Title: Axion Production in Pulsar Magnetosphere Gaps

Speakers: Anirudh Prabhu

Series: Particle Physics

Date: November 12, 2021 - 1:00 PM

URL: https://pirsa.org/21110016

Abstract: Pulsar magnetospheres admit non-stationary vacuum gaps that are characterized by non-vanishing EoB. These gaps play an important role in plasma production and electromagnetic wave emission and, as I will discuss, are very efficient axion factories. The density of axions produced in a vacuum gap can be several orders of magnitude greater than the ambient dark matter density. In the strong pulsar magnetic field, a fraction of these axions may convert to photons, giving rise to broadband radio signals. We show that dedicated observations of nearby pulsars with radio telescopes (FAST) and interferometers (SKA) can probe axion-photon couplings that are a few orders of magnitude lower than current astrophysical bounds.

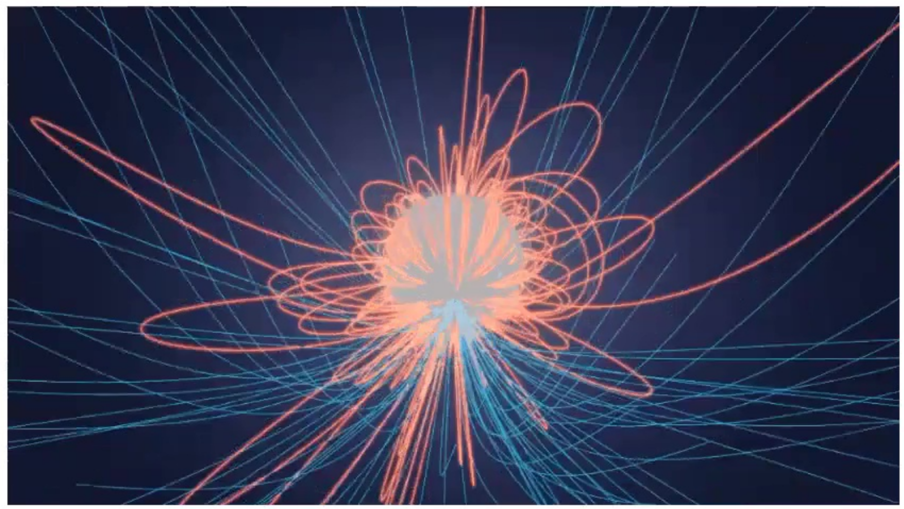
Axion Production in Pulsar Magnetosphere Gaps

Ani Prabhu (Stanford University)
PI Particle Theory Seminar
11/11/2021

Stanford University

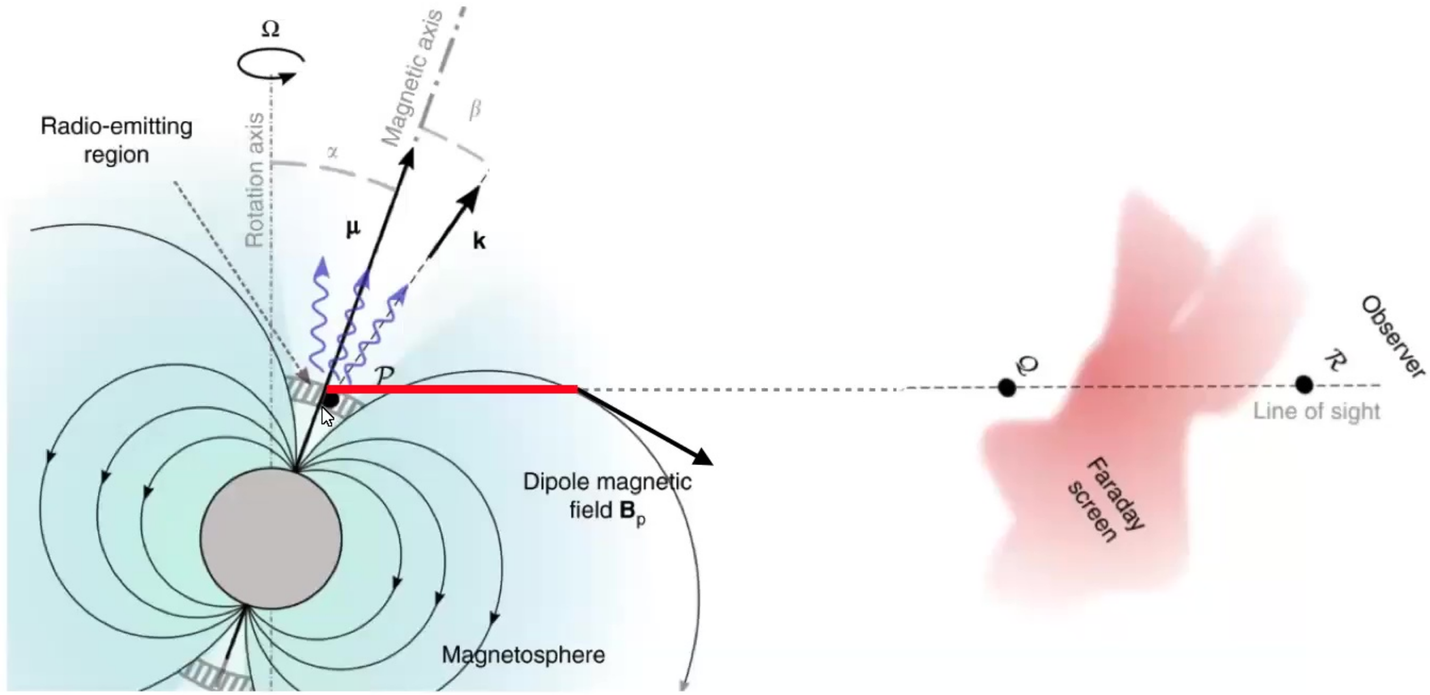
Based on:
Phys. Rev. D 104, 055038

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



Credit: NICER (2019)

Executive Summary

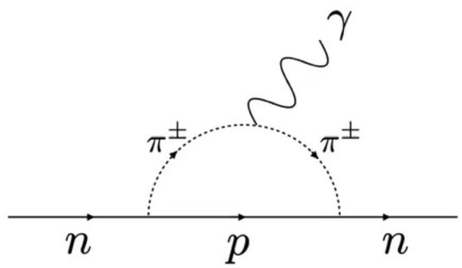


Adapted from:
Gueroult et al. (2019)

Strong-CP and PQ Solution

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

QCD may possess CP-violating θ term: $\mathscr{L}_{QCD} \supset \frac{g_s^2}{32\pi^2}\bar{\theta}\; G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$

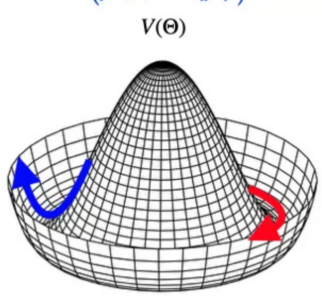


Neutron Electric Dipole Moment $\sim e\theta/m_\pi$

Experimental Bound: $\bar{\theta} \lesssim 10^{-10}$

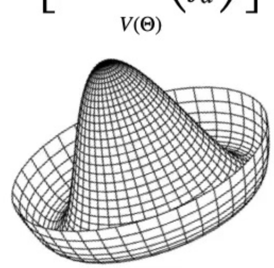
Introduce global $U(1)$
(PQ) symmetry

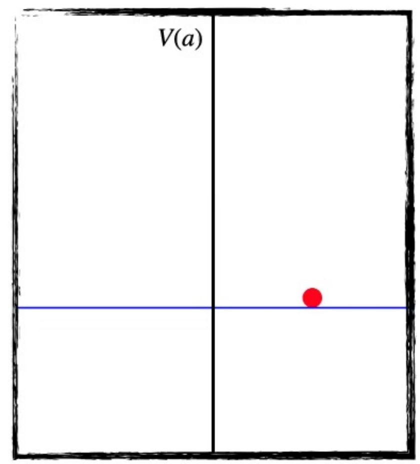
$\Theta = \big(\rho(x) + \langle\rho\rangle\big)\, e^{ia(x)/f_a}$



Instantons

$V(a) \propto \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$





Axion Phenomenology

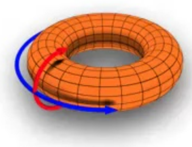
QCD Axion Parameter Space: $m_a \simeq 6\ \mu\mathrm{eV} \left(\dfrac{10^{12}\ \mathrm{GeV}}{f_a} \right)$

$$\mathscr{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V(a) + \frac{\alpha_s}{8\pi f_a} a(x)\ G_{\mu\nu}\tilde{G}^{\mu\nu} + \boxed{\frac{g_{a\gamma\gamma}}{4} a(x)\ F_{\mu\nu}\tilde{F}^{\mu\nu}} + \sum_f c_f \frac{\partial_\mu a}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\mathscr{C}$$

$\boxed{\textbf{String Theory}}$ $p-$Forms (A_p) + Extra Dimensions + Topology → Axions

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2009)



m_a, f_a, $g_{a\gamma\gamma}$, … free parameters

Axions as Dark Matter

$n_{DM}\lambda_a^3 \gg 1$

$(m_a \lesssim \text{ eV})$

Coherently oscillating classical field

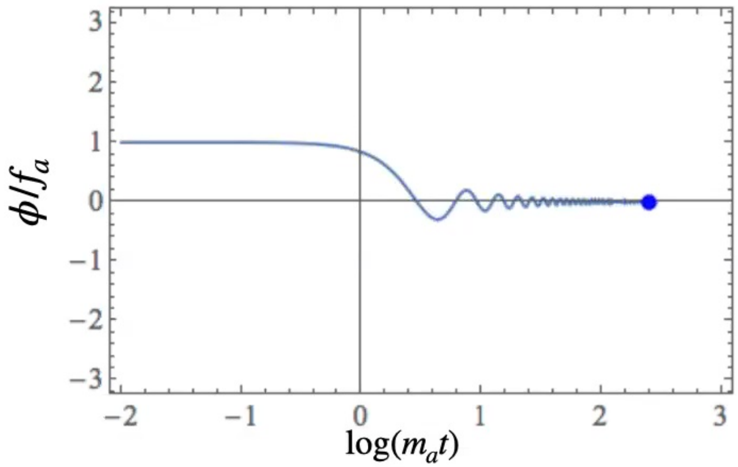
$\phi = \phi_0 \cos(m_a t + \varphi)$

$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$

$(\ddot{x} + \gamma\dot{x} + \omega^2 x = 0)$

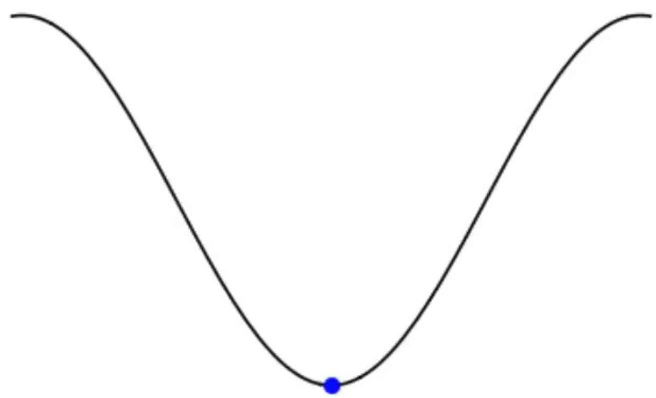
Dark Energy

Early time: $\rho_a \propto$ constant



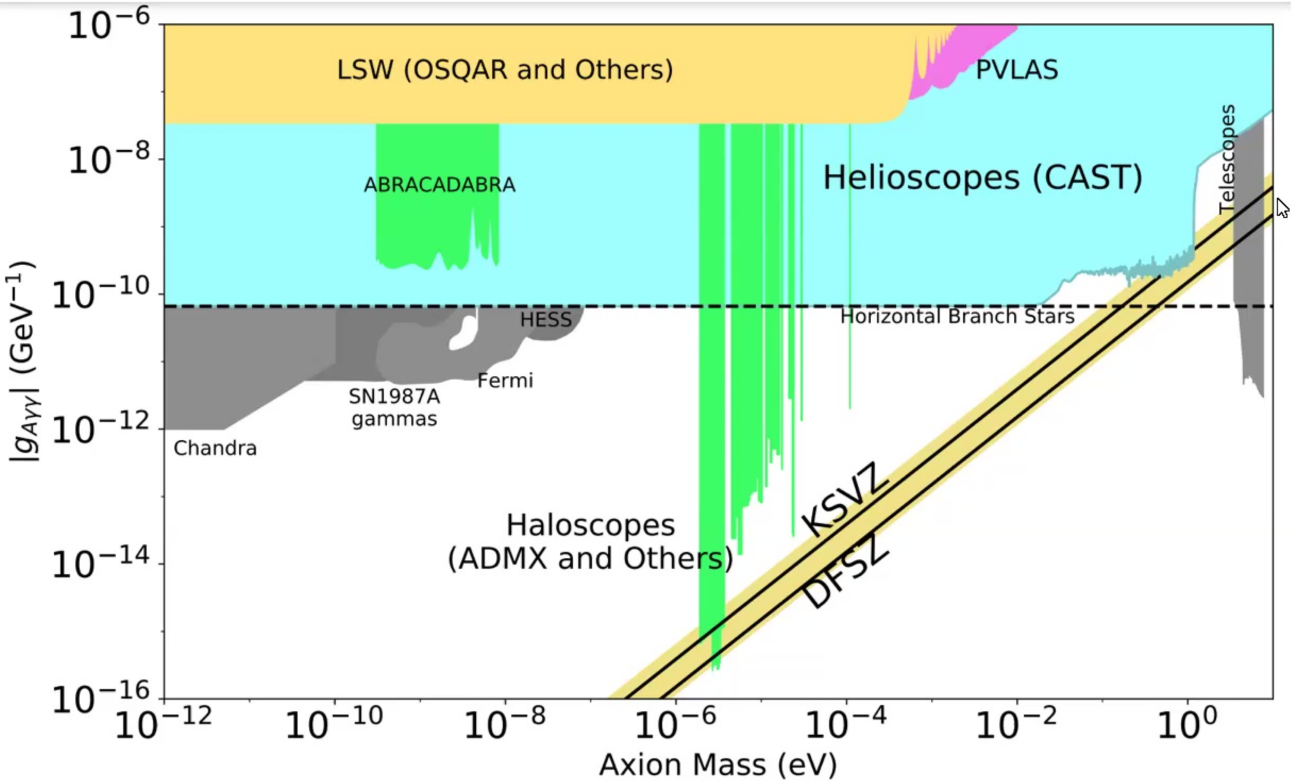
Late time: $\rho_a \propto a^{-3}$

Dark Matter



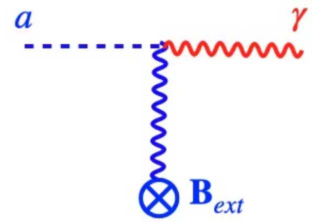
Axion-Photon Parameter Space

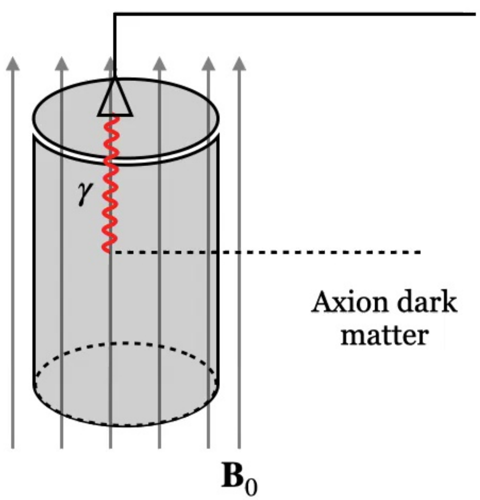
$$\mathscr{L}_{a+SM} \supset \frac{\alpha_s}{8\pi f_a} a G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f \frac{C_{a\bar{f}f}}{2f_a}\partial_\mu a \bar{\psi}\gamma_\mu\gamma_5\psi + \cdots$$



