Axion-Photon Conversion in Neutron Star Population

Utkarsh Bhura

King's College London

Based on arxiv:2407.19028

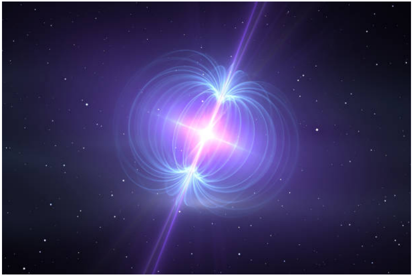
with Prof. R. Battye, Dr. J. McDonald, Dr. S. Srinivasan

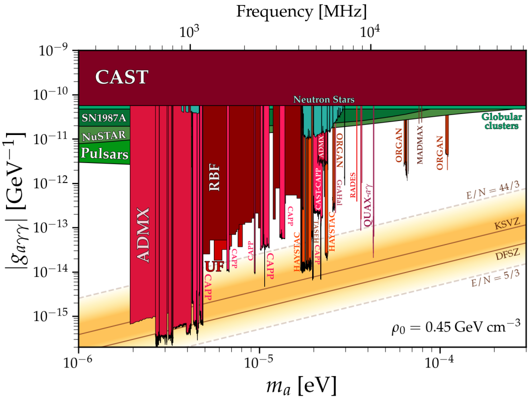
- Axions:
  - a favourable dark matter candidate
  - a solution to the strong CP problem
  - can convert into photons in high magnetic fields ($a \rightarrow \gamma$)

Ref: *The compelling case for axions as our dark matter* by Ethan Siegel

Introduction

- Neutron stars:
  - core collapse remnants of high-mass stars
  - B-fields ranging $10^{10} - 10^{14}$ G
  - $M \approx 1\ M_{\odot},\ R = 10$ km





https://github.com/cajohare/AxionLimits

Aim: Implement population analysis to detect resonant signals: better than single-star analysis? Pros and cons?

Outline

- Modelling the axion-photon conversion signal
- PsrPopPy: a Python package to simulate neutron stars in the galaxy (Bates et al. 2013)
- Results from PsrPopPy
- Galactic Center neutron star survey
- Conclusions and Summary

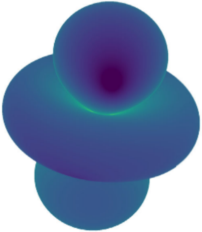
Axion-photon conversion signal

- Goldreich - Julian charge density,

$$n_{\rm GJ}(r,\theta,\phi) = \frac{2\,\vec{\Omega}\cdot\vec{B}_0}{e} \text{ where } B_0 \propto \frac{1}{r^3}.$$

- Plasma frequency,

$$\omega_{\rm P}^2 = \frac{4\pi\alpha_{\rm EM}|n_{\rm GJ}|}{m_e}. \qquad (1)$$



Leroy et al. 2019

Resonance

$$\omega_{\rm P} = m_a \implies r_c \propto \left(\frac{\Omega\, B_0}{m_a^2}\right)^{1/3}$$

Axion-photon conversion signal

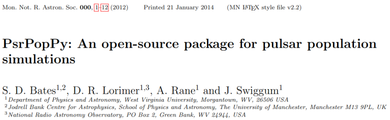
- Conversion probability, $P_{a\gamma} \propto g_{a\gamma\gamma}^2 |B_0|^2$.
- Luminosity of axion-photon conversion signal,

$$L = \int d^3k \int d\vec{\Sigma}_{\vec{k}} \cdot \vec{v}_a P_{a\gamma} \omega \rho_a \tag{2}$$

- Absorptive effects,
  - Cyclotron resonance, $L \to L \times e^{-\tau}$ where $\tau \propto \left(\frac{B_0 \Omega^3}{m_a} \right)^{1/3}$
  - Photon reconversion [~~stars with $\langle P_{a\gamma} \rangle > 0.1$~~]
- Brightness temperature,

