Identifying the fundamental nature of dark matter using cosmological data

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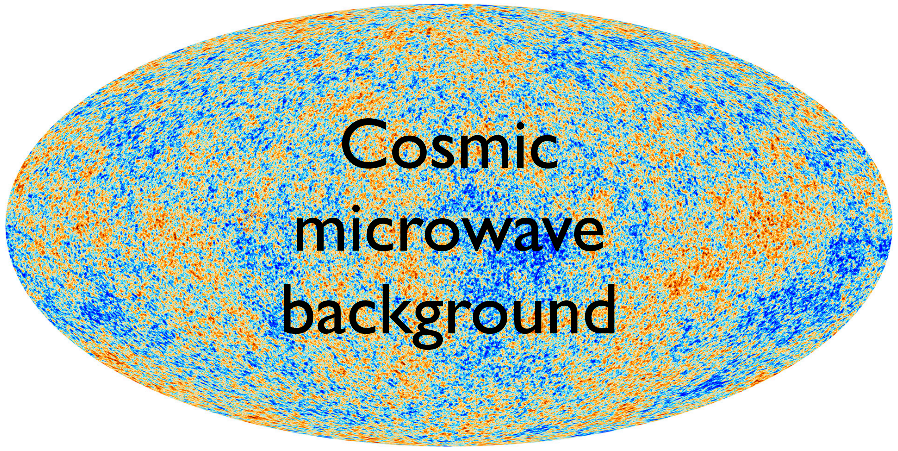
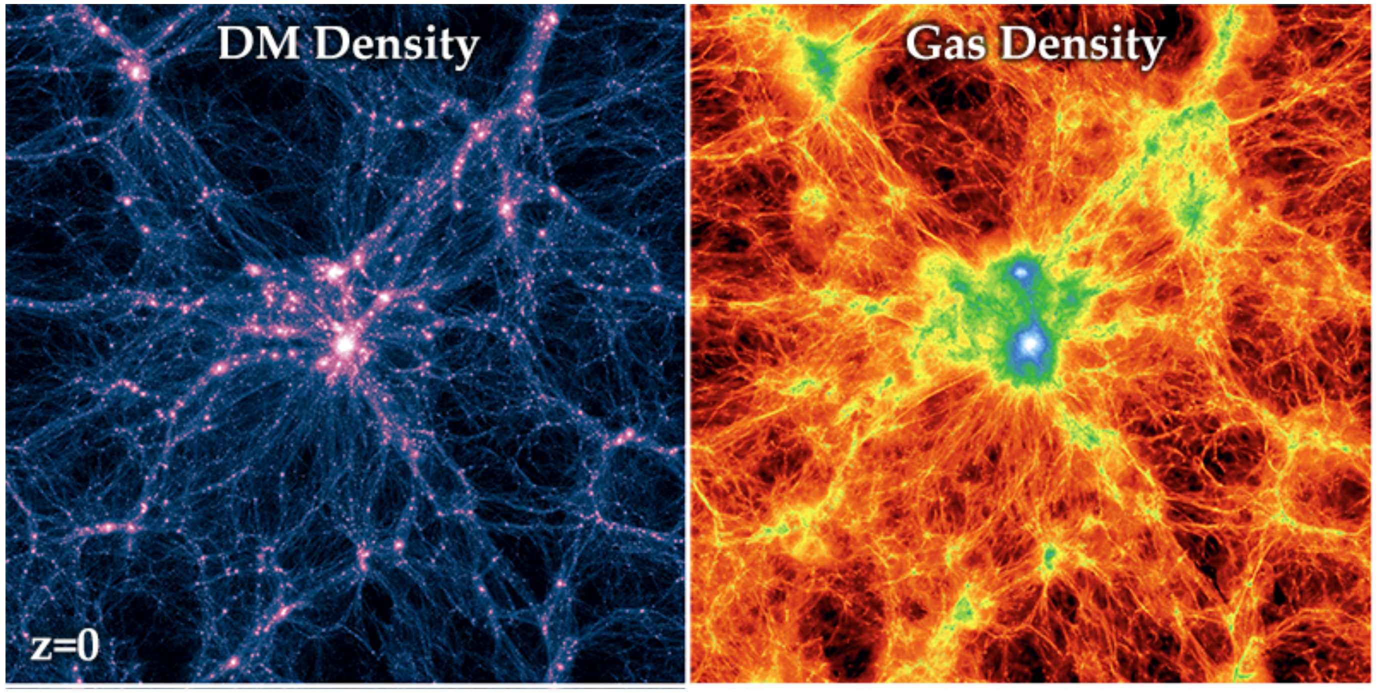
Find dark matter by only known interaction — gravity — trace DM by CMB, galaxies and intergalactic gas

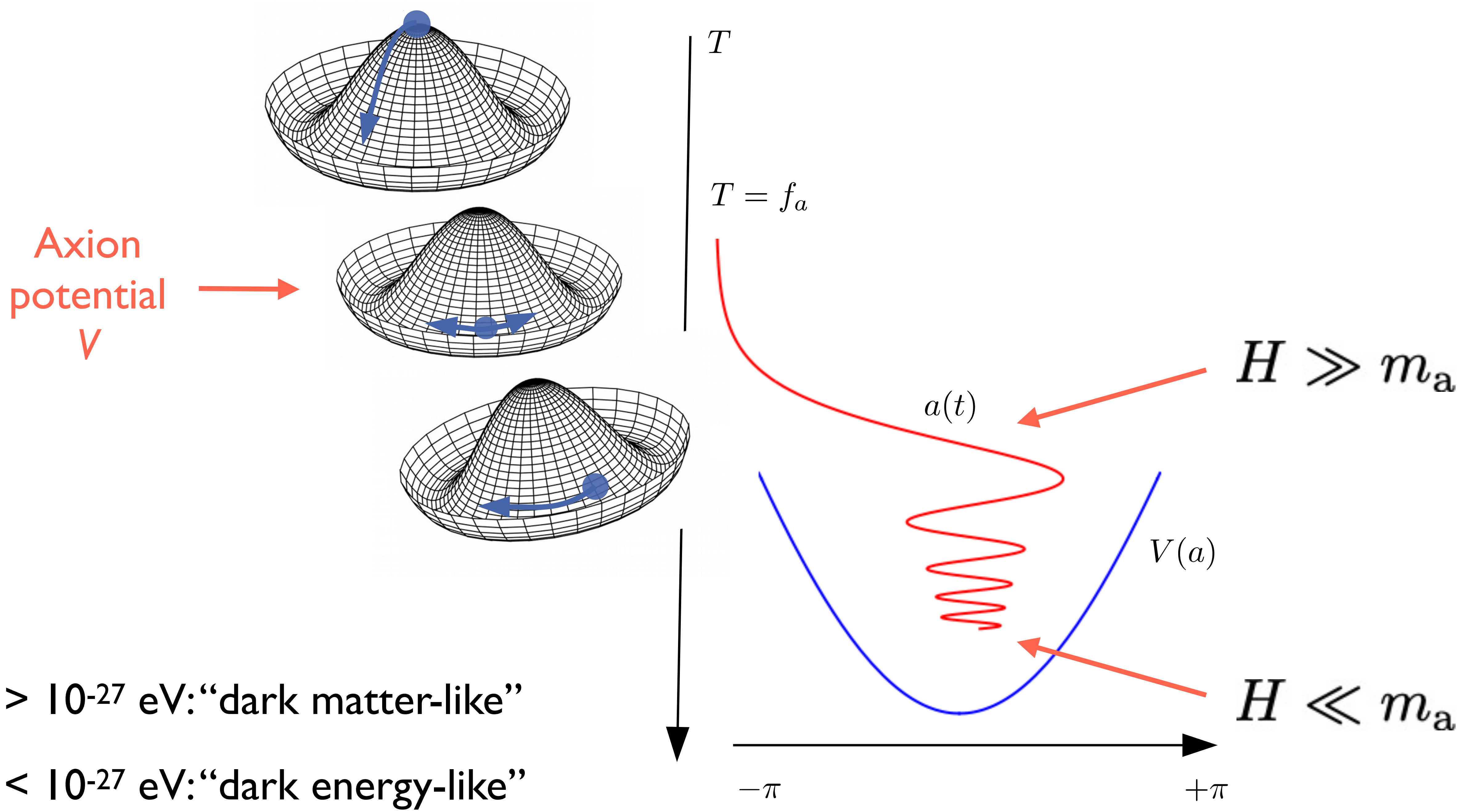


How improve consistency between CMB and LSS?