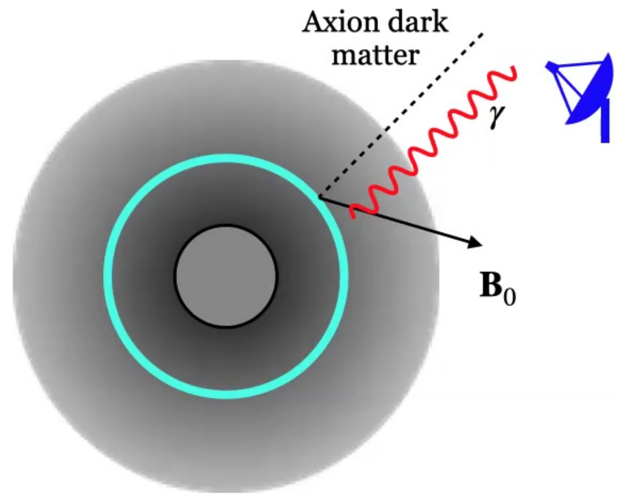
ADMX

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



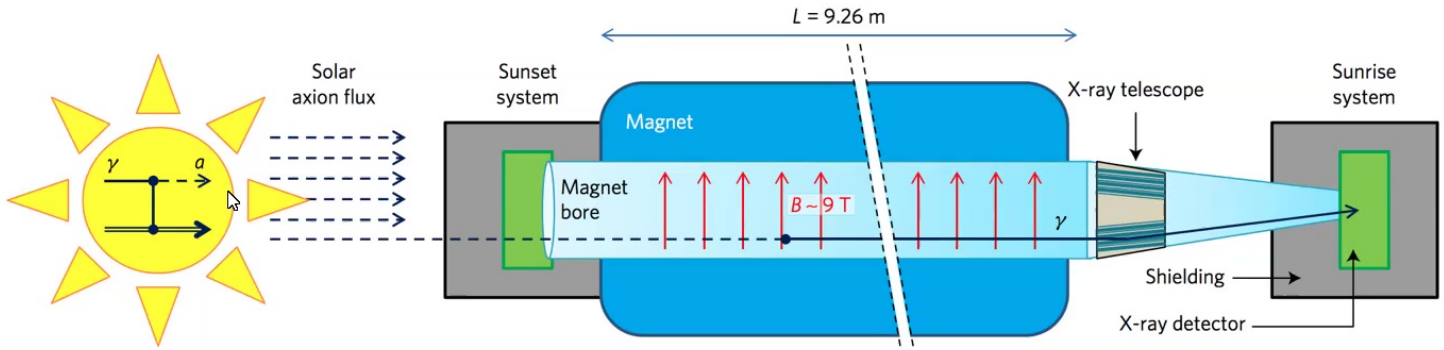


$\Longleftrightarrow$

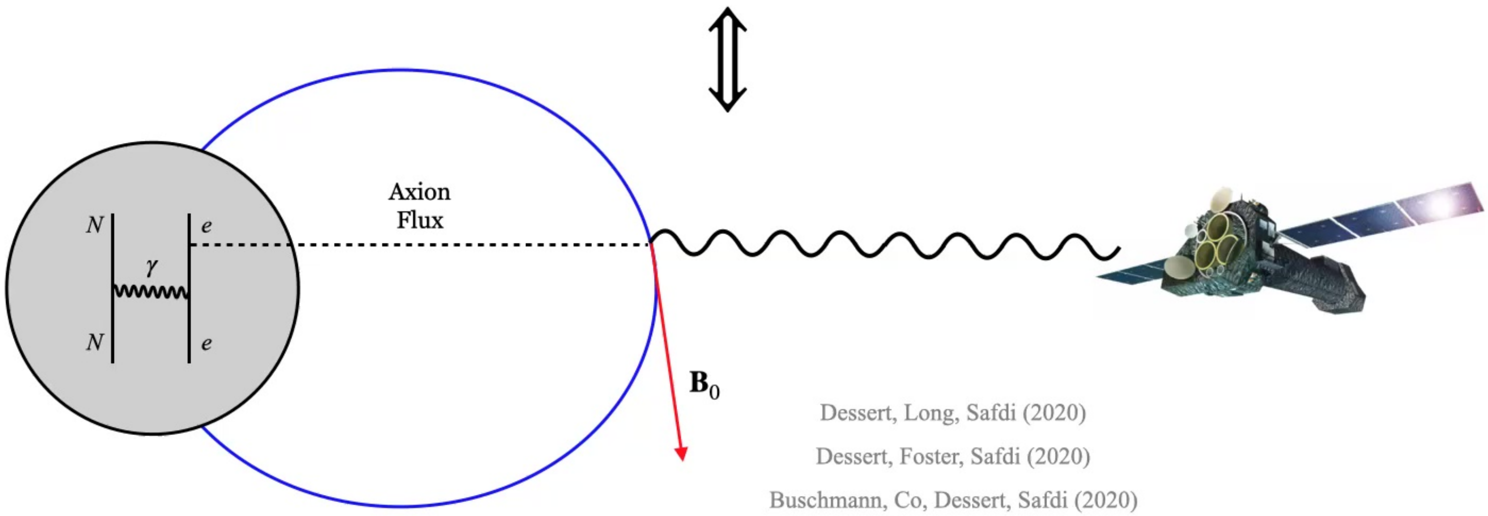


Hook, Kahn, Safdi, Sun (2018)
Safdi, Sun, Chen (2019)
Foster, Kahn, Macias, Sun, Eatough, Kondratiev, Peters, Weniger, Safdi (2020)

CAST



Credit: CAST Collaboration



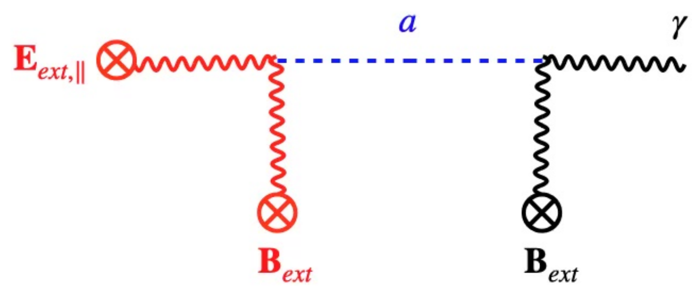
Dessert, Long, Safdi (2020)

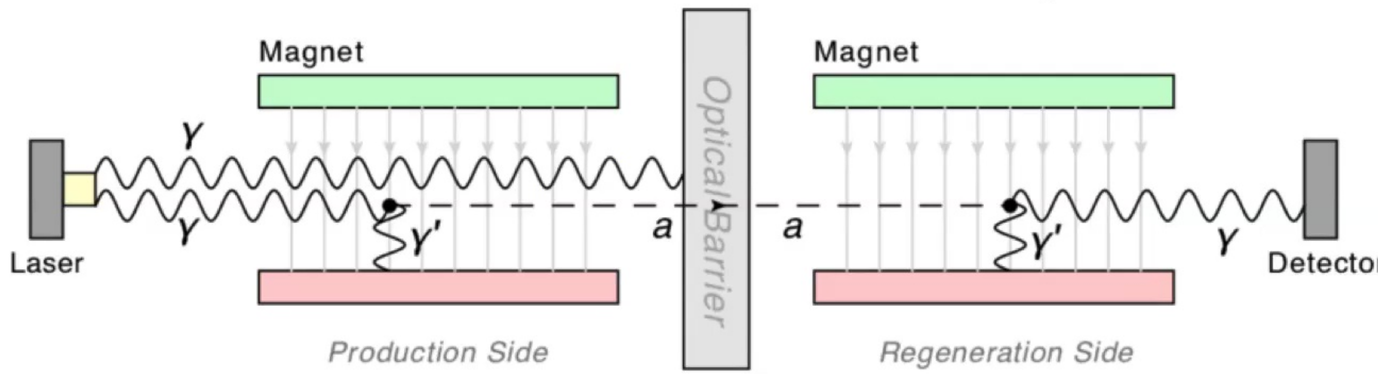
Dessert, Foster, Safdi (2020)

Buschmann, Co, Dessert, Safdi (2020)

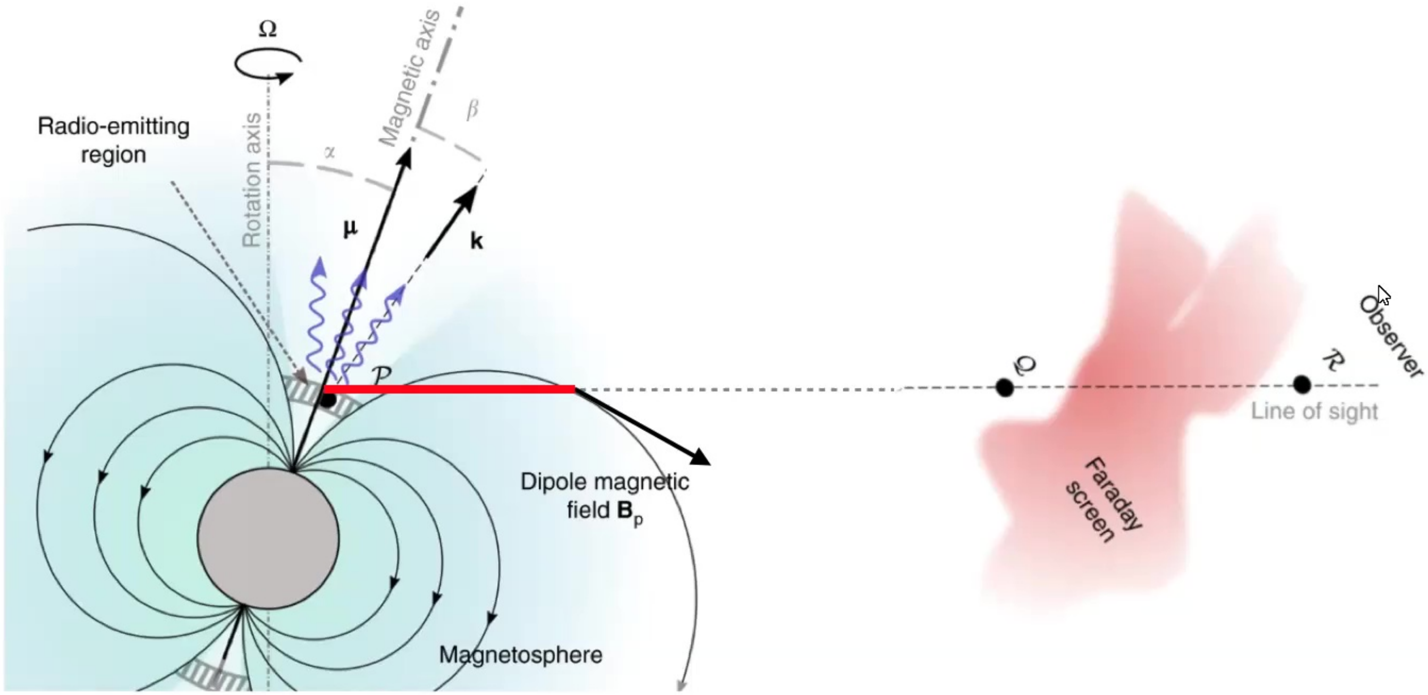
Light Shining through Walls

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





Executive Summary



Adapted from:
Gueroult et al. (2019)

Pulsar Basics

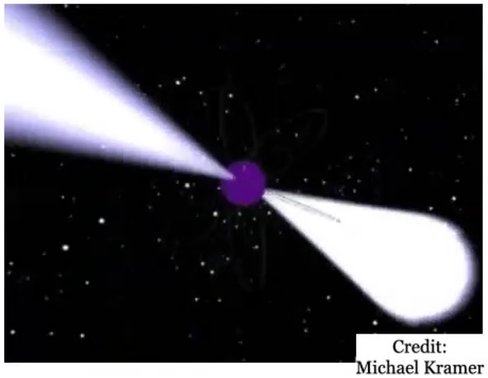
Observation of a Rapidly Pulsating Radio Source

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 gala‹y, and may be associated with oscillations of white dwarf or neutron stars.



