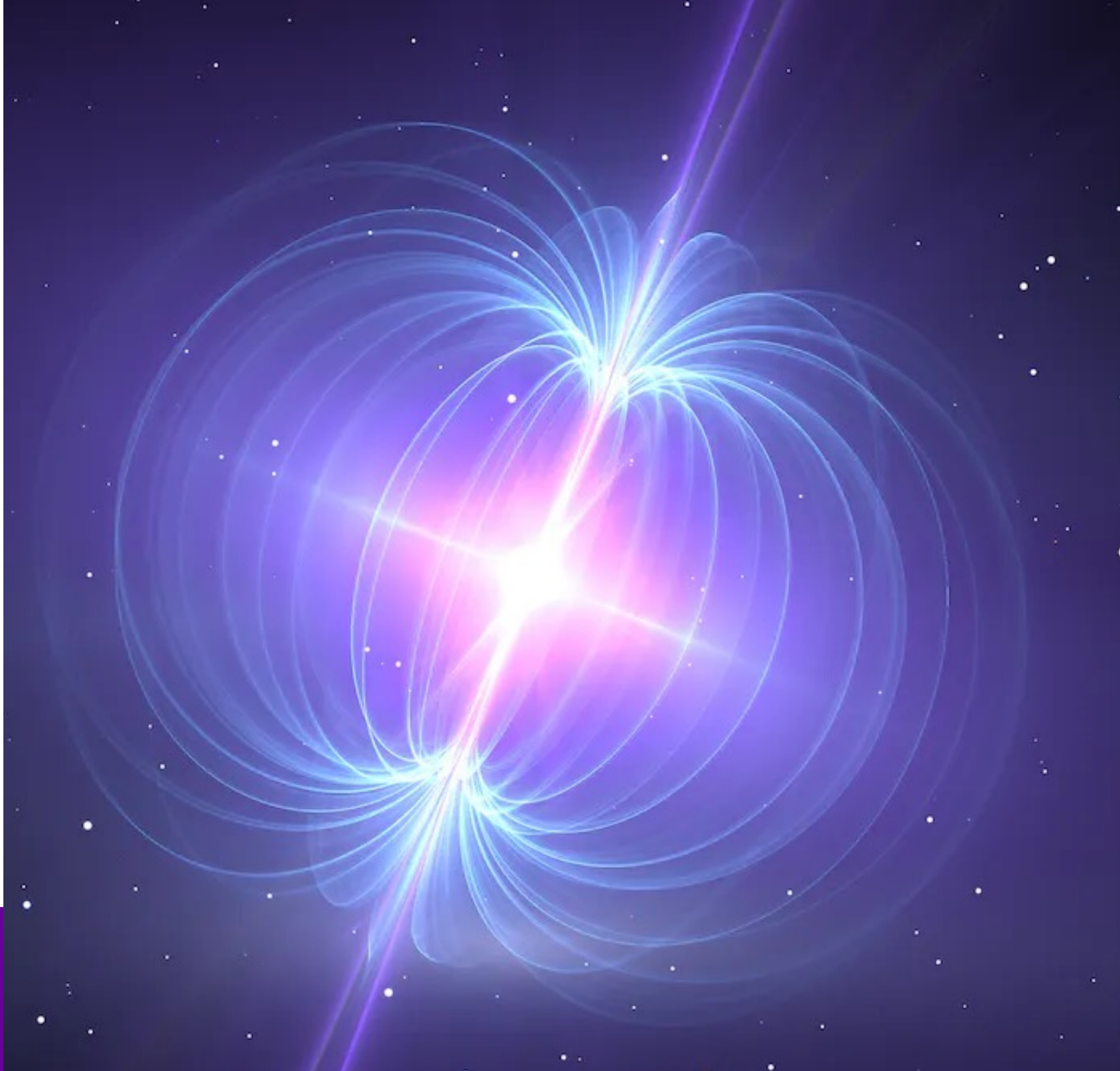
Axions and Neutron Stars

Jamie McDonald

Working Group Meeting COST Action COSMIC WISPers (CA21106)

DESY 1-2 Feb 2024

MANCHESTER 1824
The University of Manchester



Neutron Stars are Incredible Objects!

Extremely Compact

$M_{NS} \simeq M_{\odot}, R \simeq 10km$

Spin 100s of times a second

Superradiance in stars:

JCAP 12 (2022) 008 Chadha-Day, Garbrecht, **JM**

Cardoso, Brito, Rosa Phys. Rev. D 91 (2015) 12, 124026

Strongest magnetic fields in Universe $B \simeq 10^{14}\ G$

Great axion labs

In radio and X-ray

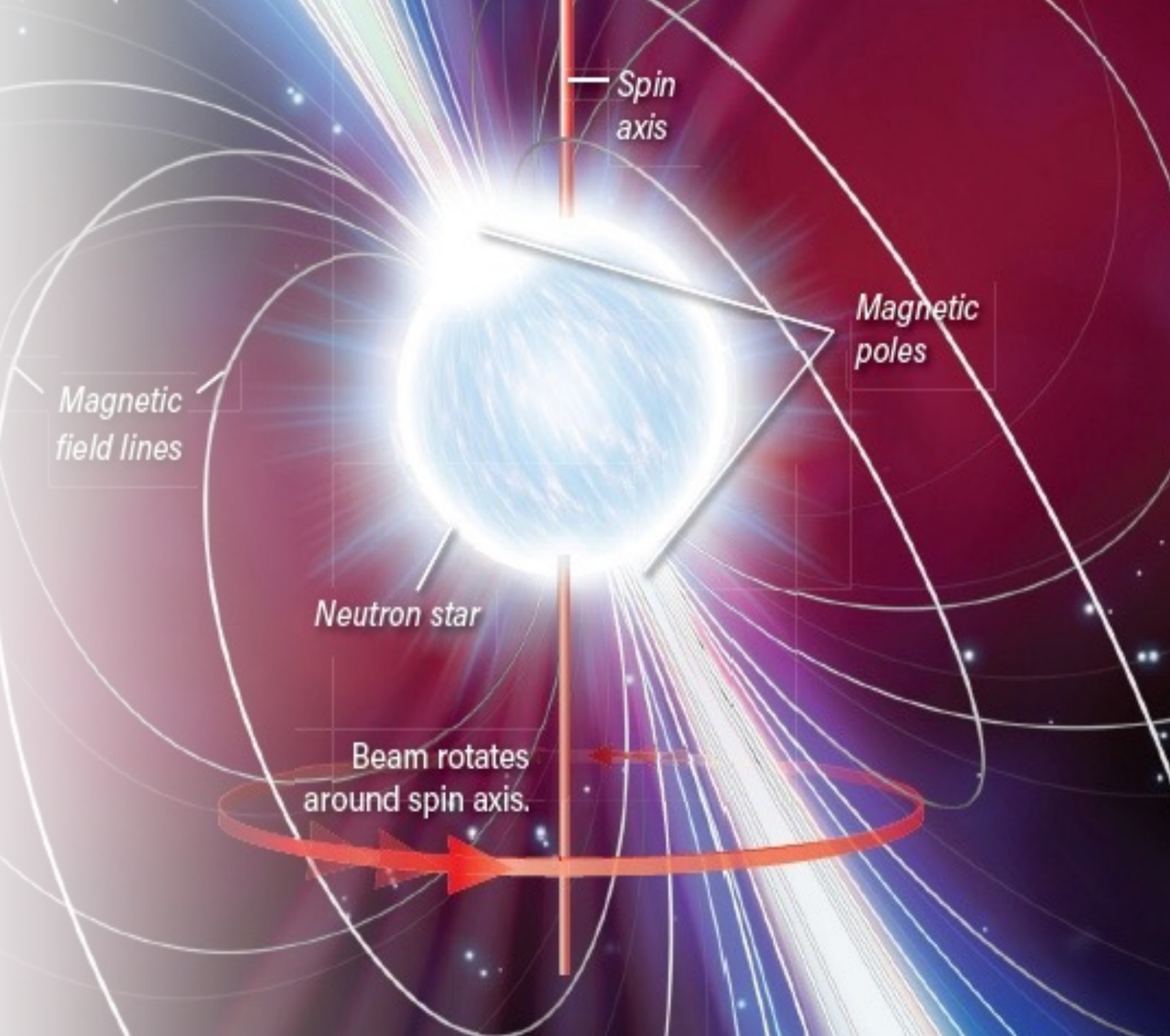
Accurate clocks

Ultra-light dark matter tests

Khmelnitskya, Rubakovb JCAP 02 (2014) 019

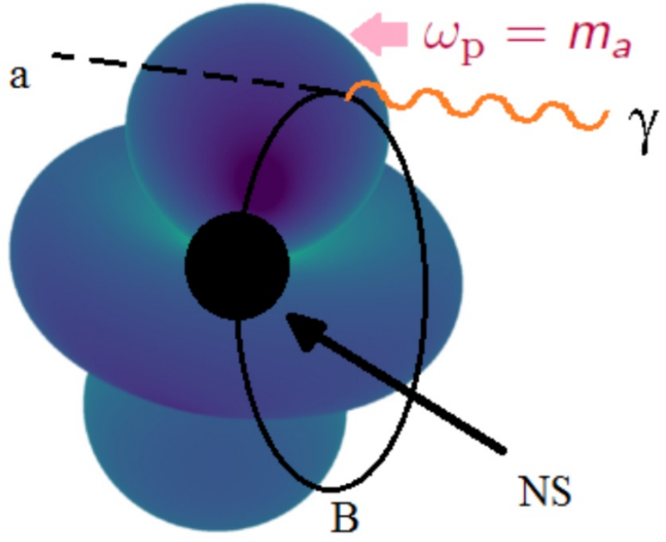
And then there's the inside…

e.g. stellar cooling, DM capture, etc etc



Resonant Axion DM Conversion Around Neutron Stars

$$L = -\frac{g_{a\gamma\gamma}}{4}\, a\, F^{\mu\nu}\, \widetilde{F}_{\mu\nu}$$
$$= g_{a\gamma\gamma}\, a\, \boldsymbol{E}.\boldsymbol{B}$$



$$P_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 L_{res}^2 \qquad L_{res}^2 \sim 1/\nabla\omega_p$$

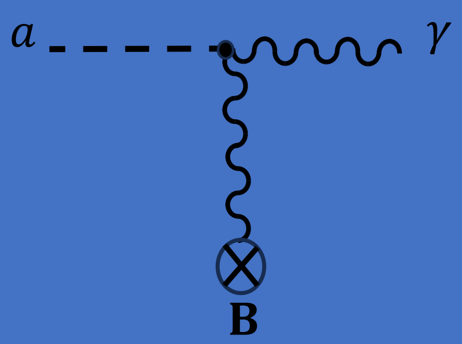
A. Hook, Y. Kahn B. Safdi, Z. Sun Phys. Rev. Lett. 121 (2018) 24, 241102

F. P. Huang, K. Kadota, T. Sekiguchi, H. Tashiro Phys.Rev.D 97 (2018) 12, 123001

M.S. Pshirkov, S.B. Popov J. Exp. Theor. Phys. 108 (2009) 384-388 (Original Proposal!)

