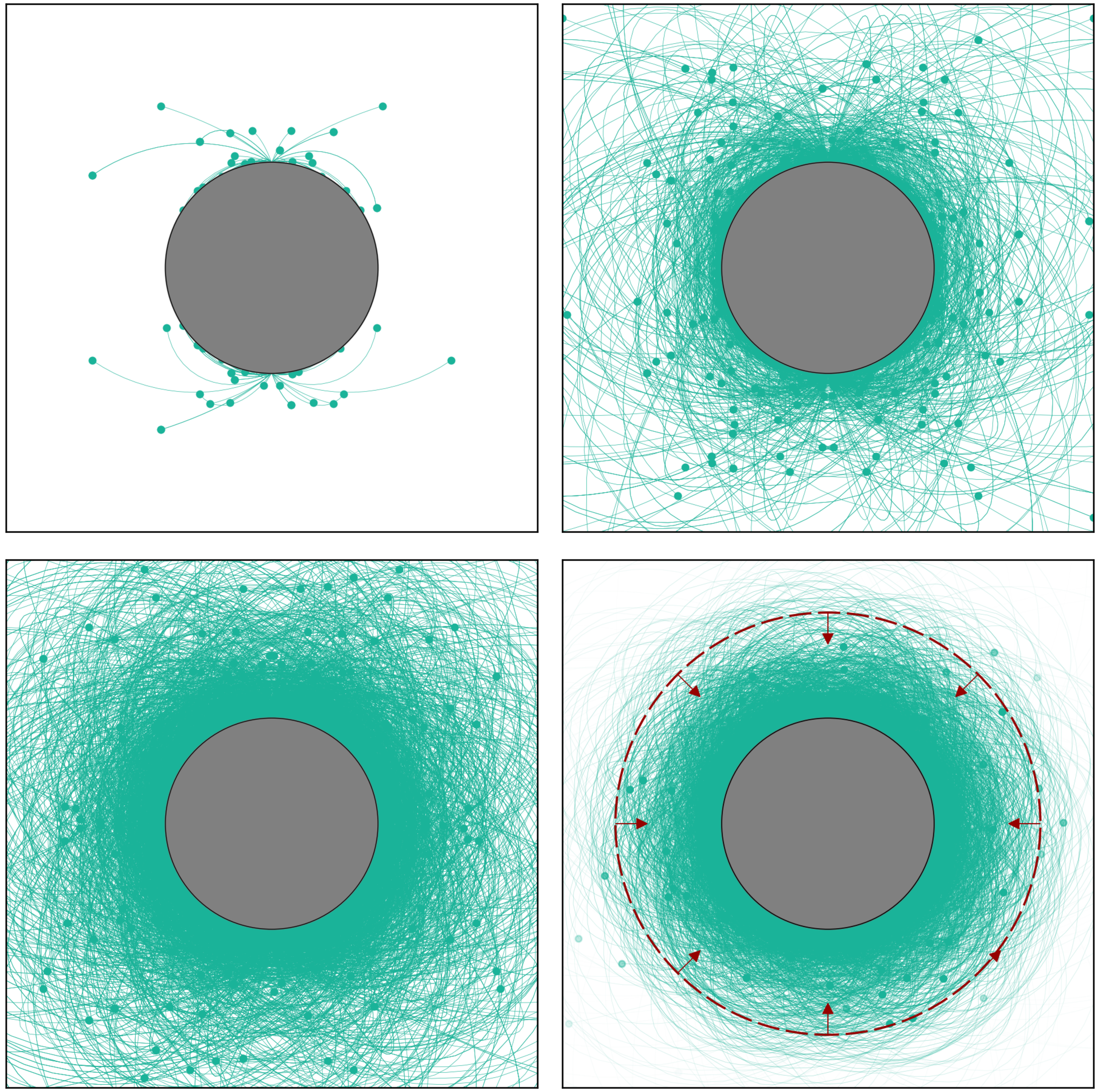
Axion Clouds around Pulsars



Samuel J. Witte

Light Dark World 2023
Karlsruhe
September 19, 2023

ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

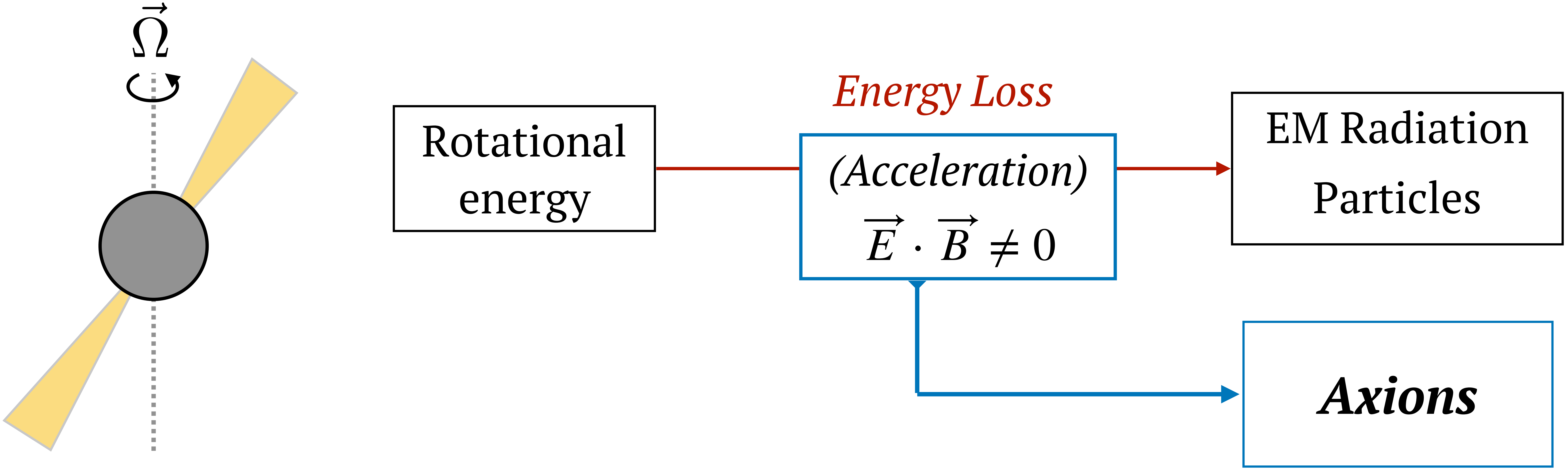
Based On:
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Axion clouds around pulsars

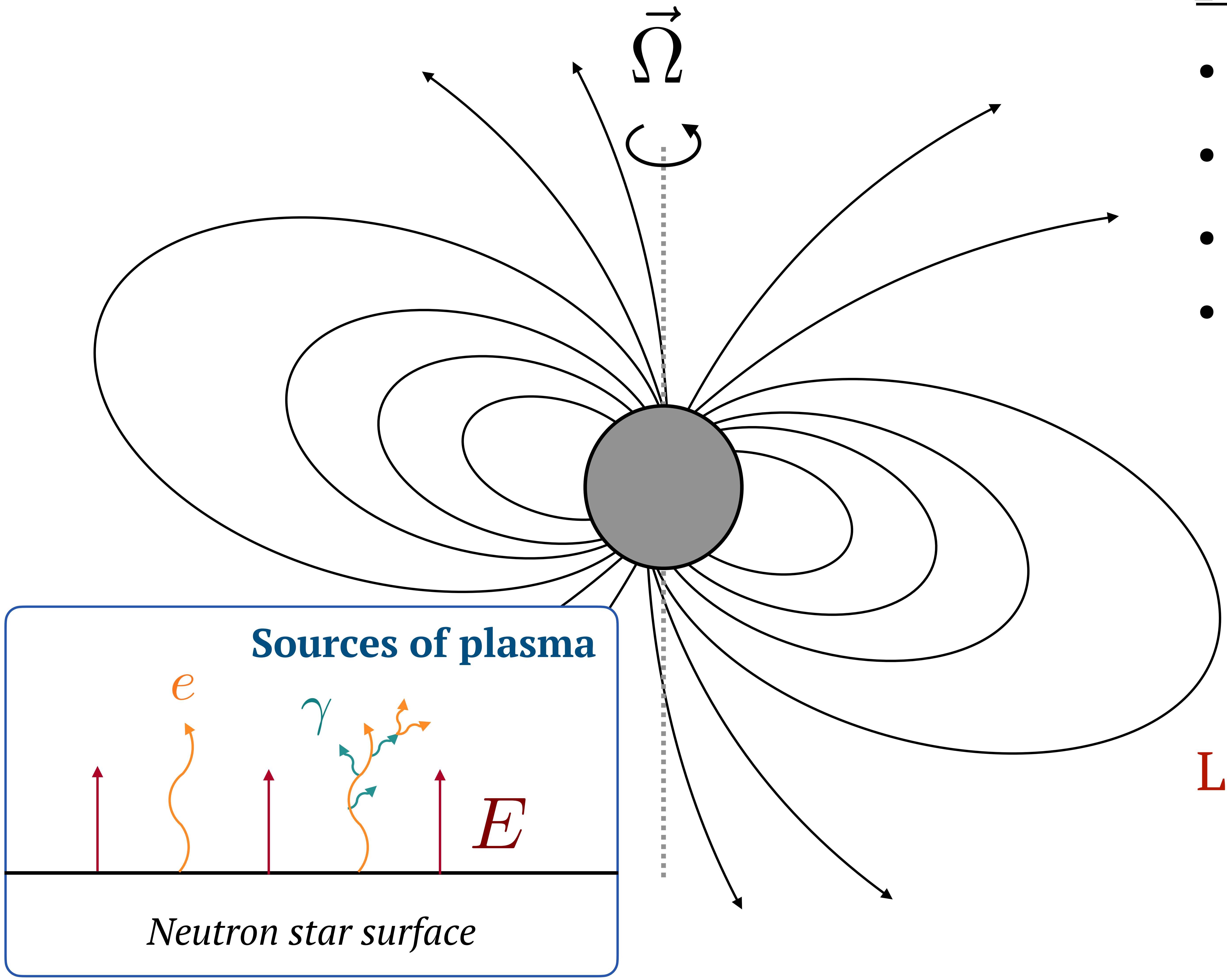
Assumptions: There exists an axion which:

1) Couples to electromagnetism $\mathscr{L} \supset -g_{a\gamma\gamma}\, a\, (\vec{E} \cdot \vec{B})$
2) Has a mass $10^{-10}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$

Take Home : *All active neutron stars (pulsars) are surrounded by dense clouds of axions*



Pulsar magnetospheres



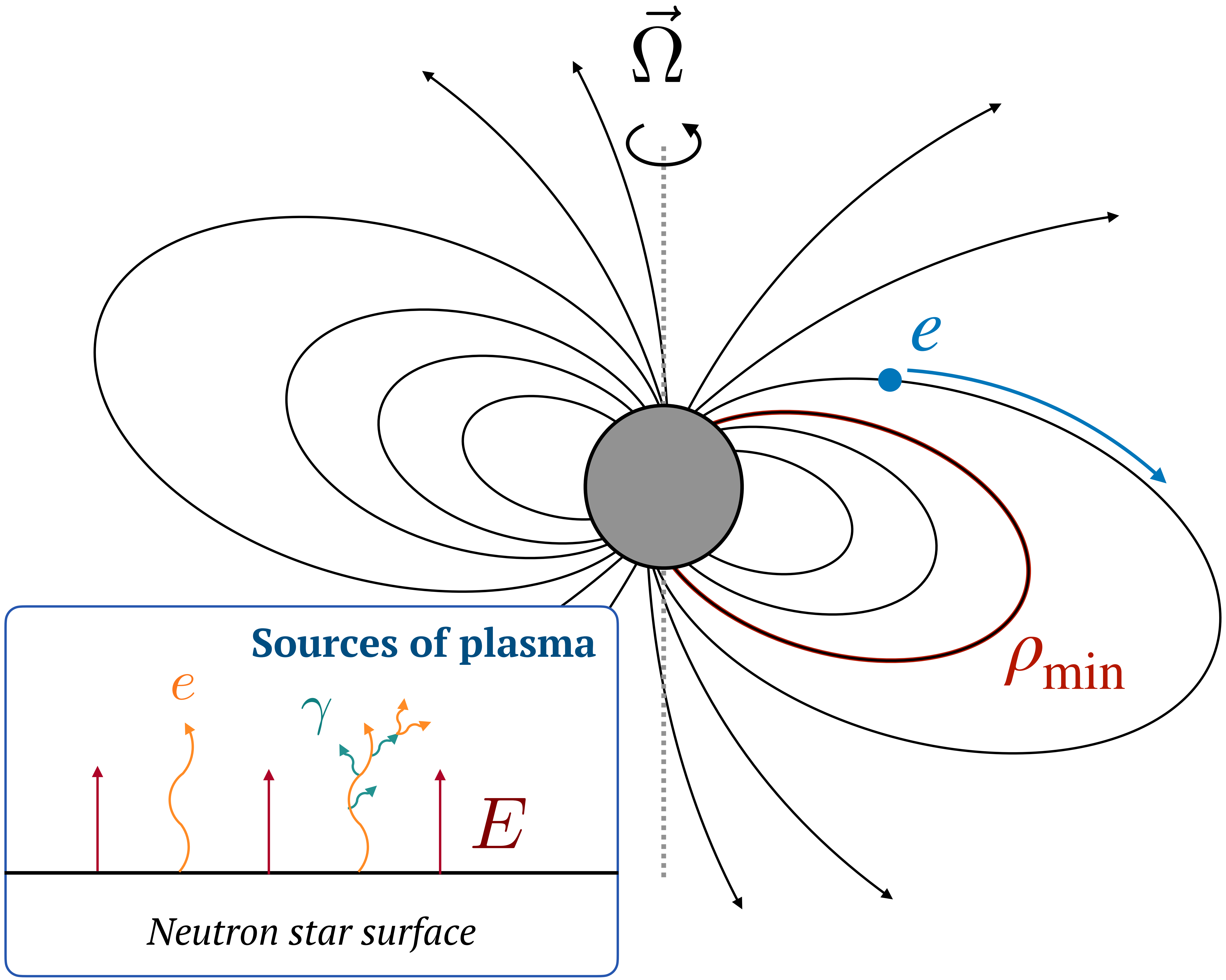
Pulsars at first order:

- $M_{NS} \sim 1 - 2\, M_{\odot}, R_{NS} \sim 10\, \mathrm{km}$
- Dipolar magnetic field $B \sim 10^9 - 10^{15}\, G$
- Rotational period $P \sim 10^{-3} - 10\, \mathrm{s}$
- Slowly spin-down on the timescale of kyr-Myr

Large $\overrightarrow{B}$ induces strong electric field $\overrightarrow{E}$

$$F_{\overrightarrow{E}} \gg F_{\mathrm{gravity}}, F_{\mathrm{binding}}$$

Pulsar magnetospheres



Plasma Behaviour

(Near the neutron star)

1. Plasma flows along magnetic field lines

Acceleration only possible if $\vec{E} \cdot \vec{B} \neq 0$

2. Plasma tries to screen electric field

If $\rho_e \geq \rho_{\rm min}$, $\vec{E} \to 0$

Stable force-free solution?

- $\vec{E}$ extracts $\rho_{\rm min}$
- $\rho_{\rm min}$ screens electric field, $\vec{E} \cdot \vec{B} \to 0$
- No $e^{\pm}$ being sourced, stable co-rotation

Goldreich-Julian Model

Goldreich & Julian 1969

Goldreich-Julian requires ***co-rotating*** plasma

Axion production from vacuum gaps

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

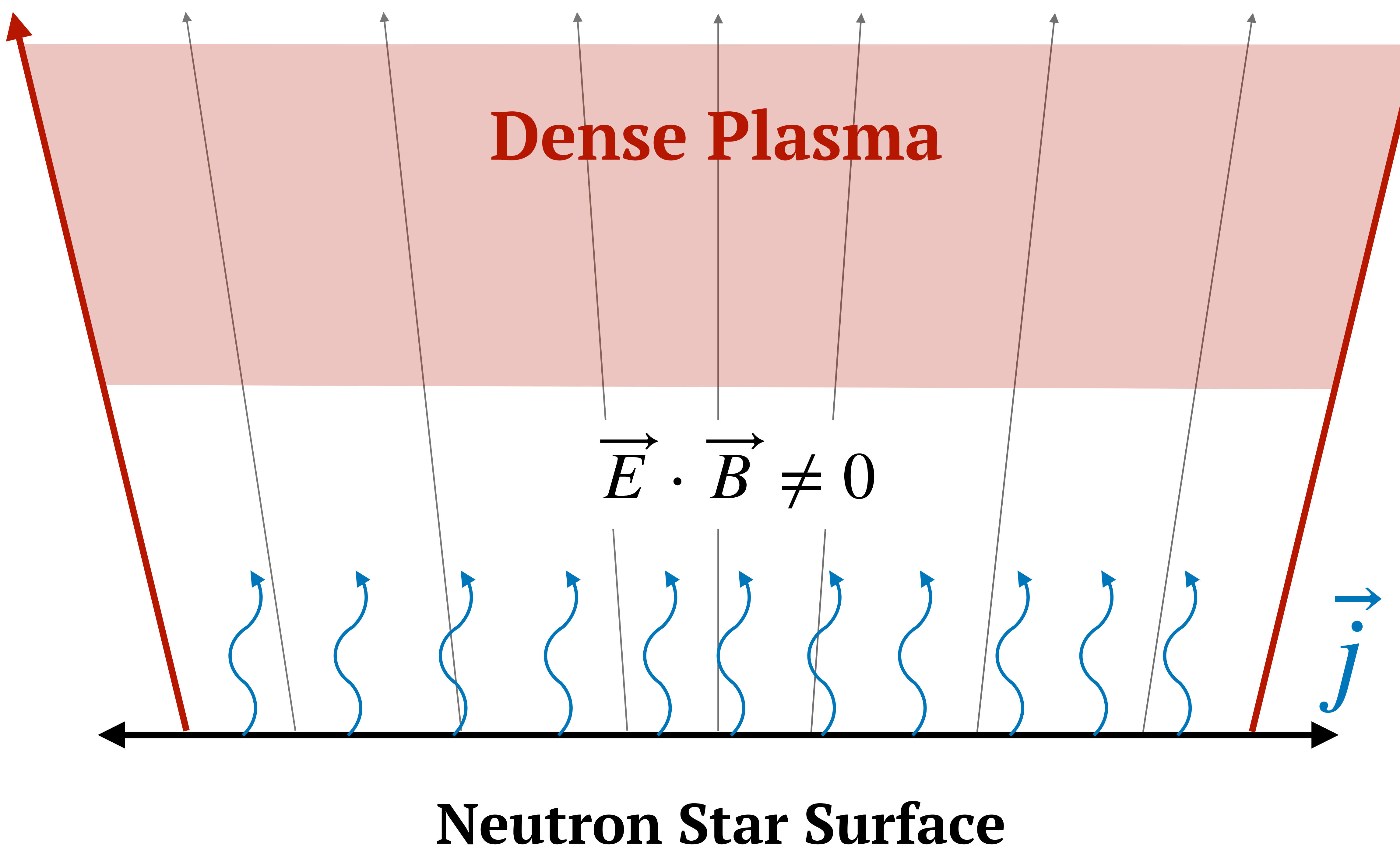
$$(\Box + m_a^2)\,a = g_{a\gamma\gamma}\,\vec E\cdot\vec B$$

Axions from Vacuum Gap Collapse:
Prabhu (2021),
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Polar cap dynamics