Credit:
Michael Kramer

Rotating Neutron Stars

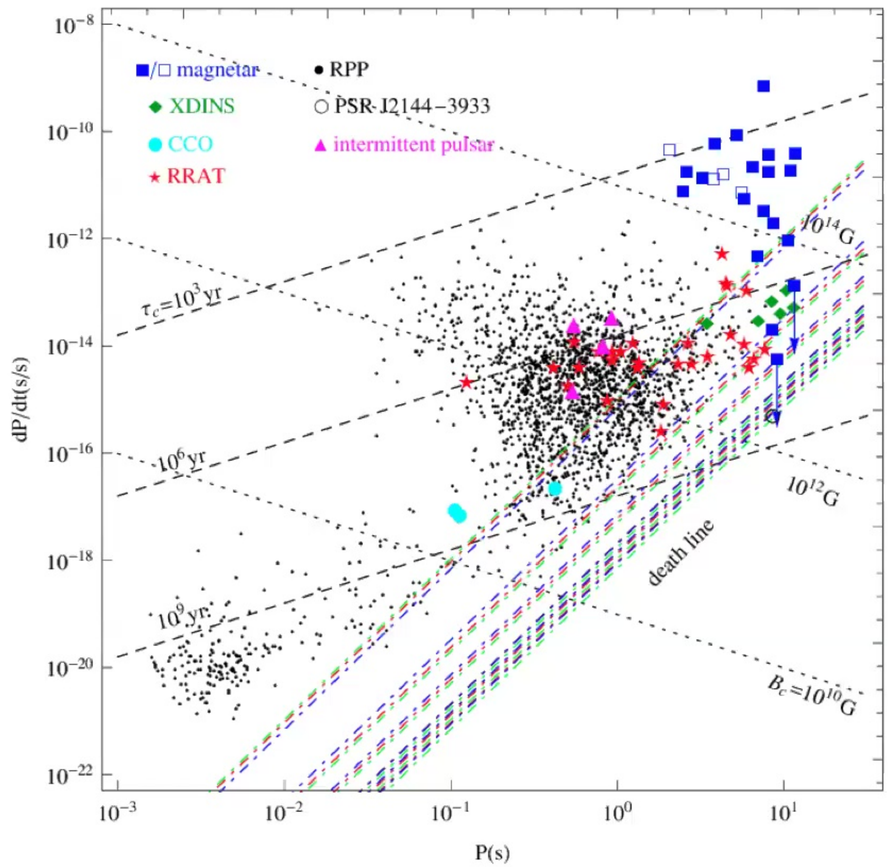
Large magnetic fields
$(10^8\ \mathrm{G} - 10^{16}\ \mathrm{G})$

Extremely stable periods
$|\dot{P}/P| \sim 10^{-16}\ \mathrm{Hz}$

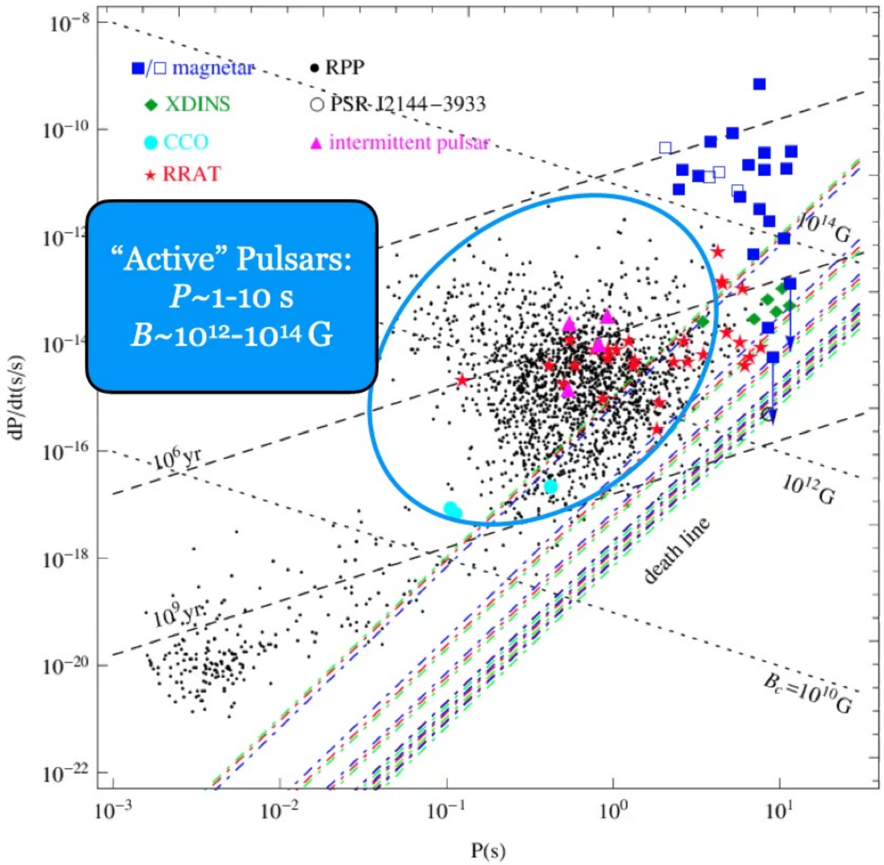
Neutron star
$GM_{ns}/R_{ns} \sim 0.2$

$\boxed{\text{Pulsars are excellent laboratories for tests of new physics}}$

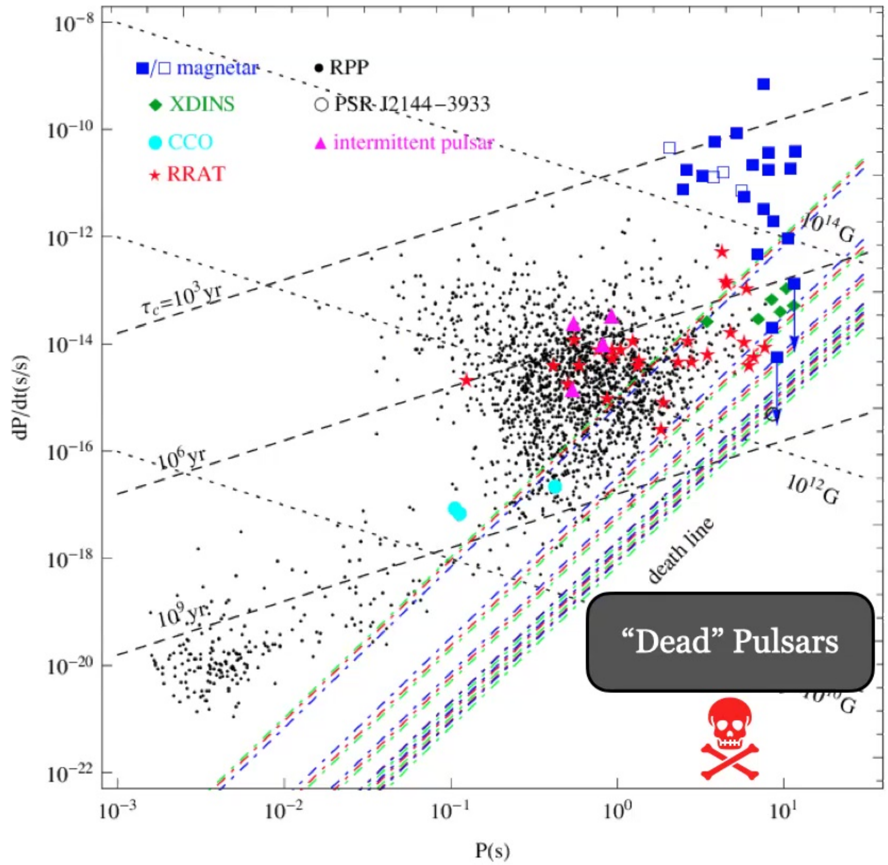
Classification



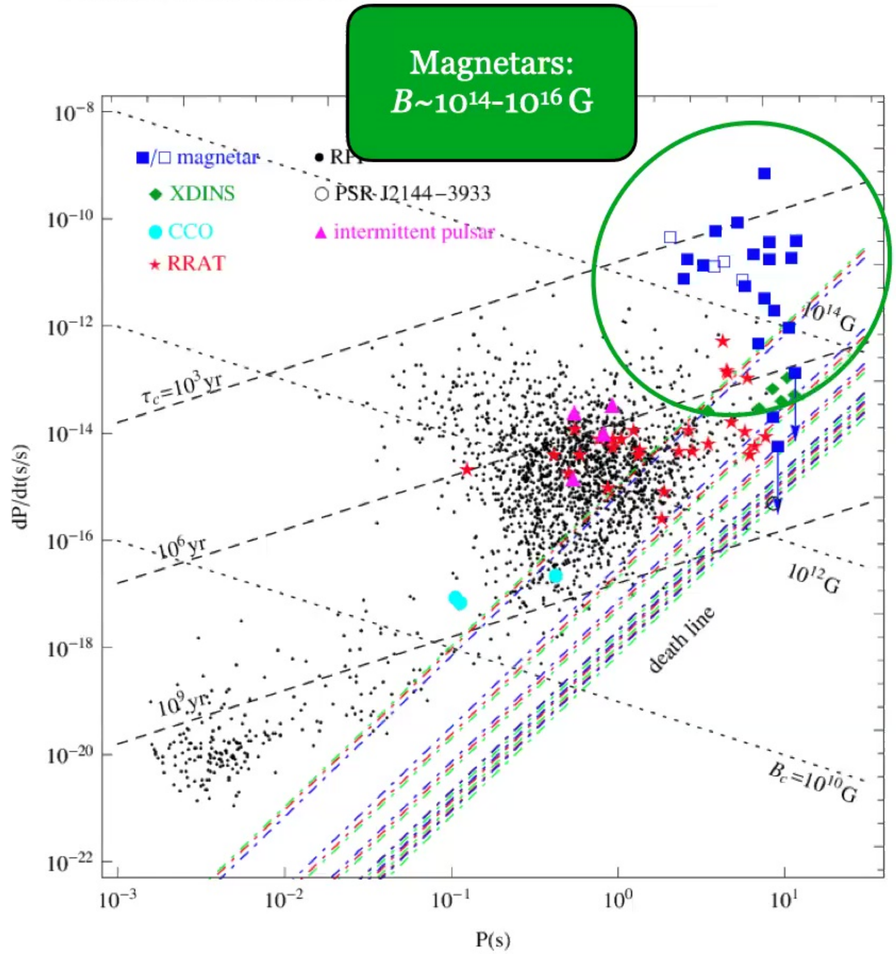
Classification



Classification

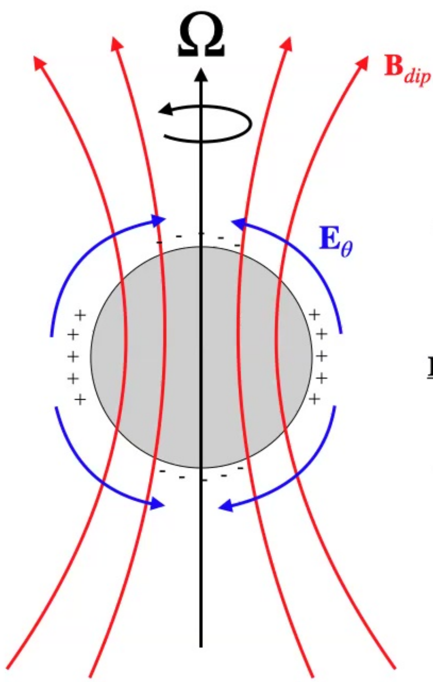


Classification



à la Goldreich & Julian

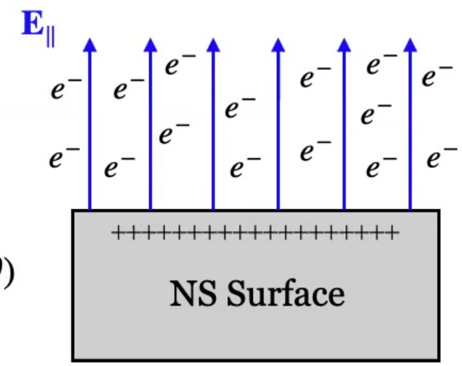
Goldreich & Julian (1969)



~~Vacuum Magnetosphere~~

$\Downarrow$

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



Force-Free Magnetosphere

Charges flow freely along magnetic field lines: $\Delta\Phi \iff \mathbf{E}\cdot\mathbf{B} = 0^*$

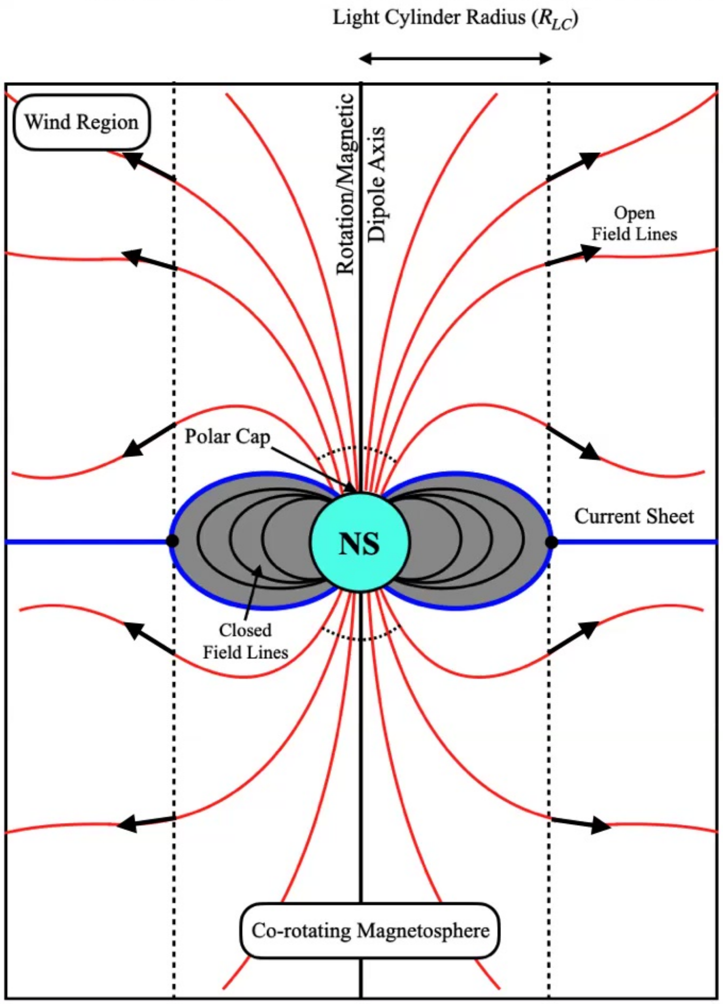
$$\boxed{\rho_{GJ} = \nabla\cdot\mathbf{E} = -\frac{2\boldsymbol{\Omega}\cdot\mathbf{B}}{1-\Omega^2 r^2 \sin^2\theta}}$$

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

Active pulsars possess many e^+e^- pairs: $\rho = \kappa\rho_{GJ}$, where κ could be $\gg 1$.

