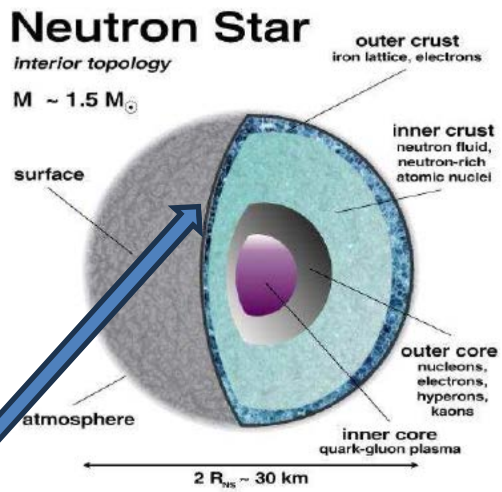
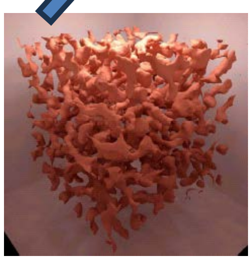
Axions inside magnetized Neutron Stars

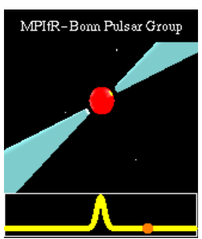
Ángeles Pérez-García
Department Fundamental Physics
Universidad de Salamanca, Spain

(in collab. with:C. Albertus and Duvier Suárez)

NEUTRON STARS IN A NUTSHELL







CRUST-- Horowitz, Pérez-García PRC (2004)

•Onion structure: crust (crystal phases) + fluid n,p core with neutron, protons and other hadrons. Possible quark deconfinement transition.

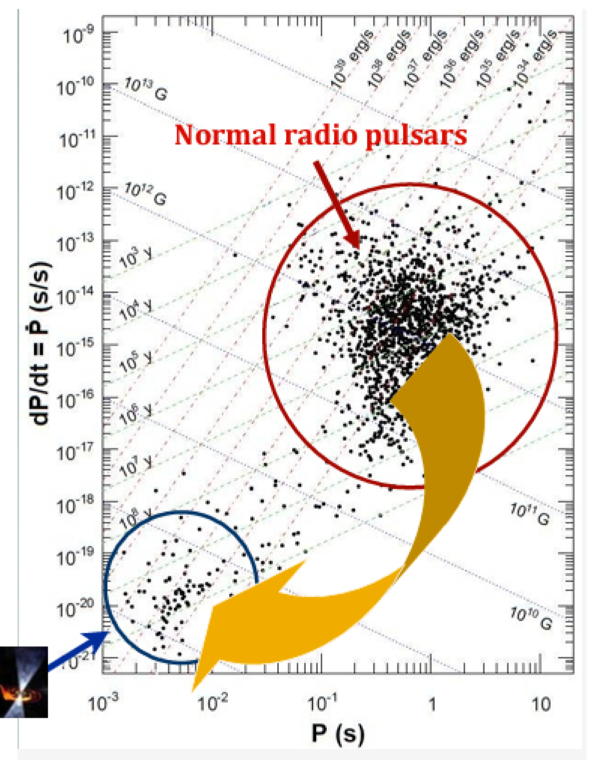
•High compactness M/R~0.1 and B field B~10^{15} Gauss (magnetars).

$$\frac{GM}{Rc^2} \quad \mathrm{sun}: 10^{-6}\ \mathrm{NS}: 10^{-1}$$

•Periods: ms to 10 s. Very regular.
•M<2M_sun, R<15 km.

