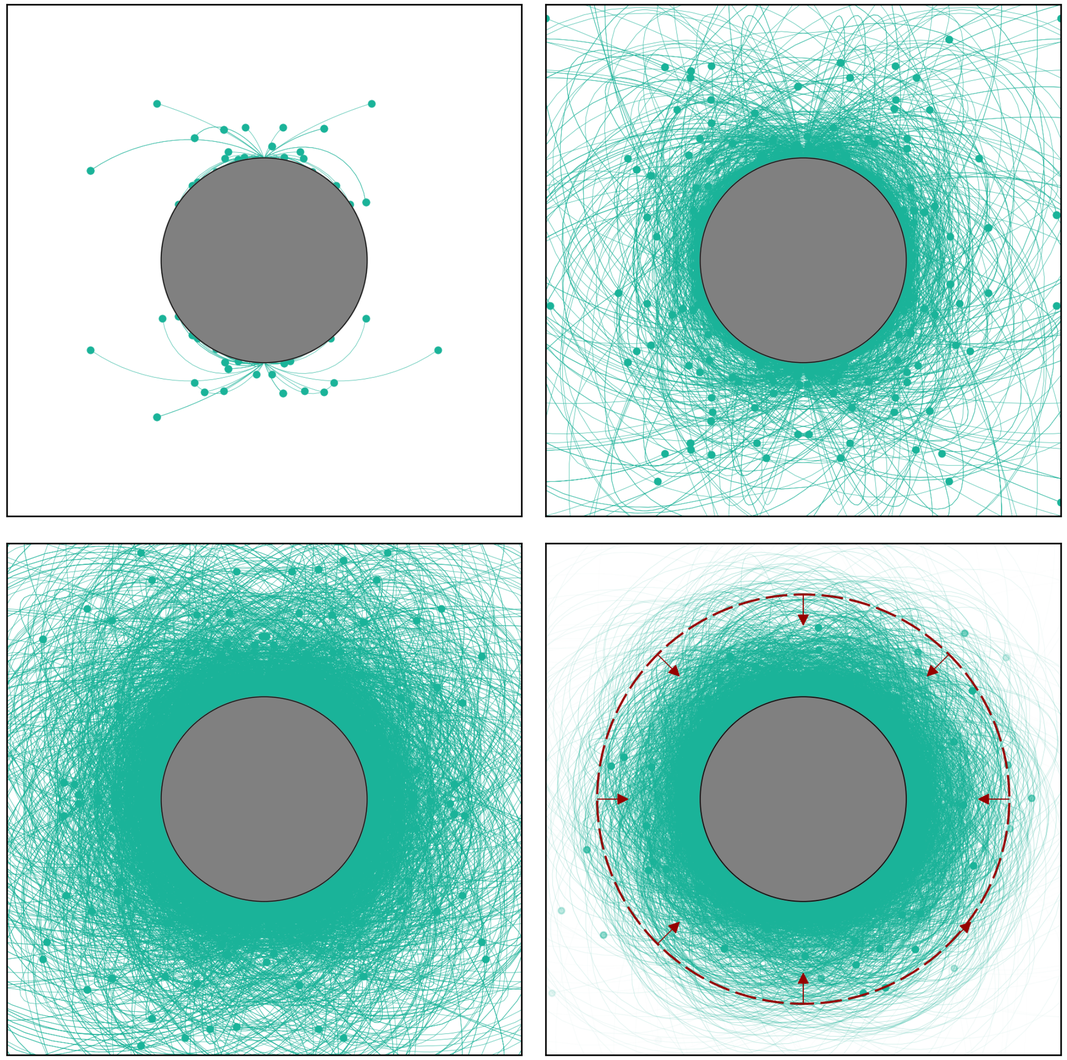
Neutron stars as axion laboratories

Samuel J. Witte

3rd EUCAPT Symposium
CERN
May 31, 2023



ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

Brief intro to axions

QCD Axion ⟶ ***Axions*** ⟵ *Axion-like particles*

- Goldstone boson introduced to solve strong CP problem

- General class of pseudo scalars (Generically appear in well-motivated high energy theories)

Brief intro to axions

QCD Axion → ***Axions*** ← *Axion-like particles*

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Dark Matter

- General class of pseudo scalars (Generically appear in well-motivated high energy theories)

Brief intro to axions

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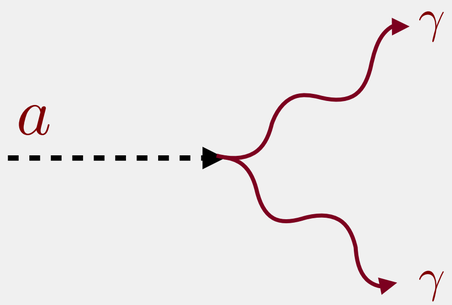
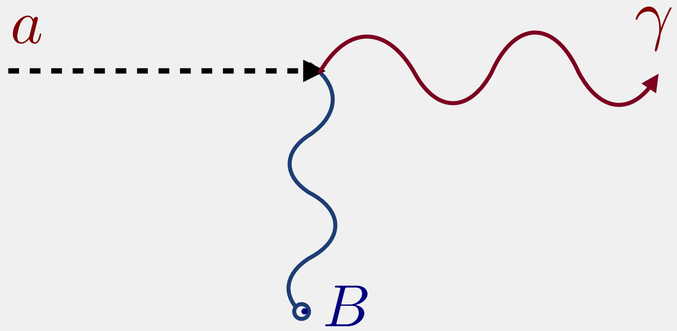
Dark Matter

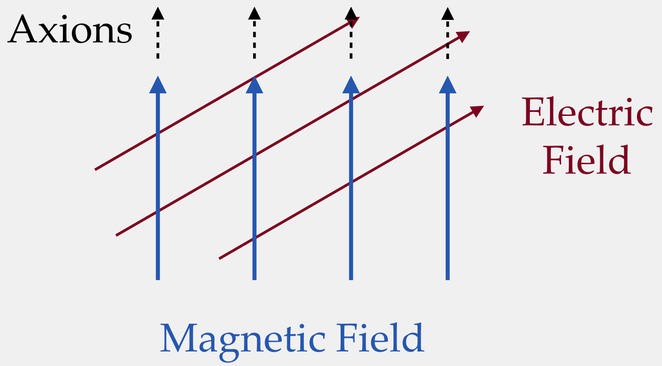
- General class of pseudo scalars (Generically appear in well-motivated high energy theories)

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

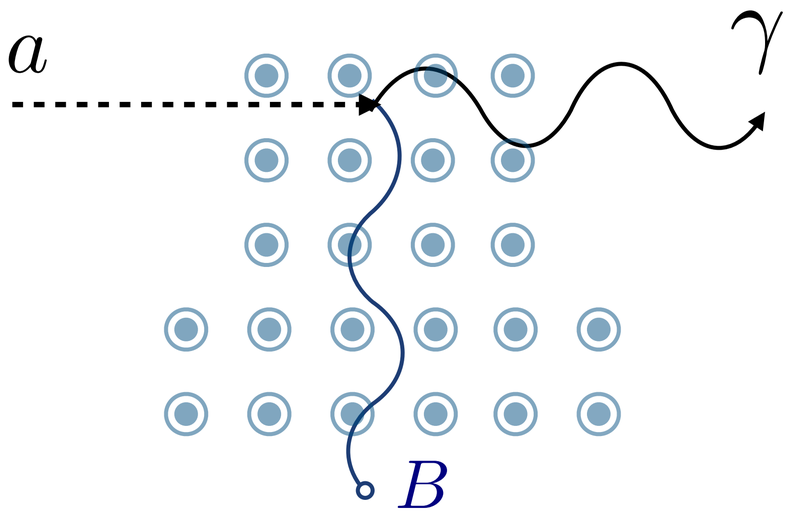






Axion detection

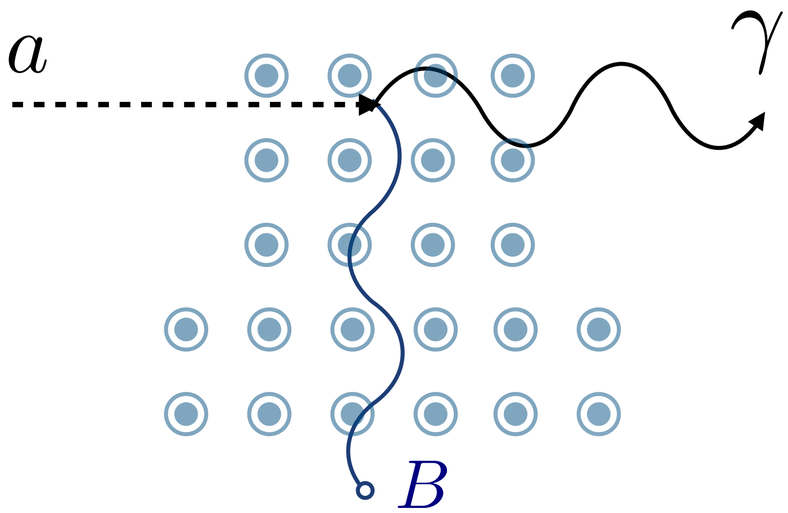
$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$$



Background magnetic field

Axion detection

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



Background magnetic field

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 \times [\text{Length}]^2$$

Large conversion probabilities require:

- Large *magnetic fields*
- Large "*Length scale*"

Axion detection

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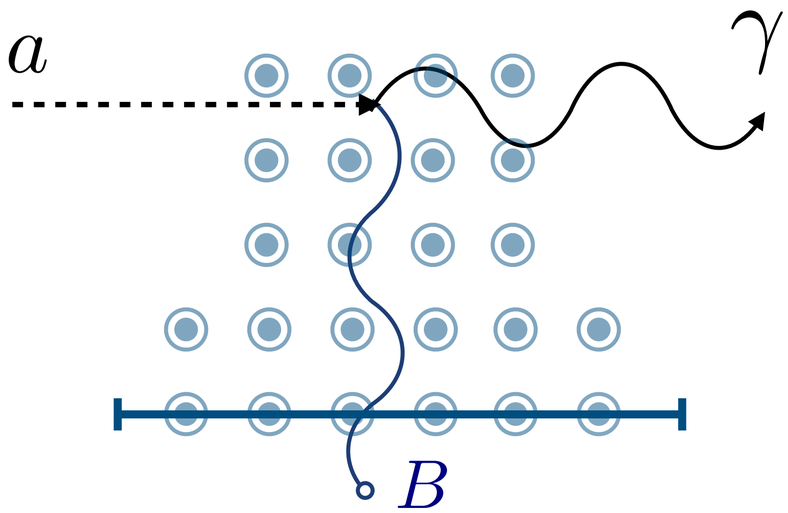

Background magnetic field

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 \times [\text{Length}]^2$$

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Length of magnetic field

Length set by momentum transfer

Axion detection

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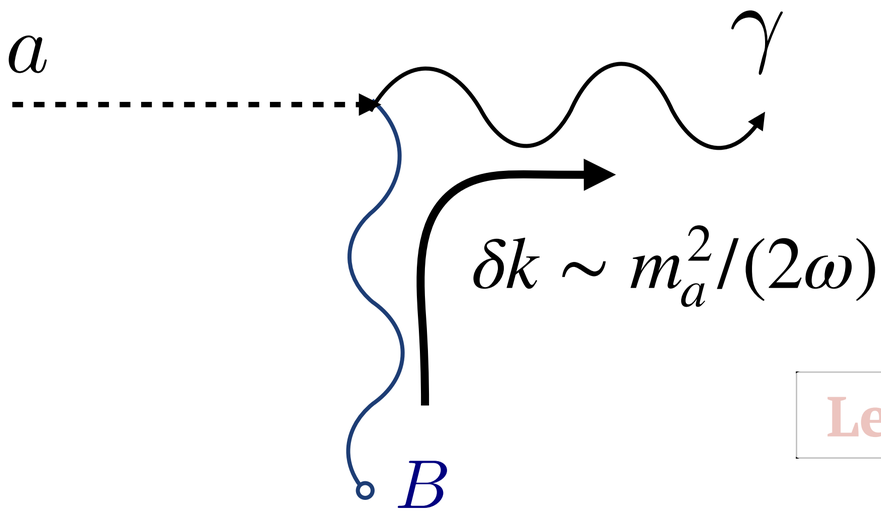

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$$L_{\delta k} \sim \delta k^{-1}$$

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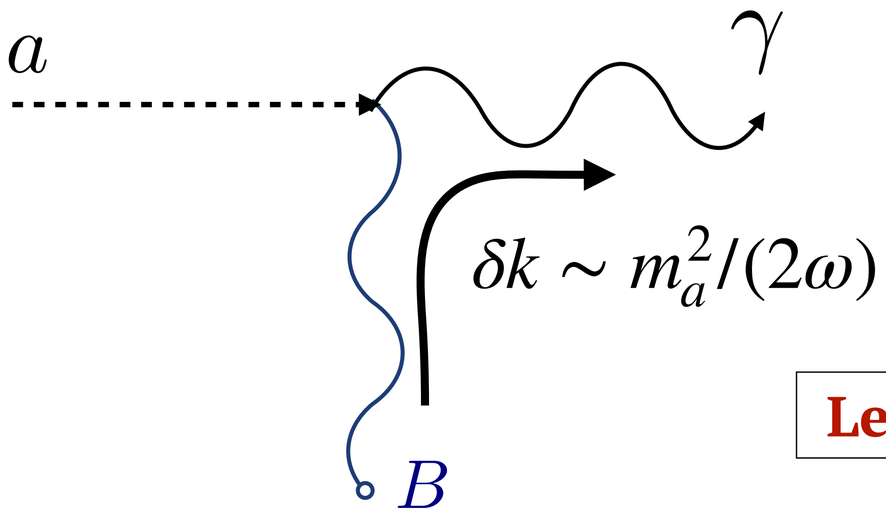


$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 \times [\text{Length}]^2$$

Large conversion probabilities require:

- Large *magnetic fields*
- Large "*Length scale*"

Length of magnetic field

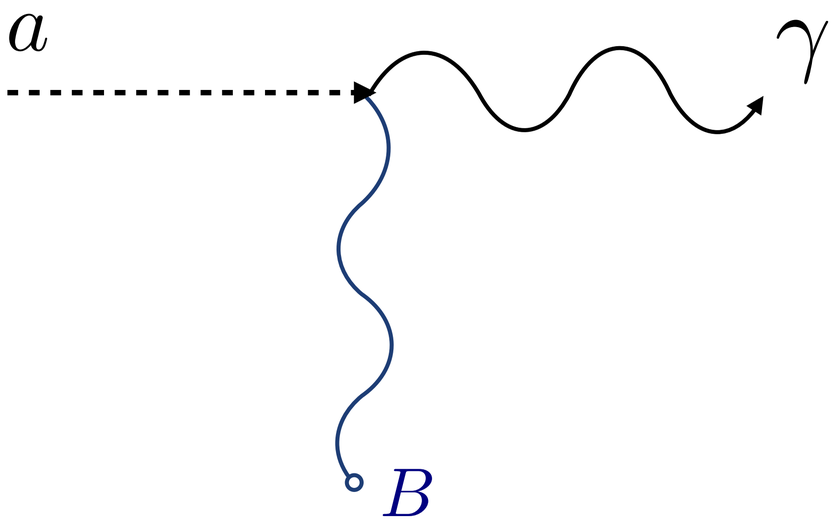
Length set by momentum transfer

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

*The relevant **Length** is the smaller of the two*

Axion-photon mixing

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



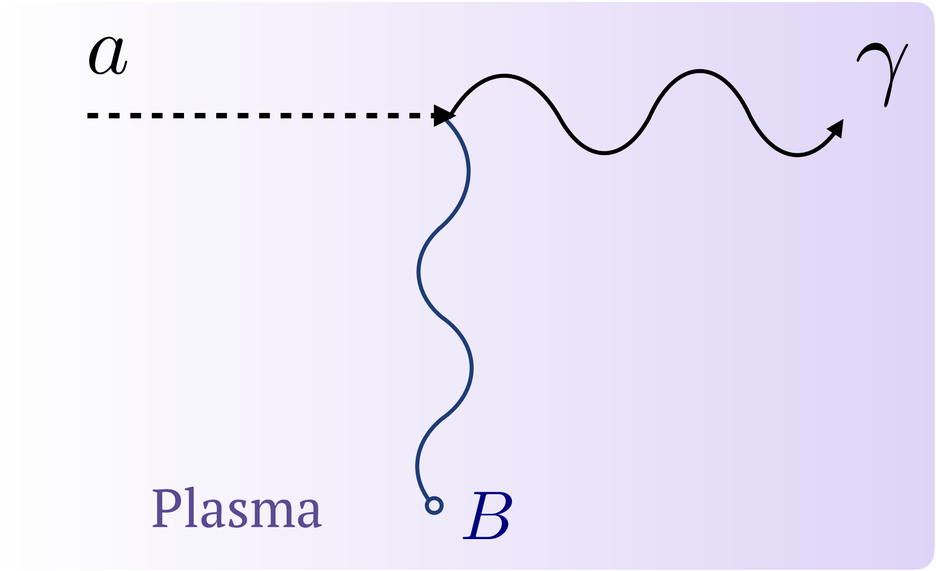
$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 \times (\text{Length})^2$$

Example: axion dark matter (vacuum)

$$L_{\delta k} \sim \left(\frac{10^{-5}\,\text{eV}}{m_a}\right) \text{cm}$$

Axion-photon mixing

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



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

Example: axion dark matter (**plasma**)

Photons acquire "effective mass" (ω_p)

$$L_{\delta k} \to \infty$$

if $m_a \sim \omega_p$

Axion-photon mixing

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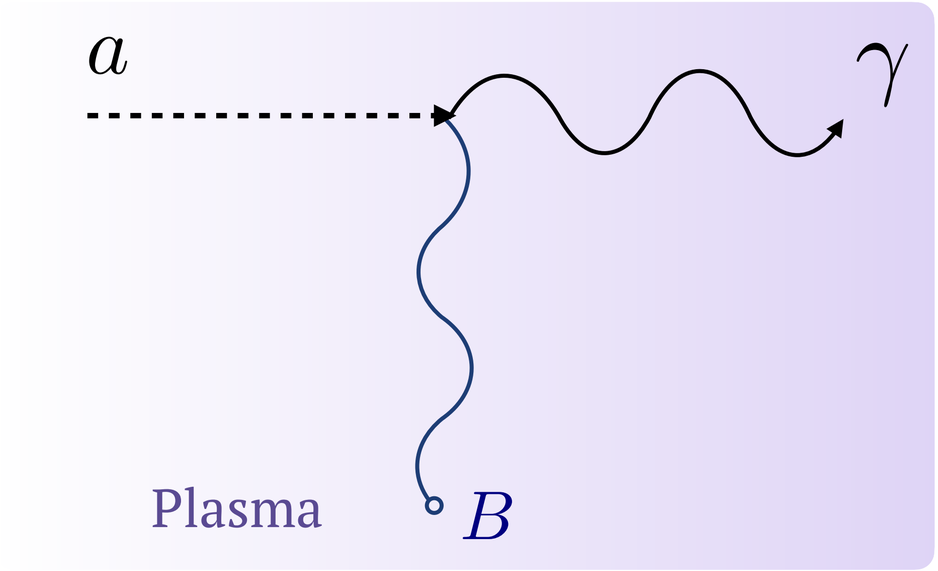