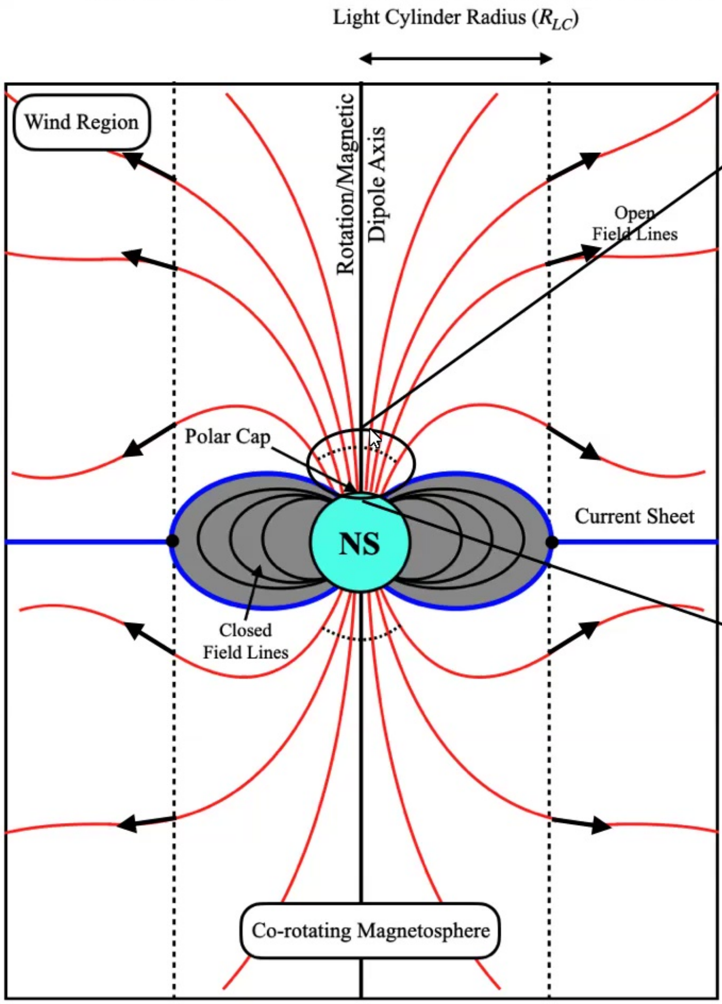
Pair multiplicity simulations required!

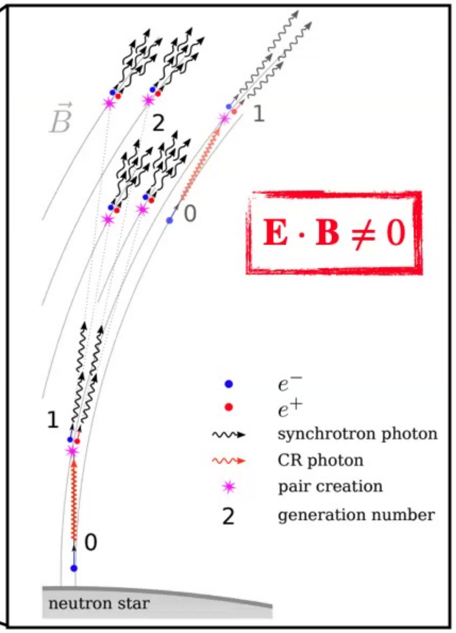
Global Pulsar Magnetosphere



<u>Closed Field Lines</u>
Co-rotation, $\mathbf{E} \cdot \mathbf{B} = 0$

Global Pulsar Magnetosphere





<u>Closed Field Lines</u>

Co-rotation, $\mathbf{E} \cdot \mathbf{B} = 0$

Pair-Cascade Processes

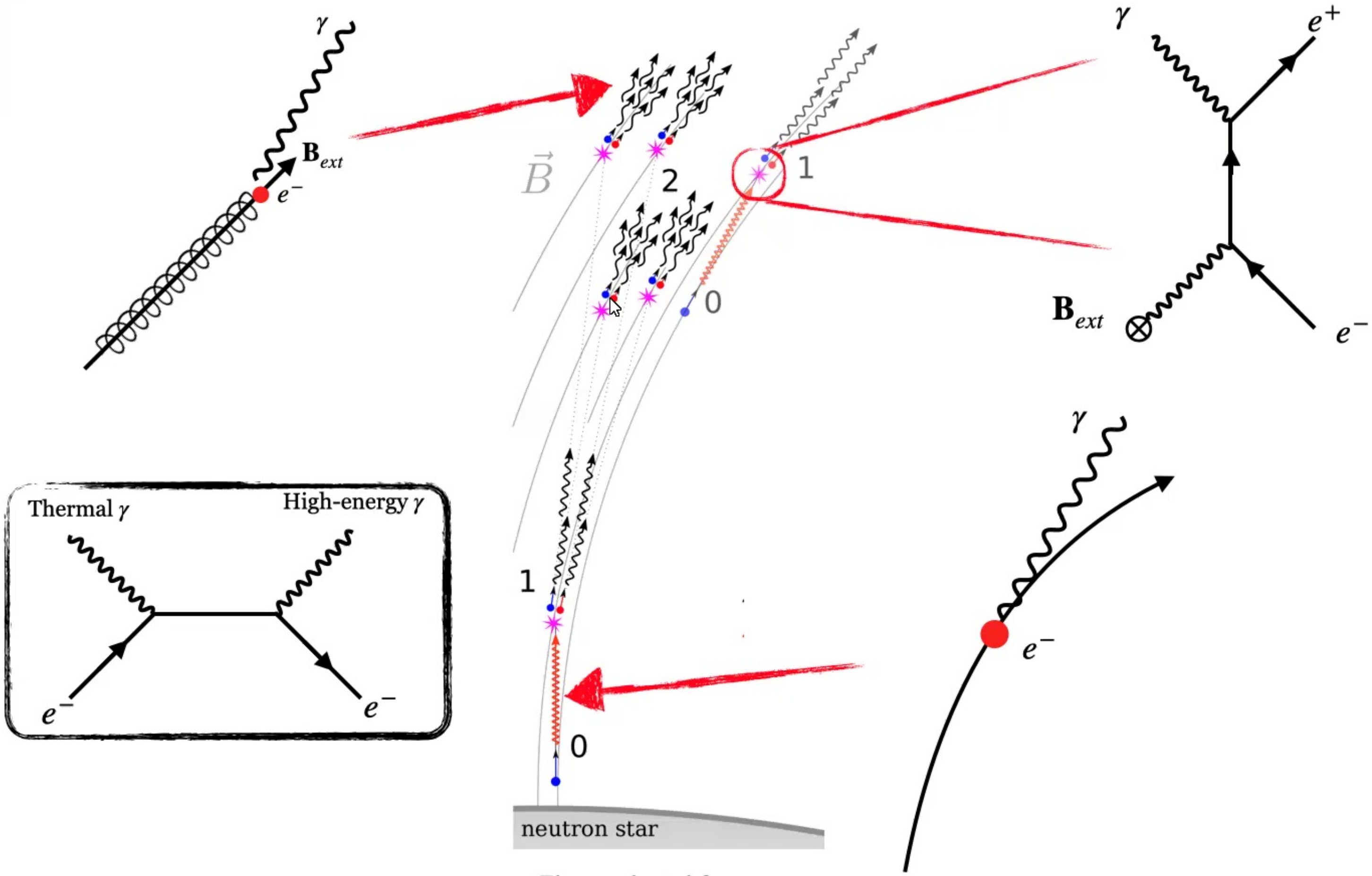


Figure adapted from
Timokhin & Harding (2015)

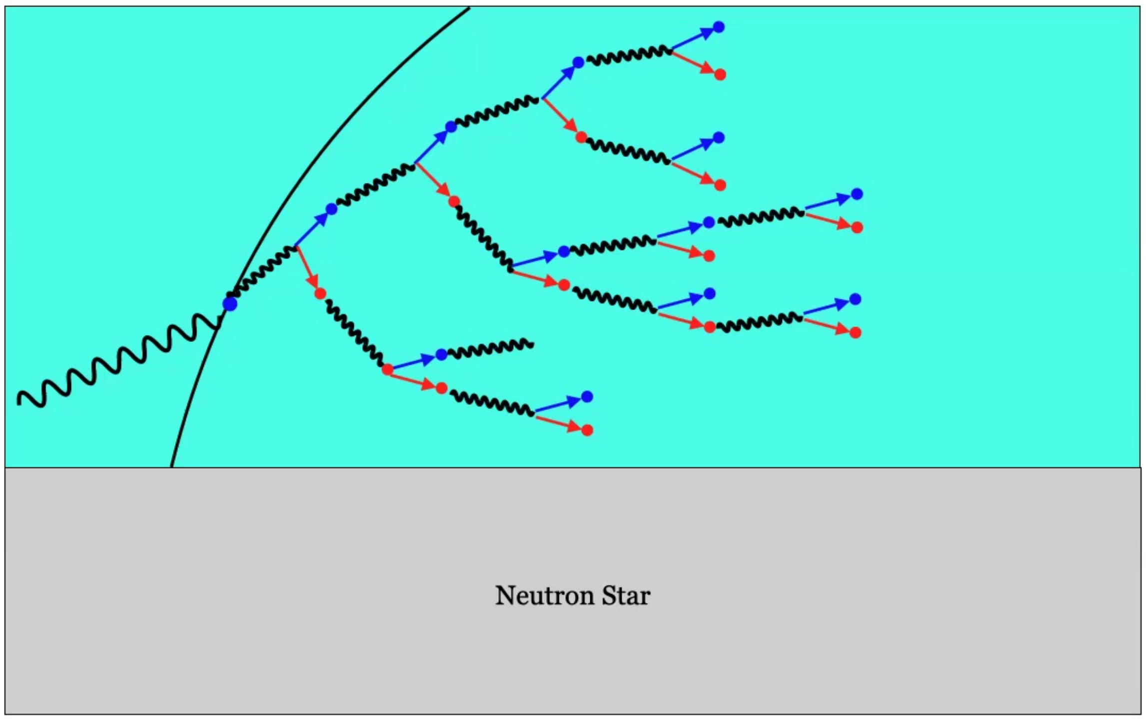
Polar Cap Dynamics

Sturrock (1971)
Ruderman & Sutherland (1974)

Step 2: Pair Cascade

$$\ell = \frac{4.4}{m_e e^2} \frac{B \sin\theta}{B_c} \exp\left(\frac{8 m_e B_c}{3\omega B \sin\theta}\right)$$

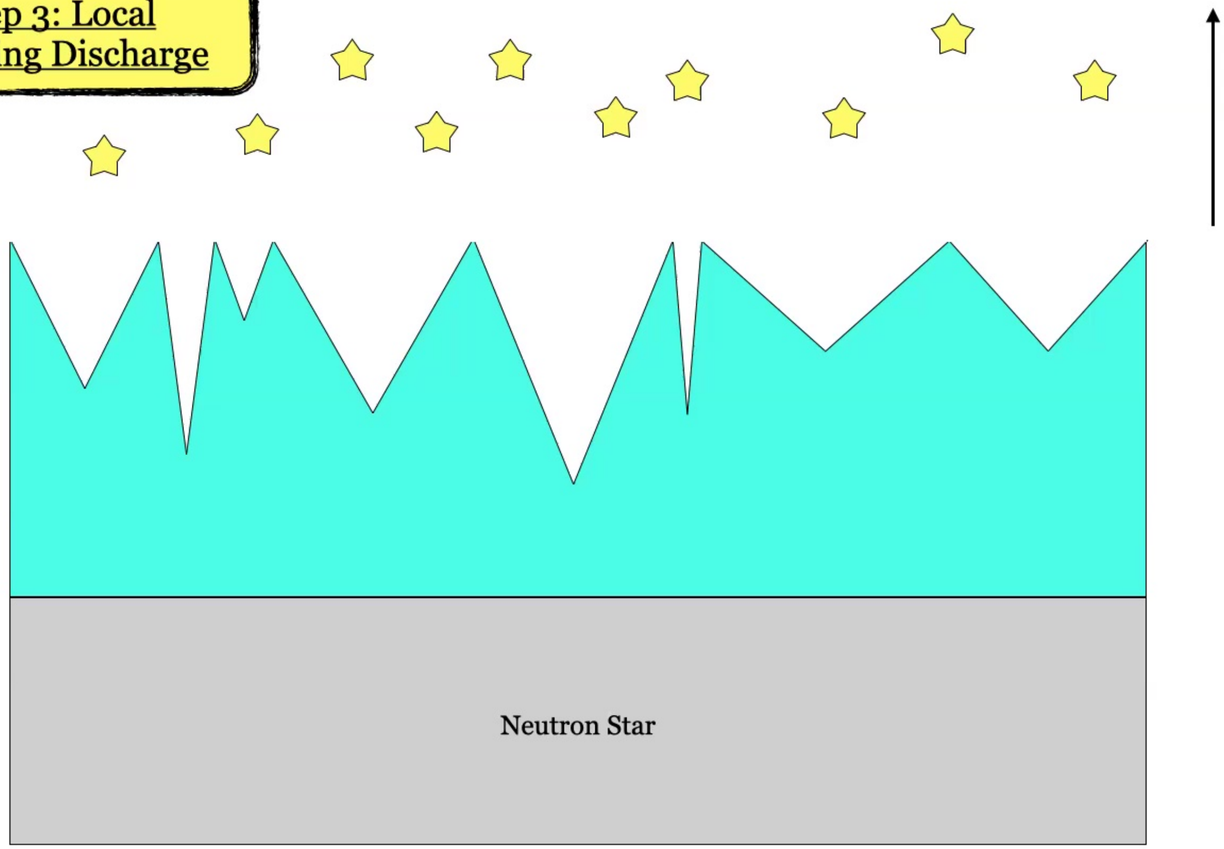
Mean free path of photon of energy $\hbar\omega$



Polar Cap Dynamics

Sturrock (1971)
Ruderman & Sutherland (1974)