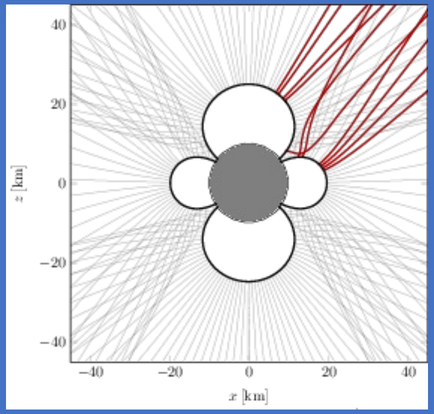
The Pipeline – State-of-the-Art

3D Production



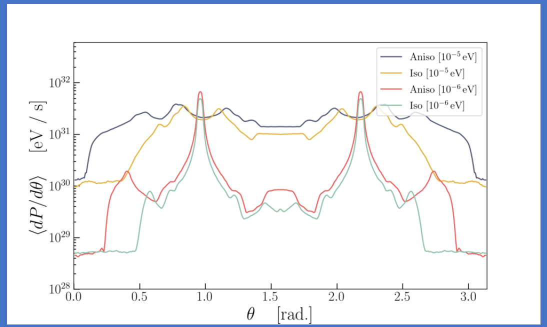
JM, *Millington, Garbrecht, JCAP* 12 (2023) 031
Millar, Baum, Lawson, Marsh JCAP 11 (2021) 013

Transport



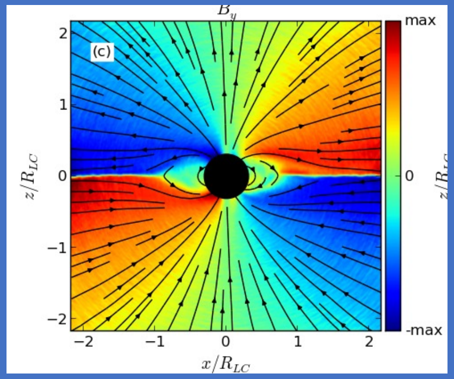
JM, *Witte, Phys. Rev. D 108 (2023) 10, 103021*
Battye, Garbrecht, **JM**, *Srinivasan JHEP 2021, 105 (2021)*
Witte et al Phys. Rev. D 104 (2021) 10, 103030

Signal Properties

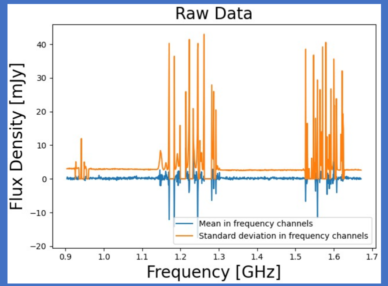


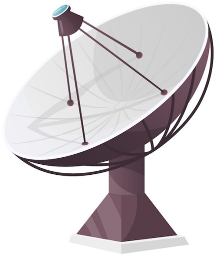
Tjemsland, **JM**, and Samuel J. Witte
Phys. Rev. D 109 (2024), 023015

Magnetosphere



Observations

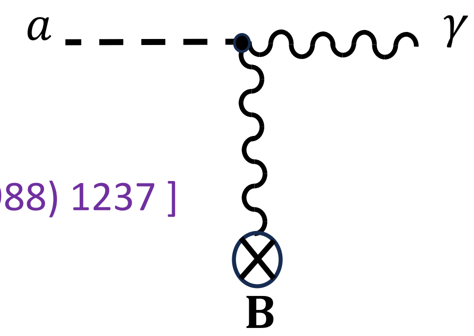




Foster et al, Phys. Rev. Lett. 129, 251102 (2022)
Battye, Keith, **JM**, et al Phys. Rev. D 108 (2023), 063001

Infer what values of $g_{a\gamma\gamma}$ have been probed (“limit”)

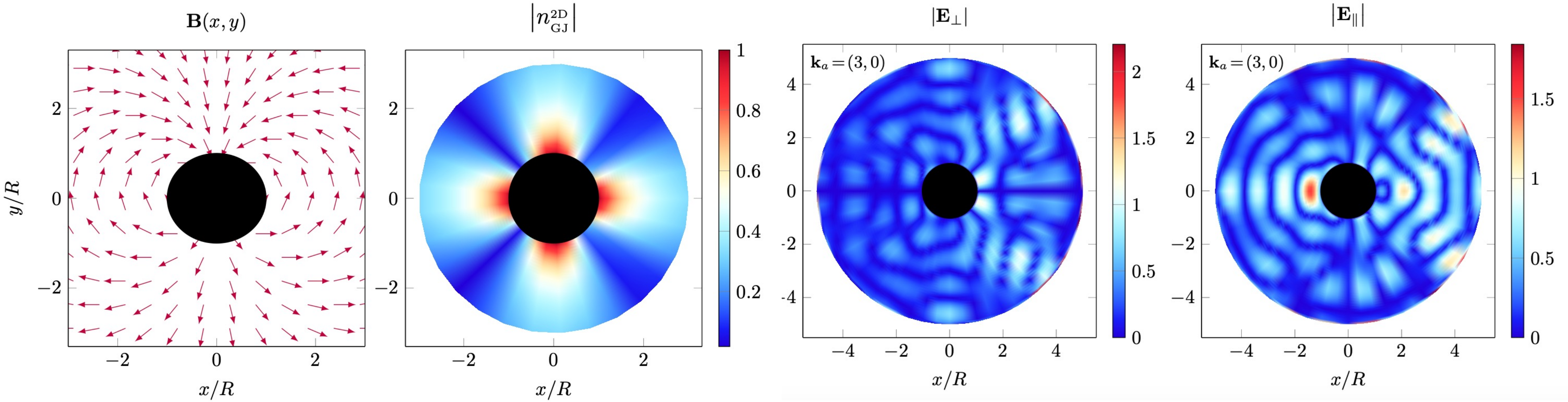
Axion-Photon Conversion in 3D Plasmas



- Early 1D calculations [Hook et al, Phys. Rev. Lett. 121 (2018) 24, 241102), Raffelt, Stodolsky Phys. Rev. D 37 (1988) 1237]

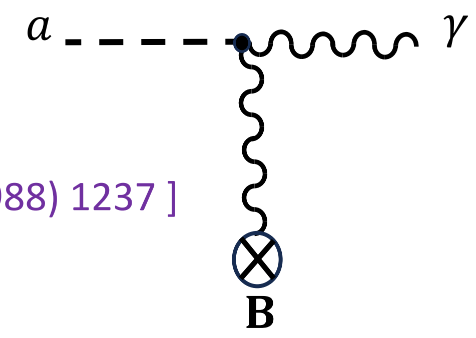
Solve 3D Equations numerically ???

$$-\nabla^2 \mathbf{E} + \nabla(\nabla \cdot E) + \omega^2 \varepsilon \cdot E = g_{a\gamma\gamma}\omega^2 a\, \mathrm{B}$$



2D Simulations
Battye, Garbrecht, **JM** et al Phys. Rev. D 102 (2020) 2, 023504

Axion-Photon Conversion in 3D Plasmas



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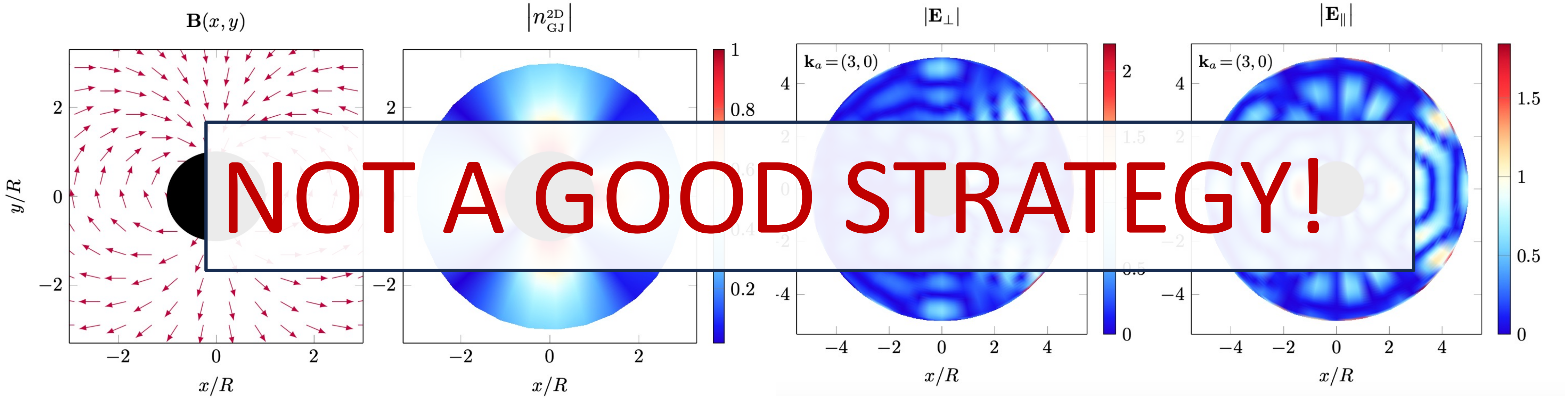