Planck Collaboration; Illustris simulation

Axions are dark energy and dark matter candidates



- $m_a > 10^{-27}$ eV: "dark matter-like"
- $m_a < 10^{-27}$ eV: "dark energy-like"
- $m_a = 10^{-33}$ eV: cosmological constant

Figure credit: Pargner (2019); Peccei & Quinn (1977); Weinberg (1978); Wilczek (1978)

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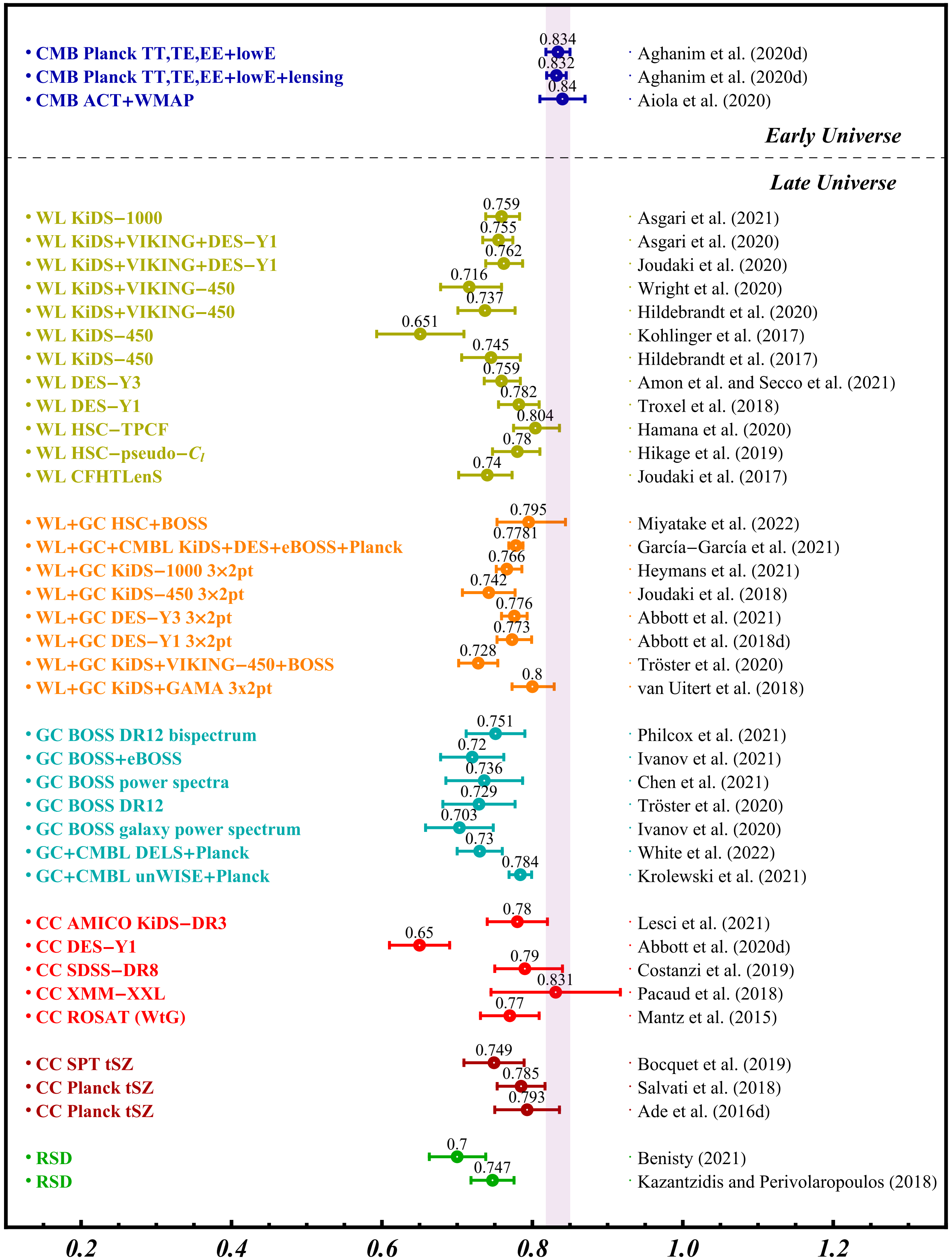
JOINT CONSTRAINTS ON ULTRA-LIGHT AXIONS FROM CMB & GALAXY SURVEYS

JCAP, 06, 023, 2023
JCAP, 01, 049, 2022
MNRAS, 515, 5646, 2022
with Hložek, Laguë, Ivanov, Philcox, Cabass, Akitsu, Marsh, Bond, Dentler, Grin

Larger scales

Smaller scales



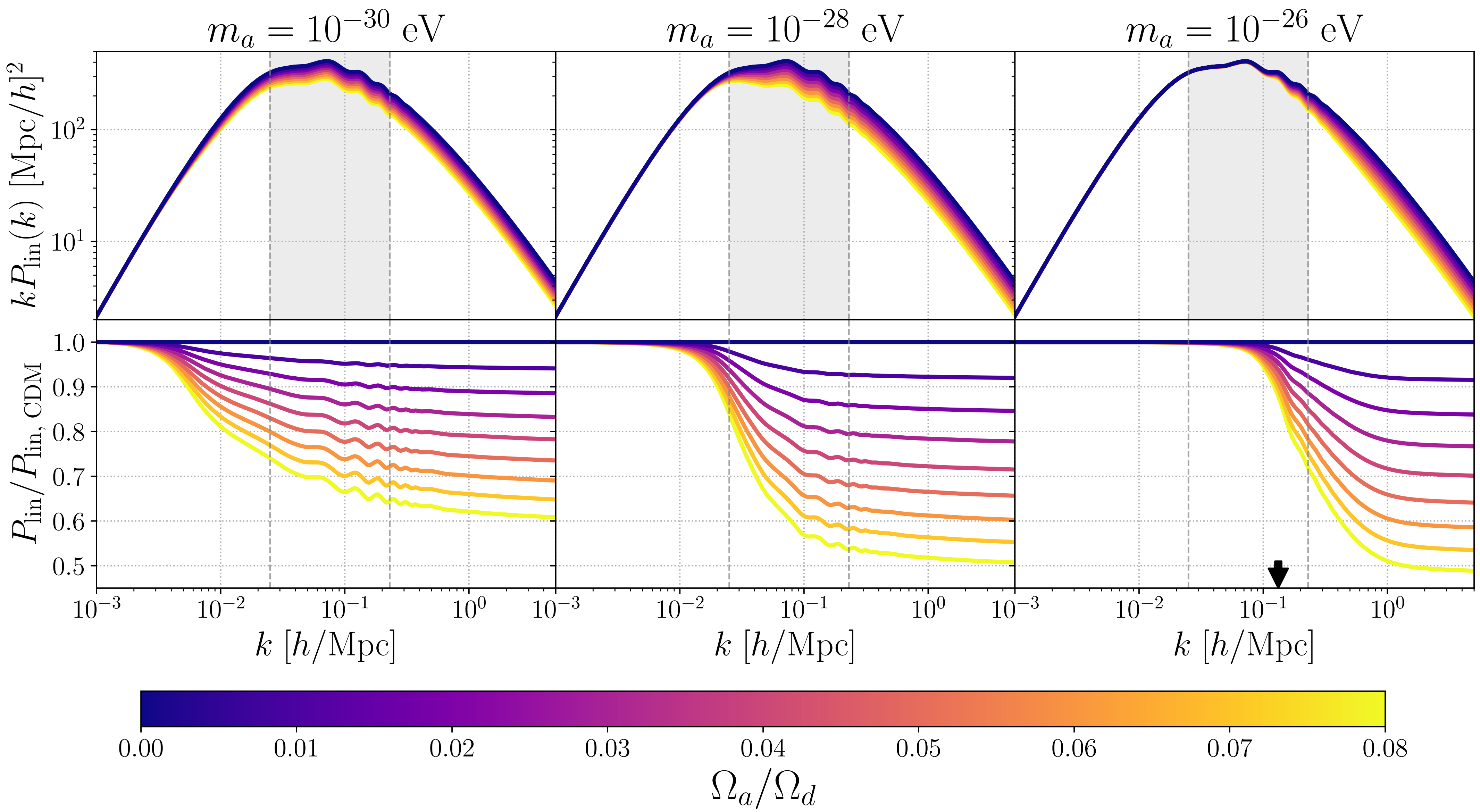
S_8 tension

S_8 ~ amplitude of density fluctuations at 8 Mpc/h

Abdalla et al. (Snowmass 2022)

