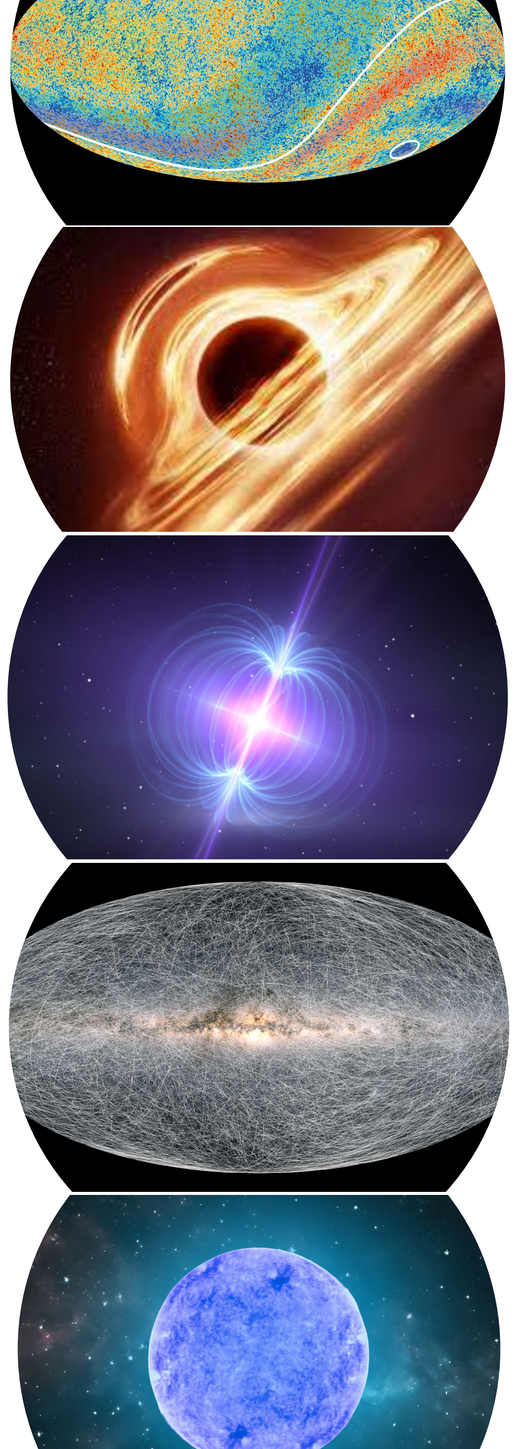
Axions in the Sky

Samuel J. Witte

Oxford Theoretical Studies of Particles and Strings Retreat
March, 2024

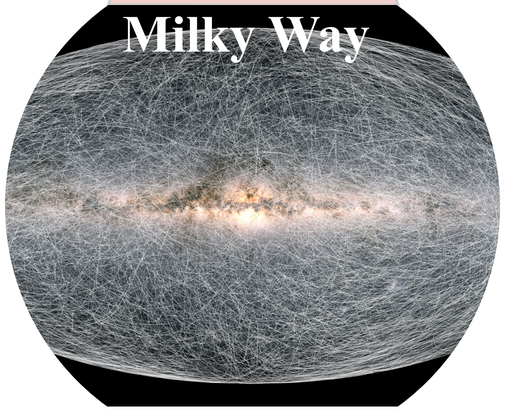


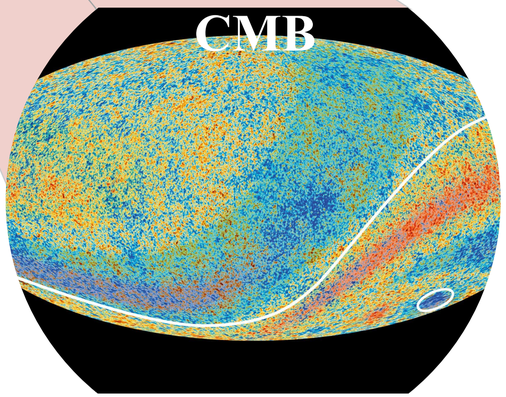
THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

Astrophysics as a laboratory

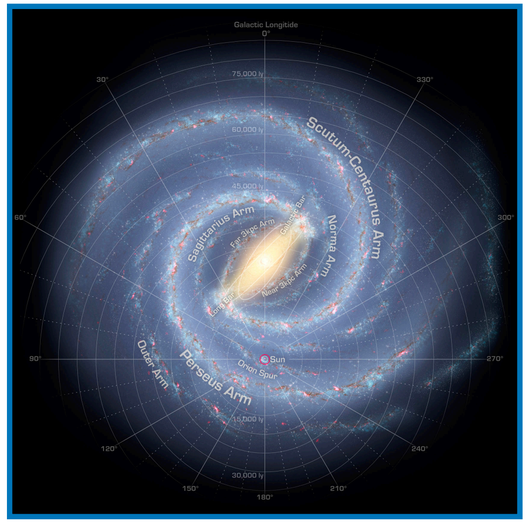
Nature's Laboratories



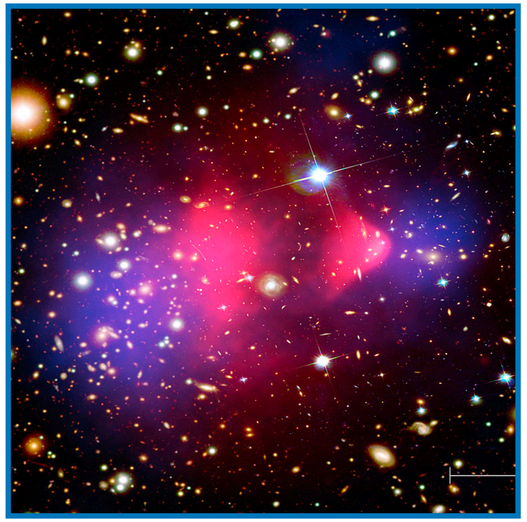


New particles in the sky: dark matter

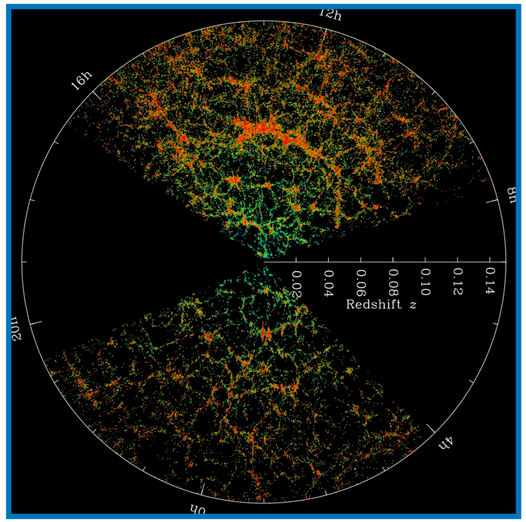
Galaxy rotation curves



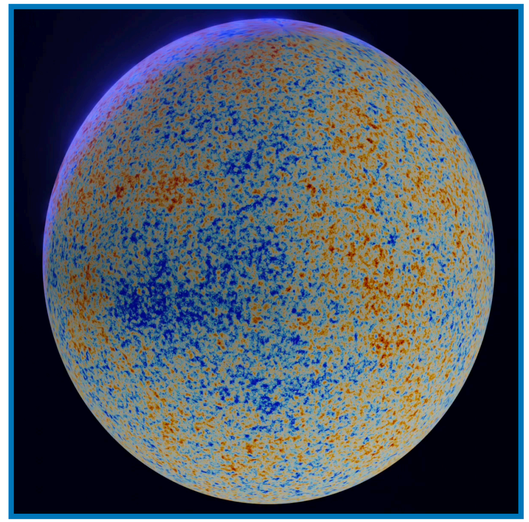
Merging galaxy clusters



Large scale structure



Cosmic microwave background



~kpc

(Today)

