Simulating axion electrodynamics near pulsars

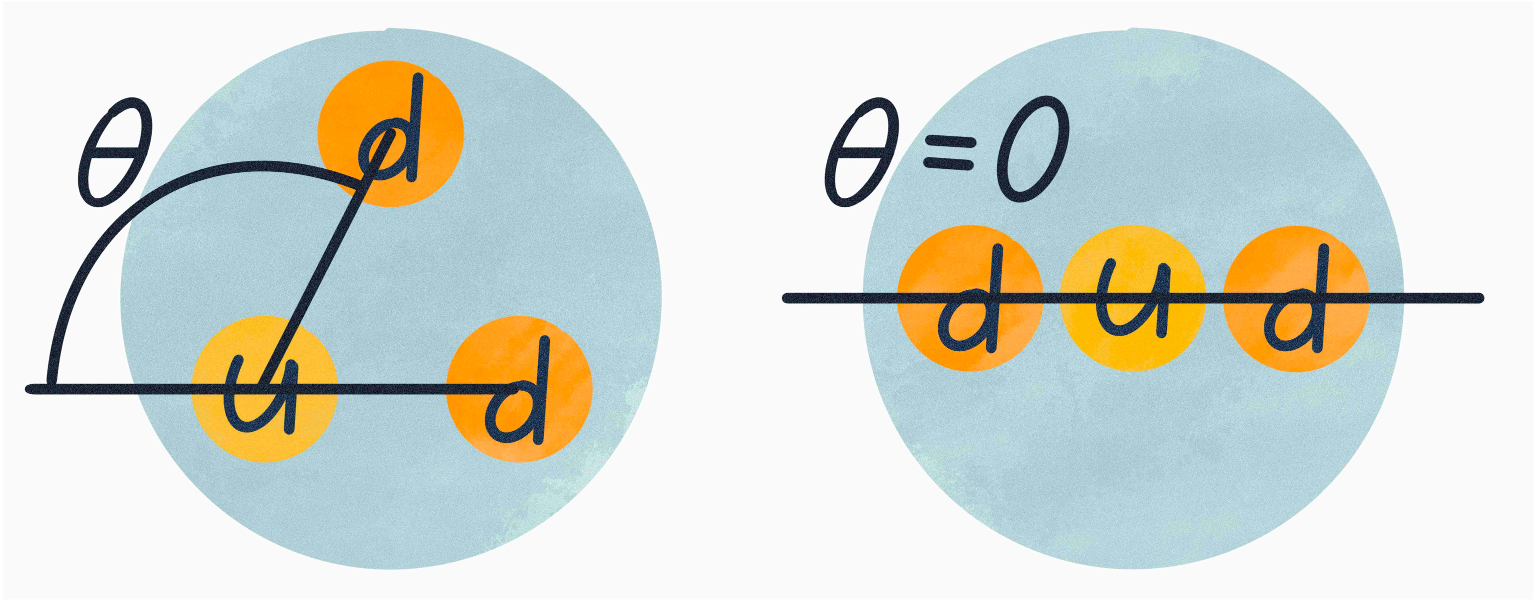
DESY Theory Workshop

Anne Freise

UNIVERSITY OF OXFORD

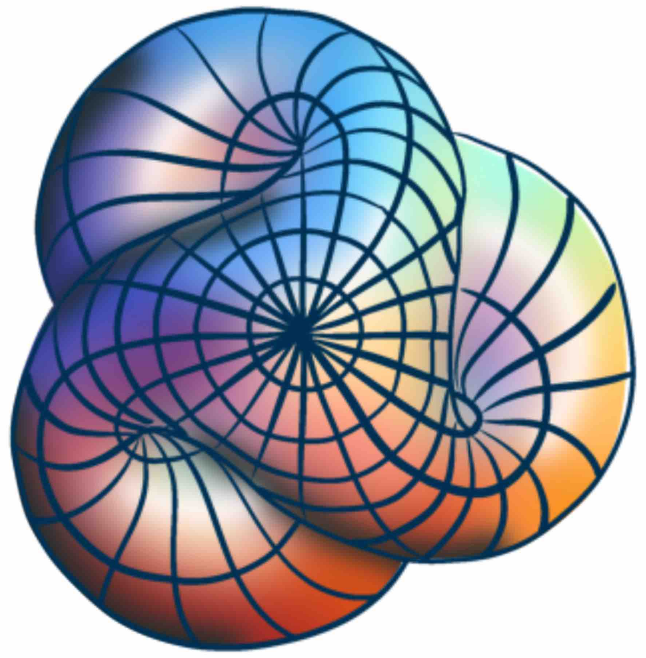
Briefly: The axion

Motivation for axions:



Strong CP-Problem

Dark matter



ALPs from UV theories

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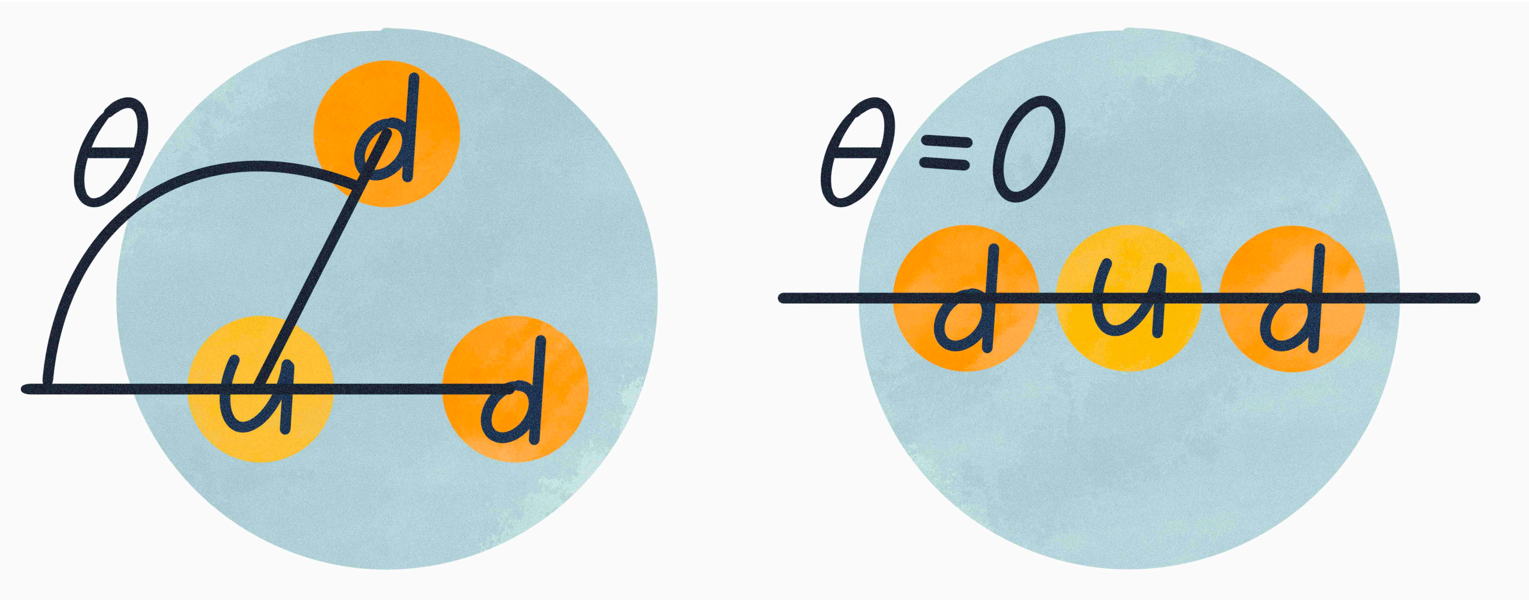

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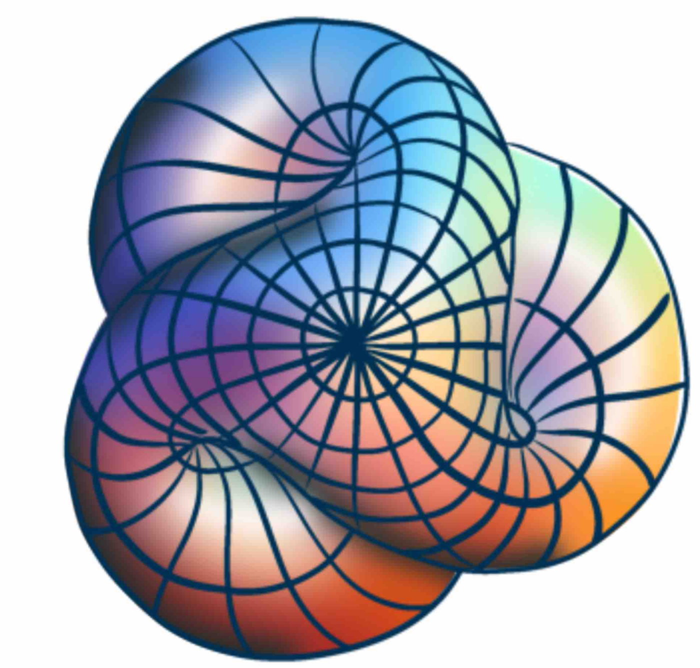

ALPs from UV theories

Axion couple to EM:

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

$$\nabla \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + g_{a\gamma\gamma} \frac{\partial a}{\partial t} \vec{B} + g_{a\gamma\gamma} \nabla a \times \vec{E}$$

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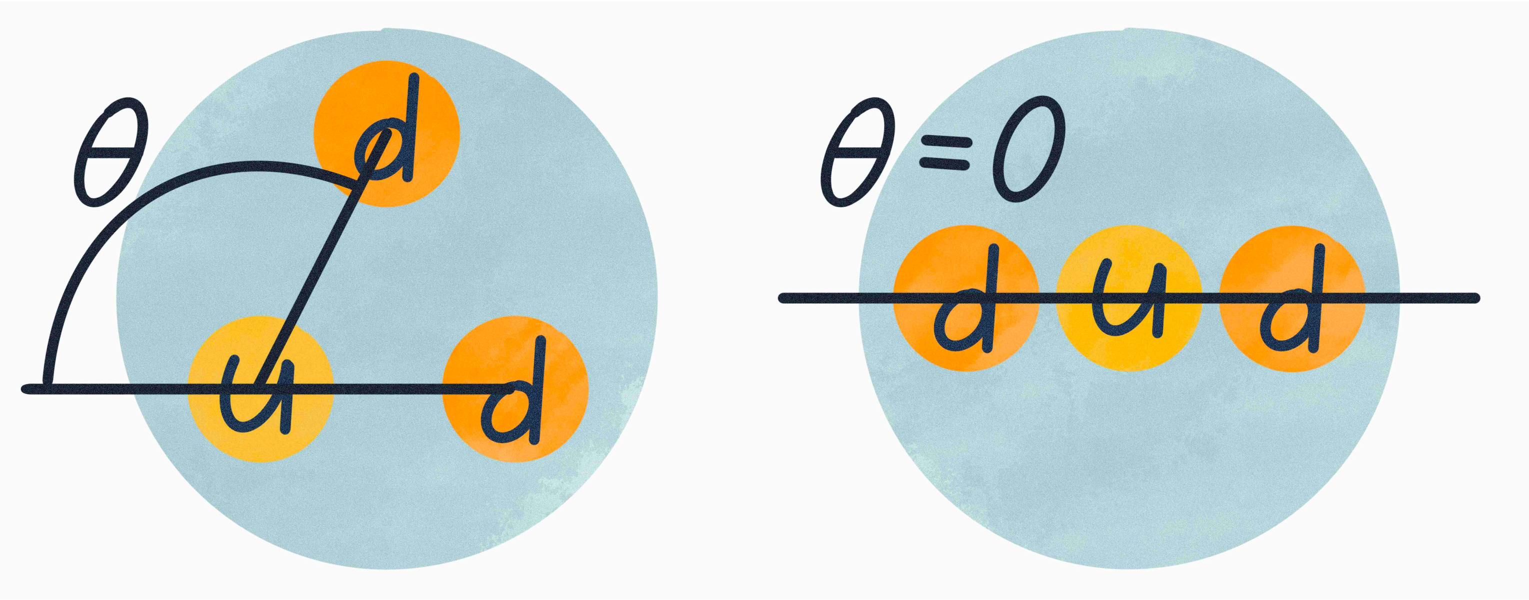

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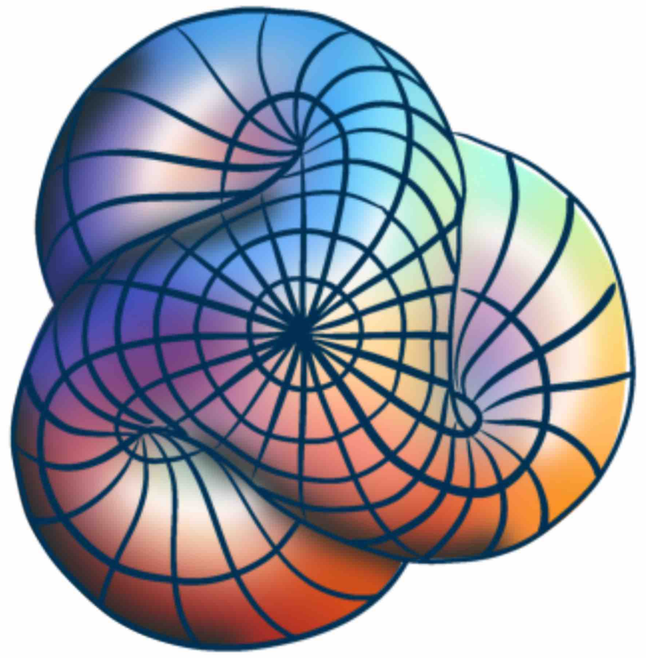

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Axion-induced charge density

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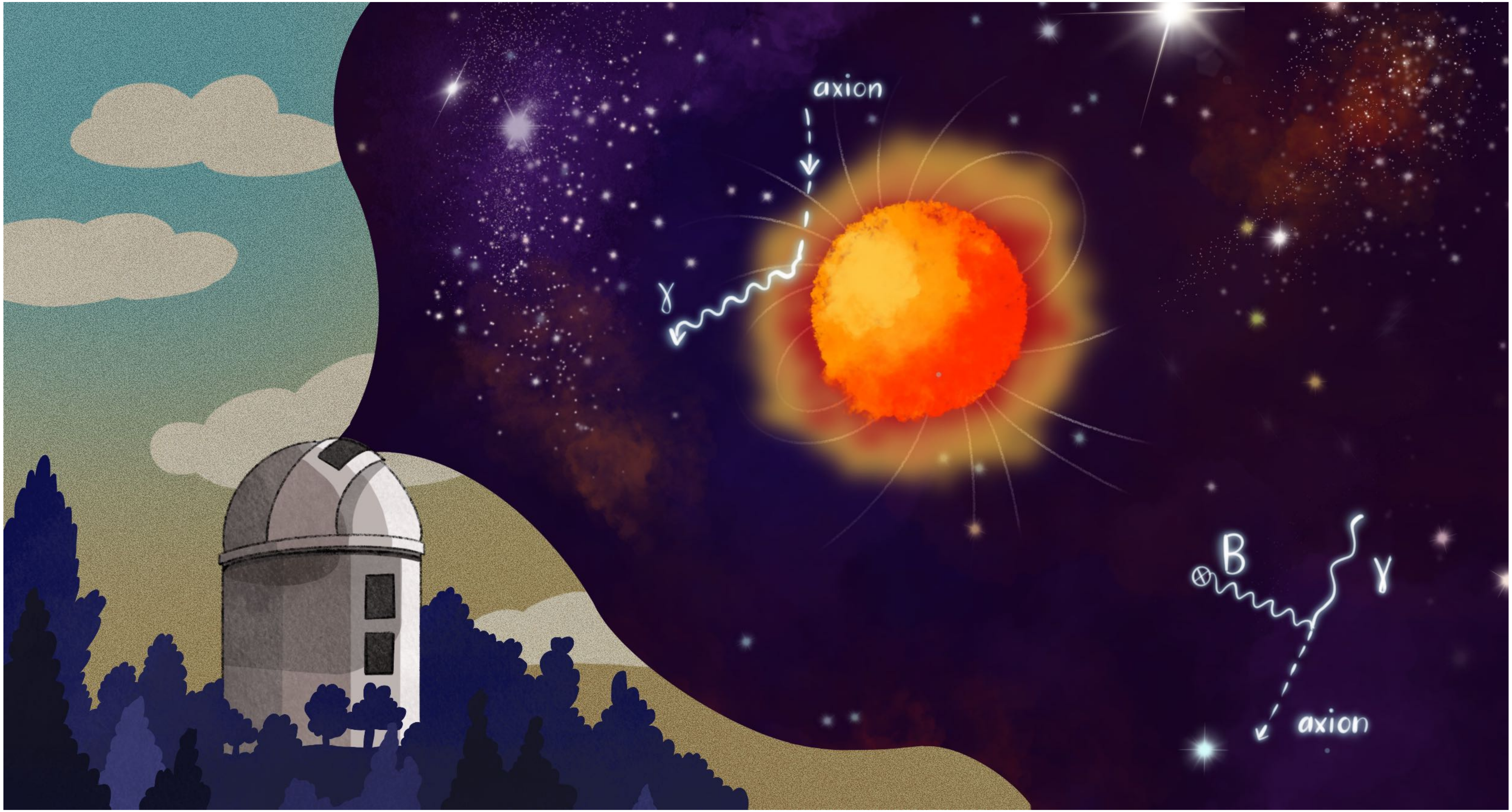
Axion-induced current density

