IDENTIFYING THE FUNDAMENTAL NATURE OF DARK MATTER USING THE COSMIC LARGE-SCALE STRUCTURE

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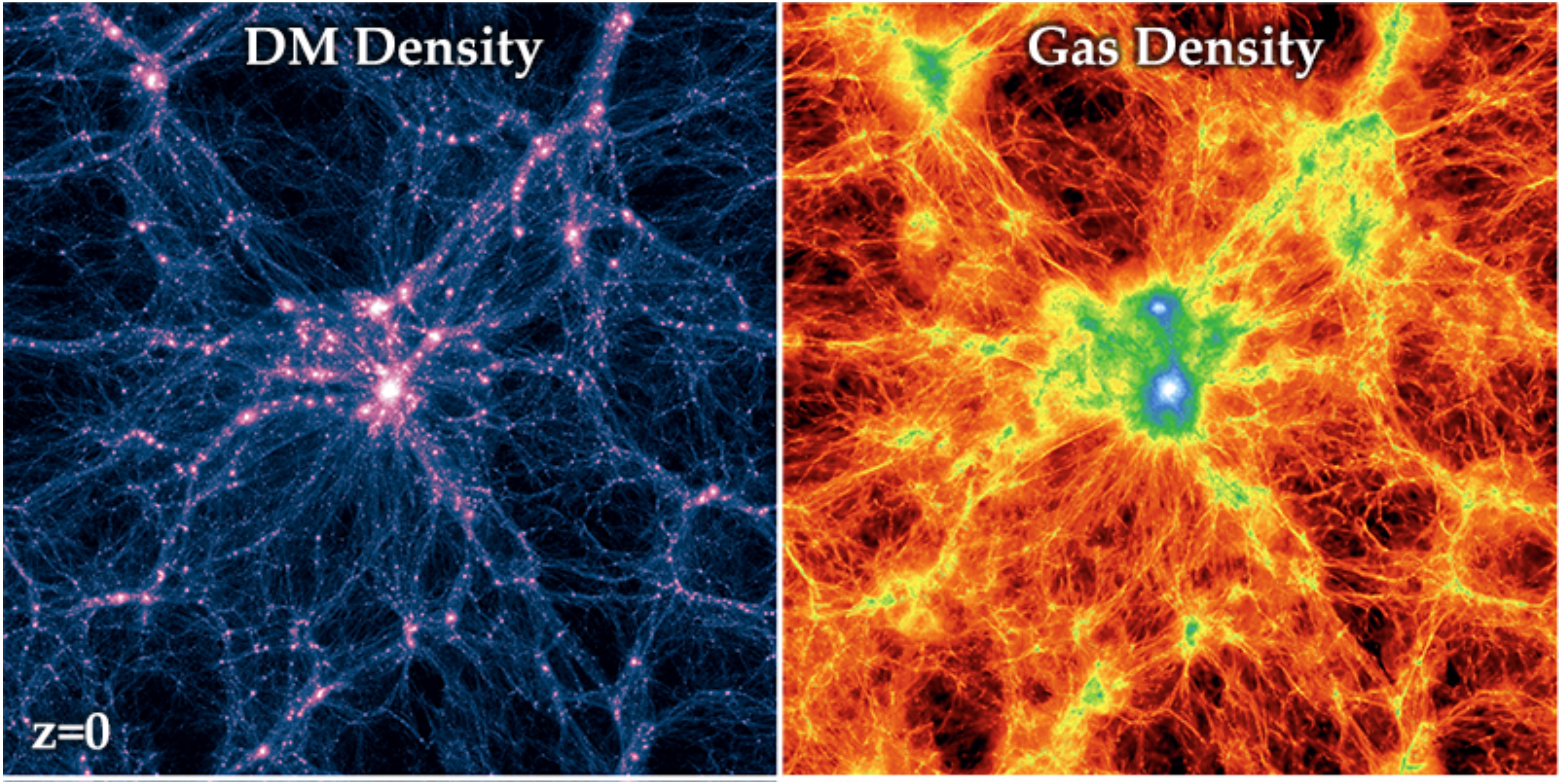
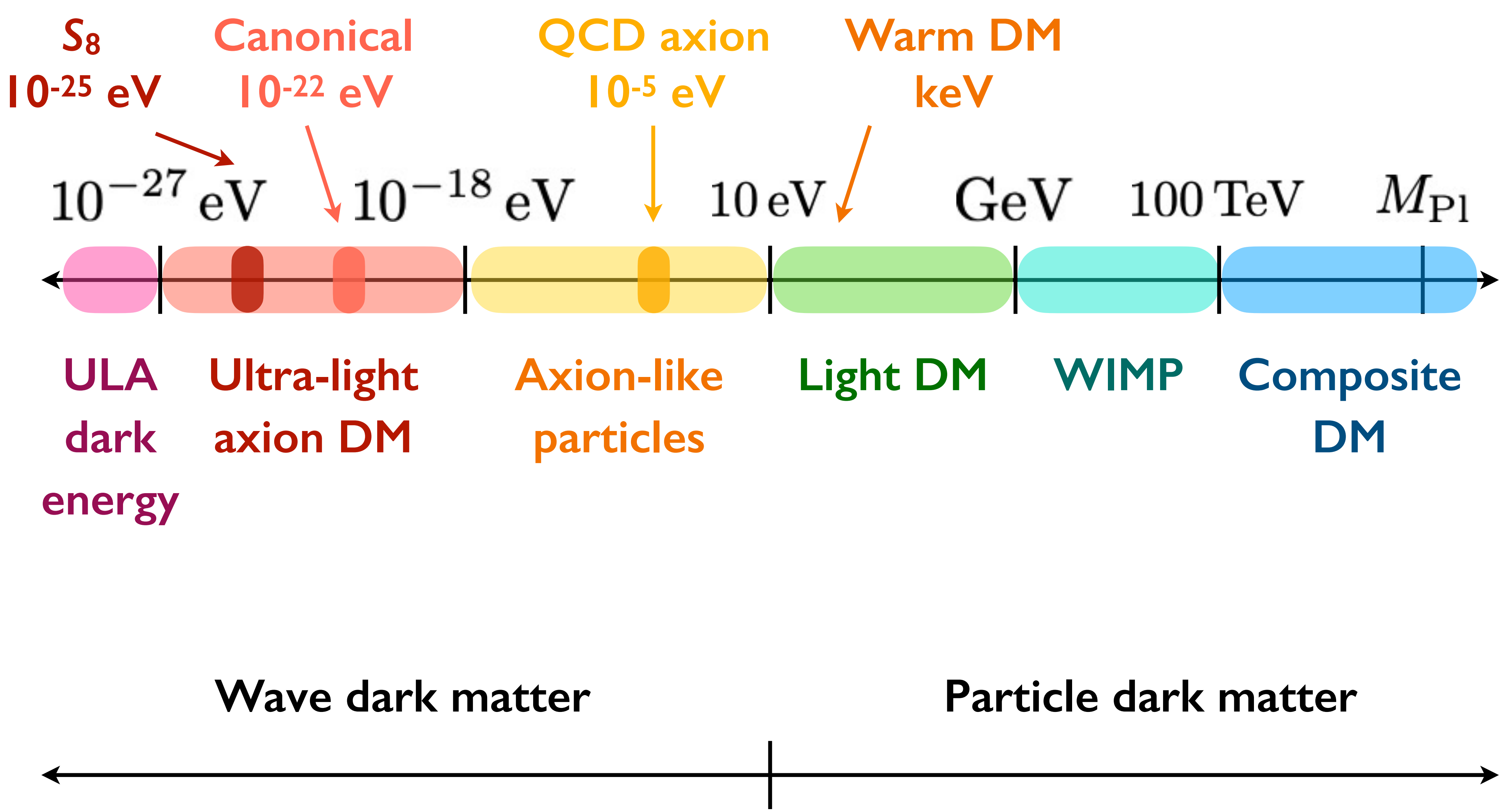
Find dark matter by only known interaction — gravity — trace dark matter by galaxies & intergalactic gas



