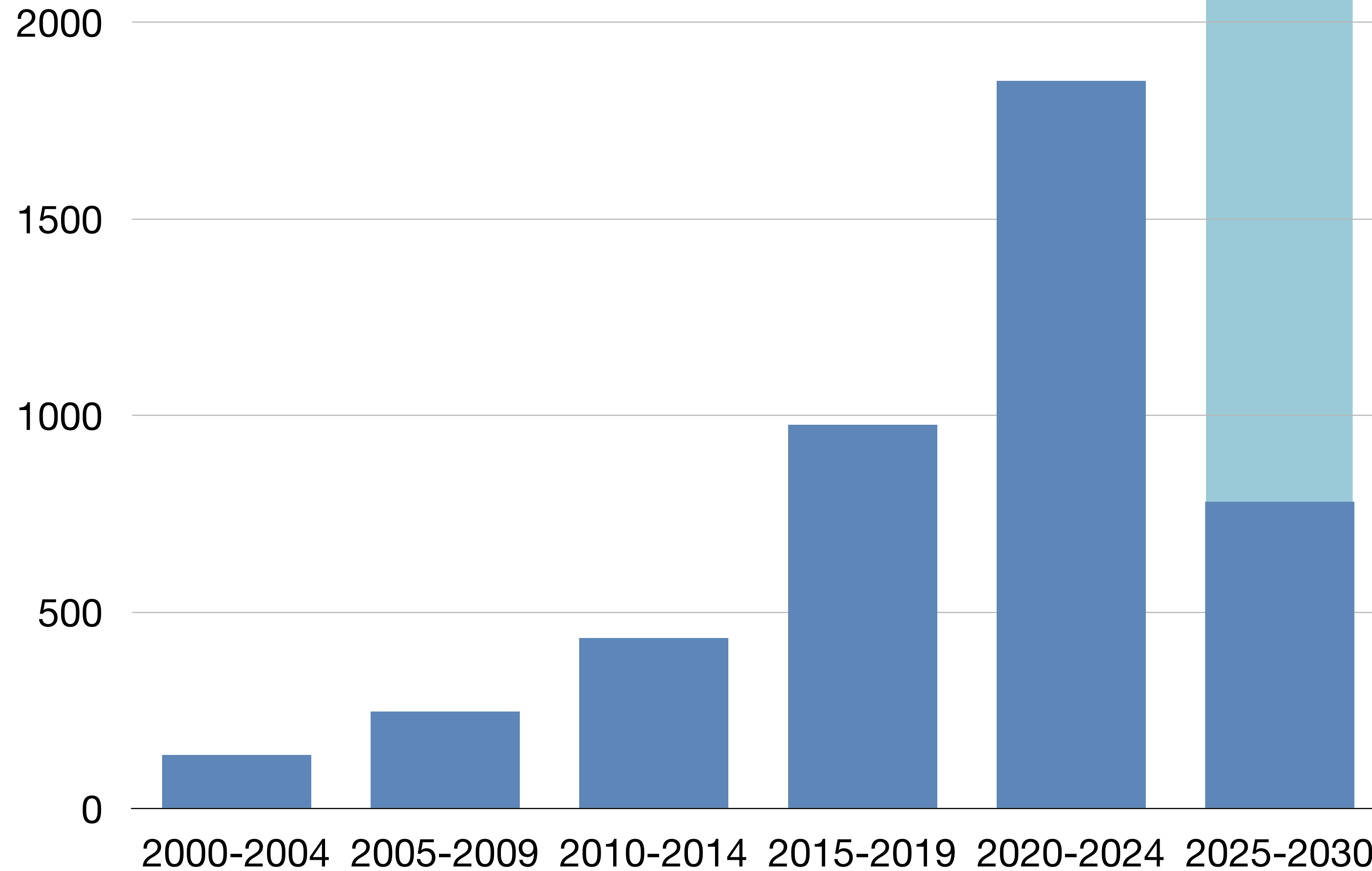


PH
THE MANY ~~F~~ACES OF
AXIONS

M.C. DAVID MARSH
STOCKHOLM UNIVERSITY

Axion papers per 5-year period



But *why now?*

**Strong DM
candidate**

**Rich astroparticle
physics and cosmology**

Deep theory

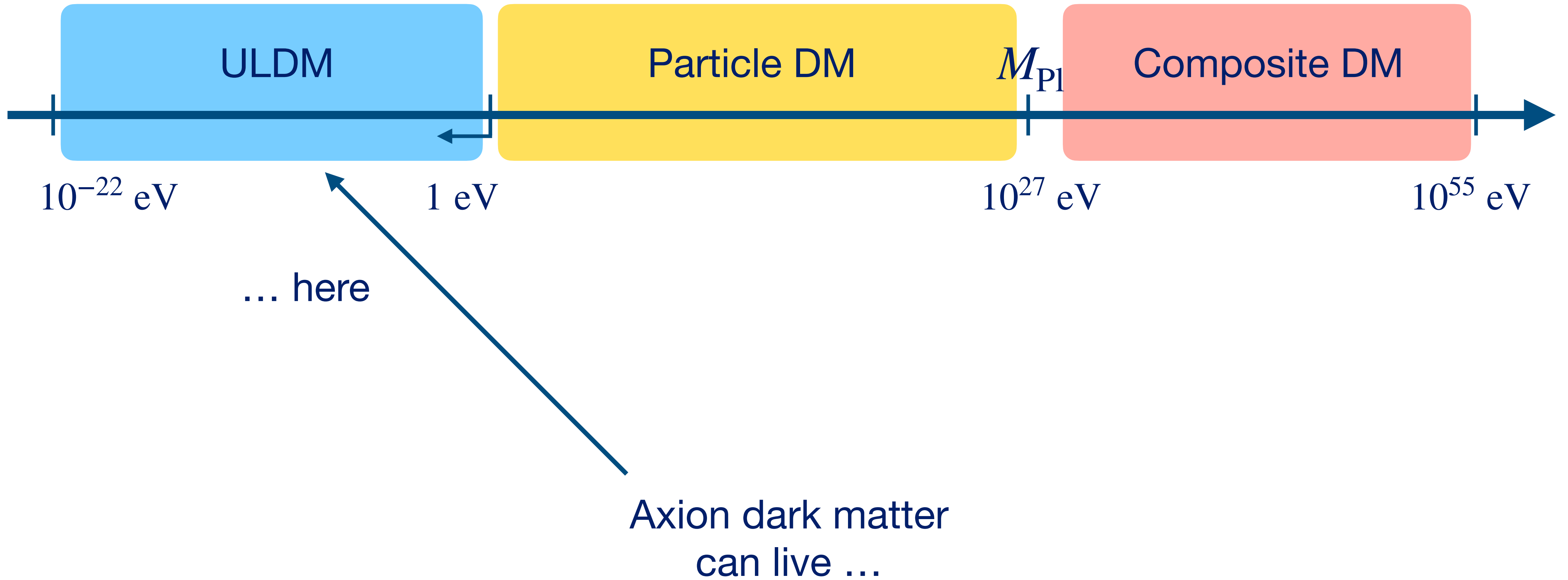
Experimentally tested

**Sense of “*drive*”
in the community.**

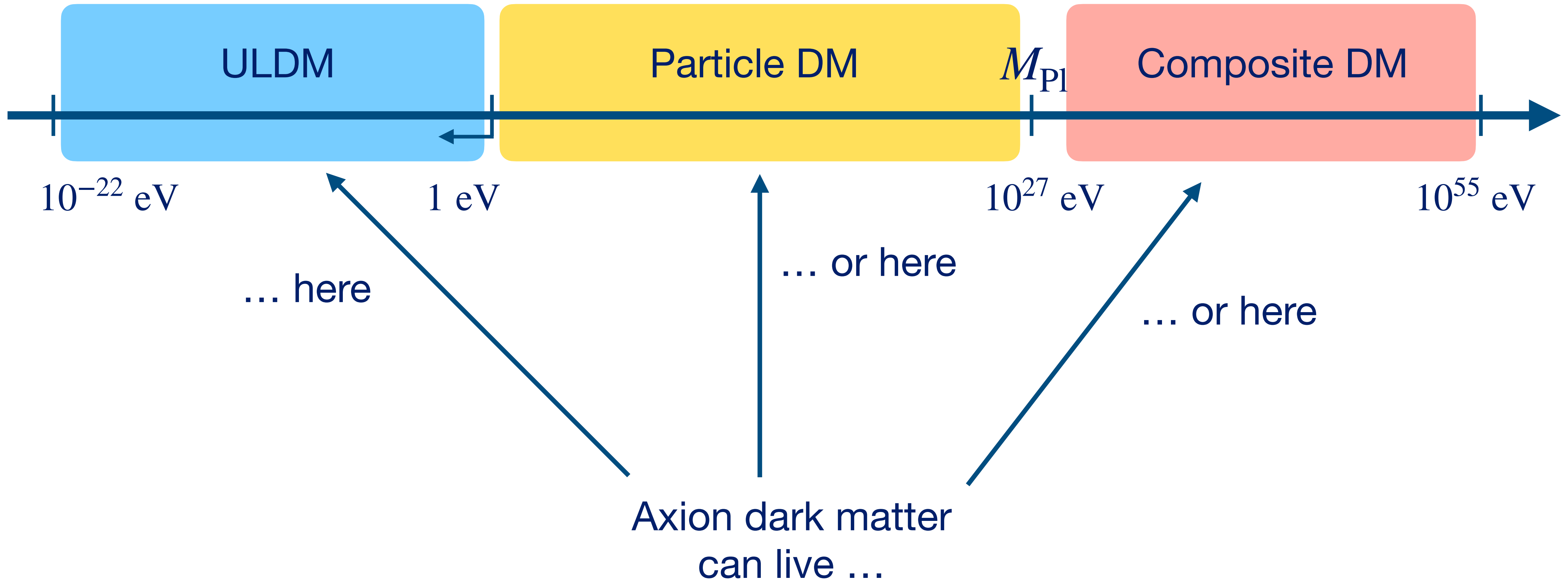
The Dark Matter Mass



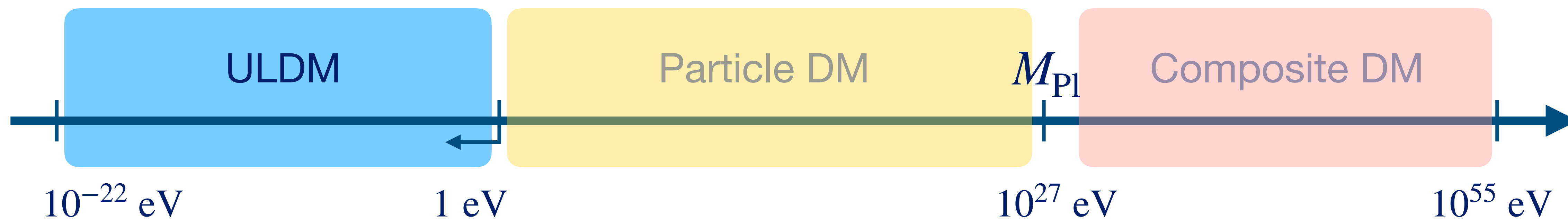
The Dark Matter Mass



The Dark Matter Mass



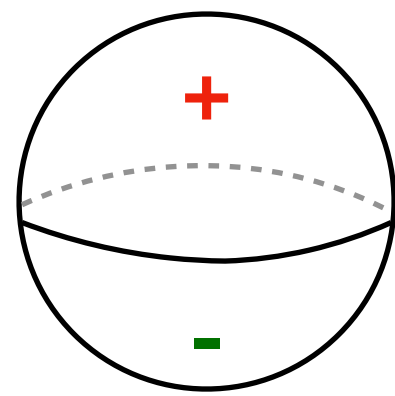
ULDM Axions



The theta angle

$$\frac{\theta}{16\pi^2} \text{tr} \left(G_{\mu\nu} \tilde{G}^{\mu\nu} \right)$$

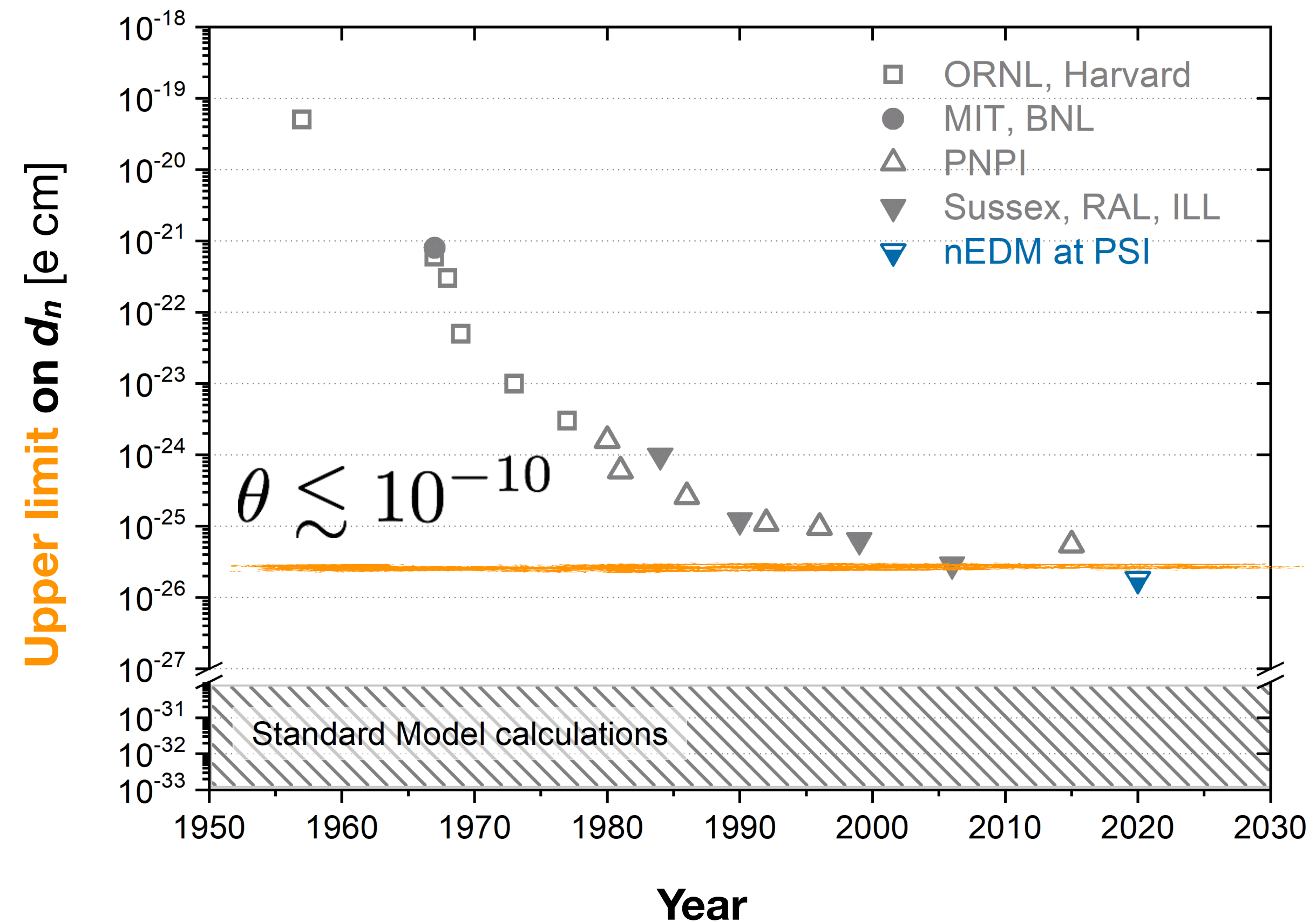
θ affects the neutron charge distribution.



