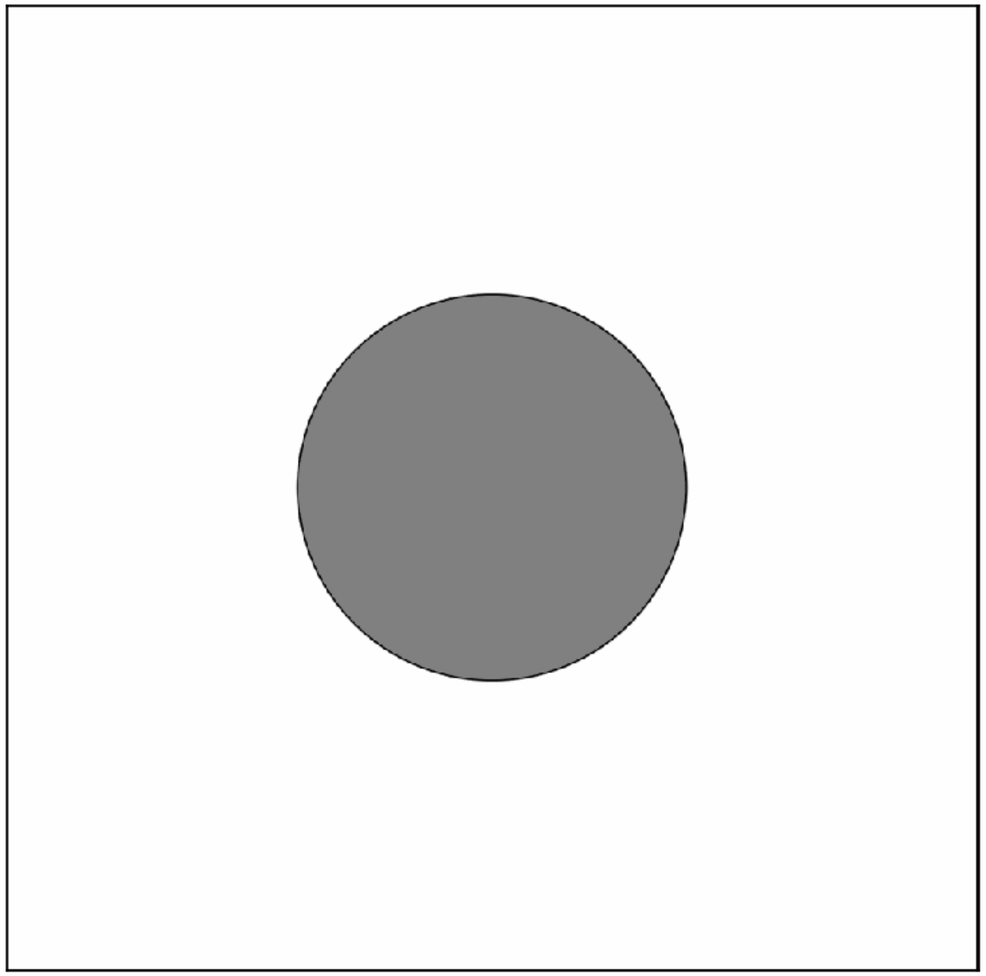
Axions from pulsar polar caps

Samuel J. Witte

BAM Axions in the Sky
Barolo, Italy
June 2024



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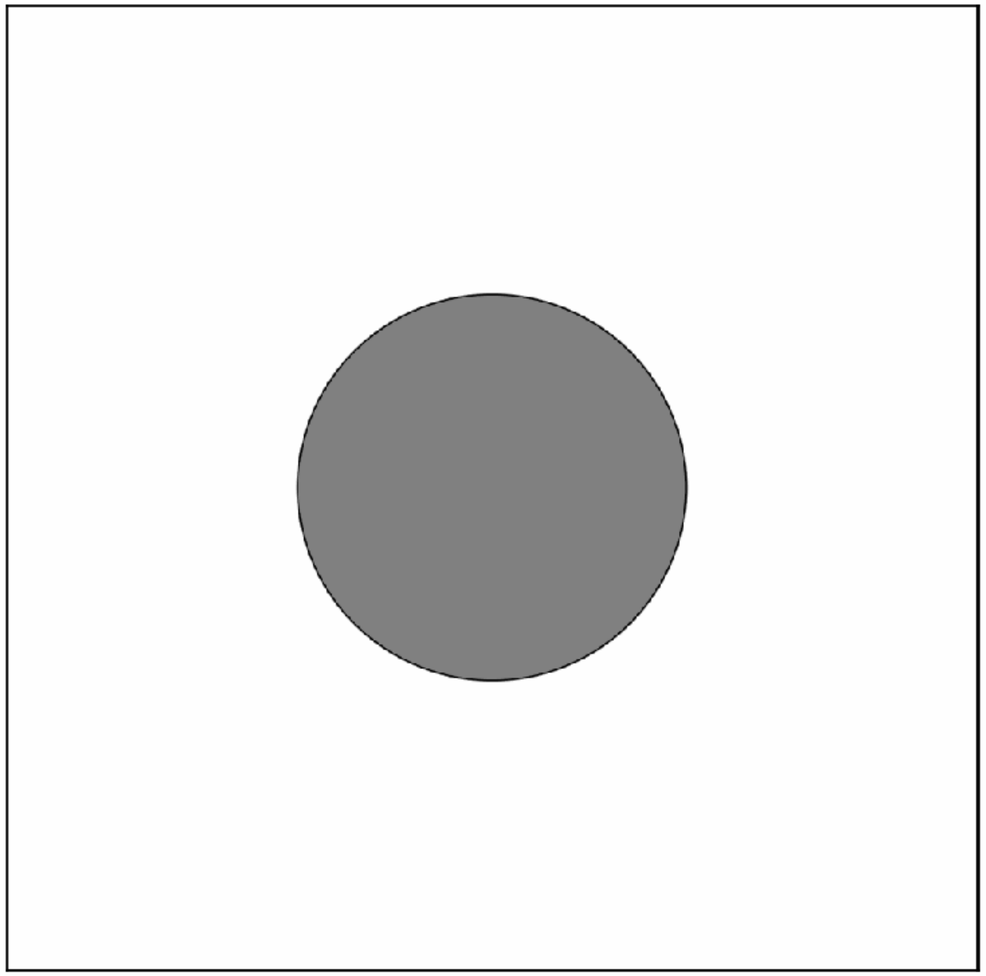

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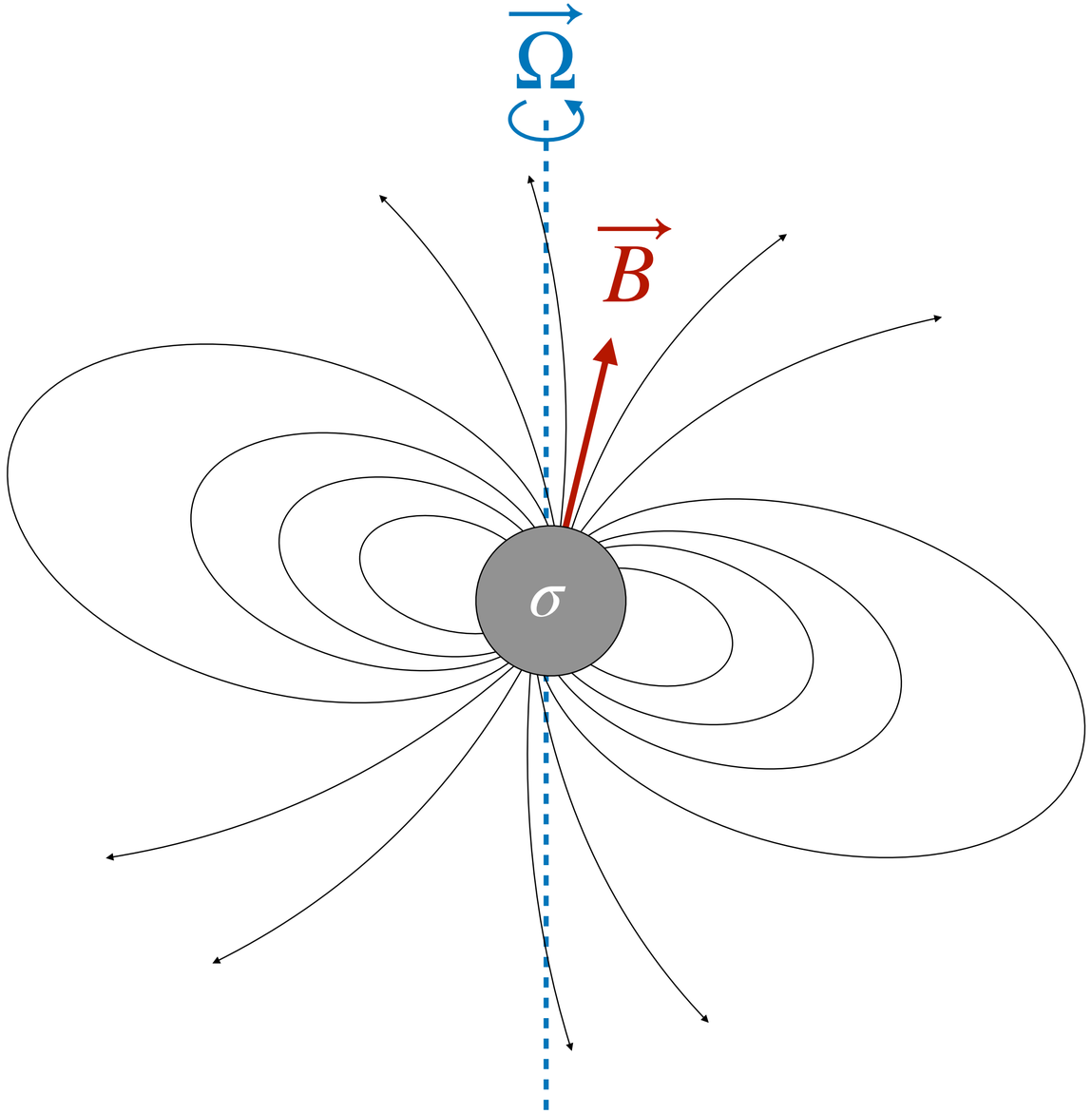
Pulsar magnetospheres

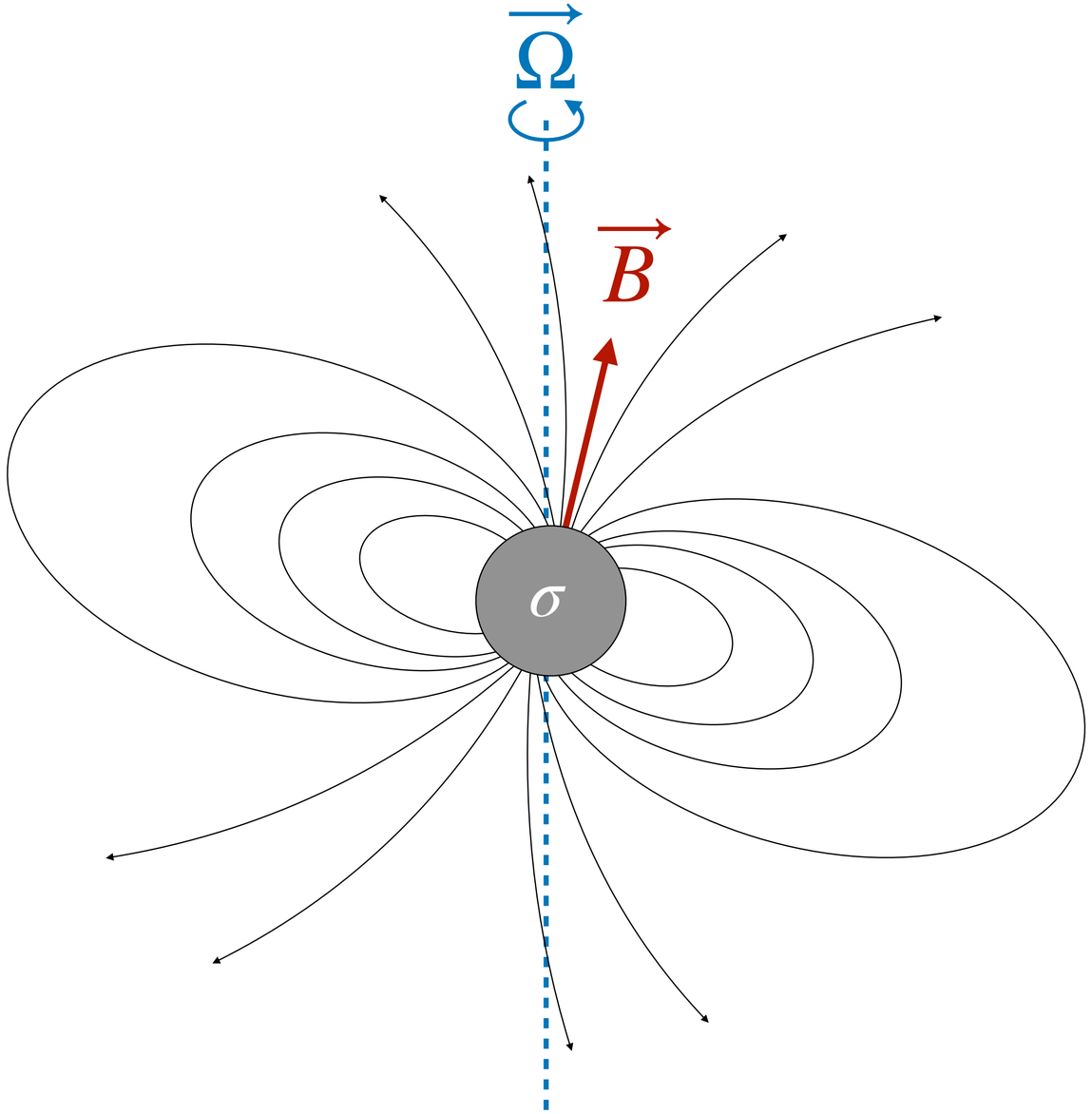


Start with a simple picture:

- Neutron star is conducting sphere
- Hosts large magnetic field B
- Rotates with frequency Ω

Implications:

Pulsar magnetospheres



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$$E_{0,\mathrm{max}} \sim B_0 R_{\mathrm{NS}} \Omega \sim \mathcal{O}(10^{-4})\, B_0$$

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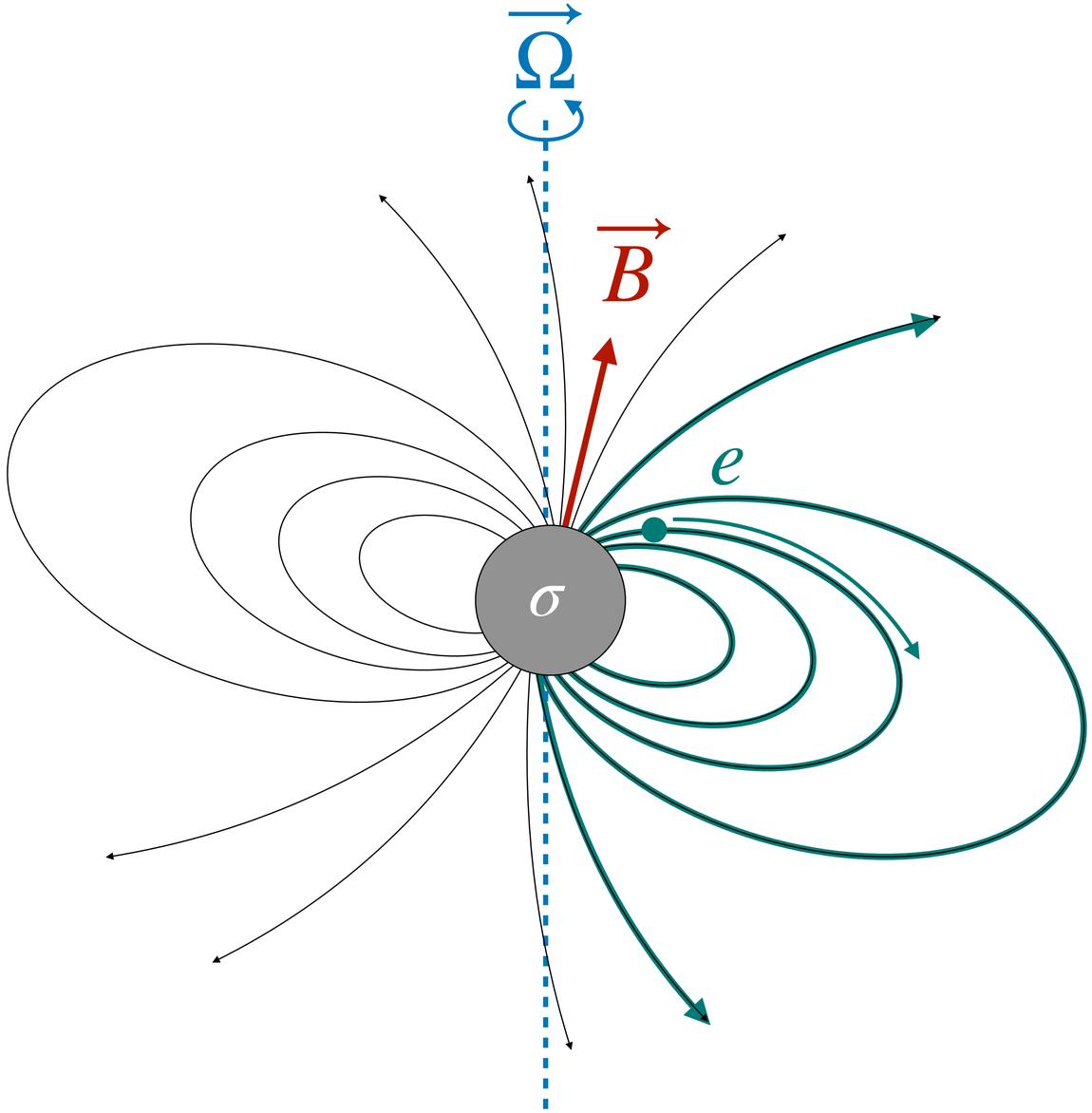

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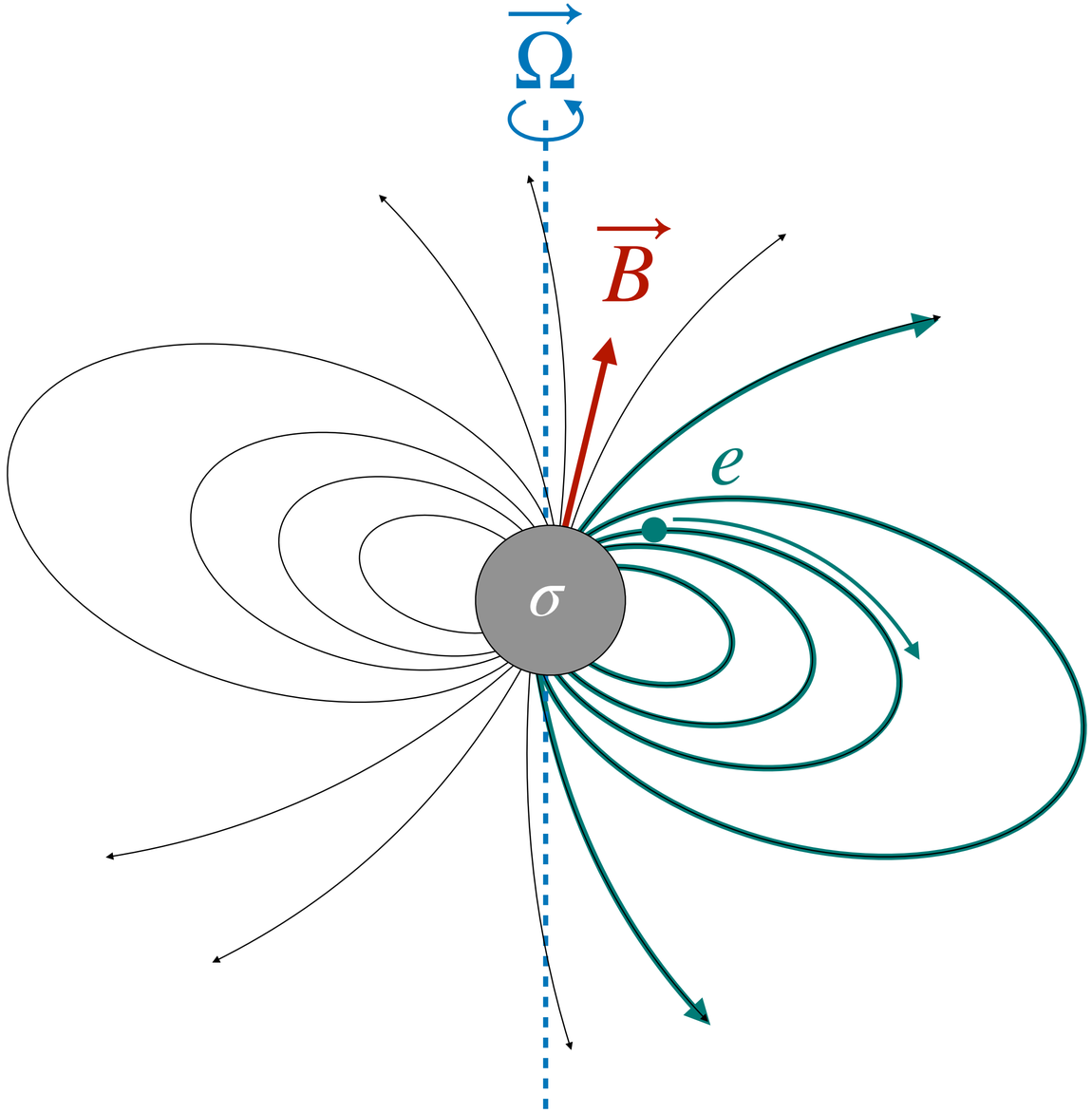