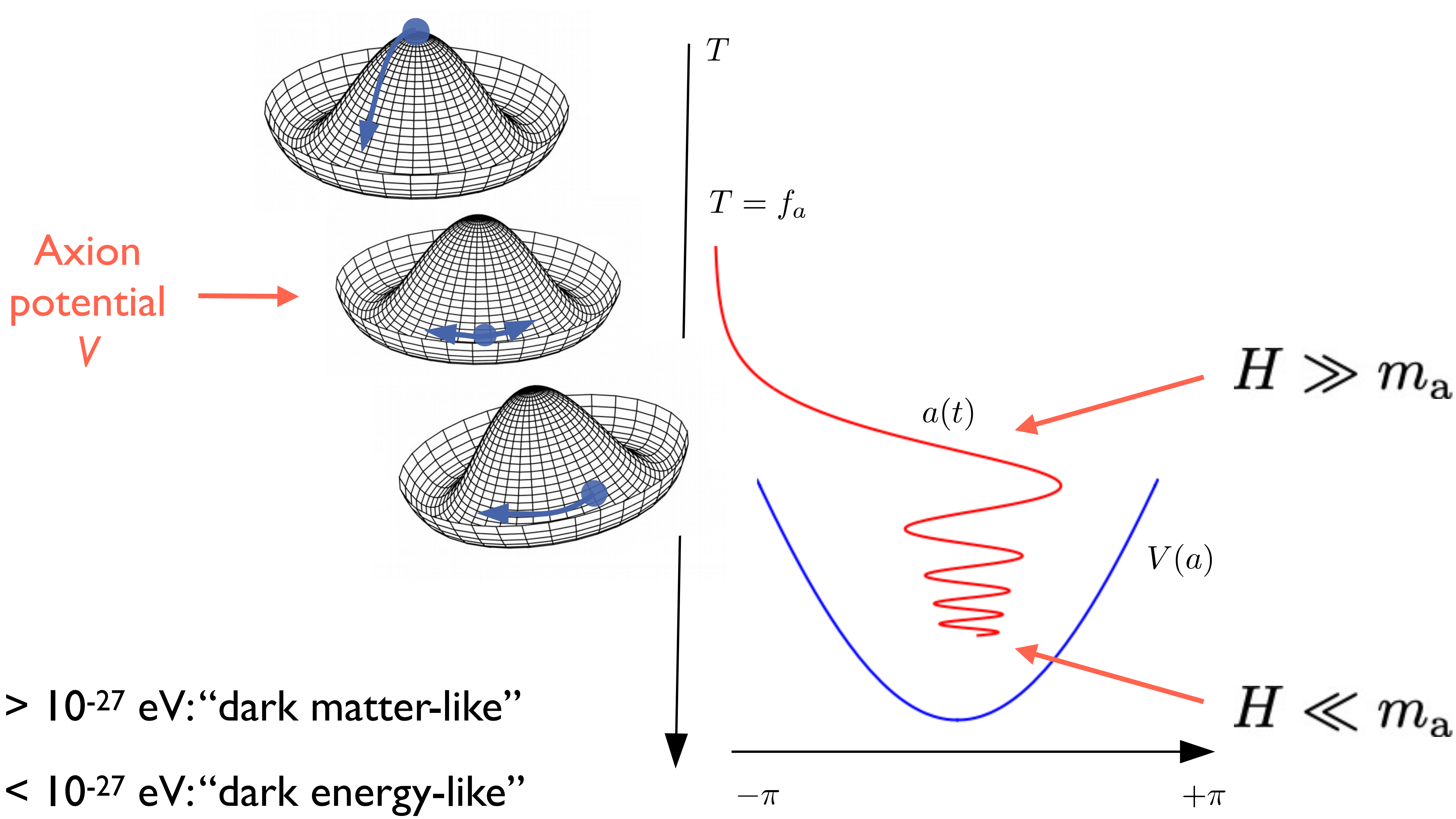
Illustris simulation

Beyond the WIMP: dark matter model space



LSS constraints on Light DM: Rogers et al. (Phys. Rev. Lett., 2022)

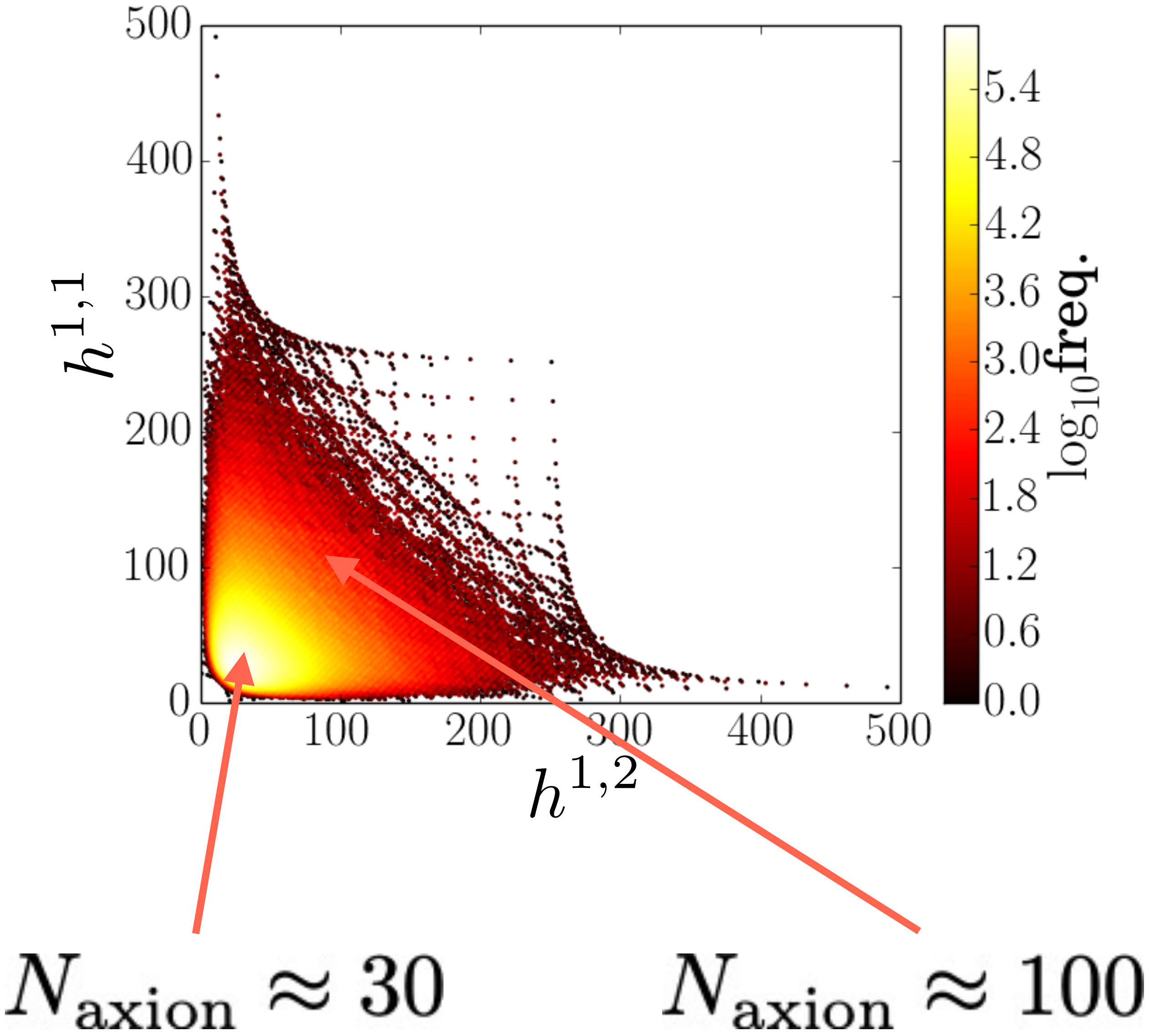
Axions are dark energy and dark matter candidates



- $m_a > 10^{-27}$ 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)

Axion-like particles abundantly produced in high-energy theory



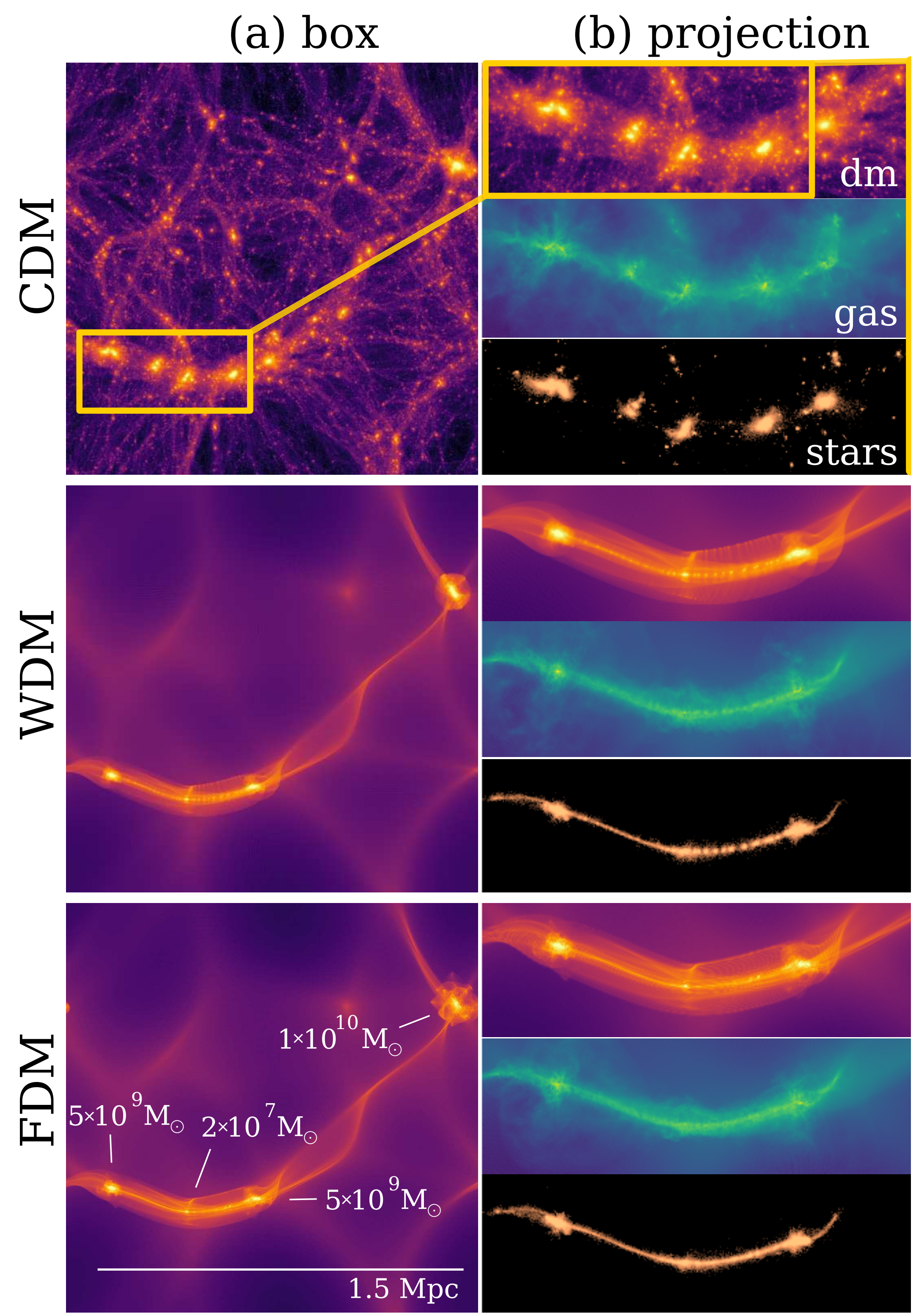
- Axion-like particles widely formed in BSM theories, inc. string models
- One/more string axions can be DM
- Ultra-light axions ($m_a < 10^{-18}$ eV) for Grand Unified Theory-scale f_a

