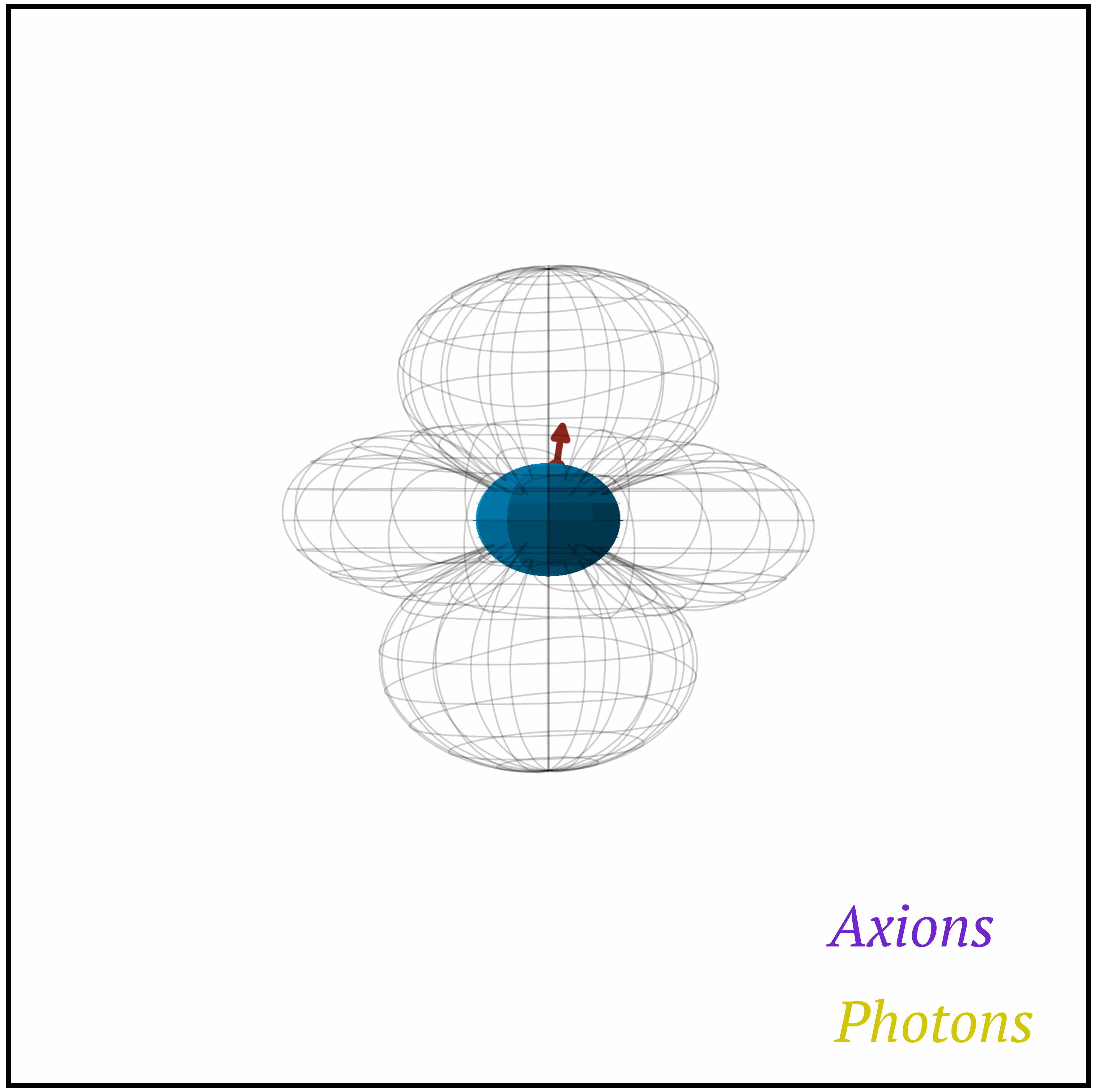
Neutron Stars as Axion Laboratories

Samuel J. Witte

28th IFT Xmas Workshop
Madrid, Spain
Dec. 15, 2022



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

GRAPPA
GRavitation AstroParticle Physics Amsterdam
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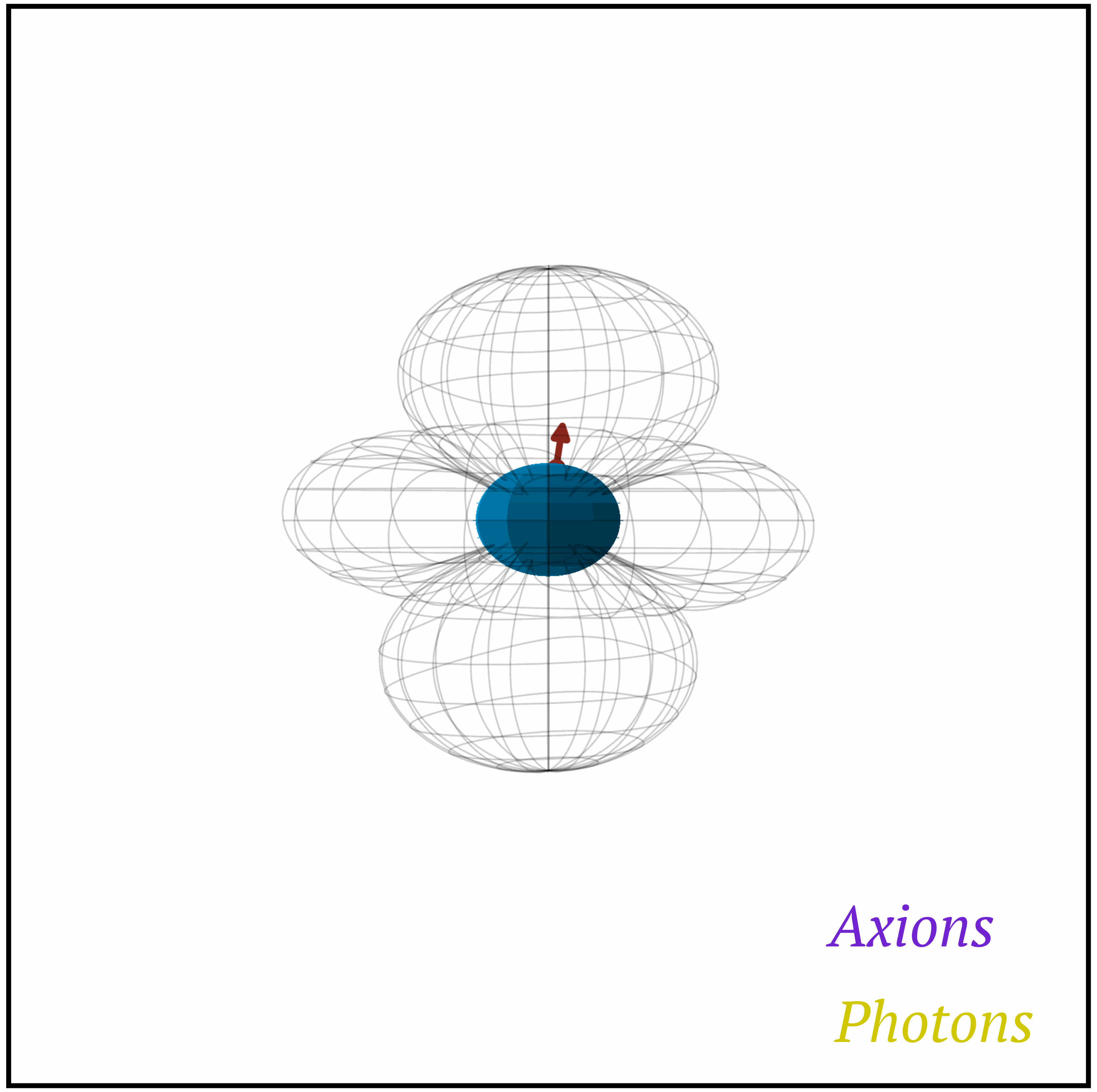

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The strong CP problem

Why does QCD seem to conserve charge-parity (CP) symmetry?

CP violating term in QCD Lagrangian:

$$\mathcal{L}_{CPV} \supset \overline{\theta}\, \frac{g_s^2}{32\pi^2}\, G\,\tilde{G}$$

Neutron electric dipole moment (eDM) $\propto \overline{\theta}$

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

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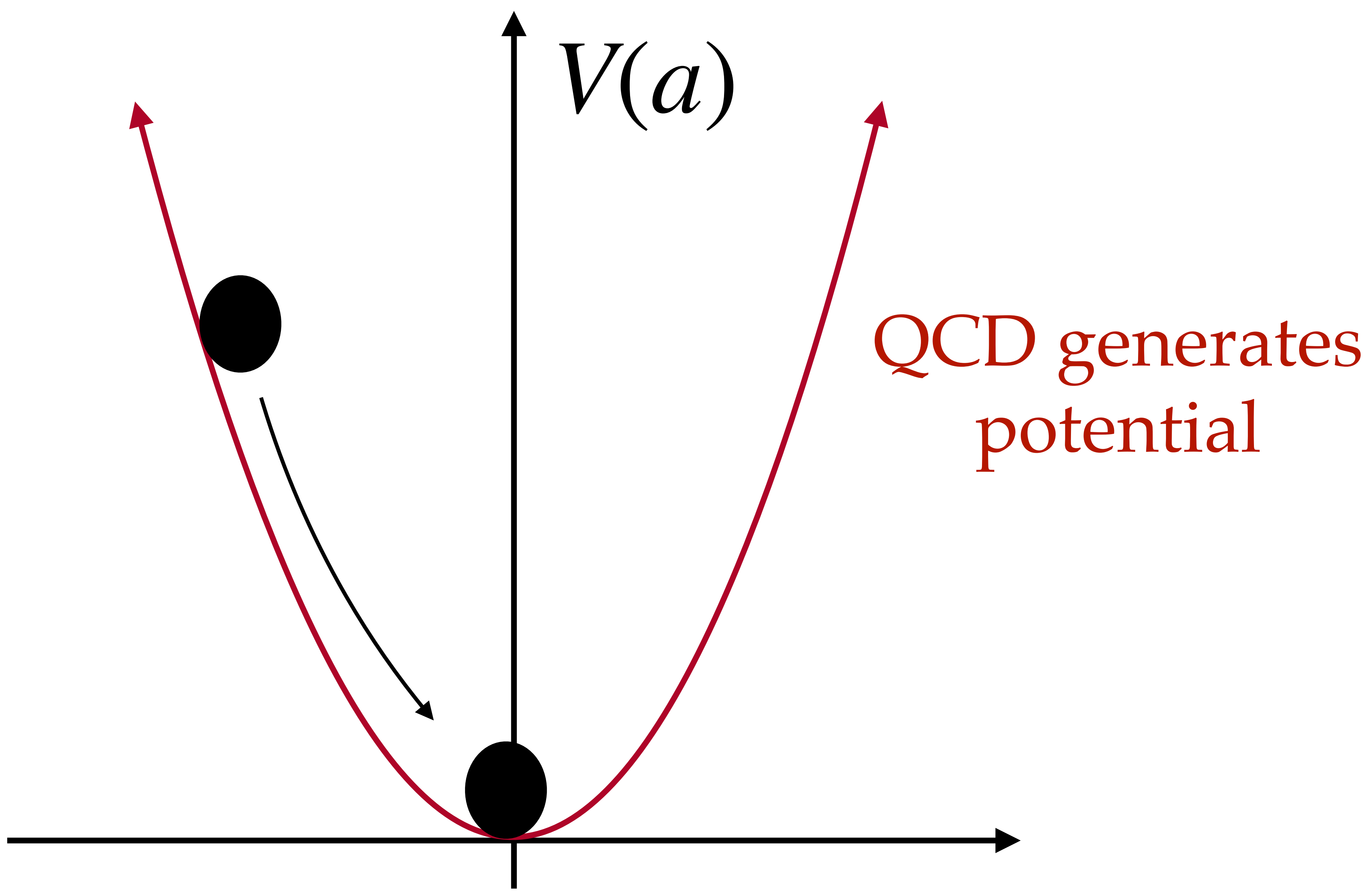
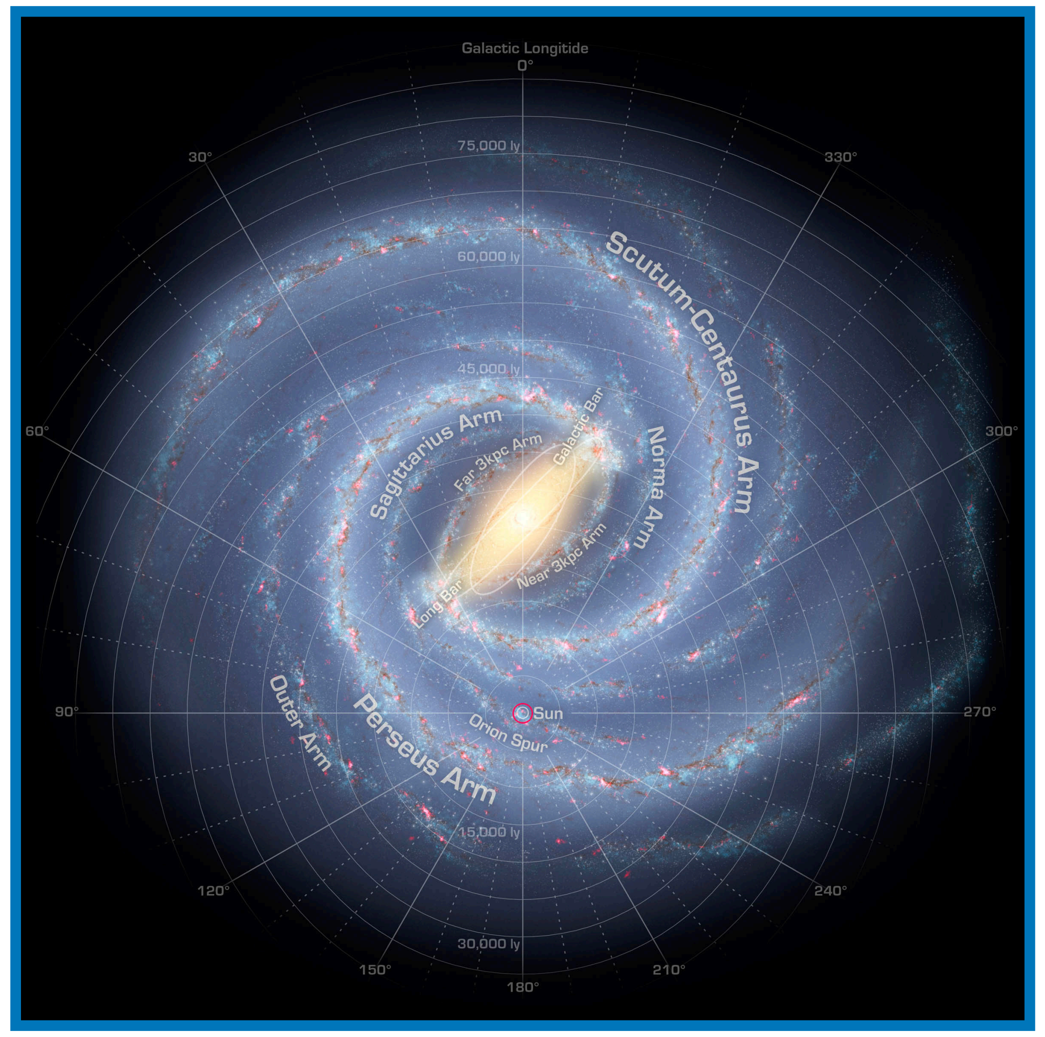


Neutron eDM = 0

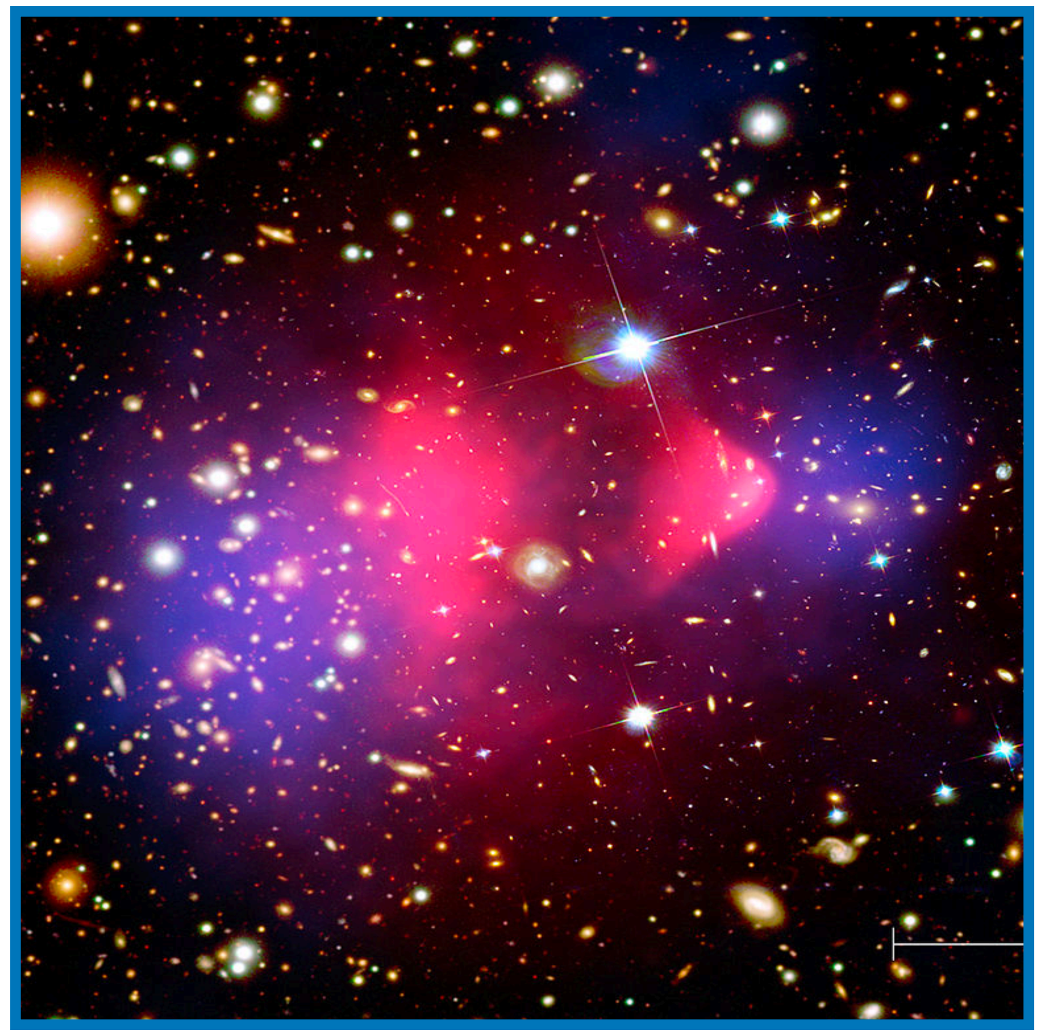
Evidence for dark matter

~26% of energy in the Universe today is in a new form of feebly interacting matter

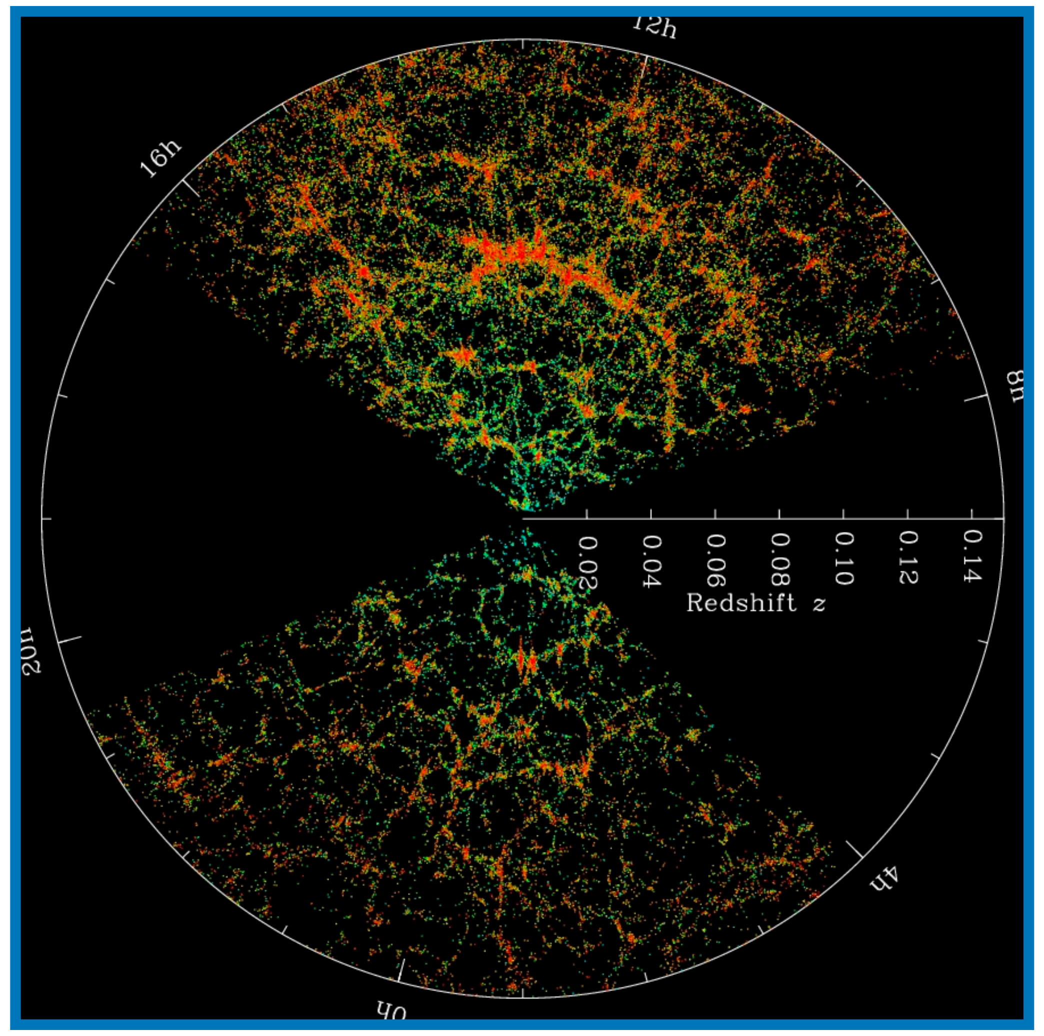
Galaxy rotation curves



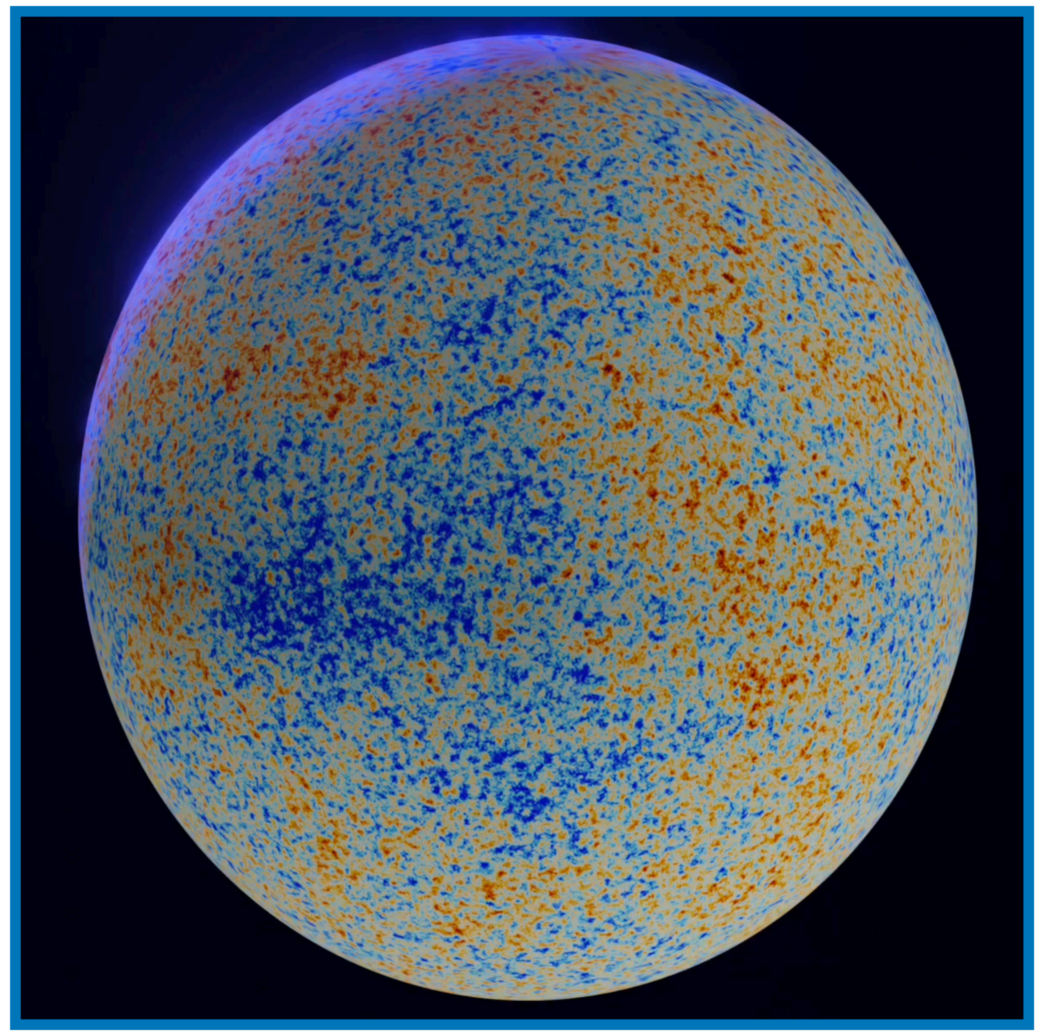
Merging galaxy clusters



Large scale structure



Cosmic microwave background



Characteristic Scale

~kpc — *(Today)*

~Mpc

~100 Mpc

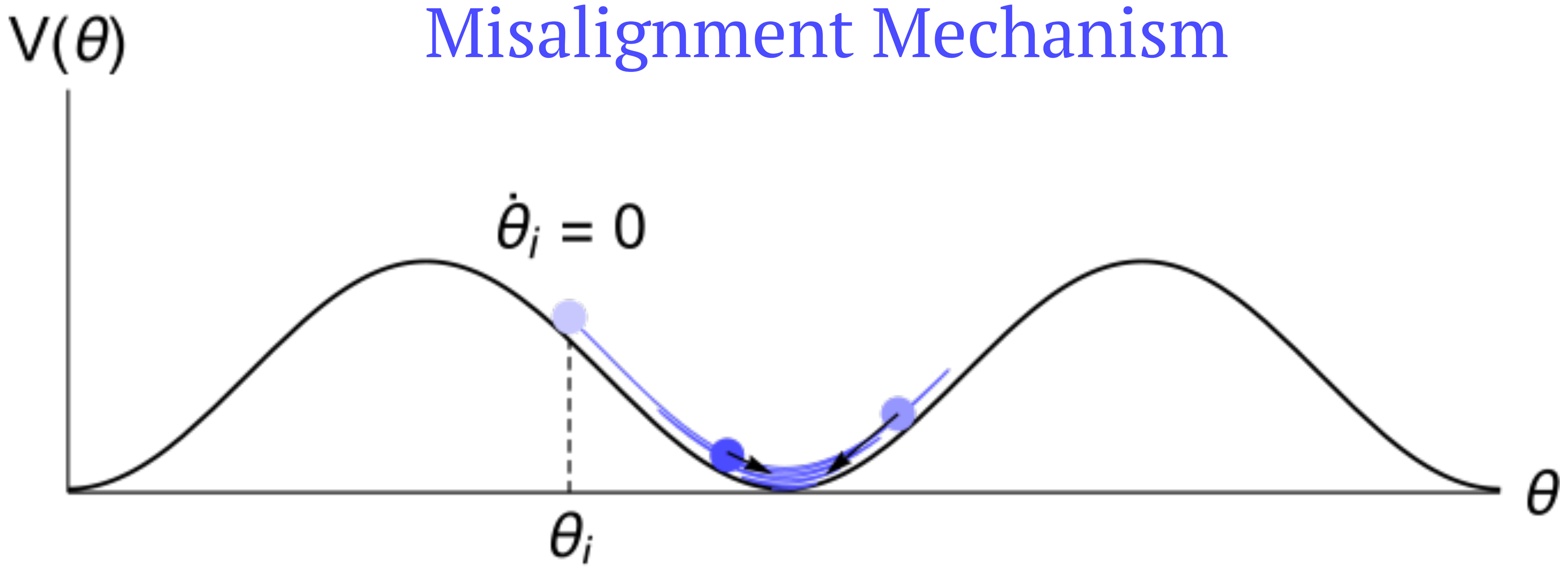
~10 Gpc — *(370,000 after big bang)*

Axions as dark matter candidates

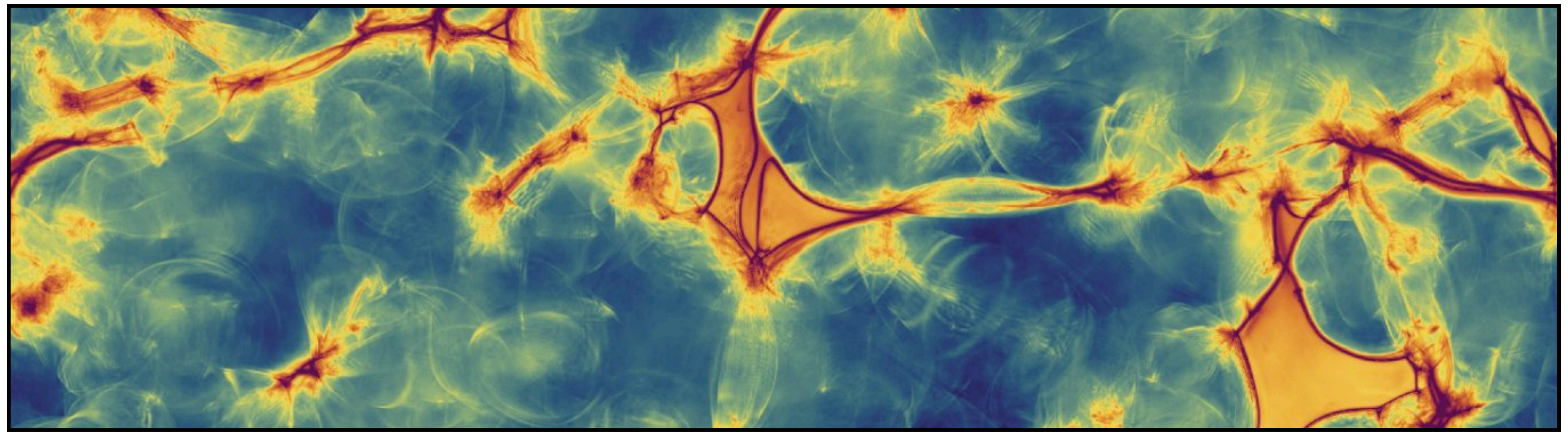
- Light axions ($m_a \ll \mathcal{O}(\mathrm{eV})$) are feebly interacting and naturally long-lived

- Can be produced non-thermally in the early Universe

Misalignment Mechanism



Decays of Topological Defects



Can easily accommodate observed abundance of dark matter

Properties of the axion

Axion Mass: $m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$

Axion Couplings: $\mathcal{L} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$ $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ $\sum_f \frac{1}{f_a}\partial_\mu a\, \bar{f}\gamma^\mu\gamma_5 f$ $\cdots$ + other terms

(Term for Strong CP Problem) (Electro-Mag) (Fermions)

(Slight model dependence in couplings)

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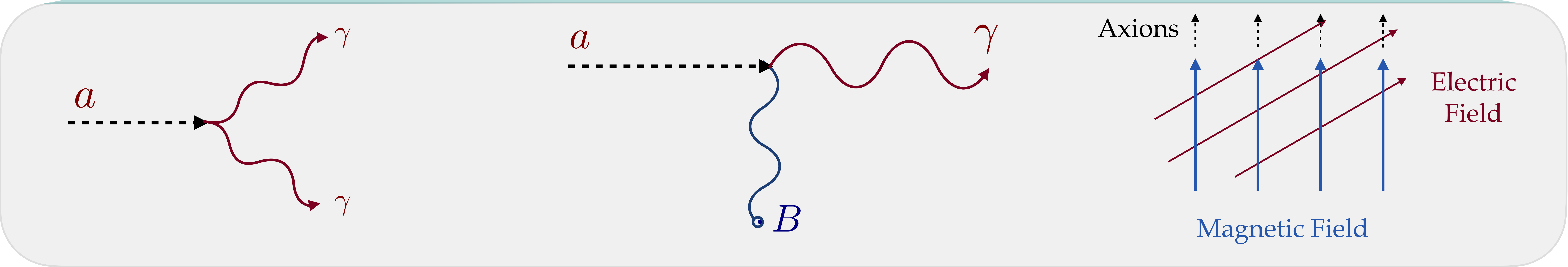
$a\,\vec{E}\cdot\vec{B}$



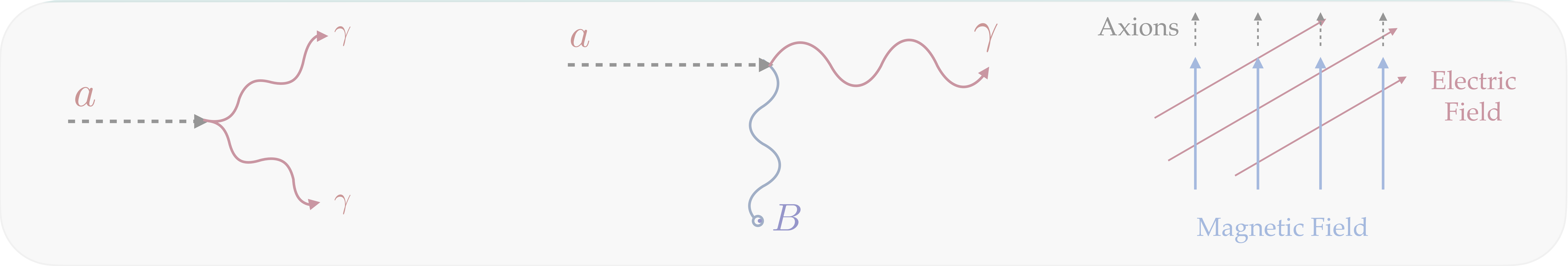
Axion-like particles (ALPs)

ALPs do not solve strong CP problem, but naturally emerge in String Theory from compactification

Axion Couplings: $\mathcal{L} \supset$ No Coupling $\quad \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ (Electro-Mag) $\quad \cdots$ + other terms

