Stockholm
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RECENT DEVELOPMENTS IN
AXION PHYSICS

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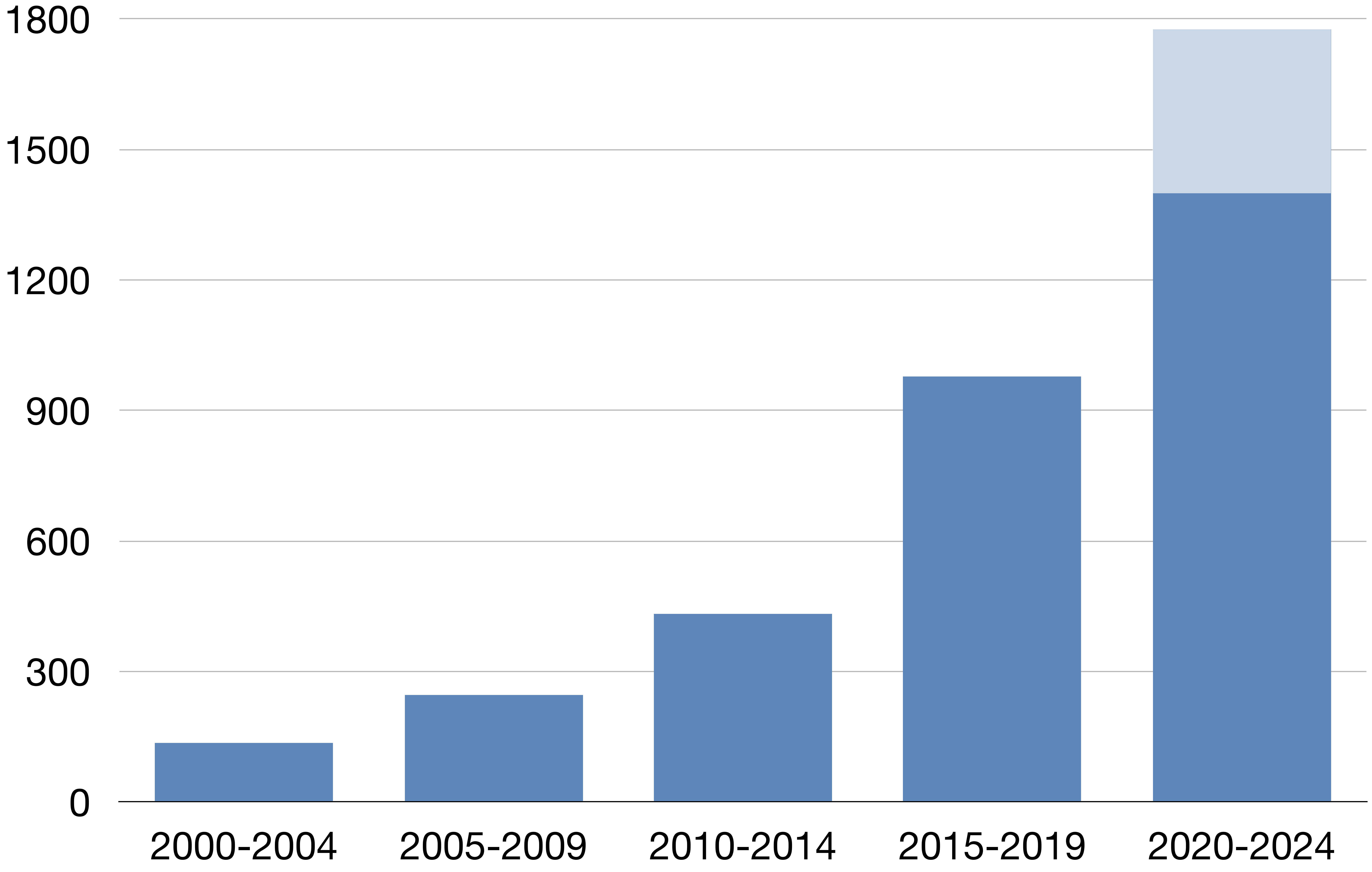
THE FIRST NORDIC COSMOLOGY MEETING

25TH OCTOBER, 2023

Axion papers per 5-year period



But *why now*?

Has emerged as one of the **strongest dark matter candidates**.

Theory connection is deep and non-trivial.

The **astroparticle physics and cosmology** of axions is incredibly rich, with potential observables from the early universe and nearby stars.

Experiments have begun to probe the most interesting parameter space; a flurry of new experiments have been proposed.

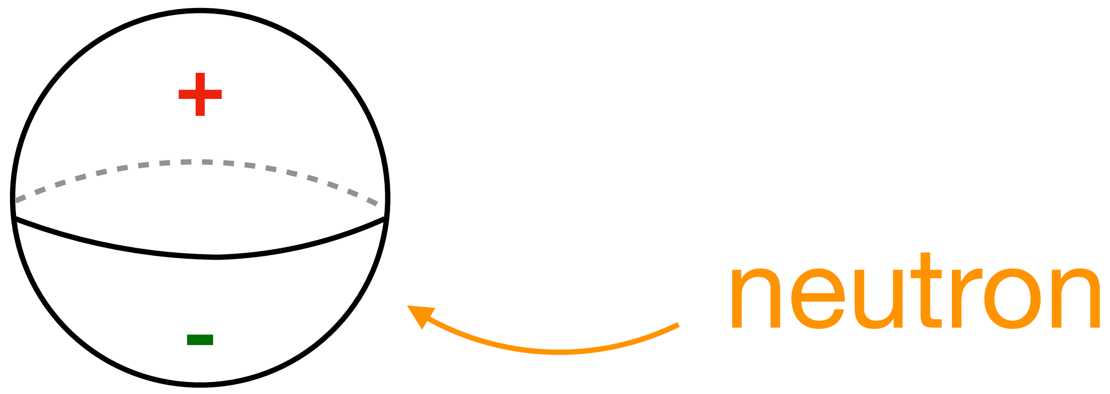
Sense of *“drive”* in the community.

This talk: a short review of basic axion physics mixed with selected new developments.

The neutron electric dipole moment

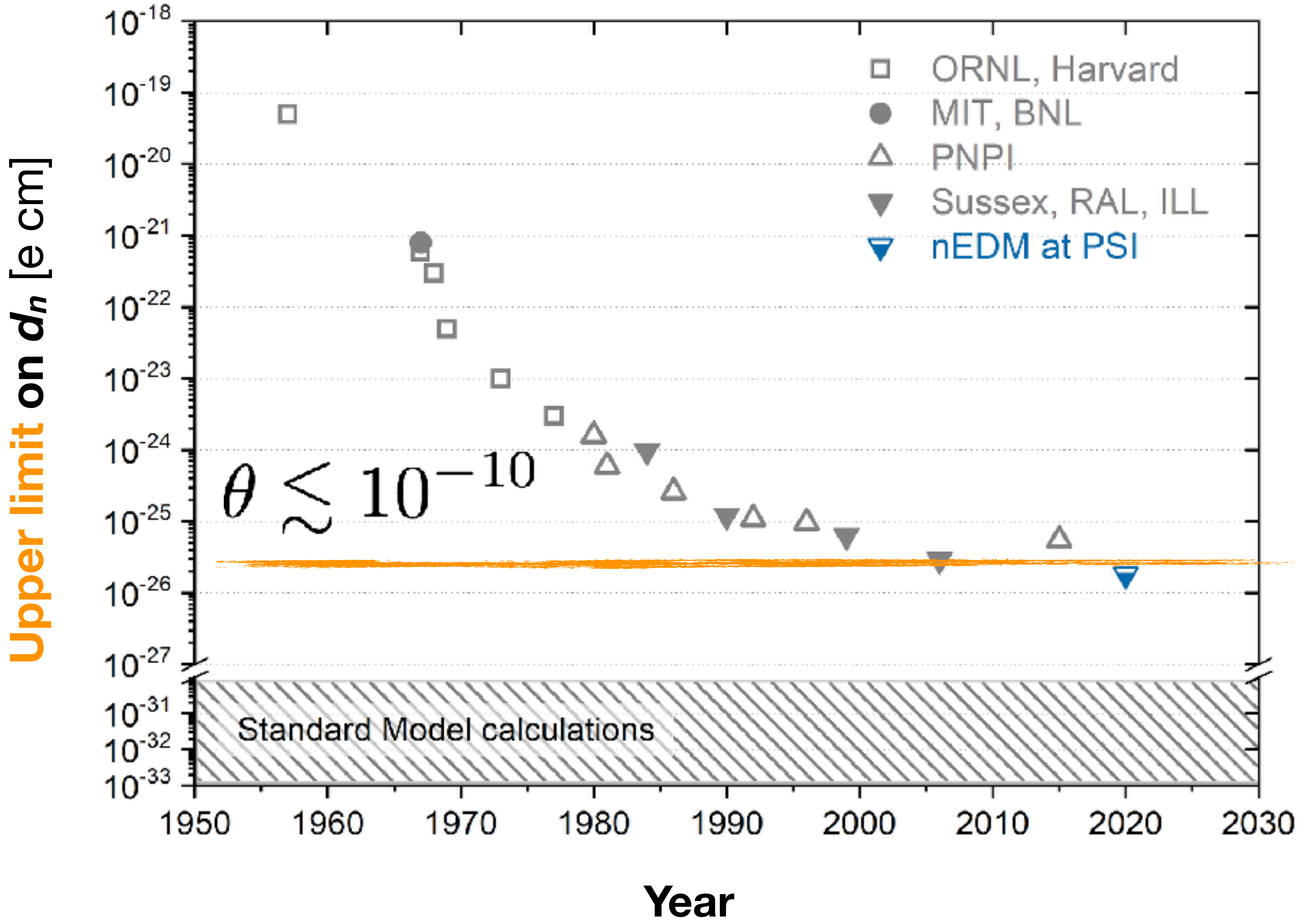
The theta angle: $\frac{\theta}{16\pi^2}\,\mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$

θ affects the neutron charge distribution.



$$d_N = \left(5.2\times 10^{-16}\,e\cdot\mathrm{cm}\right)\theta$$

$$\theta \lesssim 10^{-10}$$



Possible solutions of the strong CP-problem

- If $m_u = 0$, θ is unphysical

But lattice simulations give $m_u \neq 0$

- Spontaneous CP-violation that does not re-introduce the problem (“bare $\theta = 0$”).

But solution often more fine-tuned than the original problem

Nelson, Barr

- The axion: the pseudo-Nambu-Goldstone boson from the spontaneous breaking of a new Peccei-Quinn symmetry

Theta is promoted to a dynamical field with vanishing vev

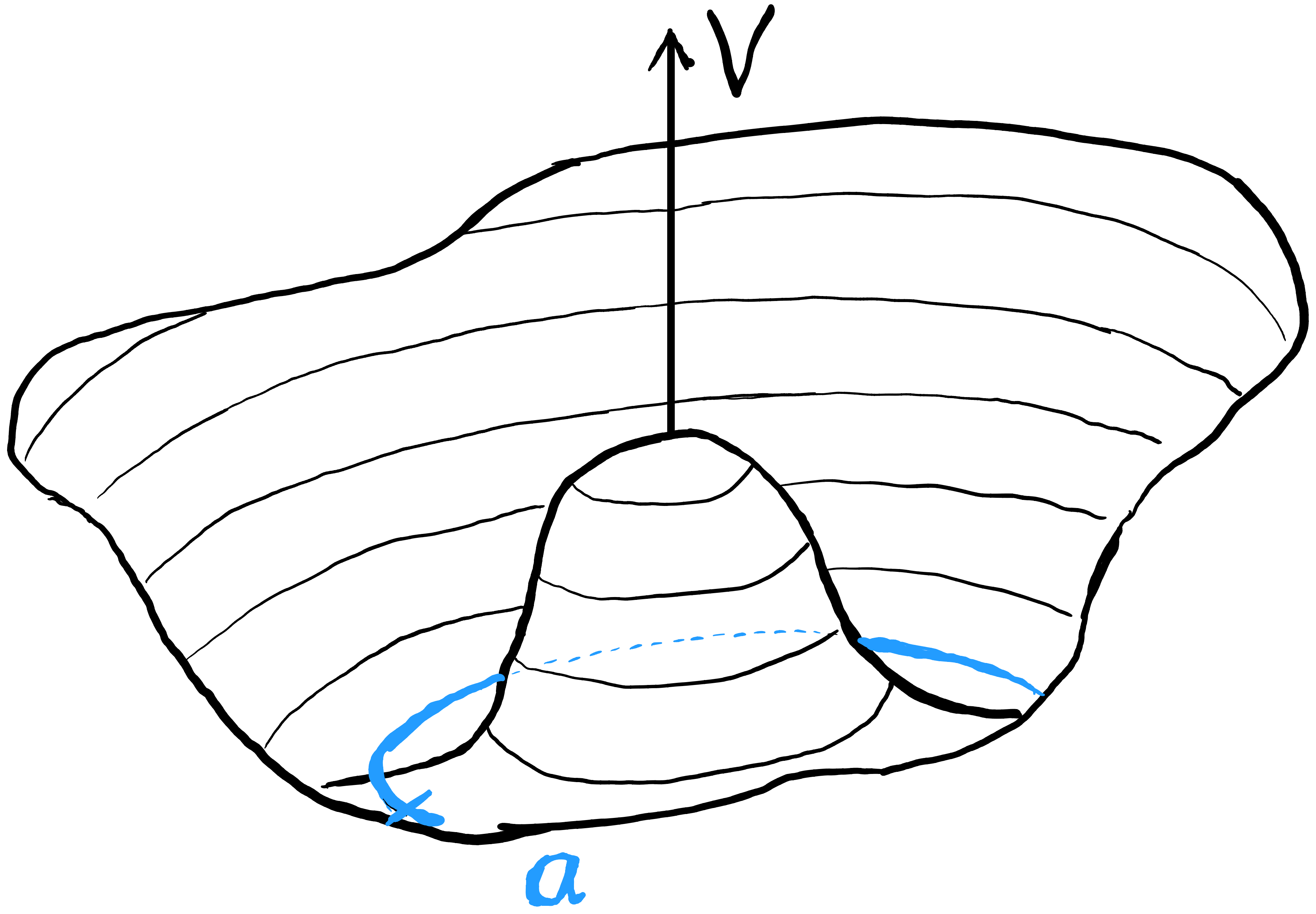
Peccei, Quinn; Weinberg; Wilczek

The QCD axion

Make θ dynamical, minimising potential energy at $\theta = 0$.

Realisation: **the axion**, a pseudo-Nambu-Goldstone boson coupled to QCD.

$$\frac{\theta - a/f_a}{16\pi^2}\,\mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$



Scales:

f_a	Axion decay constant
Λ_{QCD}	QCD scale (~330 MeV)
$m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f_a}$	Mass scale
$g_{a\gamma} \sim \frac{\alpha}{f_a}$	Axion-photon coupling scale

Axion-like particles (ALPs)

Hypothetical pseudo-Nambu-Goldstone bosons that don't couple to QCD.

Frequent in BSM theories.

Scales:	f_a	Axion decay constant	$m_a \sim \frac{\Lambda_{\text{n.p.}}^2}{f_a}$	Mass scale
	$\Lambda_{\text{n.p.}}$	Non-perturbative scale	$g_{a\gamma} \sim \frac{\alpha}{f_a}$	Axion-photon coupling

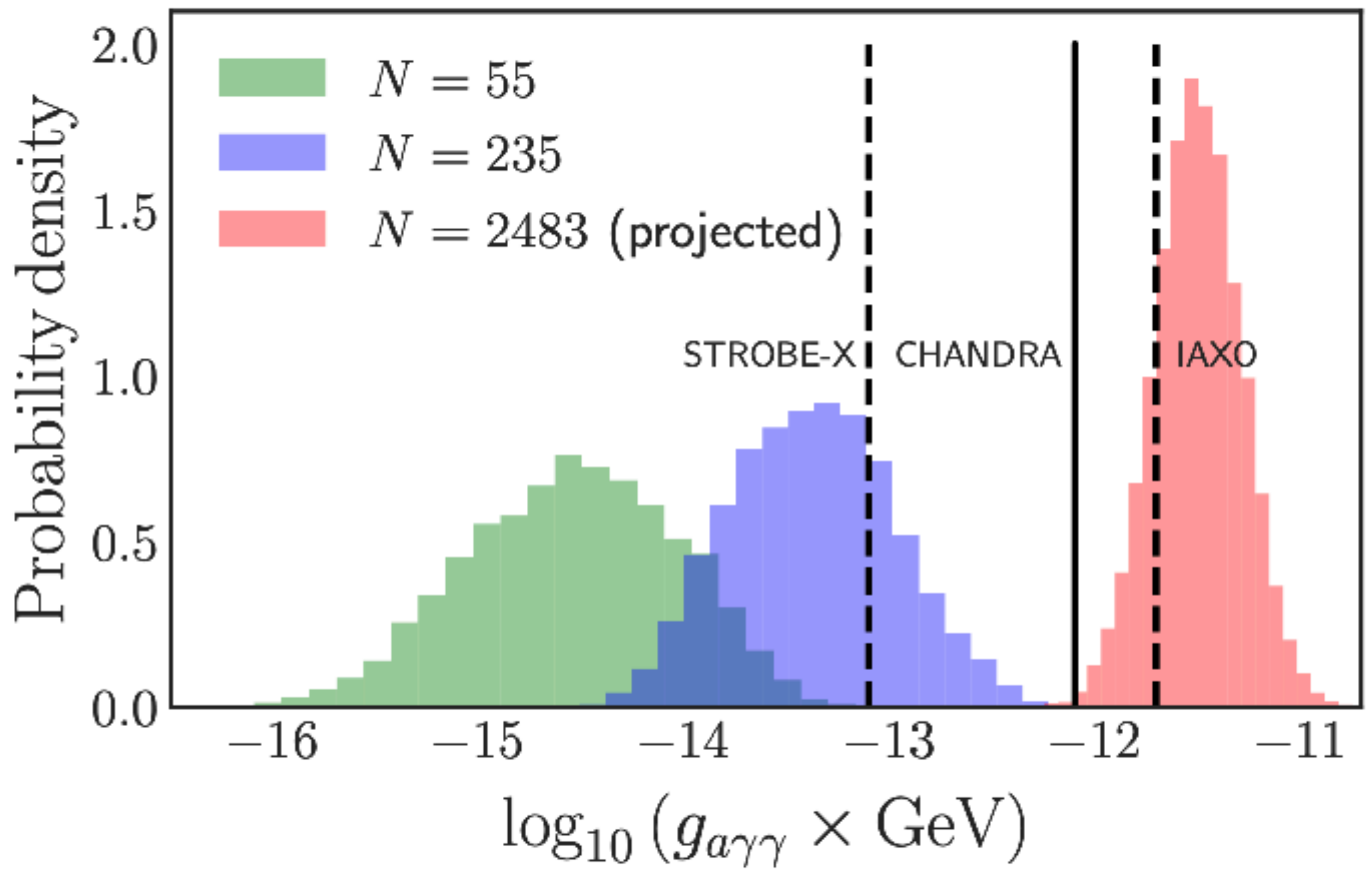
Abundant in string compactifications, cf. the "axiverse".

Recent impressive developments in the numerical realisation of compactifications with many axions.

However, unstabilised.

Halverson et al.
Demirtas et al.
Gendler et al.

