

Axion Constraints from Quiescent Soft Gamma-ray Emission from Magnetars

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Synopsis of the Talk

- Magnetars – why these are a good target for ALP studies
- ALP production from magnetars
- Results: UL $g_{a\gamma\gamma}$ and UL $g_{a\gamma\gamma}$ vs ALP mass m_a
- Conclusions and Future work – *Fermi*-Gamma Ray Burst Monitor (GBM) Observations
- Soft gamma-ray emission is a great target for axion searches and the GBM is a great instrument for measuring this emission

ALP Production from Magnetars

- Magnetars are pulsars with really strong B fields
- Relativistic ALPs emitted from pulsar core by nucleon-nucleon Bremsstrahlung where rate goes as pulsar core temperature T_c ⁶
- The ALPs convert in the pulsar magnetosphere / B field to photons, favored by stronger B field, peak expected in 300 keV – 1 MeV band
- Magnetars with their strong B fields $\sim 10^{14}$ G (100 times greater than young radio PSRs) and high T_c favour the conversion process and are thus a good target to study ALPs by their conversion to soft-gamma ray photons and set coupling constraints
- 6 Magnetars have published gamma-ray flux ULs obtained with *CGRO* COMPTEL, *INTEGRAL* SPI/IBIS/ISGRI and *Fermi* GBM

ALP-Photon Luminosity

- Assume that ALP cooling is sub-dominant to neutrino cooling in the core (produced by modified URCA process) yields the photon luminosity $L_{a \rightarrow \gamma}$. This is the master equation used to set limits on ALP-photon coupling:

$$L_{a \rightarrow \gamma} = \frac{4\pi r_0^3 \dot{q}_\nu}{3 \int_0^\infty d\omega \omega \frac{dN_a}{d\omega}} \int_0^{2\pi} d\theta \int_{\omega_i}^{\omega_f} d\omega \omega \frac{dN_a}{d\omega} P_{a \rightarrow \gamma}(\omega, \pi/2). \quad (1)$$

- Here \dot{q}_ν is the neutrino emissivity, R_M is neutron superfluidity factor ~ 1 ,

$$\dot{q}_\nu = (7 \times 10^{20} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-3}) \left(\frac{\rho}{\rho_0}\right)^{2/3} R_M \left(\frac{T}{10^9 \text{ K}}\right)^8 \quad (2)$$

- $dN_a/d\omega$ is the ALP spectrum for photon energy ω :

$$\frac{dN_a}{d\omega} = \frac{x^2(x^2 + 4\pi^2)e^{-x}}{8(\pi^2\zeta_3 + 3\zeta_5)(1 - e^{-x})}, \quad (3)$$

$$x = \omega/k_B T. \quad \text{Iwamoto 1984, Brinkmann and Turner 1988}$$

More details of the model in our paper:

<https://arxiv.org/abs/2001.10849>

and Fortin and Sinha X-ray / ALP

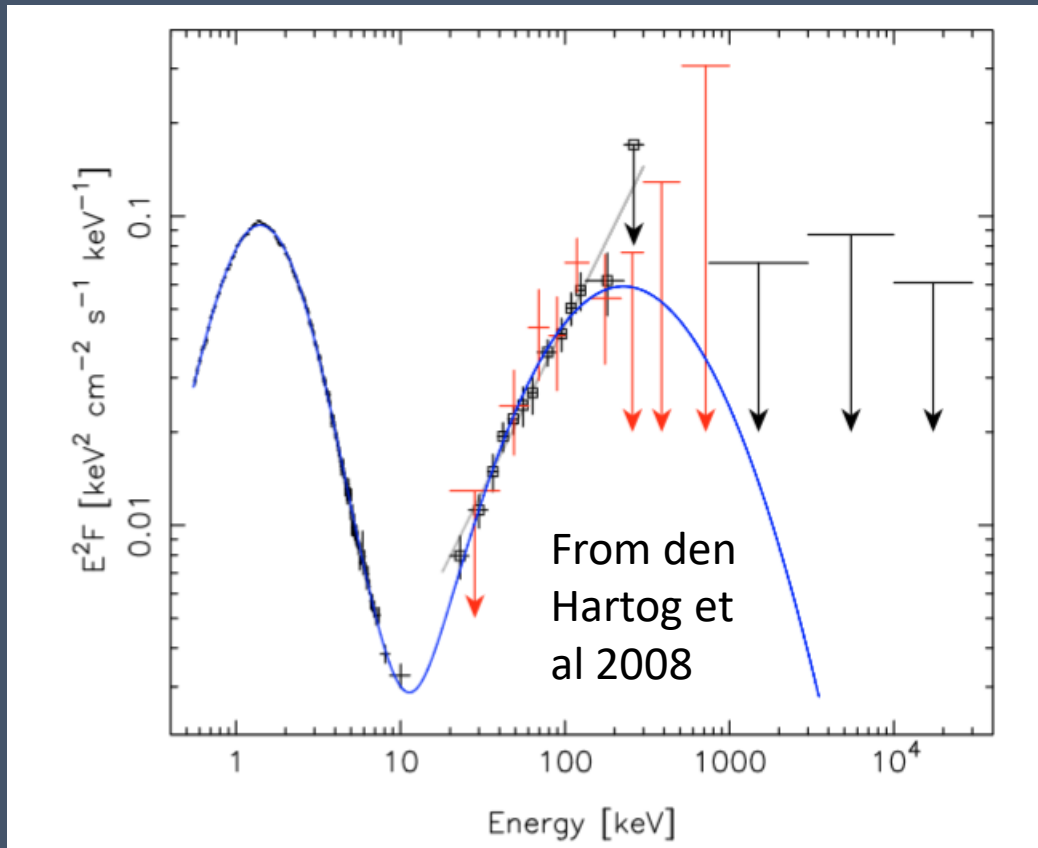
modelling refs:

[JHEP 06 \(2018\) 048](#)

[JHEP 01 \(2019\) 163](#)

[JCAP 11 \(2019\) 020](#)

4U 0142+61 – Typical Magnetar Spectra



- Black open squares *INTEGRAL*-ISGRI fluxes PL tail (10 keV – 275 keV).
- Characteristic turnover > 275 keV, also seen in other magnetars, implied by ULs (right of fig) from *INTEGRAL*-SPI (red) and *CGRO* COMPTEL (black).
- Similar spectra exist for 5 other magnetars and *Fermi*-GBM has been used to determine magnetar fluxes by ter Beek 2012

Soft Gamma-Ray Background

- Observed magnetar hard X-ray emission up to 275 keV is likely due to resonant Compton upscattering (RCU) of magnetar surface thermal X-rays by non-thermal electrons moving along field lines in magnetosphere
- Attenuation processes suppress emission due to magnetic pair creation $\gamma \rightarrow e^\pm$ and photon splitting $\perp \rightarrow ||$. Photon splitting alone constrains observed 250 keV emission to be produced outside 2-4 r_0 . For emission regions $r < 2 r_0$ photons of energy > 287 keV cannot escape, for $r > 10 r_0$ photons < 1 MeV are not attenuated (Hu et al 2019)
- The RCU process alone can generate spectral breaks at 315 keV if magnetosphere electrons are mildly relativistic (Lorentz factors of 1.7) but Lorentz factor of 22 gives flat spectra to 1 MeV (unobserved) (Zane et al 2011)
- $ALP \rightarrow \gamma\gamma$ occurs at $\sim 500 r_0$ so we assume no RCU background
- Of 440 magnetar bursts none have emission above 200 keV -Collazzi et al 2015

Magnetars Have Internal Heating

- Observational evidence – Magnetar X-ray luminosity 10^{34} - 10^{35} erg s⁻¹ > spin down luminosity 10^{32} - 10^{34} erg s⁻¹ so additional energy source required , slow periods 2-12s and lack Doppler modulation so accretion power from binary companions unlikely
- Higher than expected surface temperatures T_s indicate heating in crust for efficiency. At age 1000 yr cooling curve gives $T_c=10^{8.4}$ K and crust temperature $10^{9.1}$ K , neutrino emission heat sink (Kaminker et al 2006)
- Core heating via ambipolar diffusion $T_c=10^{8.9}$ K at 2250 yr (Dall’osso 2009)
- Also strong B field causes anisotropic thermal conductivity and suppresses neutrino emission $10^{9.6}$ K at base of crust while T_s is 10^5 - $10^{6.7}$ K depending on field parallel / radial to surface respectively compatible with 4 of the magnetars in our selection (Ho et al 2012)
- X-ray luminosity alone gives max T_c 8×10^8 K for Fe envelope Beloborodov and Li 2016

