Axions in Astrophysics

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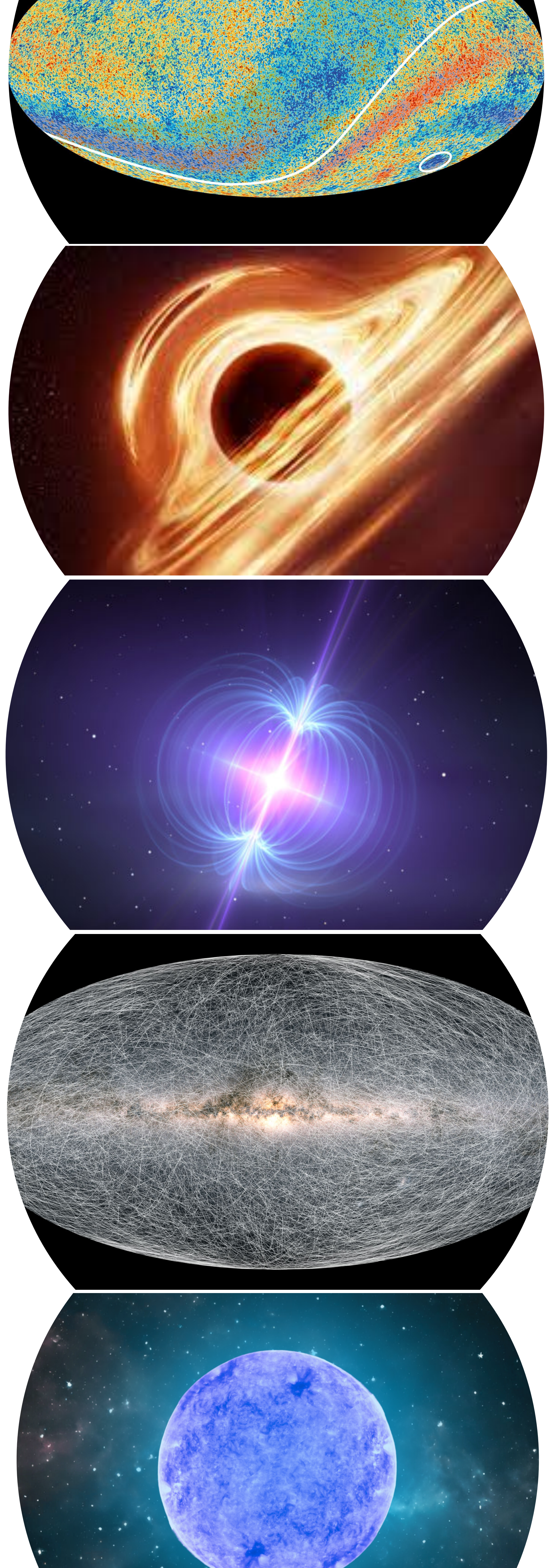
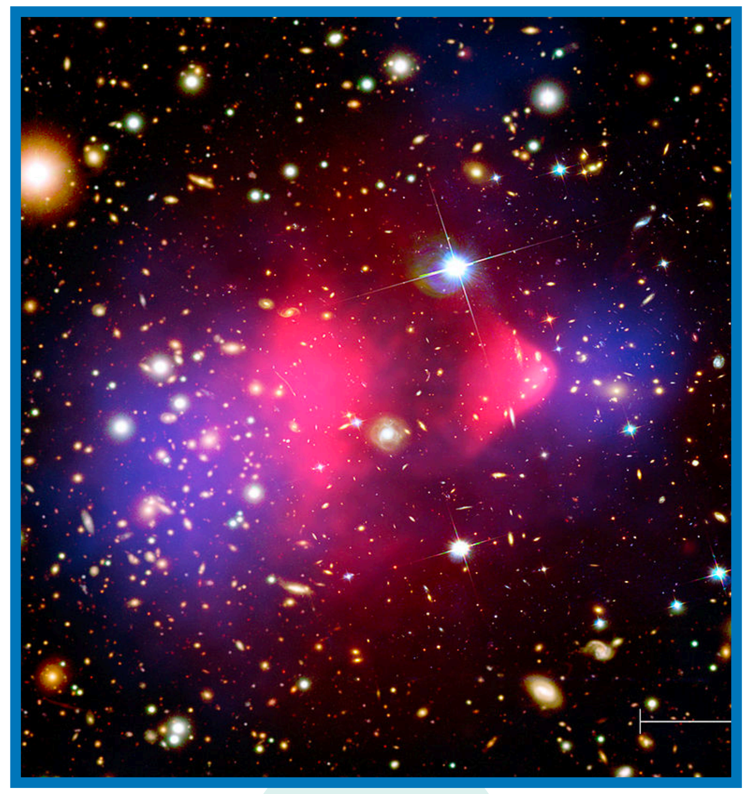
EuCAPT Virtual Colloquium
April, 2024

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

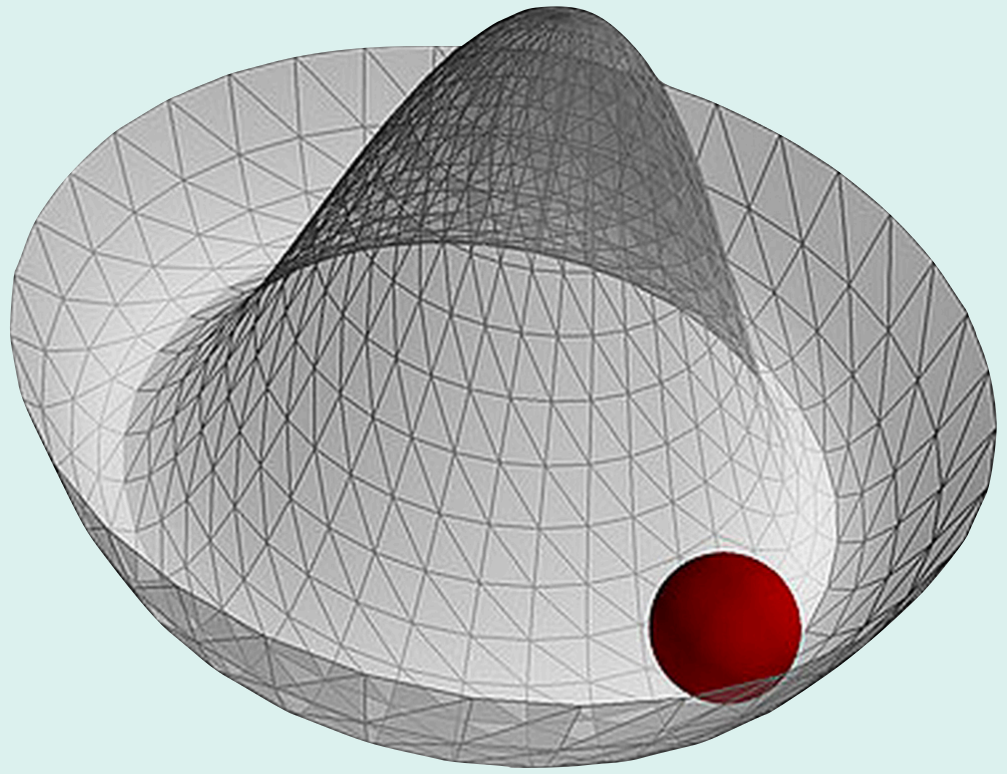


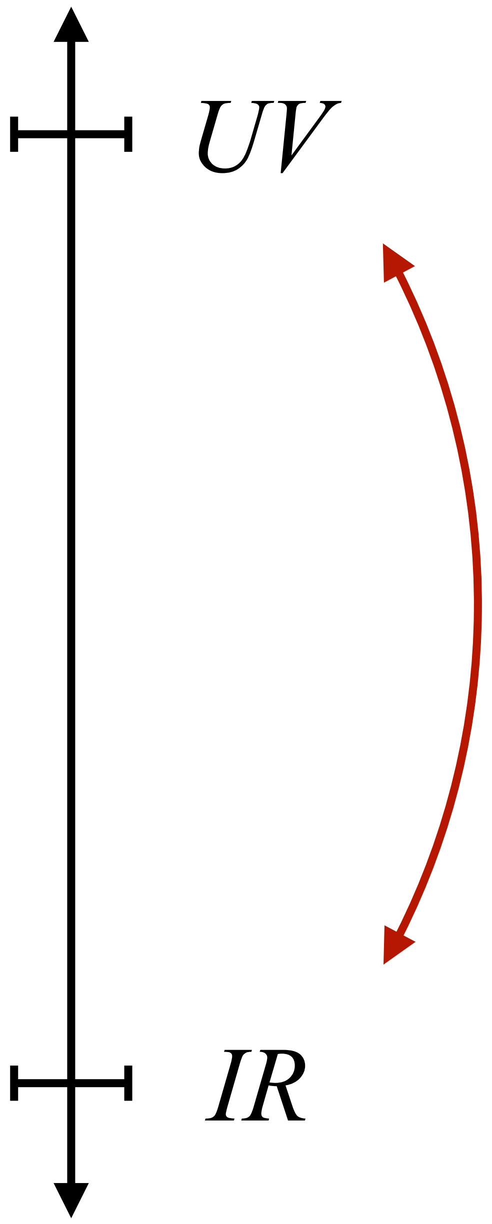
Axions: the motivation



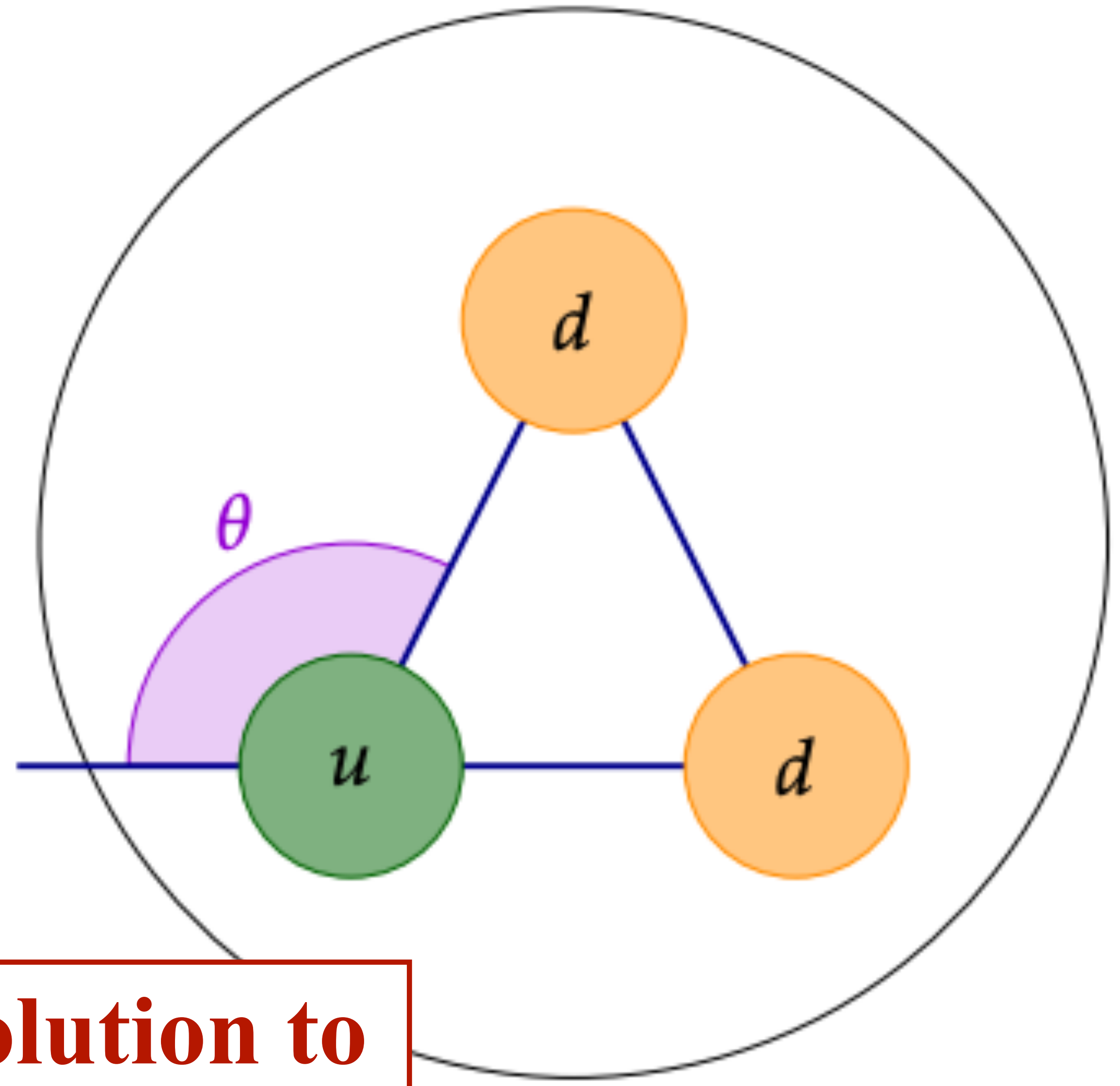
Axions as dark matter

Light Pseudoscalars





Axions as IR remnants of the UV



Axions as a solution to the strong CP problem

(QCD axion)

Motivation #1: The strong CP problem

Why does QCD seem to conserve charge-parity (CP) symmetry?

CP violating term in QCD Lagrangian:

$$\mathcal{L}_{CPV} \supset \overline{\theta}\, \frac{g_s^2}{32\pi^2}\, G\, \tilde{G}$$

Neutron electric dipole moment (eDM) $\propto \overline{\theta}$

Current limit: $\overline{\theta} \leq 5 \times 10^{-11}$ Abel et al (2020)

Peccei & Quinn (1977), Weinberg (1978), Wilczek (1978)

The strong CP problem

Solution: Introduce goldstone boson a to make theta term dynamical

$$\mathcal{L}_\theta = -\left(\bar{\theta} + \frac{a}{f_a}\right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

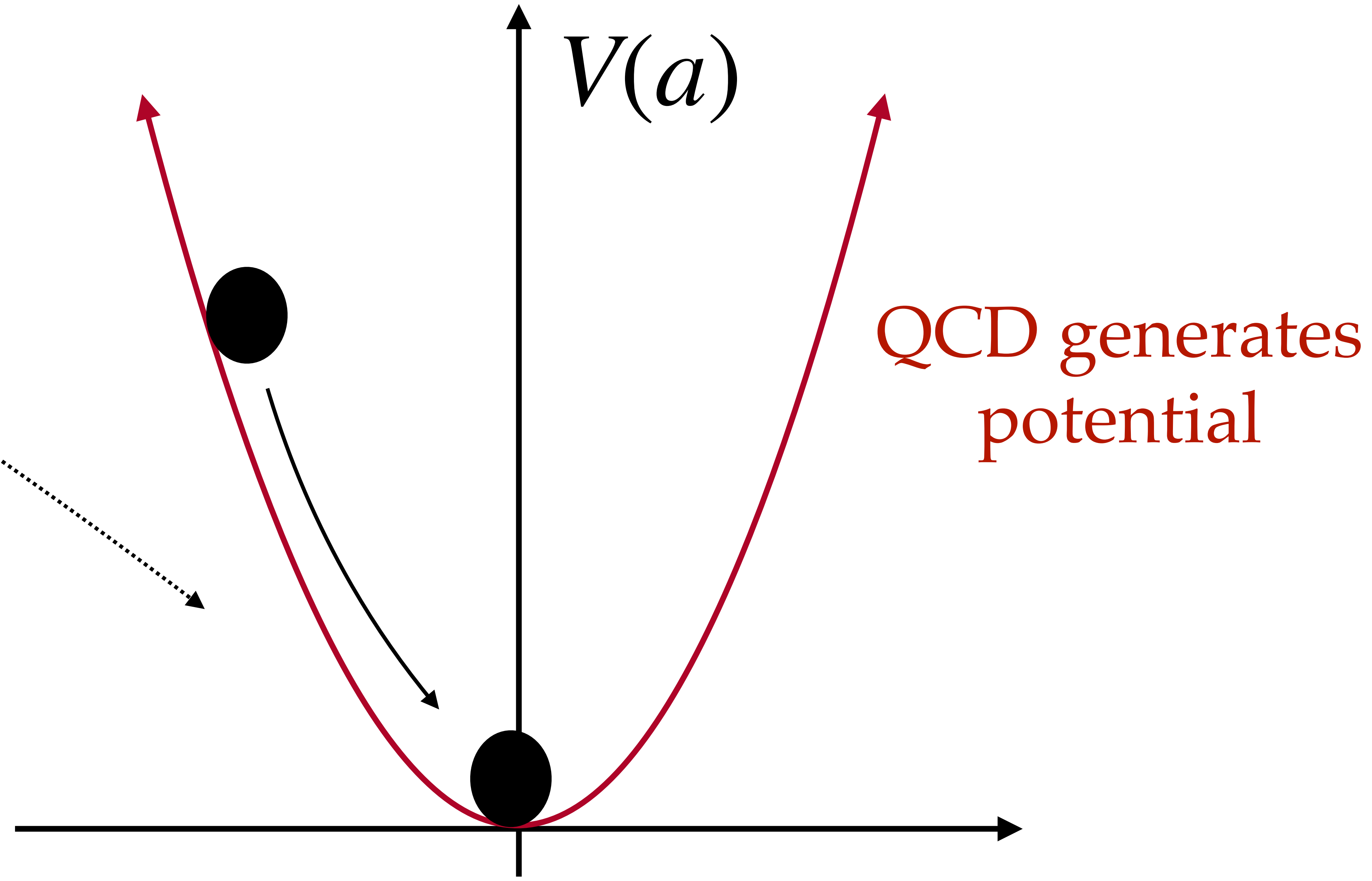
“QCD Axion”

$$\boxed{m_a \sim 10^{-6}\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)}$$

Original $f_a \sim$ EW scale

↓

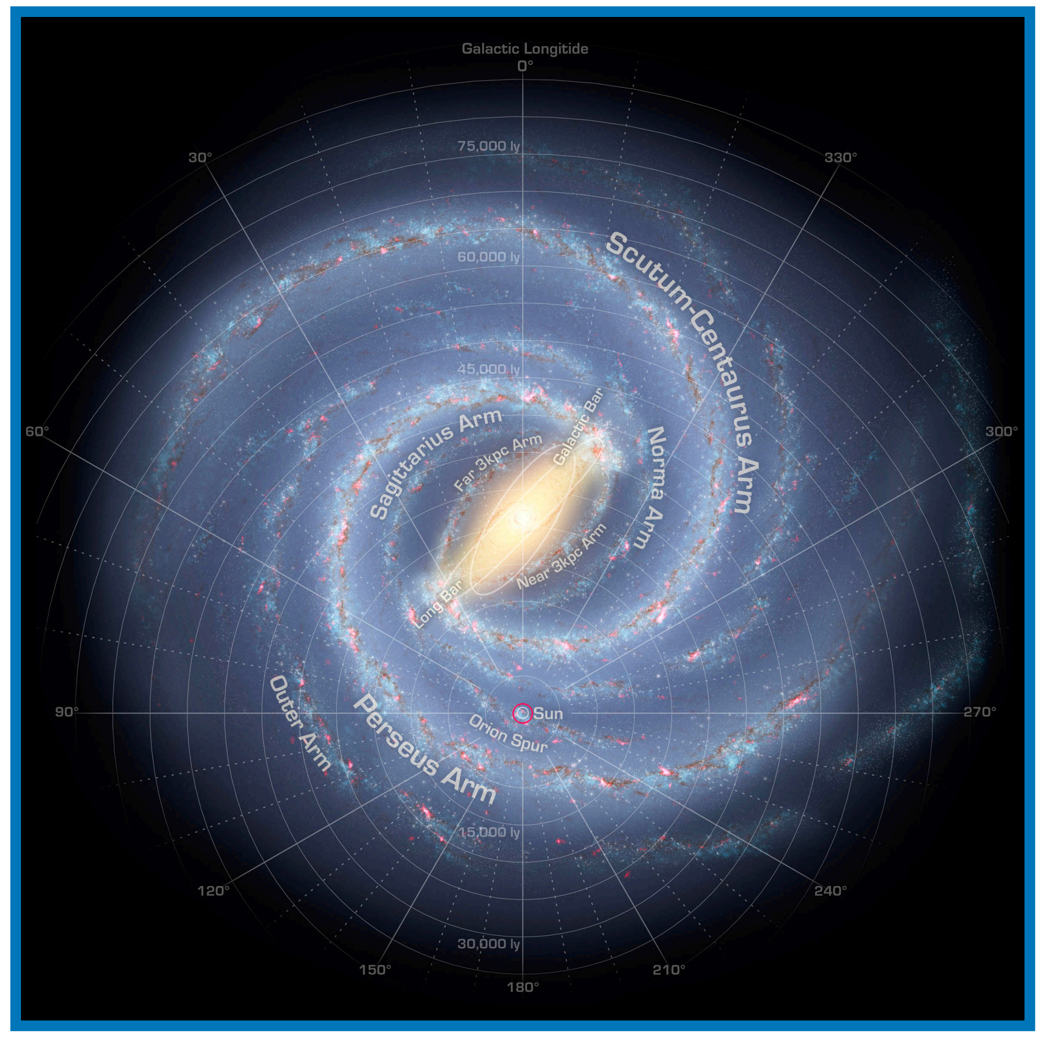
“Invisible axion”: $f_a \gg$ EW scale



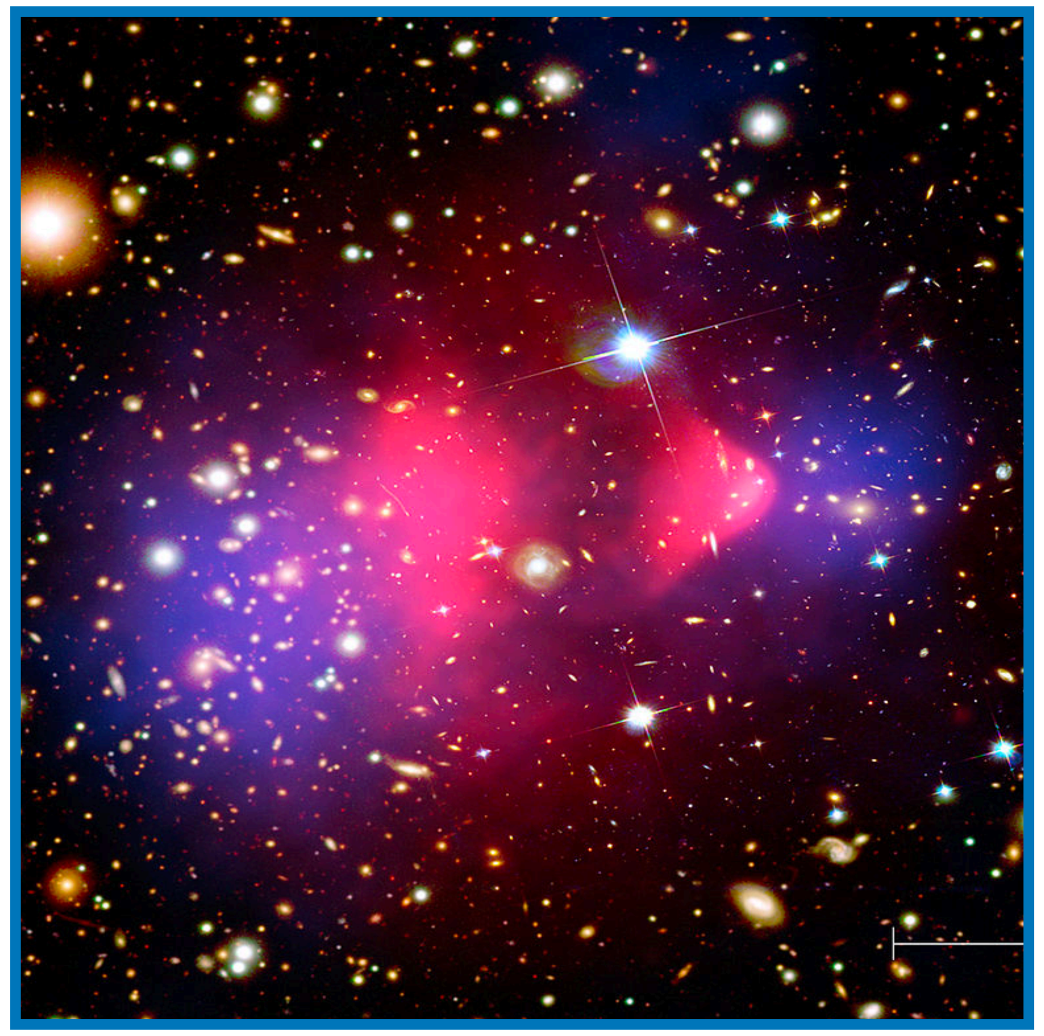
Neutron eDM = 0

Motivation #2: Dark matter

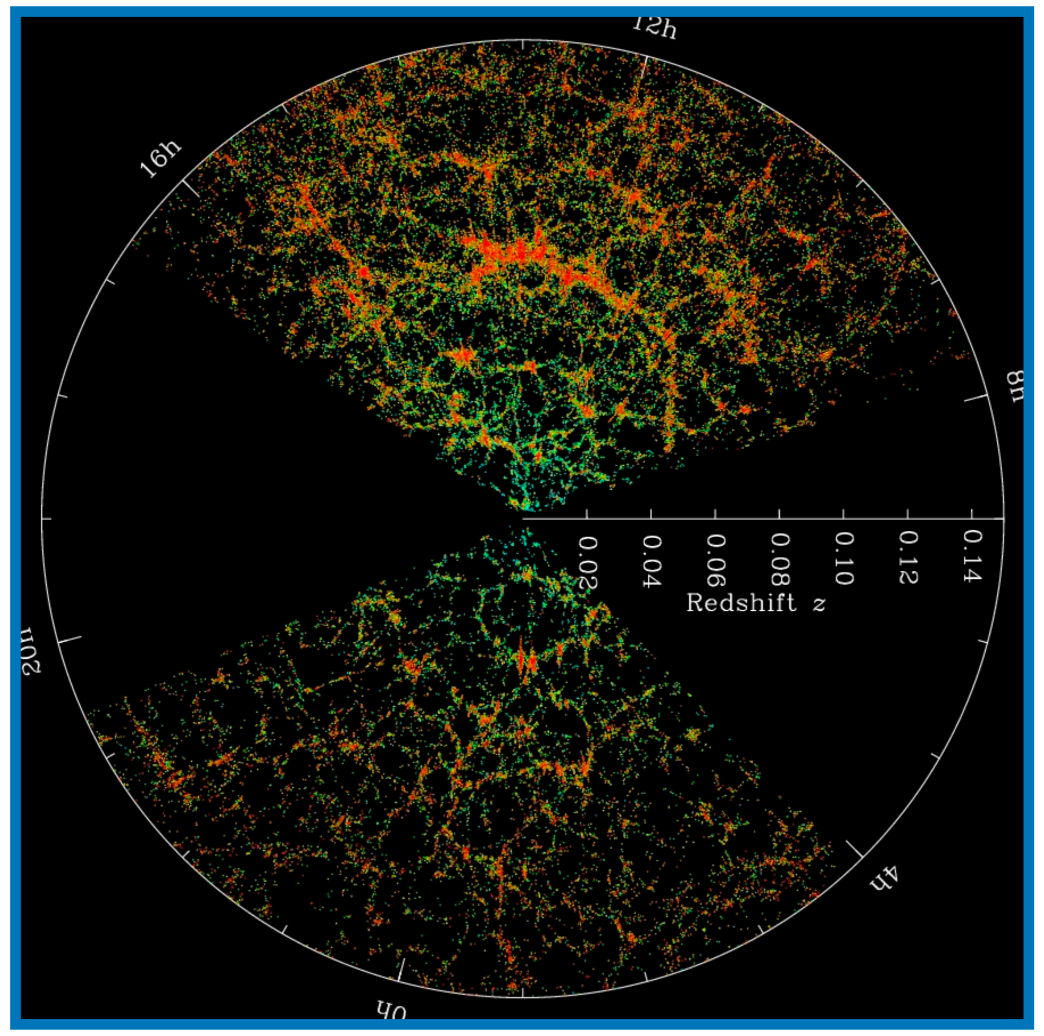
Galaxy rotation curves



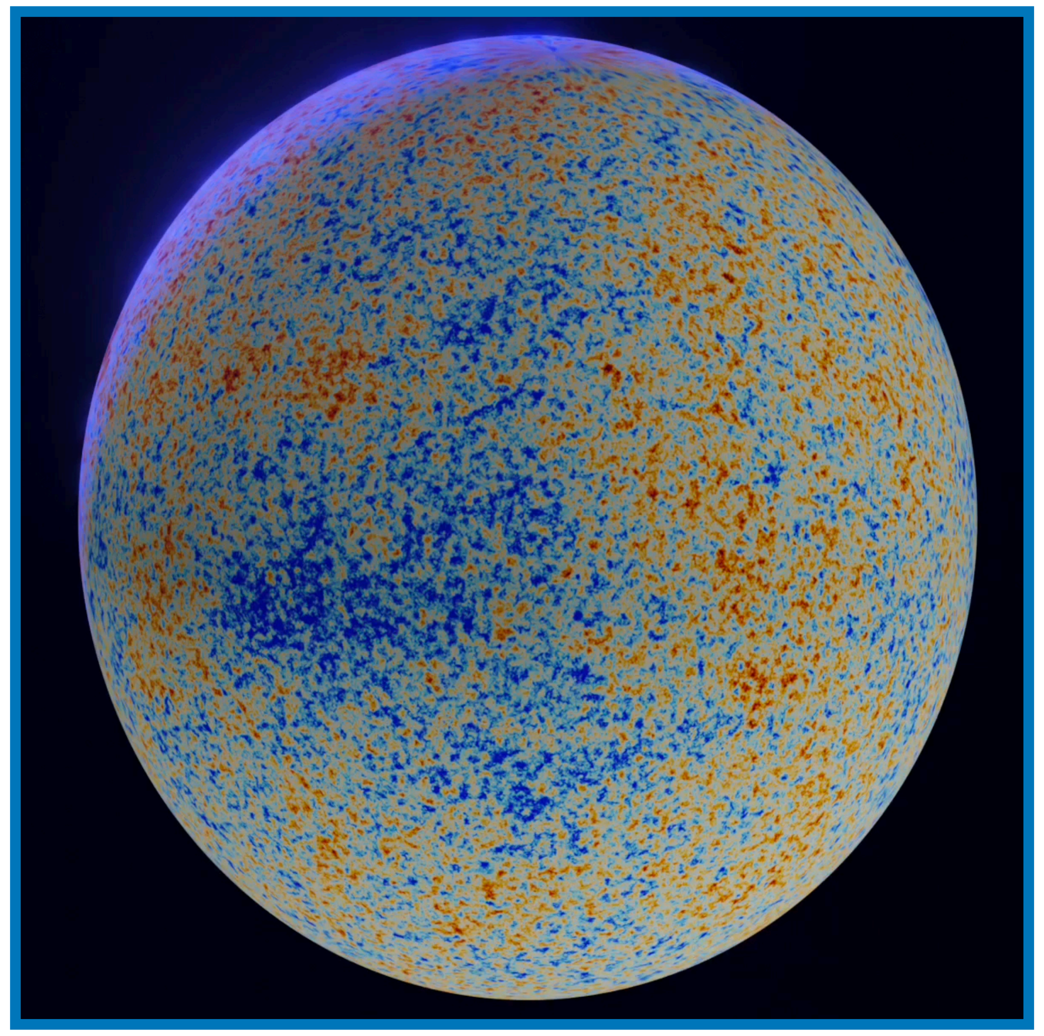
Merging galaxy clusters



Large scale structure



Cosmic microwave background



~kpc *~Mpc* *~100 Mpc* *~10 Gpc*

<u>Requirements</u>:

