Neutron stars

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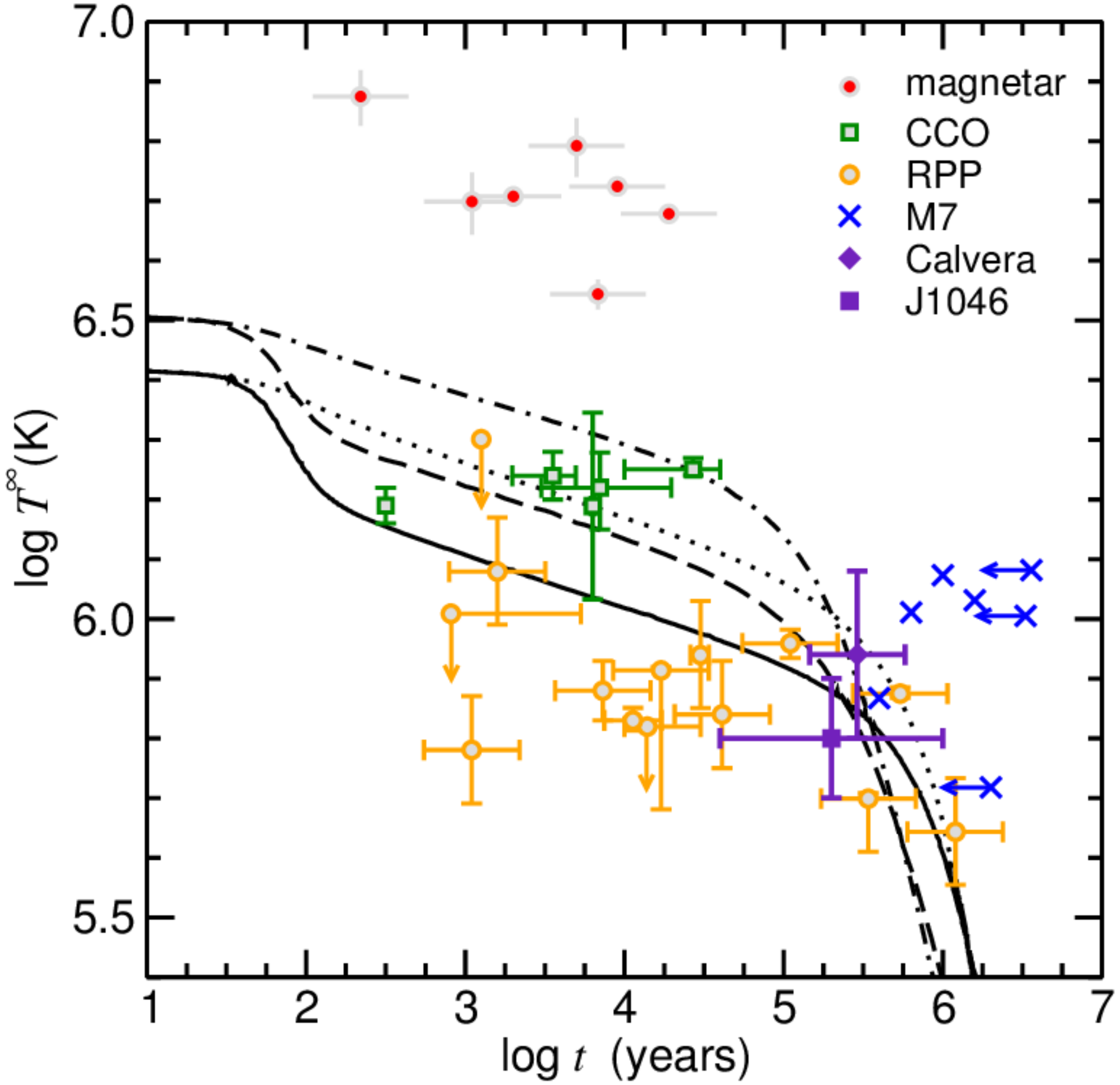
Overview

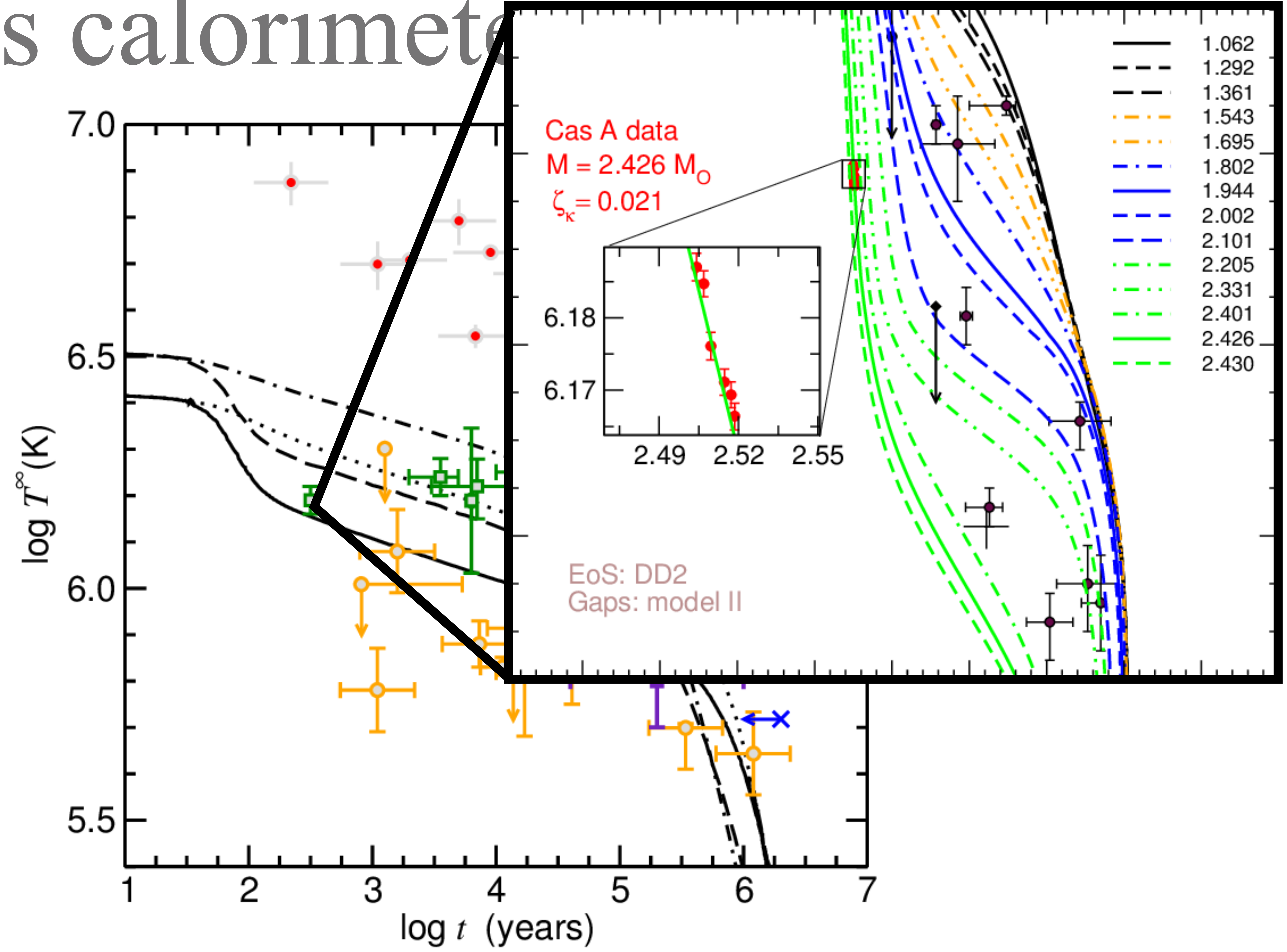
- Neutron stars as calorimeters
- Neutron stars as astrophysical axion haloscopes
- Neutron stars as axion factories
- Matter effects induced by the dense nuclear matter inside neutron stars
- Millisecond pulsars as a probe of new physics in the early Universe

(Neutron) Stars as calorimeters



Pires et al (2015)

(Neutron) Stars as calorimete



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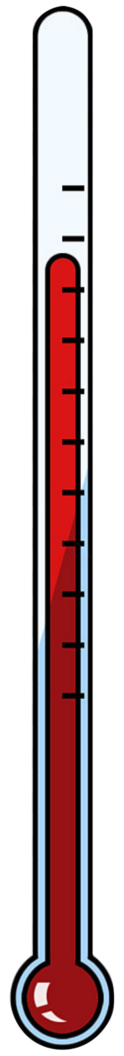
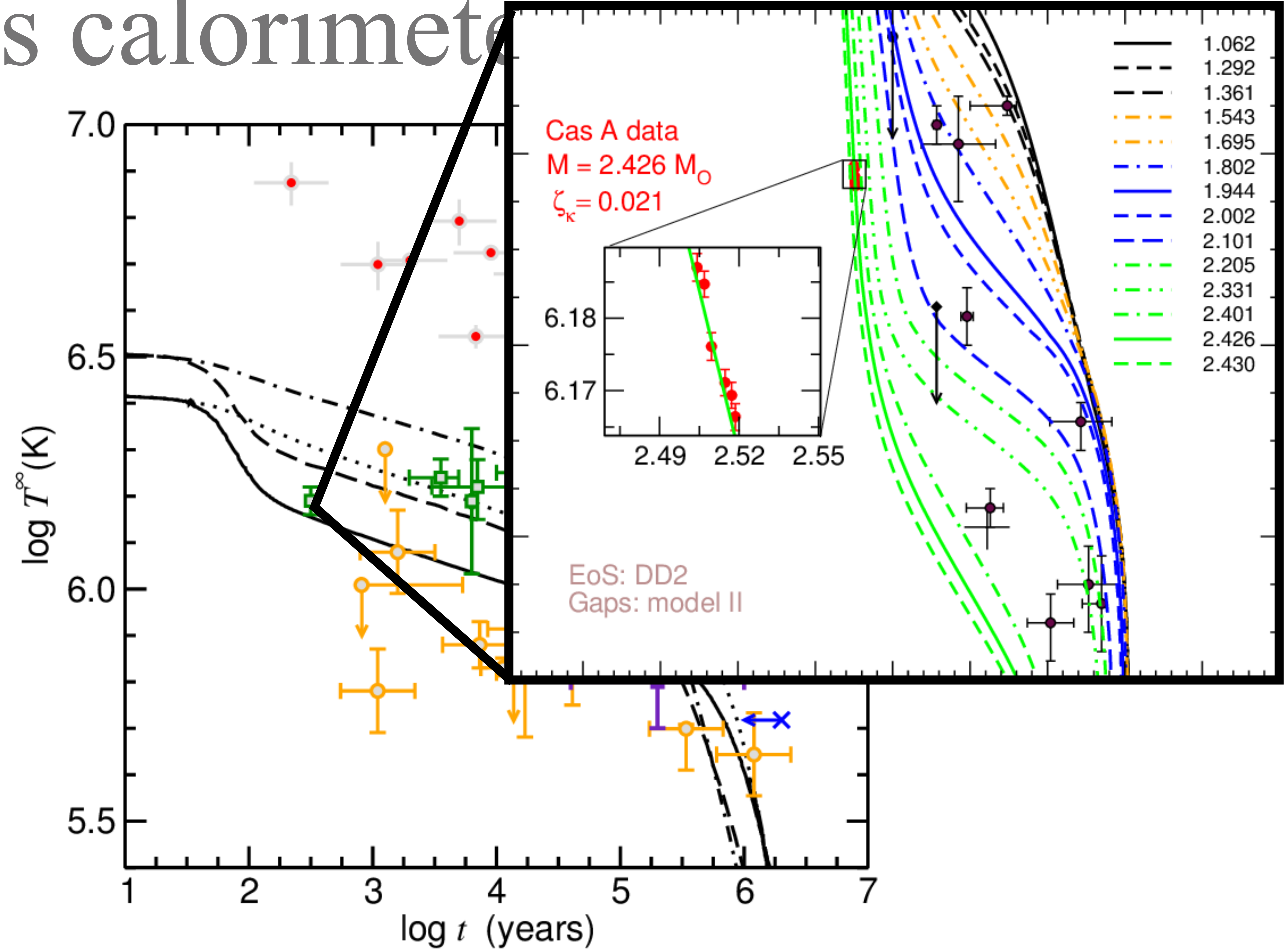




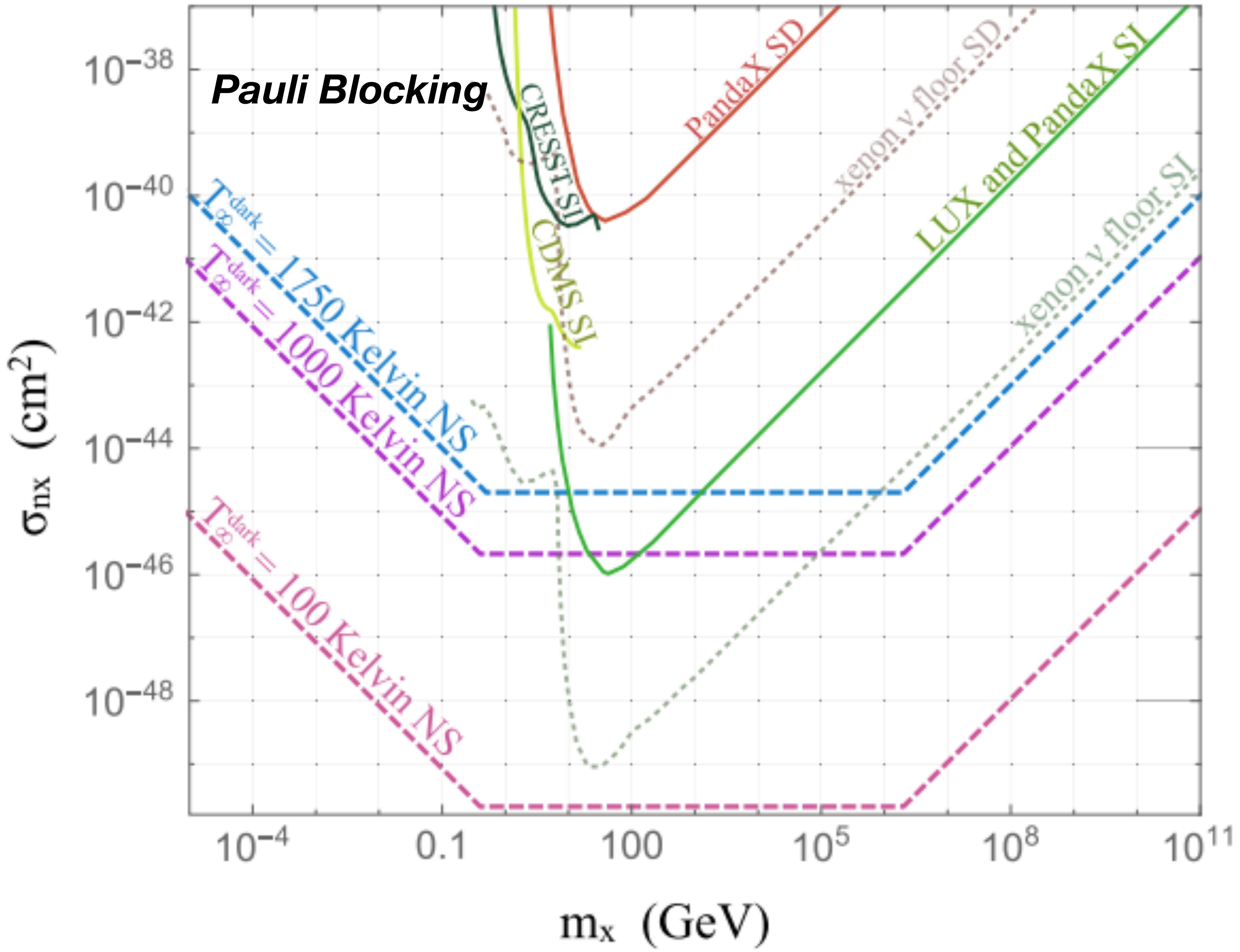
$$\rho_{\rm NS} \gtrsim \mathcal{O}(10^7)\,\rho_{WD}$$

$$R_{\rm NS} \sim R_{\rm WD}/700$$

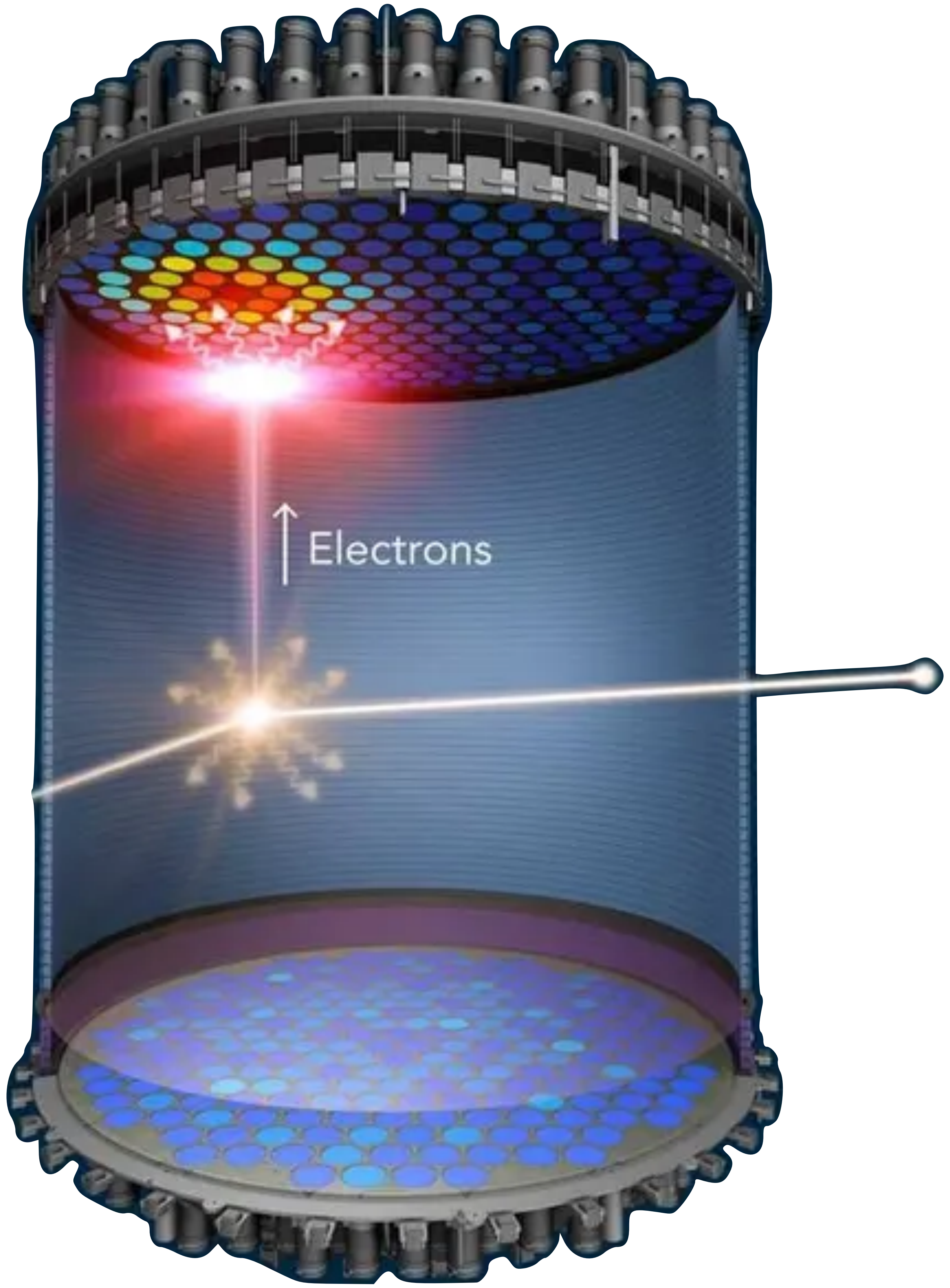
$$R/\lambda_{\rm mfp} \sim R\sigma n$$

Pires et al (2015)

Neutron stars as calorimeters



Multi-scattering

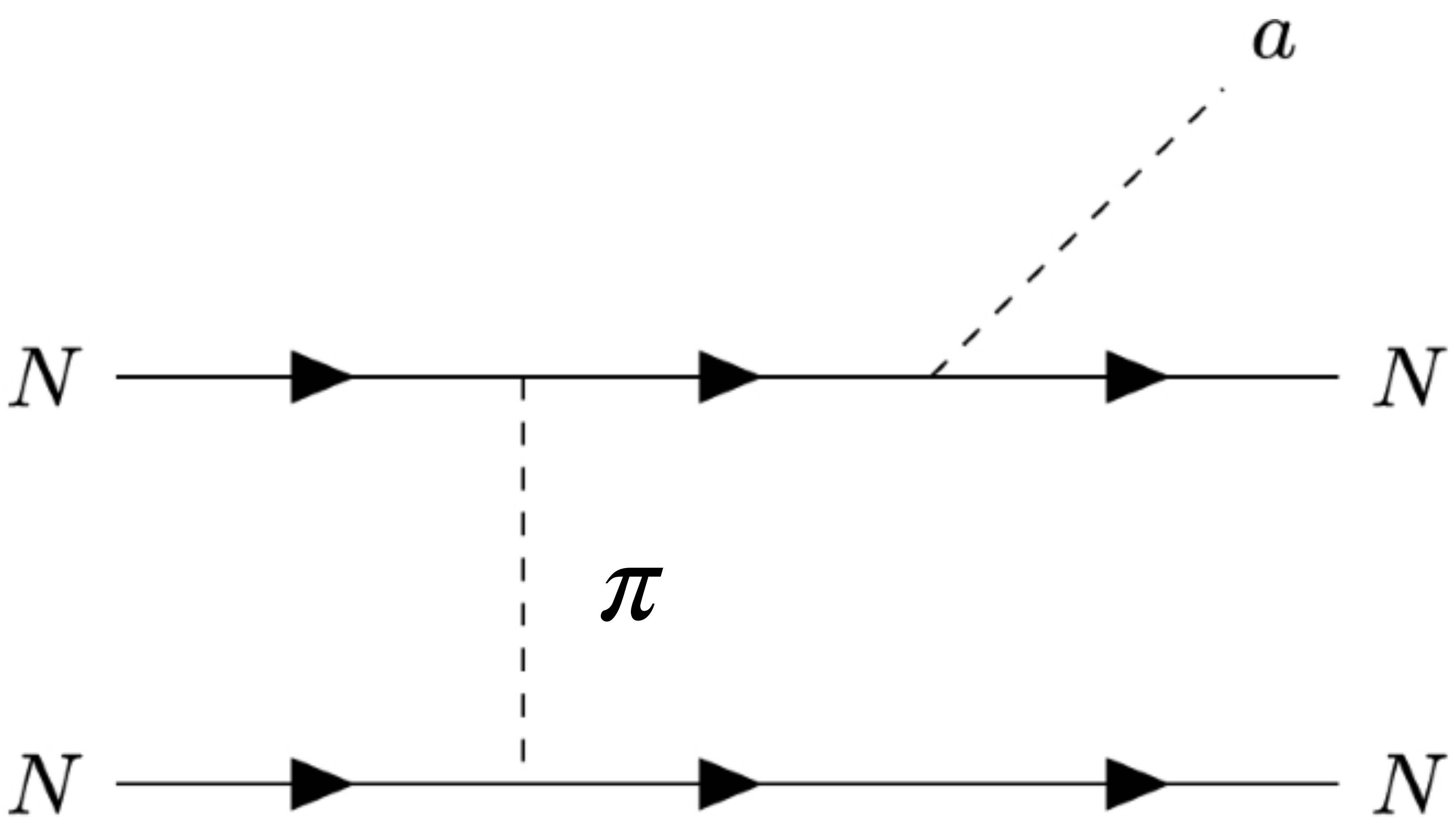


Baryakhtar et al (2017)

Neutron stars as calorimeters

$$L = -C\frac{dT_b}{dt} - L_\nu - L_a + H$$

$$\mathscr{L} \supset \frac{C_N}{2f_a}\bar{\psi}_N \gamma^\mu \gamma_5 \psi_N \partial_\mu a$$



Things to bare in mind:

- Couplings and cross sections at high densities not always well understood

  See e.g. Hardy et al (2024), Springmann et al (2024), etc

- Evolution of heat capacity, neutino cooling, etc depend on complicated high density physics

  [The hope is to marginalize]

- How important is heating?