•Milli-second pulsars (P=few ms) are recycled spun-up pulsars

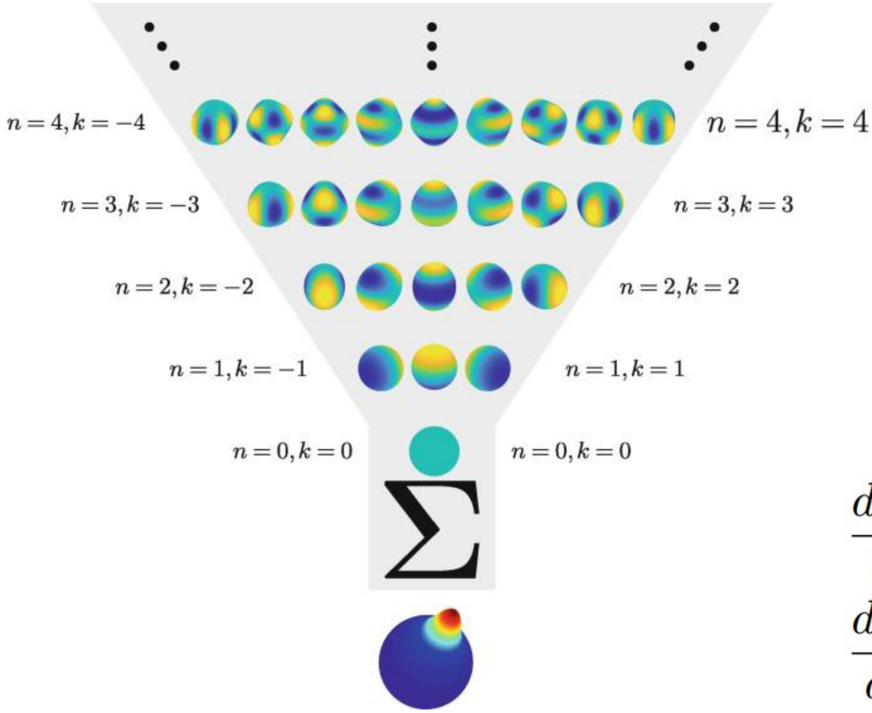
BNS mergers



ms Pulsars

NS STRUCTURE DEFORMED BY B FIELD

$$ds^2 = -e^{\nu(r)}(1+2h(r,\theta))c^2dt^2 + e^{\lambda(r)}(1+\frac{Gm(r,\theta)e^{\lambda(r)}}{rc^2})dr^2 + r^2(1+2k(r,\theta))\left(d\theta^2+\sin^2\theta d\varphi^2\right)$$



$$h(r,\theta) = h_0(r) + h_2(r)P_2(\cos(\theta)) + \ldots$$
$$m(r,\theta) = m_0(r) + m_2(r)P_2(\cos(\theta)) + \ldots$$
$$k(r,\theta) = k_2(r)P_2(\cos(\theta)) + \ldots$$

$$P = P_m + [p_0 P_0(\cos\theta) + p_2 P_2(\cos\theta)]$$

$$p_0 \equiv \frac{B^2}{24\pi} \qquad p_2 \equiv -\frac{B^2}{6\pi}$$

$$\frac{dm_0}{dr} = 4\pi r^2 \frac{p_0}{c^2},$$
$$\frac{dh_0}{dr} = 4\pi r e^{\lambda}\frac{Gp_0}{c^4} + \frac{G}{rc^2}\frac{d\nu}{dr}e^{\lambda}m_0 + \frac{G}{c^2r^2}e^{\lambda}m_0,$$
$$h_2 + \frac{e^{\lambda}}{r}\frac{Gm_2}{c^2} = 0,$$
$$\frac{dk_2}{dr} = \frac{2p_2\frac{d\nu}{dr} + \frac{dp_2}{dr}}{\varepsilon + P},$$
$$\frac{dh_2}{dr} = \frac{-p_2\frac{d\nu}{dr} - \frac{dp_2}{dr}}{\varepsilon + P},.$$

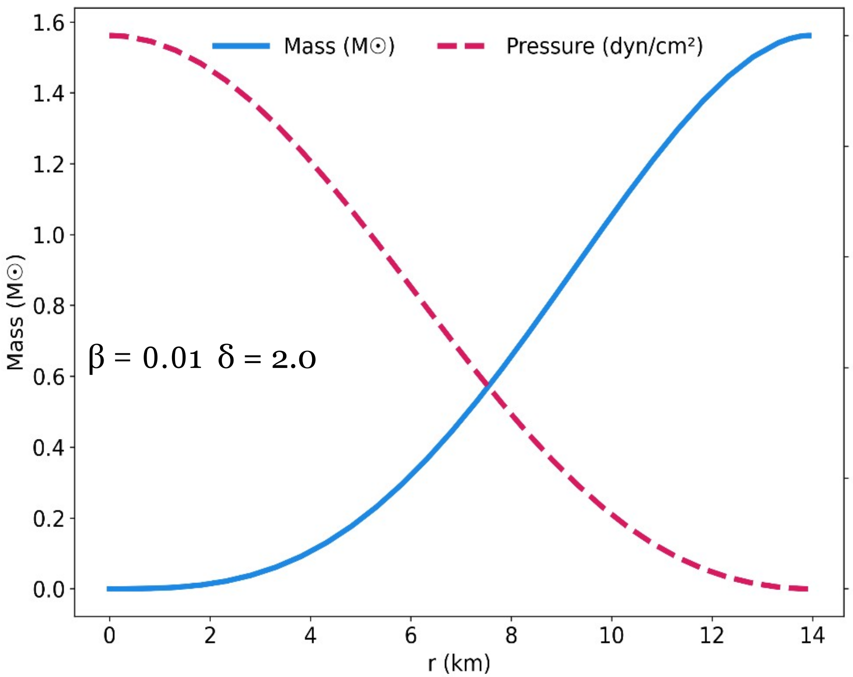
Perturbations wrt spherical symmetry due to a dipolar B via spherical harmonic expansions up to quadrupole order, Mallick+13.