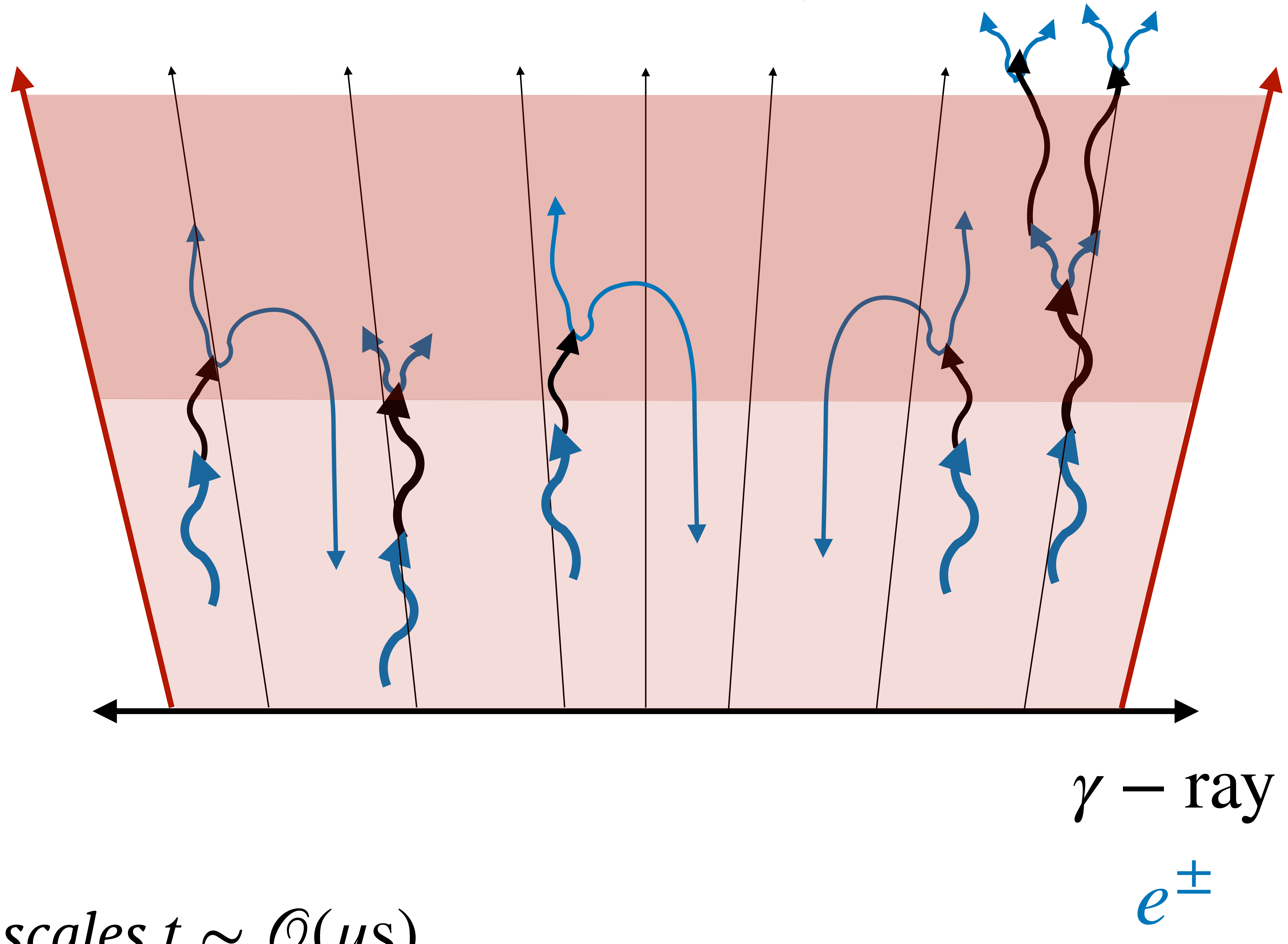
Part 1: Vacuum Phase

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



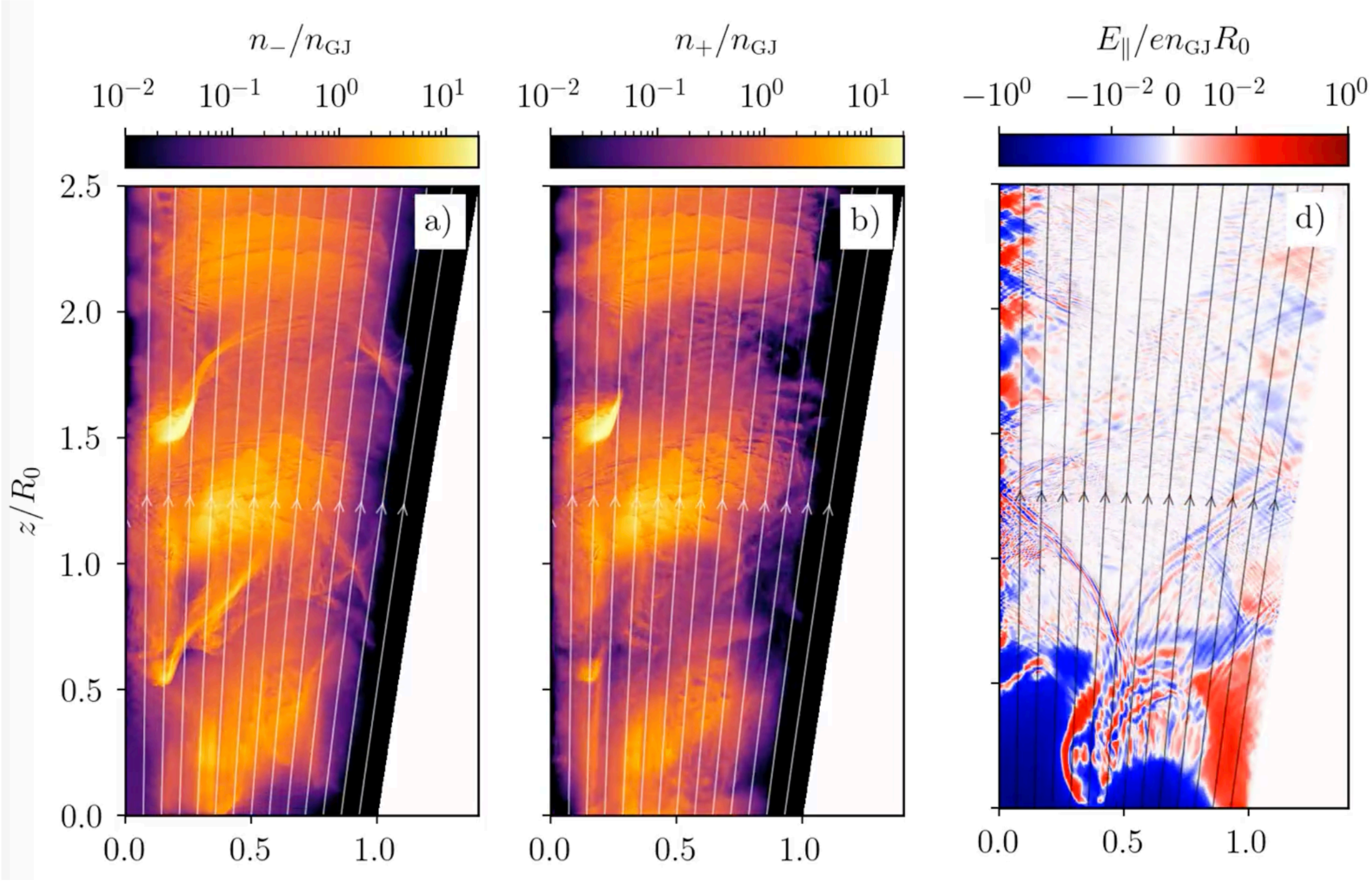
Part 2: Screening Phase

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



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

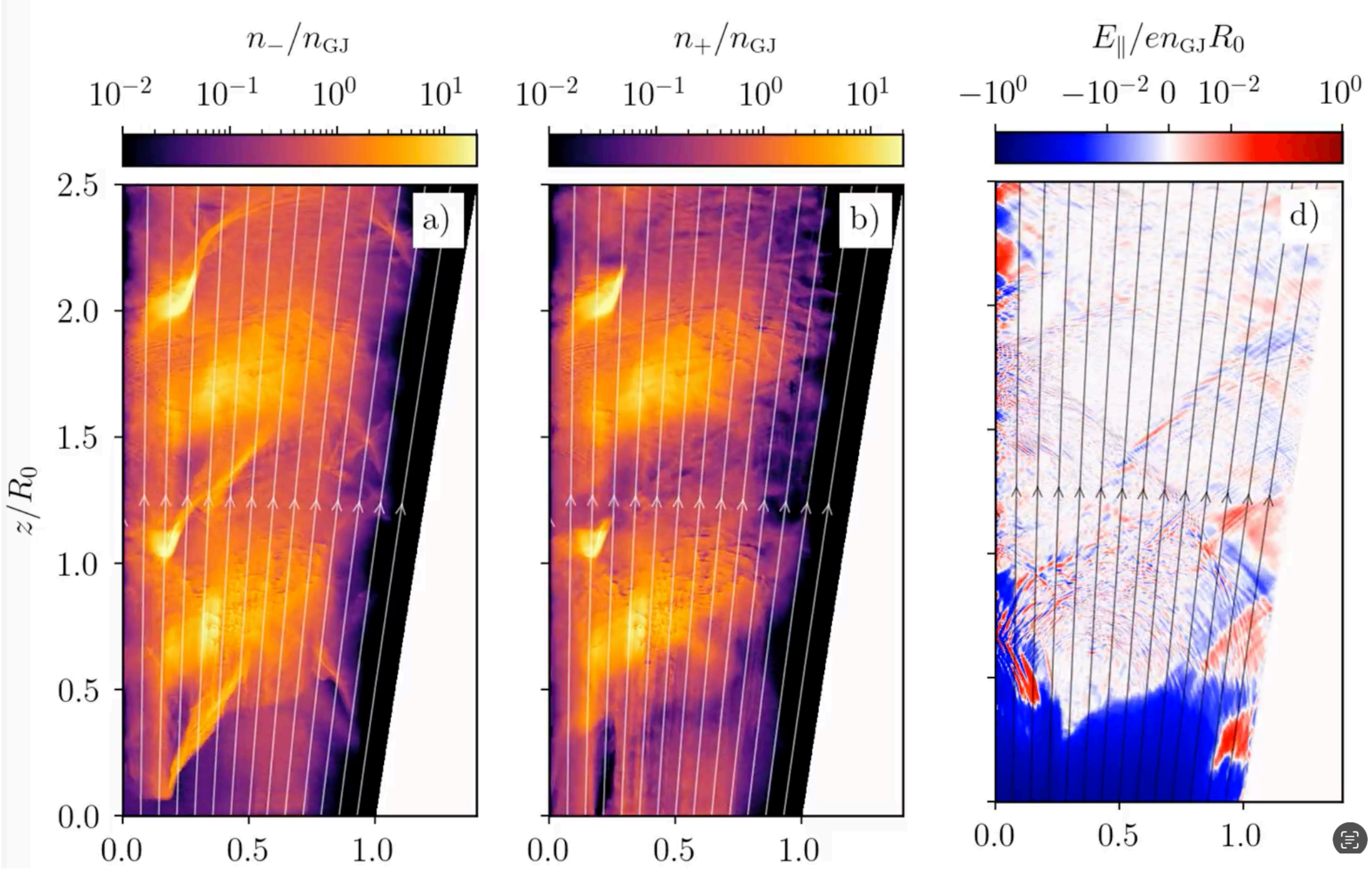
Pair production in the polar caps



MHz-GHz fluctuations source axions with MHz-GHz energies

Simulations curtesy of F. Cruz and A. Chen

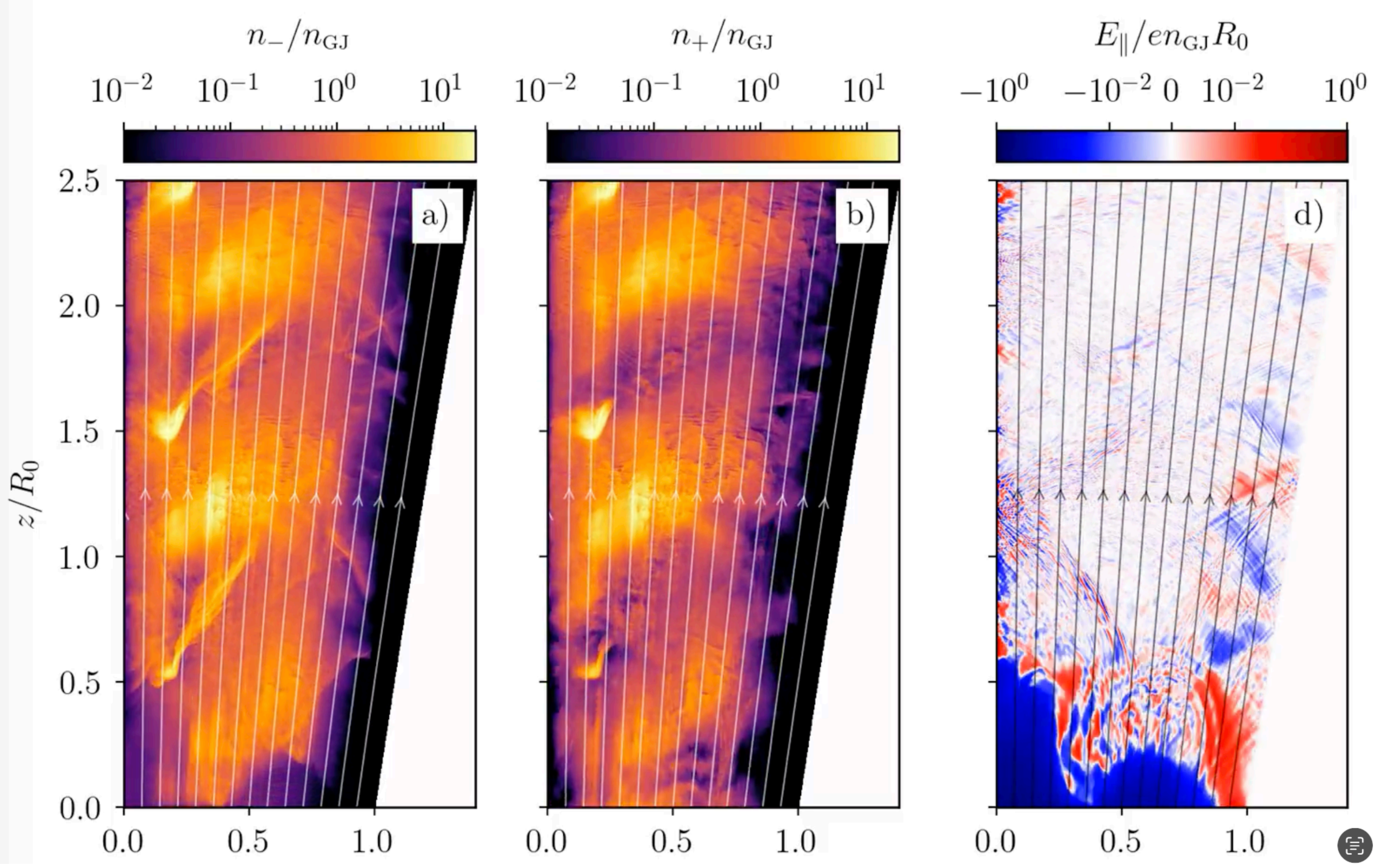
Pair production in the polar caps



MHz-GHz fluctuations source axions with MHz-GHz energies

Simulations curtesy of F. Cruz and A. Chen

Pair production in the polar caps

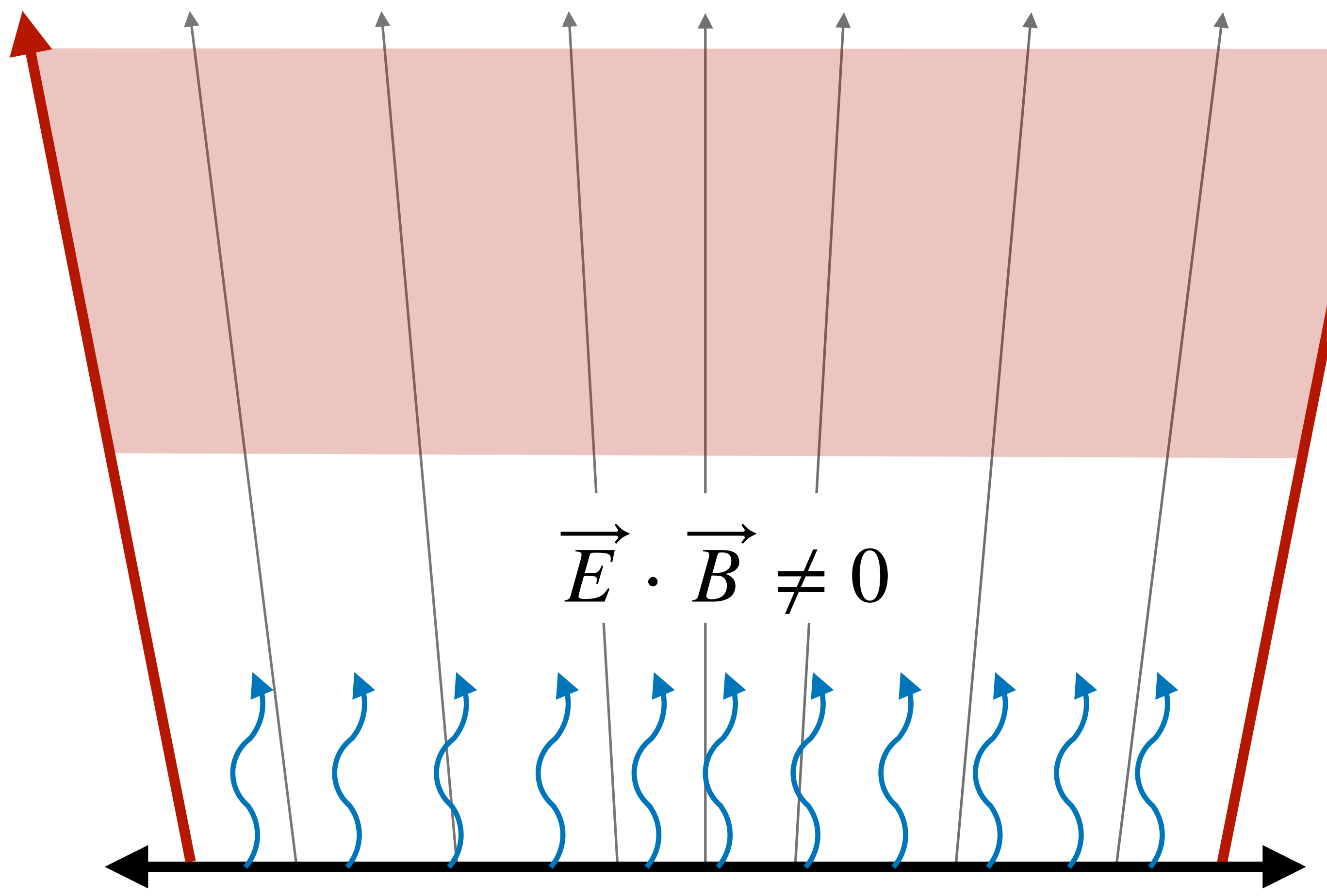


MHz-GHz fluctuations source axions with MHz-GHz energies

Simulations curtesy of F. Cruz and A. Chen

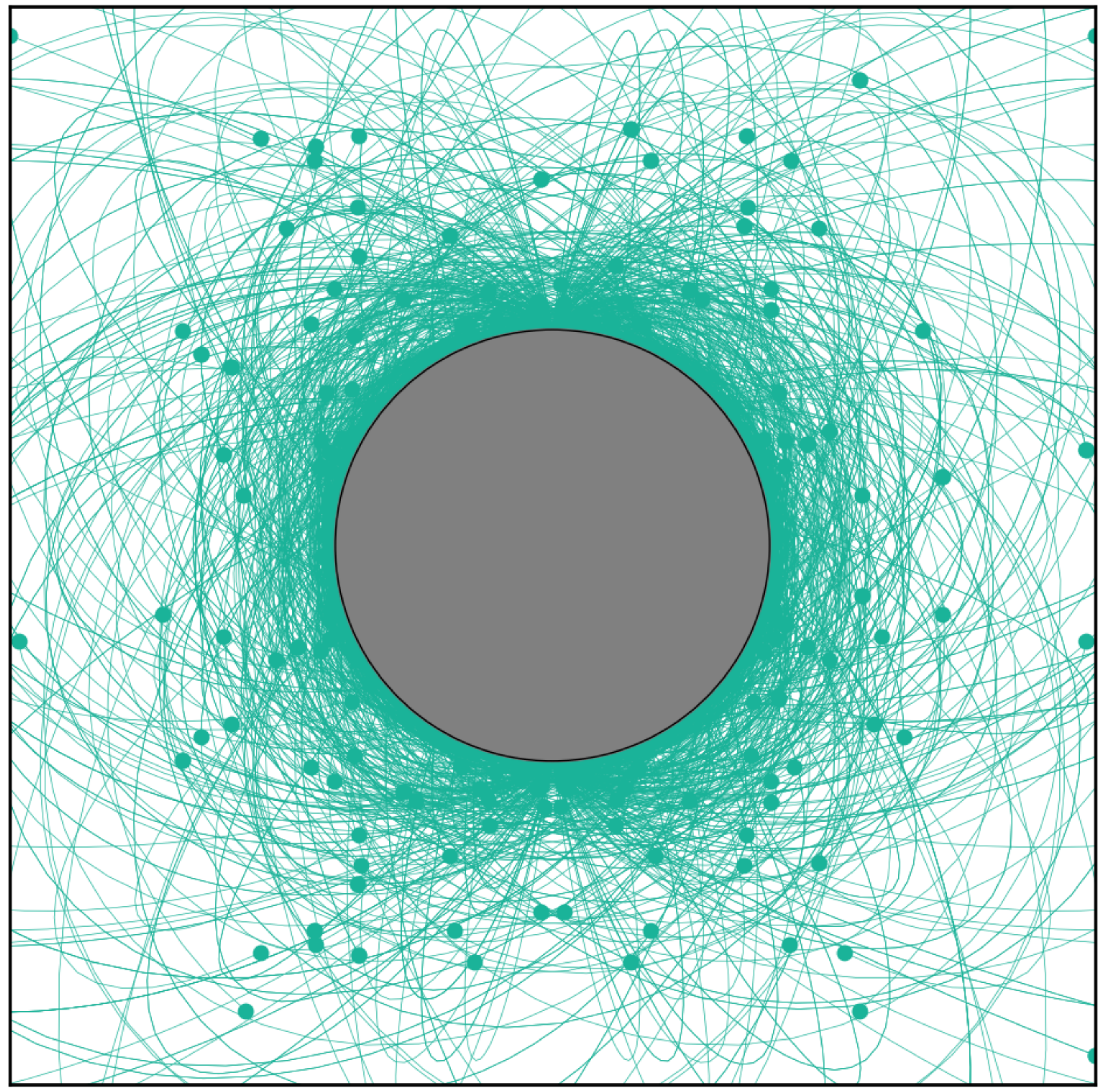
Production of axion clouds

$\dot{N}_a(\vec{k}, t_0)$ → $\rho_a(t_0)$ → $t_0 + \delta t$



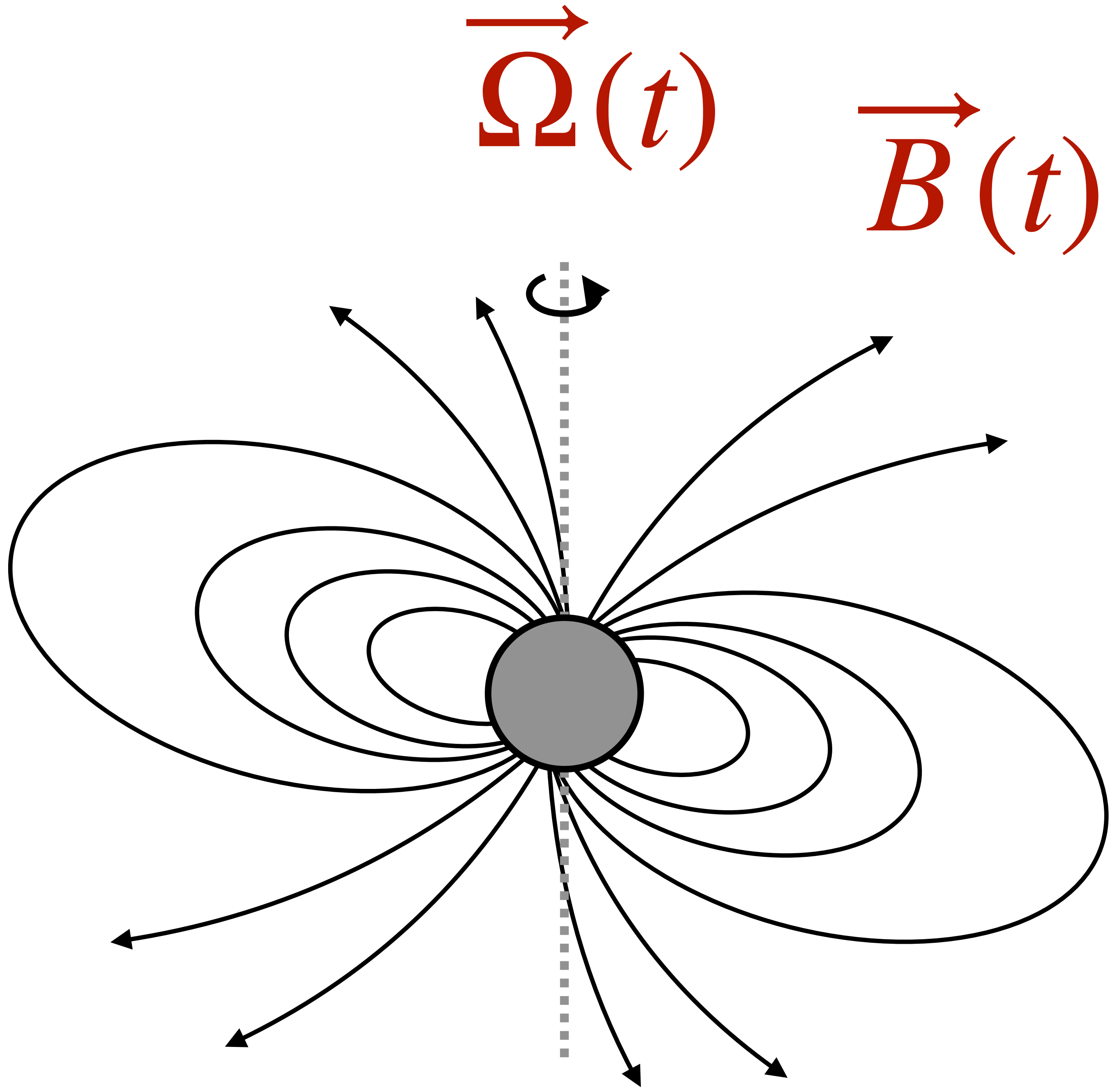
Production

($\sim\mu s$)



Evolution bound axions

(~ minutes)

