Neutron stars as axion laboratories

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3rd EUCAPT Symposium
CERN
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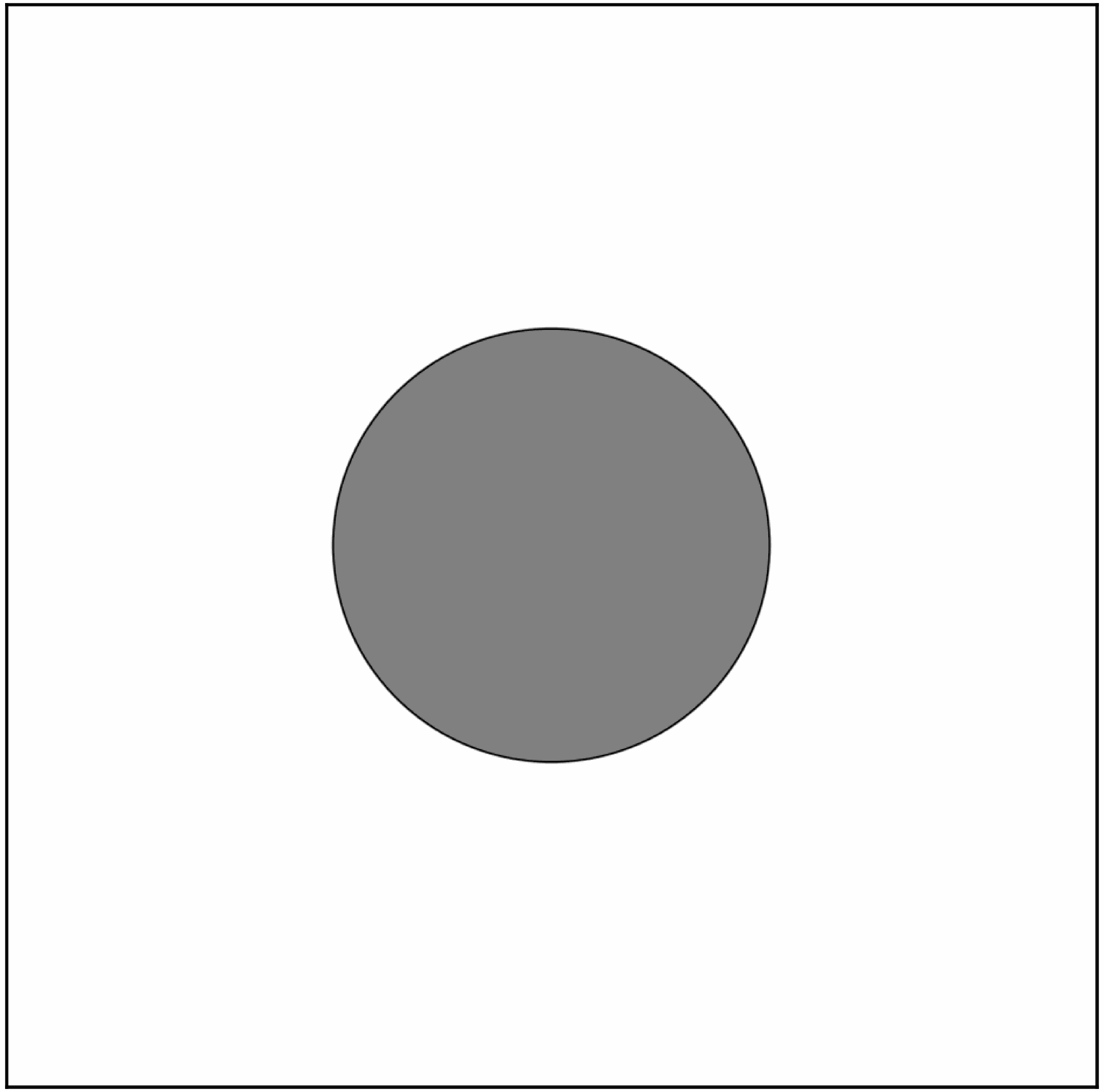

ICCUB
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UNIVERSITAT DE BARCELONA

Brief intro to axions

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

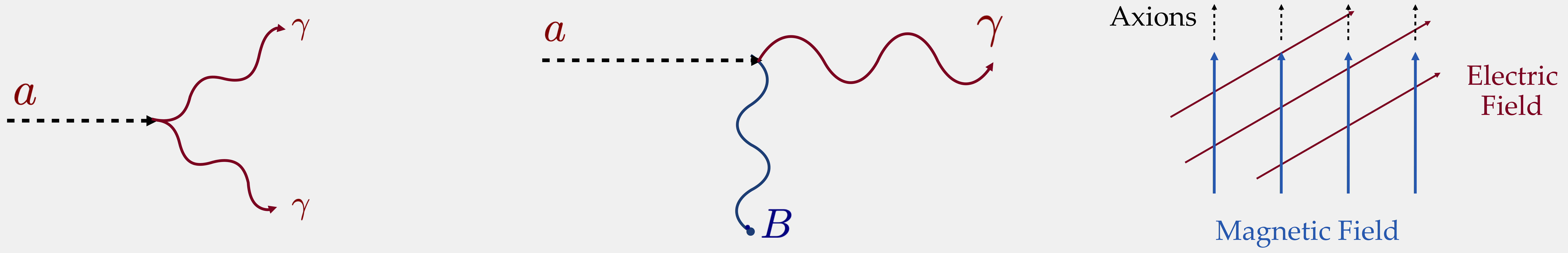
- Goldstone boson introduced to solve strong CP problem

Dark Matter

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

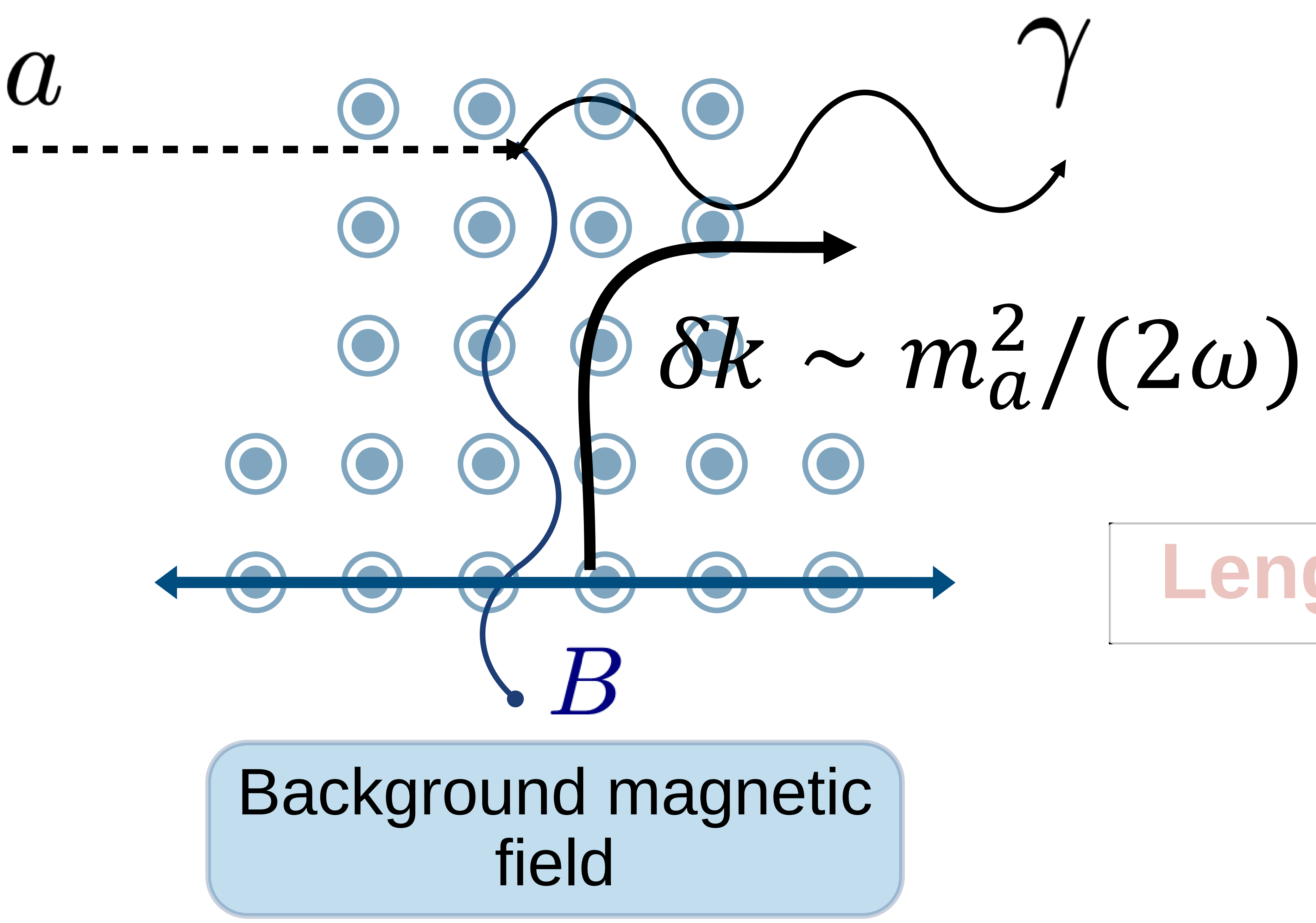
$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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



Axion detection

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



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

Large conversion probabilities require:

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

Length of magnetic field

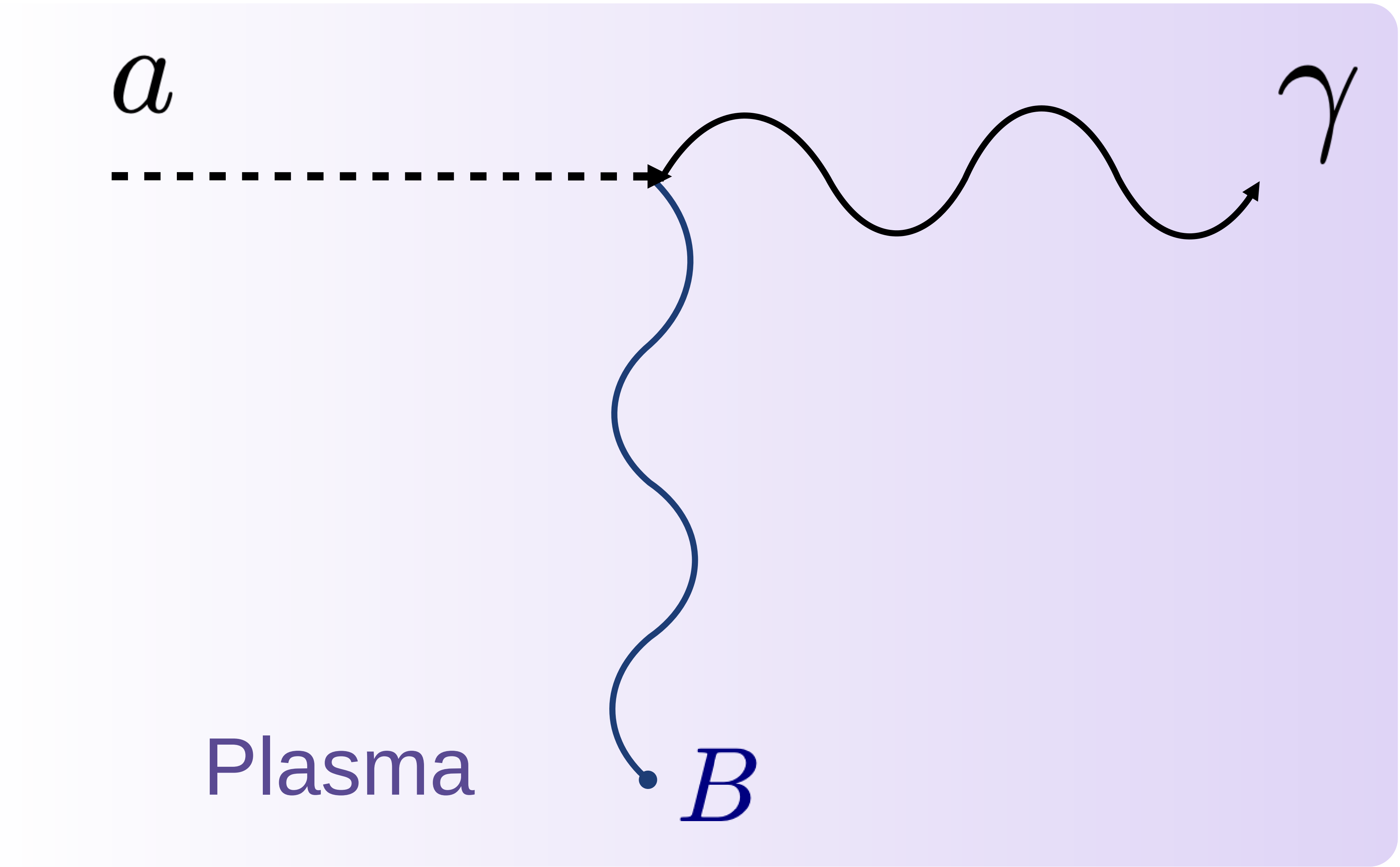
Length set by momentum transfer

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

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

Axion-photon mixing

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



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

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

Photons acquire "effective mass" (ω_p)

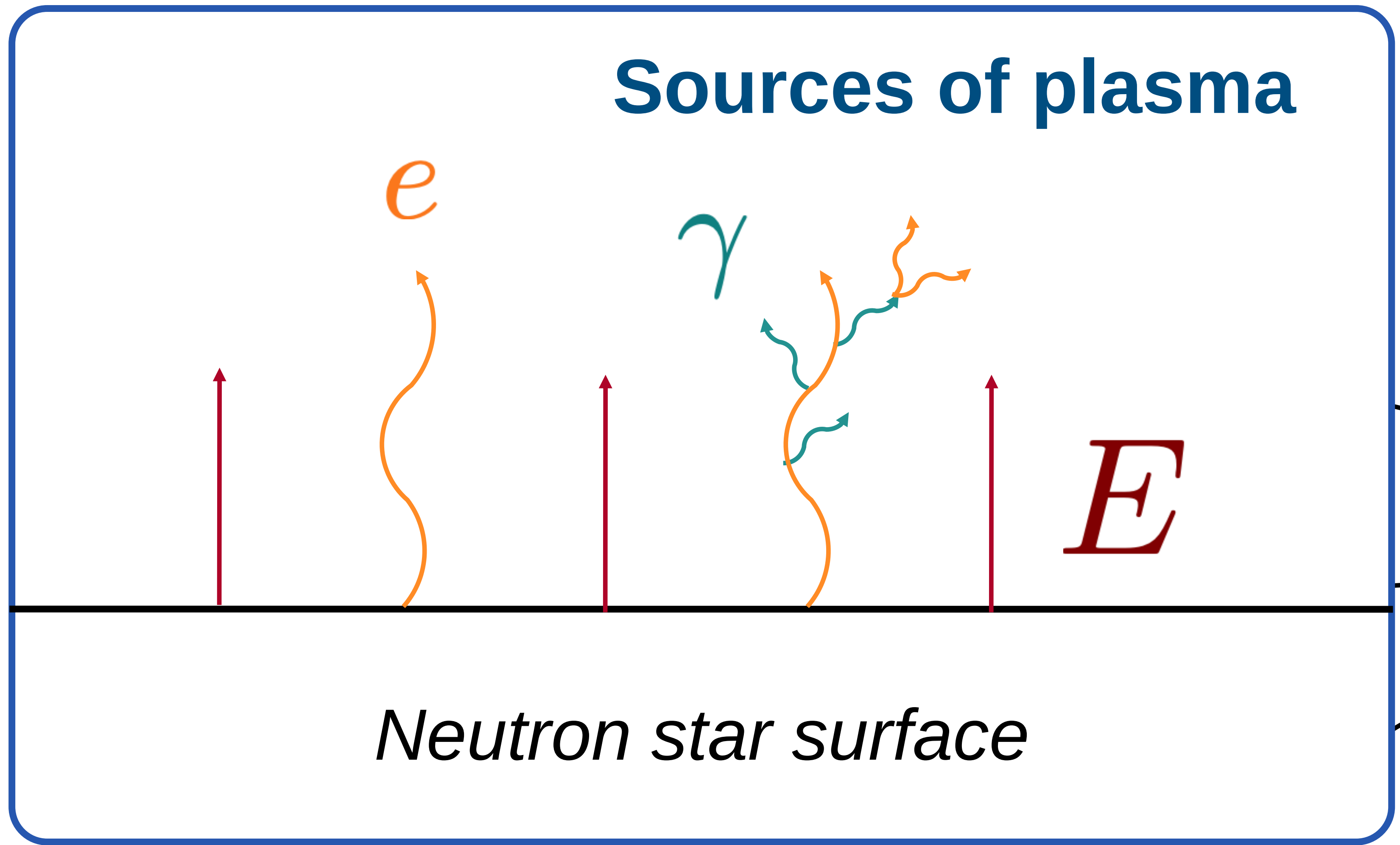
$$L_{\delta k} \to \infty$$

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

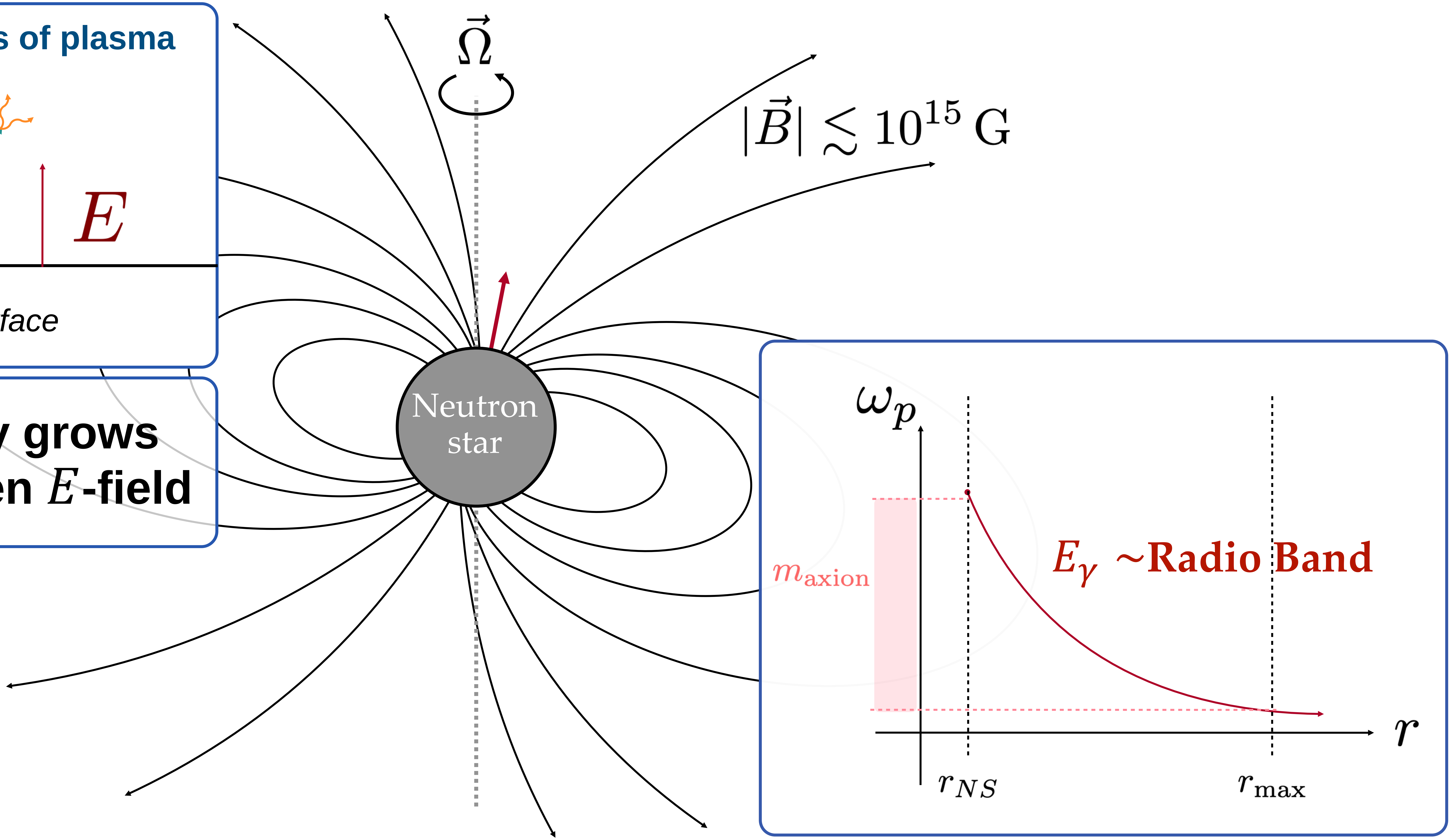
if $m_a \sim \omega_p$

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

Neutron star magnetospheres

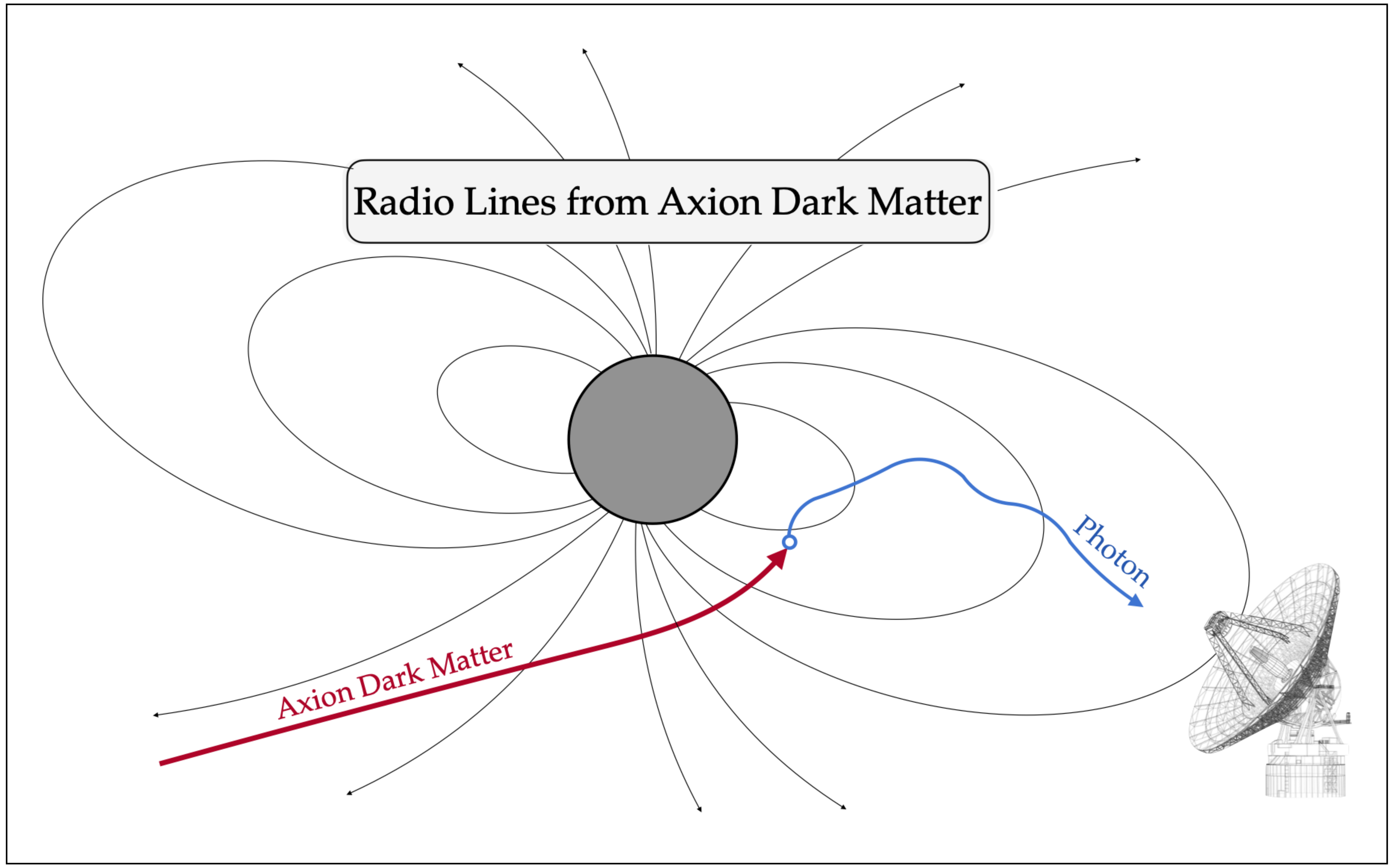


Plasma density grows until it can screen E-field

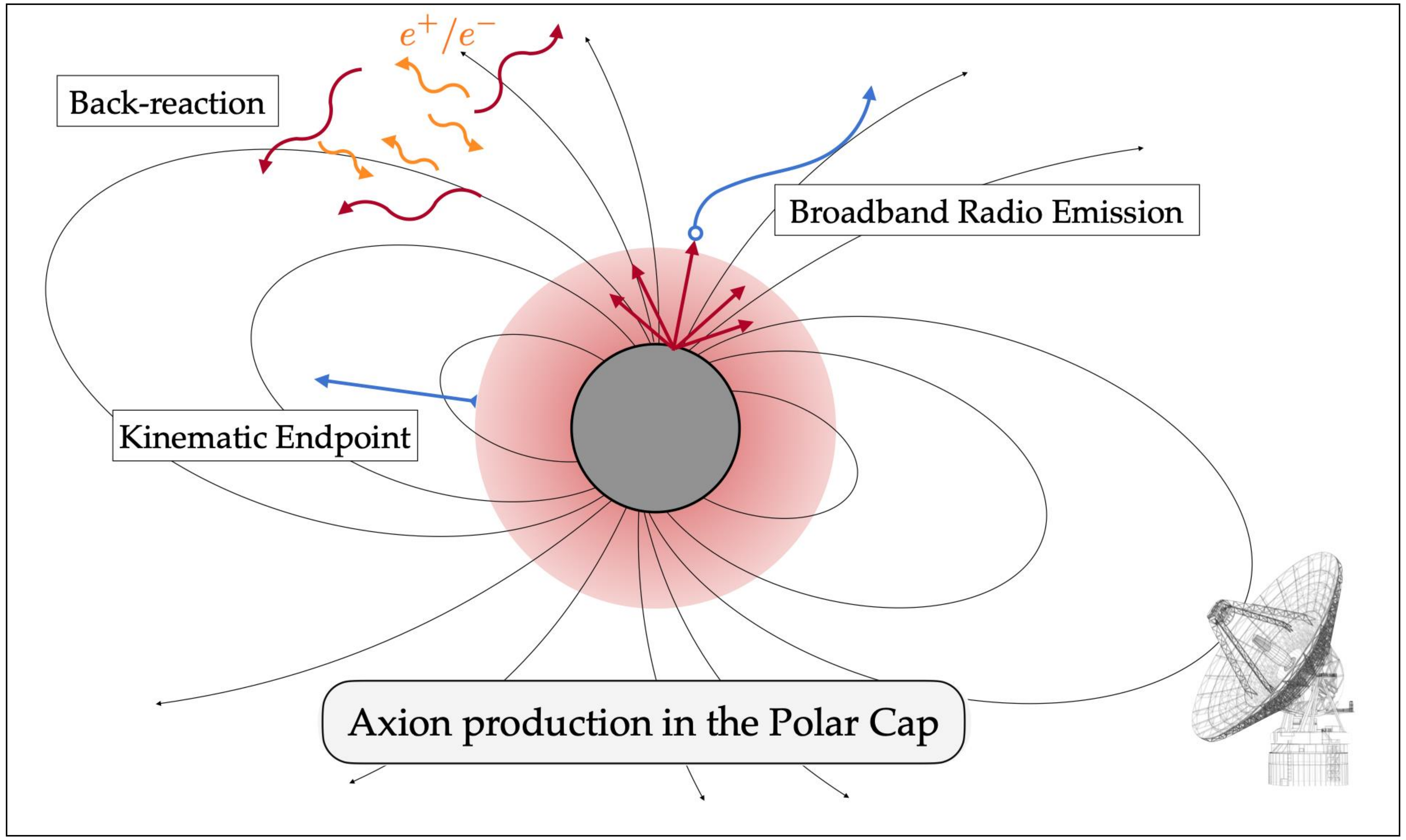


Overview: Neutron stars as axion laboratories

Part 1
Searching for axion dark matter



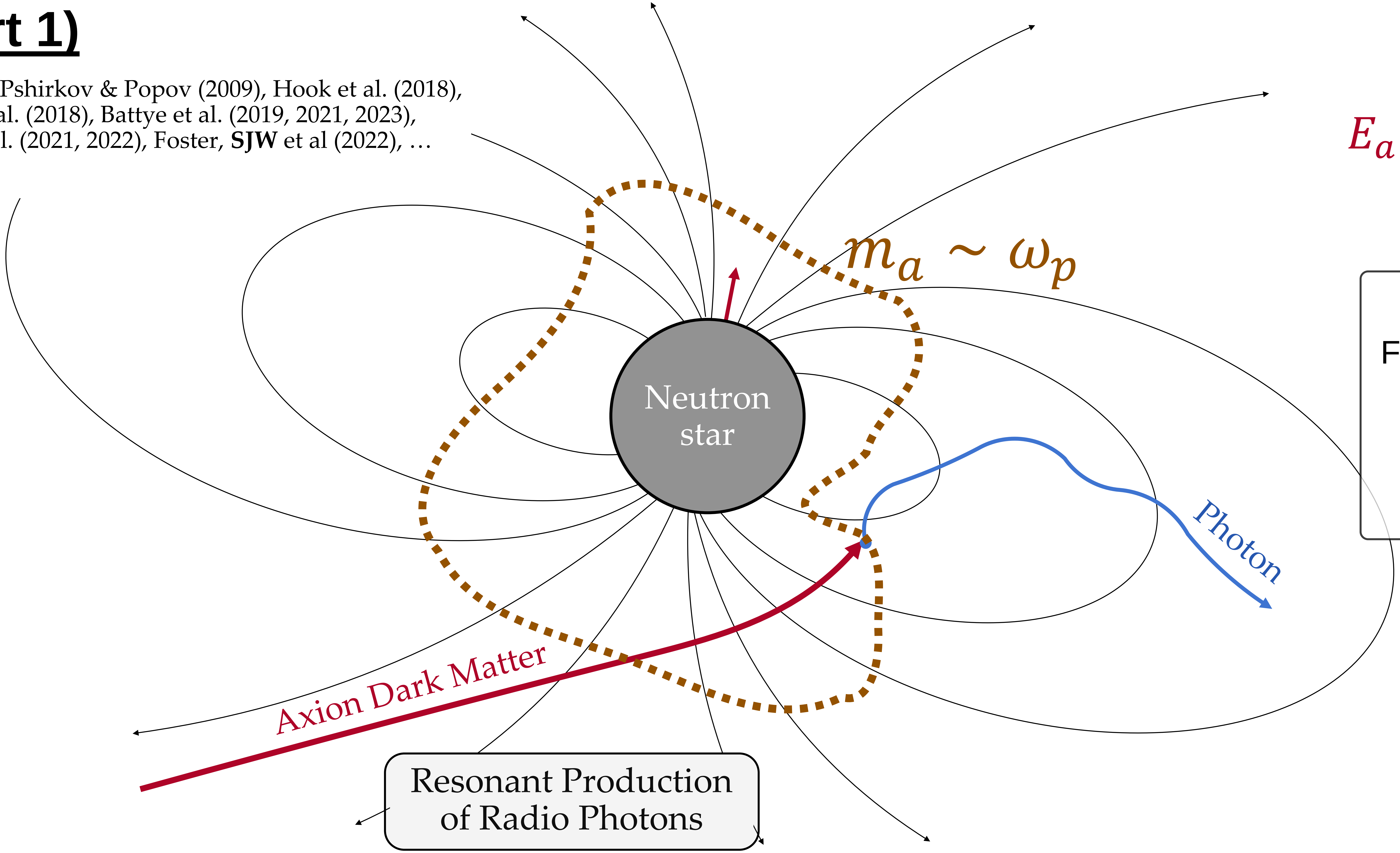
Part 2
Local production of axions



Radio Photons from Axion Dark Matter

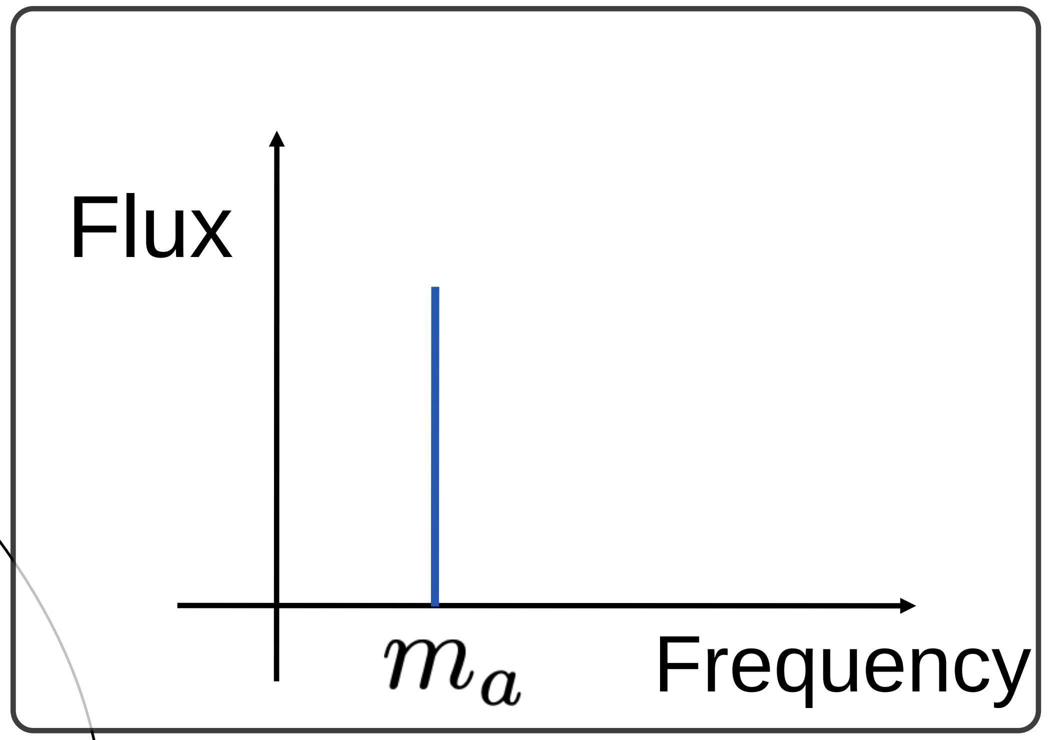
<u>(Part 1)</u>

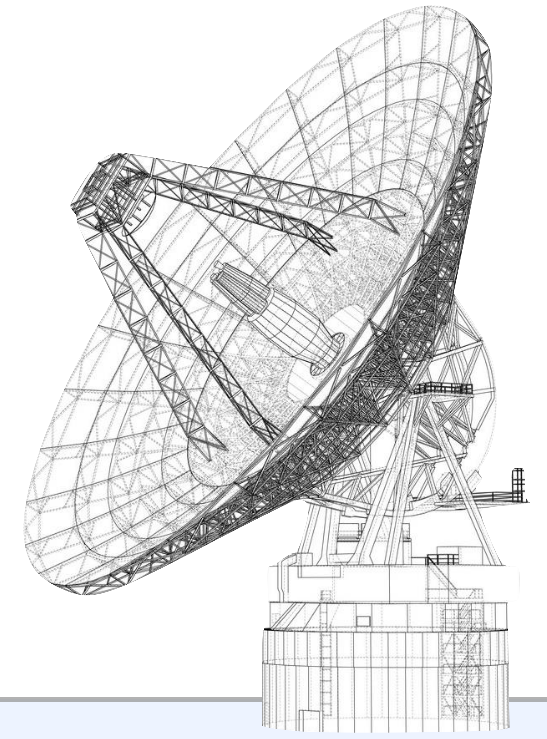
See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021, 2023), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), …



