Axion Clouds around Pulsars

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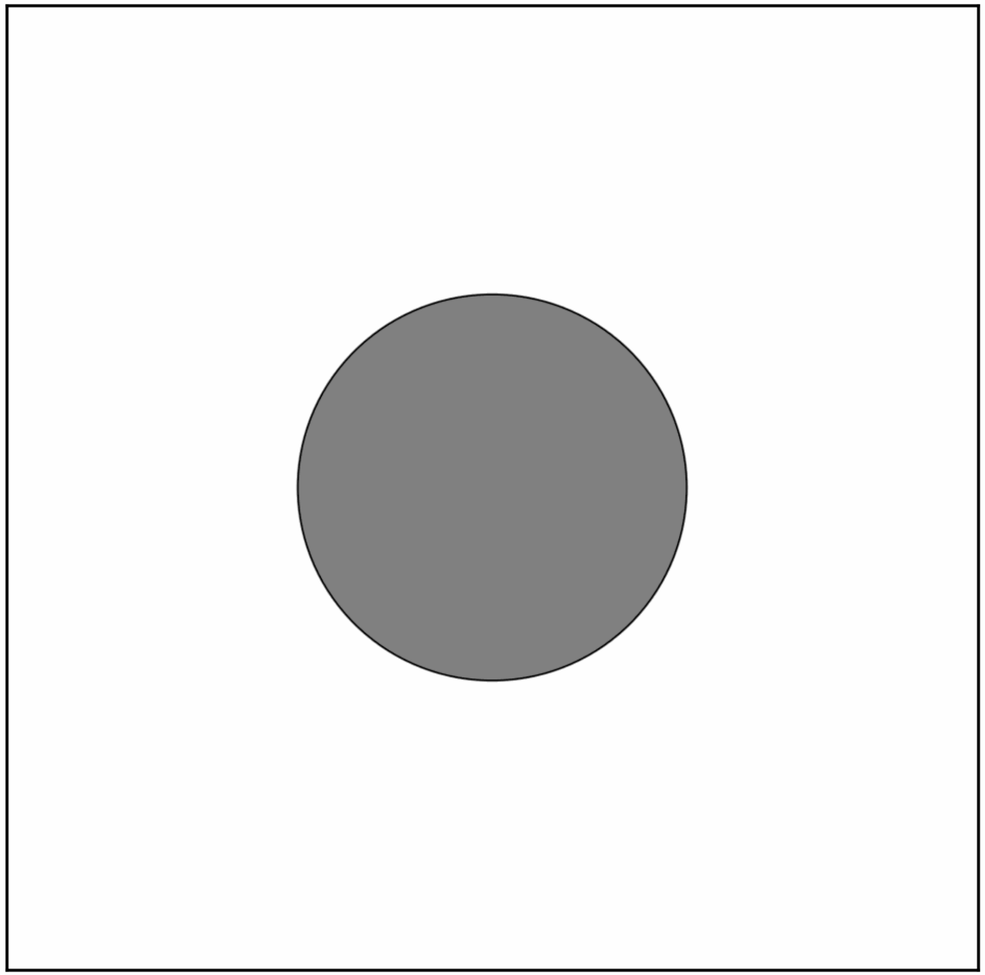
General Meeting of Cosmic Whispers
Bari, Italy
September 5, 2023



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

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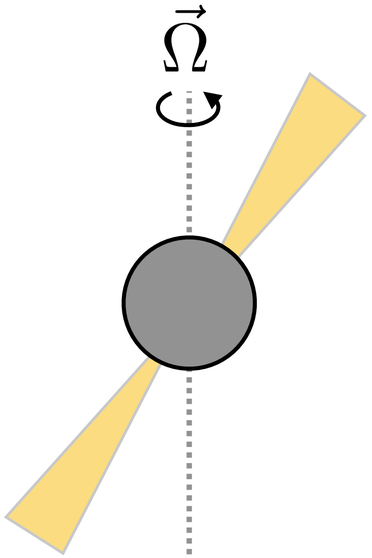
Axion clouds around pulsars

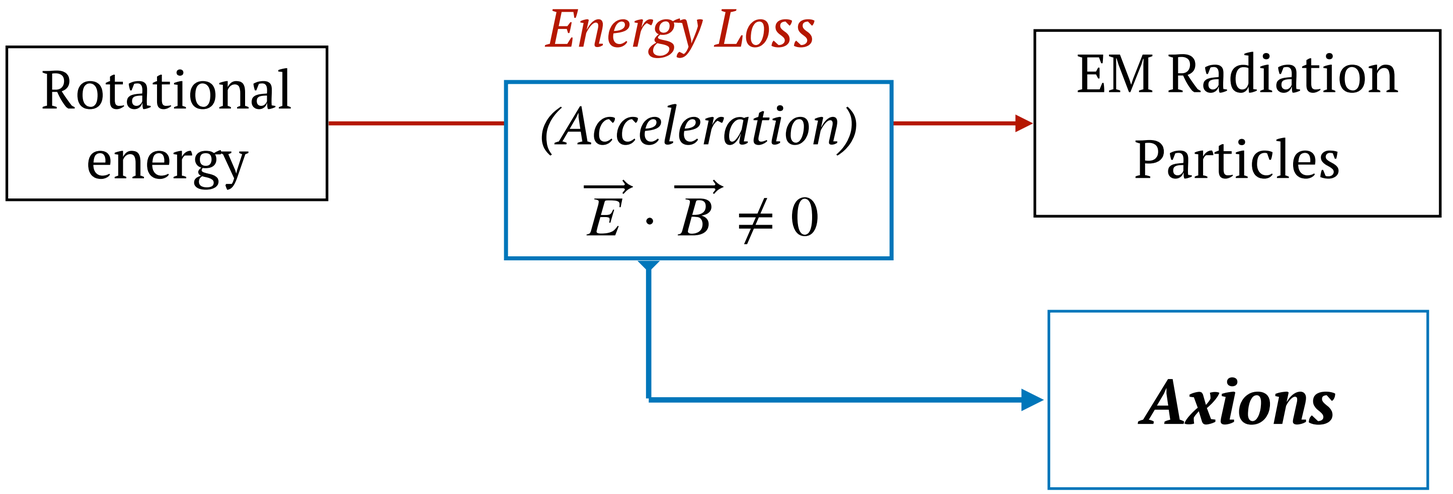
Assumptions: There exists an axion which:

1) Couples to electromagnetism $\mathscr{L} \supset - g_{a\gamma\gamma}\, a\, (\vec{E} \cdot \vec{B})$

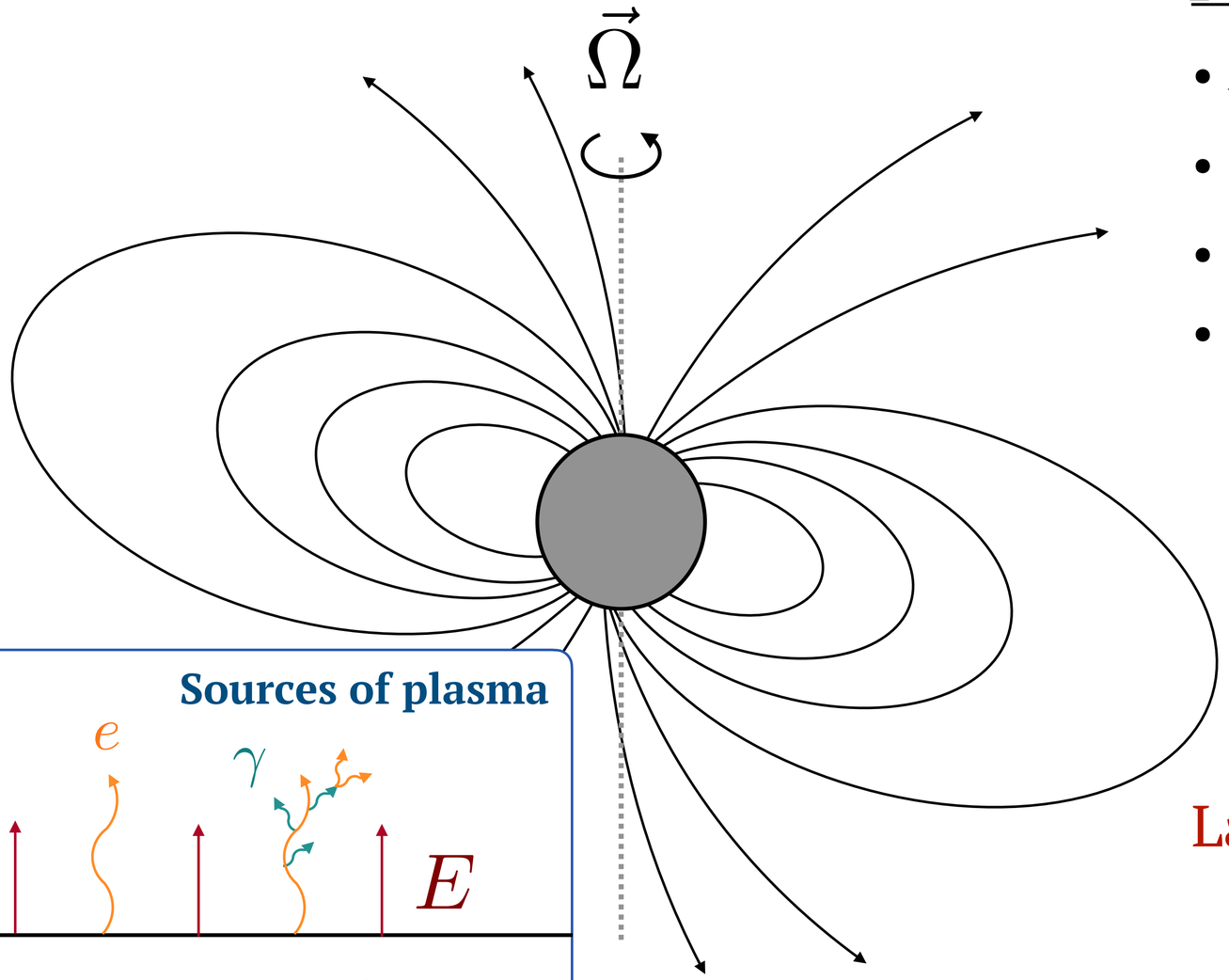
2) Has a mass $10^{-10}\,\text{eV} \lesssim m_a \lesssim 10^{-4}\,\text{eV}$

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





Pulsar magnetospheres



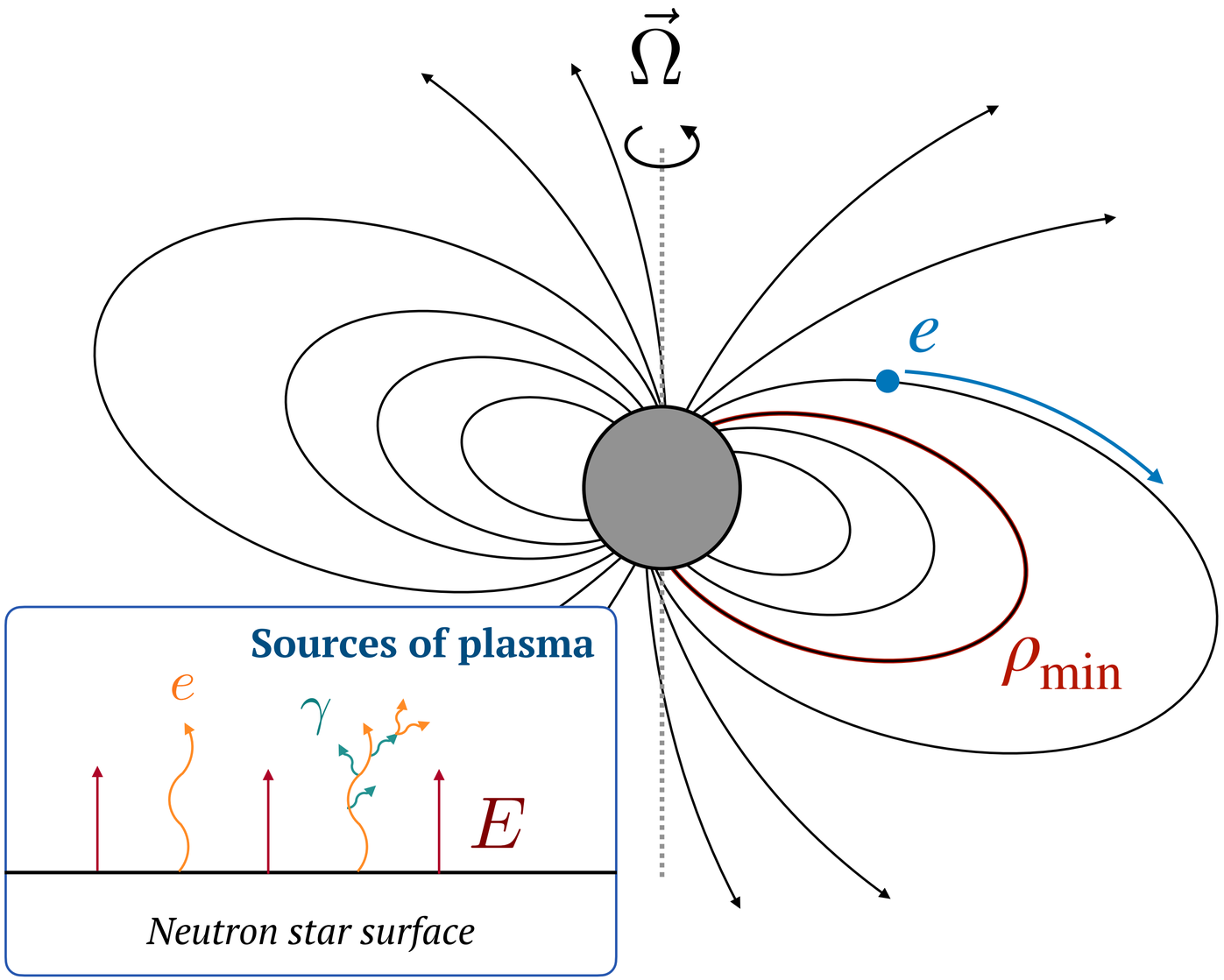
Pulsars at first order:

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

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

$$F_{\vec{E}} \gg F_{\rm gravity}, F_{\rm binding}$$

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

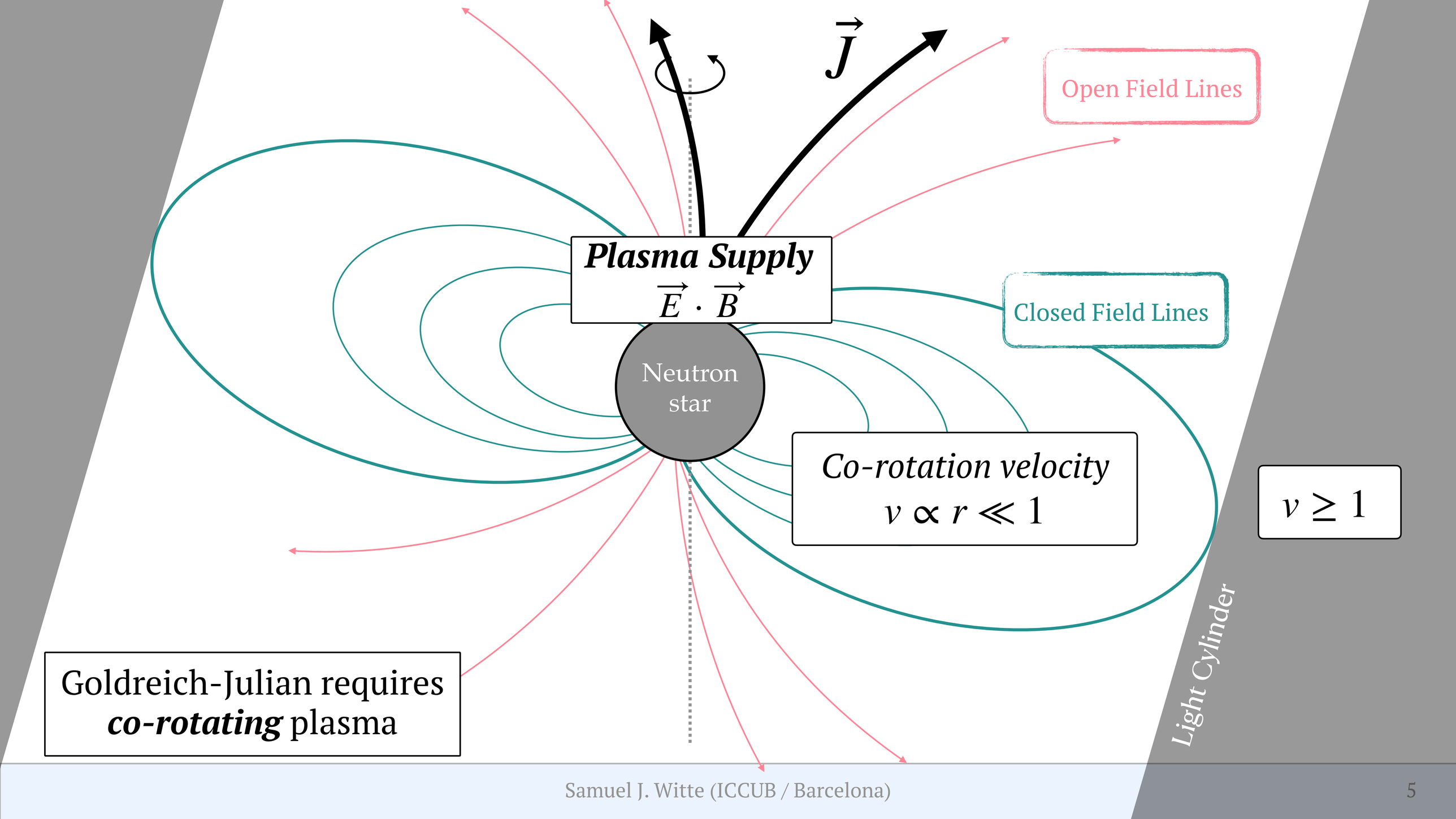
If $\rho_e \geq \rho_{\rm min}$, $\vec{E} \to 0$

Stable force-free solution?

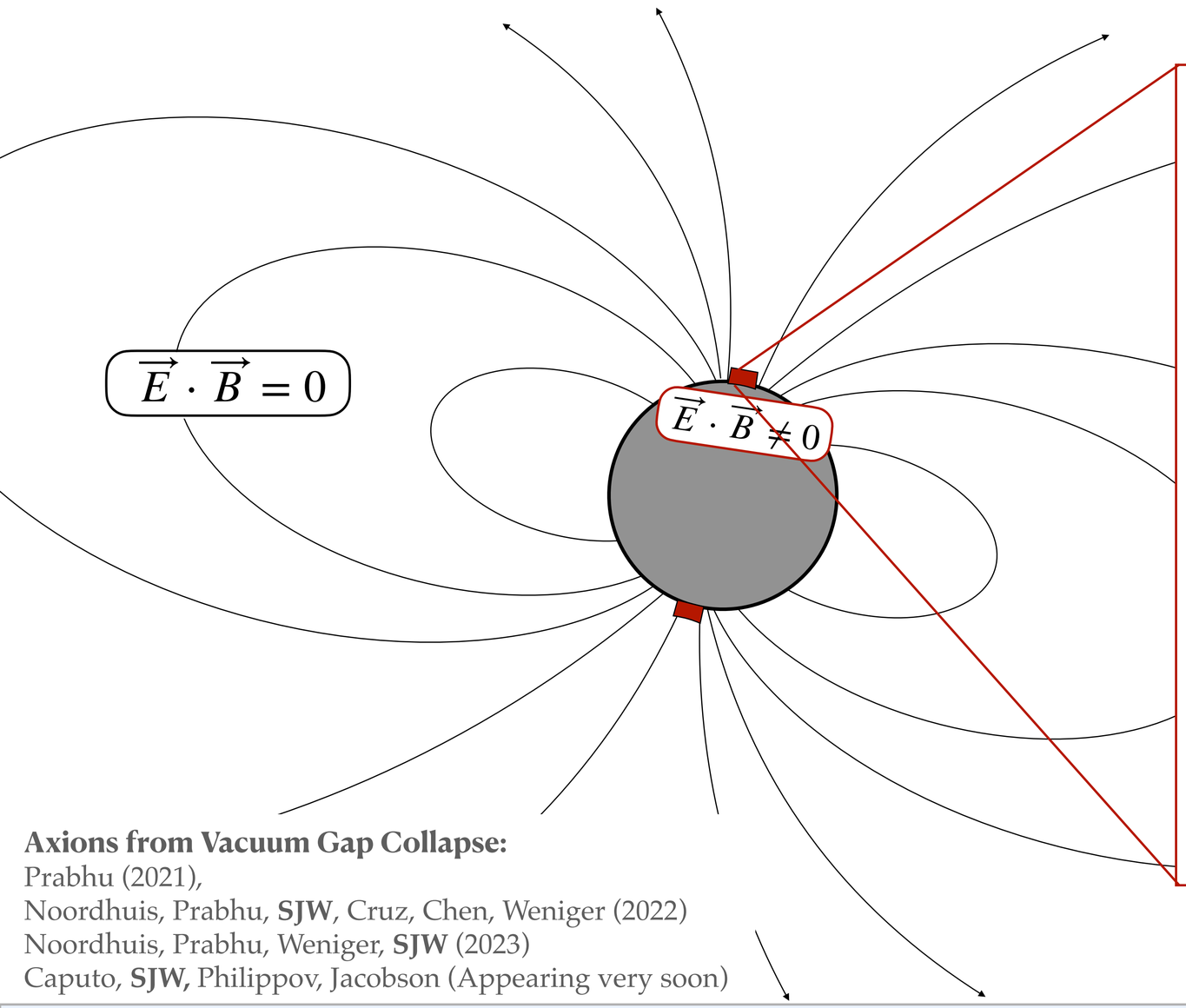
- $\vec{E}$ extracts $\rho_{\rm min}$
- $\rho_{\rm min}$ screens electric field, $\vec{E} \cdot \vec{B} \to 0$
- No $e^{\pm}$ being sourced, stable co-rotation

Goldreich-Julian Model

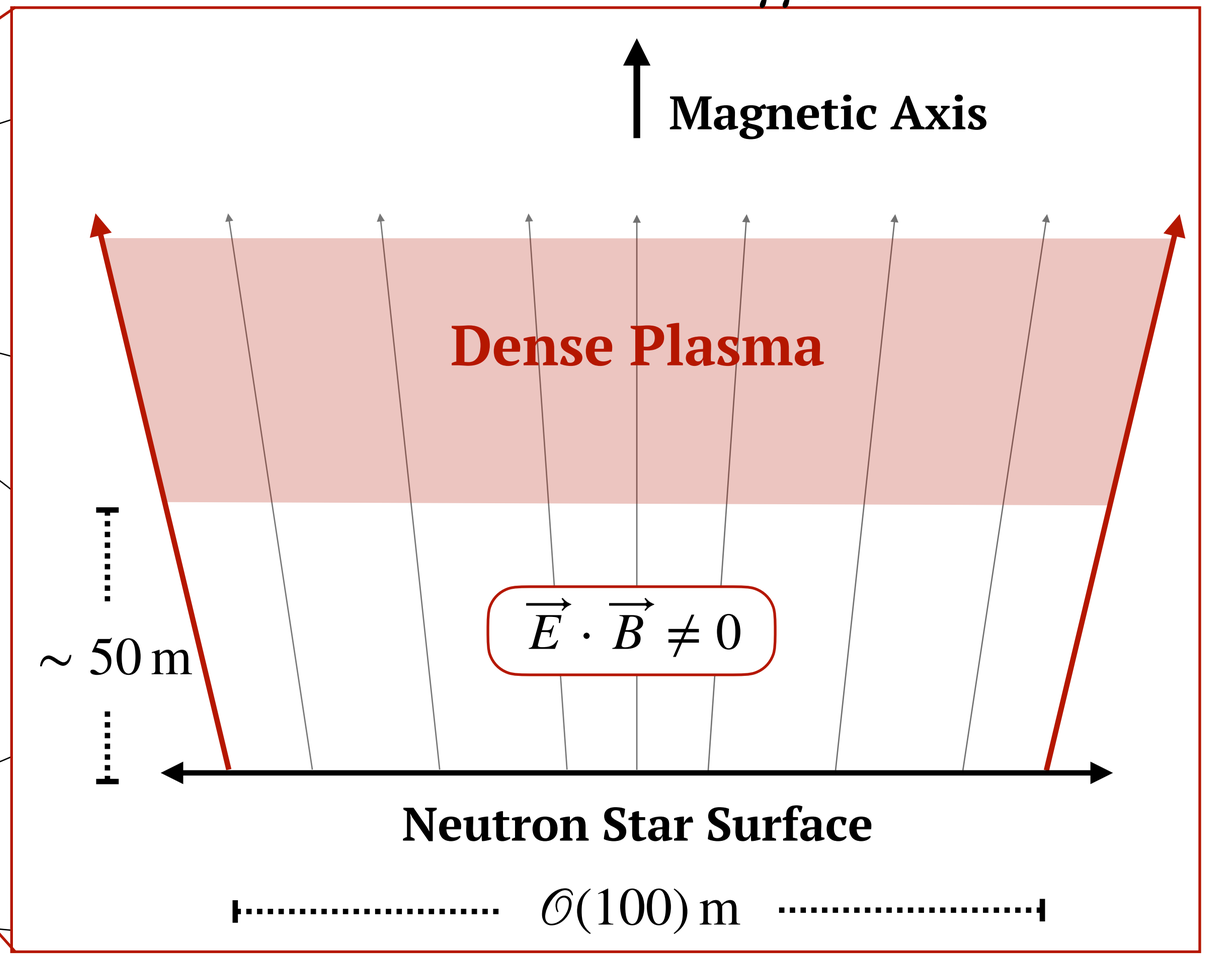
Goldreich & Julian 1969


$\vec{J}$
Open Field Lines
Plasma Supply
$\vec{E} \cdot \vec{B}$
Closed Field Lines
Neutron star
Co-rotation velocity
$v \propto r \ll 1$
$v \geq 1$
Light Cylinder
Goldreich-Julian requires
co-rotating plasma

Axion production from vacuum gaps



$$\left(\dot{N}_a(\vec{k}) = \frac{1}{m_a} \mathrm{FT}[g_{a\gamma\gamma} \vec{E} \cdot \vec{B}]\right)$$