neutron

$$d_N = (5.2 \times 10^{-16} e \cdot \text{cm}) \theta$$

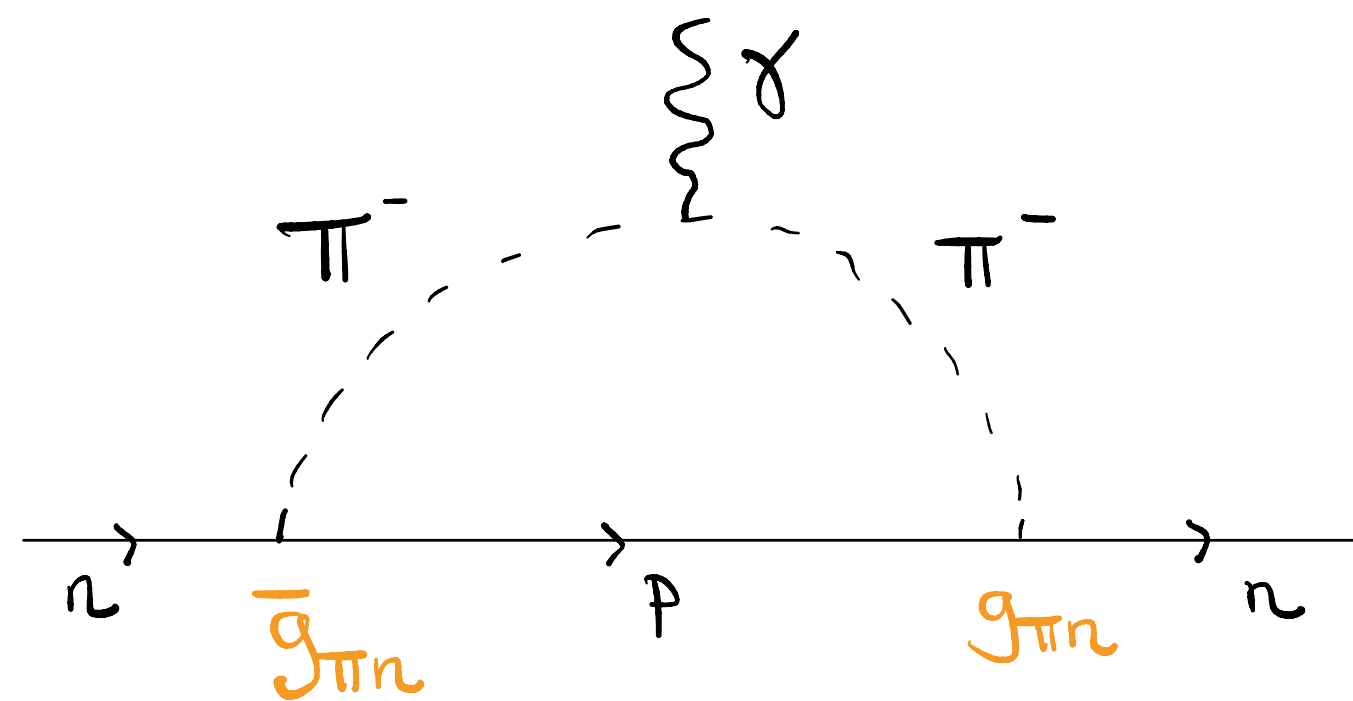
$$\theta \lesssim 10^{-10}$$



The theta angle

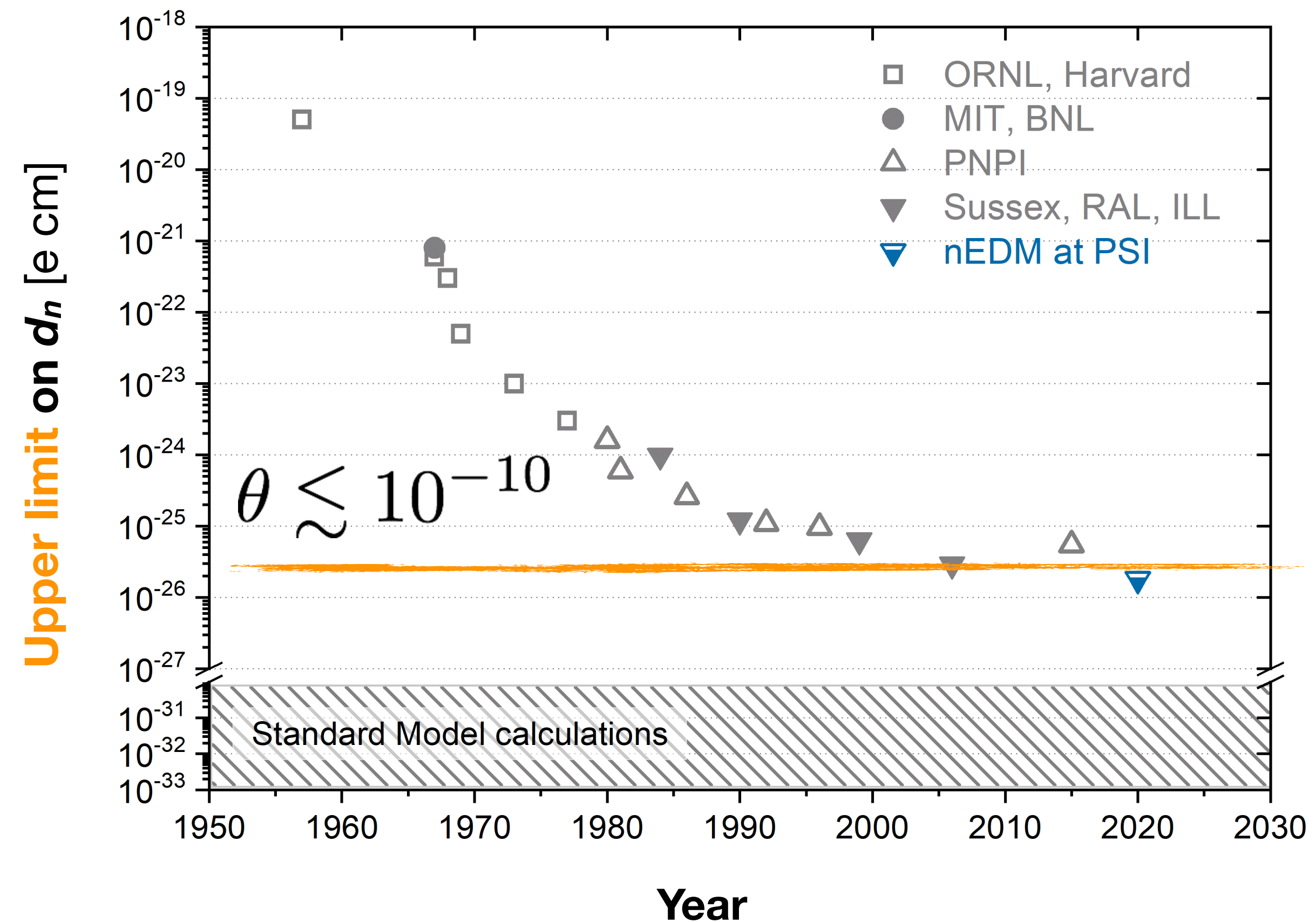
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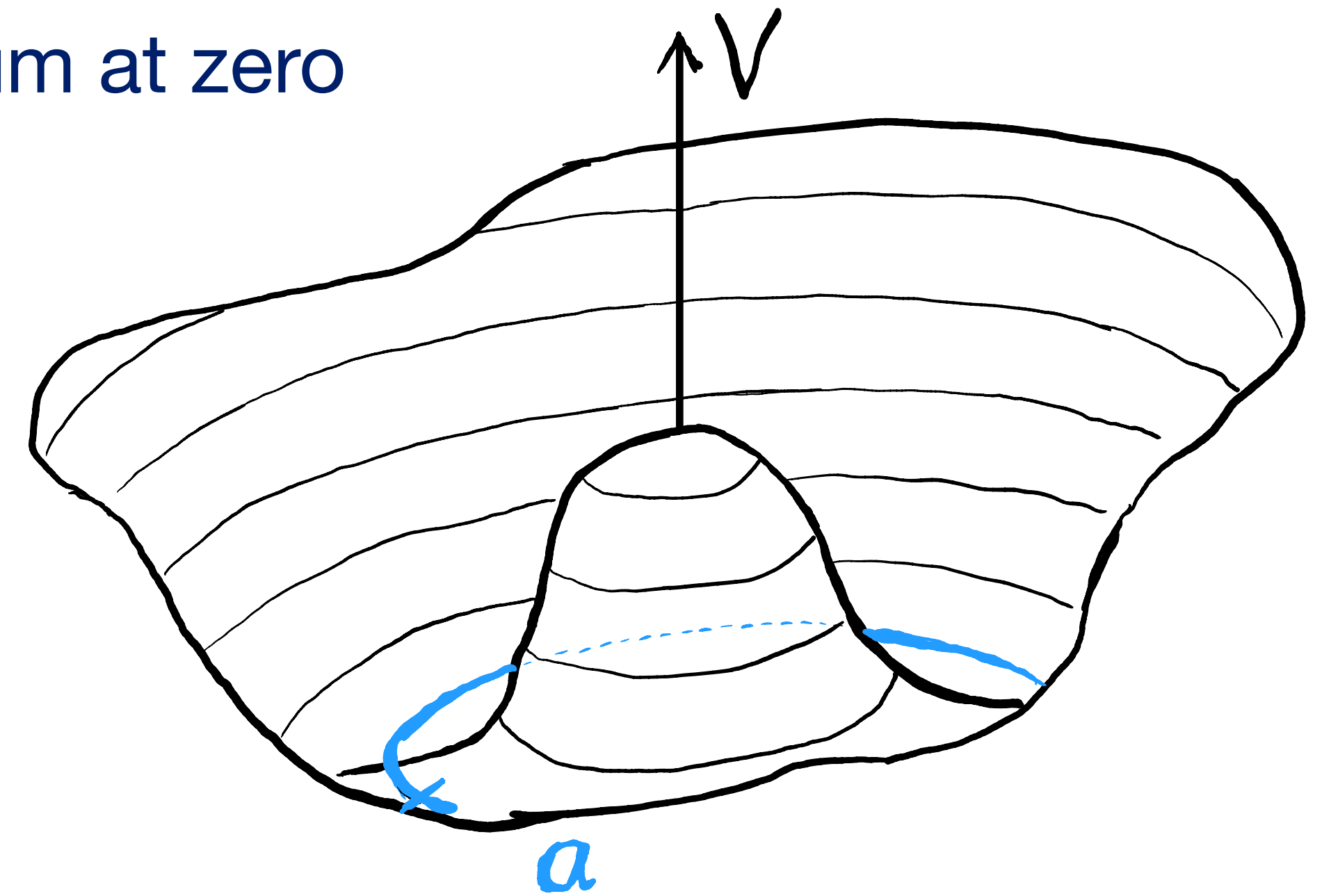
The QCD axion

$$\sim \frac{a}{f_a} \text{tr} \left(G_{\mu\nu} \tilde{G}^{\mu\nu} \right)$$

PQ mechanism

Makes θ dynamical — minimum at zero

Scales:	f_a	Axion decay constant
	Λ_{QCD}	QCD scale (~ 330 MeV)
	$m_a \sim \frac{\Lambda_{\text{QCD}}^2}{f_a}$	Mass scale



QCD axion interactions

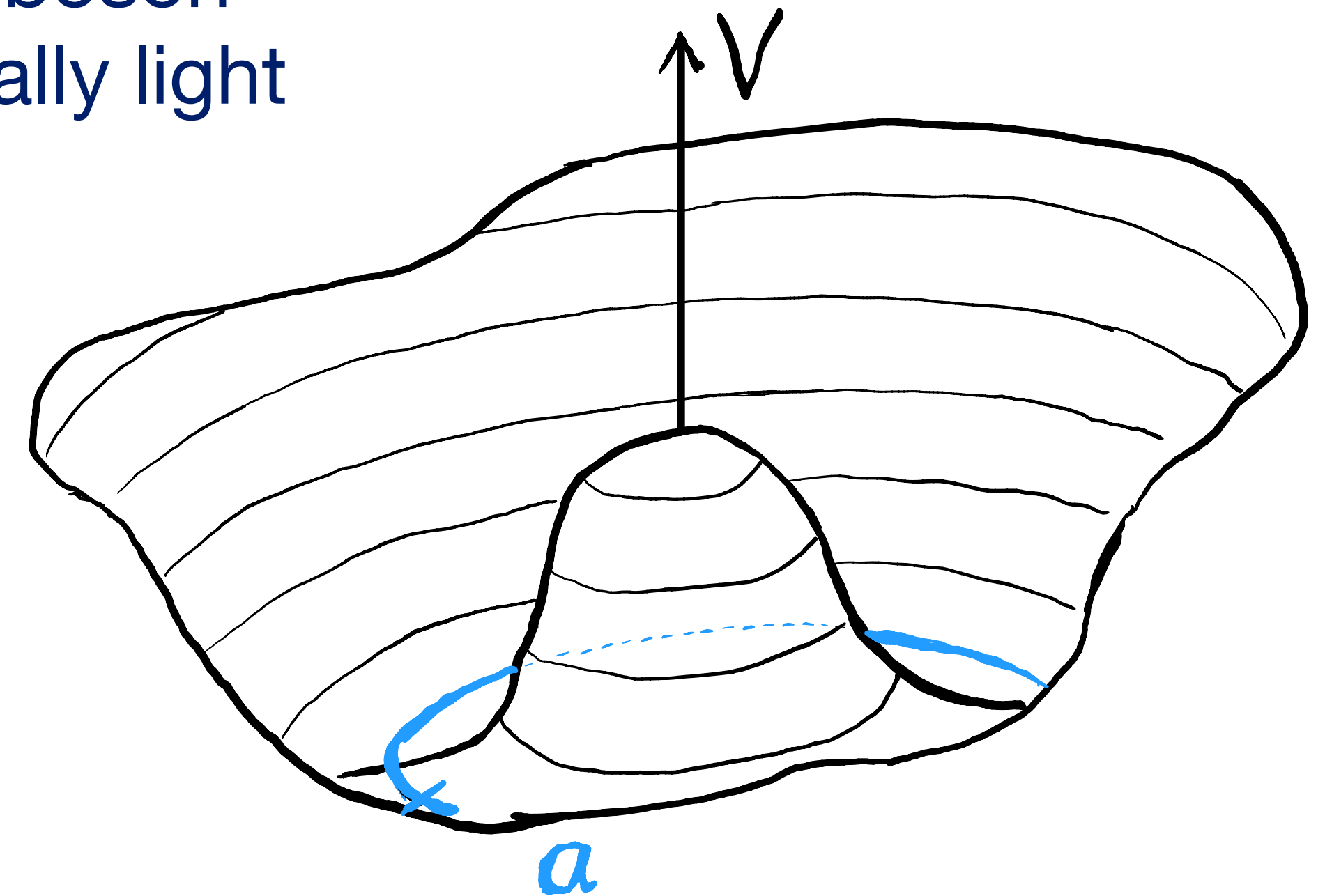
$$\sim \frac{a}{f_a} \text{tr} \left(G_{\mu\nu} \tilde{G}^{\mu\nu} \right) + g_{a\psi} \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma_5 \gamma^\mu \psi + g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Pseudo-Nambu-Goldstone boson
Derivative couplings — naturally light

Parameters:

$g_{a\psi}$ axion-fermion coupling

$g_{a\gamma}$ axion-photon coupling



Axion-like particles (ALPs)

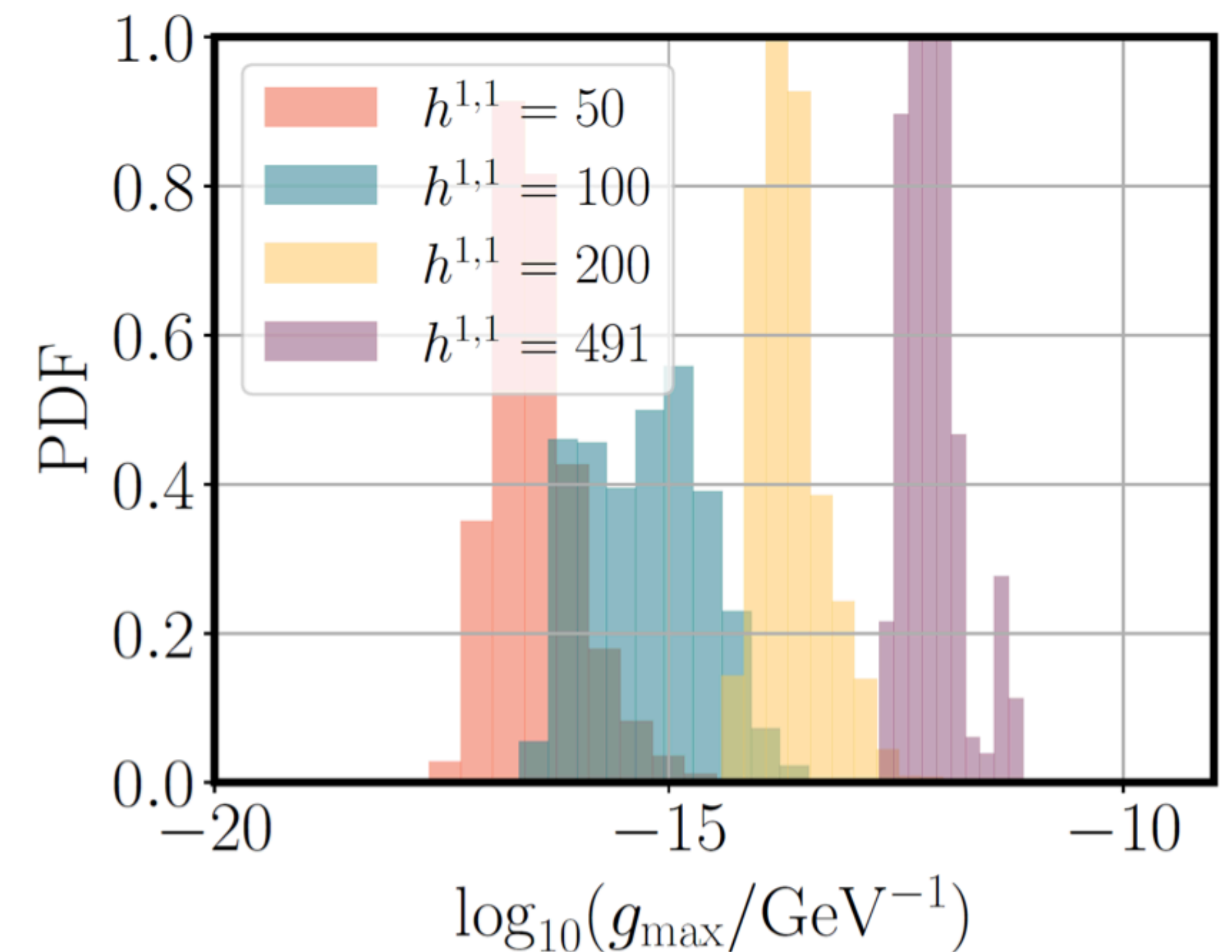
$$\sim \frac{1}{2}m_a^2 a^2 + g_{a\psi} \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma_5 \gamma^\mu \psi + g_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

PNGB that don't
couple to QCD.

Naturally light,
weakly coupled

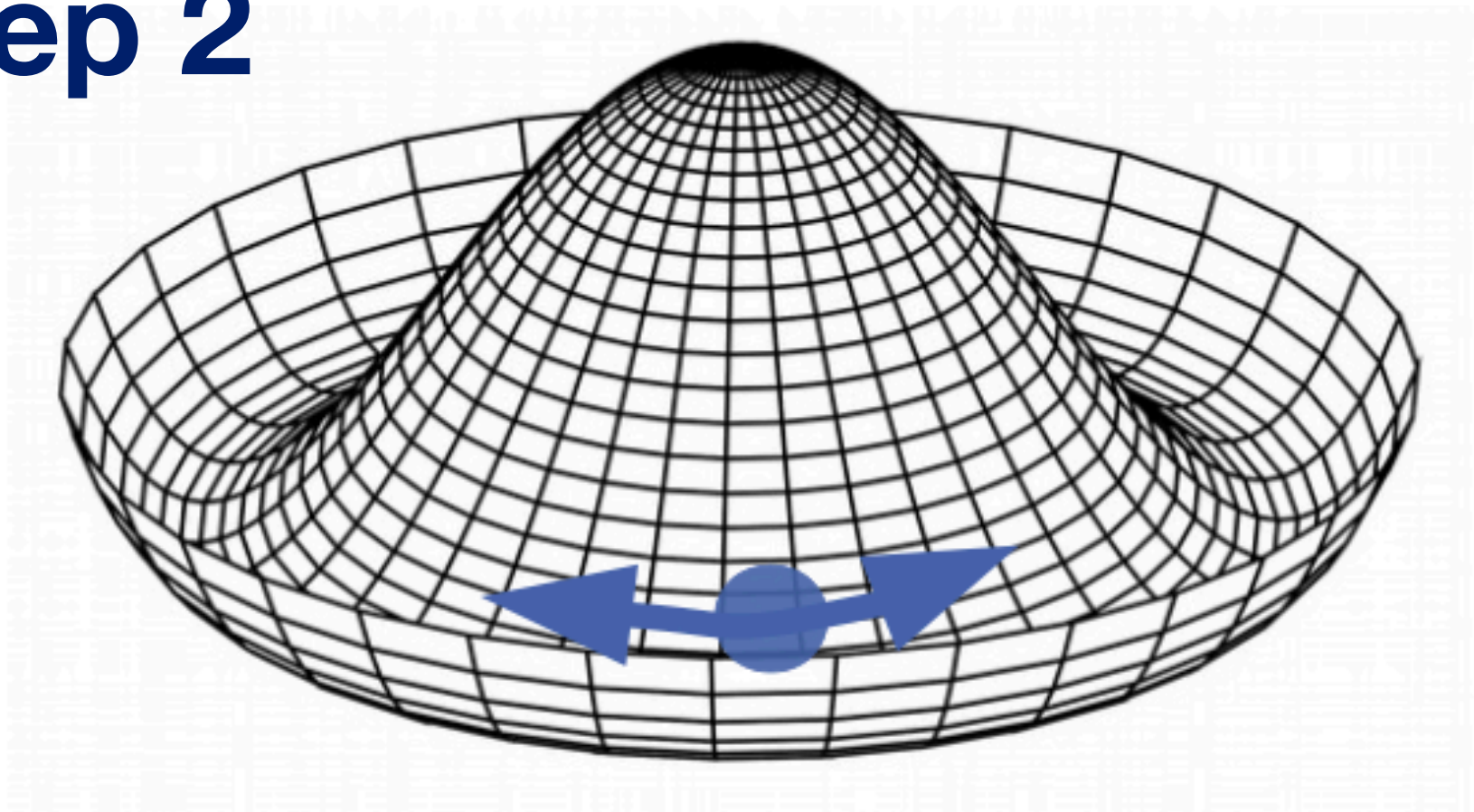
Abundant in string
compactifications
— PQ mechanism not required

