Sourcing Axions in the Magnetospheres of Neutron Stars

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TeVPA
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Based on work together with Samuel J. Witte, Anirudh Prabhu, Christoph Weniger, Alex Chen & Fábio Cruz

GRAPPA
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Axions

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  - The strong CP problem
  - The dark matter problem

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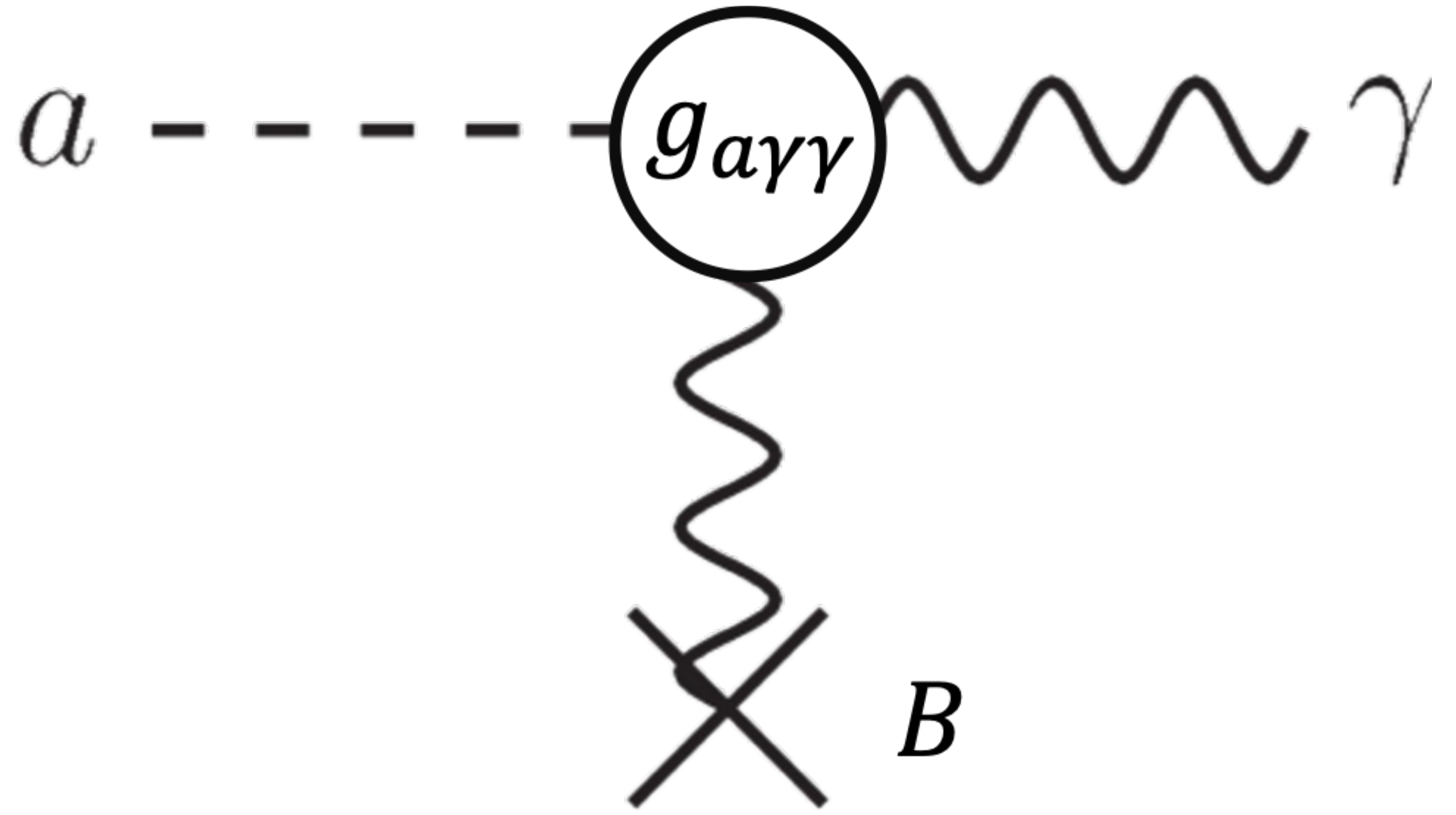
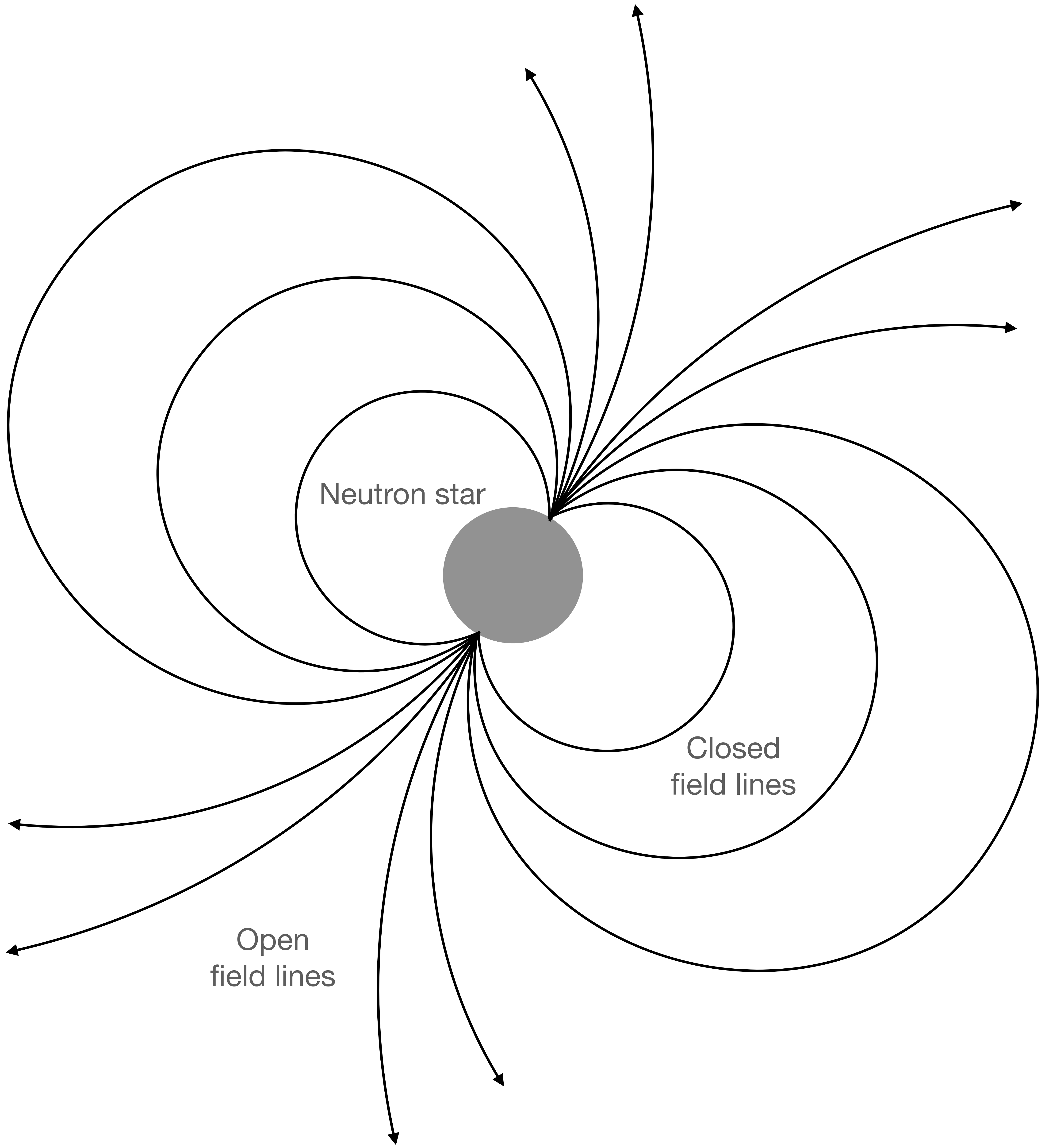
- Axions couple to the electromagnetic field via

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -\frac{1}{4} g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a$$



Sourcing of axions in vacuum gaps



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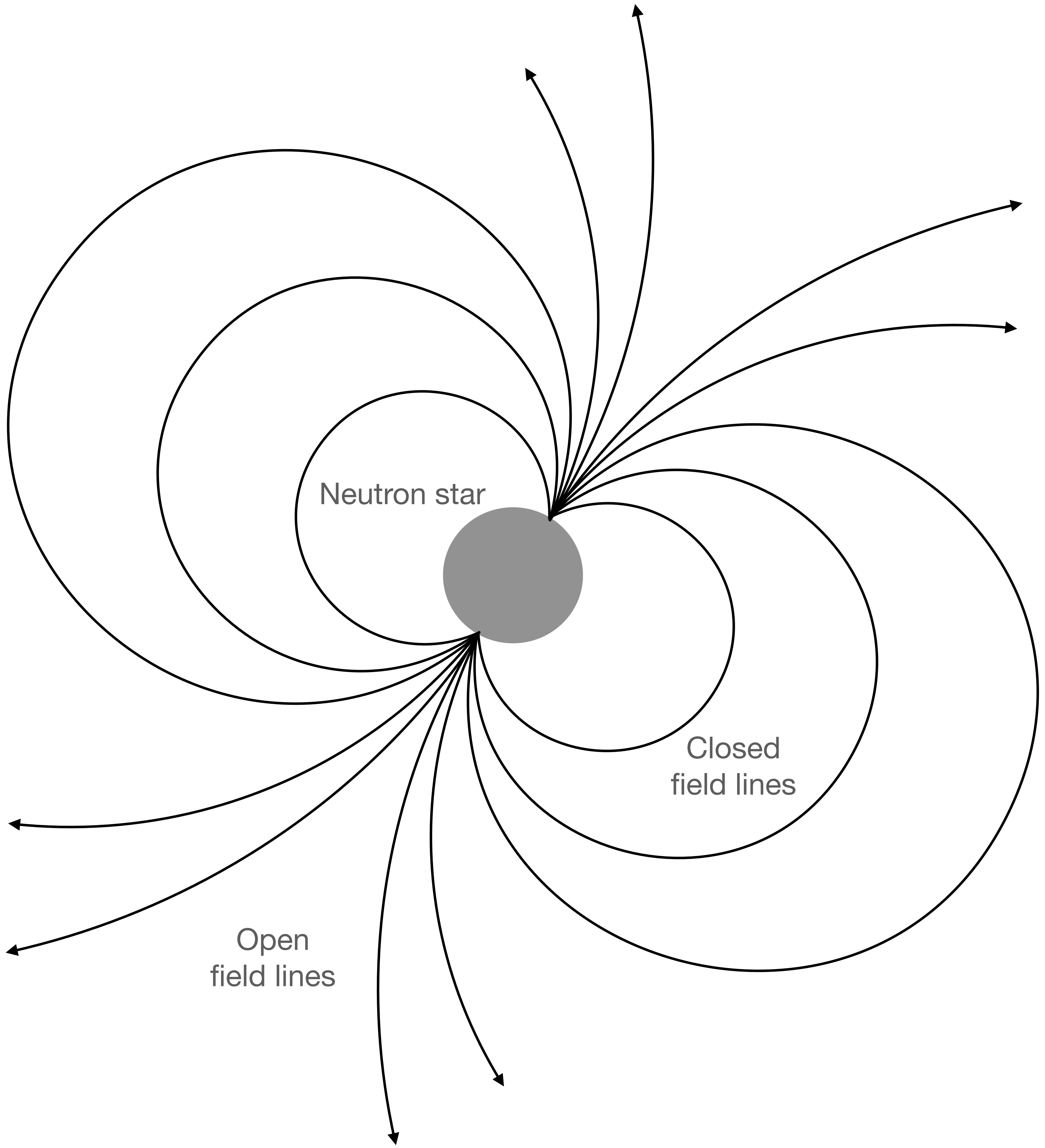

