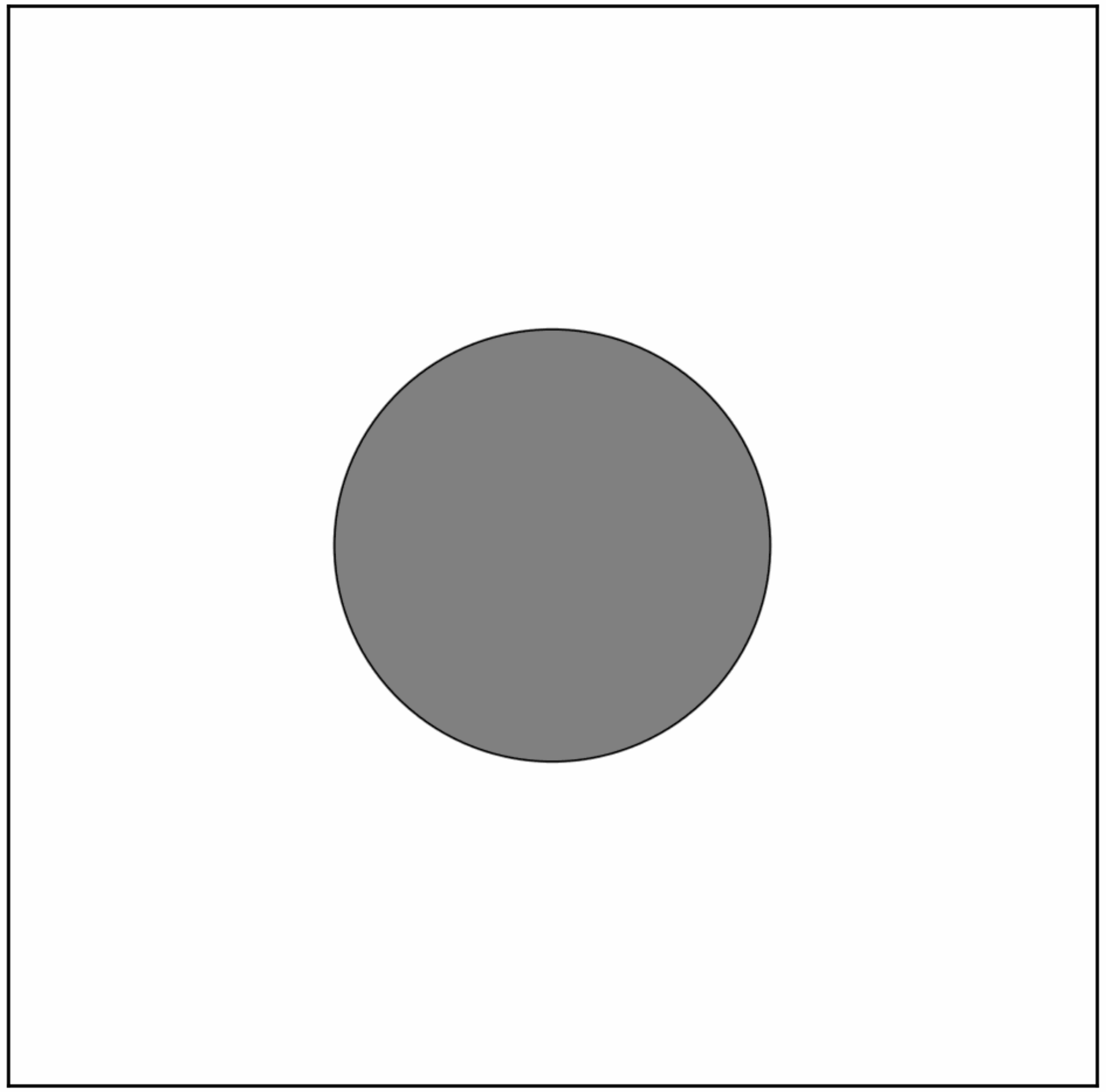
Neutron Stars as Axion Laboratories

Samuel J. Witte



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September 10, 2025

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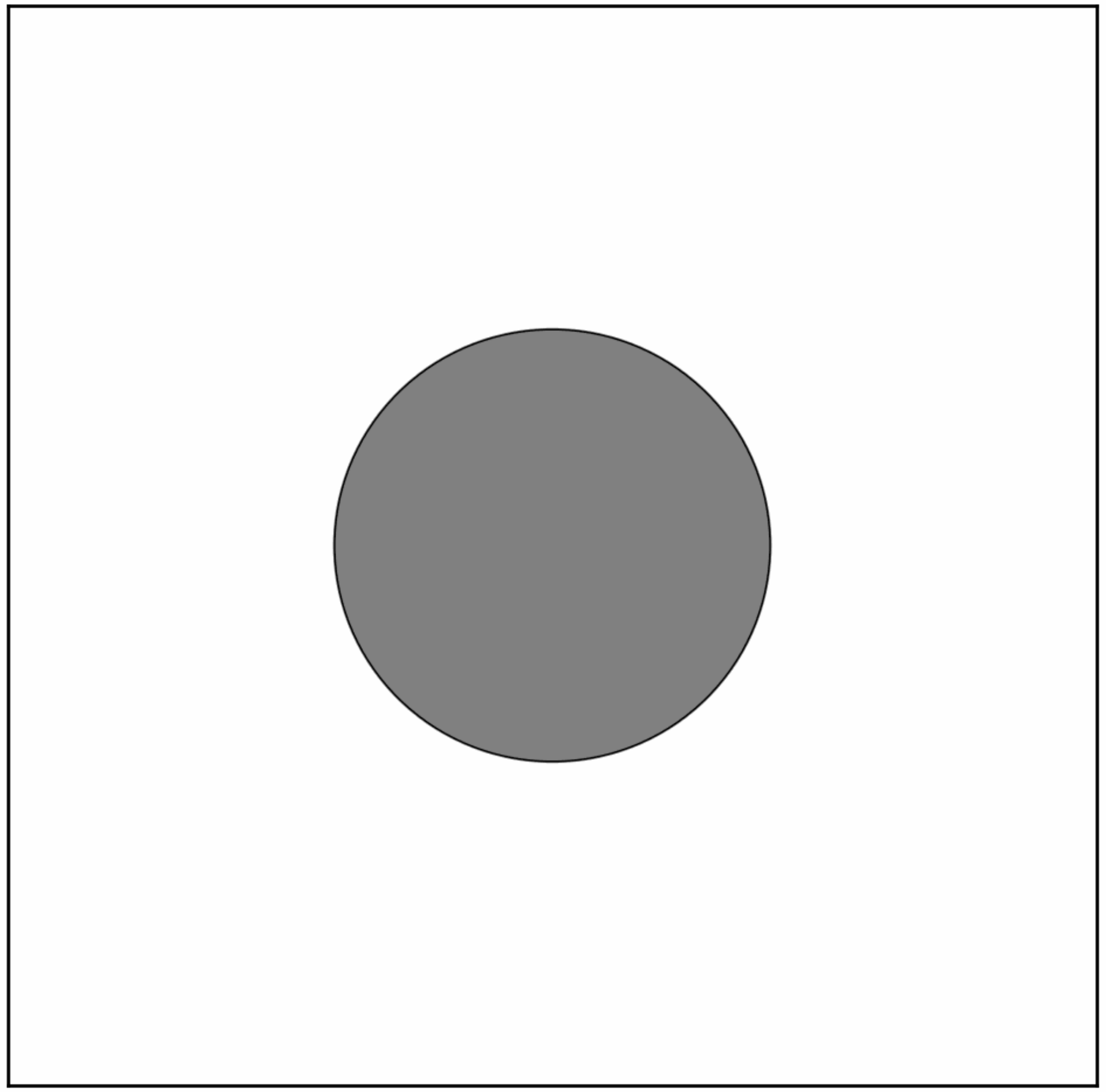

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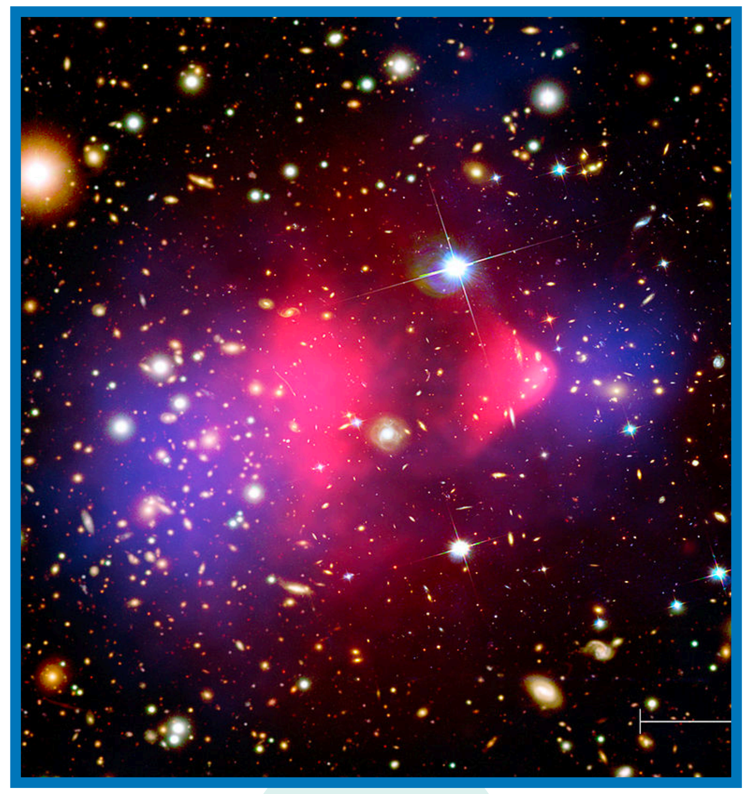
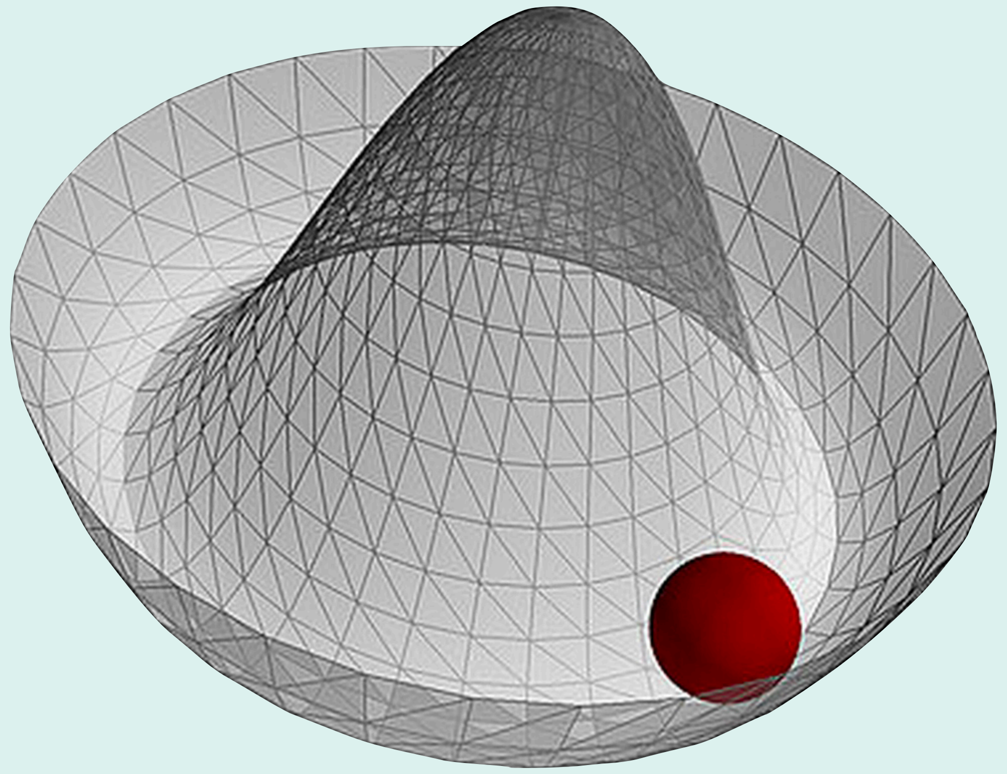
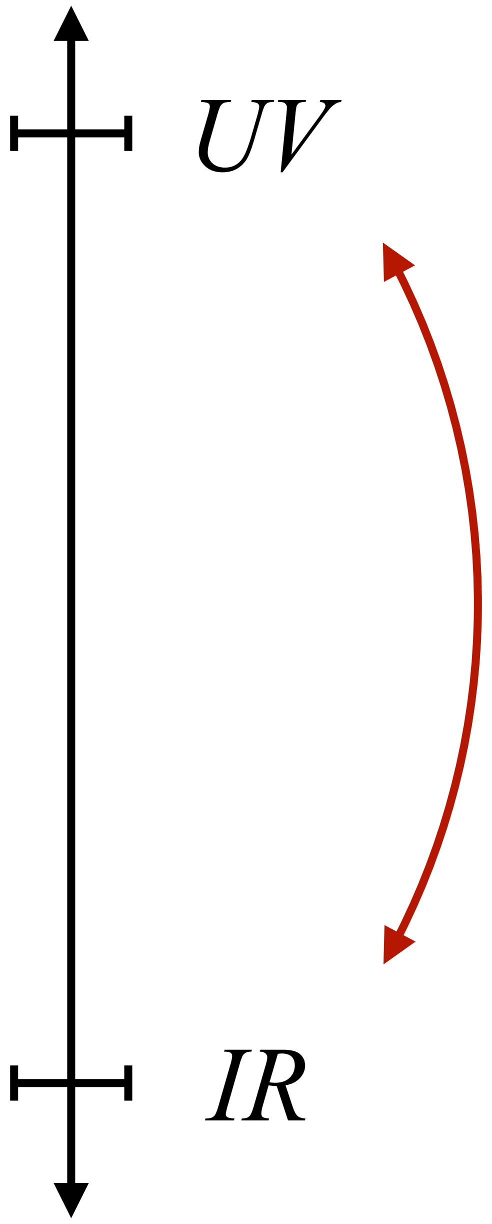
Why axions?



Axions as dark matter

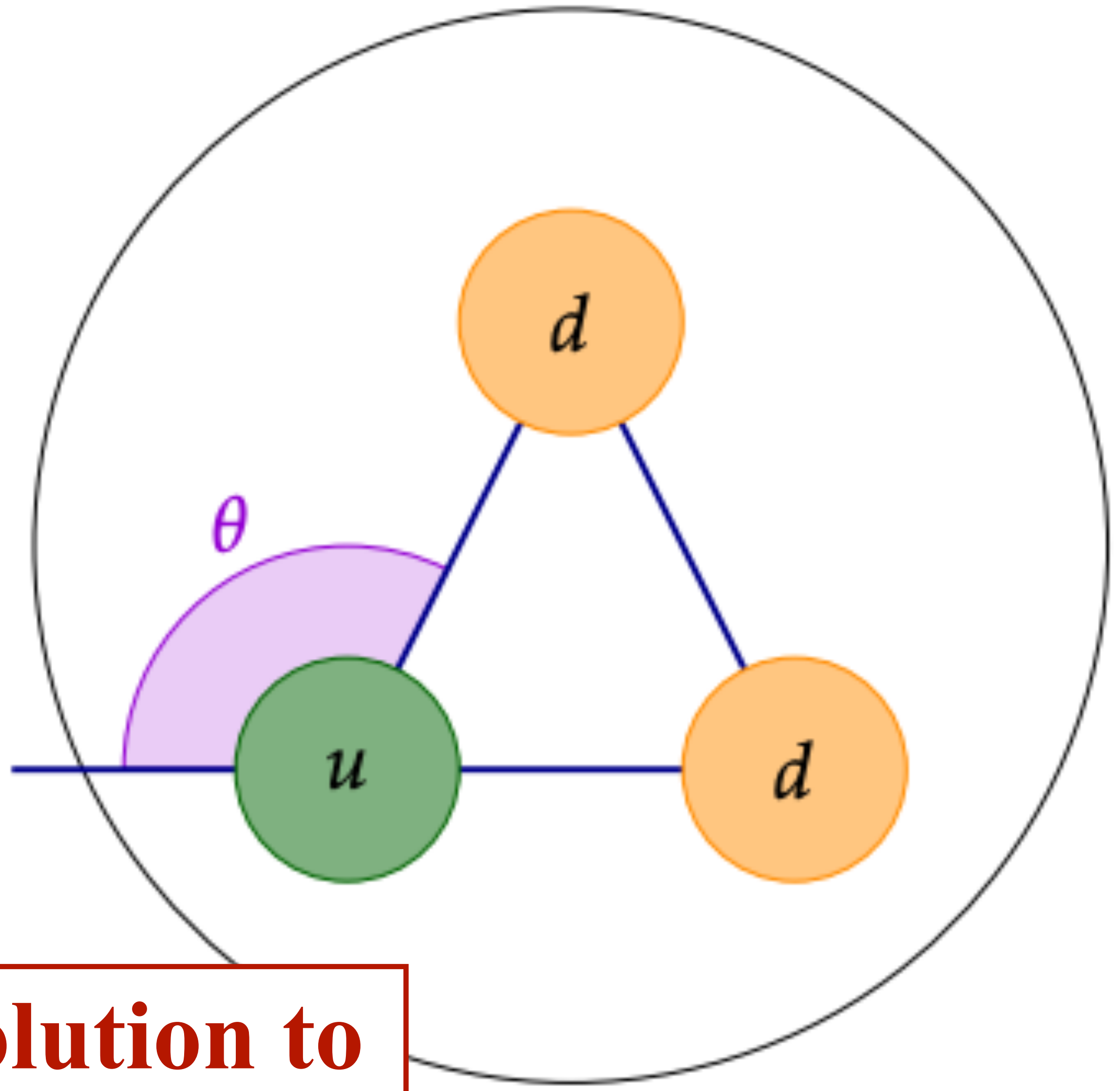
Light Pseudoscalars





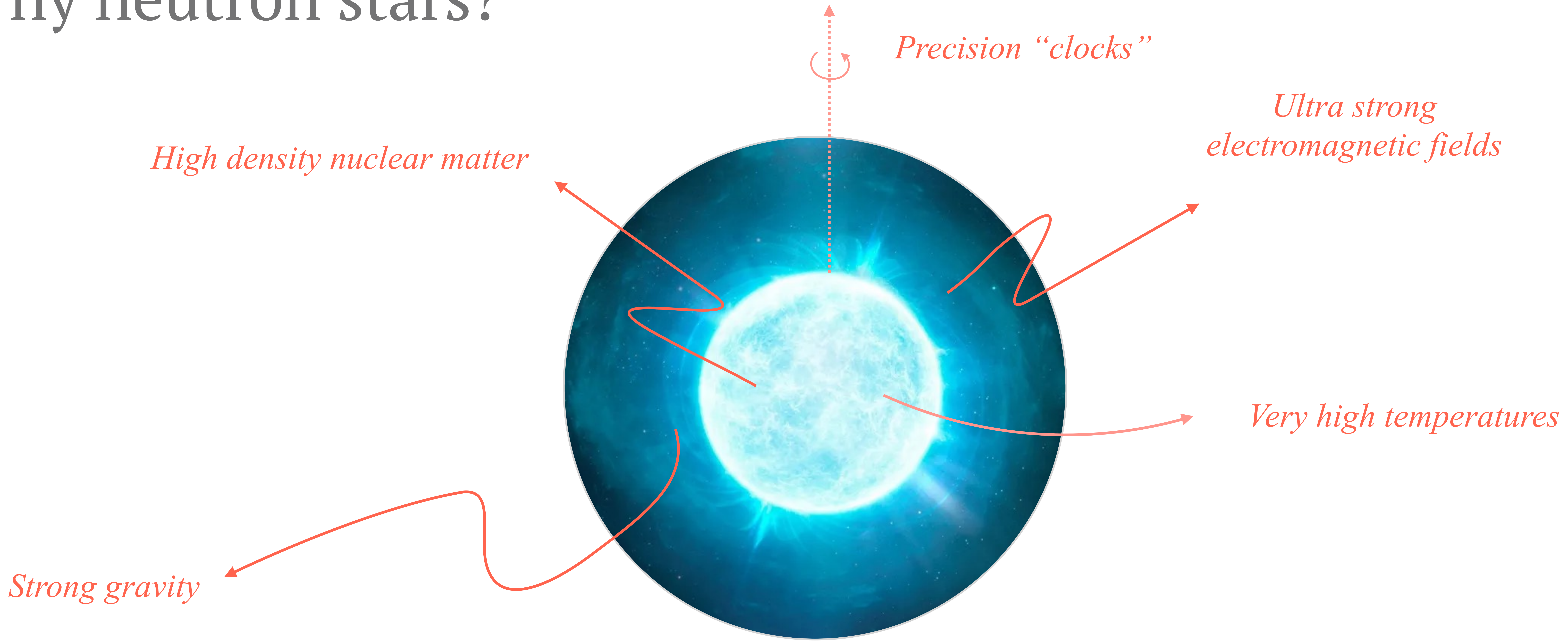
Axions as IR remnants of the UV

(QCD axion)

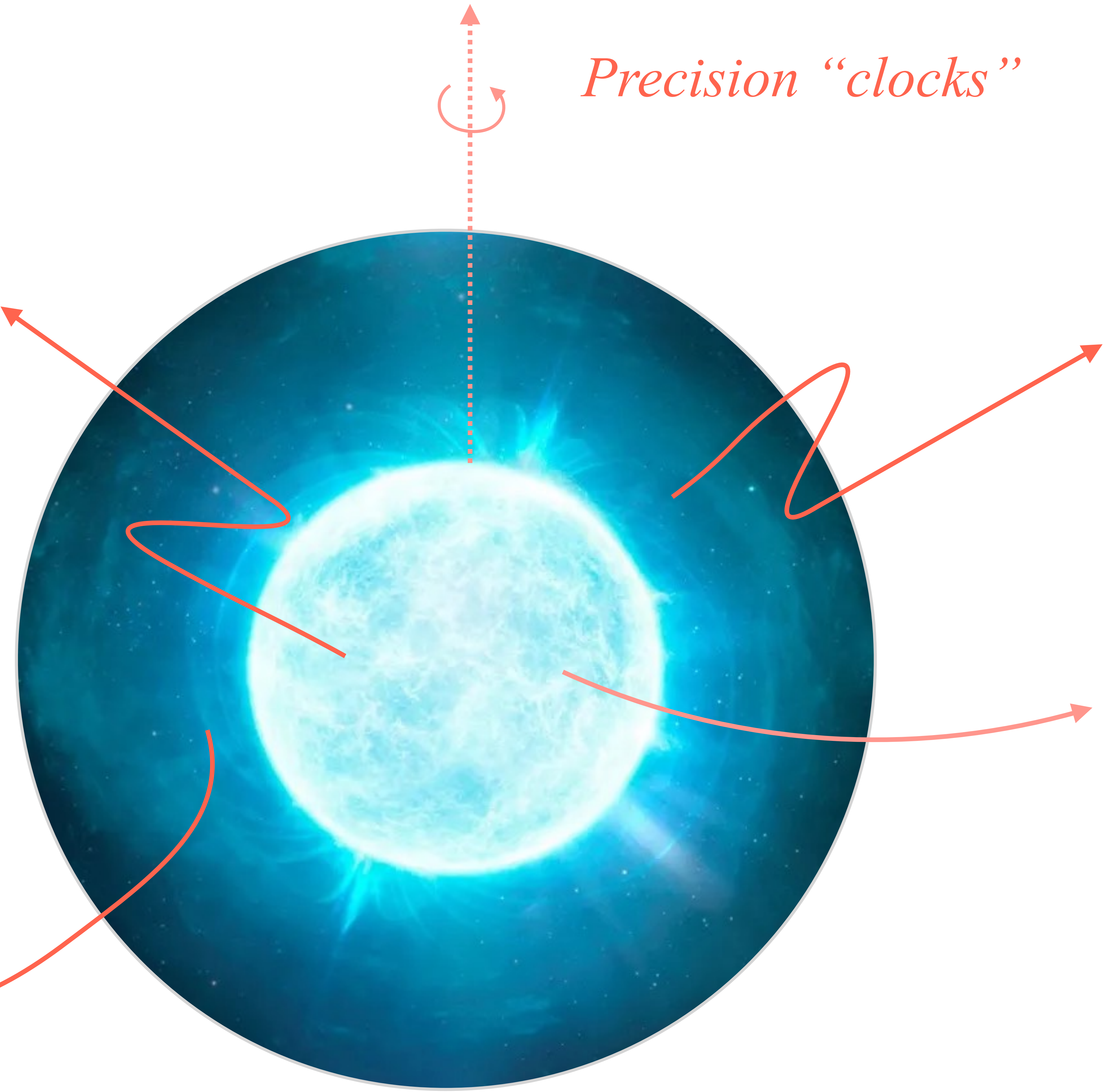


Axions as a solution to the strong CP problem

Why neutron stars?