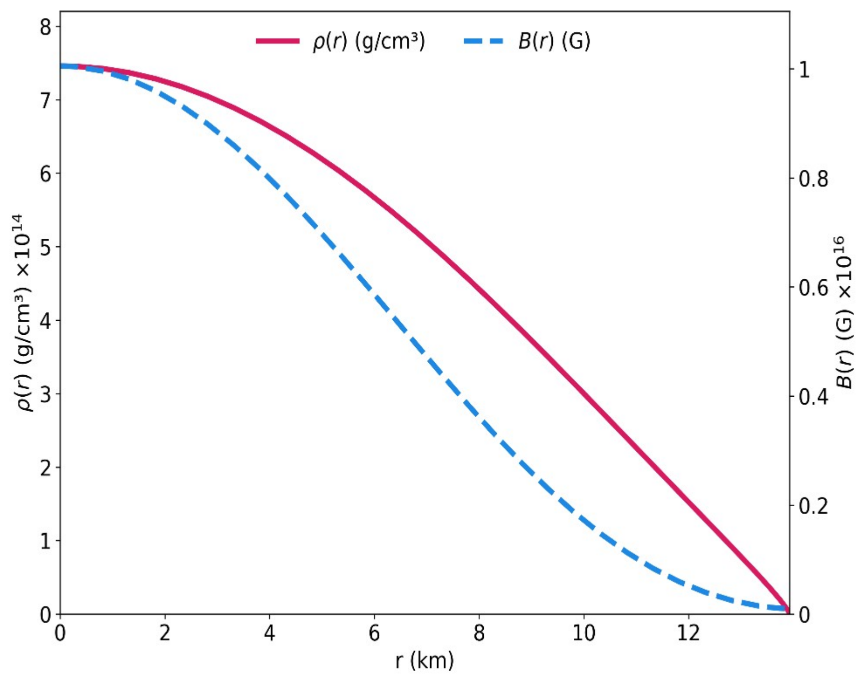
STELLAR STRUCTURE

Stellar mass and pressure radial profiles (right) for the NS with M = 1.56M⊙ and R = 13.93 km and mass density and magnetic field strength radial profiles (left). We have used a polytropic EoS with $\Gamma = 2.207$, $K = 1.5e2$

$$B(n) = B_s + B_0\left(1 - e^{-\beta\left(\frac{n}{n_0}\right)^{\delta}}\right) \qquad \varepsilon(P) = \left(\frac{P_m}{K}\right)^{\frac{1}{\Gamma}} c^2 + \frac{P_m}{\Gamma - 1}$$

with Bs and B0 the value of the magnetic field at the surface and in the center of the star..n0 is the baryonic number density at saturation.





ALP FIELDS INSIDE THE NS: coupling to fields

$$\Box a + m_a^2 a = \frac{g_{\gamma,a}}{4} Q \longleftarrow Q(F_0, G_0) \equiv \begin{cases} G_0 & \text{(pseudoscalar coupling)} \\ F_0 & \text{(scalar coupling)} \end{cases}$$

$$F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\,\mathbf{E}\cdot\mathbf{B}$$

Minimal coupling with gravity
and electromagnetic source

$$G_0 \equiv -\tfrac{1}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} = \mathbf{E}\cdot\mathbf{B}$$

CP-odd

$$F_0 \equiv -\tfrac{1}{4} F_{\mu\nu}F^{\mu\nu} = \tfrac{1}{2}(\mathbf{E}^2 - \mathbf{B}^2)$$

CP-even

$$\frac{1}{f}\partial_r^2 a + \frac{1}{r^2 k}\partial_\theta^2 a + \tilde{\xi}_1 \partial_r a + \tilde{\xi}_2 \partial_\theta a + m^2 a = g_{\rm eff} Q(F_0, G_0)$$

$$g_{\rm eff} \equiv \frac{g_{\gamma a}}{a_0}$$

$$\tilde{\xi}_1(r,\theta) \equiv \frac{\xi_1(r,\theta)}{f(r,\theta)} - \frac{f'(r,\theta)}{f(r,\theta)^2}, \qquad \xi_1(r,\theta) \equiv \frac{2}{r} + \frac{h'}{2h} + \frac{f'}{2f} + \frac{k'}{k},$$

$$\tilde{\xi}_2(r,\theta) \equiv \frac{\xi_2(r,\theta)}{r^2 k(r,\theta)} - \frac{\mathring{k}(r,\theta)}{r^2 k(r,\theta)}, \quad \xi_2(r,\theta) \equiv \cot\theta + \frac{\mathring{h}}{2h} + \frac{\mathring{f}}{2f} + \frac{\mathring{k}}{k},$$

ALP FIELDS INSIDE THE NEUTRON STAR

Free case

$$\frac{1}{f}\partial_r^2 a + \frac{1}{r^2 k}\partial_\theta^2 a + \tilde{\xi}_1 \partial_r a + \tilde{\xi}_2 \partial_\theta a + m^2 a = g_{\text{eff}} Q(F_0, G_0)$$

$g_{eff}=0$

Boundary condition

$$a(0,\theta) = a_0,$$
$$a(r_{surface},\theta) = a_{sph}(r_{\text{surface}}),$$
$$a(r,0) = a(r,\pi) = a_{sph}(r).$$

$$r_{surface} = \frac{R_e R_p}{\sqrt{R_p^2 \sin^2\theta + R_e^2 \cos^2\theta}},$$

spatially damped oscillator

$$\partial_r^2 a_{sph}(r) + \frac{1}{2}(\frac{4}{r} + \nu'(r) - \lambda'(r))\partial_r a_{sph}(r) + m^2 e^{\lambda(r)} a_{sph}(r) = 0.$$