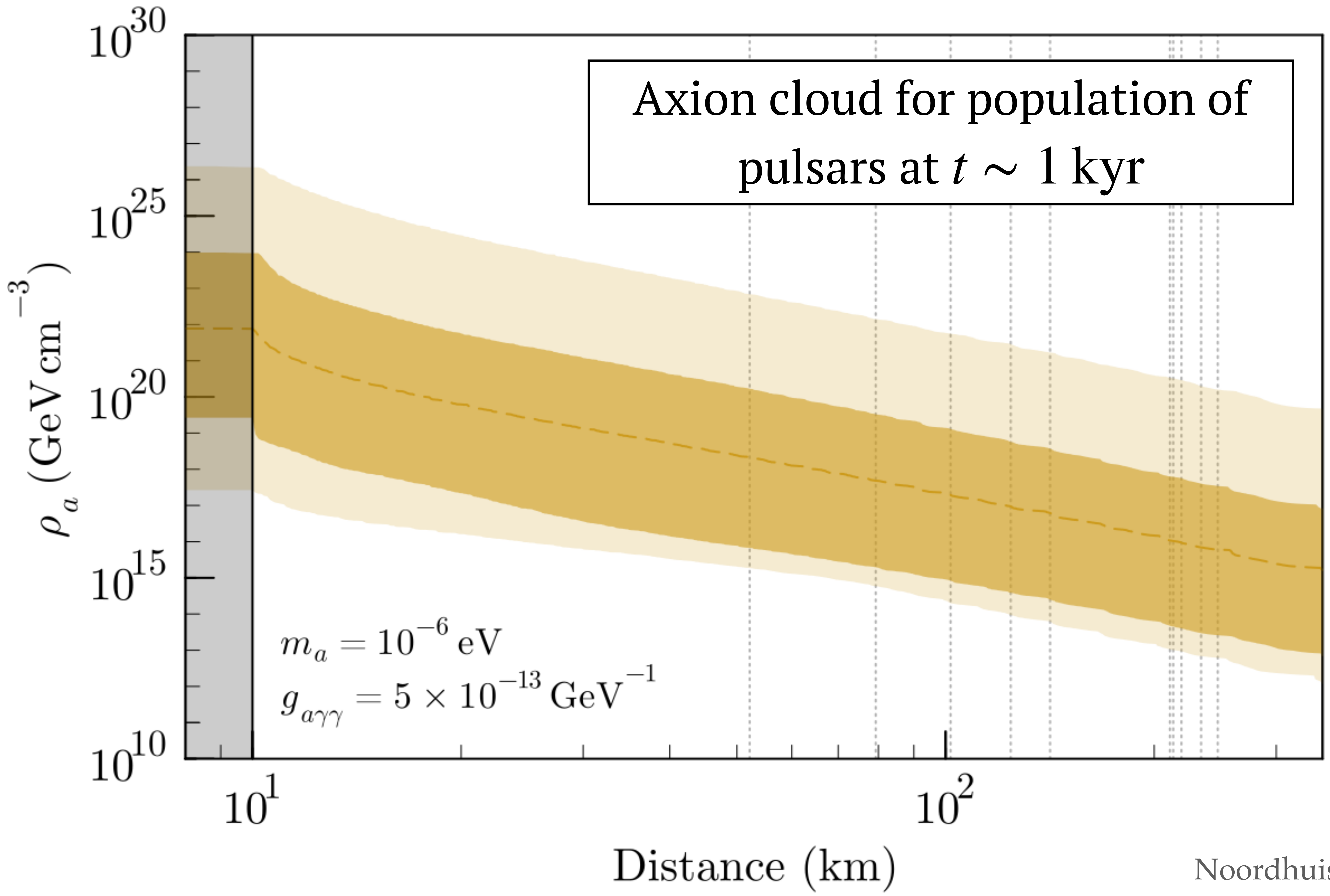


Pulsar spin-down

(kyr to Myr)

Axion Clouds

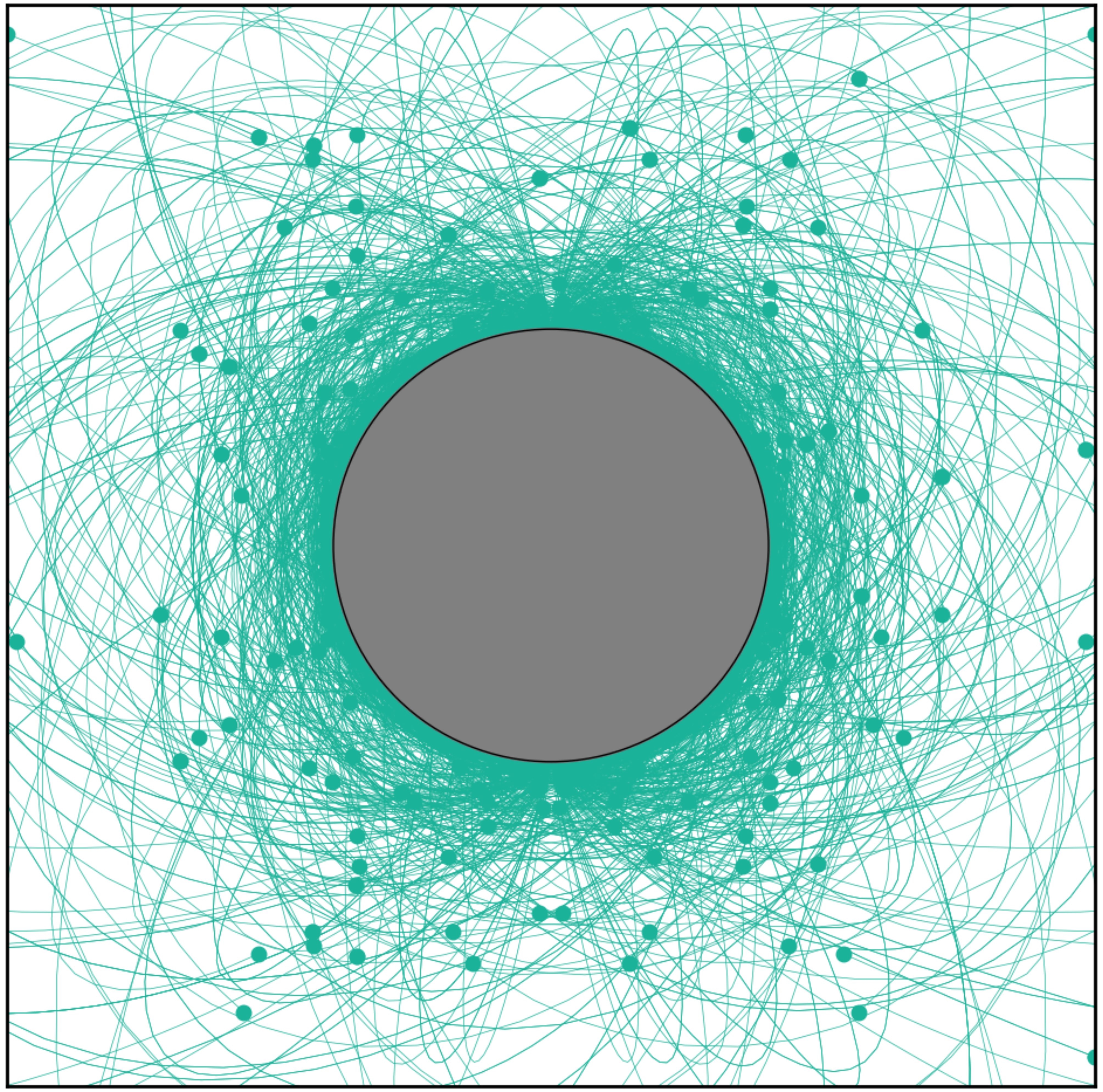
Tentative assumption: axions are produced and no longer interact



10 "mock" neutron stars

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

Evolution of bound axions



Can axions scatter inside the neutron star?

Typically, no.

Can axions self-interactions alter the evolution?

Typically, no.

Can axions convert to electromagnetic radiation?

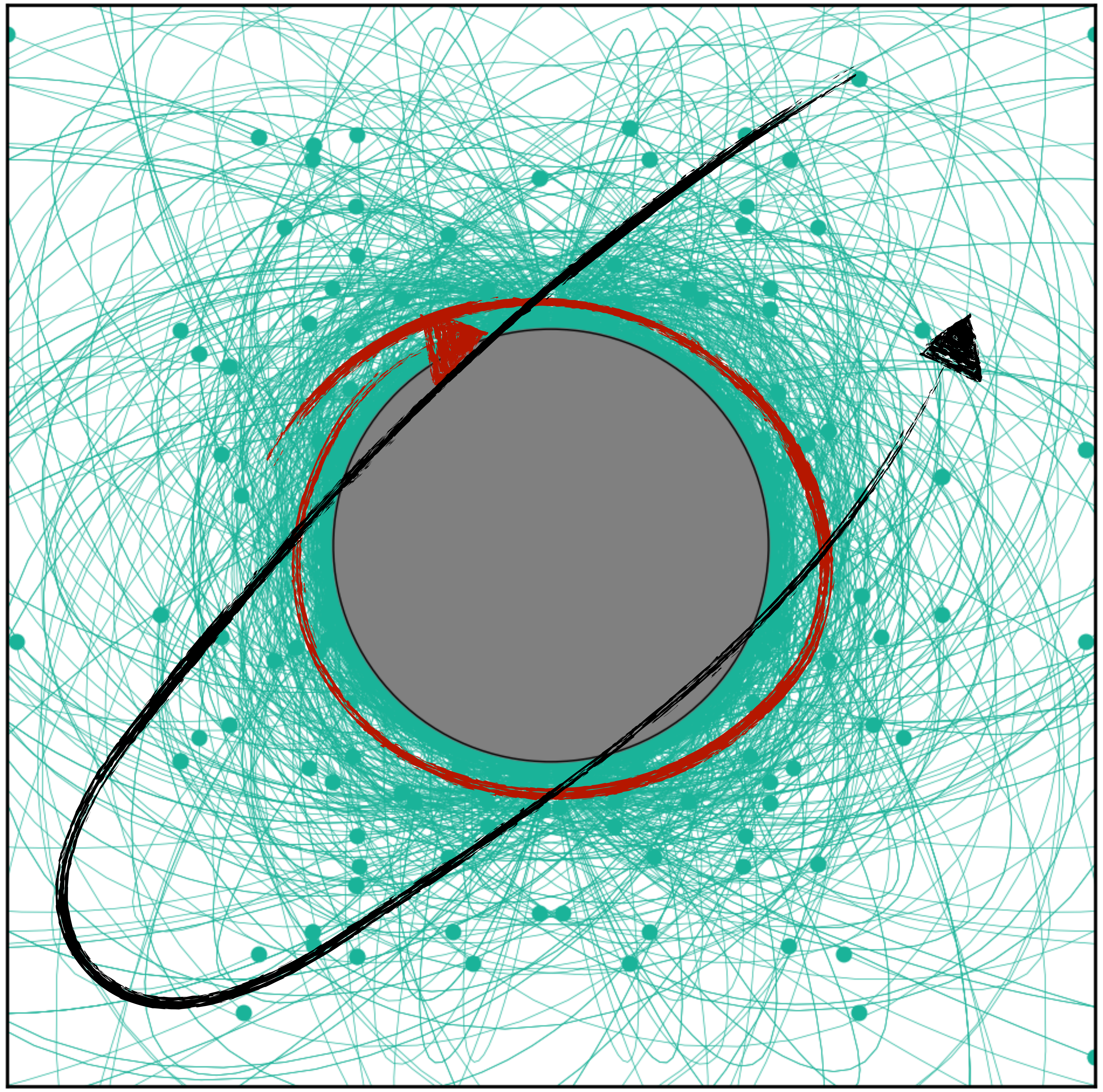
Yes & no. Is $\omega_p \leq \omega_a$?

Can axions alter the electrodynamics of the polar cap?

Yes, if the coupling is large enough.

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

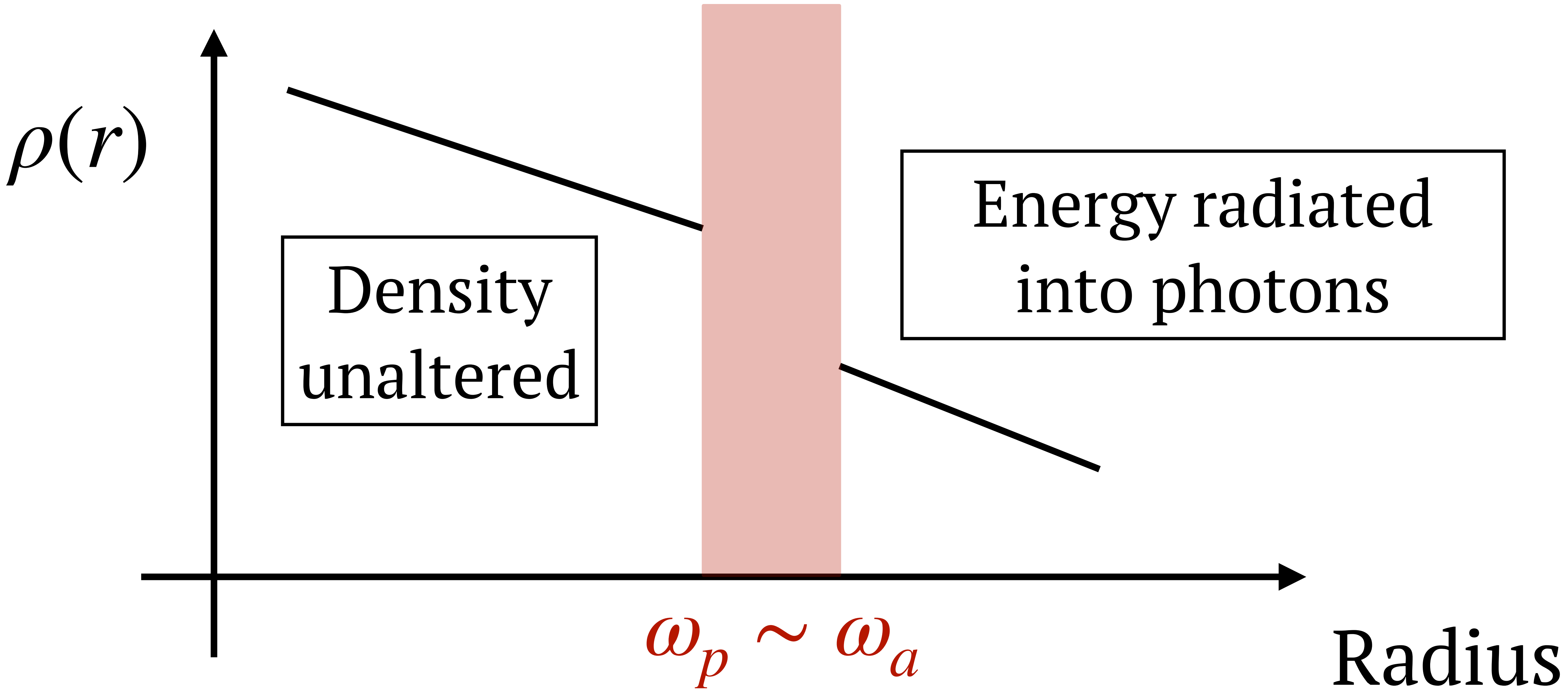
Energy losses: radiation



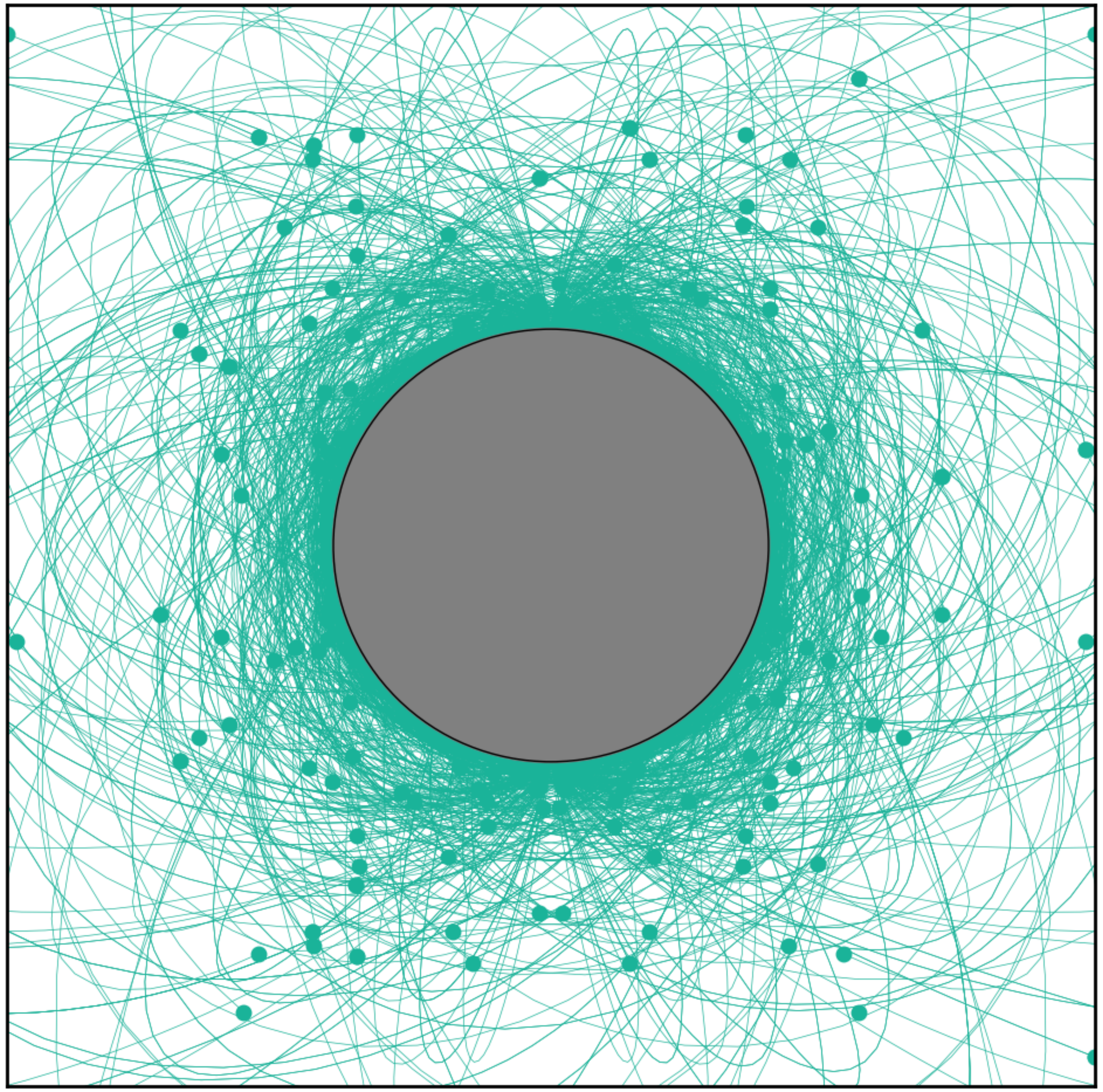
Noordhuis, Prabhu, Weniger, **SJW** (2023)

Close to the neutron star plasma too dense

Plasma frequency drops at large distances, $\omega_p \ll \omega_a$, allowing photon production



Evolution of bound axions



Can axions scatter inside the neutron star?