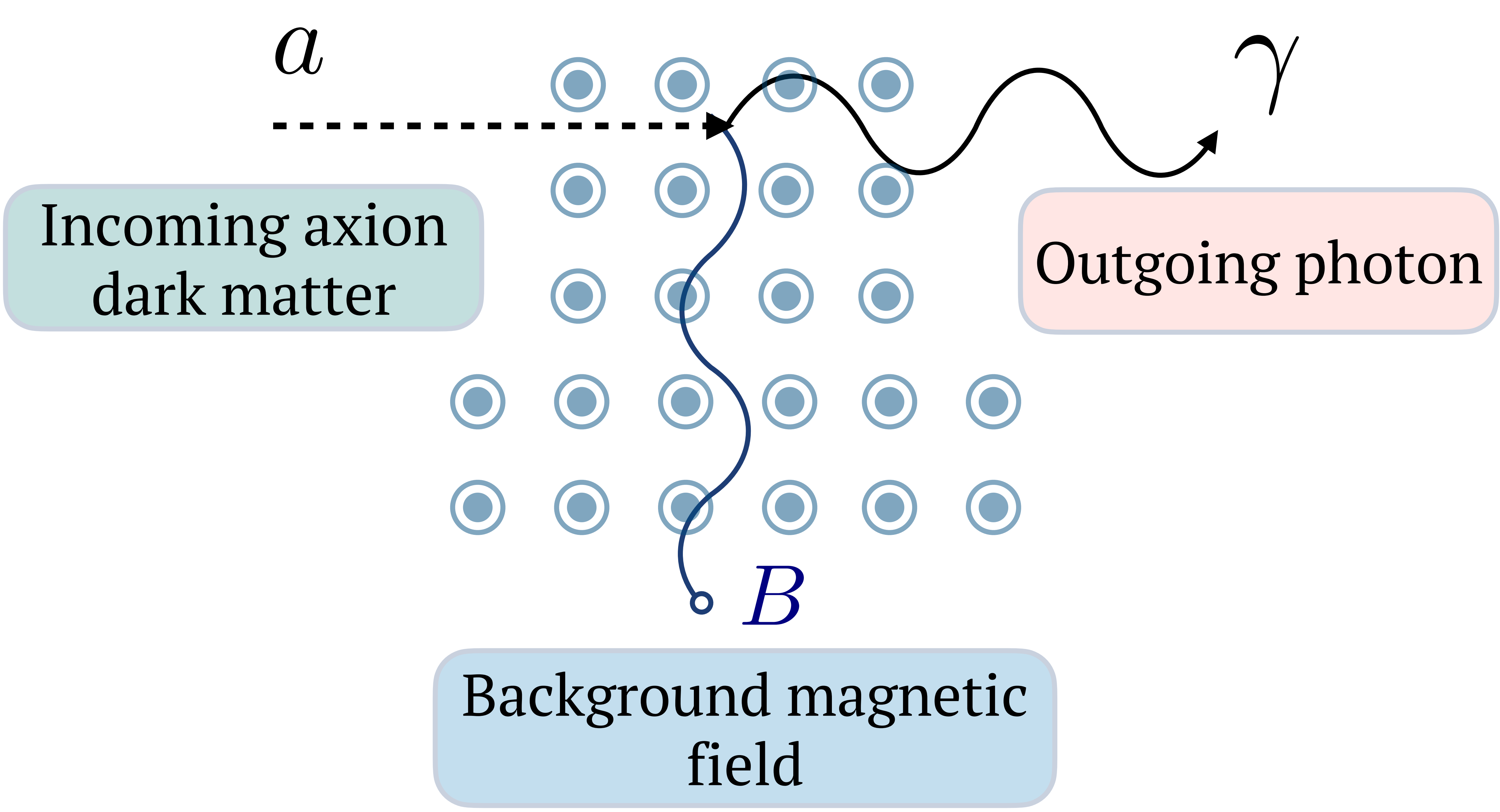
Axion mass m_a and decay constant f_a uncorrelated

$a\,\vec{E} \cdot \vec{B}$



Axion-photon mixing

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



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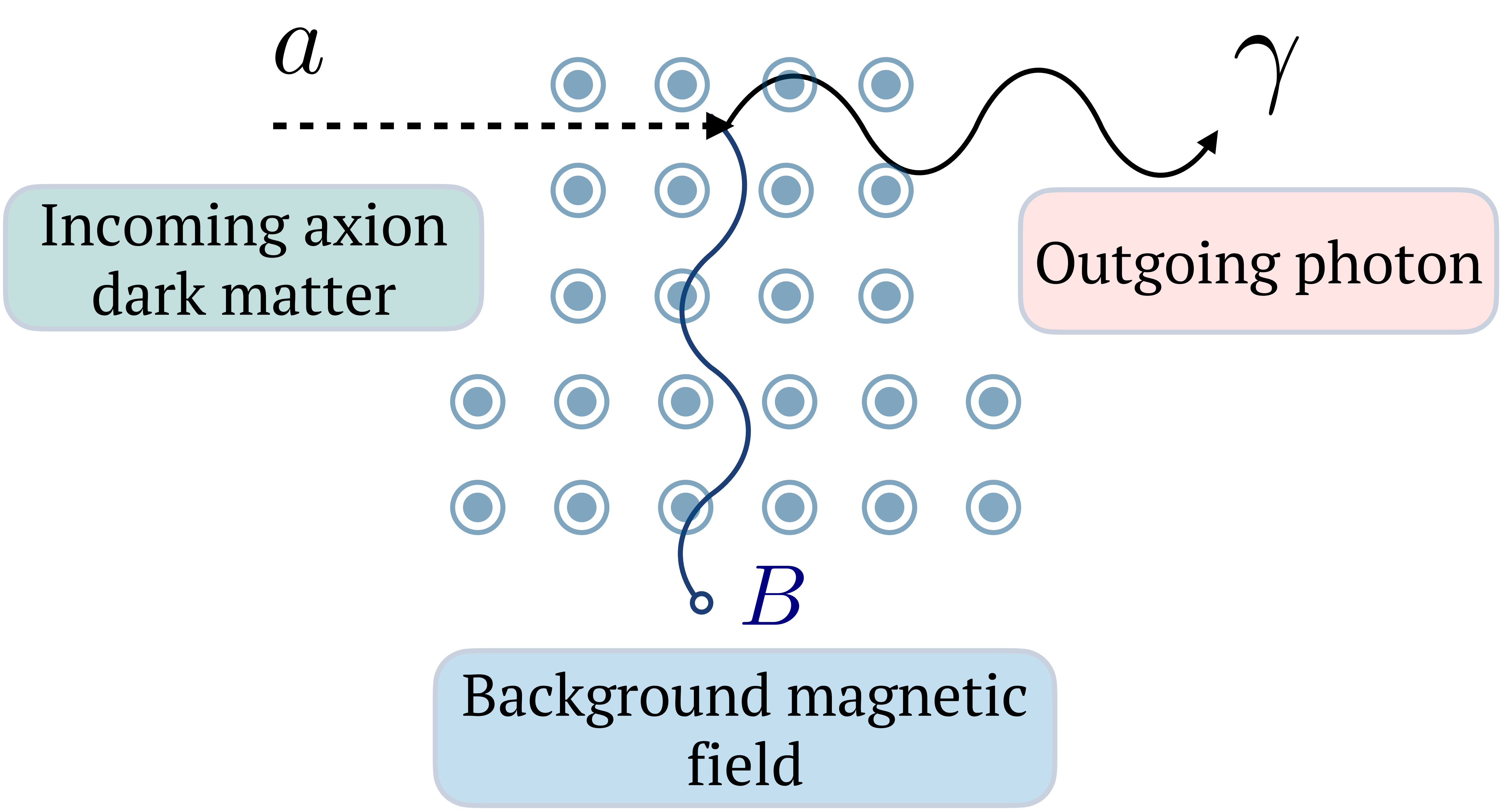
$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2\, B^2 \times (\text{Length})^2$$



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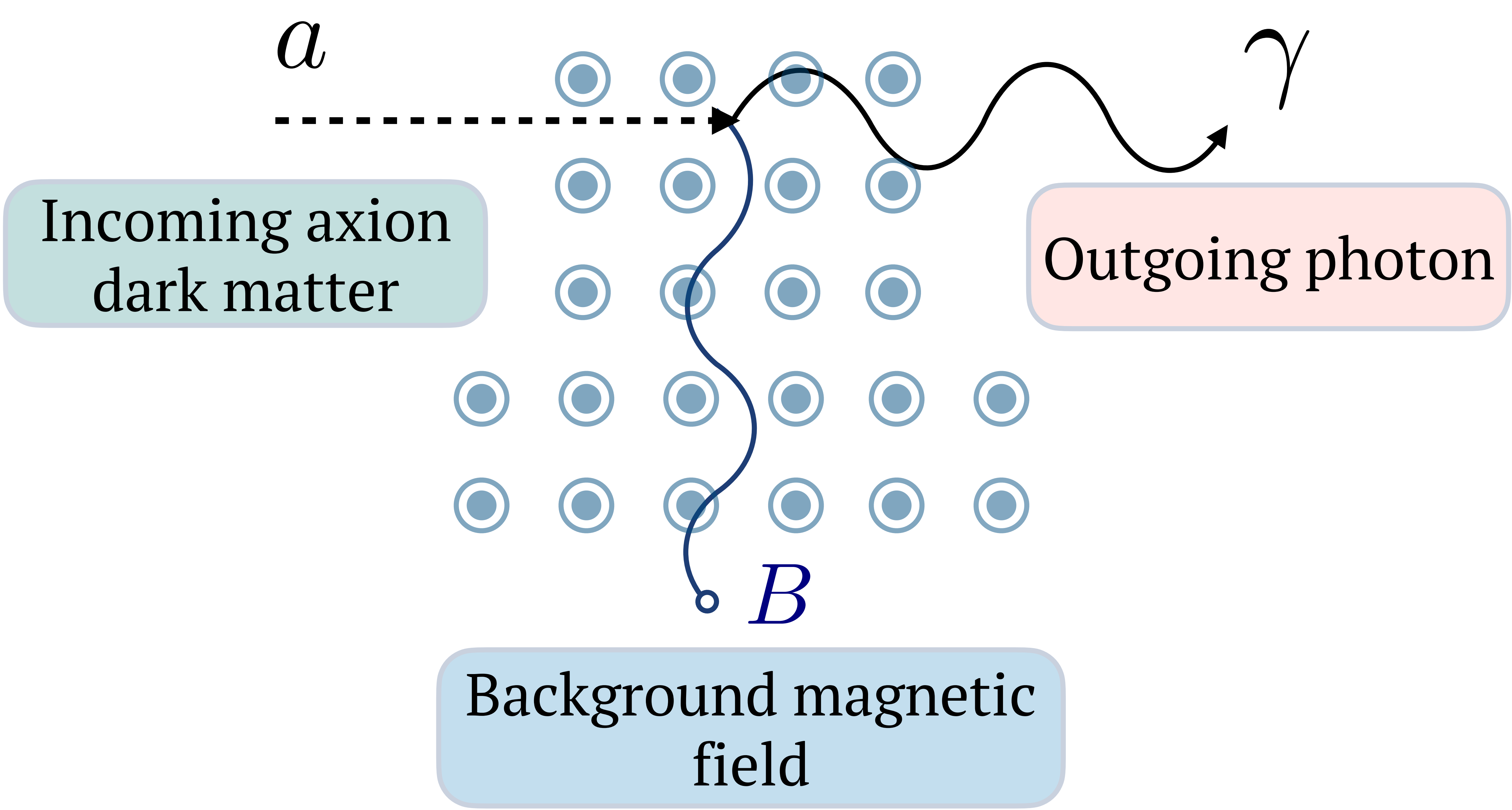

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Large conversion probabilities require:

- Large *magnetic fields*
- Large "*Lengths*"

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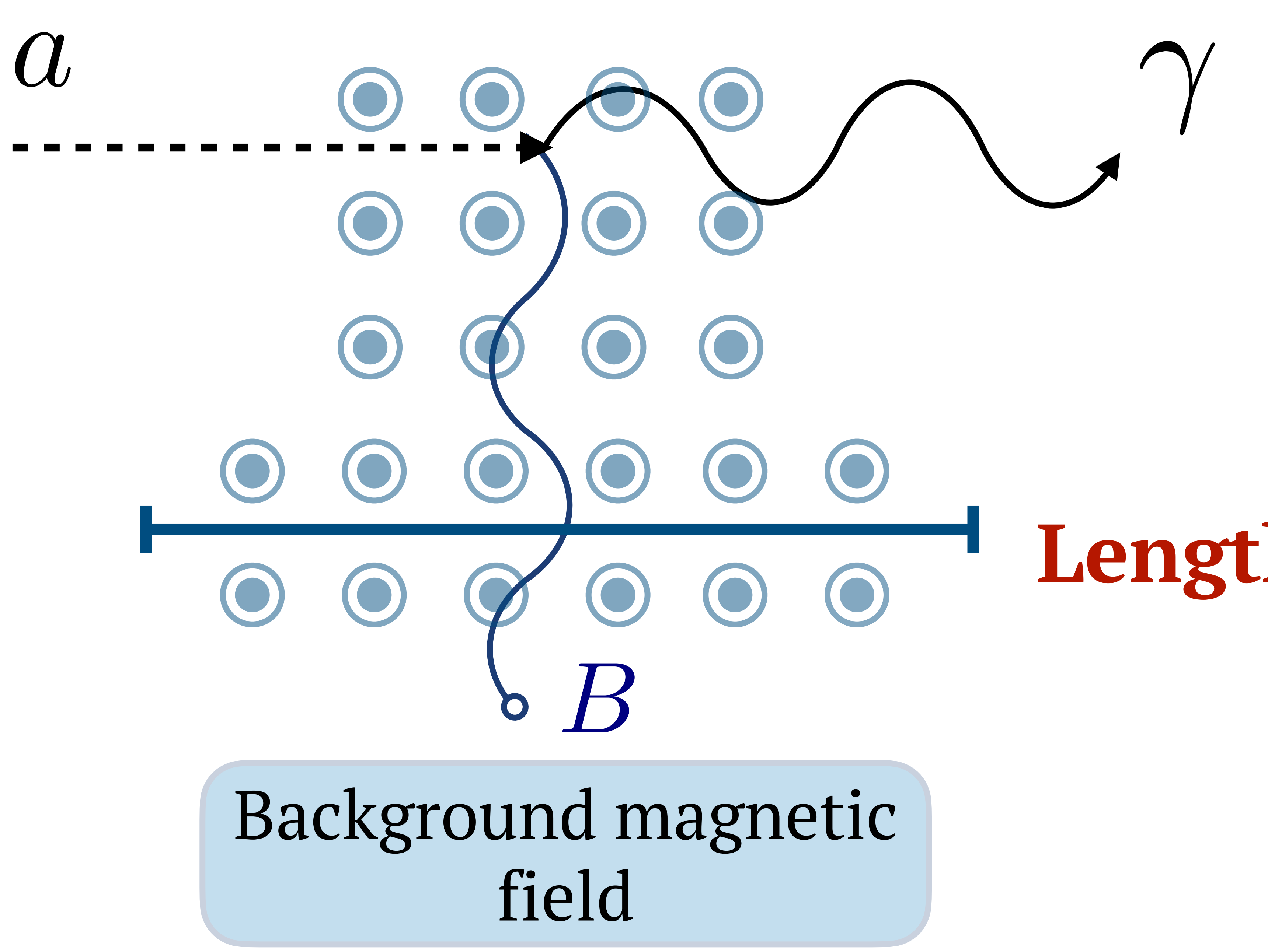

Length of magnetic field

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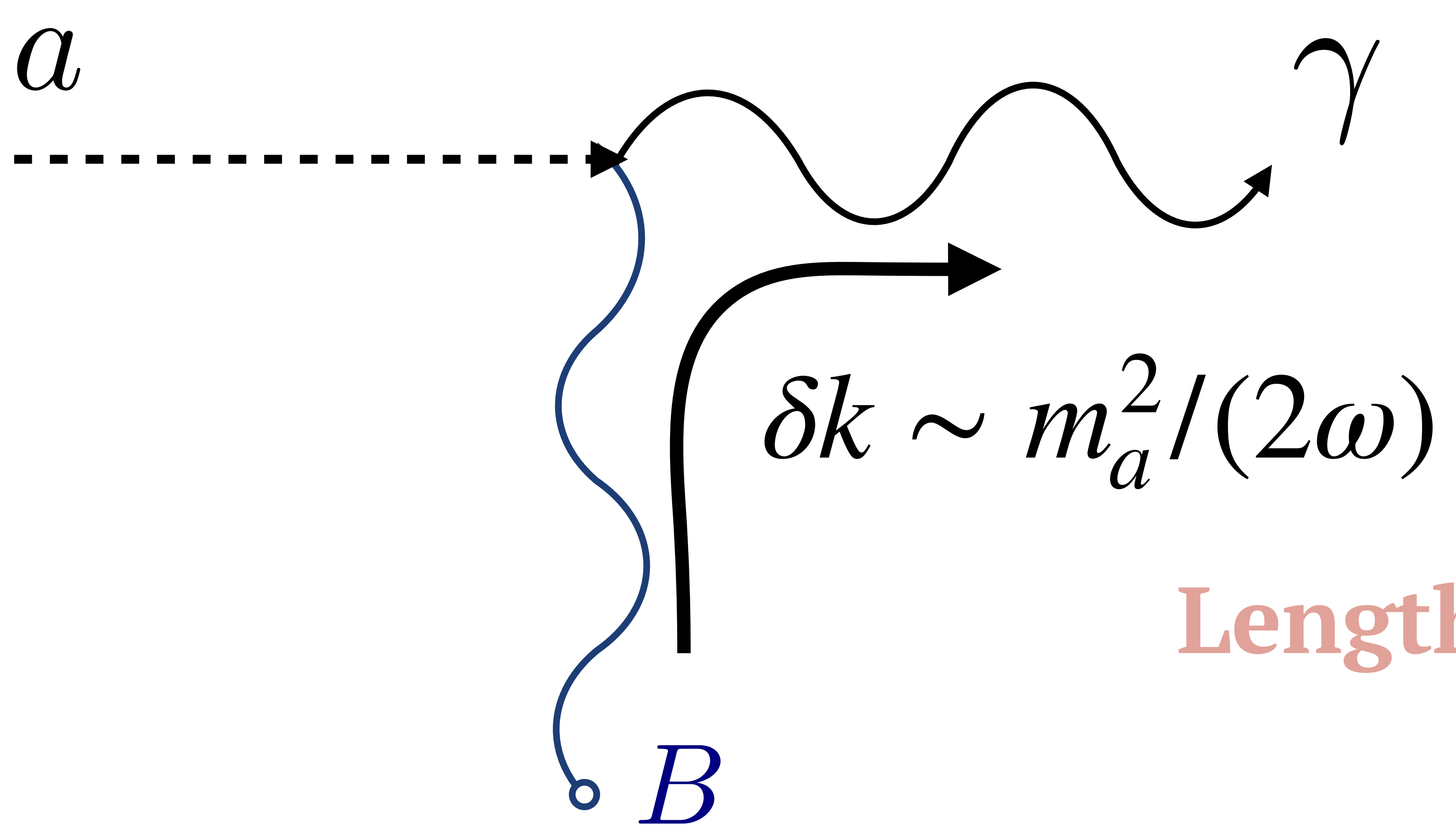

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Length of magnetic field

Length set by momentum transfer from magnetic field

$$L_{\delta k} \sim \delta k^{-1}$$

Axion-photon mixing

High-energy indirect axion searches

Axion-photon mixing

High-energy indirect axion searches

Axion parameter space

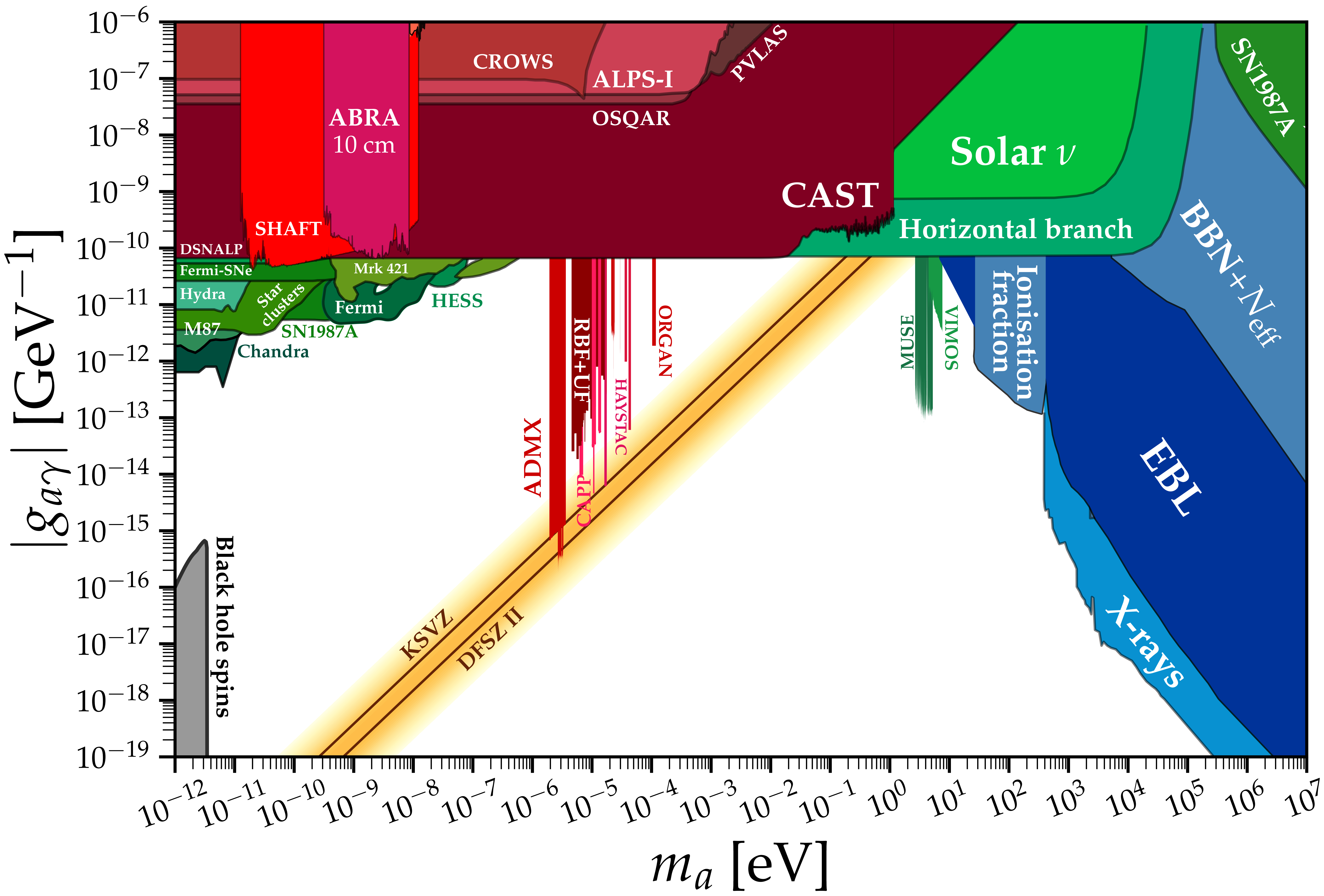

Image credit: Ciaran O'hare
(Slightly out of date — c. 2021)

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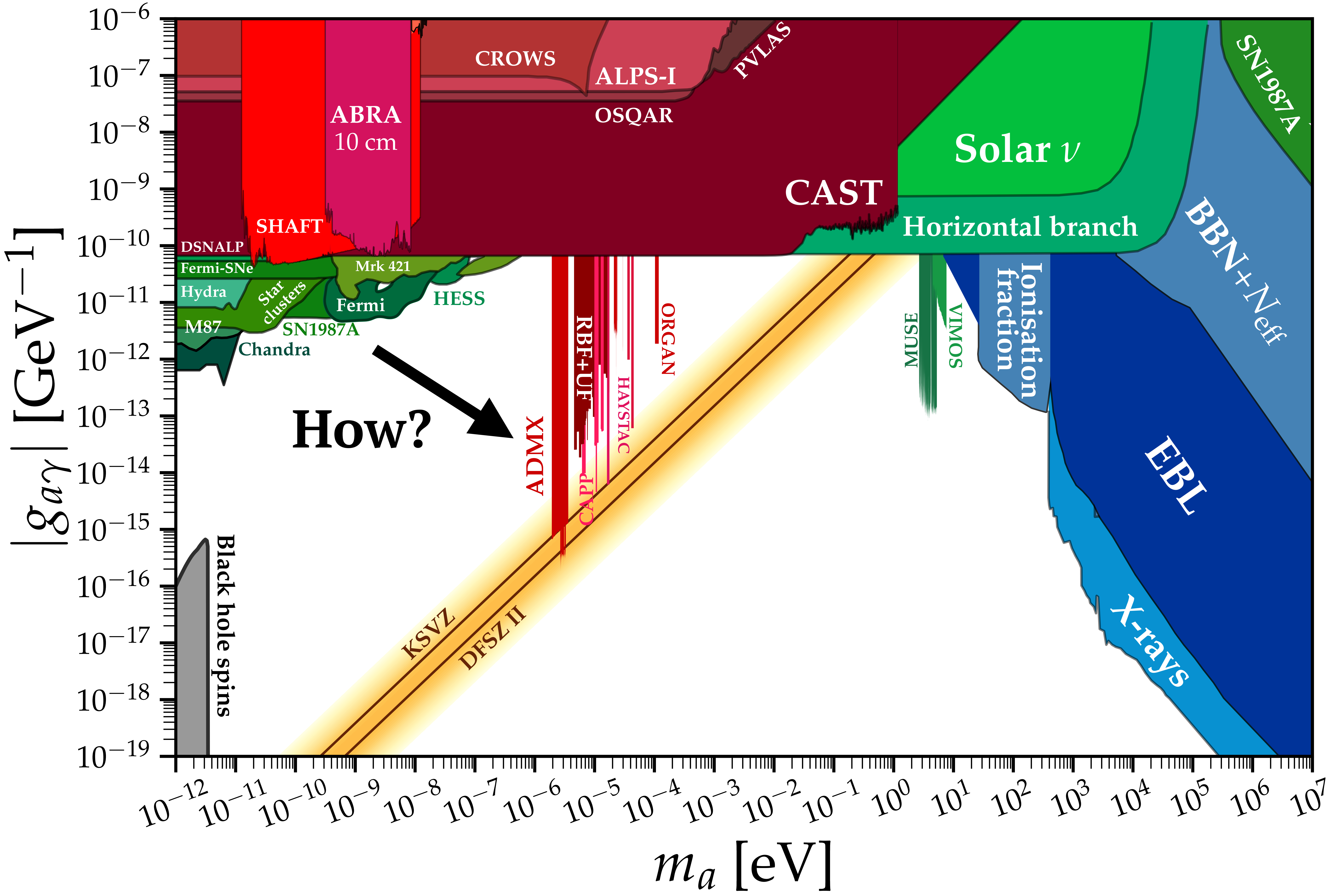

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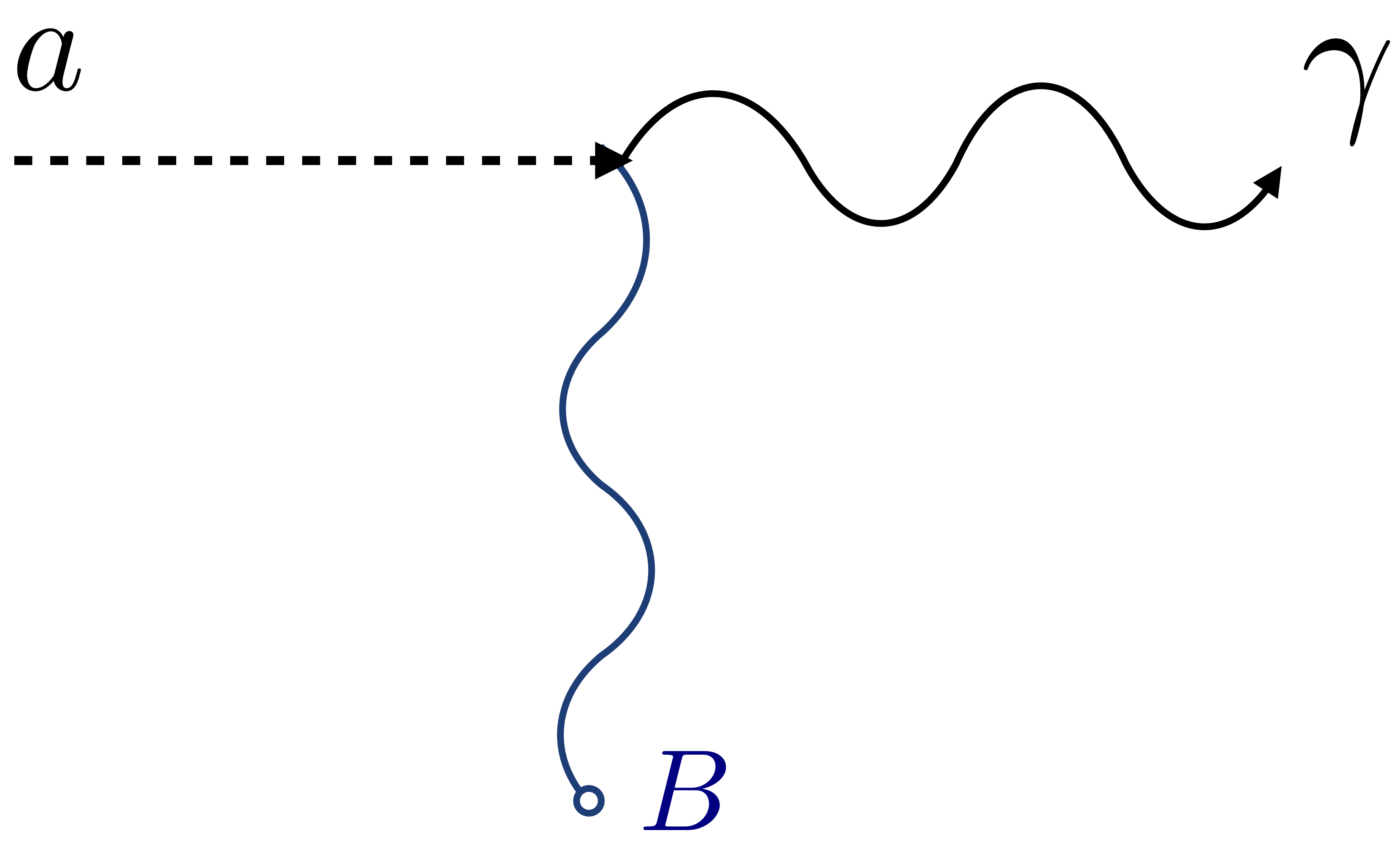

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Momentum mismatch in vacuum

$$\delta k \sim \sqrt{\omega^2 - m_a^2} - \omega$$

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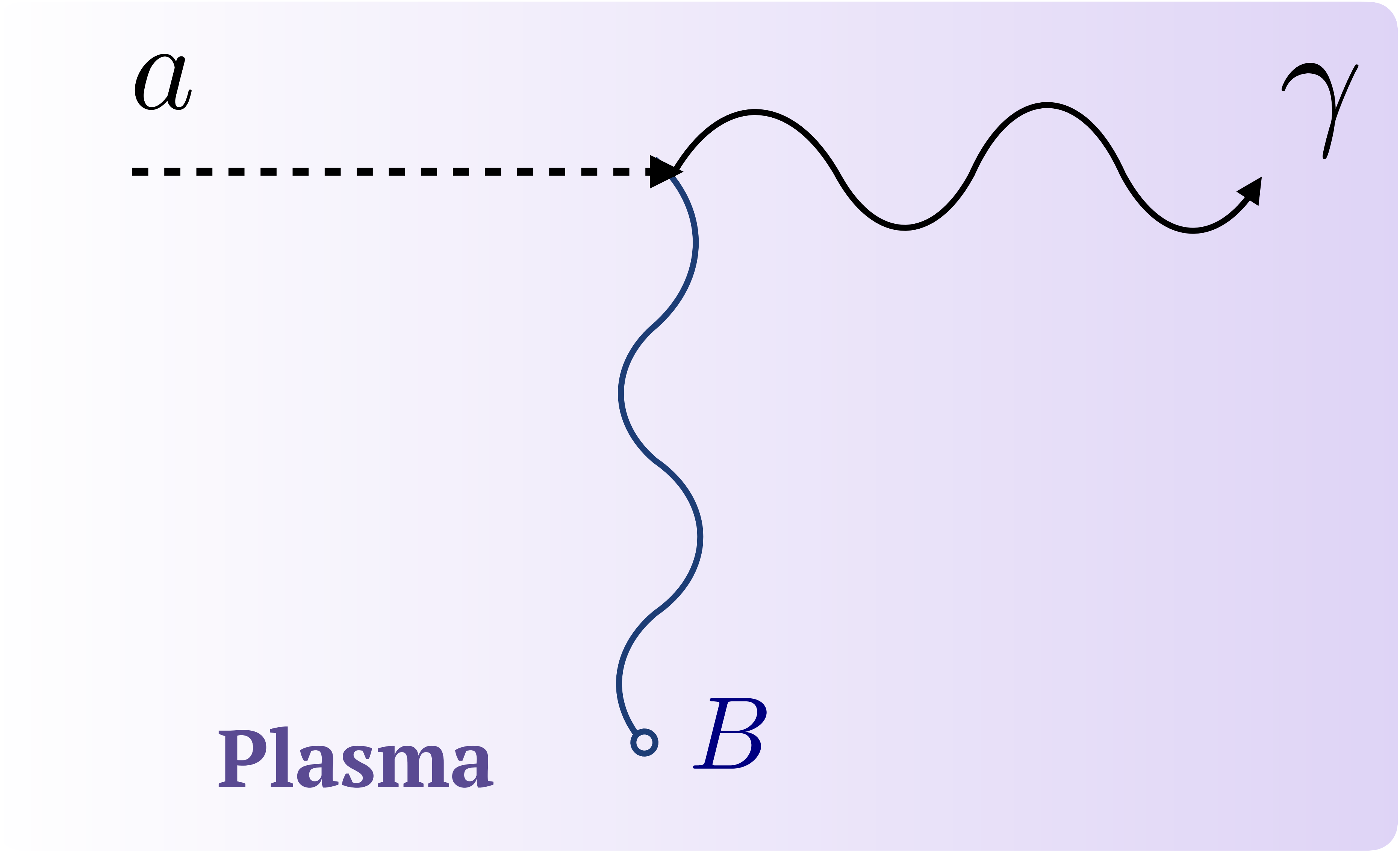

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Momentum mismatch in plasma

$$\delta k \sim \sqrt{\omega^2 - m_a^2} - \sqrt{\omega^2 - \omega_p^2}$$

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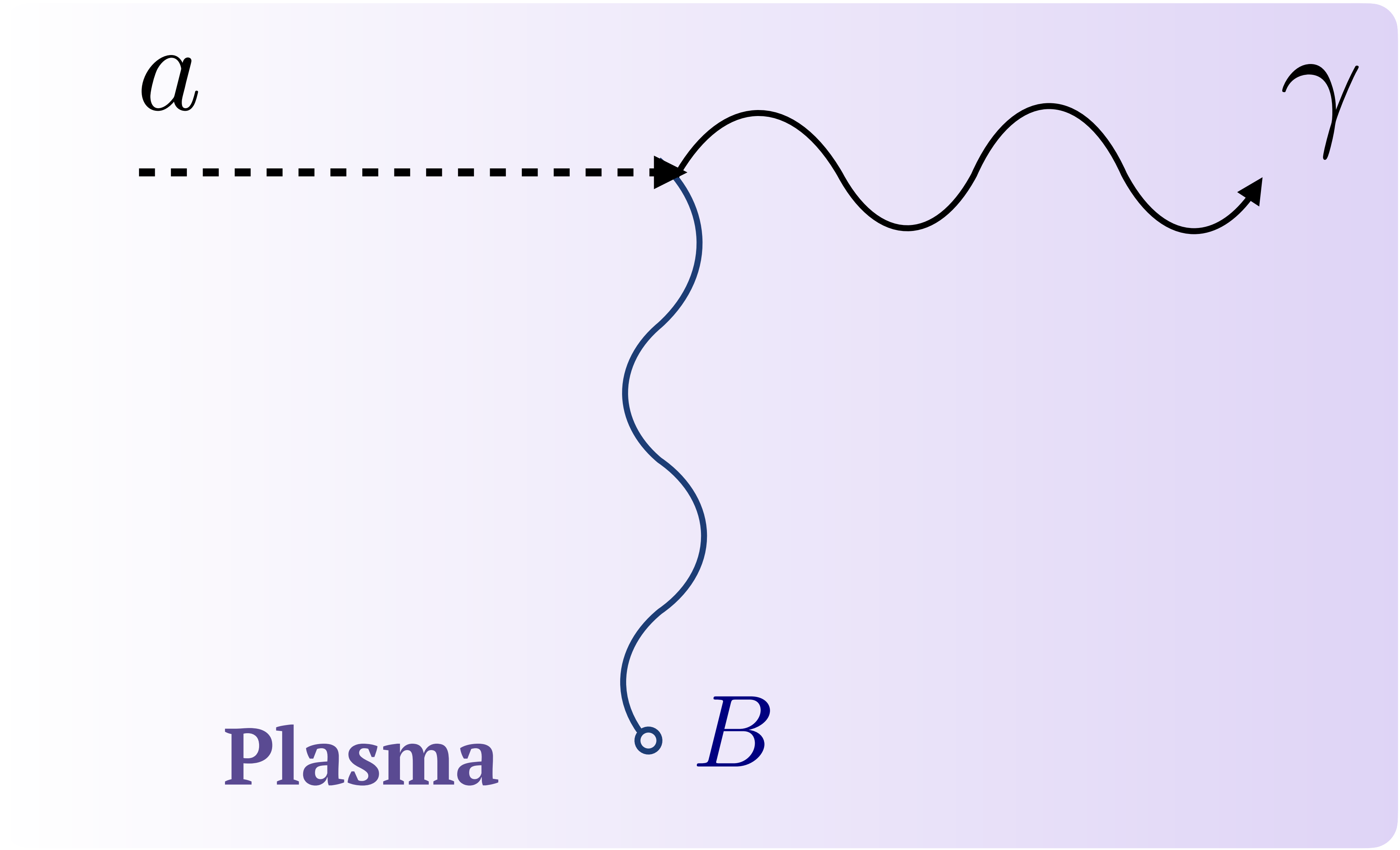