Searches for axions via coupling to photons



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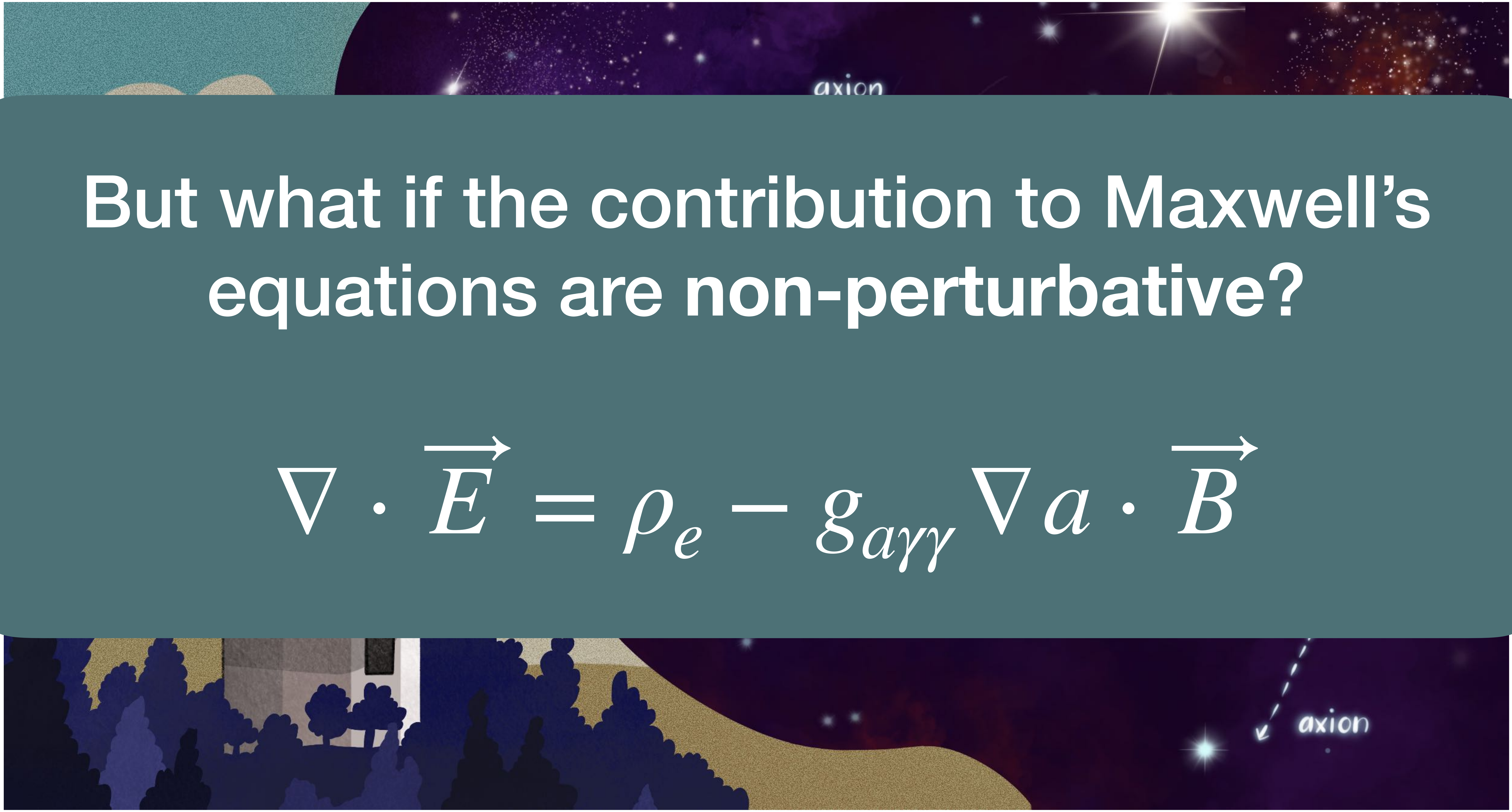

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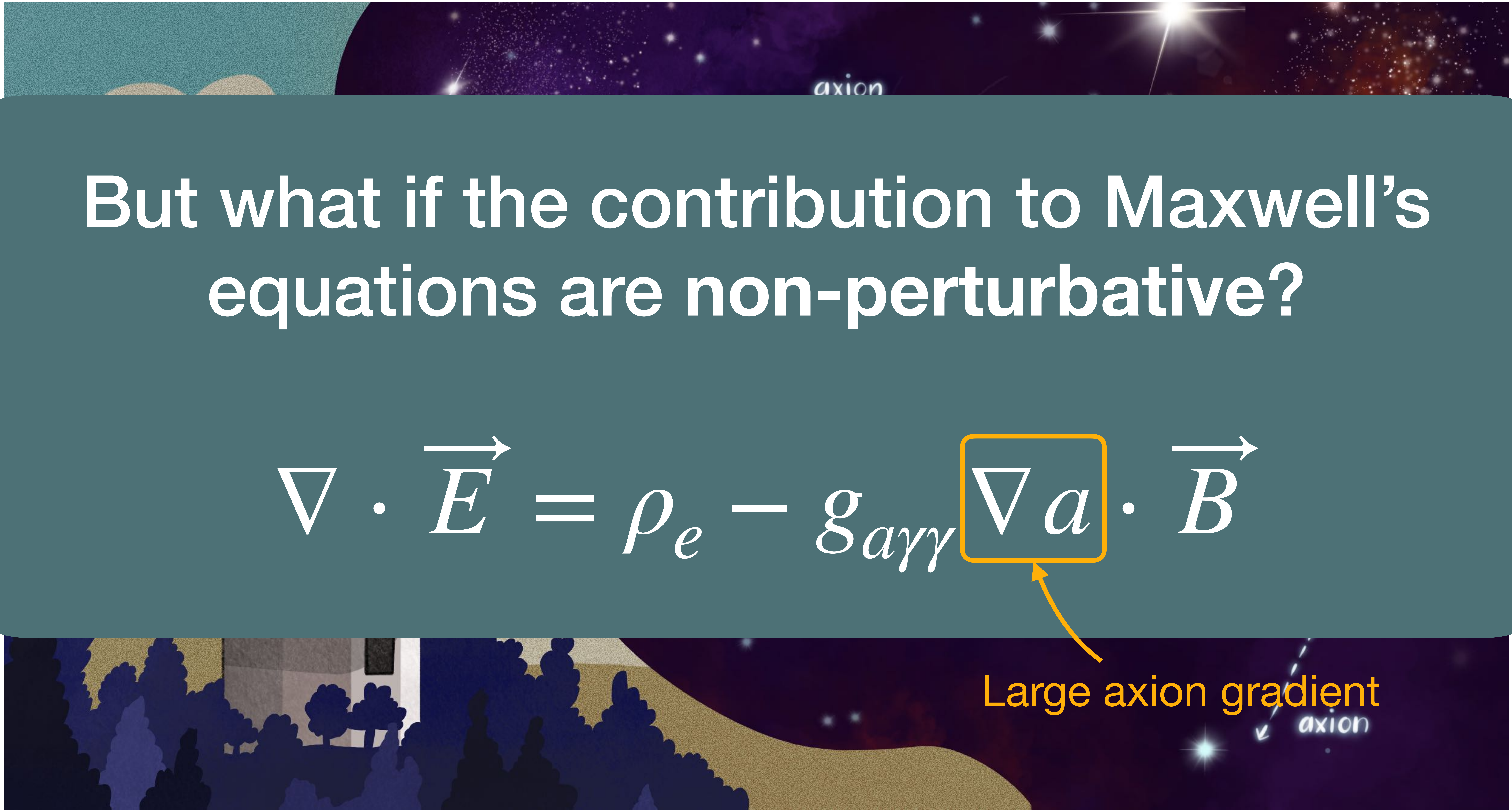

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Large axion gradient

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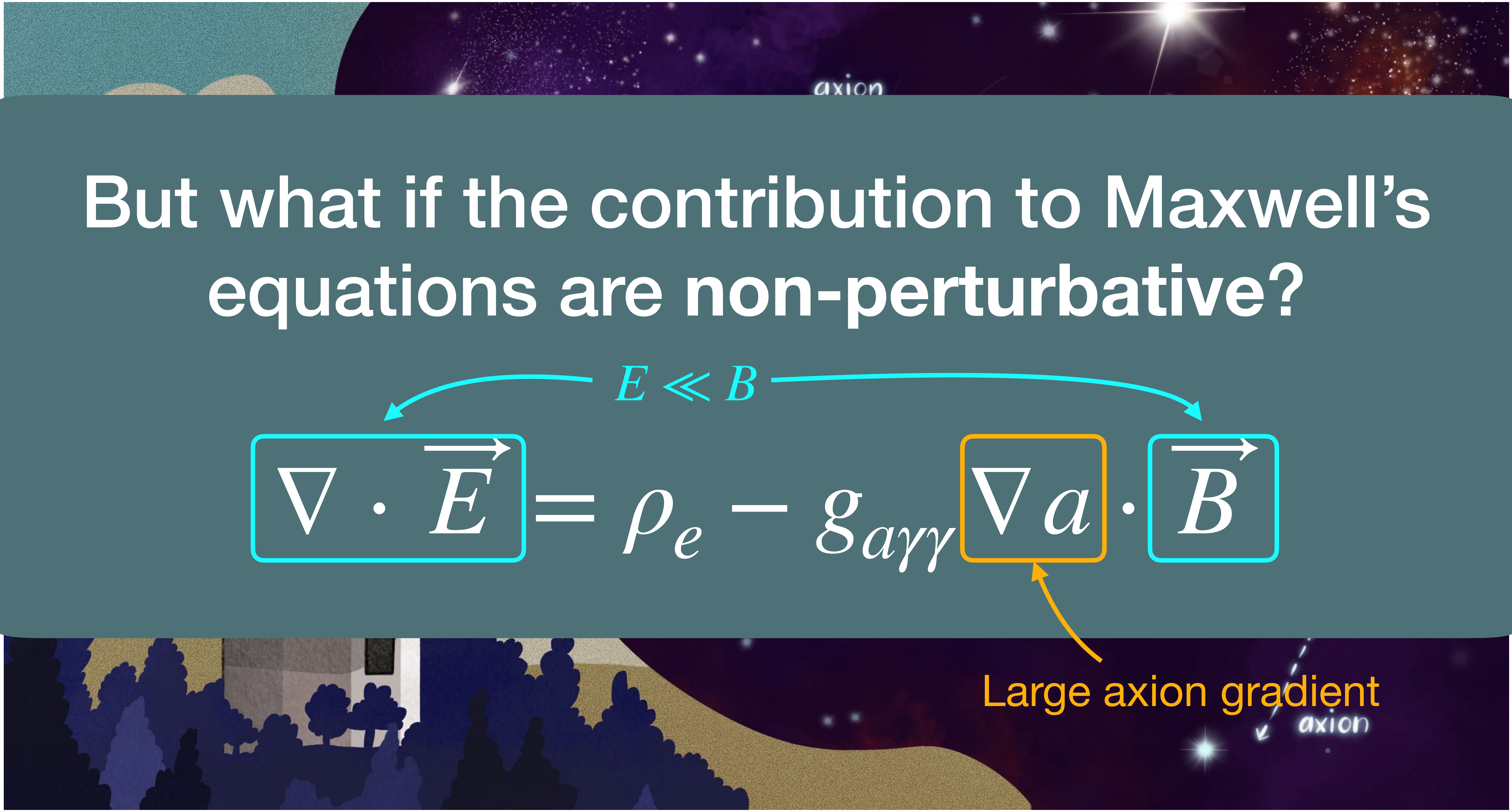

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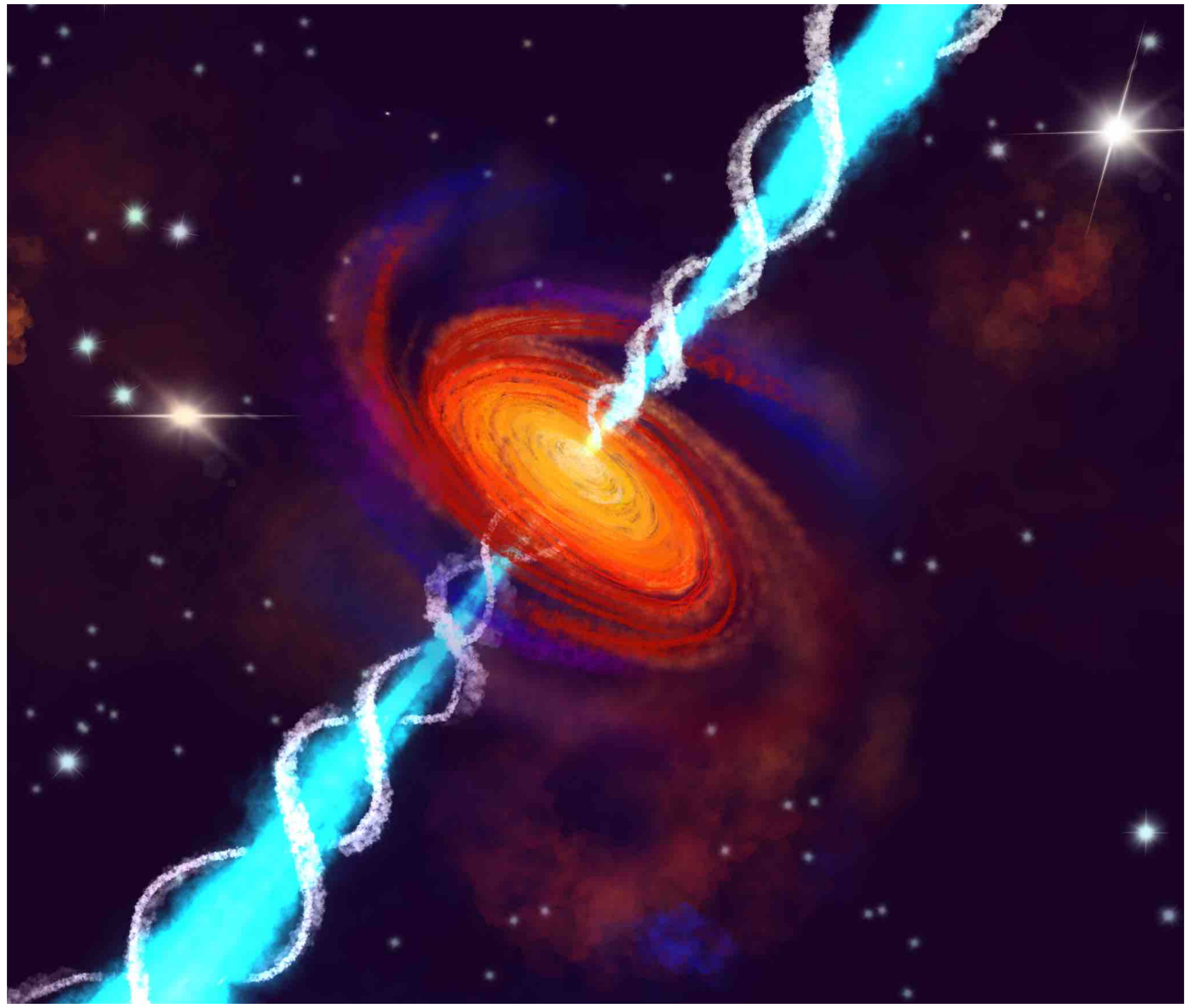
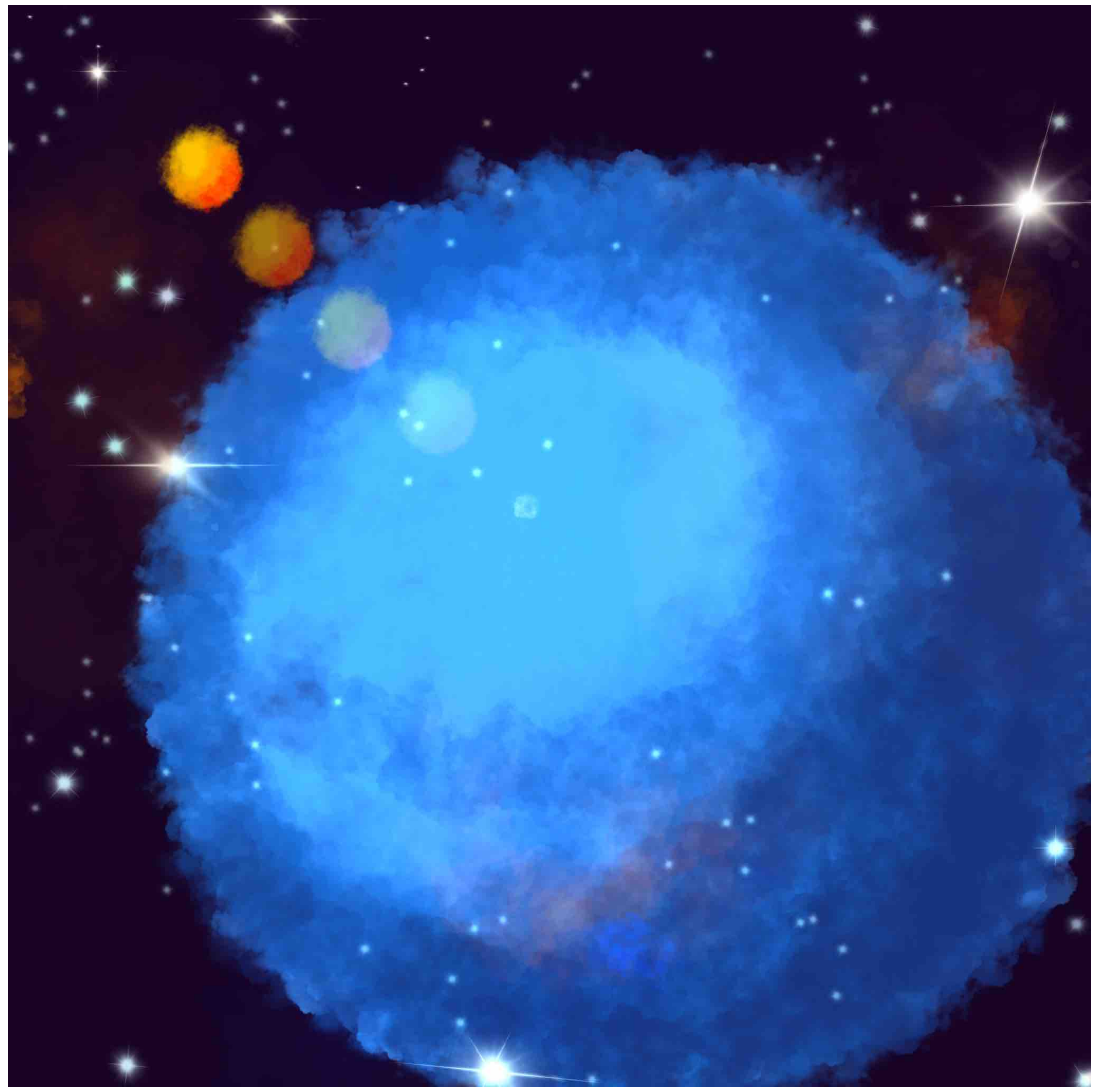
$E \ll B$