Typically, no.

Can axions self-interactions alter the evolution?

Typically, no.

Can axions convert to electromagnetic radiation?

Yes & no. Is $\omega_p \leq \omega_a$?

Can axions alter the electrodynamics of the polar cap?

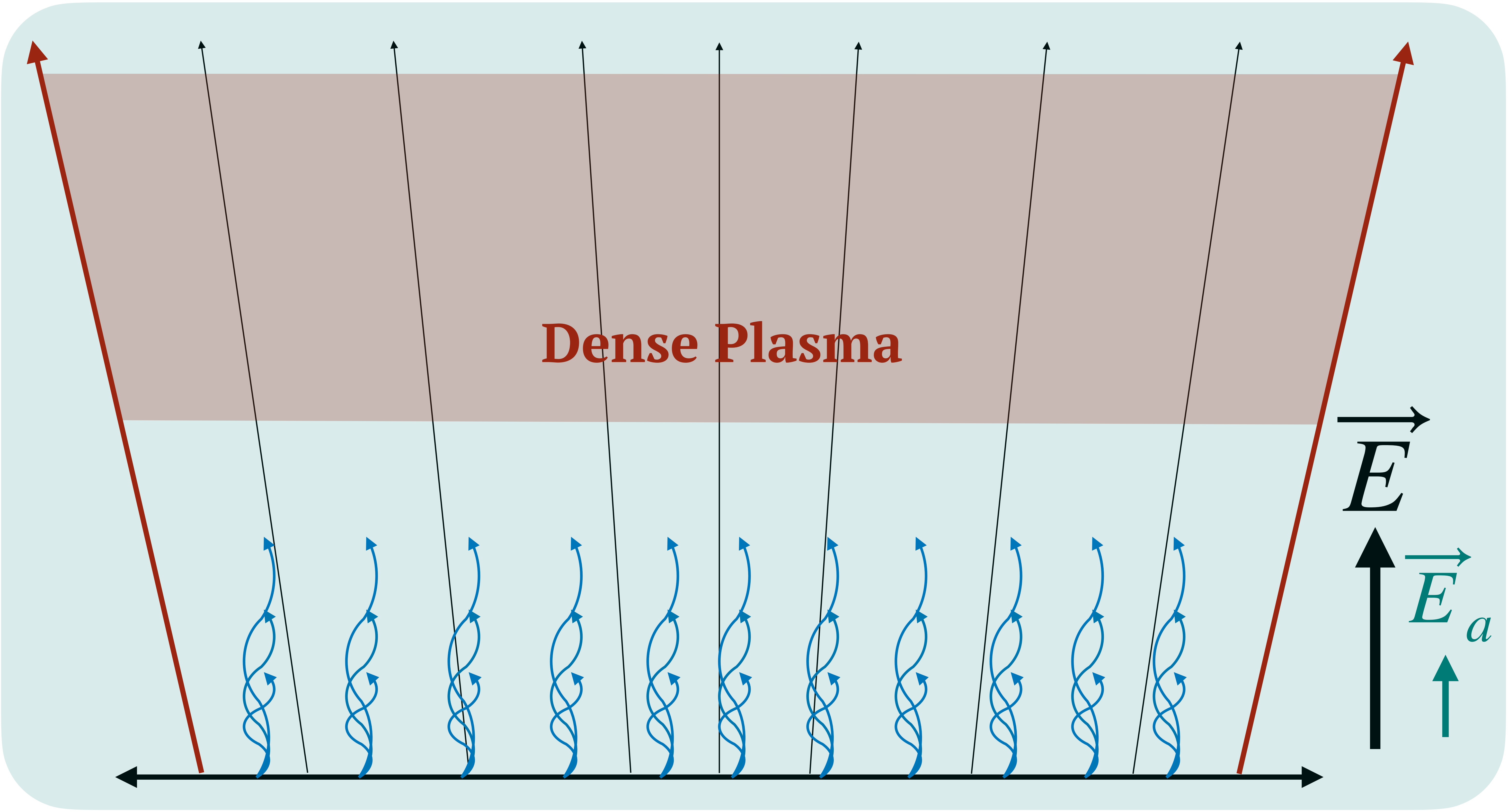
Yes, if the coupling is large enough.

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

Energy losses: the polar cap

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

Part 1: Vacuum Phase



Neutron Star Surface

Axions induce electric field:

$$\vec{E}_a \propto \sqrt{\rho_a}\, \vec{B}\, e^{-i\omega_a t}$$

(When axions are light, field is uniform)

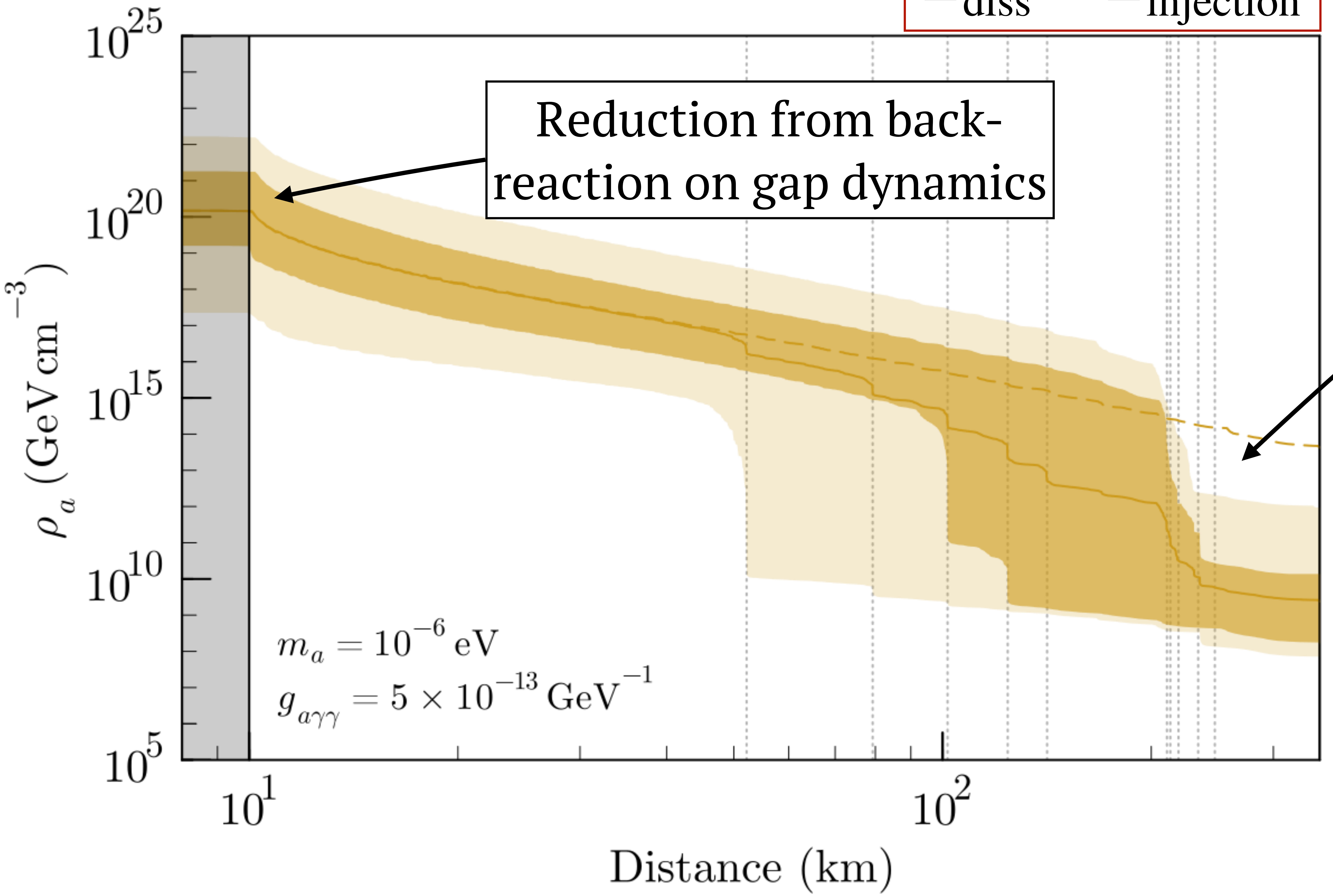
Axions can dissipate energy in the current itself

$$\rho \rightarrow \rho_{\text{saturate}}$$

$$\text{as } \dot{E}_{\text{inj}} \sim \dot{E}_{\text{diss}}$$

Axion Clouds

$\dot{E}_{\rm diss} \sim \dot{E}_{\rm injection}$



Reduction from back-reaction on gap dynamics

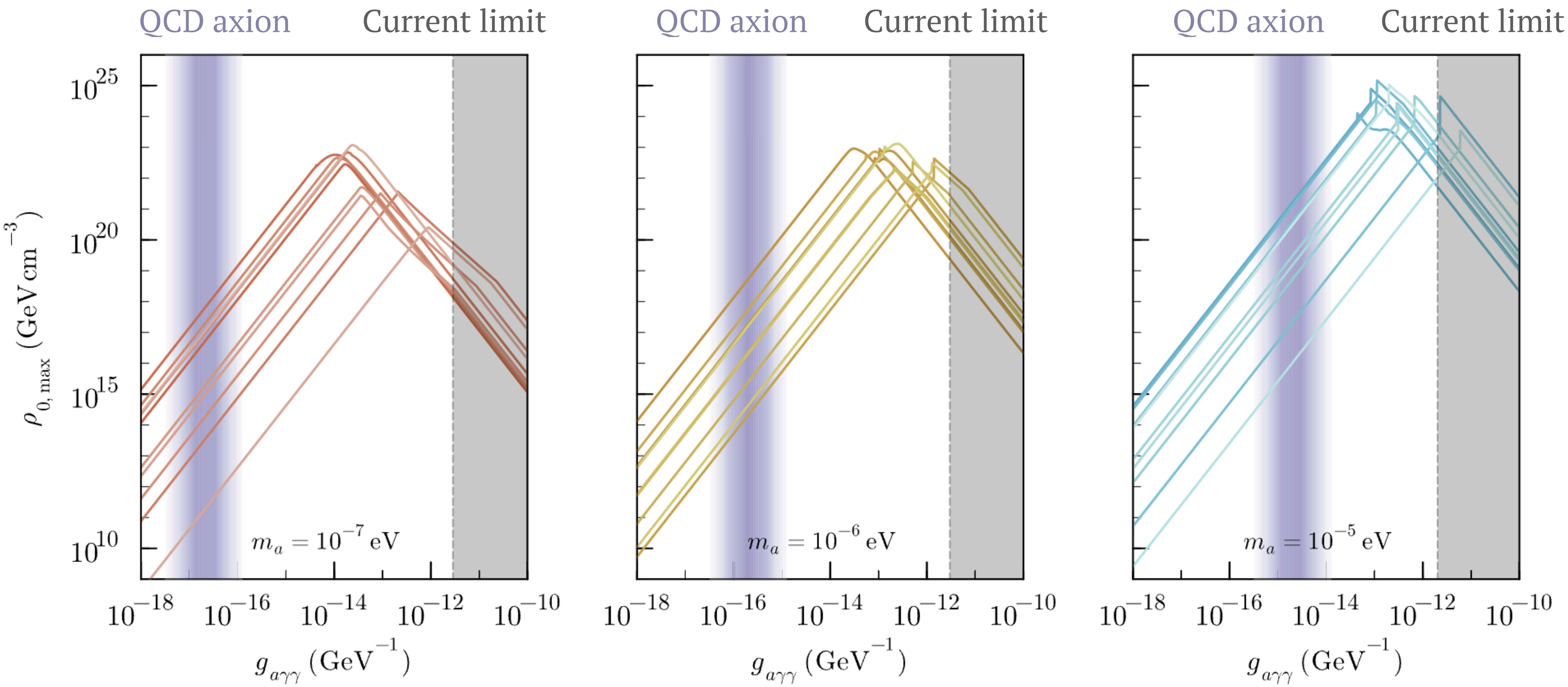
Reduction in density from resonant emission

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

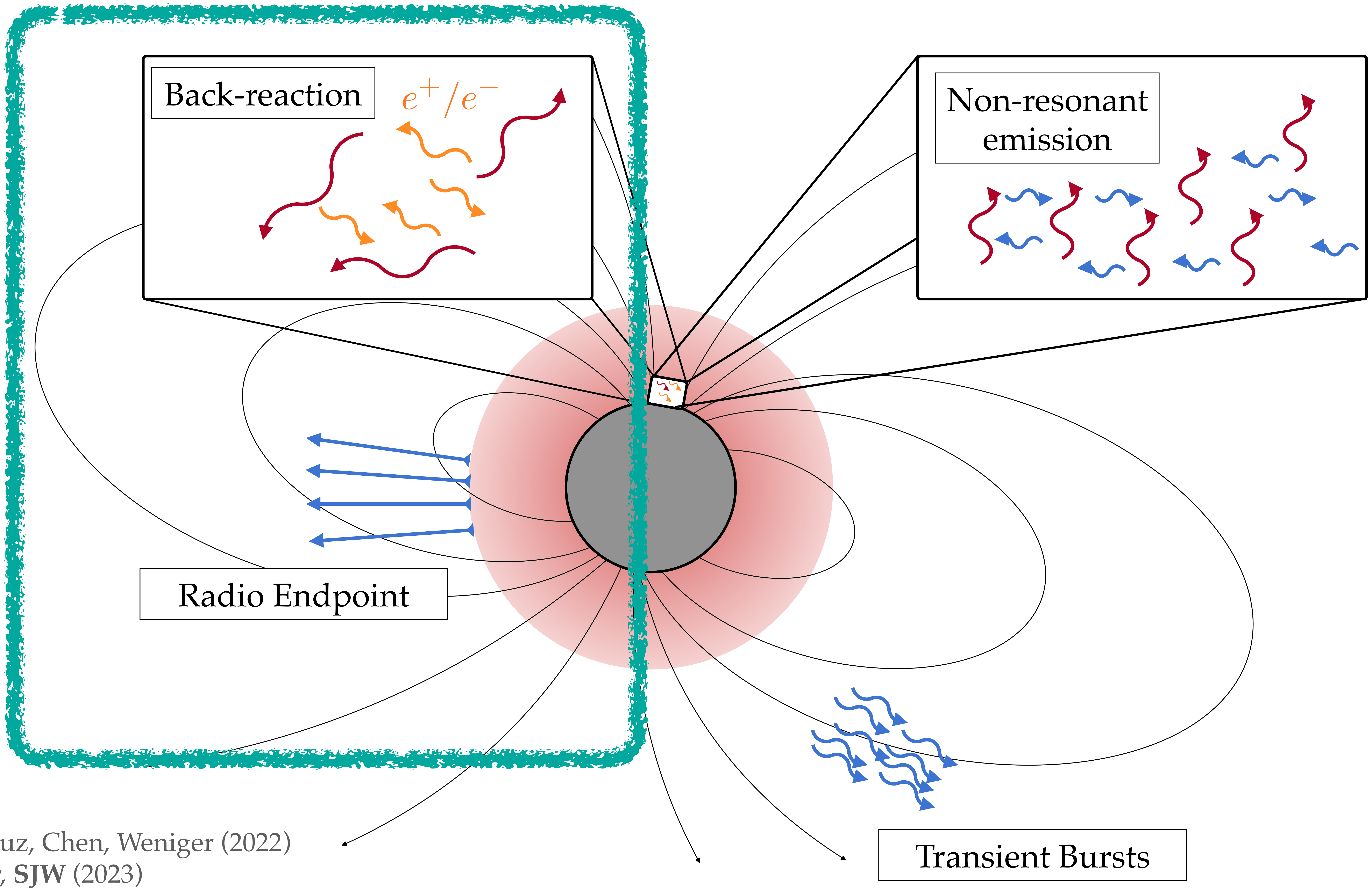
Noordhuis, Prabhu, Weniger, **SJW** (2023)

Maximum density of axion clouds

To what extent does the axion density depend on $g_{a\gamma\gamma}$?