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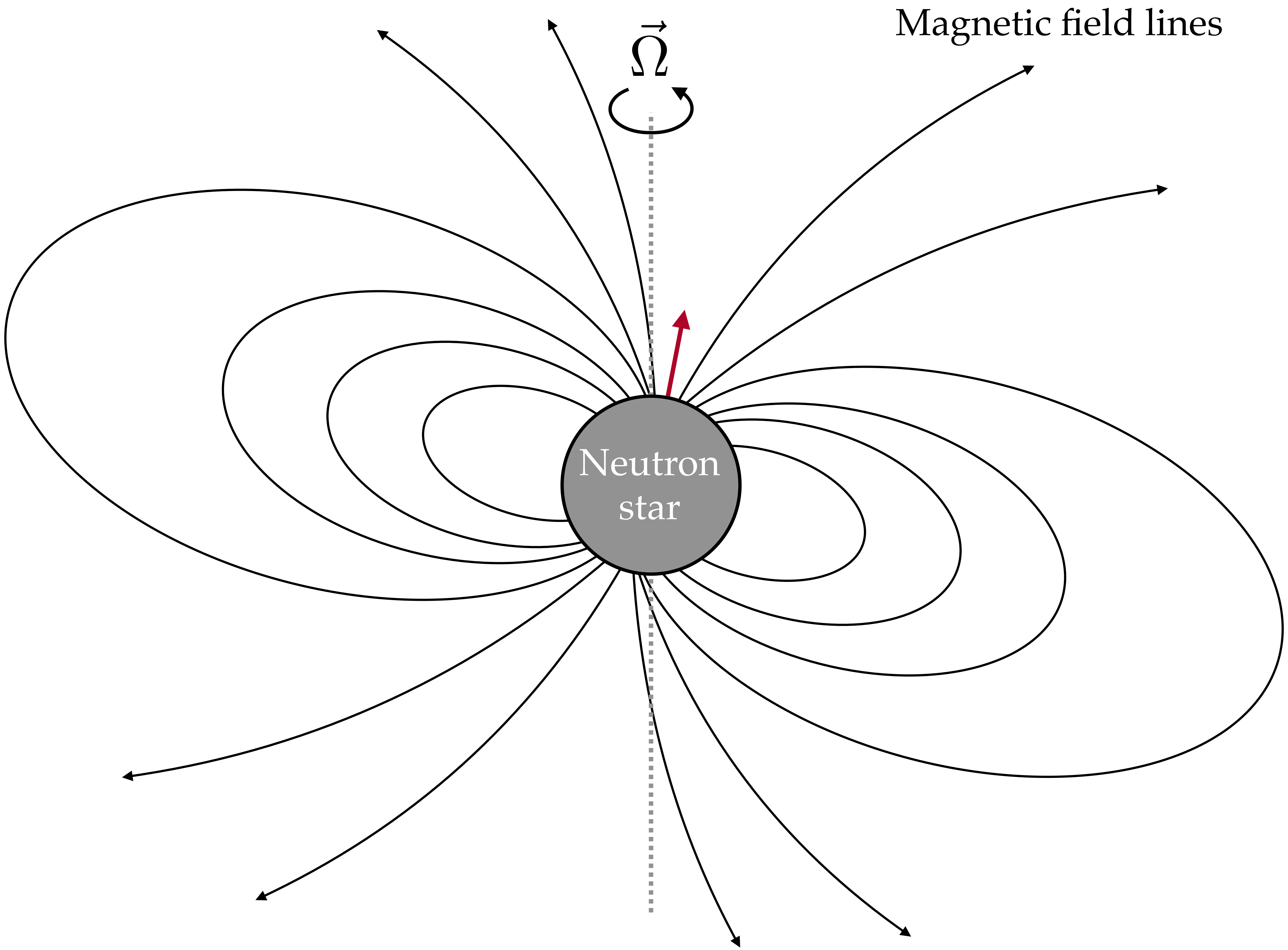
Ideal environments: ***Large coherent magnetic fields and spatially varying plasmas***

Neutron star magnetospheres



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

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

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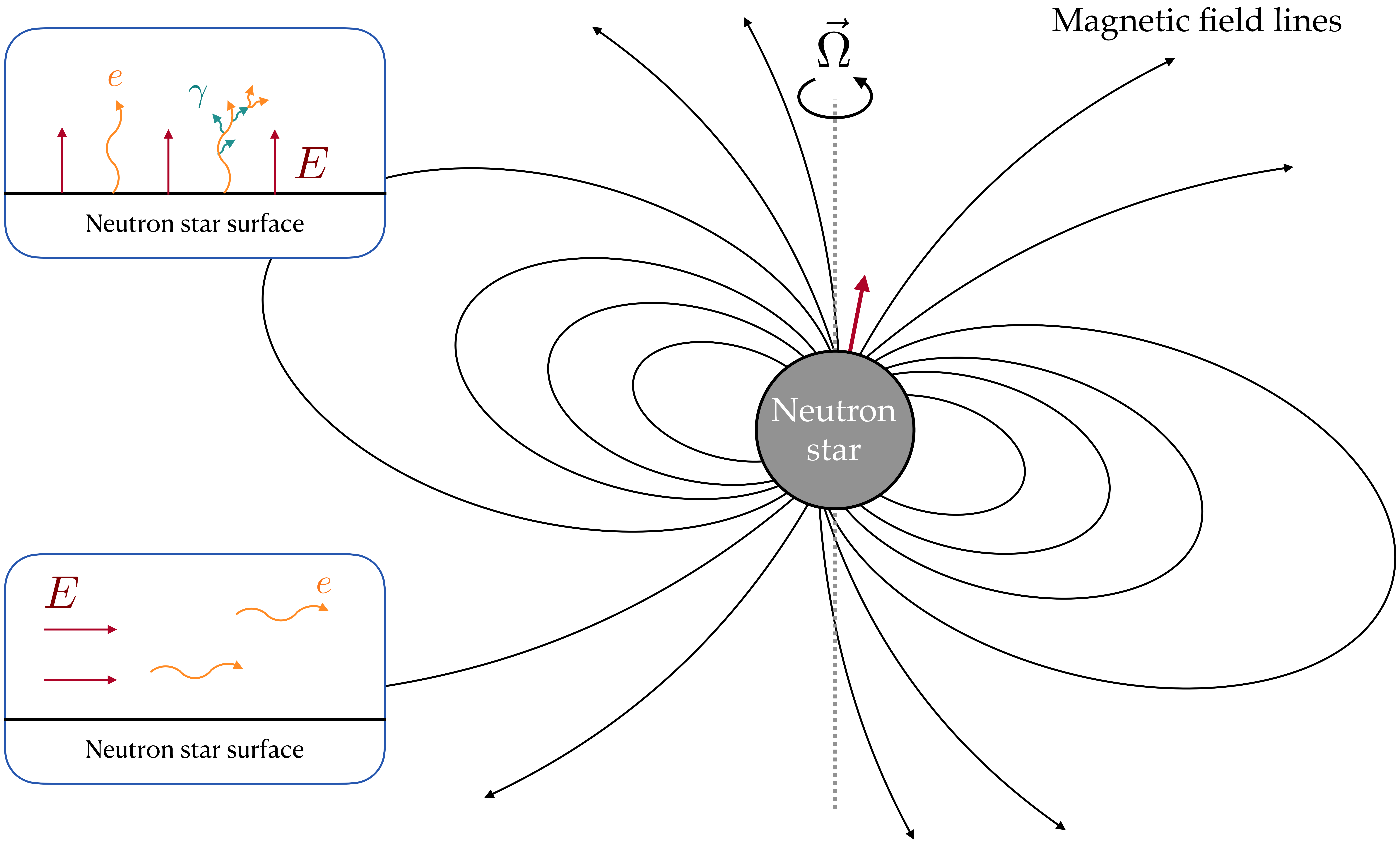

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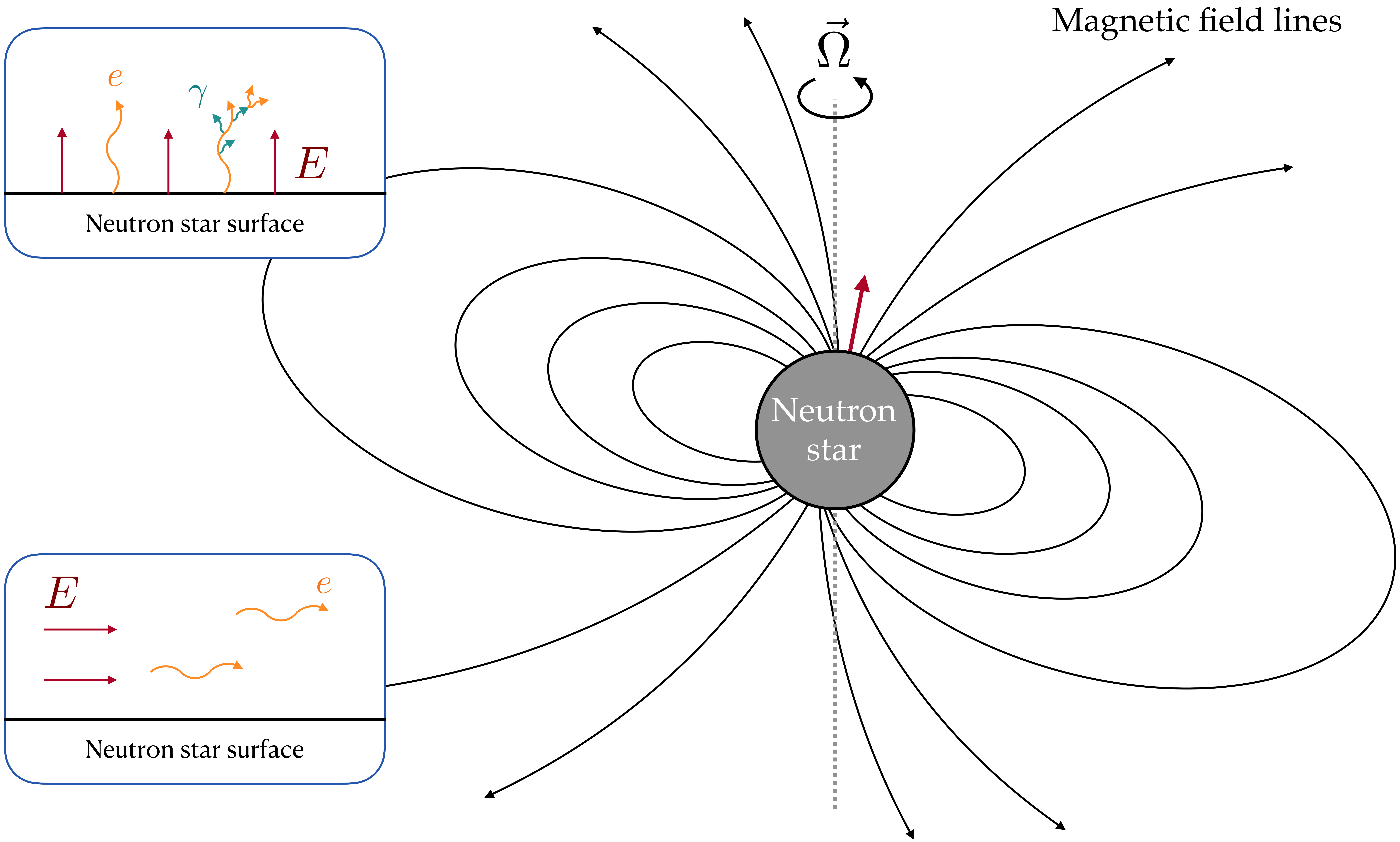

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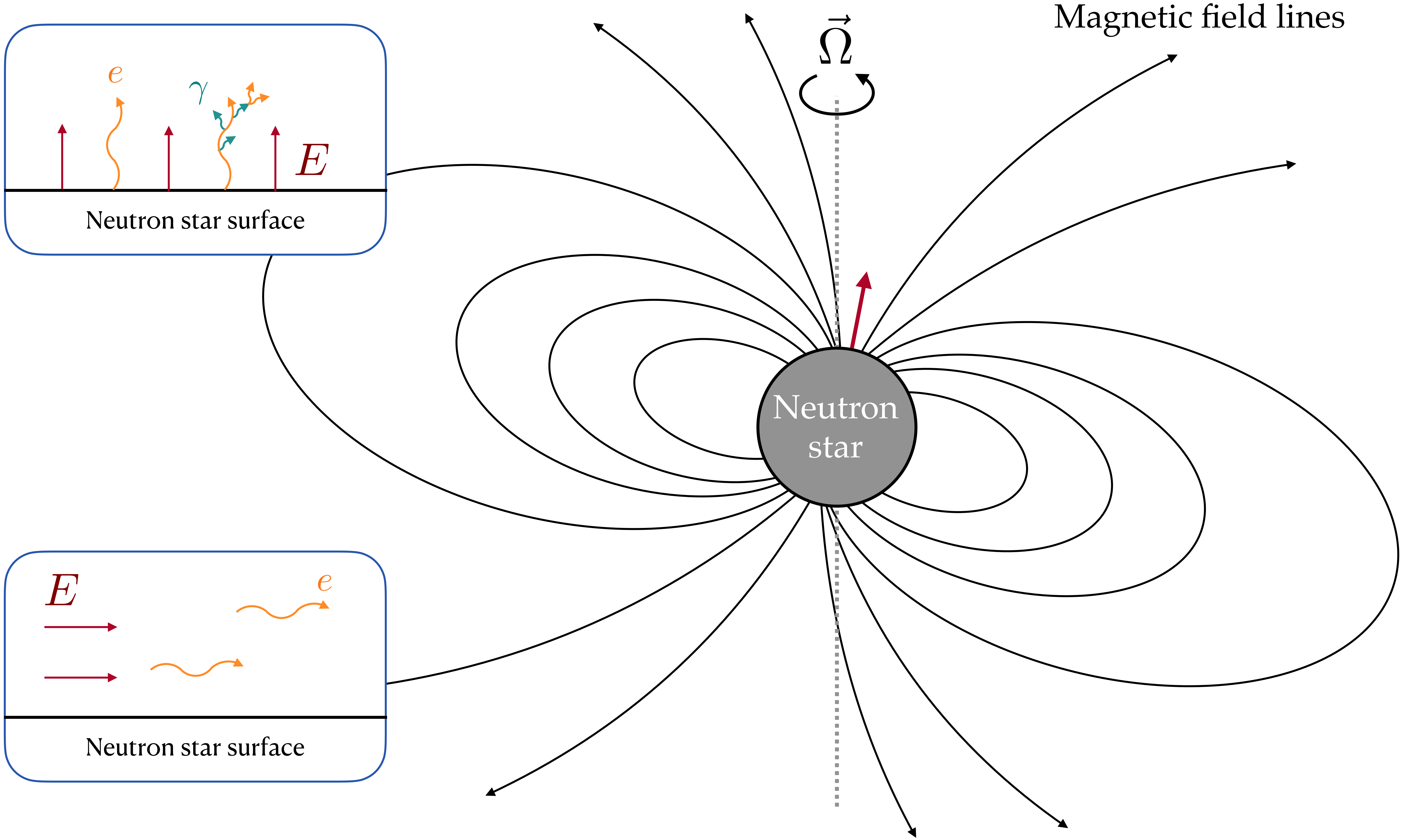
$$\vec{E} \cdot \vec{B} = 0$$

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

Goldreich-Julian Model
(Force-free solution)

Goldreich & Julian 1969

Neutron star magnetospheres



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

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

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

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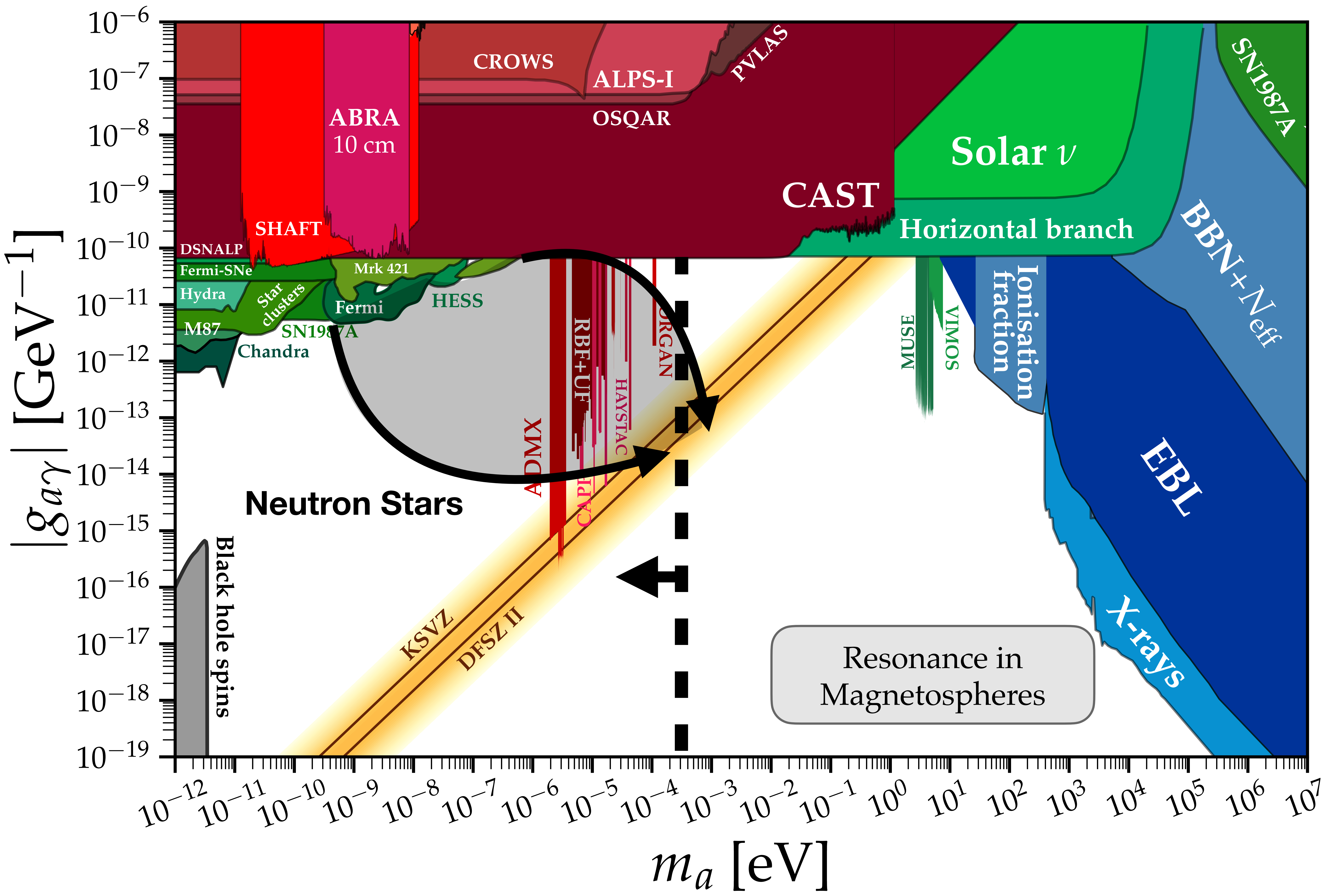

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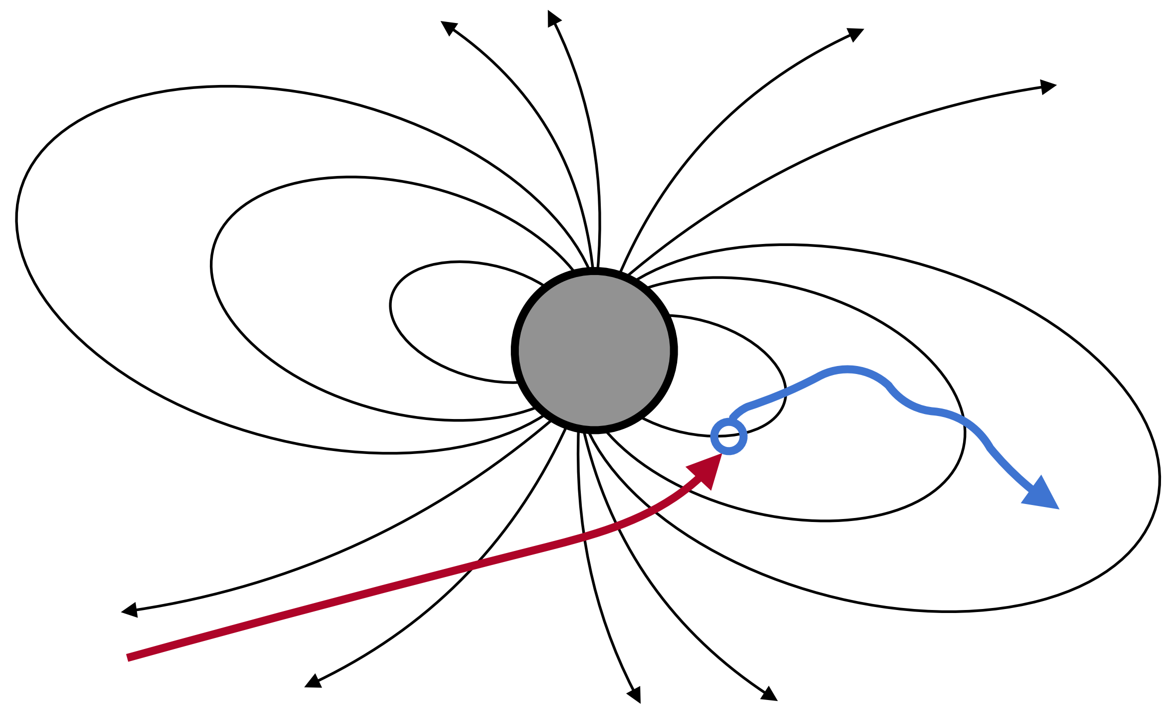
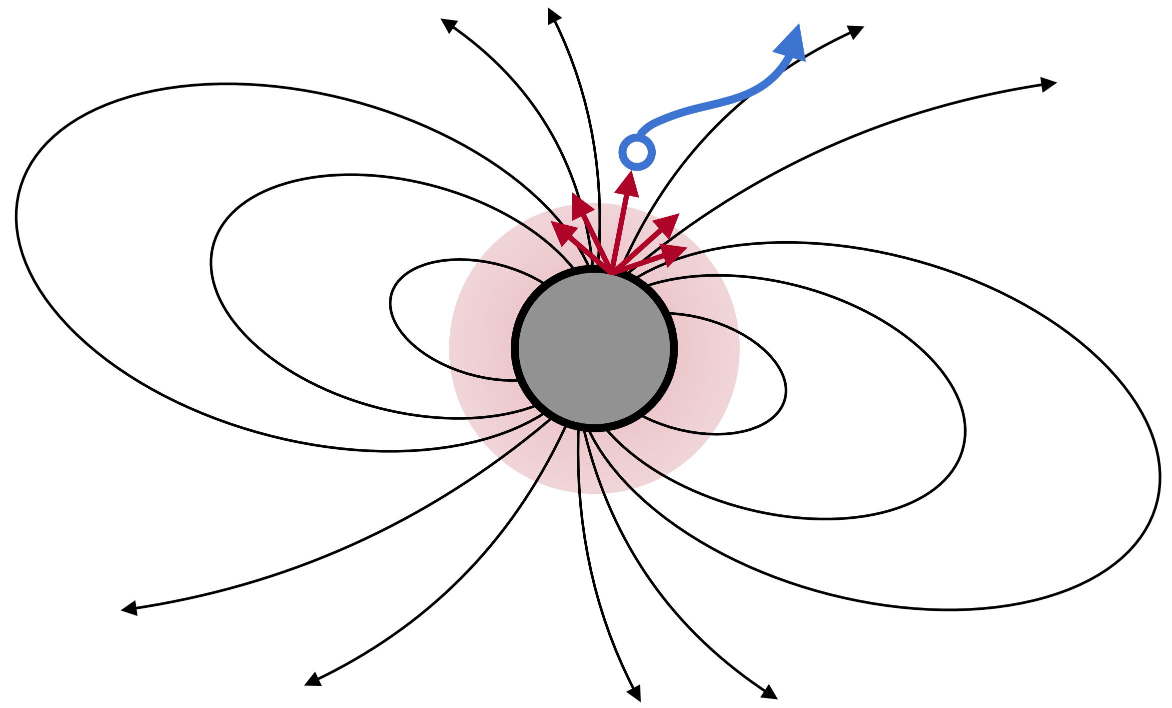
Neutron stars as axion labs



Part 1: Resonant production of radio photons from axion dark matter

See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), Thejmsland, McDonald, **SJW** (To appear), **SJW** et al (To appear), McDonald & **SJW** (To appear),…



Part 2: Axion production from pulsar pair cascades

Prabhu (2021), Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022), Noordhuis, Prabhu, **SJW**, Weniger (Appearing soon), Caputo, Philippov, **SJW** (Appearing soon)

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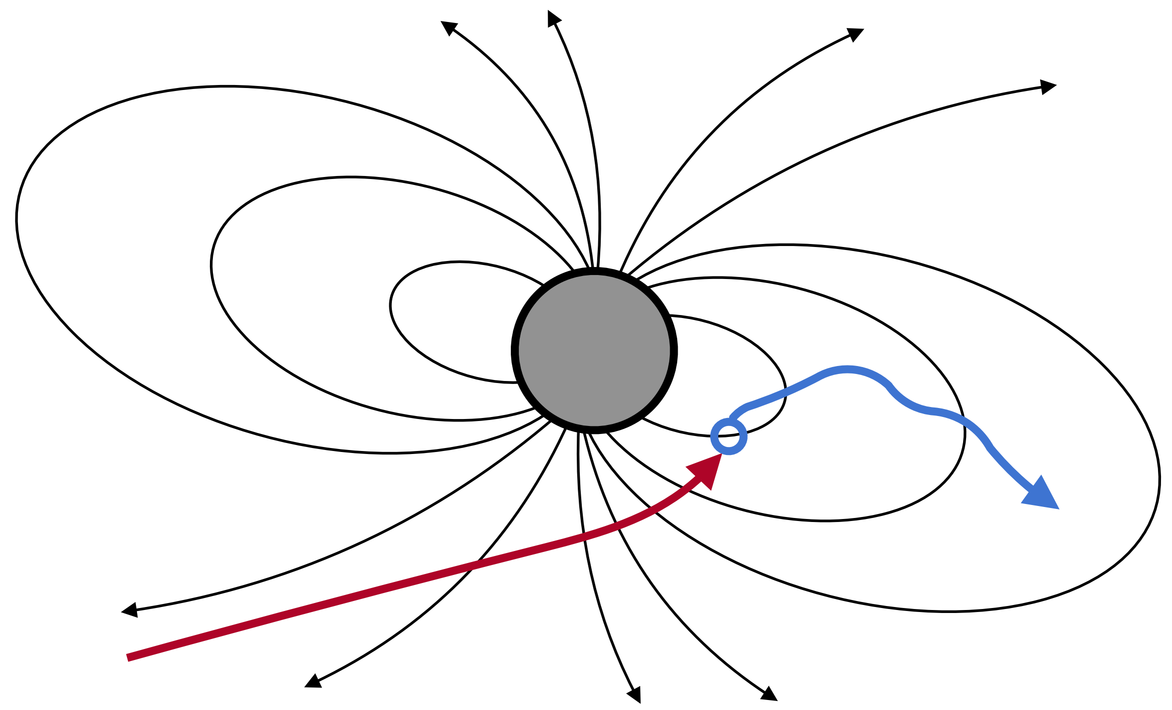

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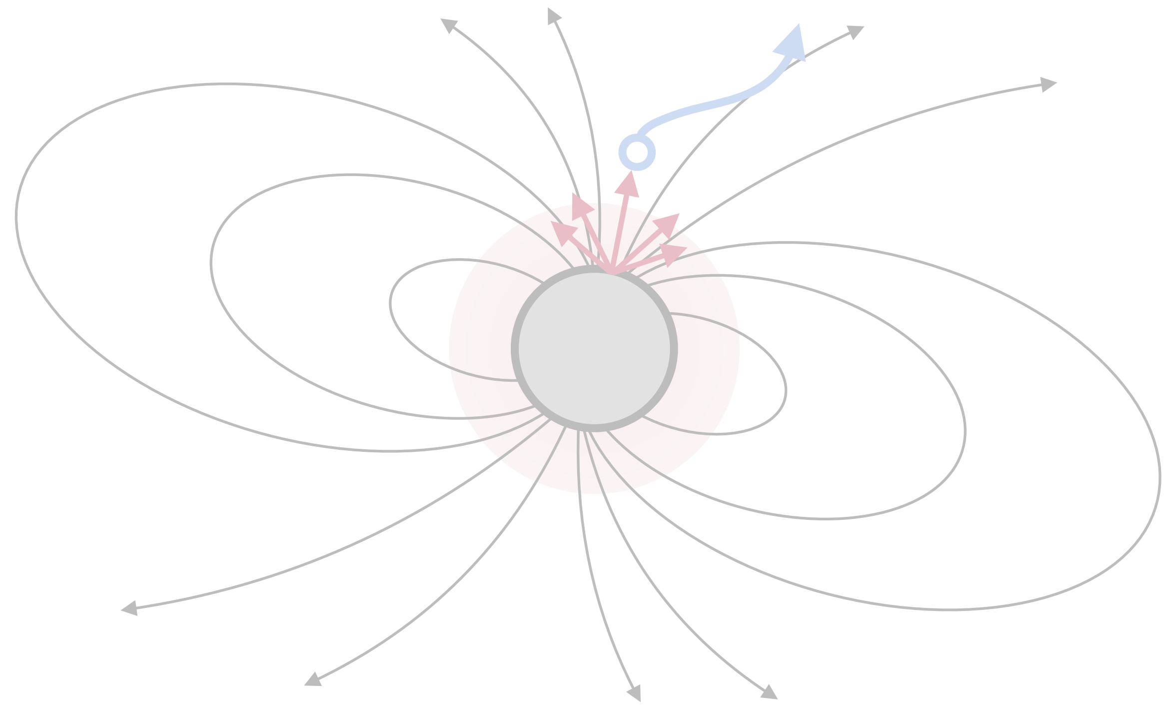

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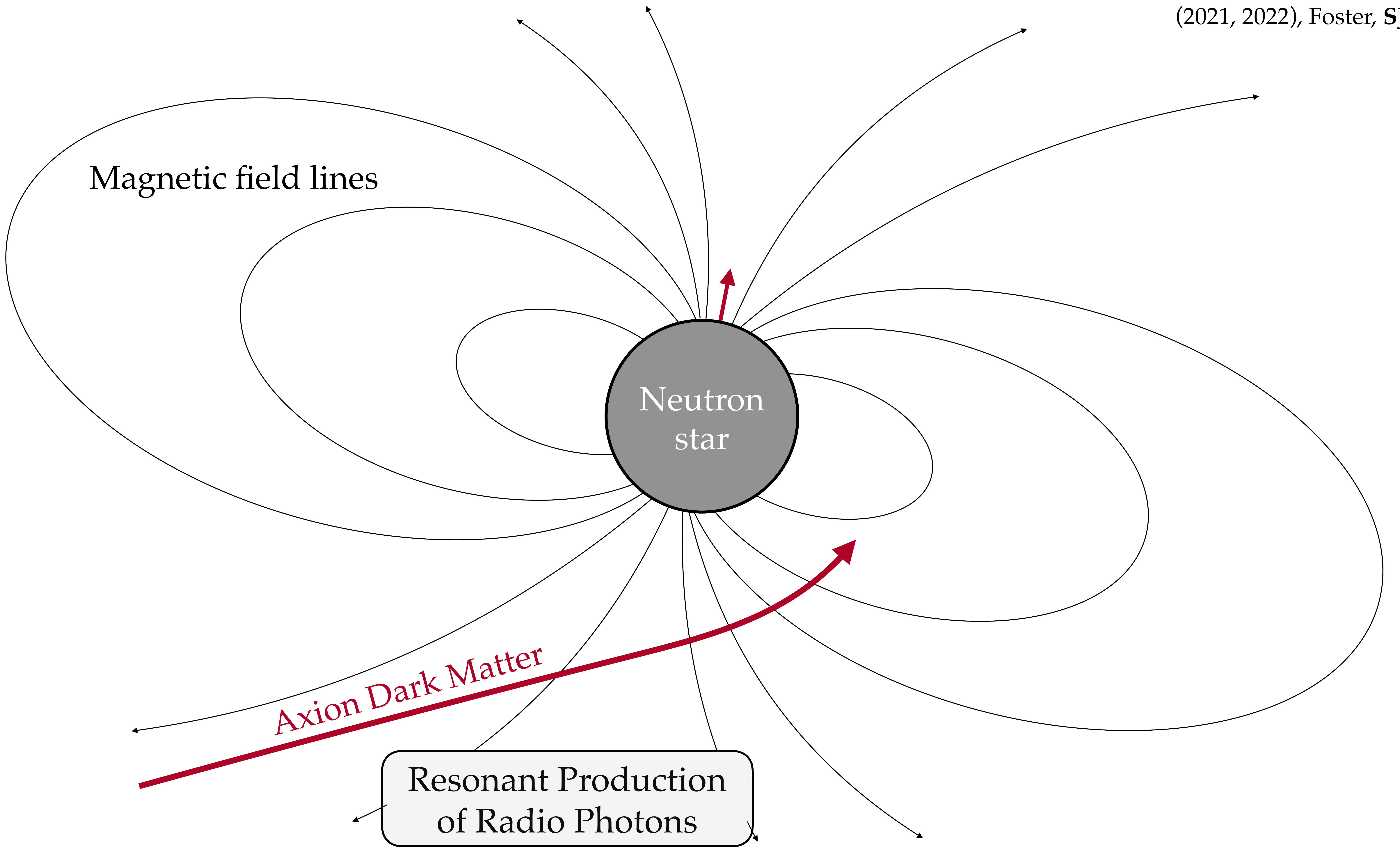