- Production mechanism
- Cosmologically long-lived
- Feeble interactions

[Requirement of generic new light physics]

$\tau \propto m_a^{-3}$

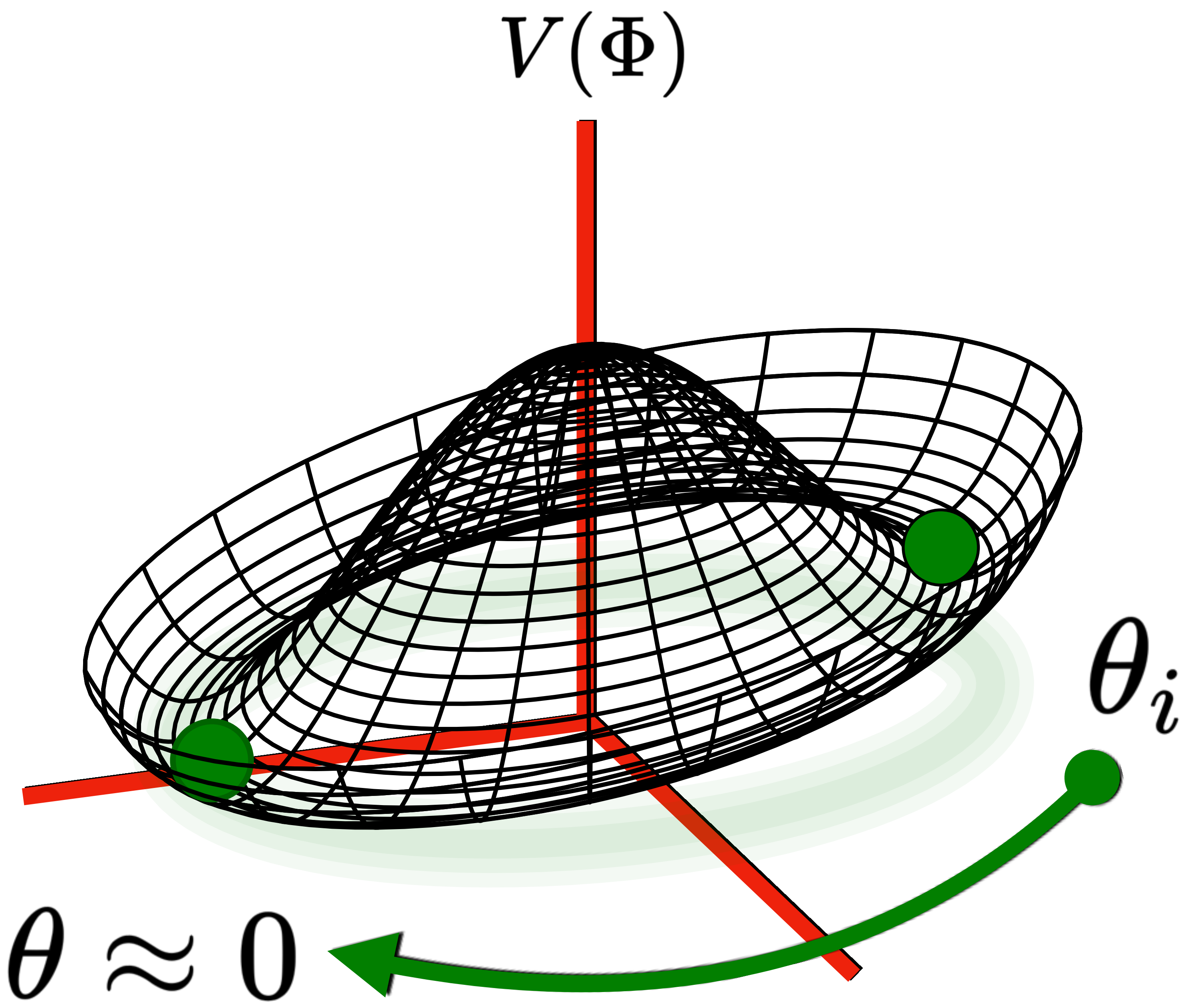
$\lambda \propto f_a^{-1}$

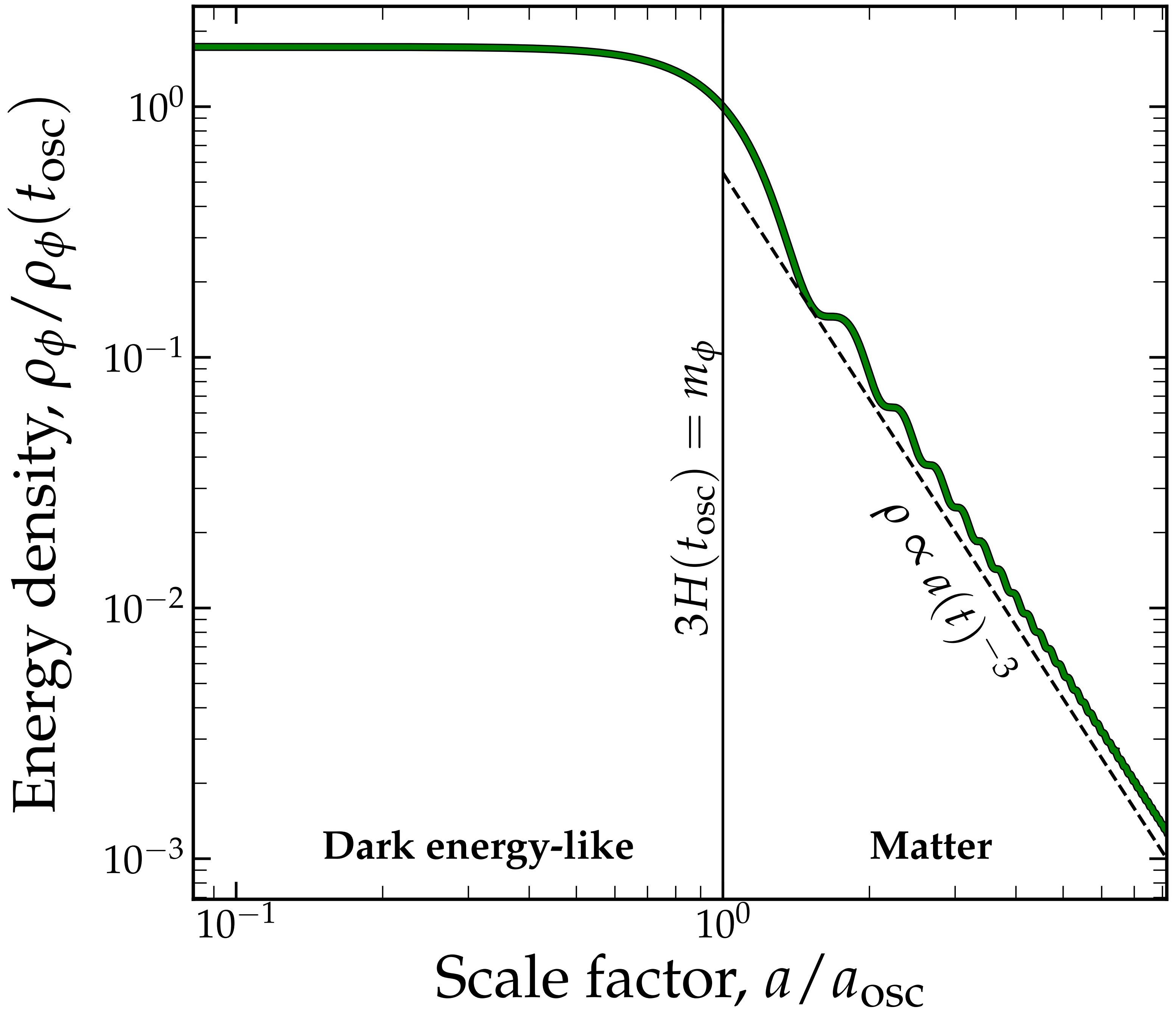
Natural for light axions from high energy scale

Figure credit: O'hare (2024)

Axions from the misalignment mechanism

Equation of motion: $\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$





$$\Omega_{\rm DM}h^2 \sim 0.05 \left(\frac{\tilde{\theta}_i}{1}\right)^2 \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

Axions from topological defects

Cosmic strings network in the early Universe

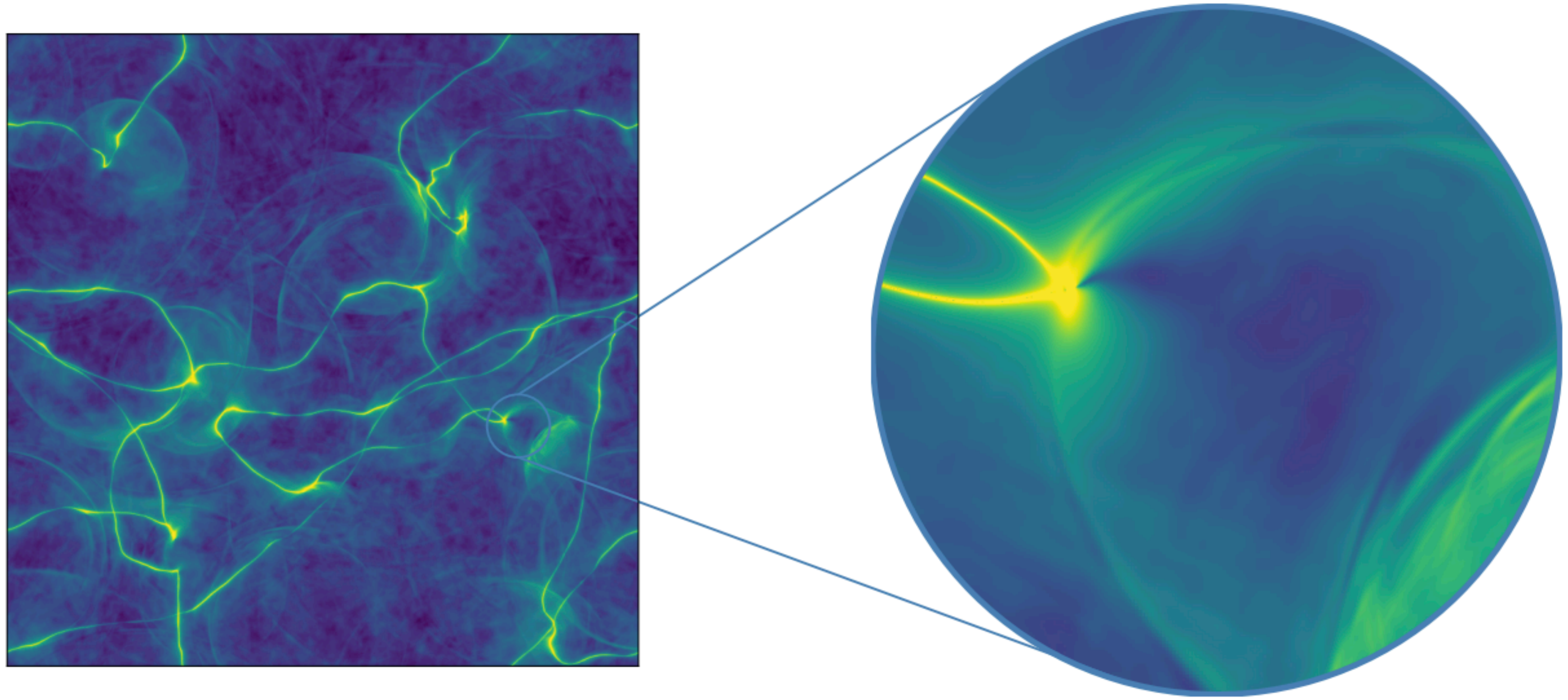
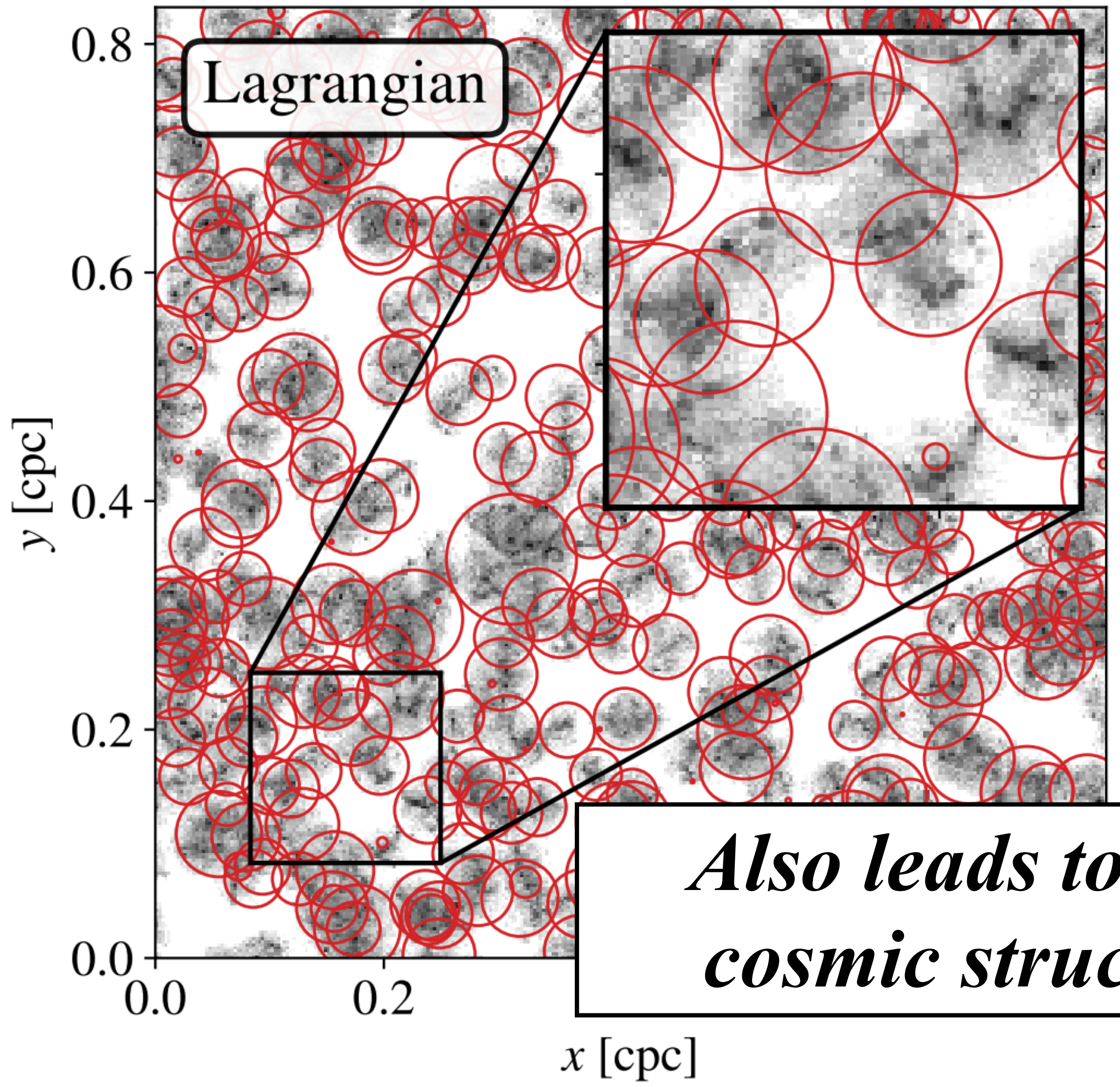


Image credit: Bernabou et al (2023)

Grilla di Cortana, Hardy, Pardo Vega, Villadoro (2016), Ghorgetto, Hardy, Villadoro (2018, 2021), Bushmann et al (2022), Saikawa et al (2024)

Strings/walls dominate for QCD axion with high inflationary scale

Axion density field

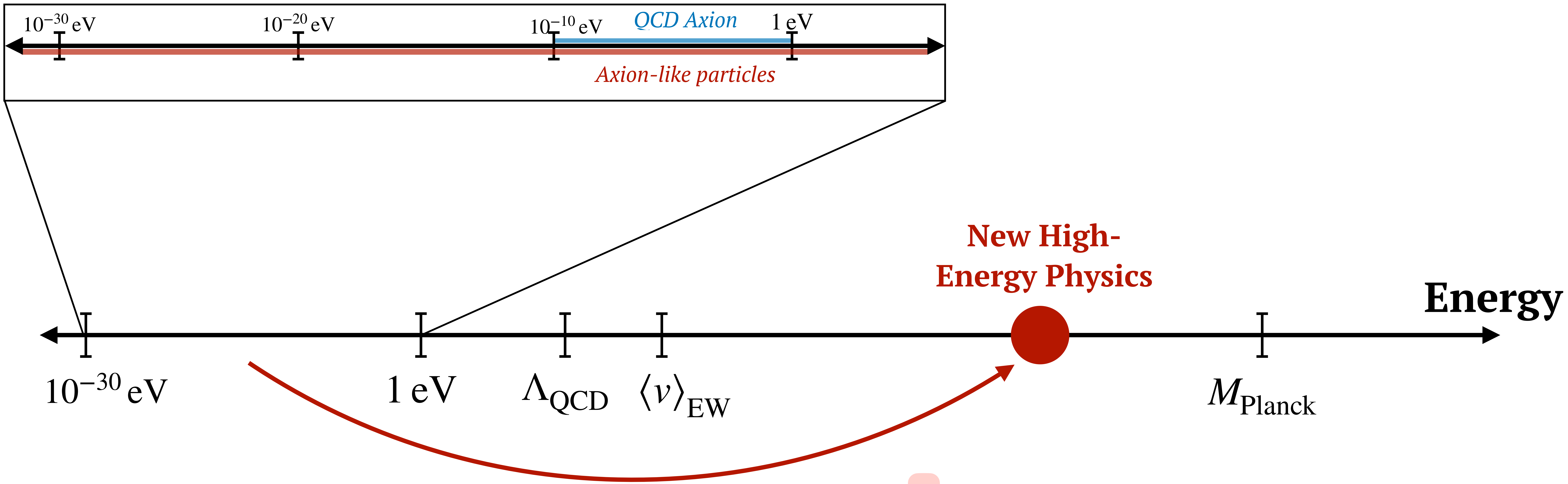


Also leads to rich cosmic structure

Image credit: Ellis et al (2022)

Collapse leads to "axion miniclusters" and "axion stars"

Motivation #3: Probes of high energies



$$\mathscr{L} \supset \frac{\xi}{f_a}\, a\, F\, \tilde{F}$$

Includes anomaly coefficient

For some recent examples see e.g.: Agrawal & Platschorre (2023), Gendler, Marsh, McAllister, Moritz (2023), Agrawal, Nee, Reig (2022), Agrawal, Hook, Huang (2020)…

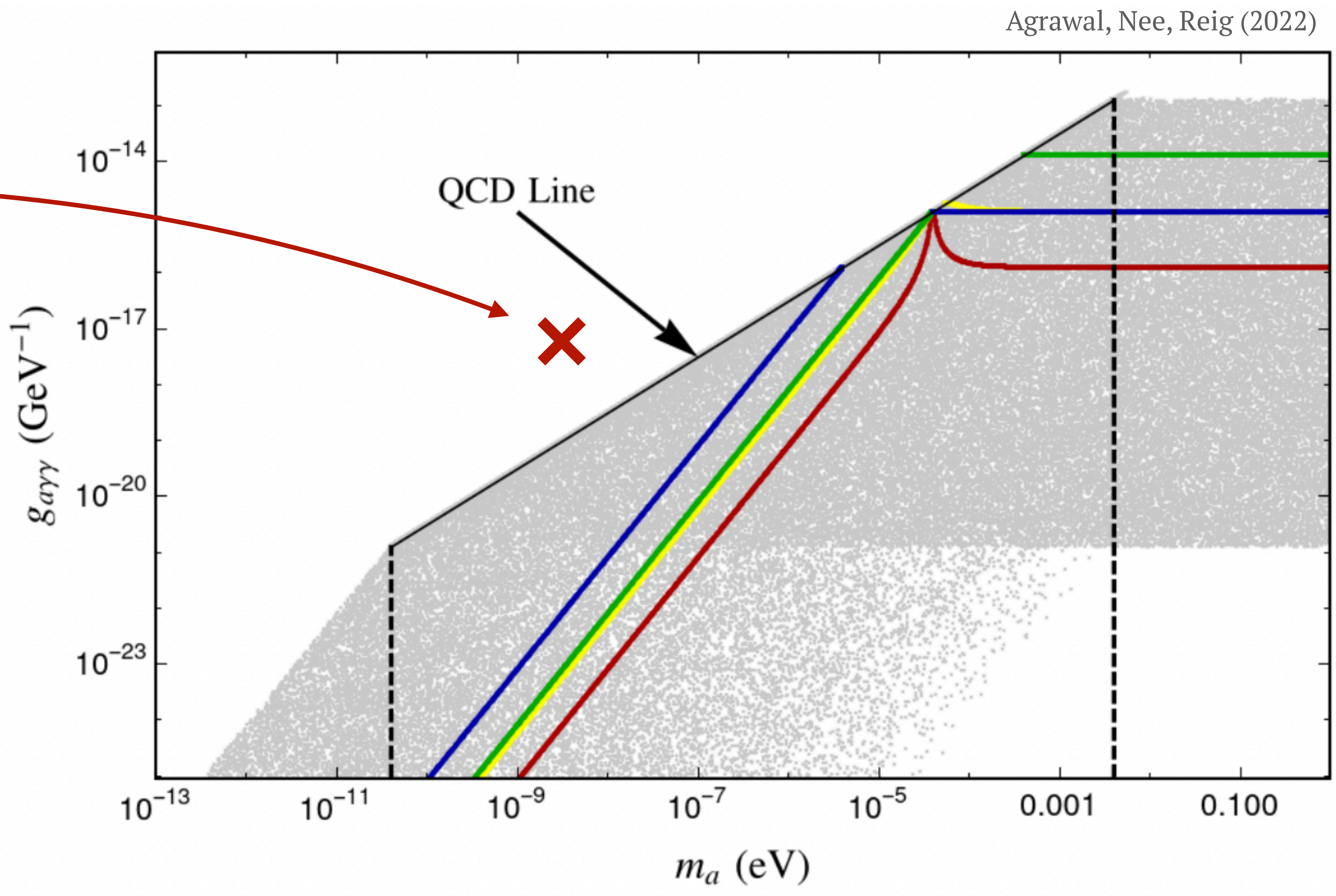
Example: axions as a probe of GUTs

Detection of axion here implies:

- QCD axion is tuned light

OR

- no GUT


Agrawal, Nee, Reig (2022)

Astrophysics as a laboratory

White dwarf

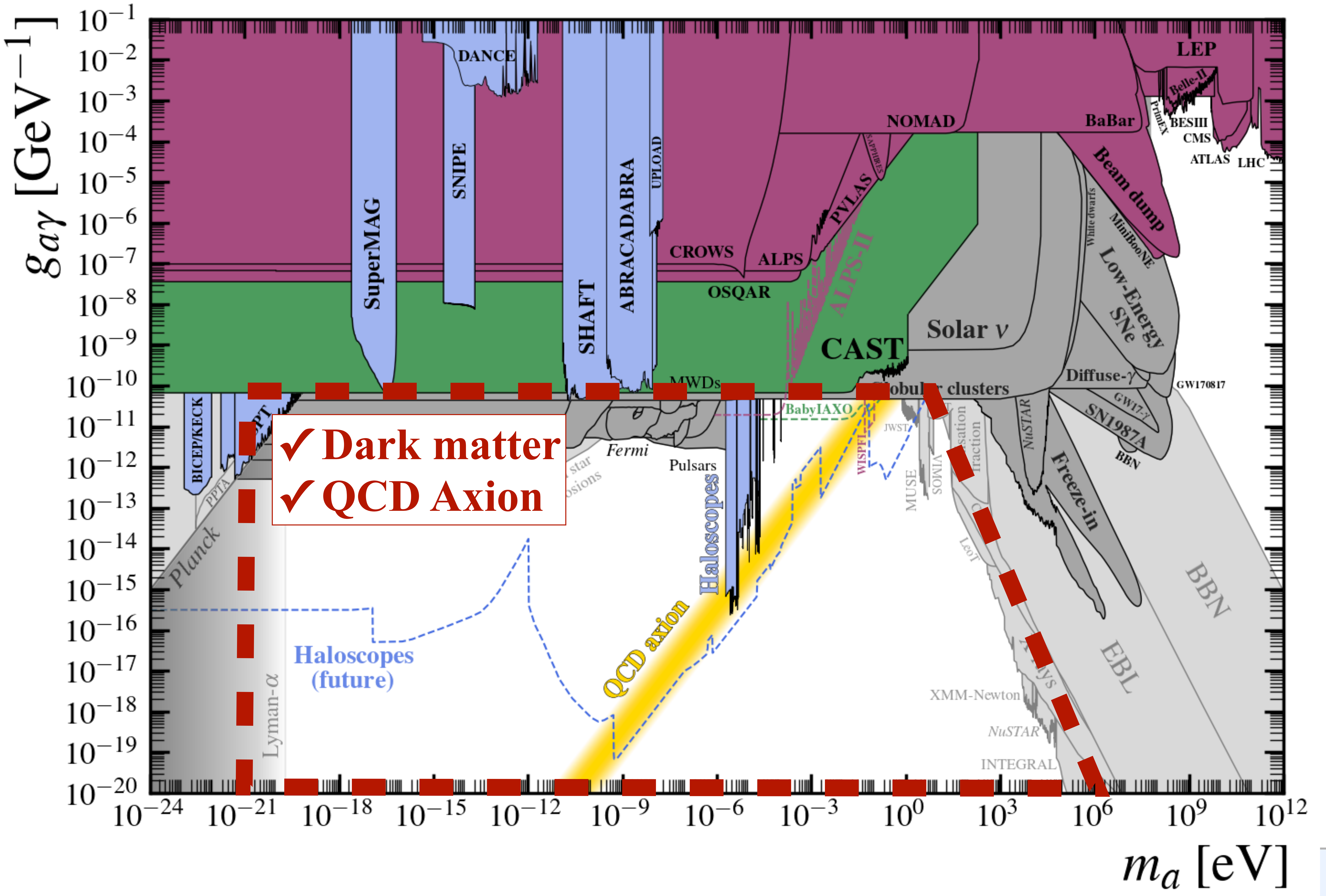
Pulsar

Black hole

Can we use Nature's laboratories to search for axions?

