Neutron Stars as Axion Laboratories

Samuel J. Witte

Based on:

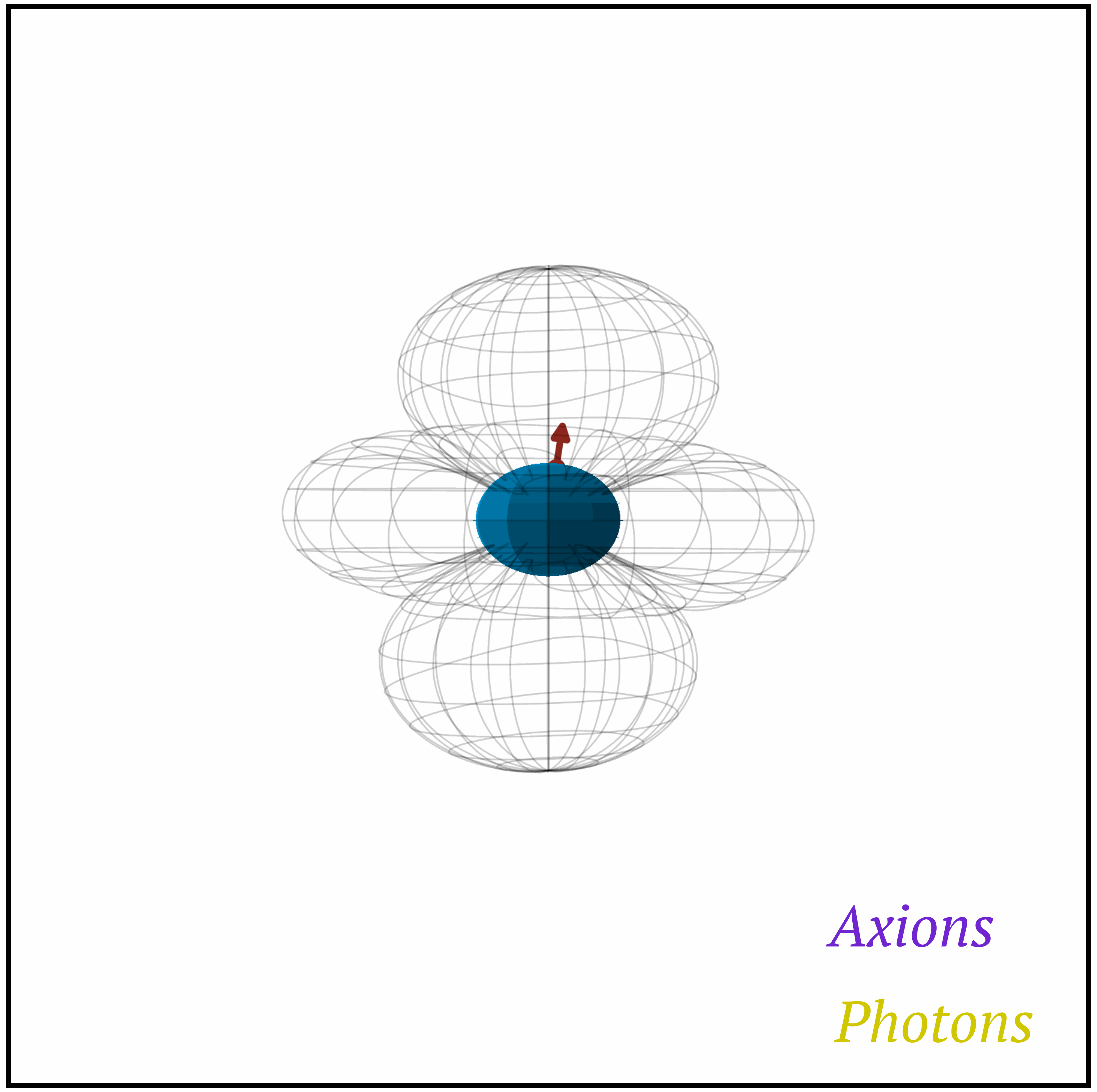
*Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)*

***SJW**, Noordhuis, Edwards, Weniger (2021)*

***SJW,** Salinas, Baum, Millar, Lawson, Marsh, Weniger (To appear soon)*

*McDonald, **SJW** (To appear soon)*

*Thjemsland, **SJW**, McDonald (To appear soon)*



Animations available at: https://github.com/SamWitte/GIF_Storage

GRAPPA
GRavitation AstroParticle Physics Amsterdam
UNIVERSITY OF AMSTERDAM

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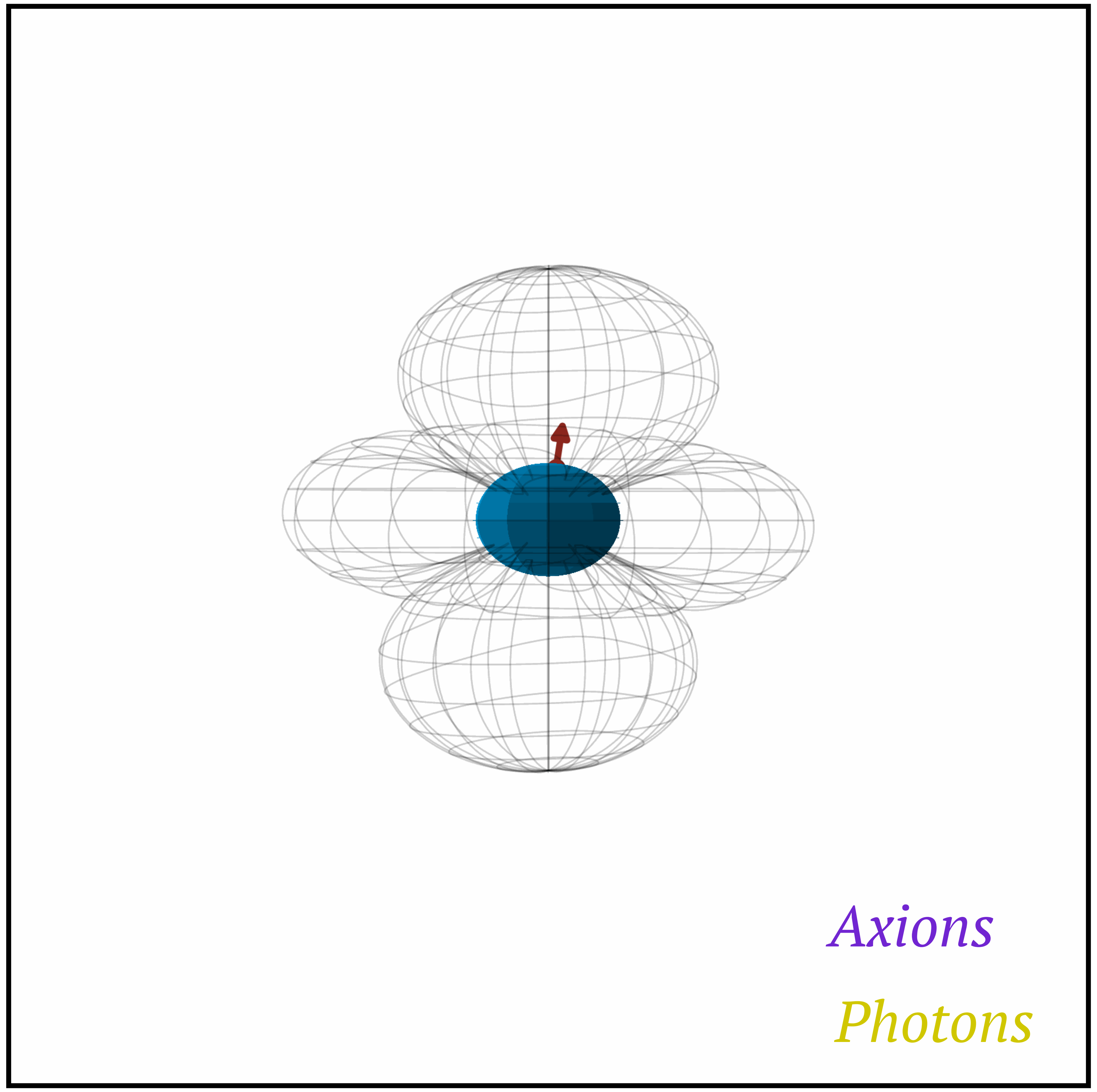

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Identification of Dark Matter July 21, 2022

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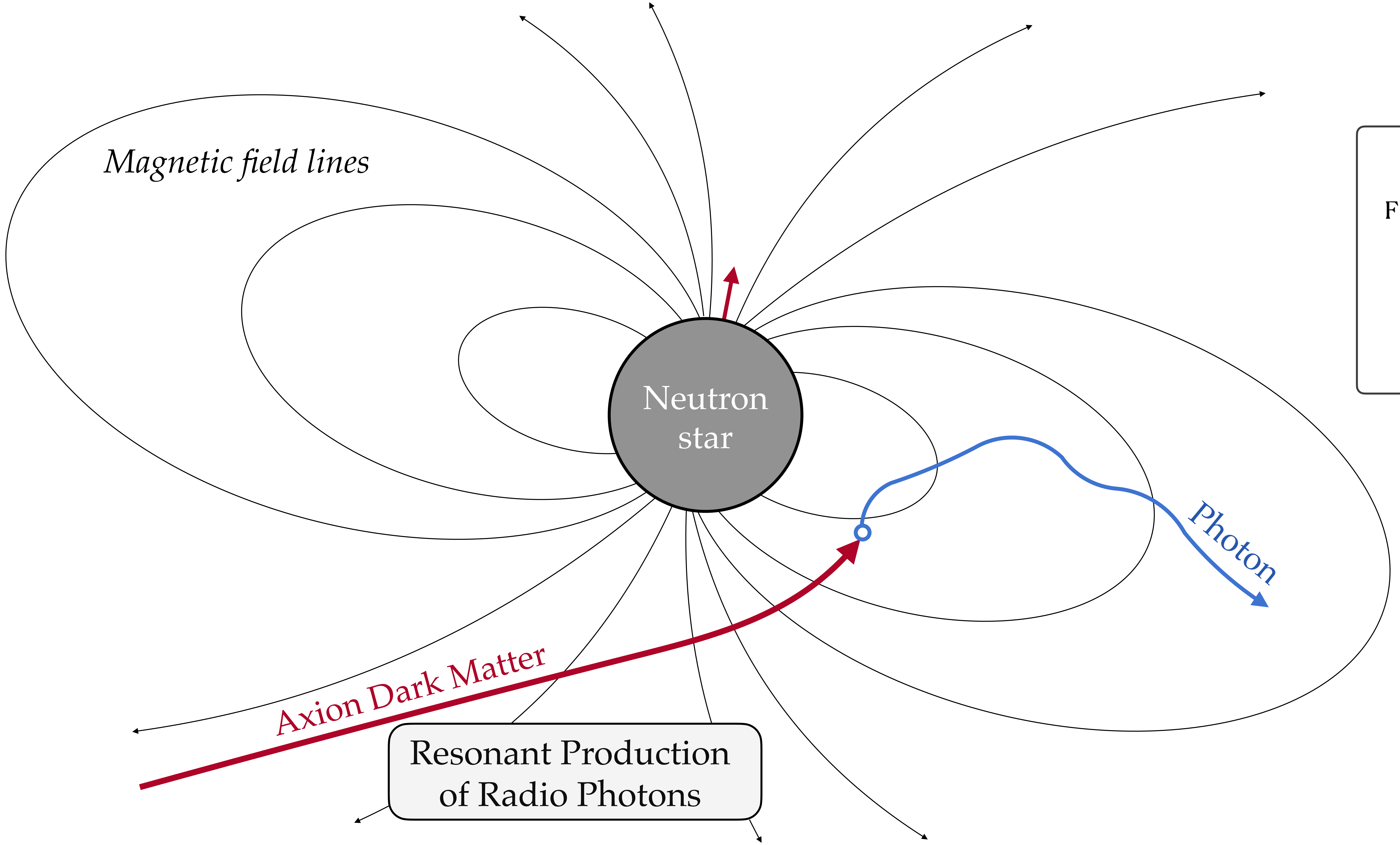
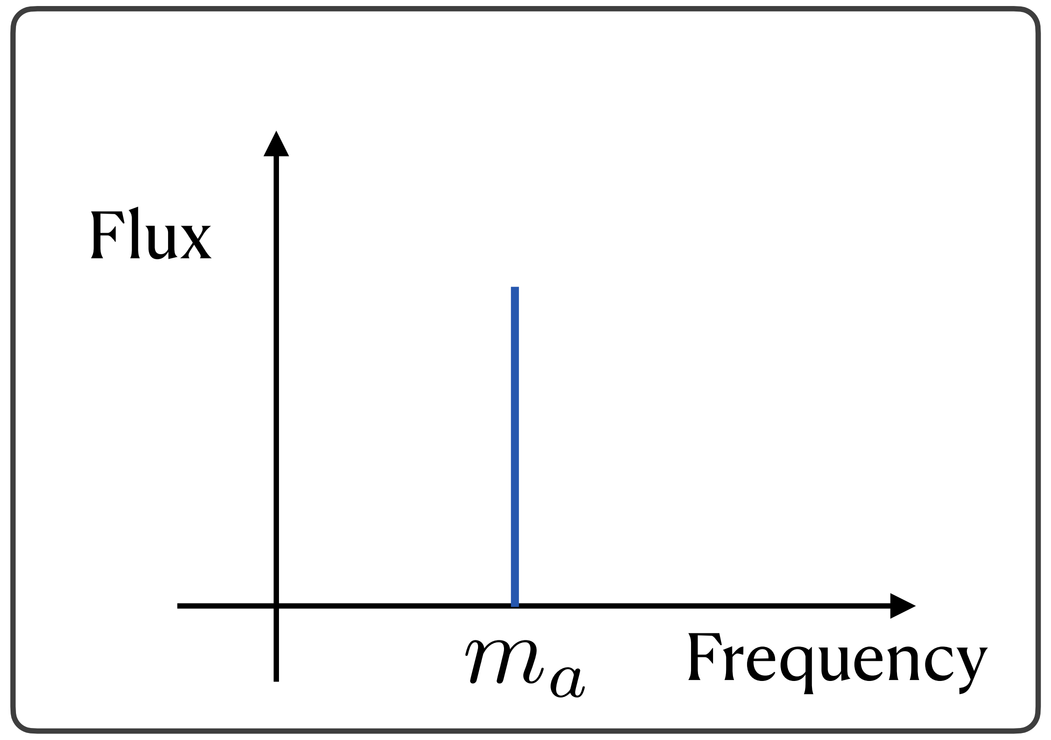
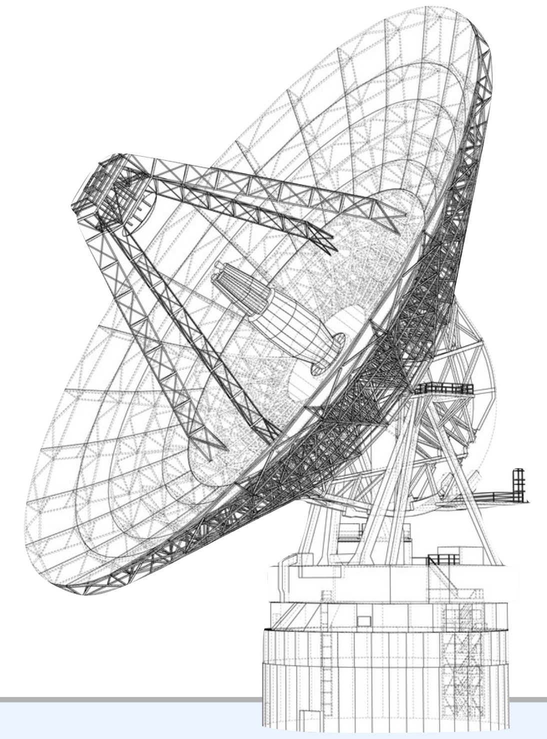






Axion-photon mixing

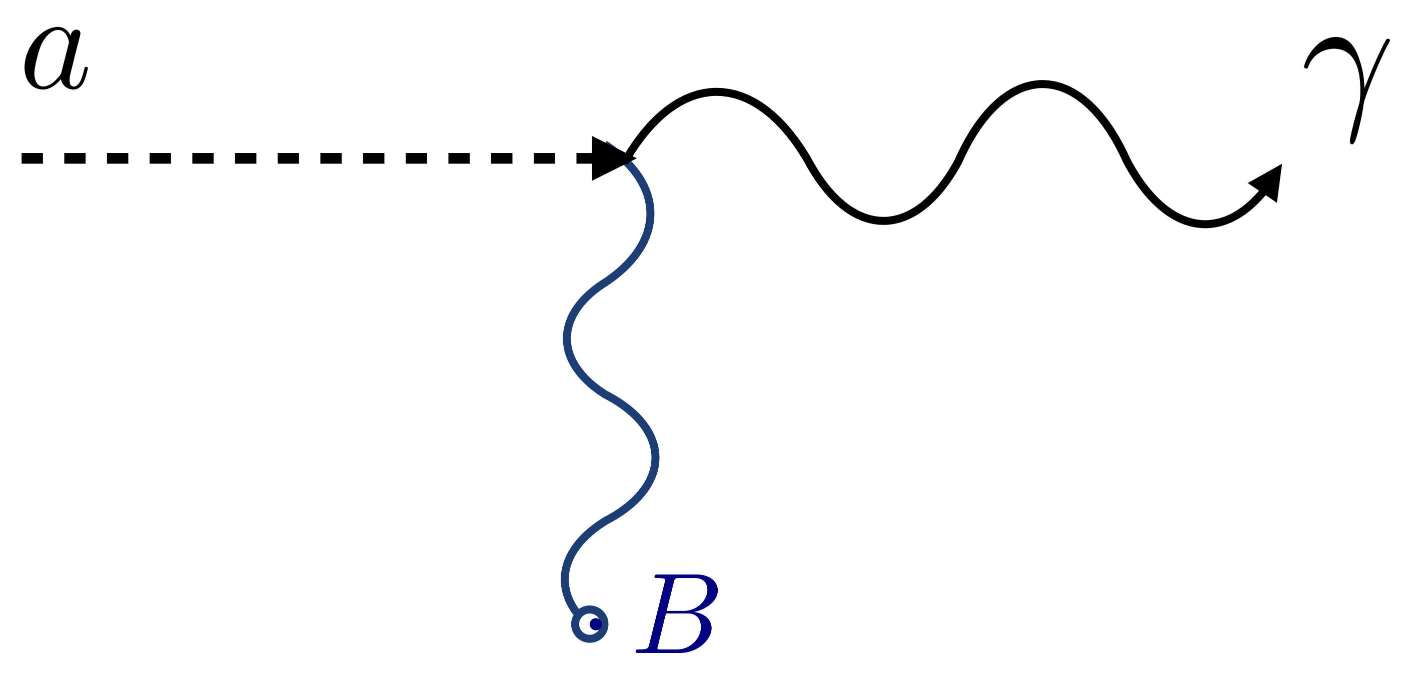
$$\mathcal{L} \sim g_{a\gamma\gamma} \; a \, E \cdot B$$

$$\downarrow$$

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

B: Magnetic Field

L: Length scale



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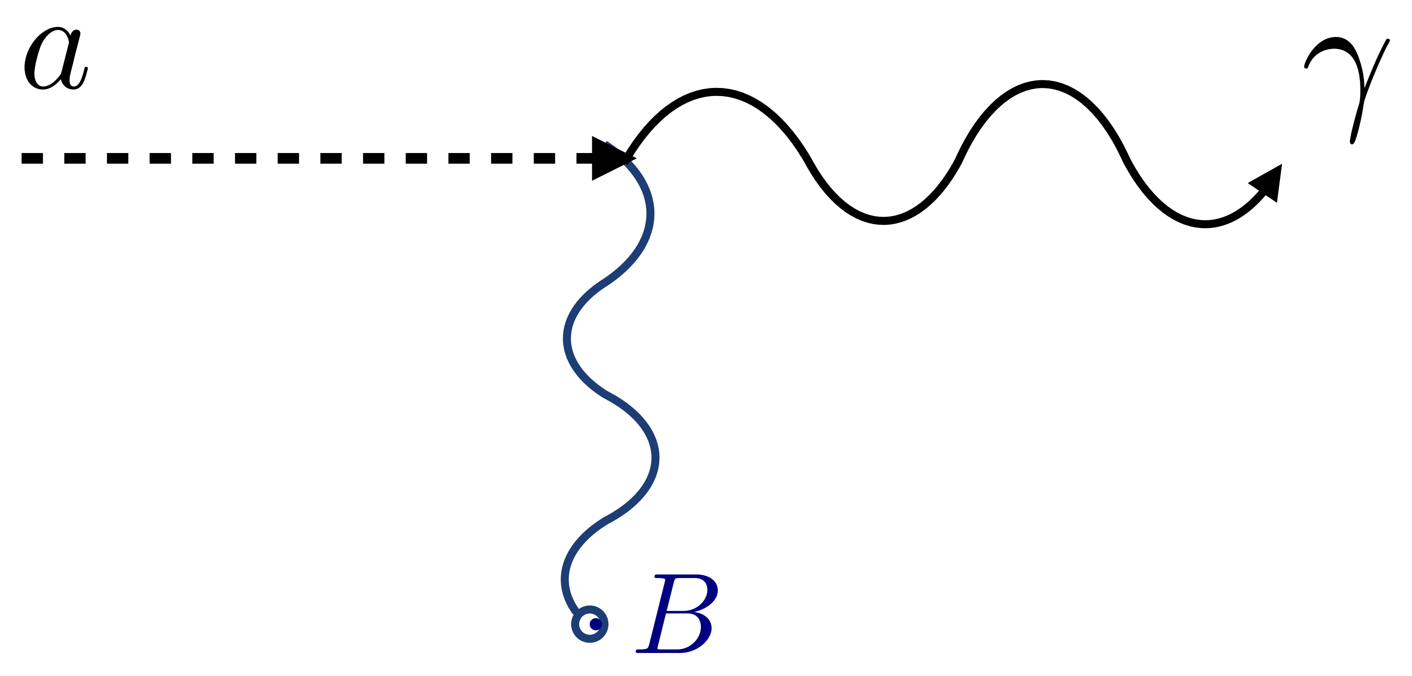

Requirements for large conversion probability of axions into photons:

- *B must be large*
- *L must be large*: for *mildly-relativistic* to *non-relativistic* axions, $L \sim (k_a - k_\gamma)^{-1}$

In vacuum, $k_a \ll k_\gamma$

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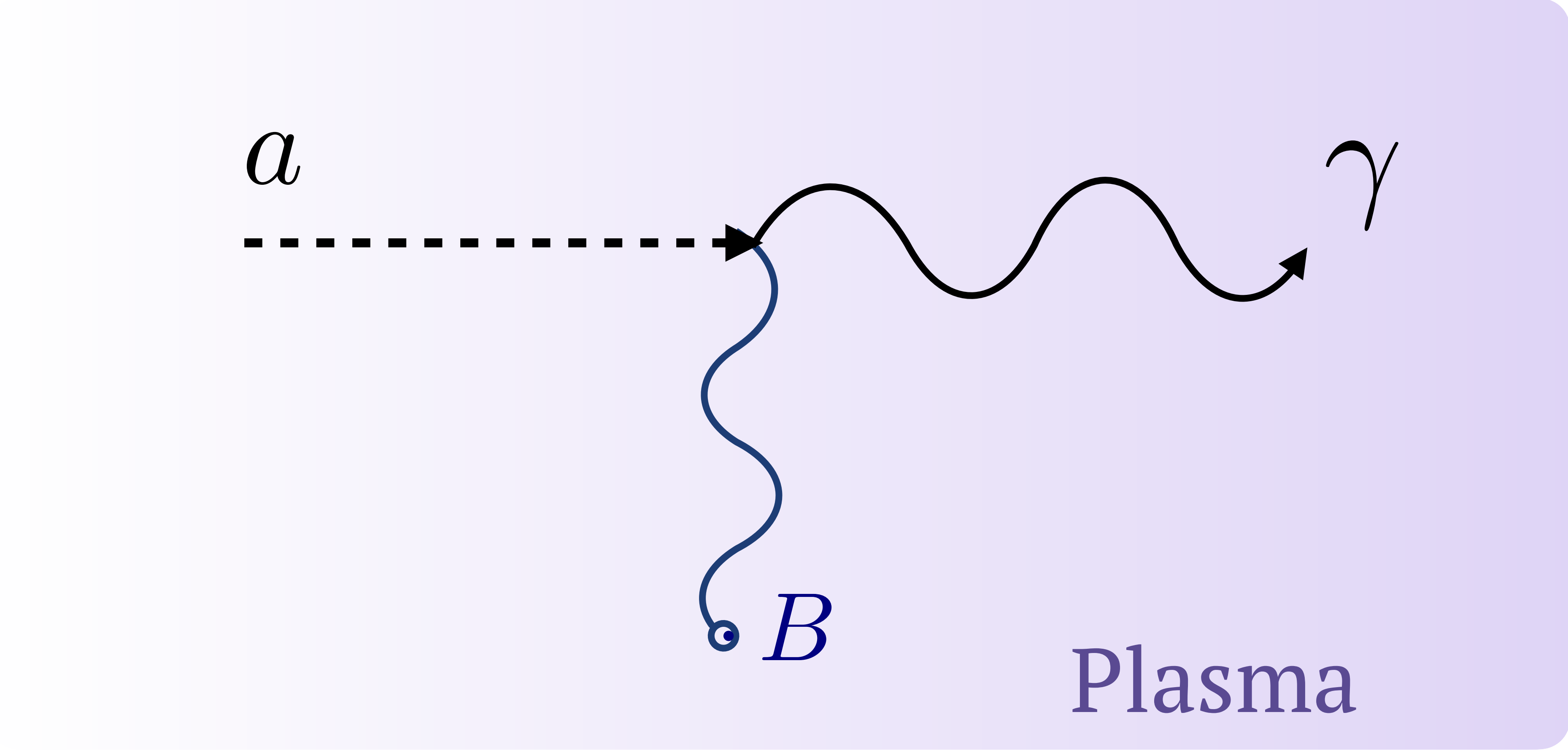