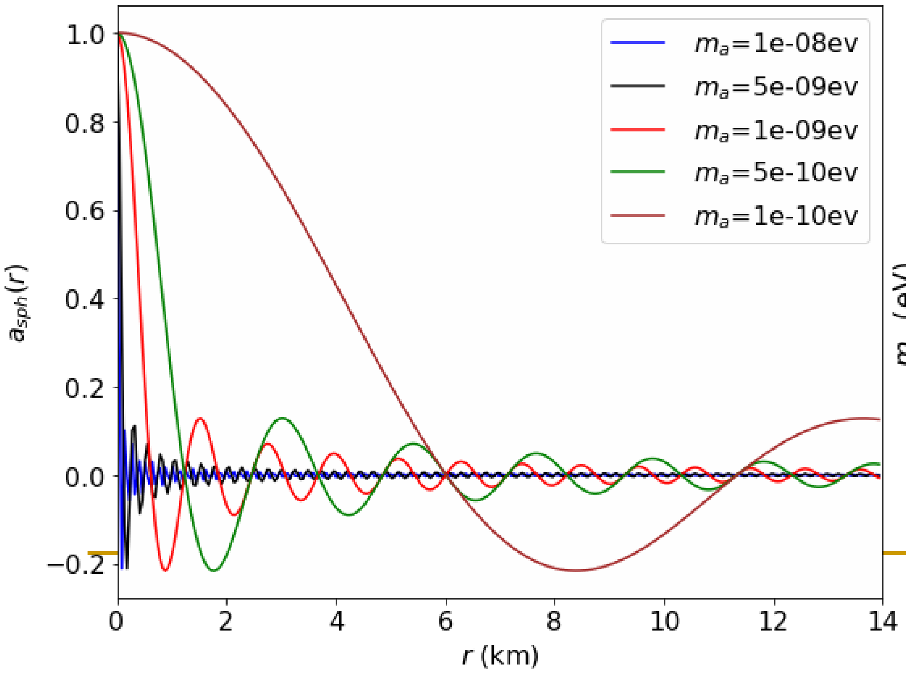
different regimes in the a(r, θ) solution, are determined by the value of the quantity

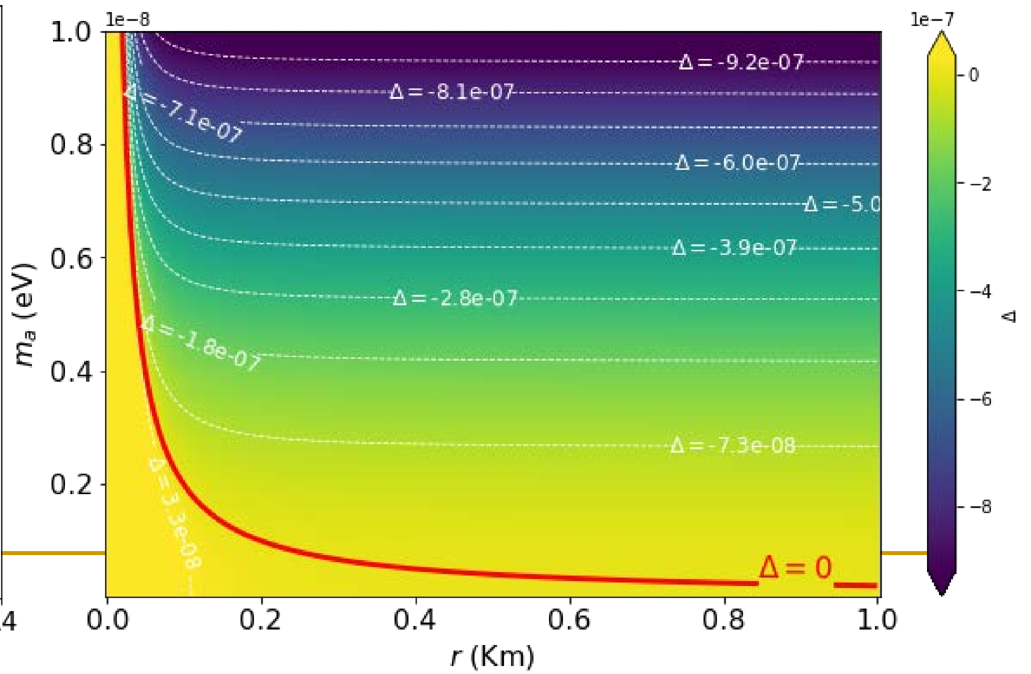
$$\Delta(r) = \frac{1}{4}(\frac{4}{r} + \nu'(r) - \lambda'(r))^2 - 4m^2 e^{\lambda(r)}$$