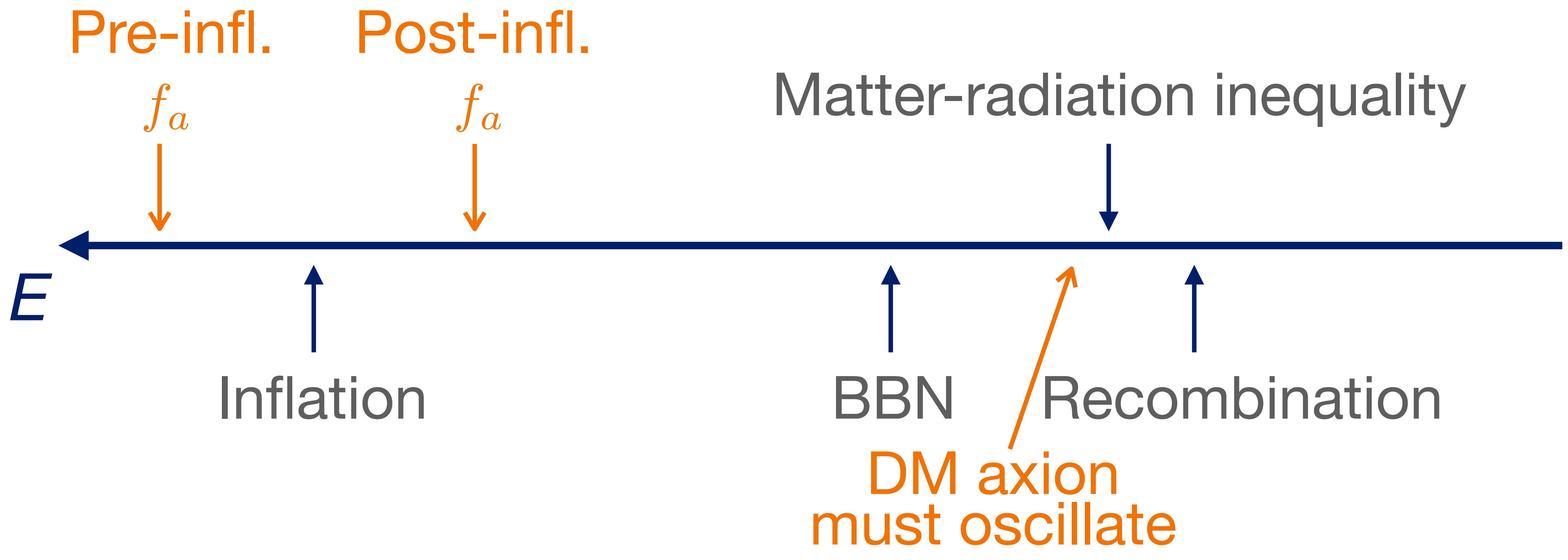
Halverson, Long, Nelson, Salinas



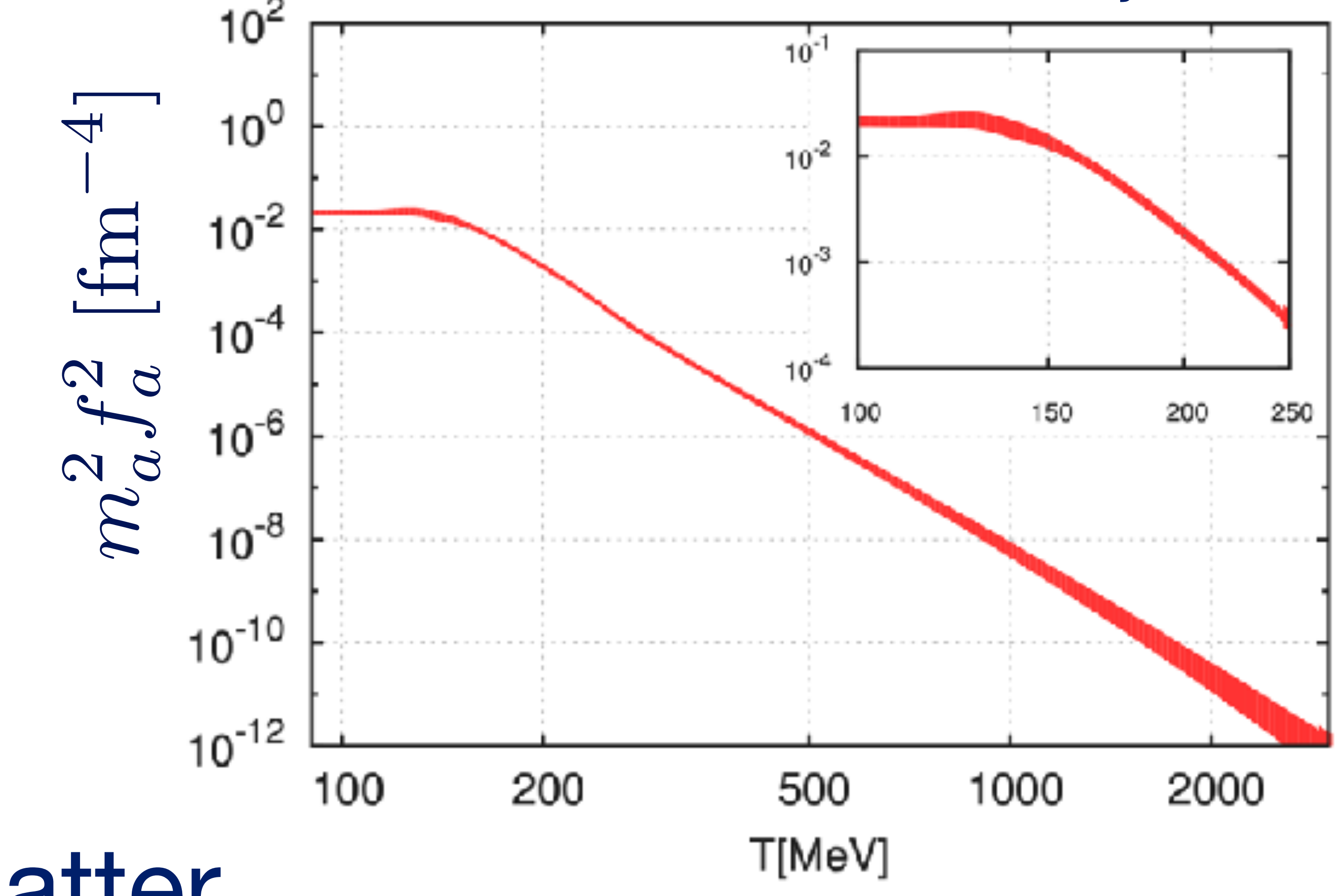
Axion dark matter

The axion was born at $E \sim f_a$.

This may have happened before (pre-inflationary scenario) or after inflation (post-inflationary scenario).



The newborn axion doesn't know its final vacuum and is over-damped by Hubble friction.



Borsanyi et al.

The axion begins to oscillate when $H \sim m_a$.

An oscillating scalar field redshifts like pressure-less dust: dark matter.

Fig. credit: Saikawa

Axion misalignment

In the pre-inflationary scenario, this “misalignment” mechanism gives a homogeneous initial value of the axion field in the observable universe.

Axion dark matter abundance depends on f_a and θ_i.

Observational limits on isocurvature severely constraining if the inflationary scale is sufficiently high.

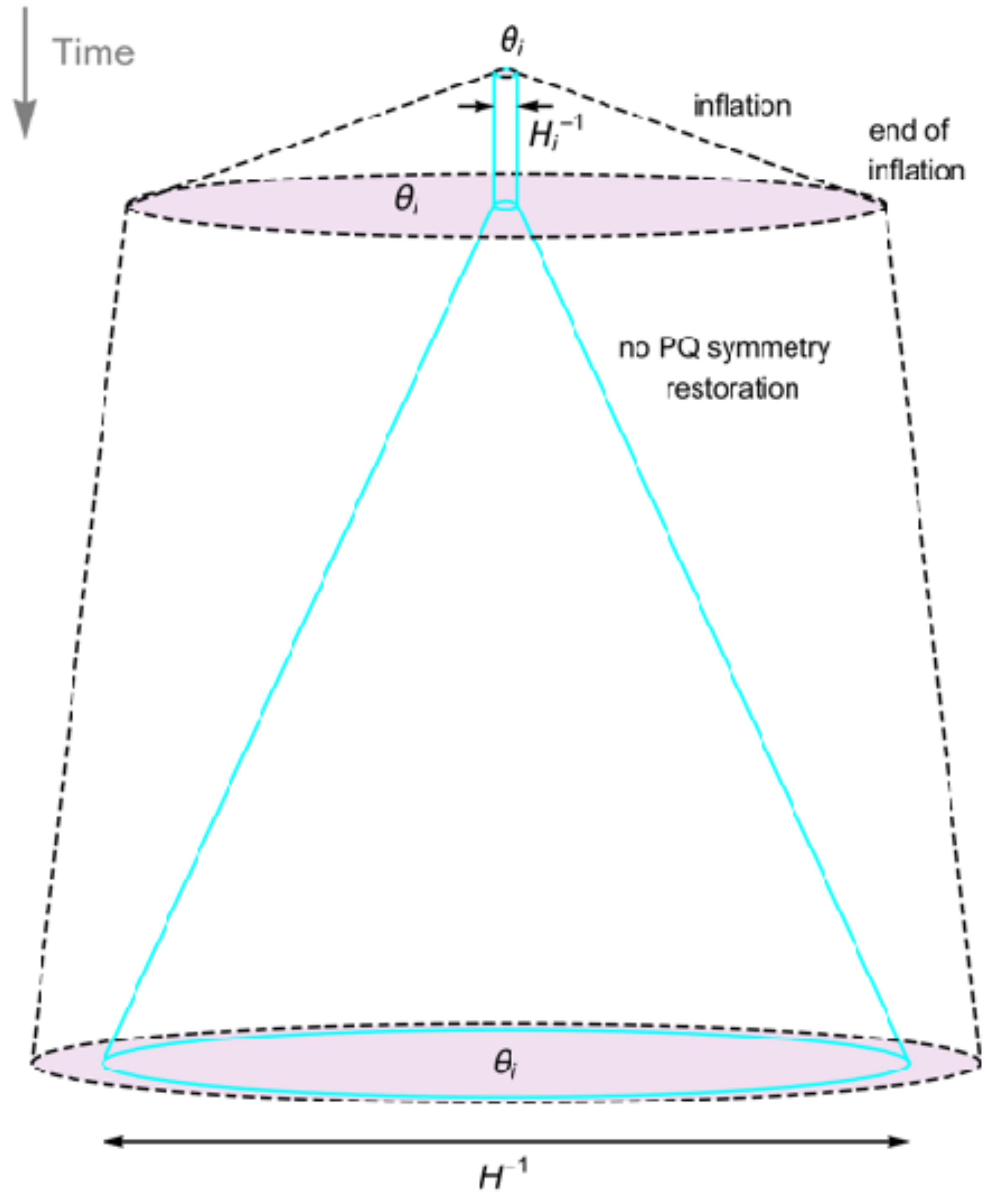
Hamann, Hannestad, Raffelt, Wong

For the QCD axion:

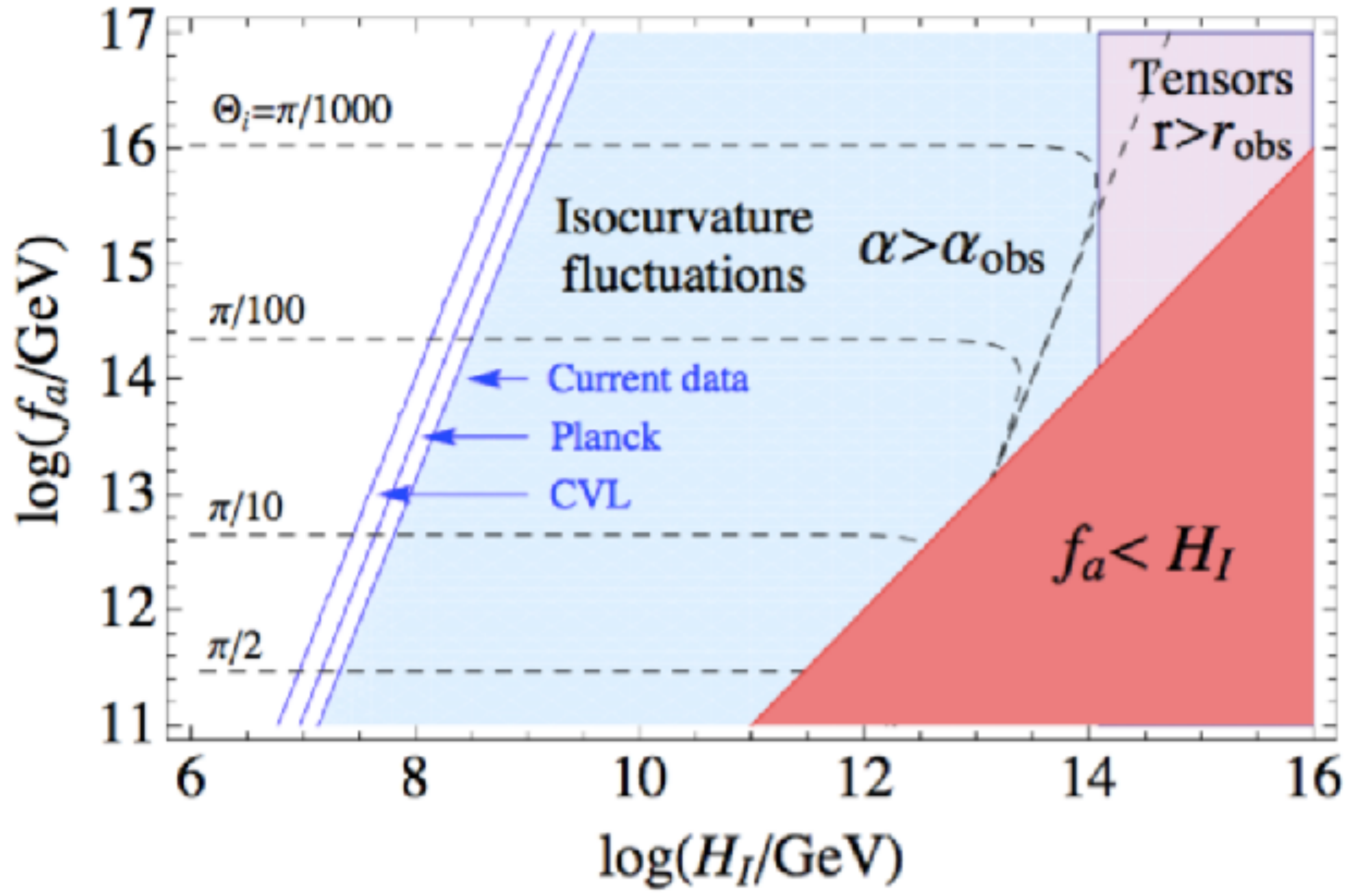
$$0.12\,\mu\mathrm{eV} \leq m_a \leq 0.2\,\mathrm{meV}$$

Hoof et al.

$H_I > \Lambda_{\mathrm{QCD}}$



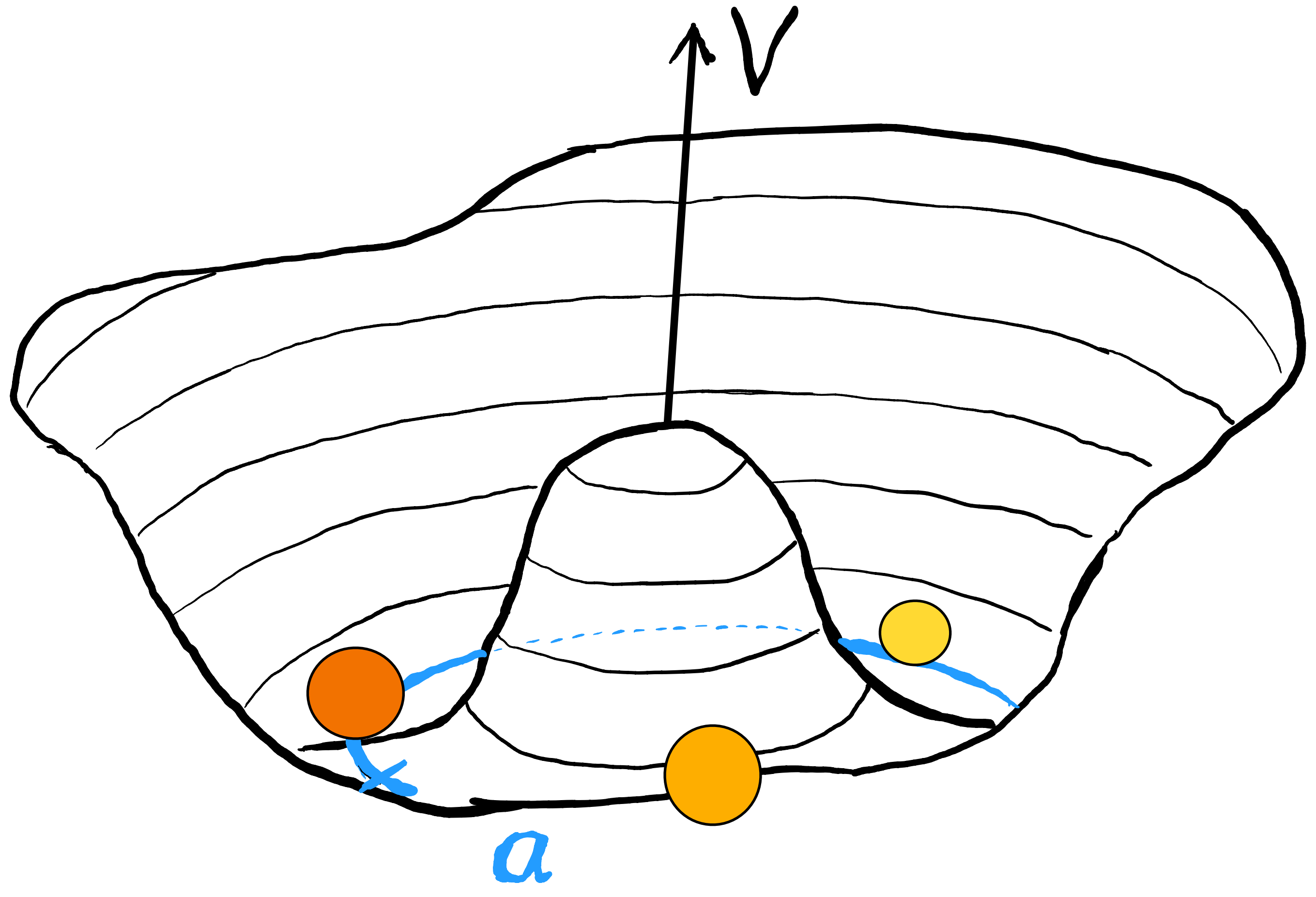
The pre-inflationary scenario.



Simulations of cosmic string production of axions

In the post-inflationary scenario, the present observable universe contains many patches with different θ_i.

Topological defects — cosmic strings and domain walls — contribute to the dark matter density.



