Sharpening the "Fuzzy" Dark Matter

Luca Visinelli

Stockholm University & NORDITA

CDM Framework

- Gas cooling and star formation within DM halos is the standard paradigm for the origin of galaxies White&Rees (1978)
- Numerical simulations of DM halos highlight a universal profile (NFW pivotal paper), with a "cuspy" halo

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- Over-prediction of DM core density

Dubinski&Carlberg (1991); Moore *et al.* (1998)

- $O(10)$ overabundance of small satellites compare to MW

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Alleviated by cutoff of $P_{\rm CDM}(k)$ at $k \sim 4.5\,h\,{\rm Mpc}^{-1}$

Kamionkowski&Liddle (1999)

Possible explanation: FDM

- deBroglie wavelength $\lambda_{\rm dB} \sim \frac{1}{mv} \sim \frac{1}{mr}(G\rho)^{-1/2}$

- For an object of size $r \sim \lambda_{\rm dB} \sim r_J \sim (G\rho)^{-1/4}\, m^{-1/2}$

$$\lambda_{\rm dB} = 0.3\,{\rm kpc}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{-1}$$

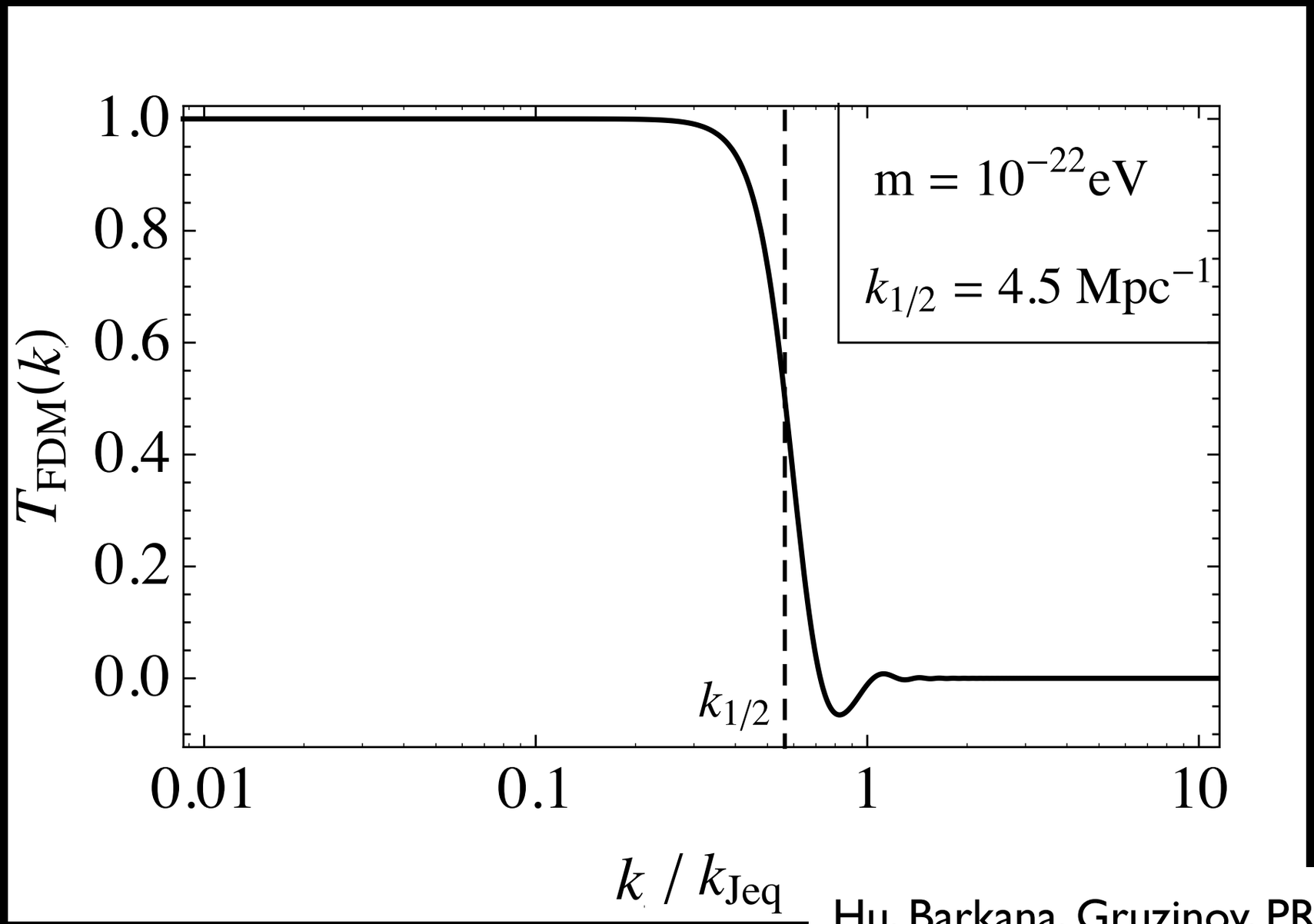
$$M_{\rm DwG} = 10^{10}\,M_\odot$$
$$r = 10\,{\rm kpc}$$

Baldeschi Gelmini Ruffini, PLB **122** 221 (1983)

Hu, Barkana, Gruzinov, PRL **85** (2000)

Possible explanation: FDM

Power spectrum $P_{\rm FDM}(k) = T^2_{\rm FDM}(k) P_{\rm CDM}(k)$



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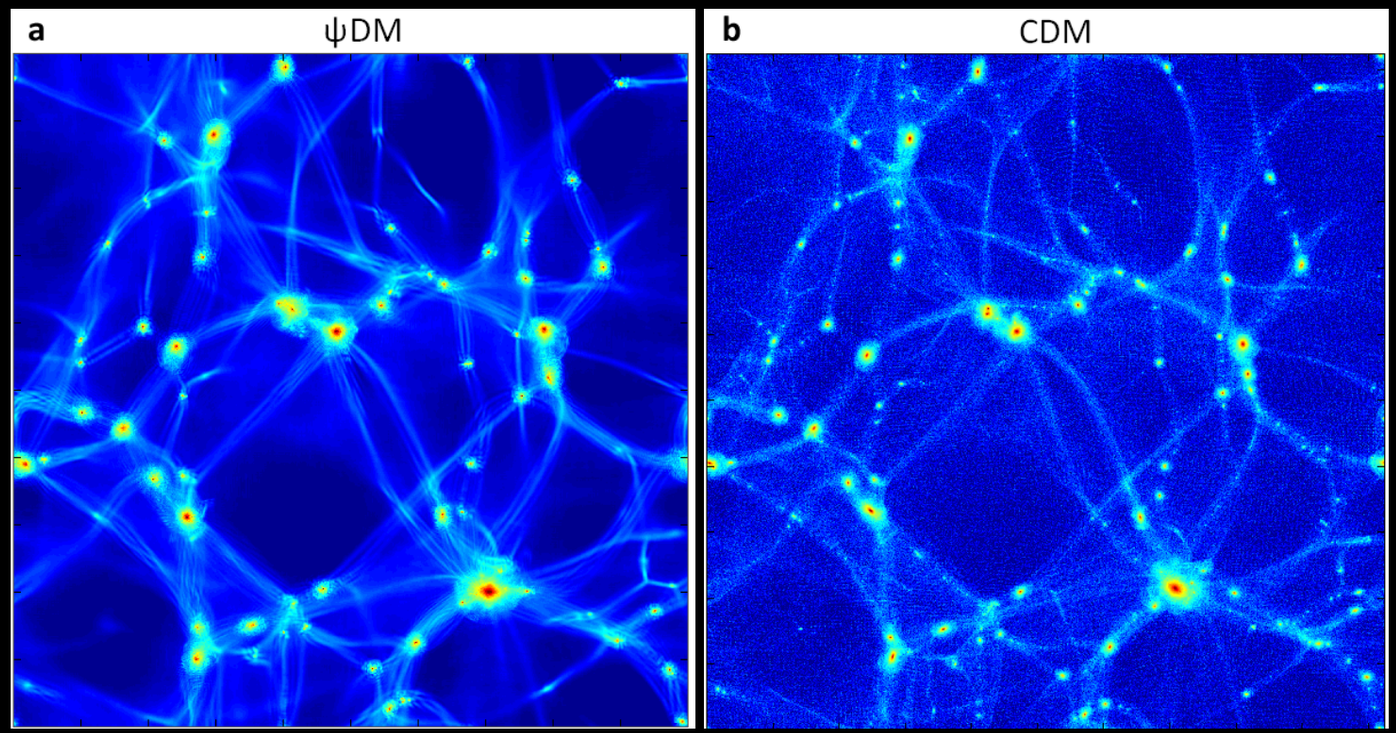
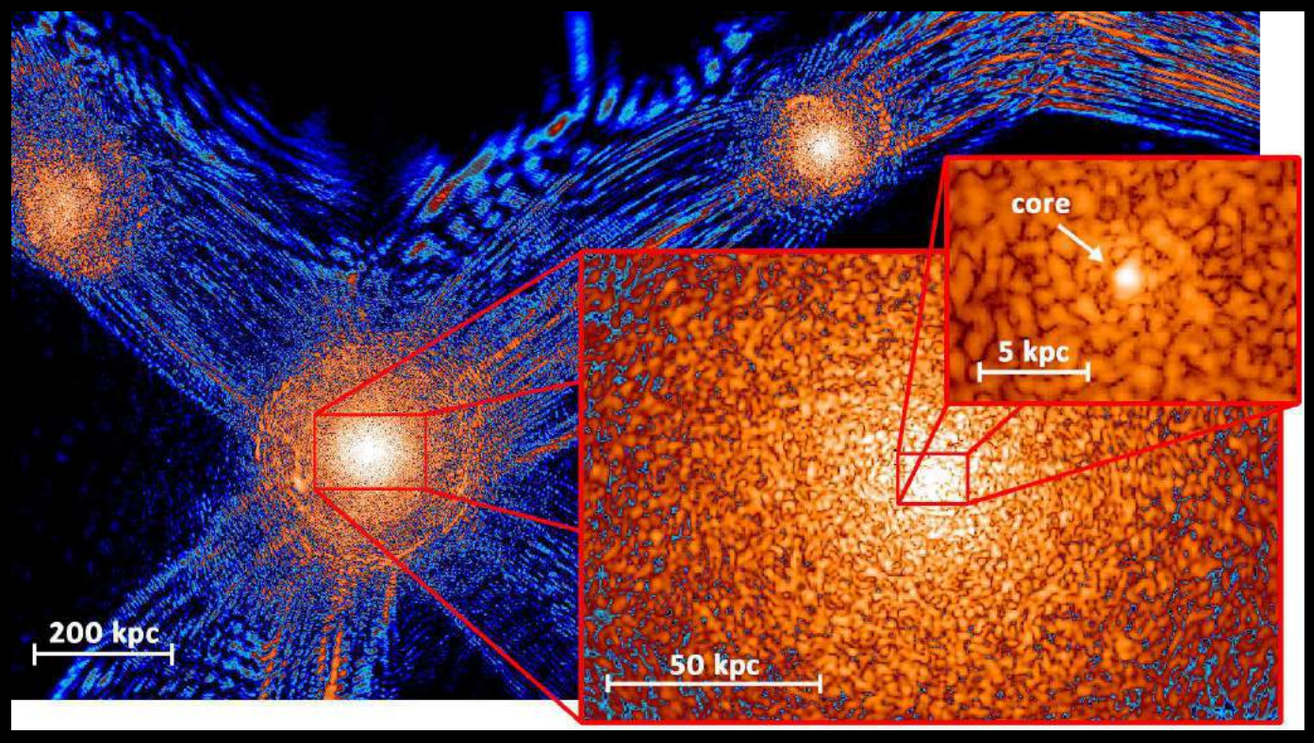


FDM is indistinguishable from CDM on large scales....