Figure credit: Marsh (2016)

Cold (massive particle) DM

Warm DM

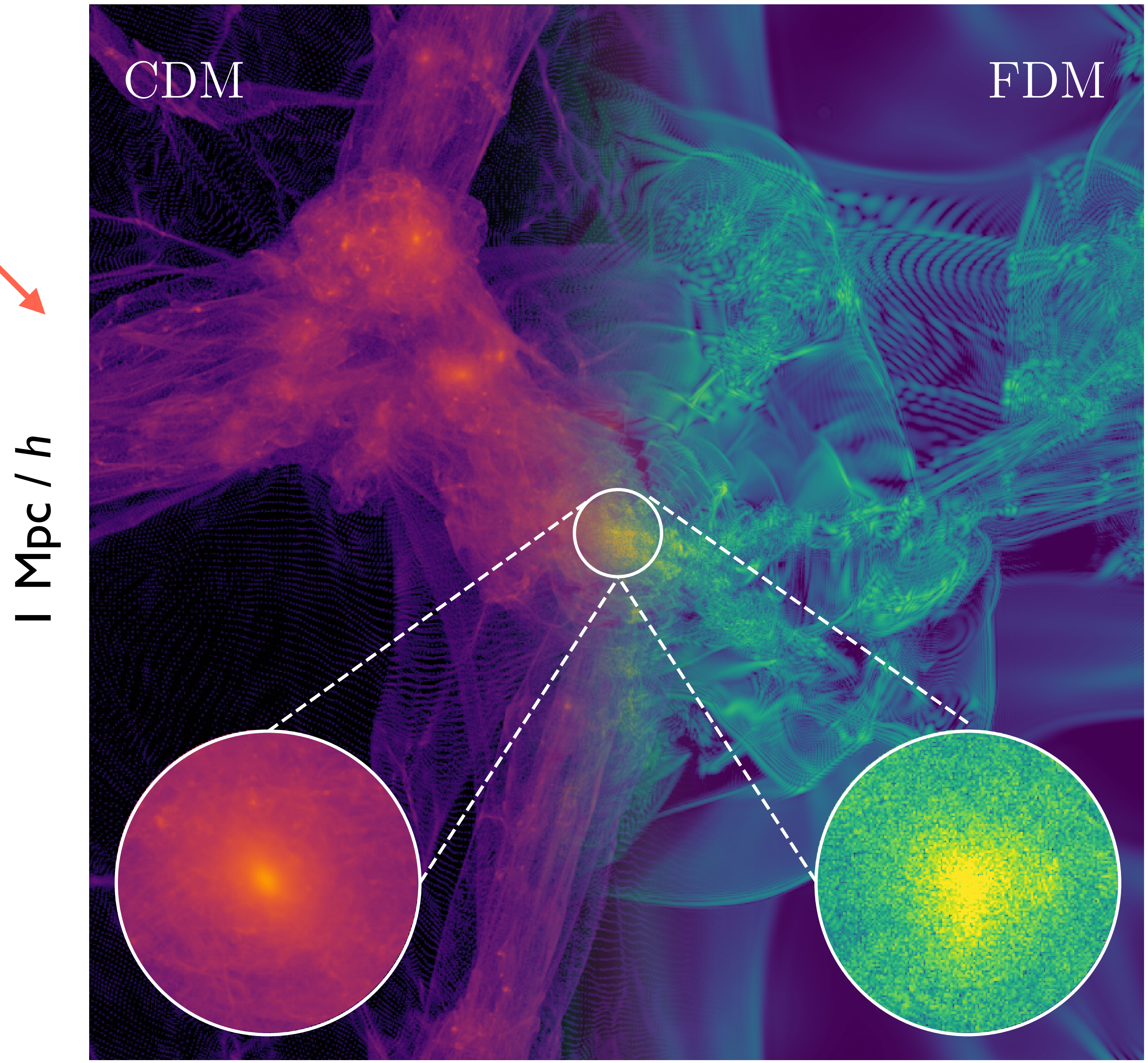
Fuzzy (wave) DM ($m = 10^{-22}$ eV)



Mocz et al. (2019)

Fuzzy dark matter forms interference fringes, halo cores and oscillating dark matter granules

Dark matter density

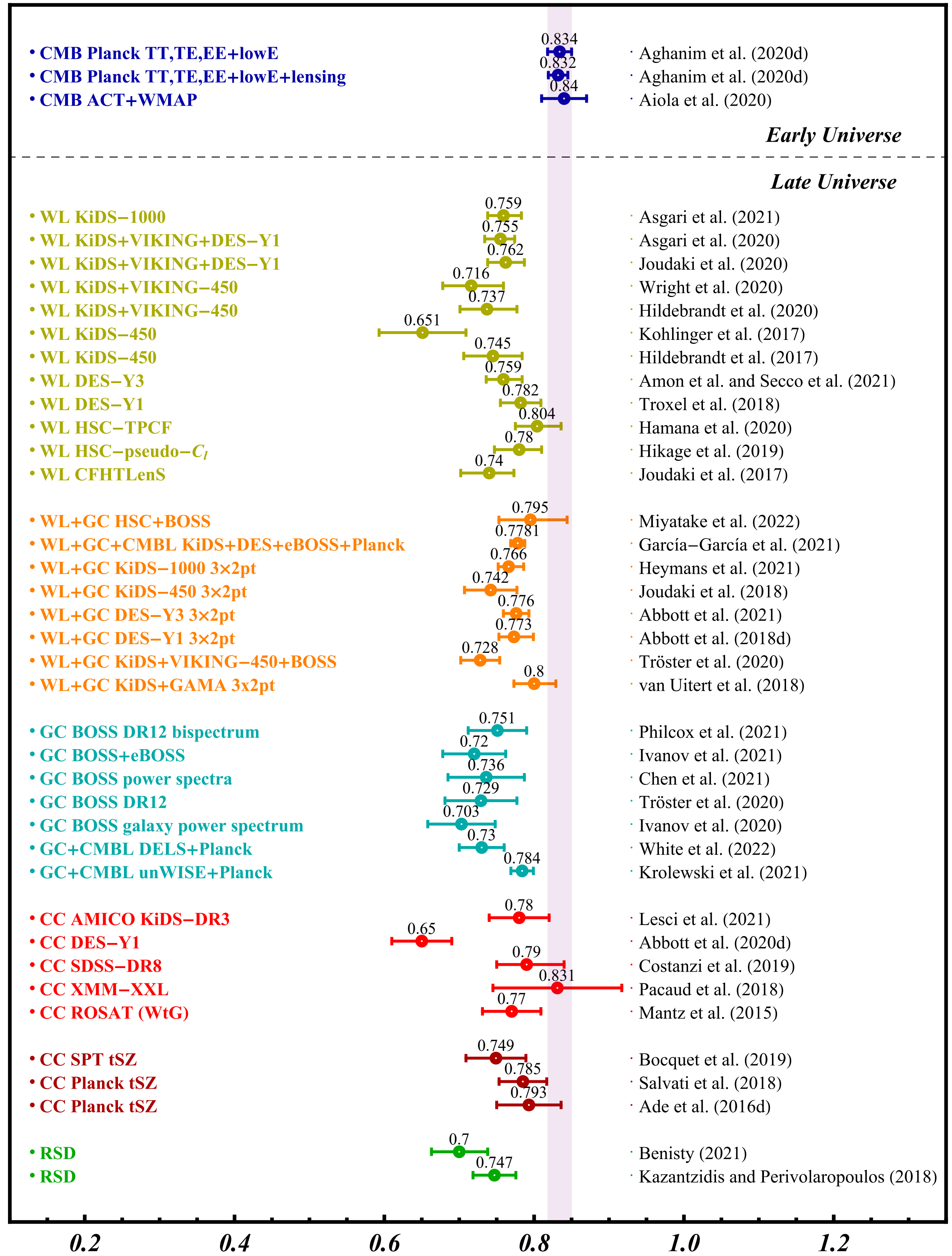


m = 10^{-22} eV
10% FDM
90% CDM

Laguë, Schwabe, Hložek, Marsh, Rogers (arXiv: 2310.20000)