- Vacuum gap regions admit a non-zero $\vec{E} \cdot \vec{B}$, allowing for the sourcing of axions

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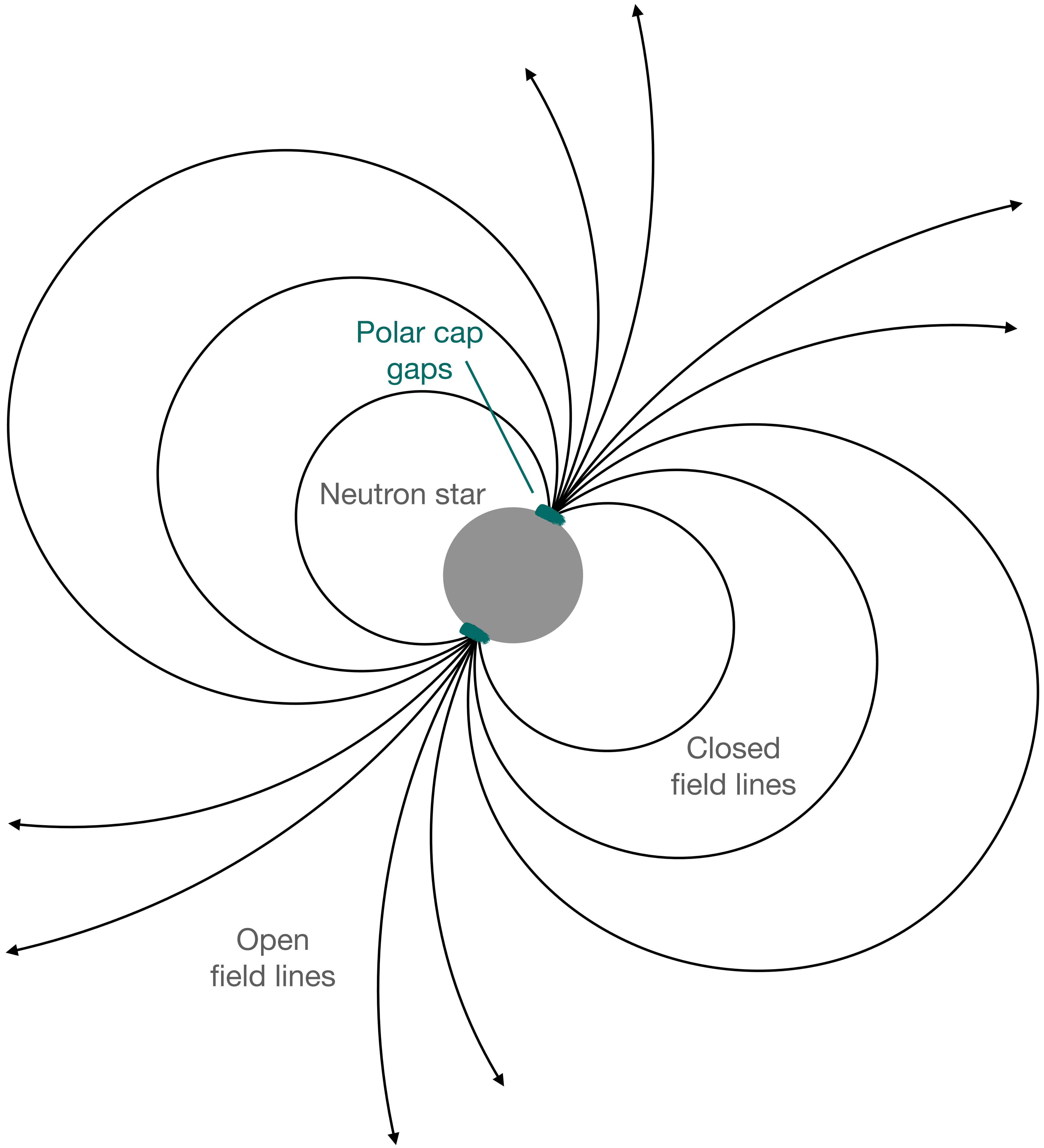

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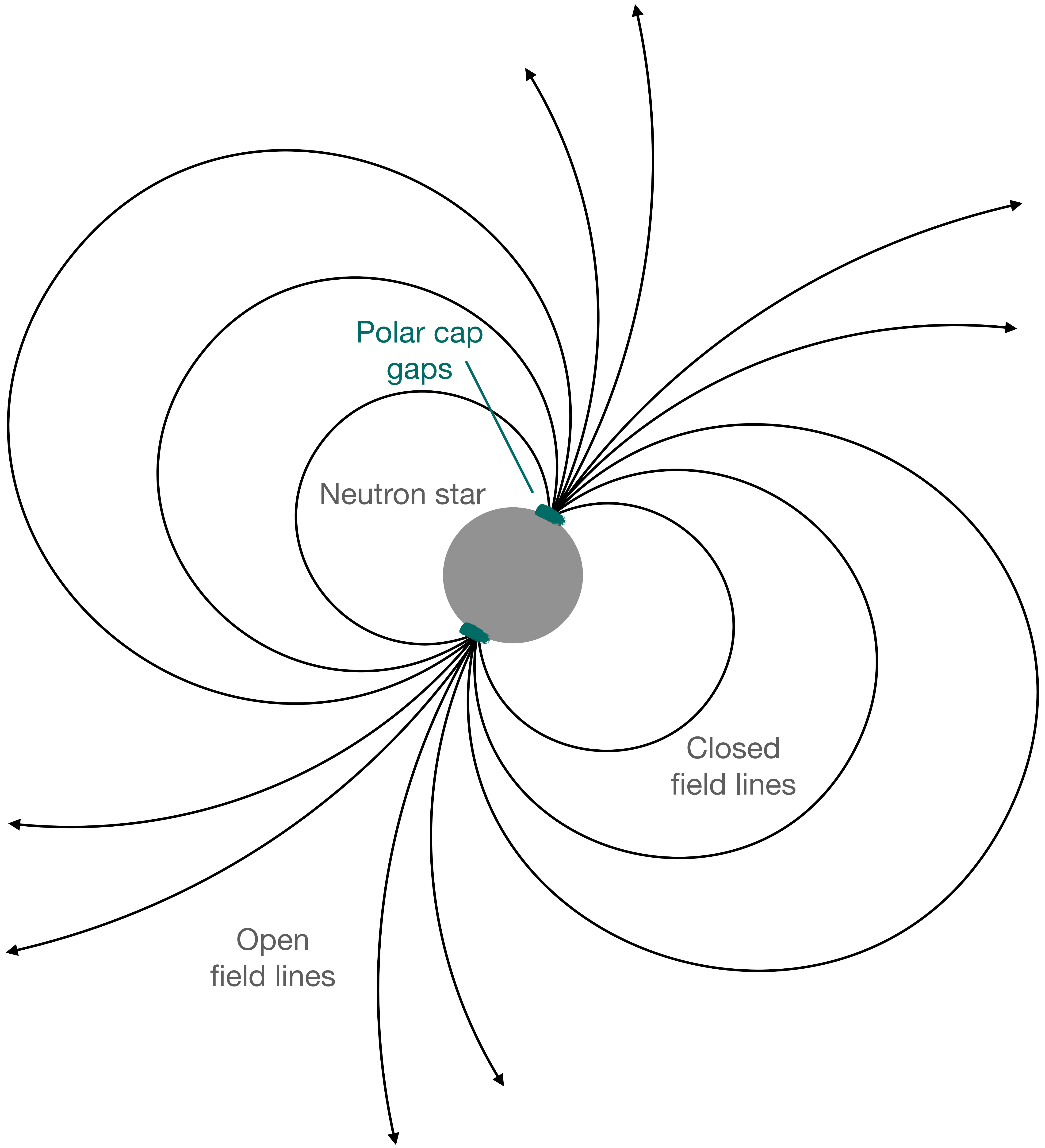
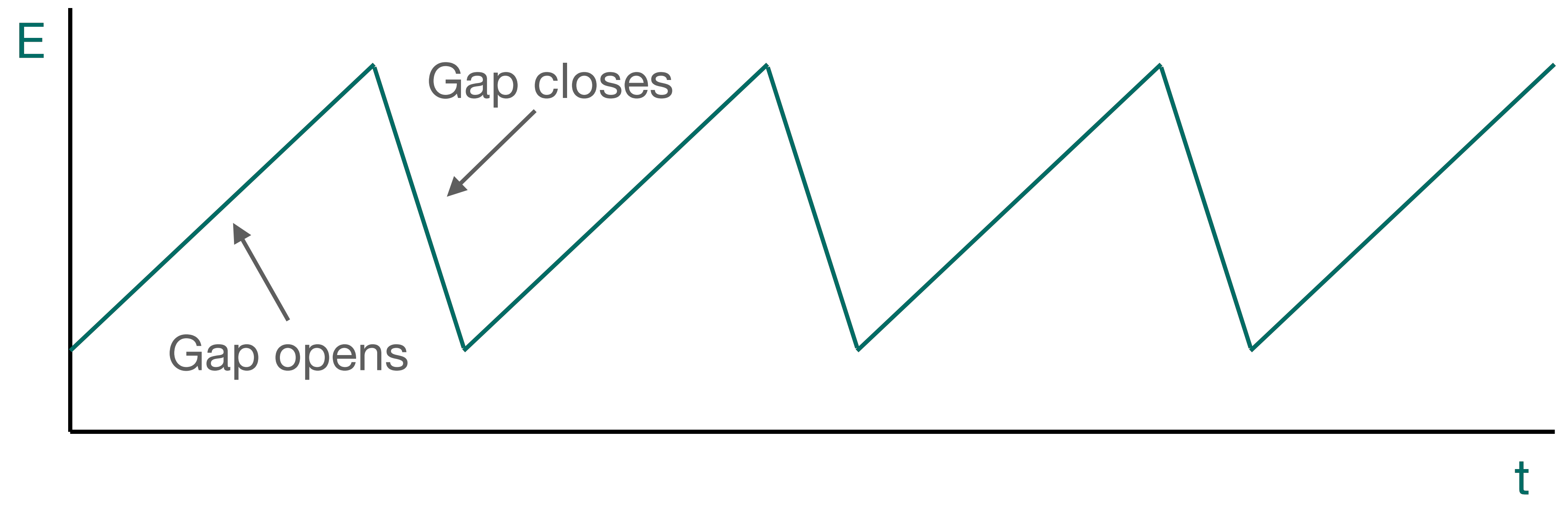