... galactic-size self-gravitating soliton cores are produced



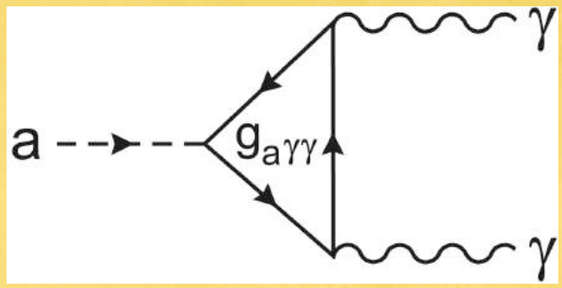
Schive *et al.* Nature **10** 496 (2014)

Axion physics primer

Motivations

QCD is CP-conserved by PQ symmetry

- Effective axion-photon coupling
- $g_{a\gamma\gamma} \propto m_a$
- $m_a f_a \propto \Lambda^2_{\rm QCD}$

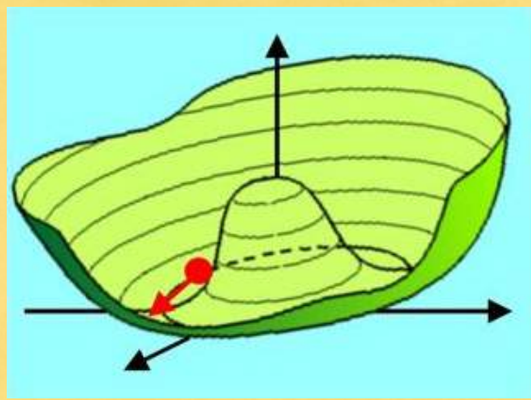


Axion cosmology

Axions are non-thermal relics

Non-relativistic, so **CDM candidates**

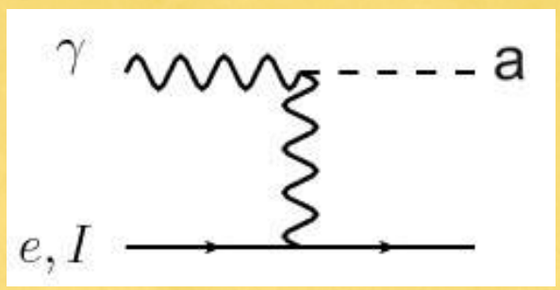
Axion mass $\sim 10 \mu eV$ (but see later....)



Solar & Stellar axions

"Primakoff" effect, look for axions emitted

CAST, Barth *et al,* JCAP **1305** 010 (2013)
IAXO, Armengaud *et al,* arXiv:1401.3233



Cavity and other lab searches

* Axion-photon convert in strong **B** field
Sikivie, PRL **51** 1415 (1983), best for $m_a \lesssim 10\,\mu\mathrm{eV}$
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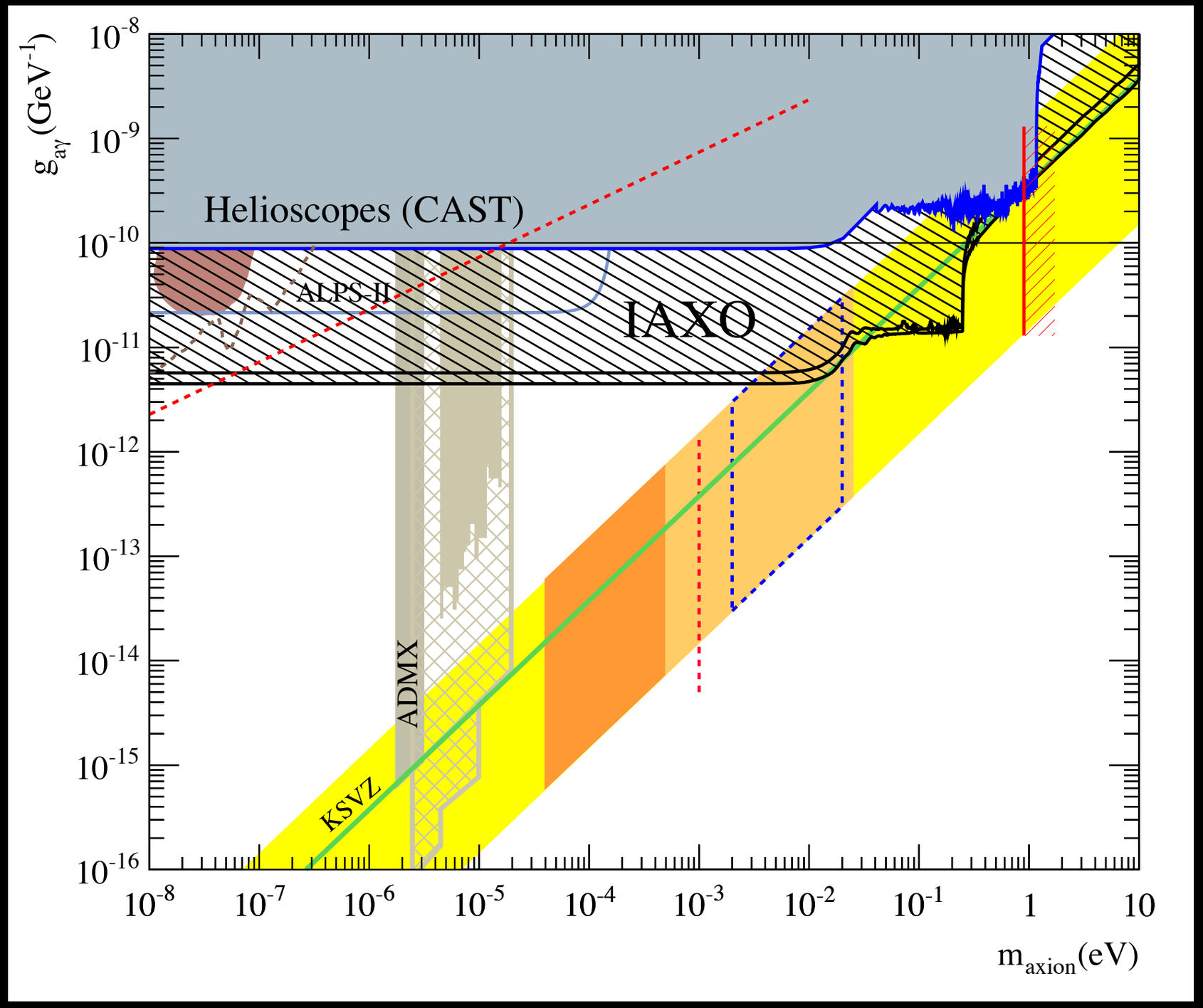
Axion parameter space



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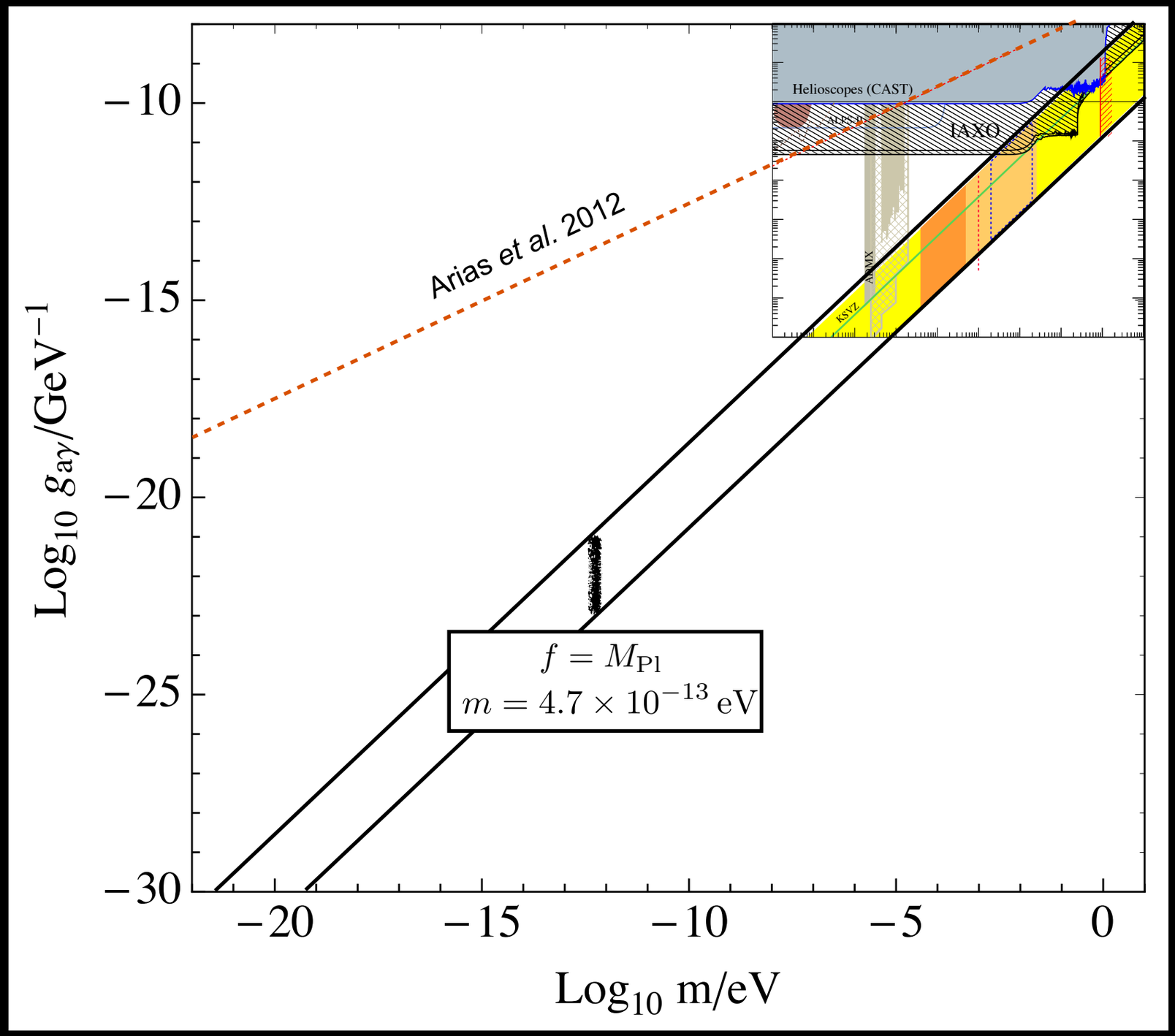

