Neutron stars as axion laboratories

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COST Action *Cosmic Whispers*
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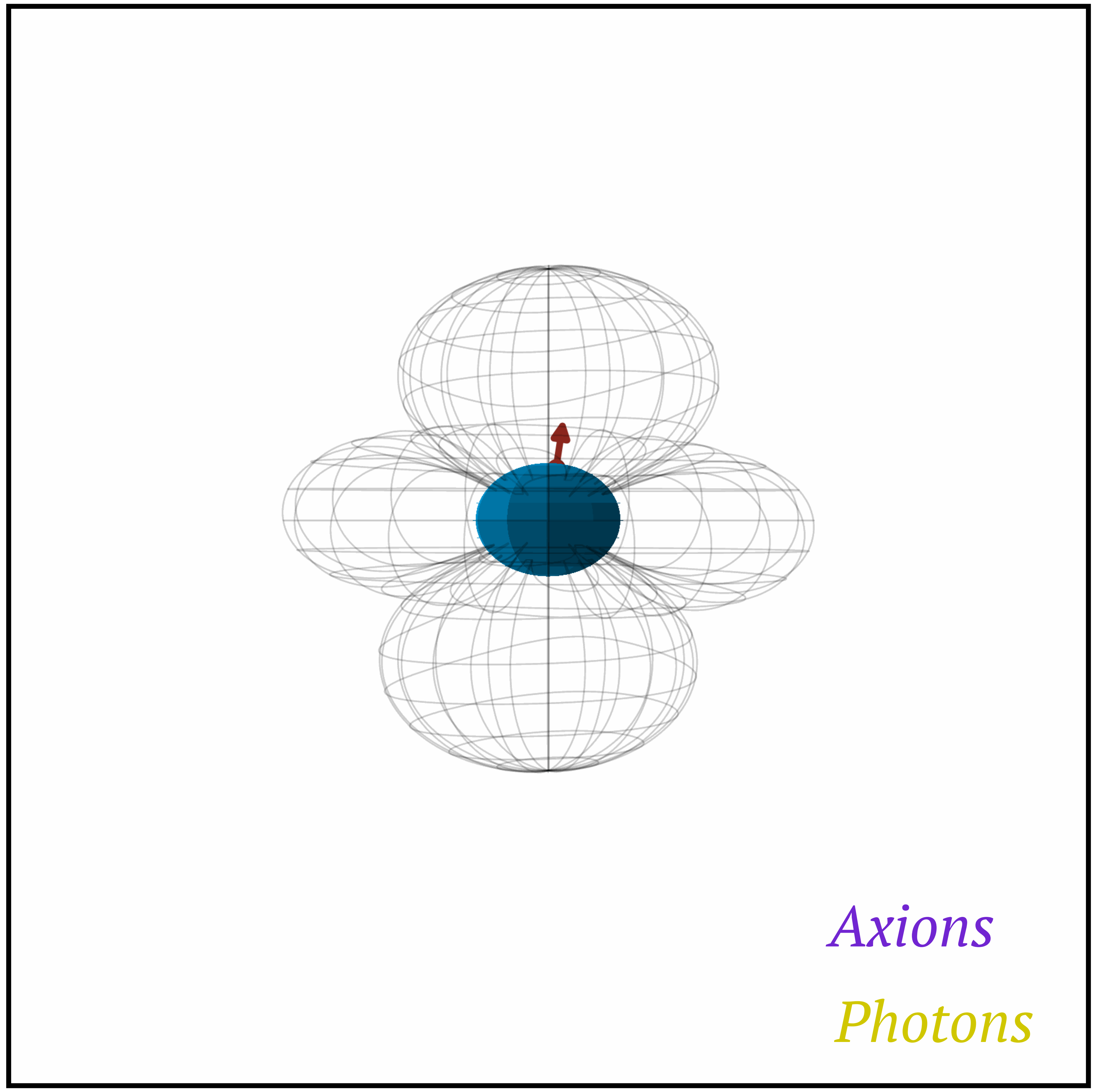
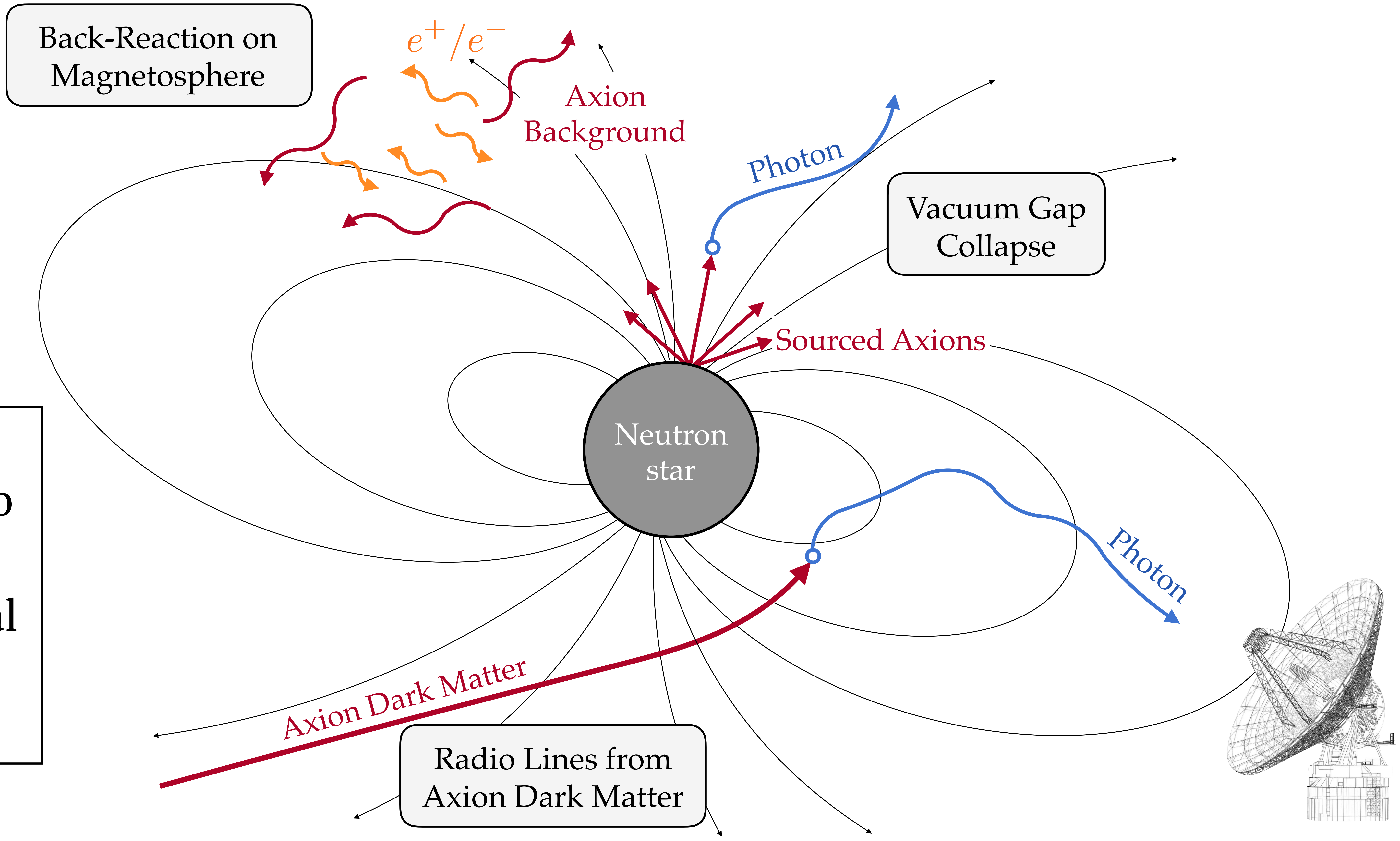
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

CA21106



Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

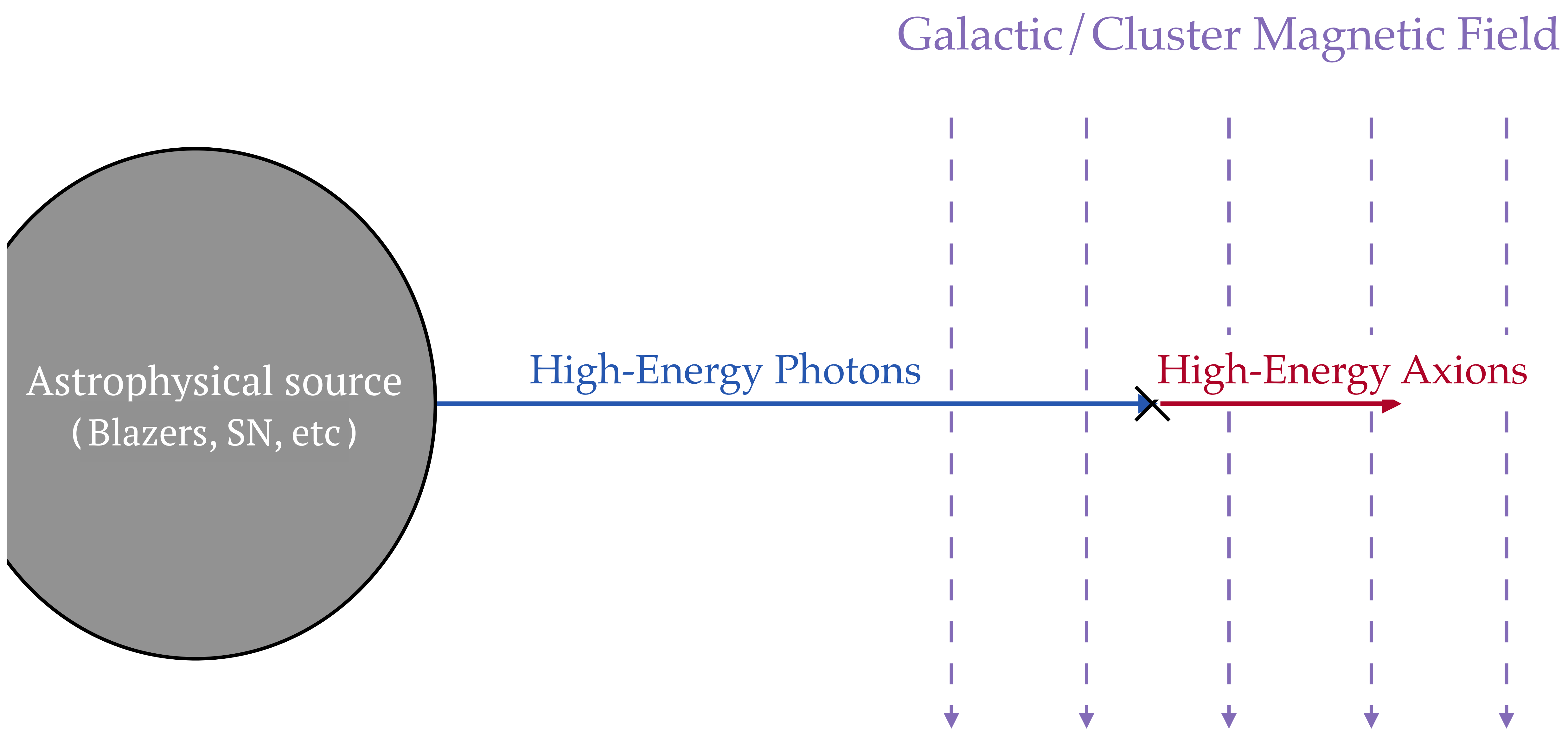
Overview: Neutron stars as axion laboratories

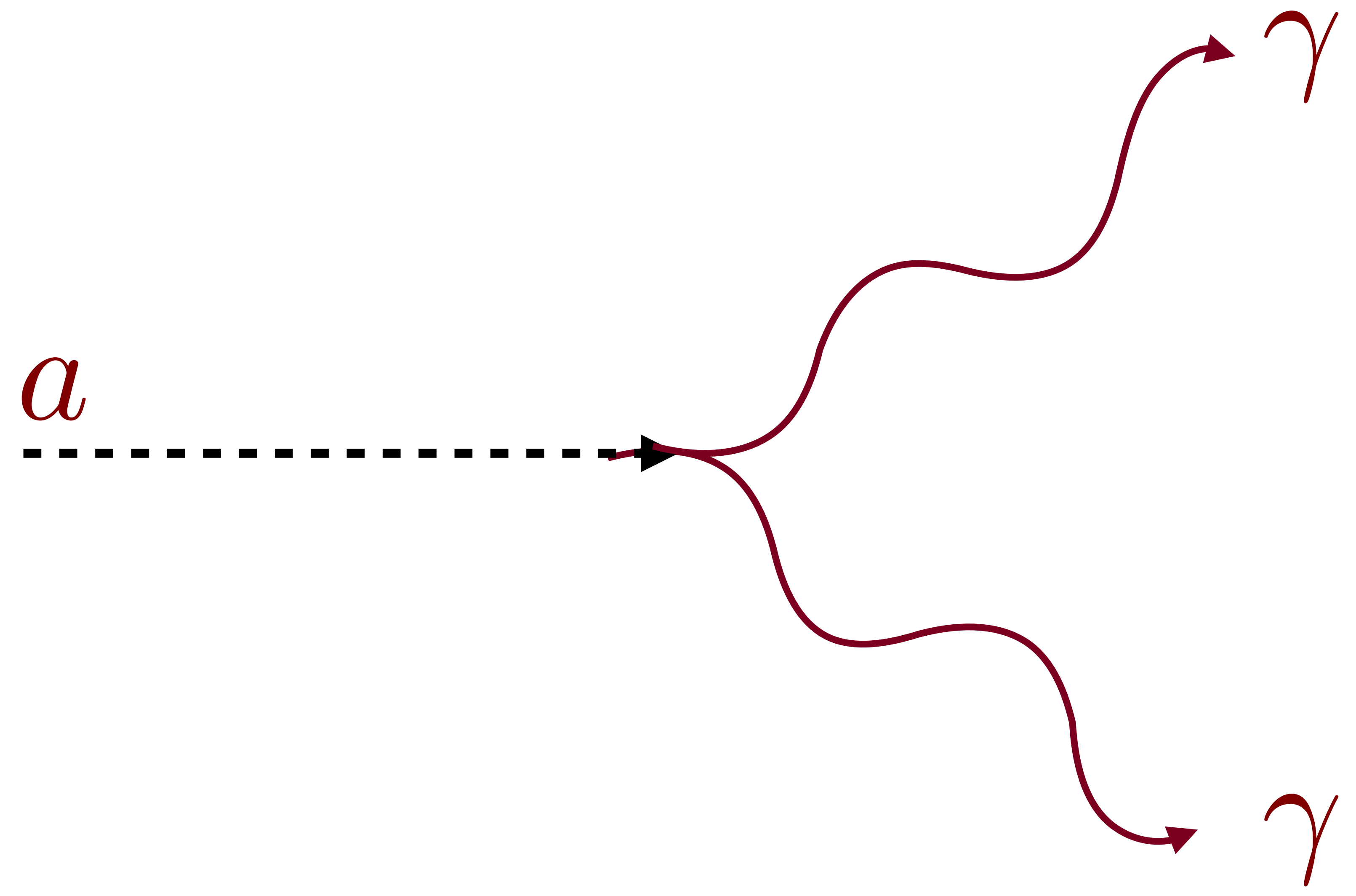


***Short take home*:**
These approaches allow us to probe axion masses that are *not accessible* to conventional indirect searches
(pushing toward QCD axion)

More “traditional” indirect axion searches

Axion-photon mixing ⟵ $\mathscr{L} \sim g_{a\gamma\gamma}\, a\, E \cdot B$ ⟶ **Axion decay**





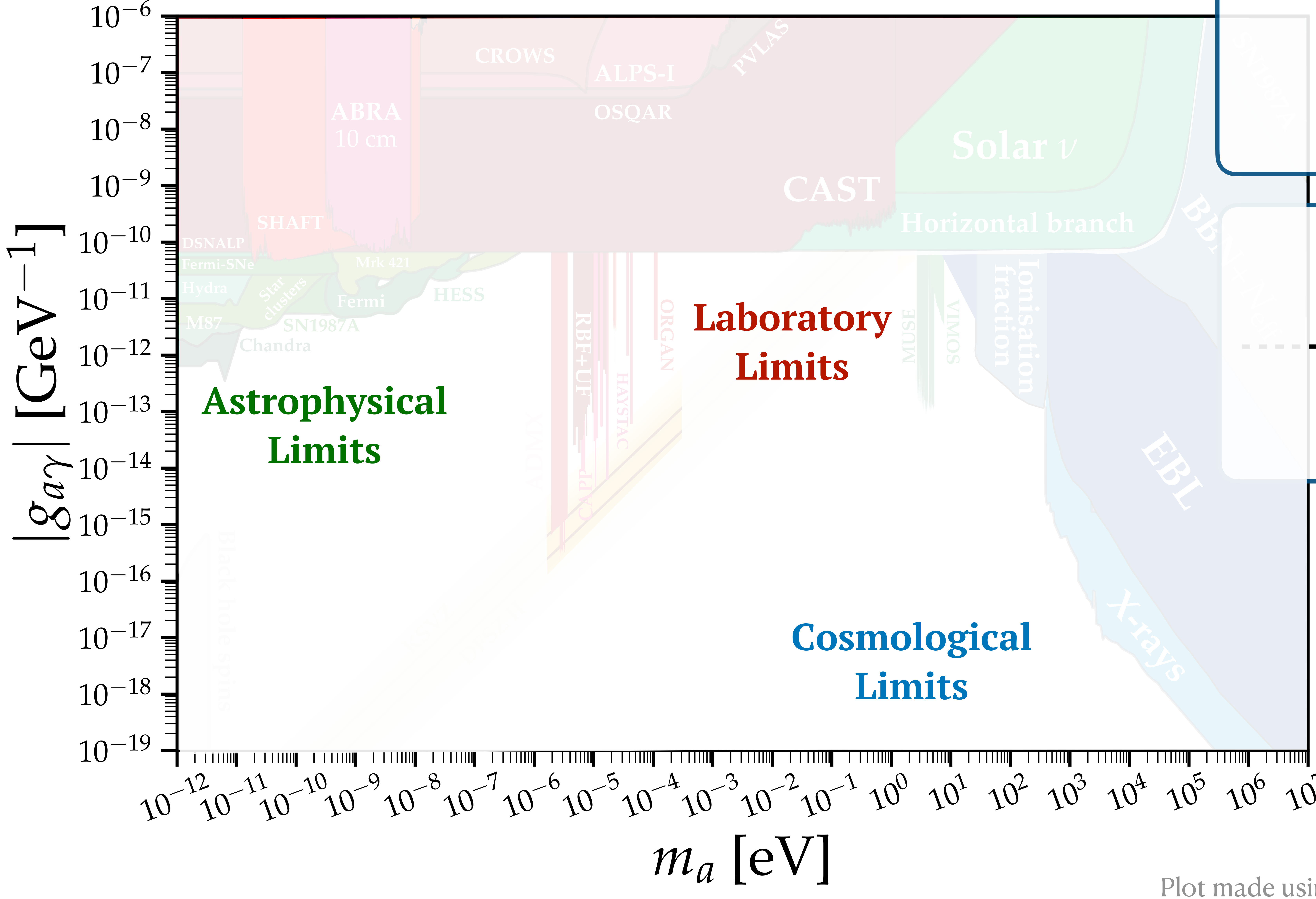
Works well at axion masses $m_a \lesssim 10^{-8}\,\mathrm{eV}$