$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 \times (\text{Length})^2$$

Example: axion dark matter (**plasma**)

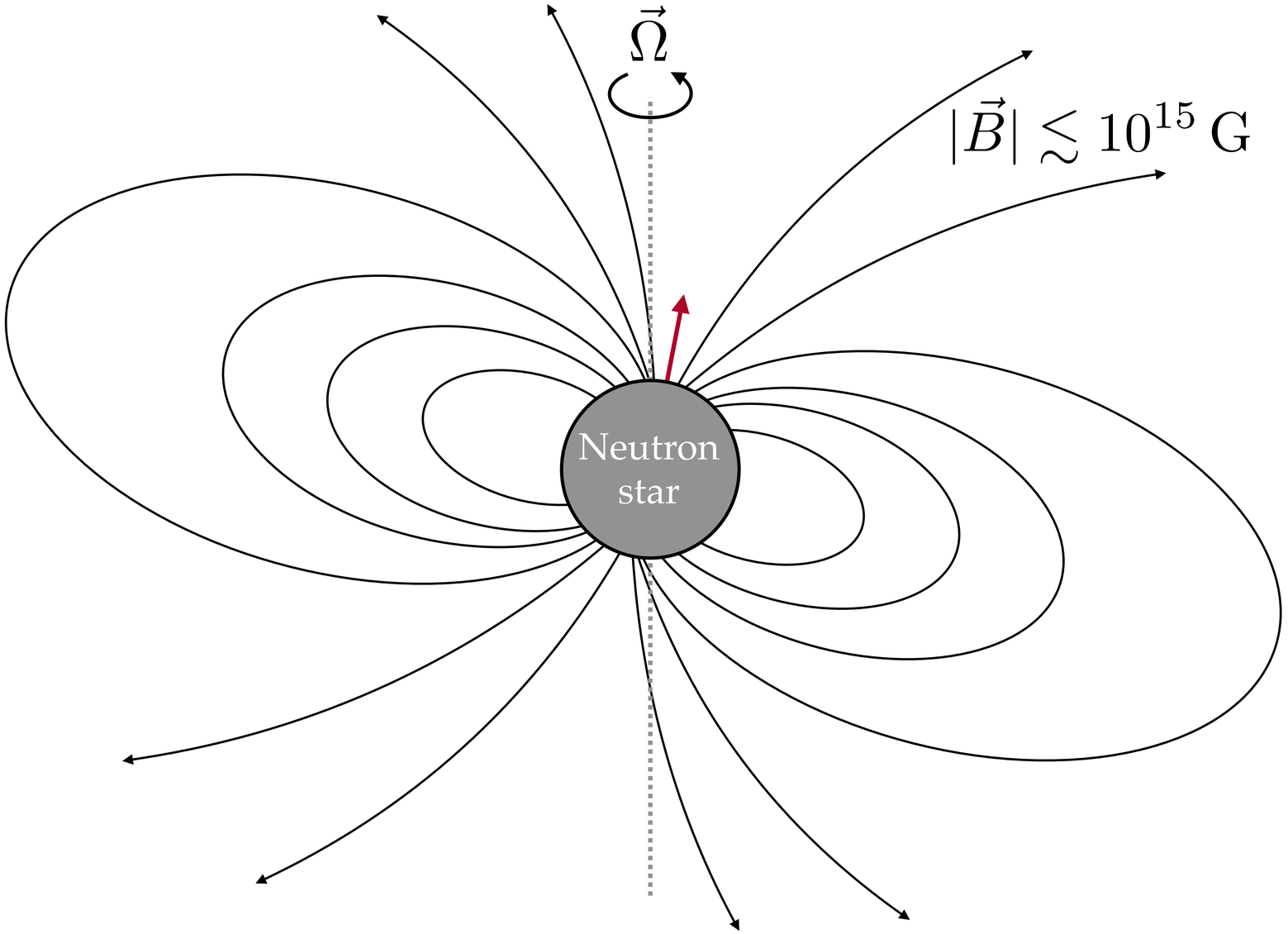
Photons acquire "effective mass" (ω_p)

$$L_{\delta k} \to \infty$$

if $m_a \sim \omega_p$

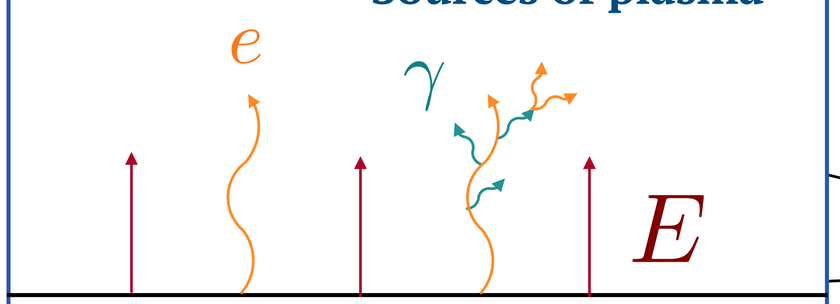
Ideal environments: *Large coherent magnetic fields and background plasma*

Neutron star magnetospheres

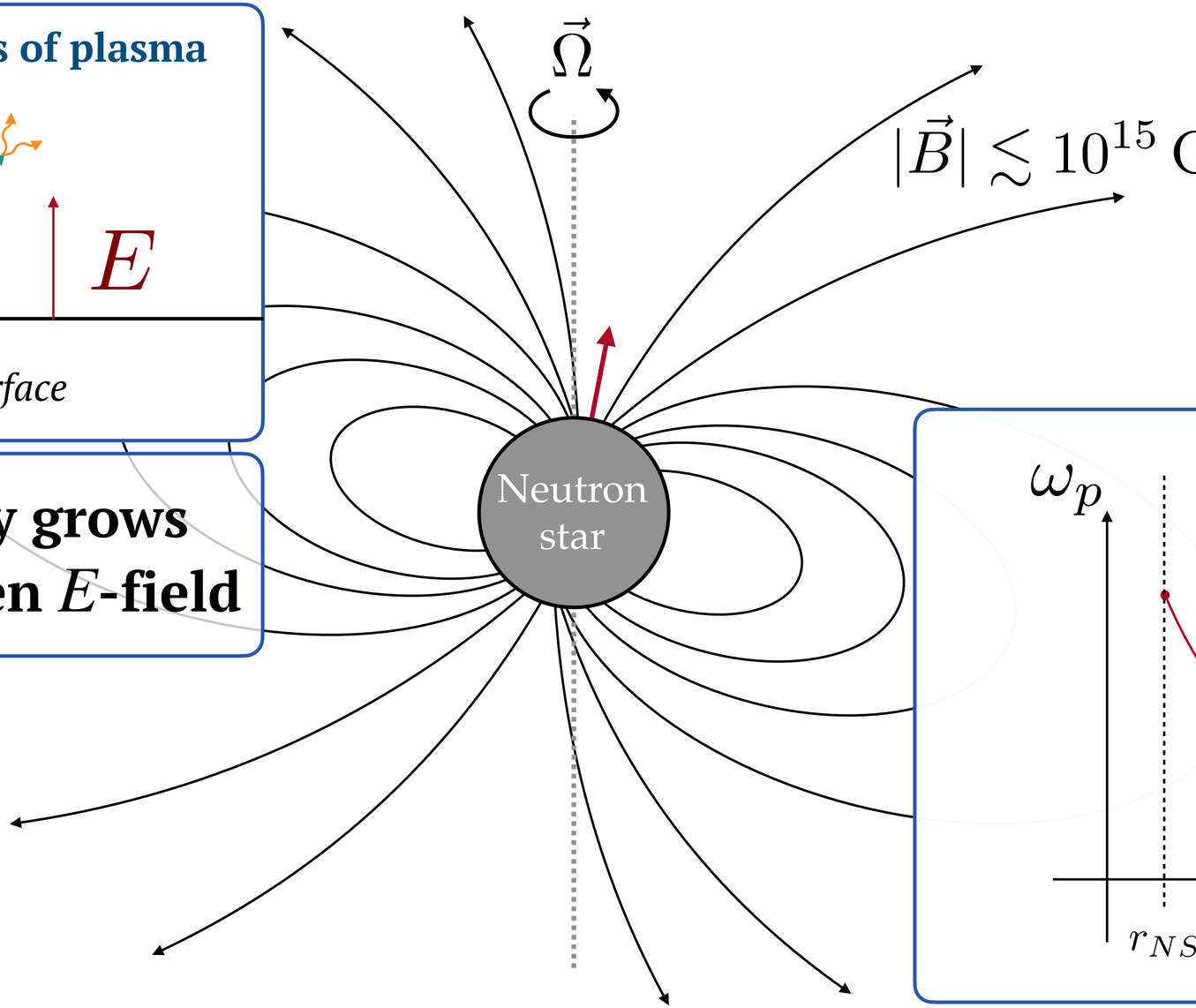


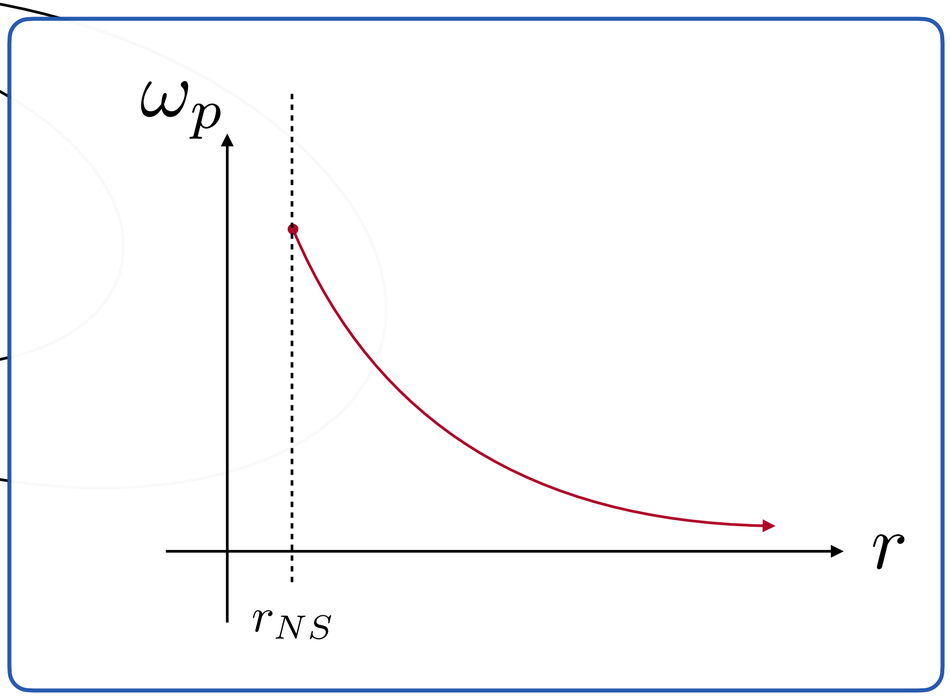
Neutron star magnetospheres

Sources of plasma



Plasma density grows until it can screen E-field





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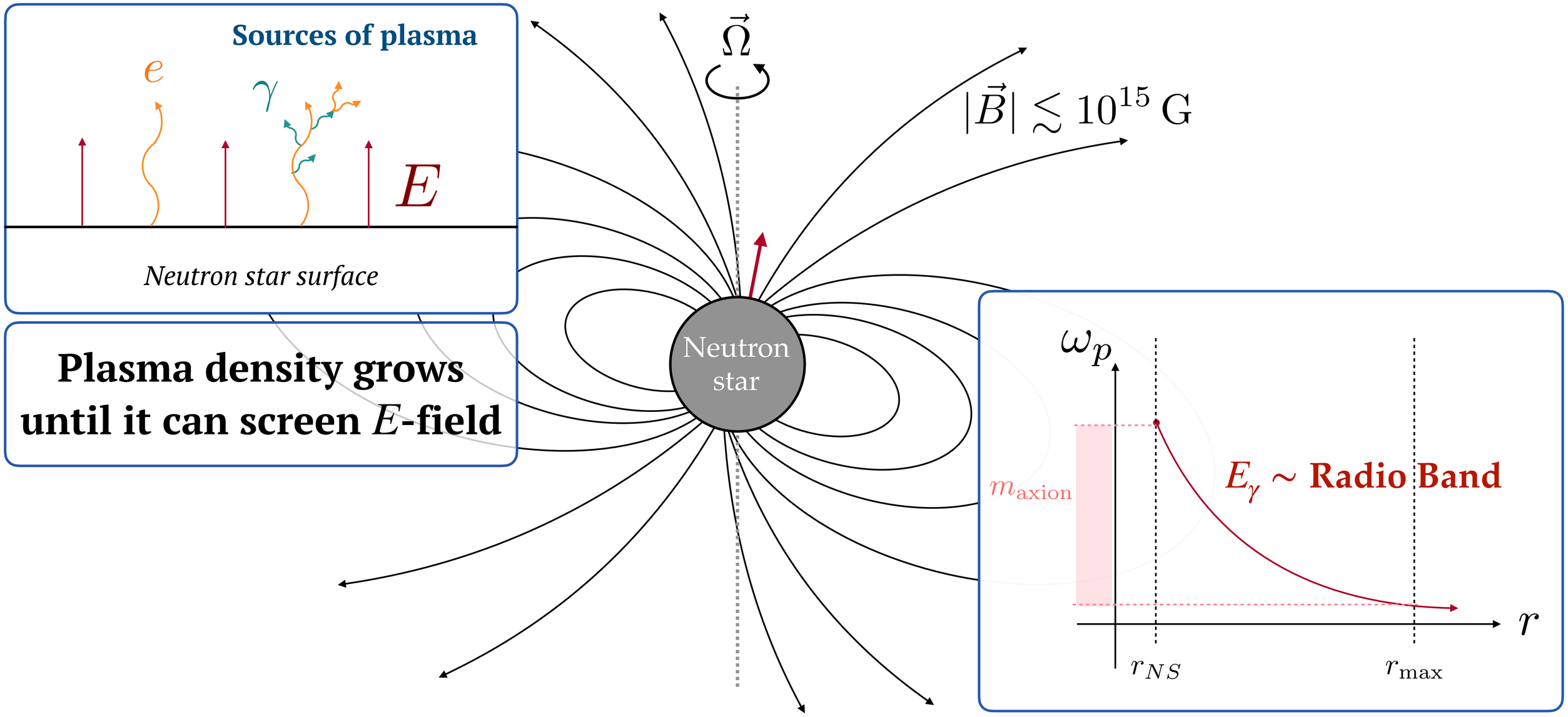
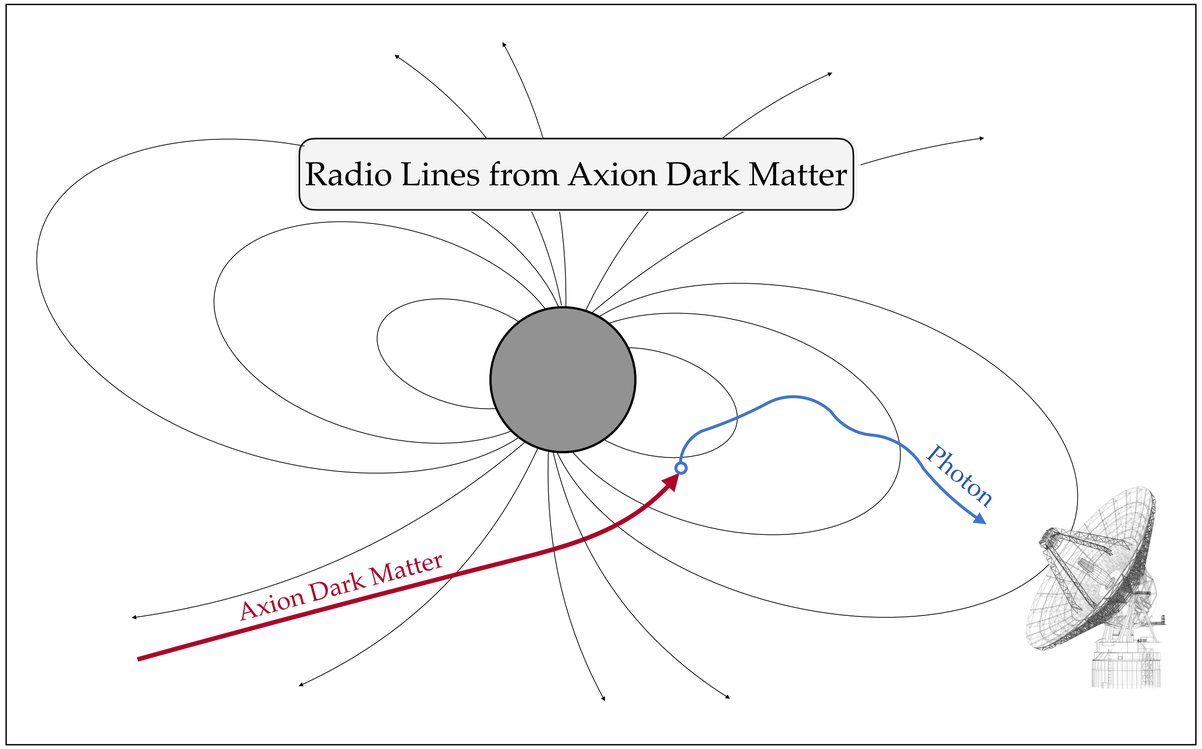