- Vacuum gap regions admit a non-zero $\vec{E} \cdot \vec{B}$, allowing for the sourcing of axions

- Due to the unstable nature of the gaps the electric field, and thereby $\vec{E} \cdot \vec{B}$, within the gaps is oscillatory

Prabhu, 2021 (arXiv 2104.14569)
DN, Prabhu, Witte, Chen, Cruz, Weniger, 2022 (arXiv 2209.09917)



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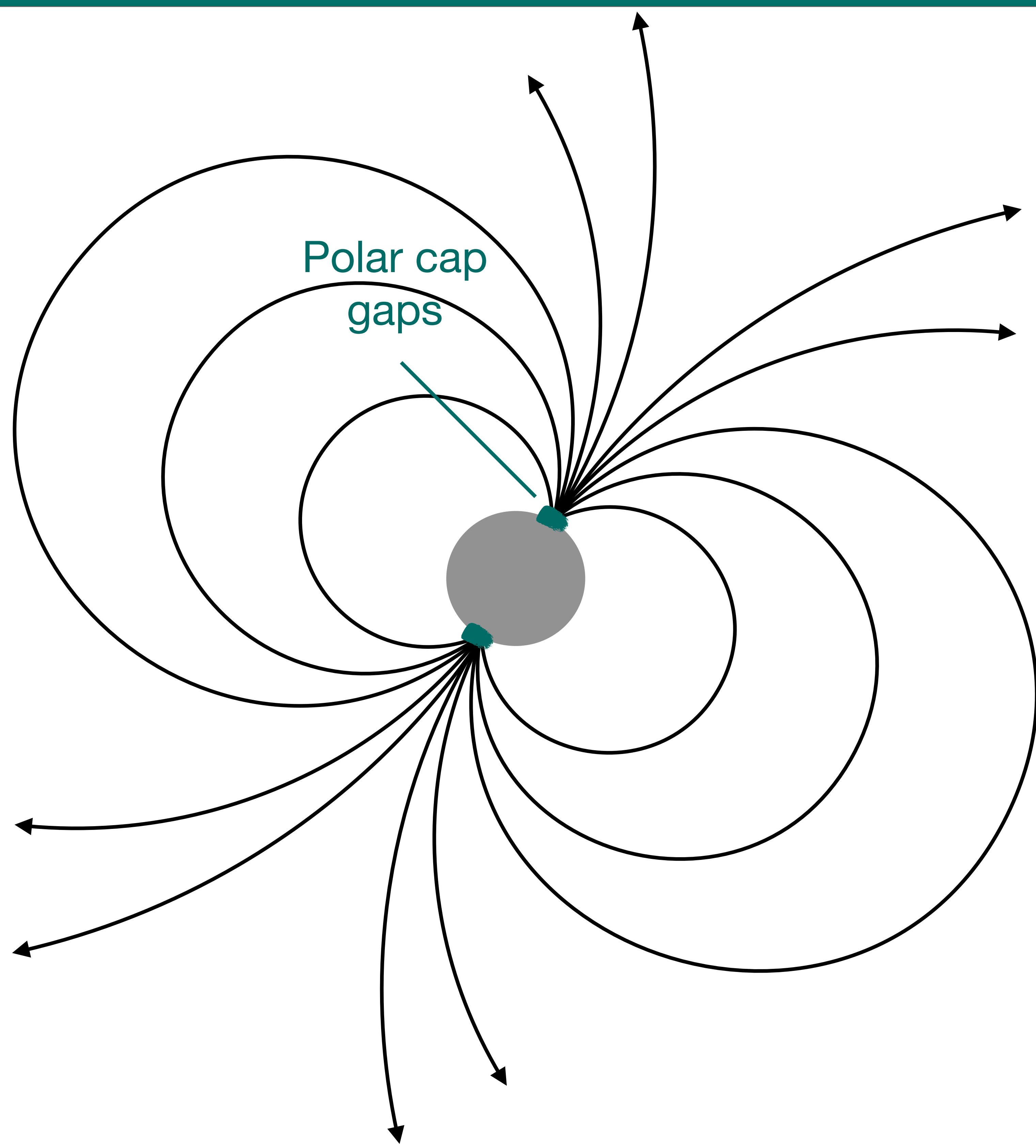