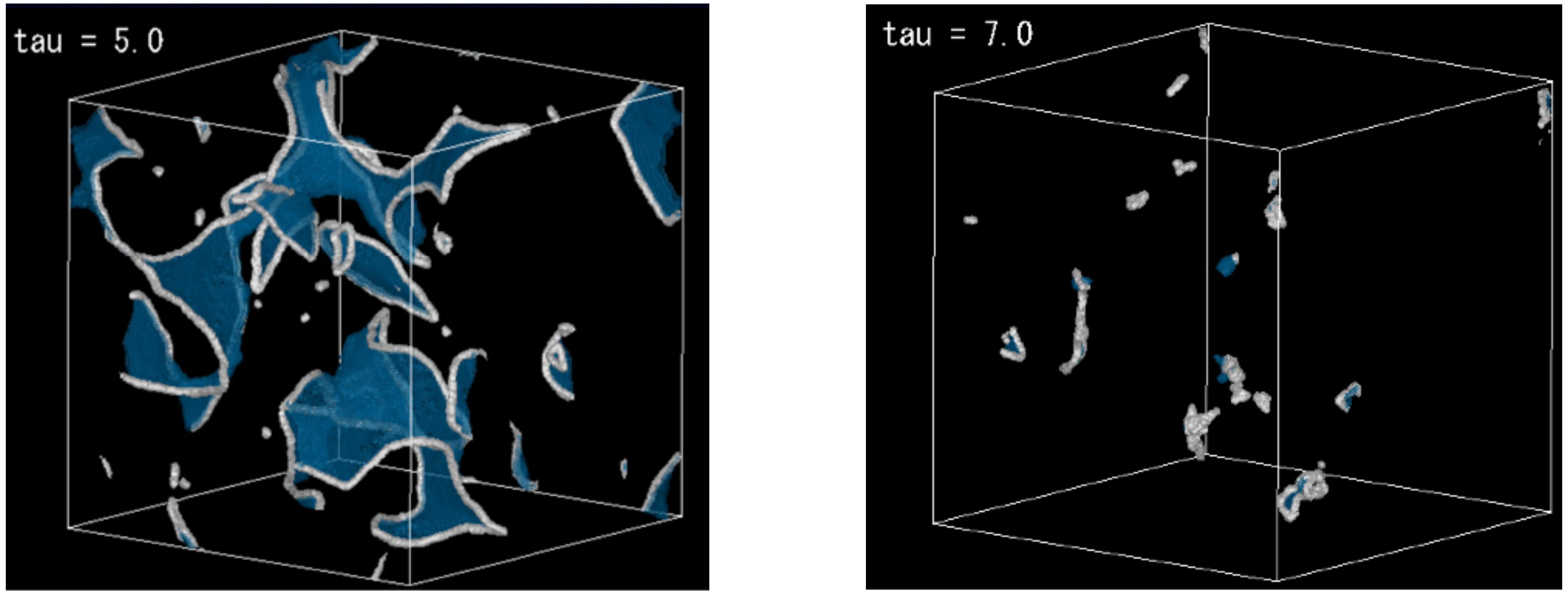
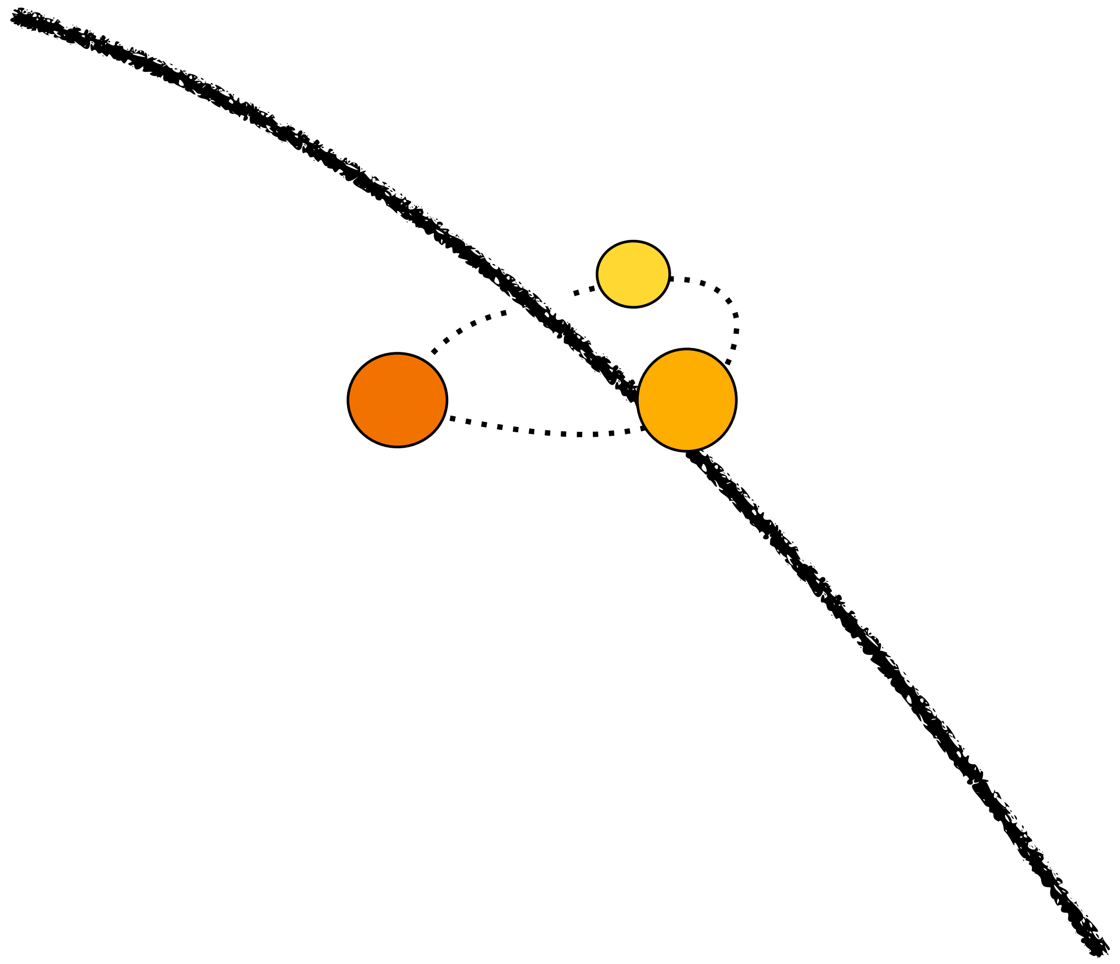


Fig. credit: Saikawa et al.



Simulations of cosmic string production of axions

For the QCD axion in the post-inflationary scenario, only a **single value of the mass** gives the right dark matter abundance.

Cosmic string contribution difficult to compute, despite numerical advances, and subject of recent debate.

Gorghetto et al.
Dine et al.
Hindmarsh et al.
Buschmann et al]

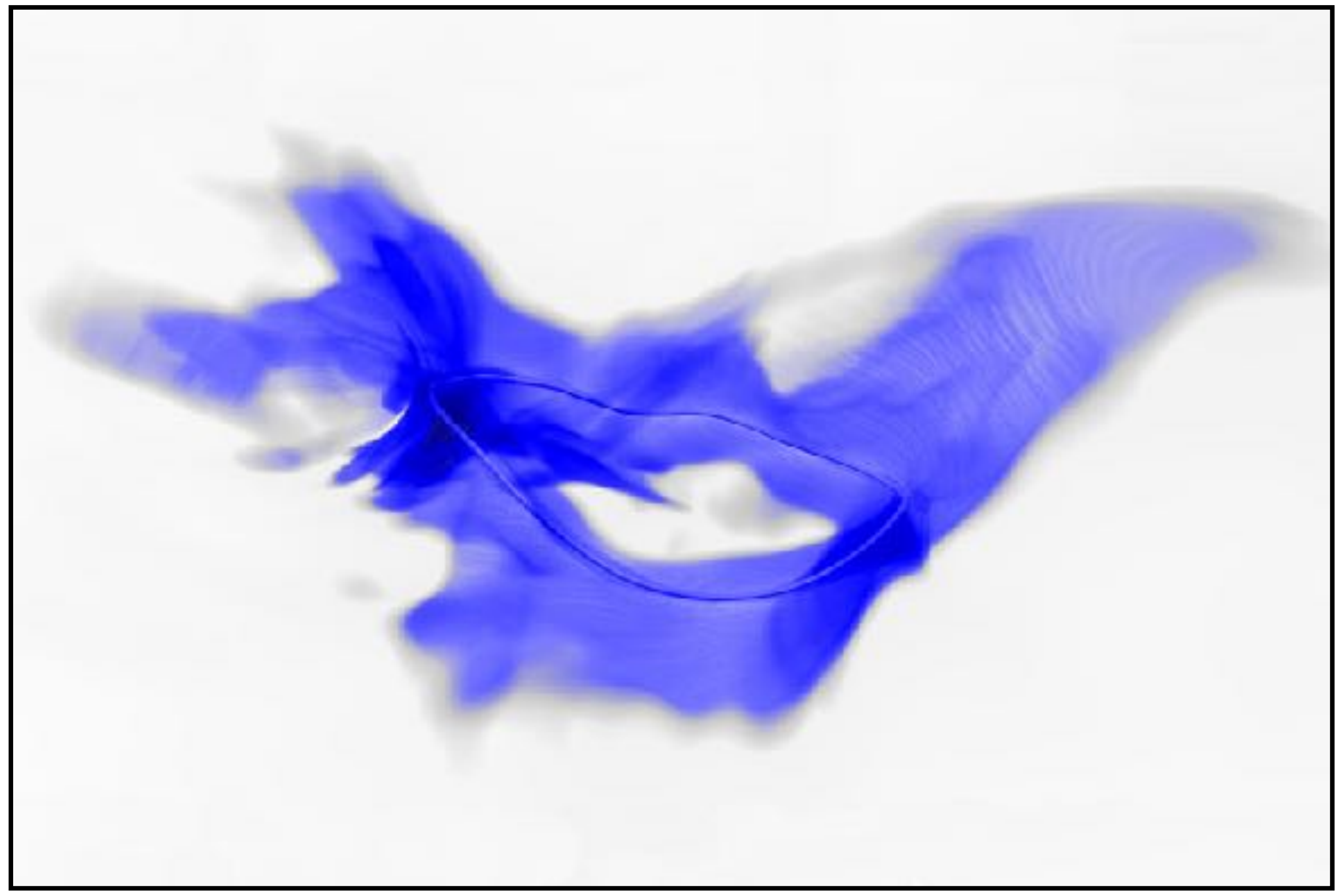
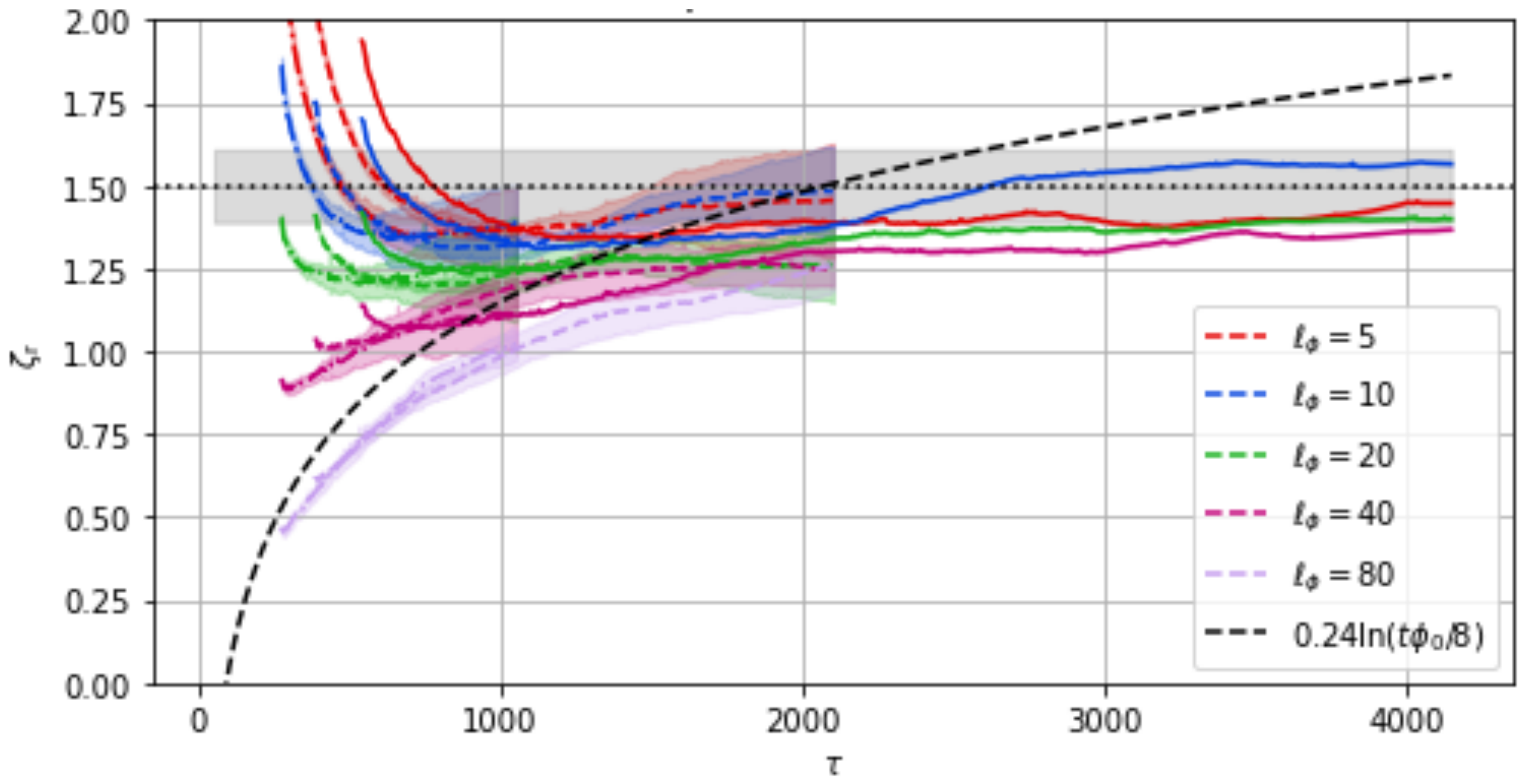


Fig. credit: Buschmann et al.

Favoured mass range:

$m_a \gtrsim 20\,\mu\mathrm{eV}$	Hiramatsu
$m_a = (26.2 \pm 3.4)\,\mu\mathrm{eV}$	Klaer, Moore
$m_a = (25.2\ \pm 11.0)\,\mu\mathrm{eV}$	Buschmann et al.
$m_a = (115 \pm 25)\,\mu\mathrm{eV}$	Kawasaki et al.
$m_a \sim 40\text{–}180\,\mu\mathrm{eV}$	Buschmann et al.



Hindmarsh, Urrestilla et al.

Progress is made, albeit not easily.

Characteristic properties

Axion dark matter is wave-like.

Suppresses structure formation on small scales. Tight constraints on ultralight dark matter from Lyman-α data:

$$m_a \gtrsim 2.5 \cdot 10^{-20}\ \mathrm{eV}$$

Rogers, Peiris

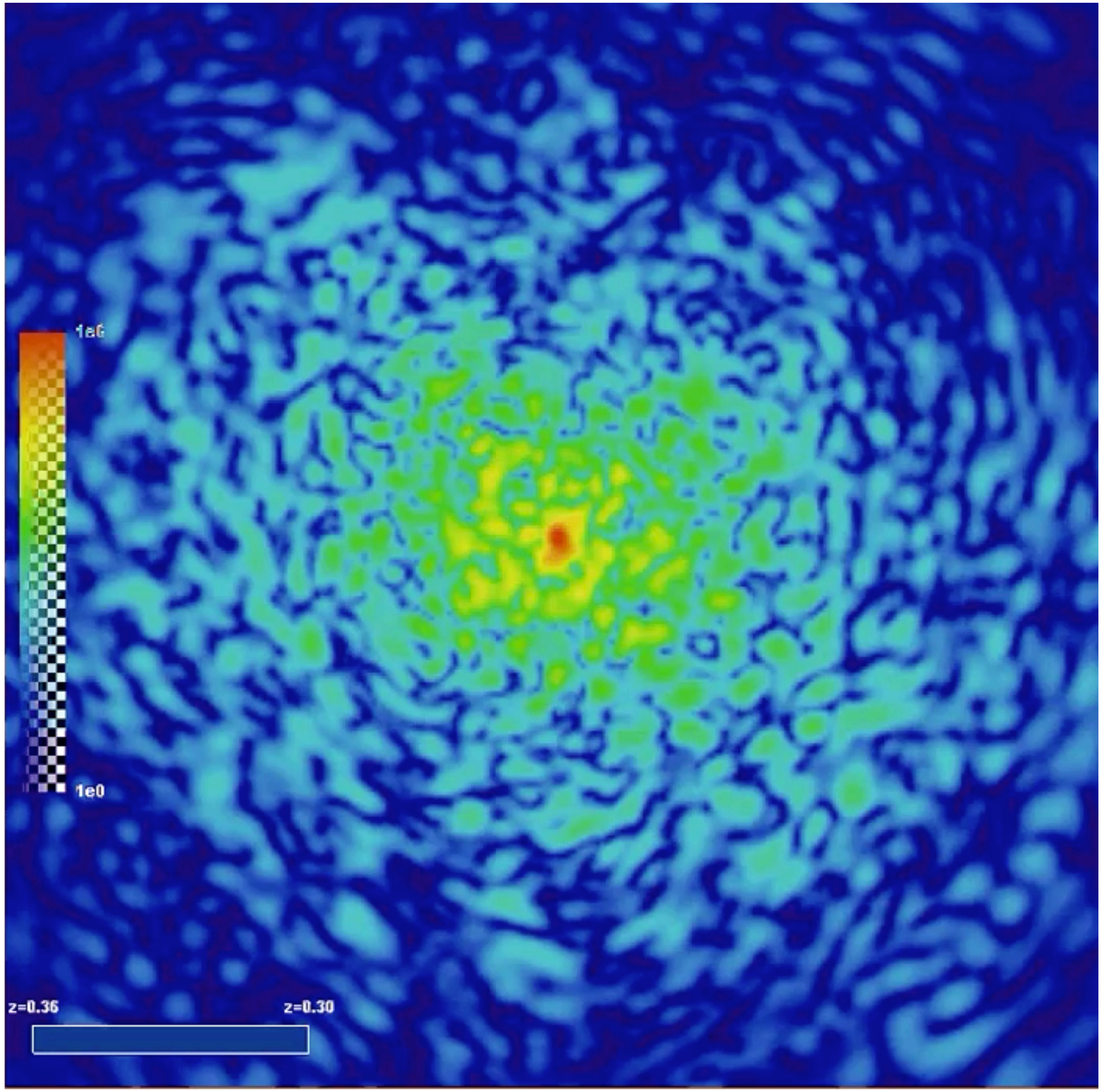
“Solitonic cores”, a.k.a. axion stars, form efficiently inside axion overdensities.

Levkov et al.

Size set by de Broglie wavelength:

$$\lambda_{\mathrm{d}B} = \frac{2\pi}{m_a\, v_{\mathrm{dm}}^2} \sim \frac{8000\,\mathrm{km}}{m_a/\mu\mathrm{eV}}$$

Schive et al.



