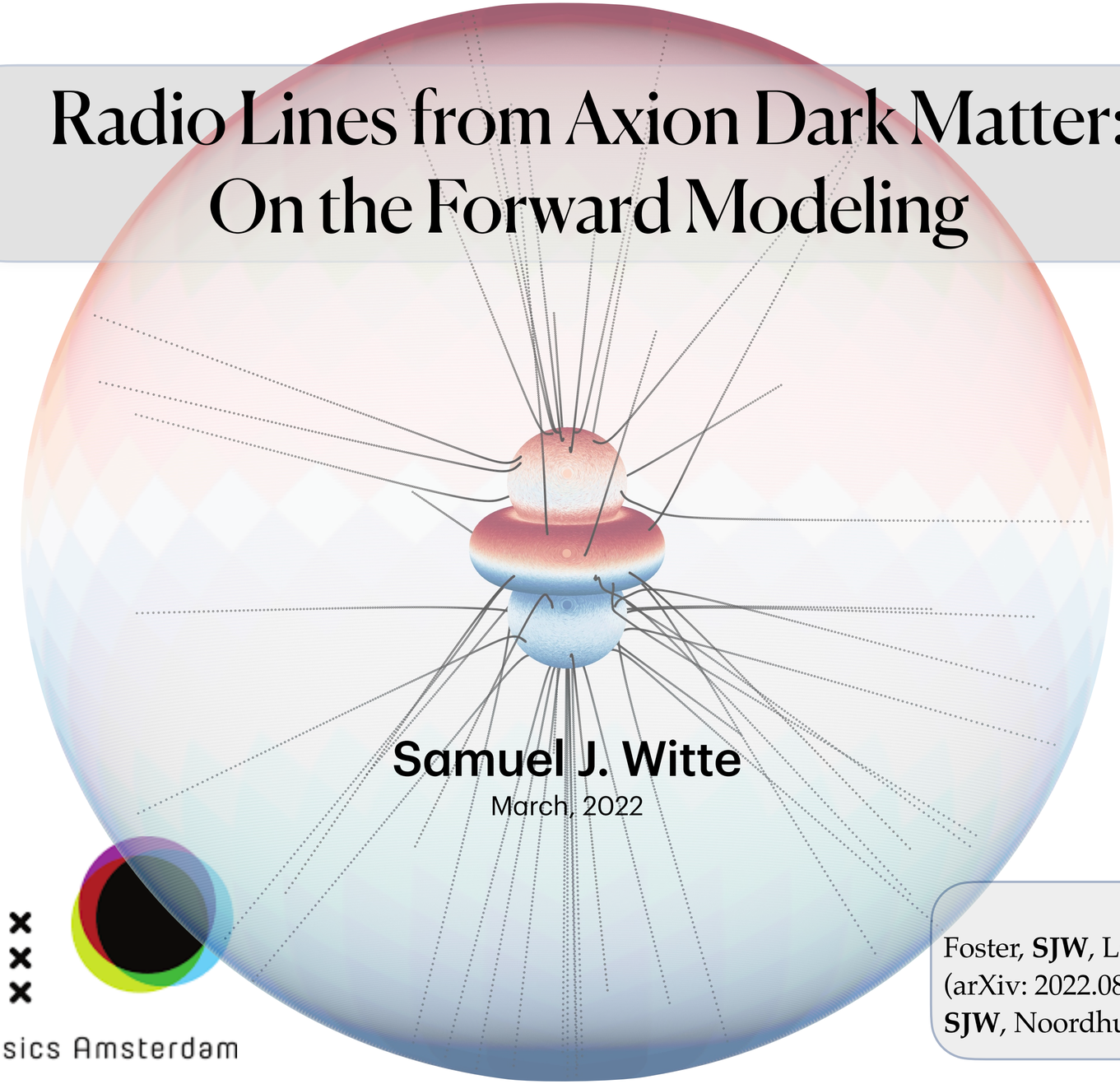
Radio Lines from Axion Dark Matter: On the Forward Modeling



Samuel J. Witte

March, 2022

GRAPPA

GRavitation AstroParticle Physics Amsterdam

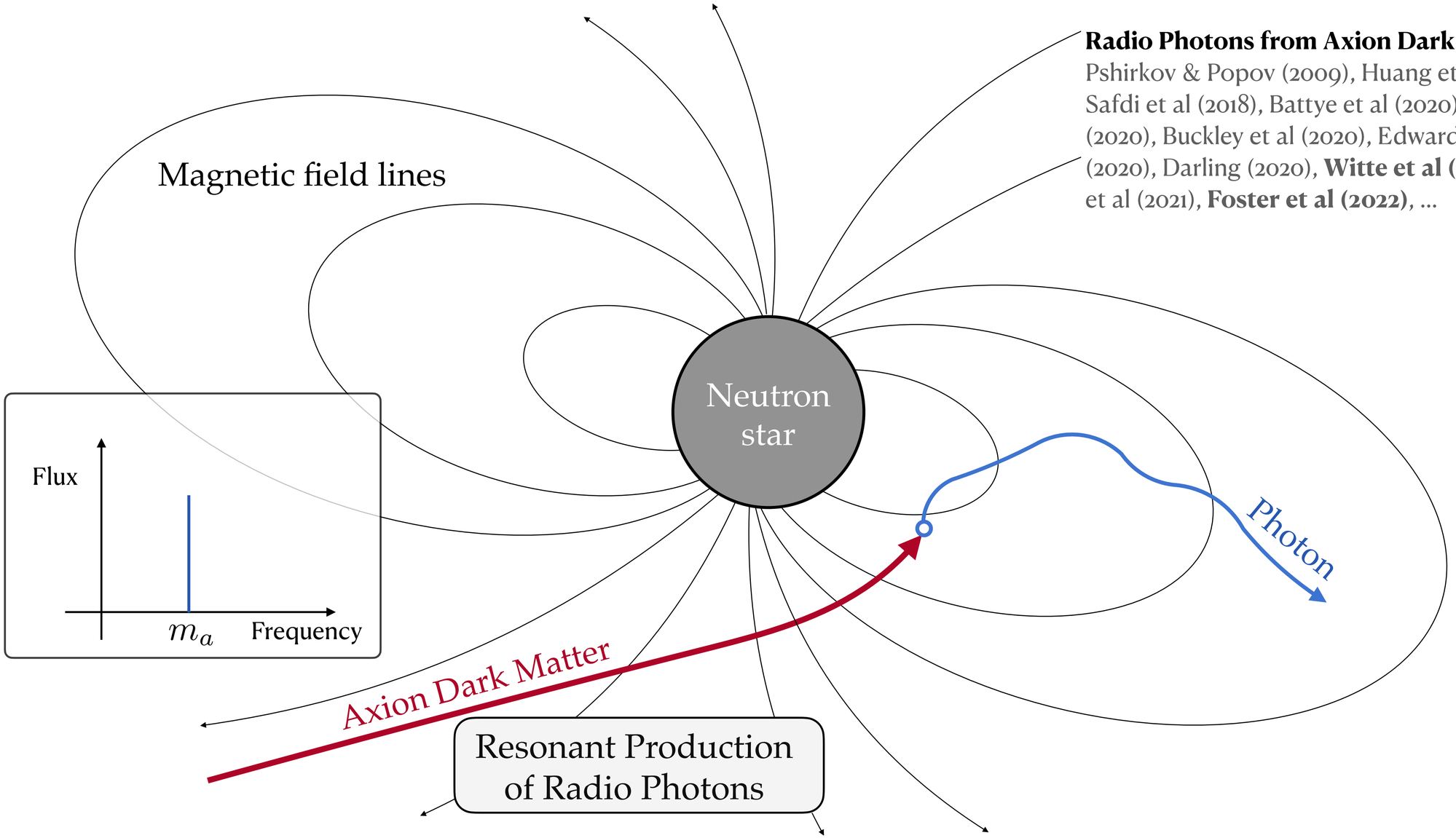
Based on:

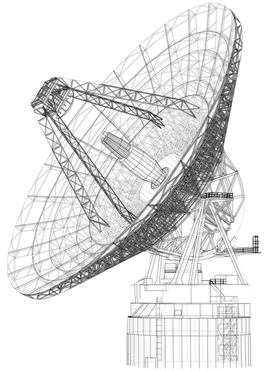
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

SJW, Noordhuis, Edwards & Weniger, PRD 2021

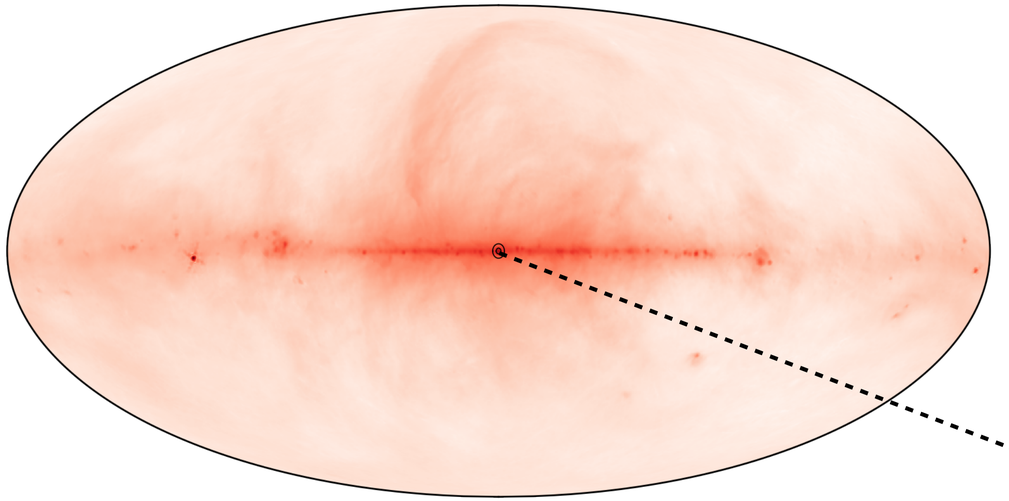
Radio Signals from Axion Dark Matter

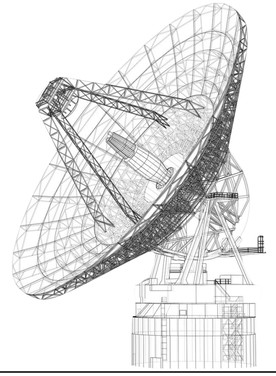
Radio Photons from Axion Dark Matter (abridged):
Pshirkov & Popov (2009), Huang et al (2018), Hook et al (2018), Safdi et al (2018), Battye et al (2020), Leroy et al (2020), Foster et al (2020), Buckley et al (2020), Edwards et al (2019), Edwards et al (2020), Darling (2020), **Witte et al (2021),** Battye et al (2021), Millar et al (2021), **Foster et al (2022)**, ...





Axion Search with the Breakthrough Listen Galactic Center Survey





Survey Details:

- **Telescope:** Green Bank Telescope, 100m Single Dish
- **Observation Frequency:** 4–8 GHz [C band]
- **Observation Target:** Milky Way Galactic Center [inner ~ few pcs]
- **Observation Time:** ~4.6 hours
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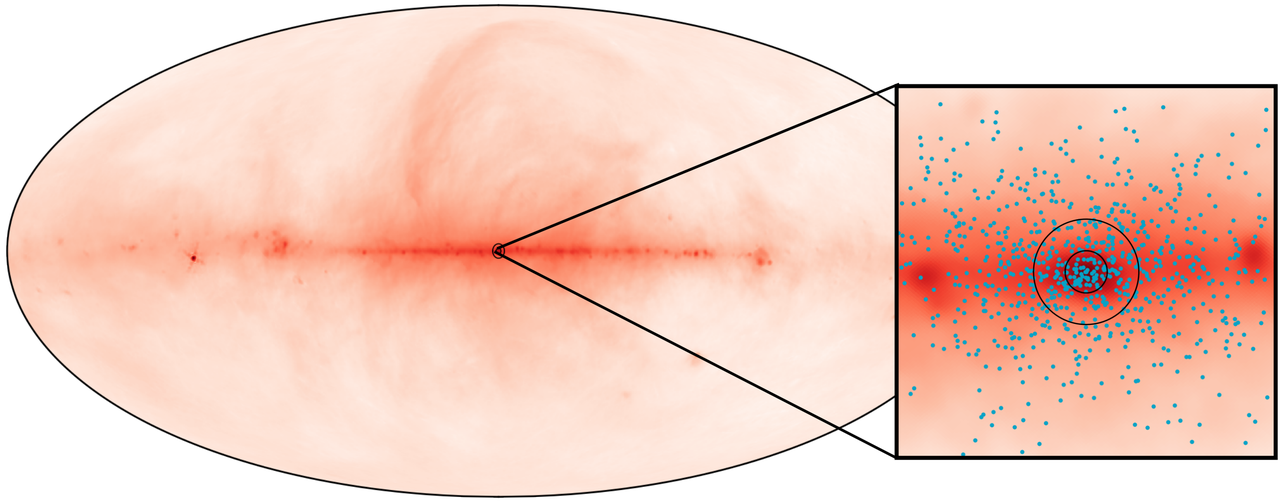

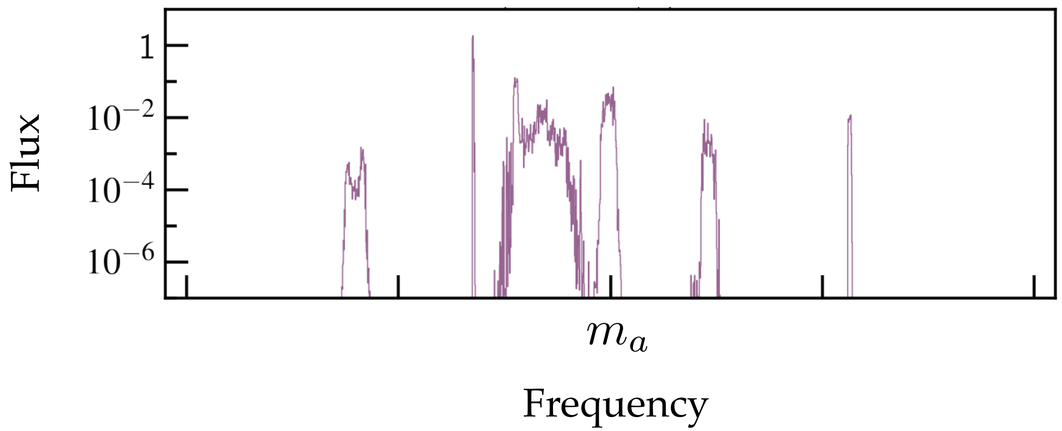

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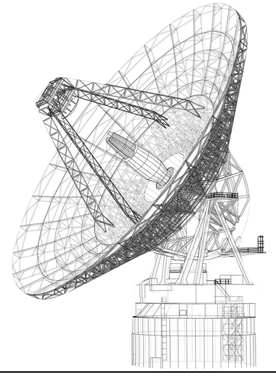