ALP FIELDS INSIDE THE NEUTRON STAR

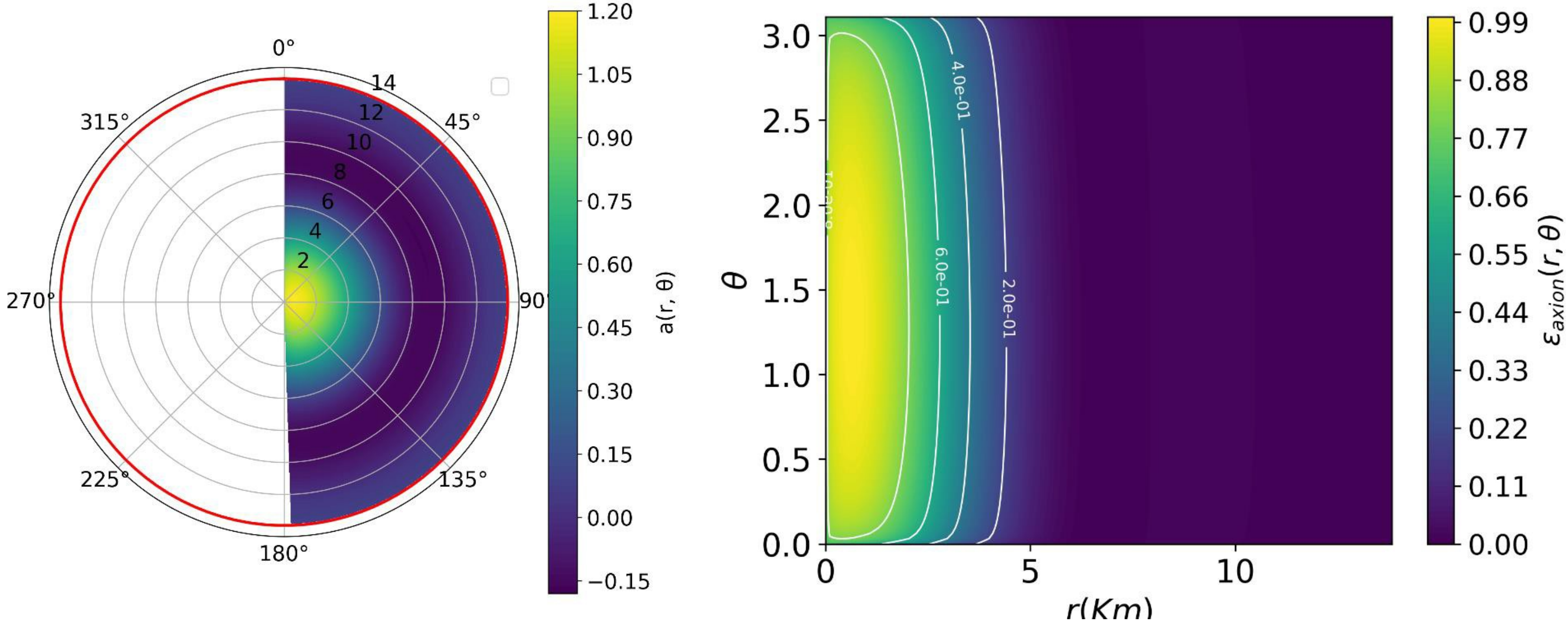
$$\Delta(r) = \frac{1}{4}\left(\frac{4}{r} + \nu'(r) - \lambda'(r)\right)^2 - 4m^2 e^{\lambda(r)}$$

The overdamped regime ($\Delta > 0$) near the stellar core indicates strong metric-induced damping, where spacetime curvature due to baryonic density minimizes axion effects. This mimics a screening mechanism. For "heavy" axions, the mass term $4\,m^2 e^{\lambda(r)}$ dominates, shrinking the overdamped region and allowing underdamped oscillations ($\Delta < 0$) to develop closer to the stellar core





ALP FIELDS INSIDE THE NS: free case



ALP field distribution with a mass $m_a = 10^{-10} eV$ $g_a = 10^{-14}\mathrm{GeV}^{-1}$ within the interior of the star, presented in an axial cross-section along the polar diameter. The star has a mass $M_{sph} = 1.56\ \mathrm{M}\odot$ and a radius R = 13.93 km. The total axion mass was taken to be 0.01% of the total baryonic mass here.

ALP FIELDS INSIDE THE NS: E.B coupling

$$\frac{1}{f}\partial_r^2 a + \frac{1}{r^2 k}\partial_\theta^2 a + \tilde{\xi}_1 \partial_r a + \tilde{\xi}_2 \partial_\theta a + m^2 a = g_{\text{eff}}\mathbf{E.B}$$

chiral magnetohydrodynamics

$$\mathbf{B} = B(\rho)\hat{\boldsymbol{k}}$$

$$\mathbf{E} = \frac{c}{4\pi\sigma}\nabla\times\mathbf{B} - \frac{1}{c}\mathbf{v}\times\mathbf{B} + \frac{e^2}{2\pi^2\sigma\hbar^2 c}\mu_5\mathbf{B} + \frac{e\mu_e}{2\pi^2\sigma\hbar^2 c^2}\mu_5\boldsymbol{\omega}$$