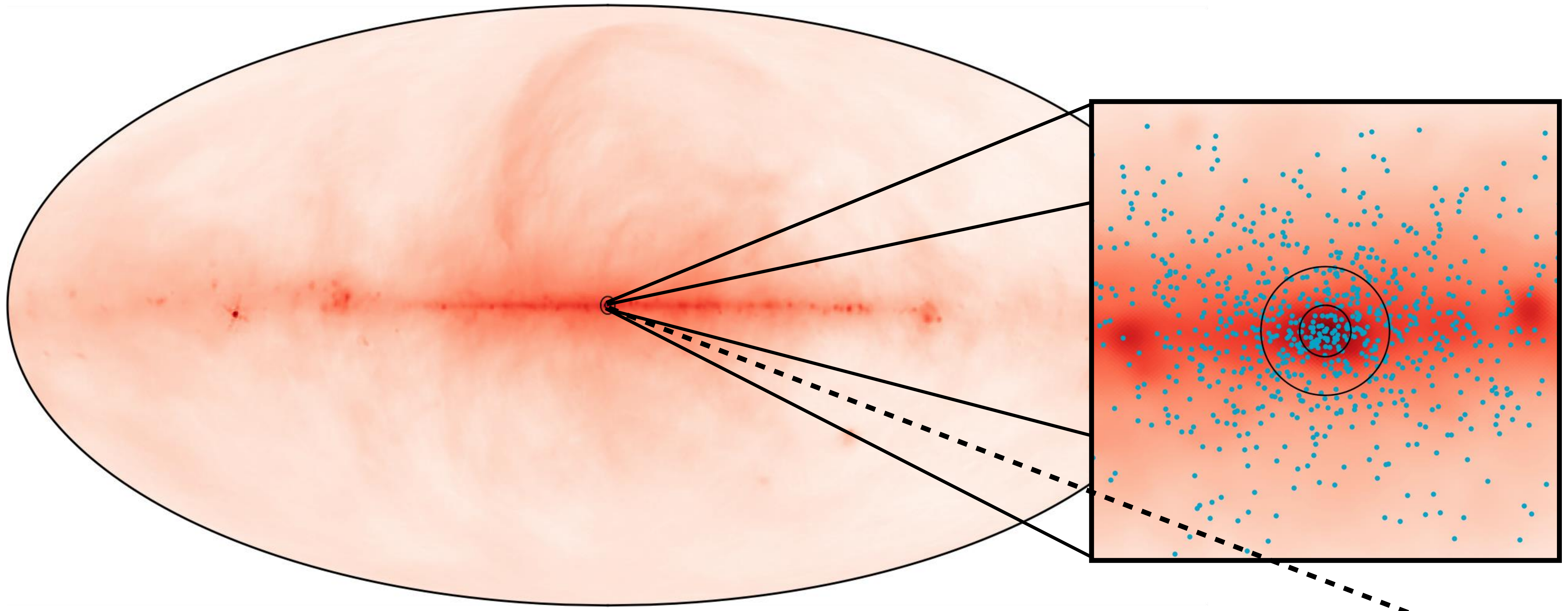
$E_a \sim m_a(1 + v^2/2)$

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





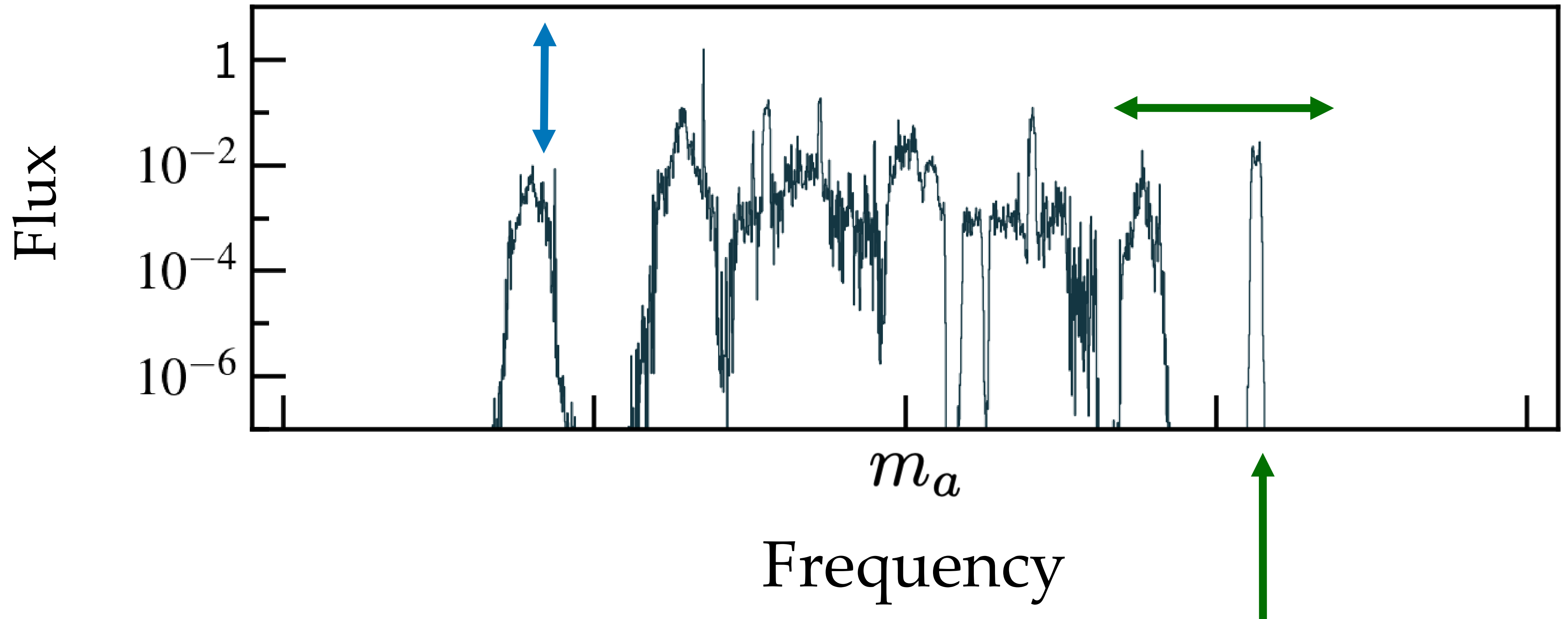
Radio searches for axions



Lines oscillate with rotation of star (seconds)

$\delta E \sim 10^{-3} m_a$

Lines shift with stellar orbit (weeks/months)



$\delta E \sim 10^{-5} m_a$

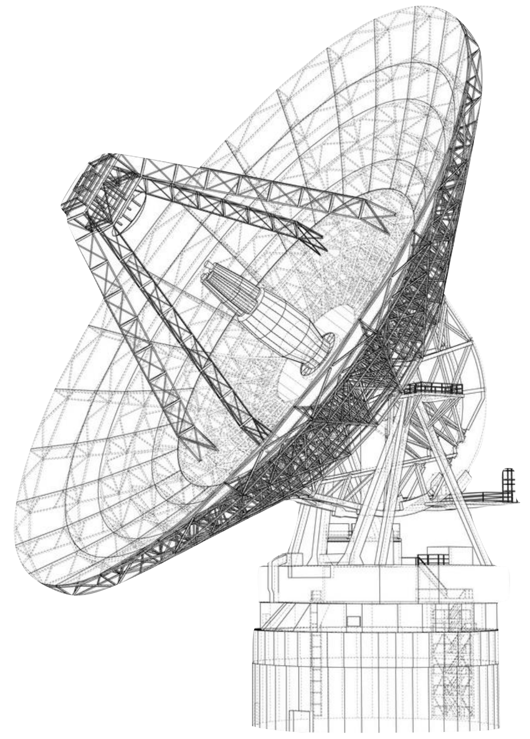
Targets:

- Galactic Center

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

- Nearby isolated neutron stars

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



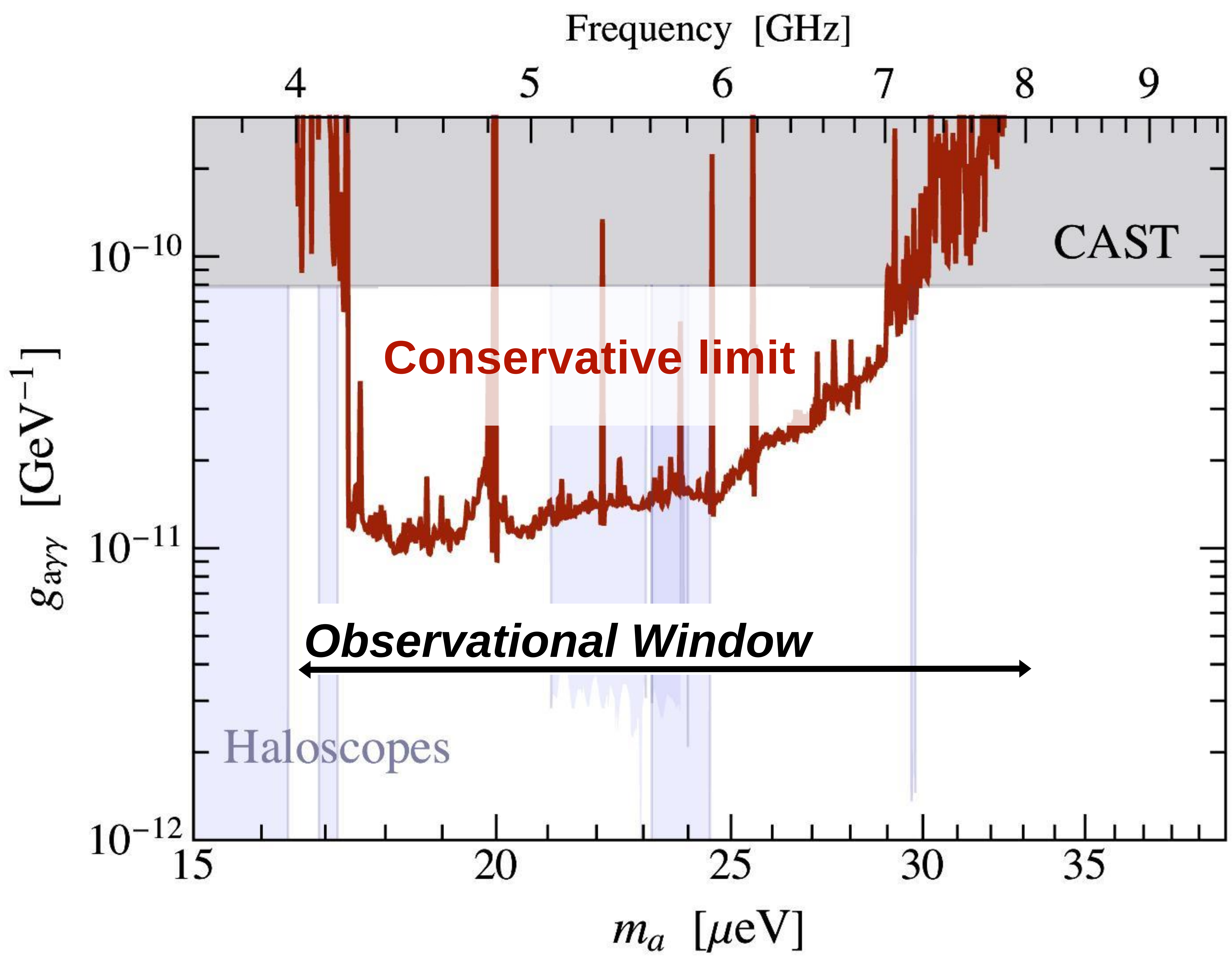
Searching for axions in the galactic center

<u>Survey Details:</u>

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

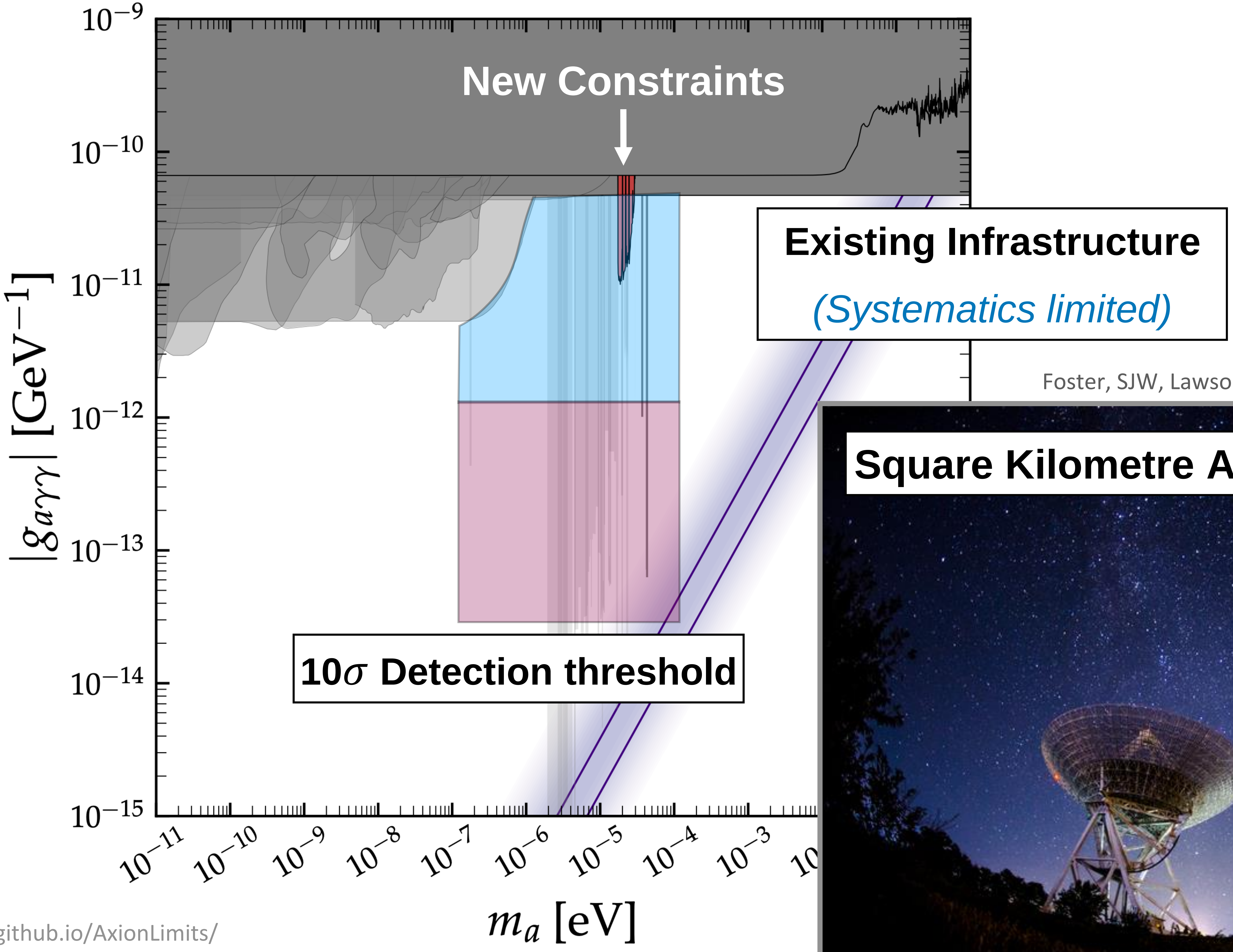
Backgrounds: Molecular lines, radio-frequency interference



(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



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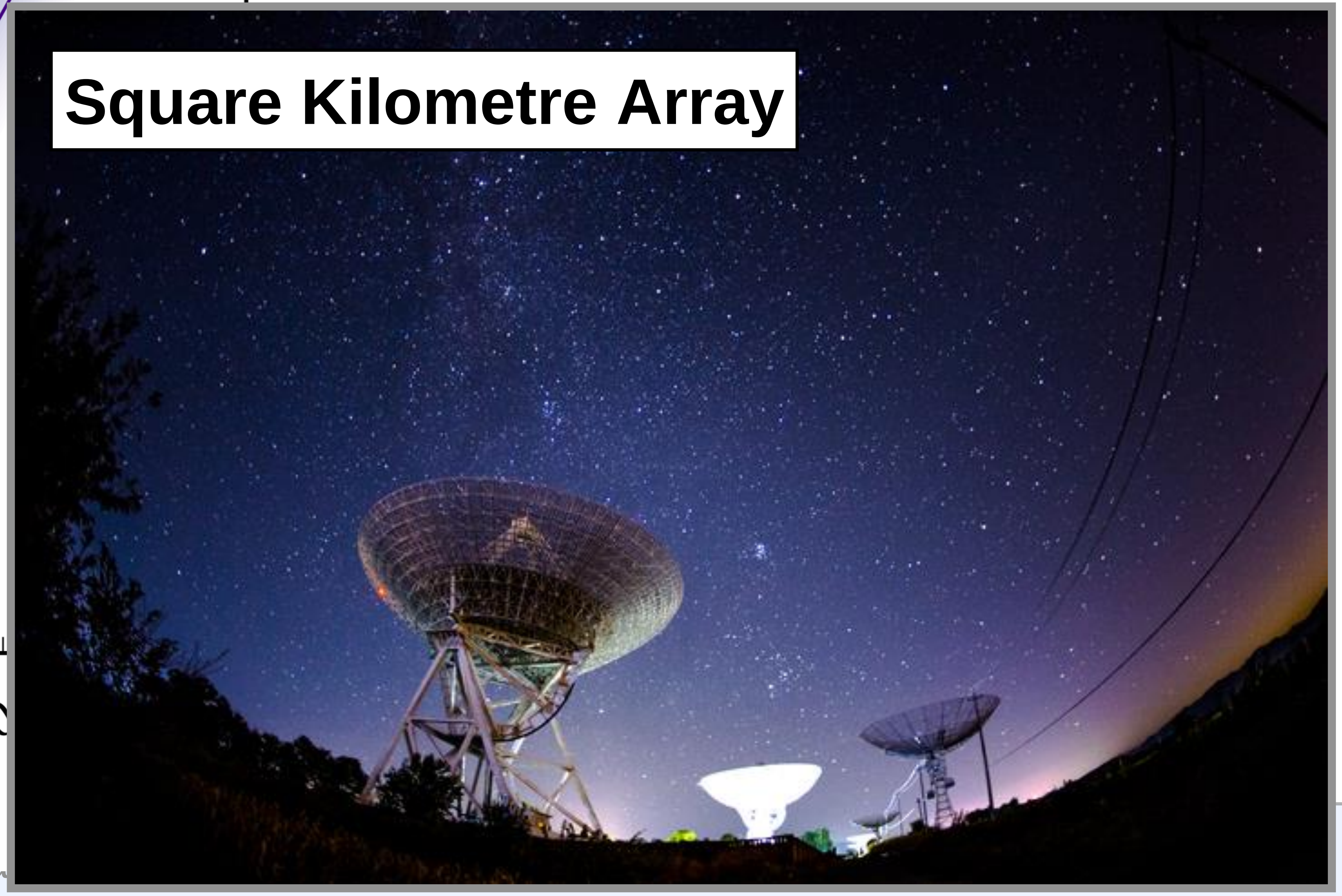


Plot made using cajohare.github.io/AxionLimits/
Date: Early 2022

Producing axions with electromagnetism

Advantage:

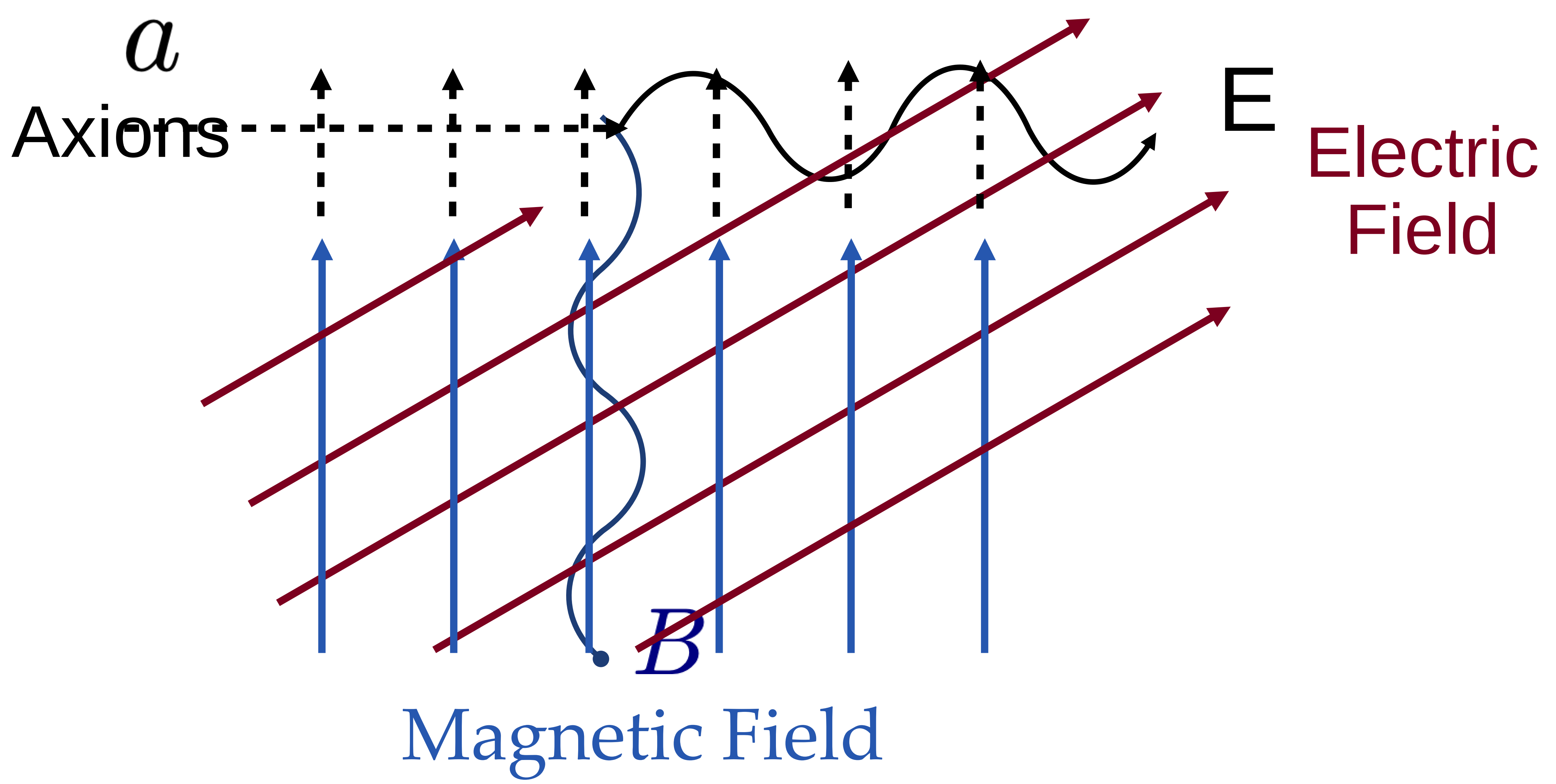
Remove dependence on dark matter density

- Larger axion densities
- Target nearby pulsar population

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

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

$\vec{B}$ + $\vec{E}$ → Axion

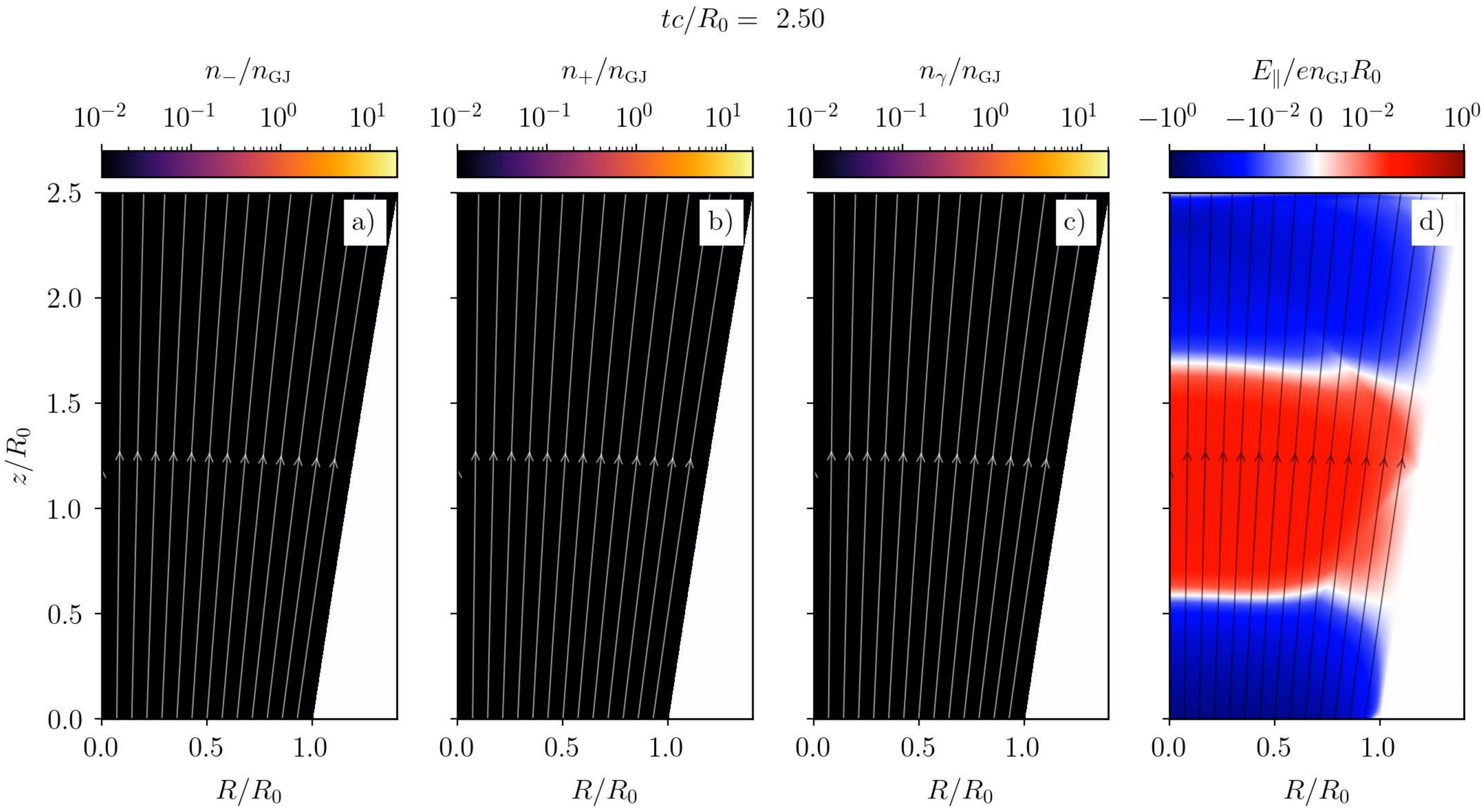


Locally sourced axions

(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)

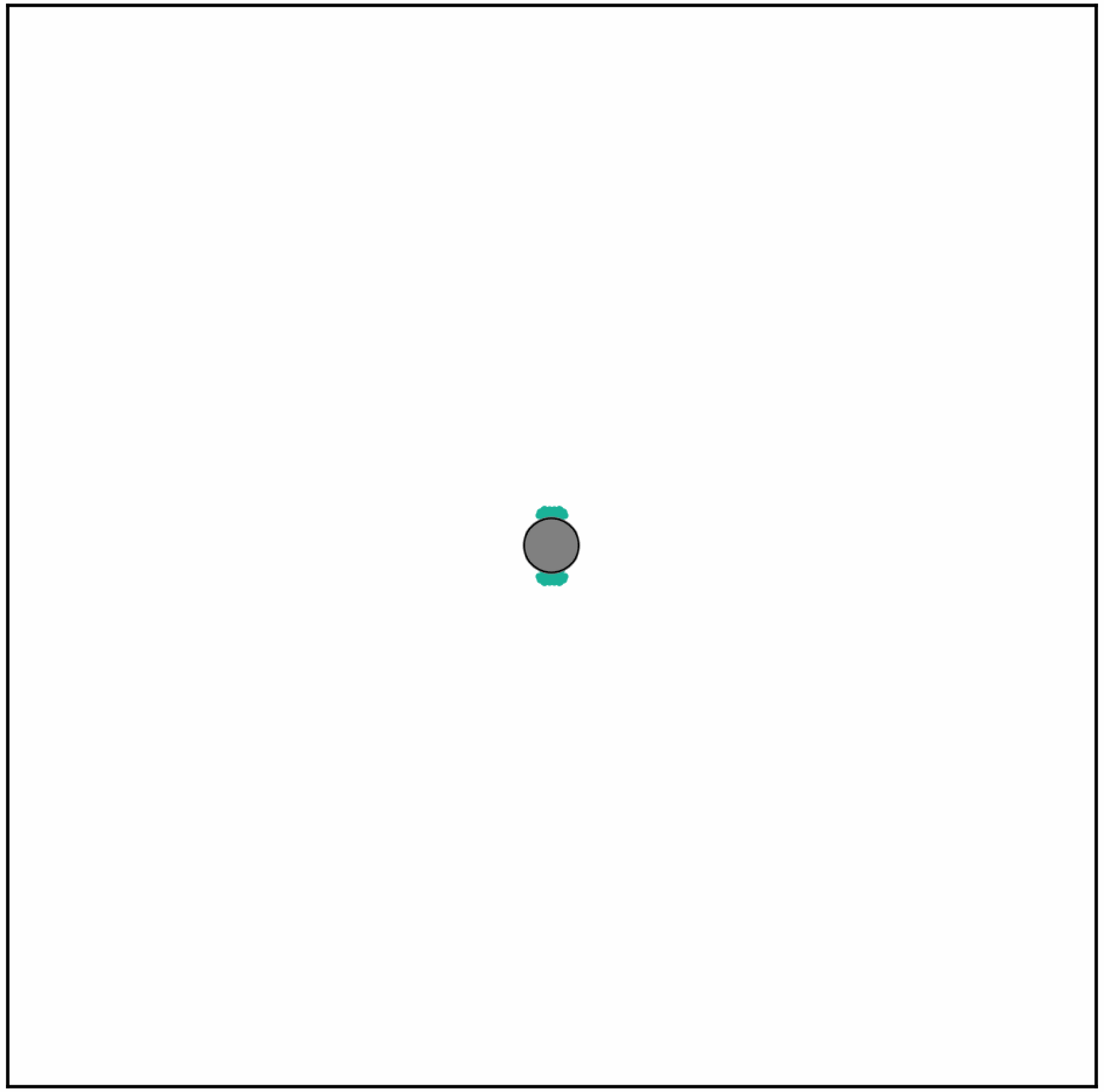
Pair production in the polar caps



MHz-GHz fluctuations source axions with MHz-GHz energies

Simulations curtesy of F. Cruz and A. Chen

Locally sourced axions



Axions *Photons*

Relativistic axion population

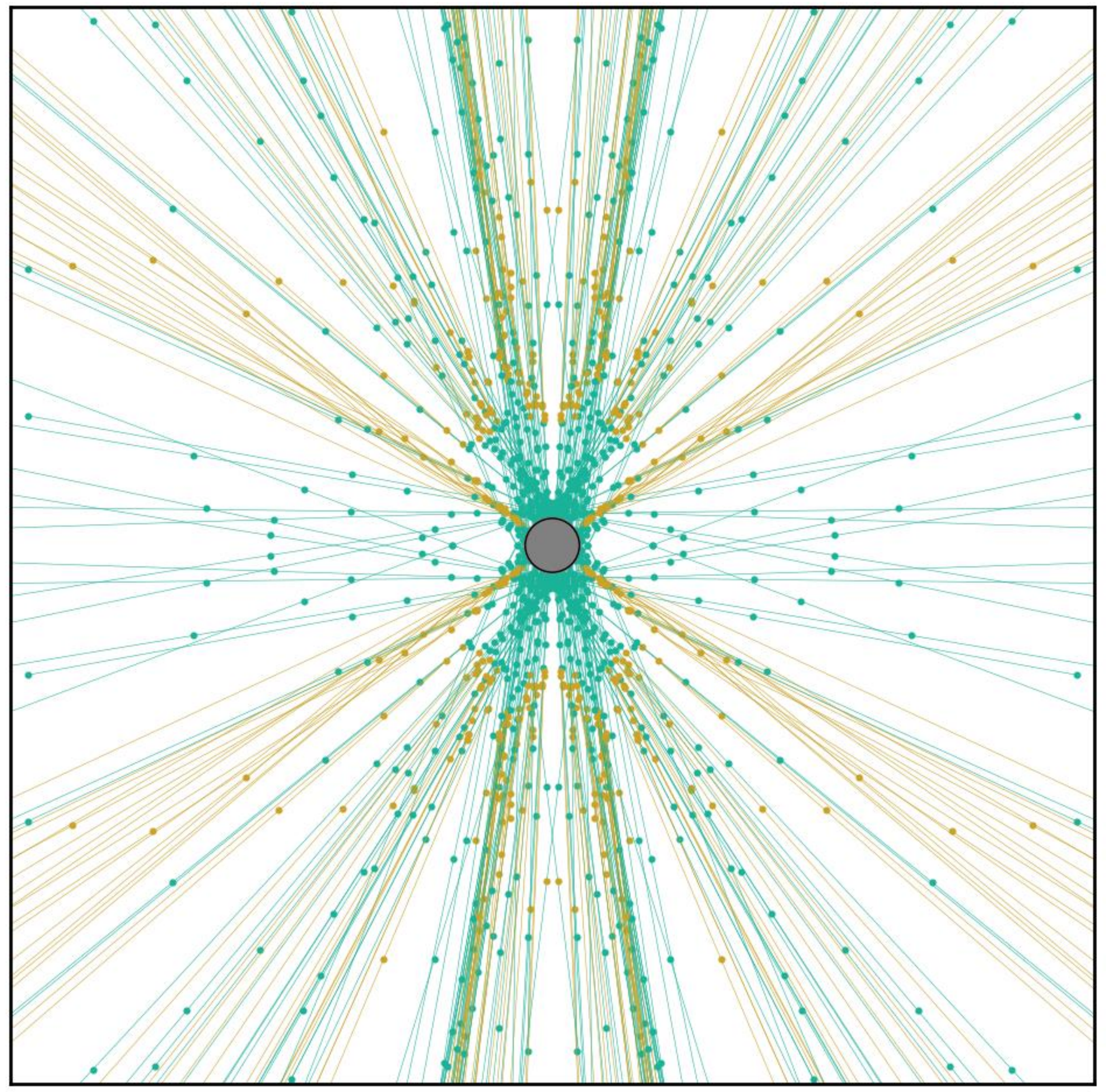
Axions free stream away from neutron star