Overview: Neutron stars as axion laboratories

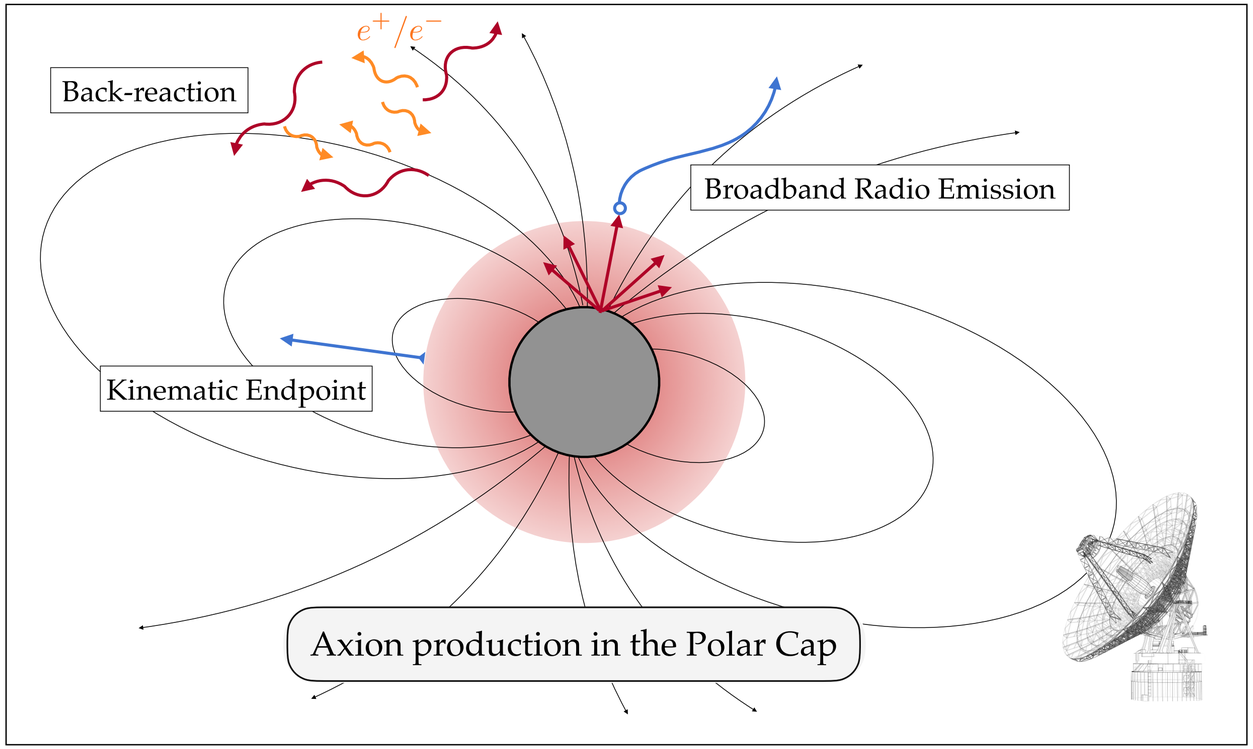
Part 1

Searching for axion dark matter



Part 2

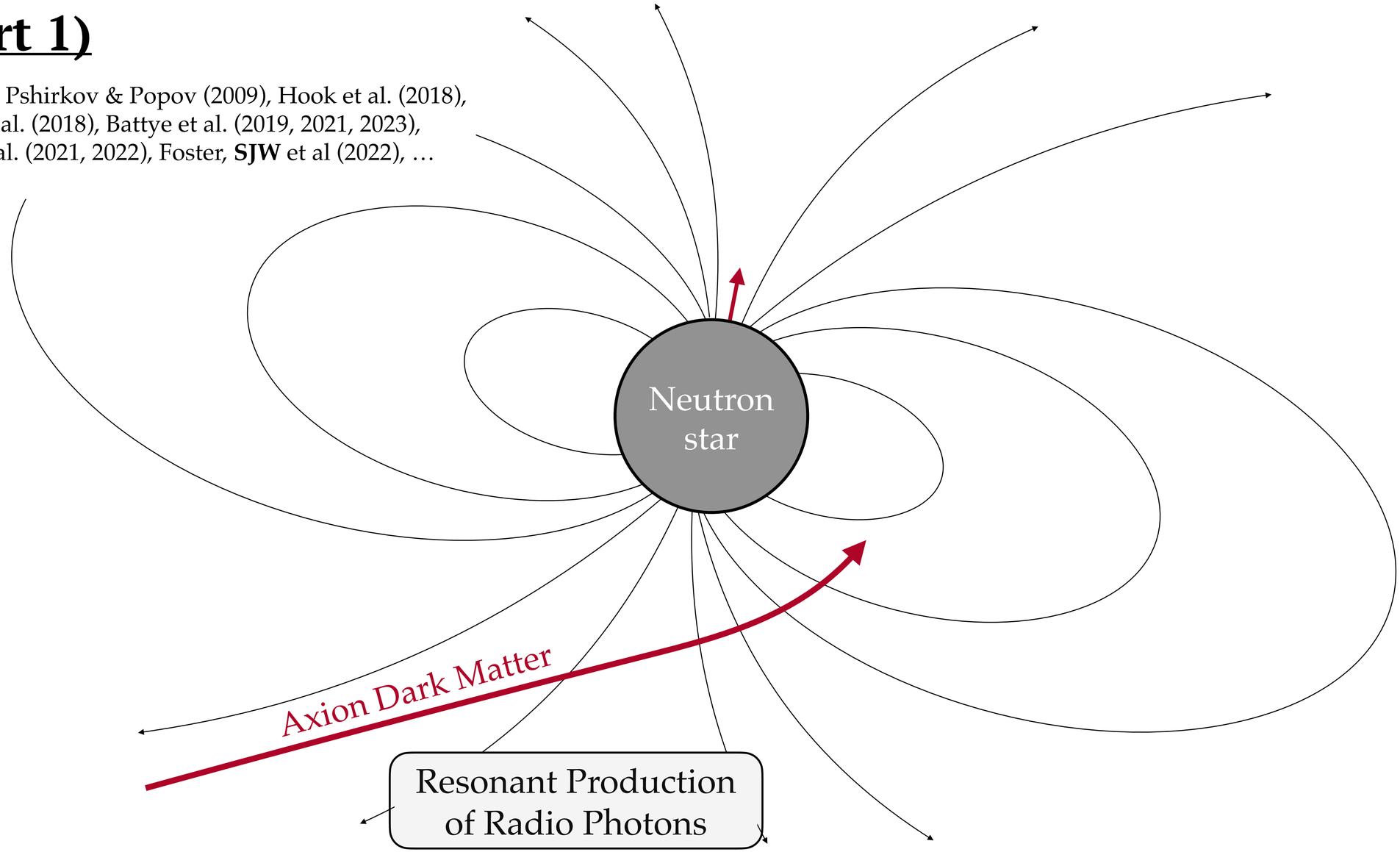
Local production of axions

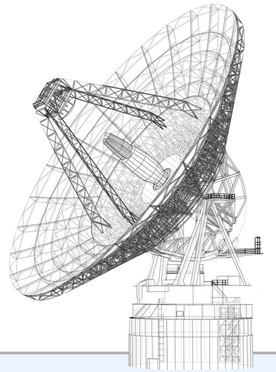


Radio Photons from Axion Dark Matter

(Part 1)

See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021, 2023), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), …





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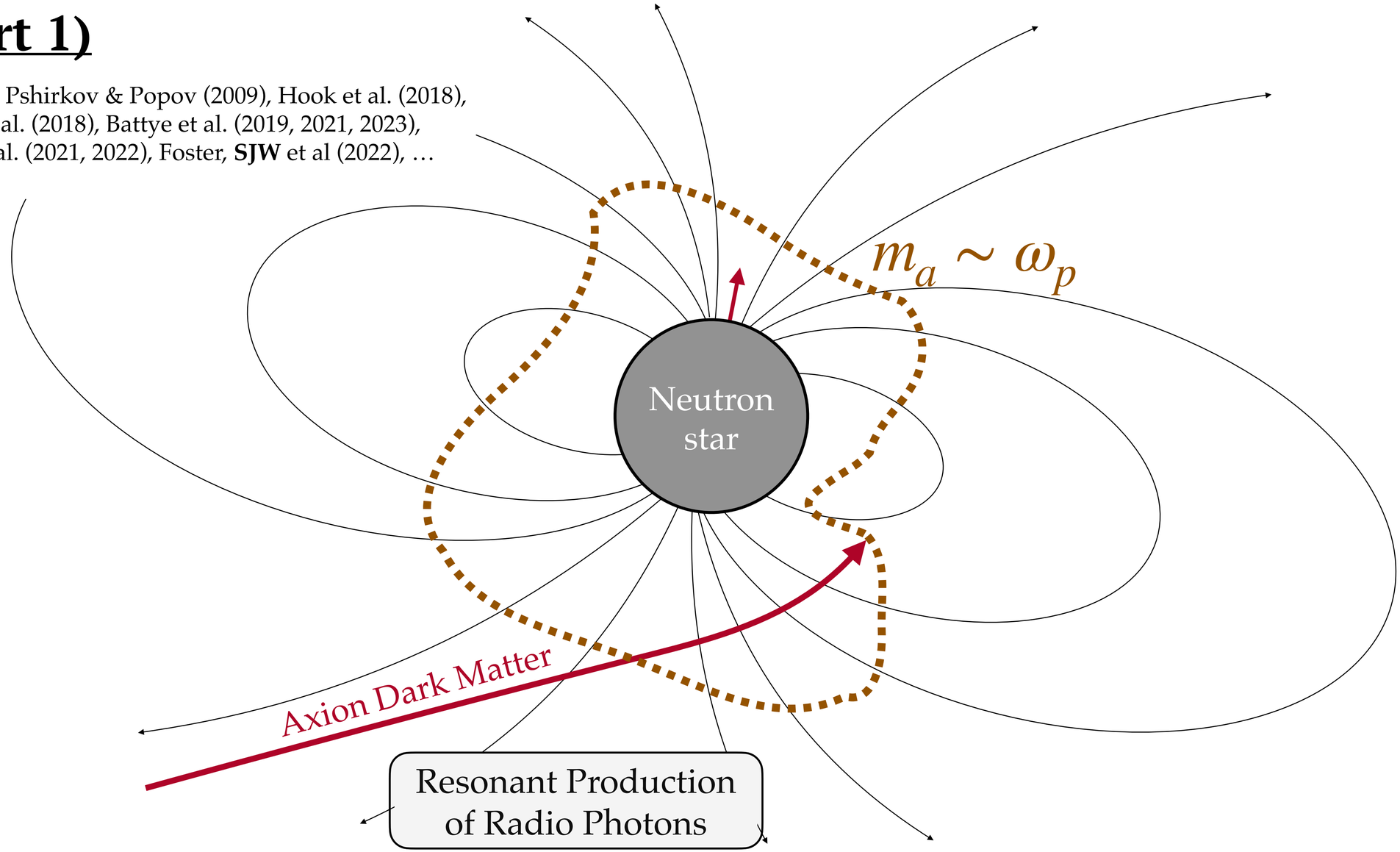

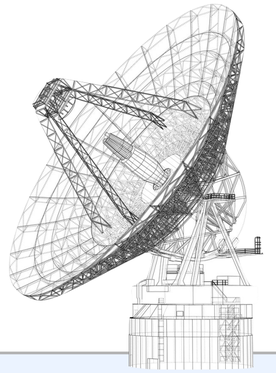

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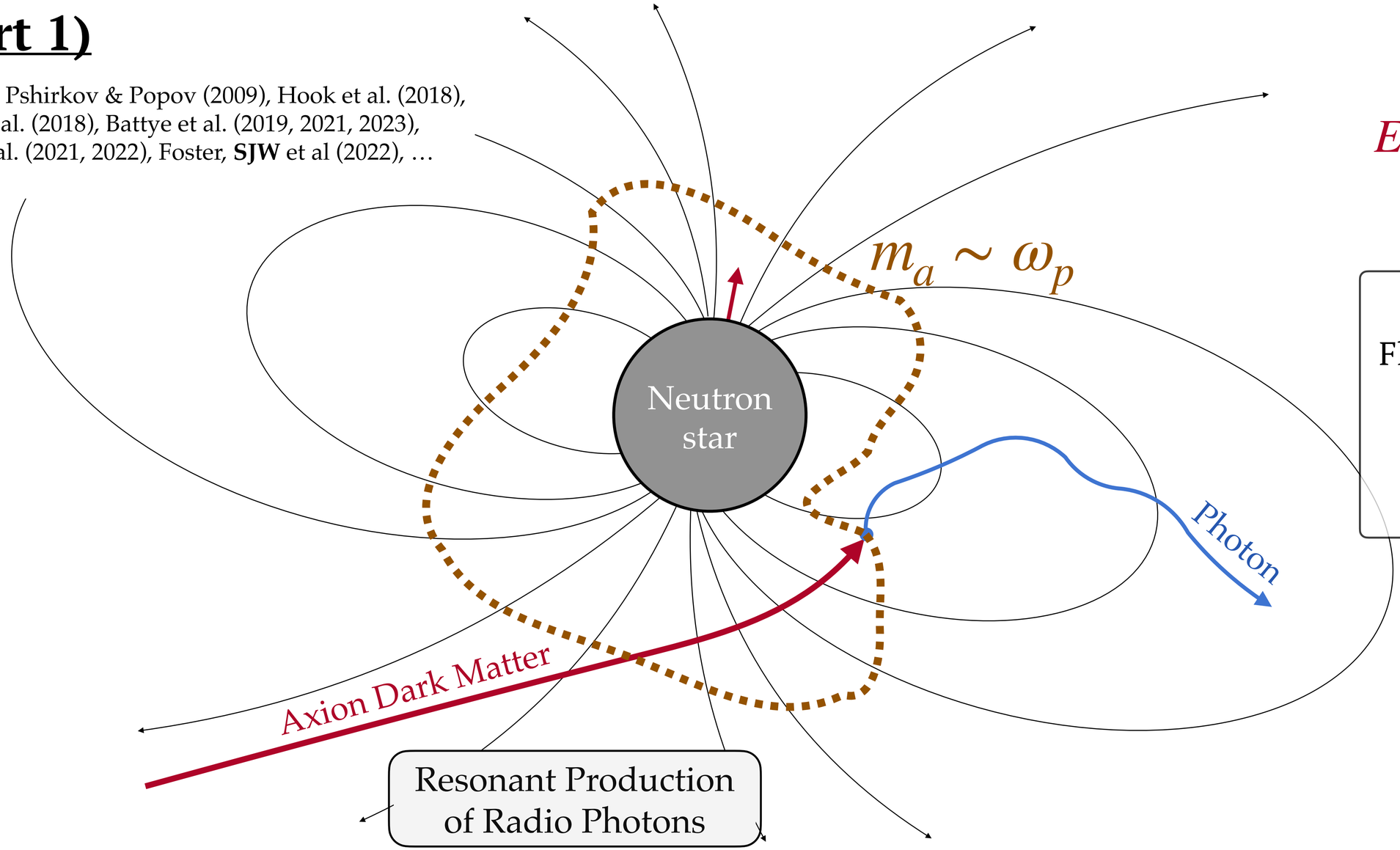
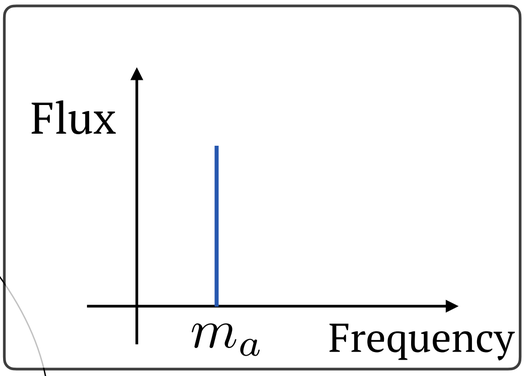
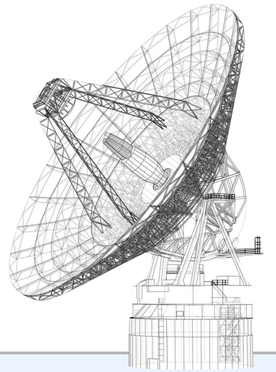
$$E_a \sim m_a (1 + v^2/2)$$

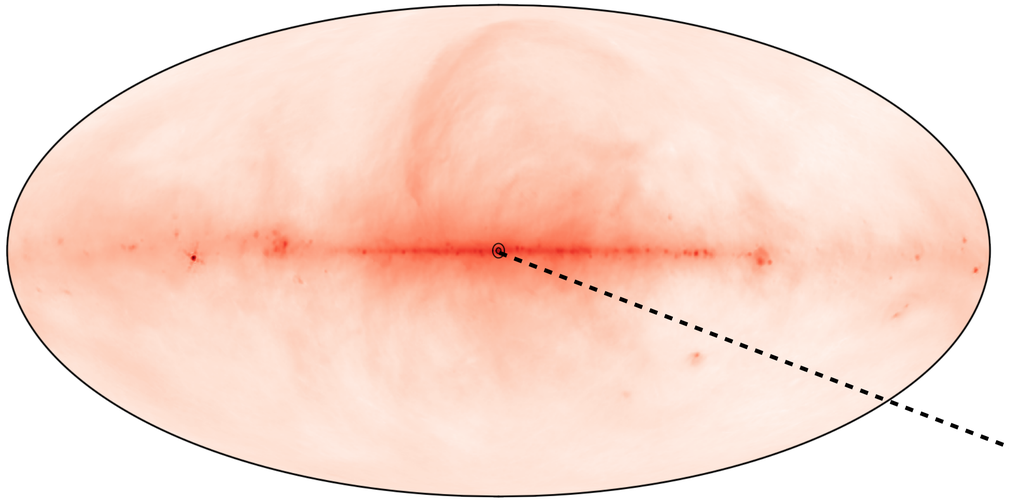
$$v \sim \mathcal{O}(10^{-3})$$

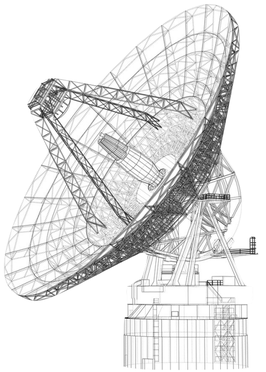






Radio searches for axions





Targets:

- Galactic Center

[pros: more dark matter & neutron stars] [cons: distance, backgrounds, complex modelling]

- Nearby isolated neutron stars

[pros: distance] [cons: less dark matter]

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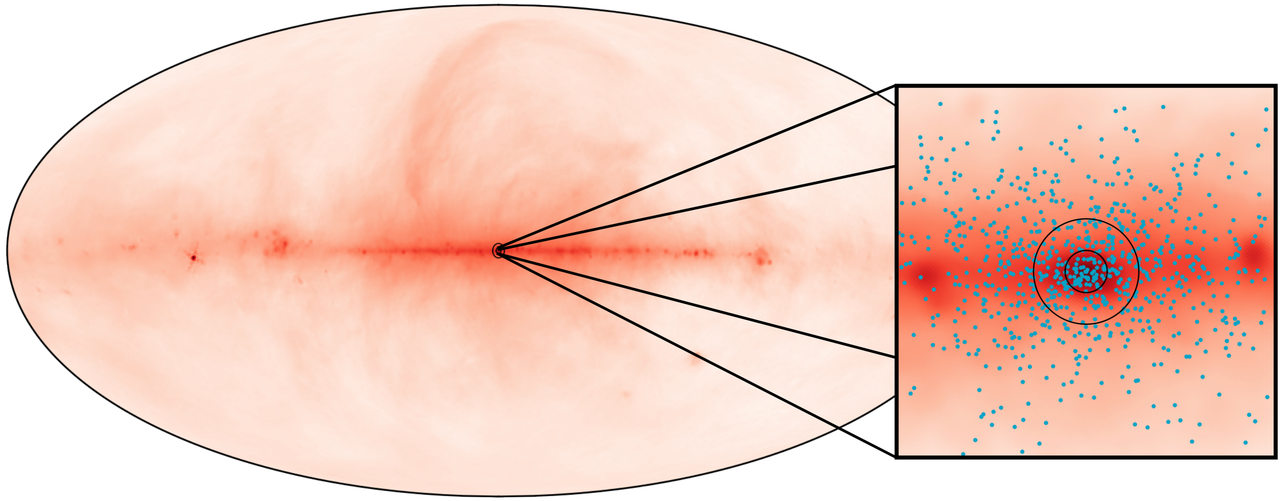