Larger scales

Smaller scales



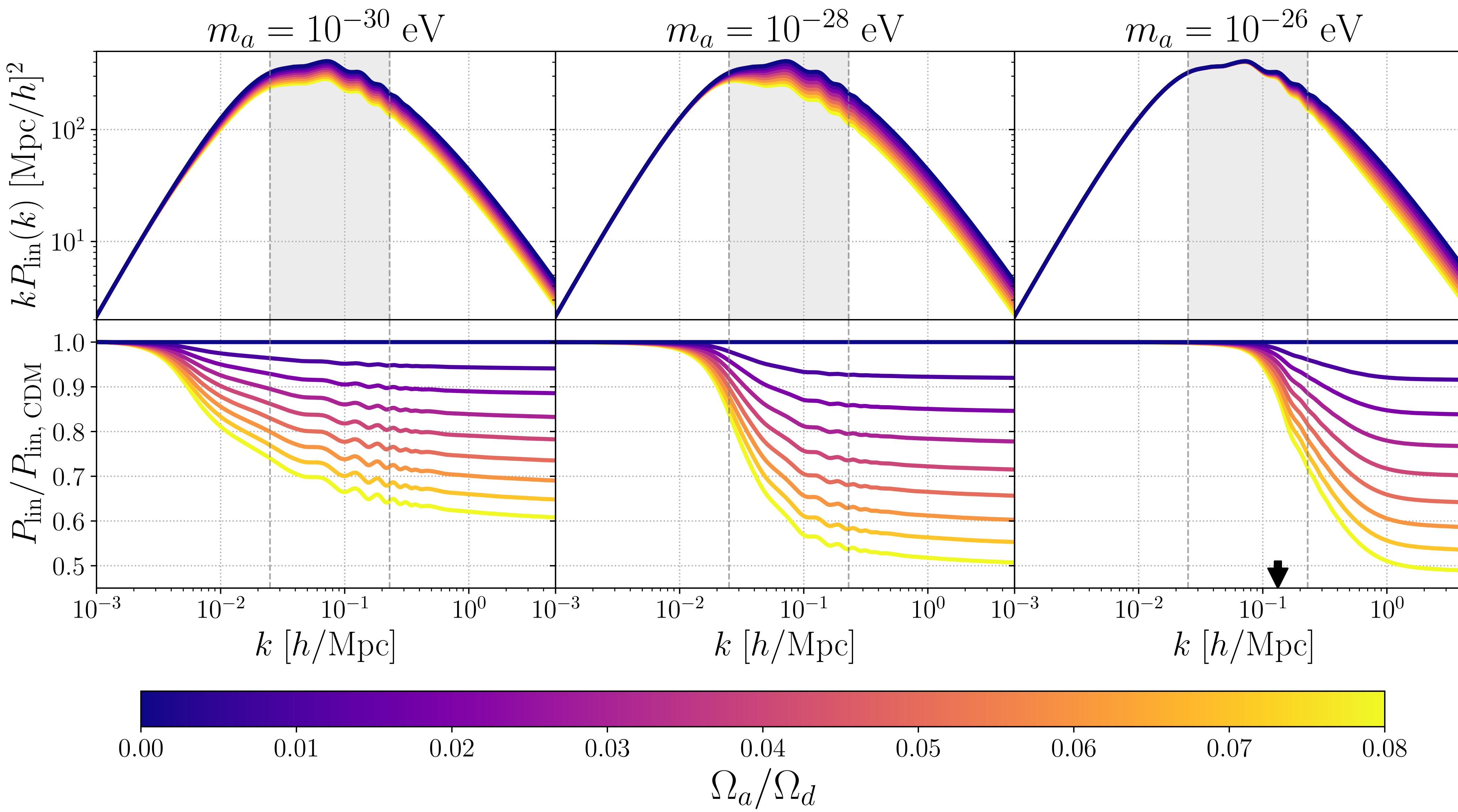
S_8 tension

S_8 ~ amplitude of density fluctuations at 8 Mpc/*h*

Abdalla et al. (Snowmass 2022)

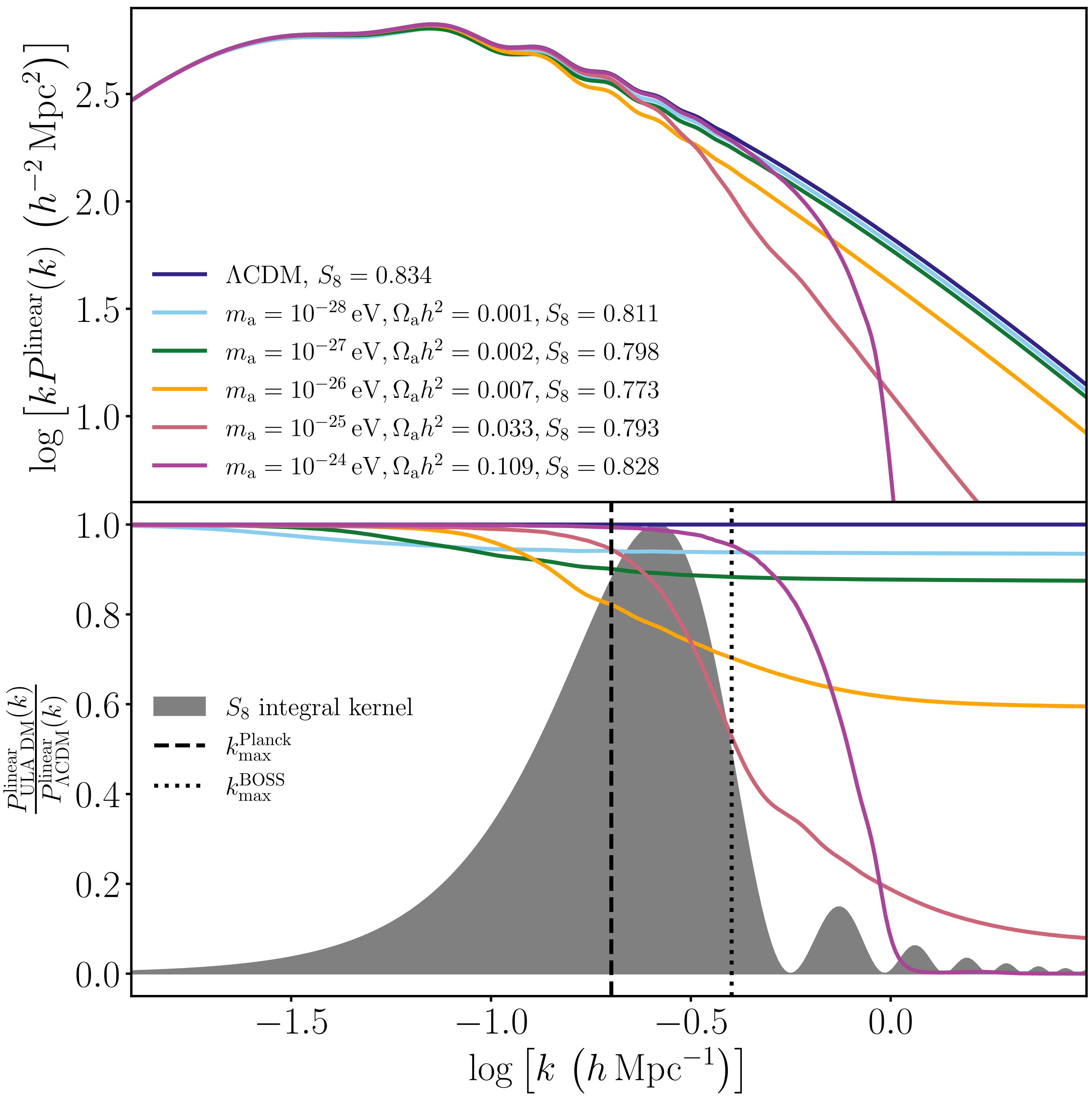
Ultra-light axion dark matter causes scale-dependent suppression in matter clustering

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



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

Axions lower S_8



Rogers, Hložek, et al. (JCAP, 2023)

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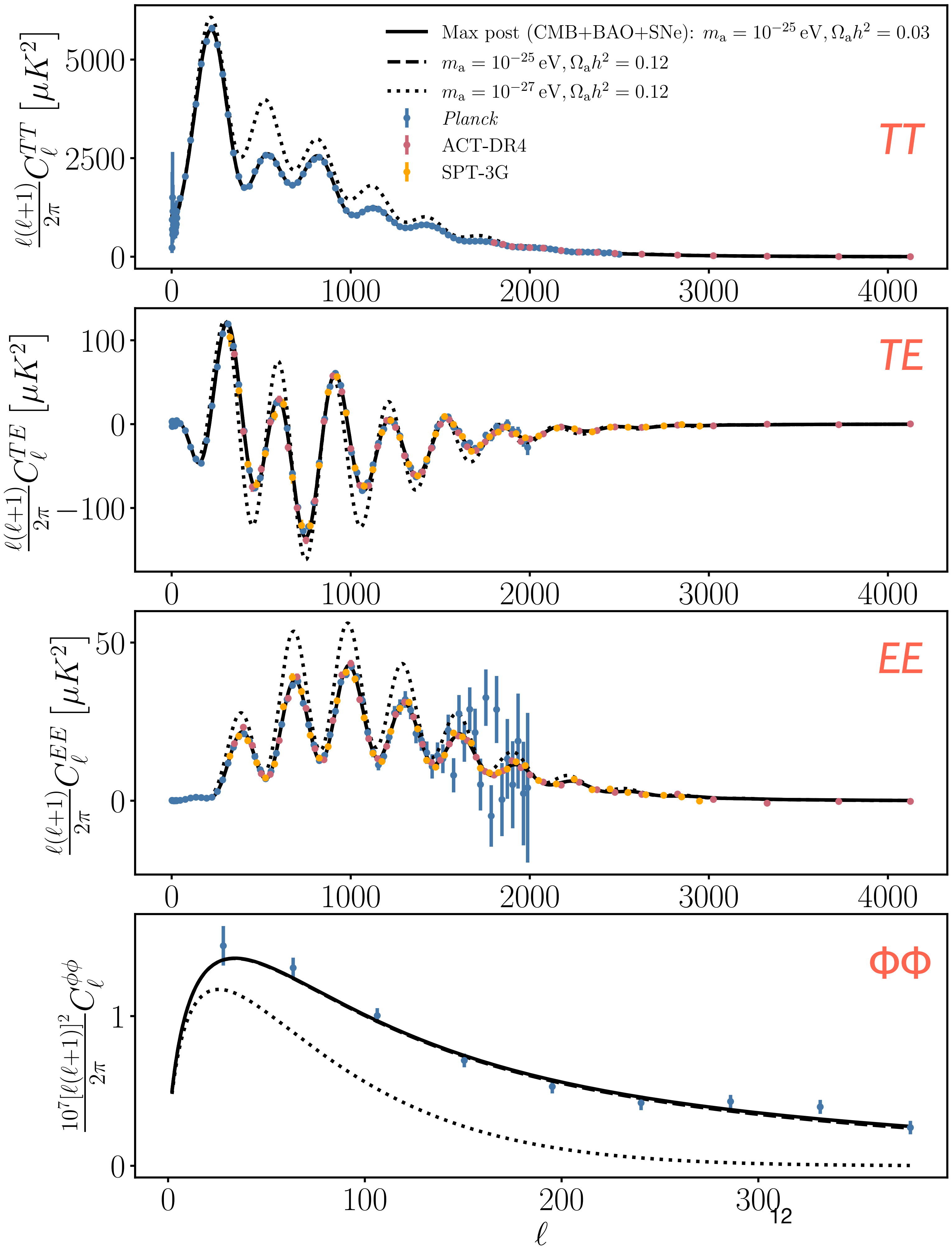
JOINT CONSTRAINTS ON ULTRA-LIGHT AXIONS FROM CMB & GALAXY SURVEYS