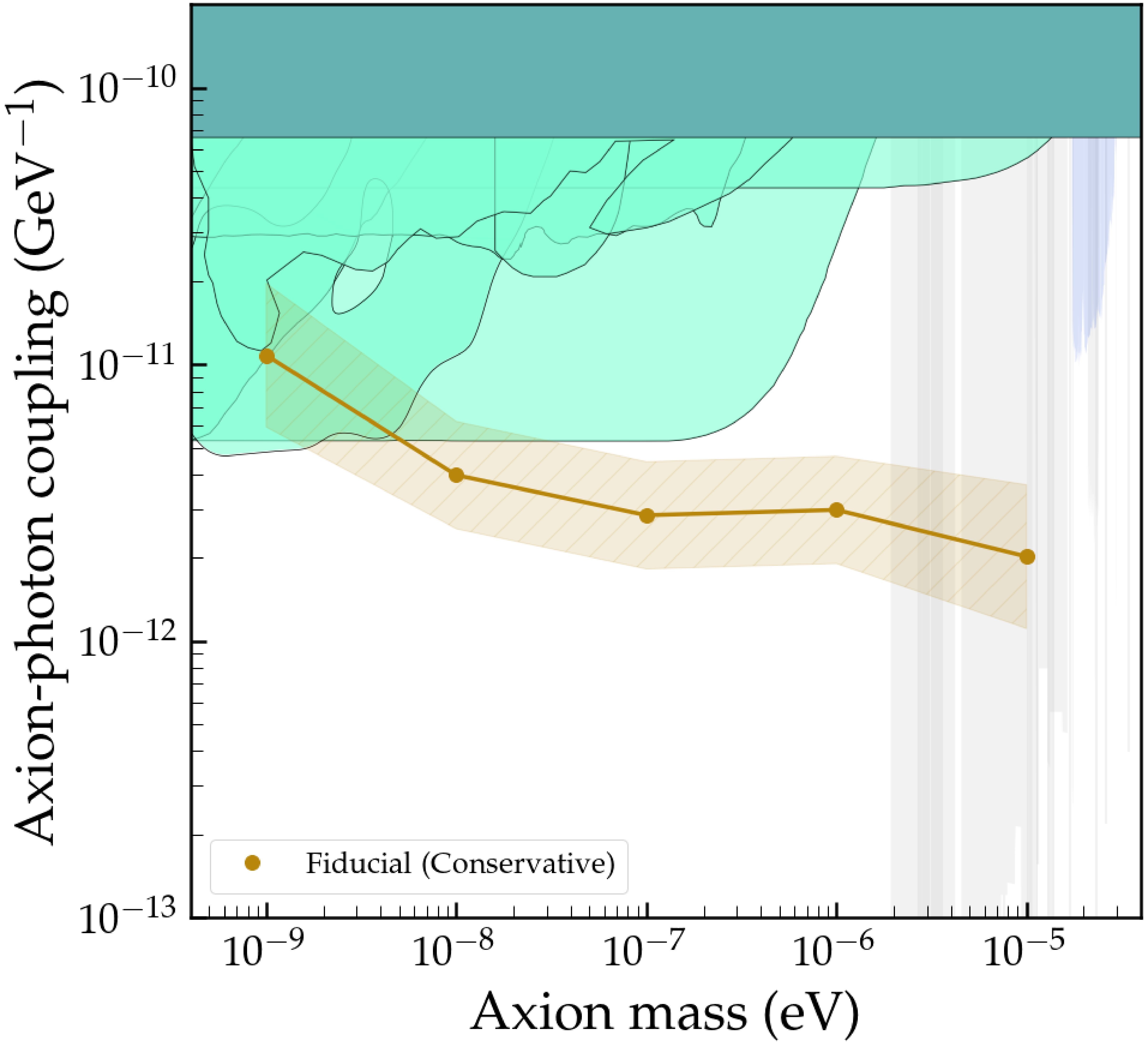
↓

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)

Locally sourced axions

Non-relativistic axion population

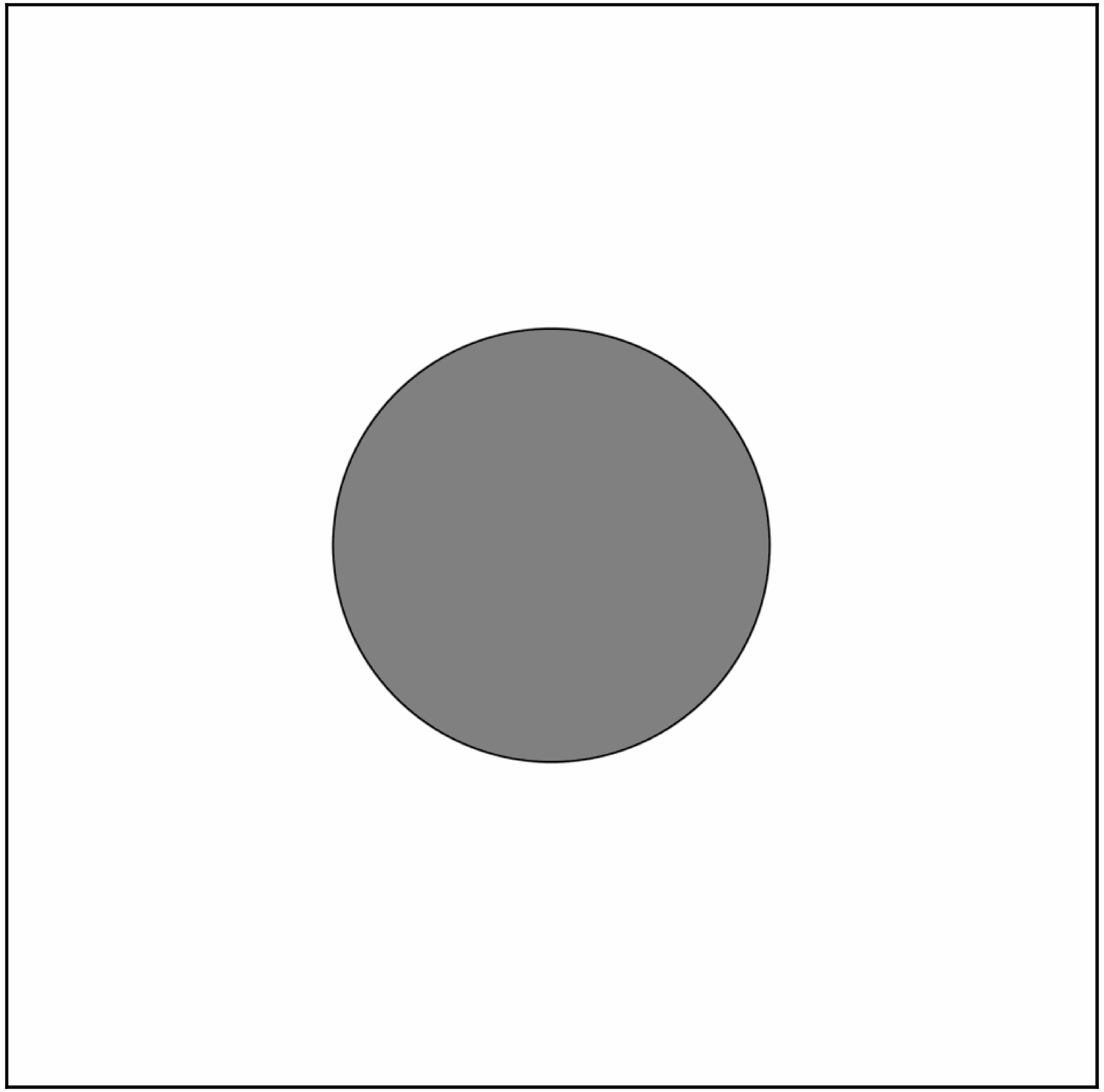
A sizeable fraction of the axion population will be *gravitationally bound* to the neutron star

↓

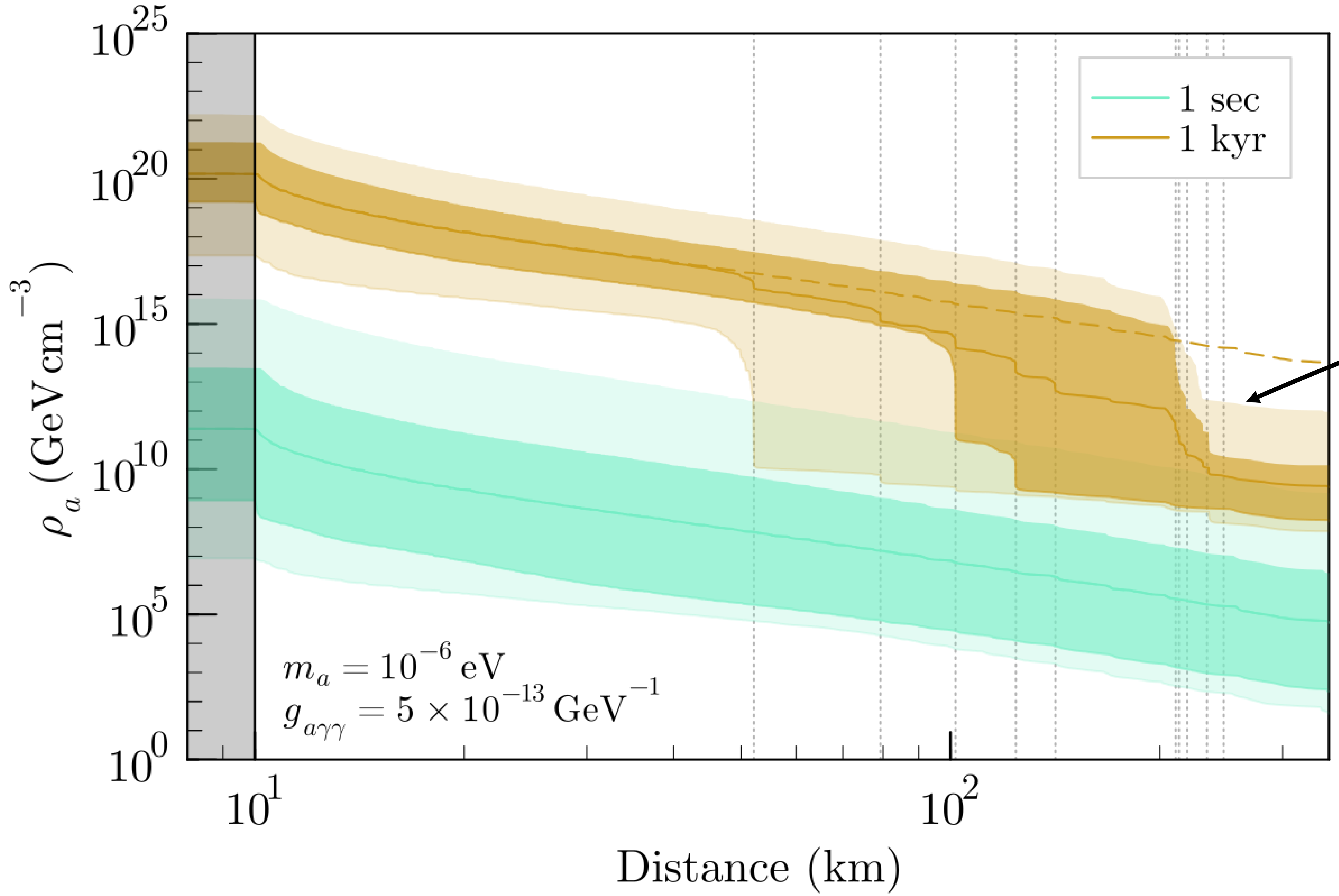
Can accumulate on kyr timescales

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

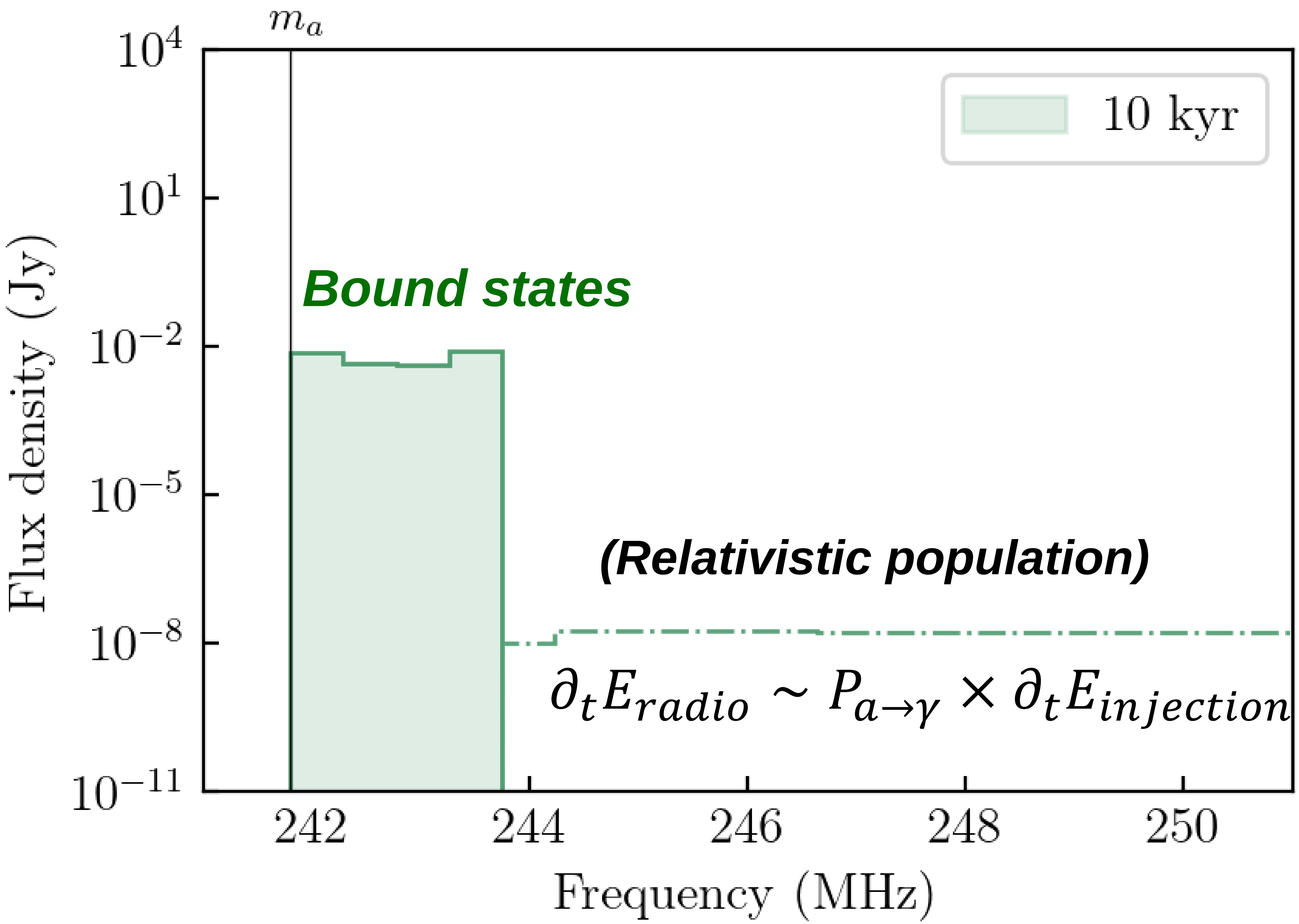
Noordhuis, Prabhu, Weniger, SJW(Appearing soon)

Radio emission of bound cloud

Sharp kinematic endpoint inevitably arises in radio spectrum

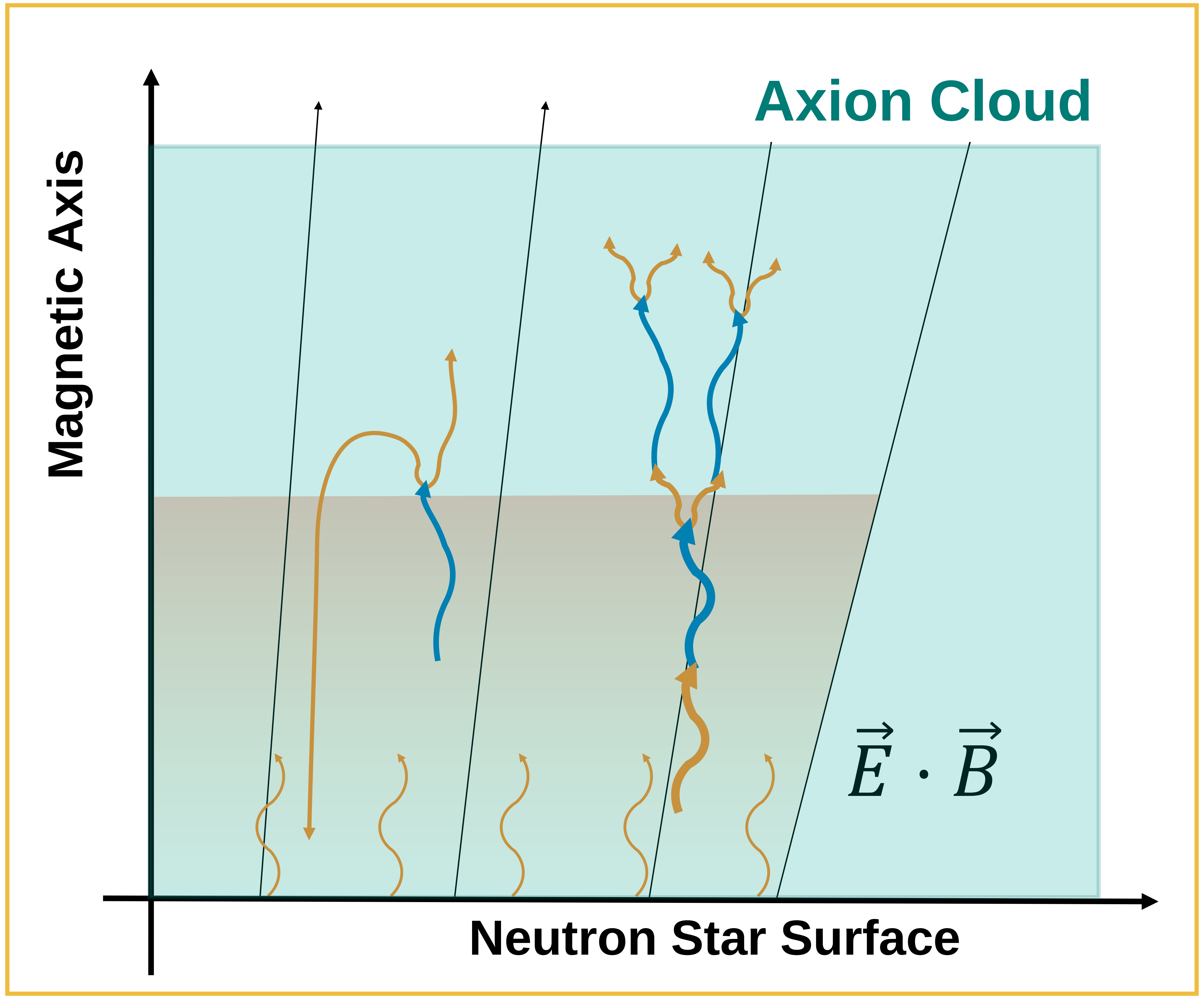
<u>Equilibrium Condition</u>

$$\partial_t\, E_{radio} \sim \partial_t\, E_{injection}$$



Noordhuis, Prabhu, Weniger, SJW(Appearing soon)

Axion back-reaction



<u>Axions directly modify Maxwell's Equations</u>

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

$$\nabla \times B - \partial_t E = J + gB\, \partial_t a - \nabla a \times E$$

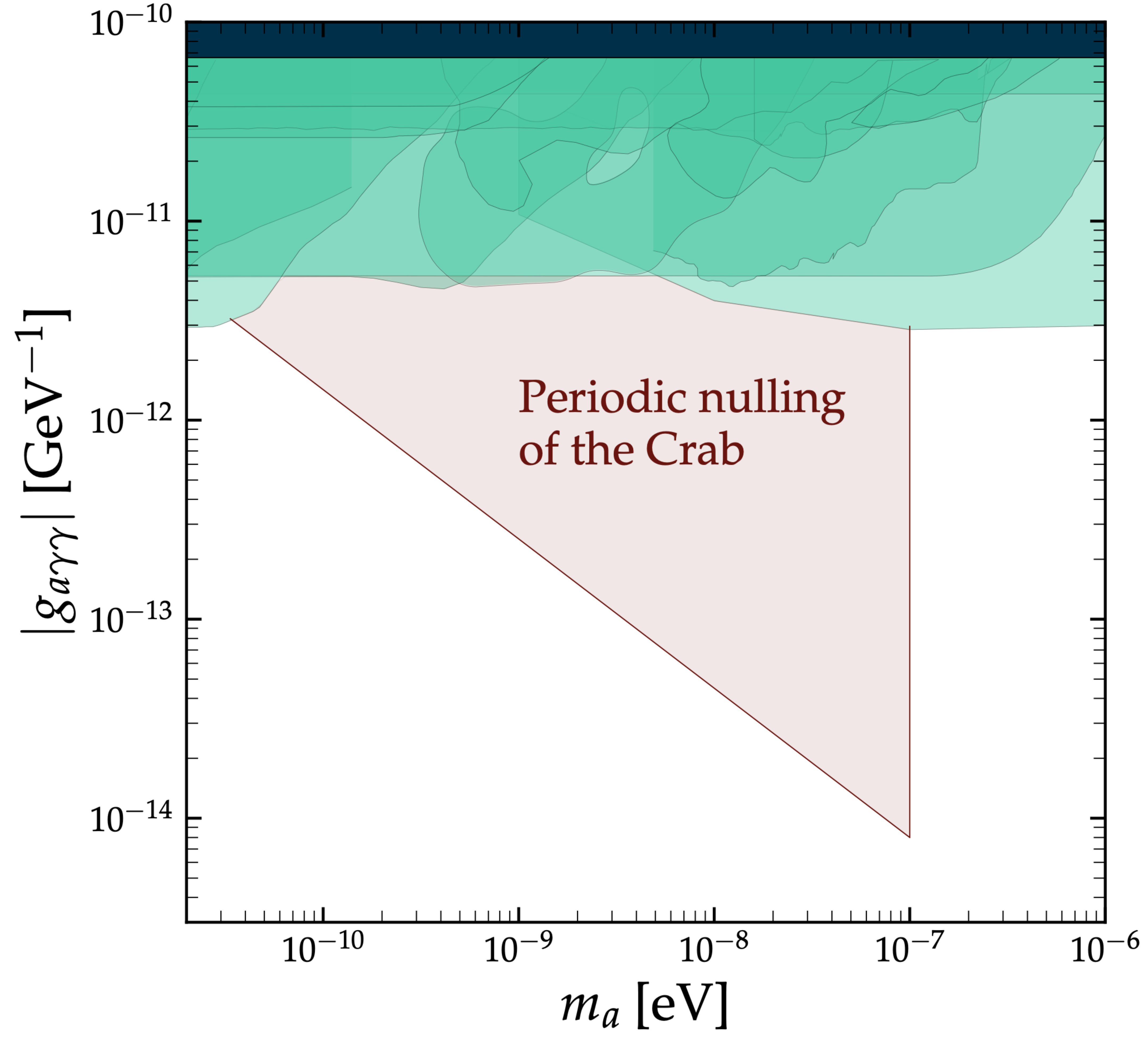
Large axion densities back-react on electrodynamics