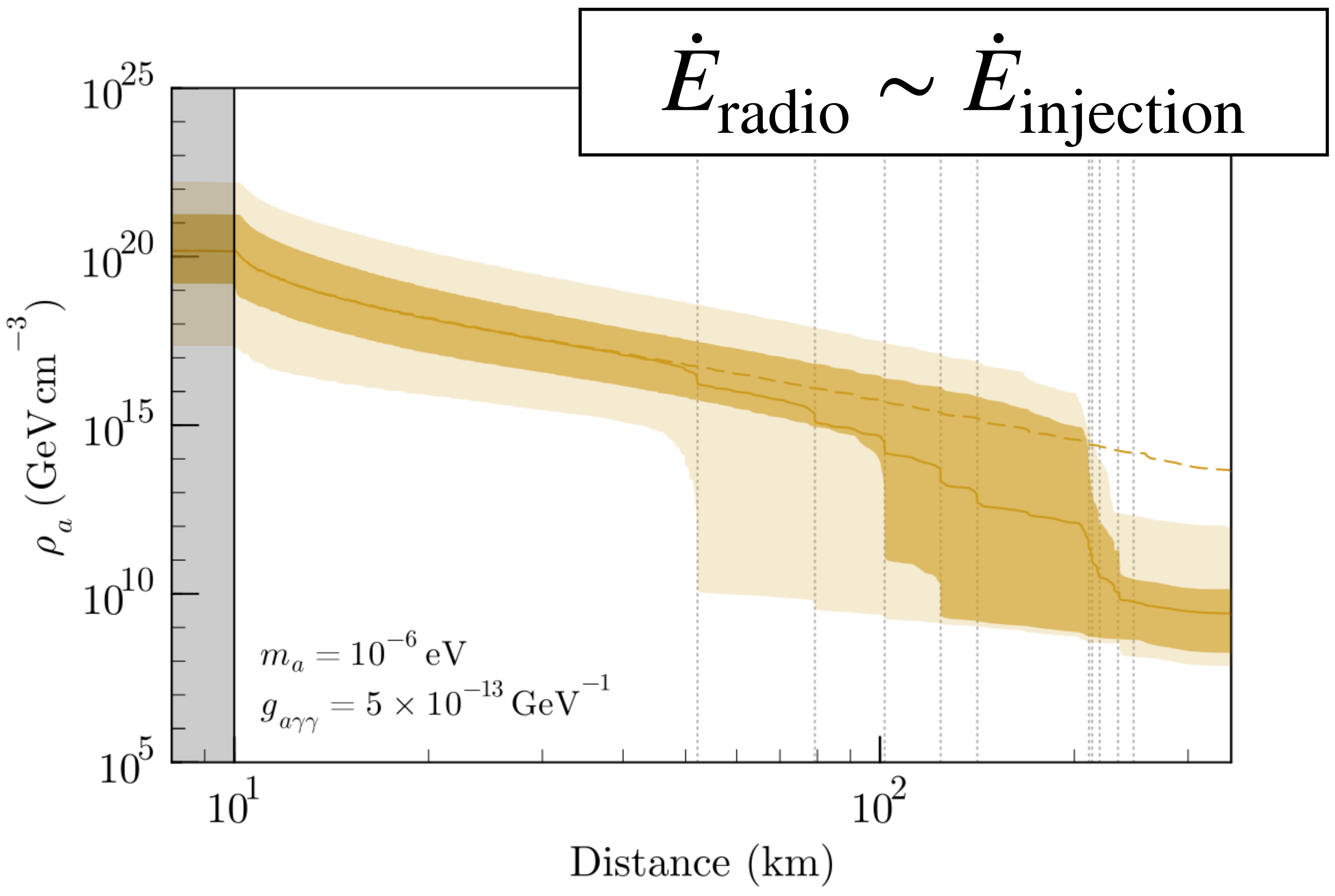
Observable Consequences



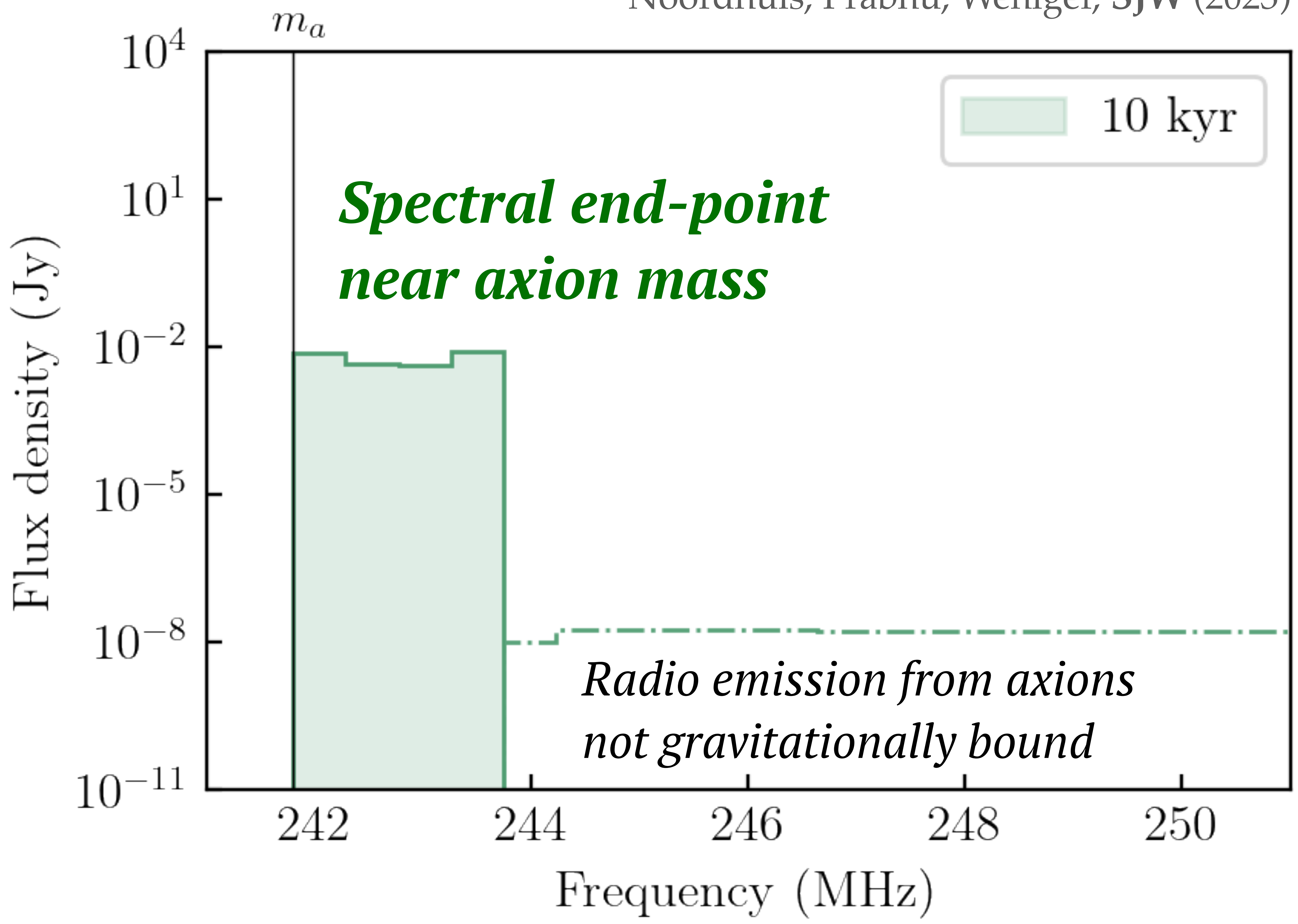
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Resonant radio emission

Sharp kinematic endpoint inevitably arises in radio spectrum

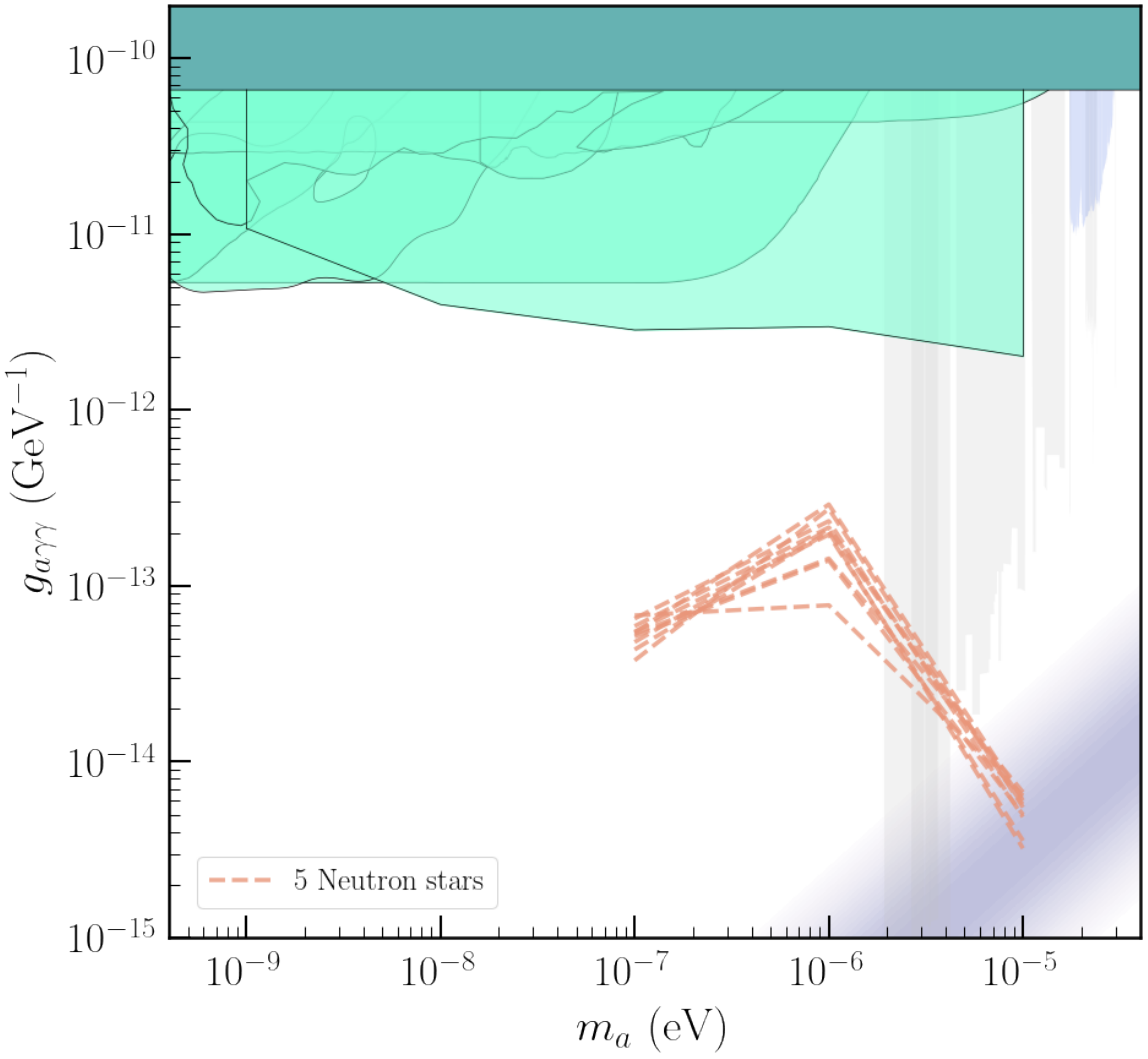


Noordhuis, Prabhu, Weniger, **SJW** (2023)



Spectral end-point (radio)

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



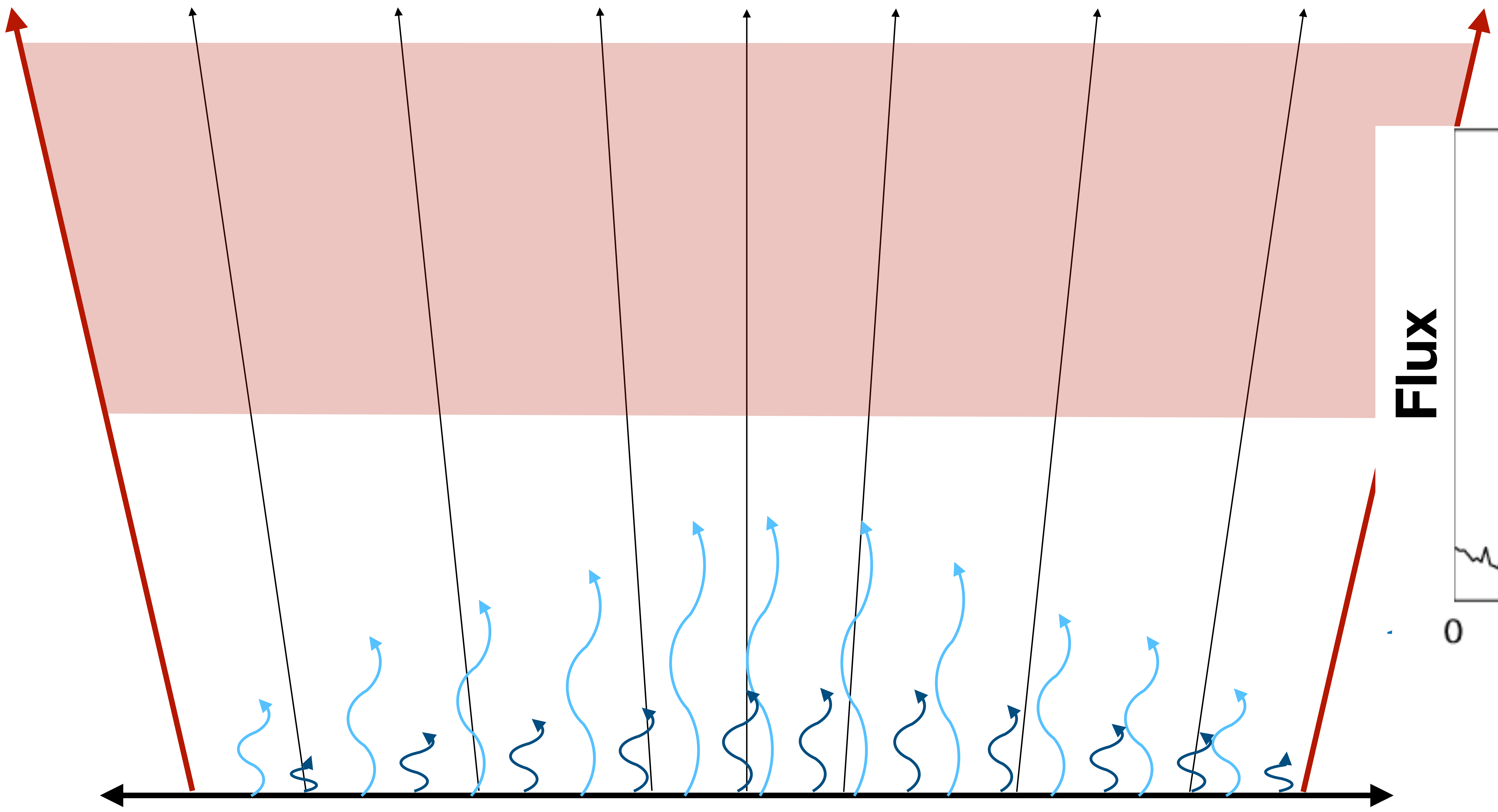
Current radio observations should have strong sensitivity to spectral line…

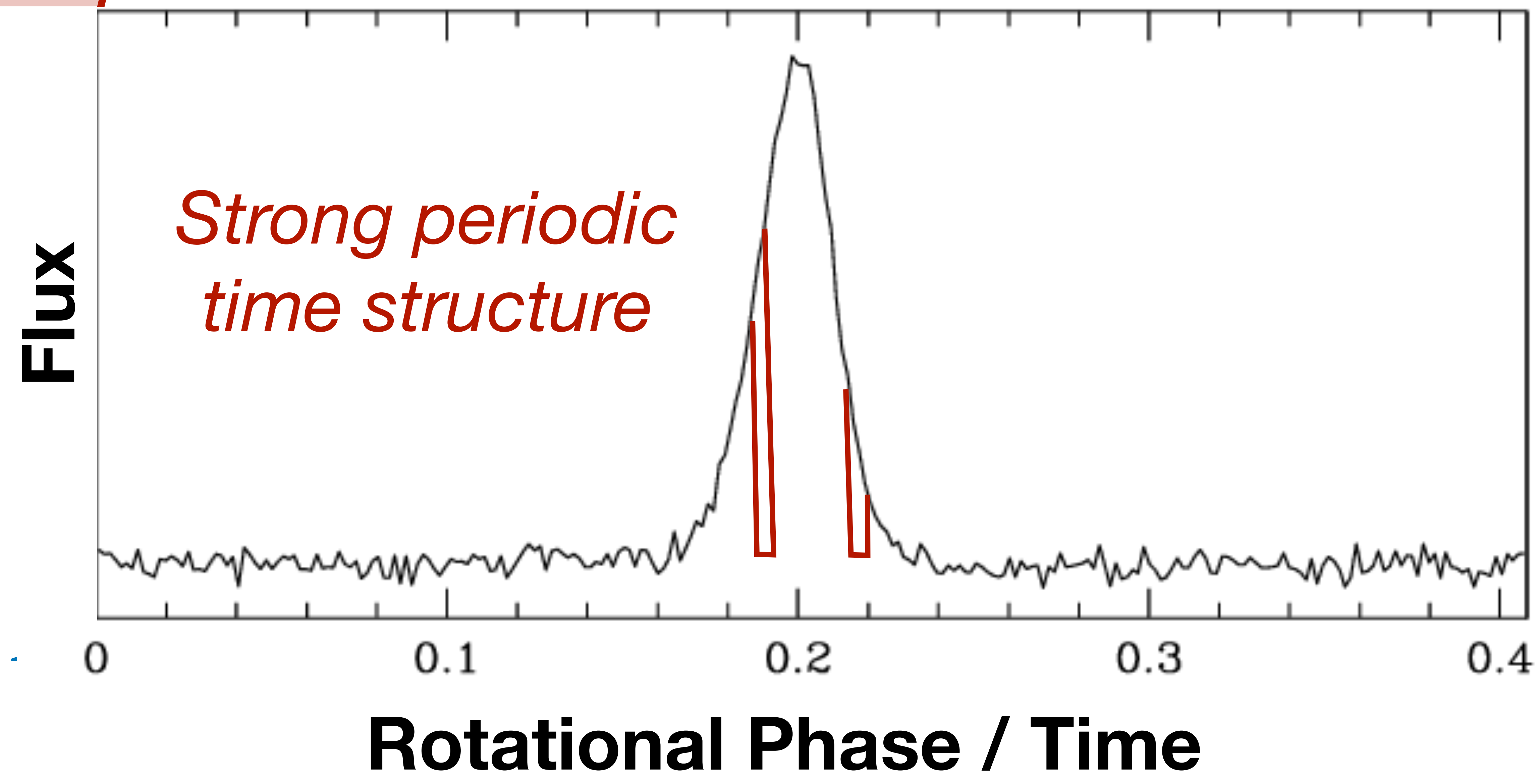
A more detailed look at systematics is in progress…

Axion back-reaction

We have assumed:
Electrodynamics not altered by axion

What if this is not true?