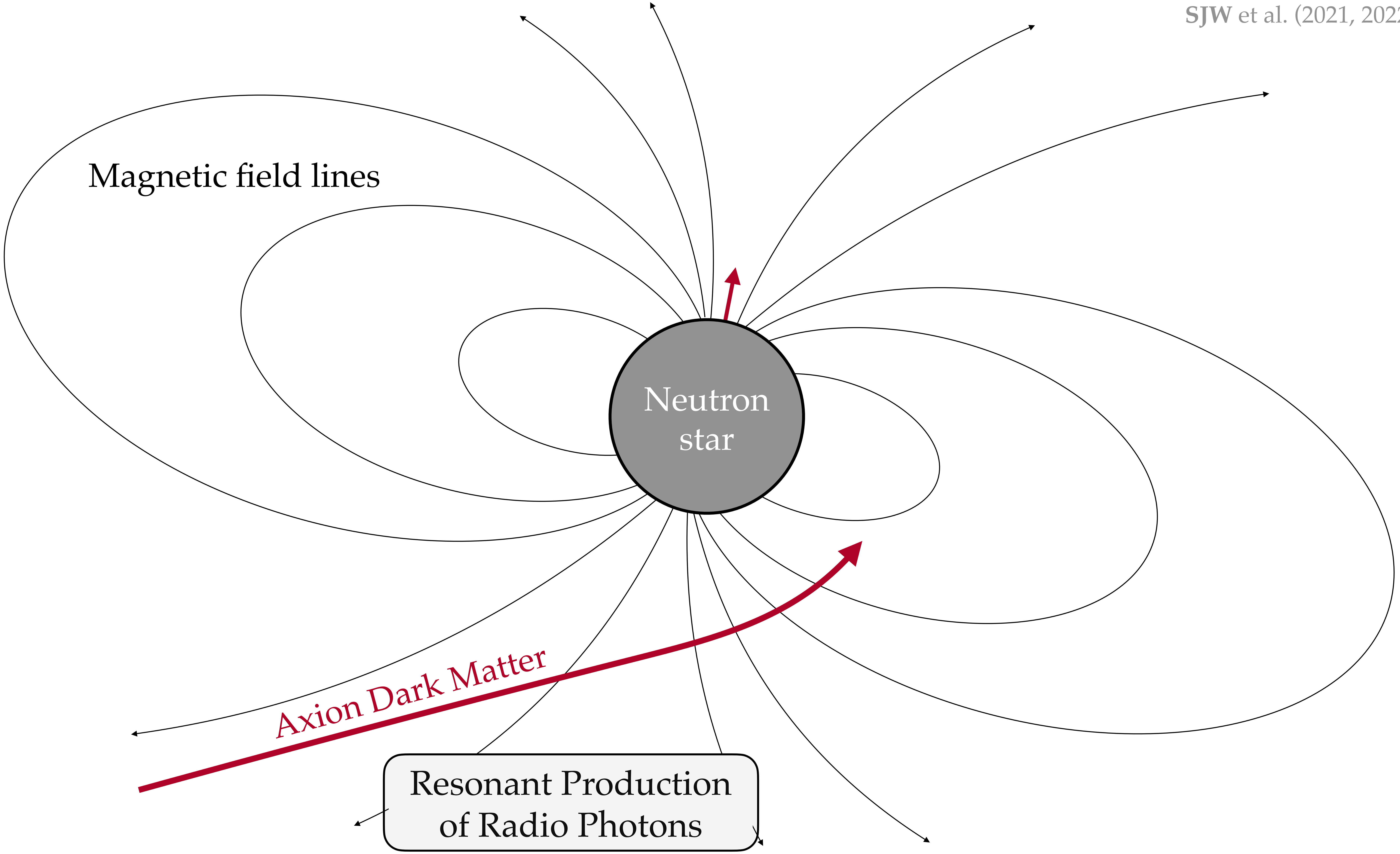
$$\boxed{m_{a,\mathrm{KSVZ}} \lesssim \mathcal{O}(10^{-2})\,\mathrm{eV}}$$

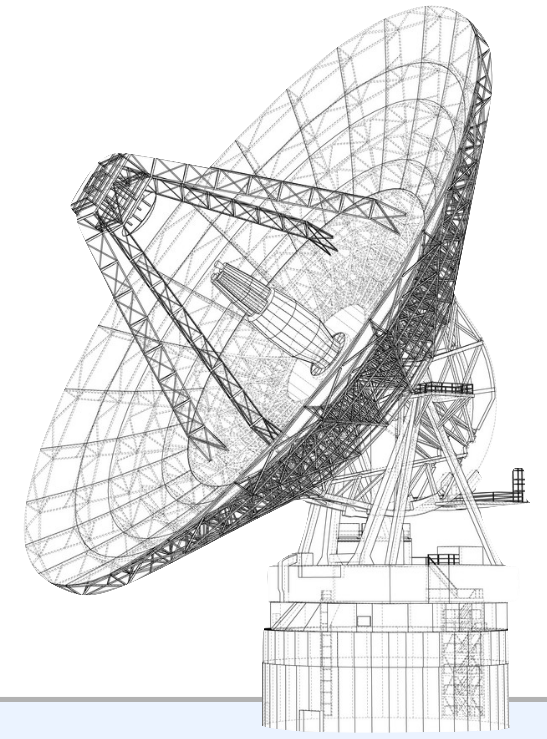
Buschmann et al (2021), …

Similar ideas applied to white dwarfs

Neutron stars as axion labs

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), …





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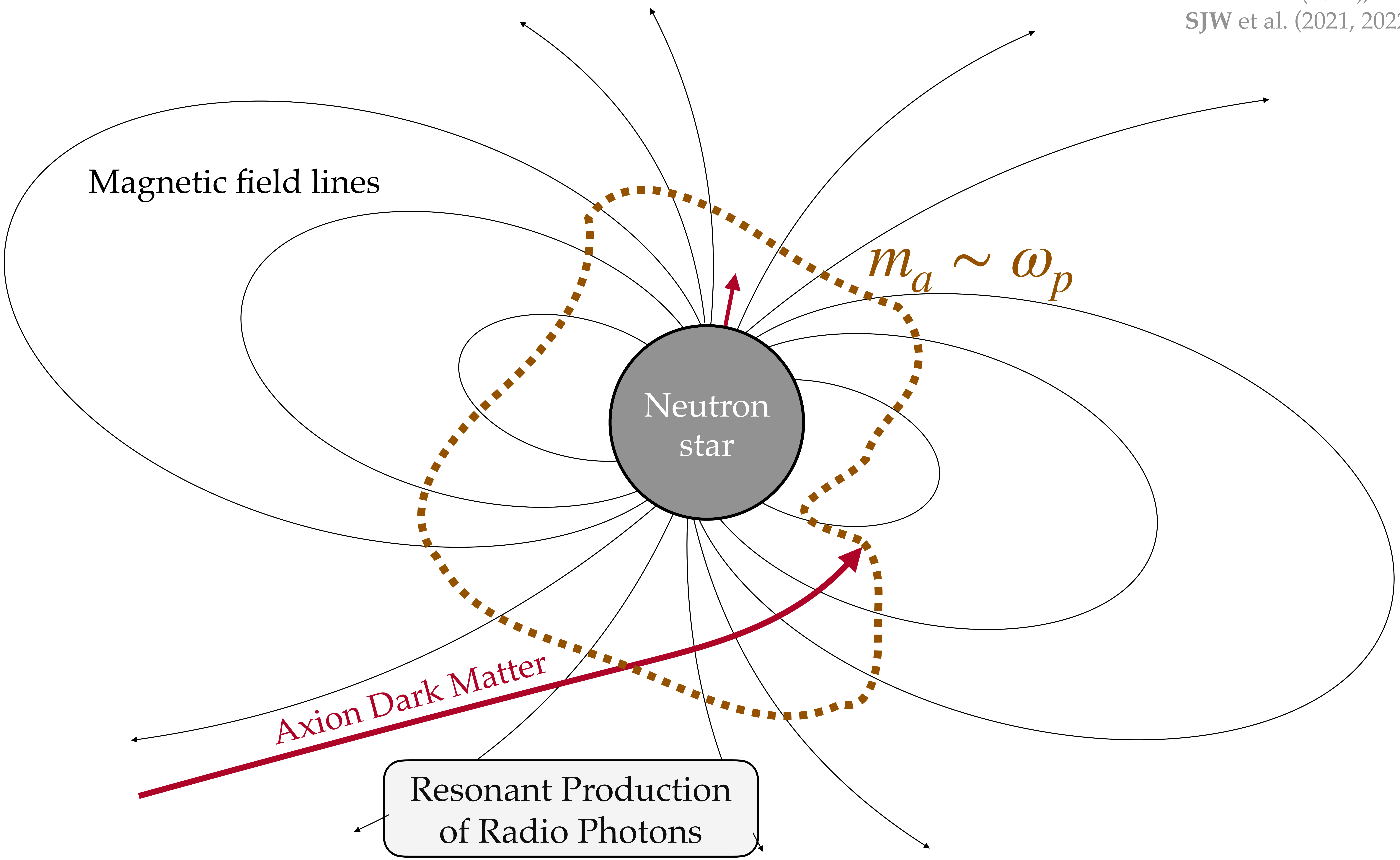

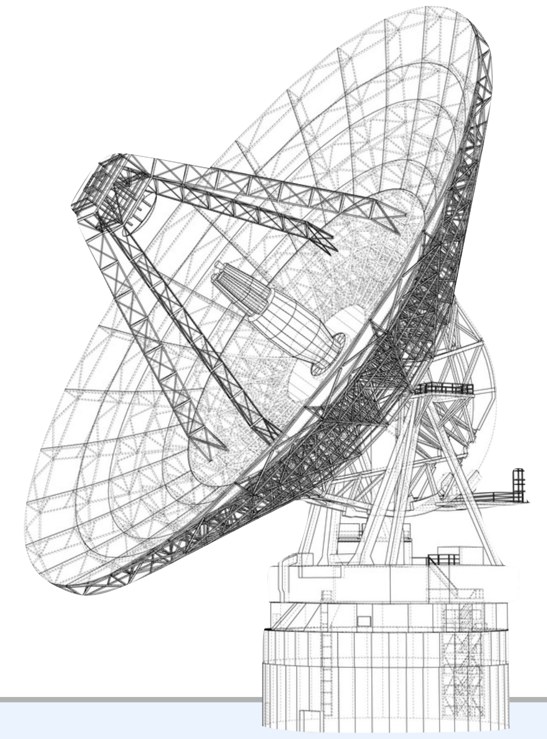

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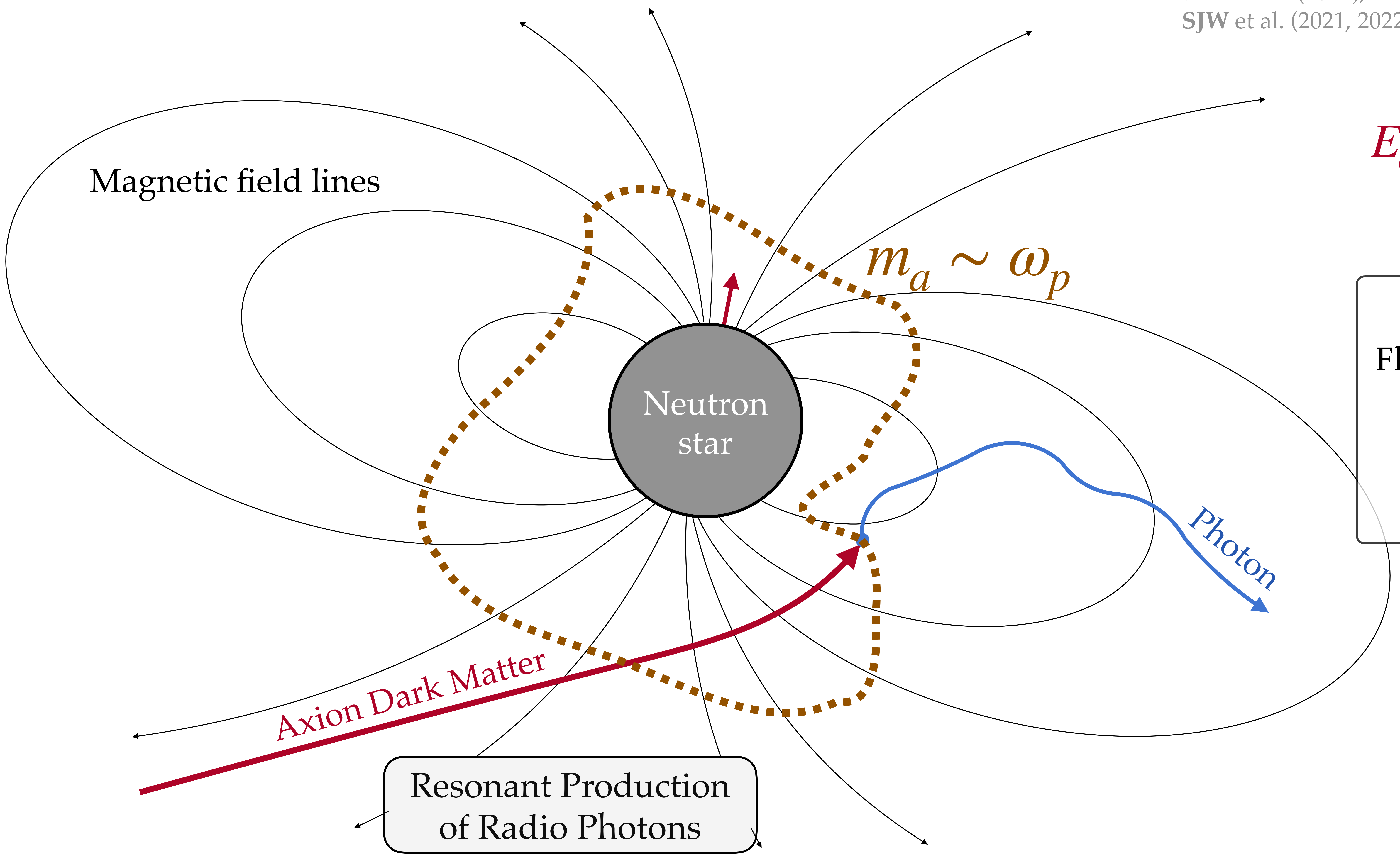
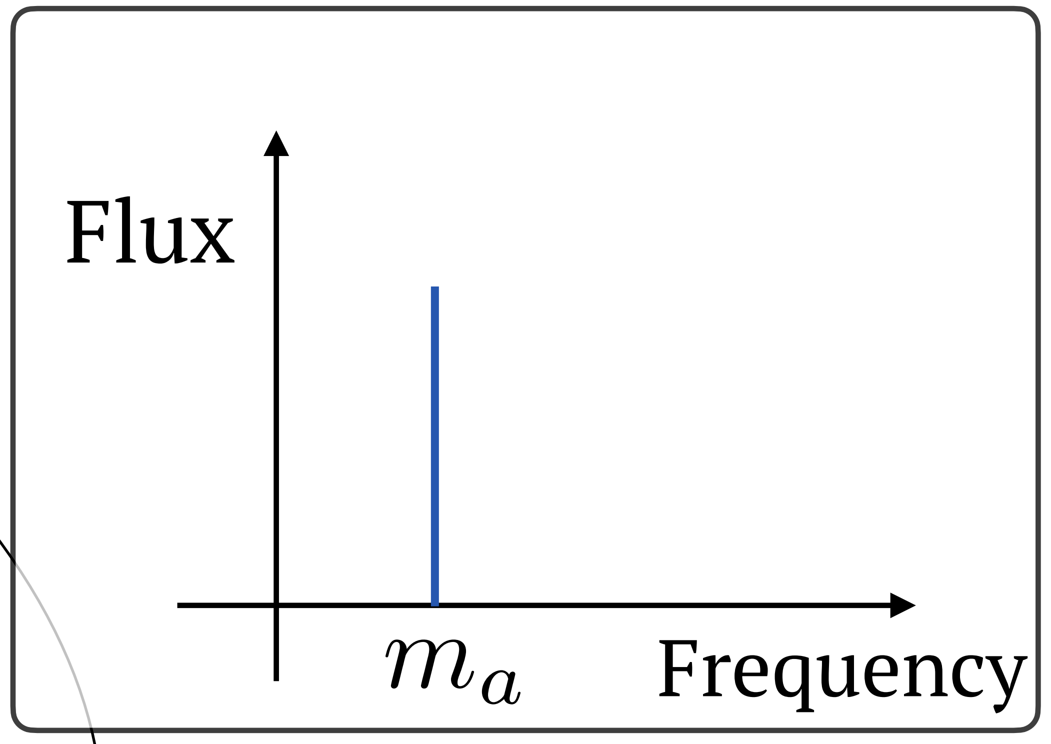
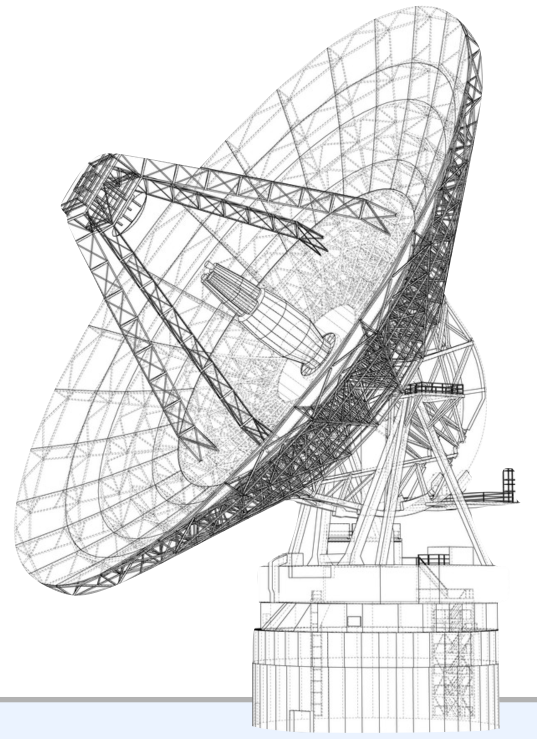


$$E_a \sim m_a (1 + v^2/2)$$

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





Neutron stars as axion labs

To the blackboard

Back of envelope calculation for detecability

Neutron stars as axion labs

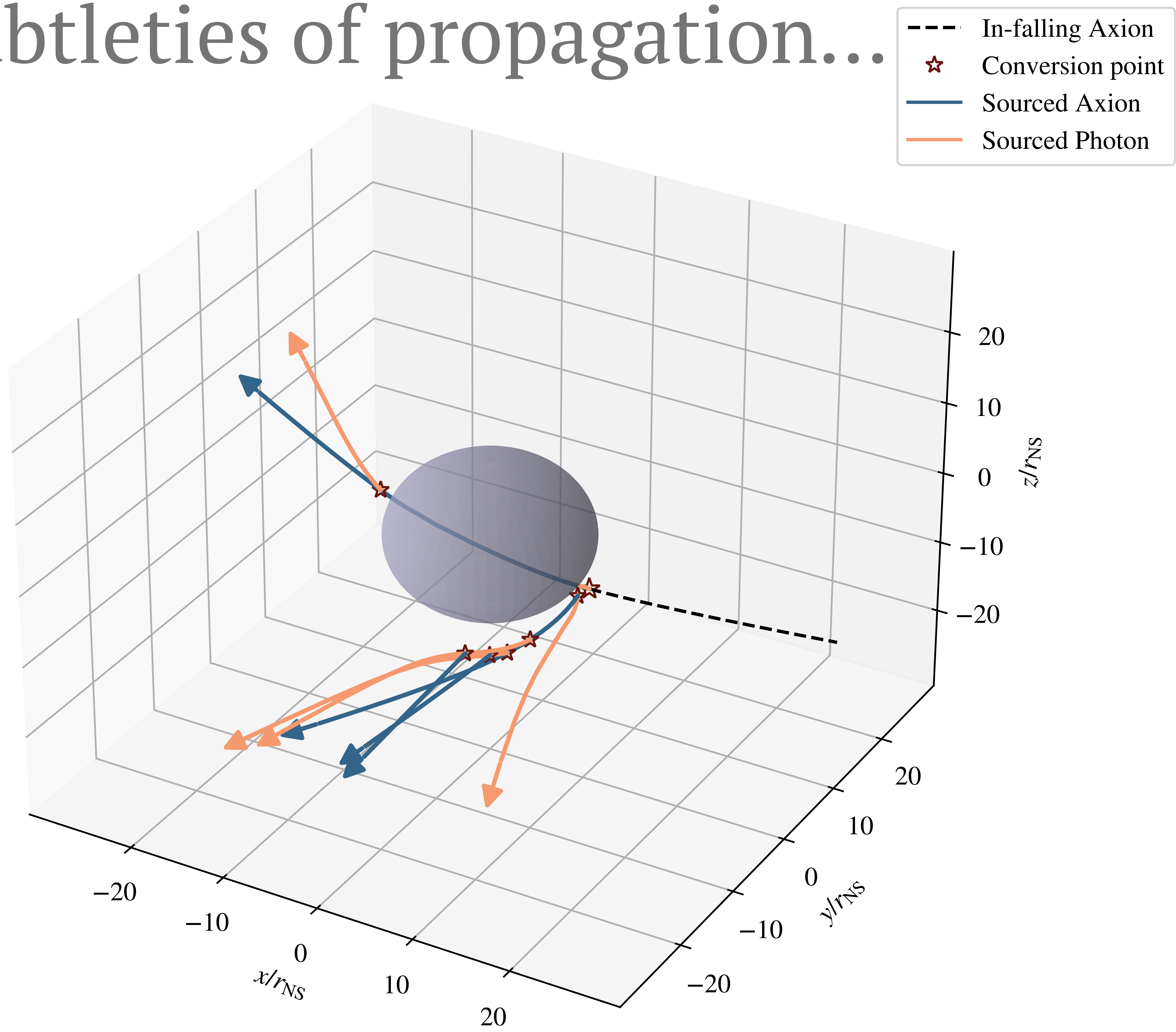
To the blackboard

Back of envelope calculation for detecability

Many subtleties associated to this problem…

- Axion-Photon mixing in highly magnetized plasma
- Non-linear photon propagation
- Linear broadening
- Photon absorption
- Deviations from minimal plasma distribution (including super-critical QED processes)
- …

Subtleties of propagation…



Ray tracing:

- Non-linear photon propagation
- Line broadening
- Photon absorption
- Back-reaction on axion phase space

λ

$$\mathscr{H} = \omega^2 - k^2 - \omega_p^2$$

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

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

Tjemsland, **SJW**, McDonald (2023)

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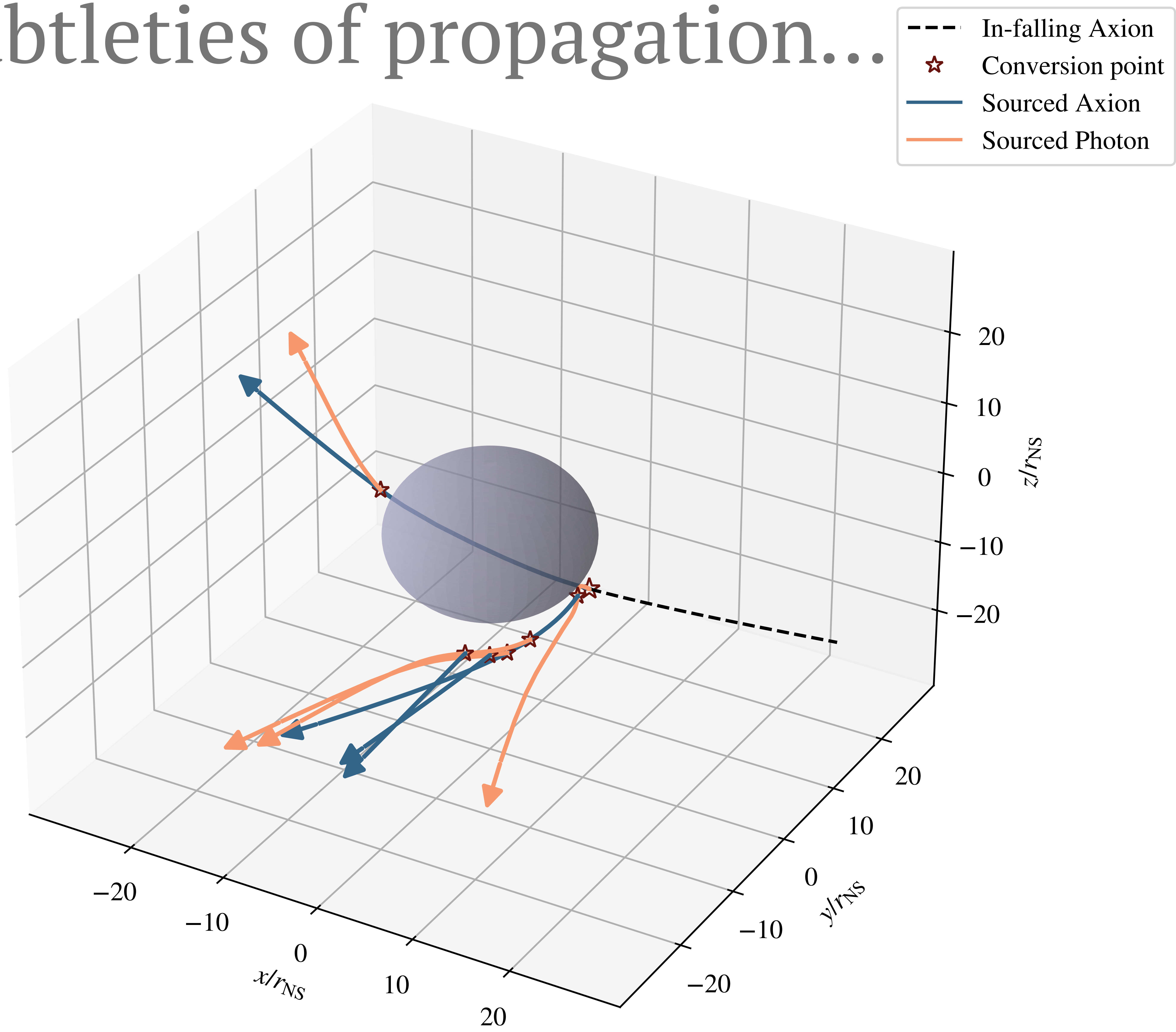