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



Axion dark matter

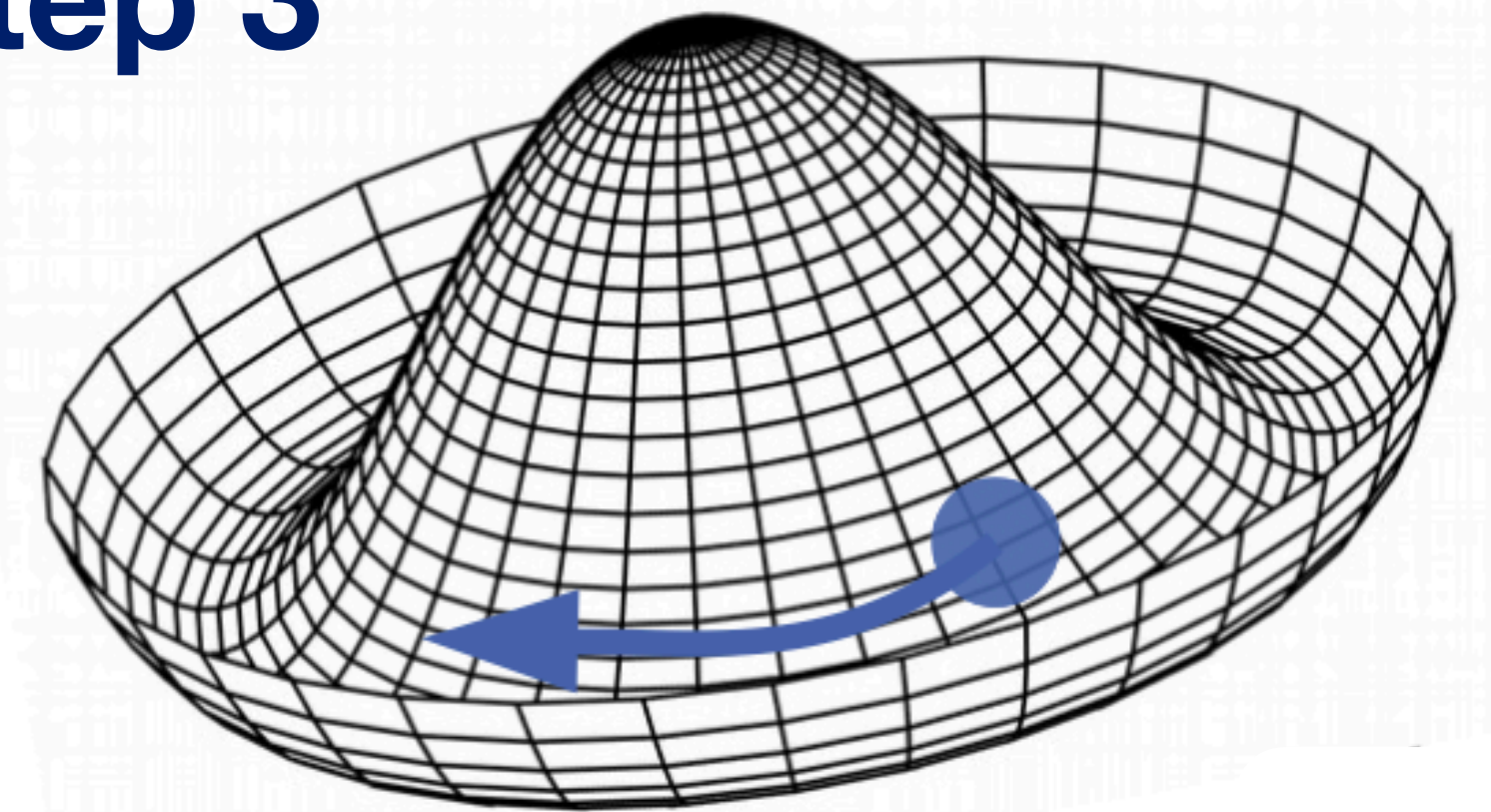
Step 2



$$m_a \ll 3H$$

Frozen field

Step 3



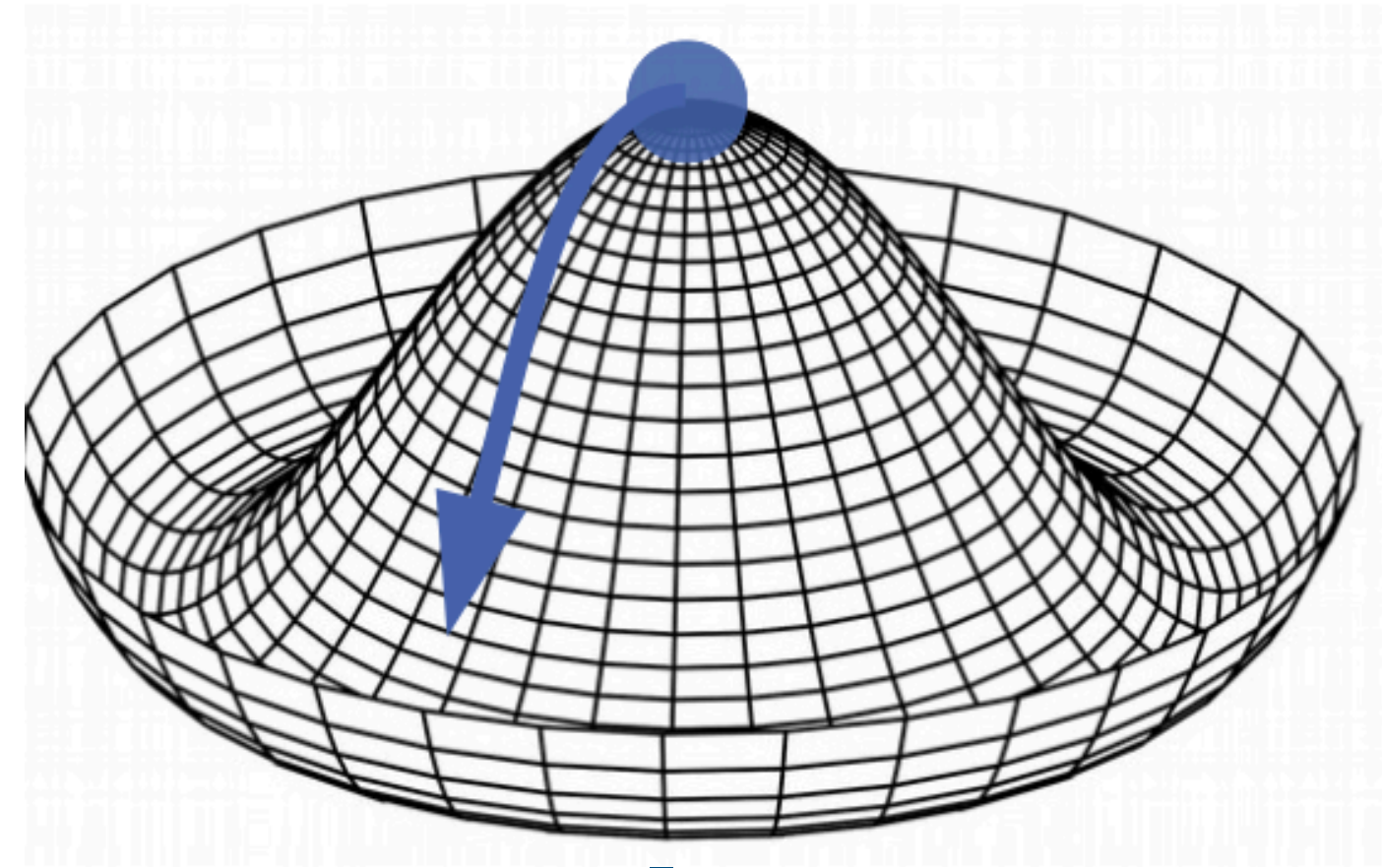
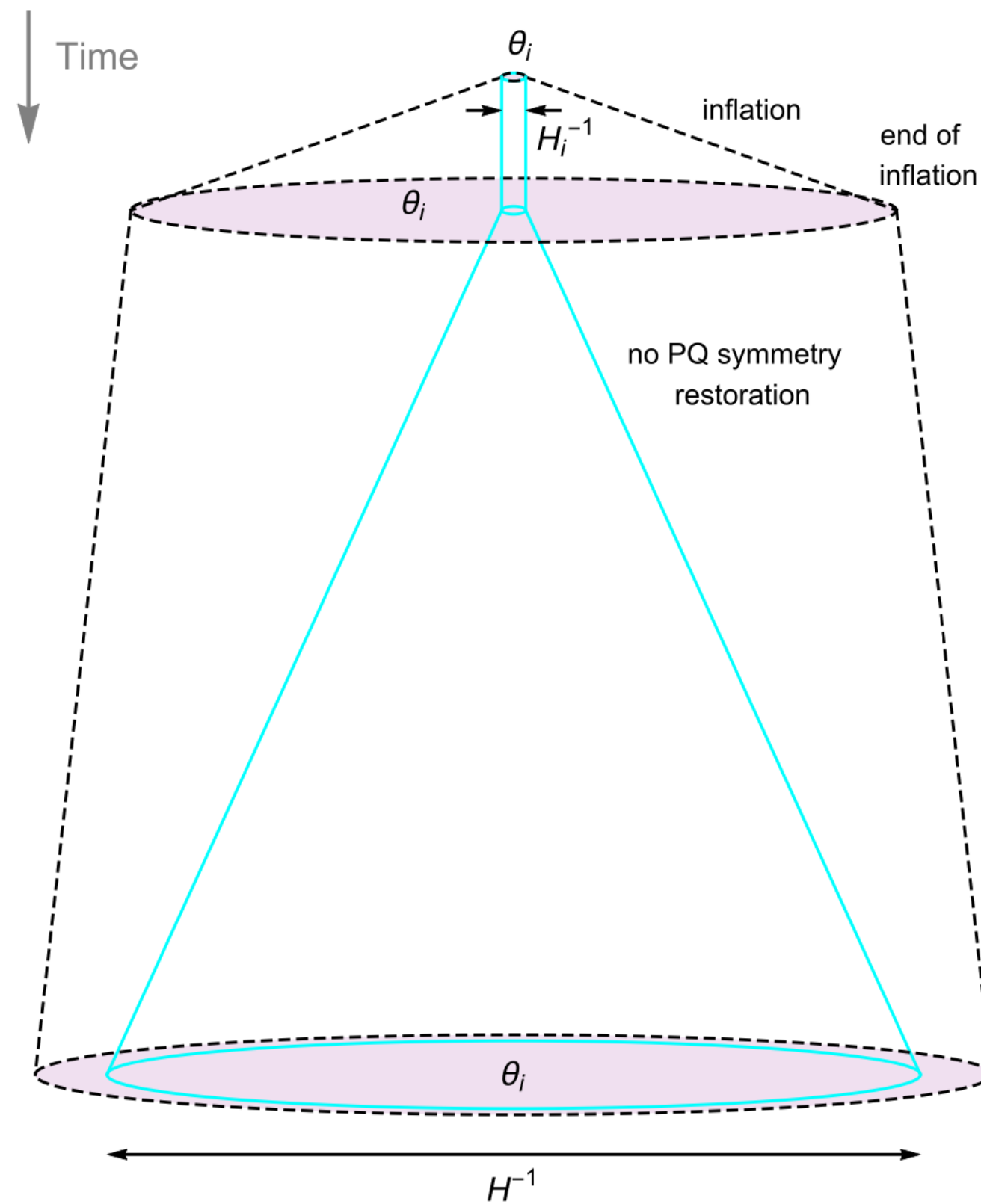
$$m_a \gtrsim 3H$$

Oscillating scalar field —
cosmological matter

Step 1? Two cosmology-dependent branches

$$E_{\text{infl}} < f_a$$

"Pre-inflationary"



$$E_{\text{infl}} > f_a$$

"Post-inflationary"

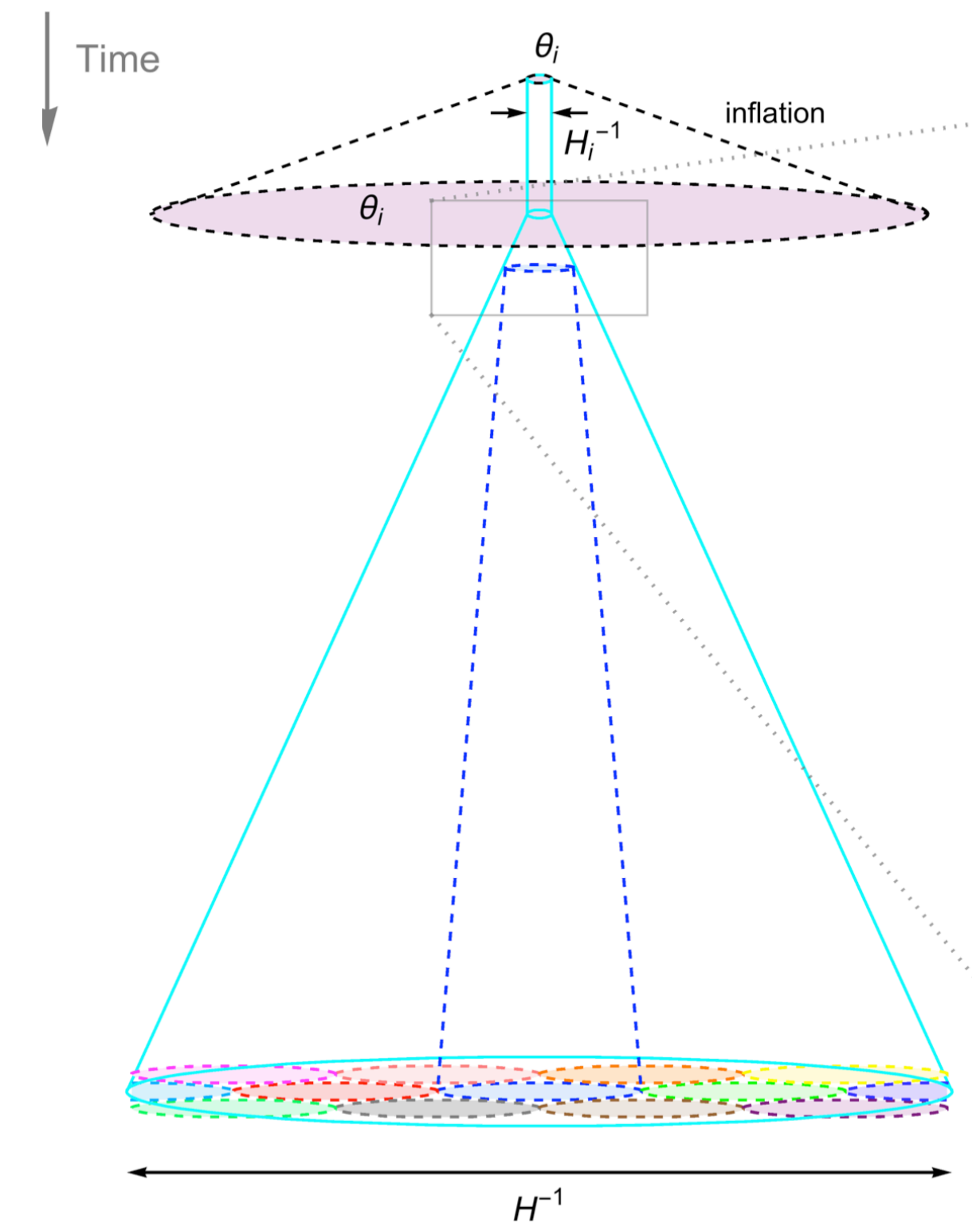
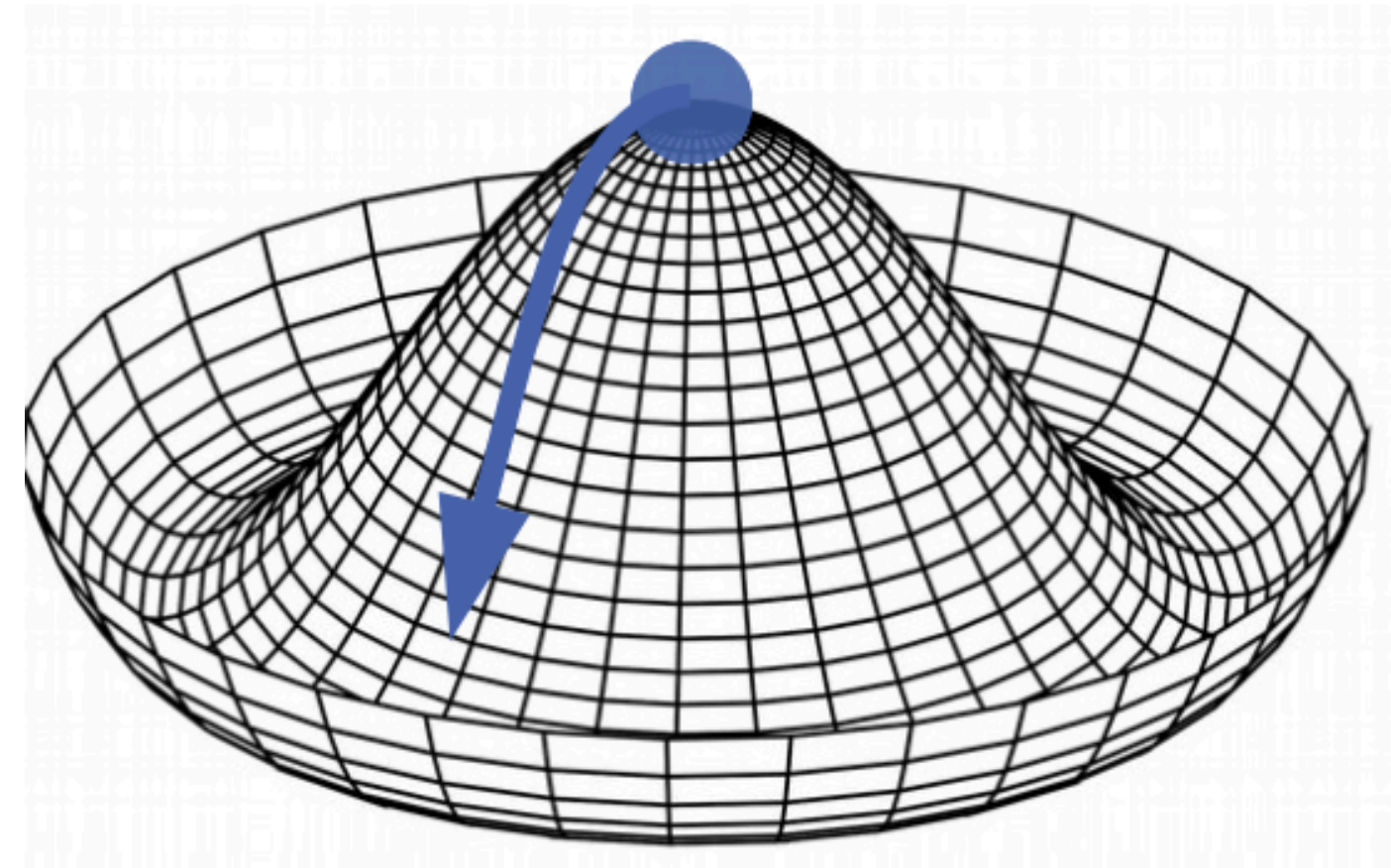
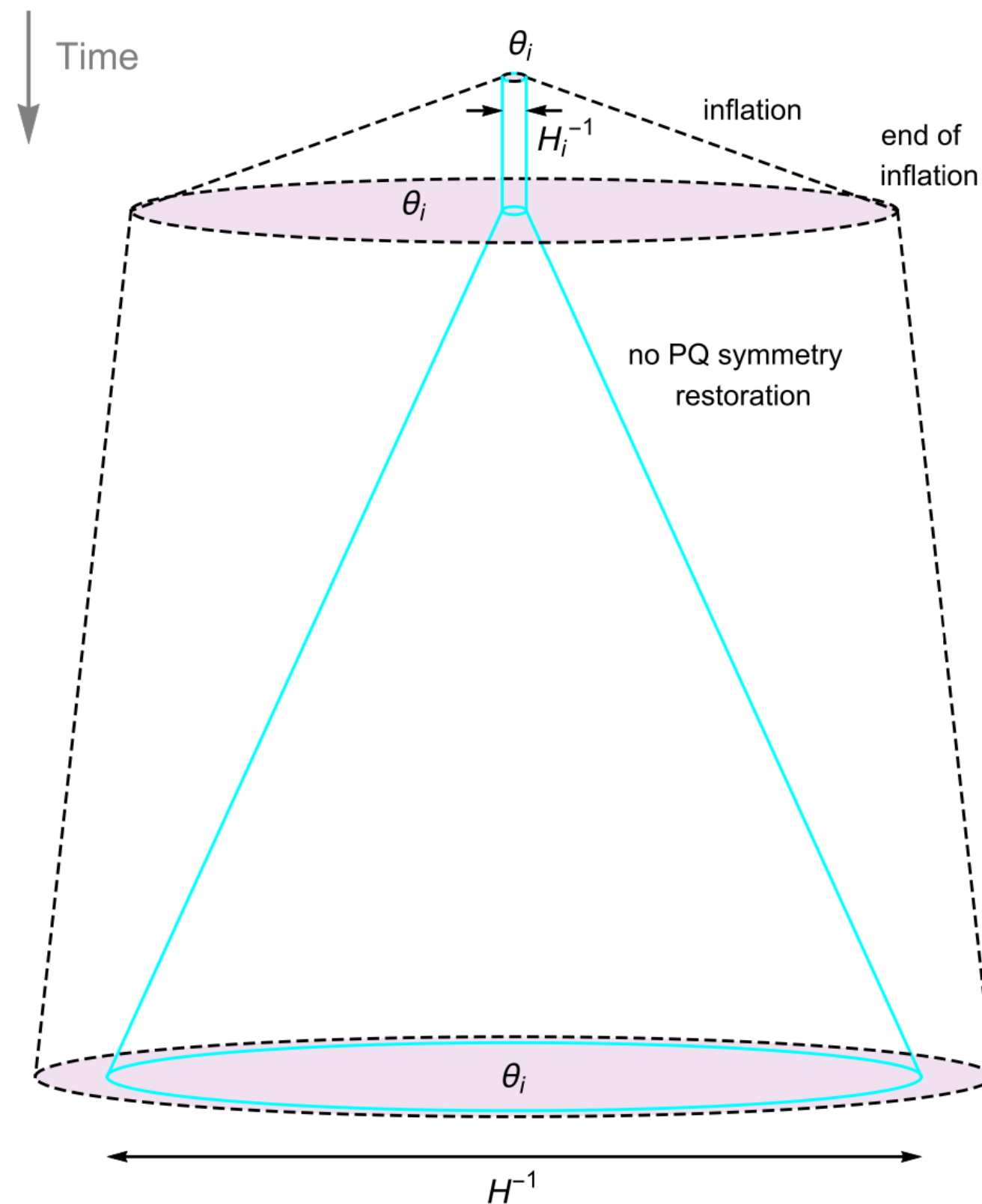


Fig. credit: Saikawa, Urrestilla

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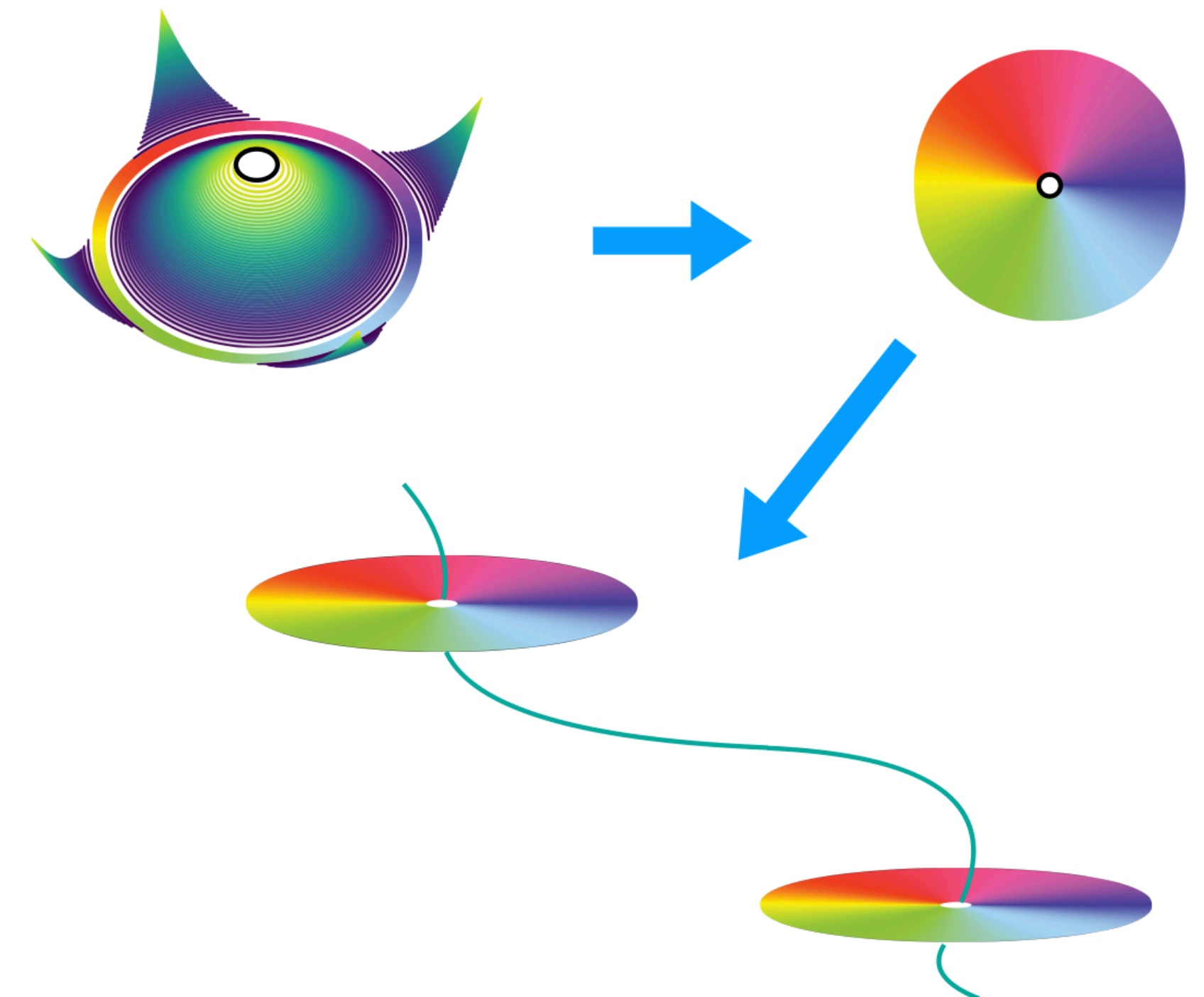


Fig. credit: Saikawa, Urrestilla

Two cosmology-dependent branches

$$E_{\text{infl}} < f_a$$

”Pre-inflationary”

$$\Omega_m h^2 \sim \theta_i^2$$

Quantum fluctuations of axion
during inflation $\rightarrow$ isocurvature.

