Detecting Axions from Neutron Stars with Radio Telescopes

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Based on Battye, Garbrecht, McDonald, **Srinivasan** (2020) (1910.11907) , Battye, Garbrecht, McDonald, **Srinivasan** (2021) (2104.08290) , Battye, Darling, McDonald, **Srinivasan** (2022) (2107.01225)

Plan

QCD axion as a dark matter candidate

- CP violating term in QCD

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm PERT} + \frac{g_{\rm S}^2}{34\pi^2}\tilde{F}^{\mu\nu}F_{\mu\nu}\,,$$

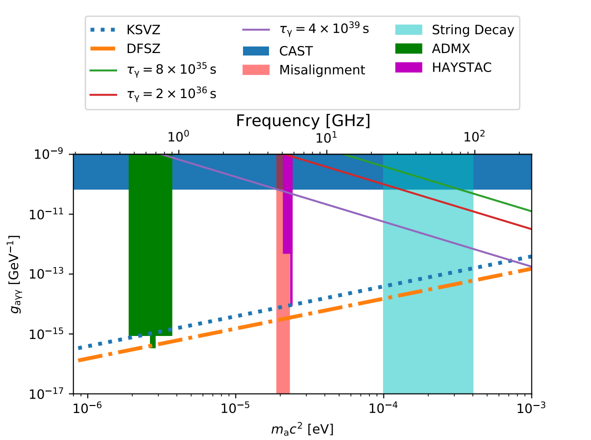
- NDM experiments constrain $|\theta| < 10^{-10}$
- θ promoted to field in PQ mechanism that contains a symmetry that is broken in the early Universe.
- Axion becomes massive in the QCD phase transition.

QCD axion as a dark matter candidate

Set $\Omega_{\mathrm{a}} h^2 = \Omega_{\mathrm{CDM}} h^2 = 0.12$ (Planck Collaboration, 2018)

Assumption $\rightarrow$ Axion is produced non-thermally

- Misalignment: $m_{\mathrm{a}} \sim 20\,\mu\mathrm{eV}$
- String decay $100\,\mu\mathrm{eV} \leq m_{\mathrm{a}} \leq 400\,\mu\mathrm{eV}$



Axion Electrodynamics

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a \,,$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma\gamma} \dot{a} \mathbf{B} - g_{a\gamma\gamma} \mathbf{E} \times \nabla a \,,$$
$$\nabla \cdot \mathbf{B} = 0 \,,$$
$$\dot{\mathbf{B}} + \nabla \times \mathbf{E} = 0 \,.$$

Assume background is dominated by B-field

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B} \,,$$
$$\mathbf{E} = 0 + \mathbf{B} \quad (\mathbf{E}_0 = 0) \,,$$
$$\mathbf{J} = \sigma \mathbf{E} \,.$$

where σ is conductivity set by plasma.

Equations of Motion

Equations of motion read

$$\Box\, a + m_{\mathrm{a}}^2 a = g_{\mathrm{a}\gamma\gamma} \mathbf{E} \cdot \mathbf{B}_0 \,,$$
$$\Box\, \mathbf{E} + \nabla(\nabla \cdot \mathbf{E}) + \sigma \cdot \dot{\mathbf{E}} = -g_{\mathrm{a}\gamma\gamma} \ddot{a} \mathbf{B}_0 \,,$$

Assume following geometry where all fields depend on one propagation variable z

$$a = a(z)\,, \qquad \mathbf{E} = \mathbf{E}(z)\,,$$
$$\mathbf{B}_0 = \mathbf{B}_0(z) \implies \mathbf{B}_0(z) \cdot \nabla\left[\nabla \cdot \mathbf{E}(z)\right] = 0\,,$$

where $\sigma \mathbf{E} = i \frac{\omega_{\mathrm{pl}^2}}{\omega^2} \mathbf{E}_{||}$, and $\mathbf{E}_{||}$ is component of $\mathbf{E}$ along $\mathbf{B}_0$.