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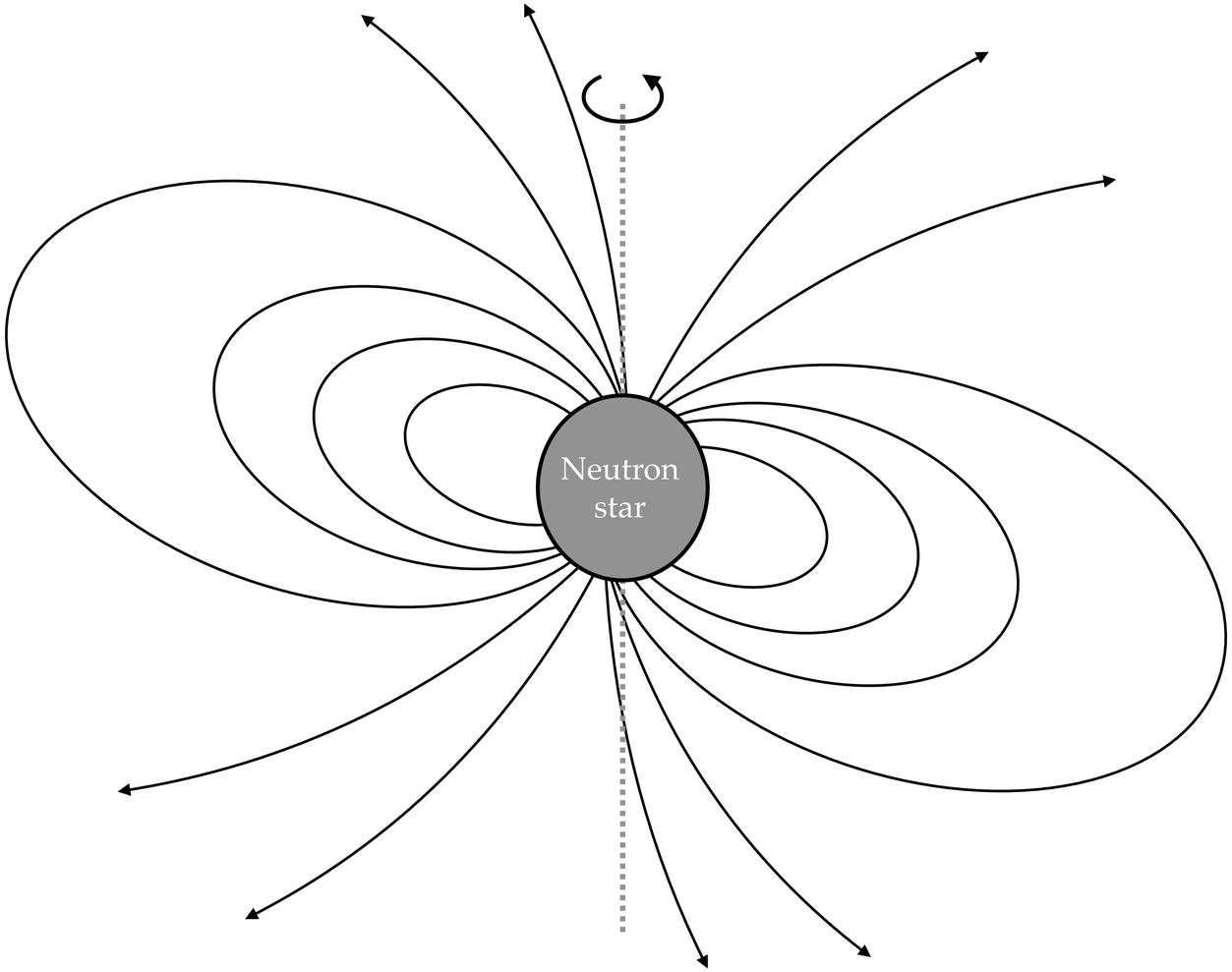
Computing the Radio Flux



For each neutron star, one must define

- Magnetic field
- Rotational period
- Misalignment angle
  [rotation & magnetic axis]
- Position
- Velocity

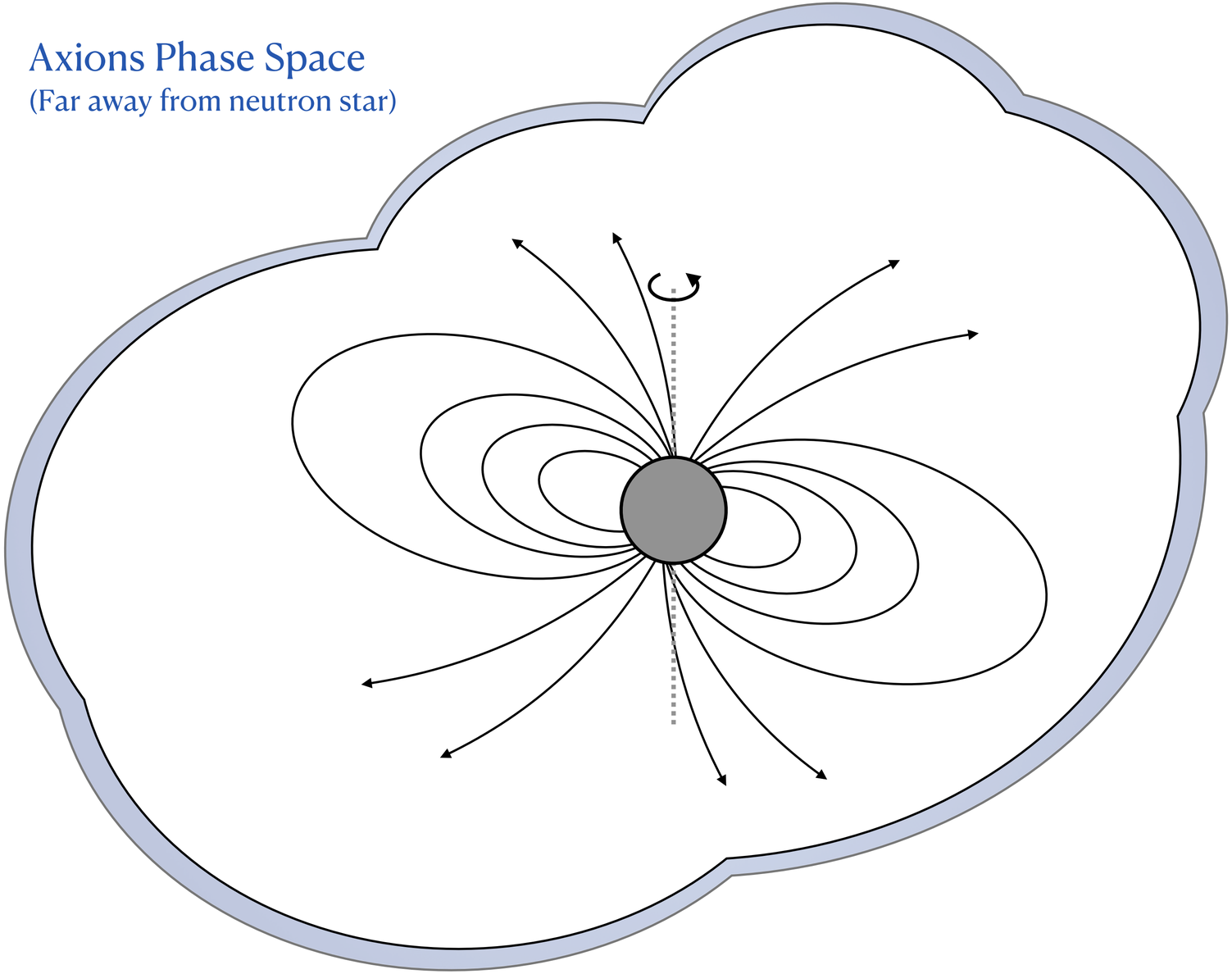
[Monte Carlo Sampled from Population]

- Mass
- Radius

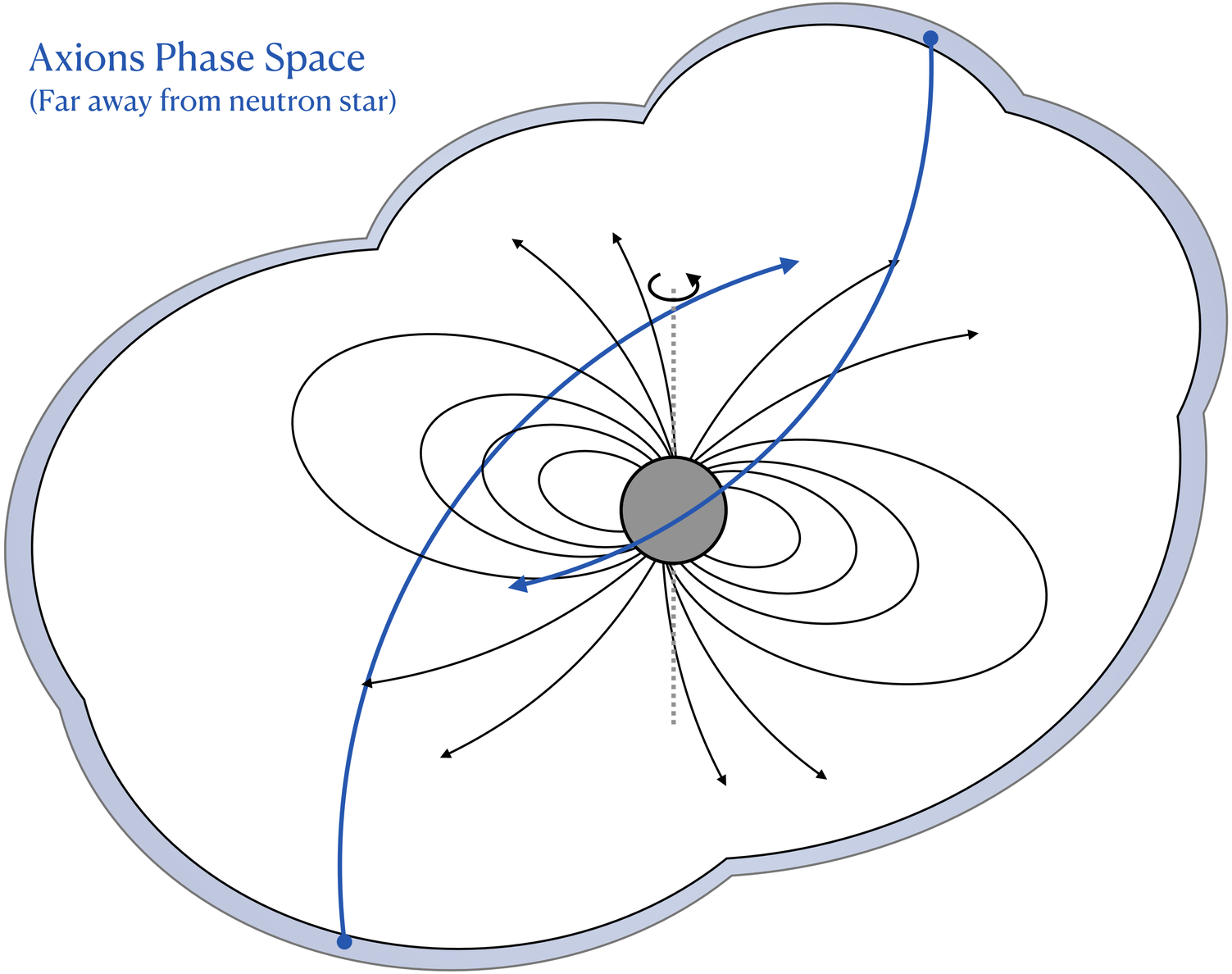
[Small Impact]

Computing the Radio Flux

Axions Phase Space
(Far away from neutron star)



Computing the Radio Flux



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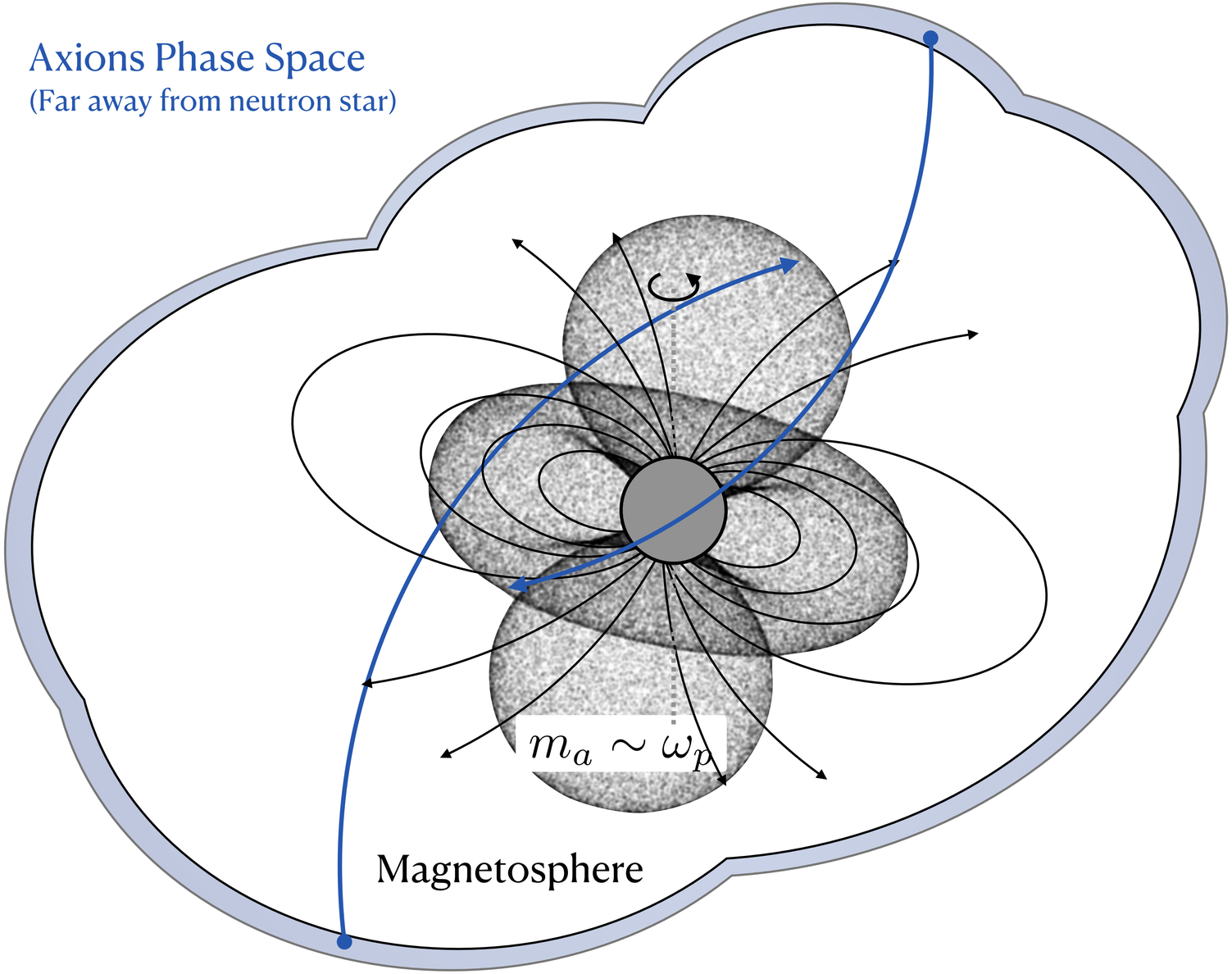

