Neutron stars as photon double-lenses: constraining resonant conversion into ALPs

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IDM 2022, Vienna, 21/06/2022

Collaboration

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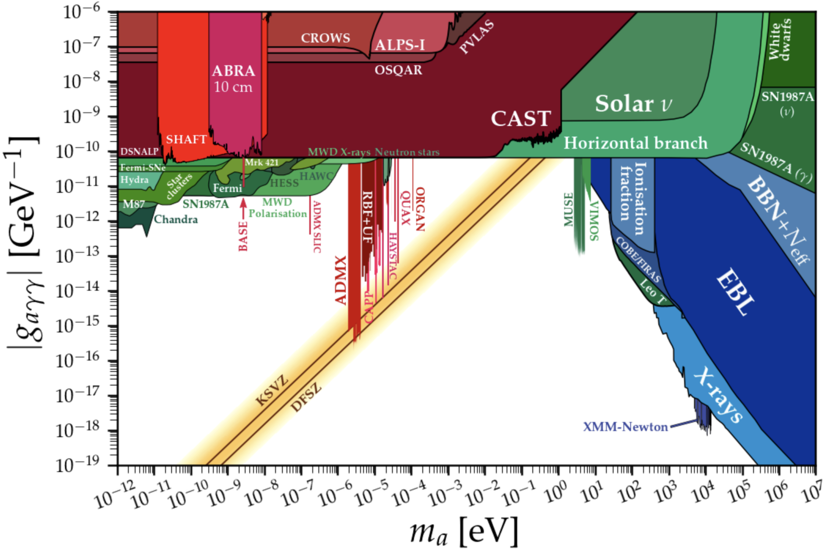
[2011.11581,2101.07207,2203.08663]

Axions and BSM physics

"**I named them after a laundry detergent, since they clean up a problem with an axial current.**"
Frank Wilczek (Nobel lecture 2004)

- A simple and natural extension of the SM is **axion** – a pseudo-scalar that has (cubic) interactions with gauge fields
- Axions can have mass in a broad mass range mass, from 10^{-20} eV till keV and GeV scales
- Additionally, axions can **play the role of DM** and shed light on the peculiar properties of QCD (the so-called "strong CP problem".)

Axion

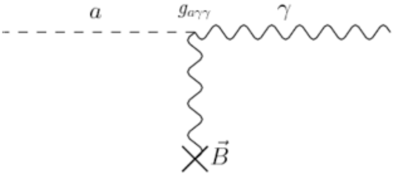


CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
DSNALP
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
MWD X-rays
Neutron stars
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
HAWC
M87
SN1987A
Chandra
MWD Polarisation
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
BBN+N_{eff}
COBE/FIRAS
Leo T
EBL
X-rays
XMM-Newton
KSVZ
DFSZ
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]

Axion conversion

- **Axion-like particles** can interact with **photons** through the effective Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma} a \vec{E}\cdot\vec{B}$$



In a **magnetic field** $\vec{B}$, the conversion of photons into axions is **possible**

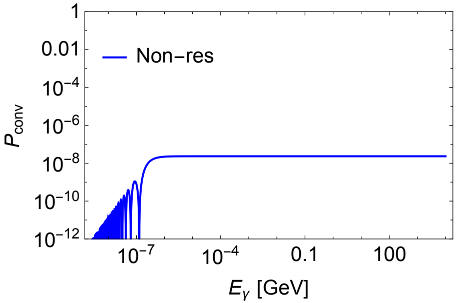
- From this Lagrangian follows that only perpendicular to the direction of the photon propagation component of the magnetic field $\vec{B}_T$ is relevant for conversion, $\vec{E}\cdot\vec{B} = \vec{E}\cdot\vec{B}_T$
- From two photon's polarizations, only one that is parallel to $\vec{B}_T$ interacts with axion

Non-resonant conversion

- The conversion probability for constant parameters is given by a simple formula for oscillations,

$$P_{\text{non-res}}(\ell) = \frac{1}{1+\left(\frac{E_*}{E_\gamma}\right)^2} \sin^2\left(\frac{g_{a\gamma} B_T \ell}{2}\left[1+\left(\frac{E_*}{E_\gamma}\right)^2\right]^{1/2}\right), \tag{1}$$