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

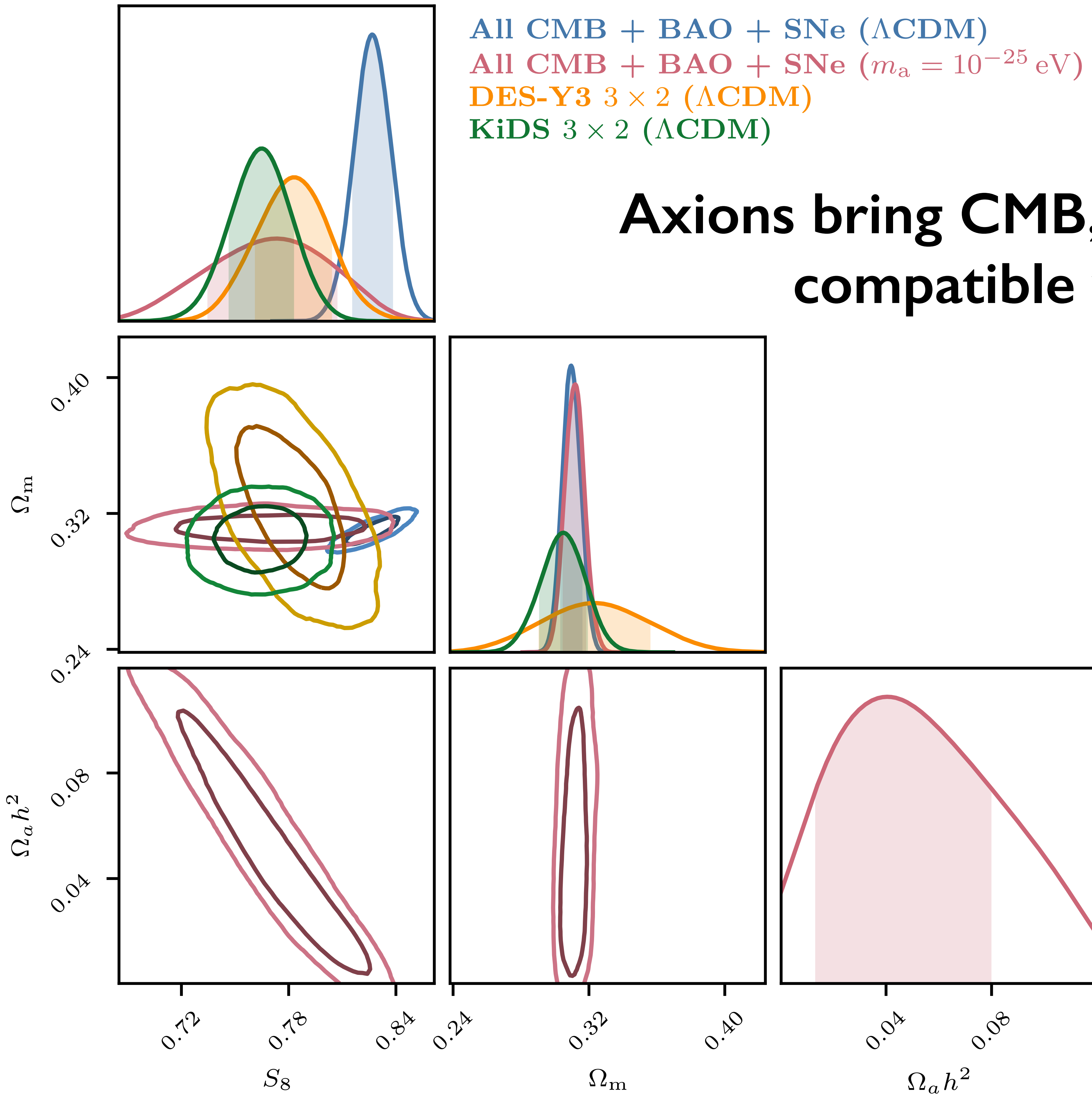


DE-like axions constrained by CMB acoustic oscillations & lensing potential

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

Rogers, Hložek, et al. (JCAP, 2023)

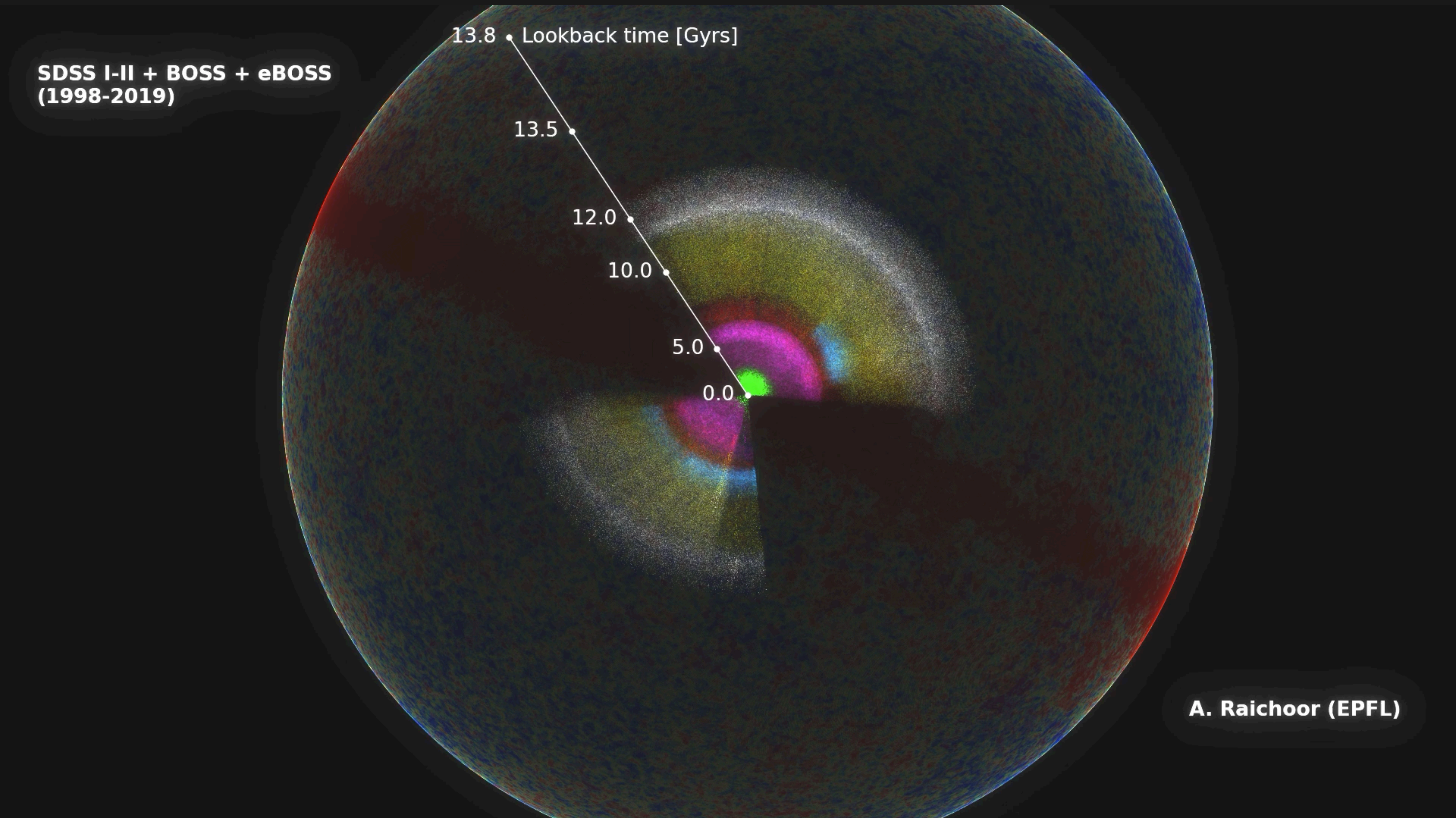
Axions bring CMB, BAO & SNe data compatible with low S_8



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

Rogers, Hložek, et al. (JCAP, 2023)

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



Model galaxy clustering into mildly non-linear regime with effective field theory of large-scale structure