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$\longrightarrow$ **Modify photon dispersion relation** (E.g. in a cold plasma $k_\gamma = \sqrt{\omega^2 - \omega_p^2}$, and $k_a \sim k_\gamma$ possible)

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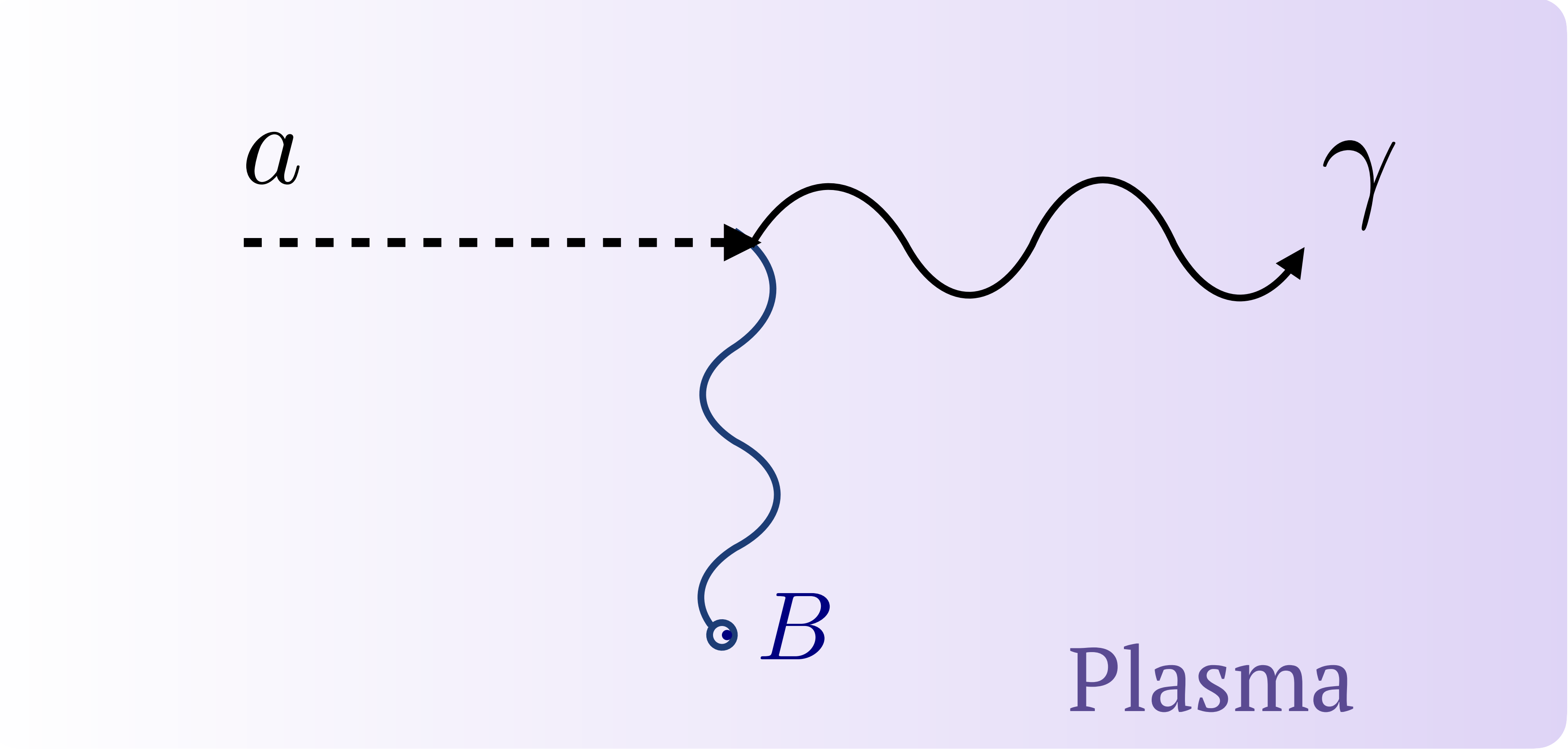

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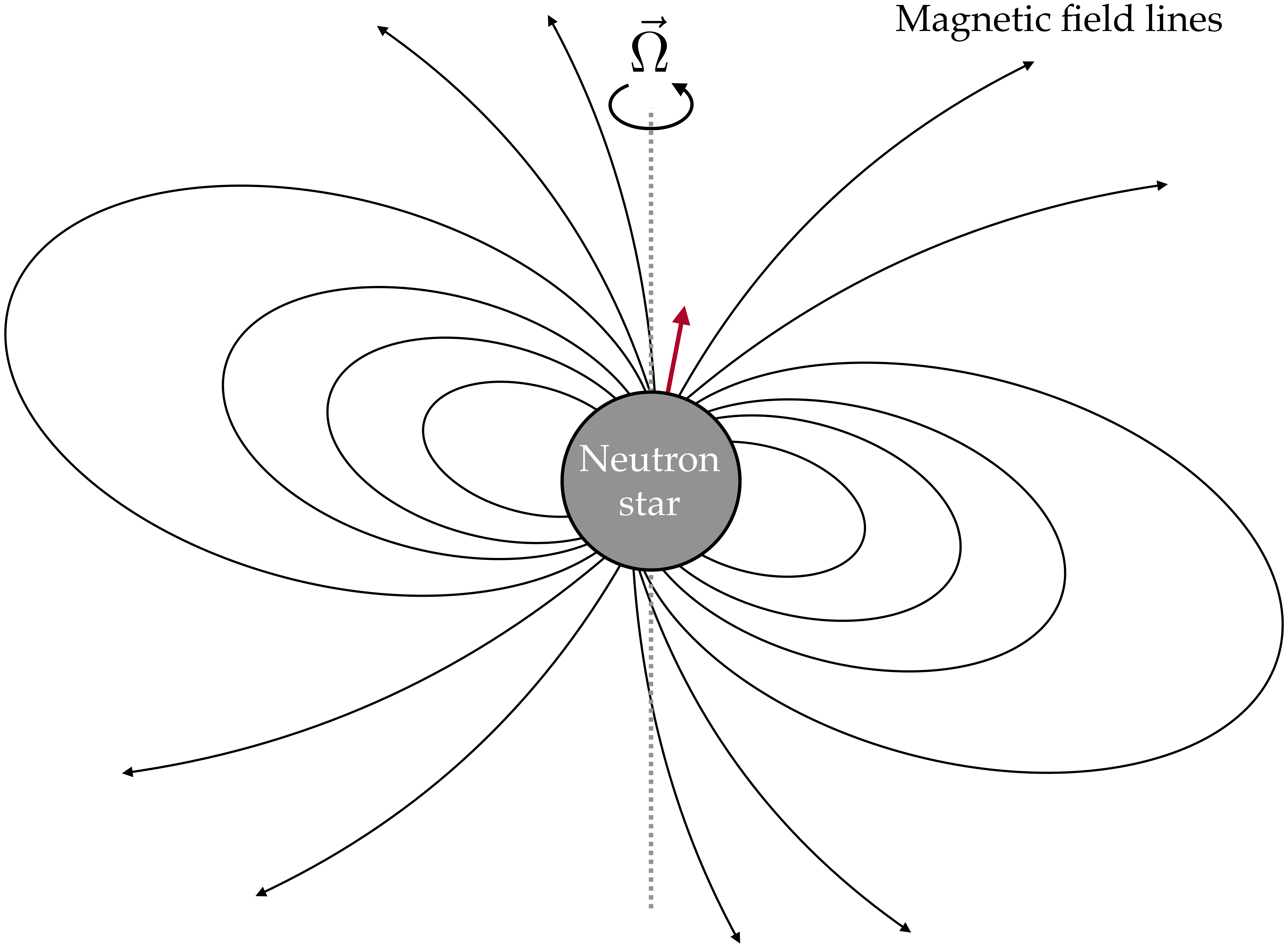
Ideal environments: ***Large coherent magnetic fields and dilute plasmas***

Neutron star magnetospheres



$|\vec{B}| \lesssim 10^{15}\,\mathrm{G}$

$r_{NS} \sim 10\,\mathrm{km}$

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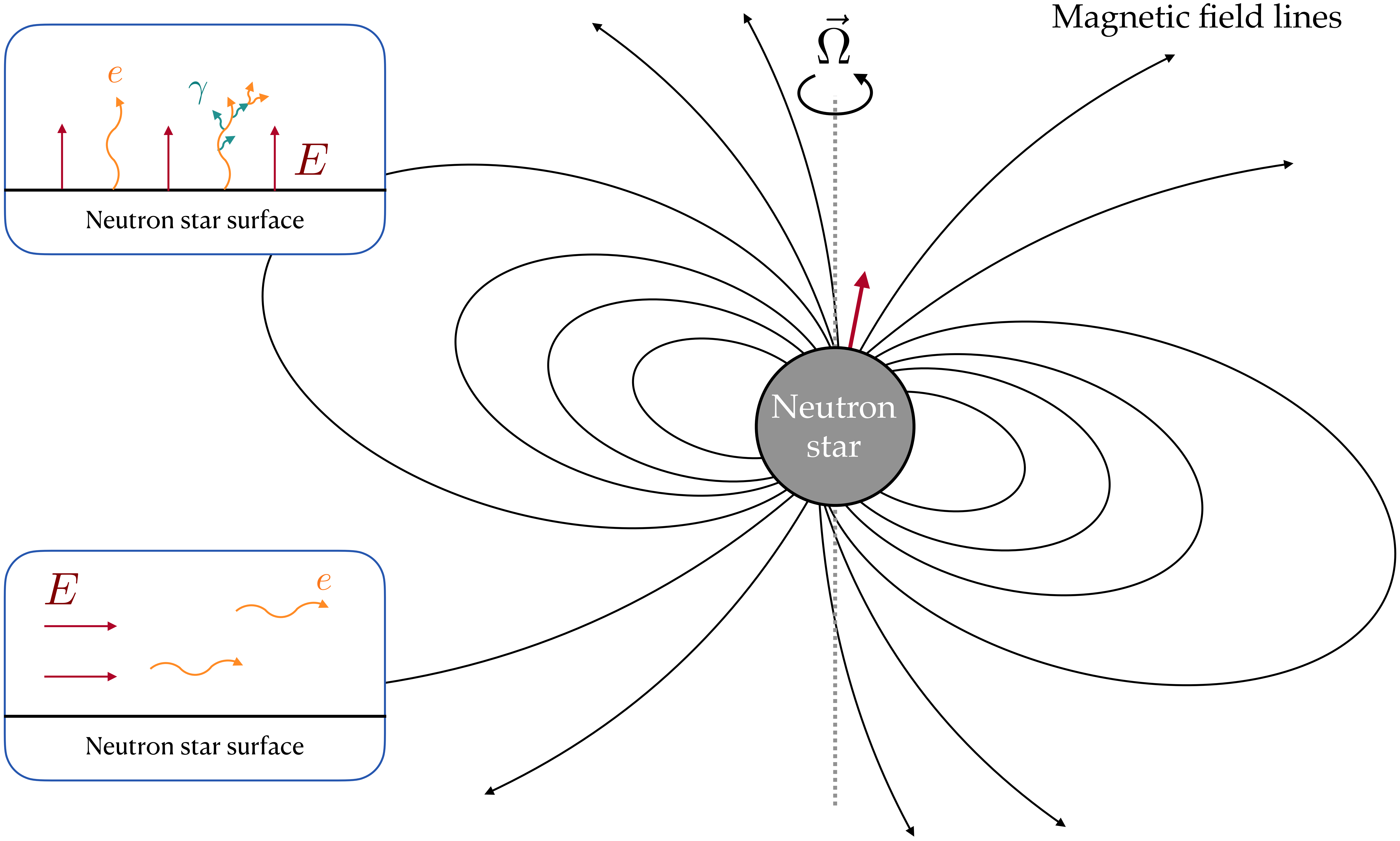

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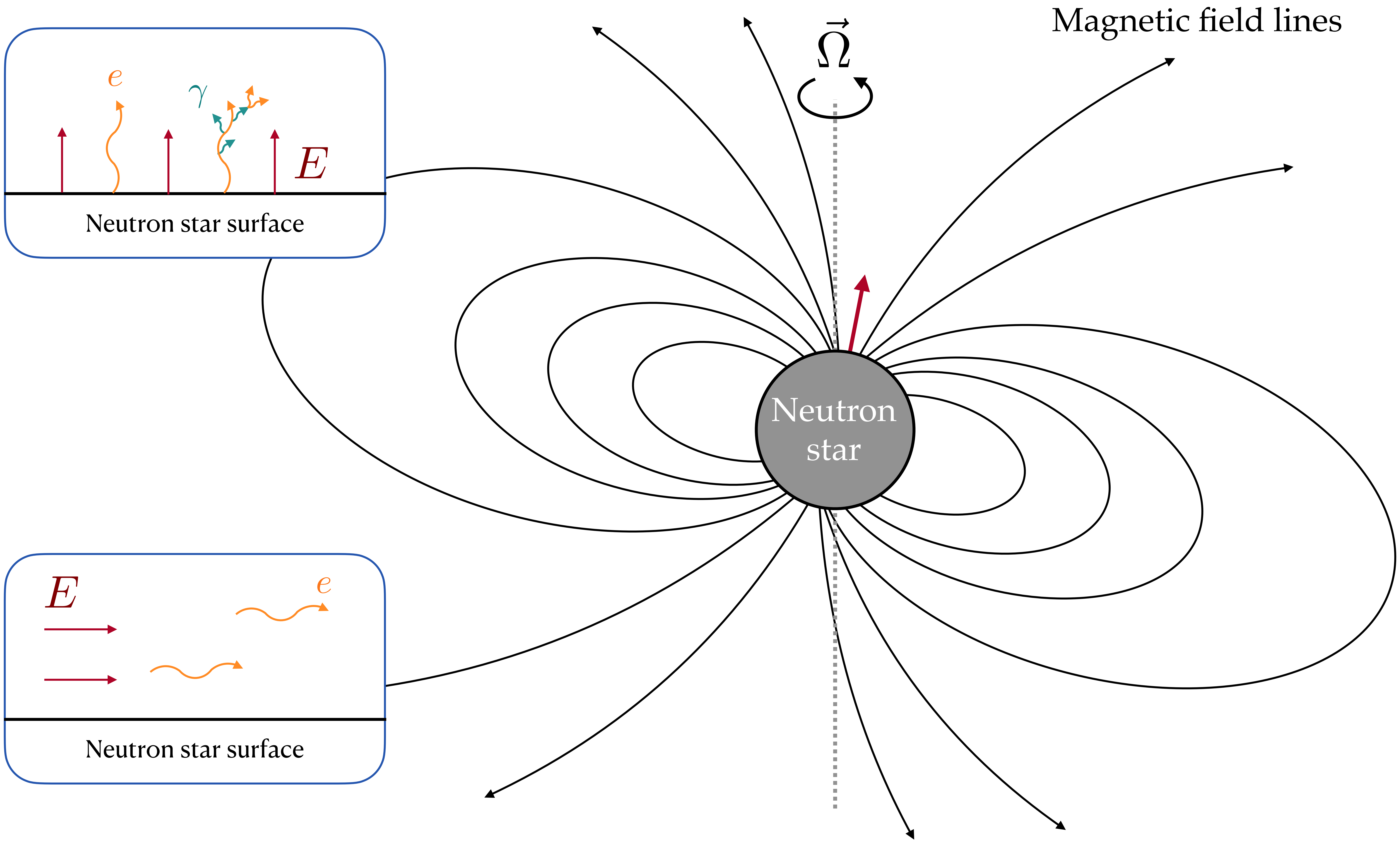


$$|\vec{B}| \lesssim 10^{15}\,\mathrm{G}$$

$$r_{NS} \sim 10\,\mathrm{km}$$

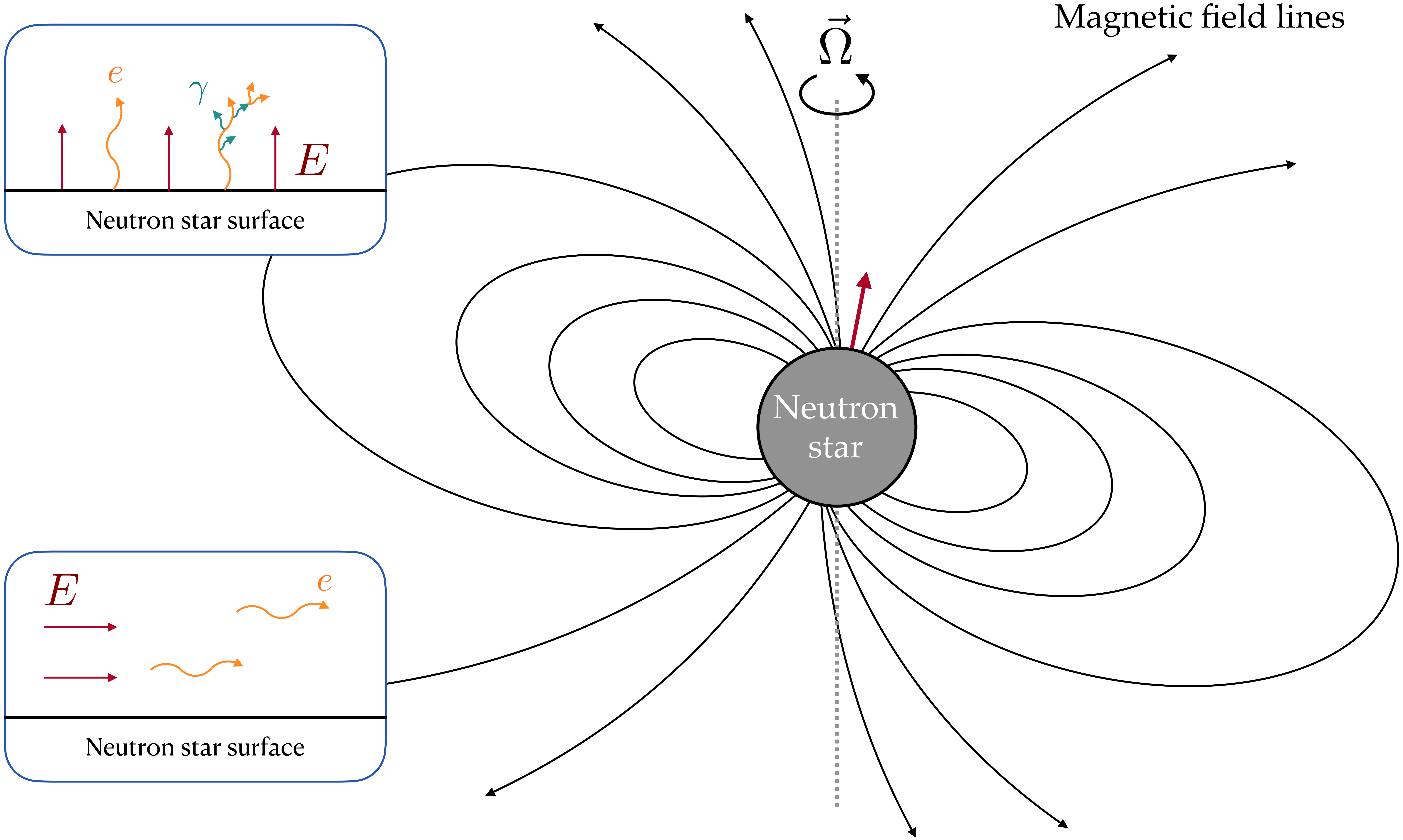
$$\vec{E} \cdot \vec{B} = 0$$

$$n_{GJ}(\vec{r}) = |n_+ - n_-|$$

Goldreich-Julian Model
(Force-free solution)

Goldreich & Julian 1969

Neutron star magnetospheres



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Resonances for:
$m_a \lesssim 10^{-4}\,\mathrm{eV}$