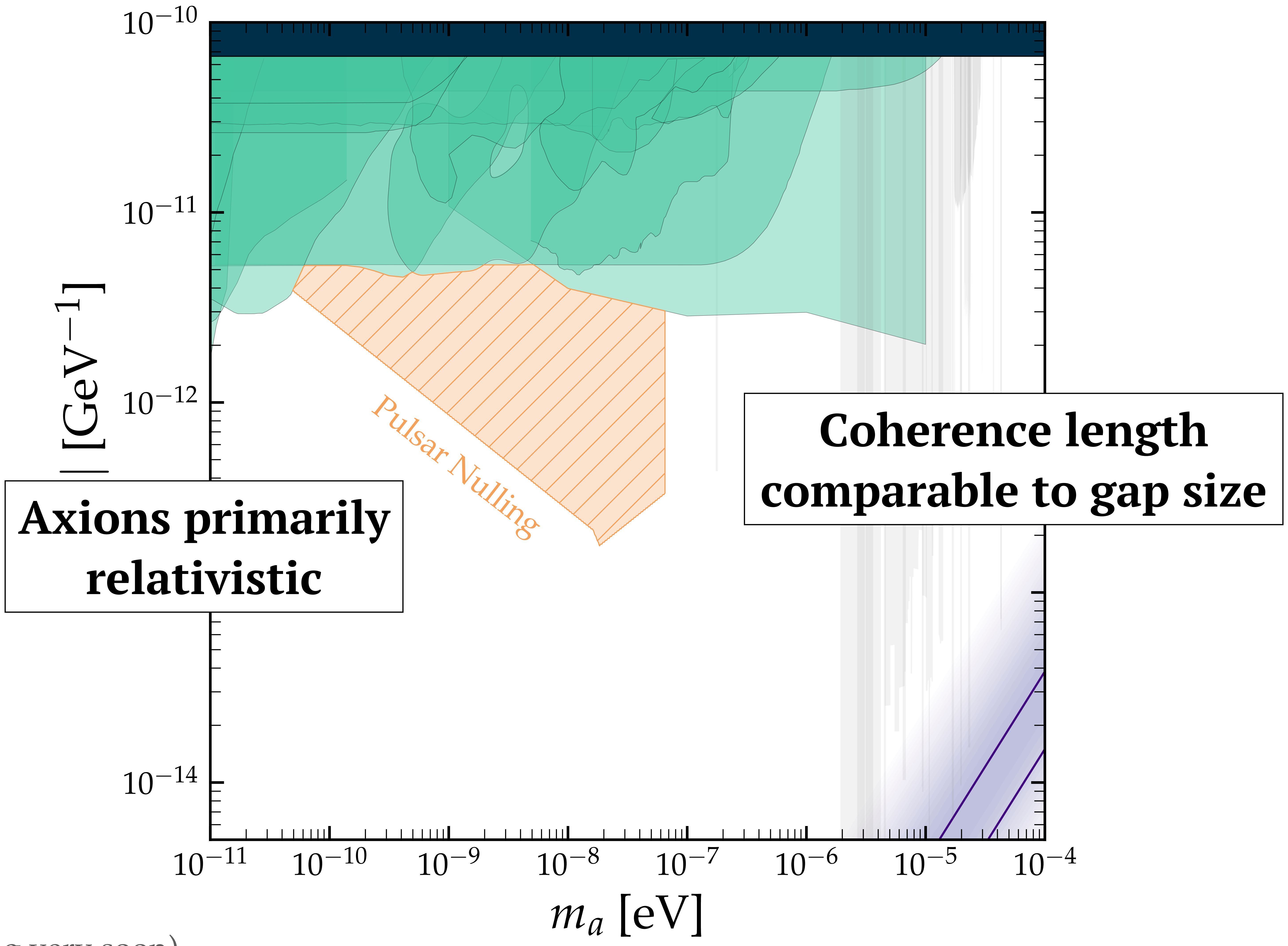




Periodic suppression of radio emission

Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

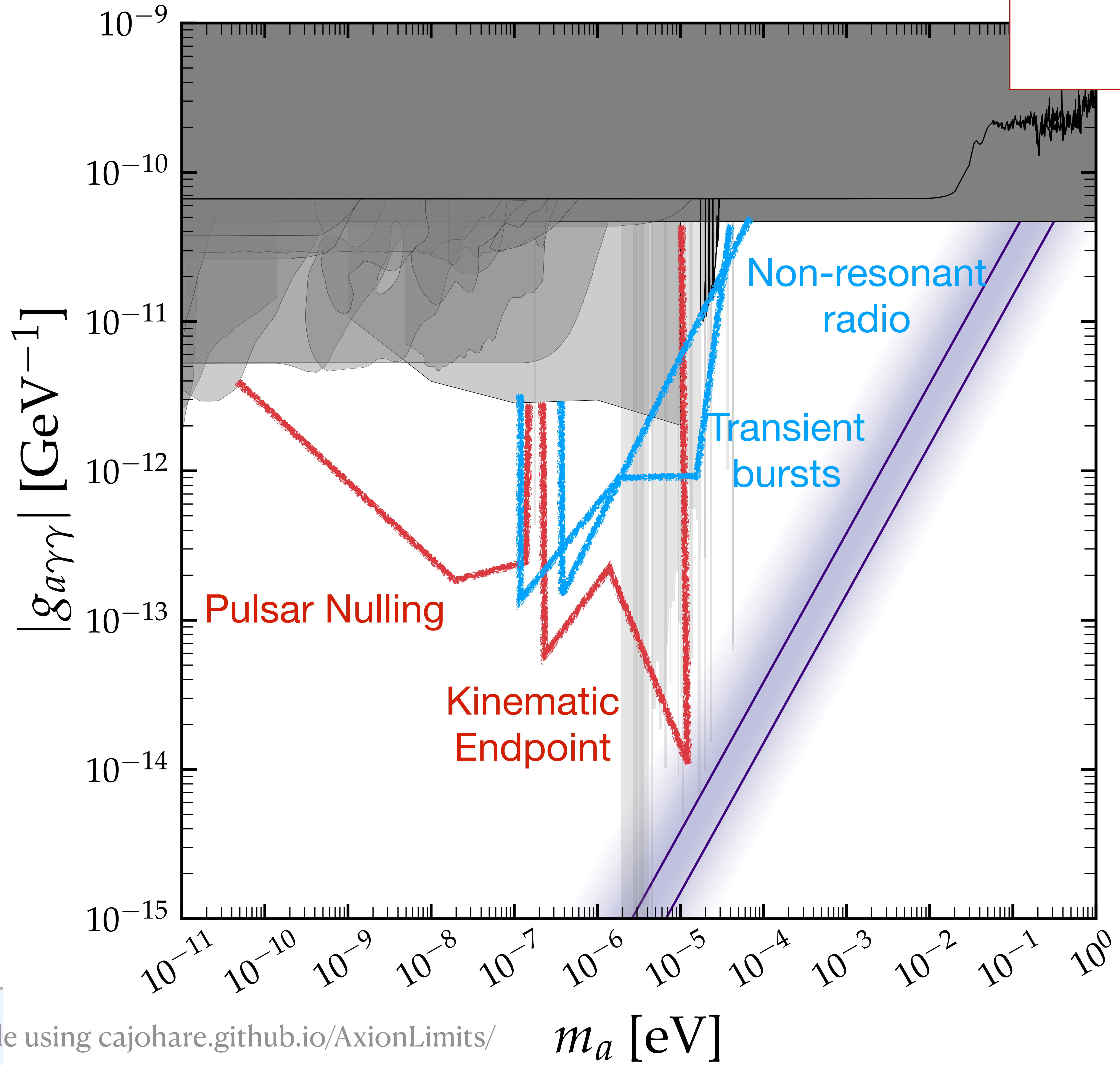
Pulsar Nulling: J1119-6127



Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Conclusions

The ubiquitous presence of dense axion clouds opens promising new avenues for detection!



Plot made using cajohare.github.io/AxionLimits/

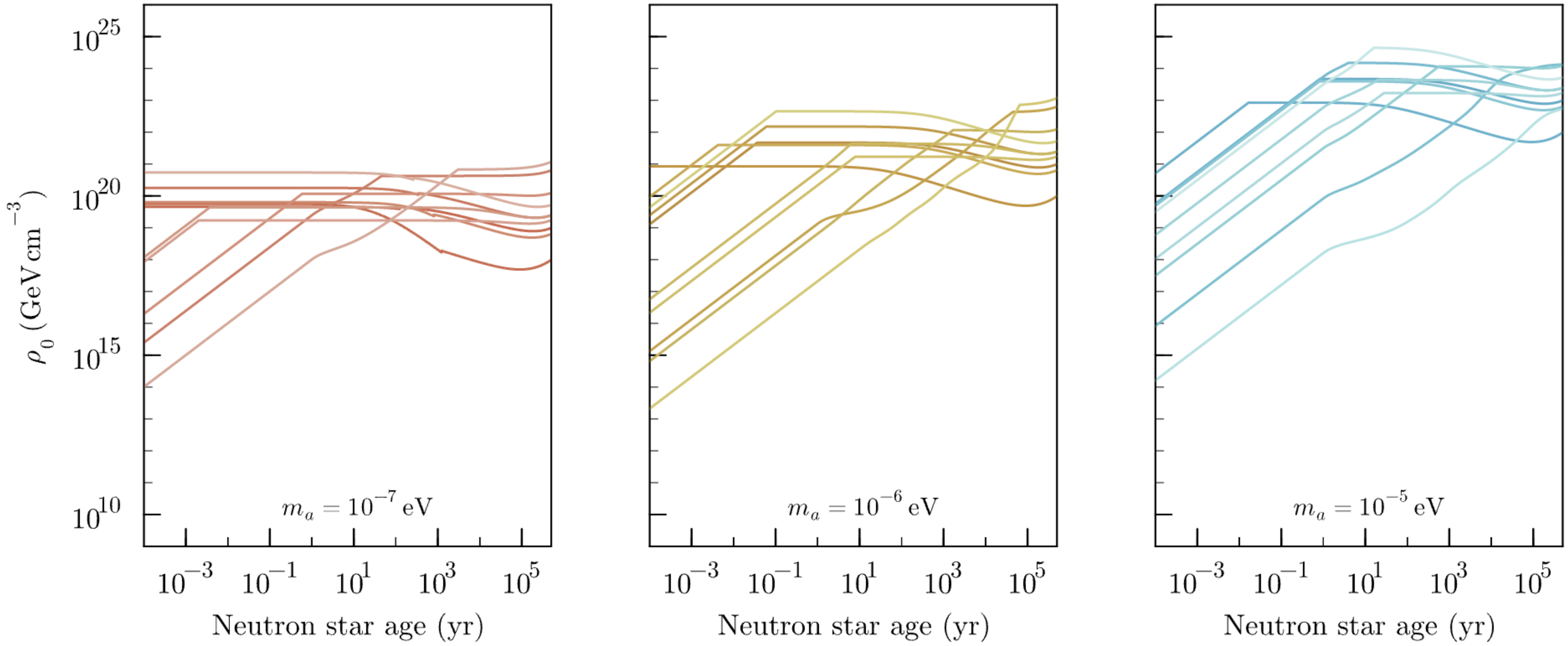
- Distinctive signatures (spectral lines/ end-points, transients bursts, pulsar nulling)
- Strong discovery potential over wide range of parameter space

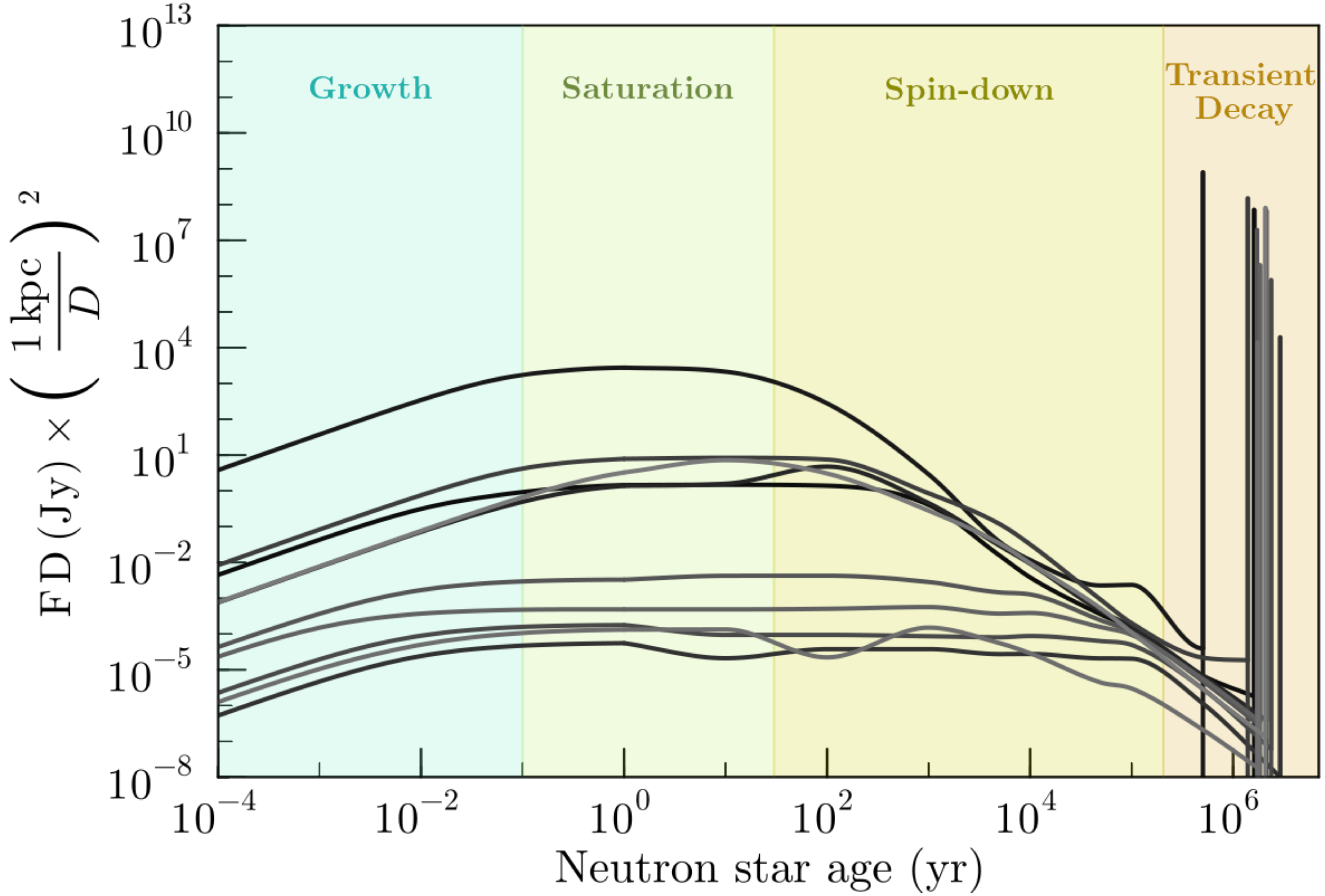
Axion Clouds
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Back-Up

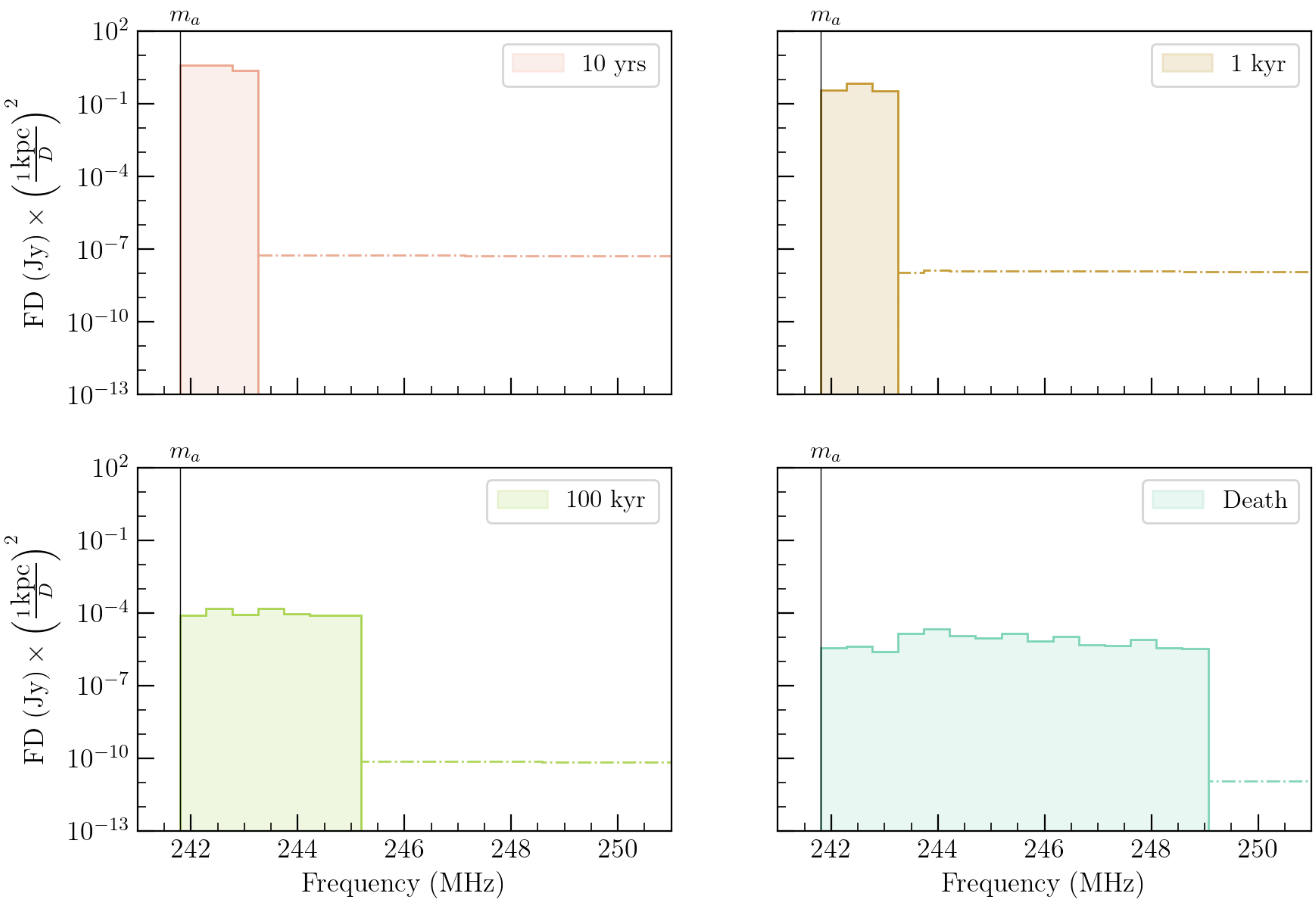
Density evolution

Maximum density achieved early in the lifetime

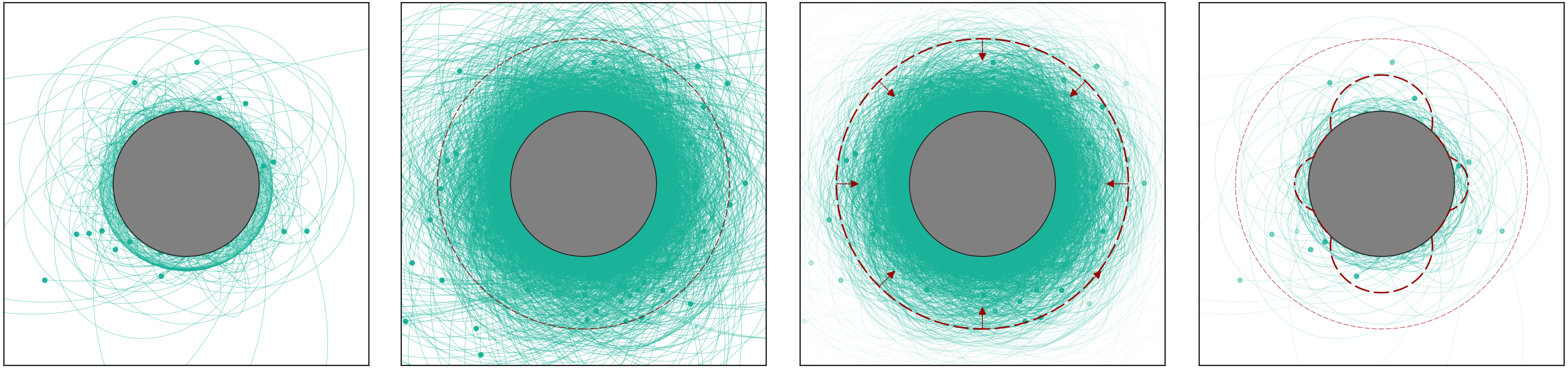




Growth
Saturation
Spin-down
Transient Decay
10^{13}
10^{10}
10^{7}
10^{4}
10^{1}
10^{-2}
10^{-5}
10^{-8}
$\mathrm{FD}\,(\mathrm{Jy}) \times \left(\frac{1\,\mathrm{kpc}}{D}\right)^2$
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Neutron star age (yr)

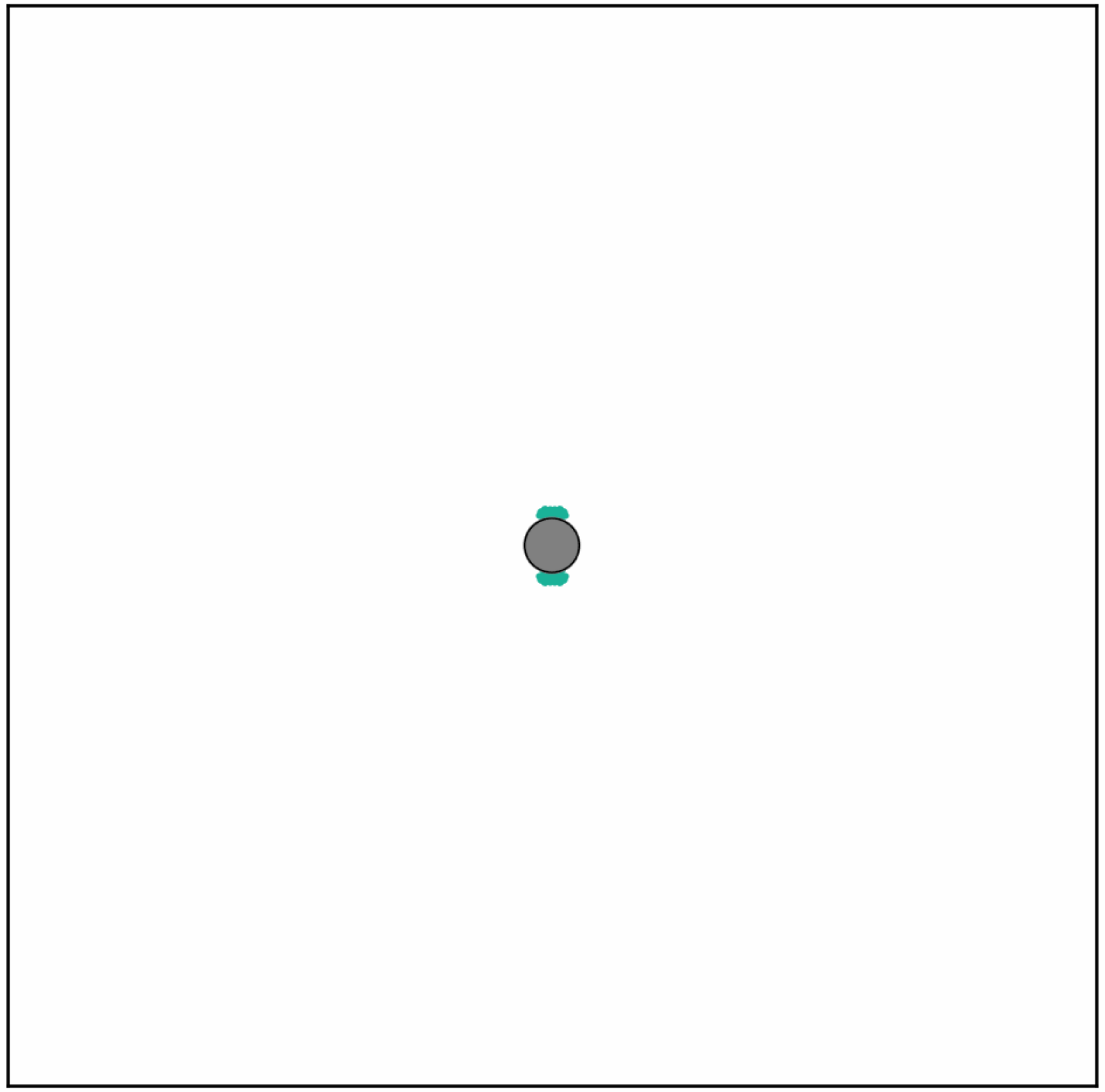

m_a
10 yrs
1 kyr
100 kyr
Death
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
FD (Jy) × $\left(\frac{1\text{kpc}}{D}\right)^2$
242
244
246
248
250
Frequency (MHz)