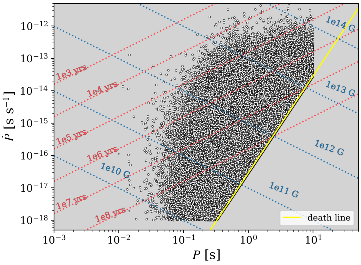
$$T \simeq \frac{\lambda_{m_a}^2}{2k_B} \sum_{x_i, B_i, P_i} \frac{L(x_i, B_i, P_i)}{4\pi x_i^2 \Delta f} n_{\mathrm{NS}}(x_i, B_i, P_i) \tag{3}$$

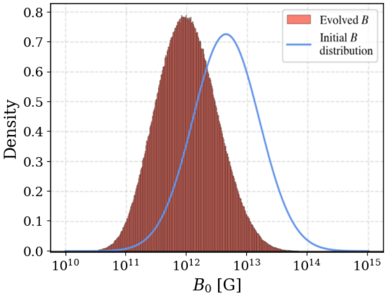
PsrPopPy

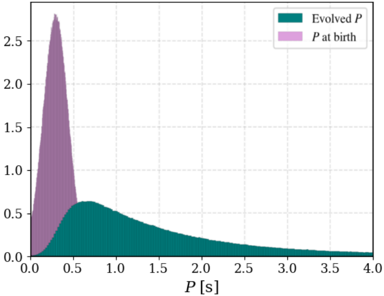

Mon. Not. R. Astron. Soc. 000, 1–12 (2012) Printed 21 January 2014 (MN LaTeX style file v2.2)

PsrPopPy: An open-source package for pulsar population simulations

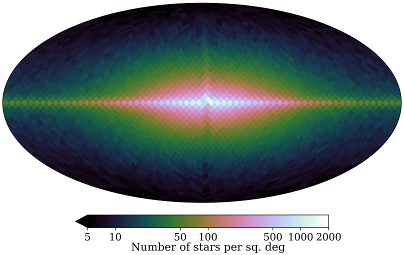
S. D. Bates[1,2], D. R. Lorimer[1,3], A. Rane[1] and J. Swiggum[1]
[1] Department of Physics and Astronomy, West Virginia University, Morgantown, WV, 26506 USA
[2] Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
[3] National Radio Astronomy Observatory, PO Box 2, Green Bank, WV 24944, USA

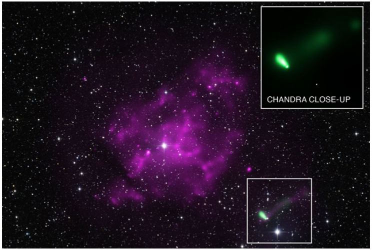


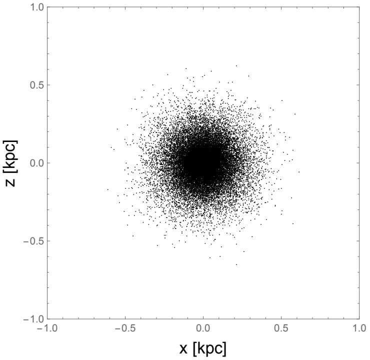




PsrPopPy



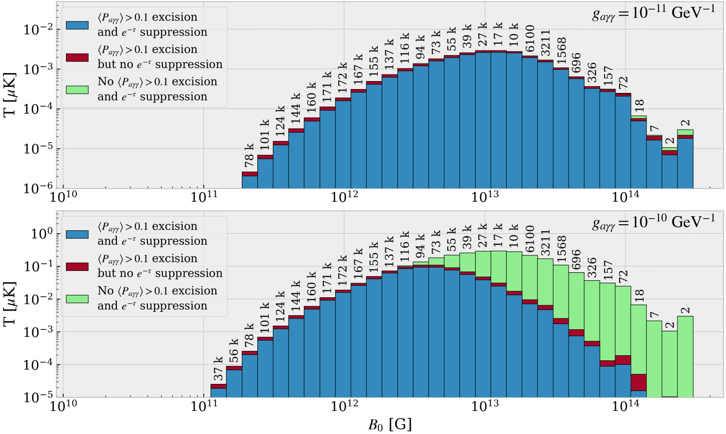




$$N_{\text{stars}} \approx 2 \times 10^6$$

↦ $m_a = 1$ GHz ($\sim 4.1\ \mu$eV)