Ray tracing:

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λ

$$\mathscr{H} = \omega^2 - k^2 - \omega_p^2$$

$$\frac{d\mathscr{H}}{d\lambda} = \frac{dk_\mu}{d\lambda}\frac{\partial \mathscr{H}}{dk_\mu} + \frac{dx^\mu}{d\lambda}\frac{\partial \mathscr{H}}{dx^\mu} = 0$$

$$\frac{dx^\mu}{d\lambda} = \frac{\partial \mathscr{H}}{dk_\mu} \qquad \frac{dk_\mu}{d\lambda} = -\frac{\partial \mathscr{H}}{dx^\mu}$$

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

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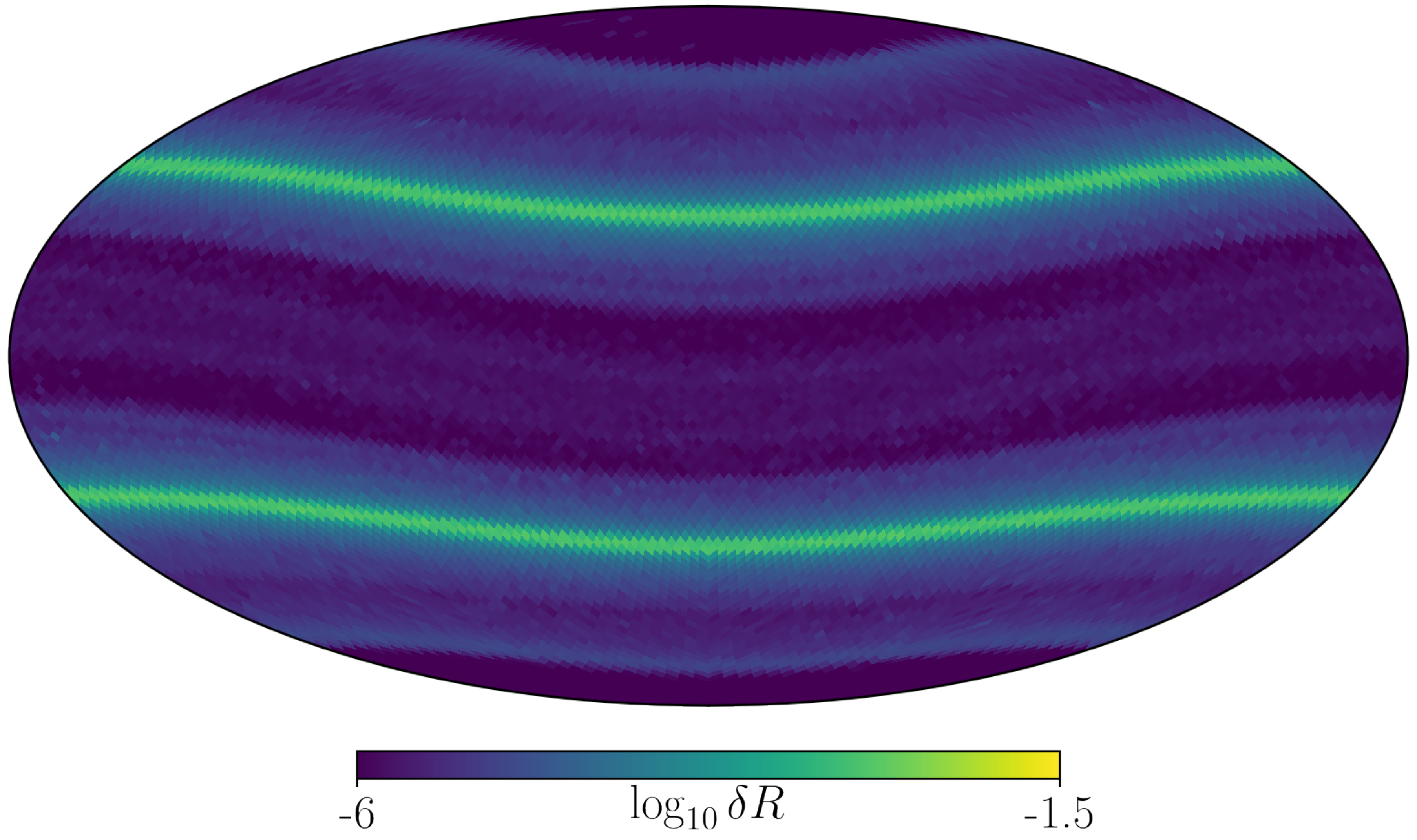
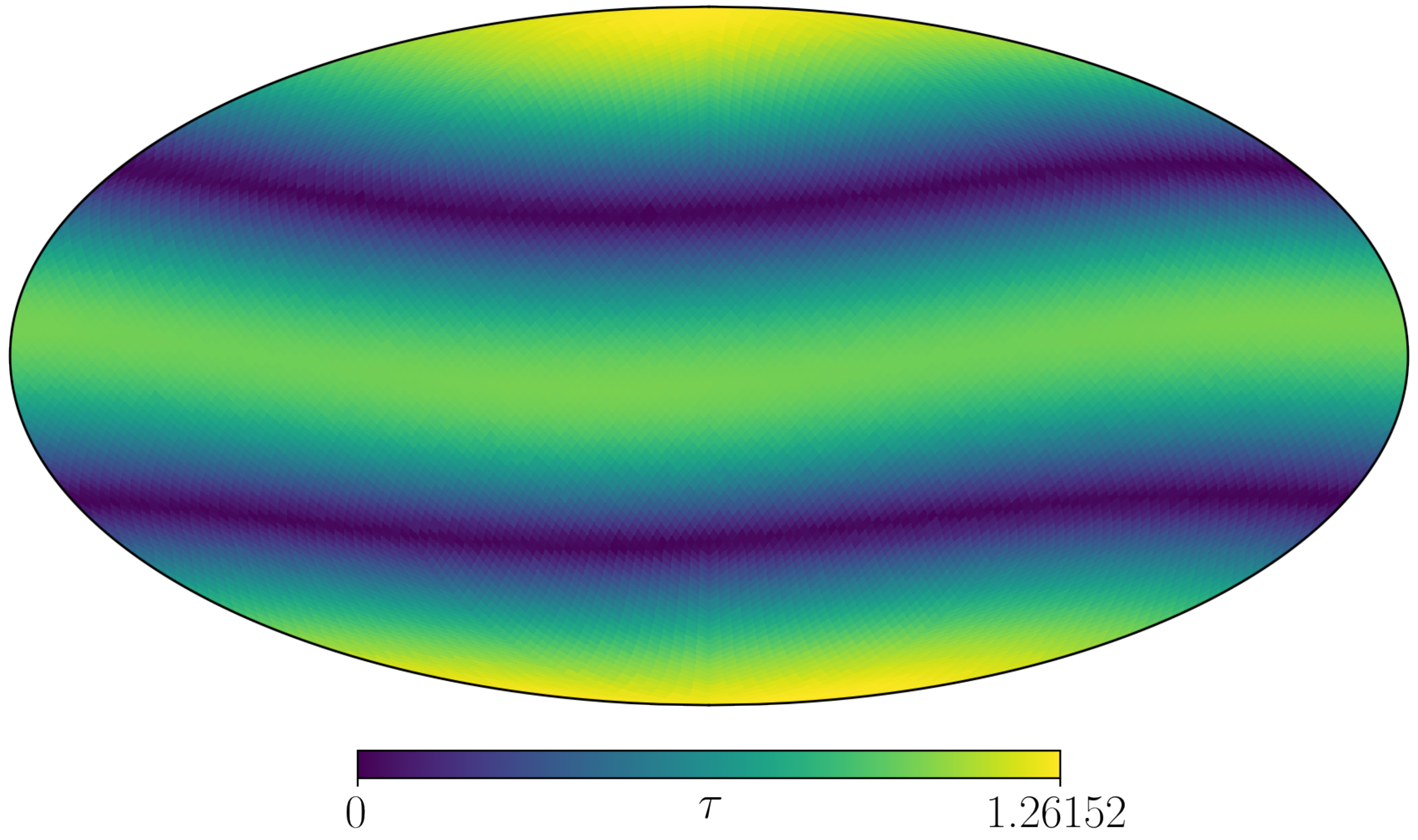
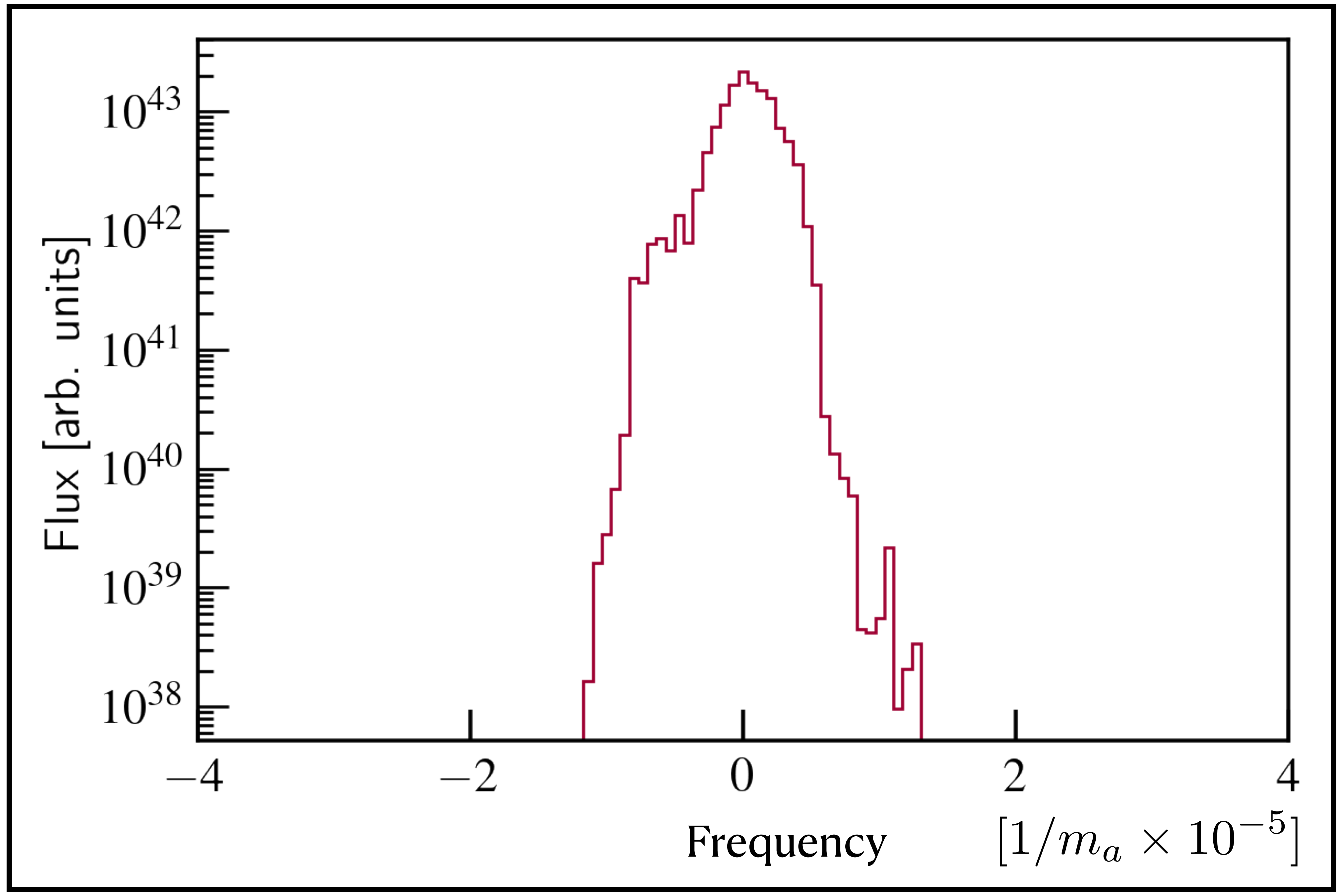


Anisotropy of the flux



Anisotropy of absorption

Line width, temporal evolution



SJW et al (2021), Battye et al (2021)
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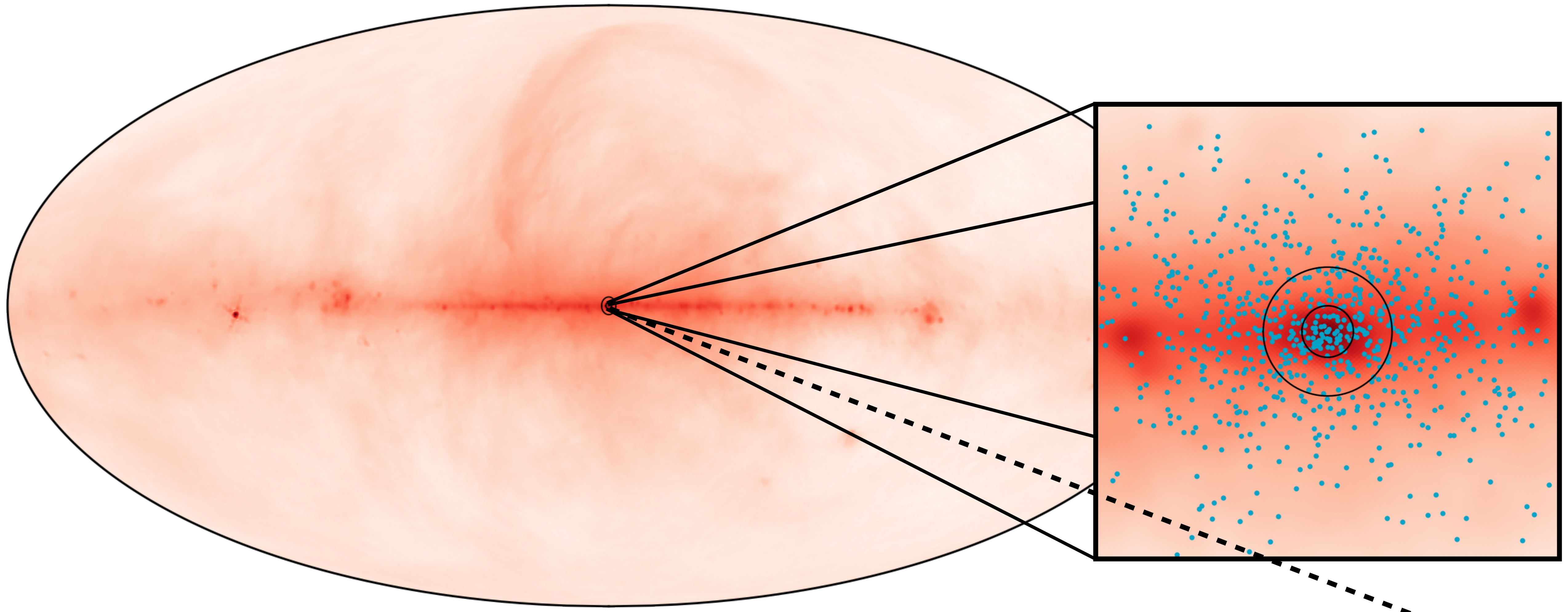
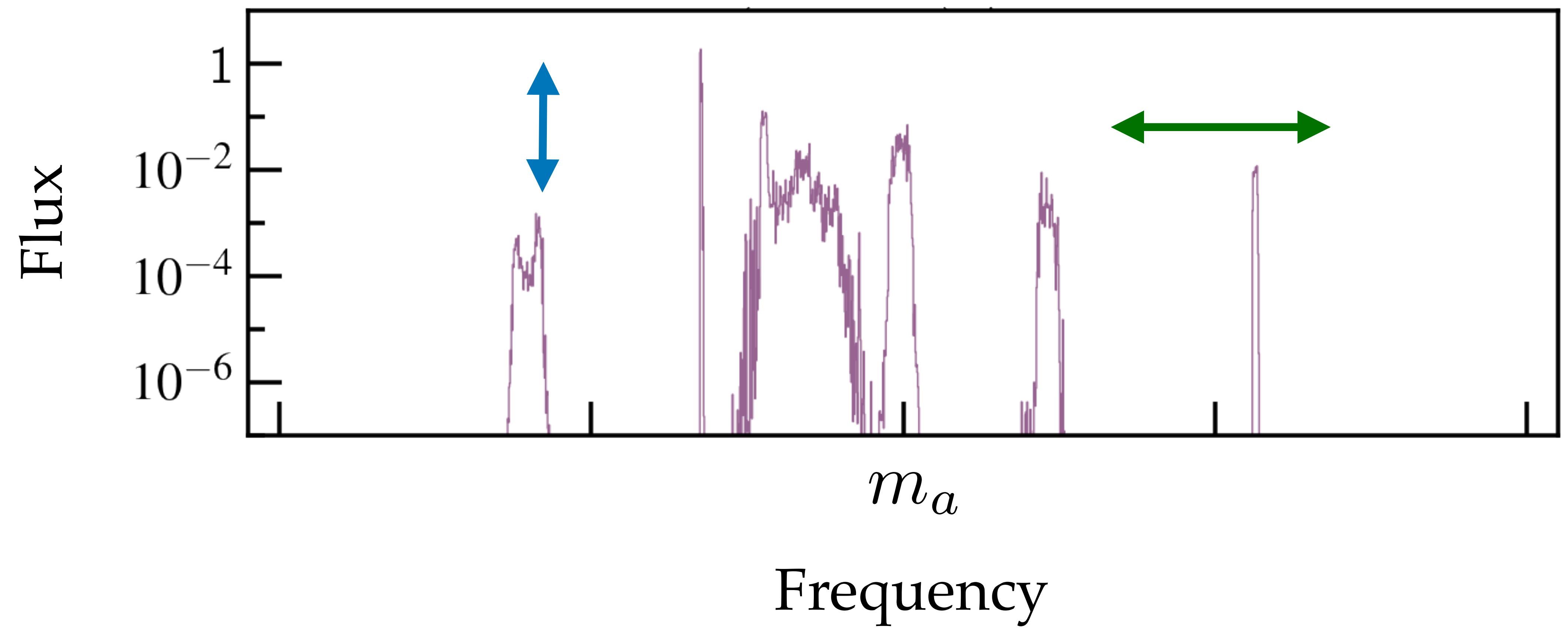
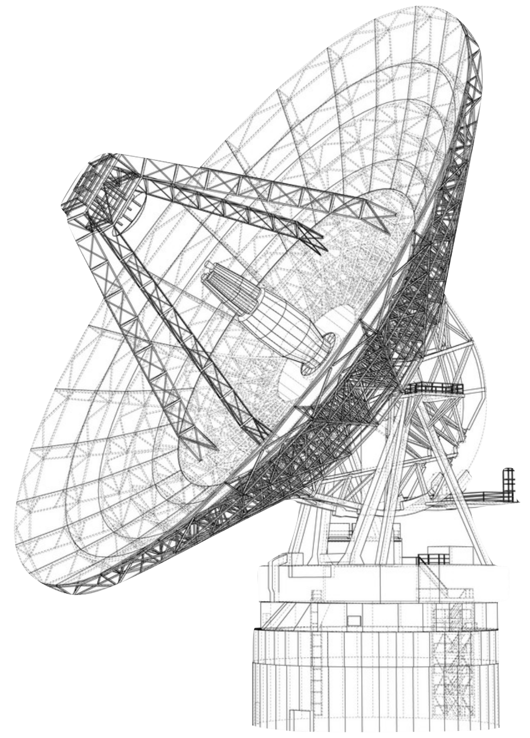
Radio searches for axions



Lines oscillate with rotation of star (seconds)

Lines shift with stellar orbit (weeks)

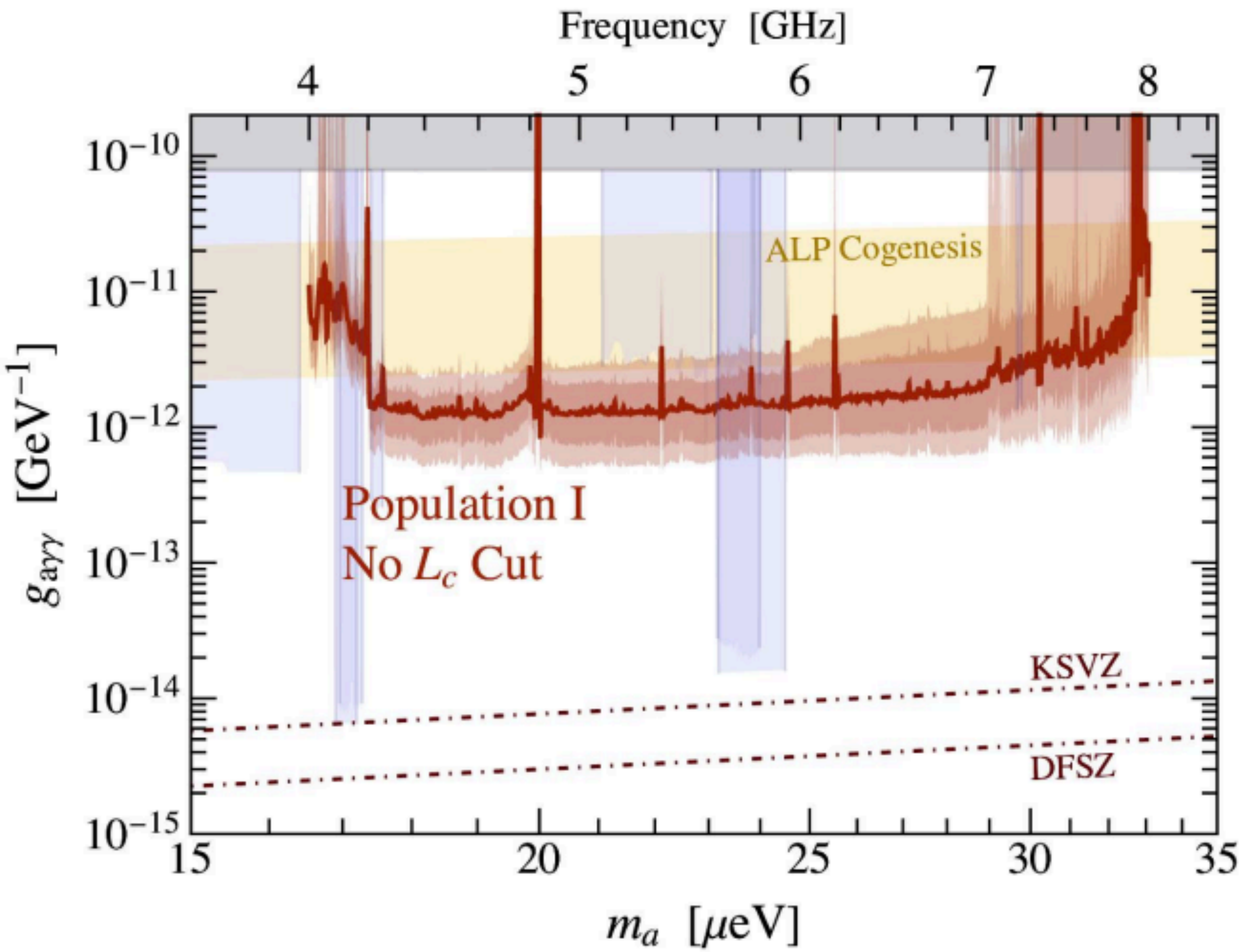


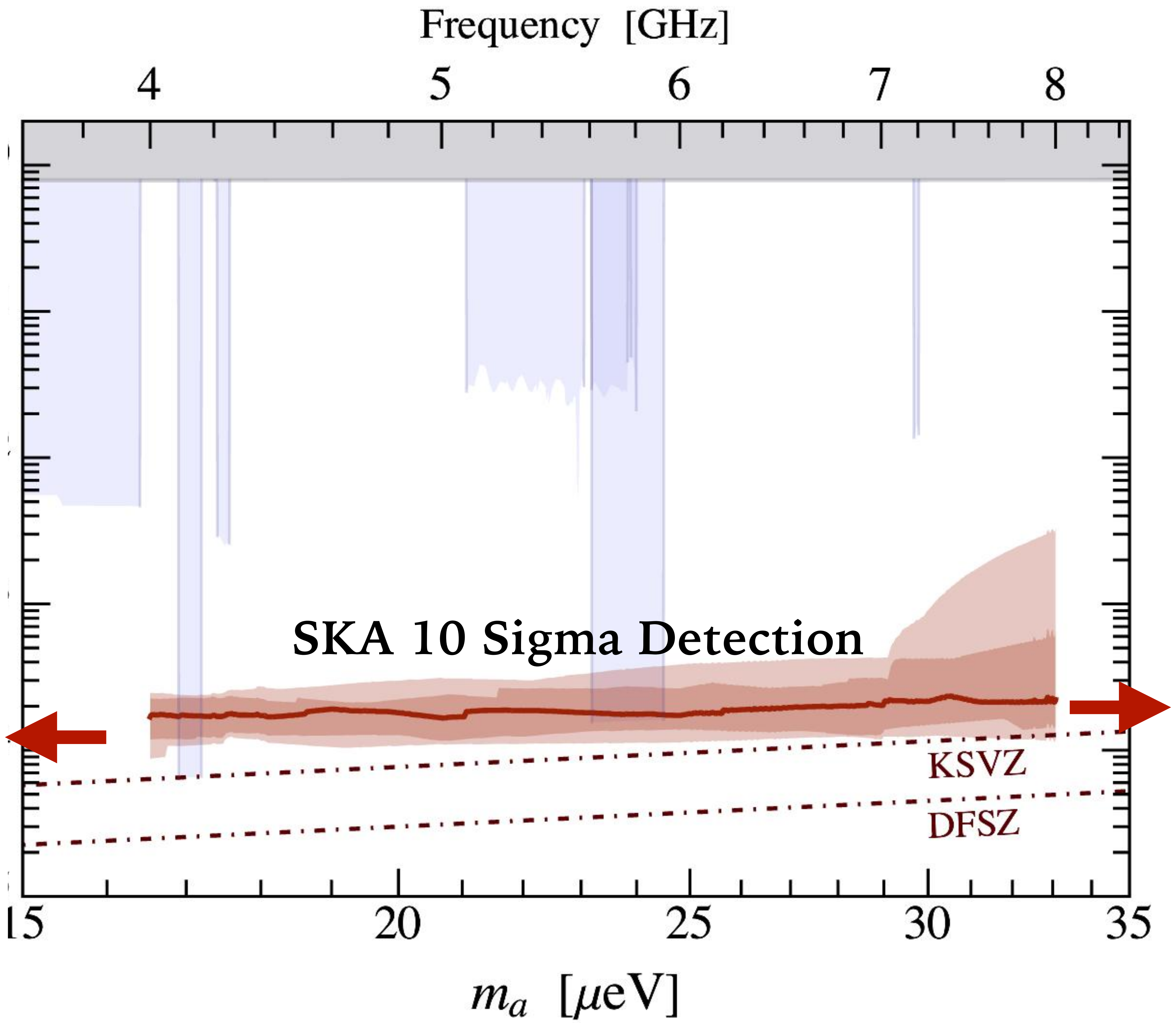


- Galactic Center

Tons of dark matter, large density of neutron stars expected, but difficult modeling…