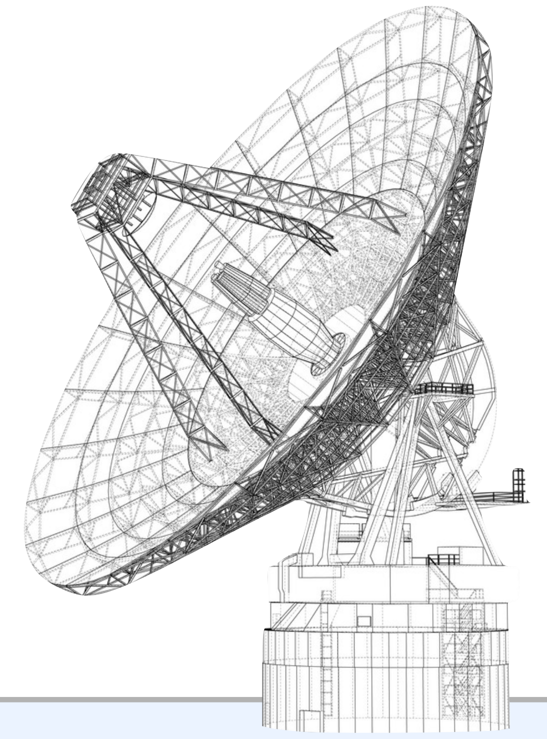

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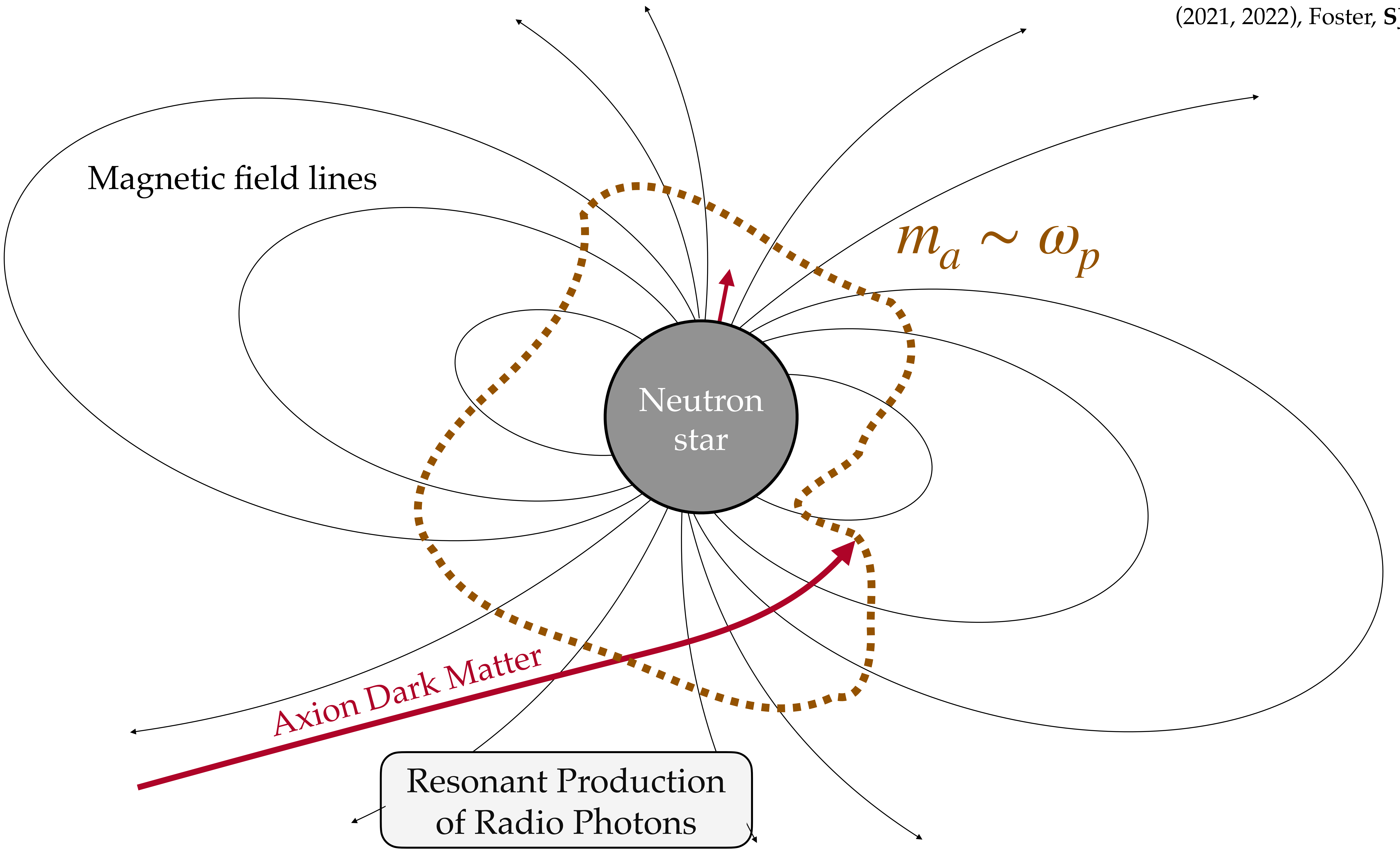

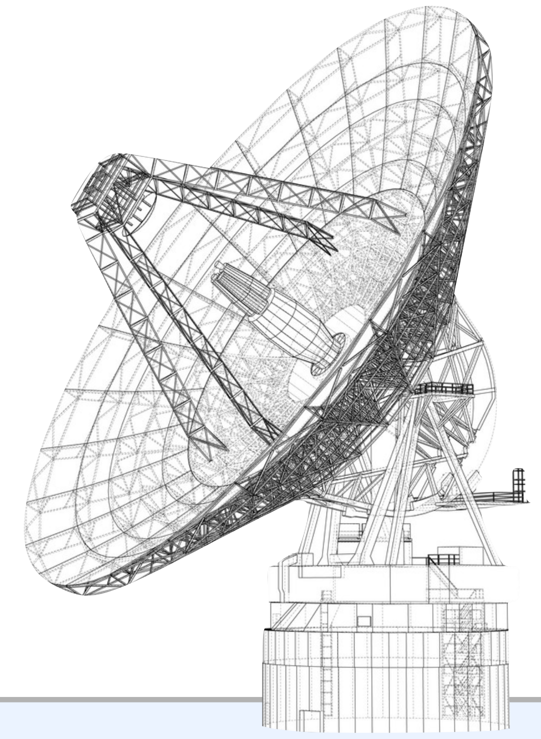

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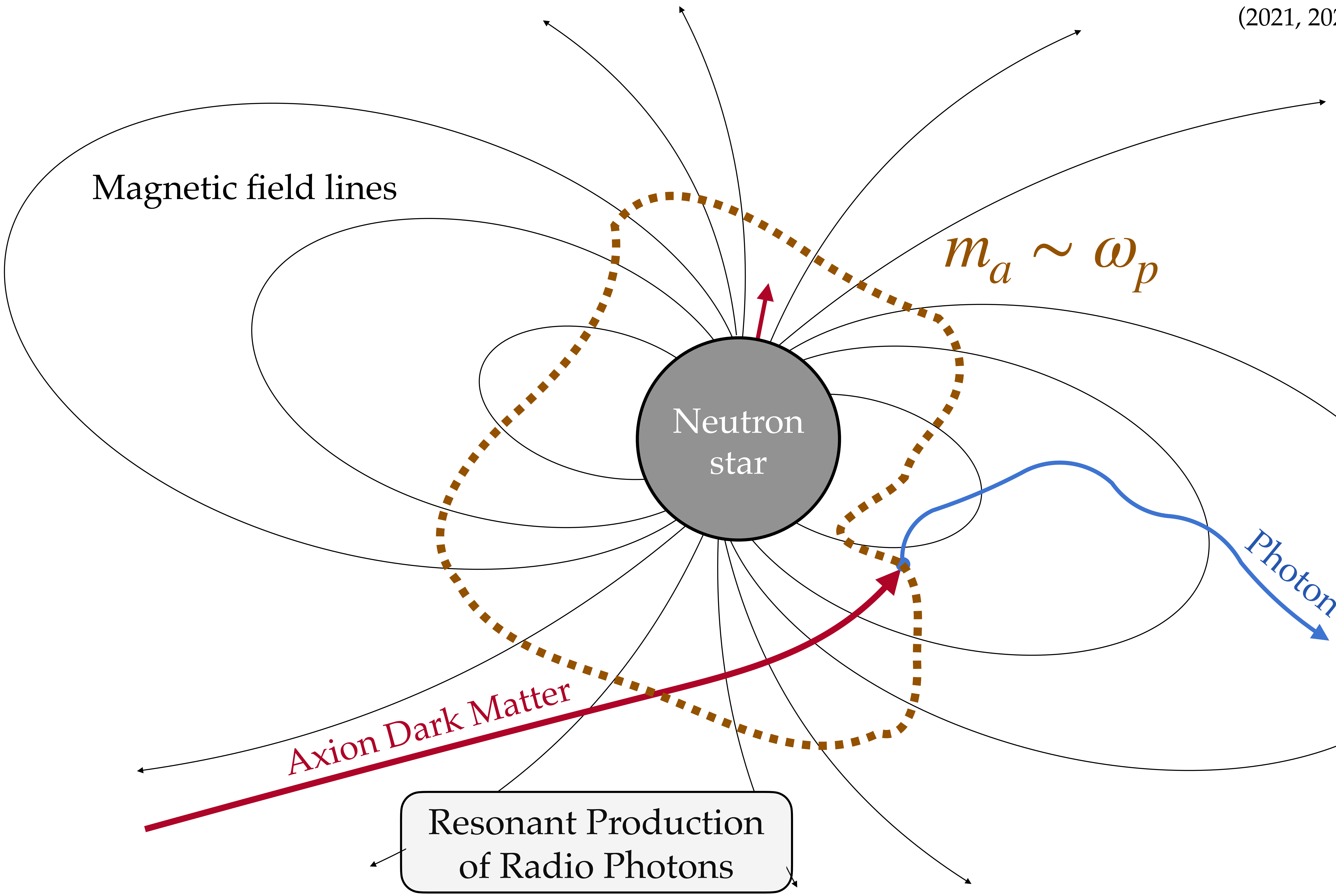
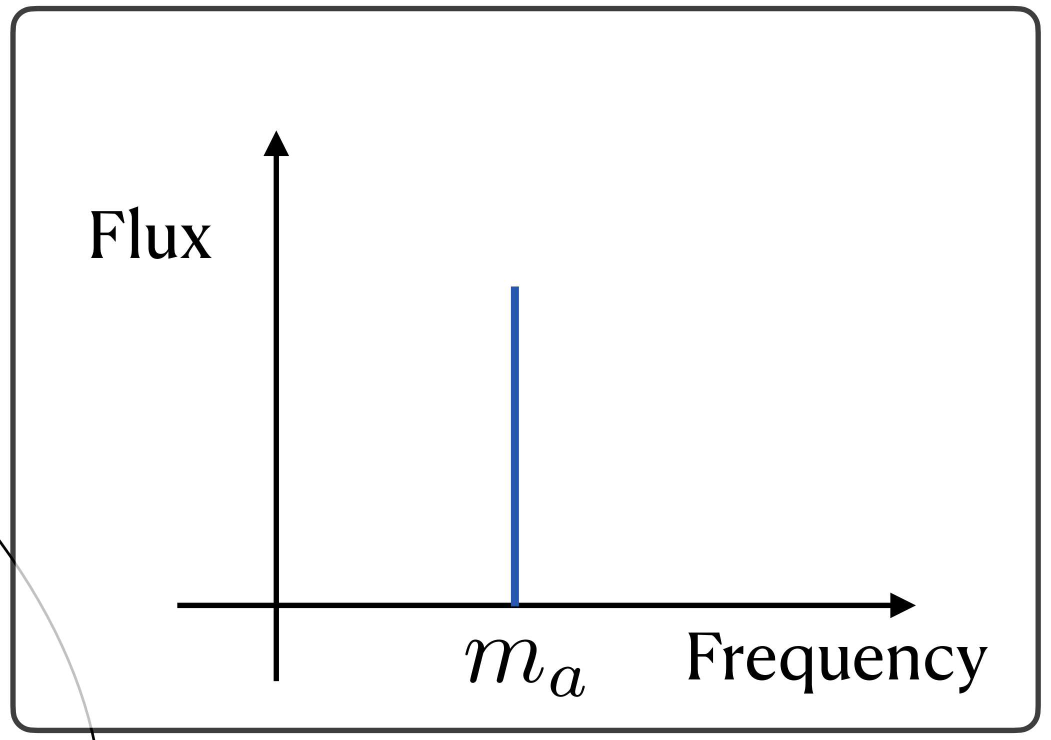
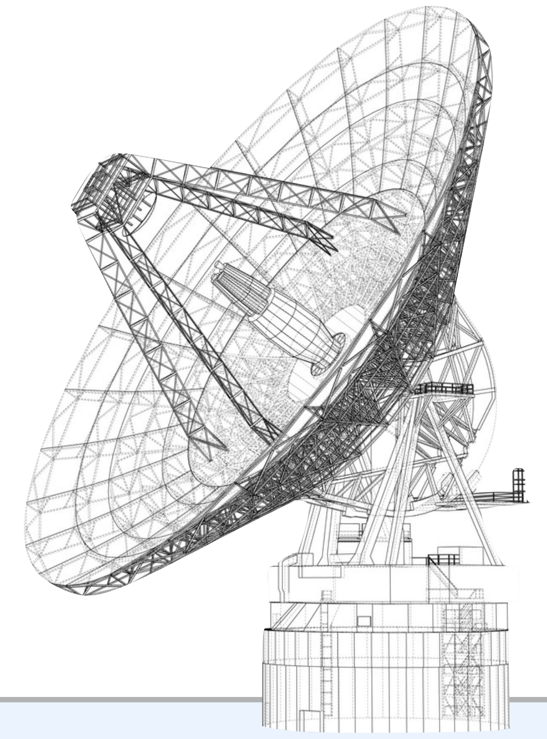




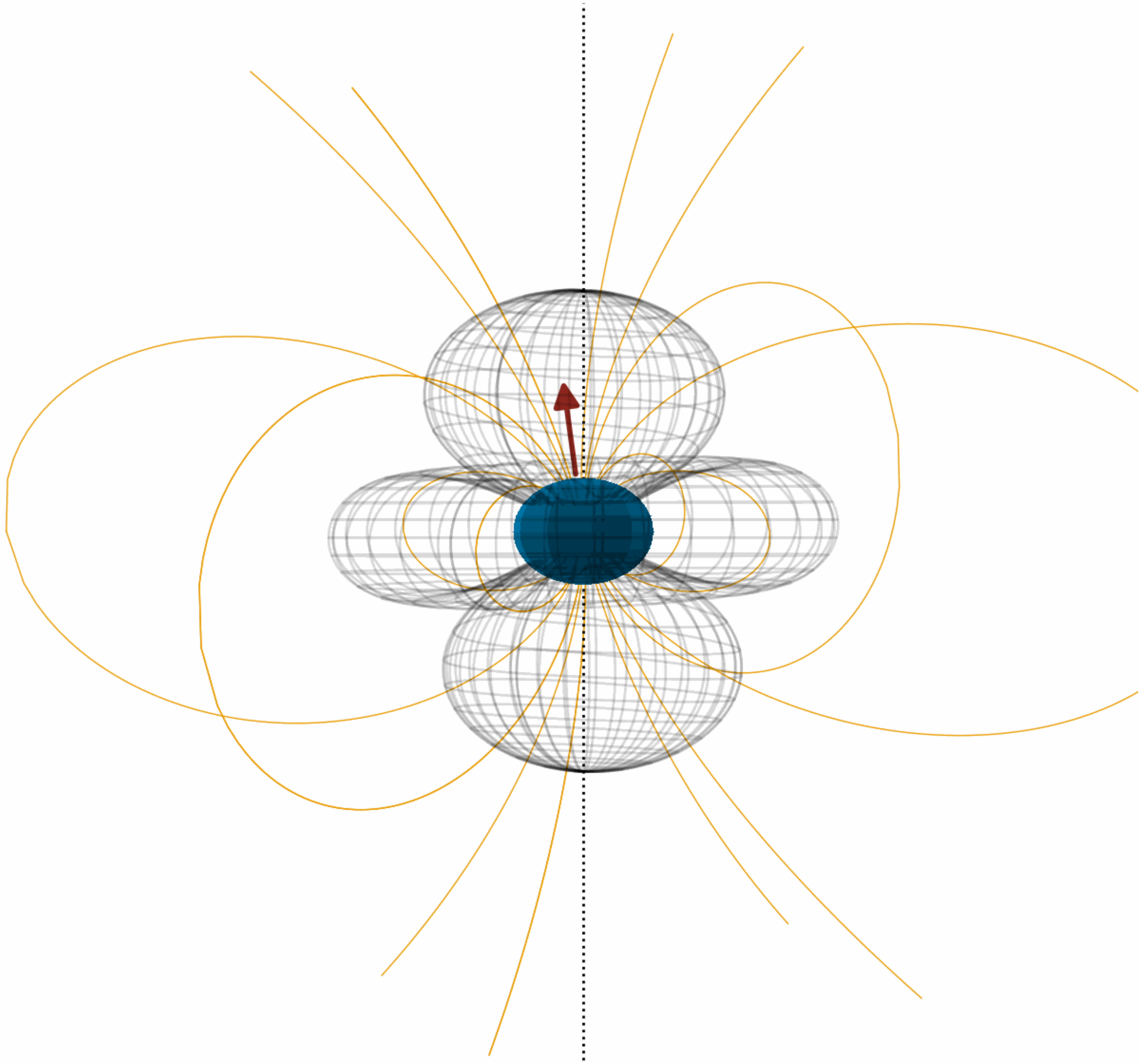


Photon production from axion dark matter

Step 1: Define plasma structure of magnetosphere

<u>*Resonant Conversion*</u>

Location: $m_a \sim \omega_p$
Efficiency: $(\partial\omega_p)^{-1}$



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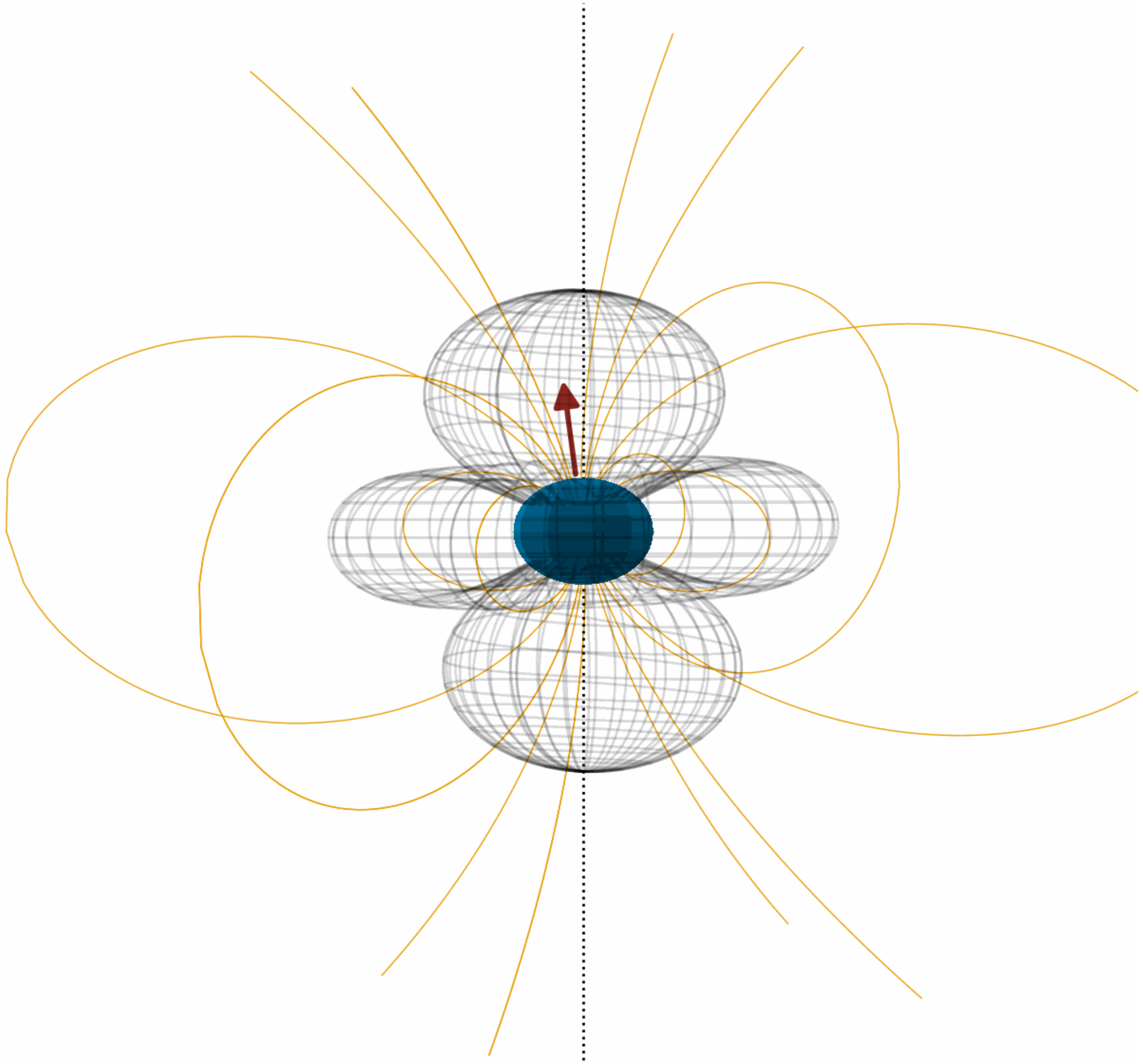

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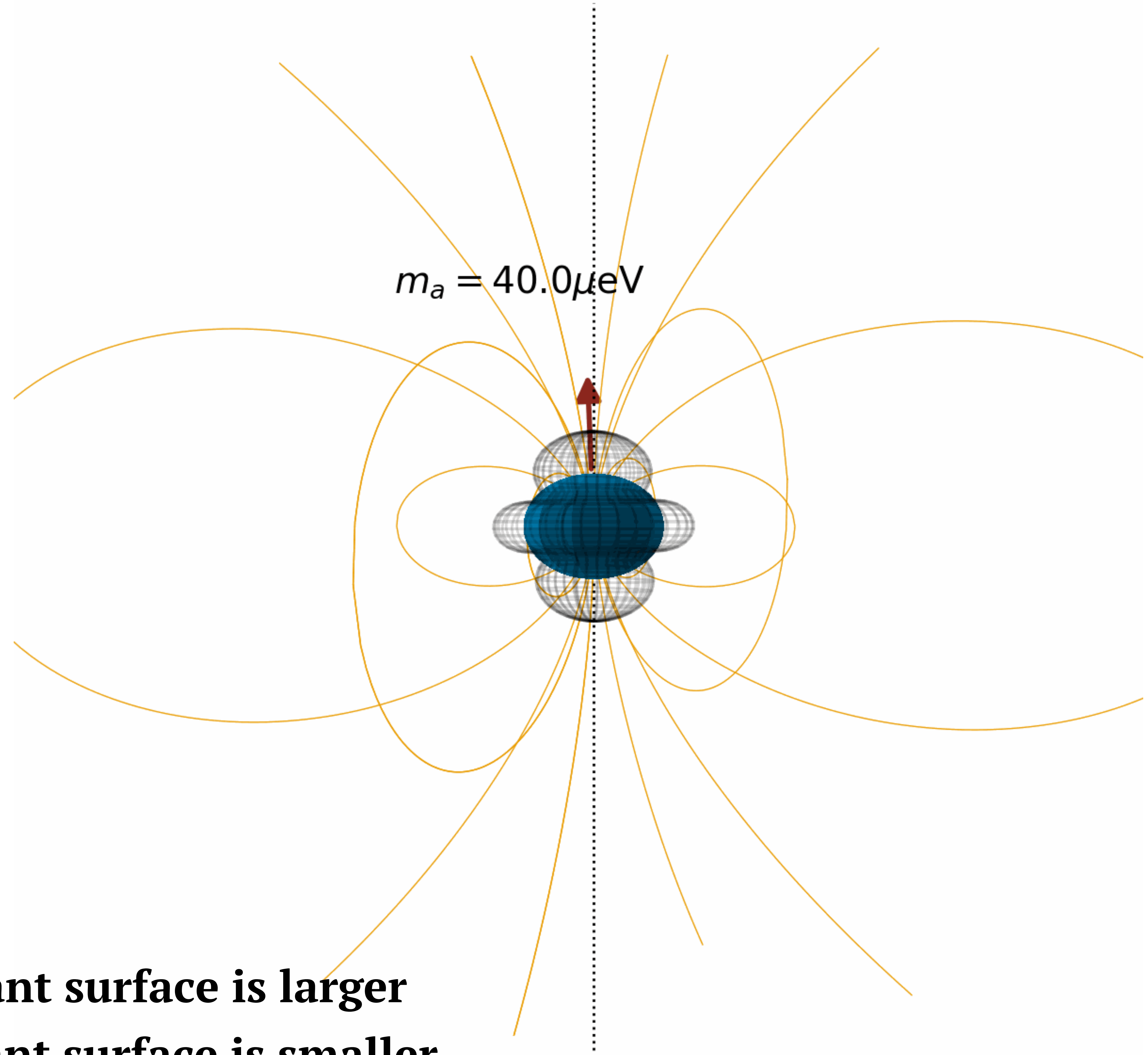

Smaller axion mass → resonant surface is larger

Larger axion mass → resonant surface is smaller

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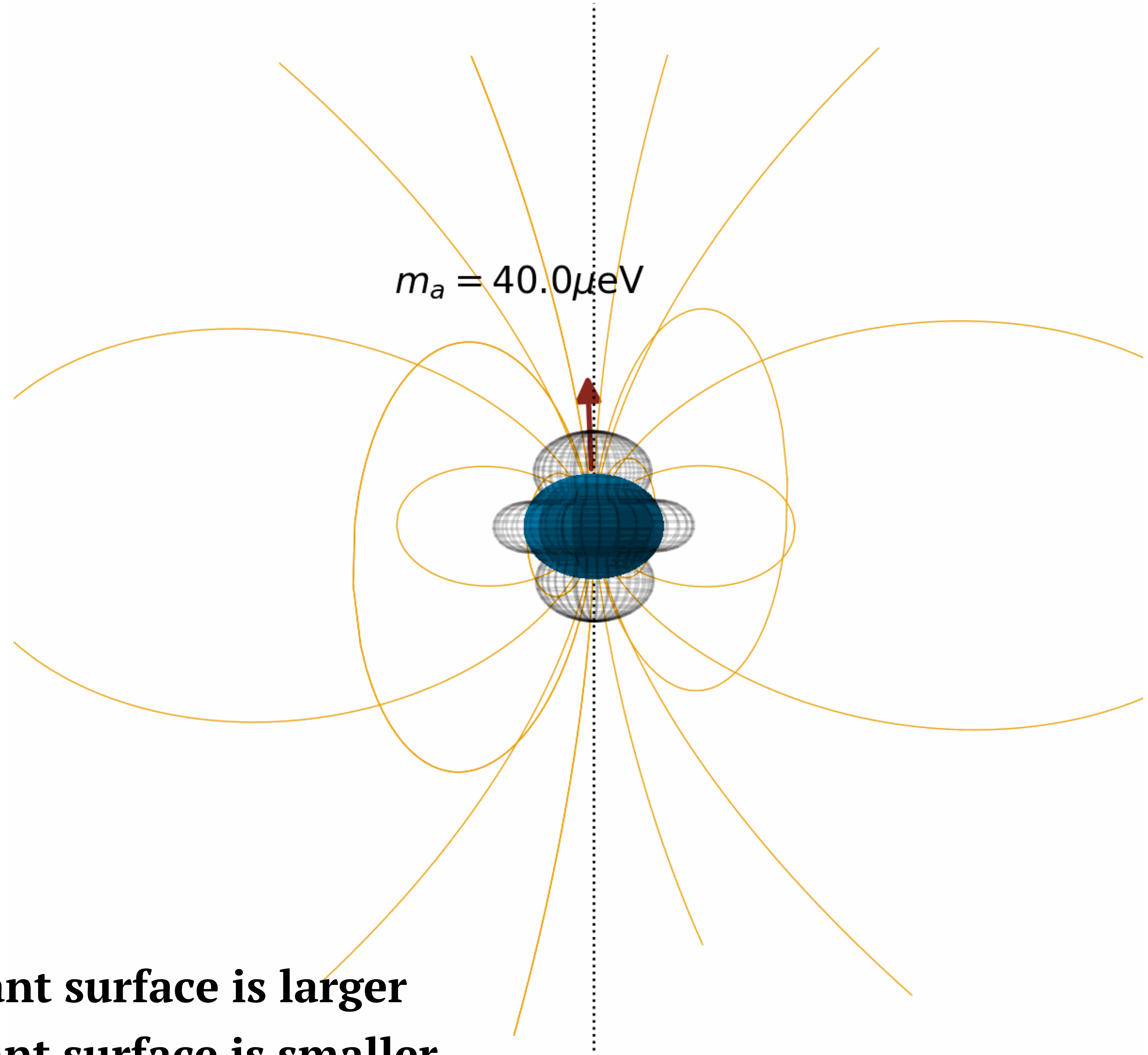
Photon production from axion dark matter



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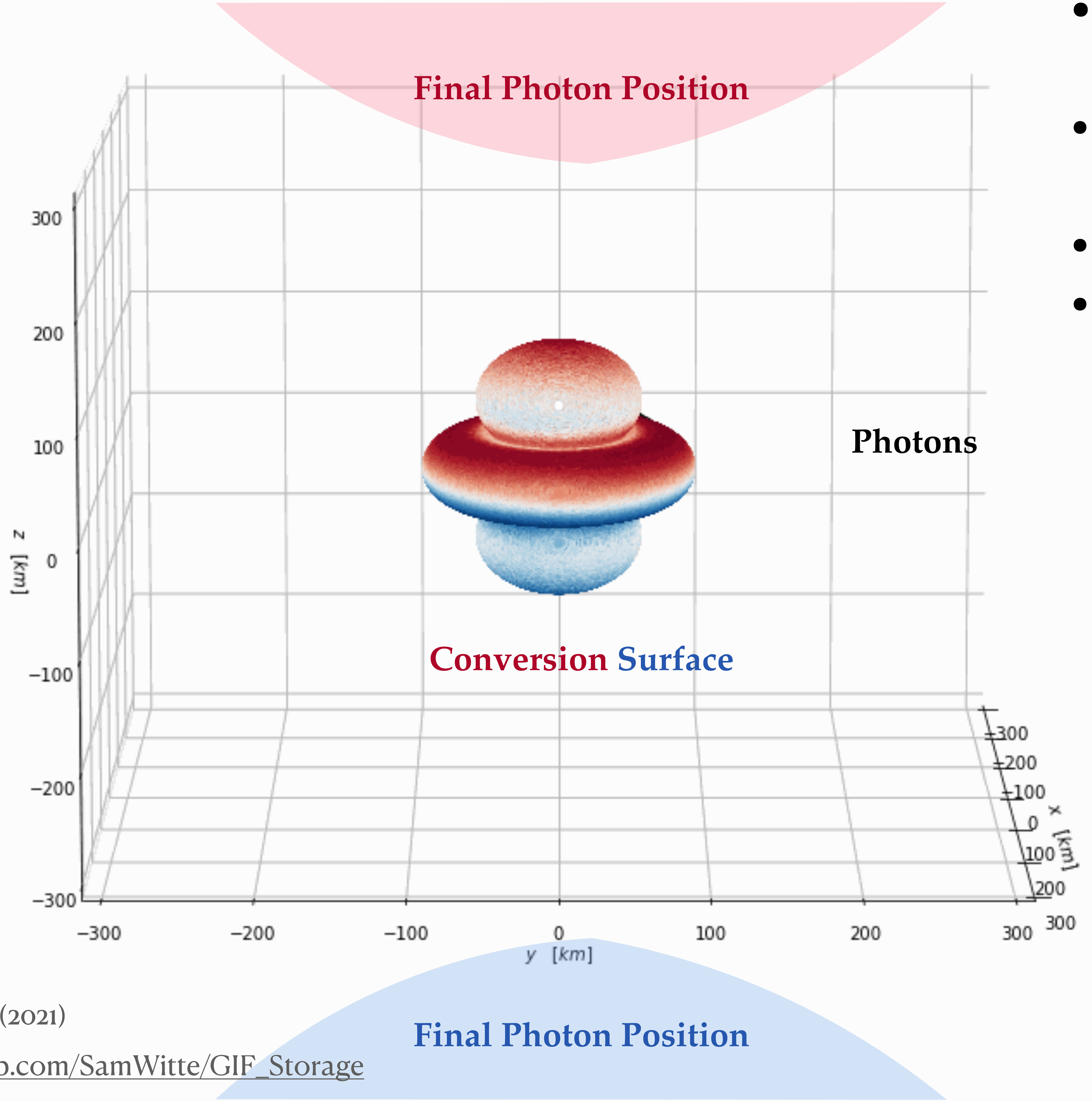
Ray tracing

Step 2: Axion phase space to photon flux



Ray tracing allows for:

- Accurate mapping of radio flux
- Back-reaction on axion phase space
- Line broadening effects
- Path-dependent absorption

SJW, Noordhuis, Edwards, Weniger (2021)

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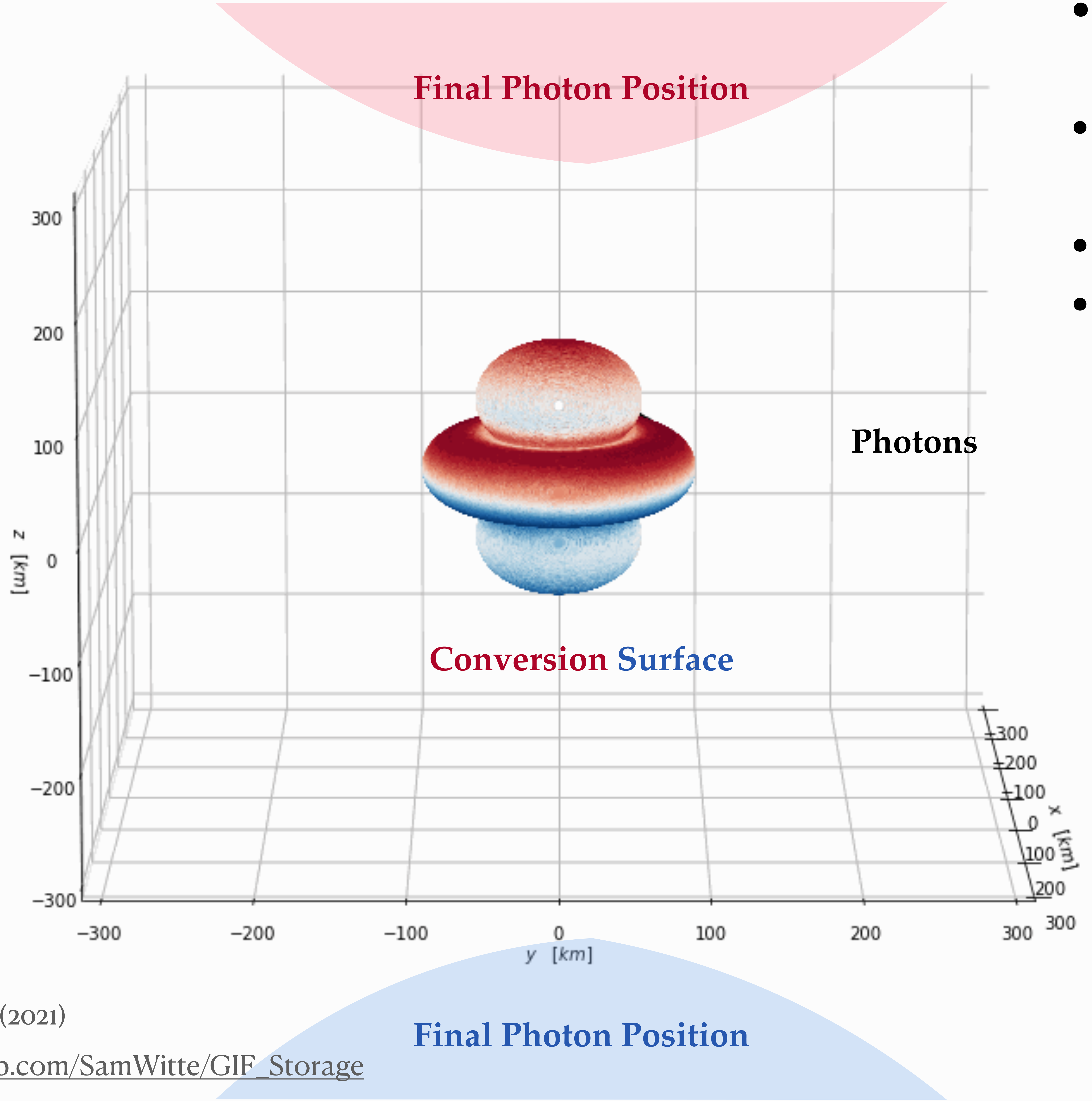
Ray tracing