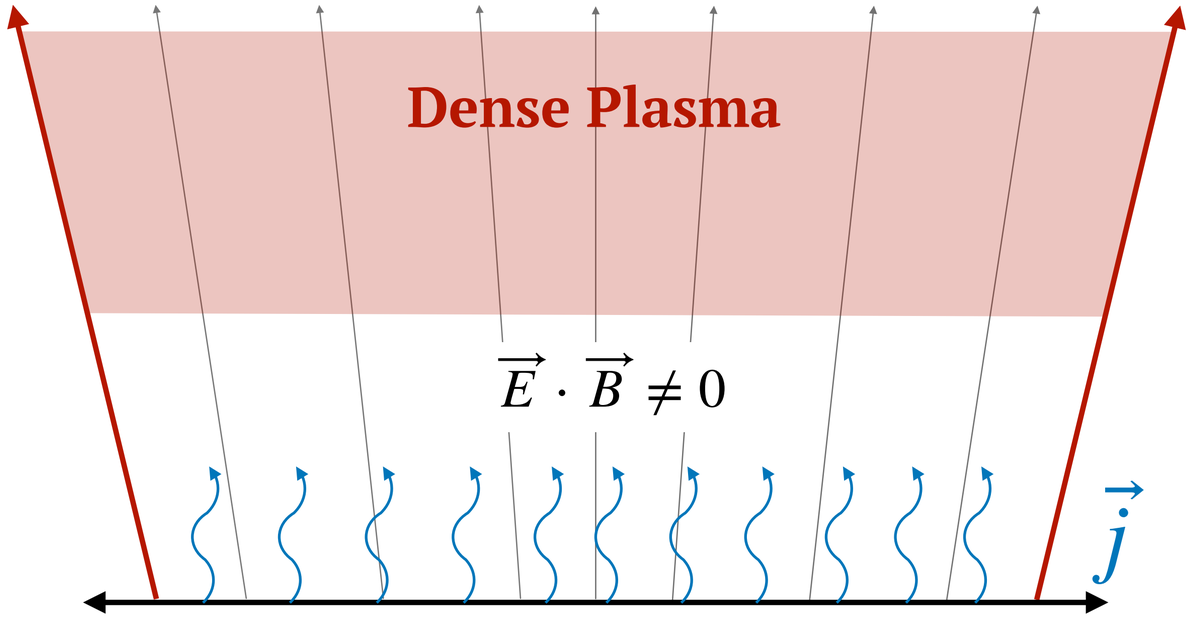


Axions from Vacuum Gap Collapse:
Prabhu (2021),
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Polar cap dynamics

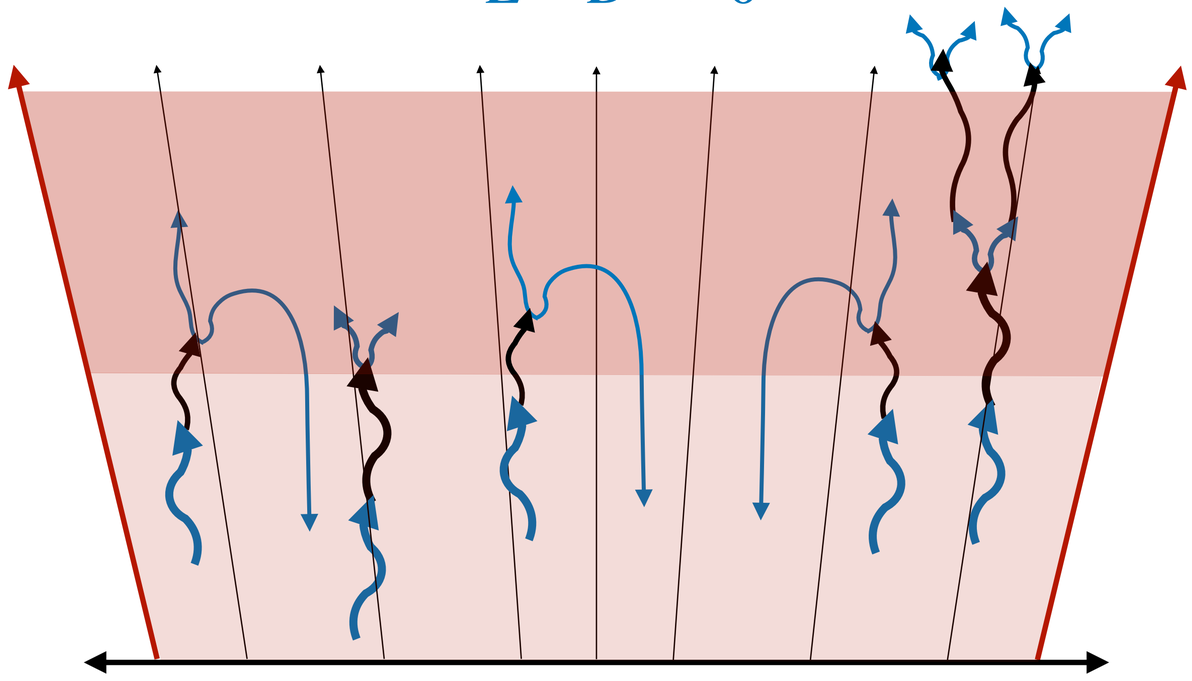
Part 1: Vacuum Phase

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



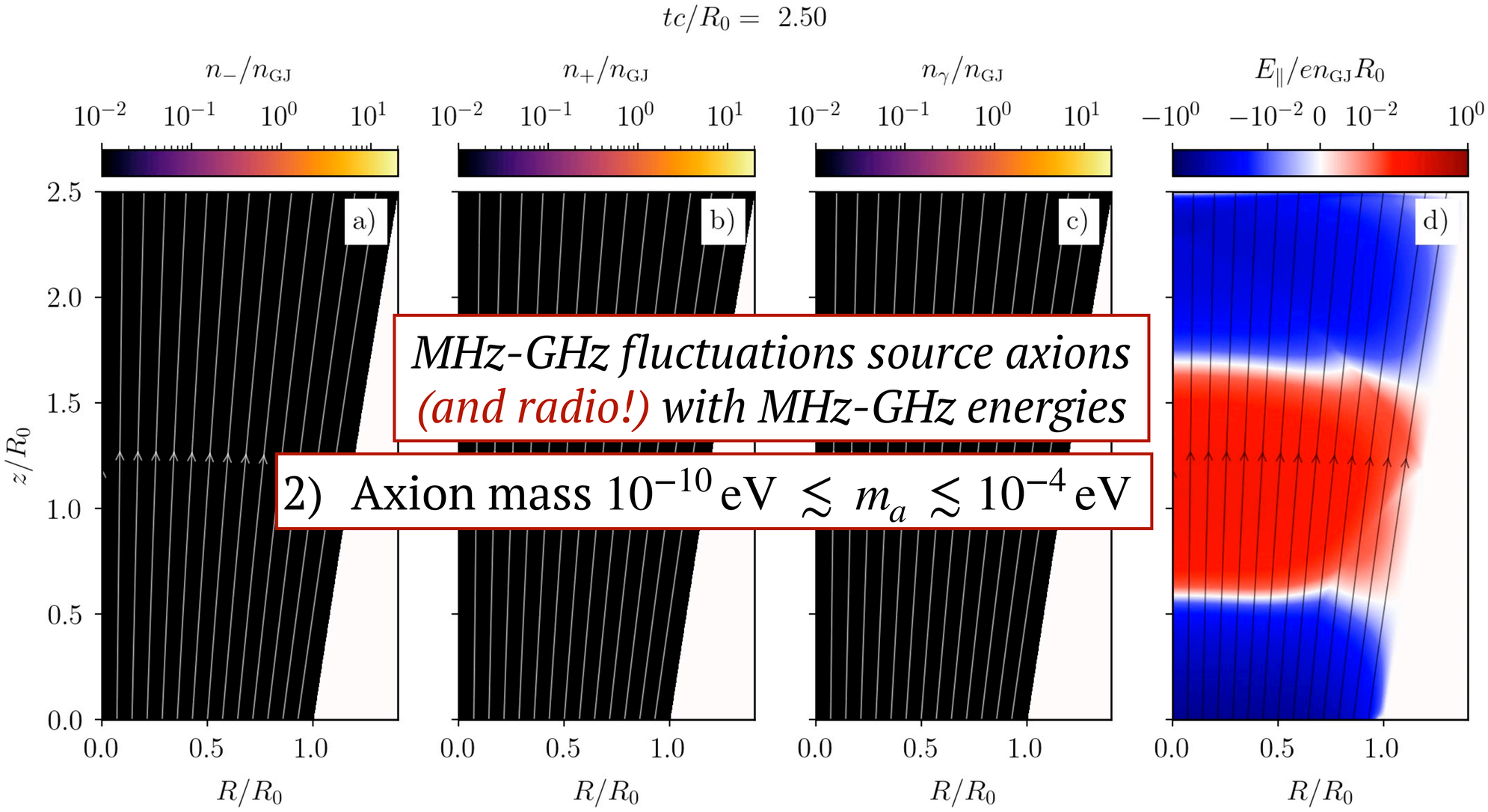
Part 2: Screening Phase

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



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

Polar cap dynamics



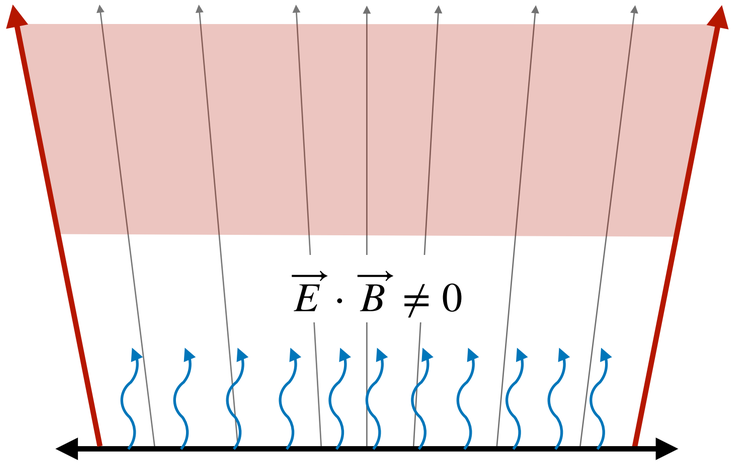
MHz-GHz fluctuations source axions (and radio!) with MHz-GHz energies

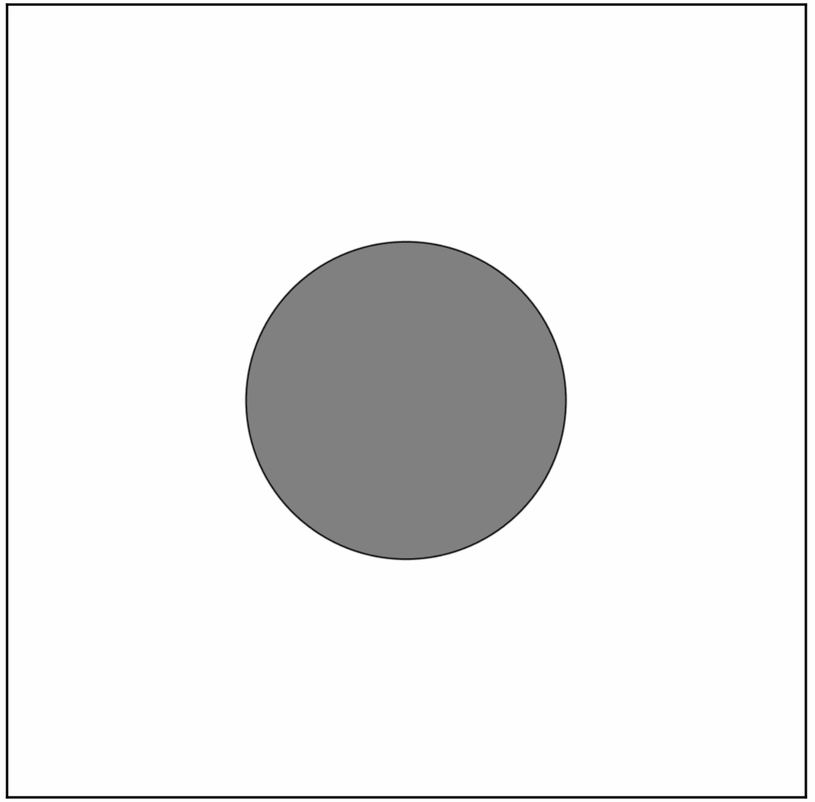
2) Axion mass $10^{-10}\,\text{eV} \lesssim m_a \lesssim 10^{-4}\,\text{eV}$

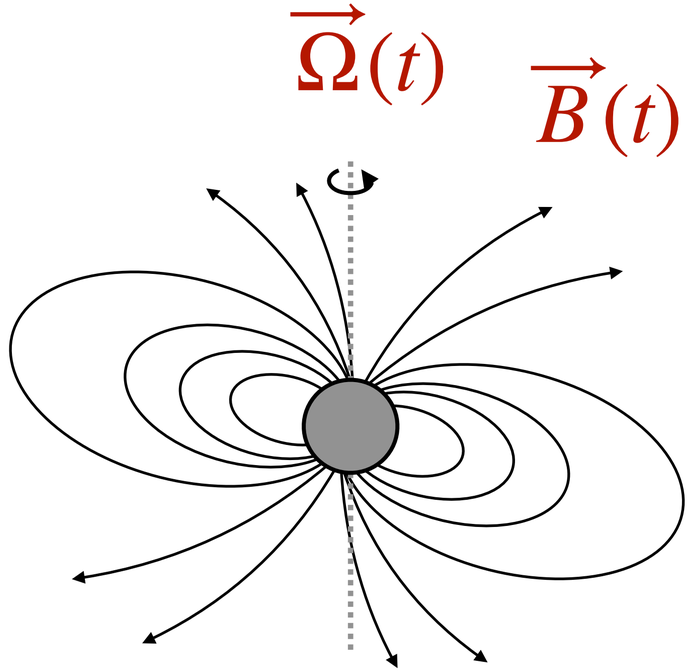
Simulations curtesy of F. Cruz and A. Chen