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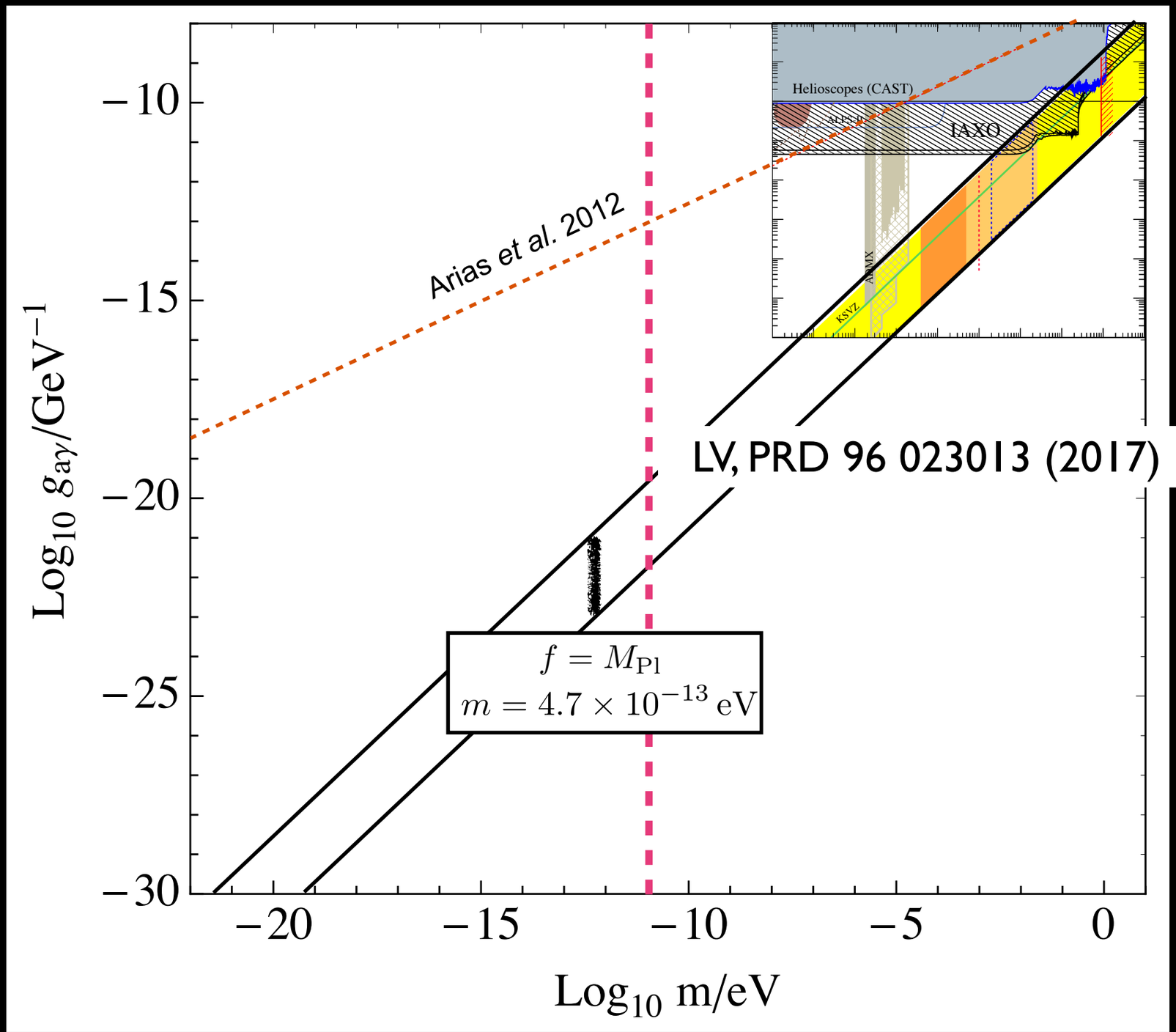

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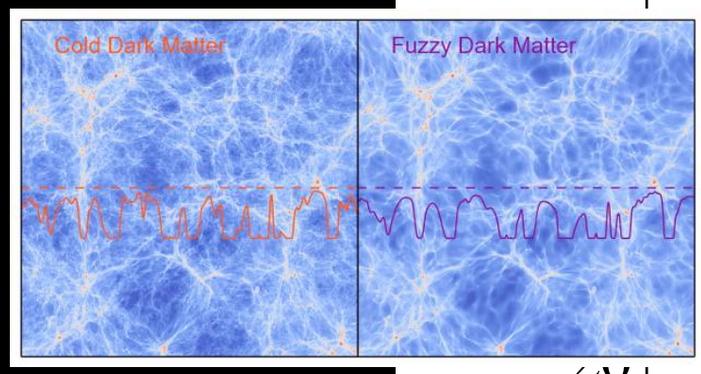

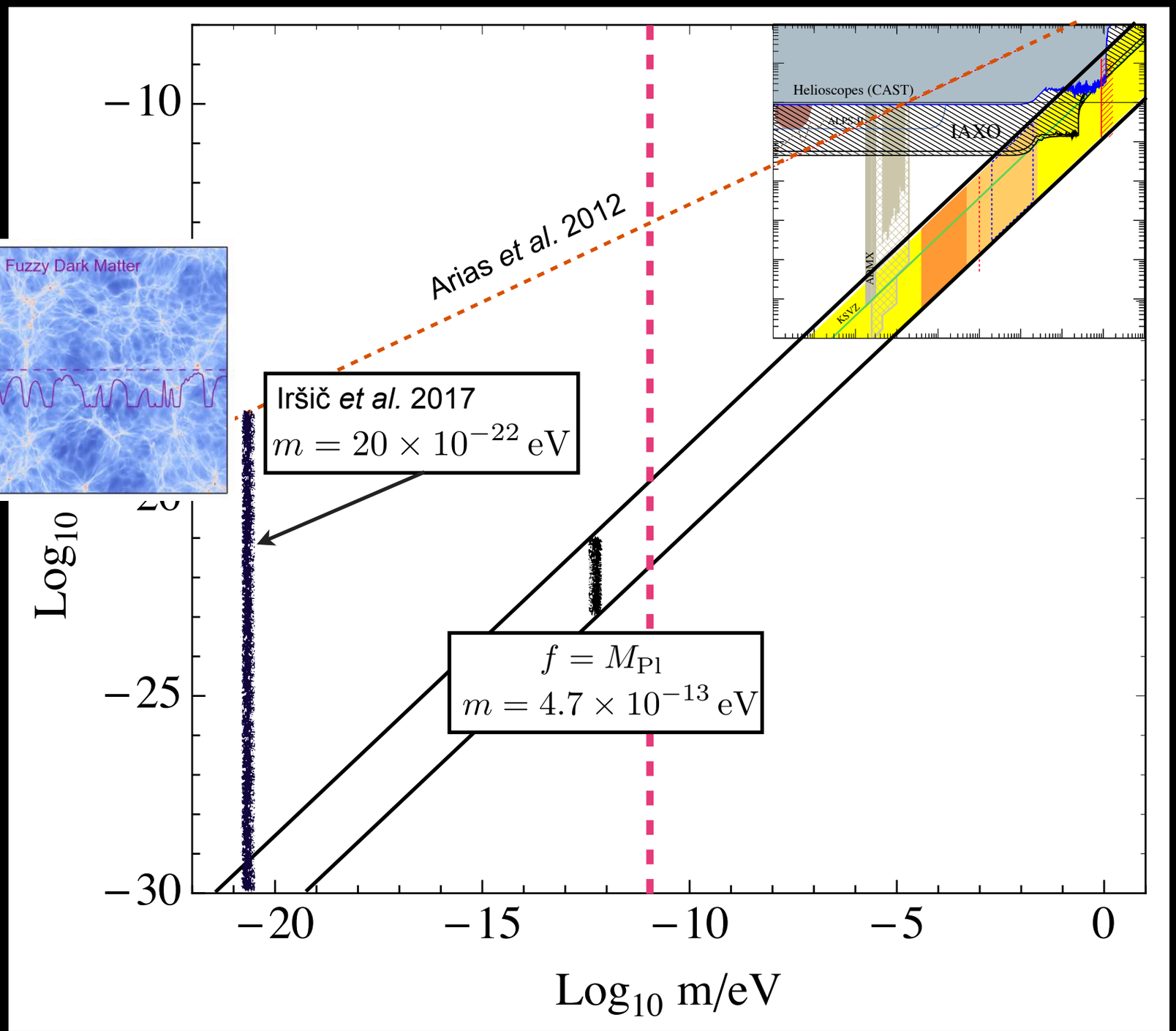

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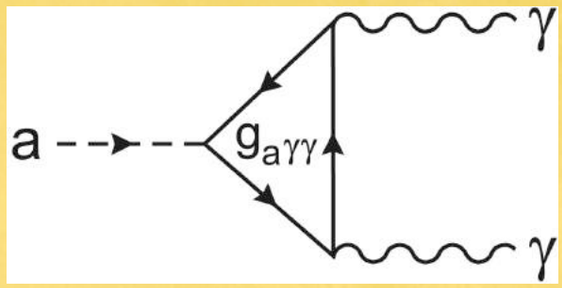