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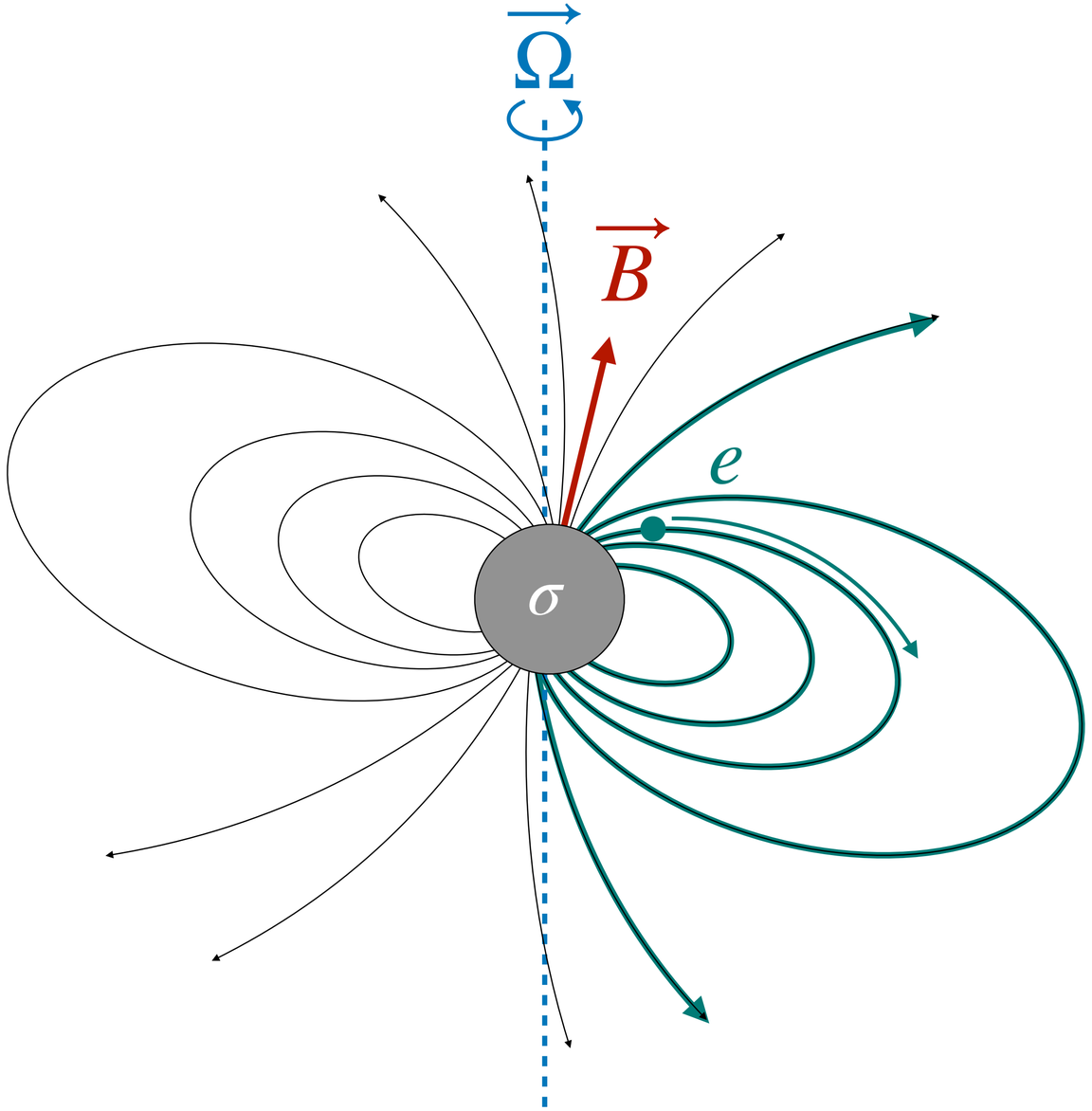

Force-free electrodynamics

- $B^2 \gg E^2$
- *Plasma screens* $\vec{E} \cdot \vec{B} \to 0$
- *No stress-energy exchange between plasma and field*

Implications:

- Rotating B induces large electric field E

$$E_{0,\mathrm{max}} \sim B_0 R_{\mathrm{NS}} \Omega \sim \mathcal{O}(10^{-4}) B_0$$

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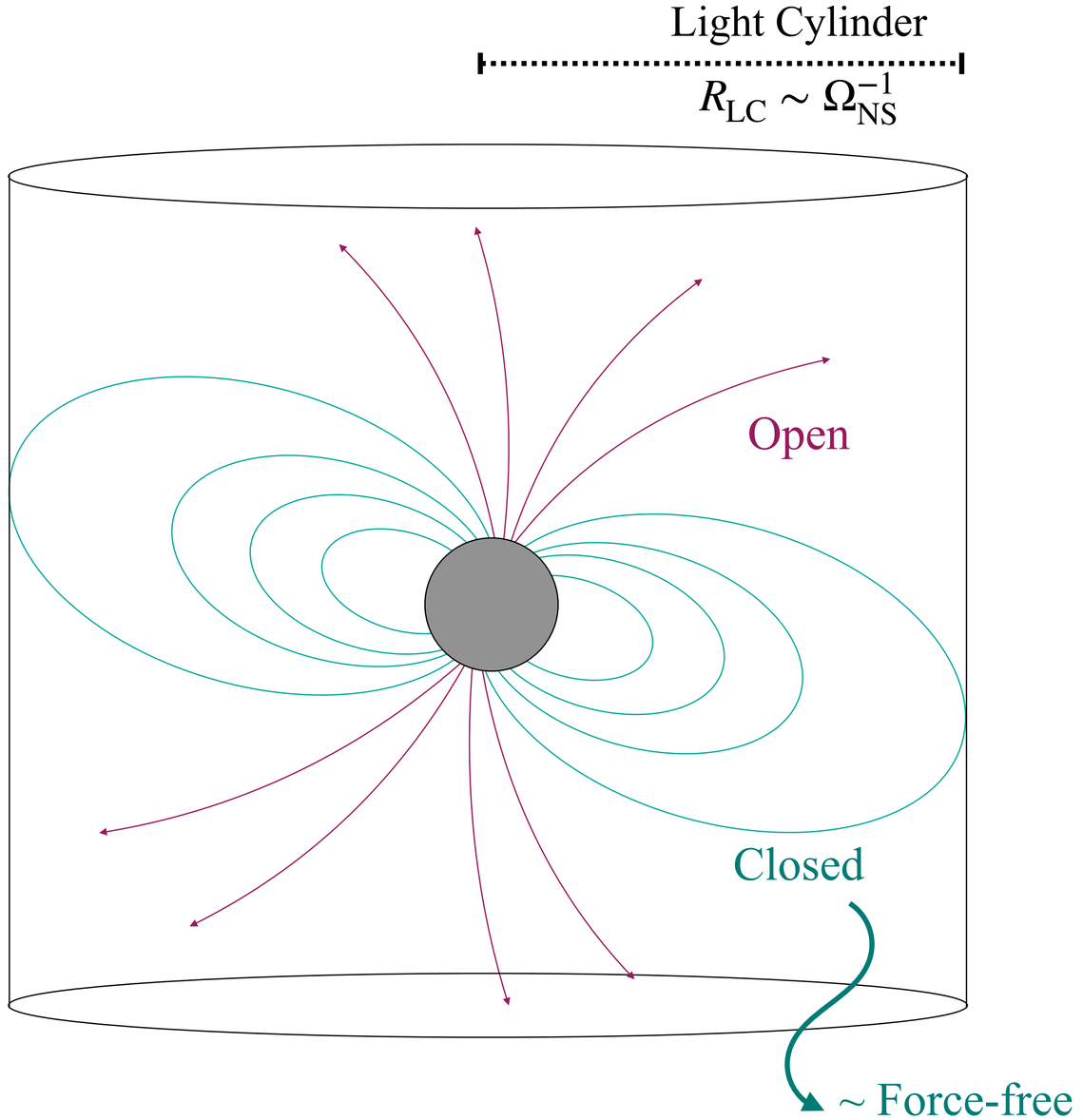
Breakdown of force-free dynamics

Problem: Emission requires acceleration

Problem: Co-rotation breaks down at large radii



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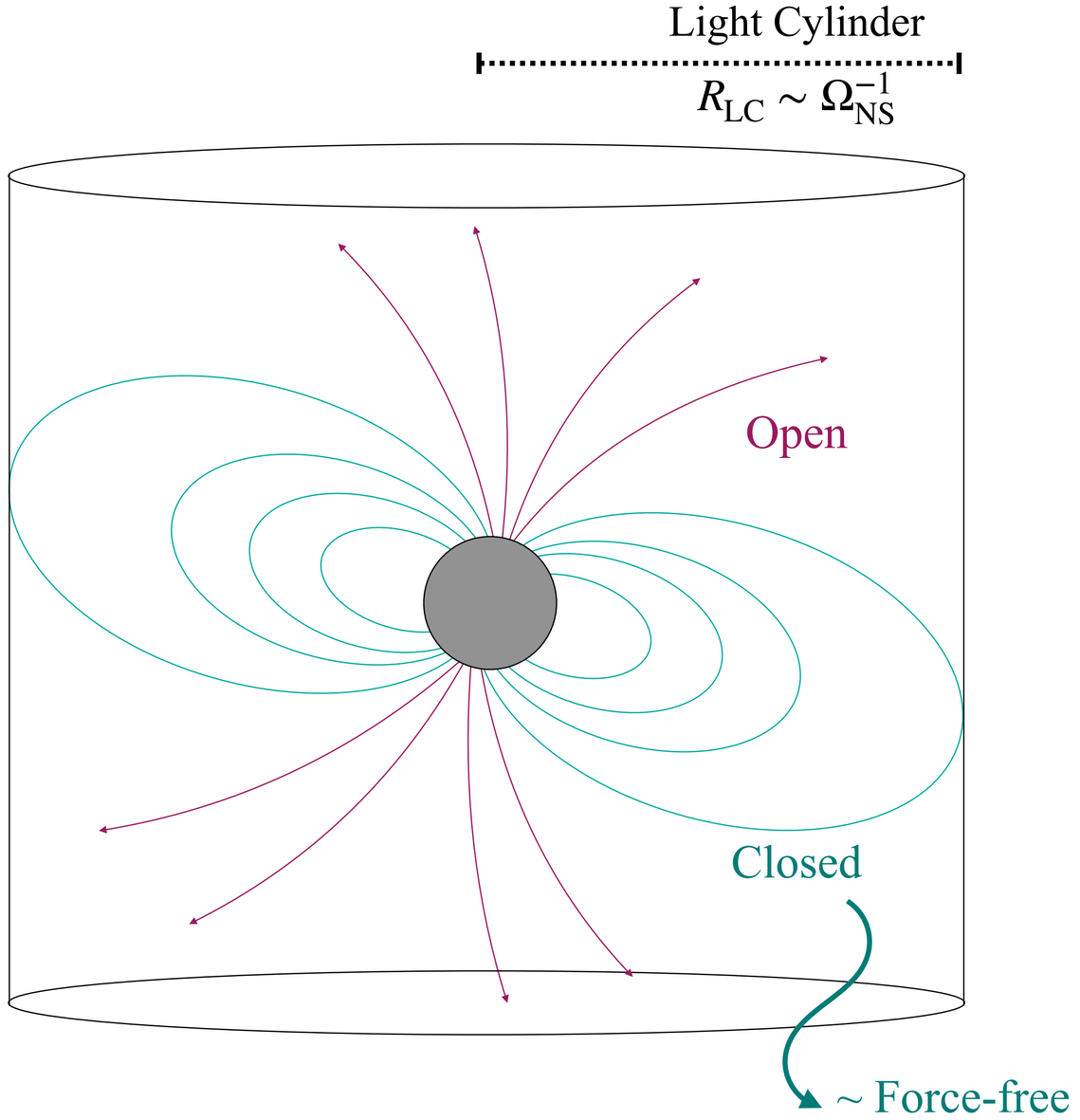


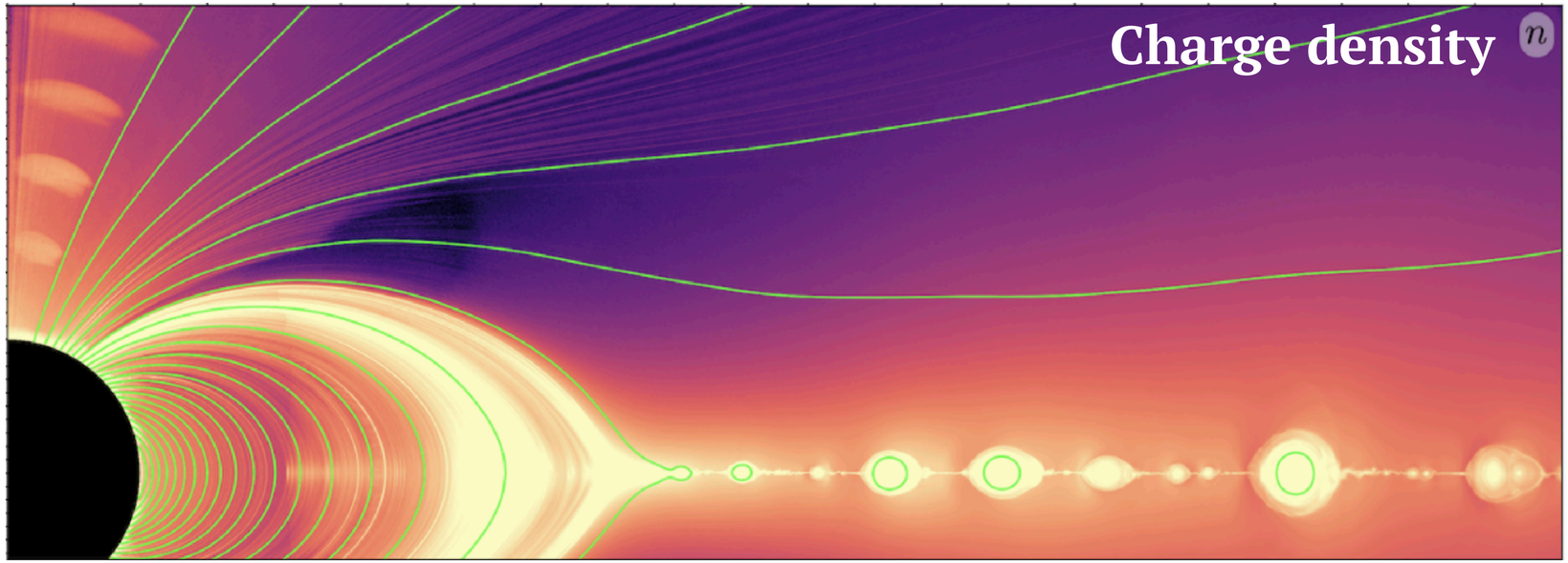
Small/Localised break-down of force-free

Confined to open field lines

- *Vacuum Gaps* $[\vec{E} \cdot \vec{B} \neq 0]$
- *High density current sheets* $[E^2 \gg B^2]$

Axions from vacuum Gaps

(Simulations not to scale)



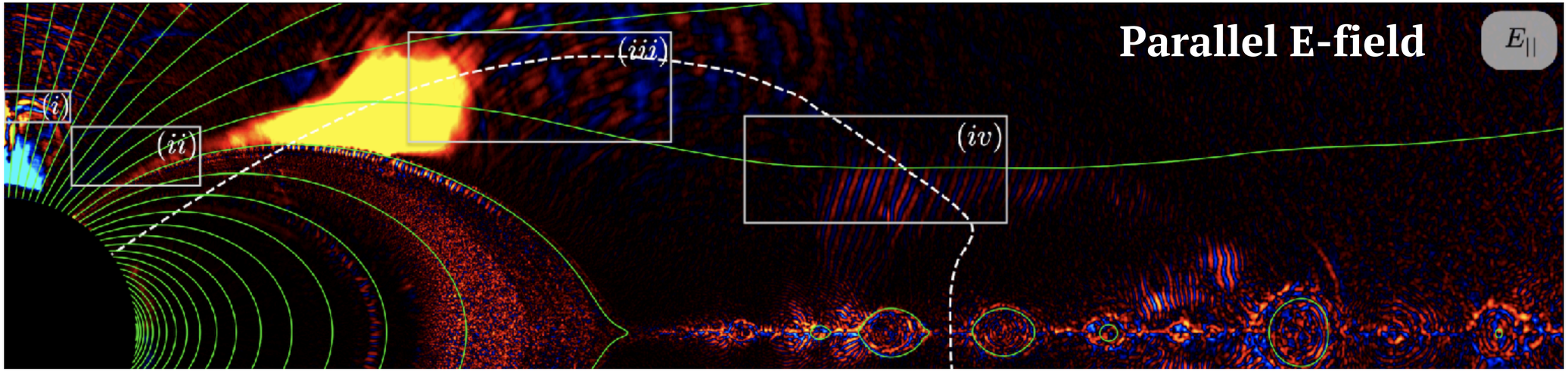


Image credit: Bransgrove, Belobodorov, Levin (2023)

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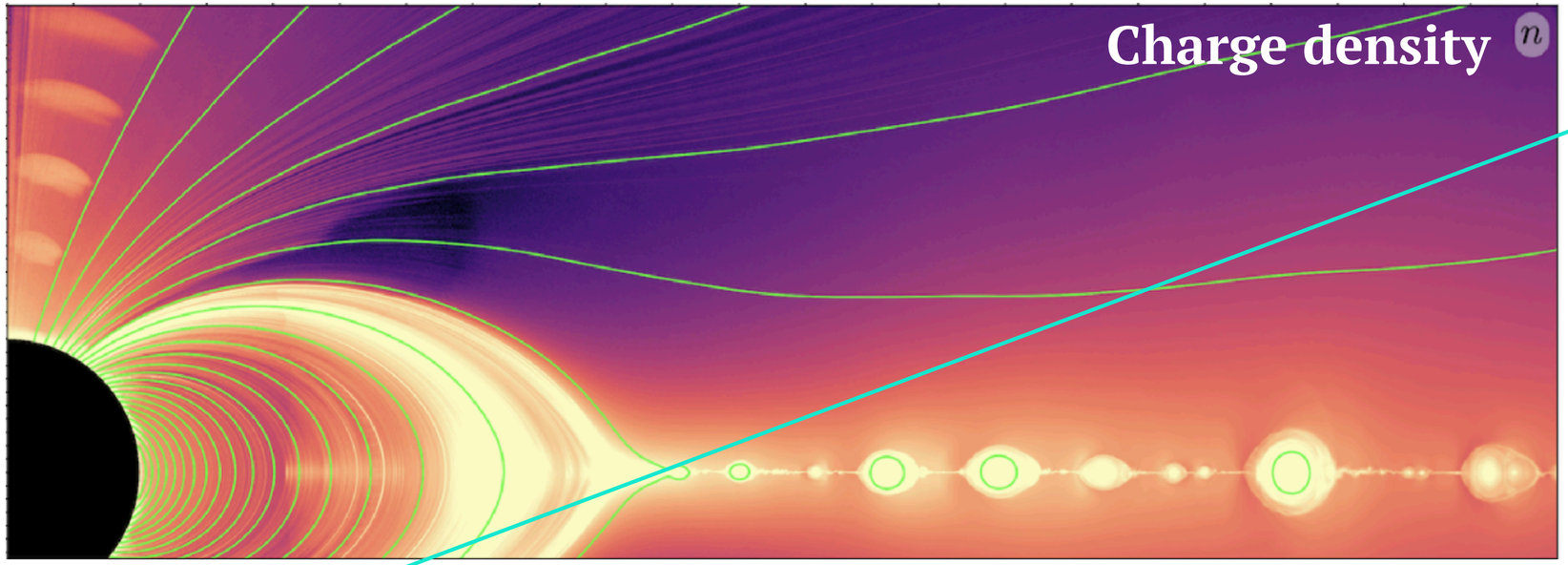


Axion Production

$$\left(\Box + m_a^2\right) a = g_{a\gamma\gamma}\, \vec{E} \cdot \vec{B}$$

$$\dot{N}_a(\vec{k}) \propto \mathrm{FT}[g_{a\gamma\gamma}\, \vec{E} \cdot \vec{B}]$$

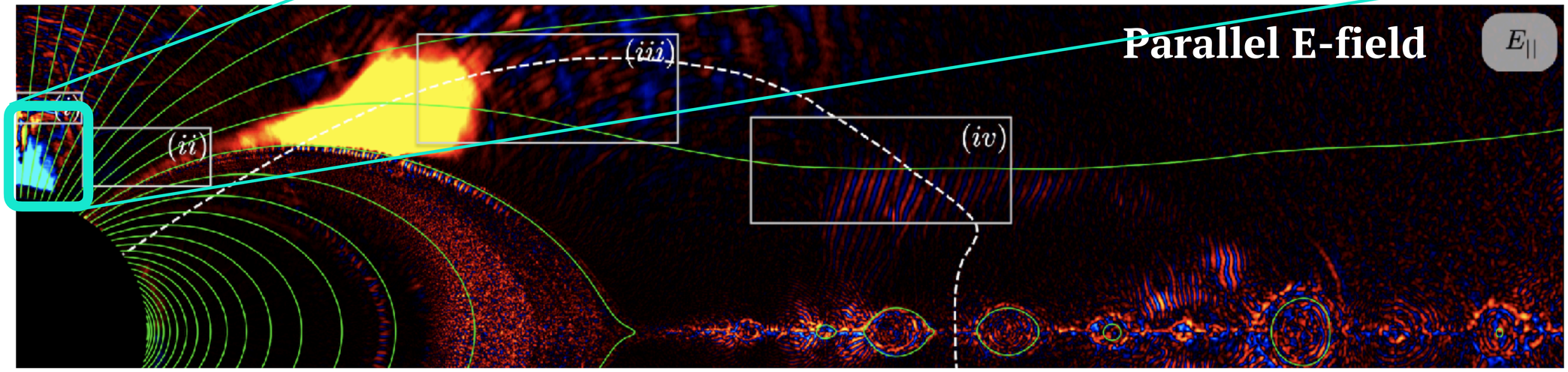
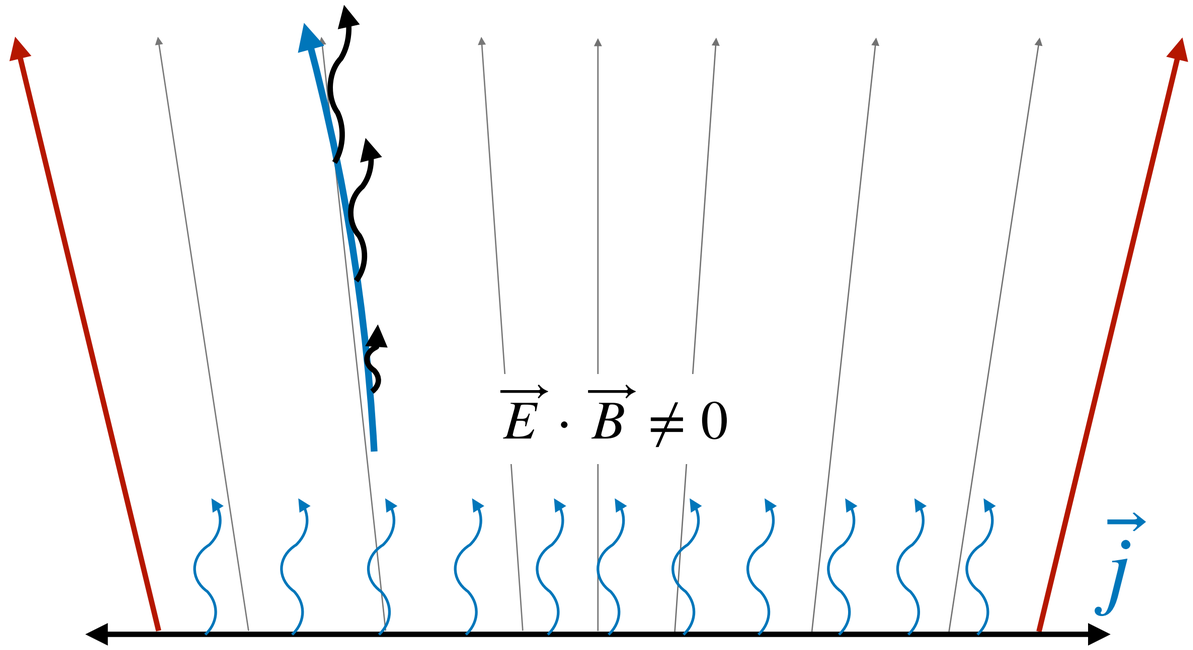