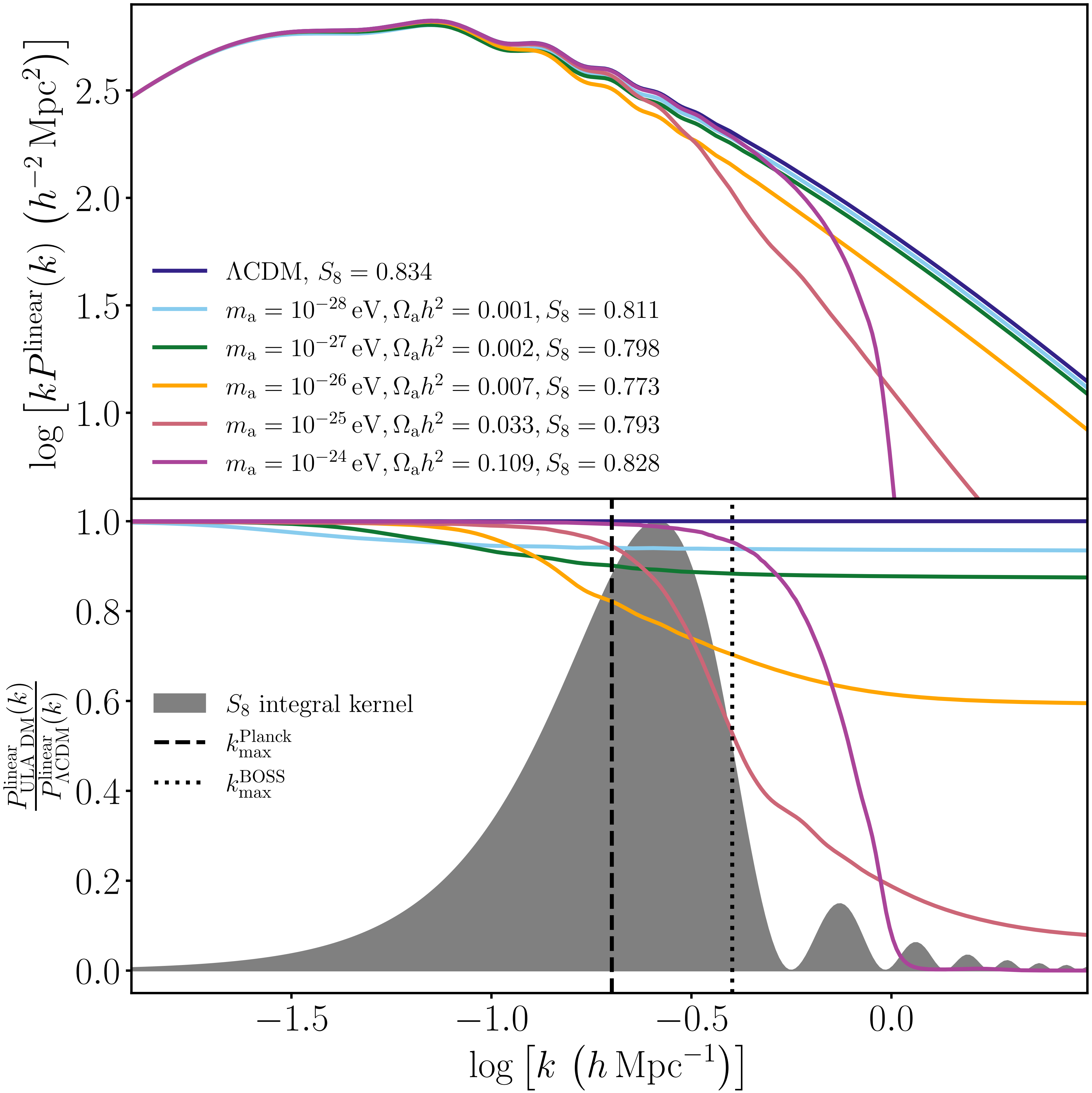
Ultra-light axion dark matter causes scale-dependent suppression in matter clustering

$$\lambda_{\mathrm{Jeans}} = 9.4\,(1+z)^{\frac{1}{4}} \left(\frac{\Omega_{\mathrm{a}} h^2}{0.12}\right)^{-\frac{1}{4}} \left(\frac{m}{10^{-26}\,\mathrm{eV}}\right)^{-\frac{1}{2}}\ \mathrm{Mpc}$$

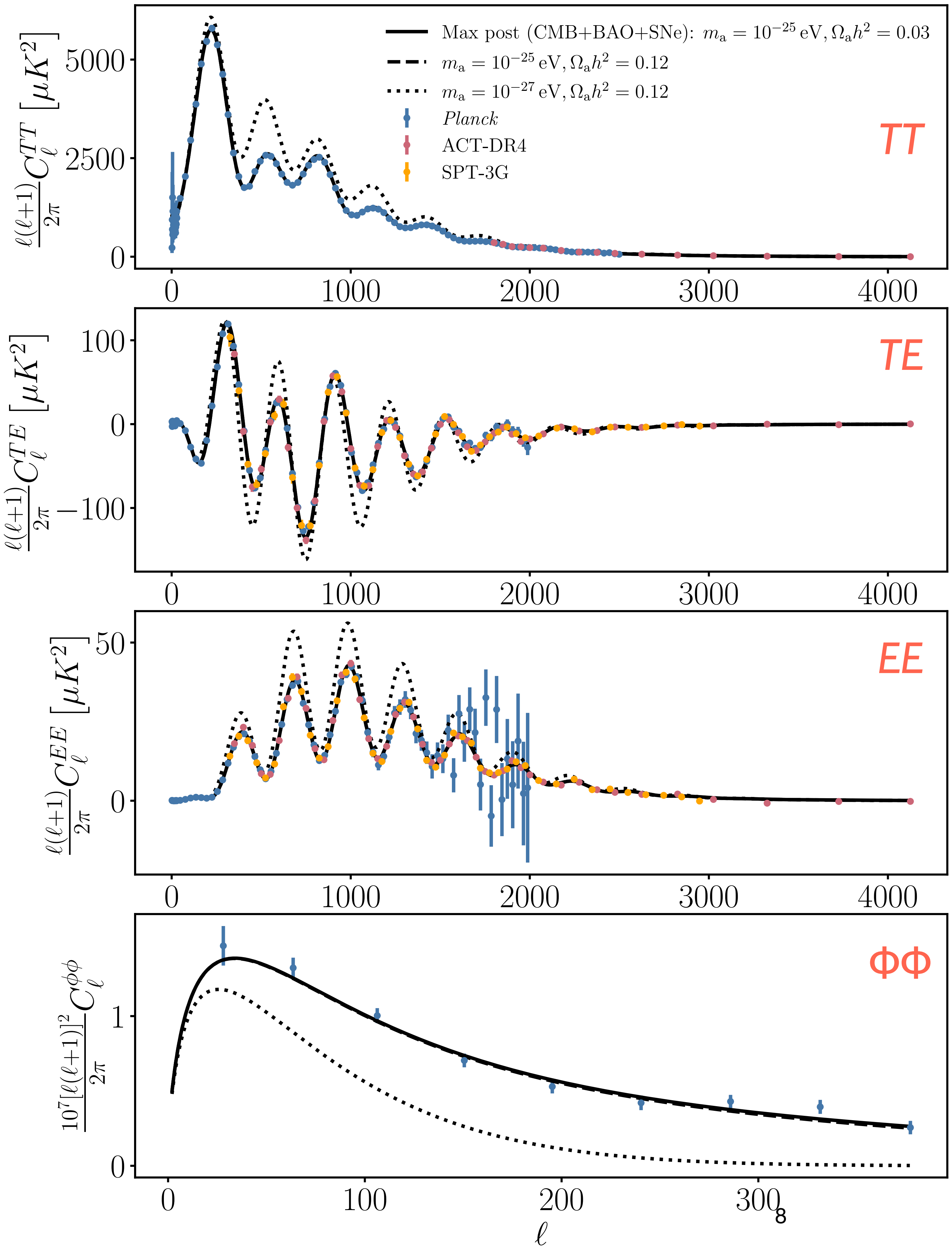


Laguë, Bond, Hložek, Rogers, Marsh, Grin (JCAP, 2022)

Axions lower S_8



Rogers, Hložek, et al. (JCAP, 2023)