Axion clouds can induce periodic nulling of radio emission

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

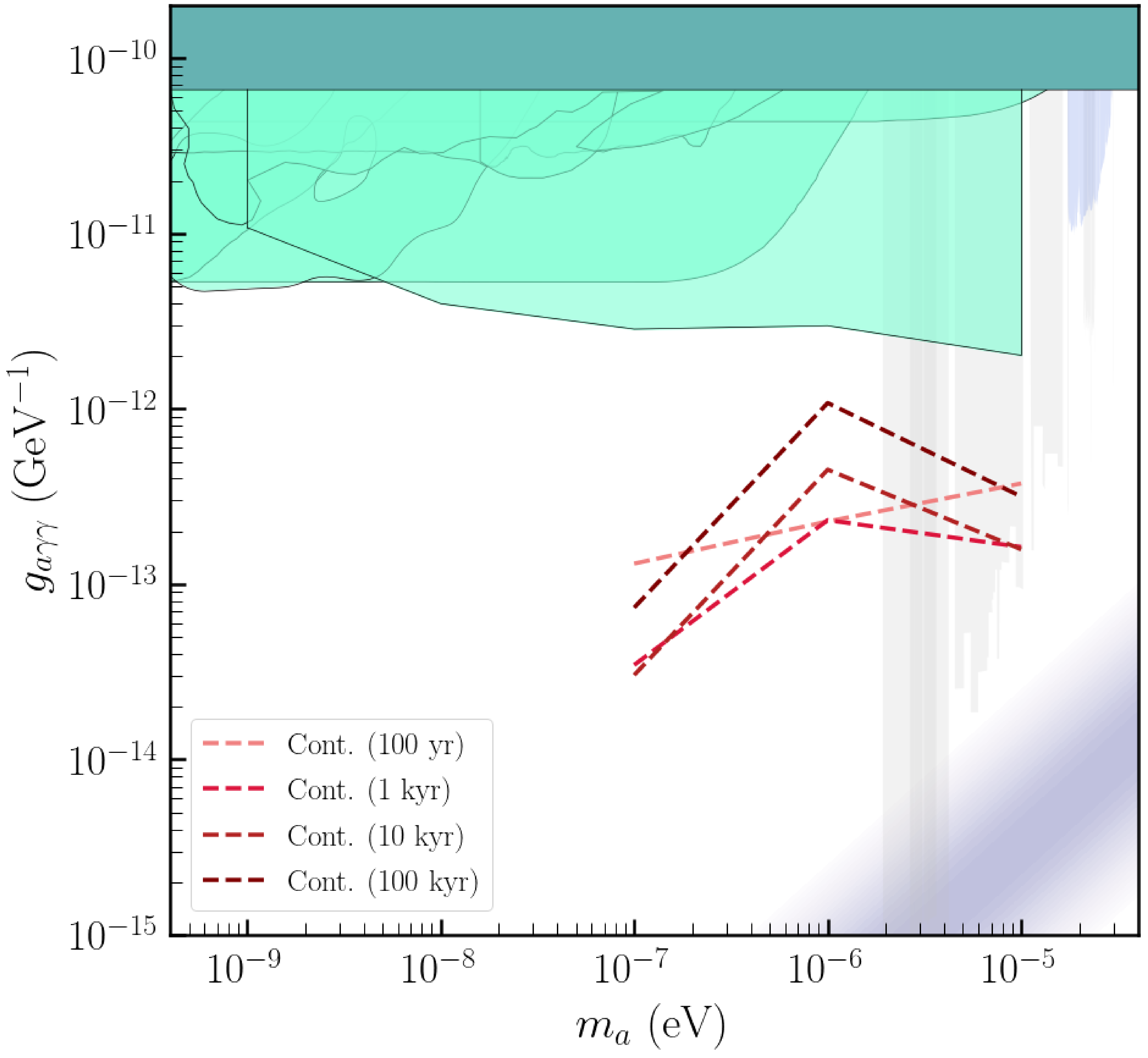
Future outlook

Axion back-reaction



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

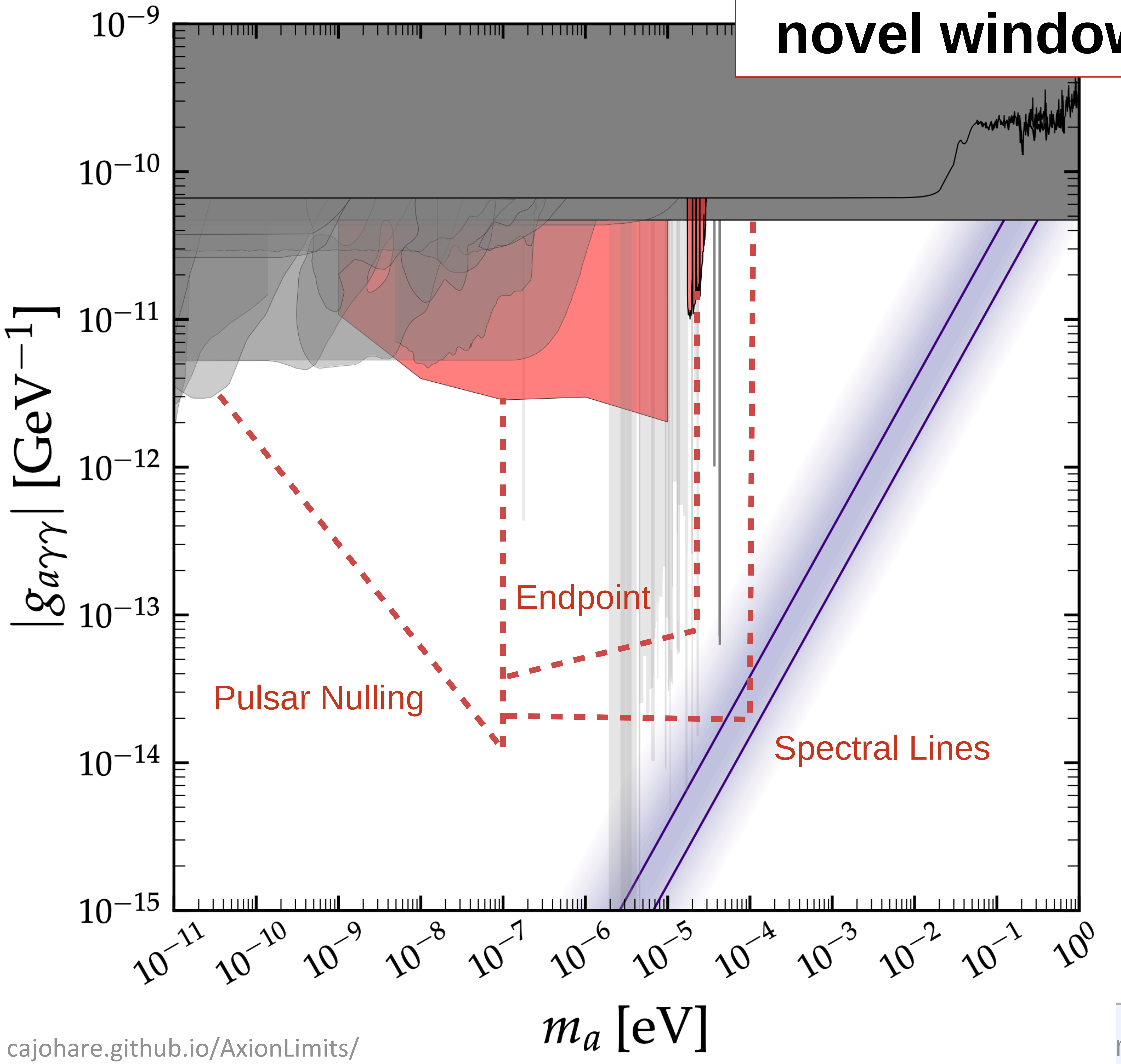
Endpoint in radio spectrum



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

Conclusions

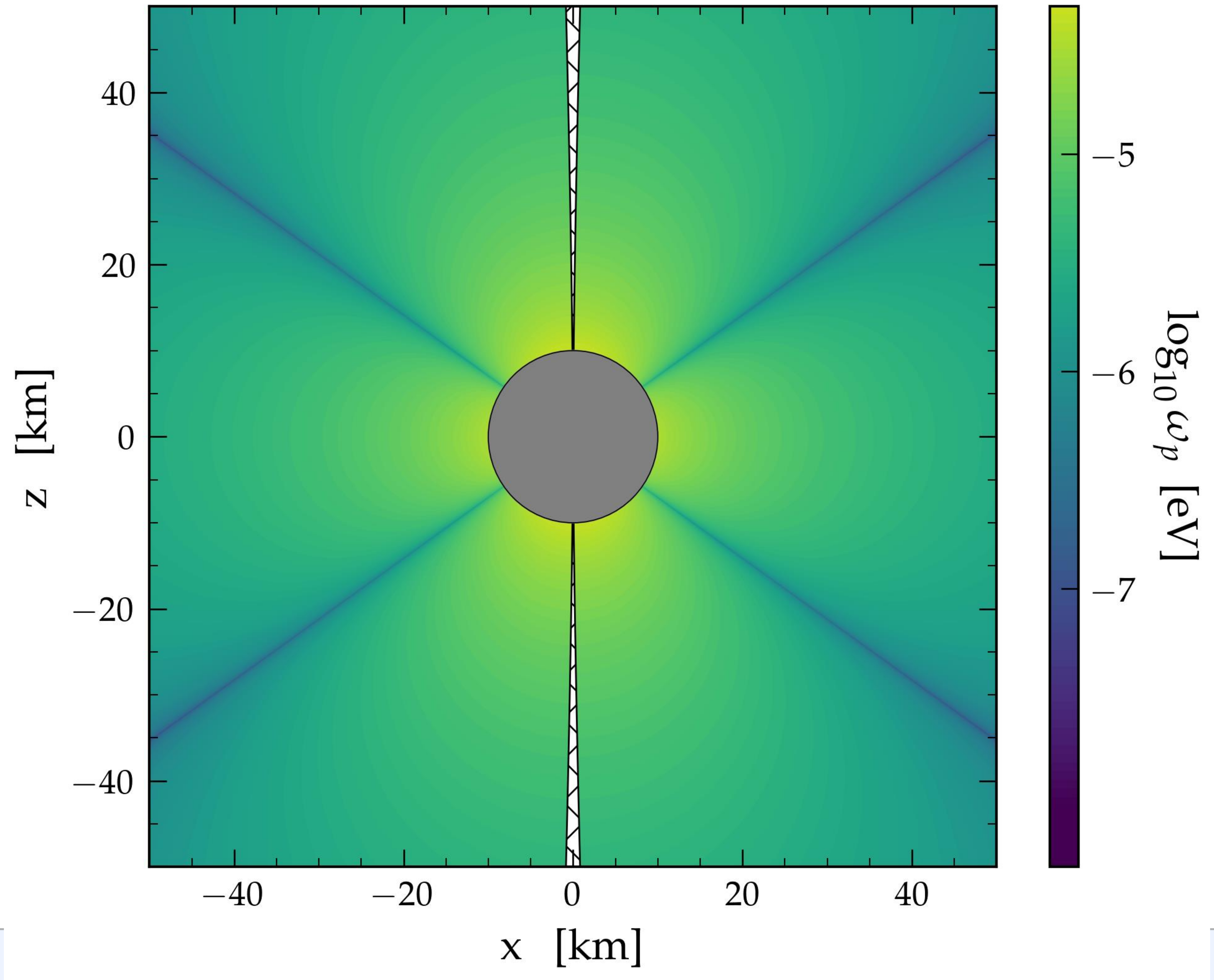
Neutron star magnetospheres are opening novel window in indirect search for axions



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

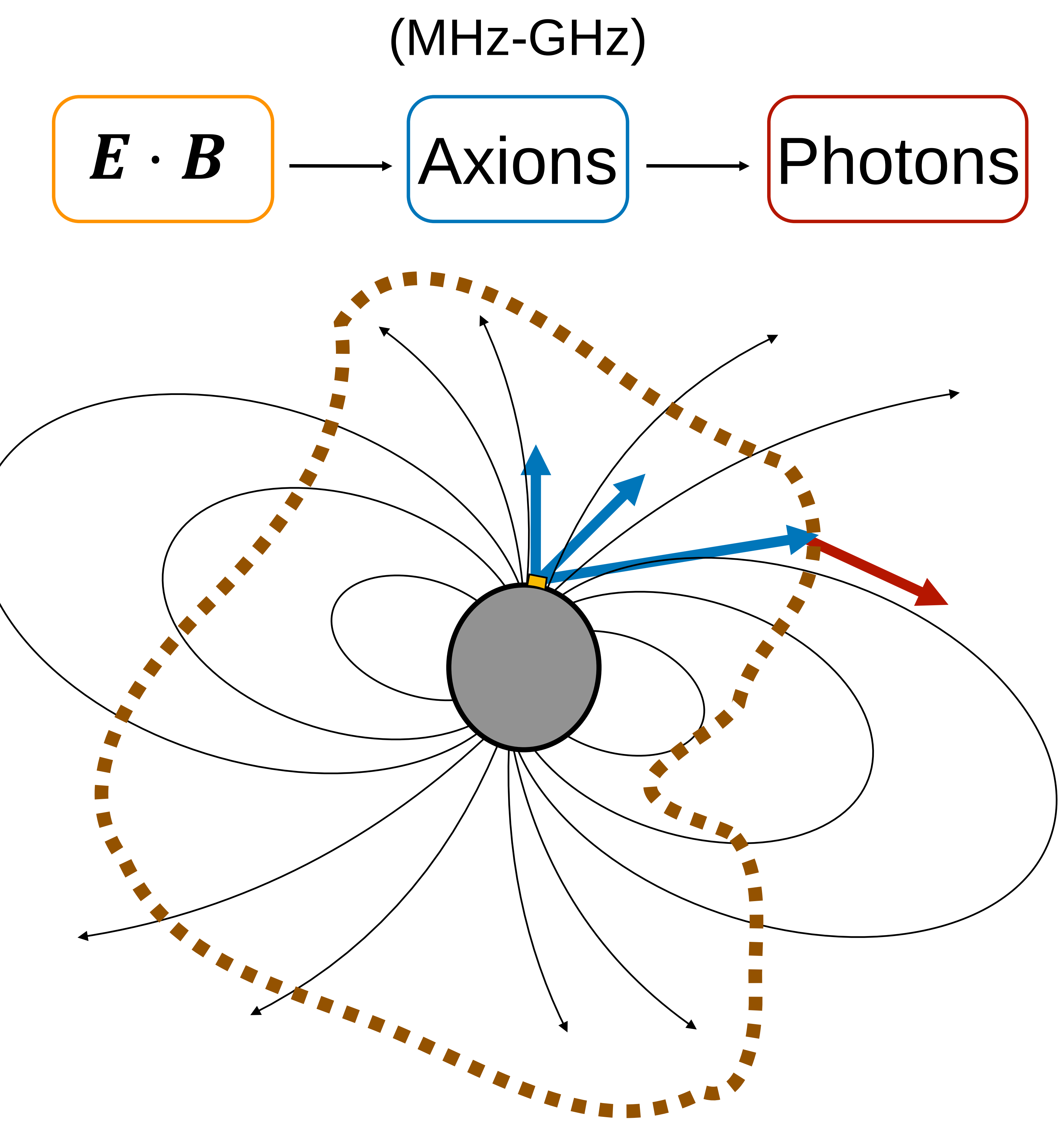
Plot made using cajohare.github.io/AxionLimits/

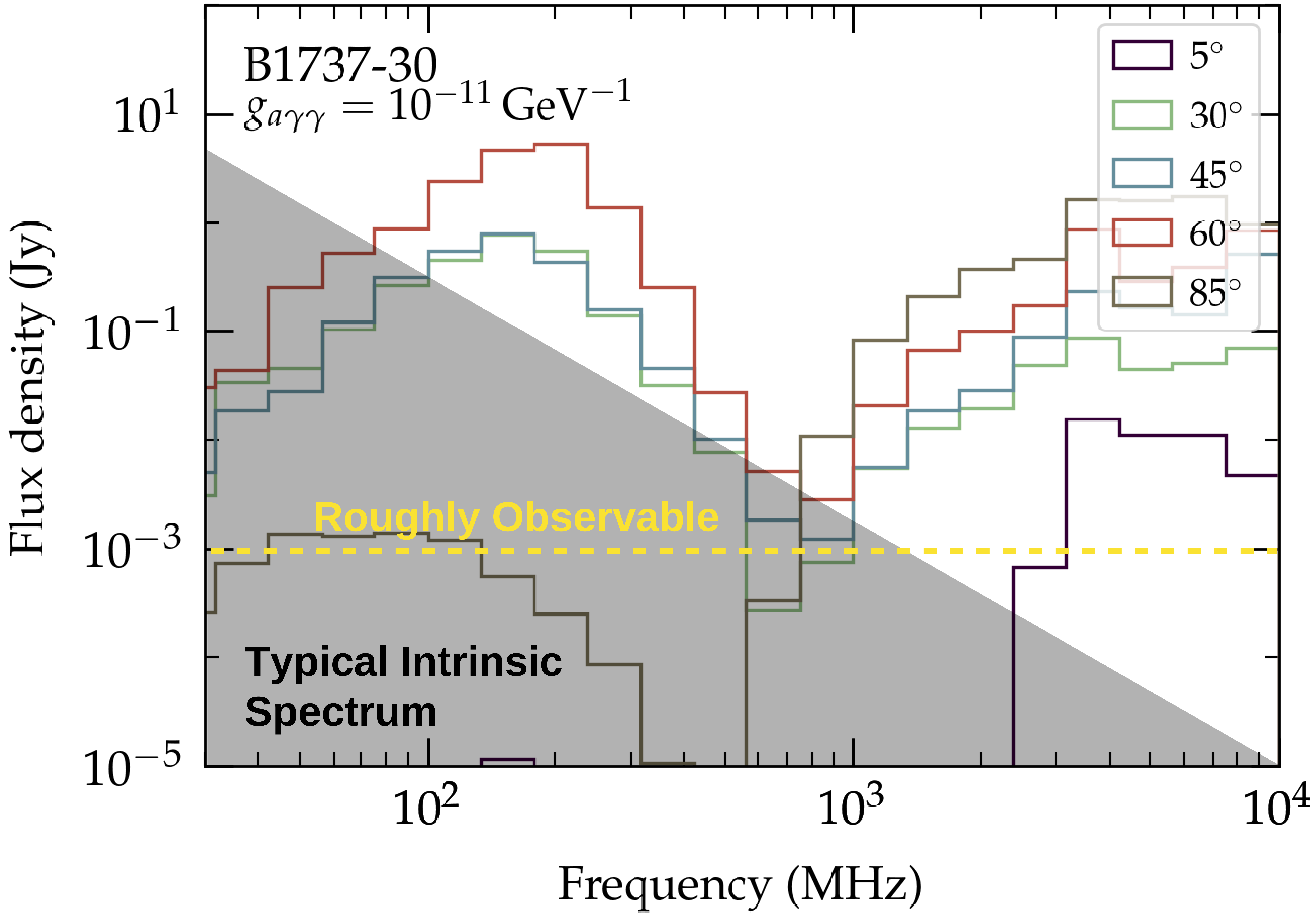
Back-Up



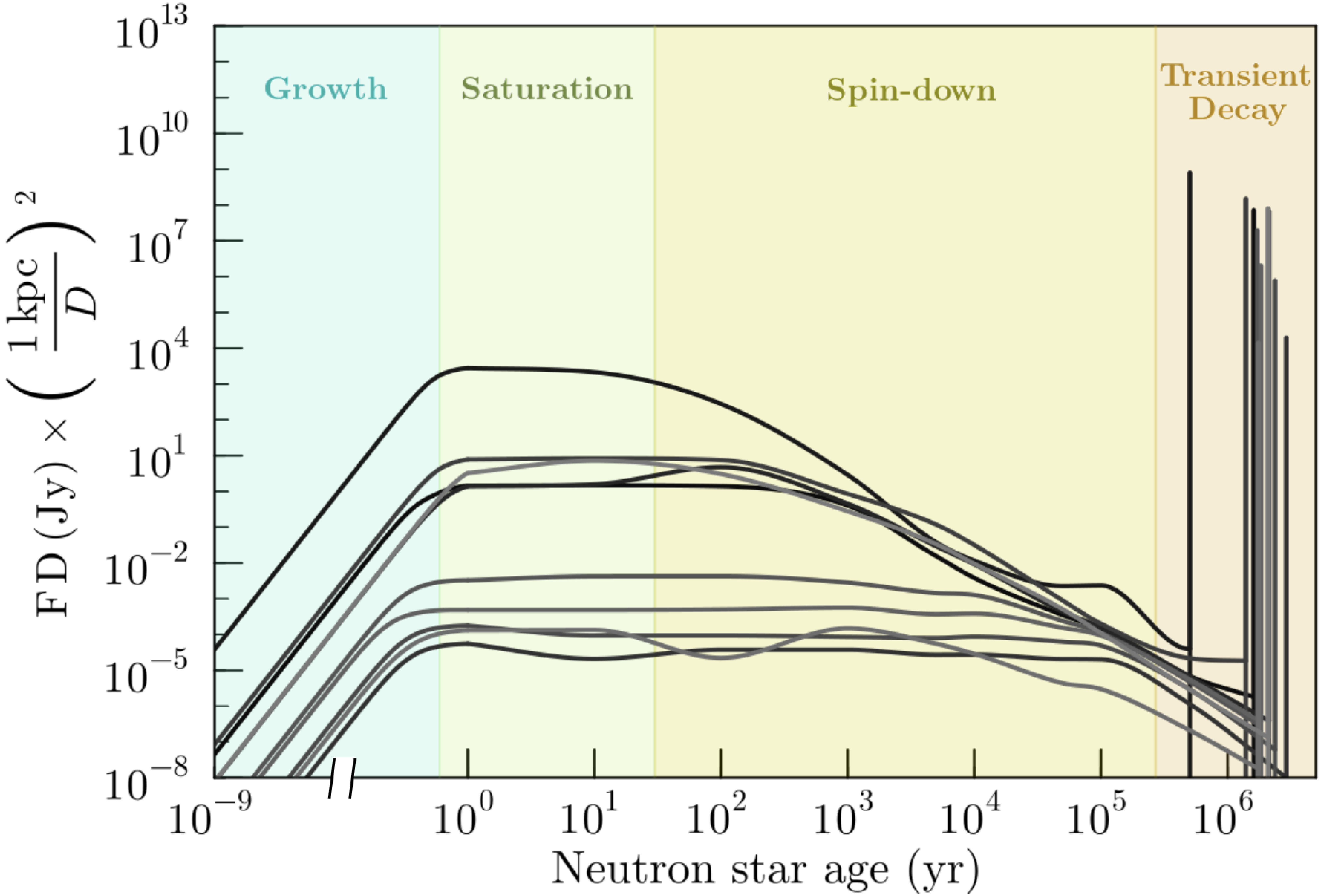
40
20
0
−20
−40
z [km]
−40
−20
0
20
40
x [km]
−5
−6
−7
$\log_{10} \omega_p$ [eV]

Radio spectrum

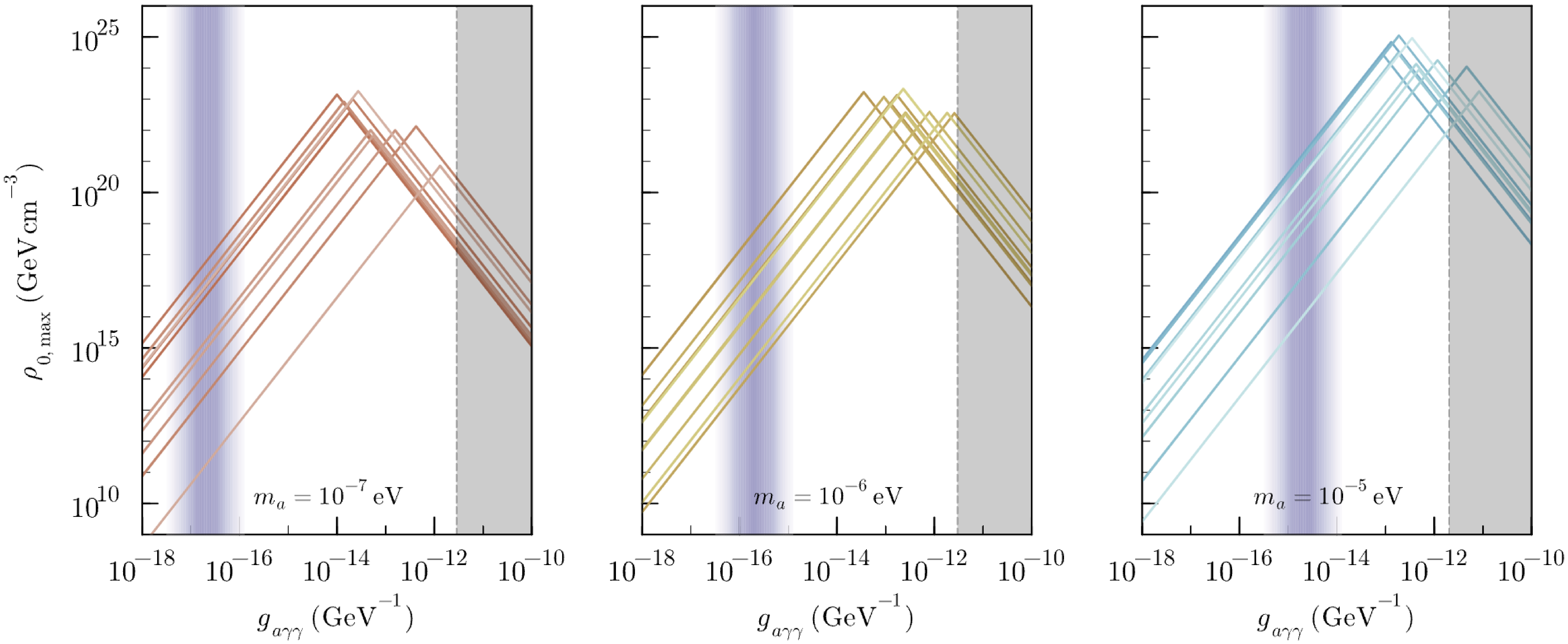




Noordhuis, Prabhu, SJW, Chen, Cruz, Weniger (2022)



Noordhuis, Prabhu, Weniger, SJW(To appear)



Noordhuis, Prabhu, Weniger, SJW(To appear)

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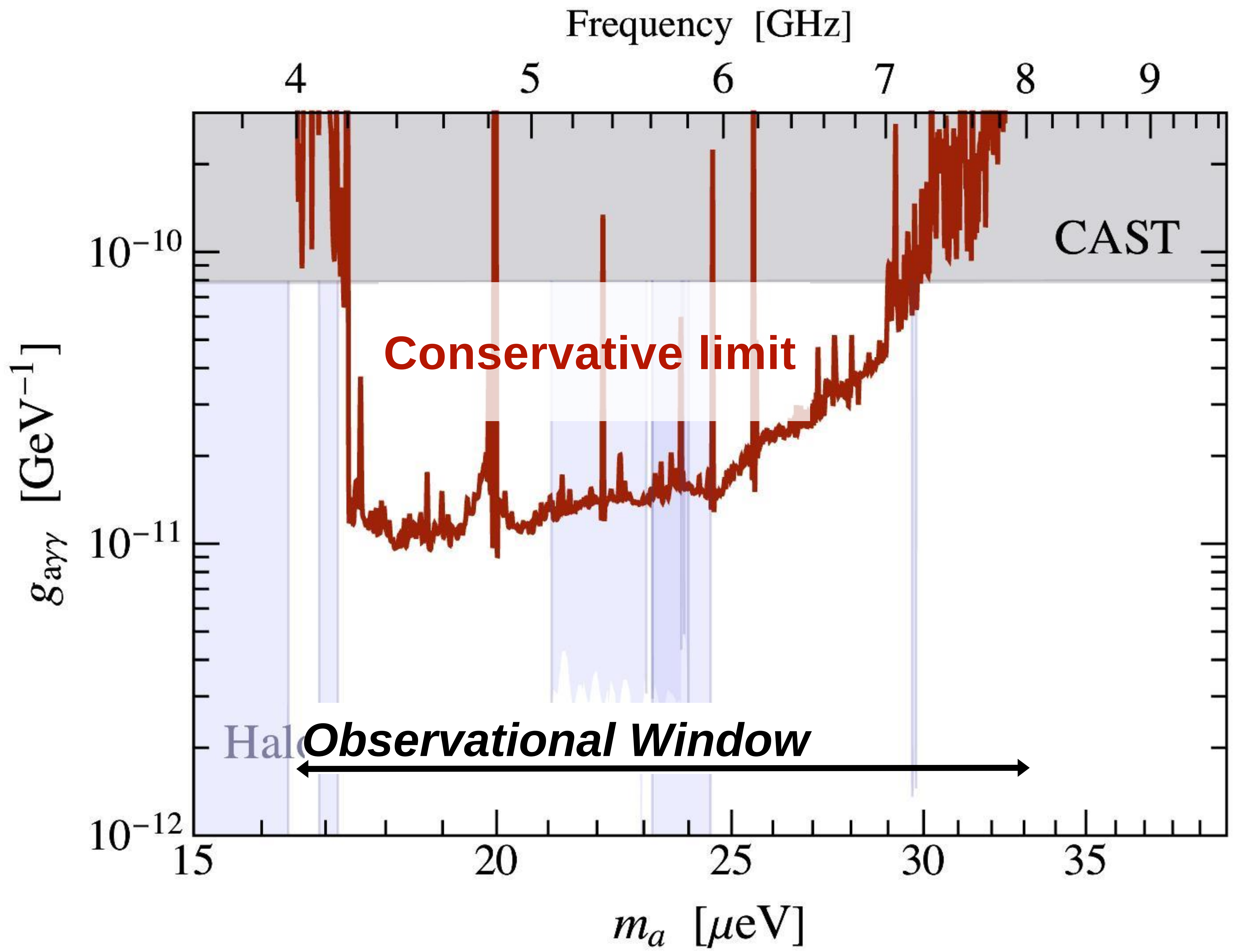


Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

What does "<u>conservative</u>" mean?

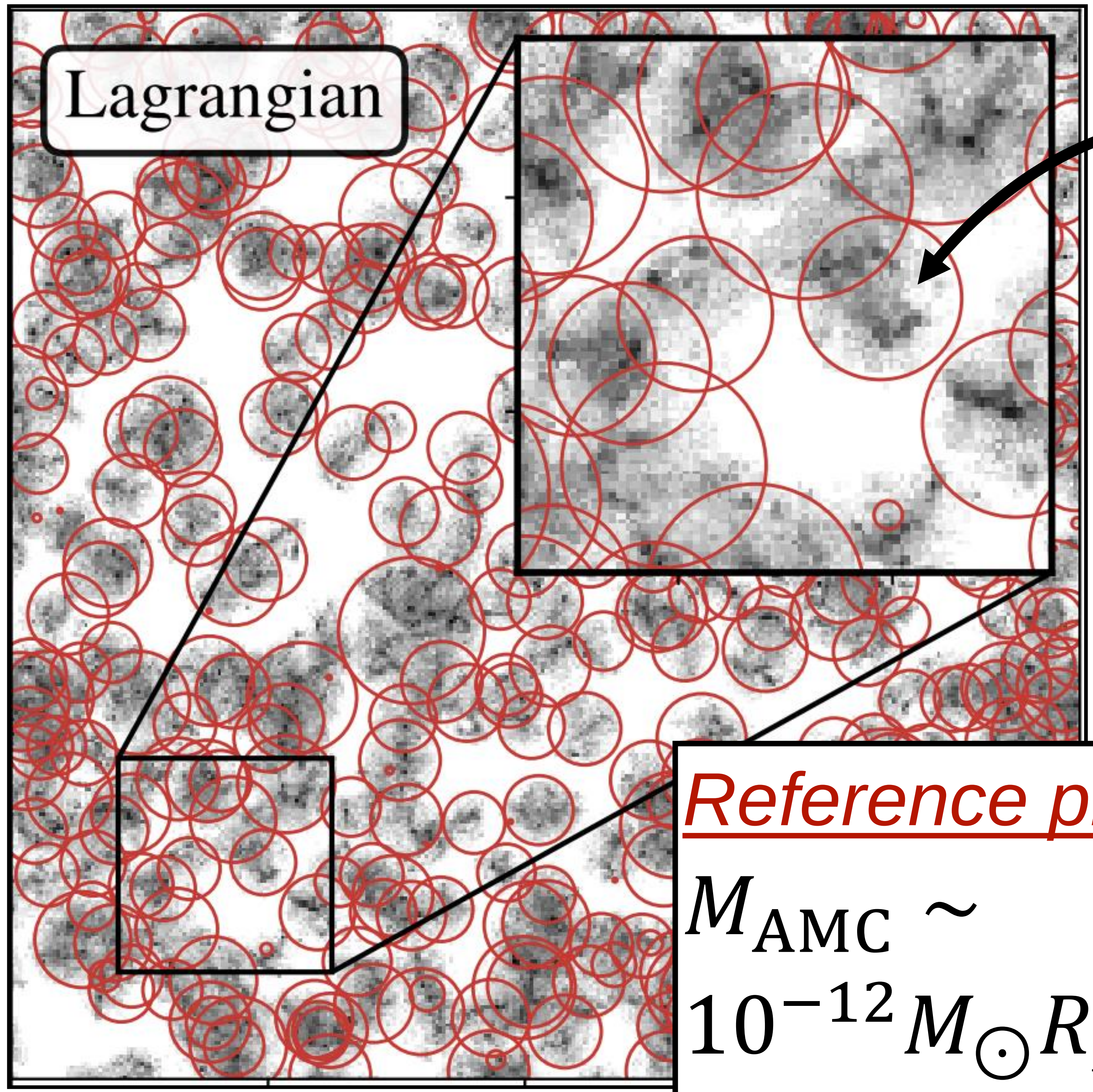
- We don't fully understand mixing
  - $p_{a\to\gamma}^{\mathrm{eff}} \sim \mathcal{O}(10^{-2}) \times p_{a\to\gamma}$
- We don't understand magnetic field decay in neutron stars
  - Exponential decay on 1 My
- We don't understand the adiabatic regime
  - Exponentially suppress flux

Tjemsland, SJW, McDonald (To appear)

ASIDE: Transient radio lines from axion miniclusters

Rare encounters of miniclusters/stars with neutron stars generate transient radio lines

Density field at matter-radiation equality



Ellis et al (2022)

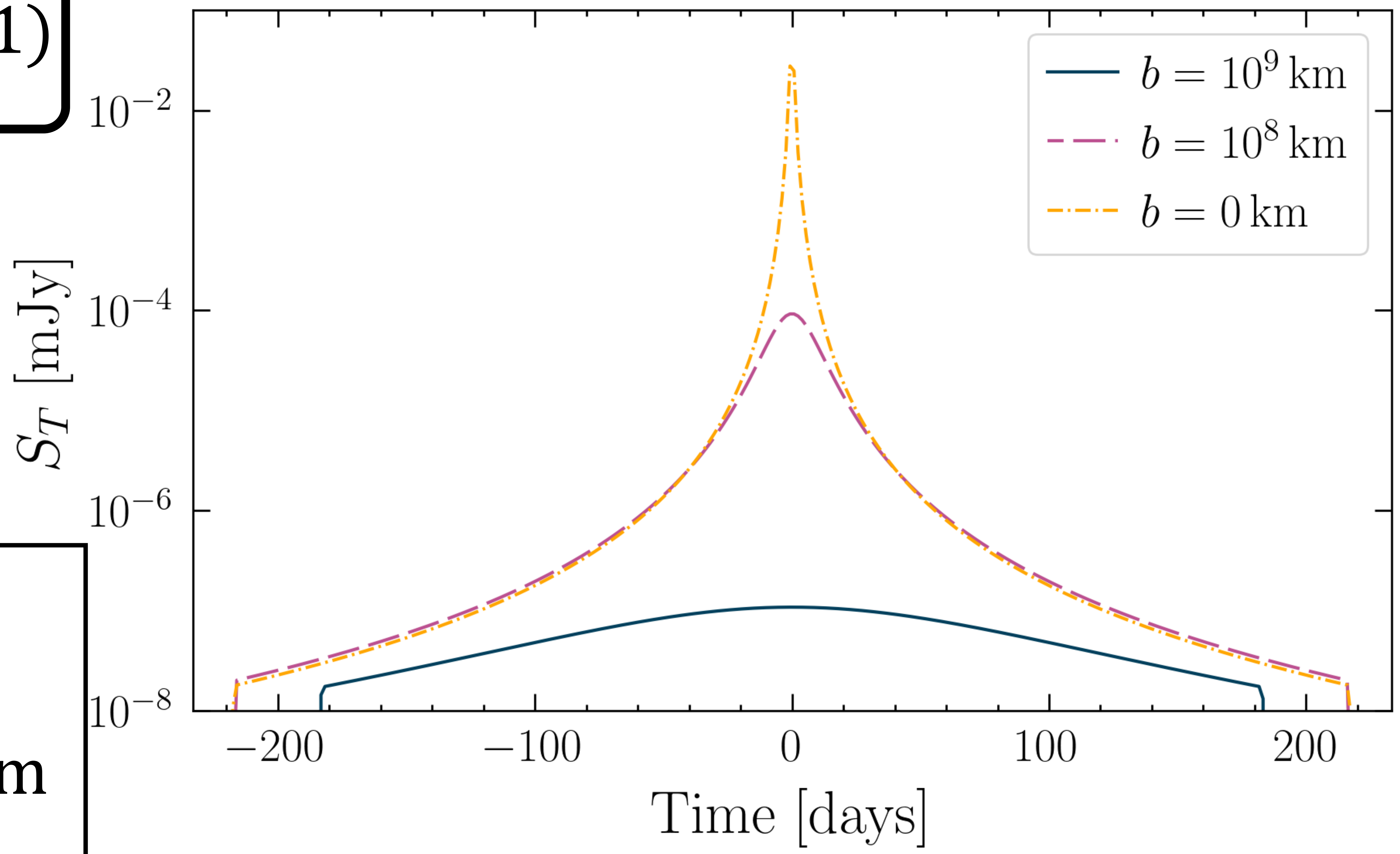
$$\frac{\delta\rho}{\rho} \sim \mathcal{O}(1)$$

<u>*Reference properties:*</u>

$M_{\mathrm{AMC}} \sim 10^{-12} M_{\odot}$ $R_{\mathrm{AMC}} \sim 10^{9}\mathrm{km}$

$\tau \sim$ [hours – years]

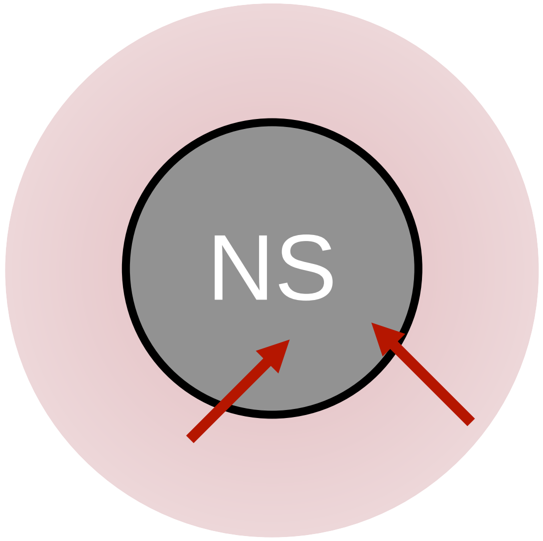
SJW, Baum, Lawson, Millar, Marsh, Salinas (2023)



Quenching of bound state growth

Absorption in Neutron Star:

Noordhuis, Prabhu, Weniger, SJW (To appear)