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Axion parameter space

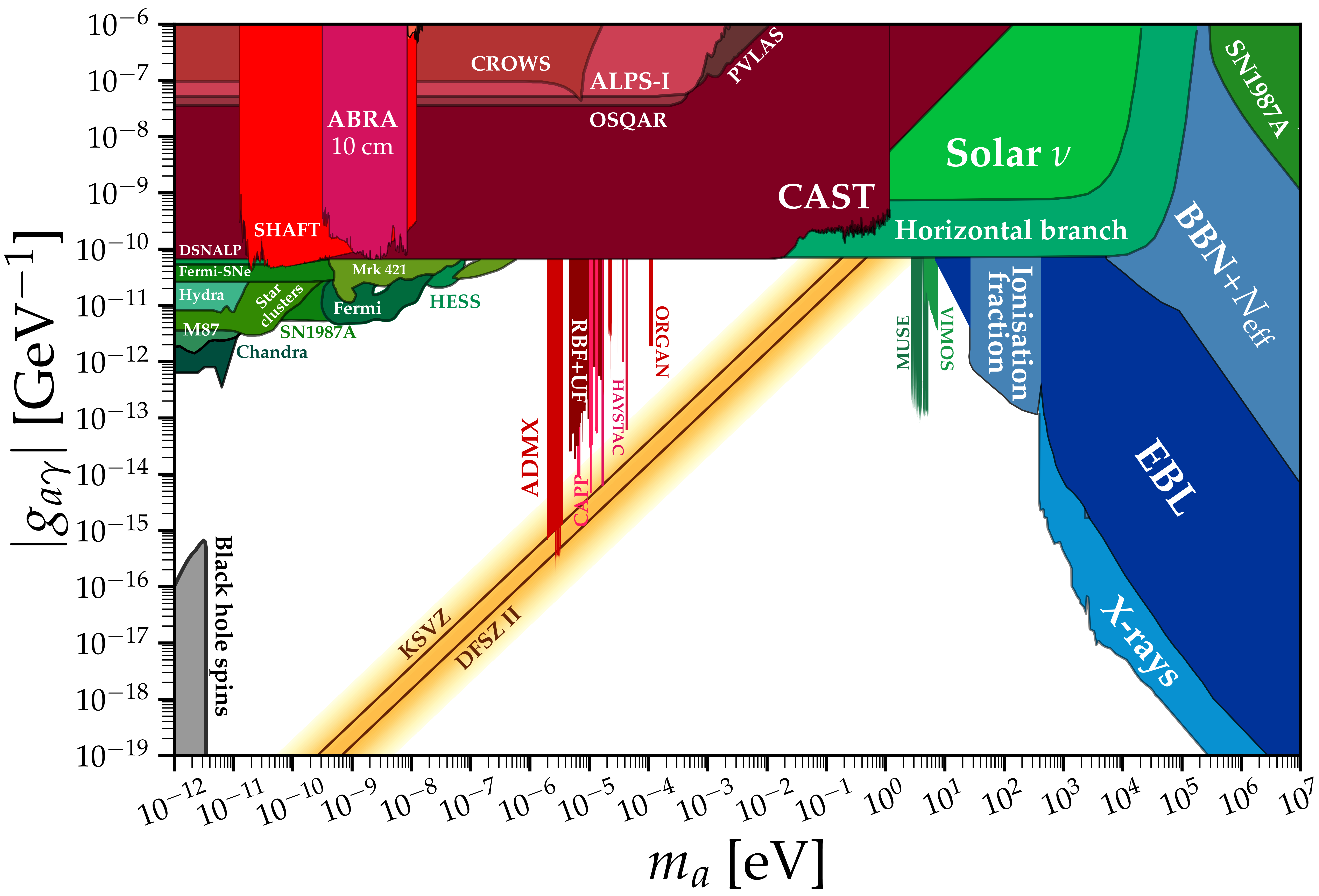

Image credit: Ciaran O'hare

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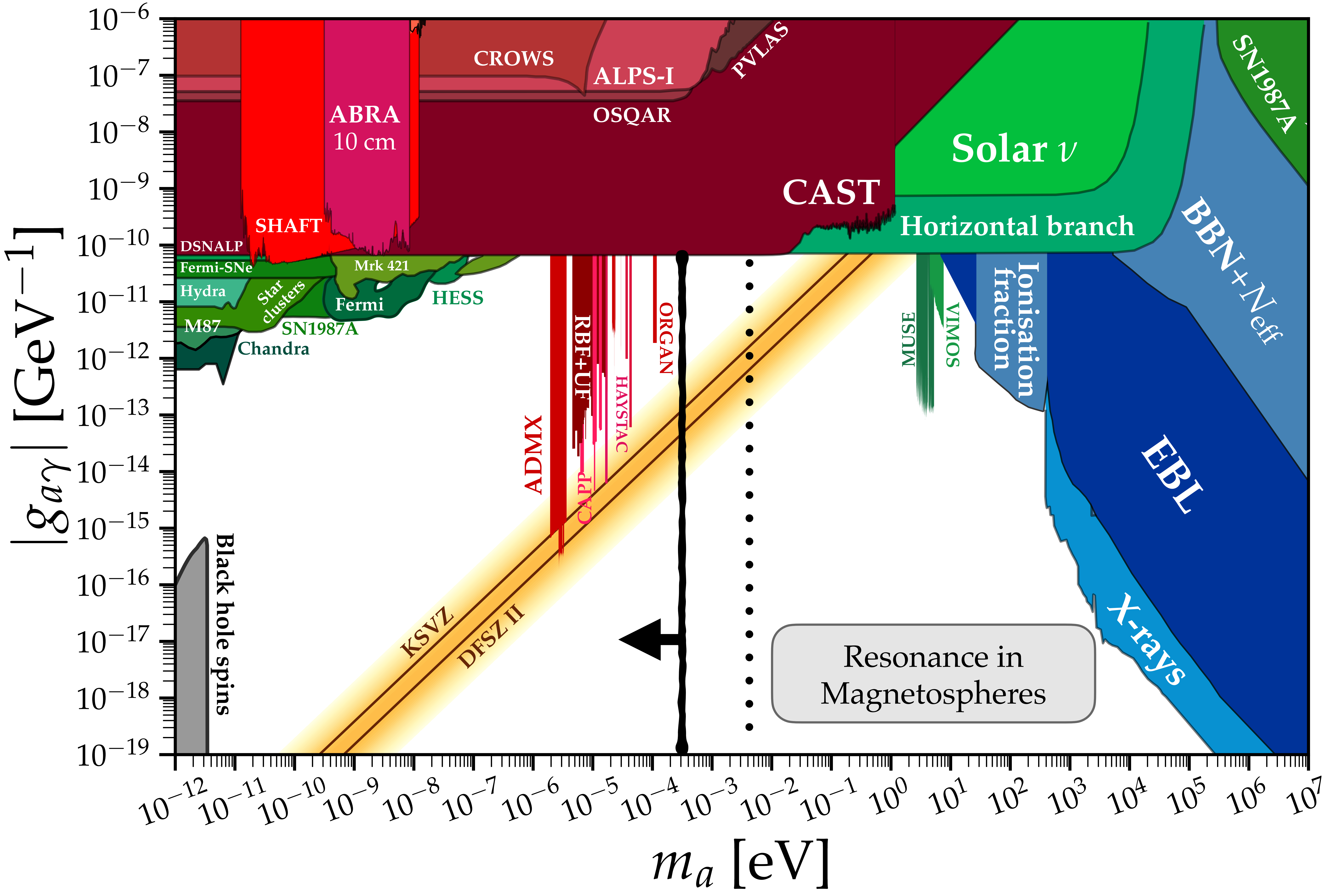

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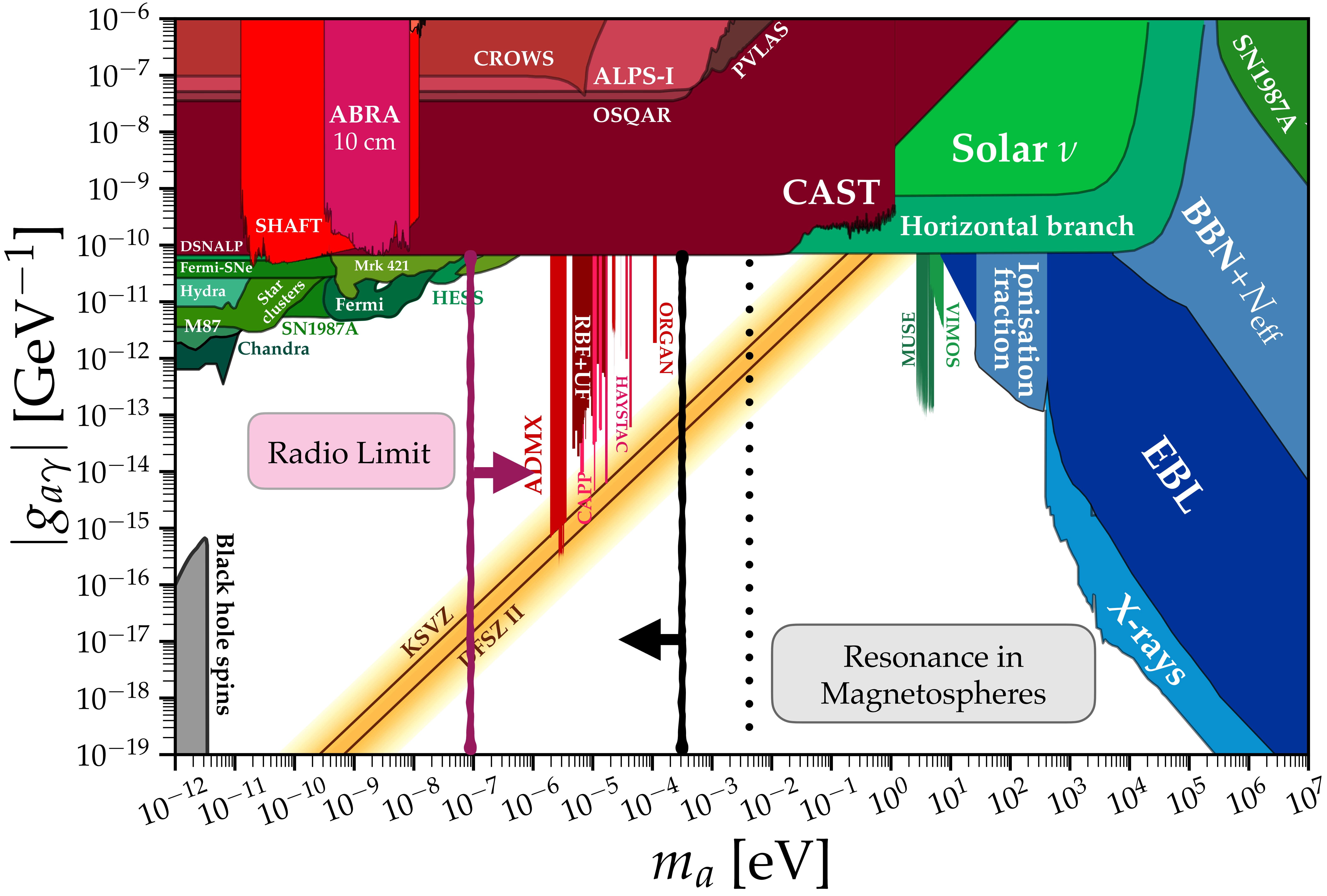

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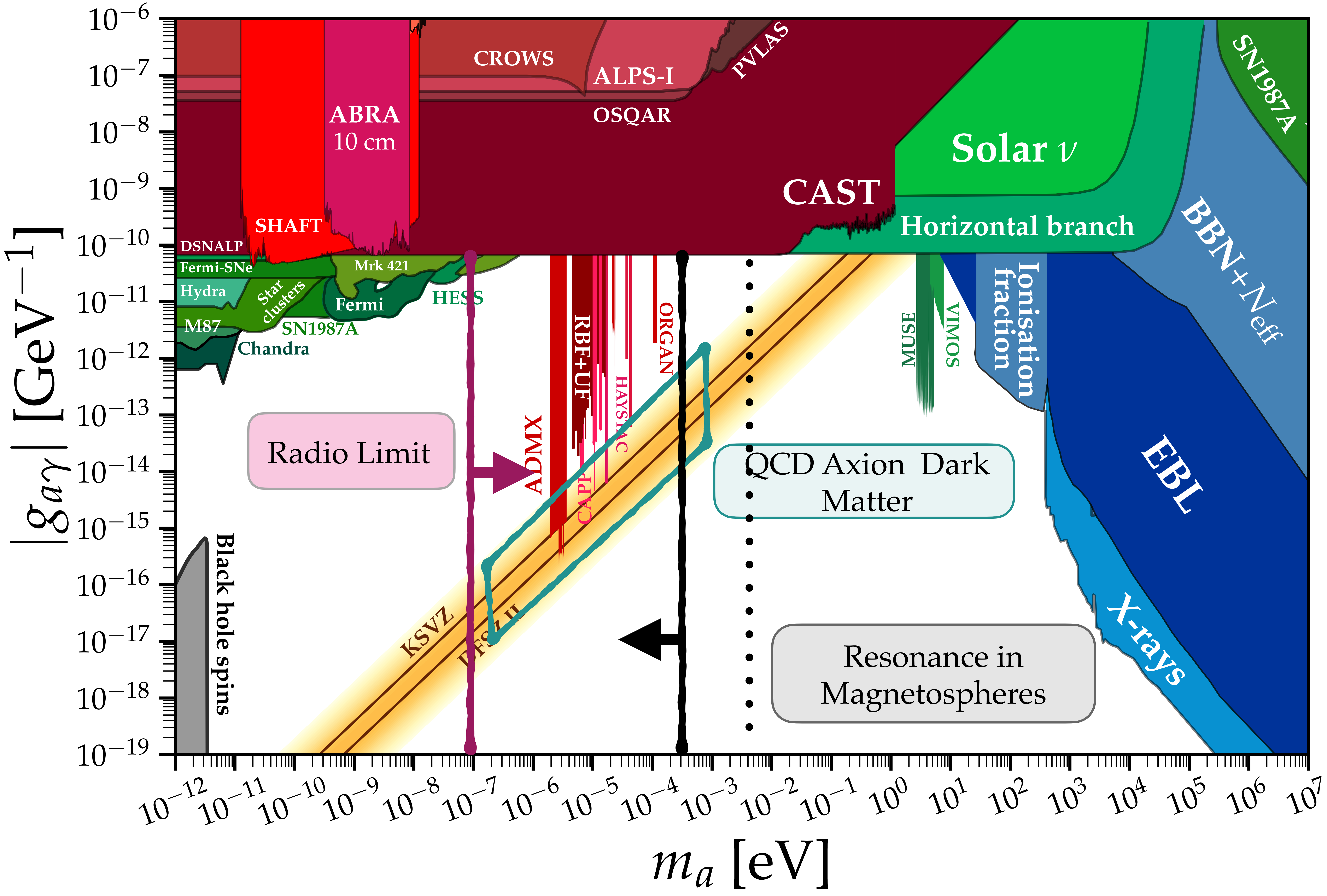

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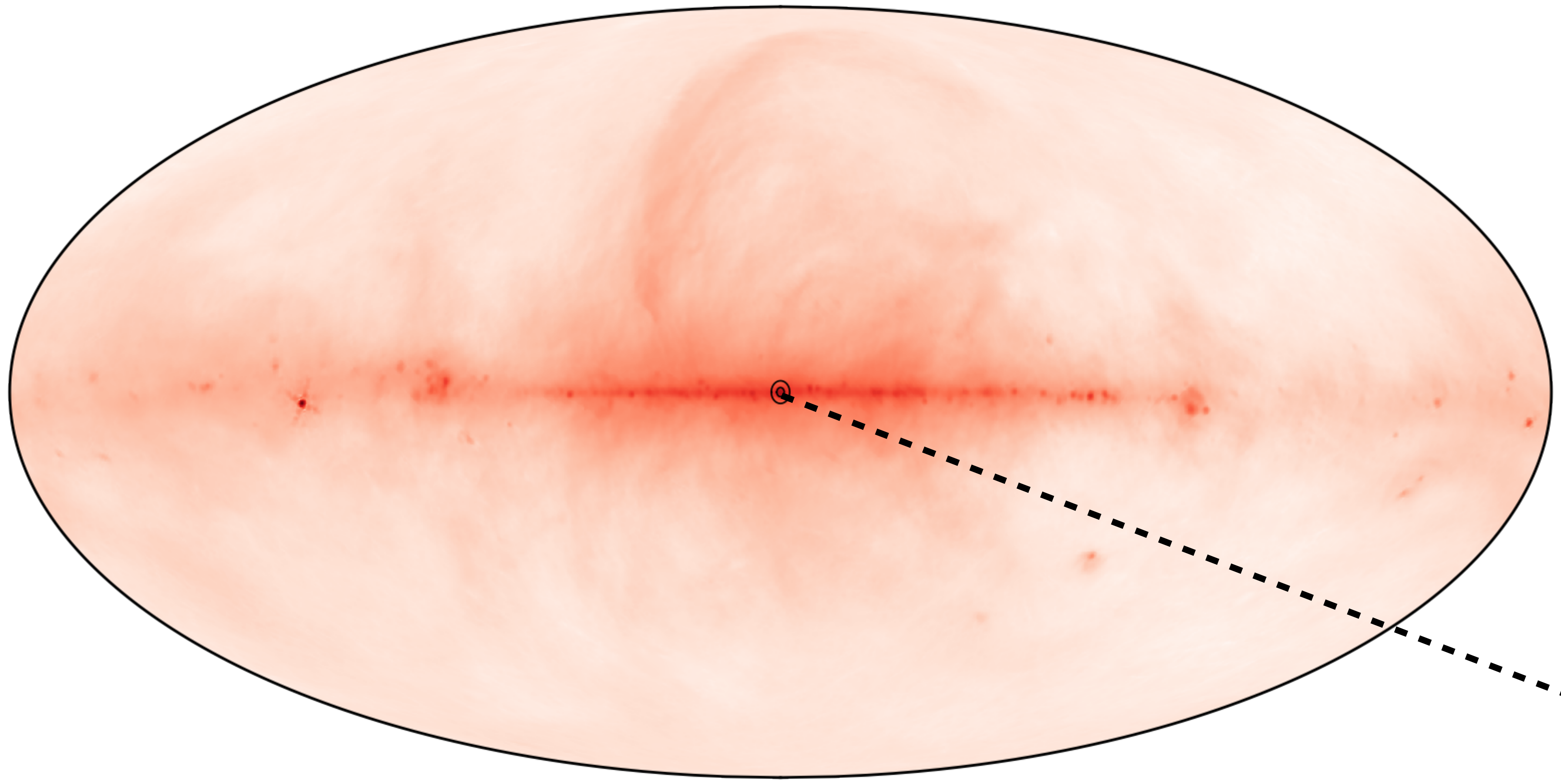
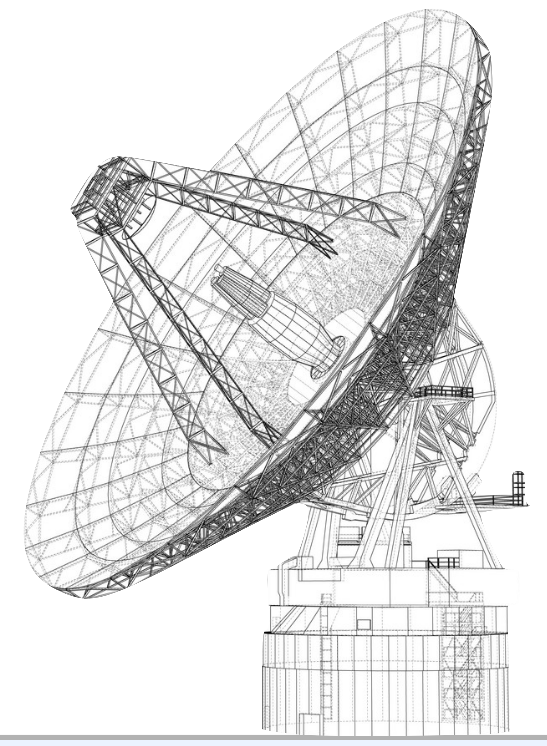
Observing the galactic center with the Green Bank Telescope





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
- **Observation Strategy:** On/off target

Data courtesy of the Breakthrough Listen Initiative

Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

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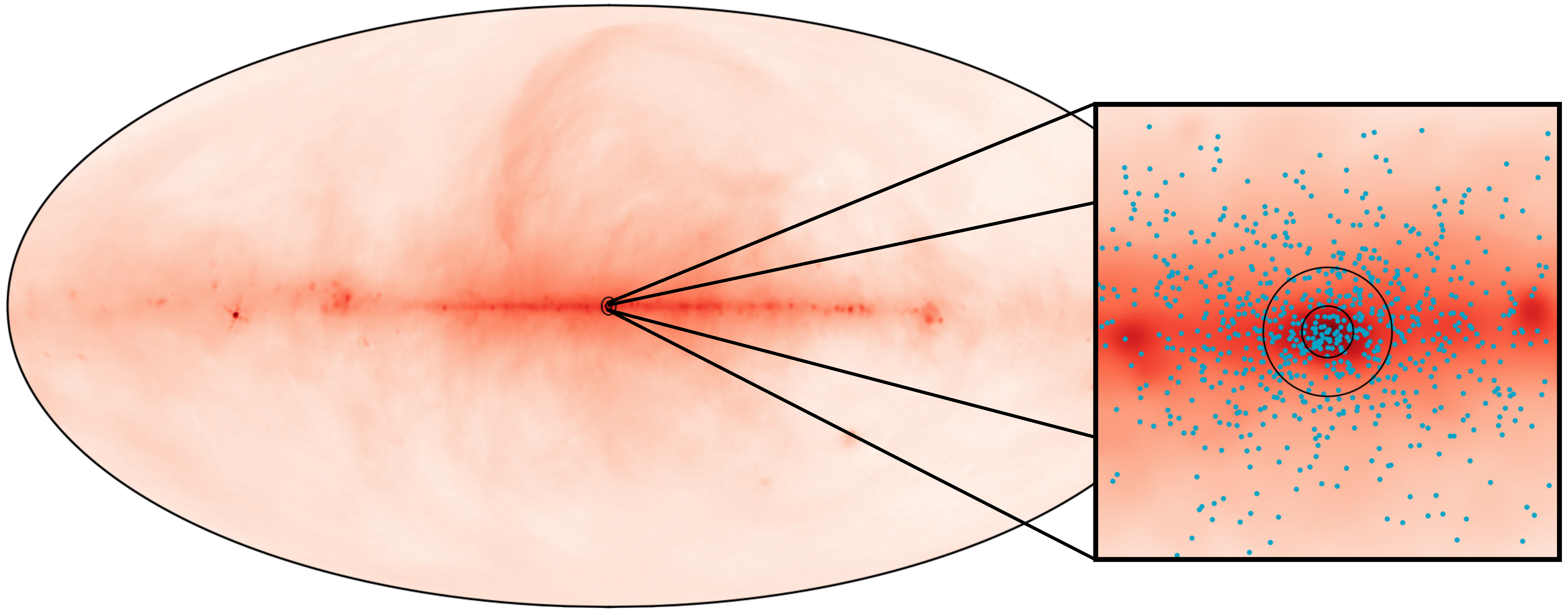

