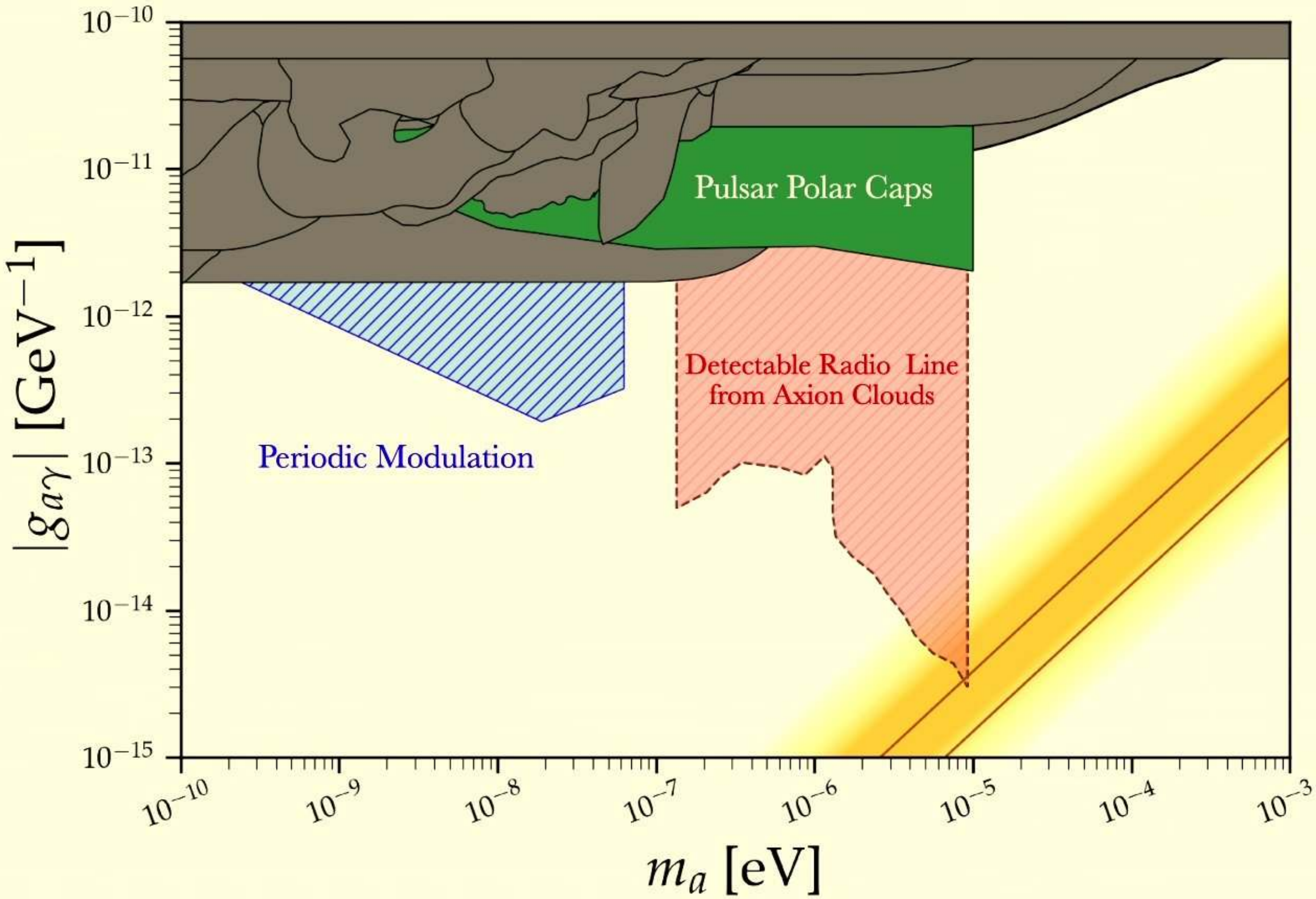
$$m_a + \frac{GM_{\rm NS}}{R} - \frac{GM_{\rm NS}}{r_c} \lesssim \omega_a \lesssim m_a \left(1 + \frac{v_{\rm esc}^2}{2}\right)$$