Equations of motion

$$\begin{pmatrix} \partial_z^2 - m_{\rm a}^2 + \omega^2 & \omega g_{\rm a\gamma\gamma} B_0(z) \\ \omega g_{\rm a\gamma\gamma} B_0(z) & \partial_z^2 - \omega_{\rm pl}^2(z) + \omega^2 \end{pmatrix} \begin{pmatrix} a \\ \mathcal{E} \end{pmatrix} = 0\,,$$

where $\mathcal{E} = \mathbf{E}_{||}/\omega$ and $\omega_{\rm pl} = e^2 n_{\rm e}/m_{\rm e}$ (Pshirkov et al (2009), Lai & Heyl (2006), Kadota et al (2018)).

WKB approximation allows reduction to 1st order (See Battye, Garbrecht, McDonald, **Srinivasan** (2020) for details)

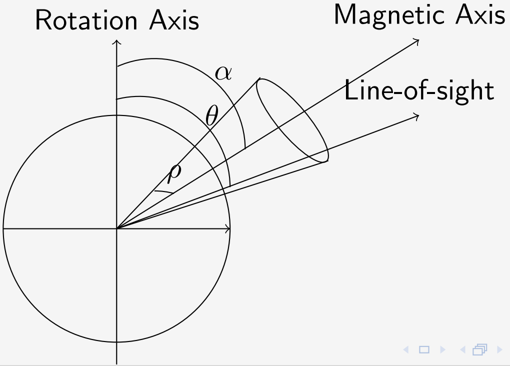
$$P_{\rm a\to\gamma} = \frac{\pi g_{\rm a\gamma\gamma}^2 B^2(z_{\rm c})\omega^2}{|\left(\omega_{\rm pl}^2(z_{\rm c})\right)'|k_{\rm a}}\,.$$

Neutron star magnetosphere

Rapidly rotating remnants of dead stars, high $B-$fields. Goldreich Julian model for charge density

$$n_\mathrm{e} = \frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi e} \,,$$

$\mathbf{B} = \mathbf{B}_0 \frac{R^3}{r^3}$ is the magnetic field and $\Omega = 2\pi / P$ is frequency of NS of period P



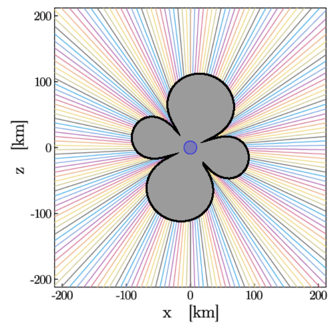
Neutron star magnetosphere

Set $\omega_{\rm pl}(r_{\rm c}) = m_{\rm a}$ to obtain the resonant conversion region

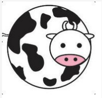
$$m_{\rm a}^{\rm max} \approx 85\,\mu{\rm eV} \left(\frac{B_0}{10^{14}\,{\rm G}}\right)^{\frac{1}{2}} \left(\frac{P}{1\,{\rm s}}\right)^{-\frac{1}{2}} \left(1 + \frac{1}{3}\cos\alpha\right)^{\frac{1}{2}} ,$$

Hook et al (2018)