Magnetar Selection

Magnetar	Distance kpc	Surface B Field 10^{14} G	Age kyr	UL Flux 300 keV–1 MeV 10^{-10} erg cm^{-2} s^{-1}	UL Luminosity 10^{35} erg s^{-1}
1E 2259+586	$3.2^{+0.2}_{-0.2}$	0.59	230	1.17	$1.43^{+0.18}_{-0.17}$
4U 0142+61	$3.6^{+0.4}_{-0.4}$	1.3	68	8.16	$12.65^{+2.97}_{-2.66}$
1RXS J170849.0-400910	$3.8^{+0.5}_{-0.5}$	4.7	9	1.92	$3.32^{+0.93}_{-0.82}$
1E 1547.0-5408	$4.5^{+0.5}_{-0.5}$	3.2	0.69	3.20	$7.75^{+1.82}_{-1.63}$
1E 1841-045	$8.5^{+1.3}_{-1.0}$	7	4.6	2.56	$22.13^{+7.28}_{-4.90}$
1E 1048.1-5937	$9.0^{+1.7}_{-1.7}$	3.9	4.5	3.04	$29.46^{+12.18}_{-10.07}$

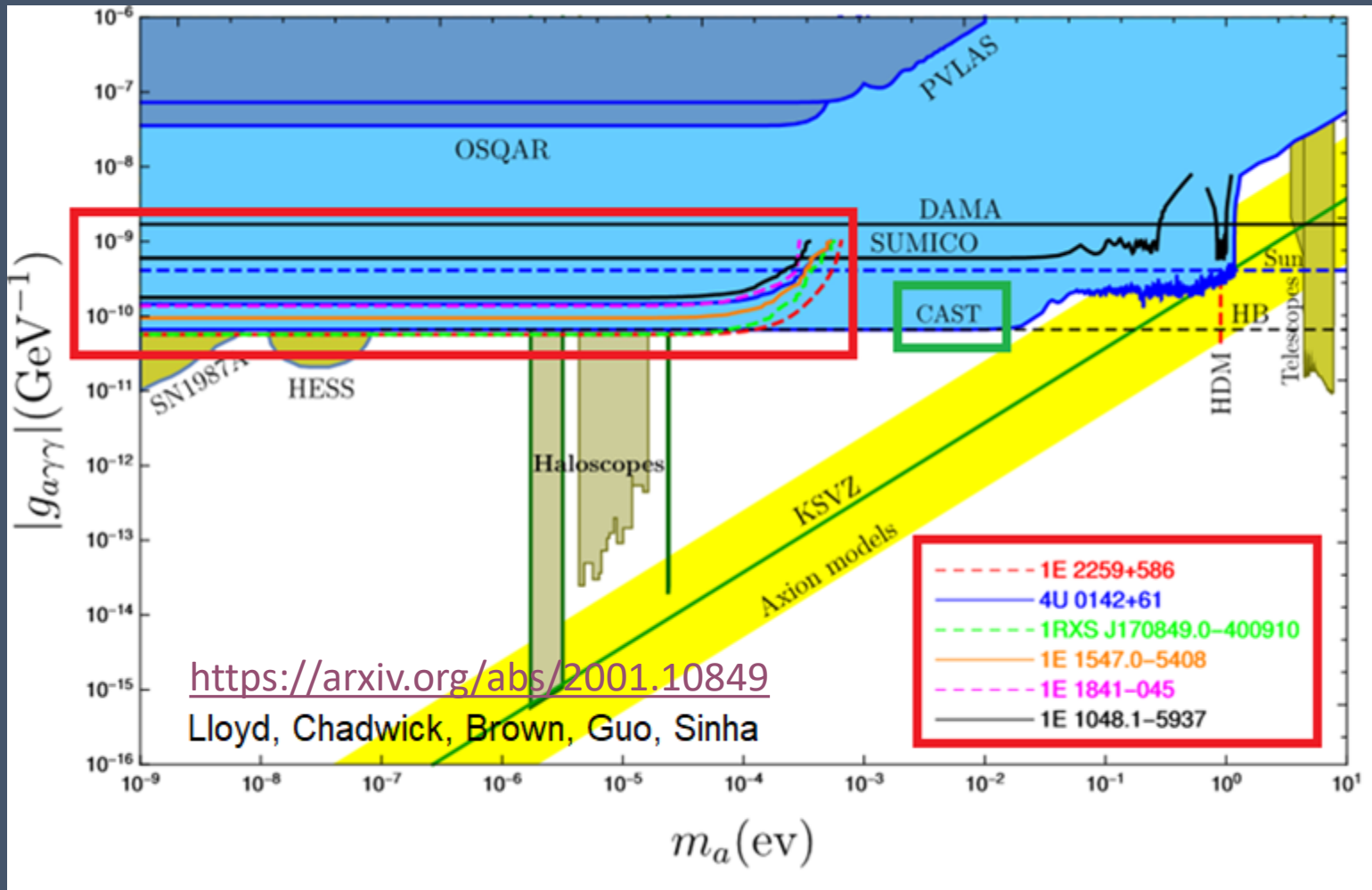
- These are the 6 magnetars with published SEDs and UL gamma fluxes
- Distances from Kothes and Foster 2012, Durant and van Kerkwijk 2006, Tiengo et al 2010, Tian and Leahy 2008
- We take fluxes derived from den Hartog et al 2008, Kuiper et al 2006 and ter Beek 2012 SEDs in a conservative manner, by summing the flux UL s in 300 keV-1MeV range.
- B field and age from McGill University Magnetar Catalog