Image credit: Bransgrove, Belobodorov, Levin (2023)

Polar cap dynamics

Part 1: Vacuum Phase

Unscreened $\vec{E} \cdot \vec{B}$ extracts, and accelerates, current



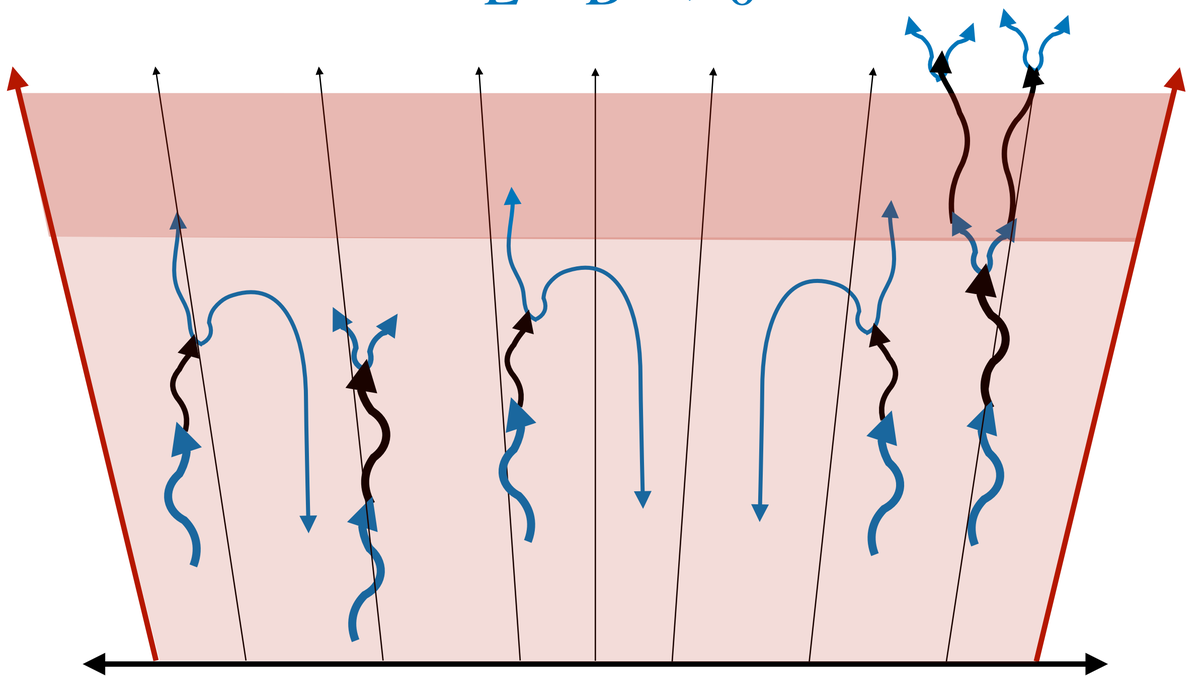
$$\sigma_{\gamma \to e^{\pm}} \propto e^{-\xi m_e^3 / (E_\gamma B_\perp)}$$

See e.g. Ruderman & Sutherland (1975), Timokhin & Harding (2015,2018), Philippov, Spitskovksy, Timokhin (2020)

Polar cap dynamics

Part 2: Screening Phase

Current generates pair cascades, which drive $\vec{E} \cdot \vec{B} \to 0$



Quasi-periodic on timescales $t \sim \mathcal{O}(\mu\mathrm{s})$

Polar cap dynamics

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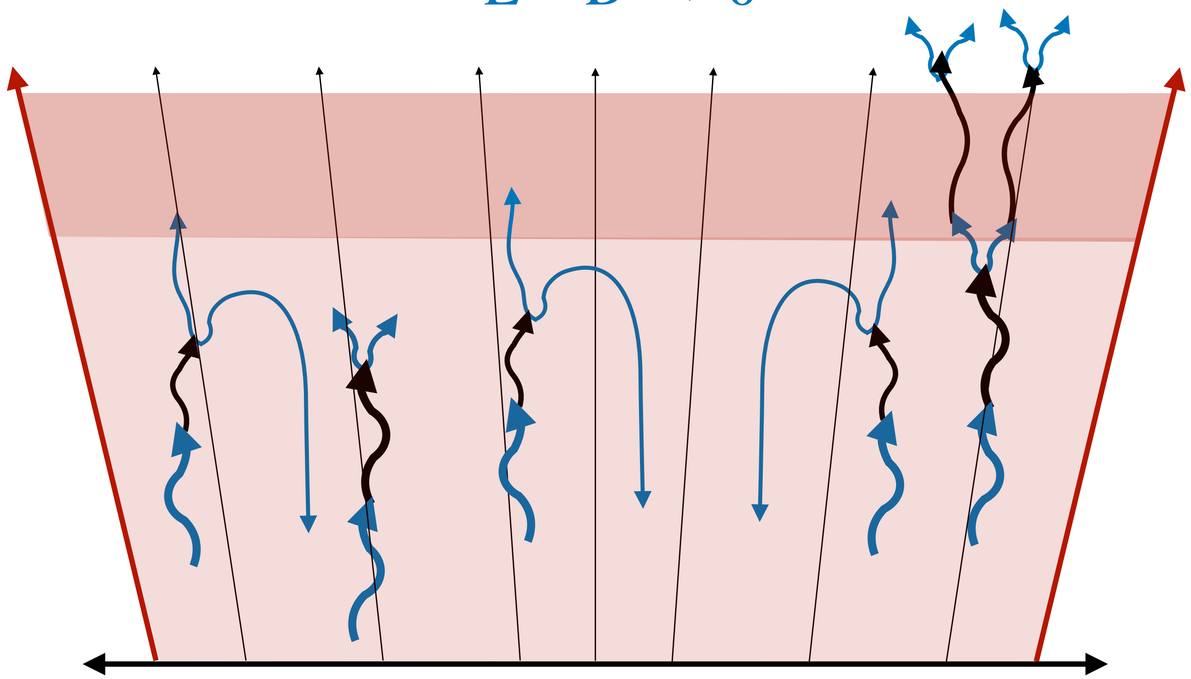

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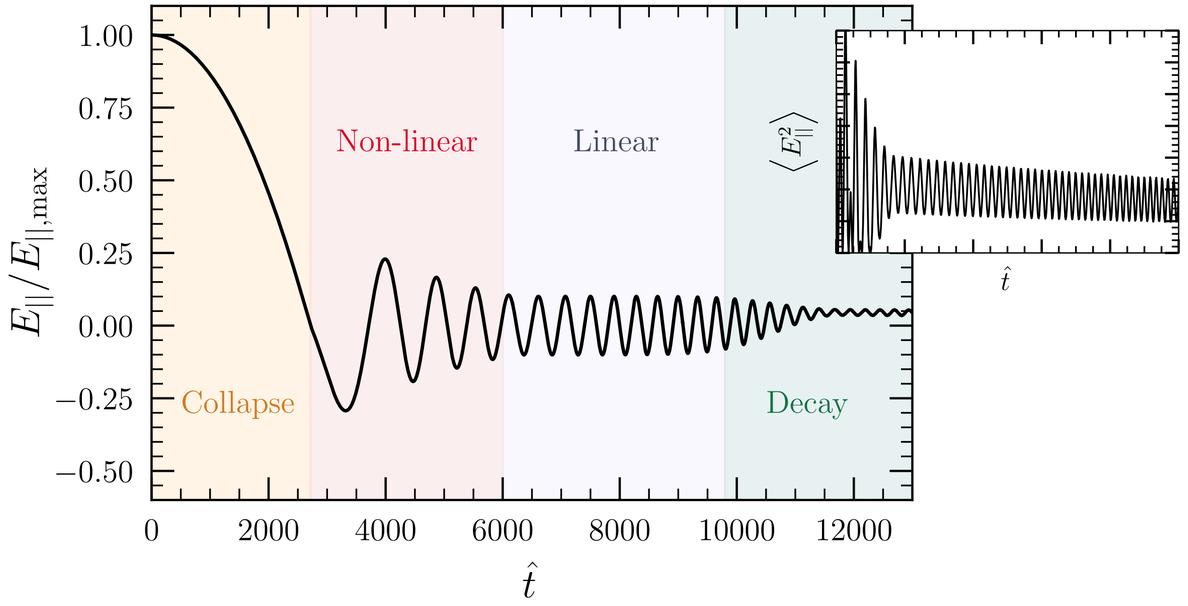
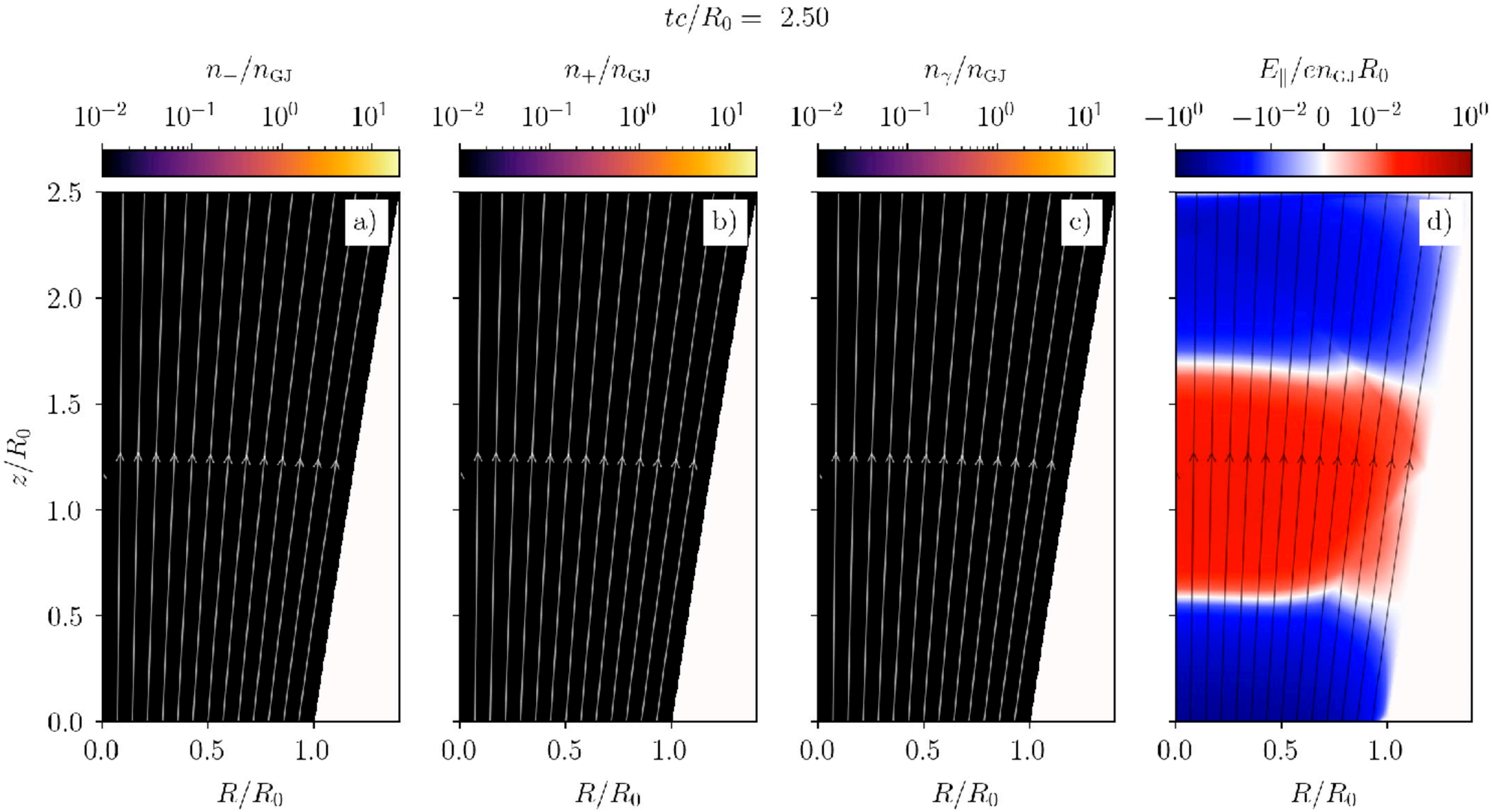
Dynamical damping of electric field



Polar cap dynamics



Simulations curtesy of F. Cruz and A. Chen

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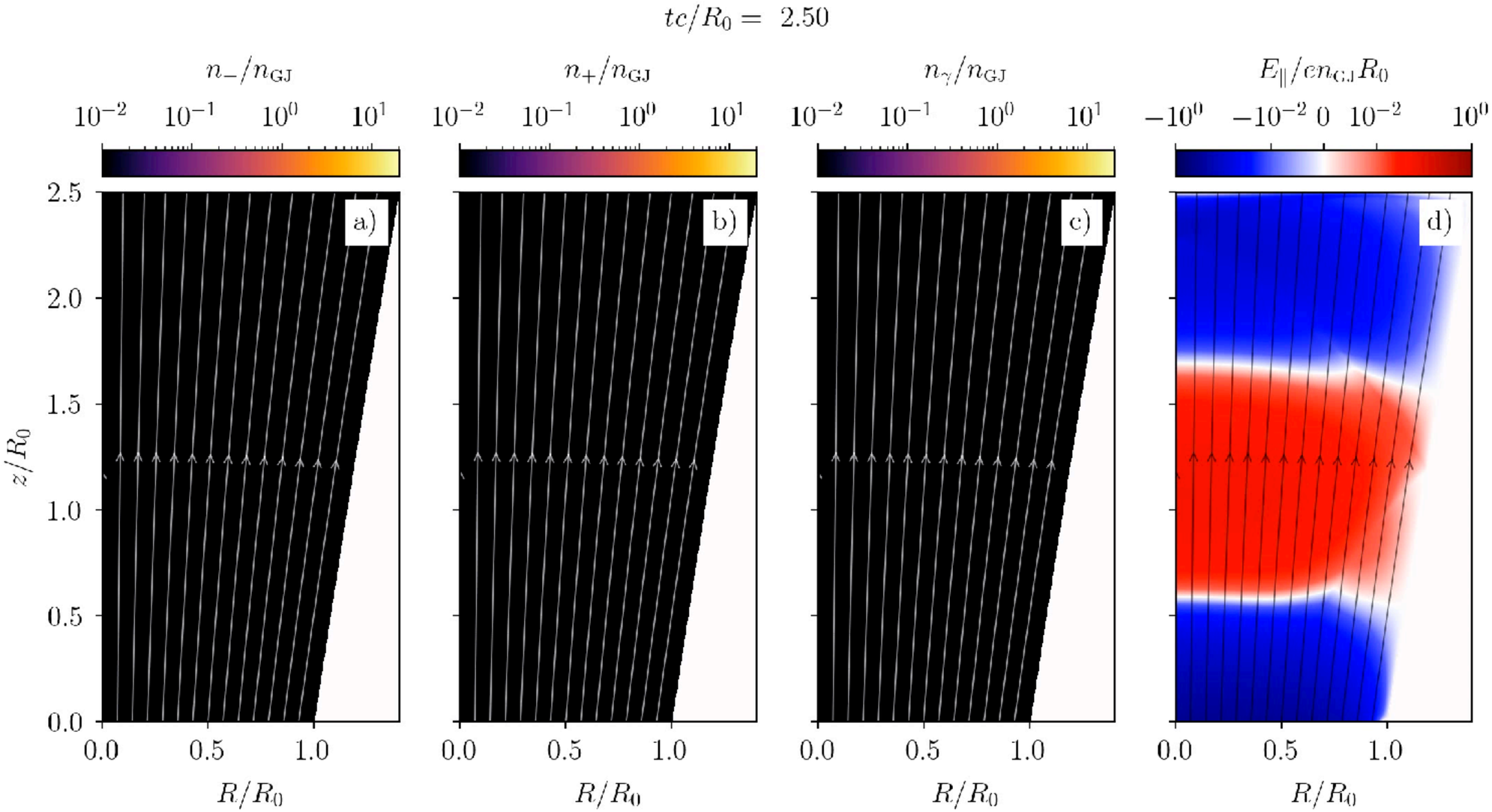

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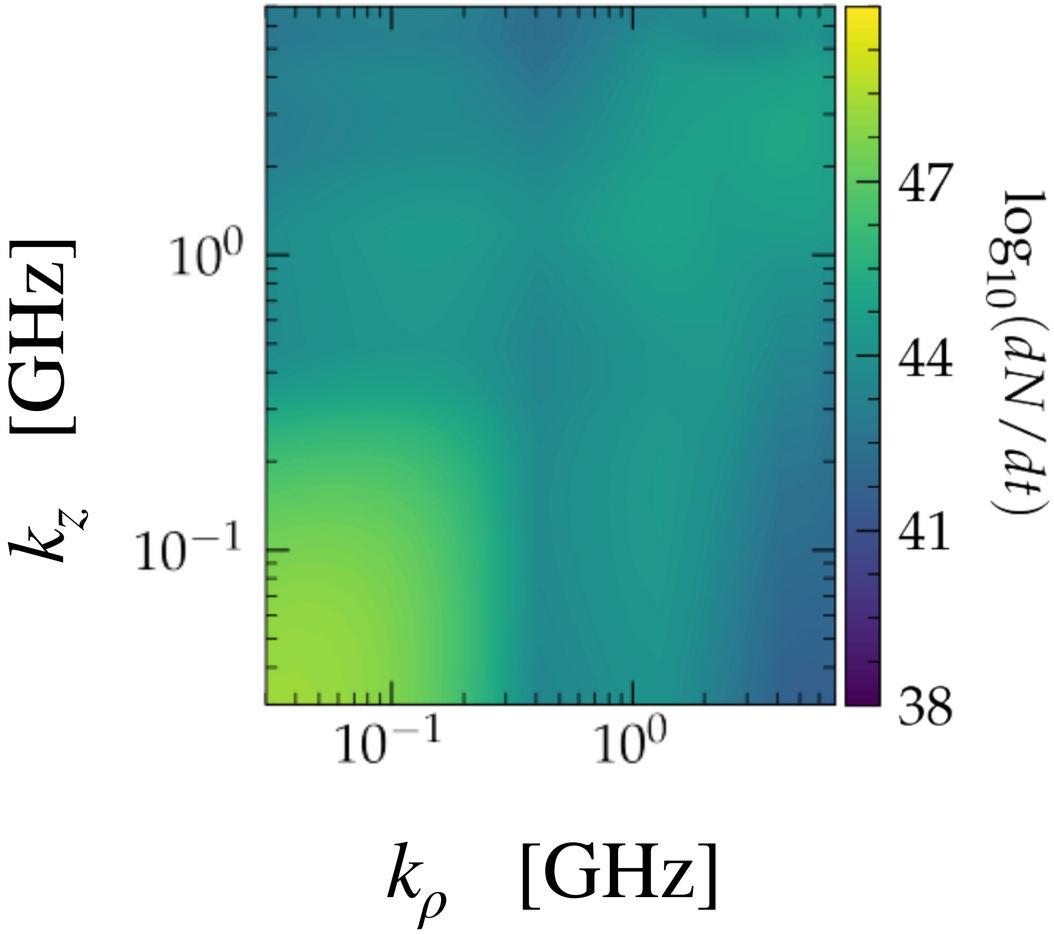
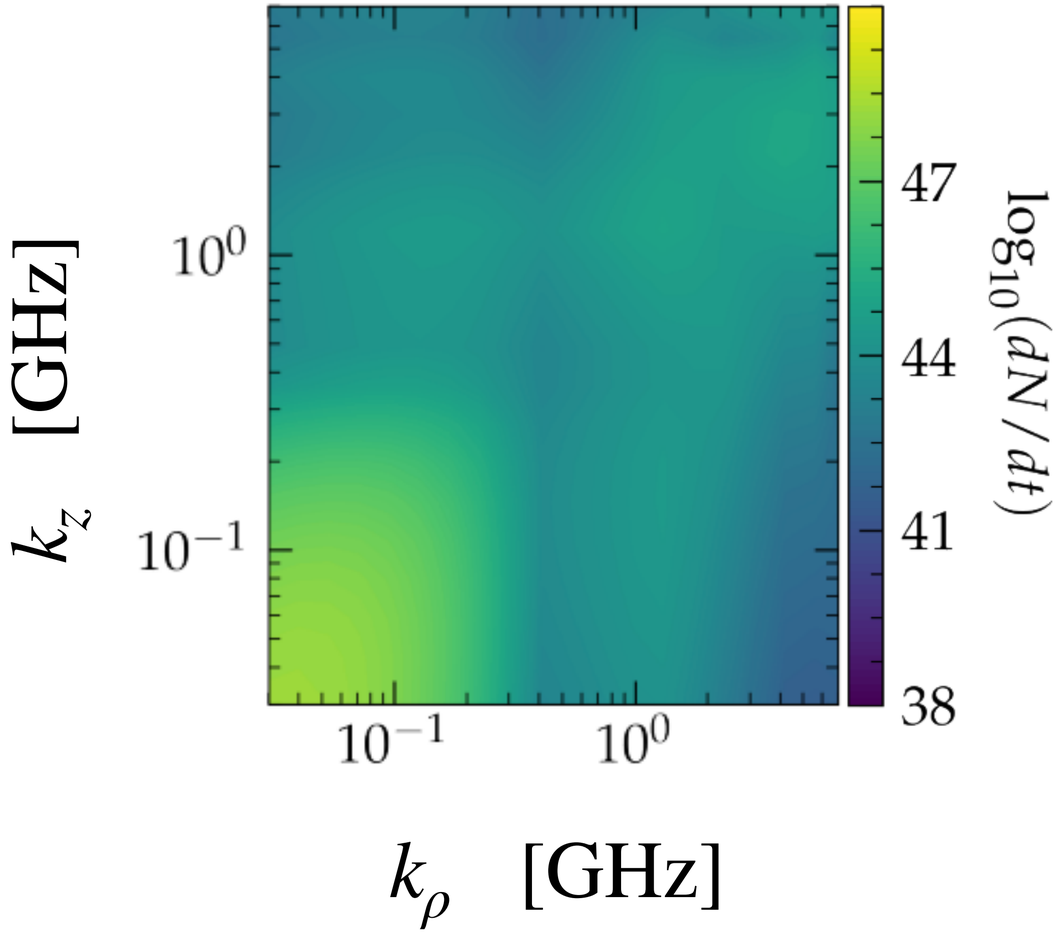
Axion spectrum