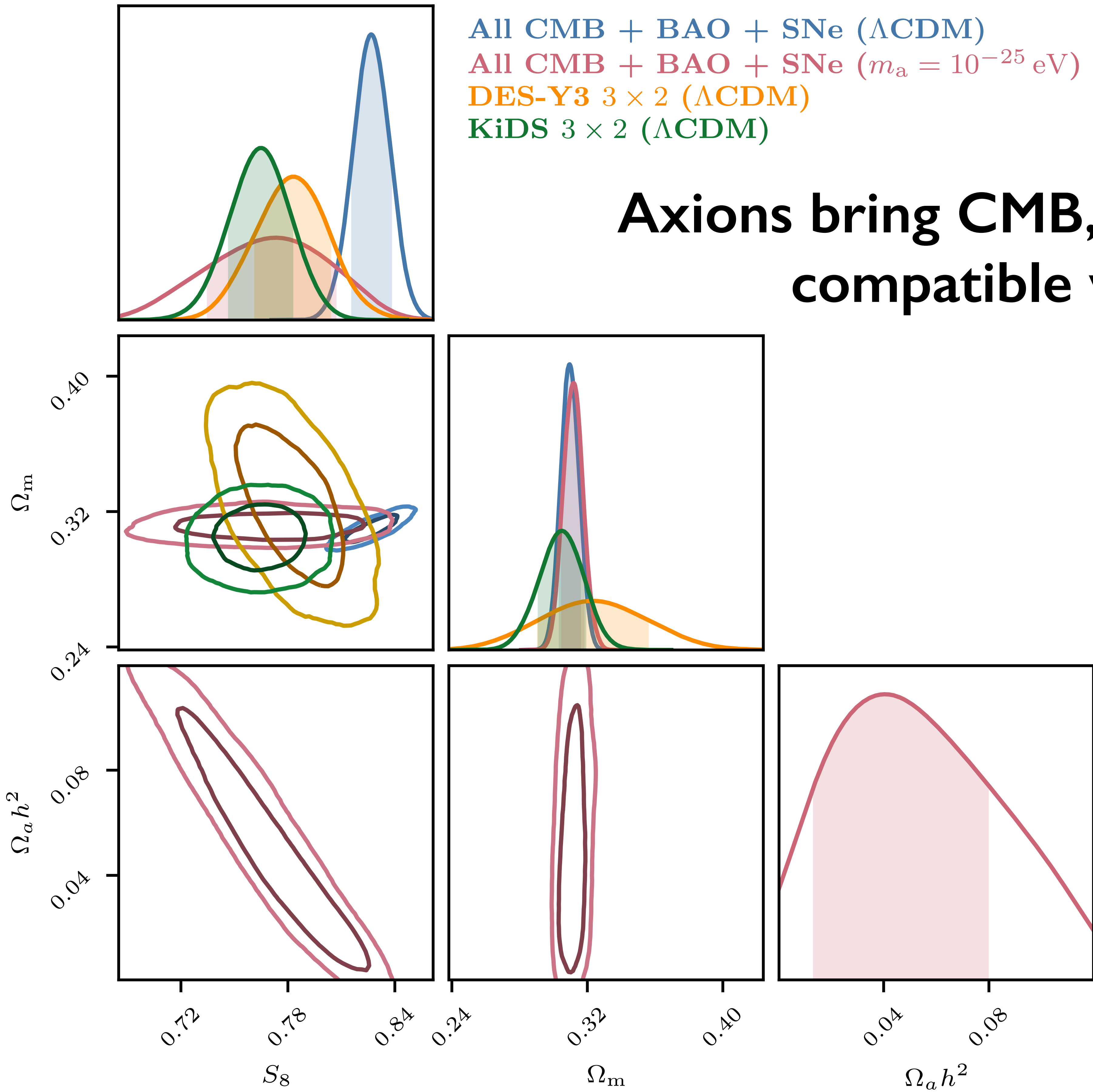


DE-like axions constrained by CMB acoustic oscillations & lensing potential

$$m_a \leq 10^{-26}\,\mathrm{eV}$$

Rogers, Hložek, et al. (JCAP, 2023)

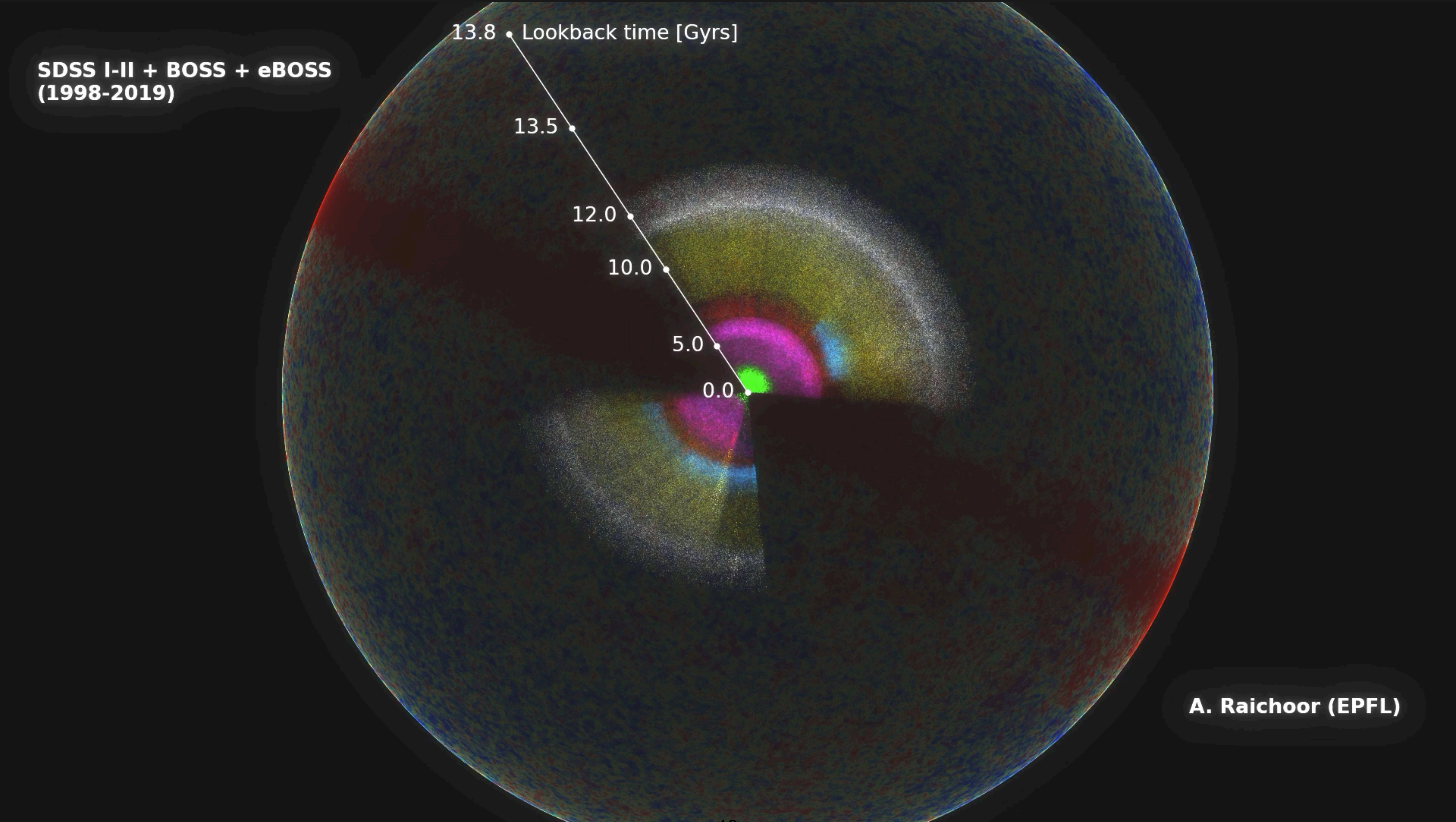
Axions bring CMB, BAO & SNe data compatible with low S_8



$$m = 10^{-25}\,\mathrm{eV}$$

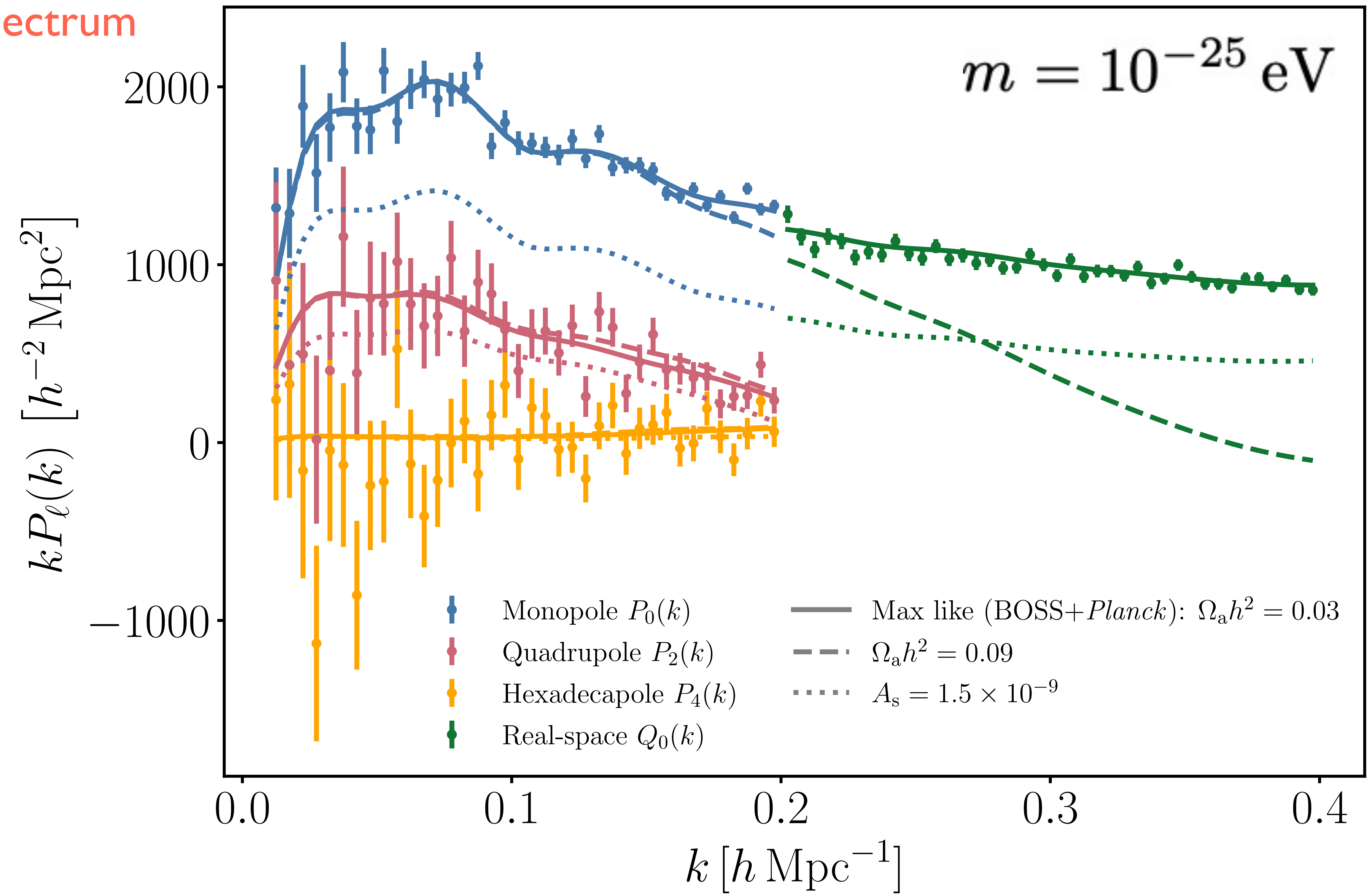
Rogers, Hložek, et al. (JCAP, 2023)