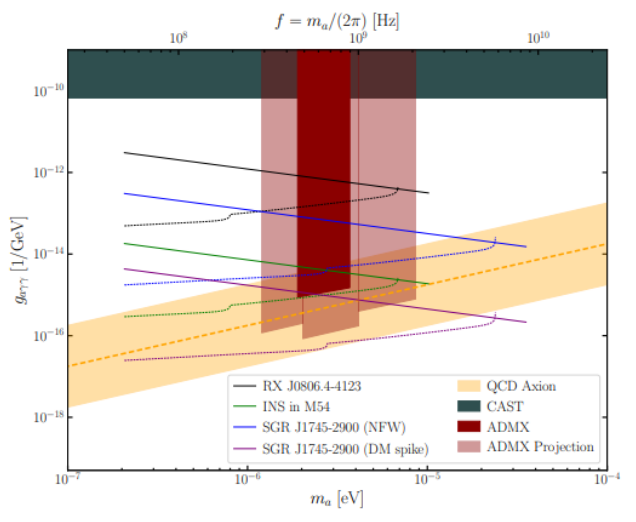
Slide courtesy : Jamie McDonald



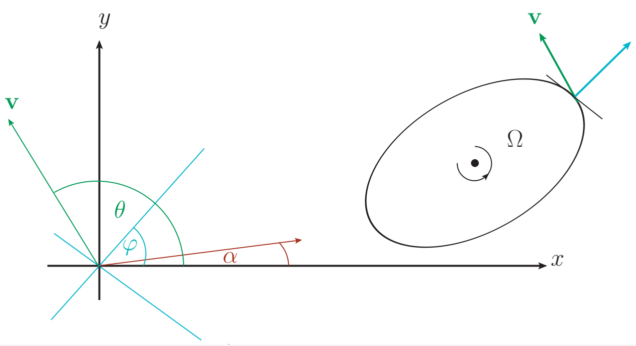
Radial Trajectories : $S = \frac{2\rho_{\mathrm{DM}} P_{\mathrm{a}\gamma} v_{\mathrm{c}} r_{\mathrm{c}}^2}{D^2 \Delta f_{\mathrm{obs}}}$.



Hook et al (2018)



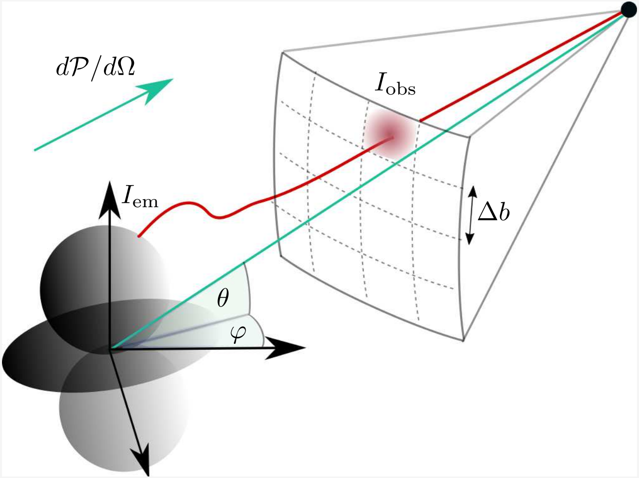
Doppler Broadening



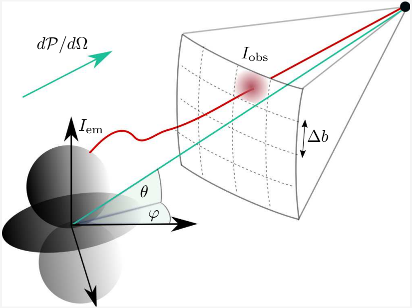
$\frac{\Delta f}{f} \sim \Omega r_c \approx 10^{-4}$, to be compared with estimate directly from DM velocity dispersion $\frac{\Delta f}{f} = \Delta v^2 \sim 10^{-7}$

Ray-tracing

See also Leroy et al (2020) (1912.08815 straight line trajectories), Witte et al (2021) (2104.07670) ,



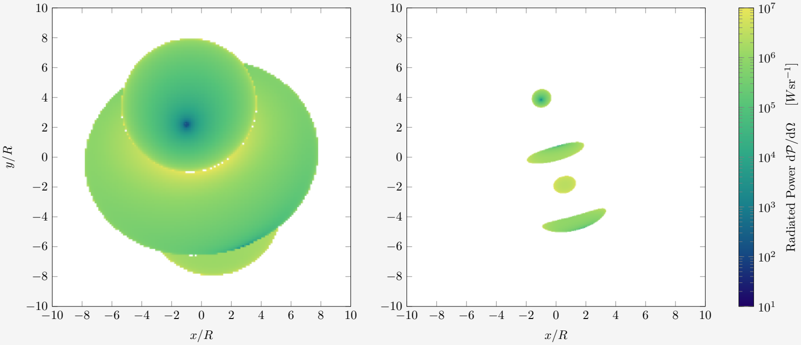
Ray-tracing



Dispersion Relation: $\underbrace{g_{\mu\nu}}_{\text{gravity}} k^\mu k^\nu + \omega_{\mathrm{p}}^2 \underbrace{(t, \mathbf{x})}_{\text{inhomogeneous}} = 0$