Axion stars

Classical solution, balancing self-gravity with gradient energy (“quantum pressure”). Heuristically, minimise:

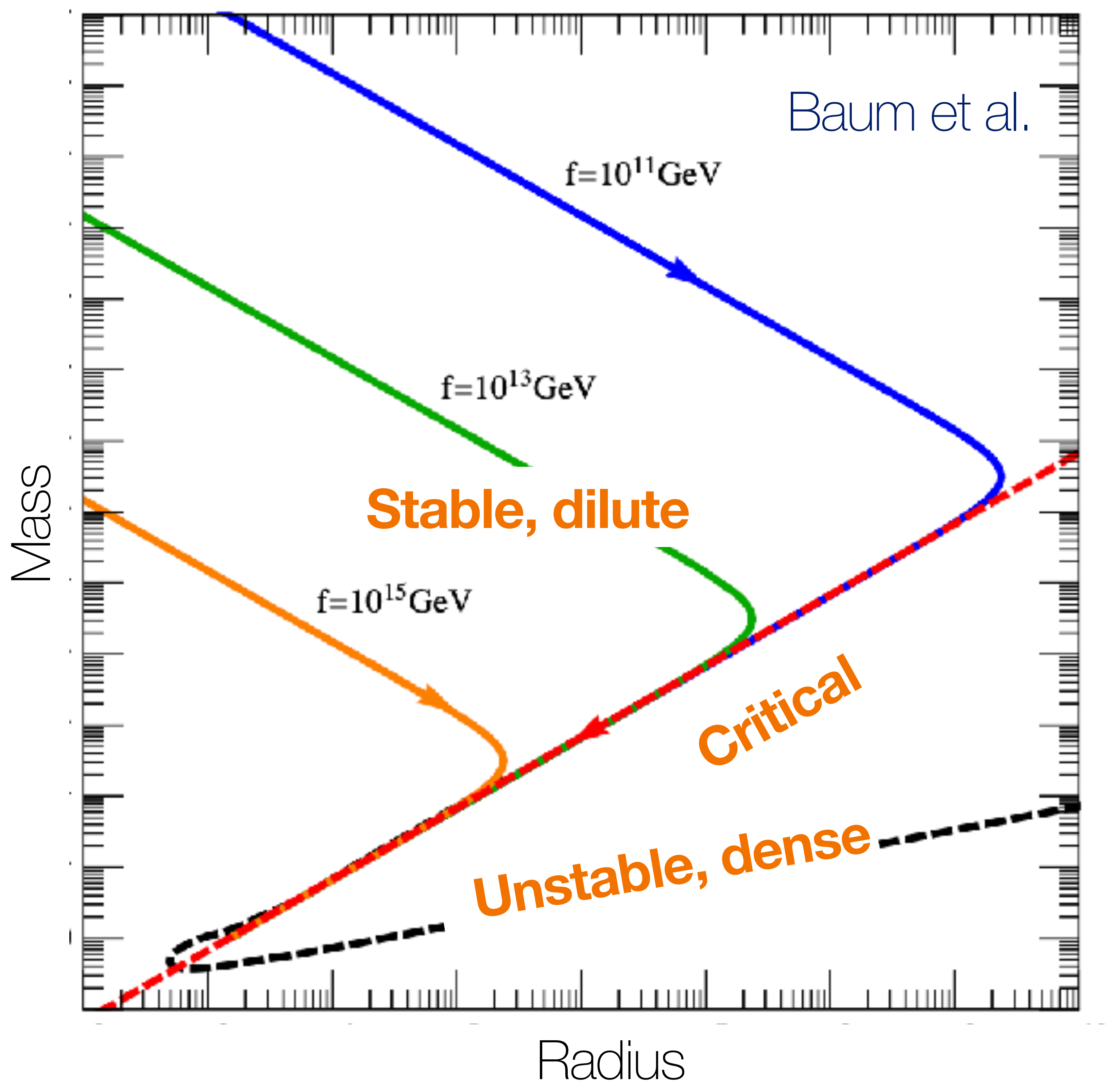
$$U \sim -\frac{GM^2}{R} + \int \mathrm{d}^3x \frac{1}{2}(\nabla a)^2 + \ldots \quad = -\frac{GM^2}{R} + \alpha_k \frac{|a_0|^2 R^3}{2R^2} + \ldots$$

Stable branch of **dilute solutions**:

$$N = \frac{f_a M_{\rm Pl}}{m_a^2}\tilde{N} \qquad M = \frac{f_a M_{\rm Pl}}{m_a}\tilde{N} \qquad R = \frac{\alpha_k}{m_a}\left(\frac{M_{\rm Pl}}{f_a}\right)\frac{1}{\tilde{N}}$$

Densest configurations held together by self-gravity.

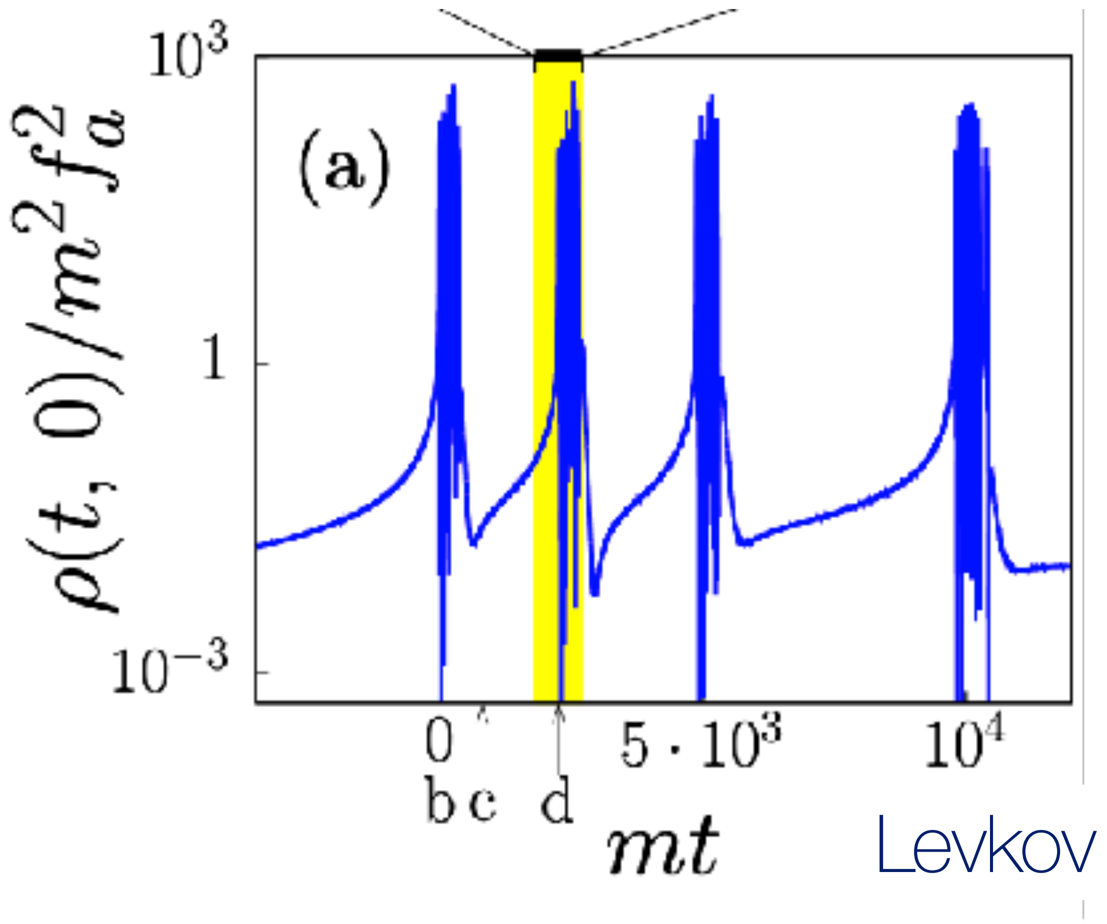
$$M_{\rm max} \simeq 7.0 \times 10^{-12}\, M_\odot \left(\frac{f_a}{6 \times 10^{11}\ \mathrm{GeV}}\right)\left(\frac{10\,\mu\mathrm{eV}}{m_a}\right)$$



Axion star collapse

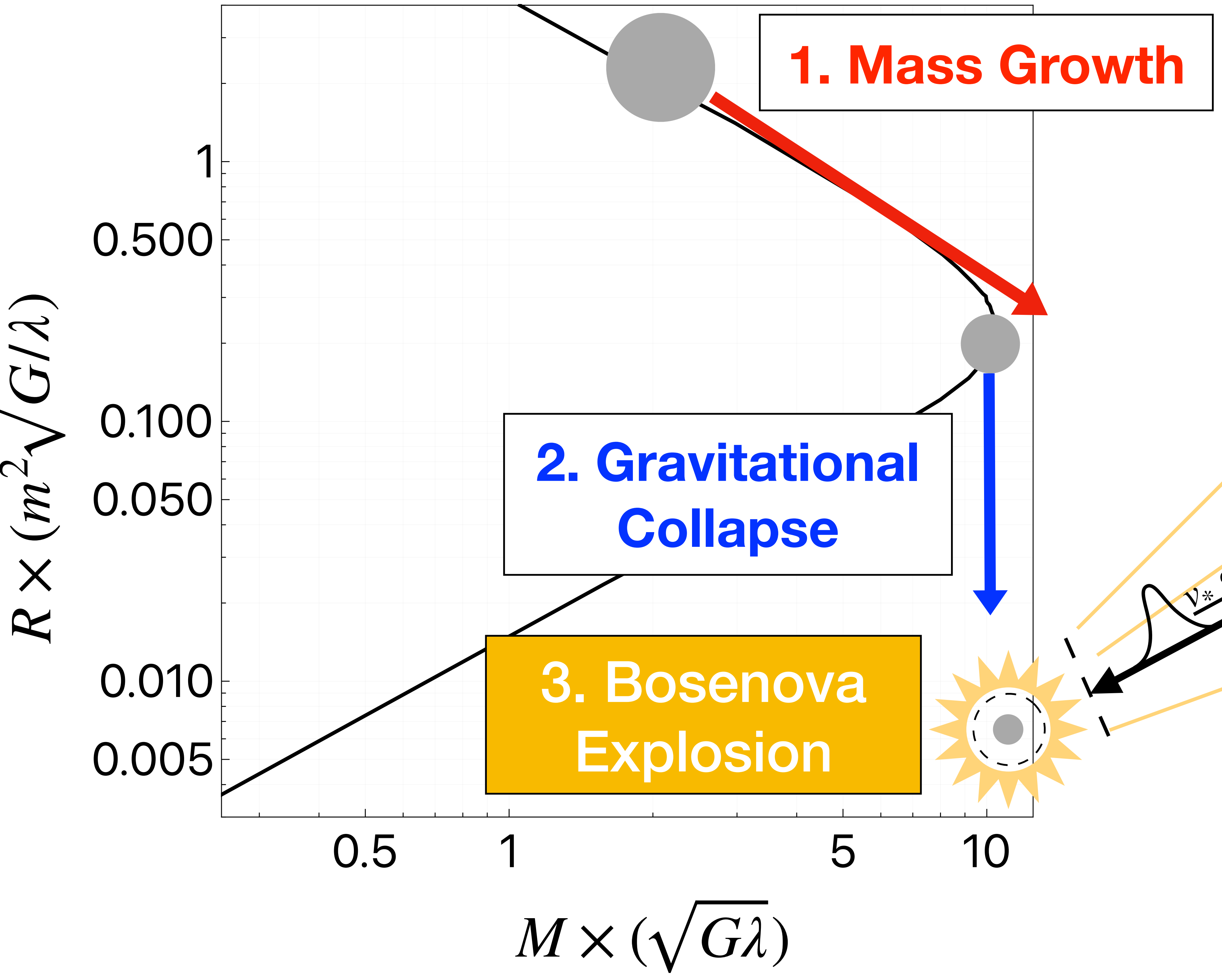
Too massive axion stars explode in a “bosenova”, emitting relativistic axions.

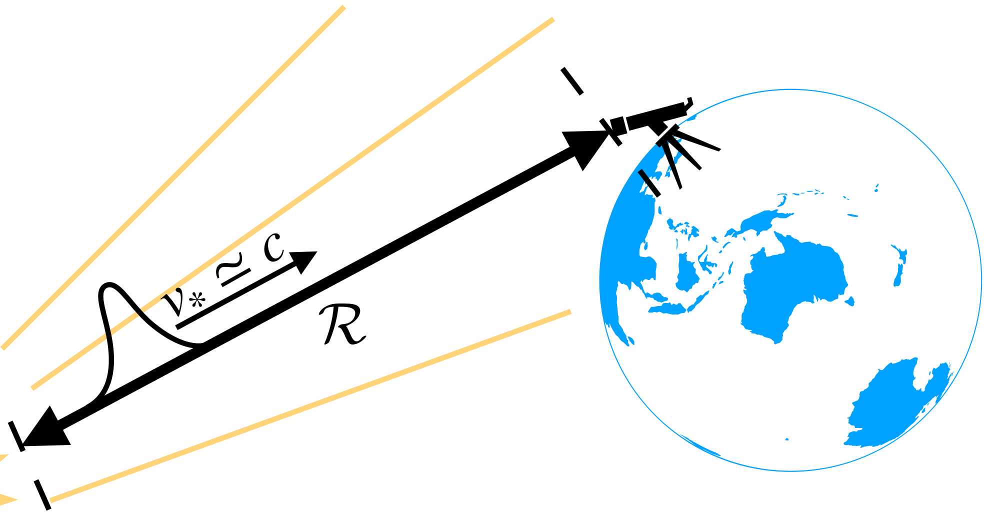
Eby et al.

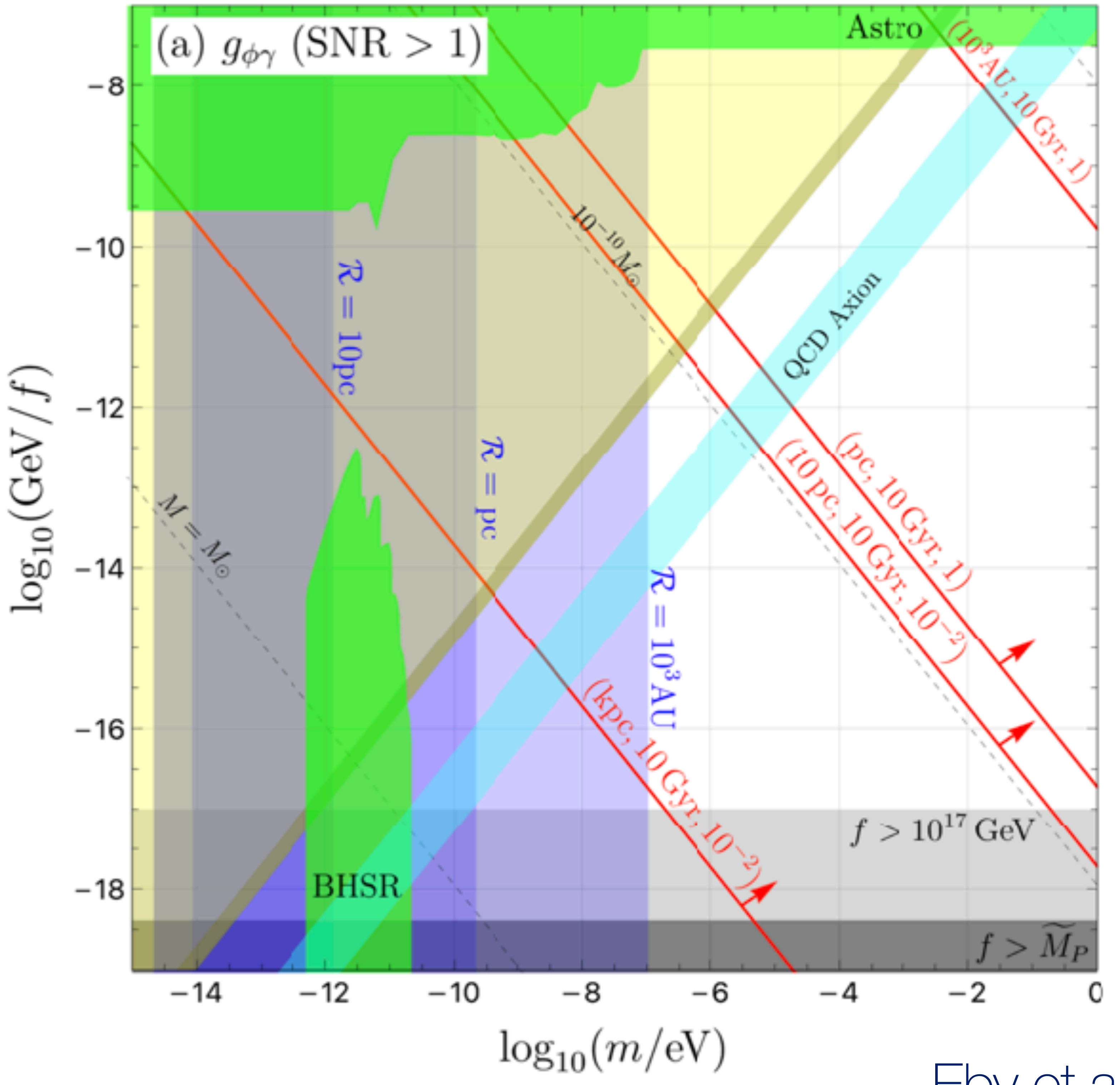


Levkov et al.

Fig. credit: Eby







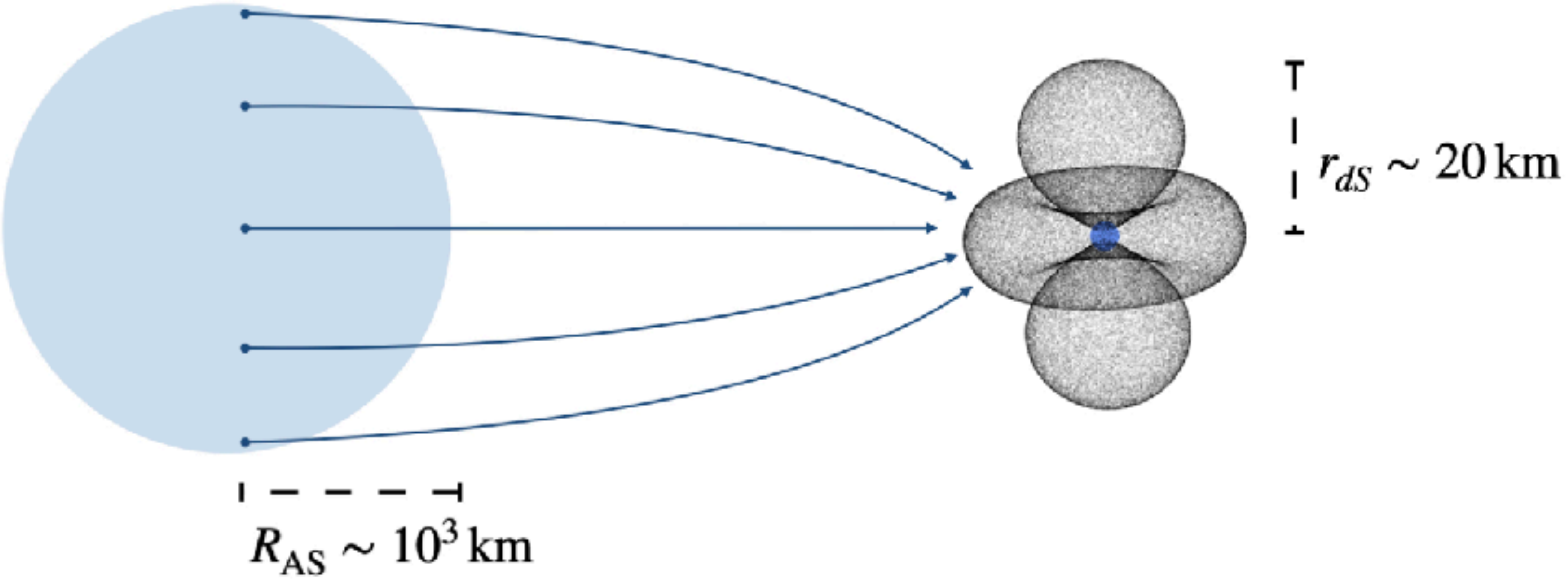
Eby et al.

Axion star collisions with neutron stars

Axion star

Macroscopic number of axions

Extremely coherent



Neutron star

strong magnetic fields (~10^{14} Gauss)

suitable plasma density

Axion-photon level-crossing (resonant conversion) near the star is possible.
Smoking gun radio signals from μeV - meV axions?

Complications:

Axions star *stream* past neutron star.

Standard mixing formalism breaks down due to anisotropy. Millar et al.

Photon propagation in plasma non-trivial. Witte et al.