Sloan Digital Sky Survey maps galaxies and intergalactic gas towards edge of observable Universe



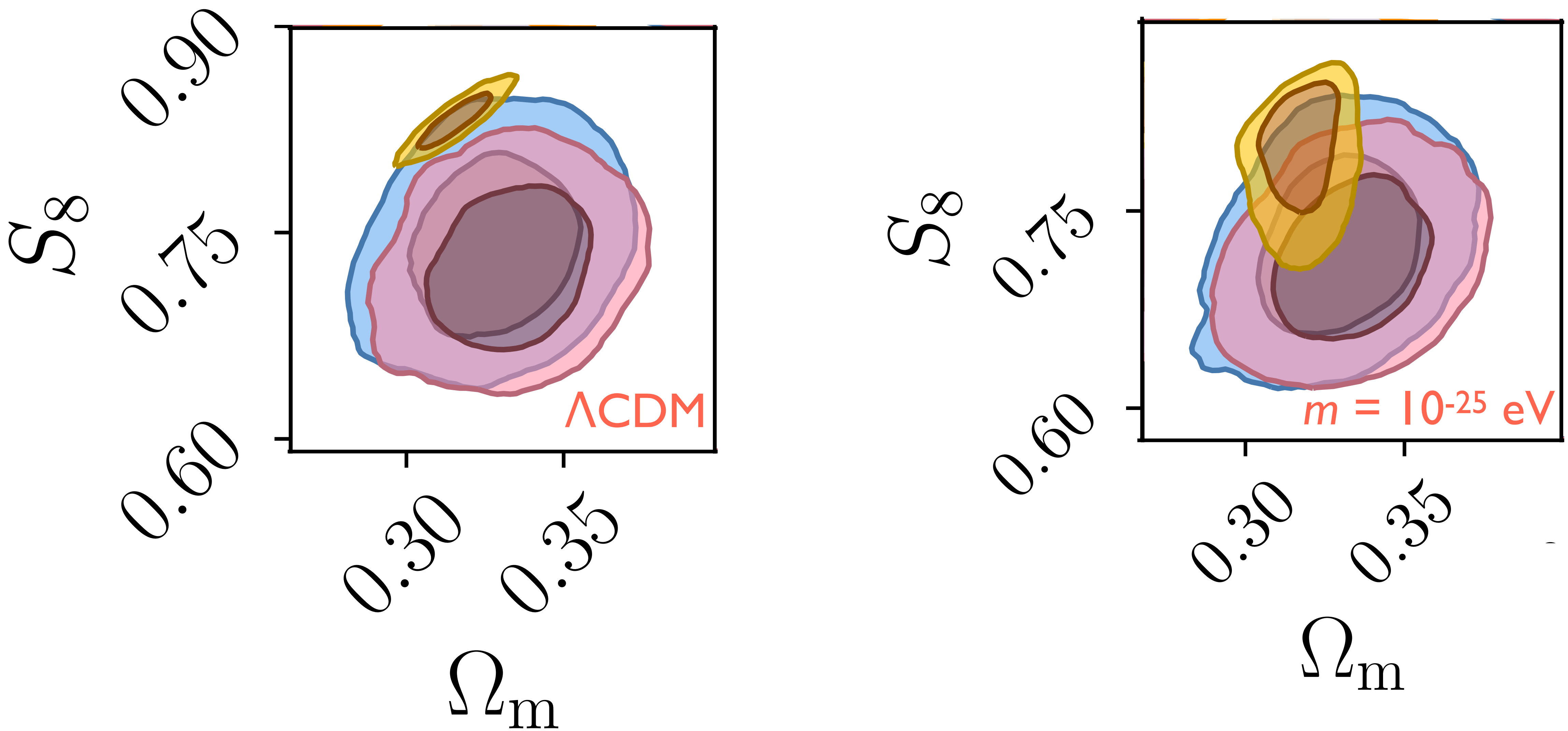
Full-shape BOSS galaxy power spectrum increases sensitivity to ultra-light axions

Power spectrum



Rogers, Hložek, et al. (JCAP, 2023)

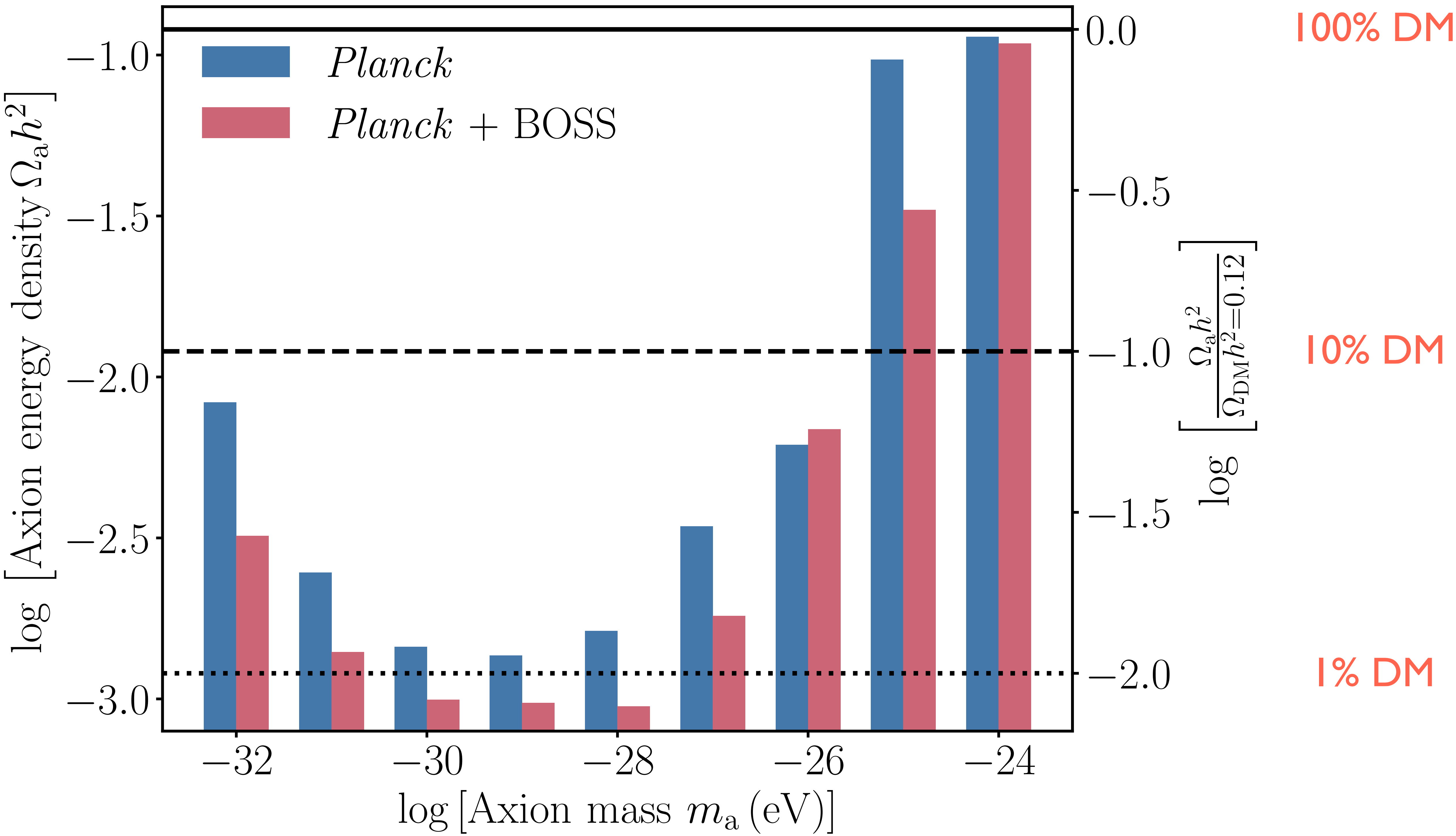
Axions improve consistency between *Planck* and BOSS-EFT



- *Planck* cosmic microwave background
- BOSS-EFT galaxy power spectrum
- BOSS-EFT galaxy power spectrum + bispectrum

Rogers, Hložek, et al. (JCAP, 2023)

Strongest axion limits come from combining cosmic microwave background & galaxy clustering



Rogers, Hložek, et al. (JCAP, 2023)