Step 3: Local Sparking Discharge



Pair-Cascade Processes

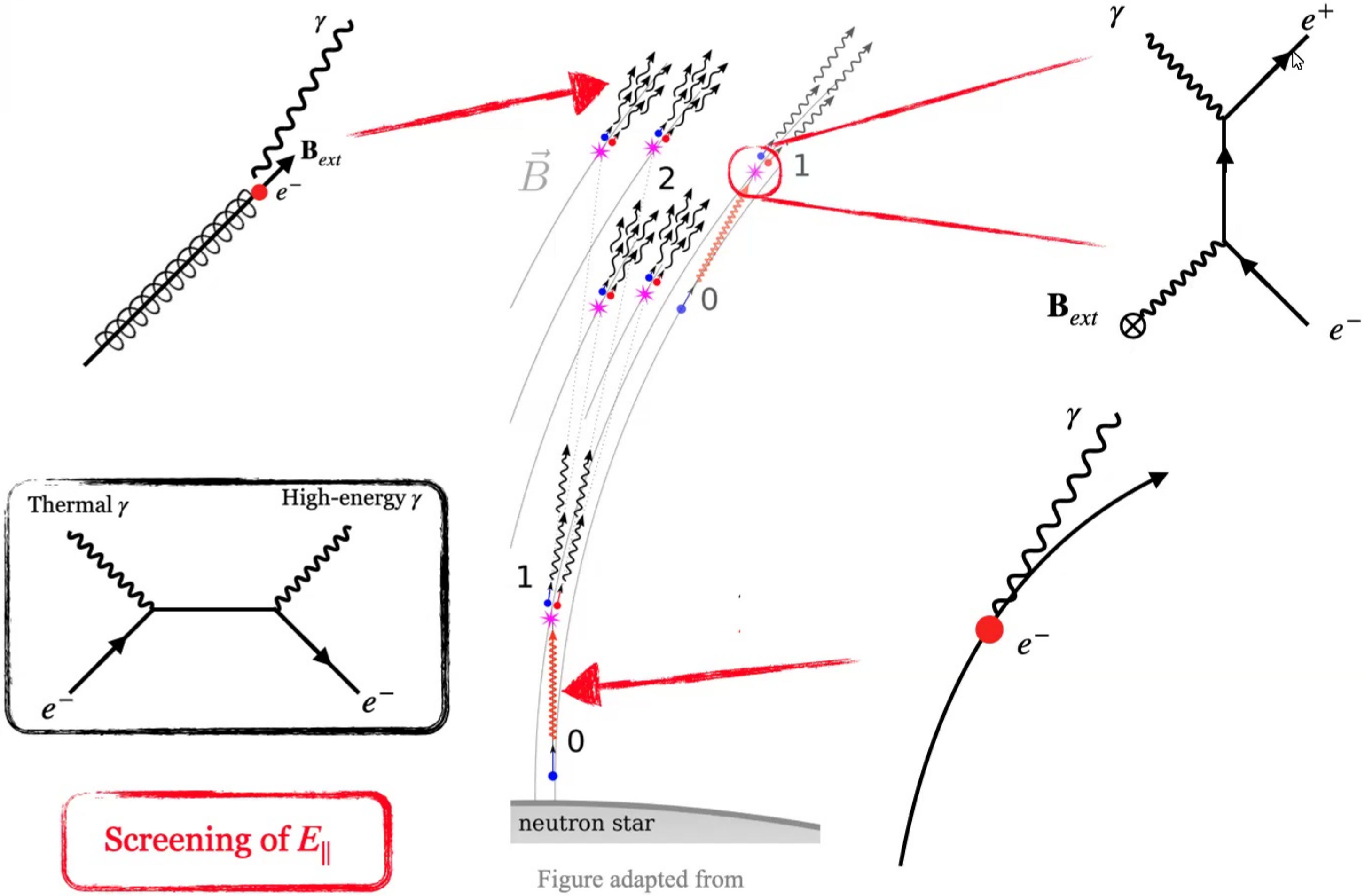


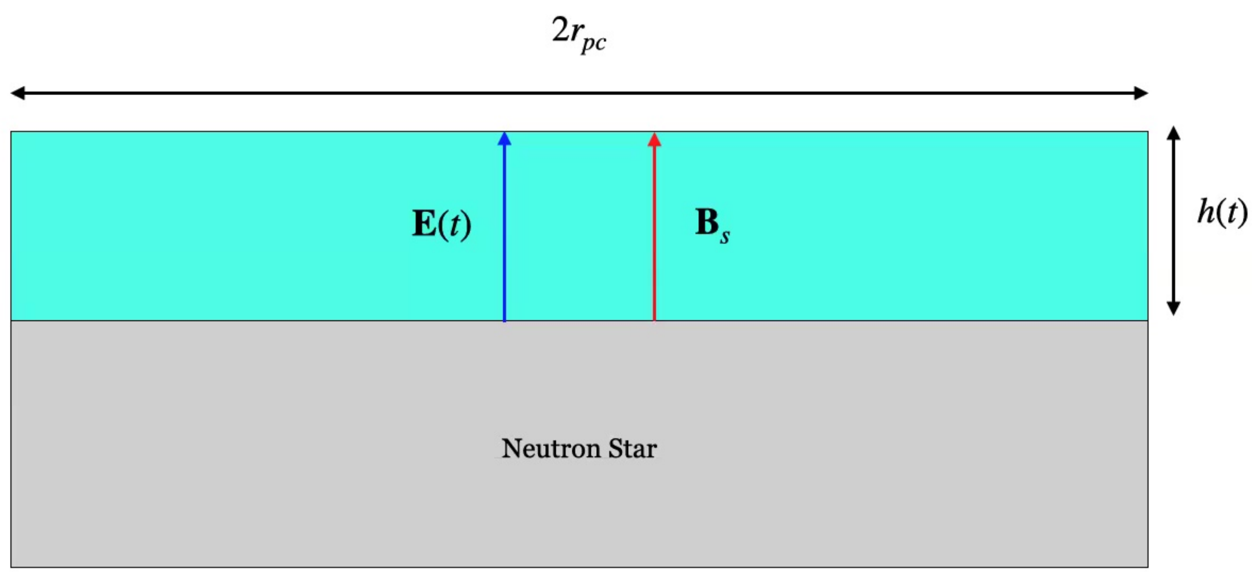
Figure adapted from
Timokhin & Harding (2015)

Polar Cap Dynamics

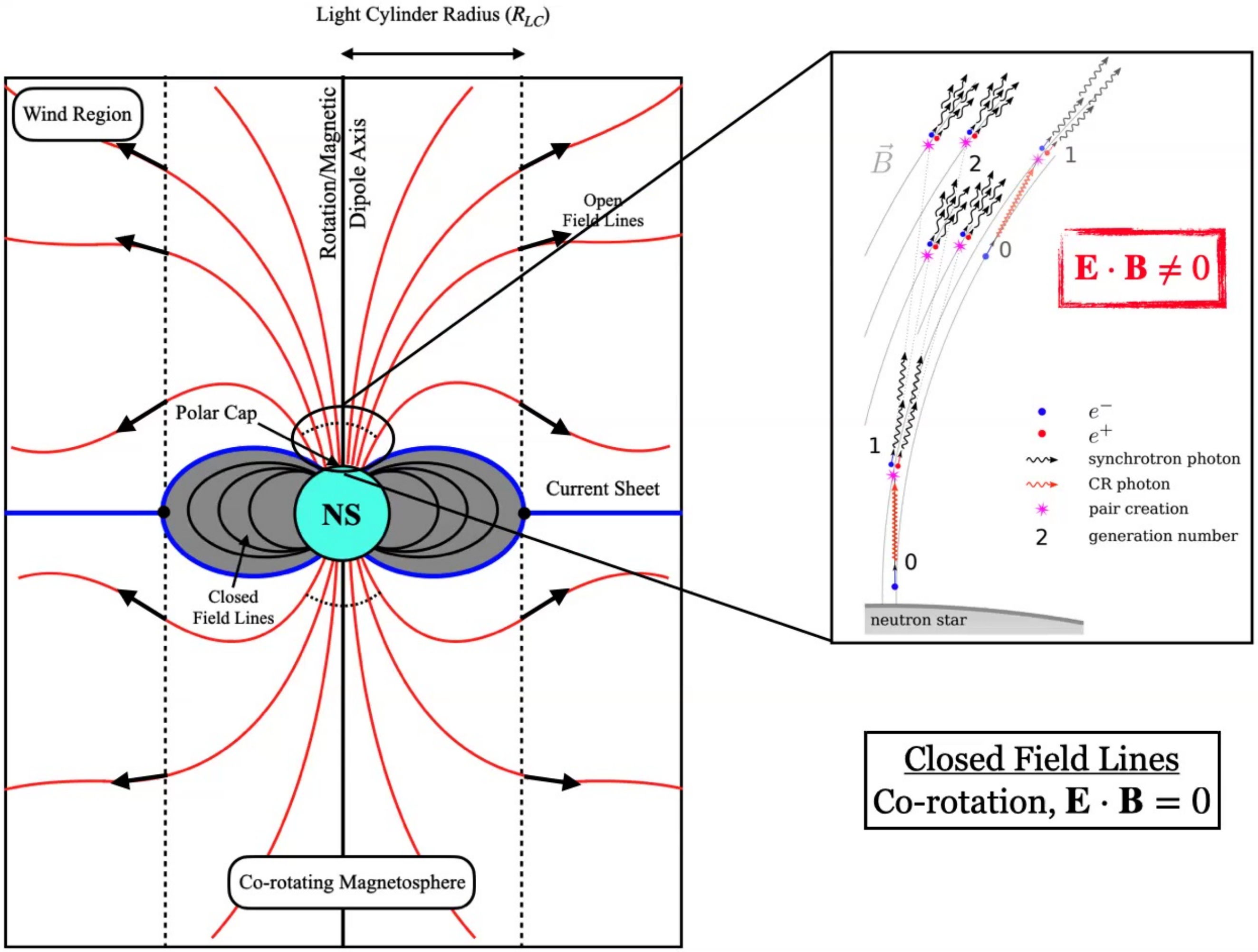
Sturrock (1971)
Ruderman & Sutherland (1974)

Step 1: Gap Growth

$$\mathbf{E}(t) \approx 2\Omega B_s h(t),$$
$$\Delta V(t) \approx \Omega B_s h^2(t)$$



Global Pulsar Magnetosphere

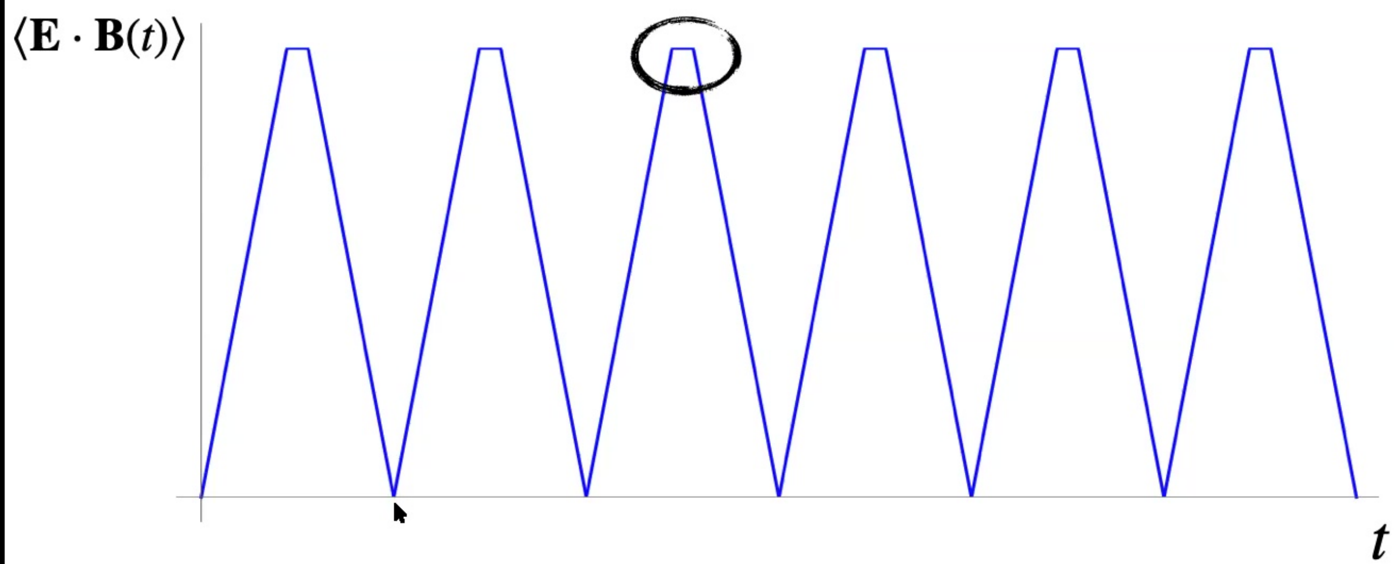


<u>Closed Field Lines</u>
Co-rotation, $\mathbf{E} \cdot \mathbf{B} = 0$

A Toy Model

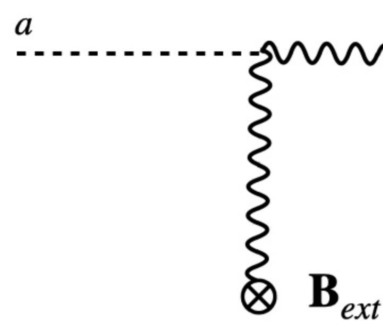
$$\mathbf{E}\cdot\mathbf{B}(\mathbf{x},t) = 2\Omega B_s^2 h \begin{cases} t/h & 0 \le z \le t, & 0 \le t \le h \\ 1 & 0 \le z \le h, & h < t \le T-h \\ \left(\frac{T-t}{h}\right) & z \le 0 \le T-t, & T-h < t \le T \end{cases}$$