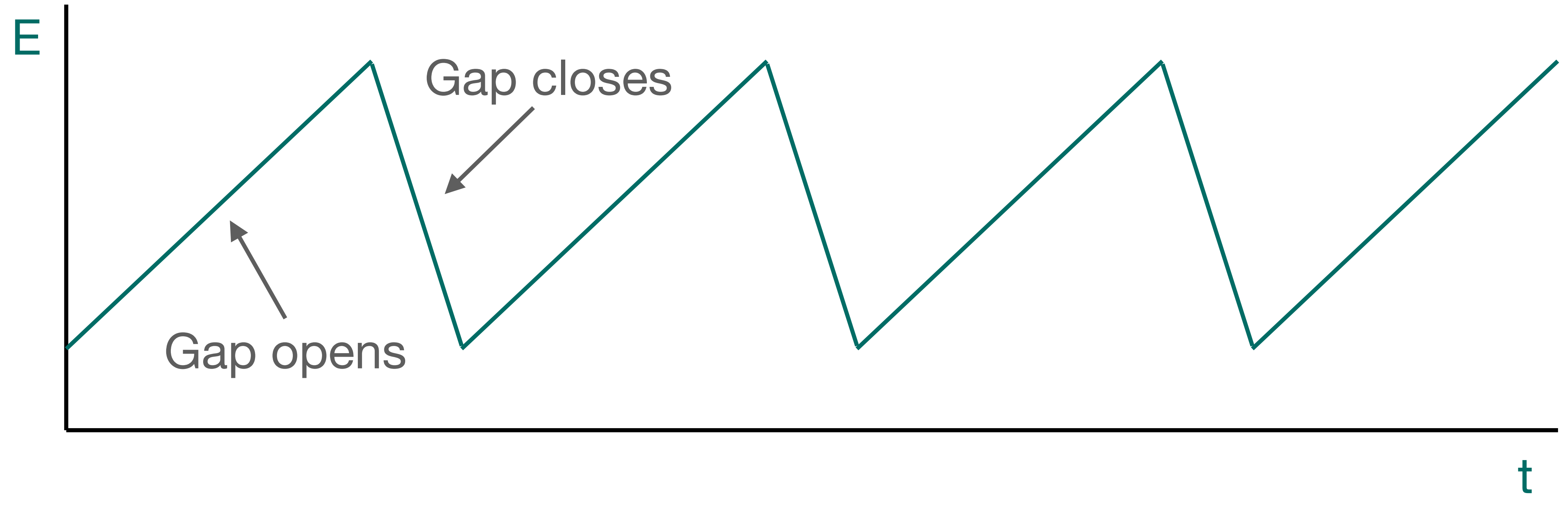

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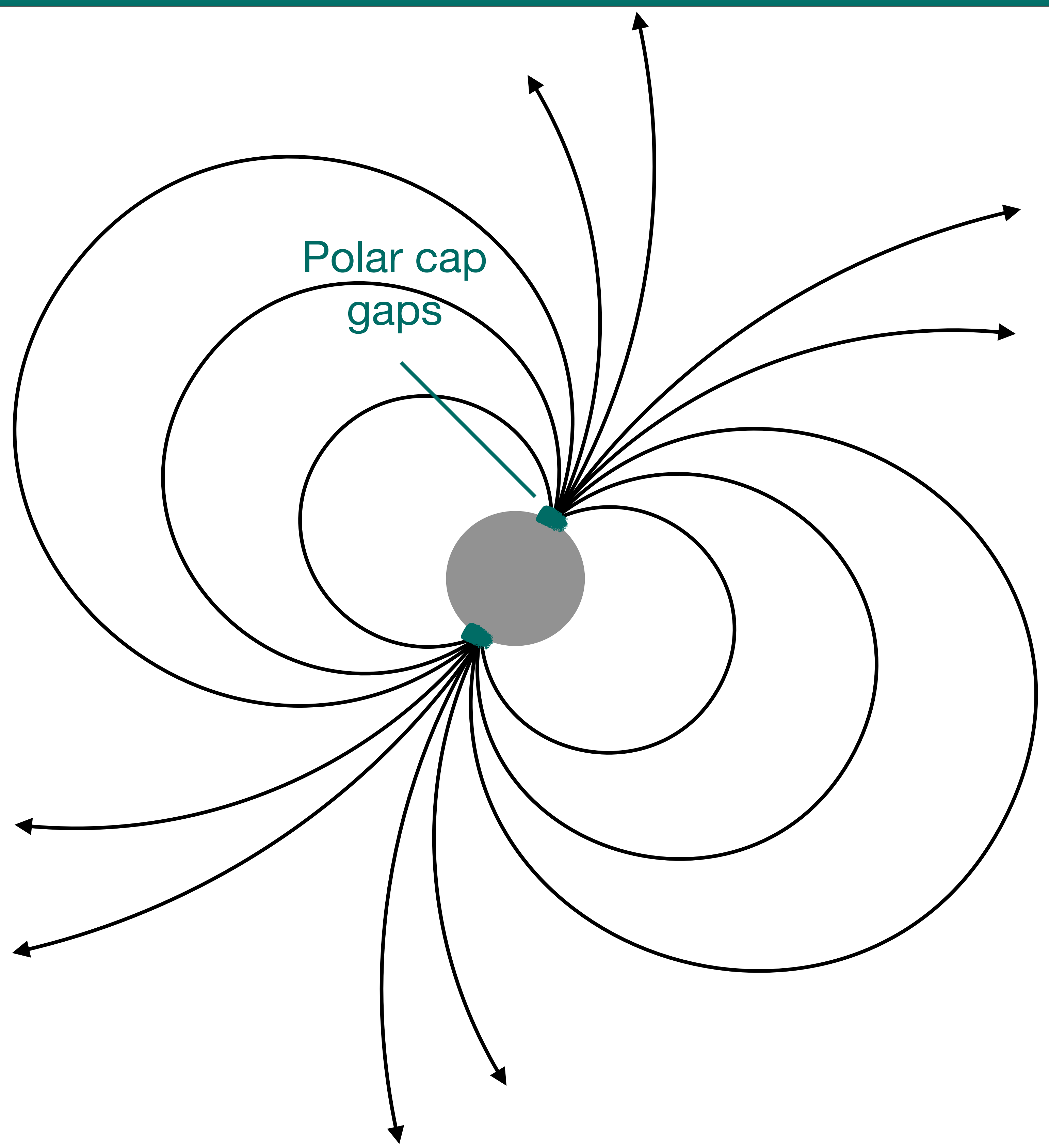
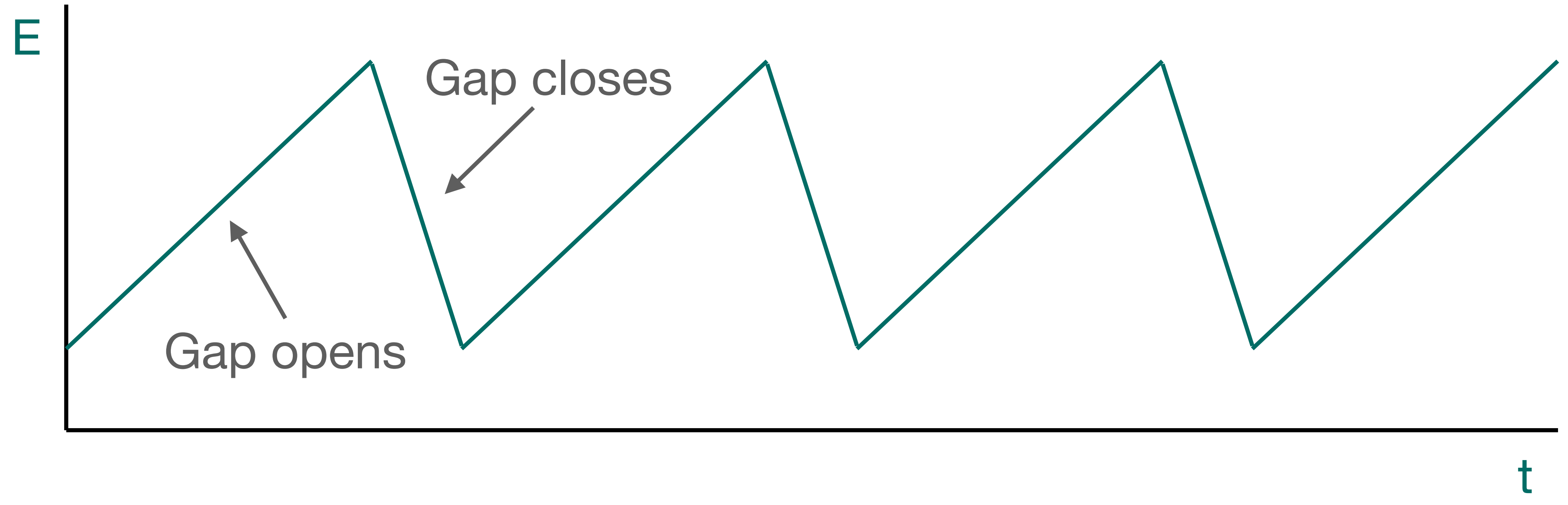
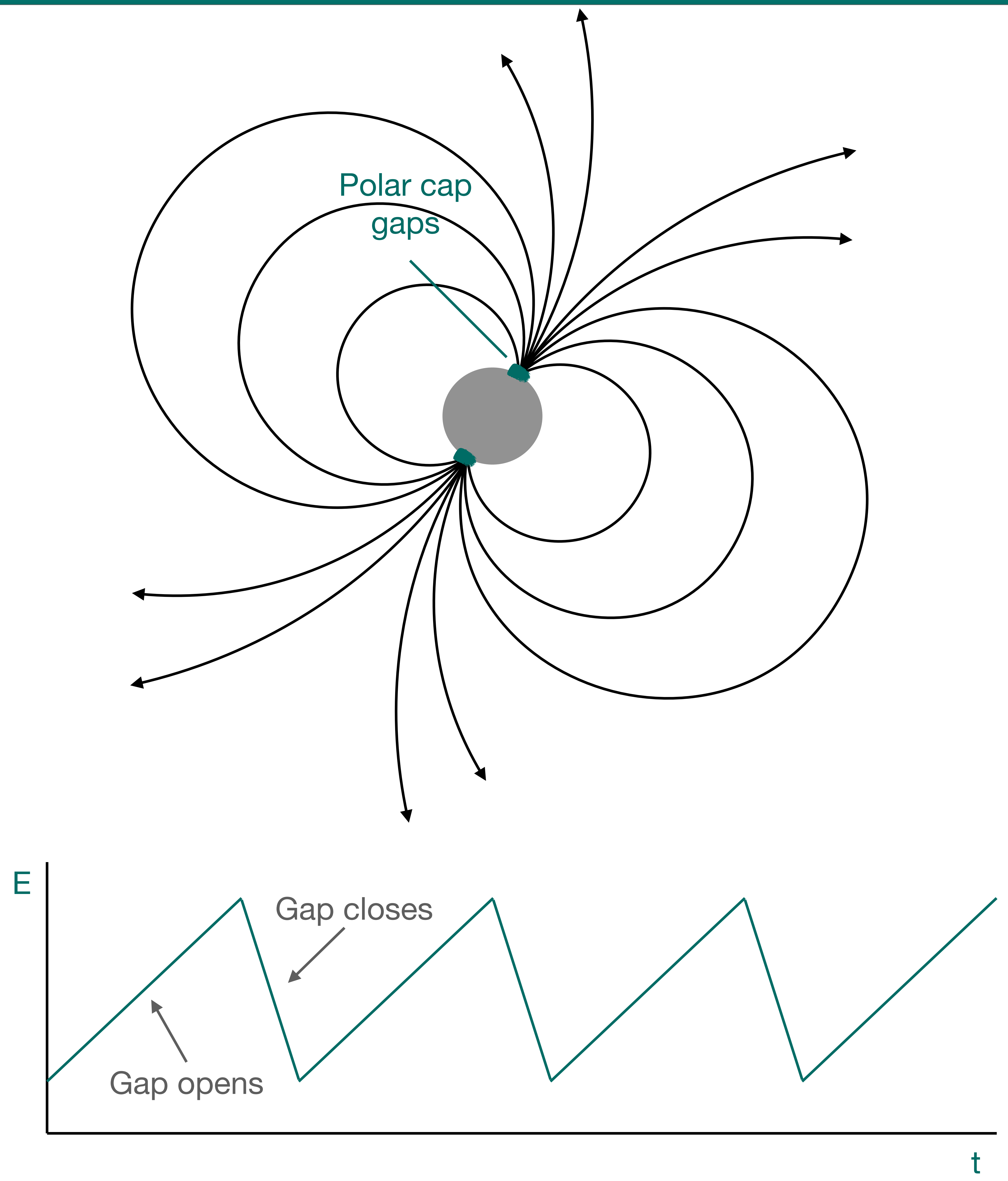




- The oscillating electric field in the gap determines the initial axion spectrum

- Initial axion energies correspond to Fourier modes of the electric field oscillation