Current and future status

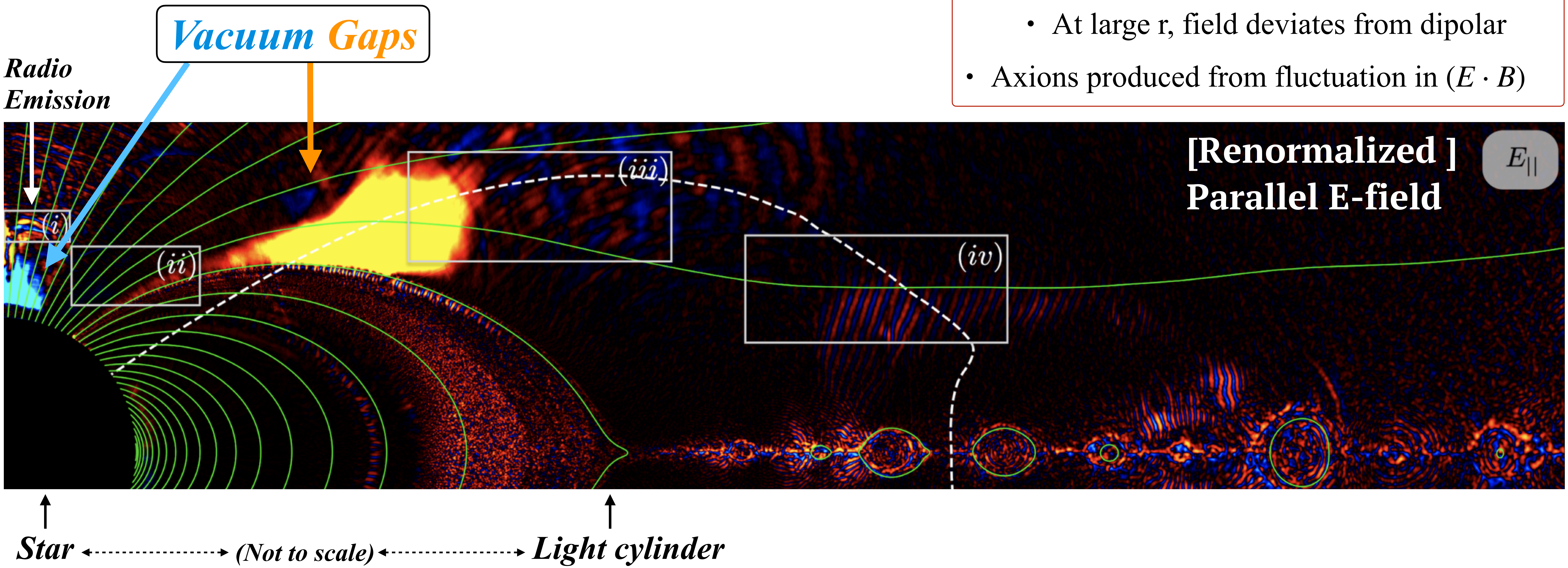




Foster, **SJW**, Lawson, Linden, Gajjar, Weniger, Safdi (2022)

Neutron stars as axion factories

- Dense plasma $(E \cdot B) \to 0$ ***almost*** everywhere
  - At large r, field deviates from dipolar
- Axions produced from fluctuation in $(E \cdot B)$



Polar Cap Dynamics in the Last Half Century (See e.g.):
Sturrock (1971), Ruderman & Suntherland (1974), Arons & Scharlemann (1979), Timokhin (2013), Timokhin & Harding (2015, 2018), Philippov, Timokhin & Spitkovsky (2020), Bransgrove, Belobodorov, Levin (2023)

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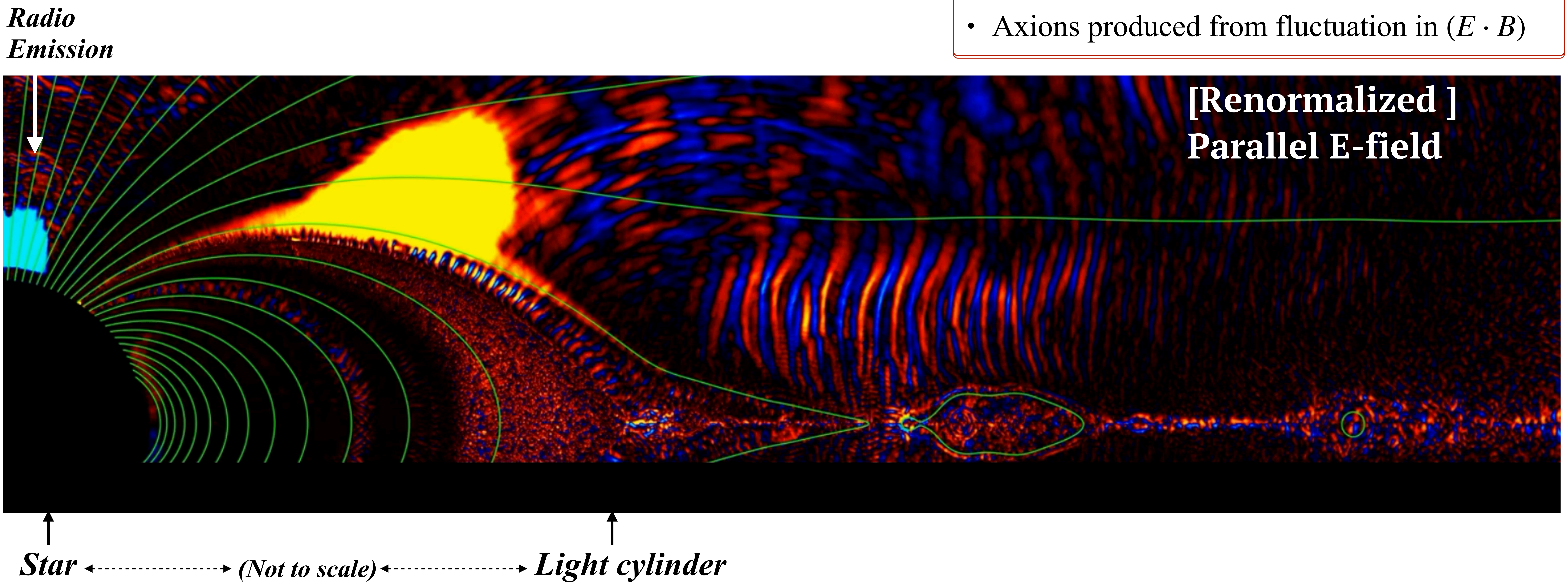

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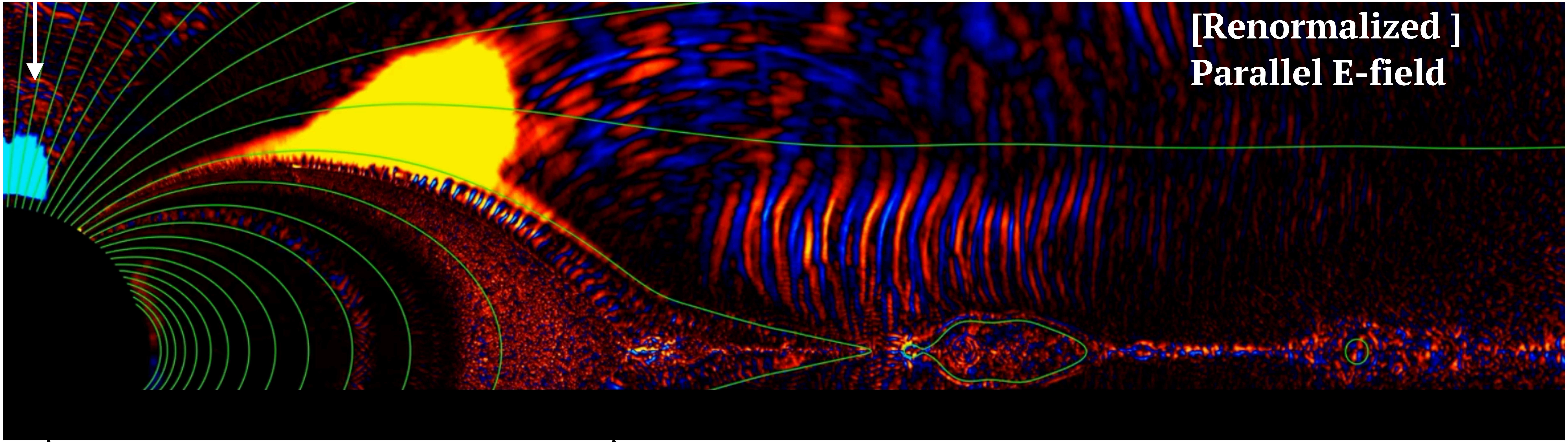
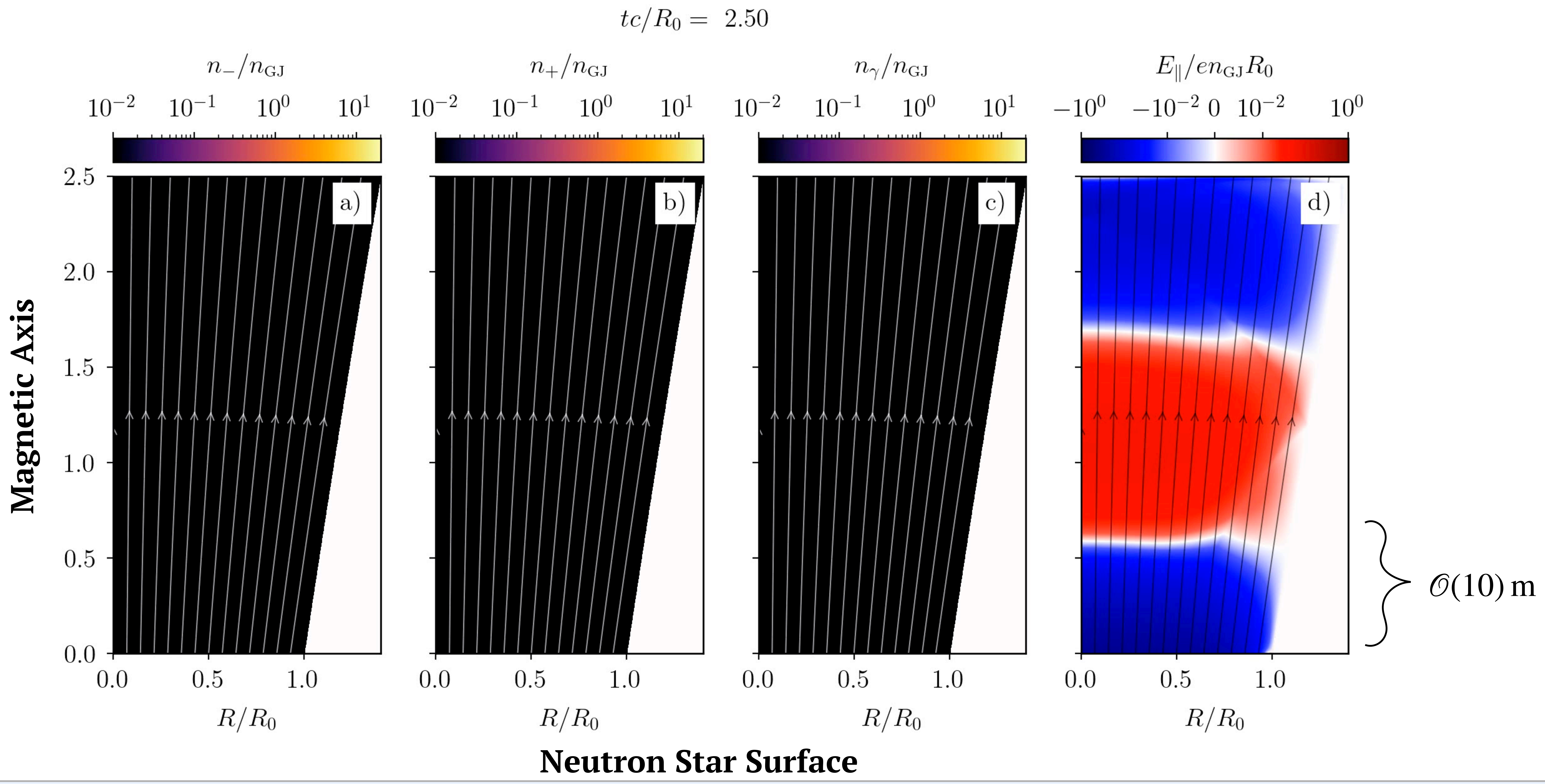
Radio Emission

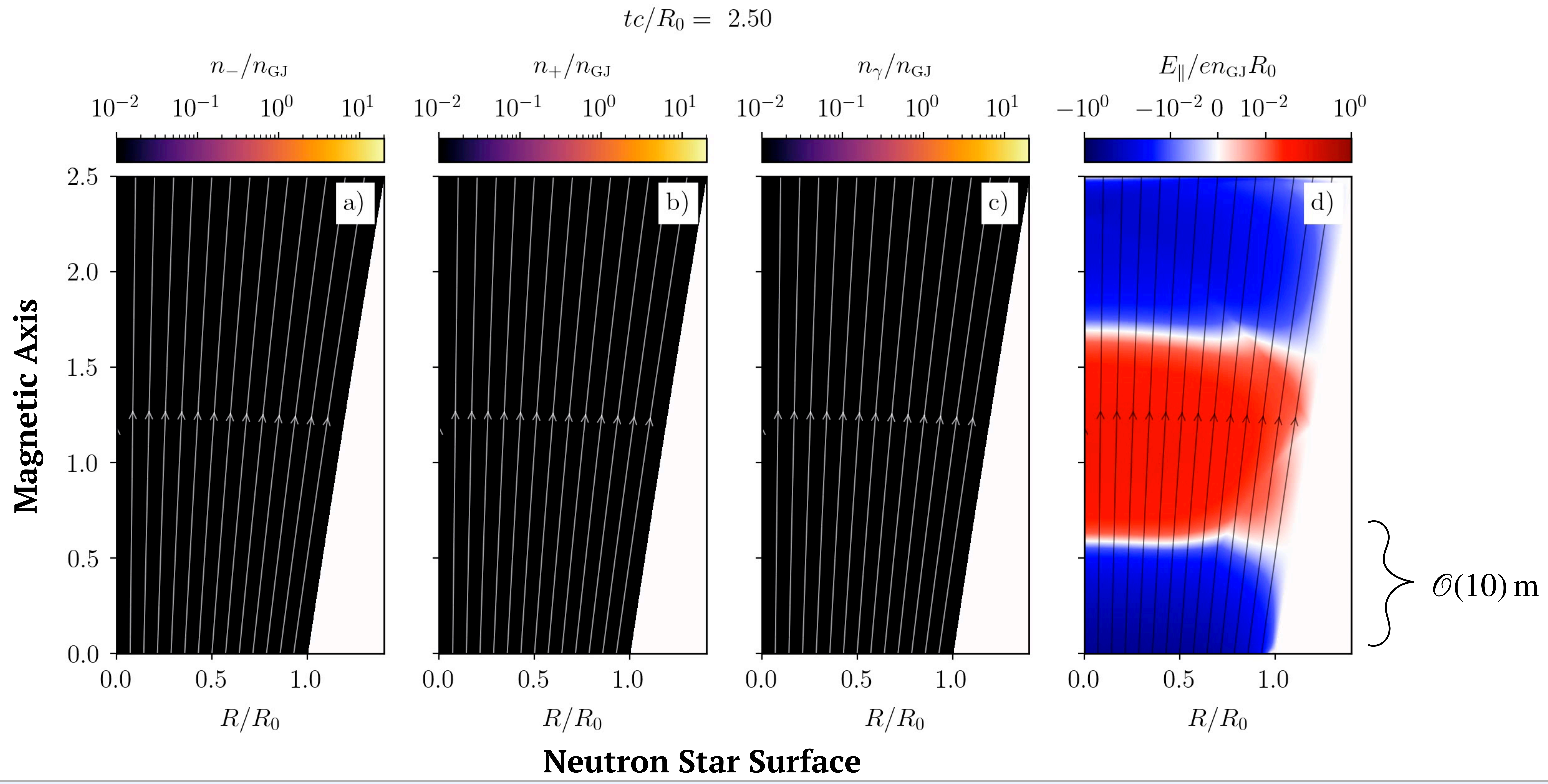


Star *(Not to scale)* ***Light cylinder***

Polar cap dynamics



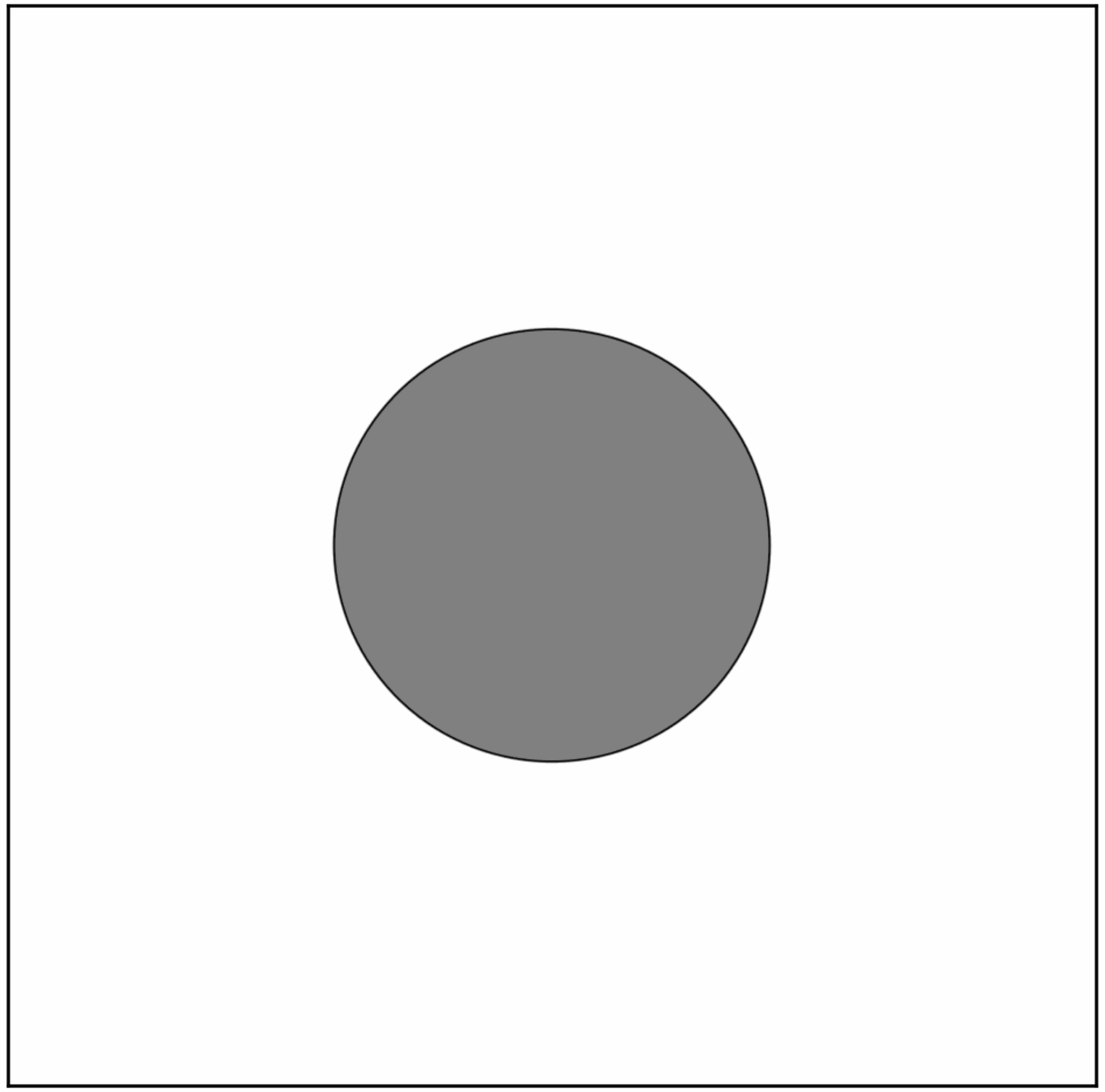
Polar cap dynamics



Bound axion configurations

$E \cdot B$ fluctuations driven at radio frequencies

Axions with $10^{-9}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-5}\,\mathrm{eV}$ are bound!