~Mpc

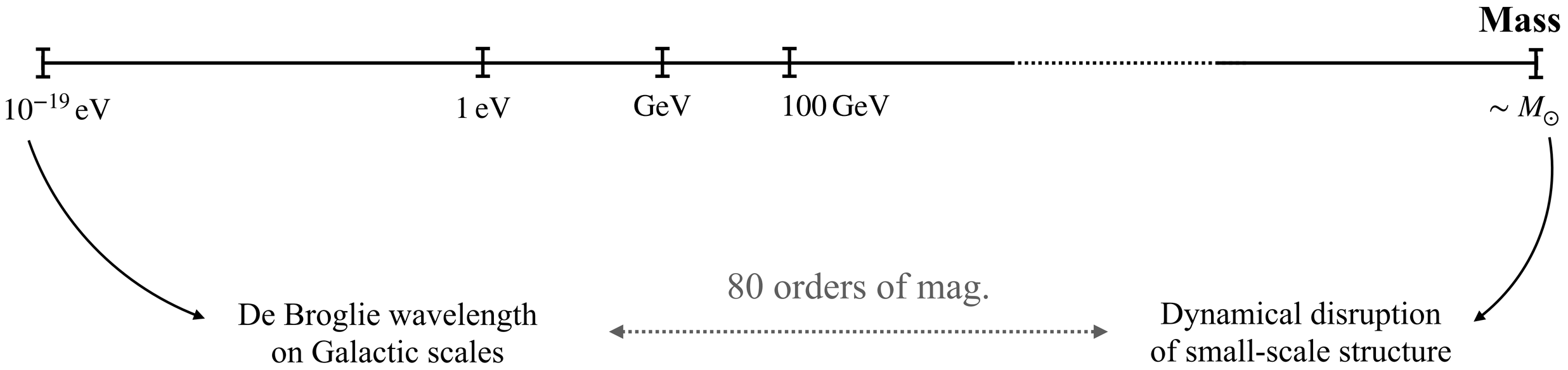
~100 Mpc

~10 Gpc

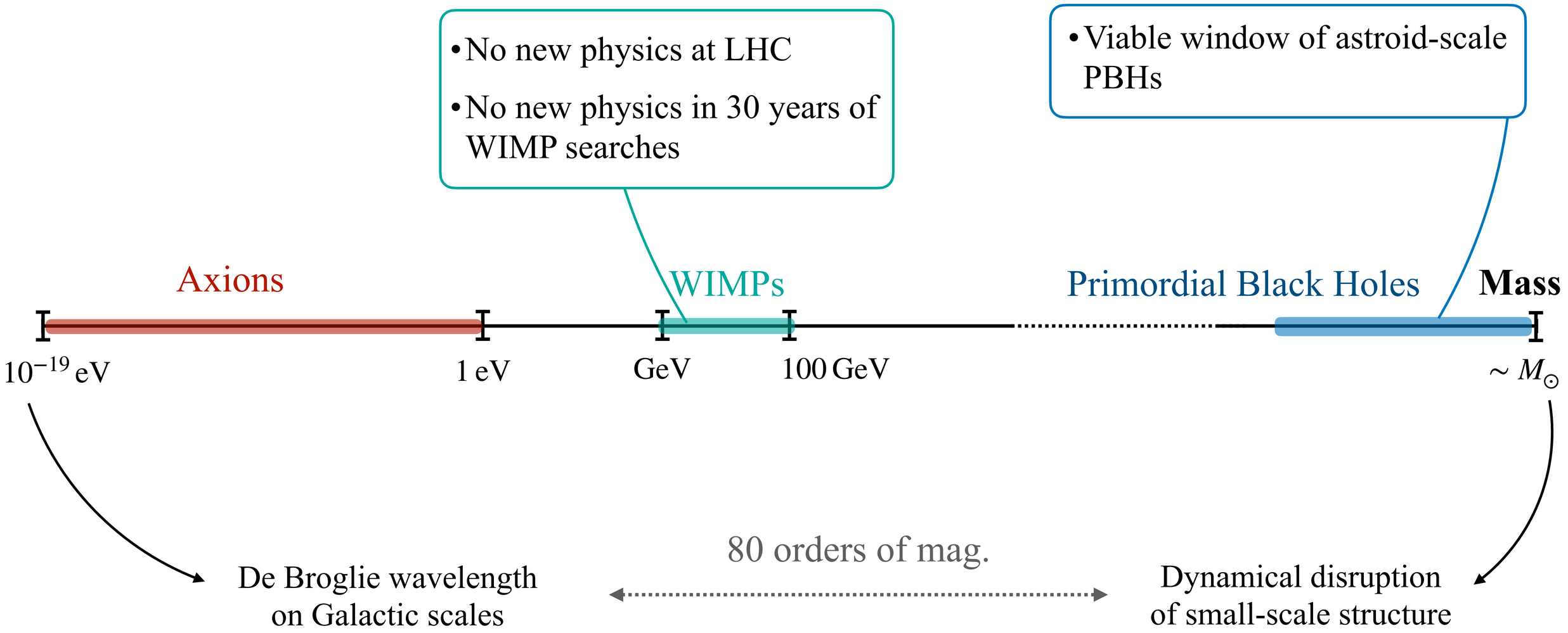
(370,000 yrs after big bang)

Characteristic Scale

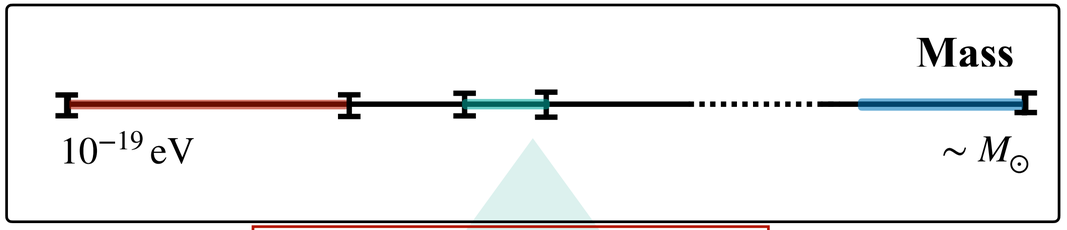
Dark matter candidates



Dark matter candidates

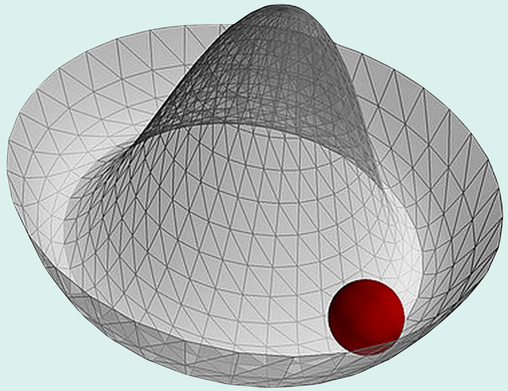


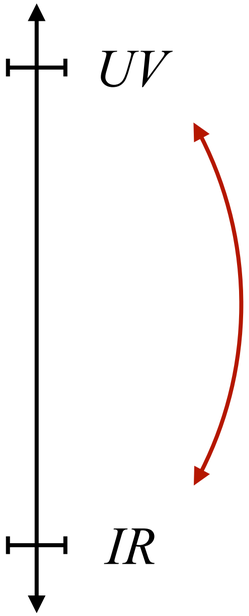
Axions



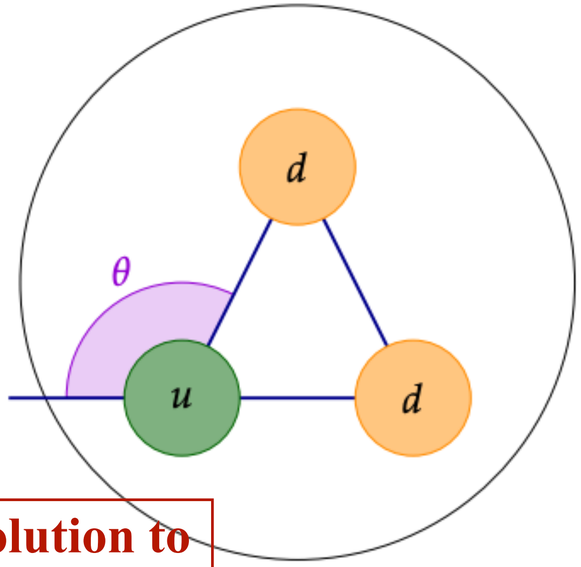
Axions as dark matter

Light Pseudoscalars





Axions as IR remnants of the UV



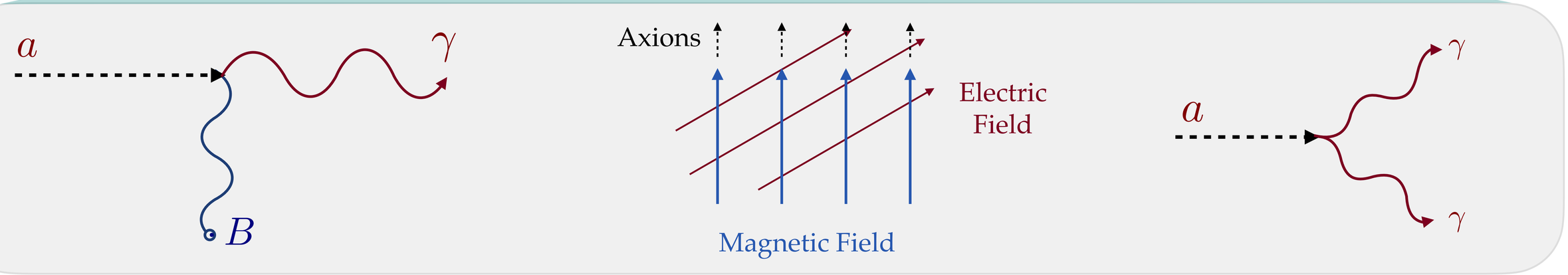
Axions as a solution to the strong CP problem

How do we search for these particles and what can we learn from their detection?