Step 2: Axion phase space to photon flux



Ray tracing allows for:

- Accurate mapping of radio flux
- Back-reaction on axion phase space
- Line broadening effects
- Path-dependent absorption

SJW, Noordhuis, Edwards, Weniger (2021)

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

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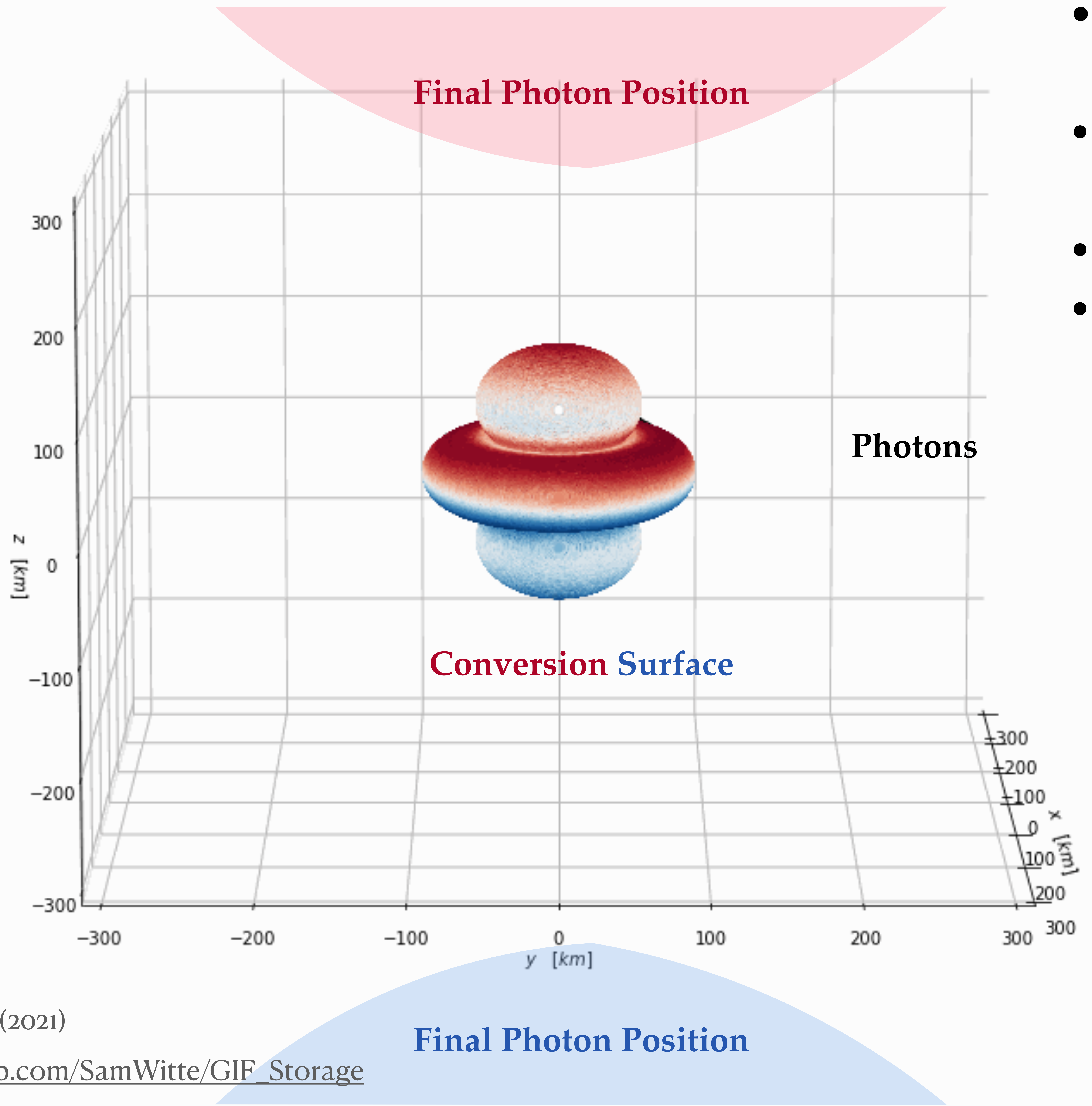

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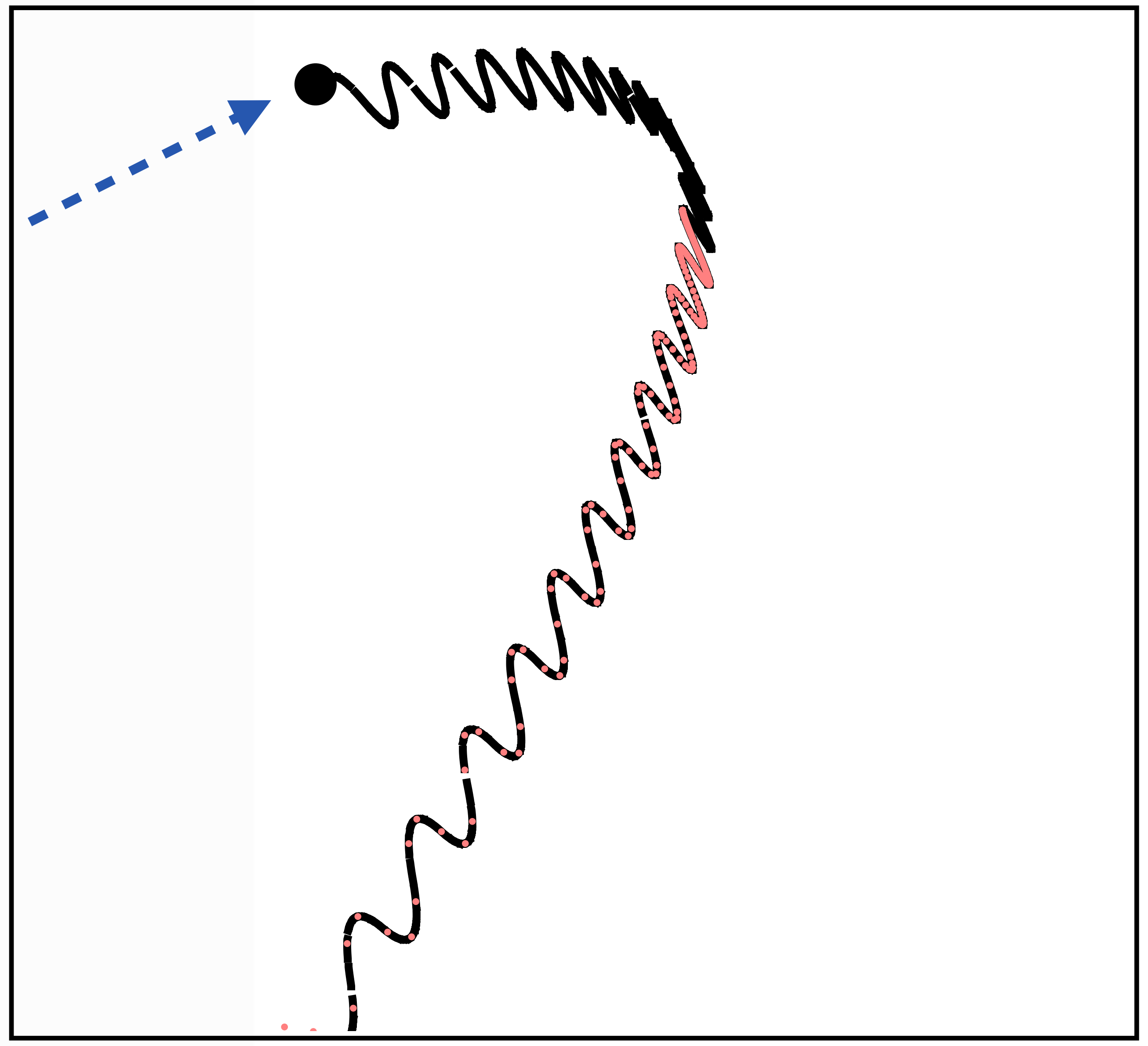

~ 500 meters

SJW, Noordhuis, Edwards, Weniger (2021)

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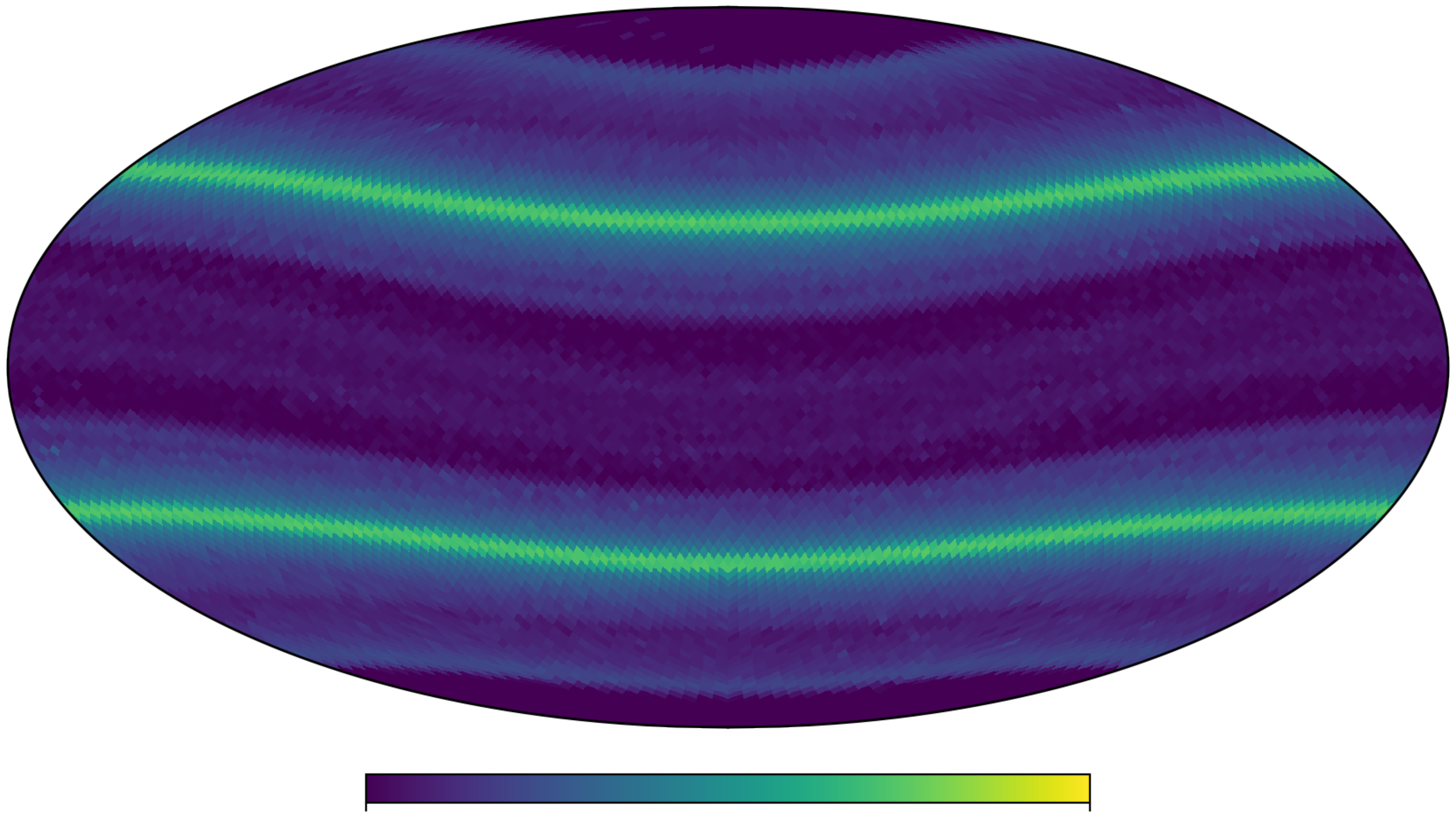
Radio signal from isolated neutron star

Projected sky flux as viewed from neutron star



Log10 (Flux)

[Arb. Units]

SJW, Noordhuis, Edwards, Weniger (2021)

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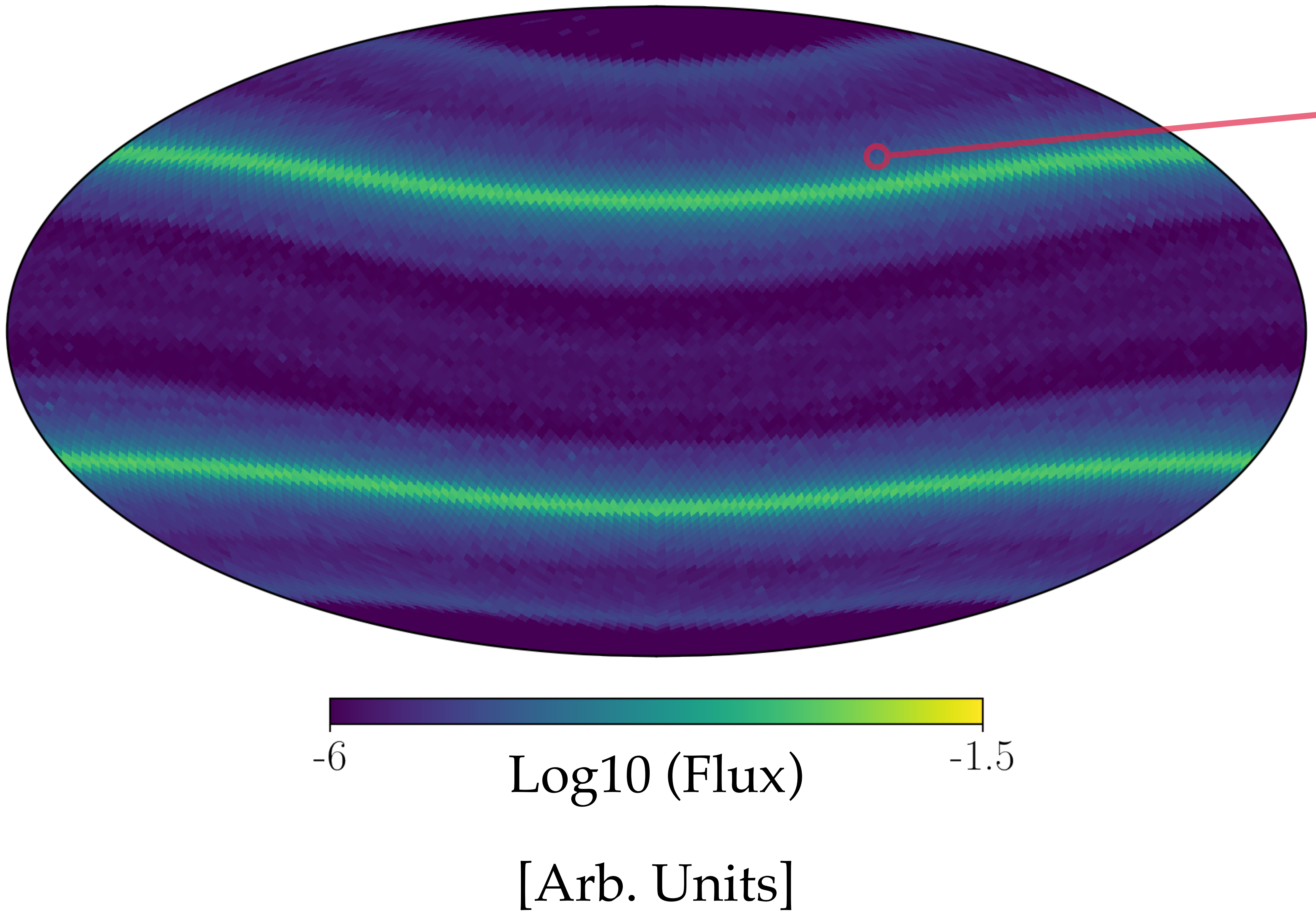

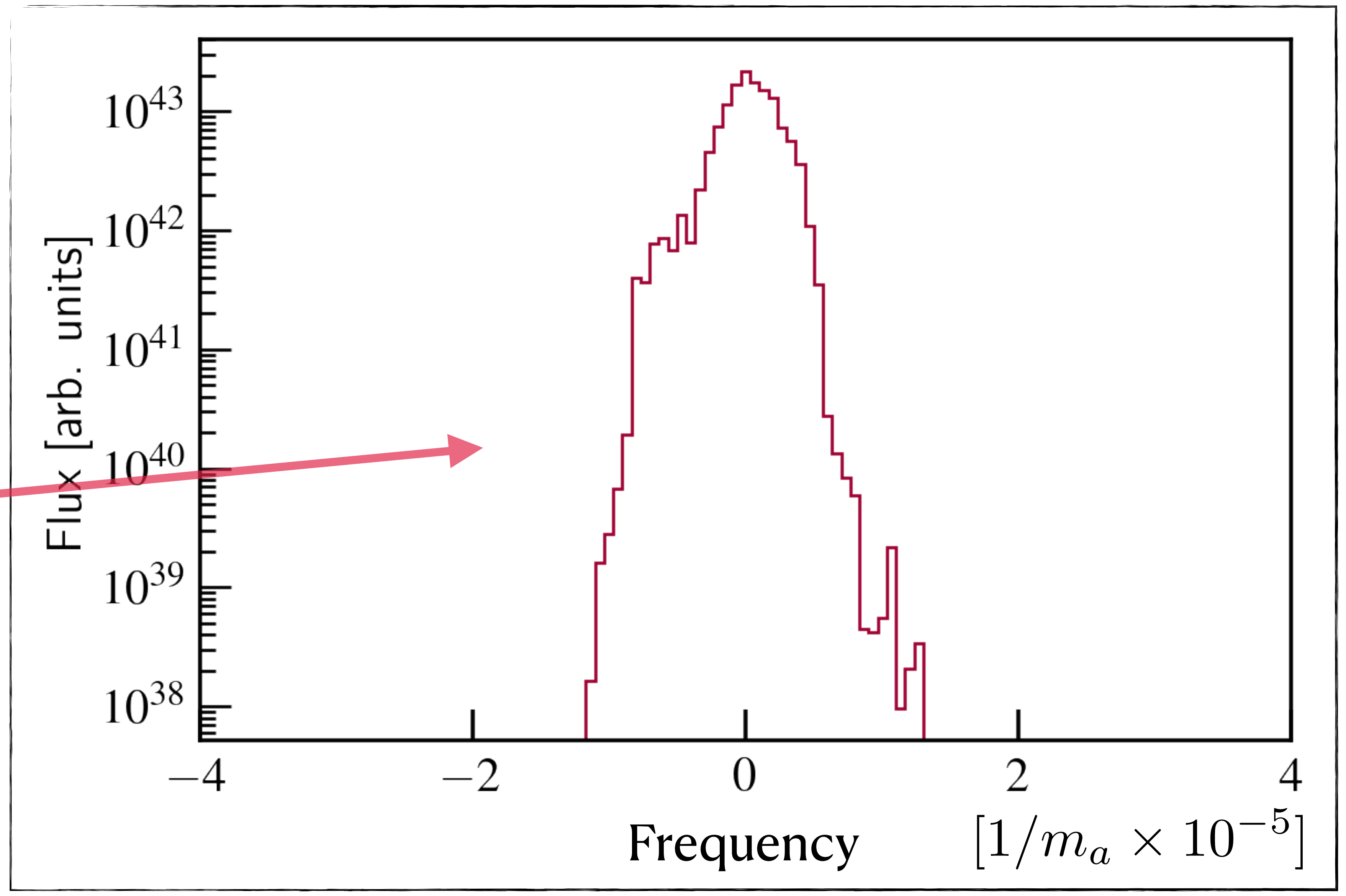

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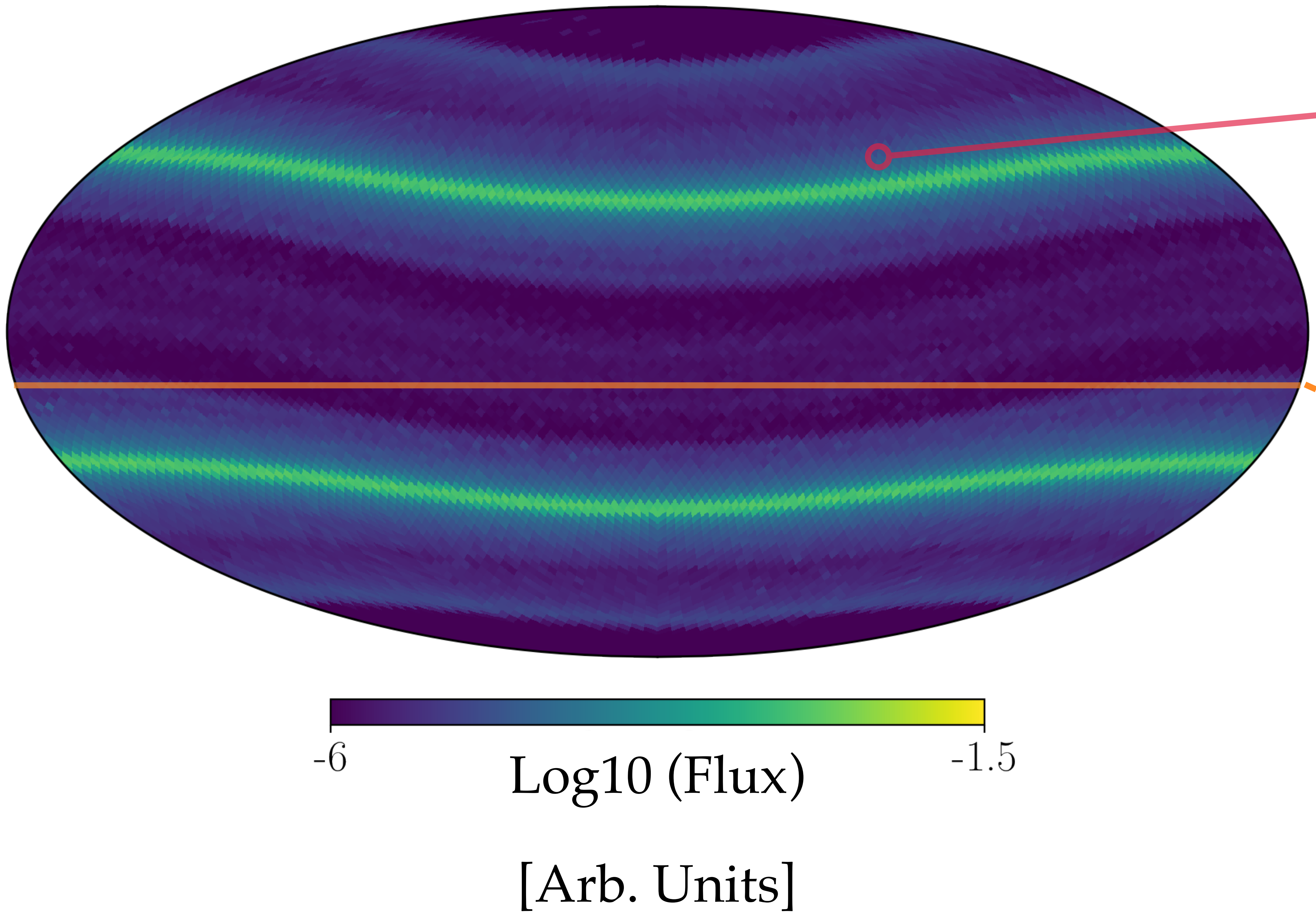
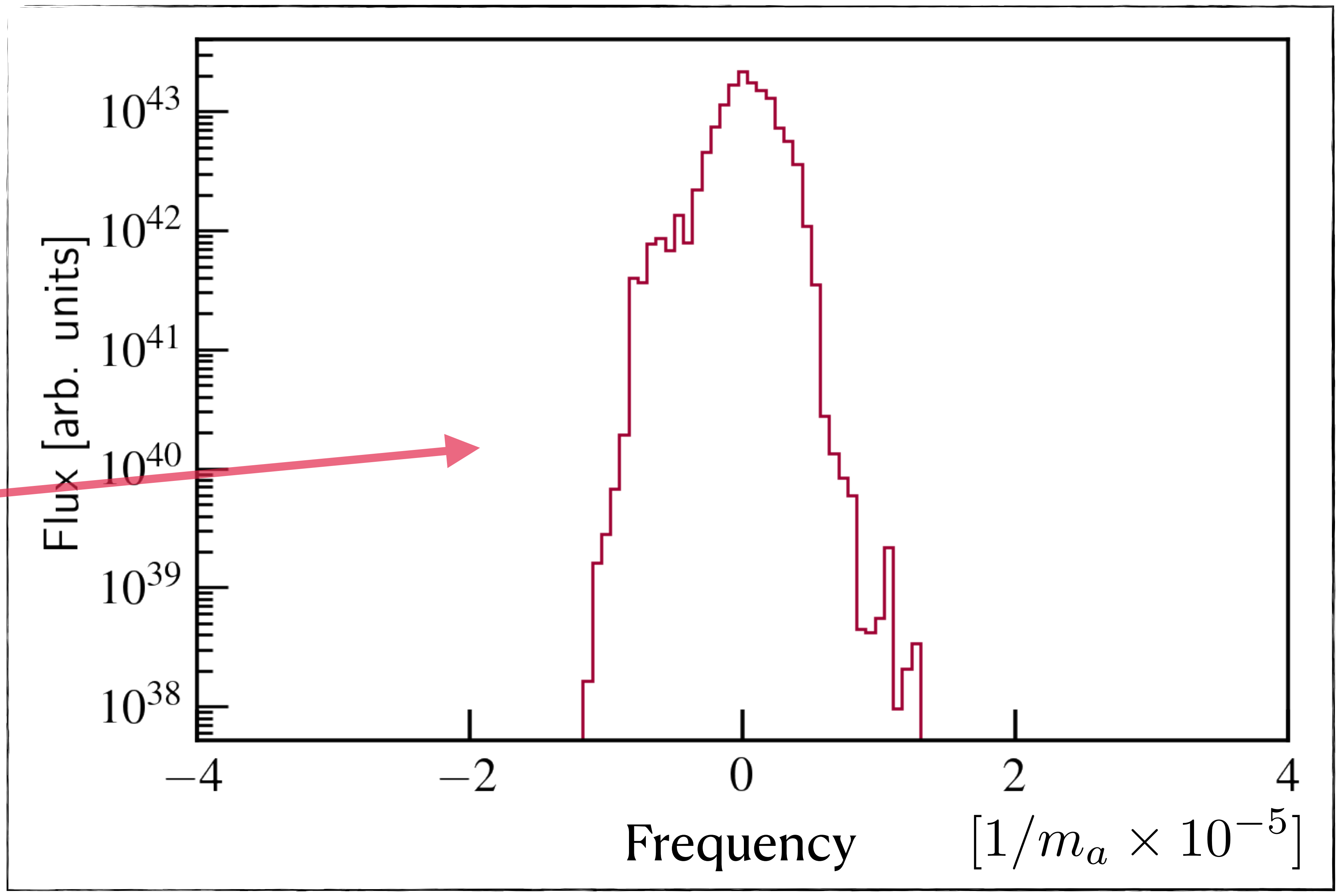
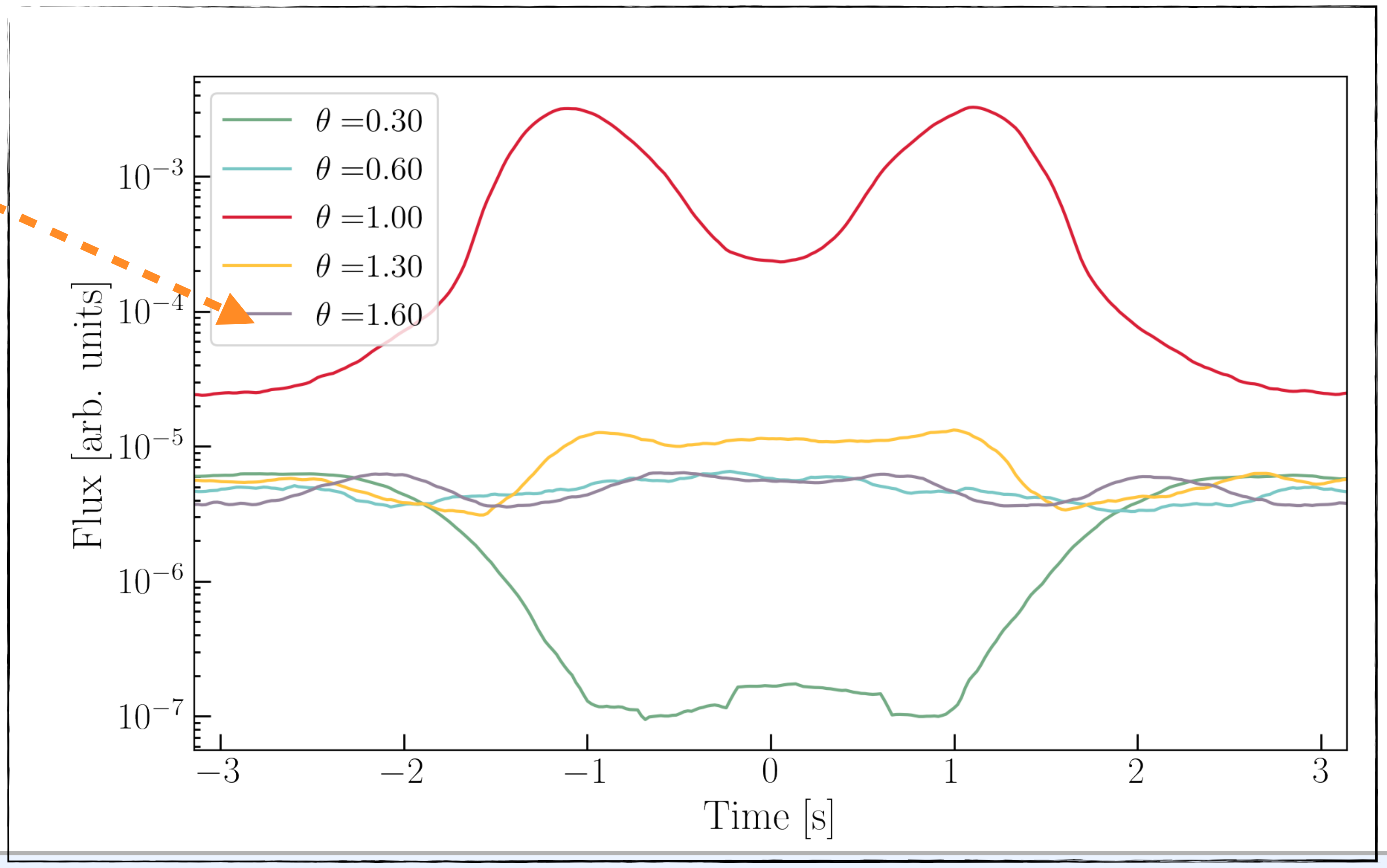
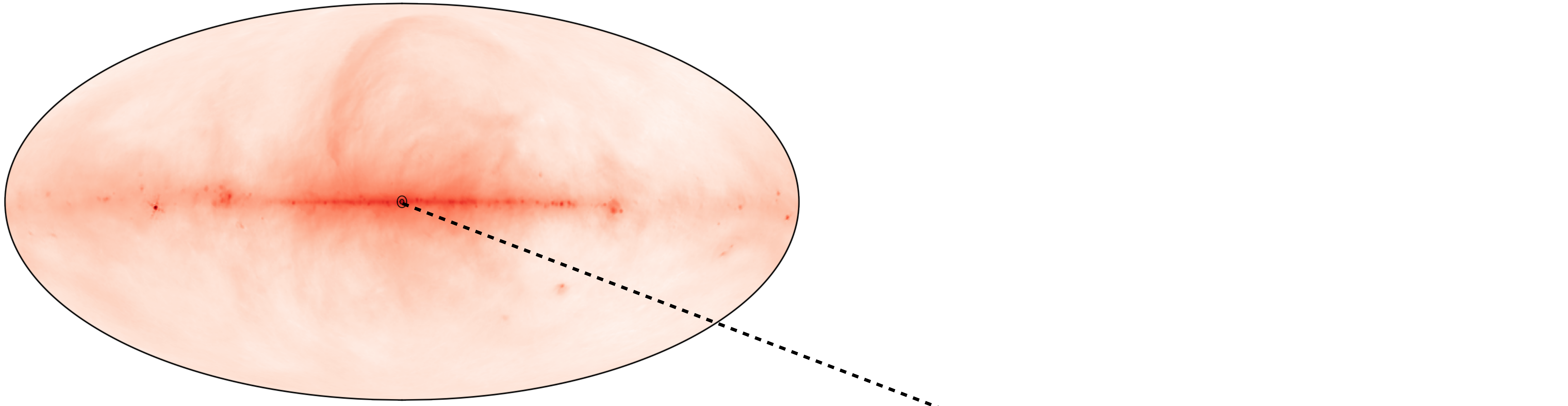


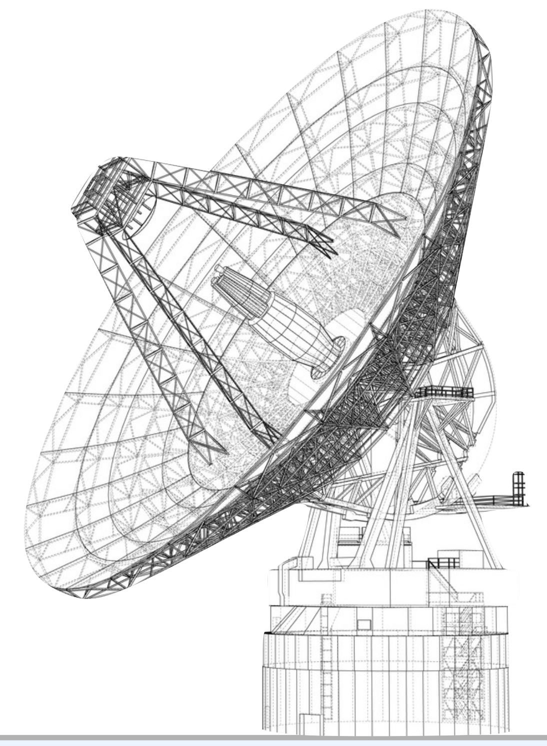
SJW, Noordhuis, Edwards, Weniger (2021)





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]
  (need high dark matter densities)
- **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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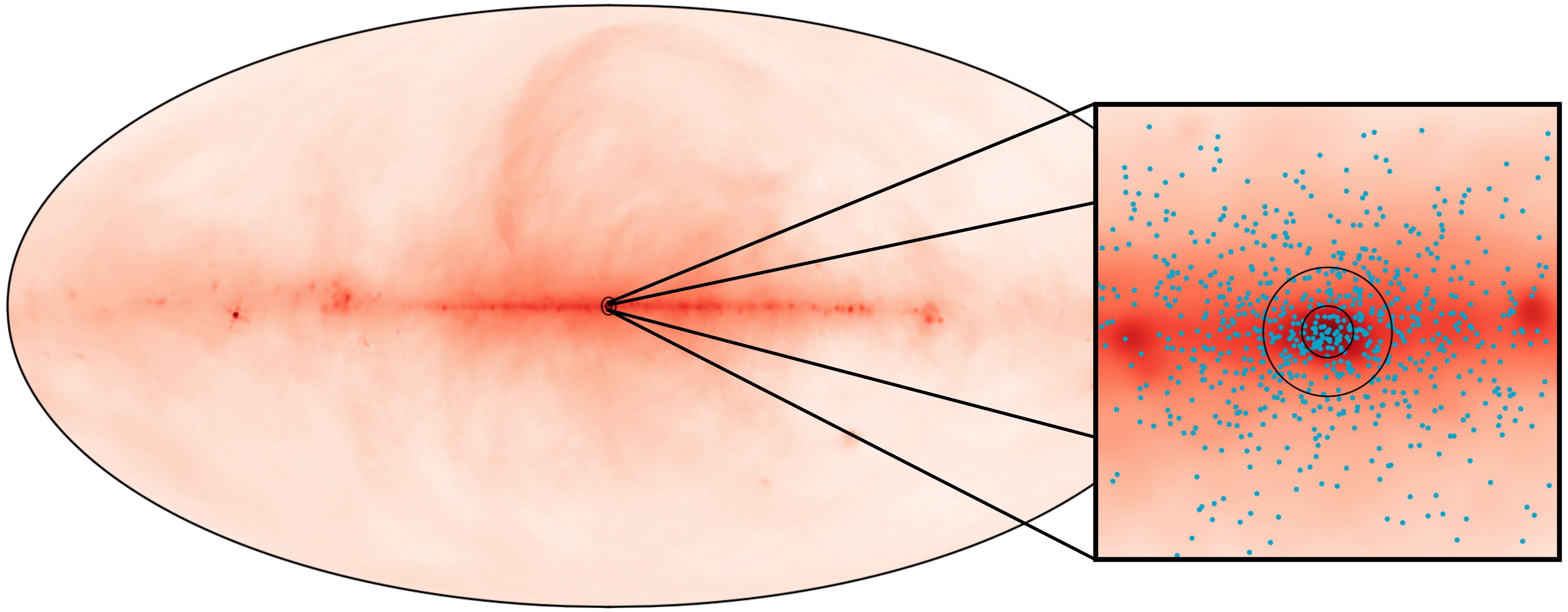