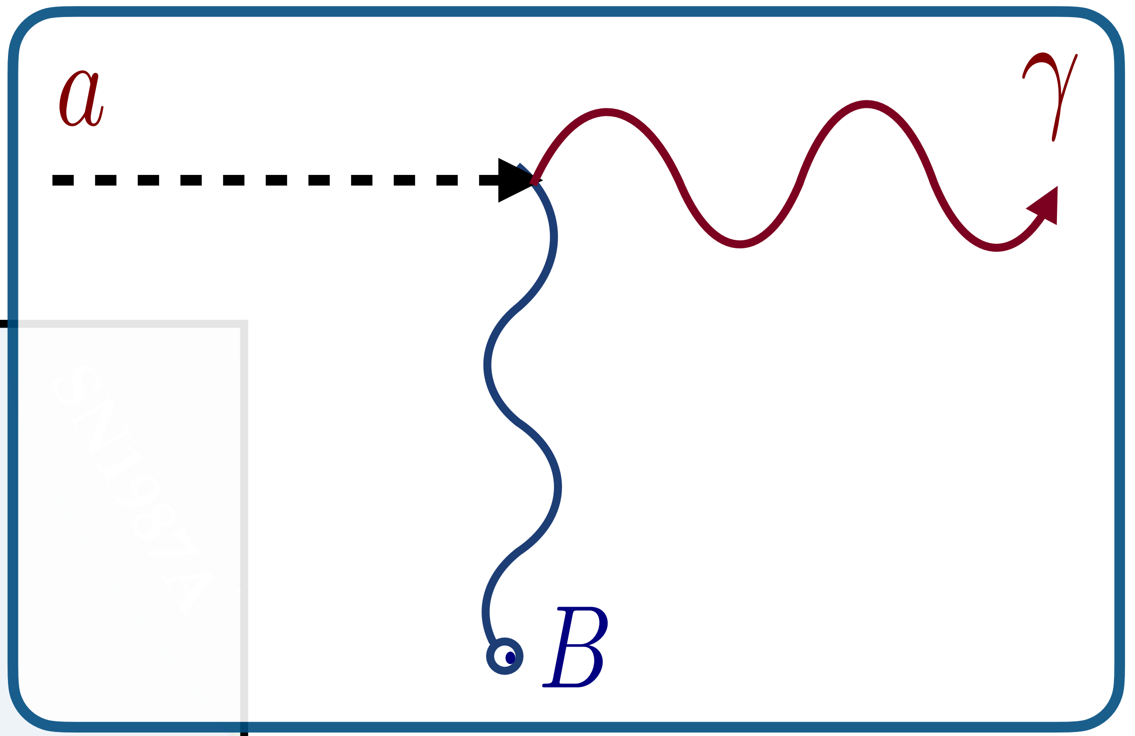
Mass Gap

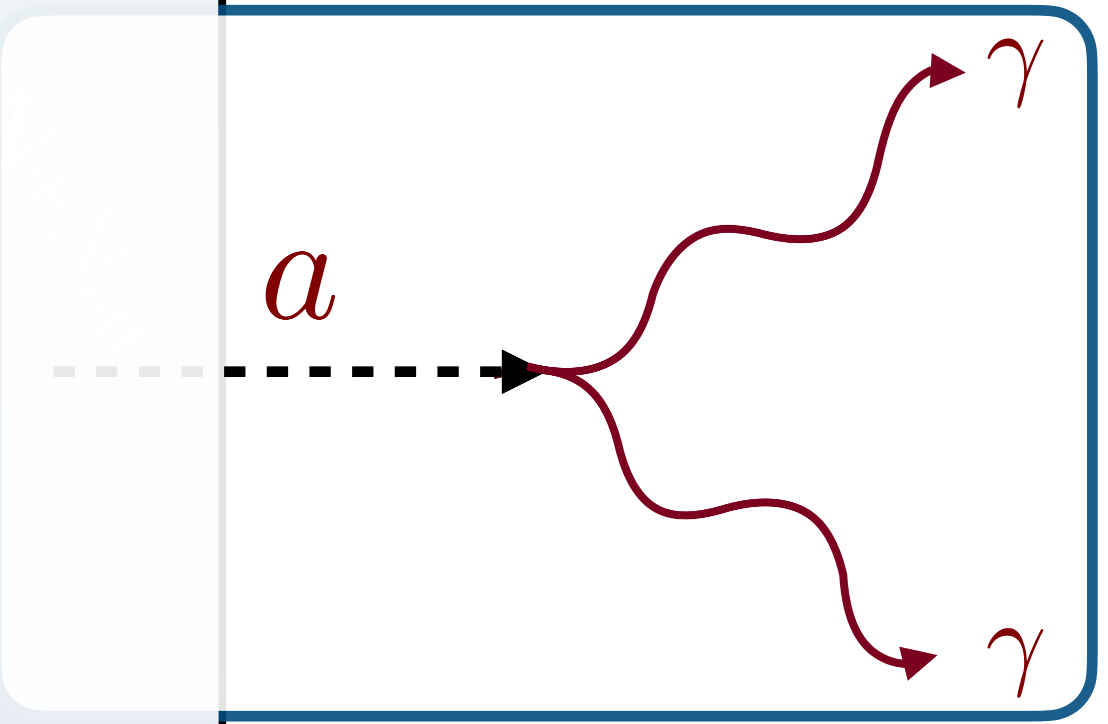
Works well at axion masses $m_a \gtrsim 1\mathrm{eV}$

⟶ Neutron star magnetospheres

Axion searches (circa 2021)

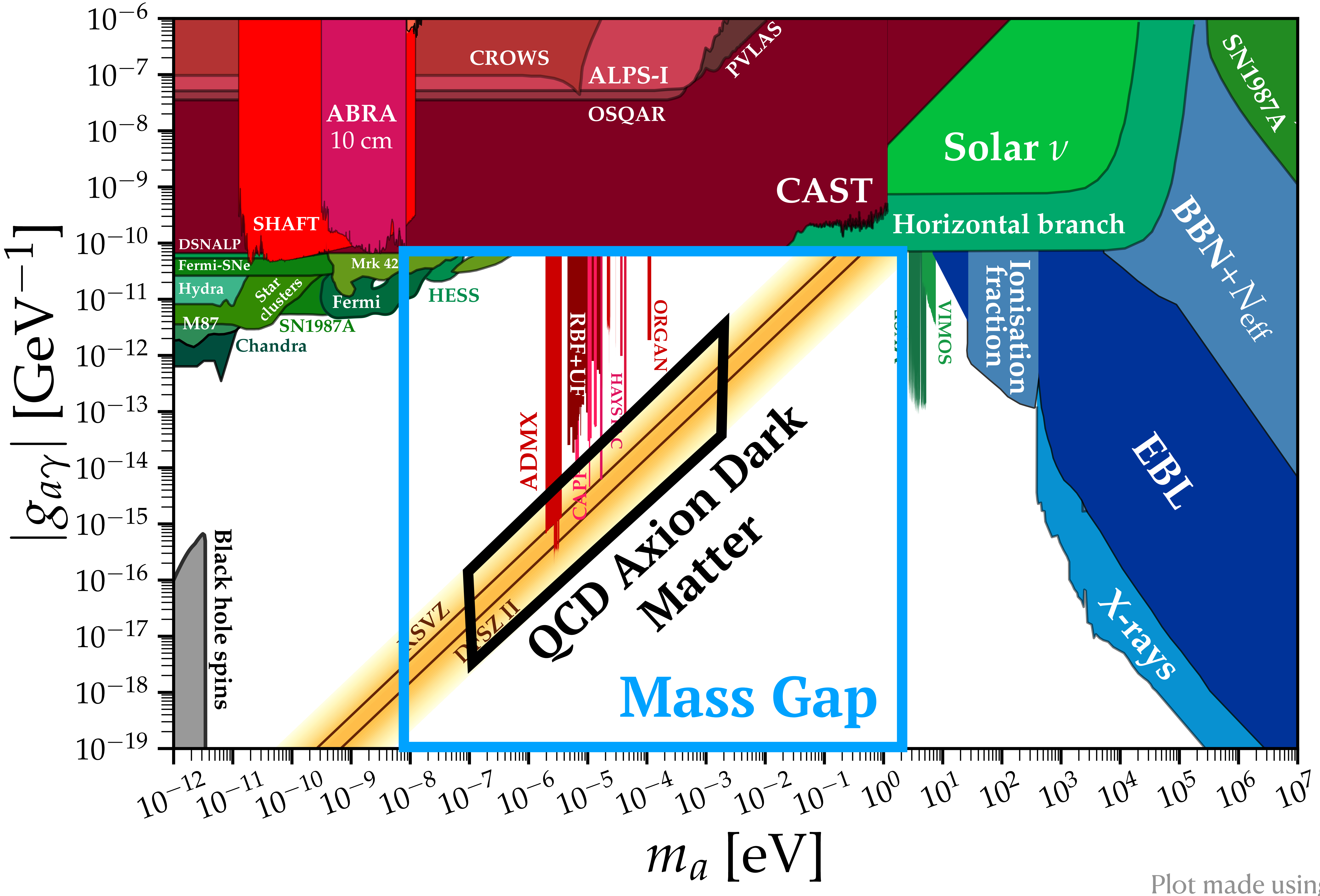






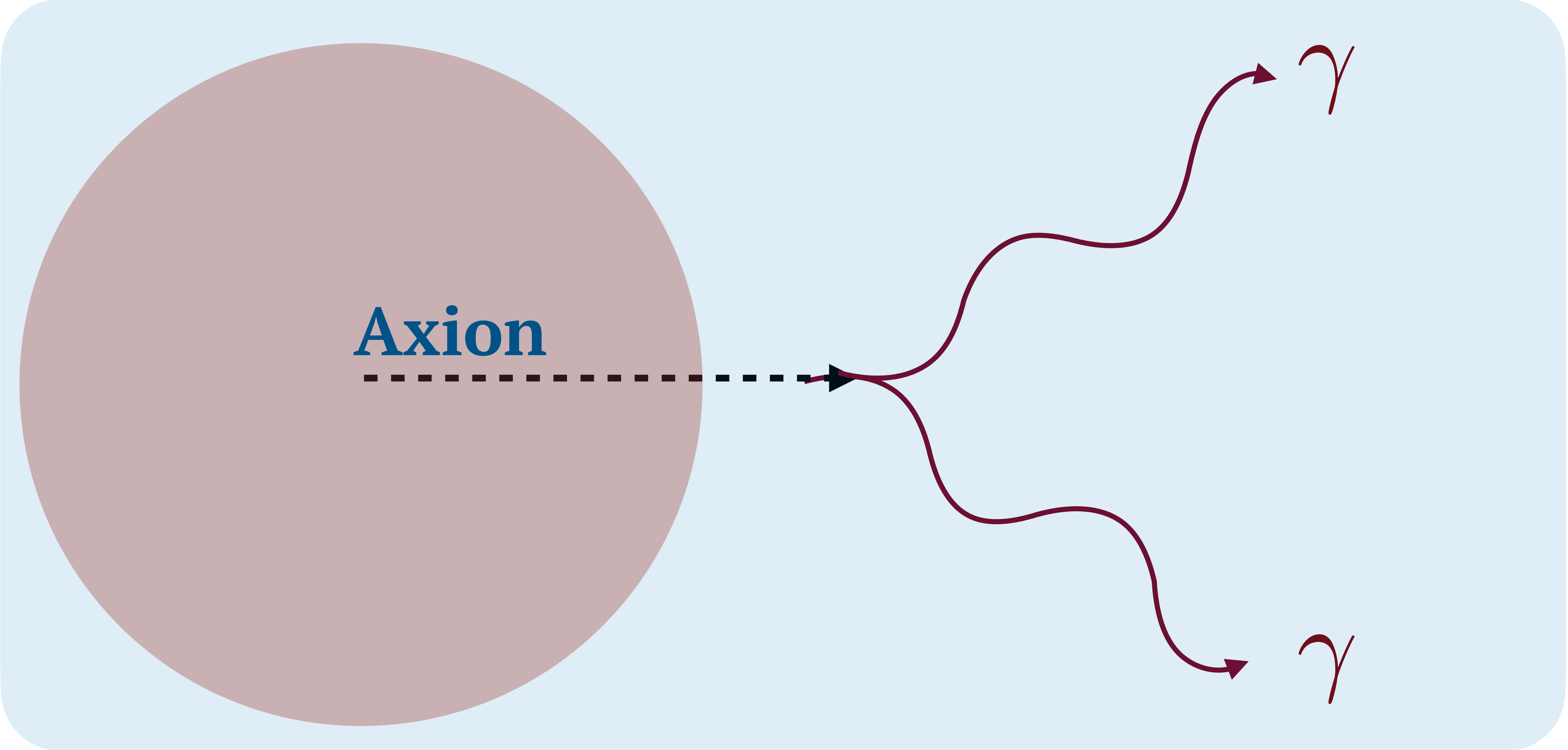
Plot made using cajohare.github.io/AxionLimits/

Axion searches (circa 2021)



Plot made using cajohare.github.io/AxionLimits/

A look at axion decay



Dense homogeneous axion background

Can we be sensitive to the decay at lower masses?

$$\tau \propto \frac{1}{m_a^3 \, g_{a\gamma\gamma}^2} \, \frac{1}{1 + 2 f_\gamma}$$

$$\tau \gg \tau_{\text{Universe}} \text{ for } m_a \ll \mathcal{O}(\text{eV})$$

Background photons with $E_\gamma \sim m_a/2$

Simulated decay by photon background: Caputo, Garay, **SJW** (2018), Caputo, Regis, Taoso, **SJW** (2018), Ghosh et al (2020), Sun et al (2022), Buen-Abad et al (2022)

Parametric resonance can lead to exponential decay

Tkachev (1987, 2015), Azra (2018), Hertzberg et al (2018), Alonso-Alvarez et al (2020), Levkov et al (2020), Arza et al (2020)

Difficultly stems from 2 requirements:

1.) Large axion occupation numbers

2.) Strong homogeneity (gravitational de-tuning)

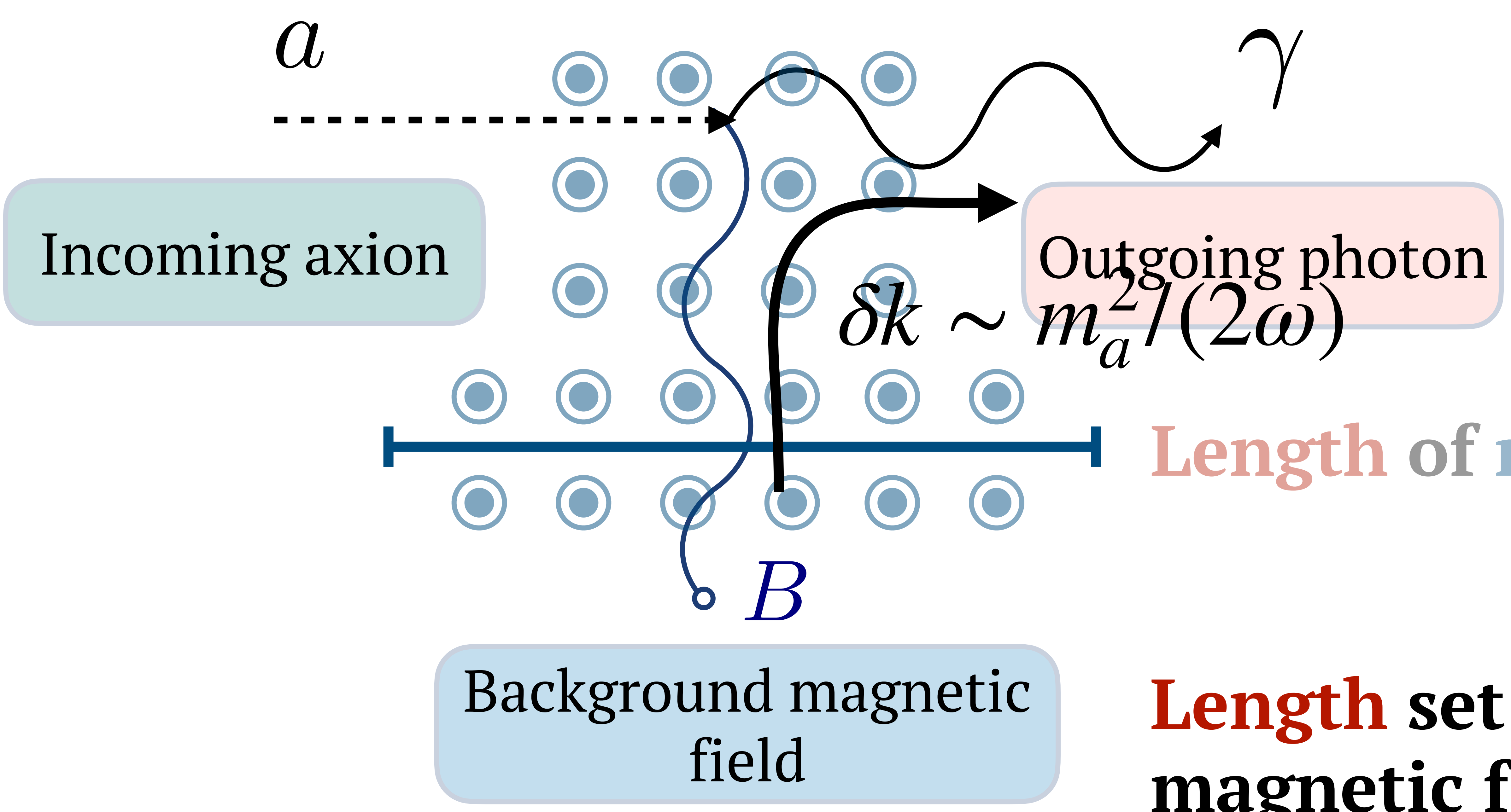
Moral of the story

Using decay to probe lower masses is very difficult

A look at axion-photon mixing

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

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



Large conversion probabilities require:

- Large *magnetic fields*
- Large "*Lengths*"

Length of magnetic field

Length set by momentum transfer from magnetic field

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

*Which **Length** is smaller?*

Example:

High-energy indirect axion searches

Galactic/Cluster Magnetic Field

Astrophysical gamma-ray source (e.g. galaxy, supernovae)