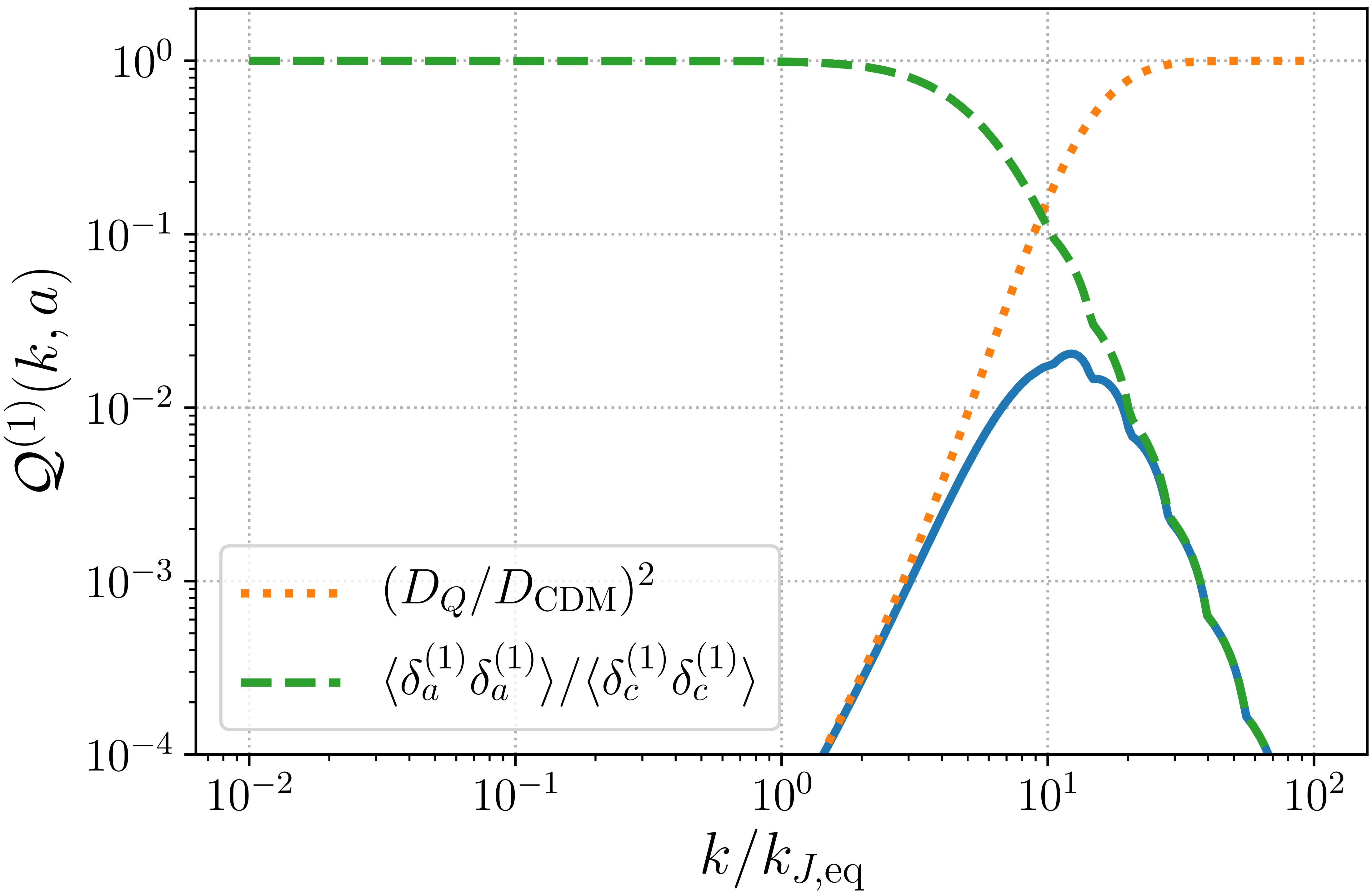
$$P_\ell(k) = P_\ell^{\mathrm{Tree}}(k) + P_\ell^{1-\mathrm{loop}}(k) + P_\ell^{\mathrm{Counter}}(k) + P_\ell^{\mathrm{Stoch}}(k)$$

- $P_\ell^{\mathrm{Tree}}(k)$: Linear theory (Kaiser model) $\propto P^{\mathrm{Linear}}(k)$
- $P_\ell^{1-\mathrm{loop}}(k)$: Perturbation theory $\propto k^2\, P^{\mathrm{Linear}}(k)$
- $P_\ell^{\mathrm{Counter}}(k)$: Ultraviolet counterterms $\propto k^2\, P^{\mathrm{Linear}}(k)$
- $P_\ell^{\mathrm{Stoch}}(k)$: Stochastic (shot noise/RSD)

+ Infrared resummation
+ Alcock-Paczynski distortion

Rogers, Hložek, et al. (JCAP, 2023); Baumann et al. (2012); Chudaykin et al. (2020)

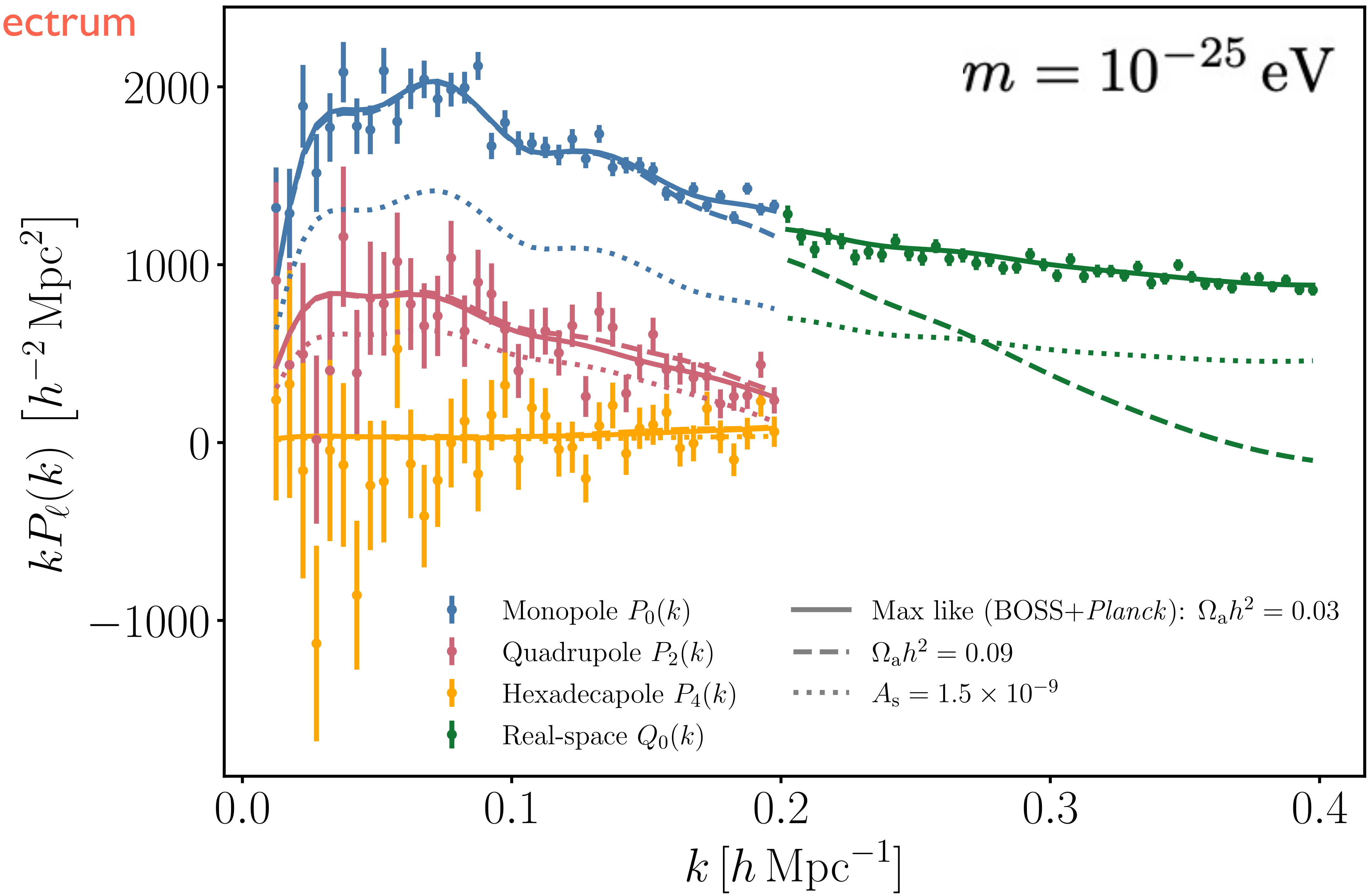
Axion "quantum" corrections suppressed by Jeans scale