Anisotropic mixing

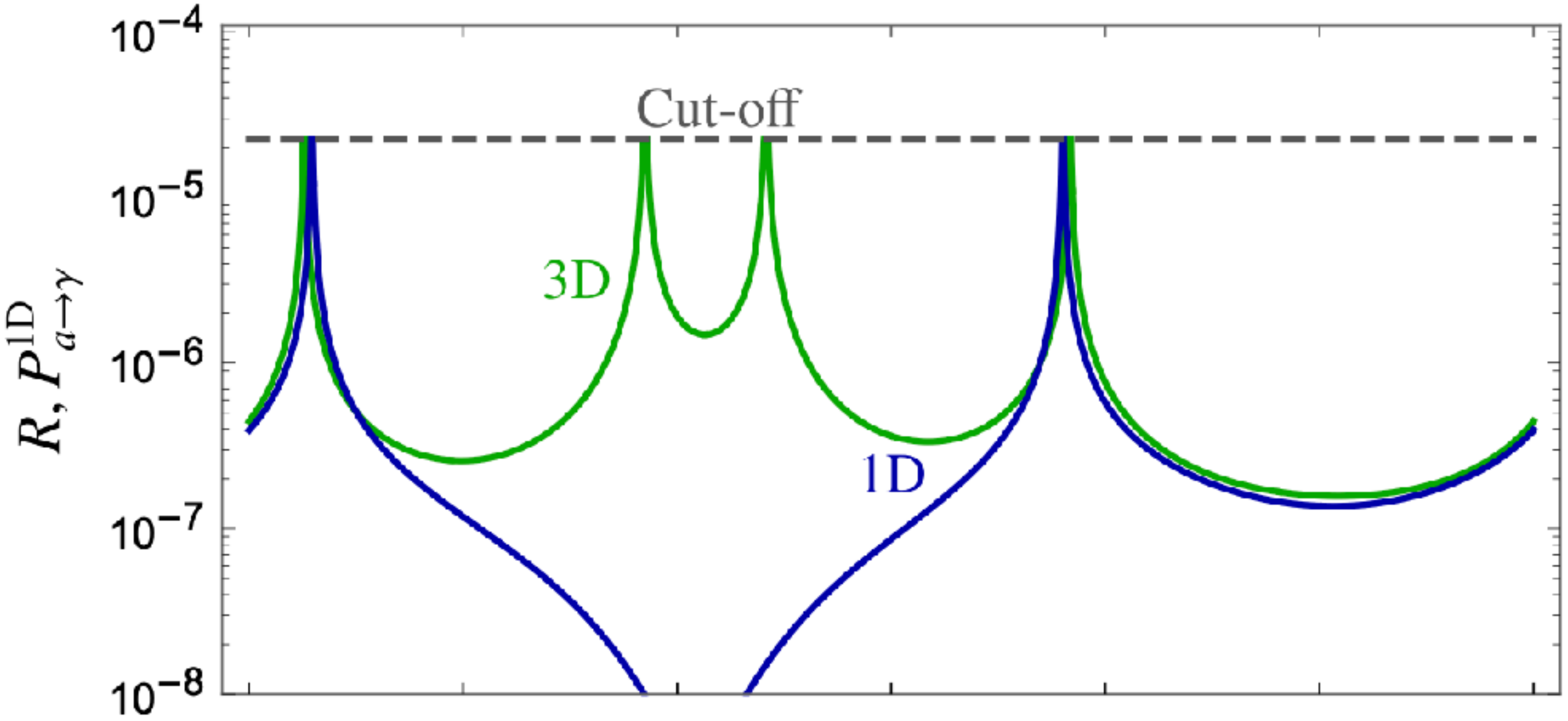
$$\frac{\partial^2 E_y}{\partial z \partial y} \simeq \left(\omega^2 - \omega_p^2 \cos^2\theta\right) E_z + \omega_p^2 \cos\theta \sin\theta E_y + \omega^2 g_{a\gamma} a B_{\rm NS} \cos\theta$$

$\uparrow$

Previously neglected.

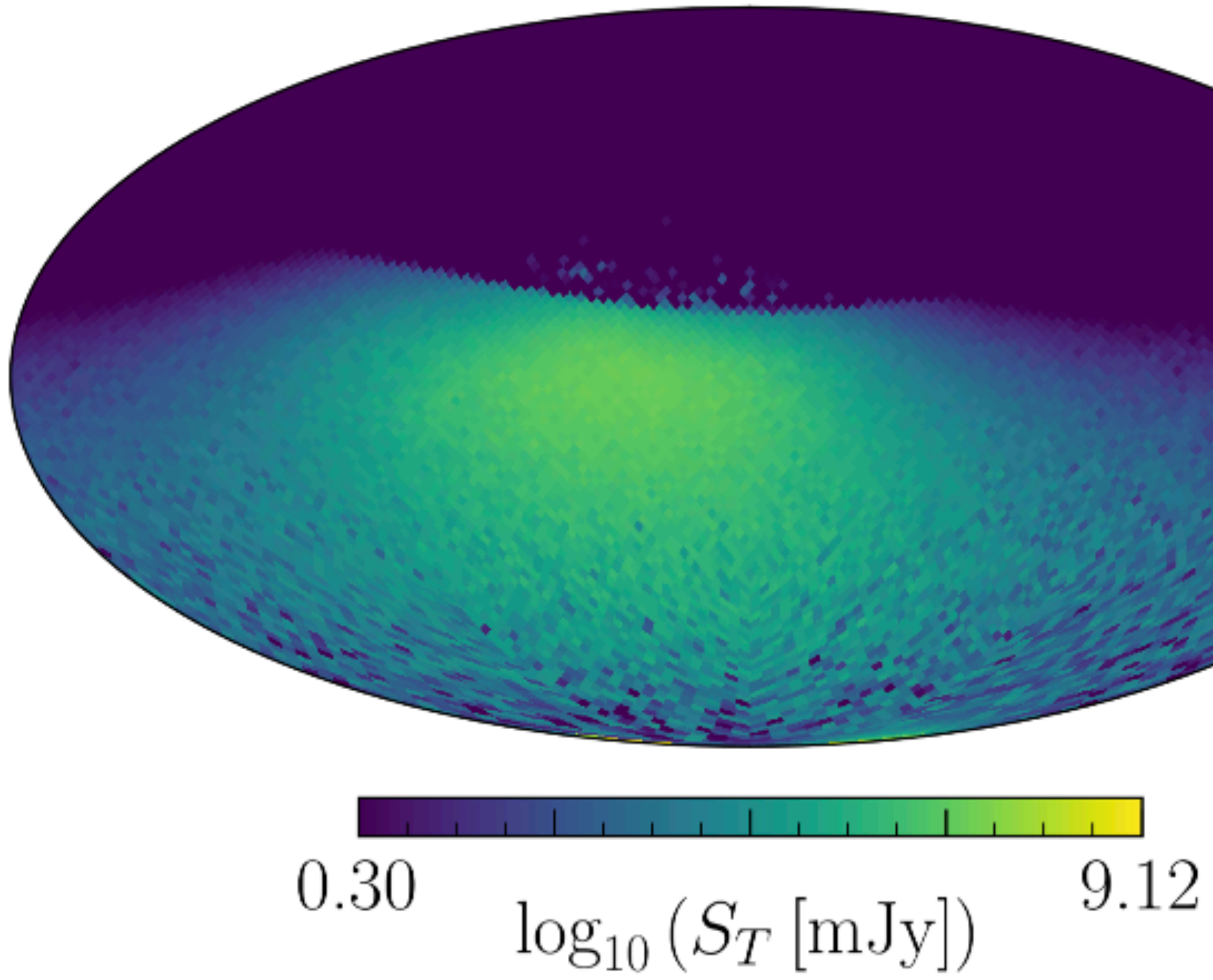
Direction of evolution of Langmuir O-mode different from incoming axion.

Significant impact on “conversion probability”.

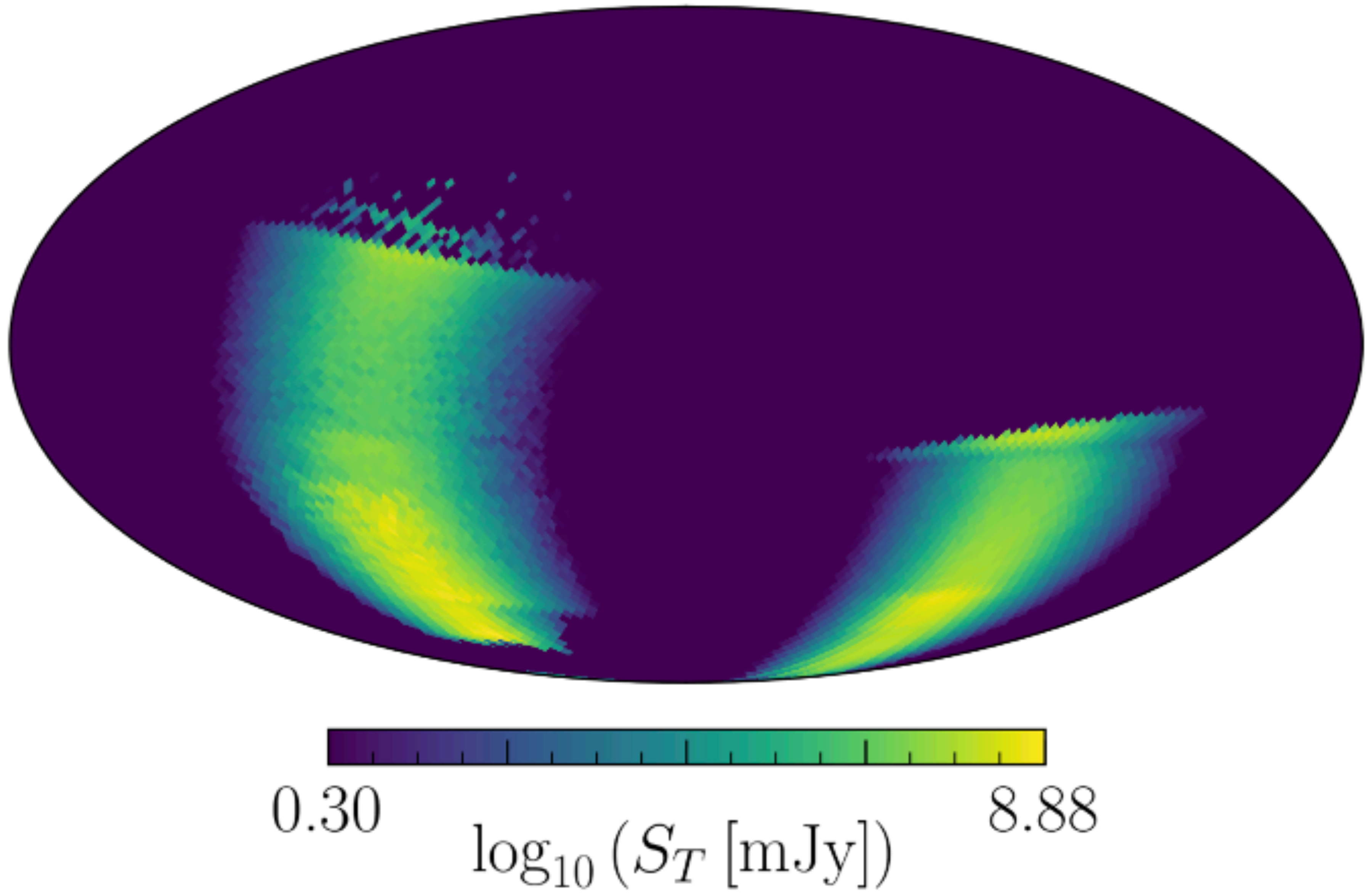


Transient radio signals

Head-on



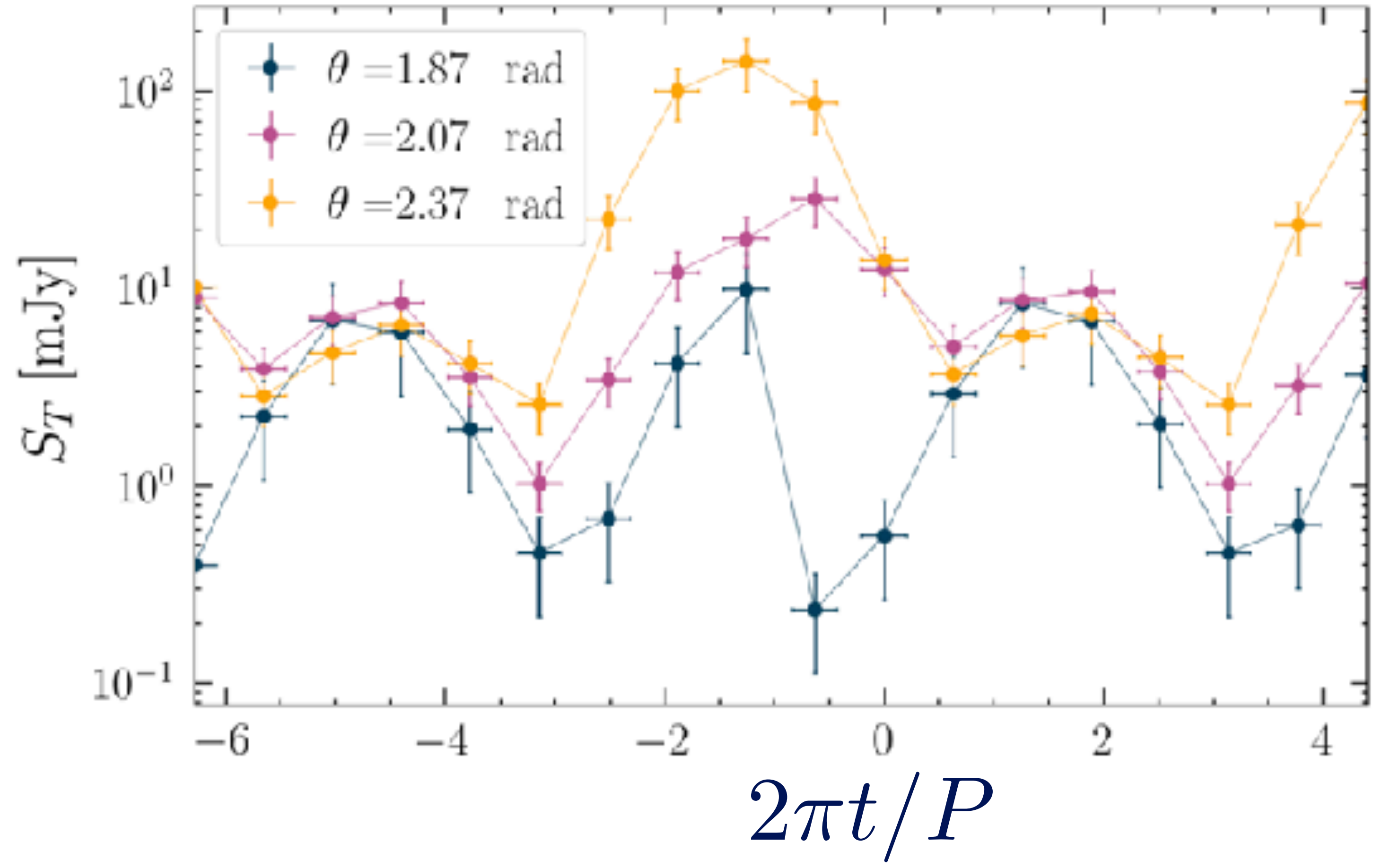
Non-zero impact parameter



Line width: $10^{-8} - 10^{-3}$

Duration: substantial sub-second variations

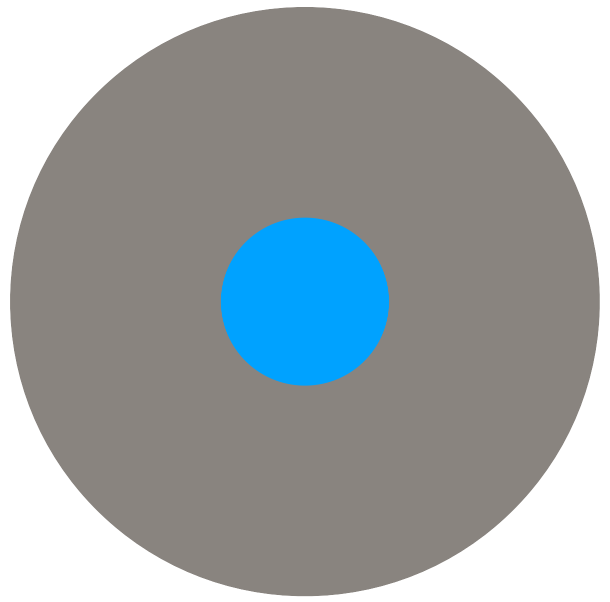
Observational strategy depends on axion star distribution in the galaxy (still poorly known).



Axion gravitational atoms

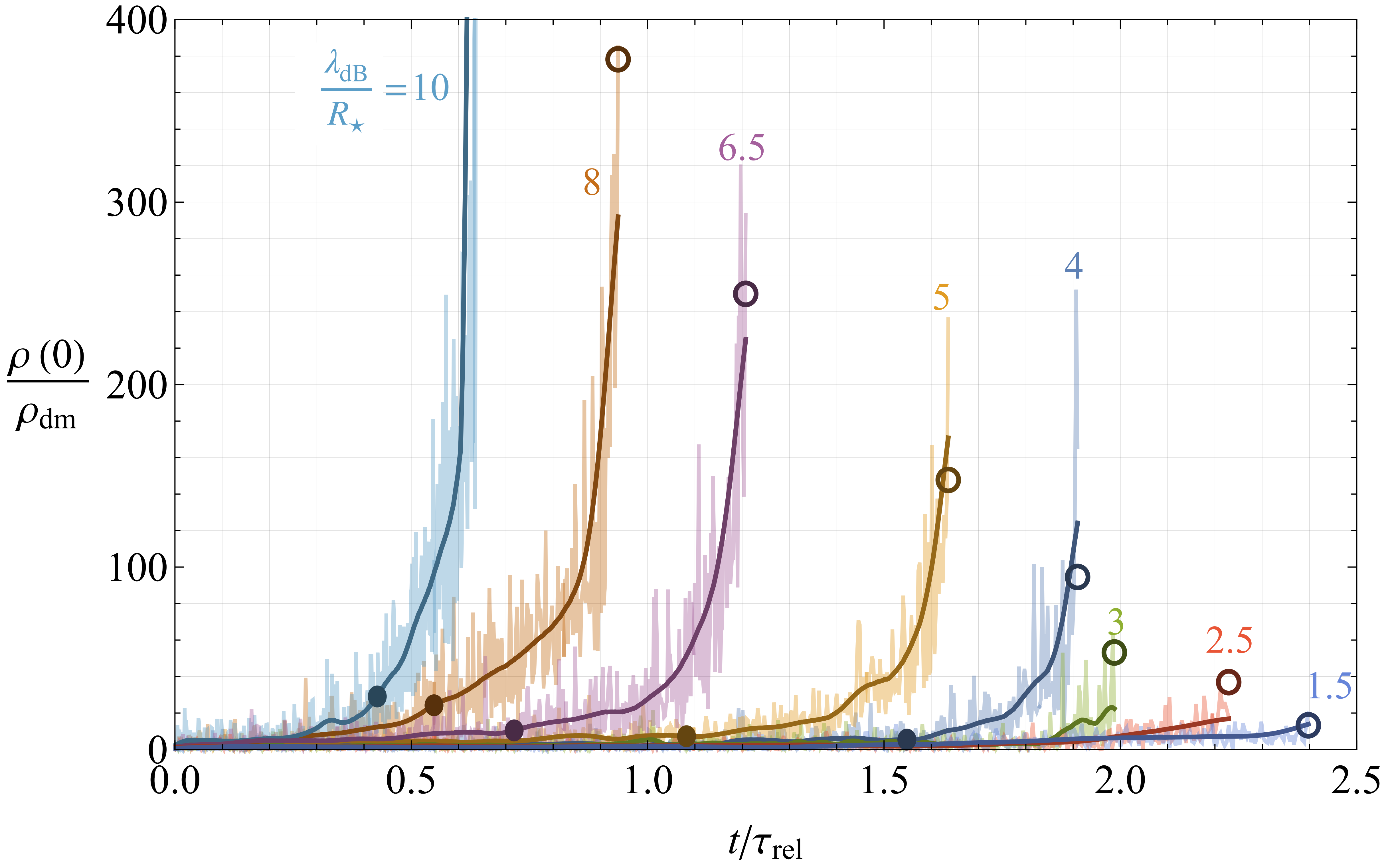
Localised axion clumps can form around astrophysical objects.