Why neutron stars?



Axion physics carries strong environmental sensitivity

Behaviour on Earth $\neq$ Behaviour Elsewhere

Overview

Part I:

Creating dense `axion clouds'

Part II:

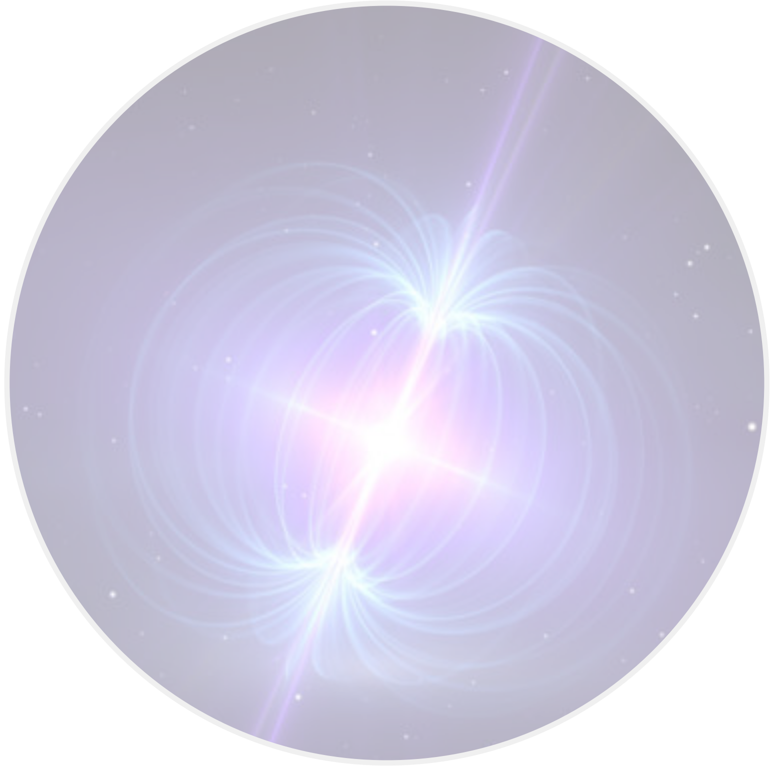
Sourcing "axion hair"

Overview

Part I:

Creating dense `axion clouds'

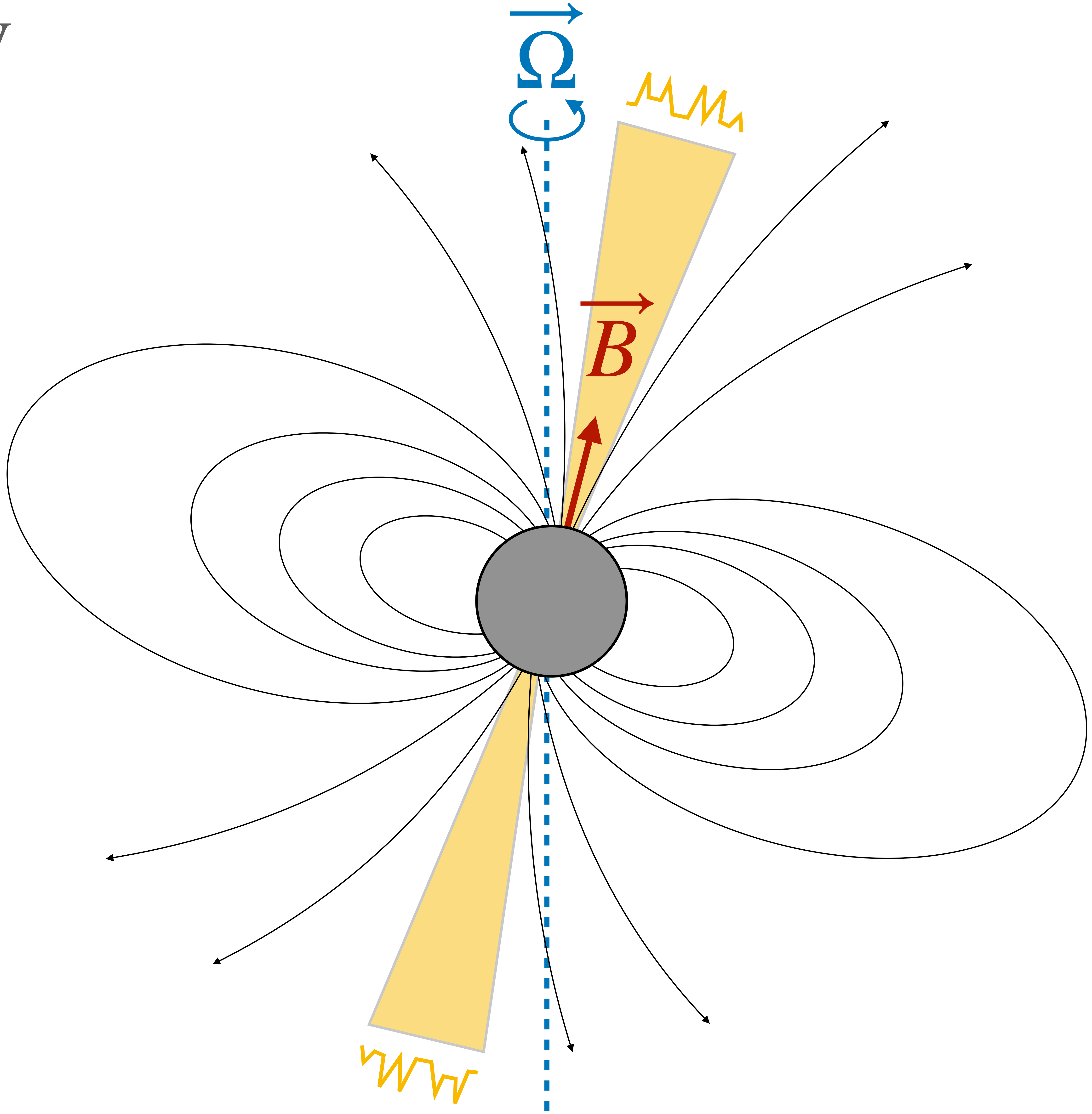
Part II:



Sourcing "axion hair"

Sourcing axion clouds around pulsars

$E_{\text{rotational}} \sim \mathcal{O}(10^{60})\,\text{eV}$



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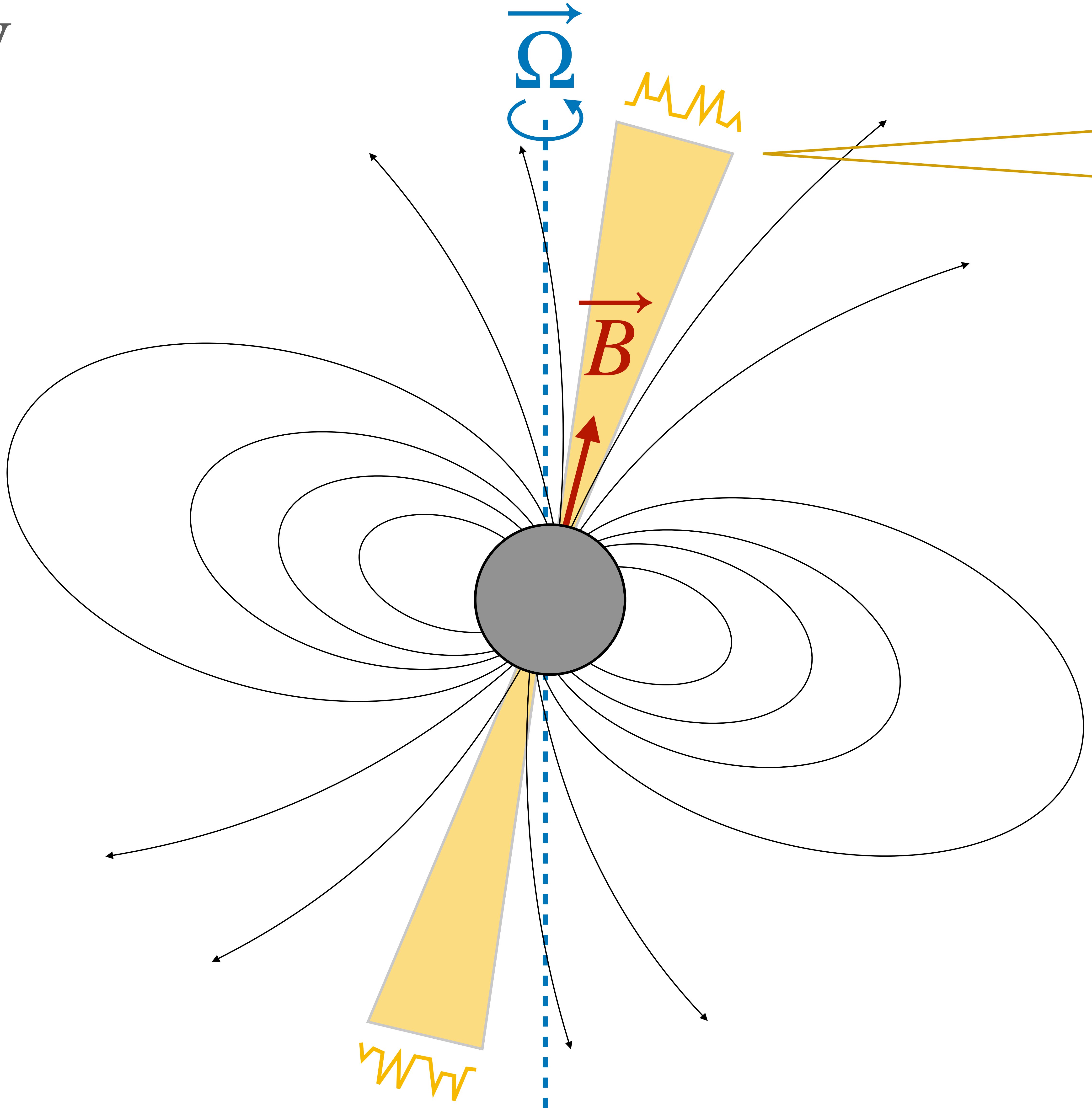

Rotational energy losses:

- *Particle acceleration*
- *Particle production*
- *Radiation*

$$\vec{E} \neq 0$$

Sourcing axion clouds around pulsars

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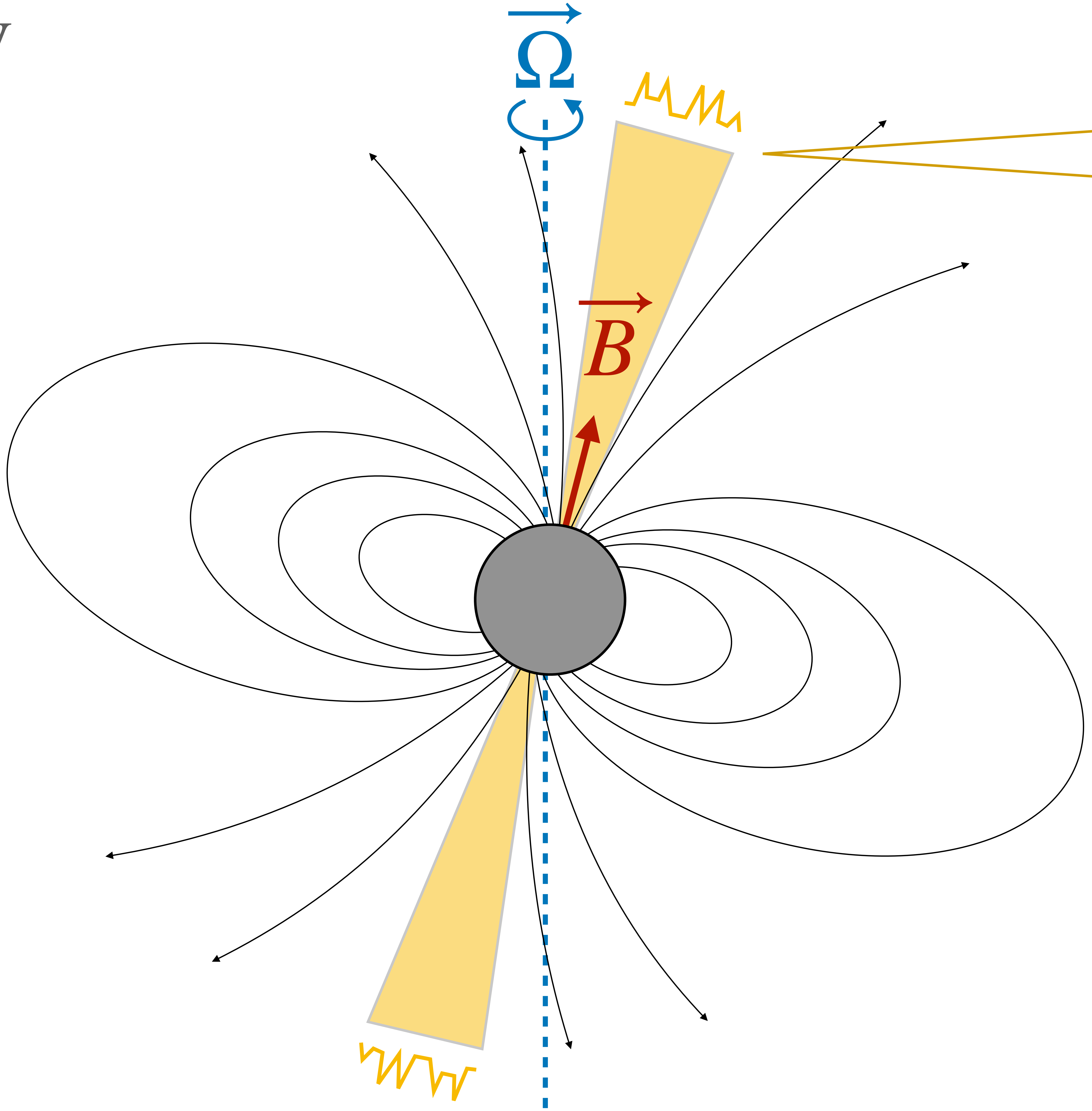

Rotational energy losses:

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$$\vec{E} \cdot \vec{B} \neq 0$$

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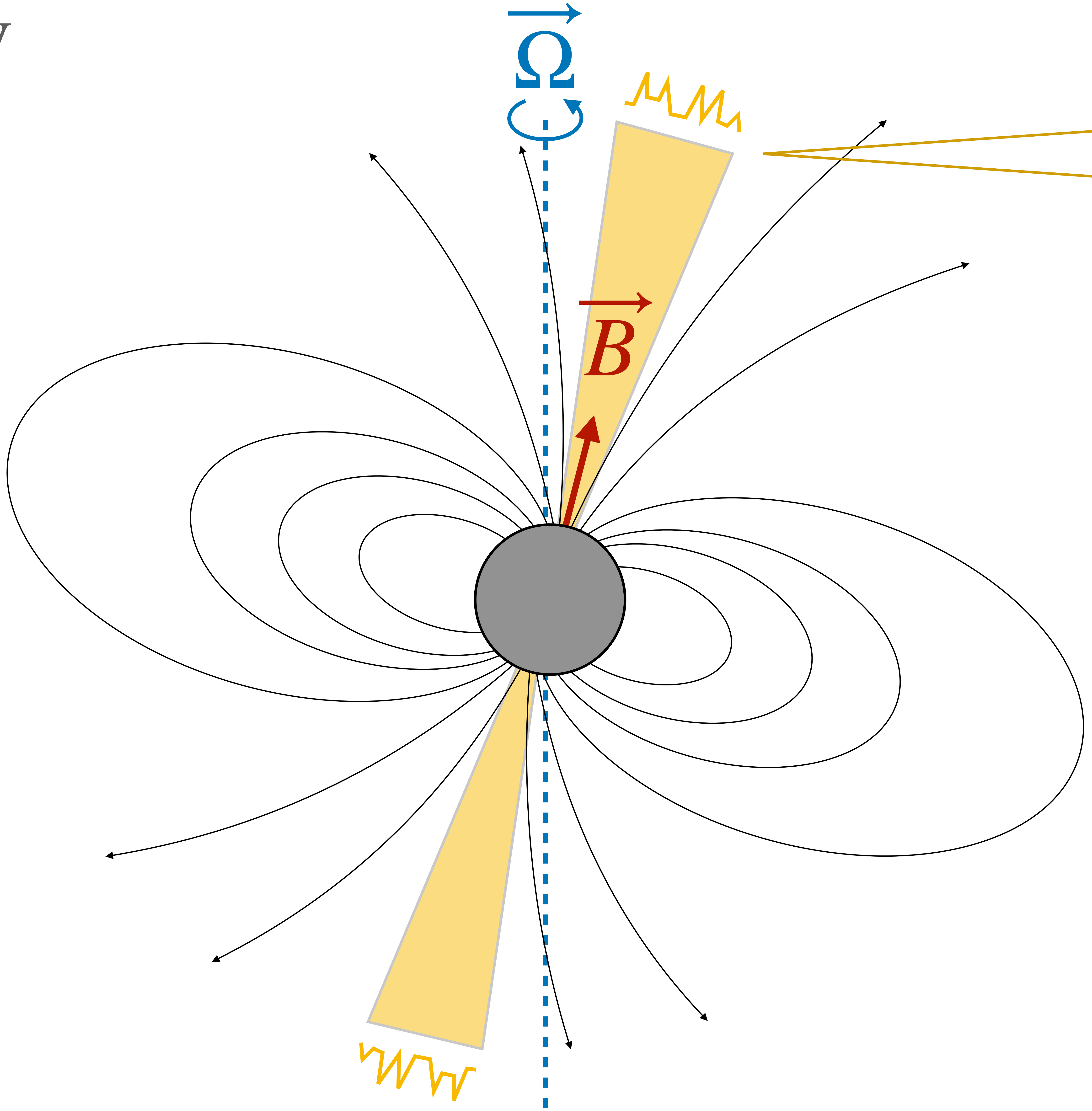
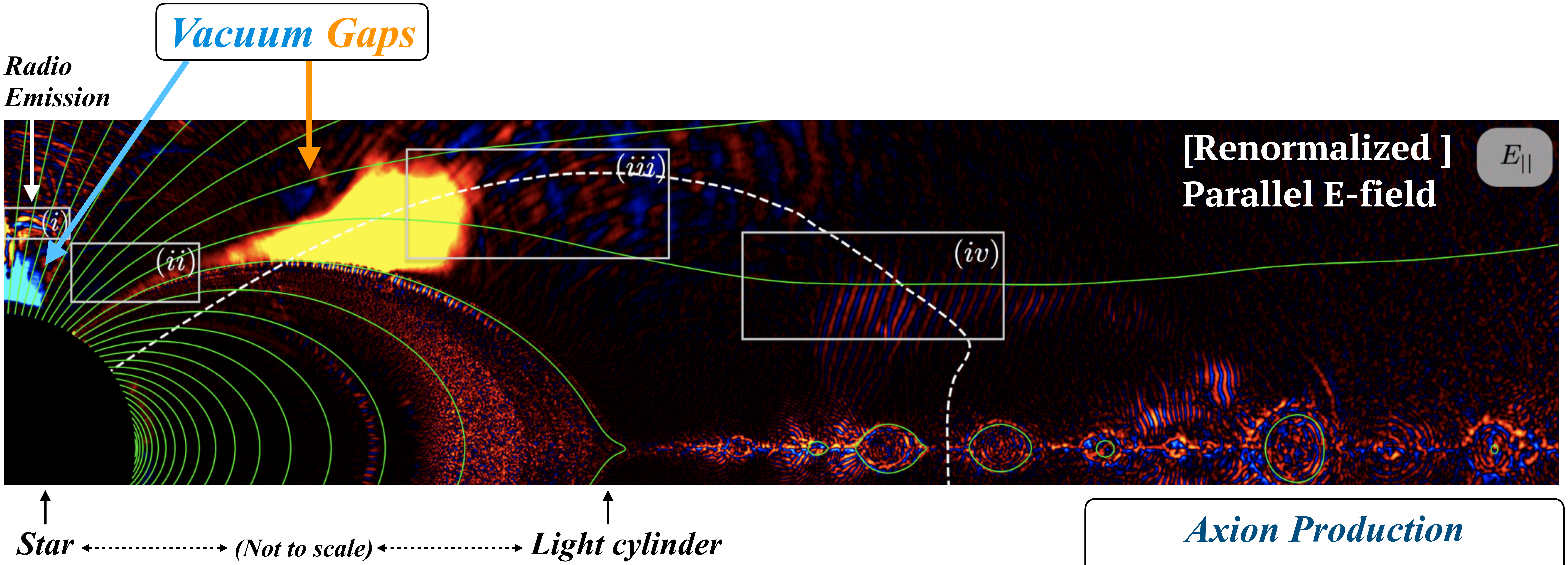


<u>Rotational energy losses:</u>

- *Particle acceleration*
- *Particle production*
- *Radiation*

$$(\vec{E} \cdot \vec{B})(t) \neq 0$$

Axions from "vacuum gaps"



Axion Production

$$\left(\Box + m_a^2\right) a = g_{a\gamma\gamma} \vec{E} \cdot \vec{B}$$

$$\dot{N}_a(\vec{k}) \propto \mathrm{FT}[g_{a\gamma\gamma} \vec{E} \cdot \vec{B}]$$