Growth	Saturation	Spin-down	Transient Decay



$t \lesssim \mathcal{O}(1\,\mathrm{yr})$	$\mathrm{yr} \lesssim t \lesssim \mathrm{kyr}$	$\mathrm{kyr} \lesssim t \lesssim \mathrm{Myr}$	$t \gtrsim \mathrm{Myr}$

Locally sourced axions



Axions *Photons*

Relativistic axion population

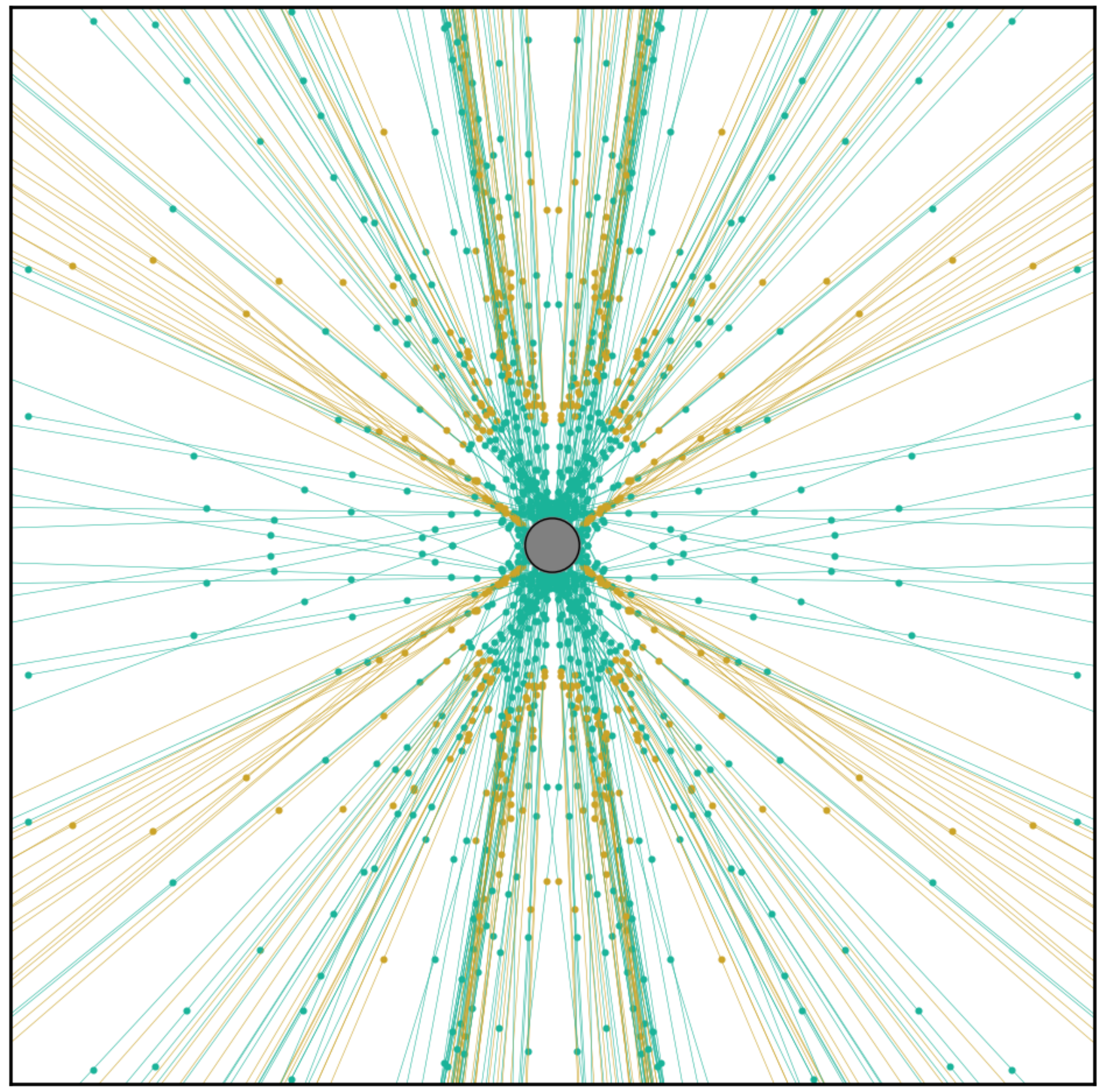
Axions free stream away from neutron star

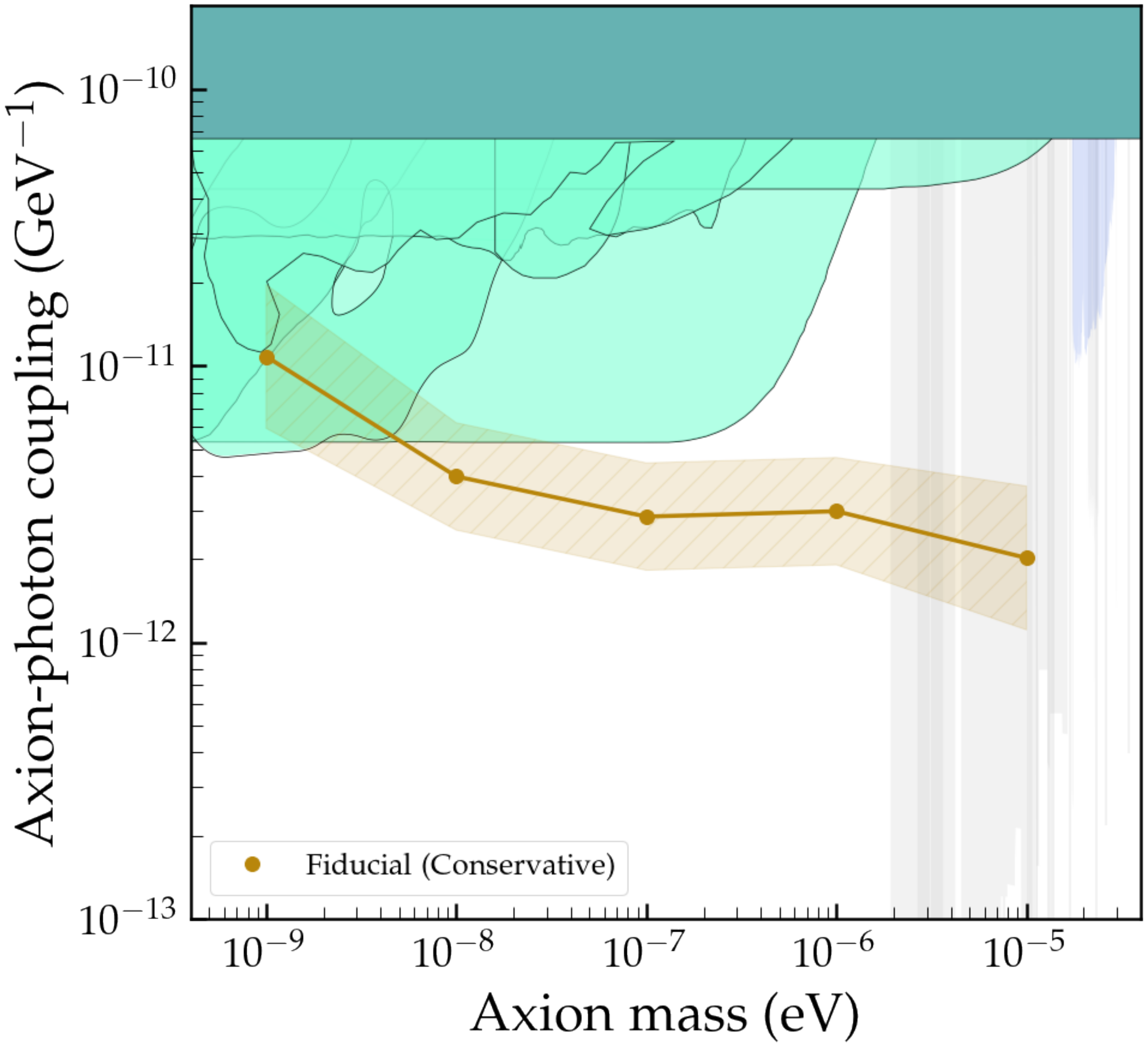
↓

Can resonantly source radio photons during escape

Observable: Broadband radio flux (on top of pulsar radio emission)

Relativistic Population



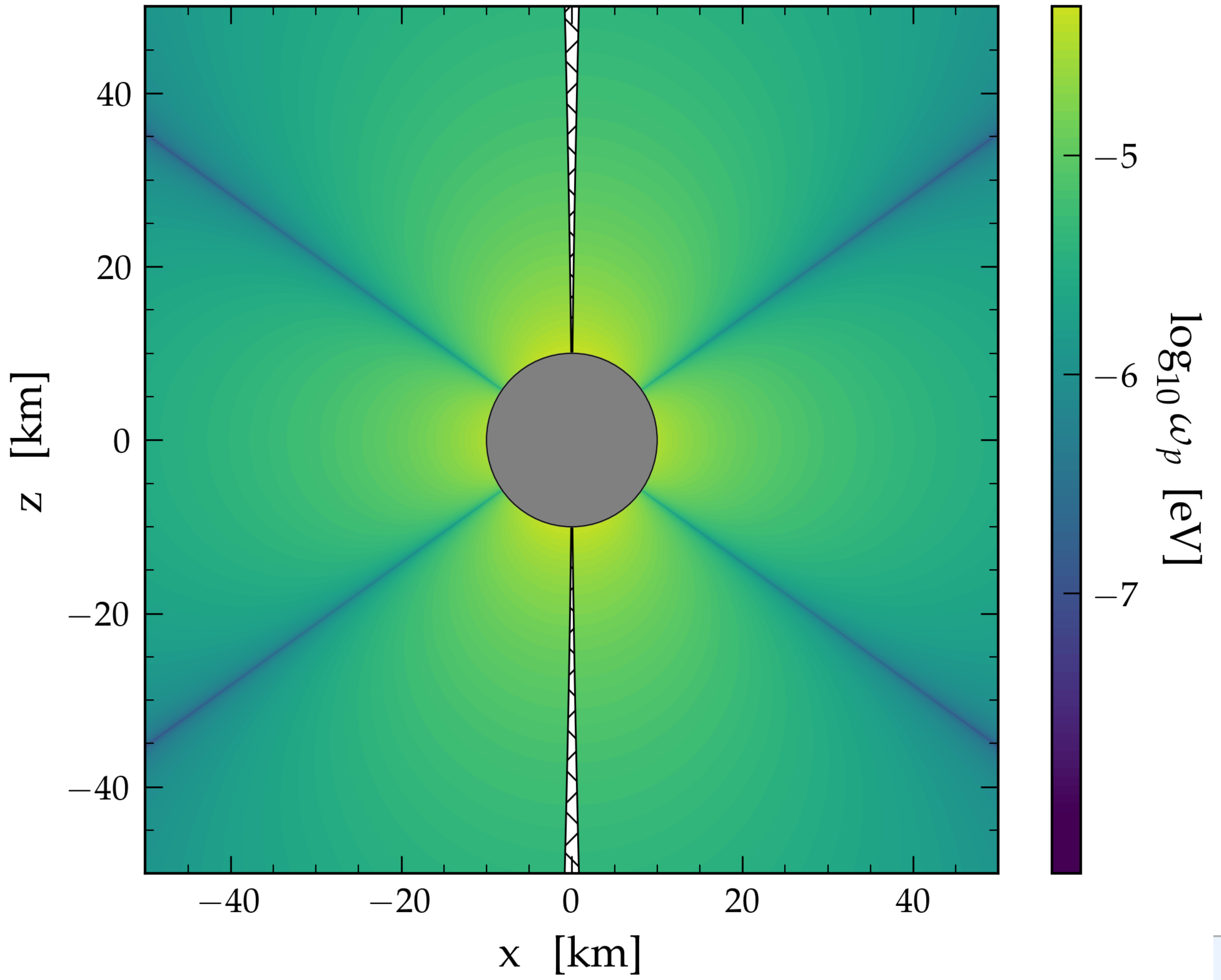


First search for radio emission from locally sourced axions

- Uses only 27 well-studied pulsars
- No assumption that axions are dark matter!

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

Back-Up

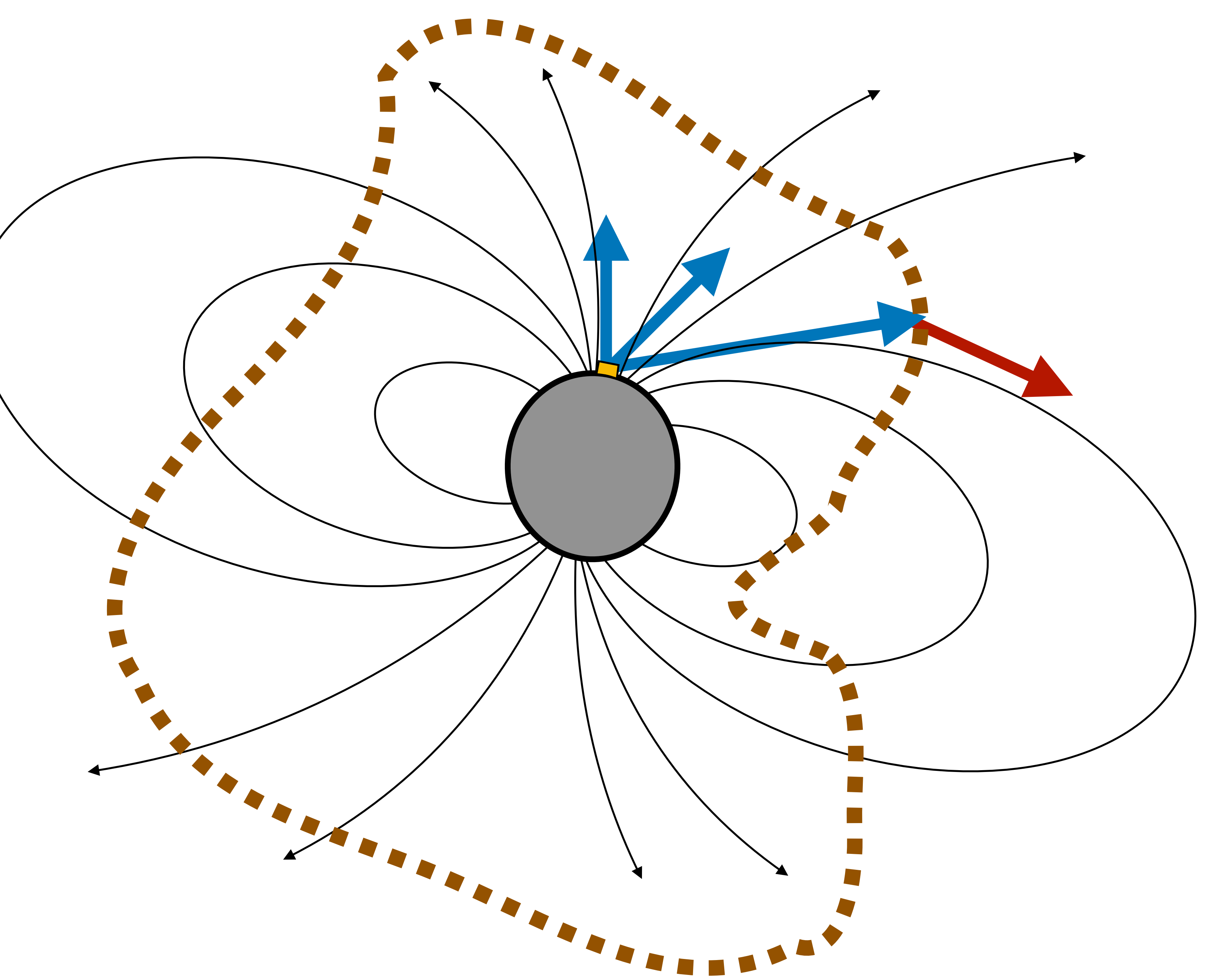


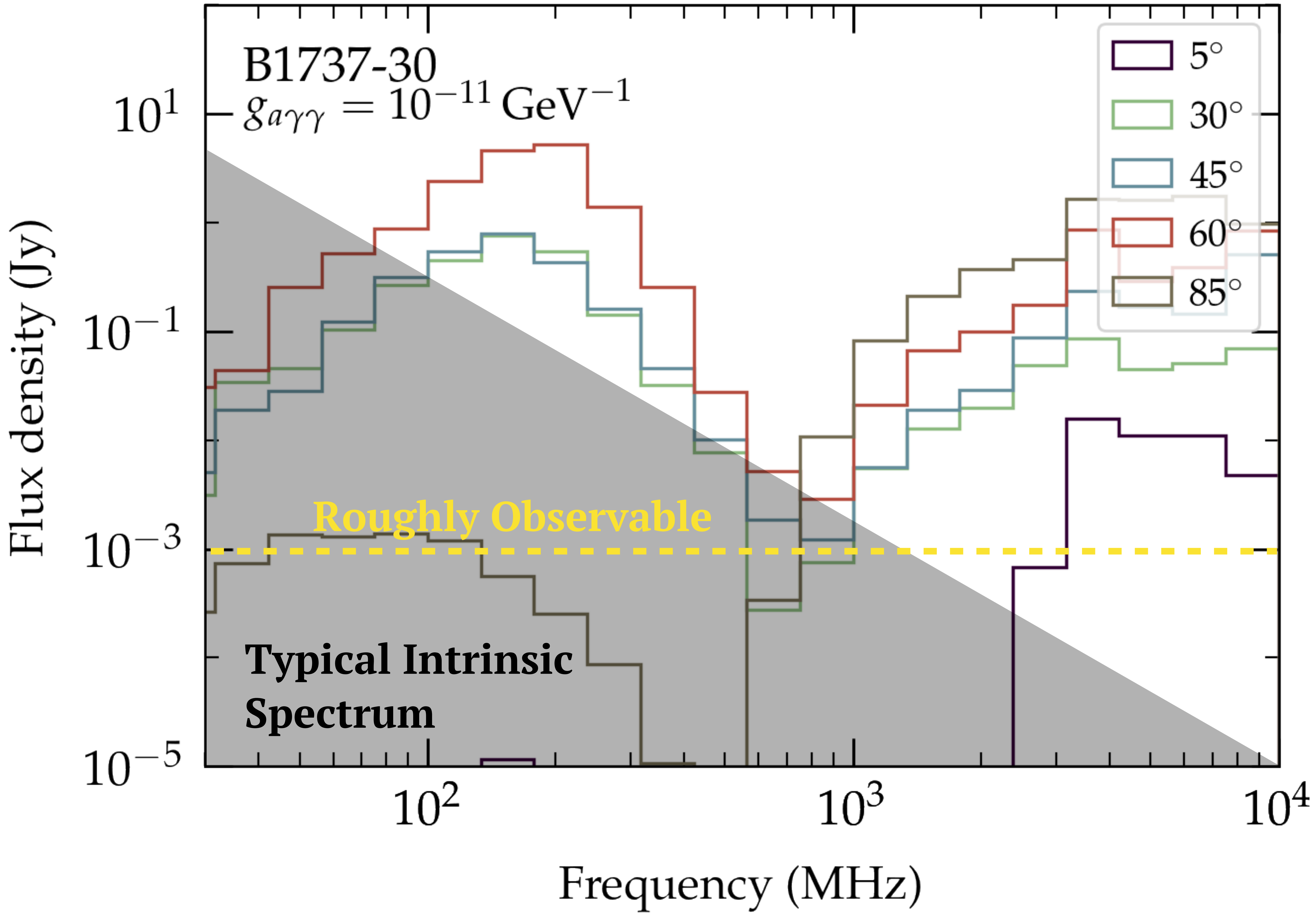
40
20
0
−20
−40
z [km]
−40
−20
0
20
40
x [km]
−5
−6
−7
$\log_{10}\omega_p$ [eV]