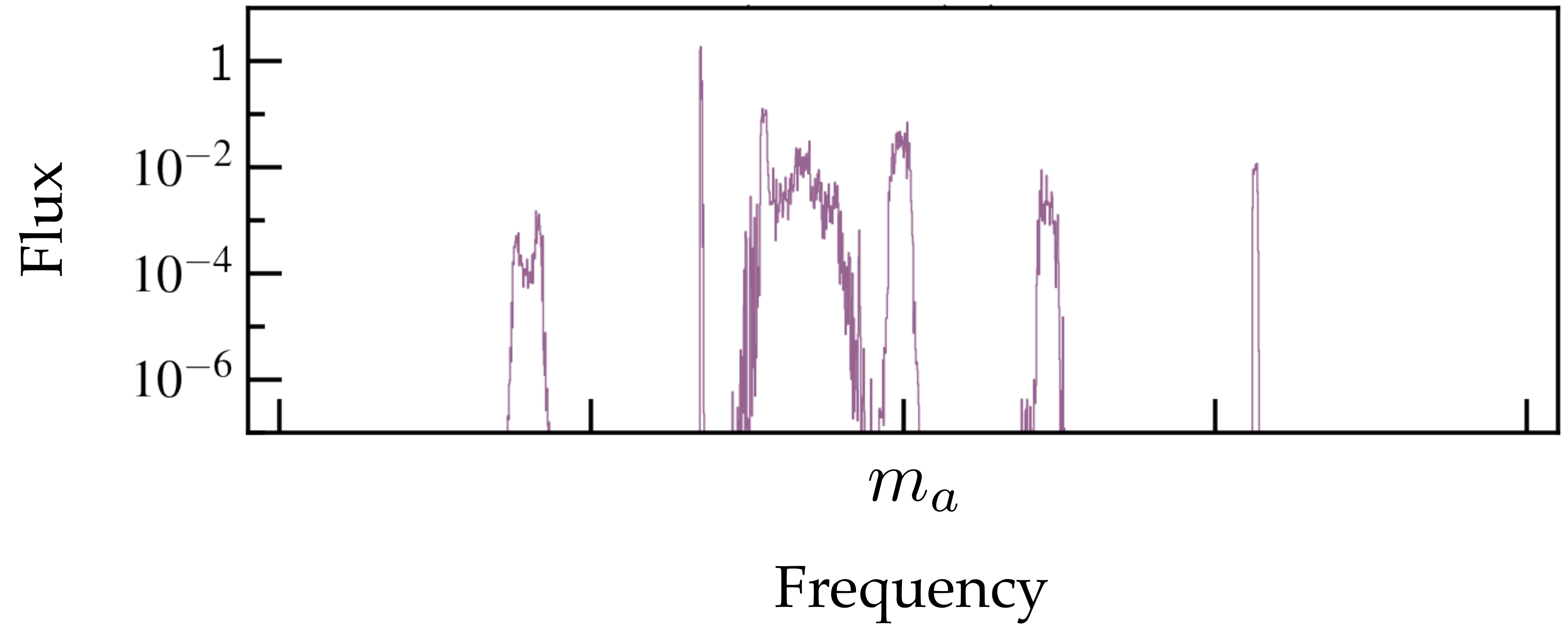

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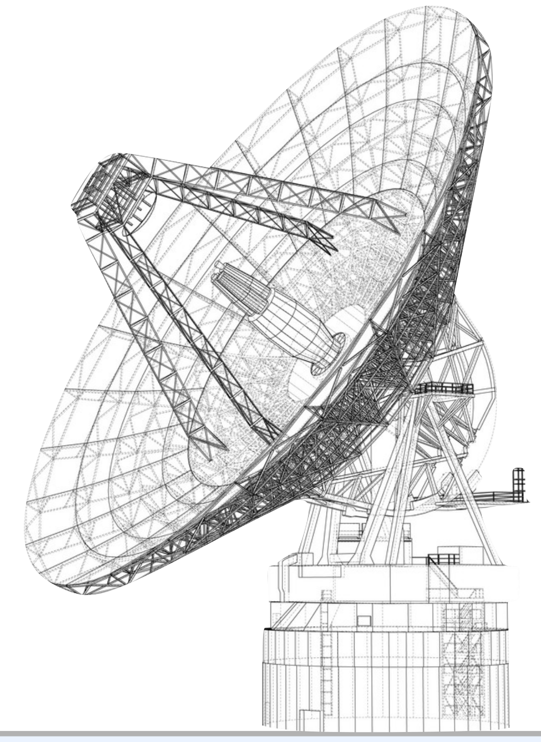
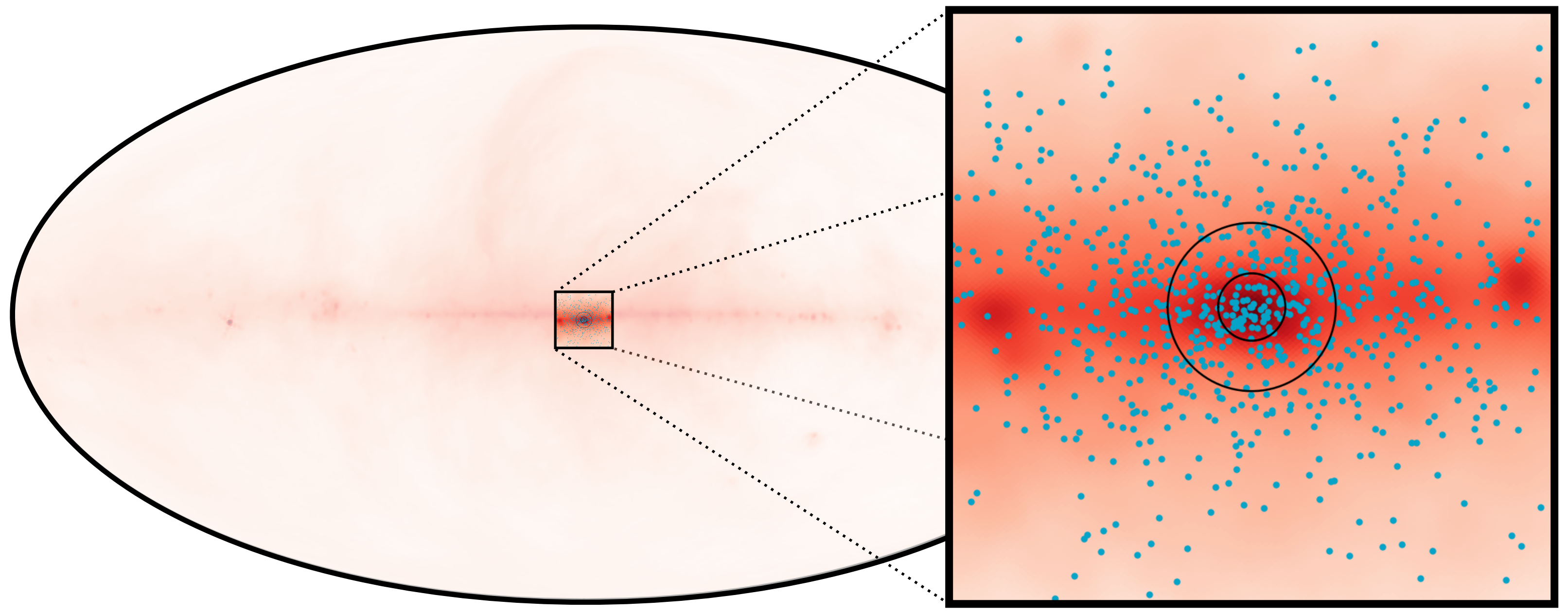
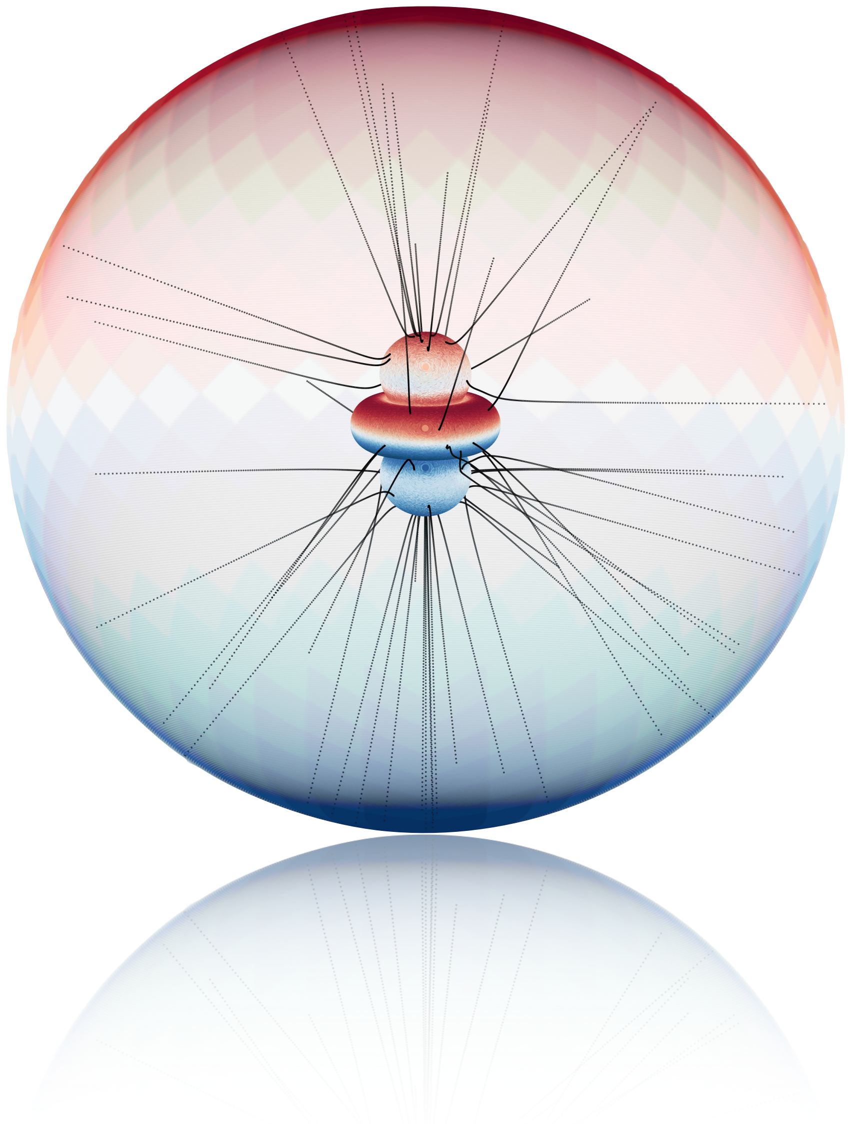


GBT observations of galactic center

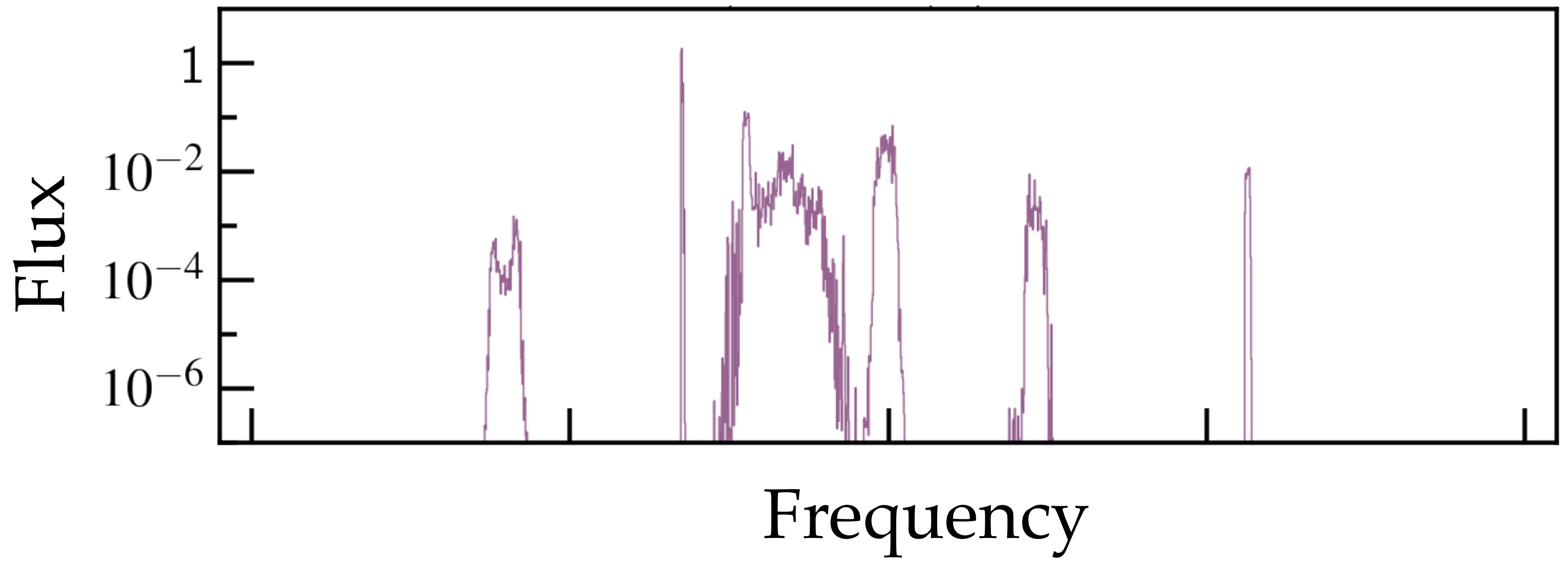
Population Synthesis



Radio Signal



Data Analysis



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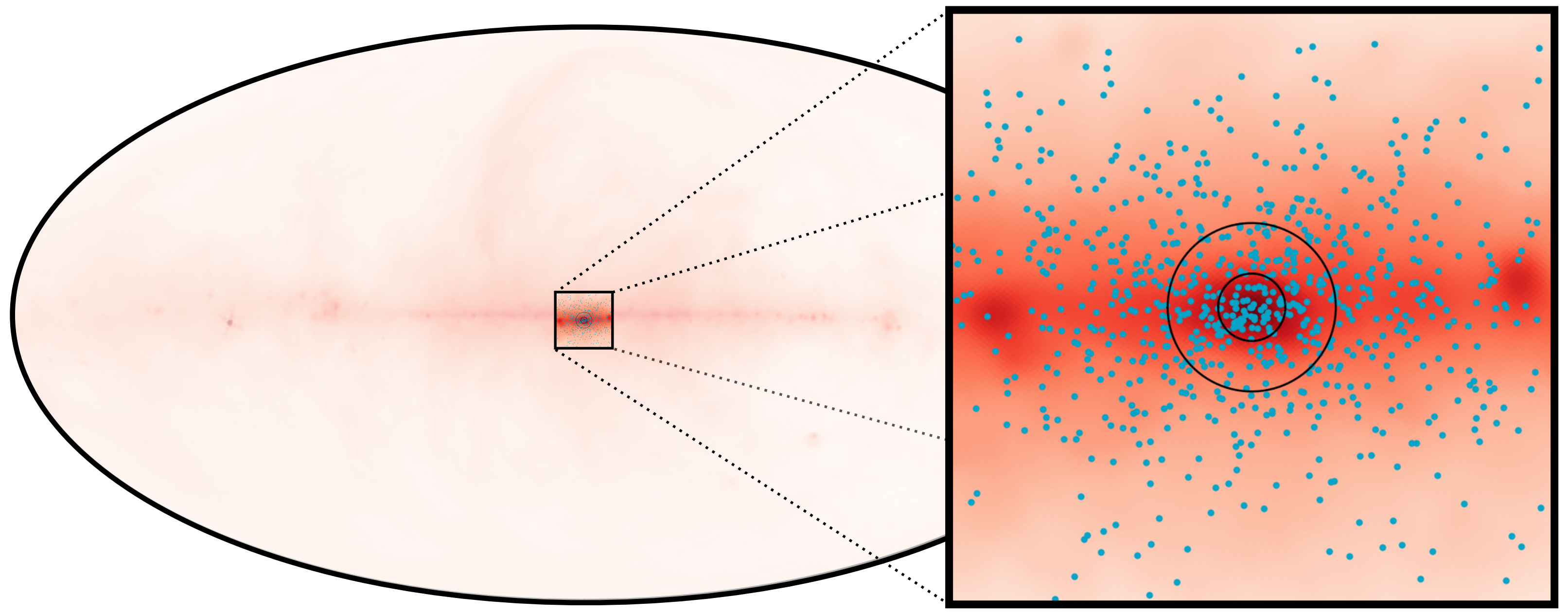

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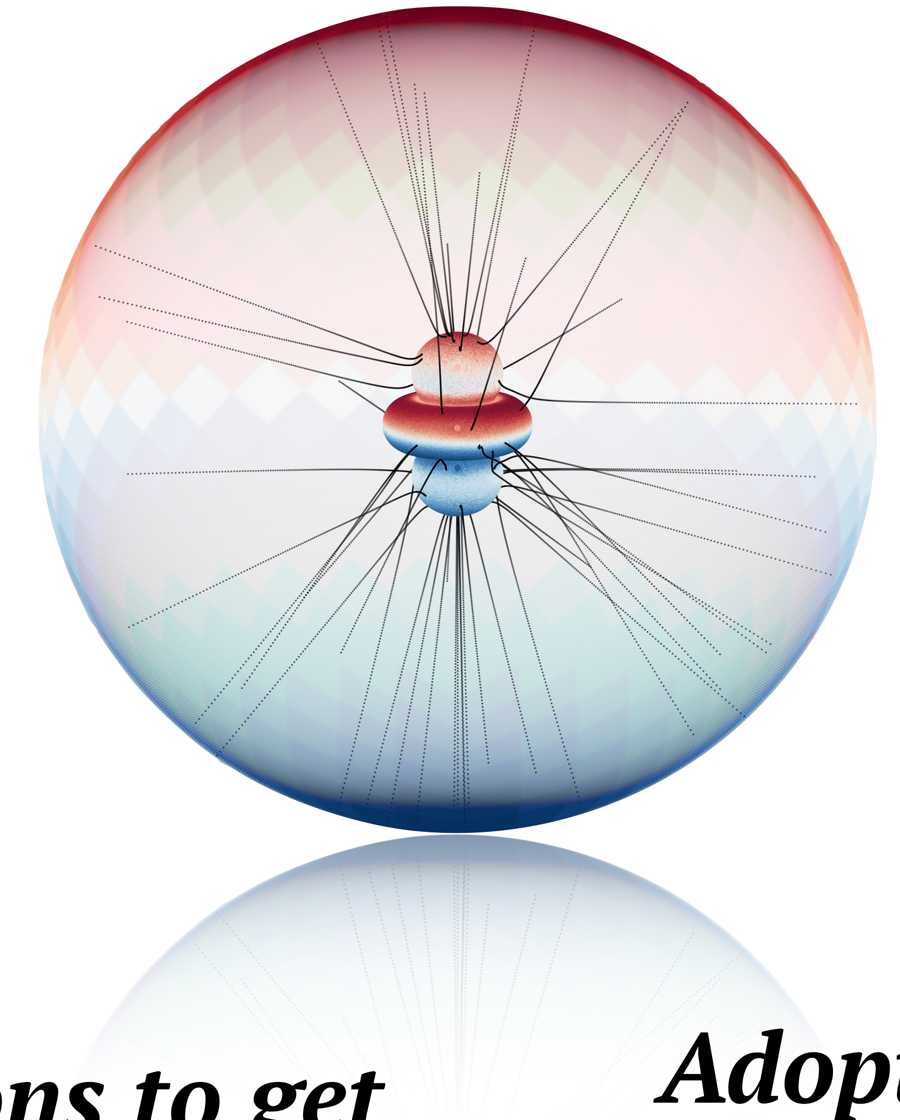

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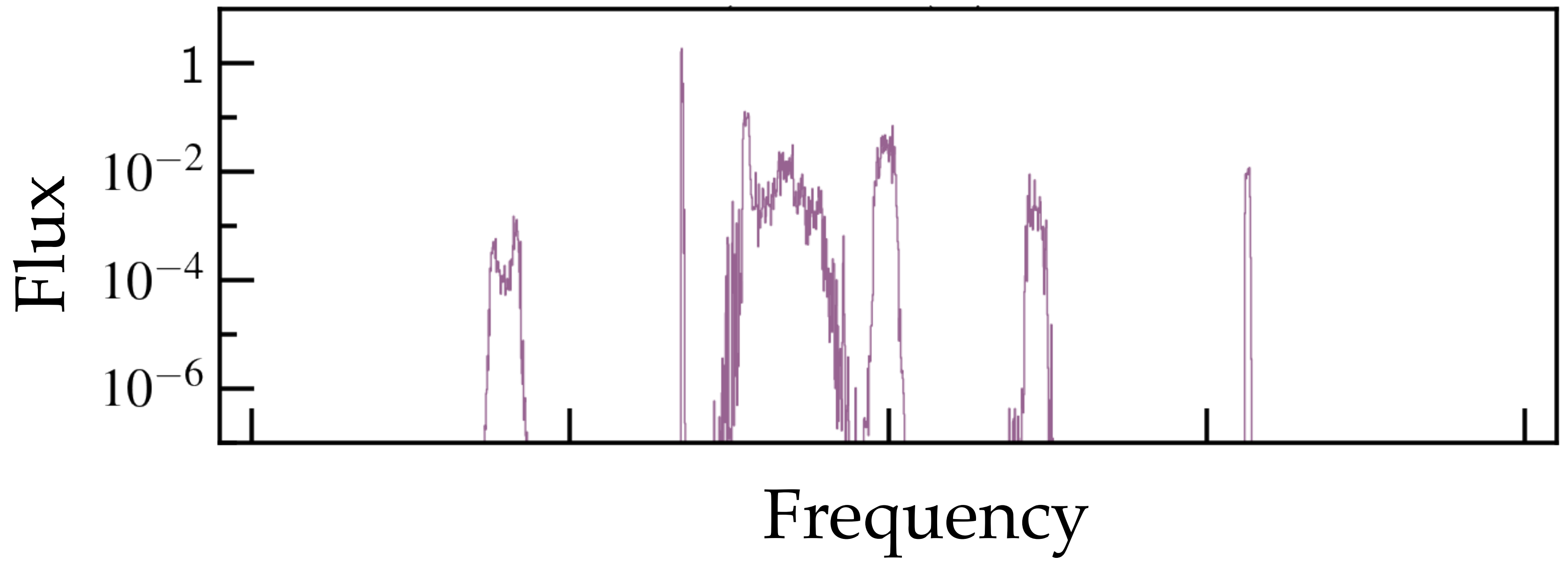

Use star formation rates & stellar distributions to get

1.) Distributions of neutron star birth rate $p(t_{\rm NS-birth})$

2.) Spatial distribution of young neutron stars $n_{NS}(\vec{r})$

Do et al (2013), Lu et al (2013), Yusef-Zadeh (2017)

Adopt initial distributions, simulate evolutionary tracks, and fit to the distributions we observe today

$$p(P, B_0, \theta_m \,|\, t_{age})$$

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GBT observations of galactic center

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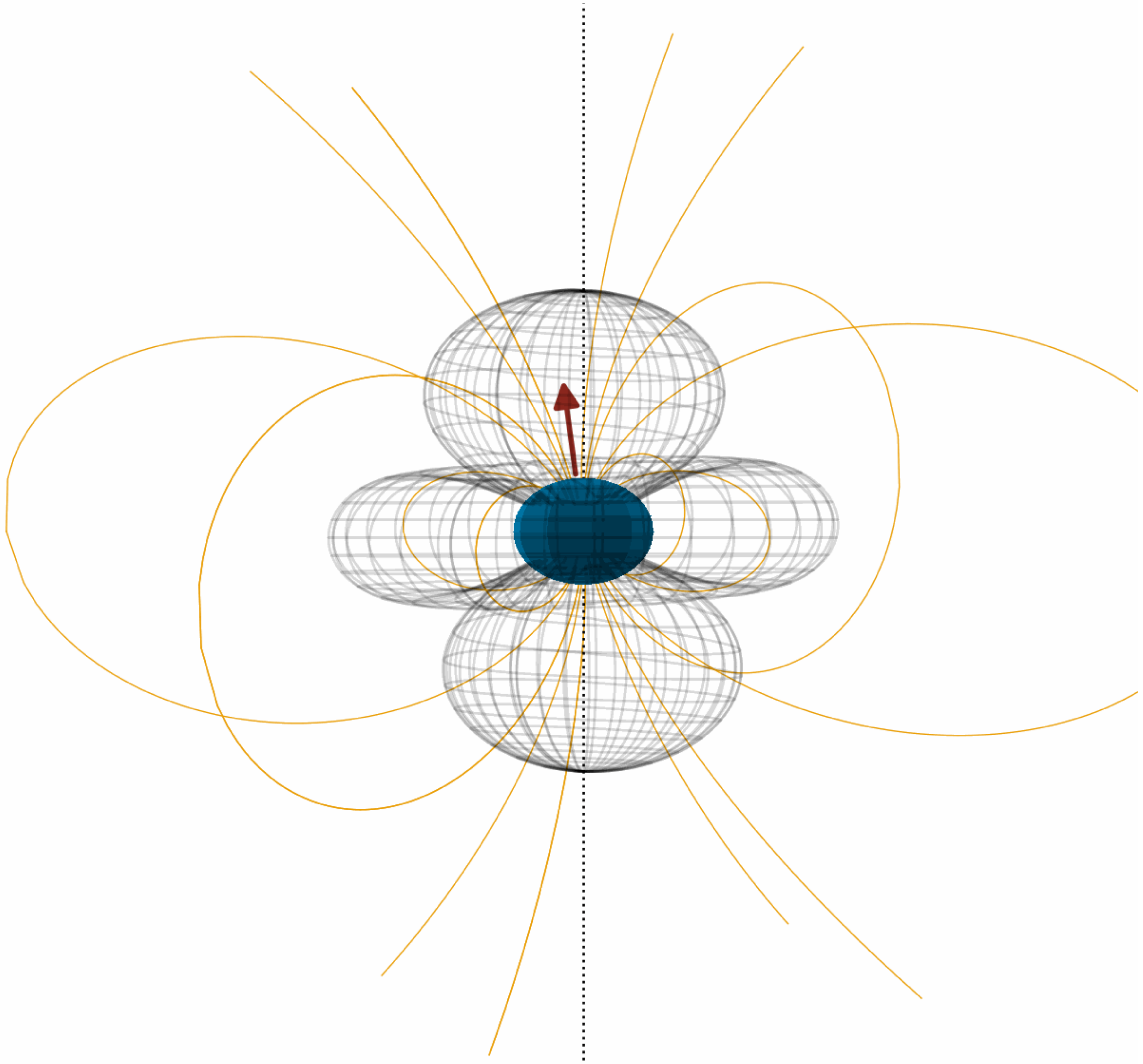
Photon production from axion dark matter

Step 1: Define plasma structure of magnetosphere

Resonant Conversion

Location: $m_a \sim \omega_p$

Efficiency: $\propto (\partial_x \omega_p)^{-1}$



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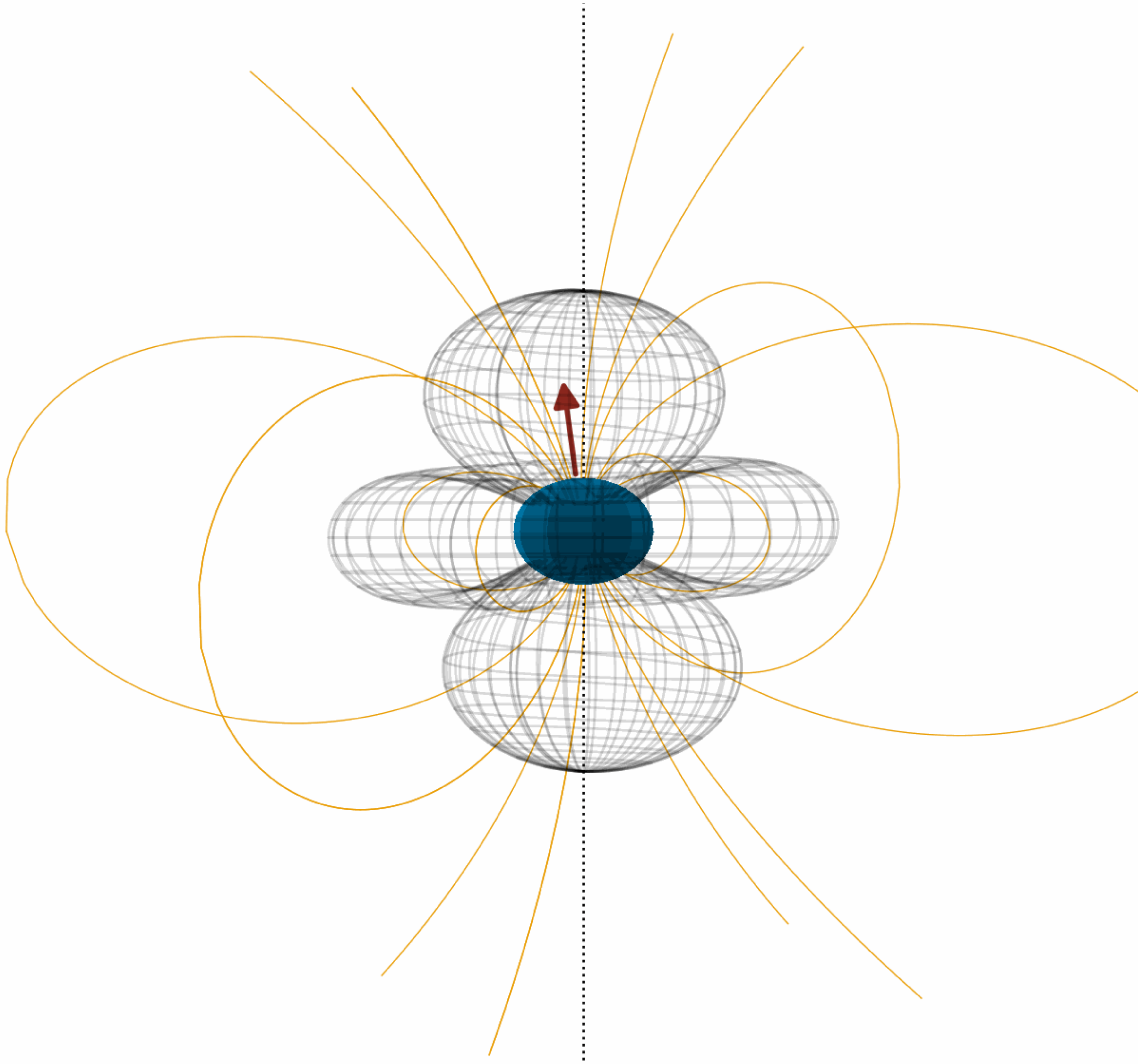