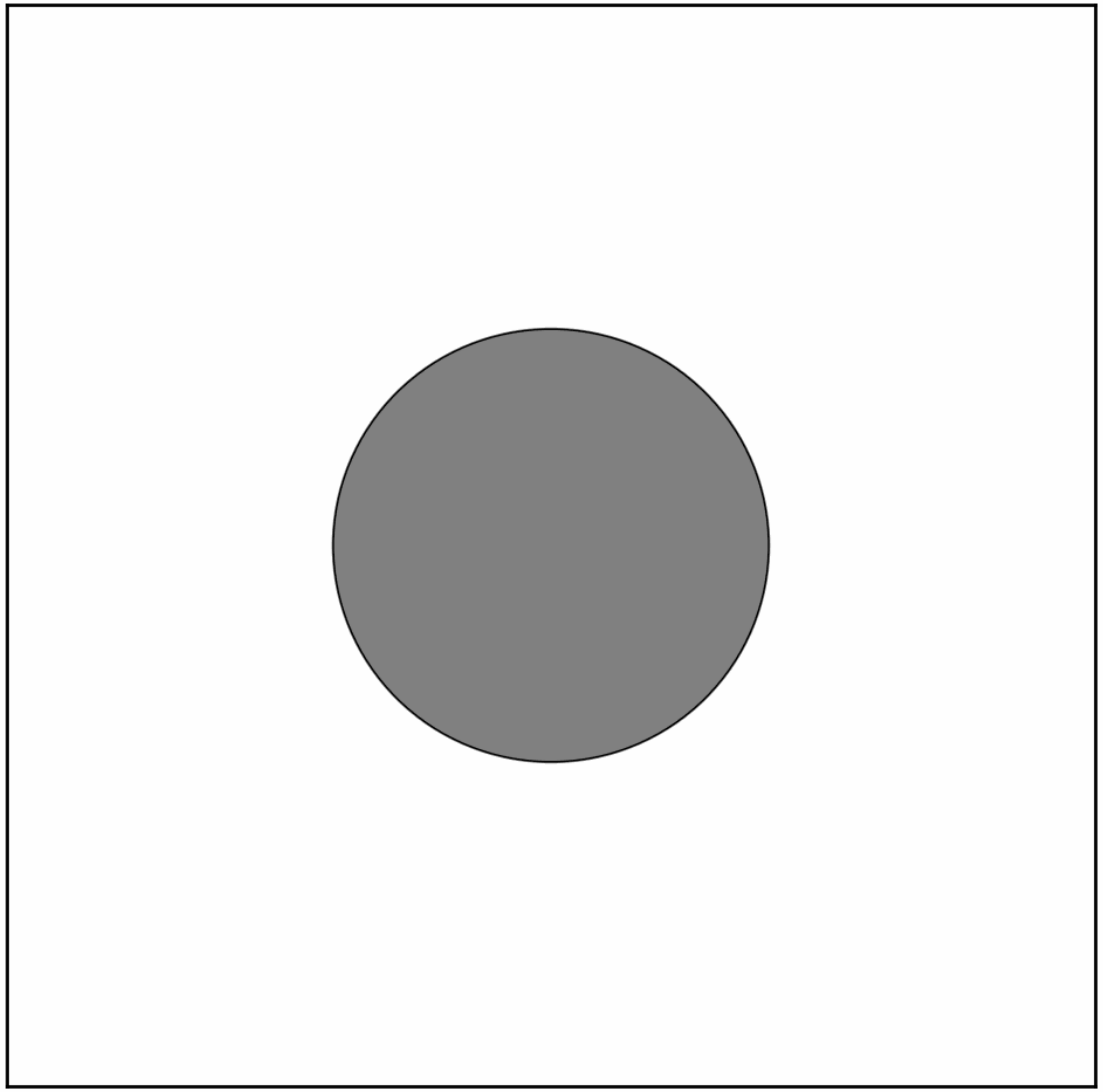
Polar Cap Dynamics in the Last Half Century (See e.g.):

Sturrock (1971), Ruderman & Suntherland (1974), Arons & Scharlemann (1979), Timokhin (2013), Timokhin & Harding (2015, 2018), Philippov, Timokhin & Spitkovsky (2020), Bransgrove, Belobodorov, Levin (2023)

Polar cap dynamics

Polar cap dynamics

Forming axion clouds



<u>Rotational energy losses:</u>

- *Particle acceleration*
- *Particle production*
- *Radiation*

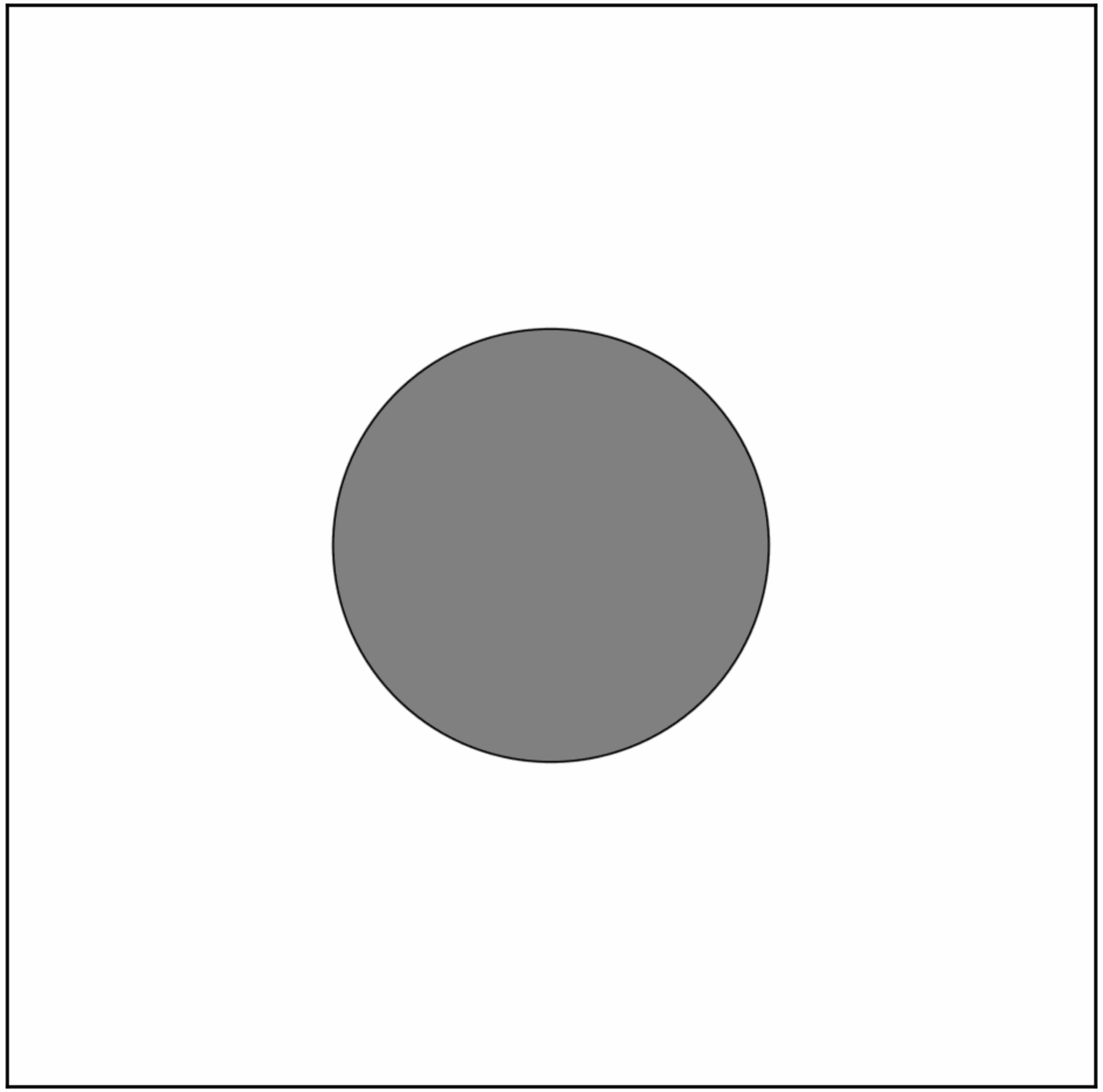
$$\vec{E} \cdot \vec{B} \neq 0$$

- *Axions*

$$\mathcal{L}_{a\gamma} \supset g_{a\gamma}\, a \left(\vec{E} \cdot \vec{B}\right)$$

$$10^{-9}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$$

Forming axion clouds



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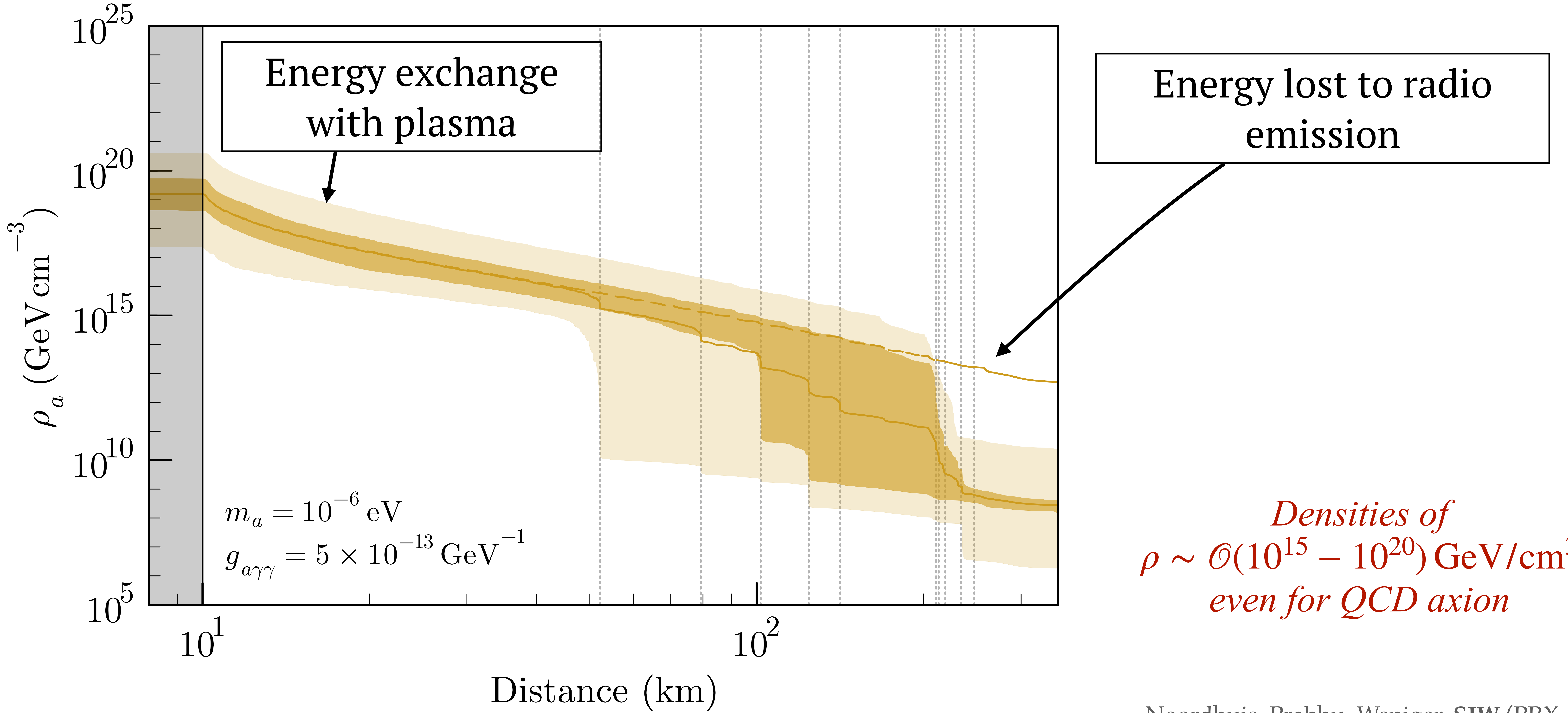
Axion Clouds

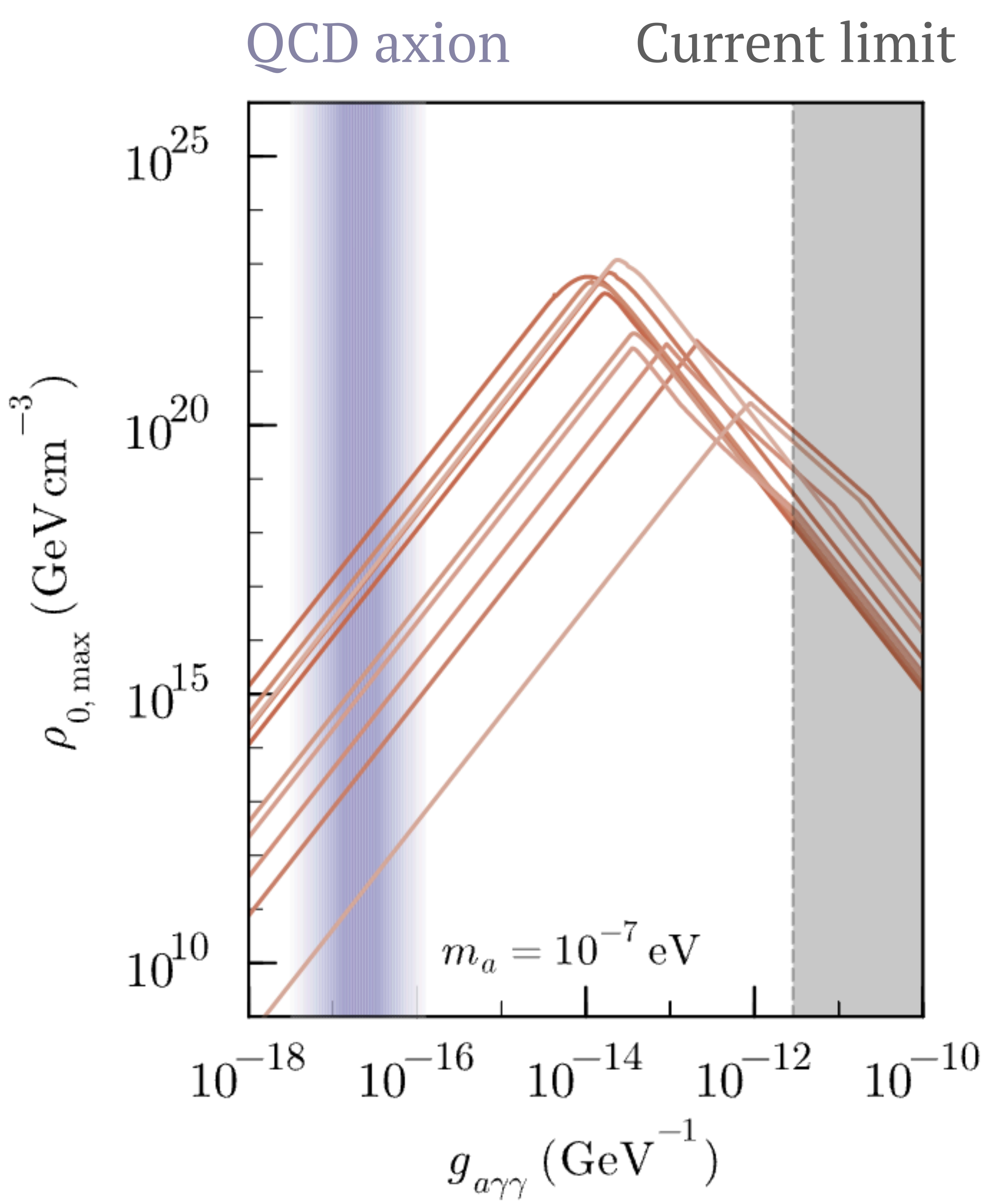


Densities of
$\rho \sim \mathcal{O}(10^{15} - 10^{20})\,\mathrm{GeV/cm^3}$
even for QCD axion

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

Maximum density of axion clouds

To what extent does the axion density depend on $g_{a\gamma\gamma}$?



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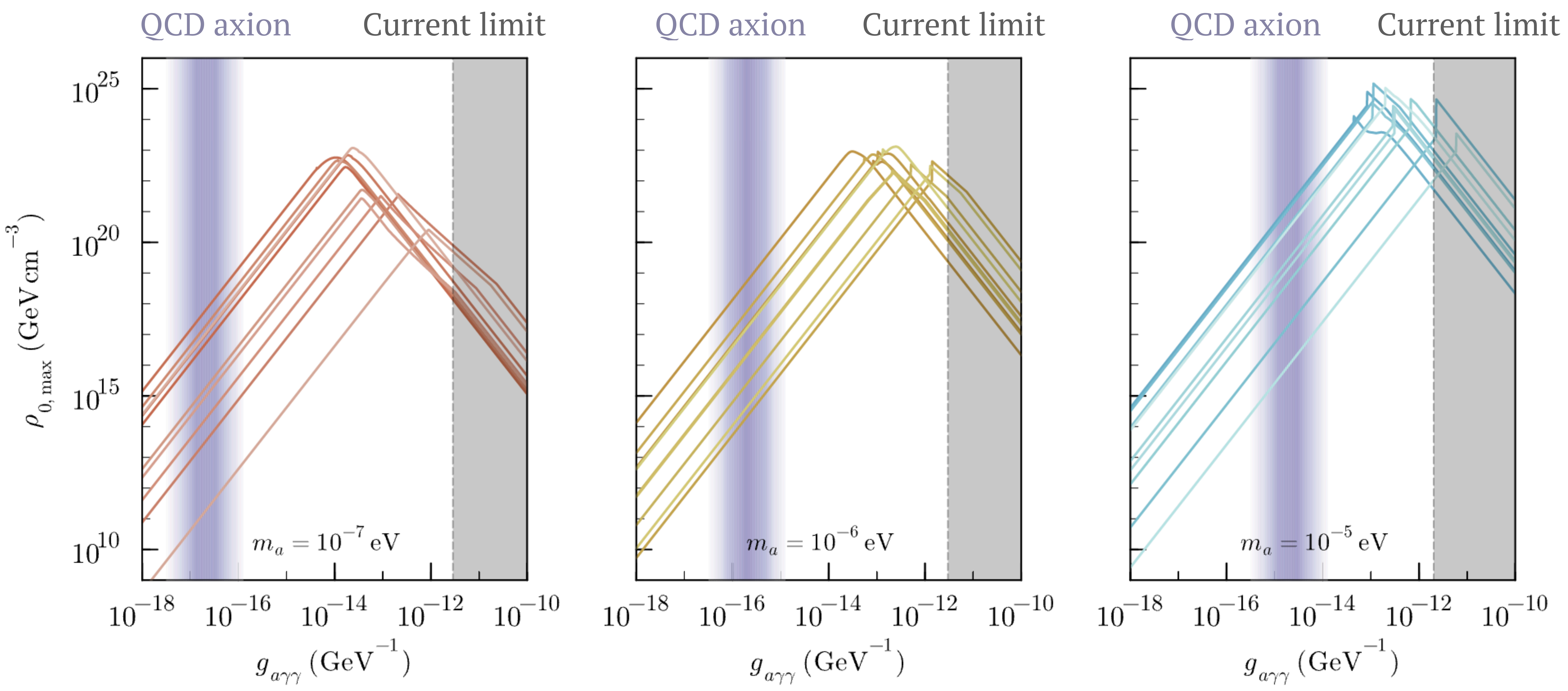
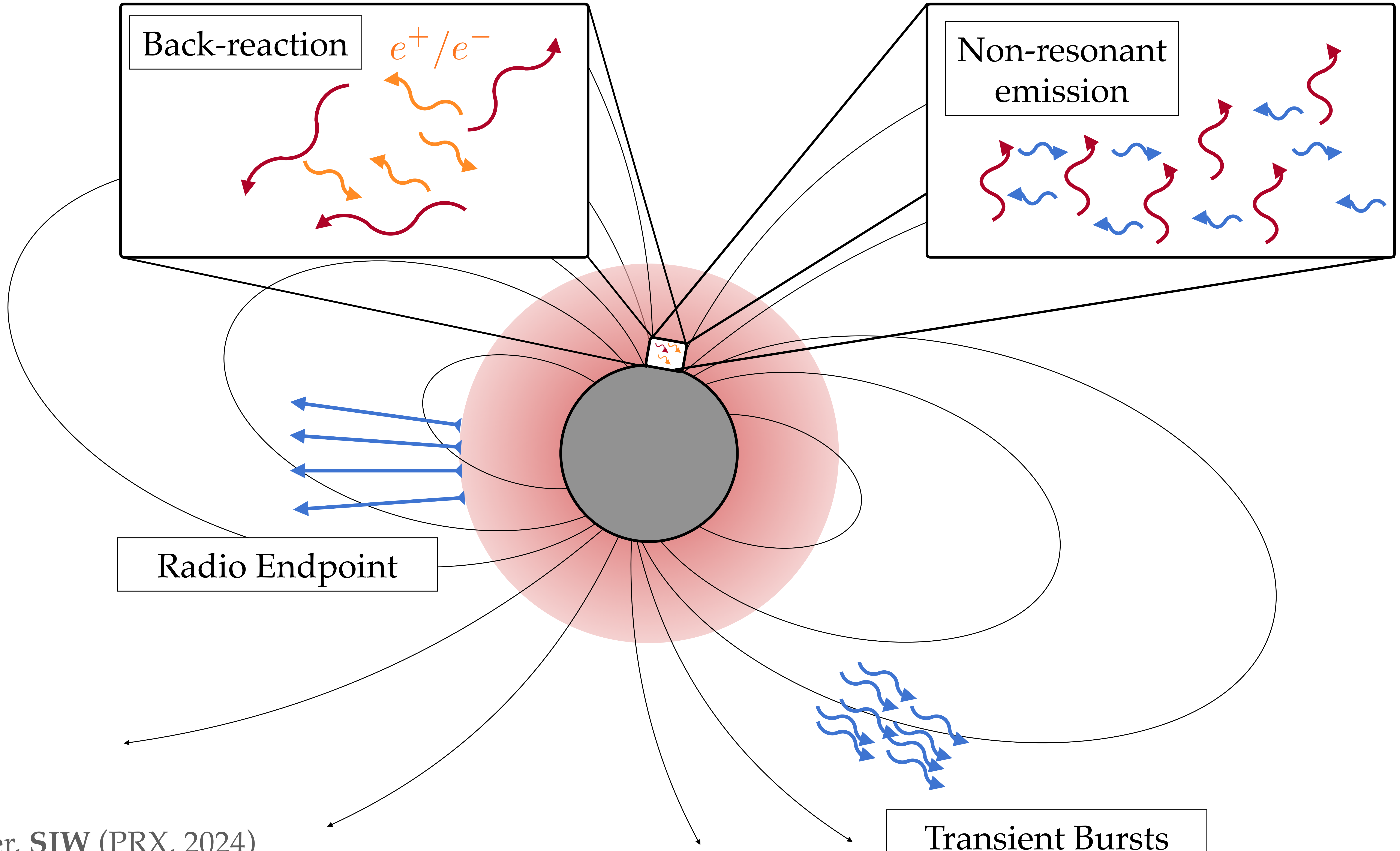


Observable Consequences



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

Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)