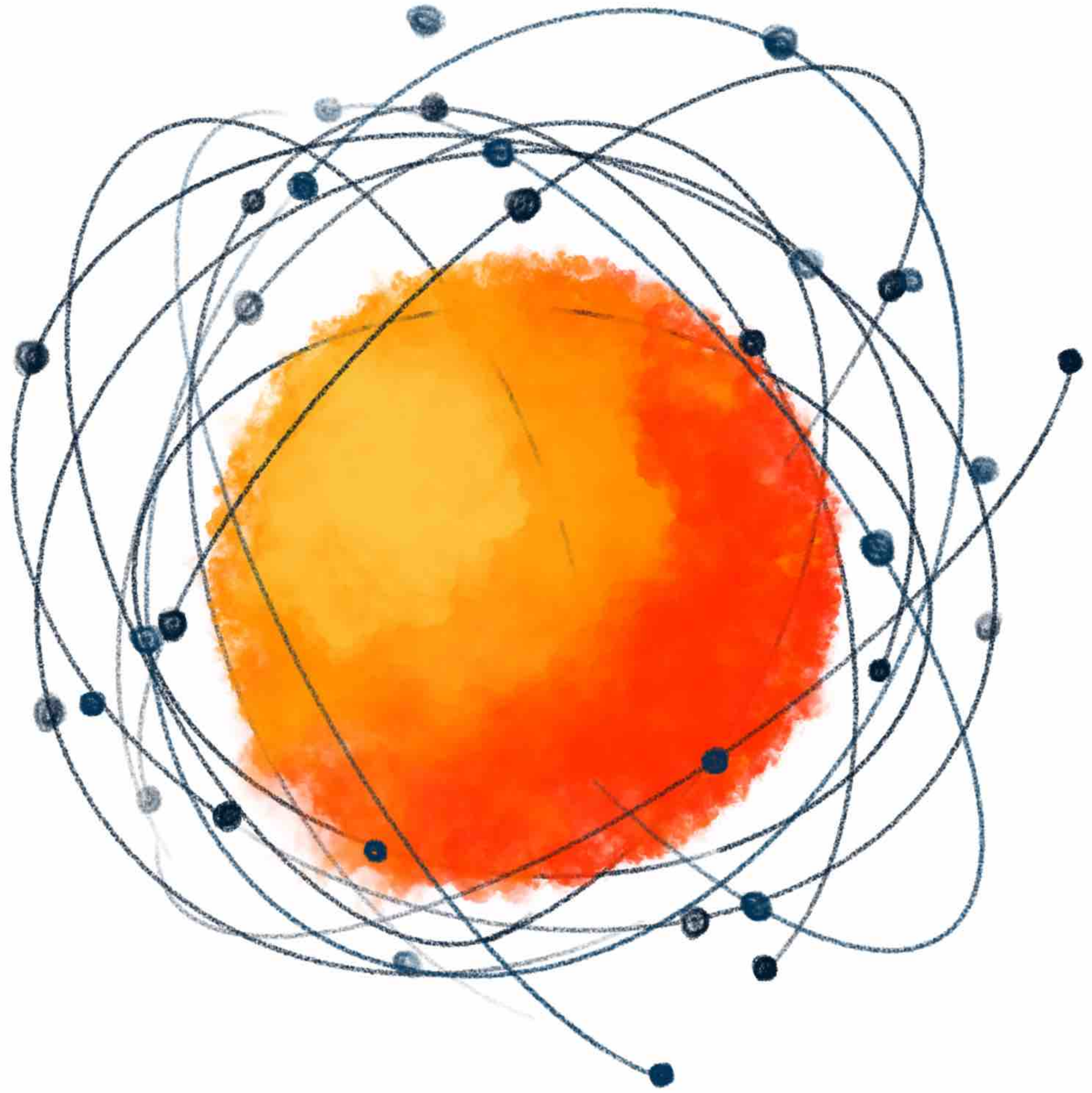
$$\nabla \cdot \vec{E} = \rho_e - g_{a\gamma\gamma} \nabla a \cdot \vec{B}$$

Large axion gradient

Non-perturbative axion electrodynamics: Black holes, axion stars and axion clouds







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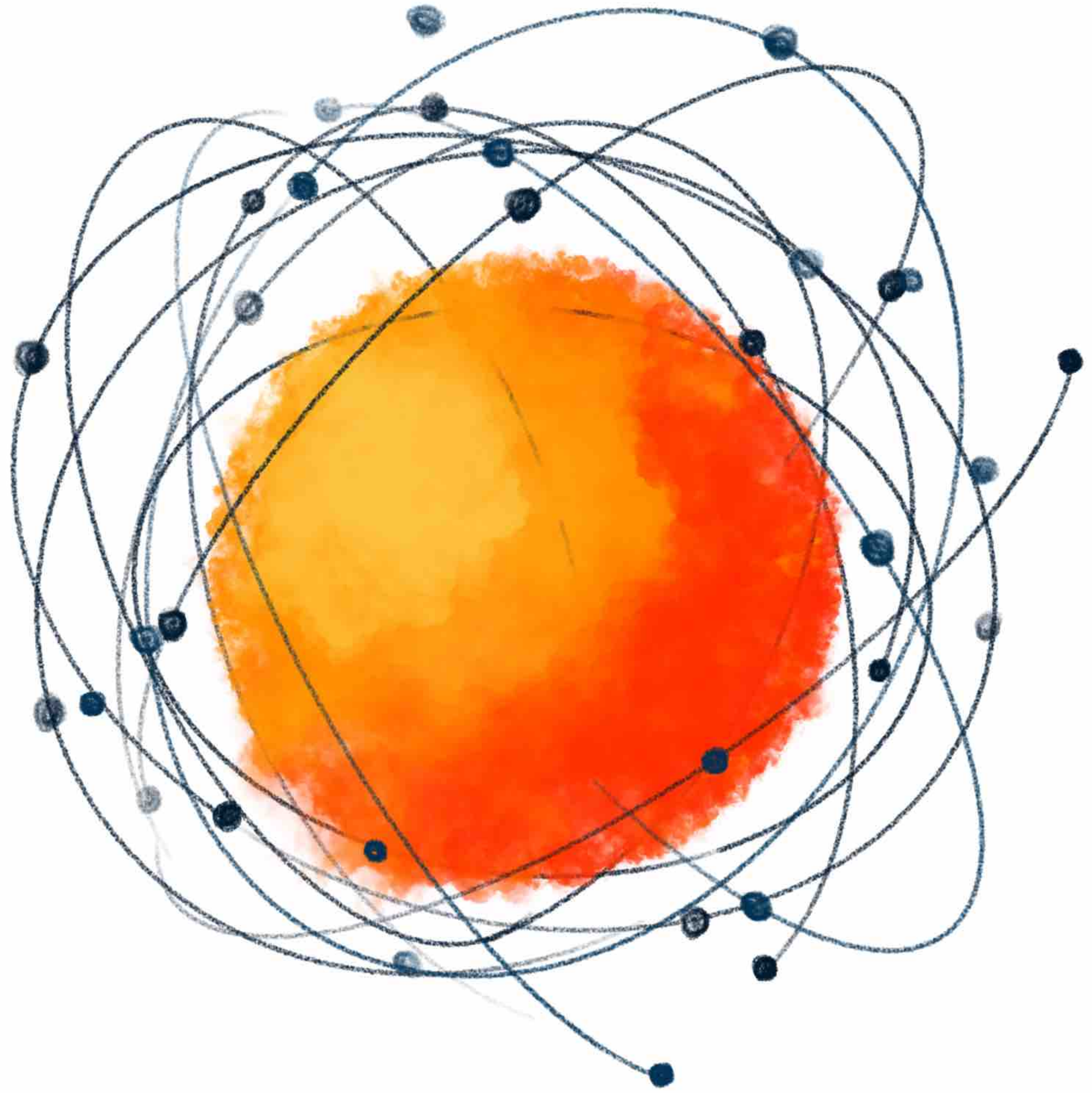
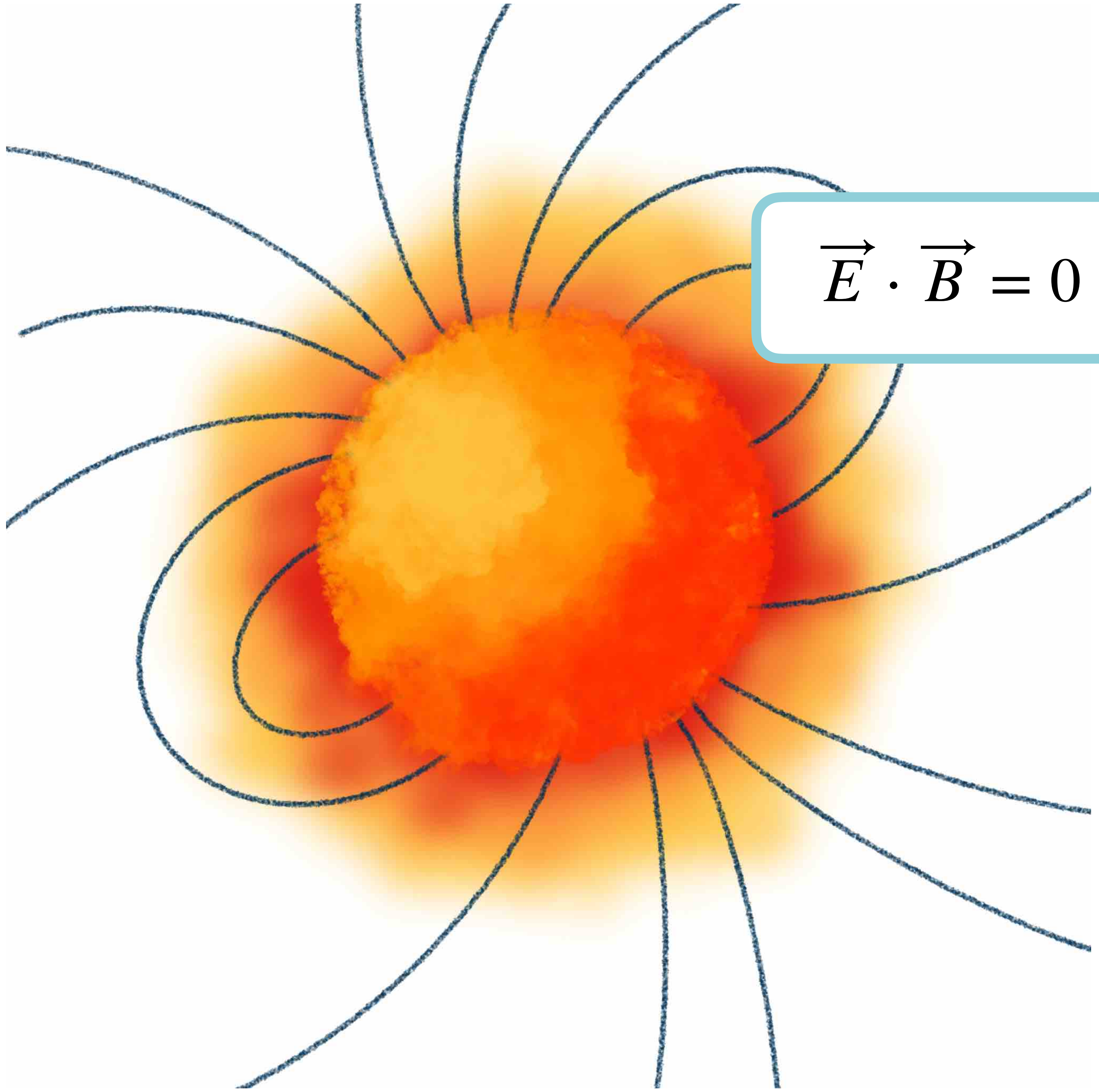


Briefly: Neutron stars

- **Neutron star** = rotating ideal conductor
- Dipolar magnetic field and plasma-filled magnetosphere
- Equilibrium configuration with $\vec{E} \cdot \vec{B} = 0$