High-Energy Photons

High-Energy Axions

Absorption, Excess Emission

Length Scales

$$L_{\delta k} \sim \delta k^{-1} \sim \frac{2\omega}{m_a^2}$$

Example: Galactic supernova

$\omega \sim \mathcal{O}(10)\,\text{MeV}$

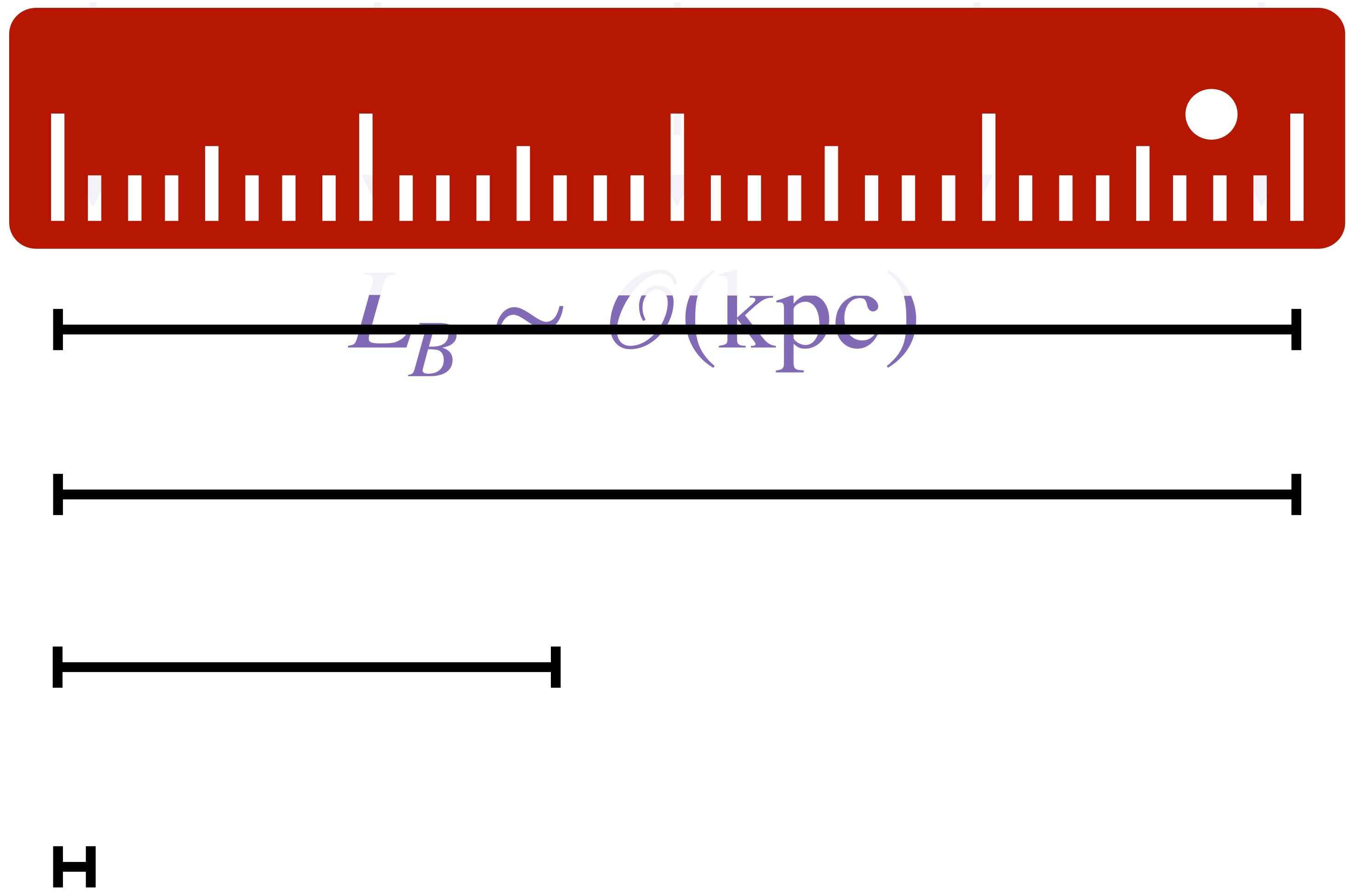
Axion Mass

$m_a \sim 10^{-11}\,\text{eV}$

$m_a \sim 10^{-10}\,\text{eV}$

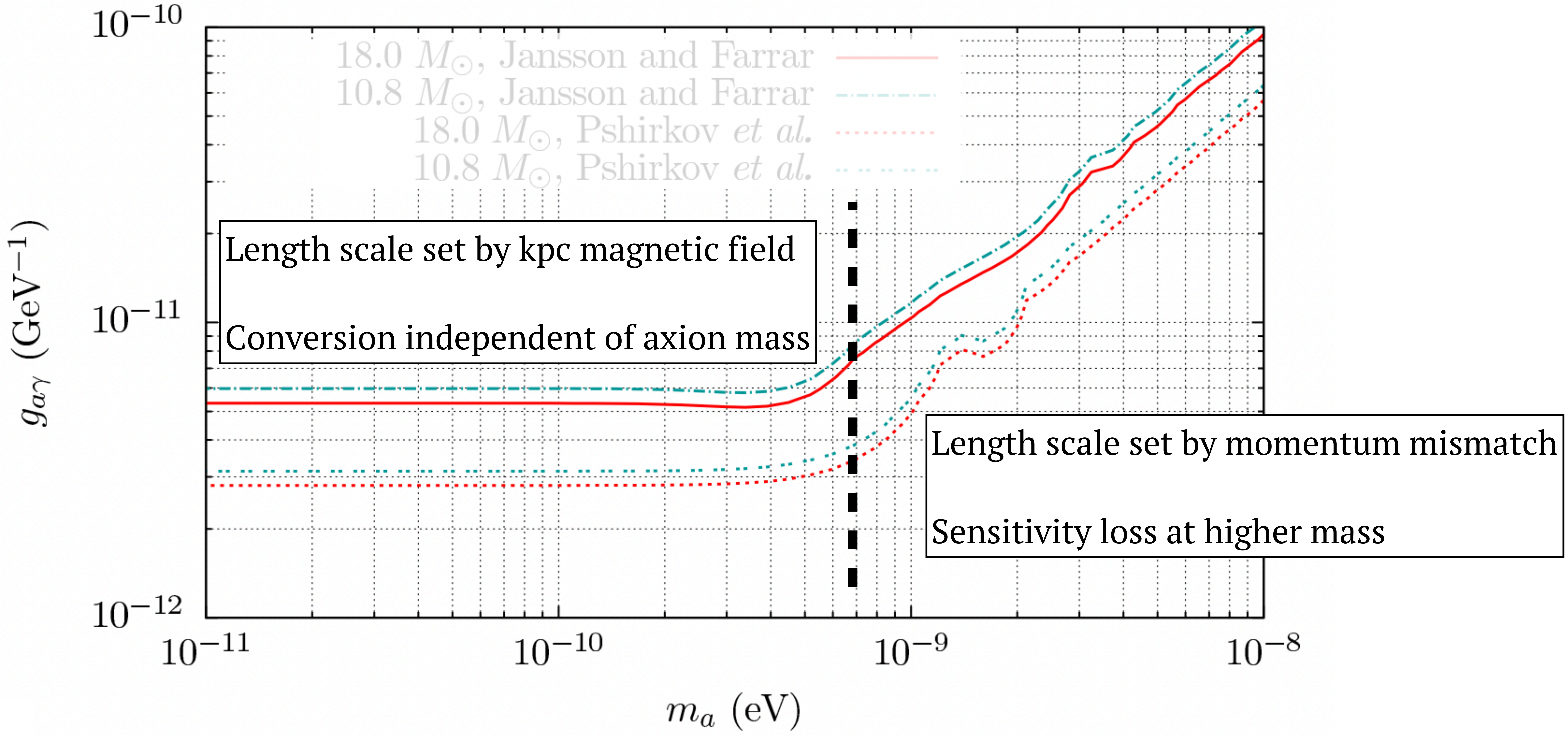
$m_a \sim 10^{-9}\,\text{eV}$

$m_a \sim 10^{-8}\,\text{eV}$



Axion-photon mixing

Search for gamma ray burst associated to SN 1987A

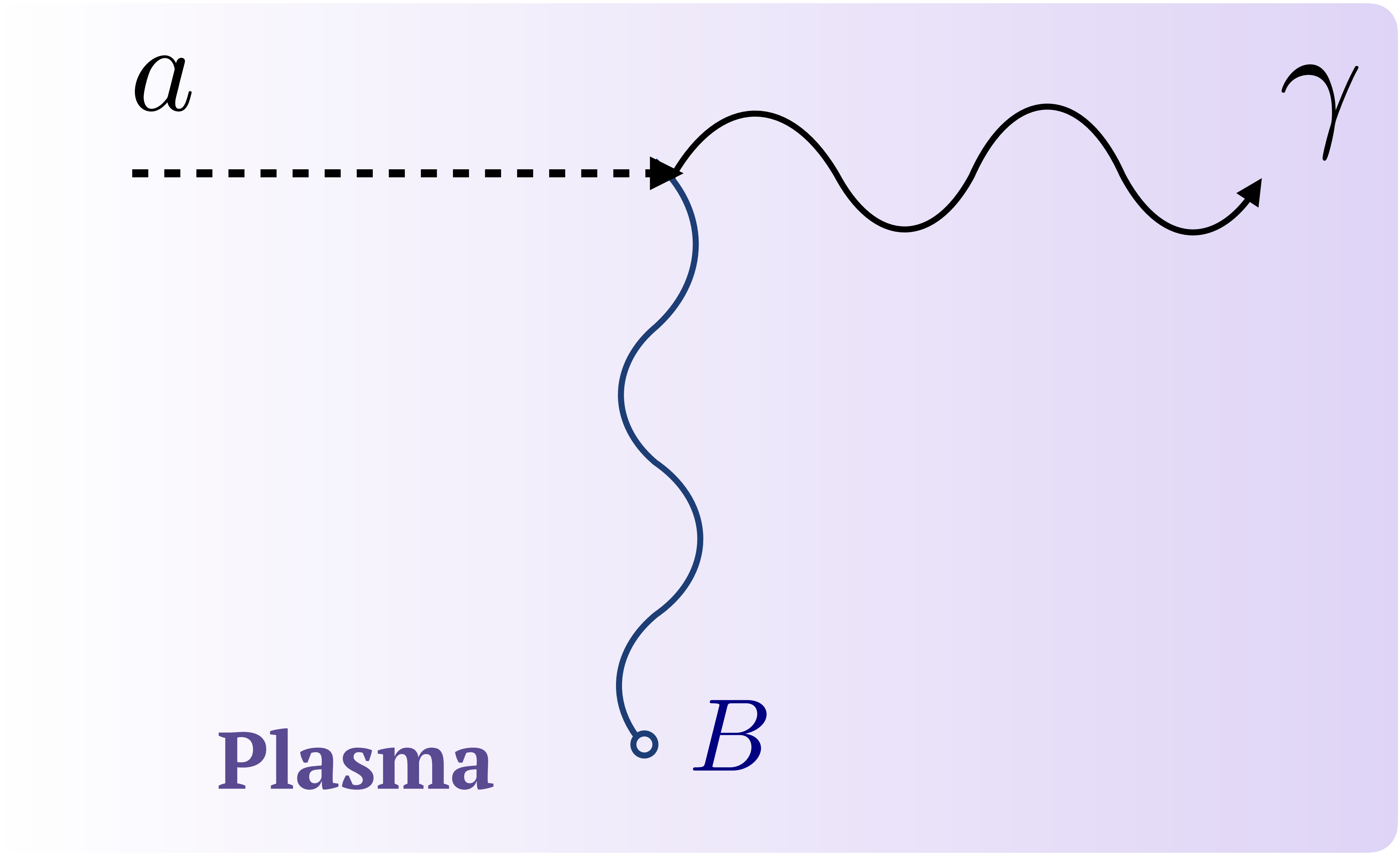


Payez et al. 2015

Axion-photon mixing

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

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



Indirect axion searches fundamentally limited at large masses by momentum mismatch

Momentum mismatch in vacuum plasma

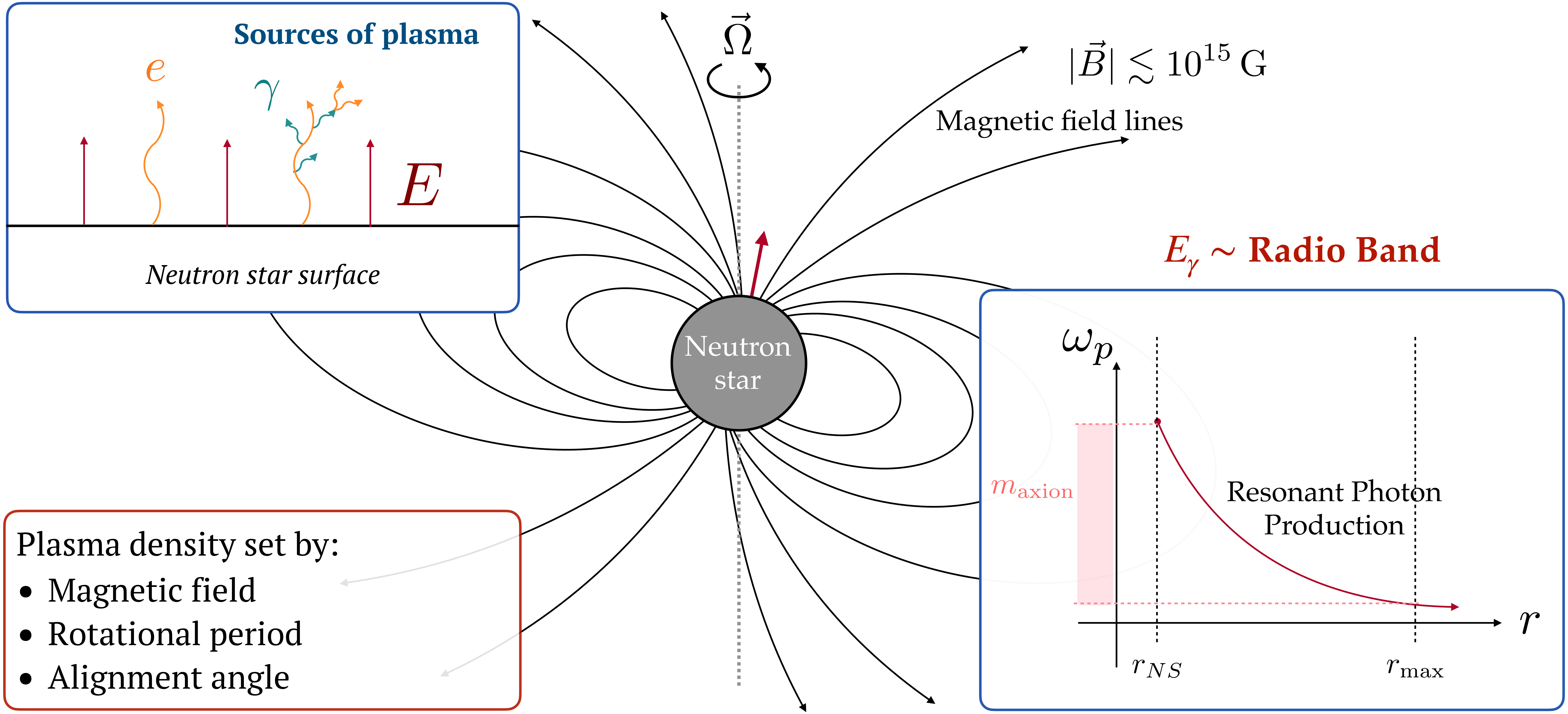
$$\delta k \sim \sqrt{\omega^2 - m_a^2} - \omega \sim \frac{m_a^2}{\omega}$$

$$\delta k \sim \sqrt{\omega^2 - m_a^2} - \sqrt{\omega^2 - \omega_p^2}$$

$$\delta k \sim 0 \quad \text{if} \quad m_a \sim \omega_p$$

We can reach higher masses by using: ***Large coherent magnetic fields and background plasma***

Neutron star magnetospheres



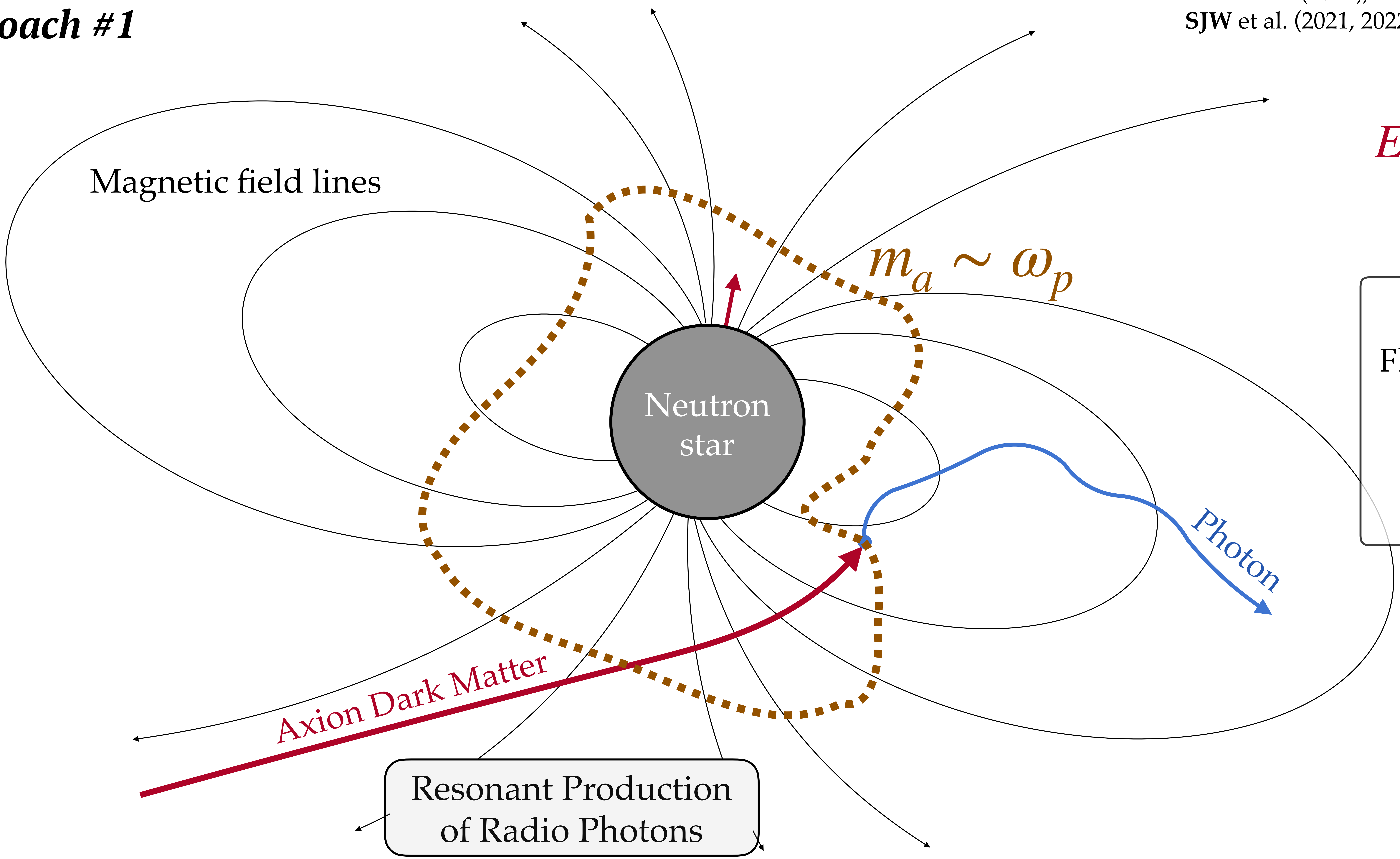
Plasma density set by:

- Magnetic field
- Rotational period
- Alignment angle

Neutron stars as axion labs

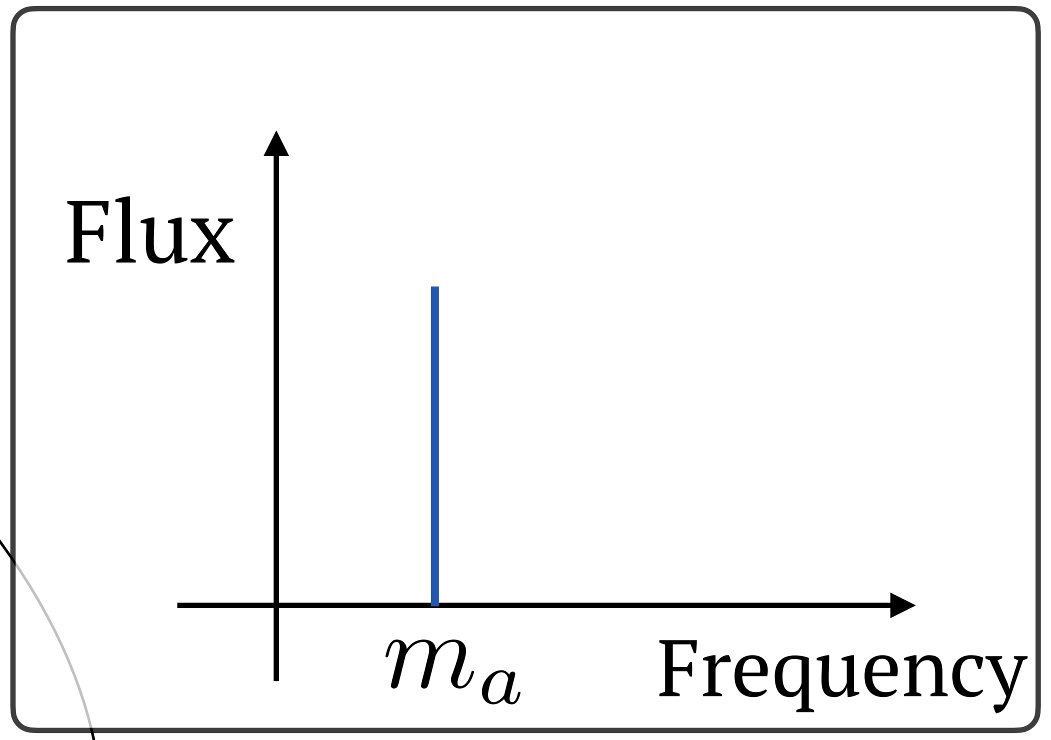
Approach #1

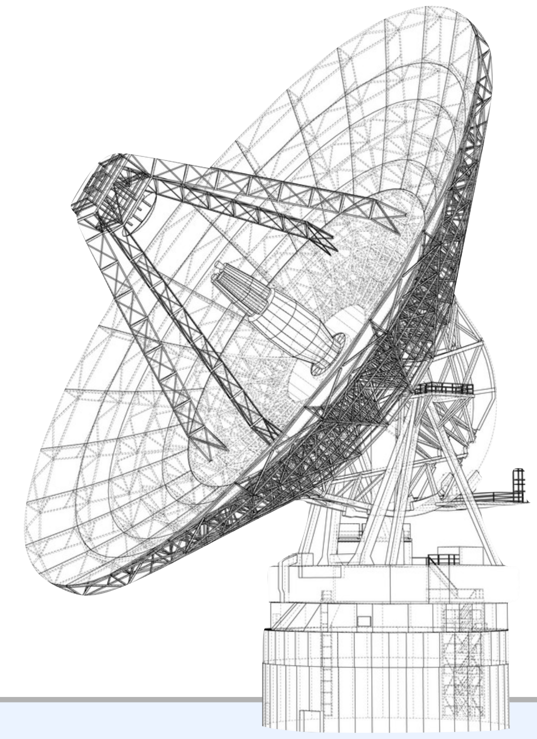
Spectral Lines from Axion Dark Matter:
See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021, 2023), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), …