Pair cascade



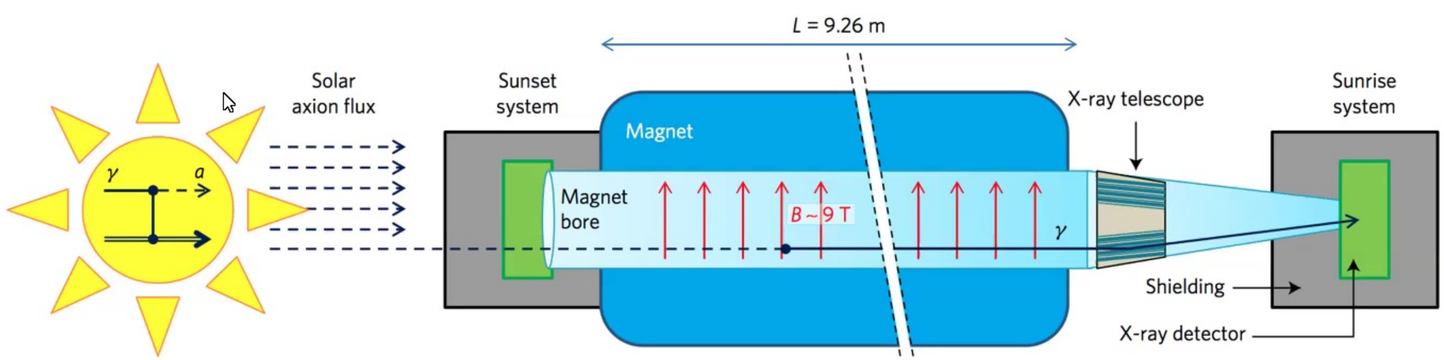
Axion-Photon Conversion: Warm-up

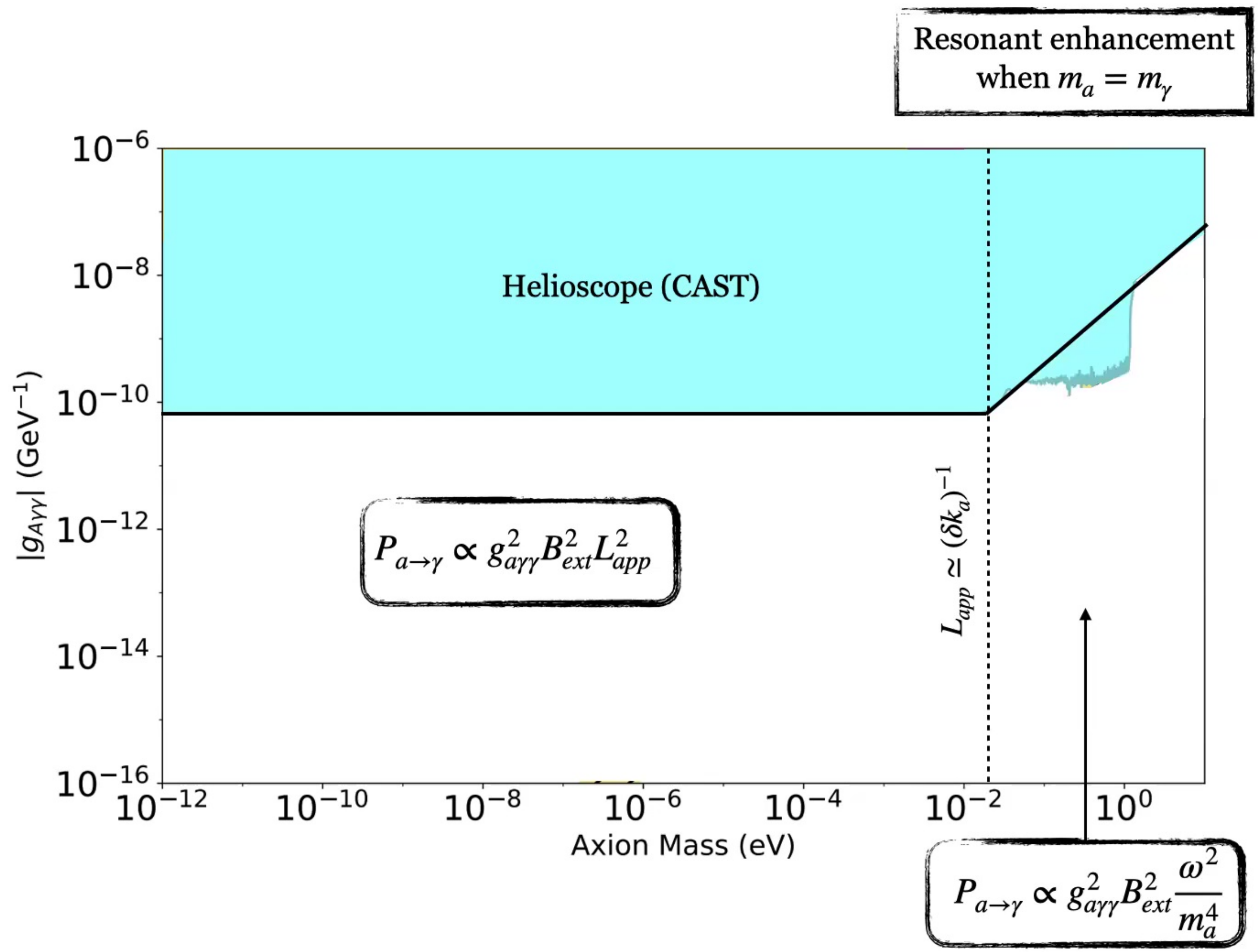
Uniform Magnetic Field



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

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



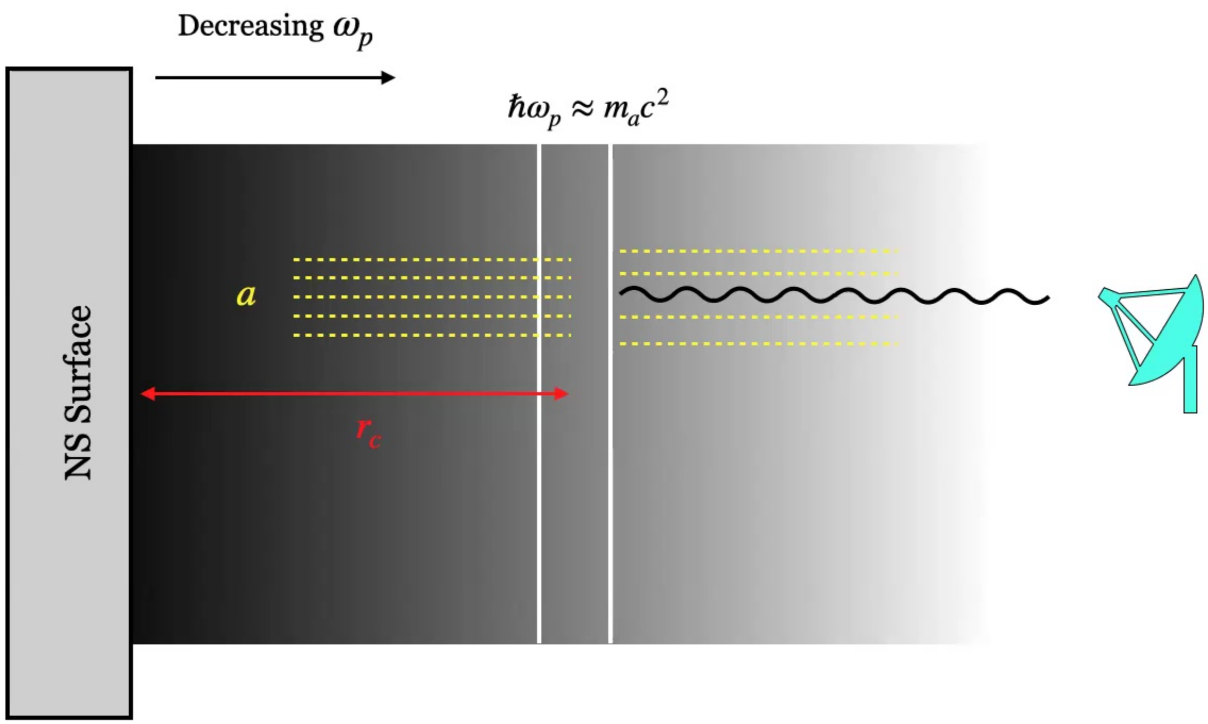


Resonant enhancement
when $m_a = m_\gamma$
Helioscope (CAST)
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 L_{app}^2$
$L_{app} \simeq (\delta k_a)^{-1}$
$P_{a\to\gamma} \propto g_{a\gamma\gamma}^2 B_{ext}^2 \frac{\omega^2}{m_a^4}$
$|g_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass (eV)
10^{-6}
10^{-8}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

Pulsar Plasma (1D)

$$\omega_{p,GJ}(r) = \sqrt{\frac{2e^2\ \Omega\ B_0\ R_0^3\ \kappa}{m_e r^3}} \implies P_{res} \sim g_{a\gamma\gamma}^2 B_0 R_0^2 \left(\frac{m_a^2 m_e}{\Omega}\right)\frac{1}{\kappa}$$

$$1 \leq \kappa \lesssim 10^5(?)$$

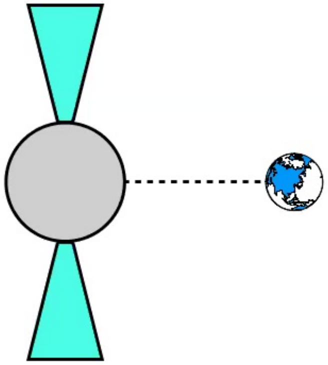


Neutron Star Targets: Magnetars

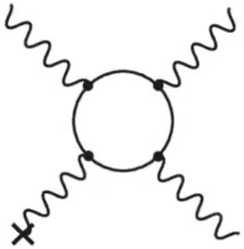
Magnetars

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

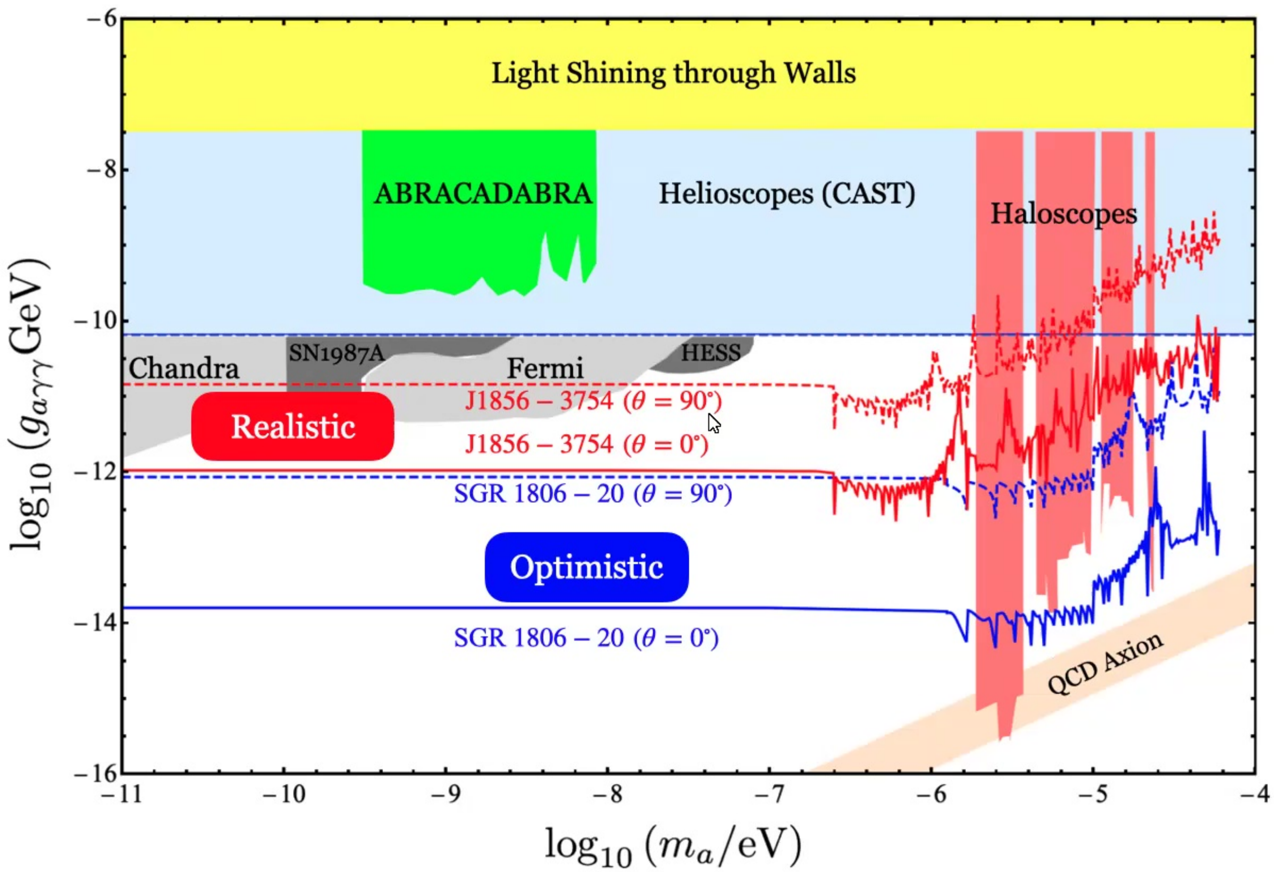
Reason for absence of radio emission crucial to understanding e^+e^- production and axion production!



Magnetar simulations required!