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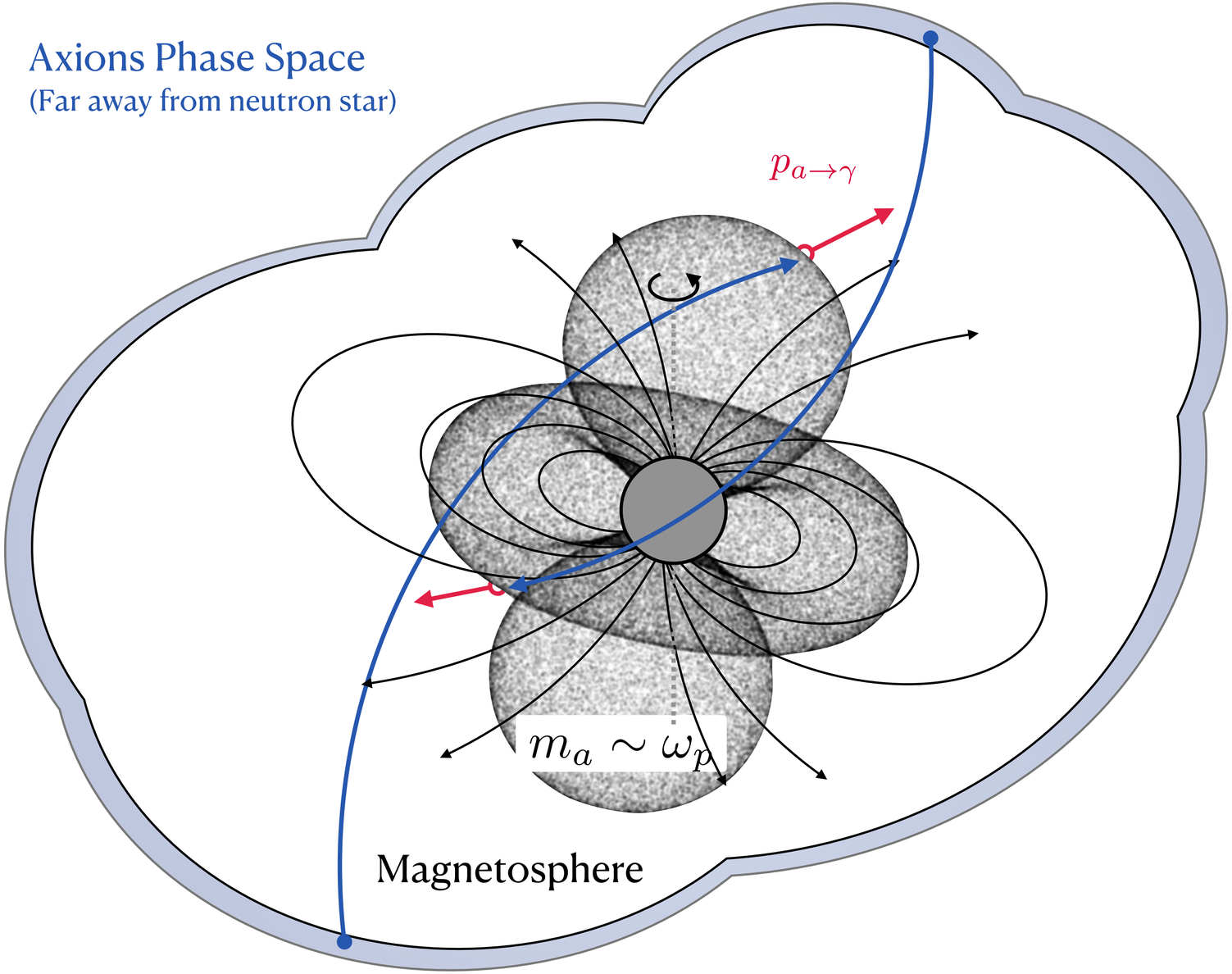

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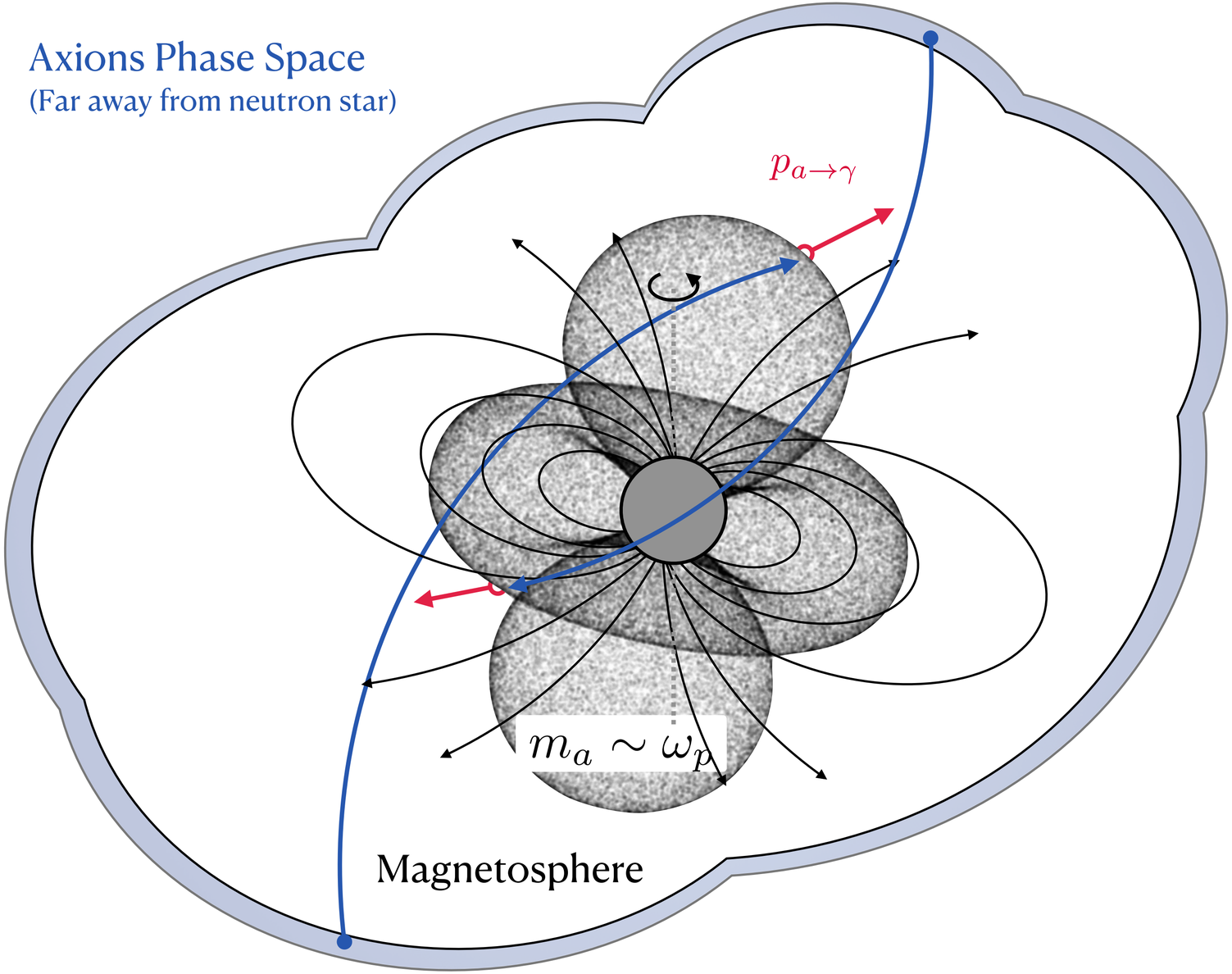


(Assuming conversion probability small)

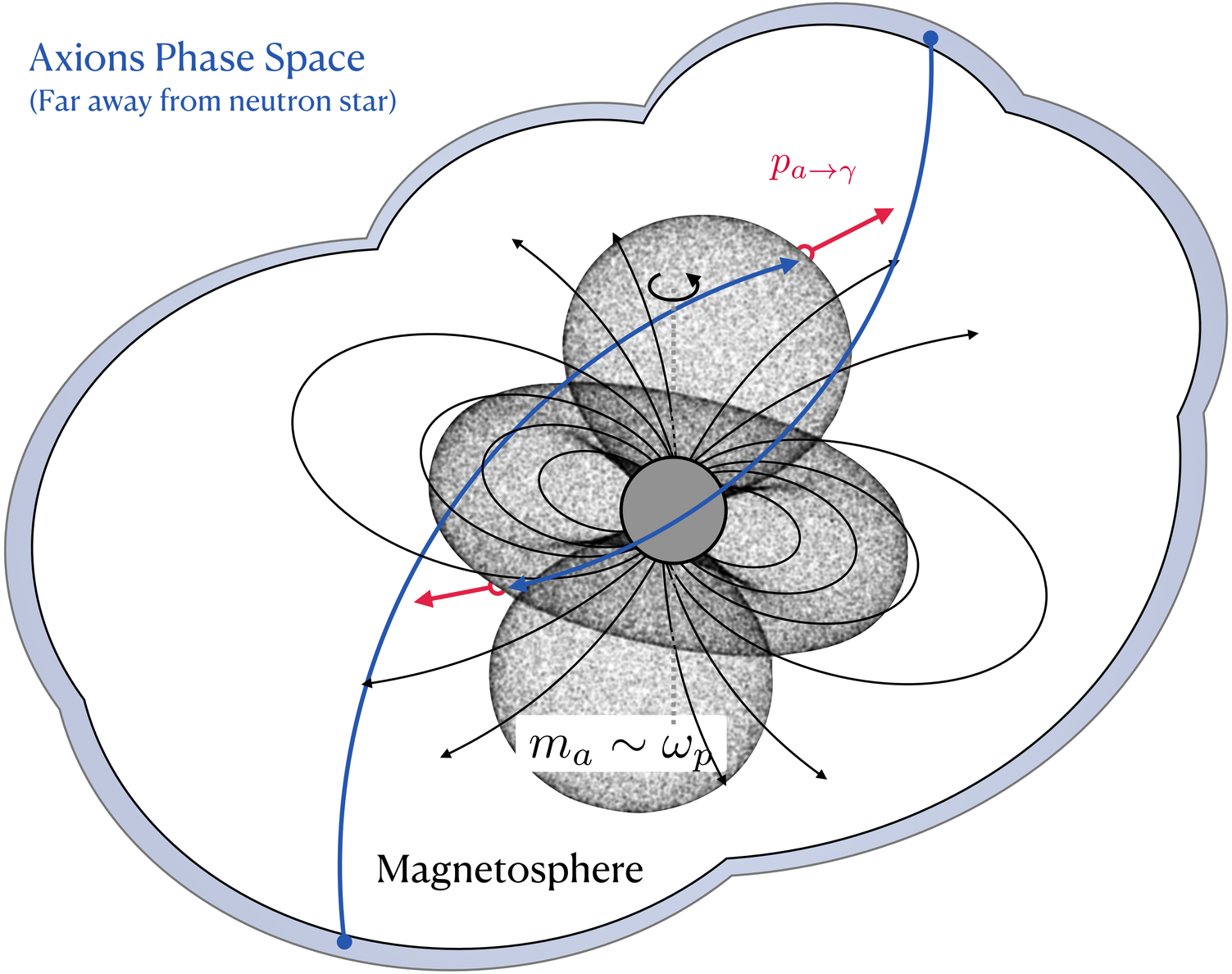
$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 \, B^2 \, L^2$$

Length scale

$$L \propto \sqrt{\frac{1}{|\partial_s k_\gamma|}}$$

[L ~ O(100) m]

Computing the Radio Flux



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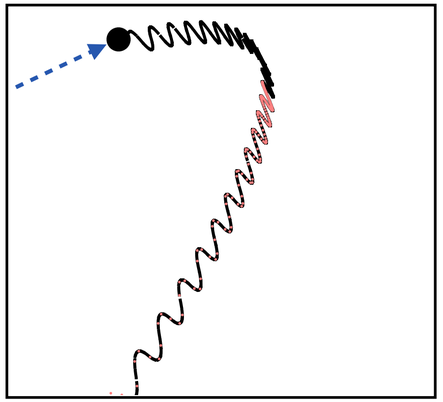
Caveat # 1

Assumes straight trajectories

Hook et al (2018), Millar et al (2021)



~ 500 meters

De-phasing approximations

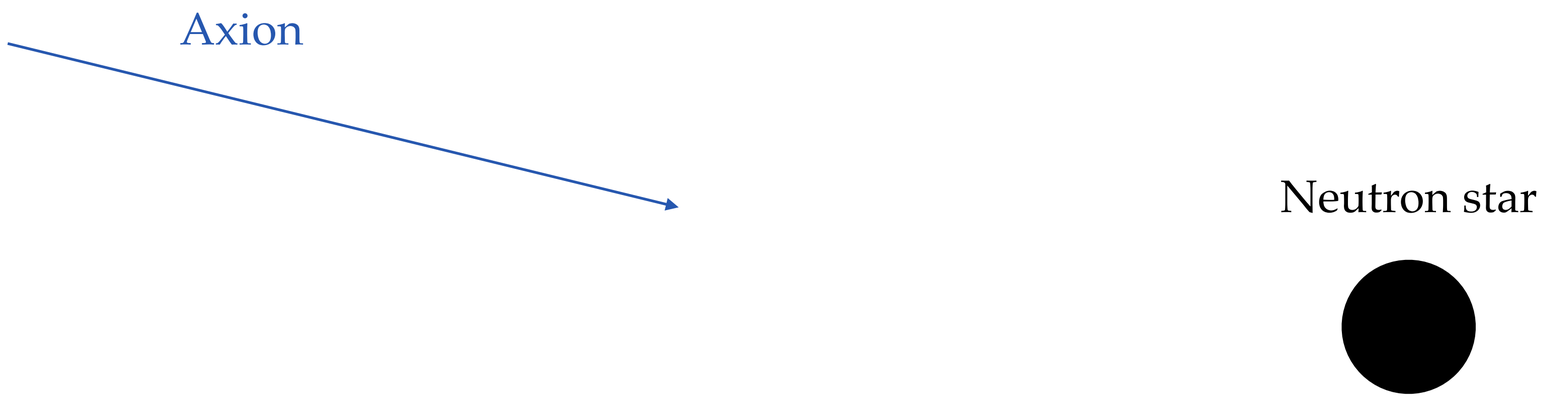
SJW, Noordhuis, Edwards, Weniger (2021)