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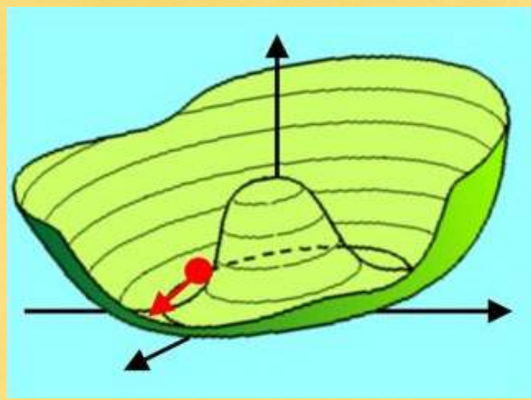

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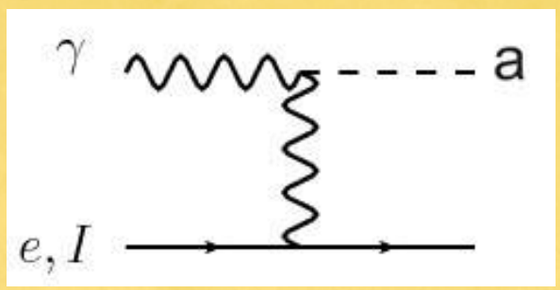

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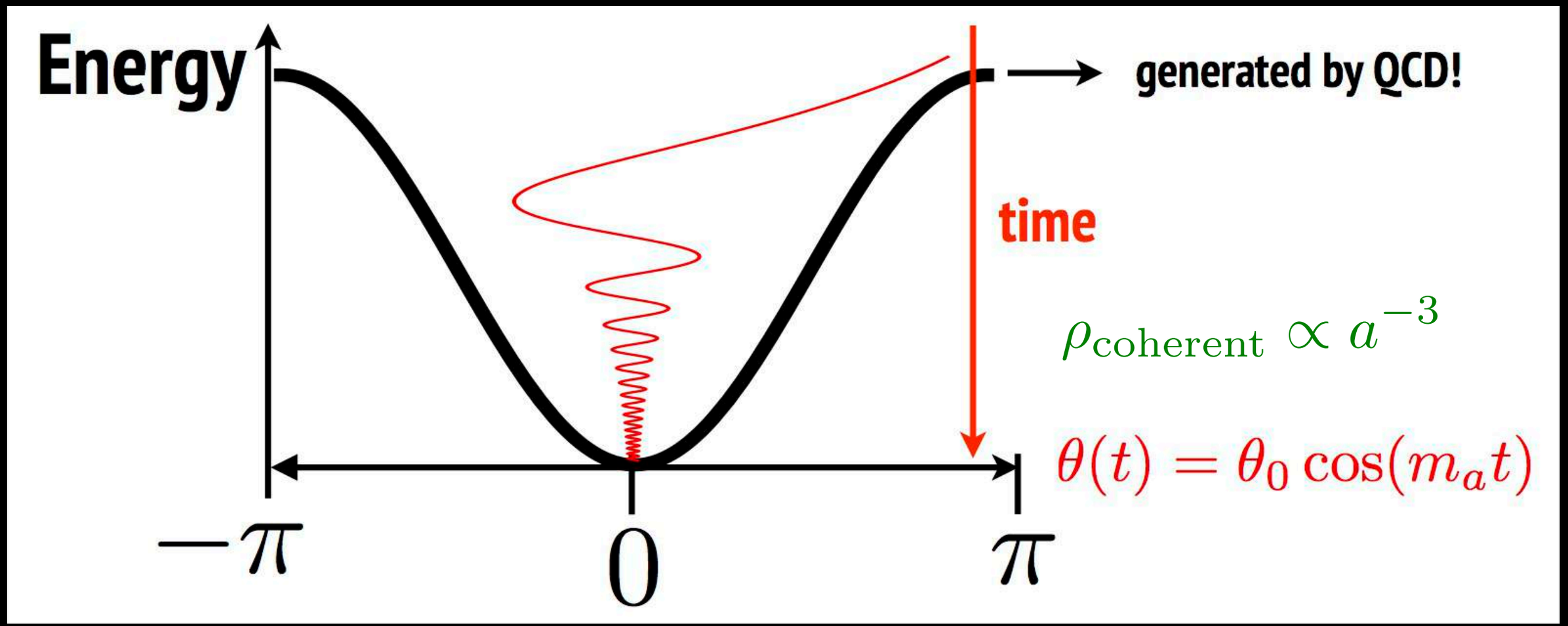
Axion coherent oscillations

Non-thermal production of ULAs:

1) Misalignment
2) Strings?

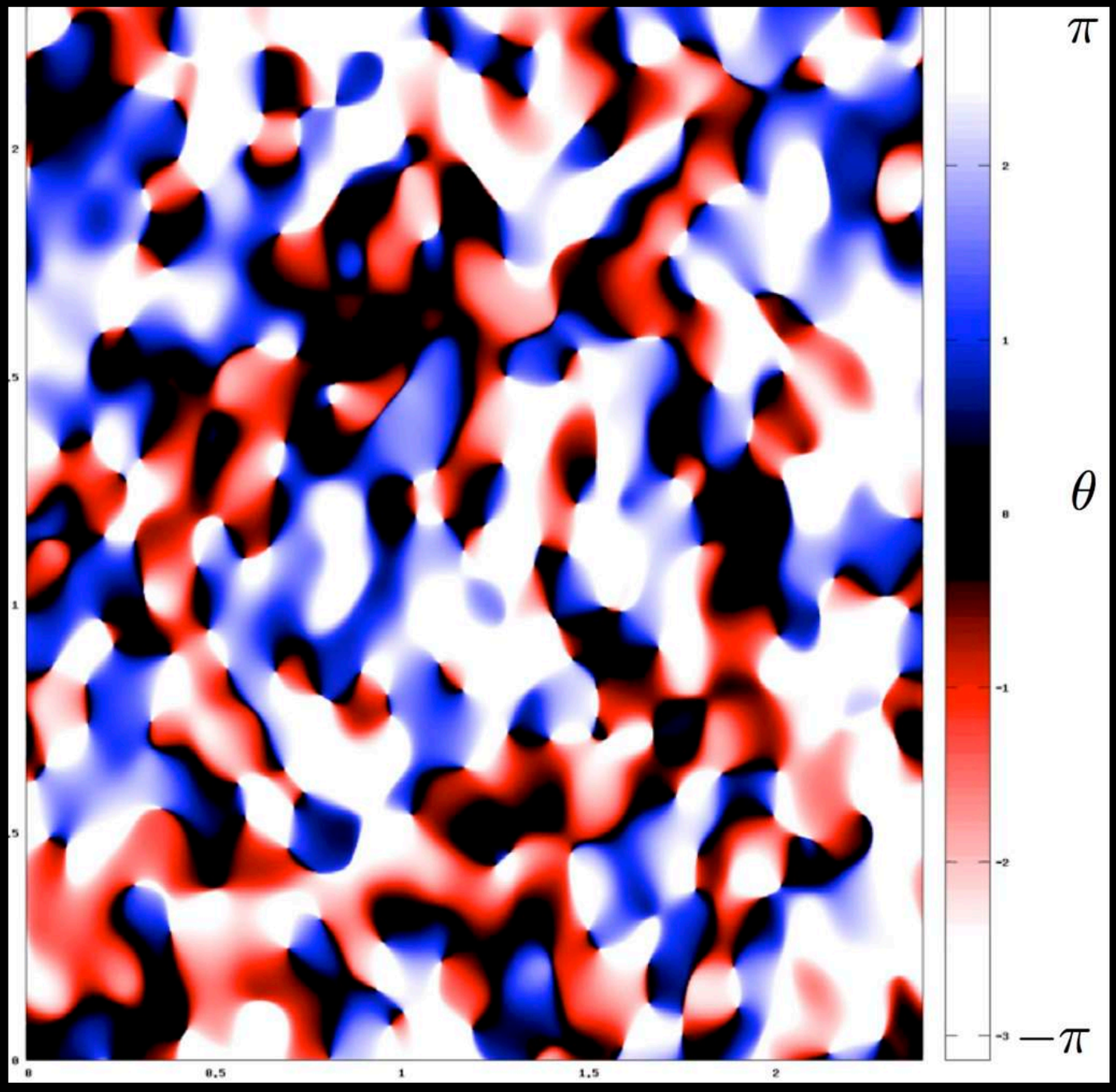
$$\ddot{\phi} + 3H\dot{\phi} + m^2 \sin\phi = 0$$

