

Axion-Photon Conversion in Magnetospheres

The Role of the Plasma

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June, 2021

GRAPPA 

GRavitation AstroParticle Physics Amsterdam

Based on arXiv: 2104.07670

SJW, Noordhuis, Edwards, Weniger

Strong CP Problem

CP-violating ‘Theta therm’



Controls size of neutron electric dipole

$$\mathcal{L}_\theta = -\bar{\theta} \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$|\vec{d}| = 3.6 \times 10^{-16} \bar{\theta} \text{ e cm}$$

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Current limit: $\bar{\theta} \leq 5 \times 10^{-11}$ Abel et al (2020)

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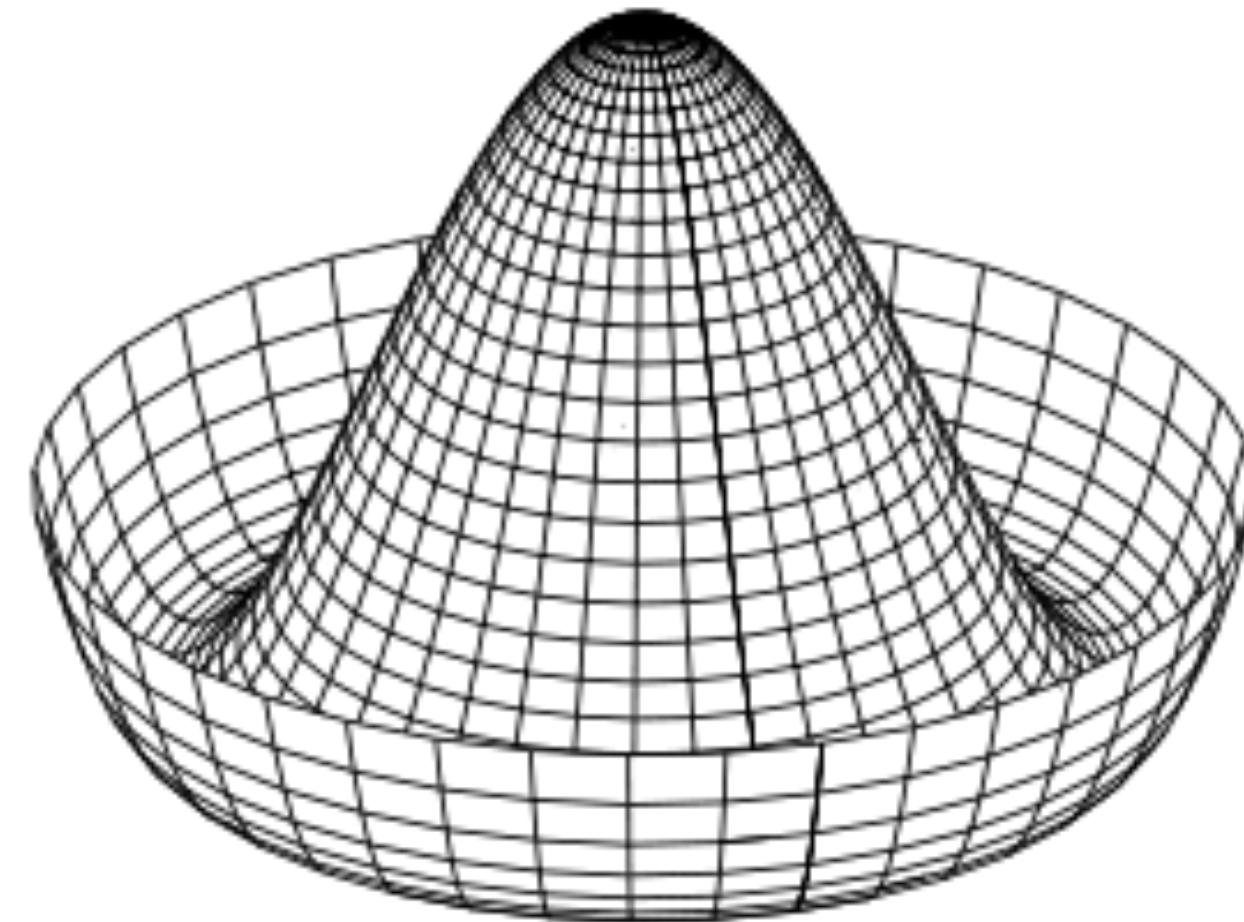
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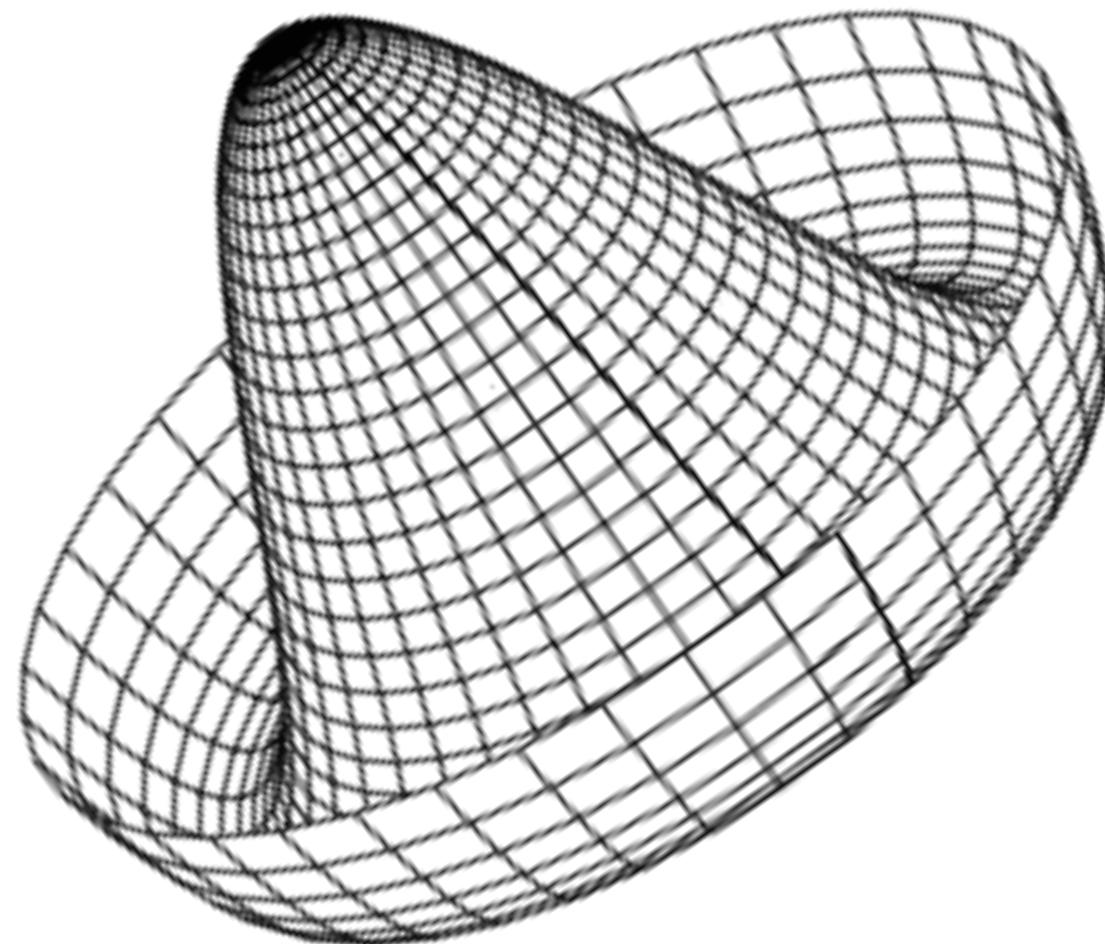
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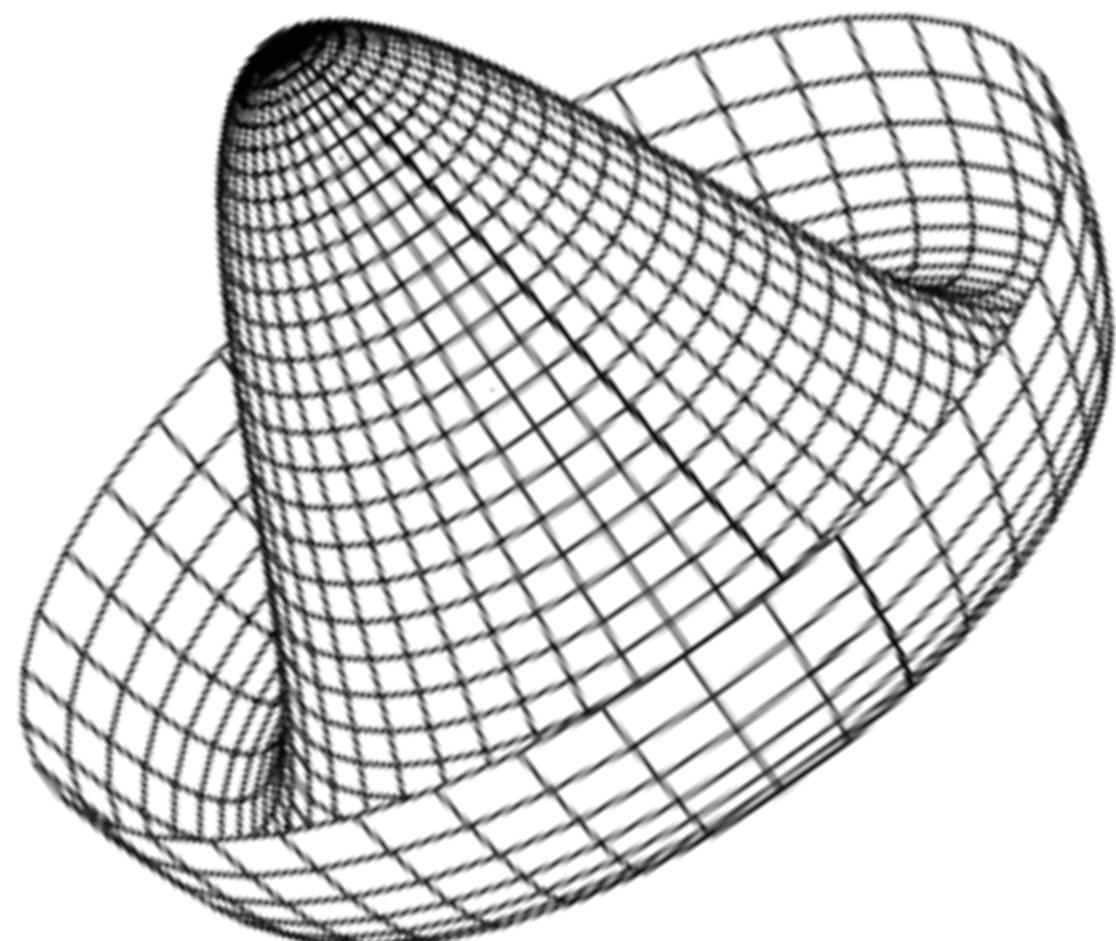
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The QCD Axion as Dark Matter

Cosmologically stable: $m_a \lesssim 10 \text{ eV}$

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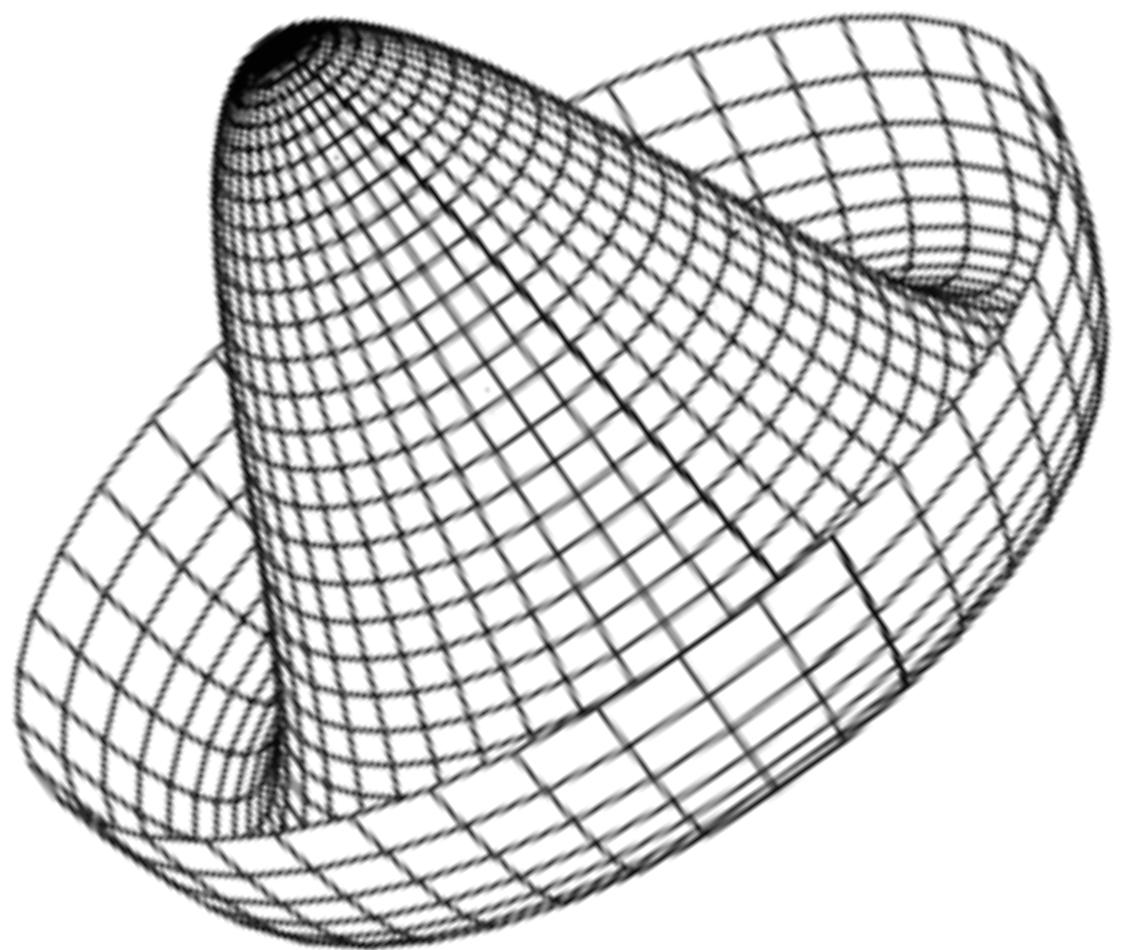