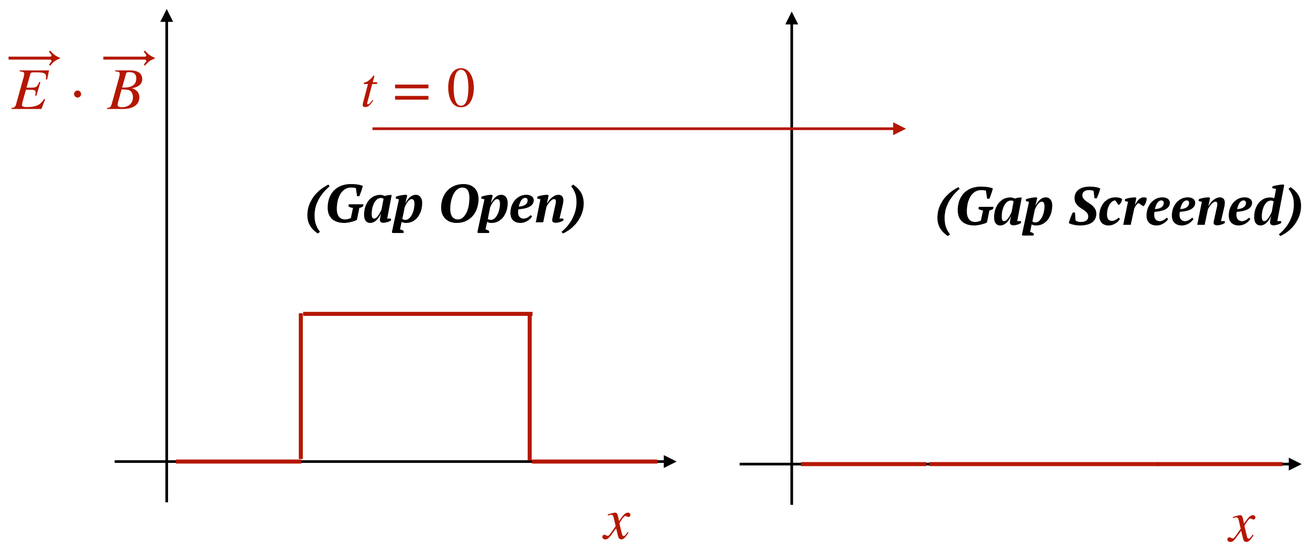


Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)

Axion spectrum

$$\frac{d\dot{N}}{d^3k} \propto \left| \mathrm{FT}\left[g_{a\gamma\gamma}(\vec{E}\cdot\vec{B}) \right] \right|^2$$



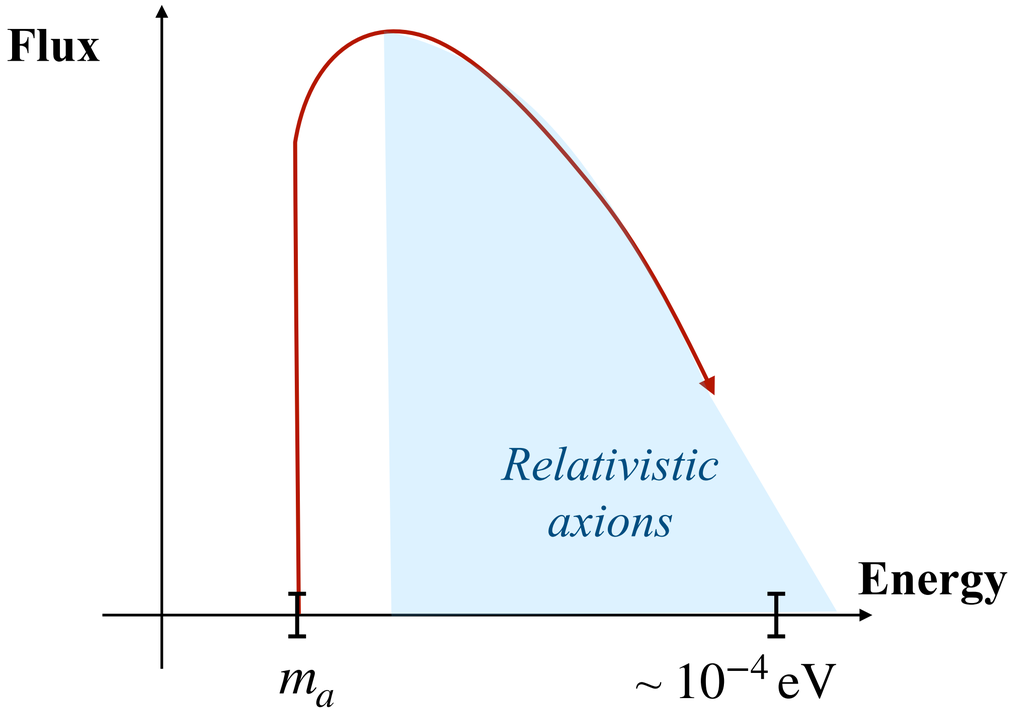


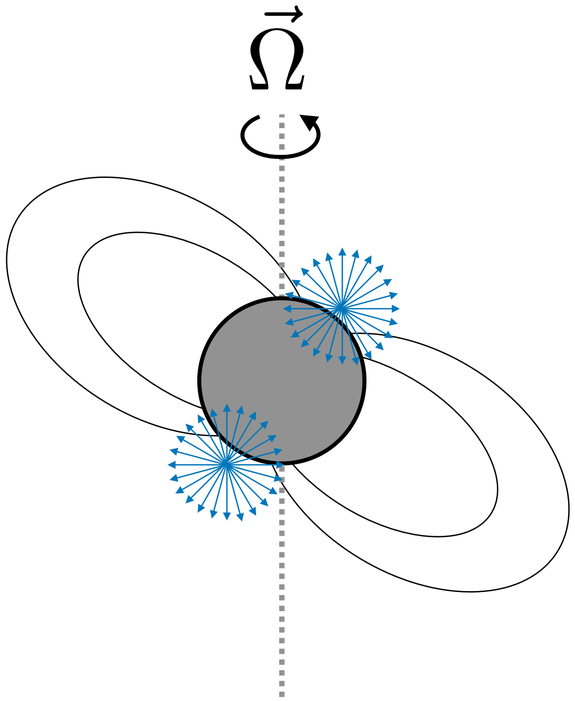
$$r_{\mathrm{pc}} \sim 150\mathrm{m}$$

$$h_{\mathrm{gap}} \sim \mathcal{O}(0.1-1) \times r_{\mathrm{pc}}$$

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

The fate of axions produced in the polar cap





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

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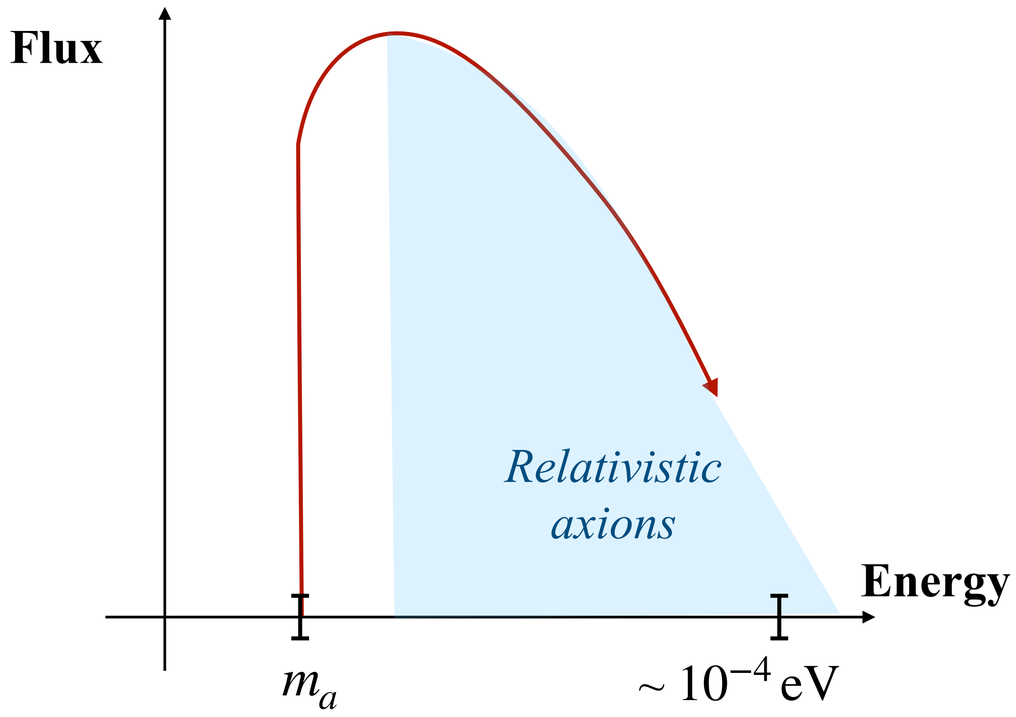

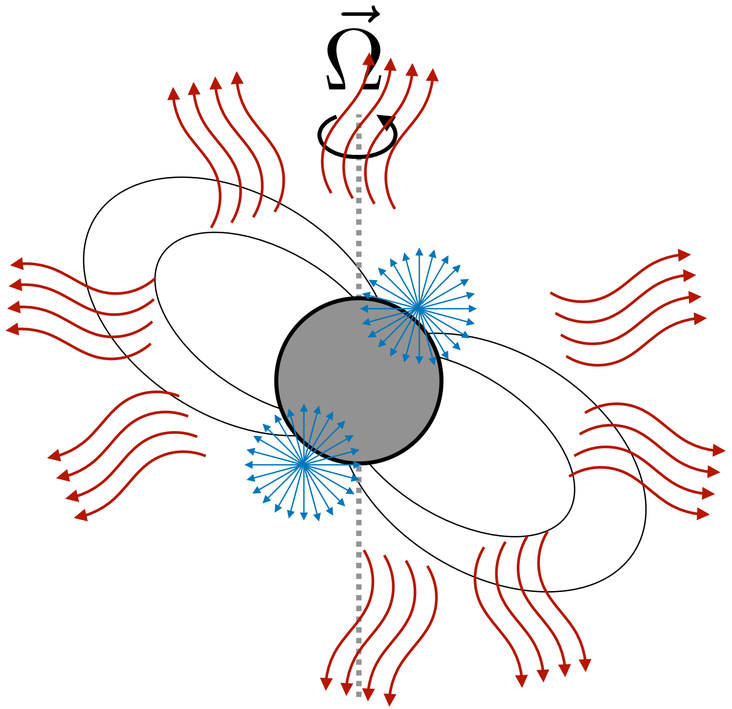

Resonant photon production

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

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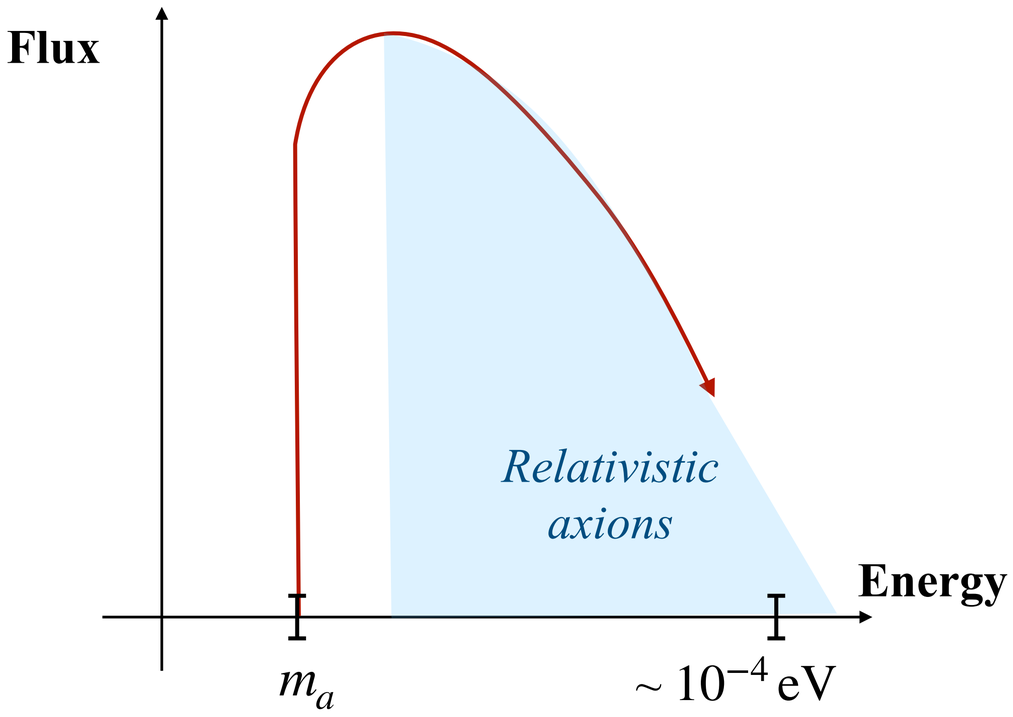
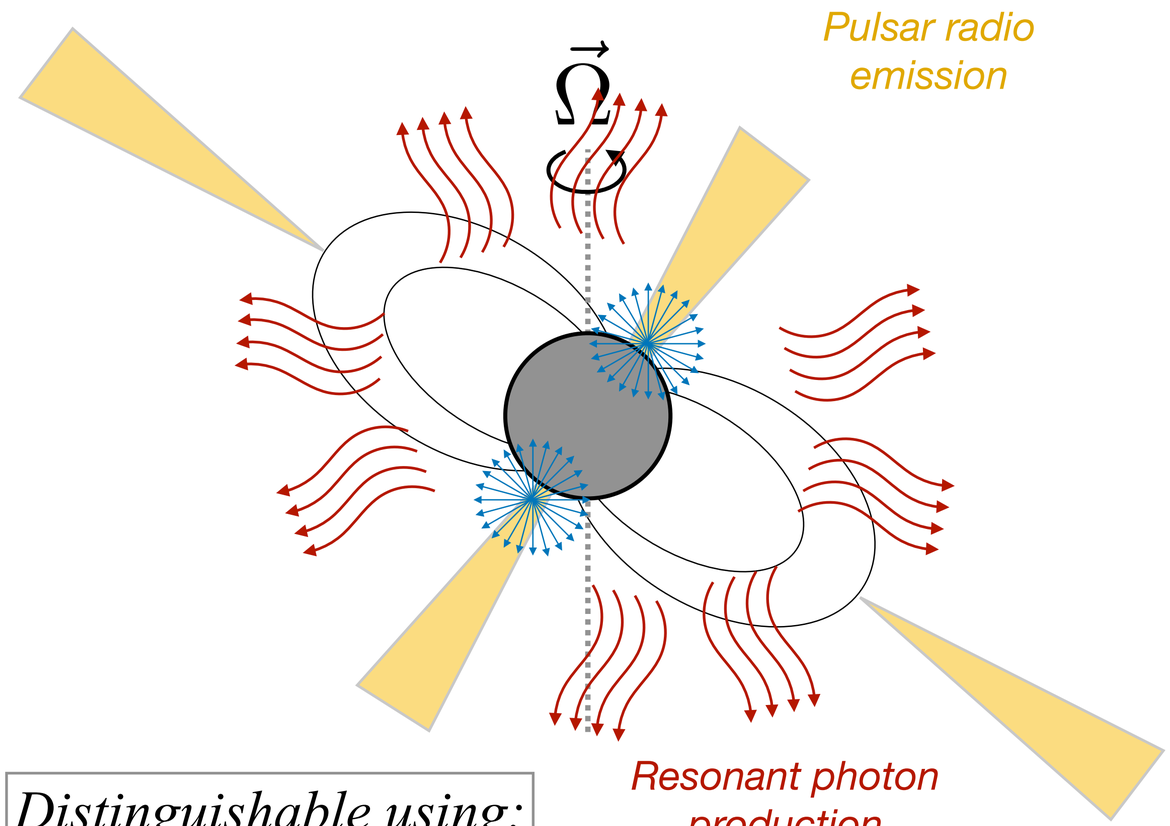




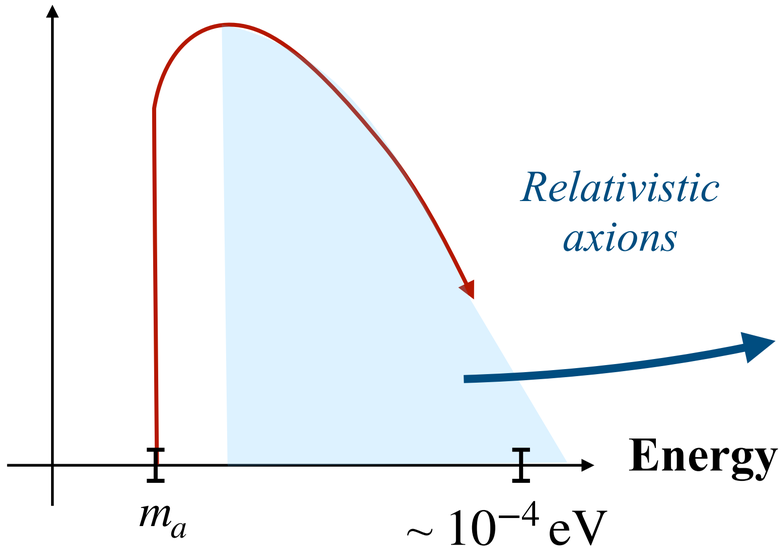
Distinguishable using:

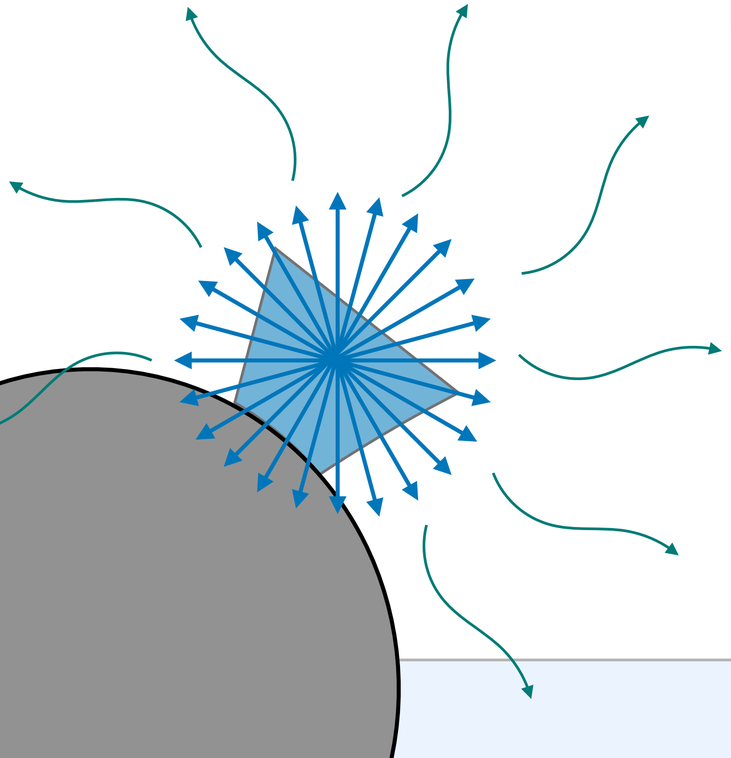
- Phase information
- Amplitude

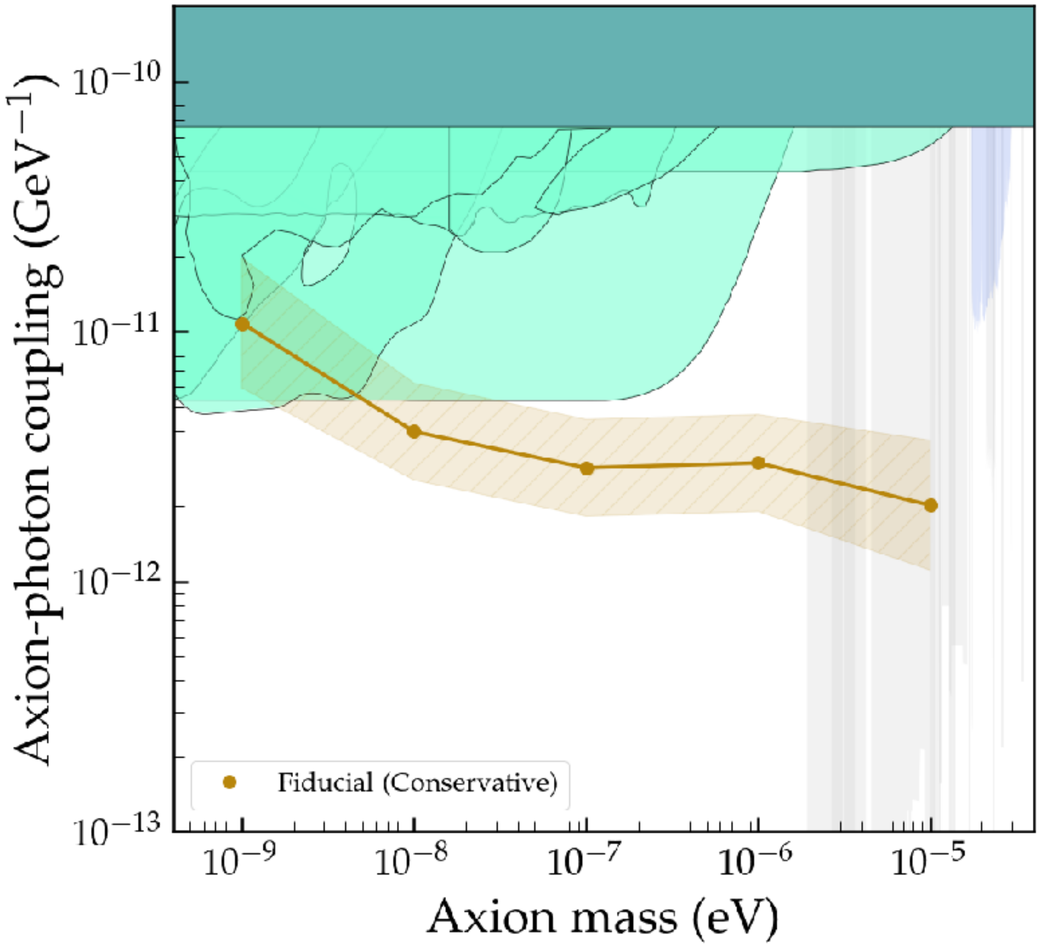
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)