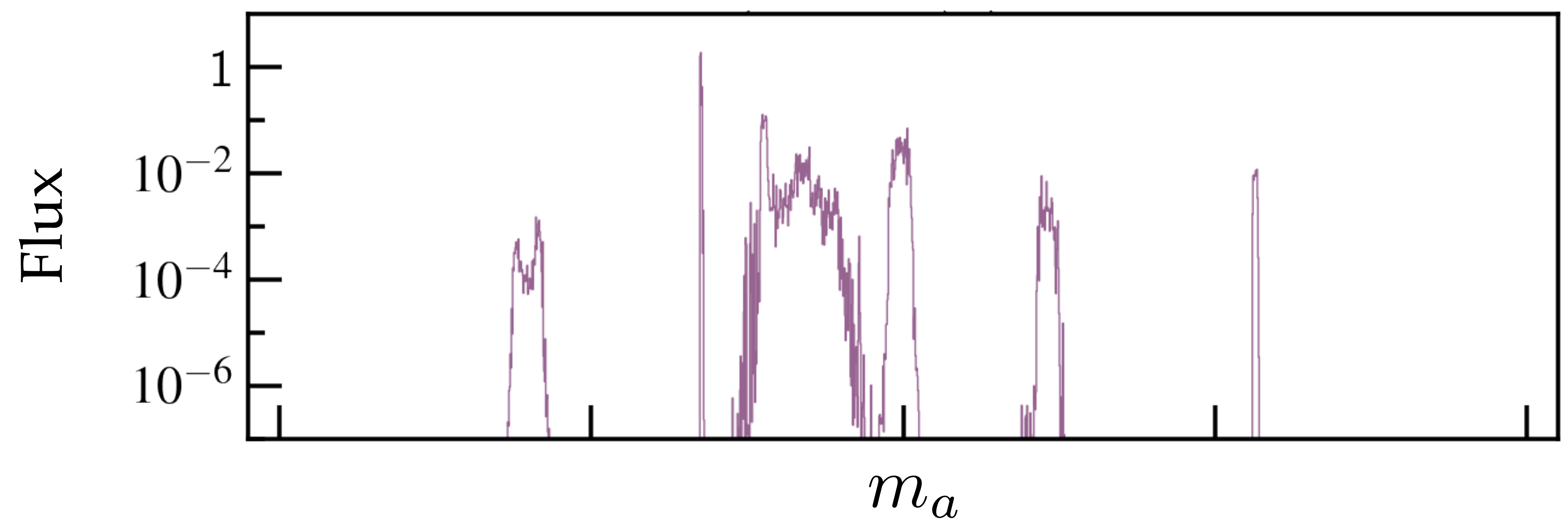

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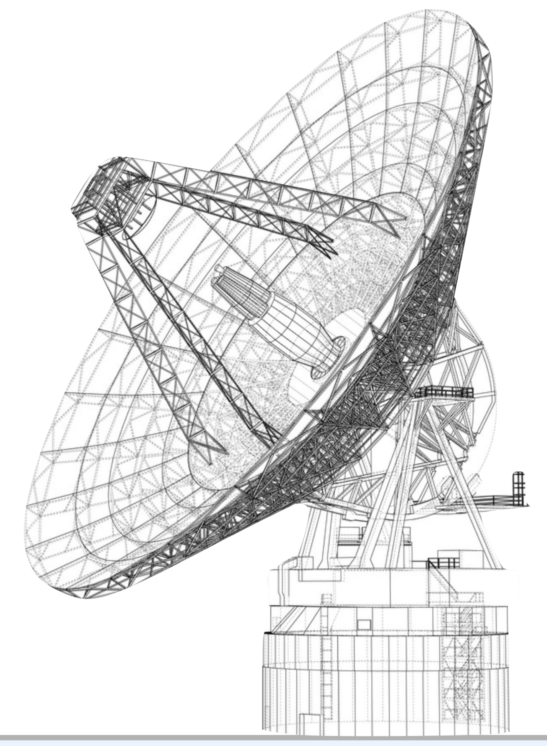


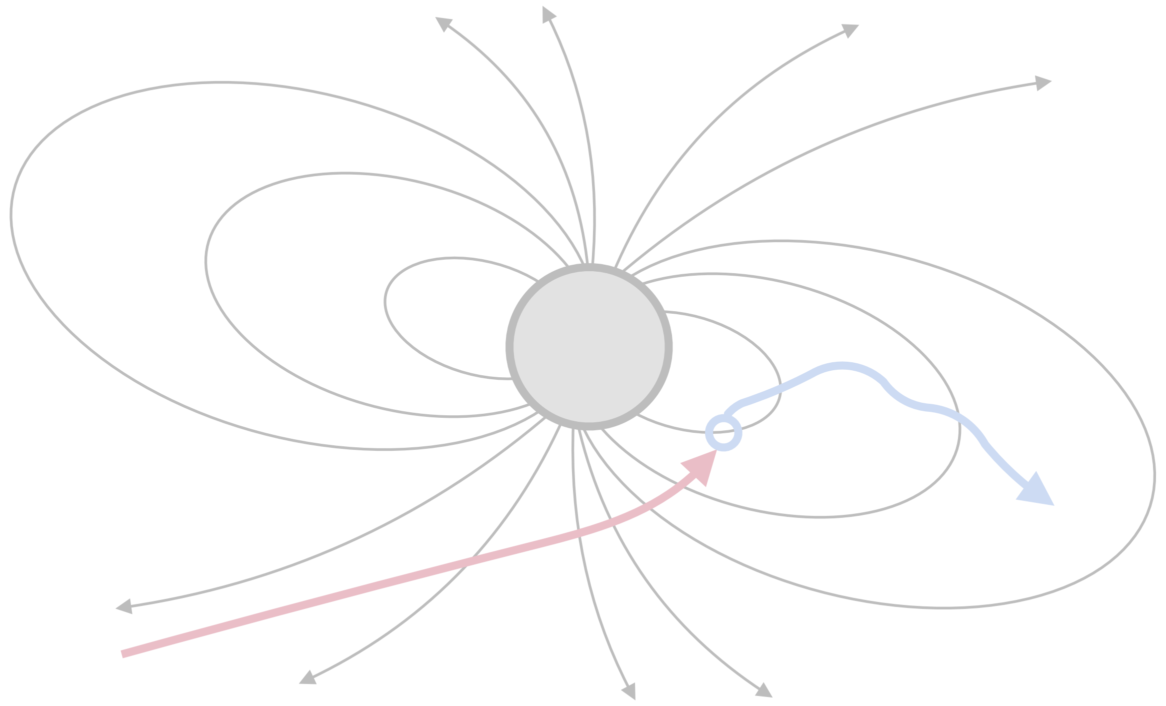
Data courtesy of the Breakthrough Listen Initiative

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

Searching for axions in the galactic center

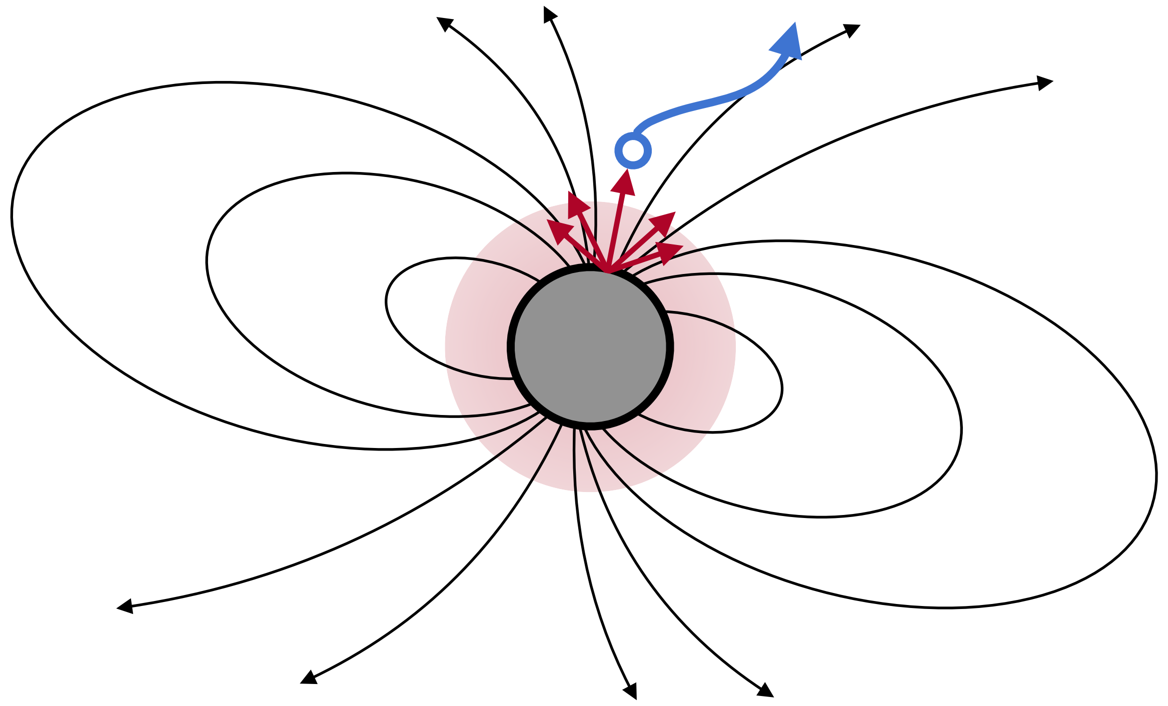
Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Neutron stars as axion labs



Part 1: Resonant production of radio photons from axion dark matter

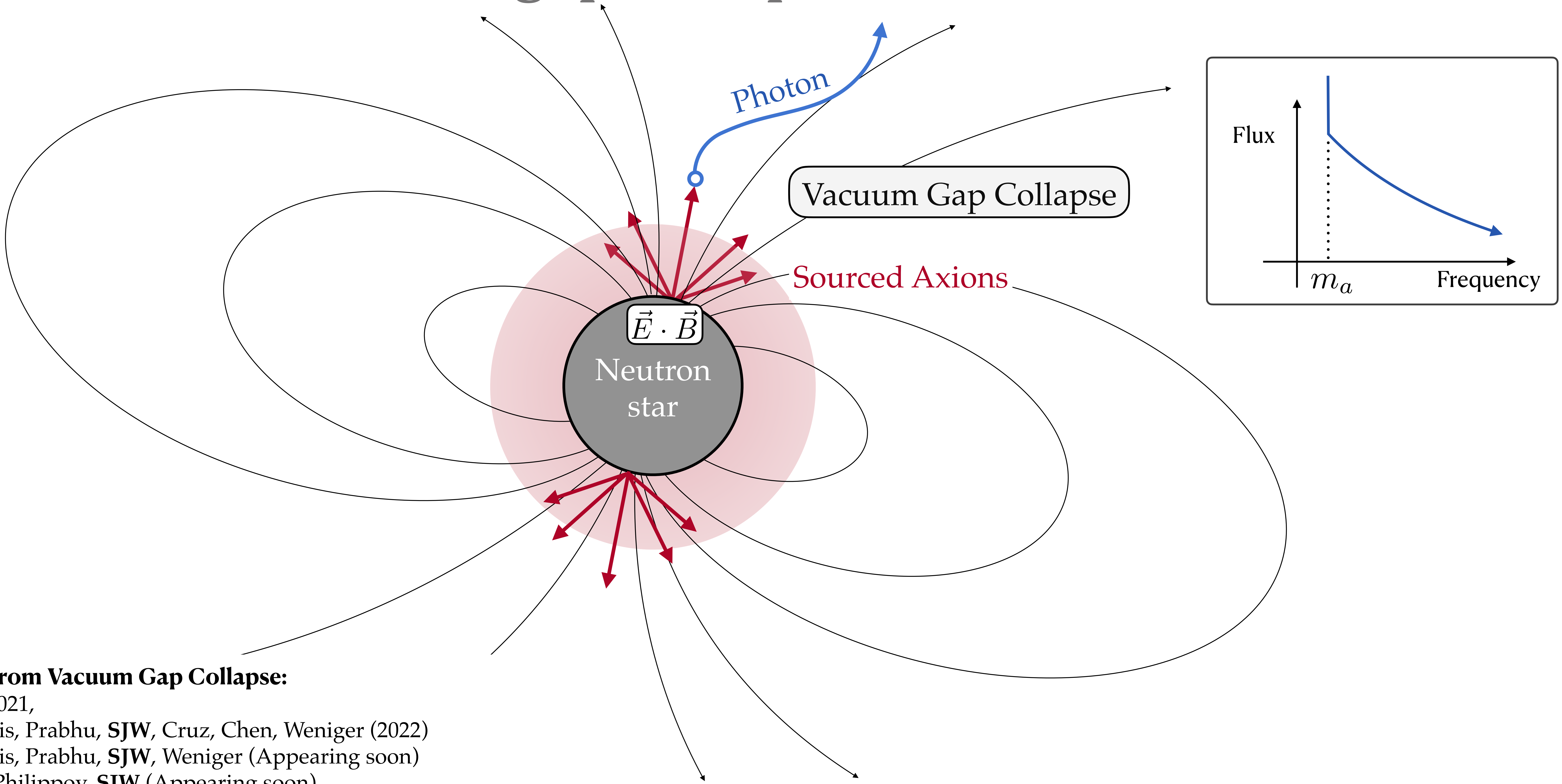
See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), Thejmsland, McDonald, **SJW** (To appear), **SJW** et al (To appear), McDonald & **SJW** (To appear),…



Part 2: Sourcing axions from the vacuum gap collapse

Prabhu (2021), Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022), Noordhuis, Prabhu, **SJW**, Weniger (Appearing soon), Caputo, Philippov, **SJW** (Appearing soon)

Axions from vacuum gap collapse



Axions from Vacuum Gap Collapse:
Prabhu 2021,
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, **SJW**, Weniger (Appearing soon)
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$$\vec{E} \cdot \vec{B} = 0$$

(Force-free solution)

Requires co-rotating plasma along the entire field line

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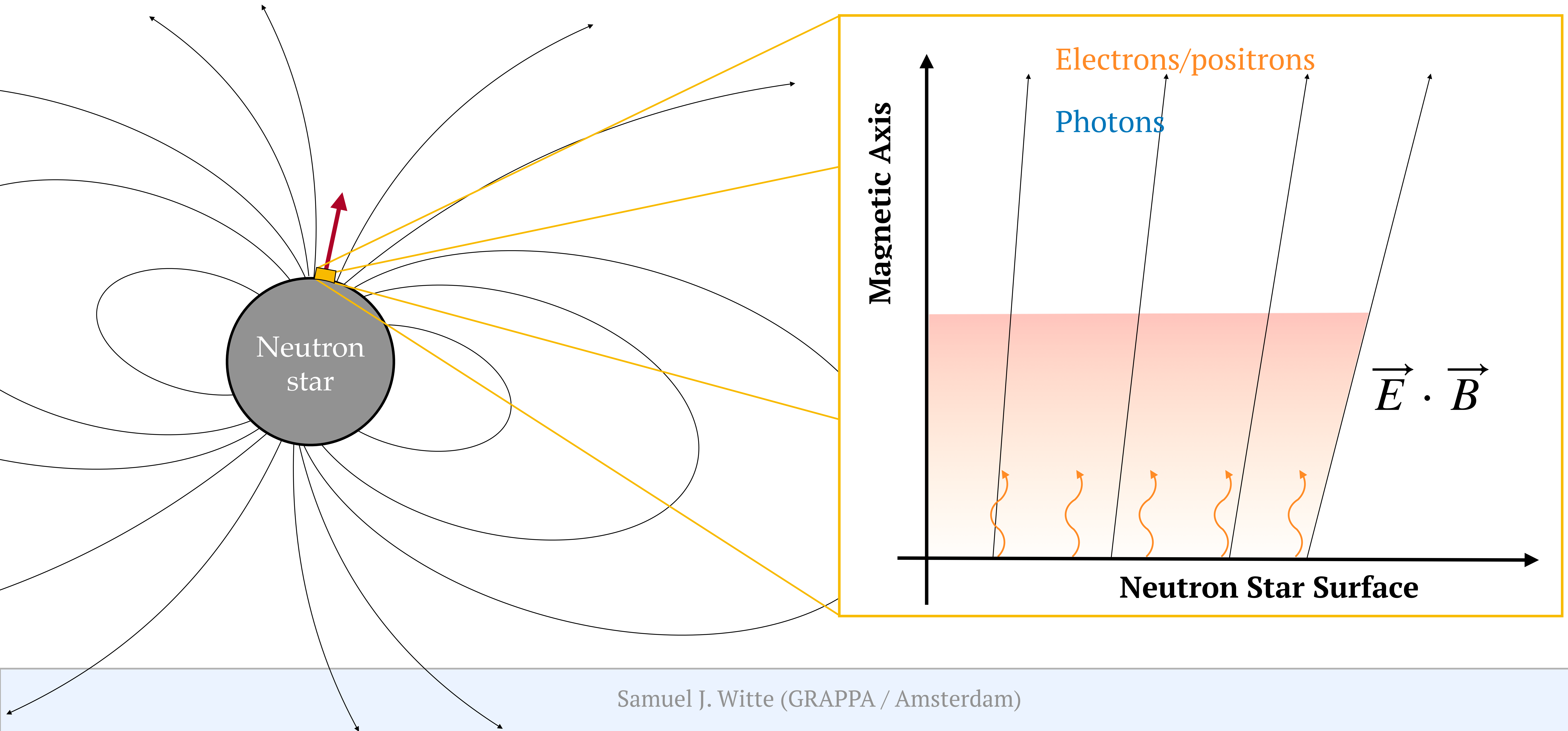

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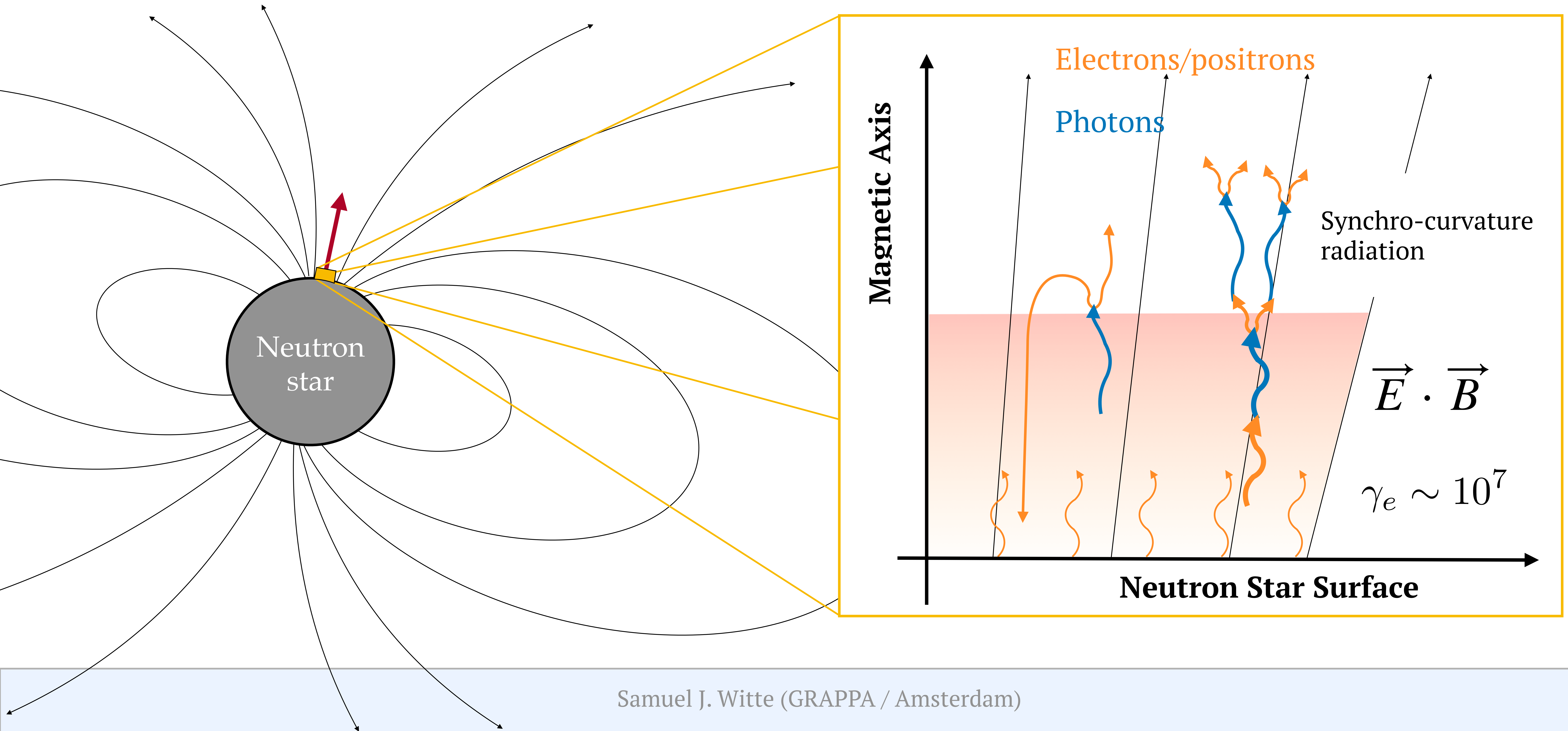

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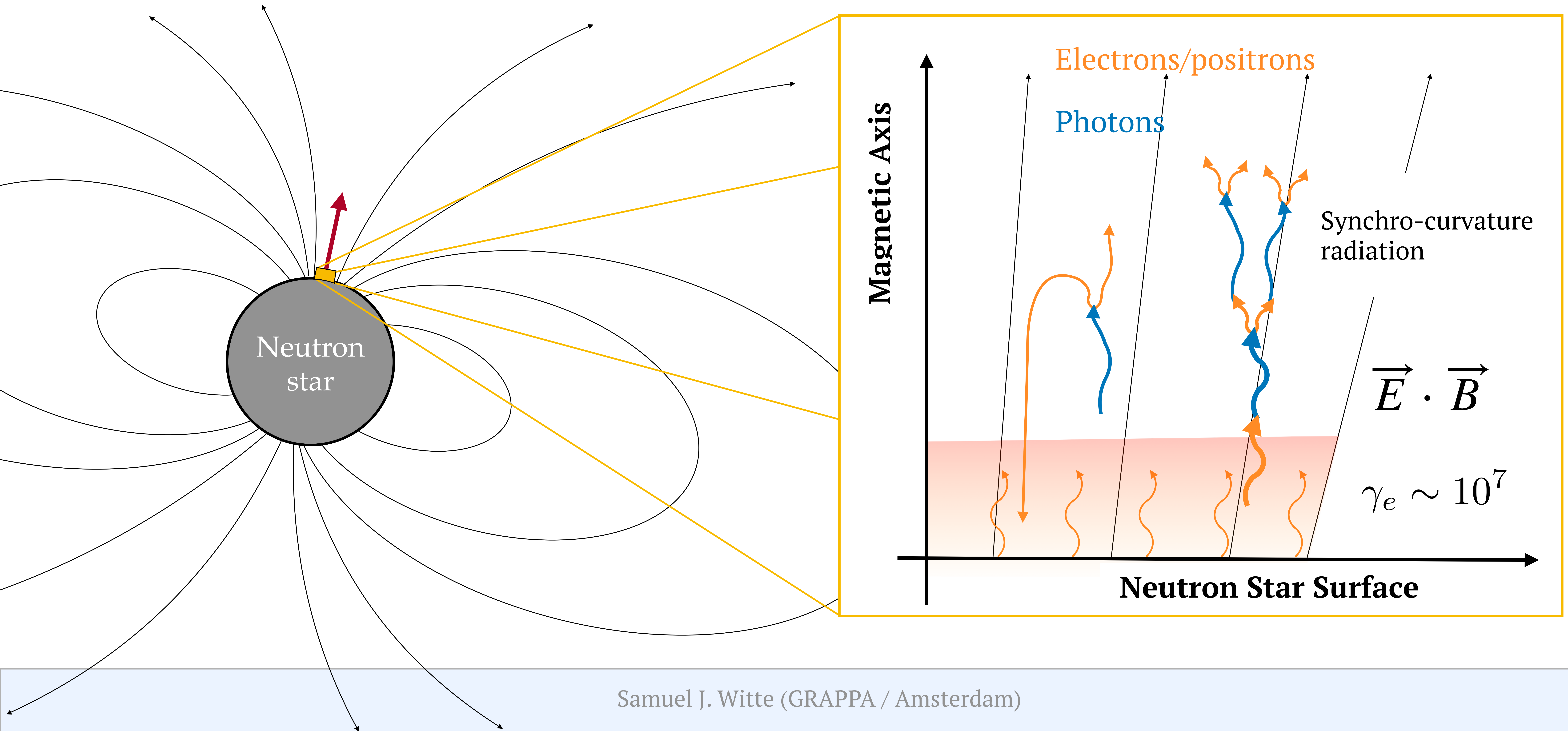
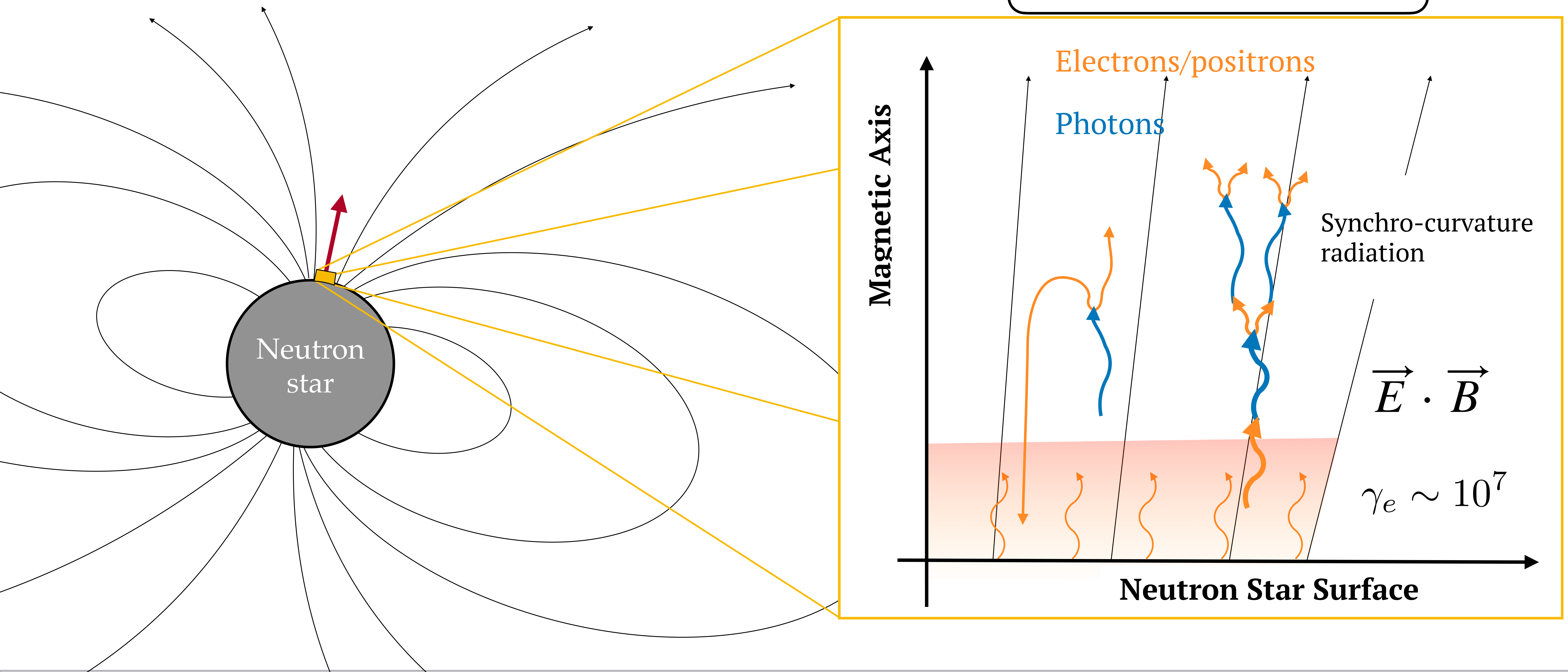