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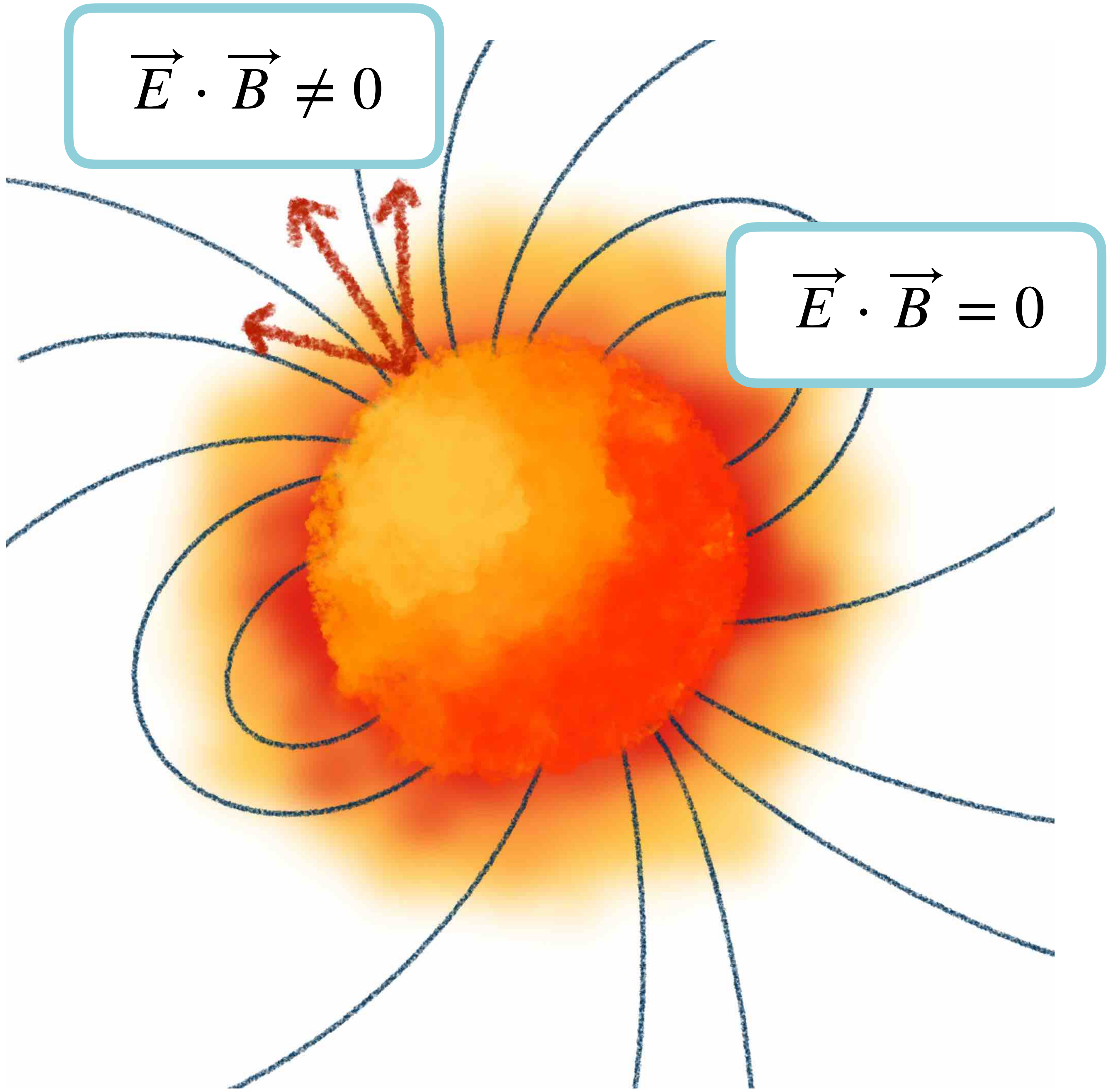
→ But we observe pulsar emission

- Have localised region with **unscreened electromagnetic** fields (responsible for emission)



Axion production in vacuum gaps

Fluctuations in $(\vec{E} \cdot \vec{B})$ produce axions

Figure credit: Ashley Bransgrove

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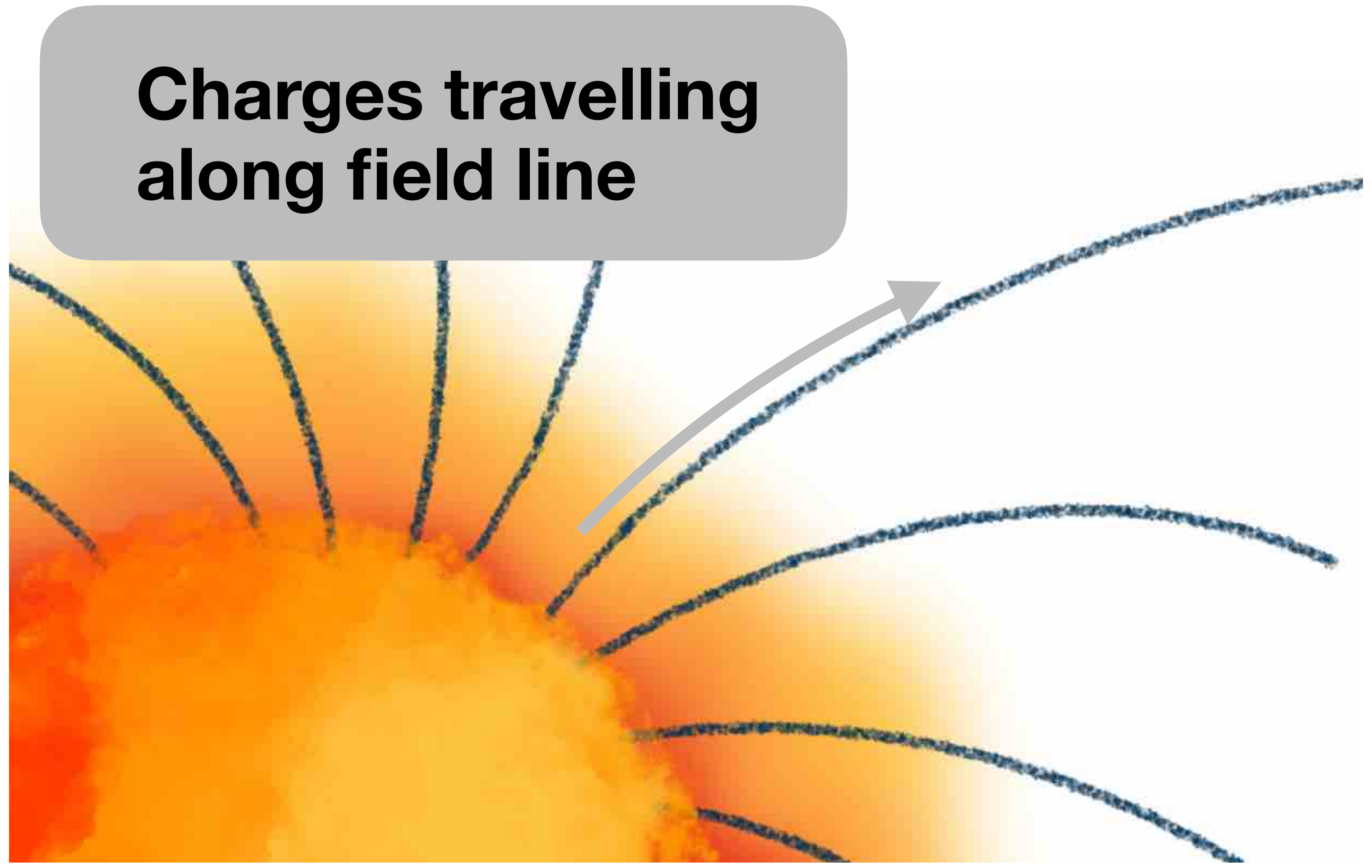
Unscreened region: 1d example



Evolution of charges: $\frac{dE}{dx} = -(\rho - \rho_{GJ})$

- **Current supplied** to sustain twist in the magnetic field lines $j_m = \nabla \times B$

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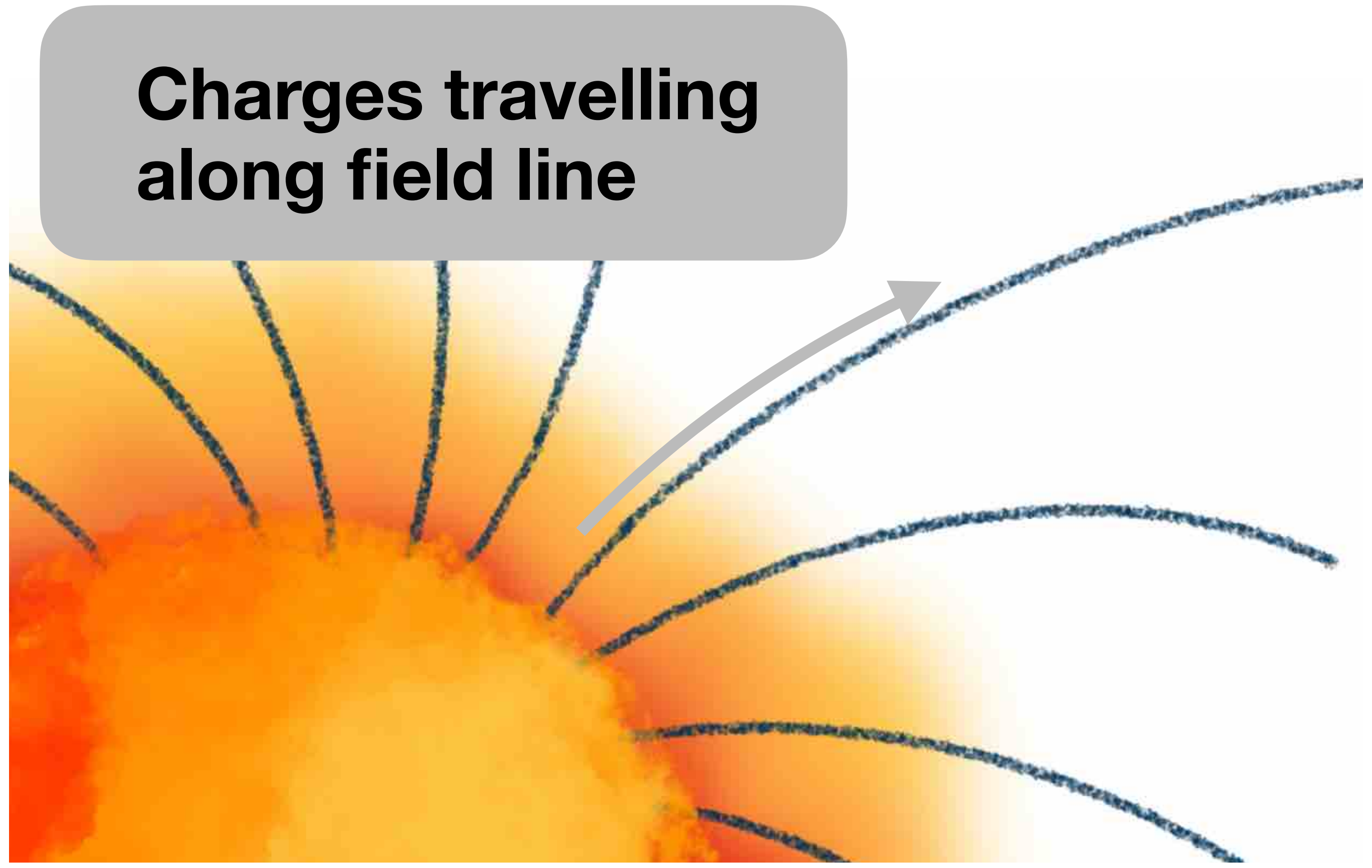

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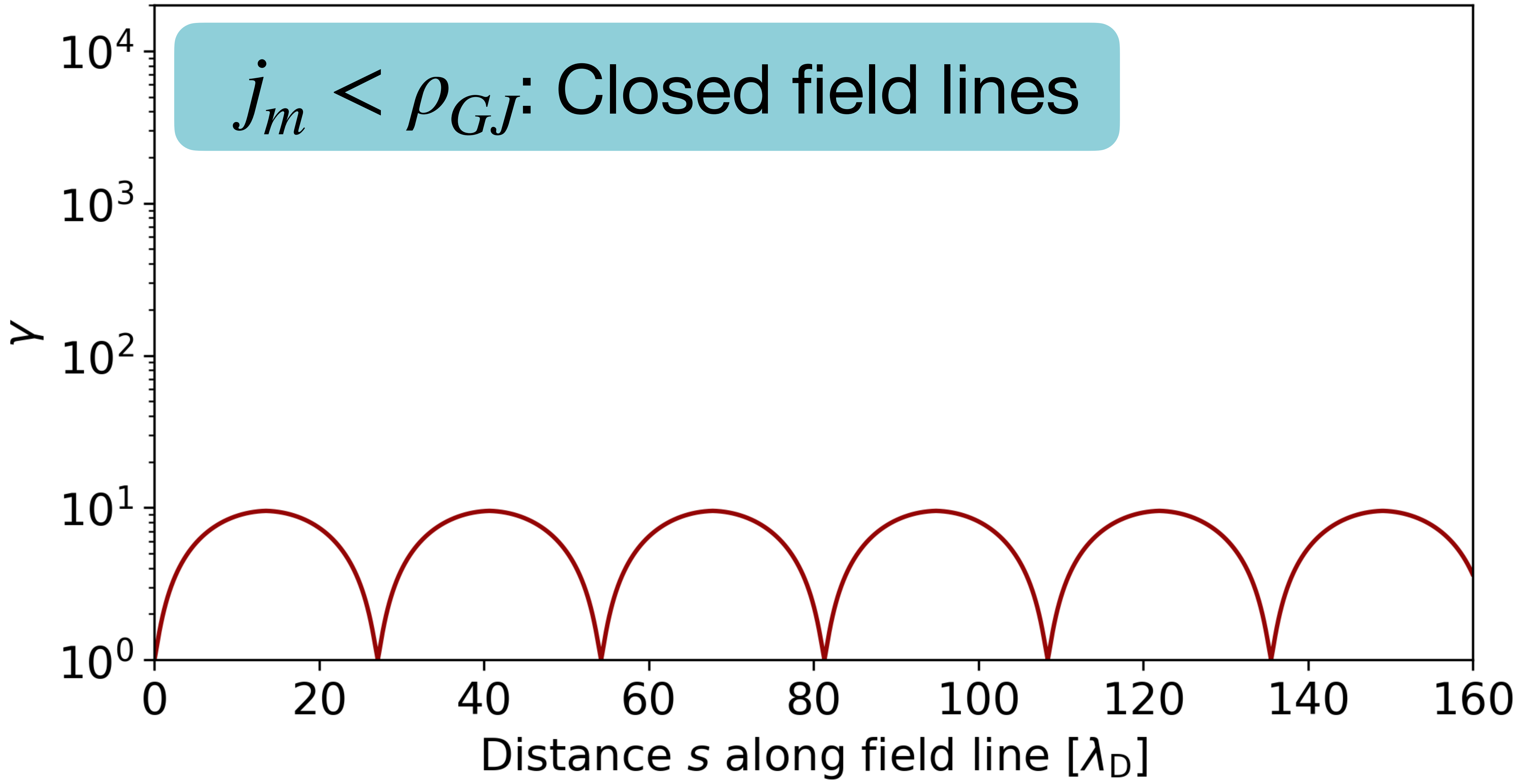

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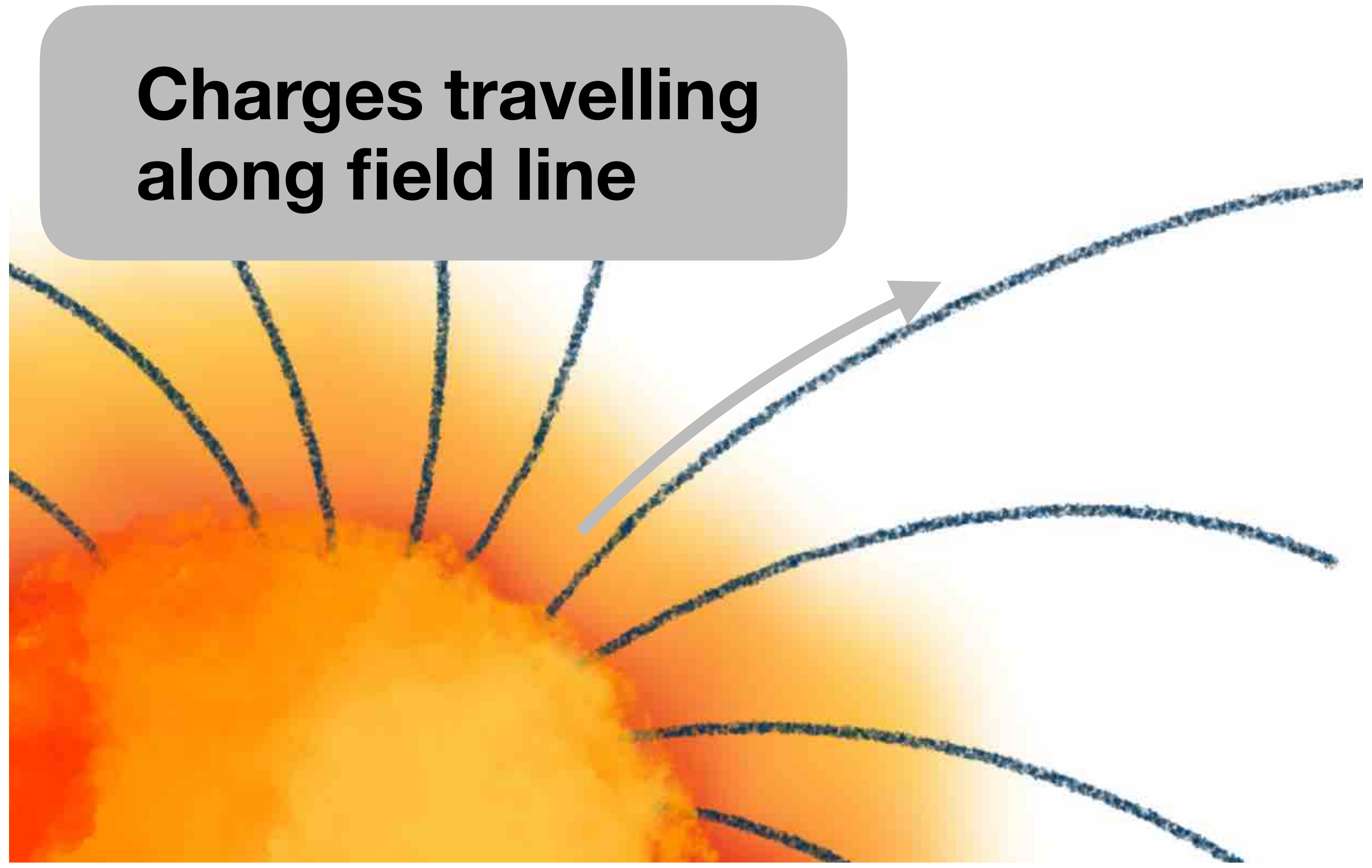