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

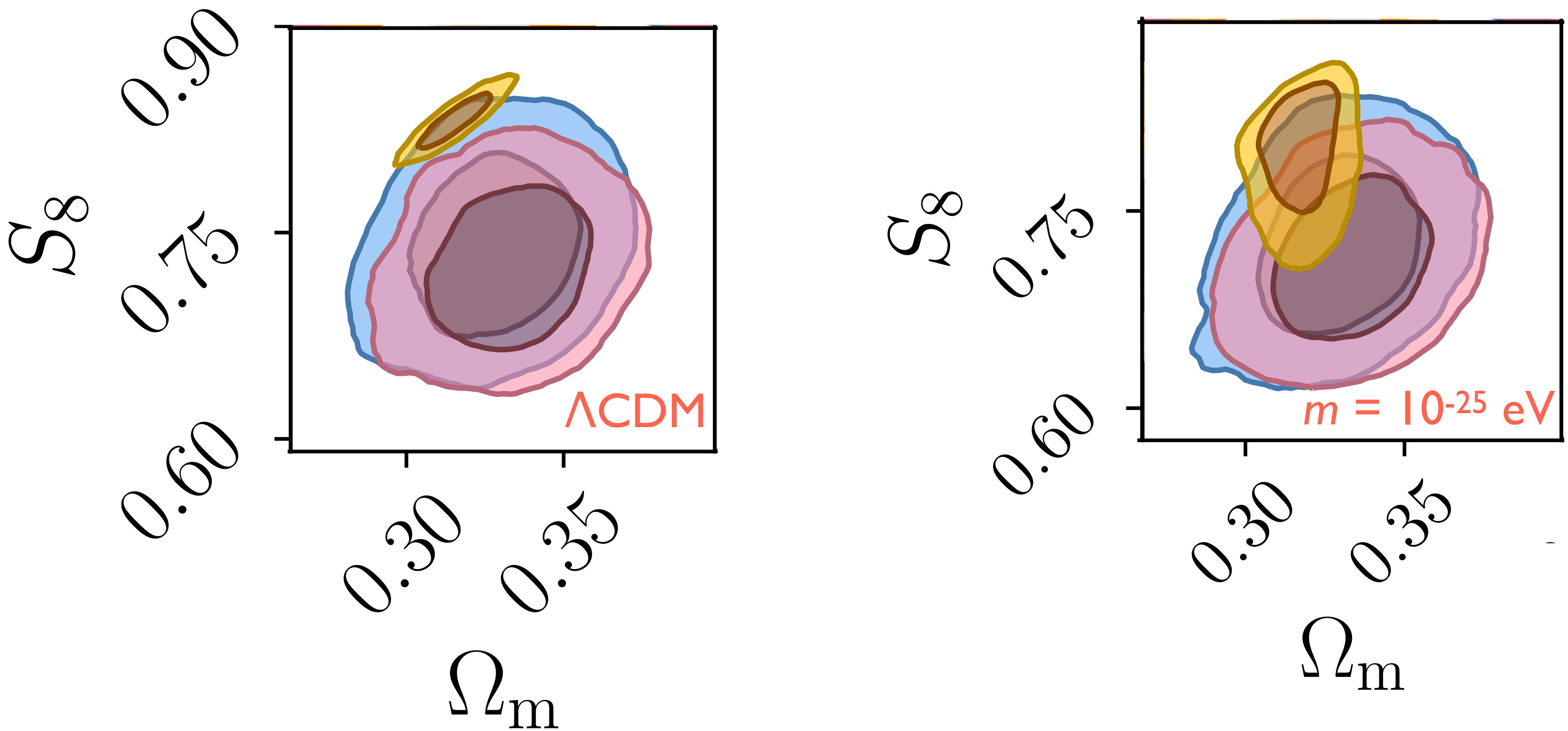
Full-shape BOSS galaxy power spectrum increases sensitivity to ultra-light axions

Power spectrum



Rogers, Hložek, et al. (JCAP, 2023)

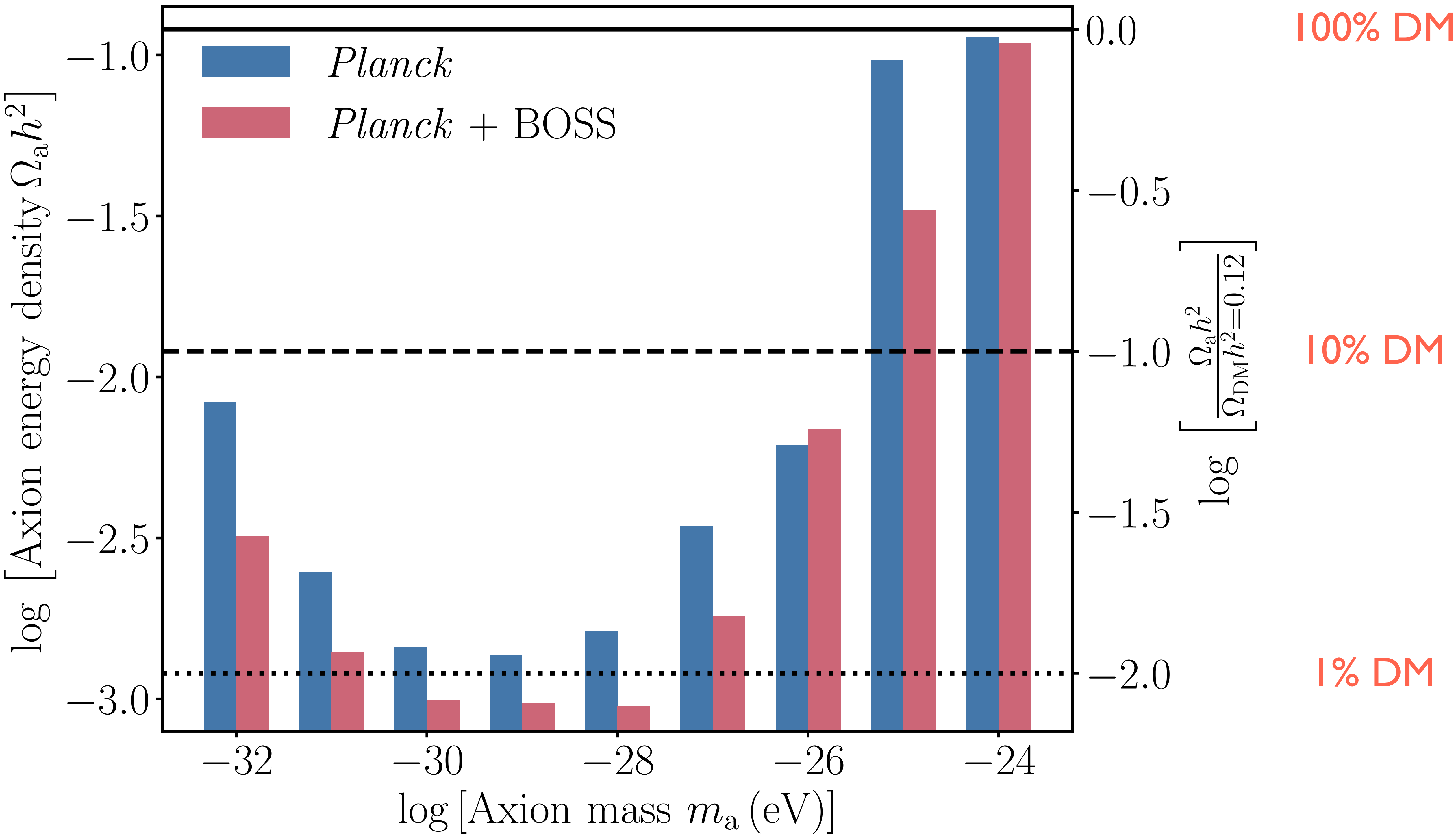
Axions improve consistency between *Planck* and BOSS-EFT



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

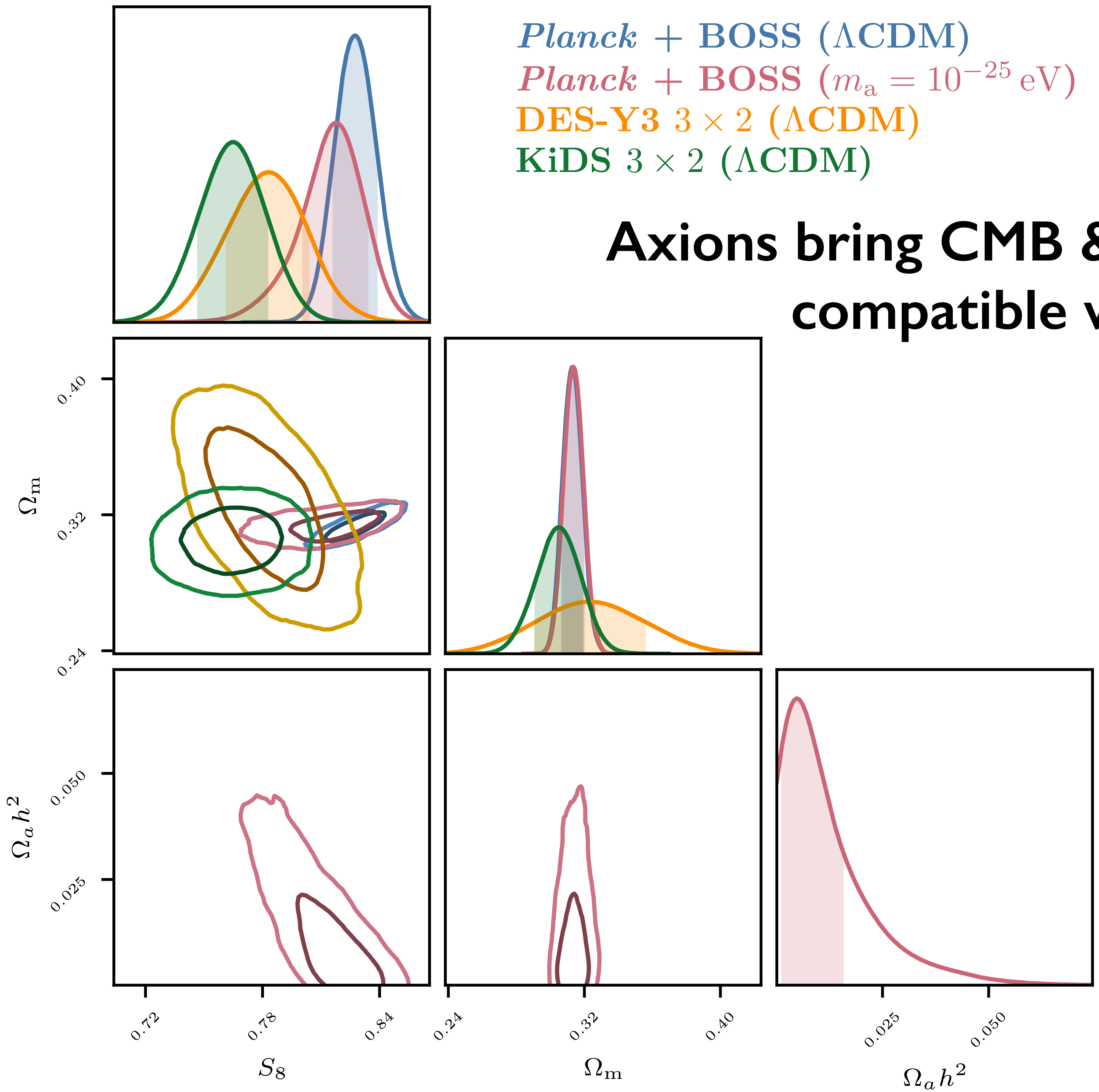
Rogers, Hložek, et al. (JCAP, 2023)