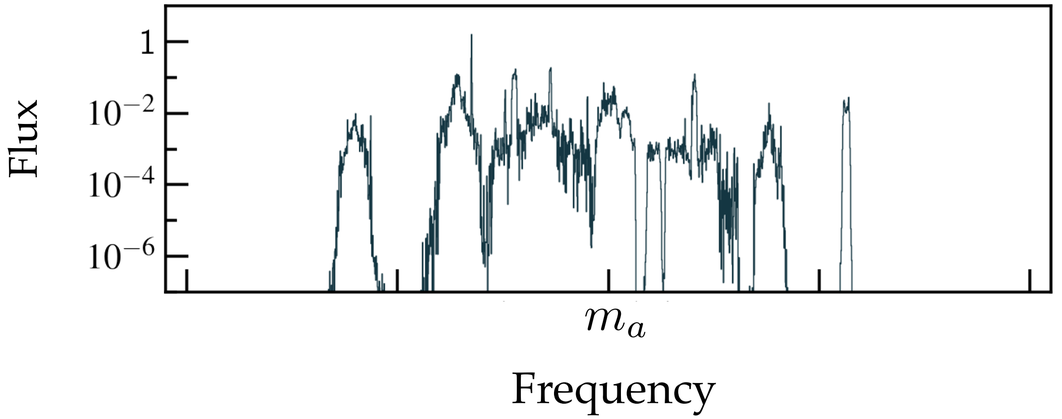

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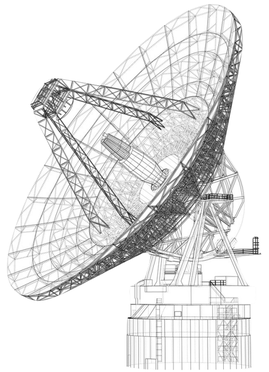

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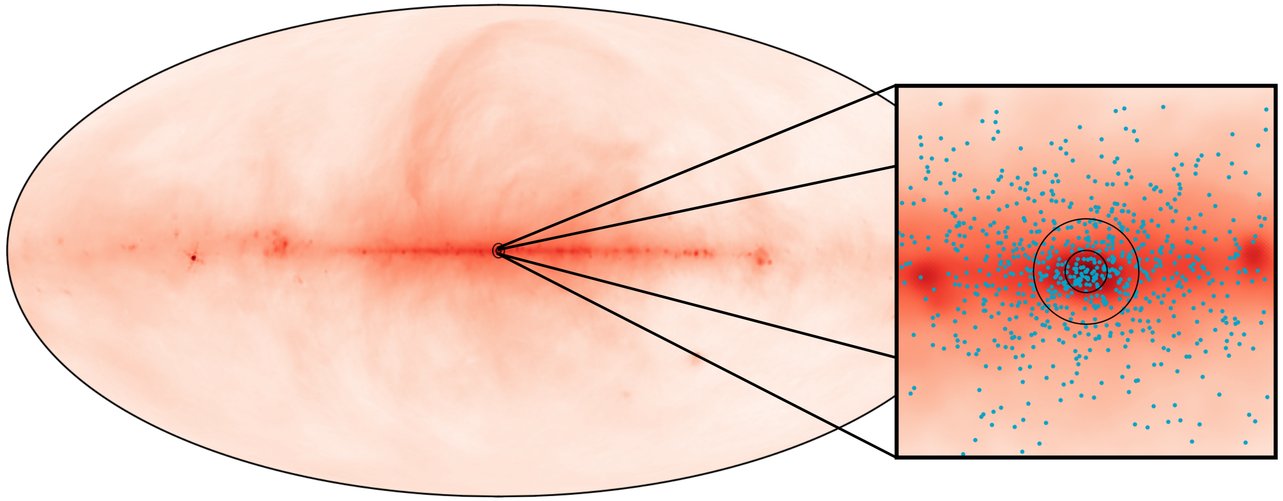

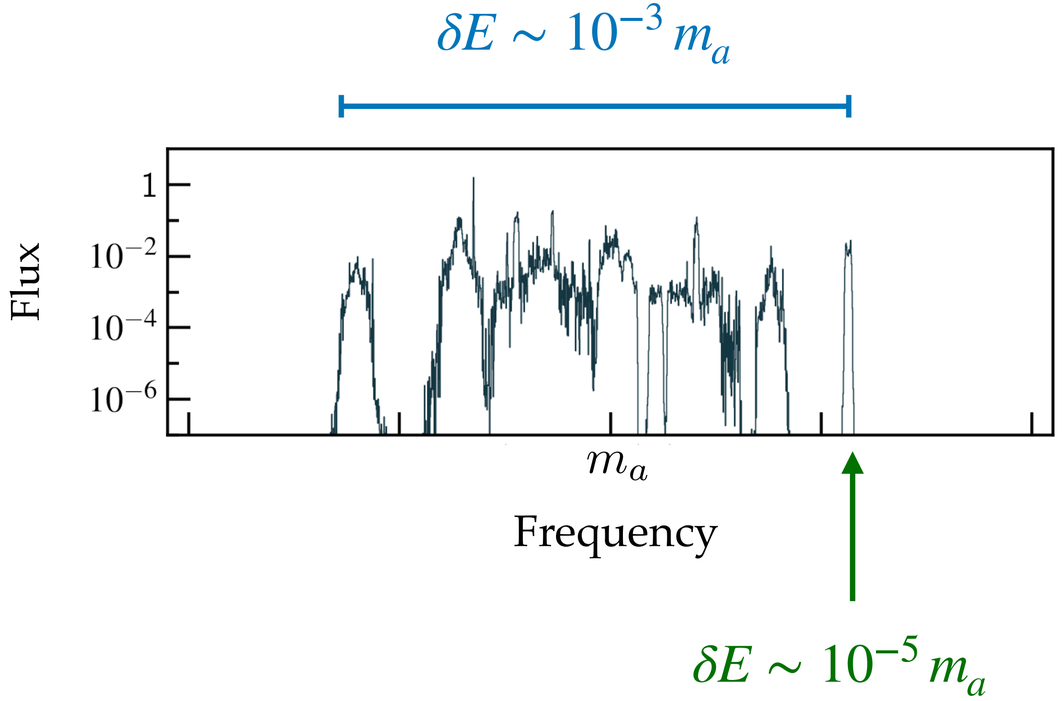

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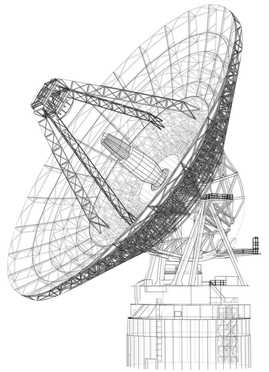

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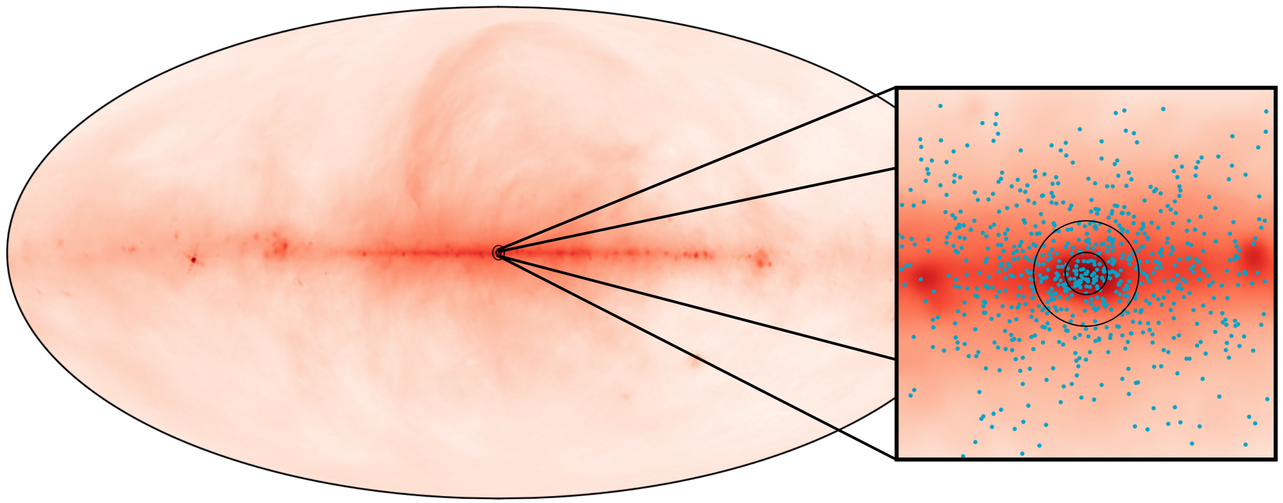
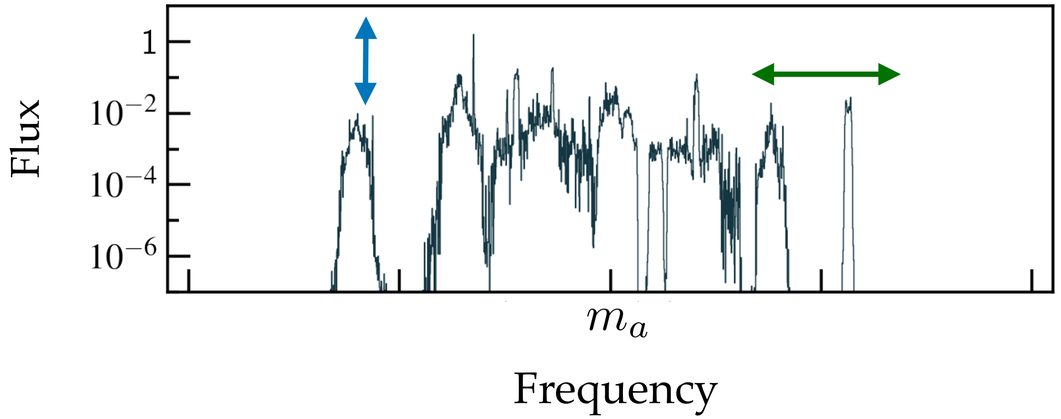


Lines oscillate with rotation of star (seconds)

Lines shift with stellar orbit (weeks/months)



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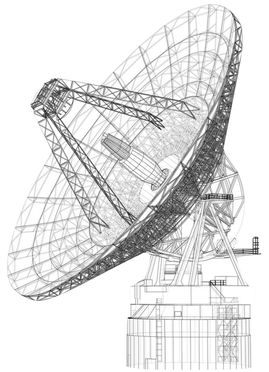


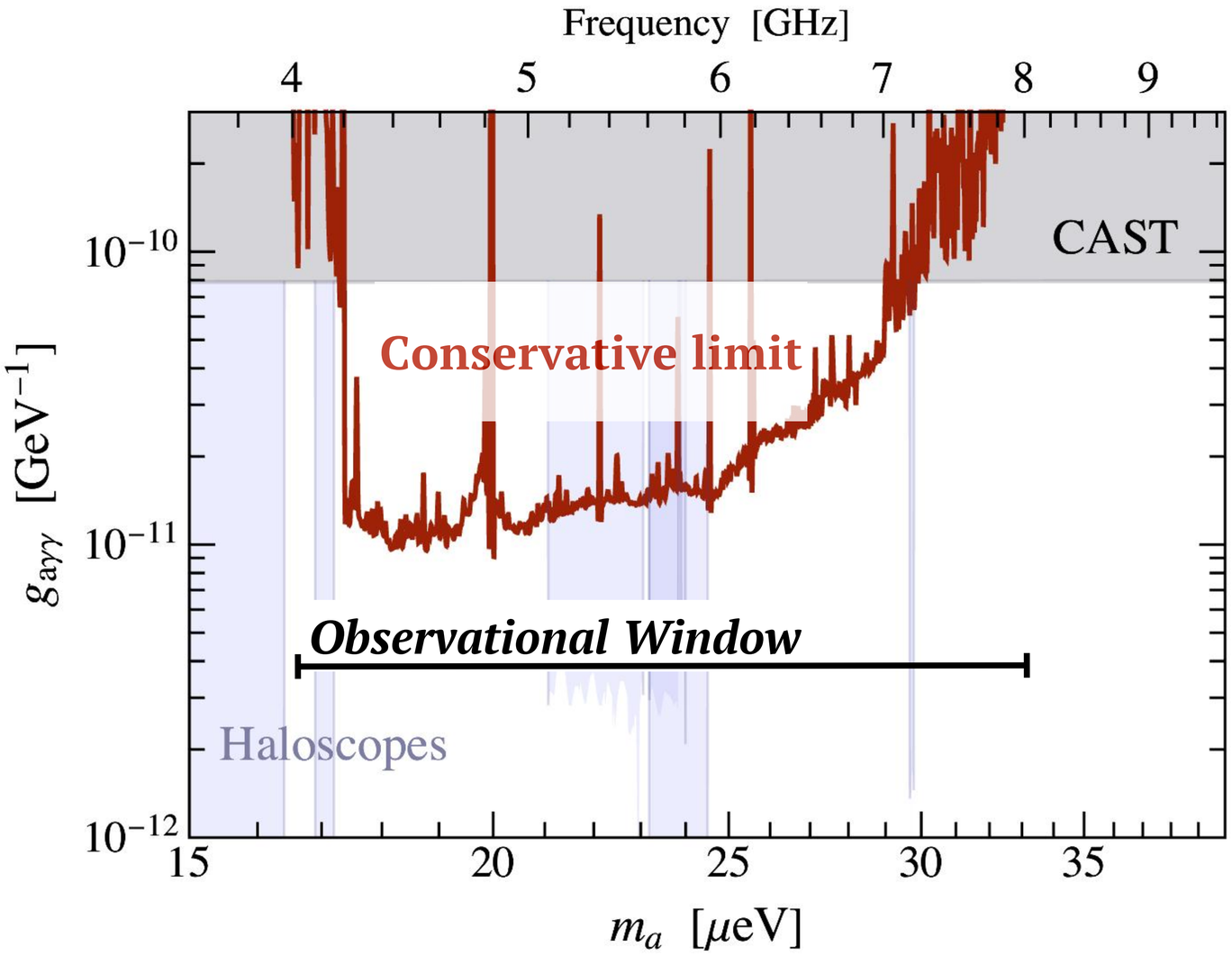
Searching for axions in the galactic center

Survey Details:

Data courtesy of the Breakthrough Listen Initiative

- **Telescope:** Green Bank Telescope (100m)
  Observation Frequency: 4–8 GHz
- **Observation Target:** Galactic Center
- **Observation Time:** ~4.6 hours

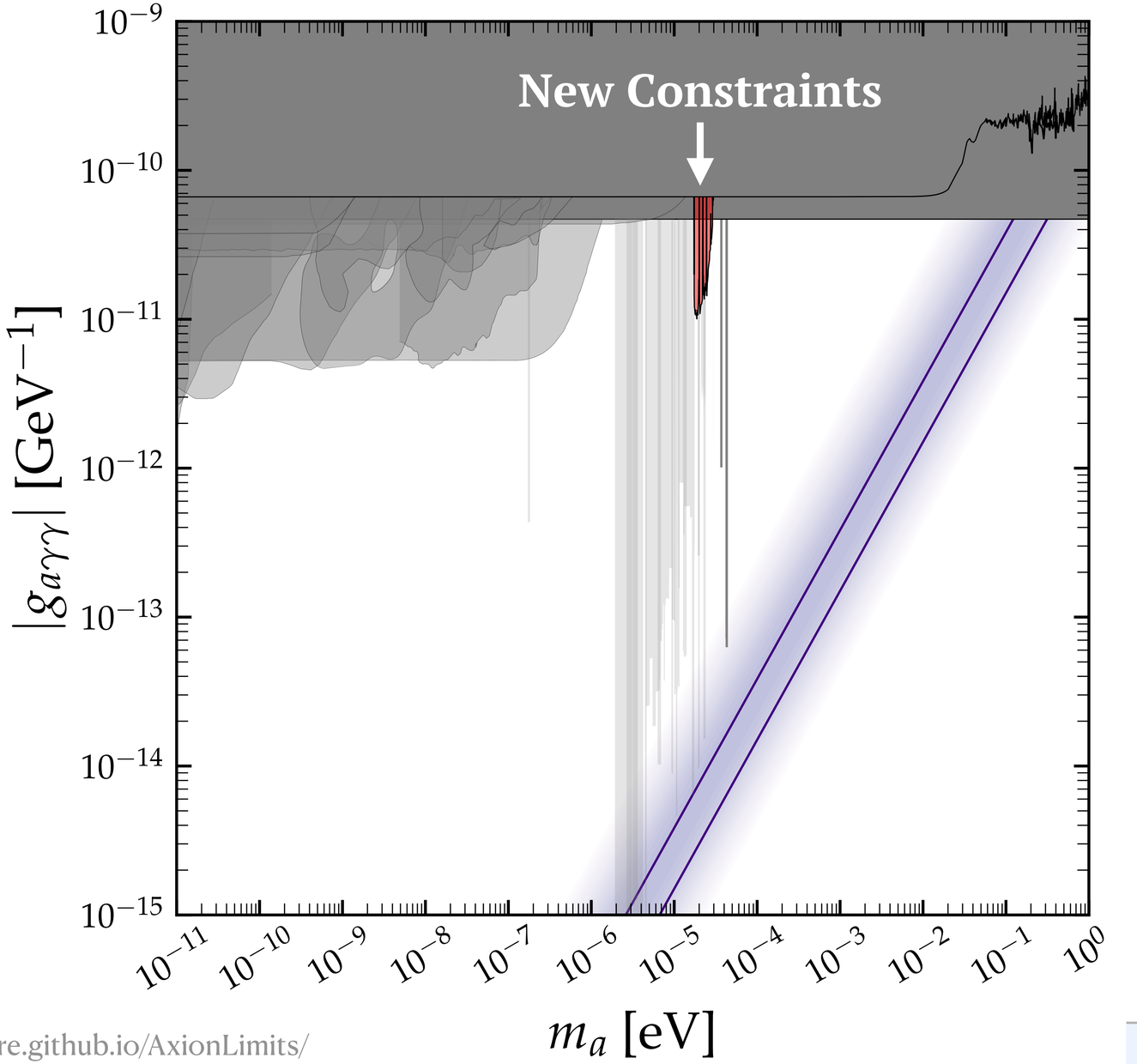
Backgrounds: Molecular lines, radio-frequency interference



(See also e.g. Battye et al (2023) for search using time domain)