Conversion Probability: Caveat #2

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

<u>Small coupling regime</u>

$$P_{a\to\gamma} \ll 1$$



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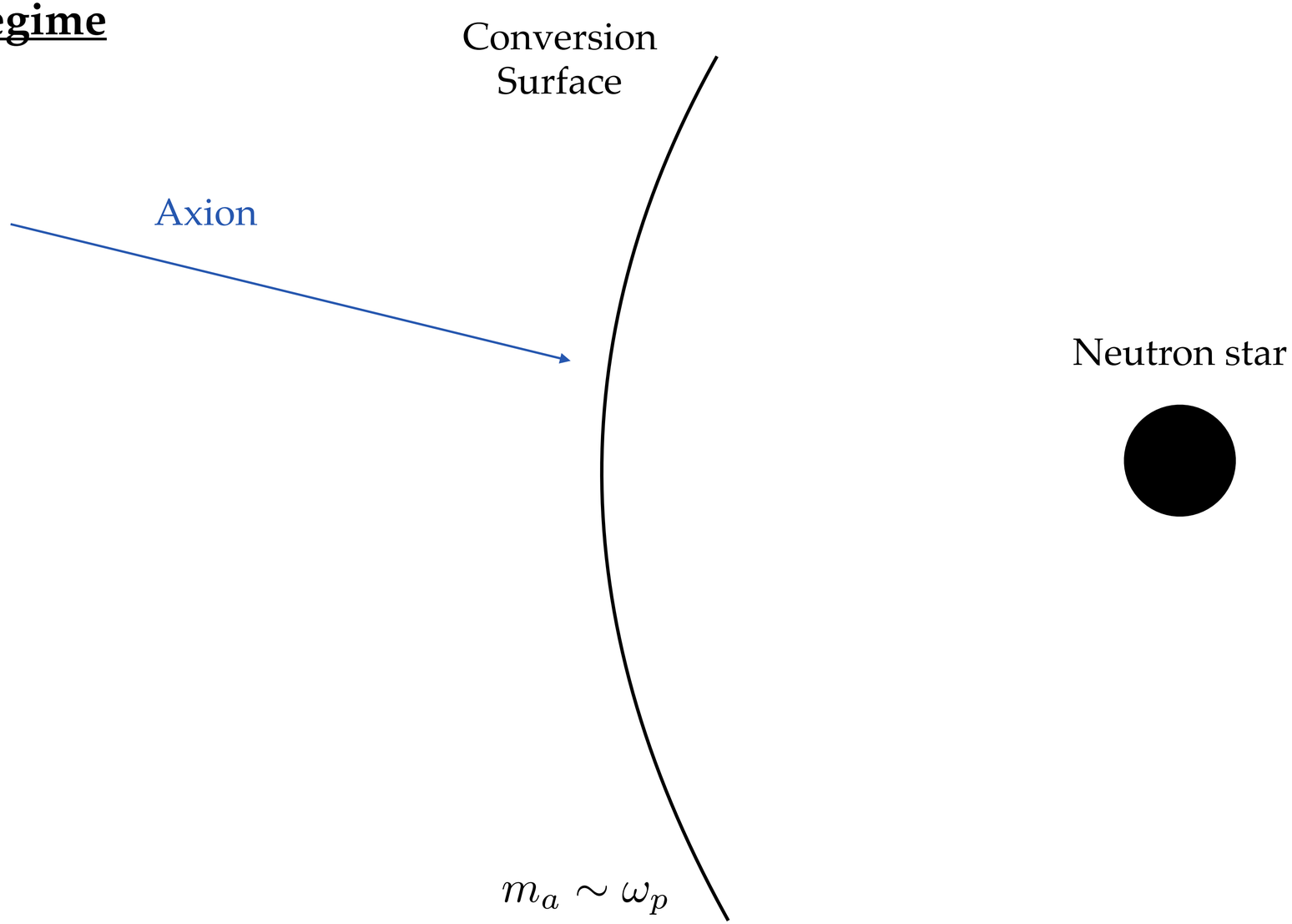

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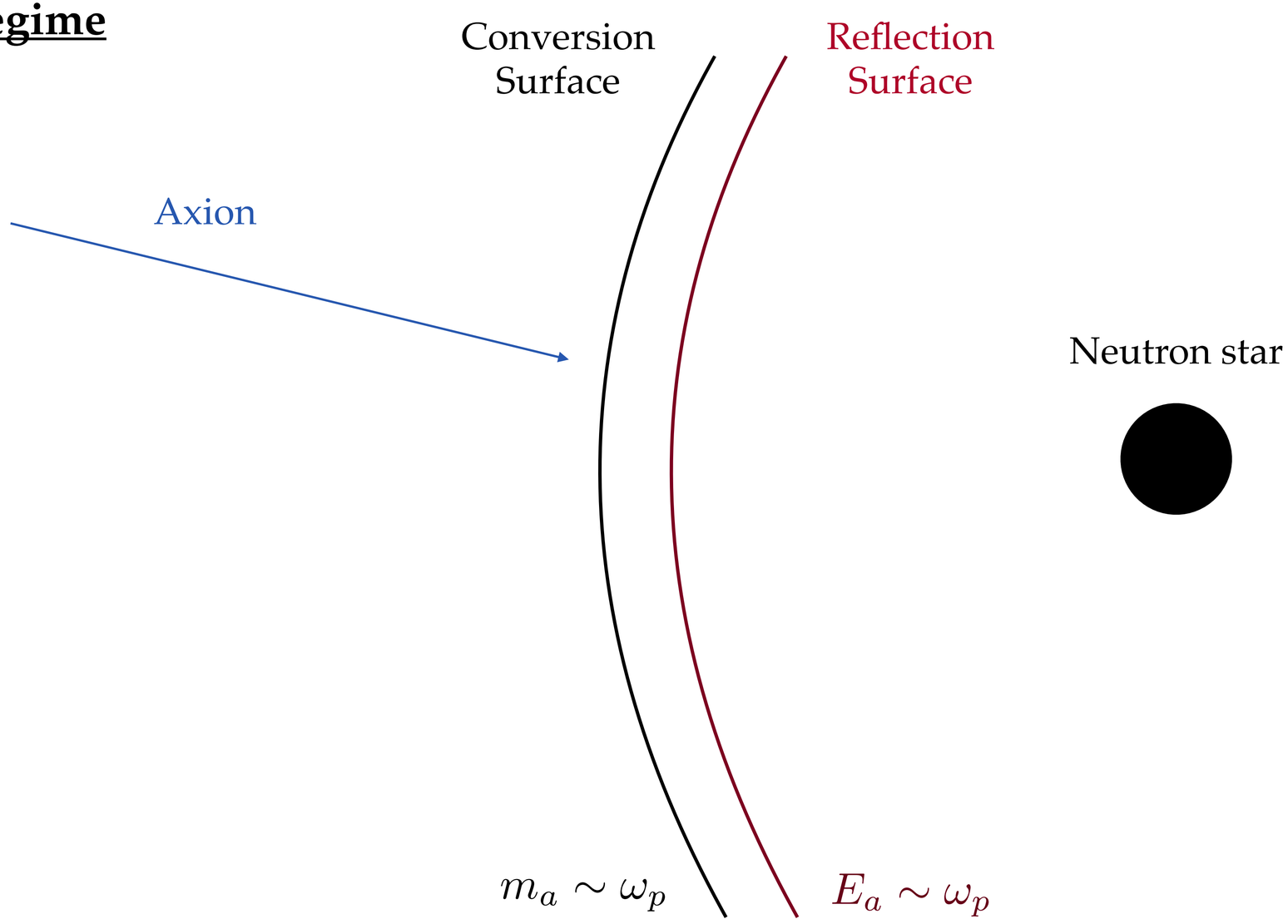

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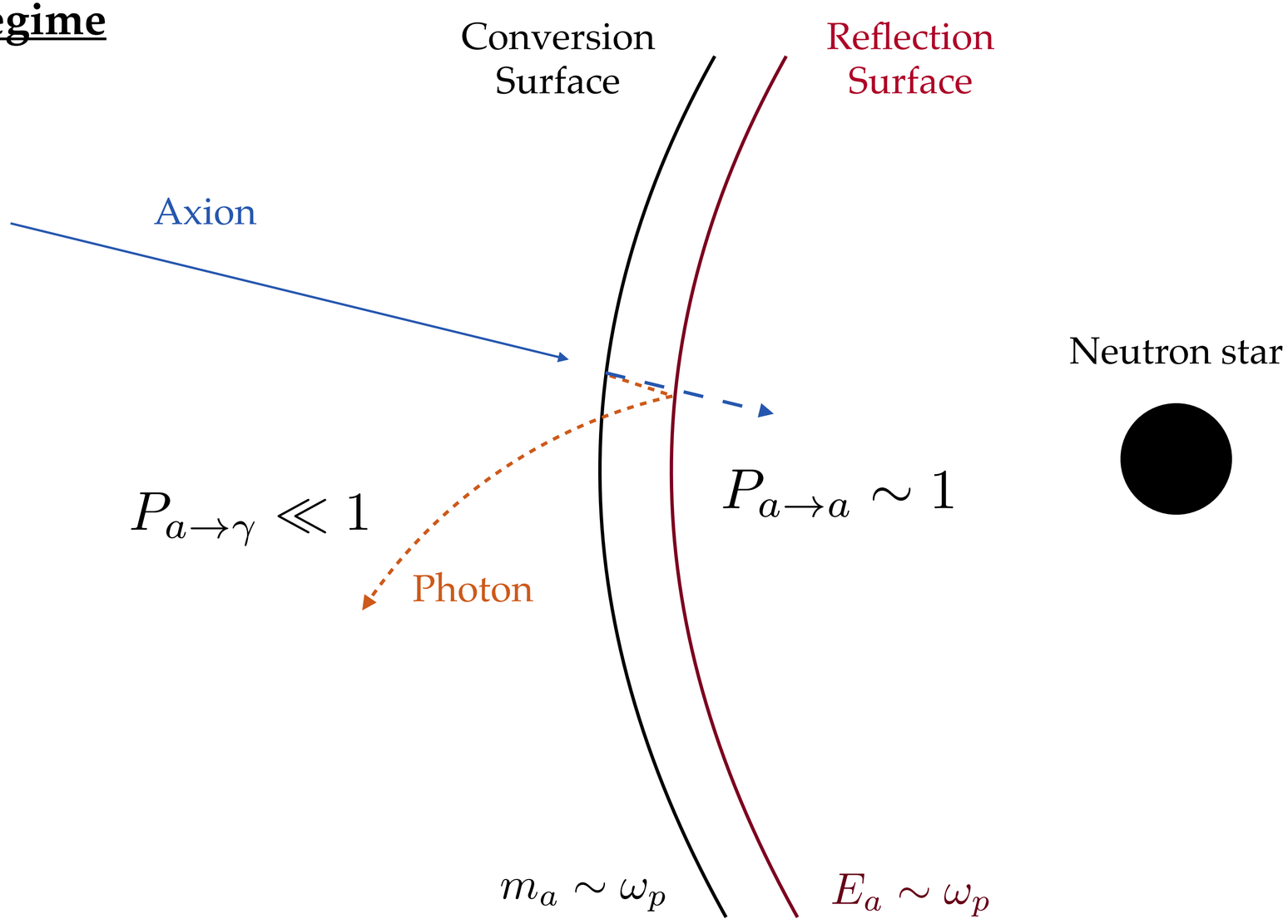

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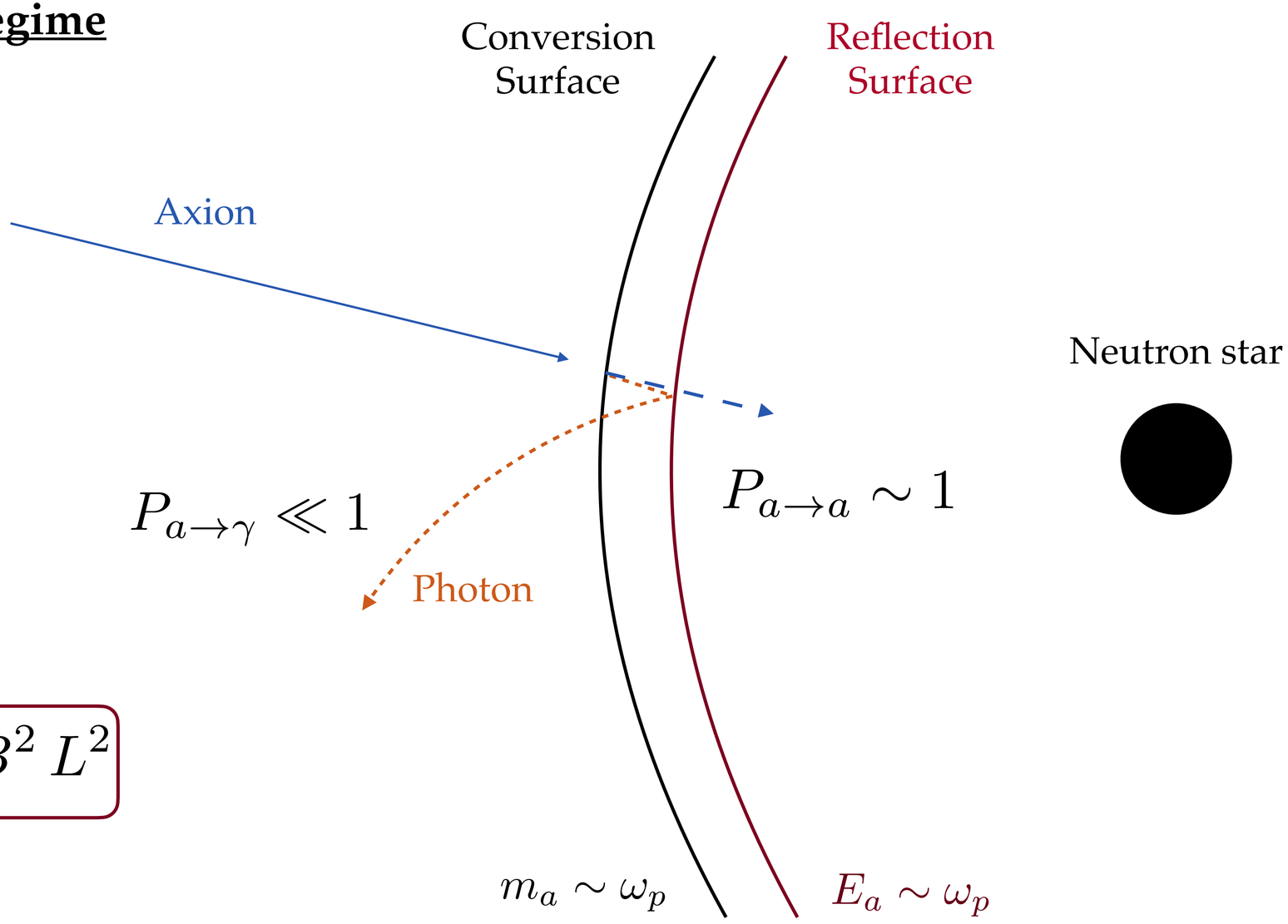

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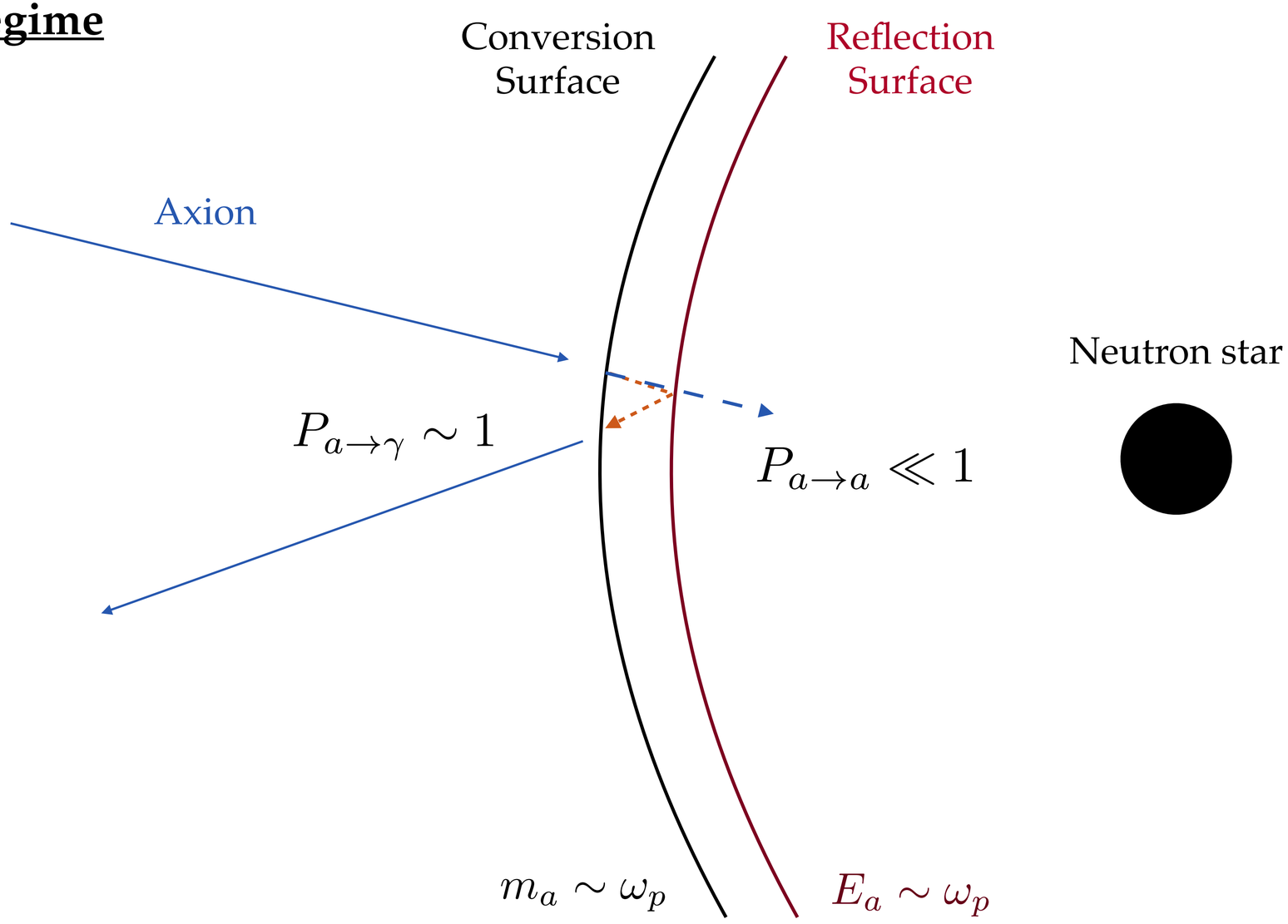