Sourcing of axions in vacuum gaps



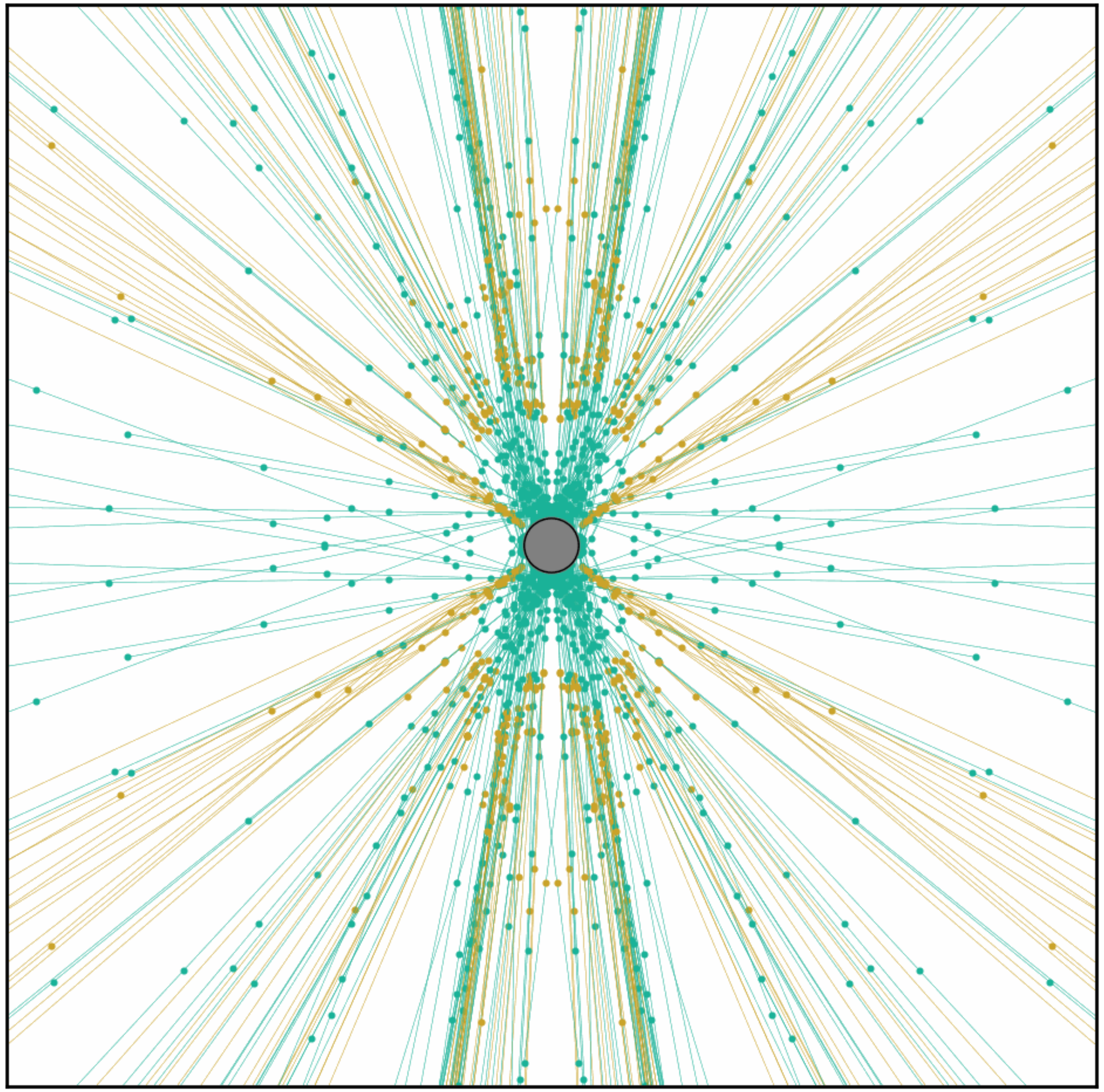
- The oscillating electric field in the gap determines the initial axion spectrum
- Initial axion energies correspond to Fourier modes of the electric field oscillation
- Axions can be produced relativistically and escape, or non-relativistically and lead to bound states.

Prabhu, 2021 (arXiv 2104.14569)
DN, Prabhu, Witte, Chen, Cruz, Weniger, 2022 (arXiv 2209.09917)

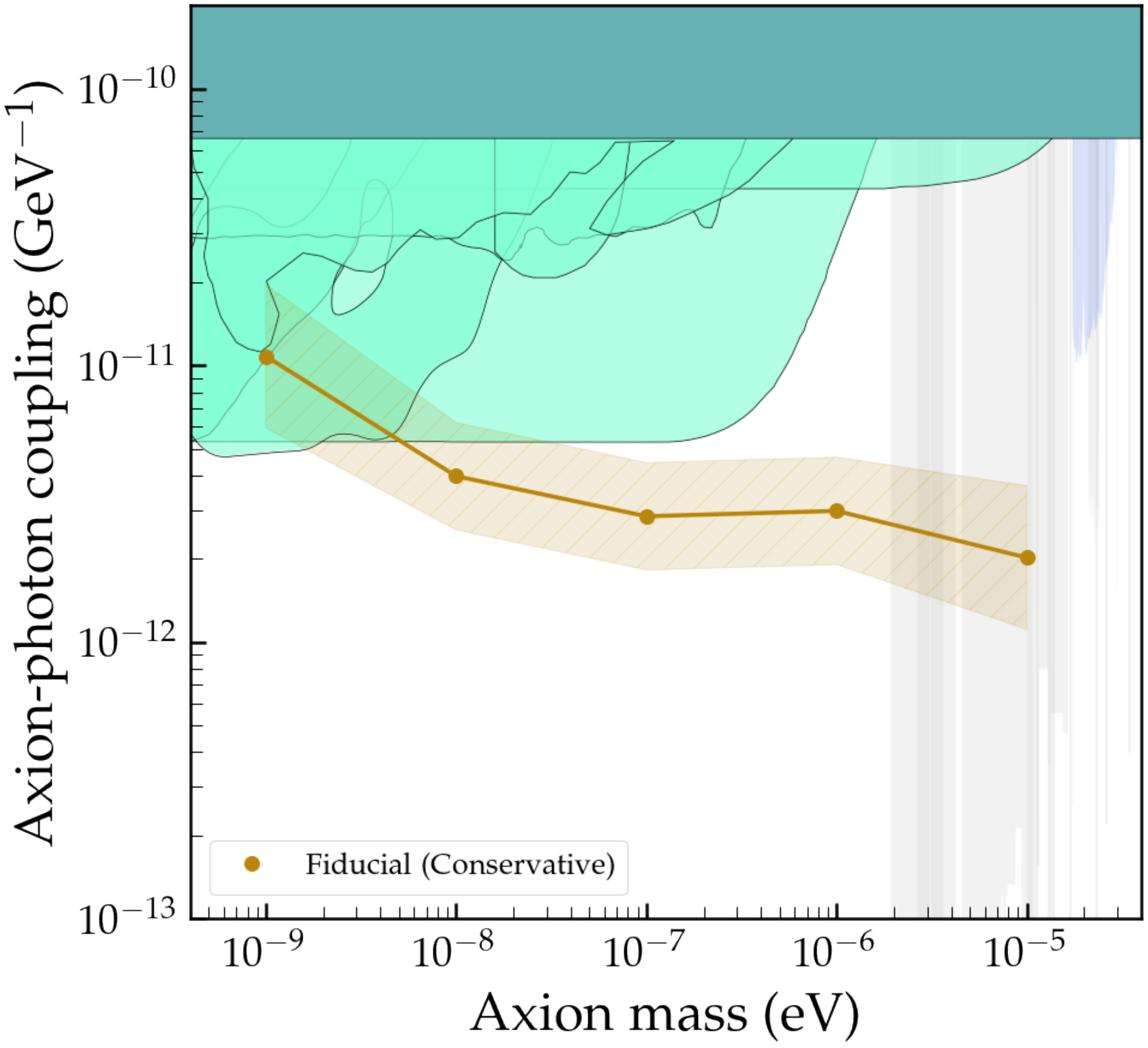
Escaping axions

- Escaping axions can resonantly convert into photons
- Resonant conversion takes place when $k_a \simeq k_\gamma$
- This process produces a large flux of radio photons

DN, Prabhu, Witte, Chen, Cruz, Weniger, 2022 (arXiv 2209.09917)