Back-reaction on Electrodynamics

Assumption: *Dynamics governed by Maxwell's equations*

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

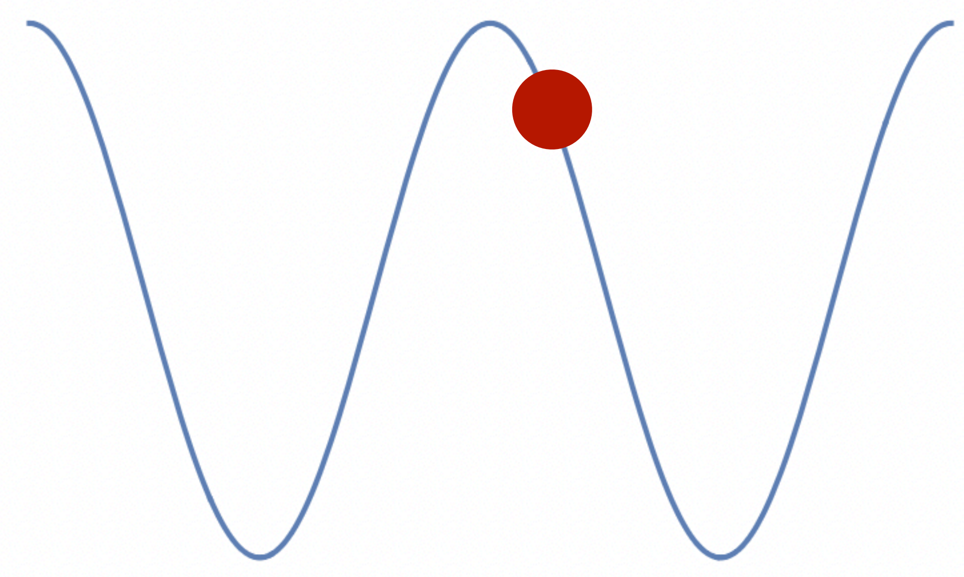
$$\boxed{(\nabla \times B) - \partial_t E = j} + g_{a\gamma\gamma} B \partial_t a - g_{a\gamma\gamma} \nabla a \times E$$

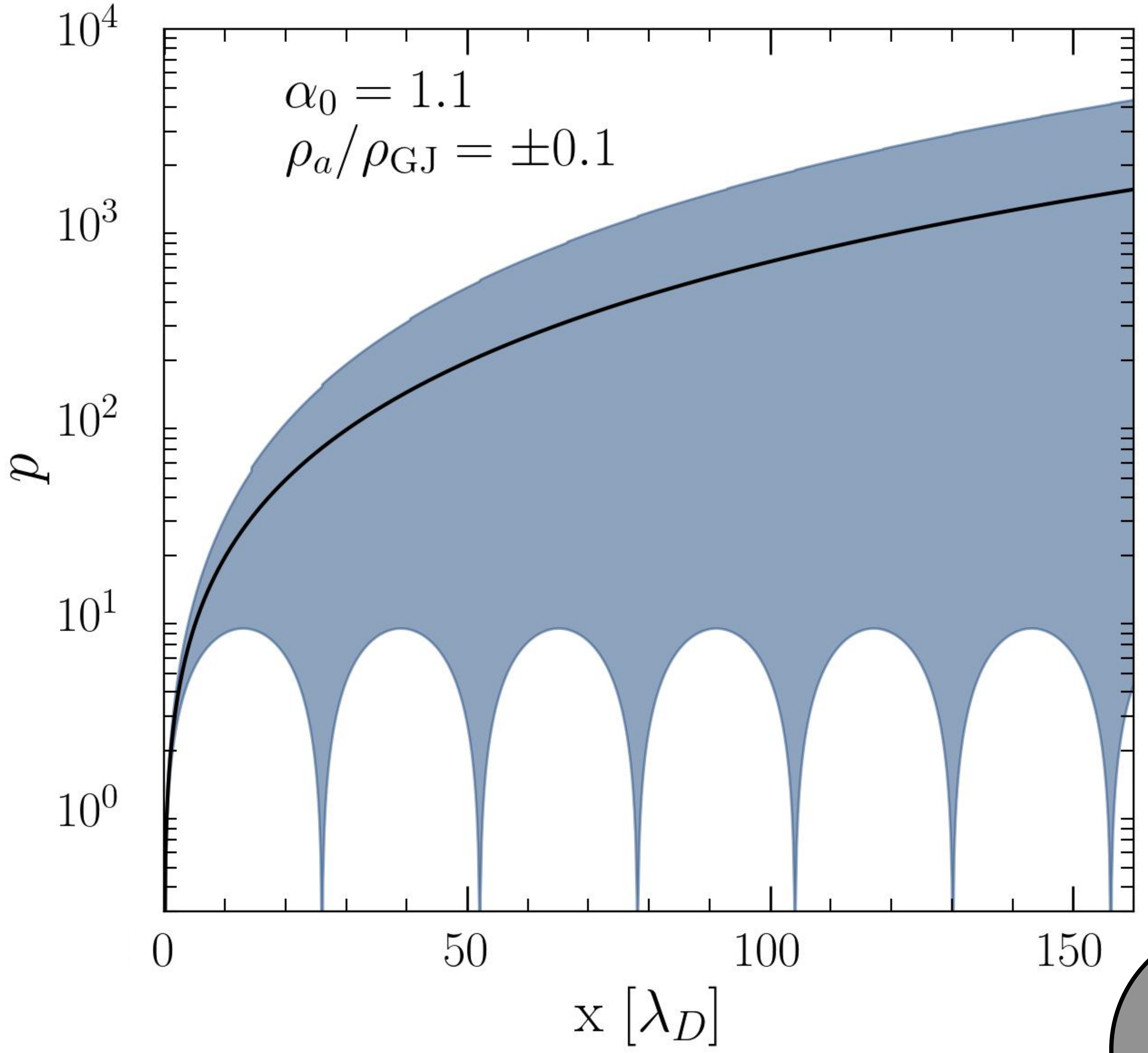
… are axions still perturbative correction?

Back-reaction on Electrodynamics

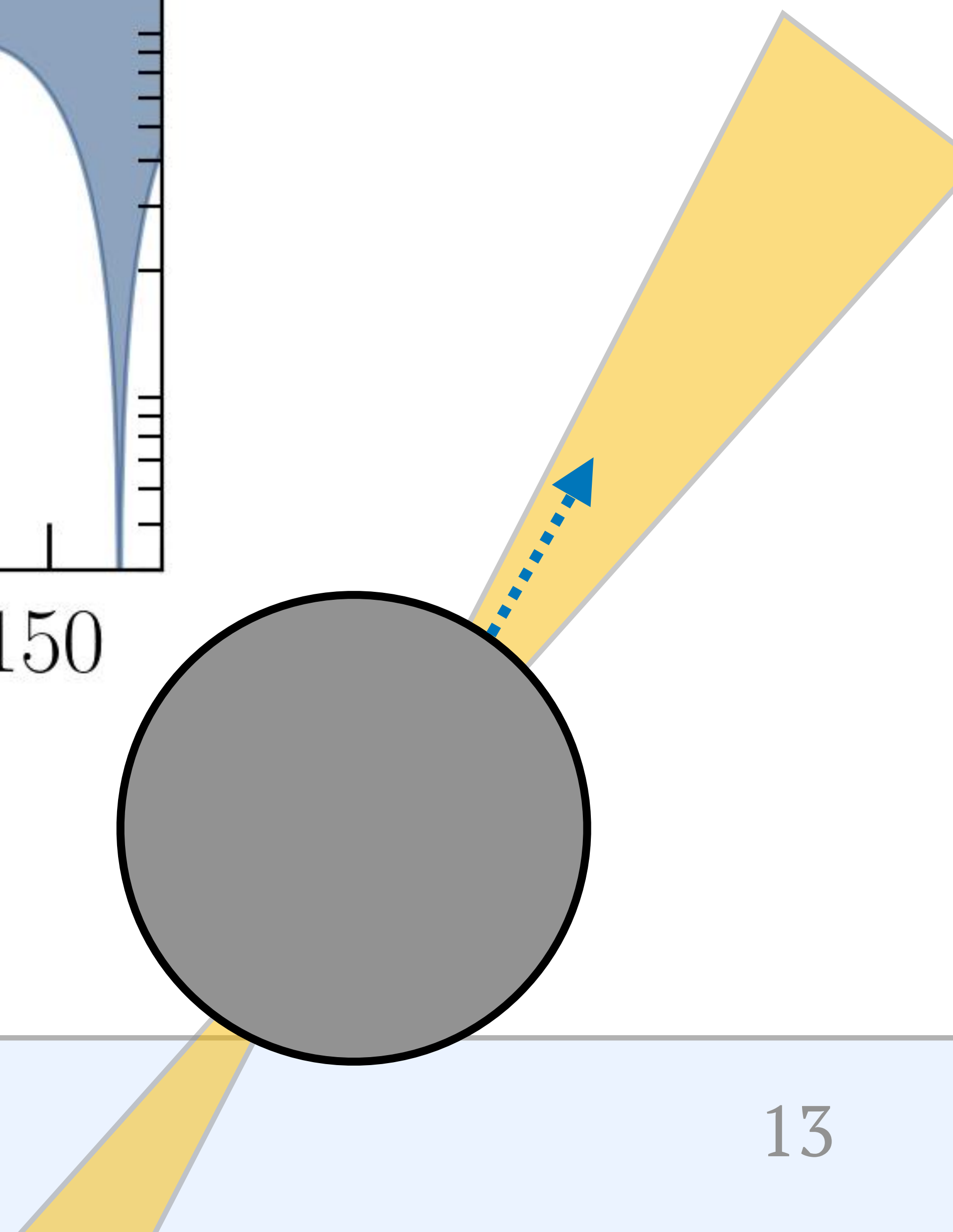
Analytic control in $m_a \to 0$ limit

$[\partial_\mu a = \text{constant}]$





Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)



Back-reaction on Electrodynamics

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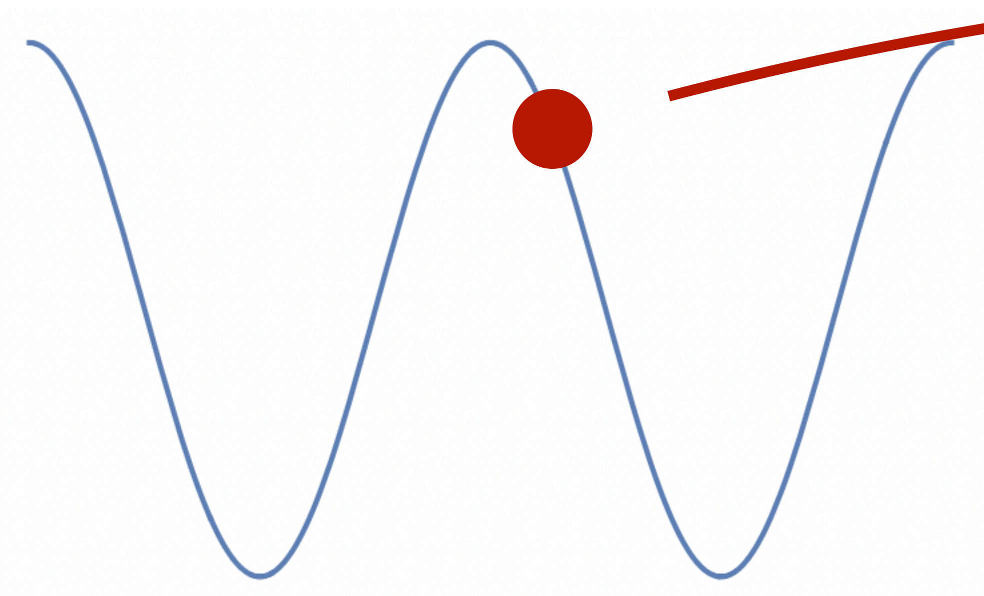
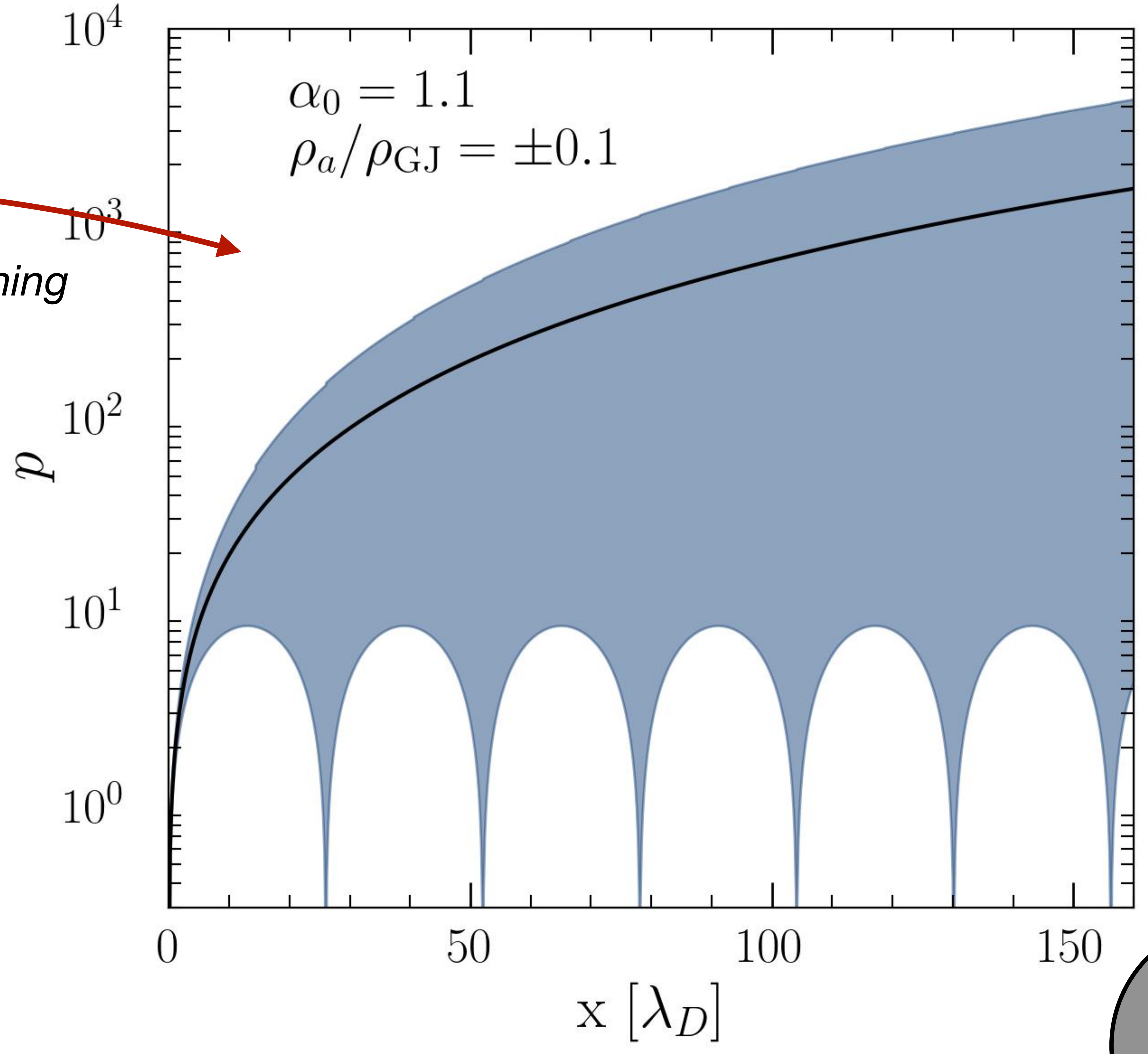
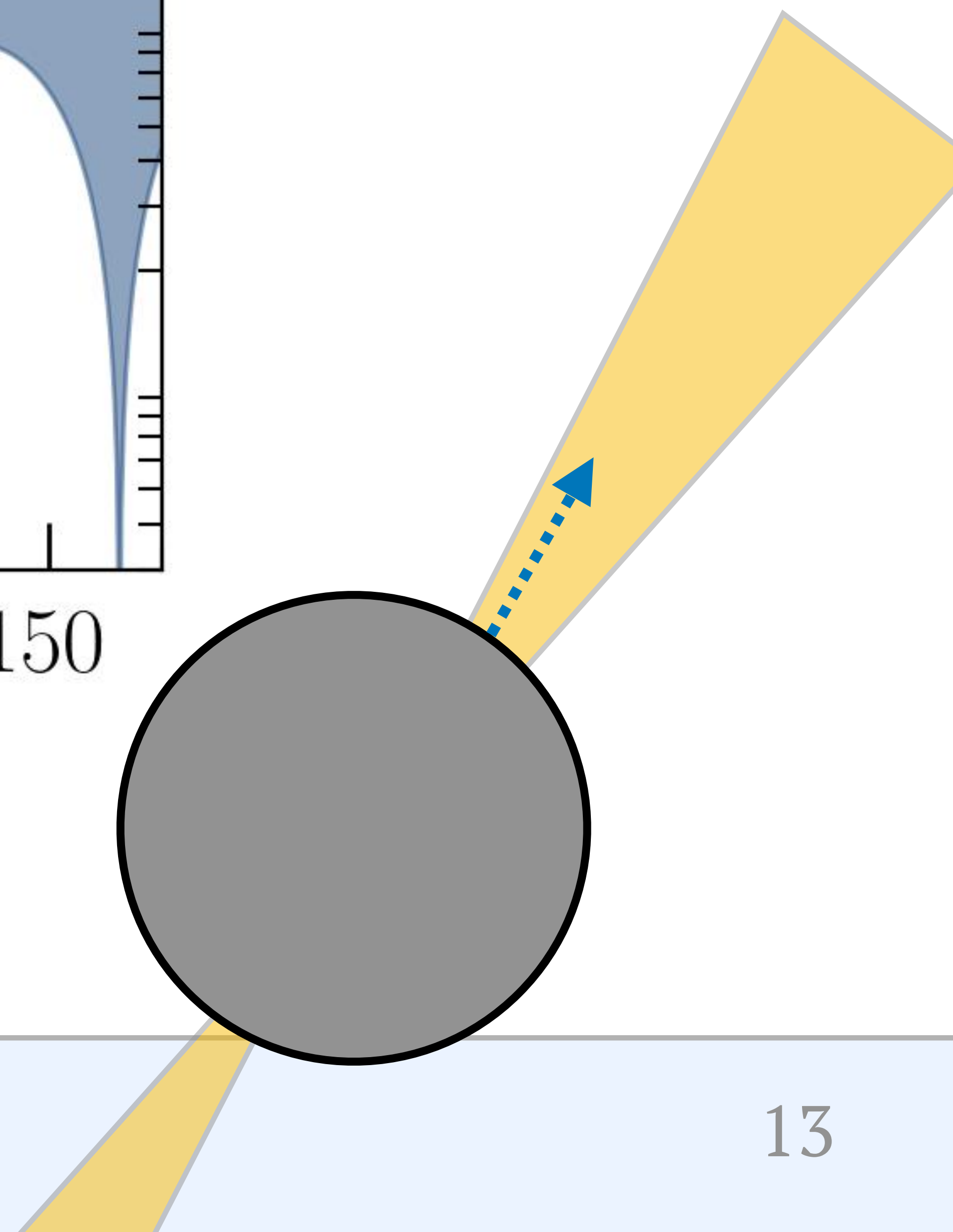


More acceleration / less screening



Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)



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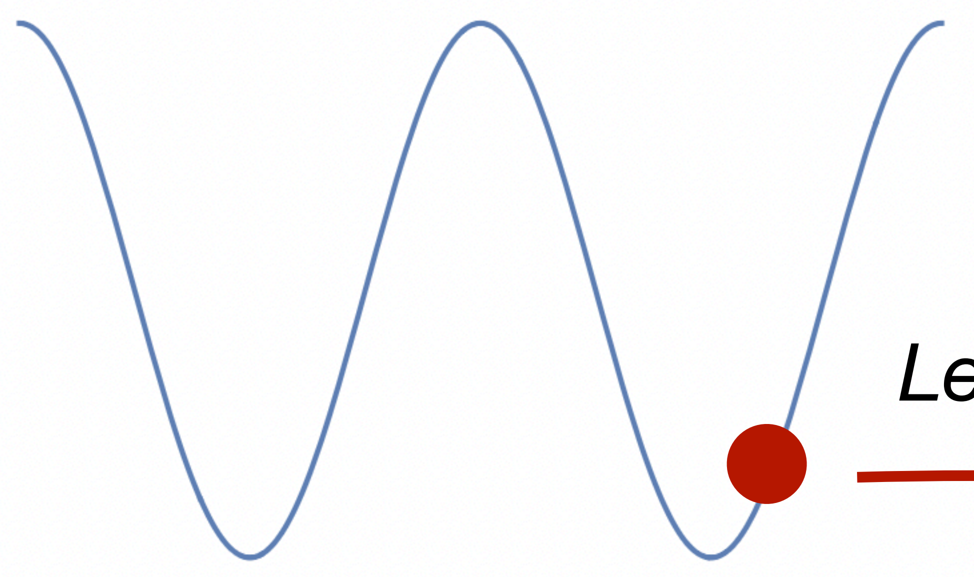
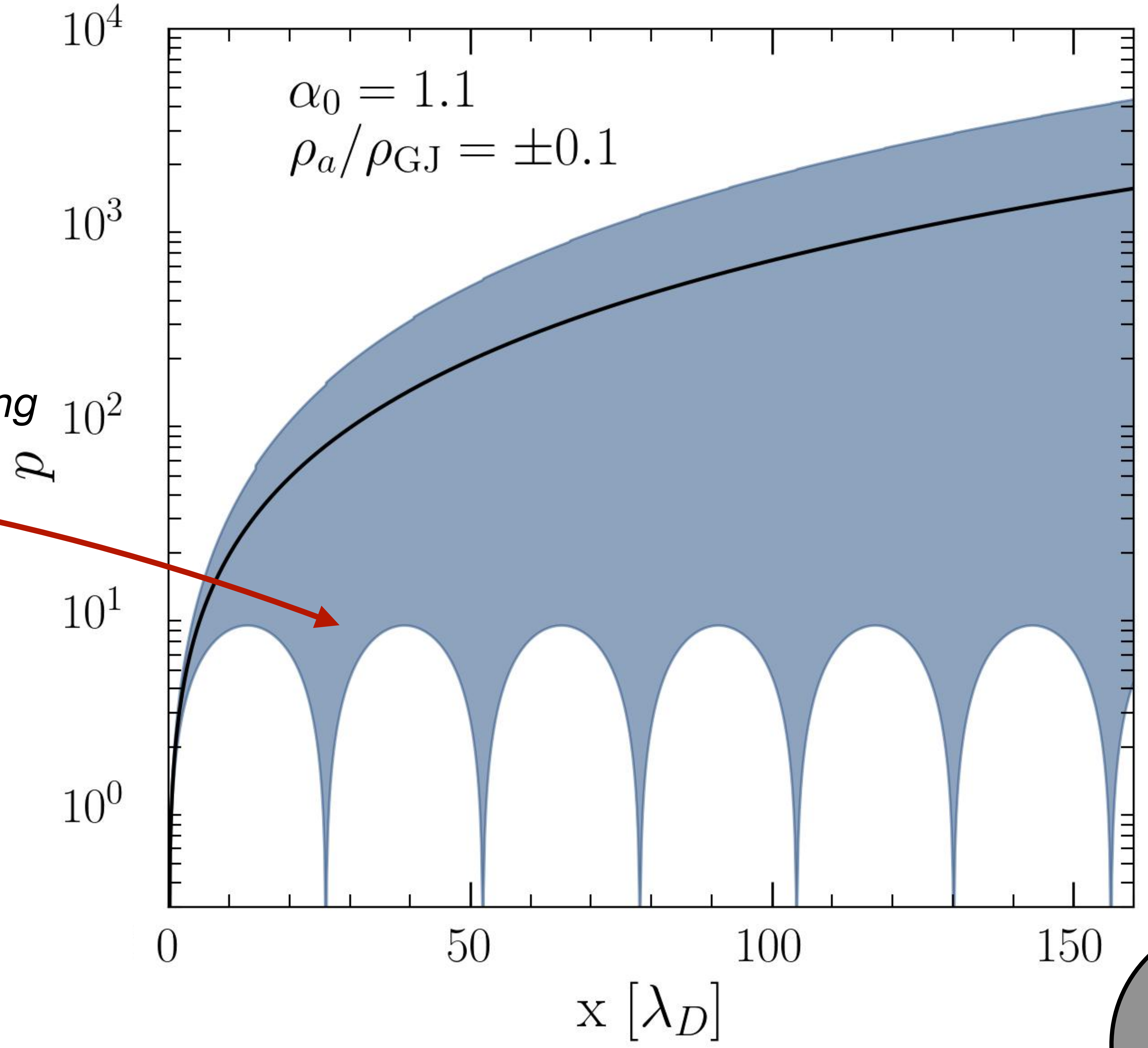
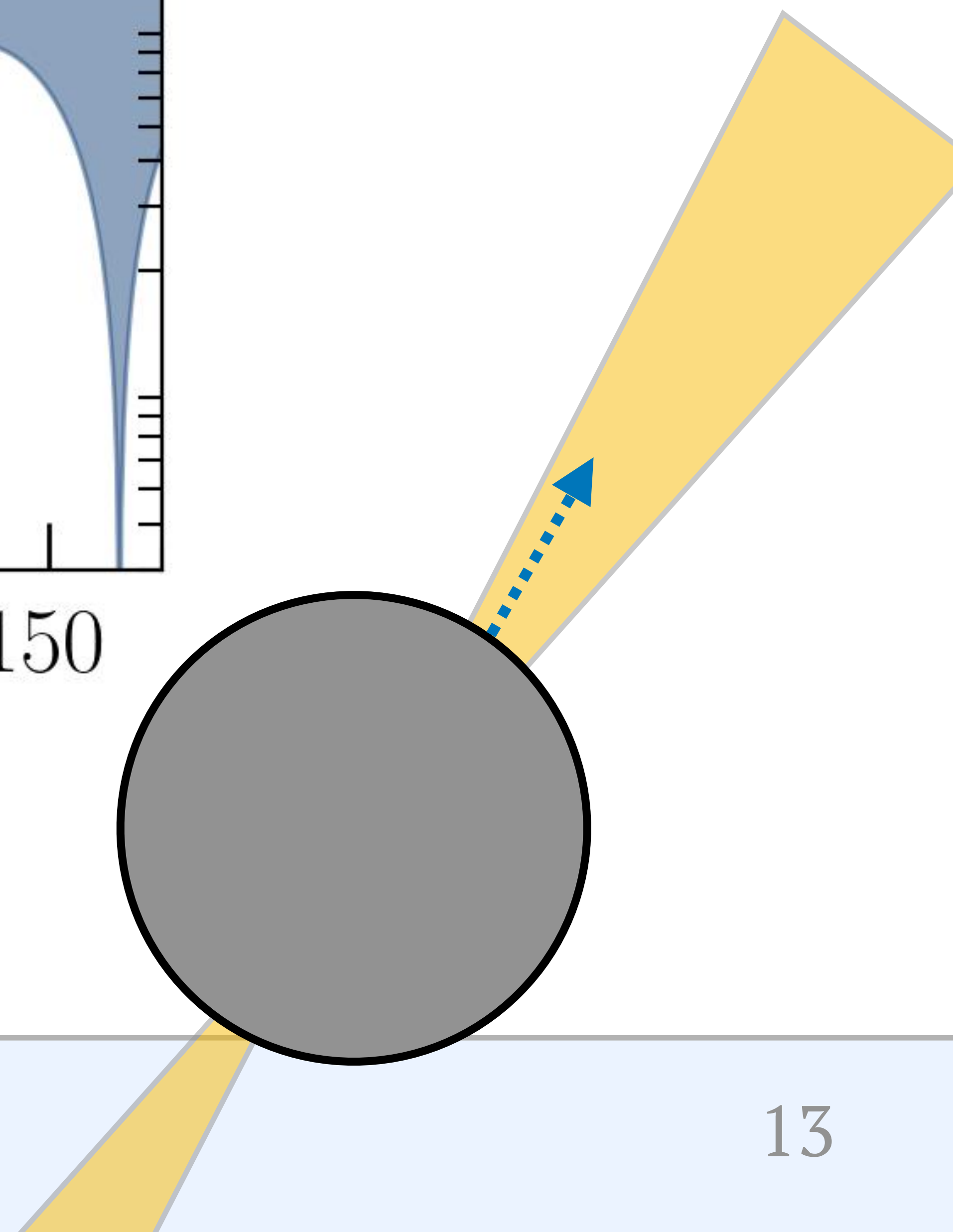