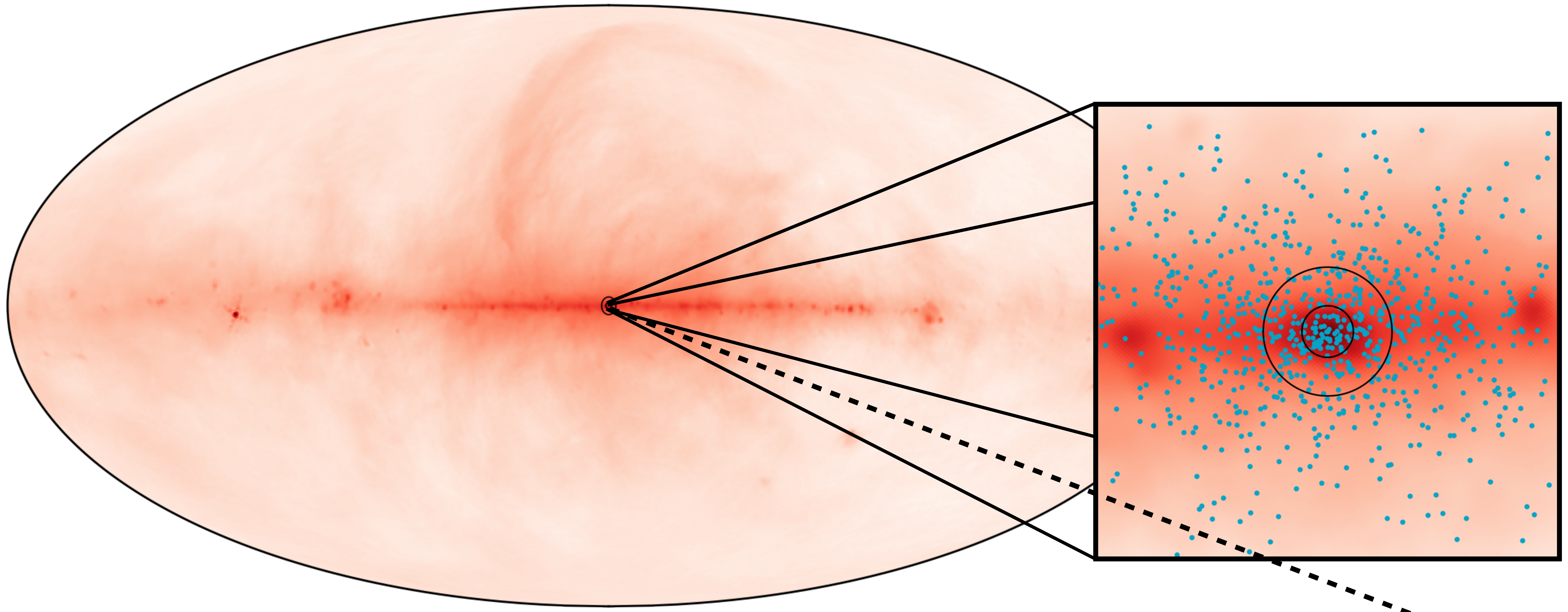
$$E_a \sim m_a (1 + v^2/2)$$

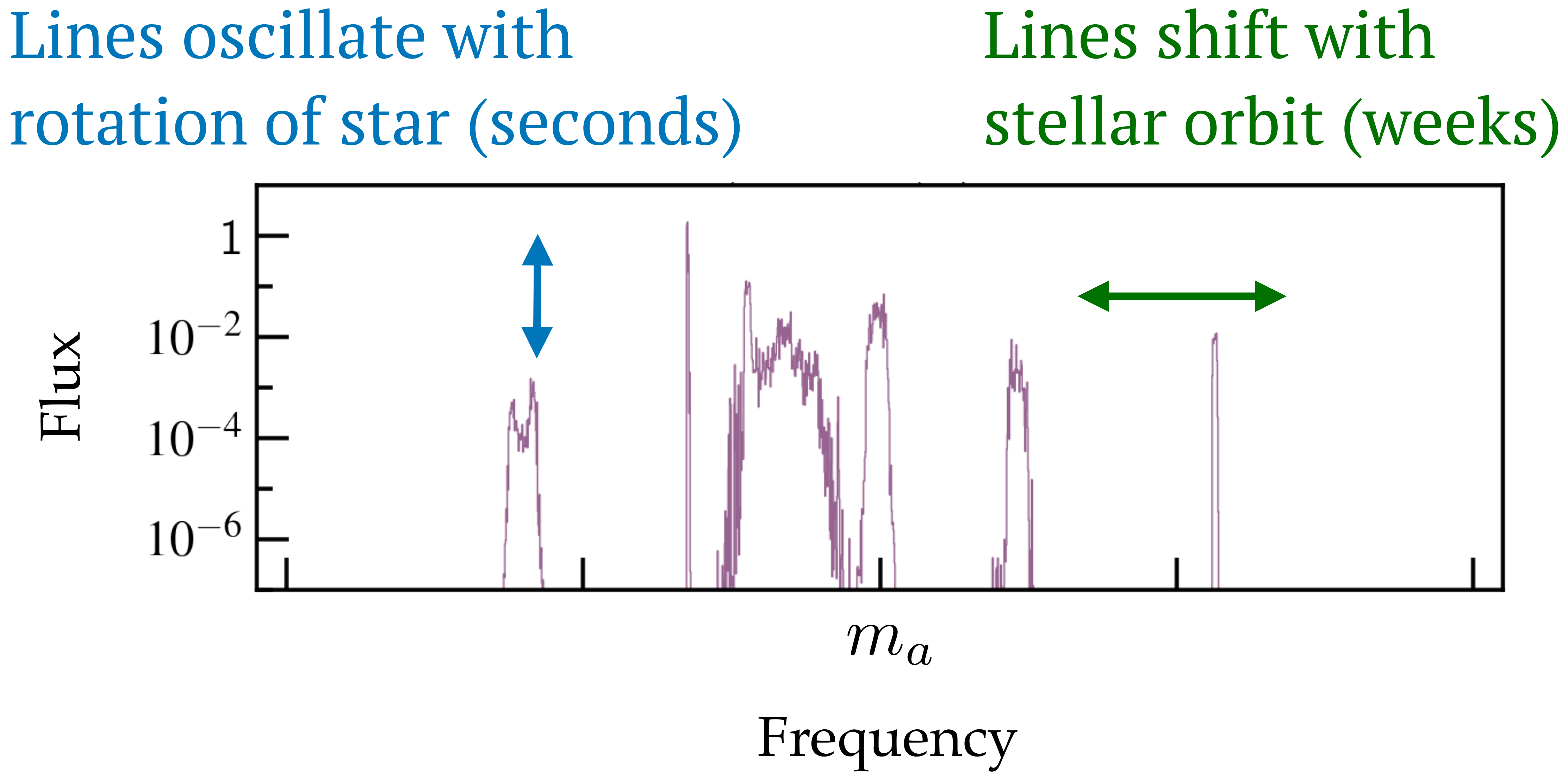
$$v \sim \mathcal{O}(10^{-3})$$





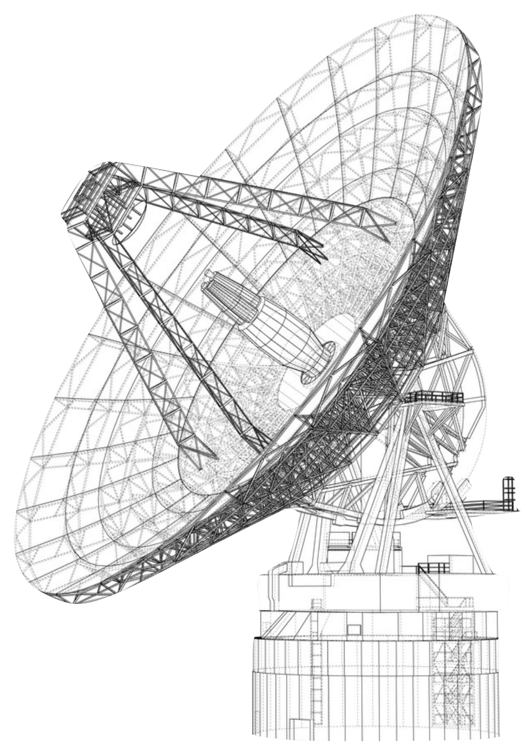
Radio searches for axions





Potential targets:

- Galactic Center
  [pros: more dark matter & neutron stars] [cons: complex modelling]
- Nearby isolated neutron stars
  [pros: distance] [cons: less dark matter]

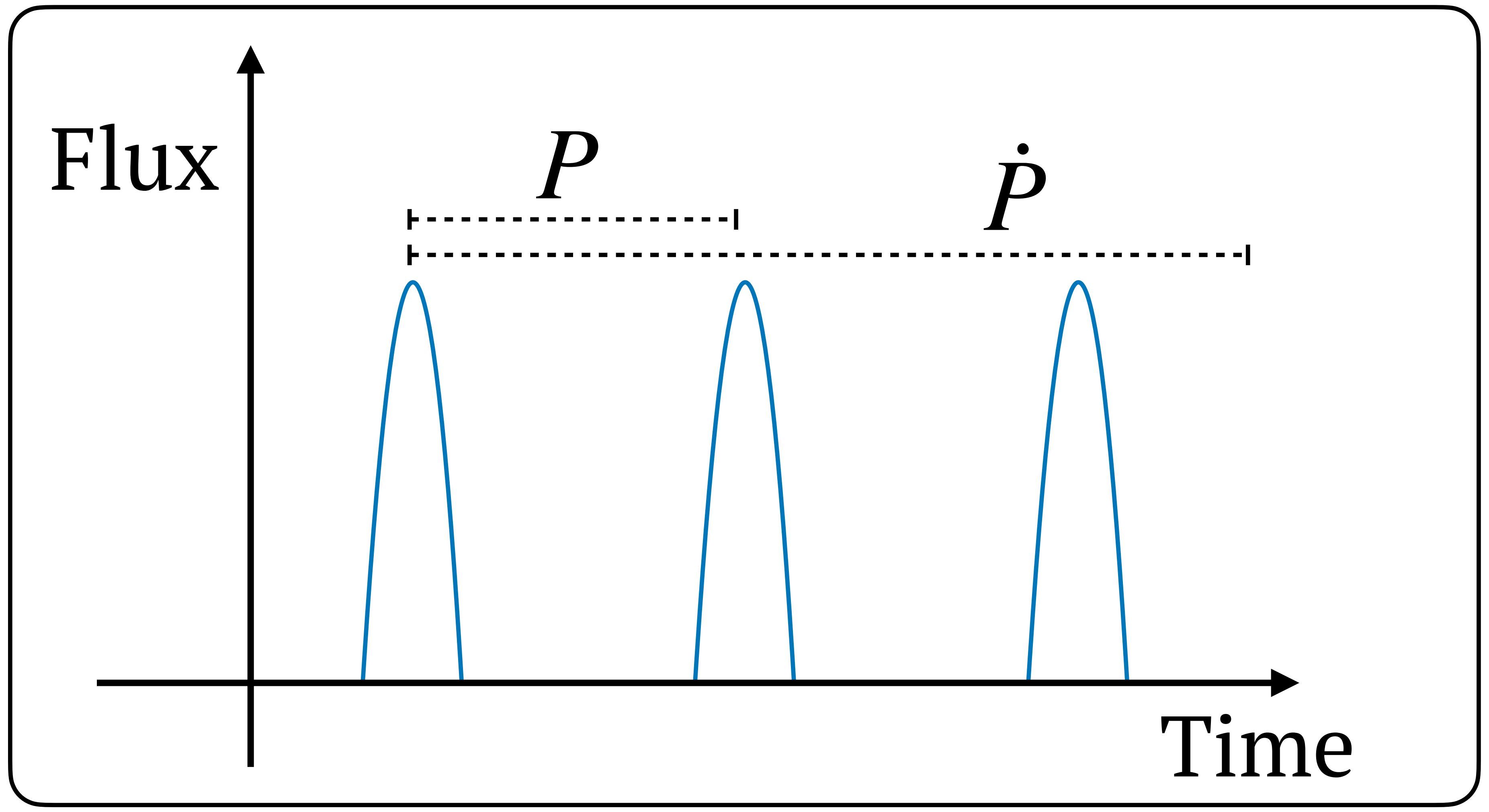


Backgrounds: Molecular lines, radio-frequency interference

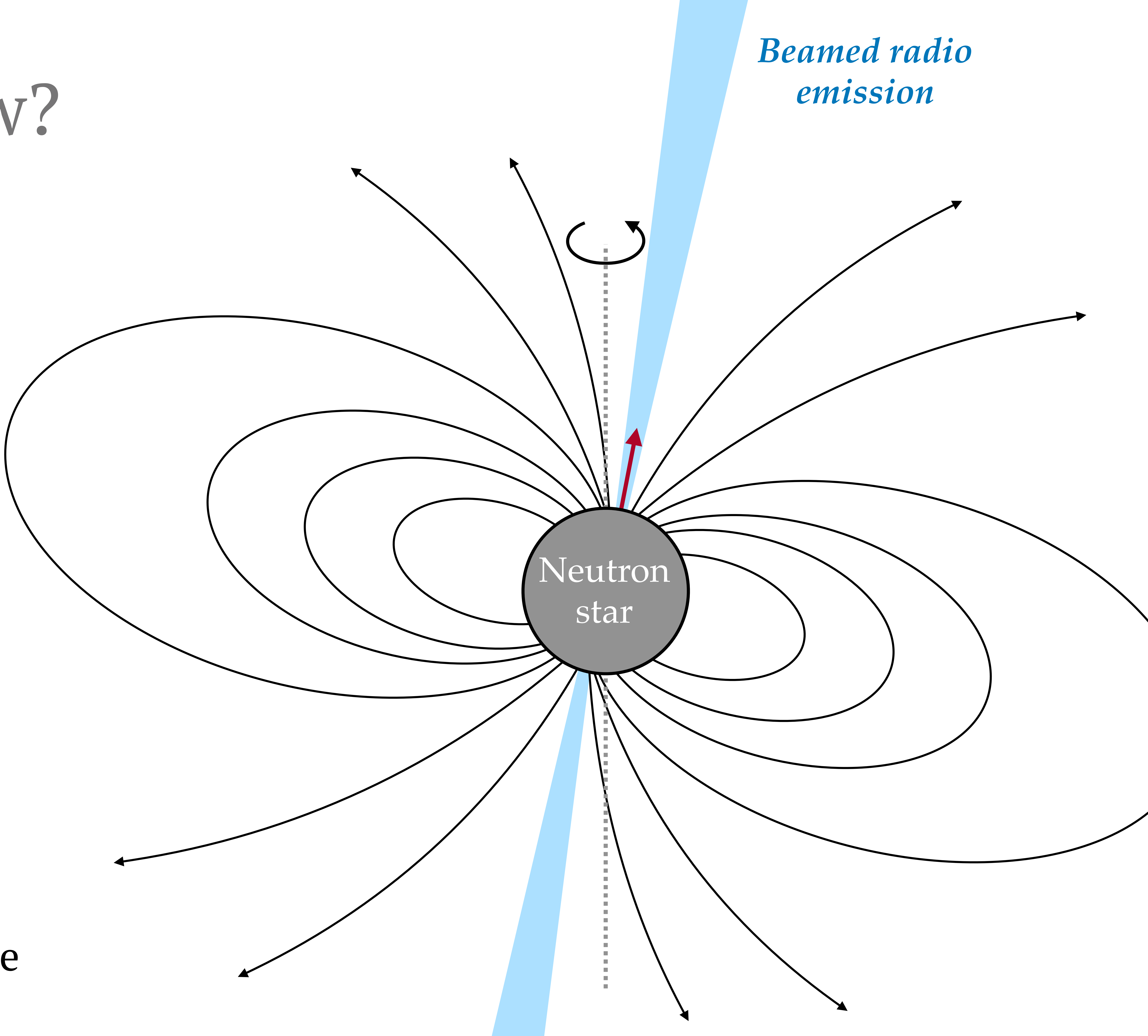
Observational Strategy: On/off target, time-domain analysis

See recent paper: Battye et al (2023)

Pulsars, what do we know?

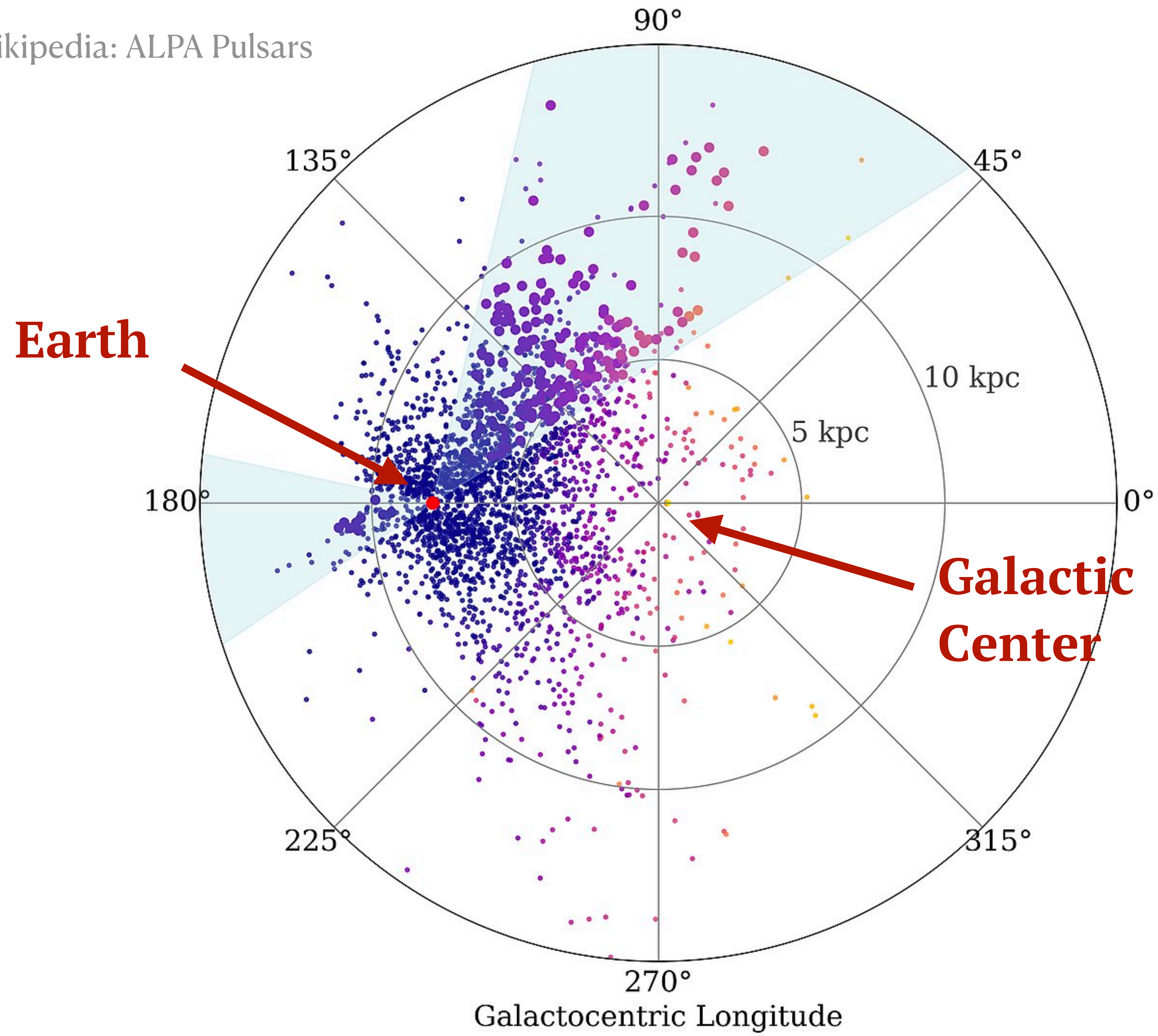


- Rotational period P
- Spin-down rate $\dot{P}$
    - Dipolar field strength $B_0 \propto \sqrt{P\dot{P}}$
- Characteristic age $\propto P/\dot{P}$
- Distance inferred from dispersion measure (frequency dependent time delay)



Pulsars in the galaxy

Wikipedia: ALPA Pulsars



Targeting the Galactic Center requires population modelling

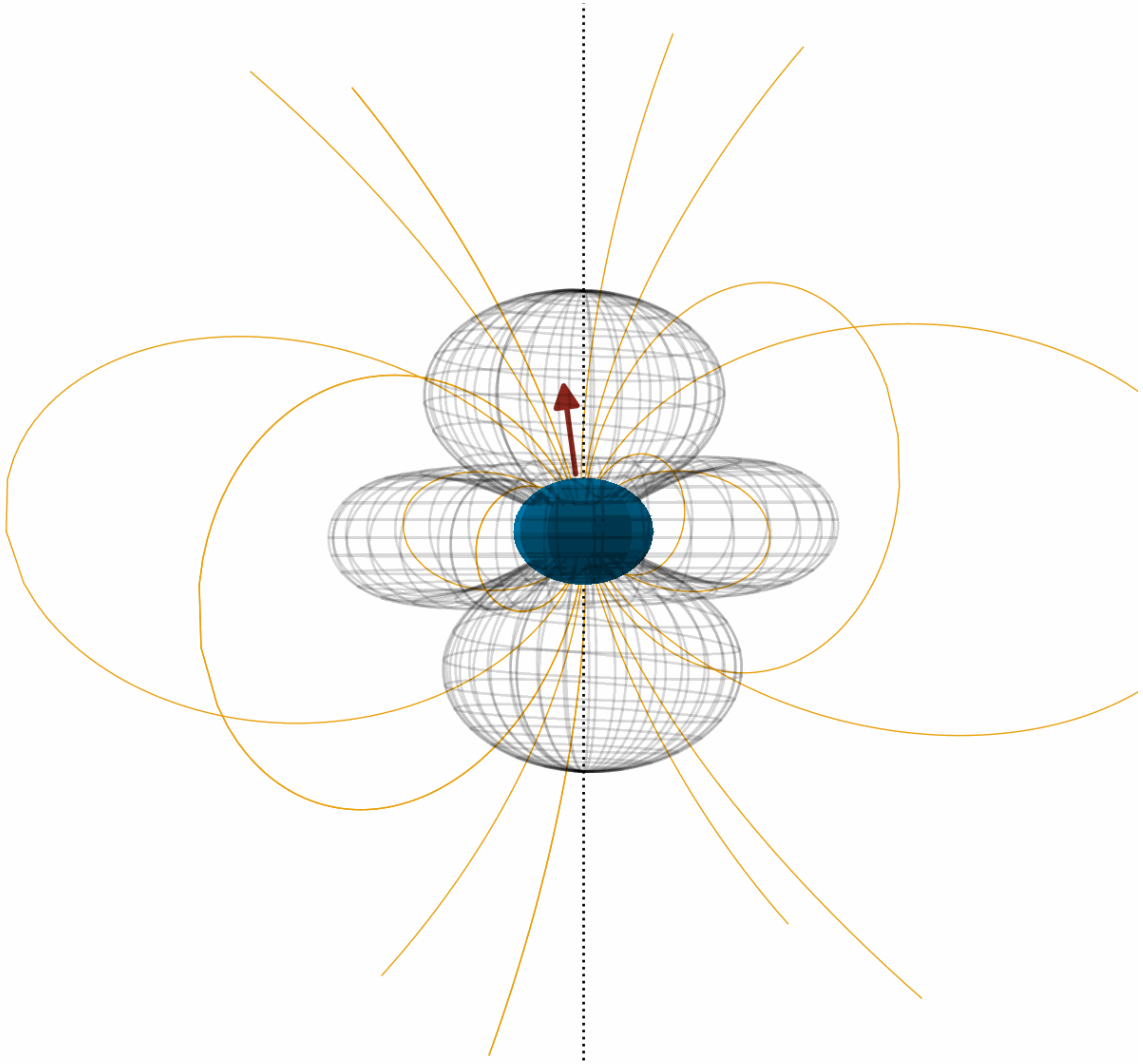
- Star formation rates & stellar mass distributions tells us about neutron star formation rate
- Young neutron stars trace stellar distribution
- Synthesize neutron star population consistent with the observed population