Eby et al.
cf. also Sloth et al.



Gravitational Atom

$$\tau_{\rm rel} = \frac{64 m_\phi^7 v_{\rm dm}^2}{\lambda^2 \rho_{\rm dm}^2} \simeq 9\,{\rm Gyr}\left(\frac{f_a}{10^8\,{\rm GeV}}\right)^4 \left(\frac{m_\phi}{10^{-14}\,{\rm eV}}\right)^3 \left(\frac{0.4\,{\rm GeV/cm^3}}{\rho_{\rm dm}}\right)^2 \left(\frac{v_{\rm dm}}{240\,{\rm km/sec}}\right)^2$$



Formation can be sufficiently fast for e.g. the sun.

A range of probes possible.

Axions from astrophysical explosions

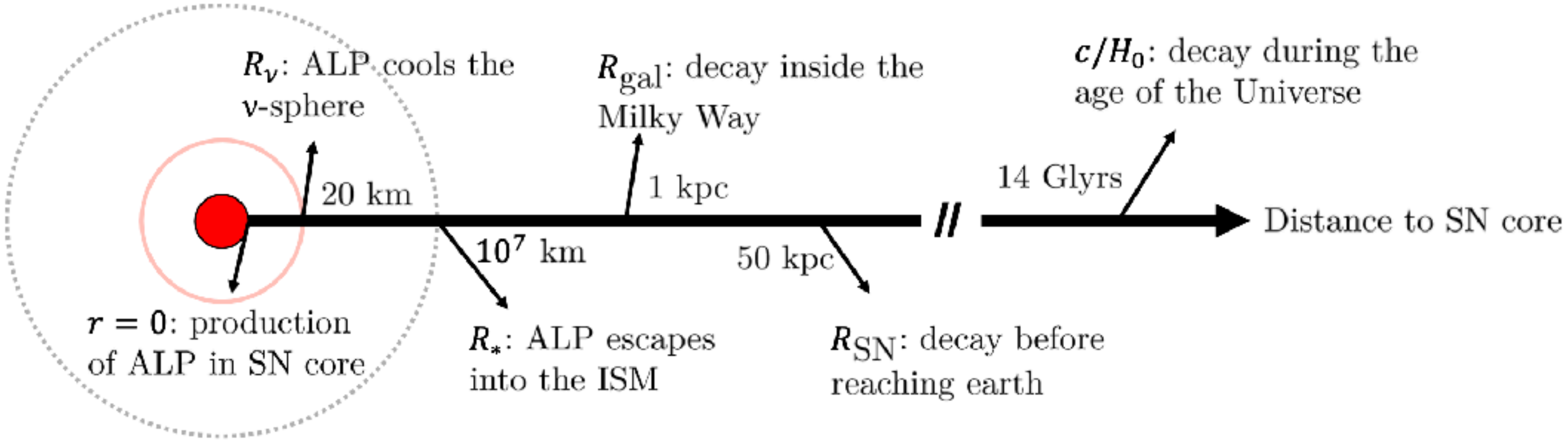
Axion astroparticle physics is undergoing a renaissance.

What types of astrophysical process could provide compelling hints for ALPs?

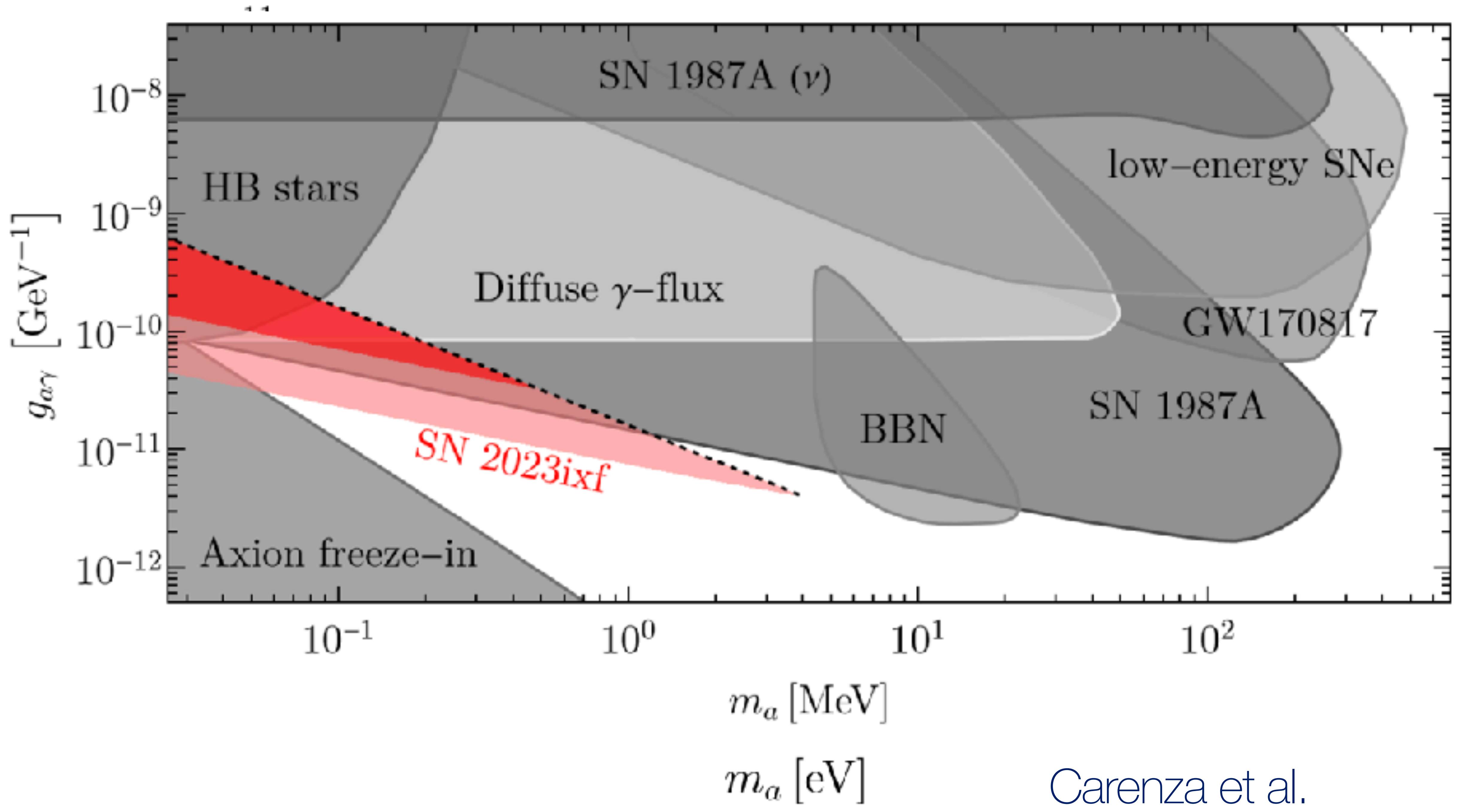
1. Nearby supernovae
2. Gamma-ray bursts: the BOAT
3. ….


SN 1987A
X-ray/Optical

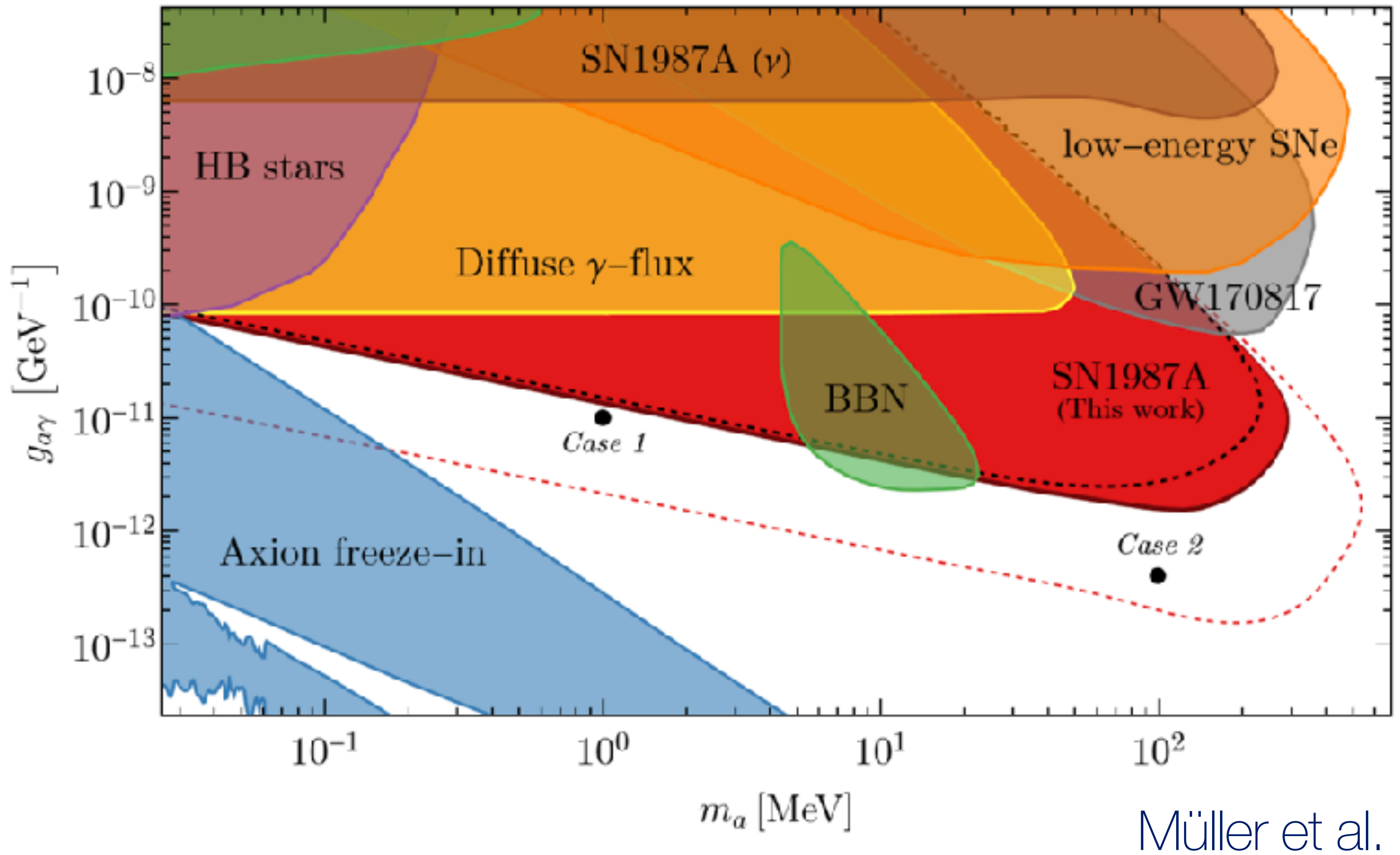
Axions from supernovae



From thesis of Eike Ravensburg (Müller)



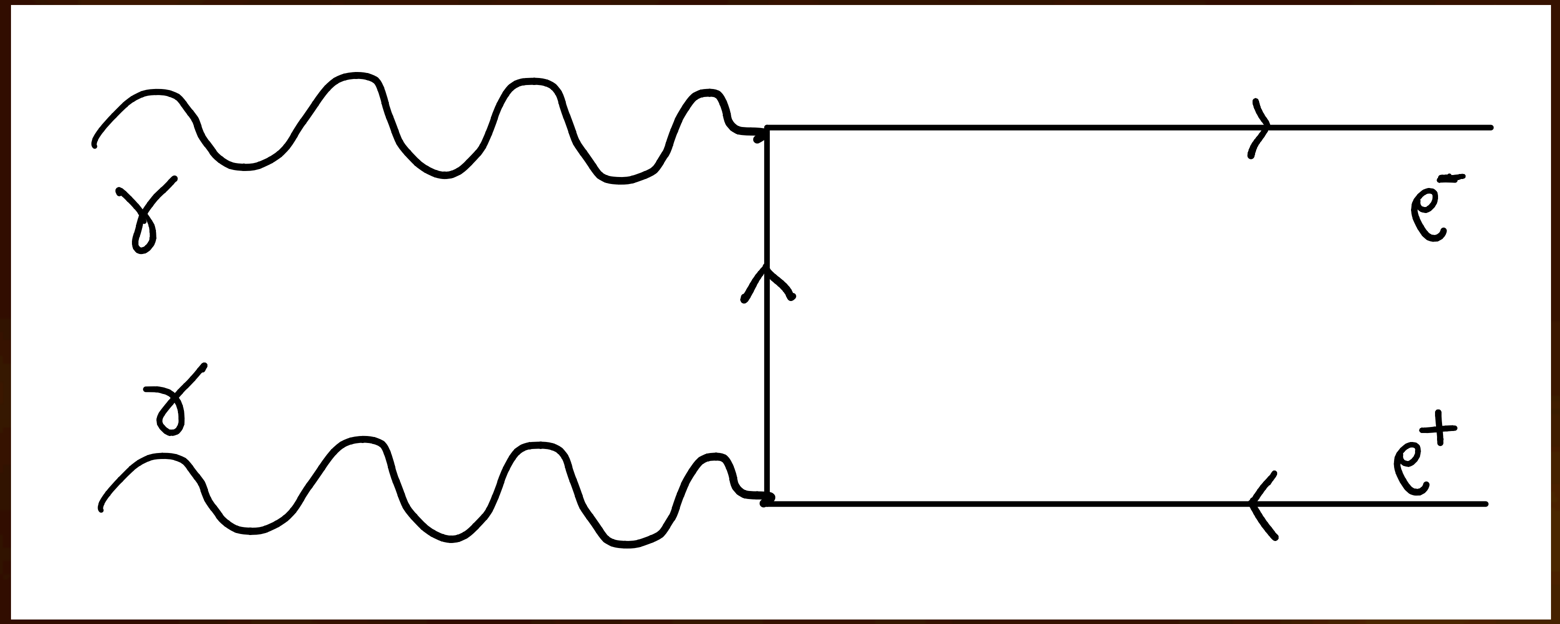
Carenza et al.



Müller et al.

The BOAT

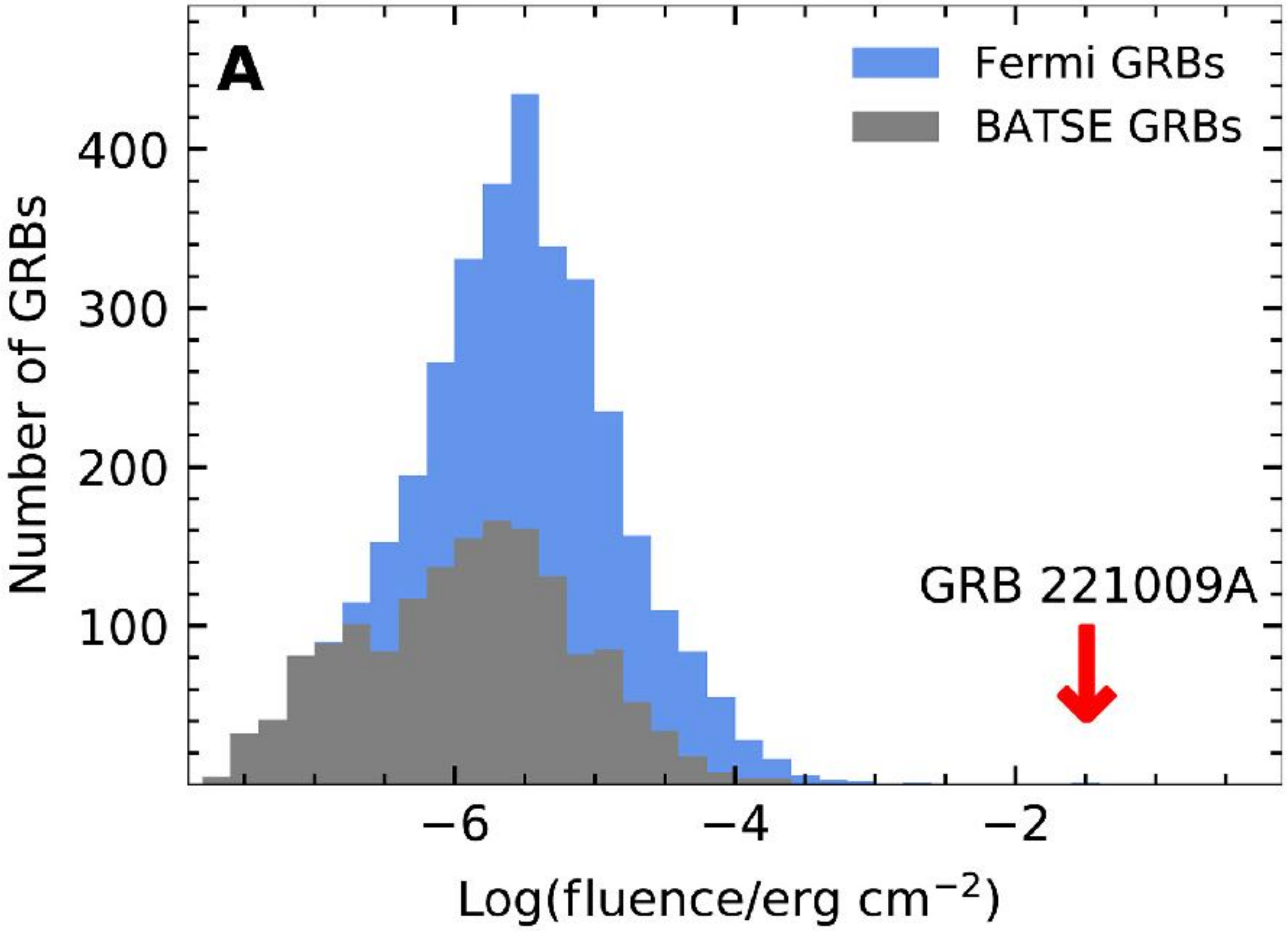
Gamma-ray bursts



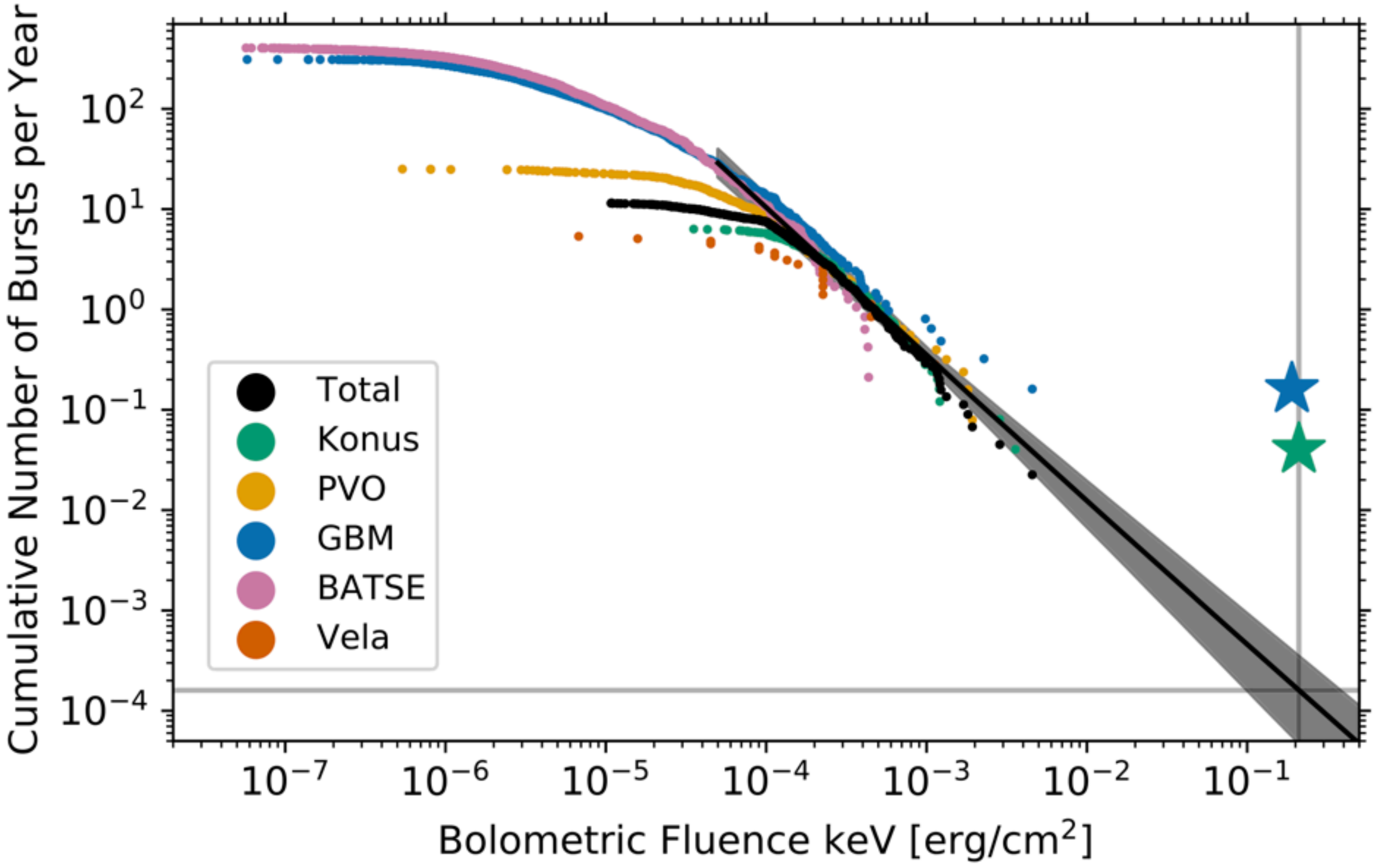
Credit: NASA's Goddard Space Flight Center

Once in a civilisation …

[O’Connor et al., 2023]



[Burns et al., 2023]



TeV detections

Since 2019, a handful of GRBs have been detected at TeV energies.