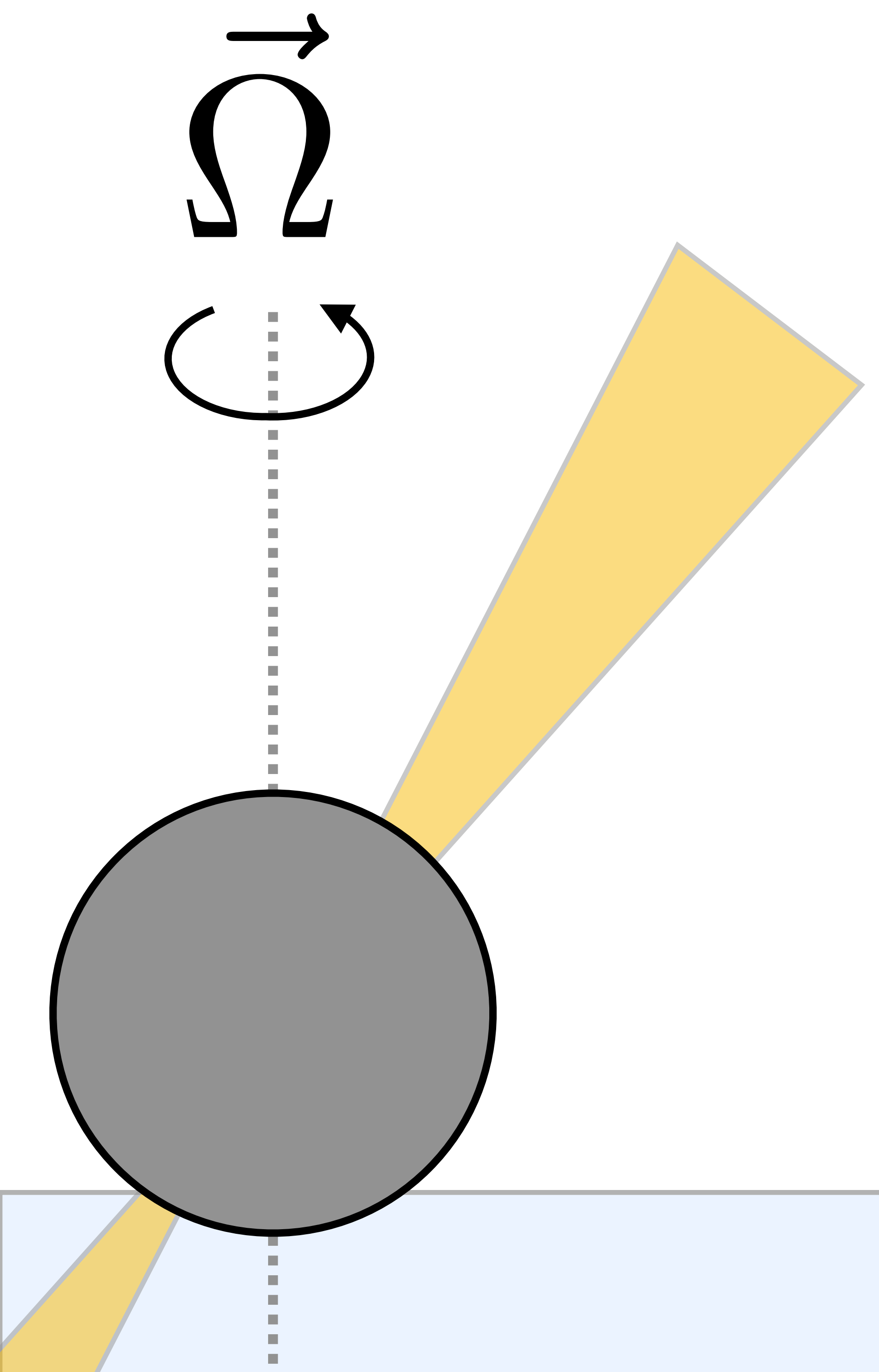
Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)

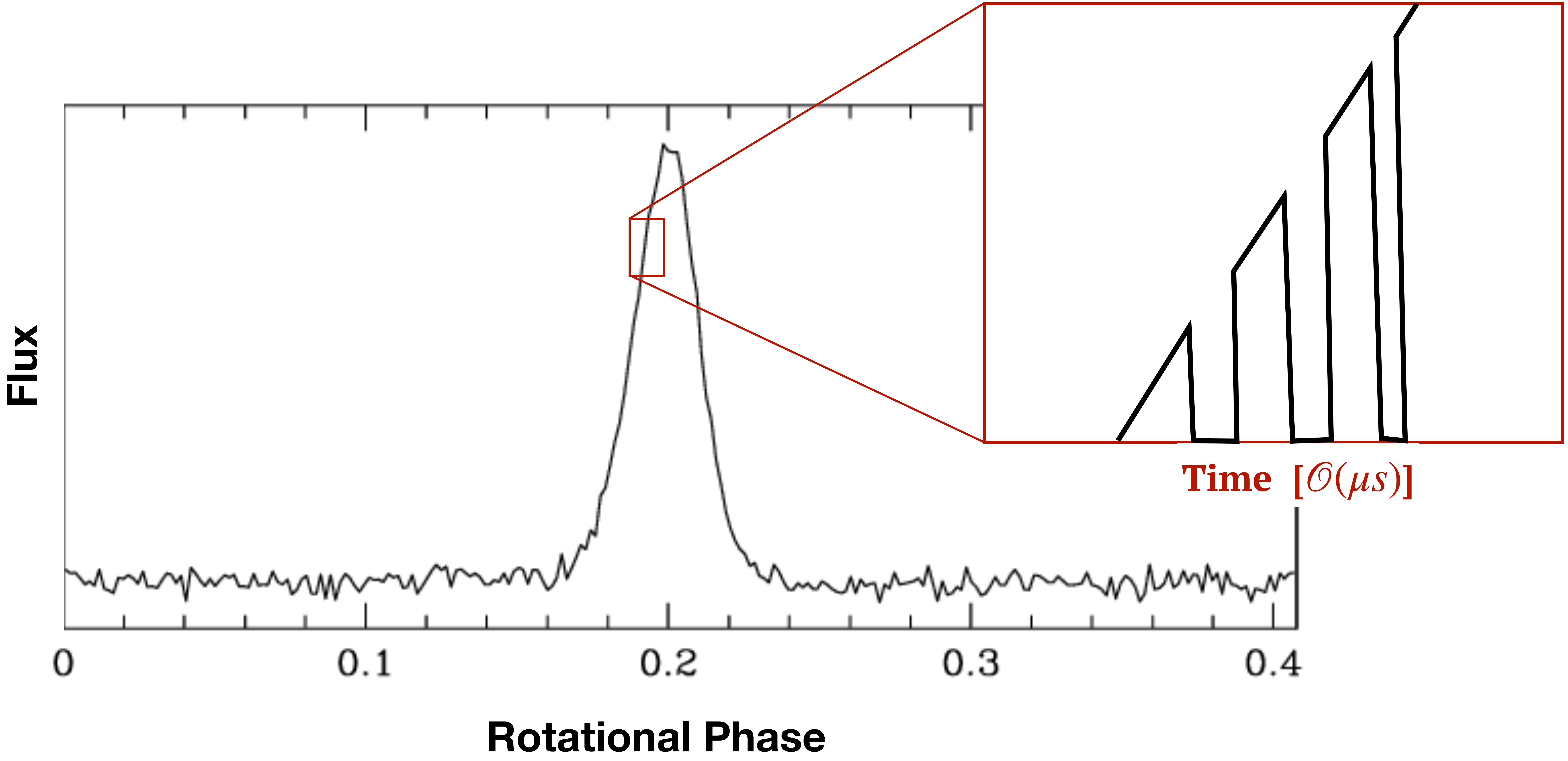


Axion back-reaction

Only occurs for some neutron stars

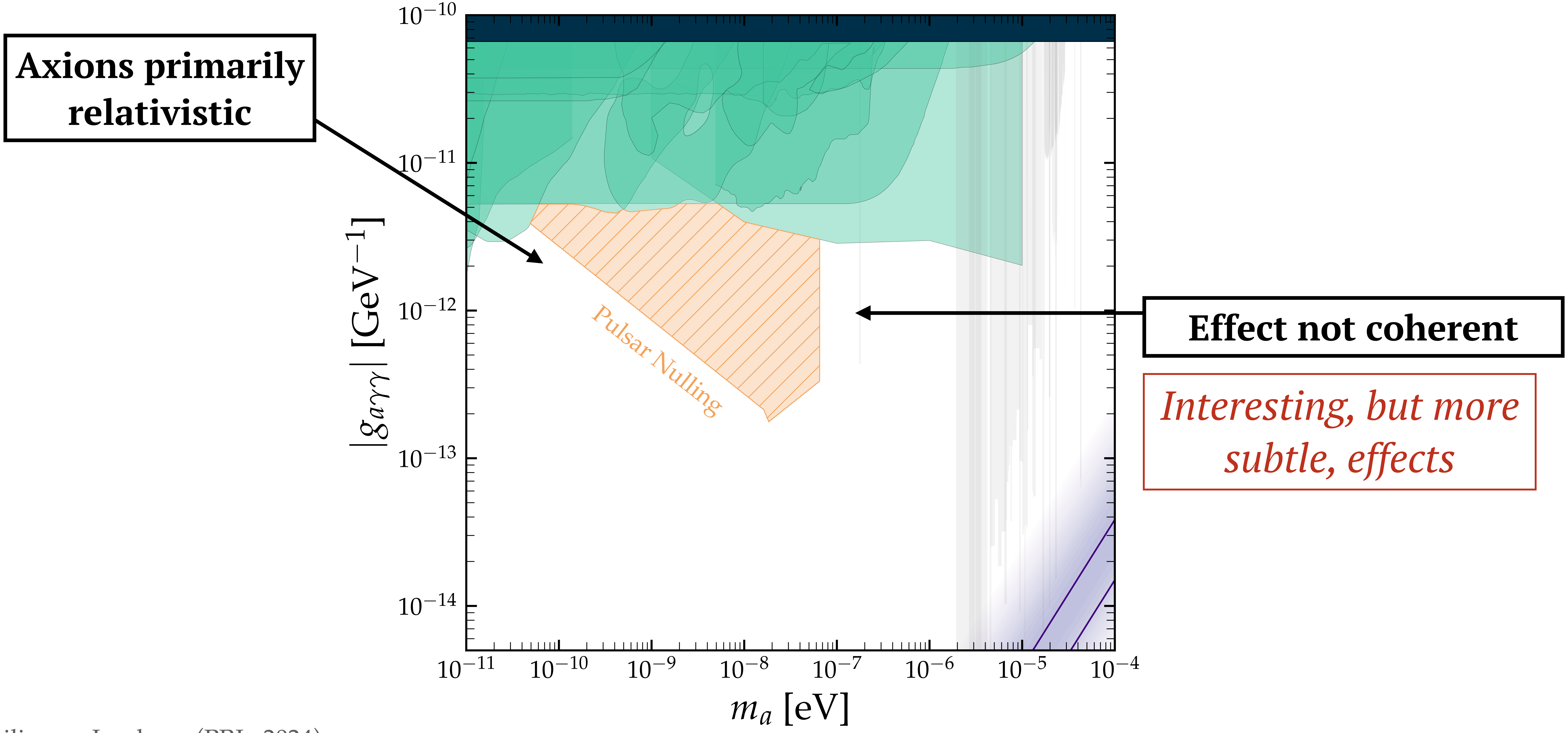
(overly exaggerated for simplicity)





Caputo, **SJW,** Philippov, Jacobson (PRL,2024)

Pulsar Nulling: J1119-6127



Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)

Kinetic simulation with axions

*Ongoing work, lead by **Anne Freise** (Oxford) & in collab. w/ E. Hardy (Oxford), A. Caputo (CERN/Sapeinza), S. Philippov (Maryland), S. Chernoglazov (IAS)*

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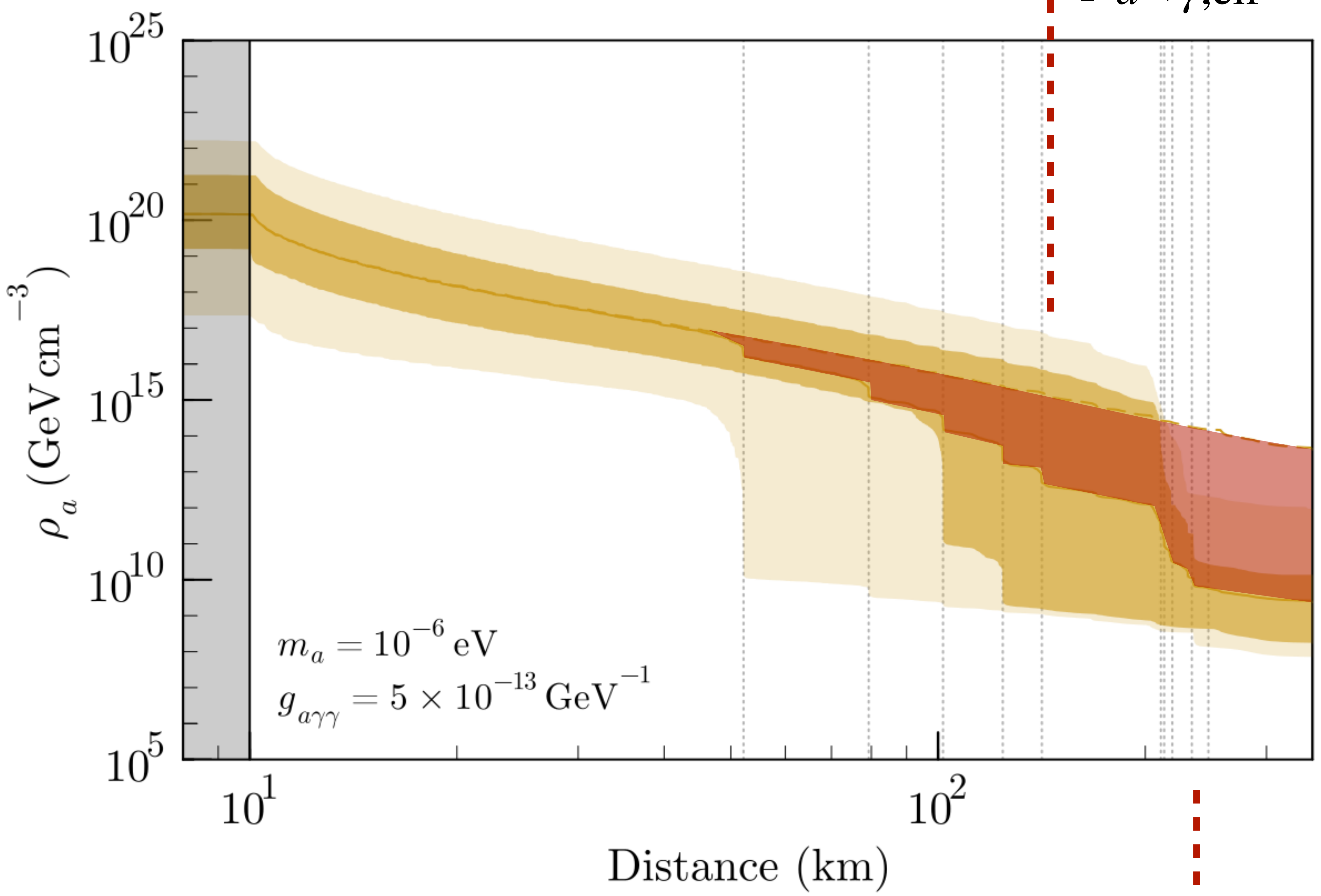
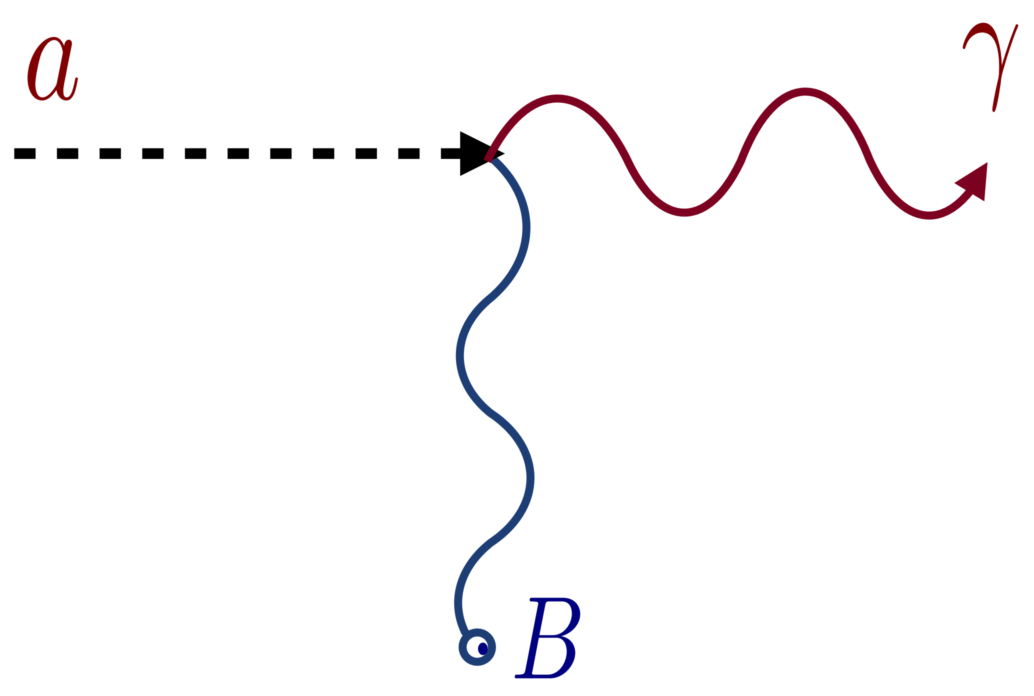
Sharp endpoint in radio spectrum