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

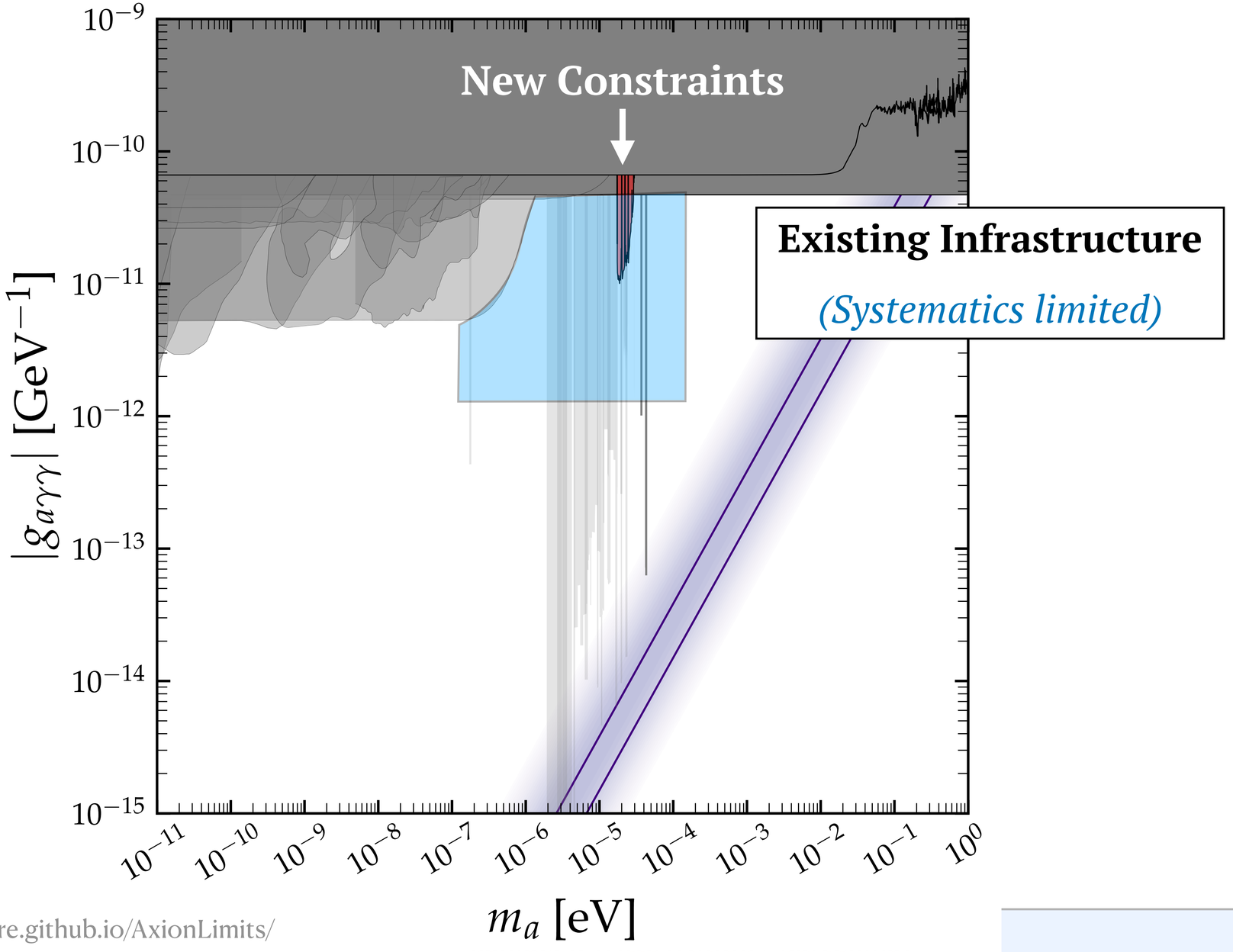
Searching for axions in the galactic center



Plot made using cajohare.github.io/AxionLimits/

Date: Early 2022

Searching for axions in the galactic center



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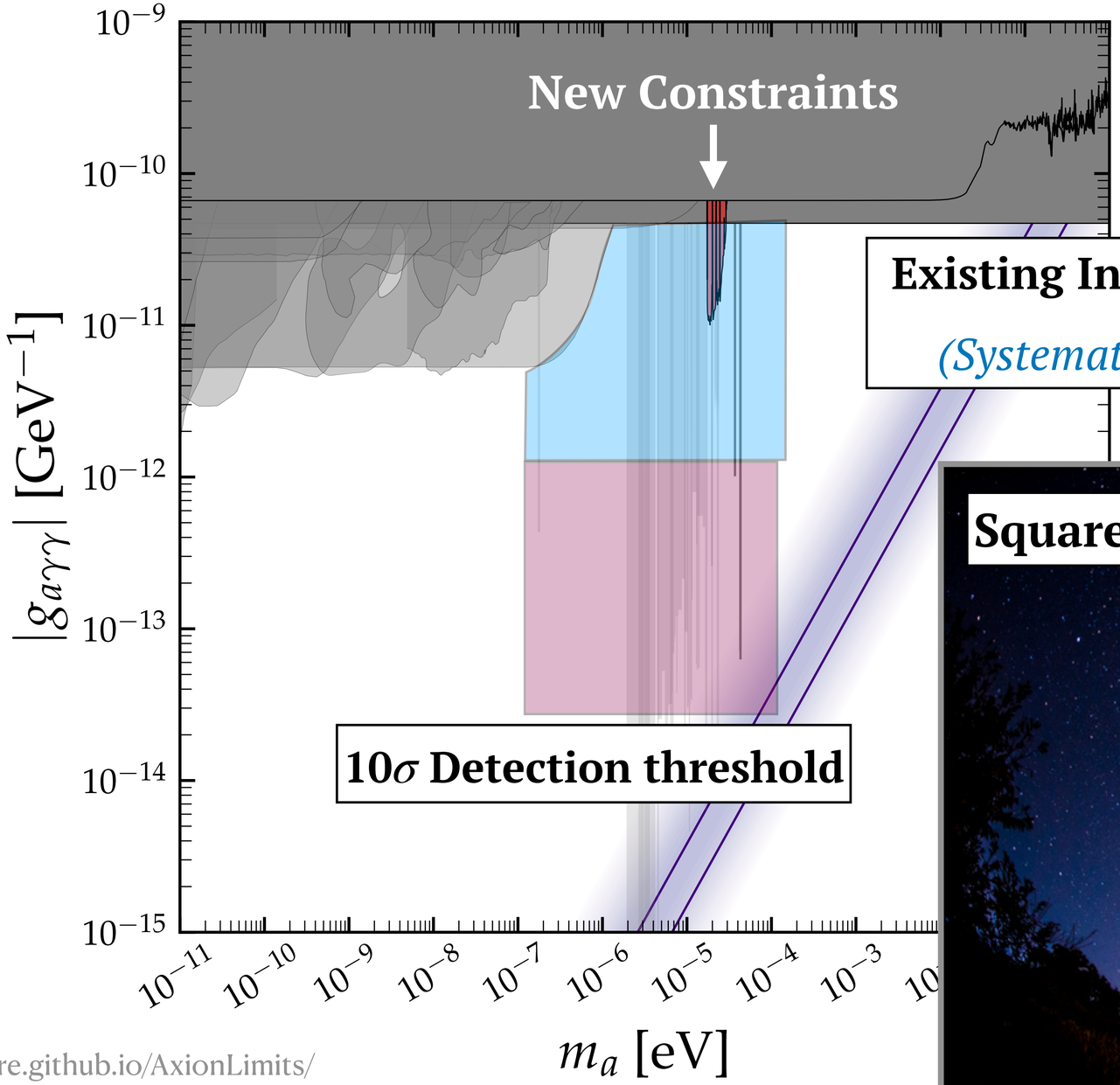

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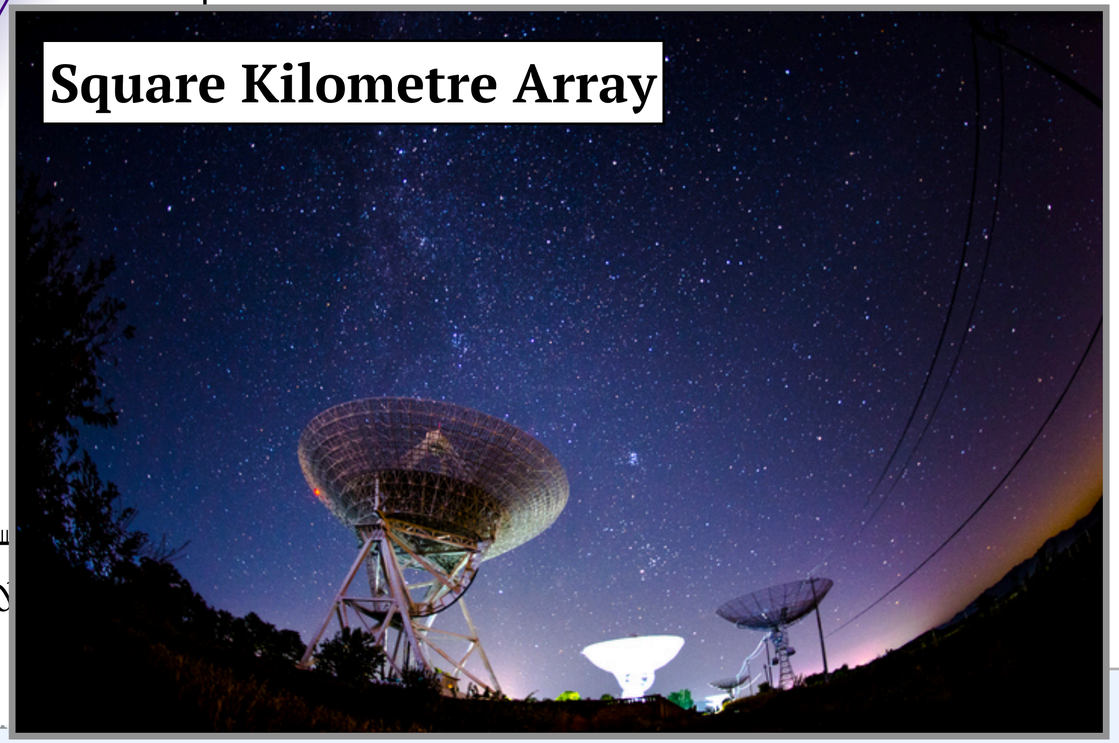


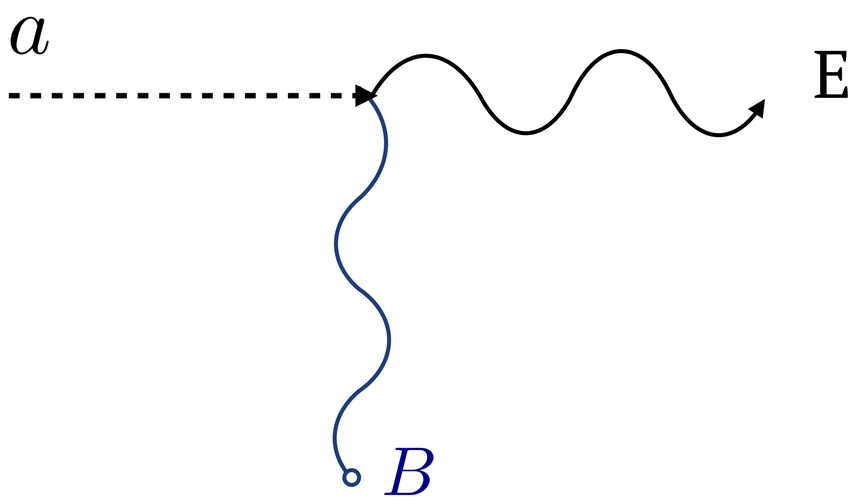
Plot made using cajohare.github.io/AxionLimits/

Date: Early 2022

Producing axions with electromagnetism

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

Axion + $\vec{B}$ → Photon ($\vec{E}$)



Producing axions with electromagnetism

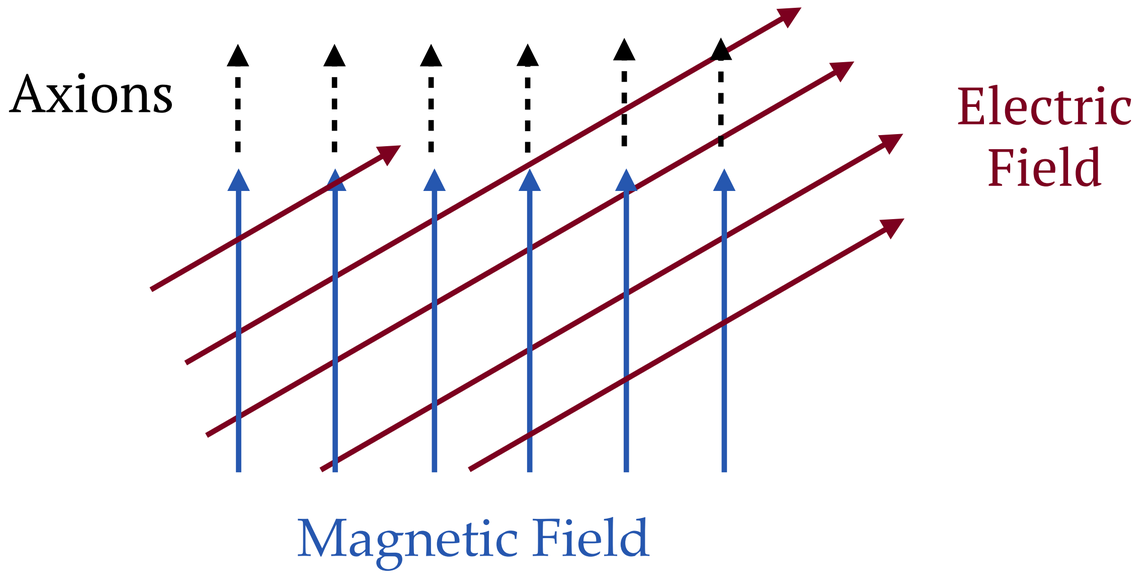
Advantage:

Remove dependence on dark matter density

- Larger axion densities
- Target nearby pulsar population

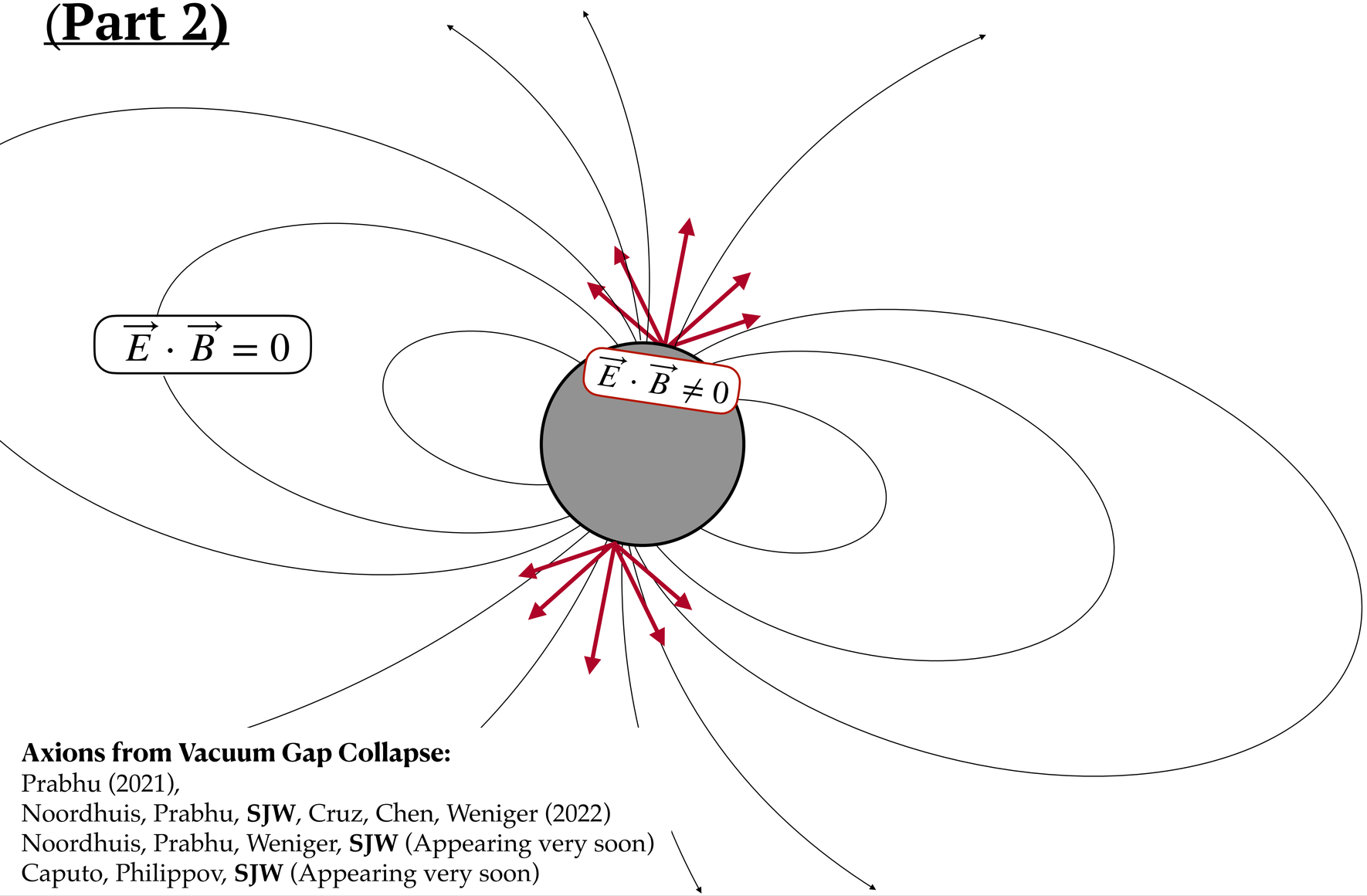
$$\mathscr{L} \sim g_{a\gamma\gamma}\, a\, \vec{E} \cdot \vec{B}$$

$$\vec{B} \cdot \vec{E} \rightarrow \text{Axion}$$



Locally sourced axions

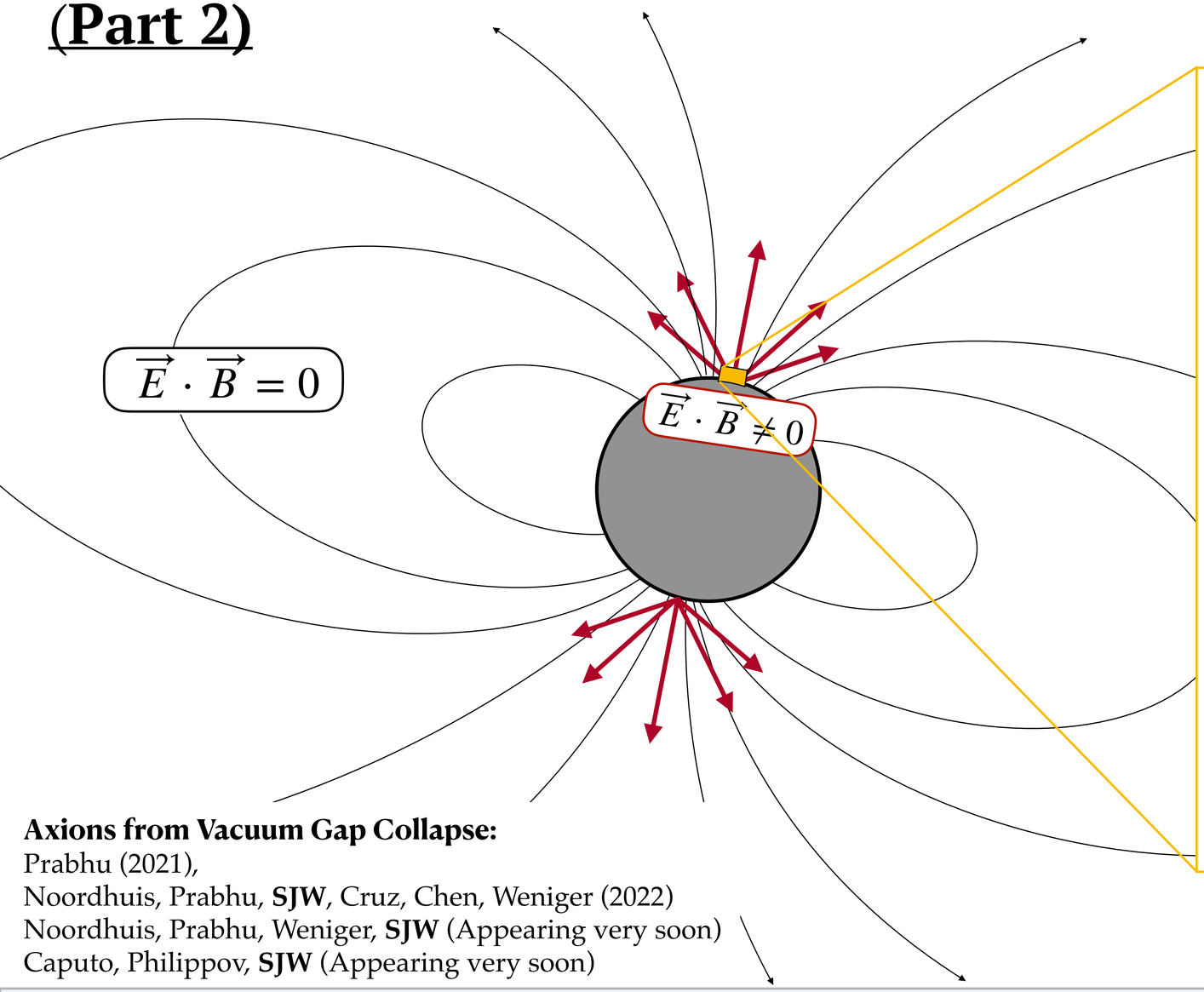
(Part 2)