Parameter space overview

$$\mathscr{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

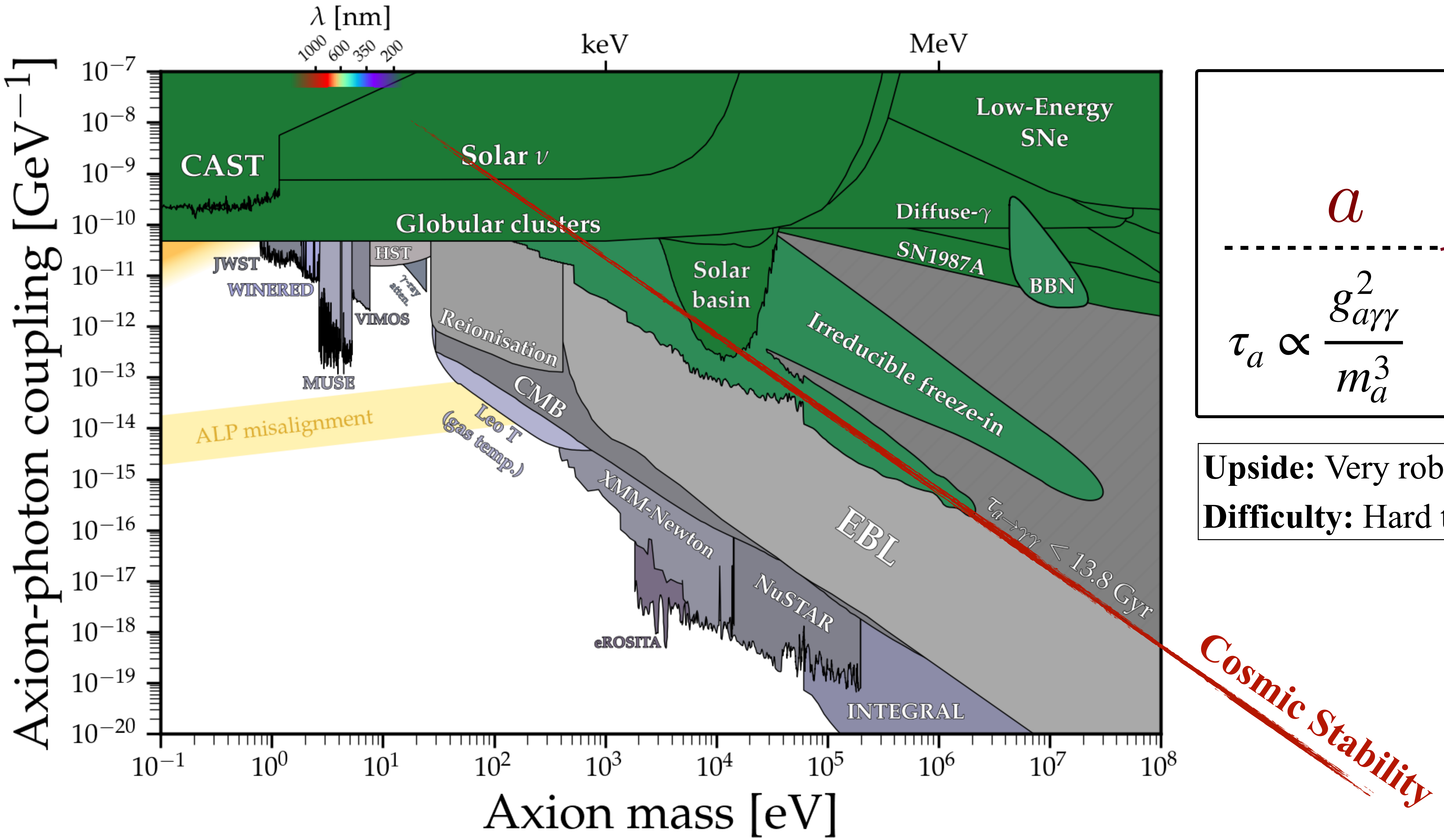


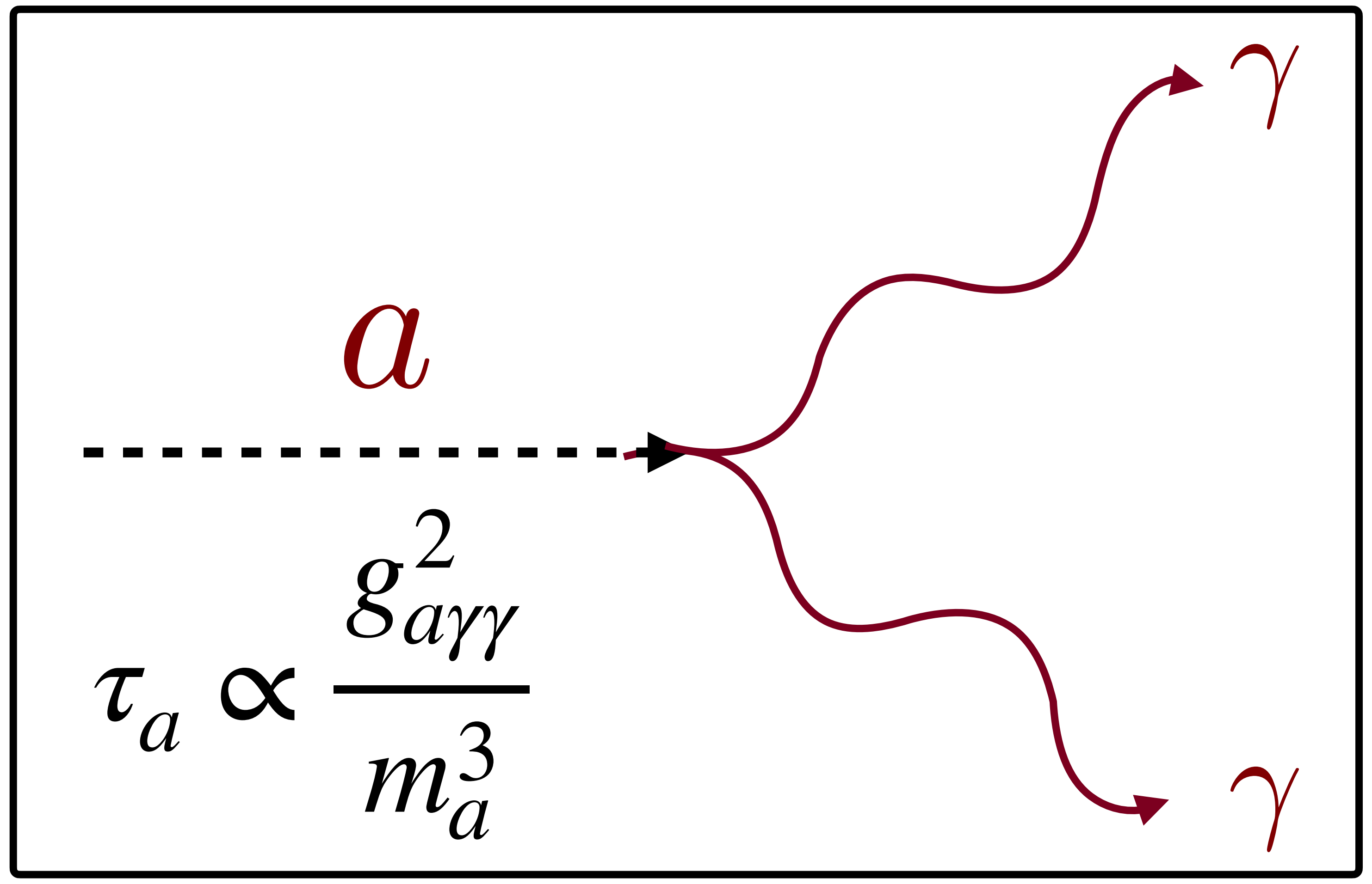
✓ Dark matter

✓ QCD Axion

https://cajohare.github.io/AxionLimits/

Axion decay





$$\tau_a \propto \frac{g_{a\gamma\gamma}^2}{m_a^3}$$

Upside: Very robust

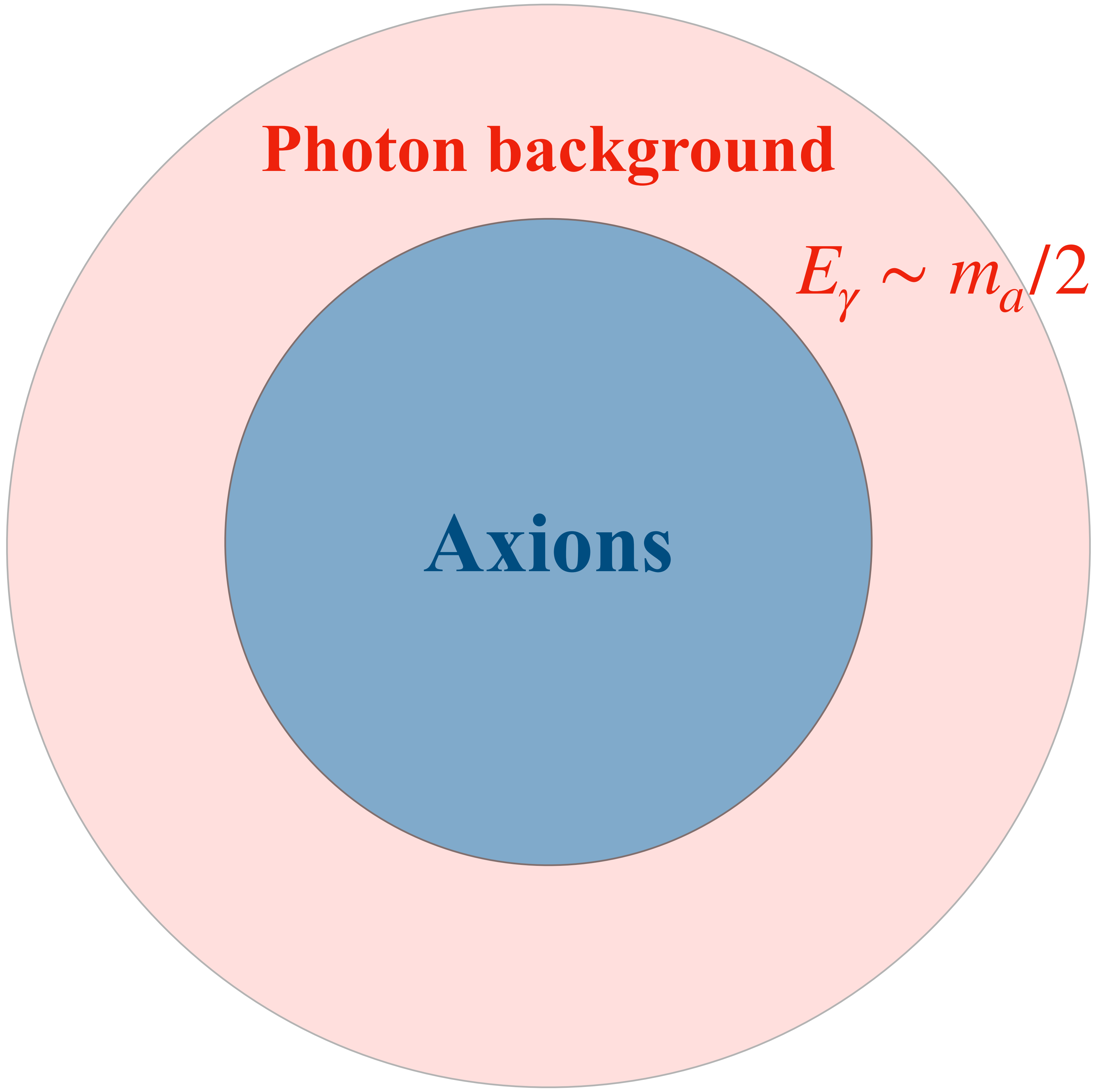
Difficulty: Hard to make progress

https://cajohare.github.io/AxionLimits/

Simulating axion decay

$$\tau_a \propto \frac{g_{a\gamma\gamma}^2}{m_a^3}\left(1 + 2f_\gamma\right)^{-1}$$

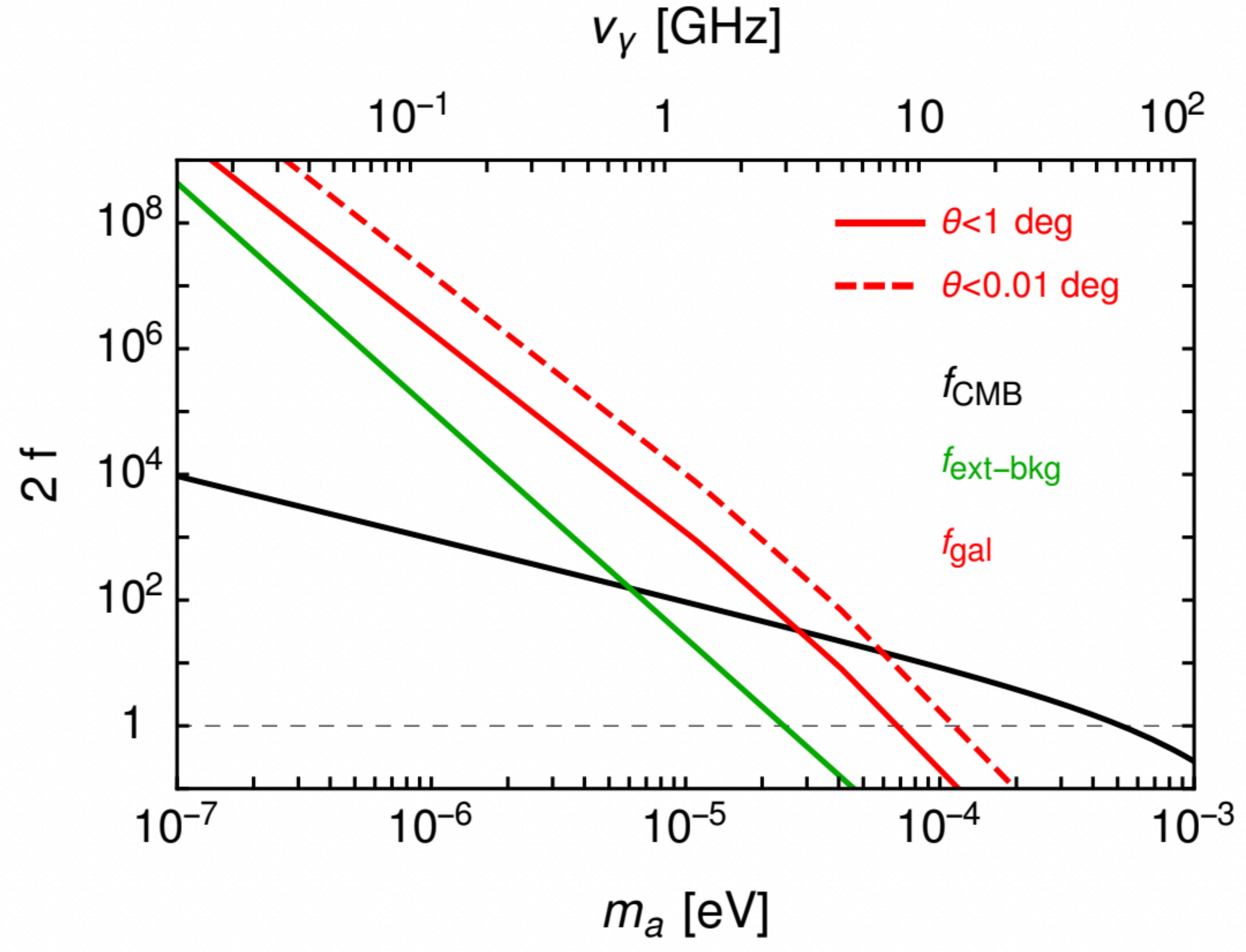
Tkachev (1987, 2015), Kephart & Weiler (1995), Caputo, Peña-Garay, **SJW** (2018), Caputo, Regis, Taoso, **SJW** (2018), Azra & Skive (2019), Battye et al (2019), Sigl & Trivedi (2019), Carenza, Mirizzi, Sigl (2020), Ghosh, Savlado, Miranda (2020), Arza, Schwetz, Todarello (2020), Sun et al (2022, 2023), Buen-Abad, Fan, Sun (2022), Escudero et al (2023)........



Photon background

$E_\gamma \sim m_a/2$

Axions



Caputo, Regis, Taoso, **SJW** (2018)

Simulating axion decay

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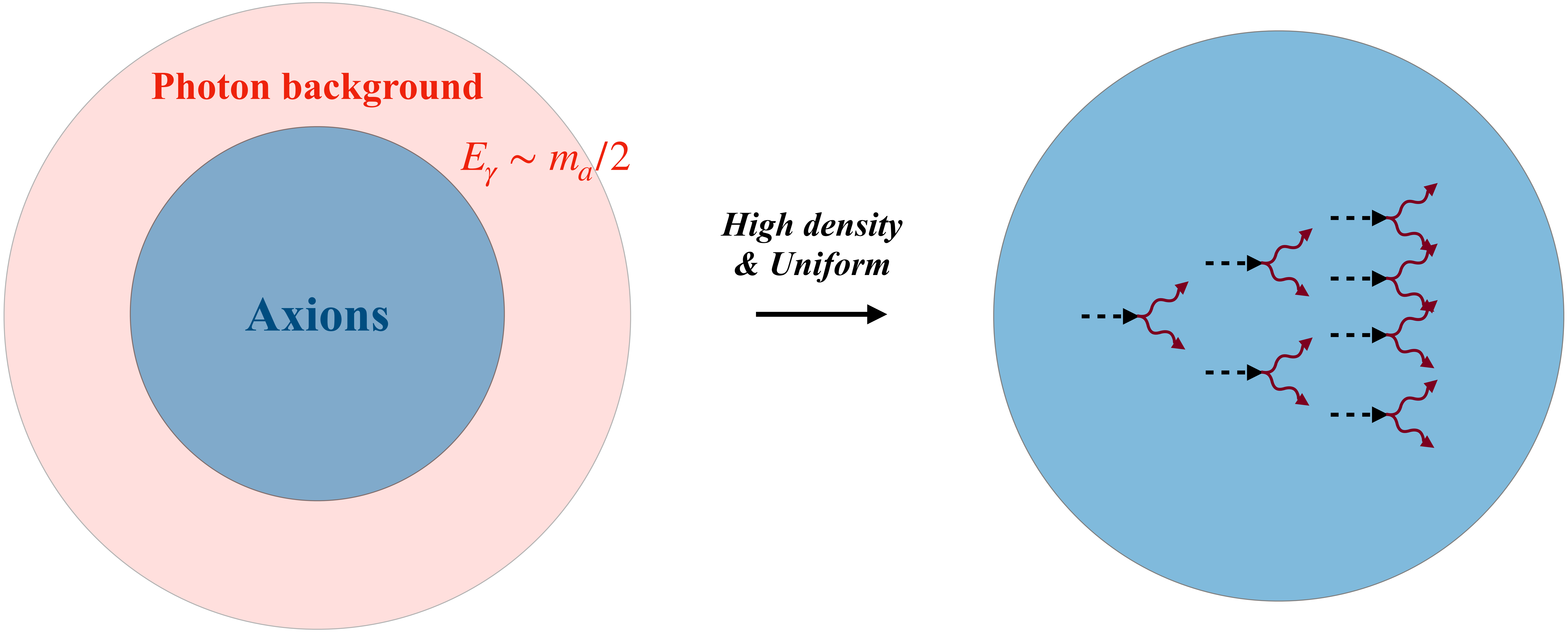


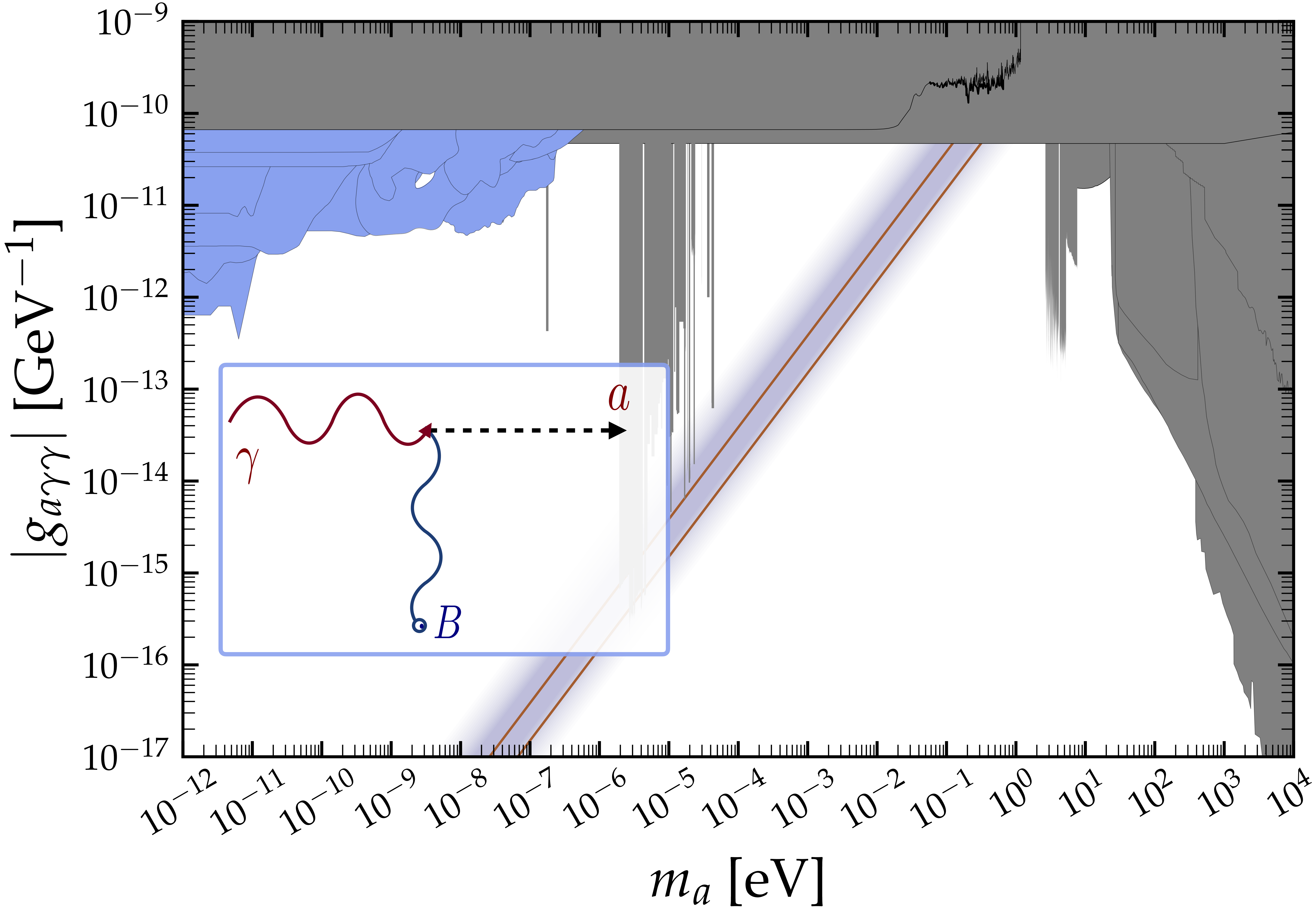
Photon background

$E_\gamma \sim m_a/2$

Axions

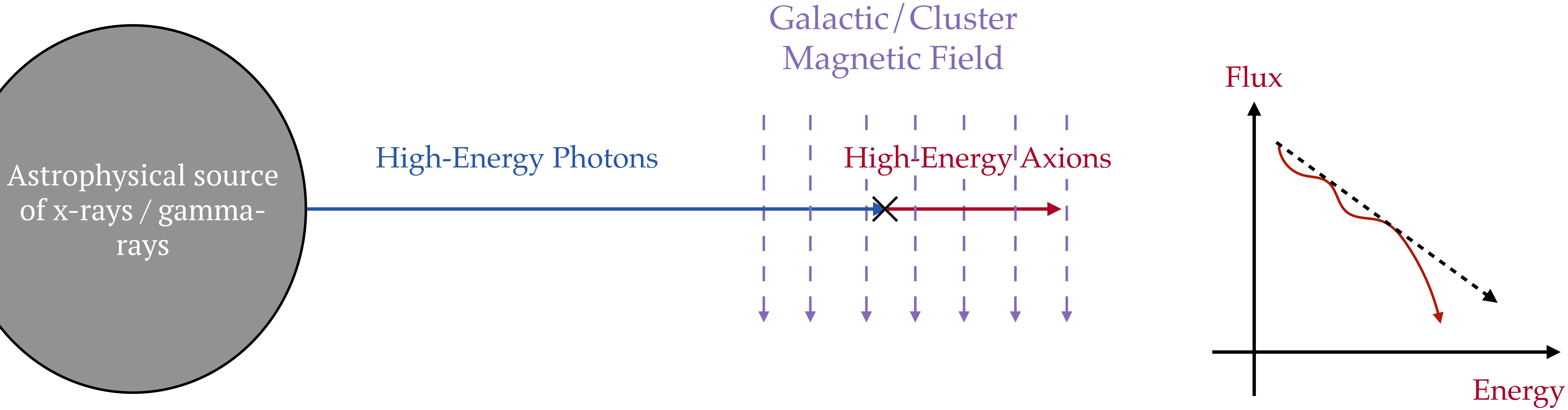
High density & Uniform

X-ray / Gamma-ray searches for axions



Plot made using cajohare.github.io/AxionLimits/

X-ray / Gamma-ray searches for axions



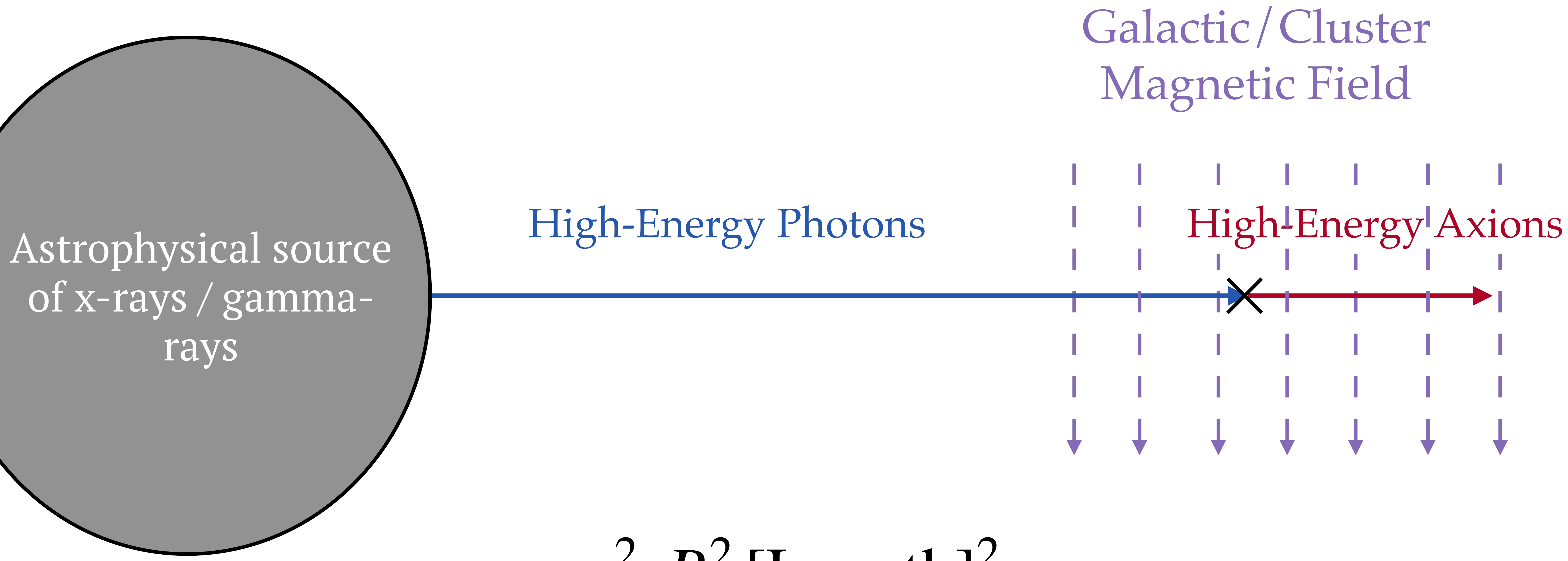
Astrophysical source of x-rays / gamma-rays