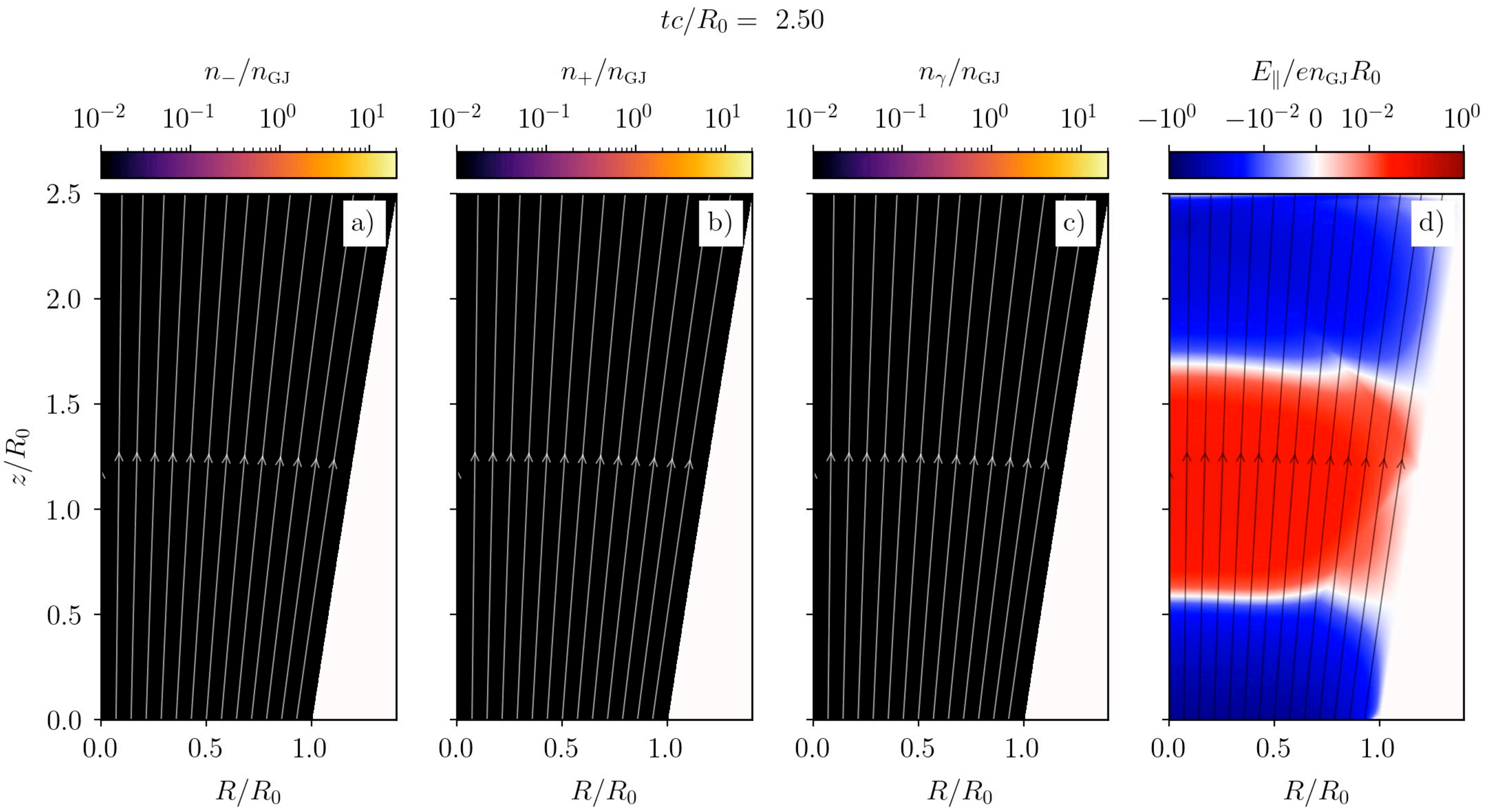
Axions from vacuum gap collapse

Axion spectra

$$\dot{N}_a(\vec{k}) \propto |FT(g_{a\gamma\gamma}\vec{E}\cdot\vec{B})|^2$$

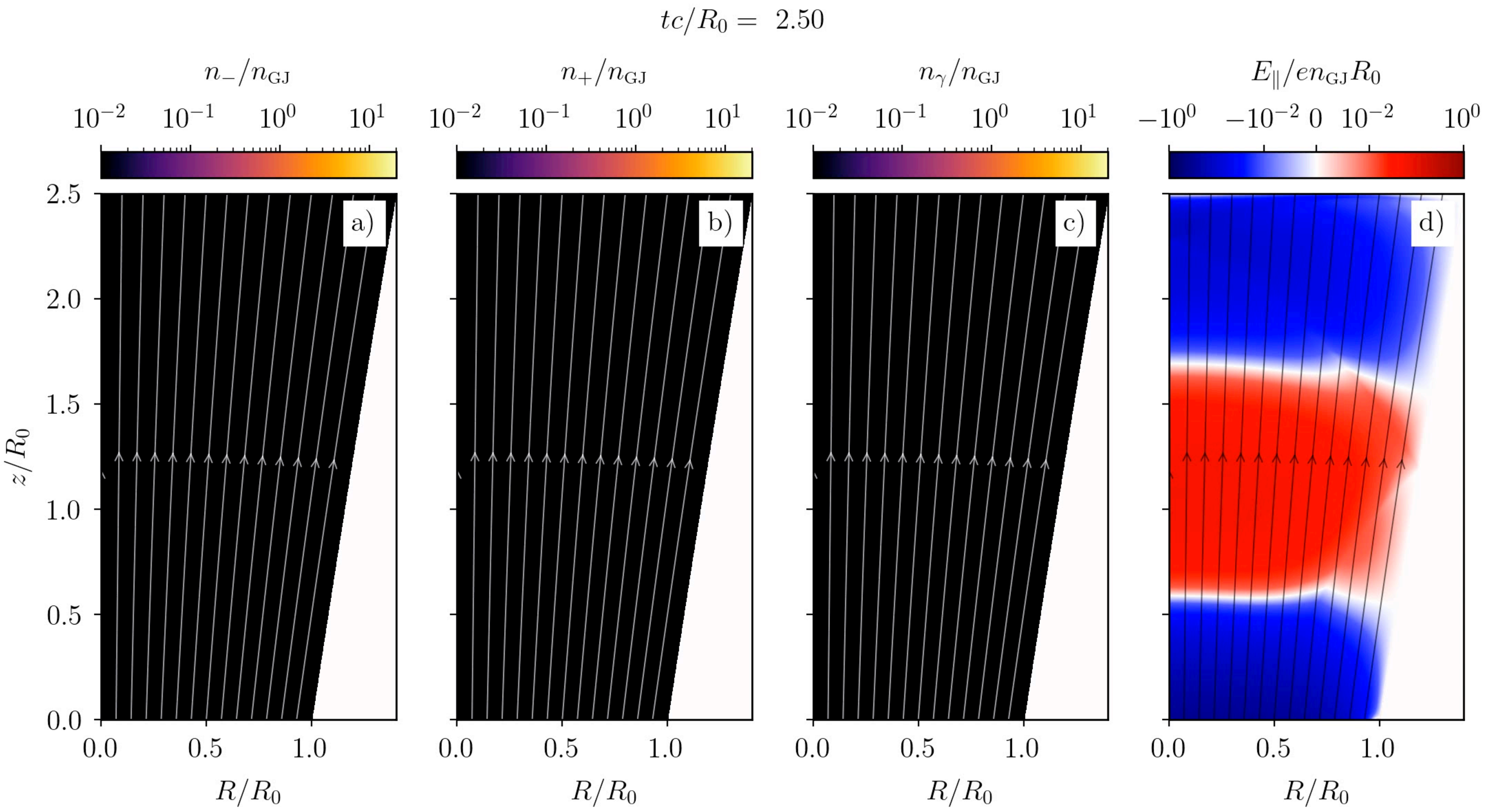


Vacuum gap collapse



Simulations curtesy of F. Cruz and A. Chen

Vacuum gap collapse



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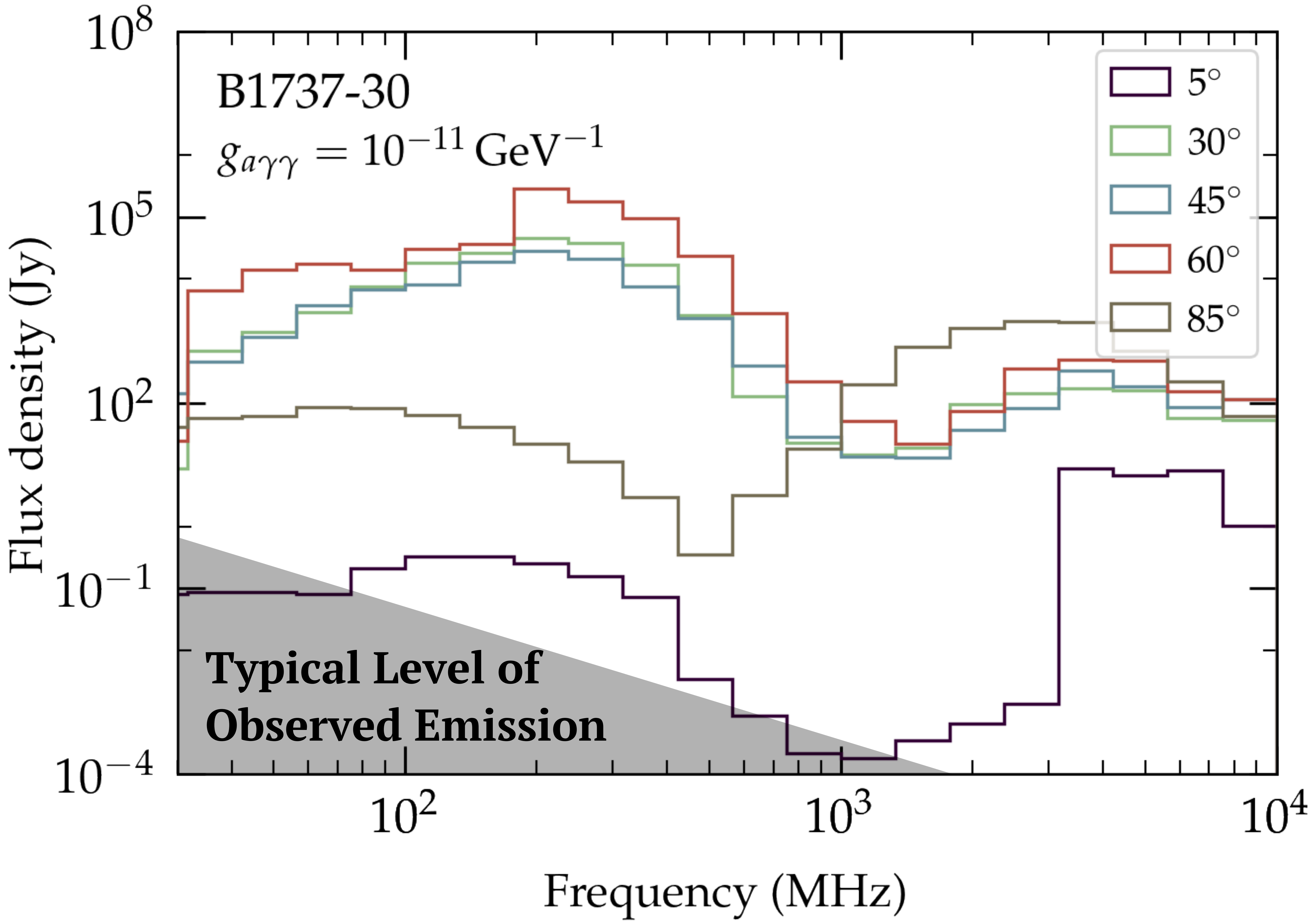
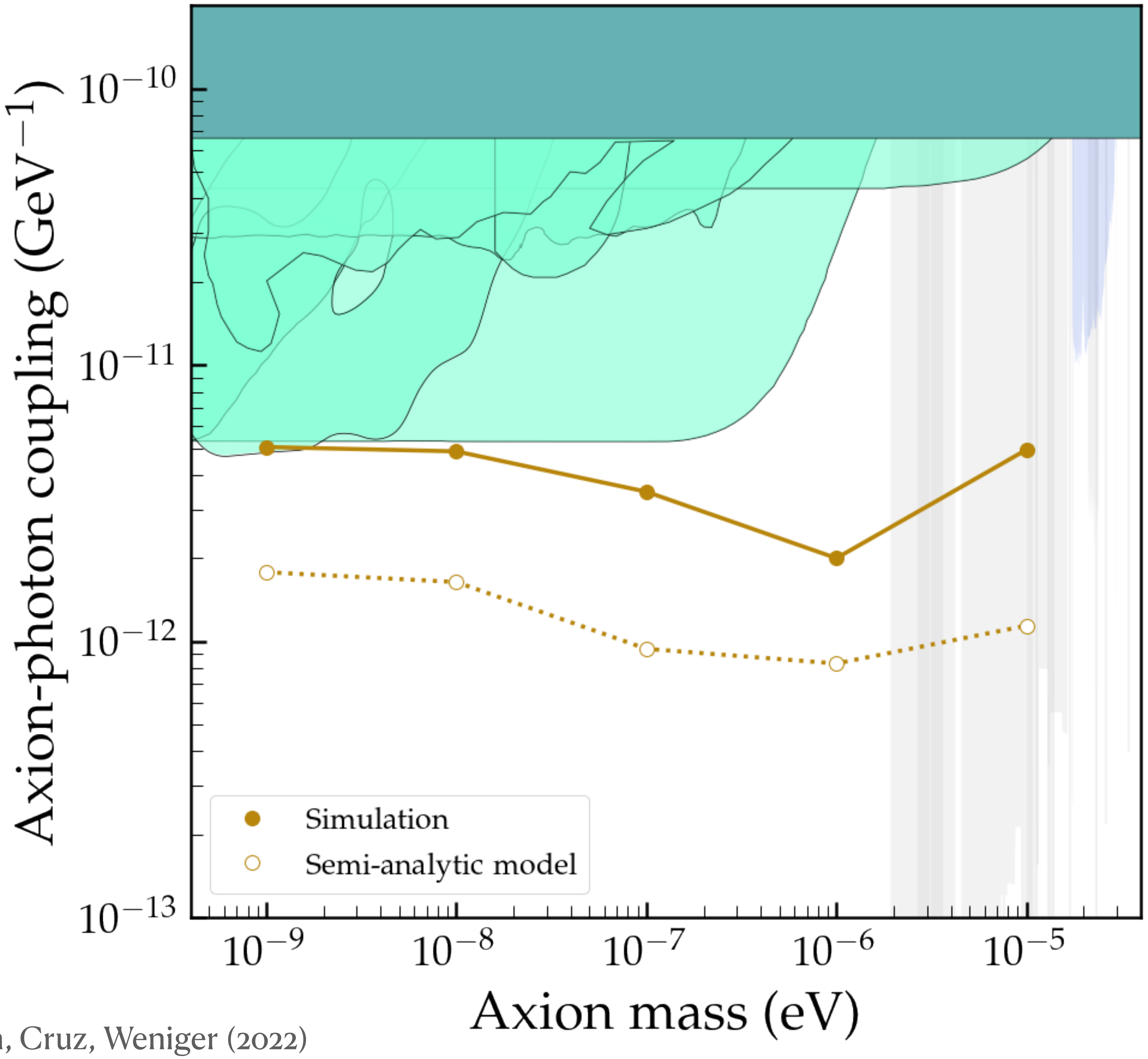
Radio Spectrum



Noordhuis, Prabhu, **SJW**, Chen, Cruz, Weniger (2022)

Constraints



Current search:

- Uses only 27 well-studied pulsars!

Future outlook:

- Wider frequency observations
- Full population in ATNF pulsar catalogue
- 3D PIC simulations

Noordhuis, Prabhu, **SJW**, Chen, Cruz, Weniger (2022)
Plot made using cajohare.github.io/AxionLimits/

If there exists an axion with a mass

$$10^{-8}\text{eV} \lesssim m_a \lesssim 10^{-5}\text{eV}$$

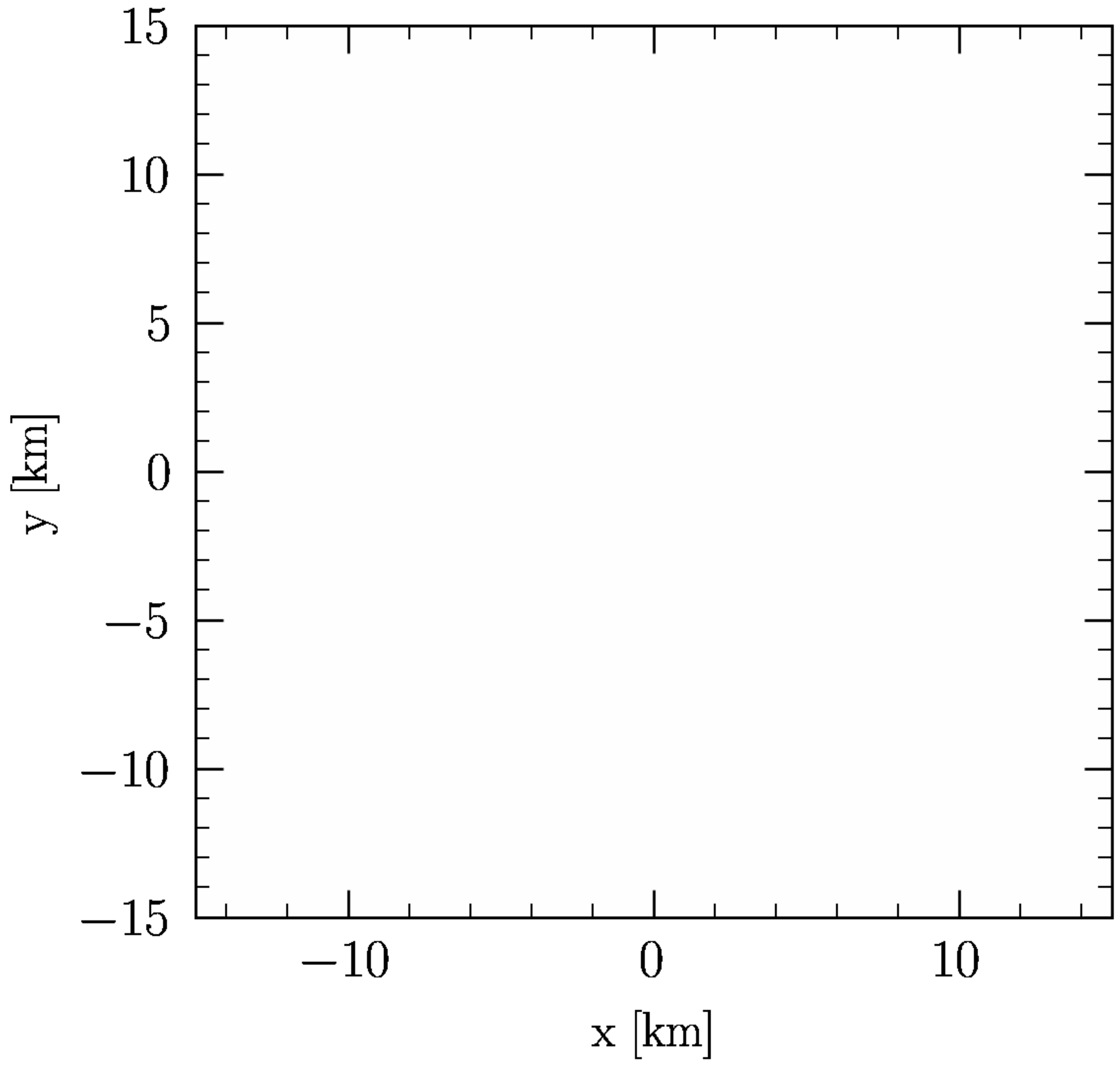
↓

All pulsars are surrounded by extremely dense clouds of axions.

Axion clouds

For these masses, most energy goes into gravitationally bound states…

Can accumulate for ~kyr timescales



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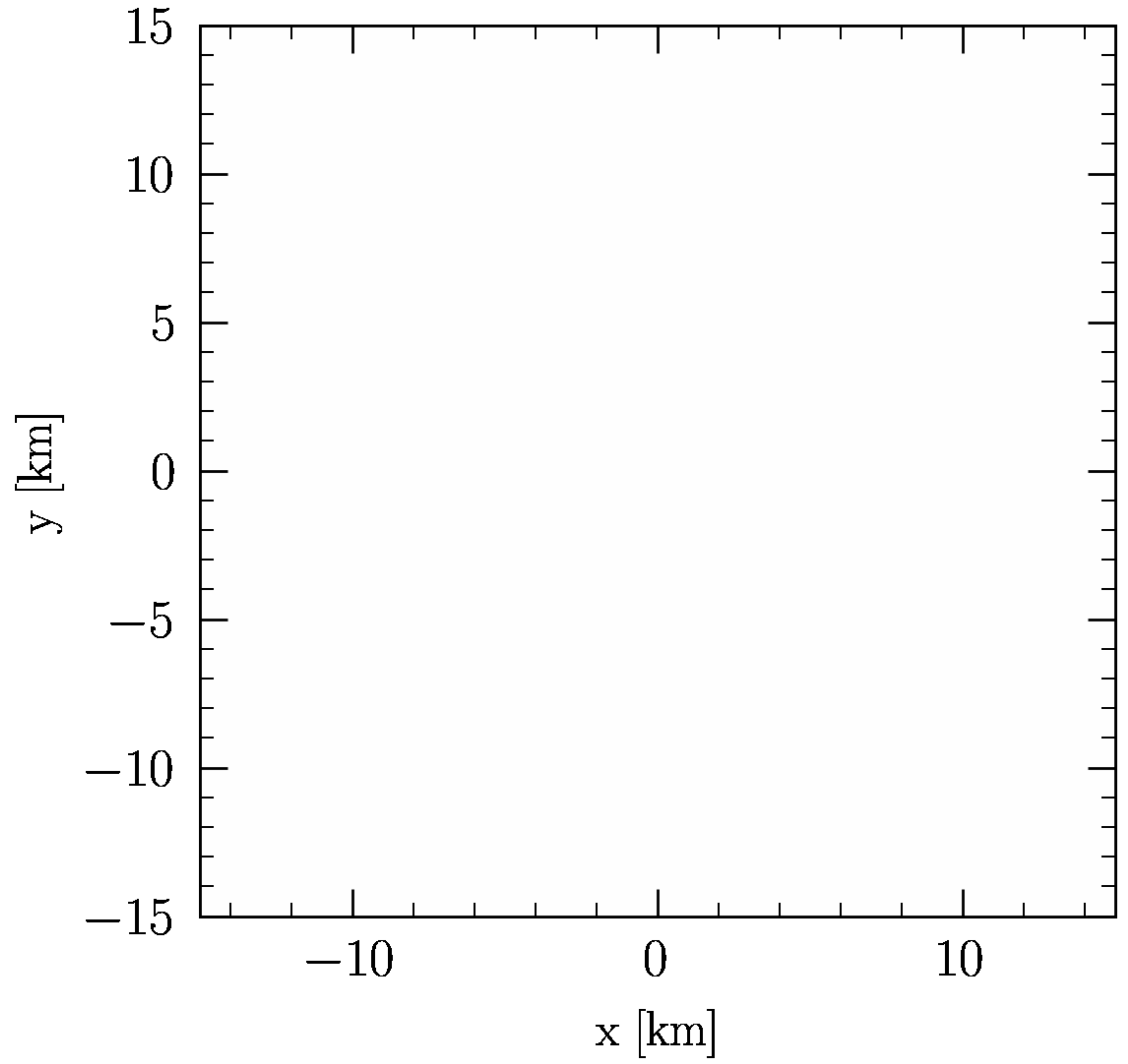
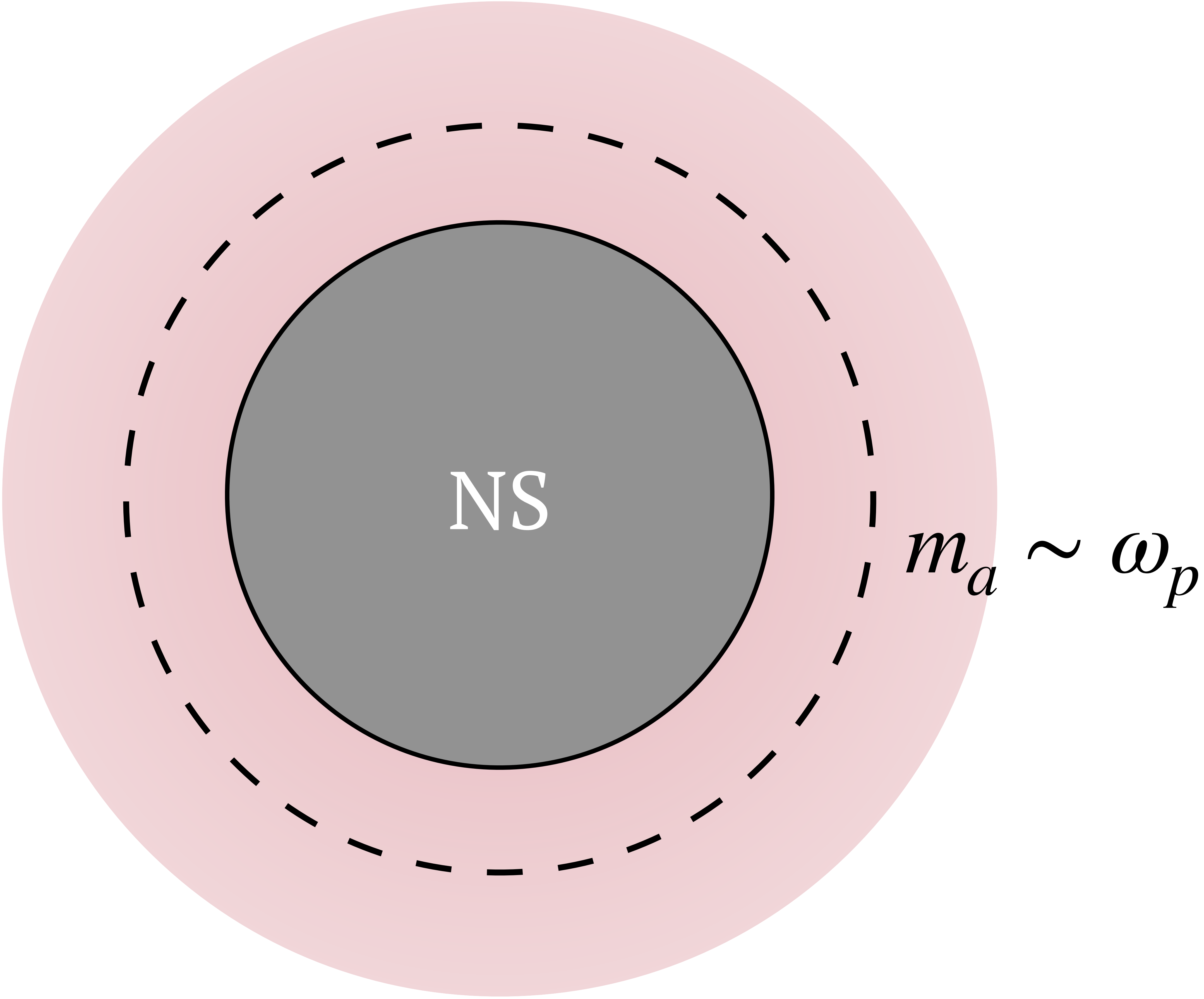


Quenching of bound state growth

Emission from resonant conversion:

Noordhuis, Prabhu, Weniger, **SJW** (To appear)



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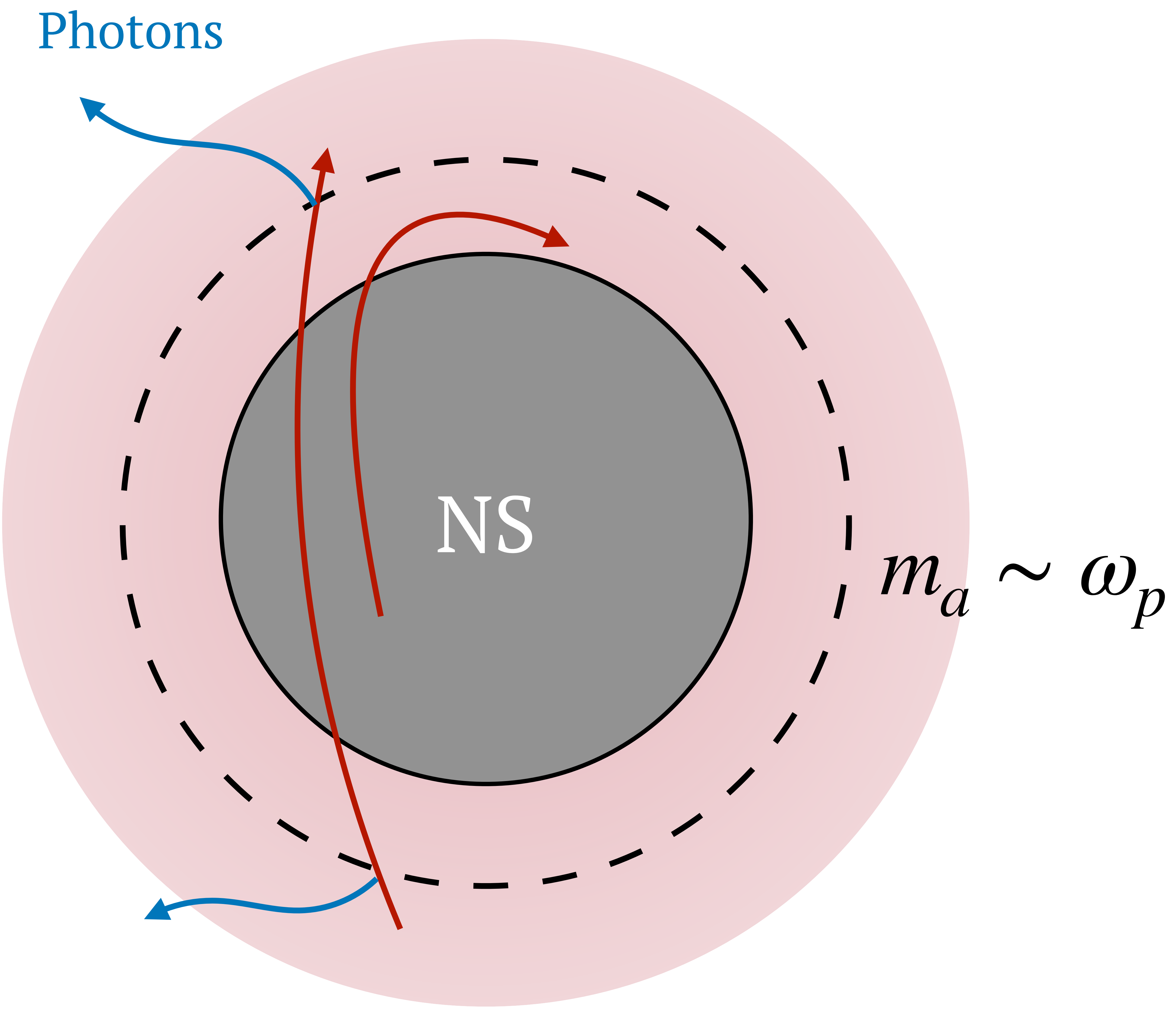

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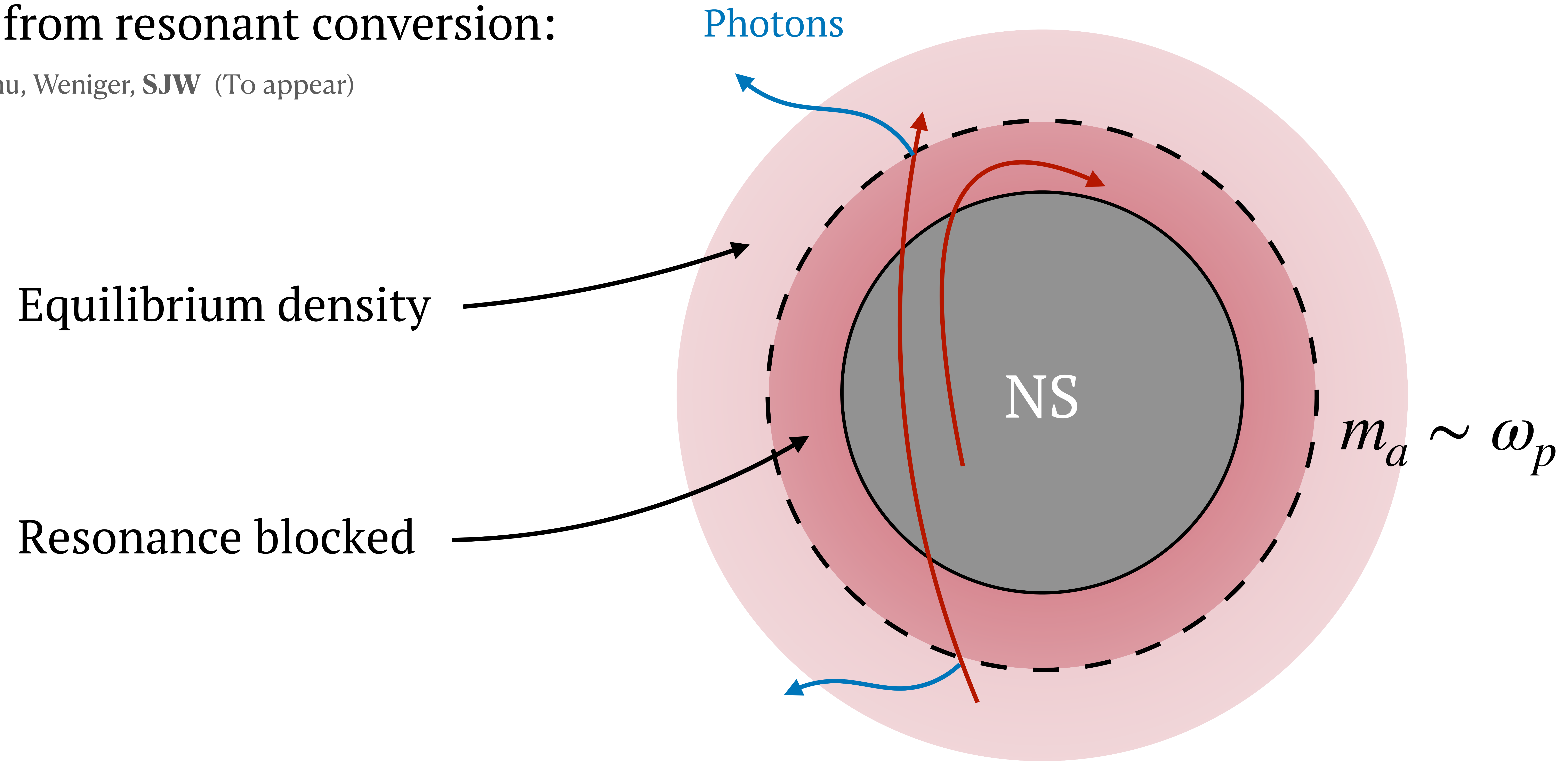
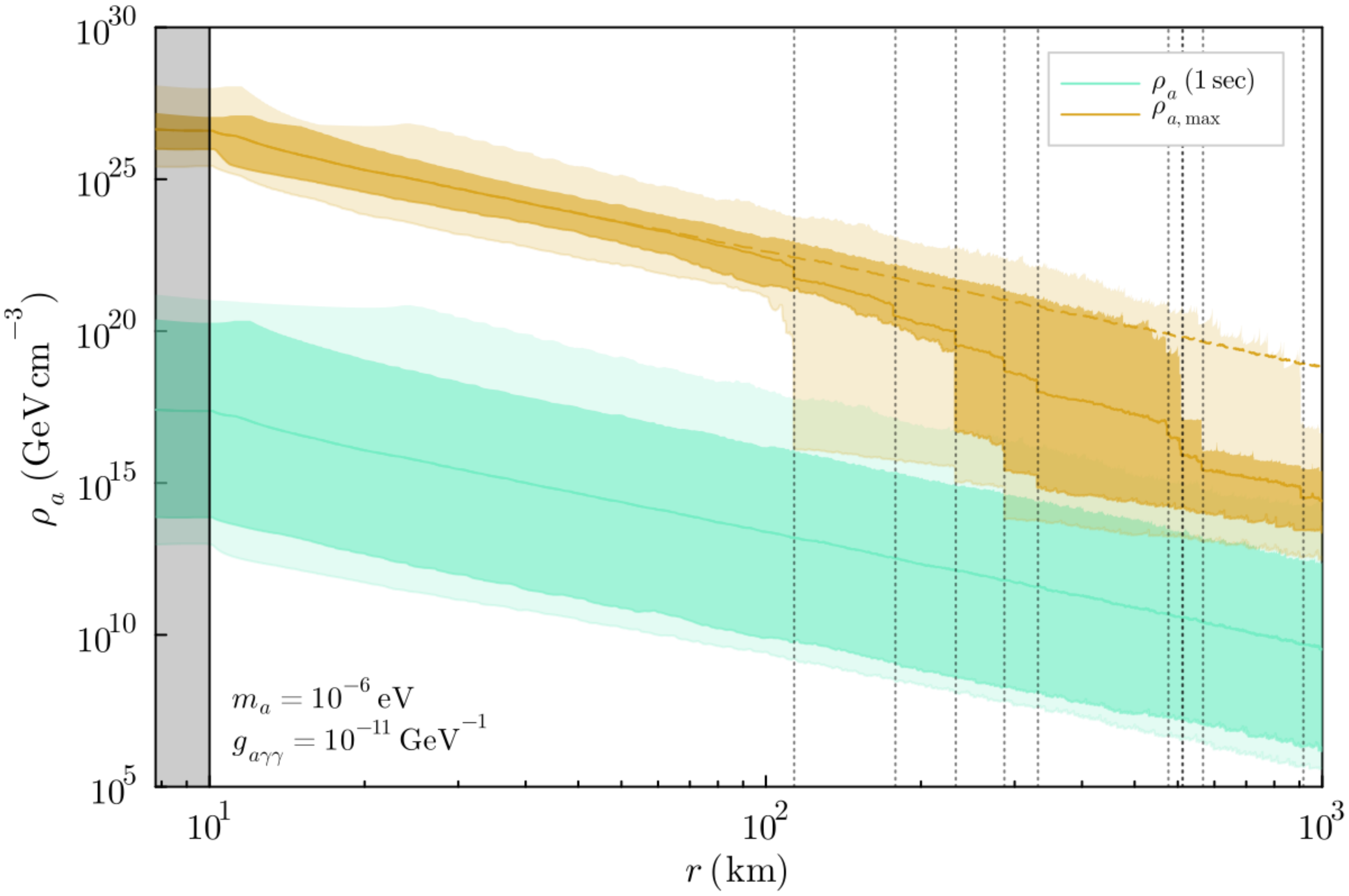


Bound state profiles

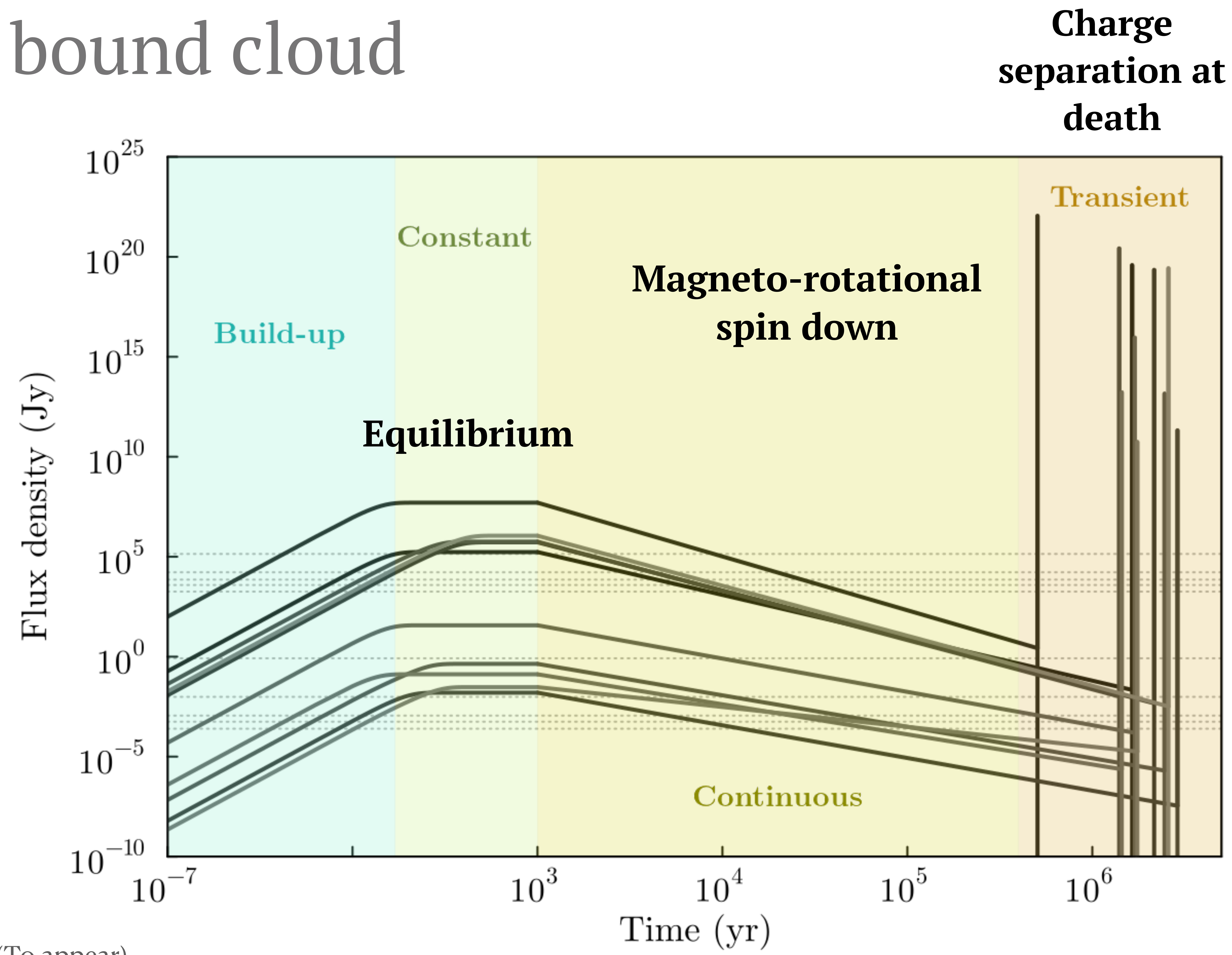


Noordhuis, Prabhu, Weniger, **SJW**(To appear)