2D Simulations

Battye, Garbrecht, **JM** et al Phys. Rev. D 102 (2020) 2, 023504

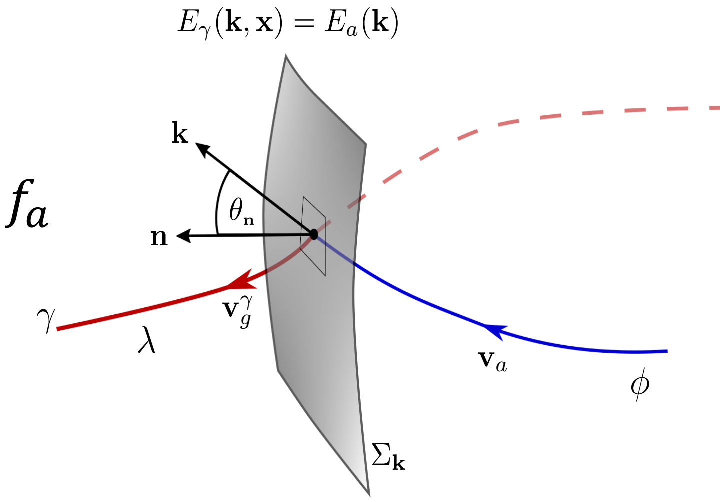
New Approach in 3D – **Transport Equations**

[**JM**, *Millington, Garbrecht, JCAP* 12 (2023) 031]

$$\partial_t f_\gamma + \boldsymbol{v_g} \cdot \nabla_{\mathbf{x}} f_\gamma - \nabla_{\boldsymbol{x}} E_\gamma \nabla_{\boldsymbol{k}} f_\gamma = \delta\left(E_\gamma^2 - E_a^2\right) g_{a\gamma\gamma}^2 E_\gamma \left|\boldsymbol{B} \cdot \boldsymbol{\epsilon}_\gamma\right|^2 \frac{U_E}{U} f_a$$

Project along photon worldlines:

$$\frac{d\boldsymbol{x}_\gamma}{d\lambda} = v_g, \qquad \frac{d\boldsymbol{k}_\gamma}{d\lambda} = -\nabla_x E_\gamma: \qquad \frac{df_\gamma}{d\lambda} = \delta(E_\gamma^2 - E_a^2)\, g_{a\gamma\gamma}^2\, E_\gamma^2 \left|\boldsymbol{B} \cdot \boldsymbol{\epsilon}_\gamma\right|^2 \frac{U_E}{U} f_a$$



$$P_{a\to\gamma}^{3D} = \frac{f_\gamma}{f_a} = \frac{\pi\, g_{a\gamma\gamma}^2 E_\gamma \left|\boldsymbol{B}\cdot\boldsymbol{\epsilon}_\gamma\right|^2}{\left|\boldsymbol{k} \cdot \nabla_{\boldsymbol{x}} E_\gamma\right|} \frac{U_E}{U}$$

[see also earlier attempts by Millar, Baum, Lawson, Marsh JCAP 11 (2021) 013]

New Approach in 3D – **Transport Equations**

[**JM**, *Millington, Garbrecht, JCAP* 12 (2023) 031]

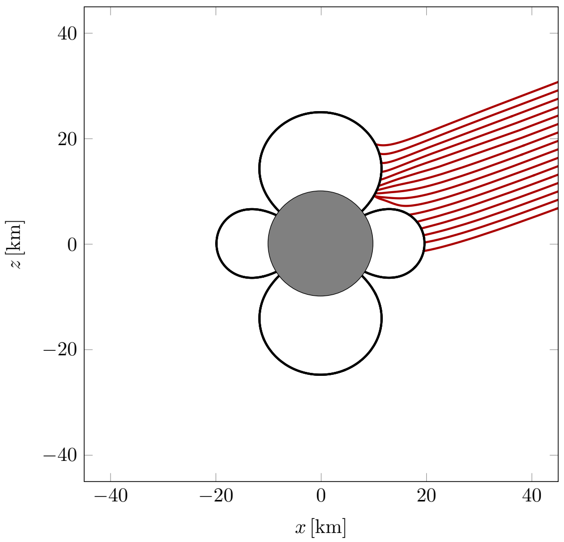
$$P^{3D}_{a\to\gamma} = \frac{\pi\, g^2_{a\gamma\gamma} E_\gamma \left|\boldsymbol{B}\cdot\boldsymbol{\epsilon}_\gamma\right|^2}{\left|\boldsymbol{k}\cdot\nabla_{\boldsymbol{x}} E_\gamma\right|} \frac{U_E}{U}$$

- ☑ Easily adaptable for arbitrary particles/spins (dark photons, gravitons etc)
- ☑ Incorporates photon refraction
- ☑ No "dephasing" (photon bending seems not to suppress conversion)
- ☑ Valid for any medium, any polarization/dispersion relation (for k in WKB regime)
- ☑ Divergence free! $power \sim \int d^3k \int dA.\, k\, P_{a\to\gamma} f_a$ $\quad dA \parallel \nabla E_\gamma$

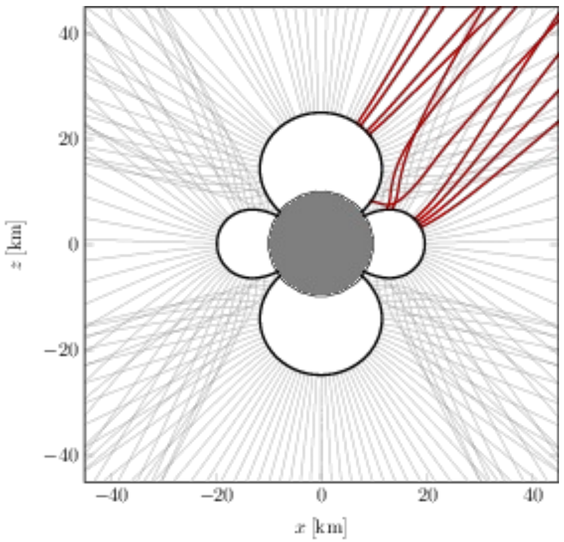
Transport and ray-tracing – A Metanalysis

$$\frac{d\boldsymbol{x}_\gamma}{dt} = v_g, \qquad \frac{d\boldsymbol{k}_\gamma}{dt} = -\nabla_x E_\gamma \qquad E_\gamma^2 = k^2 + \omega_p^2 + [k^4 + \omega_p^4 + k^2\omega_p^2(1 \, - 2\left(\hat{k}.\hat{B}\right)^2]$$

JM's Code

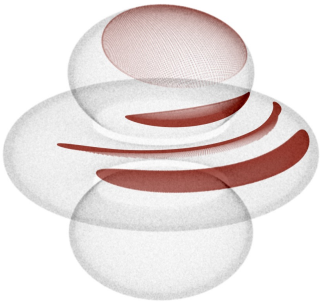


SW's Code



JM, Witte,
Phys. Rev. D 108 (2023) 10, 103021

Backward Ray-Tracing



Forward Ray-Tracing

Two Independent Initial Works

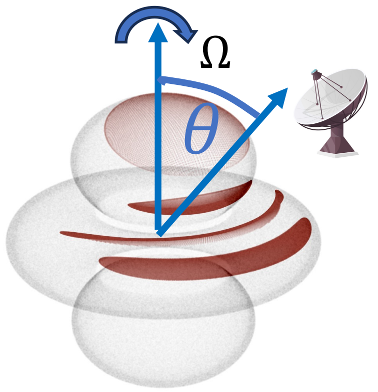
Battye, Garbrecht, **JM**, Srinivasan JHEP 2021, 105 (2021)
Witte et al Phys. Rev. D 104 (2021) 10, 103030

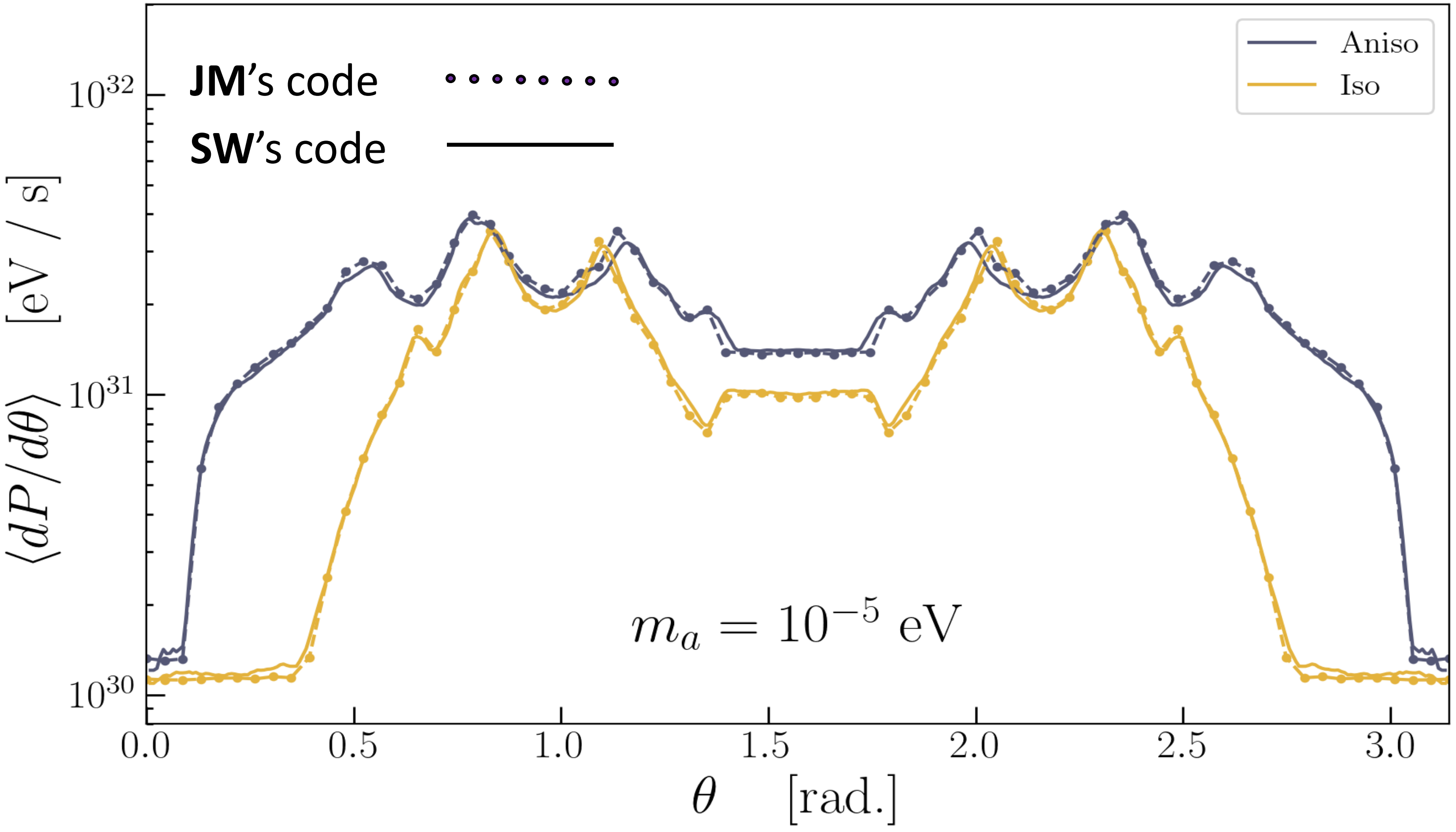
Transport (ray-tracing)