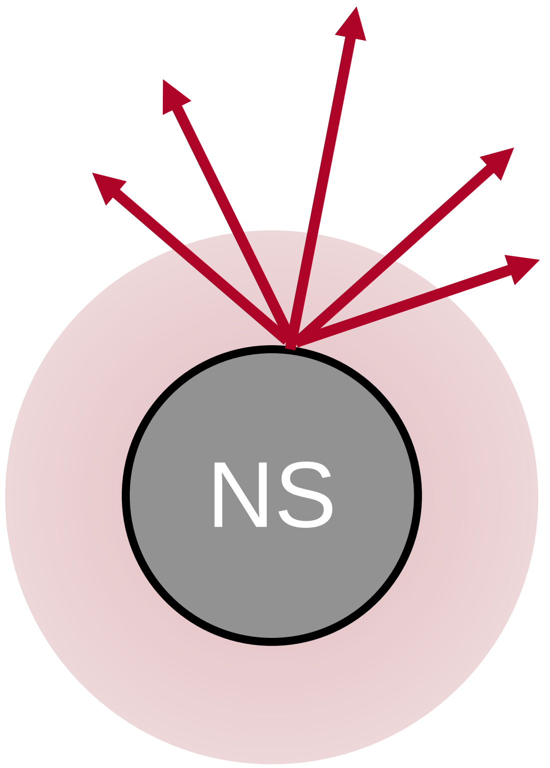
$$aNN \to NN$$

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

Absorption heavily suppressed in low energy limit

Back-reaction on vacuum gap:

Caputo, SJW, Phillipov (In progress)

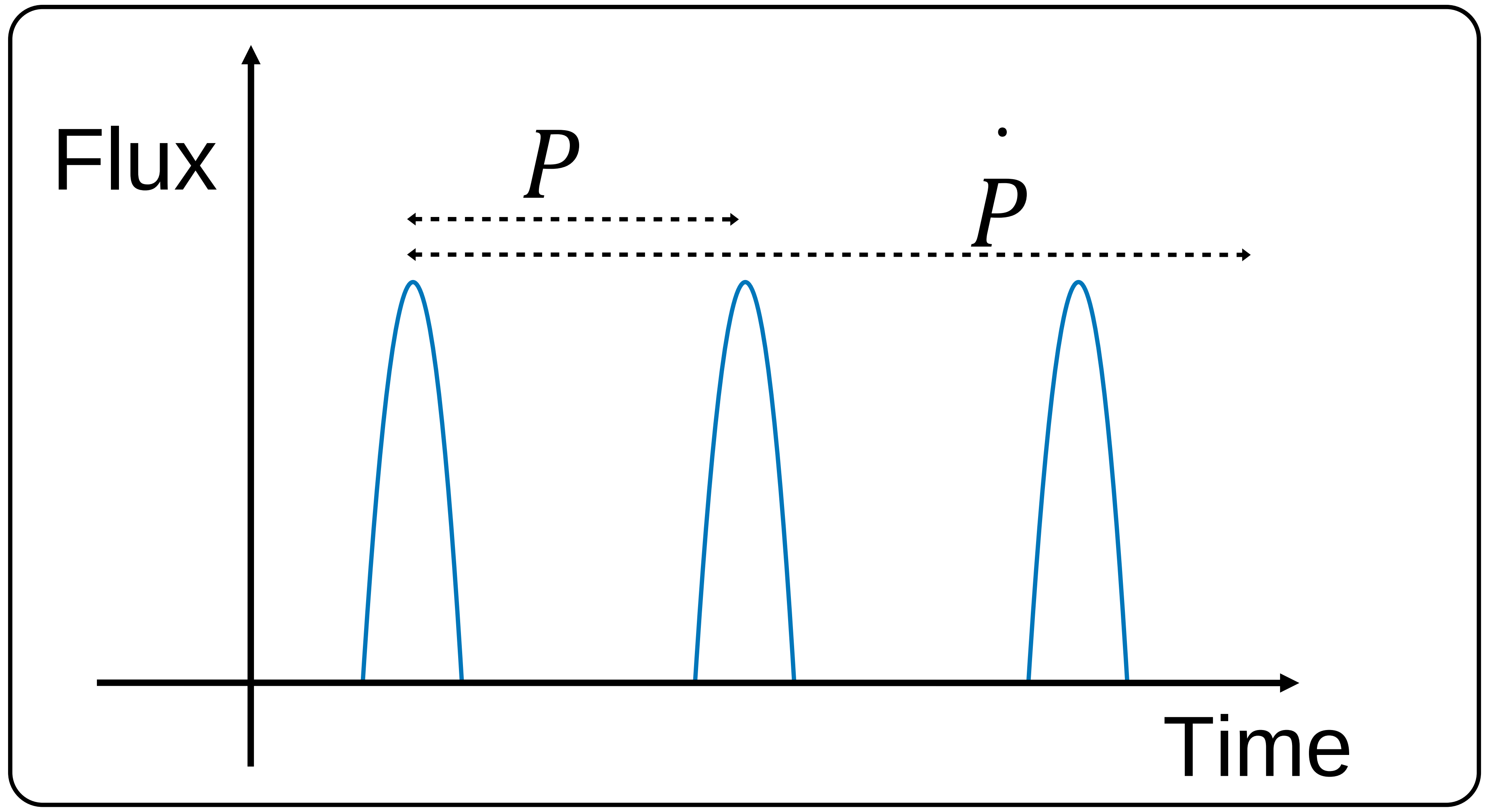


$$\nabla \cdot \vec{E} = \rho - g_{a\gamma\gamma} \vec{B} \cdot \nabla a$$

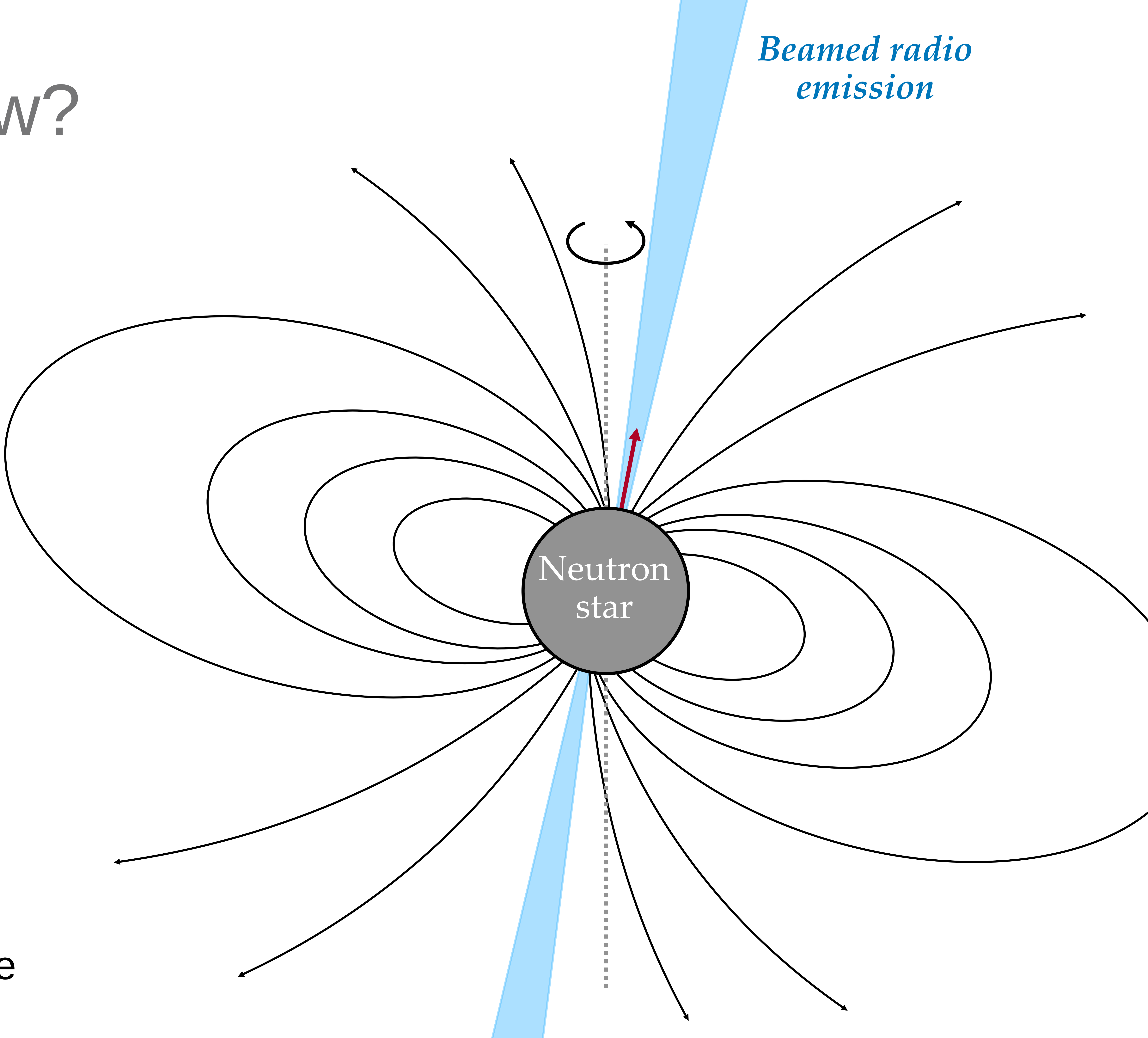
Large axion cloud can modify the plasma dynamics that drive production

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

Pulsars, what do we know?

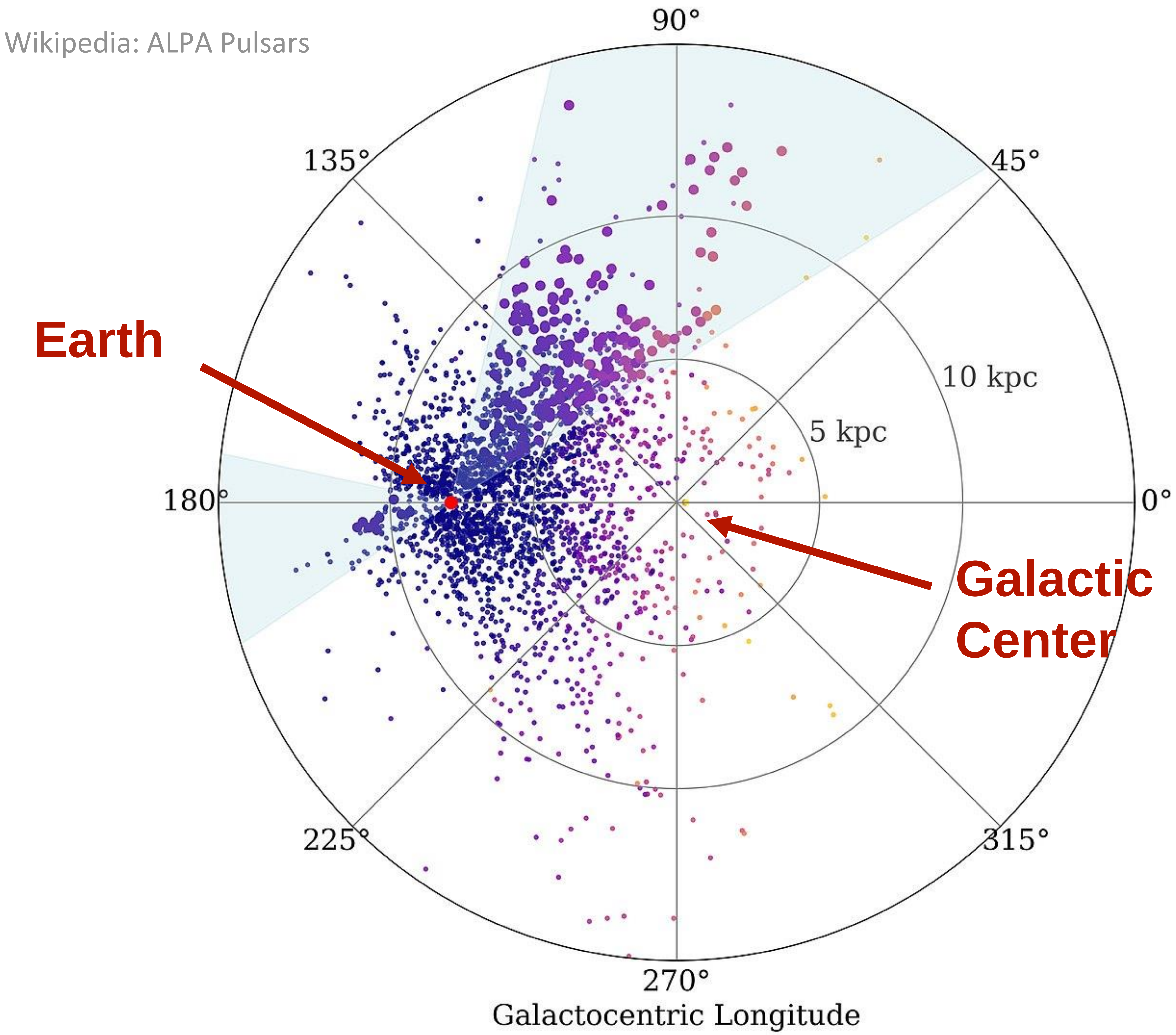


- Rotational period P
- Spin-down rate $\dot{P}$
  - Dipolar field strength $B_0 \propto \sqrt{P\dot{P}}$.
- Characteristic age $\propto P/\dot{P}$
- Distance inferred from dispersion measure (frequency dependent time delay)



Pulsars in the galaxy

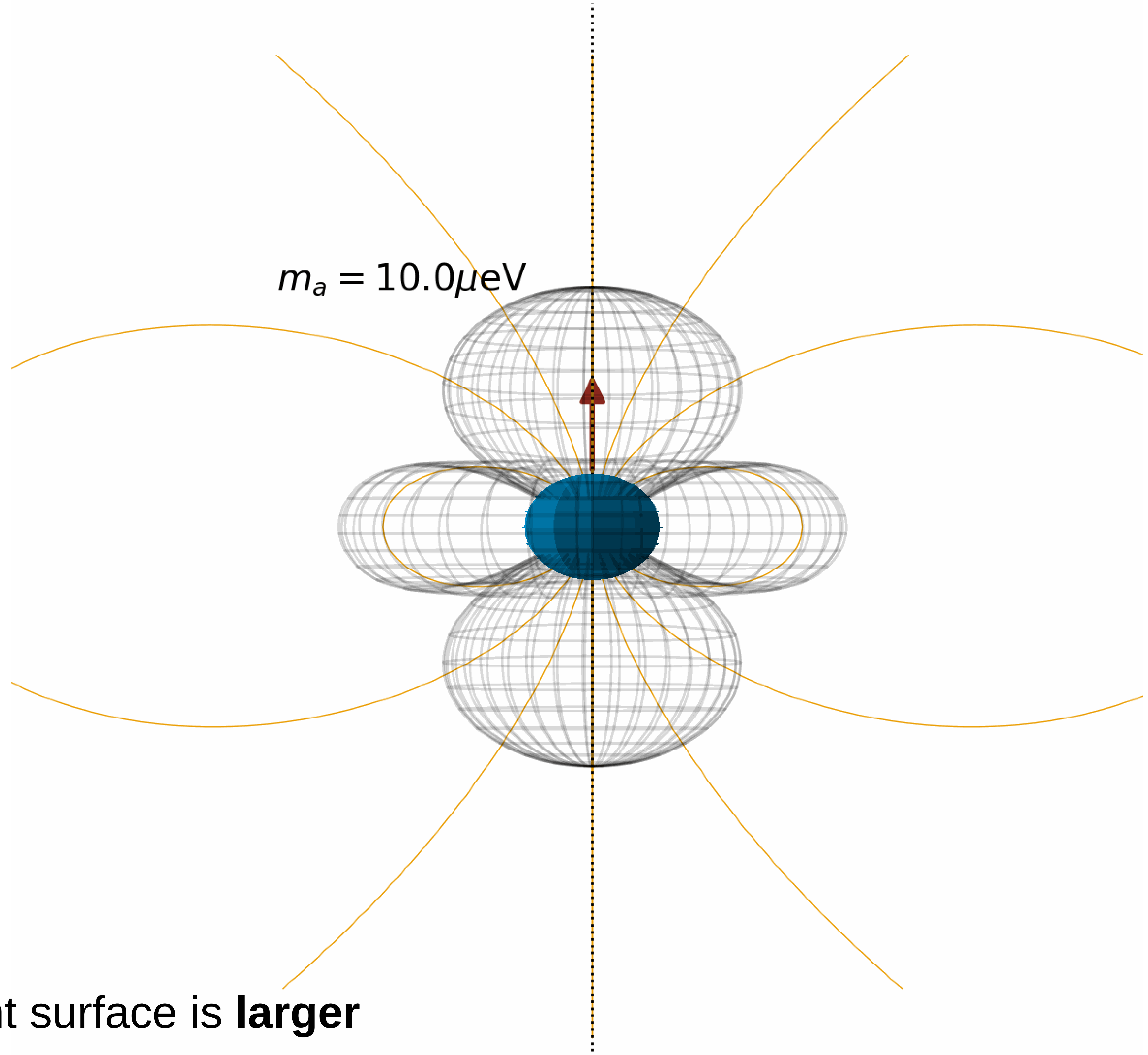
Wikipedia: ALPA Pulsars



Targeting the Galactic Center requires population modelling

- Star formation rates & stellar mass distributions tells us about neutron star formation rate
- Young neutron stars trace stellar distribution
- Synthesize neutron star population consistent with the observed population

Signals from individual neutron stars



Smaller axion mass → resonant surface is **larger**
Larger axion mass → resonant surface is **smaller**

Animations available at: https://github.com/SamWitte/GIF_Storage

Photon production

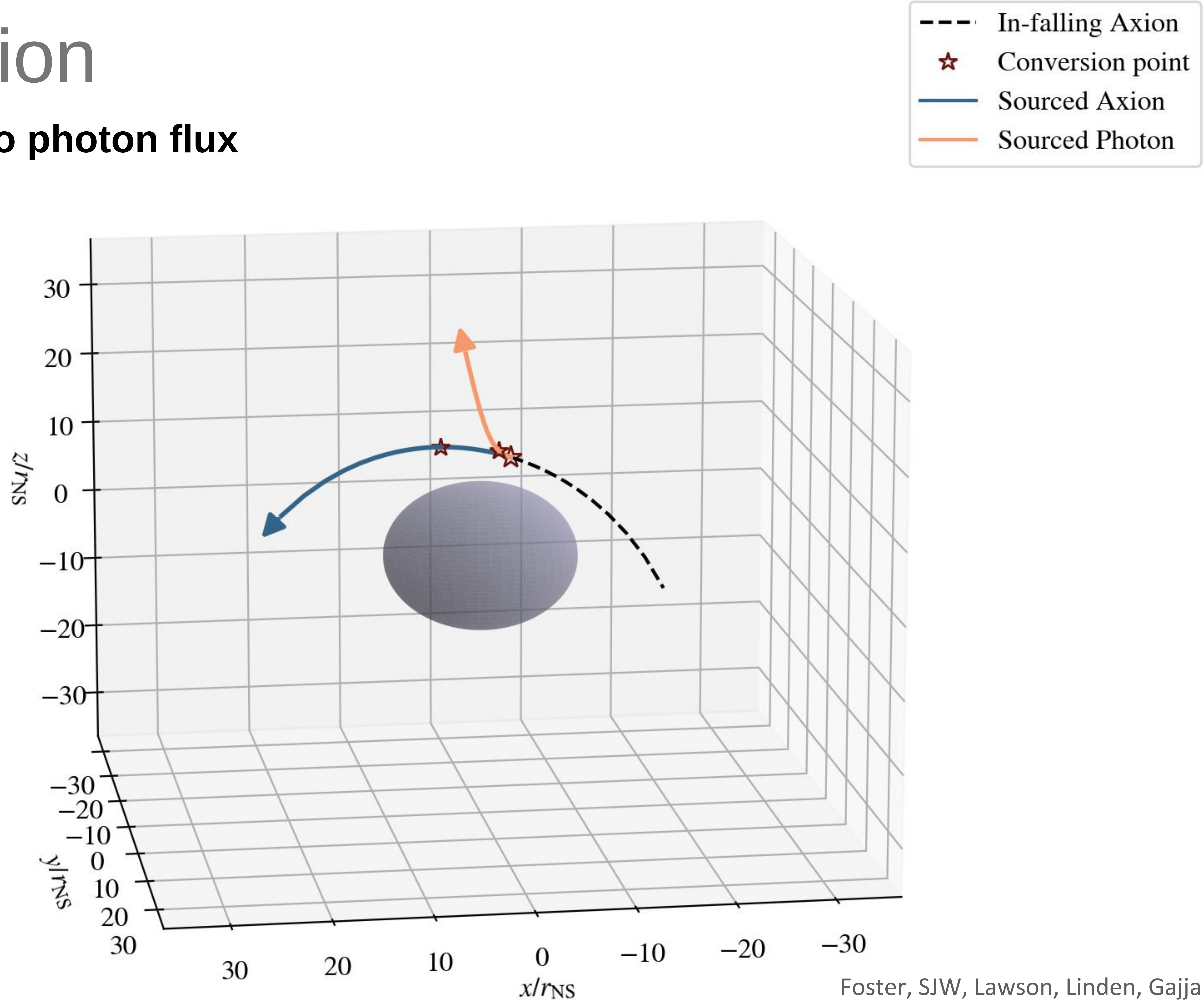
Step 2: Axion phase space to photon flux

Inefficient conversion

[Limit $g_{a\gamma\gamma} \to 0$]

$p_{a\to a} \sim 1$

$p_{a\to\gamma} \sim \epsilon$

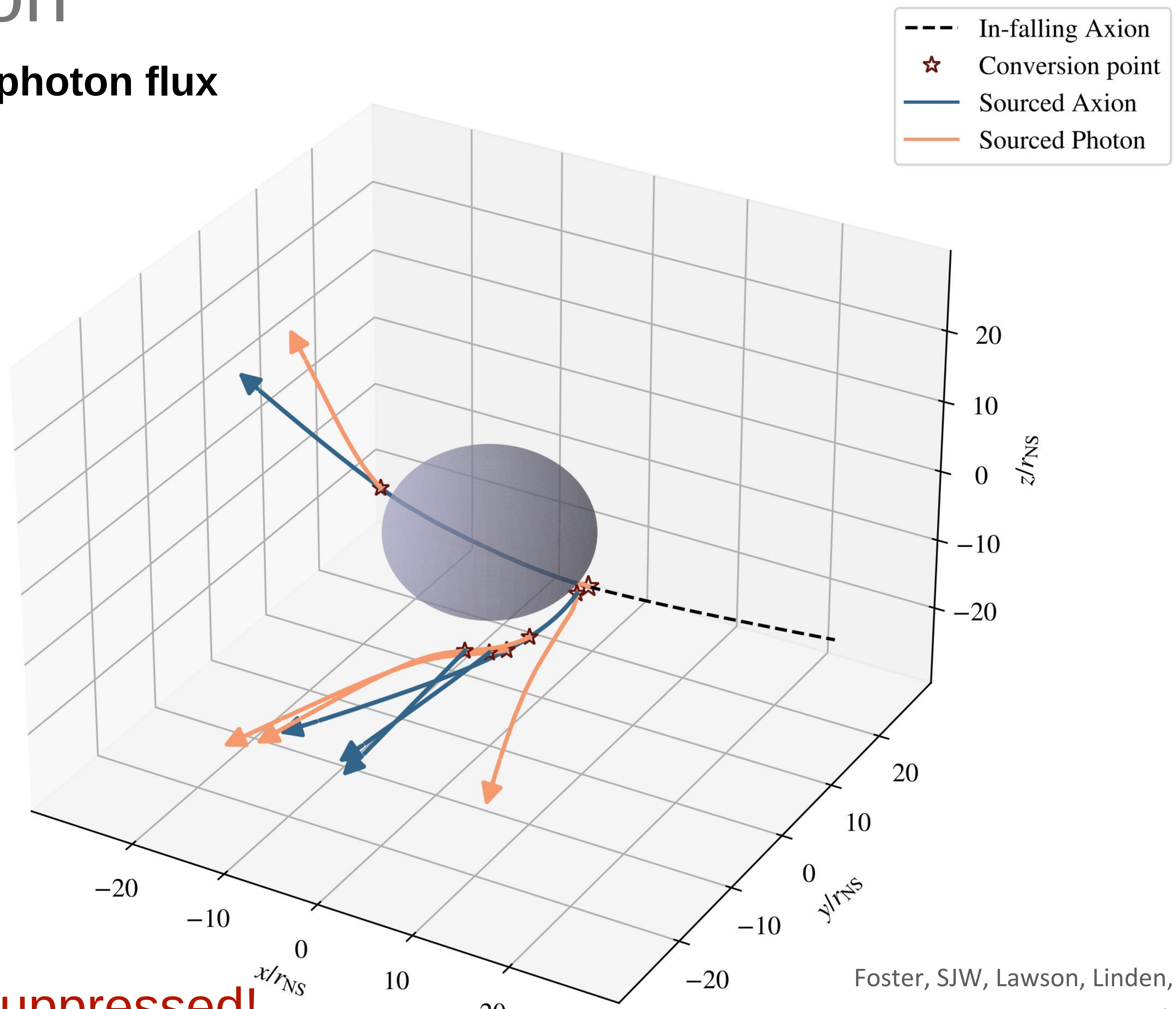


Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (2021)

Tjemsland, SJW, McDonald (To appear)

Photon production

Step 2: Axion phase space to photon flux



Efficient conversion

$[g_{a\gamma\gamma} \to \text{Large}]$

$p_{a\to a} \sim e^{-x}, x \gg 1$

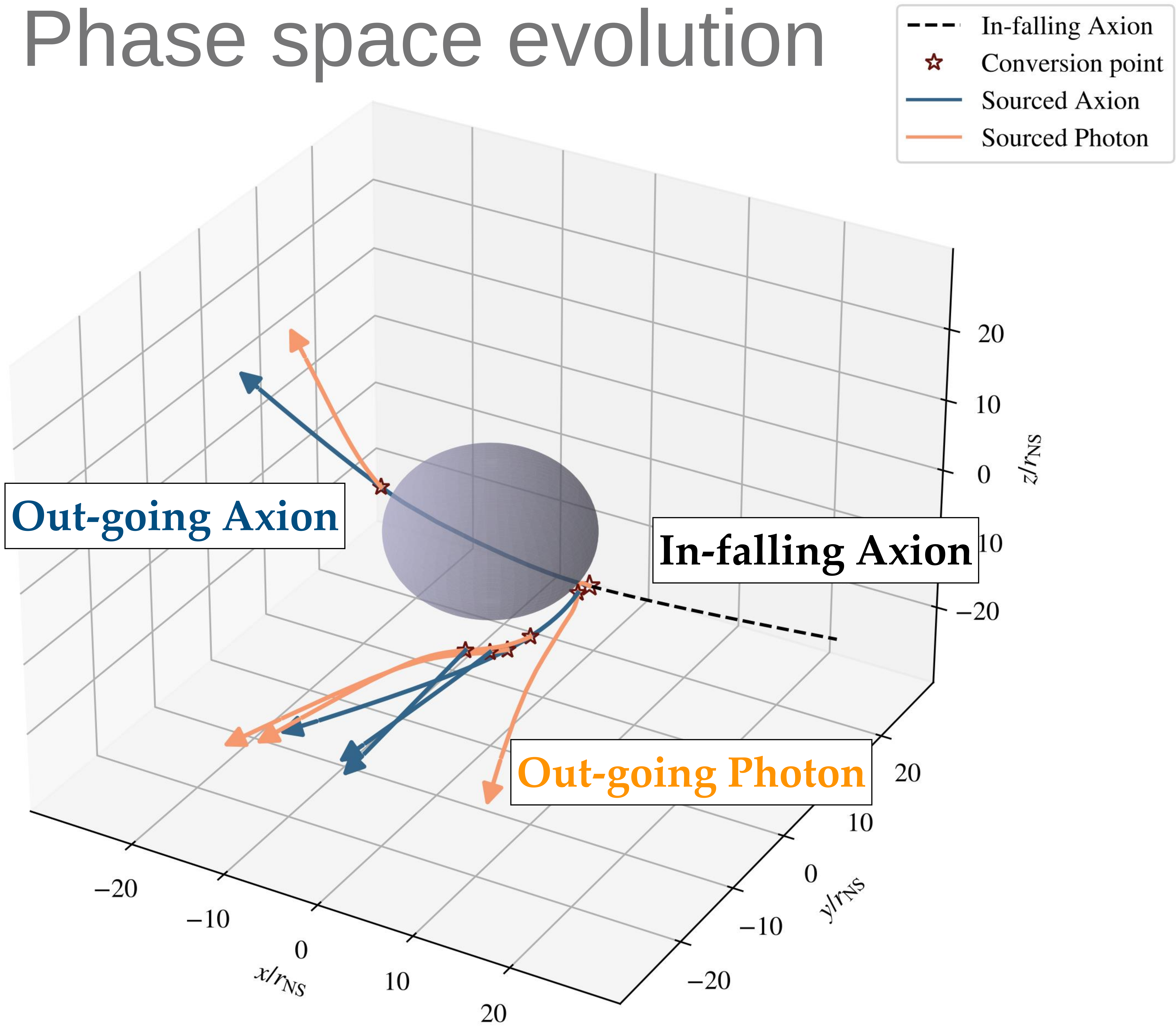
$p_{a\to\gamma} \sim 1$

Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (2021)

Tjemsland, SJW, McDonald (To appear)

Radio flux exponentially suppressed!