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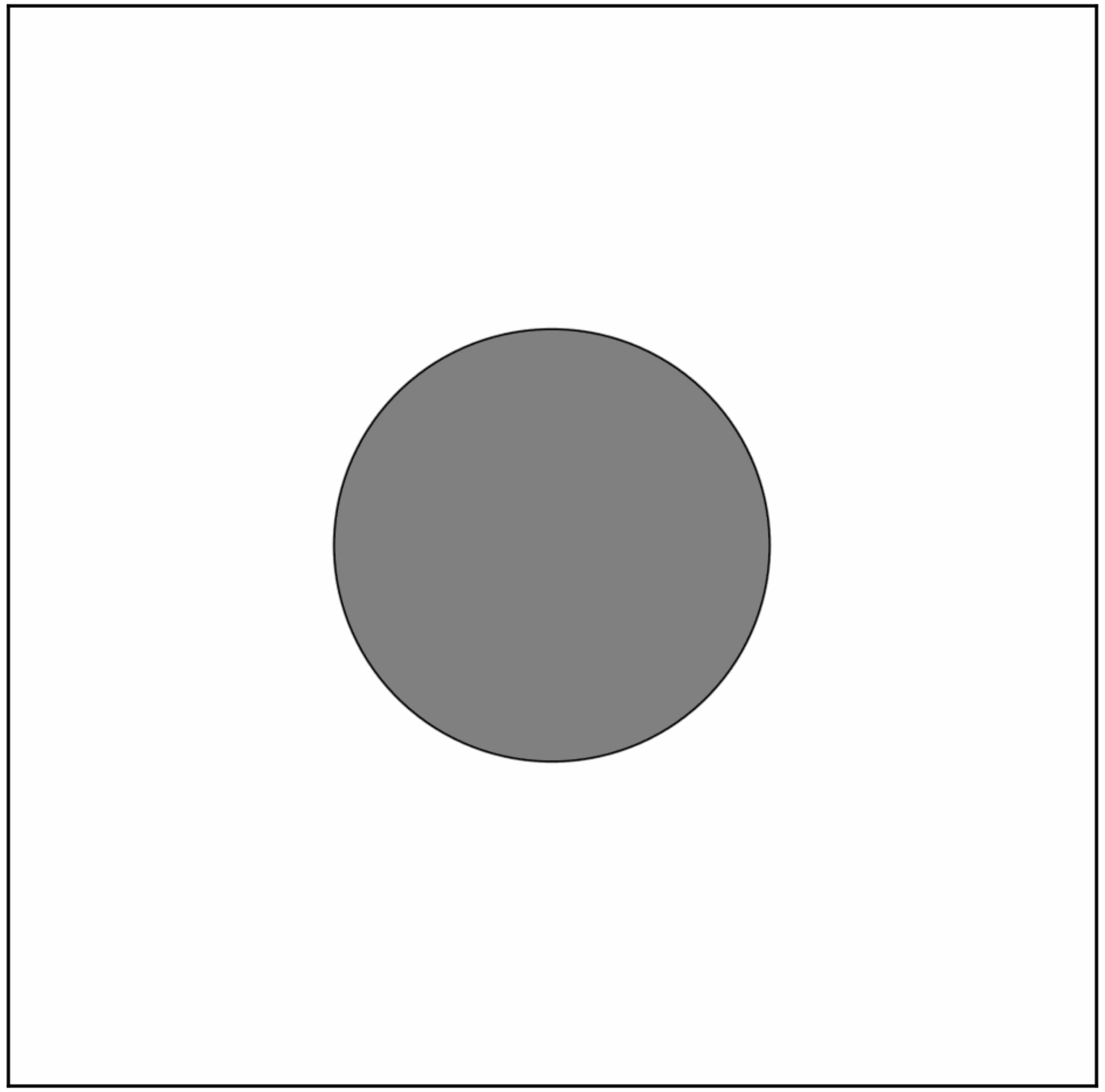
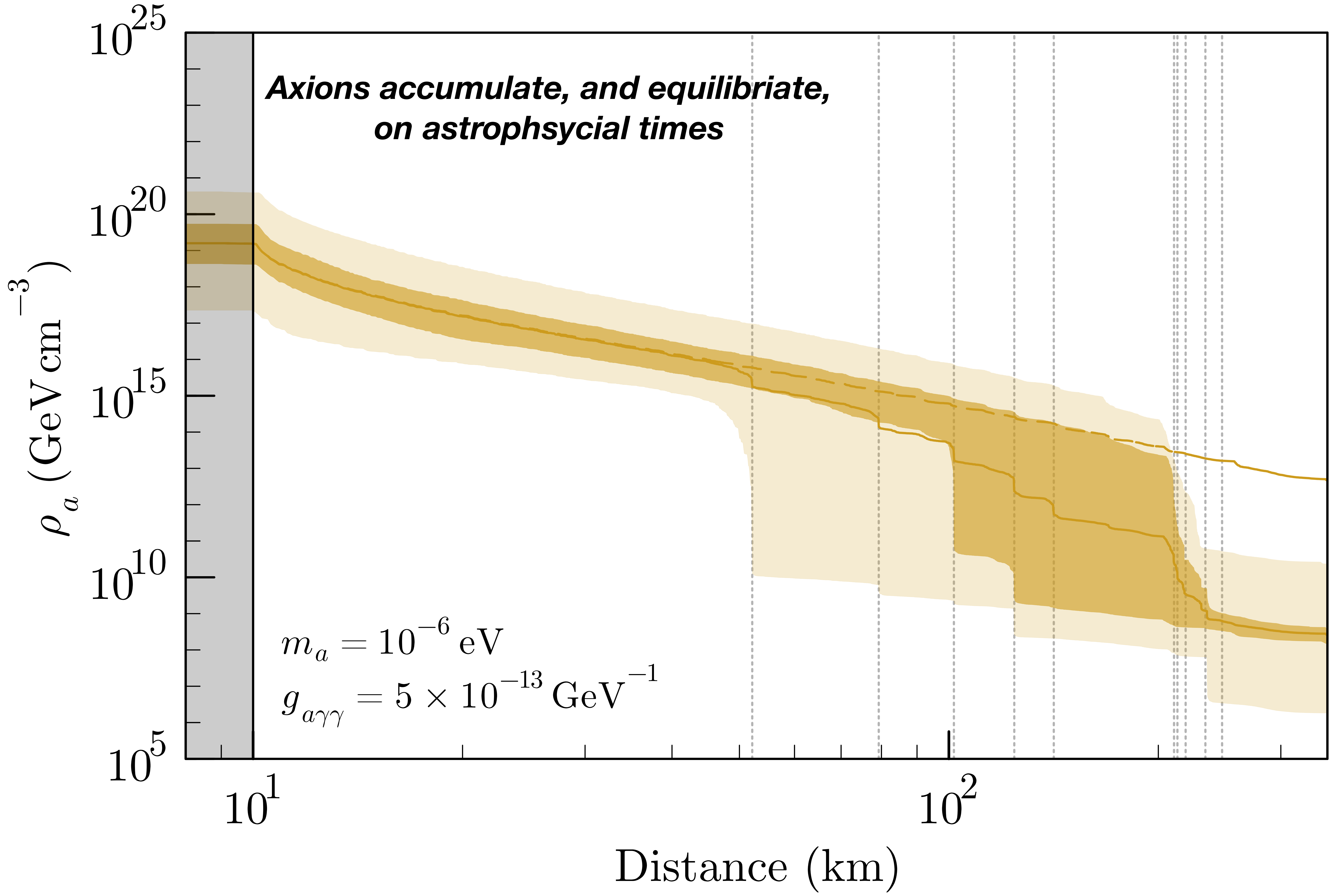


Gravitationally bound axions



Noordhuis, Prabhu, Weniger, **SJW** (PRX, 2024)

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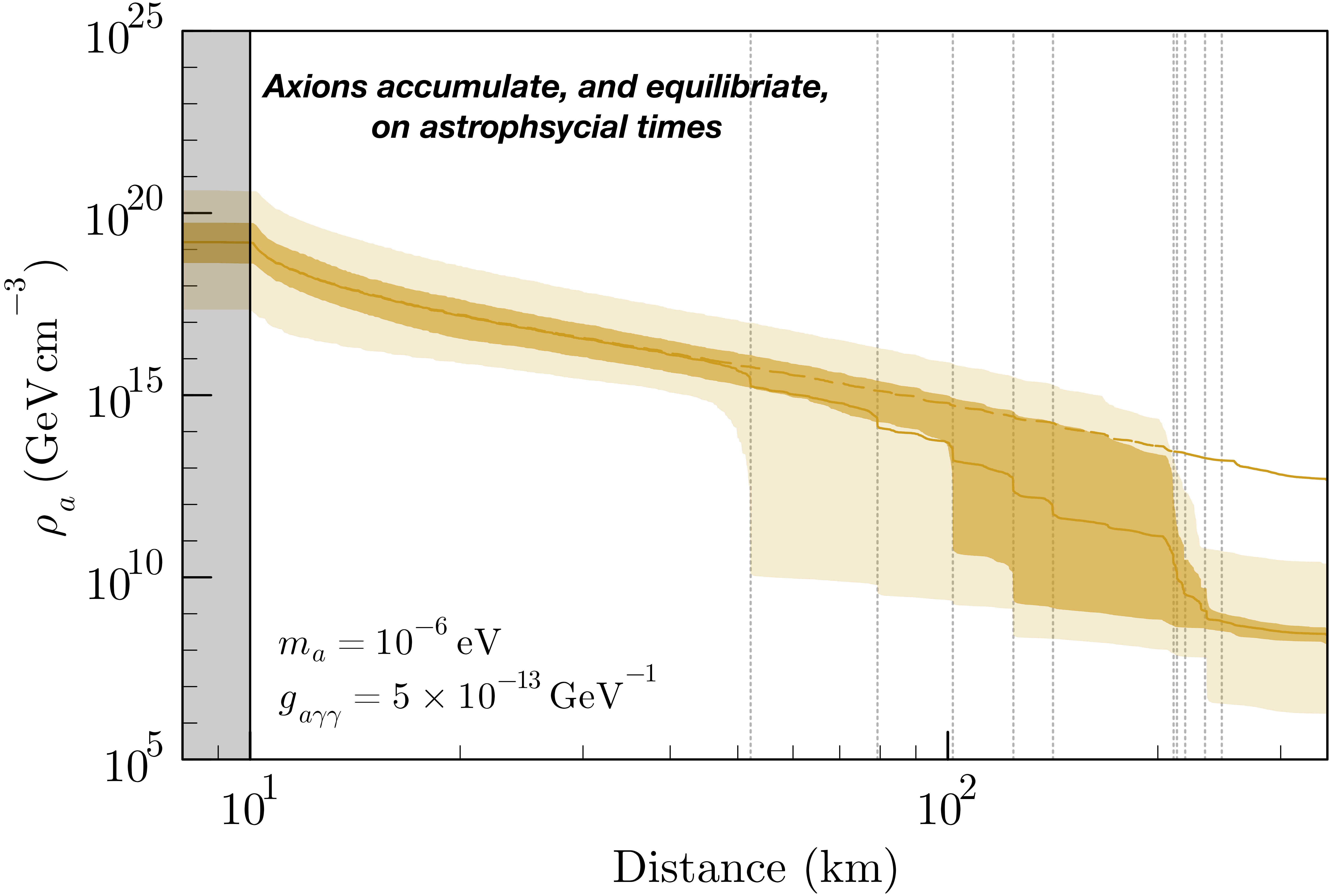
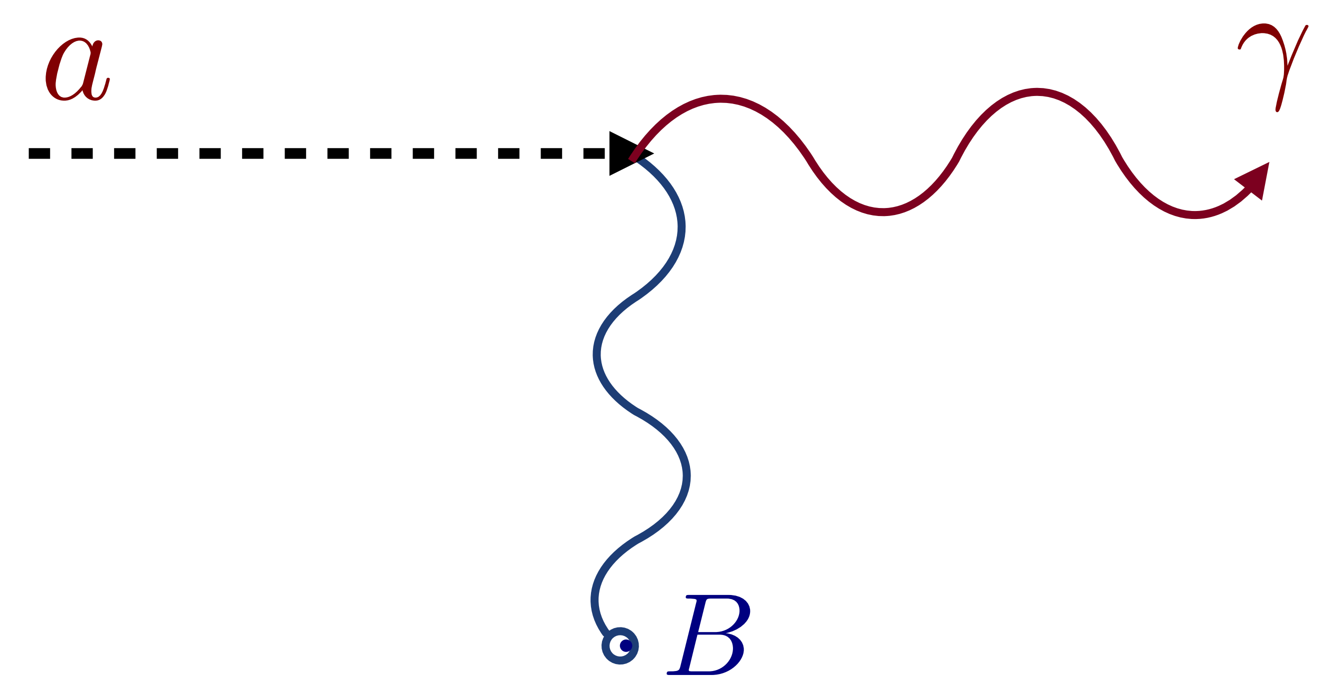
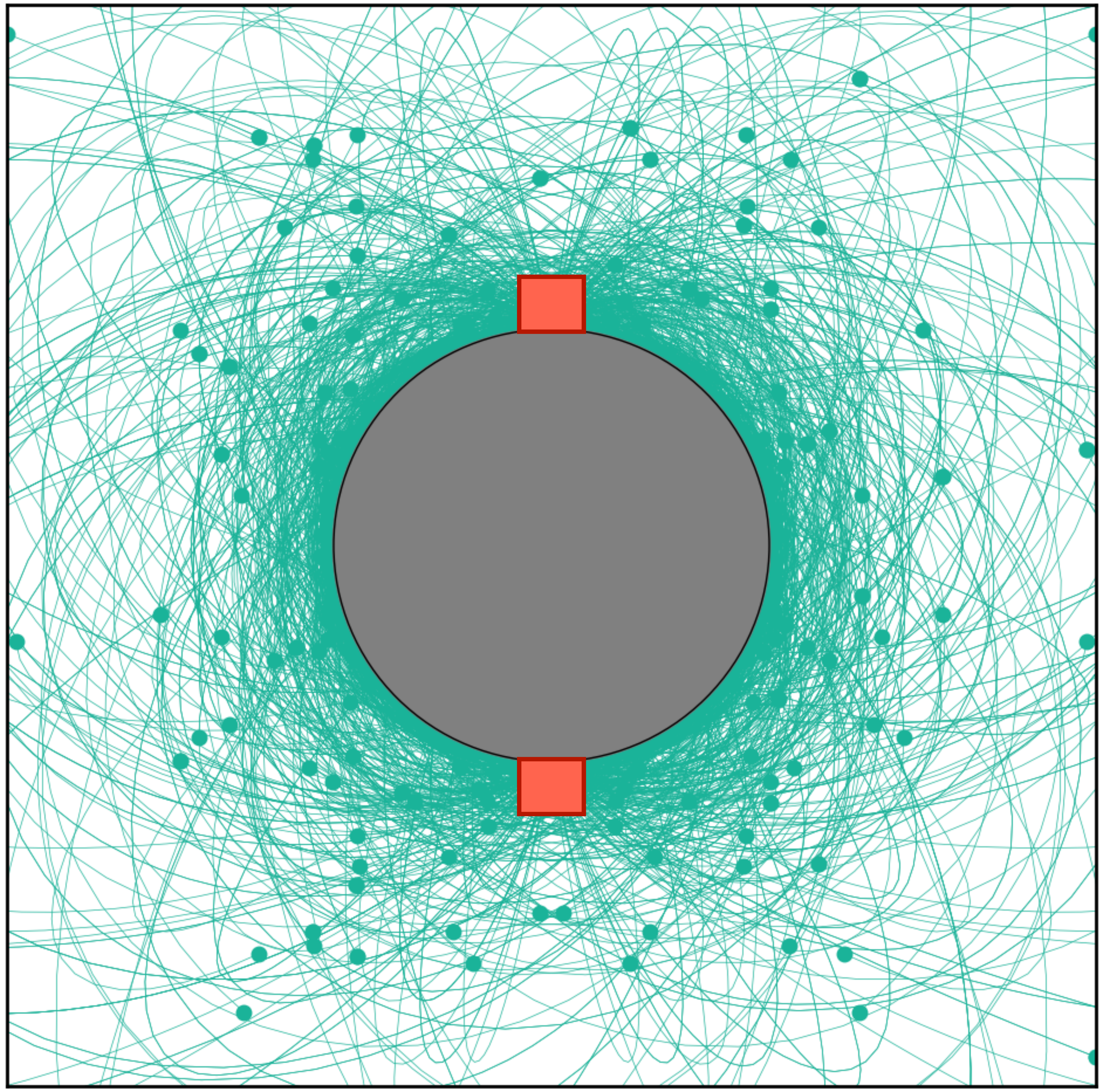




Noordhuis, Prabhu, Weniger, **SJW** (PRX, 2024)

Back-reaction



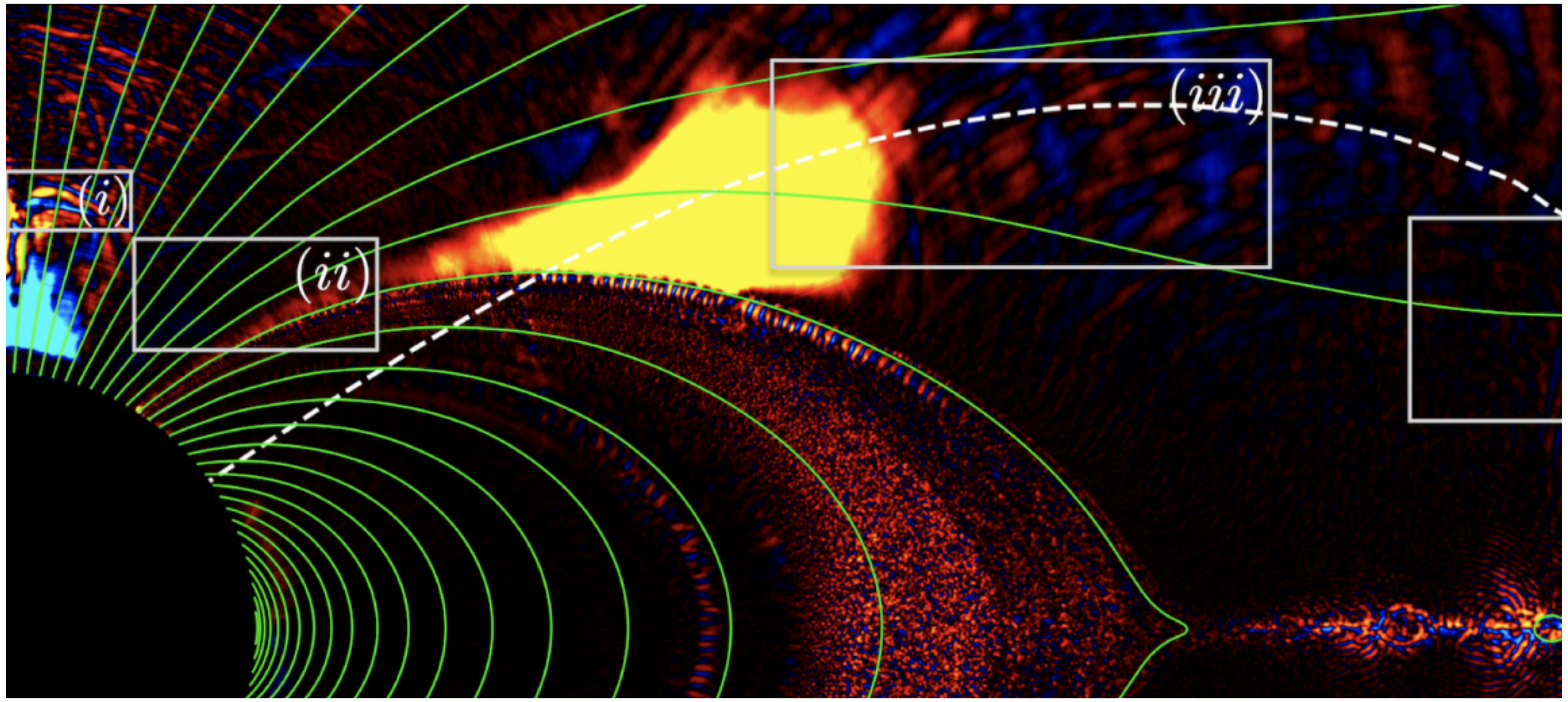
Dynamics governed by Maxwell's equations

… are axions still perturbative correction?

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

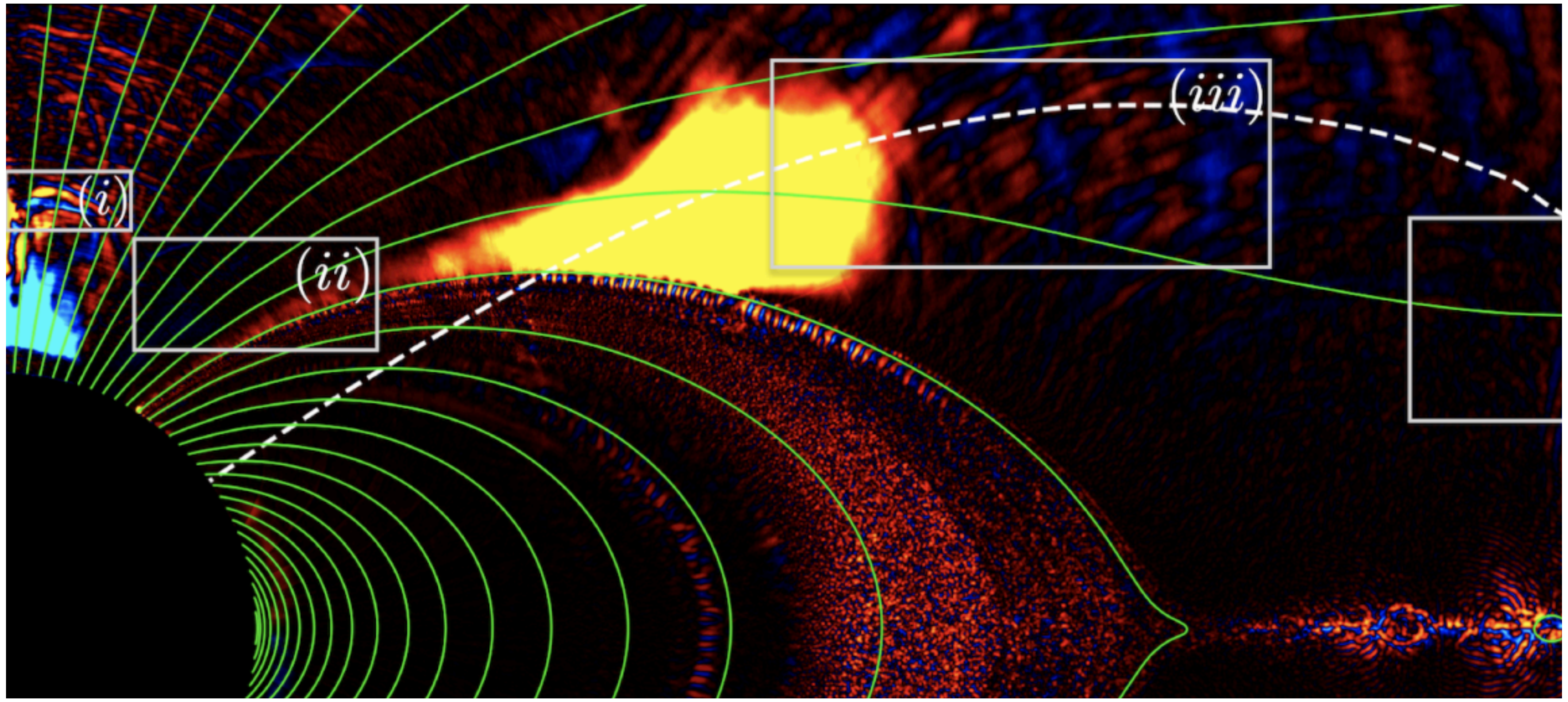
$$(\nabla \times B) - \partial_t E = j + g_{a\gamma}(B \partial_t a - E \times \nabla a)$$

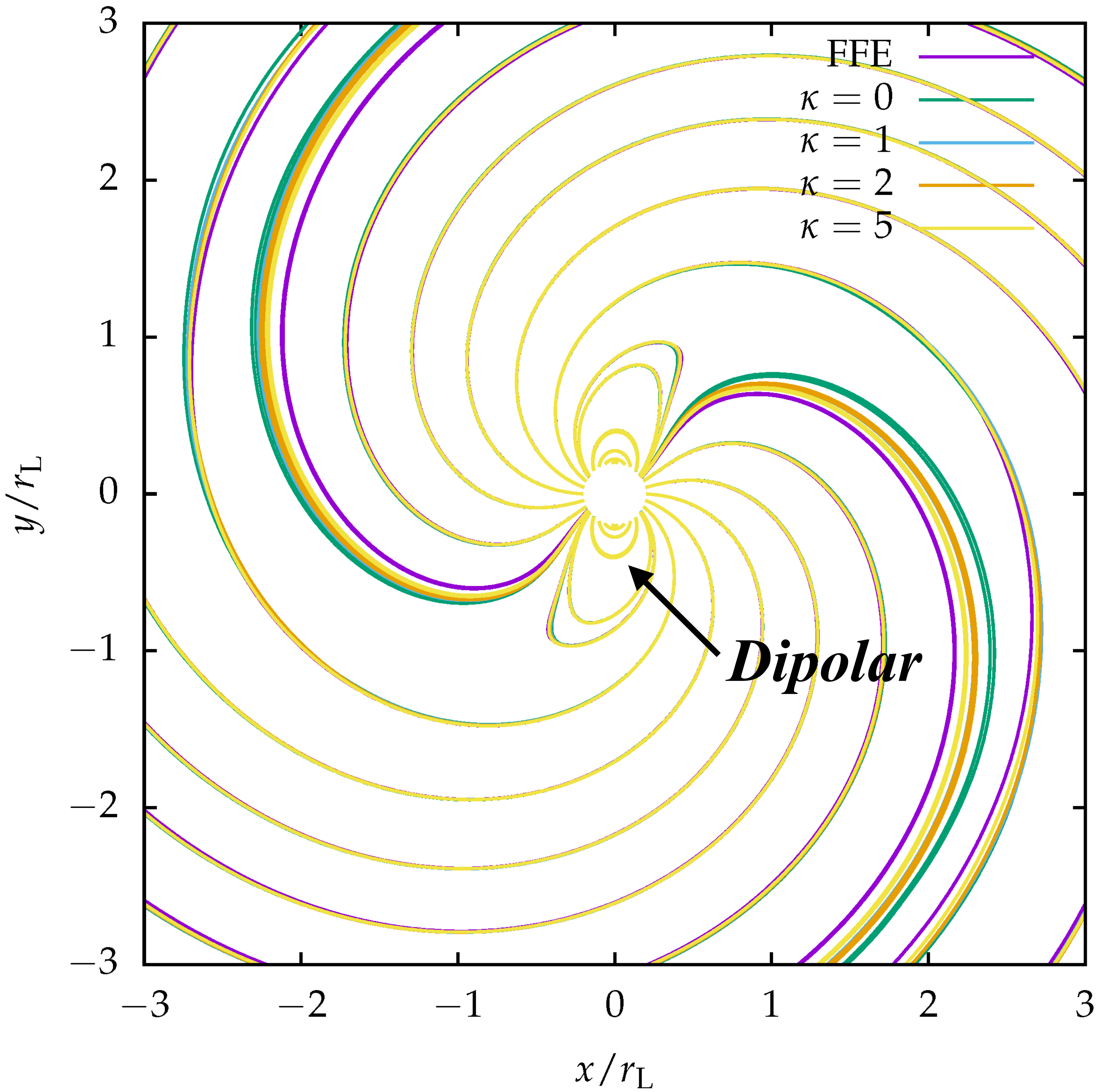
Toy example: electrostatics in 1D



See e.g. Belobodorov (2008), Timokhin & Arons (2013)