$$E_{\text{infl}} > f_a$$

”Post-inflationary”

$$\Omega_m h^2 \sim \langle \theta_i^2 \rangle + \text{string contrib.}$$

Two cosmology-dependent branches

$$E_{\text{infl}} < f_a$$

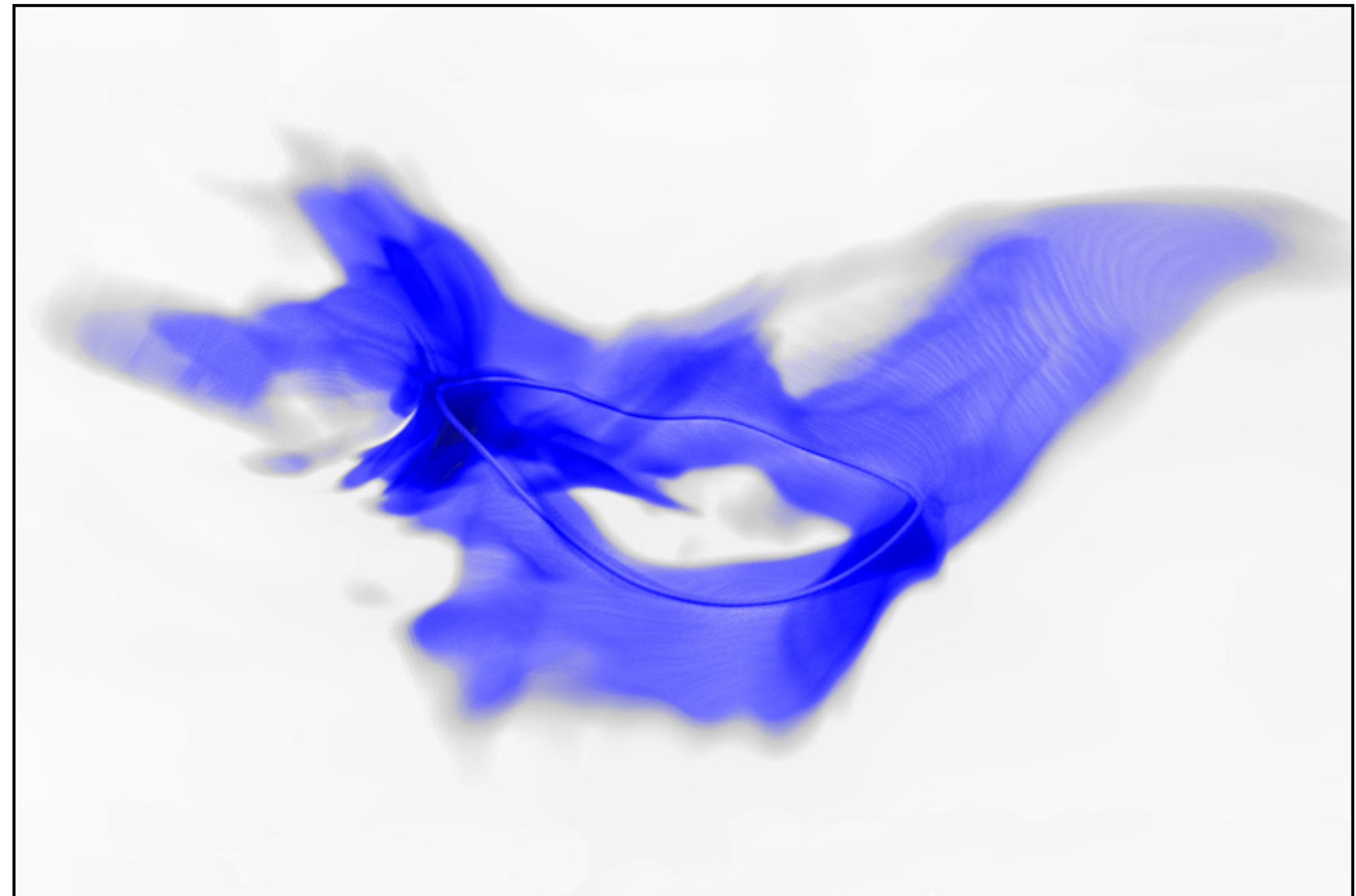
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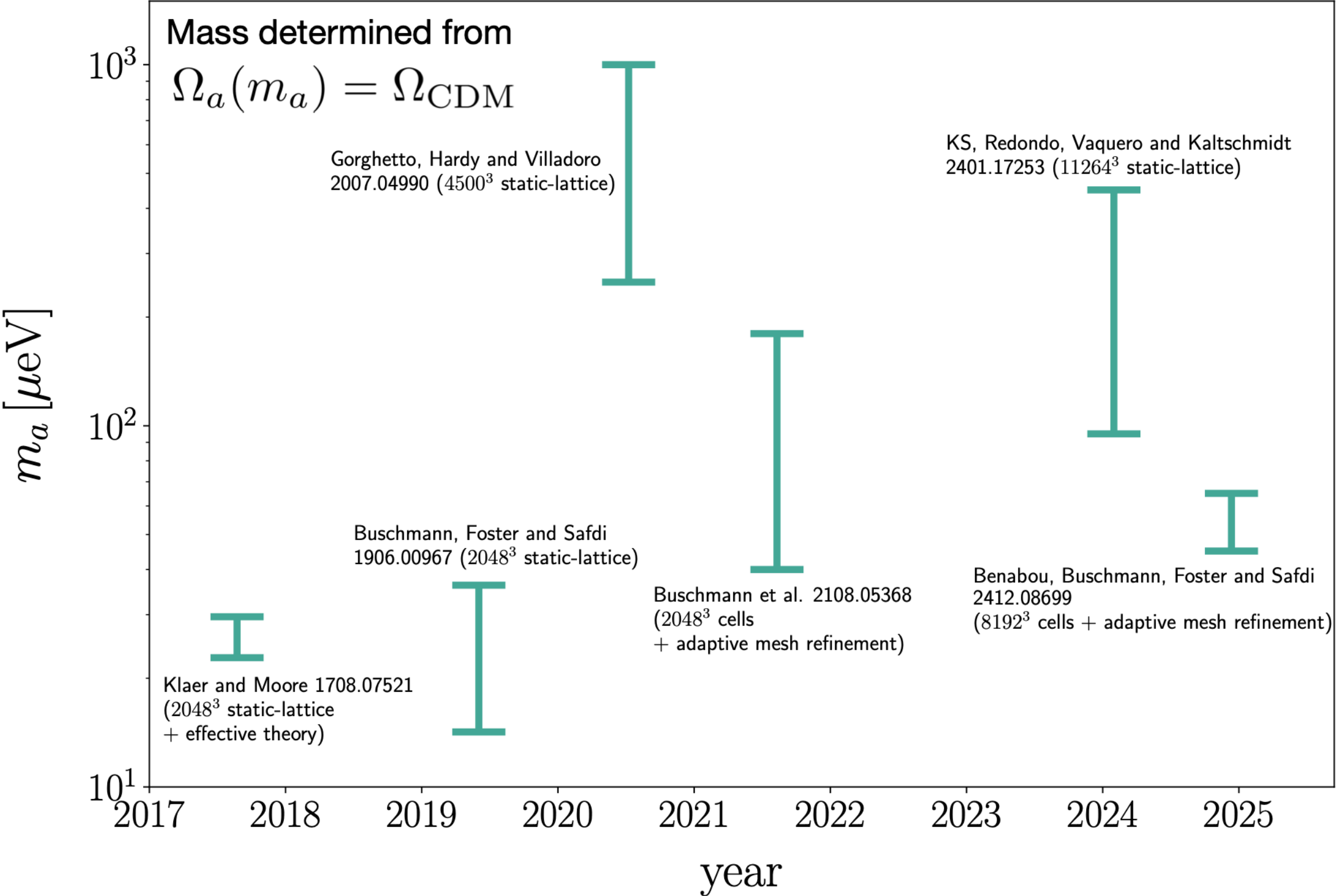
QCD Axion DM

”Pre-inflationary”

$$0.12 \mu\text{eV} \leq m_a \leq 0.2 \text{ meV}$$

Hoof et al.

”Post-inflationary”



ALP ULDM

$$10^{-22} \text{ eV} \lesssim m_a \lesssim 1 \text{ eV}$$

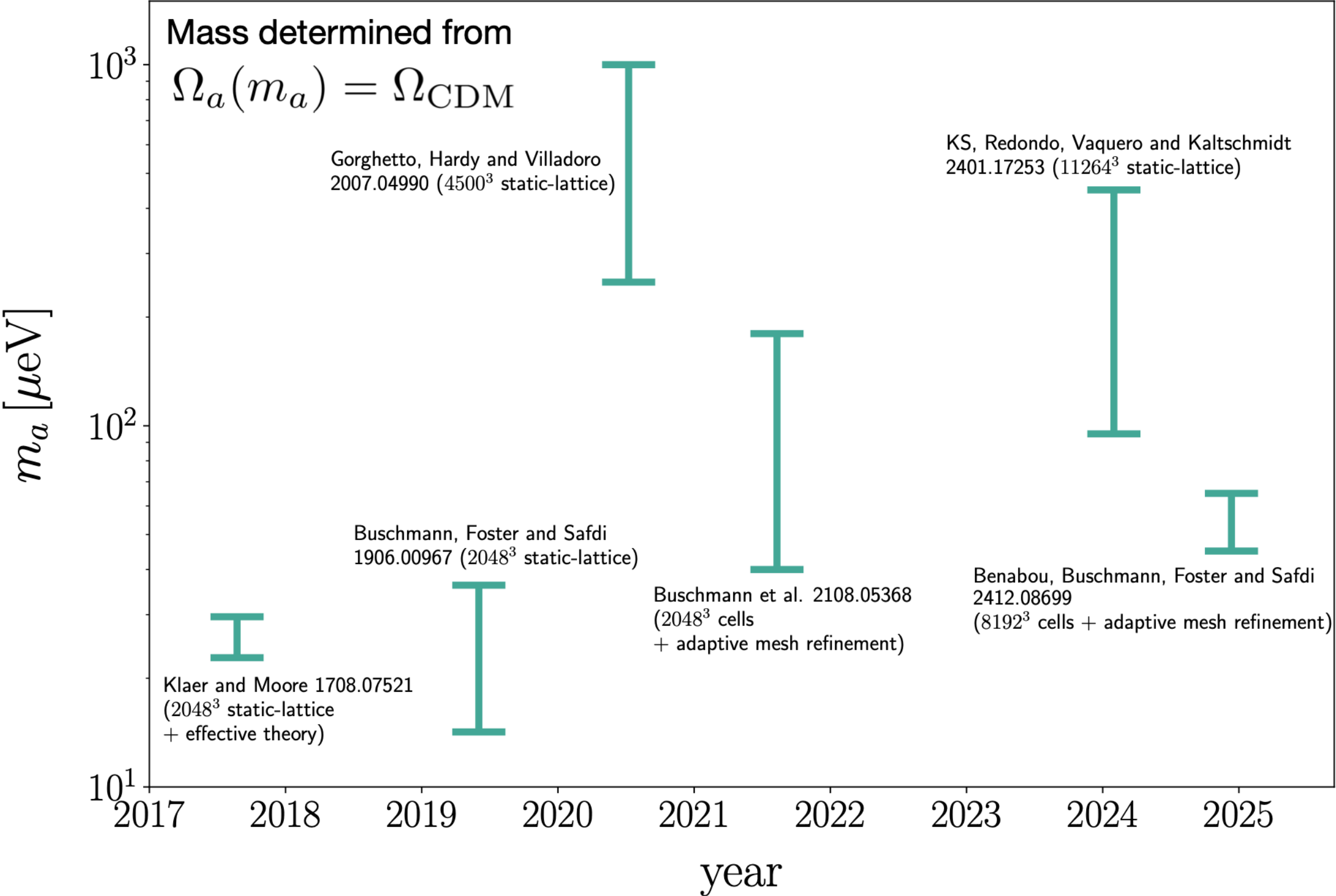
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How to probe?

Fuzzy dark matter

Predicts matter power spectrum suppression on small scales.

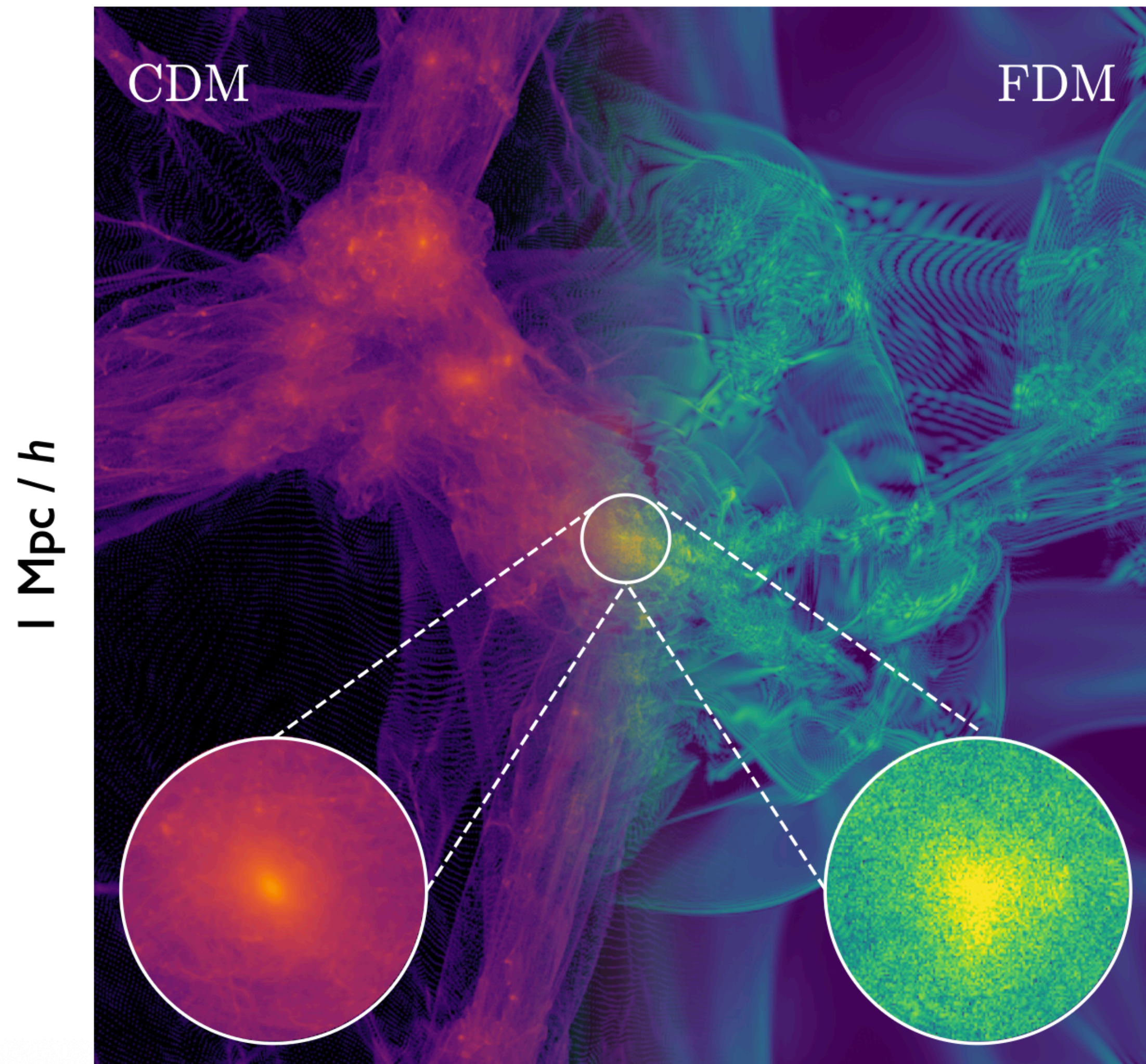
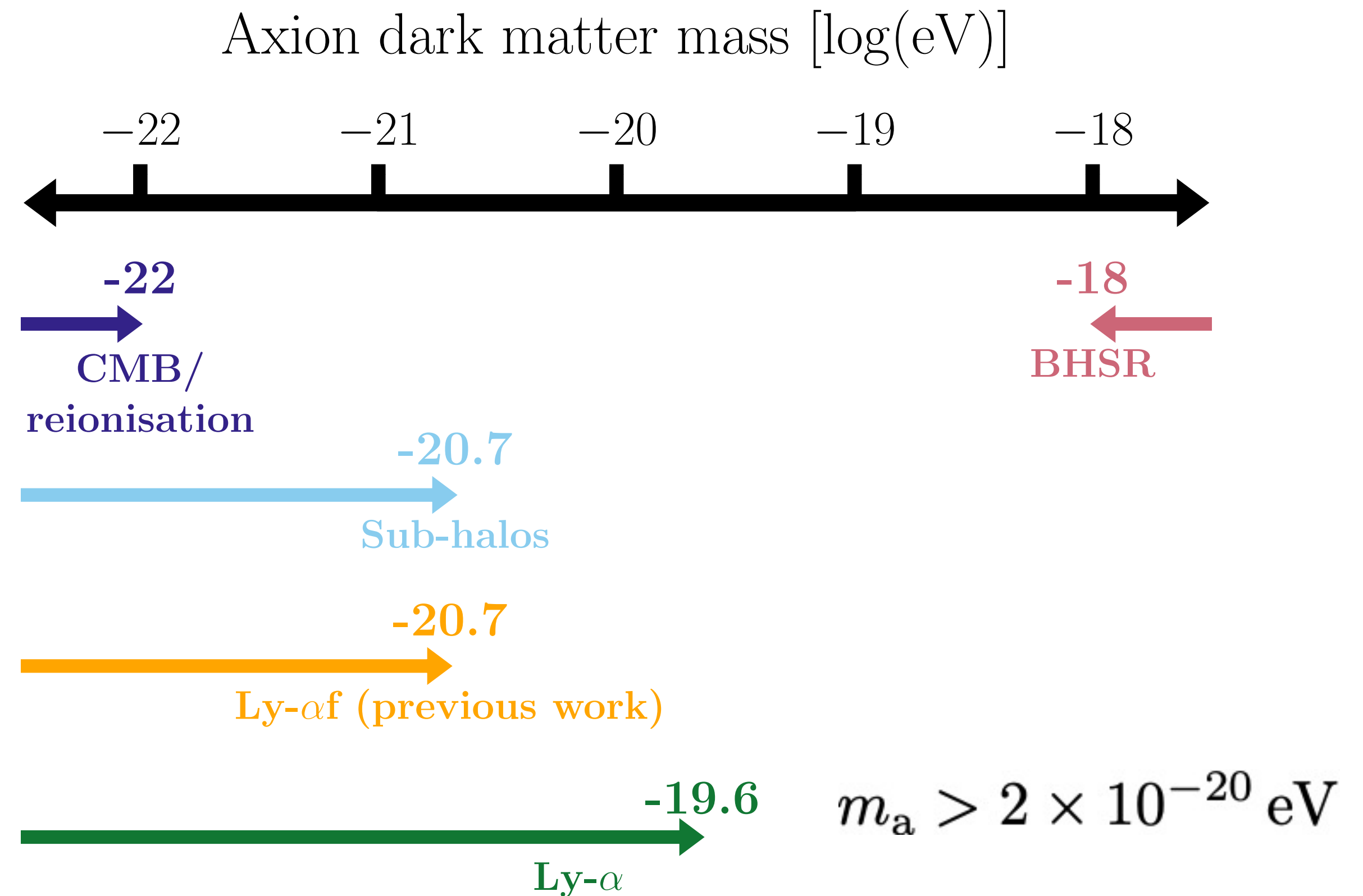


Fig. credit: Rogers



Axion clumps

Schive et al.

In the post-inflationary scenario, large overdensities lead to axion miniclusters.

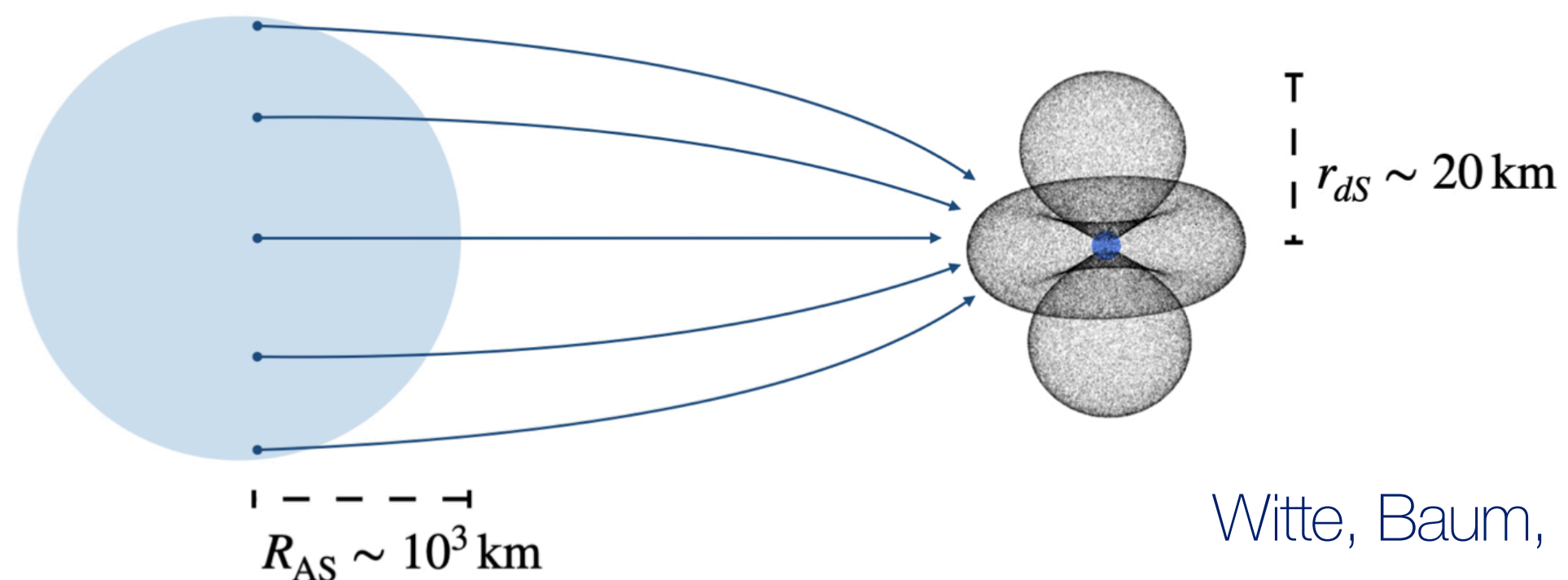
“Solitonic cores”, a.k.a. axion stars, form efficiently inside axion overdensities.

Levkov et al.