Chiral Magnetic Effect
L-R imbalance

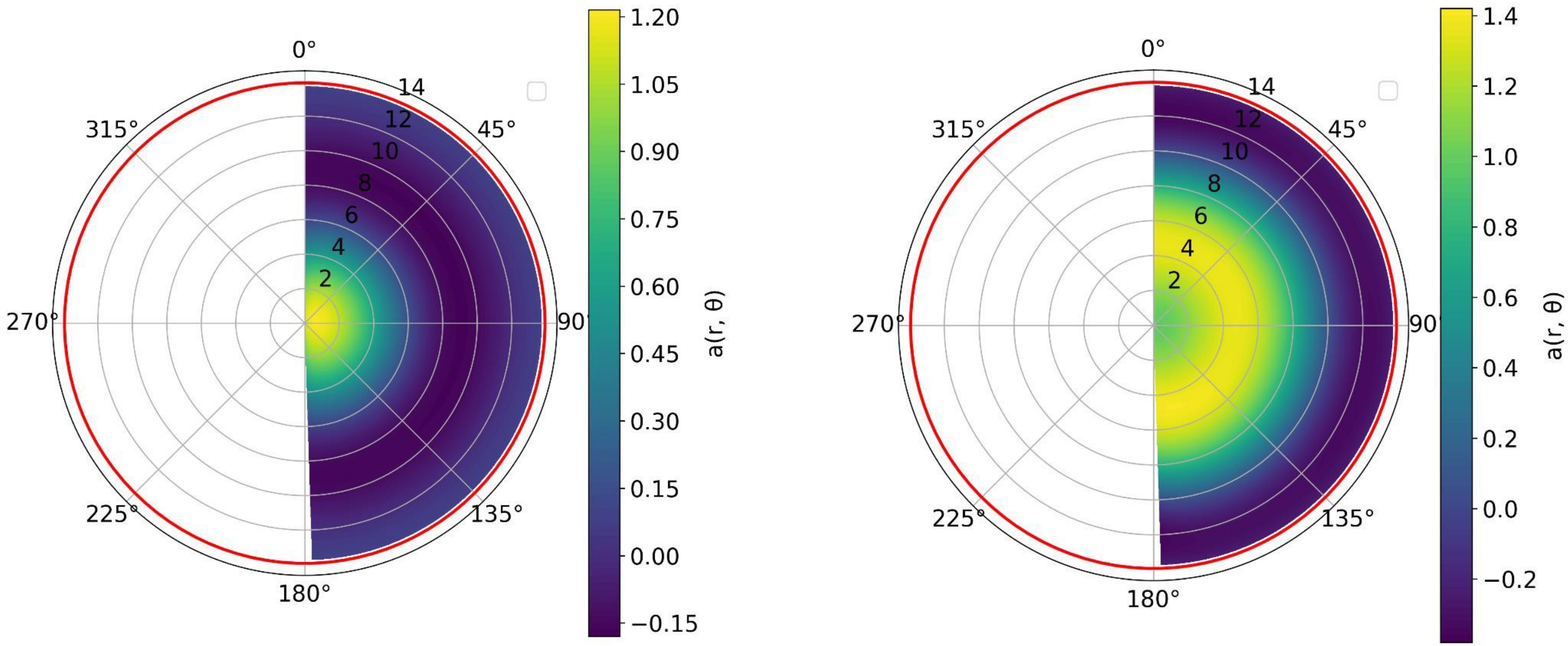
Chiral Vortical
Effect

The combination of strong magnetic fields and chiral asymmetry in particle interactions can lead to a separation of electric charge or axial currents

$$\frac{1}{f(r,\theta)}\partial_r^2 a(r,\theta) + \frac{1}{r^2 k(r,\theta)}\partial_\theta^2 a(r,\theta) + \tilde{\xi}_1(r,\theta)\partial_r a(r,\theta) + \tilde{\xi}_2(r,\theta)\partial_\theta a(r,\theta) + m^2 a(r,\theta)$$
$$= \alpha_1 B(r)^2 + \alpha_2 B(r)\cos(\chi).$$

$$\alpha_1 = g_{\text{eff}}\frac{e^2\mu_5}{2\pi^2\sigma\hbar^2 c} \qquad \alpha_2 = g_{\text{eff}}\frac{e\mu_e\mu_5\Omega}{\pi^2\sigma\hbar^2 c^2}$$

PS-ALP FIELDS INSIDE THE NEUTRON STAR



Meridional slice of the star (left) corresponds to an axion (dm) field density of $\rho_{dm} = 1 \times 10^{12} g\ cm^{-3}$, whereas the right column corresponds to a lower density of $\rho_{dm} = 1 \times 10^{-3} gcm^{-3}$

We use $m_a = 10^{-10} eV$ $g_a = 10^{-14} \mathrm{GeV}^{-1}$

S-ALP FIELDS INSIDE THE NS: coupling to E^2-B^2

$$\frac{1}{f}\partial_r^2 a + \frac{1}{r^2 k}\partial_\theta^2 a + \tilde{\xi_1}\partial_r a + \tilde{\xi_2}\partial_\theta a + m^2 a = g_{\rm eff}(E^2 - B^2)$$

scalar coupling

chiral magnetohydrodynamics

$$\frac{1}{f(r,\theta)}\partial_r^2 a(r,\theta) + \frac{1}{r^2 k(r,\theta)}\partial_\theta^2 a(r,\theta) + \tilde{\xi_1}(r,\theta)\partial_r a(r,\theta) + \tilde{\xi_2}(r,\theta)\partial_\theta a(r,\theta) + m^2 a(r,\theta)$$

$$= \beta_1 B^2(r) - 2\beta_2 B(r)\frac{dB(r)}{dr}\sin^2\theta + \beta_2\left(\frac{dB(r)}{dr}\right)^2 \sin^2\theta.$$