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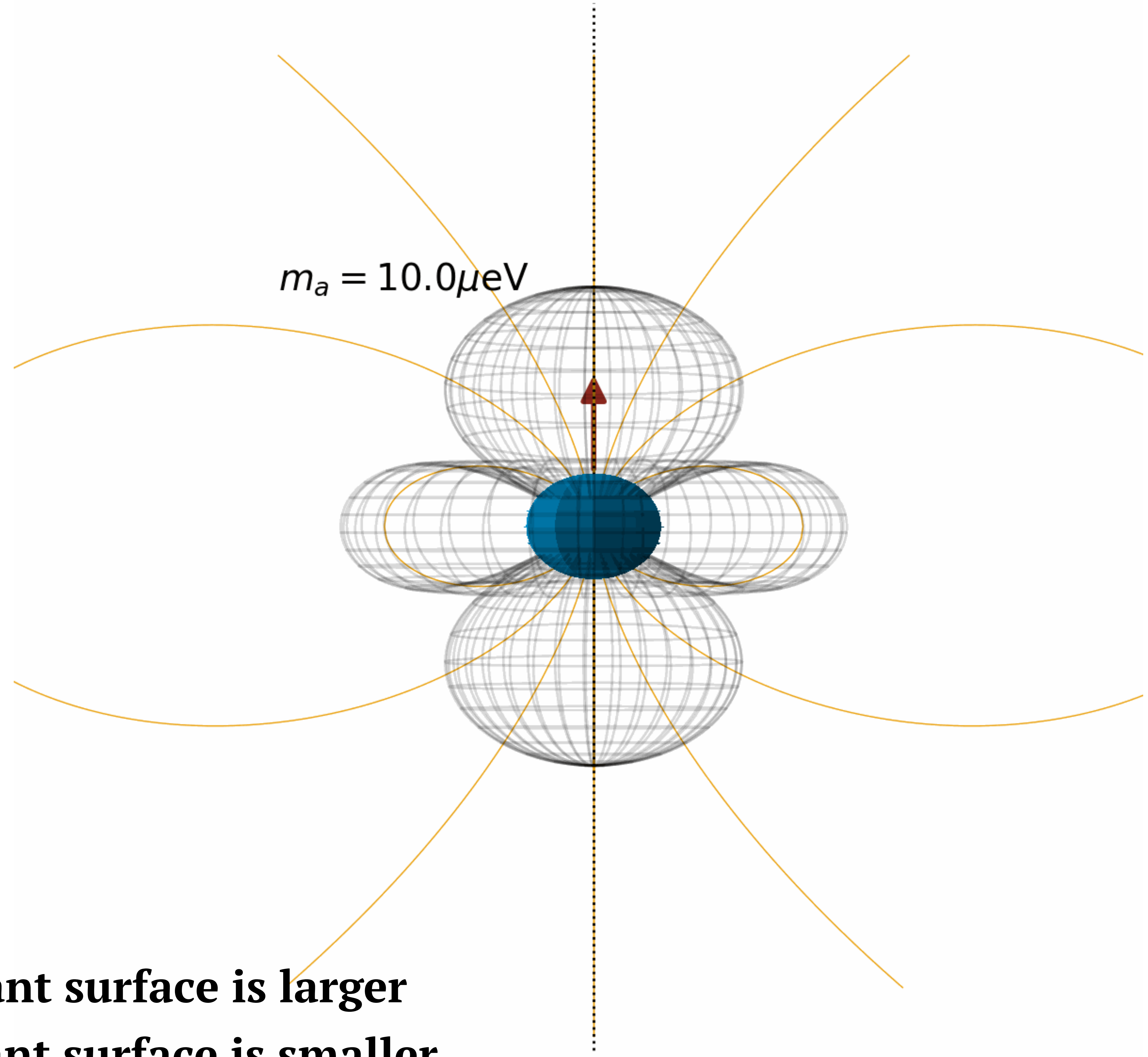

Smaller axion mass → resonant surface is larger

Larger axion mass → resonant surface is smaller

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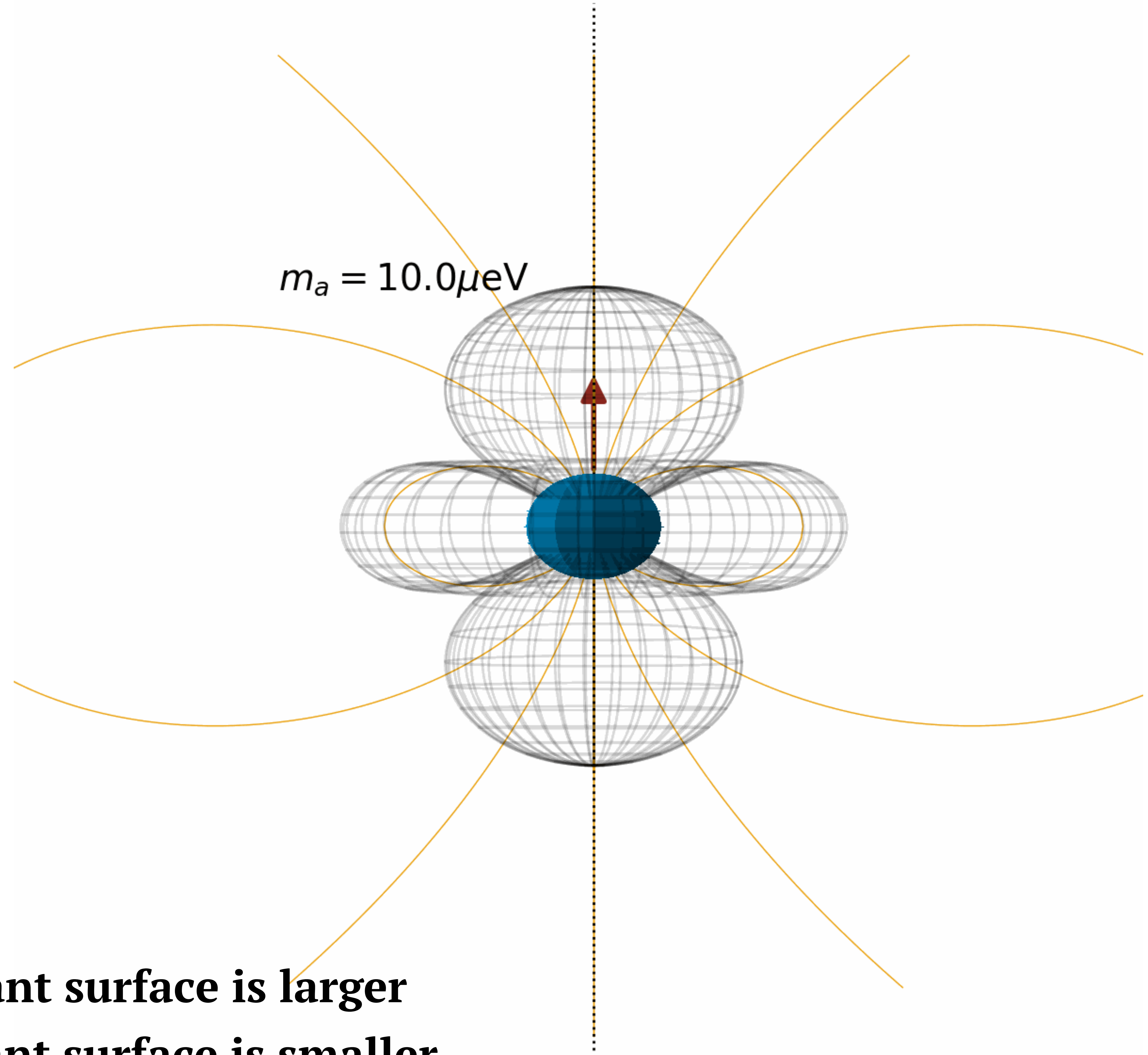

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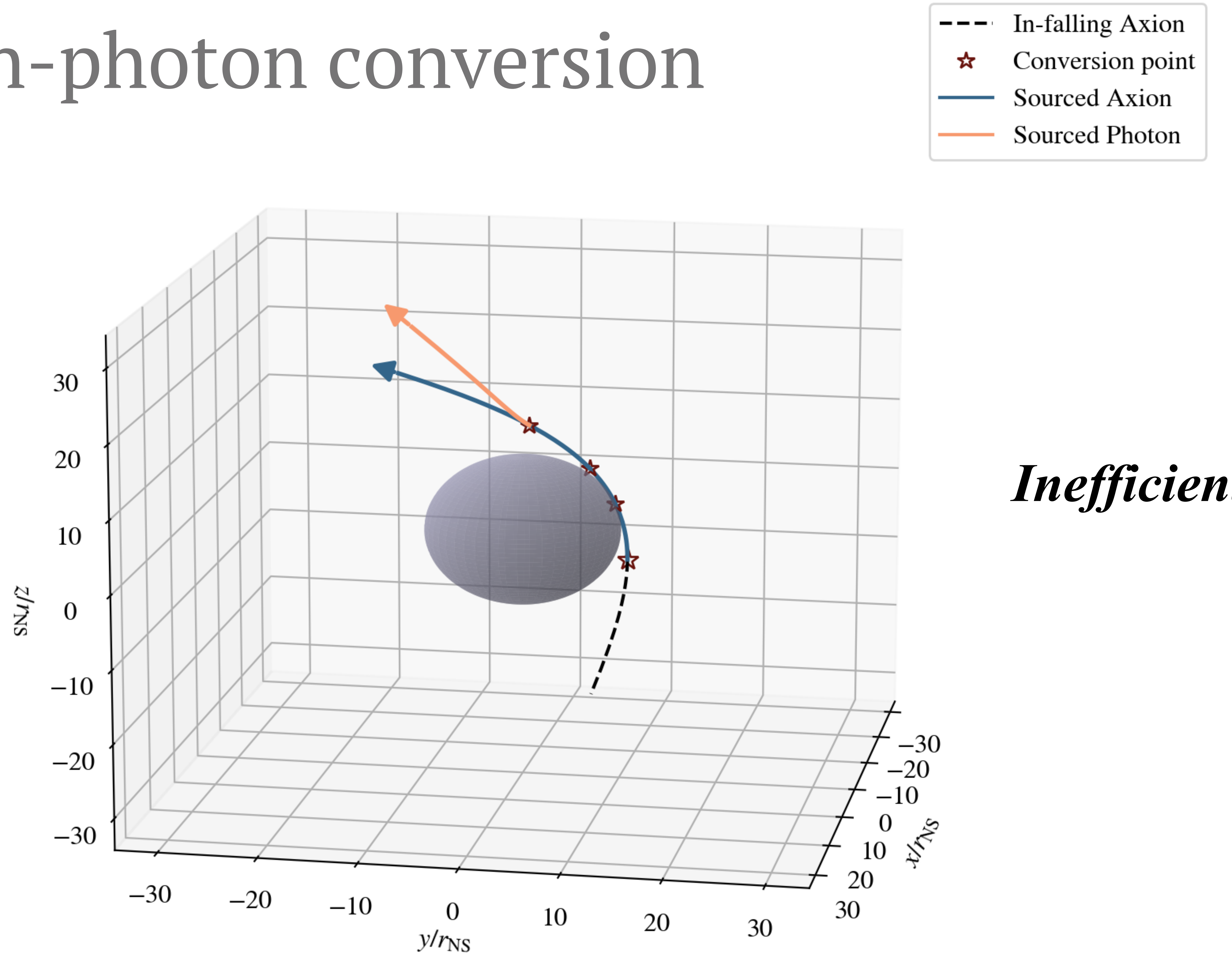
Tracking axion-photon conversion

Step 2: Axion phase space to photon flux



Inefficient conversion

Non-adiabatic: **SJW**, Noordhuis, Edwards, Weniger (2021)
Adiabatic: Thjemsland, **SJW**, McDonald (To appear)

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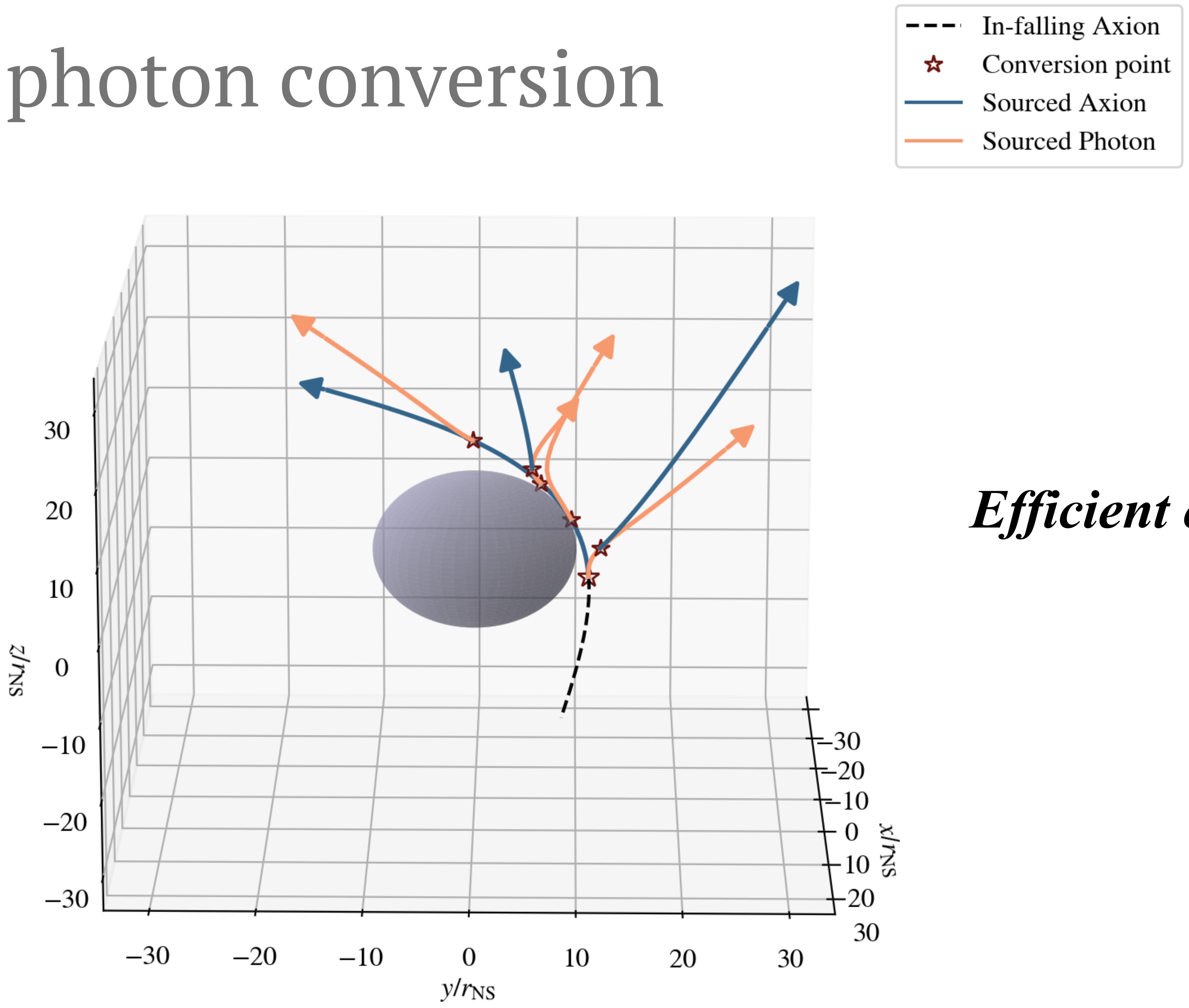

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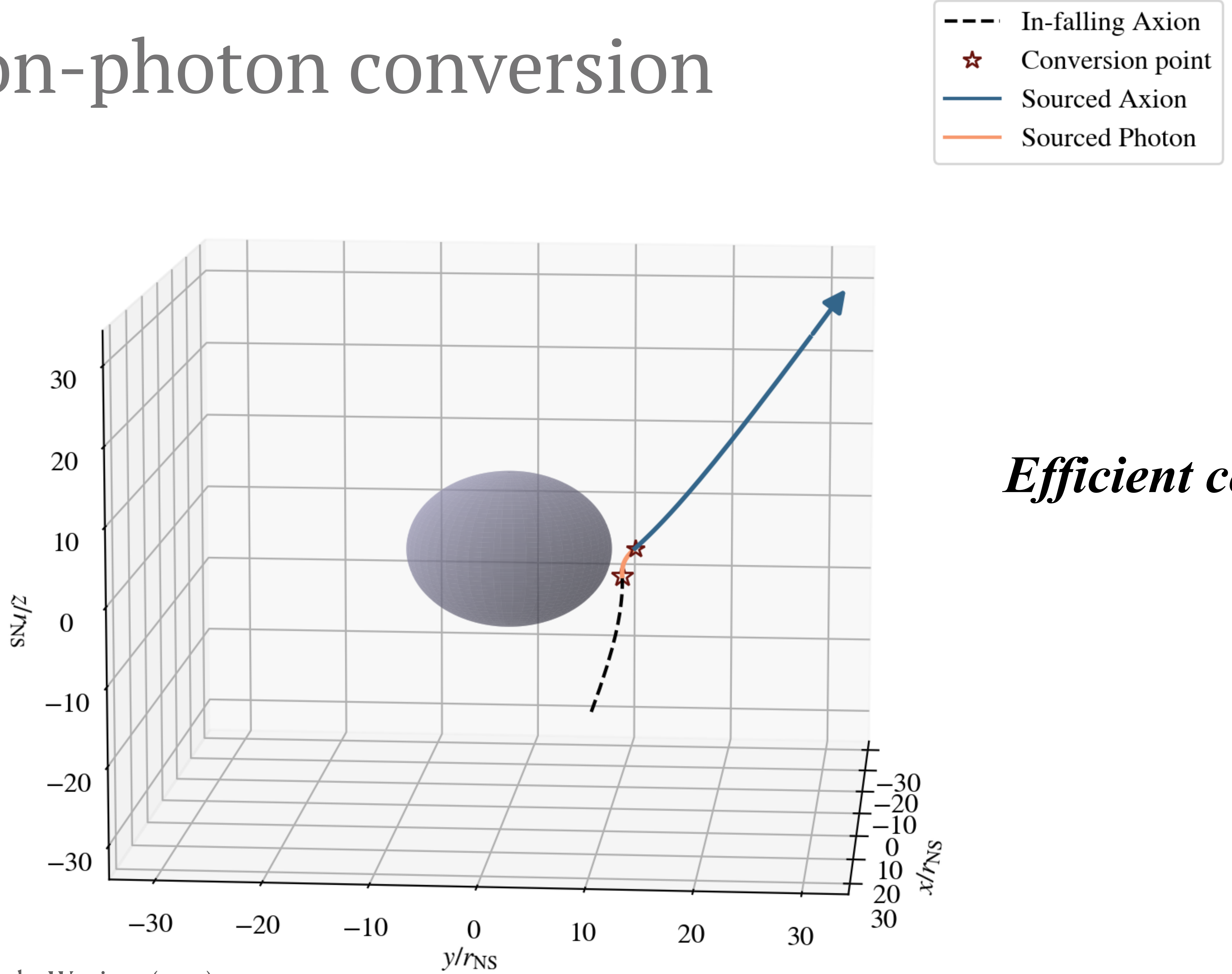

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Ray tracing

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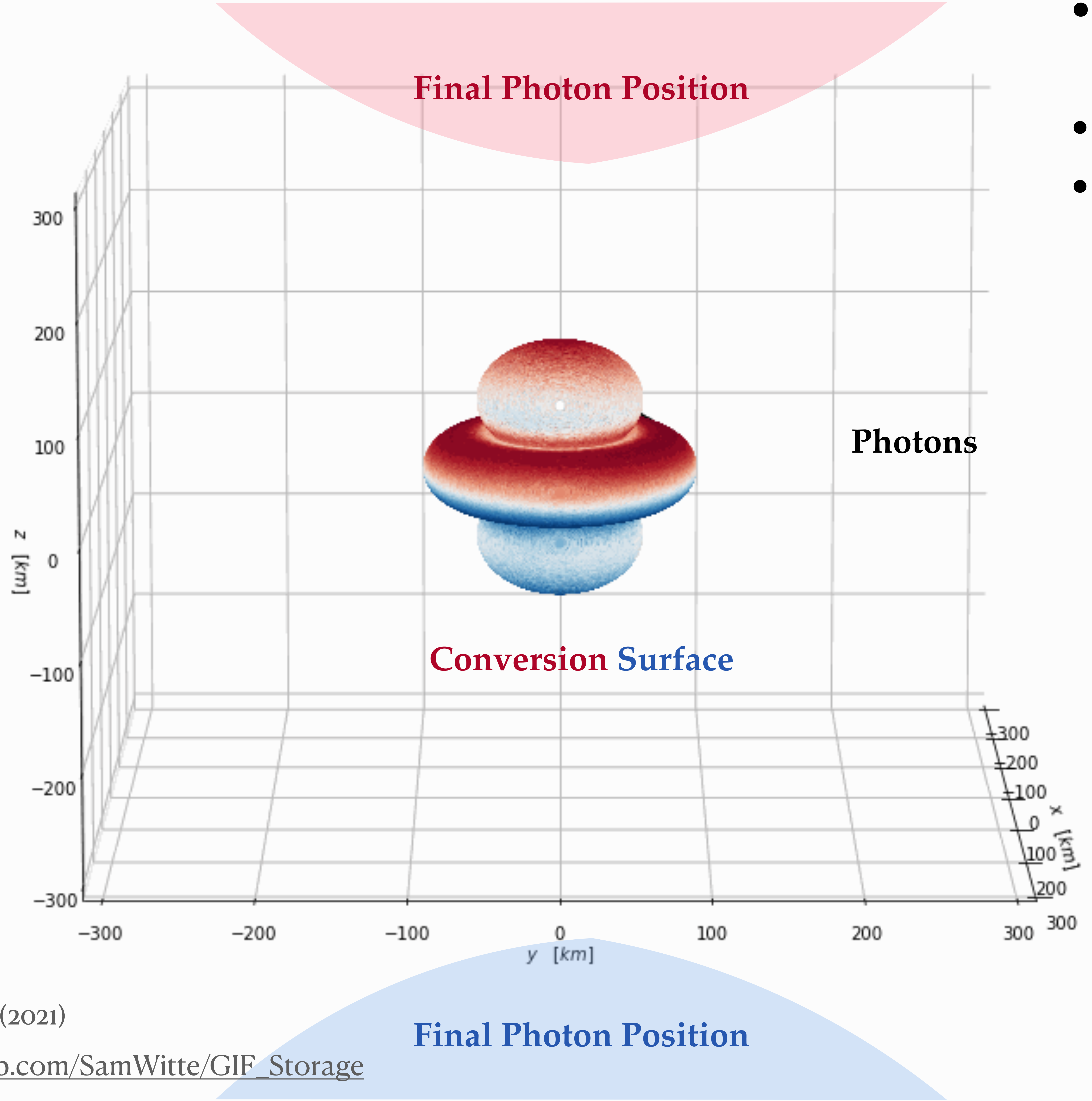

Ray tracing allows for:

- Accurate mapping of radio flux
- Line broadening effects
- Path-dependent absorption

SJW, Noordhuis, Edwards, Weniger (2021)