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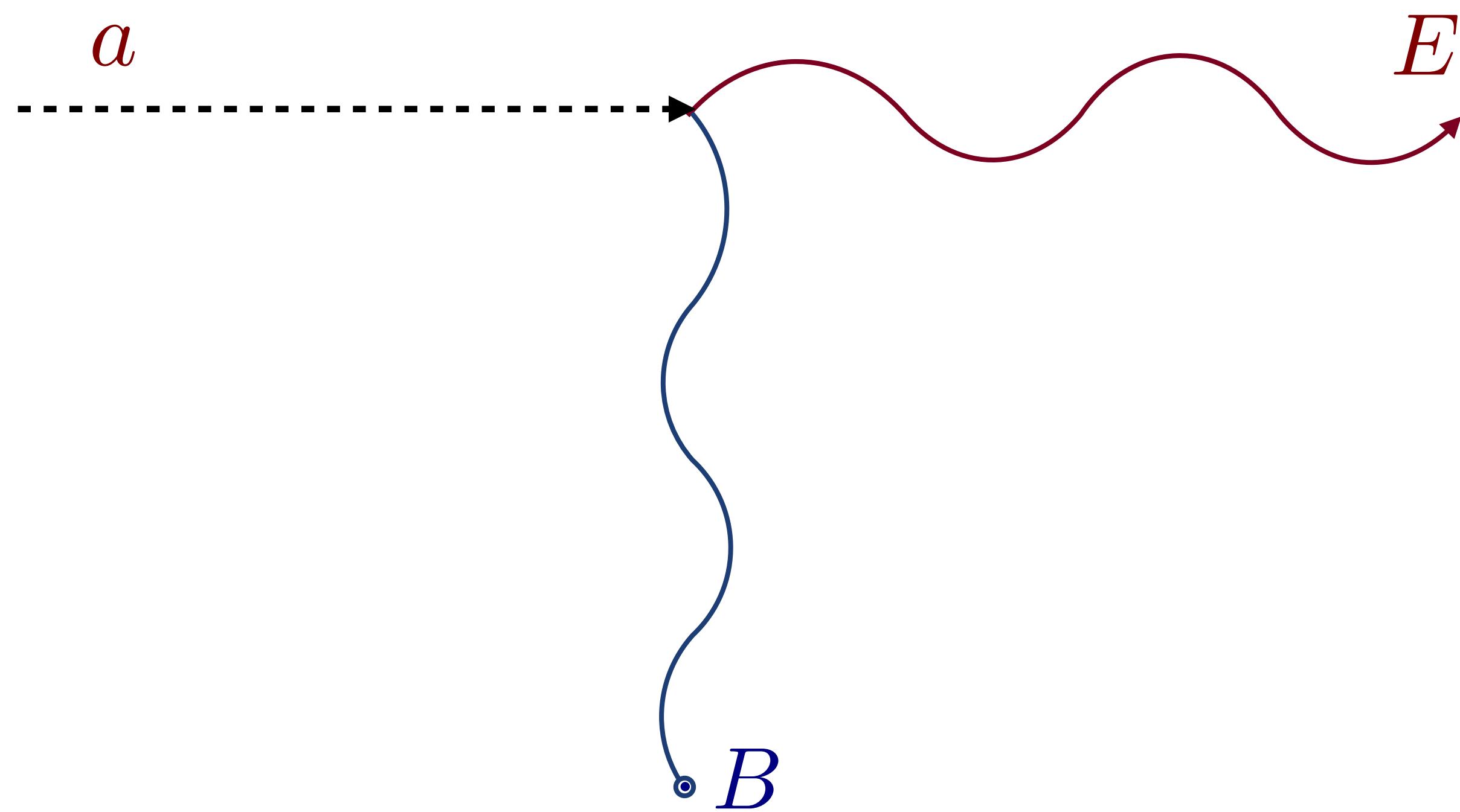
Avoid over-production: $m_a \gtrsim 10^{-6} \text{ eV}$

Astrophysical constraints: $m_a \lesssim \text{few} \times 10^{-3} \text{ eV}$

Axion Detection

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \sim g_{a\gamma\gamma} a E \cdot B$$

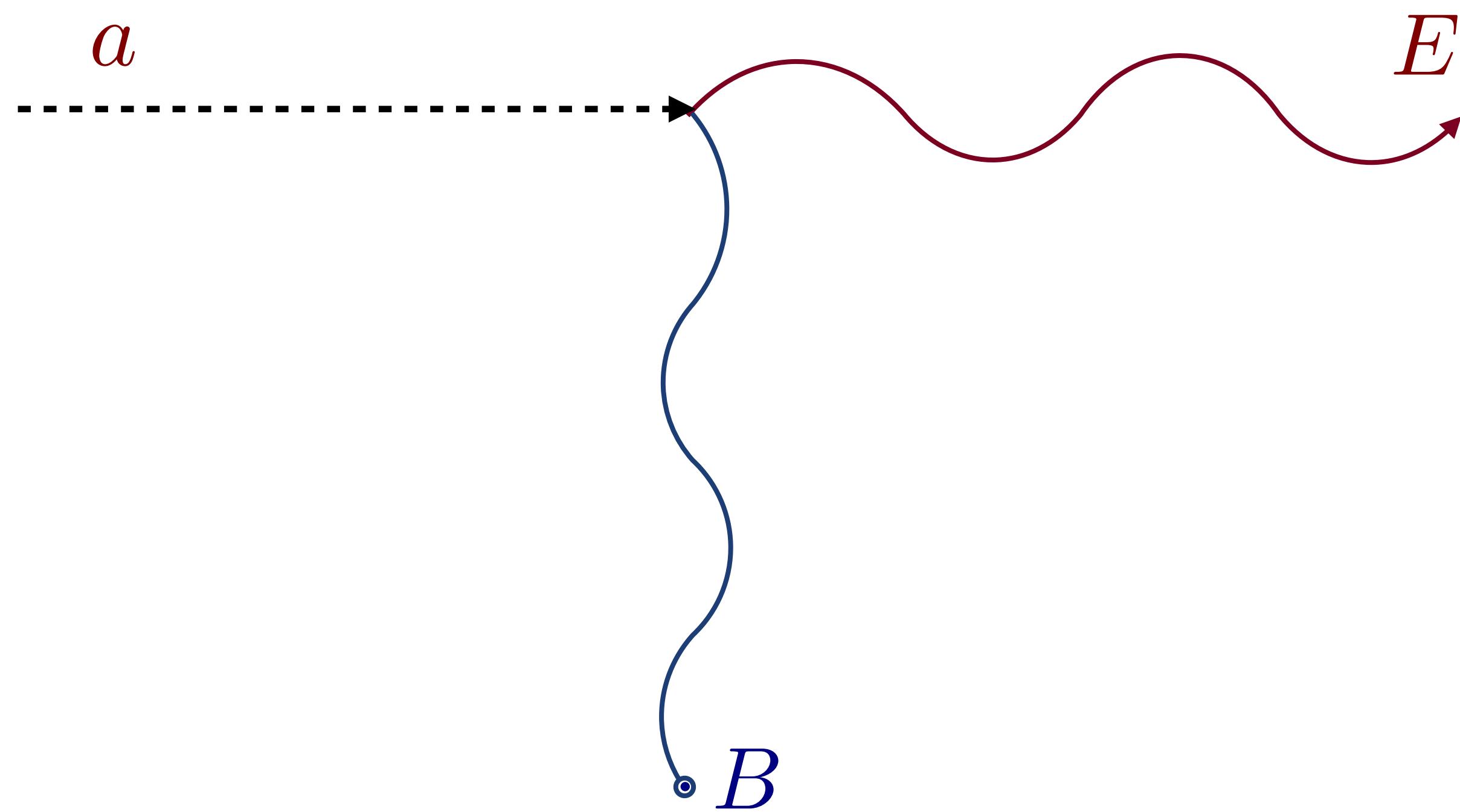
(Static)



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

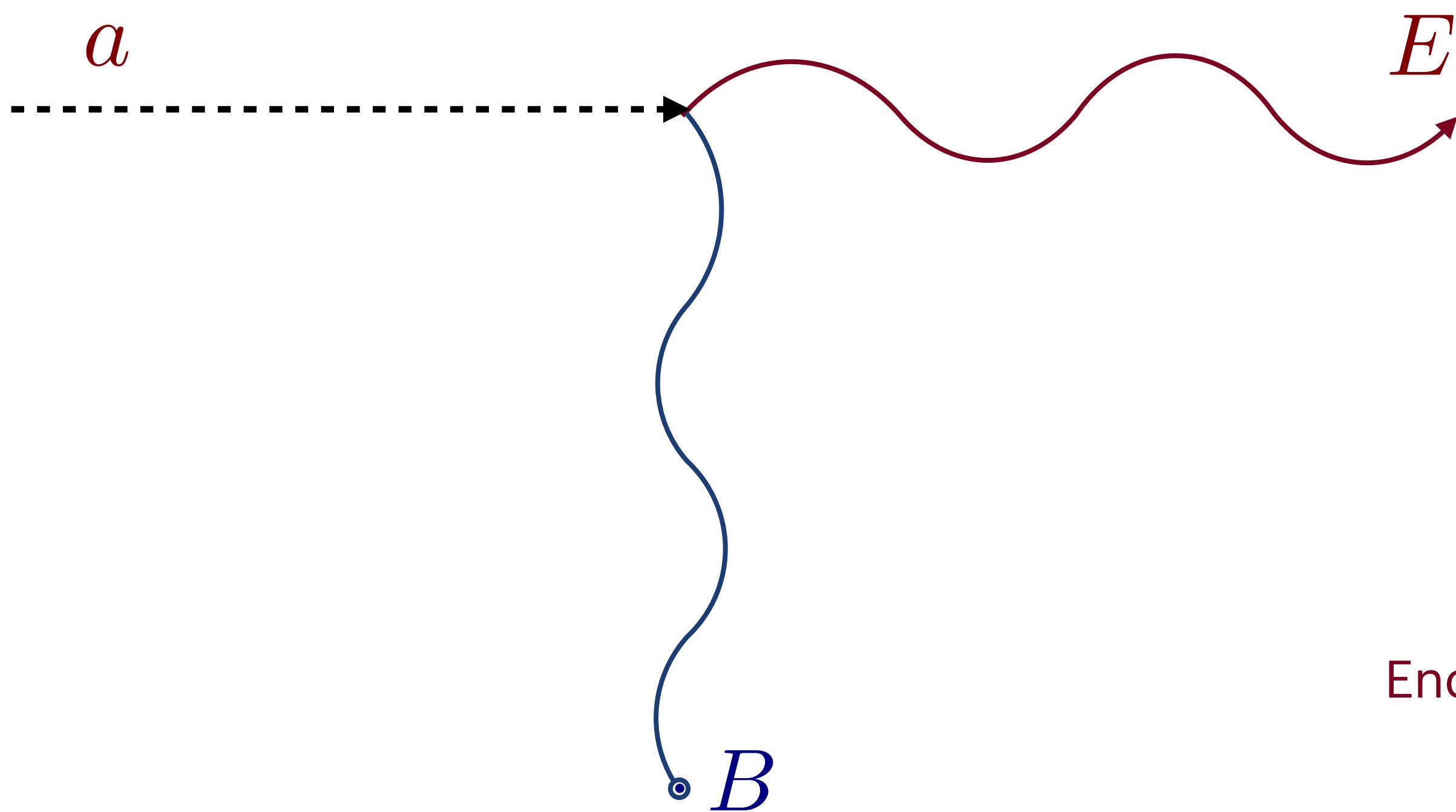
Length scale set by axion-photon coherence
(In non-adiabatic limit)

$$\delta k \equiv (k_a - k_\gamma)$$

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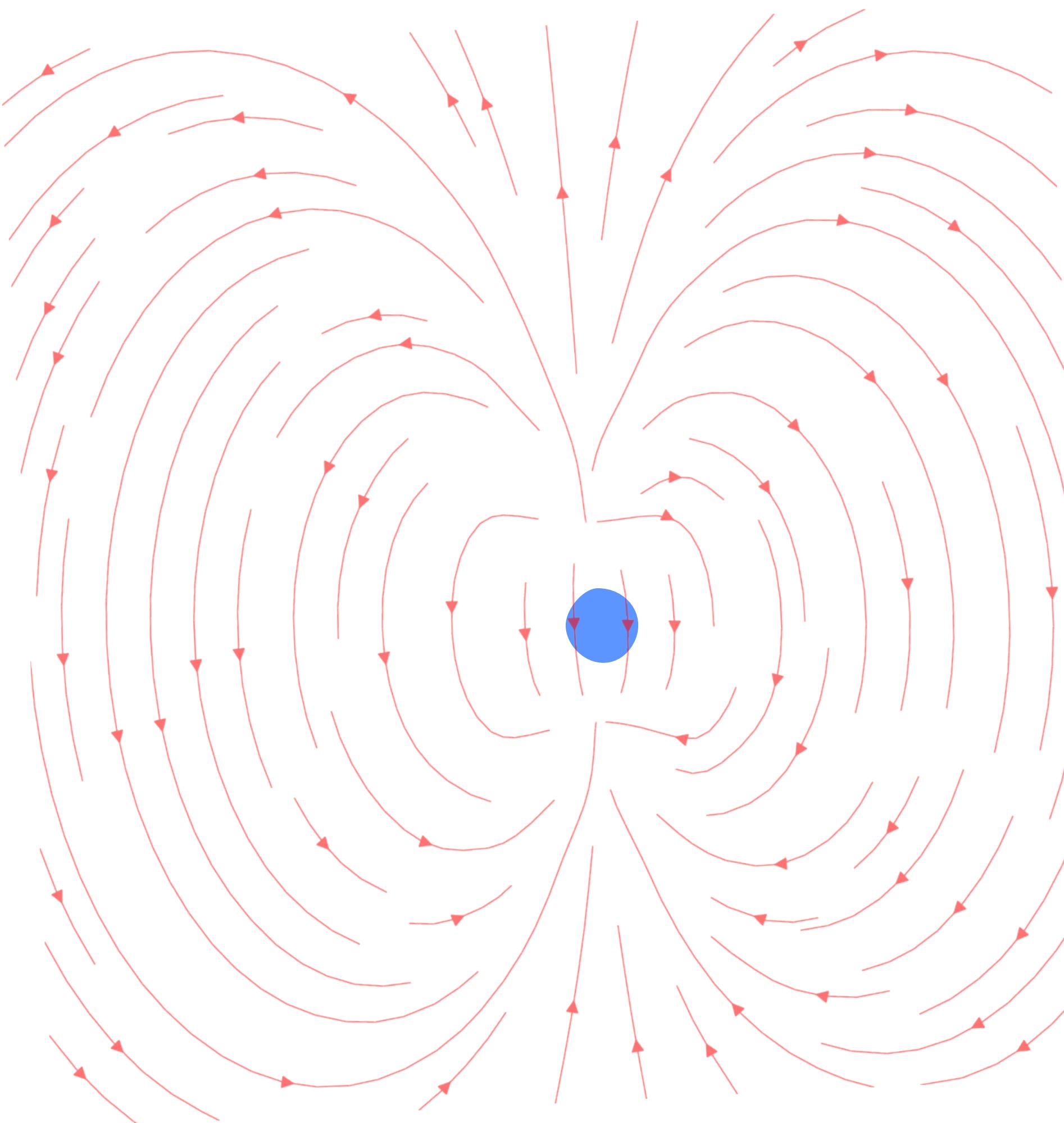
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Endow photon with effective mass, increase coherence length