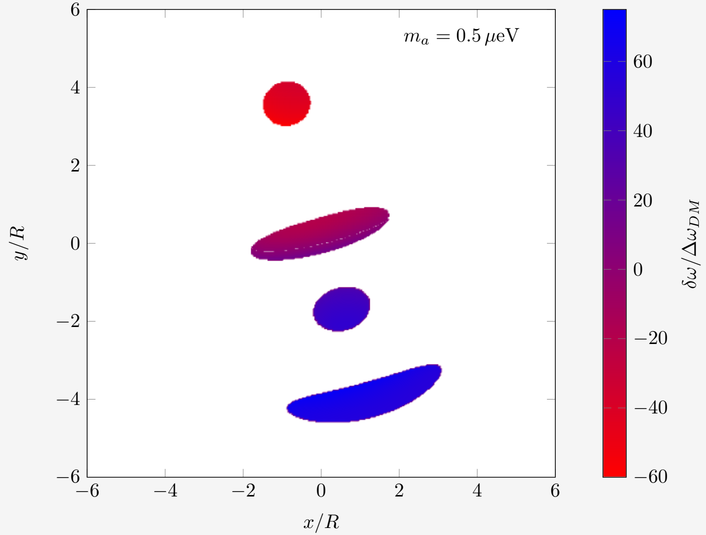
$$S_{\mathrm{obs}} = \frac{1}{D^2 \Delta f_{\mathrm{obs}}} \sum_i \left(\frac{dP}{d\Omega} \right)_i ,$$

Ray-tracing



y/R
x/R
x/R
Radiated Power $d\mathcal{P}/d\Omega$ $[W\,sr^{-1}]$
10^7
10^6
10^5
10^4
10^3
10^2
10^1

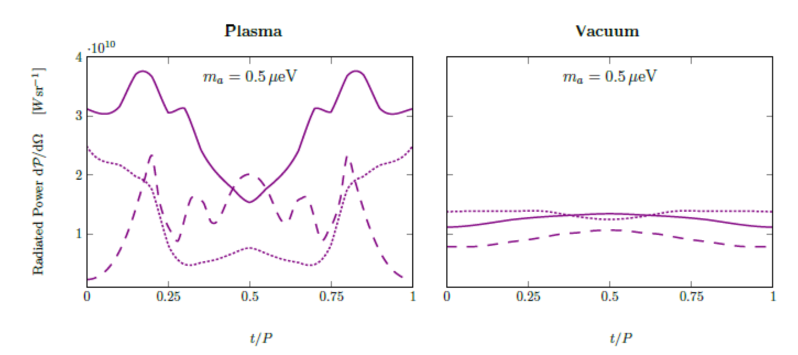
Ray-tracing


$m_a = 0.5\,\mu$eV
y/R
x/R
6
4
2
0
−2
−4
−6
60
40
20
−20
−40
−60
$\delta\omega/\Delta\omega_{DM}$

Ray-tracing

Slide courtesy : Jamie McDonald

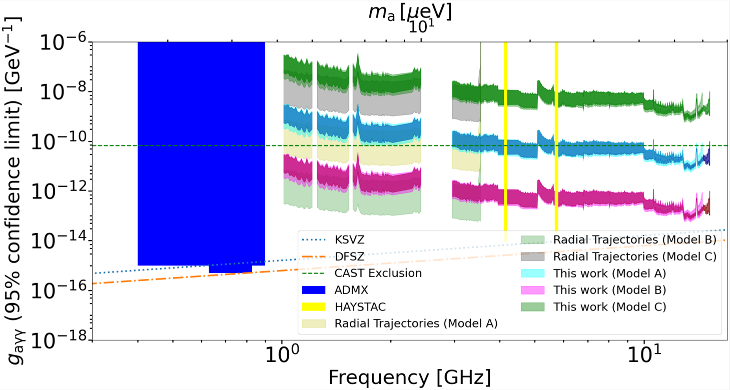
Pulse Profiles



Our Work: signal more pulsed due to strong + time-dependent lensing!