Production of axion clouds

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







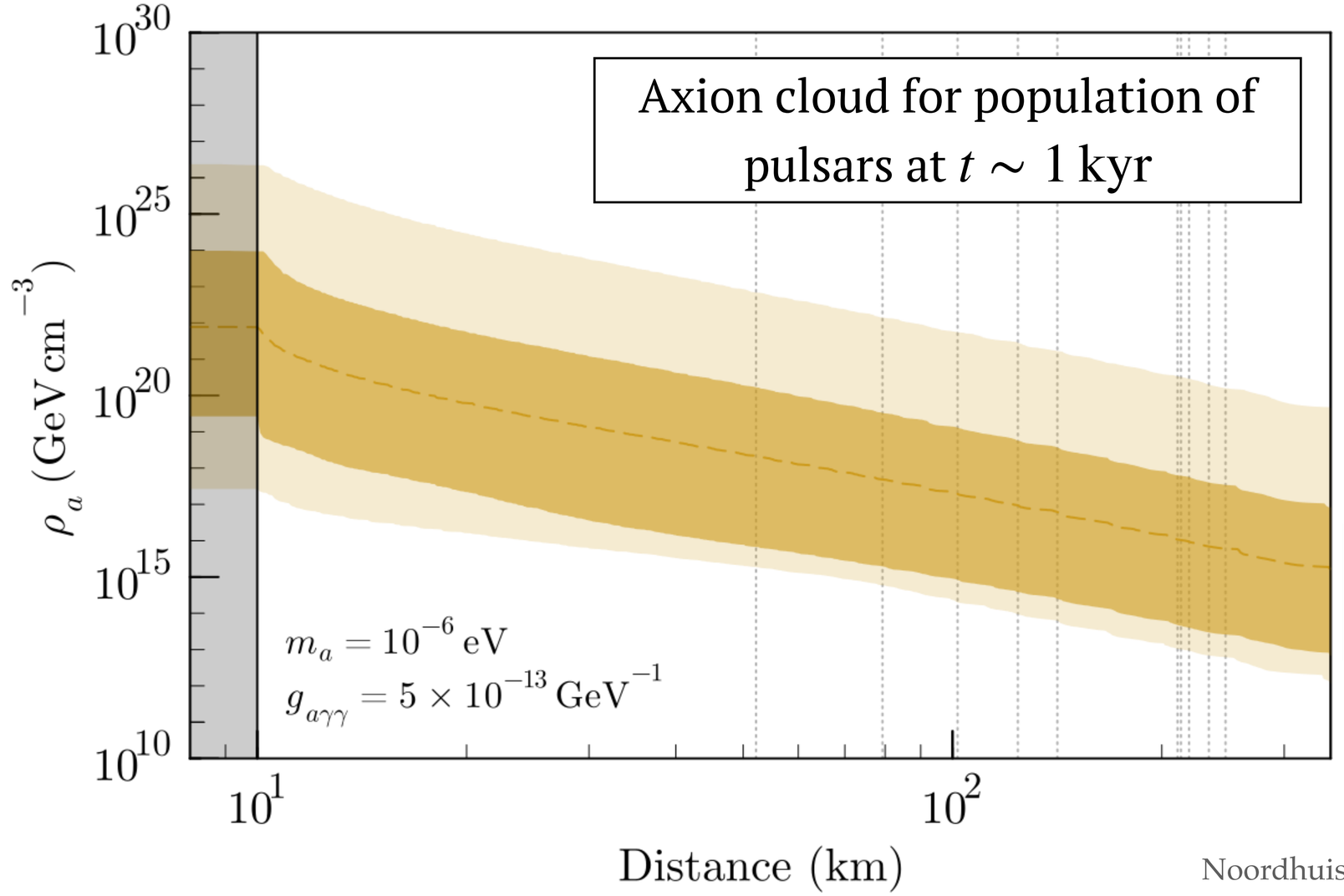
Production
(~μs)

Evolution bound axions
(~ minutes)

Pulsar spin-down
(kyr to Myr)

Axion Clouds

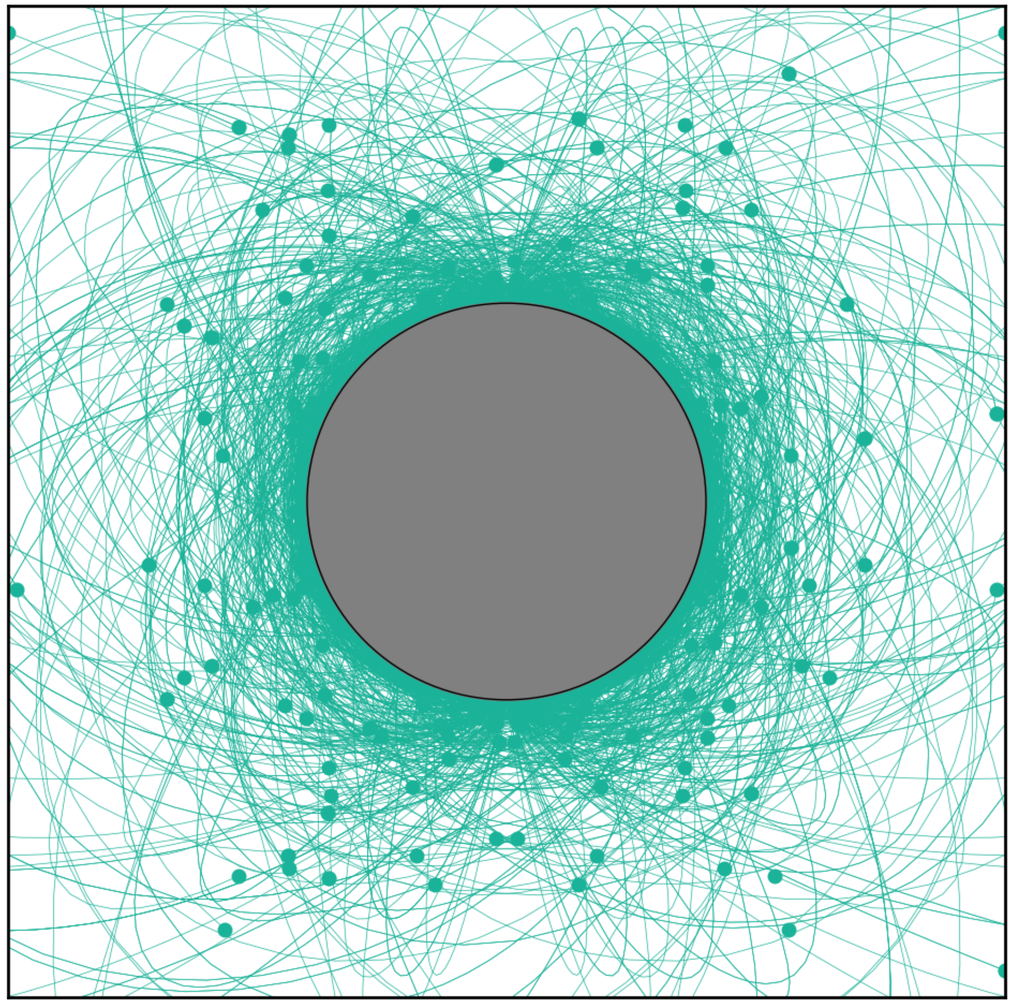
Tentative assumption: axions are produced and no longer interact



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?

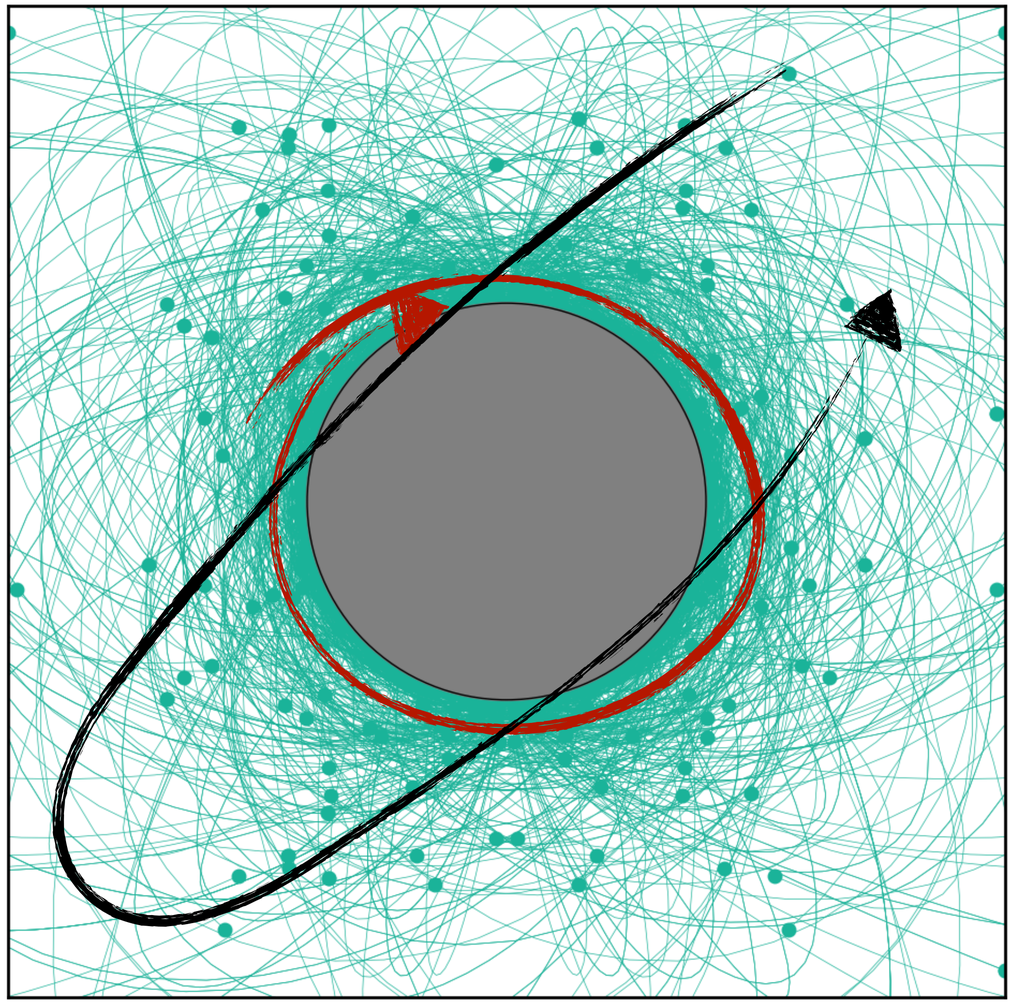
Yes & no. Is $\omega_p \leq \omega_a$?

Can axions alter the electrodynamics of the polar cap?

Yes, if the coupling is large enough.

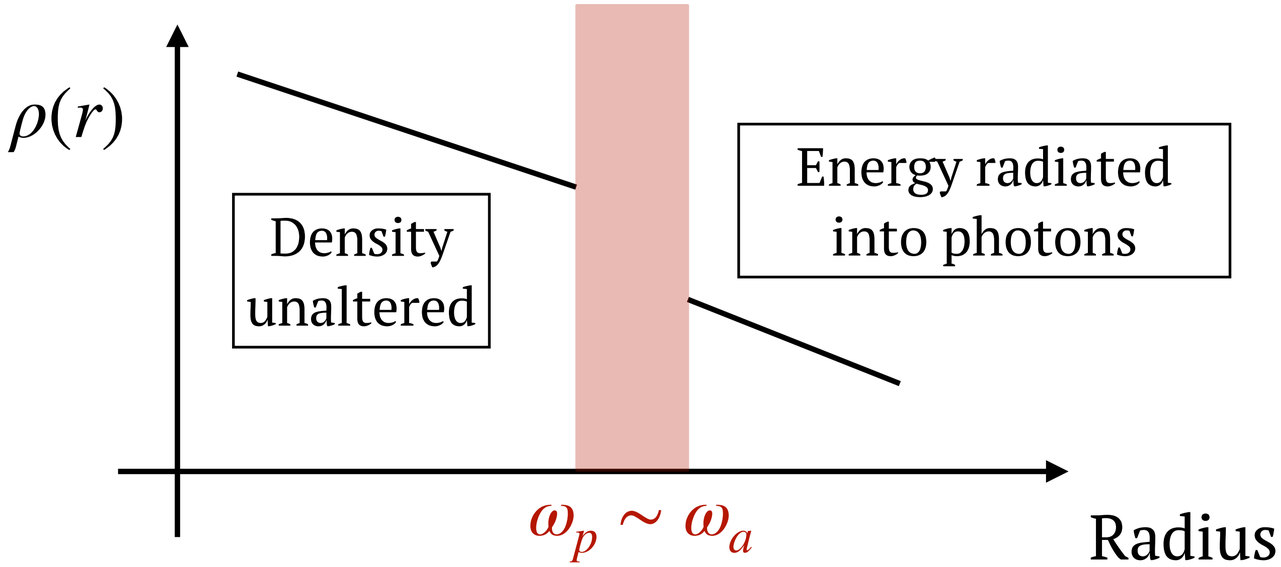
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW,** Philippov, Jacobson (Appearing very soon)