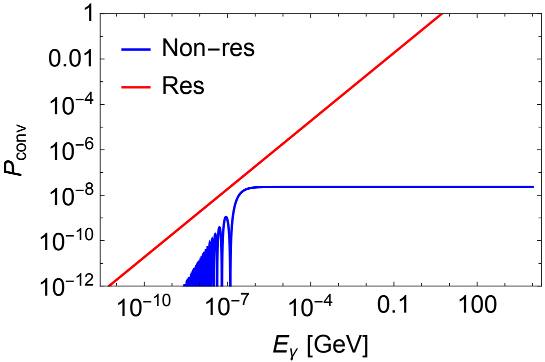
where $E_* \equiv |m_a^2 - m_{\text{eff}}^2|/(2g_{a\gamma}B_T)$ and m_{eff} is the **effective photon mass**



Resonant conversion

- If the condition $\boxed{m_a^2 = m_{\text{eff}}^2}$ is satisfied, such conversion becomes **resonant**
- The overall photon-to-axion conversion probability is

$$\boxed{P \sim \frac{g_{a\gamma}^2 E_\gamma}{m_a^2} B_T^2 R}, \qquad \text{where} \qquad R = \left| \frac{d \log m_{\text{eff}}^2(\ell)}{d\ell} \right|_{\ell=\ell_{res}}^{-1}$$



- The resonant conversion

$$P \sim \frac{g_{a\gamma}^2 E_\gamma}{m_a^2} B_T^2 R \quad (2)$$

can be rewritten in the form

$$\boxed{P = \epsilon g_{a\gamma} B \cdot R}$$

- Where $\epsilon = \dfrac{g_{a\gamma} B E_\gamma}{m_a^2} \ll 1$ is the necessary condition for the resonant conversion

Resonance conversion depends on the **effective mass** of a photon and the **magnetic field**. What do we know about these quantities in our Universe?

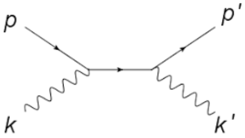
Effective photon mass

Effective photon mass

- Photons that travel through the Universe, **interact with surrounding particles**. Because of these interactions, they became **effectively massive**
- We are interested in the **effective mass of photons** due to:
  1. **free electrons** (protons);
  2. **other photons** (CMB photons, EBL photons, other)
  3. **magnetic field**
  4. neutrinos
  5. neutral hydrogen (and helium) atoms

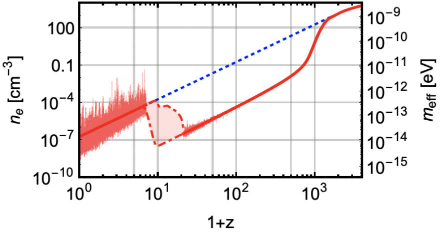
- For photon scattering on **free electrons**, the effective mass is

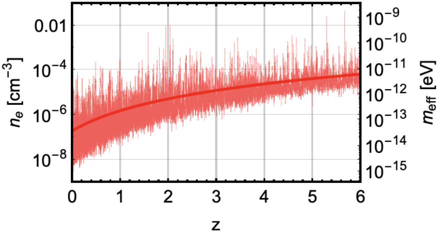
$$|m^2_{e,\mathrm{eff}}| = \frac{4\pi\alpha n_e}{m_e}$$



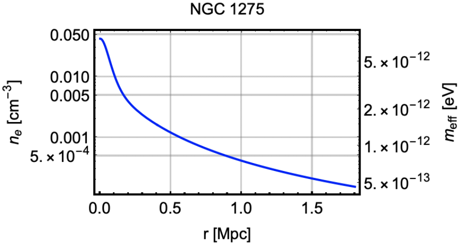
which is the well-known result for a **plasma frequency**
- **The question is: which plasma frequency we have in the Universe?**

Electron number density in the Universe



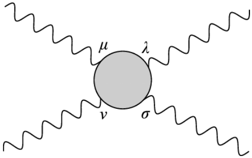


- We show the electron number density in the IGM and the galaxy cluster
- Range of values for $m_{\rm eff}$ at low redshifts is $10^{-15} - 10^{-11}$ eV
- In a NS the number density is $n_e \sim 10^{17} \text{cm}^{-3}$ that corresponds to $m_{\rm eff} \sim 0.01$ eV