$$m \approx 3H$$



Courtesy of J. Redondo

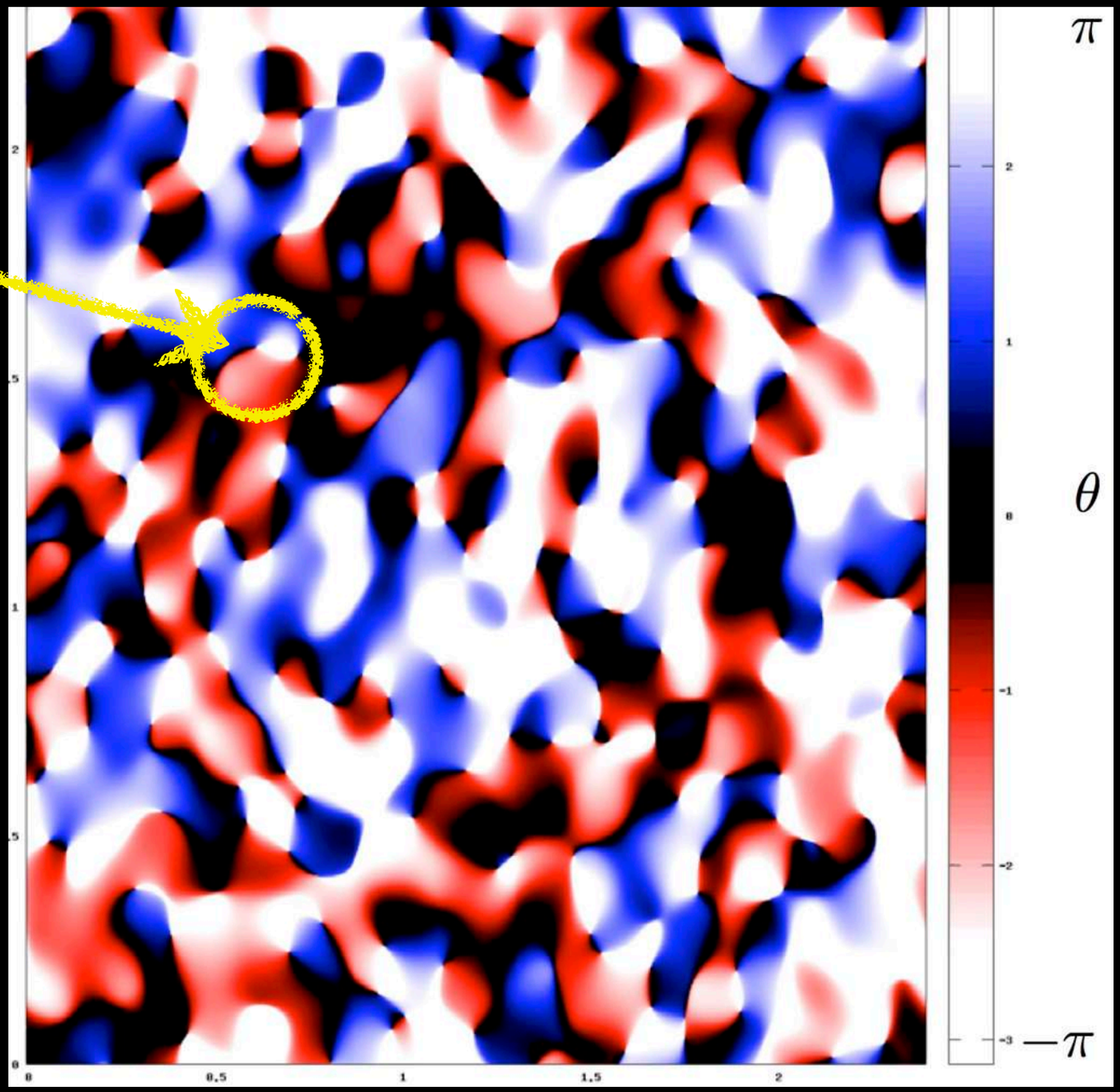
Scenario A: PQ breaks after inflation



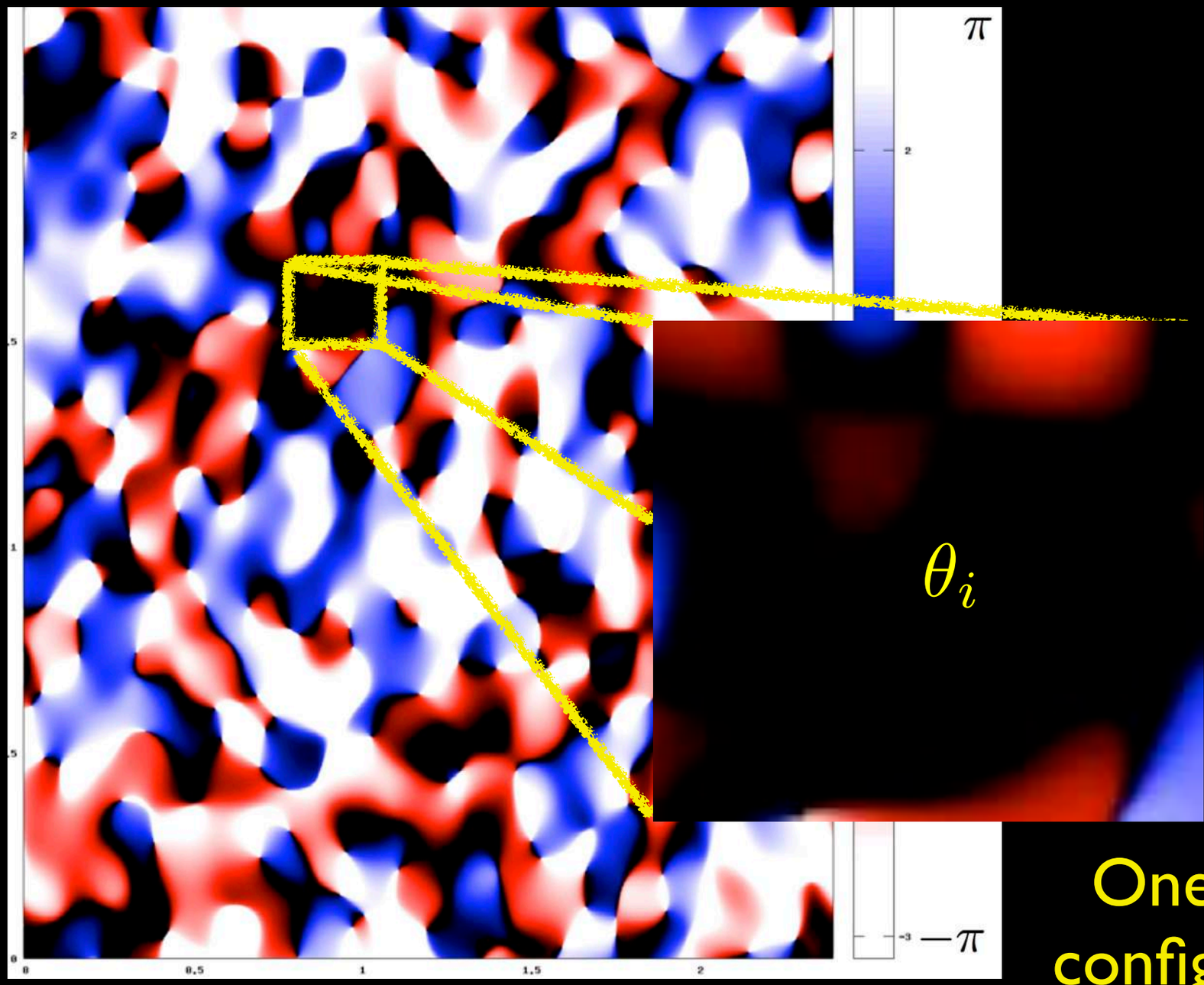
Scenario A: PQ breaks after inflation

Axion strings!

CDM axions also from defects...

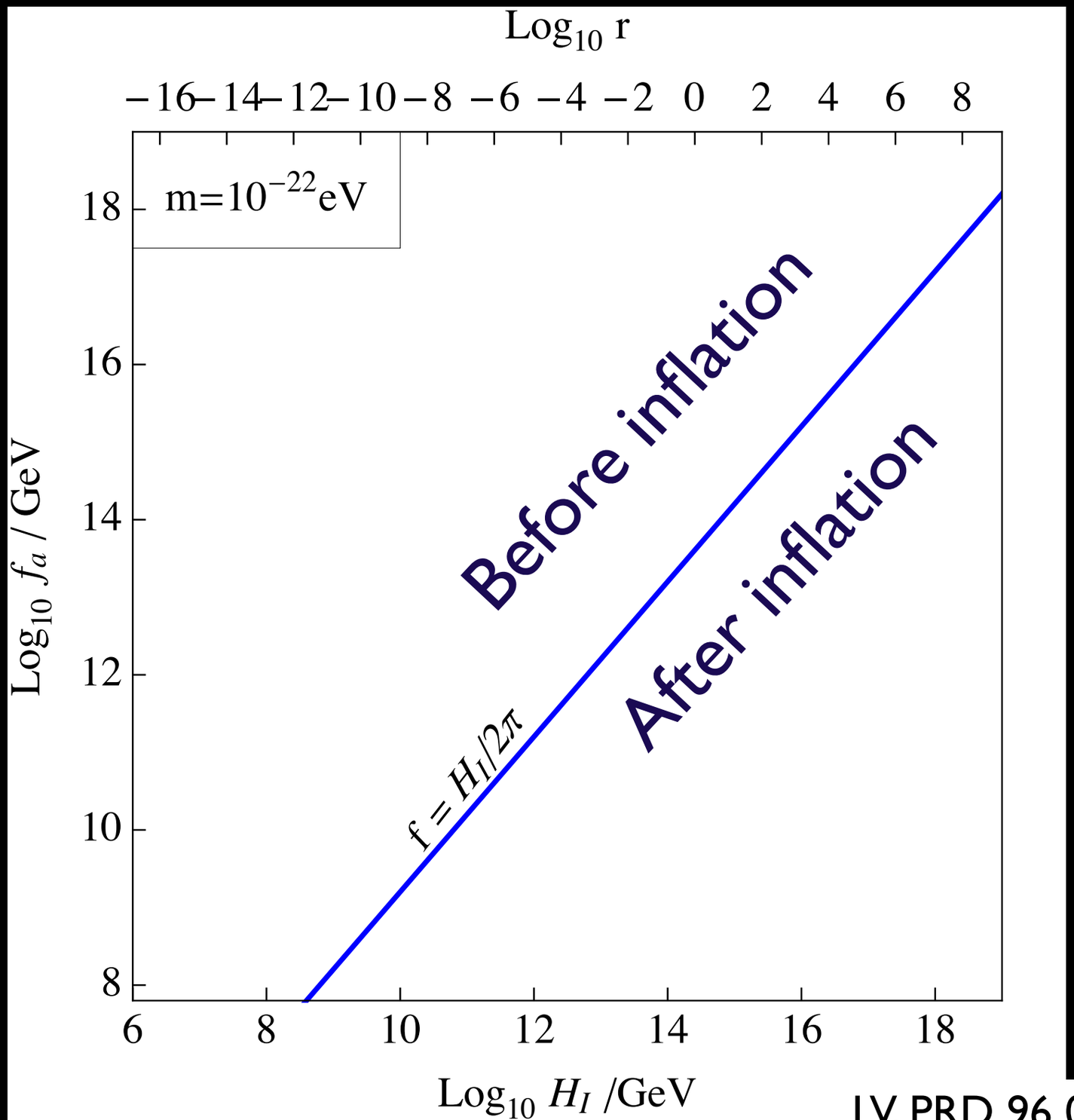


Scenario B: PQ breaks during inflation



One initial configuration is singled out

ALP parameter space



LV, PRD 96 023013 (2017)