Axion production

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



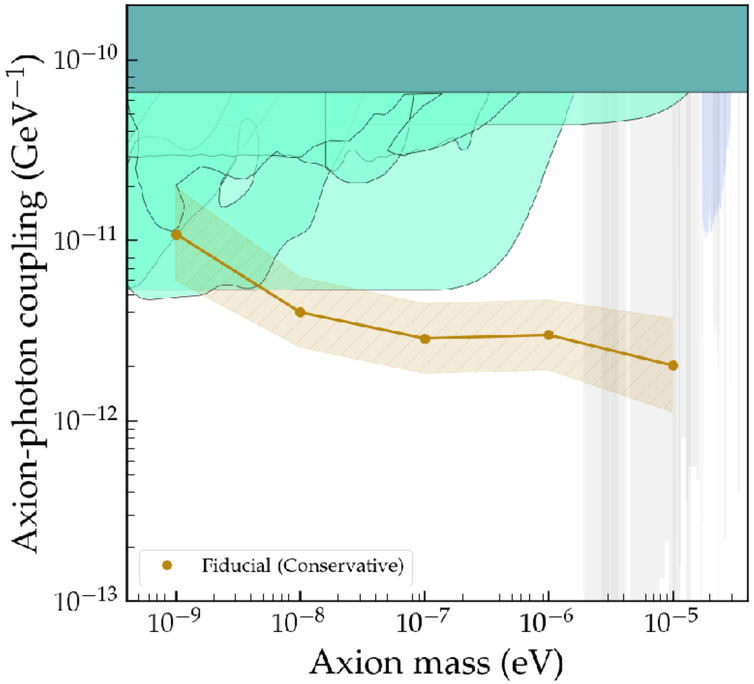


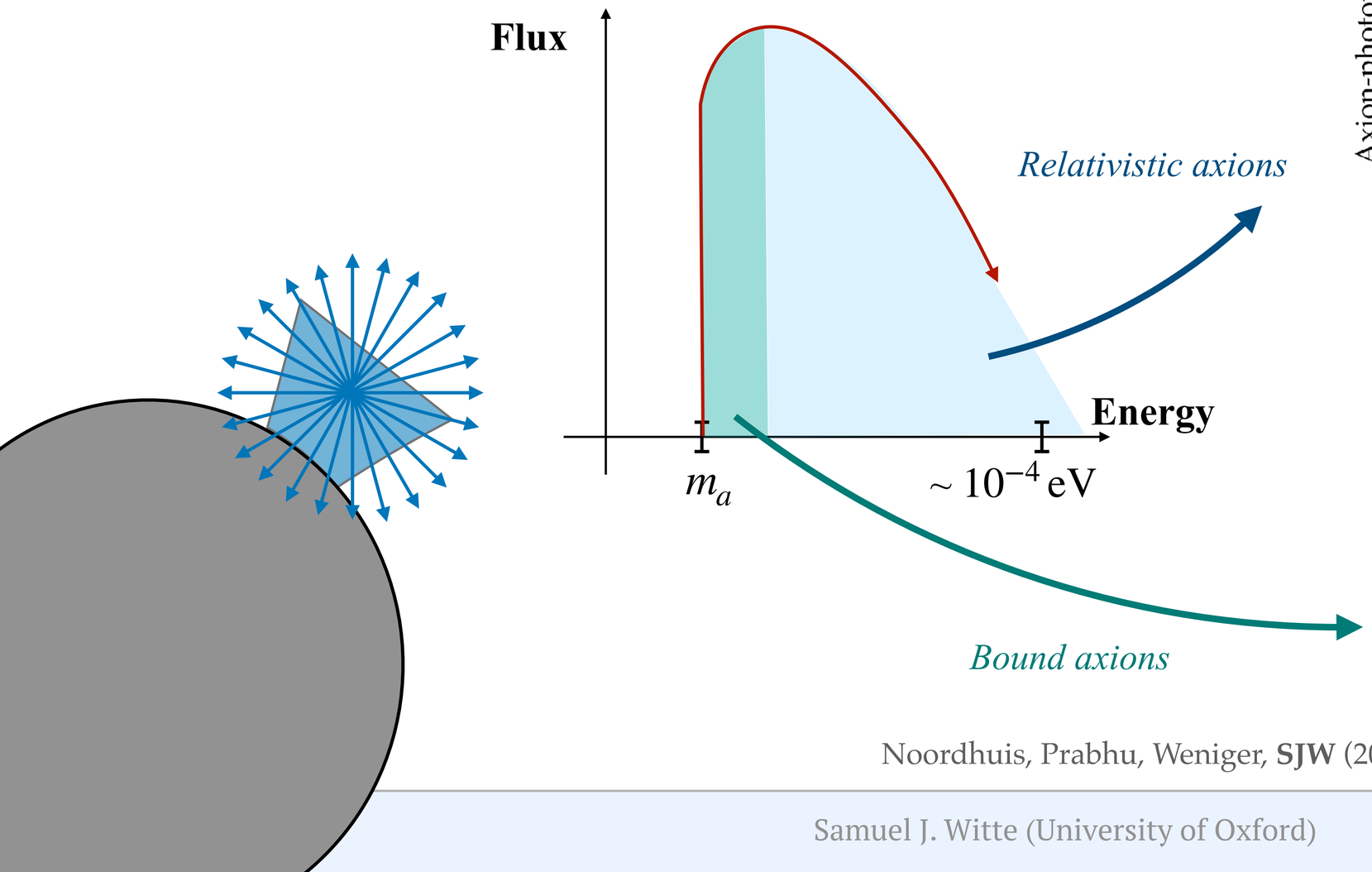


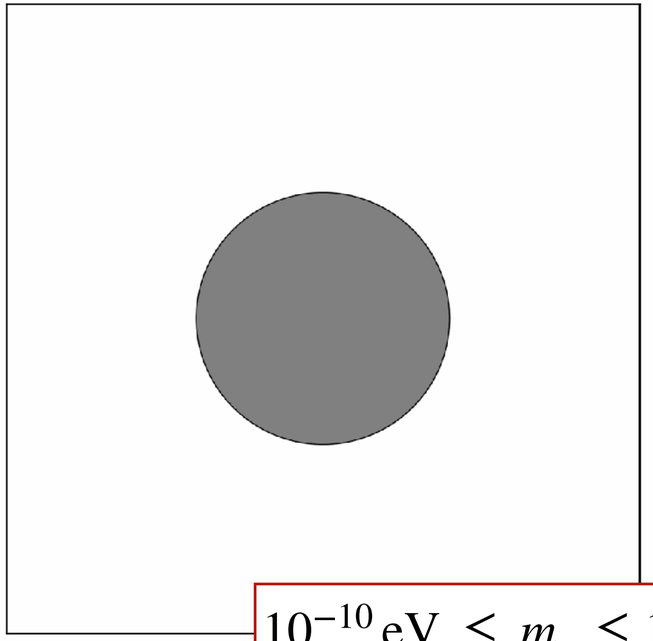
- *Archival data of 27 pulsars*
- *No phase information used*

Axion production

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





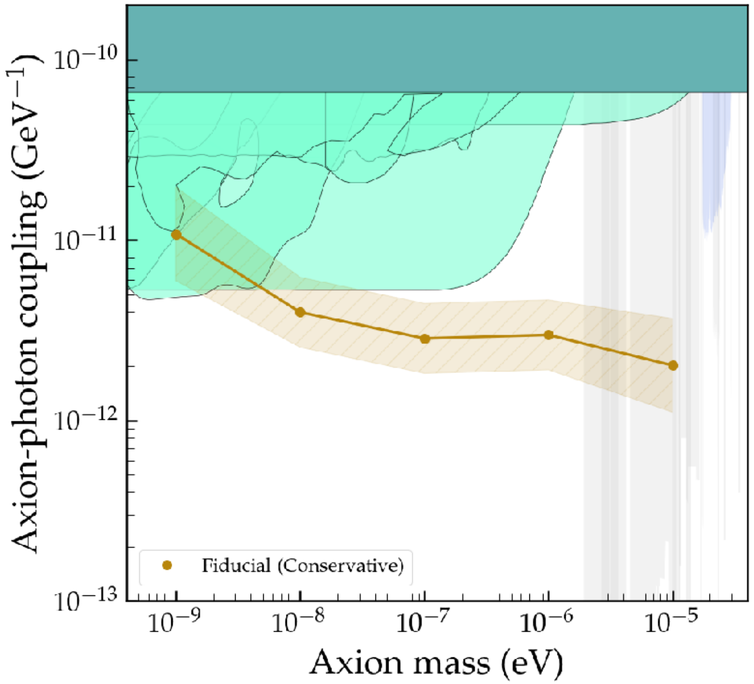


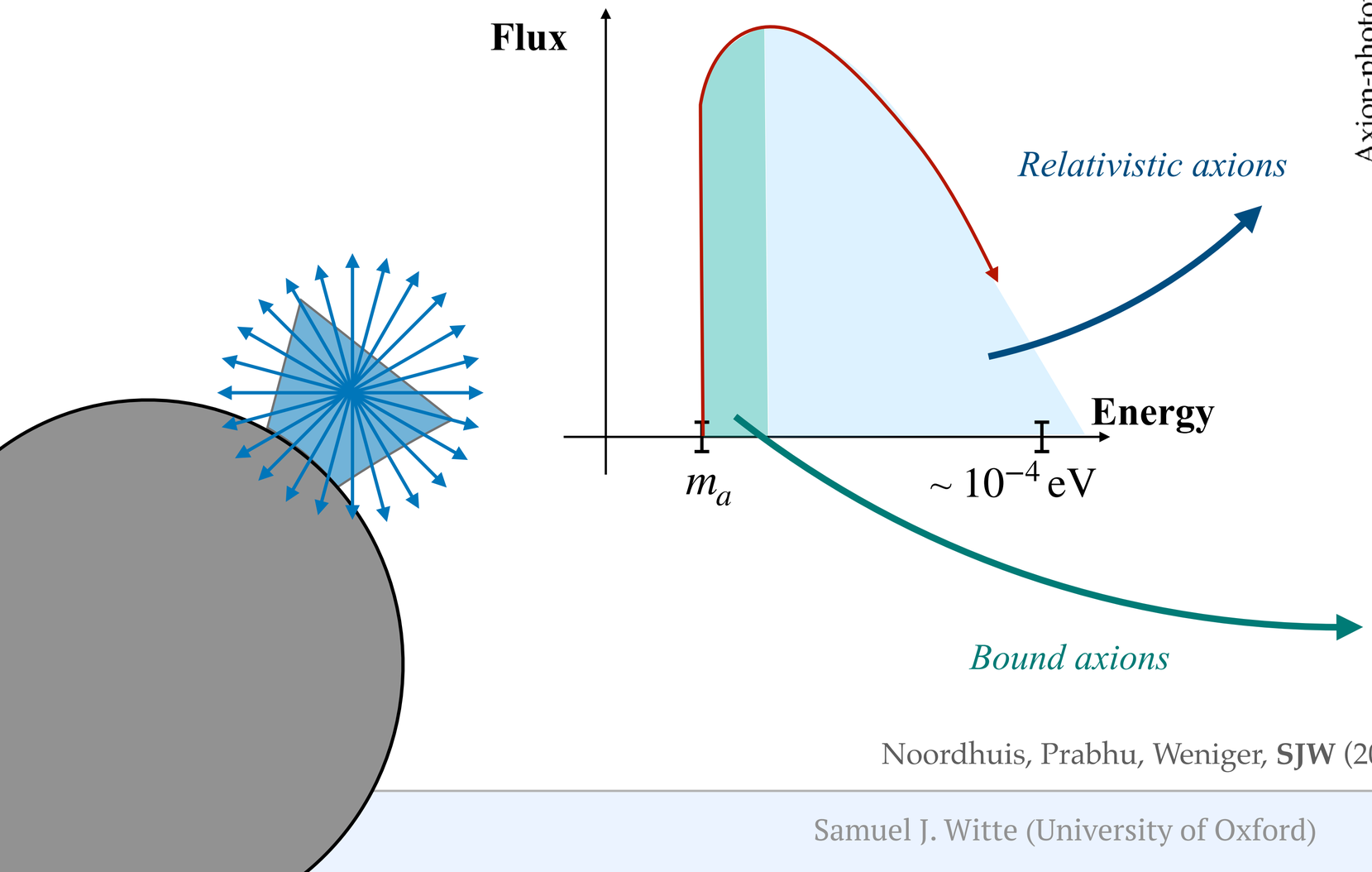
Noordhuis, Prabhu, Weniger, **SJW** (2023)

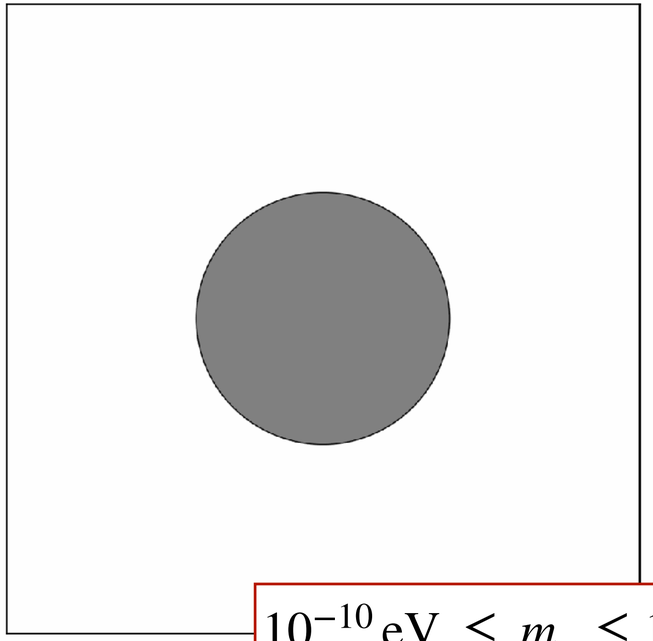
$10^{-10}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$

Axion production

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







Noordhuis, Prabhu, Weniger, **SJW** (2023)

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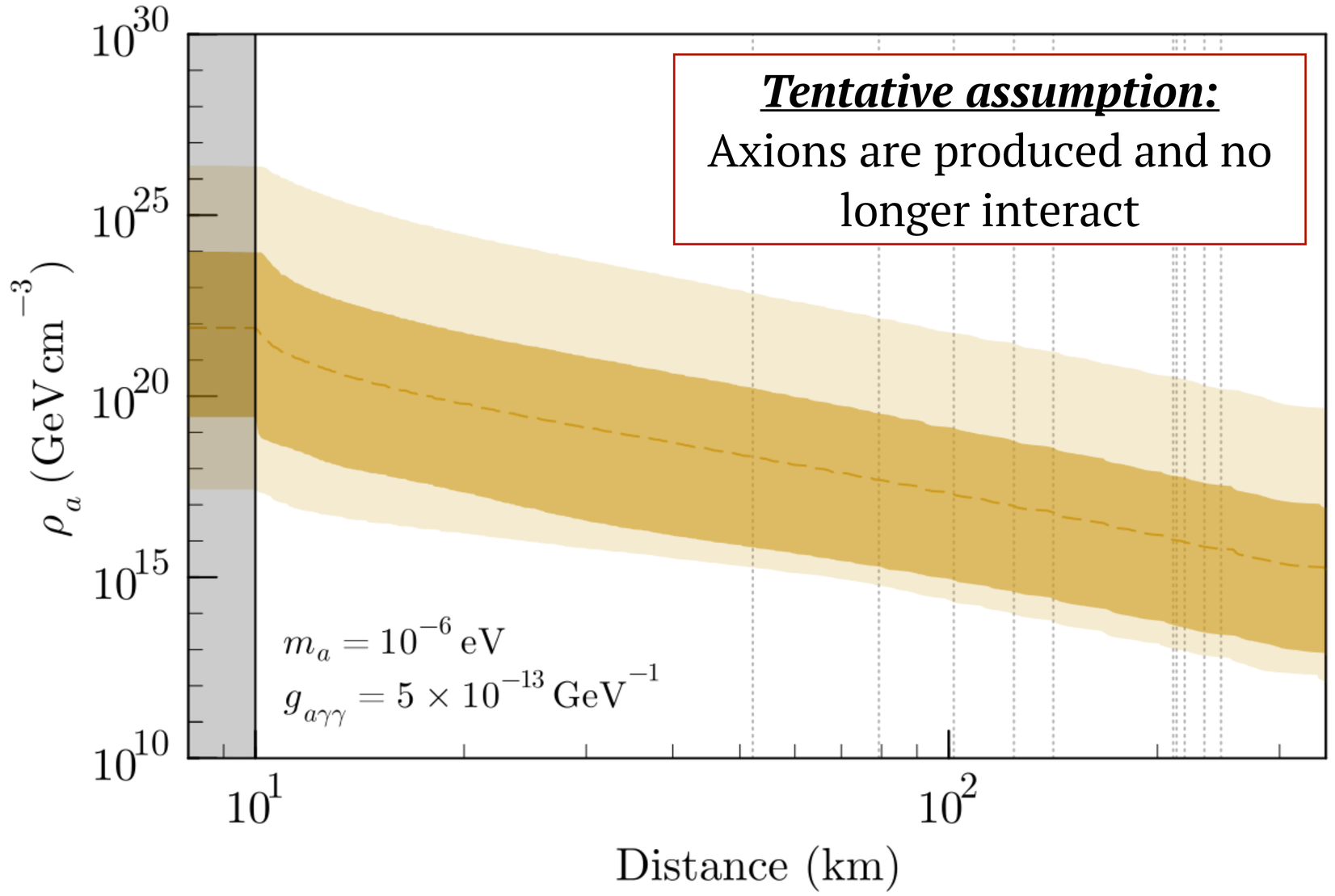
Axion Clouds



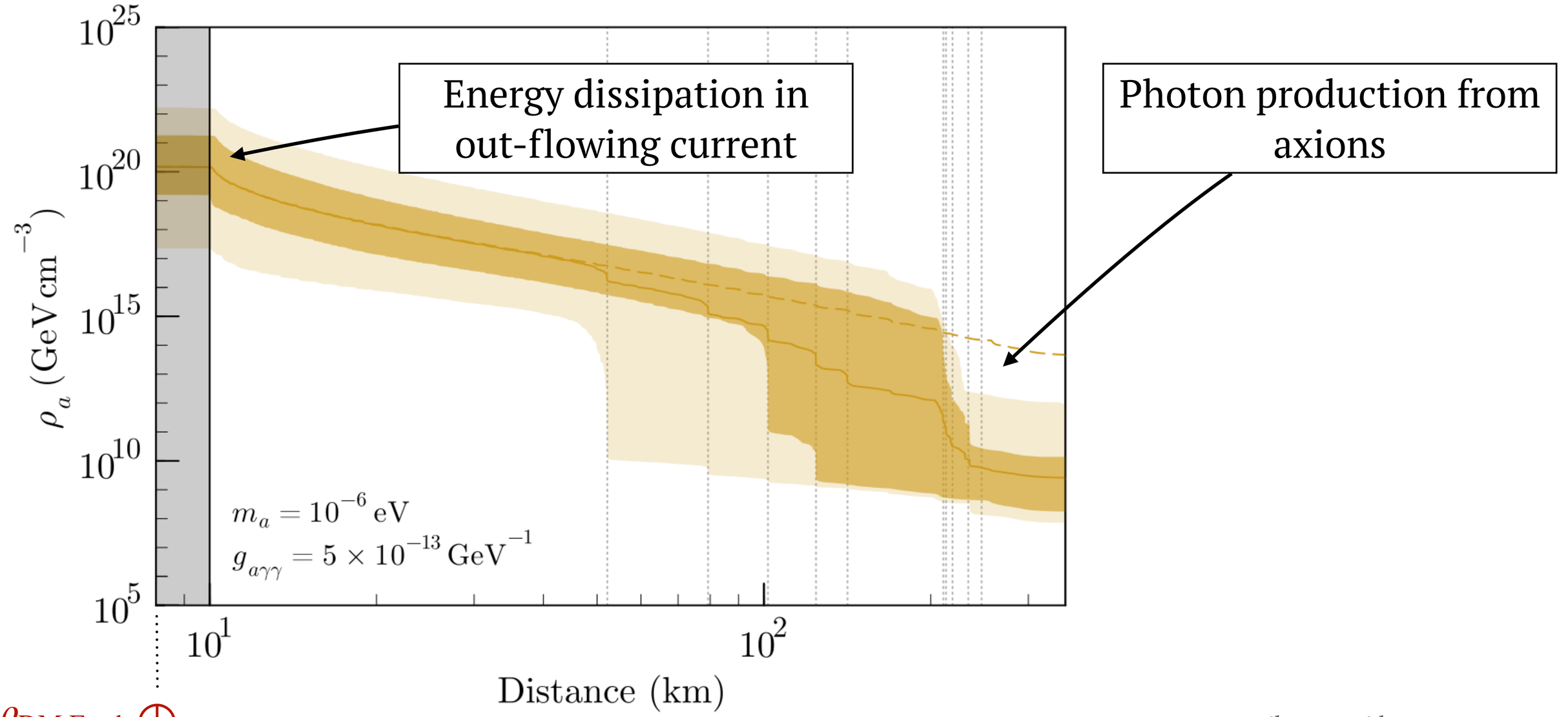
Tentative assumption:
Axions are produced and no longer interact