Toy example: electrostatics in 1D

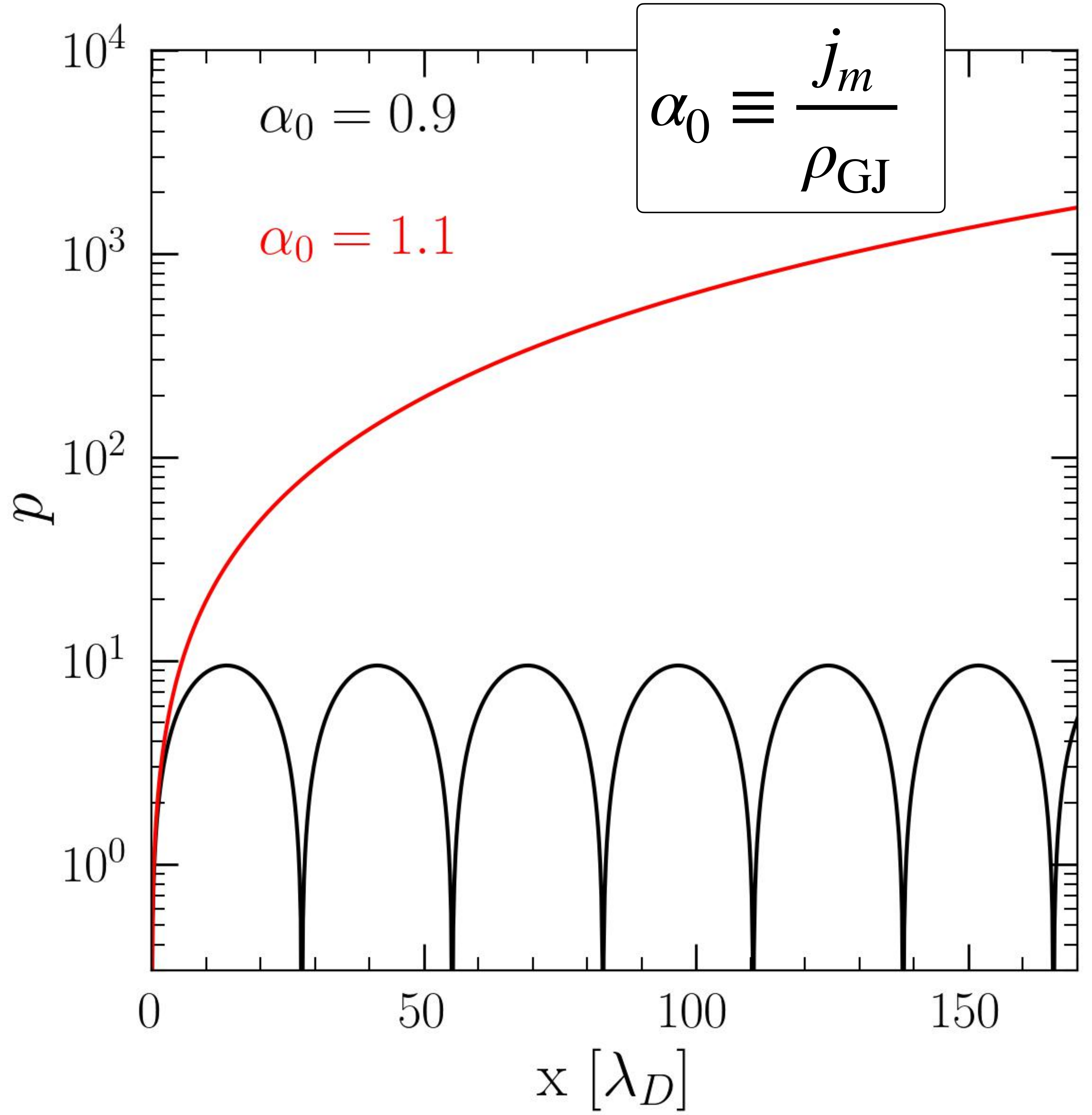




Twist forced on open field lines: $(\nabla \times B) = j_m$

See e.g. Timohkin & Arons (2012)

Toy example: electrostatics in 1D



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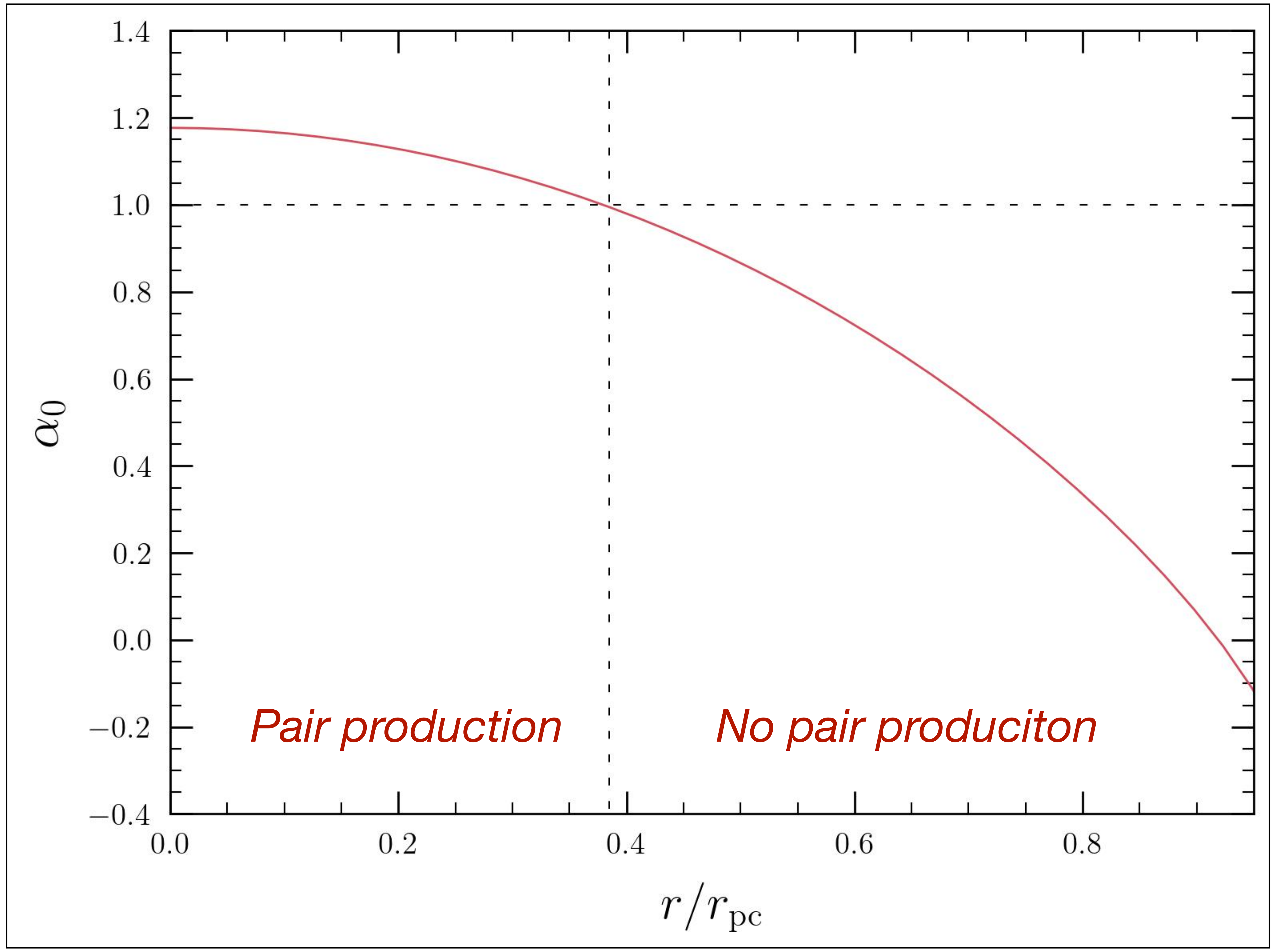

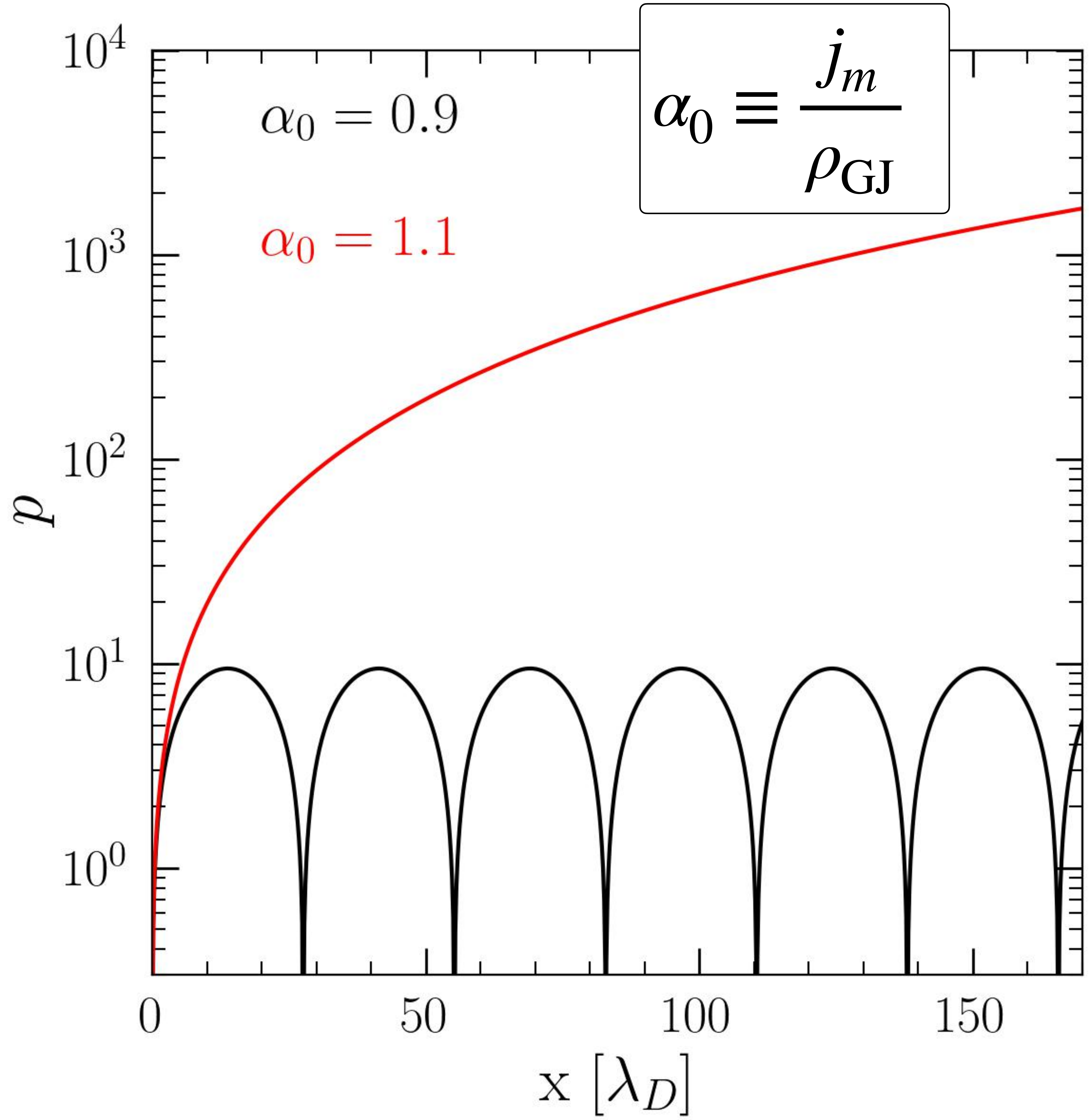

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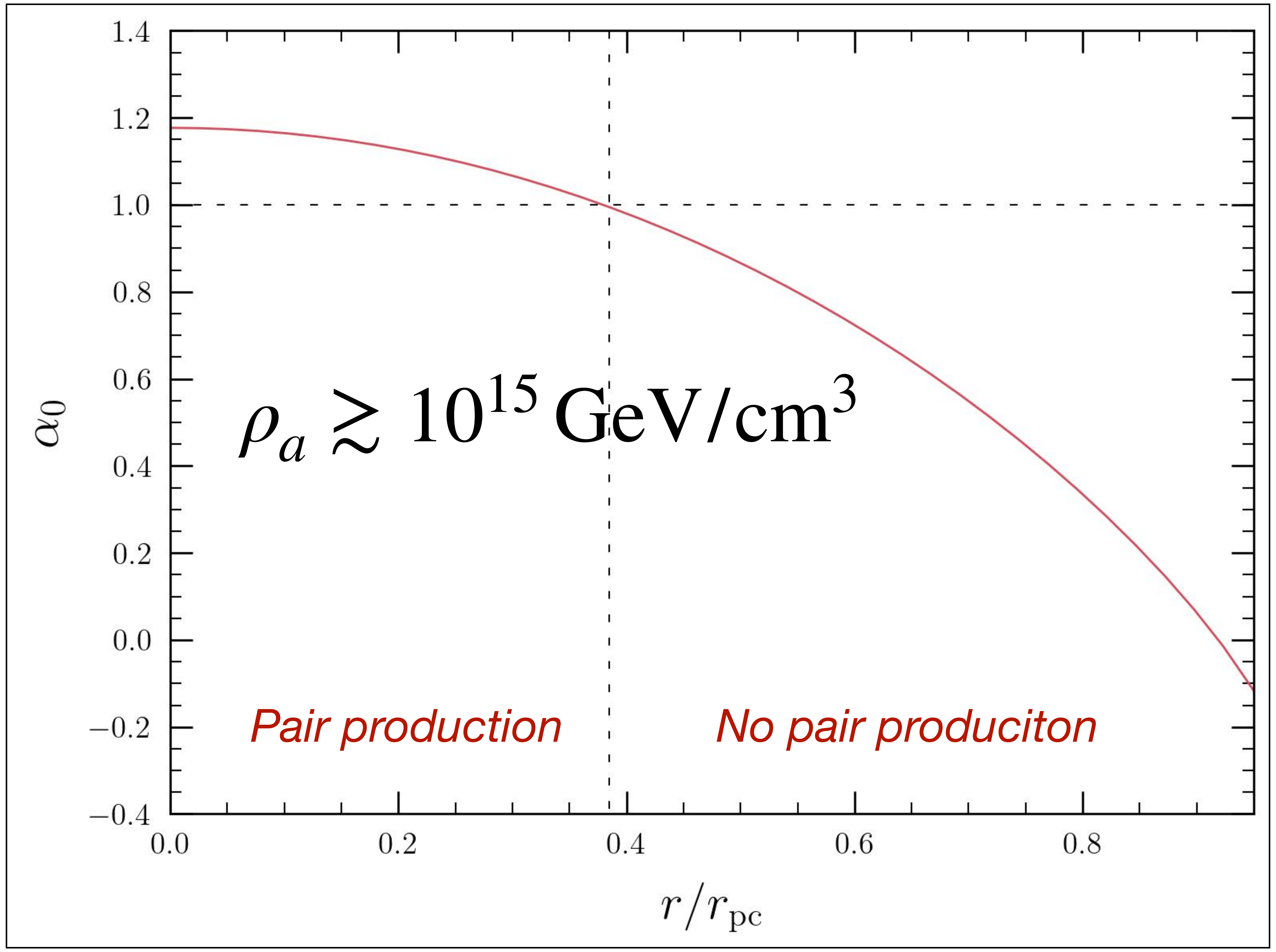
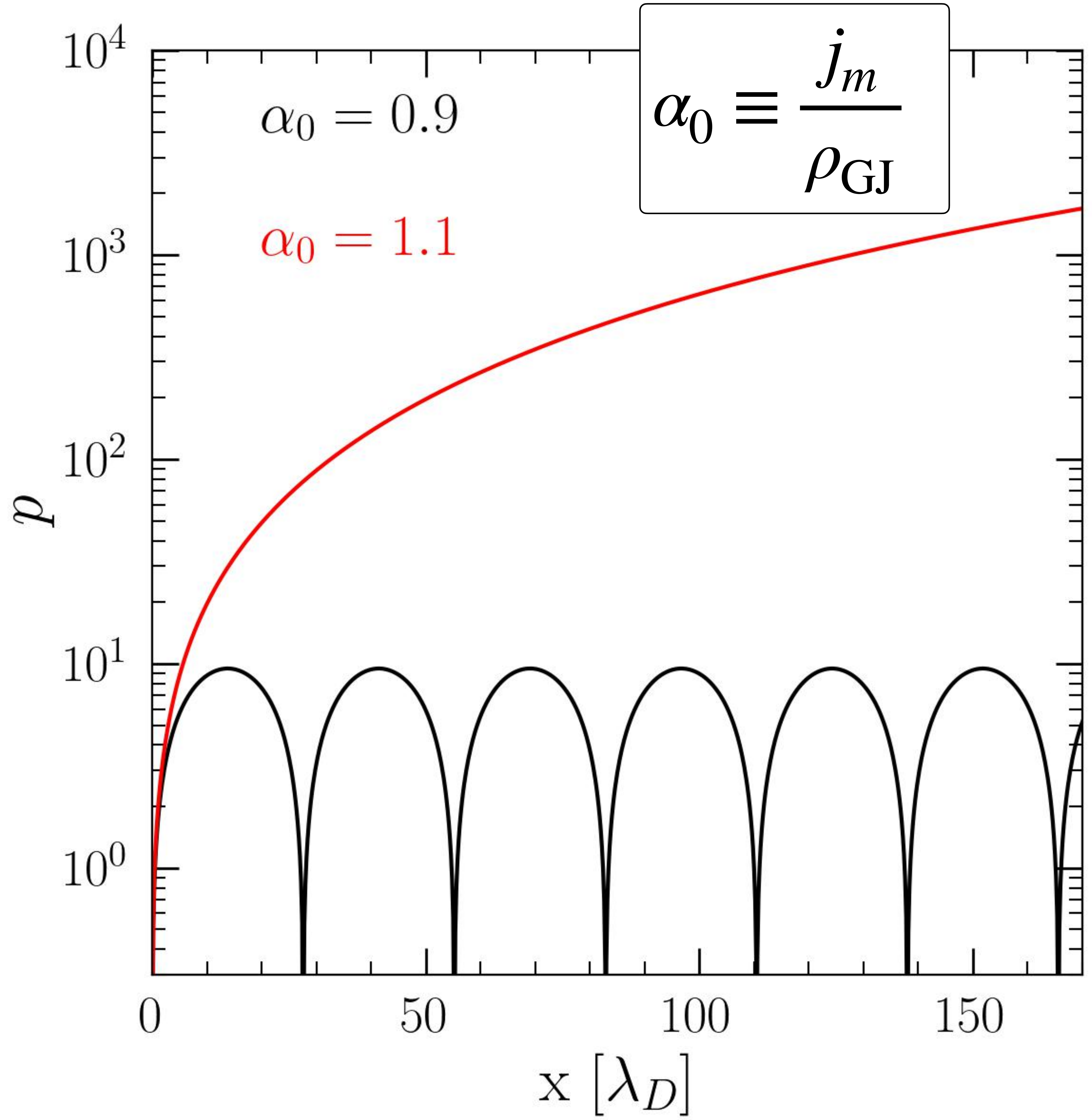
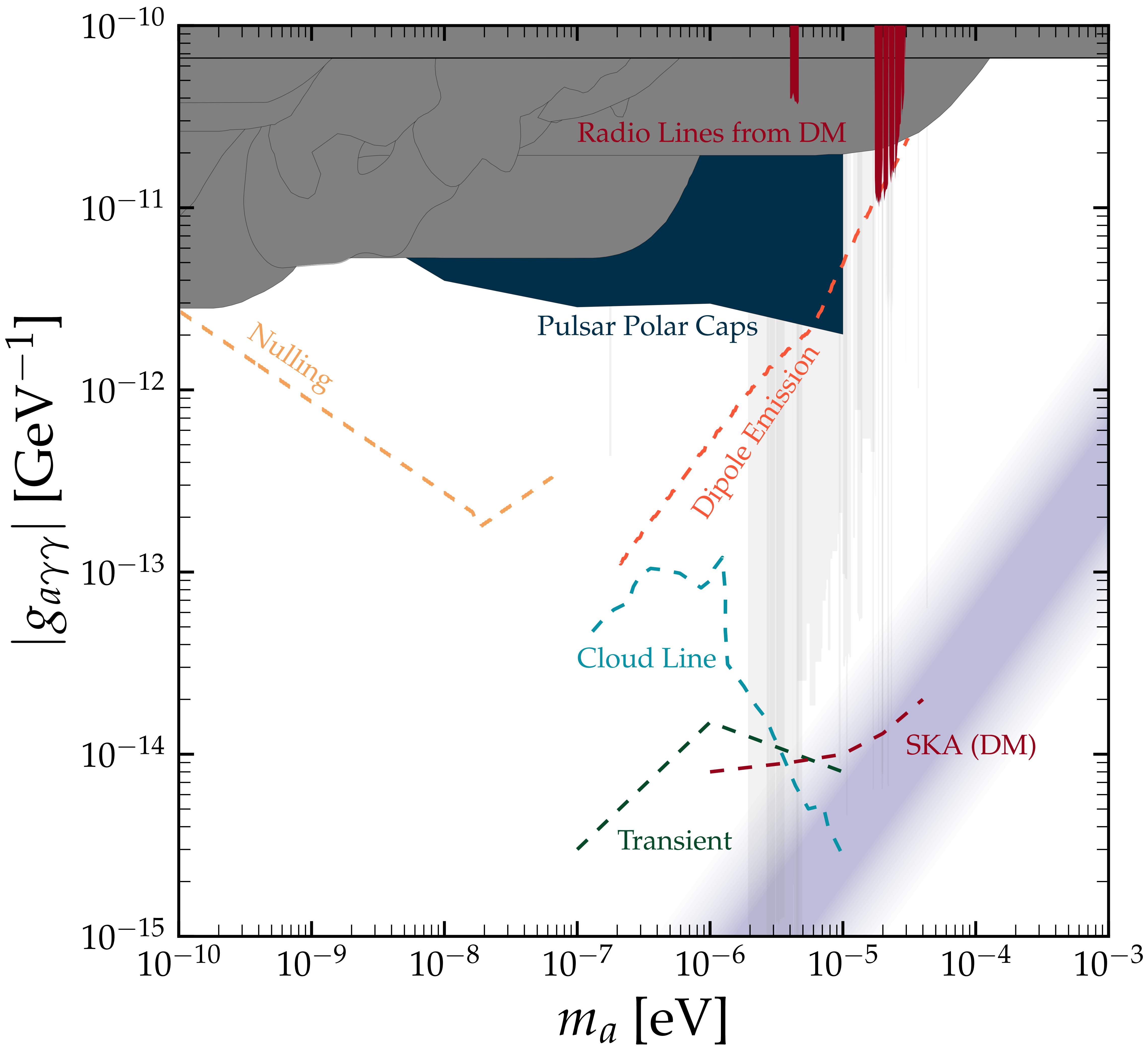