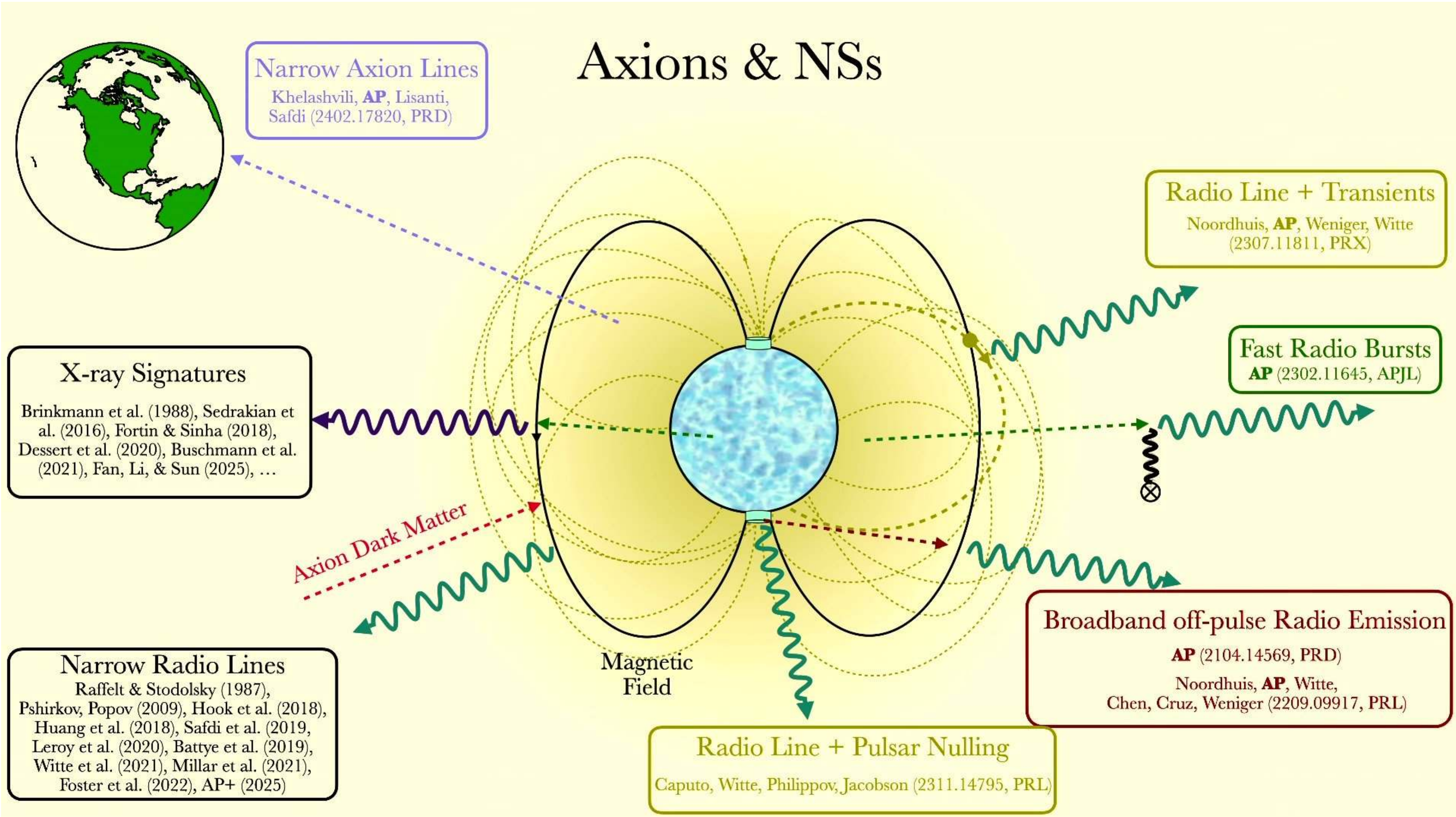
Backreaction of axion cloud
onto gap EM

$$\nabla \cdot \mathbf{E} = \rho_{\rm gap} - g_{a\gamma\gamma} \nabla a \cdot \mathbf{B}_0$$

Caputo, Witte, Philippov, Jacobson (2311.14795, PRL)

Axion Clouds and Radio Emission




Axions & NSs
Narrow Axion Lines
Khelashvili, **AP**, Lisanti, Safdi (2402.17820, PRD)
Radio Line + Transients
Noordhuis, **AP**, Weniger, Witte (2307.11811, PRX)
Fast Radio Bursts
AP (2302.11645, APJL)
X-ray Signatures
Brinkmann et al. (1988), Sedrakian et al. (2016), Fortin & Sinha (2018), Dessert et al. (2020), Buschmann et al. (2021), Fan, Li, & Sun (2025), …
Axion Dark Matter
Broadband off-pulse Radio Emission
AP (2104.14569, PRD)
Noordhuis, **AP**, Witte, Chen, Cruz, Weniger (2209.09917, PRL)
Narrow Radio Lines
Raffelt & Stodolsky (1987), Pshirkov, Popov (2009), Hook et al. (2018), Huang et al. (2018), Safdi et al. (2019), Leroy et al. (2020), Battye et al. (2019), Witte et al. (2021), Millar et al. (2021), Foster et al. (2022), AP+ (2025)
Magnetic Field
Radio Line + Pulsar Nulling
Caputo, Witte, Philippov, Jacobson (2311.14795, PRL)