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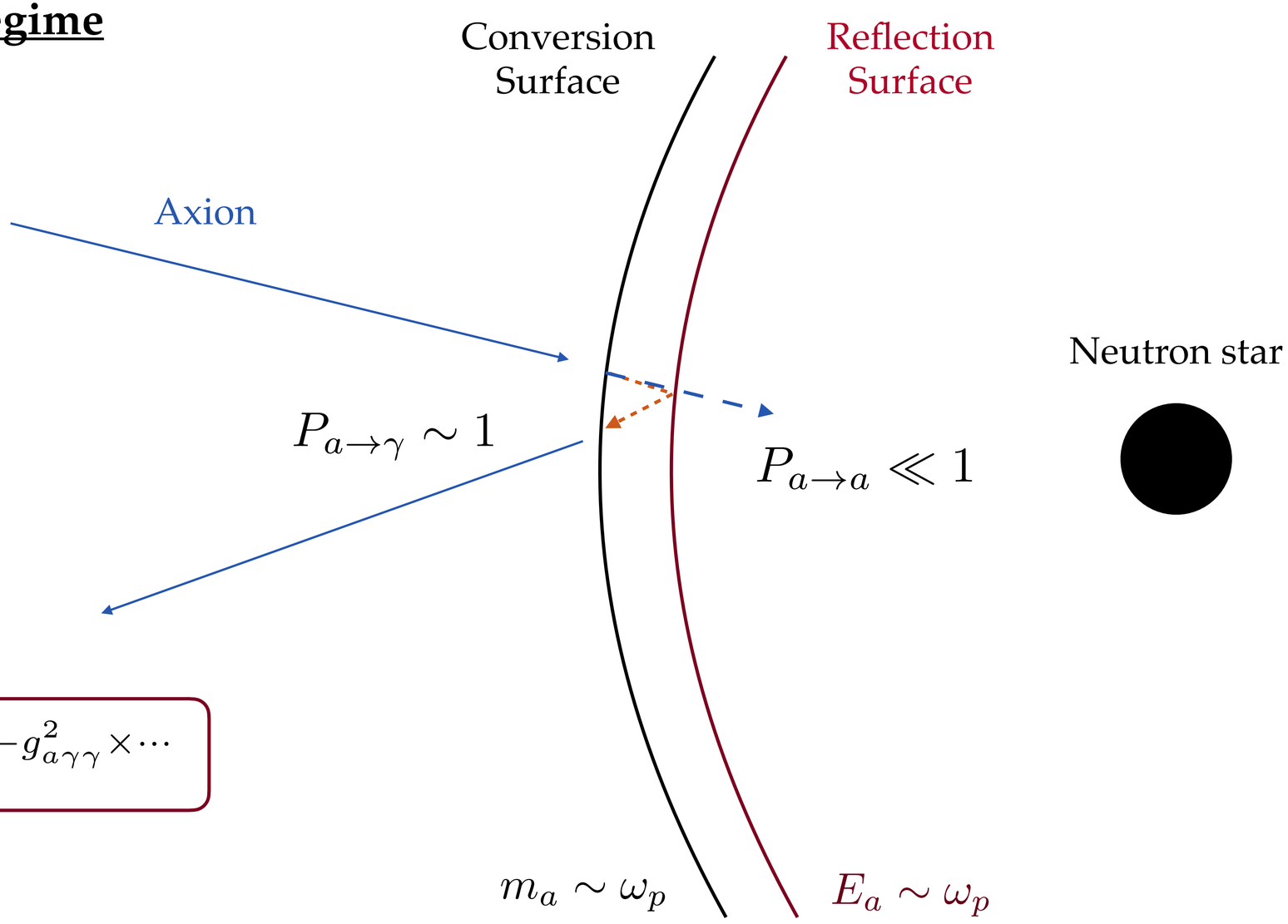

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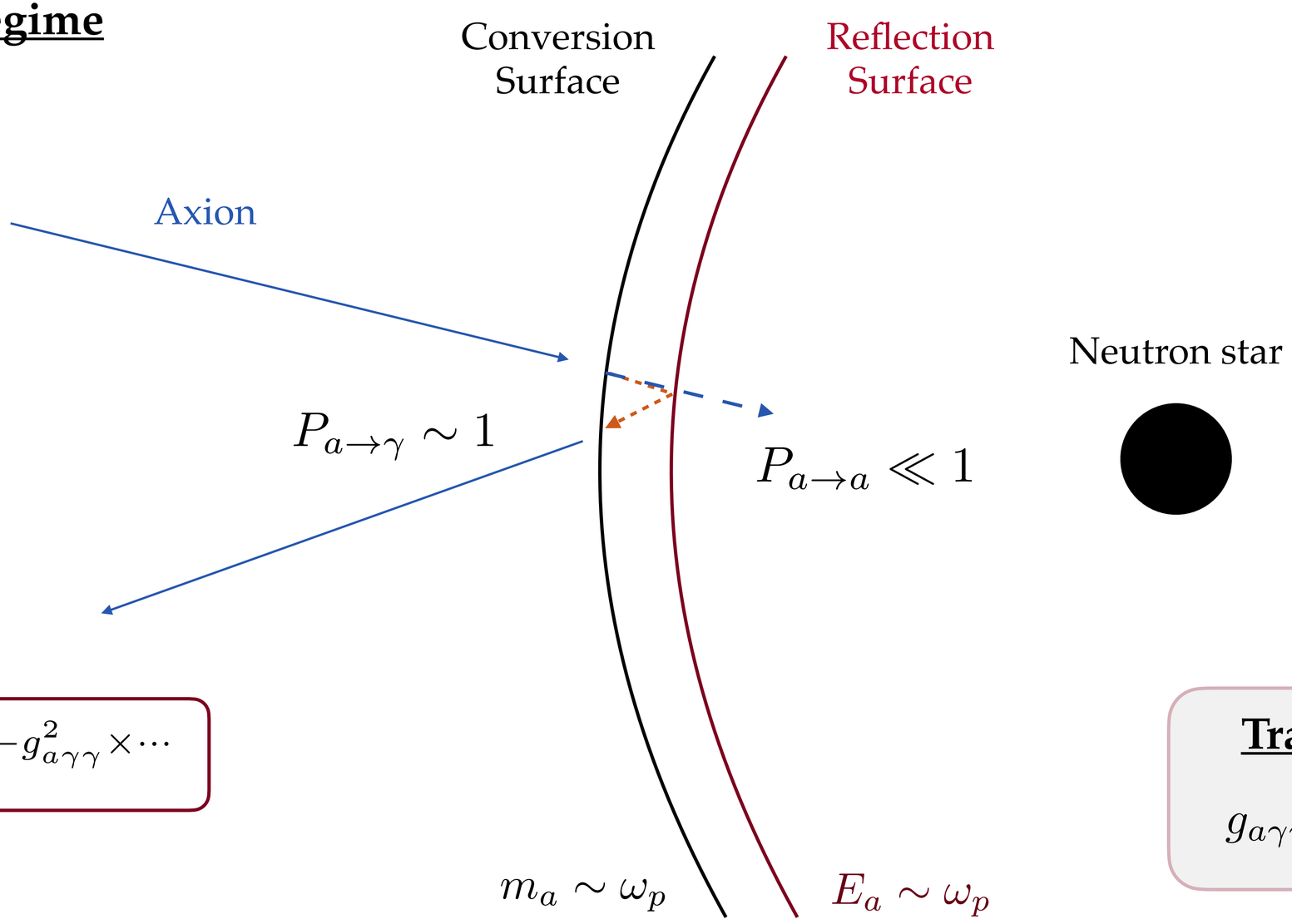

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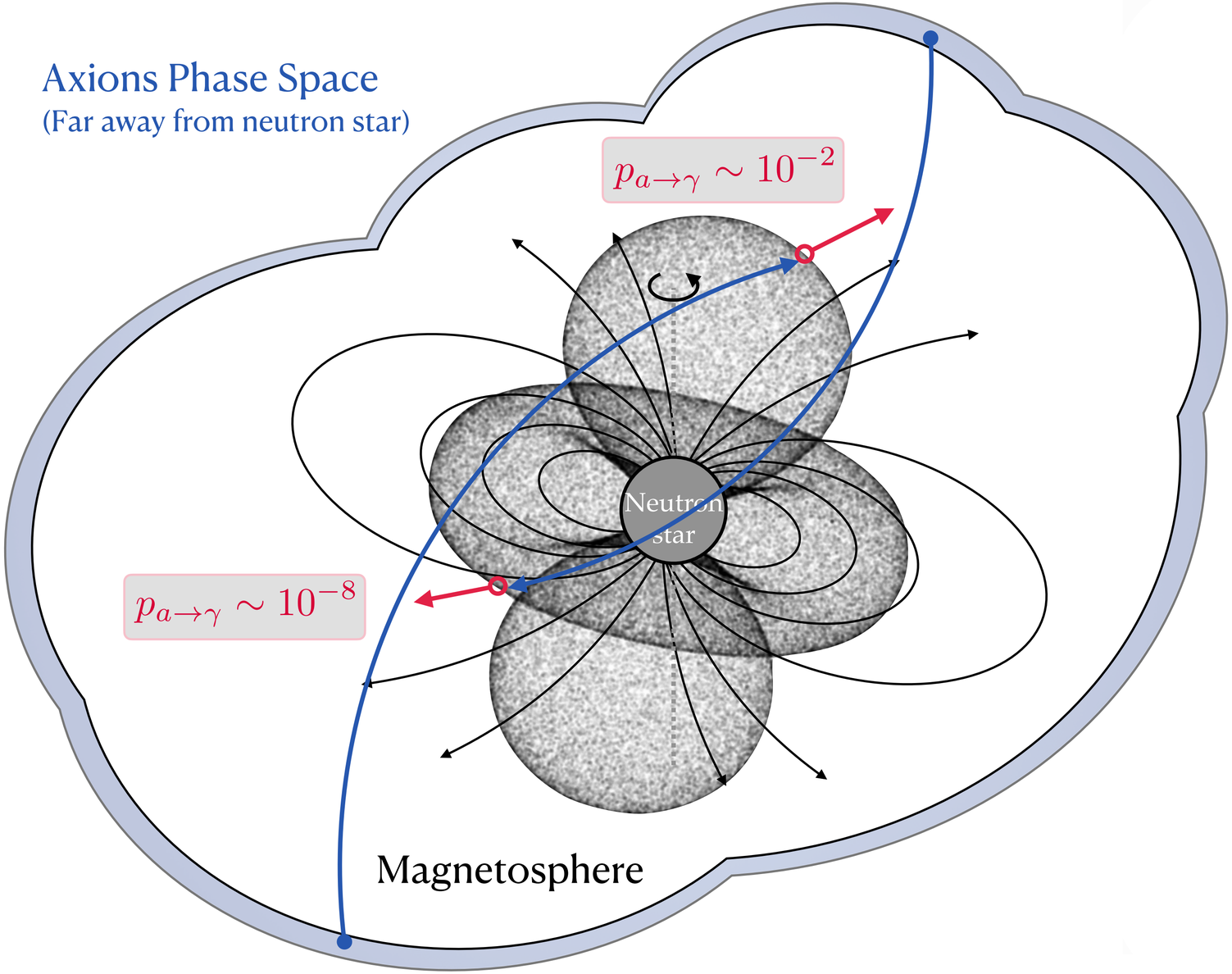
Transition Regime

$g_{a\gamma\gamma} \sim 10^{-12}\,\mathrm{GeV}^{-1}$

Computing the Radio Flux



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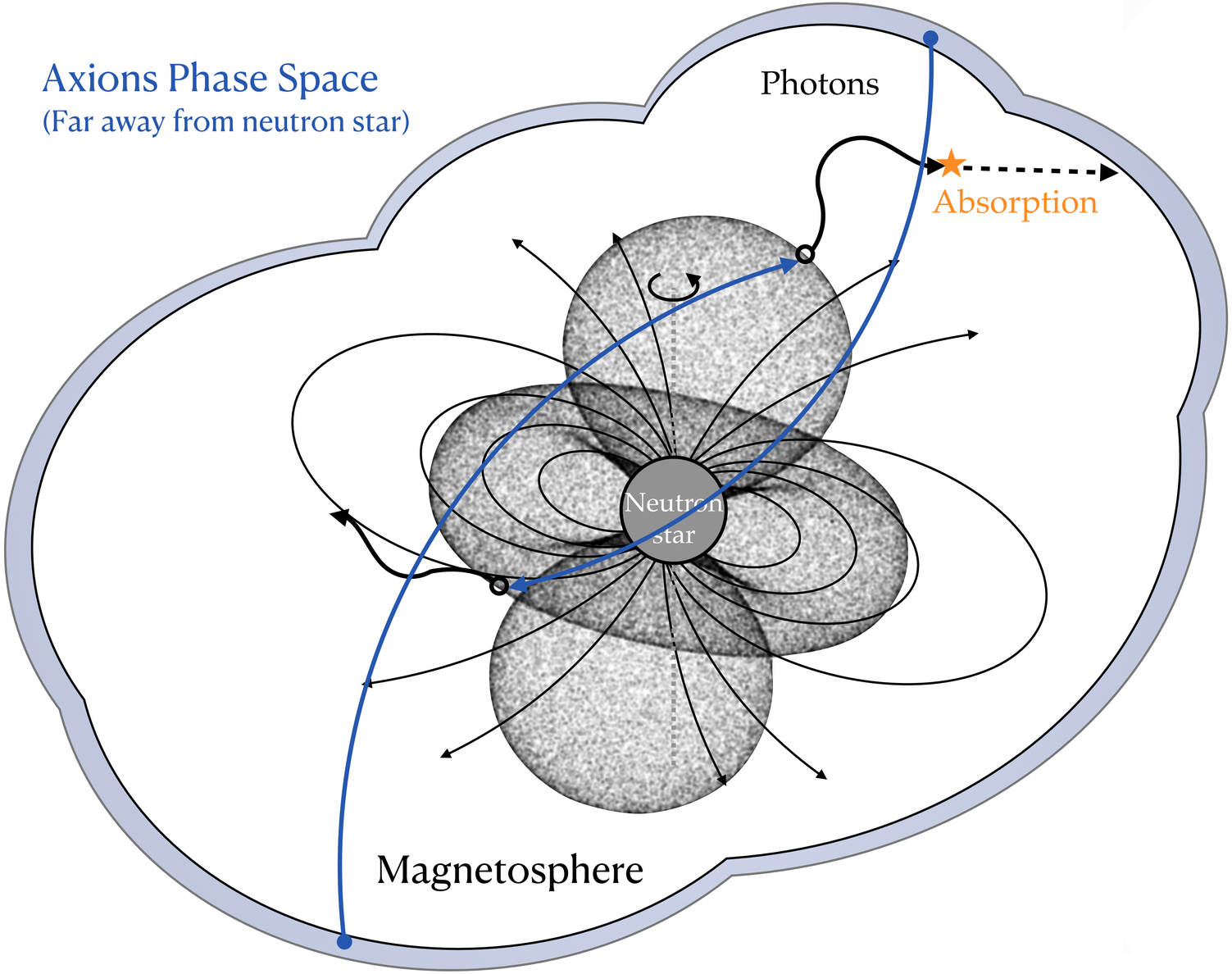