Ideal targets: Large B field and dilute plasma

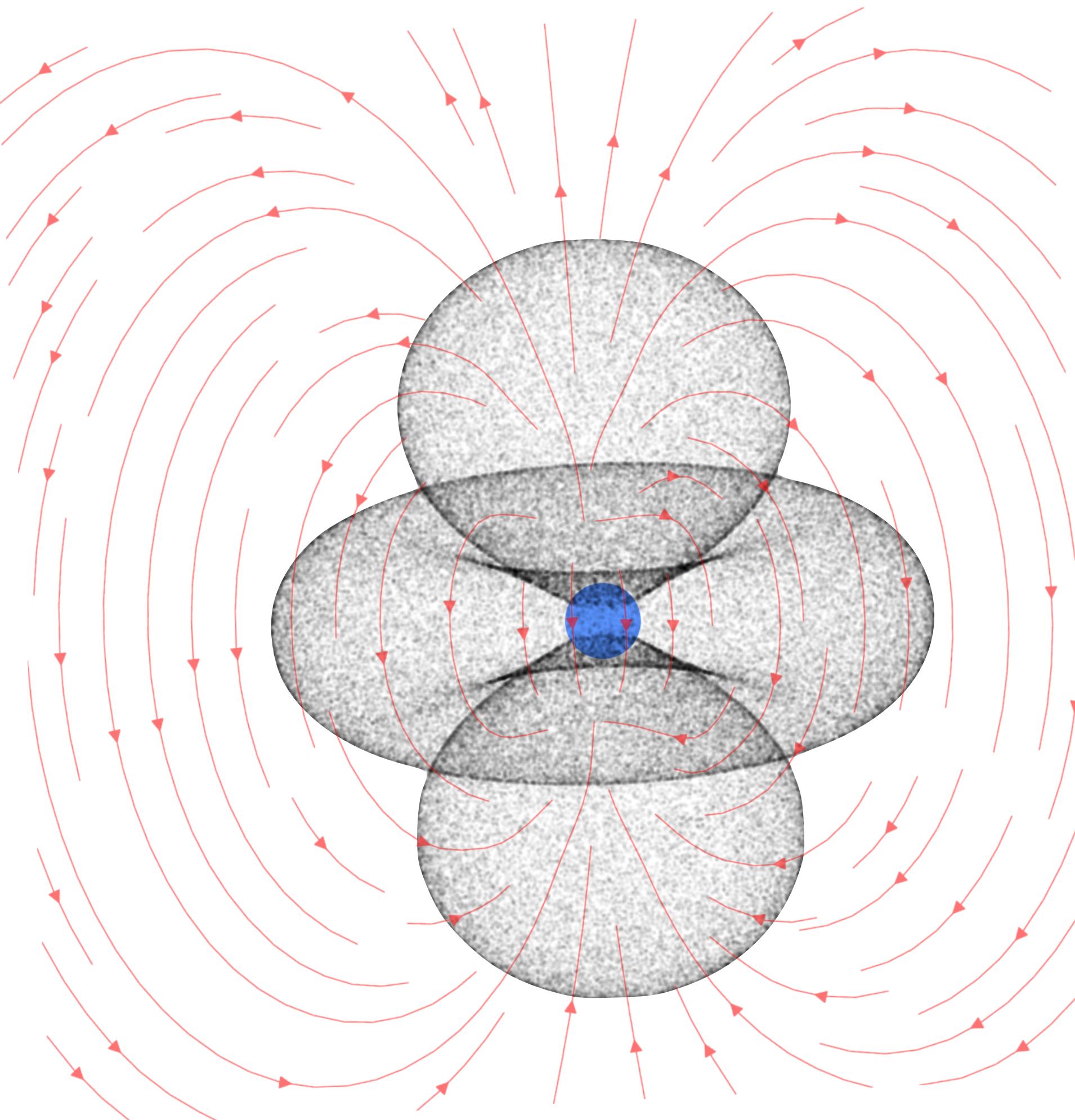
Neutron stars



Enormous magnetic dipole

$$B_0 \sim 10^{14} G$$

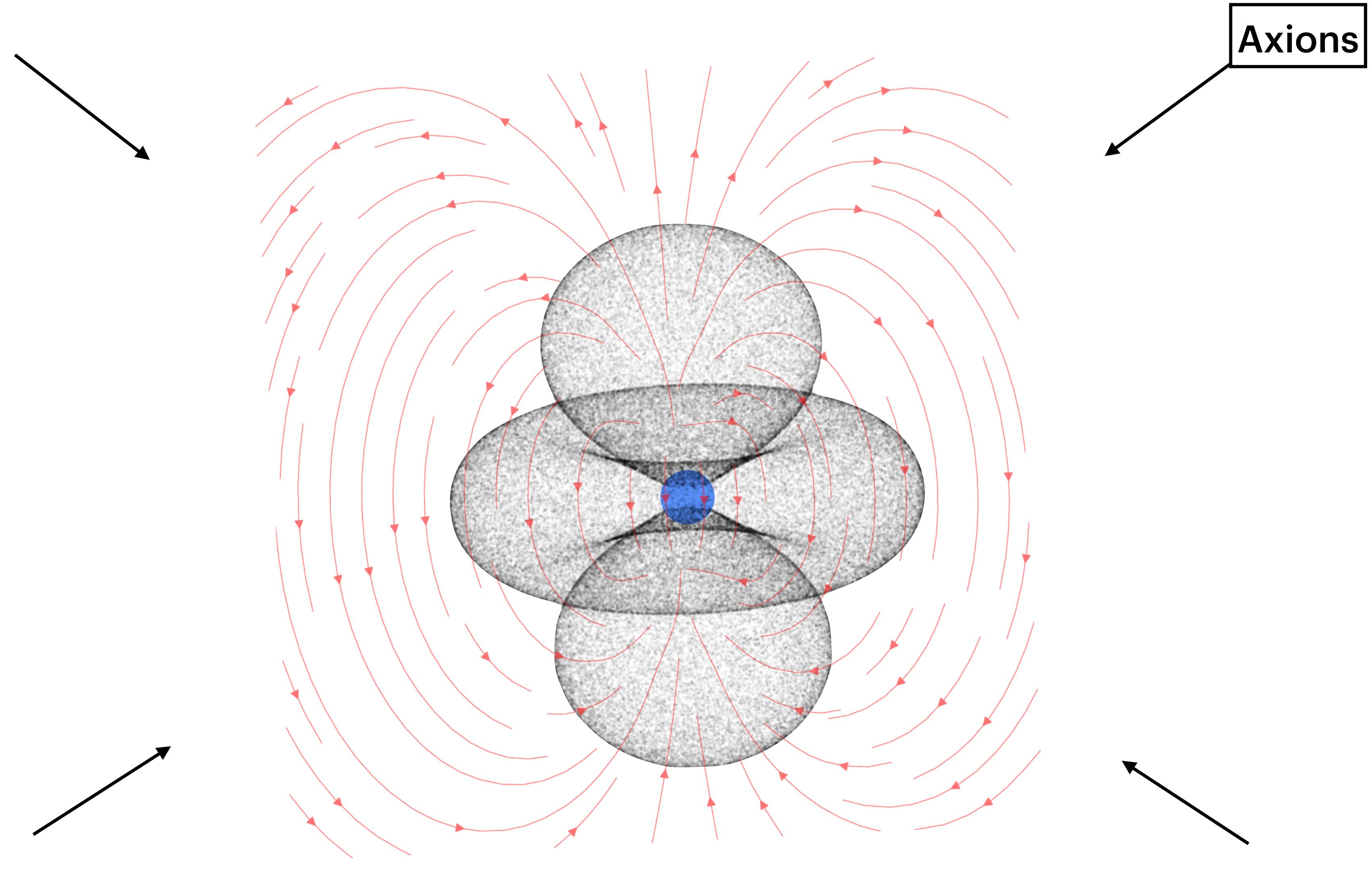
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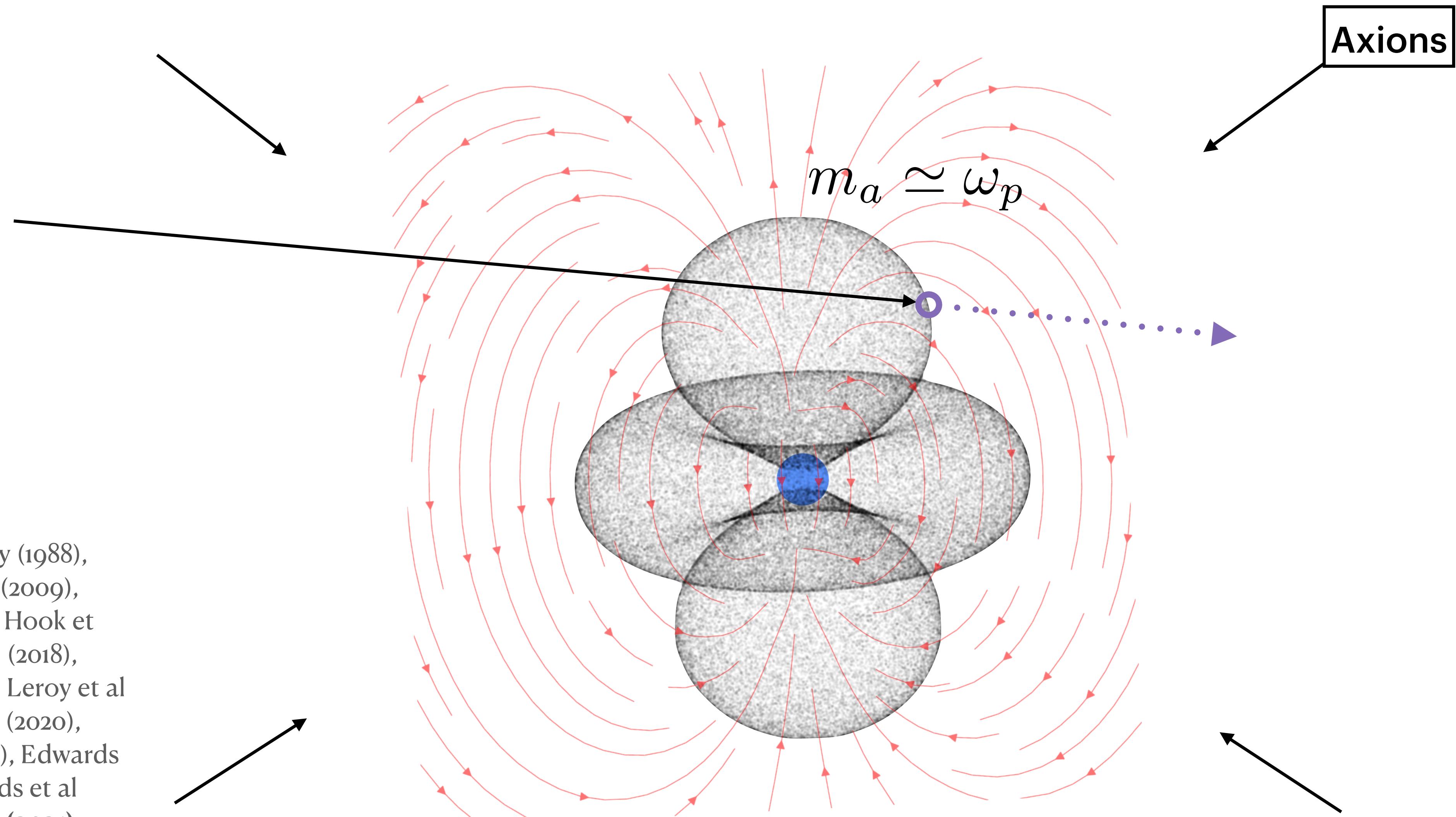
**Rough illustration