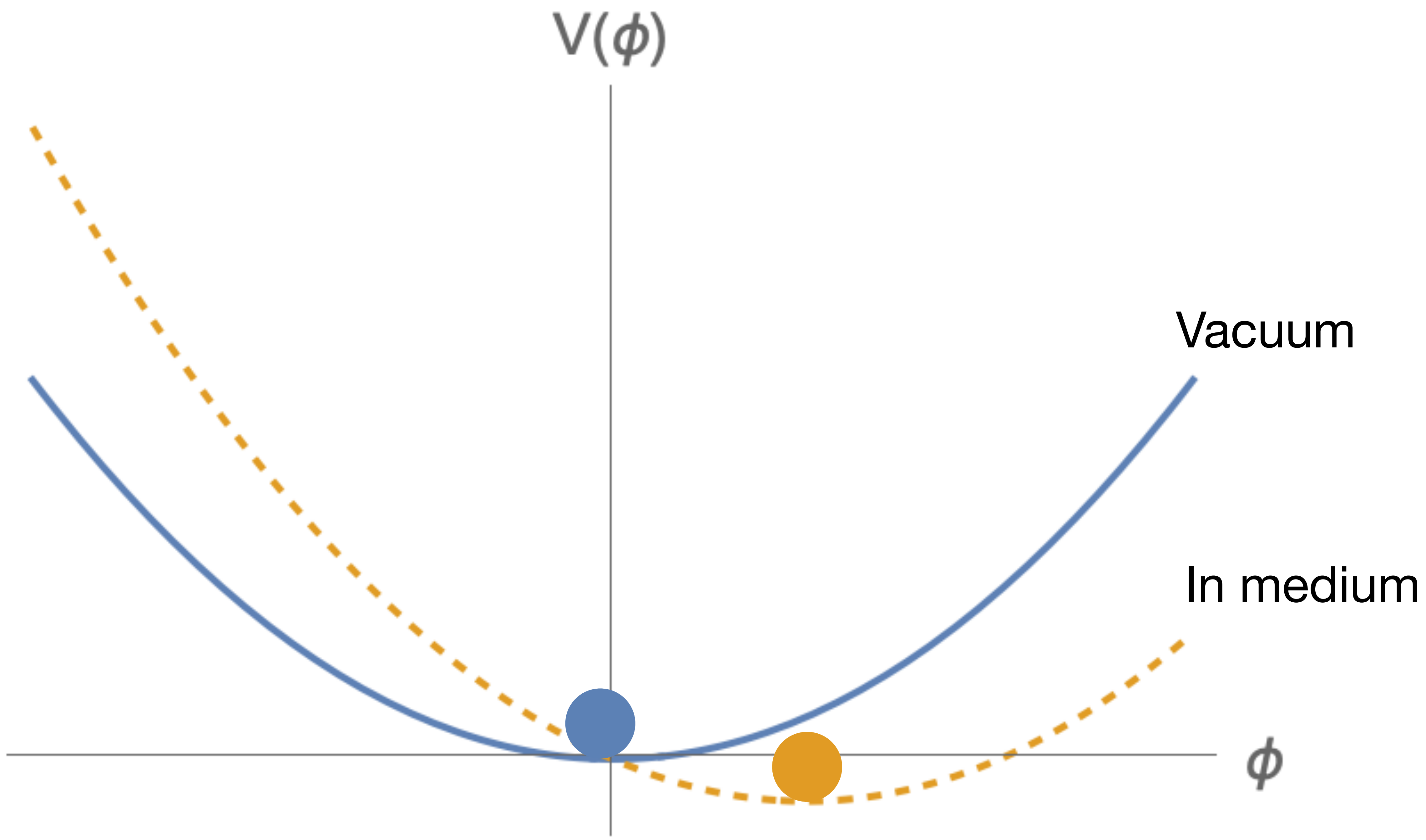


Axion clouds from the polar cap



Matter effects in neutron stars

$$\mathscr{L} \supset \frac{m_N}{f_a} \phi \, \bar{N} N$$



Matter effects in neutron stars

To the blackboard

Scalar gradients in stellar objects

See e.g. discussion in Balkin et al (2023)

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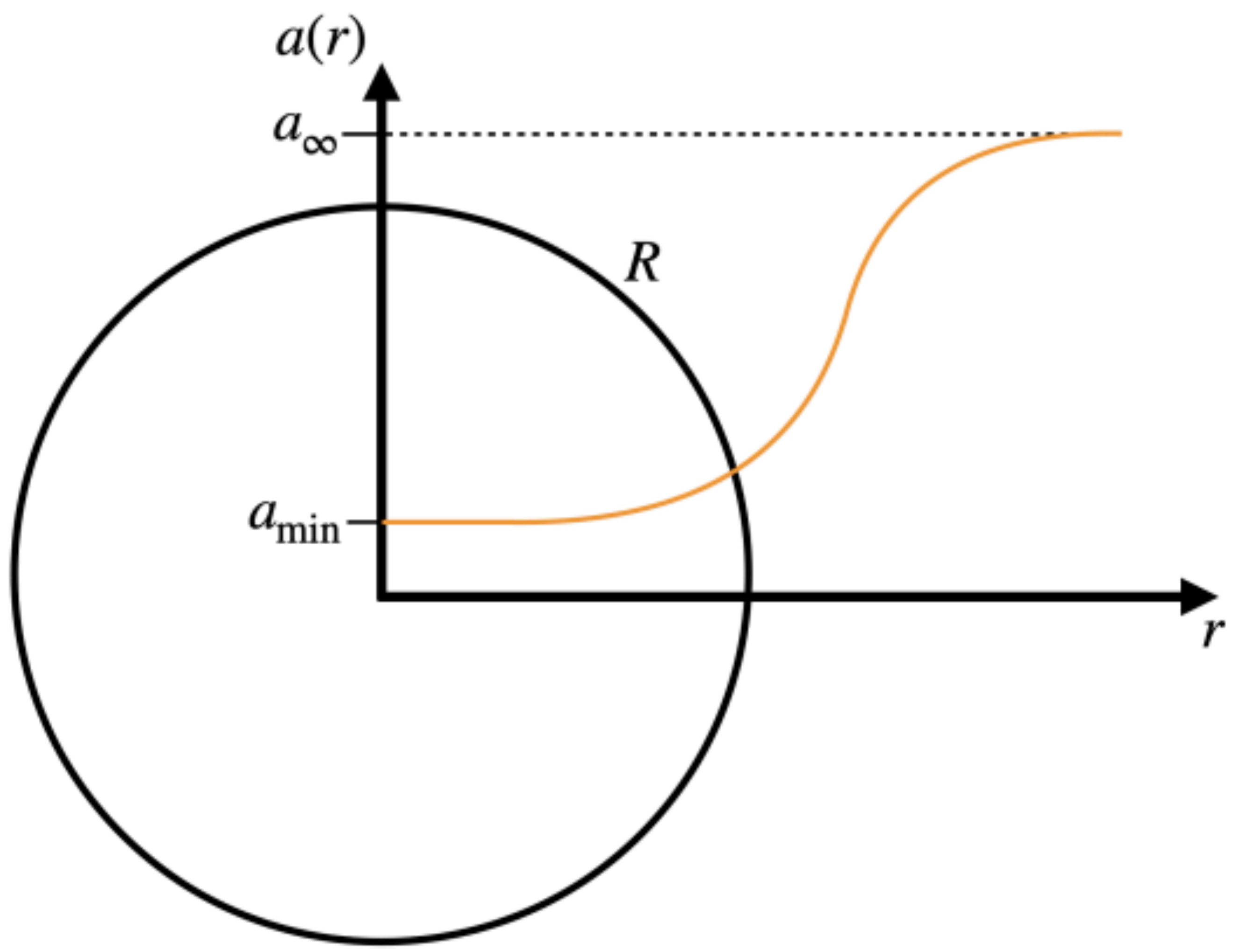


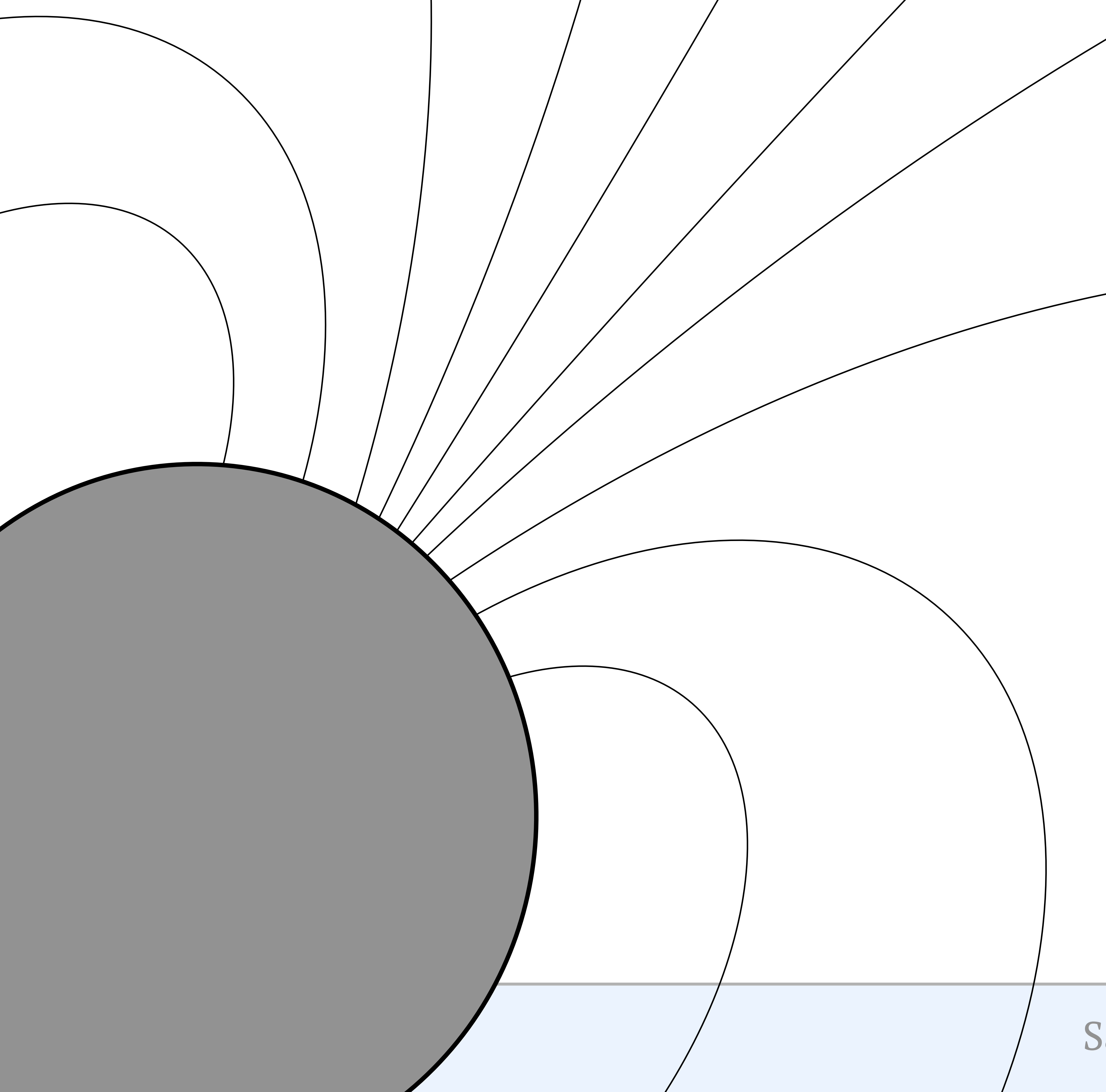
$$a(r) \sim a_0 \frac{r_*}{r} e^{-m_a(r-r_*)}$$

Figure credit: Ramadan et al (2024)

See e.g. discussion in Balkin et al (2023)

Contextualized: The light QCD axion

See e.g. Hook & Huang (2017), Hook(2018), Di Luzio et al (2021), Balkin et al (2021,2022, 2023), Gomez-Banon et al (2024), Kumaoto, Huang, Drischler, Baryakhtar, Reddy (2024)



$$\mathscr{L} \supset \; + \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G \tilde{G}$$

Nucleon coupling

$$V_{NN} \propto - \langle \bar{N} N \rangle \, V_{\rm vac}$$

Standard Potential

$$V_{\rm vac} \simeq - m_\pi^2 f_\pi^2 \left[\sqrt{1 - z^2 \sin^2 \frac{a}{2f_a}} - 1 \right]$$

Dense medium can flip potential!

Static axion configurations

Observables

- Destabilize star

  Ramadan, Sakstein, Croon (2024)

$$\delta m_N / m_N \gtrsim 1$$

- Long-range forces

  Hook & Huang (2017)

- Modification to equation of state

  Balkin et al (2021,2022, 2023), Kumaoto, Huang, Drischler, Baryakhtar, Reddy (2024)

- Cooling rate (via envelope thickness)

  Gomez-Banon et al (2024)

- Mass distribution in crust (related to glitching)

  Kumaoto, Huang, Drischler, Baryakhtar, Reddy (2024)

- *Electrodynamics of magnetosphere*

  Caputo, Philippov, Rajendran, Stelzl, **SJW** (In progress)

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$$V \sim -q_{\text{eff}}^2 e^{-m_a r}/r$$

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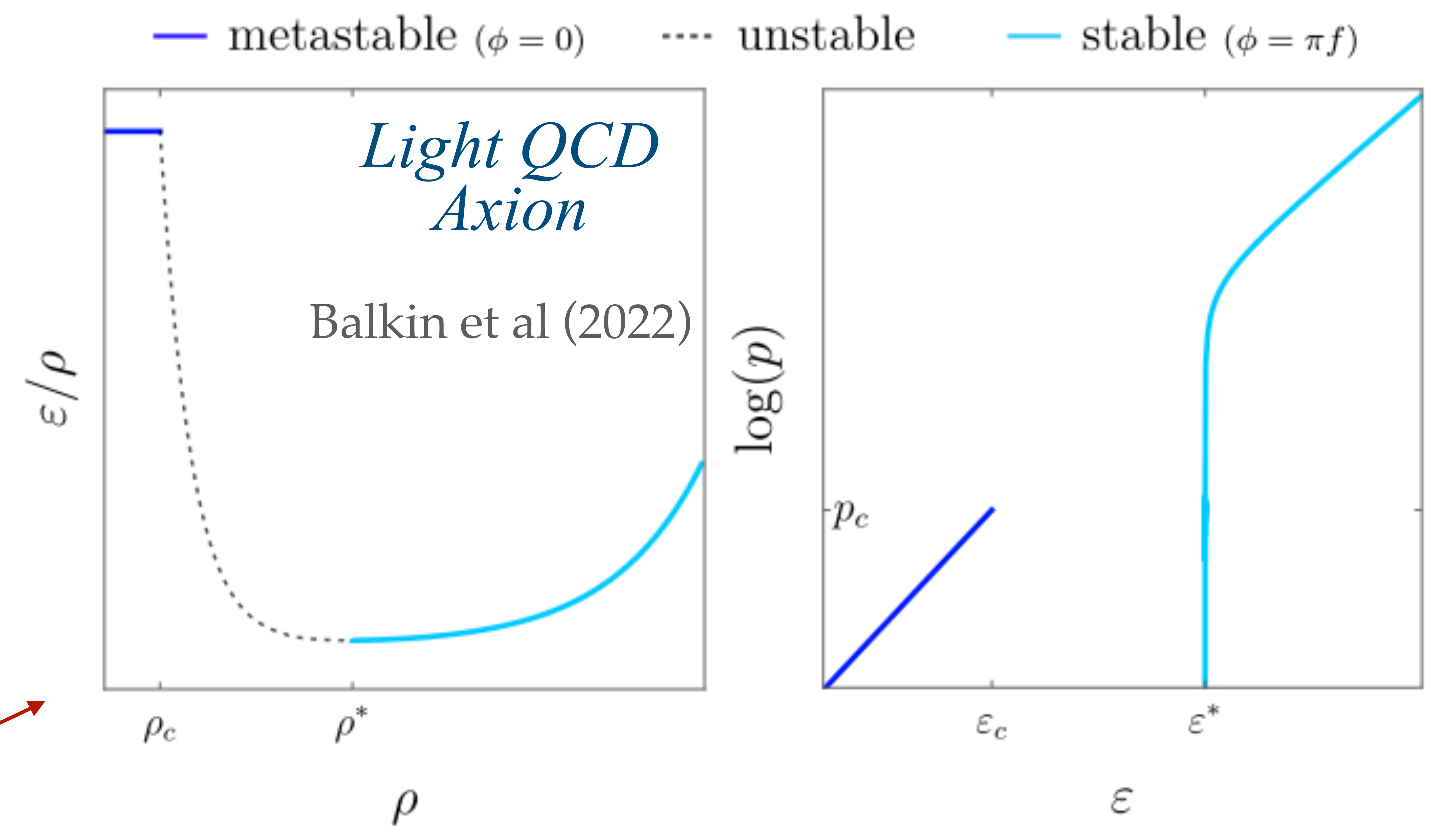

Static axion configurations

Observables

- Destabilize star

  Ramadan, Sakstein, Croon (2024)

$$\delta m_N / m_N \gtrsim 1$$

- Long-range forces

  Hook & Huang (2017)

$$V \sim -\, q_{\rm eff}^2 e^{-m_a r}/r$$

- Modification to equation of state

  Balkin et al (2021,2022, 2023), Kumaoto, Huang, Drischler, Baryakhtar, Reddy (2024)

- Cooling rate (via envelope thickness)

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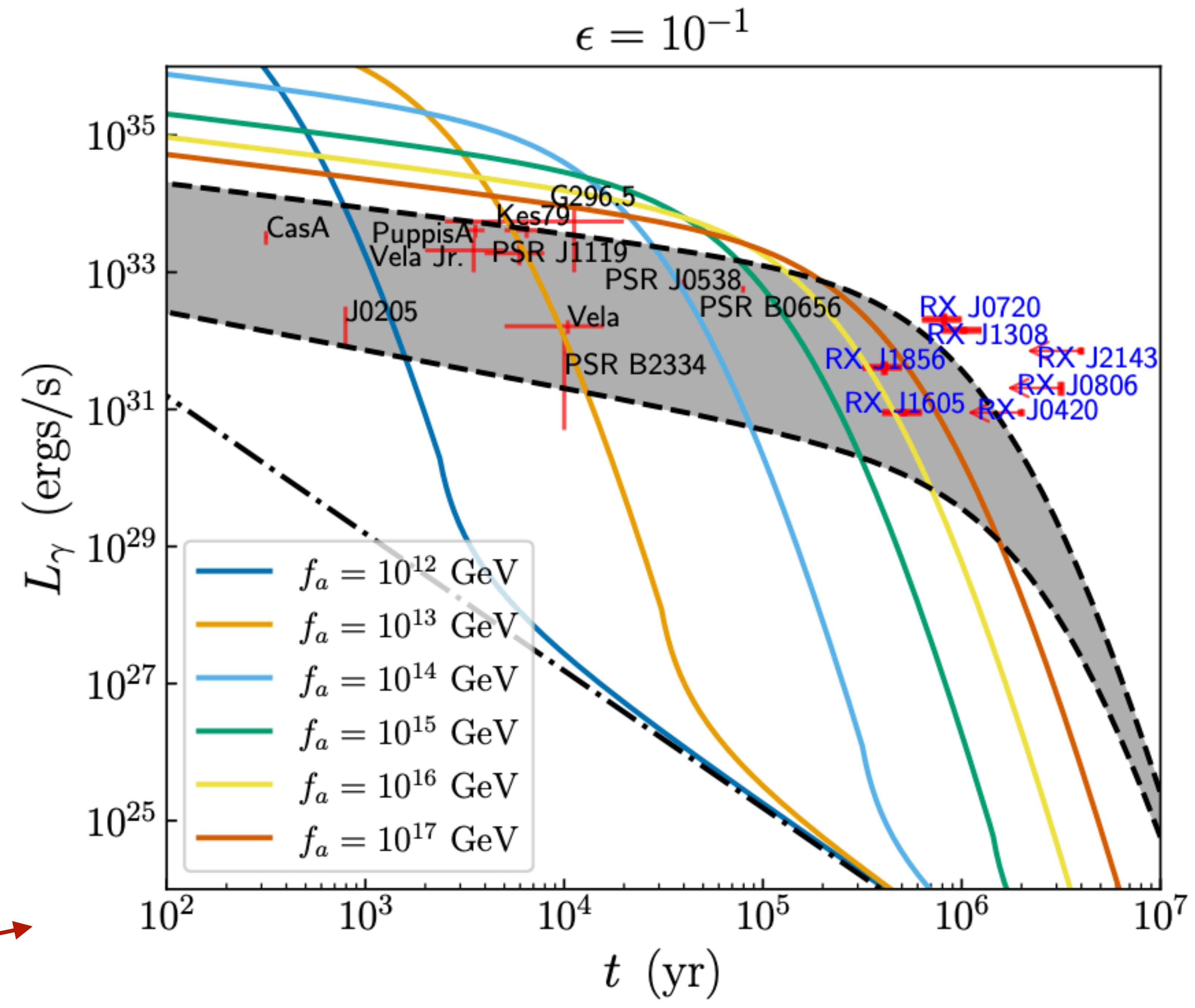

- Mass distribution in crust (related to glitching)

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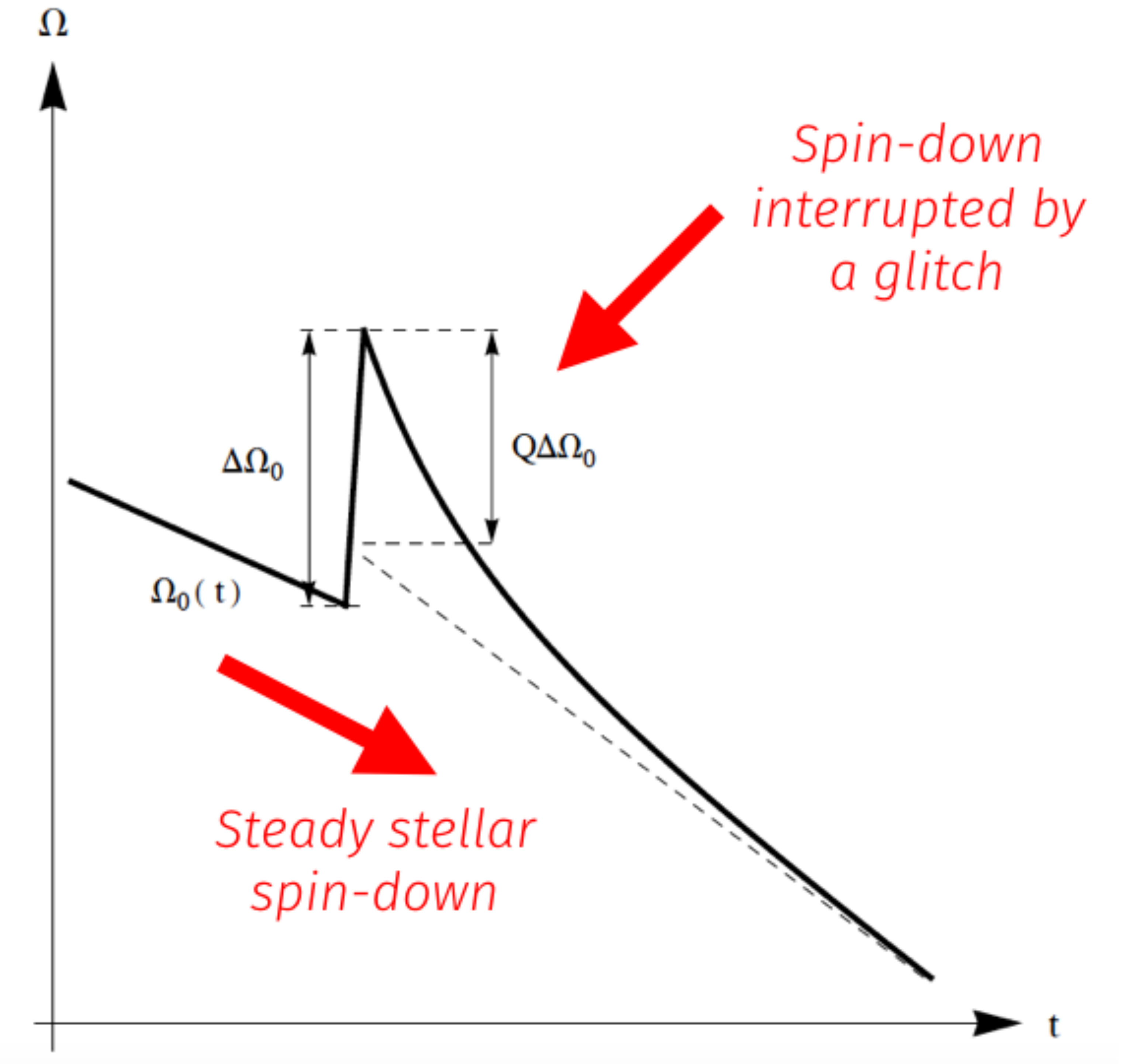