Scattering on the EM field

- The next significant contribution to the effective mass comes from the **light-by-light** interaction
- **Light-by-light scattering** is described by the Euler–Heisenberg effective interaction



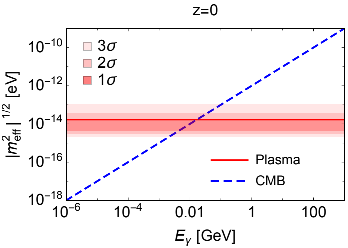
$$\mathcal{L}_{\rm HE} = \frac{2\alpha^2}{45 m_e^4}\left((\boldsymbol{E}^2 - \boldsymbol{B}^2)^2 + 7(\boldsymbol{E}\cdot\boldsymbol{B})^2\right)$$

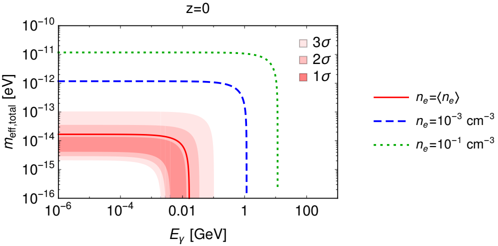
- The **effective photon mass** due to **interactions with the EM field**

$$\boxed{m_{\rm eff,\gamma}^2 \sim -\frac{\alpha^2 E_\gamma^2}{m_e^4}\rho_{\rm EM}} \qquad (3)$$

- **Important properties of this contribution**:
  - it is **negative**
  - it **grows** with photon energy
  - it is **always present**, as at least CMB is everywhere (there are compact systems where the effect of MF is even stronger)

Effective photon mass





- CMB gives a negative contribution to the effective photon mass
- The energy at which the **effective mass becomes negative**

$$E_\gamma < 11.6\ \text{GeV}\ (1+z)^{-2}\sqrt{\frac{n_{e,\max}}{0.1\ \text{cm}^{-3}}} \tag{4}$$

Important consequence: For any density of electrons, there is large enough photon energy at which plasma frequency and light-light scattering contributions almost cancel each other. Therefore, the resonant condition can be satisfied for **arbitrarily small axion mass**!

Magnetic field

B·R

- Reminder: the **necessary condition** of the resonant conversion:

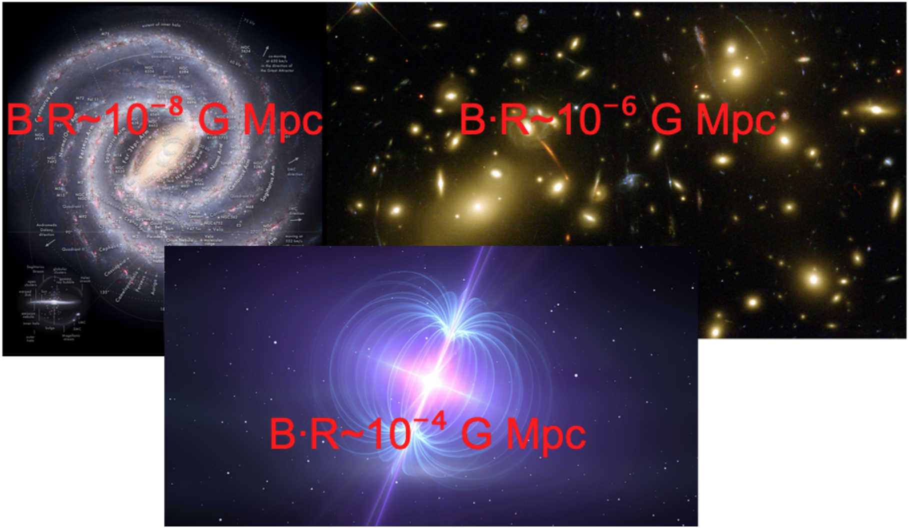
$$\epsilon = \frac{g_{a\gamma} B E_\gamma}{m_a^2} \ll 1 \quad (5)$$

and **conversion probability** $\boxed{P = \epsilon g_{a\gamma} B \cdot R}$ is **suppressed** by $\epsilon \ll 1$

- Therefore, in order to have a large probability, one should search for systems with **larger** $\boldsymbol{B \cdot R}$