10 "mock" neutron stars

Axion cloud for population of pulsars at $t \sim 1\,\mathrm{kyr}$

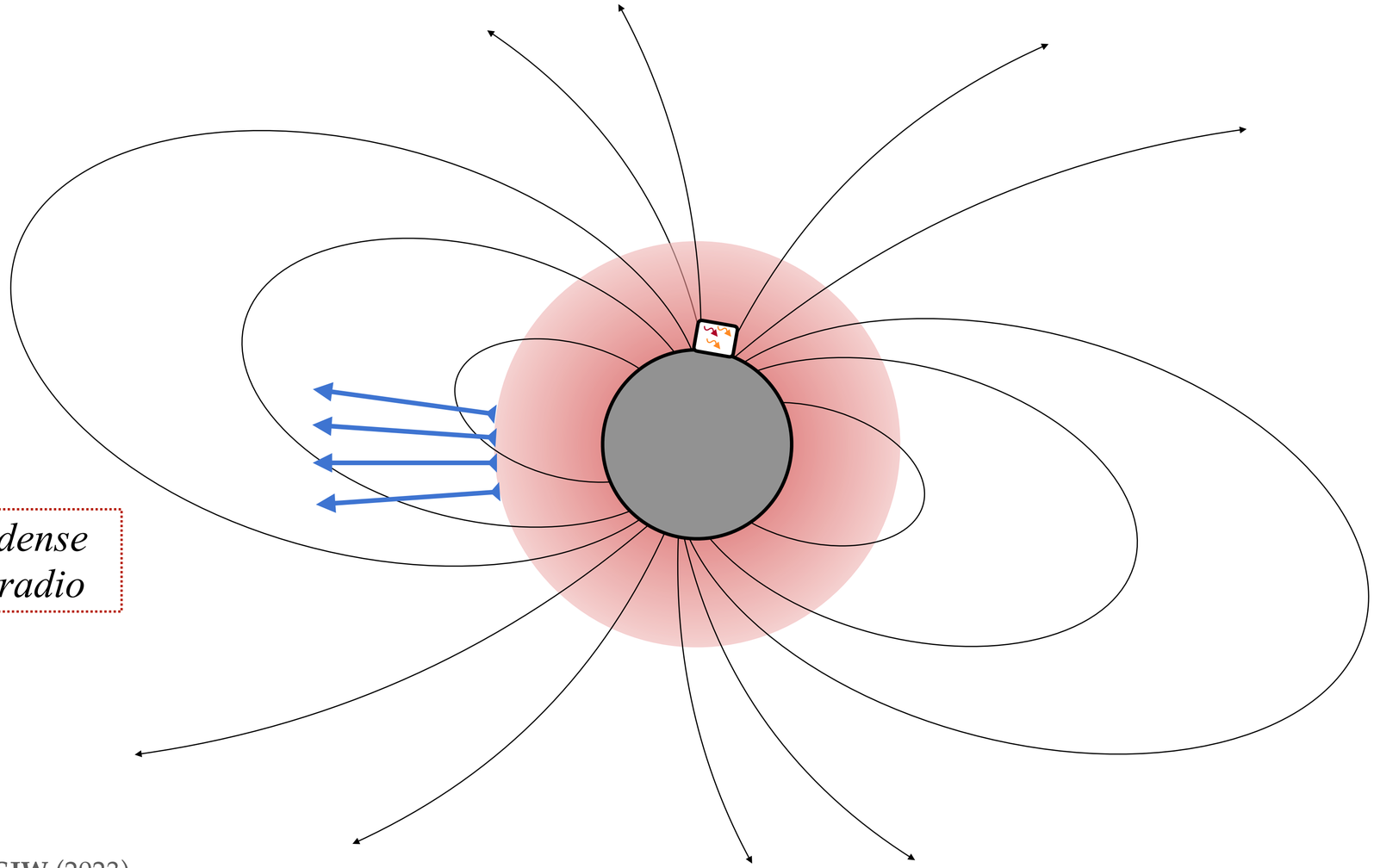
Noordhuis, Prabhu, Weniger, **SJW** (2023)

Axion Clouds



Noordhuis, Prabhu, Weniger, **SJW** (2023)

Observables from axion clouds

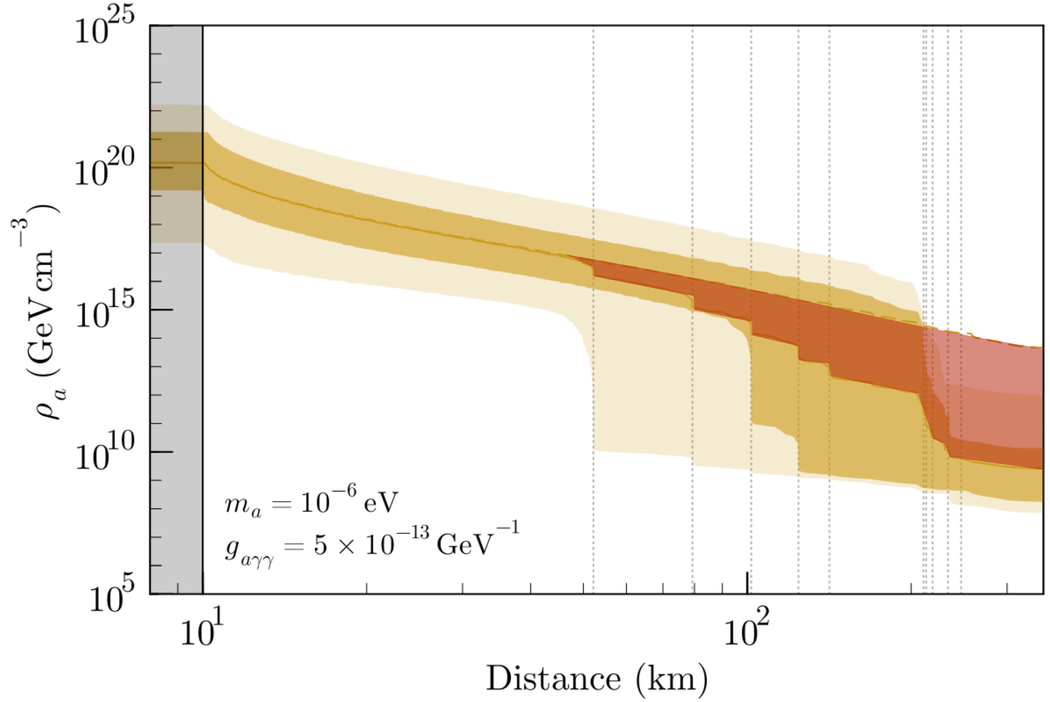


Radio Line

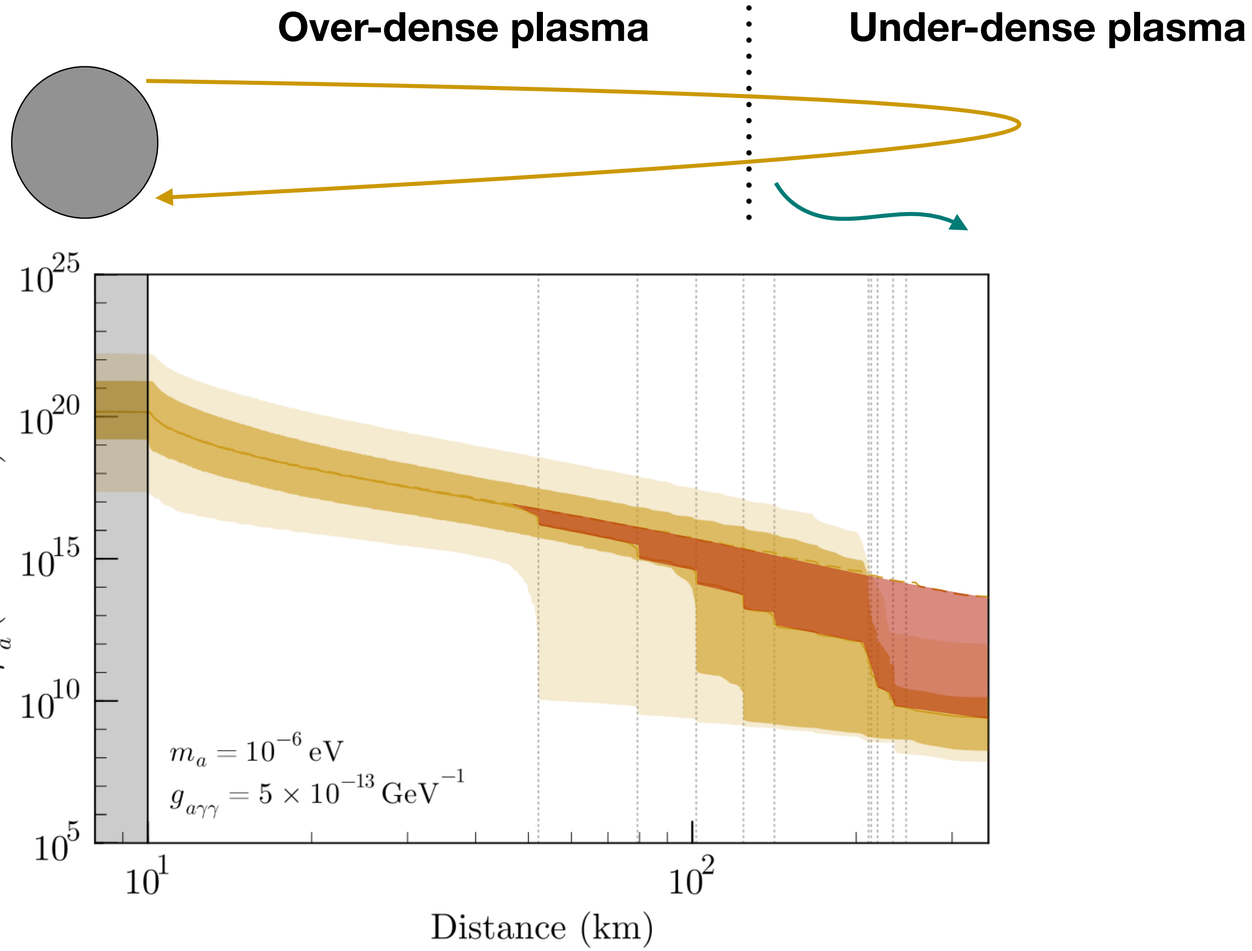
Axions in under-dense plasma produce radio

Noordhuis, Prabhu, Weniger, **SJW** (2023)

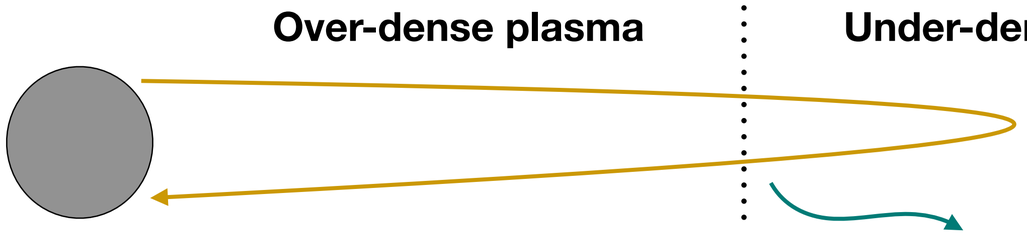
Sharp endpoint in radio spectrum

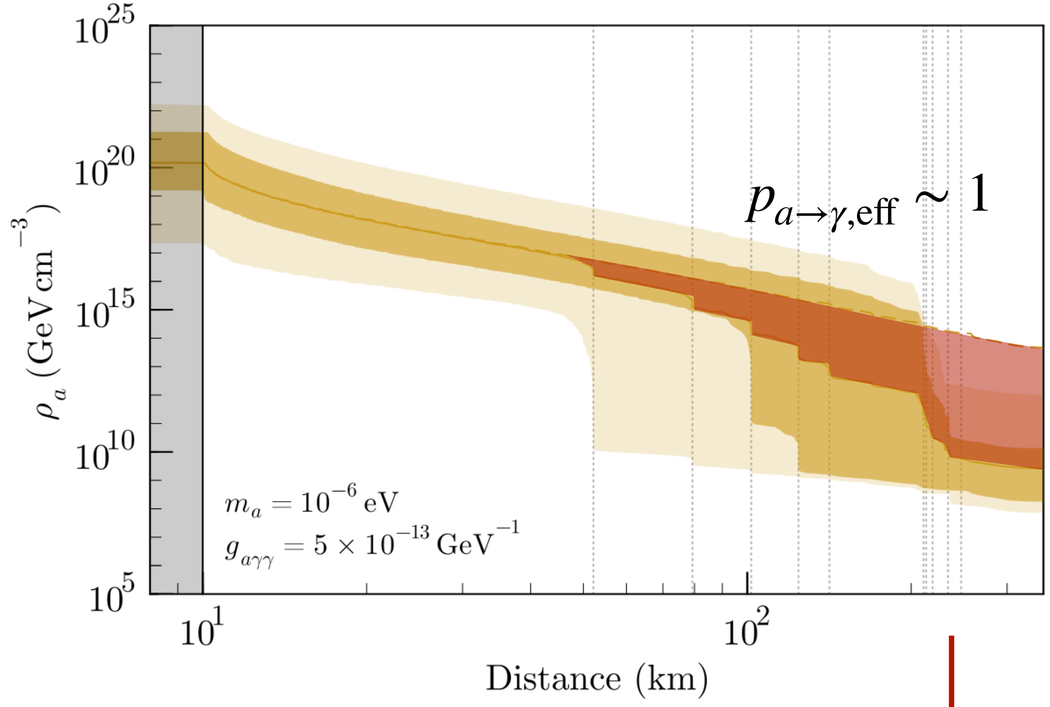


Sharp endpoint in radio spectrum



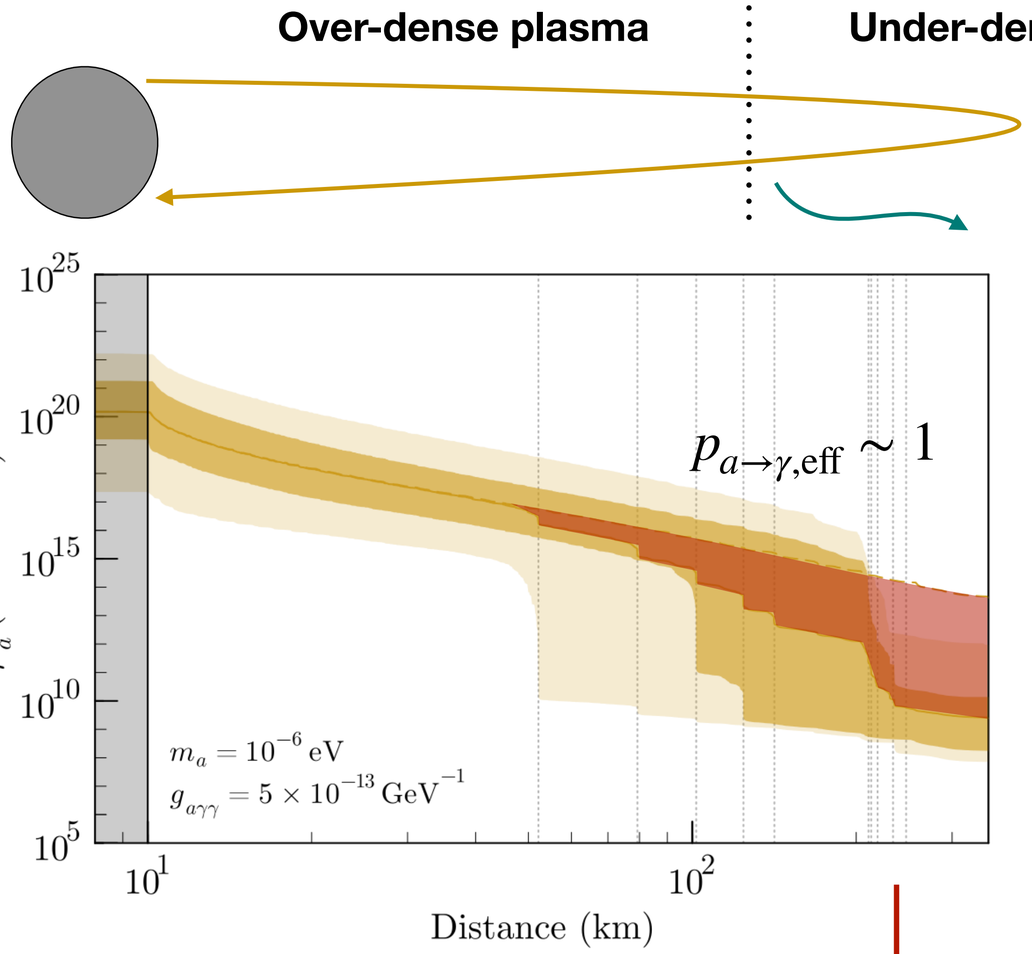
Sharp endpoint in radio spectrum





Kinematics fix: $m_a \leq \omega \lesssim m_a\sqrt{1+v_{\mathrm{esc}}^2}$

Sharp endpoint in radio spectrum



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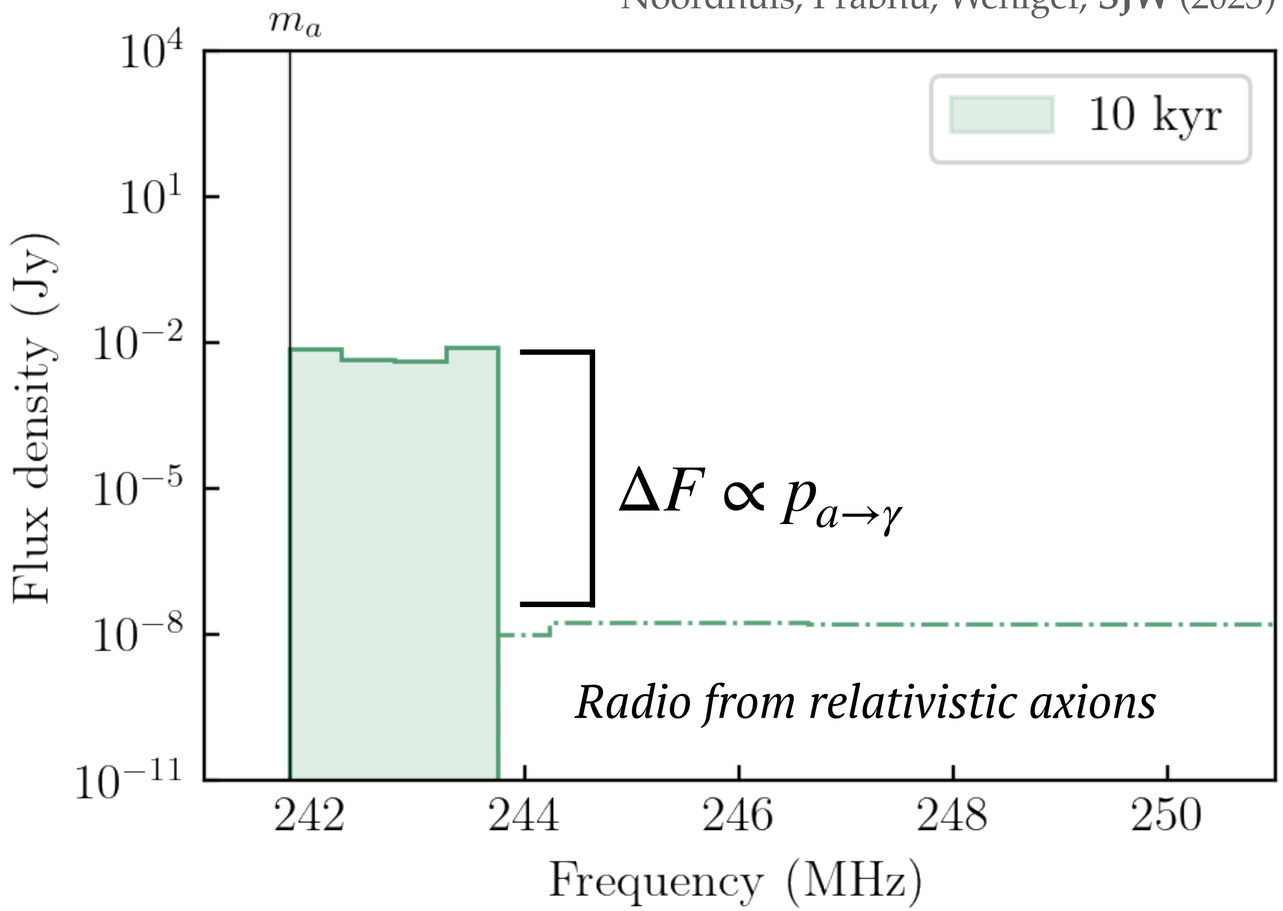
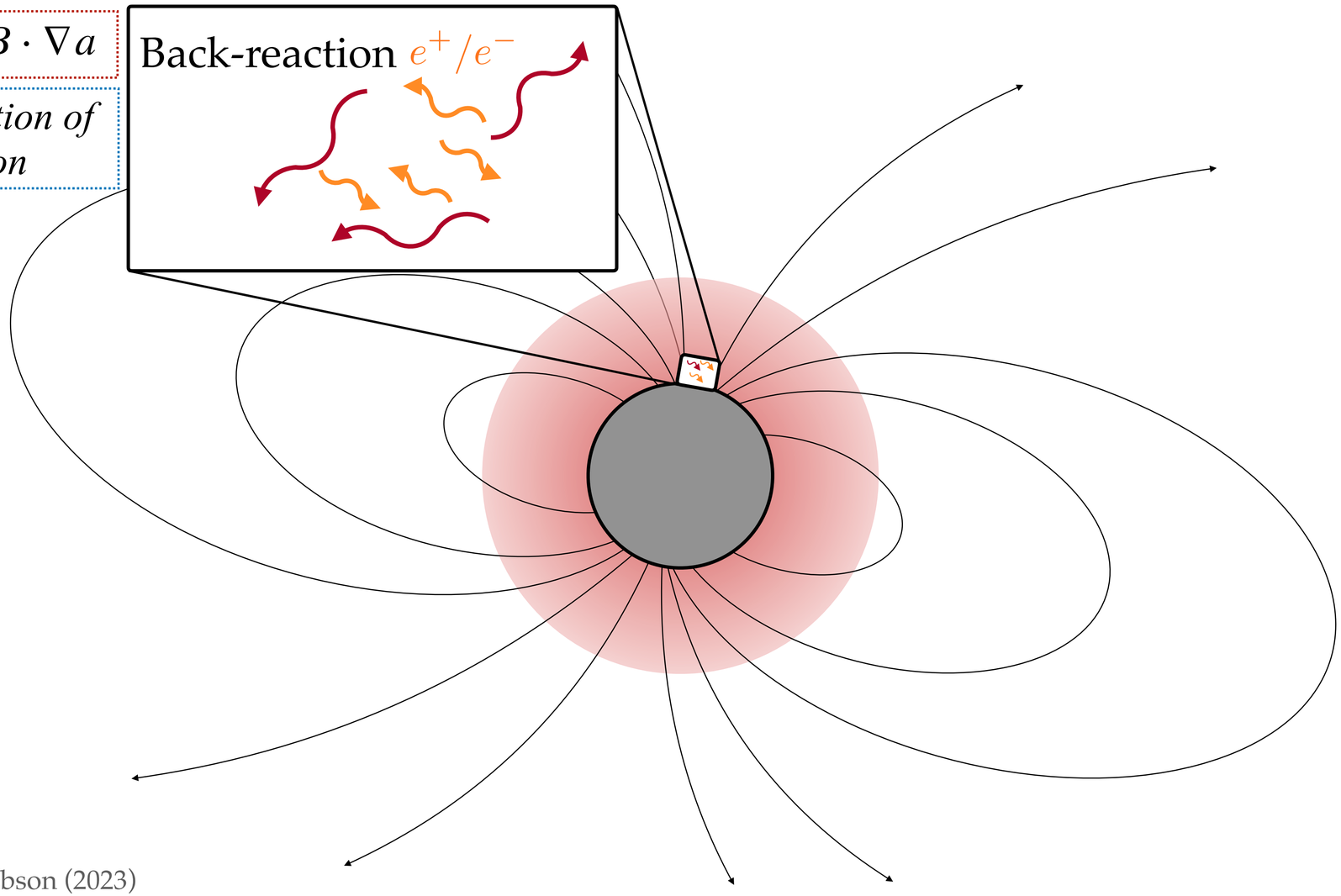
Noordhuis, Prabhu, Weniger, **SJW** (2023)