Sensitivity



Improving the Model

Spark Gap Toy Model

Spectrum concentrated at ω_n

Spatial variations within the gap

No prediction of pair cascade time

Simulation-Based Model

Realistic spectrum (consistent w/ radio)

Accounts for spatial variation

First-principle calculation of pair cascade

1D Conversion Model

Refraction, reflection of photons ✗

Time dependence ✗

Spectral Distortions ✗

3D Conversion Model

Follows particle trajectories (ray-trace)

Accounts for plasma effects on photons

Time dependence

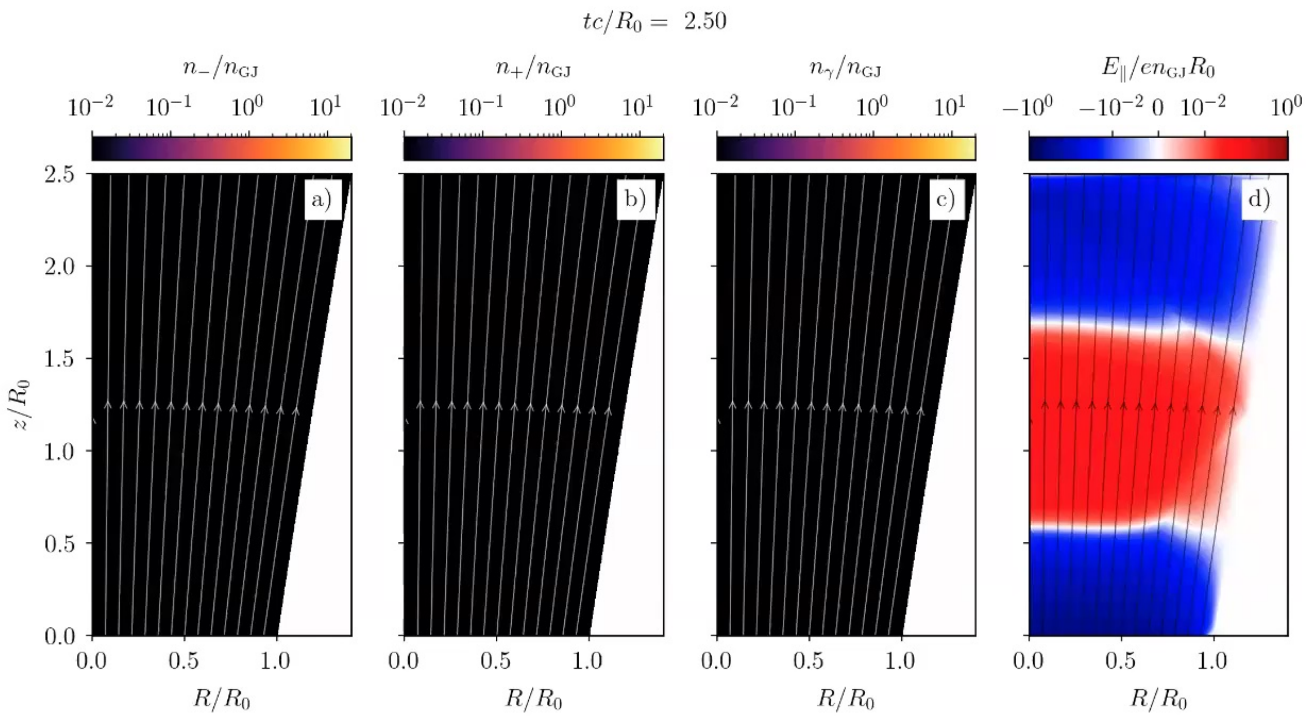
Spectral Distortions

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

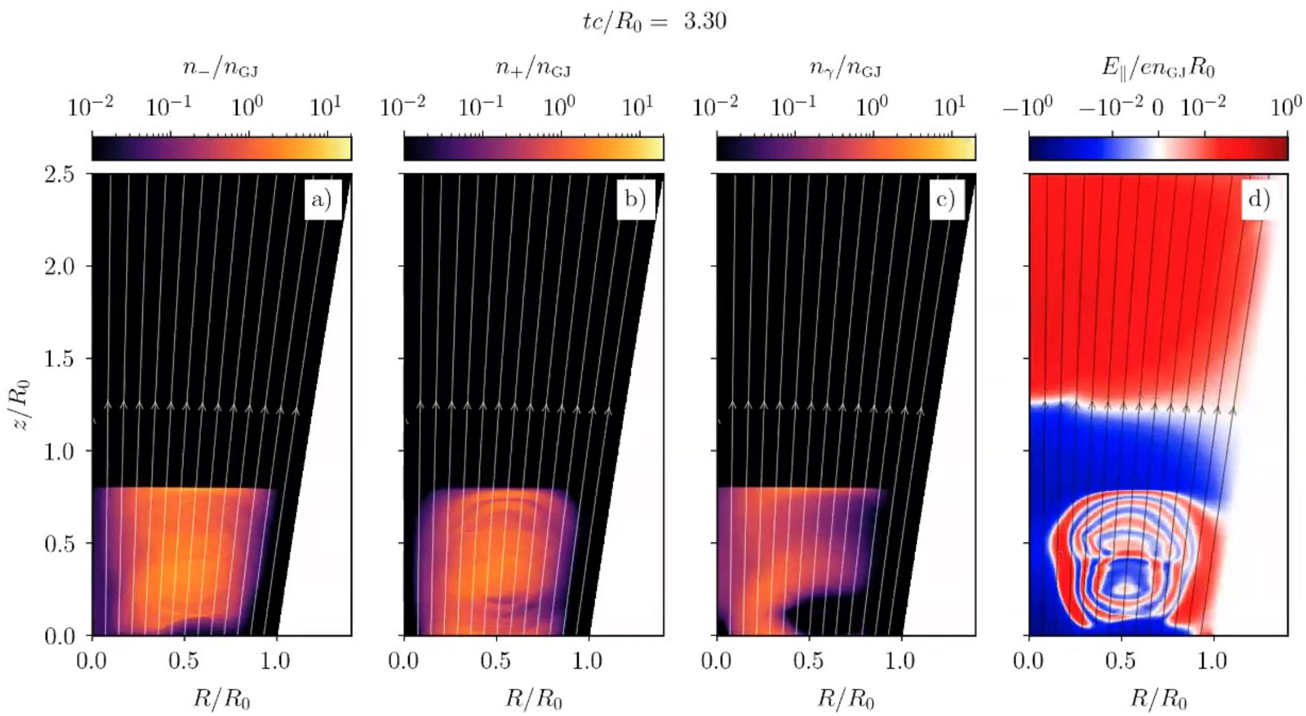


2D PIC Simulations [arXiv:2108.11702]

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]

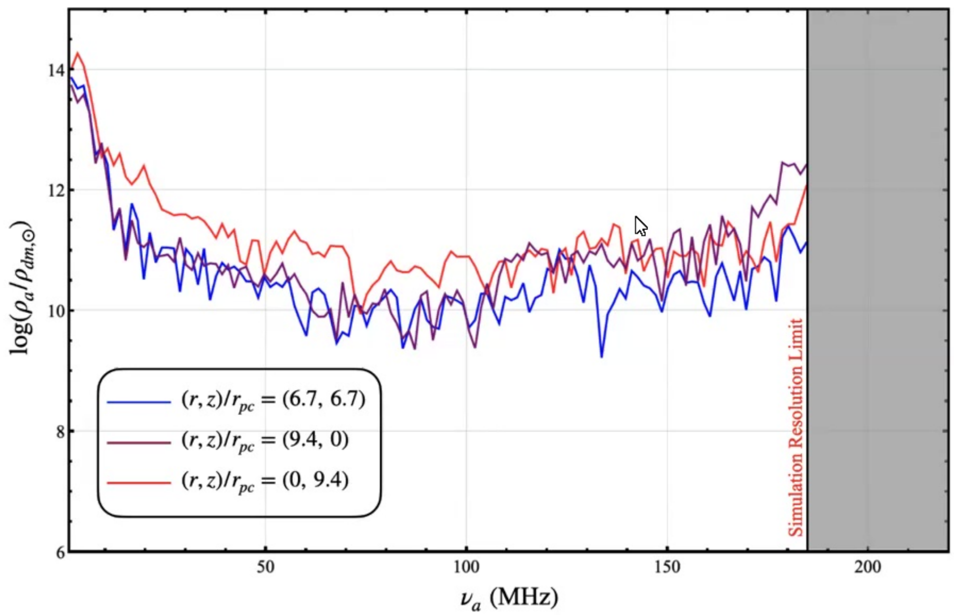
[1] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
[2] JILA, University of Colorado Boulder, 440 UCB, Boulder, CO 80309, USA
[3] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA



Gap-Sourced Axion Population

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

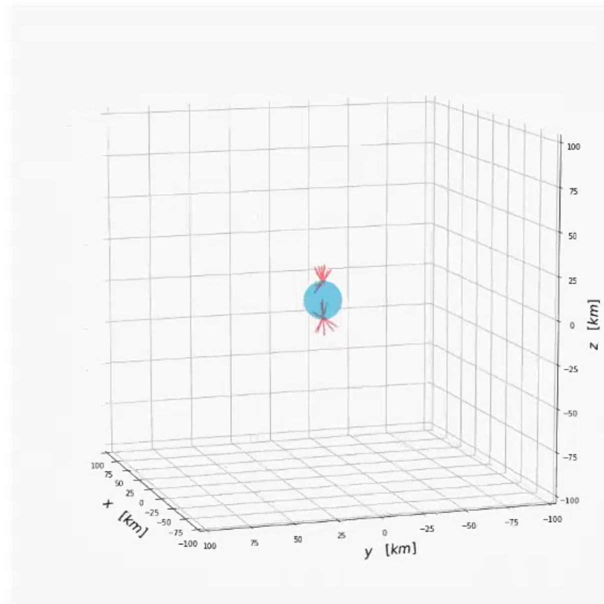
$$\boxed{m_a = 10^{-10}\ \text{eV},\ g_{a\gamma\gamma} = 10^{-11}\ \text{GeV}^{-1}}$$



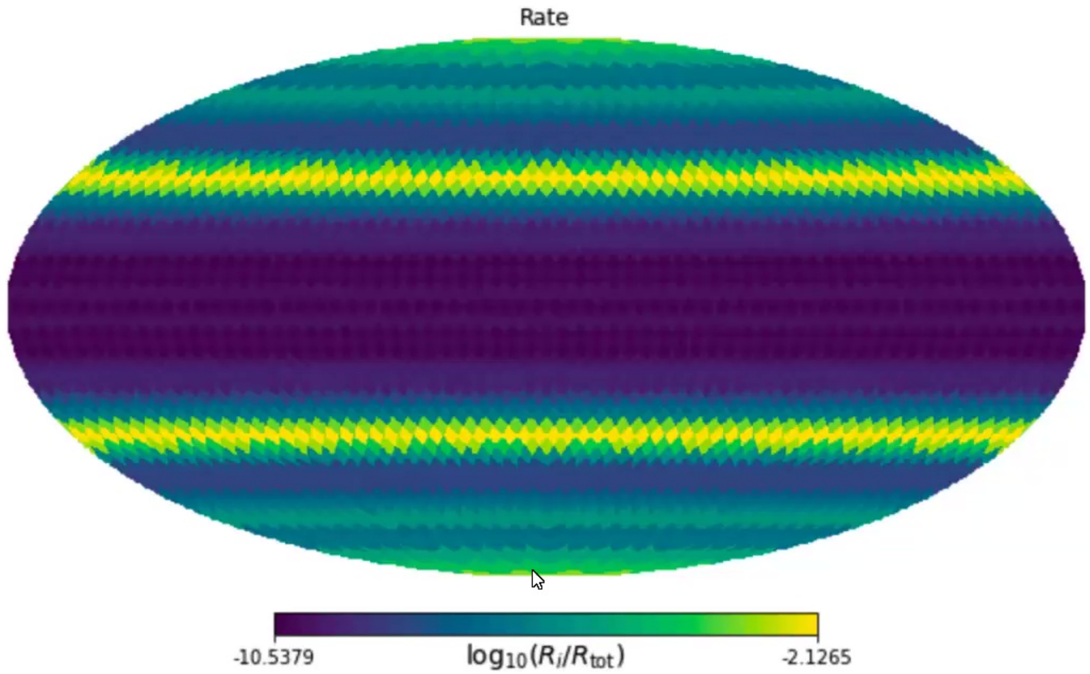
Conversion Simulations

Witte, Noordhuis, Edwards, Weniger (2021)

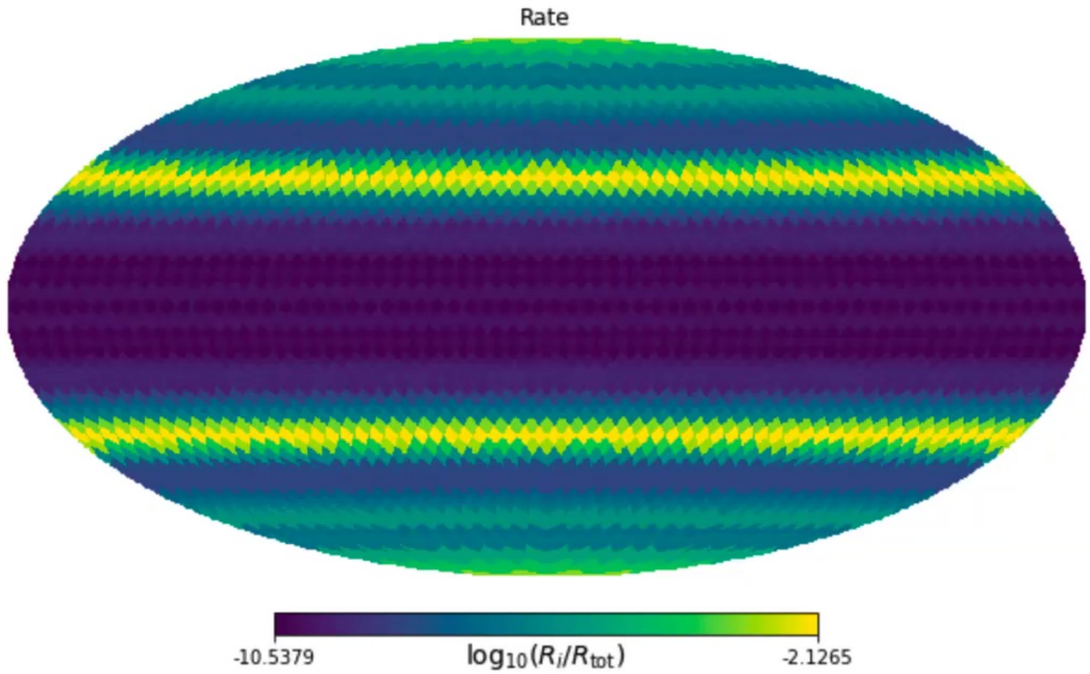
- Ray tracing analysis of outgoing axions.
- Reflection and refraction of radio photons.
- Spectral distortions due to magnetosphere plasma.
- Temporal features?
- Photon absorption in the plasma.
- In progress!