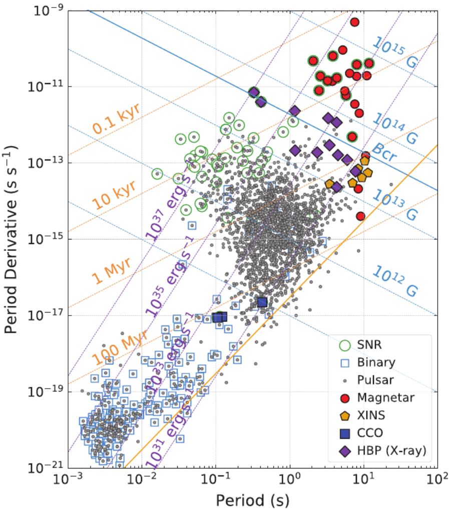
Which values of $\boldsymbol{B \cdot R}$ do we have in the Universe?

B·R for different systems

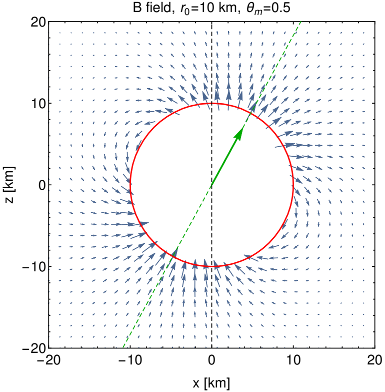


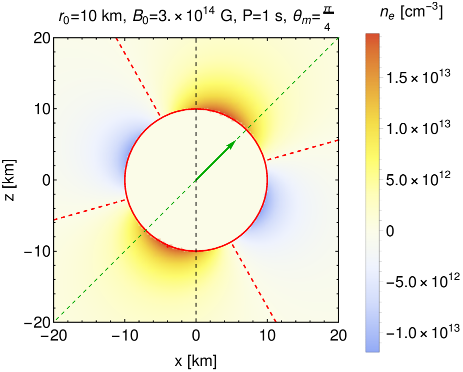
Magnetars

- Magnetars are special neutron stars with **super-strong magnetic field**
- Observationally **magnetars** distinguished from other NS by
  - Large period of rotation ($P = 1 - 10$ s)
  - Large spin-down power
  - Strong X-ray flares
  - The source of at least one FRB was identified as a magnetar in the MW
- These extreme properties are explained by existence of **super-strong magnetic field** ($B \sim 10^{14} - 10^{15}$ G)
- Great system to search for axions! But we need a model



[Enoto 2019]



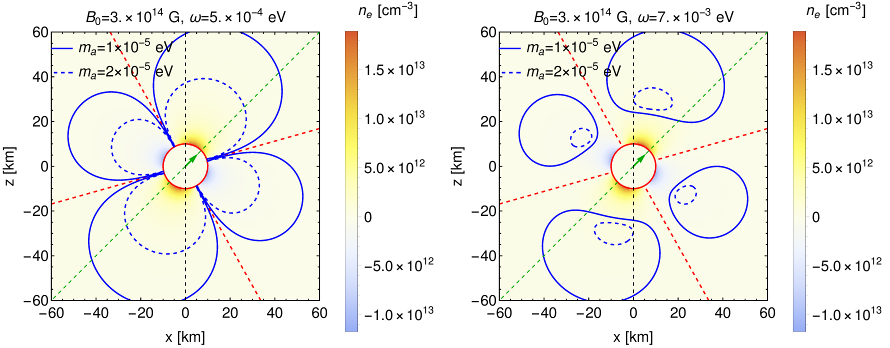


Popular toy model of a NS:

- Magnetic field – **dipole** with a misalignment
- **Charge density distribution** – should compensate the electric field cause by the time dependent magnetic field (Goldreich-Julian model):

$$n_c = \frac{\vec{\Omega} \cdot \vec{B}}{\sqrt{\pi\alpha}} \frac{1}{1 - \Omega^2 r^2 \sin^2\theta}$$