High-Energy Photons

Galactic/Cluster Magnetic Field

High-Energy Axions

X-ray / Gamma-ray searches for axions



Galactic / Cluster Magnetic Field

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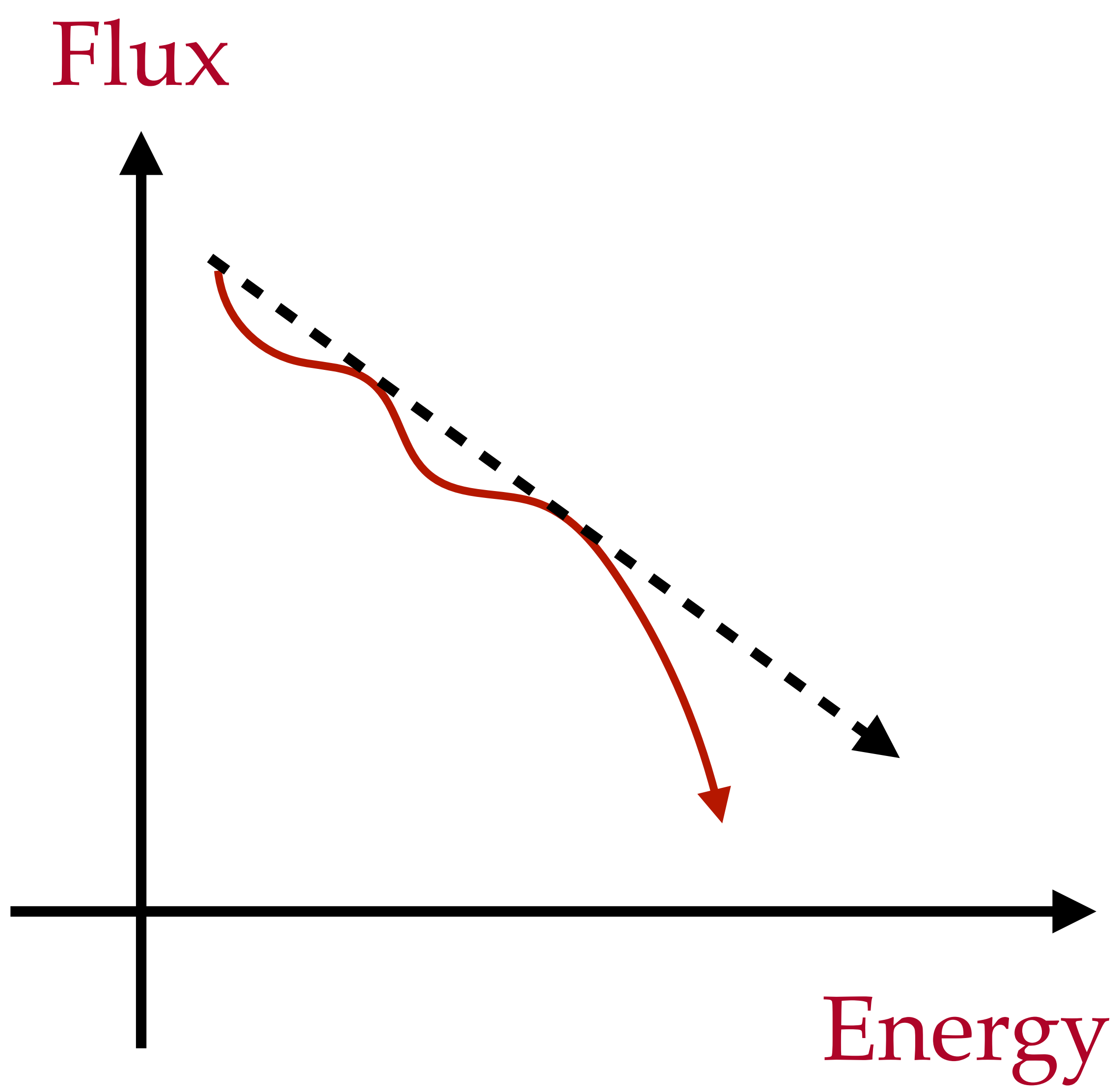
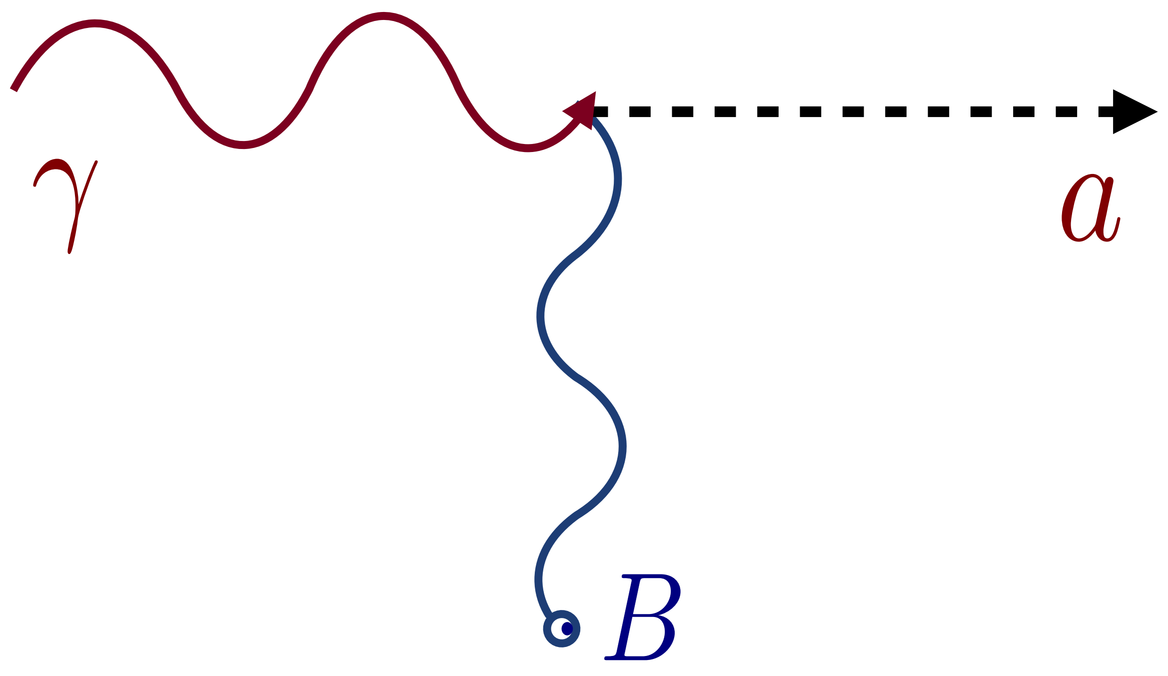


$$p_{\gamma\to a} \sim g_{a\gamma}^2\, B^2\, [\mathrm{Length}]^2$$



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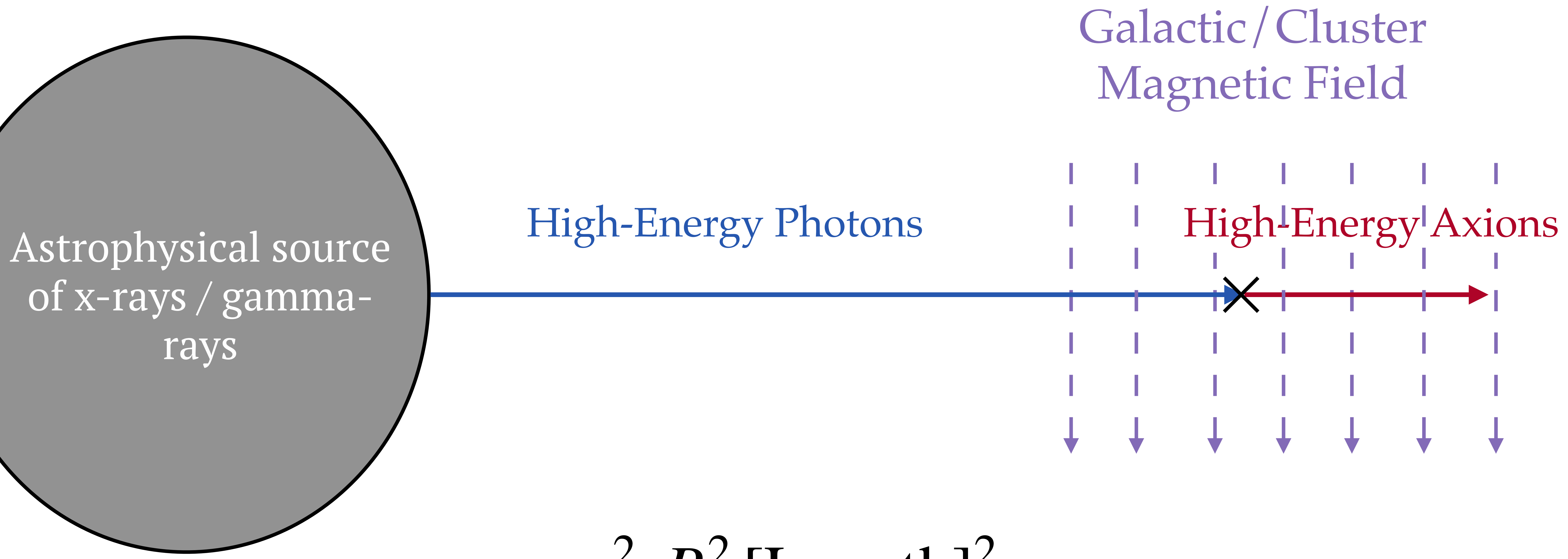

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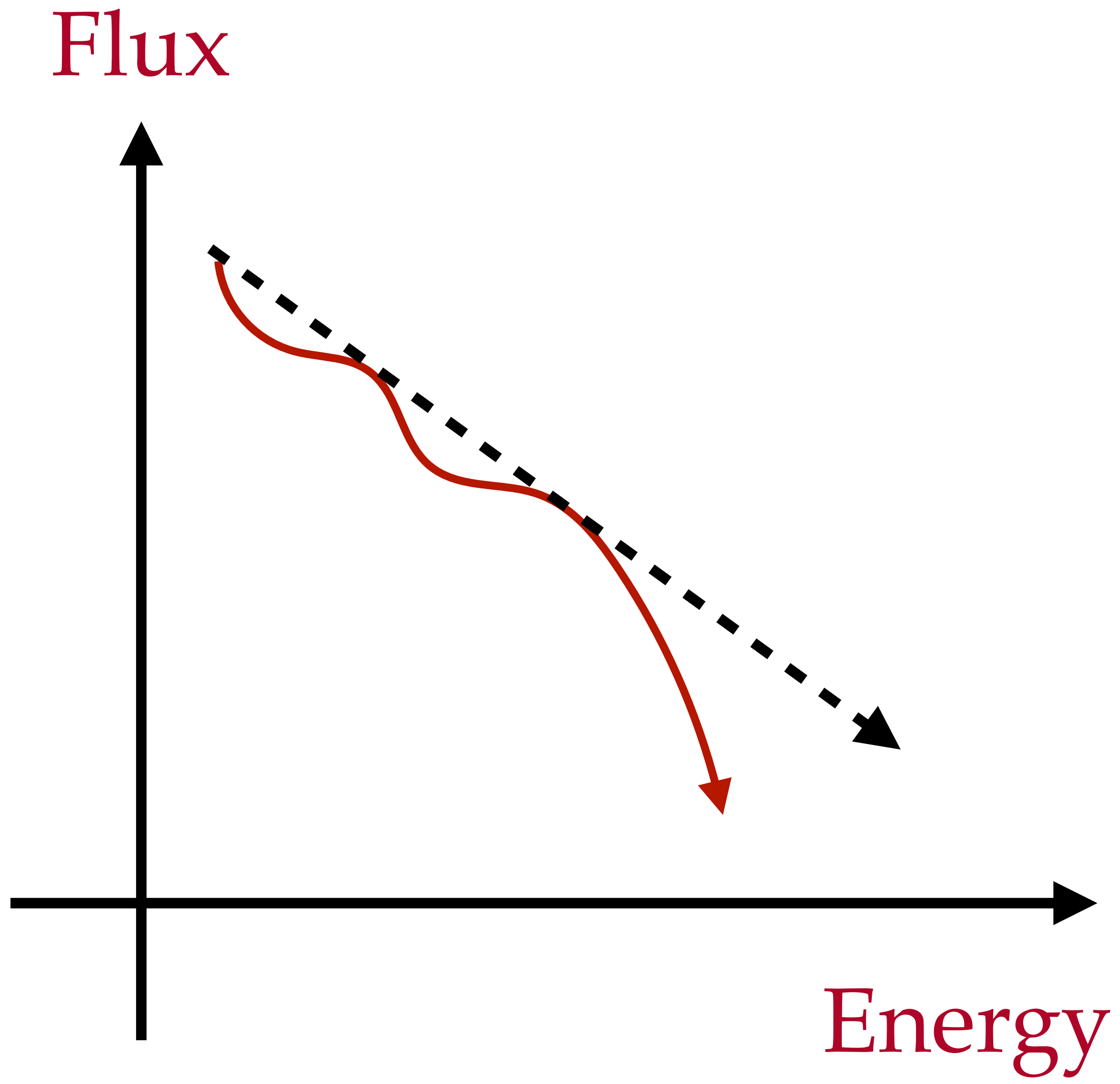

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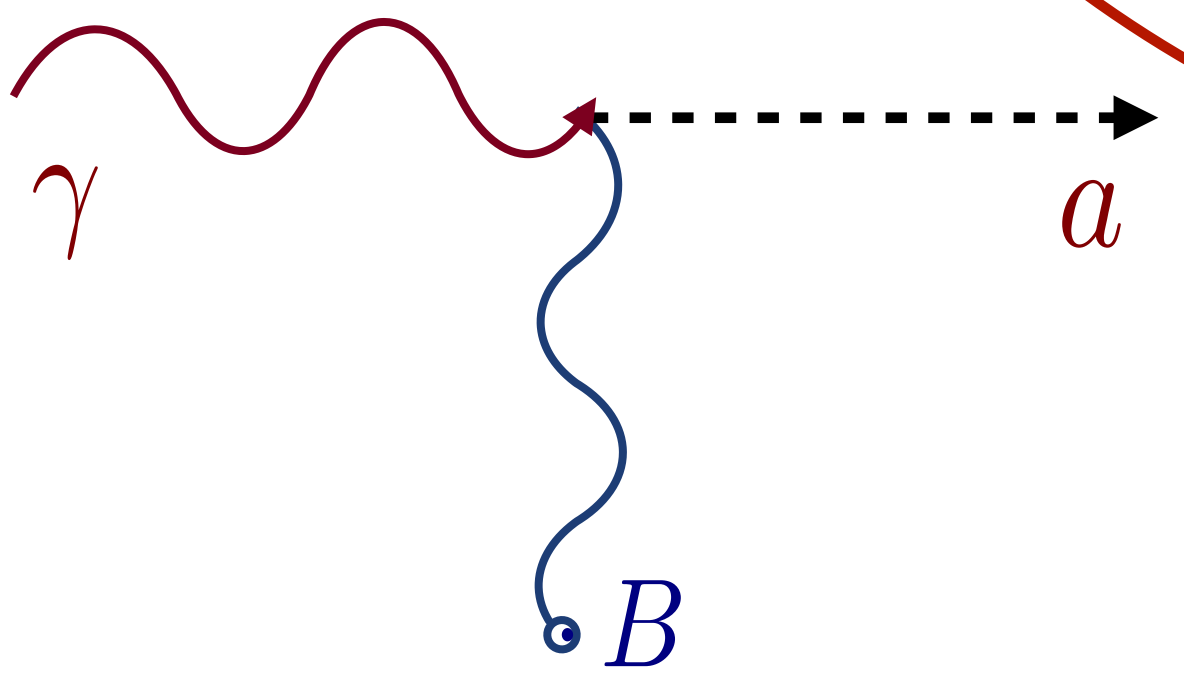
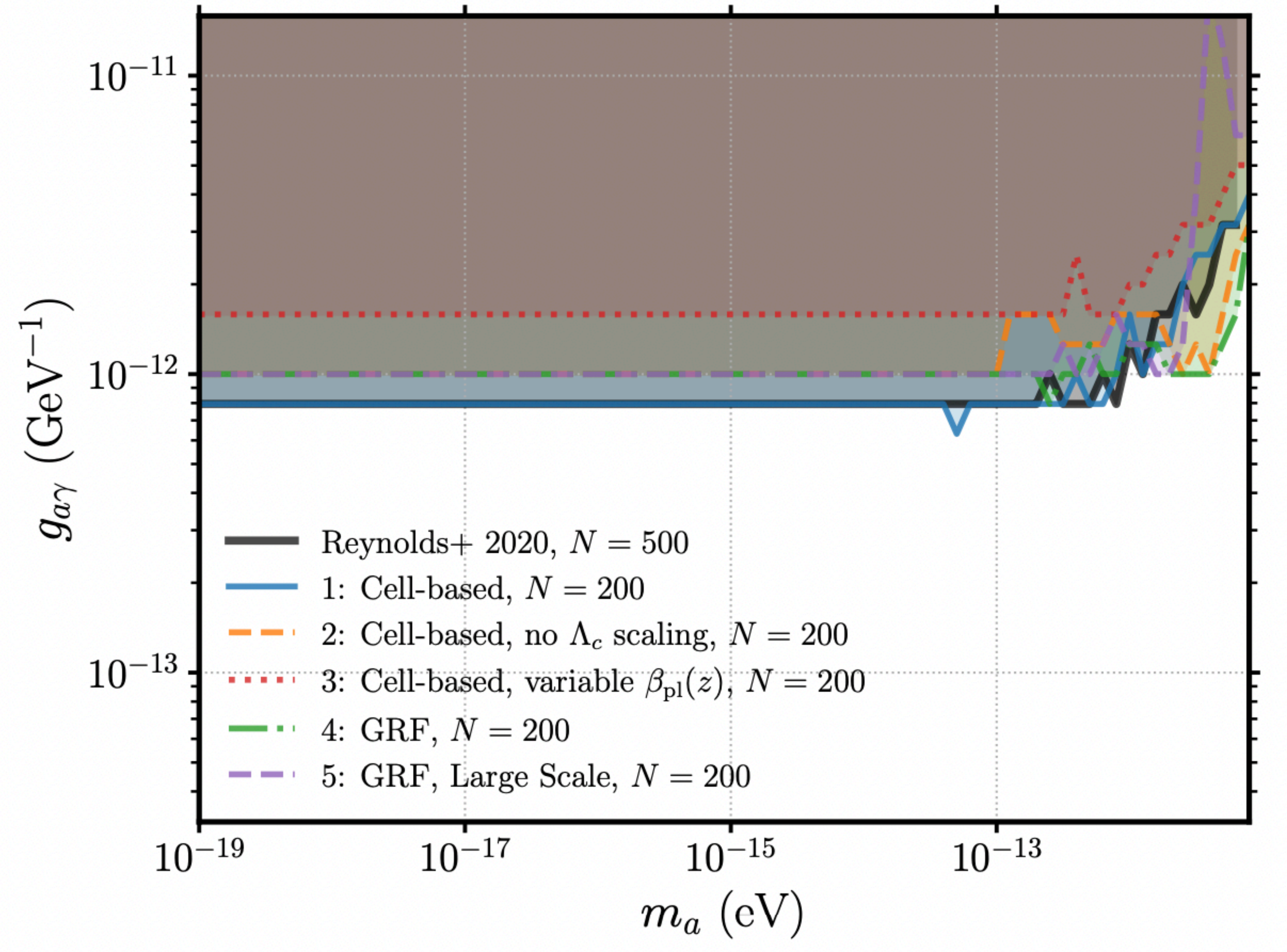


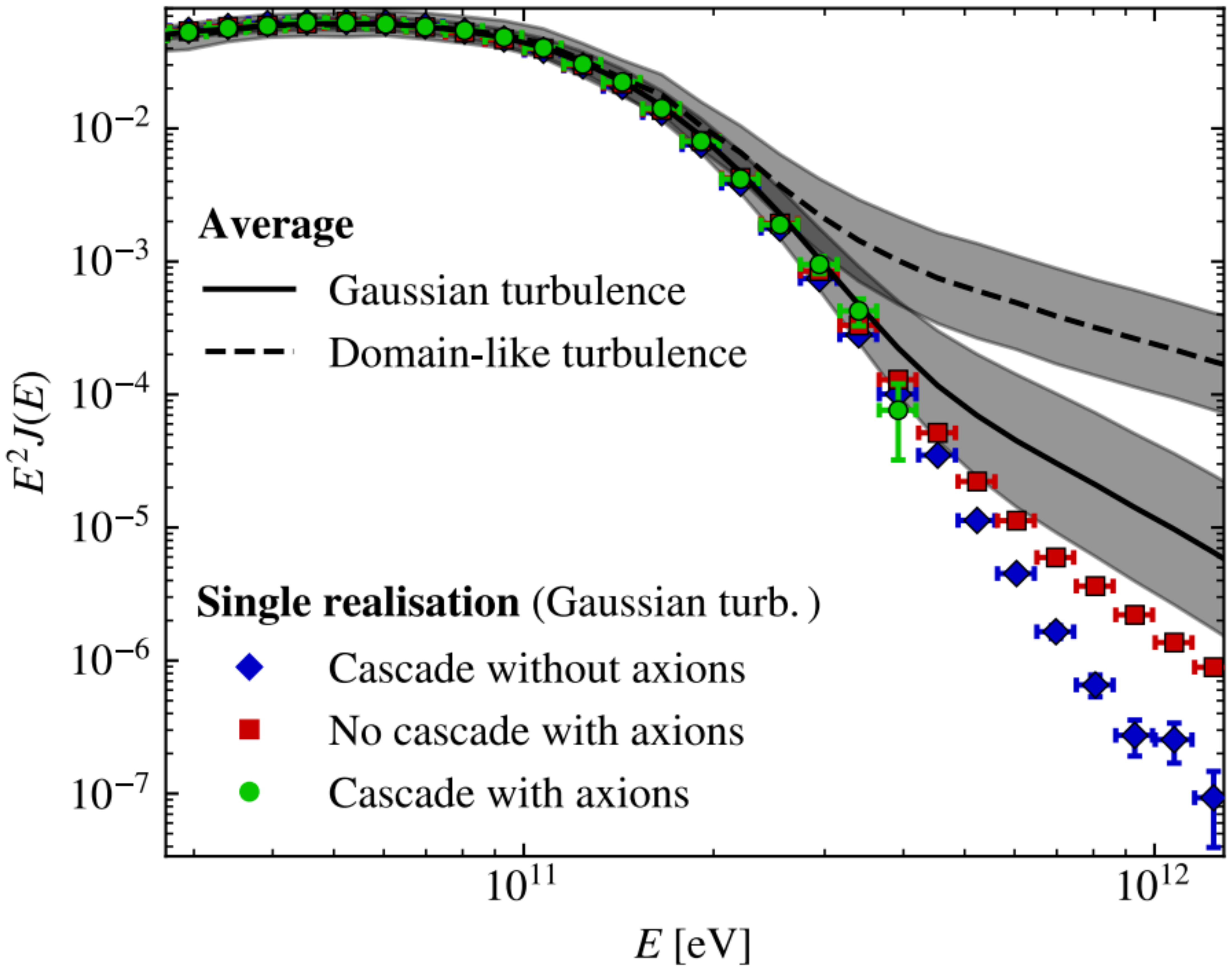
$$\begin{cases} \text{Length of magnetic field} & (m_a \to 0) \\ (k_\gamma - k_a)^{-1} \sim 2E_\gamma / m_a^2 & (\text{Large } m_a) \end{cases}$$

Magnetic fields, ugh….

See e.g. Matthews et al (2022), Carenza et al (2023)



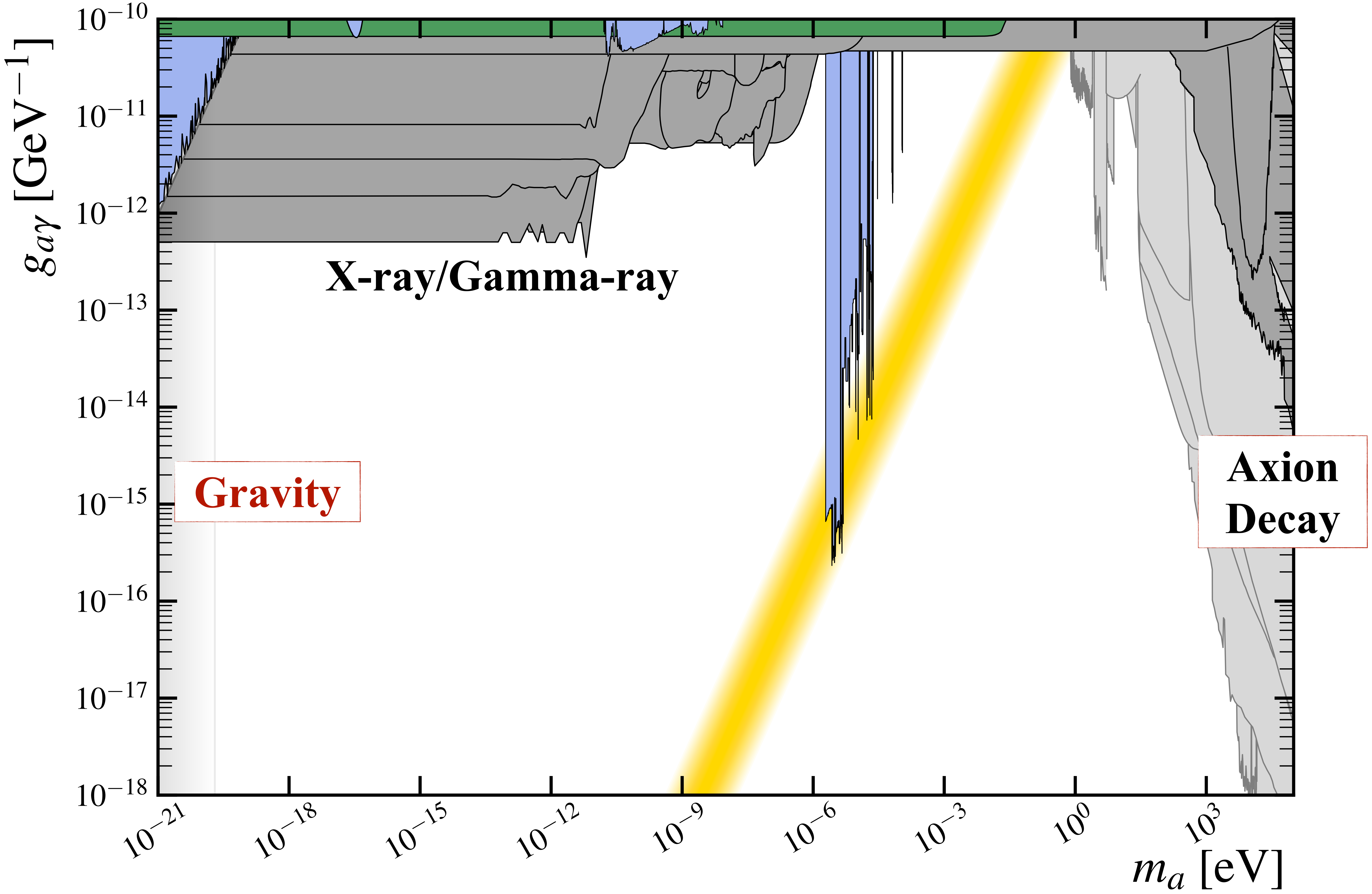
Kachelrieß & Tjemsland (2022)



Upside: Reasonably straight-forward physics

Difficulty: Large-scale magnetic fields *(progress limited by finding idealised systems that we understand)*