Our Results – UL $g_{a\gamma\gamma}$ for Selected Magnetars

Magnetar	$g_{a\gamma\gamma}$ (GeV^{-1})
1E 2259+586	5.68×10^{-11}
4U 0142+61	1.47×10^{-10}
1RXS J170849.0-400910	5.69×10^{-11}
1E 1547.0-5408	9.43×10^{-11}
1E 1841-045	1.37×10^{-10}
1E 1048.1-5937	1.77×10^{-10}

- ALP mass is assumed to be 10^{-7} eV for this calculation
- T_c assumed to be 10^9 K
- Our $g_{a\gamma\gamma}$ determination rivals CAST at core temperatures of 9.63×10^8 K and exceeds it for 2 magnetars at 10^9 K

Results - $g_{a\gamma\gamma}$ vs ALP mass



1RXS J170849.0-400910 and 1E 2259+586 rival CAST limits for $m_a < 10^{-4}$ eV and $T_c = 10^9$ K

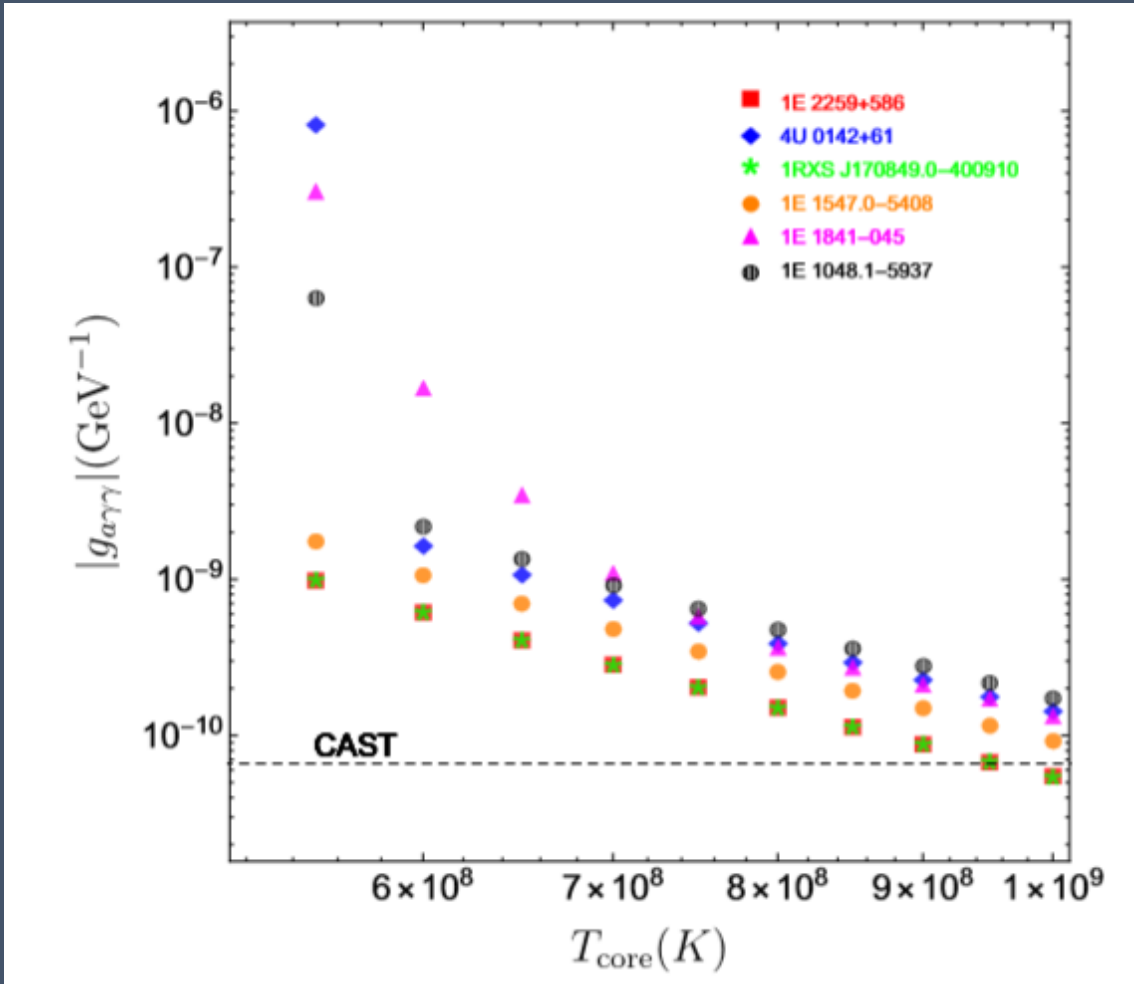
Future Work

- The *Fermi*-GBM monitors 248 sources by an Earth Occultation Technique in 8 keV – 1 MeV range
- We propose to add the known 23 Magnetars to this and get ULs in 300 keV - 1MeV band
- In addition we can use the ephemerides of the Magnetars to set ULs using the photon counts returned by the GBM CTIME data product and then determine an SED by an effective area calculation has as been done for 4 magnetars by ter Beek (2012)
- We have submitted a *Fermi* collaboration guest investigator proposal for the current cycle – under consideration as I speak
- Also we are refining this analysis to use a single UL flux and peak of axion flux to use the UL statistical confidence limits in our result

Conclusions

- ALPs emitted from magnetar core can convert to soft γ -ray flux in the magnetosphere
- We give an expression for gamma-ray luminosity for this conversion
- We obtain constraints on axion-photon coupling $g_{a\gamma\gamma}$ from published gamma-ray UL fluxes for a range of reasonable core temperatures offered in published cooling / heating simulations