Production ~ Dissipation

$p_{a\to\gamma,\mathrm{eff}} \sim 1$

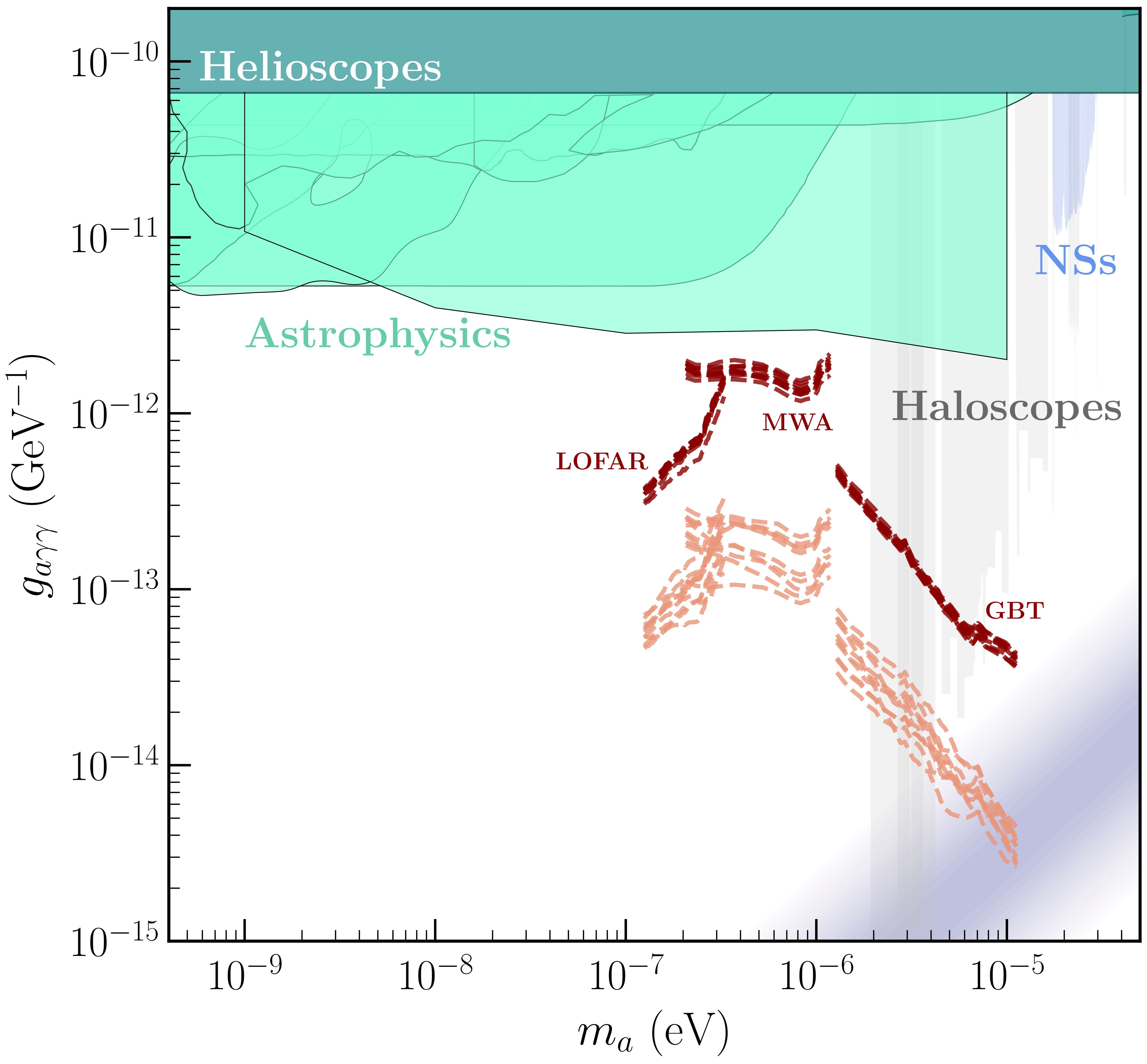




$\mathcal{O}$(1%)-width spectral line centered near axion mass

Kinematics fix: $m_a \leq \omega \lesssim m_a\sqrt{1+v_{\mathrm{esc}}^2}$

Spectral end-point (radio)

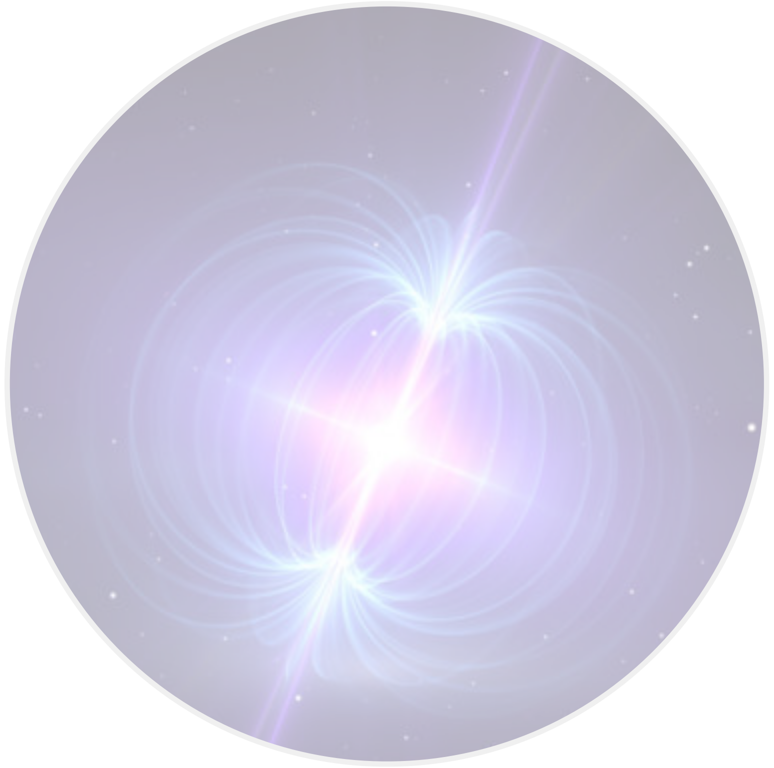


~ O(50) pulsars have observable line

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

Overview

Part I:



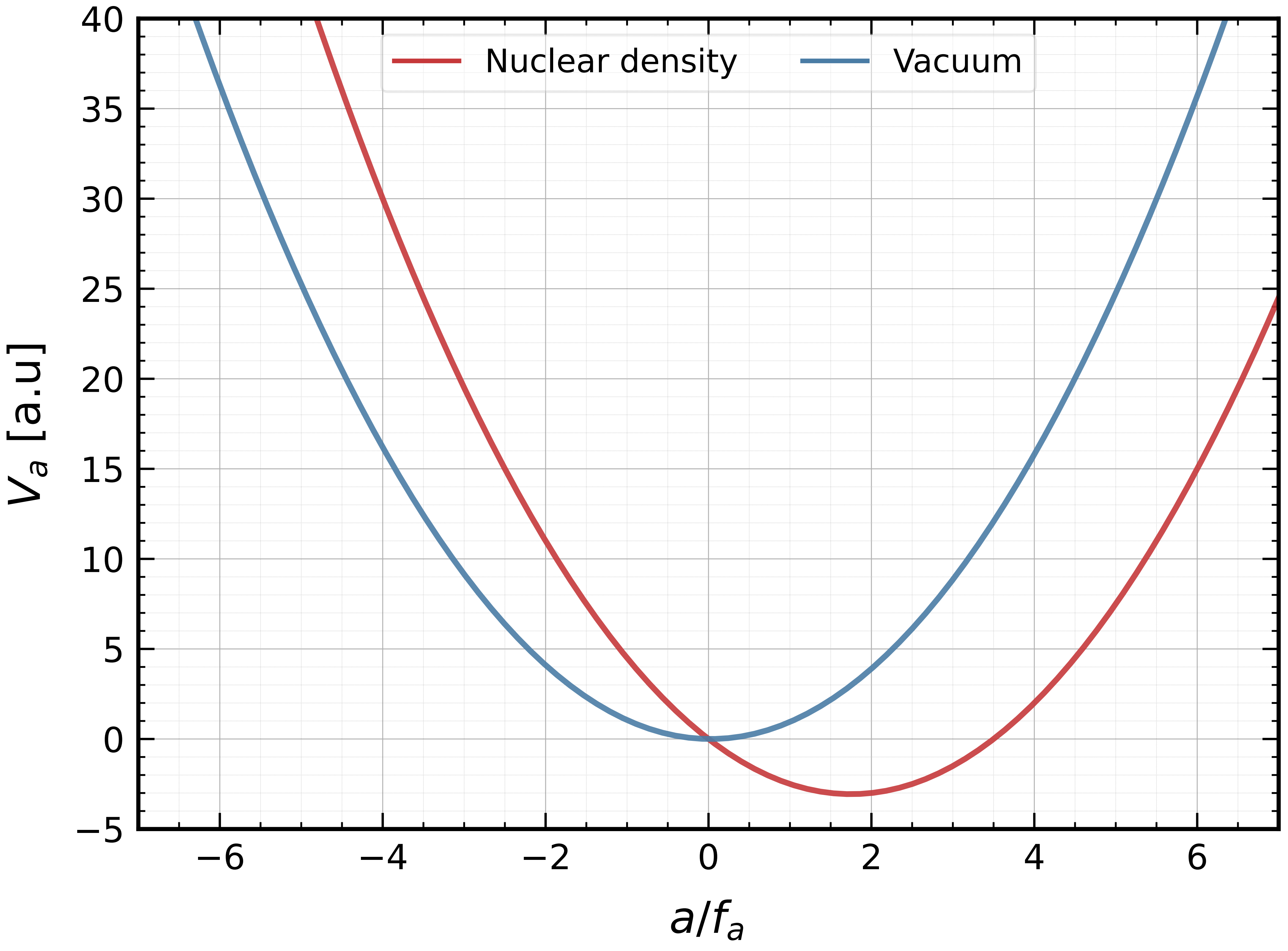
Creating dense `axion clouds'

Part II:

Sourcing "axion hair"

Sourcing axion hair

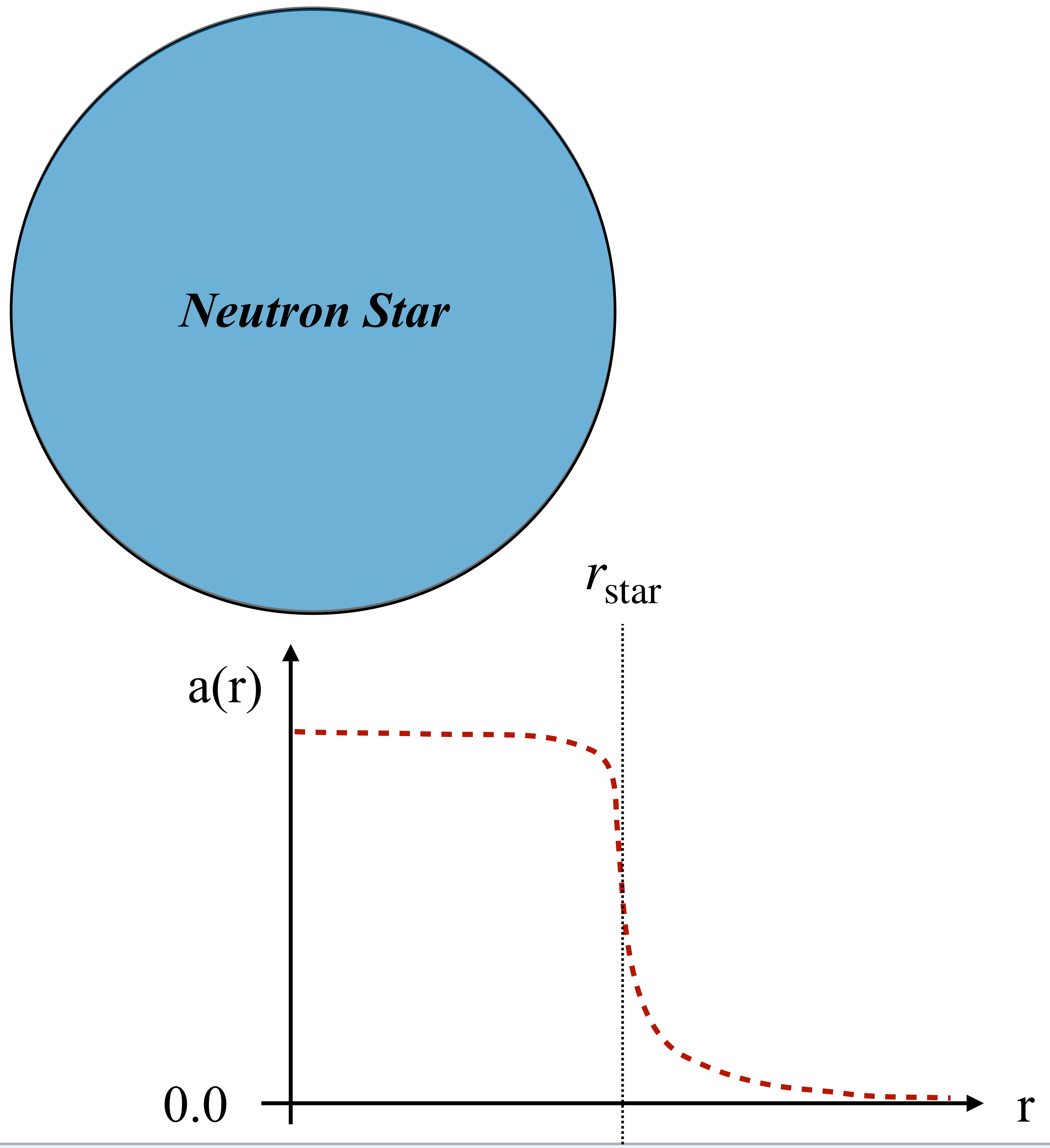
$$\mathscr{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + g_N a \bar{N} N$$



Finite nucleon density shifts the minimum of the potential

$$a_{\rm min} \sim g_N \frac{\langle \bar{N} N \rangle}{m_a^2}$$

Sourcing axion hair



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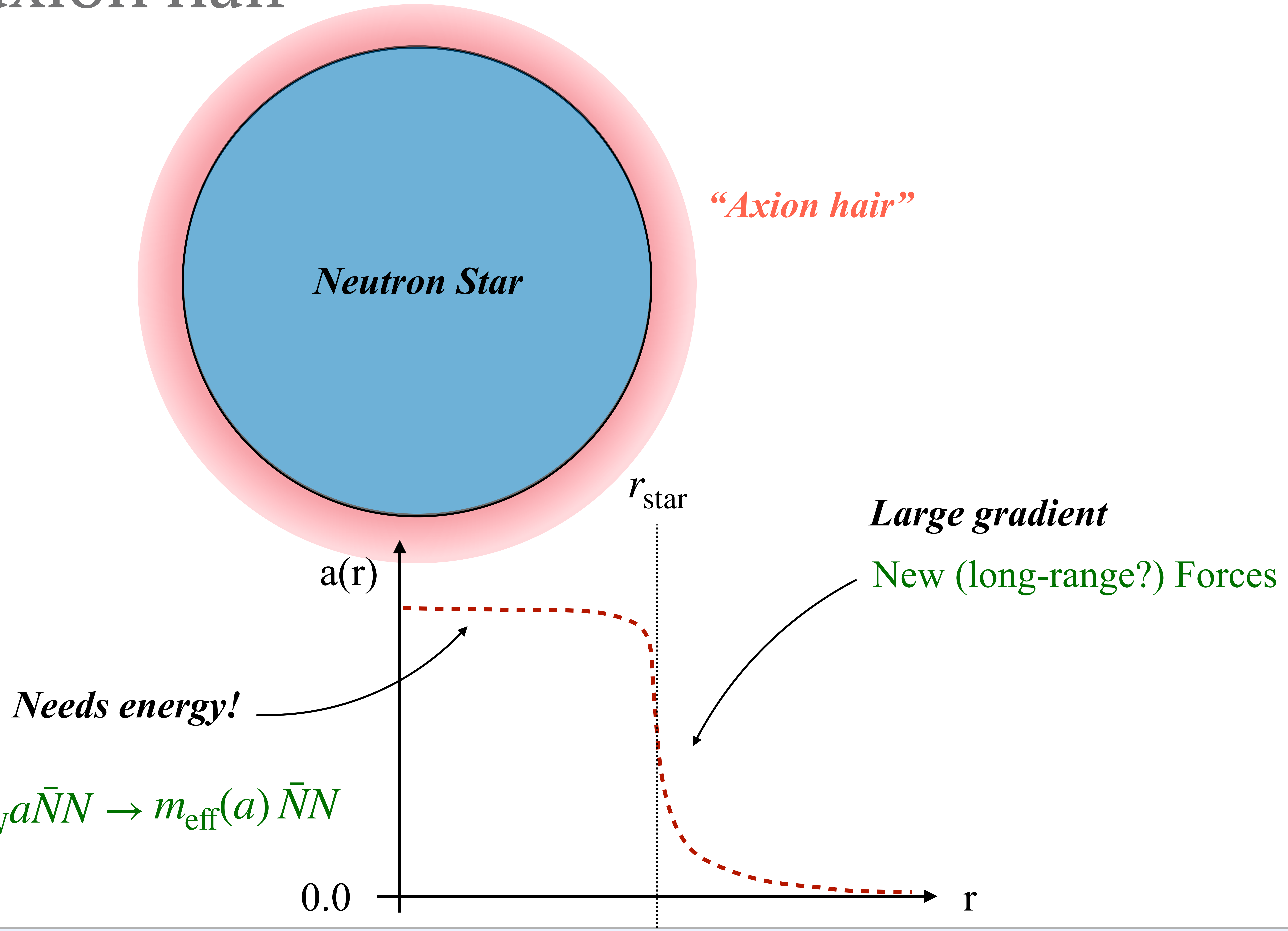

$$\mathscr{L} \supset g_N a \bar{N} N \to m_{\text{eff}}(a)\, \bar{N} N$$

Aside: *the "light QCD axion"*

Current example: $\mathscr{L} \supset \; g_N a \bar{N} N$

<u>*QCD axion*</u>

$$\mathscr{L}_\theta \propto \frac{a}{f_a} G \tilde{G}$$

Vacuum potential

$$V_{\rm vac} \sim -m_\pi^2 f_\pi^2 \left[\cos\frac{a}{f_a} - 1\right]$$

$$\sim m_a^2 a^2 + \cdots$$

Nucleon coupling

$$\mathscr{L}_{NN} \sim \left[\cos\frac{a}{f_a} - 1\right] \bar{N} N$$

$$\sim -a^2 \bar{N} N + \cdots$$

See e.g. Hook & Huang (2017), Hook(2018), Di Luzio et al (2021), Banerjee et al (2025)

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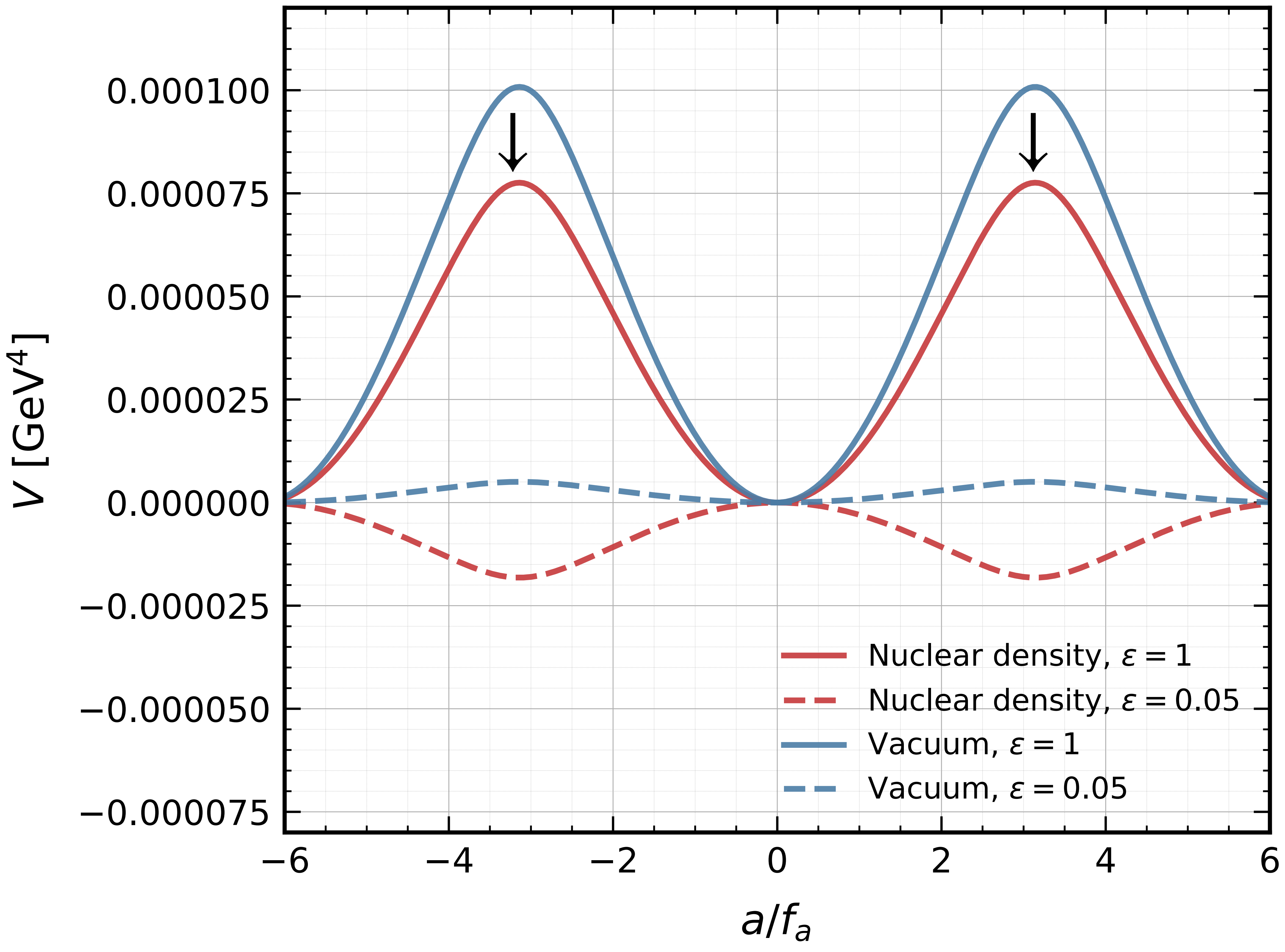

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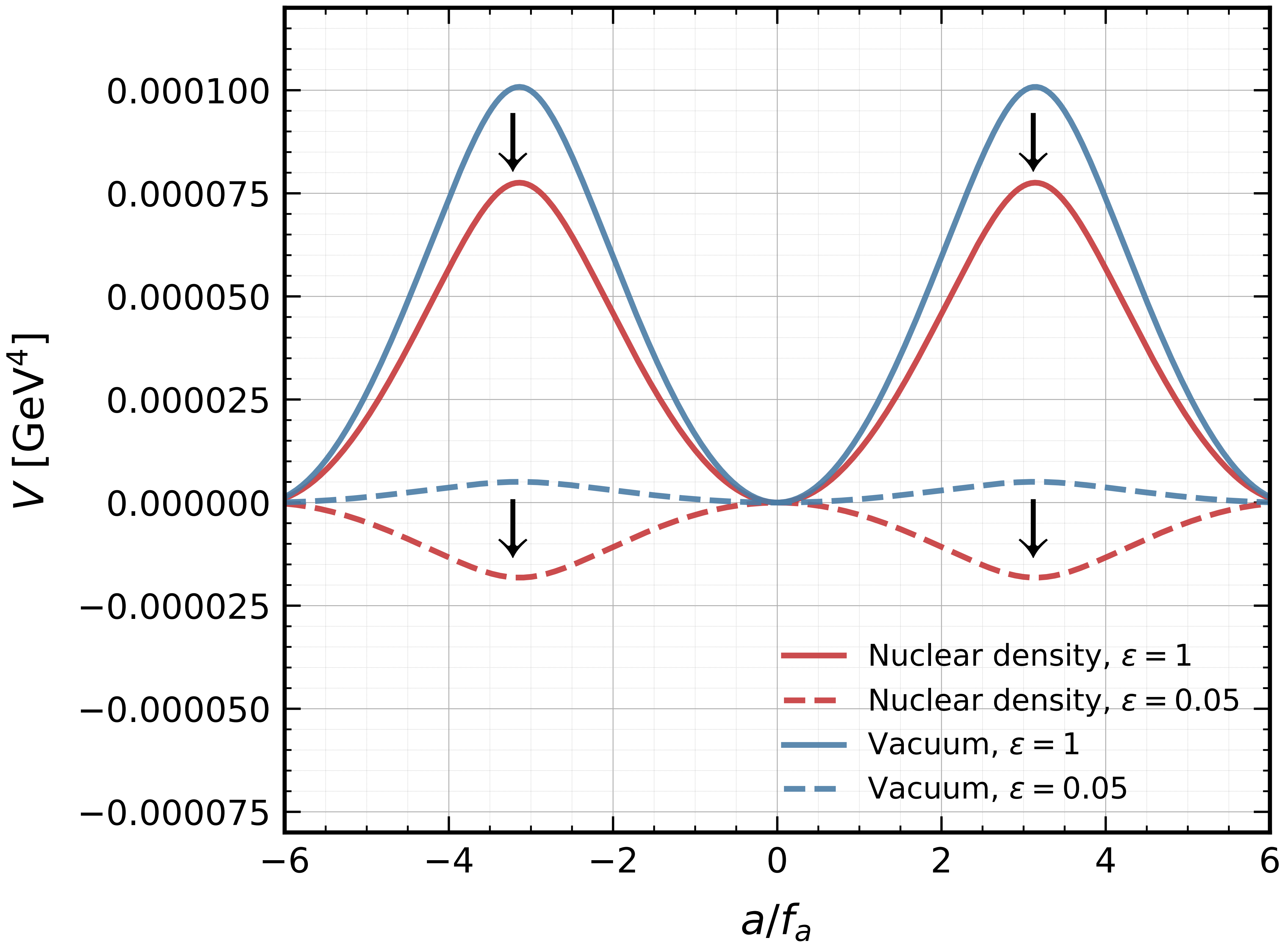