Escaping axions - limits on $g_{a\gamma\gamma}$



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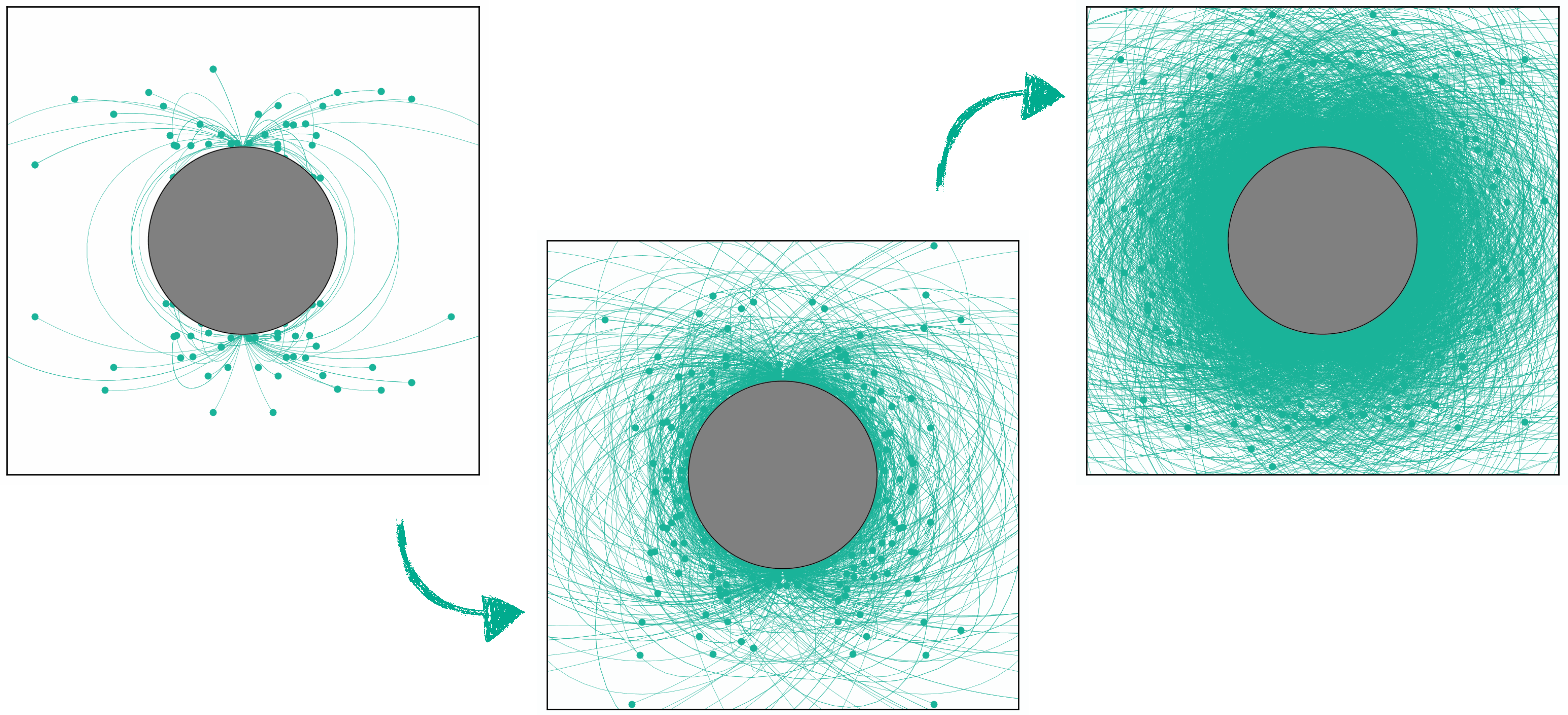
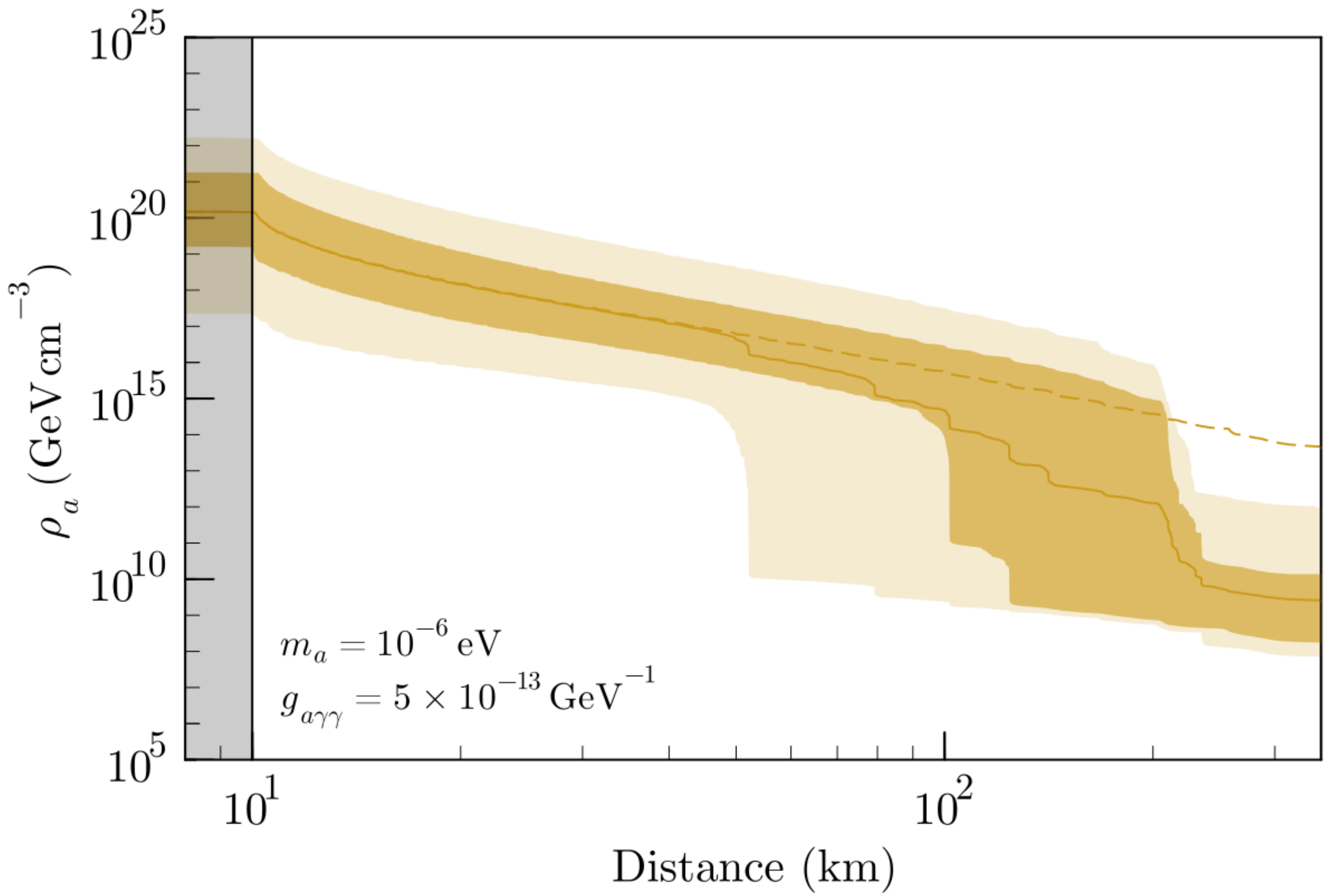
Made using: https://github.com/cajohare/AxionLimits

Bound axions



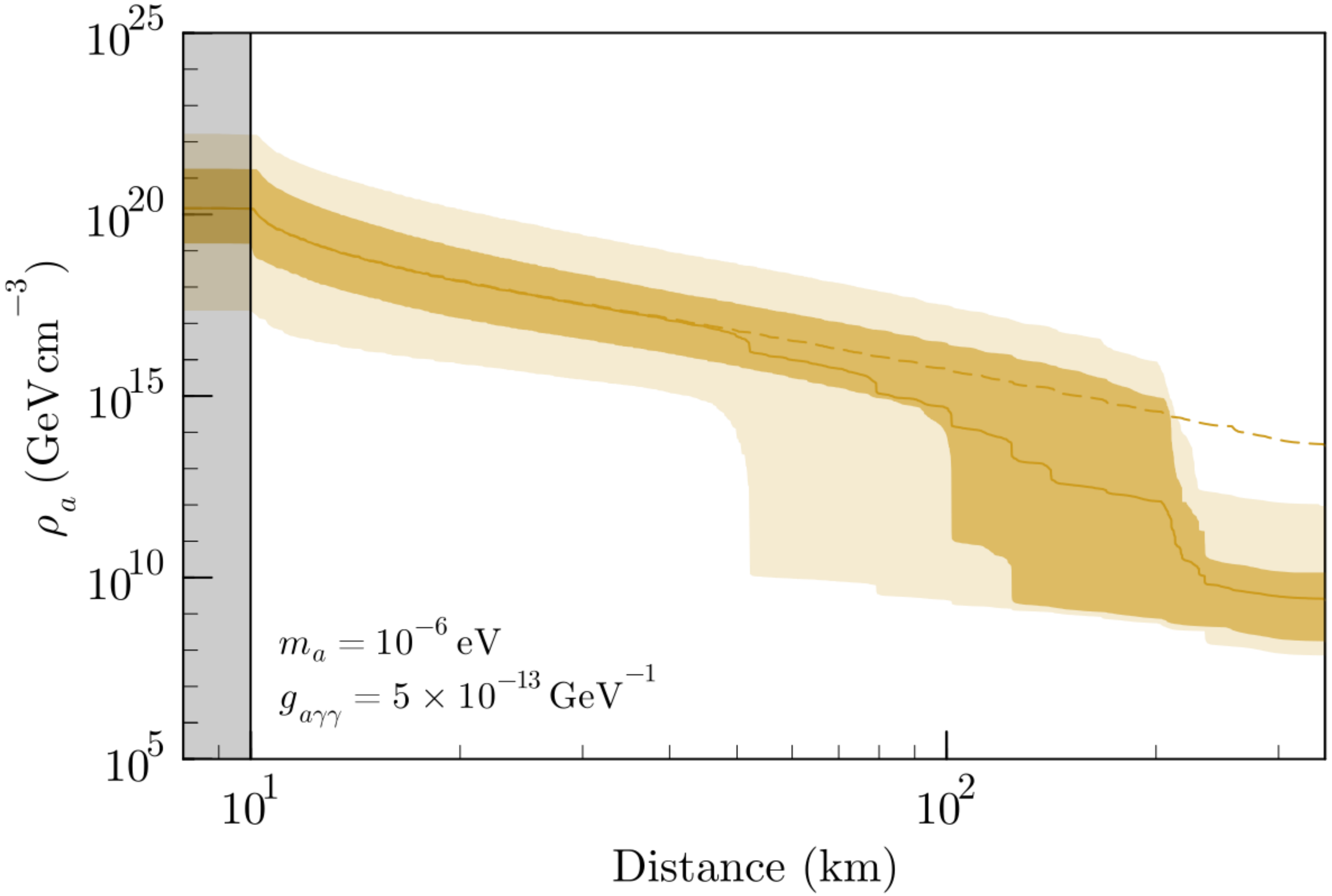
Bound axions - cloud density



Bound axions - cloud density

- Axion cloud densities can reach, and potentially exceed, values as high as $10^{25}\,\mathrm{GeV\,cm^{-3}}$