- Our $g_{a\gamma\gamma}$ determination rivals CAST at core temperatures of 9.63×10^8 K and exceeds it for 2 magnetars at 10^9 K as in our paper <https://arxiv.org/abs/2001.10849>
- We can't wait to extend this work using Fermi-GBM observations and we are undertaking an energy resolved analysis at the axion peak in 1 gamma-ray flux bin

BACKUP - $g_{a\gamma\gamma}$ determination vs T_c



- Our determination of UL $g_{a\gamma\gamma}$ is quite temperature sensitive *but* can still rival CAST at temperatures at the upper end of a reasonable core temperature range
- CAST limits dashed horizontal line
- For $T_c < 9.6 \times 10^8$ K our constraints weaker than CAST
- Assumed m_a is 10^{-7} eV

BACKUP – Determine UL $g_{a\gamma\gamma}$

- Determine photon refractive indices in parallel and perpendicular directions to the B field in different field regimes
- Use these indices to numerically solve a mixing equation to obtain the varying probability of axion-to-photon conversion $P_{a\rightarrow\gamma}$ as axions propagate outwards from the pulsar. This mixing equation and hence $P_{a\rightarrow\gamma}$ also depends on terms incorporating $g_{a\gamma\gamma}$ and m_a
- Numerically solve a luminosity equation for the photons produced by ALP conversion in the B field by making this photon flux bounded by the observed magnetar soft-gamma ray flux UL. As this luminosity equation uses $P_{a\rightarrow\gamma}$ a range of $g_{a\gamma\gamma}$ and m_a solutions can be found
- The temperature dependence enters through incorporating neutrino emissivity as a constraint to ALP to photon luminosity and in the ALP spectrum