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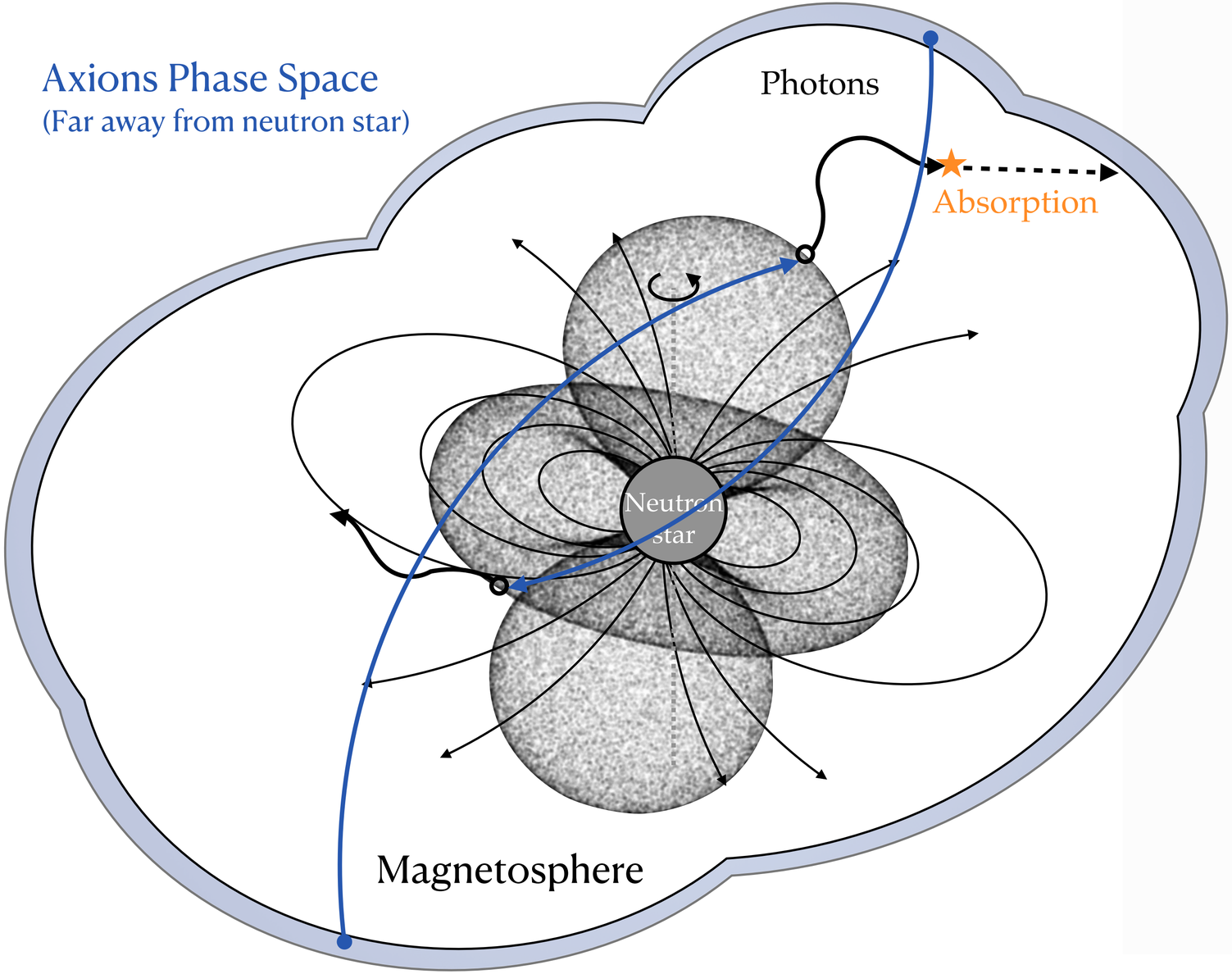

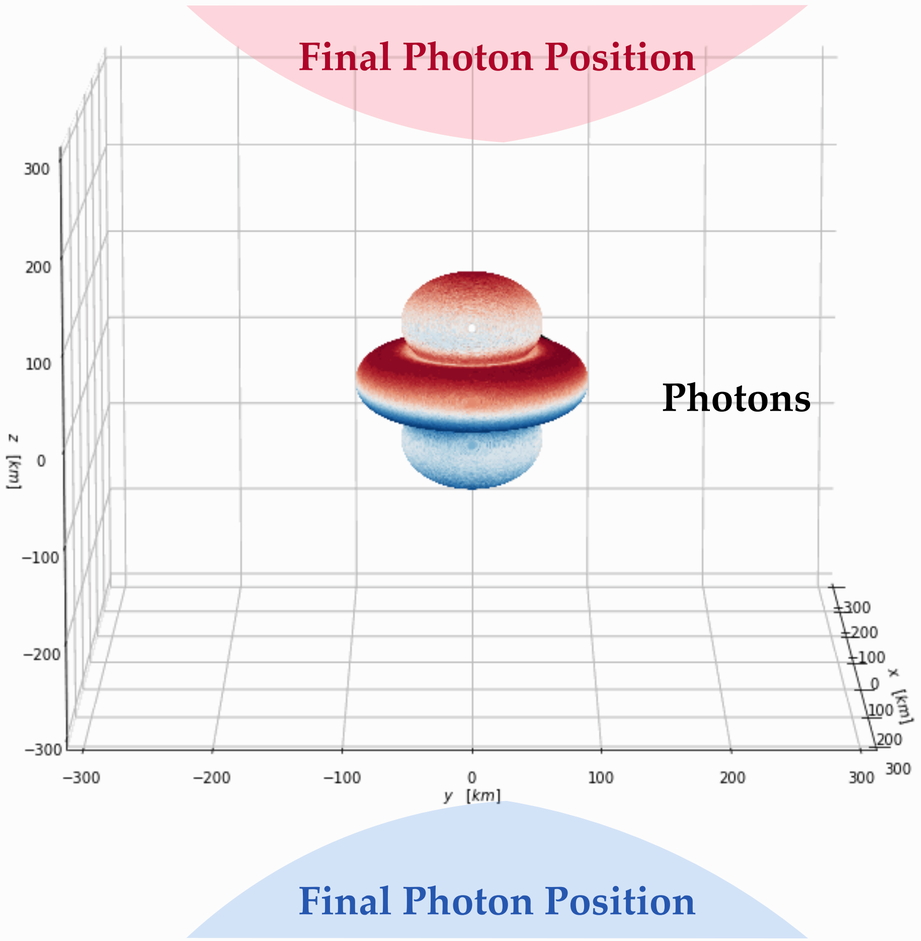

SJW, Noordhuis, Edwards, Weniger (2021)

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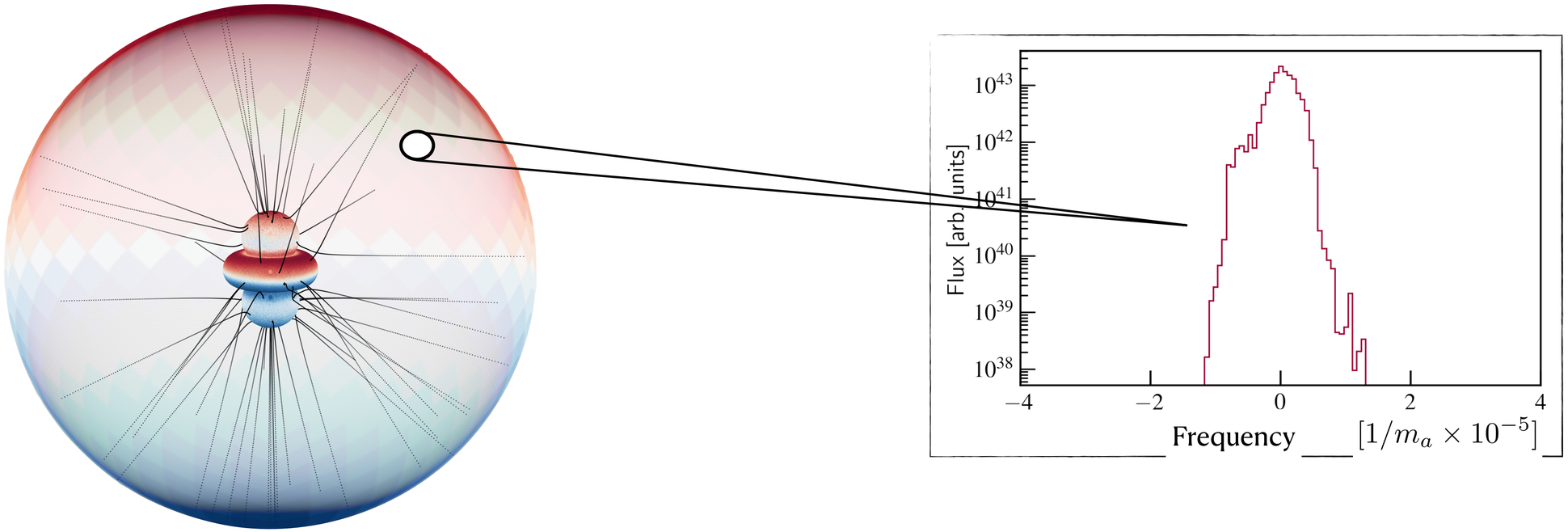
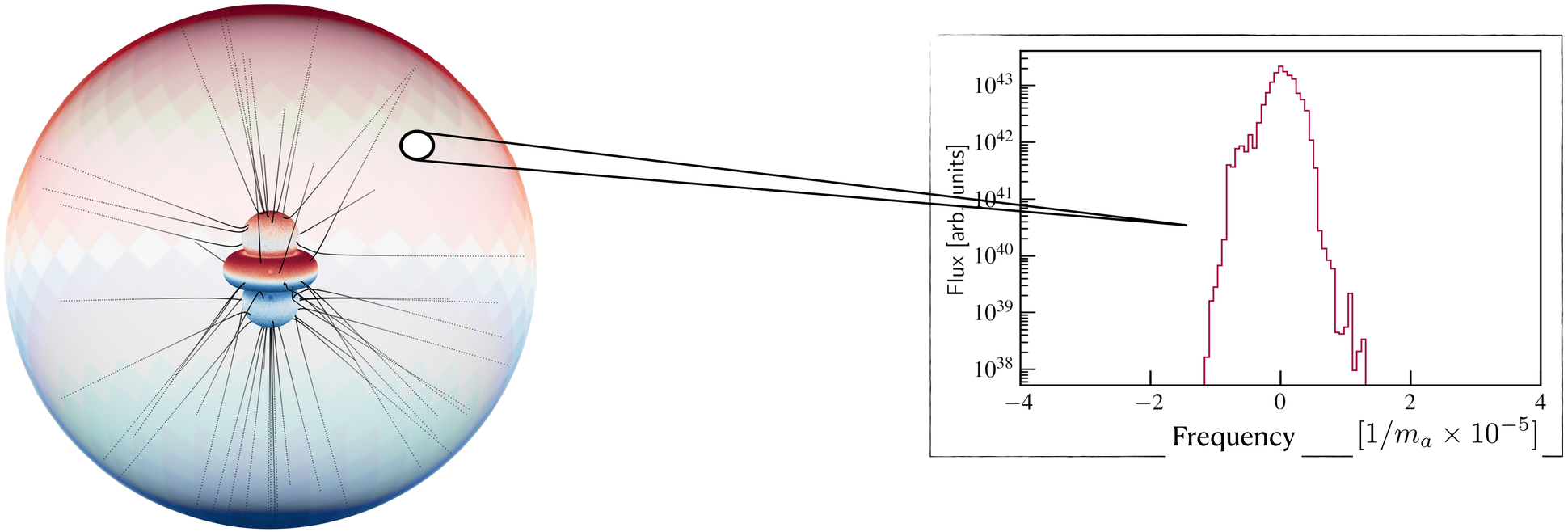


Sample Viewing Angle

Construct spectrum

Computing the Radio Flux



Sample Viewing Angle

Construct spectrum

Radio flux from individual neutron star, given: $B_0,\ P,\ \theta_m,\ \vec{r},\ \vec{v}$