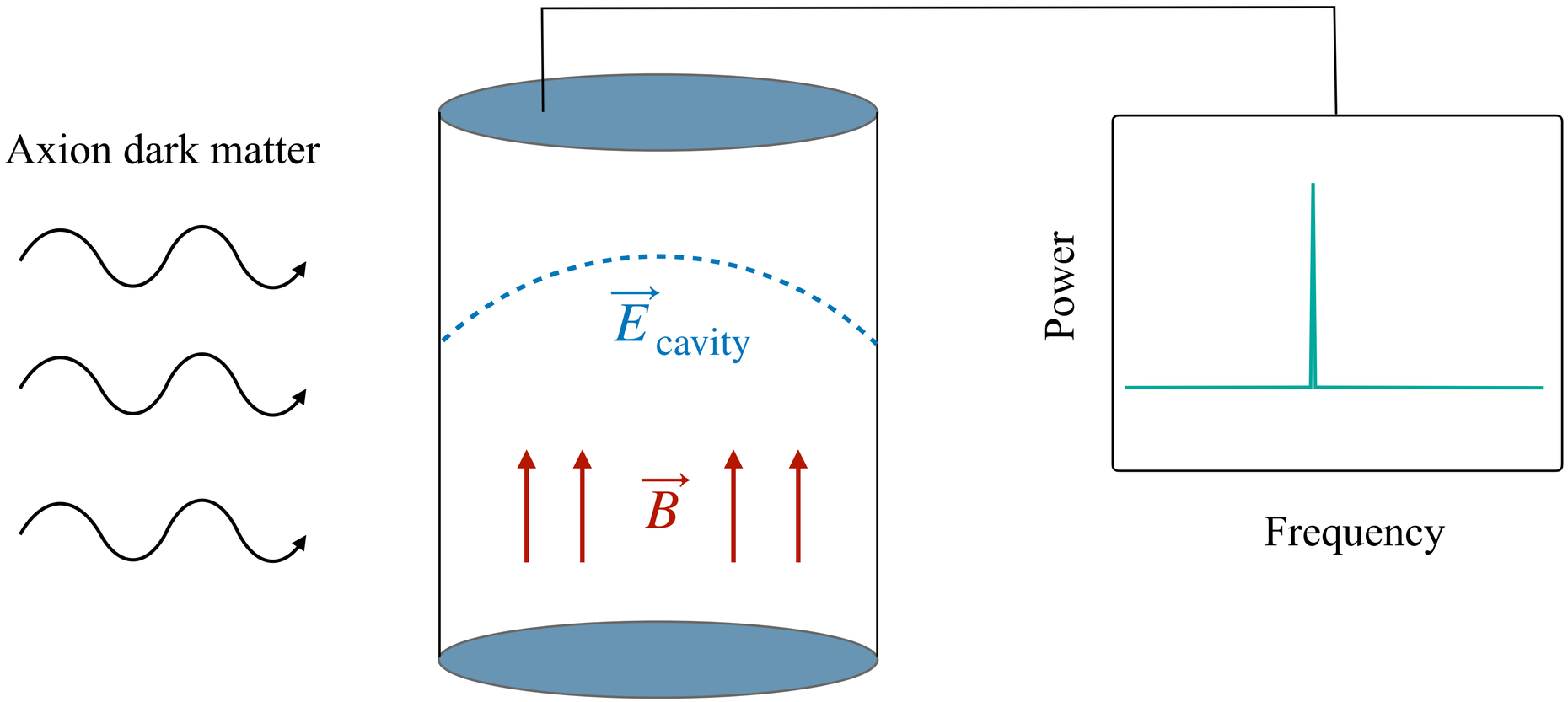
Axions and the Standard Model

$$\mathscr{L} \supset \mathscr{V}_{\mathrm{QCD}}(a) + g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{f_a}\partial_\mu a \bar{\psi}\gamma^\mu\gamma^5\psi + \cdots$$

$$\propto a(\vec{E}\cdot\vec{B})$$



Axion detection in the lab: the haloscope



Can understand as broken translational invariance allows $k_a^\mu \simeq k_\gamma^\mu + \delta k^i$

Fundamental Limitations: Magnetic field strength, must re-tune cavity for each mass

Predicting the axion mass

- ***Assume QCD axion is dark matter (& high inflationary scale)***

Cosmic strings network in the early Universe

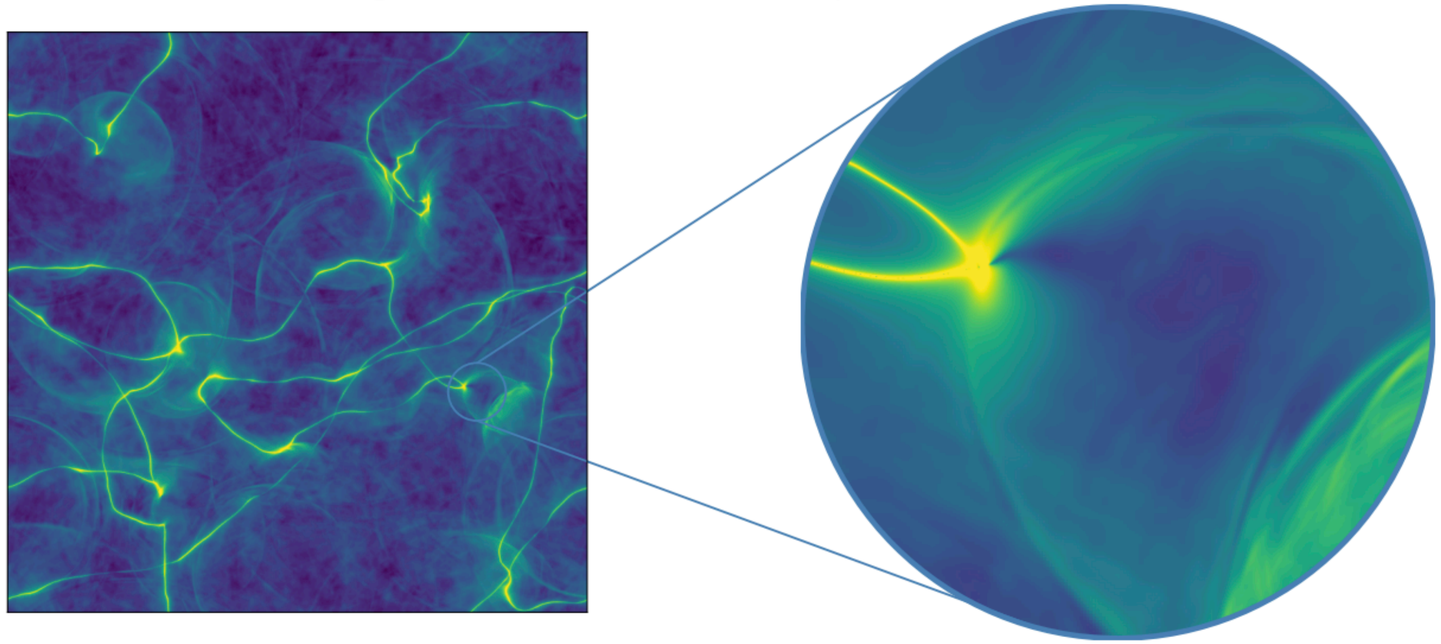


Image credit: Bernabou et al (2023)

Grilla di Cortana, **Hardy**, Pardo Vega, Villadoro (2016), Ghorgetto, **Hardy**, Villadoro (2018, 2021), Bushmann et al (2022), Saikawa et al (2024), Beyer & **Sarkar** (2023)