BACKUP - ALP Production from Magnetars

- Relativistic ALPs emitted from pulsar core by nucleon-nucleon Bremsstrahlung from the Lagrangian term :

$$\mathcal{L} \supset g_{aN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N \quad (1)$$

- The ALPs convert in the pulsar magnetosphere / B field to photons, favored by stronger B field, peak expected in 300 keV – 1 MeV band:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad (2)$$

More details in the Fortin and Sinha papers for X-ray / ALP conversion as follows:

Fortin/Sinha - (1) JHEP 06 (2018) 048,

Fortin/Sinha - (2) JHEP 01 (2019) 163

Fortin/Sinha - (3) JCAP 11 (2019) 020

BACKUP - Photon Refractive Indices

- In the B field $<$ critical field strength regime, ALPs can convert to gamma-ray photons at around $500 r_0$ (r_0 is the magnetar radius), we have derived the the parallel and perpendicular refractive indices from the photon polarization tensor as :

$$\begin{Bmatrix} n_{\parallel} \\ n_{\perp} \end{Bmatrix} = 1 + \frac{\alpha}{4\pi} \left(\frac{B}{B_c} \right)^2 \sin^2 \theta \frac{2}{45} \begin{Bmatrix} 7 \\ 4 \end{Bmatrix} + \mathcal{O}((eB)^4) \quad (3)$$

- Here θ is the the angle between the axion propagation direction and the pulsar B field, α is fine structure constant $\approx 1/137$ and $e = \sqrt{4\pi\alpha}$, B_c is the quantum critical field limit $= m_e^2/e = 4.413 \times 10^{13}$ G

BACKUP - Mixing Equation

- Assume a dipolar magnetic field :

$$B = B_{surf} \left(\frac{r_0}{r} \right)^3 \quad (4)$$

- The mixing equation is :

$$i \frac{d}{dx} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} \omega r_0 + \Delta_a r_0 & \Delta_M r_0 & 0 \\ \Delta_M r_0 & \omega r_0 + \Delta_{\parallel} r_0 & 0 \\ 0 & 0 & \omega r_0 + \Delta_{\perp} r_0 \end{pmatrix} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix} \quad (5)$$

- E_{\parallel} and E_{\perp} parallel and perpendicular electric fields , a is the axion field, ω is the photon energy and other terms are:

$$\Delta_a = -\frac{m_a^2}{2\omega}, \quad \Delta_{\parallel} = (n_{\parallel} - 1)\omega, \quad \Delta_{\perp} = (n_{\perp} - 1)\omega, \quad \Delta_M = \frac{1}{2} g_{a\gamma\gamma} B \sin \theta. \quad (6)$$

BACKUP - ALP-Photon Luminosity

- Assume that ALP cooling is sub-dominant to neutrino cooling in the core (produced by modified URCA process) yields the photon luminosity $L_{a \rightarrow \gamma}$. This is the master equation used to set limits on ALP-photon coupling:

$$L_{a \rightarrow \gamma} = \frac{4\pi r_0^3 \dot{q}_\nu}{3 \int_0^\infty d\omega \omega \frac{dN_a}{d\omega}} \int_0^{2\pi} d\theta \int_{\omega_i}^{\omega_f} d\omega \omega \frac{dN_a}{d\omega} P_{a \rightarrow \gamma}(\omega, \pi/2). \quad (7)$$

- Here \dot{q}_ν is the neutrino emissivity, R_M is neutron superfluidity factor (~ 1),

$$\dot{q}_\nu = (7 \times 10^{20} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-3}) \left(\frac{\rho}{\rho_0} \right)^{2/3} R_M \left(\frac{T}{10^9 \text{ K}} \right)^8 \quad (8)$$

- $dN_a/d\omega$ is the ALP spectrum for photon energy ω with Euler Zeta functions:

$$\frac{dN_a}{d\omega} = \frac{x^2(x^2 + 4\pi^2)e^{-x}}{8(\pi^2\zeta_3 + 3\zeta_5)(1 - e^{-x})},$$

$$(9) \quad \text{where} \quad x = \omega/k_B T. \quad (10)$$

BACKUP – RCU Escape energies

Hu et al 2019 <https://arxiv.org/abs/1904.03315>

Opacities for Photon Splitting and Pair Creation in Neutron Star Magnetospheres 13