Signals from individual neutron stars

Resonant Conversion

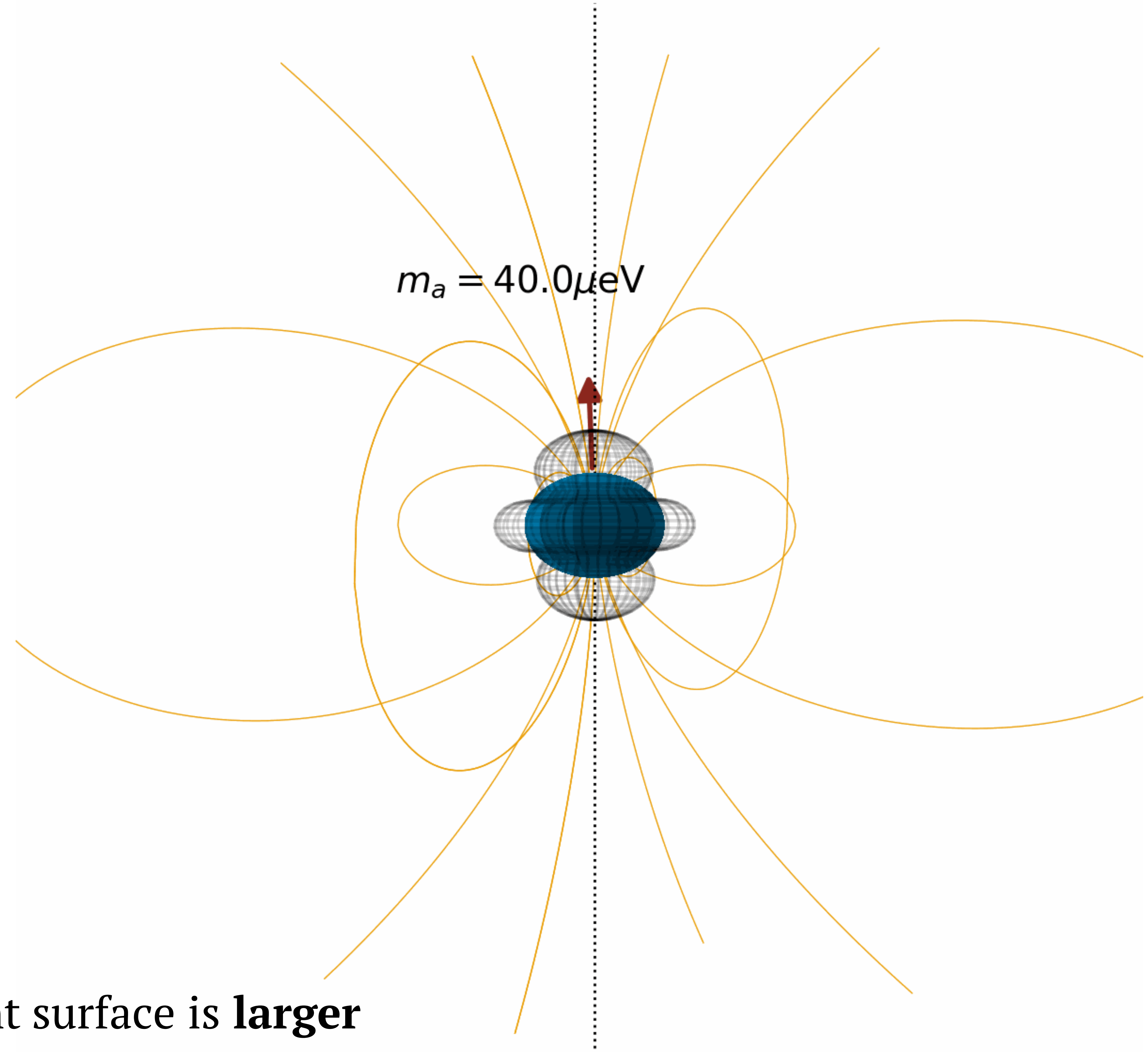
Location: $m_a \sim \omega_p$

Efficiency: $(\partial\omega_p)^{-1}$



Example for dead neutron star

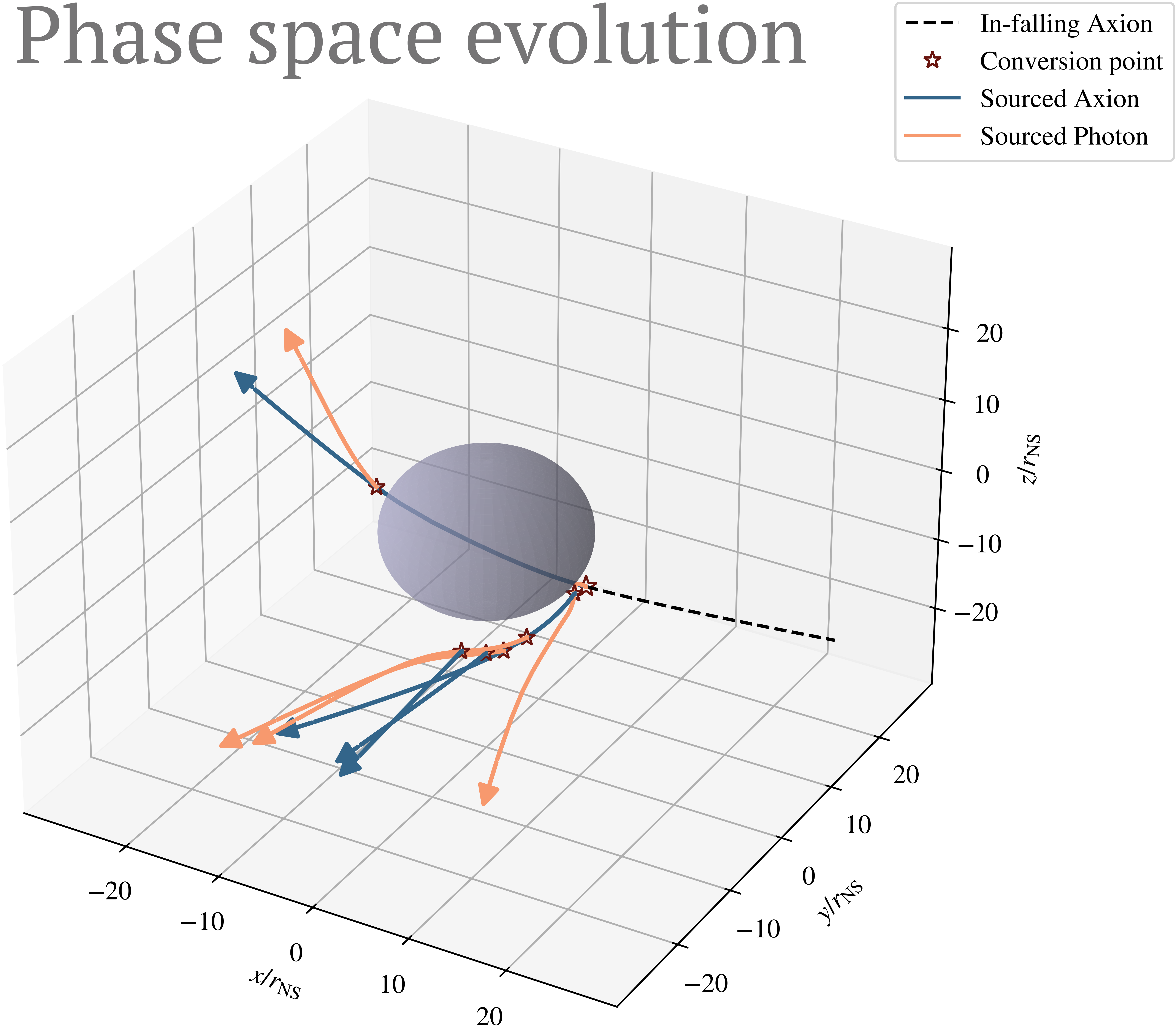
Signals from individual neutron stars



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

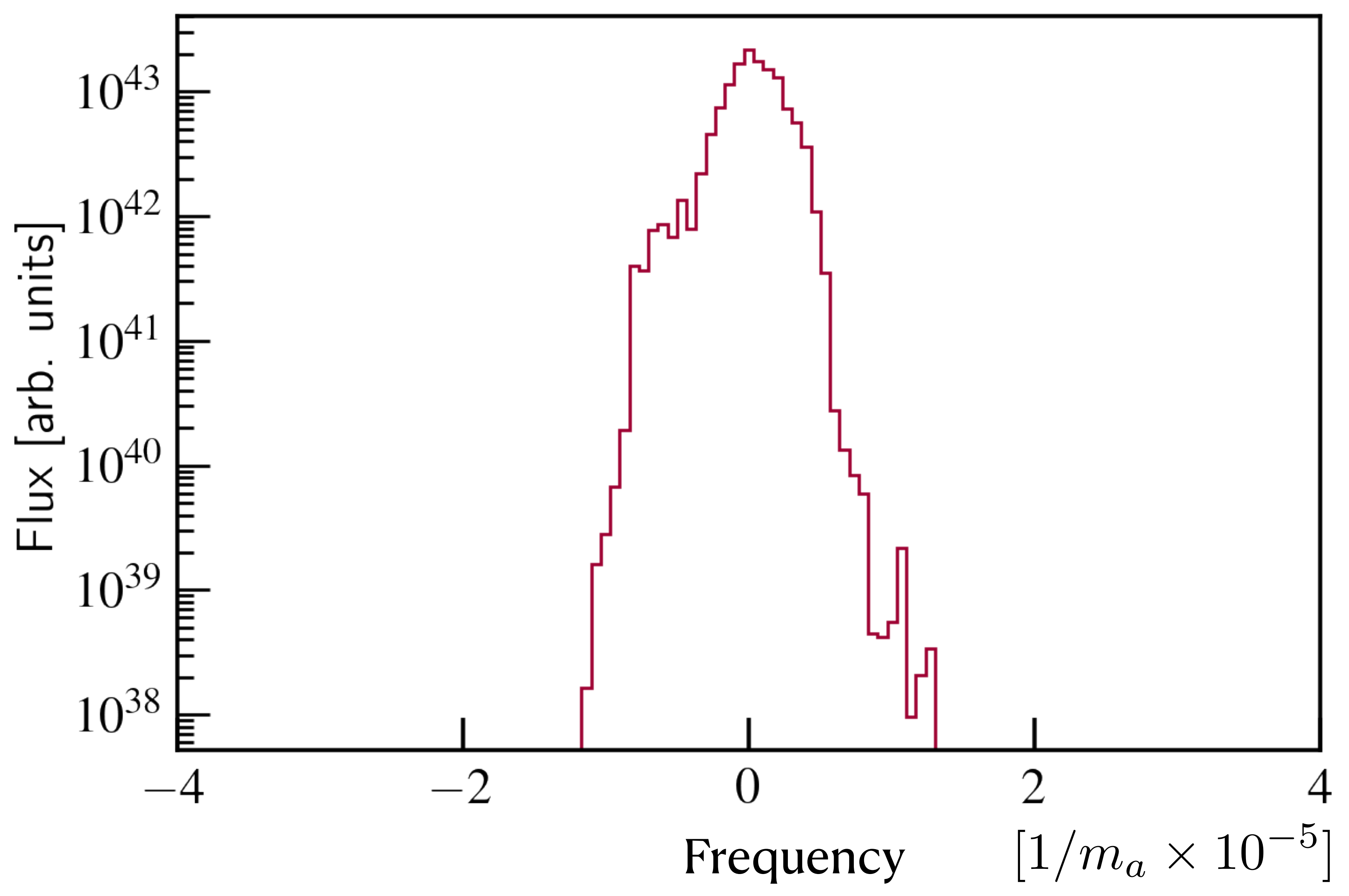
Larger axion mass → resonant surface is **smaller**

Phase space evolution



Use ray tracing to treat:

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



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

Foster, **SJW,** Lawson, Linden, Gajjar, Weniger, Safdi (2021)
Tjemsland, **SJW**, McDonald (To appear)

Searching for axions in the galactic center

<u>Survey Details:</u>

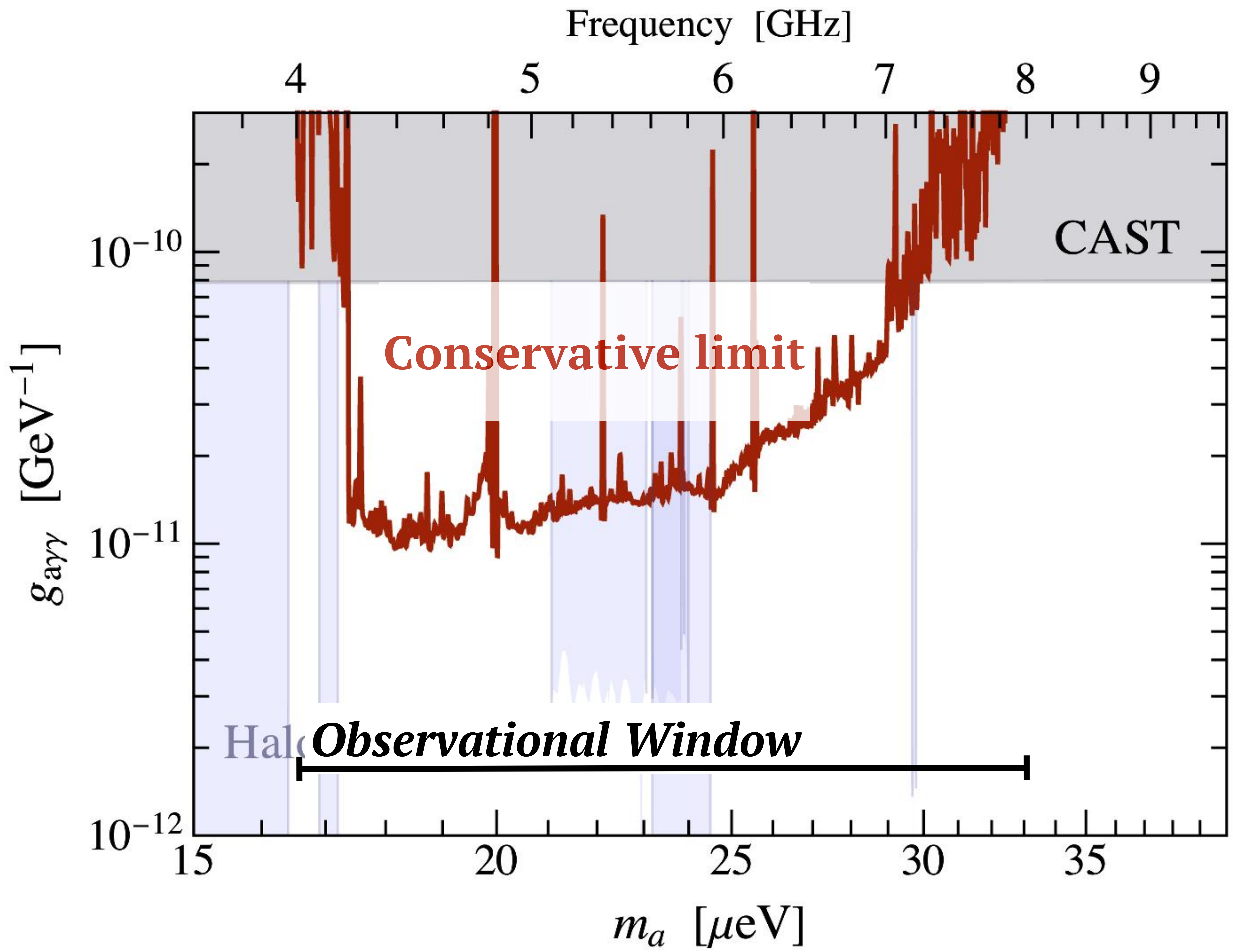
Data courtesy of the Breakthrough Listen Initiative

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

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

- We don't fully understand mixing
  - $p_{a\to\gamma}^{\rm eff} \sim \mathcal{O}(10^{-2}) \times p_{a\to\gamma}$
- 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)

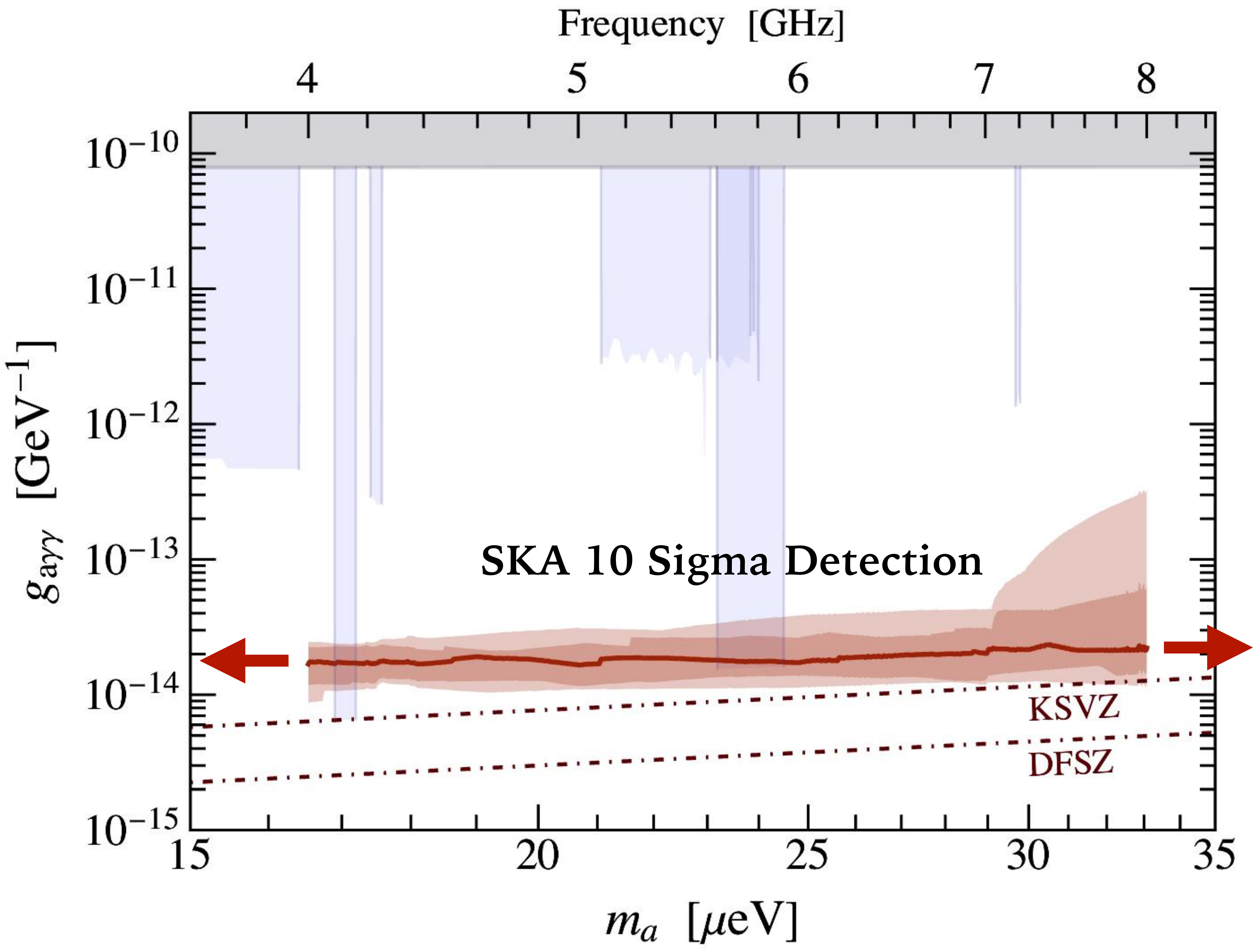


Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Offering a slightly more optimistic look at the future

<u>Keys for improving sensitivity:</u>

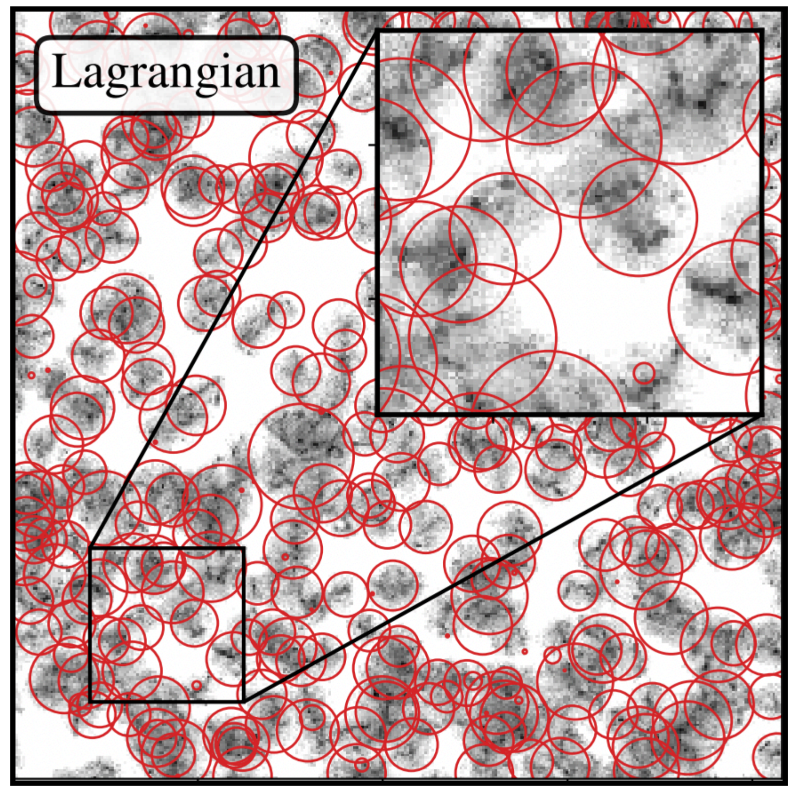
- Understand axion-photon mixing
- Get out of adiabatic regime
  Tjemsland, **SJW**, McDonald (To appear)
- Exploit time dependence?
  See recent paper: Battye et al (2023)
- Exploit frequency domain info?
- Extend to other frequencies
  This will occur! Recent collaboration with Breakthrough Listen Initiative