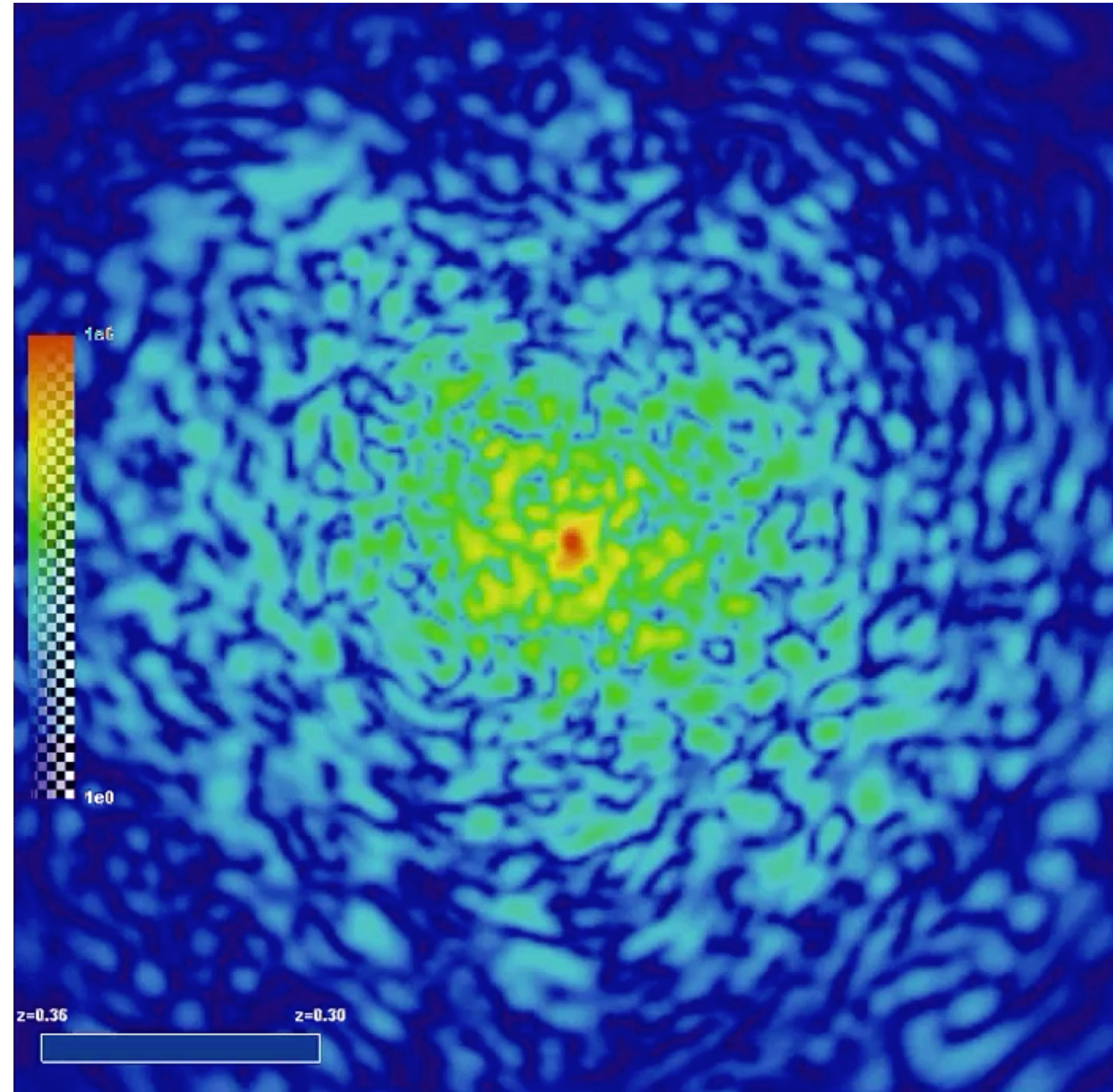
Size set by de Broglie wavelength:

$$\lambda_{dB} = \frac{2\pi}{m_a v_{dm}^2} \sim \frac{8000 \text{ km}}{m_a / \mu\text{eV}}$$

Signals from clump/neutron star collisions:



Witte, Baum, DM, Millar



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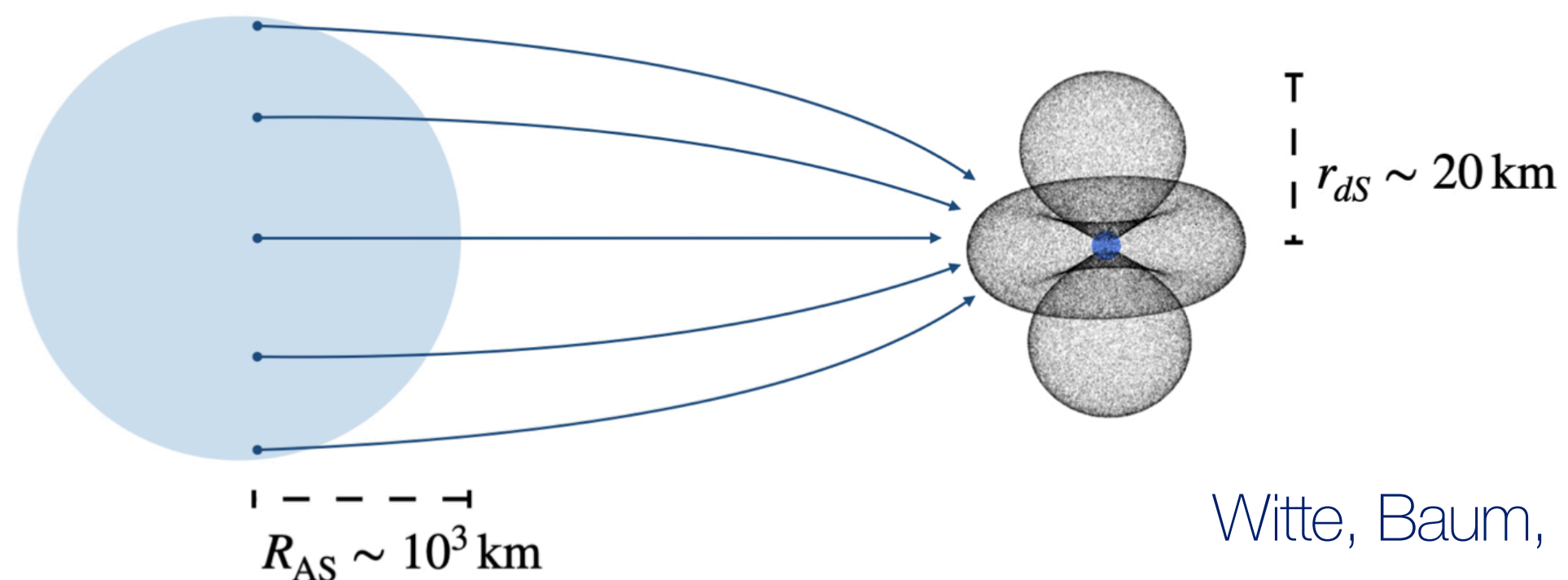
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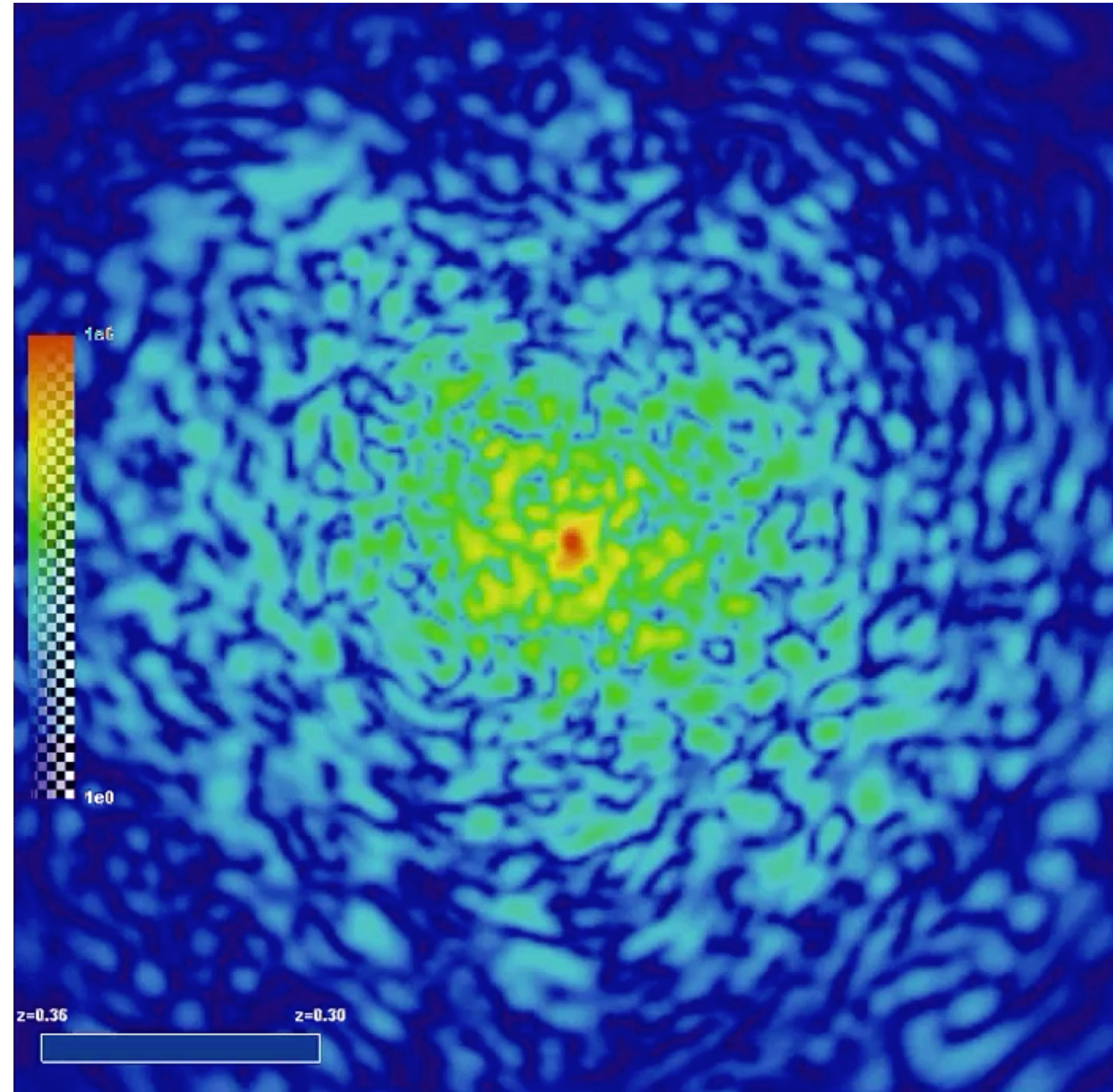
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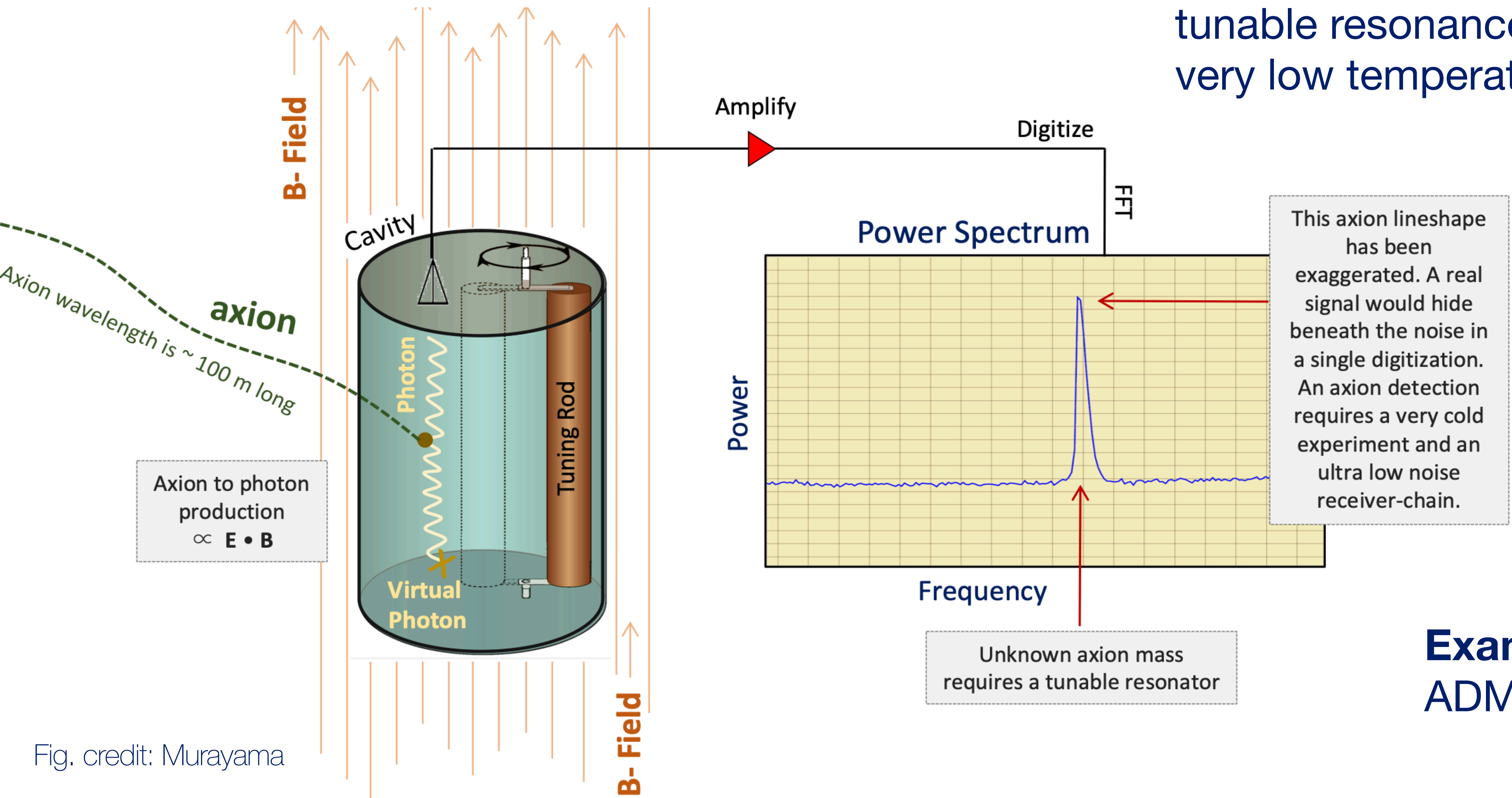


Witte, Baum, DM, Millar



Traditional haloscopes

Essence: High-Q cavities with tunable resonance frequencies at very low temperature.

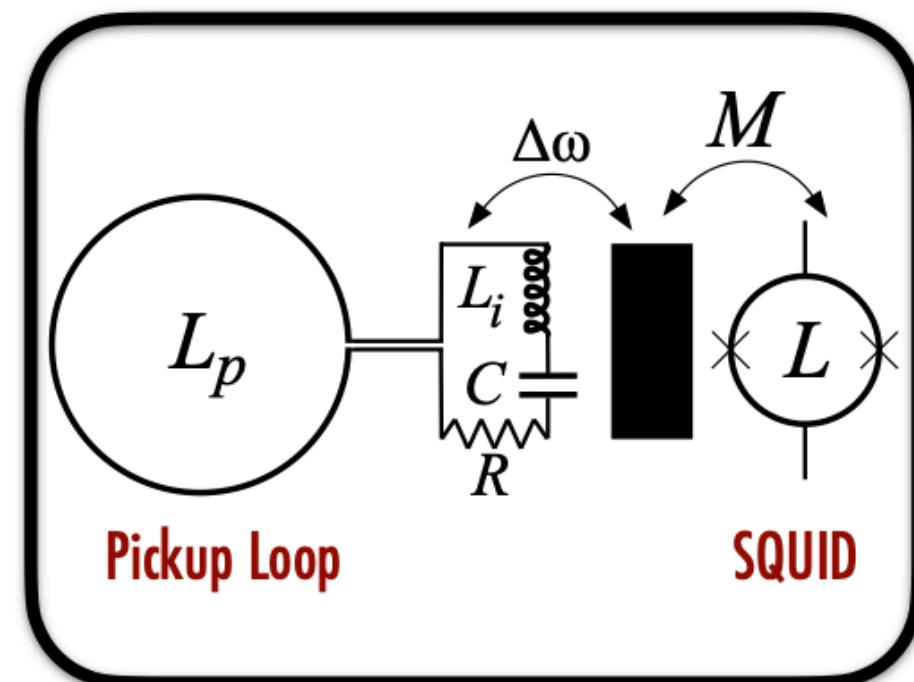
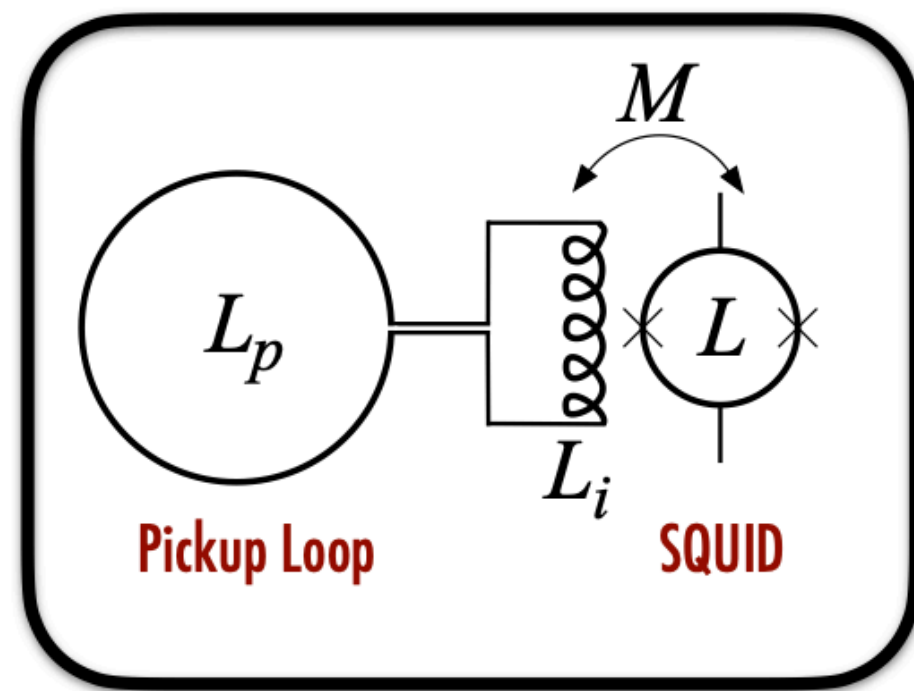


Examples:
ADMX, Haystack

Fig. credit: Murayama

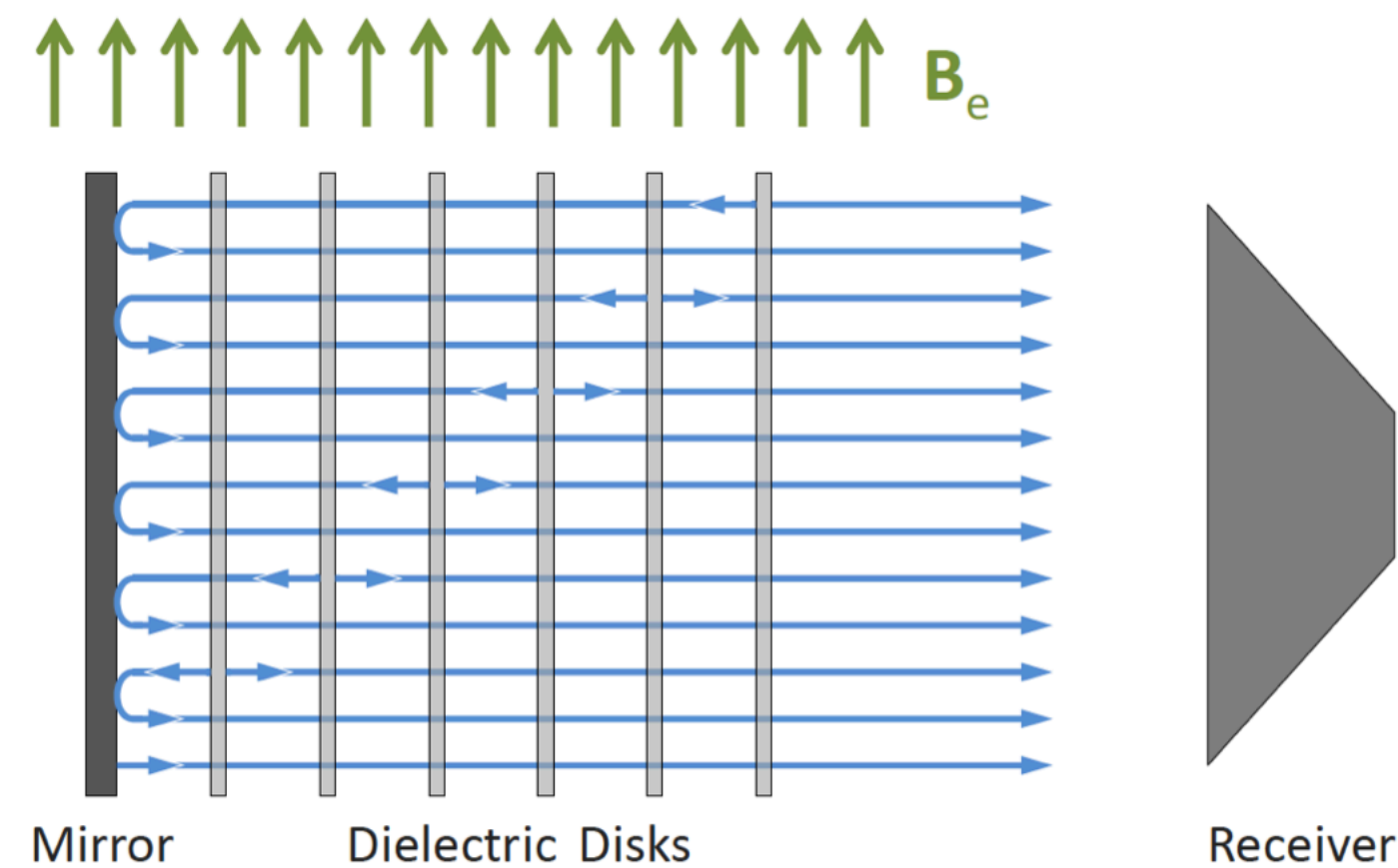
Newer ideas

Abracadabra → DM-radio



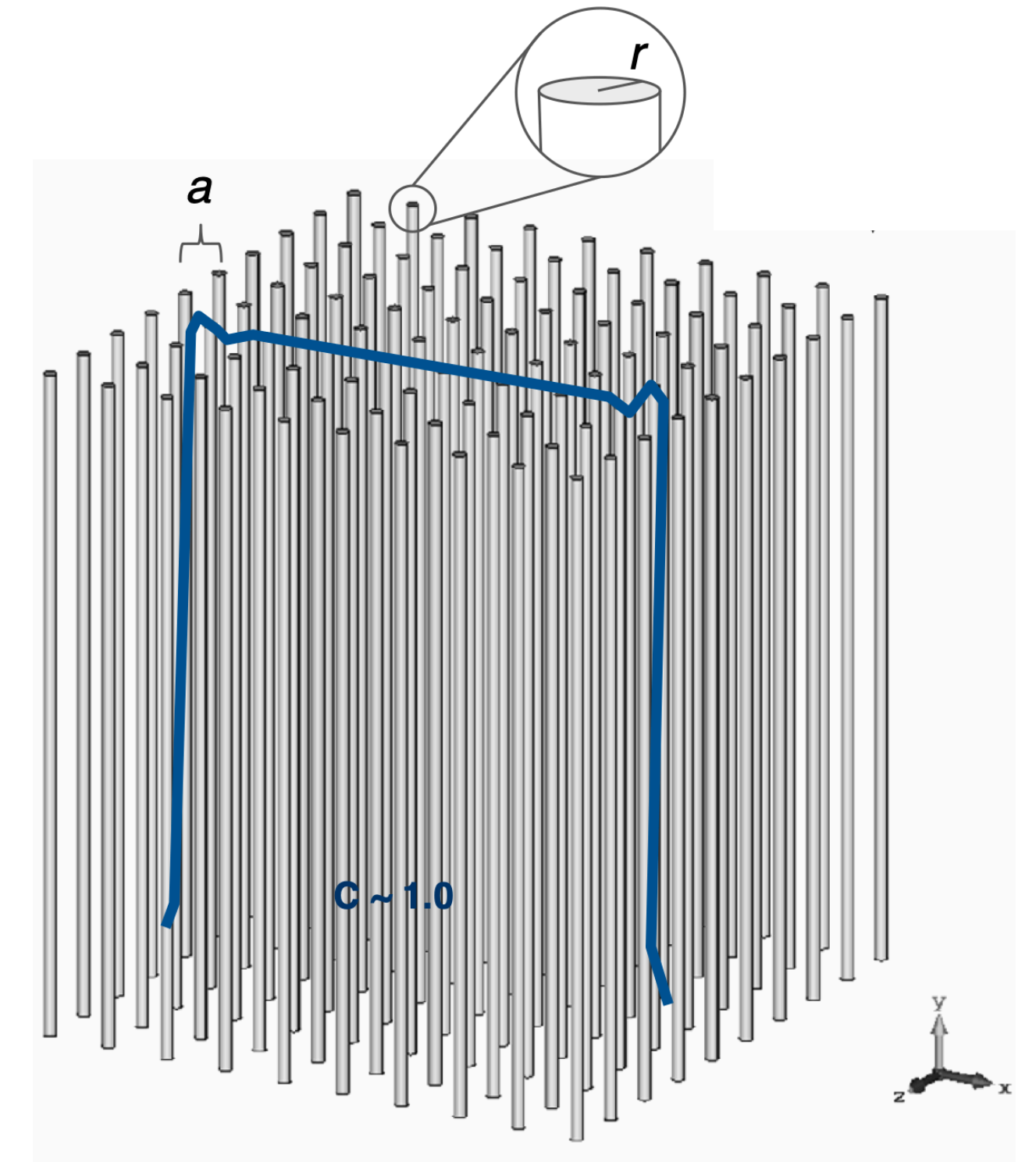
Essence: Axion-induced current gives oscillating B in toroidal/solenoidal core

MadMax



Essence: Signal boosted by tunable stack of dielectrics

ALPHA



Essence: Use metamaterials with high, tunable plasma frequency

Newer ideas

GrAHal - Grenoble Axion Haloscope

Essence: Haloscope with 9T/43T magnet;

Collaboration between CNRS, U. Grenoble & CAPP in South Korea.