Axion density field

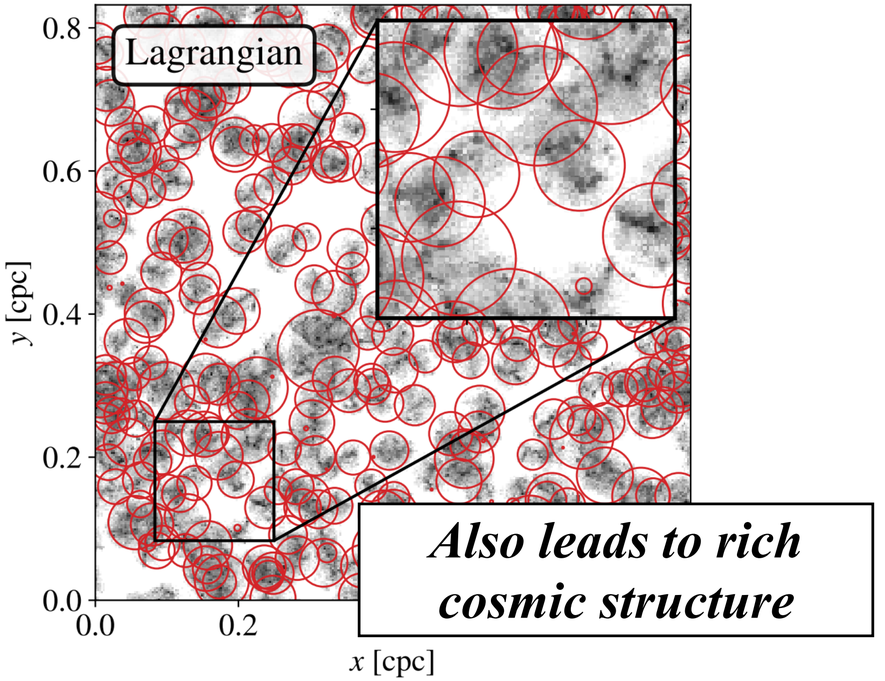


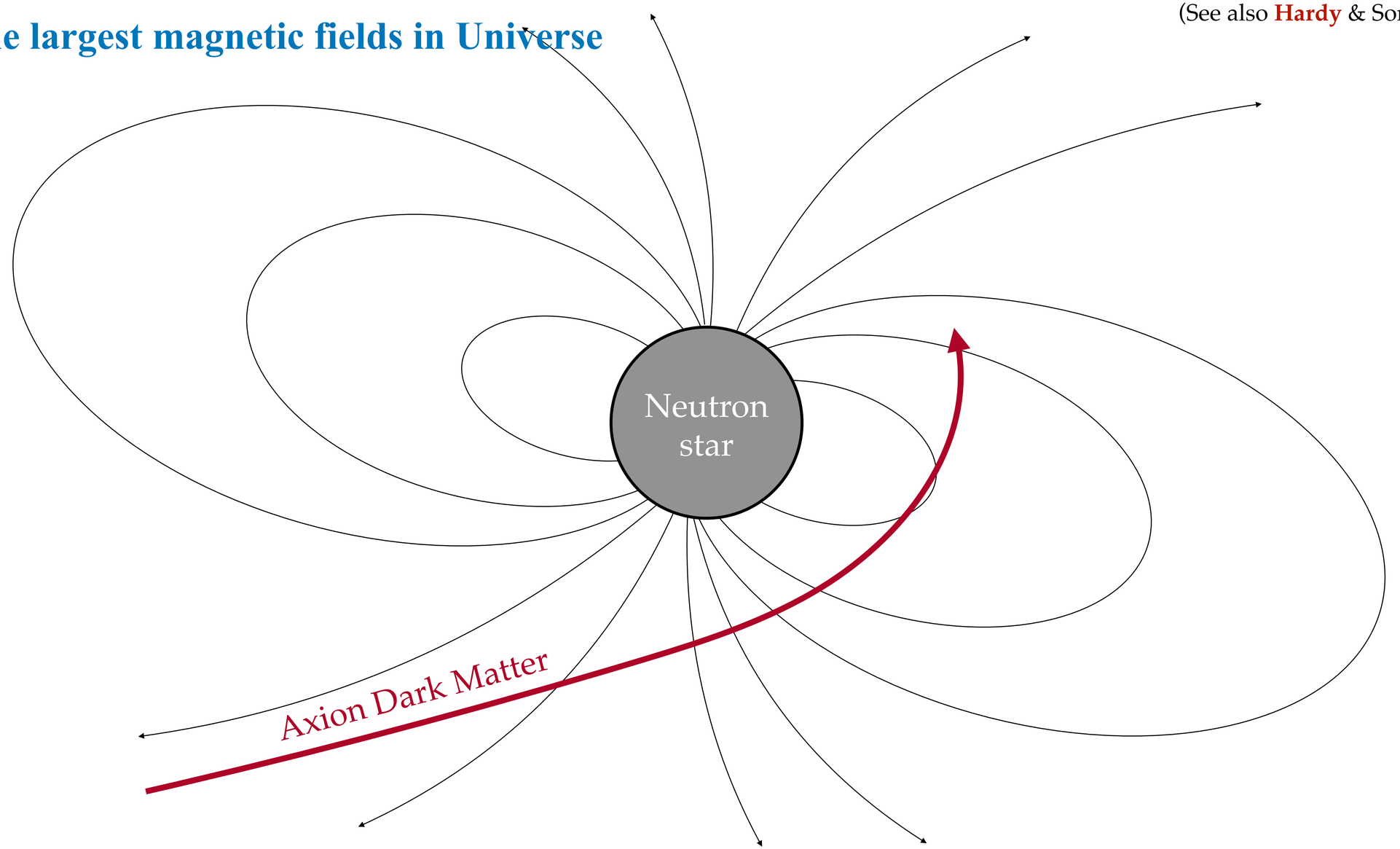
Image credit: Ellis et al (2022)

See also Ghorghetto, **Hardy, March-Russell**, Song and West (2023) for related idea with dark photon

Broadband resonators in Nature

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), …
(See also **Hardy** & Song (2023) for dark photon)

In the largest magnetic fields in Universe



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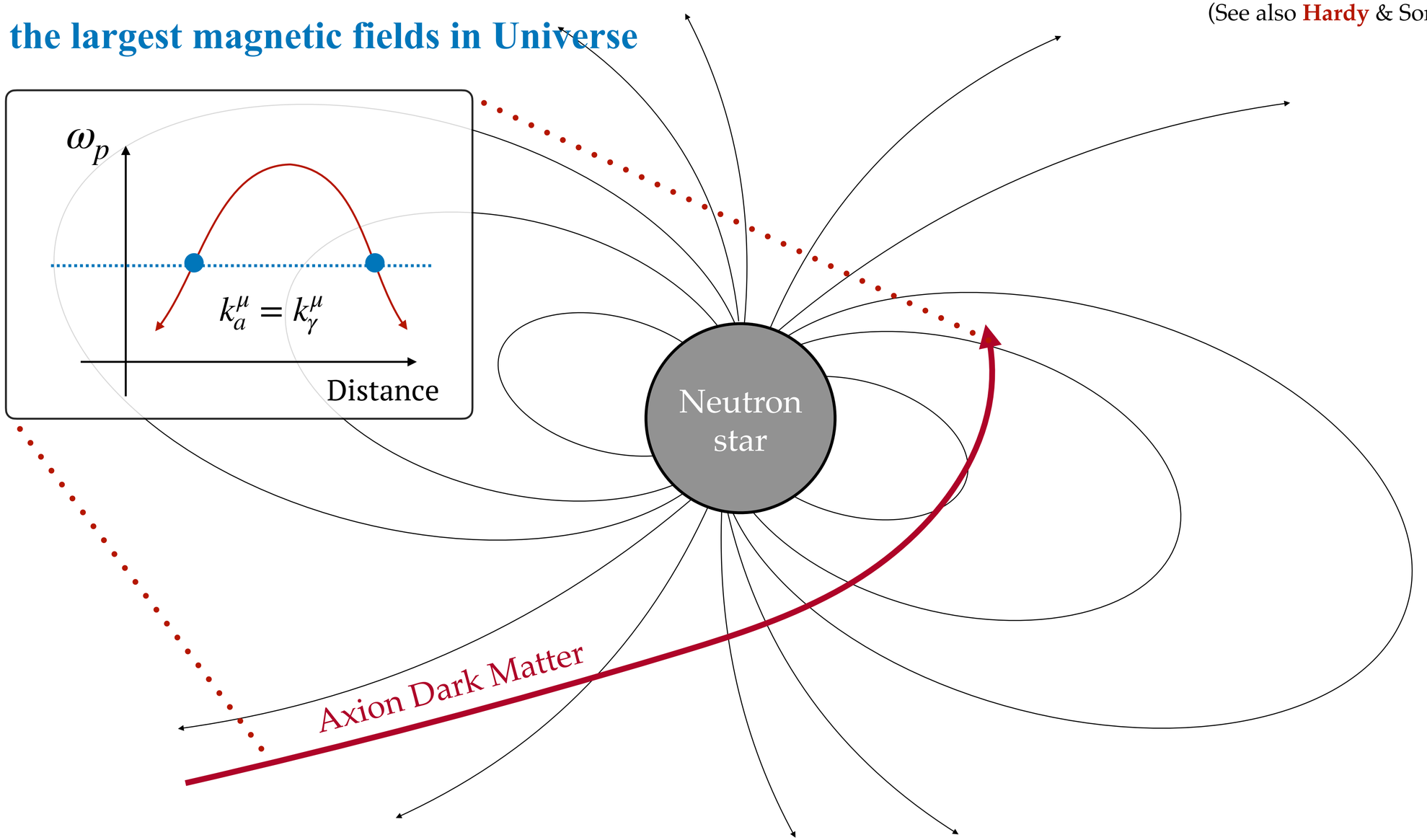