Axions & Gravity



https://cajohare.github.io/AxionLimits/

The gravitational footprint of ultralight axions

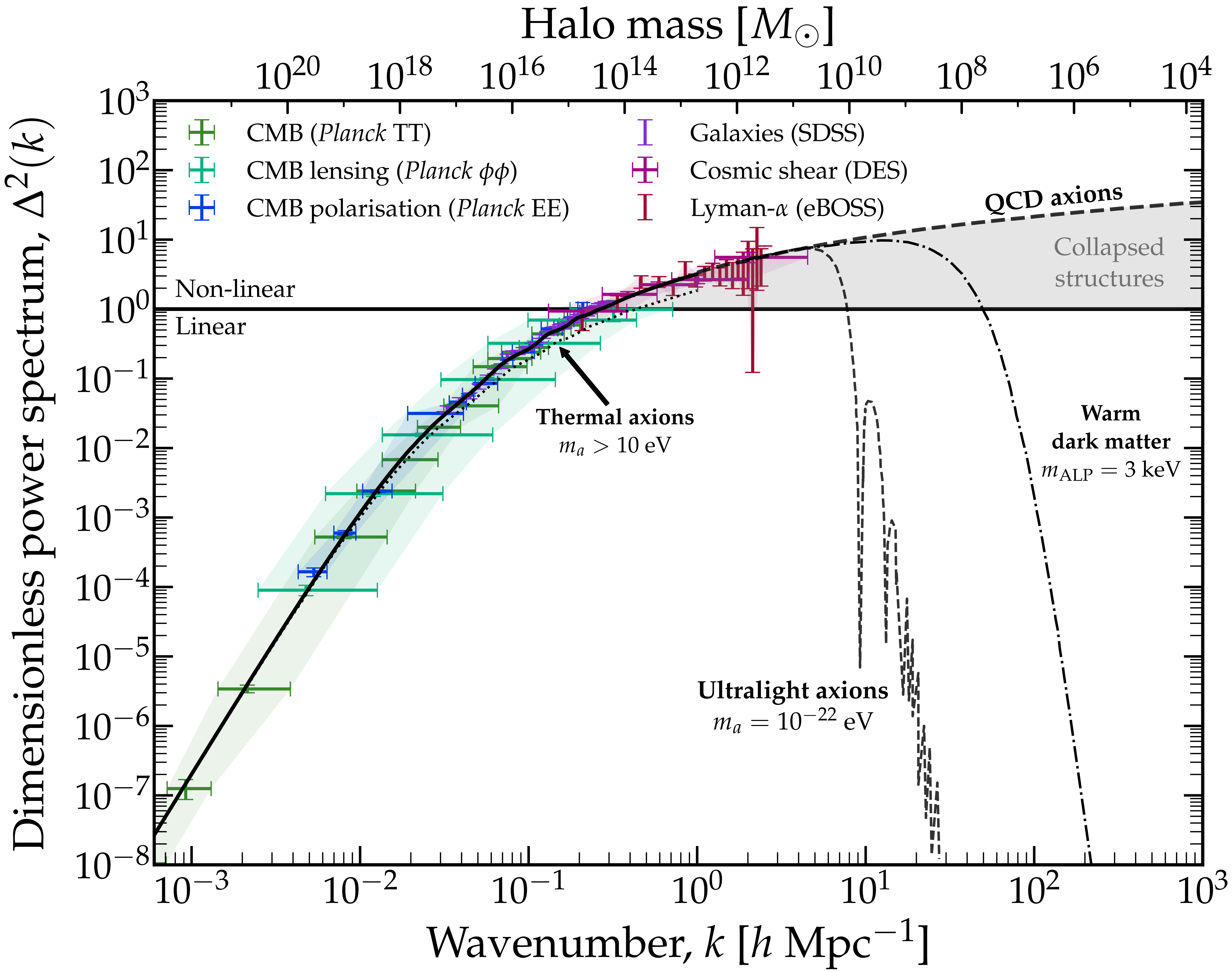


Figure credit: O'Hare (2024)

Gravitational evolution of classical field

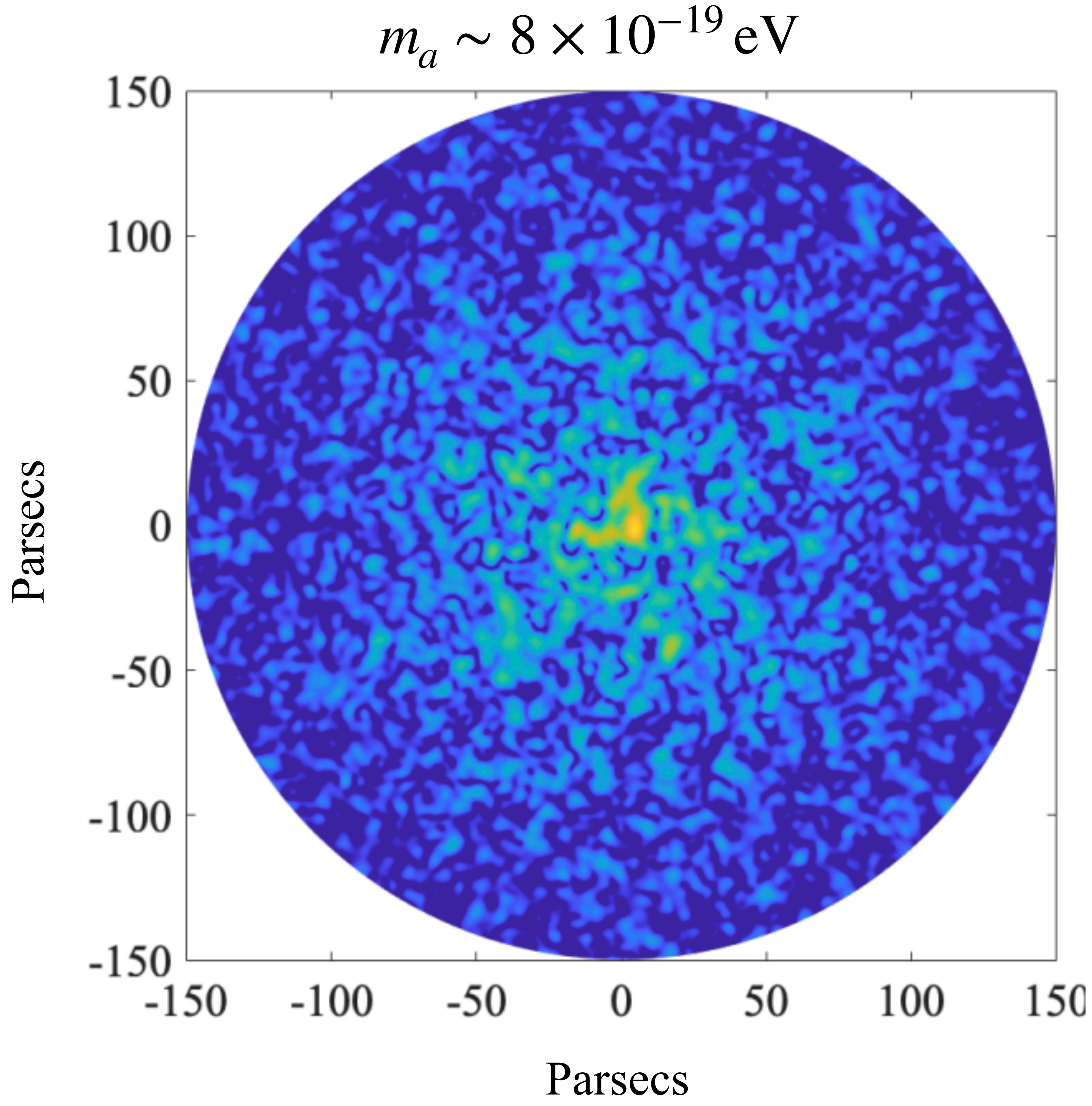
$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{k^4}{4m^2a^2} - 4\pi G\bar{\rho}\right)\delta_k = 0$$

Gradient ("quantum") pressure

Quantum mechanics limits "packing" of low mass particles

$$\delta x \times \delta v \gtrsim m^{-1}$$

The gravitational footprint of ultralight axions



Density profile ultra-faint dwarf

Implications:

- Soliton core at center
- Heat stellar orbits

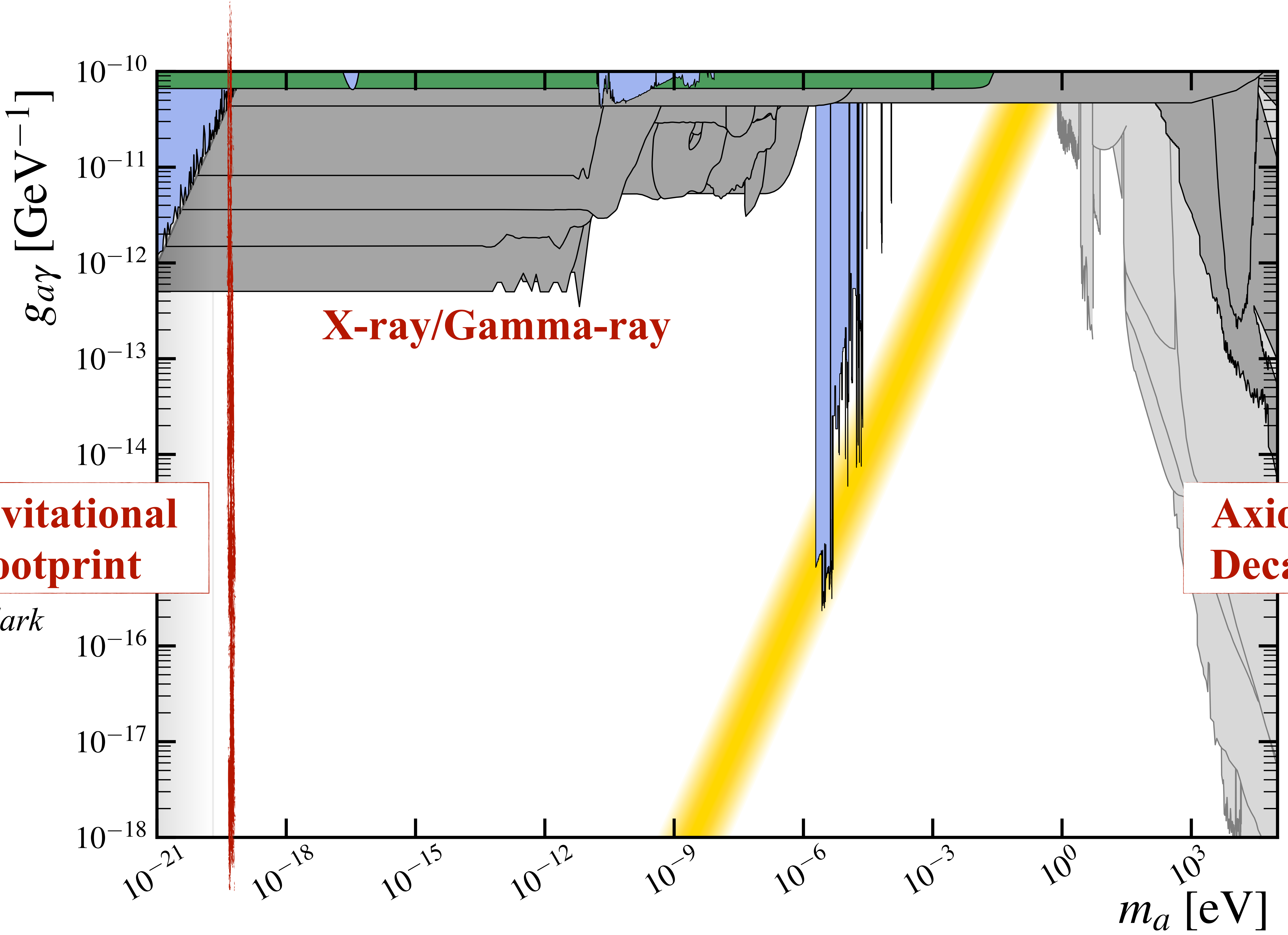
Upside: Purely gravitational

Difficulty: Modelling small scales / feebly bound objects

Image credit: Dalal & Kravtsov (2022)

See e.g. reviews by Hui (2014), Niemeyer (2020), Ferreira (2021), O’Hare (2024)

Axions near extreme compact objects



X-ray/Gamma-ray

Gravitational Footprint

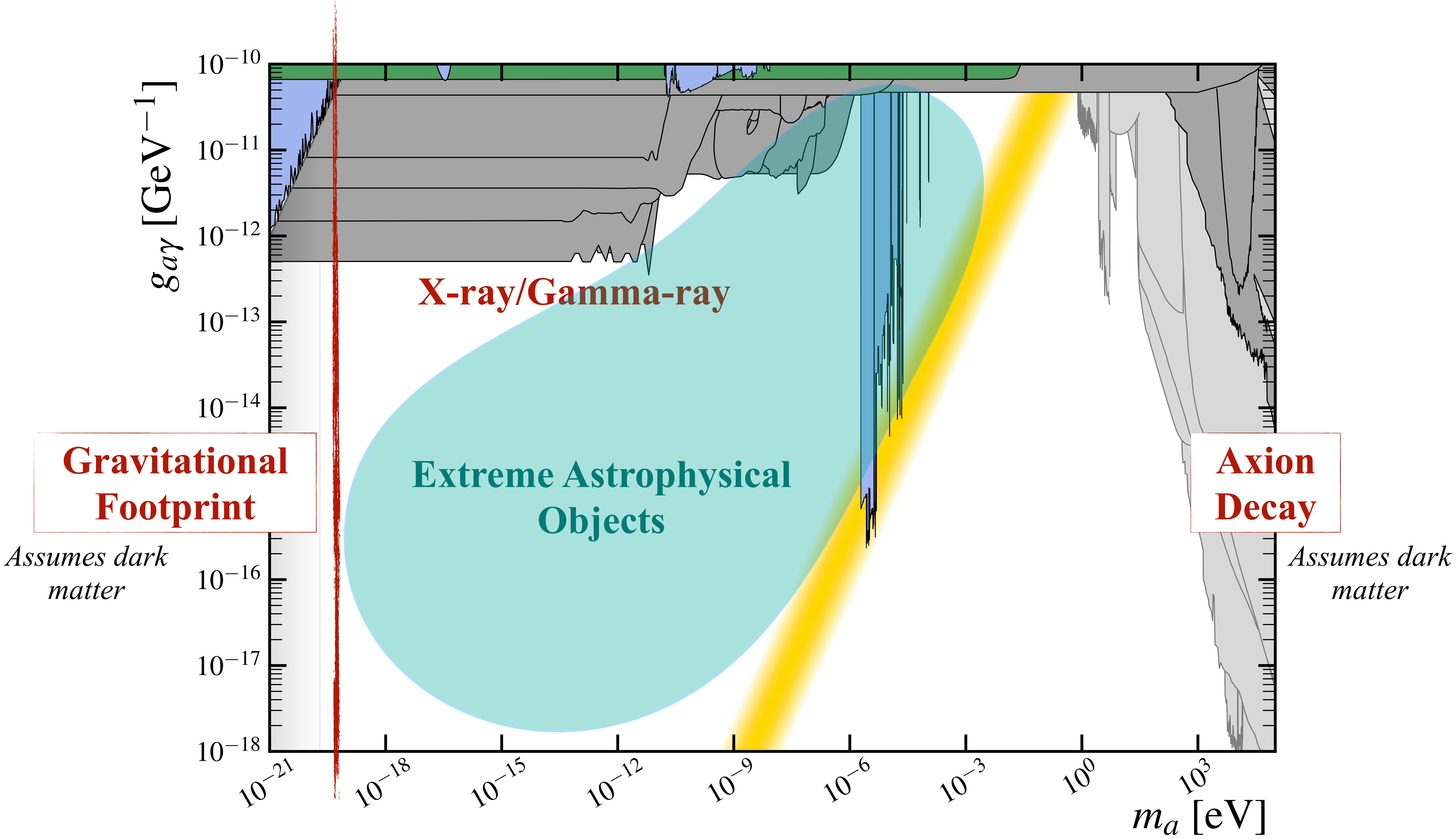
Assumes dark matter

Axion Decay

Assumes dark matter

https://cajohare.github.io/AxionLimits/

Axions near extreme compact objects



Assumes dark matter

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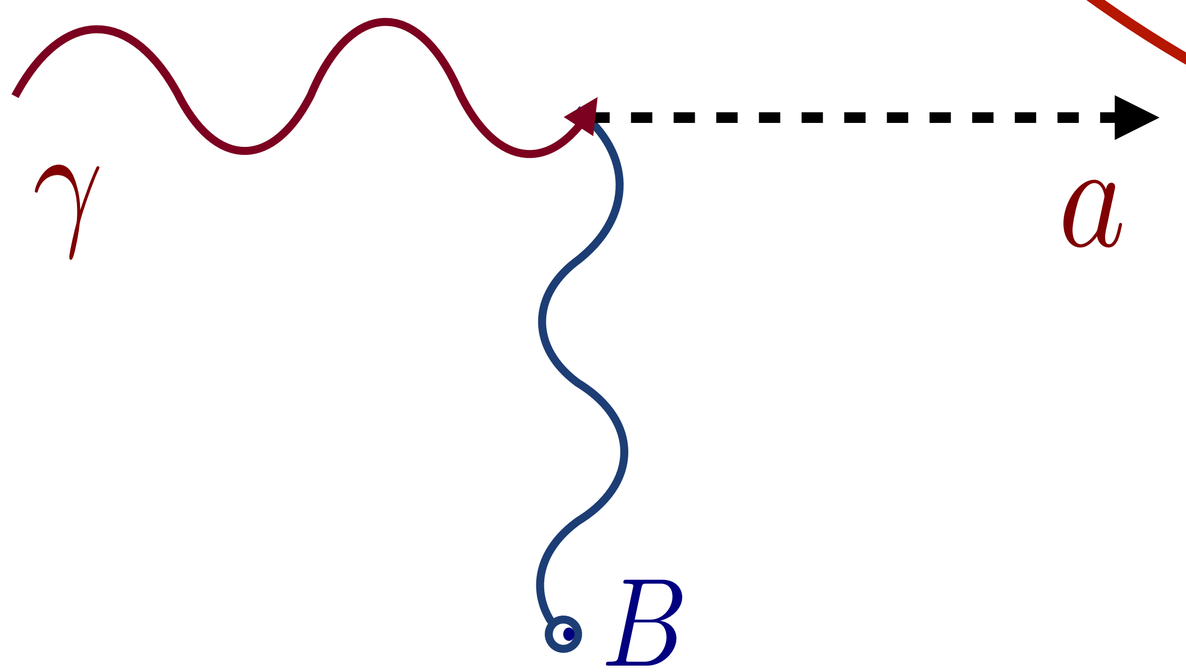
https://cajohare.github.io/AxionLimits/

Enhancing axion-photon transitions

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



$$\begin{cases} \text{Length of magnetic field} & (m_a \to 0) \\ (k_\gamma - k_a)^{-1} \sim 2E_\gamma / m_a^2 & (\text{Large } m_a) \end{cases}$$

Limitation: Strength of ***B*** *and* $(k_\gamma - k_a)$

Enhancing axion-photon transitions

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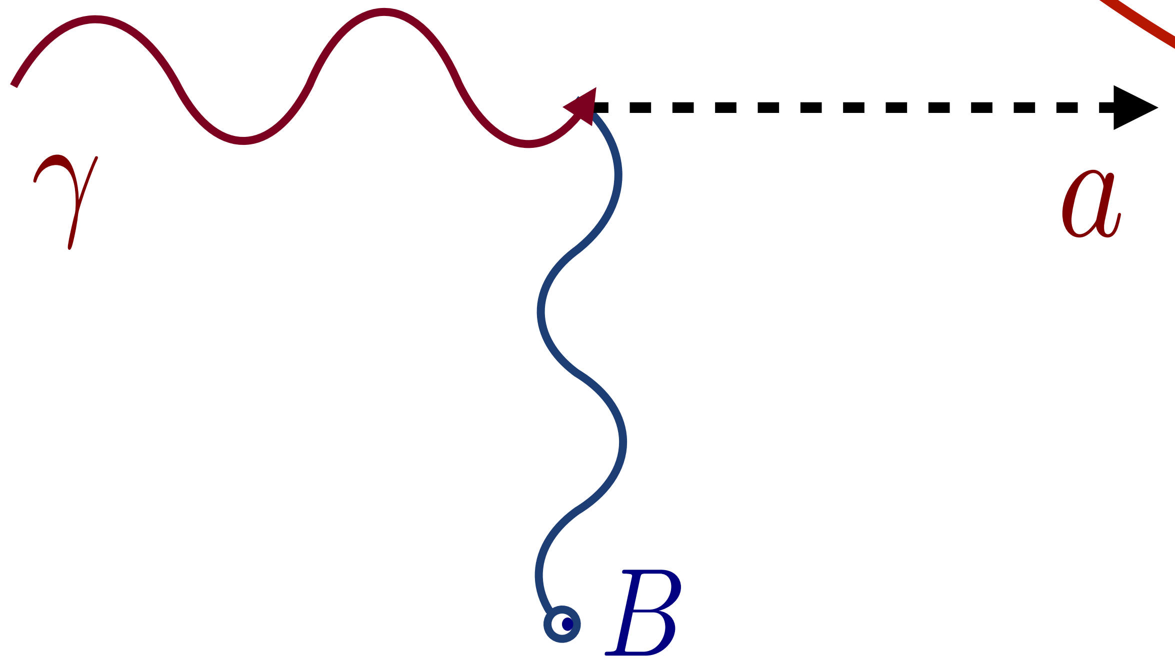

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Limitation: Strength of ***B*** *and* $(k_\gamma - k_a)$

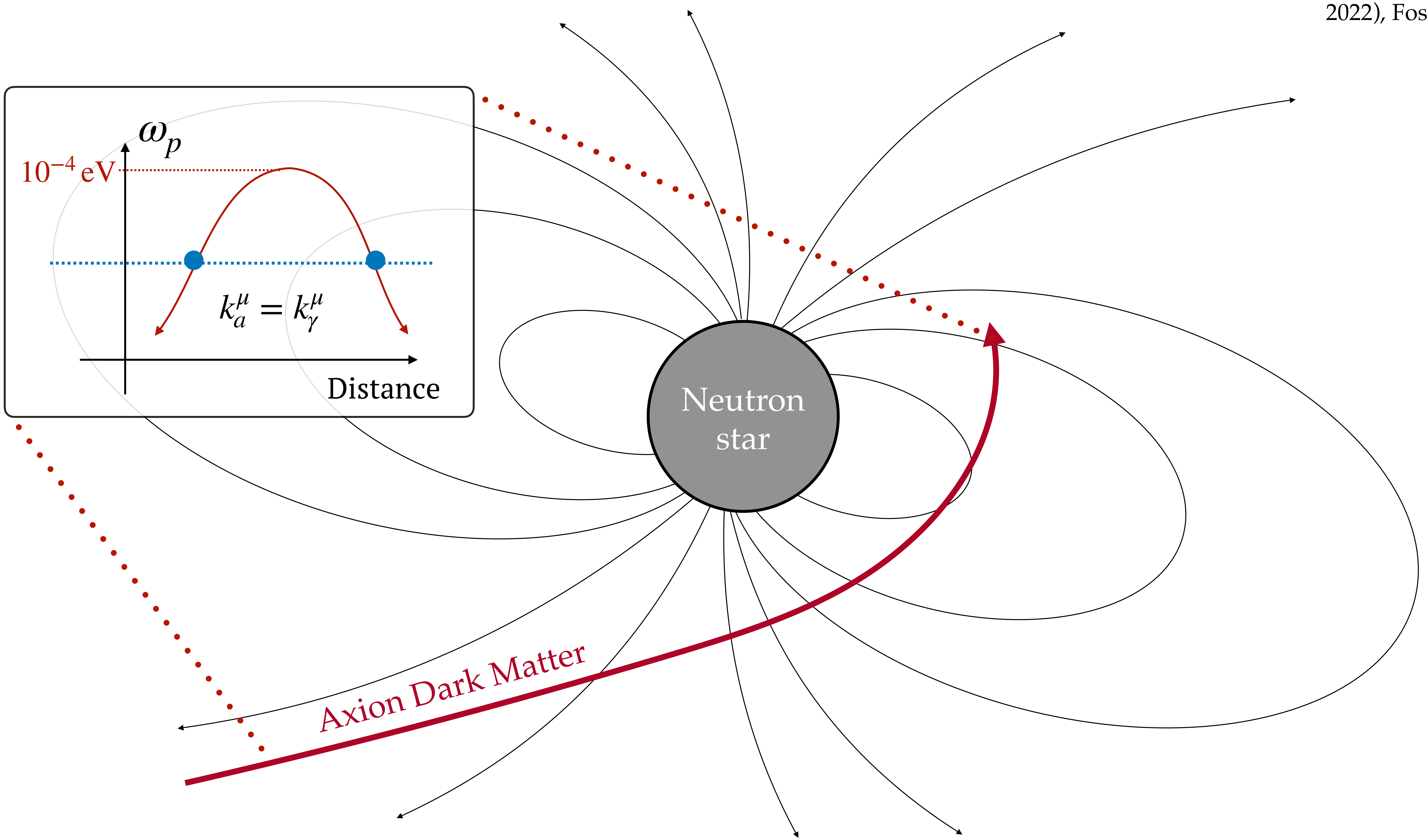
Modify photon dispersion relation

(E.g. in a cold plasma $k_\gamma = \sqrt{\omega^2 - \omega_p^2}$, and $k_a \sim k_\gamma$ possible)