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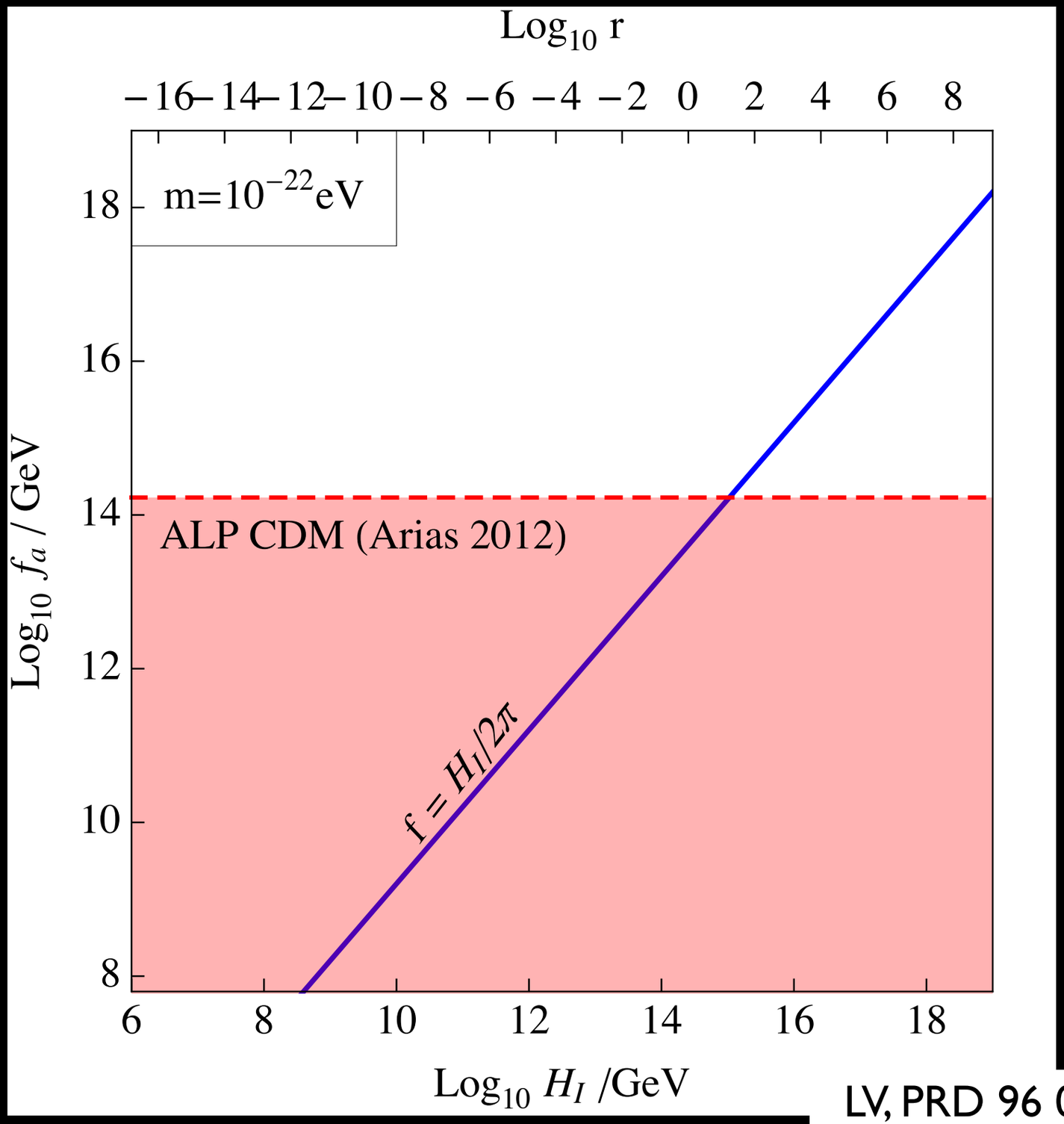

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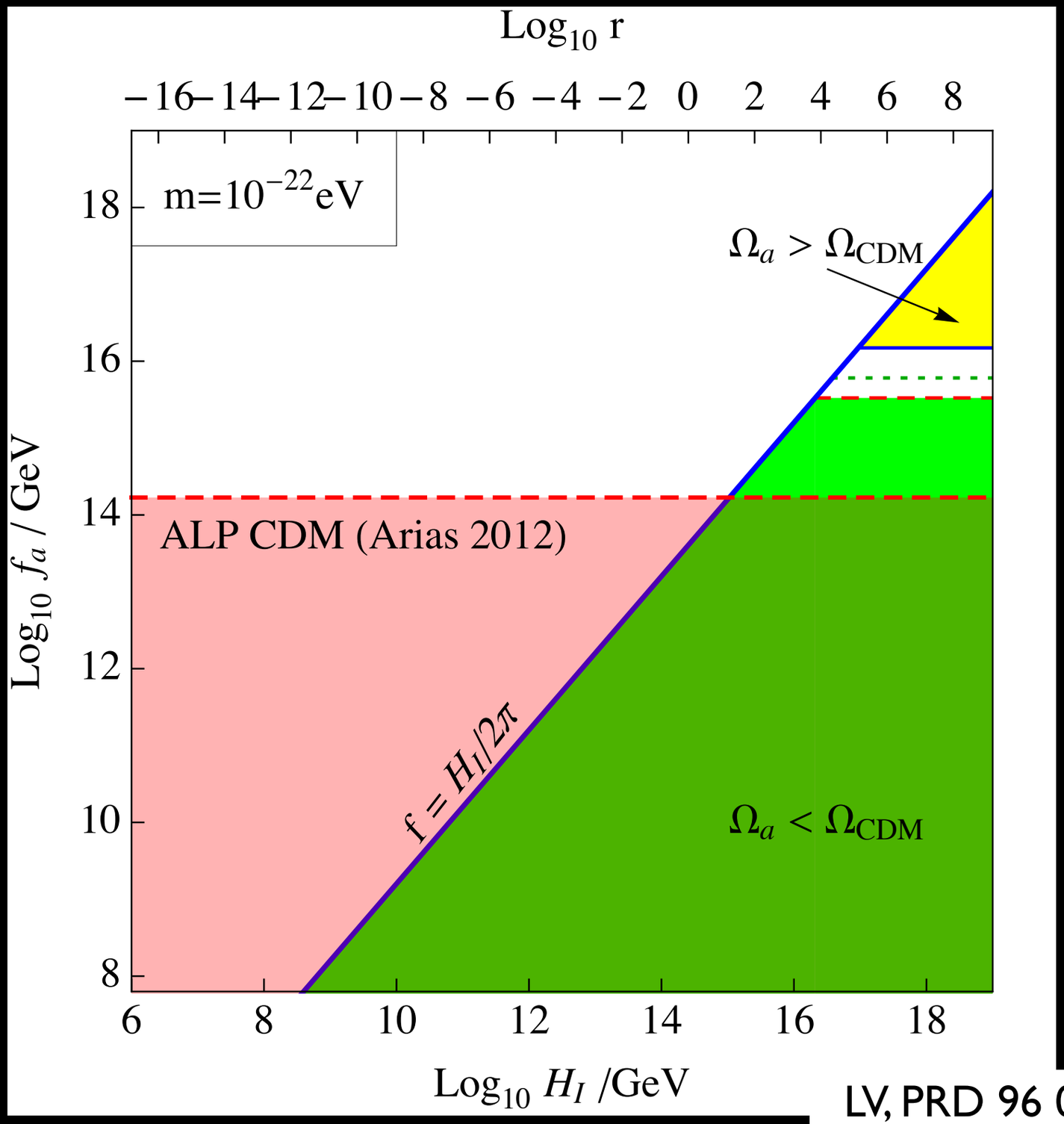

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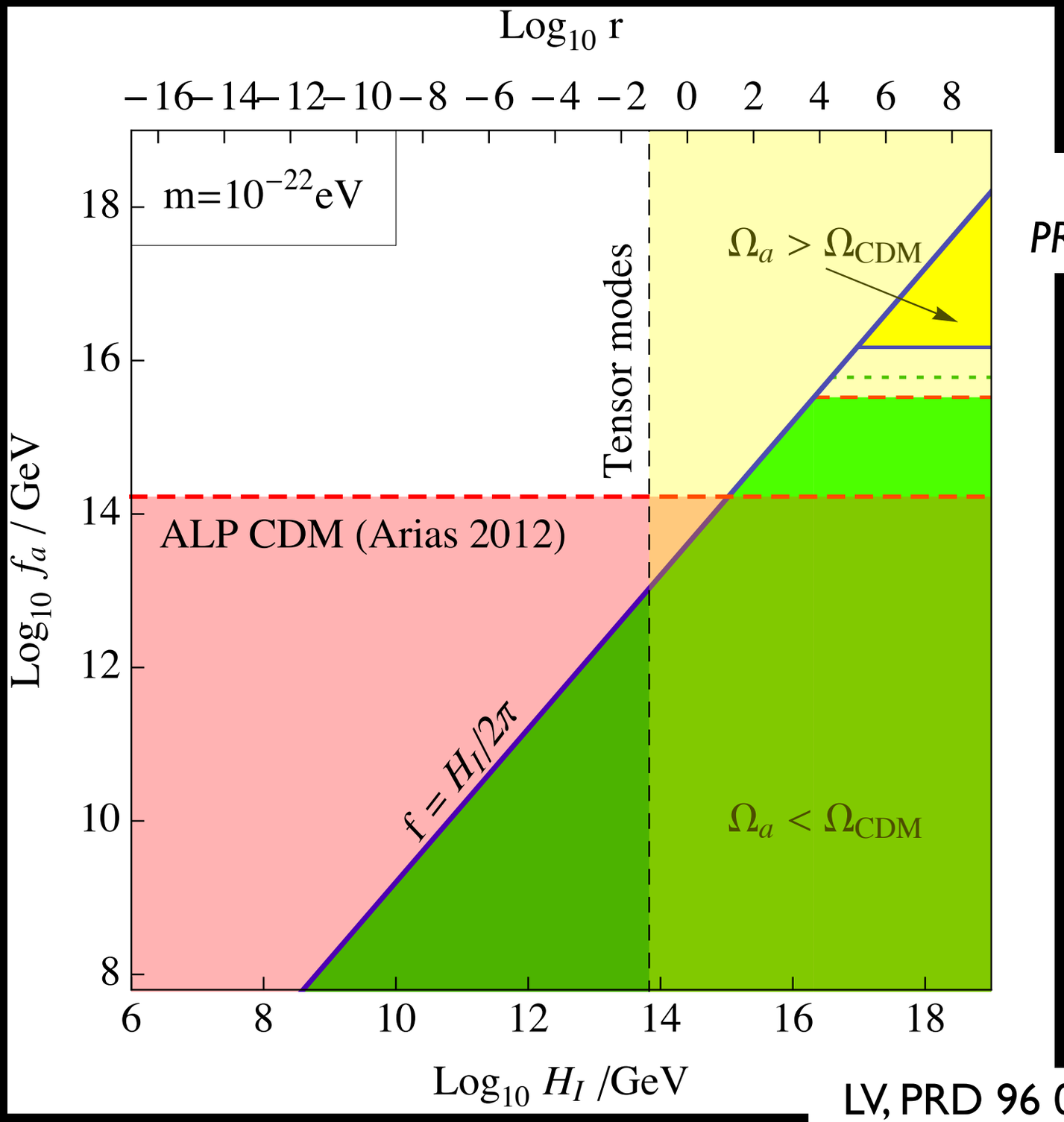