Constraints from observational data

Data from Very Large Array of magnetar (PSR J1745 2900) at galactic centre (Jeremy Darling at UC Boulder)



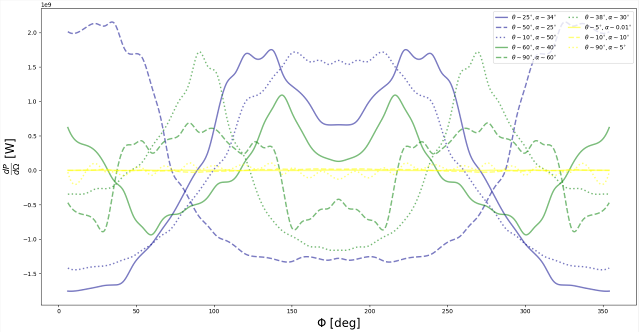
Battye, Darling, McDonald, **Srinivasan** (2022) (2107.01225)

Why a time-domain analysis?

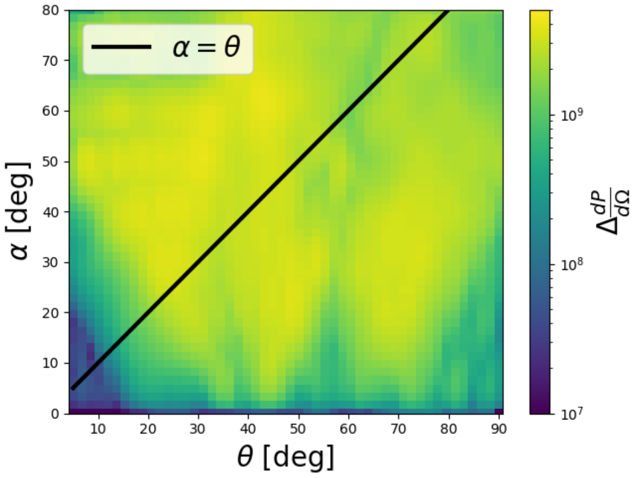
- Huge amounts of archival data available on many pulsars
- Pulsars are well-characterised in the time-domain, noise levels are well-controlled
- In case of large time variations in axion signal, easier detection in comparison to a total flux measurement

Time-domain analysis

Typical time-domain data contains average baseline subtraction



Signal Characterisation



Matched Filters

Signal amplitude S_0 with shape $\mathbf{F}(\mathbf{p})$ as a function of set of parameters $\mathbf{p}$.

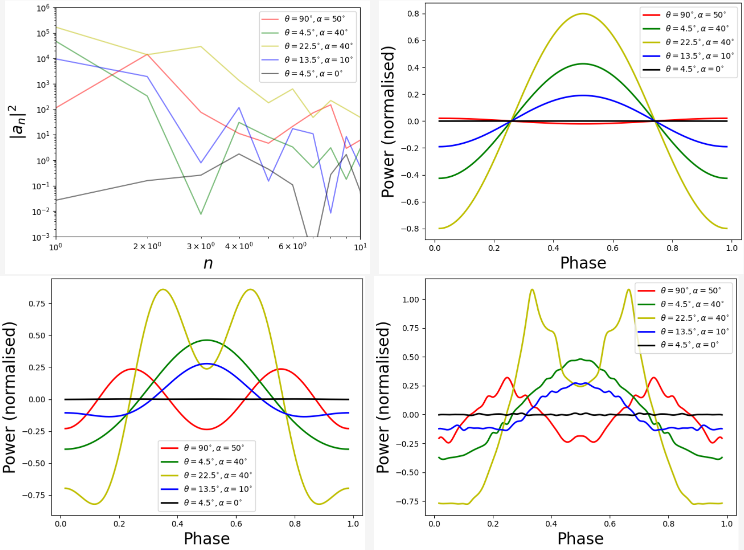
$$\mathbf{d} = S_0\mathbf{F}(\mathbf{p}) + \hat{\mathbf{n}}\,,$$