[**JM**, S. J. Witte, Phys. Rev. D 108 (2023) 10, 103021]

$$\frac{d\boldsymbol{x}_\gamma}{dt} = v_g, \qquad \frac{d\boldsymbol{k}_\gamma}{dt} = -\nabla_x E_\gamma \qquad E_\gamma^2 = k^2 + \omega_p^2 + [k^4 + \omega_p^4 + k^2\omega_p^2(1 - 2\left(\hat{k}.\hat{B}\right)^2]$$

- ☑ Curved Spacetime Effects
- ☑ Anisotropic plasma effects
- ☑ Latest Expression for $P^{3D}_{a\to\gamma}$



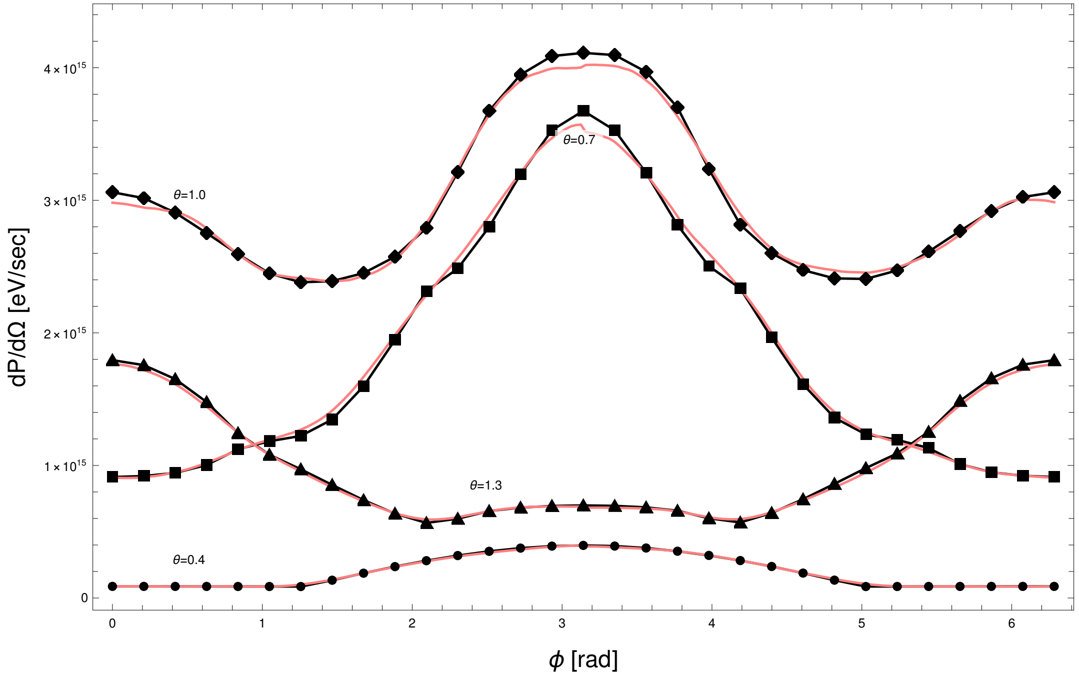


[observing direction of star]

Signal Properties

Periodic Time Dependence of Signals

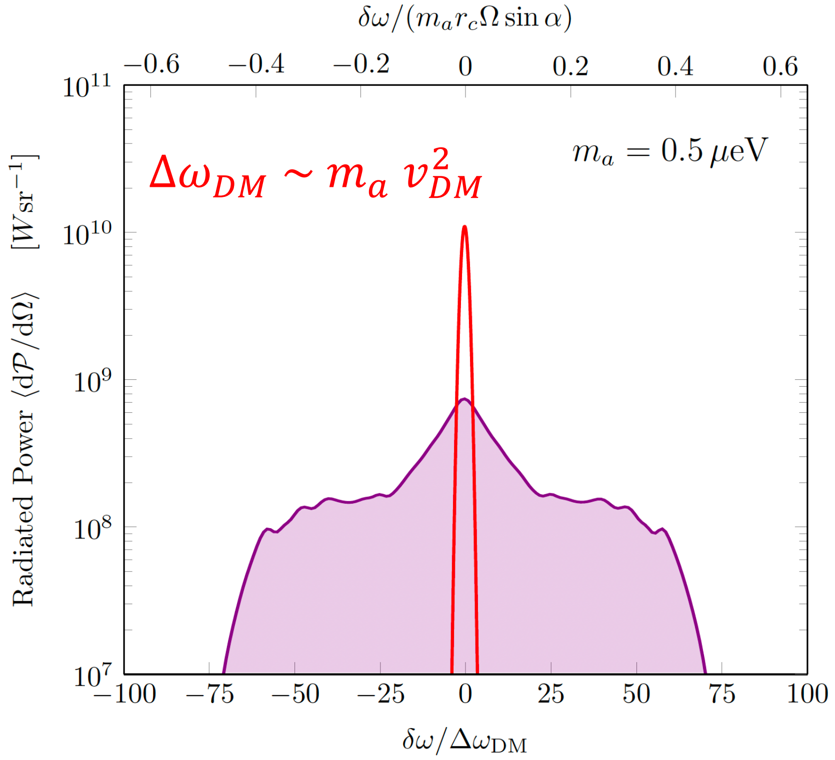
JM, Witte (unpublished)



[Rotational Phase of Star]

Bandwidth/Spectral Properties

Battye, Garbrecht, JM, Srinivasan JHEP 2021, 105 (2021)



← **frequency** →

$$\frac{d\omega(x(t),t)}{dt} = \frac{1}{2\omega}\underbrace{\partial_t \omega_{\rm p}^2(t,\mathbf{x}(t))}_{\rm t-dep\,plasma}$$

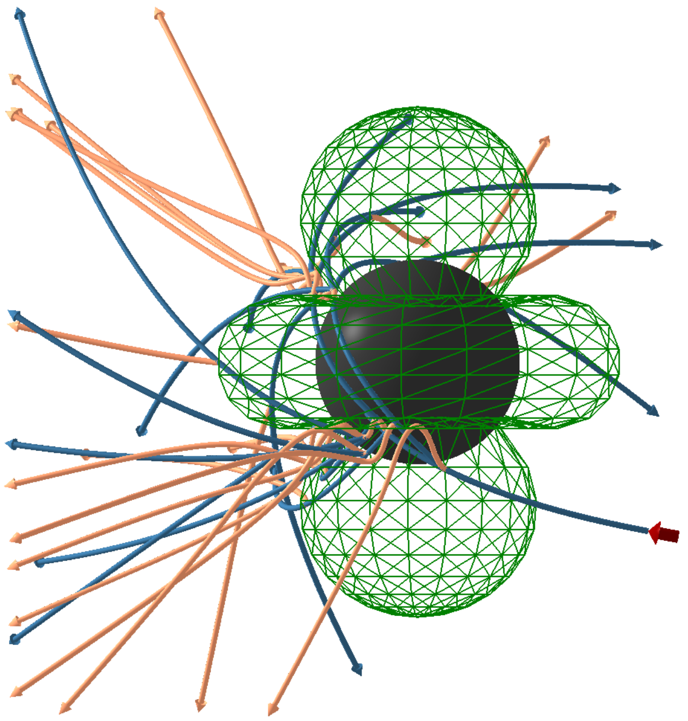
Tjemsland, **JM**, and Samuel J. Witte
Phys. Rev. D 109 (2024), 023015

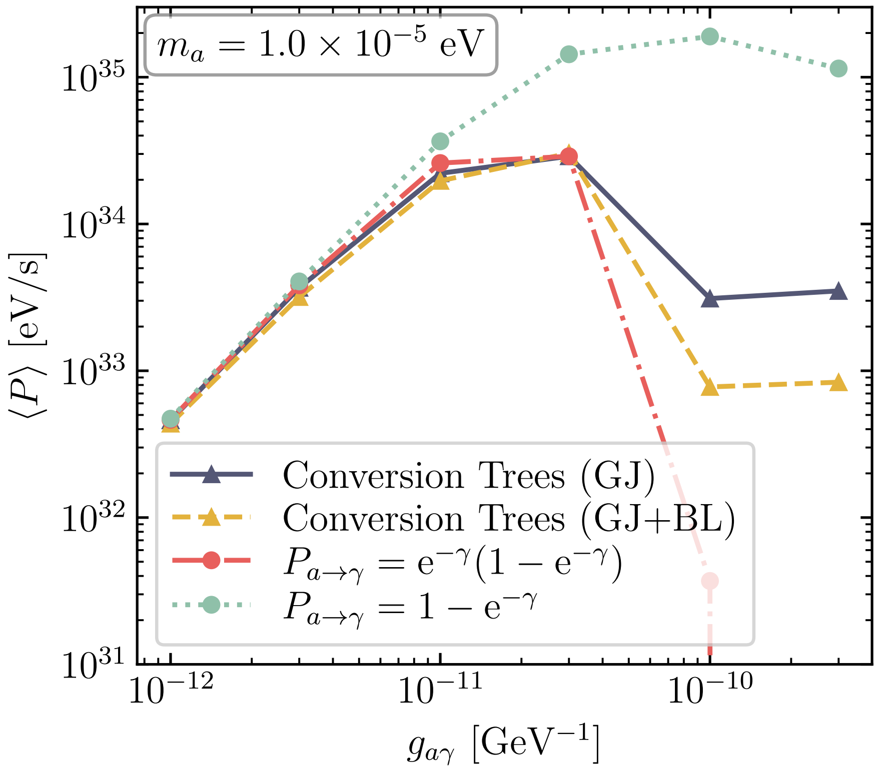
Signal Properties

Dependence on $g_{a\gamma\gamma}$: $a \to \gamma \to a \to \gamma \to a \cdots$

For large values of $g_{a\gamma\gamma}$**B** weird things happen $P_{a\to\gamma} = 1 - \exp(-g_{a\gamma\gamma} B^2 L_{res}^2) \to 1$
(Important for Magnetars)