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

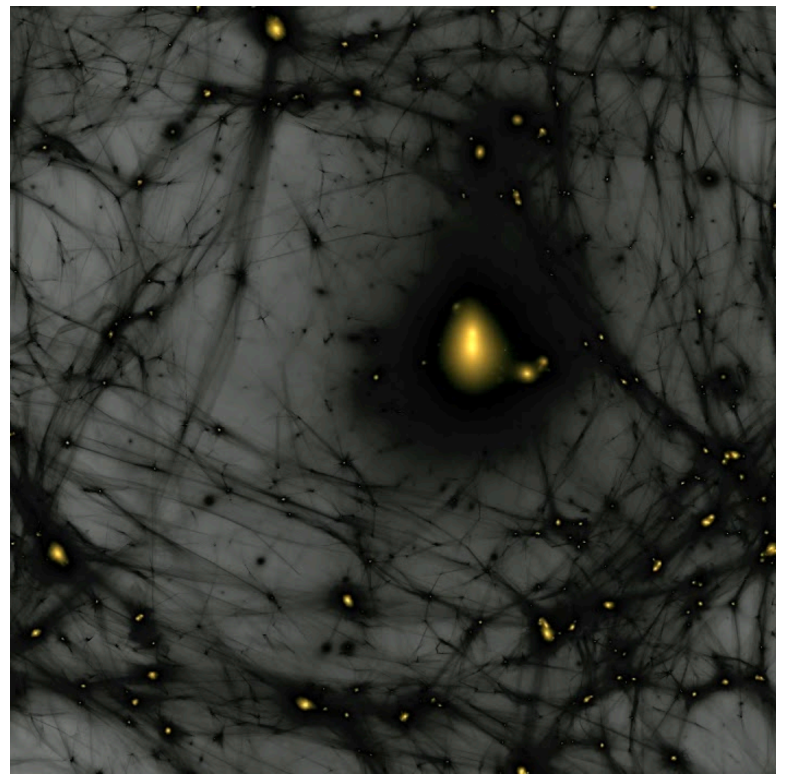
ASIDE: Transient radio lines from axion miniclusters

Minicluster formation

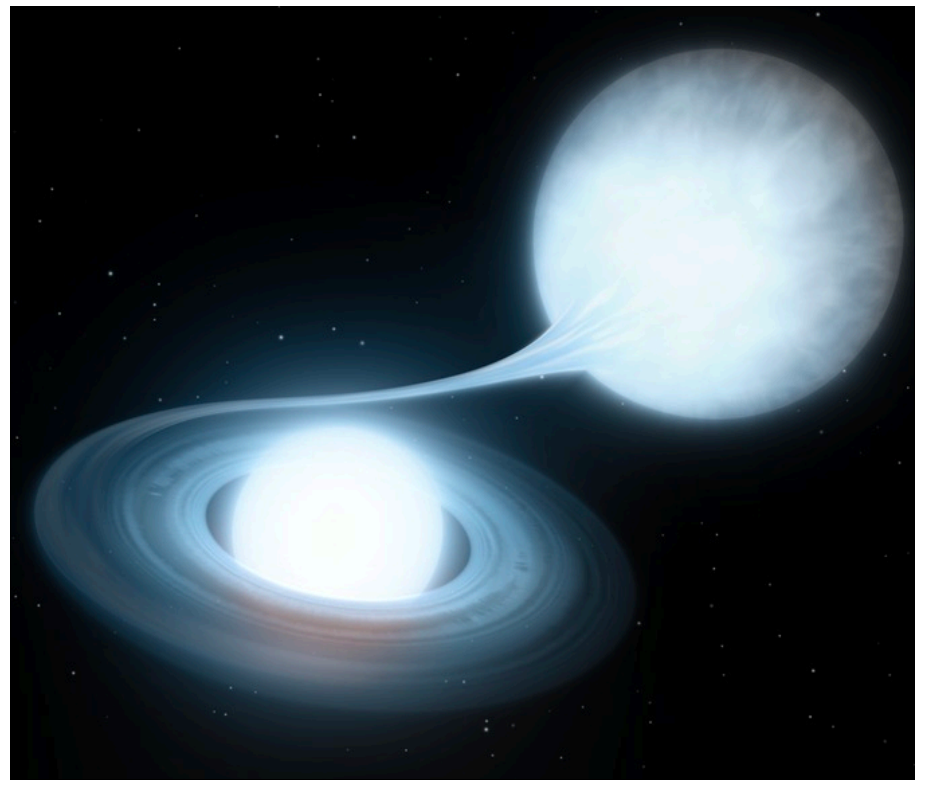


See e.g. Ellis et al (2022)

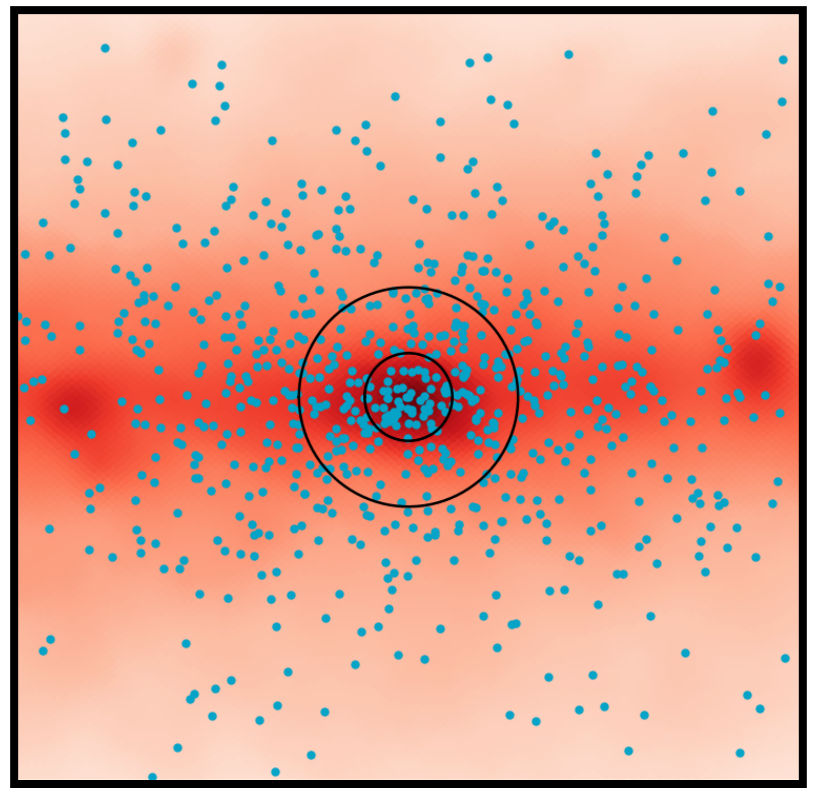
Structure formation



Tidal stripping



Neutron star population



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

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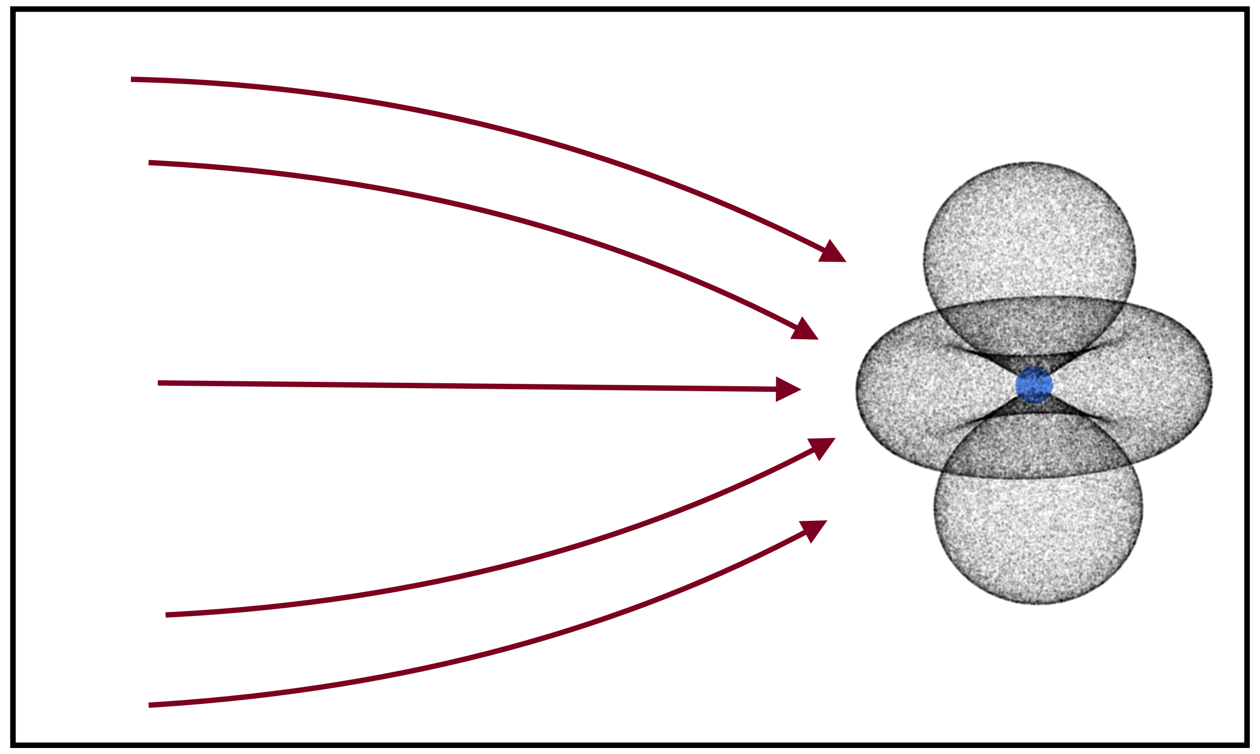
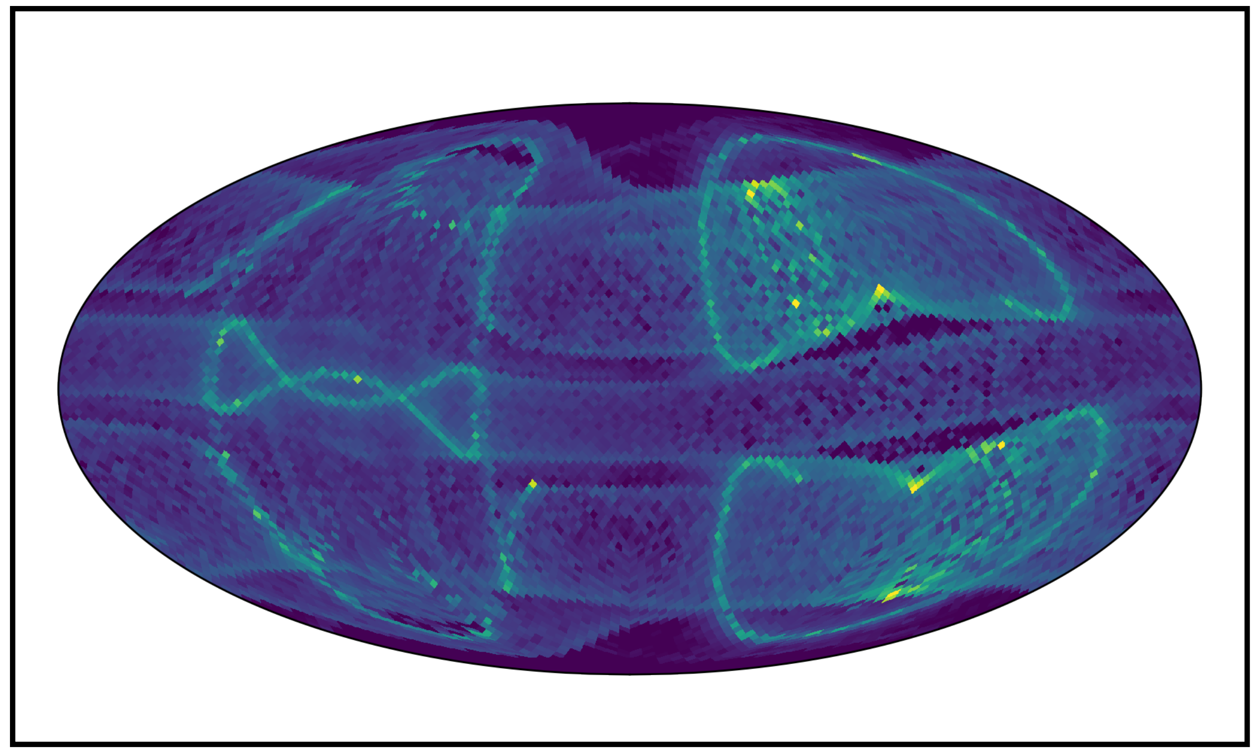
.
.
.
.
Encounter #N

Minicluster in-fall

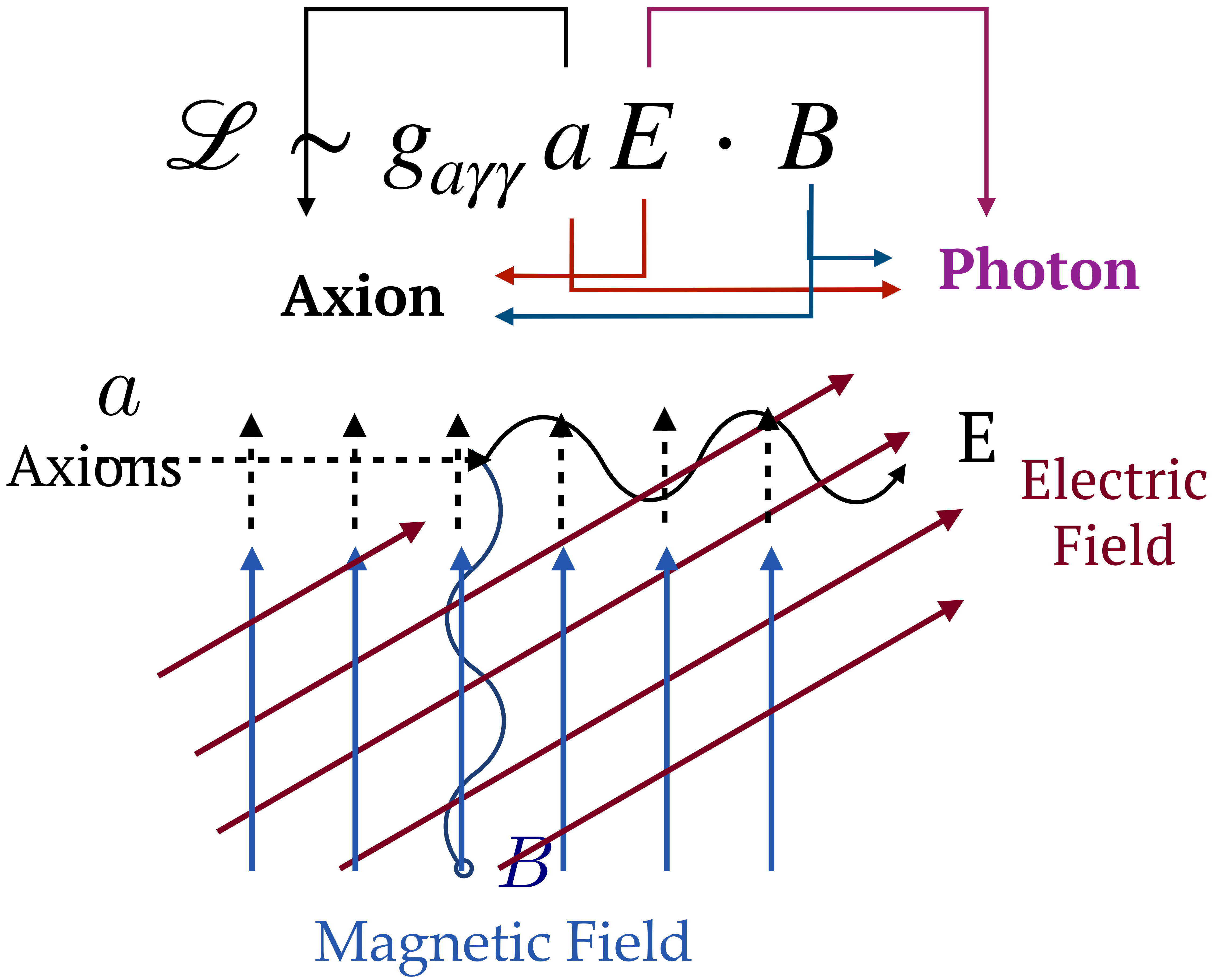


Radio Signal



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

Producing axions with electromagnetism



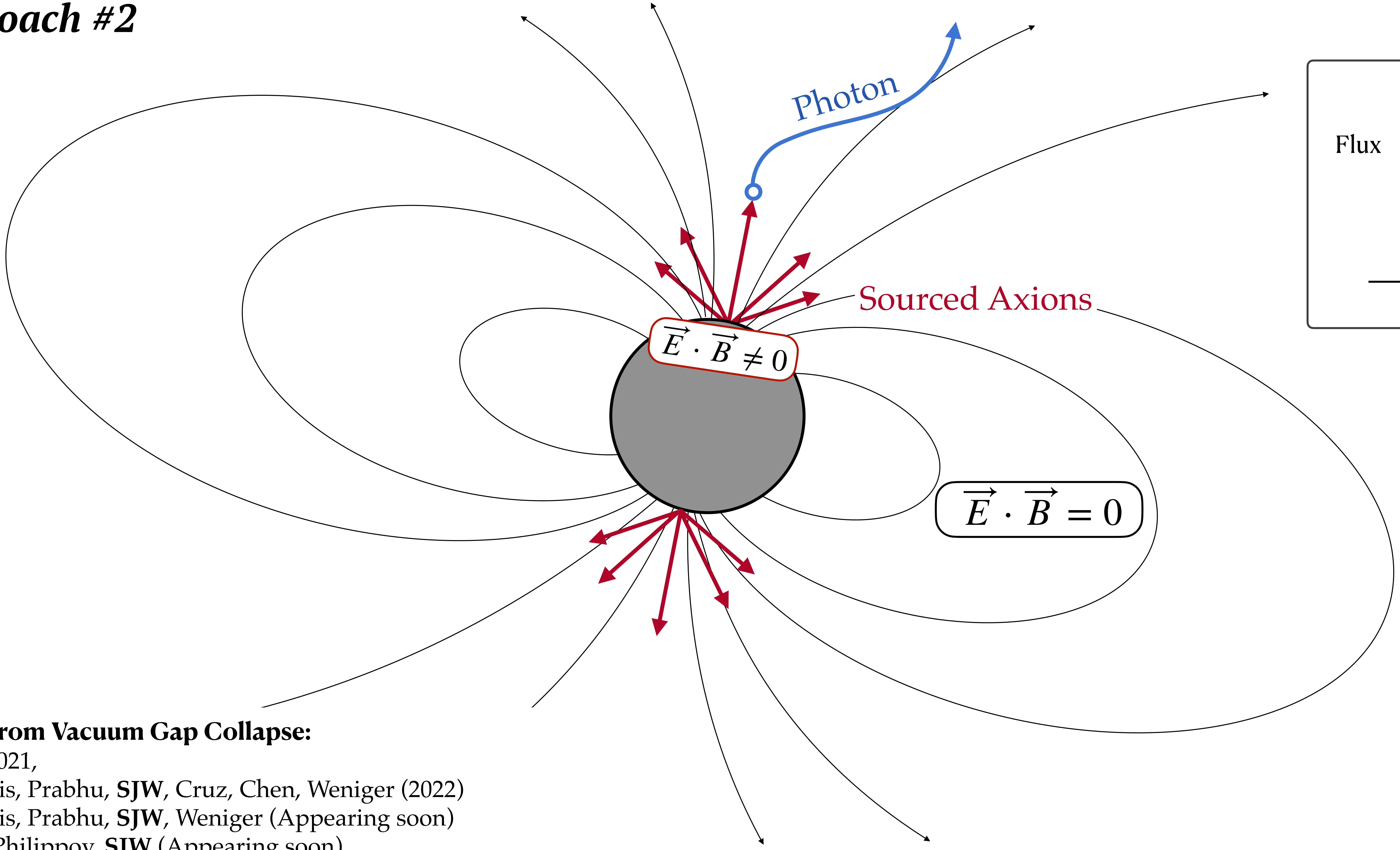
Advantage:

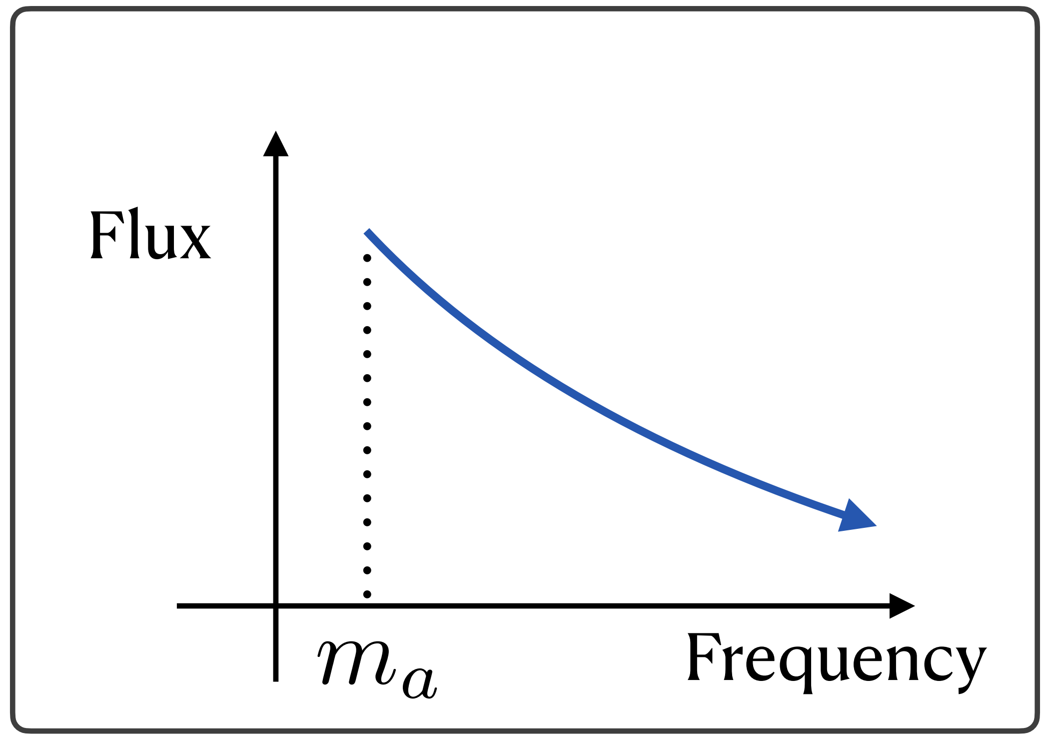
Remove dependence on dark matter density