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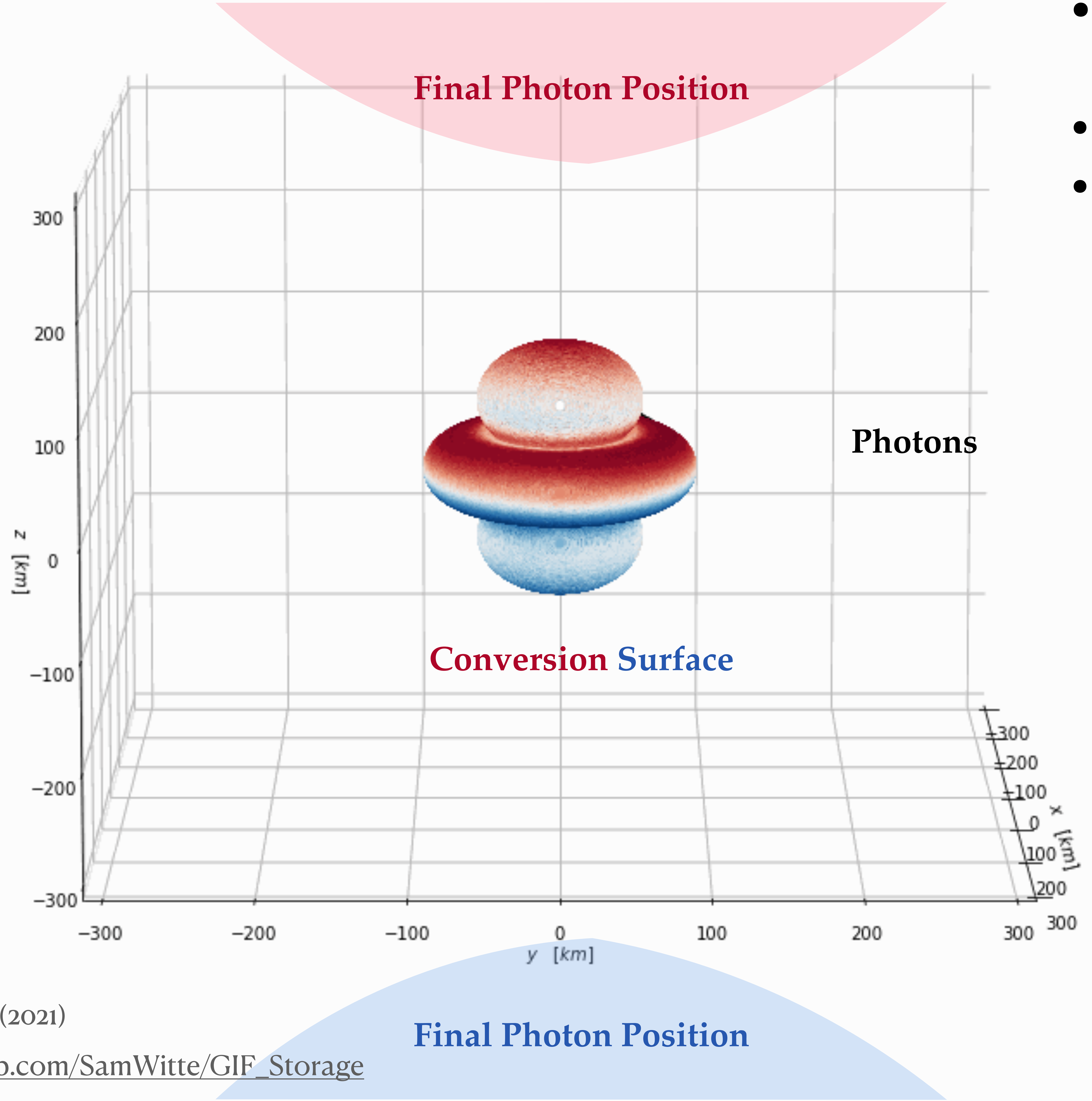

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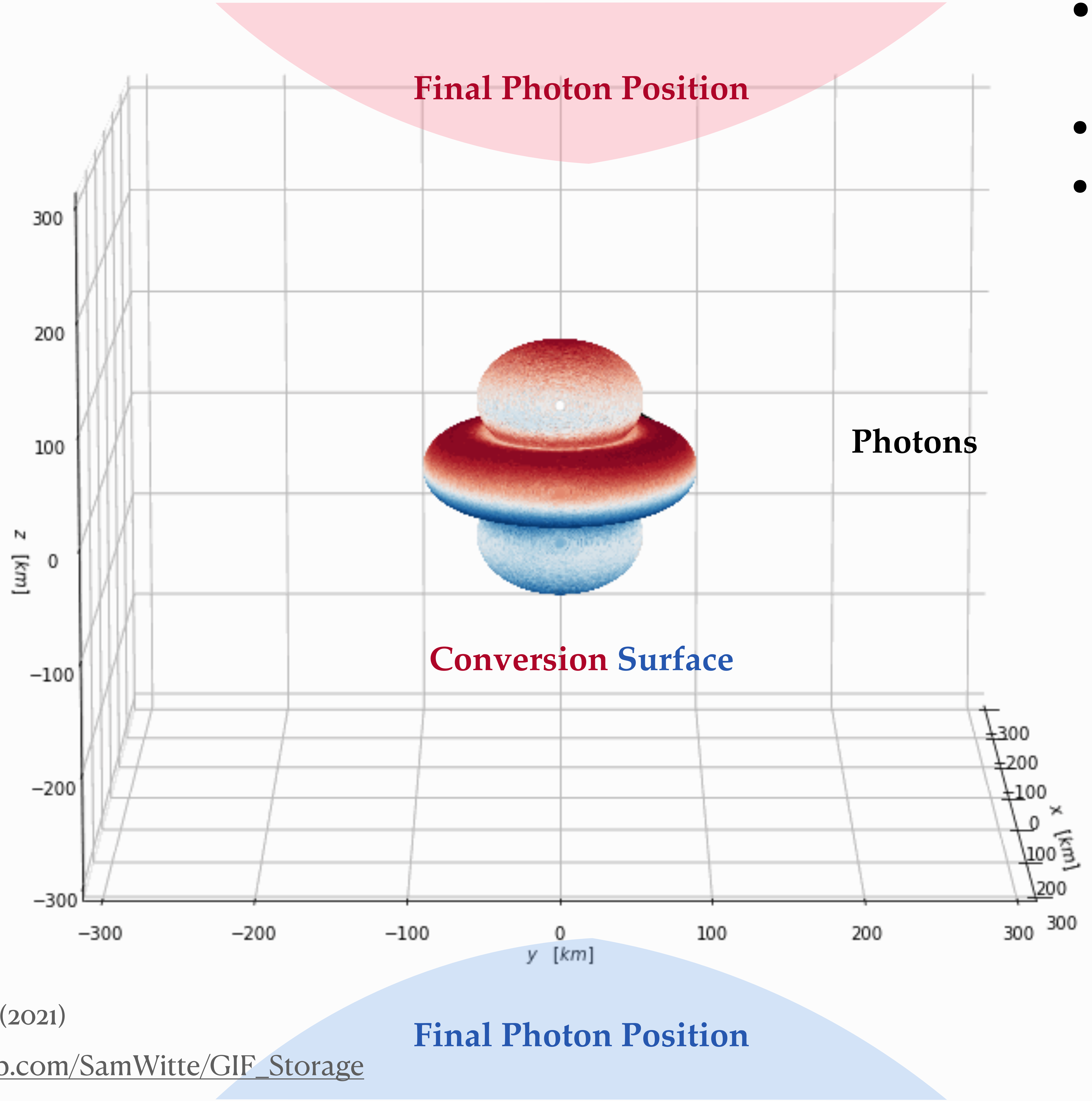

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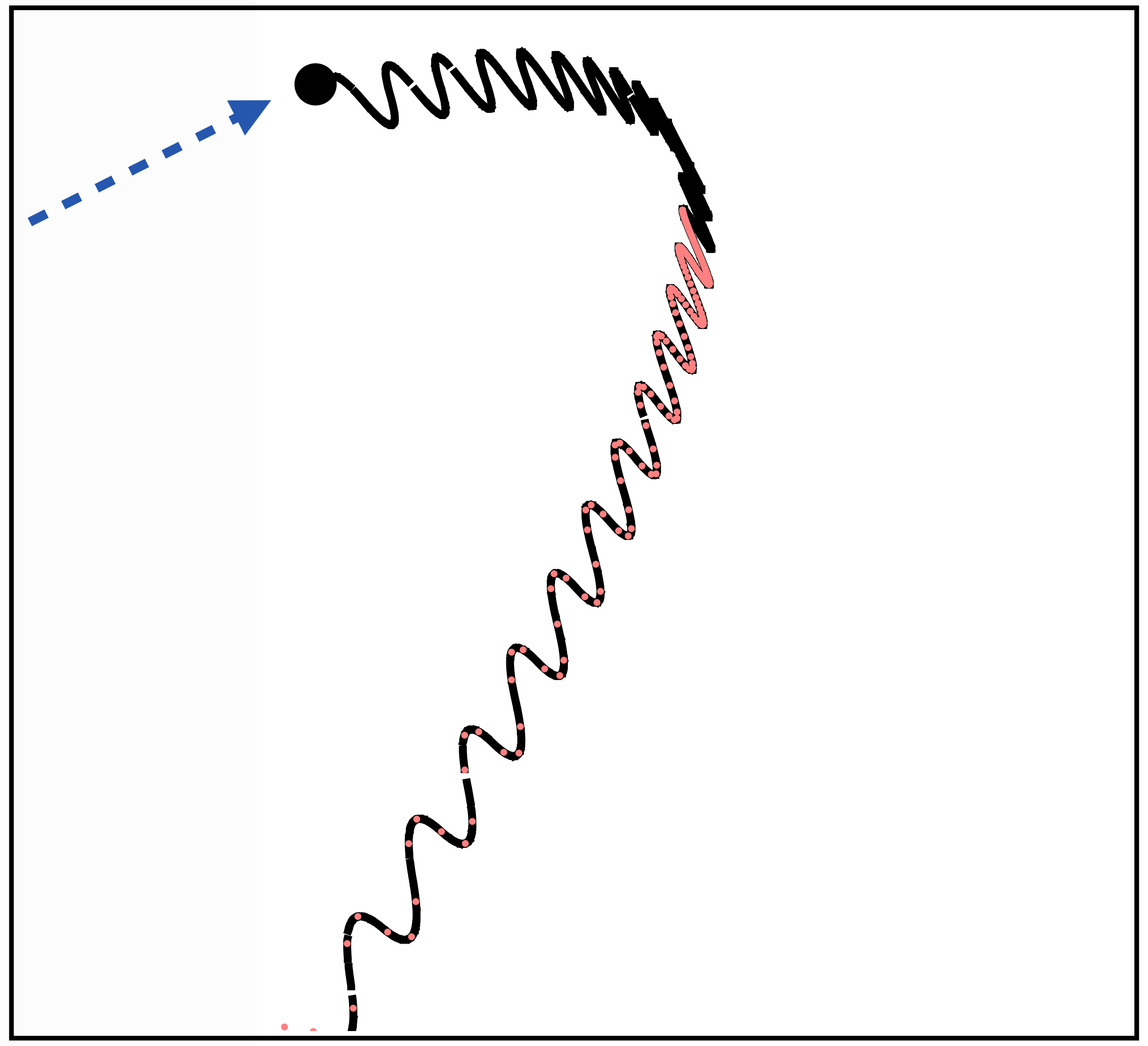
Zoom In



~ 500 meters

SJW, Noordhuis, Edwards, Weniger (2021)

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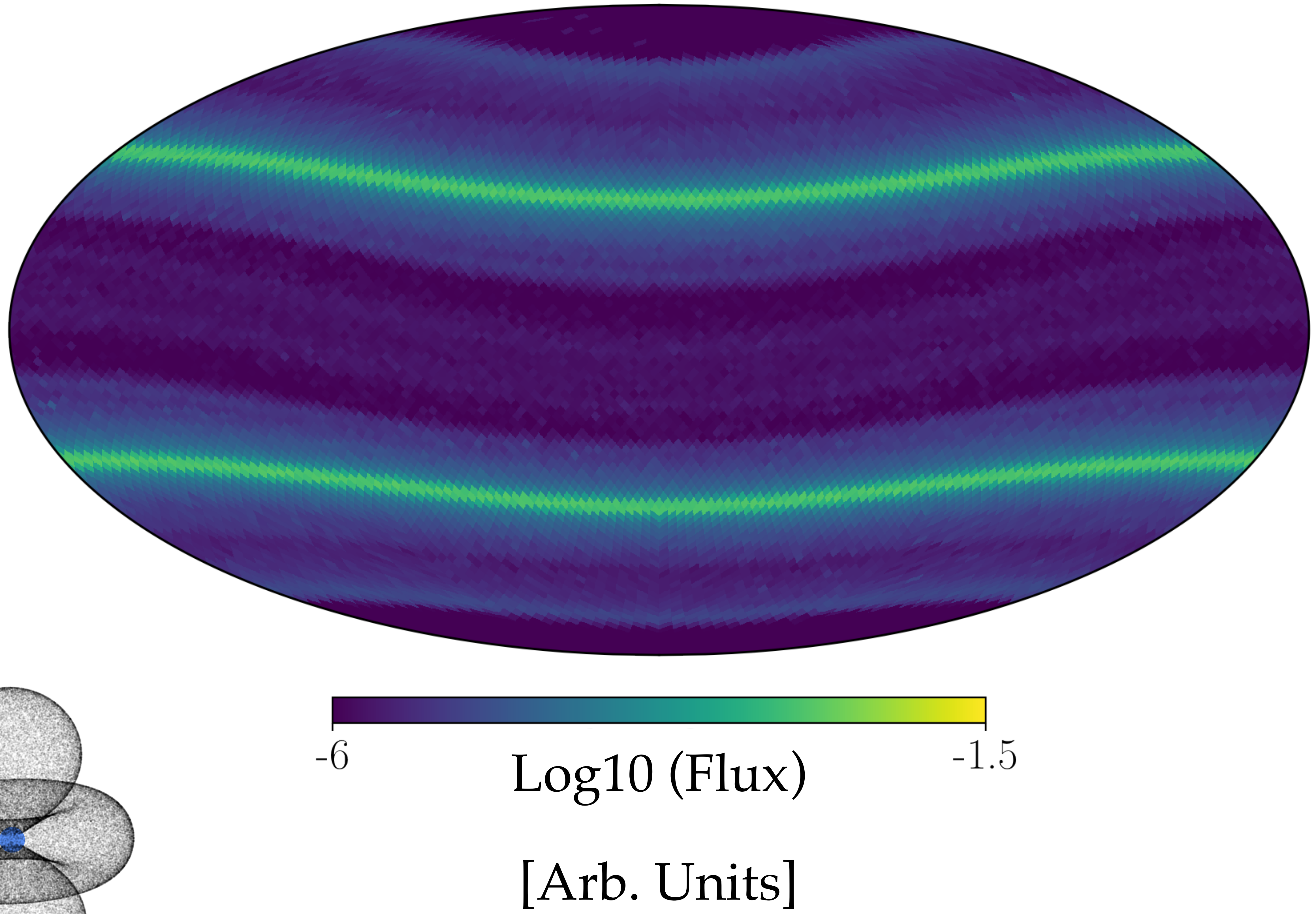
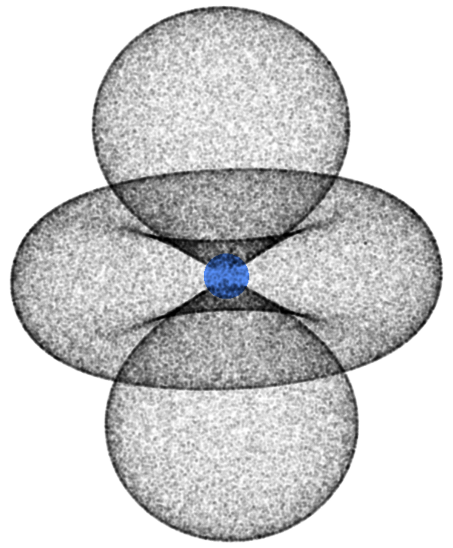
Radio signal from isolated neutron star

Projected sky flux as viewed from neutron star





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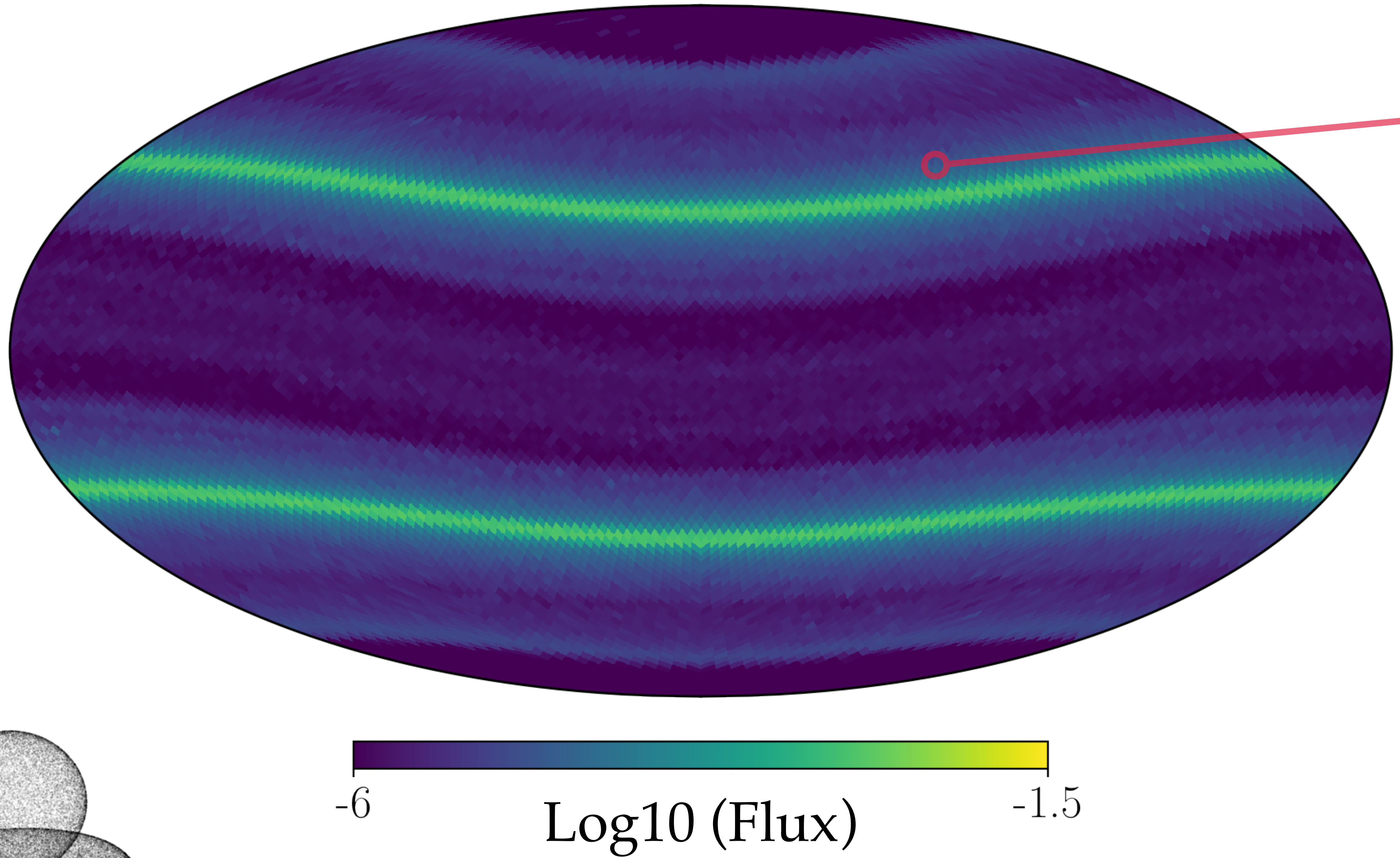