$B = 10^{14}\ G$





Observations

Stellar Populations

Foster et al, Phys. Rev. Lett. 129, 251102 (2022)
[GBT, Galactic Centre]

Foster et al *Phys. Rev. Lett.* 125 (2020) 17, 171301]
[GBT, Effelsberg, Galactic Centre + Isolated NSs]

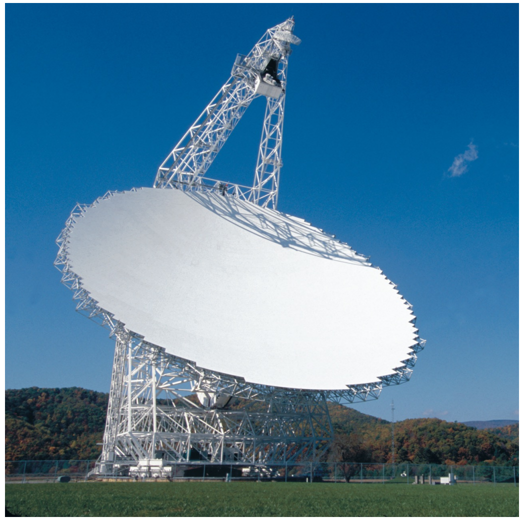
Battye, Bhura, **JM**, Srinivasan (in prep)

Single Objects

Darling [*Phys. Rev. Lett.* 125 (2020) 12, 121103]

Battye, Darling, **JM**, Srinivasan
[Phys. Rev. D 105 (2022) 2, L021305]
[Galactic Centre Magnetar, VLA, PSR J1745−2900]

Battye, Keith, **JM**, Srinivasan, Stappers, Weltevrede
[Phys. Rev. D 108 (2023) 6, 063001]
[MeerKAT, **matched-filter/time-domain search** PSR J2144-3933]



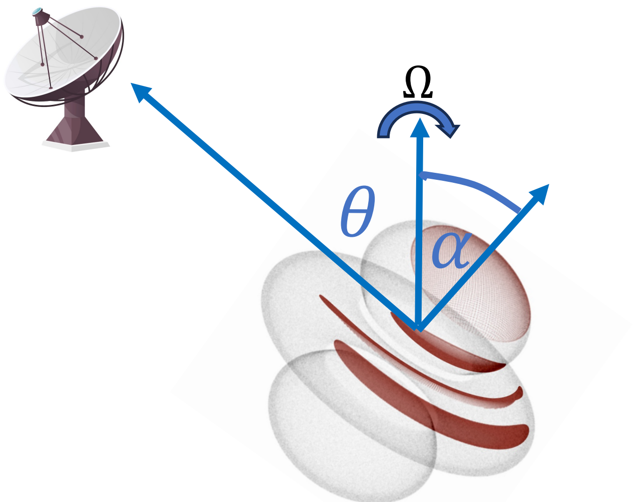
Green Bank Telescope (GBT) - USA

Effelsberg - Germany

Very Large Array (VLA) - USA

MeerKAT – S. Africa

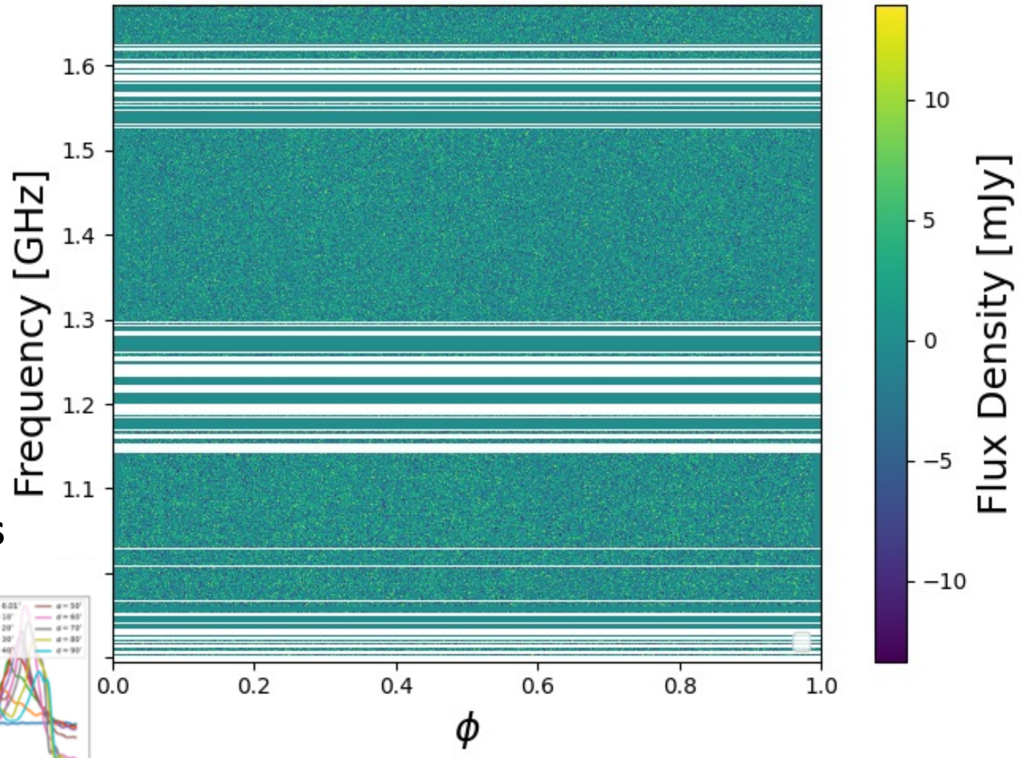
Observations



Periodic Signal Search - MeerKAT (a test case with PSR J2144-3933)

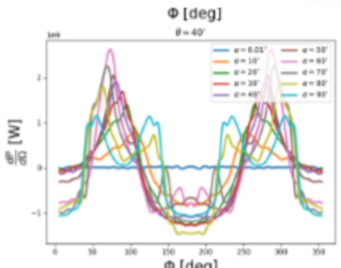
Battye, Keith, **JM**, Srinivasan, Stappers, Weltevrede
[Phys. Rev. D 108 (2023) 6, 063001]
[**matched-filter/time-domain search**]

Time-Frequency Data

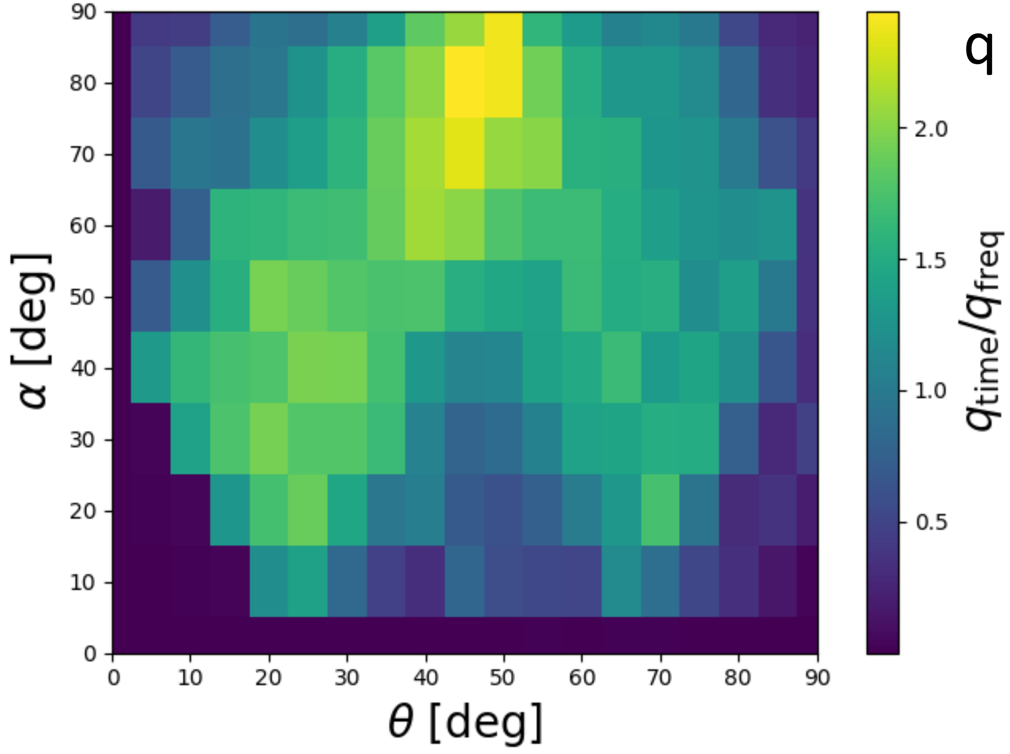


Time (pulse phase)