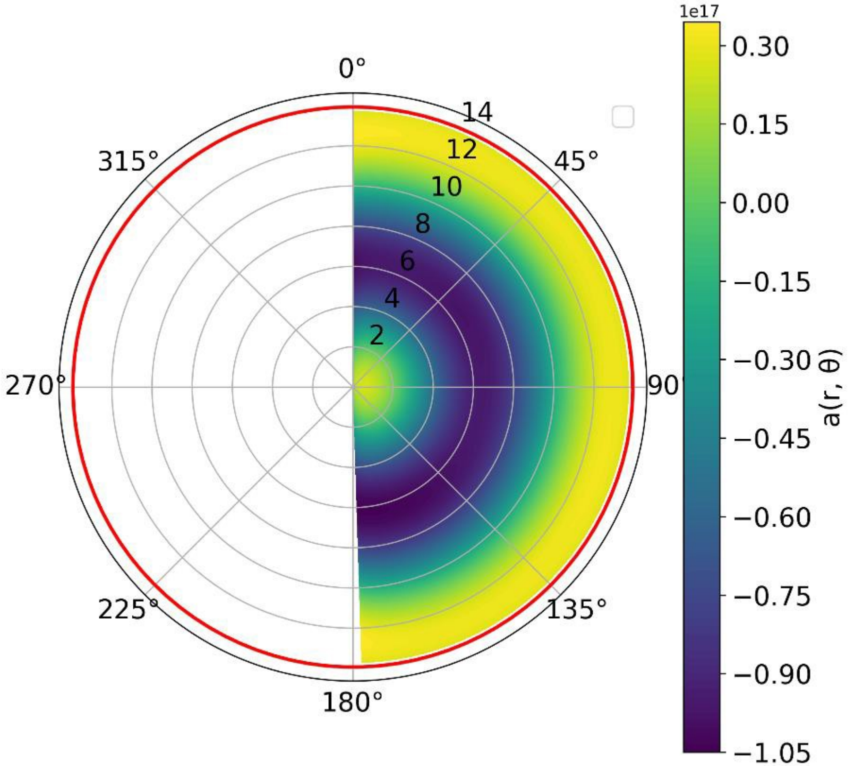
$$\beta_1 \equiv g_{\rm eff}\left(-1 + \frac{c^2}{32\pi^2\sigma^2} + \frac{e^4\mu_5^2}{4c^2\pi^4\sigma^2\hbar^2} - \frac{c^2\cos 2\theta}{32\pi^2\sigma^2}\right) \qquad \beta_2 \equiv g_{\rm eff}\frac{c^2}{\sigma^2}$$

We note that for the dominant term, there is an asymmetry factor depending on cos 2θ. We can derive an expression for this asymmetry by comparing the values of β1 along the z-direction and the equatorial direction.

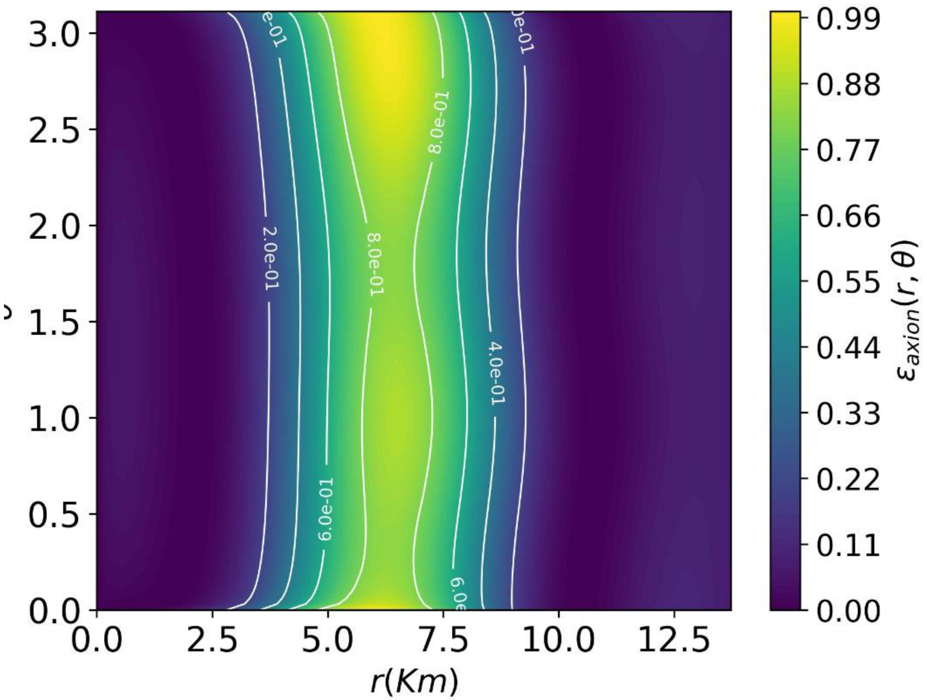
$$F_0[\theta = \tfrac{\pi}{2}] - F_0[\theta = 0]$$

$$S_{\rm asym} = \frac{c^2\left(B(r) - \frac{dB(r)}{dr}\right)^2}{16\pi^2\sigma^2}$$