- Larger axion densities
- Target nearby pulsar population

Broadband radio emission from locally sourced axions

Approach #2



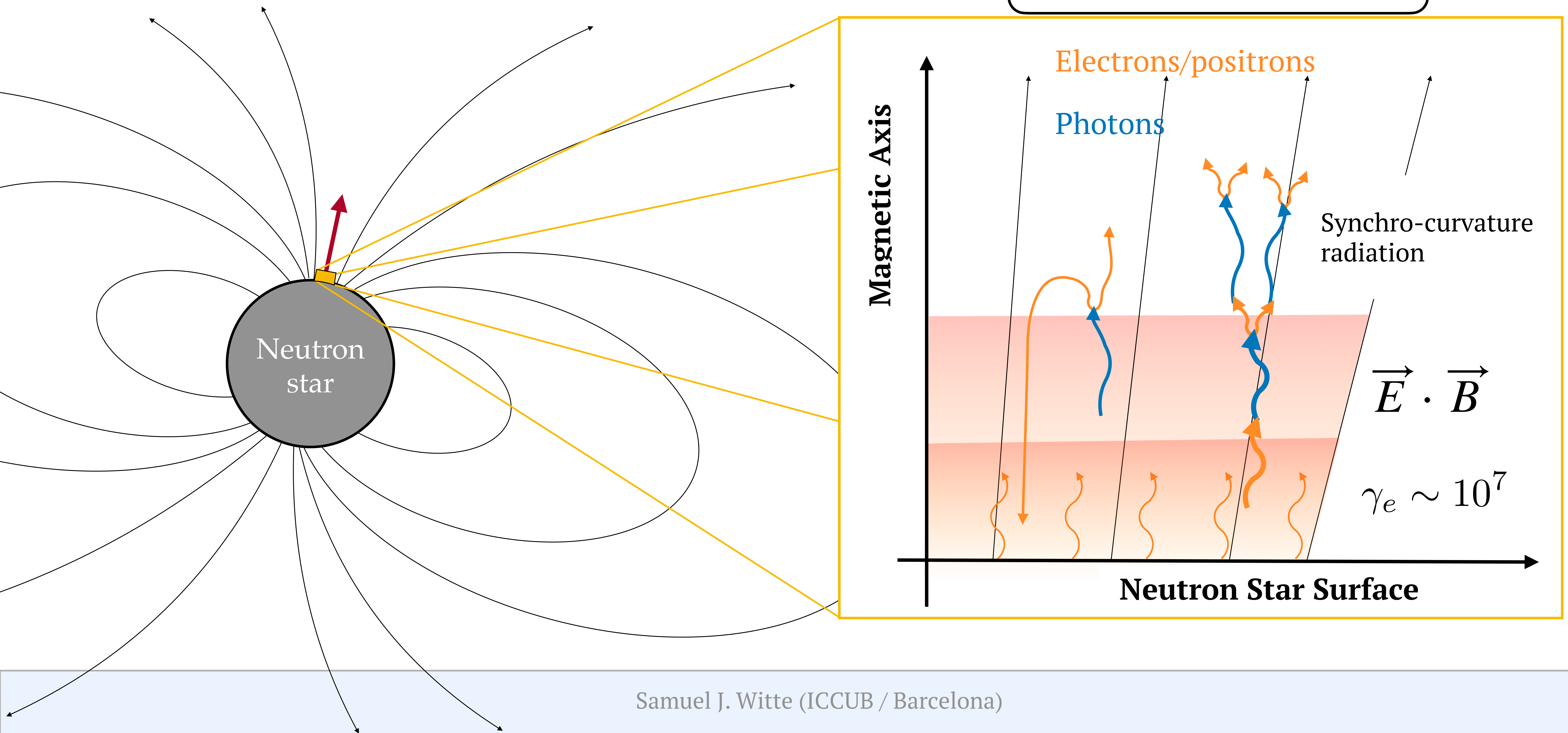


Axions from Vacuum Gap Collapse:
Prabhu 2021,
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)
Noordhuis, Prabhu, **SJW**, Weniger (Appearing soon)
Caputo, Philippov, **SJW** (Appearing soon)

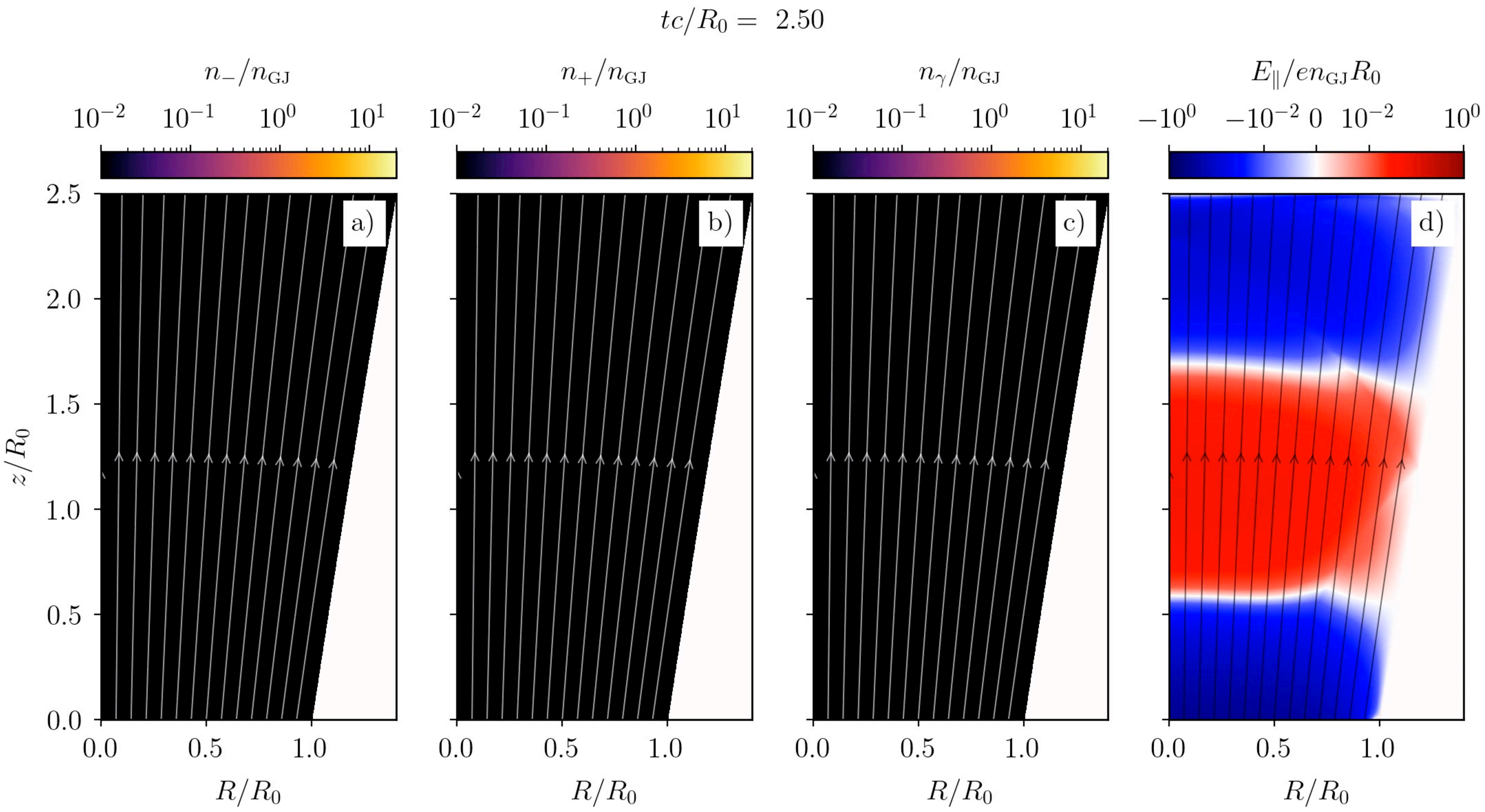
Axions from vacuum gap collapse

Axion spectra

$$\dot{N}_a(\vec{k}) \propto |FT(g_{a\gamma\gamma} \vec{E} \cdot \vec{B})|^2$$

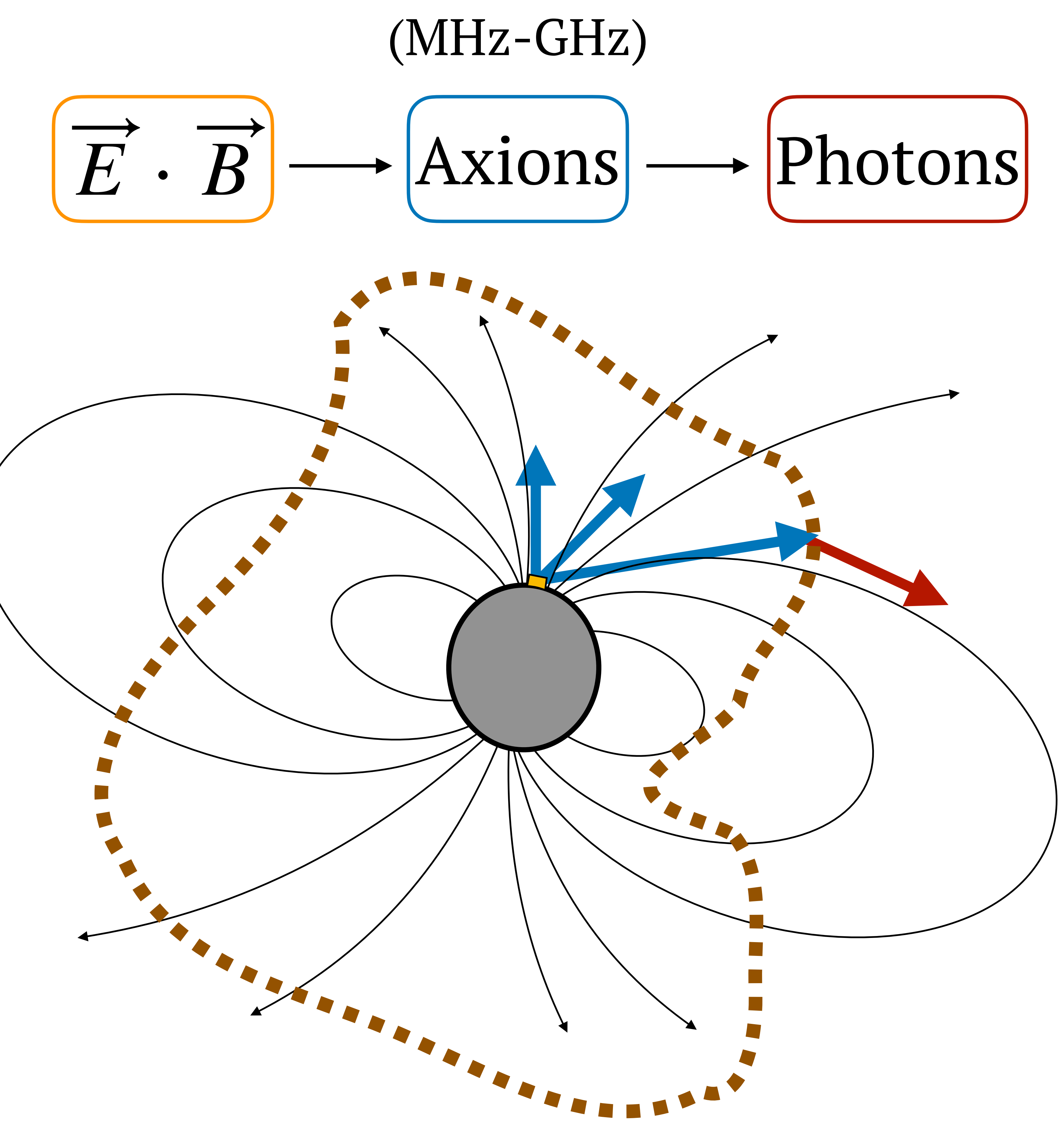


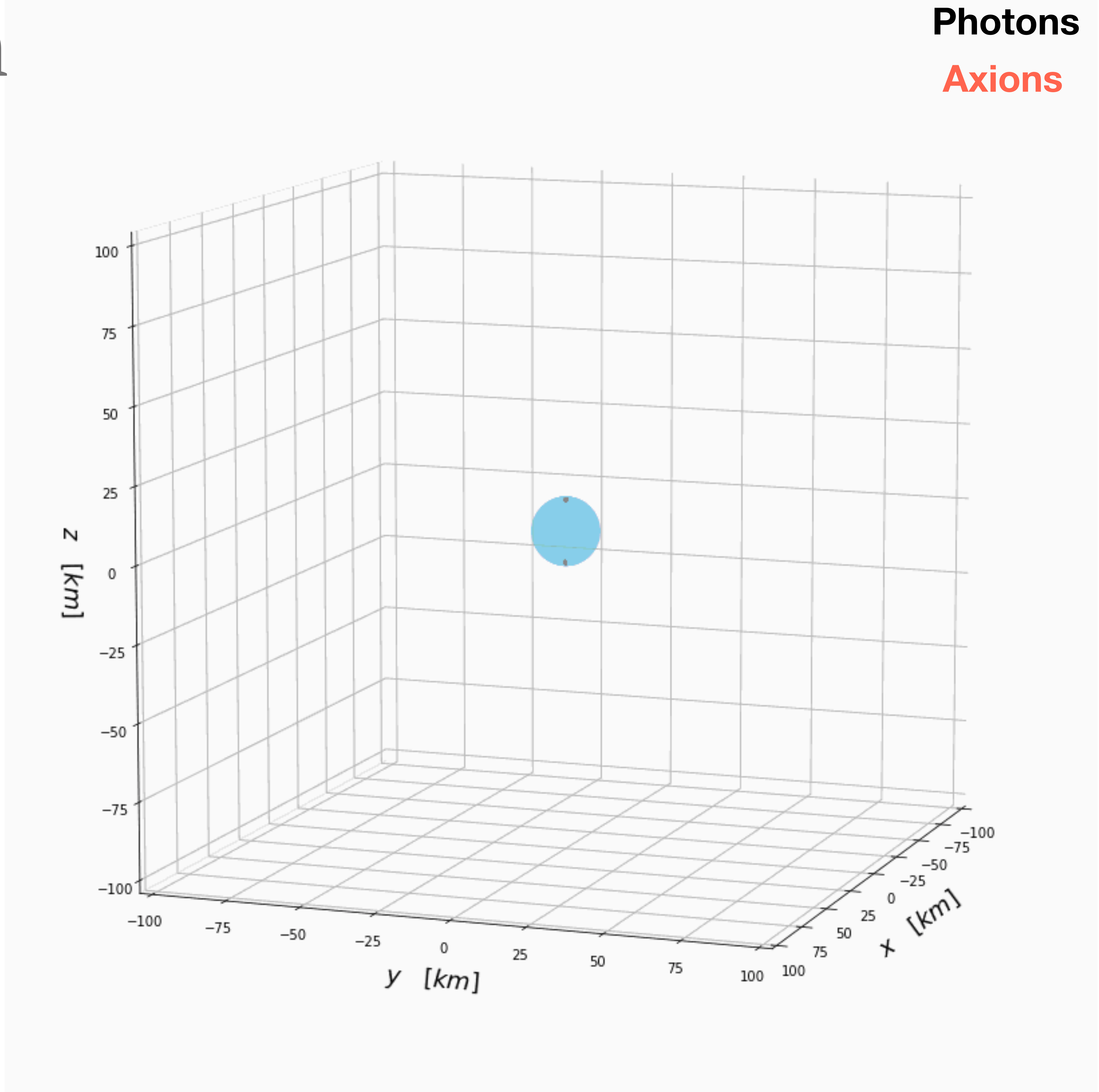
Vacuum gap collapse



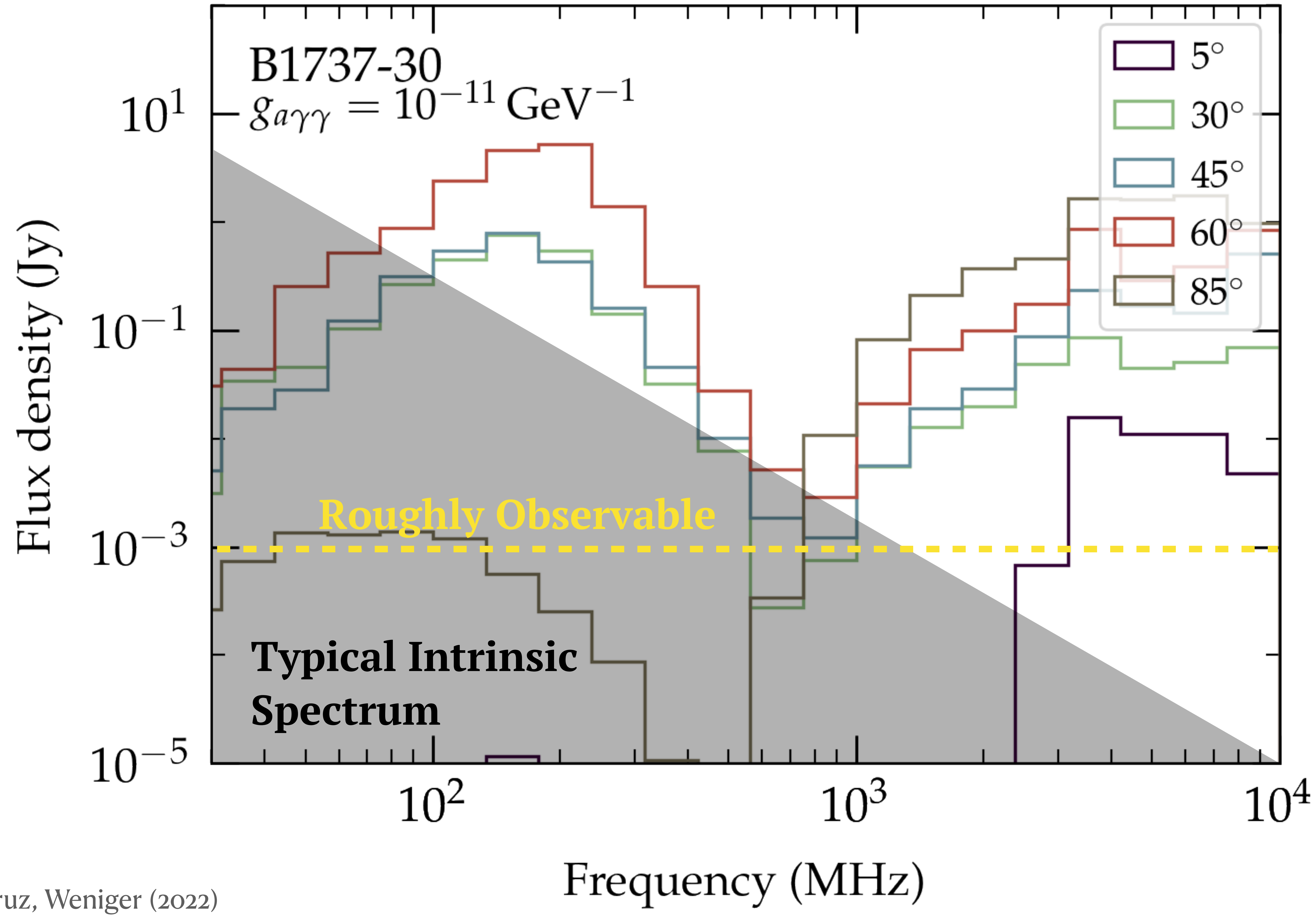
Simulations curtesy of F. Cruz and A. Chen

Broadband radio emission



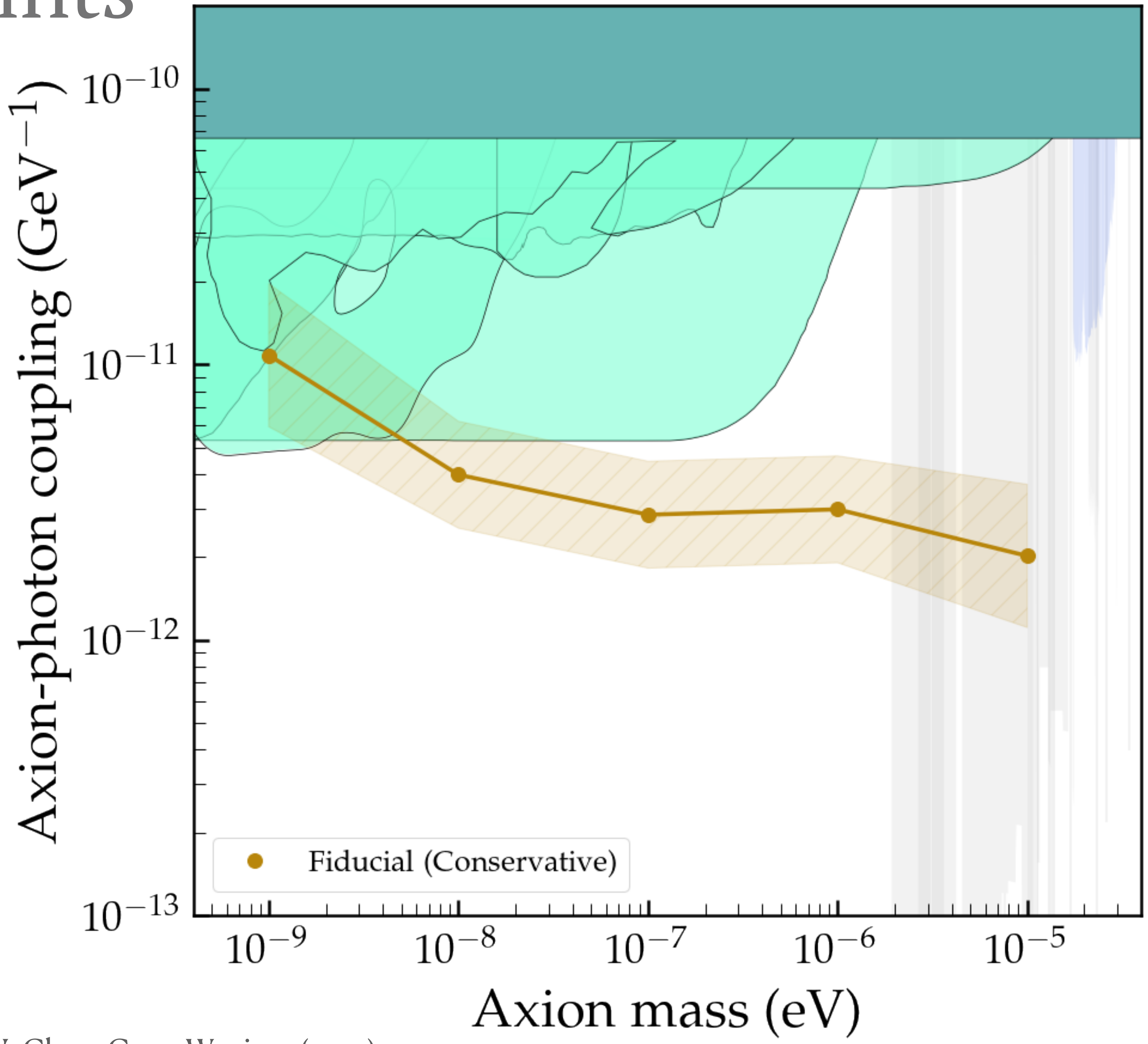


Radio spectrum



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

Constraints



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

Current search:

- Uses only 27 well-studied pulsars
- Observations at 408 MHz, 1.4 GHz, and 8.7 GHz

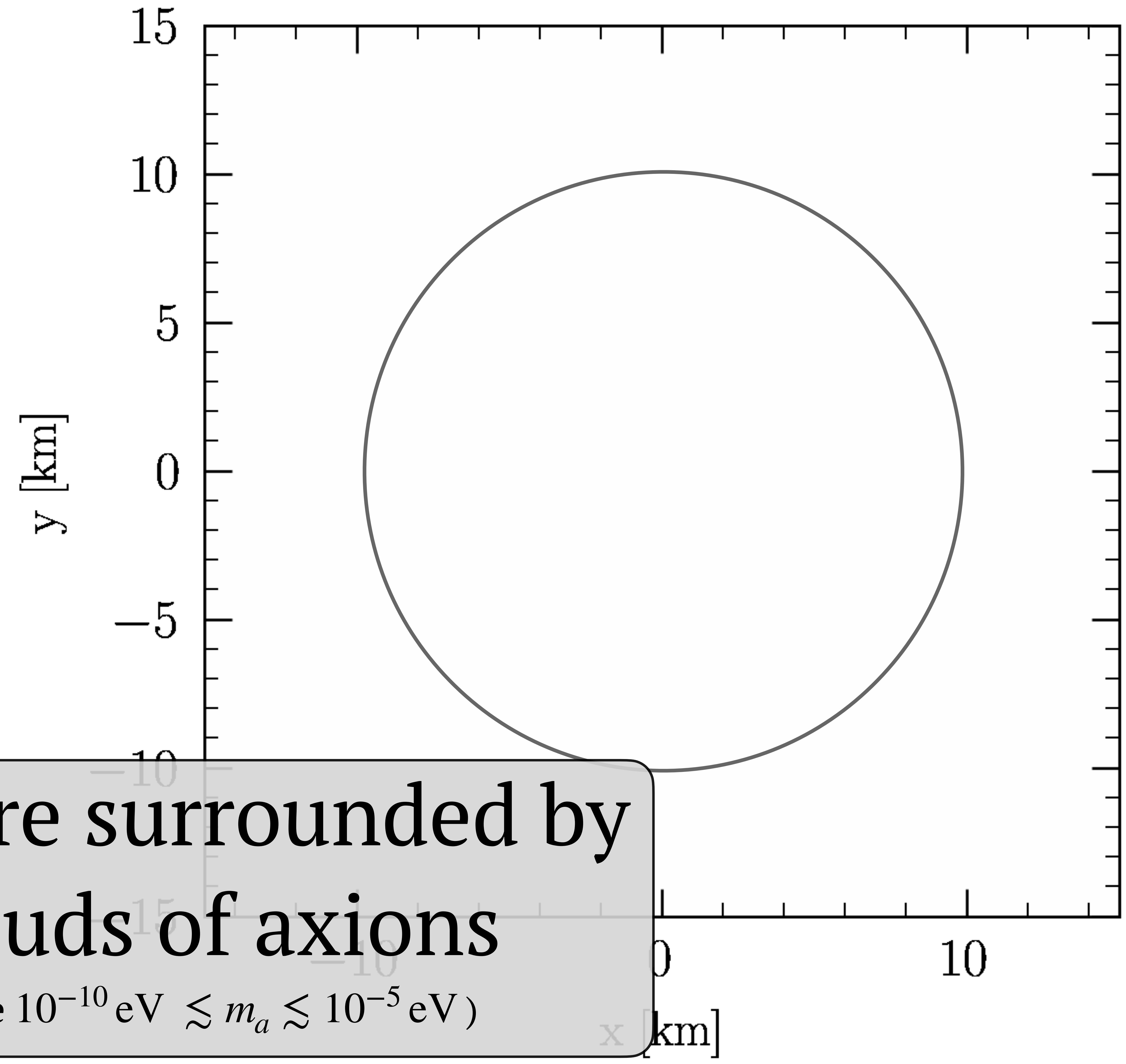
Strong agreement between:

- PIC simulation (accurate non-linear dynamics, but not easy to rescale to other pulsars)
- Semi-analytic model (applicable to all pulsars, but non-linear response difficult to capture)

Axion clouds

Large fraction of axions go into gravitationally bound orbits

Density can grow over ~kyr timescales

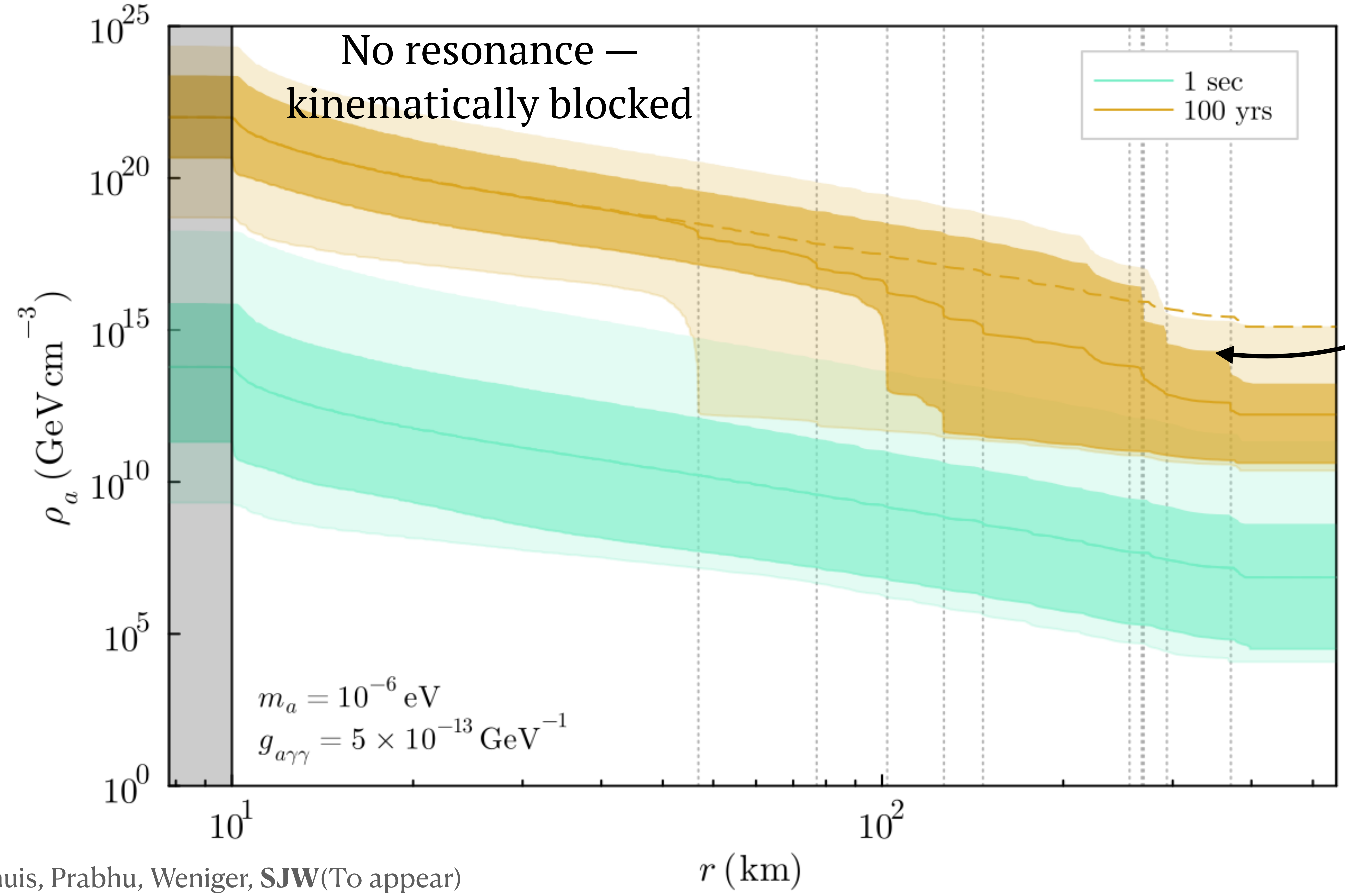


All pulsars are surrounded by dense clouds of axions

(assuming they have $10^{-10}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-5}\,\mathrm{eV}$)

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

Axion clouds

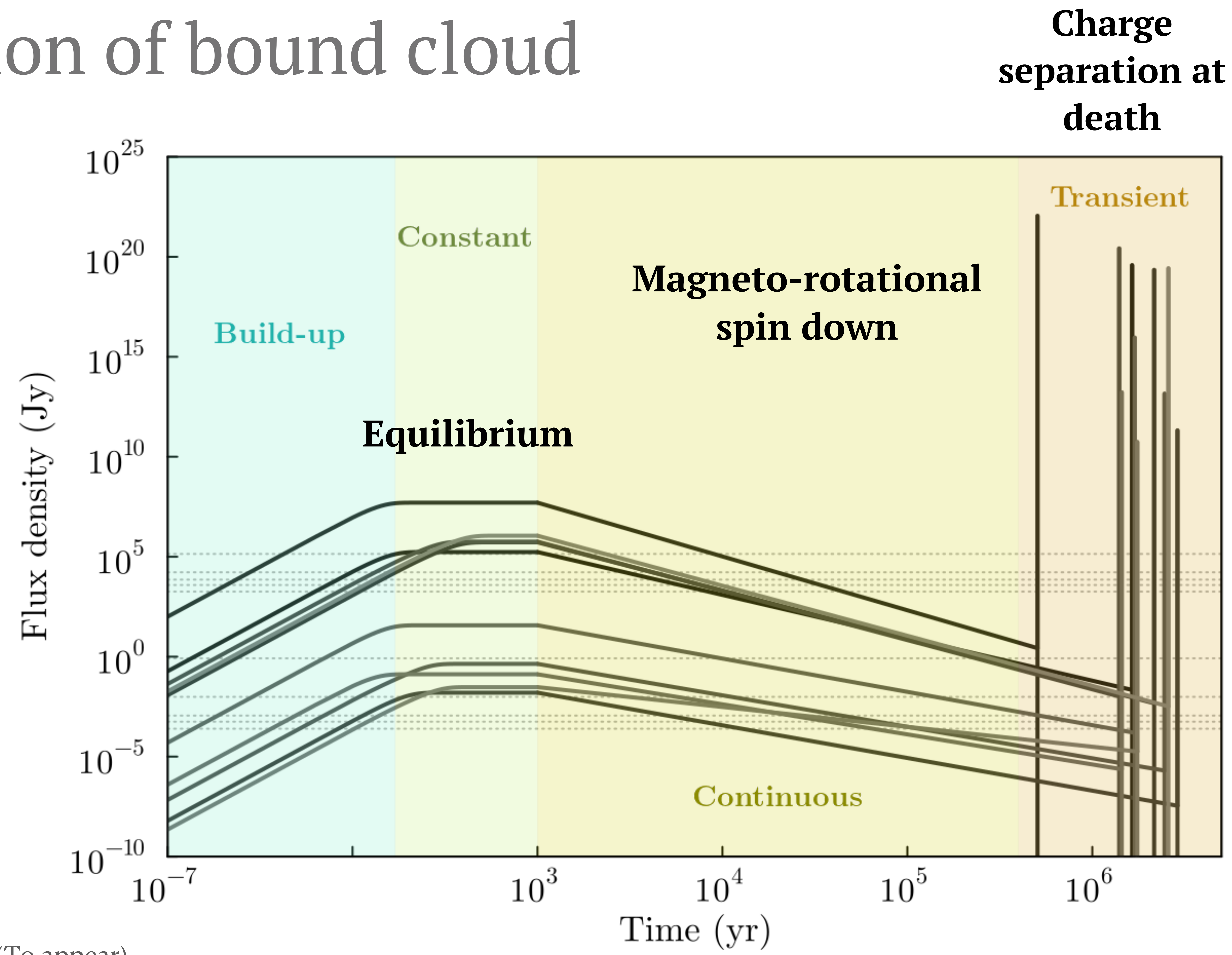


Reduction in density from resonant emission

Bands reflect variation of pulsar population

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

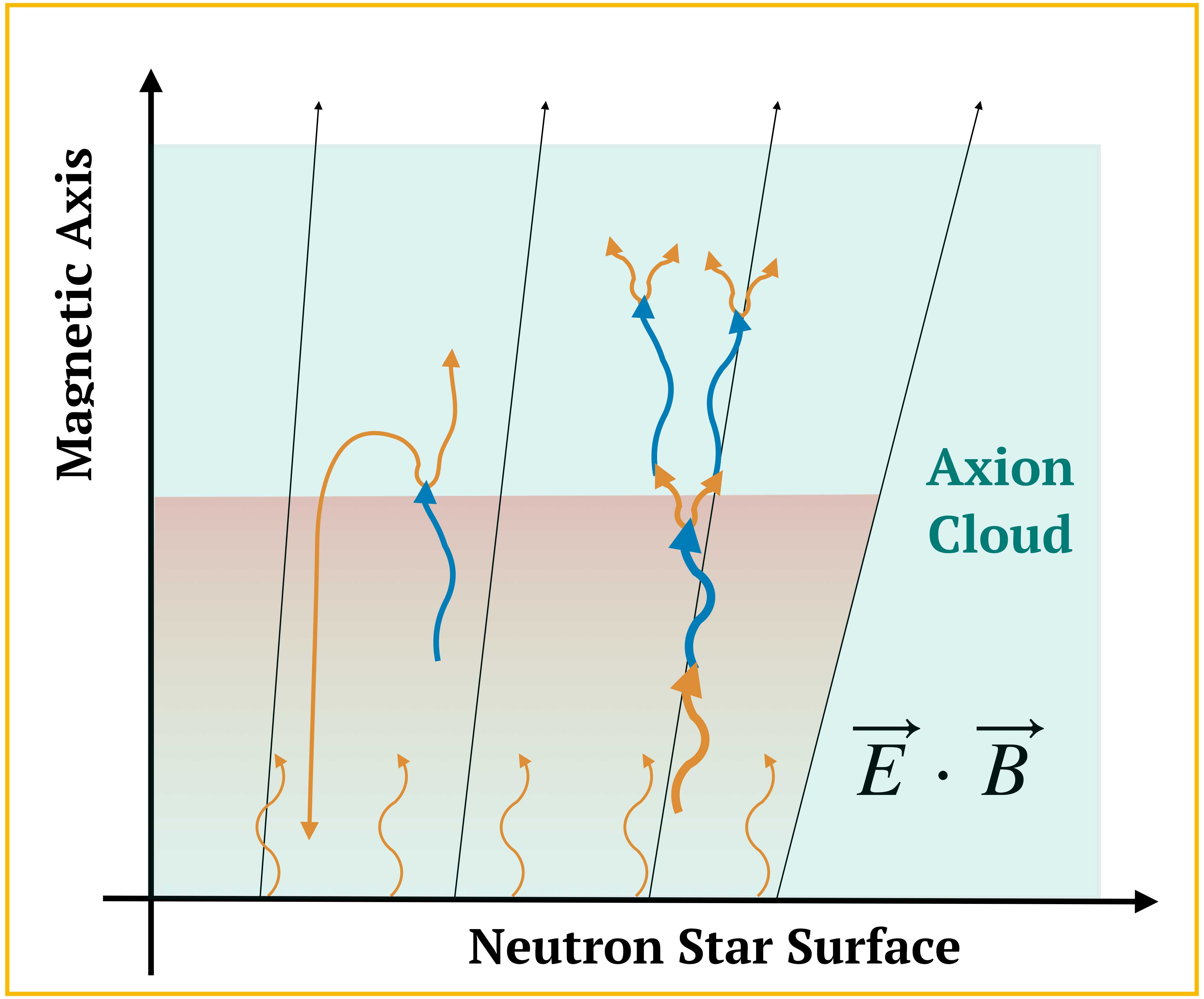
Radio emission of bound cloud



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

Axion back-reaction

Approach #3



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

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

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

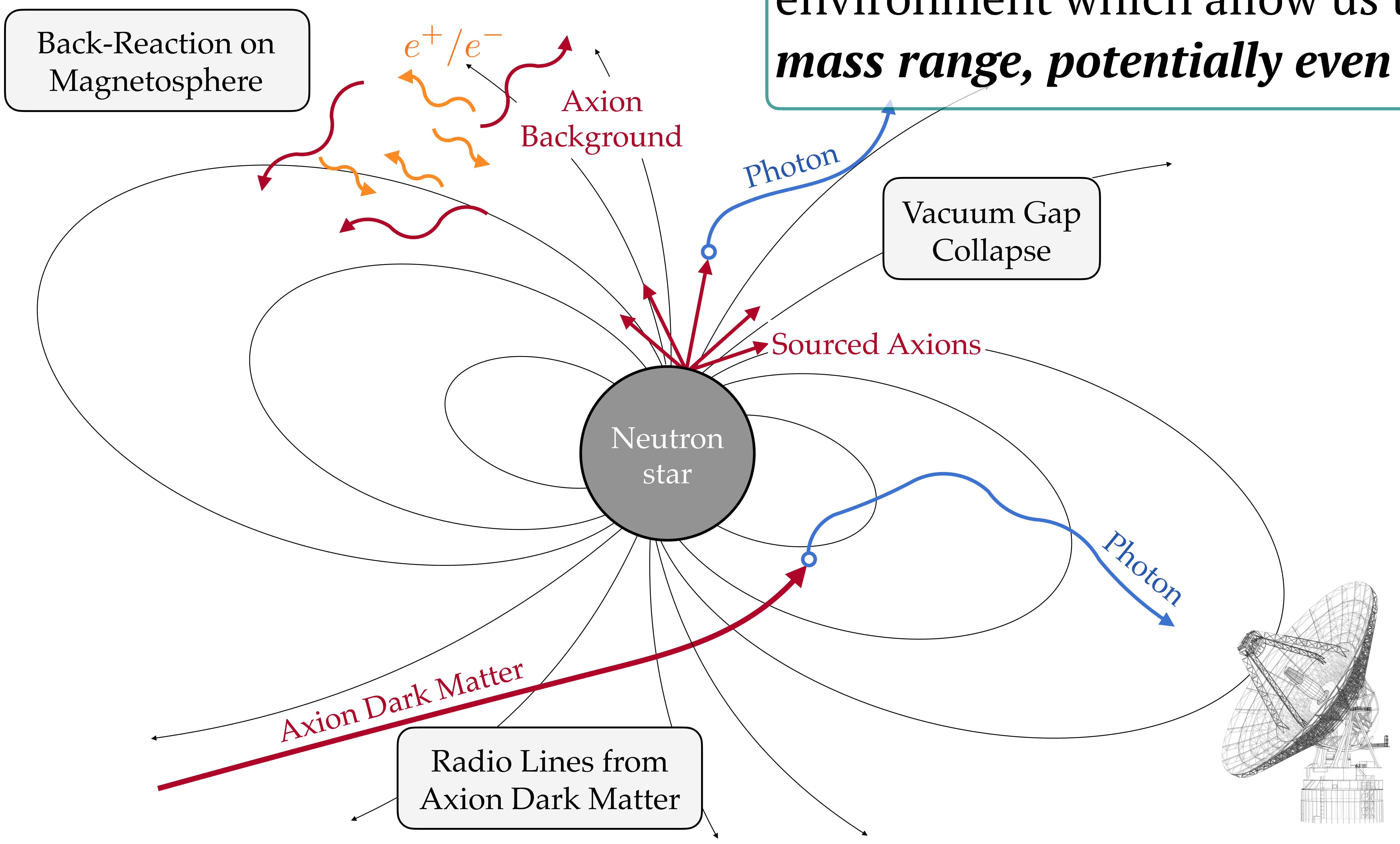
Large axion densities back-react on electrodynamics

Axion clouds can induce periodic nulling of radio emission

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

Conclusions

Neutron star magnetospheres offer a powerful environment which allow us to probe ***axions in a new mass range, potentially even reaching the QCD axion***



Back-Up