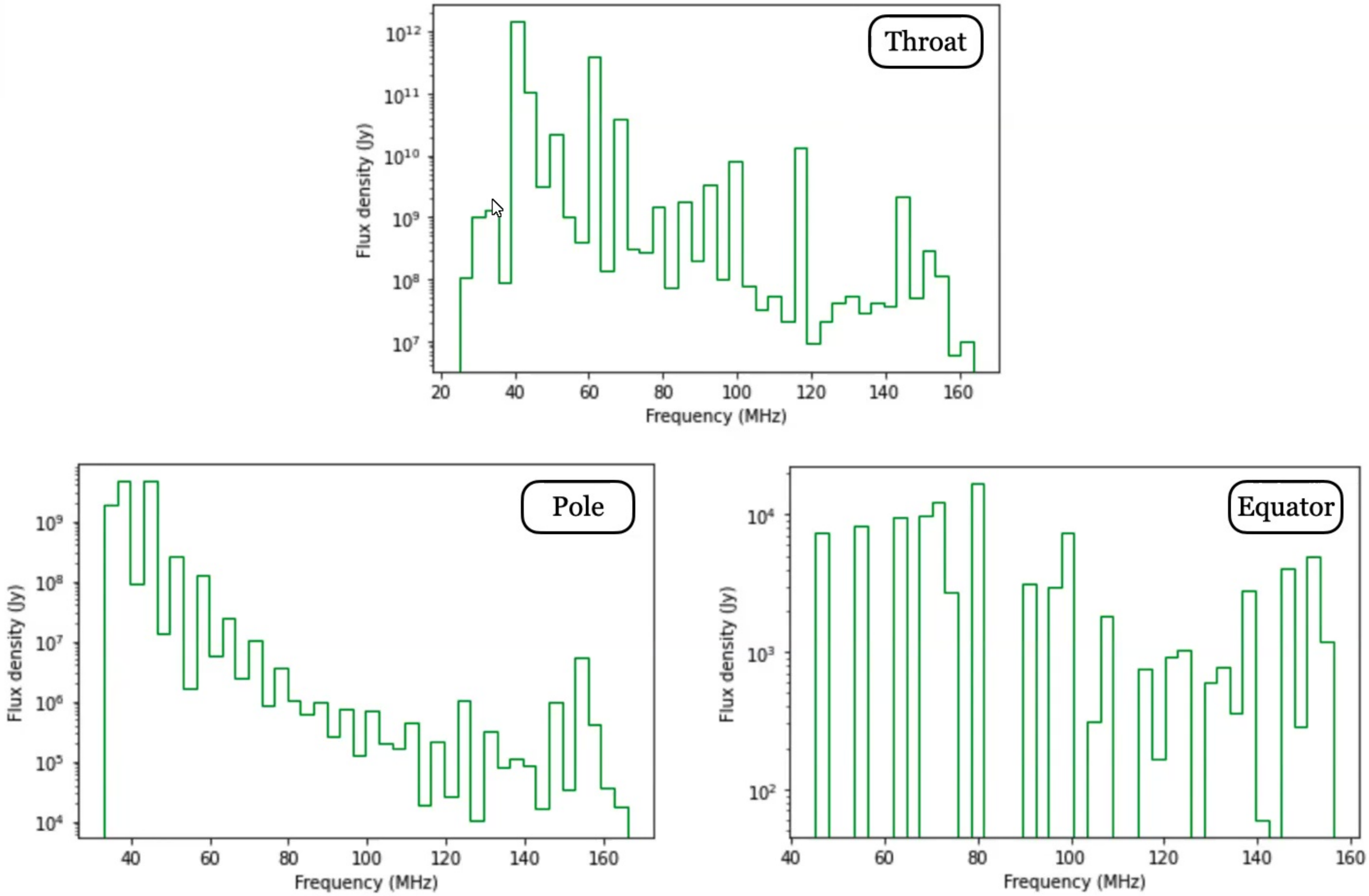
Sky Map



Sky Map



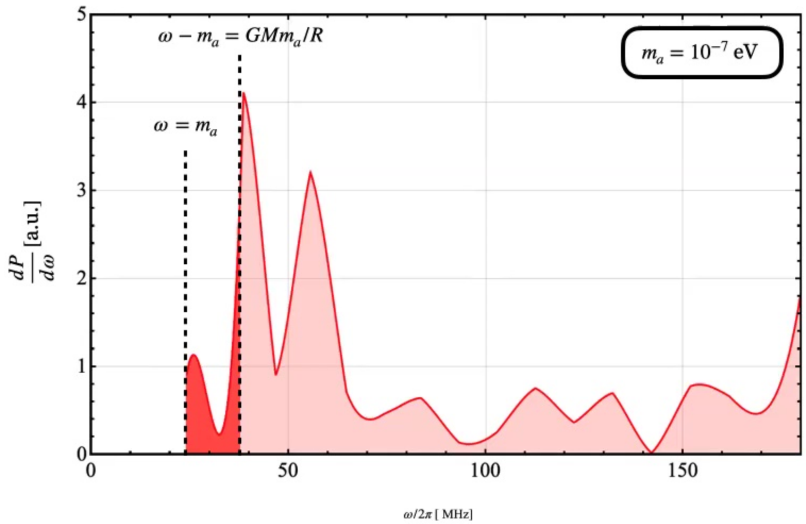
Sky Map


Throat
Flux density (Jy)
Frequency (MHz)
Pole
Flux density (Jy)
Frequency (MHz)
Equator
Flux density (Jy)
Frequency (MHz)

Aside: Bound States

Small fraction of axion emitted into bound "orbits" → $\omega - m_a - \dfrac{GMm_a}{R} < 0$

Case I: Bound axion population grows over τ_{pulsar} → Basin



Case II: Production/ conversion equilibrium → $P_{a\to\gamma} \sim \mathcal{O}(1)$

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, bound states.
- Axion production in additional magnetosphere gaps (slot gap, outer gap, current sheet), other astrophysical settings (BHs?).

- Computing pair multiplicity in generic pulsars (simulations).
- Understand gap dynamics and pair production in magnetars.

Thank you!
More questions?

Neutron Star Targets: Magnificent Seven

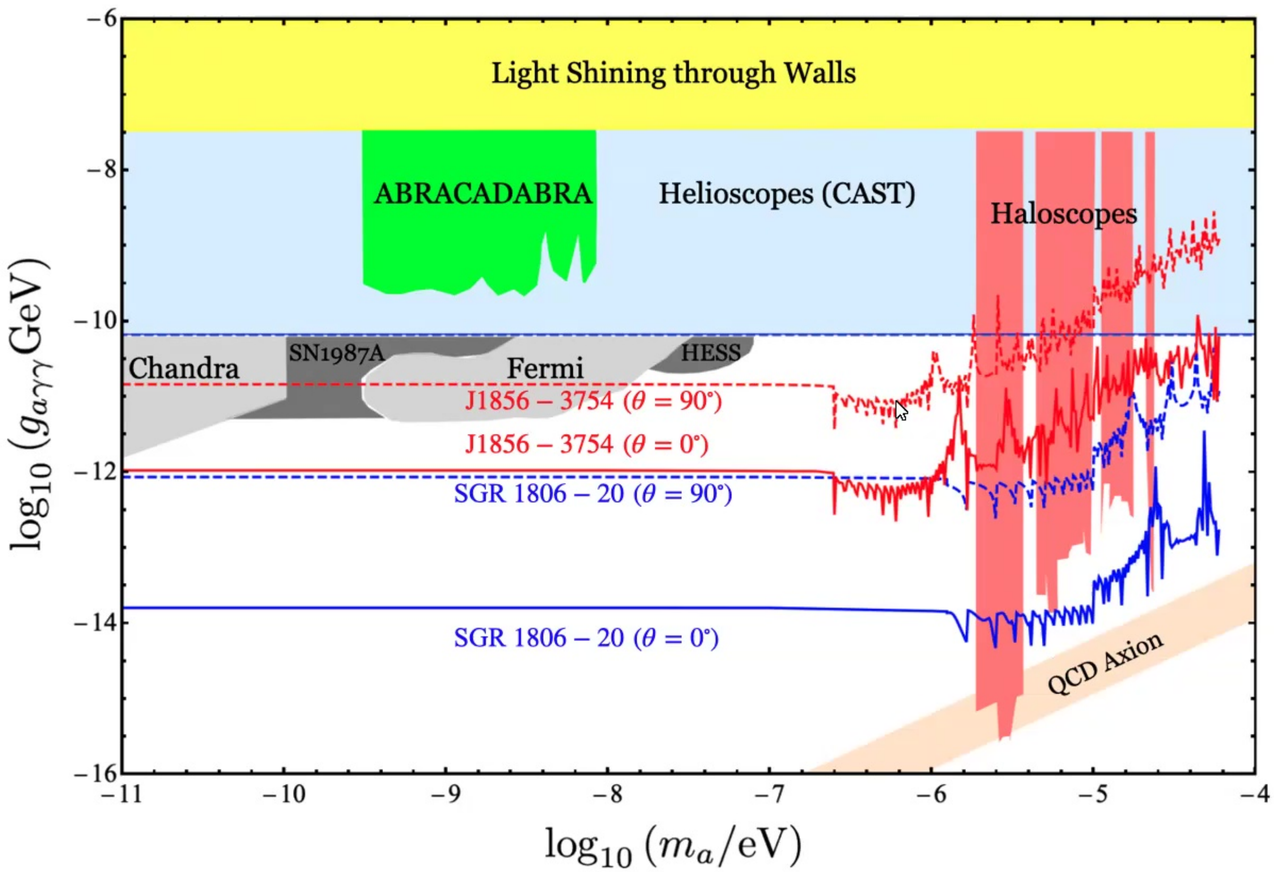
Magnificent Seven

- 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 ≈ 70 MHz (FAST), ≈ 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	$\gtrsim 250$

Sensitivity



Noise and Backgrounds

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

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

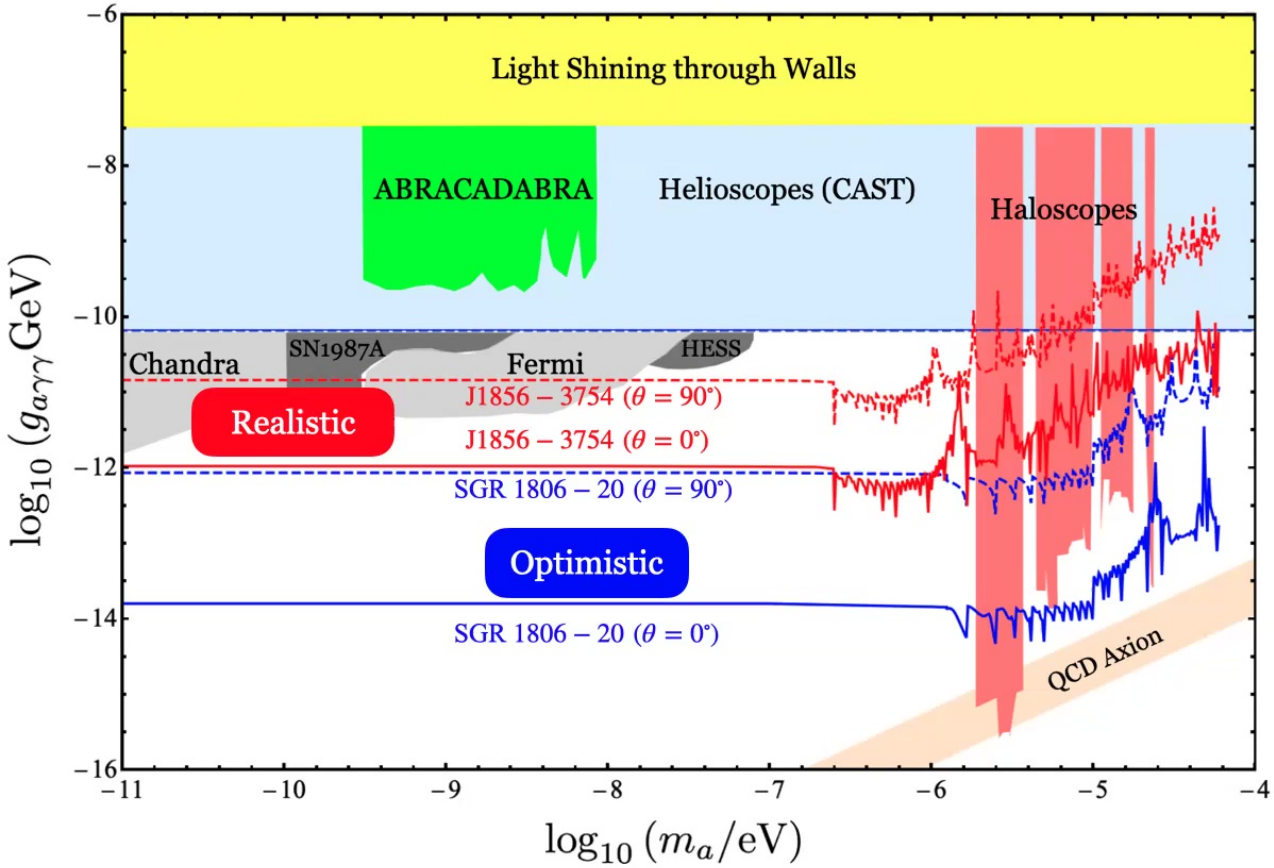
$$A_{eff} = A_0\sqrt{N(N-1)}$$

(Interferometer)

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

(Single-dish)

Sensitivity



Relativistic Axions ($\omega \approx k$)

1. Consider simplified set-up: constant **B**, $\theta = \pi/2$.

$$\left[i\partial_z + \omega + \omega \begin{pmatrix} \Delta_{\parallel}(z) & \Delta_B(z) \\ \Delta_B(z) & \Delta_a \end{pmatrix} \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0$$

$$\Delta_{\parallel} = -\frac{\omega_p^2}{2\omega^2} + \frac{14\alpha^2}{45}\frac{B^2}{m_e^4}$$

$$\Delta_B = \frac{g_{a\gamma\gamma}\omega B}{2(\omega^2 - \omega_p^2)}, \qquad \Delta_a = -\frac{m_a^2}{2\omega^2}$$

$$\Downarrow$$

$$P_{a\to\gamma}(z) = \frac{(2\Delta_B)^2}{(2\Delta_B)^2 + (\Delta_{\parallel} - \Delta_a)^2} \sin^2\left(\frac{\omega z}{2}\sqrt{(2\Delta_B)^2 + (\Delta_{\parallel} - \Delta_a)^2} \right)$$

$$\boxed{\begin{array}{c}\text{Weak Mixing} \\ \Delta_B \ll |\Delta_{\parallel} - \Delta_a|\end{array}}$$