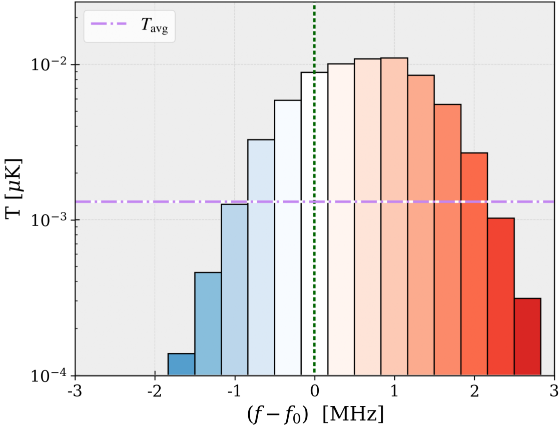
- Impact of absorptive effects:



Results from PsrPopPy

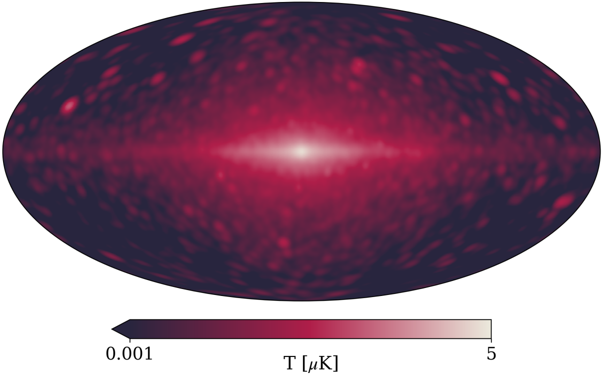
- $\mapsto$ $m_a = 1$ GHz ($\sim 4.1\ \mu$eV)
- $\mapsto$ $g_{a\gamma\gamma} = 10^{-11}\ \mathrm{GeV}^{-1}$
- $\mapsto$ $\dfrac{\Delta f}{f(m_a)} \approx 10^{-3}$

- Dispersion due to relative motion of stars:



- ↦ $m_a = 1$ GHz ($\sim 4.1\ \mu$eV)
- ↦ $g_{a\gamma\gamma} = 10^{-11}\ \mathrm{GeV}^{-1}$
- ↦ DM density profile - NFW

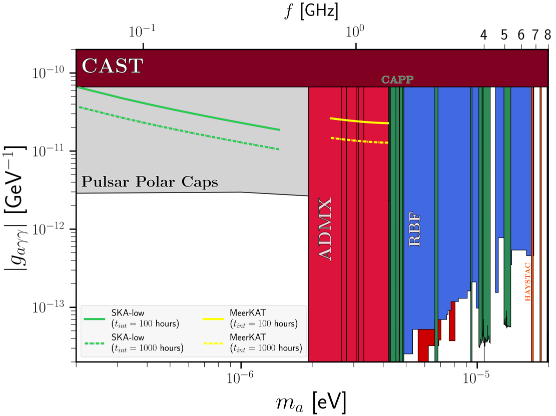
- Dependence on a star's spatial position:



$\theta_{\mathrm{pix}} = 3.7^\circ$

Results from PsrPopPy

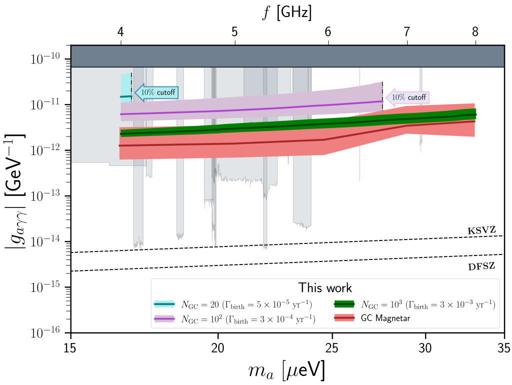
- Constraints on $g_{a\gamma\gamma}$:



Radiometer equation: $T_\sigma = \dfrac{T_{\rm sys}}{\sqrt{\Delta f \; t_{\rm int}}}$, $g_{a\gamma\gamma,constr} = \sqrt{\dfrac{2T_\sigma}{T_{\rm sys}}}\, g_{a\gamma\gamma}$

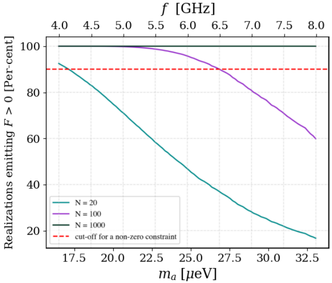
Galactic Center

- Flux NFW boosted
- Home to Magnetars
- Simulate a neutron star population similar to PsrPopPy.