- Achieved densities are substantial even for low axion-photon couplings



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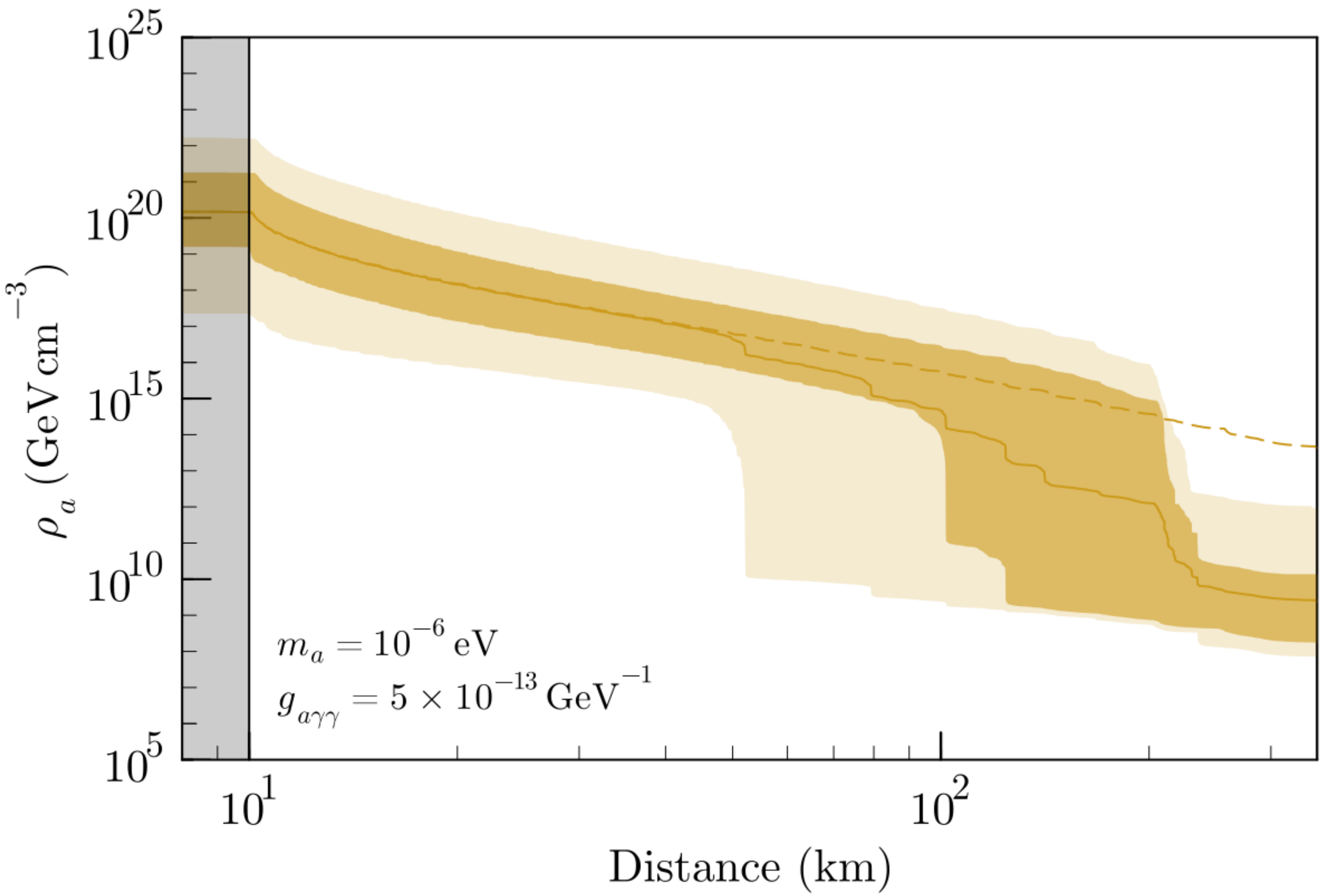

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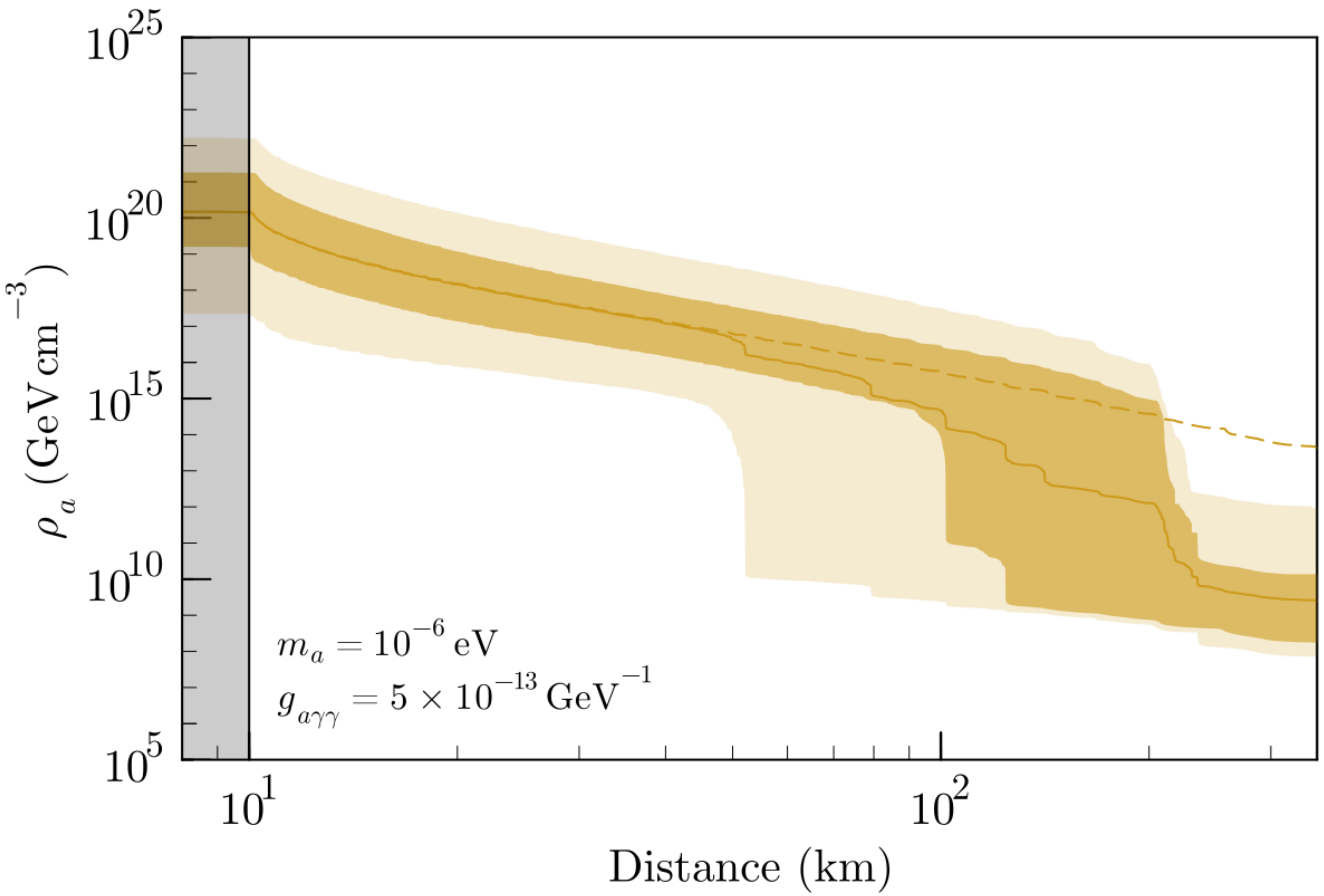
- Not including dissipation mechanisms, the density profile scales like $\rho(r) \propto r^{-4}$
- Resonant axion-photon conversions provide a strong observable in the form of radio signals



DN, Prabhu, Weniger, Witte 2023 (arXiv 2307.11811)

Conclusions

- Axions can be sourced in neutron star vacuum gaps ⇒ relativistic axions escape, non-relativistic axions lead to bound states and an axion cloud

- Resonant conversion of the axions provides a strong observable ⇒ our pipeline facilitates an end-to-end calculation from initial axion spectra to final radio fluxes

- Method yields the strongest constraints to date on $g_{a\gamma\gamma}$ for the mass range $m_a \approx 10^{-8} - 10^{-5}\,\mathrm{eV}$

Thank you for your attention!