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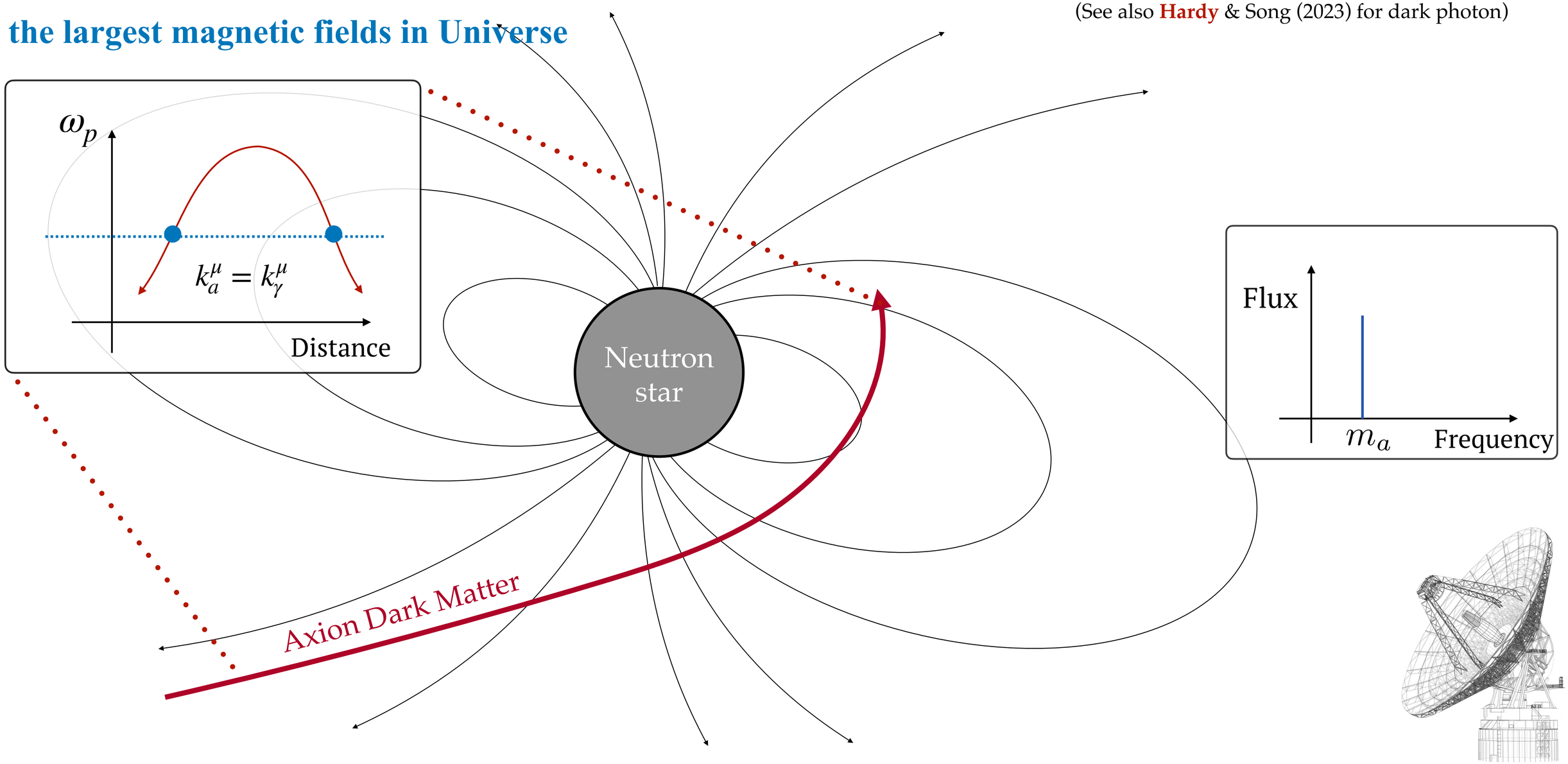
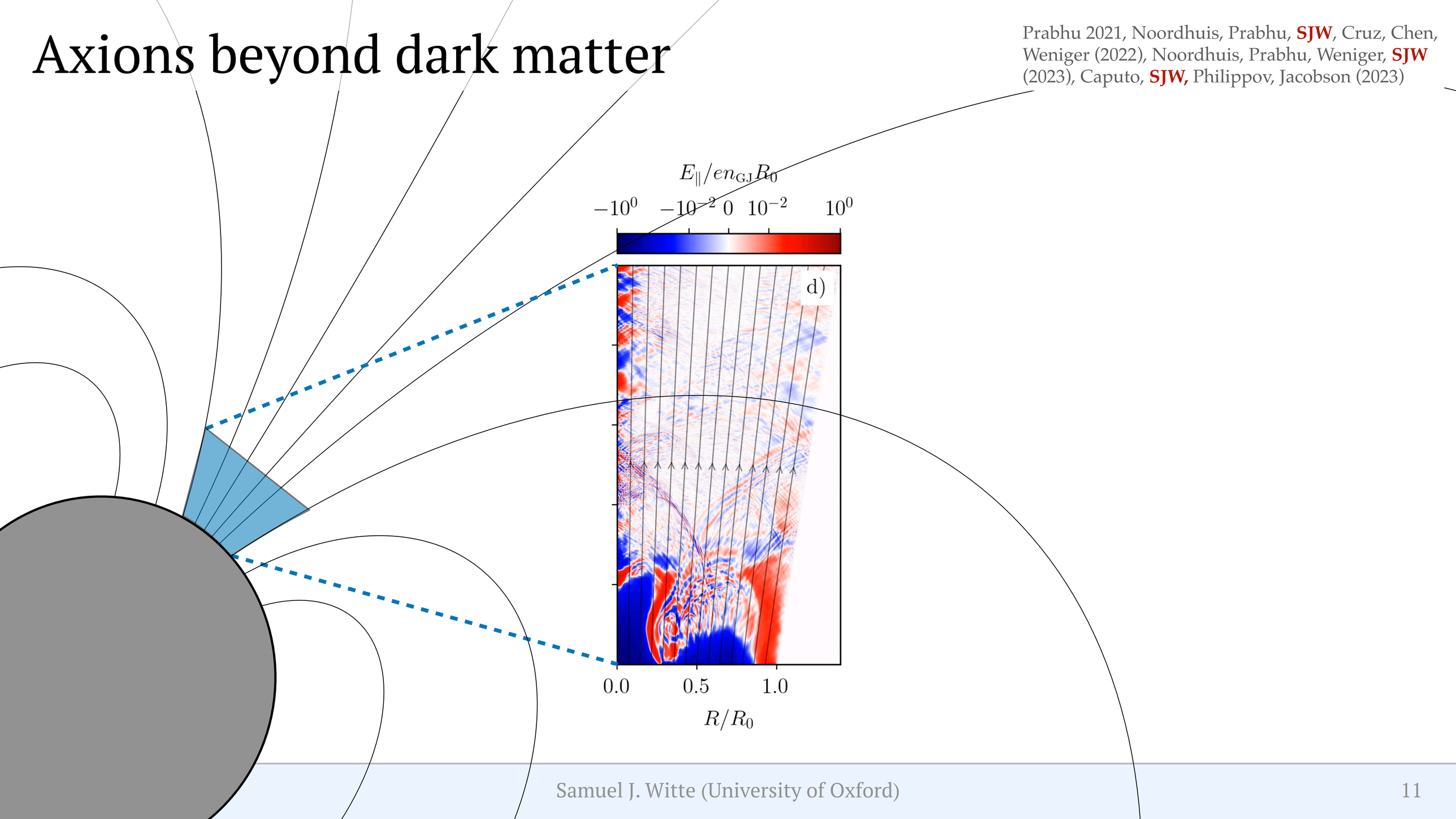