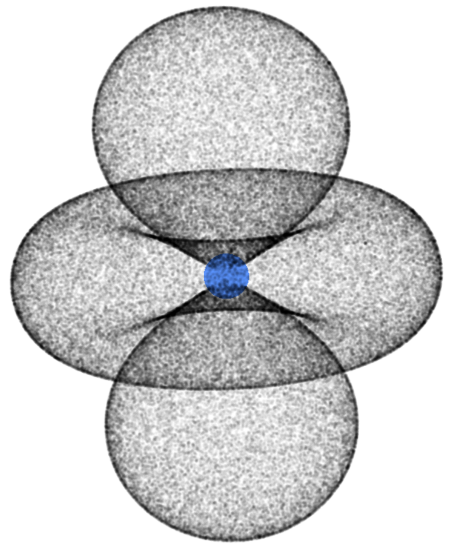

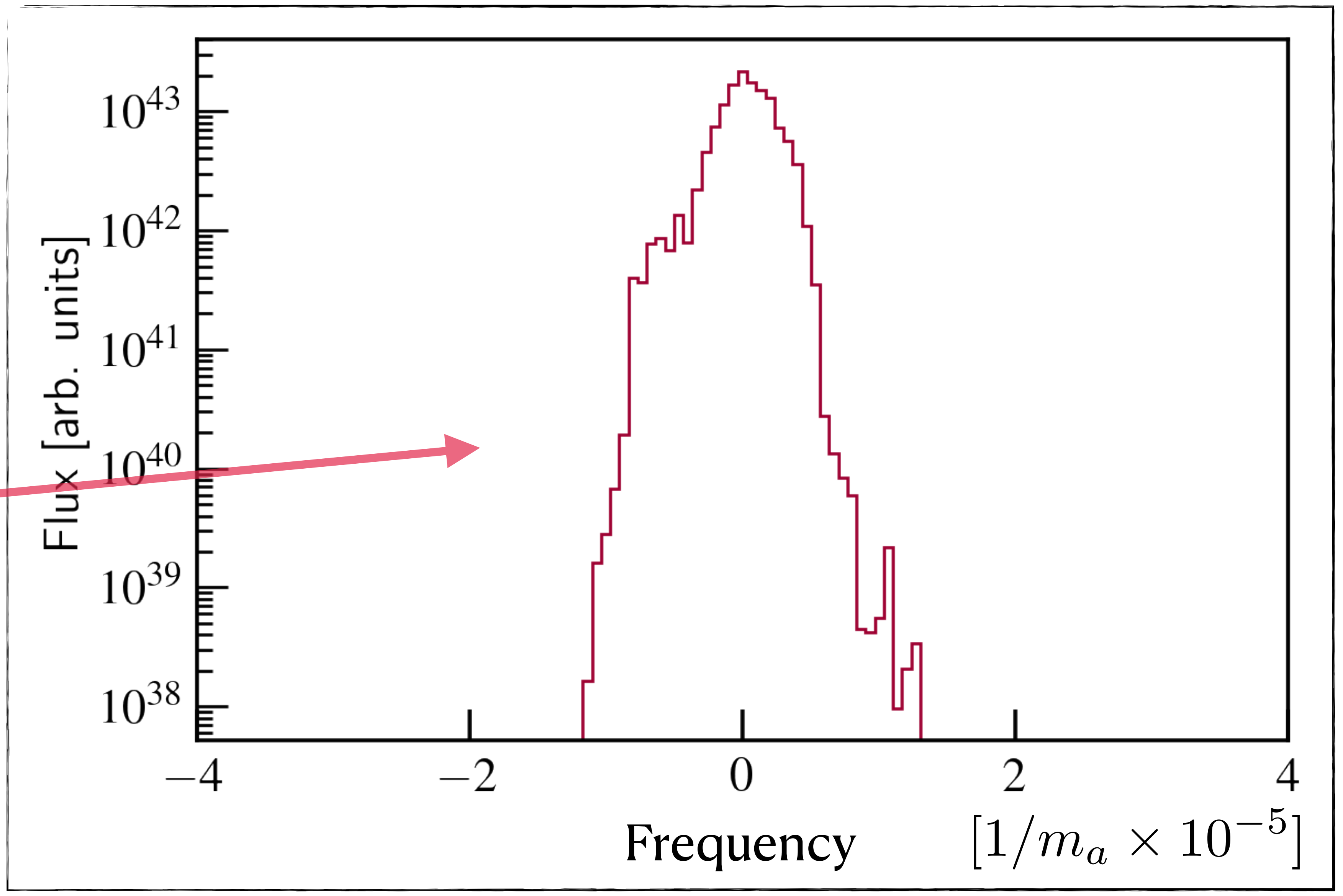

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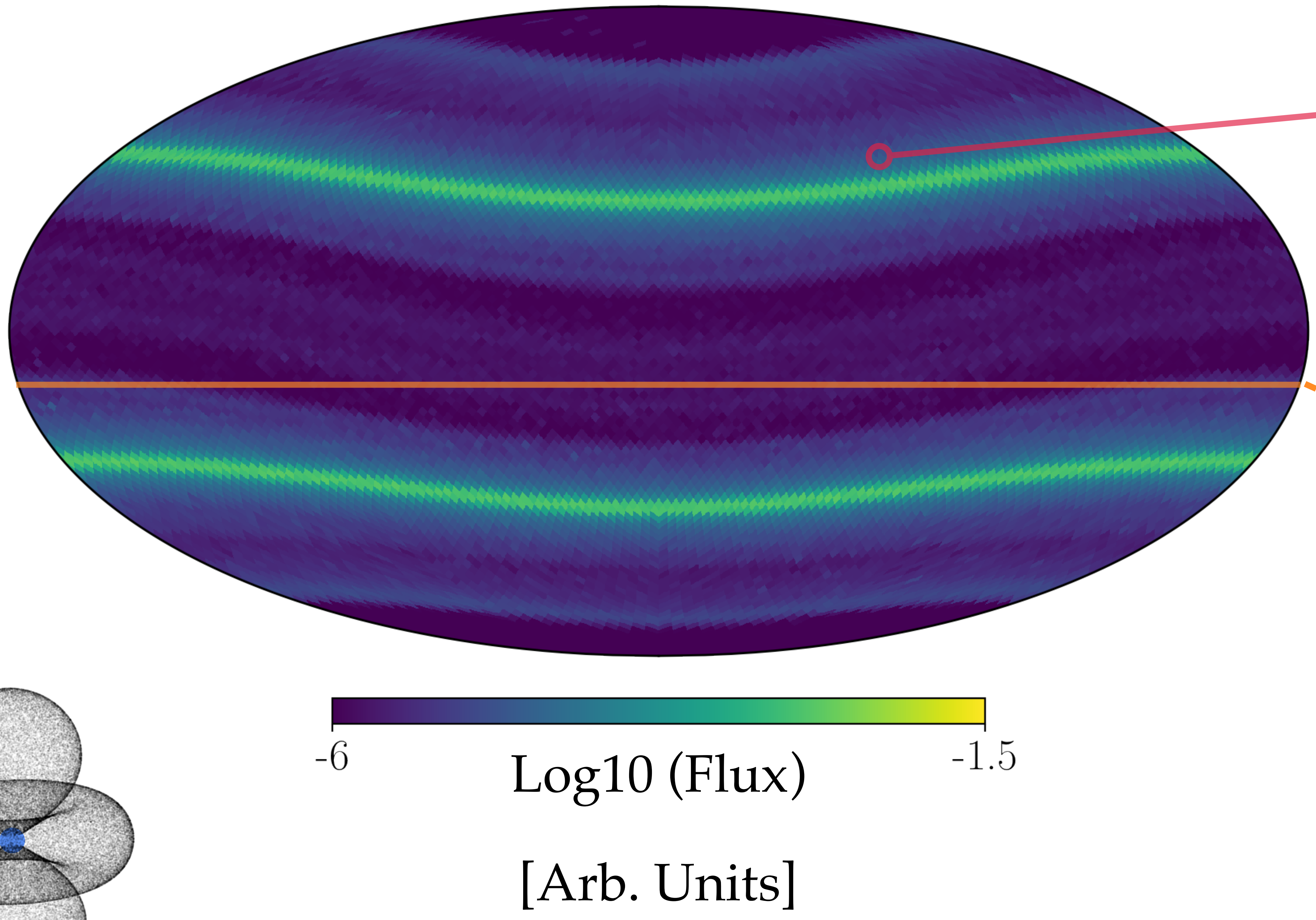
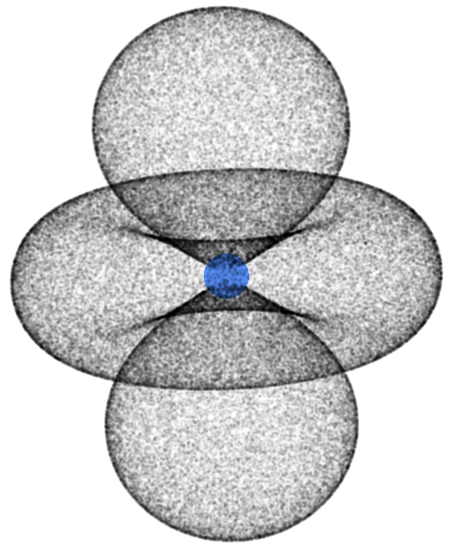
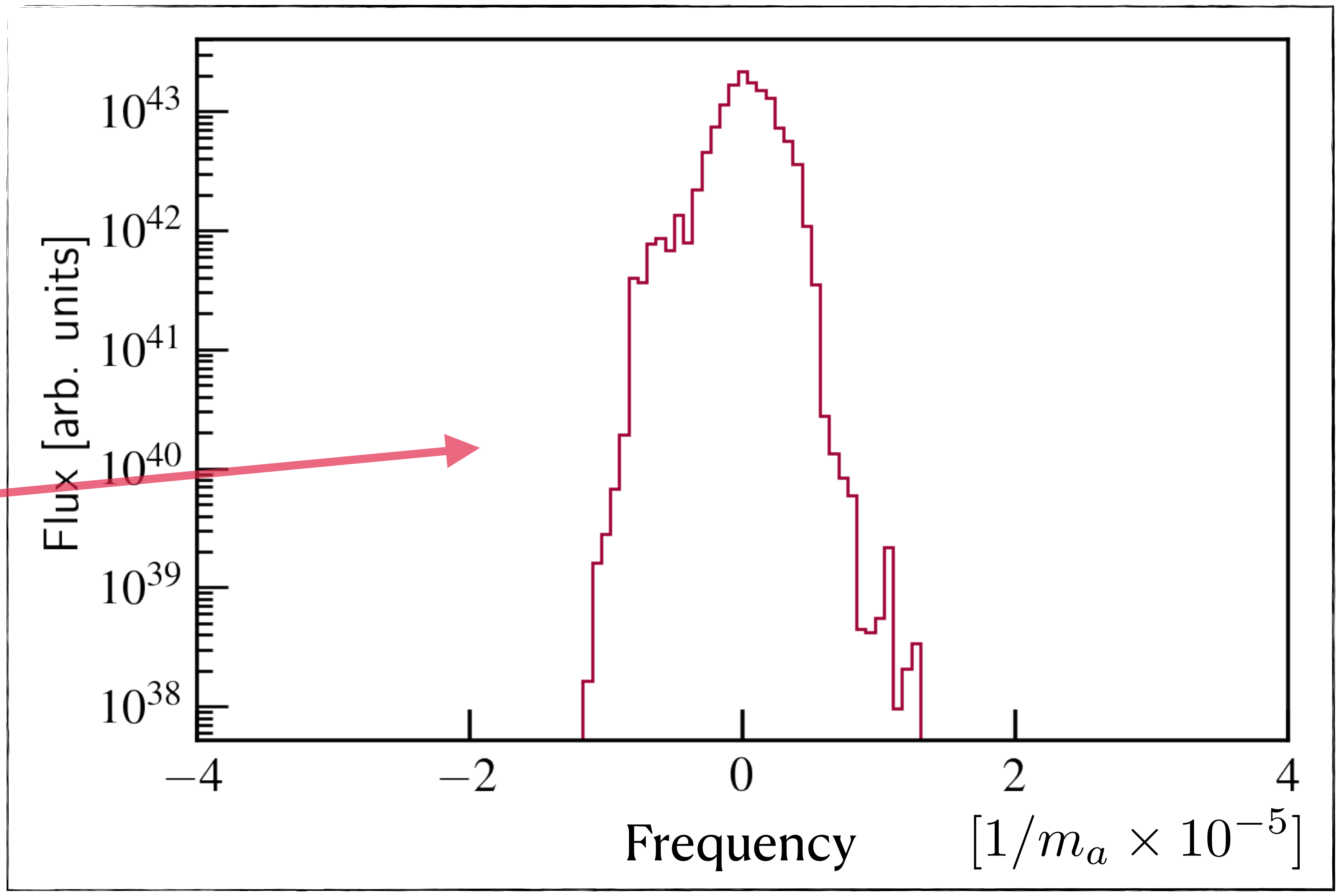
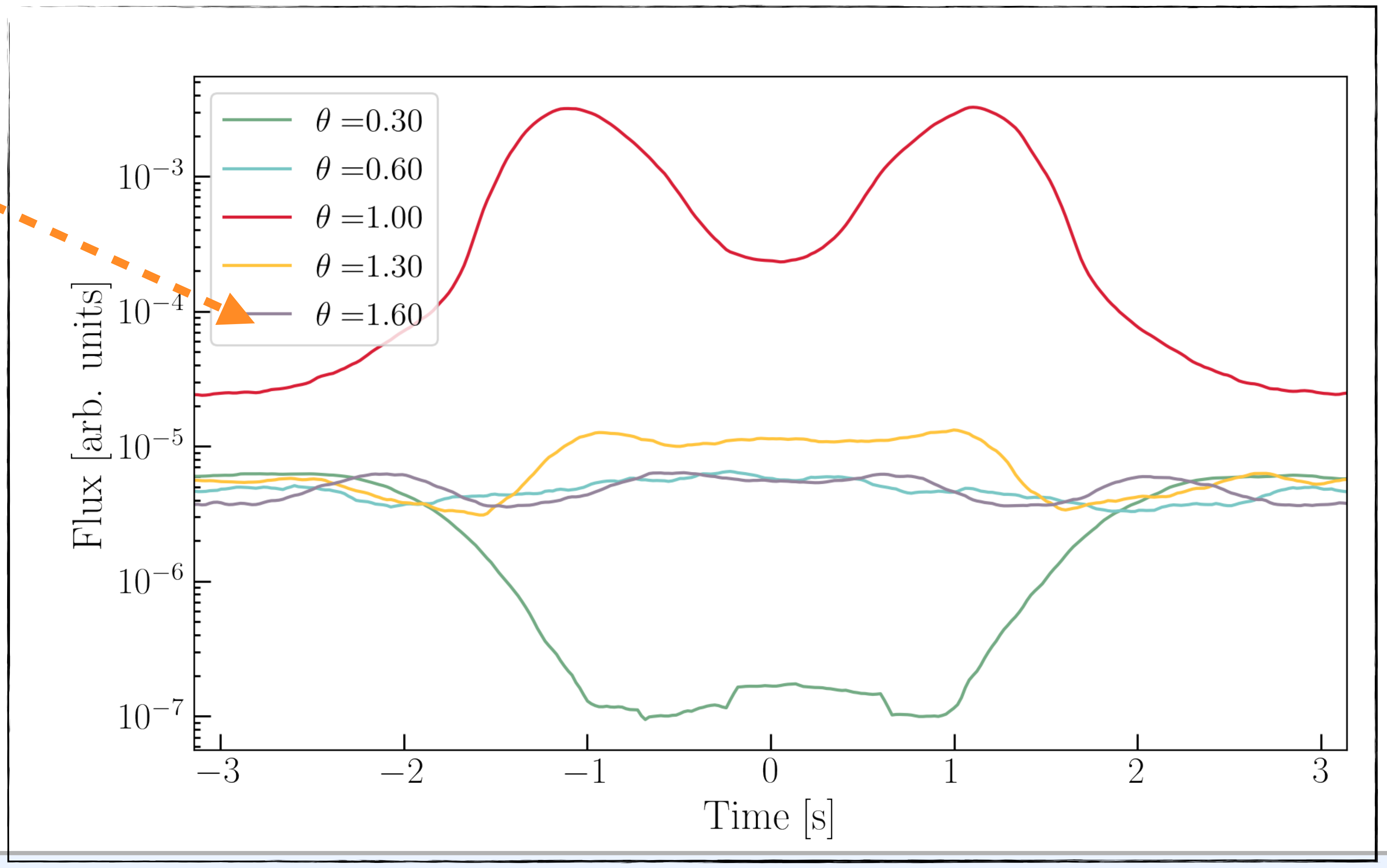




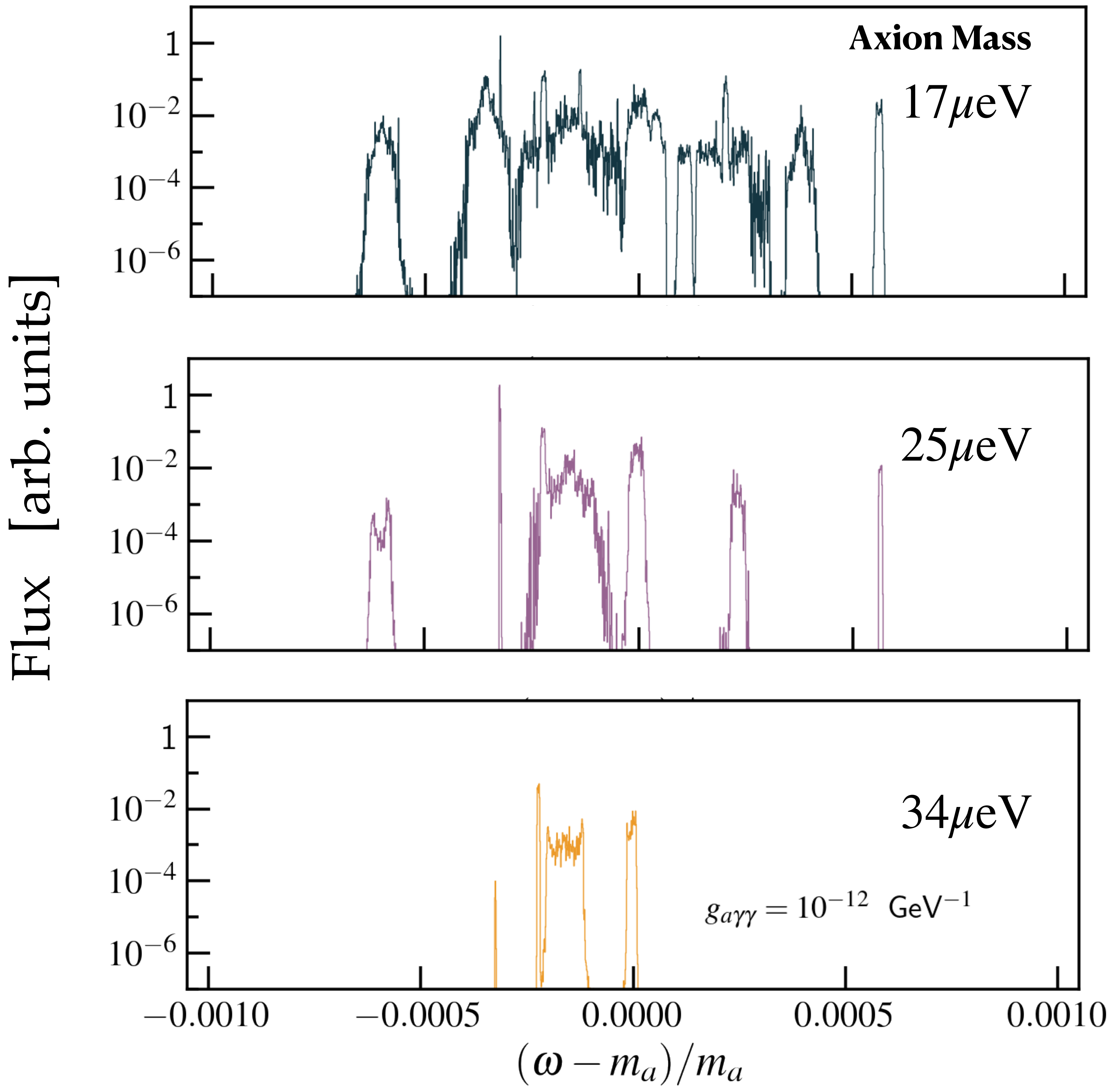




SJW, Noordhuis, Edwards, Weniger (2021)

Stacked signal

Step 3: Generating the axion 'forest'



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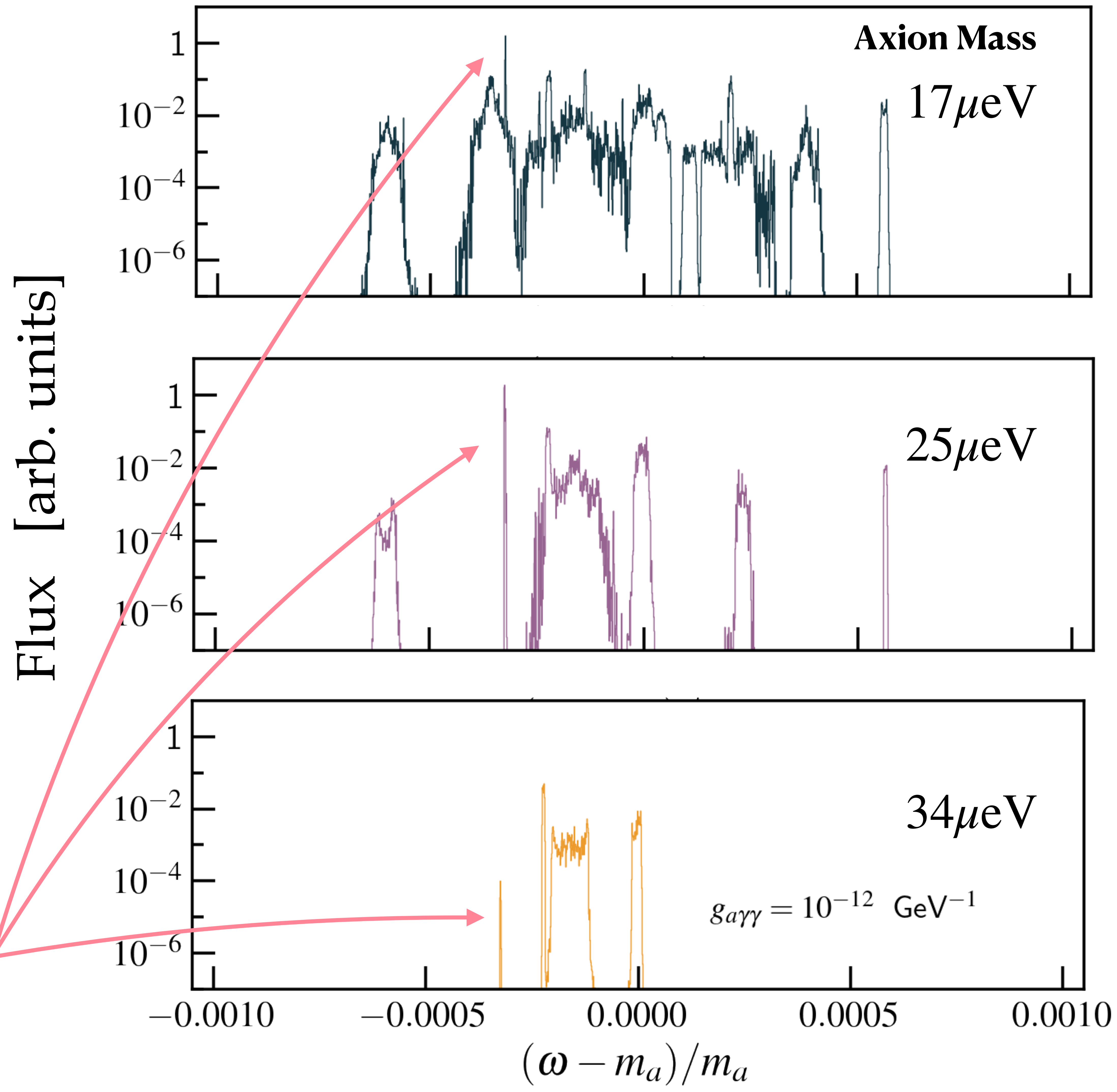

Individual Neutron Stars

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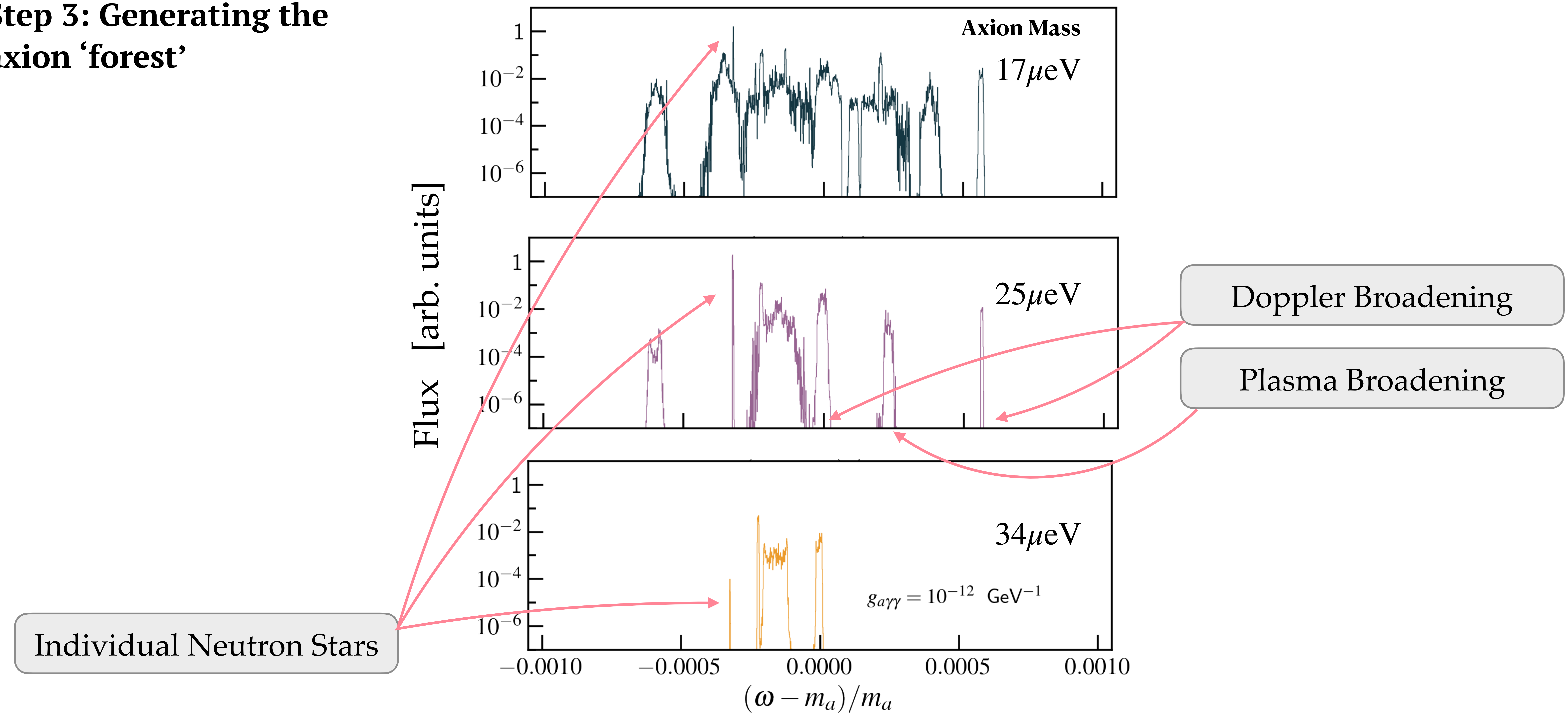
Stacked signal

Step 3: Generating the axion 'forest'



Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

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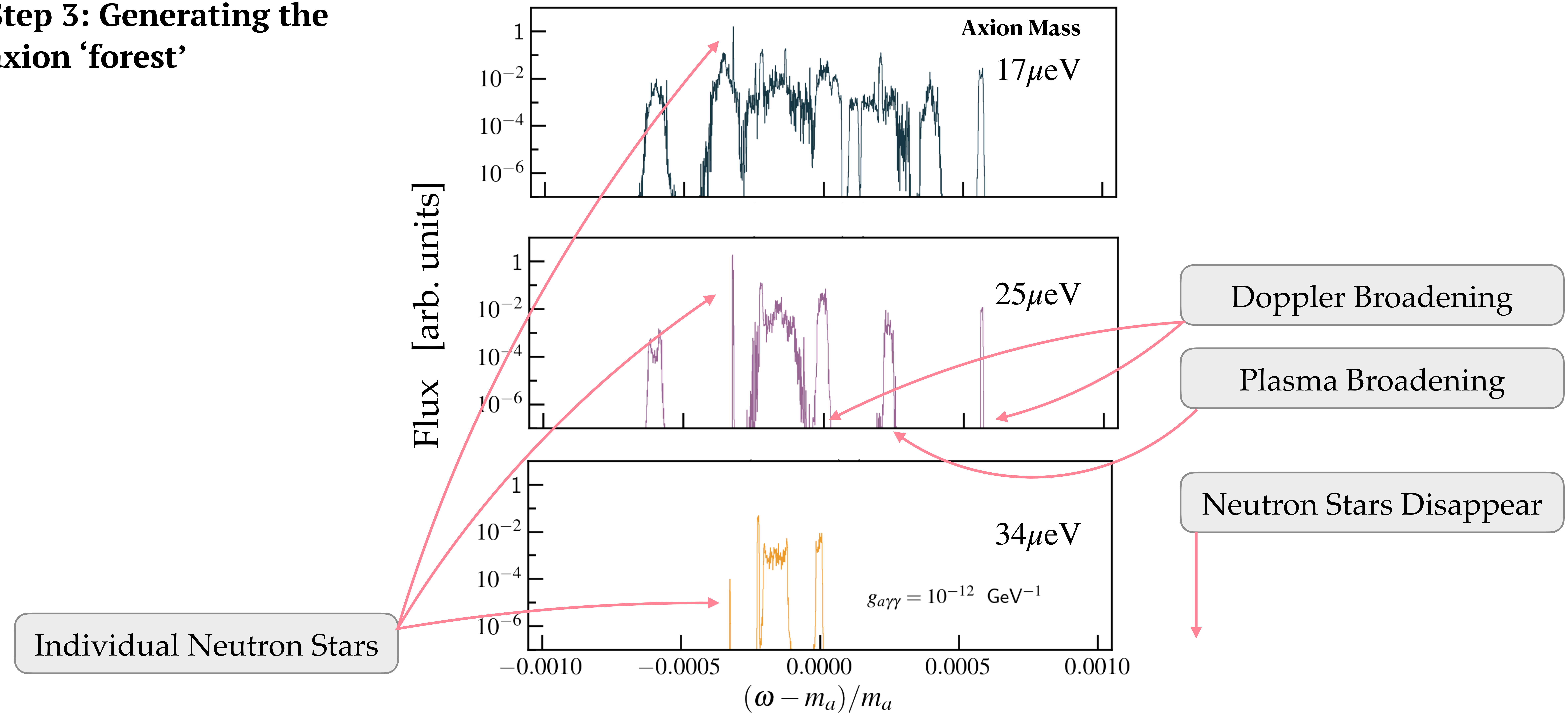
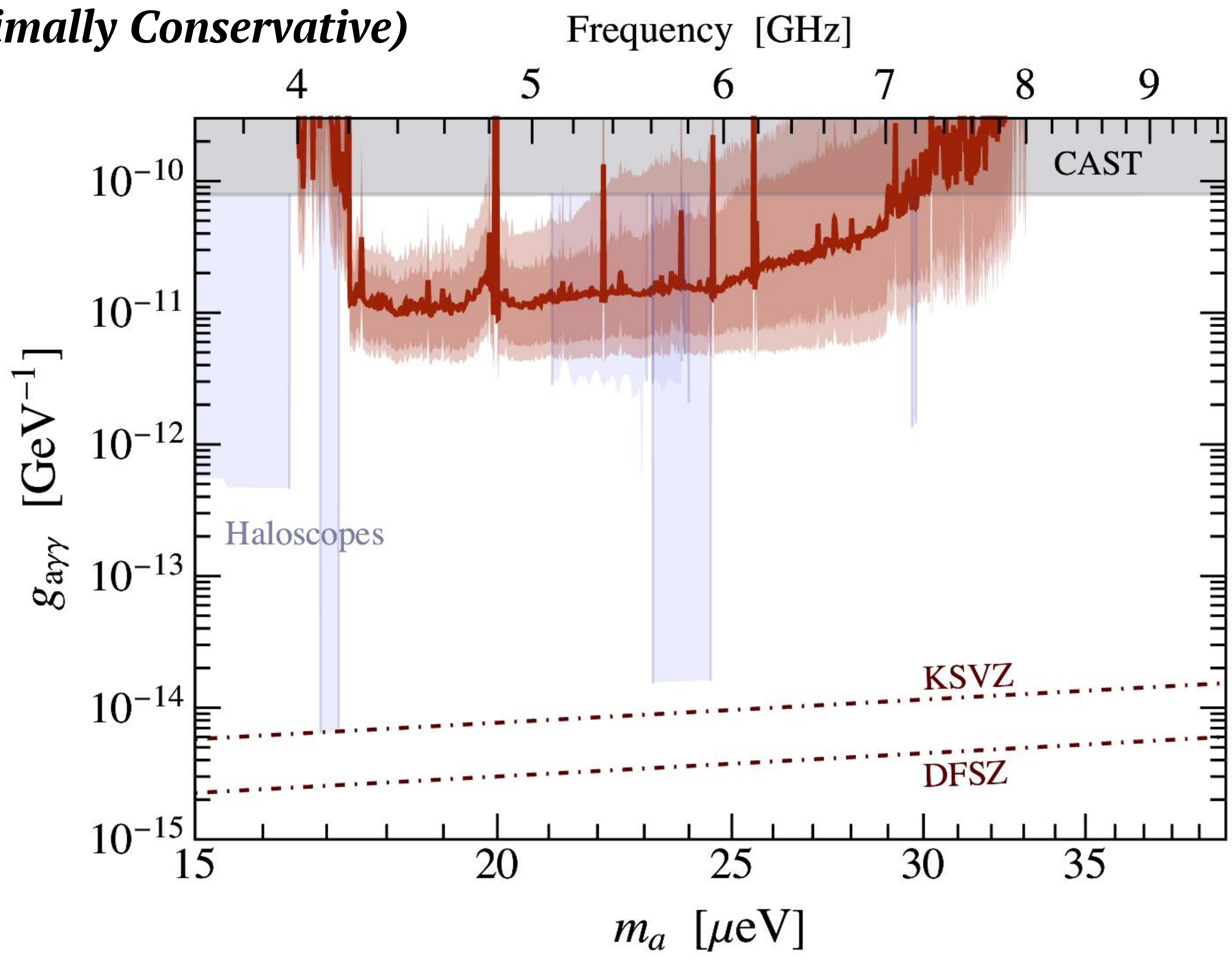


Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

GBT axion search

Fiducial Model (Maximally Conservative)



QCD axion benchmarks

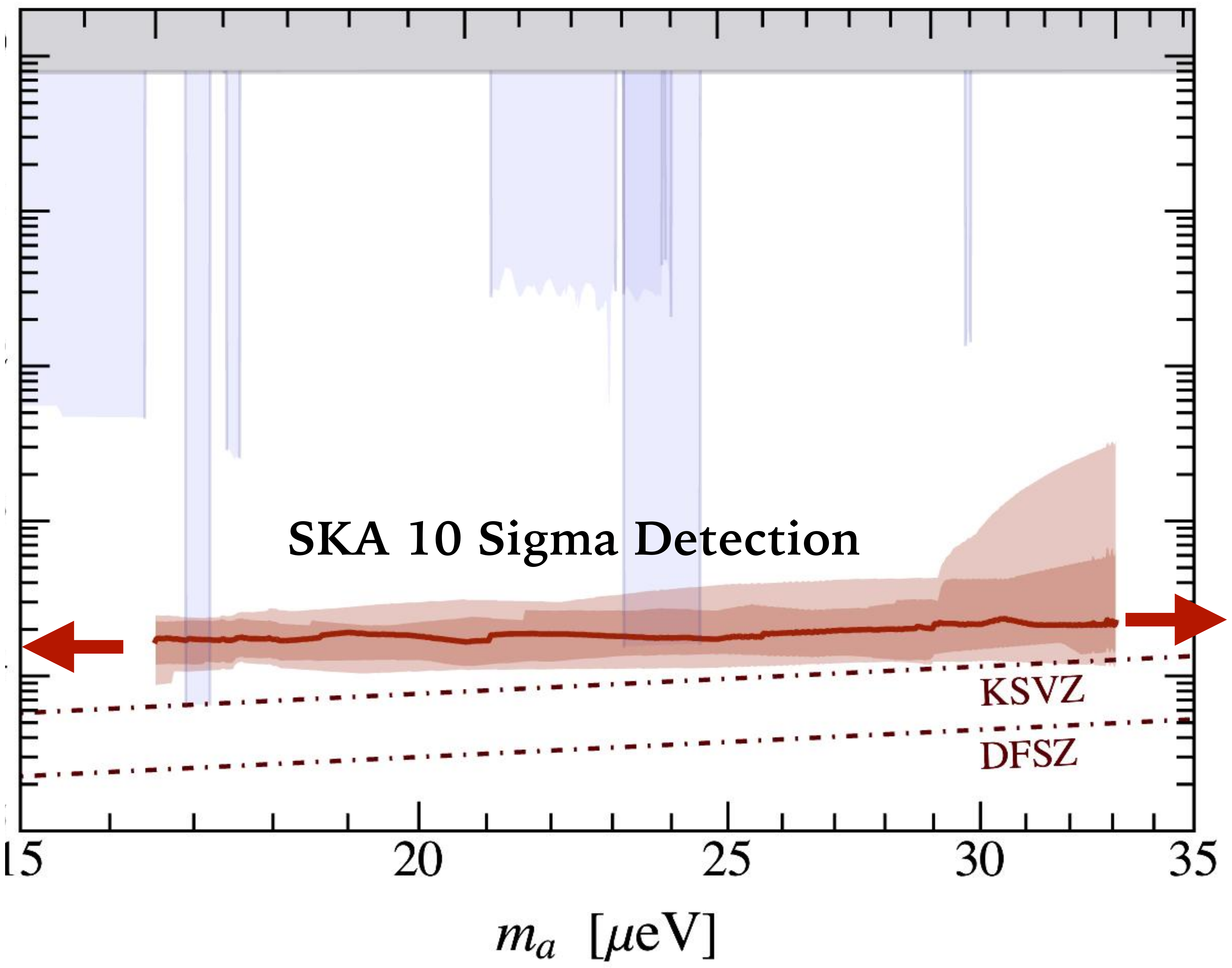
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Future prospects

Improvements:

- Better understanding of axion-photon mixing
- Exploit time / frequency domain information
- Better telescopes
- ....

Improvement needed from theory + experiment

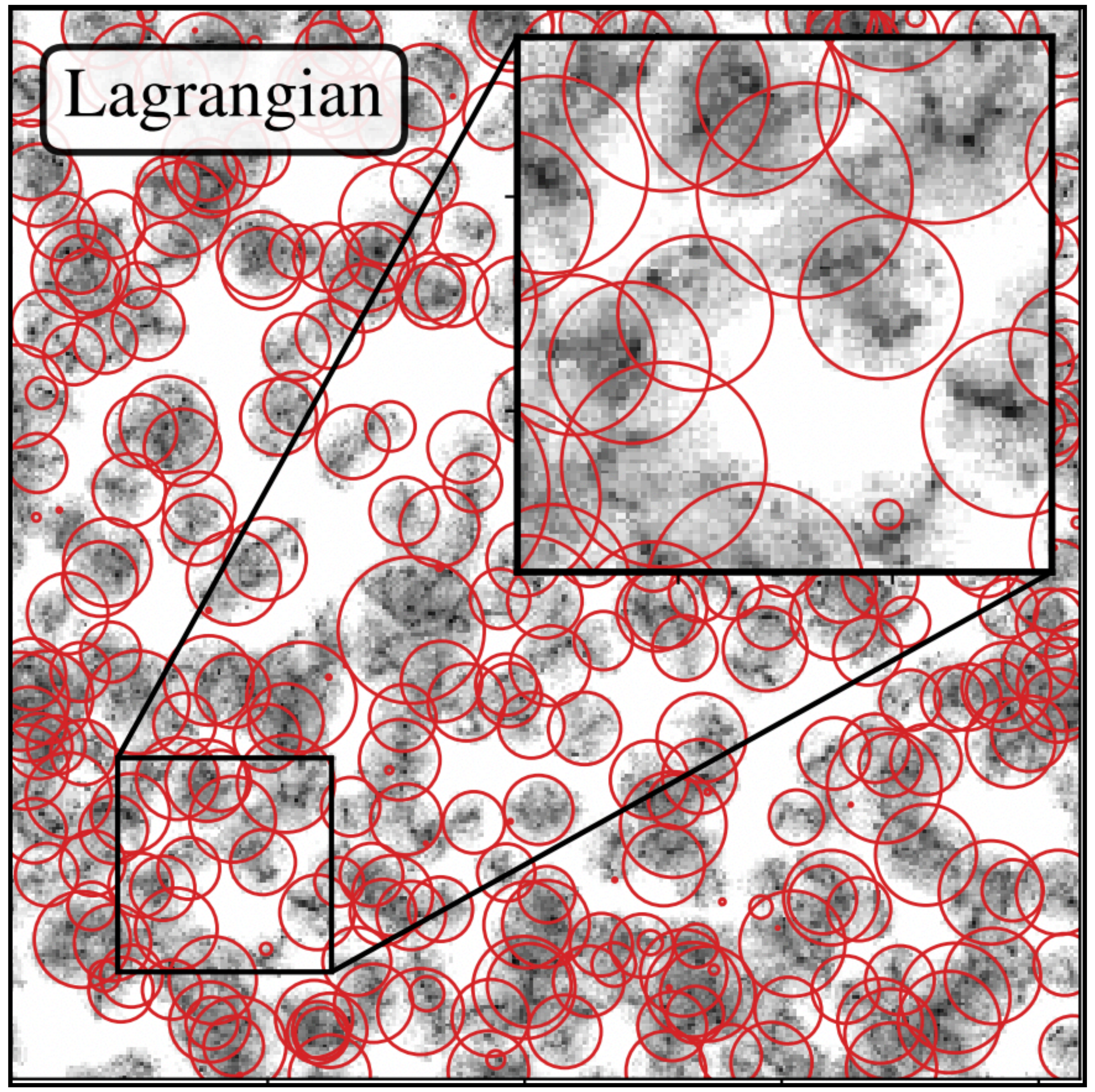


Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Transient radio lines from axion miniclusters

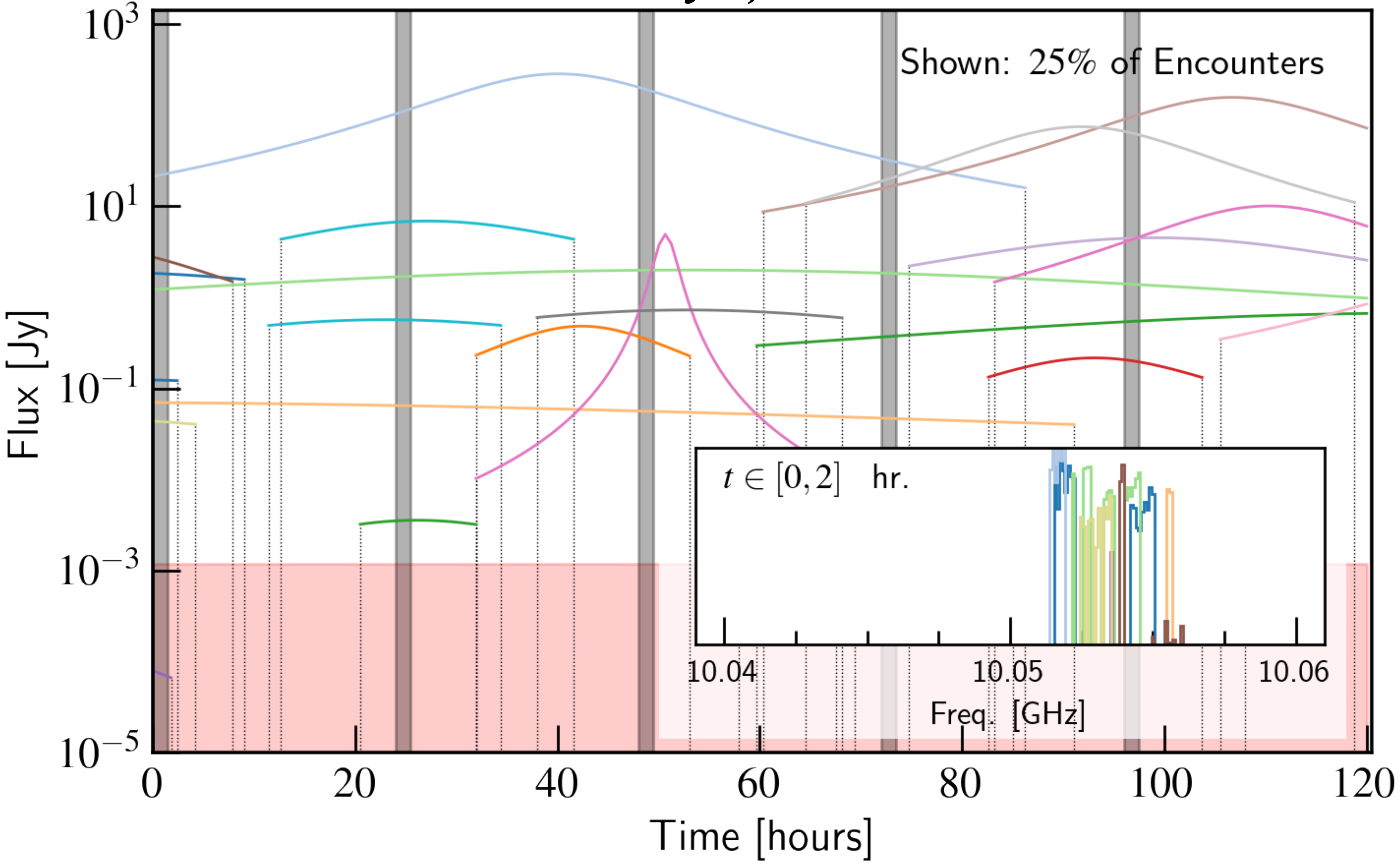
Rare encounters of miniclusters (& axion stars) with neutron stars generate transient radio lines

Density field at matter-radiation equality



Ellis et al (2022)

The taxonomy of axion transients



SJW, Salinas, Baum, Lawson, Millar, Marsh, Weniger (To appear)
Agrawal, Johsnon, Edwards, Kavanaguh, Marsh, Ransom, Shroyer, Visinelli, **SJW**, Weniger (Data analysis ongoing)

Conclusions

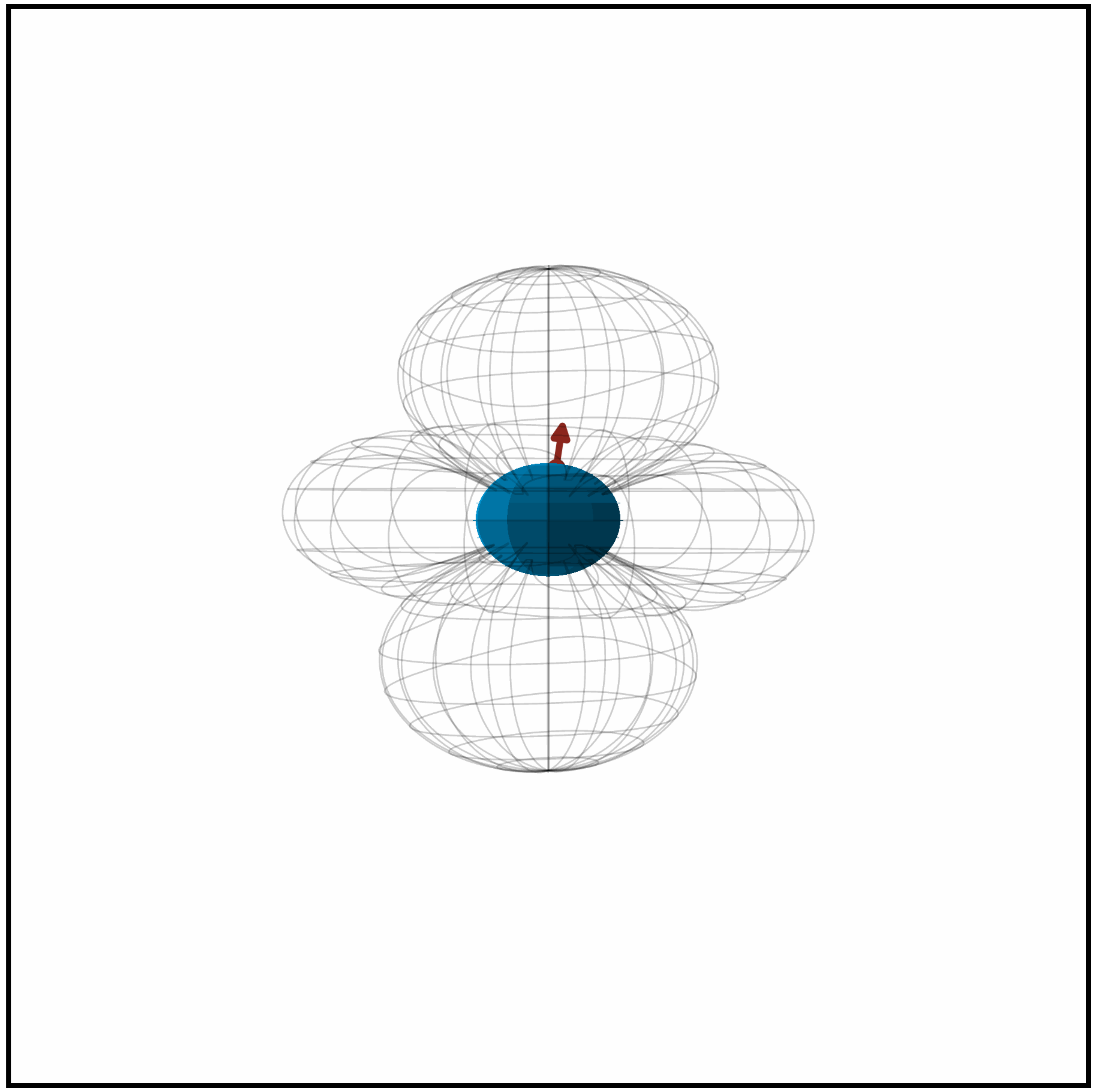
Neutron stars offer powerful and rich laboratory in which to look for axion physics

Probes of axion dark matter:

- *Look for:* Radio lines from smooth dark matter distribution
- *Look for:* Transient lines from minicluster and axion star encounters (extragalactic / cosmological)

Currently developing novel ways to probe axions even if they aren't dark matter!

Stay tuned for talk by Dion Noordhuis (next!)



Animations available at: https://github.com/SamWitte/GIF_Storage

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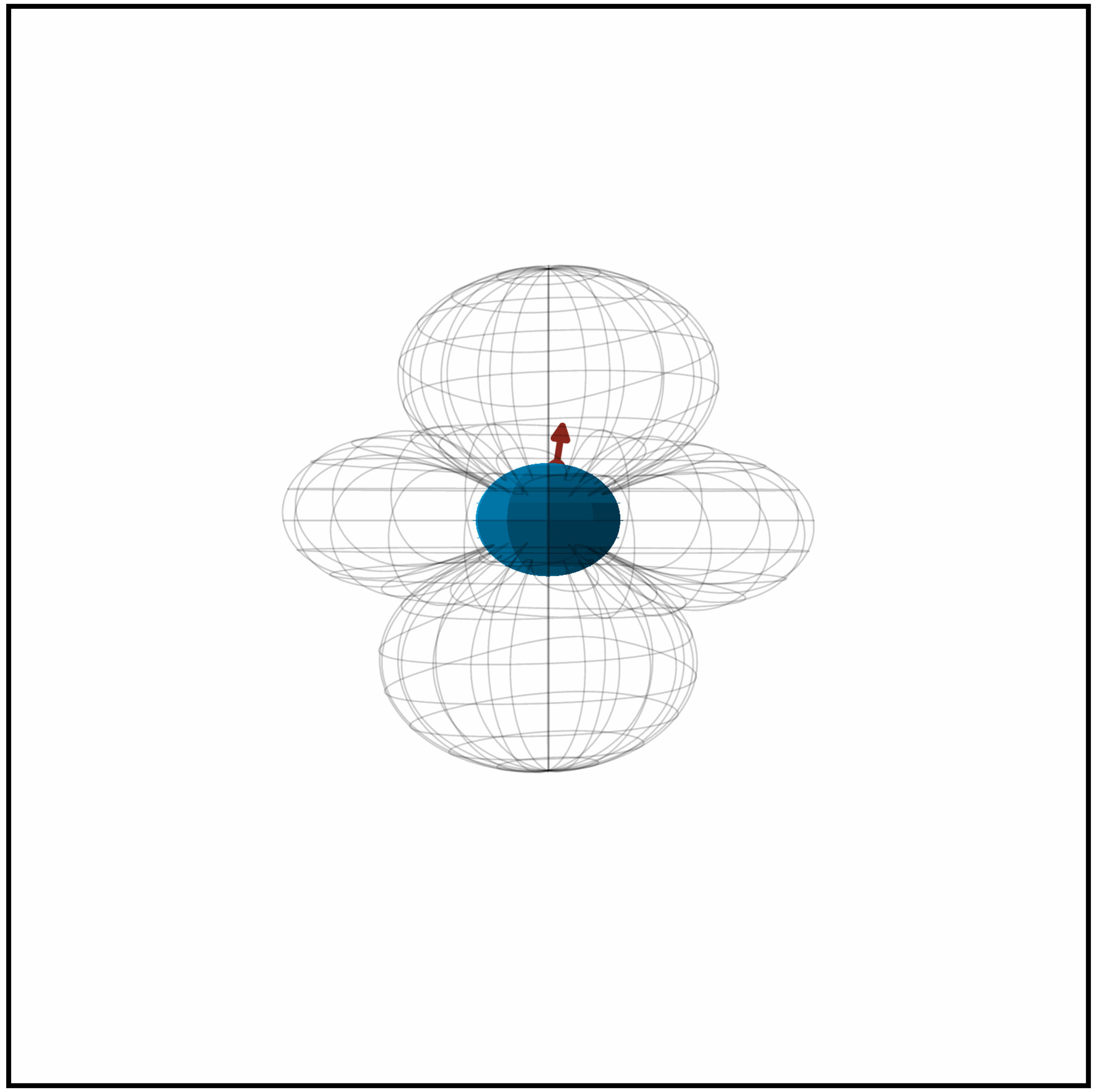

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