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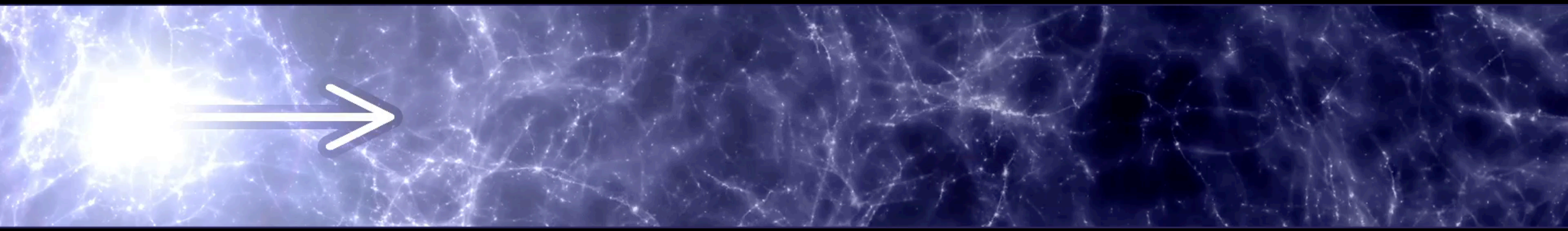
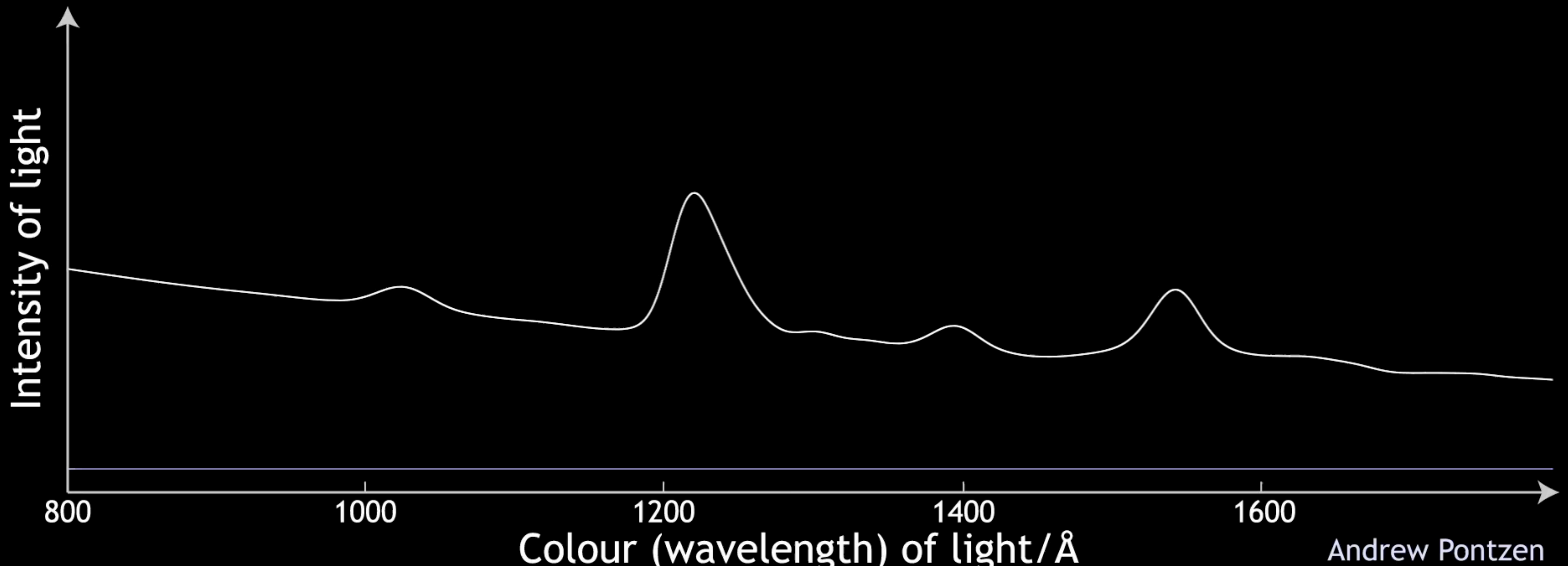
5σ tension between *Planck* CMB and eBOSS Lyman-α forest and constraints on physics beyond ΛCDM