Energy losses: radiation



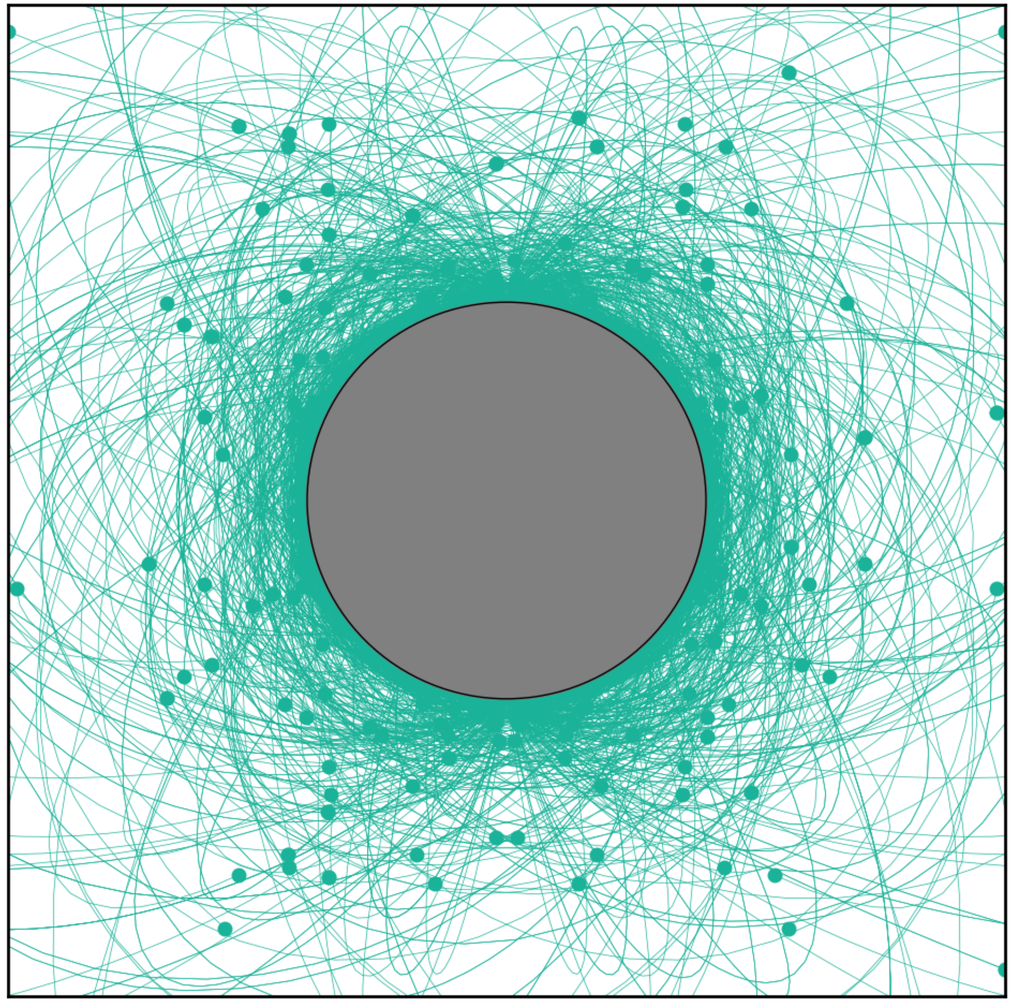
Close to the neutron star plasma too dense

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



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

Evolution of bound axions



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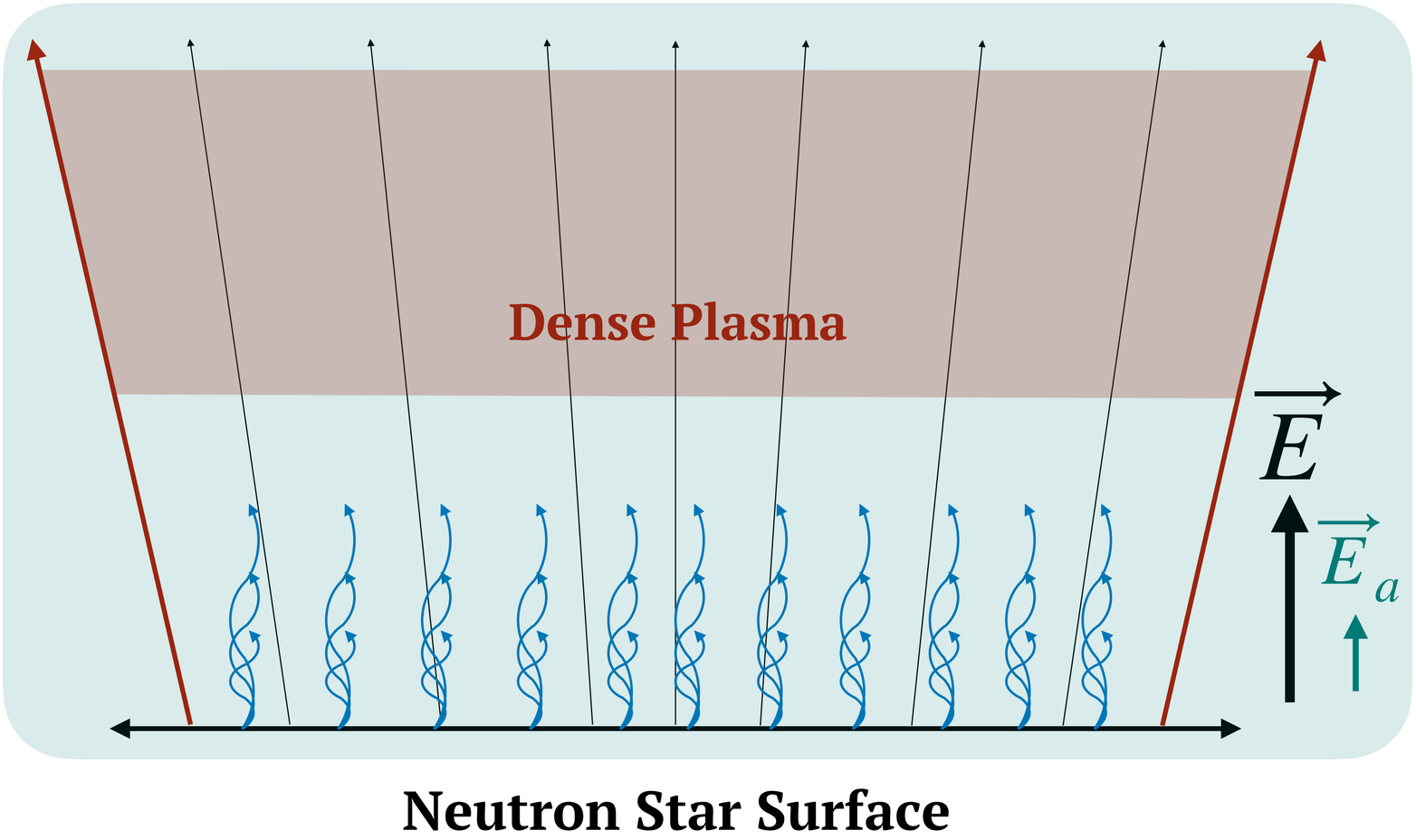
Energy losses: the polar cap

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

Part 1: Vacuum Phase



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)

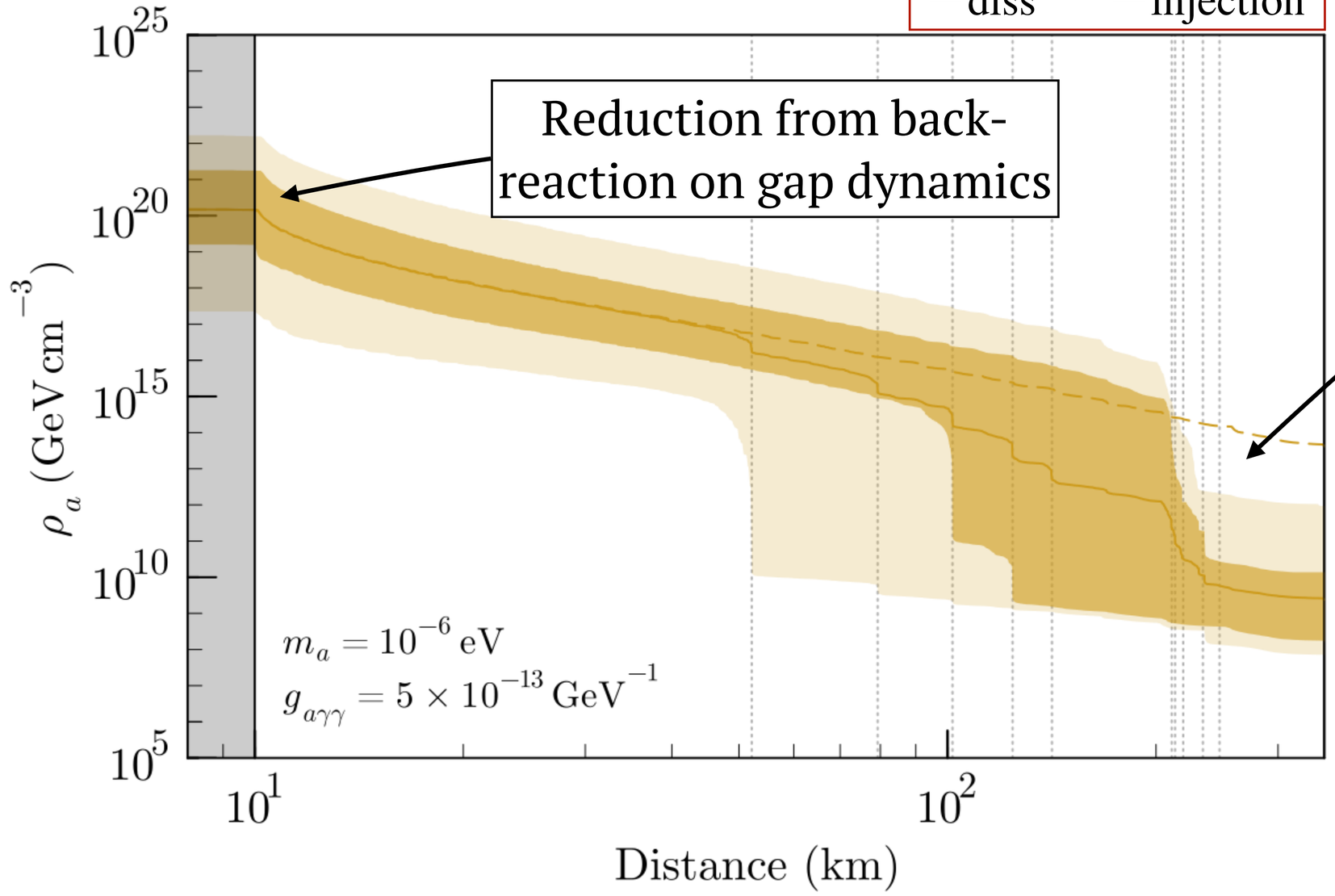
Axions can dissipate energy in the current itself

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

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

Axion Clouds

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



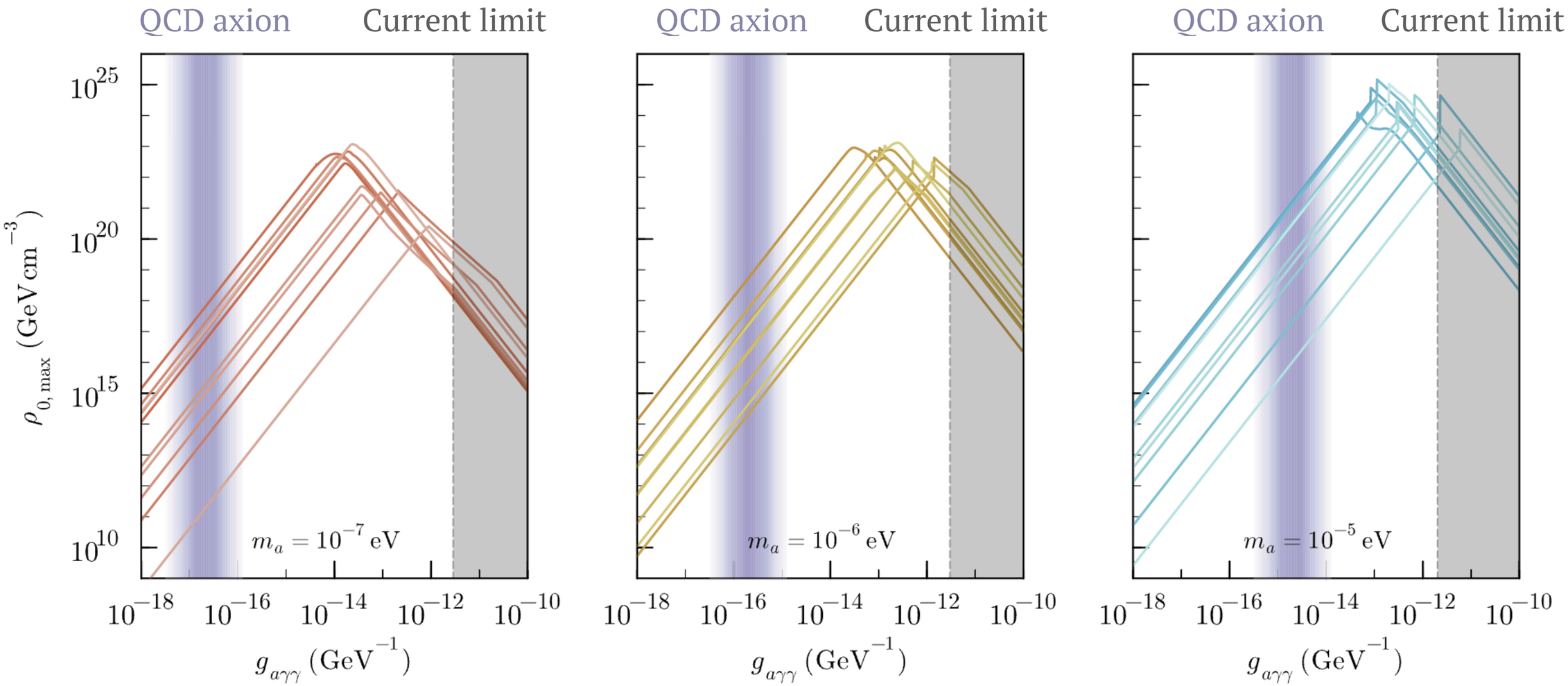
Reduction from back-reaction on gap dynamics