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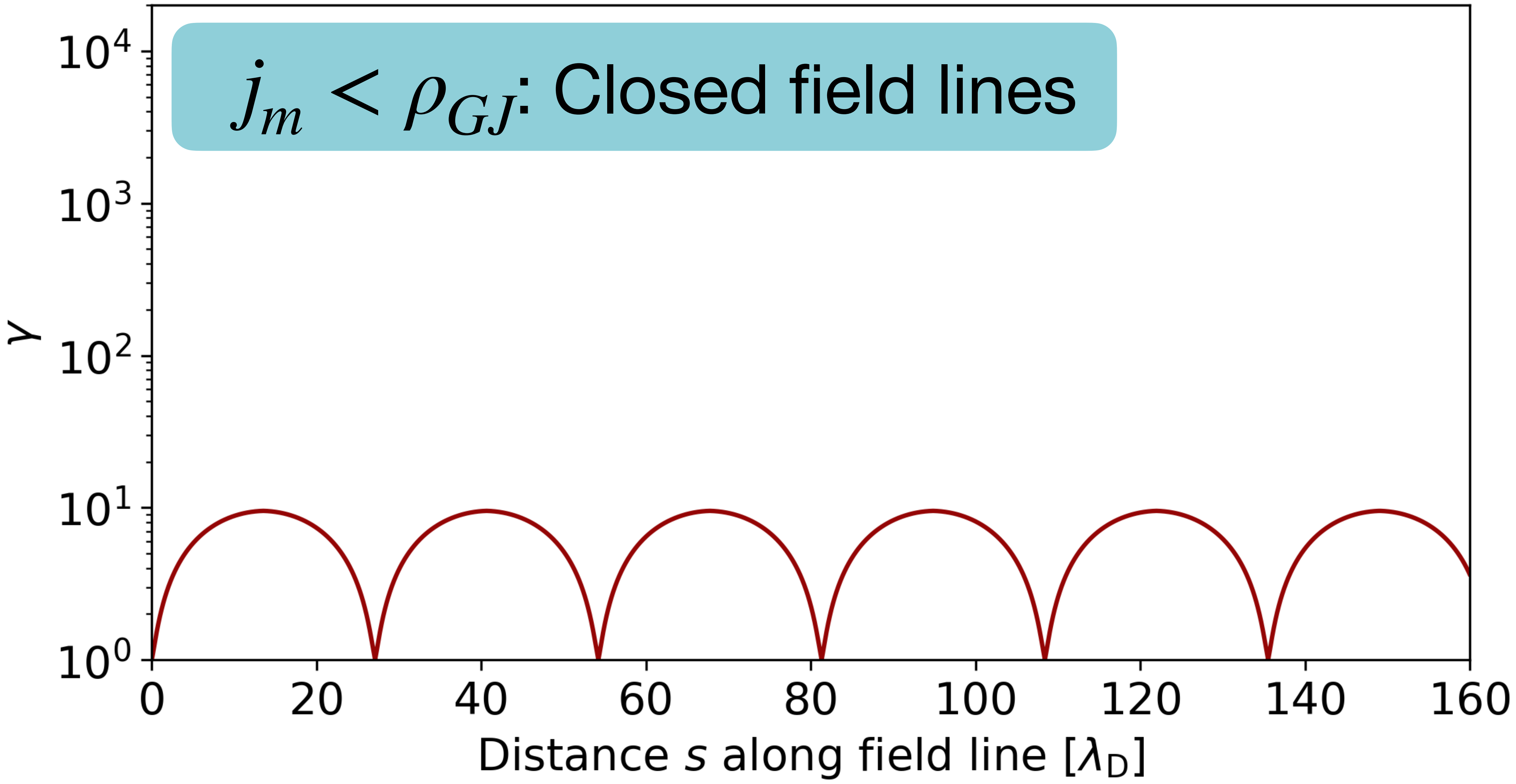
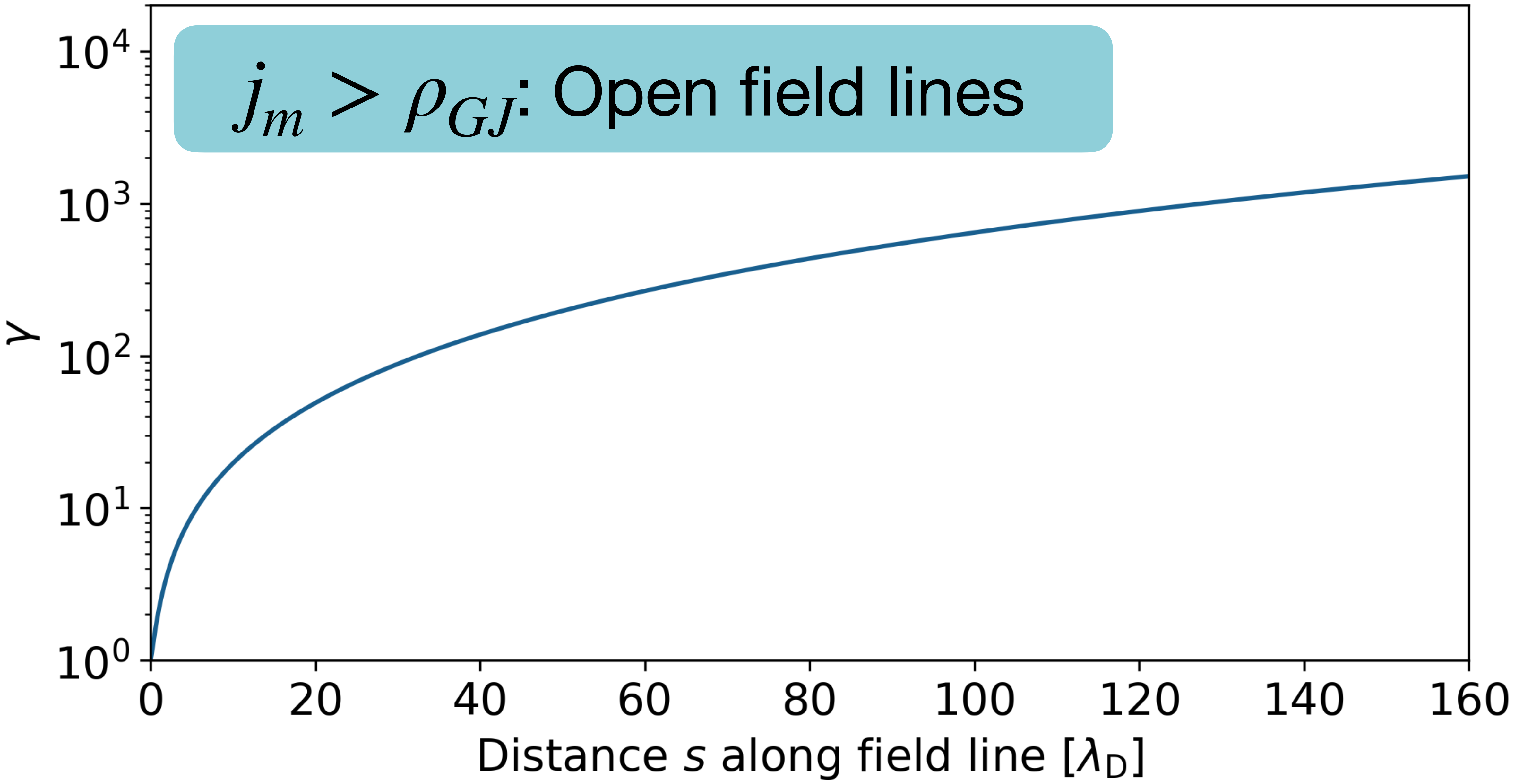
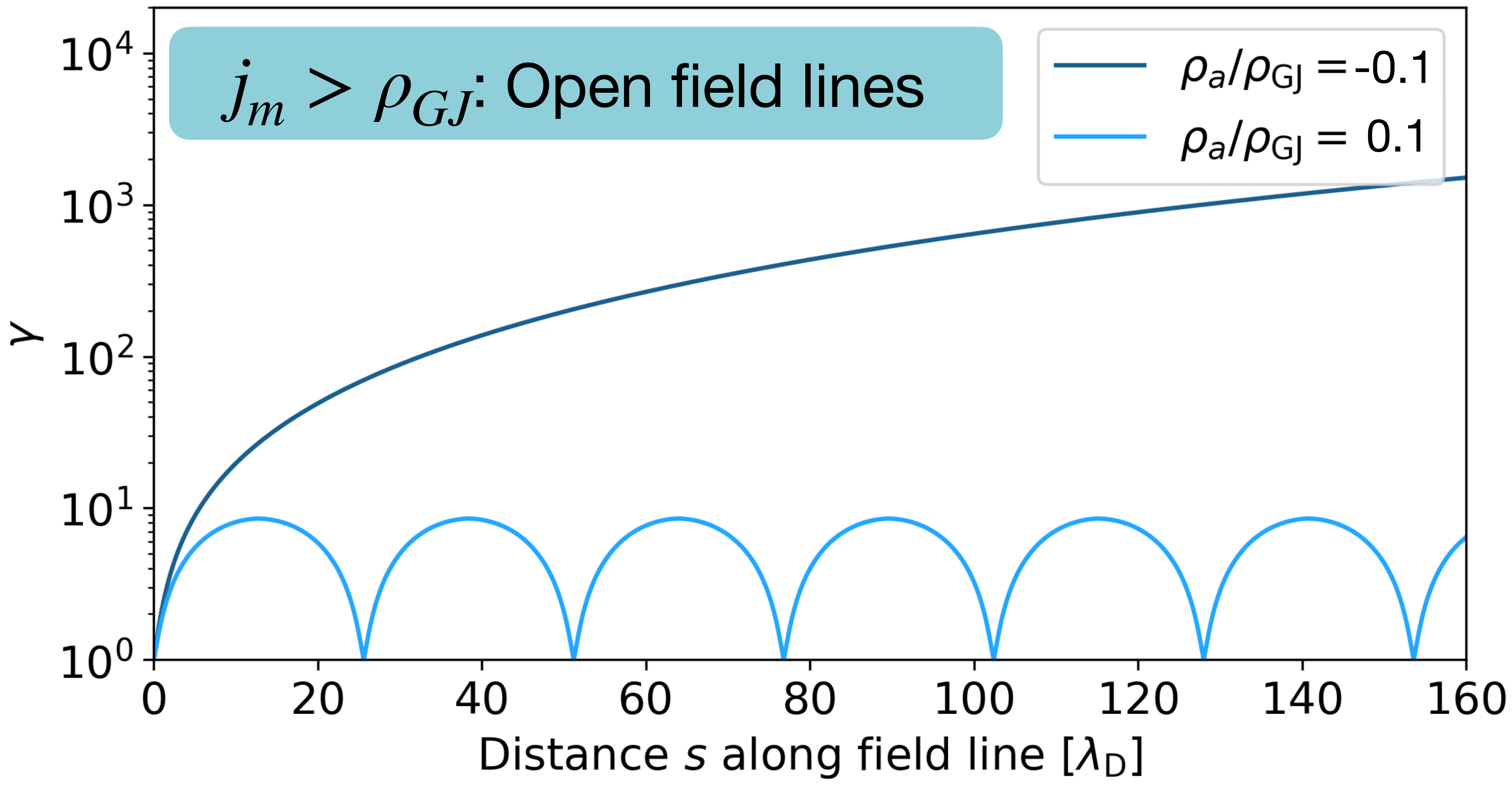




So what if we add axions?

Evolution of charges in 1d: $$\frac{dE}{dx} = -(\rho - \rho_{GJ} - \rho_a)$$

- Axions can **change evolution** dramatically:



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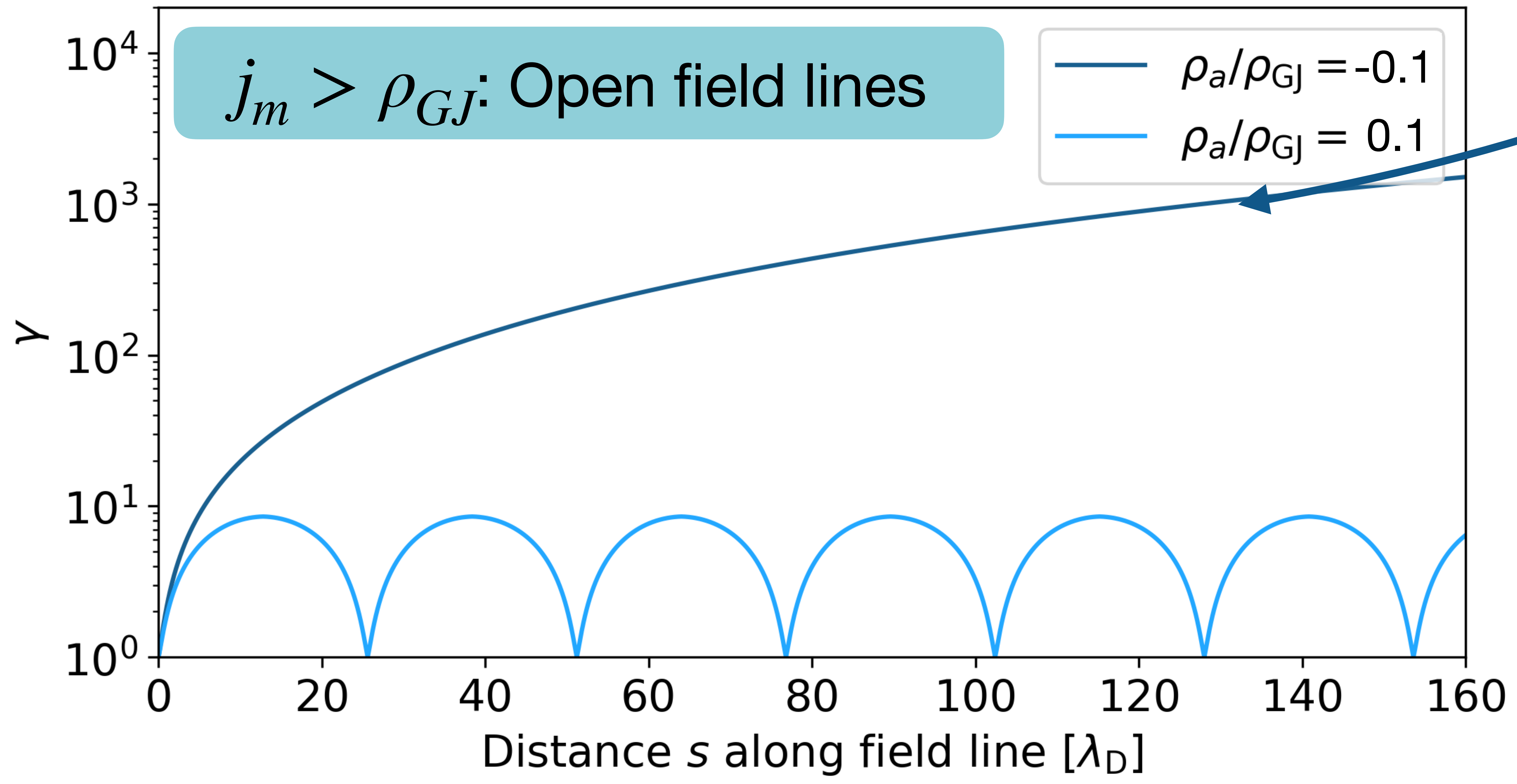
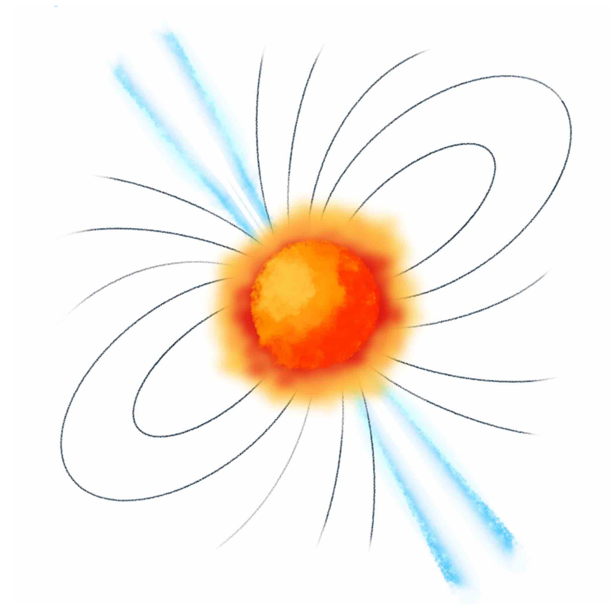
Pair production happens
→ Pulsar **produces emission**