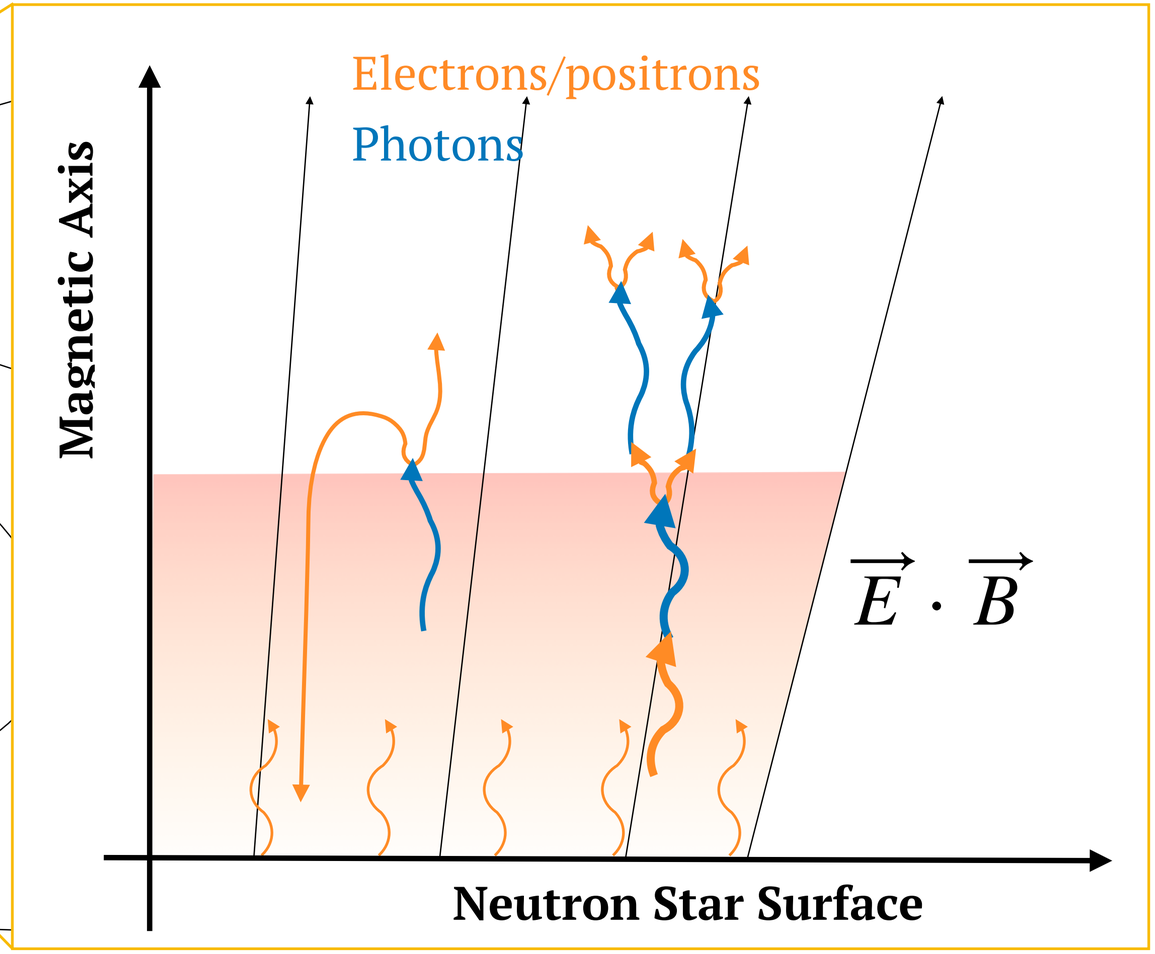


Axions from Vacuum Gap Collapse:
Prabhu (2021),
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, Weniger, **SJW** (Appearing very soon)
Caputo, Philippov, **SJW** (Appearing very soon)

Locally sourced axions

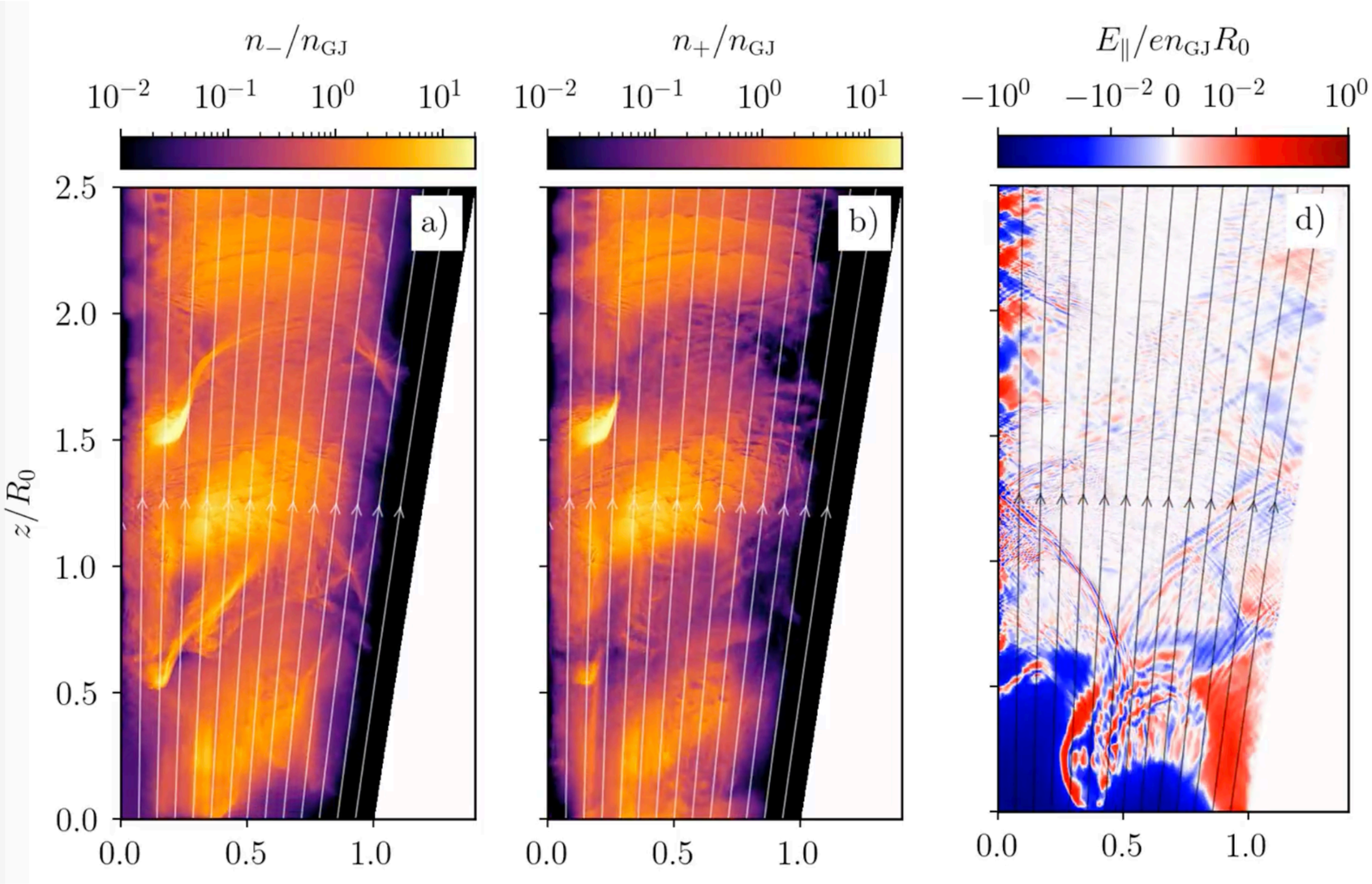
(Part 2)





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

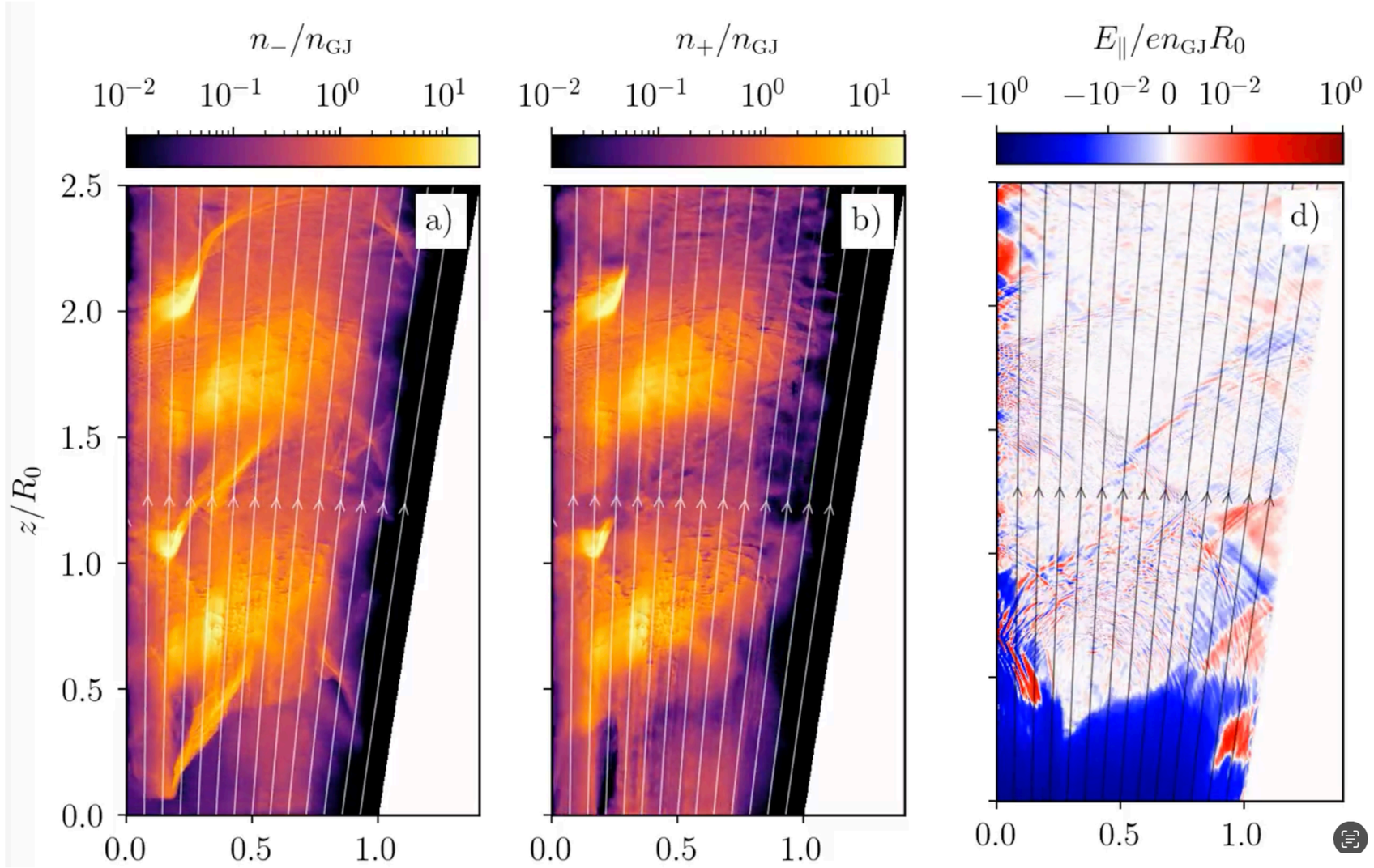
Pair production in the polar caps



MHz-GHz fluctuations source axions with MHz-GHz energies

Simulations curtesy of F. Cruz and A. Chen

Pair production in the polar caps



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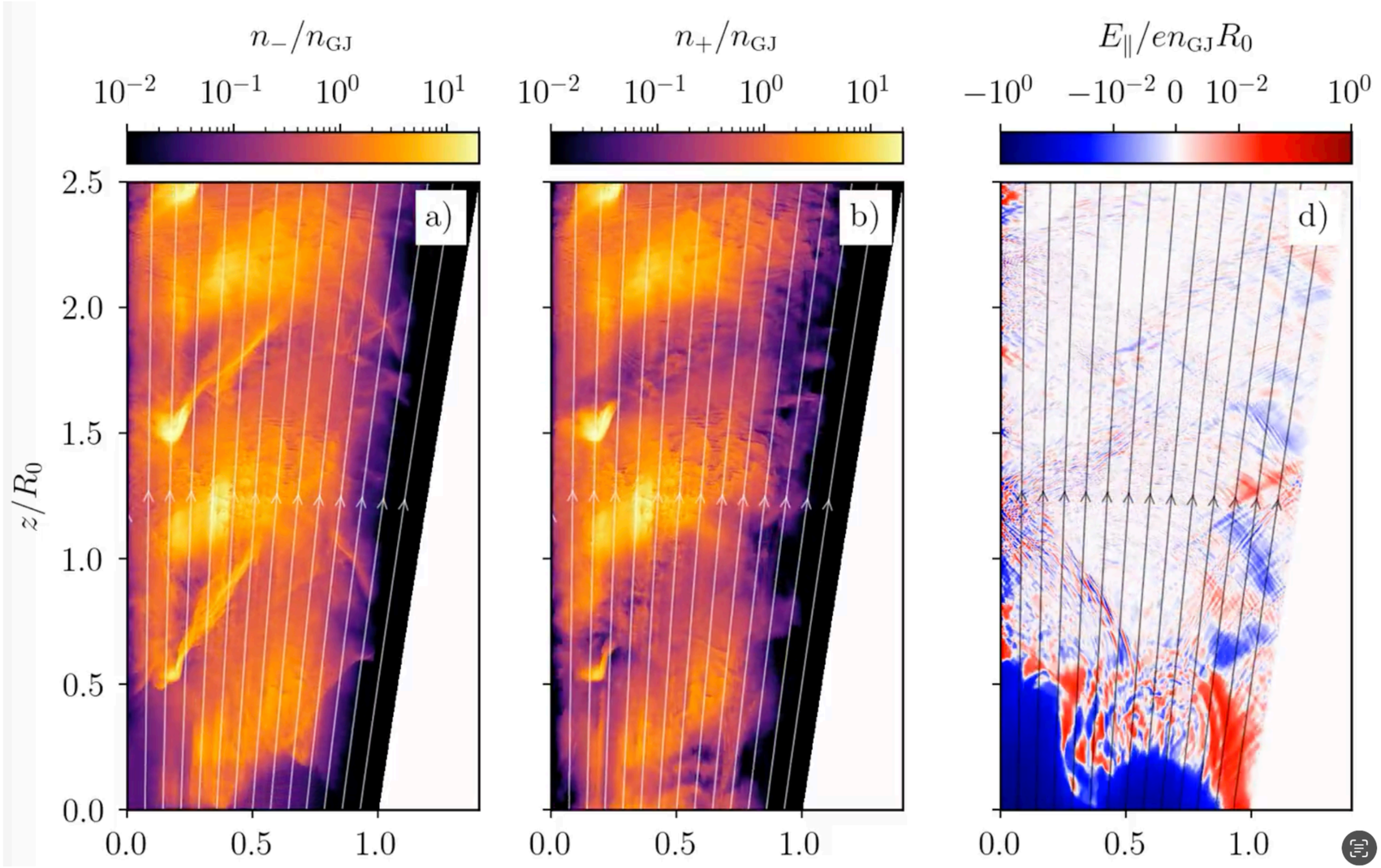