Axions beyond dark matter

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



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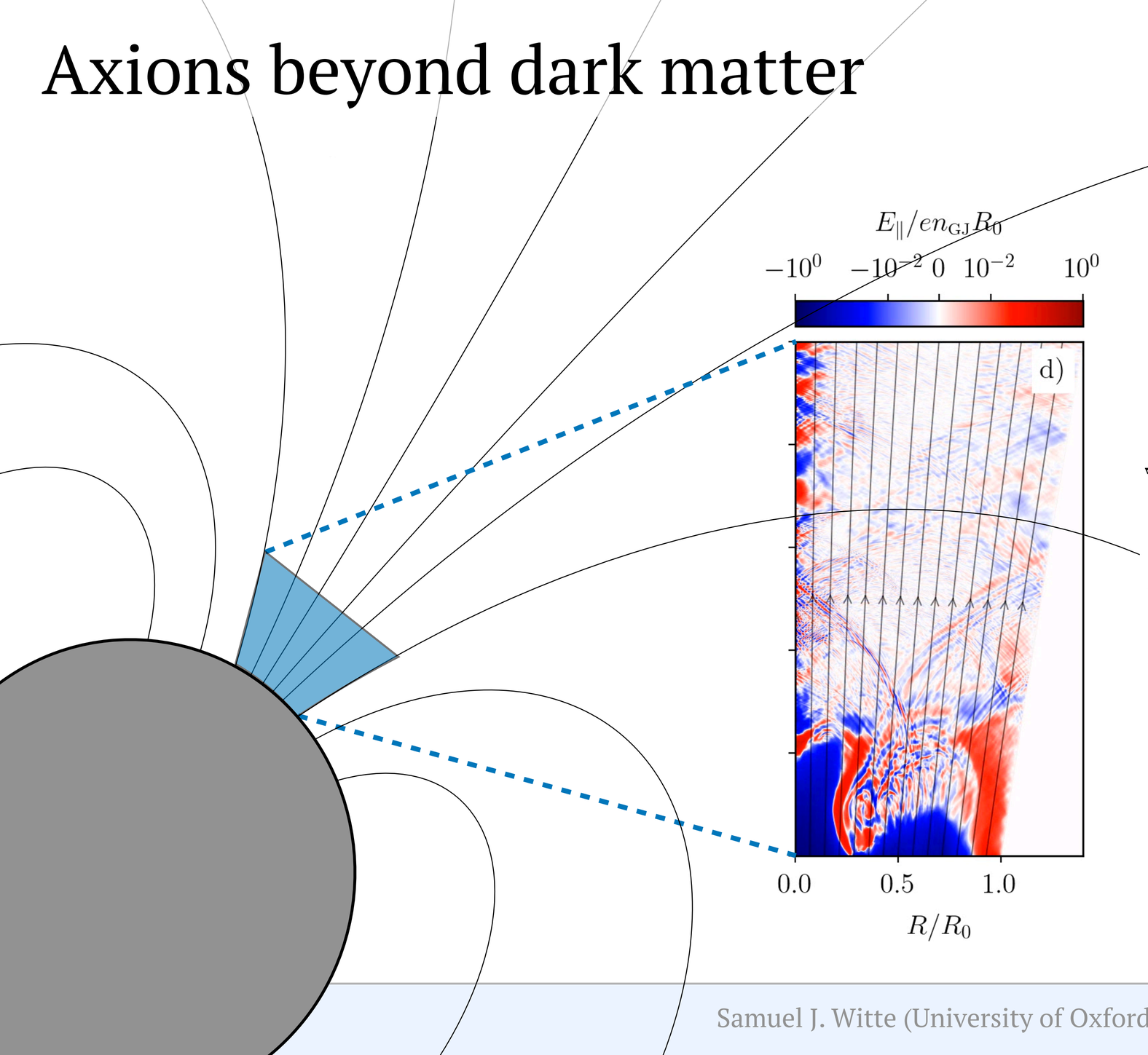
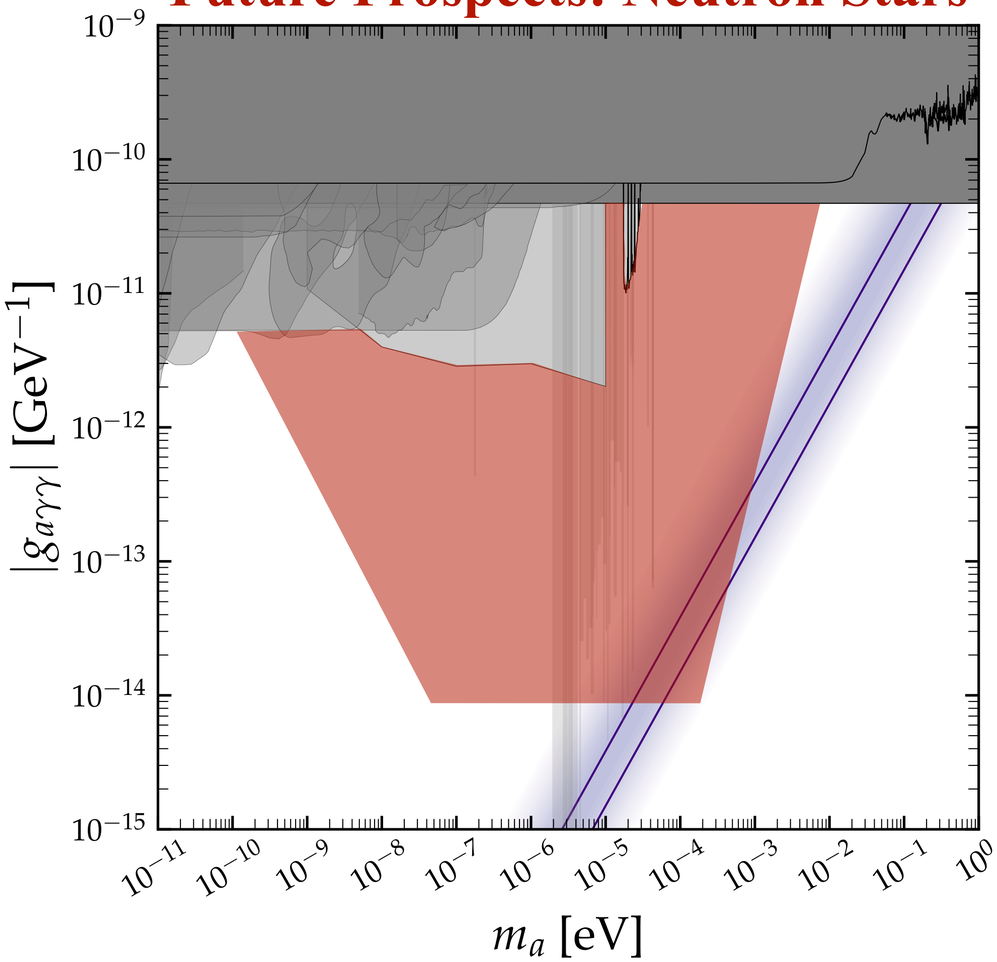
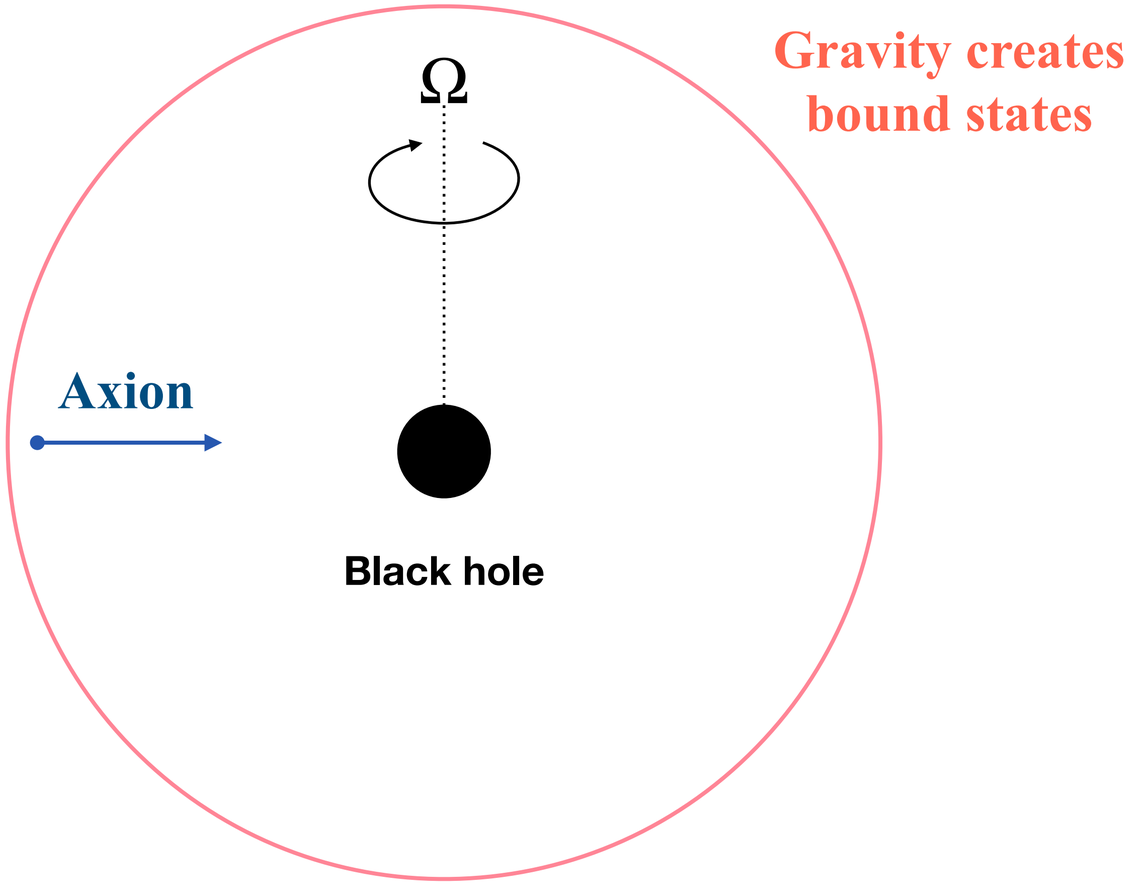