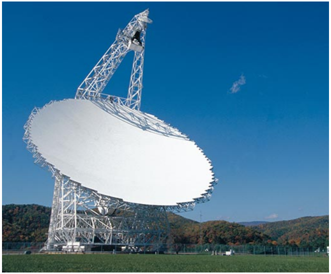
cyan:Foster et al 2022

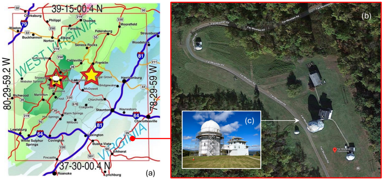
- $\mapsto$ $m_a = 4 - 8$ GHz (~ 16 to 33 μeV)
- $\mapsto$ $g_{a\gamma\gamma} = 10^{-11}\ \mathrm{GeV}^{-1}$
- $\mapsto$ $\dfrac{\Delta f}{f(m_a)} \approx 10^{-3}$



Conclusion

- Future,
  - > Galactic centre census
  - > Axion miniclusters



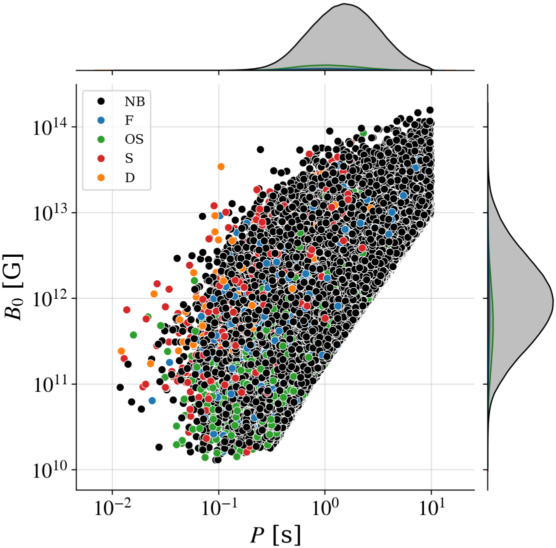


Left: The Green Bank telescope. **Right**: The Fan Mountain telescope.

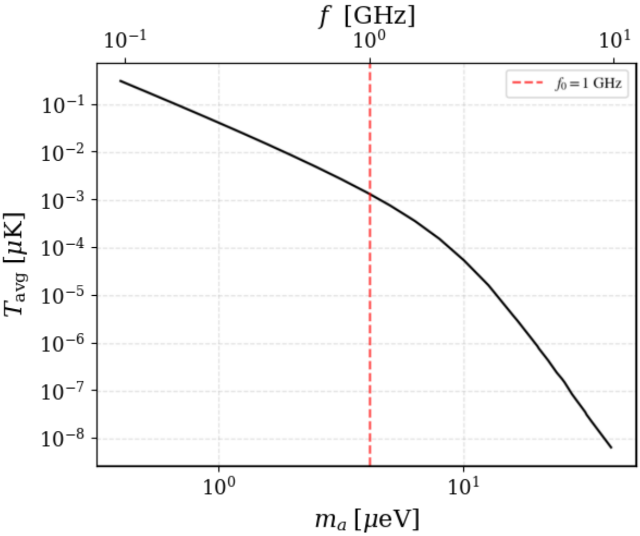
Summary

- PsrPopPy
  - > Signal weakens with m_a
  - > Signal is Doppler shifted
  - > Resonance signals are stronger near Galactic center
- The Galactic center
  - > Highly magnetic neutron stars (Magnetars)
  - > NFW boosted flux
- arxiv:2407.19028

Backup I



Backup II



f [GHz]
10^{-1}
10^{0}
10^{1}
$f_0 = 1$ GHz
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
T_{avg} [μK]
10^{0}
10^{1}
m_a [μeV]