arXiv: 2311.16377

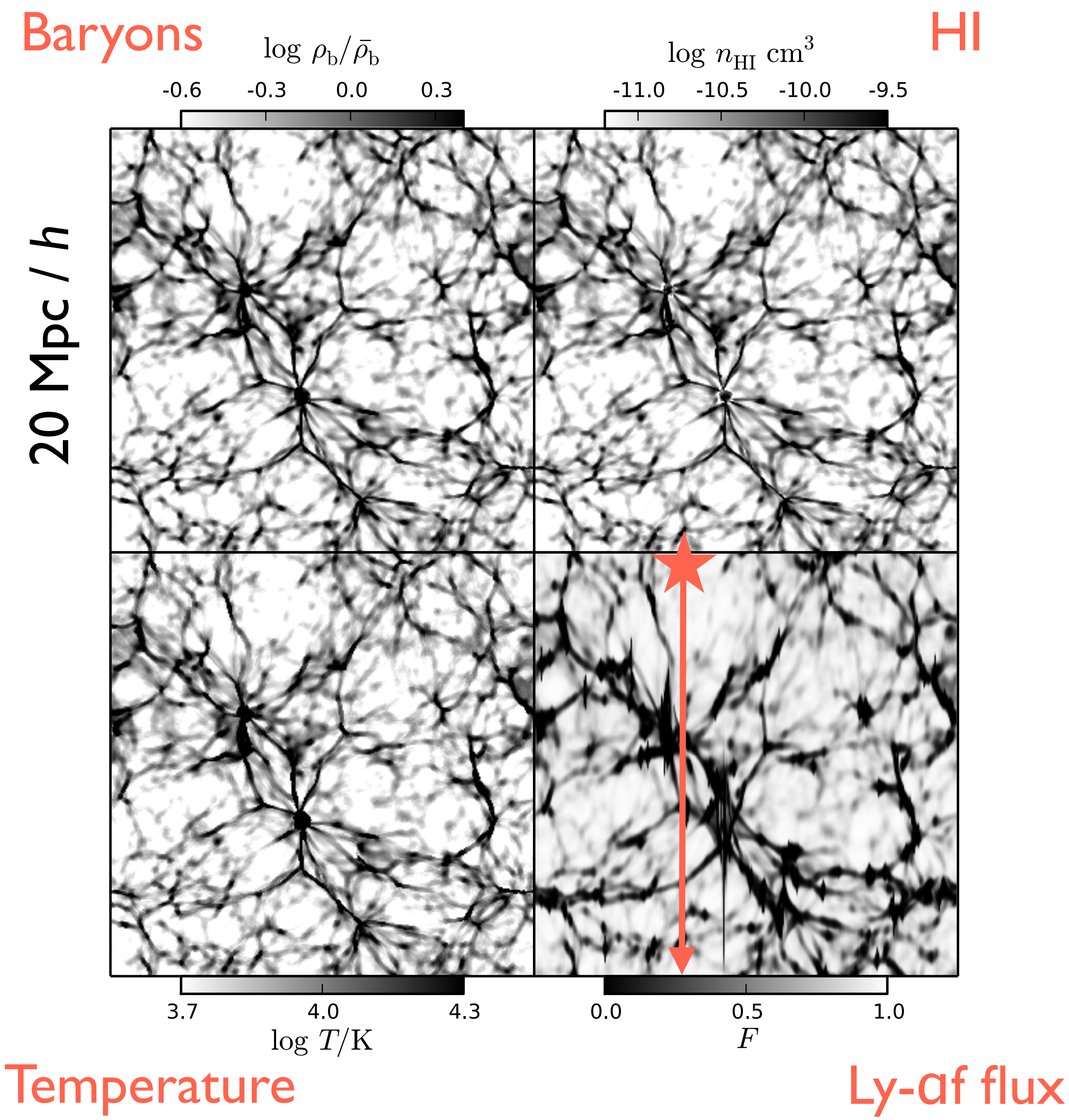
with Vivian Poulin

Lyman-alpha forest traces intergalactic medium around mean cosmic density



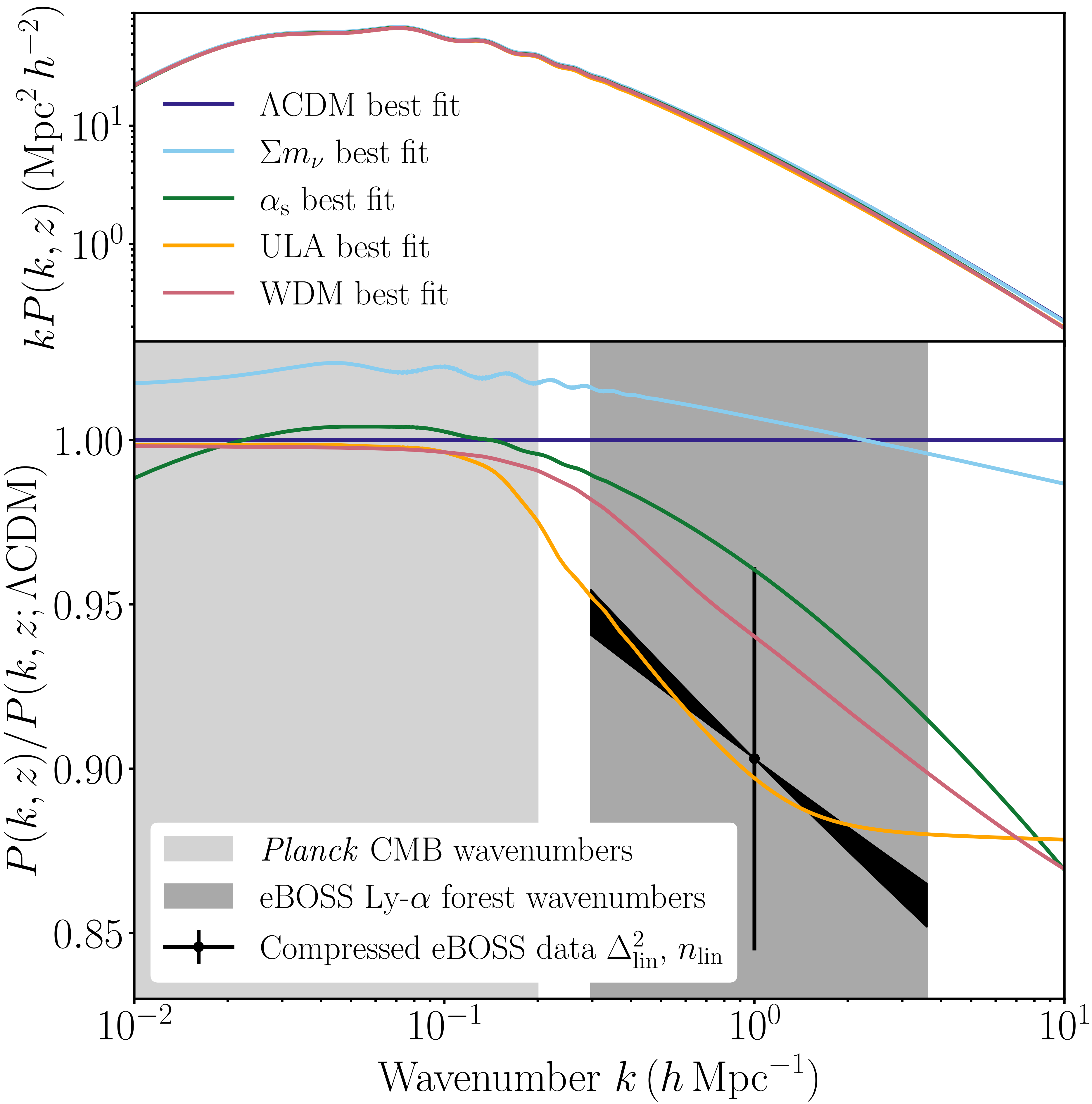


Lyman-alpha forest probes smallest cosmic scales — robustly account for range of astrophysical states



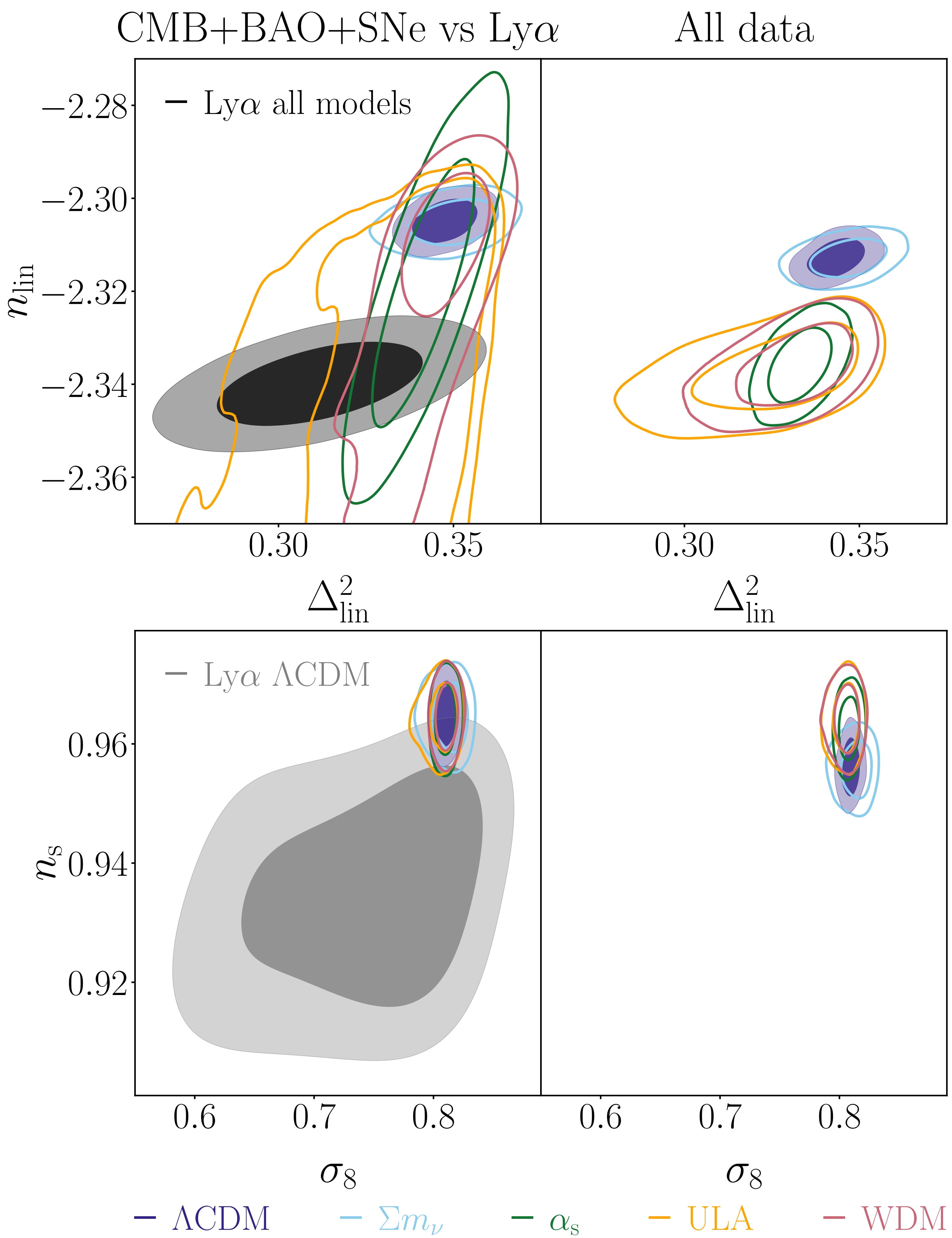
- Ly-alpha forest traces DM & intergalactic medium astrophysics
- ~ 3000 CPU-hours per simulation in 12-D parameter space
- ⇒ need ML-accelerated emulator

Figure: Lukić et al. (2015); Rogers et al. (JCAP, 2019); Rogers & Peiris (Phys. Rev. D, 2021)



4.9σ tension between eBOSS Ly-αf & *Planck* CMB

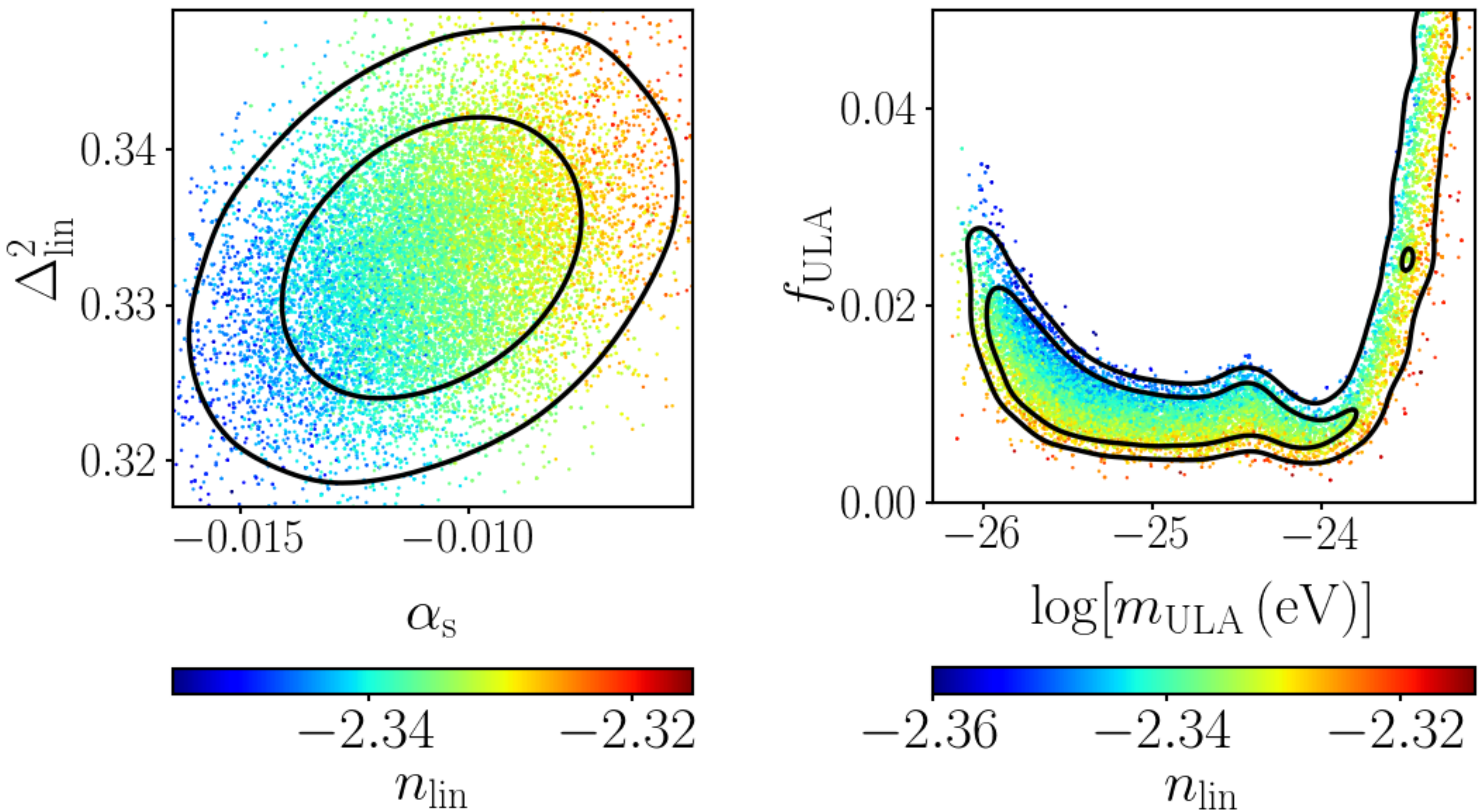
Rogers & Poulin (arXiv: 2311.16377)