Ade *et al* (BICEP2)
PRL **116** *031302* (2016)

LV, PRD 96 023013 (2017)

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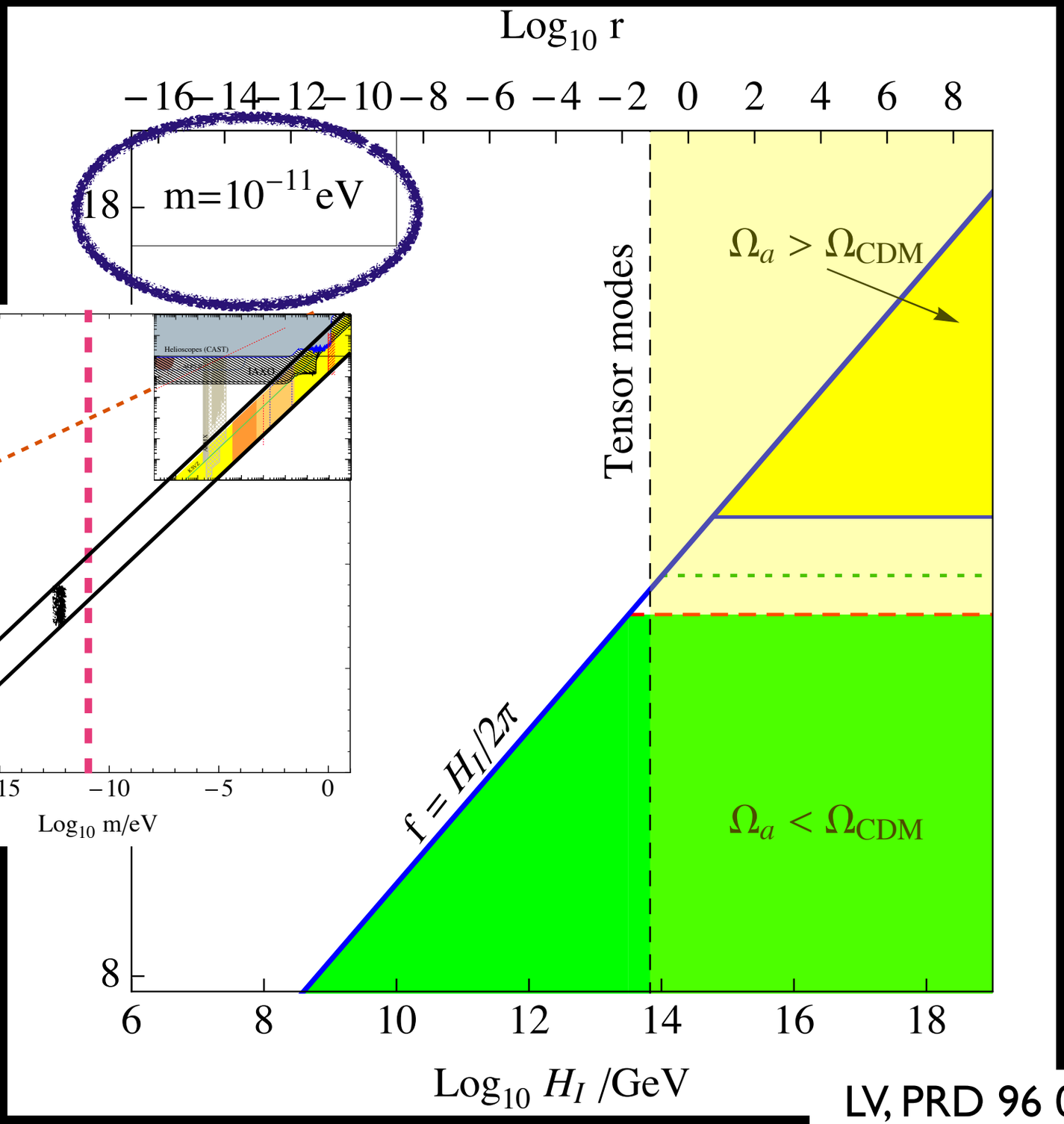

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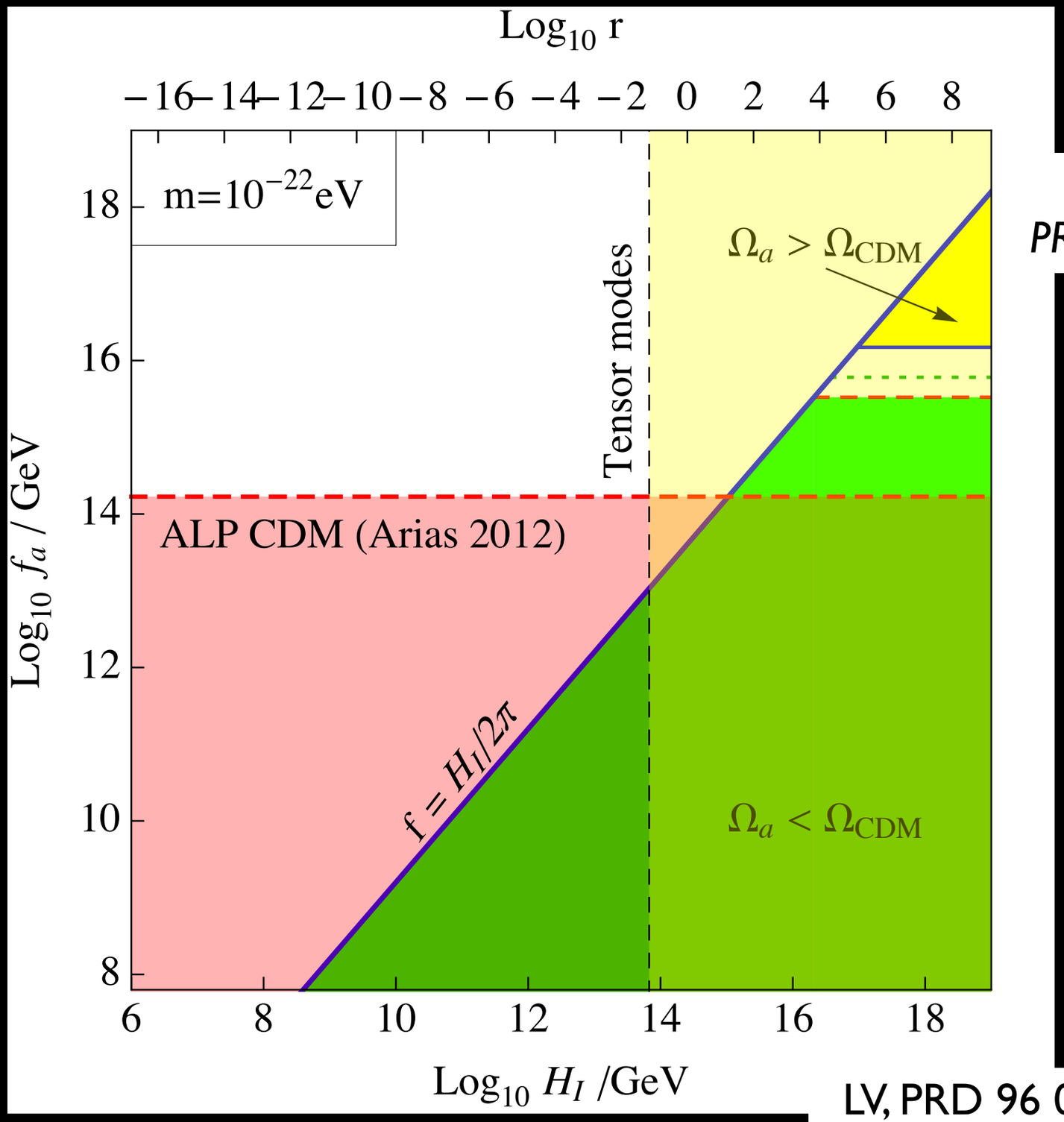