Observables from axion clouds

$\nabla \cdot E = \rho - g_{a\gamma} B \cdot \nabla a$

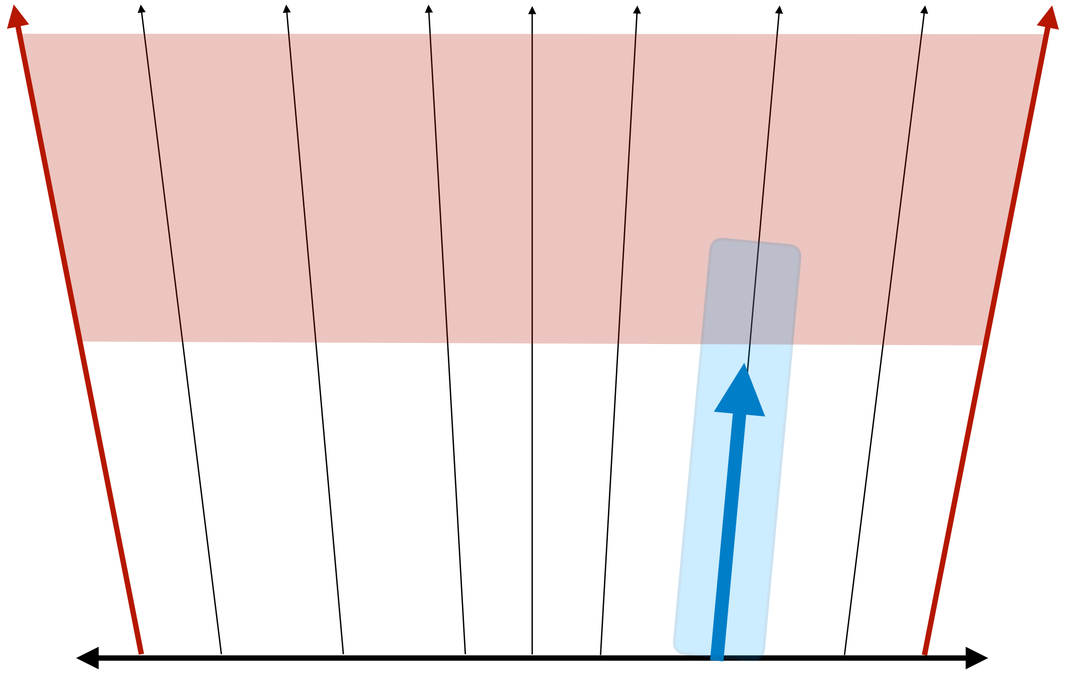
Periodic modulation of radio emission



Caputo, **SJW**, Philippov, Jacobson (2023)

Electrodynamics of the gap in 1D

See e.g. Timohkin & Arons (2012)



Evolve primary particle evolution along field lines

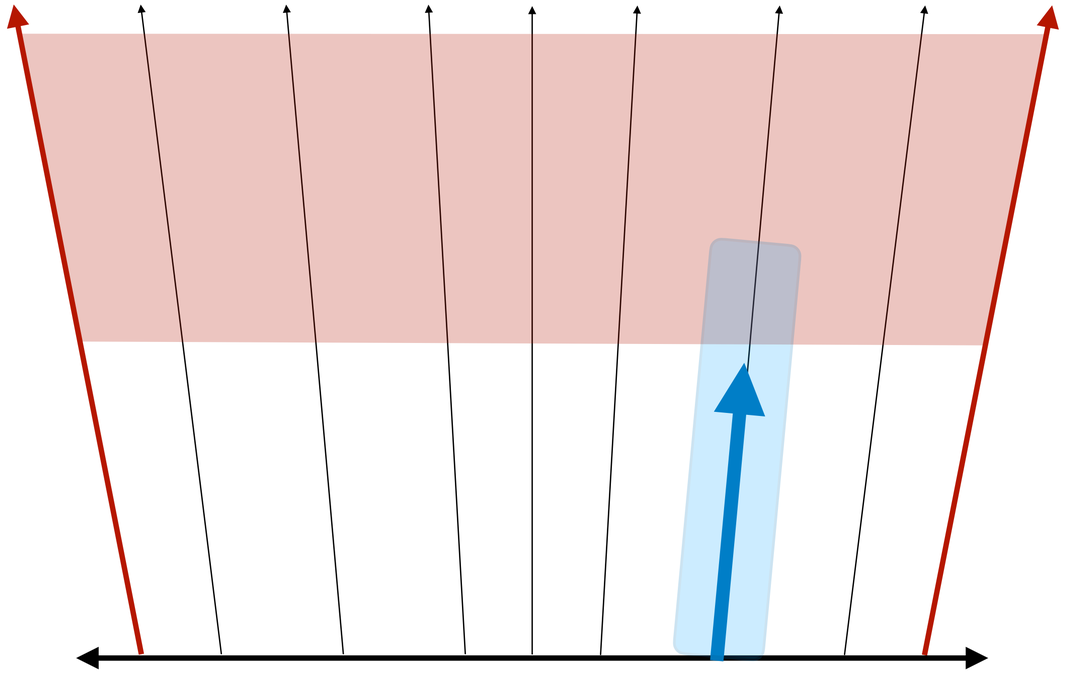
Ampere's law: Open field lines demand current $j_m \equiv (\nabla \times B)_{||}$

Gauss law + Energy Cons: How does E-field / electrons evolve

See e.g. Belobodorov (2008), Timokhin & Arons (2013)

Electrodynamics of the gap in 1D

See e.g. Timohkin & Arons (2012)



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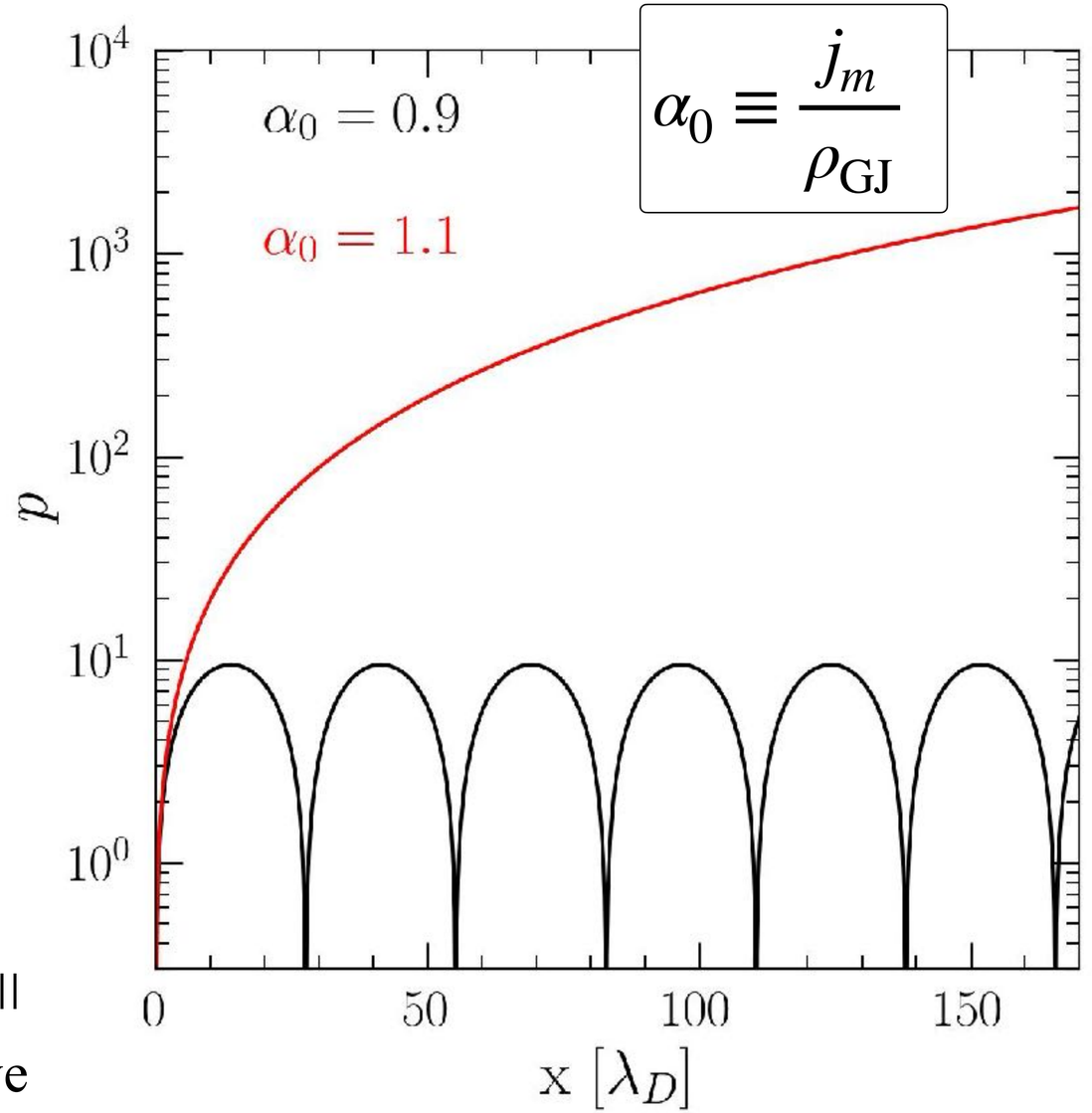

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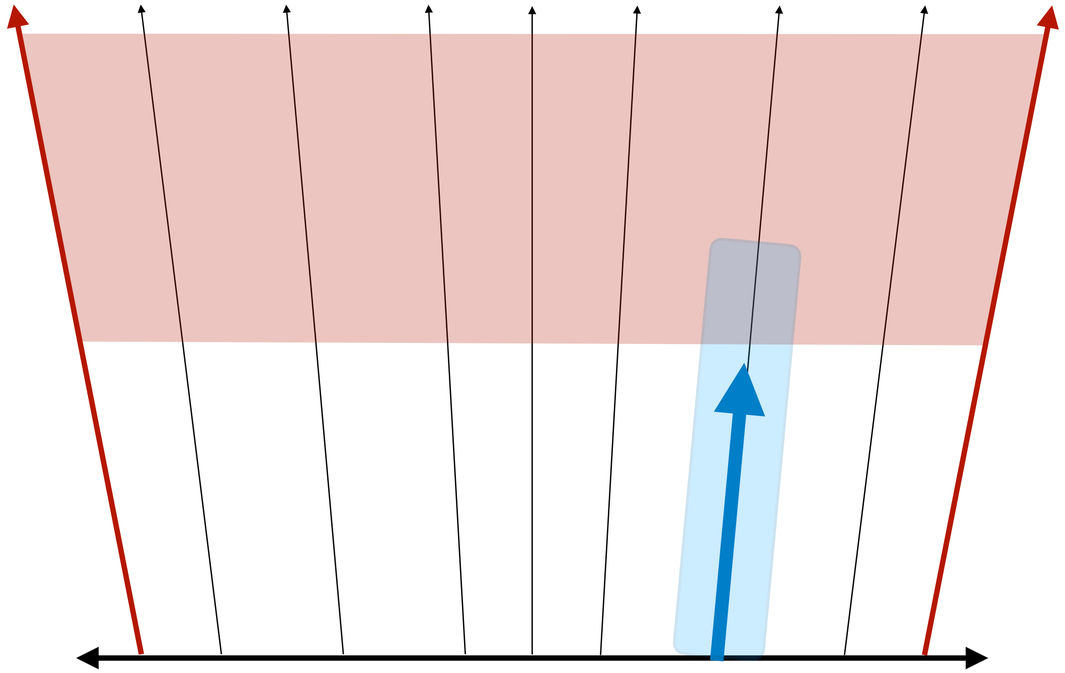
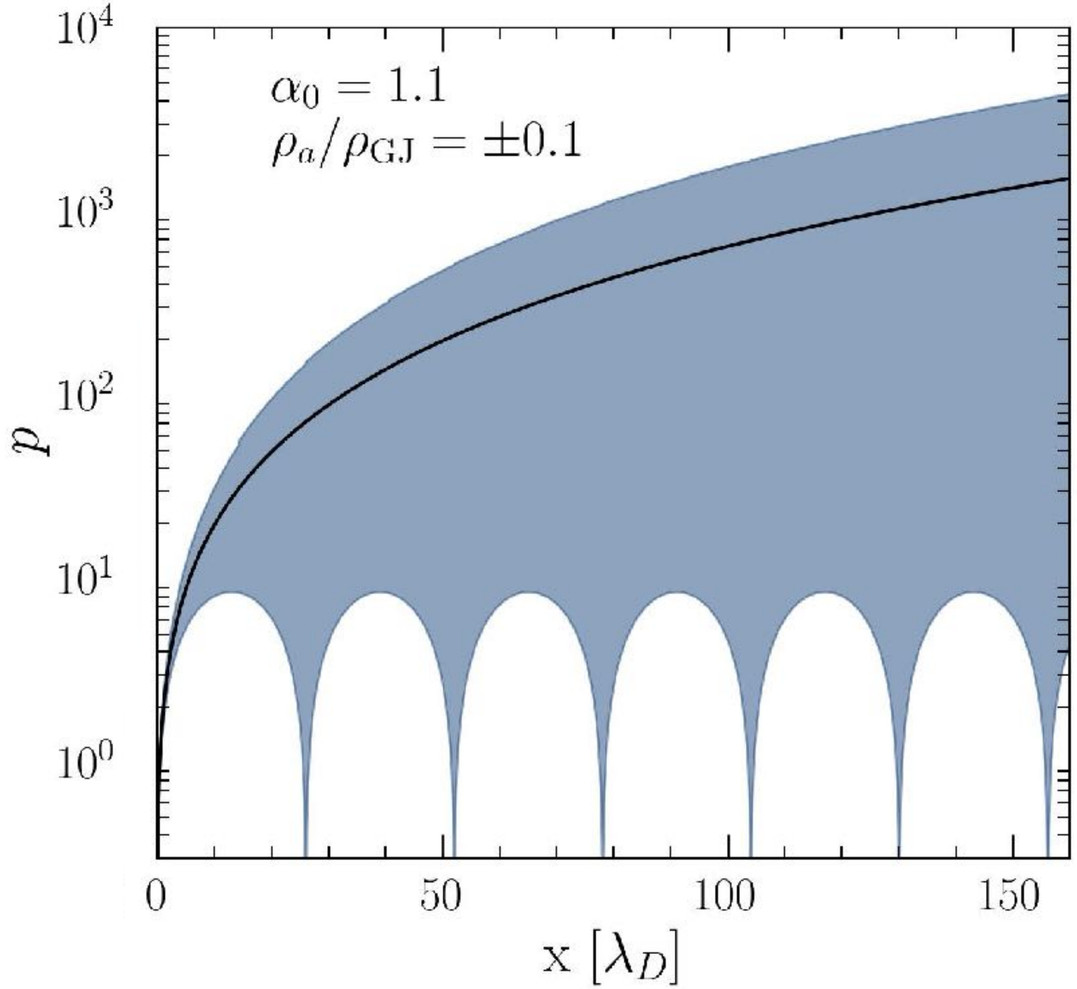
Electrodynamics of the gap in 1D

Caputo, **SJW,** Philippov, Jacobson (2023)



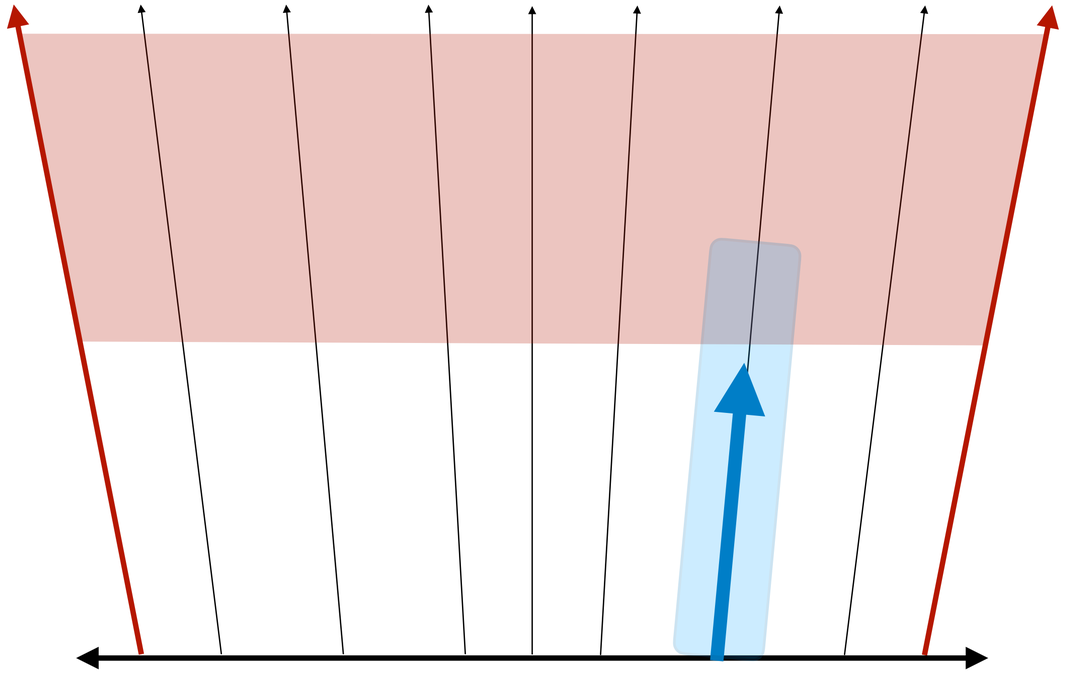


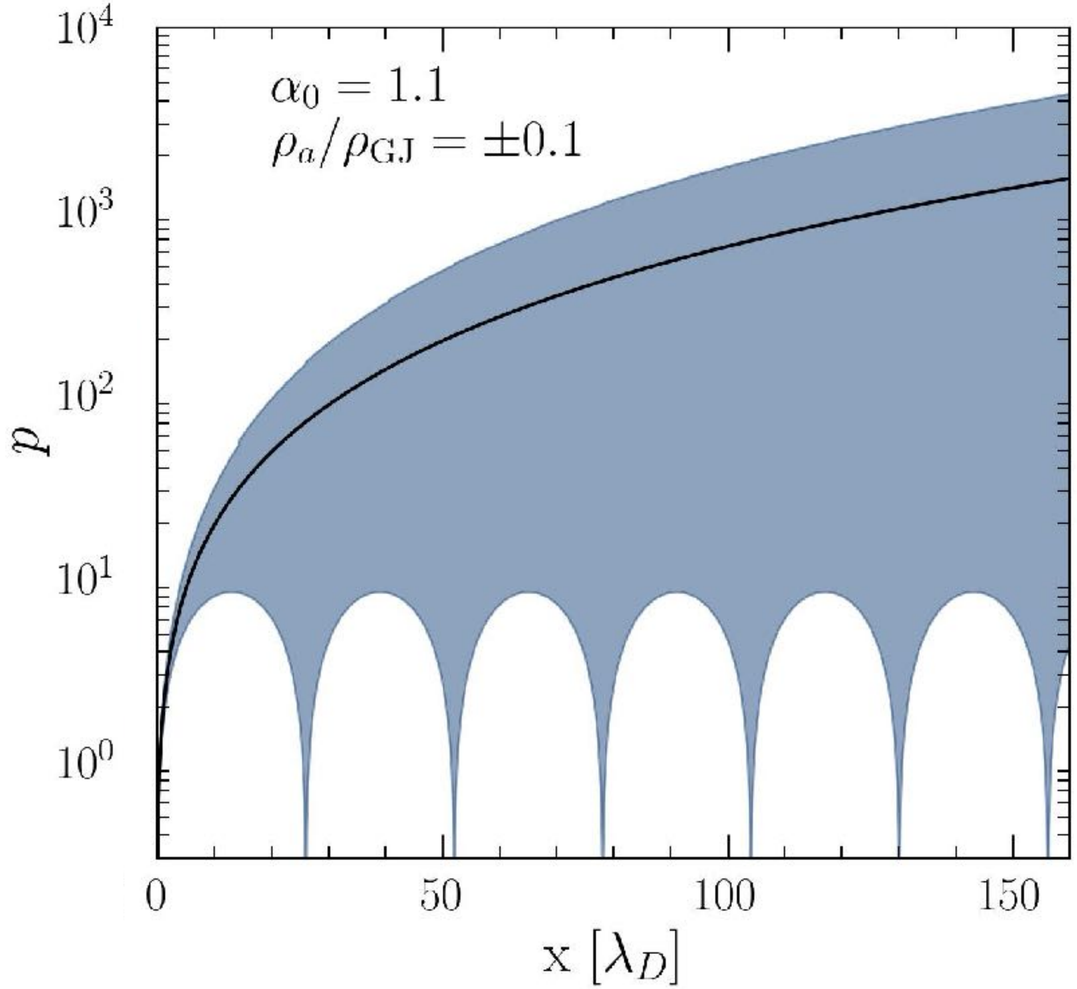
$$\partial_x E = \rho - \rho_{\rm GJ} + g_{a\gamma\gamma} B \cdot \nabla a$$

+ modifications to Ampere's law

Electrodynamics of the gap in 1D

Caputo, **SJW,** Philippov, Jacobson (2023)





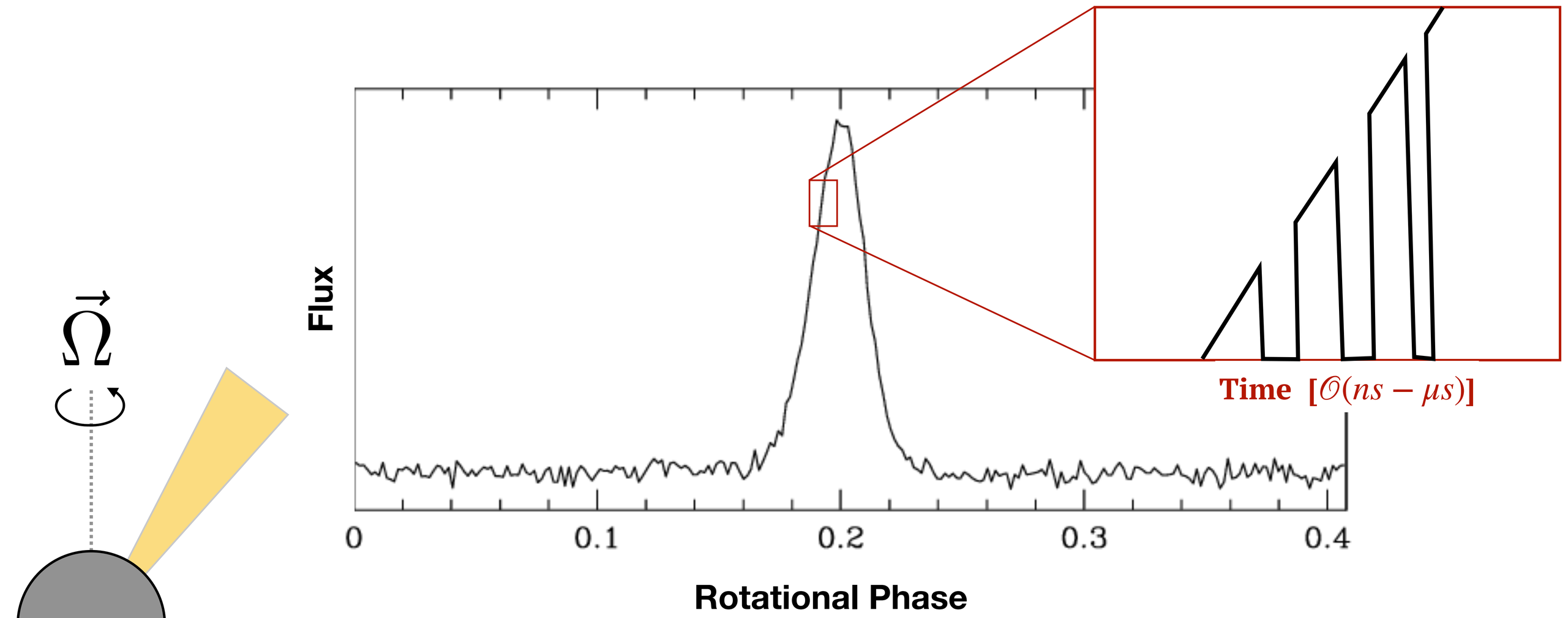
$$\partial_x E = \rho - \rho_{\rm GJ} + g_{a\gamma\gamma} B \cdot \nabla a$$

+ modifications to Ampere's law

For light axions, effect is coherent!