Evolution of bound cloud

$m_a = 10^{-6}\,\mathrm{eV}$

$g_{a\gamma\gamma} = 10^{-11}\,\mathrm{GeV}^{-1}$



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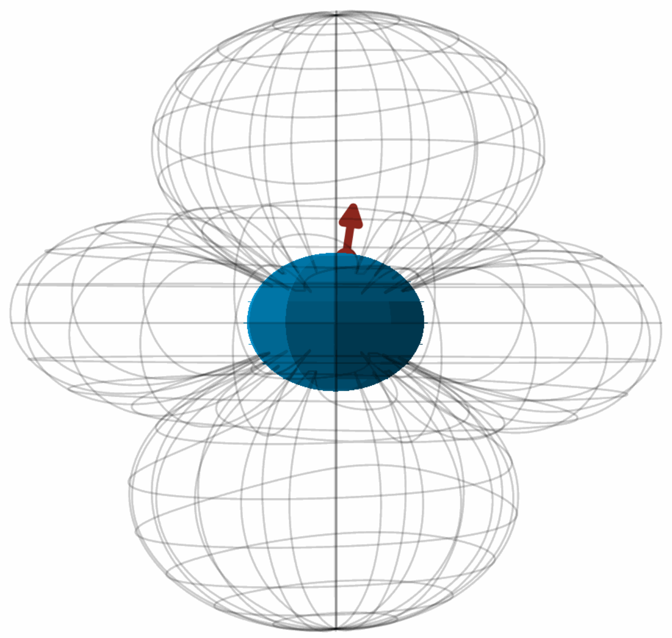
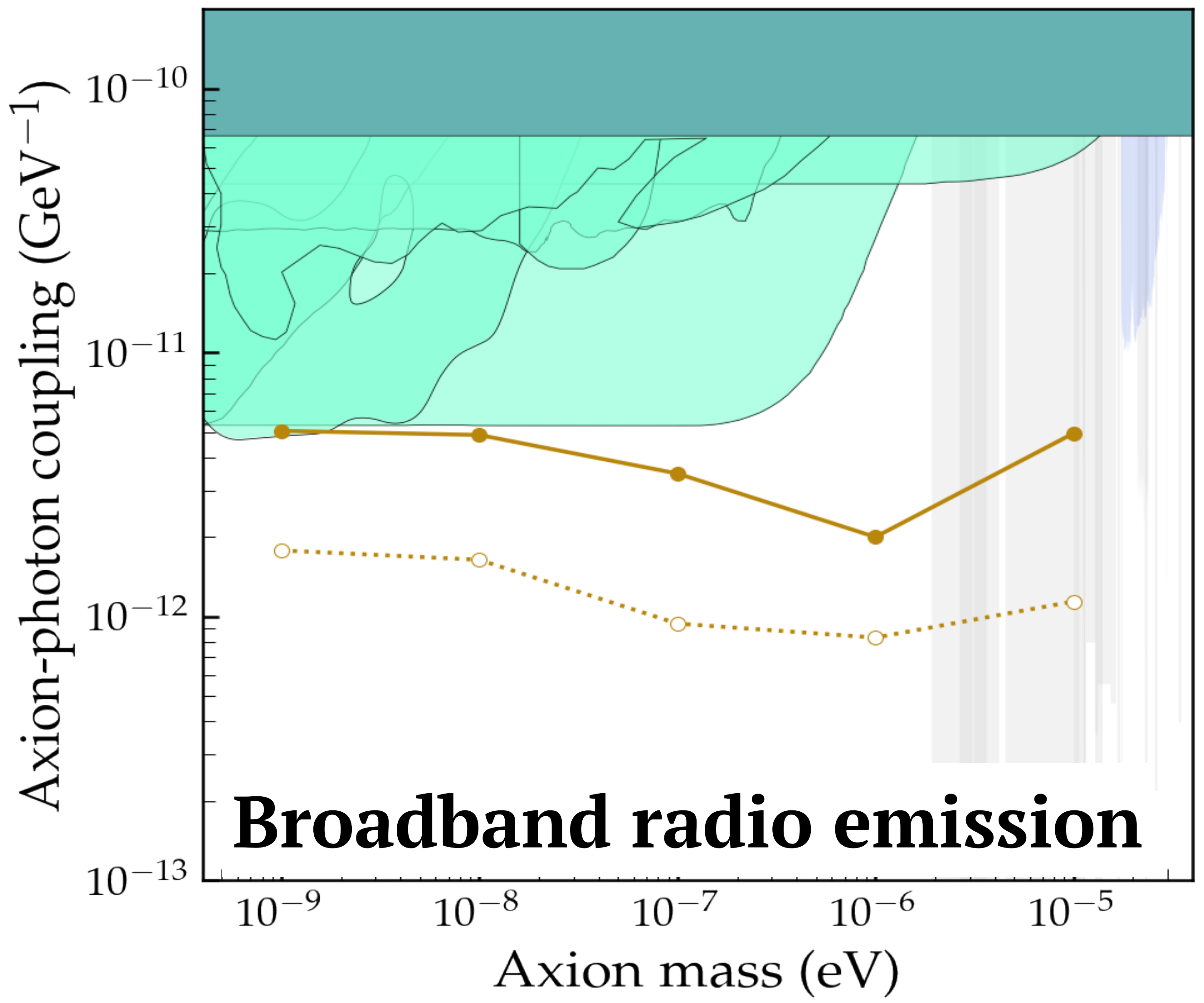
Take-Home Message

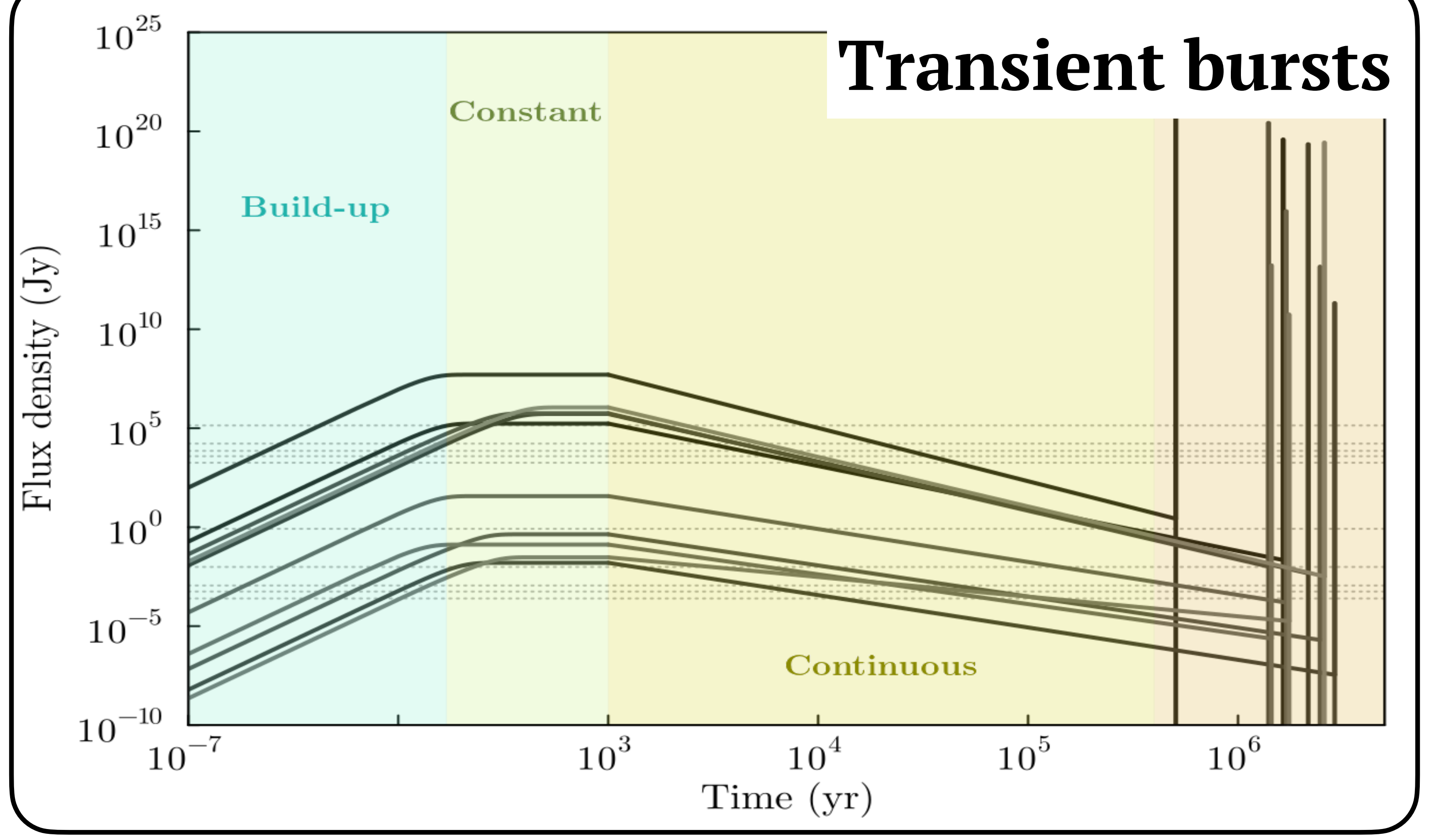


Spectral lines from axion dark matter

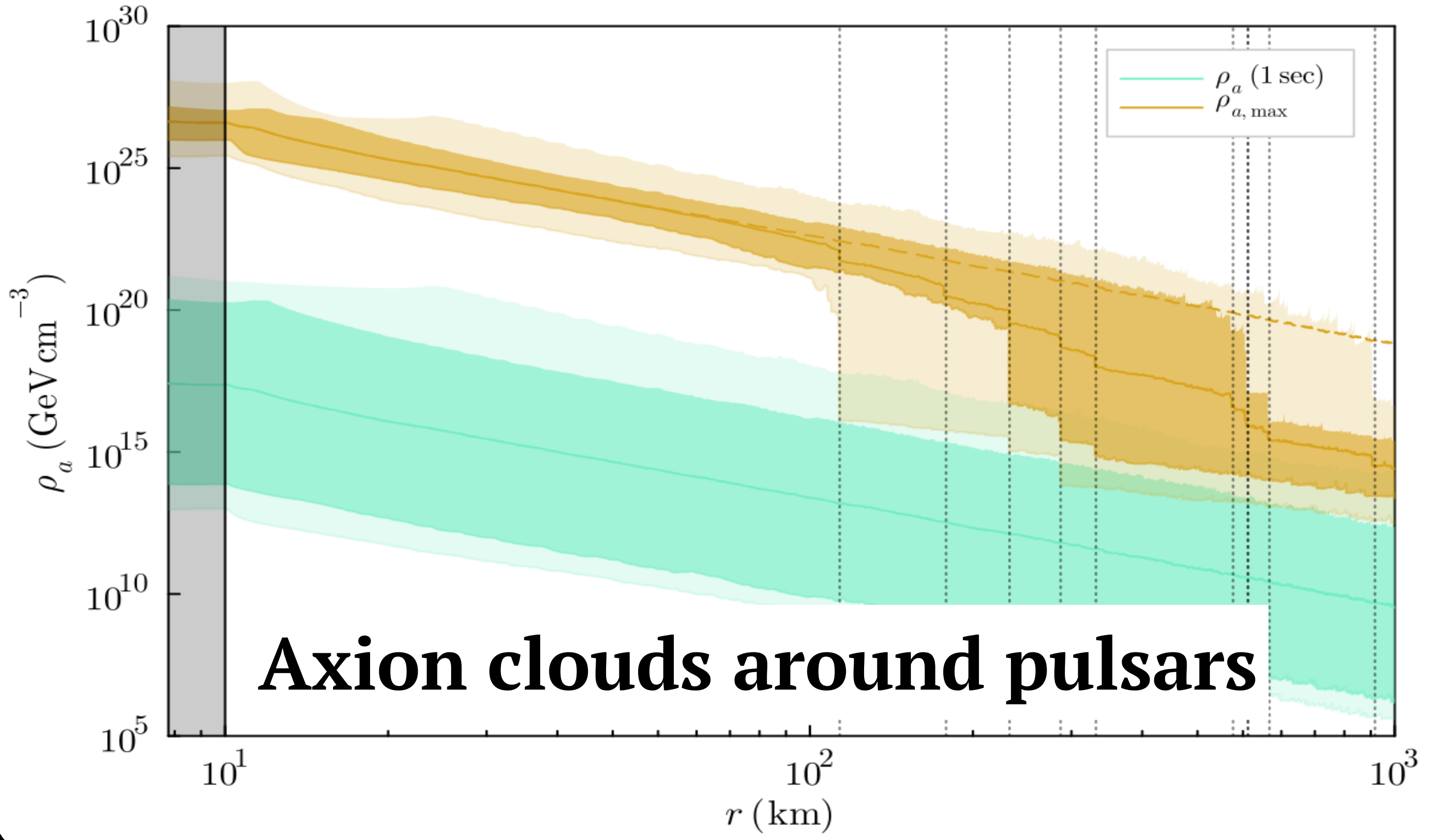
Neutron stars are incredible axion laboratories, with rich and powerful signatures



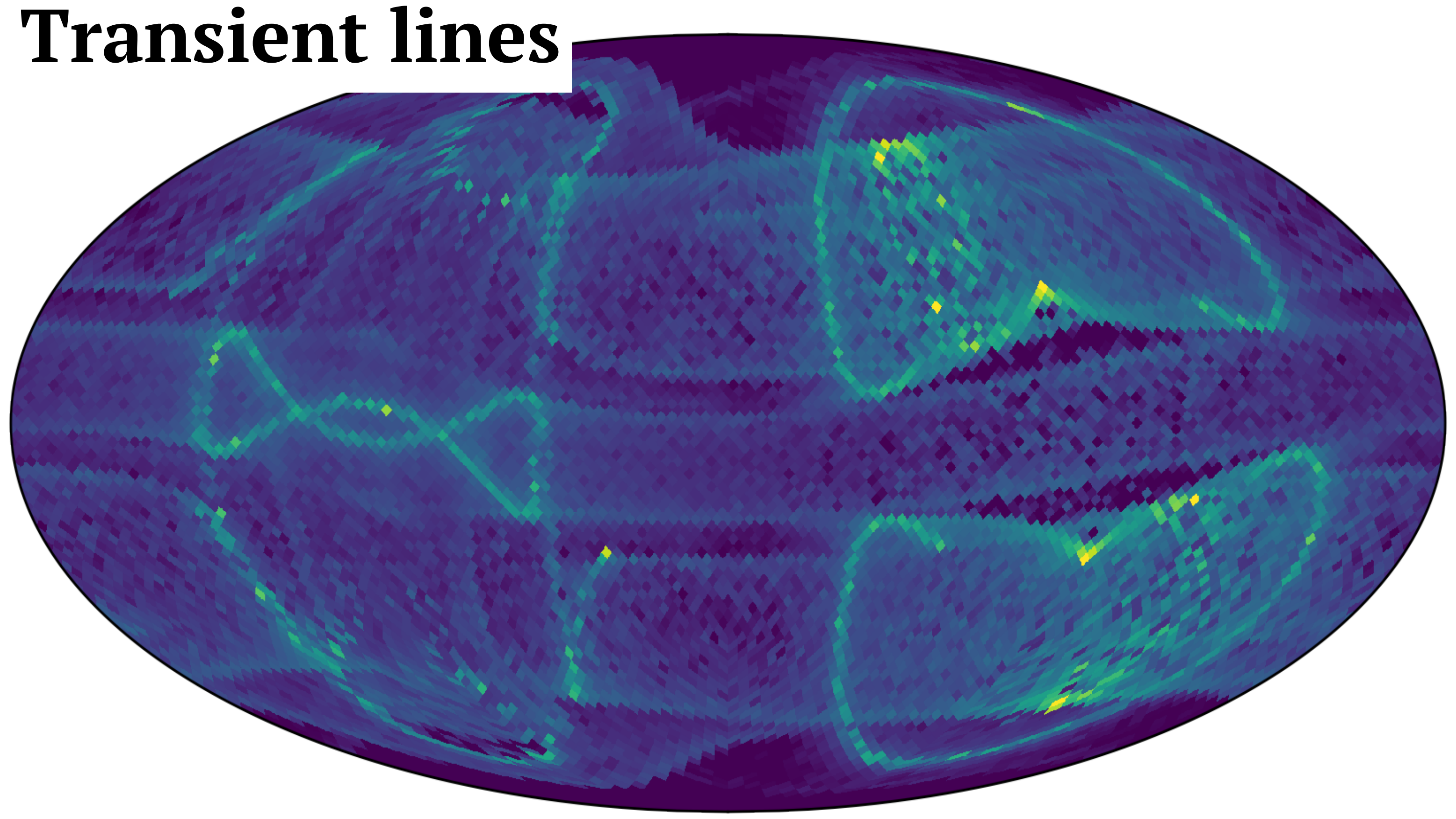
Broadband radio emission



Transient bursts

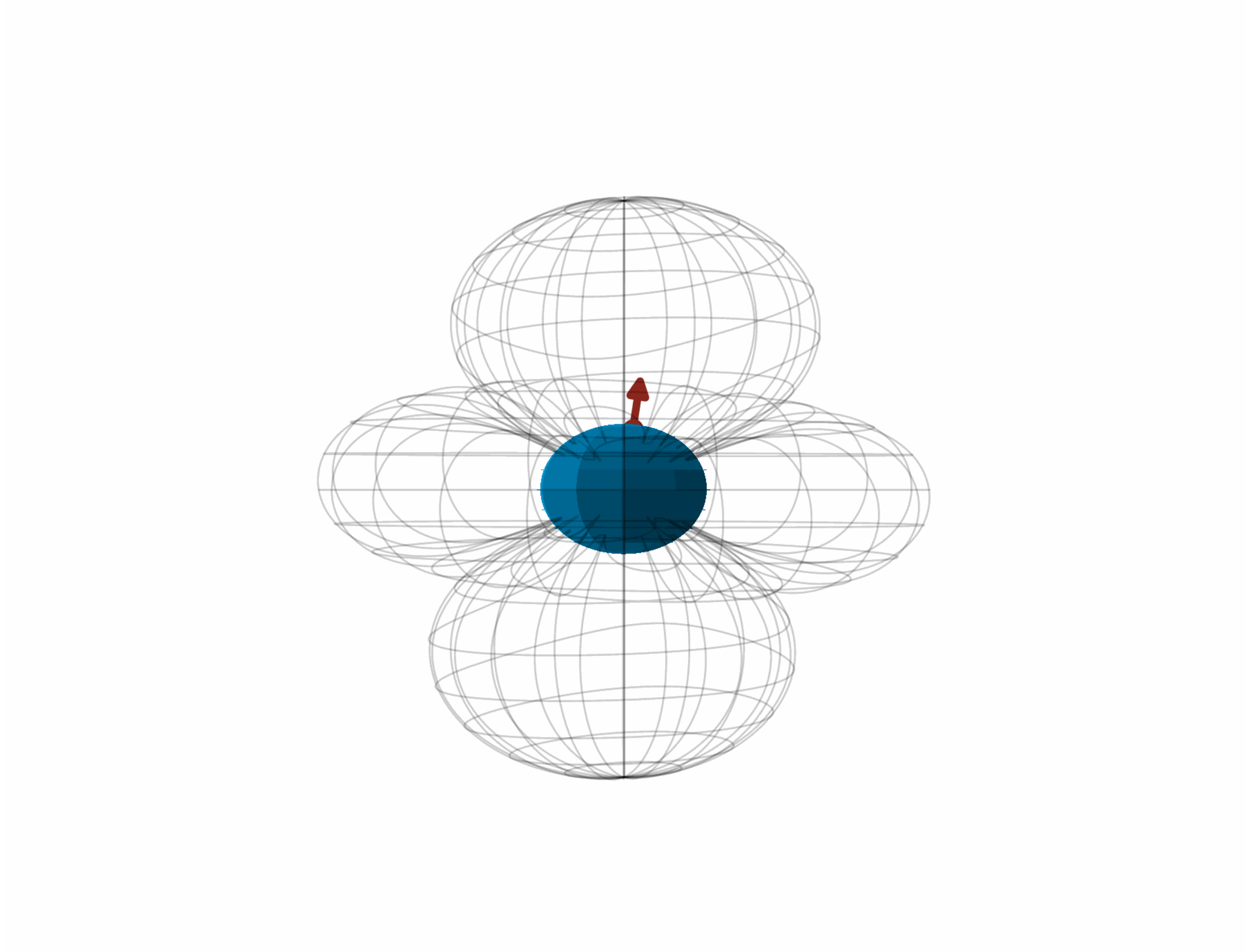


Axion clouds around pulsars



Transient lines

Take-Home Message



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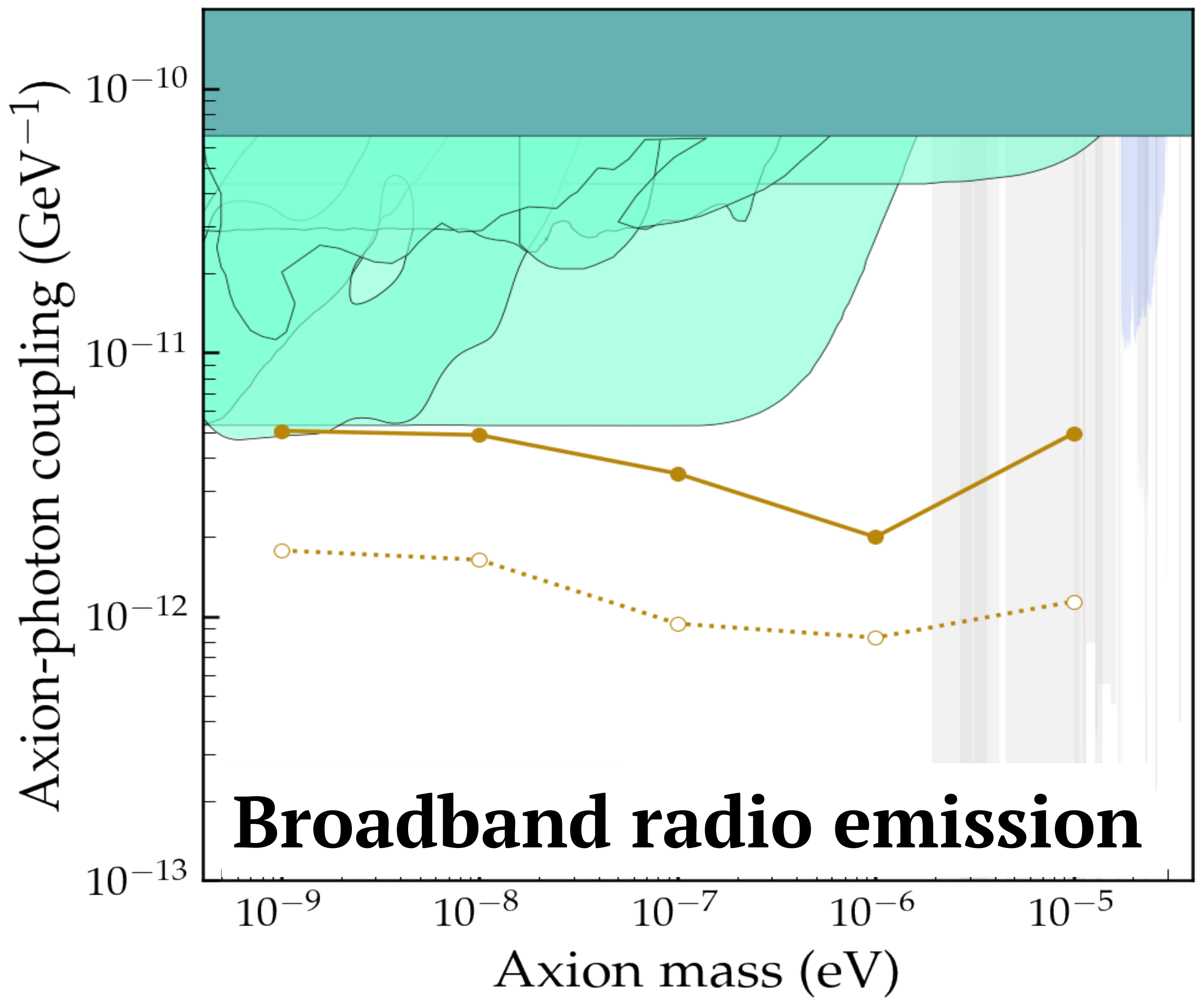

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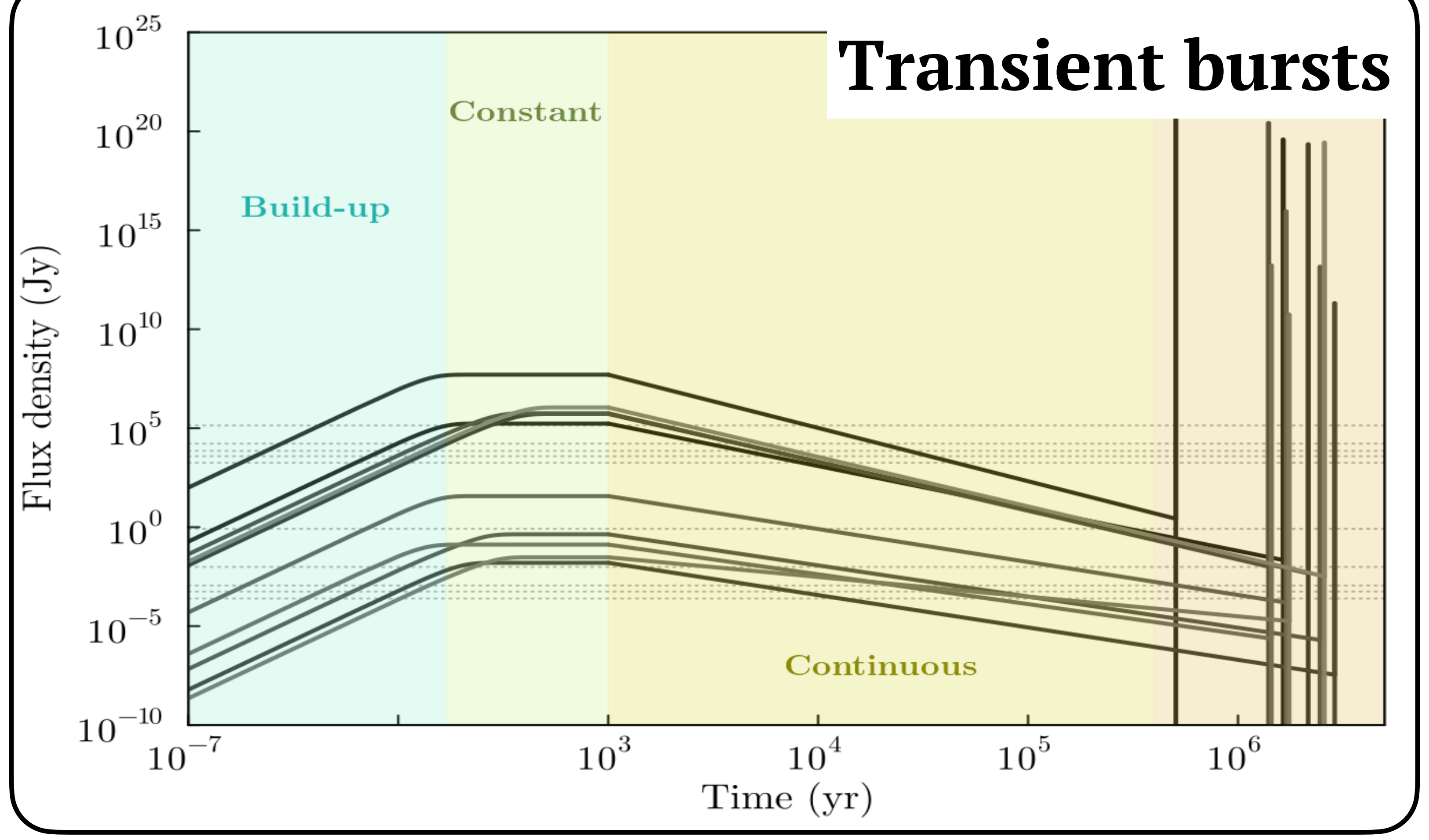

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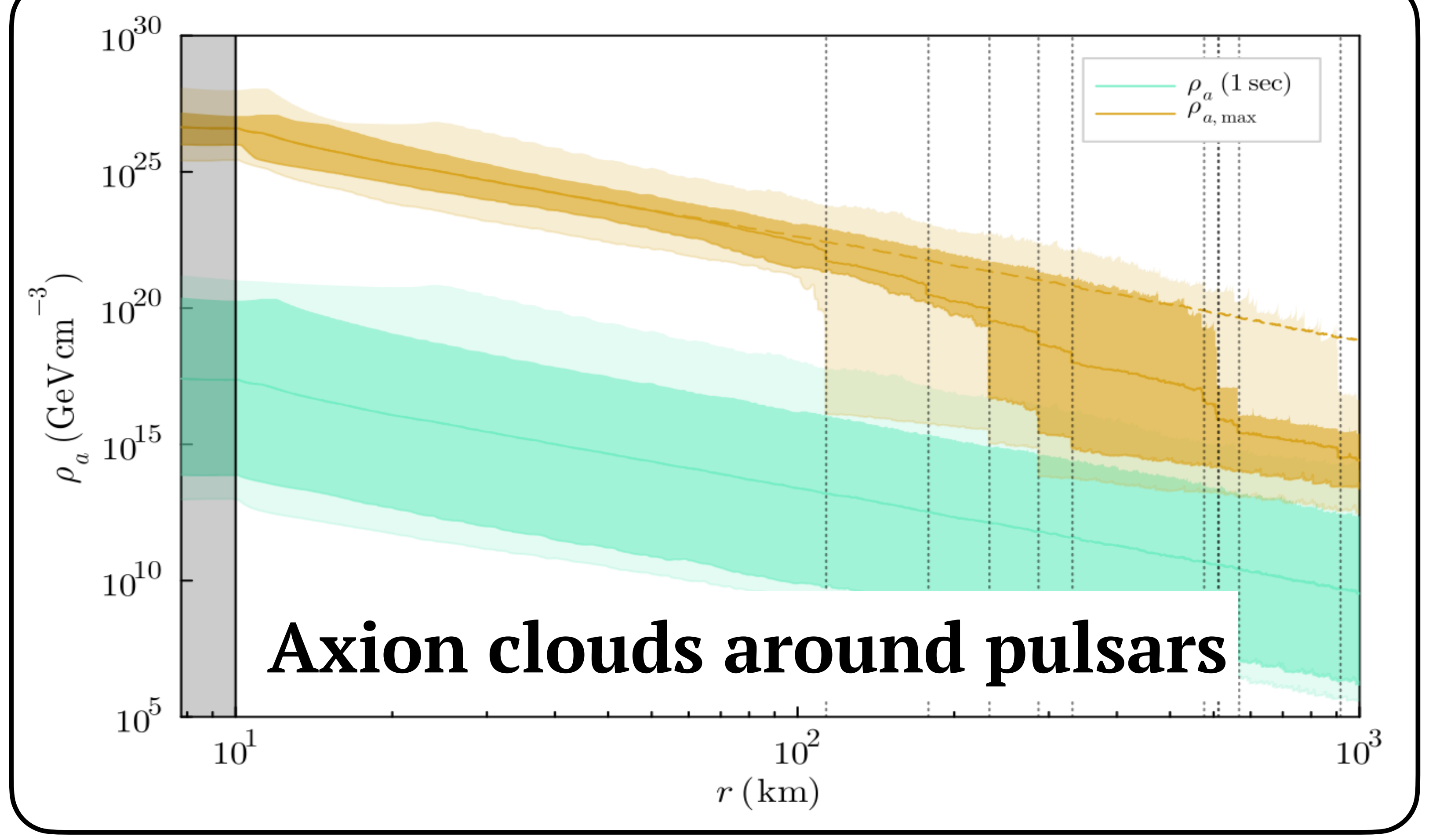

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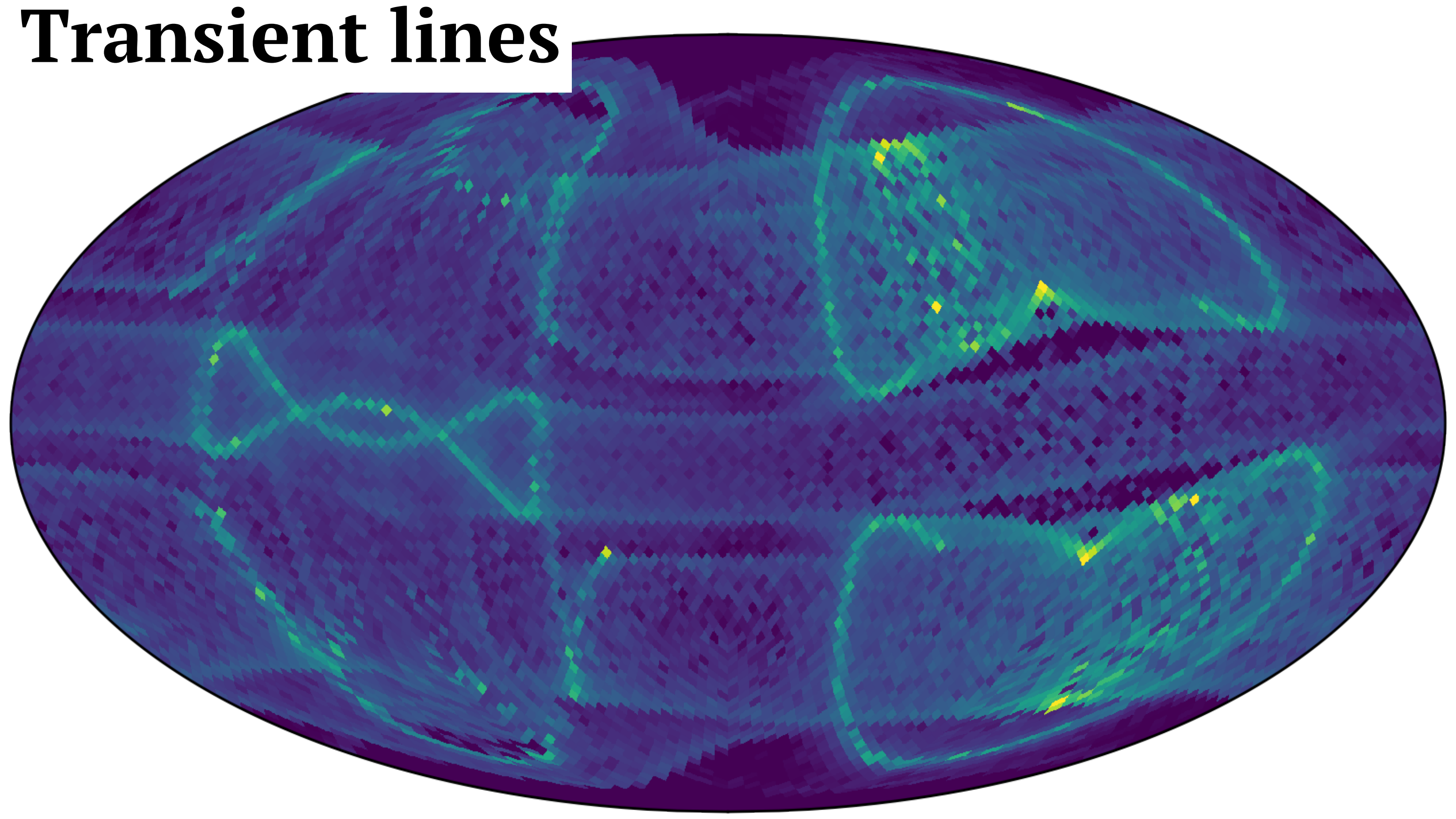

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