[Mirzoyan 2019]

LHAASO circular:

Detection with WCDA; "100σ".

Detection with air shower detector KM2A; "10σ".

More than 5000 photons above 500 GeV
Highest photon energy: 18 TeV (KM2A)

[Huang et al. (LHAASO), GCN, 2022]

Carpet-2 circular:

Air shower consistent with being caused by a photon of 251 TeV energy (t_0 +4536s)

Naive statistical significance 3.8σ

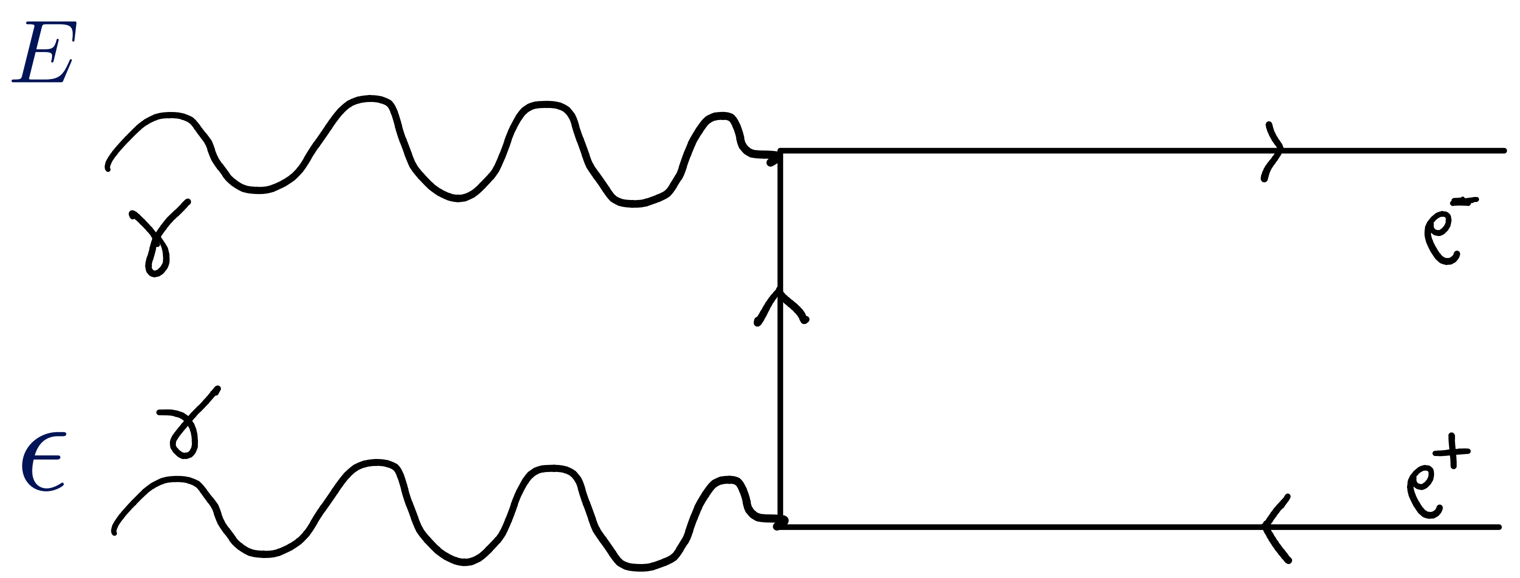
[Dzhappuev et al. (Carpet-2), 2022]

However, two candidate galactic sources relatively close.

A rare opportunity

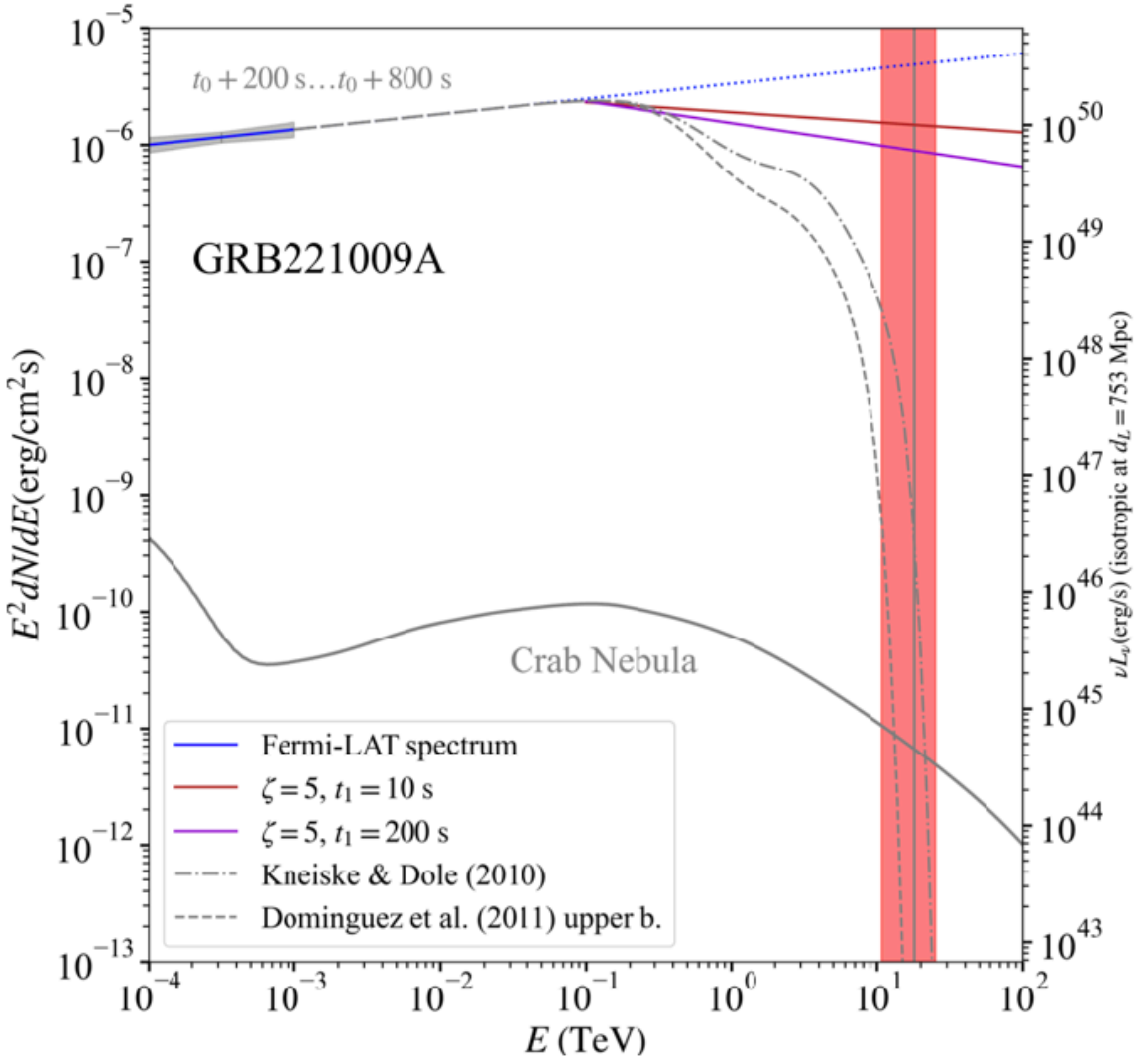
Could this be a Standard-Model-breaking event?

At TeV energies, photons shouldn't be able to propagate very far due to the Breit-Wheeler effect:



$$E\epsilon \geq \frac{2m_e^2}{1-\cos\theta}$$

$$\tau(E) = \int dz\, \frac{d\ell}{dz} \int_{-1}^{+1} dx\, \frac{1-x}{2} \int d\epsilon\, n_{\mathrm{EBL}}\sigma(E,\epsilon,x)$$



Baktash, Horns, Meyer

A strong hint?

Quickly after GRB 221009A, a few groups sought to explain the VHE events through ALPs by calculating photon survival probability in models of the astrophysical magnetic fields.

Claim: ALPs can explain *both* the LHAASO events and the Carpet-2 event.

[Galanti, Roncadelli, Tavecchio, 2022]
[Troitsky, 2022]

“ALPs strongly suggested” and may be the dark matter.

[Galanti, Roncadelli, Tavecchio, 2022]

Parameter space:

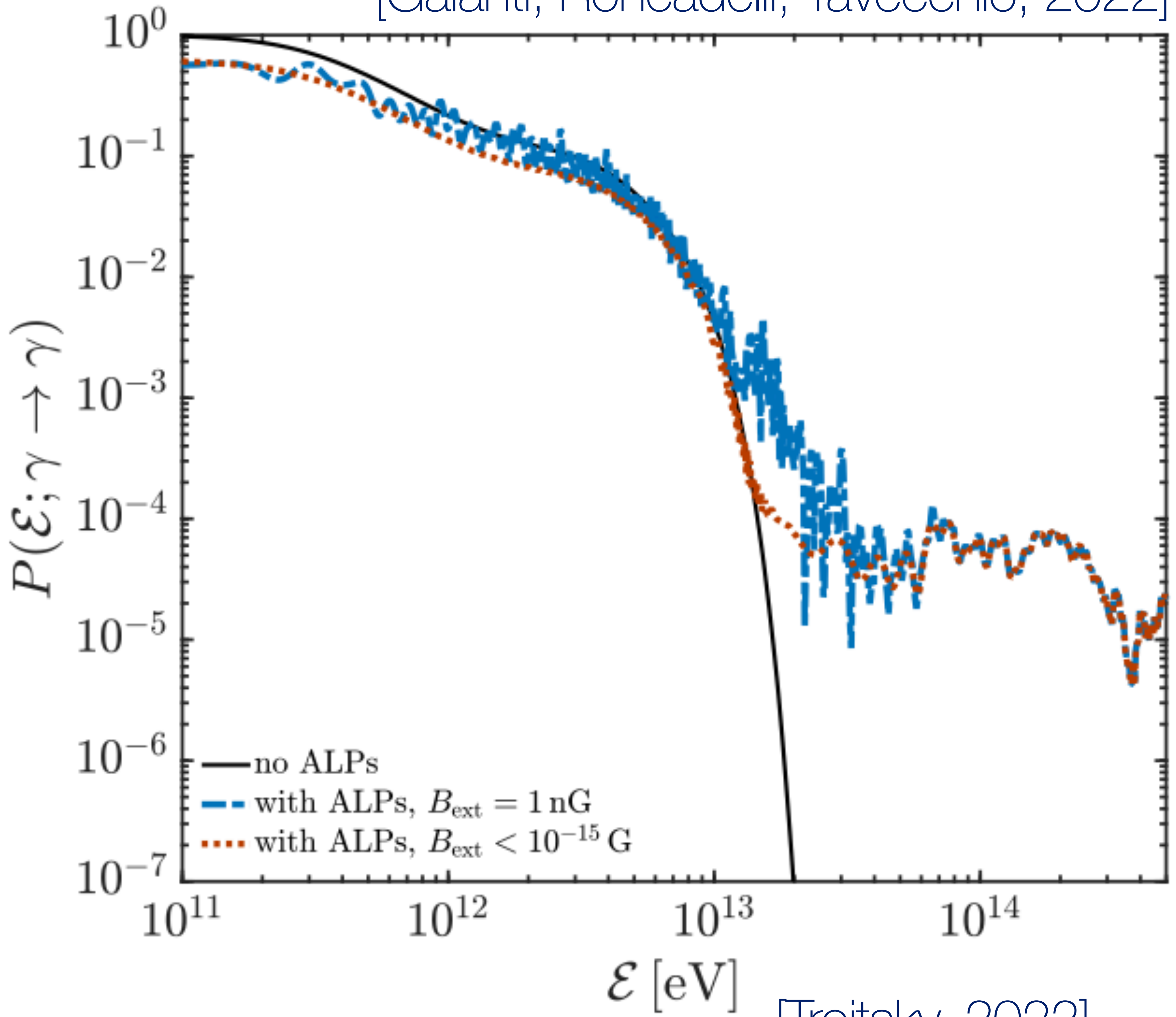
$$g_{a\gamma} \approx 5 \cdot 10^{-12}\,\mathrm{GeV}^{-1} \quad \text{and} \quad m_a \approx 10^{-10}\,\mathrm{eV}\,.$$

[Galanti, Roncadelli, Tavecchio, 2022]

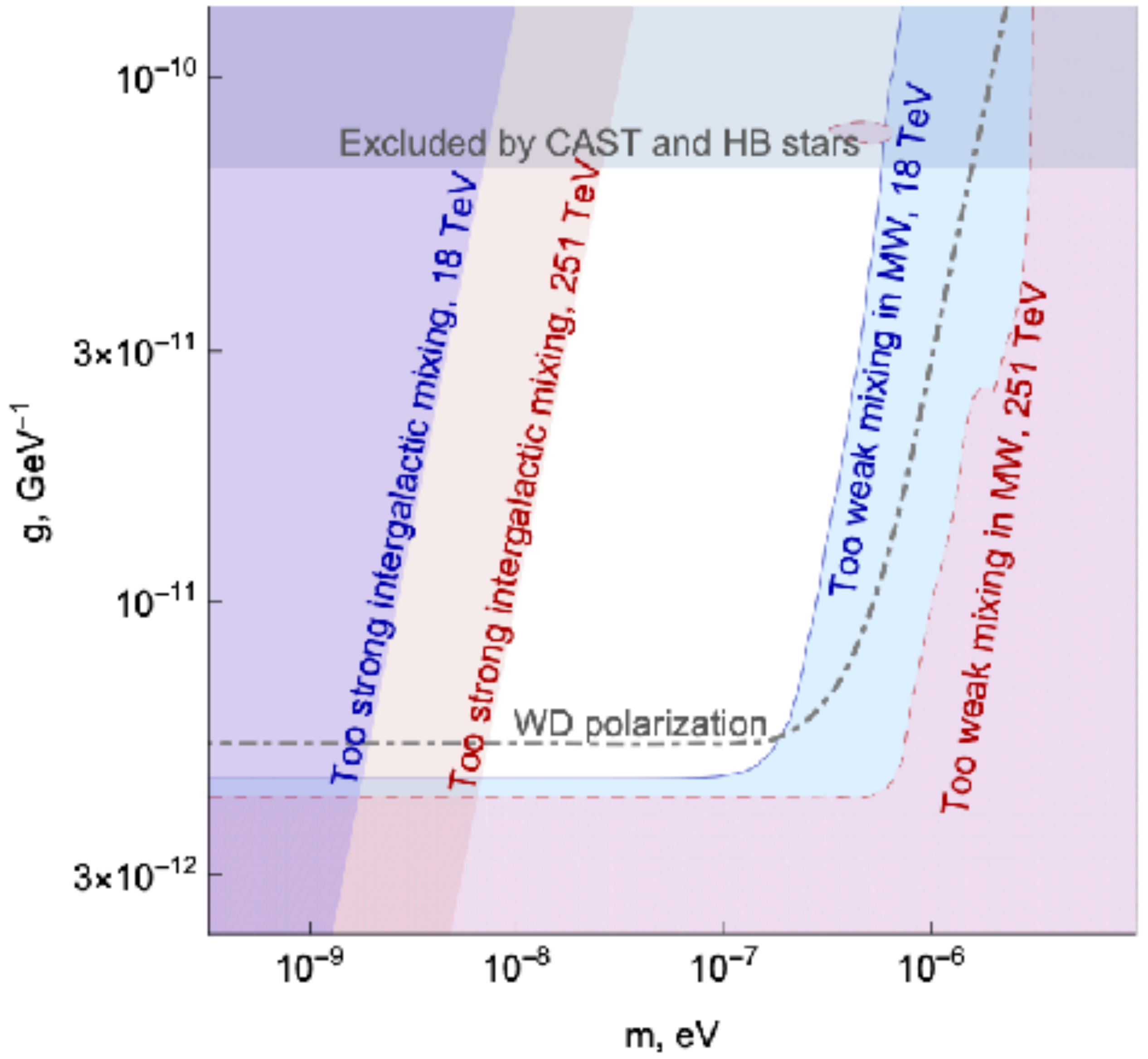
$$g_{a\gamma} \gtrsim 5 \cdot 10^{-12}\,\mathrm{GeV}^{-1} \quad \text{and} \quad 10^{-8}\,\mathrm{eV} \lesssim m_a \lesssim 5 \cdot 10^{-7}\,\mathrm{eV}\,.$$

[Troitsky, 2022]

[Galanti, Roncadelli, Tavecchio, 2022]