$$S_0 = \frac{\mathbf{F}^T C^{-1}\mathbf{d}}{\mathbf{F}^T C^{-1}\mathbf{F}}\,,$$

$$\sigma = \left(\mathbf{F}^T C^{-1}\mathbf{F}\right)^{-1/2}\,,$$

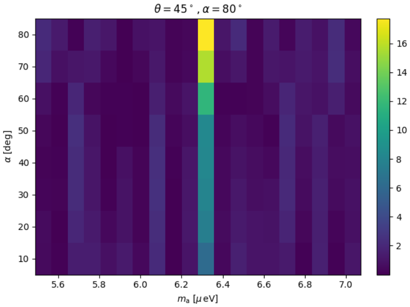
$$q = \frac{S_0}{\sigma} = \frac{\mathbf{F}^T C^{-1}\mathbf{d}}{\left(\mathbf{F}^T C^{-1}\mathbf{F}\right)^{1/2}}\,.$$

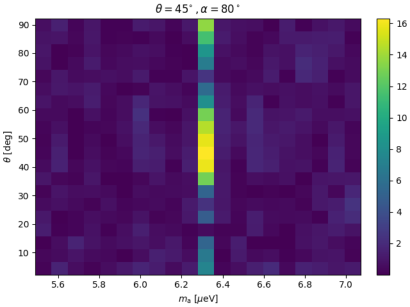
Matched Filters



Testing filter response

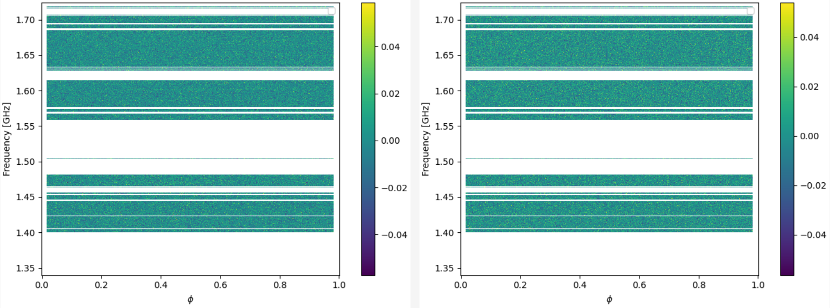
Inject signal into random Gaussian noise with amplitude set by threshold in pulsar data catalogue





Data from JBCA catalogue

768 frequency channels, of which ~ 300 are RFI dominated (these have been excised), 1024 time channels



Surviving data is Gaussian

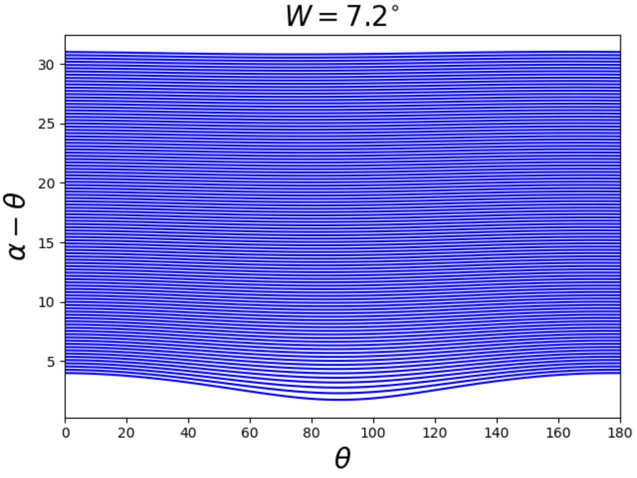
Constraining observing angles

$$\cos\rho = \cos\alpha\cos\theta + \sin\alpha\sin\theta\cos(W/2)\,.$$

$$\rho \simeq \sqrt{\frac{9\pi h_{\rm em}}{2cP}}.$$

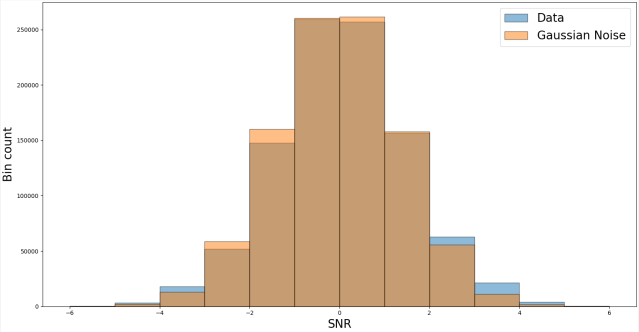
- The pulse width W is measured, tightly constrained.
- Currently, pulsar magnetosphere simulations are at odds with previous data on ρ.
- $\alpha > 20^\circ \implies h \approx 3200\,\mathrm{m}$