Radio spectrum

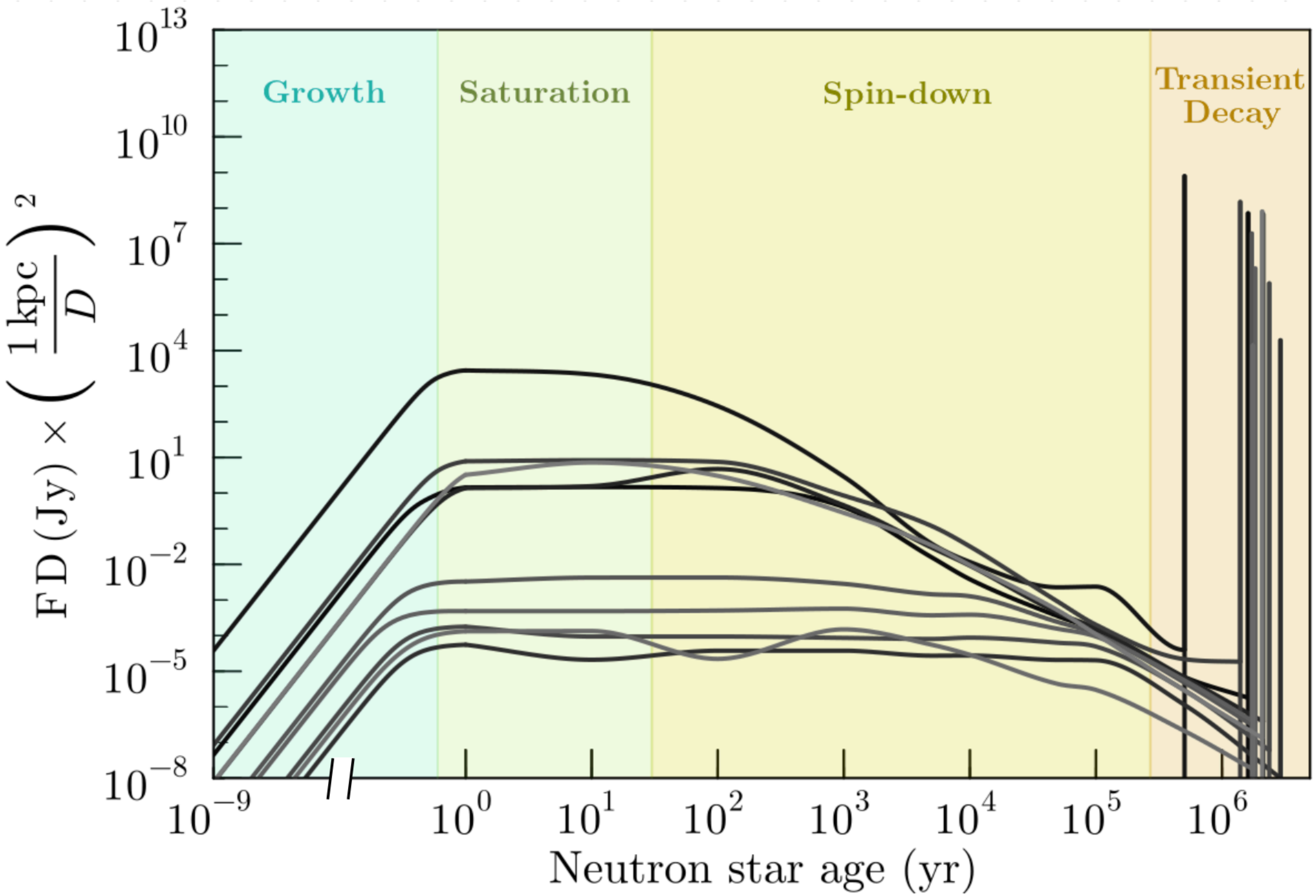
(MHz-GHz)

$\vec{E} \cdot \vec{B}$ → Axions → Photons





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

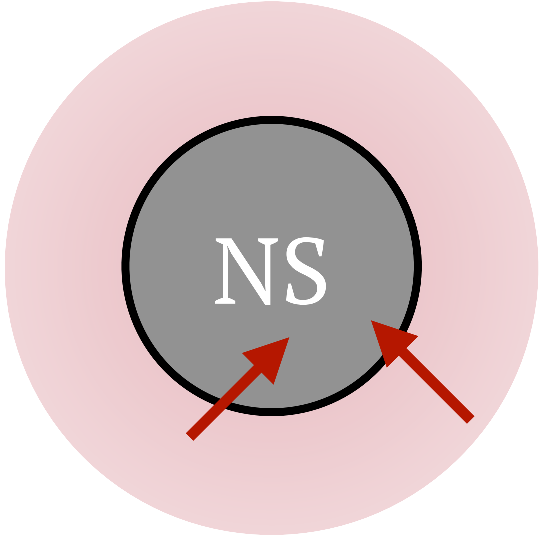


Noordhuis, Prabhu, Weniger, **SJW** (To appear)

Quenching of bound state growth

Absorption in Neutron Star:

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



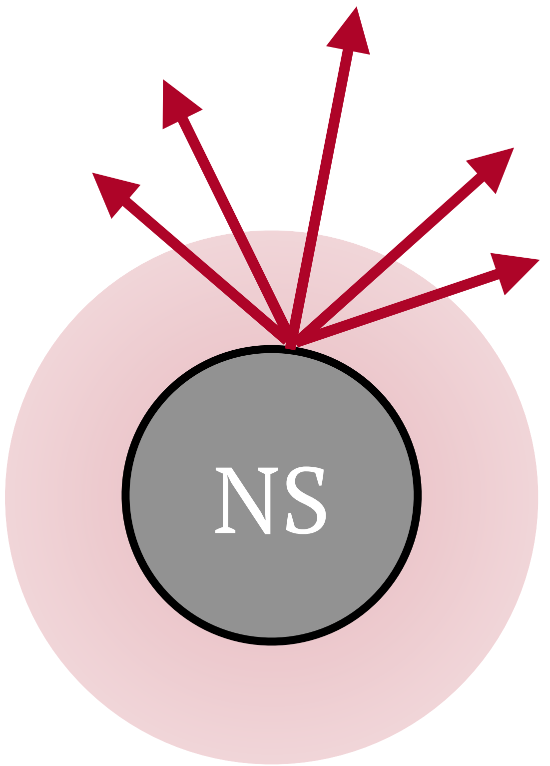
$$aNN \to NN$$

$$\Gamma_{\rm abs,eff} = \Gamma_{\rm abs}\left(1 - e^{-E/T}\right) \sim \left(\frac{E}{T}\right)\Gamma_{\rm abs}$$

Absorption heavily suppressed in low energy limit

Back-reaction on vacuum gap:

Caputo, **SJW**, Phillipov (In progress)

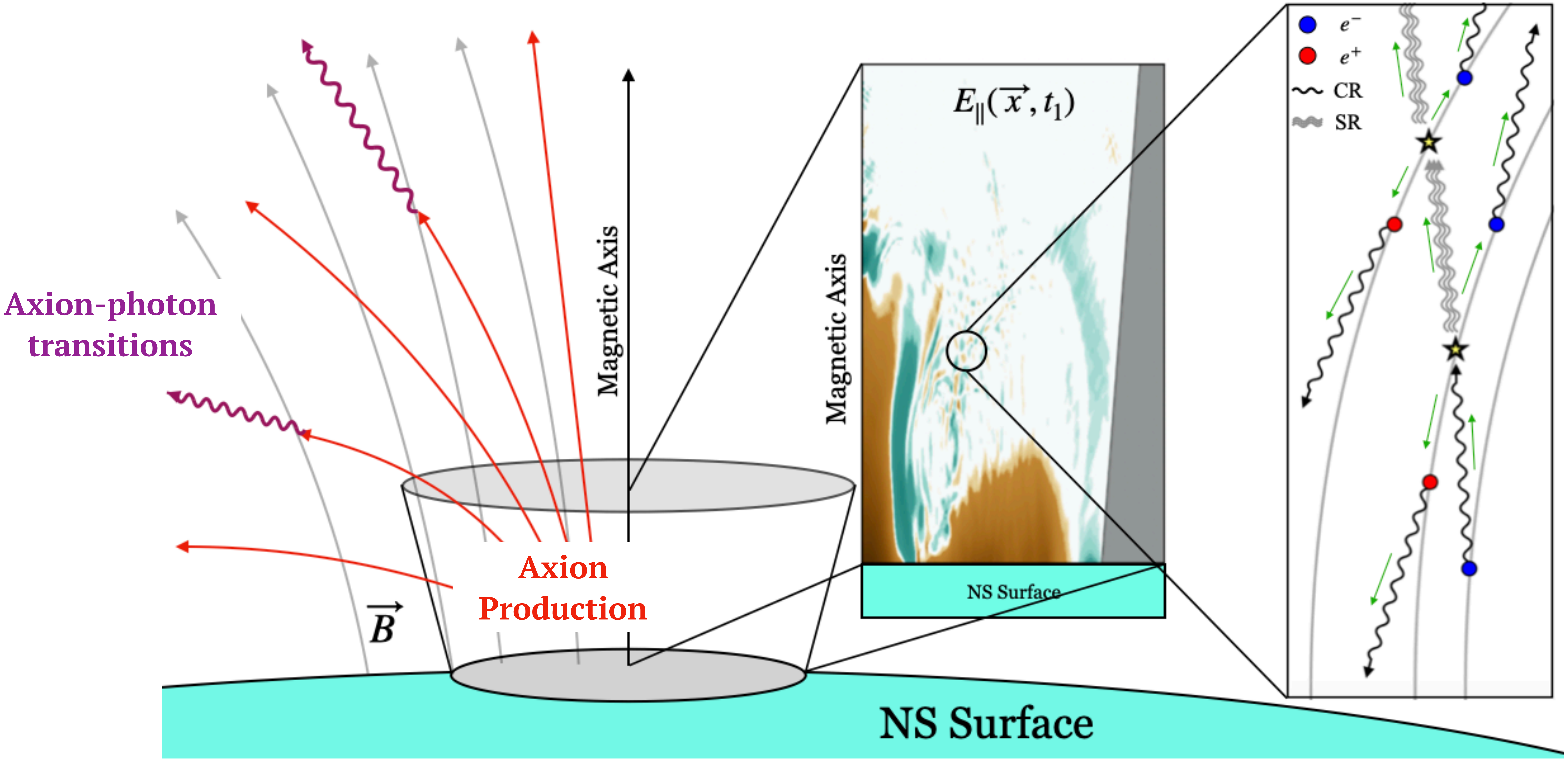


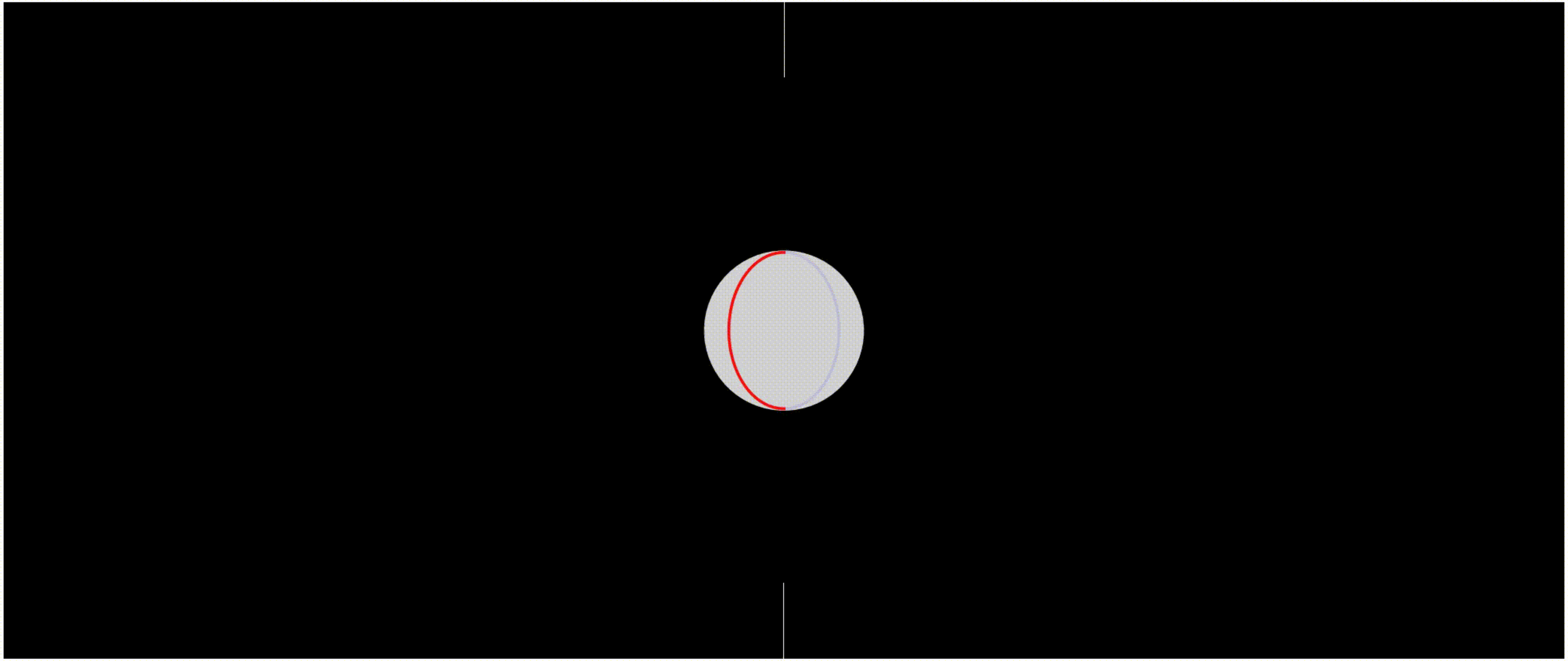
$$\nabla \cdot \vec{E} = \rho - g_{a\gamma\gamma}\vec{B} \cdot \nabla a$$

Large axion cloud can modify the plasma dynamics that drive production

$$\rho^{br}_{\rm max}(g_{a\gamma\gamma}, z = R_{\rm NS})$$

Overview


Axion-photon transitions
Magnetic Axis
Axion Production
$\vec{B}$
NS Surface
$E_{\parallel}(\vec{x}, t_1)$
Magnetic Axis
NS Surface
e^-
e^+
CR
SR



Credit: Rui Hu, Pigeon code, https://github.com/hoorayphyer/Pigeon

Magnetosphere Axisymmetric Rotator

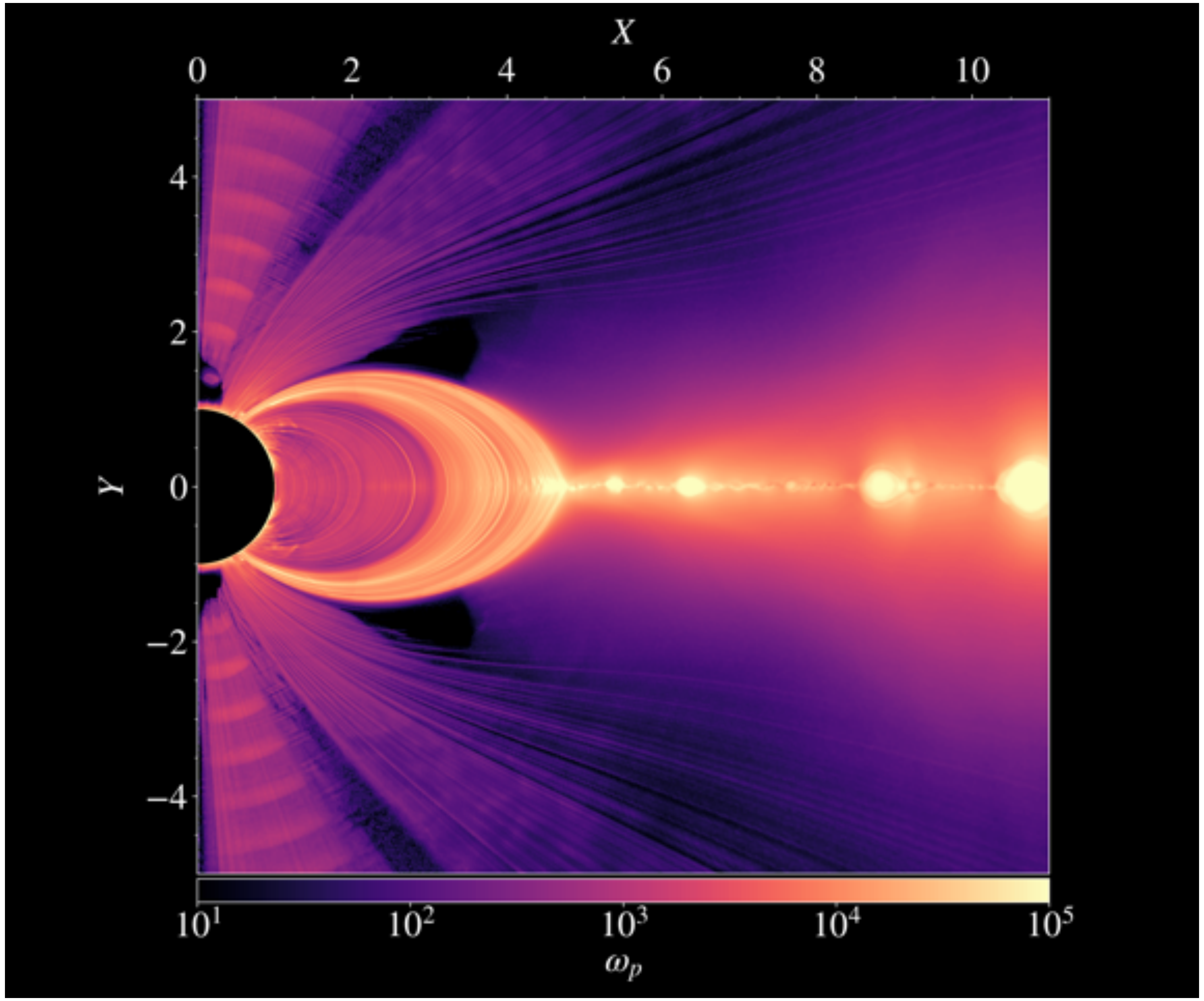
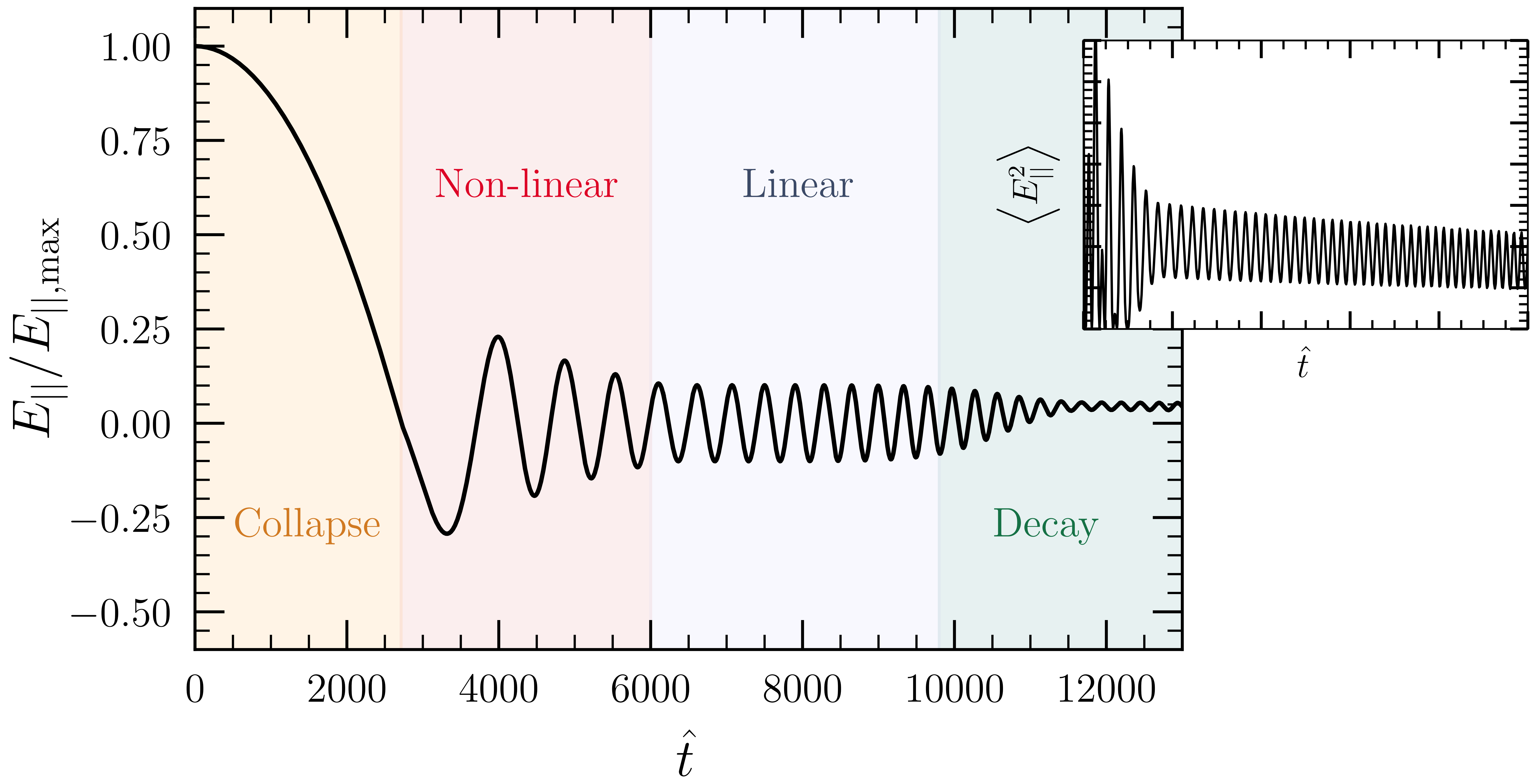


Image credit: Bransgrove & Beloborodov



$E_{||}/E_{||,\max}$
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
0
2000
4000
6000
8000
10000
12000
$\hat{t}$
Collapse
Non-linear
Linear
Decay
$\langle E_{||}^2 \rangle$
$\hat{t}$