MHz-GHz fluctuations source axions with MHz-GHz energies

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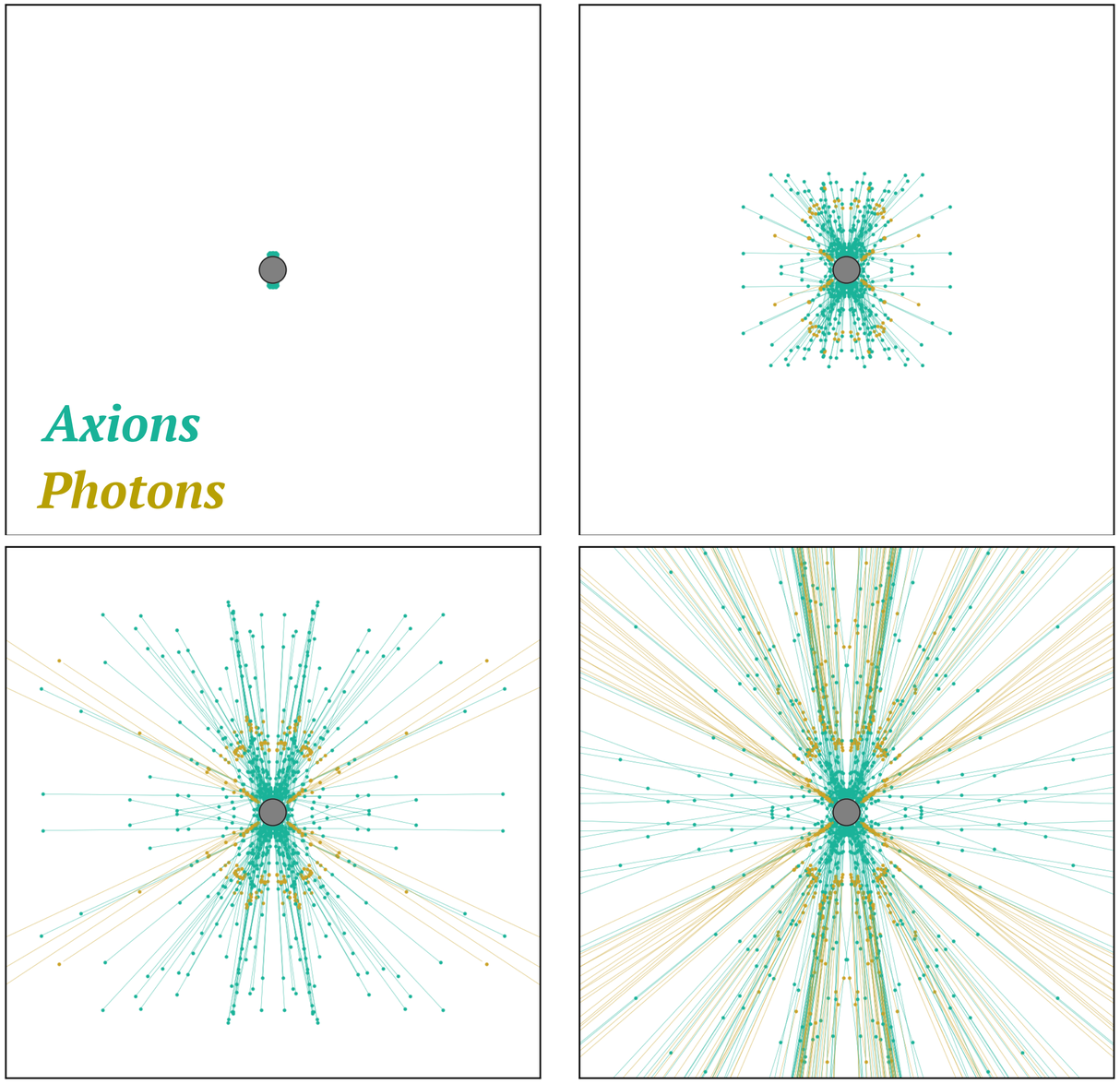
Locally sourced axions



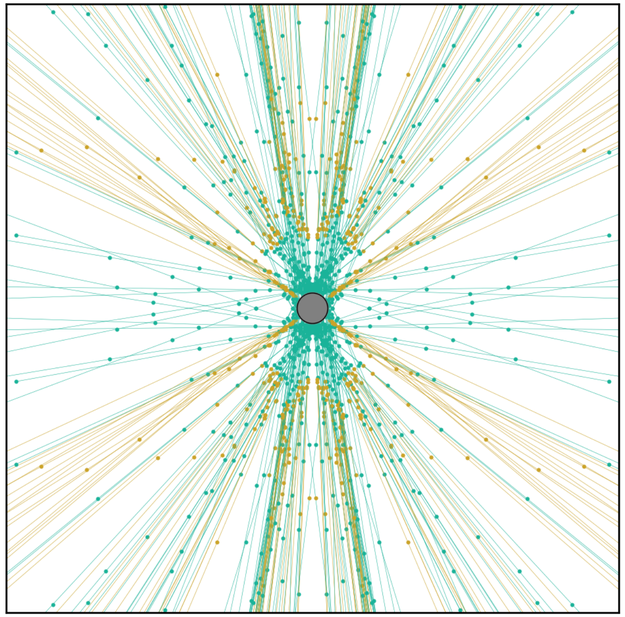
Relativistic axion population

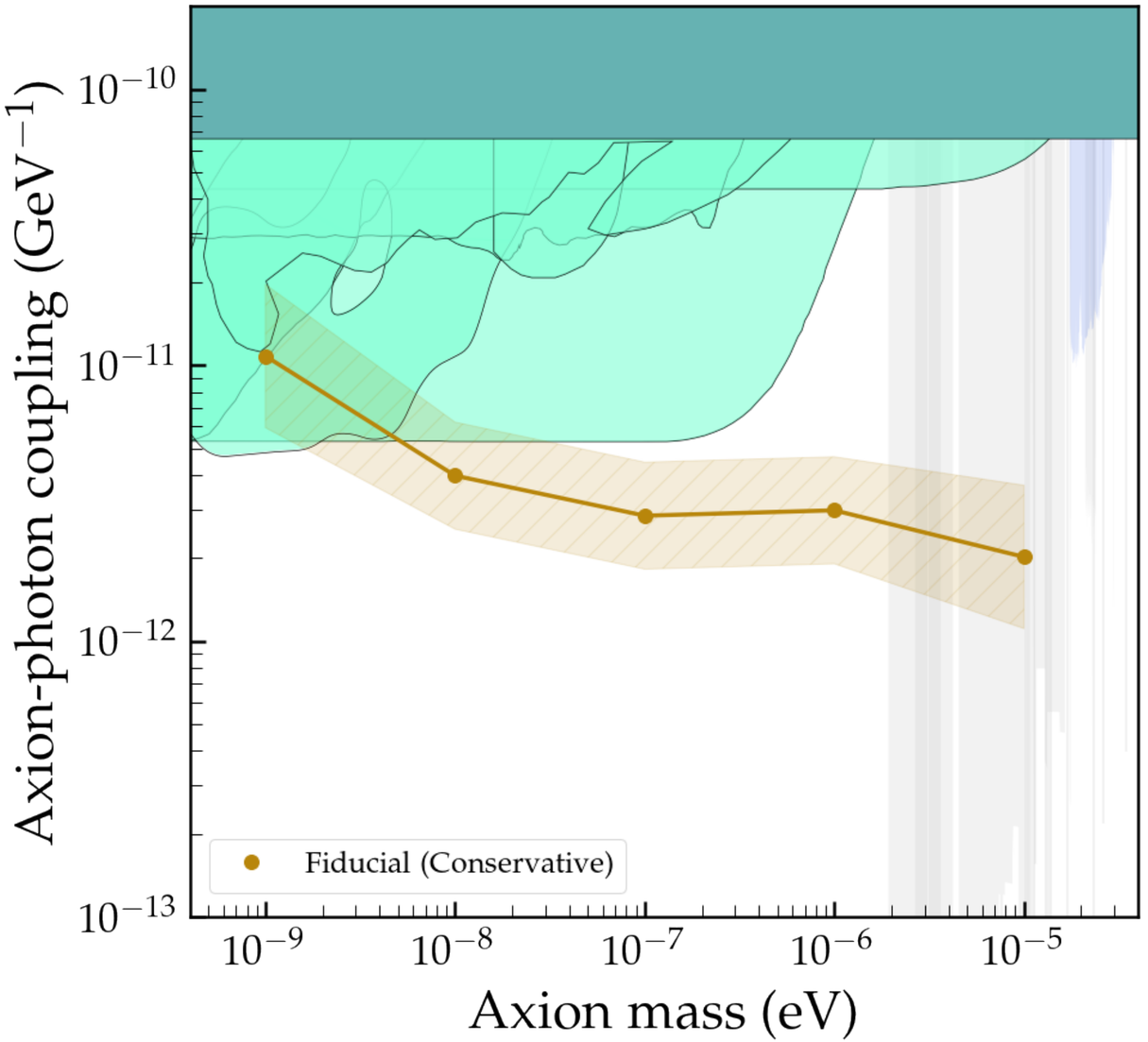
Axions free stream away from neutron star

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)

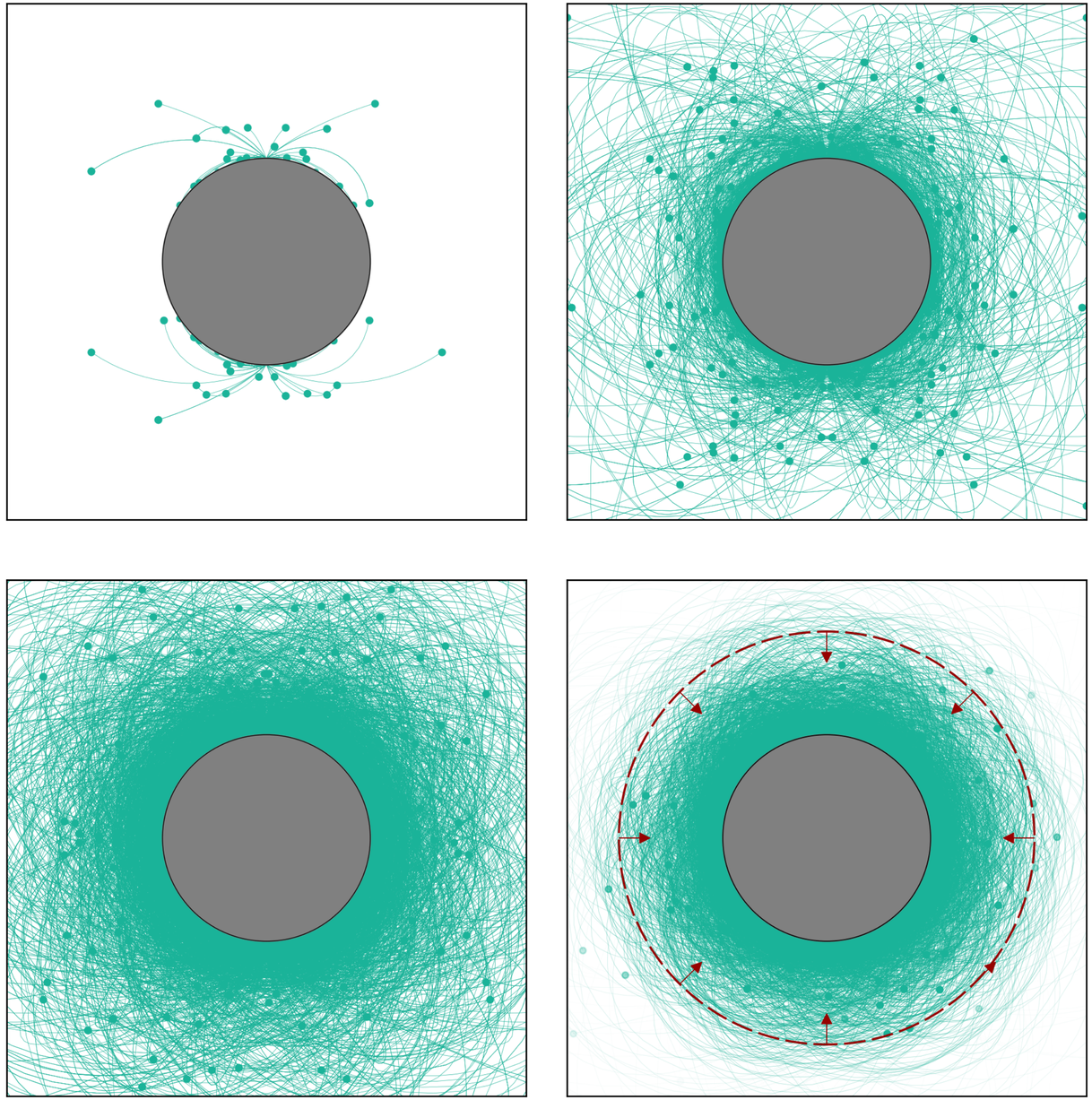
Locally sourced axions

Non-relativistic axion population

A sizeable fraction of the axion population will be *gravitationally bound* to the neutron star

↓

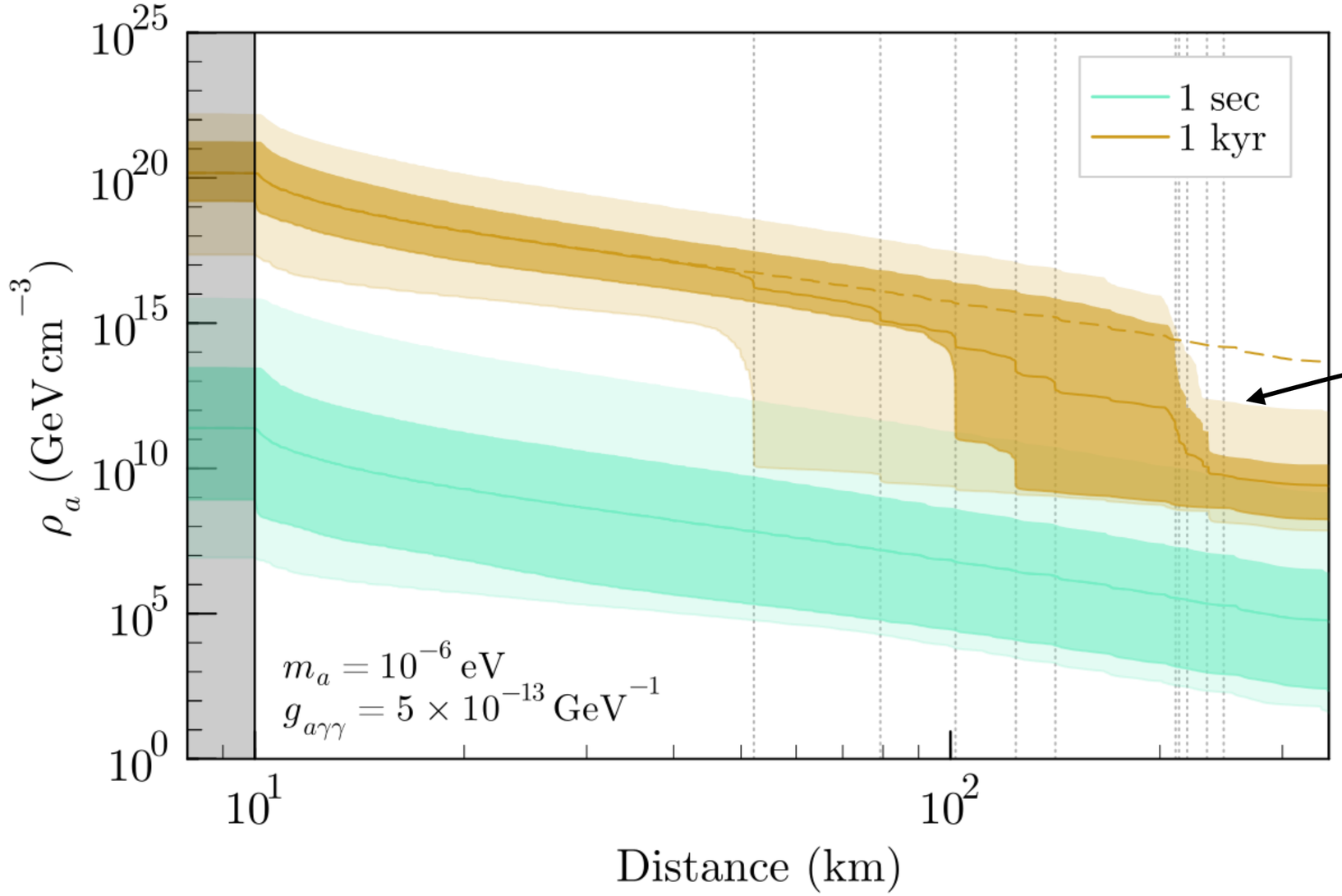
Can accumulate on kyr timescales



Observables: Kinematic endpoint in radio emission, back-reaction on electrodynamics

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

Evolution of axion clouds



Reduction in density from resonant emission

Bands reflect variation of pulsar population

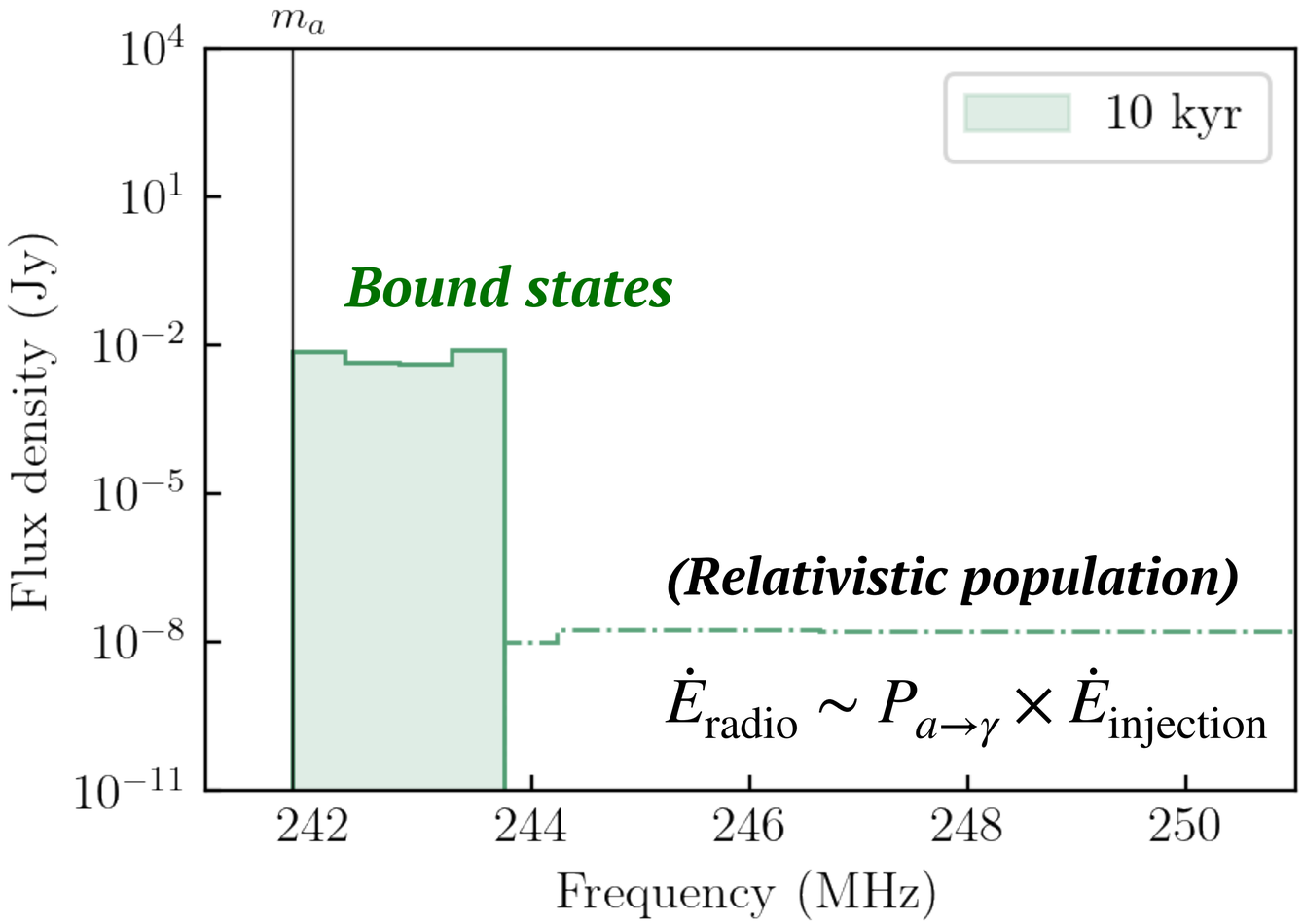
Noordhuis, Prabhu, Weniger, **SJW**(Appearing soon)