Compact Objects

Resonant axion transitions in radio

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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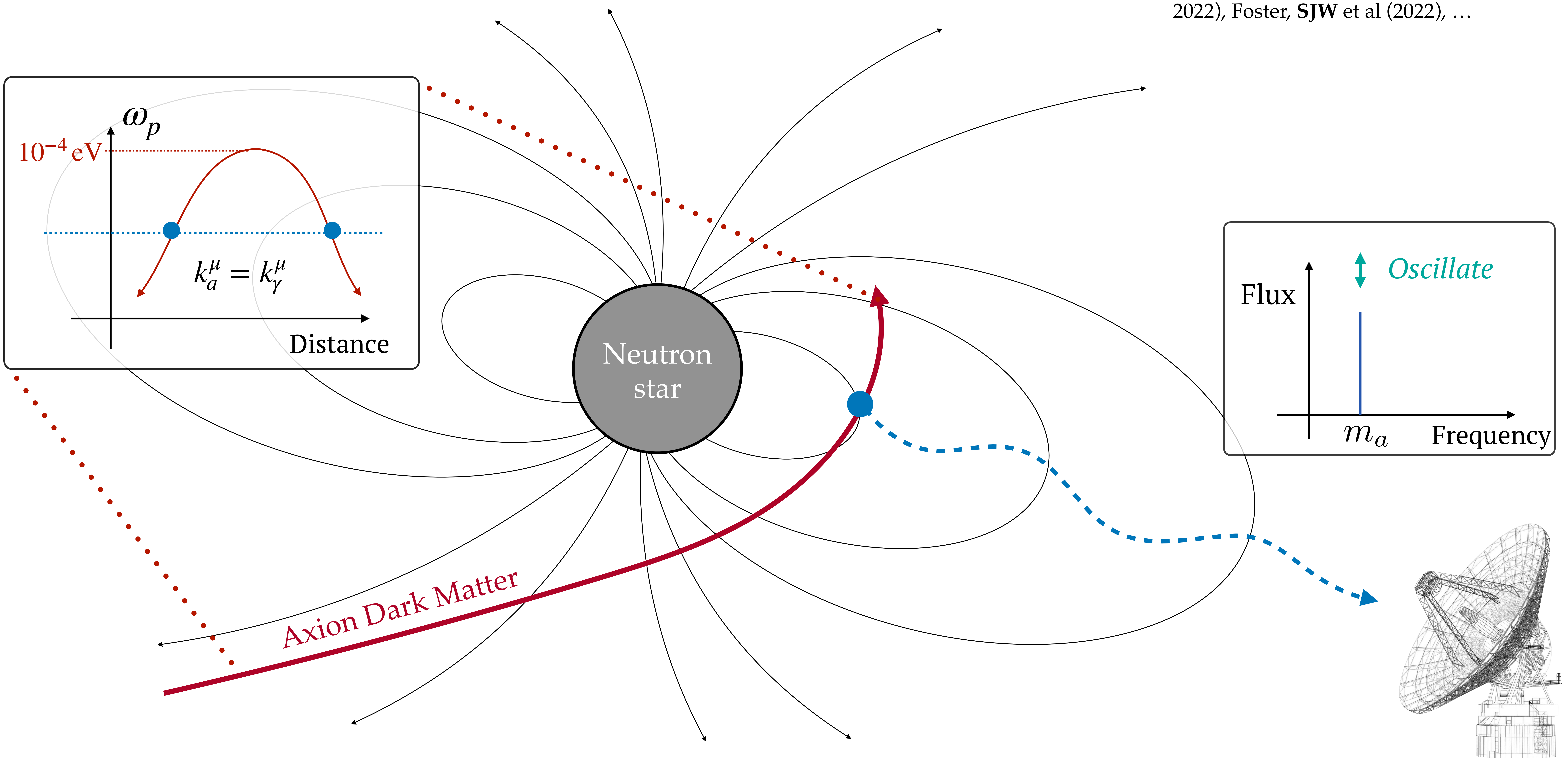
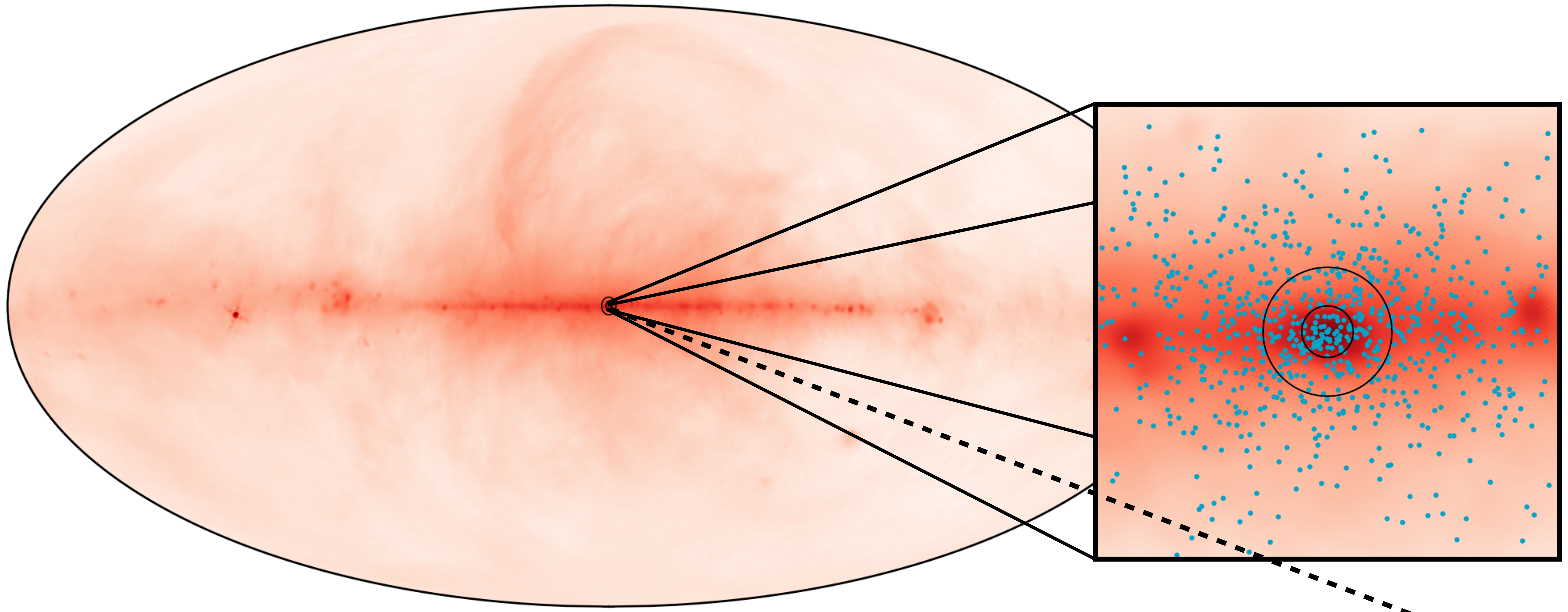
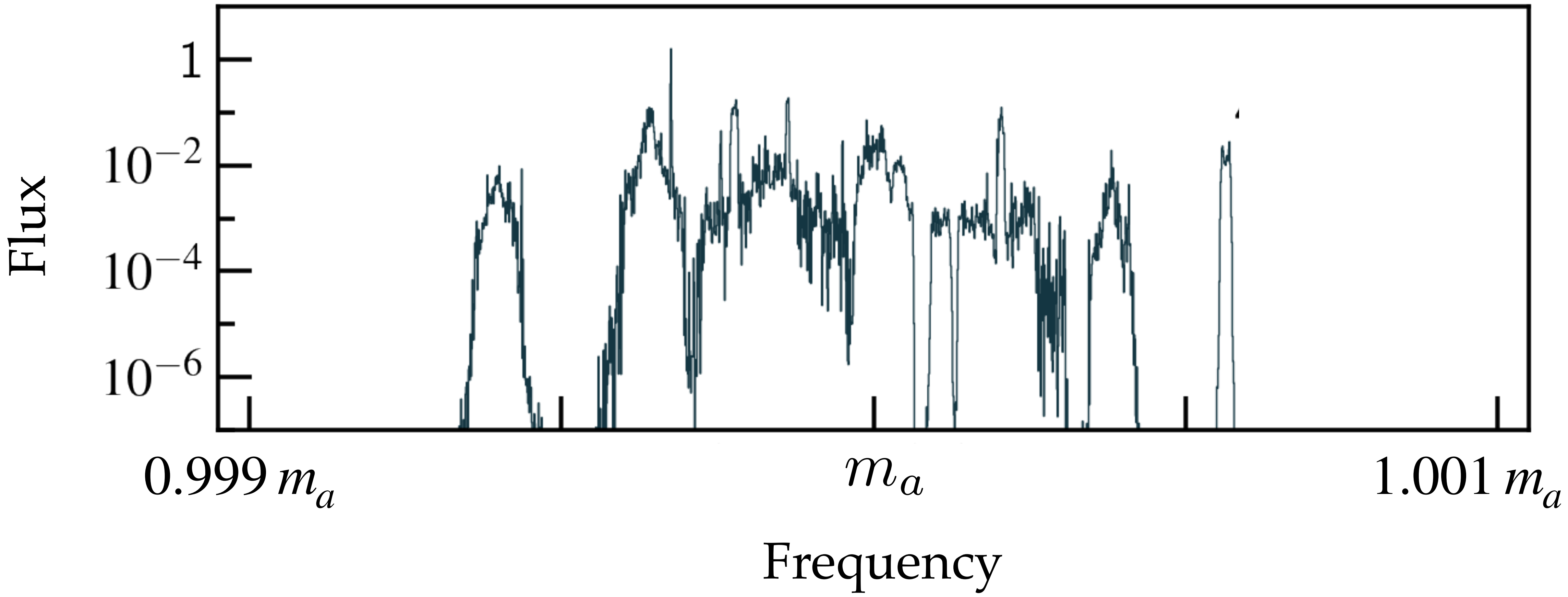
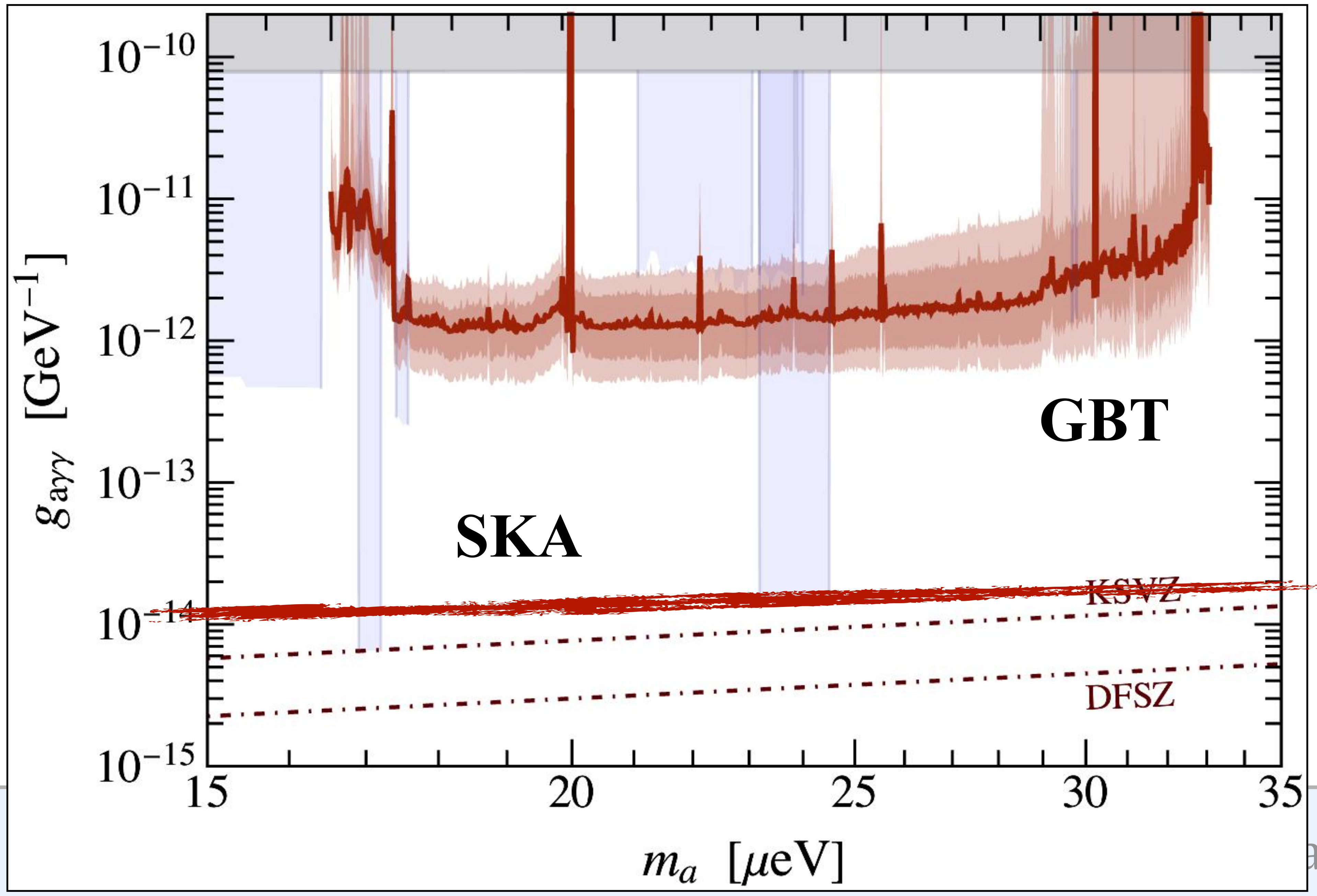


Radio lines near neutron stars

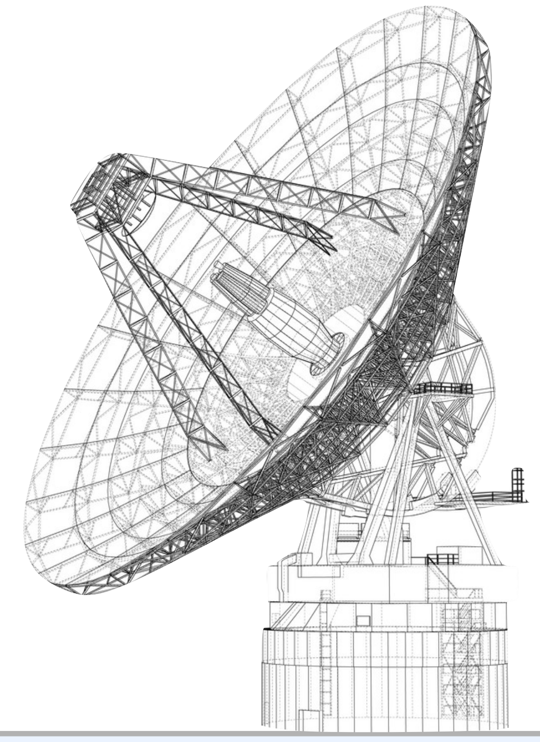
See e.g.: Pshirkov & Popov (2009), Hook et al. (2018), Safdi et al. (2018), Battye et al. (2019, 2021, 2023), **SJW** et al. (2021, 2022), Foster, **SJW** et al (2022), …







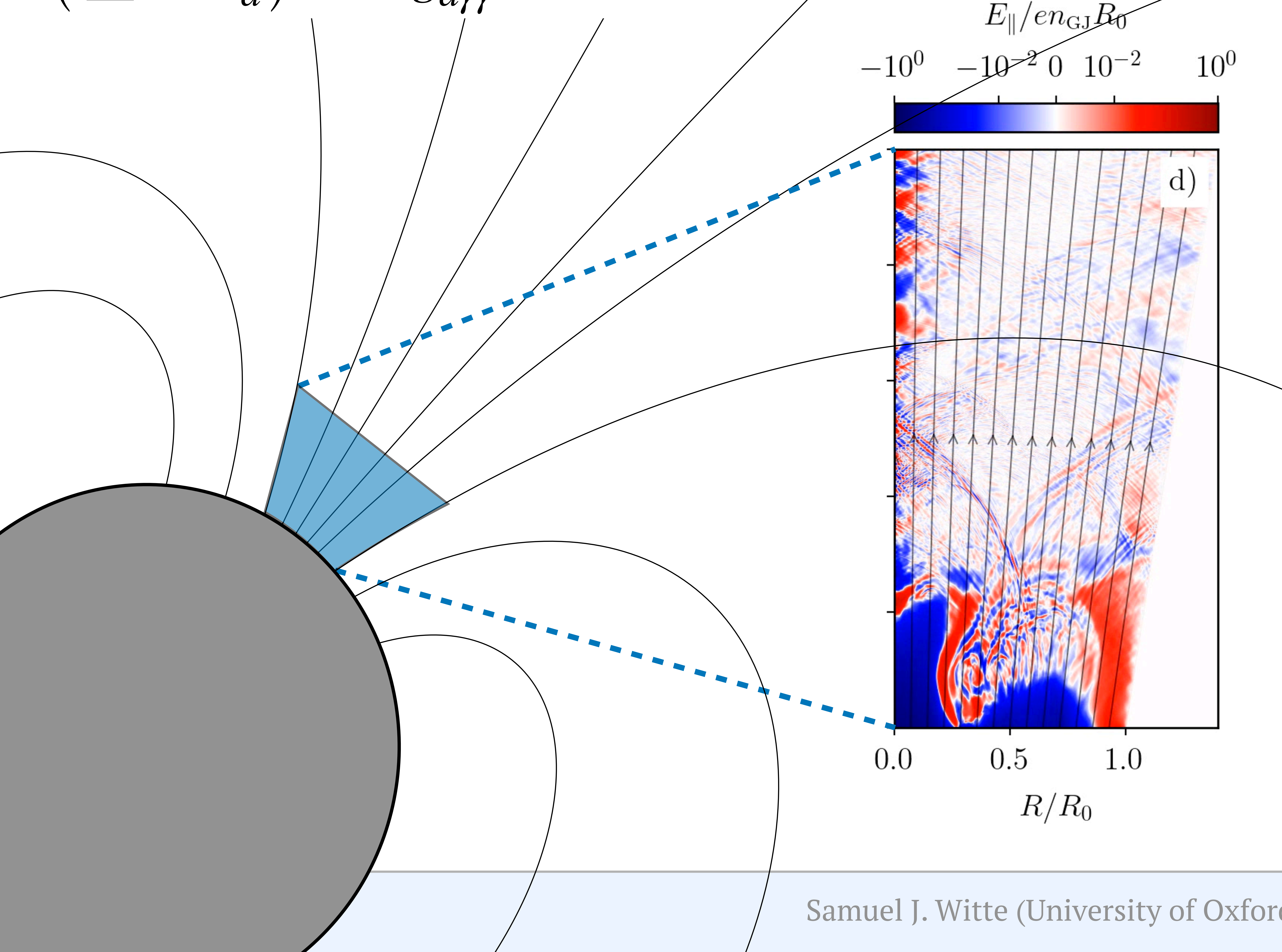
Upside: Unique signatures
Difficulty: Modelling



Axion production in pulsars

Prabhu 2021, Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022), Noordhuis, Prabhu, Weniger, **SJW** (2023), Caputo, **SJW**, Philippov, Jacobson (2023), Khelashvili et al (2024)

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



Rotating $\vec{B}$ induces $\vec{E}$

↓

Plasma cannot screen $\vec{E}$ everywhere

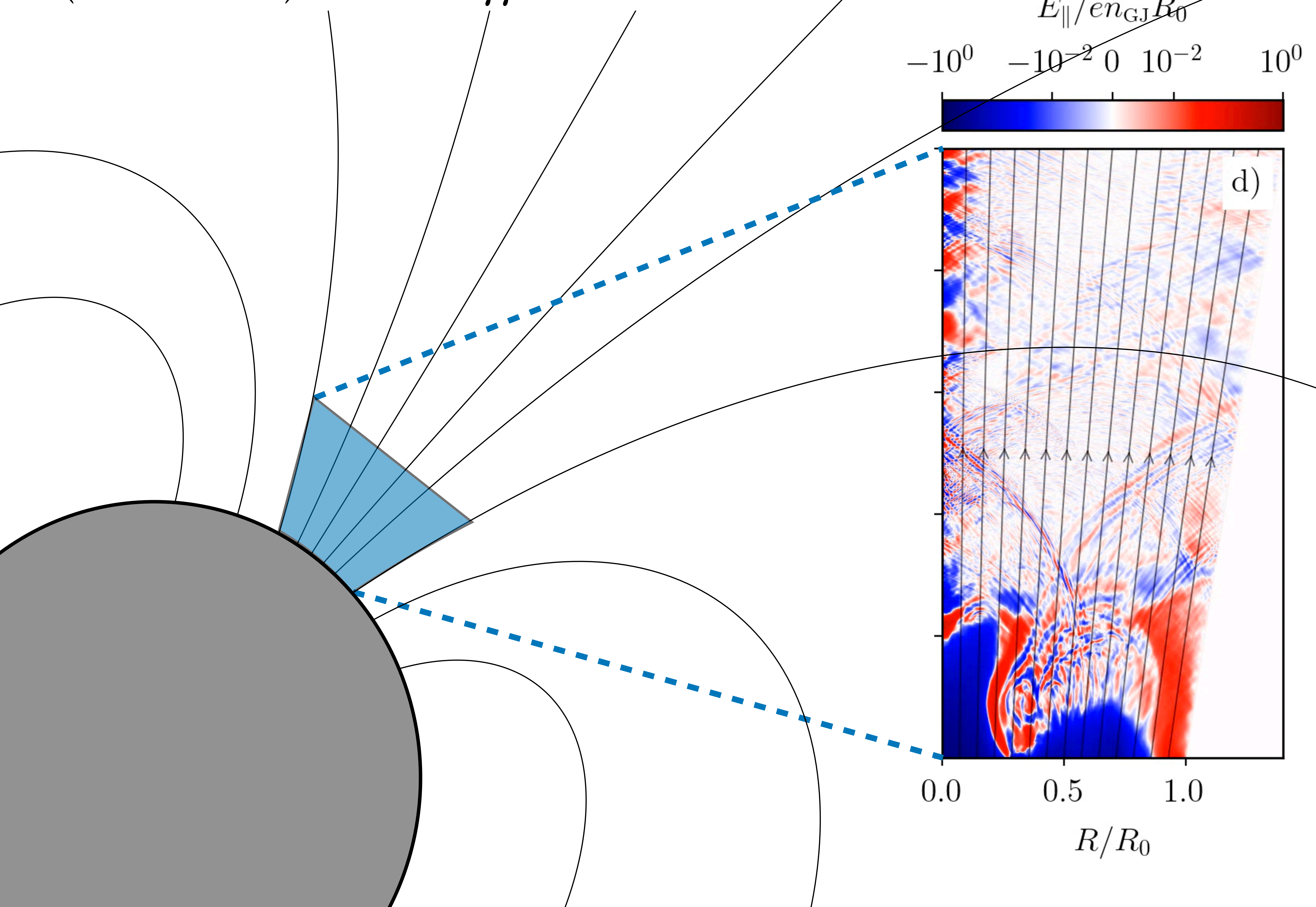
↓

“Vacuum gaps” support $(\vec{E} \cdot \vec{B})(t) \neq 0$

Axion production in pulsars

Prabhu 2021, Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022), Noordhuis, Prabhu, Weniger, **SJW** (2023), Caputo, **SJW**, Philippov, Jacobson (2023), Khelashvili et al (2024)