QCD axion

$$\mathscr{L}_\theta \propto \frac{a}{f_a} G \tilde{G}$$

Vacuum potential

$$V_{\rm vac} \sim -\epsilon\, m_\pi^2 f_\pi^2 \left[\cos\frac{a}{f_a} - 1\right]$$

$$\sim \epsilon\, m_a^2 a^2 + \cdots$$

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Implications of a distorted axion potential

1.) $m_N(a) \rightarrow$ modifications to the EoS

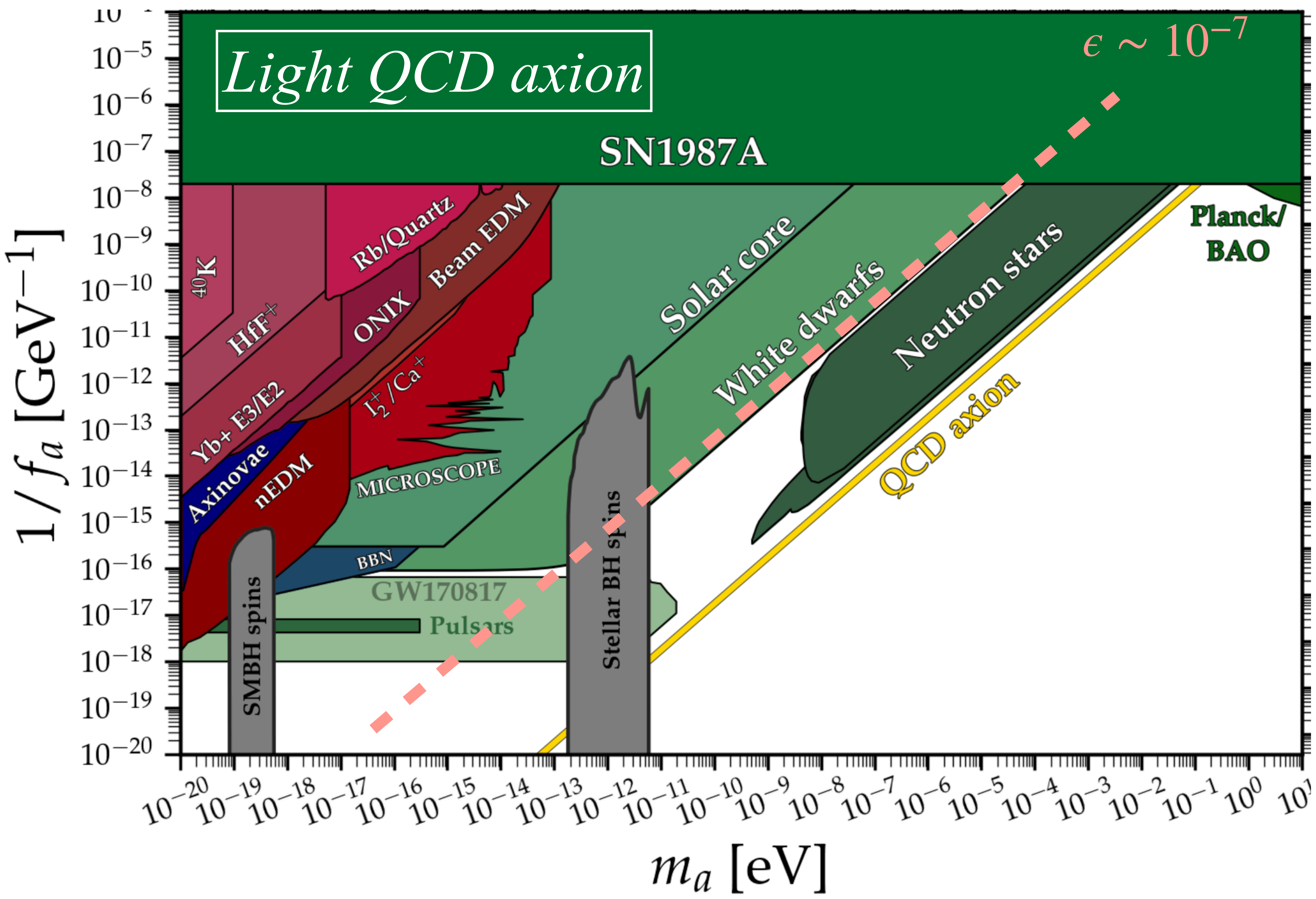
Difficult to compute at high density

See e.g. Balkin et al (2023)

1b.) Modified thermal envelope

Gómez-Bānön et al (2024), Kumamoto et al (2024)

Fig credit: C. O'hare (GitHub)



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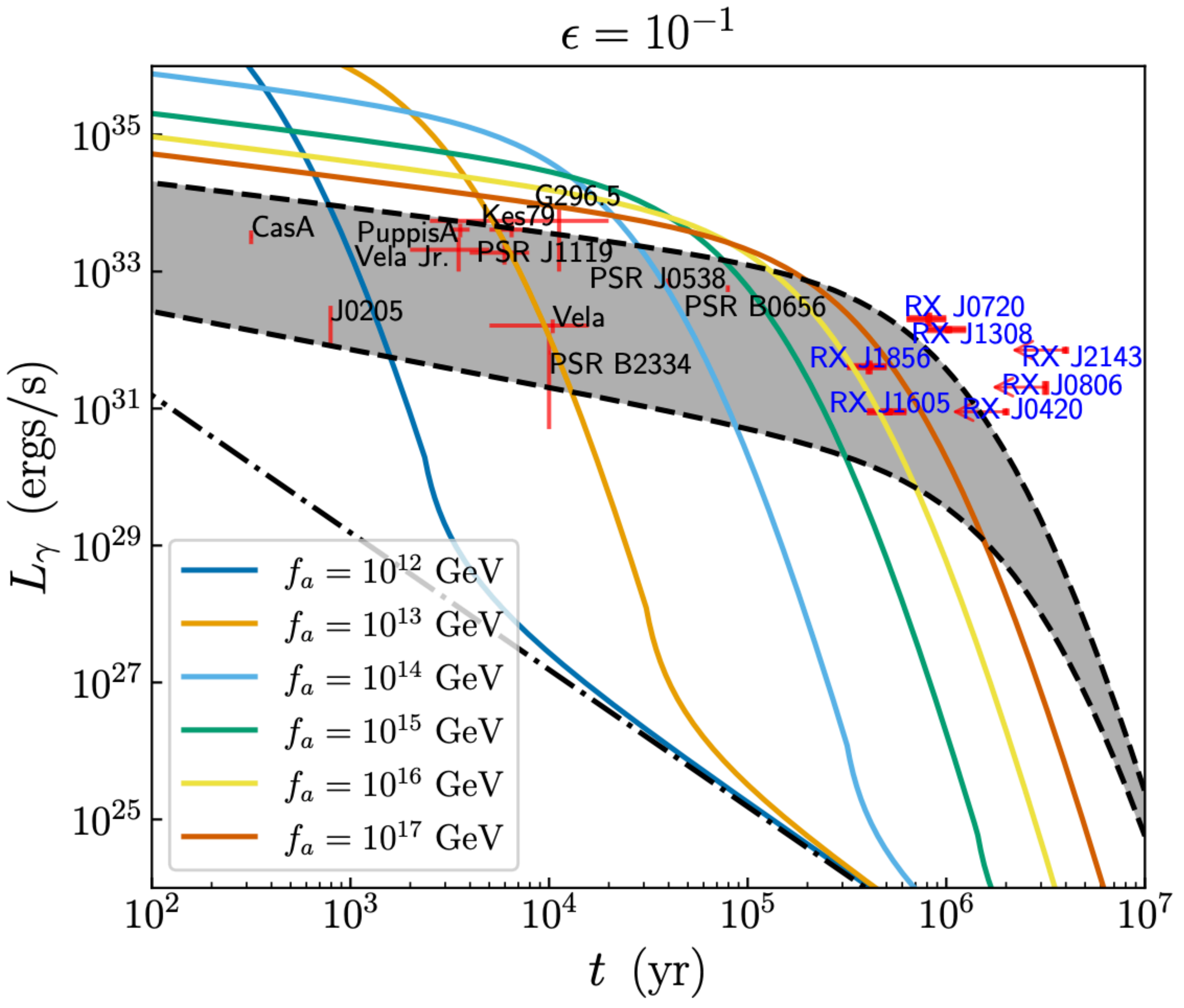

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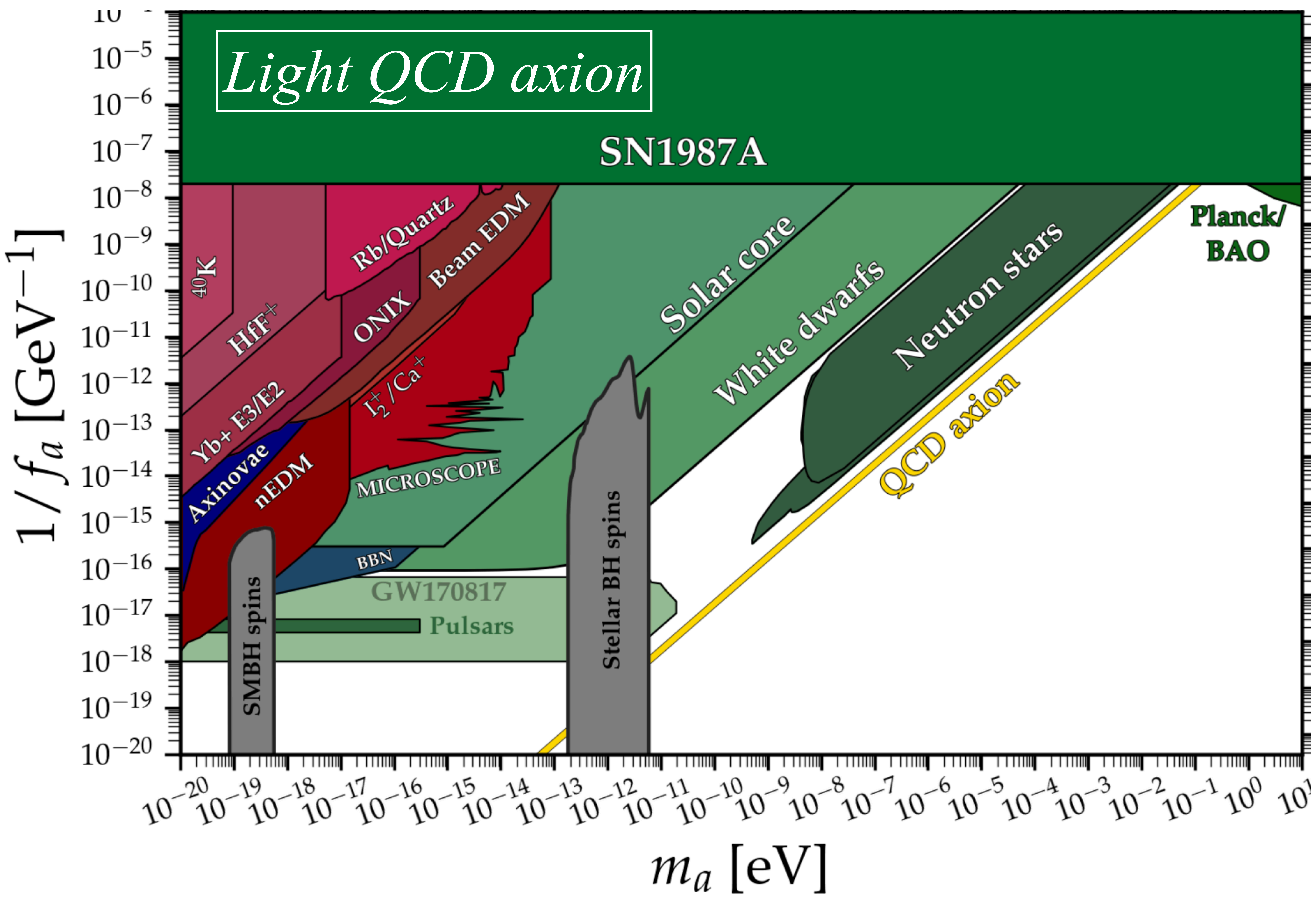

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1b.) Modified thermal envelope

Gómez-Bānön et al (2024), Kumamoto et al (2024)

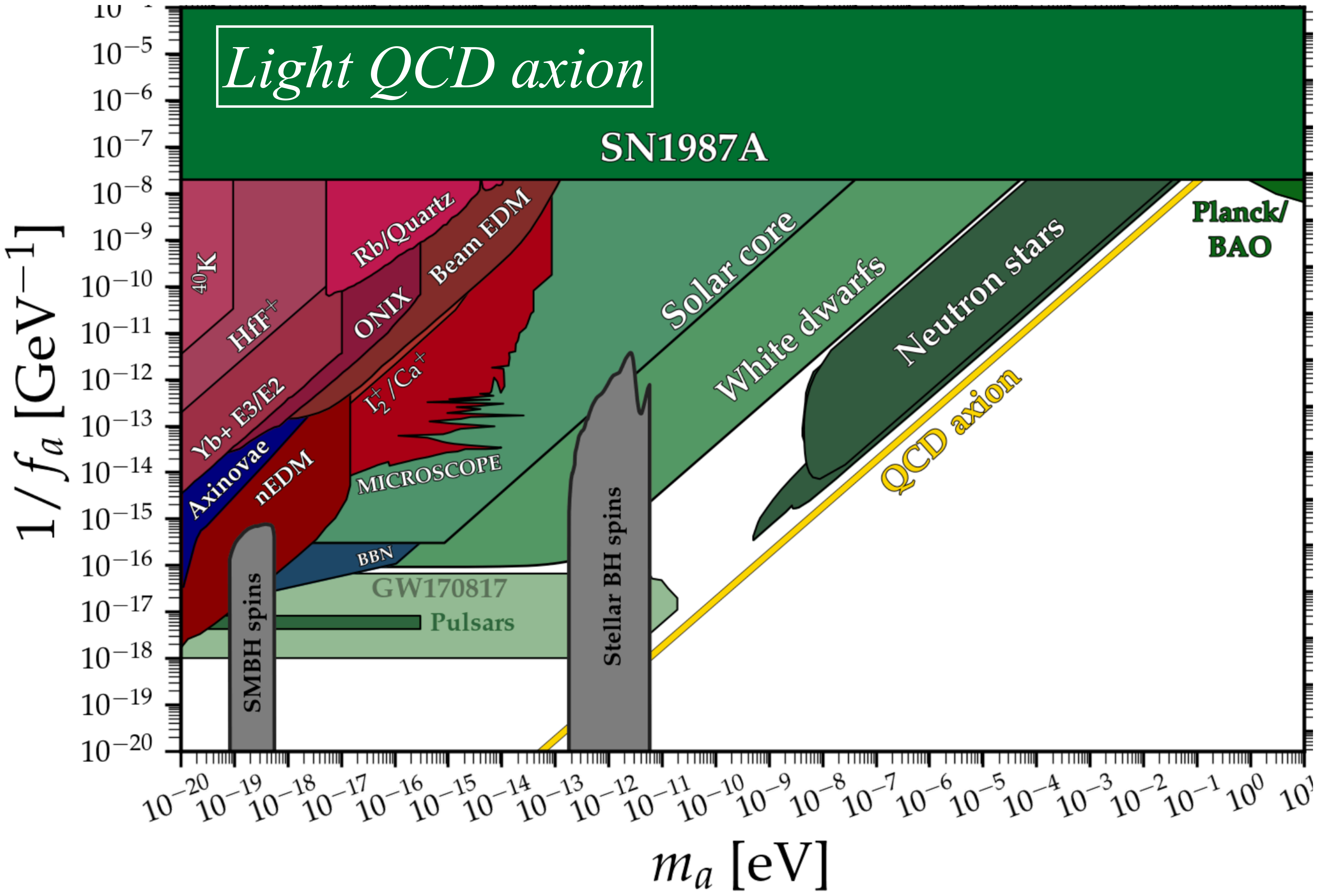
2.) New long range (m_a^{-1}) force

3.) Axion radiation in binary systems

Modified inspired GWs

Hook & Huang (2017), Di Luzio et al (2021), Zhang et al (2021)

Fig credit: C. O'hare (GitHub)

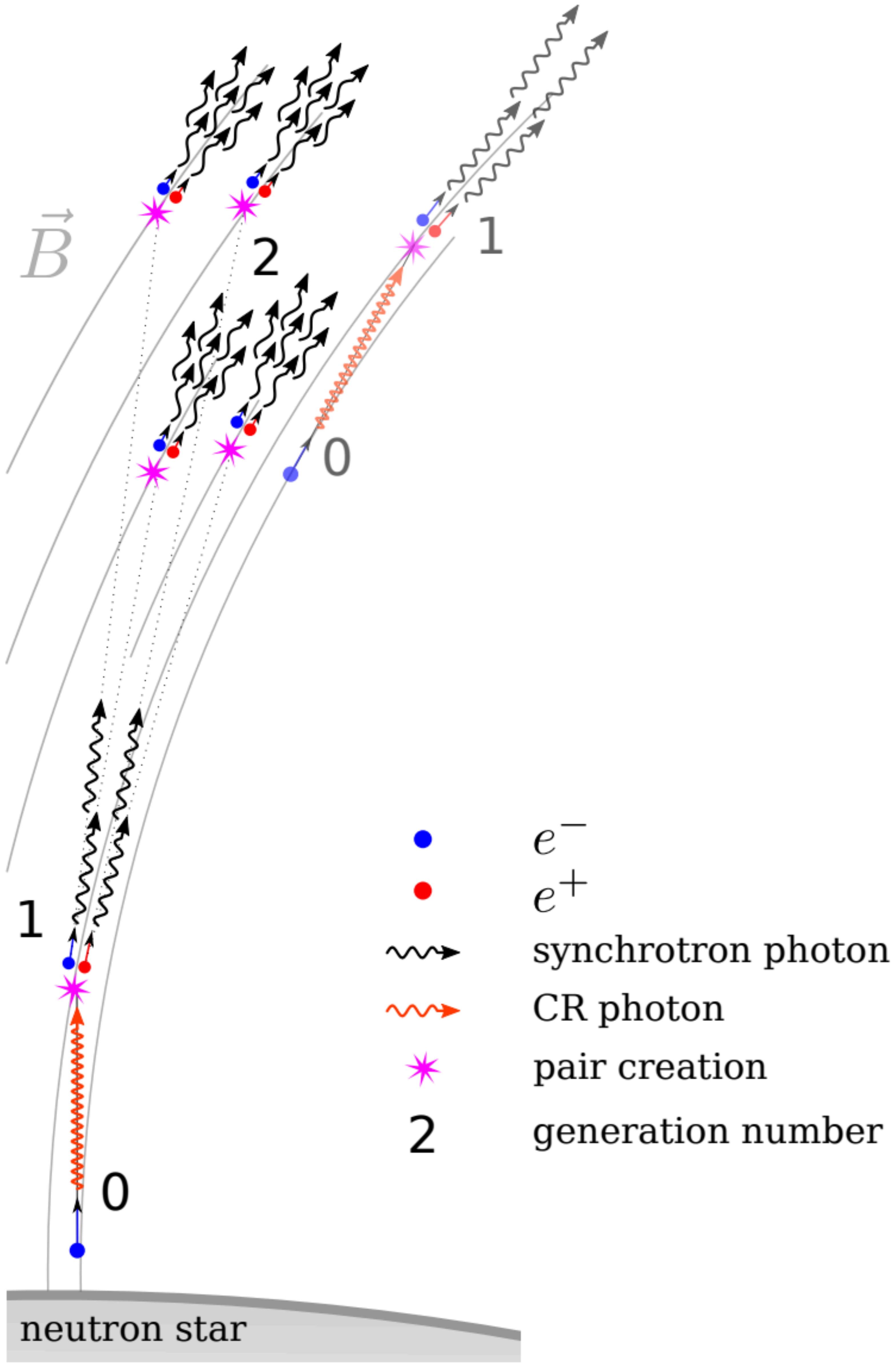


Implications of axion hair

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

Electric fields generated by axion $\gg$ those of pulsar

(Needed for plasma generation and radio emission)



SJW, Caputo, Stelzl, Chernoglazov, Philippov, Rajendran (*Appearing any week now….*)

Fig credit: Timokhin & Harding (2015)