Resonance condition

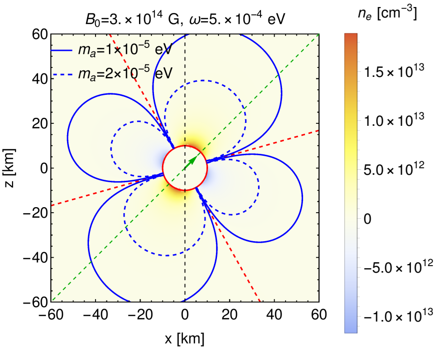


- The condition for the resonant conversion is

$$m_a^2 = m_{\rm eff}^2 = C_1 |\cos\theta_B| B - C_2 E_\gamma^2 B^2$$

with $C_1 = \frac{4\Omega\sqrt{\pi\alpha}}{m_e}$ and $C_2 = \frac{44\alpha^2}{135 m_e^4}$

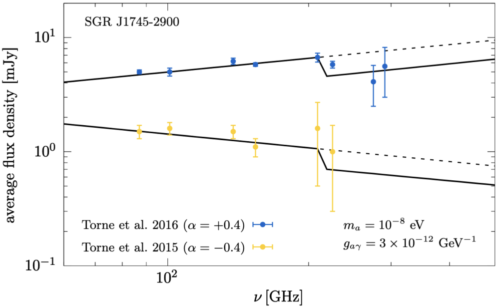
Resonance condition

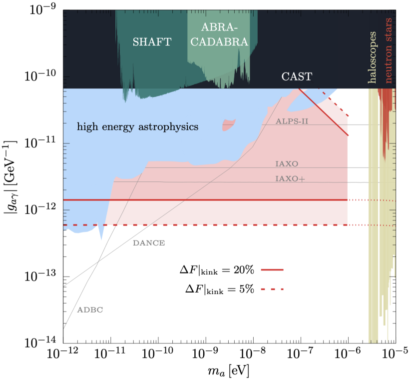


N.B.! This toy model may contain artificial features:

- The Goldreich-Julian model predicts **charge density**, i.e. $n_{e^-} - n_{e^+}$, while we need $m^2_{\text{eff}} \sim n_{e^-} + n_{e^+}$ that can be orders of magnitude off!
- Likely, there are **strong small-scale** contributions to the dipole magnetic field (c.f. very small diffusion coefficients for CRs near NS)
- ...

Summary





- **Resonant conversion** is a powerful tool to search for ALPs
- The "double-lenses"effect – negative contribution to $m_\gamma^{\rm eff}$ from light-on-light scattering – enables resonant conversion in a broad range of a m_a
- Large $B \cdot R$ in **magnetars** provide an excellent environment for axion searches

Backup slides

Resonance condition

- The condition for the resonant conversion can be written as

$$m_a^2 = C_1|\cos\theta_B|B - C_2\omega^2 B^2$$

- There are two solutions that in the limit $\omega \ll \omega_{cr}$ are

$$B_- \approx \frac{m_a^2}{C_1|\cos\theta_B|} \approx \frac{10^{12}\ \text{G}}{|\cos\theta_B|}\left(\frac{P}{1\ \text{s}}\right)\left(\frac{m_a}{10^{-5}\ \text{eV}}\right)^2$$

and

$$B_+ \approx \frac{C_1|\cos\theta_B|}{C_2\omega^2} \approx 10^{15}\ \text{G}\,|\cos\theta_B|\left(\frac{1\ \text{s}}{P}\right)\left(\frac{10^{-3}\ \text{eV}}{\omega}\right)^2$$

- B_+ corresponds double lens effect. It has large value of magnetic field and stronger contribution to the conversion probability

Simplified magnetar model

- Strongly magnetized neutron stars are still not enough studied system, both theoretically and experimentally. Because of this there are a lot of uncertainty in the real configurations of magnetic field near the surface and electron number density
- Firstly, there can be toroidal and turbulent magnetic field components of comparable strength close to the NS surface **[1703.00068]**
- Secondly, the actual electron density may differ from the GJ one and definitely there is no directions of zero electron number density

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Simplified (but probably more robust) model:

- The radial scaling of magnetic field is the same as for the magnetic dipole, $B = B_0(r_0/r)^3$, but we consider its direction to be random
- We take $\langle|\cos\theta_B|\rangle = 1/2$ in charge number density and assume $n_e = |n_c| = \Omega B/e$
- Also we take $\langle\sin^2\theta_B\rangle = 2/3$ in the conversion probability
- Radio emission is emitted close to the magnetar's surface