Relevant work:
Raffelt & Stodolsky (1988),
Pshirkov & Popov (2009),
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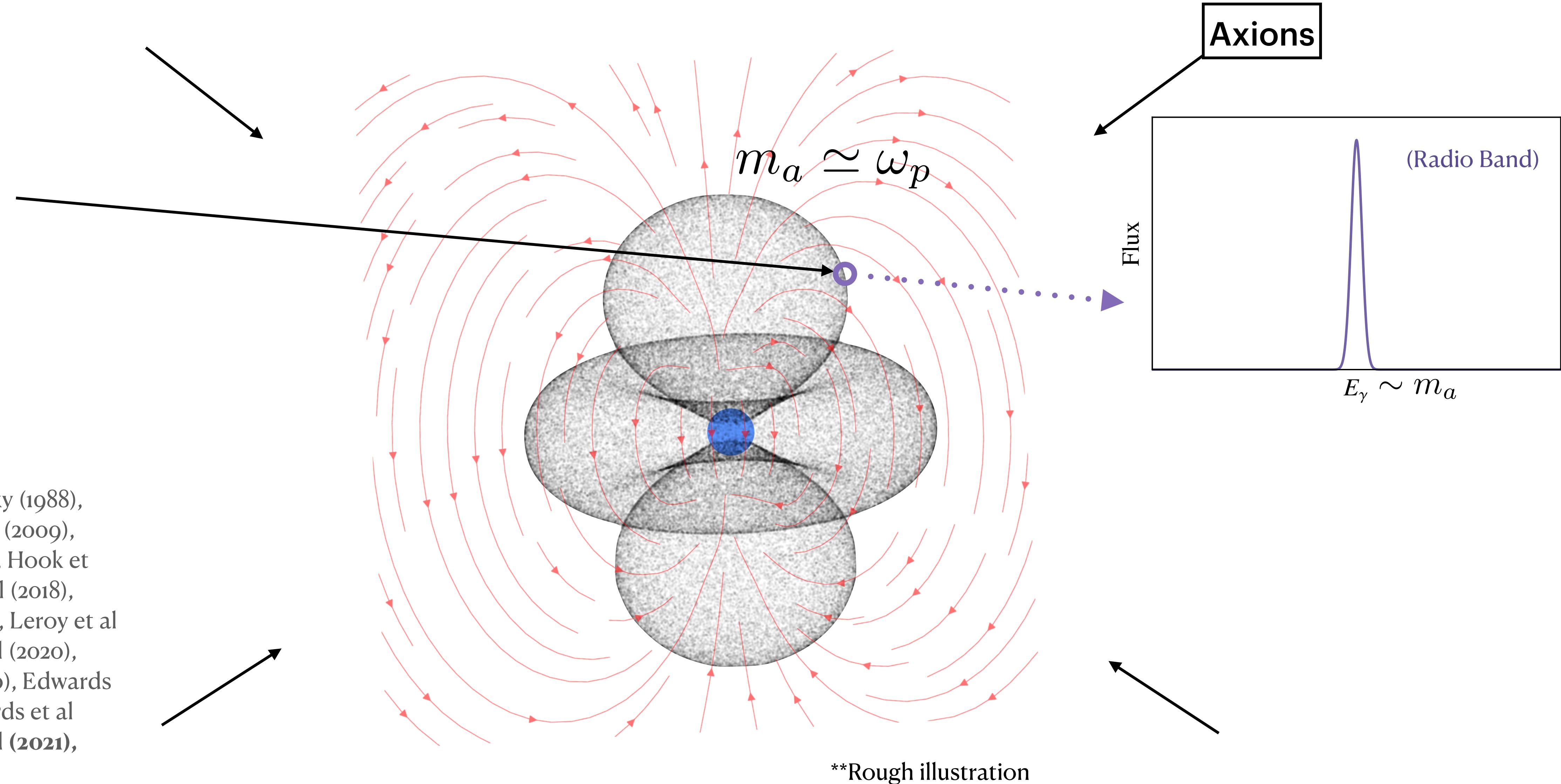
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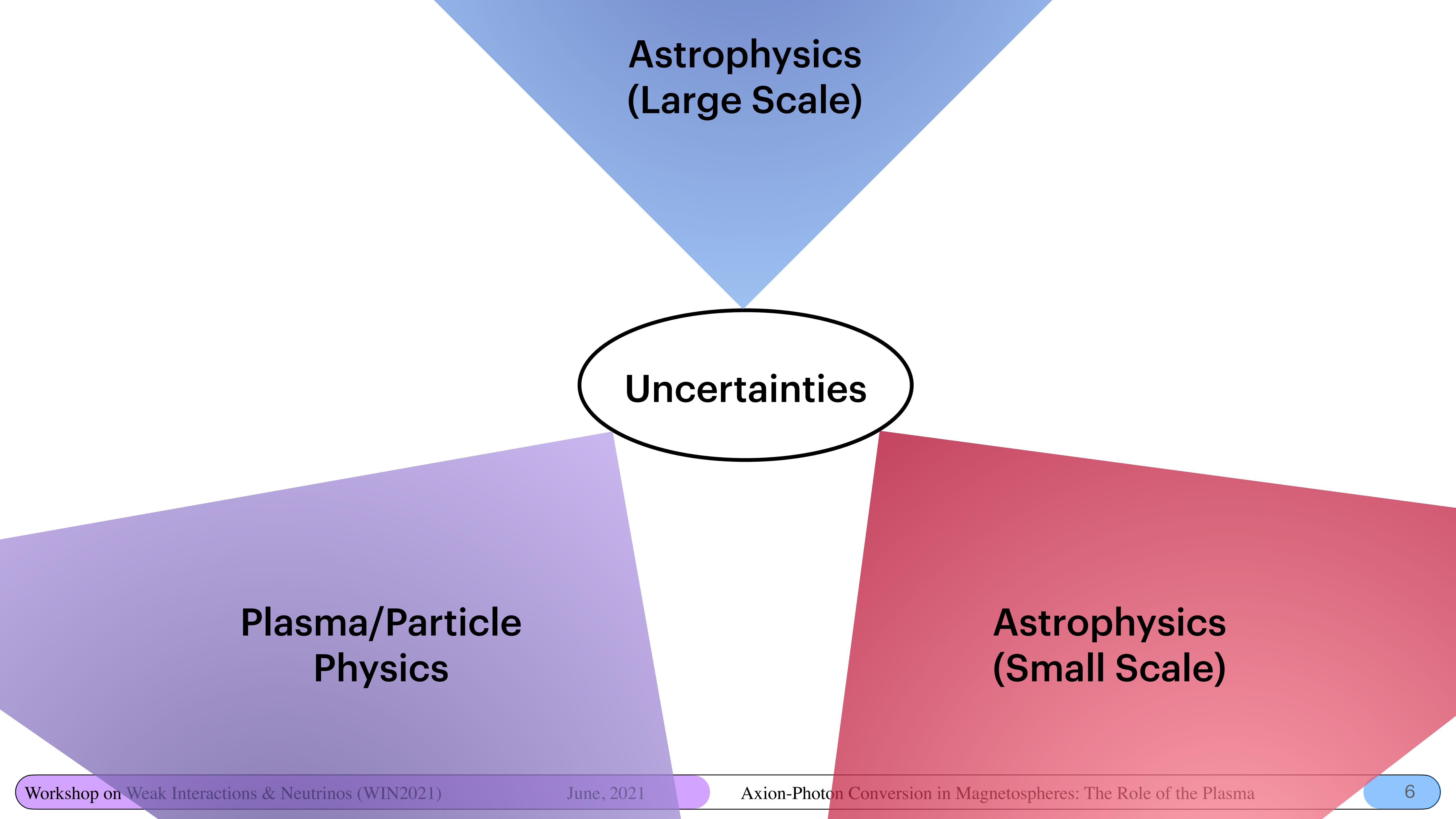


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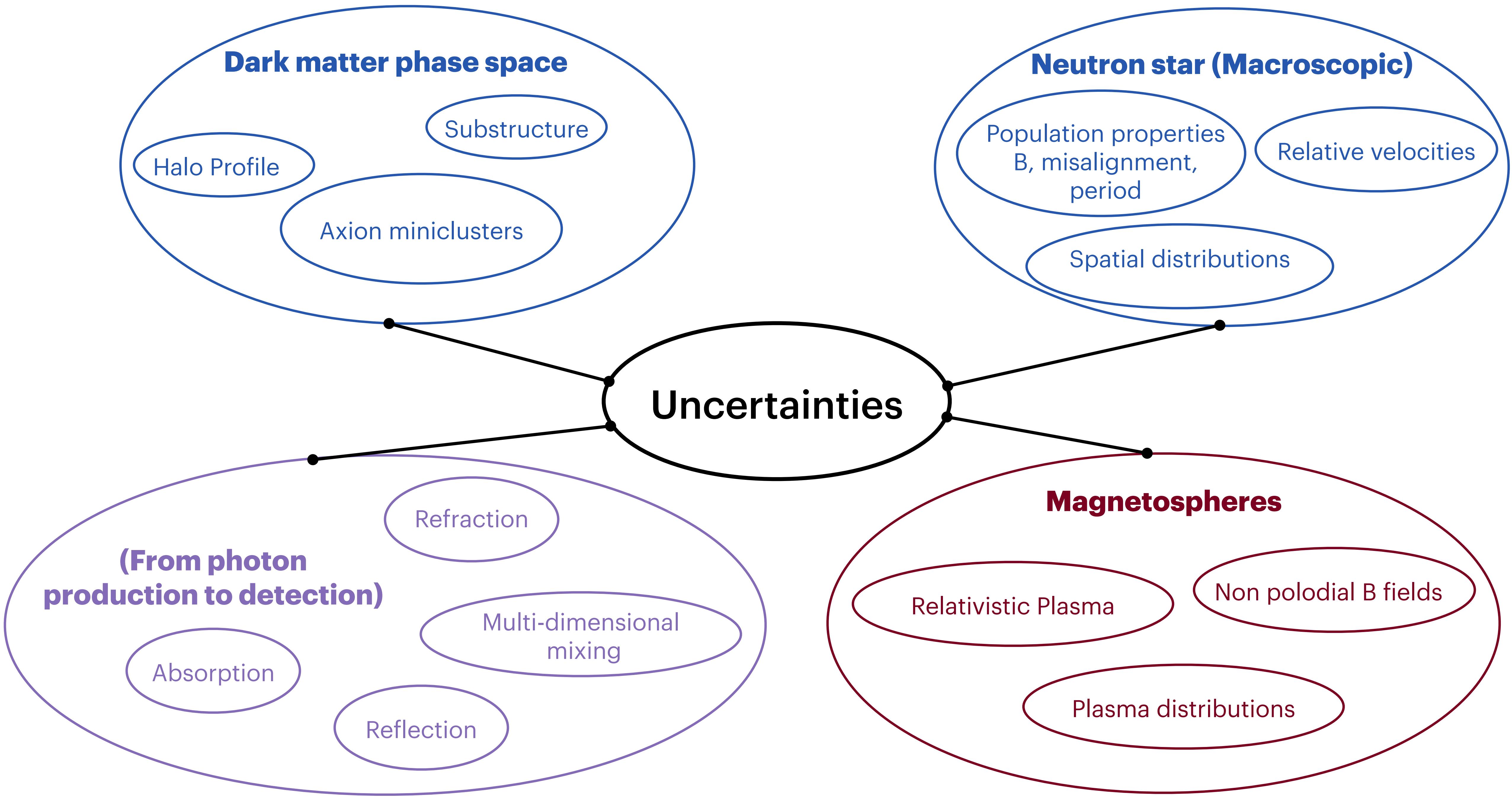


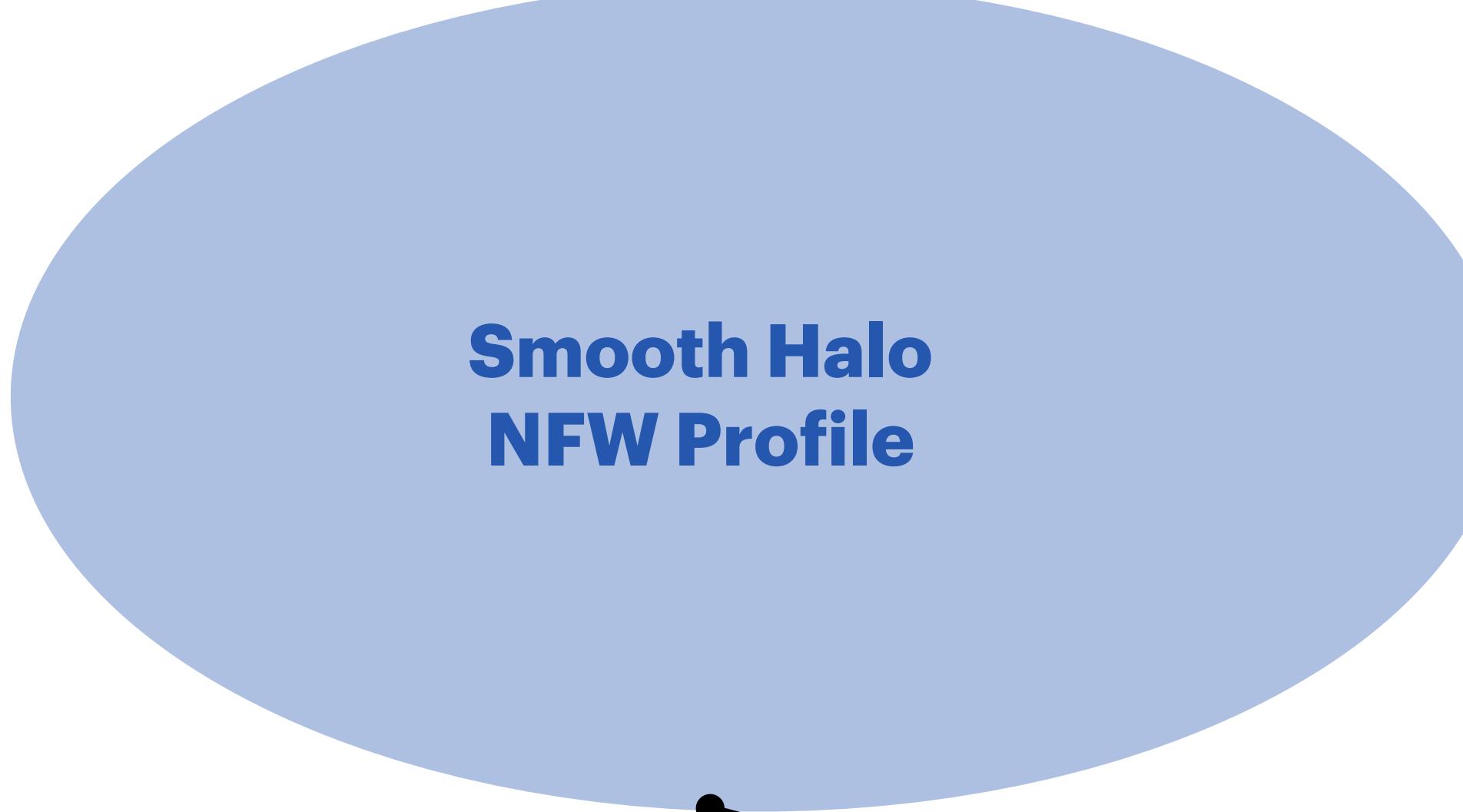
**Astrophysics
(Large Scale)**

Uncertainties

**Plasma/Particle
Physics**

**Astrophysics
(Small Scale)**





Uncertainties

Plasma/Particle
(From production to detection)