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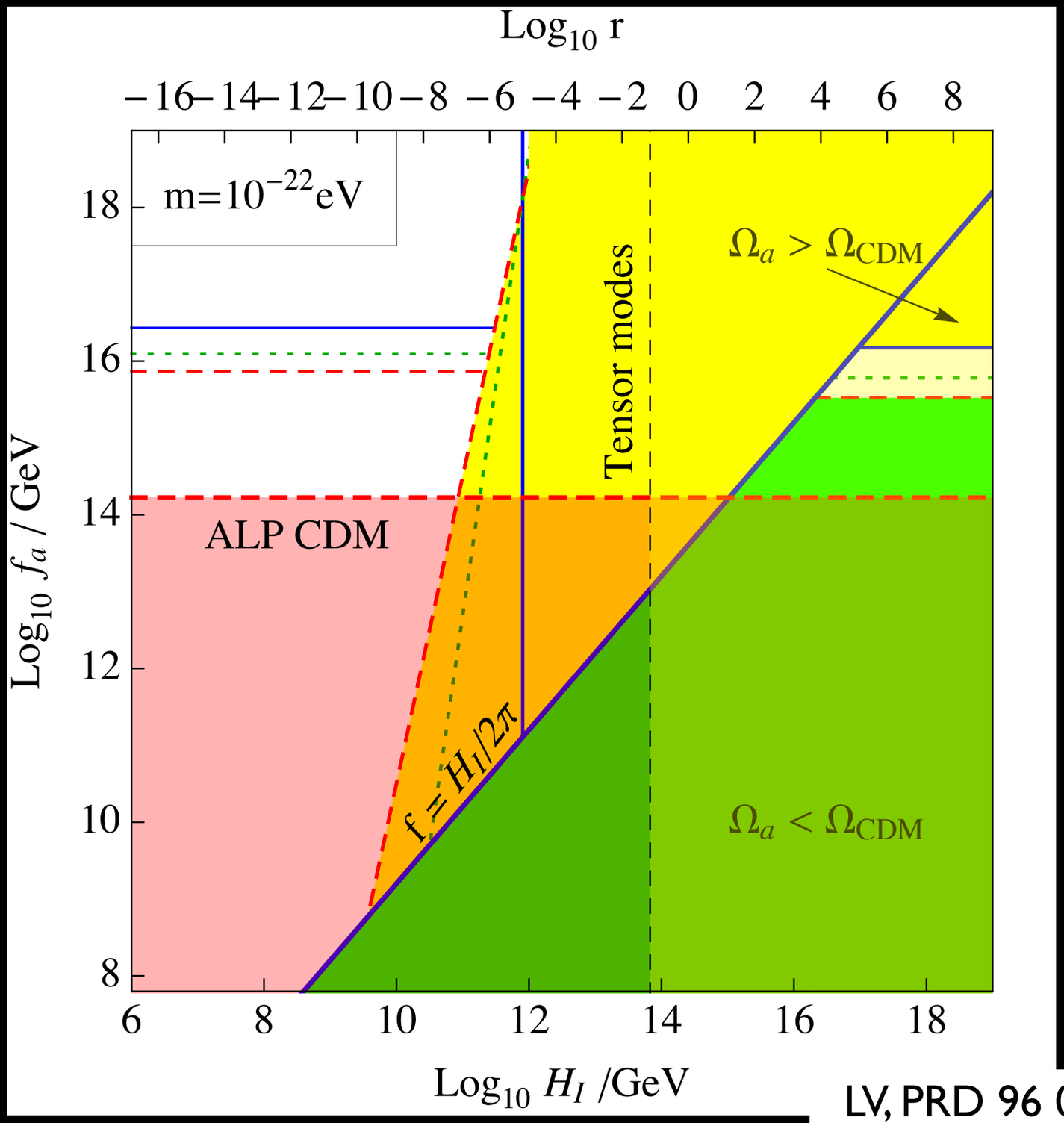


LV, PRD 96 023013 (2017)

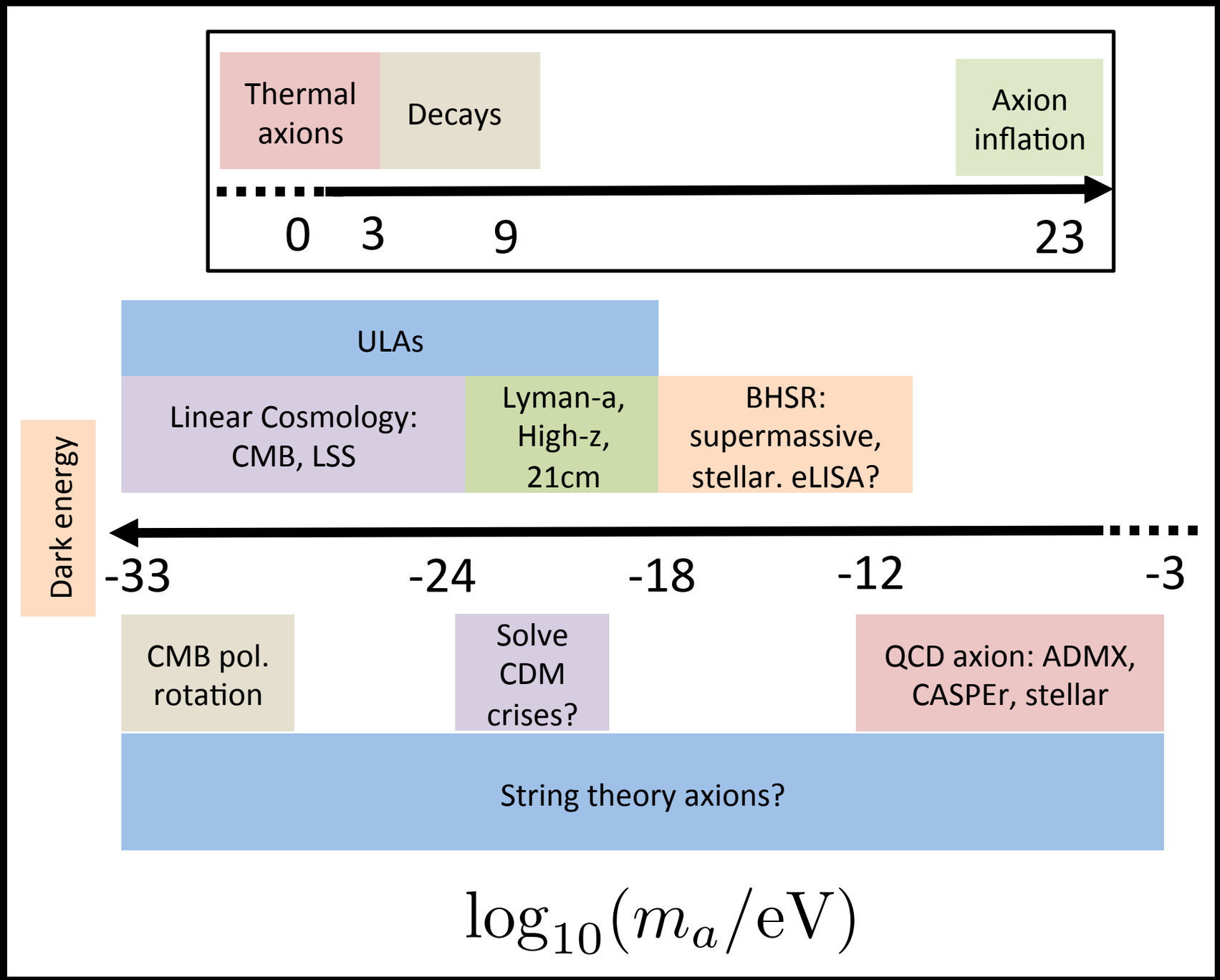
Conclusions

- FDM models address the missing satellite problem;

- Axion-like particles are suitable FDM candidates, thanks to the non-thermal production;

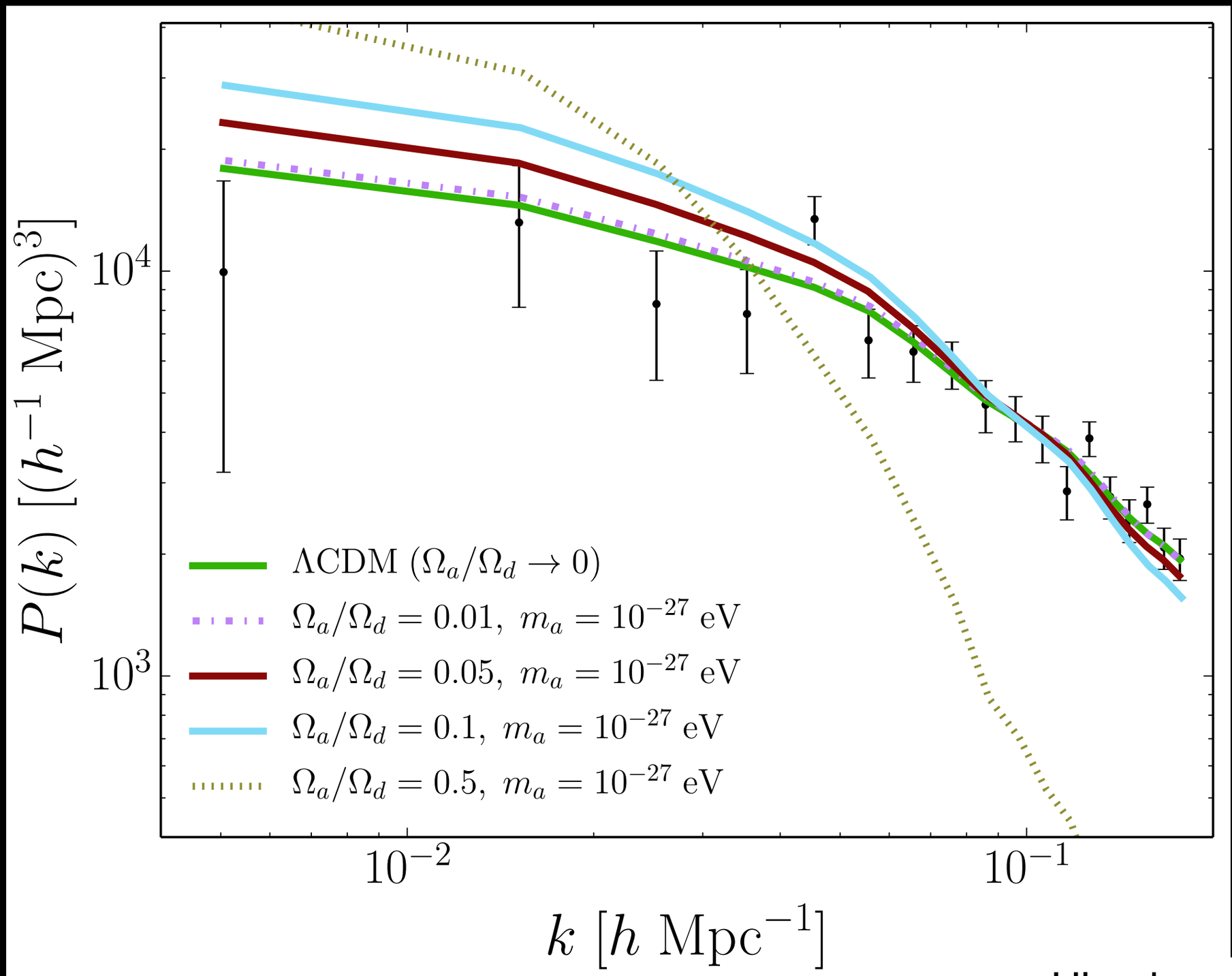
- A measurement of primordial gravitational waves in the near future might severely cripple Axion FDM.

FDM Candidate: the Axion



Courtesy of DJE Marsh

Galaxy power spectrum



Hlozek *et al.* 2014