Axion-induced nulling

Only occurs for some neutron stars



Caputo, **SJW,** Philippov, Jacobson (2023)

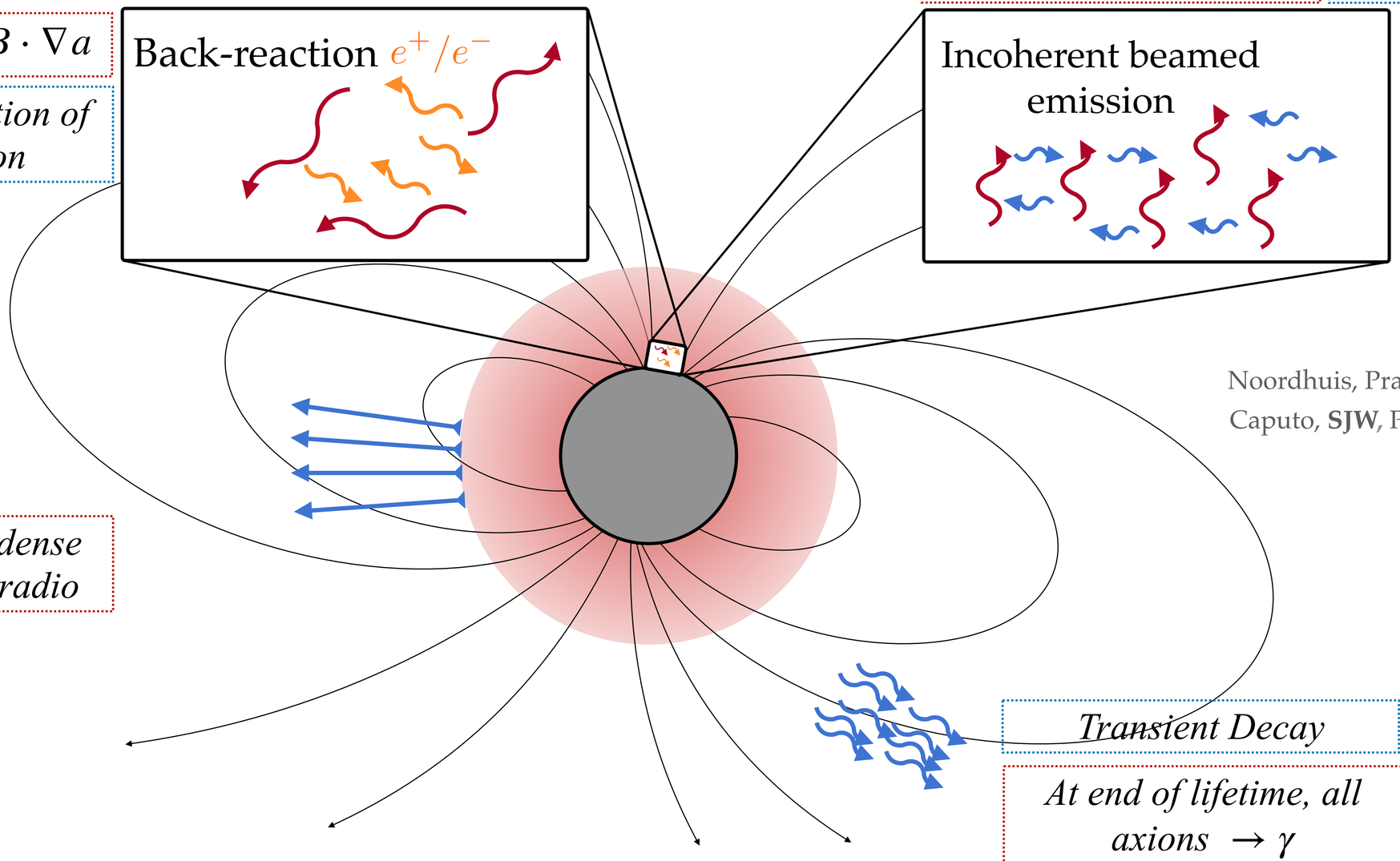
Observables from axion clouds

$\nabla \cdot E = \rho - g_{a\gamma} B \cdot \nabla a$

Periodic modulation of radio emission

Axion + Magnetic field = Oscillating E dipole

Radio Line



Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW**, Philippov, Jacobson (2023)

Radio Line

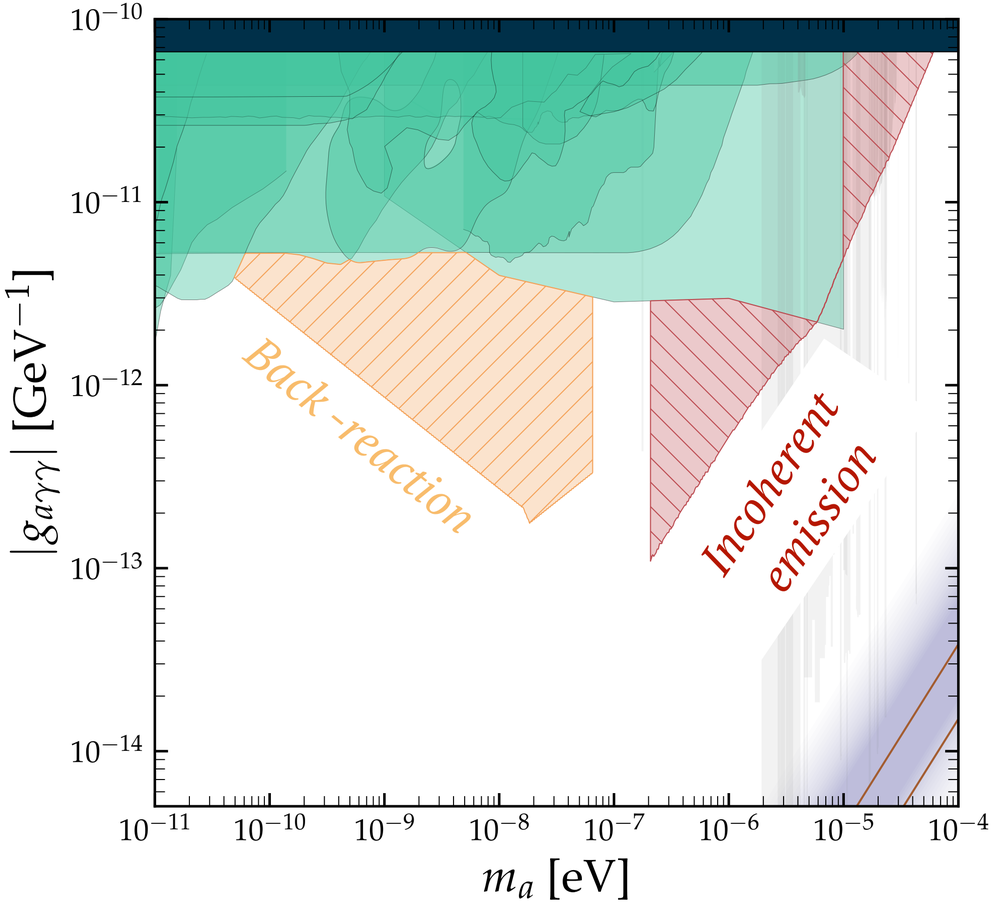
Axions in under-dense plasma produce radio

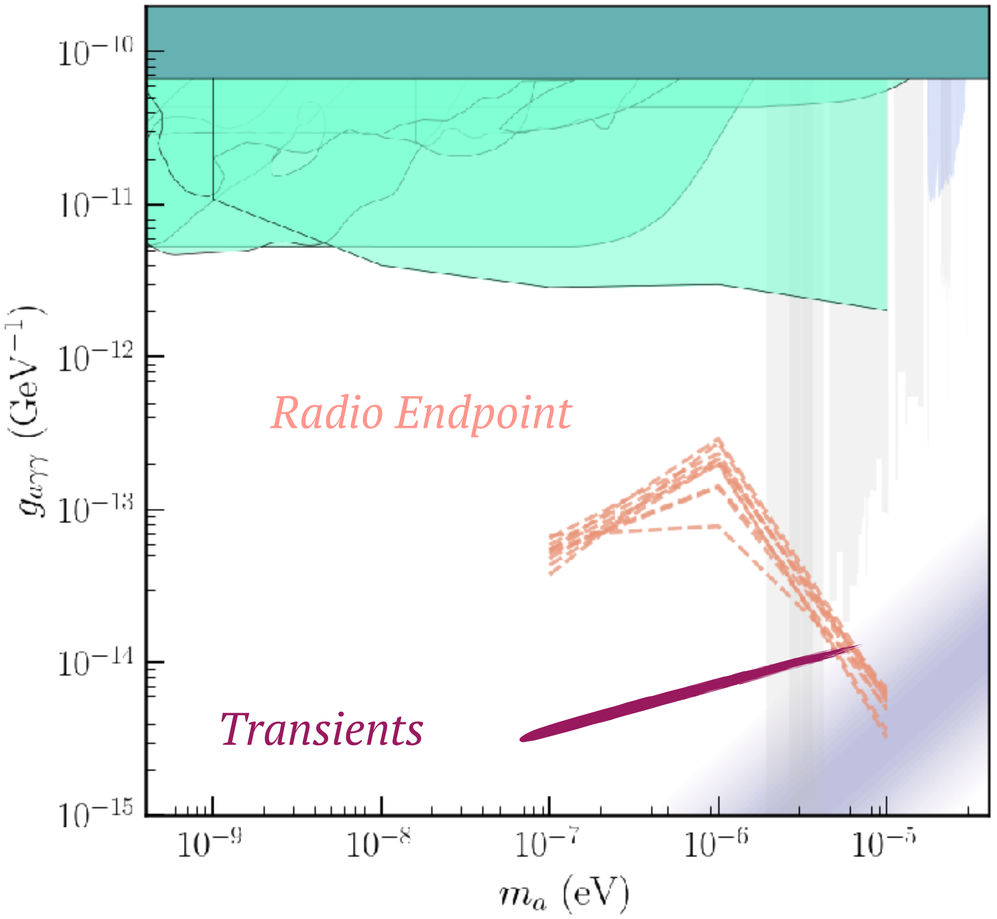
Transient Decay

At end of lifetime, all axions $\rightarrow \gamma$

Sensitivity to axion clouds

Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW**, Philippov, Jacobson (2023)





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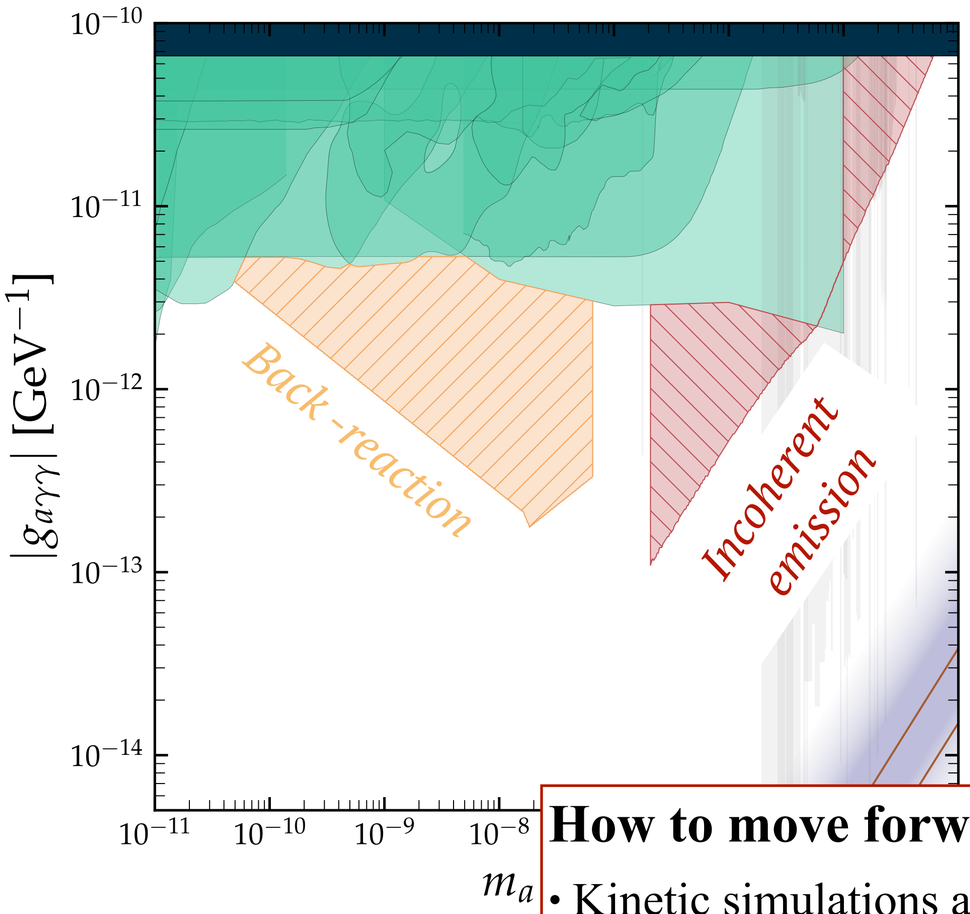
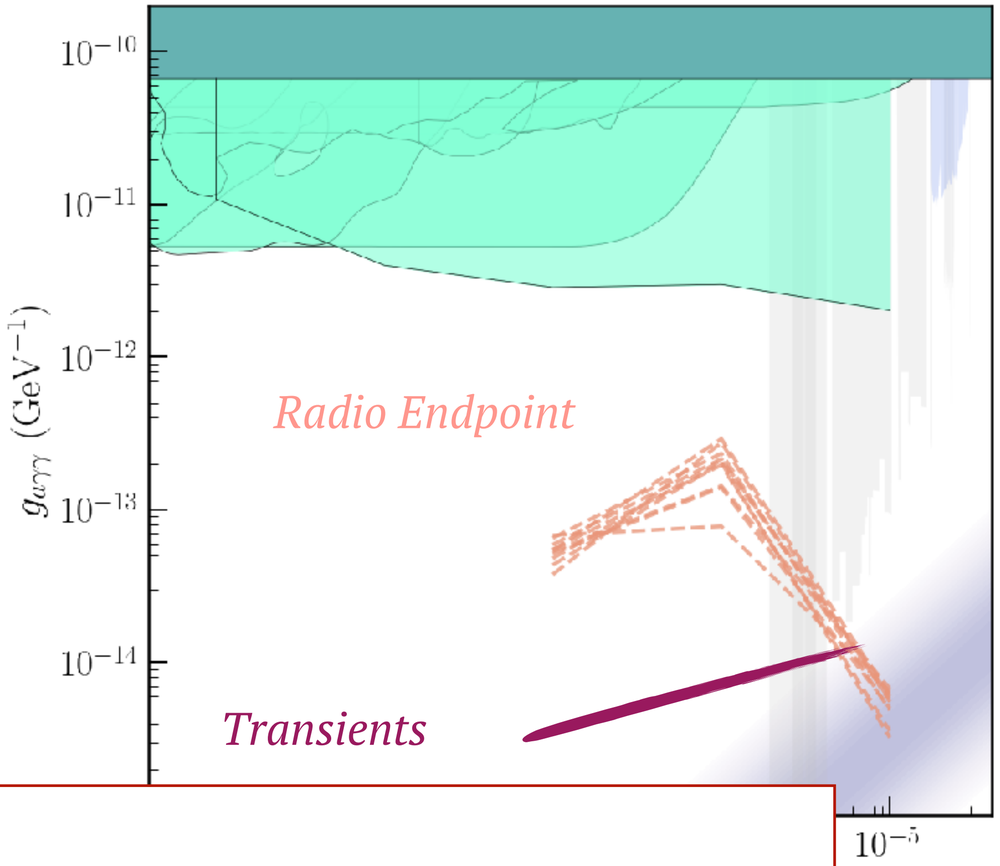


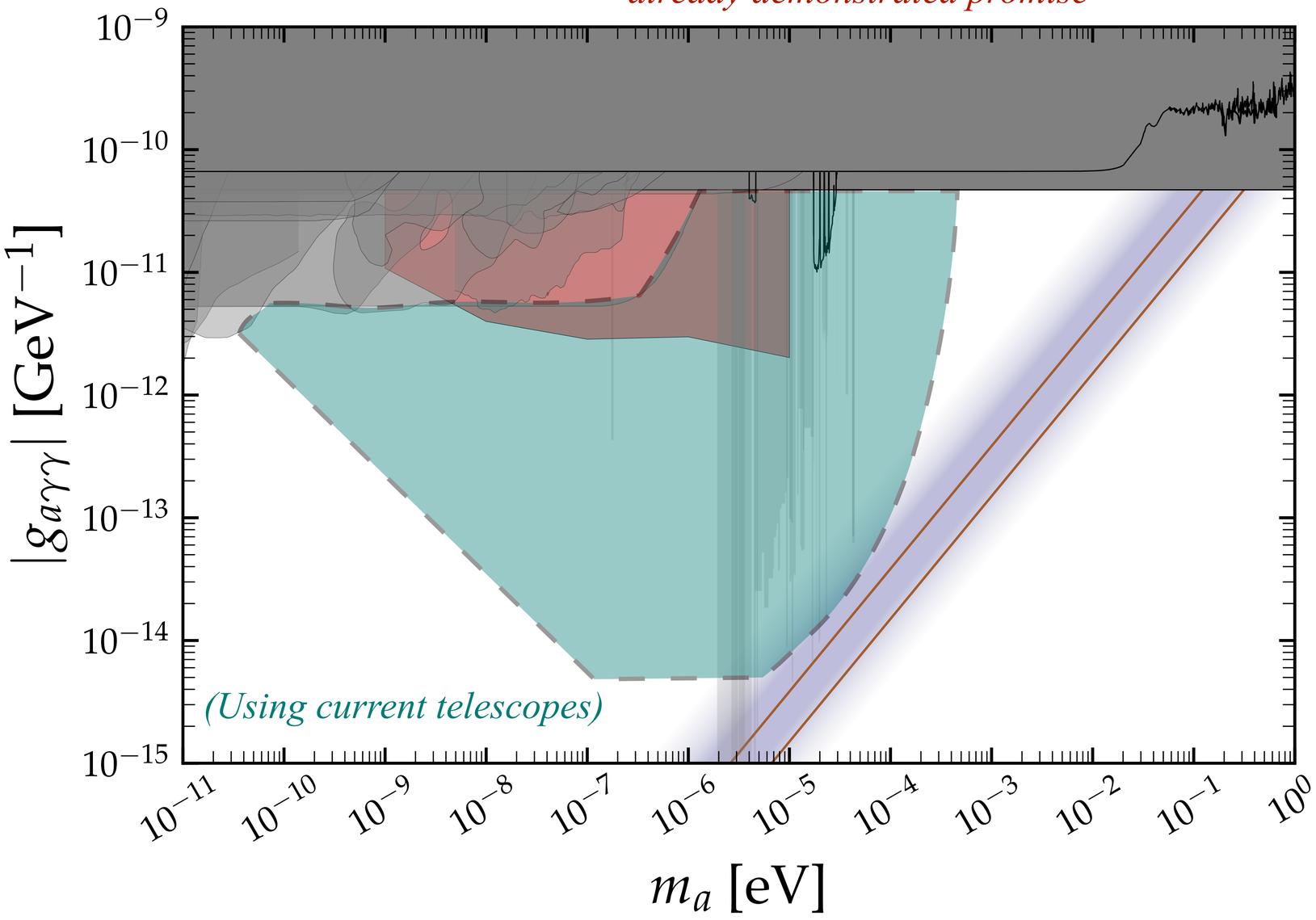


How to move forward:

- Kinetic simulations axion electrodynamics
- Understanding systematics of individual systems & population statistics
- Dedicated observations

Conclusions

Early "proof of principle" searches have already demonstrated promise



Local production in neutron stars offer promising future

But a lot of work still to be done!