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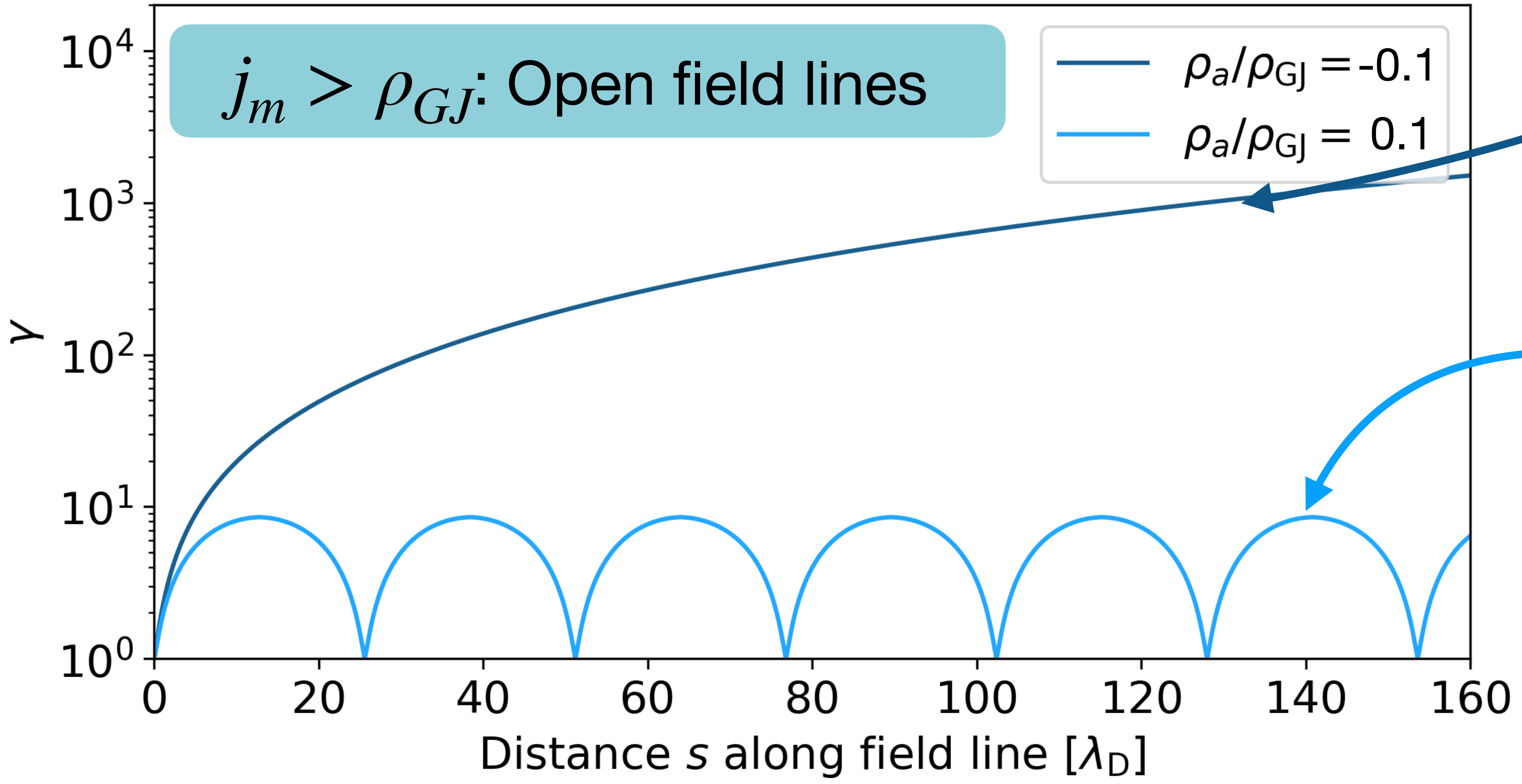

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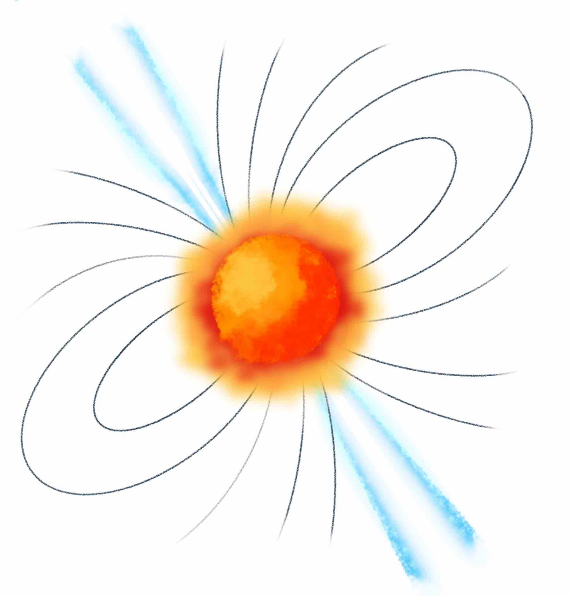
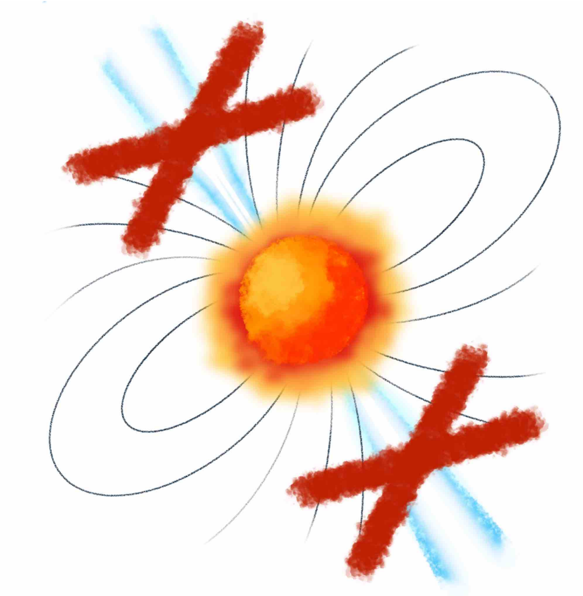
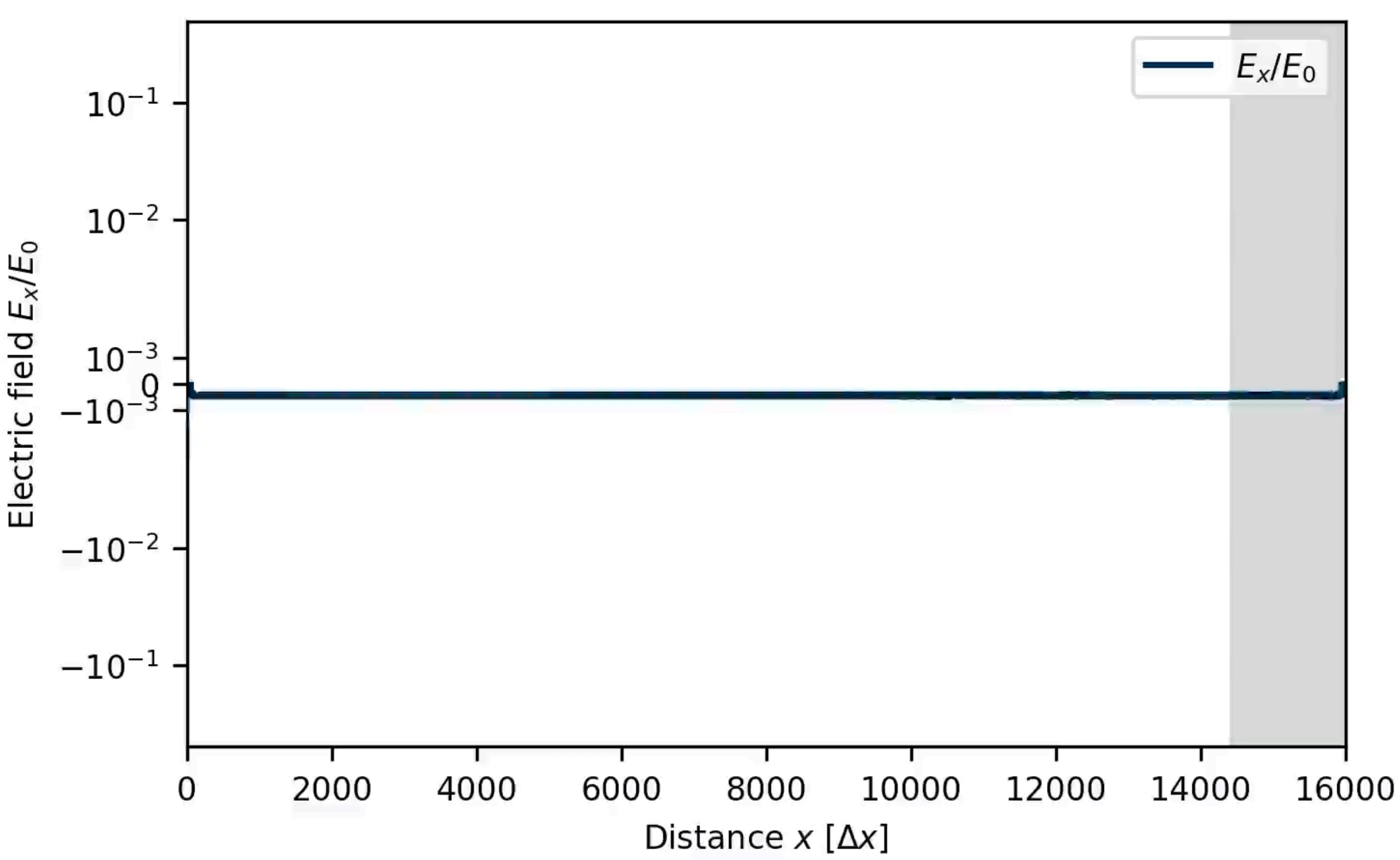


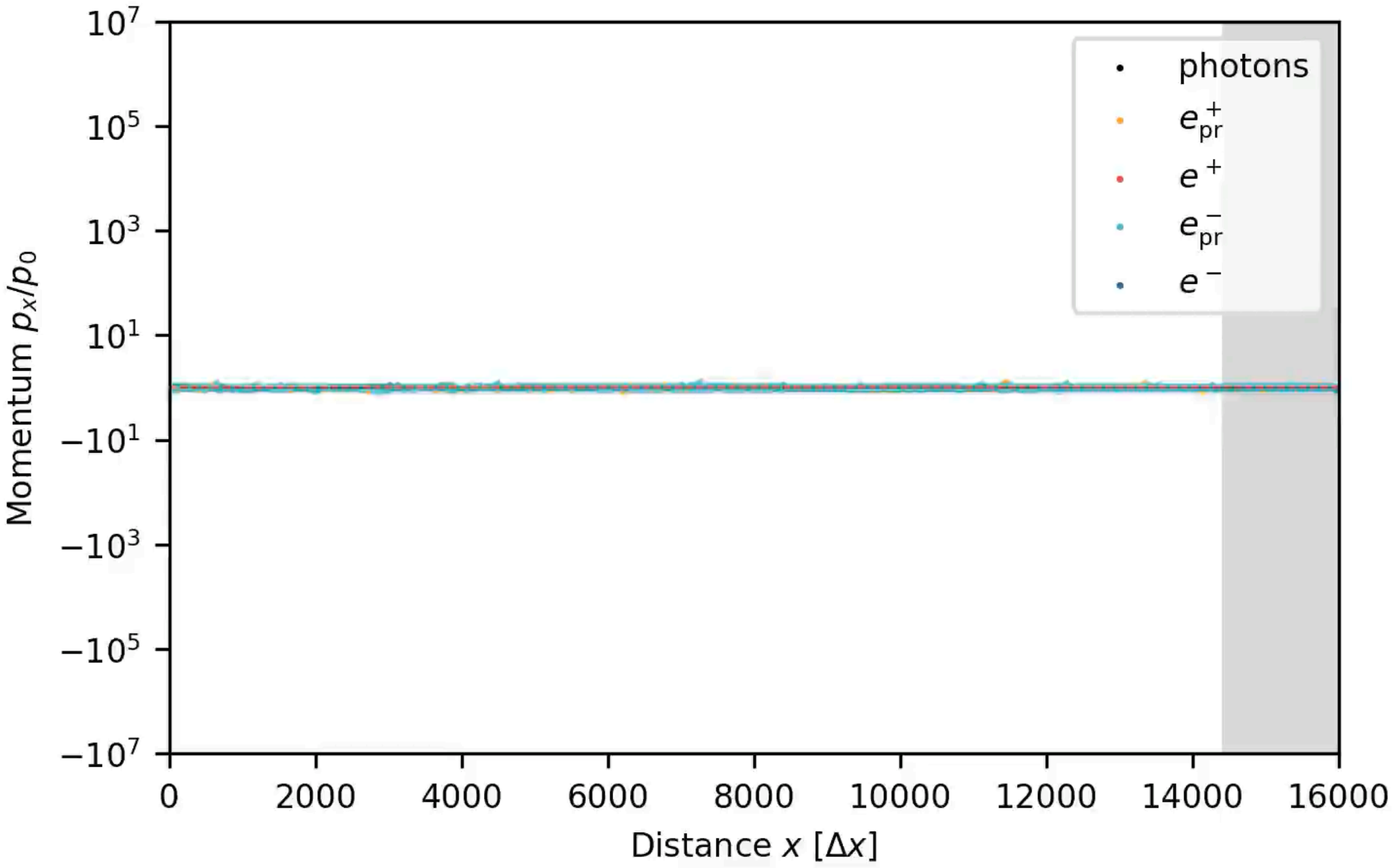
No pair production!
→ No emission = **pulsar nulling**



So … how do we add axions?