Refraction

Absorption

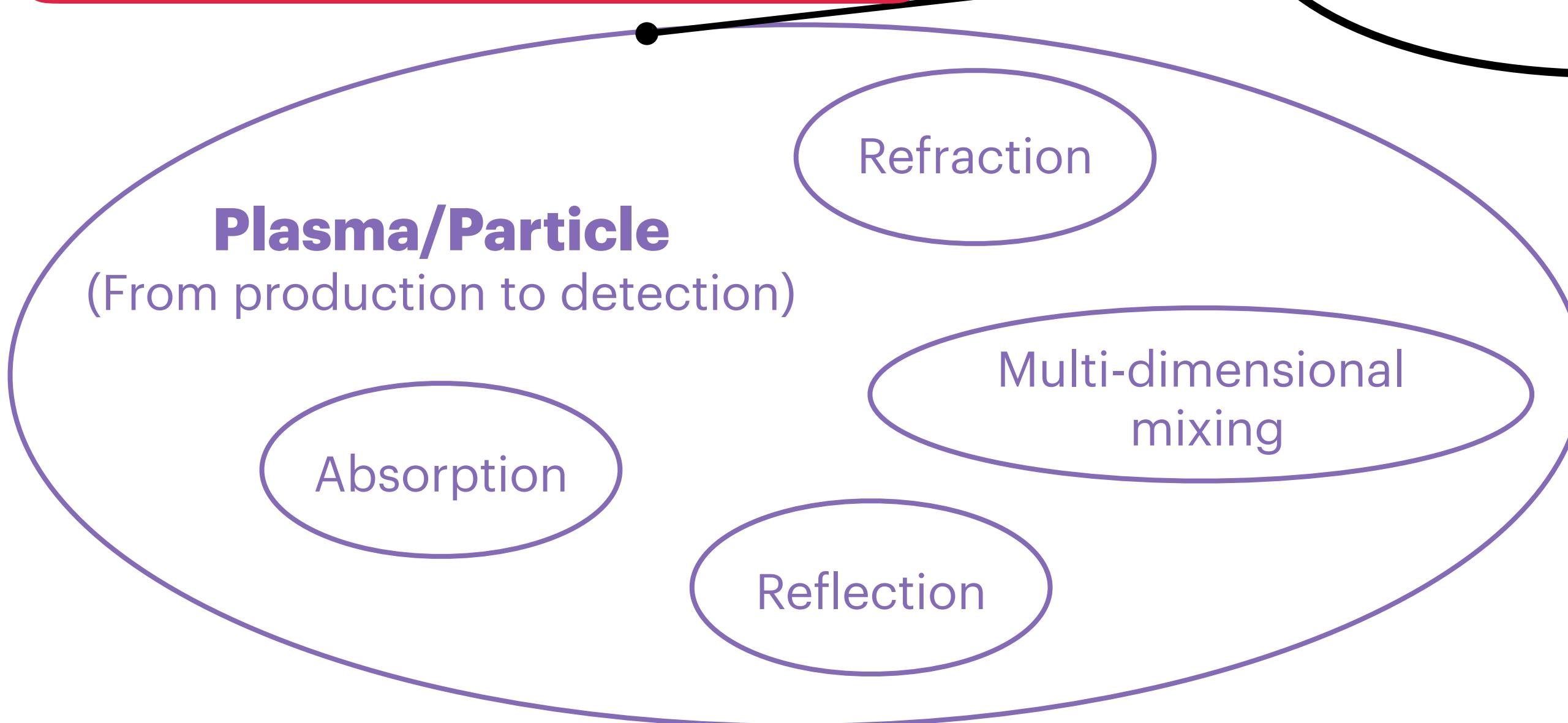
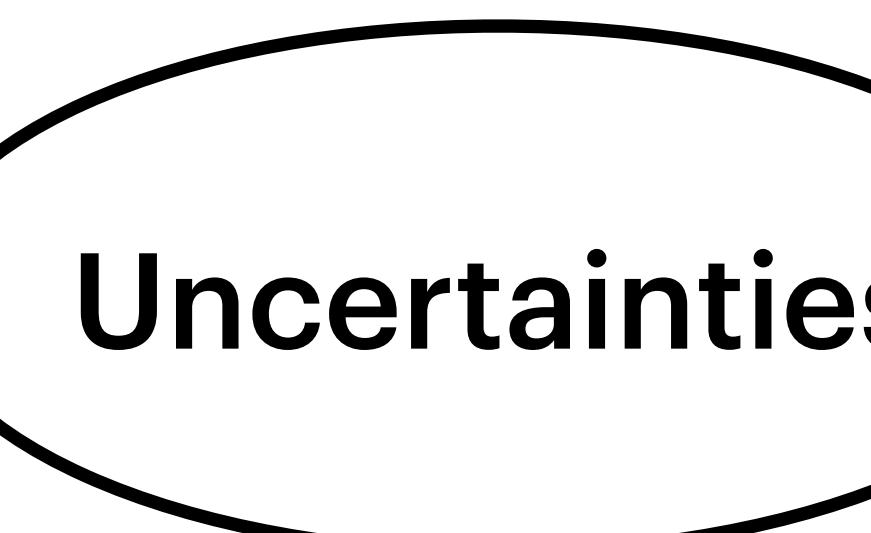
Multi-dimensional
mixing

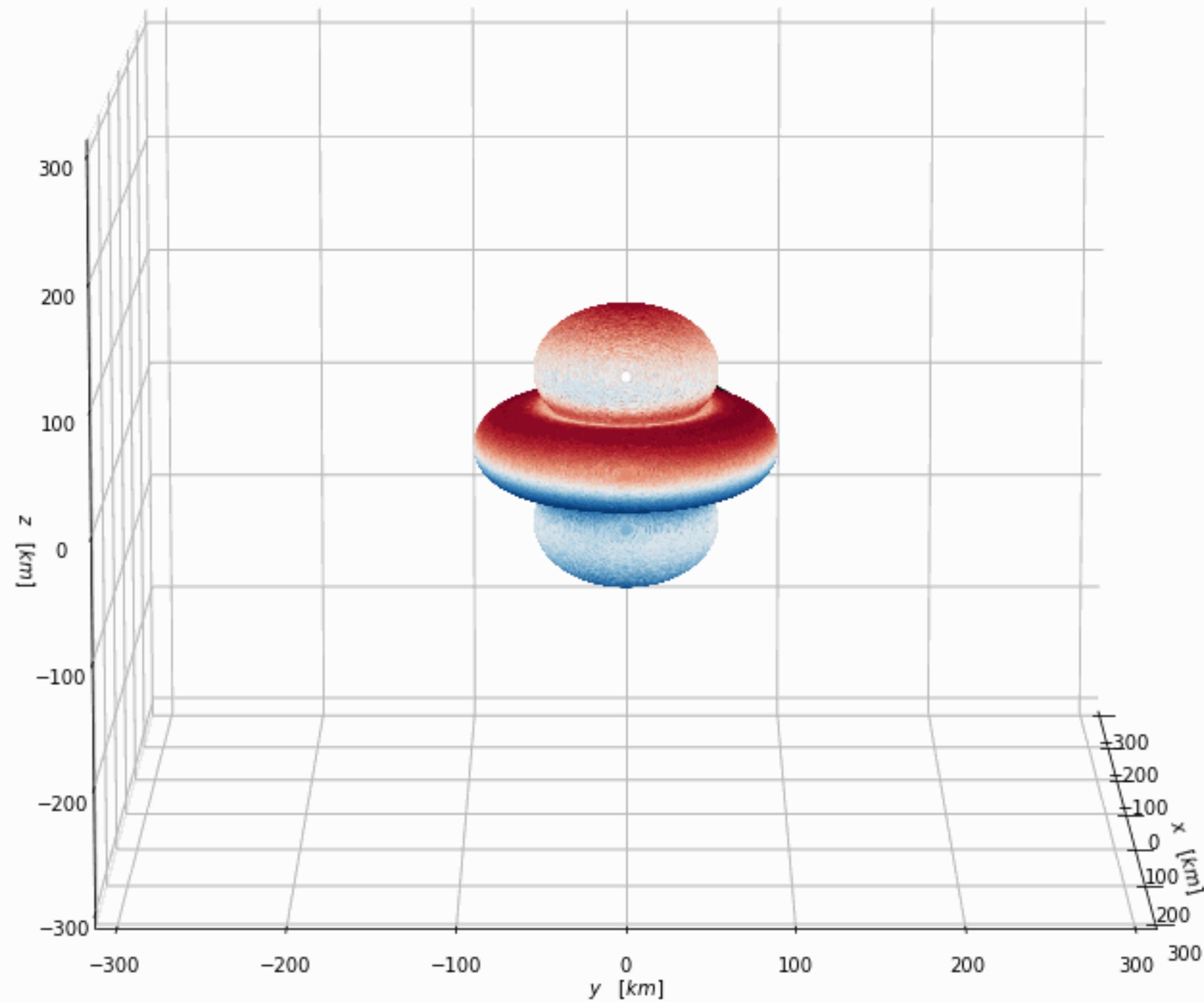
Reflection

Goldreich-Julien Magnetosphere



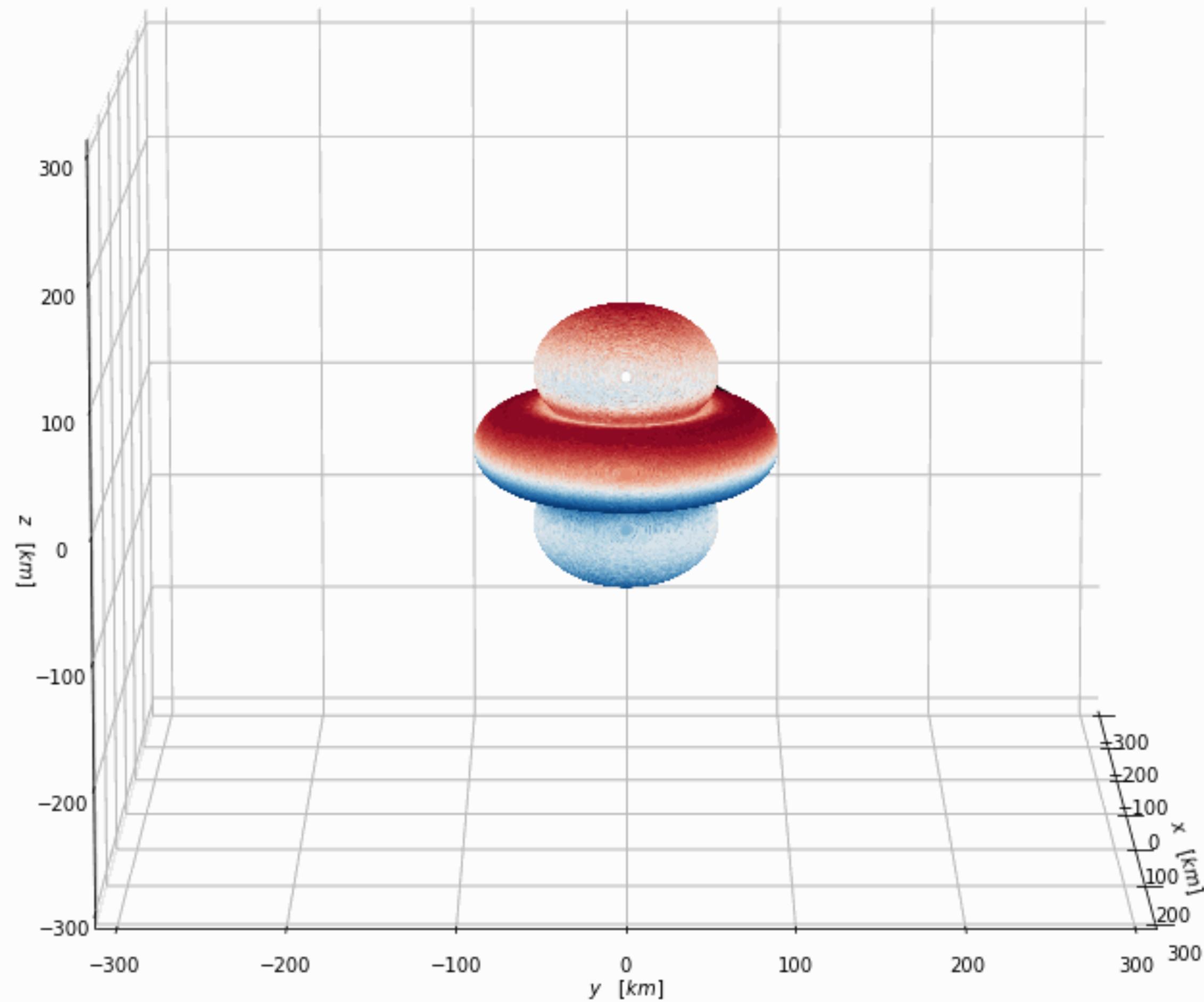
How accurate is the current formalism?
 $\sigma_F \sim 5?$, $10^5?$