Constraining observing angles



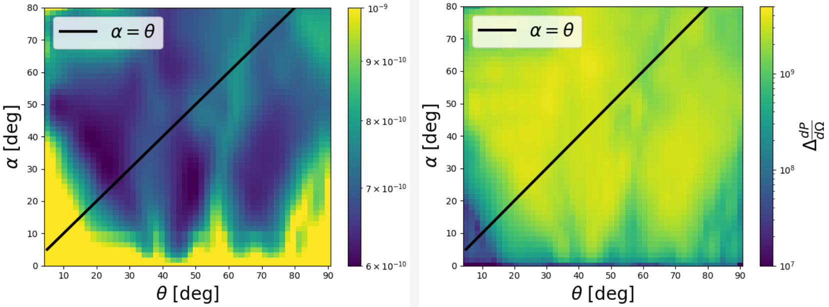
Applying filter to data

Apply filter to data, scan over $(\alpha, \theta, m_{\mathrm{a}})$.



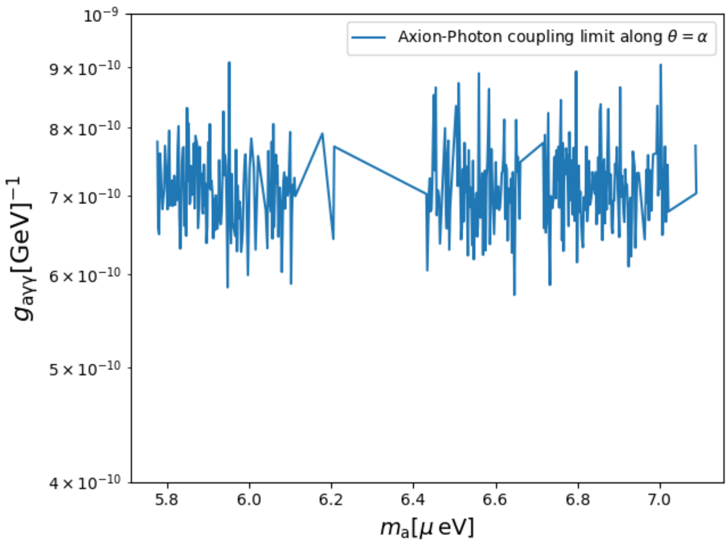
Upper Limit

Upper limit inferred by comparing measured SNR when signal is injected to when it is not



Constraints proportional to size of time-variation

Upper Limit


Axion-Photon coupling limit along $\theta = \alpha$
10^{-9}
9×10^{-10}
8×10^{-10}
7×10^{-10}
6×10^{-10}
5×10^{-10}
4×10^{-10}
$g_{a\gamma\gamma}[\mathrm{GeV}]^{-1}$
5.8
6.0
6.2
6.4
6.6
6.8
7.0
$m_a[\mu\,\mathrm{eV}]$

Future?

- Interferometers like MeerKat can bring down noise level by factor 10, while SKA can in principle achieve noise levels of $10\,\mu\mathrm{Jy}$.
- Strategic optimisation of target objects can result in signal factors of 100 stronger
- Archival data on magnetars to be explored
- Population study?

Conclusion

- Indirect detection efforts complement laboratory searches, can potentially accelerate detection.
- Resonance and large magnetic fields make neutron stars great candidates.
- Needs better modelling of pulsar magnetosphere.
- Typical observations are in time domain, need better optimisation for targets based on time-variation.
- Current Ray-tracing simulations are state-of-the-art, but does 1D probability need to be updated?