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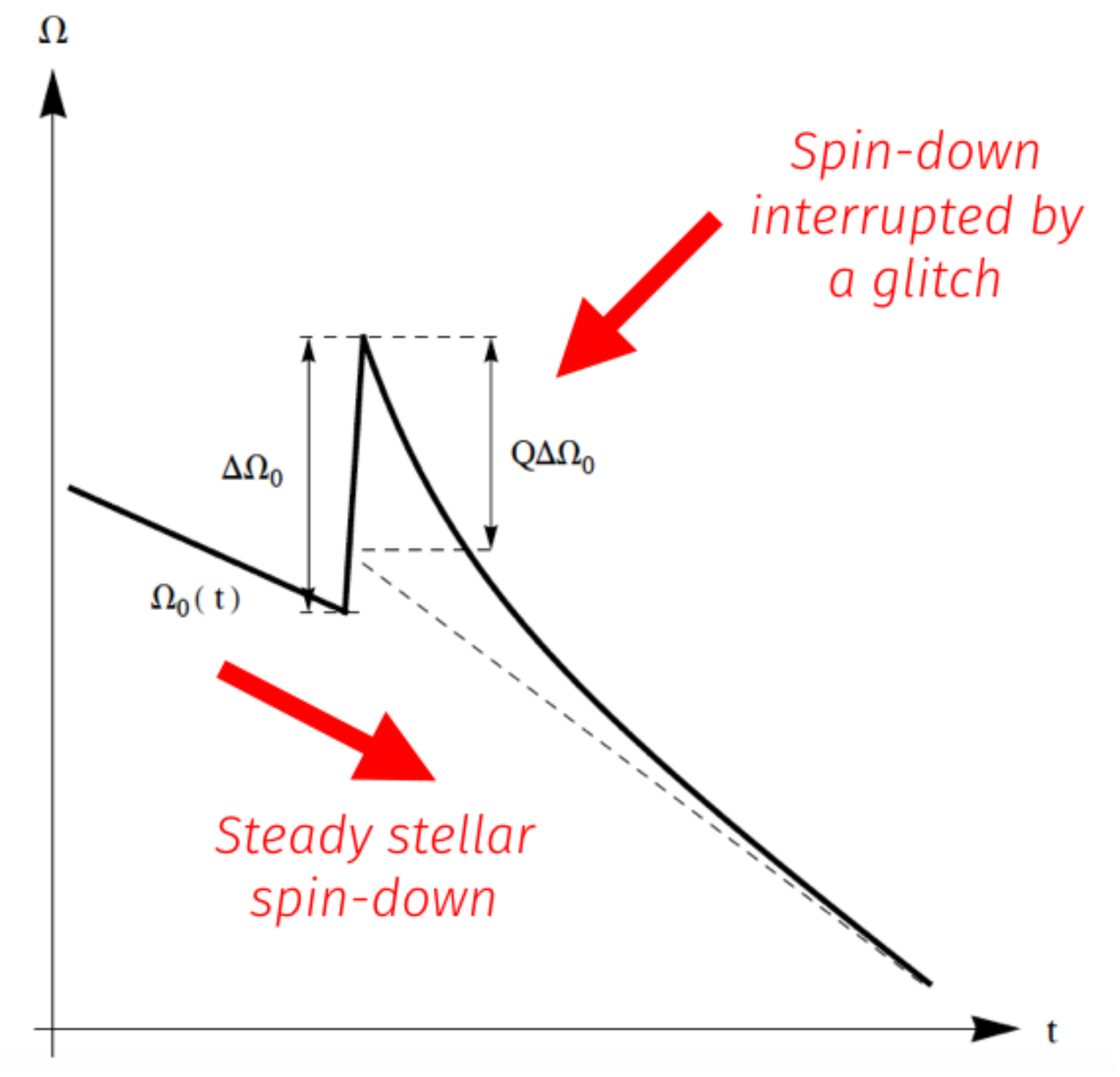
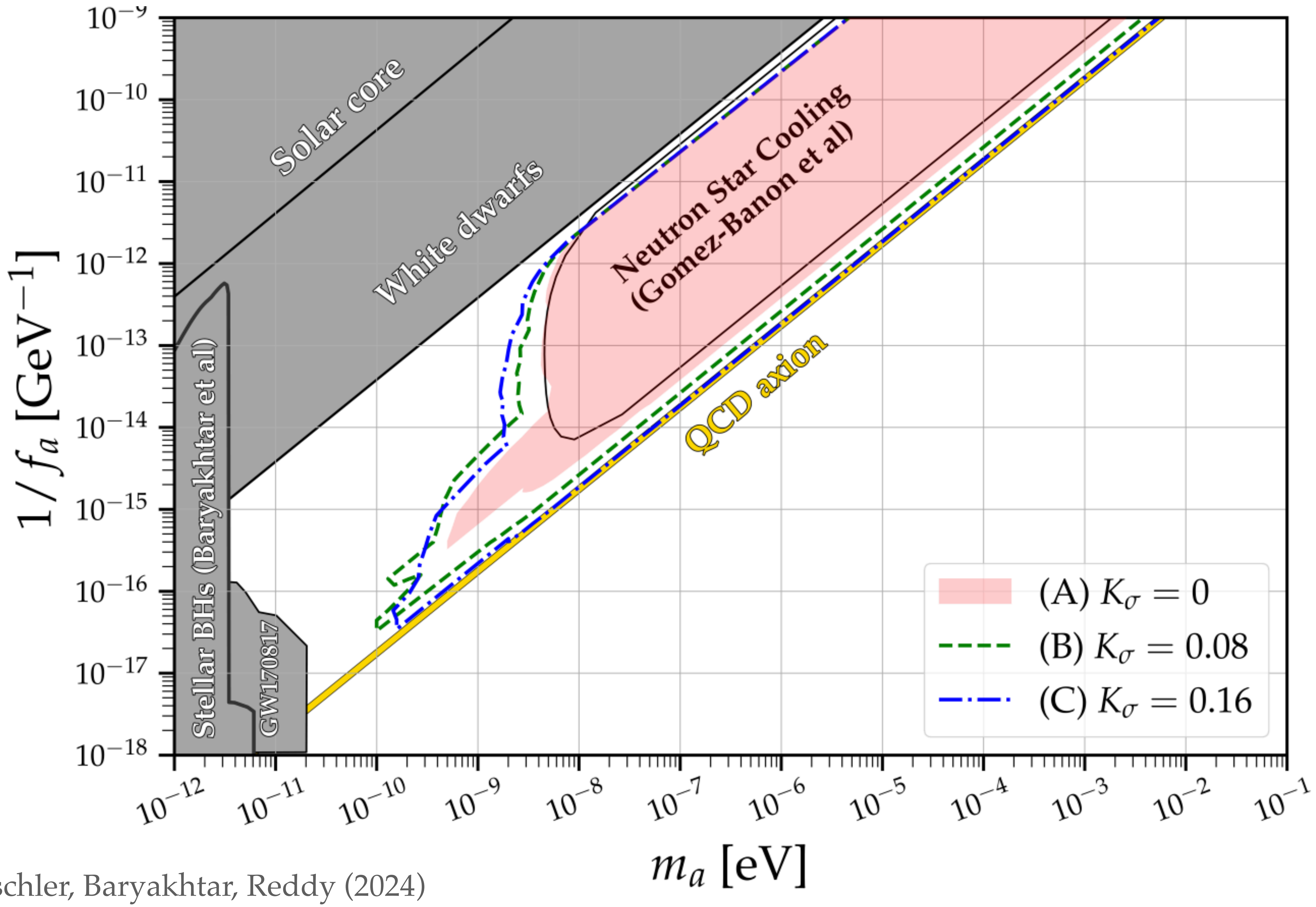


$$\nabla \cdot E = \rho + gB \cdot \nabla a$$

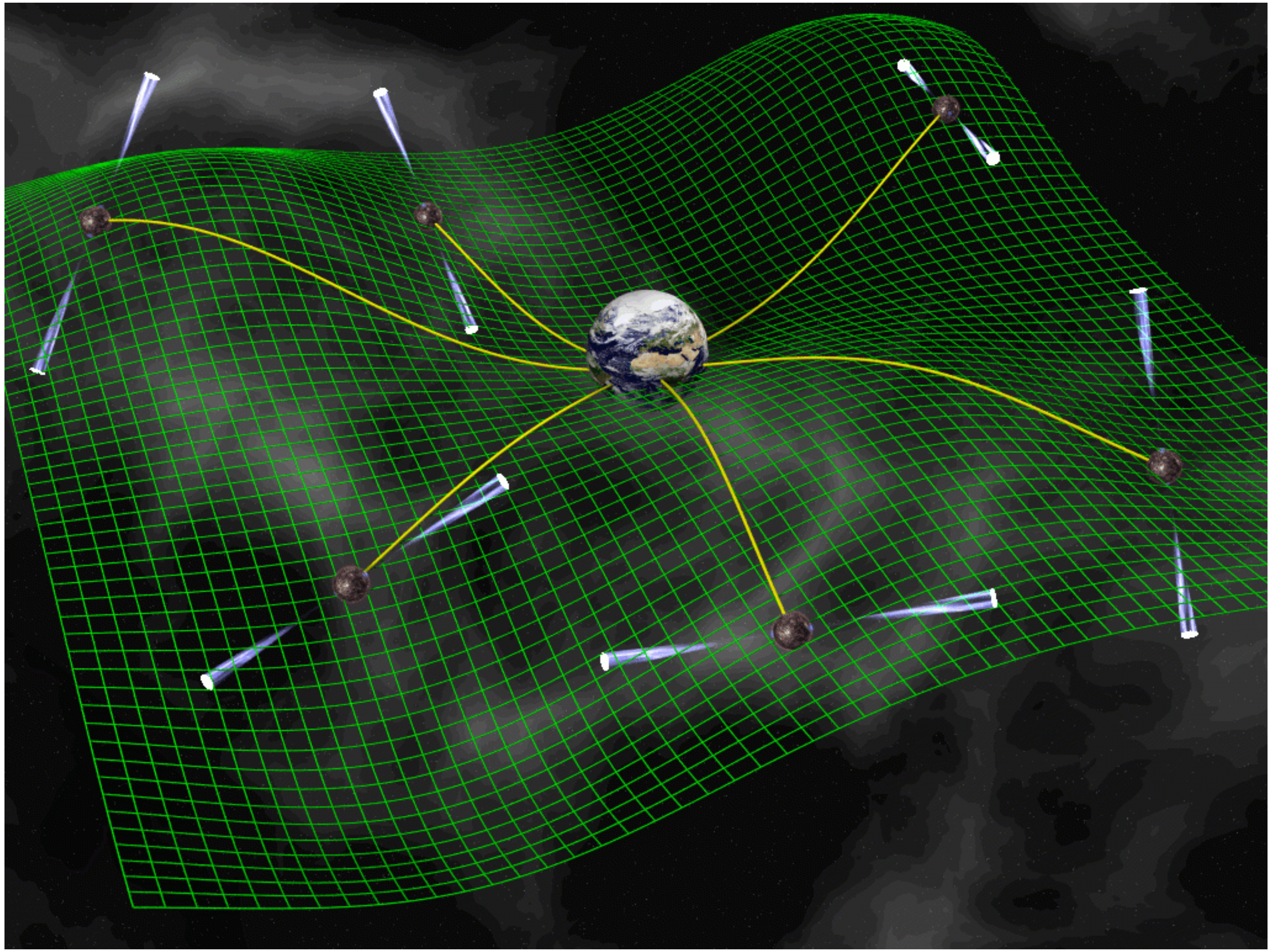
Electric field sourced by axion can dominate, de-correlating pair production from pulsar properties

Constraints on Light QCD axion



Kumaoto, Huang, Drischler, Baryakhtar, Reddy (2024)

Millisecond pulsars as probes of GWs

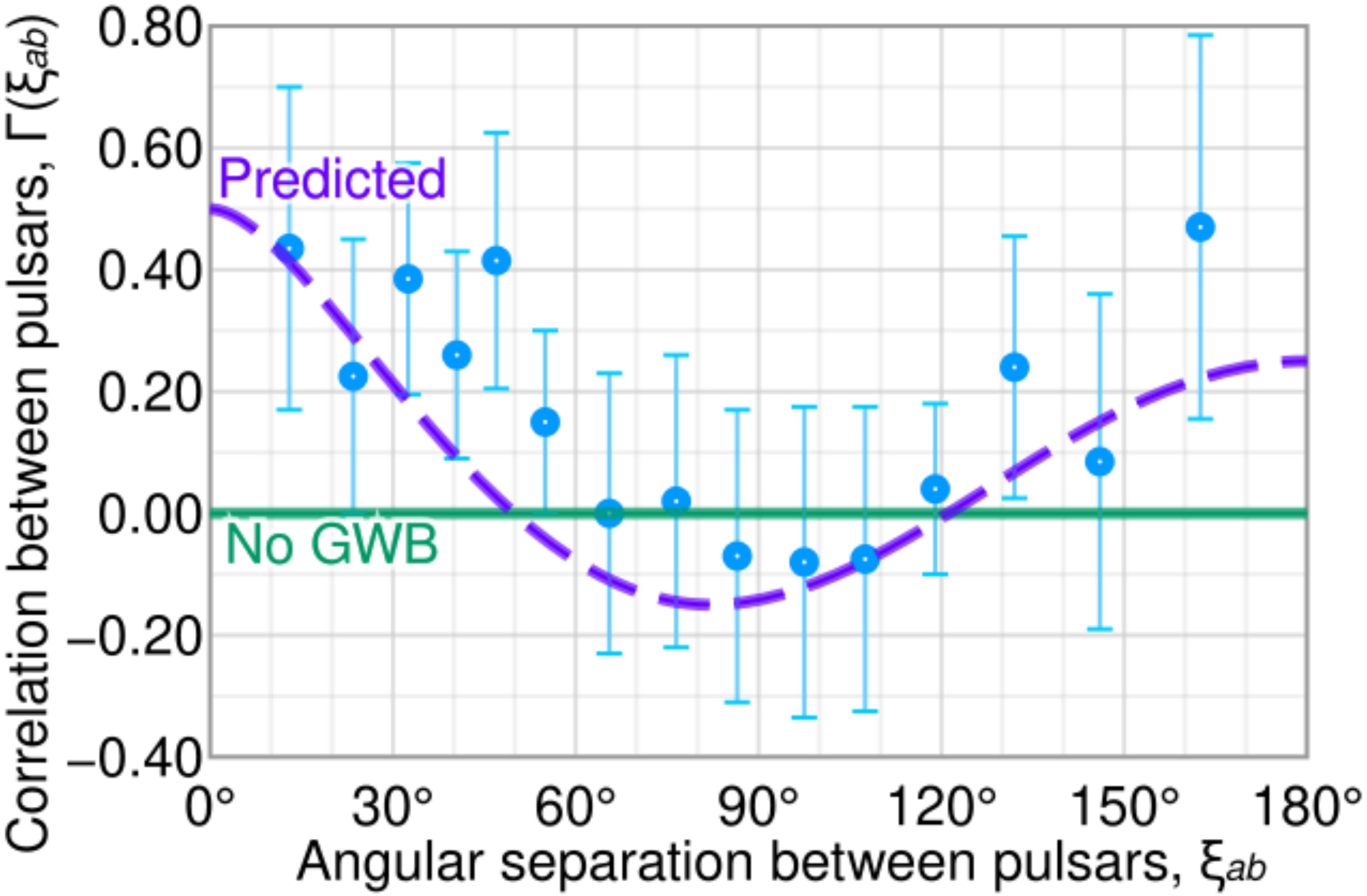


Long wavelength gravitational waves induce oscillating effects along the baseline

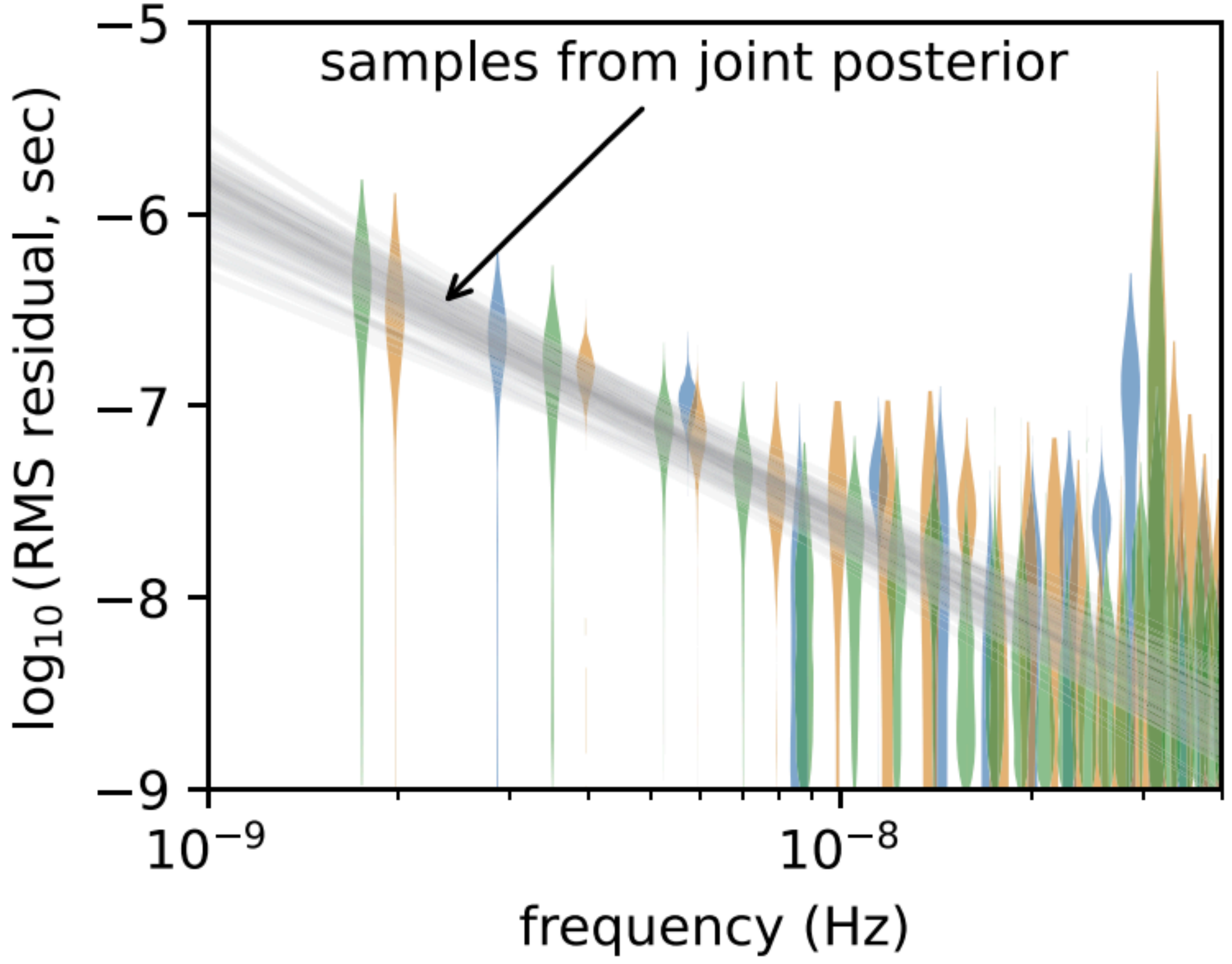
Ideal for probing nHz-scale freq

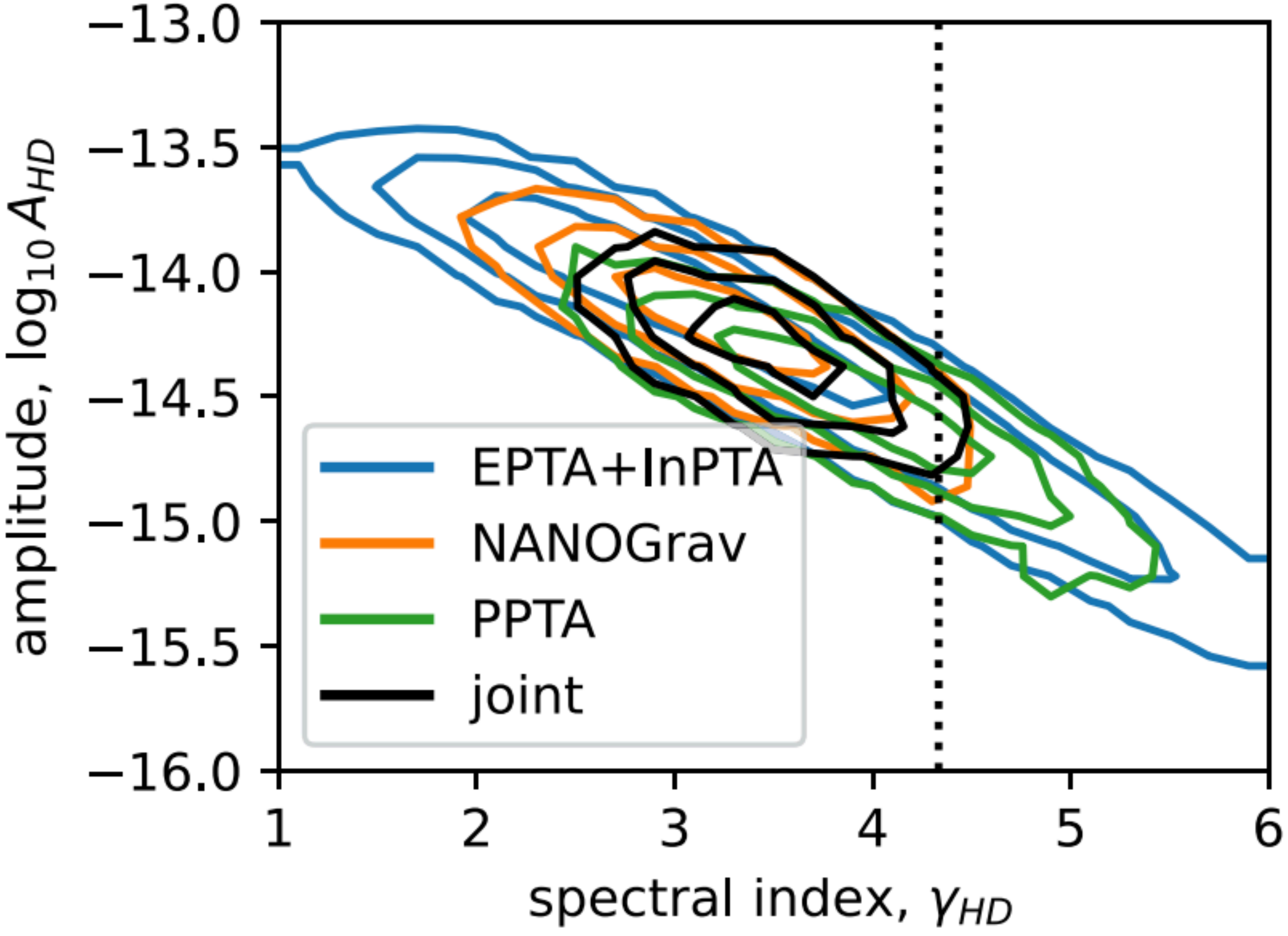
The Hellings-Downs Curve

Well defined spatial correlation predicted from stochastic backgrounds



The observed stochastic GW background at nHz





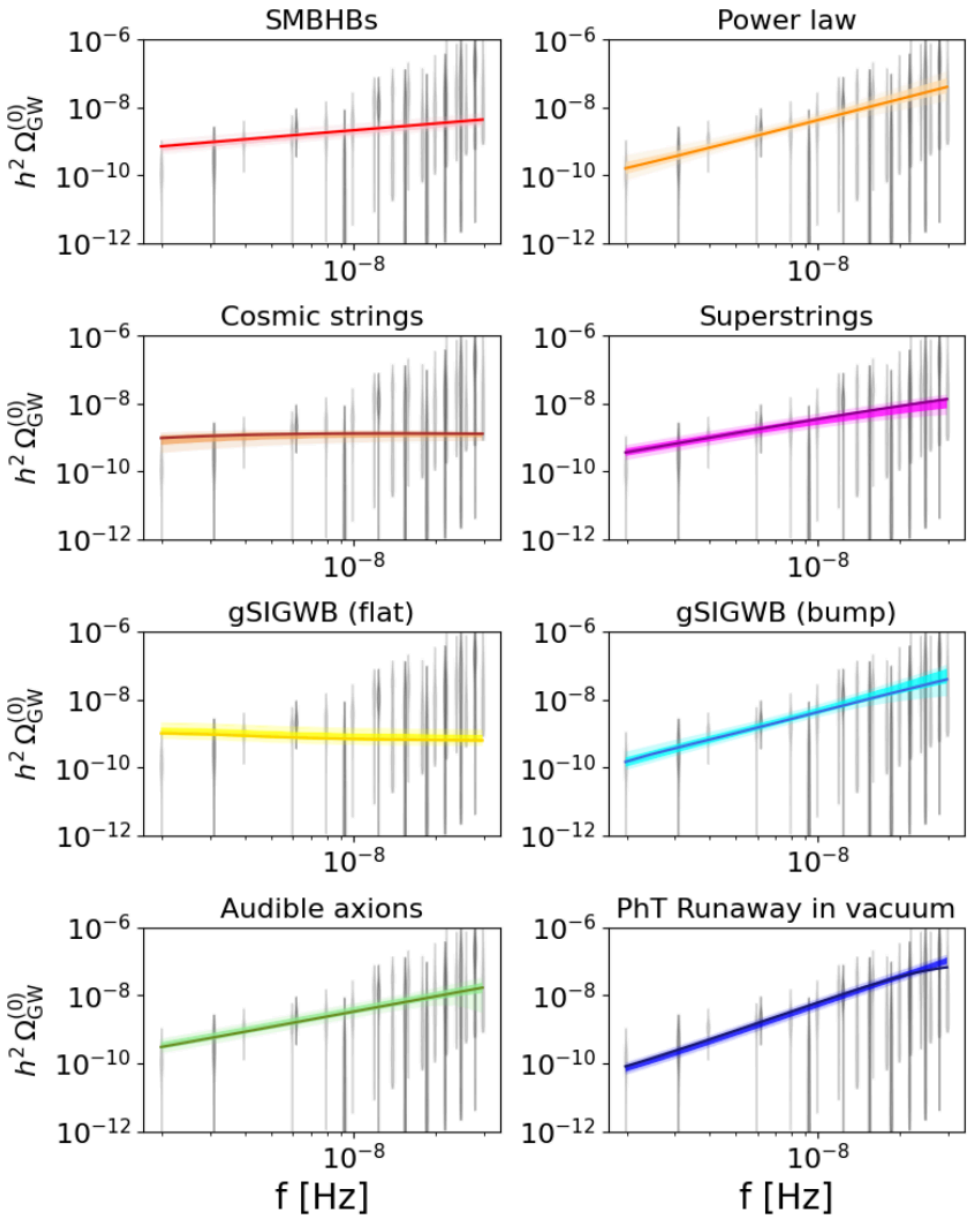
Agazie et al (2024)

Figueroa et al (2023)

Interpretations of PTA Signal

Most likely to be caused by merging supermassive black holes

But amplitude and spectrum not perfect fit to current modeling, leaving open the possibility of new physics



<u>Possible sources include:</u>

- Non-minimal inflation
- Phase transitions
- Decaying topological defects
- Enhanced scalar perturbations
- …

See e.g. 2306.16219 (NanoGrav)