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



Rotating $\vec{B}$ induces $\vec{E}$

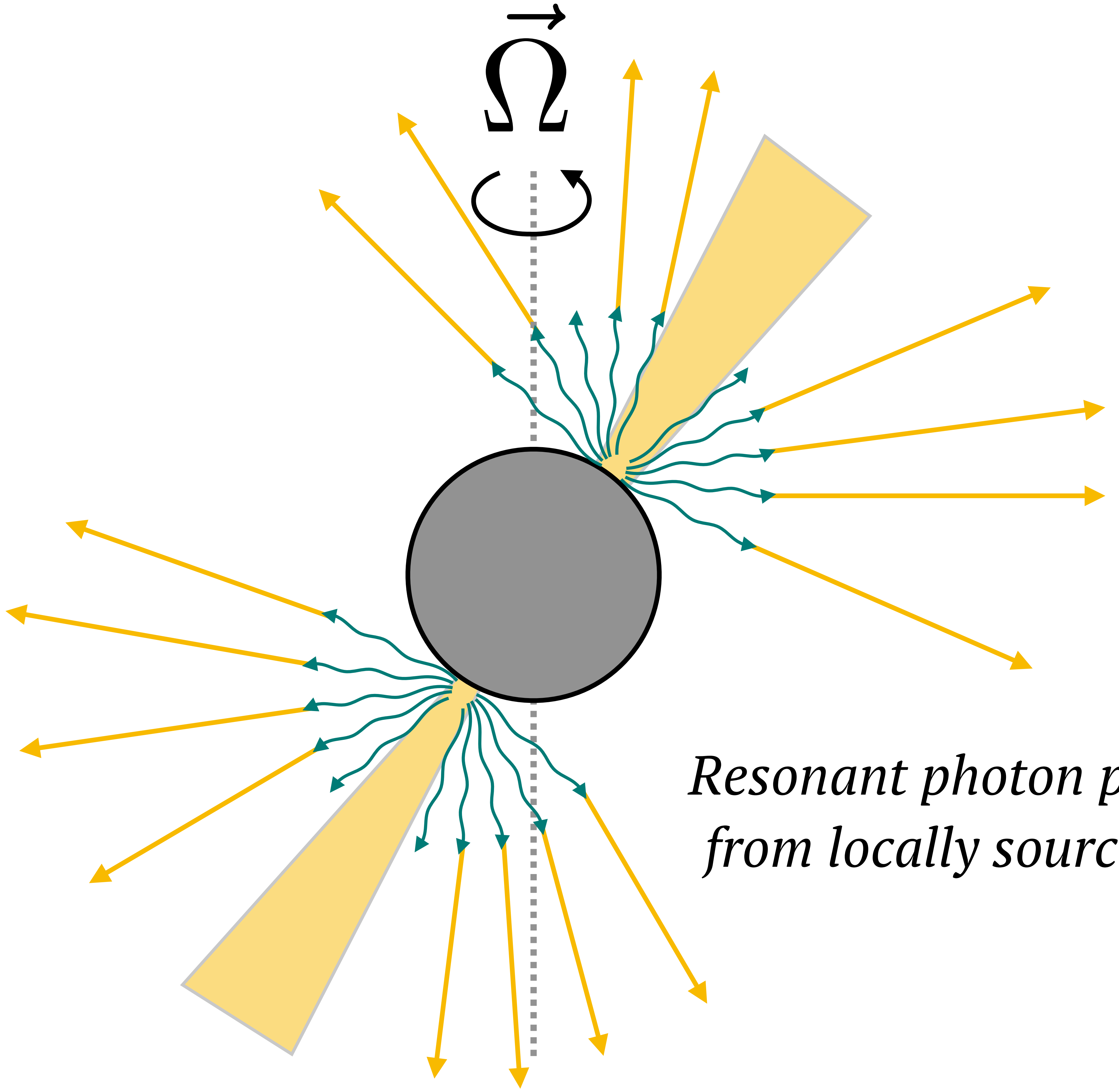
↓

Plasma cannot screen $\vec{E}$ everywhere

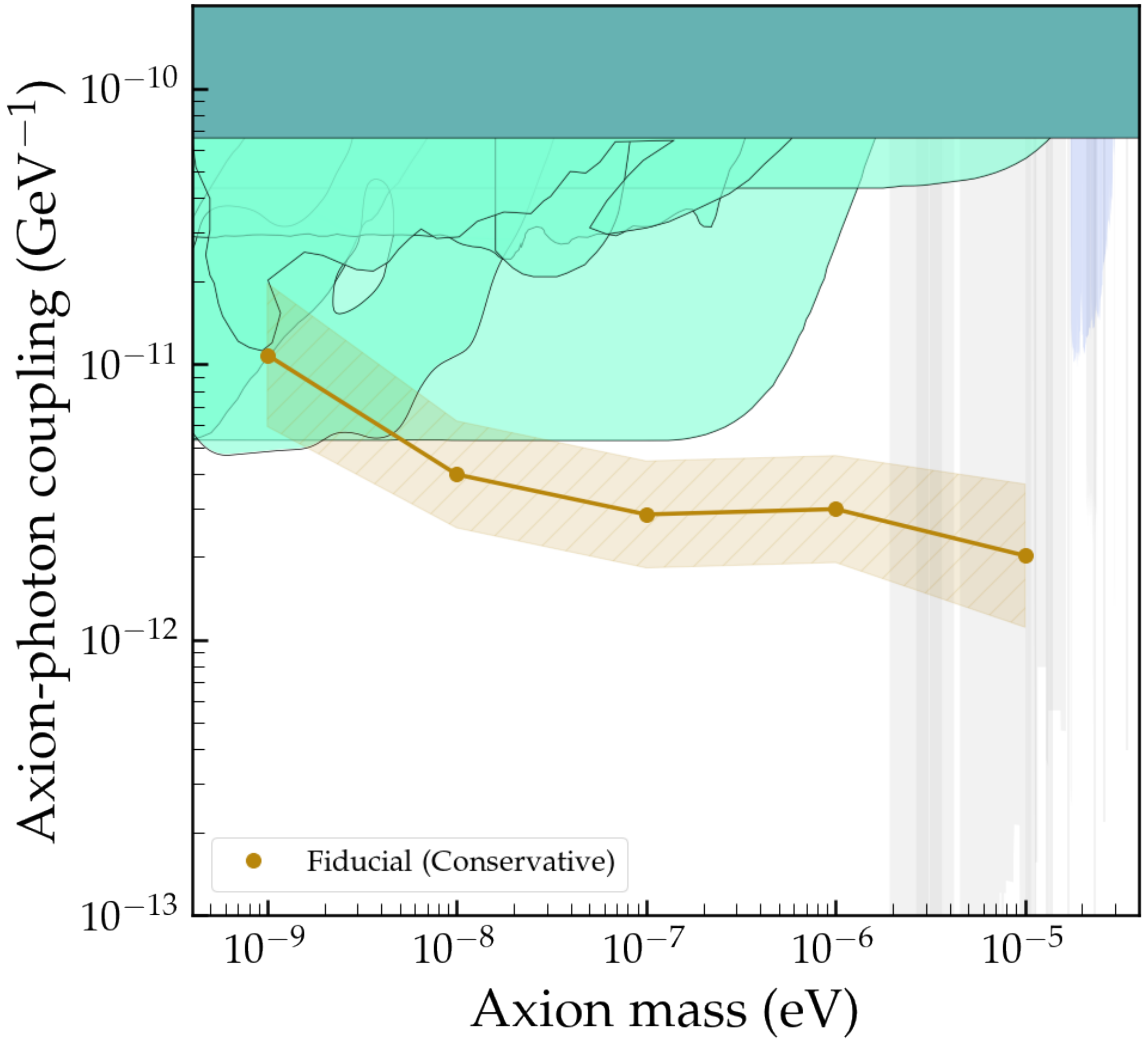
↓

“Vacuum gaps” support $(\vec{E} \cdot \vec{B})(t) \neq 0$

Axion production in pulsars



Resonant photon production from locally sourced axions



Upside: No assumption of dark matter

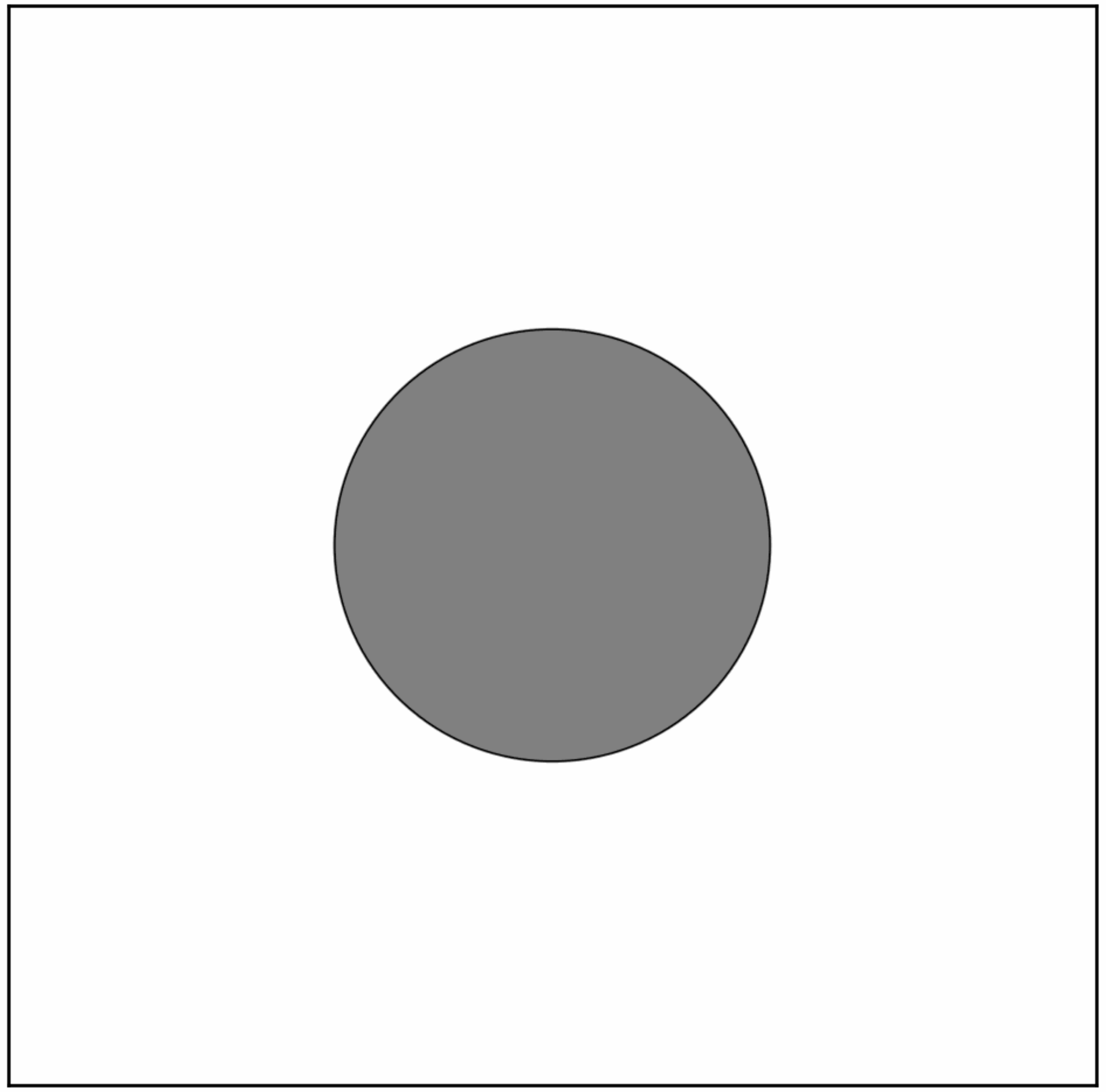
Difficulty: Modelling more difficult

Difficulty/Upside: Emission scales like $g_{a\gamma\gamma}^4$

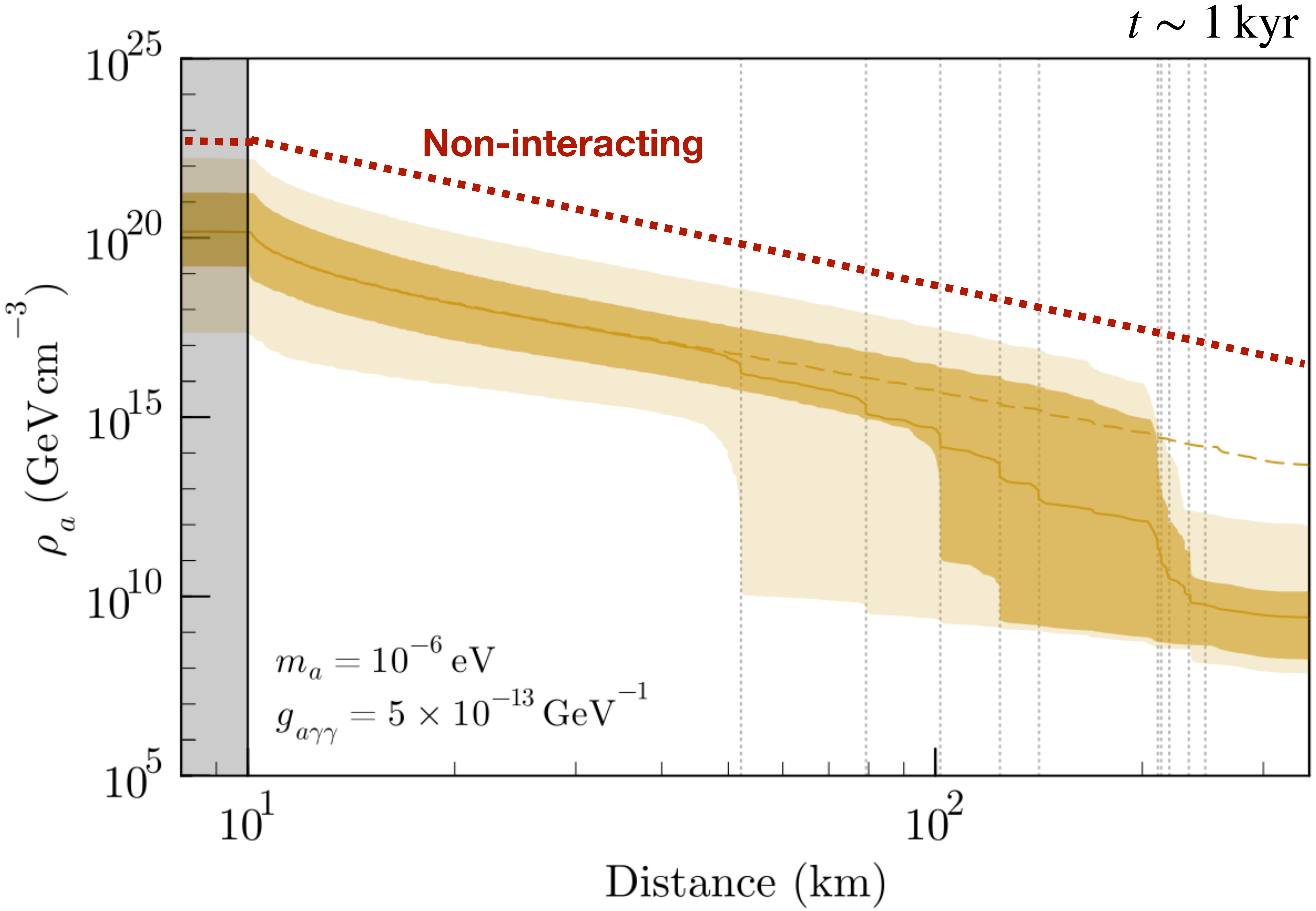
Noordhuis, Prabhu, **SJW**, Cruz, Chen, Weniger (2022)

Axion clouds around pulsars

Noordhuis, Prabhu, Weniger, **SJW** (2023), Caputo, **SJW**, Philippov, Jacobson (2023)



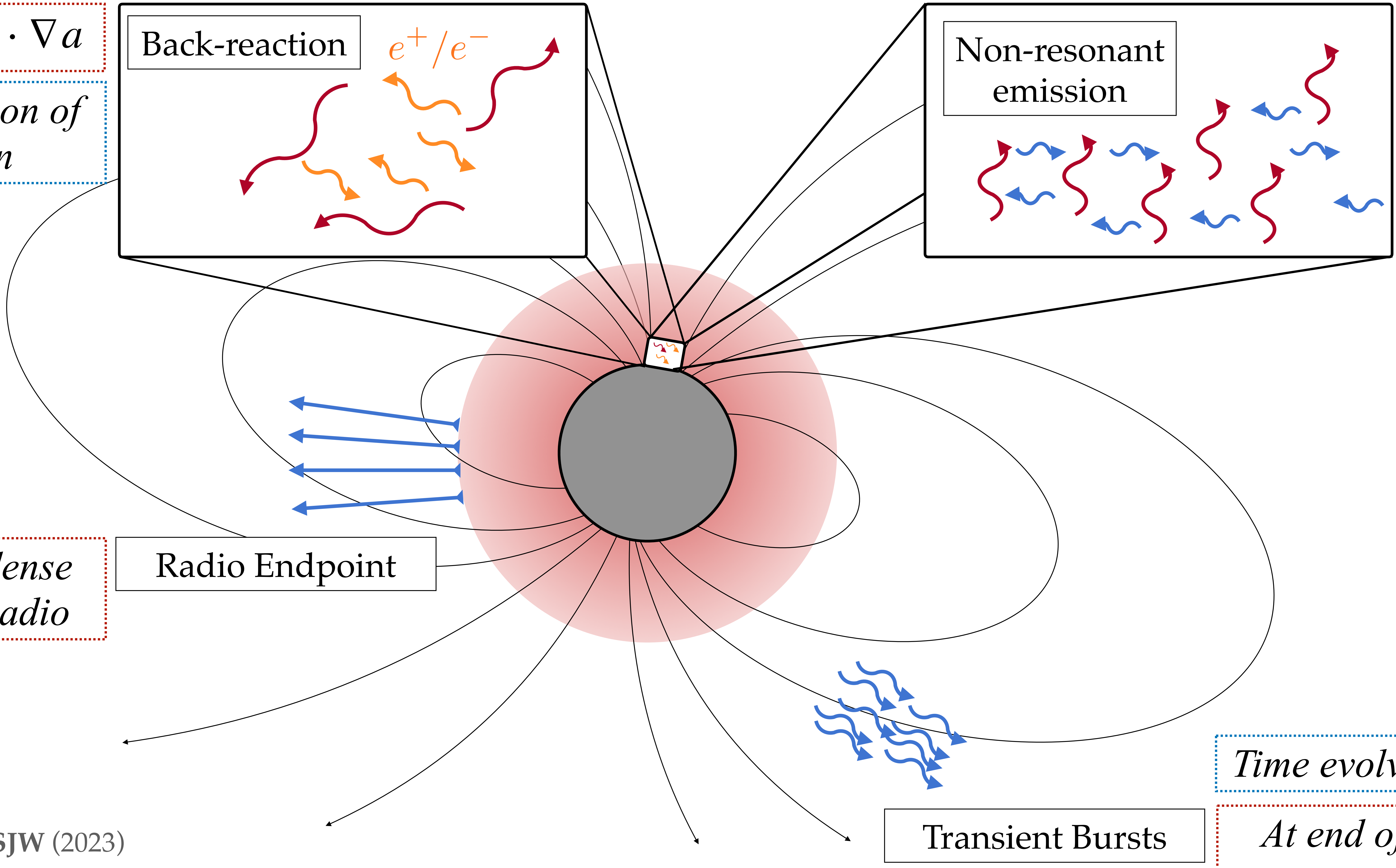
Axion mass
$10^{-10}\,\text{eV} \lesssim m_a \lesssim 10^{-4}\,\text{eV}$



Observables from axion clouds

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

Periodic modulation of radio emission



Axion + Magnetic field = Oscillating E dipole

Radio Line

Axions in under-dense plasma produce radio

Radio Line

Time evolving radio line

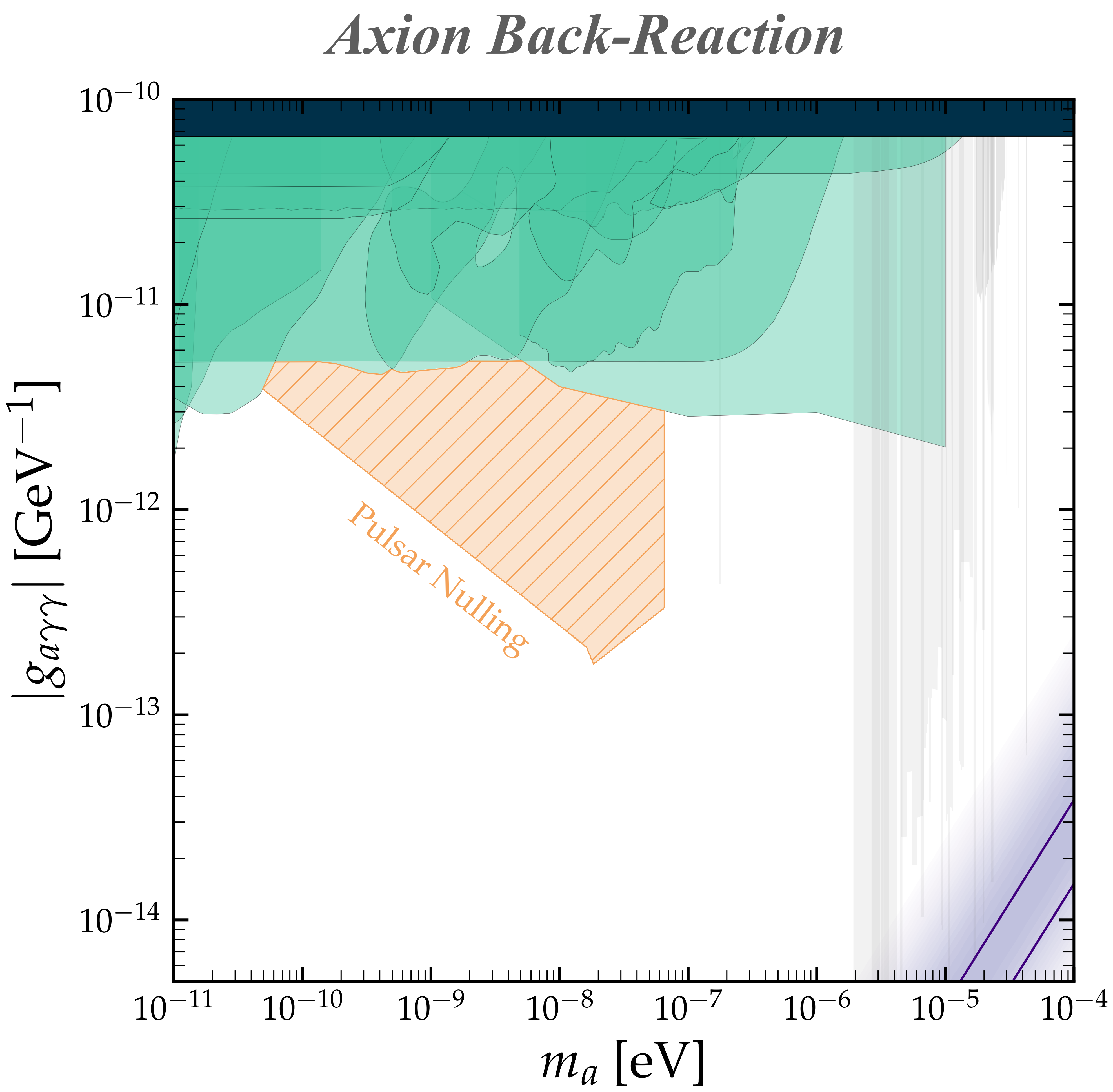
At end of lifetime, all axions $\rightarrow \gamma$

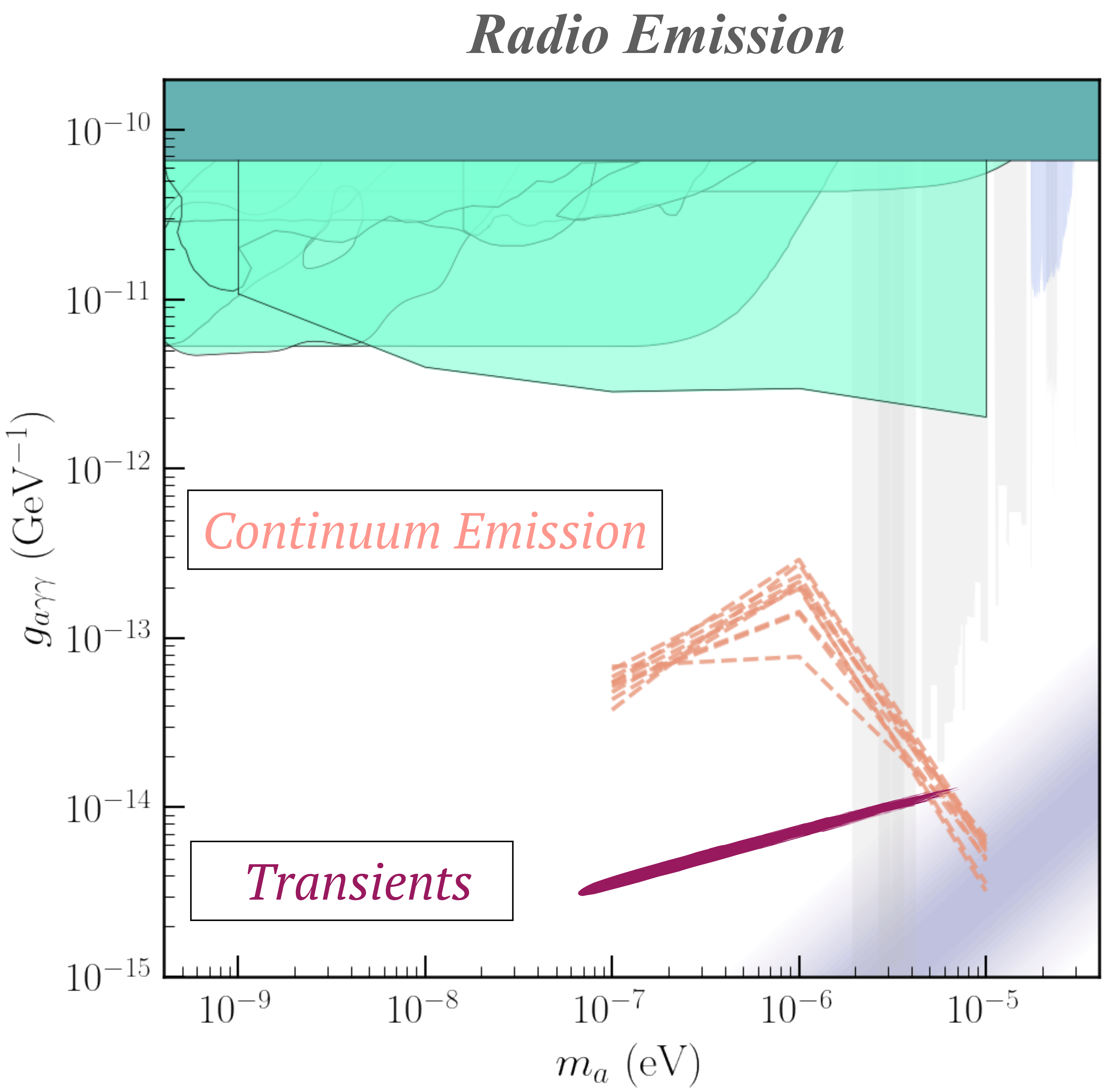
Noordhuis, Prabhu, Weniger, **SJW** (2023)
Caputo, **SJW**, Philippov, Jacobson (2023)

Sensitivity to axion clouds

Noordhuis, Prabhu, Weniger, **SJW** (2023)

Caputo, **SJW**, Philippov, Jacobson (2023)

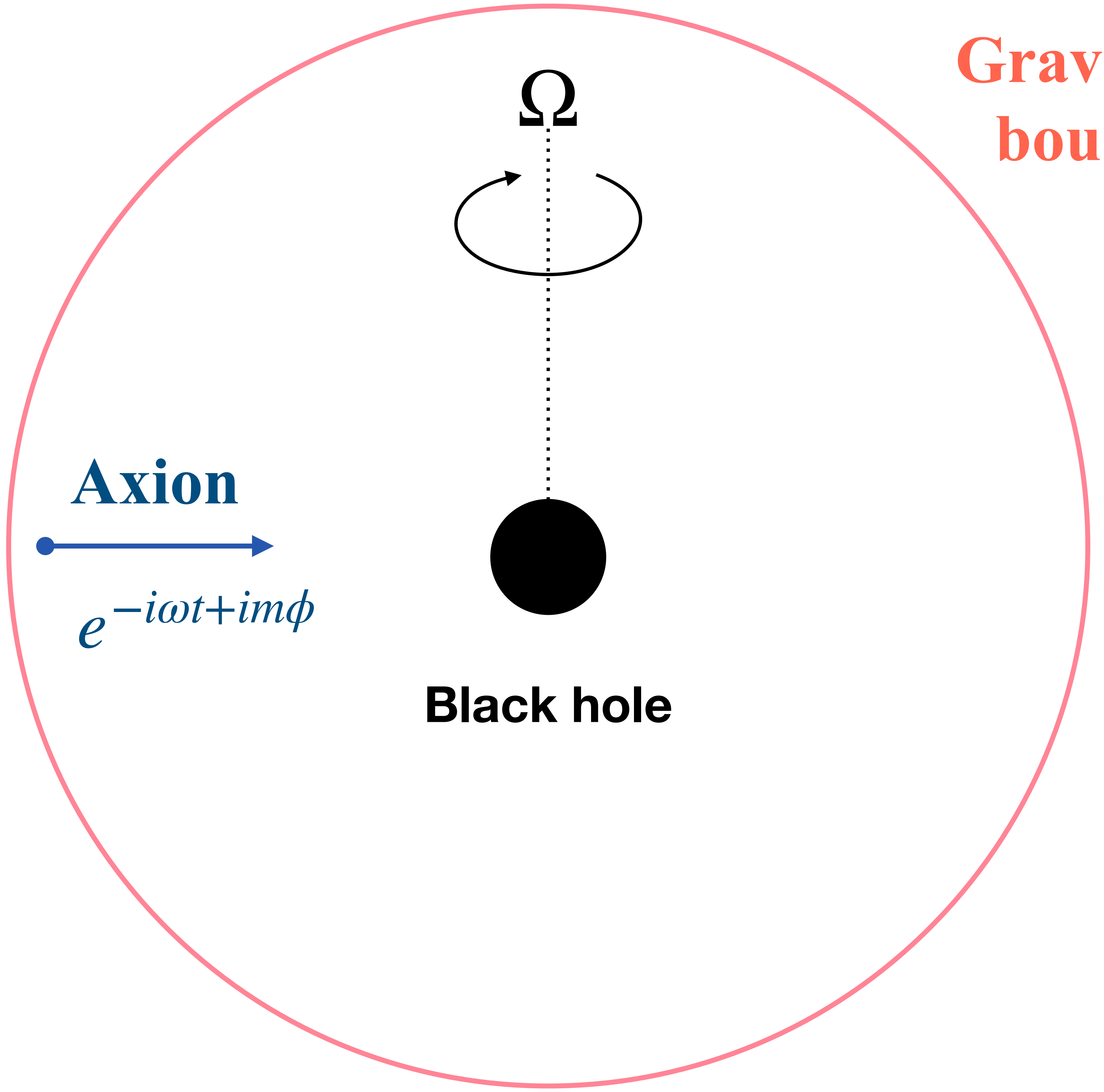




Upside: Very powerful new probes

Difficulty: Work to be done on modelling

Black hole superradiance



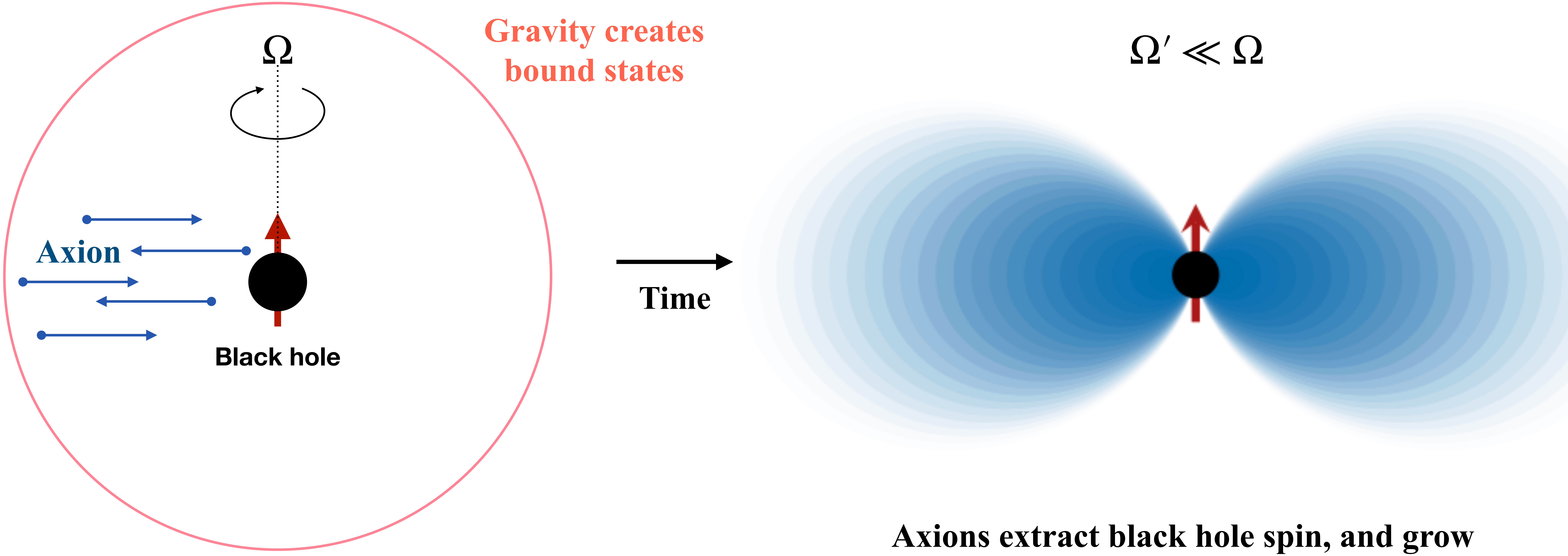
Gravity creates bound states

Amplification

$$\boxed{\omega < m\Omega}$$

Zeldovich (1972) Press & Teukolsky (1972), Arvanitaki, Dimopoulos, Dubovsky. Kaloper, J. March-Russell (2010), Arvanitaki & Dubovsky (2011), Brito, Cardoso, Pani (2015)

Black hole superradiance



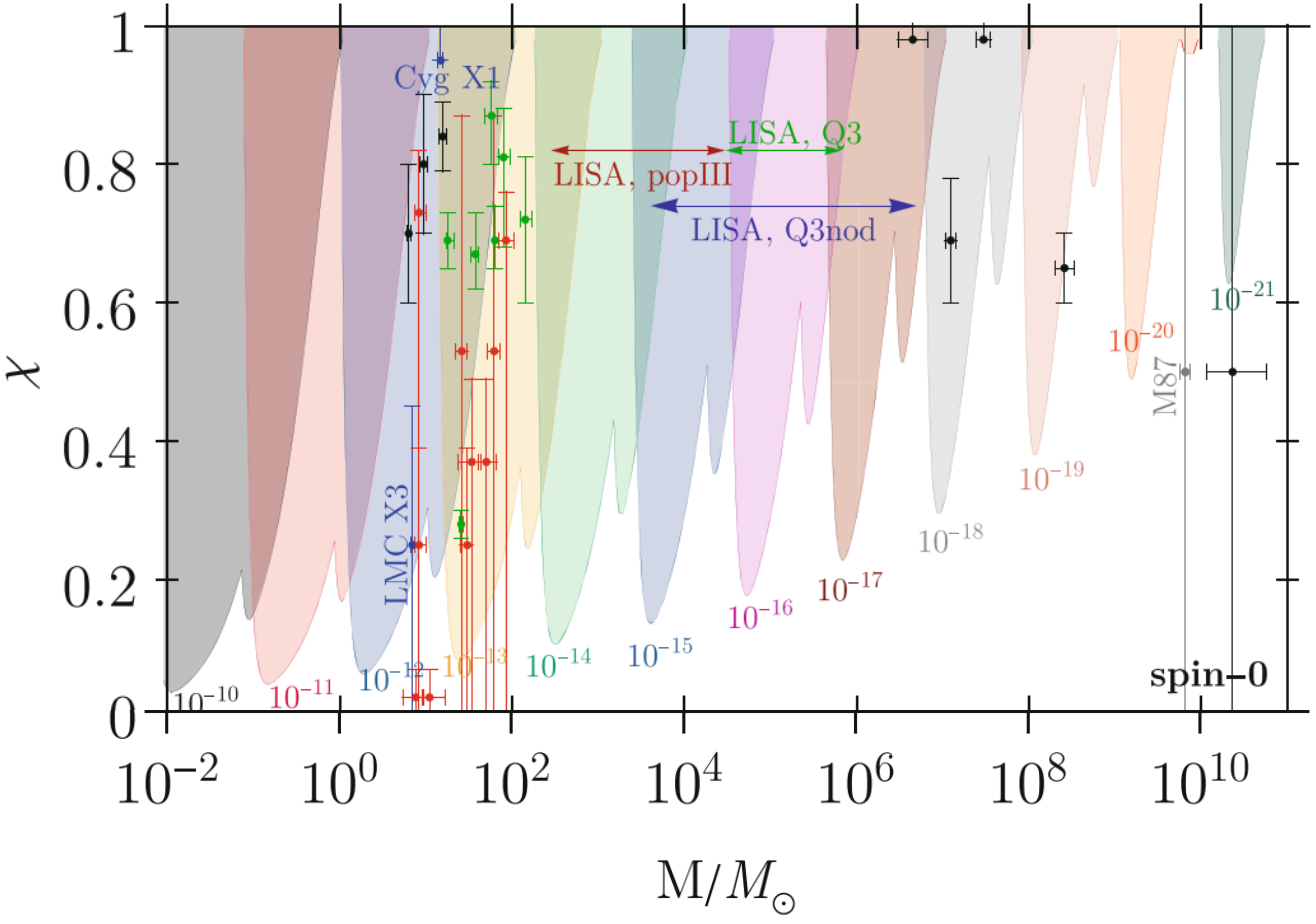
Gravity creates bound states

Axions extract black hole spin, and grow dense clouds

Zeldovich (1972) Press & Teukolsky (1972), Arvanitaki, Dimopoulos, Dubovsky. Kaloper, J. March-Russell (2010), Arvanitaki & Dubovsky (2011), Brito, Cardoso, Pani (2015)