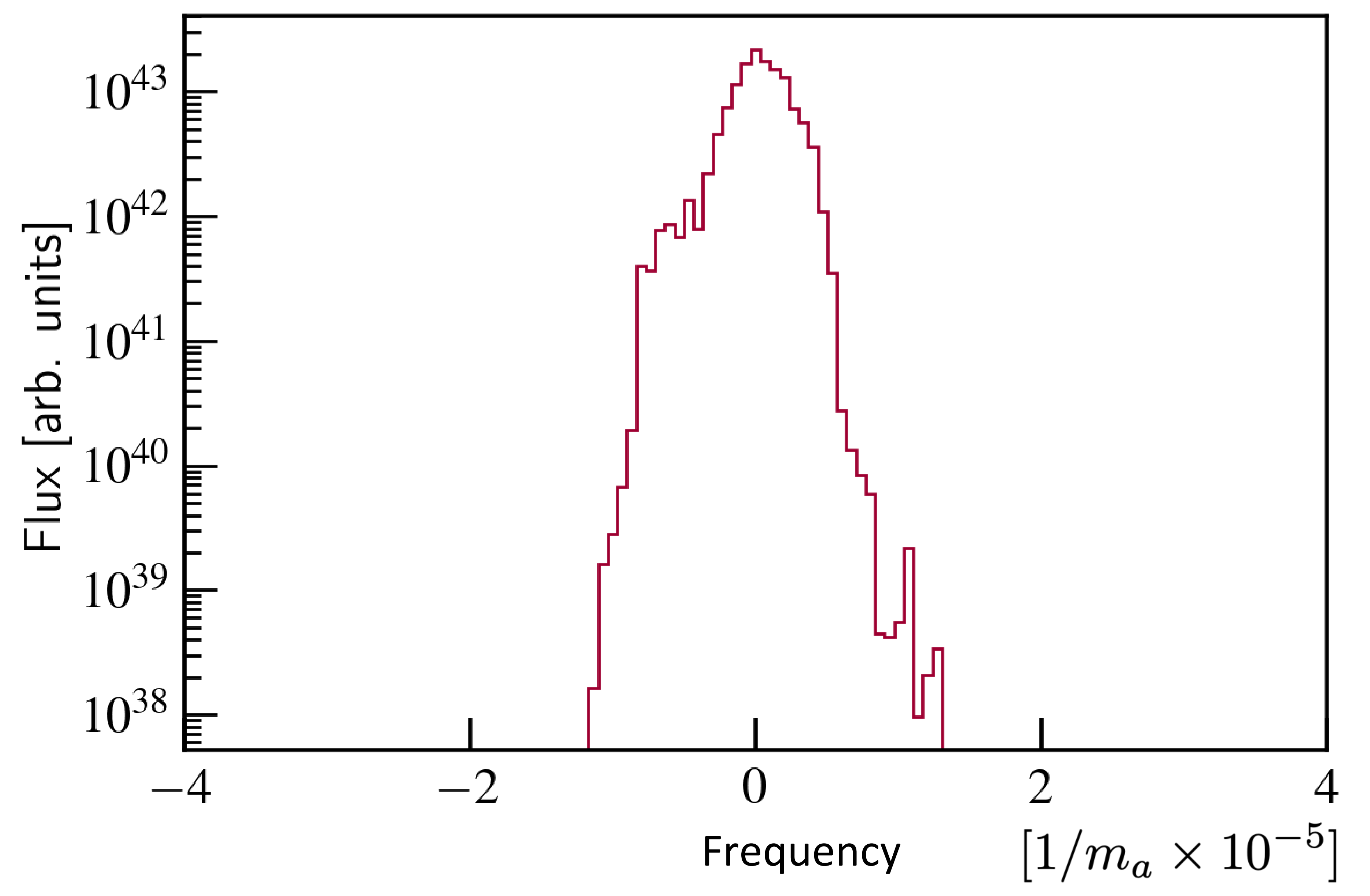
Phase space evolution



SJW et al (2021), Battye et al (2021)

__Use ray tracing to treat:__

- Evolution of axion-photon and photon-axion conversions
- Non-linear photon propagation
- Plasma broadening
- Photon absorption



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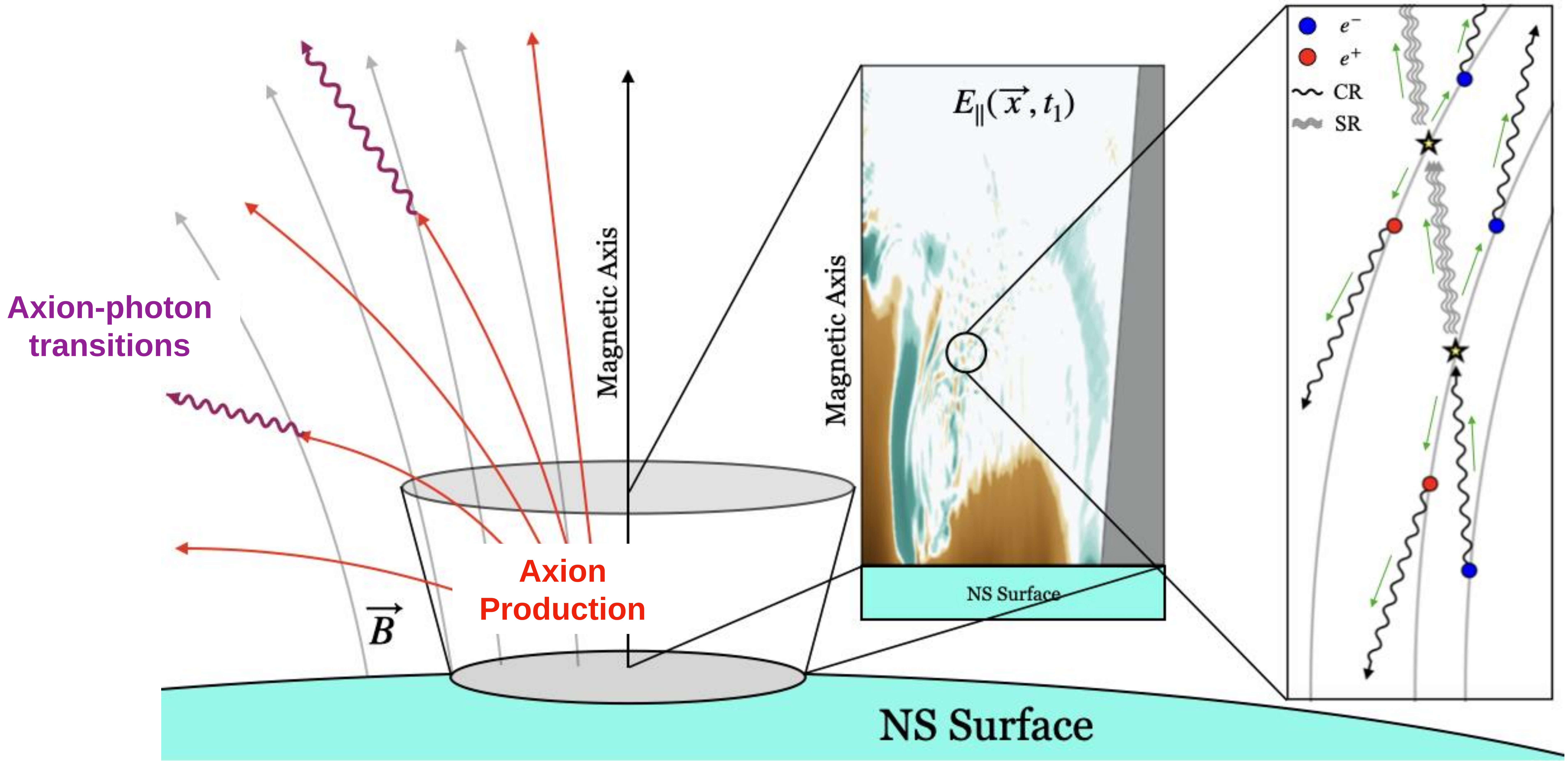
Tjemsland, SJW, McDonald (To appear)

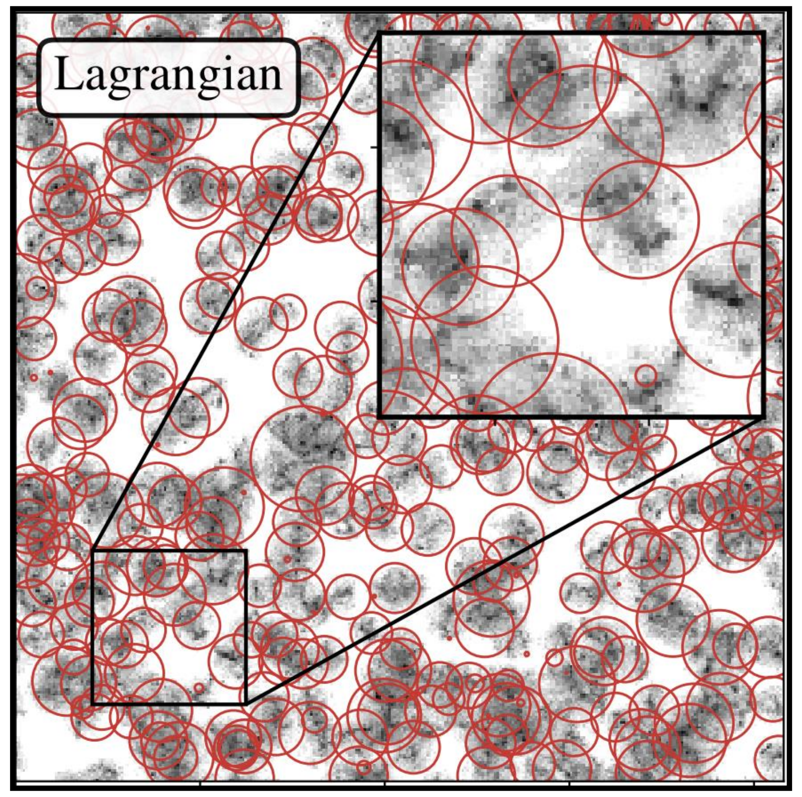
Overview



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

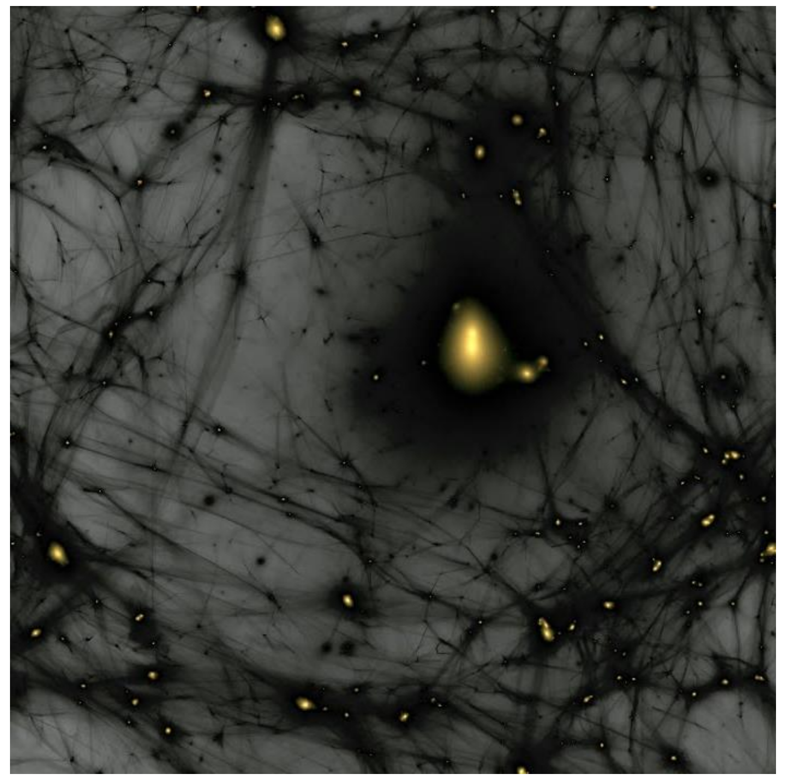
ASIDE: Transient radio lines from axion miniclusters

Minicluster formation

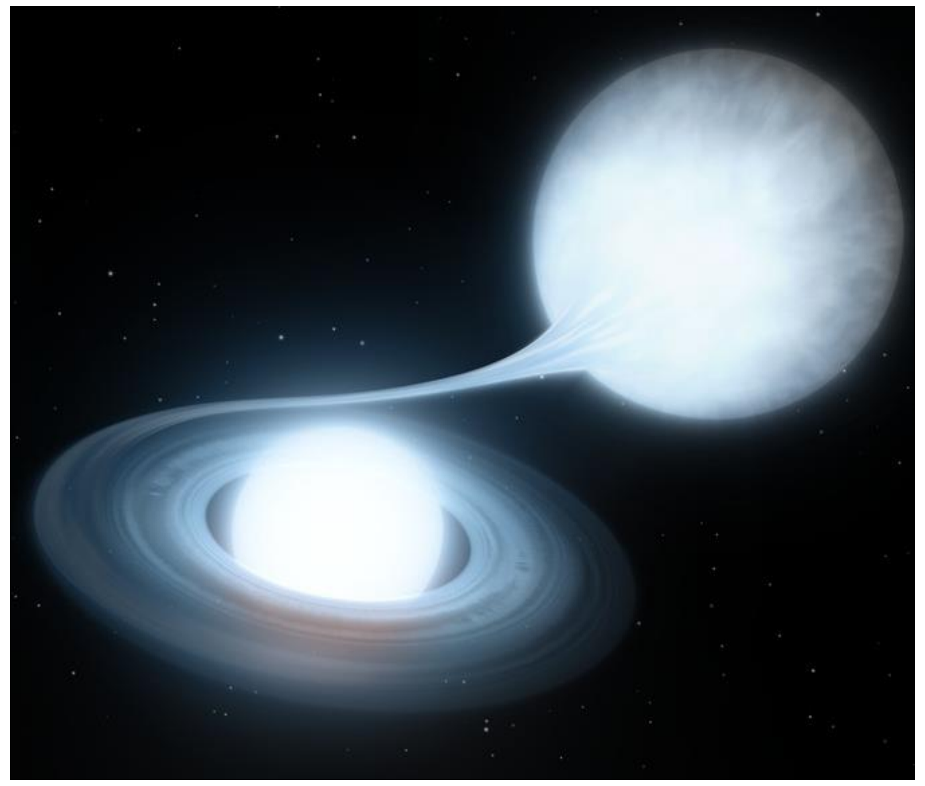


See e.g. Ellis et al (2022)

Structure formation

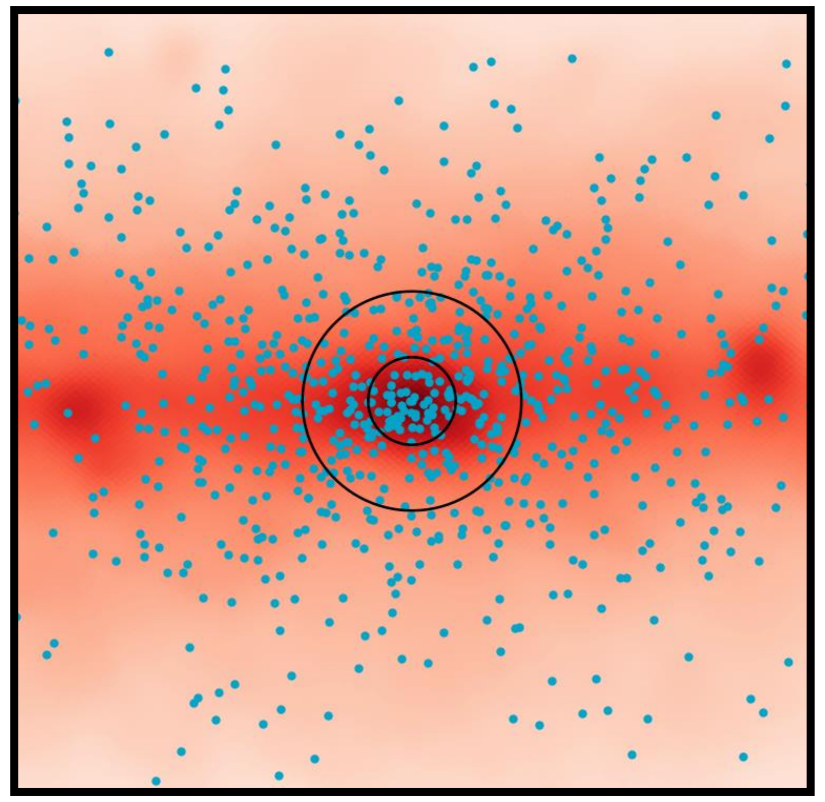


Tidal stripping



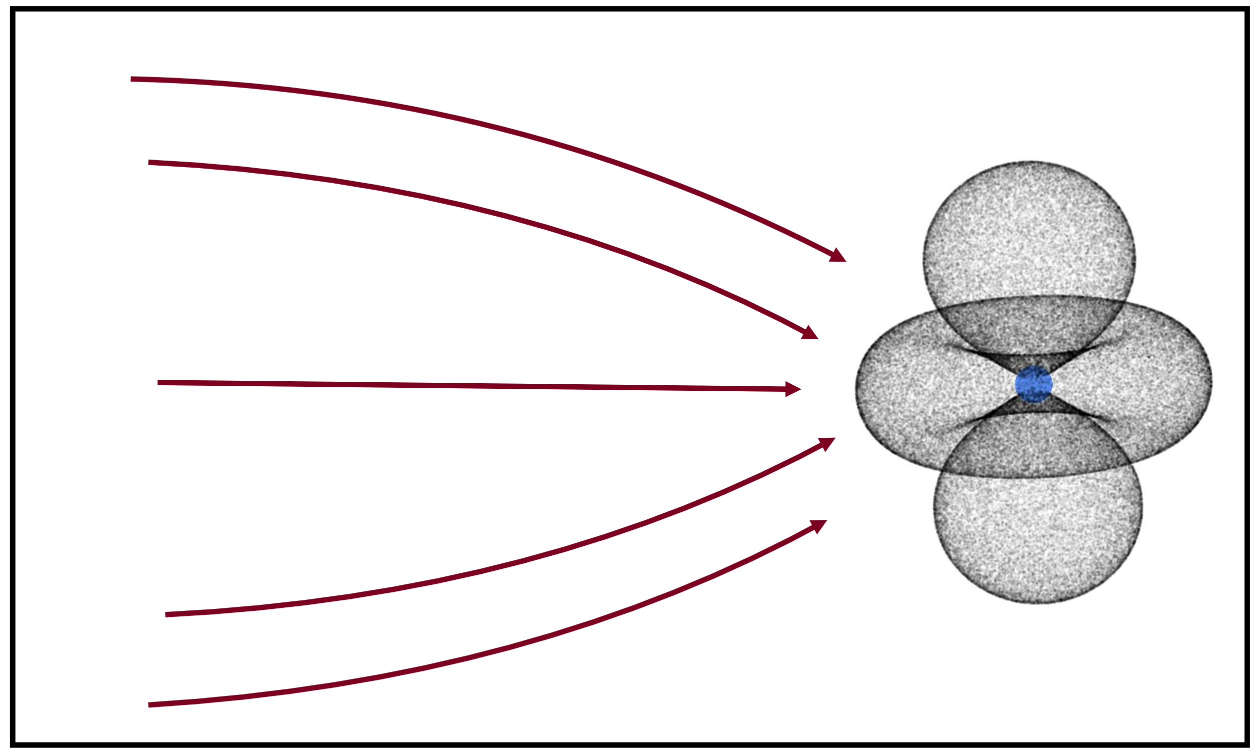
Kavanagh et al (2021), Shen et al (2022)

Neutron star population

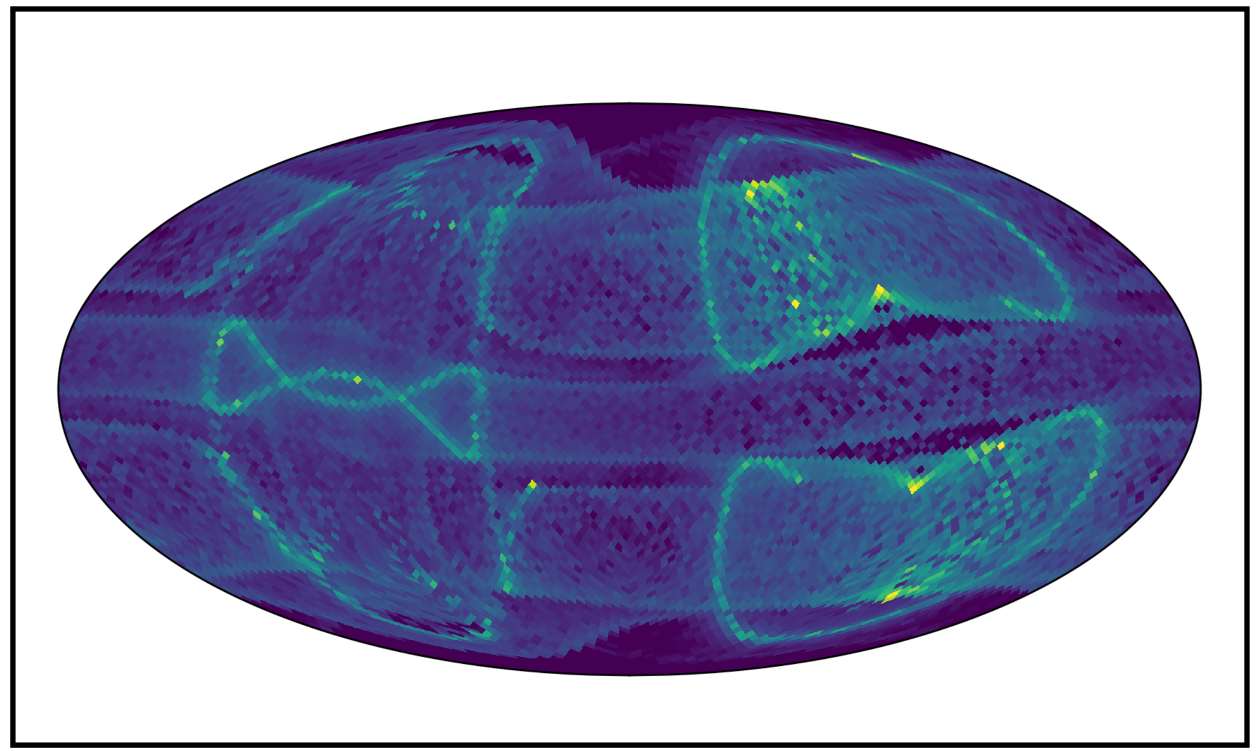


Encounter #1
Encounter #2
.
.
.
.
.
Encounter #N

Minicluster in-fall



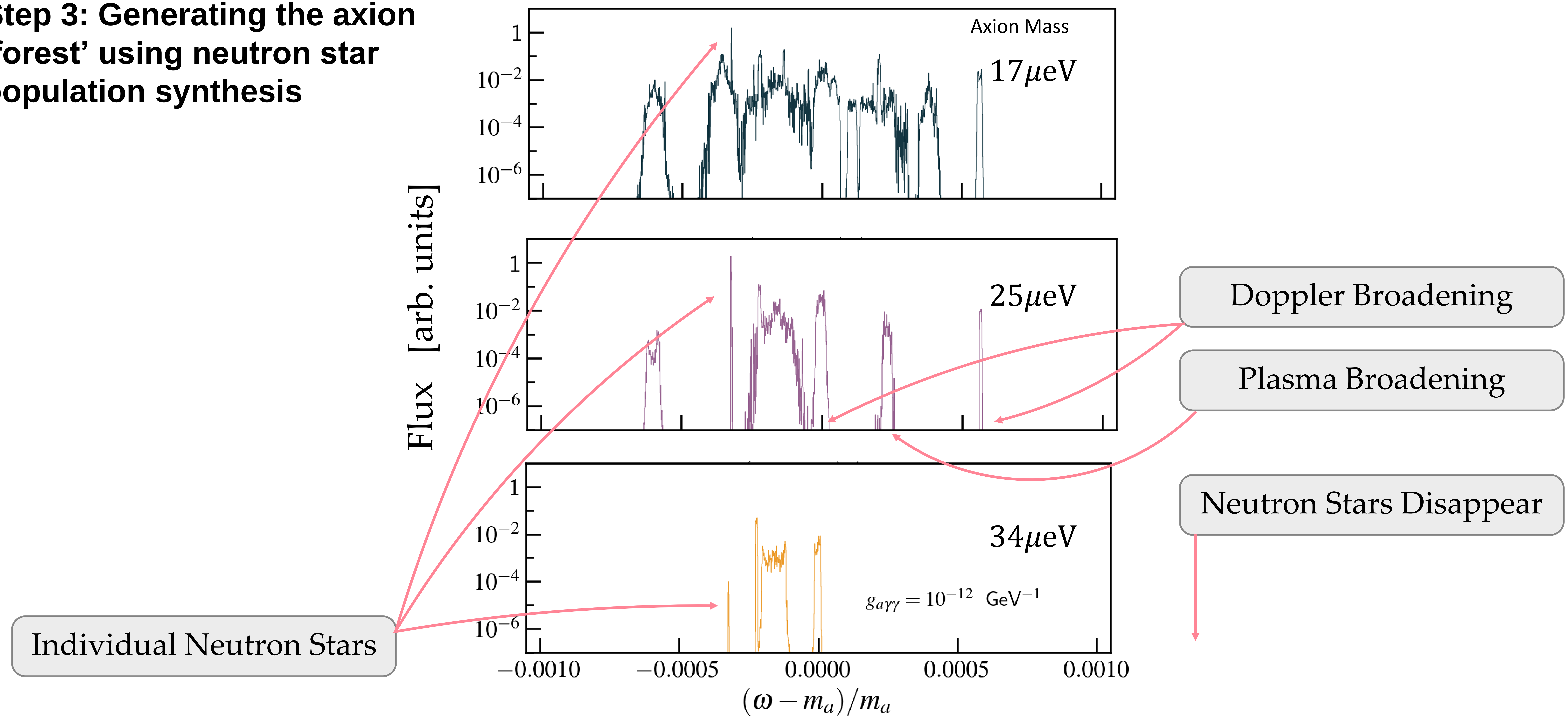
Radio Signal



SJW, Baum, Lawson, Millar, Marsh, Salinas (2023)

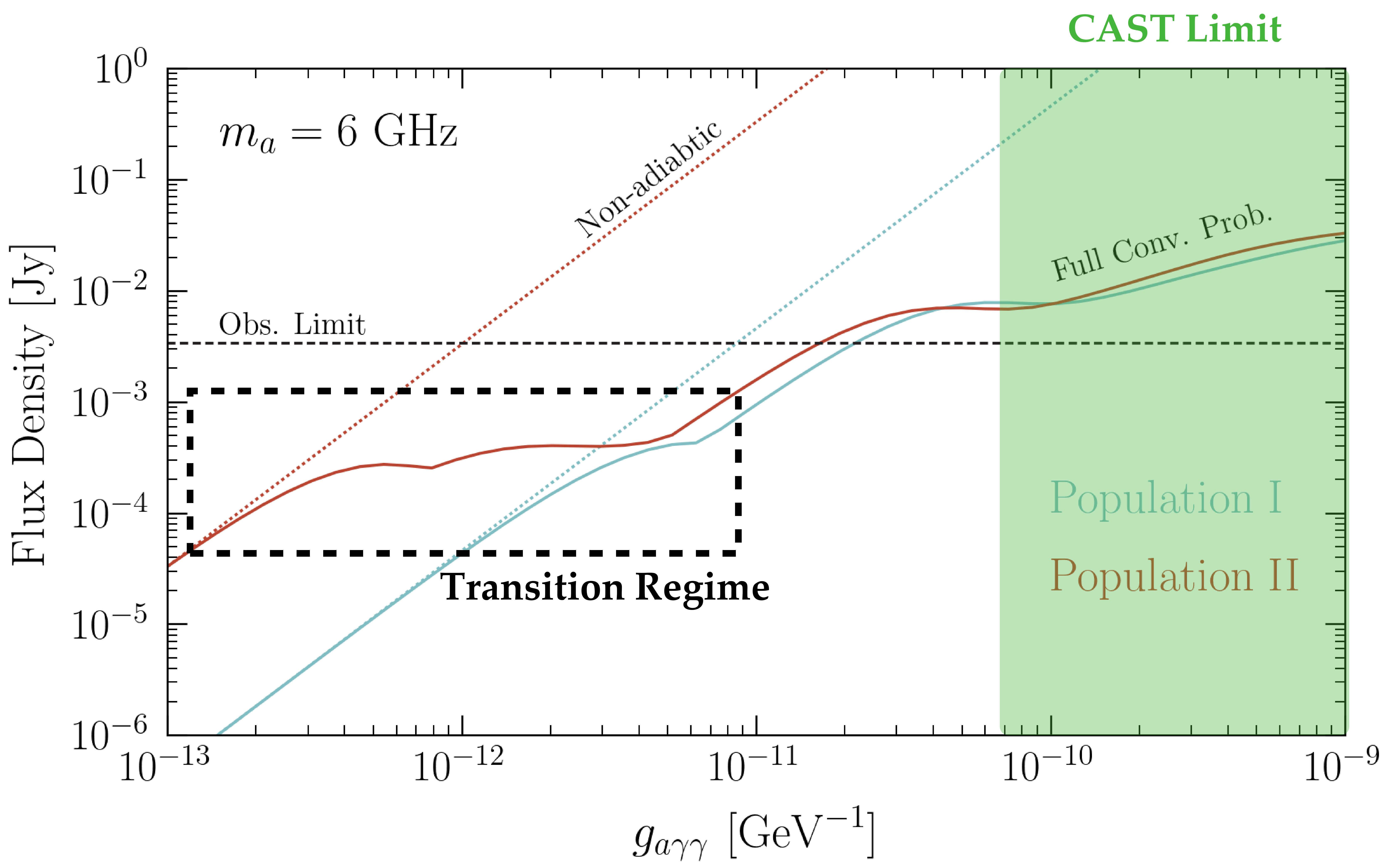
Stacked signal

Step 3: Generating the axion 'forest' using neutron star population synthesis



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

Adiabatic Conversion



Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Magnetosphere Axisymmetric Rotator

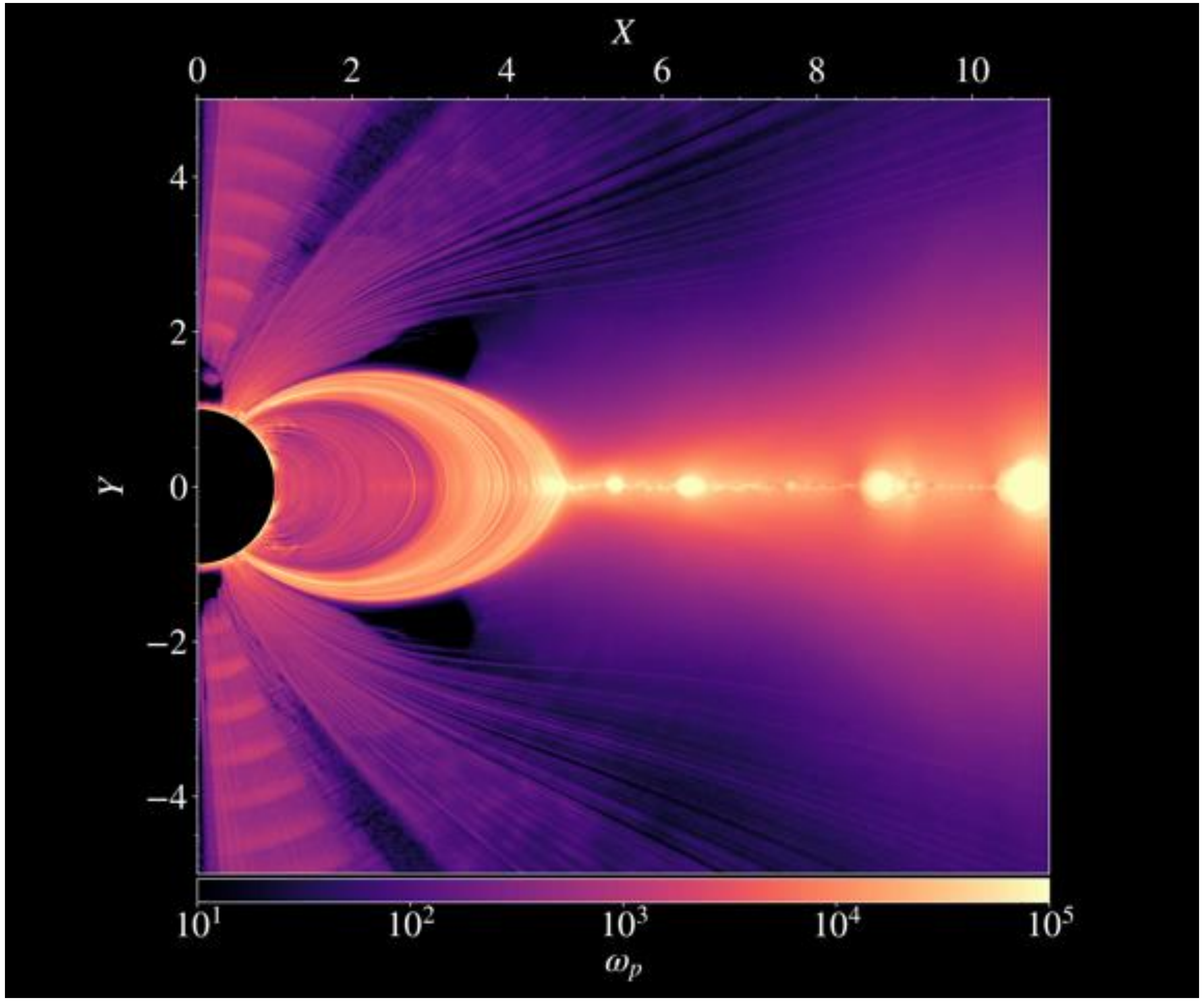
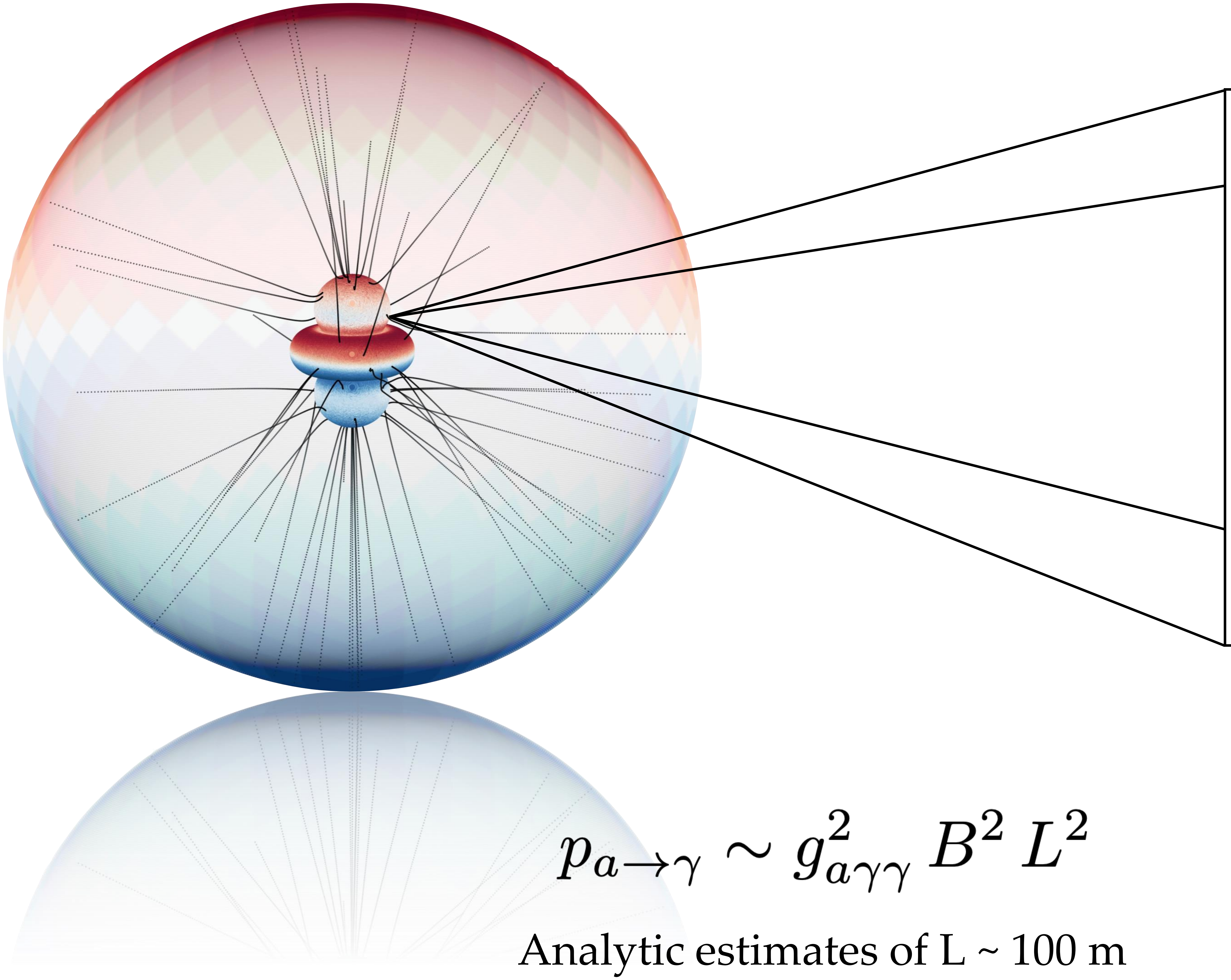
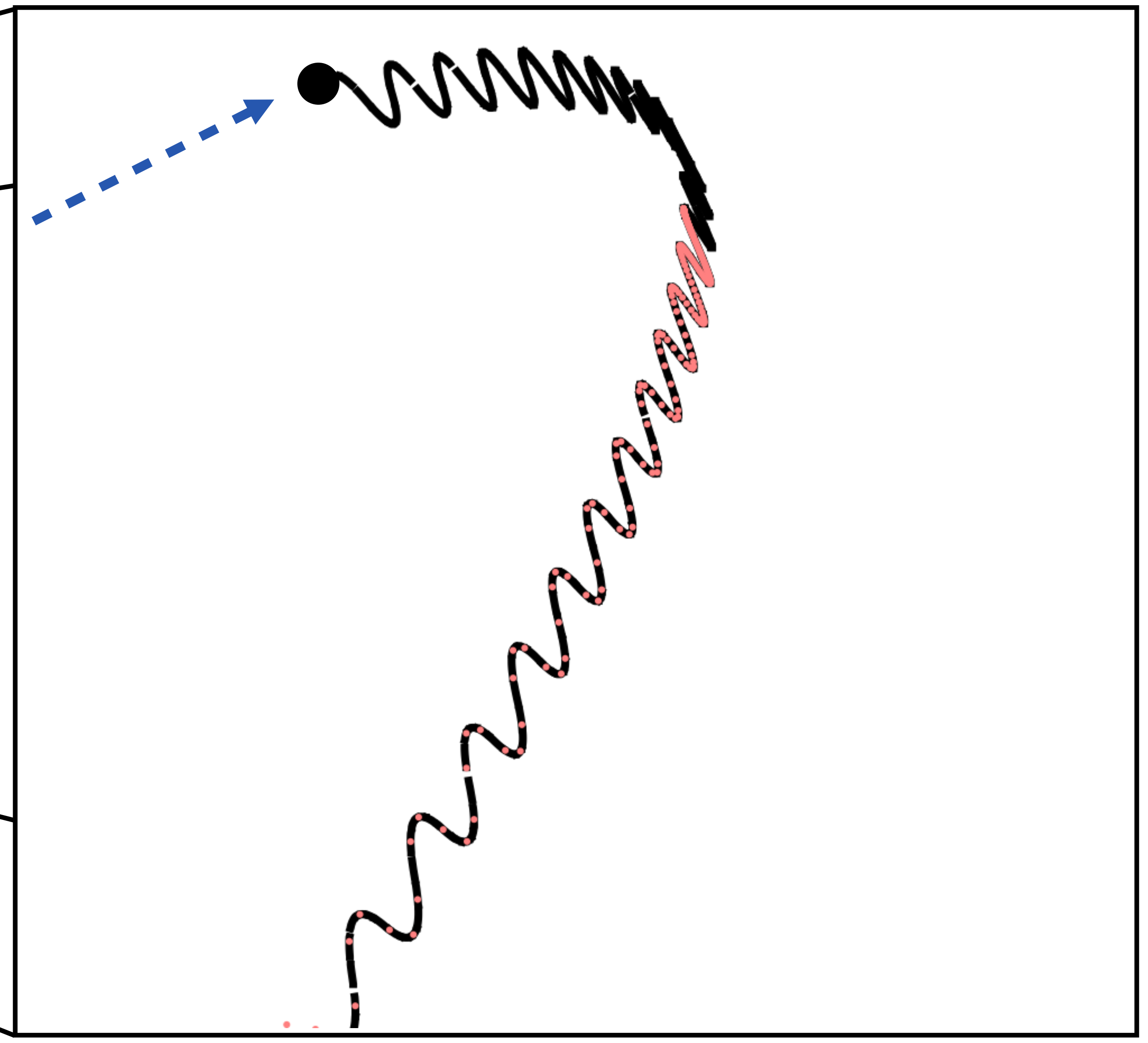