Future Prospects: Neutron Stars



Approaches for lighter axions: superradiance



Zeldovich (1972) Press & Teukolsky (1972),
Related to **Penrose** process (1971)

Arvanitaki, Dimopoulos, Dubovsky. Kaloper, **J. March-Russell** (2010),
Arvanitaki & Dubovsky (2011), Brito, Cardoso, Pani (2015)

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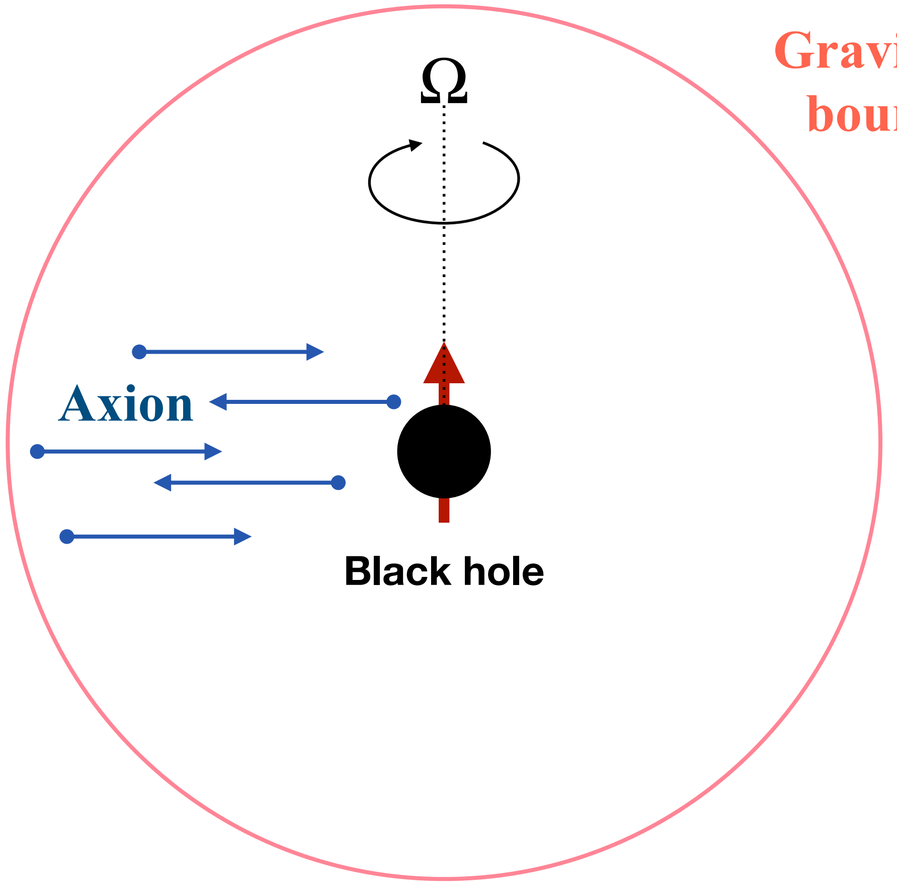
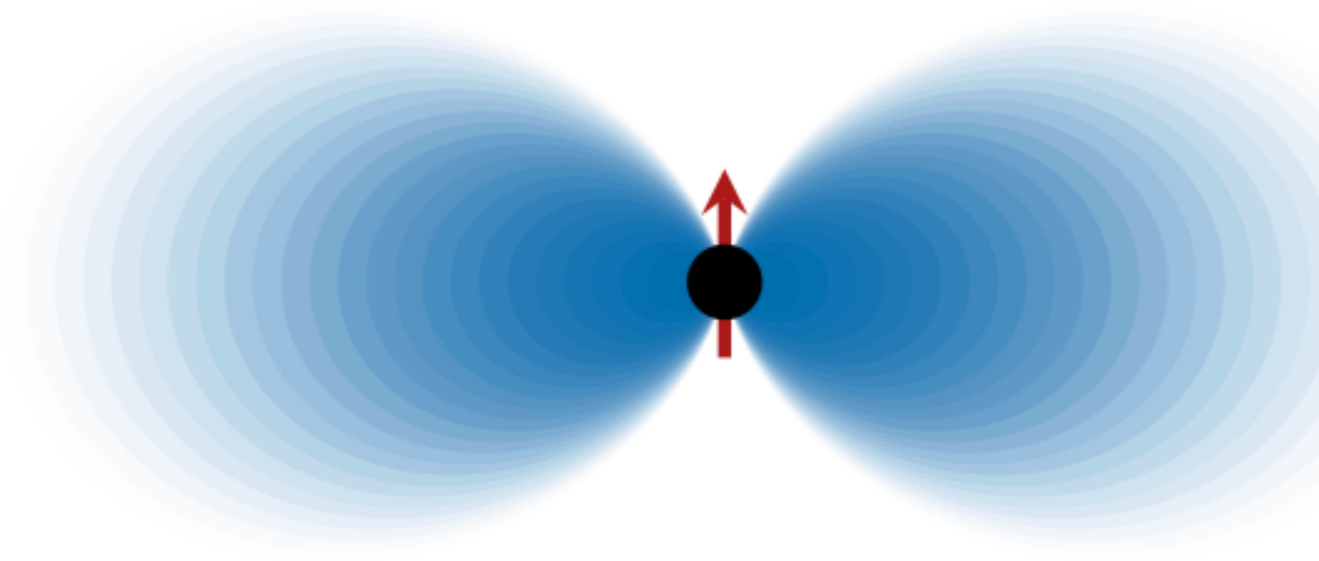


Gravity creates bound states

Time

$\Omega' \ll \Omega$



Axions extract black hole spin, and grow dense clouds

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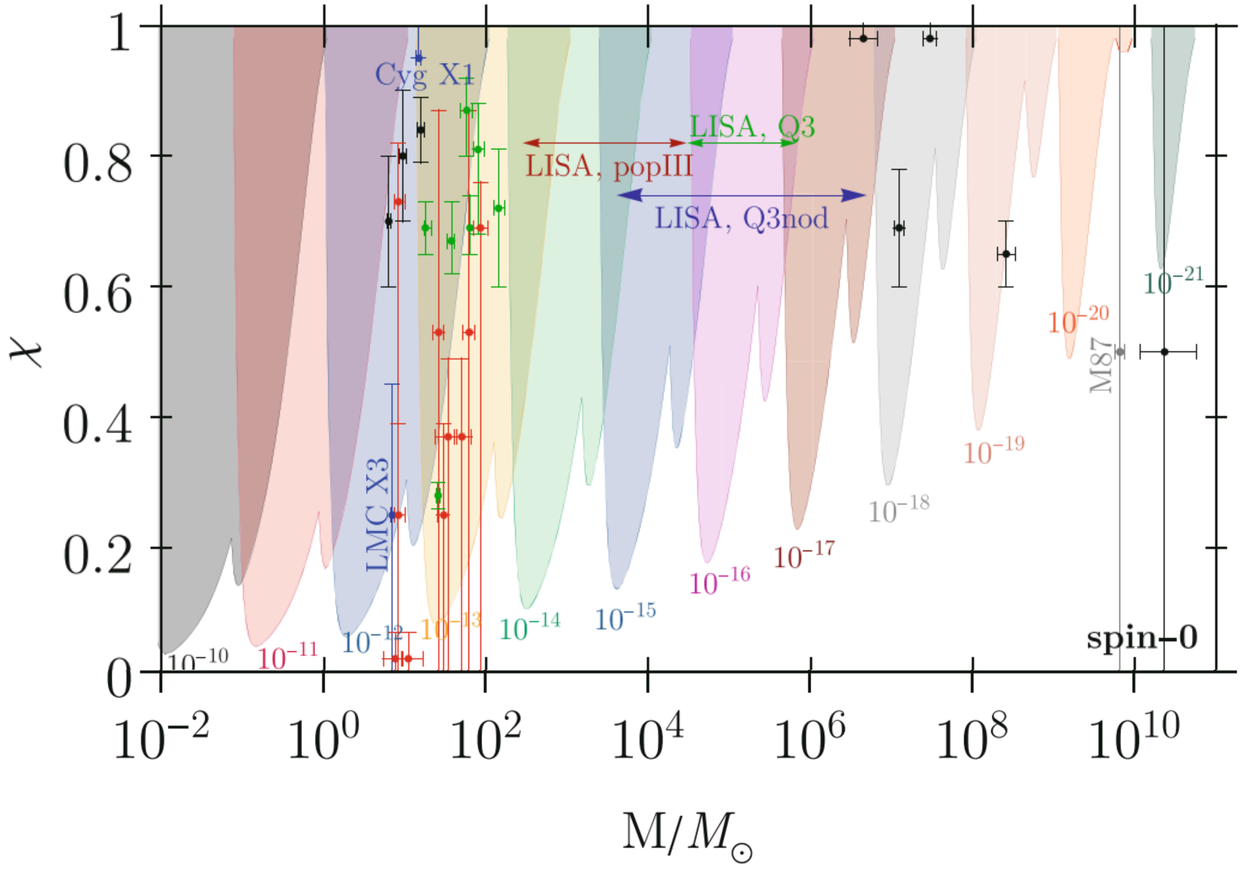
Black hole superradiance