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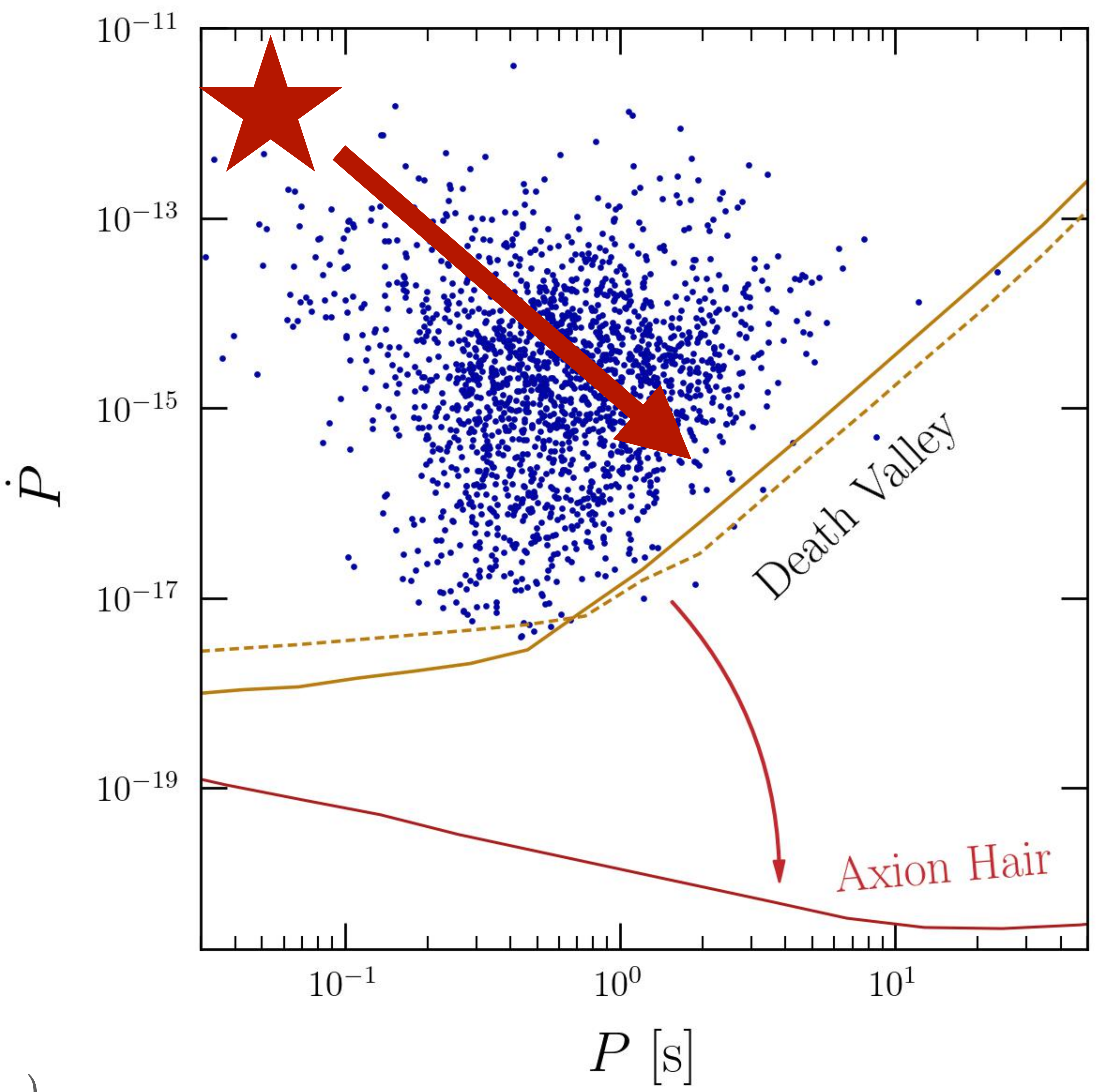

<u>Typical Pulsar Life:</u>

Born fast and strong → become slow and weak → "die"

$$(\Delta V)_{\max} \sim B\Omega^2$$

SJW, Caputo, Stelzl, Chernoglazov, Philippov, Rajendran (*Appearing any week now….*)

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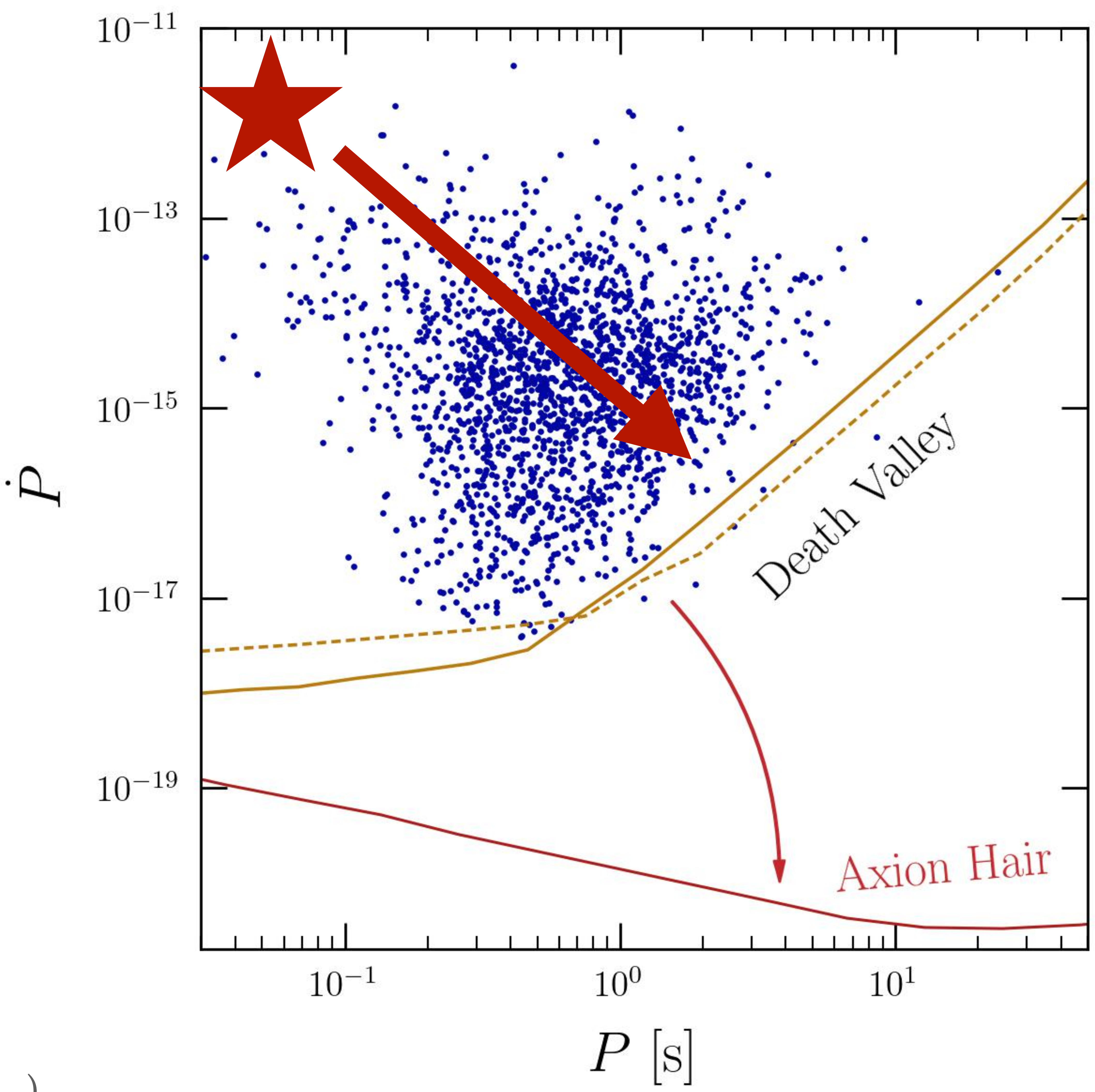
$$\nabla \cdot E = \rho + g_{a\gamma\gamma} \nabla a \cdot B$$

Electric fields generated by axion ≫ those of pulsar



<u>Typical Pulsar Life:</u>

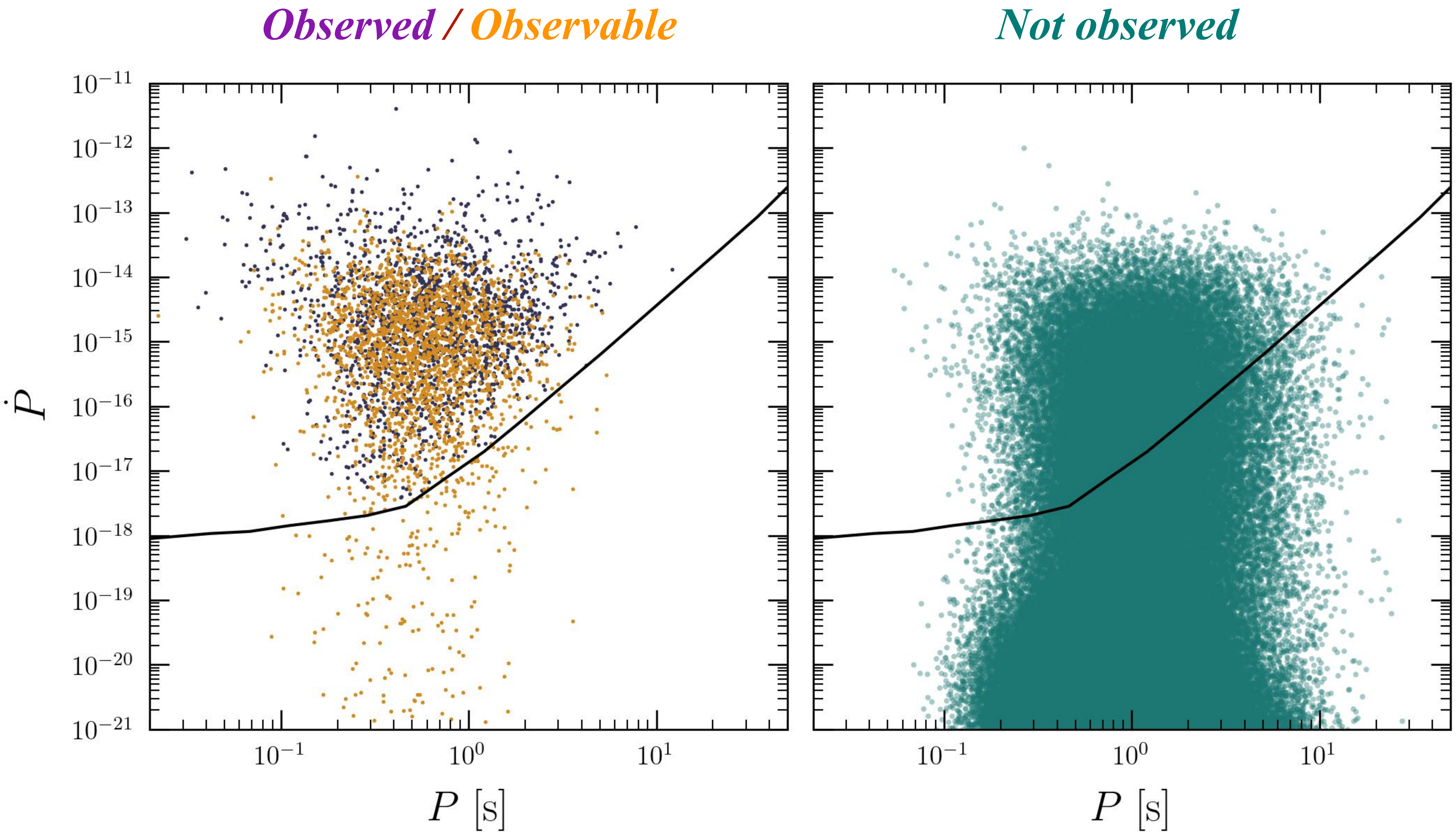
Born fast and strong → become slow and weak → "die"

$$(\Delta V)_{\max} \sim B\Omega^2$$

Axion hair extends pulsar lifetime

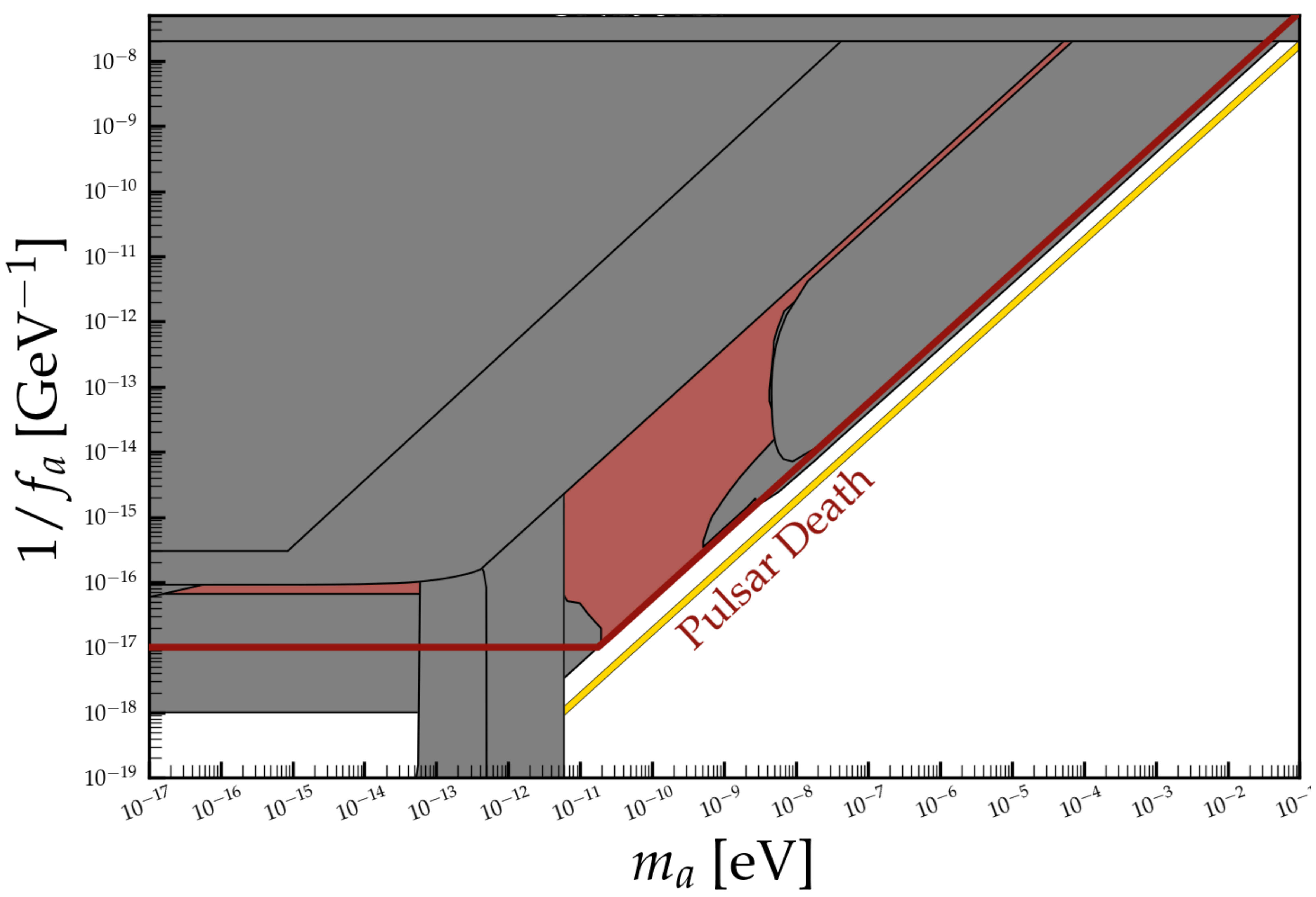
SJW, Caputo, Stelzl, Chernoglazov, Philippov, Rajendran (*Appearing any week now….*)

Pulsars below the death line

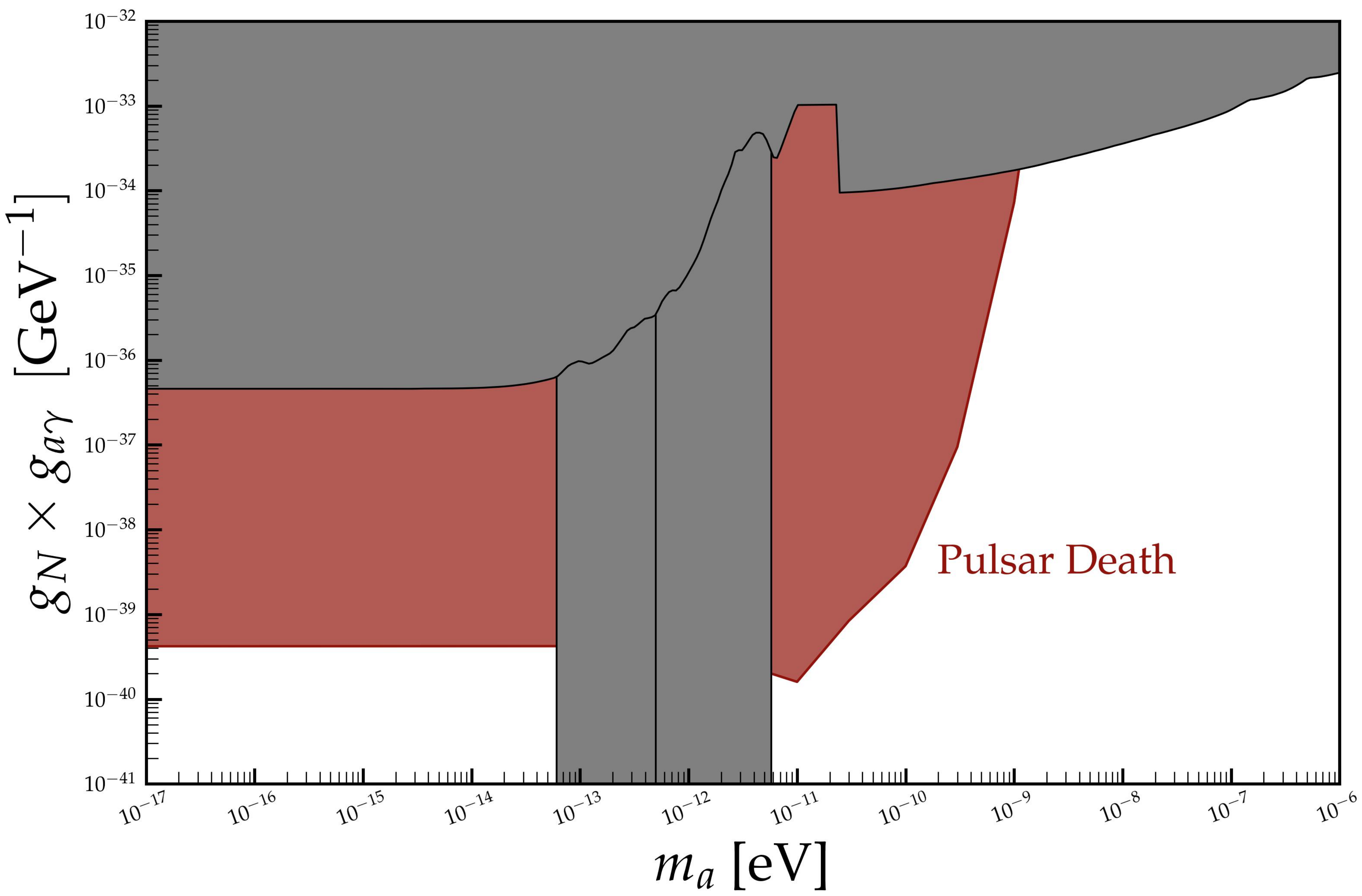


Extending the life of dying pulsars

Light QCD axion



$\mathscr{L} \supset \; g_N a \bar{N} N$



SJW, Caputo, Stelzl, Chernoglazov, Philippov, Rajendran (*Appearing any week now….*)

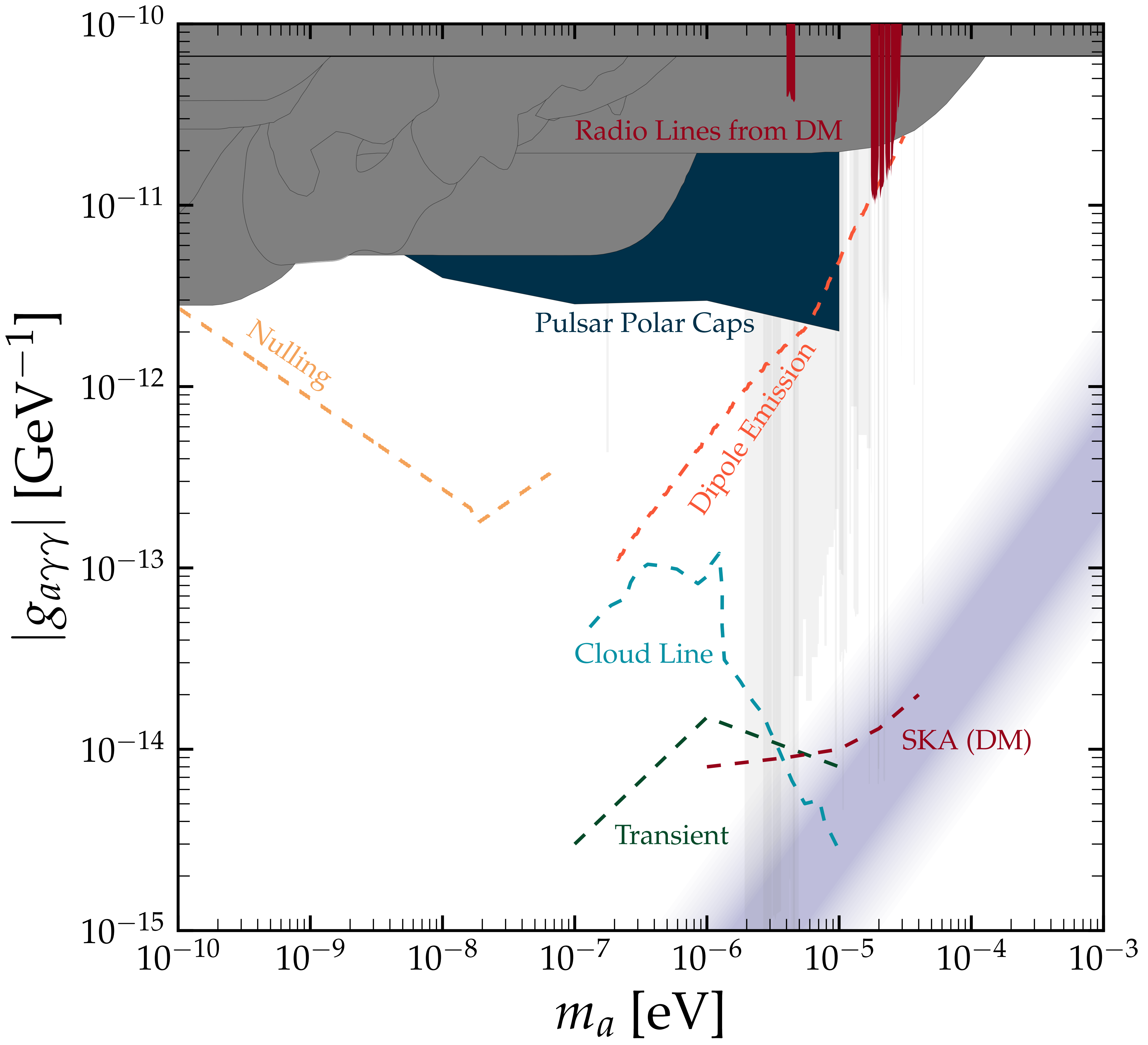
Conclusions

Recent ideas I've highlighted:

- Large static axion gradients from nuclear interactions
- Slow construction of axion clouds from pair discharges

Hook & Huang (2017), Hook(2018), Di Luzio et al (2021), Banerjee et al (2025) , Balkin et al (2023, 2024, 2025), Gómez-Bānön et al (2024), Kumamoto et al (2024), **SJW,** et al (*2509.xxxx.*), …

Noordhuis, Prabhu, Weniger, **SJW** (PRX, 2024), Caputo, **SJW,** Philippov, Jacobson (PRL, 2024)



There are many more ideas I haven't had time to cover:

- Neutron star cooling of QCD axions
- Resonant axion-photon mixing in magnetospheres
- PTAs as probes of axions
- …. (+ more)

Dessert et al (2022), ….

Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), Prabhu (2021), Noordhuis, Prabhu, **SJW**, et al (2022), …

De Martino et al (2017), Lee et al (2021), Servant et al (2023), Blast et al (2023), Tasinato (2023)…..