Reduction in density from resonant emission

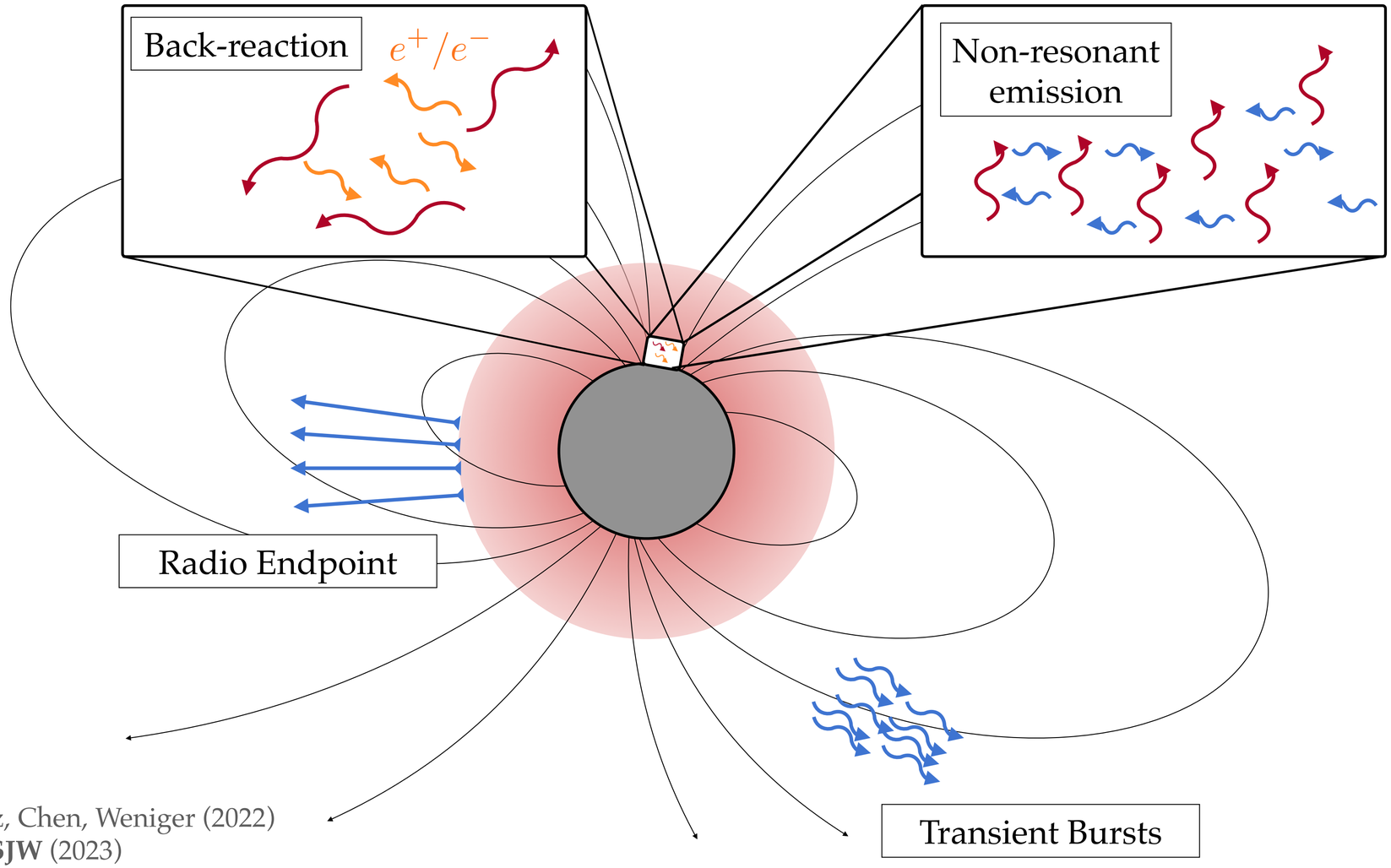
Noordhuis, Prabhu, Weniger, **SJW** (2023)

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)
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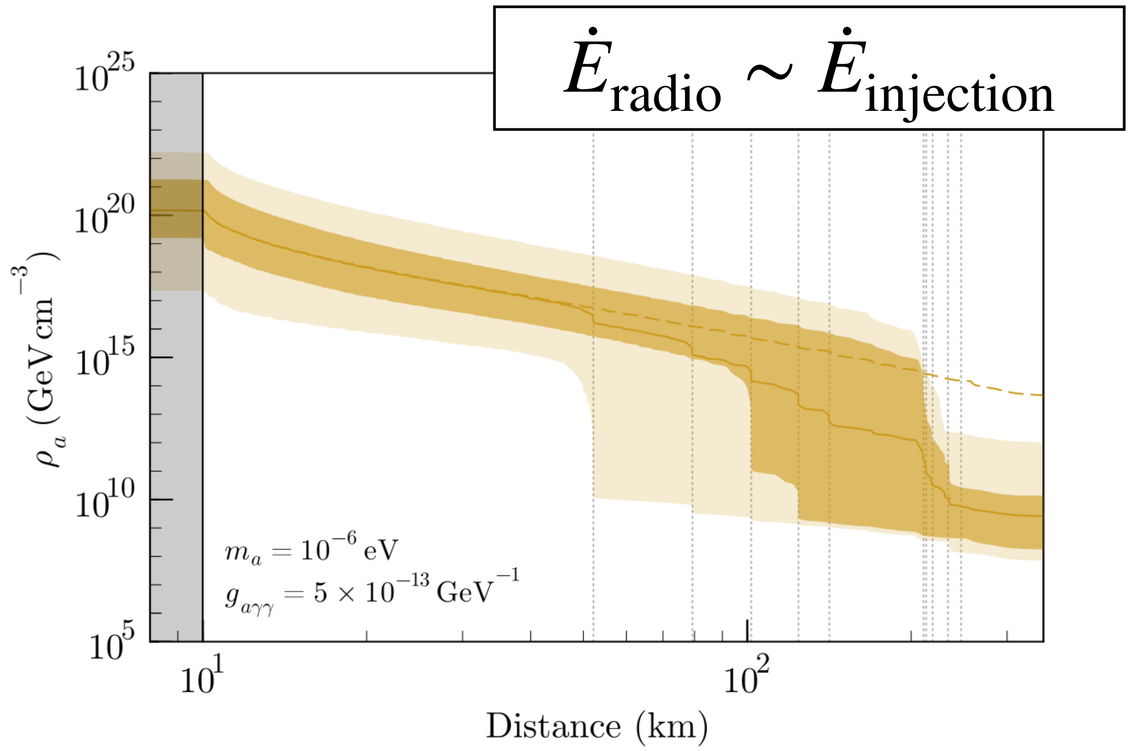
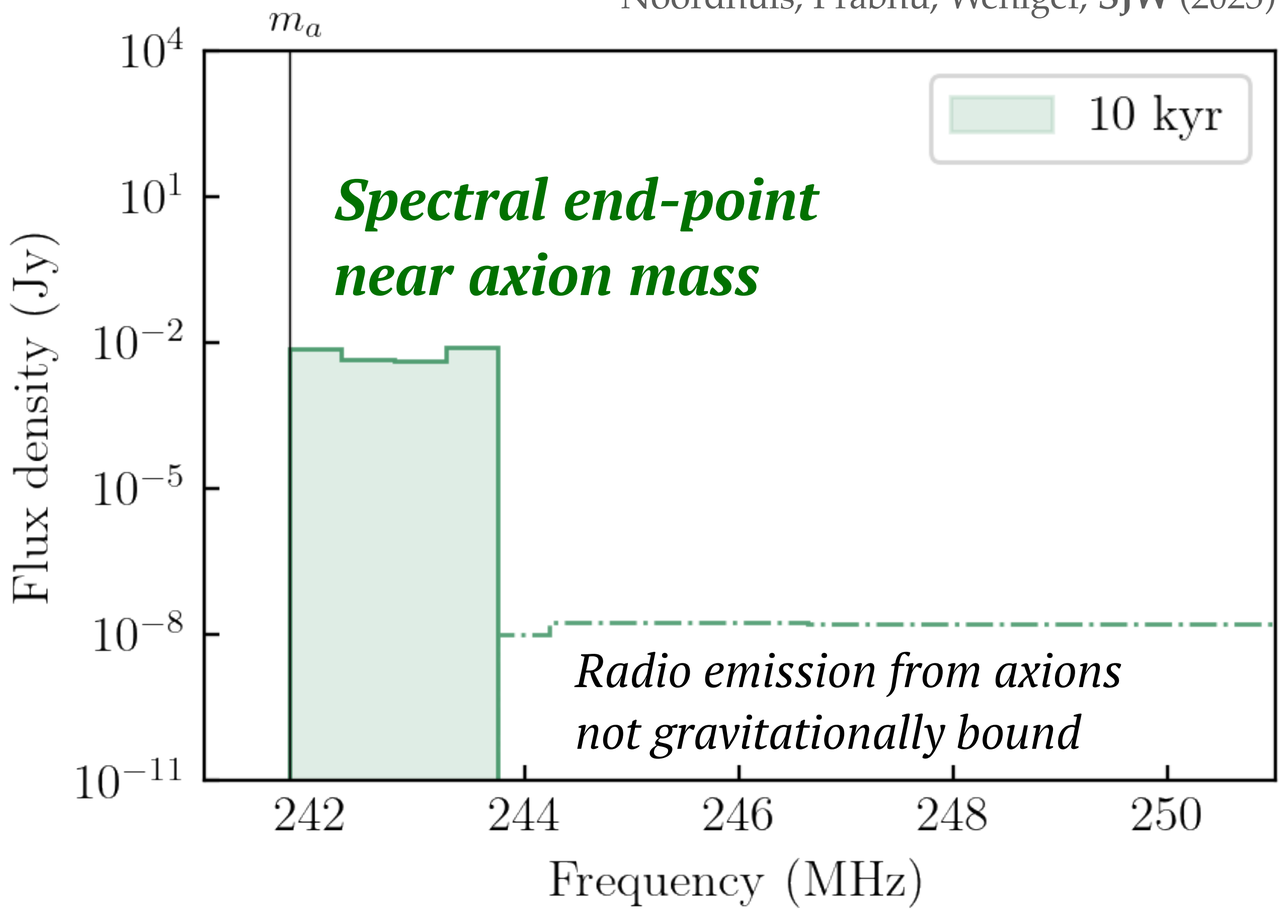
Resonant radio emission

Sharp kinematic endpoint inevitably arises in radio spectrum



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

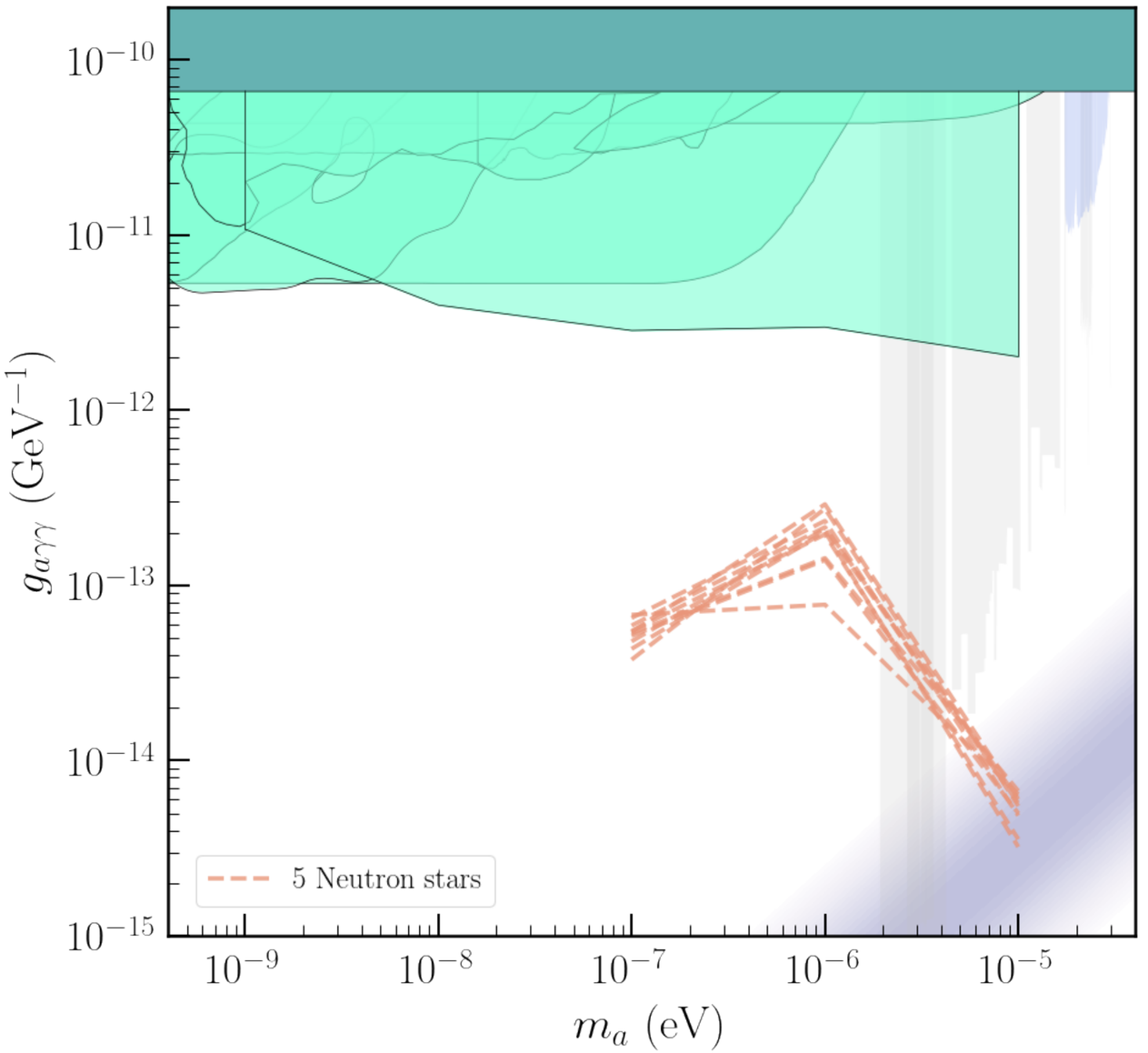


Spectral end-point (radio)