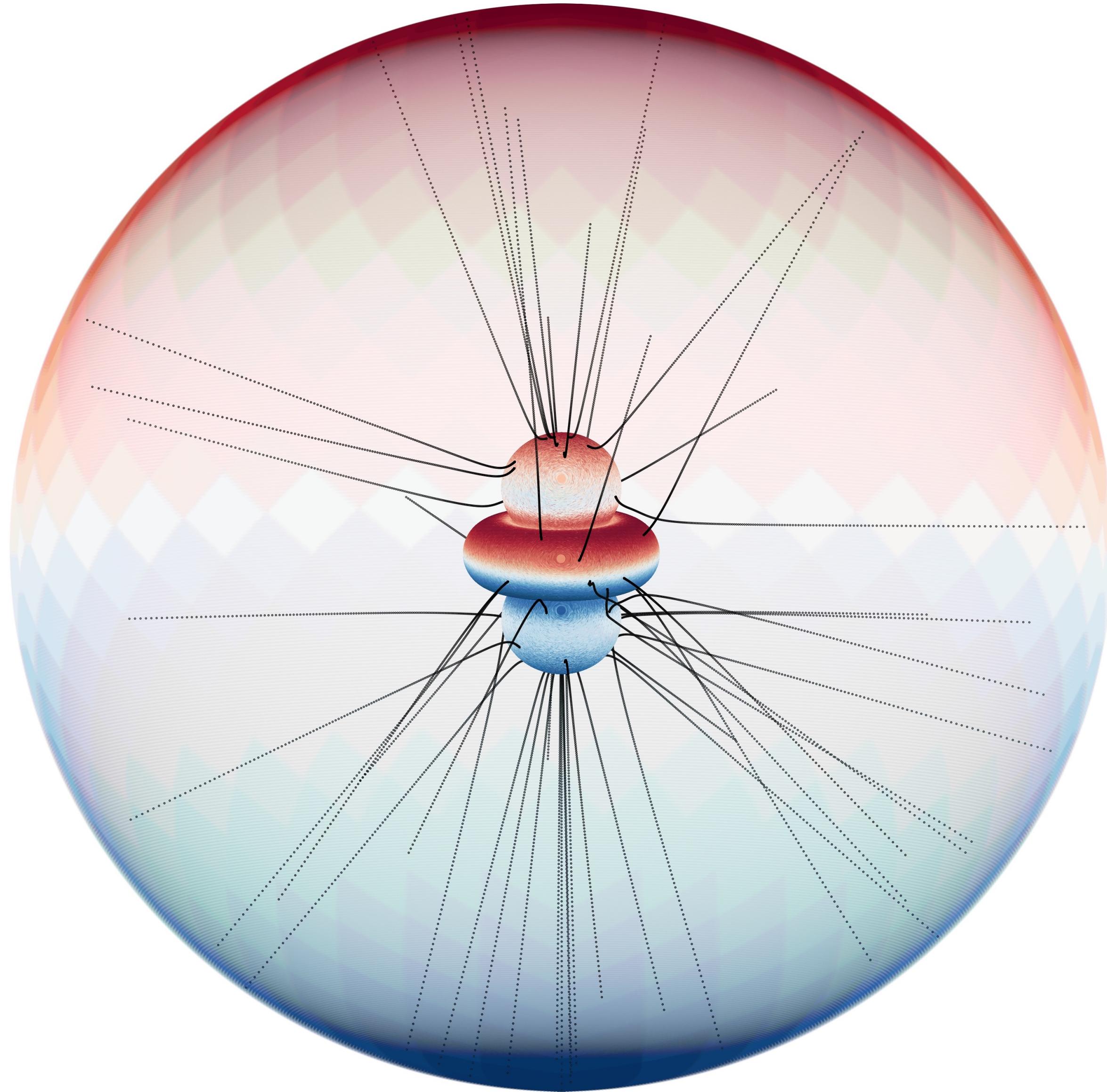
Steps:

- 1.) Sample axion phase space at conversion surface using Monte Carlo integration
- 2.) Compute conversion probability of each photon
- 3.) Ray trace photons to asymptotic infinity
- 4.) During ray-tracing, account for energy exchange with the plasma
- 5.) Re-weight photons accounting for absorption and pre-mature axion-photon de-phasing



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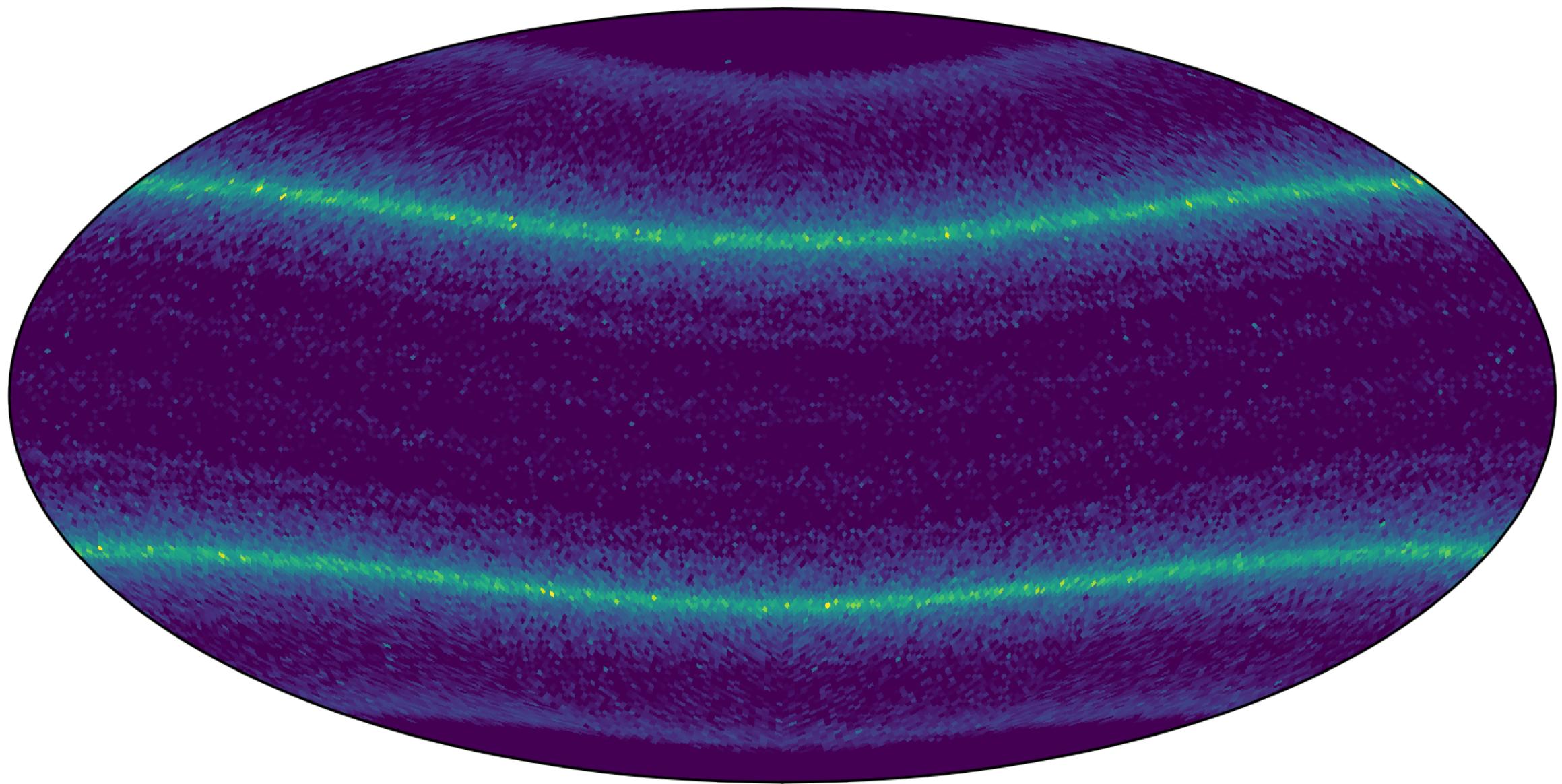


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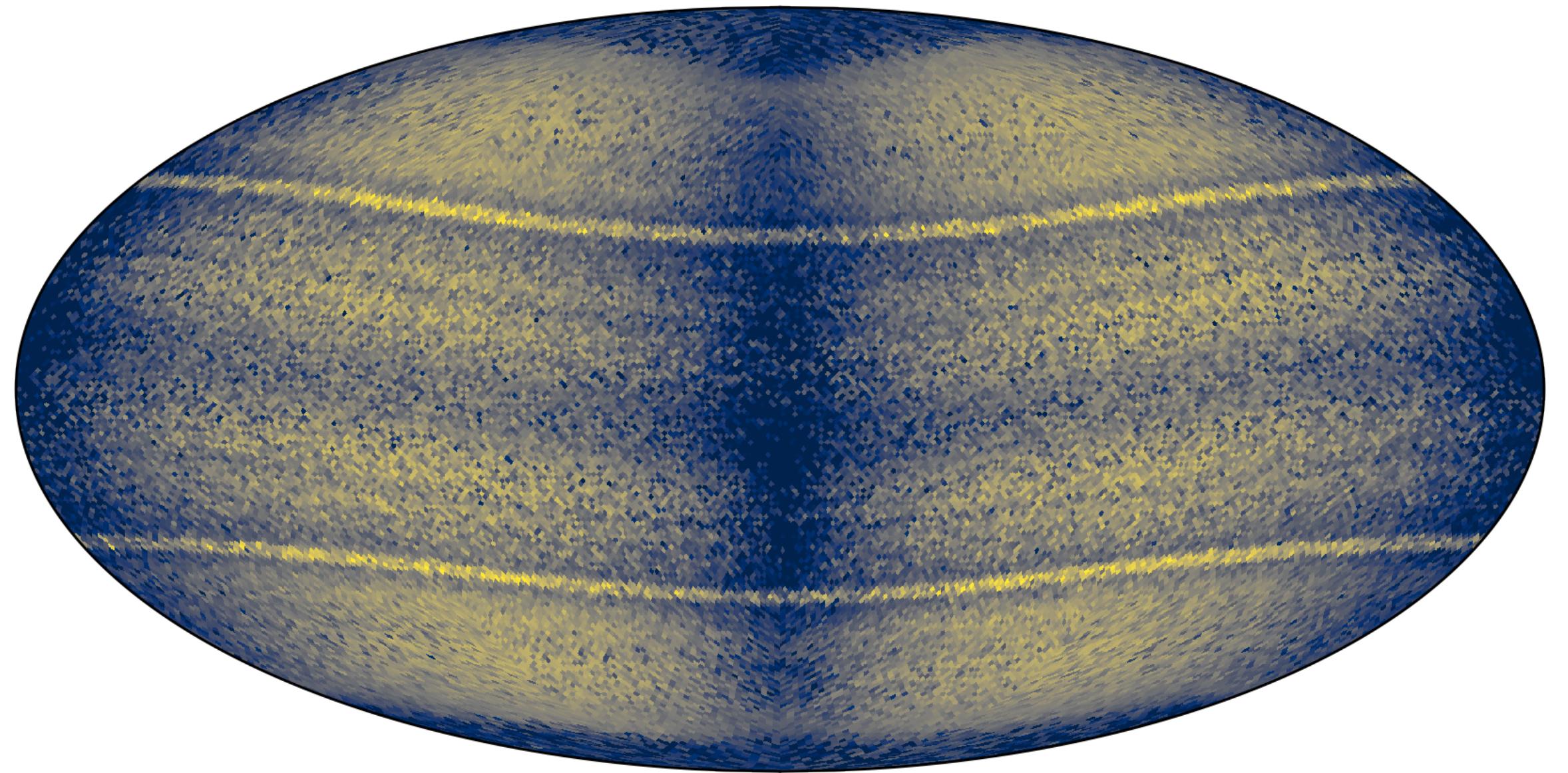
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- 6.) Generate sky maps characterizing radio signal

Relative Flux

SJW, Noordhuis, Edwards, Weniger (2021)



$$\log_{10} \delta R$$



$$\log_{10} \Delta B$$

$$\delta R \equiv \frac{R_{\text{pixel}}}{R_{\text{tot}}}$$

$$\Delta B \sim \frac{\delta\omega_\gamma - m_a}{m_a}$$

Assumptions of Analytic Formalism

1. Photon trajectories at the conversion surface are radial
 - ♦ And the conversion surface is approximately radial
2. Axion-photon conversion can be treated in 1D
3. Radio line width set by asymptotic axion velocity distribution
4. Refraction does not play a major role in inducing anisotropy
5. Radio photons exit the magnetosphere without being absorbed