Templates



Relative SNR gain of time-dependent analysis

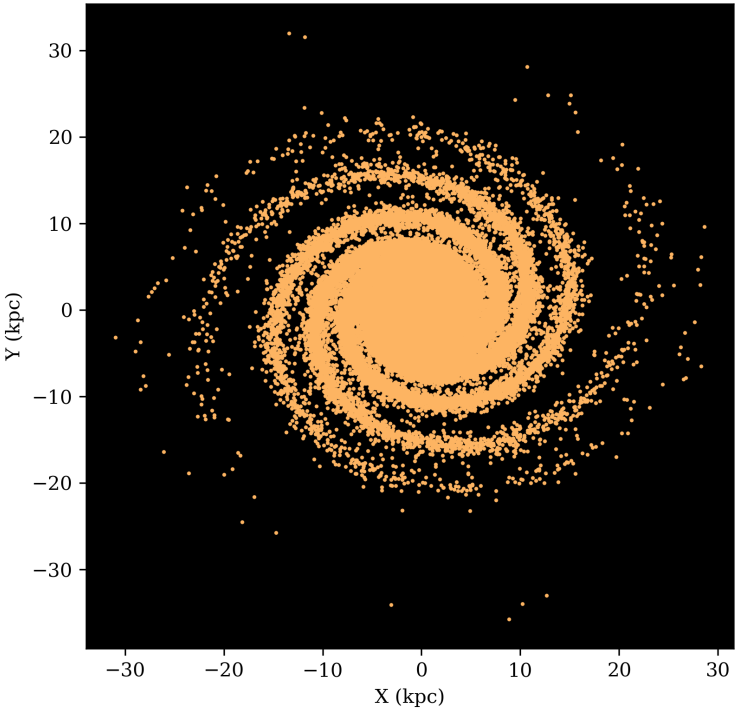


q =SNR

Observations

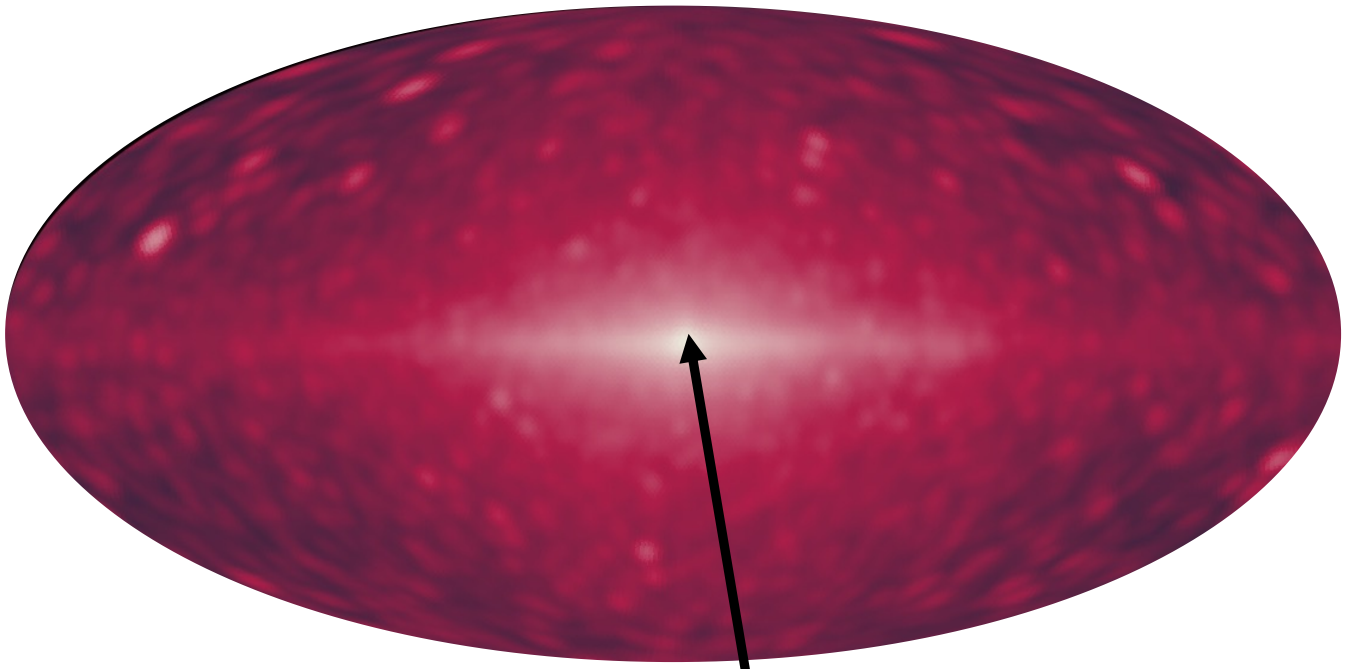
Populations

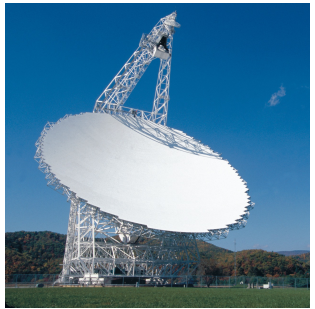
(initial) Distribution of Neutron Stars
[Simulations via PsRPopPy]



Battye, Bhura, **JM**, Srinivasan (in prep)

Axion Signal From PsrPopPy

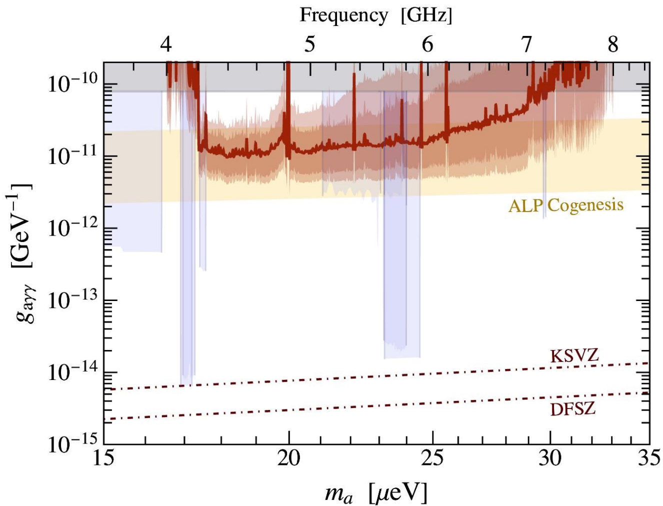




"Breakthrough Listen"

Foster et al (2022)
assume NS
population at Galactic Centre

Foster et al, Phys. Rev. Lett. 129, 251102 (2022)



Populations

Observations

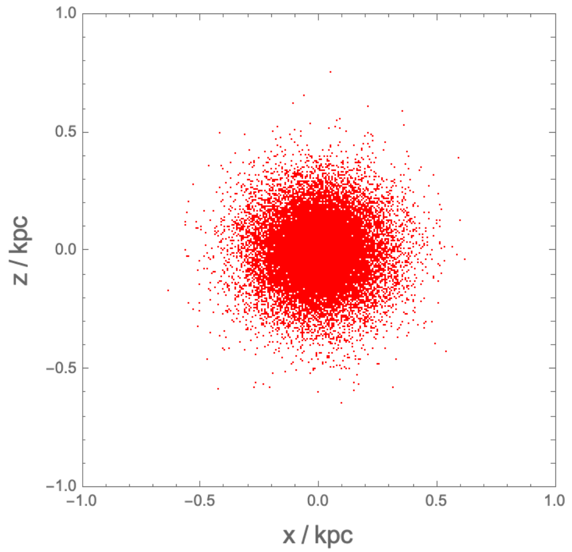
Some Issues on Galactic Centre observations

- **Uncertainty on number of stars in GC**

(Pulsars are "obscured" at galactic centre so almost none observed)
-> Presence NSs inferred through birth rate models

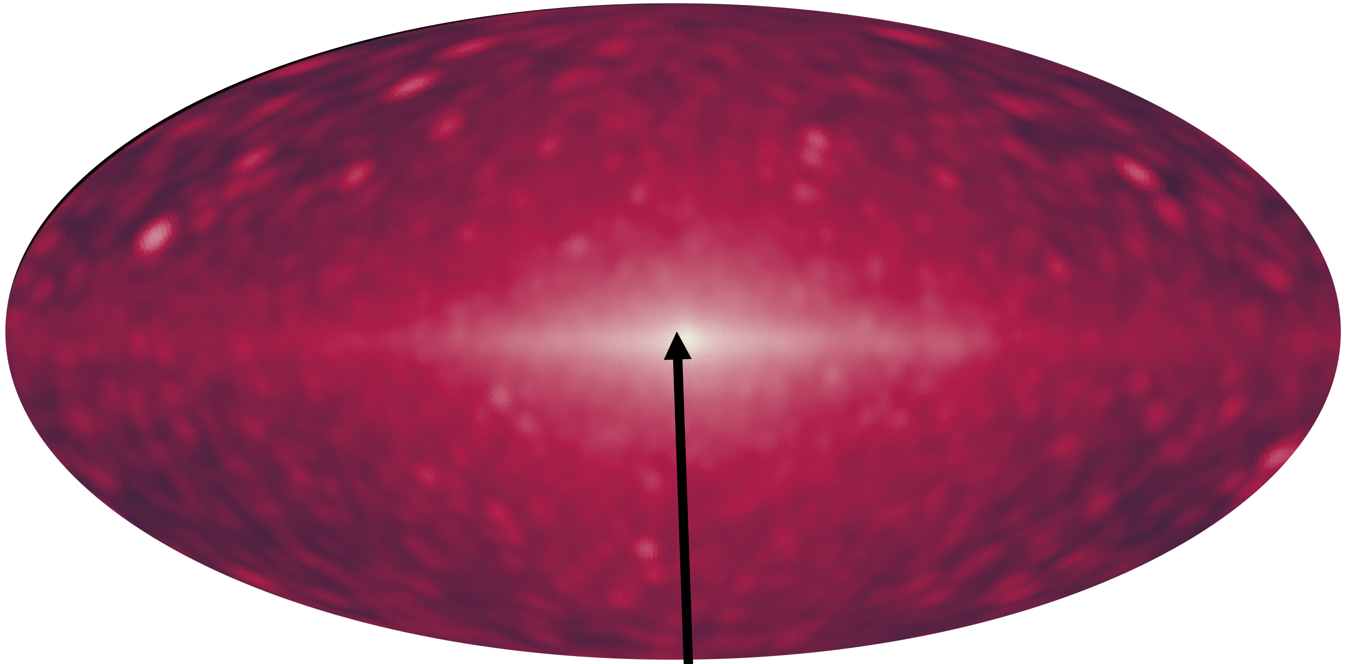
- **Need to take into account "drift" of stars**