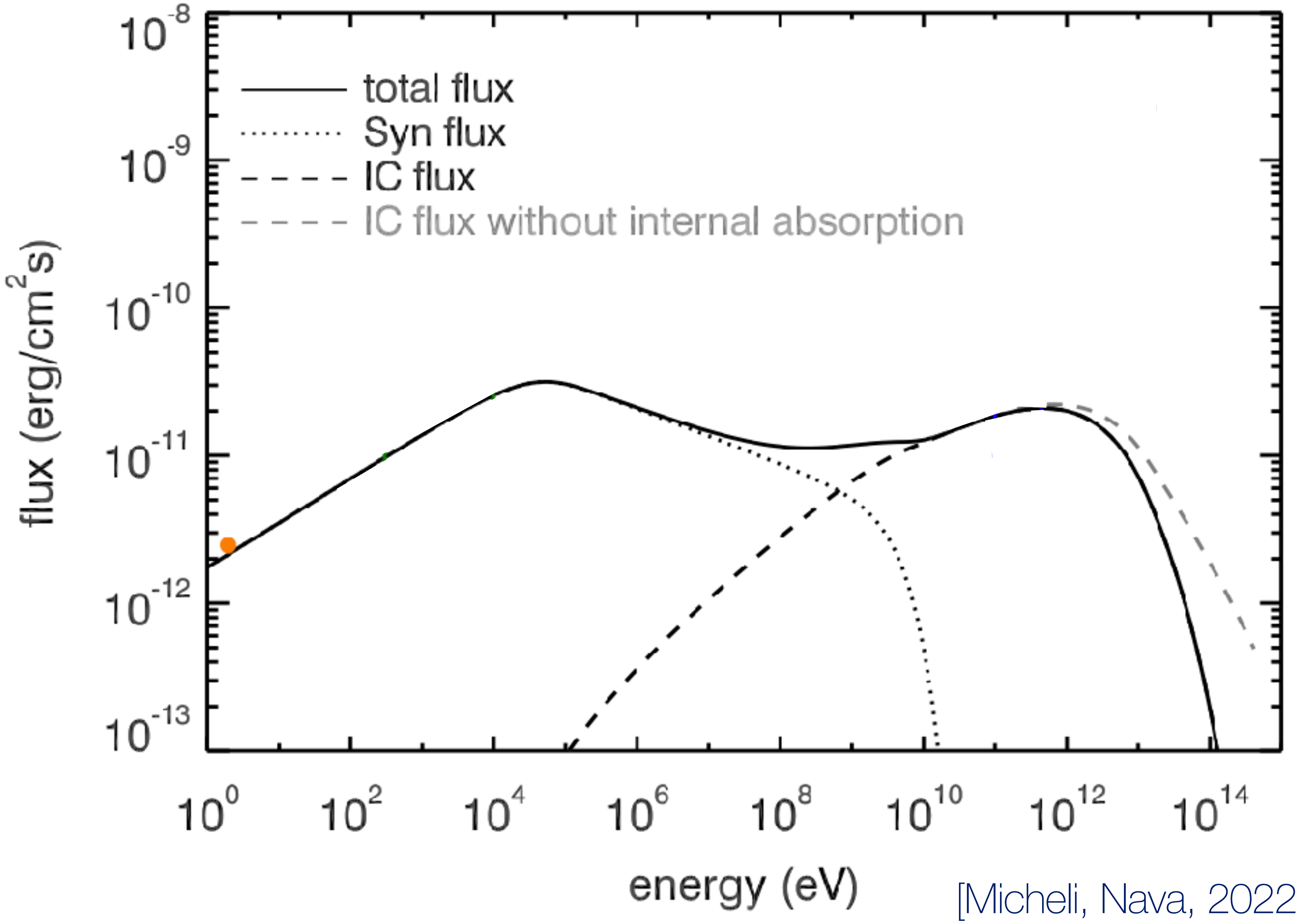


[Troitsky, 2022]



Main problem with ALP explanation

Schematic afterglow spectrum



[Micheli, Nava, 2022]

Problem for ALPs: diving VHE spectra

Moderate energies:
synchrotron

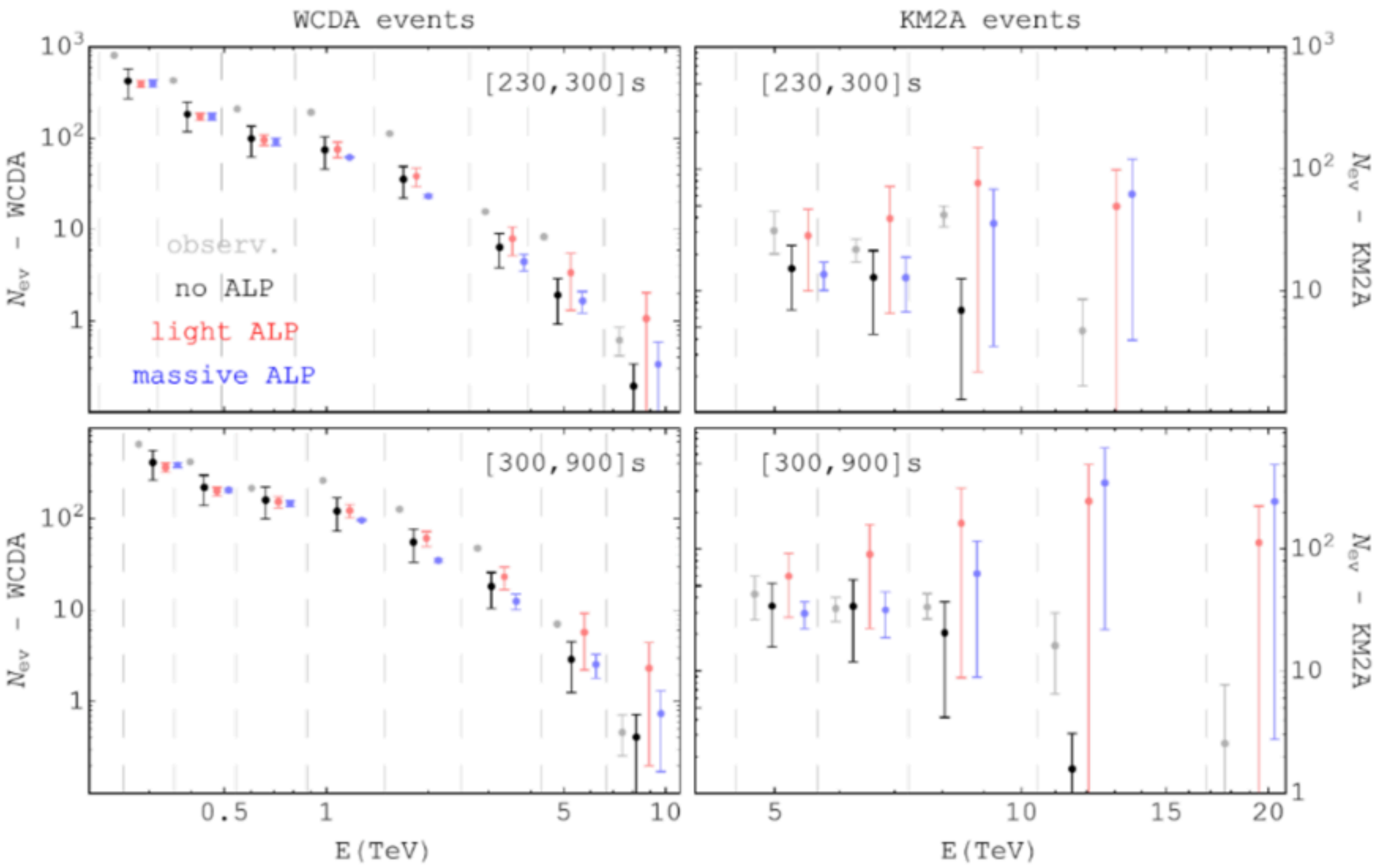
Higher energies:
synchrotron-self-Compton,
(*and/or* proton synchrotron).

Suppressed intrinsic flux beyond IC peak.

LHAASO:
SSC explains data well;
inverse Compton peak at < 300 GeV.

What ALPs can and can’t do

Can help explain photons in the 10-20 TeV range

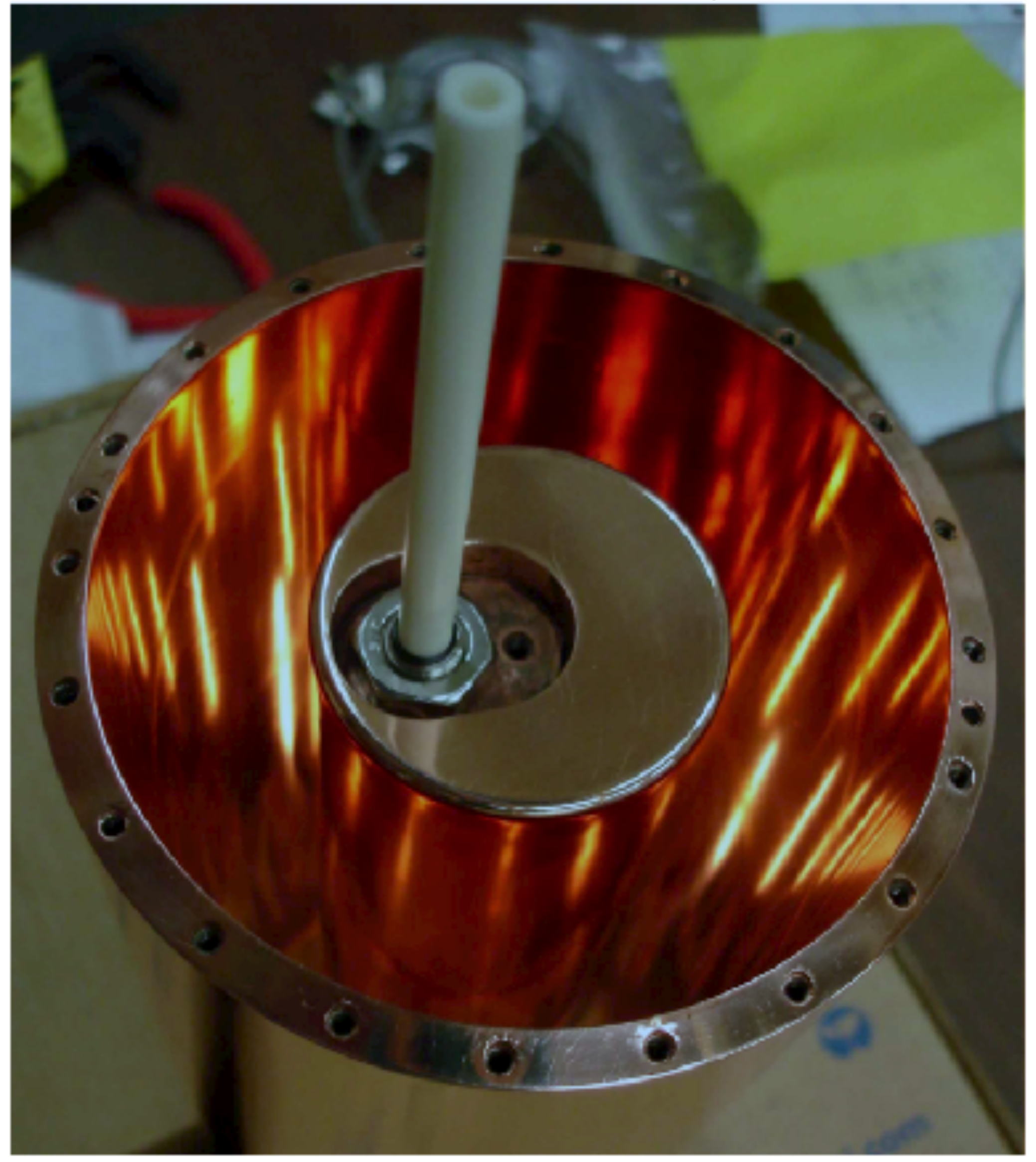


Probability of observing photon at 251 TeV in Carpet-2: $P \lesssim 10^{-4}$

New experimental ideas

Conserving energy & momentum in axion-photon conversion

Traditionally:



$$h\nu_{\text{cav}} = m_a c^2$$

[ADMX]

New idea:
Metamaterials

$$m_{\text{eff},\gamma} \to m_a$$

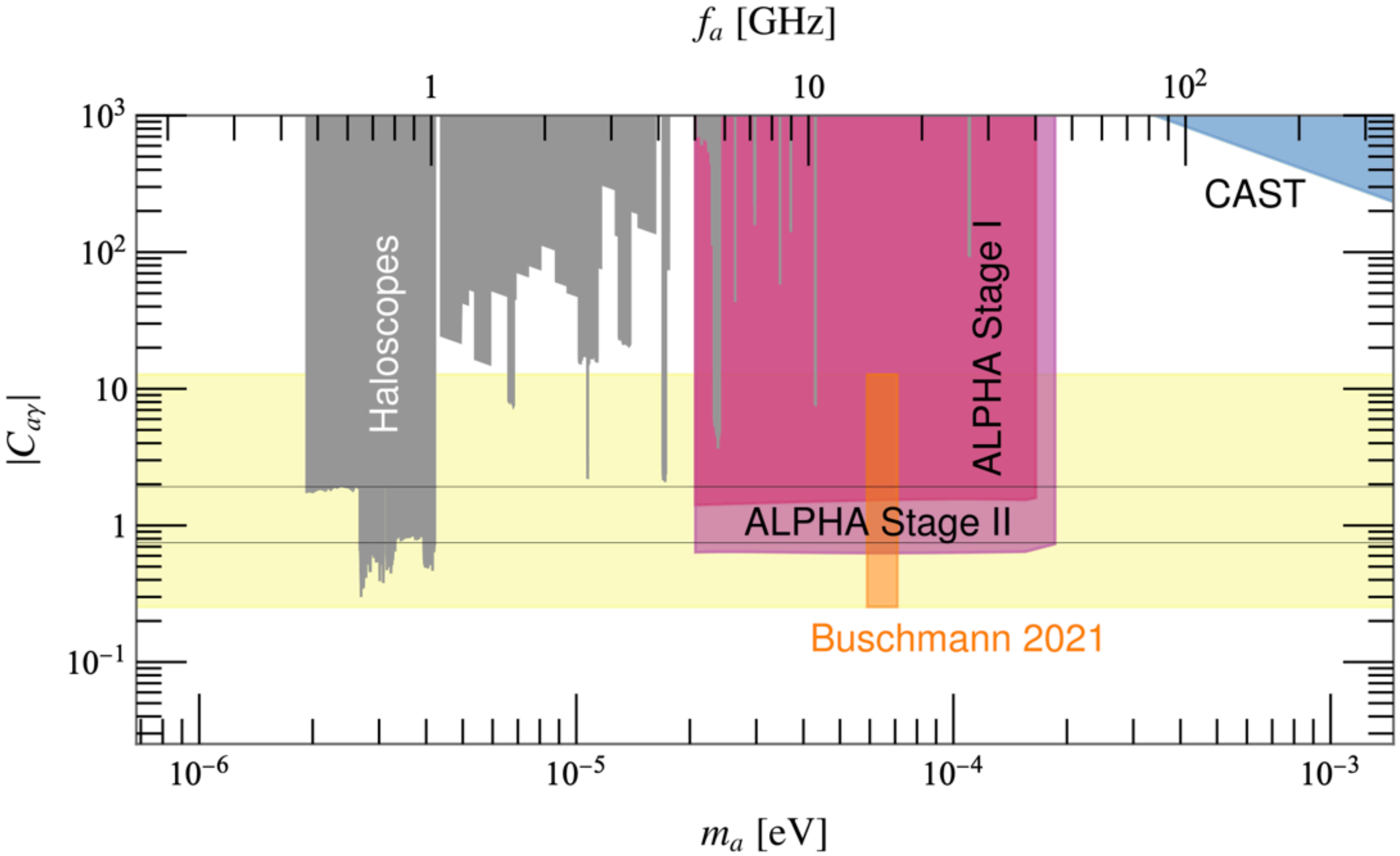
Realisable at low T

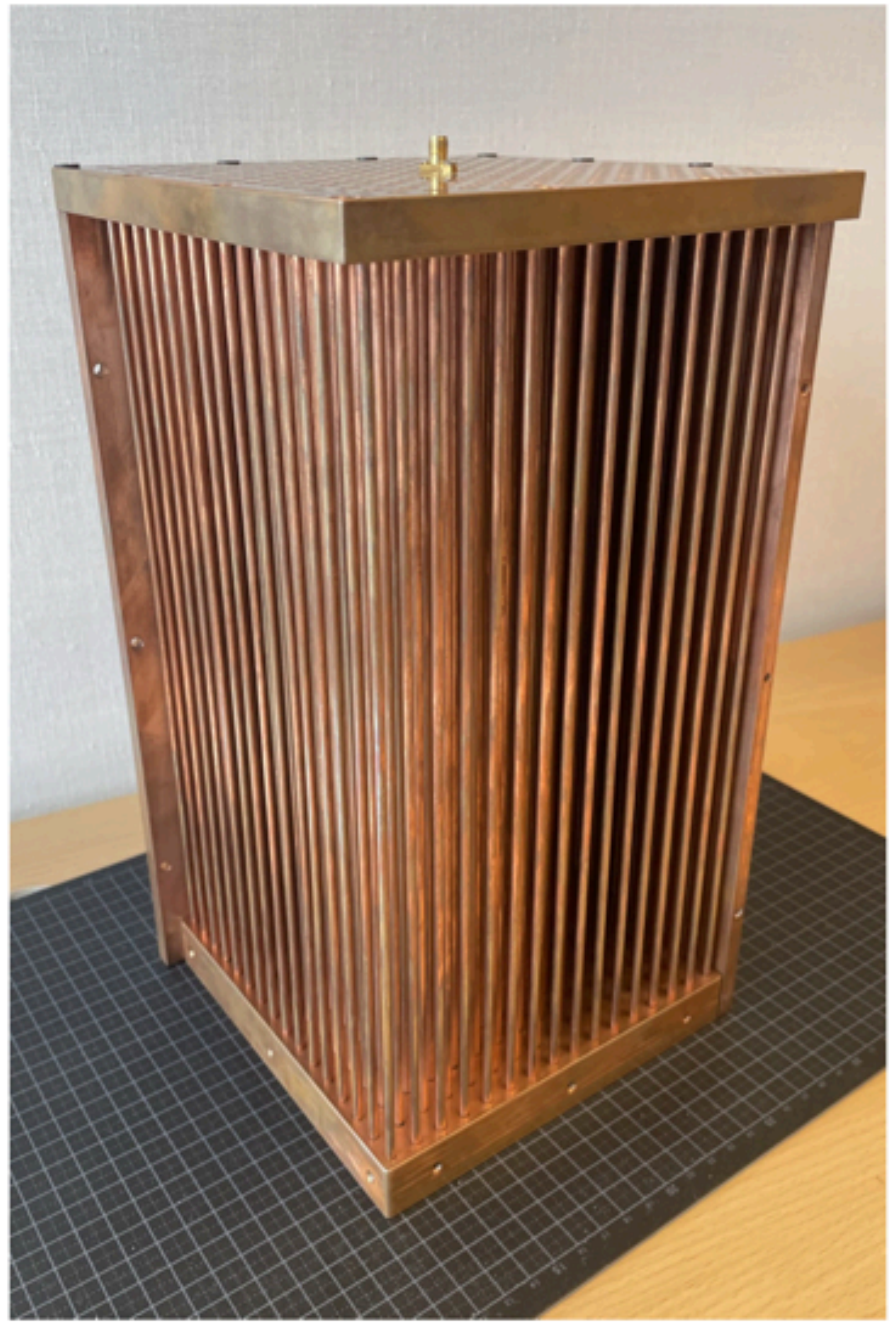
Photon mass depends on wire spacing —tuneable

Wire metamaterials simplest example, but other candidates exist

Lawson, Millar, Pancaldi, Vitagliano, Wilczek

The ALPHA collaboration





Lab tour at 14:00!

Summary

Has emerged as one of the **strongest dark matter candidates**.

Theory connection is deep and non-trivial.

The **astroparticle physics and cosmology** of axions is incredibly rich, with potential observables from the early universe and nearby stars.

Experiments have begun to probe the most interesting parameter space; a flurry of new experiments have been proposed.

Sense of *"drive"* in the community.