Assumption

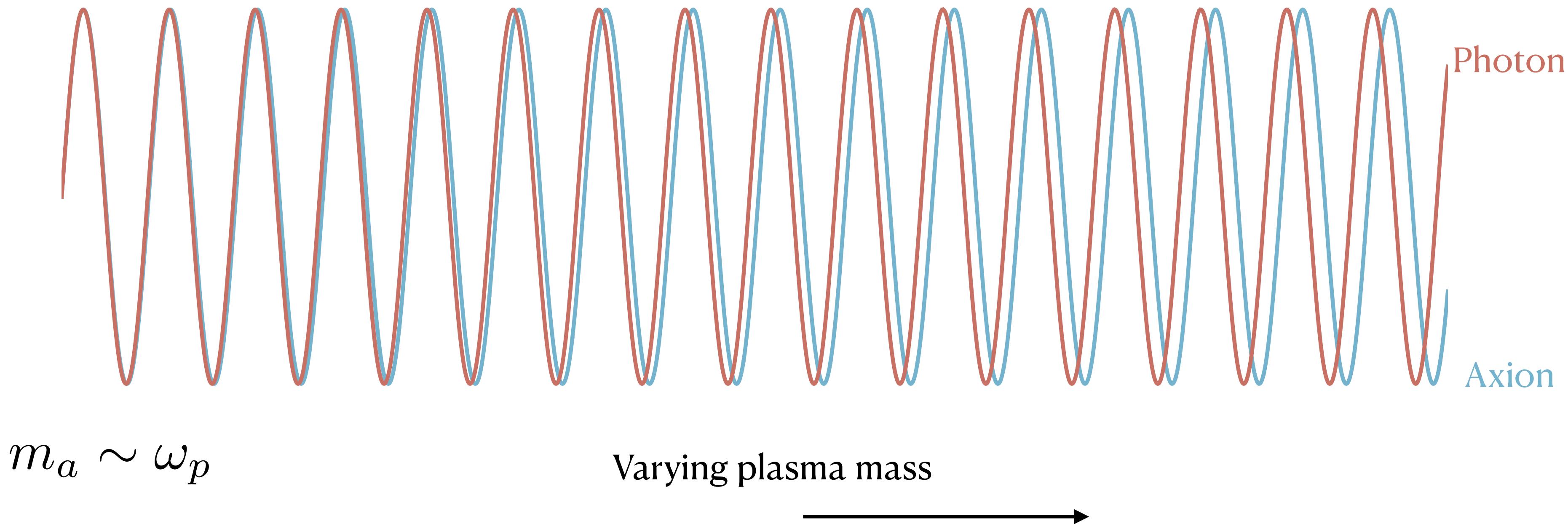
Photon trajectories at the conversion surface are radial

Axion-Photon Conversion (1D)

Conversion probability $\propto L_c^2$

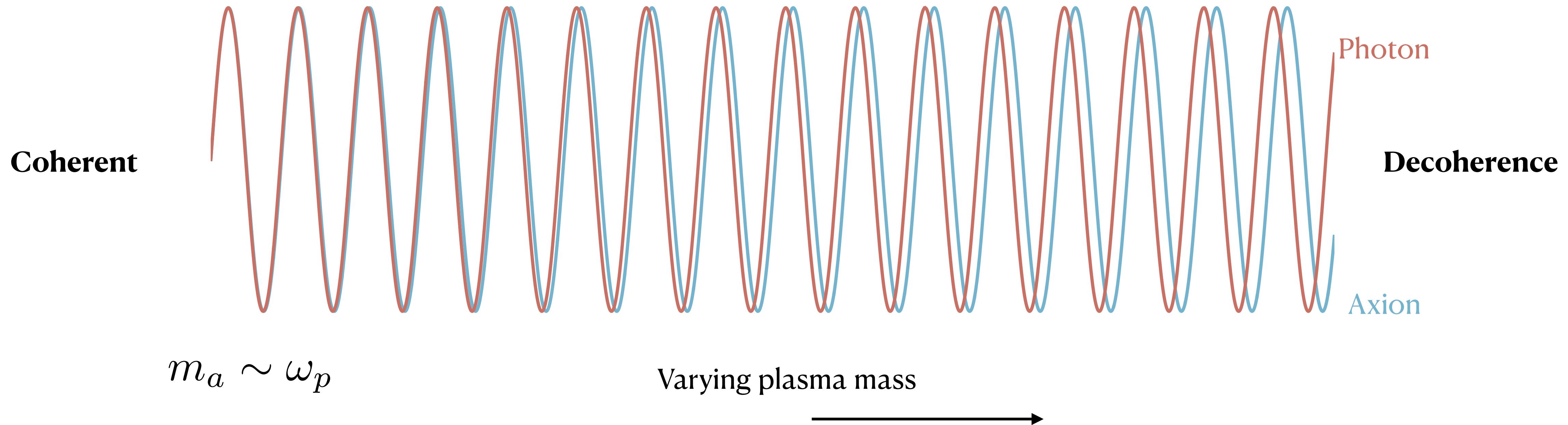
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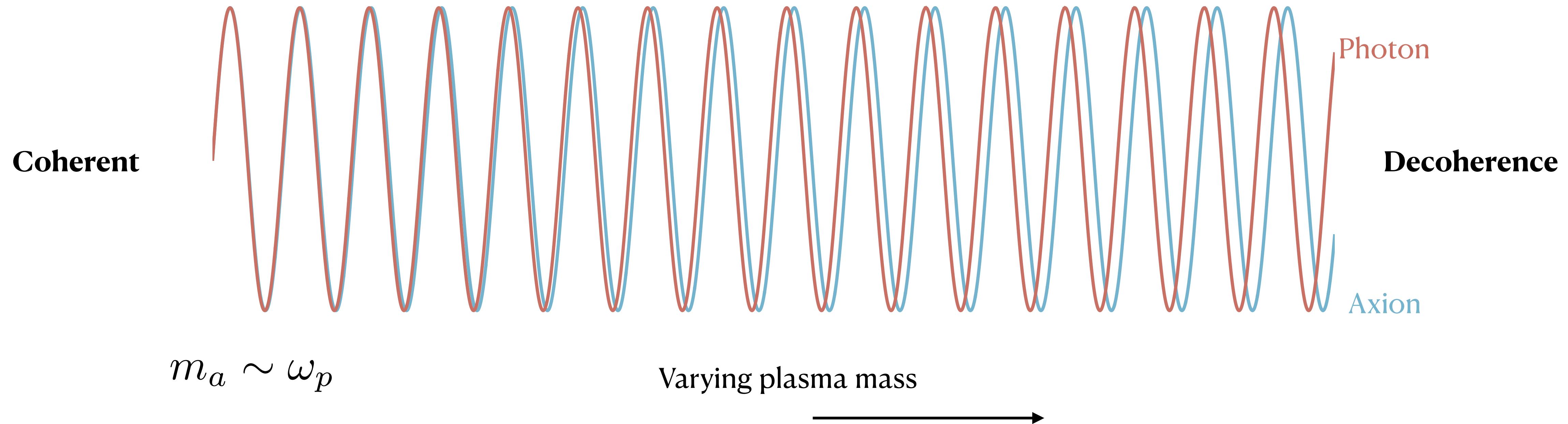
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$$L_c^2 \propto \frac{1}{|\partial_\ell k_\gamma|}$$



$$m_a \sim \omega_p$$



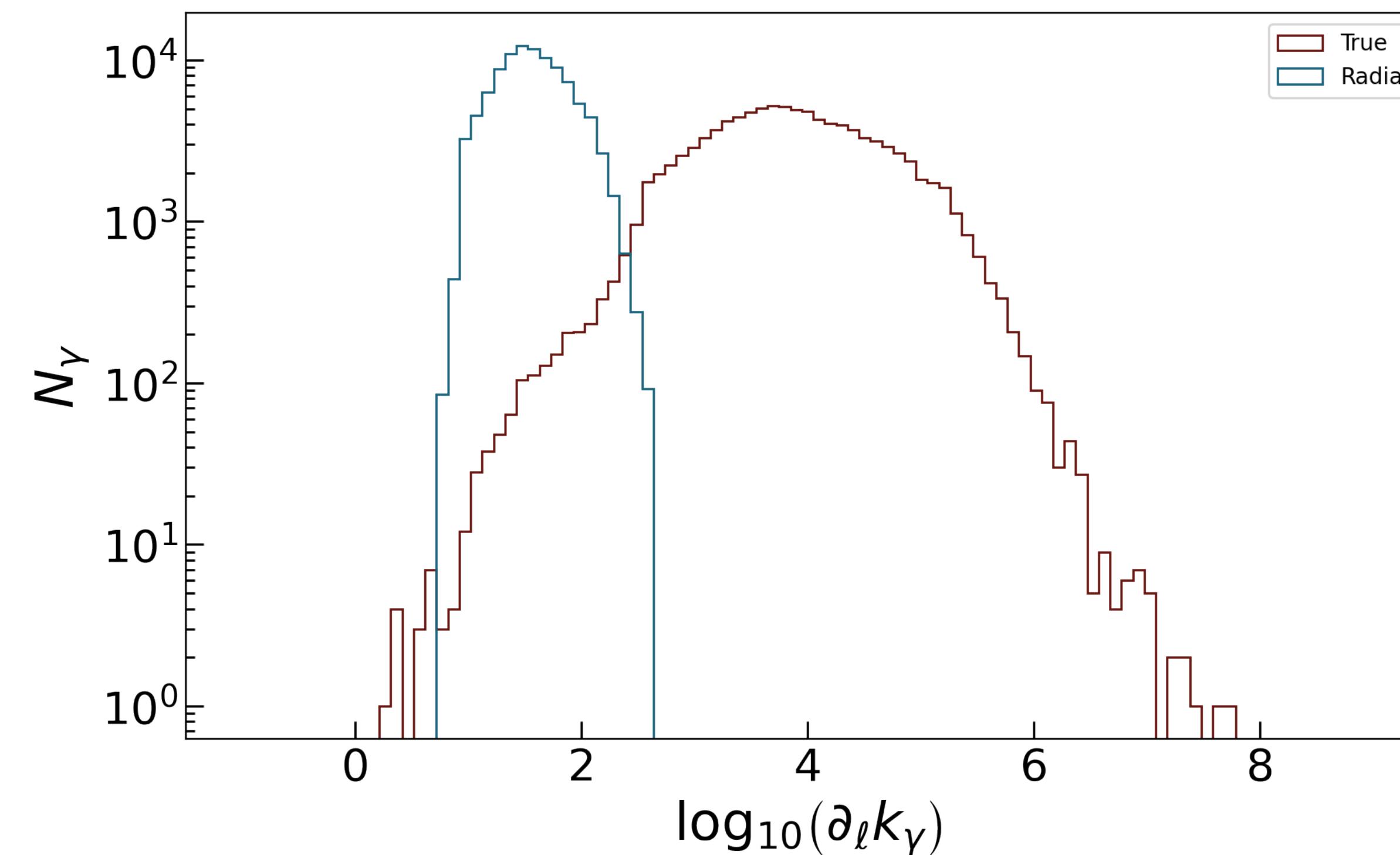
Assumption #1

We can approximate photon trajectories as being radial at the conversion surface

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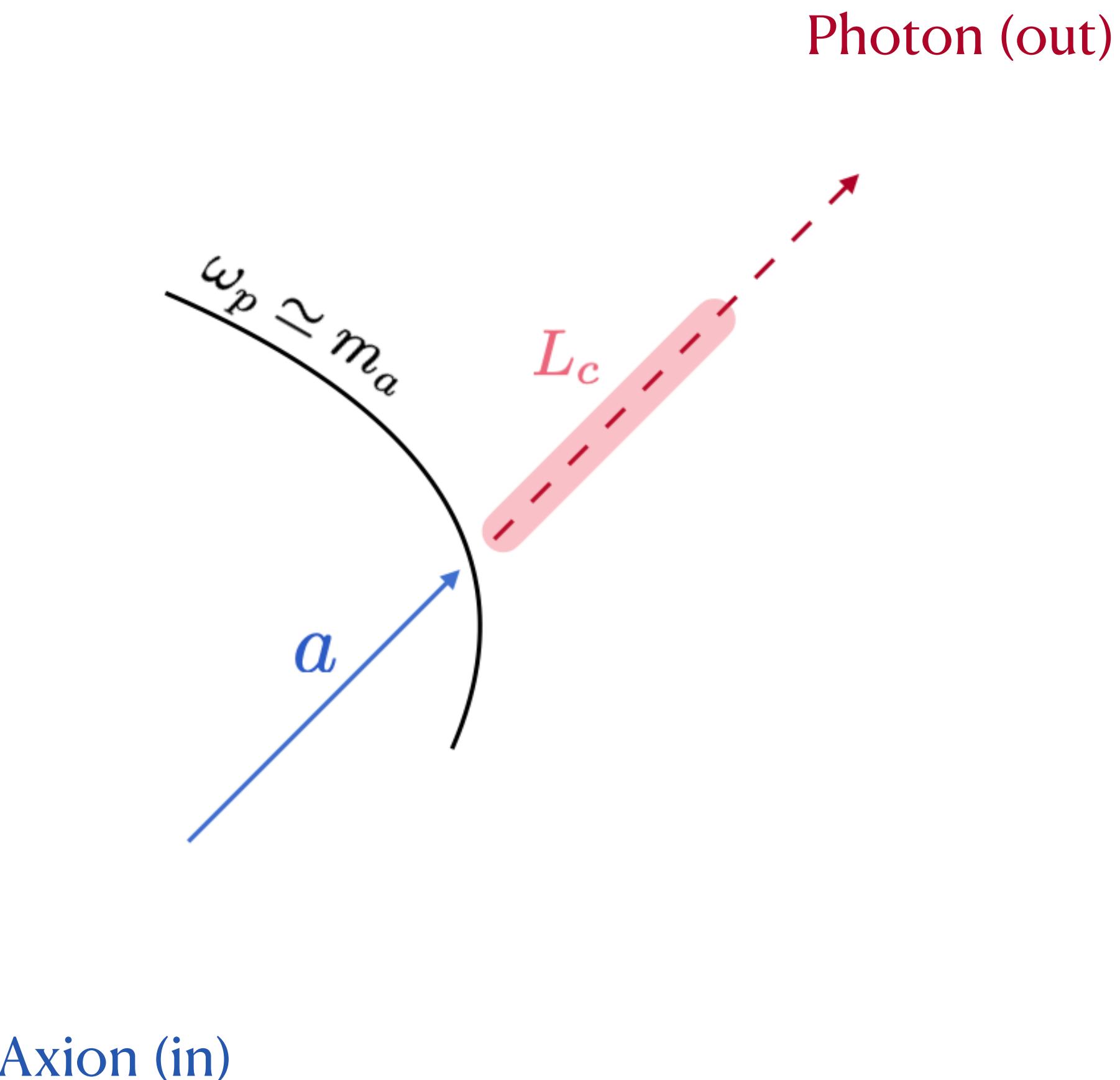
The conversion probability is strongly dependent upon the incident angle