Axion superradiance

Black hole spin distributions



Gravitational waves from axion cloud

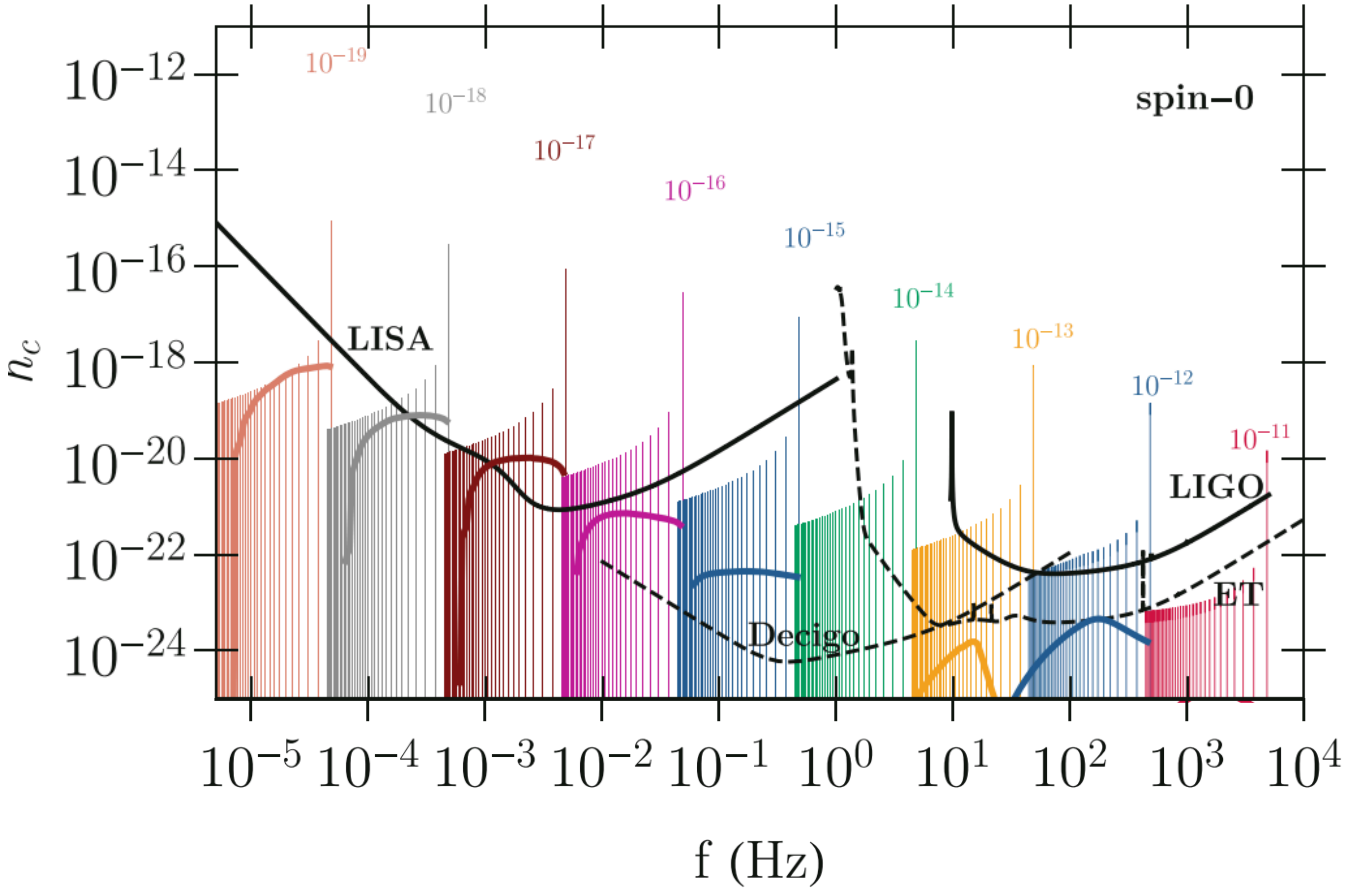


Image credit: Brito & Pani (2022)

Superradiance in the non-interacting limit

$(\Box + \mu^2)\, a = 0$

Bound states form discrete hydrogen-like energy spectrum: $|nlm\rangle$

$$\omega_{nlm} = E_{nlm} + i\Gamma_{nlm}$$

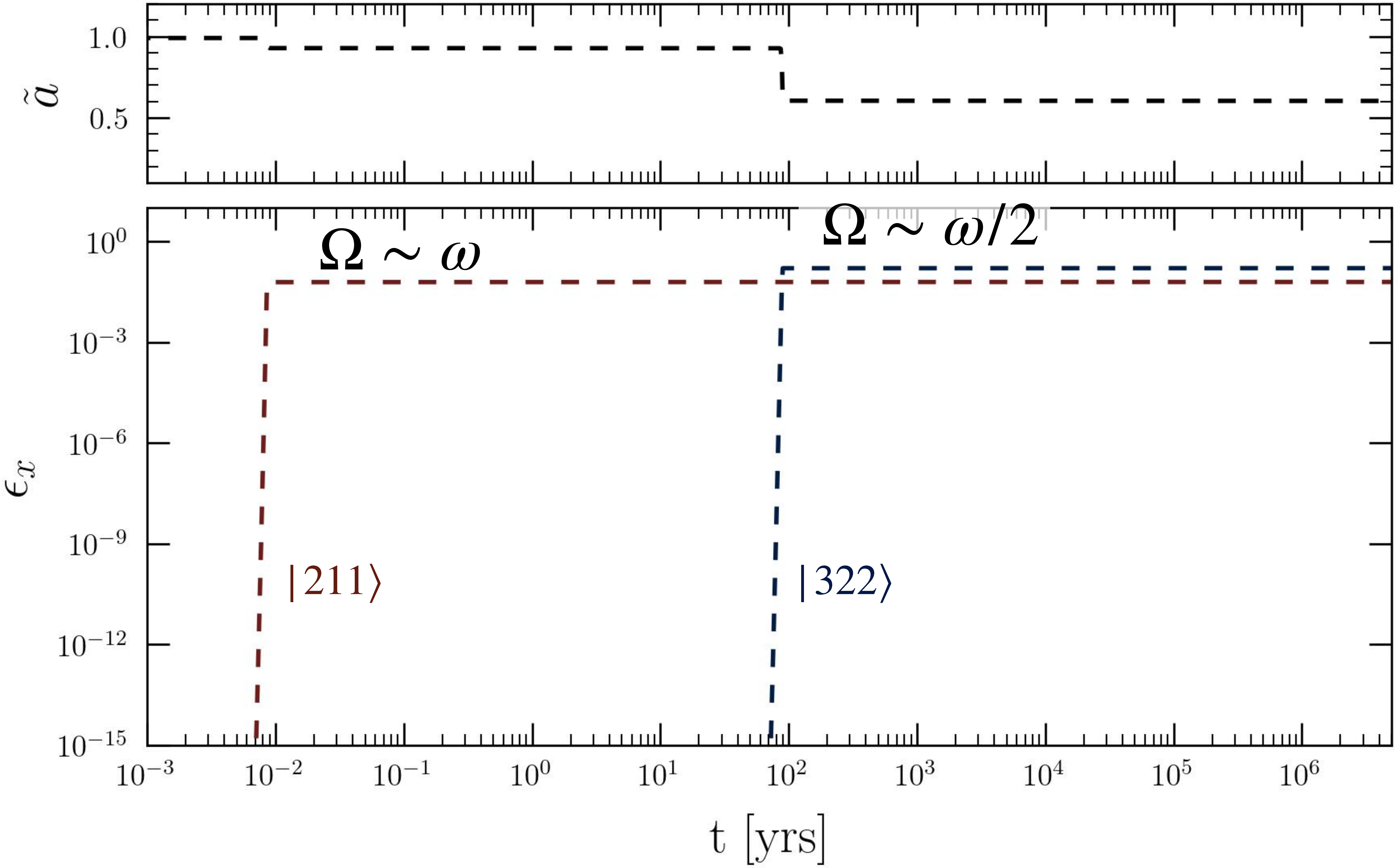
Superradiance in the non-interacting limit

$$(\Box + \mu^2)\, a = 0$$

Bound states form discrete hydrogen-like energy spectrum: $|nlm\rangle$

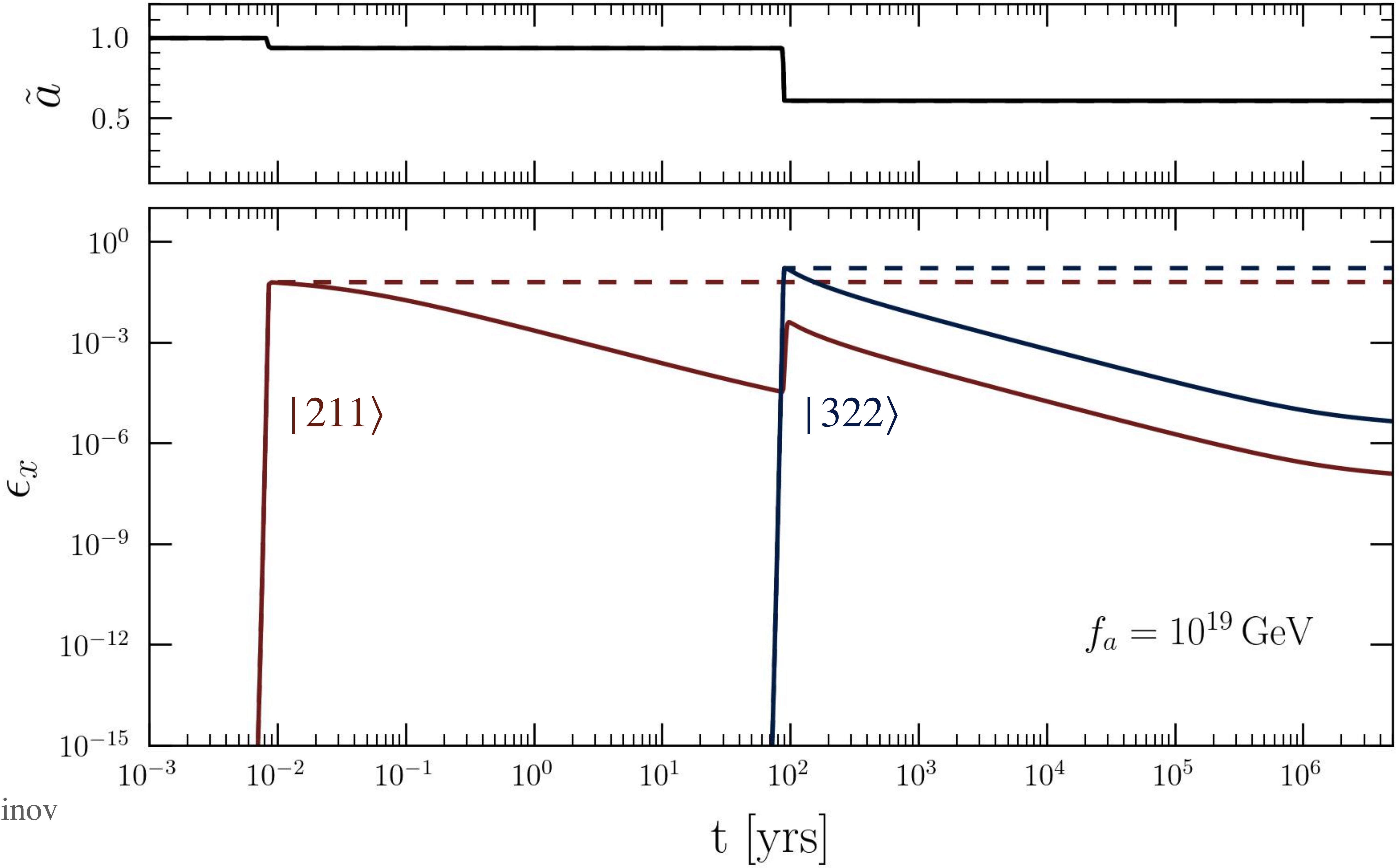
Black hole spin

Normalized occupation numbers



Self-interactions in superradiance

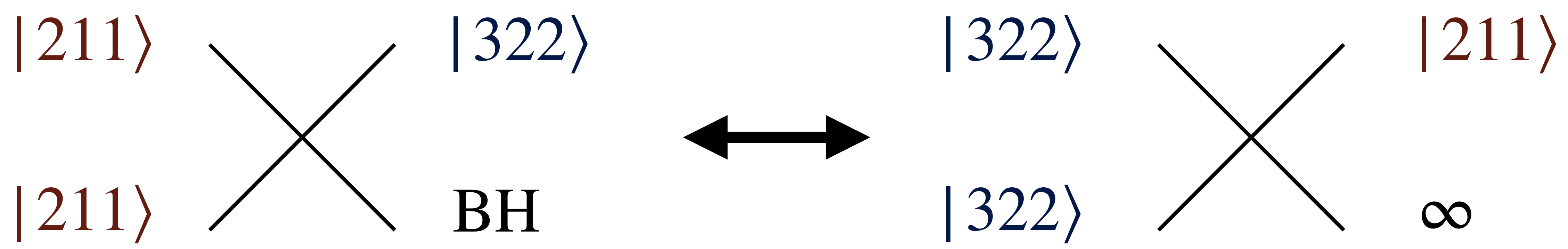
$$\mathscr{L} \supset \frac{m_a^2}{f_a^2}\, a^4 \xrightarrow{\text{e.g.}}$$

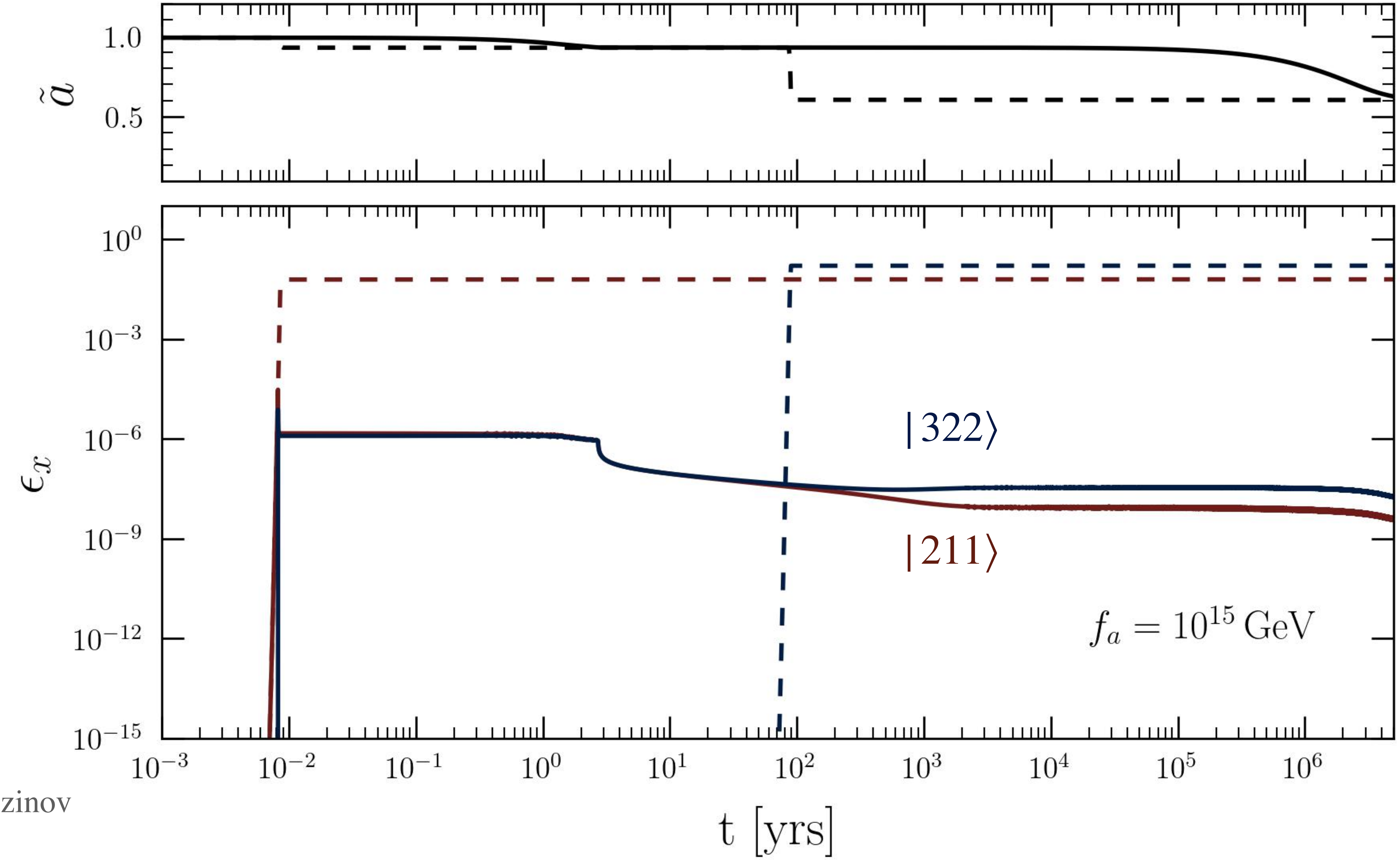


Arvanitaki & Dubovsky (2011), Gruzinov (2016), Baryakhtar et al (2021)

Self-interactions in superradiance

Large self couplings dramatically slow spin extraction!

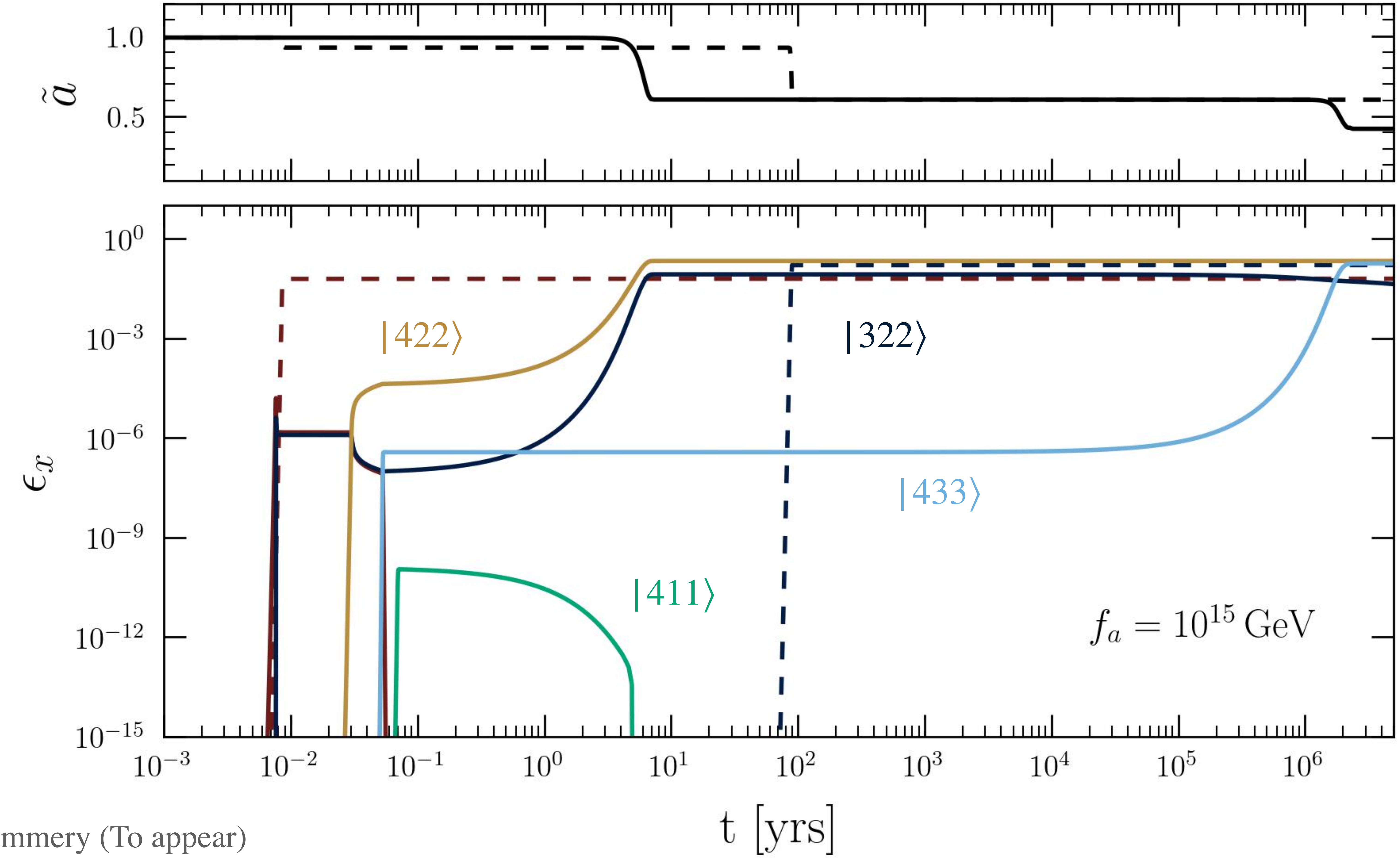




Arvanitaki & Dubovsky (2011), Gruzinov (2016), Baryakhtar et al (2021)

Self-interactions in superradiance

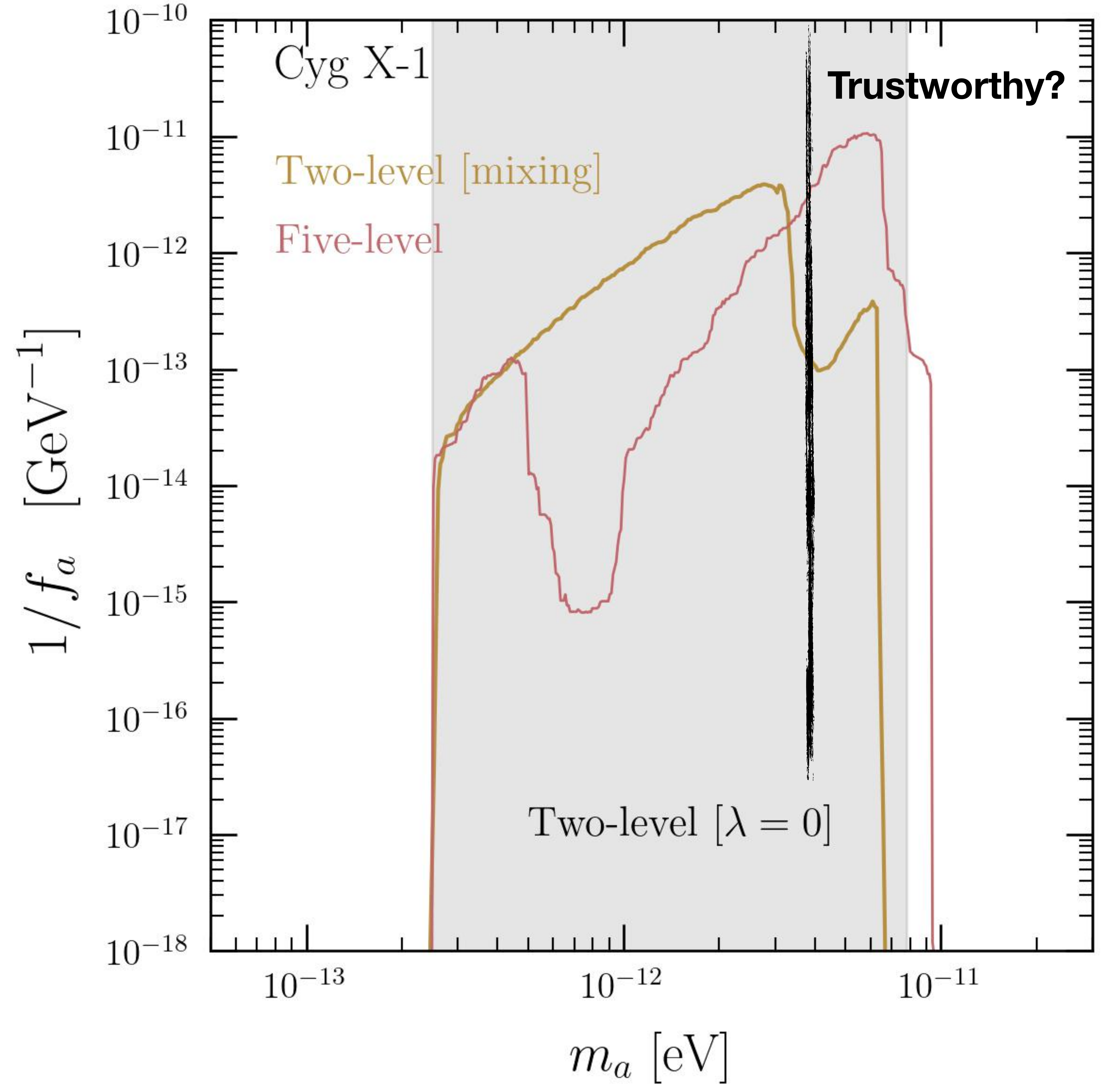
n = 4 is a mess….



Baryakhtar et al (2021), **SJW** & Mummery (To appear)

Superradiance limits

SJW & Mummery (To appear)



Upside: Very powerful, can cover huge range of parameter space

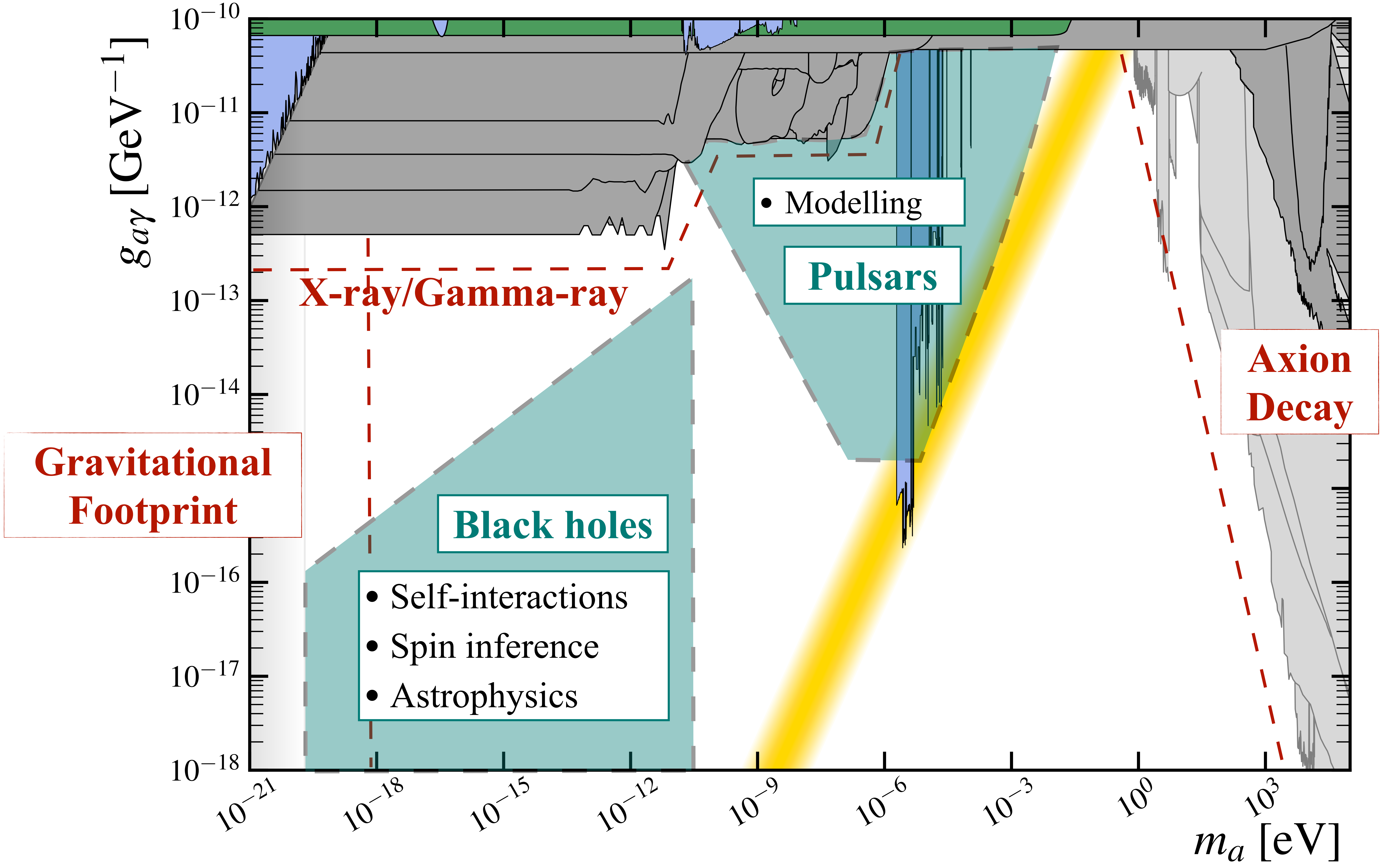
Difficulty: Modelling self-interactions (especially near black hole) is not fully understood

Difficulty from astro side:

- How to do we obtain reliable spin measurements
- Environmental effects (*not isolated objects!*)

See e.g. Baumann et al (2019, 2022)

Conclusions



X-ray/Gamma-ray

- Modelling

Pulsars

Axion Decay

Gravitational Footprint

Black holes

- Self-interactions
- Spin inference
- Astrophysics

https://cajohare.github.io/AxionLimits/