Radio emission of bound cloud

Sharp kinematic endpoint inevitably arises in radio spectrum

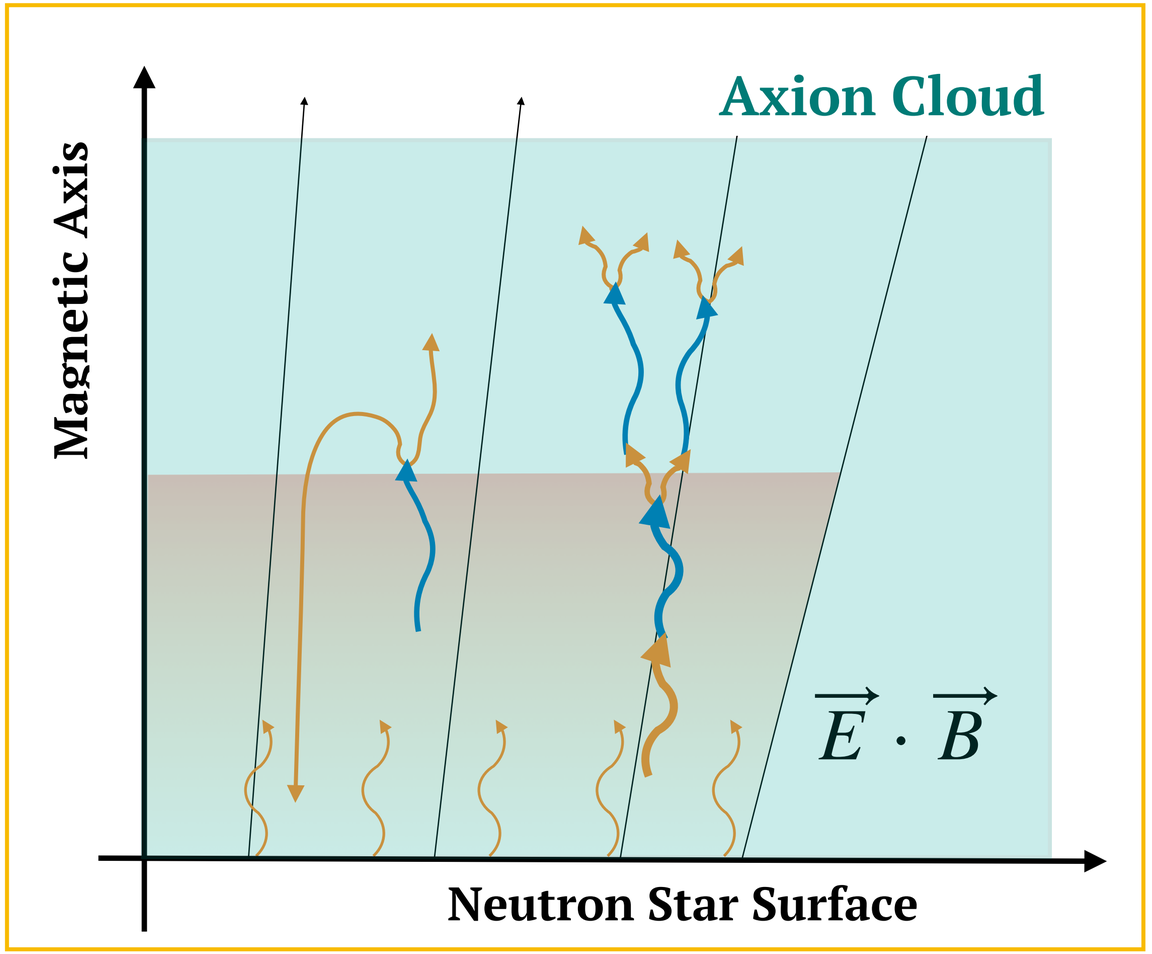
Equilibrium Condition

$$\dot{E}_{\text{radio}} \sim \dot{E}_{\text{injection}}$$



Noordhuis, Prabhu, Weniger, **SJW**(Appearing soon)

Axion back-reaction



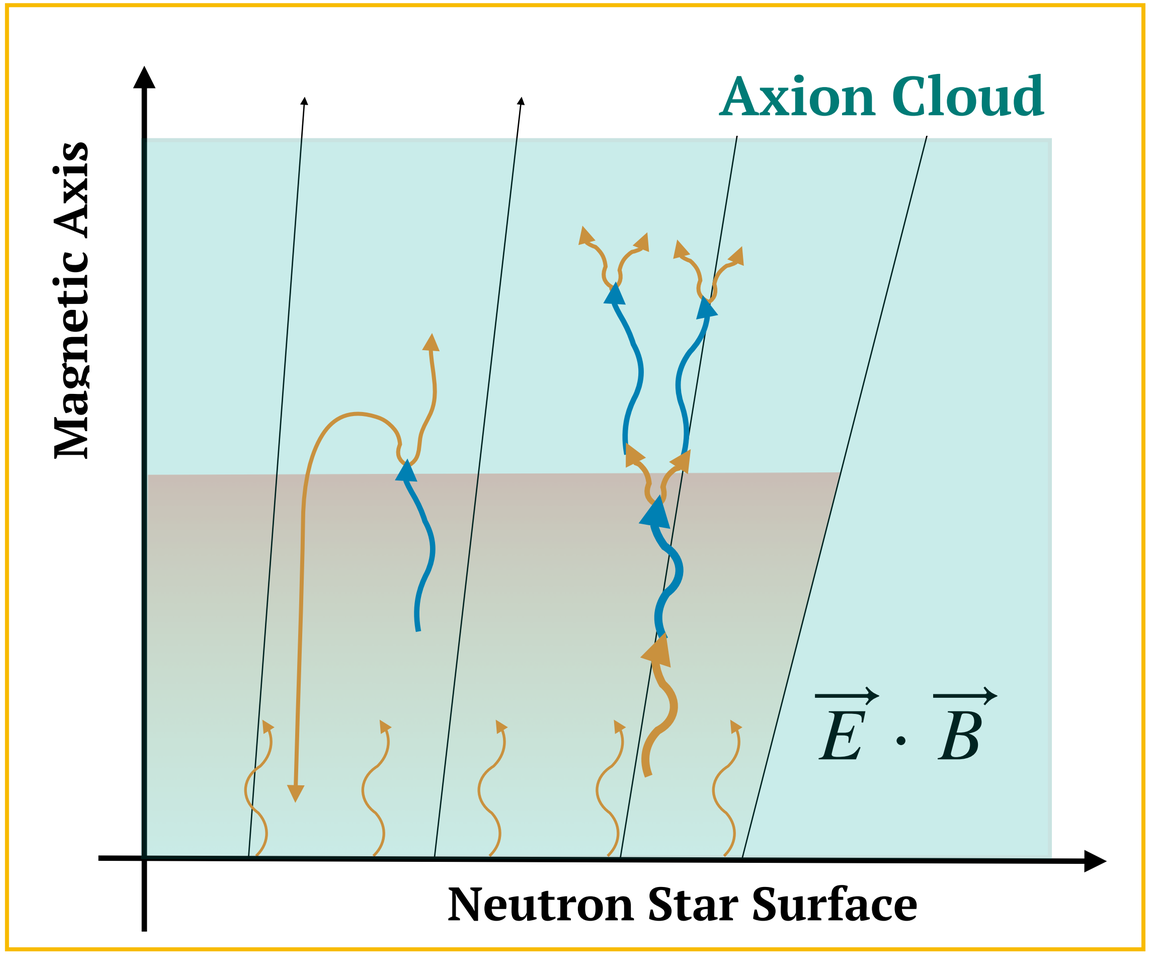
Axions directly modify Maxwell's Equations

$$\nabla \cdot E = \rho - gB \cdot \nabla a$$

$$\nabla \times B - \dot{E} = J + g\dot{a}B - \nabla a \times E$$

Large axion densities back-react on electrodynamics

Axion back-reaction



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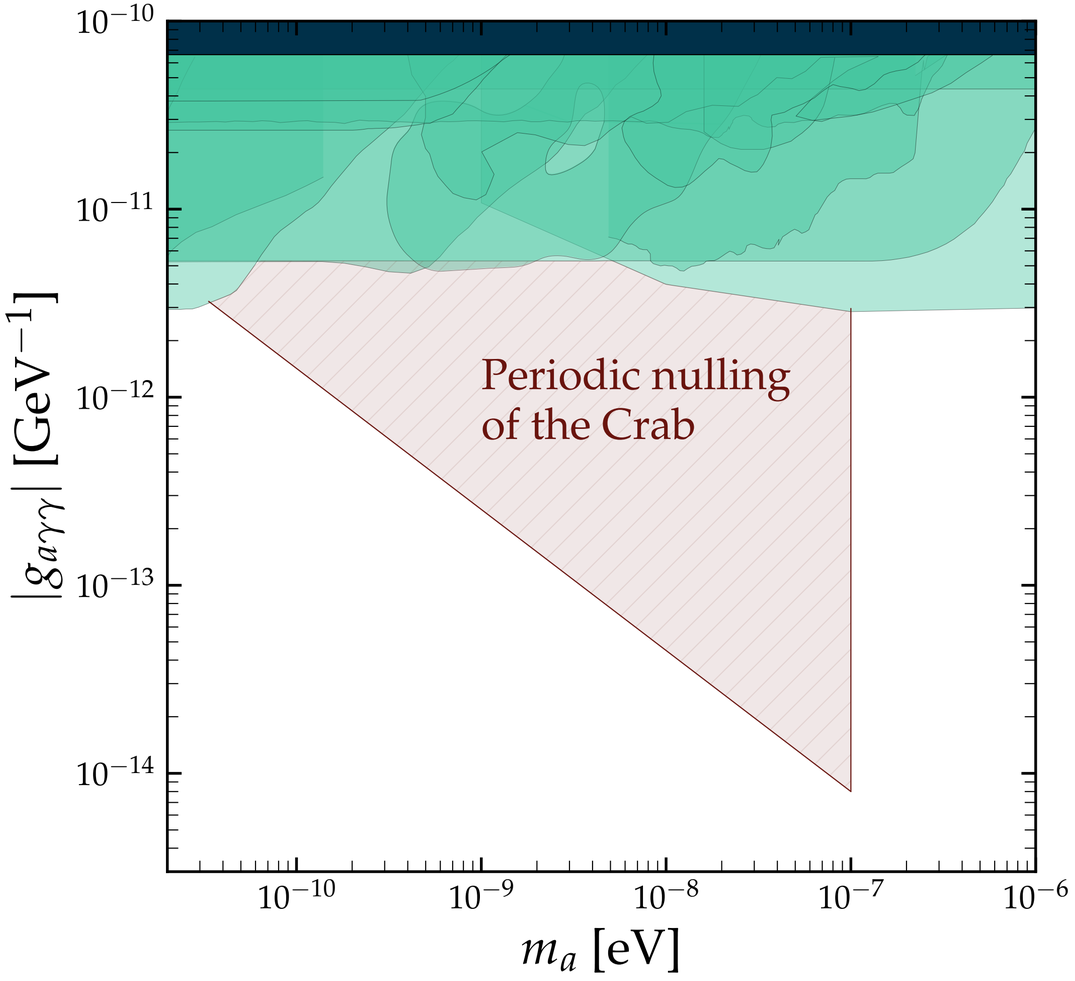
Large axion densities back-react on electrodynamics

Axion clouds can induce periodic nulling of radio emission

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

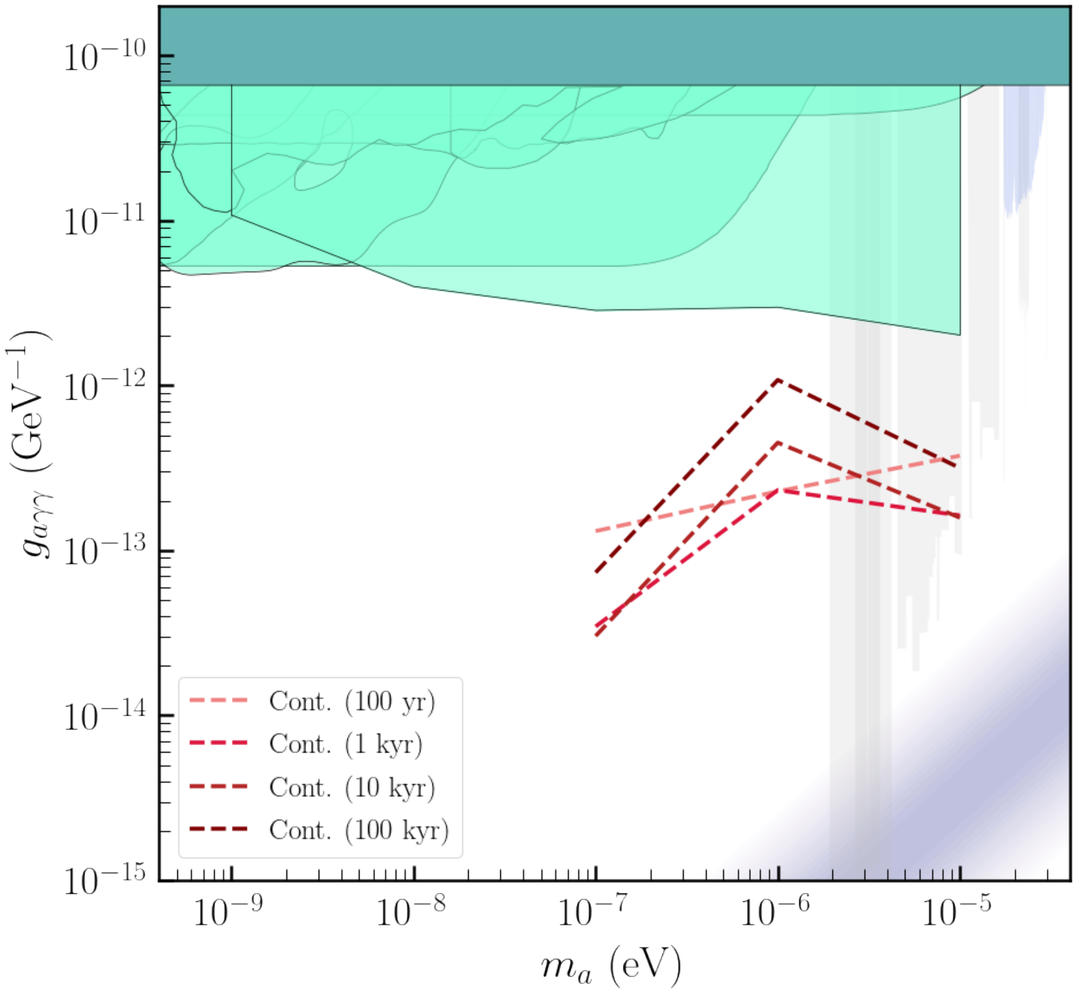
Future outlook

Axion back-reaction



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

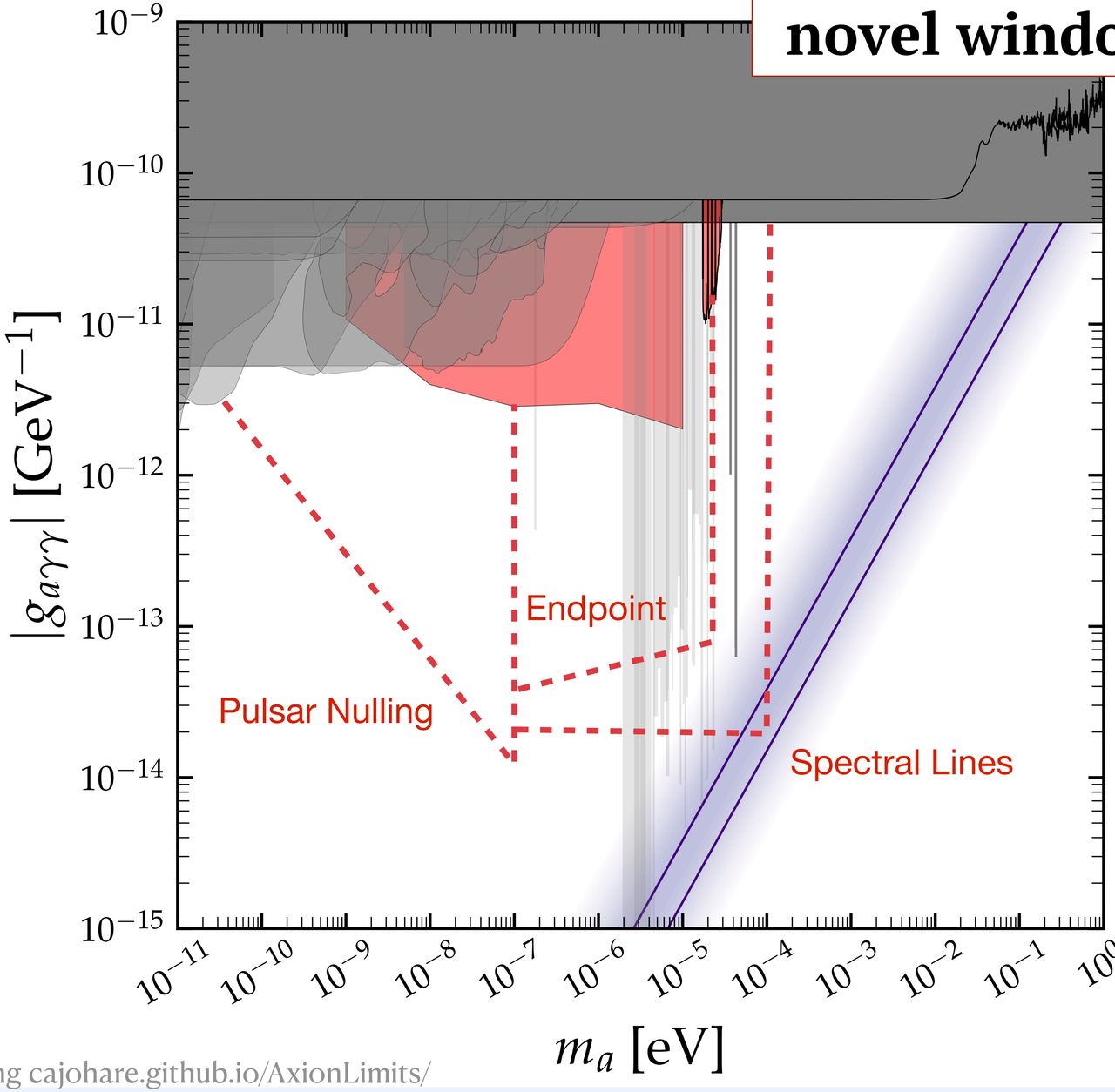
Endpoint in radio spectrum



Noordhuis, Prabu, Weniger, **SJW** (Appearing soon)

Conclusions

Neutron star magnetospheres are opening novel window in indirect search for axions



- Distinctive signatures (spectral lines, transients, kinematic endpoints)
- Strong discovery potential over wide range of parameter space
- Highly complementary to laboratory searches

Plot made using cajohare.github.io/AxionLimits/