Assumption

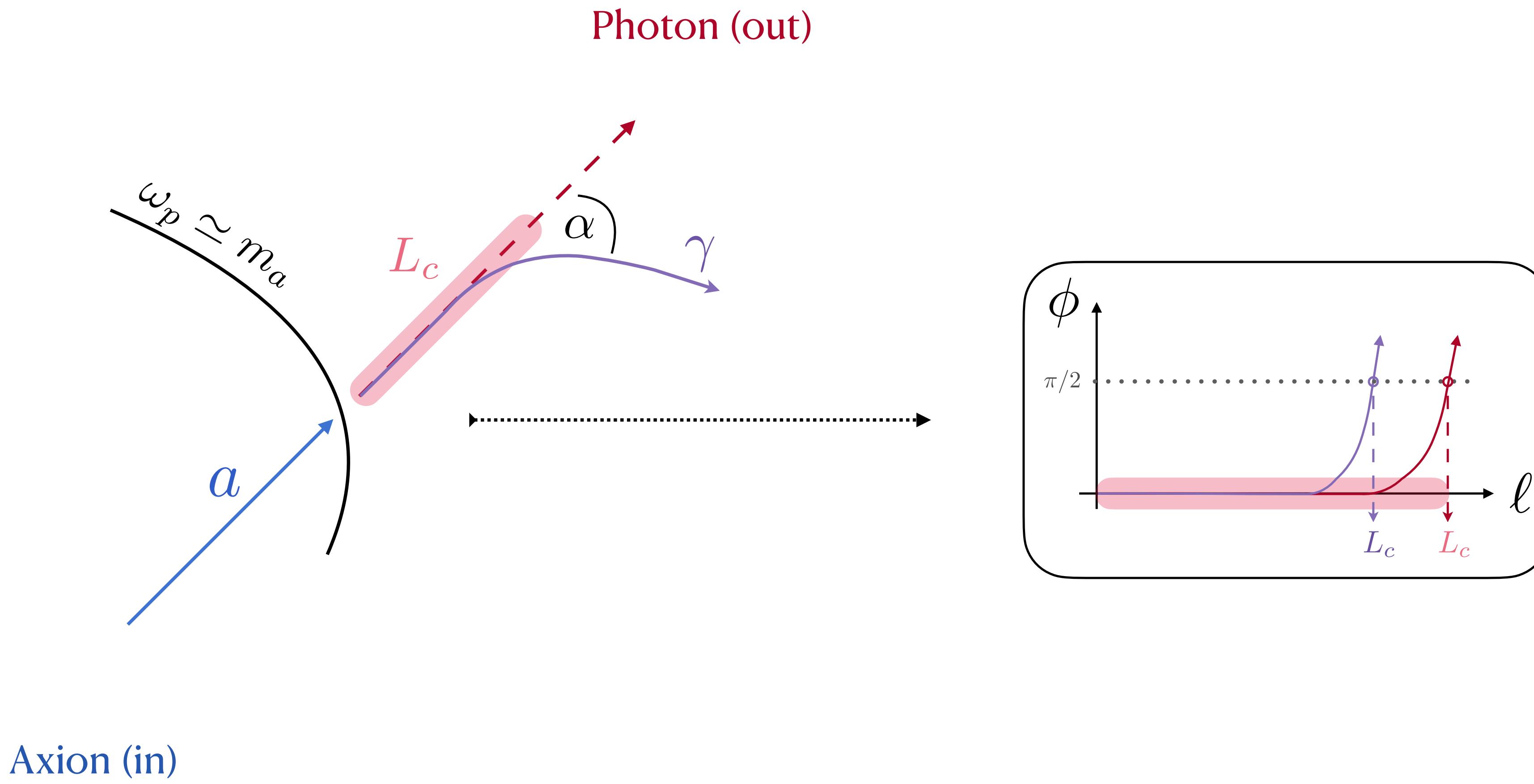
We can approximate the axion-photon mixing using the 1D conversion formula

Axion-Photon Conversion (2D)



SJW, Noordhuis, Edwards, Weniger (2021)

Axion-Photon Conversion (2D)



SJW, Noordhuis, Edwards, Weniger (2021)

Assumption

Radio photons exit the magnetosphere without being absorbed

Photon Absorption

SJW, Noordhuis, Edwards, Weniger (2021)

Landau Levels



⋮



$$\Delta E = qB/m_e$$

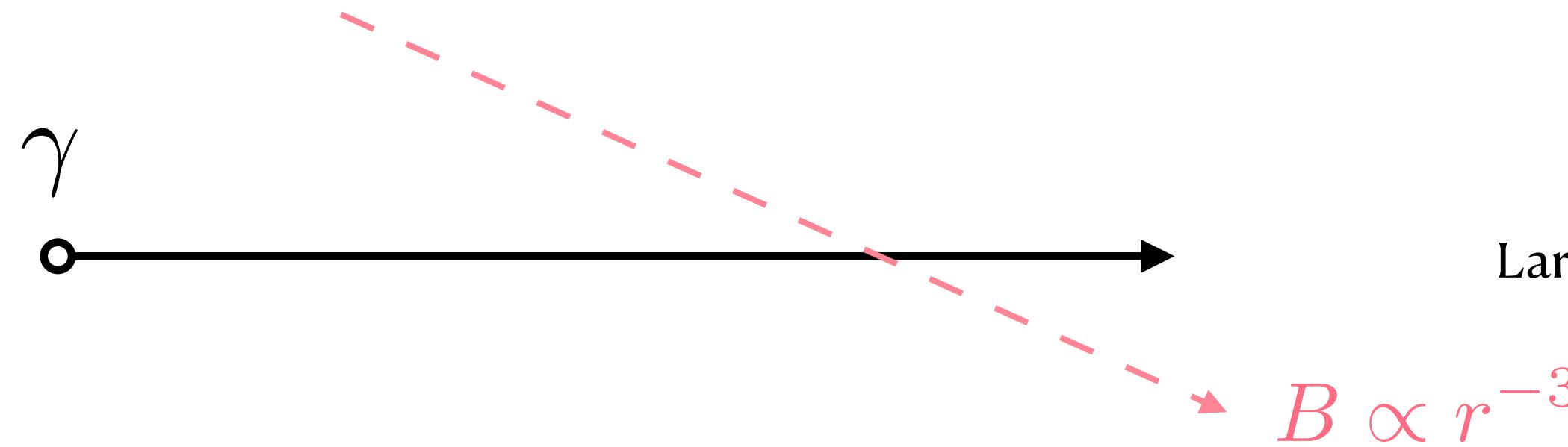
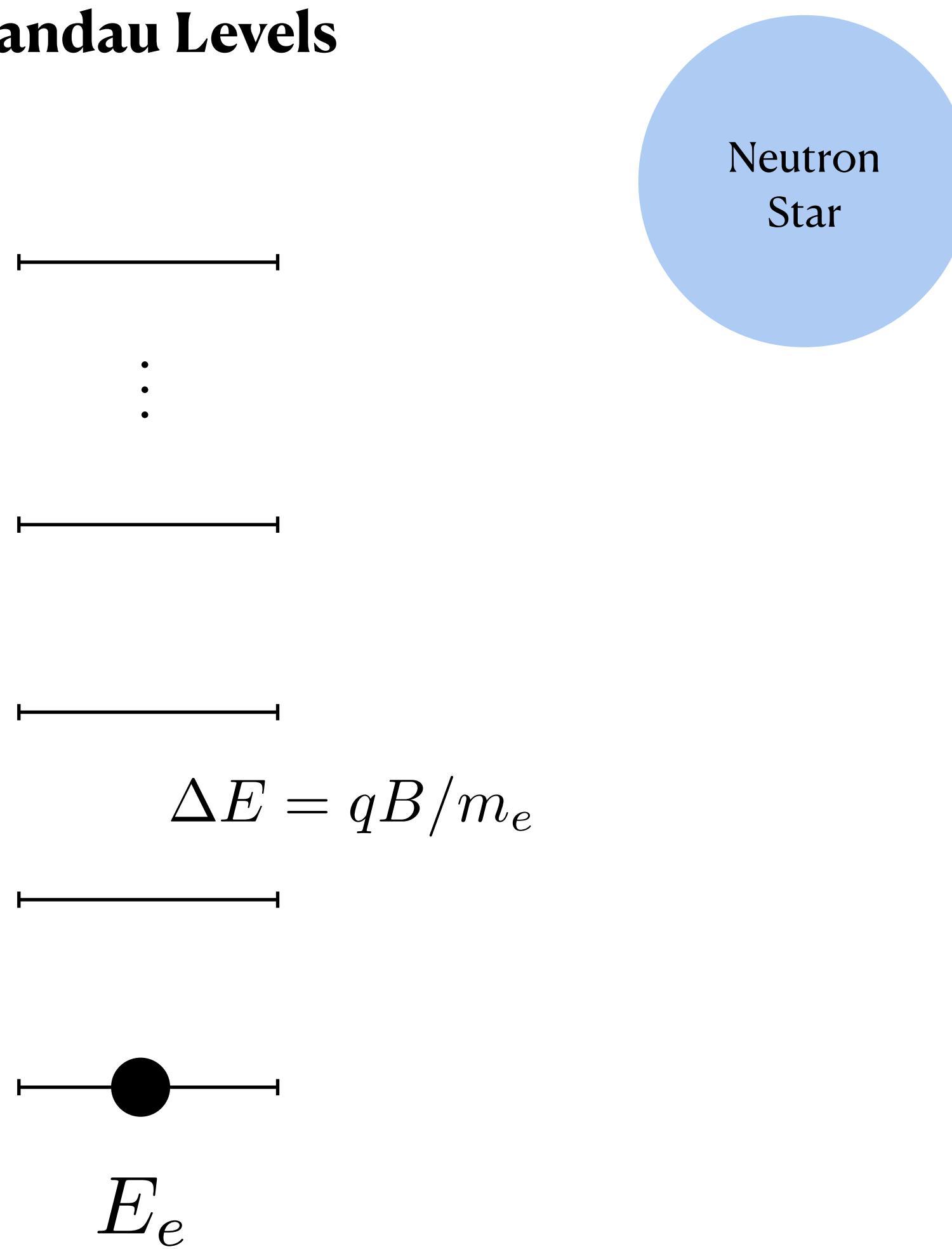


$$E_e$$

Photon Absorption

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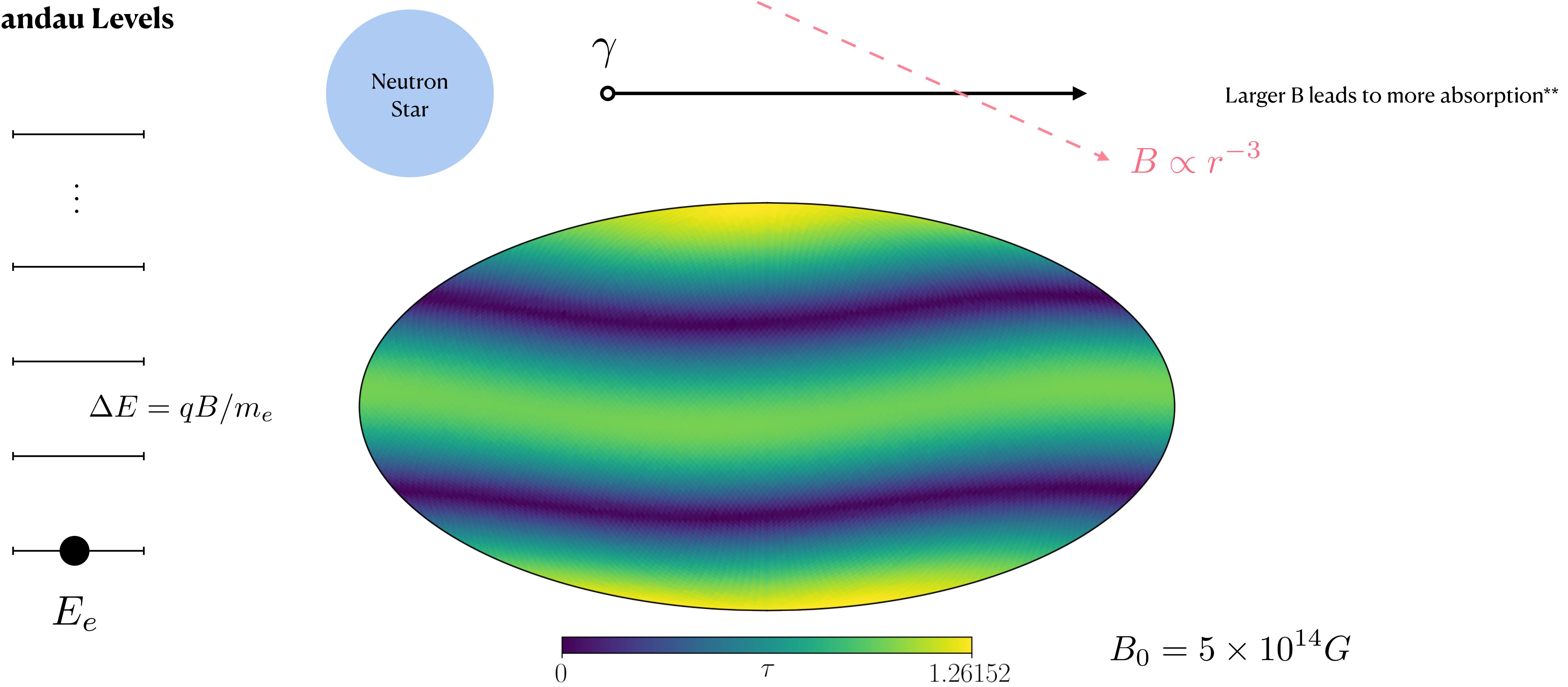
Larger B leads to more absorption**

$$B \propto r^{-3}$$

Photon Absorption

SJW, Noordhuis, Edwards, Weniger (2021)

Landau Levels



Projected Sensitivity (SKA)

SJW, Noordhuis, Edwards, Weniger (2021)