ALP FIELDS INSIDE THE NS: Scalar ALP

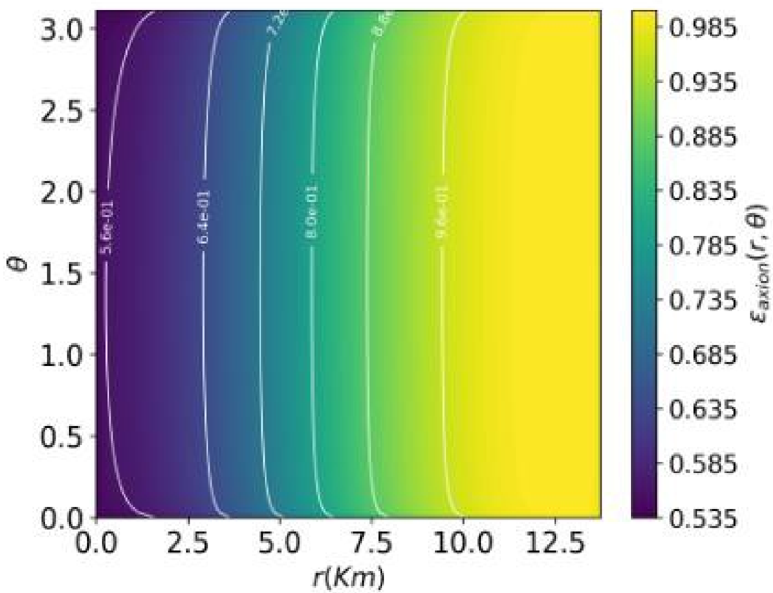


Left panel shows the S-ALP field in a meridional slice of the star, while the rigth panel displays the energy density normalized to its central value



This result is obtained for an axion density equal to 1% of the baryonic density, implying that significant effects arise even at high densities. We use $m_a = 10^{-10} eV$ $g_a = 10^{-14} \mathrm{GeV}^{-1}$

AXION RESONANT CONVERSION



$$P_{a\to\gamma} = \frac{4\Delta_{a\gamma}^2}{(\Delta_a - \Delta_\gamma - \Delta_5)^2 + 4\Delta_{a\gamma}^2}\sin^2\left(\frac{1}{2}\Delta_{osc}L\right)$$

$$\Delta_{osc} = \sqrt{(\Delta_a - \Delta_\gamma - \Delta_5)^2 + 4\Delta_{a\gamma}^2}$$

$$\Delta_{a\gamma} = g_{a\gamma\gamma}B_T/2$$

$$\Delta_\gamma = -\frac{m_\gamma^2}{2\omega} \qquad \Delta_5 = \frac{C\mu_5}{2}$$

$$\Delta_a = -\frac{m_a^2}{2\omega}$$

$$\omega_{pl} = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$$

Resonance condition, efficient magnetar km-size crust, P>0.001

$$\Delta_{eff} = \frac{m_a^2 - m_\gamma^2}{2\omega} - \frac{C\mu_5}{2} = 0$$

$m_a = 1\times10^{-11}$eV condensate $g_a = 10^{-14}\text{GeV}^{-1}$

$$\Phi_\gamma = P_{a\to\gamma}\cdot\Phi_a$$

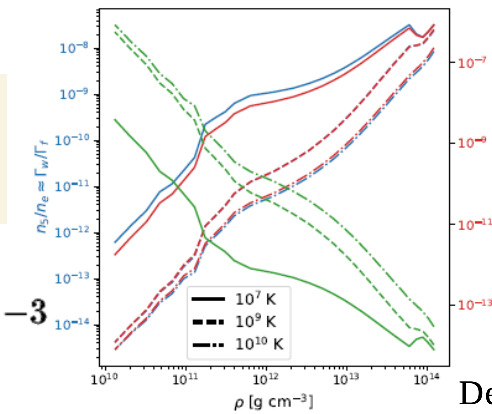
$$m_\gamma^2 = m_a^2 - m_a\mu_5$$

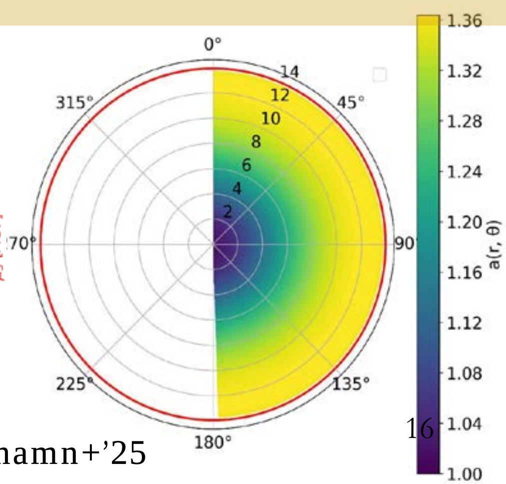
$$\omega \approx m_a$$

$$L_\gamma = \int \Phi_\gamma E_\gamma dA$$

$m_a = 2\times10^{-7}$eV
$\mu_5 = 1\times10^{-7}$eV
$n_e \approx 1.8\times10^{26}$ cm^{-3}

$$g_{a\gamma} \gtrsim 6.4\times10^{-17}\text{GeV}^{-1} \Rightarrow P_{a\to\gamma}^{res} > 10^{-3}$$





Dehamn+’25

ALP parameter space