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

Current radio observations should have strong sensitivity to spectral line…

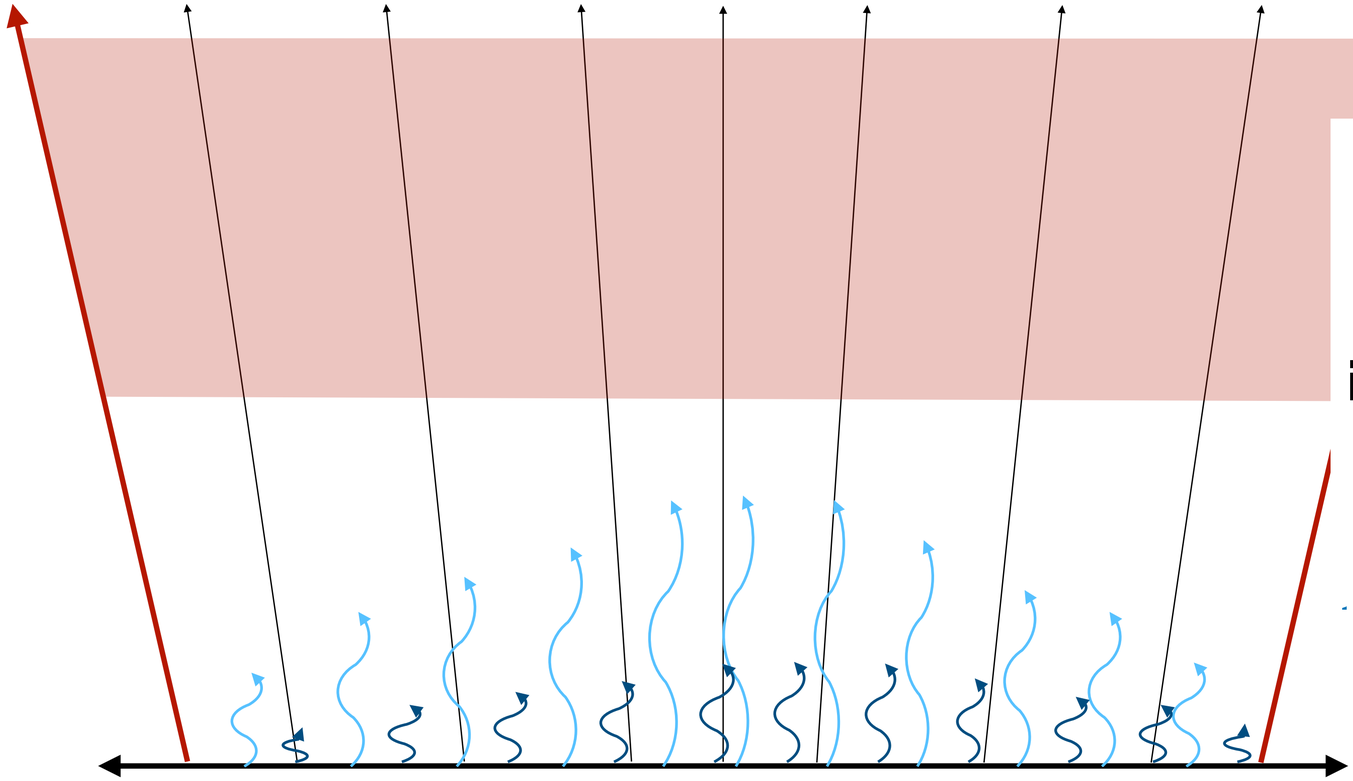
A more detailed look at systematics is in progress…



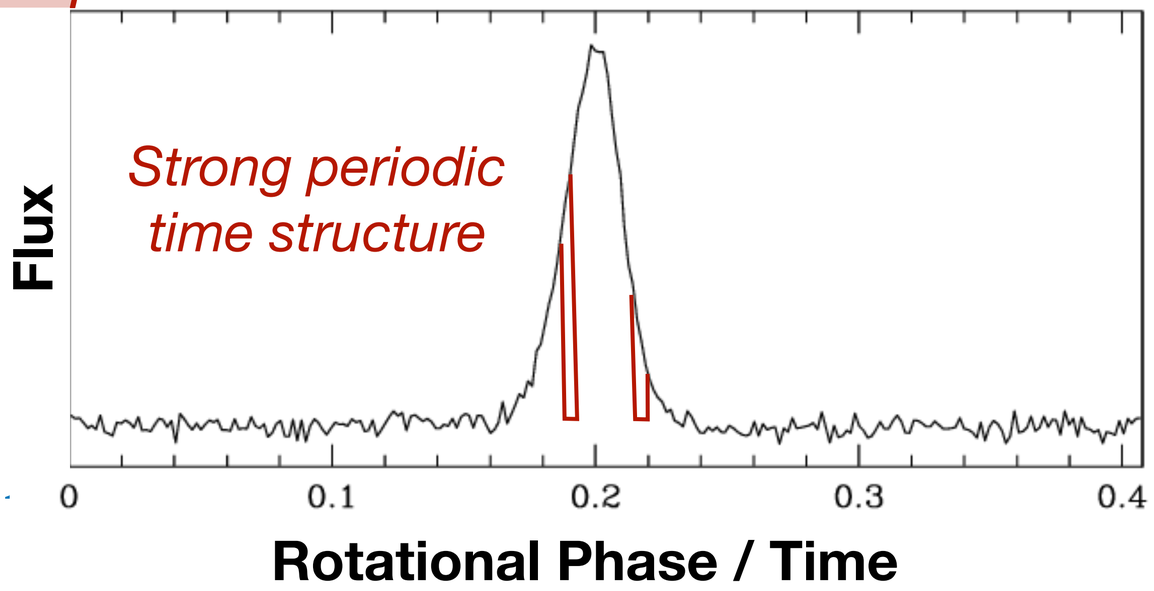
Axion back-reaction

We have assumed:
Electrodynamics not altered by axion

What if this is not true?



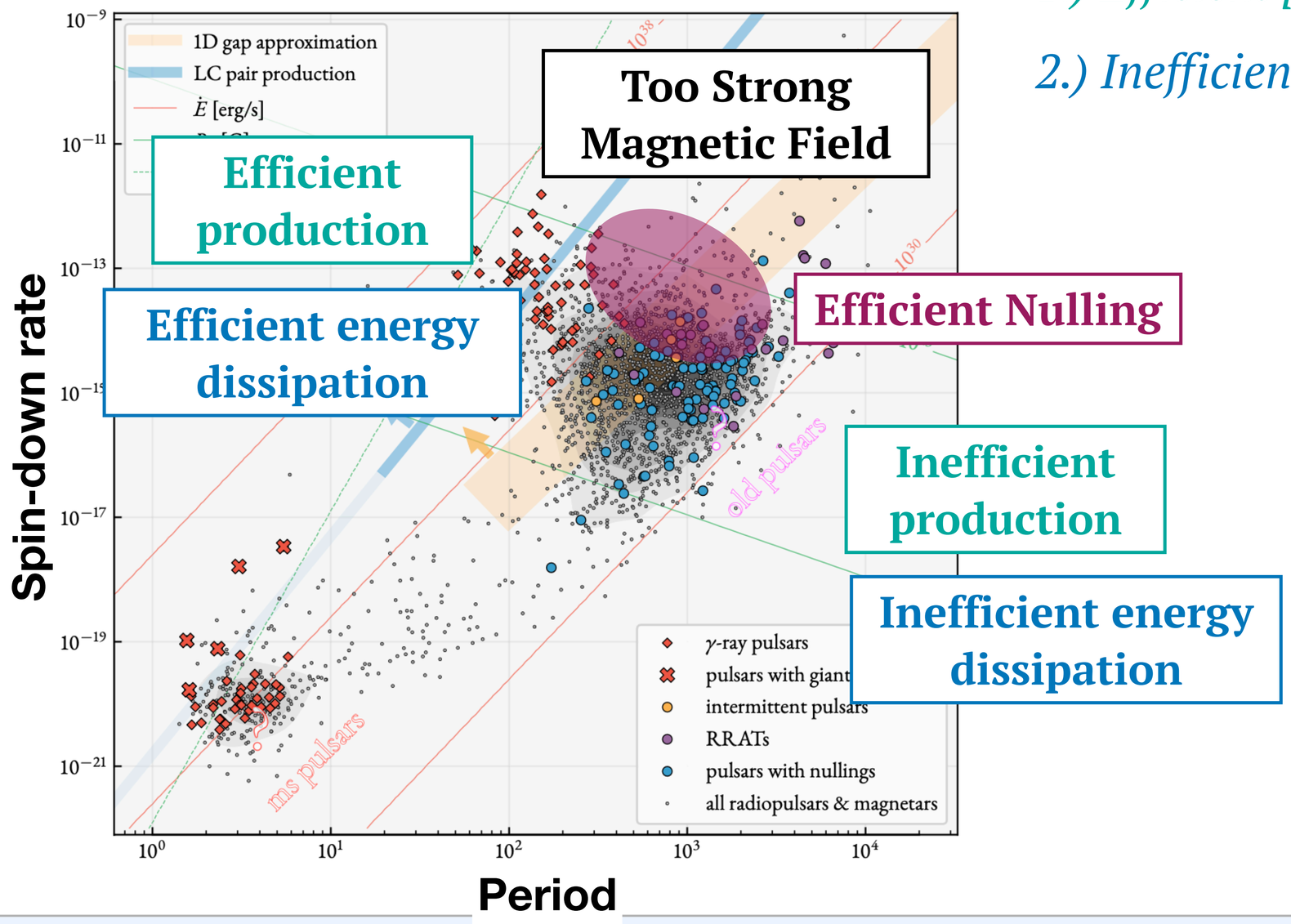
Neutron Star Surface



Periodic suppression of radio emission

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

Pulsar Nulling

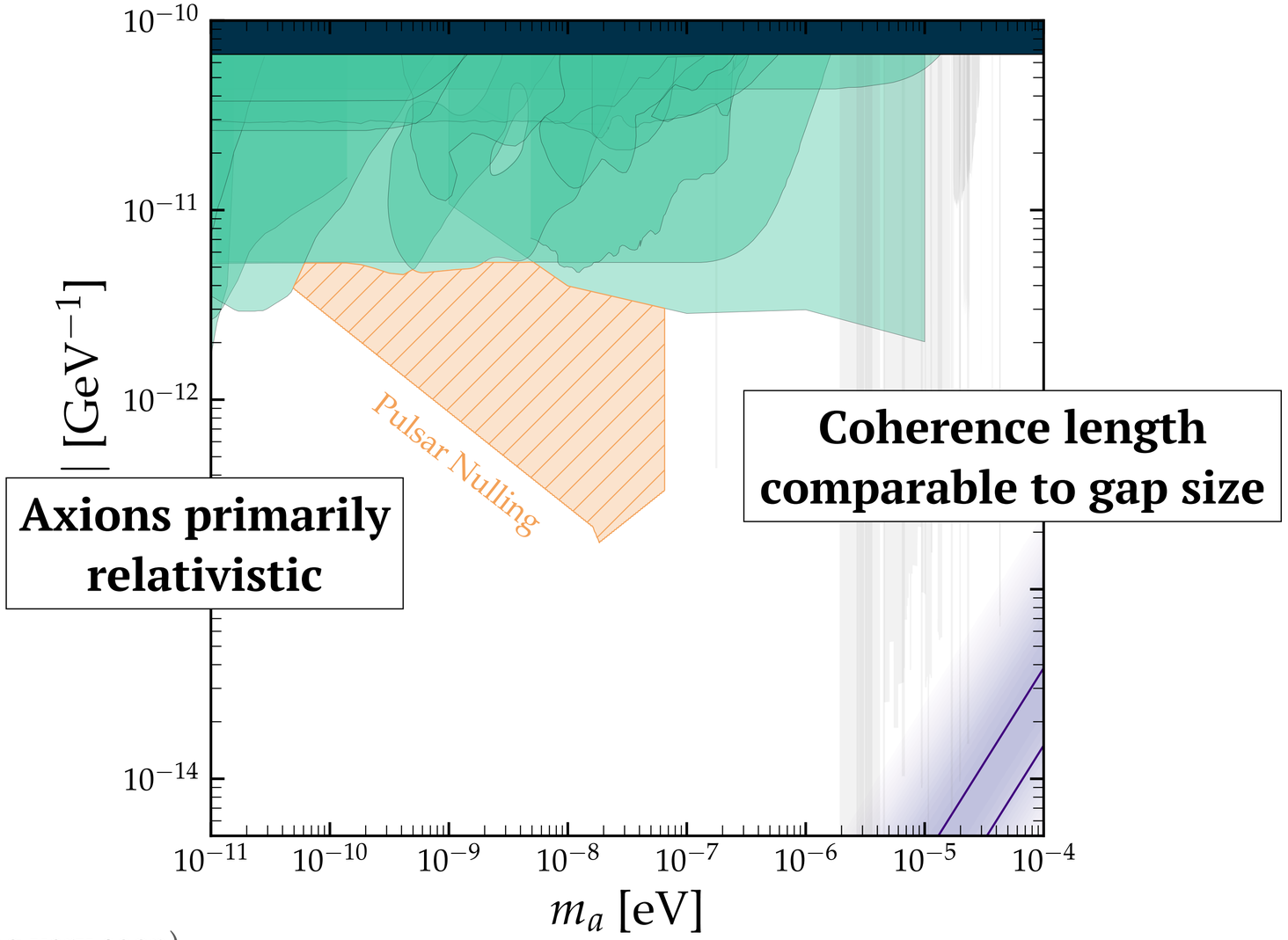


Conditions for pulsar nulling:

1.) Efficient production axion bound states

2.) Inefficient energy dissipation

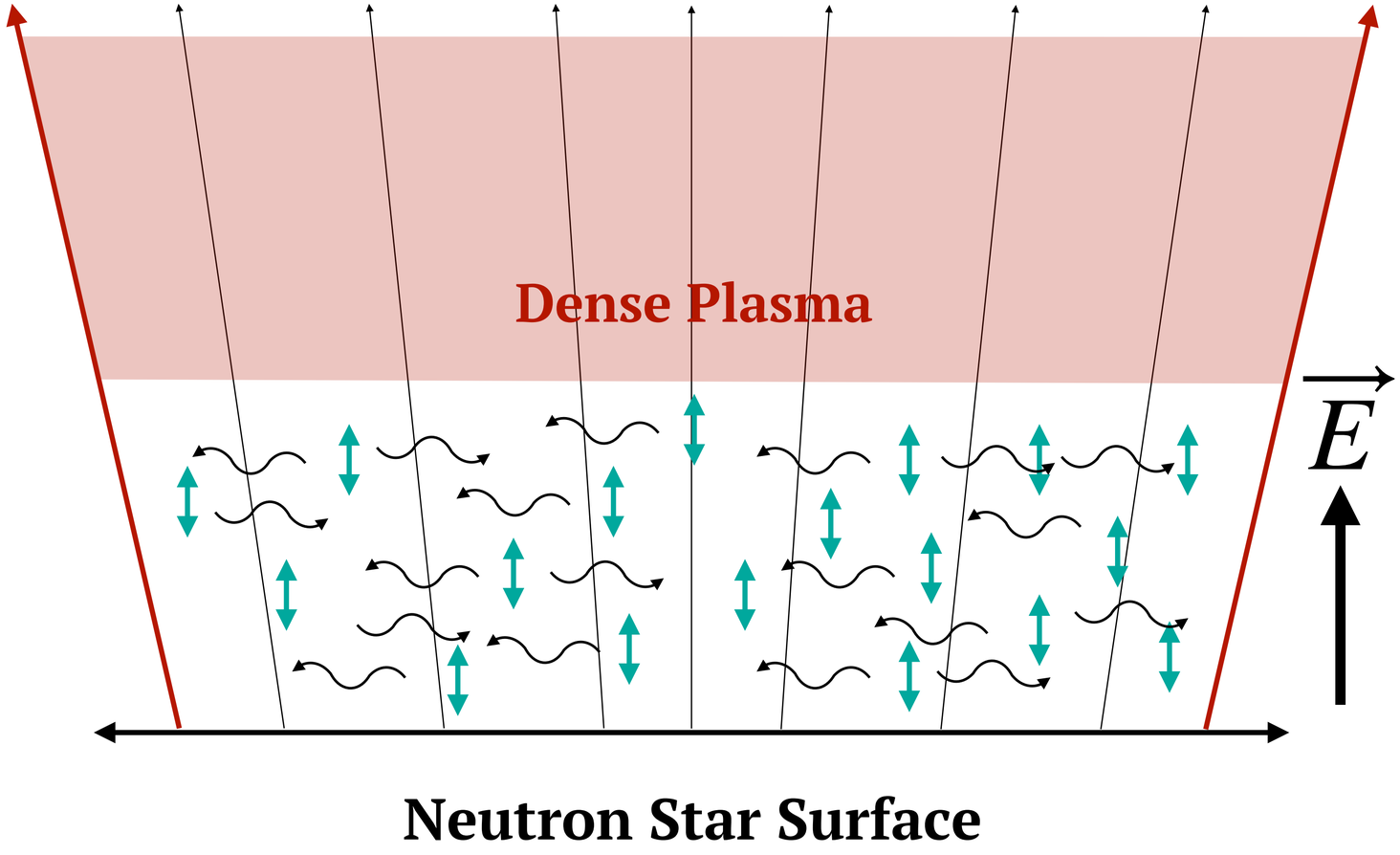
Pulsar Nulling: J1119-6127



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

Non-resonant, beamed, radio emission

Part 1: Vacuum Phase



Heavier axions are incoherent, effects tend to wash out…

But, small scale oscillations can drive electromagnetic emission

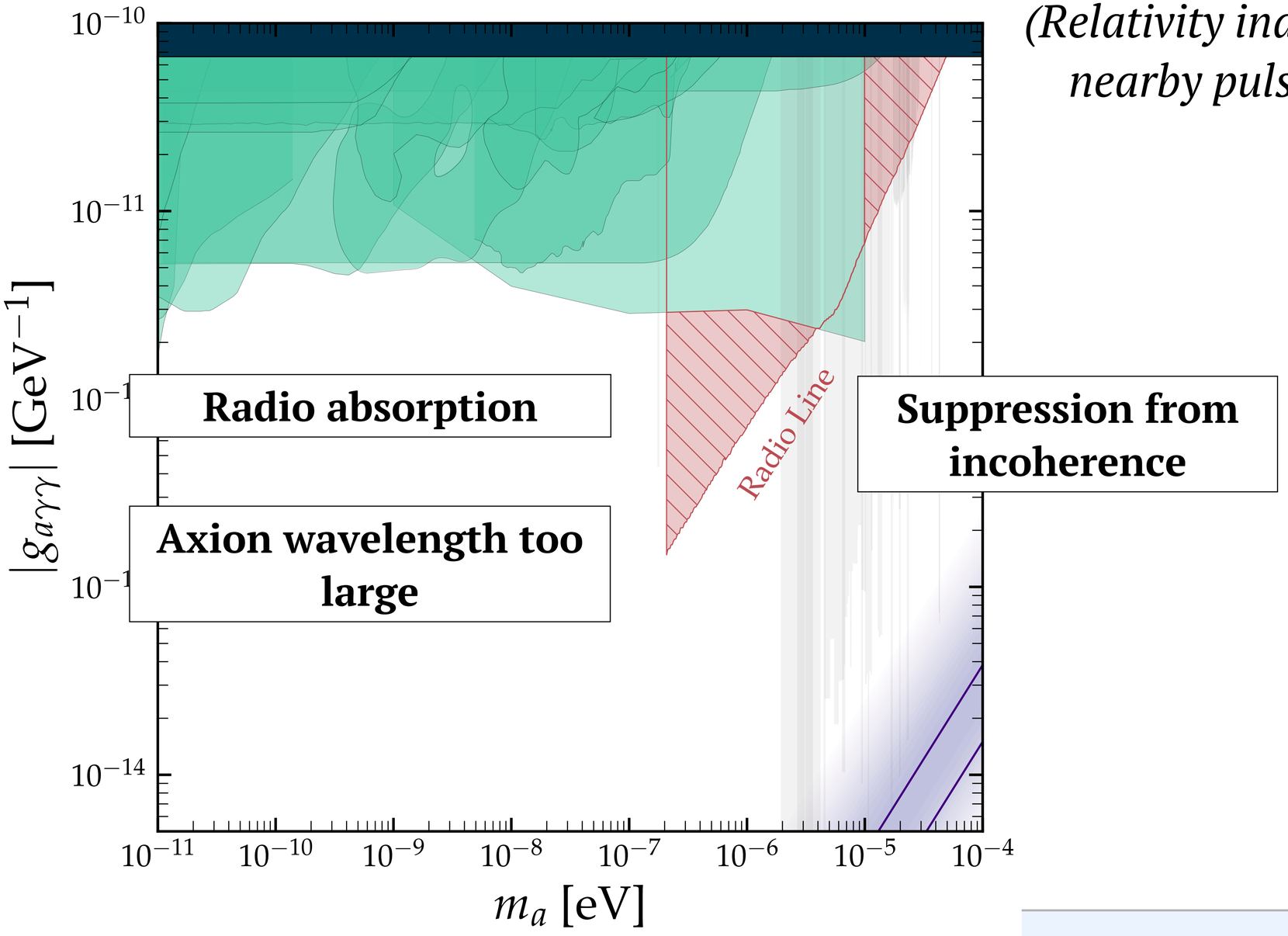
$$\vec{j}_{\mathrm{eff,a}} \sim g_{a\gamma\gamma}\, \dot{a}\, \vec{B}$$

Plasma barriers confine and reflect photons along magnetic axis

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

Non-resonant, beamed, radio emission: B1055-52

(Relativity inactive, nearby pulsar)

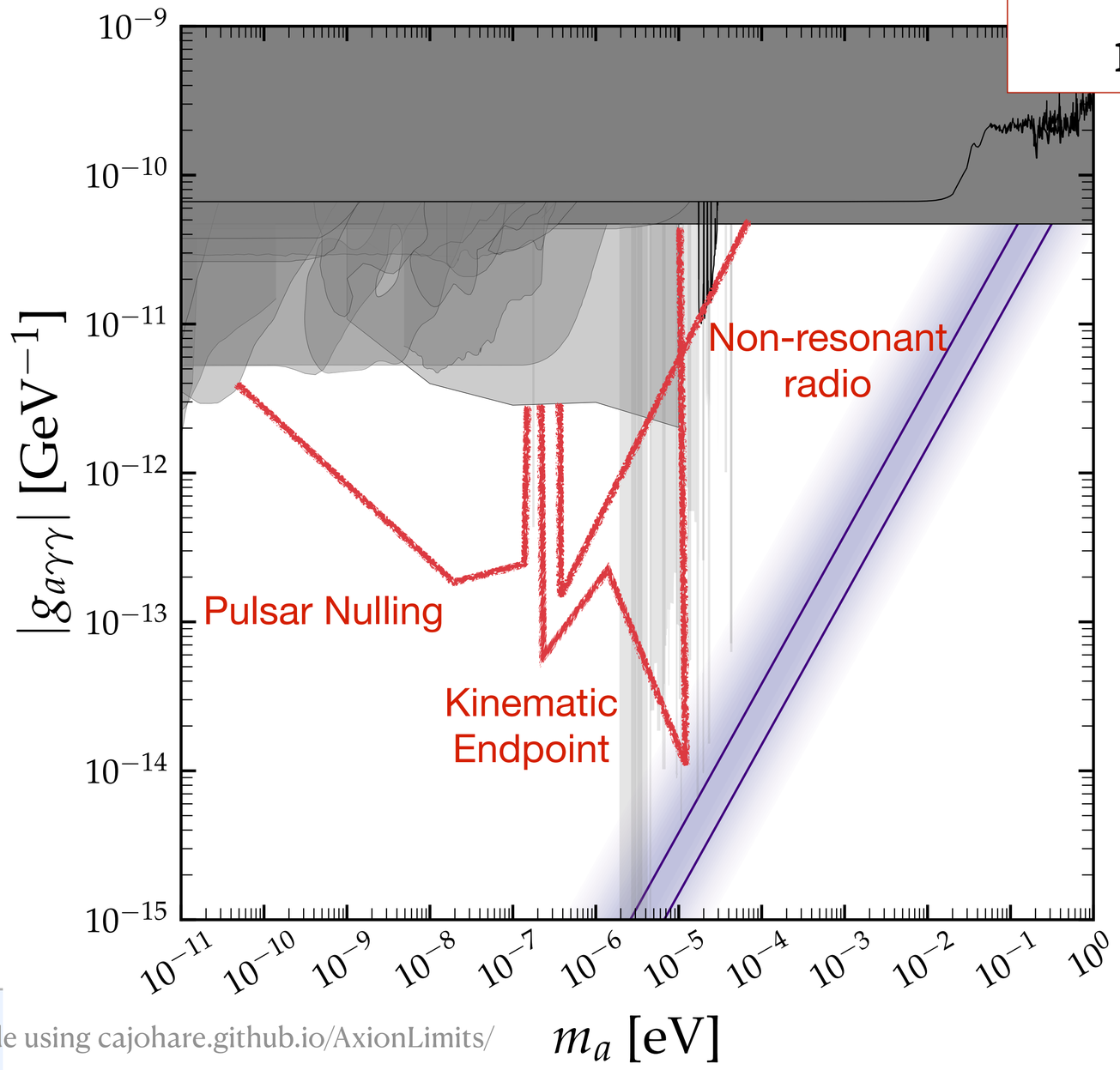


Caputo, **SJW,** Philippov, Jacobson (Appearing soon)

Plot made using cajohare.github.io/AxionLimits/

Conclusions

Axions can form dense clouds around pulsars, potentially opening novel observational strategies



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

Plot made using cajohare.github.io/AxionLimits/