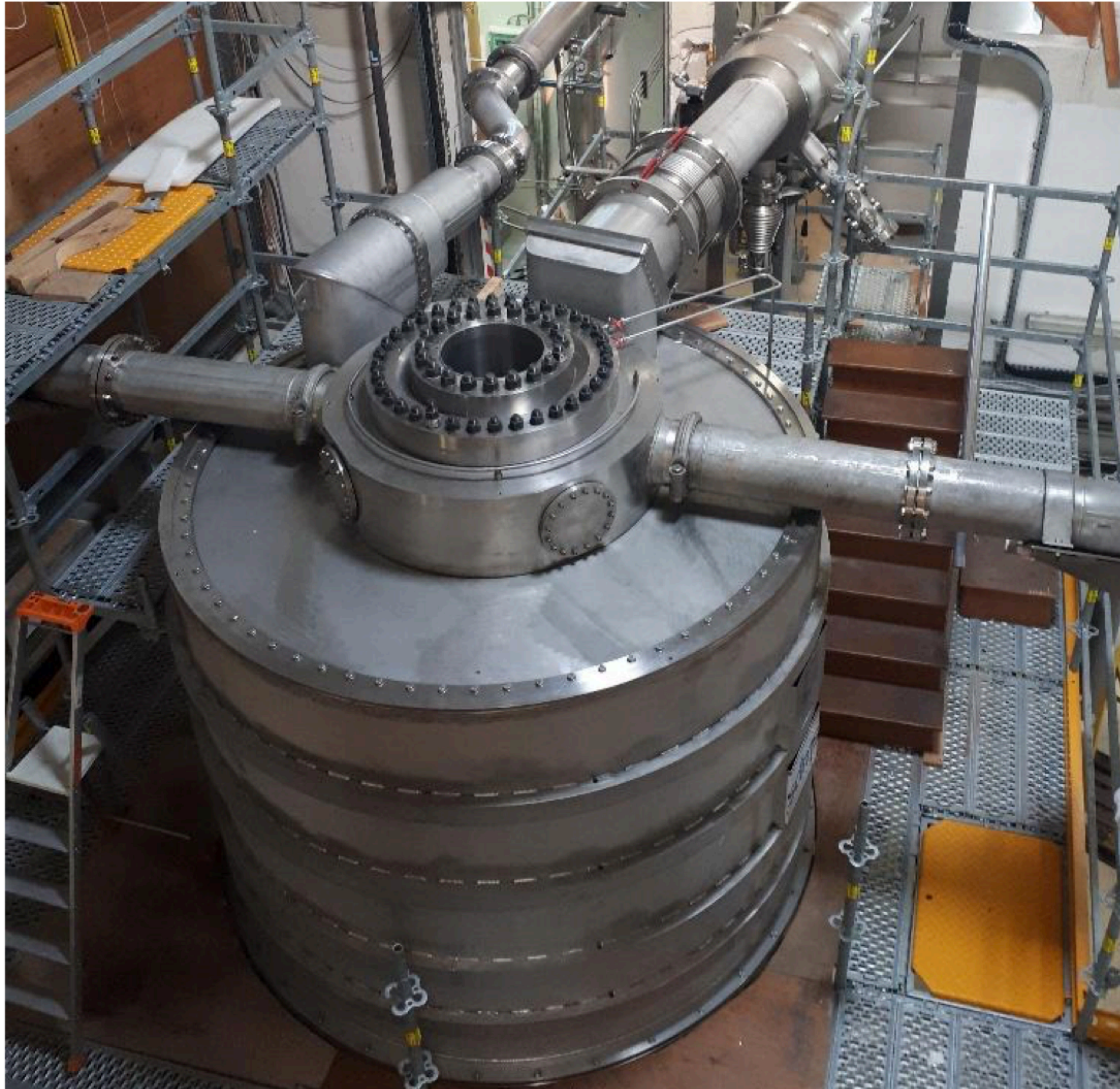
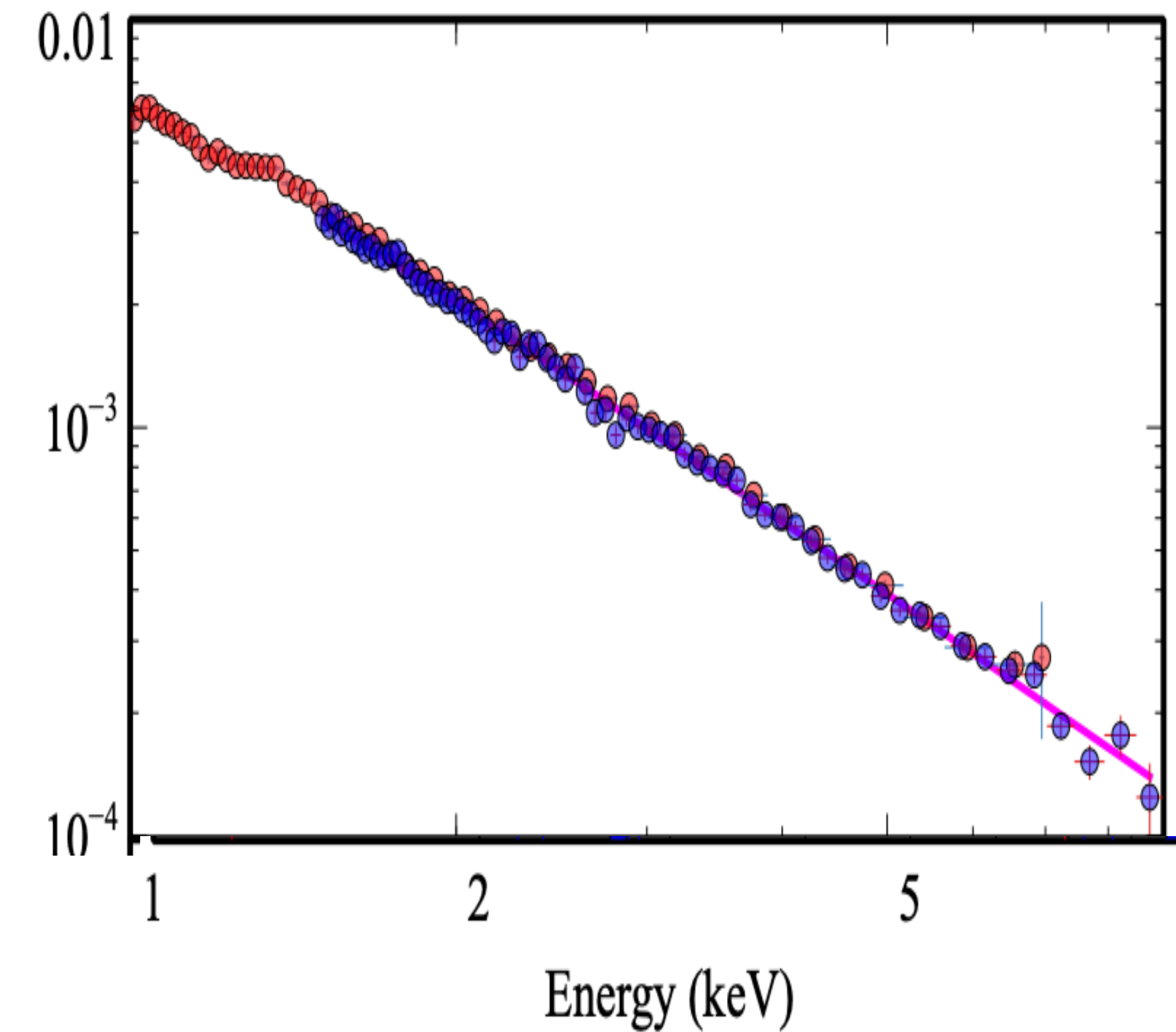
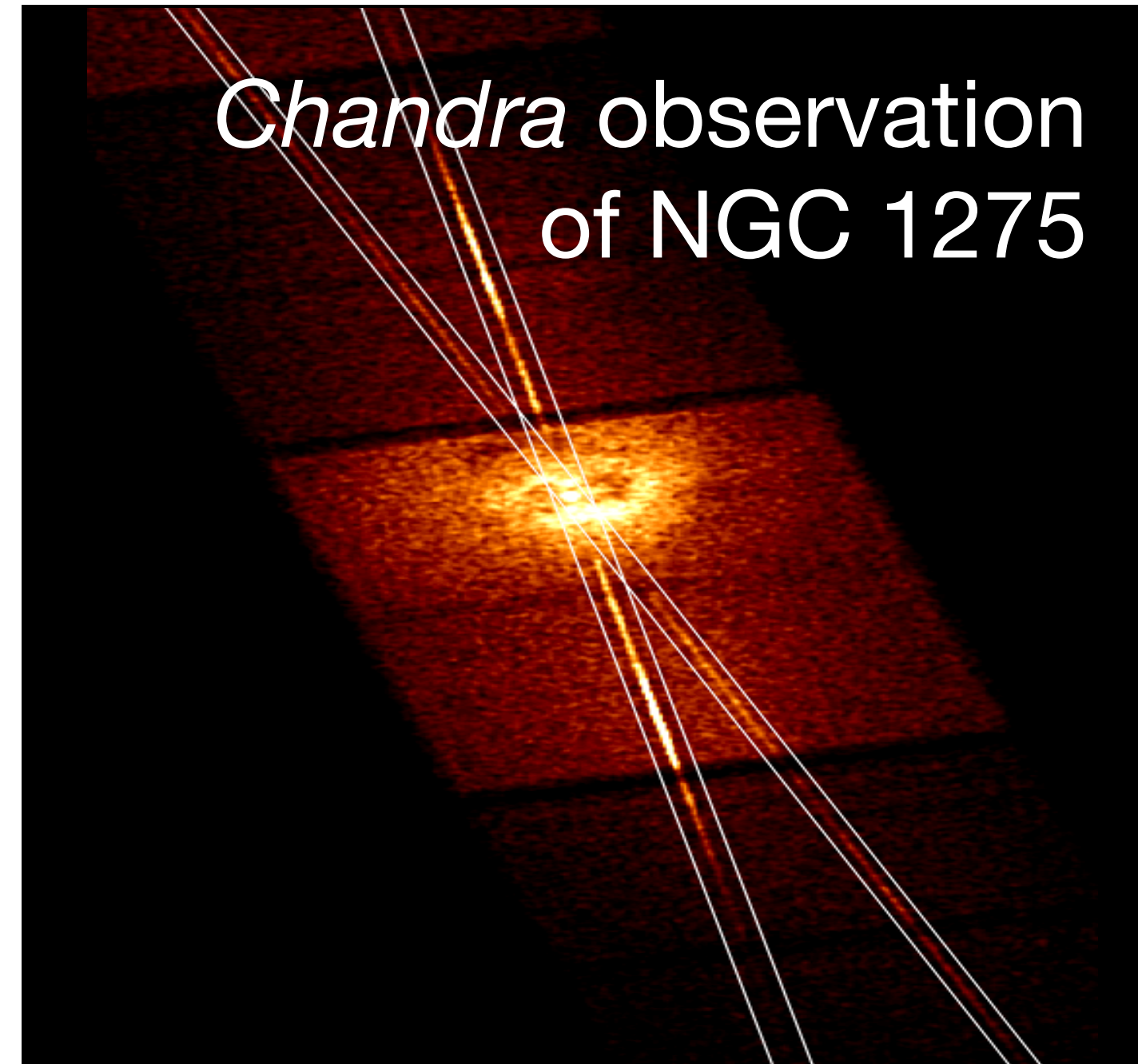


Image credit: Pugnati

Dark matter-independent probes

X-ray/ γ -ray disappearance channel

Reynolds, DM, et al.;
Sisk-Reynes, DM, et al.



Black hole superradiance

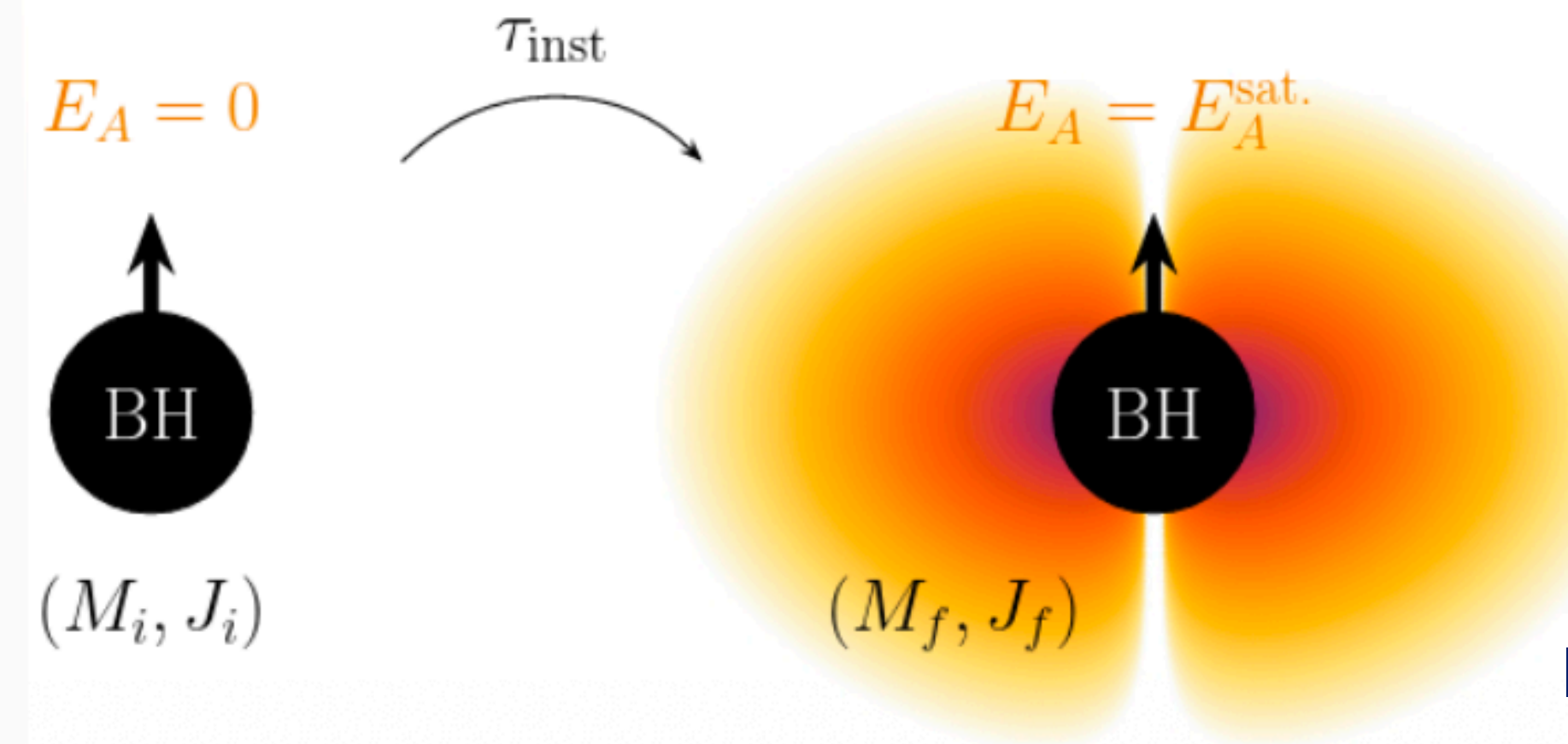


Image credit: Boskovic

Off-the (most) beaten path

Massive axions



Massive Axions

Production:

Misalignment mechanism.

$$\Omega_a/\Omega_{\text{dm}} \sim \sqrt{\frac{m_a}{\text{eV}}} \left(\frac{a_i}{3 \cdot 10^{11} \text{ GeV}} \right)^2$$

Arias et al.;

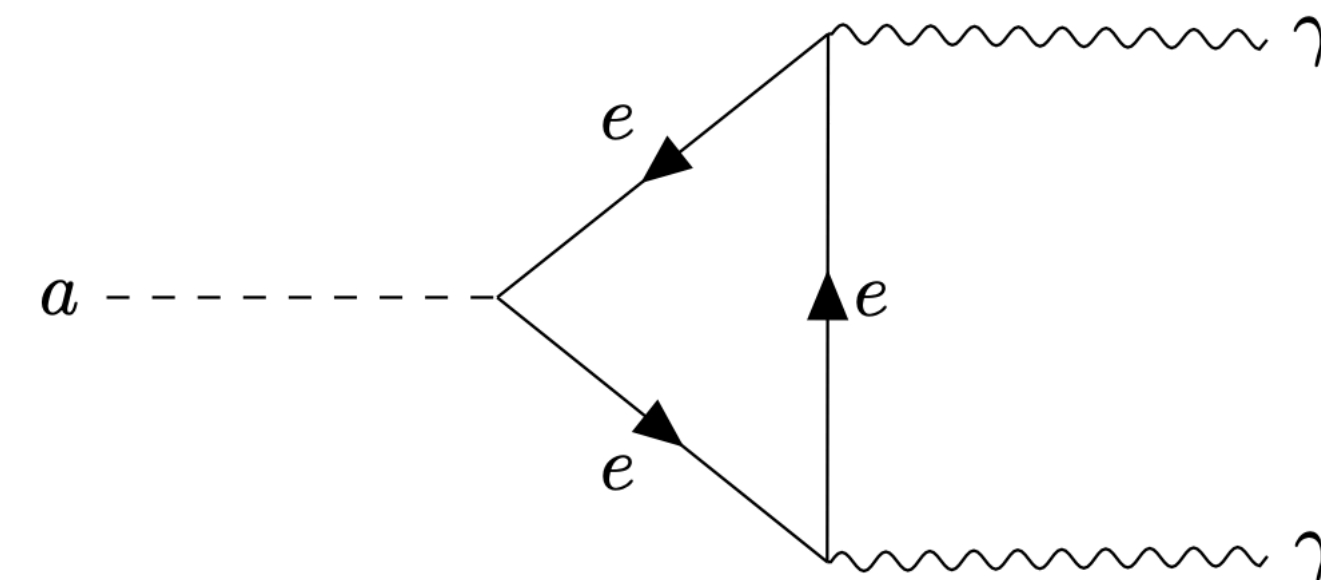
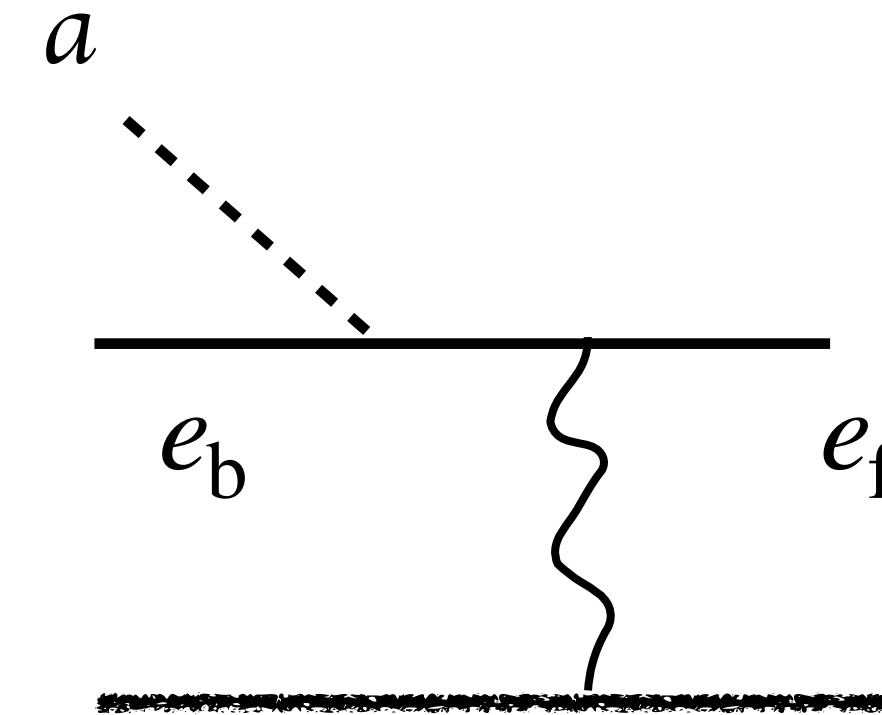
(Quasi-)thermal: “super-WIMPs”, freeze-in, ...