Power spectrum running: 0.92σ; ultra-light axions: 0.56σ

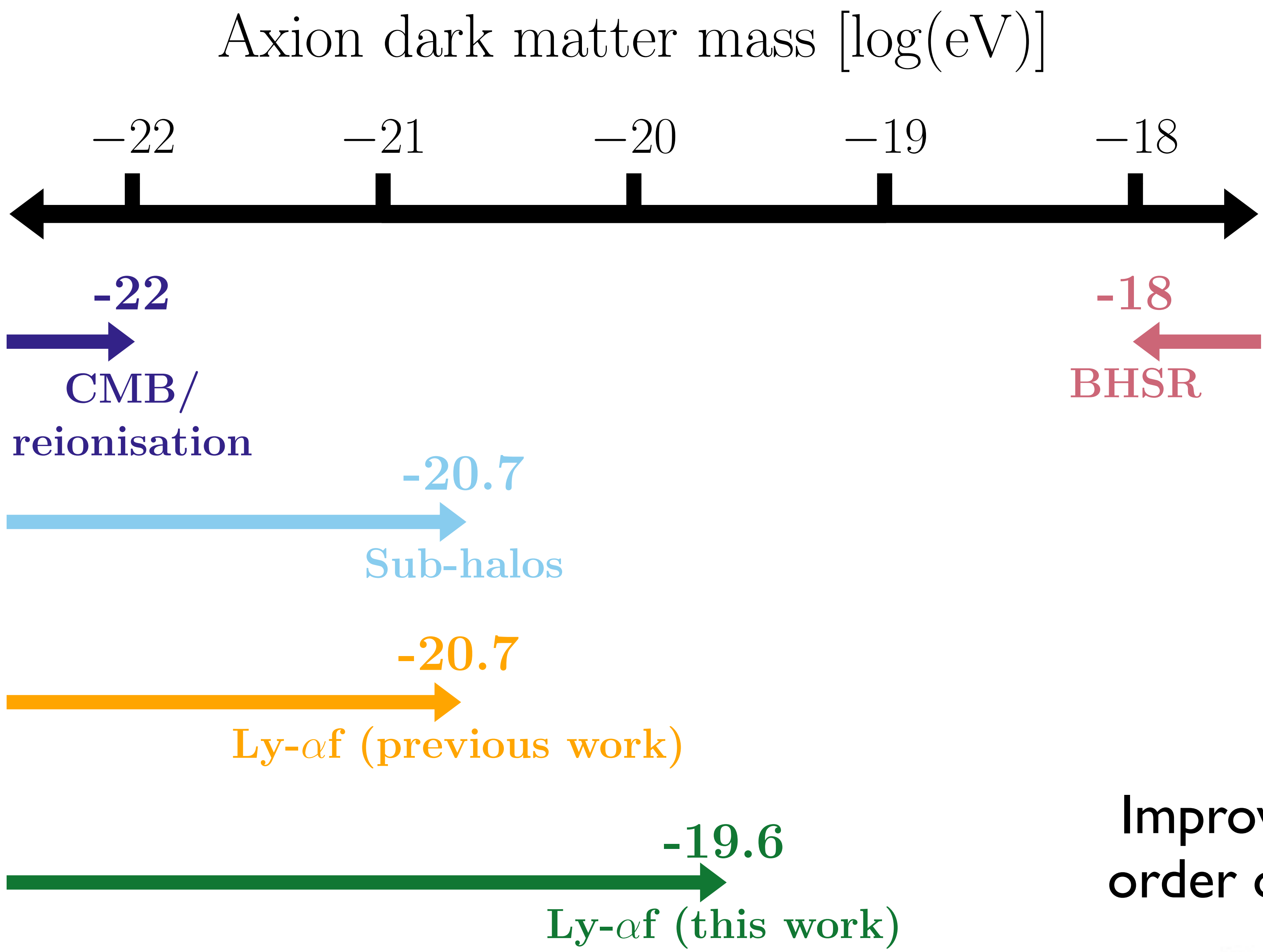
Rogers & Poulin (arXiv: 2311.16377)

Planck CMB + BAO + SNe + eBOSS Lyman-α forest constraints on running and ultra-light axion DM



Rogers & Poulin (arXiv: 2311.16377)

Traditional "small-scale crisis" axion ruled out — but axiverse compatible with data



Improve bound by order of magnitude

$$m_{\rm a} > 2 \times 10^{-20}\,{\rm eV}$$

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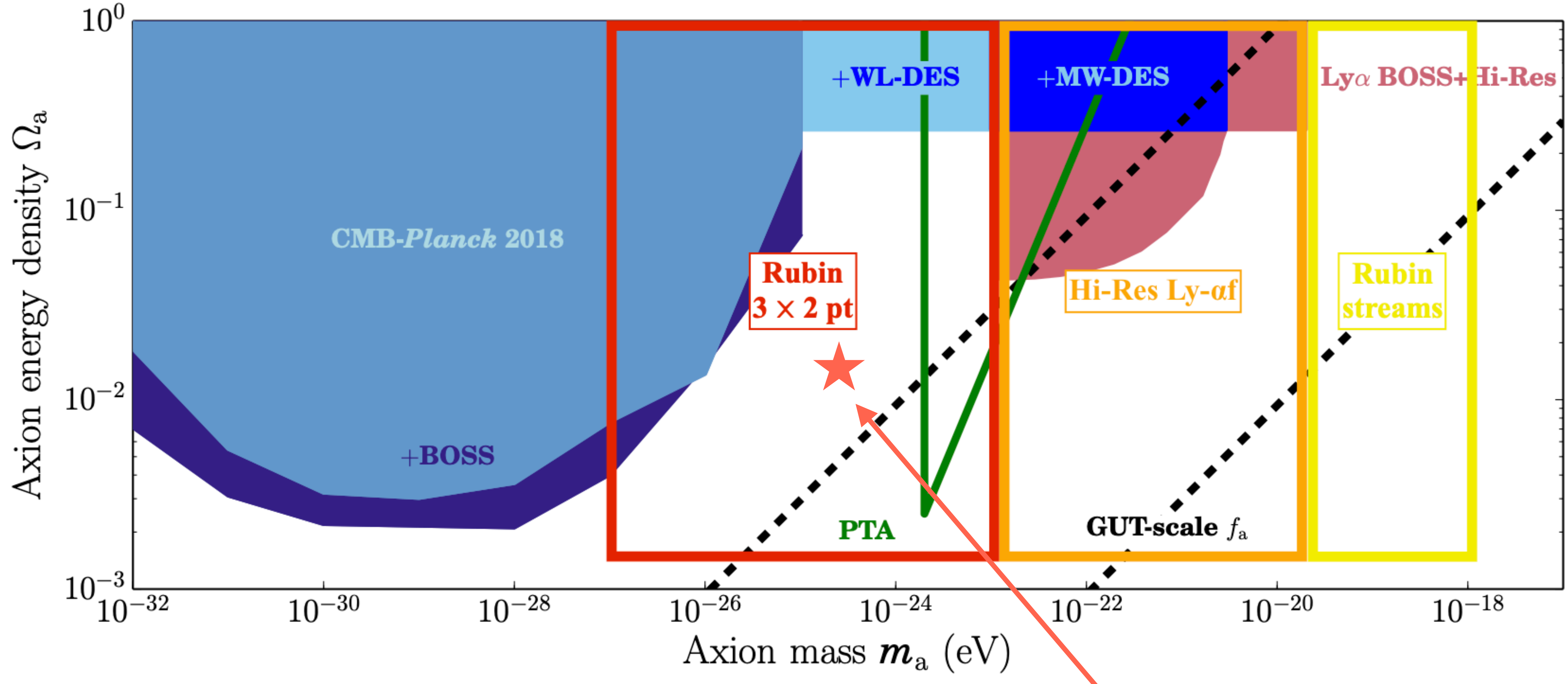
Rogers & Peiris (Phys. Rev. Lett., Phys. Rev. D, 2021ab)

Multi-probe approach to detect ultra-light axions



Improve consistency between CMB & LSS

Lyman-α forest: Rogers et al. (PRL, 2022; PRL, 2021); https://keirkwame.github.io/DM_limits

Summary

- **Joint analysis of CMB & large-scale structure** strengthens axion sensitivity
- **5σ tension between CMB & Ly-αf** alleviated by small-scale suppression
- *Rubin* and DESI data poised to **disentangle DM effects and astrophysics**