- Take PIC (Particle-In-Cell) simulation …





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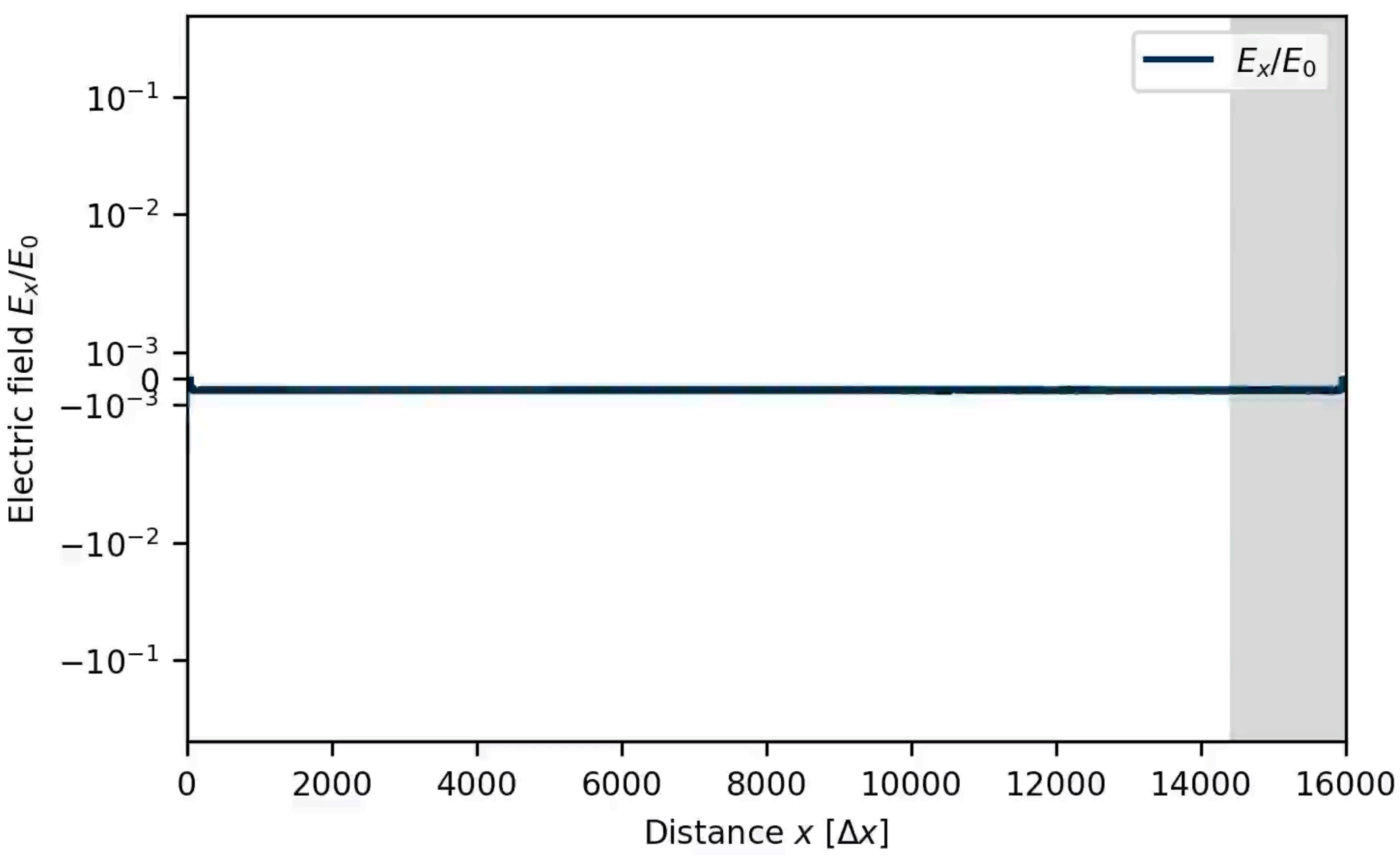
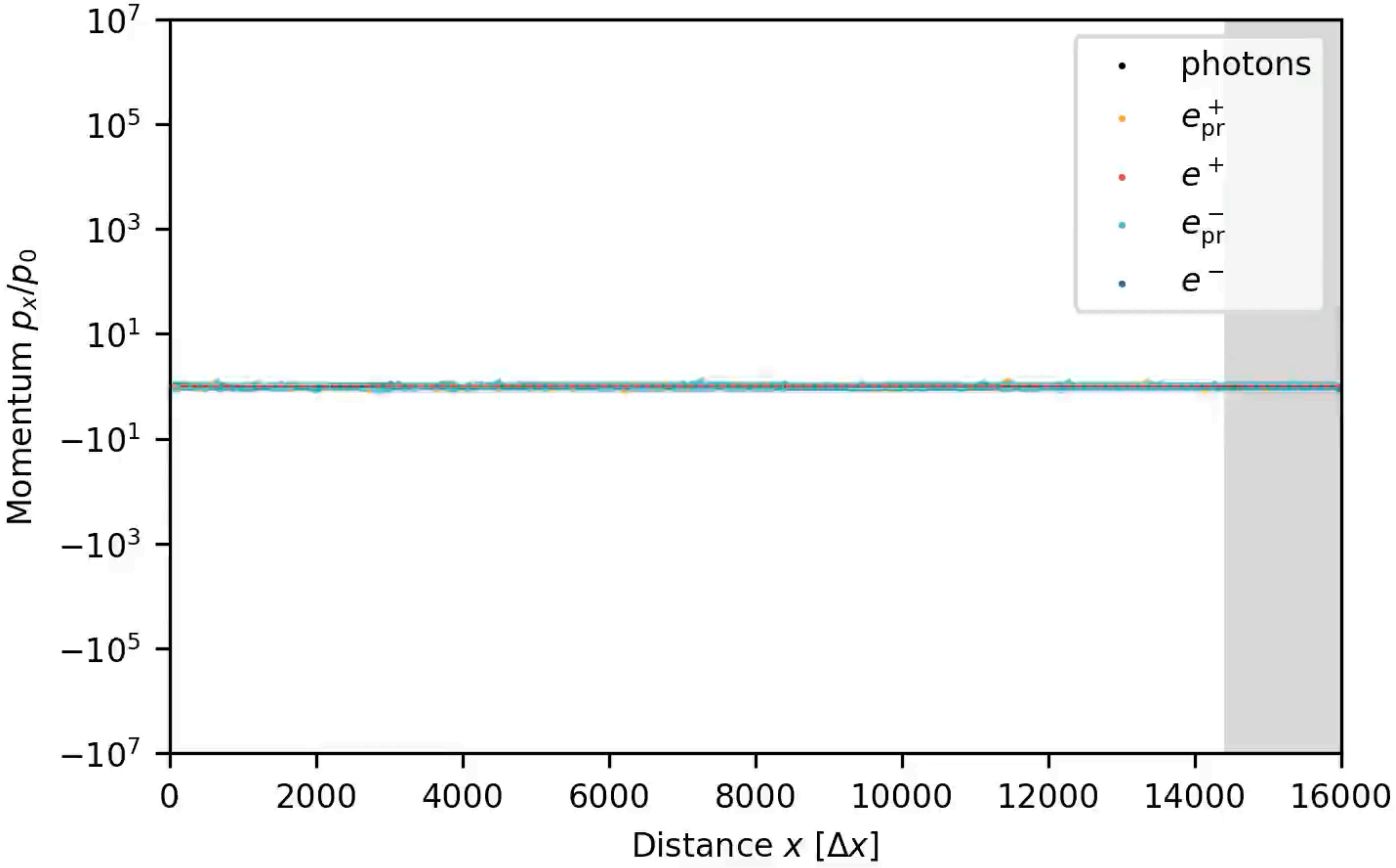




… and add the axion field!

Axions-PIC: Sanity check 1

Preliminary

- Axion production: **Energy distribution** over time

$$\frac{dE}{dk} \sim \text{FT}[g_{a\gamma\gamma}\vec{E}\cdot\vec{B}]$$

$$\frac{dE}{dk} \sim \text{FT}[(\nabla a)^2 + \dot{a}^2 + m_a^2 a^2]$$

Axions-PIC: Sanity check 2

Preliminary

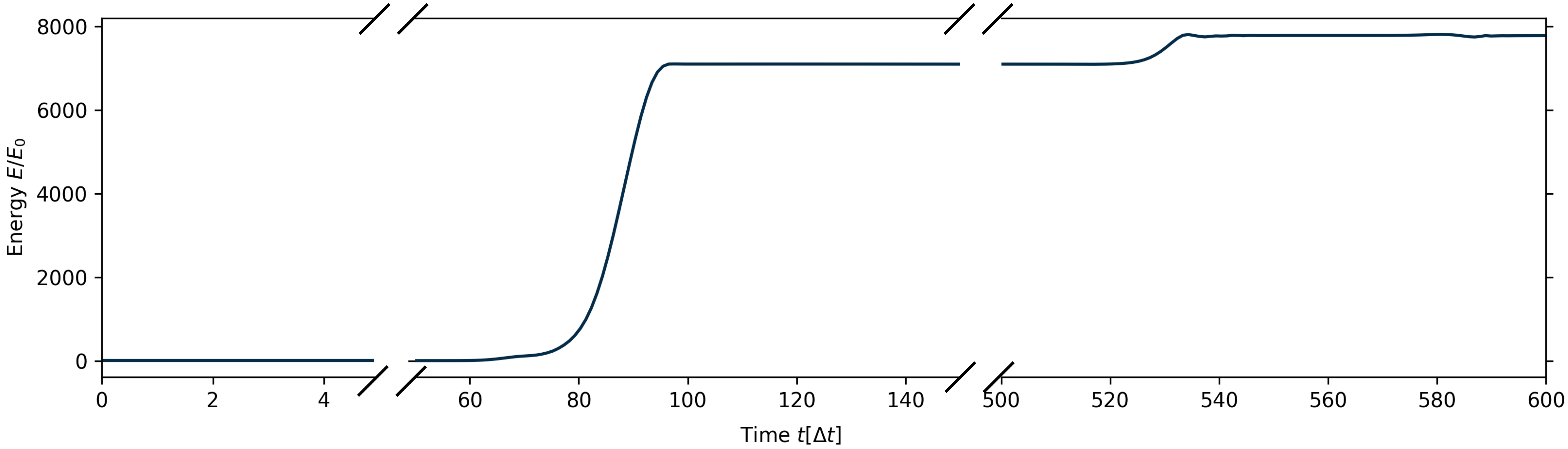
- Axion production: **Energy distribution** in k-space

$$\frac{dE}{dk} \sim \mathrm{FT}[g_{a\gamma\gamma}\vec{E}\cdot\vec{B}]$$

$$\frac{dE}{dk} \sim \mathrm{FT}[(\nabla a)^2 + \dot{a}^2 + m_a^2 a^2]$$

Back-reaction: Effect on pair cascade

- Consider regime where axion charge density ρ_a becomes dominant:



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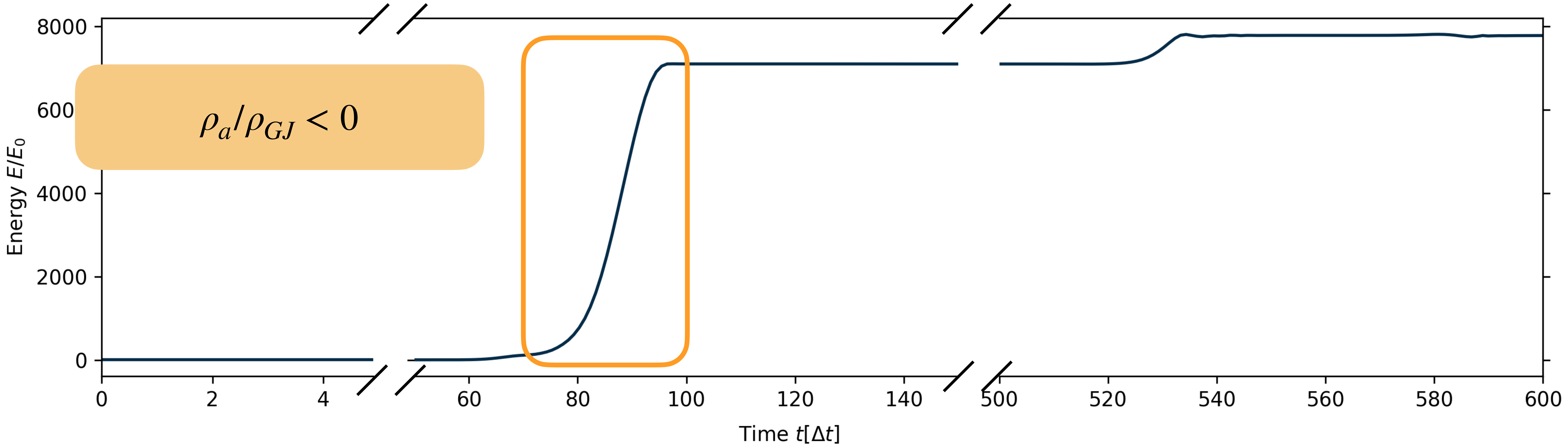

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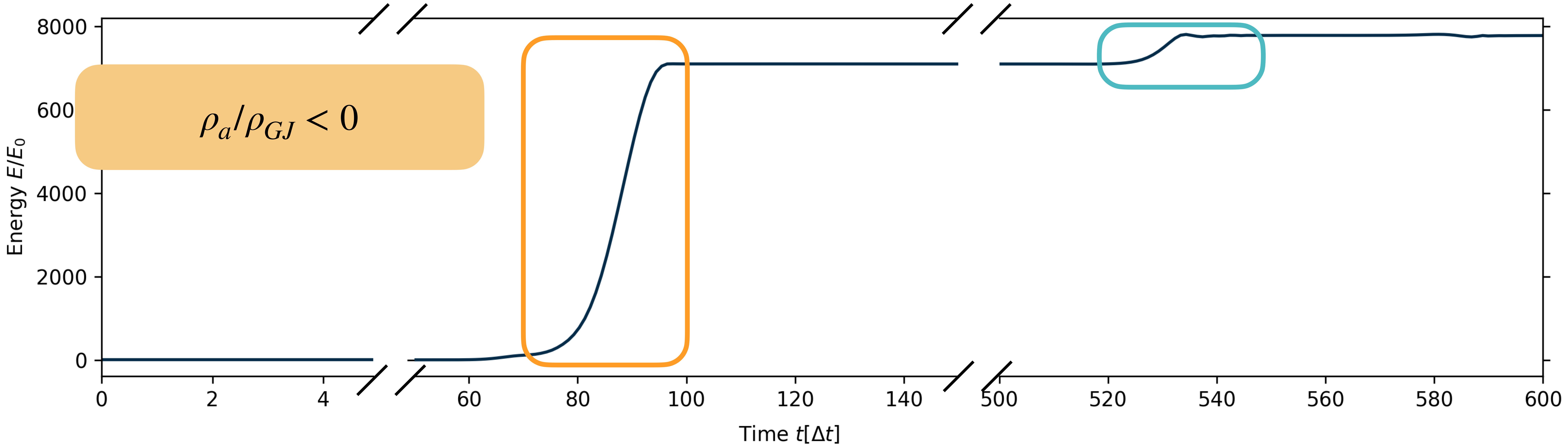
$\rho_a/\rho_{GJ} > 0$



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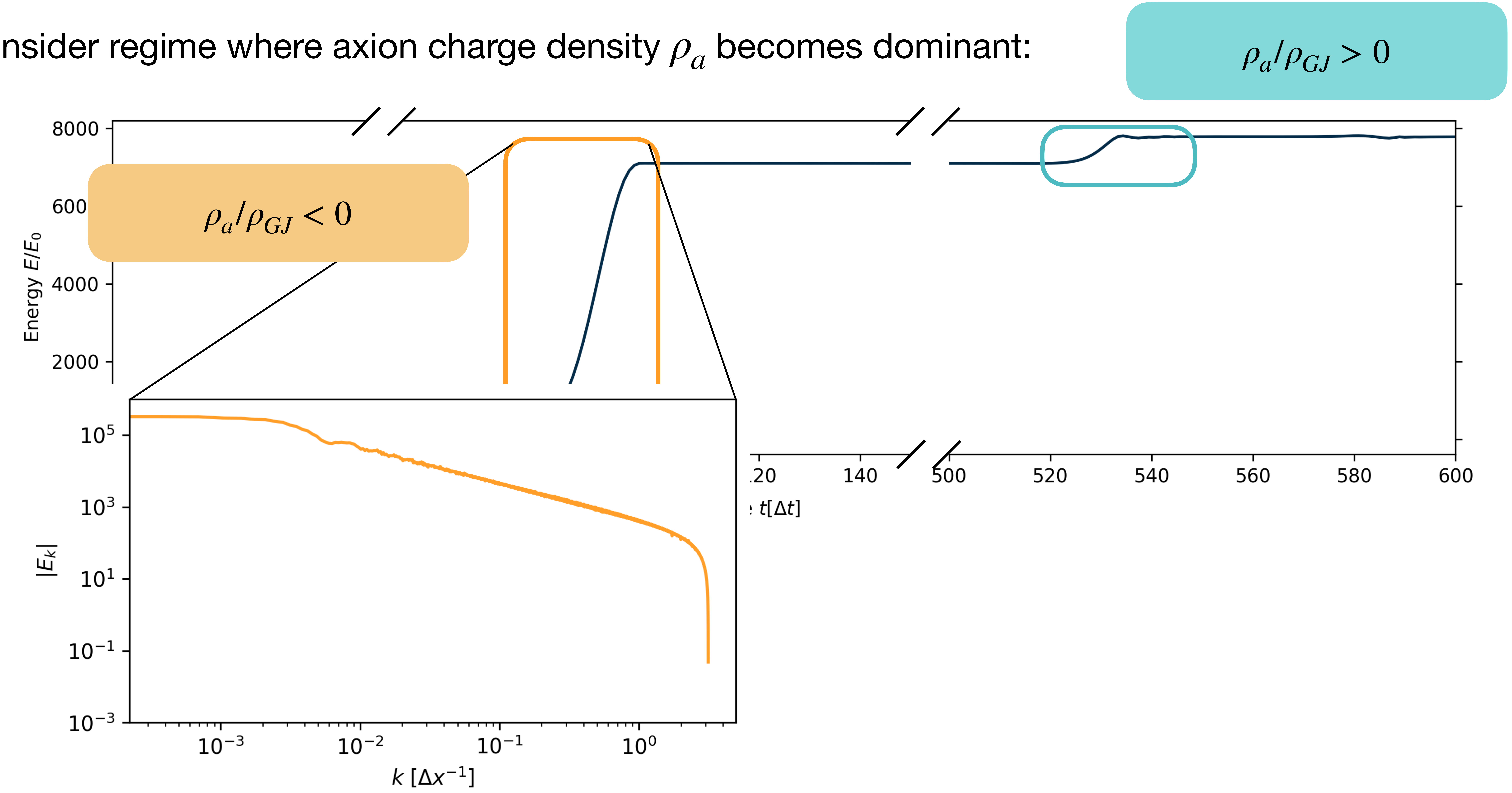