Black hole spin distributions



Gravitational waves from axion cloud

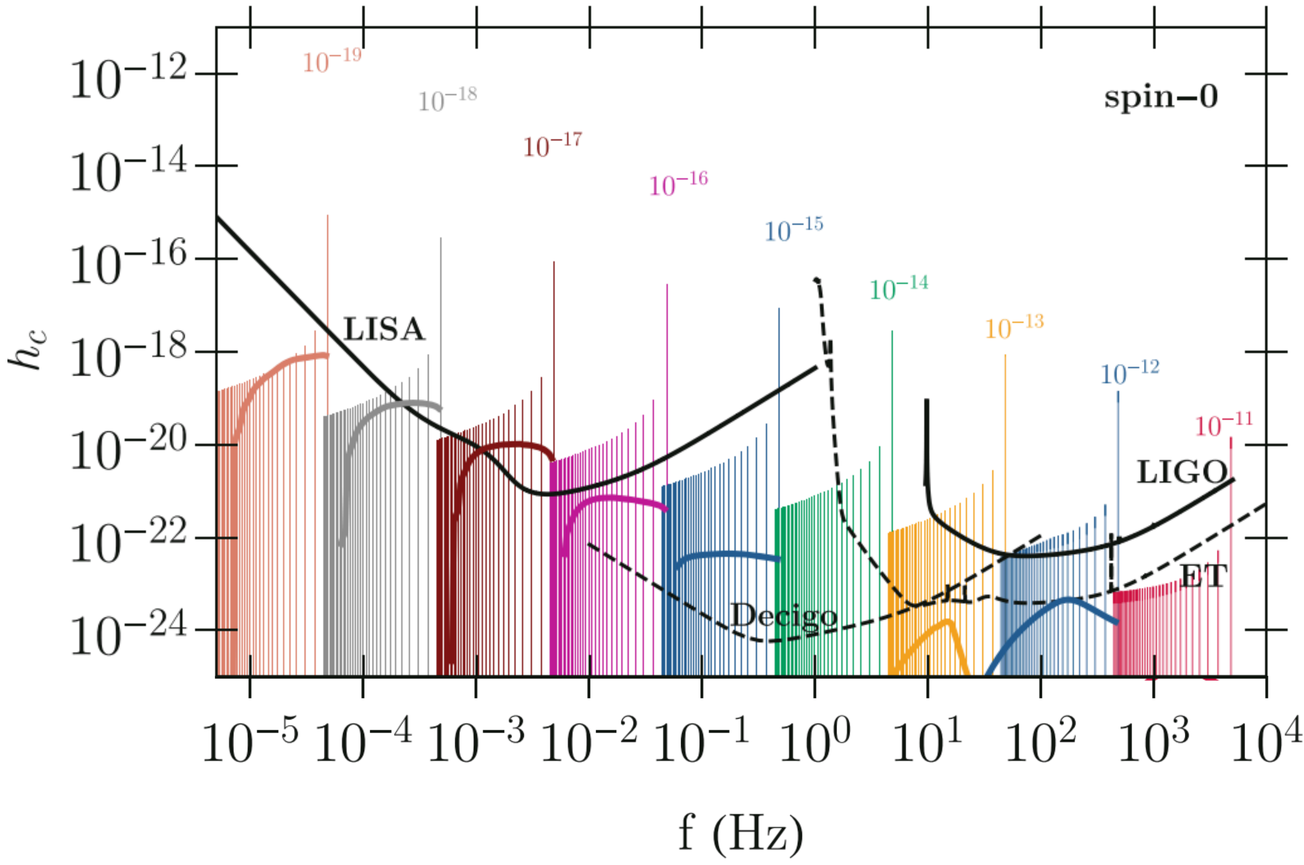
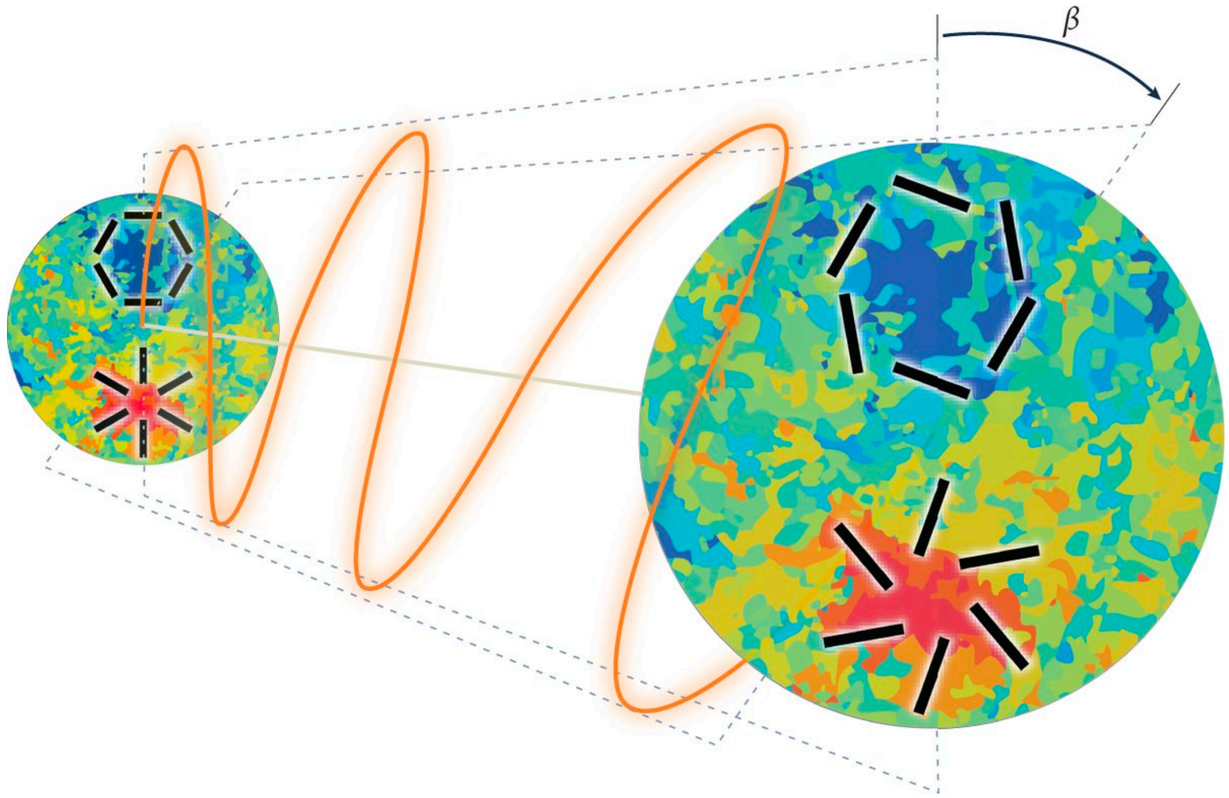


Image credit: Brito & Pani (2022)

Approaches for ***even*** lighter axions

Cosmic Birefringence



Light axions can rotate polarisation of CMB

$$m_a \lesssim 10^{-27}\,\mathrm{eV}$$

- Quintessence — Carroll (1998)
- Axion string network — P. Agrawal, Hook, Huang (2020); P. Agrawal, Hook, Huang, Marques-Tavares (2021)

Tentative evidence in Planck data @ $\sim 3.6\sigma$ See e.g. Komatsu (2022), Eskilt & Komatsu (2022)

Conclusions: so what can we learn?

- Strong CP problem?
- Dark Matter?

- What can a detection tell us about physics at high energies?

Axion detection can probe:

- GUTs / structure of gauge symmetries
- Existence of magnetic monopoles and heavy degrees of freedom

Multiple axions could hint toward stringy "axiverse"

See e.g.
P. Agrawal, Nee, M. Reig (2022)
P. Agrawal & Platshorre (2023)
Sokolov & Ringwald (2022, 2023)
P. Agrawal, Hook, Huang (2020)
P. Agrawal, Hook, Huang, Marques-Tavares (2021)

Arvanitaki, Dimopoulos, Dubovsky. Kaloper, J. March-Russell (2010)