— increasingly important at $m_a \gtrsim 100 \text{ eV}$

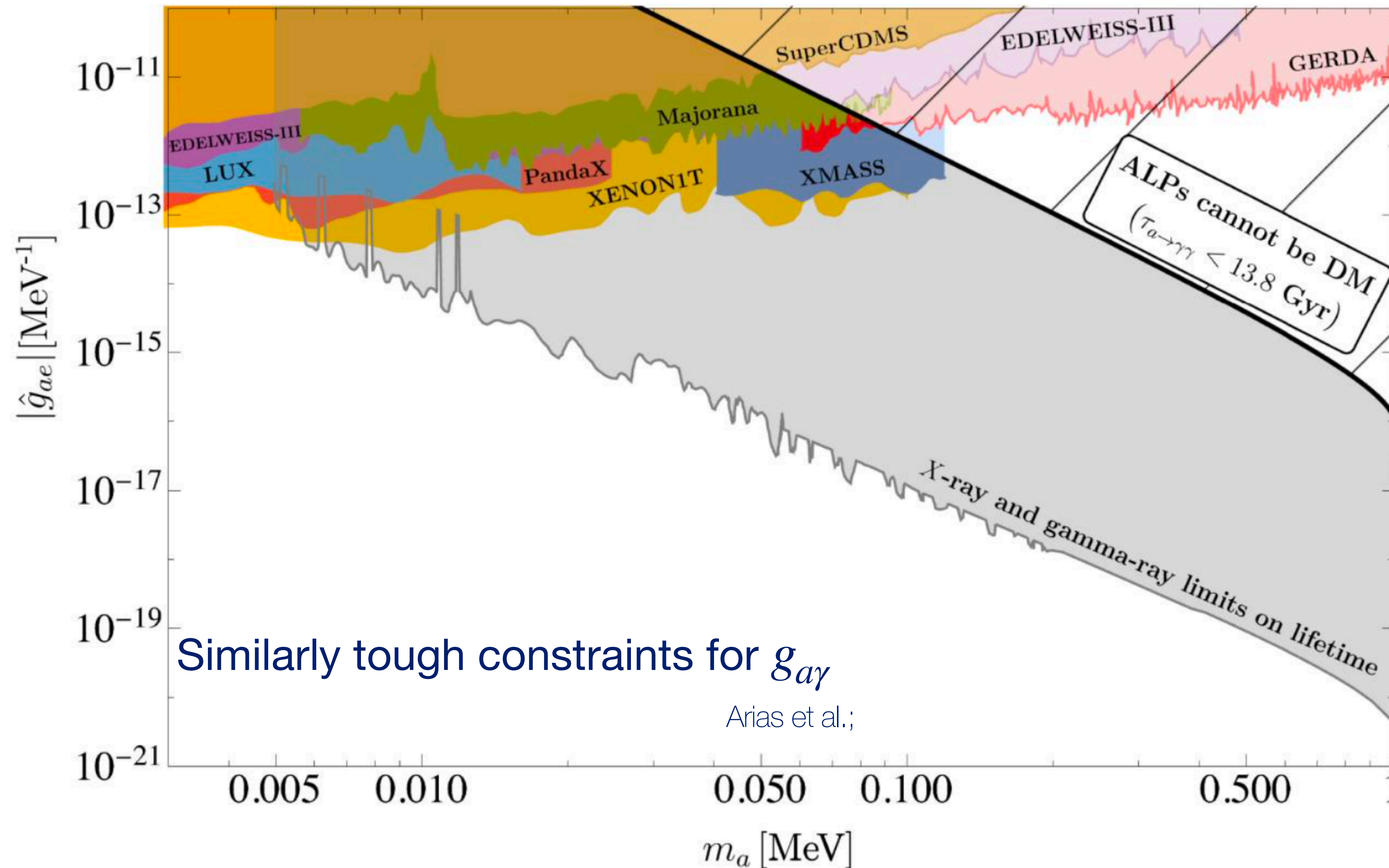
Pospelov et al.; Cadamura, Redondo; Langhoff et al.

Detection & constraints:

Axion-absorption processes



Massive Axions Severely Constrained



NEW

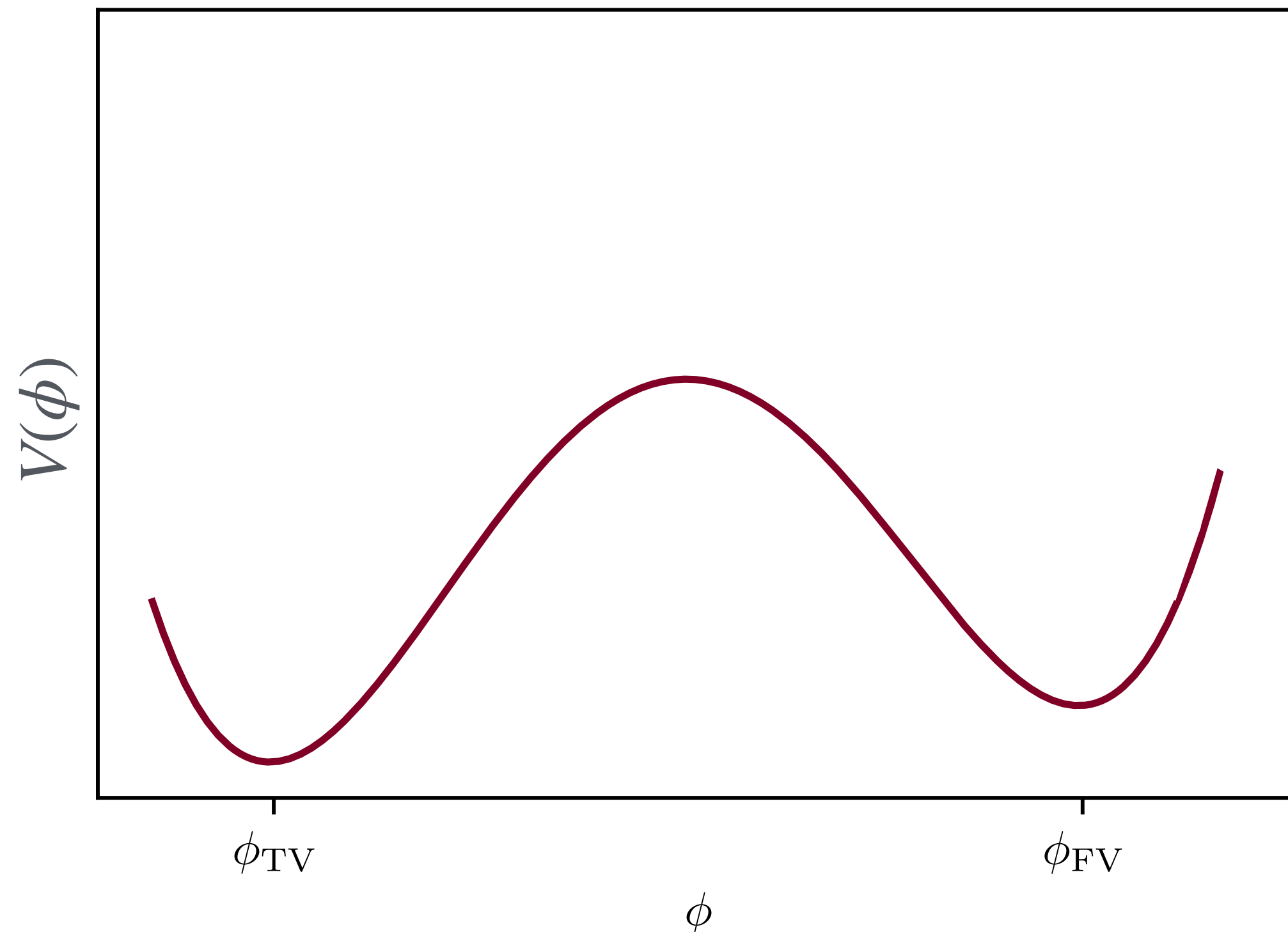
Composite dark matter from relativistic axions

A gauge theory has two parameters — quantum gravity has none

$$\mathcal{L} = -\frac{\phi}{2\Lambda}\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \frac{a}{16\pi^2 f_a}\mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

$$\phi : \text{'dilaton'} \\ \langle \phi / \Lambda \rangle = \frac{1}{g^2}$$

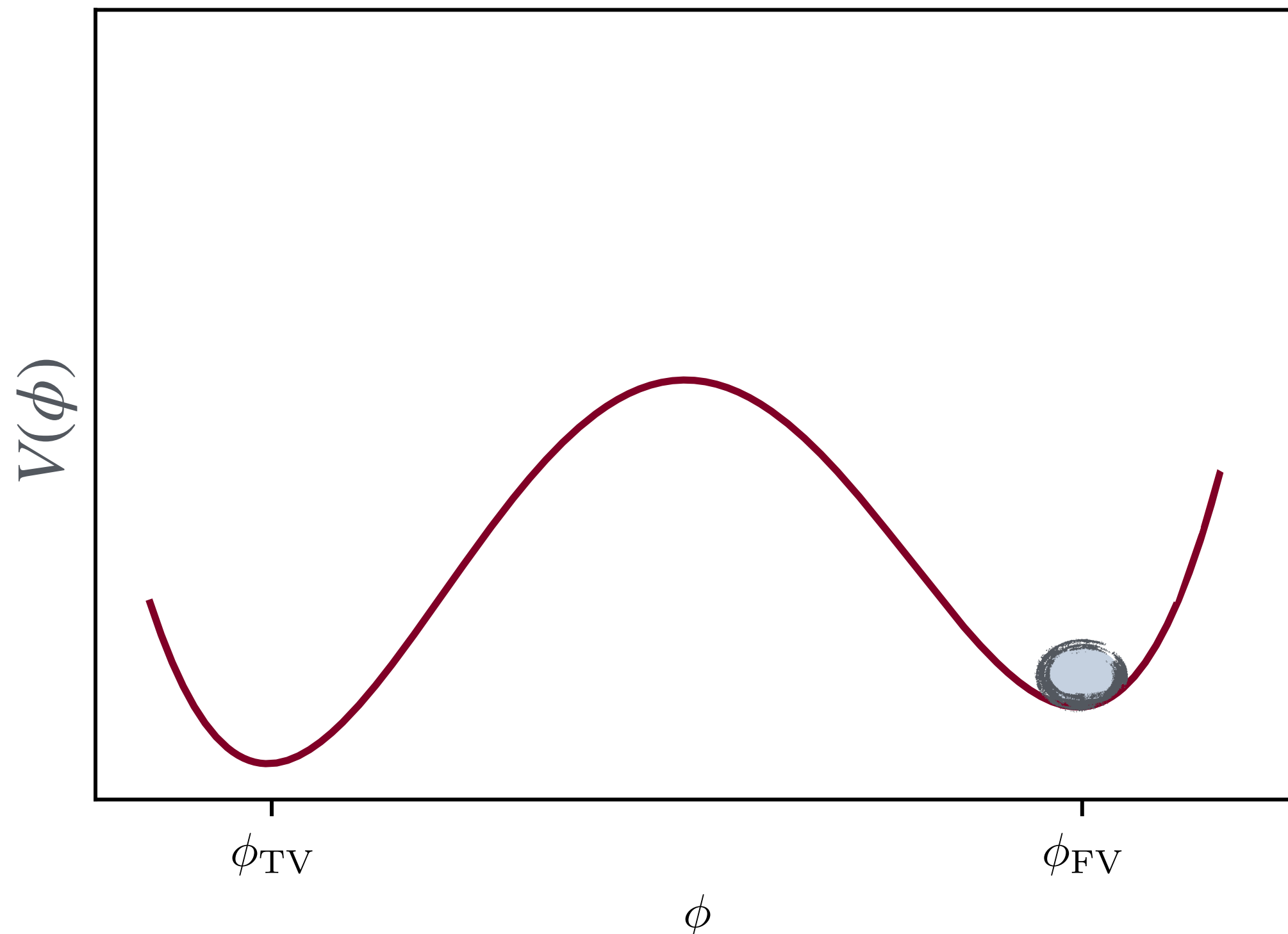
$$a : \text{axion} \\ \langle a / f_a \rangle = \theta$$



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ϕ : 'dilaton' a : axion
 $\langle\phi/\Lambda\rangle = \frac{1}{g^2}$ $\langle a/f_a\rangle = \theta$



The axion potential is exponentially sensitive to ϕ .

$$V(\phi, a) = M^4 e^{-S(\phi)} \left(1 - \cos\left(\frac{a}{f_a}\right) \right)$$

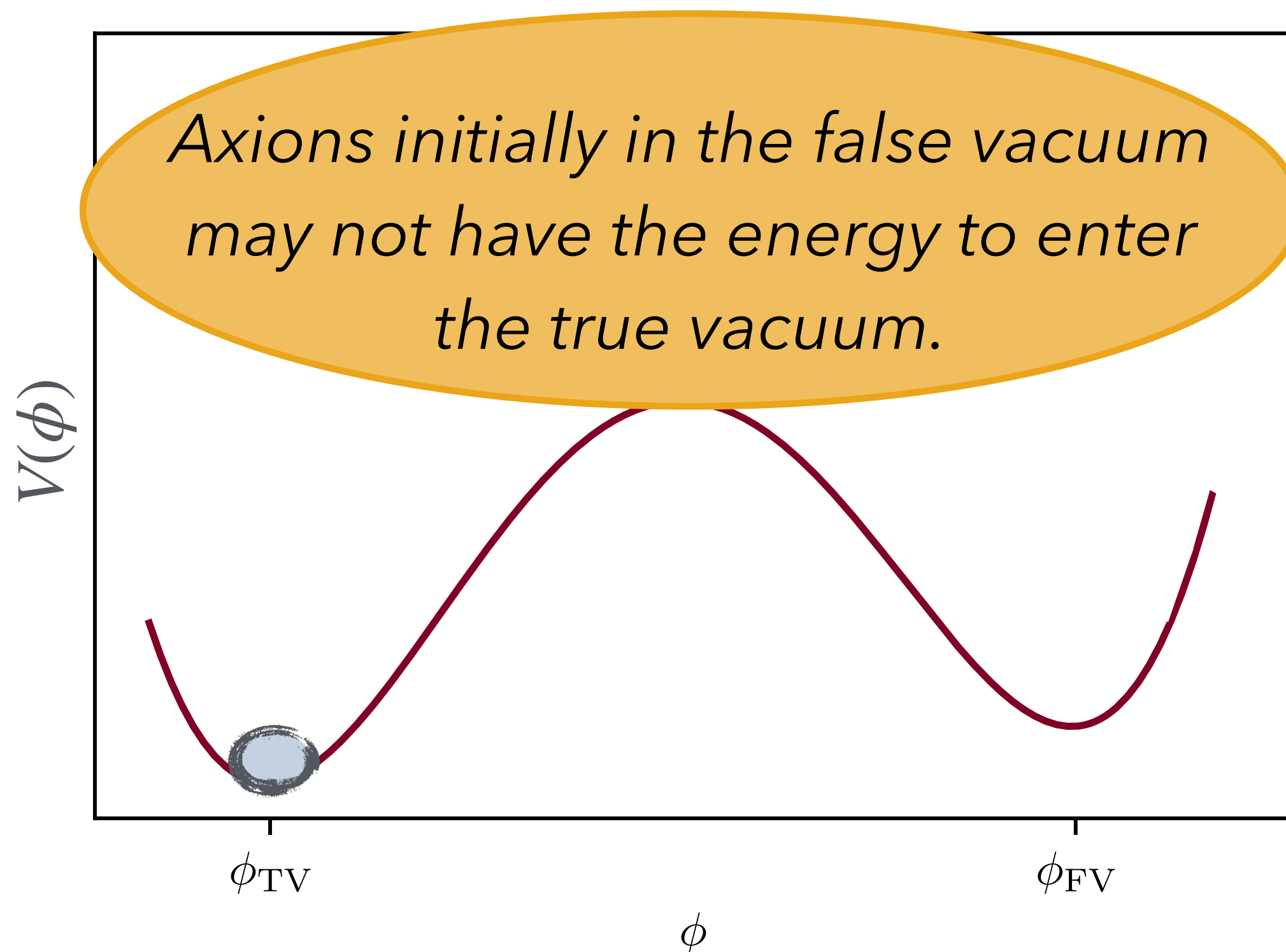
$$m_a^2 \Big|_{TV} = m_a^2 \Big|_{FV} \exp\left(S_{FV} \cdot \frac{|\Delta f|}{f_{FV}}\right)$$

Often $\mathcal{O}(100 - 1000)$

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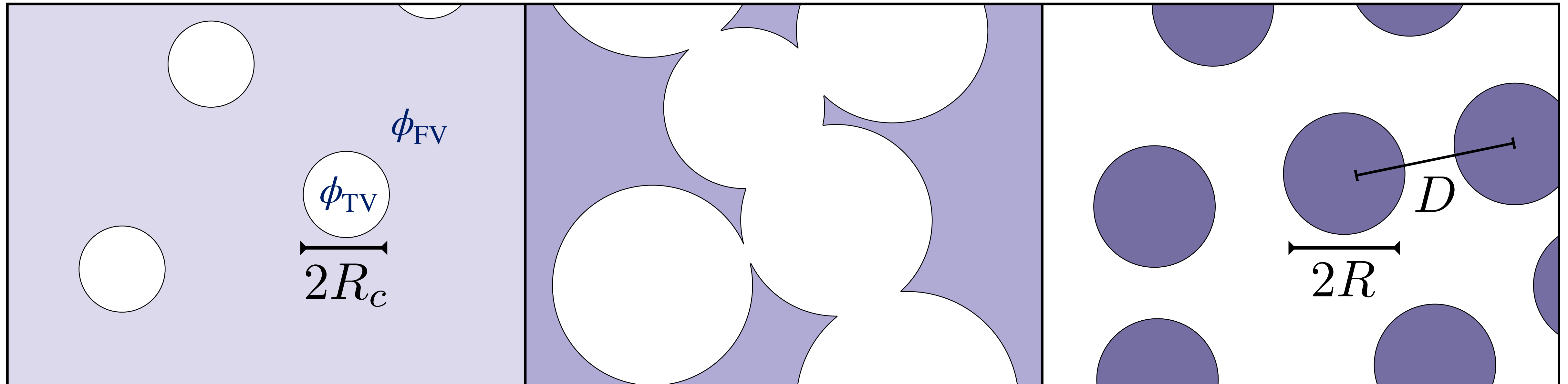
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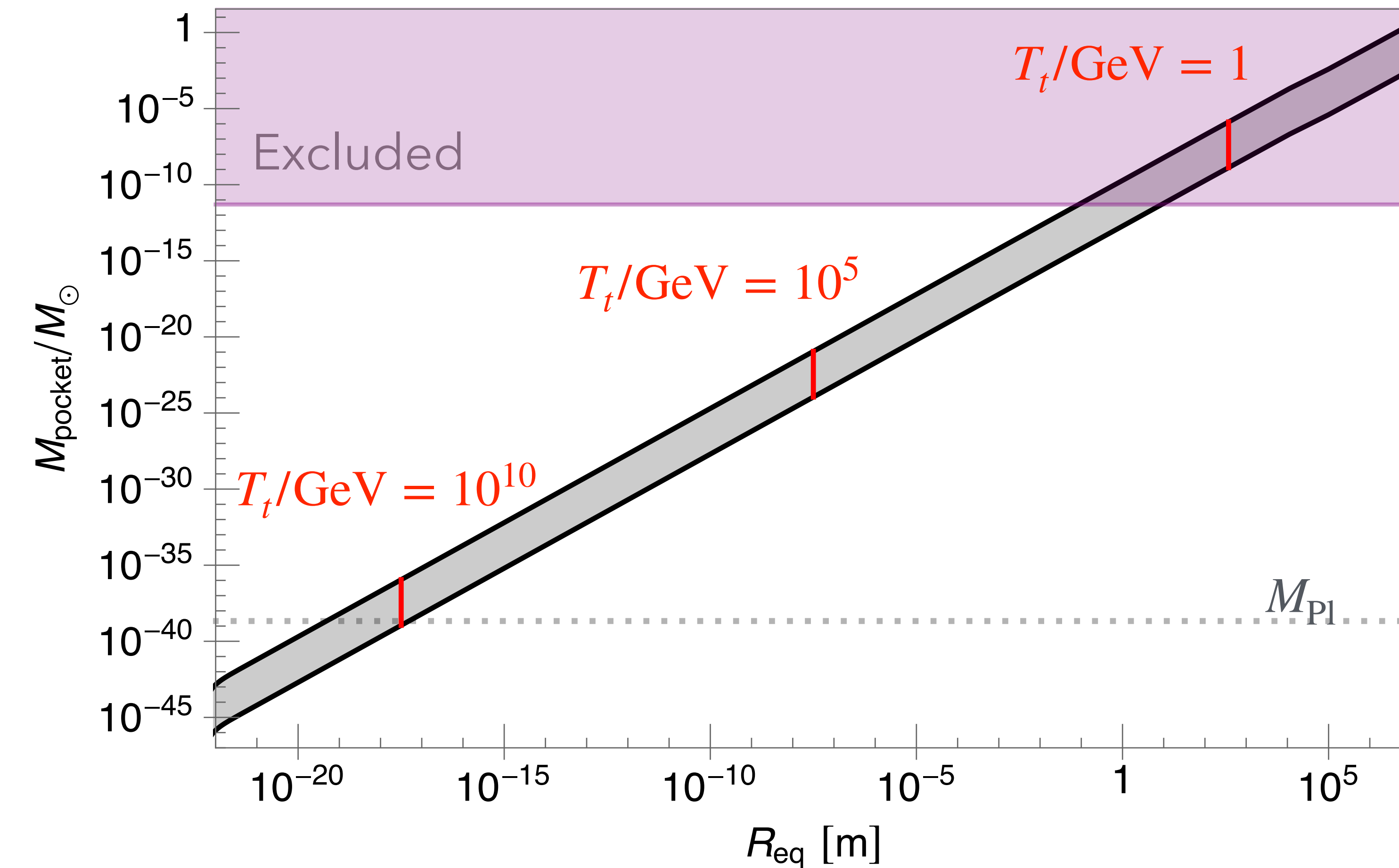
Formation of Axion Relic Pockets



Axions compressed, but have nowhere to go.