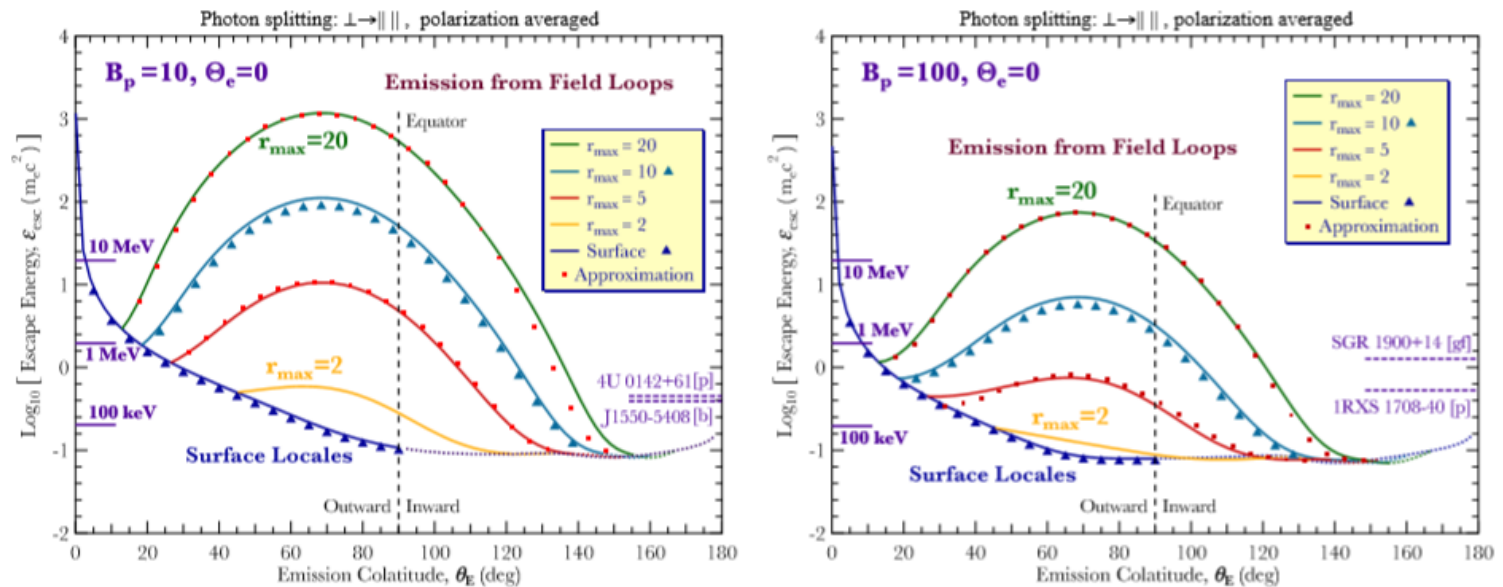


Figure 5. Photon splitting escape energies in flat spacetime for the mode $\perp \rightarrow \parallel$ (curves) and also averaged over polarization modes (triangles), for emission initially parallel to the local magnetic field line ($\Theta_e = 0$). The left and right panels are for surface polar fields $B_p = 10$ and $B_p = 100$, respectively. The abscissa is the emission colatitude θ_E , spanning outward propagation cases to the left of the equatorial marker line, to inward propagation to the right of this vertical dashed line. Four of the $\perp \rightarrow \parallel$ curves are for magnetospheric emission at points along dipolar magnetic field loops, labelled by $r_{\max} = 2, 5, 10, 20$, the maximum loop altitude in units of R_{NS} . In contrast, the dark blue curves for both panels are not for loop emission, but are surface emission cases that are displayed in the left hand panel of Fig. 4. All curves include dotted portions in the inward trajectory hemisphere that demarcate cases where photons would impact the stellar surface if not attenuated beforehand; these are generally near $\theta_E \sim 180^\circ$ for magnetospheric loop examples. In addition, escape energies for polarization-averaged opacities are exhibited as triangles for the surface emission and $r_{\max} = 10$ cases only. At the lower right of each panel are marker energies (purple dashed lines) signifying the approximate maximum energy observed in several magnetars with polar fields somewhat close to the illustrated values, SGR J1550-5408 (bursts, [b]), AXPs 4U 0142+61 and 1RXS 1708-40 (persistent emission, [p]), and SGR 1900+14 (giant flare, [gf]); see text for details.