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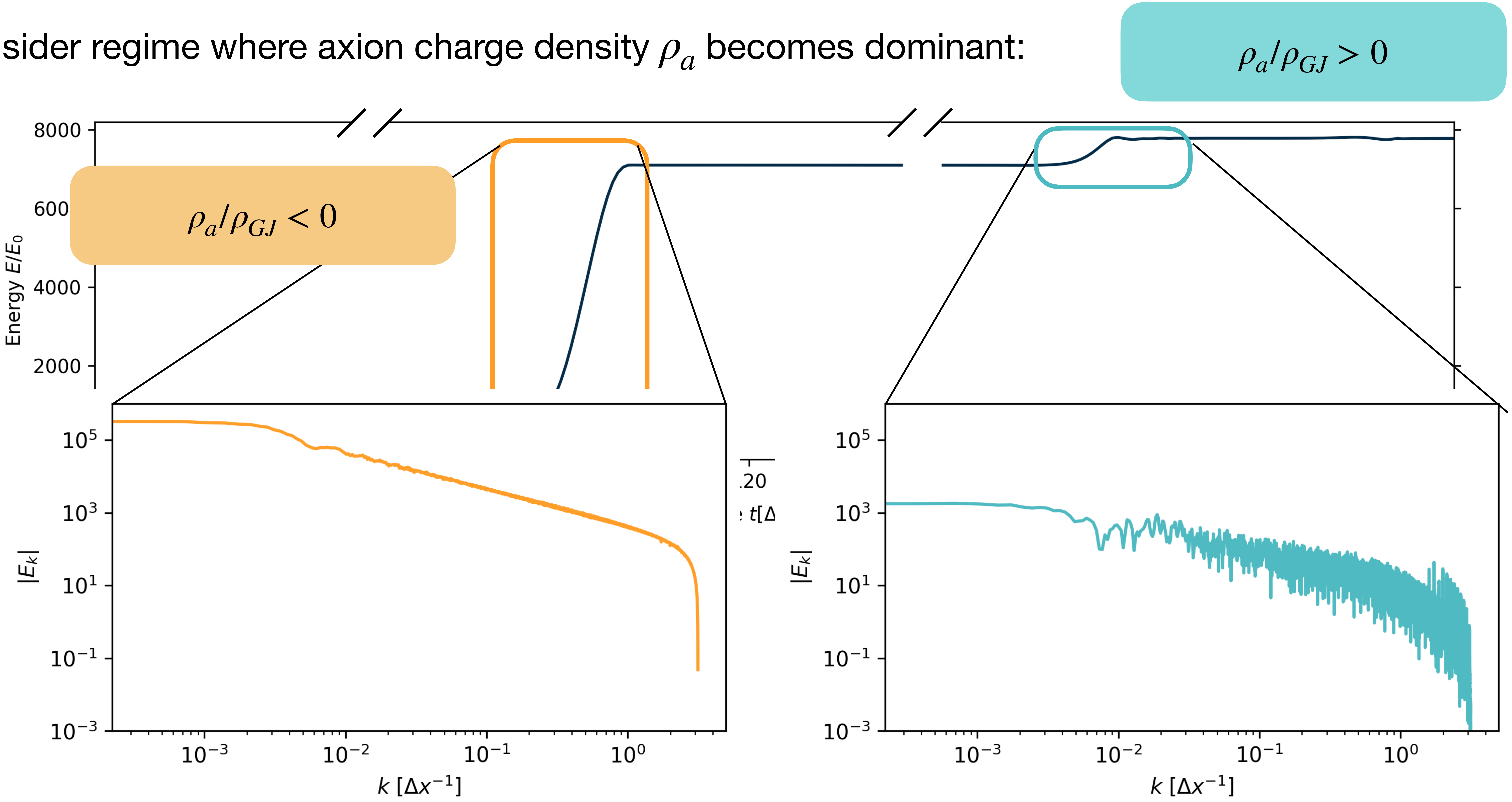
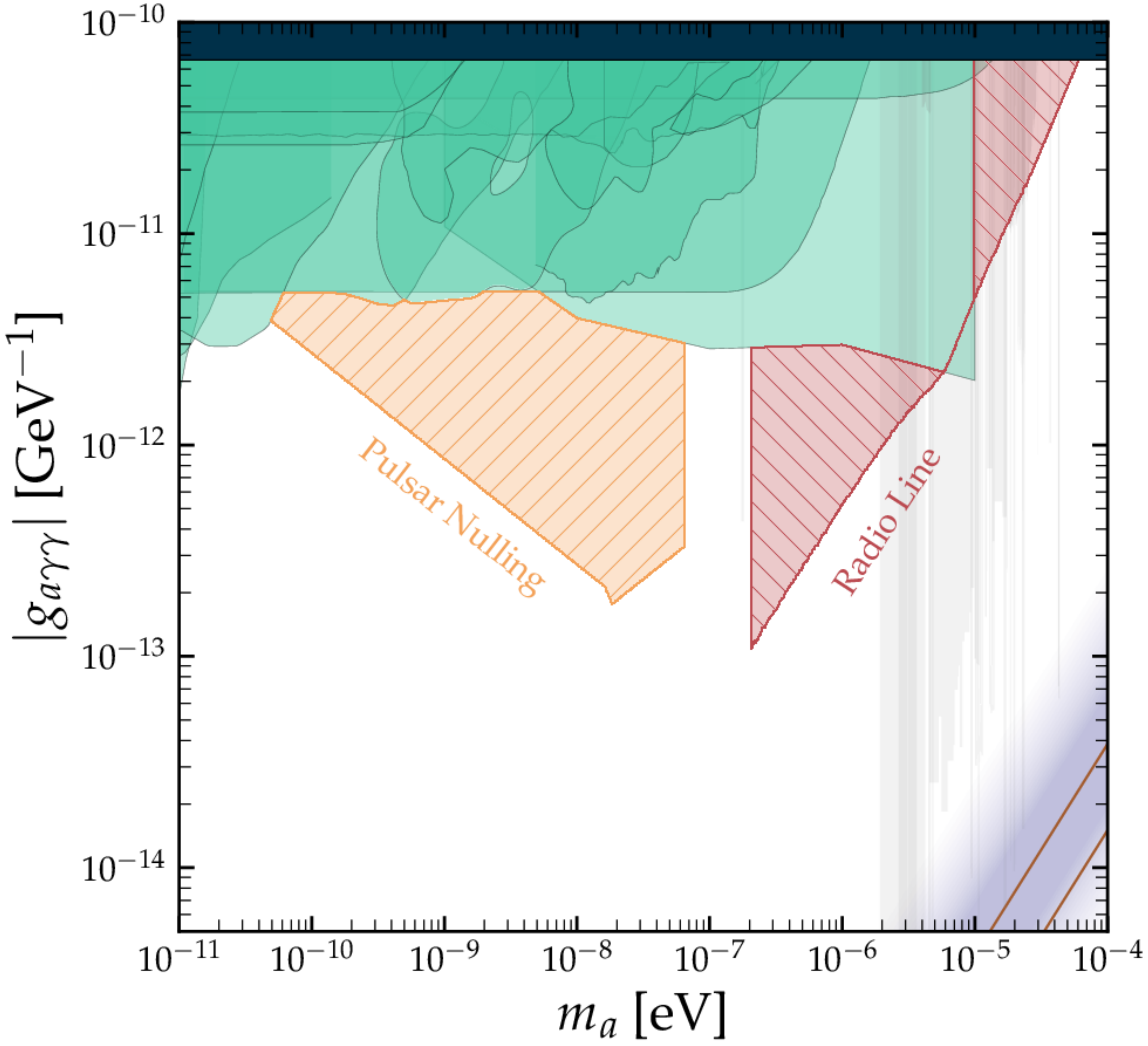


Outlook:
Region of interest in parameter space



Caputo et al, [2311.14795]

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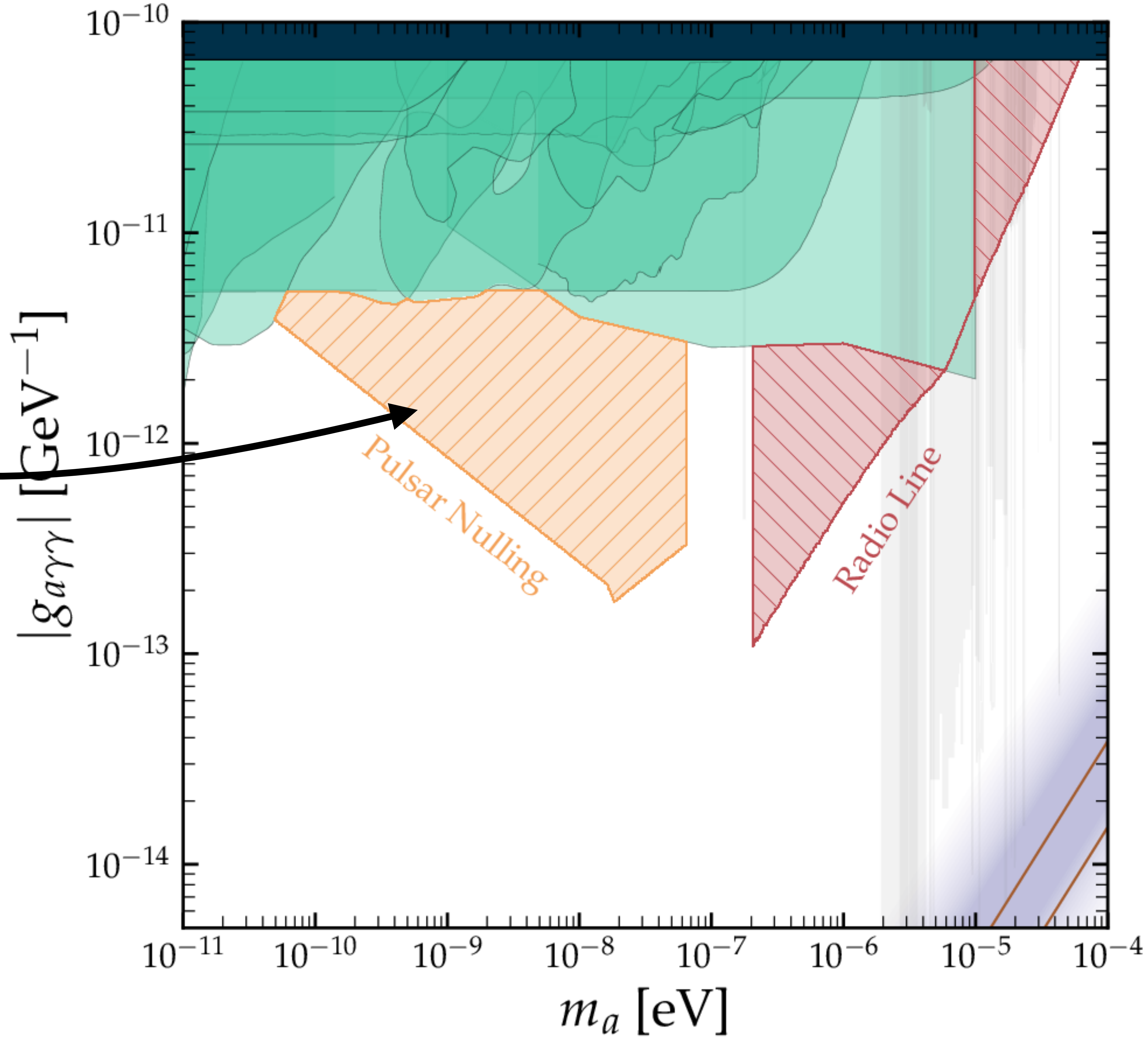
Parameter space of direct interest



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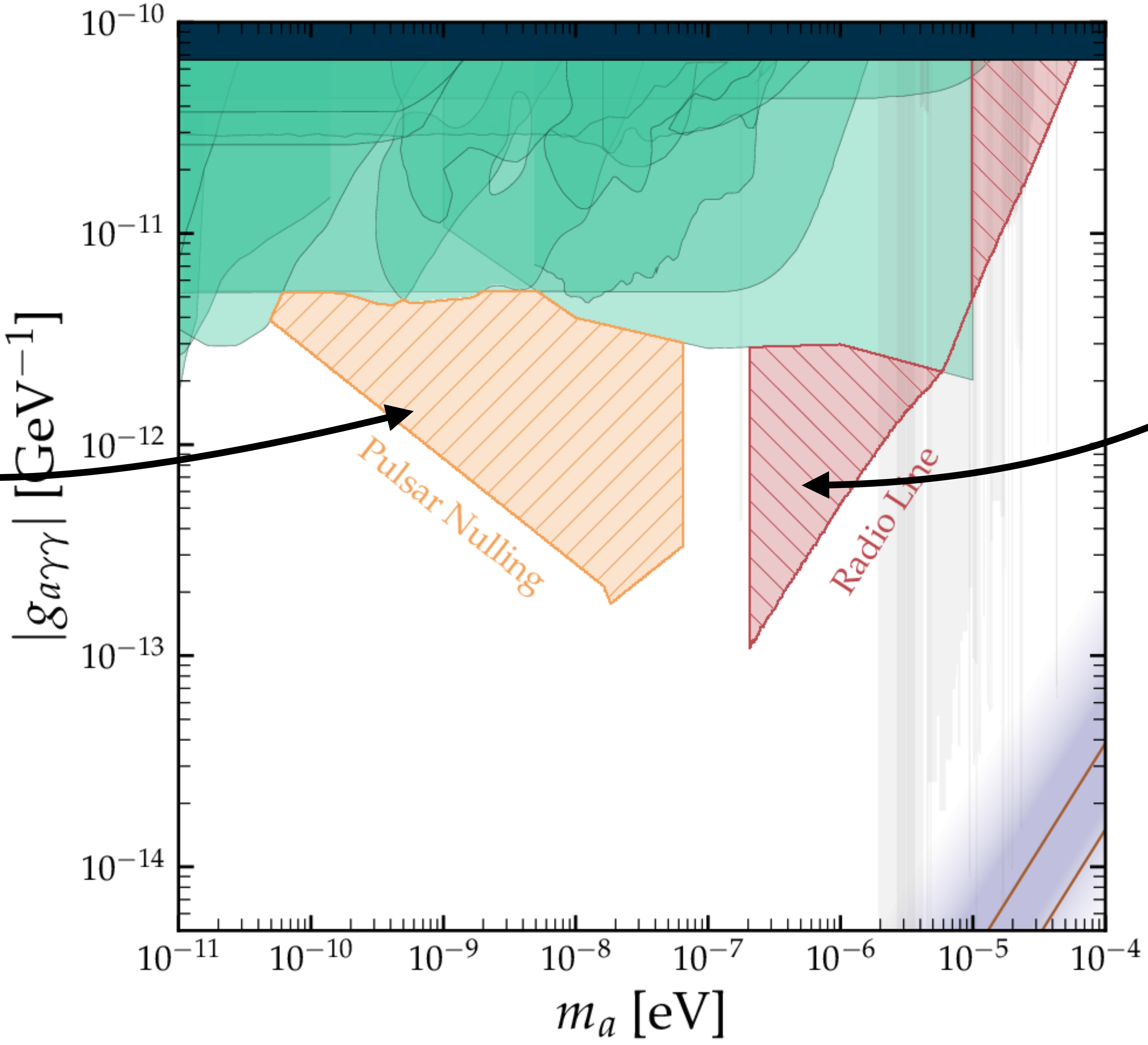
Parameter space of direct interest

Additional signature arising in vacuum gaps



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Summary and outlook

- Dense axion cloud around pulsars can lead to **dramatic experimental signatures**
- Build first PIC axion electrodynamic simulation to explore non-perturbative effects
- More results to come soon!
- Extend simulation to **2+1 dimension** to model coherent radio emission
- Can we show that a similar effect occurs in **black holes**?