Magneto-rotational Evolution

Neutron star formation rate

Neutron star evolution

Population Today

Magneto-rotational Evolution

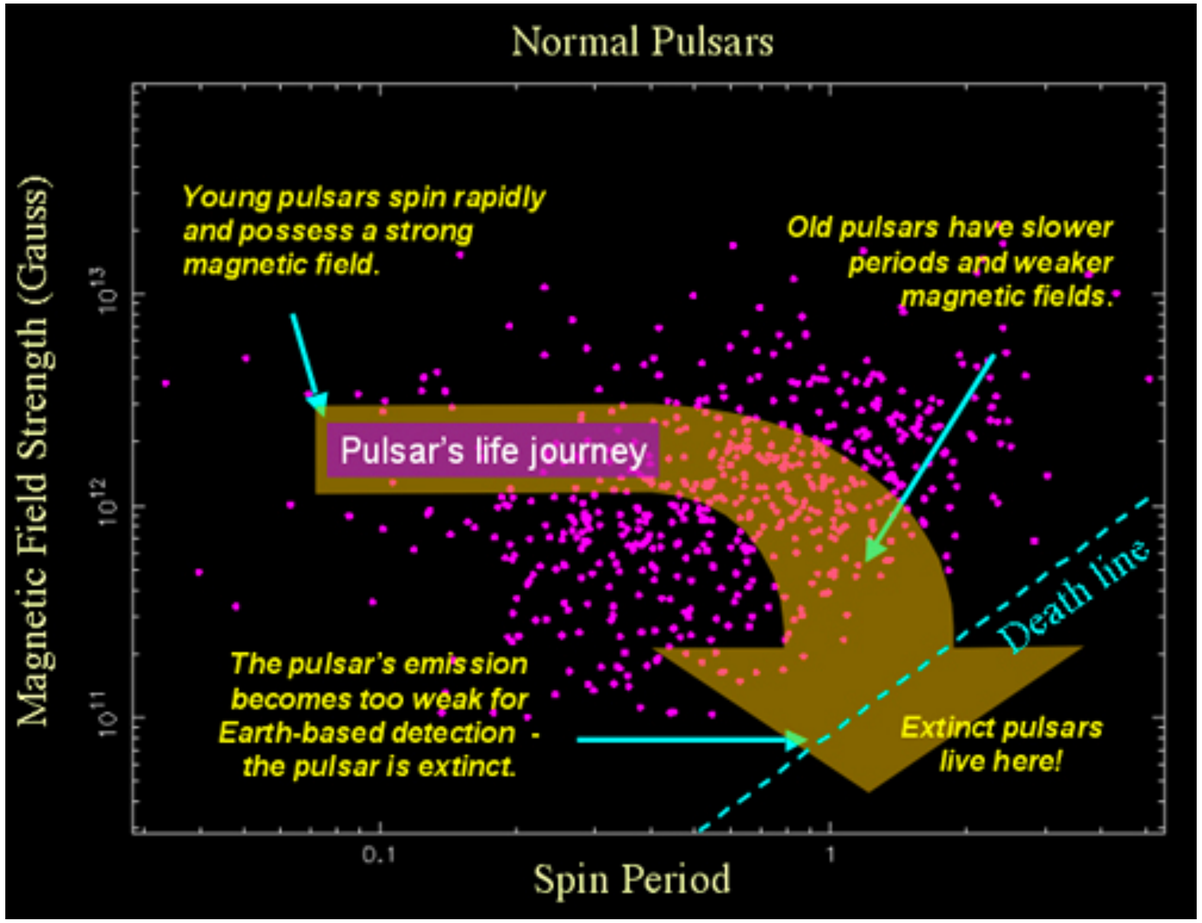


Image credit: https://astronomy.swin.edu.au/cosmos/p/Pulsar+Evolution

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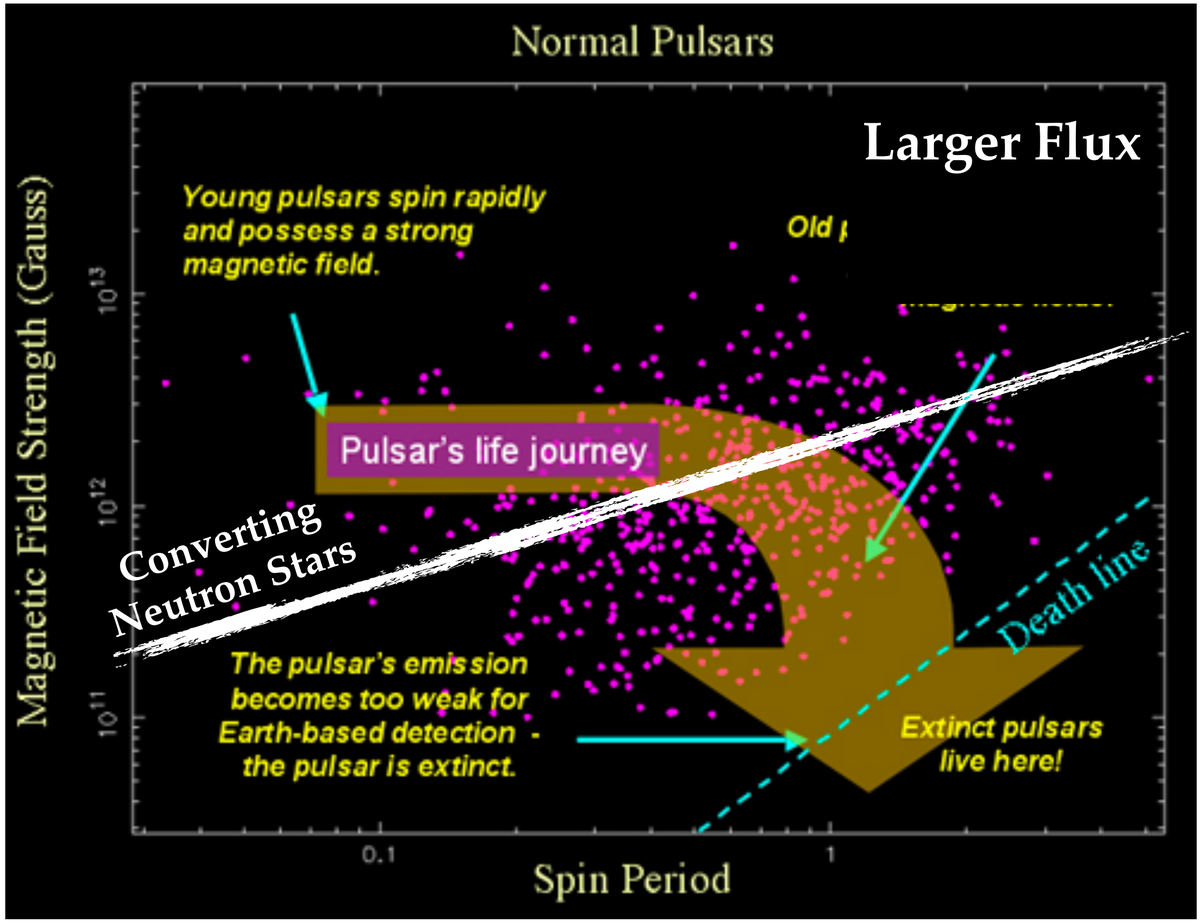

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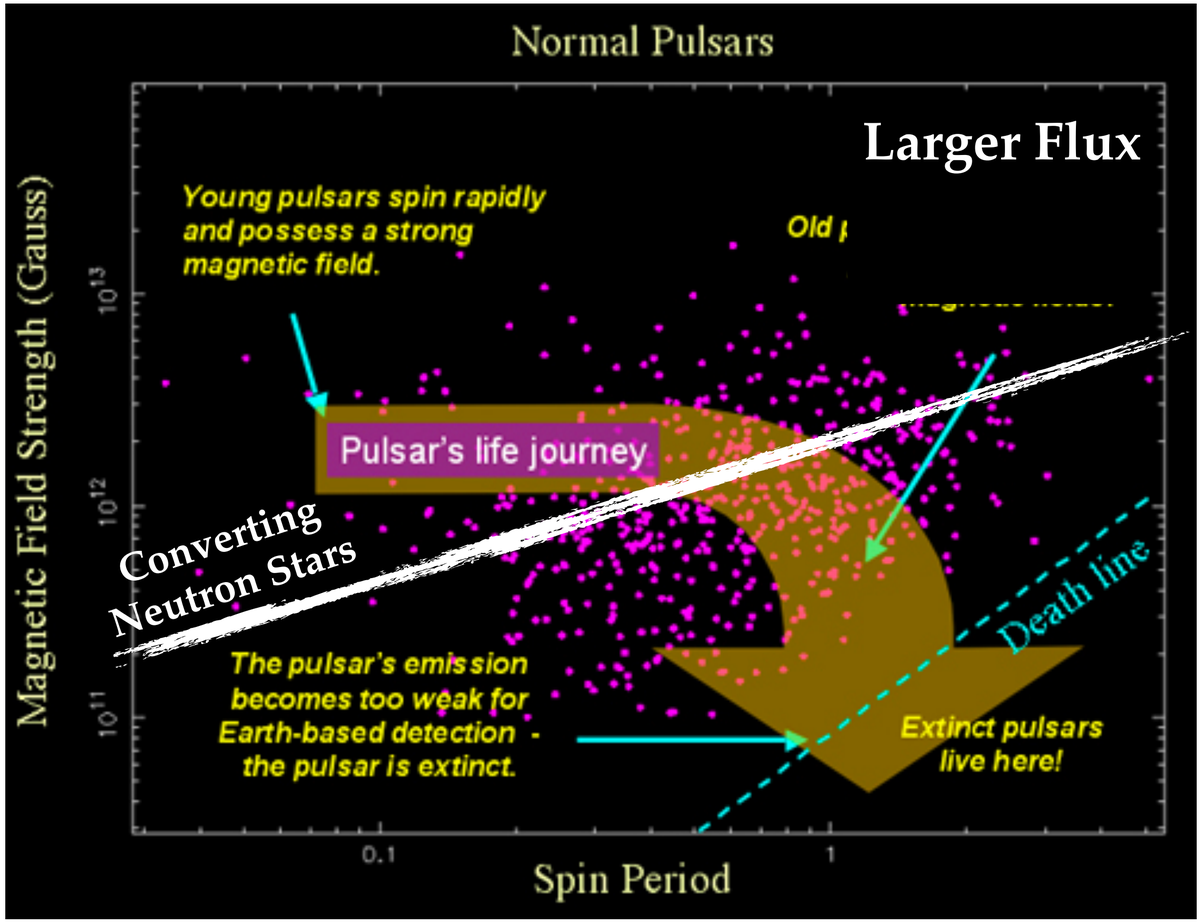

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Neutron star formation rate → Population Today

Neutron star evolution → Population Today

Initial distribution at formation $(B_0, P, \theta_{\rm mis})_{\rm Birth}$

↓

Magneto-rotational evolution $(B_0, P, \theta_{\rm mis})_{\rm Today}$

Phillips et al (2014)
Cumming et al (2004)

↓

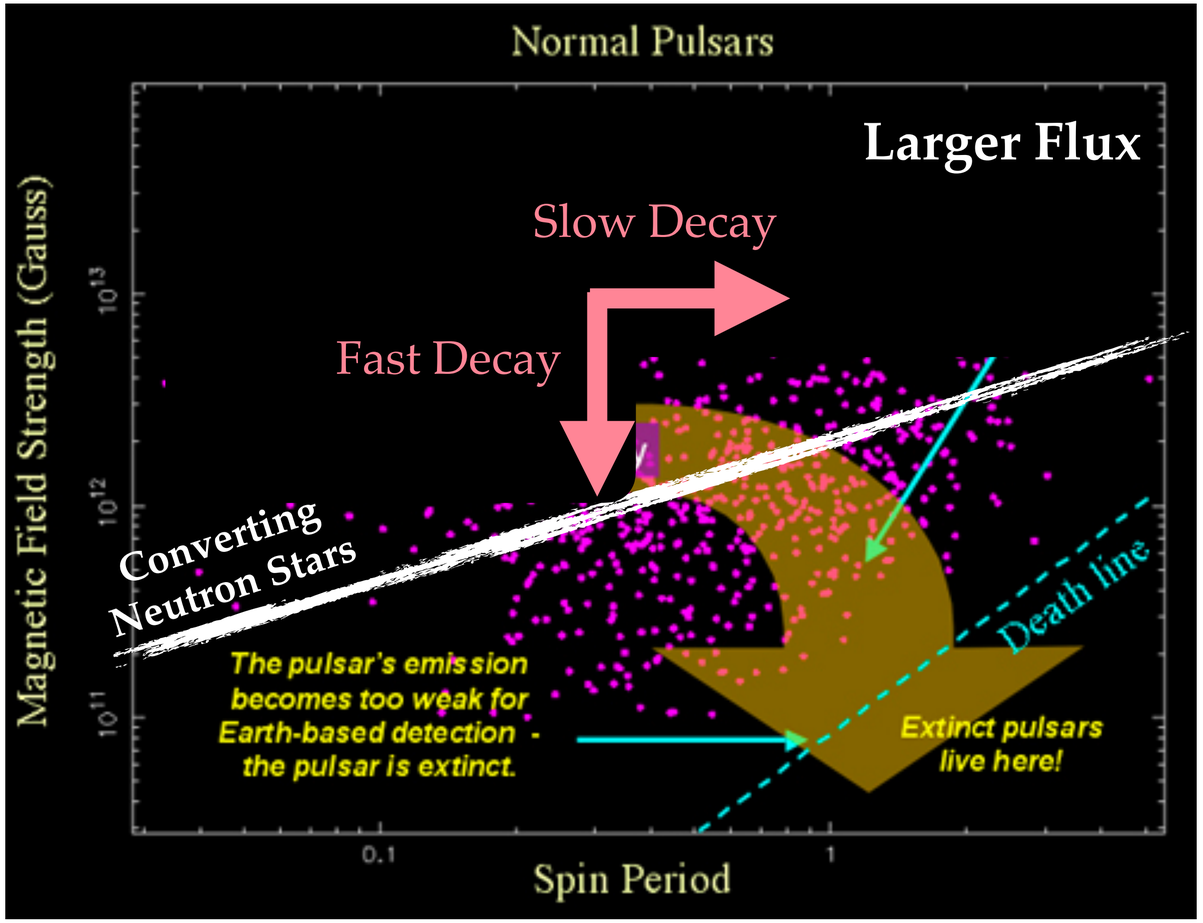
Luminosity

Gullón et al (2014)

Fit to pulsar catalog

Bracket uncertainties using highly optimistic and highly pessimistic models

Magneto-rotational Evolution



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Population Synthesis

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Fast Magnetic Field Decay

Dominated by young neutron stars
Gullón et al (2014)

"Data driven approach"

Recent star formation provides insight into spatial distribution and number densities
Yusef-Zadeh et al (2008)

~1500 NSs [Age < 30 Myr in inner pc]

Slow Magnetic Field Decay

Both young and old neutron stars contribute

Population Modeling

Neutron star birth and disruption of globular clusters in Galactic Center
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300,000 NSs inner few pcs

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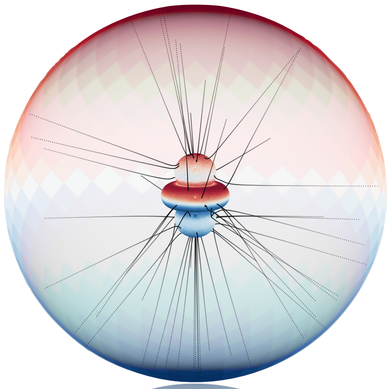
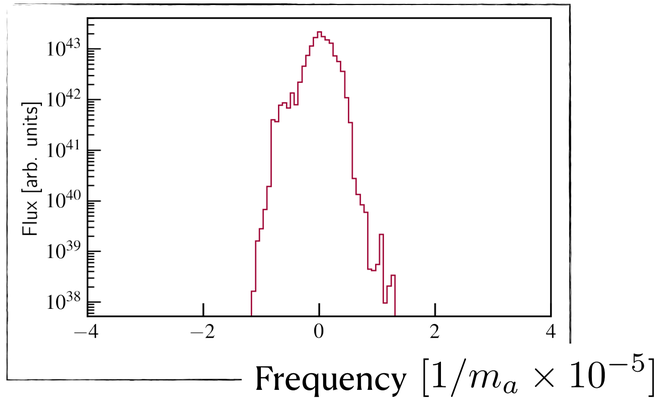