Backup slides

Pipeline

(1) Calculate initial axion spectrum

↓

(2) Axion propagation

↓

(3) Compute resonant axion-photon conversion

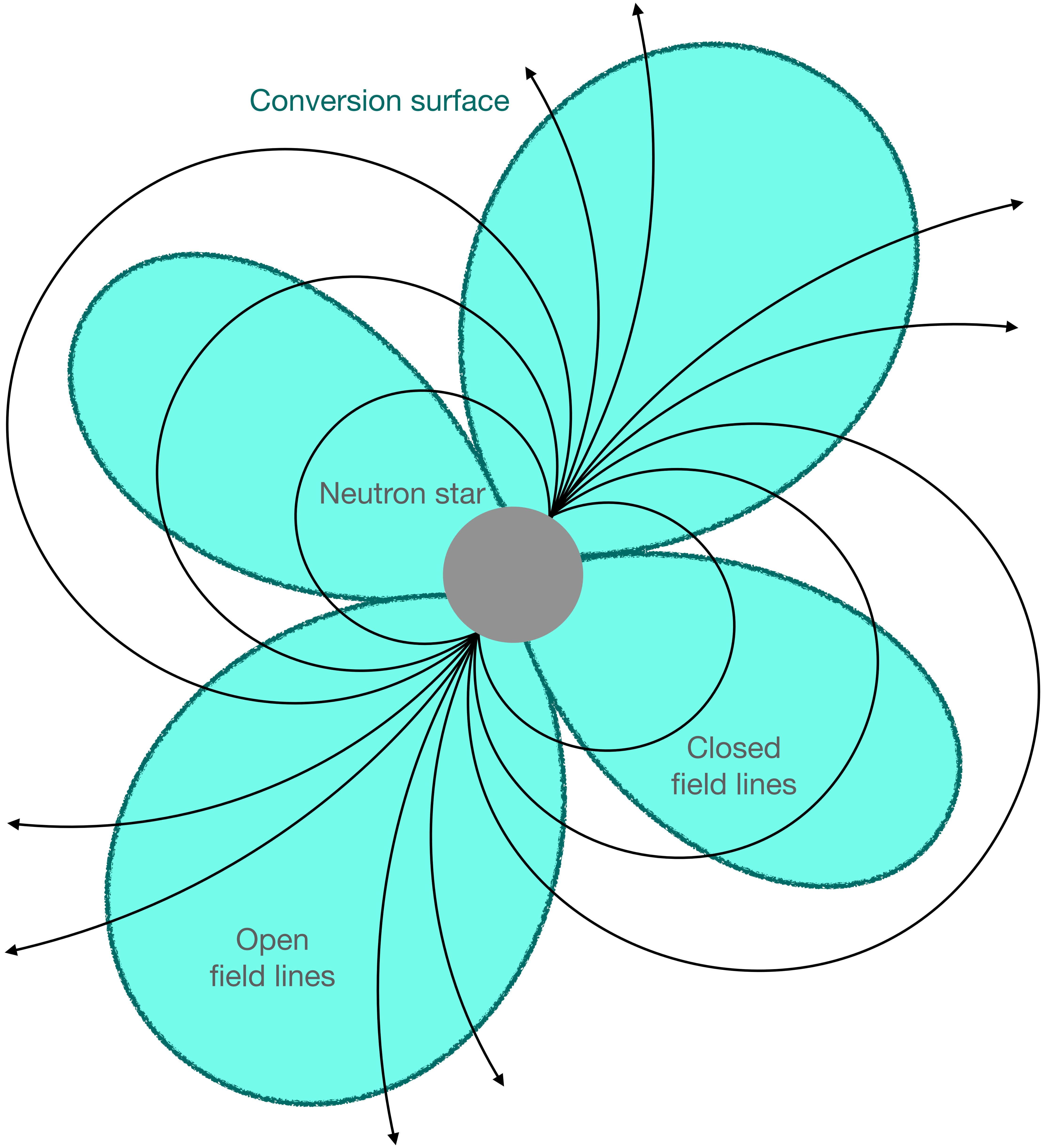
↓

(4) Photon propagation

↓

(5) Find final radio flux

Resonant axion-photon conversion



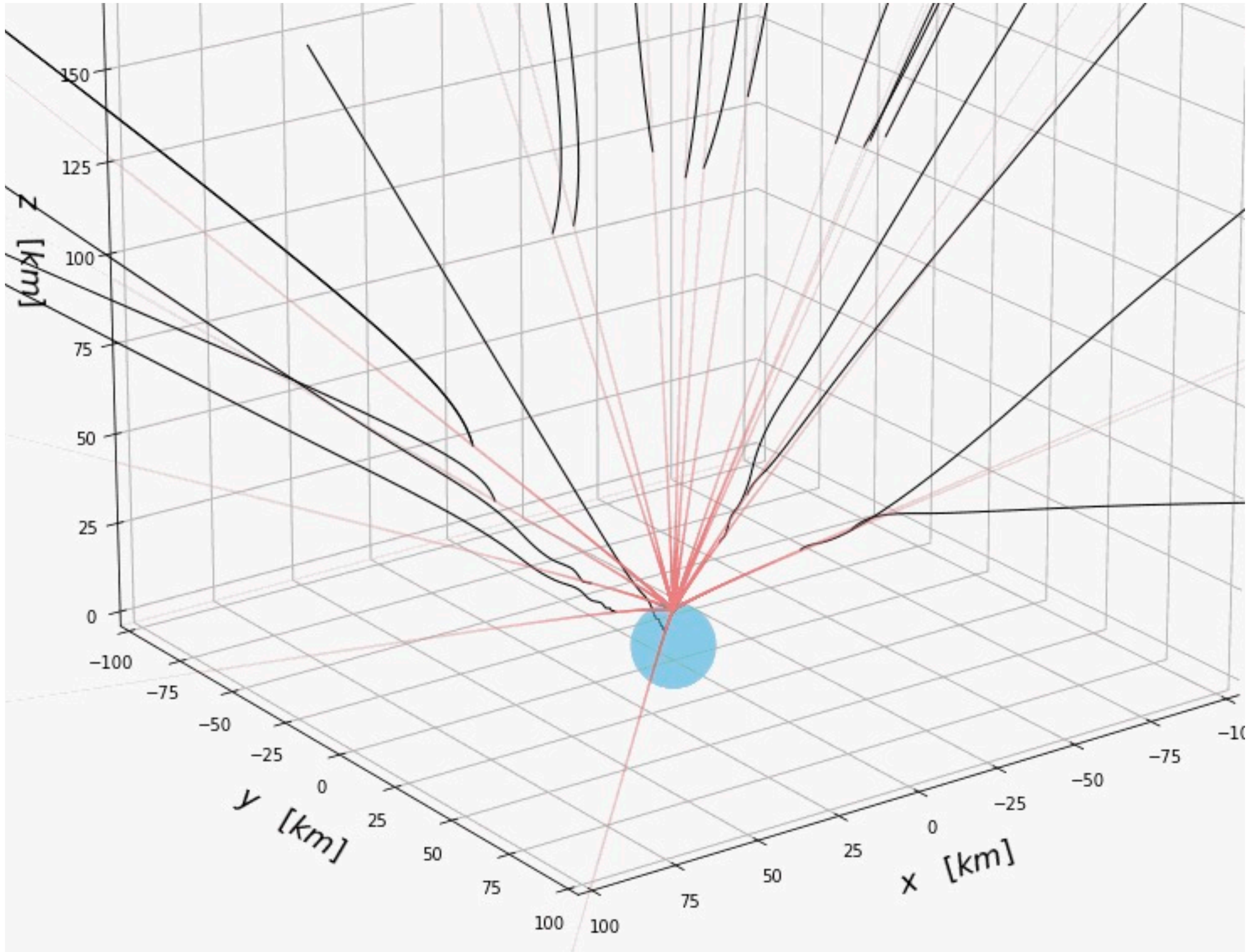
- For non-relativistic axions resonant conversion occurs when $\omega_p \approx m_a$, defining a conversion surface around the NS

- For relativistic axions angular dependencies enter the resonance condition, and the conversion surface isn't as well-defined

Hook, Kahn, Safdi, Sun, 2018 (arXiv 1804.03145)

Witte, **DN**, Edwards, Weniger, 2021 (arXiv 2104.07670)

Photon propagation



- Photon trajectories are heavily affected by the plasma in the magnetosphere

- Photon evolution is governed by the ray-tracing equations

$$\frac{d\vec{x}}{dt} = \nabla_k \omega(\vec{x}, \vec{k}, t)$$

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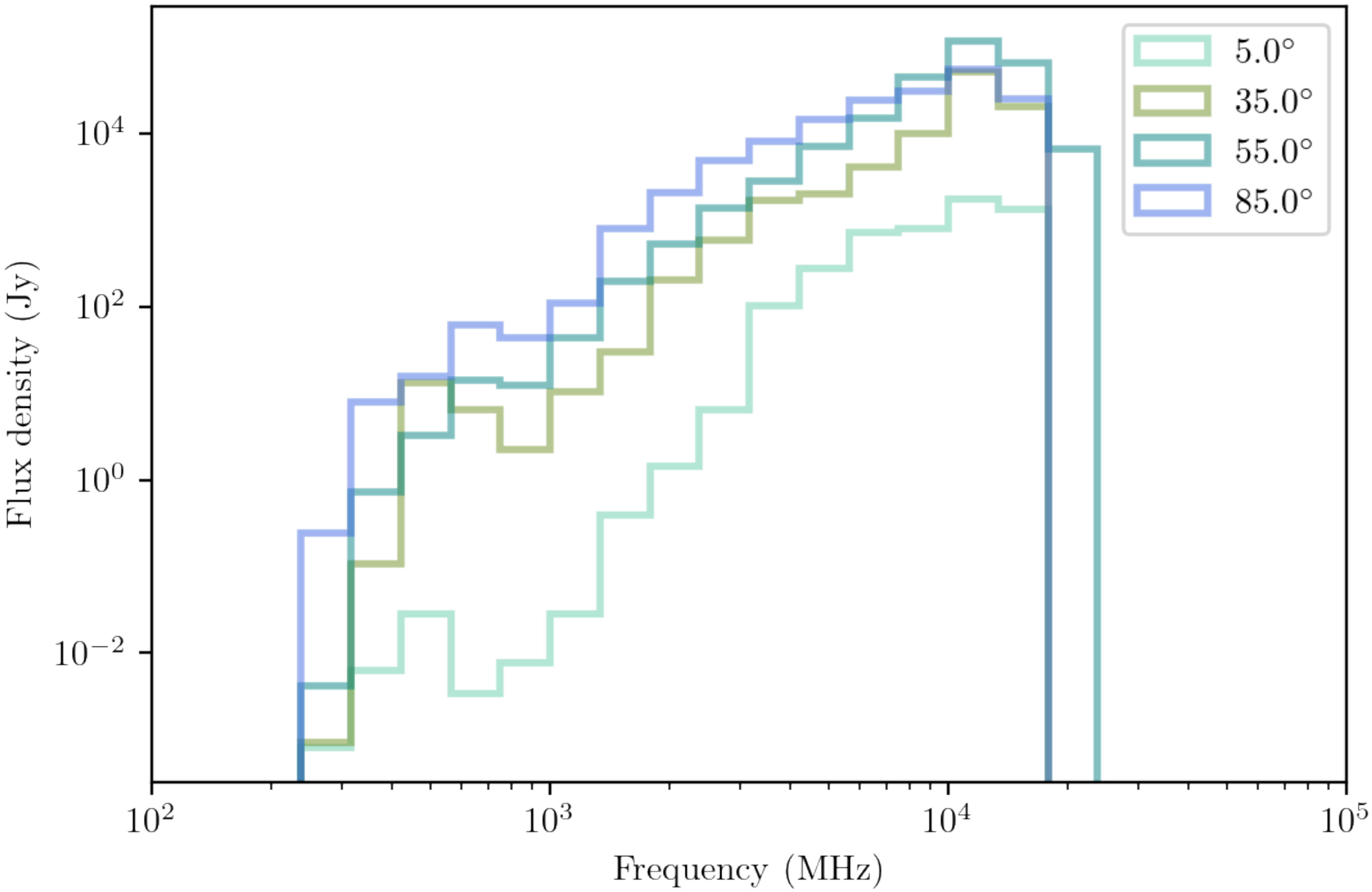
Witte, **DN**, Edwards, Weniger, 2021 (arXiv 2104.07670)

Example radio spectrum



- Axion parameters:
  - $m_a = 1.0 \times 10^{-6}\,\mathrm{eV}$
  - $g_{a\gamma\gamma} = 7.0 \times 10^{-11}\,\mathrm{GeV}^{-1}$