Mass v. Radius

Single-parameter solution, but with a broad range.



A priori, radius may run from point-like to galactic.

Microlensing constraints:
 $T_t \gtrsim 13 \text{ GeV}$.

Viable range:

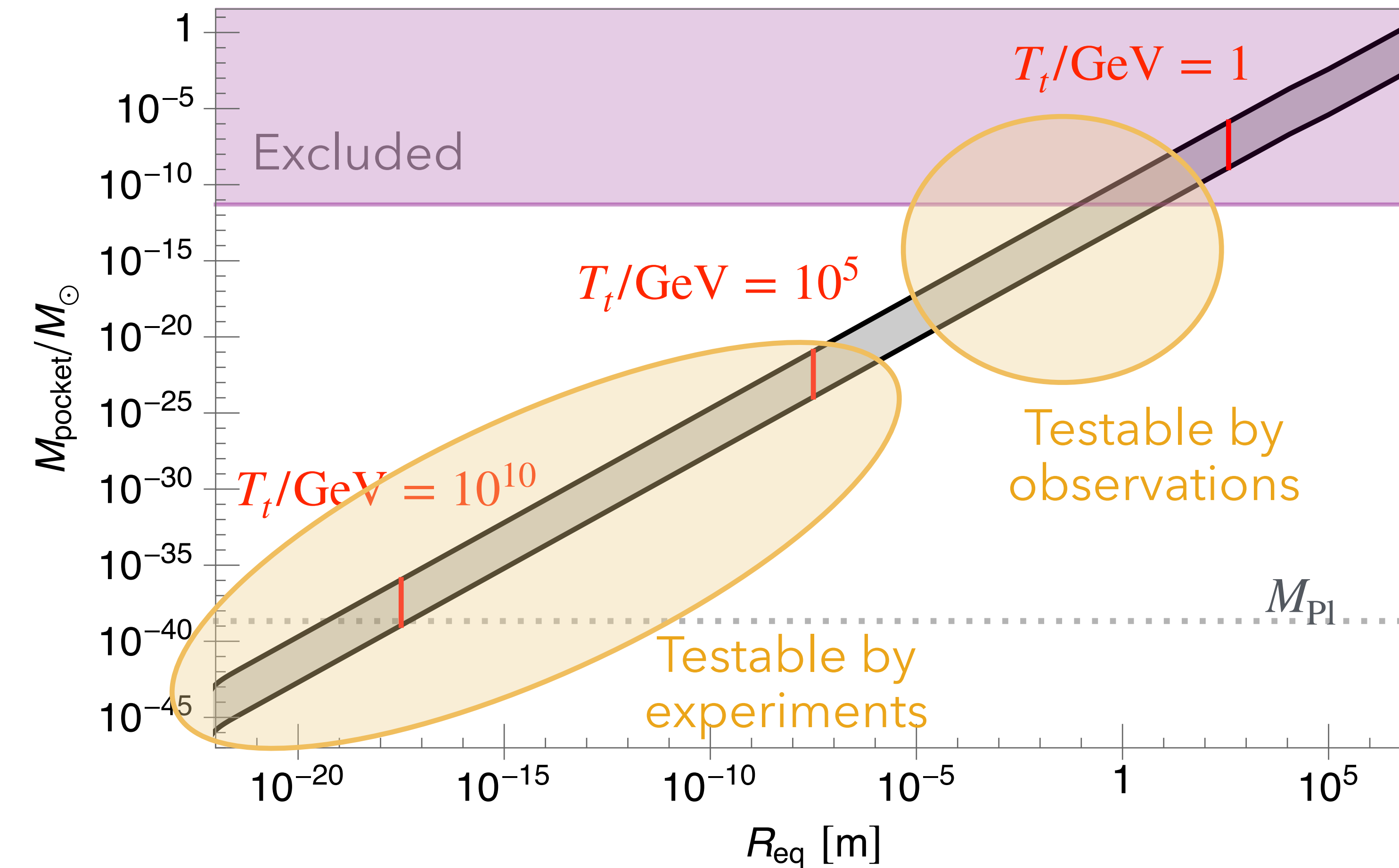
$$10^{10} \text{ GeV} < M_{\text{pocket}} \lesssim 5 \cdot 10^{-12} M_{\odot}$$

$$10^{-25} \text{ m} \lesssim R_{\text{pocket}} \lesssim 20 \text{ cm}$$

$$10^{10} \text{ GeV} \gtrsim T_{\text{eq}} \gtrsim 5 \text{ GeV}$$

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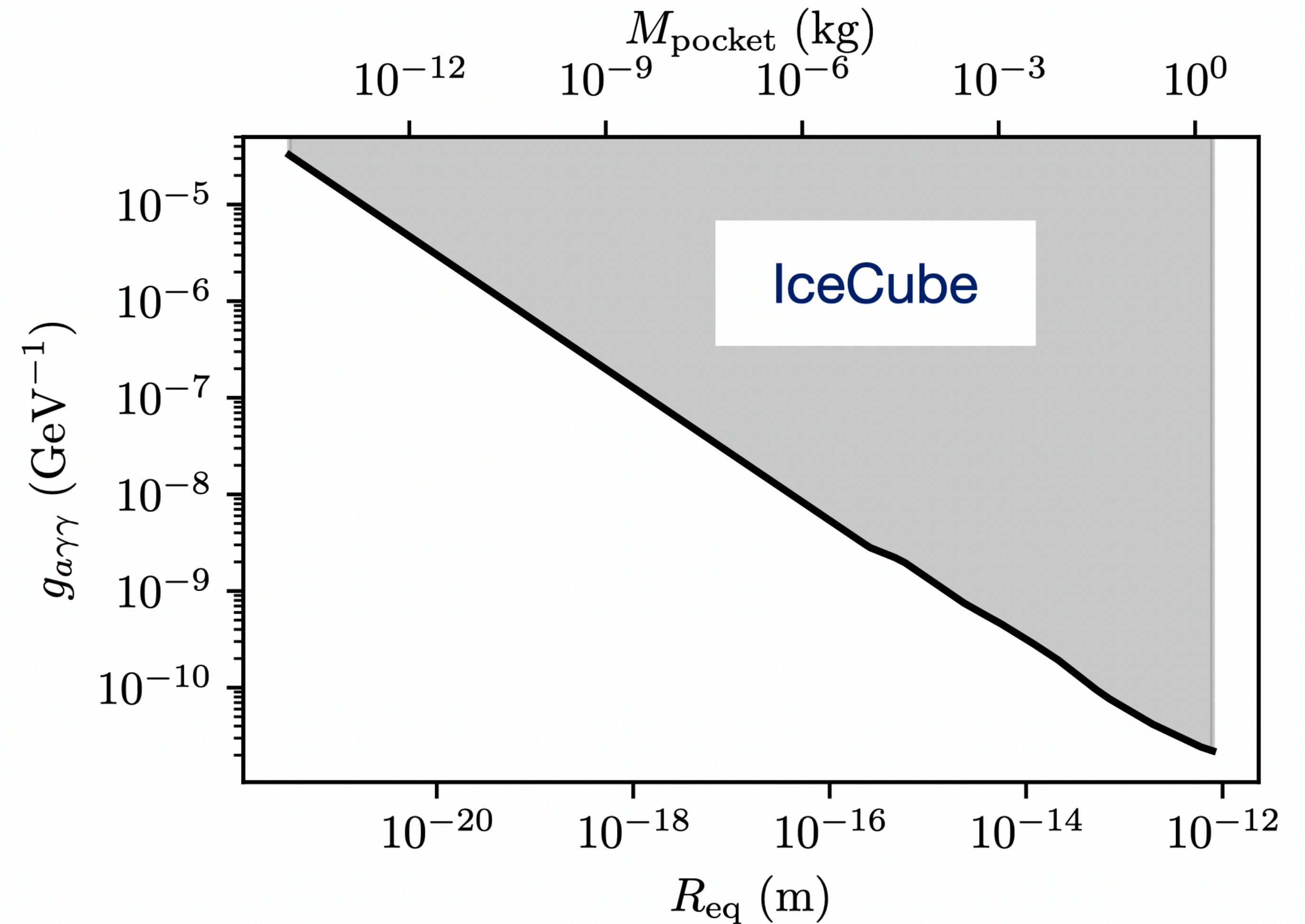
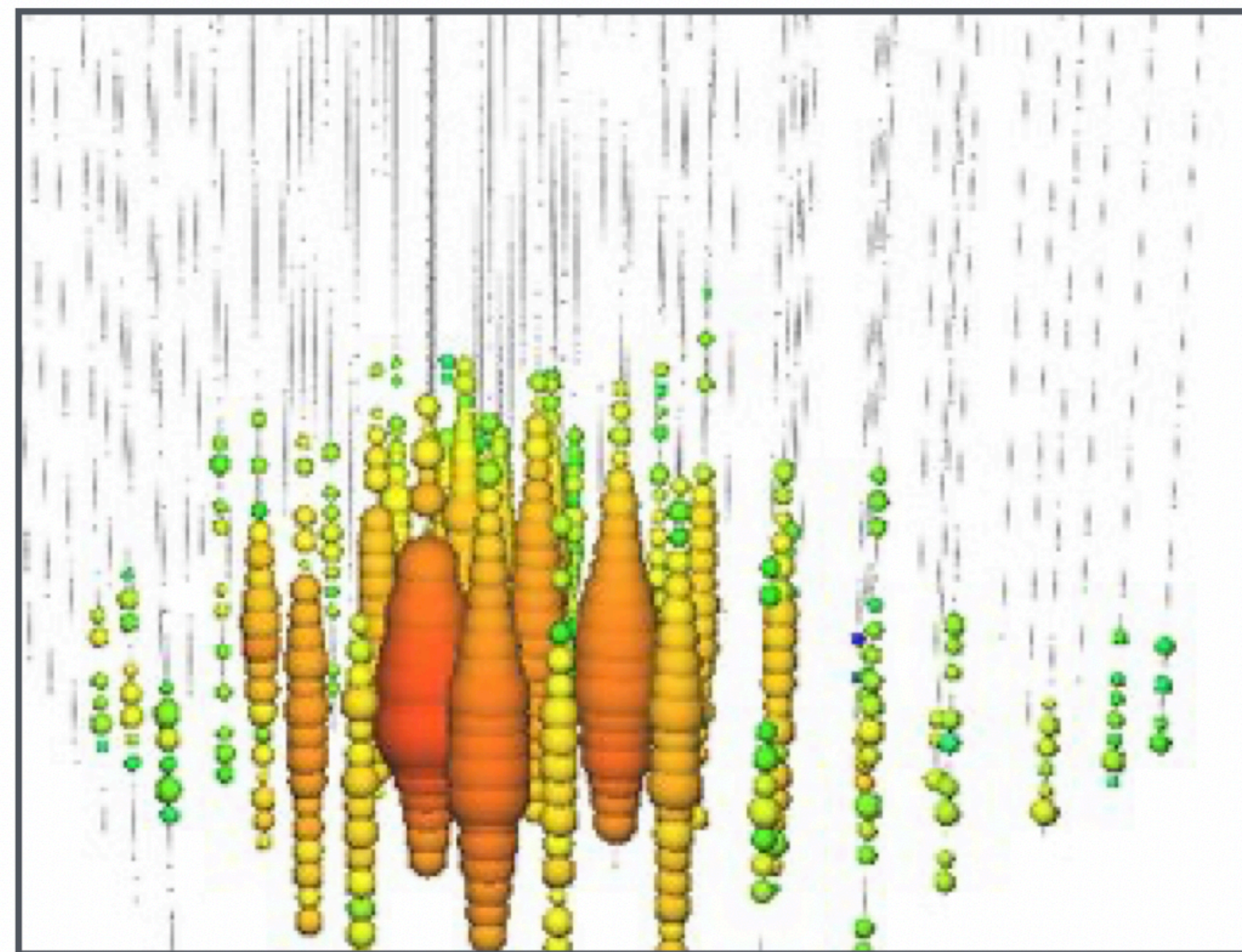
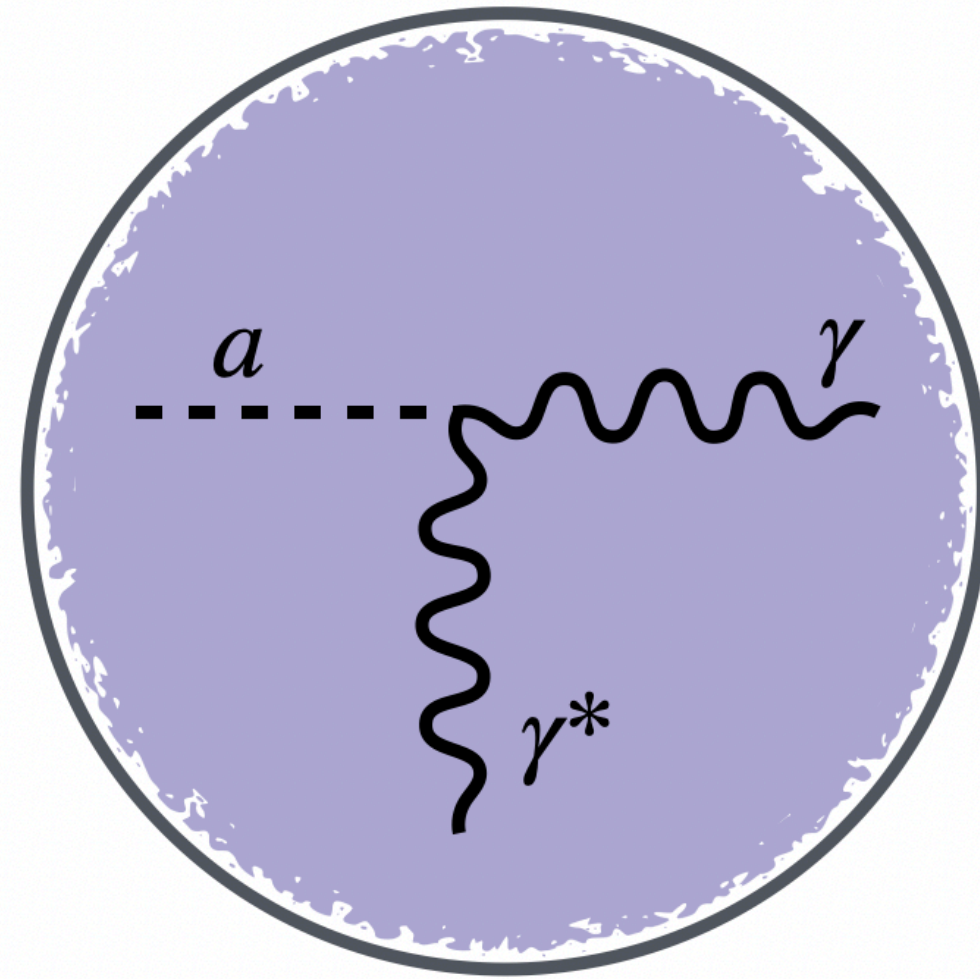
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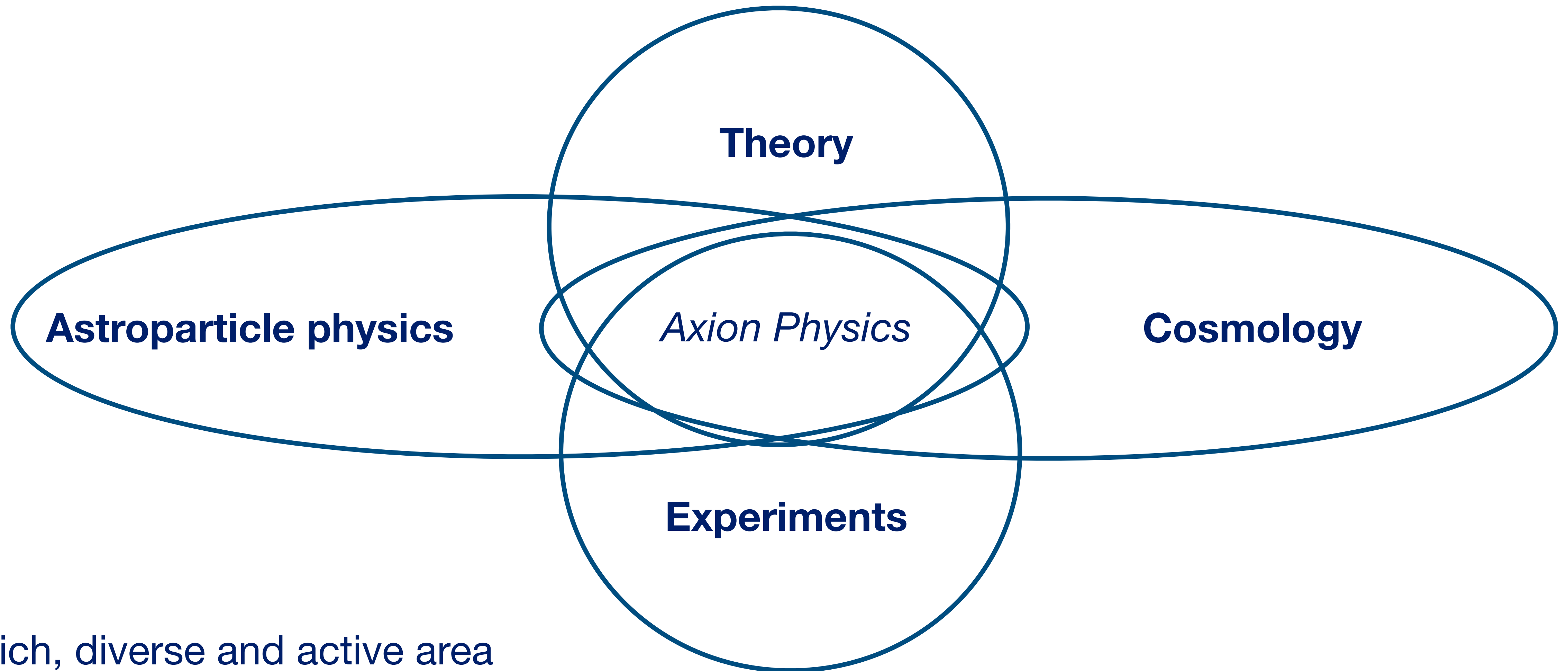
$$10^{10} \text{ GeV} \gtrsim T_{\text{eq}} \gtrsim 5 \text{ GeV}$$

Terrestrial Axion Relic Pockets searches



Isotropic distribution of EM cascades
with TeV - EeV energies.

Conclusions

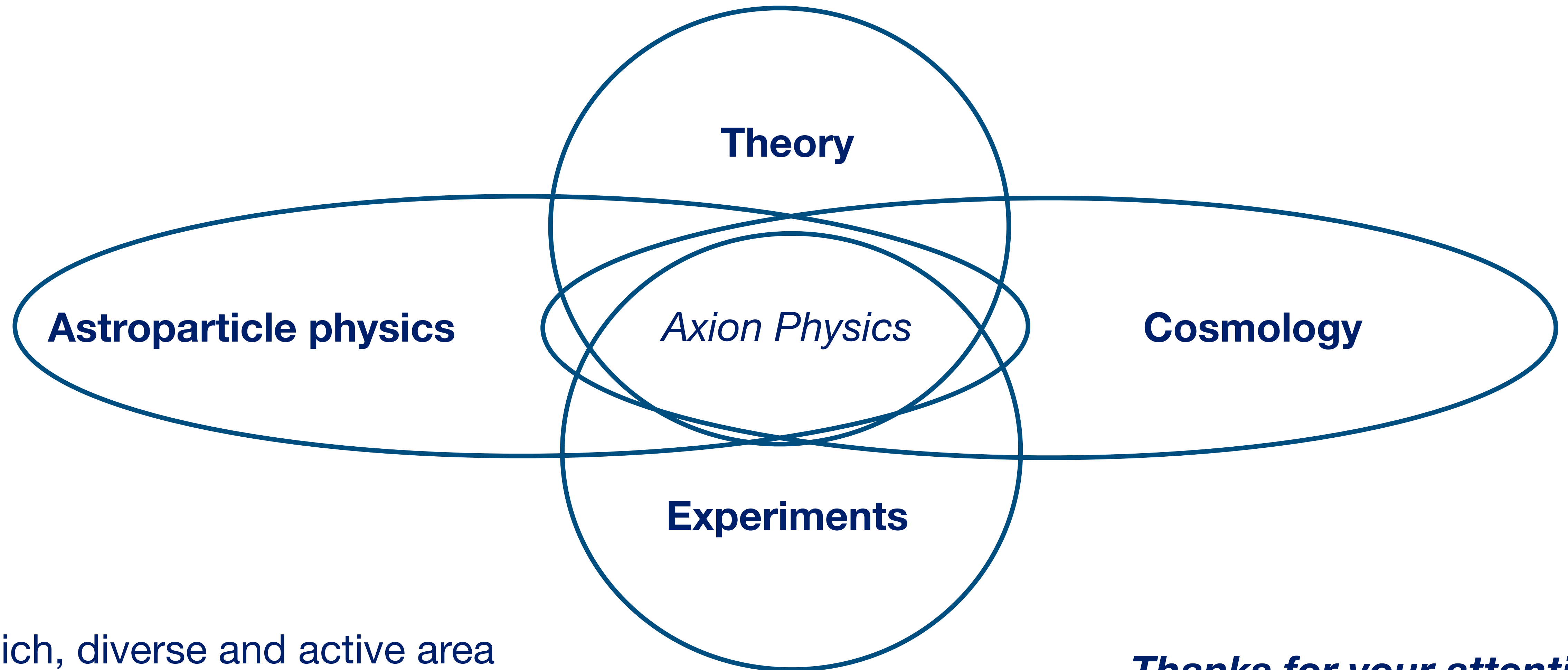


Rich, diverse and active area

Central ideas increasingly directly tested

New ideas still developing; strong interplay between theory & experiments

Conclusions



Rich, diverse and active area

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Thanks for your attention!