Image credit: Bransgrove & Beloborodov





~ 500 meters

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 \, B^2 \, L^2$$

Analytic estimates of L ~ 100 m

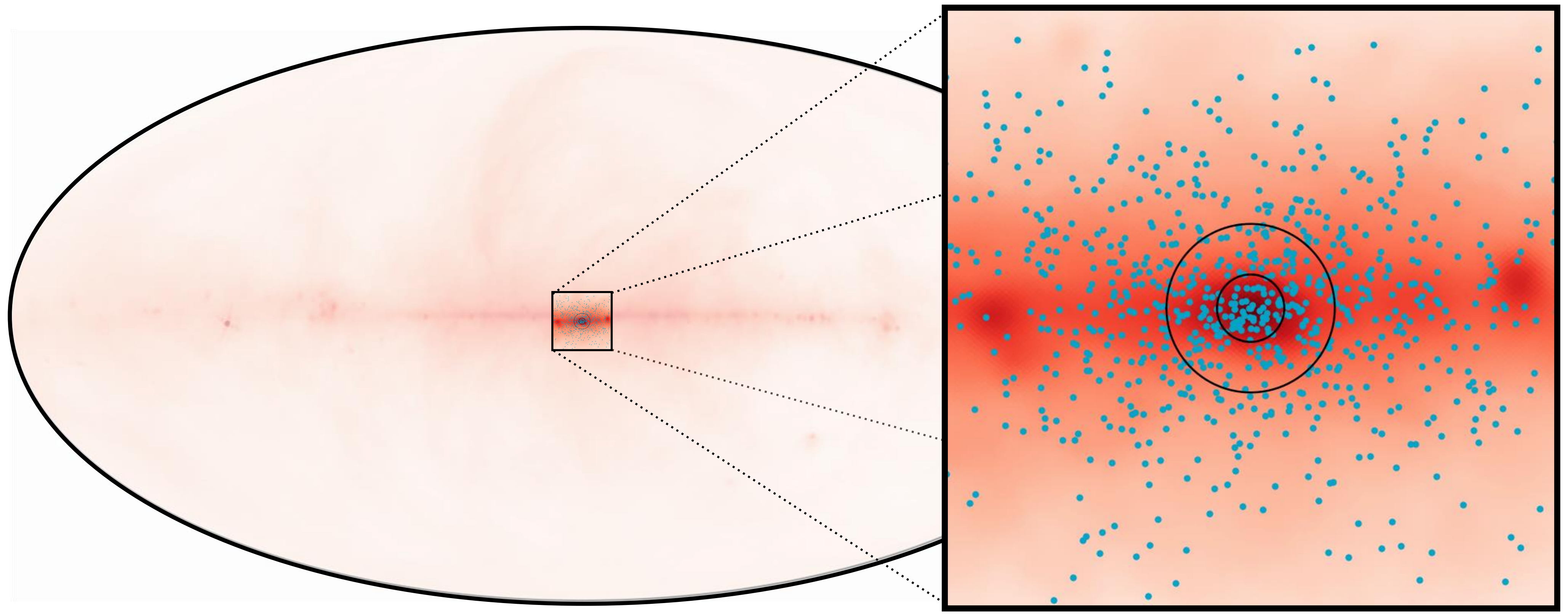
Neutron star population modeling

How are they distributed?

Young population:
- Stellar distribution

Old population:
- Numerical simulations of the dynamics, in-fall, and capture

Generozov et al (2018)



How many are there?

Young population:
- Star formation + stellar mass distribution

Old population:
- Globular cluster infall, mass segregation, *in situ* star formation

How do we view each NS?

- Marginalize

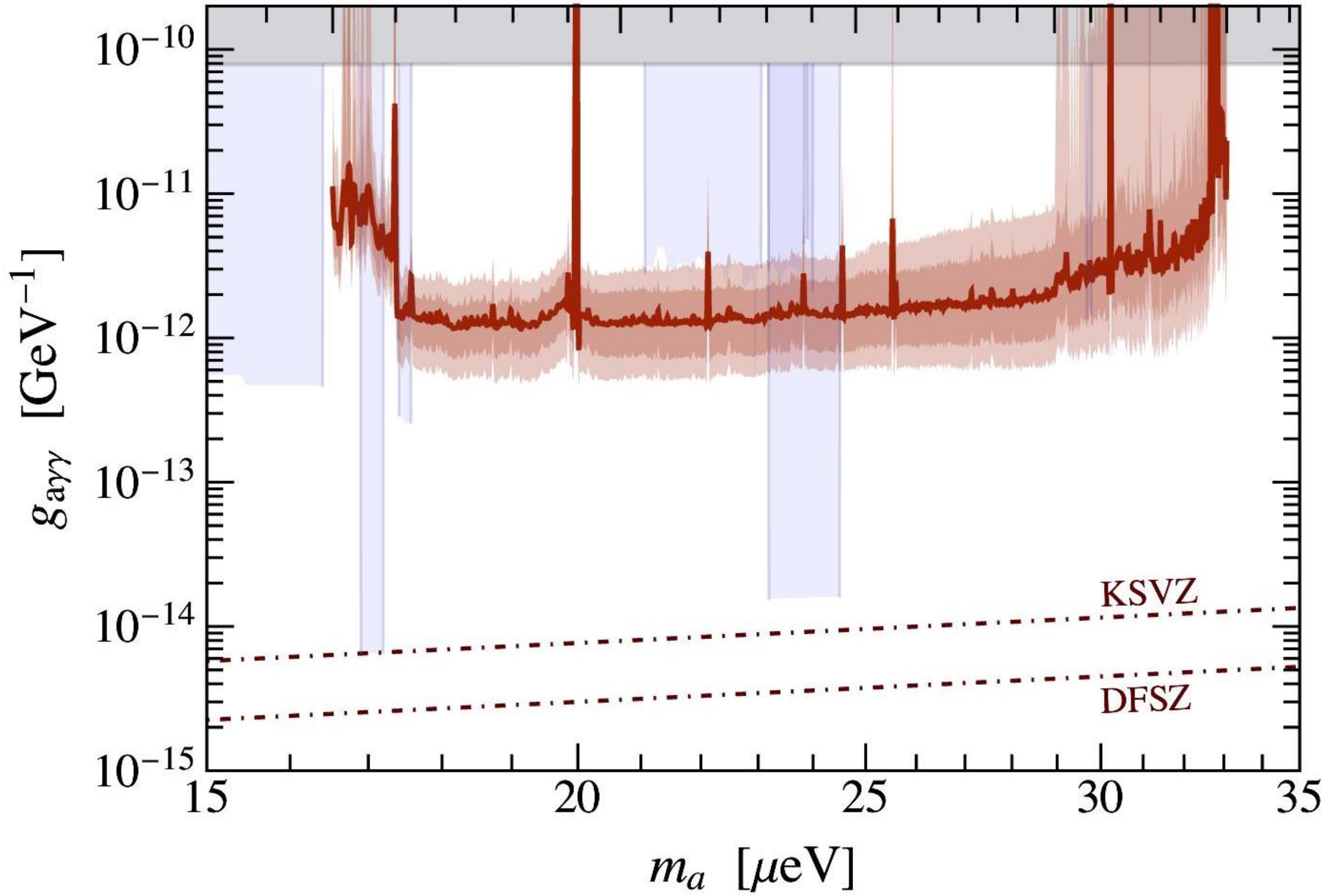
What are their properties?

- Use models to spin-down each pulsar and decay magnetic field
- Fit initial distributions to observed populations

Future prospects

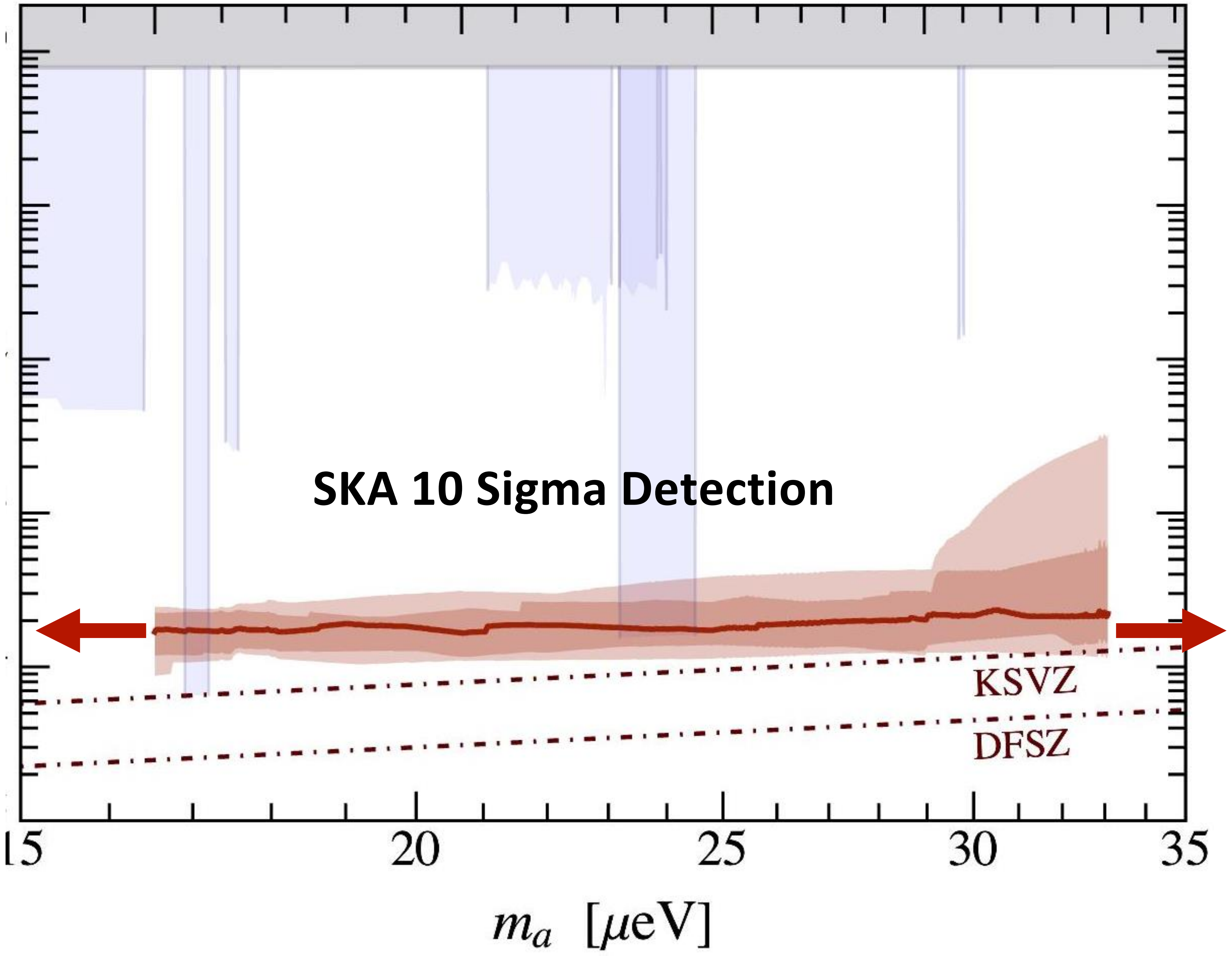
Improvement needed from theory…

(e.g. Axion-photon mixing)



+ experiment…

(e.g. better telescopes, time domain information)



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

Radio Telescope Sensitivity

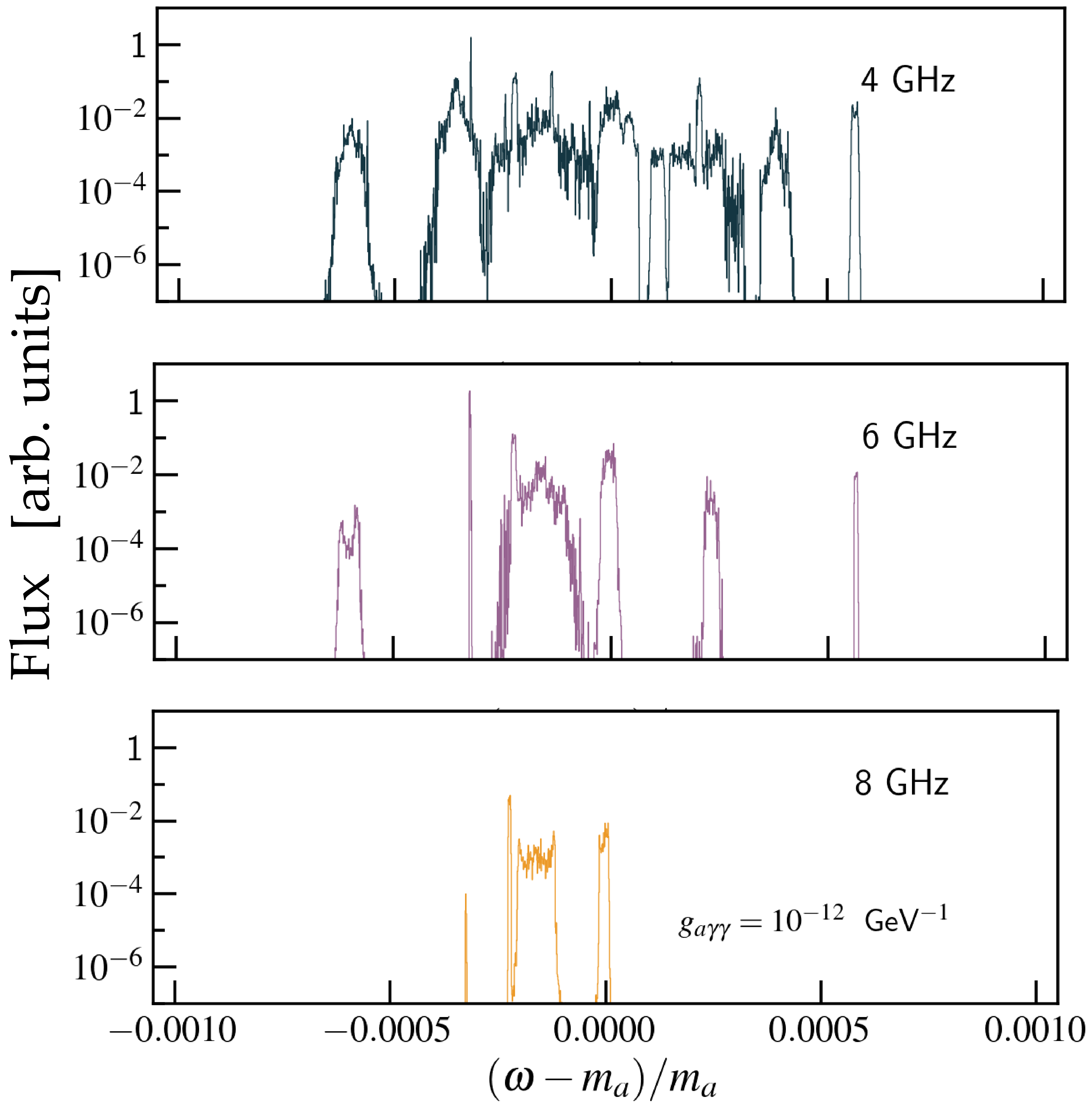
Radiometer Equation:

$$S/N \propto \sqrt{\Delta t/\Delta f}$$

Idealized Searches:

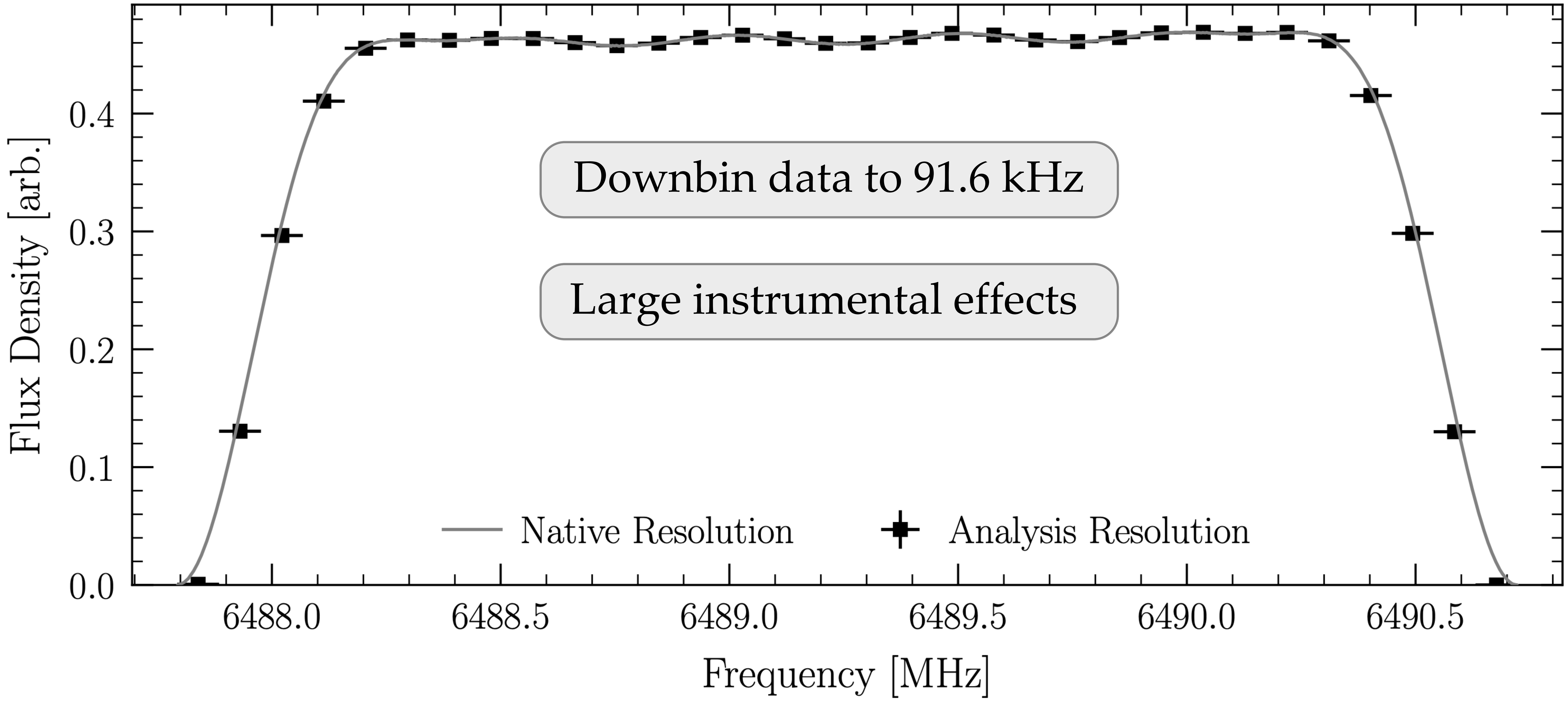
- More Time
- Narrower Line

Tradeoff between looking for brightest neutron star and exploiting the entirety of the signal



GBT Observations

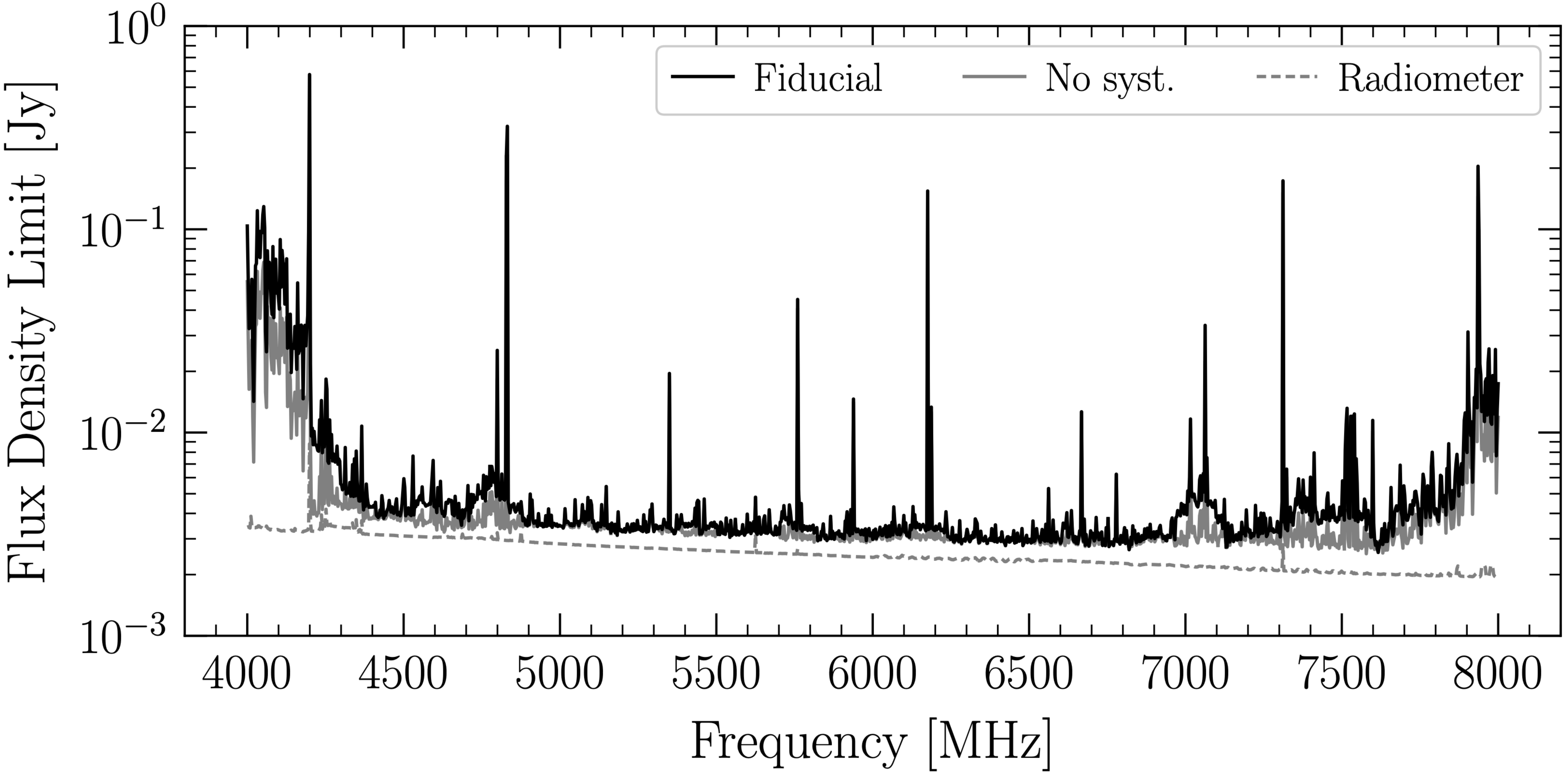
Single "coarse channel"



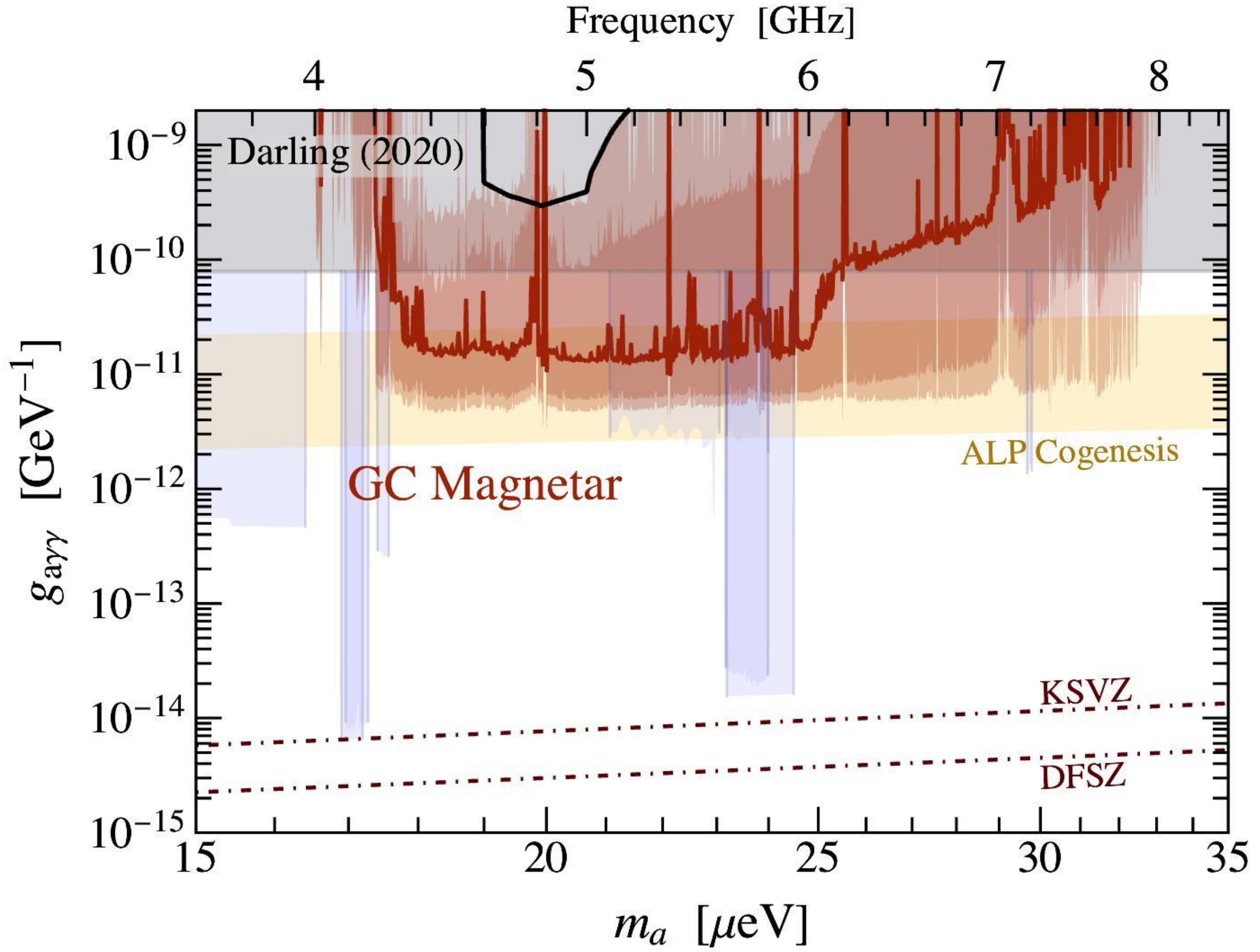
Use parametric modeling and Gaussian processes to model smooth background

Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)

Fiducial Limits



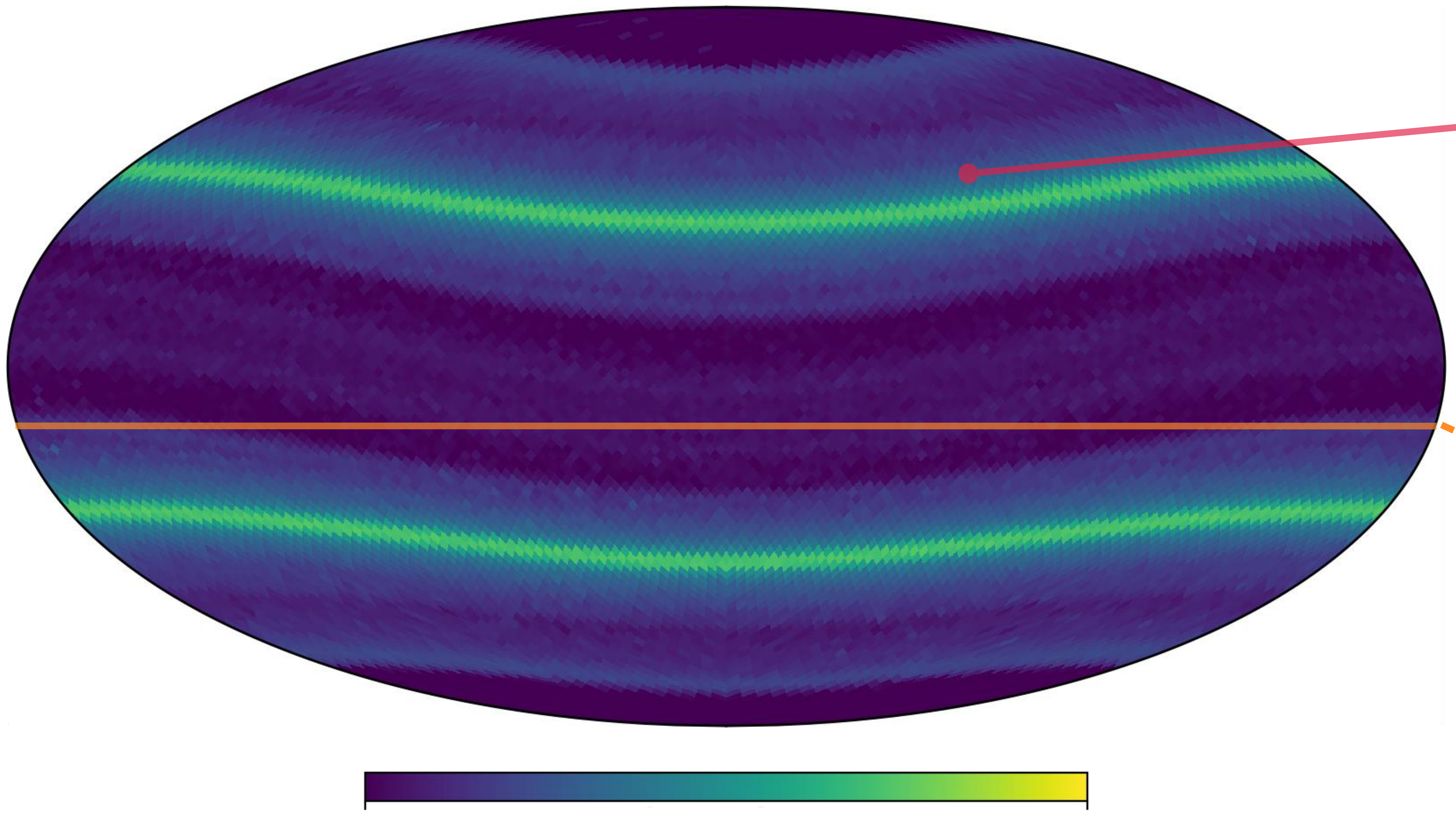
Foster, SJW, Lawson, Linden, Gajjar, Weniger, Safdi (arXiv: 2022.08274)