Distribution after $t = 10^6$yr

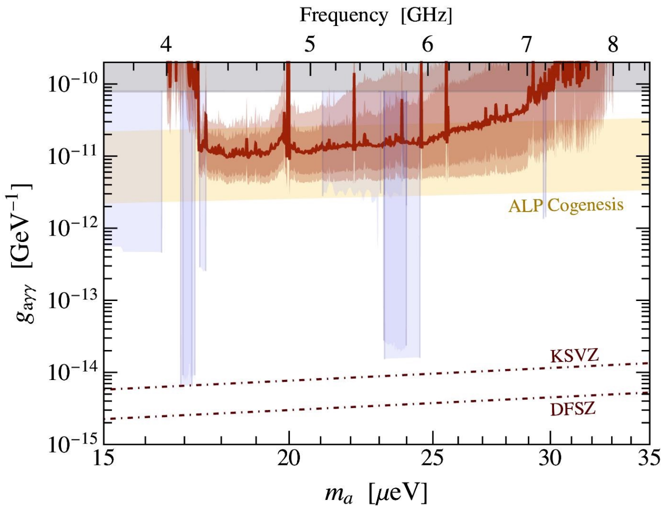


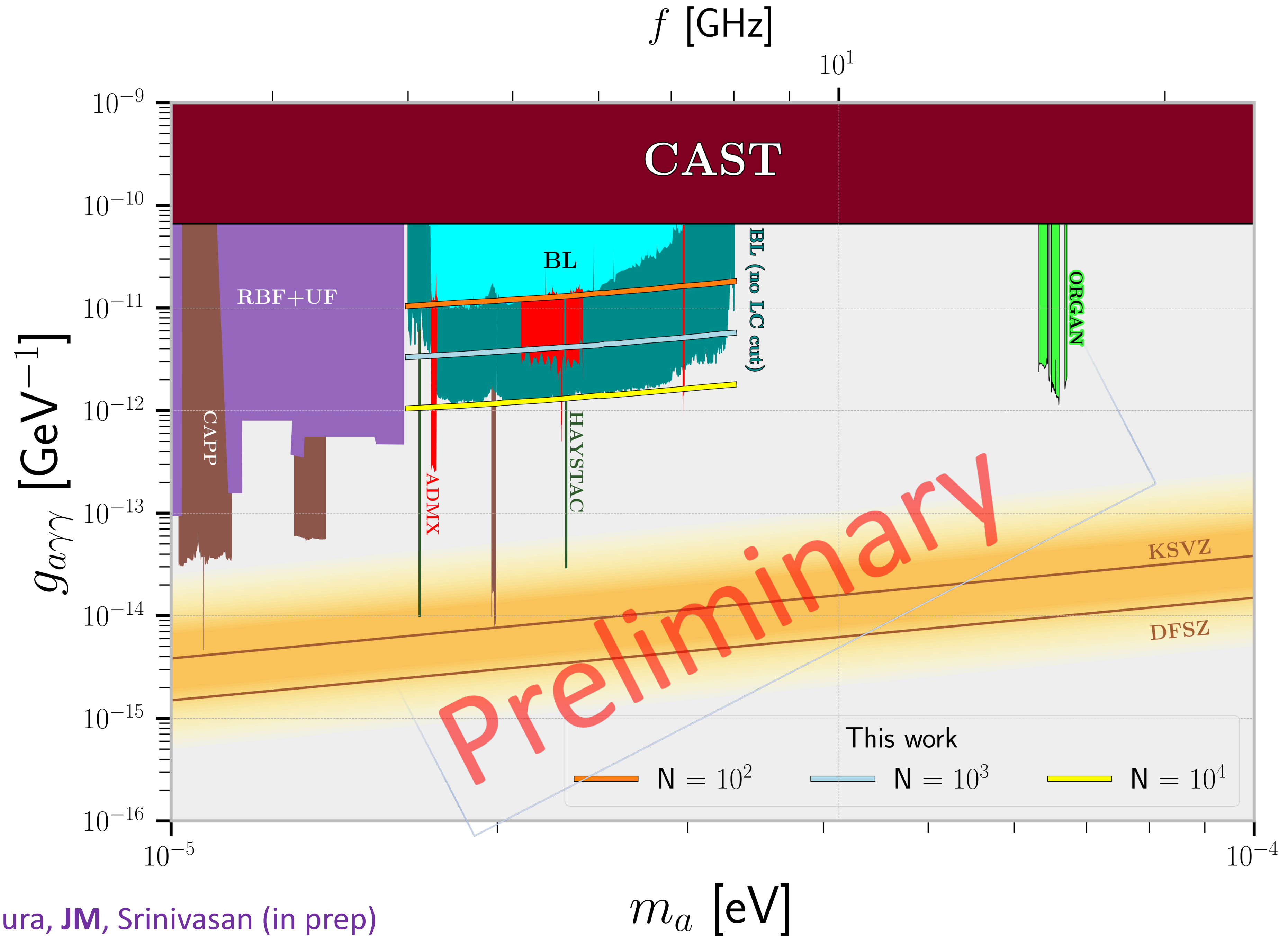
$v_{NS} \sim 100s\ km/s$

Axion Signal From PsrPopPy
Battye, Bhura, **JM**, Srinivasan (in prep)



Foster et al (2022) assume NS population at Galactic Centre
Foster et al, Phys. Rev. Lett. 129, 251102 (2022)





Battye, Bhura, **JM**, Srinivasan (in prep)

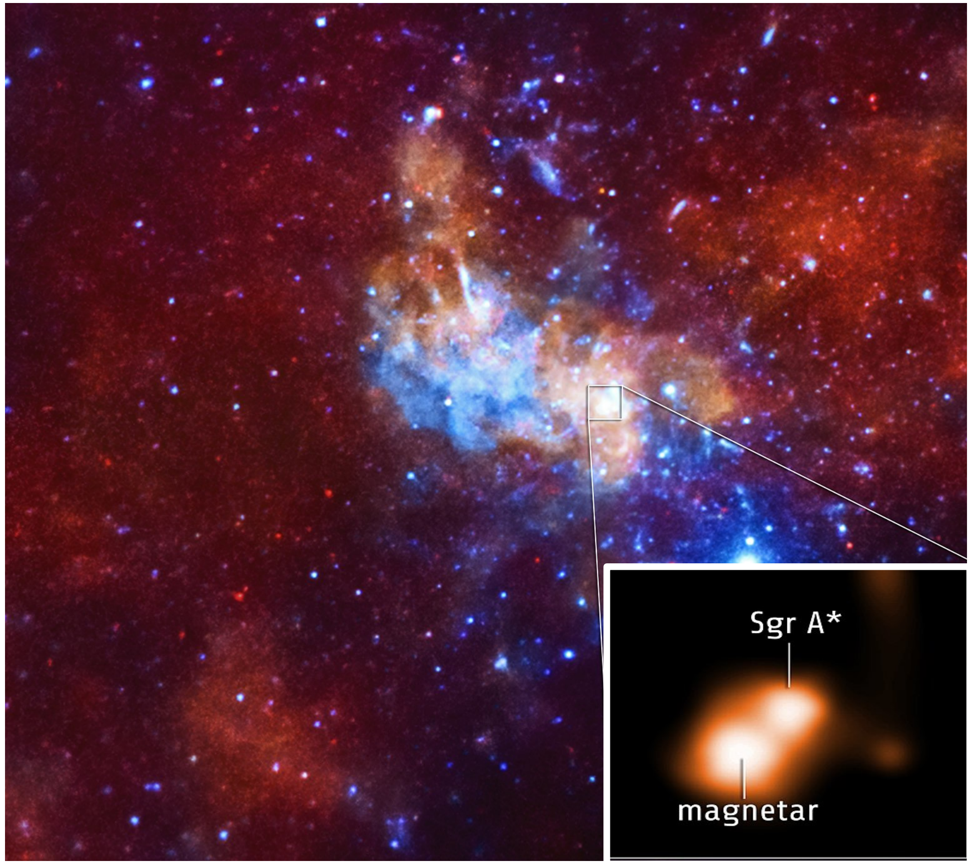
Populations vs **Galactic Centre Magnetar**

Galactic Centre Magnetar PSR J1745–2900

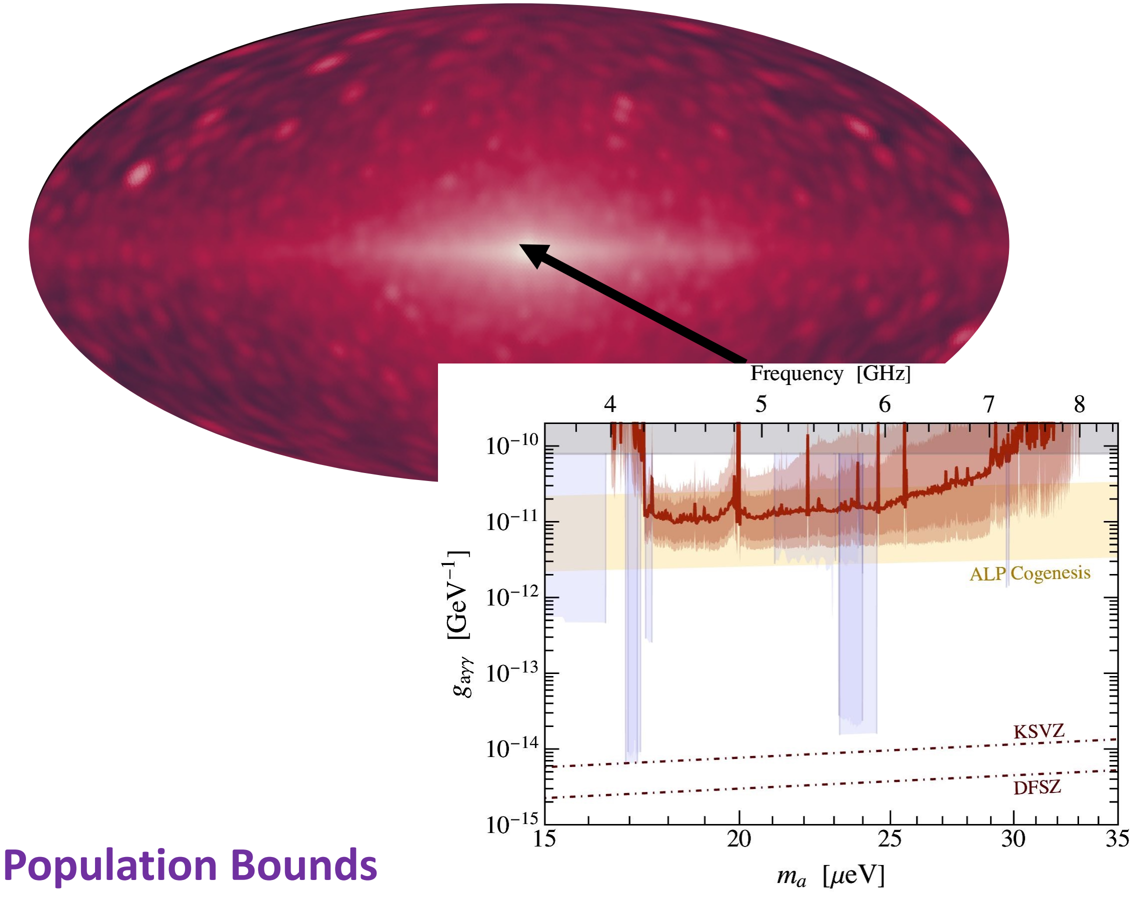
Darling [*Phys. Rev. Lett.* 125 (2020) 12, 121103]