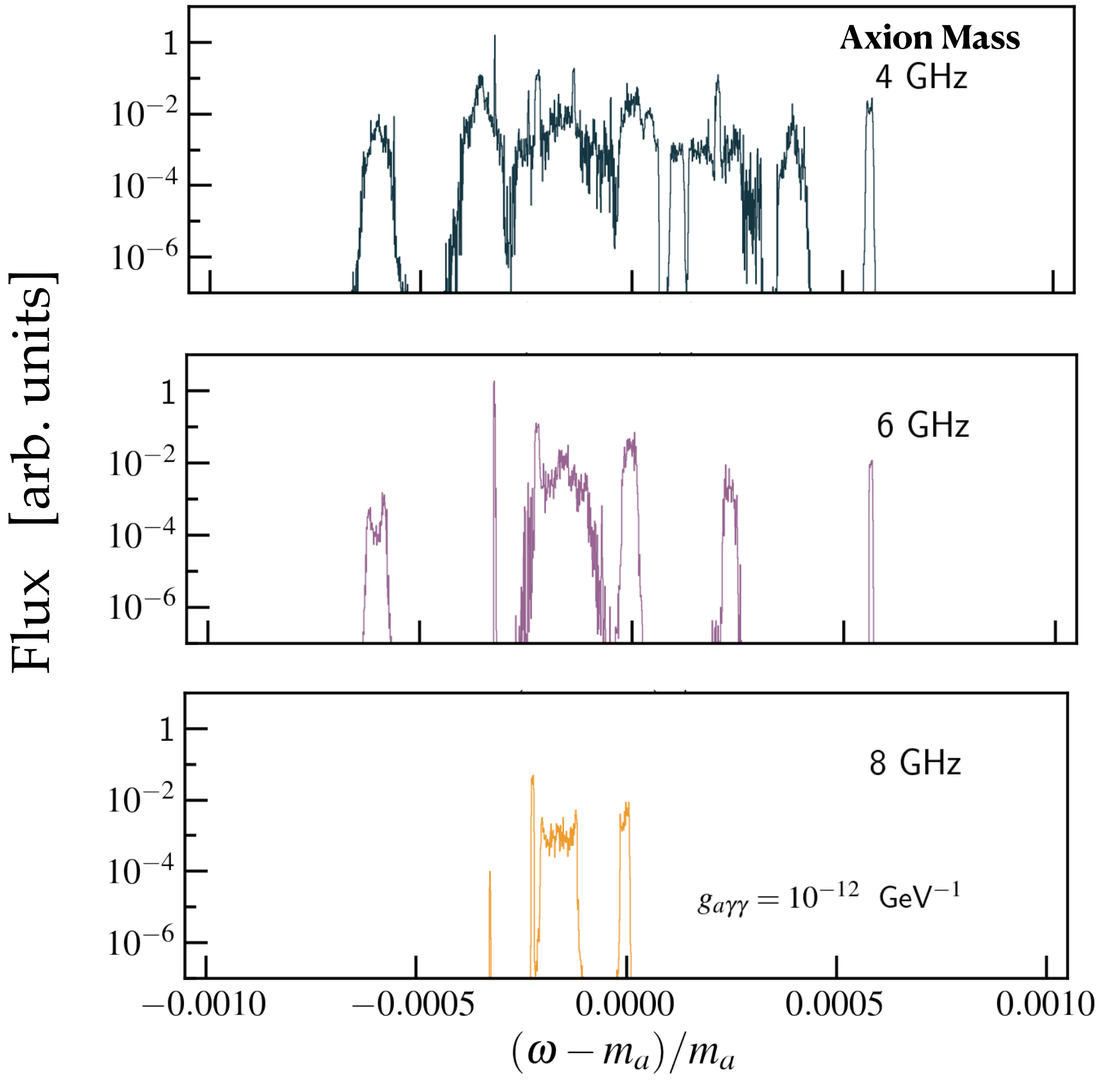


Sample neutron star-Earth orientation

Doppler shift line

Stack samples

Population Synthesis



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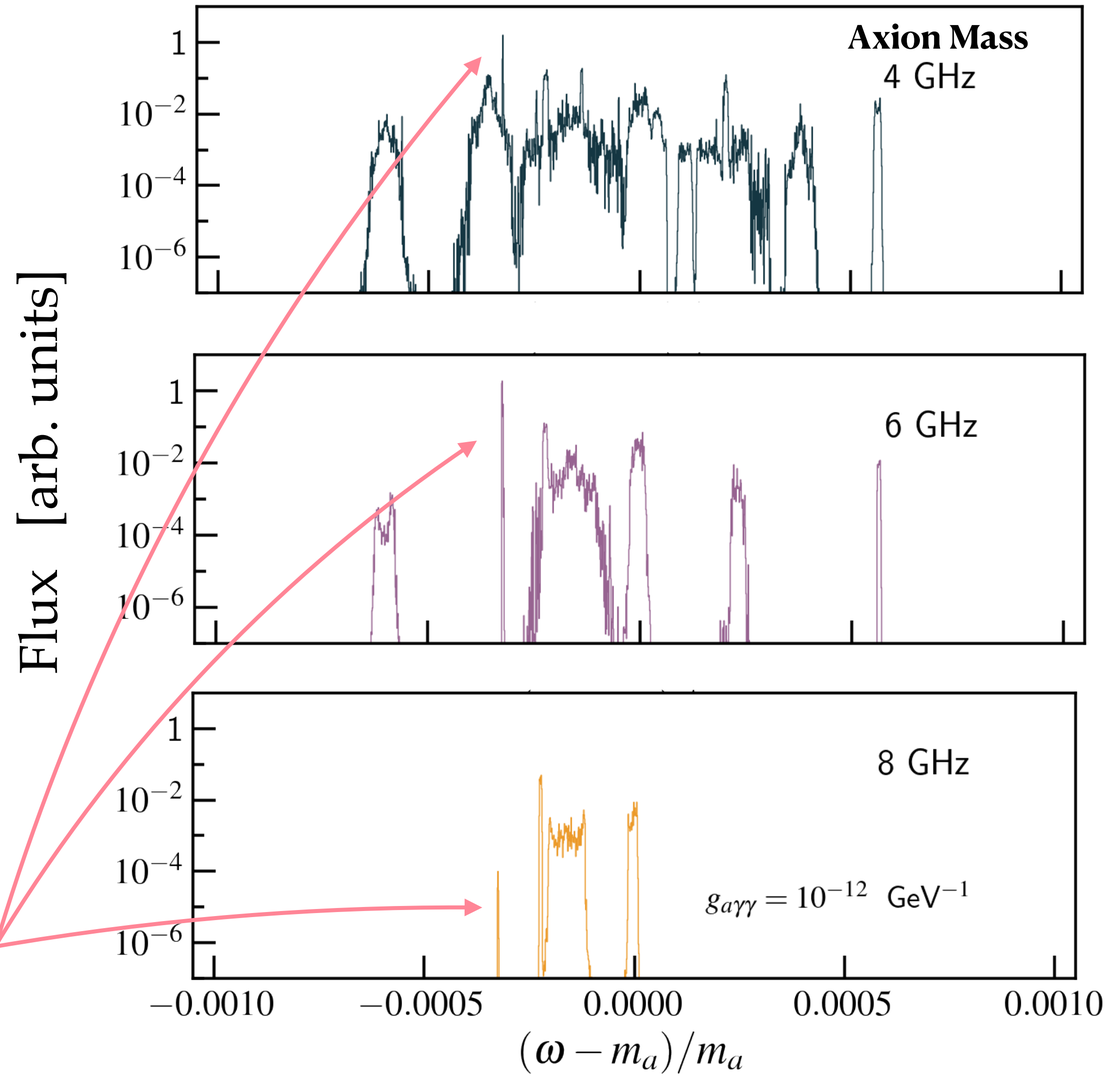
Population Synthesis



Individual Neutron Stars

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

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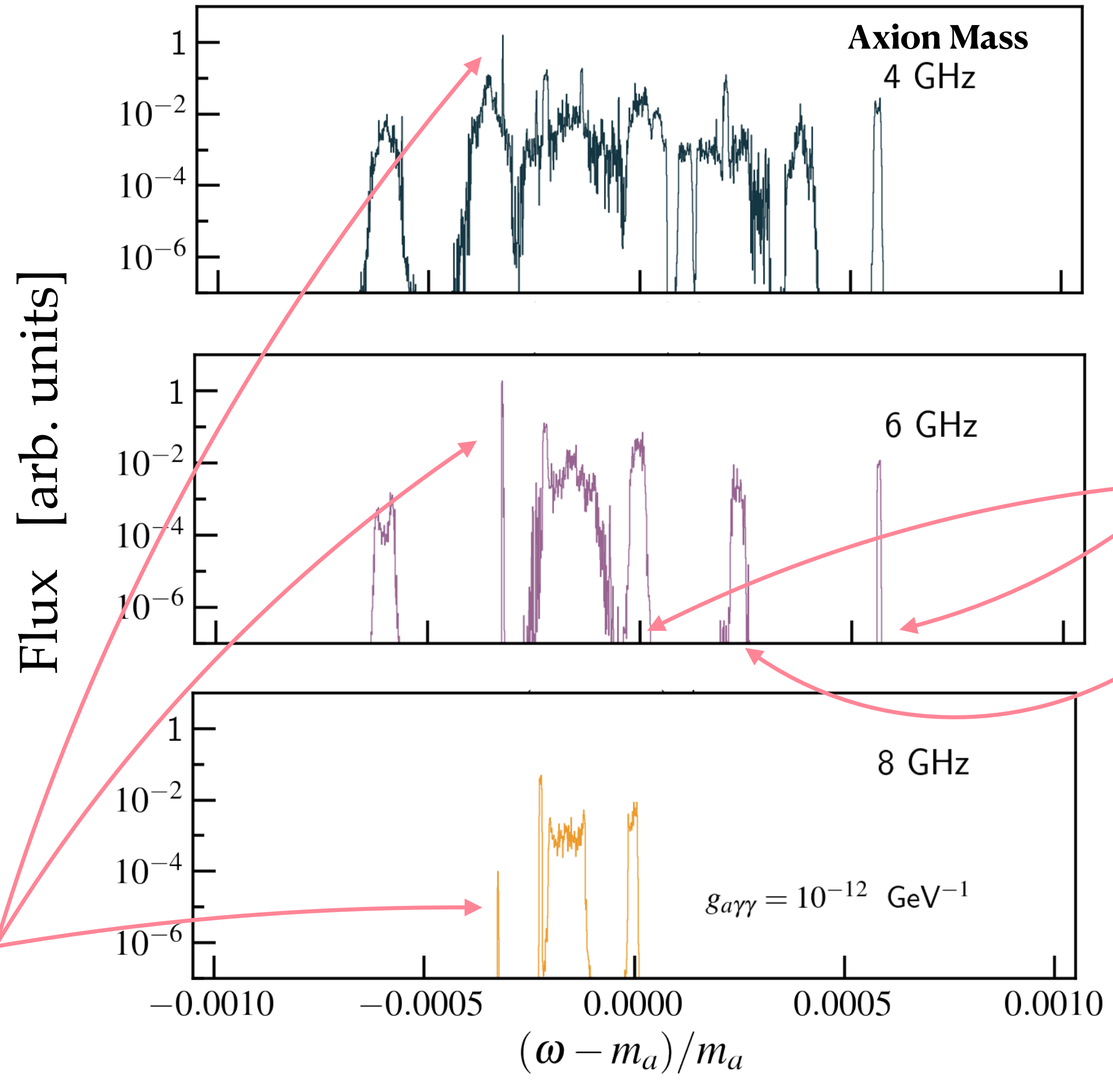


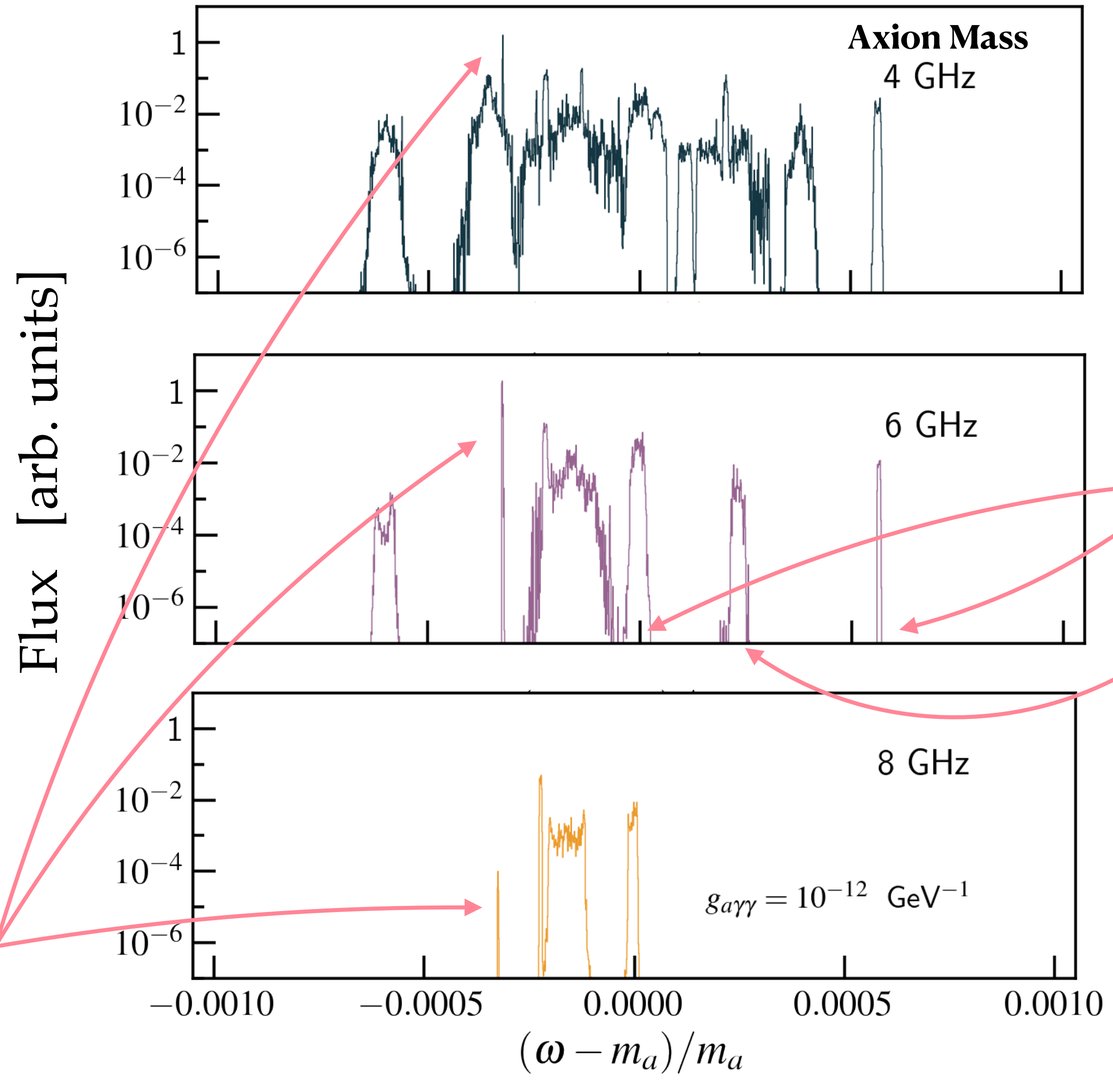
Doppler Broadening

Plasma Broadening

Individual Neutron Stars

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Population Synthesis



Doppler Broadening

Plasma Broadening

Neutron Stars Disappear

Individual Neutron Stars

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Conclusions

Last few years have shown major developments in forward modeling of these systems

Analysis now including:

- Computation of radio flux at level of individual neutron stars using ray tracing
- Boosted neutron stars (with respect to dark matter) — induces anisotropy in local phase space
- Improved conversion probability calculation (includes estimate of axion-photon de-phasing and generalizes to adiabatic regime)
- State-of-the-art population models for the Galactic Center neutron star population
- More rigorous investigation of theoretical systematics

Results & interpretation to be shown in Josh Foster's talk!

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)