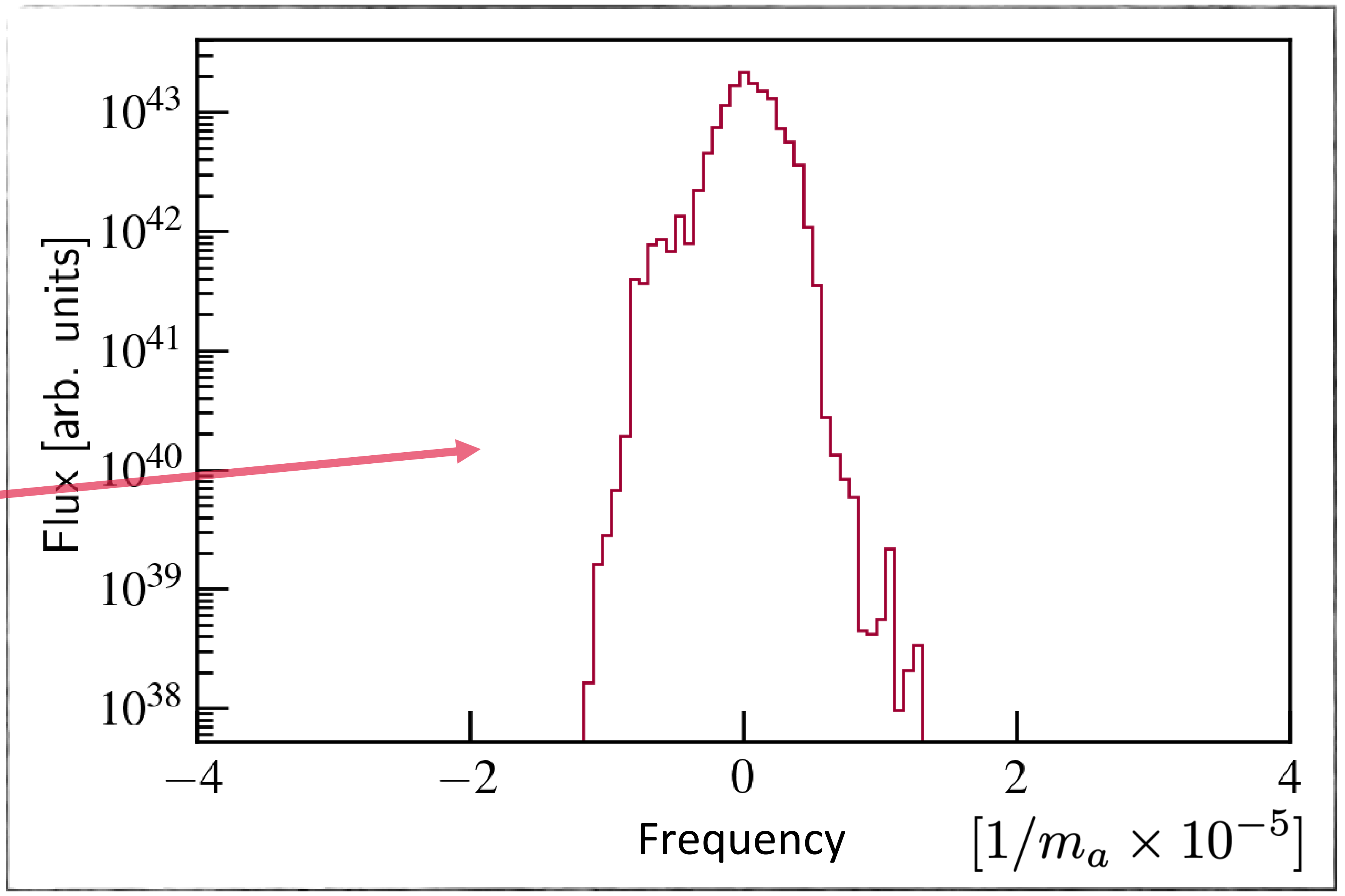
Frequency [GHz]
4
5
6
7
8
Darling (2020)
GC Magnetar
ALP Cogenesis
KSVZ
DFSZ
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$g_{a\gamma\gamma}$ [GeV^{-1}]
15
20
25
30
35
m_a [μeV]

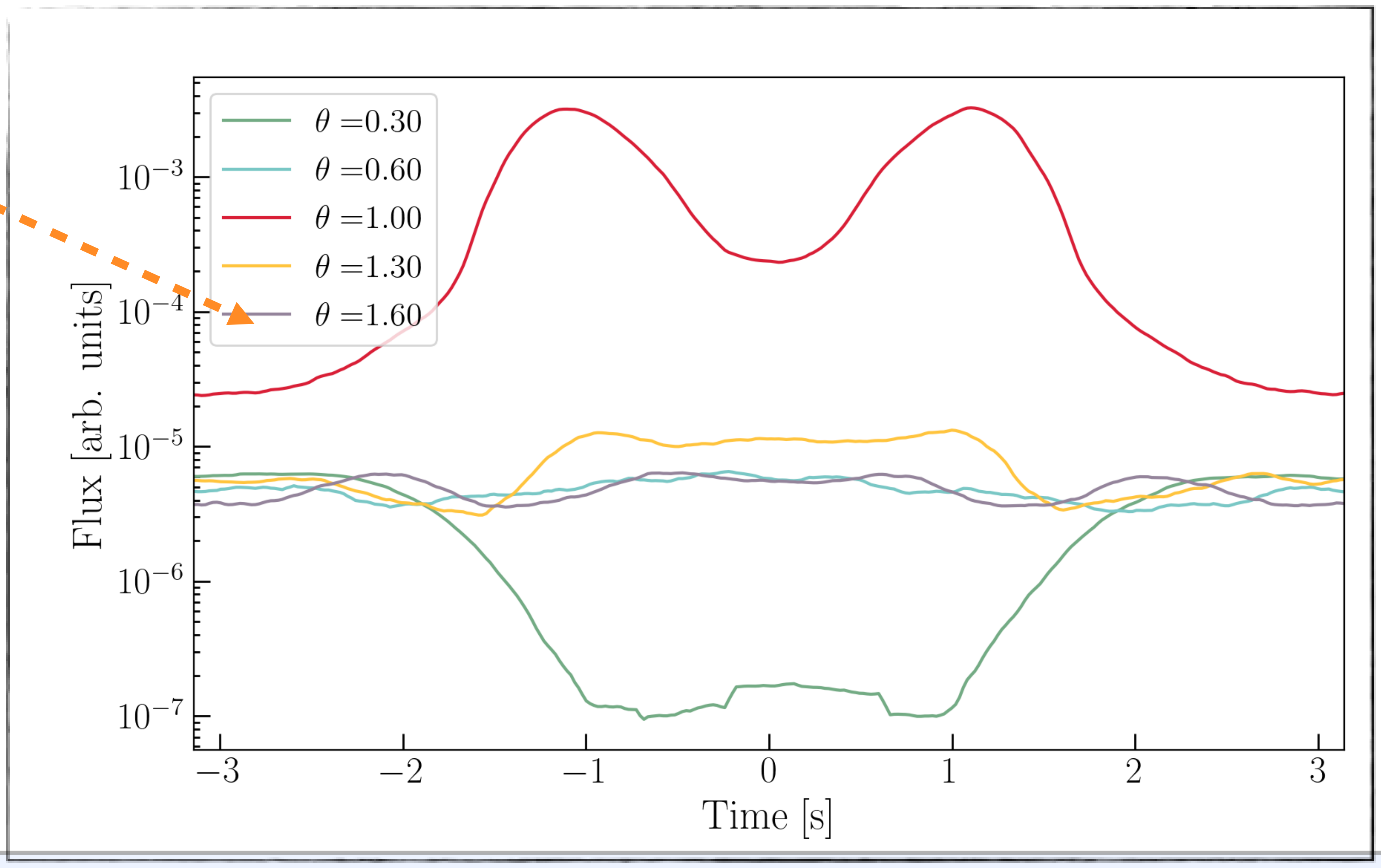
Radio signal from isolated neutron star

Projected sky flux as viewed from neutron star



SJW, Noordhuis, Edwards, Weniger (2021)





Neutron star population modeling

What about the properties of these neutron stars?

We want conditional probability: $p(P, B_0, \theta_m | t_{age})$

Well-measured quantities:

- Rotational period P
- Spin-down rate $\dot{P}$

Values today…

- $B_0 \propto \sqrt{P\dot{P}}$
- $\theta_m(t_{\rm birth})$ random, and evolution known

Adopt initial distributions, simulate evolutionary tracks, and fit to the distributions we observe today

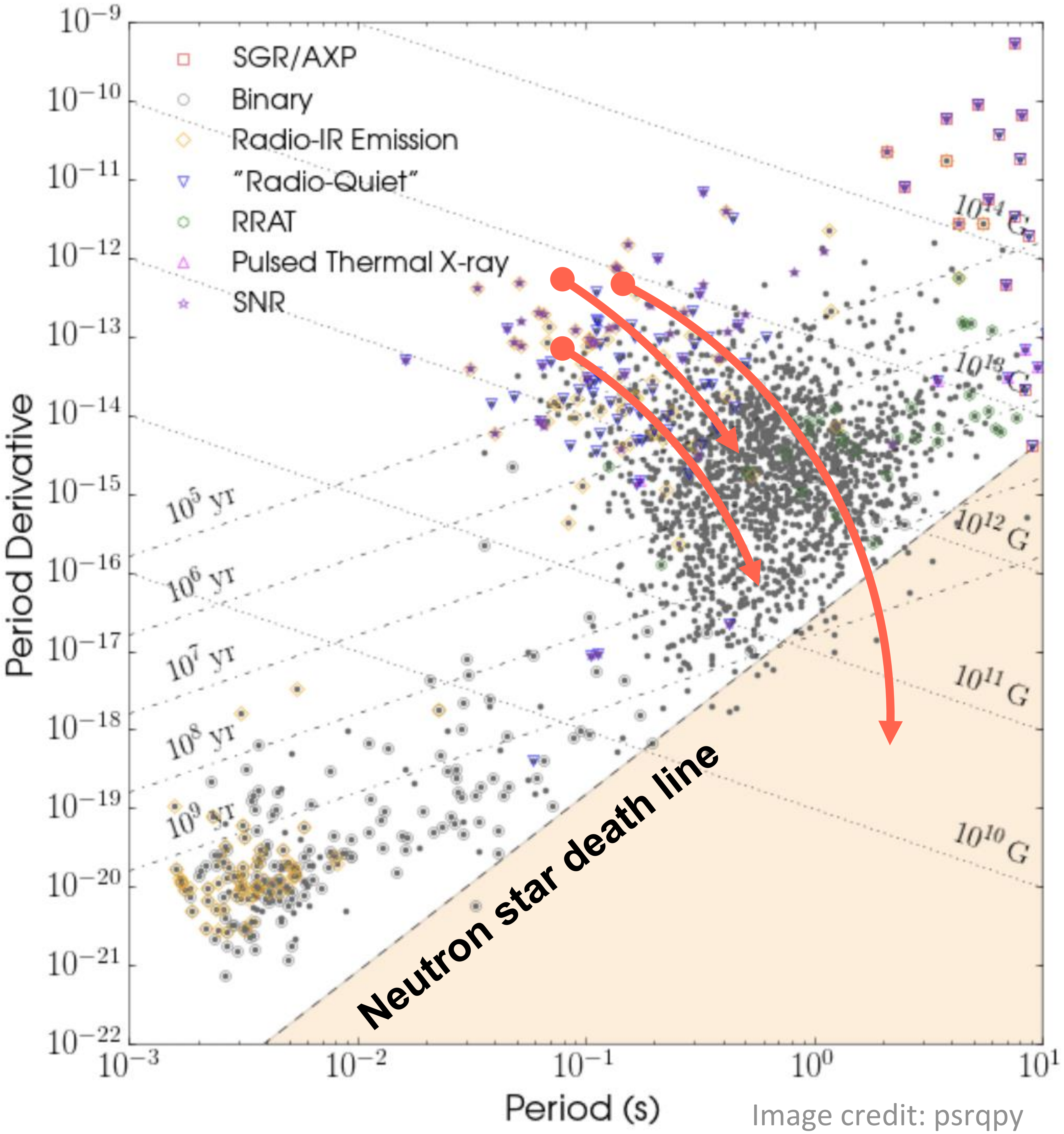


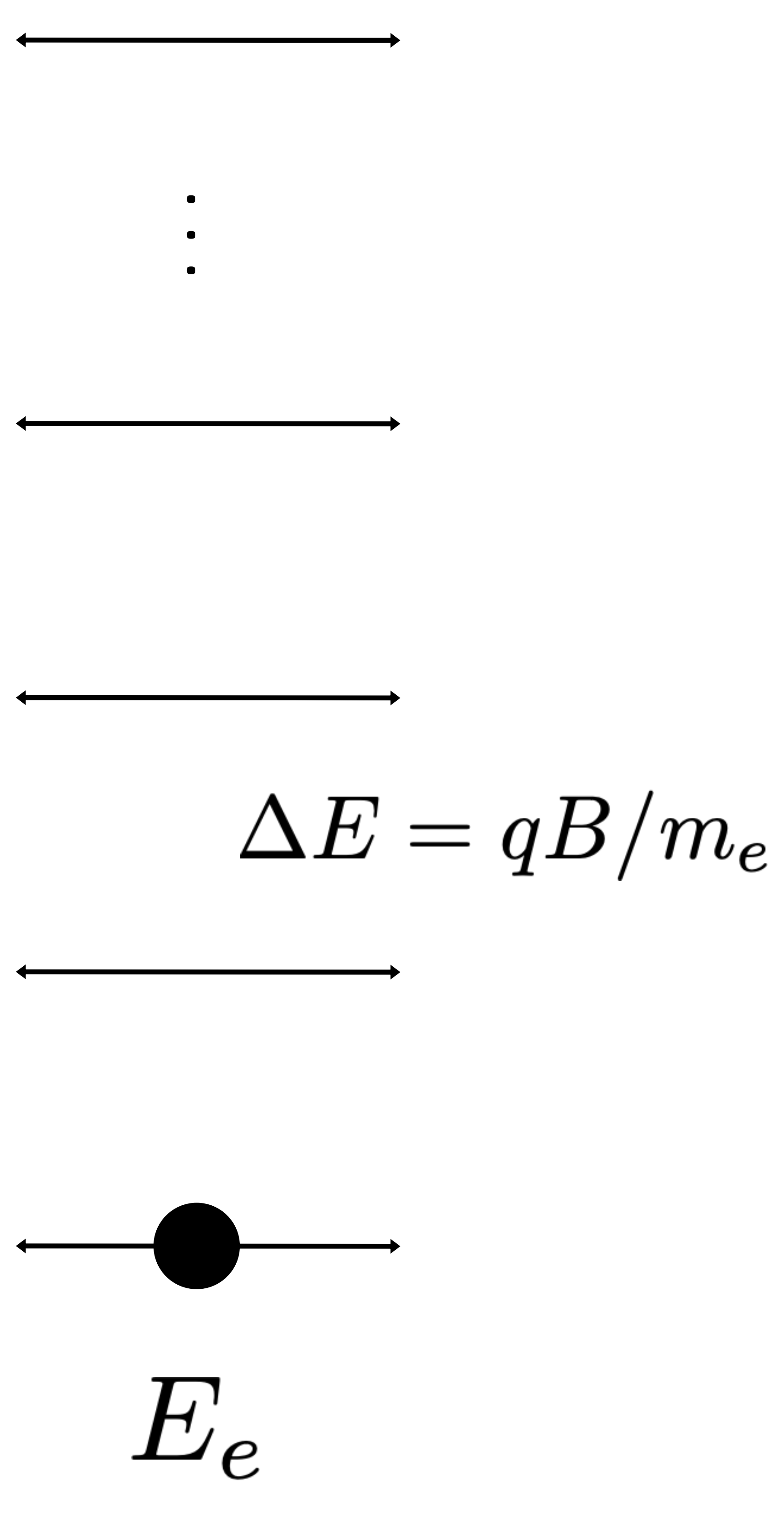
Image credit: psrqpy

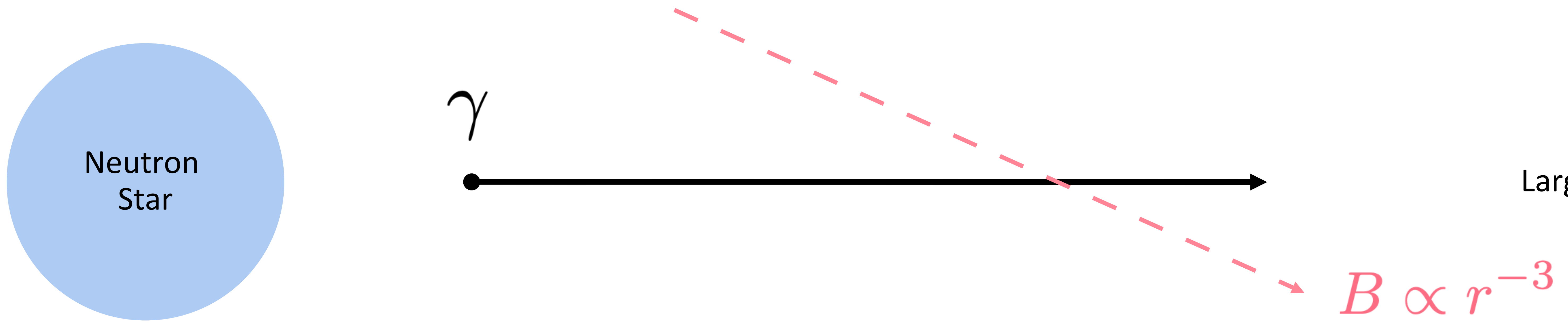
Philippov, Tchekhovskoy, Li (2014)
Gullón et al (2014)

Photon Absorption

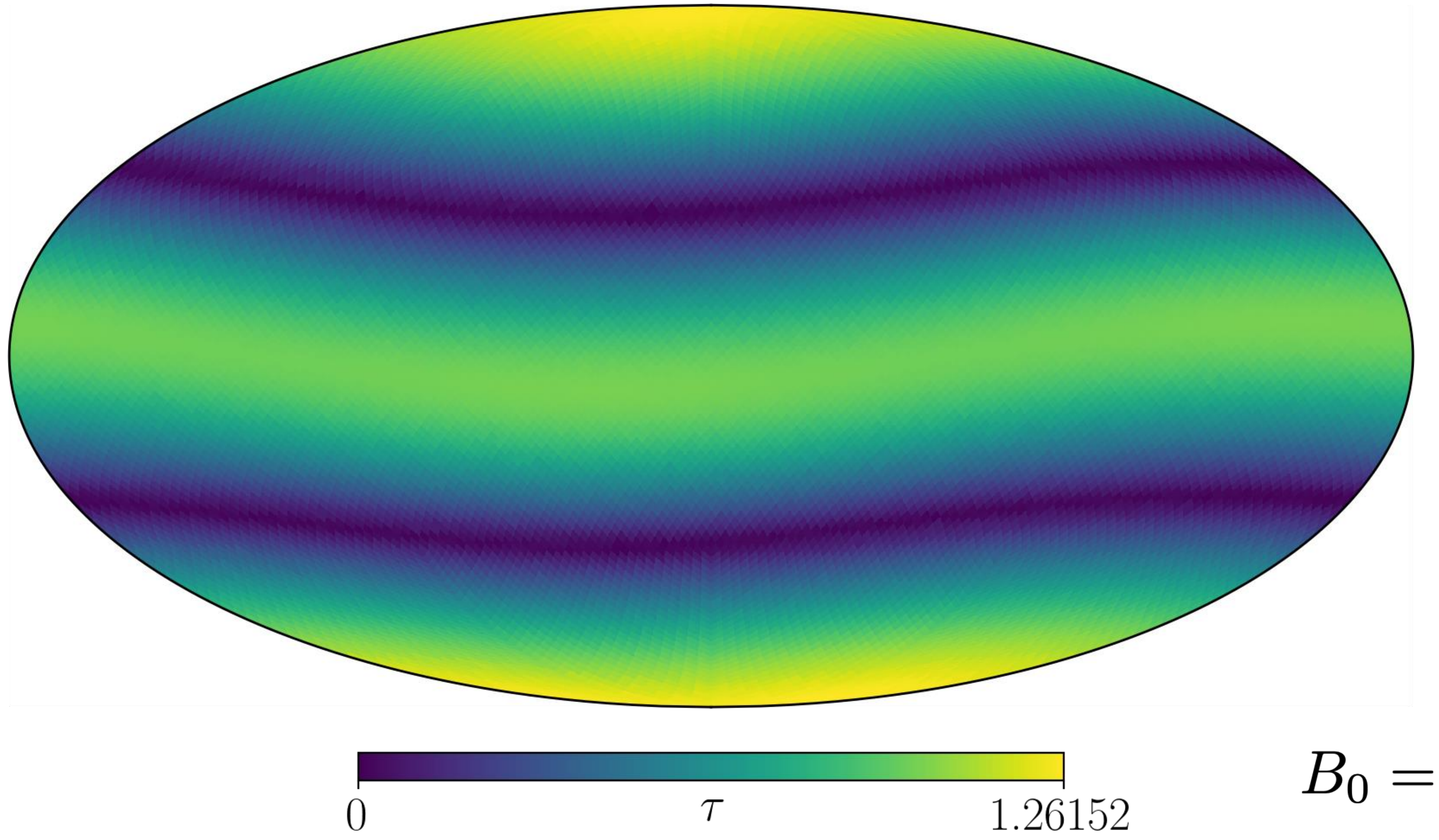
SJW, Noordhuis, Edwards, Weniger (2021)

Landau Levels

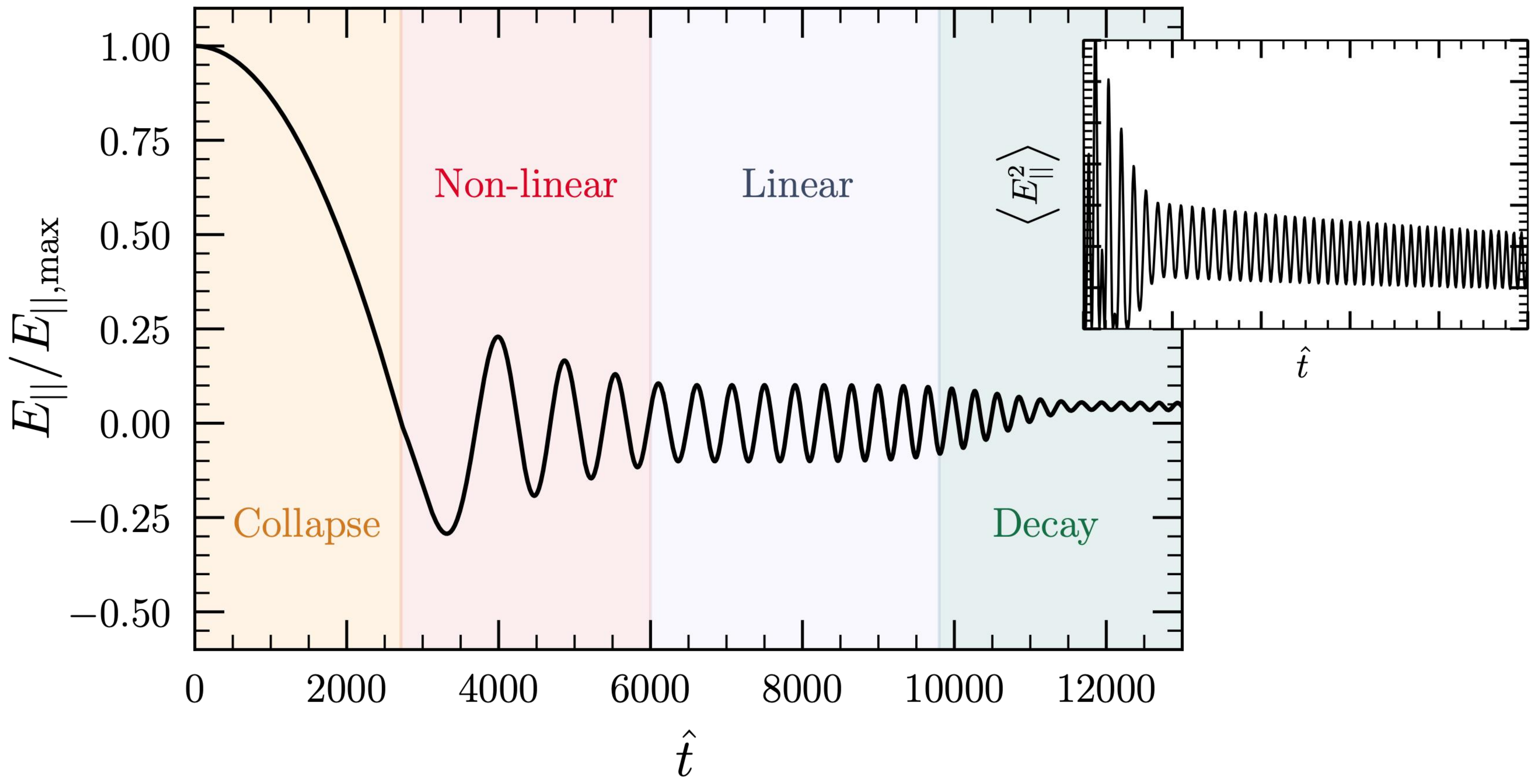


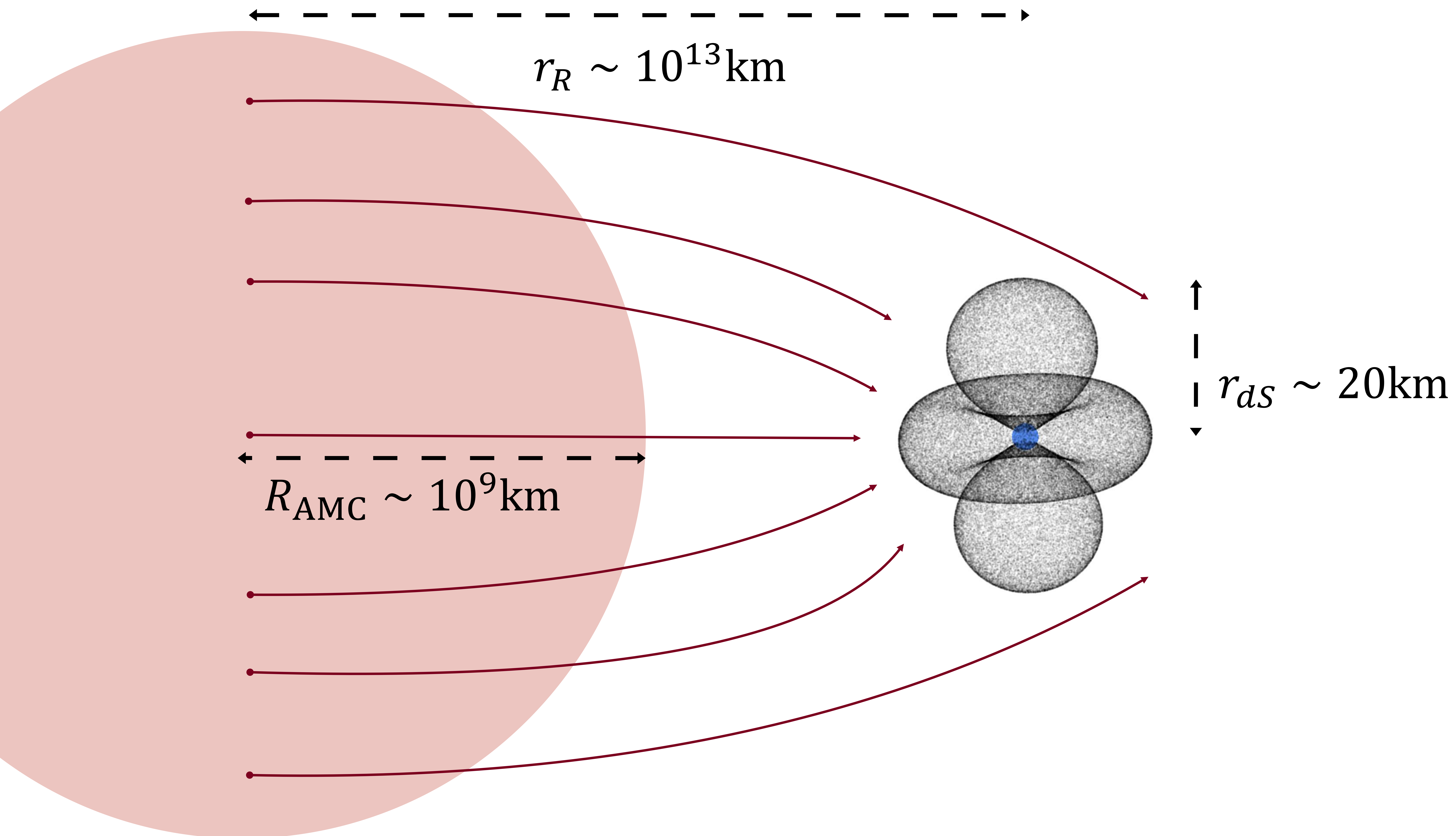


Larger B leads to more absorption**

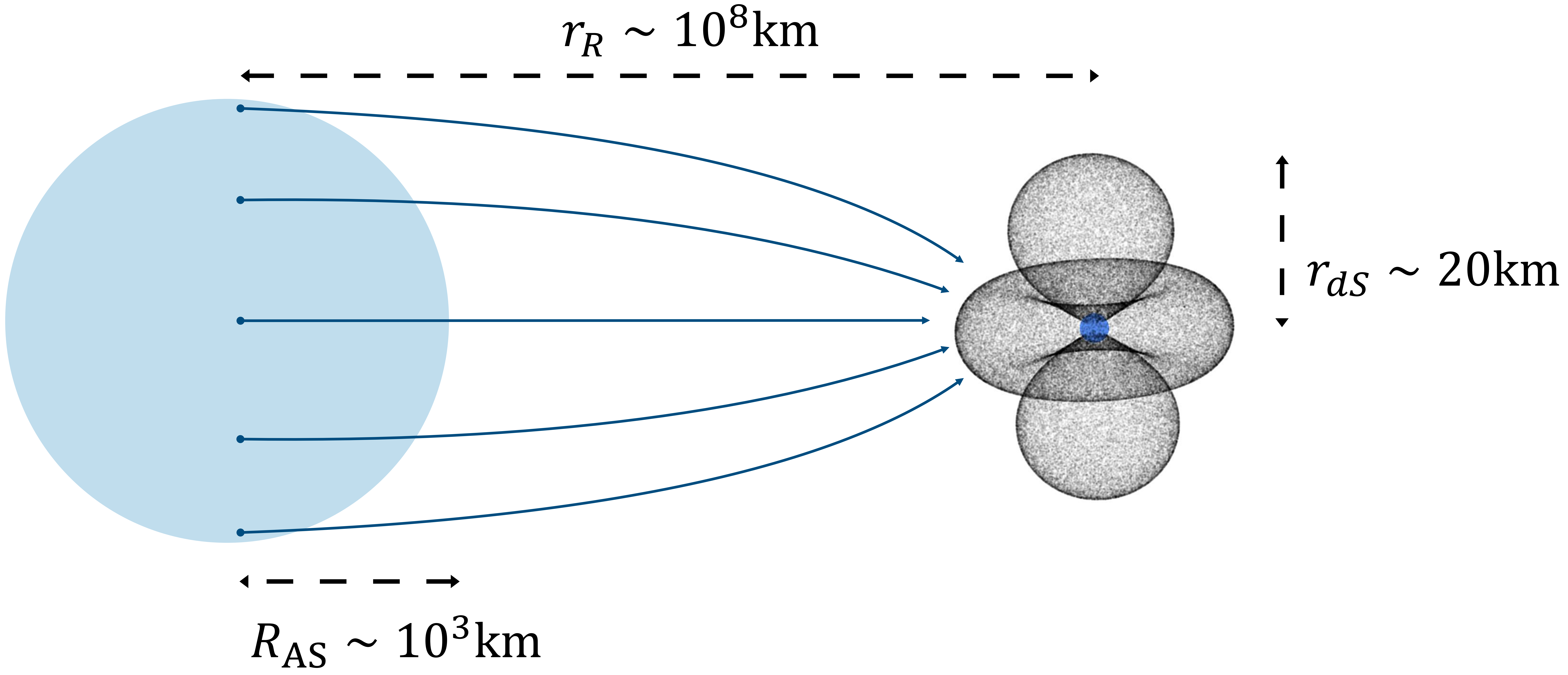


$B_0 = 5 \times 10^{14} G$


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



$r_R \sim 10^{13}\mathrm{km}$
$r_{ds} \sim 20\mathrm{km}$
$R_{\mathrm{AMC}} \sim 10^{9}\mathrm{km}$


$r_R \sim 10^8$km
$r_{dS} \sim 20$km
$R_{\rm AS} \sim 10^3$km