Battye, Darling, **JM**, Srinivasan

[Phys. Rev. D 105 (2022) 2, L021305]



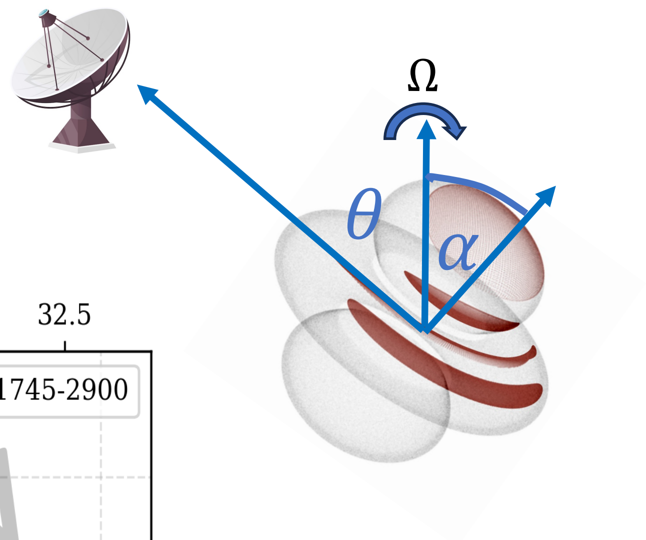
Battye, Bhura, **JM**, Srinivasan (in prep)



Population Bounds

Foster et al, Phys. Rev. Lett. 129, 251102 (2022)

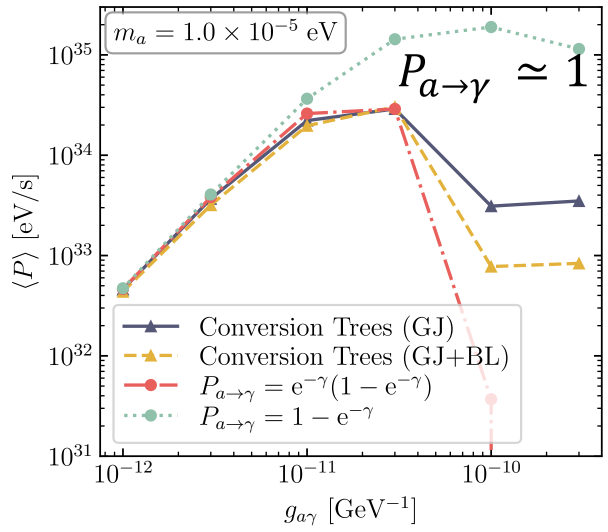
Populations vs Galactic Centre Magnetar

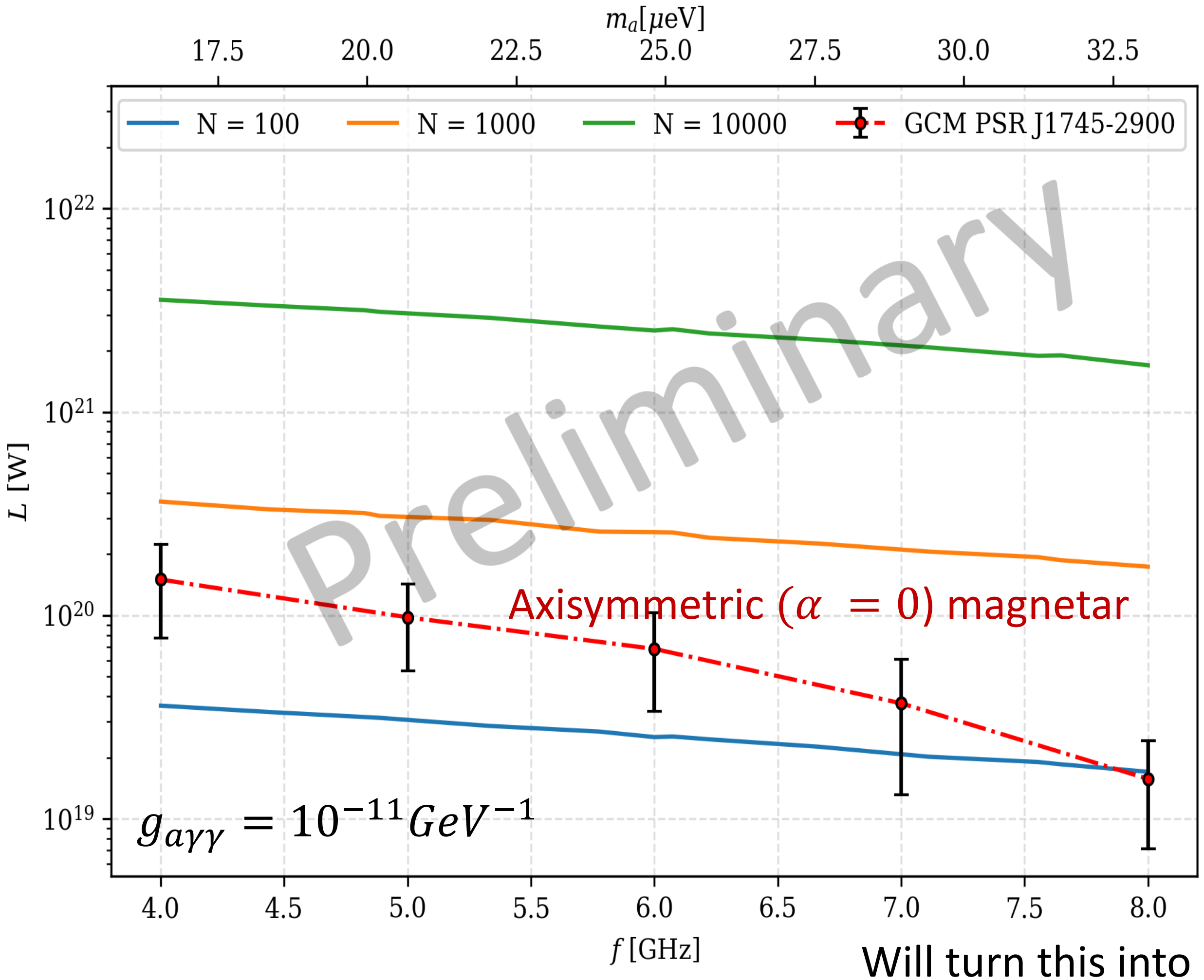


Magnetar uses latest non-perturbative $g_{a\gamma\gamma}$ code

Tjemsland, **JM**, and Samuel J. Witte
Phys. Rev. D 109 (2024), 023015

$B \simeq 10^{14} G$

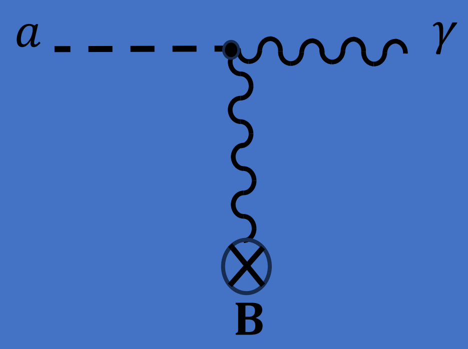




Will turn this into limits soon!
Battye, Bhura, **JM**, Srinivasan (in prep)

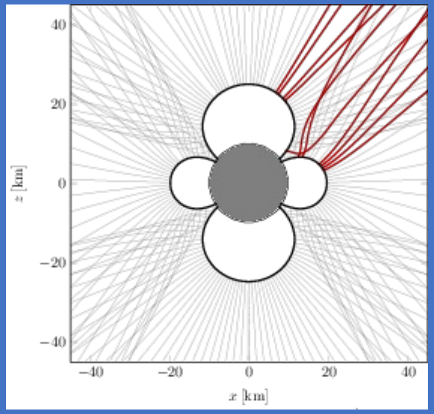
The Pipeline – State-of-the-Art

3D Production



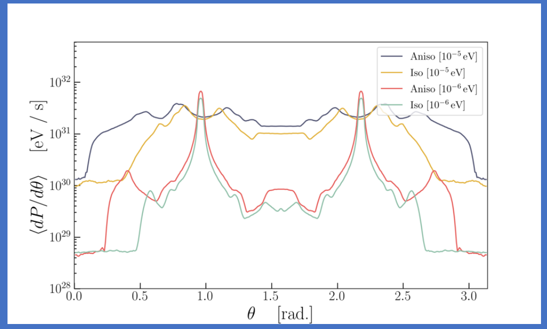
JM, *Millington, Garbrecht, JCAP* 12 (2023) 031
Millar, Baum, Lawson, Marsh JCAP 11 (2021) 013

Transport



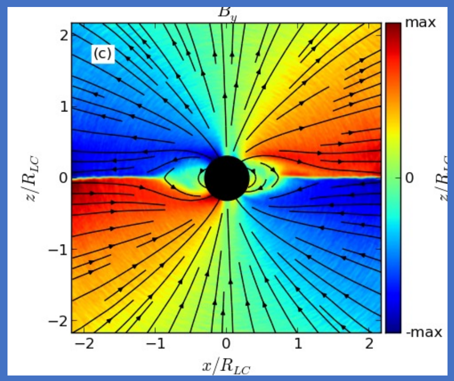
JM, *Witte, Phys. Rev. D 108 (2023) 10, 103021*
Battye, Garbrecht, **JM**, *Srinivasan JHEP 2021, 105 (2021)*
Witte et al Phys. Rev. D 104 (2021) 10, 103030

Signal Properties



Tjemsland, **JM**, and Samuel J. Witte
Phys. Rev. D 109 (2024), 023015

Magnetosphere



Ready for dialogue with pulsar modellers?

Safdi, Sun, **Chen** Phys.
Rev. D 99 (2019) 12, 123021

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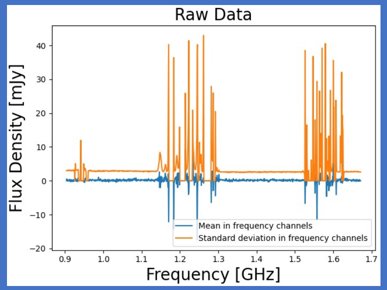
Observations



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Conclusions

- Neutron stars strong probes of fundamental physics
- Extensive computational pipeline developed
- Active observational programme
- **To Do** :
  Magnetar vs Populations
  magnetosphere/uncertainties (MITP, MIAPP workshop?)
- **Future: Square Kilometre Array (SKA) very exciting**
- **Theorists: keep going! Find new mechanisms !**