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



Rogers, Hložek, et al. (JCAP, 2023)

Axions bring CMB & galaxy clustering compatible with low S_8



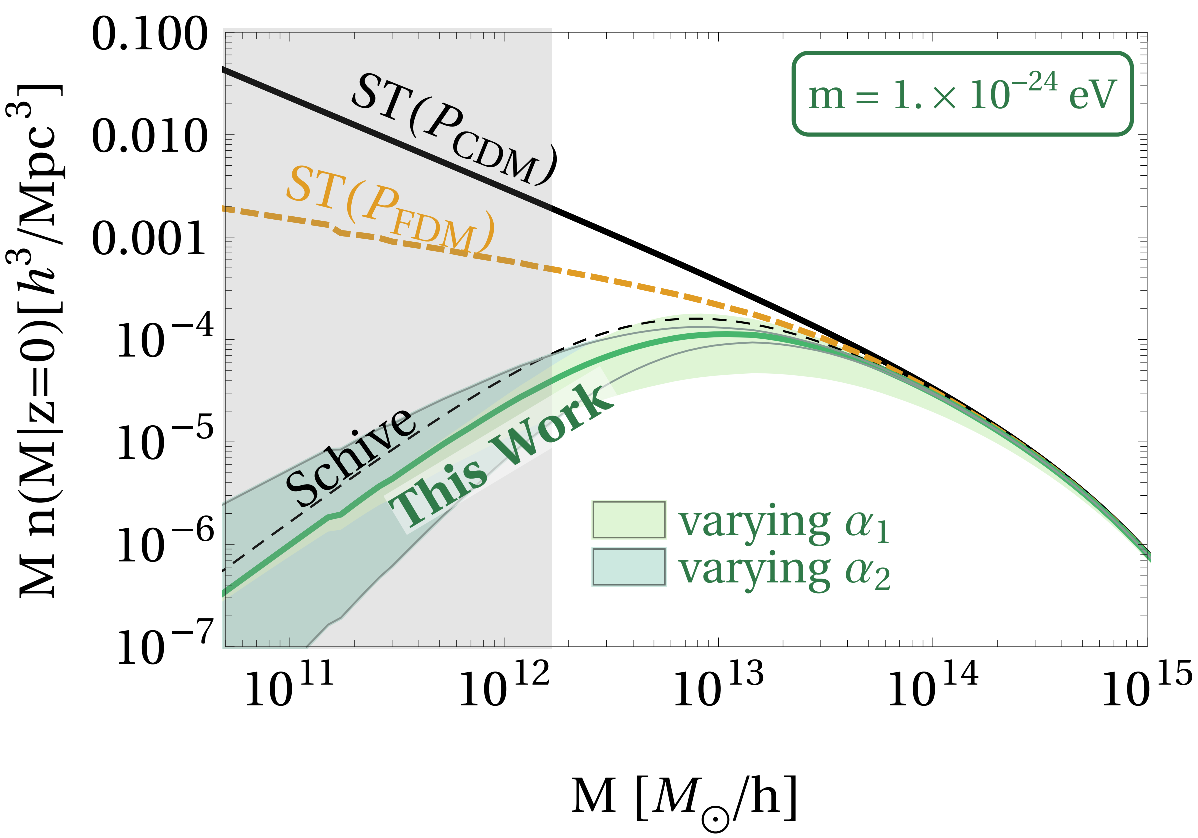
$m = 10^{-25}$ eV

Rogers, Hložek, et al. (JCAP, 2023)

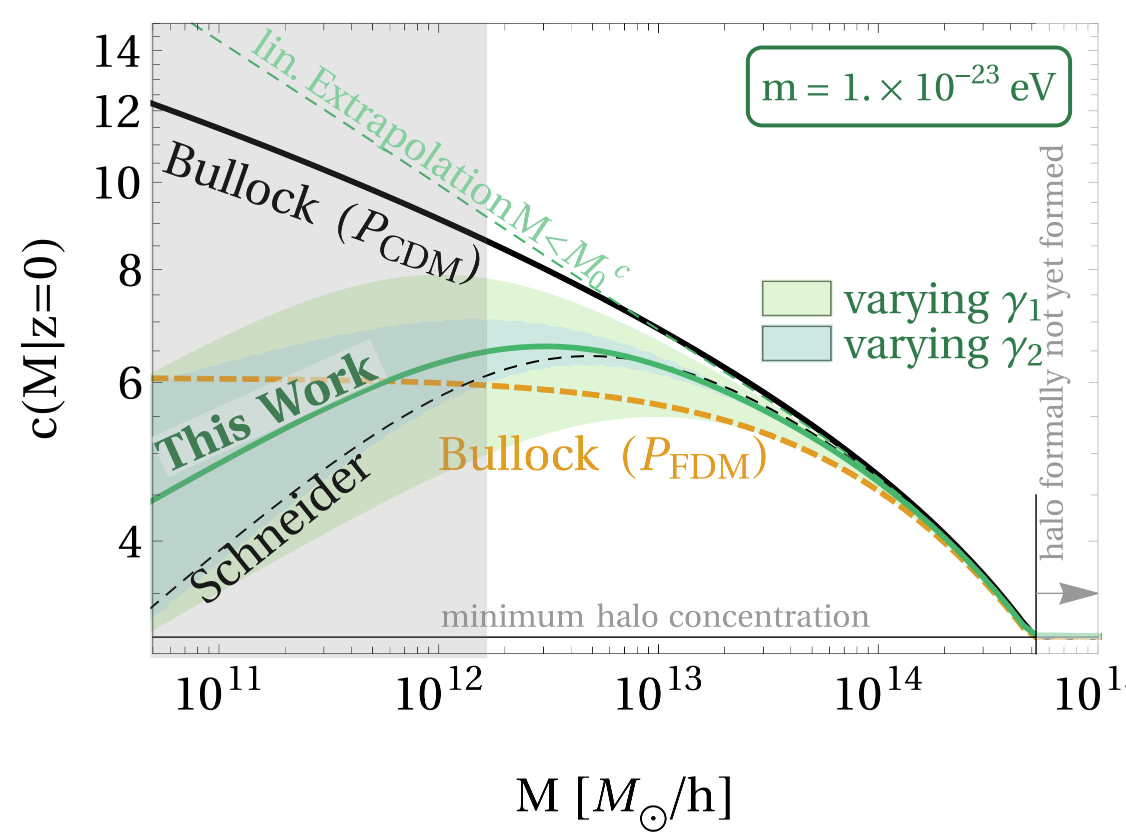
Model galaxy weak lensing into fully non-linear regime with axion halo model

Matter power spectrum = Two-halo power spectrum + One-halo power spectrum

Halo mass function

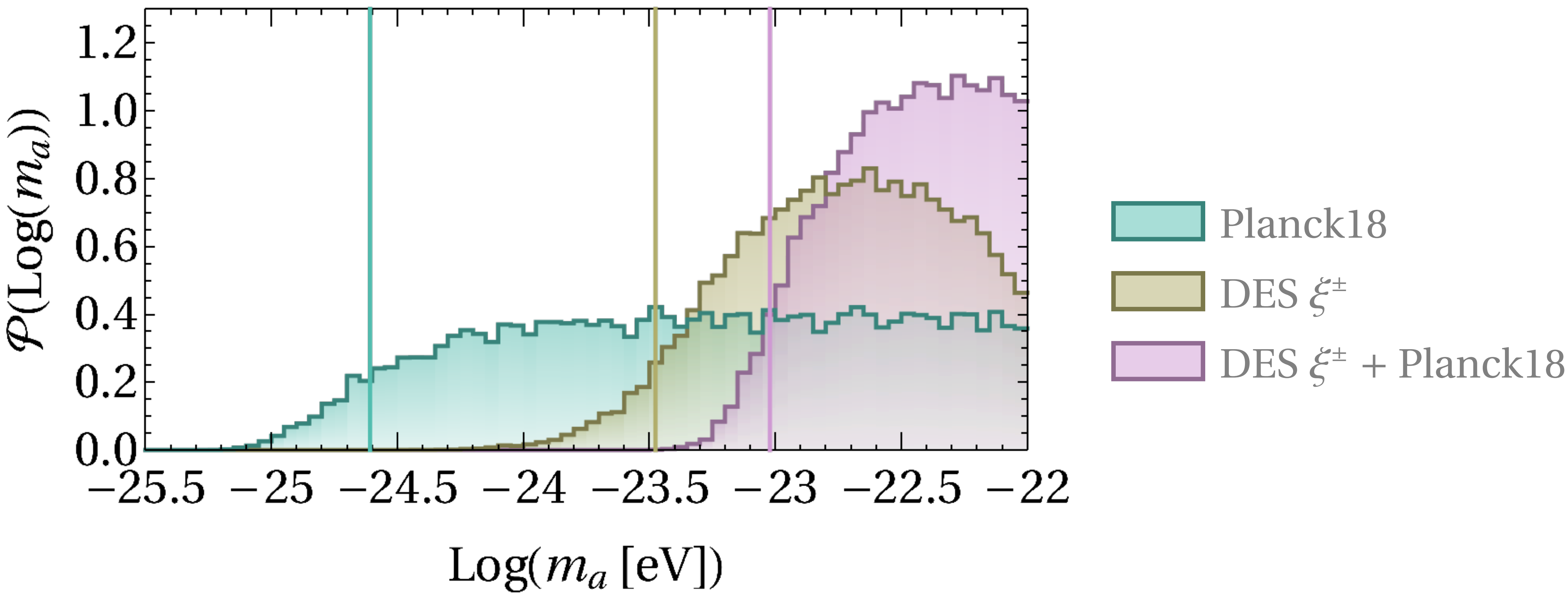


Concentration-mass function



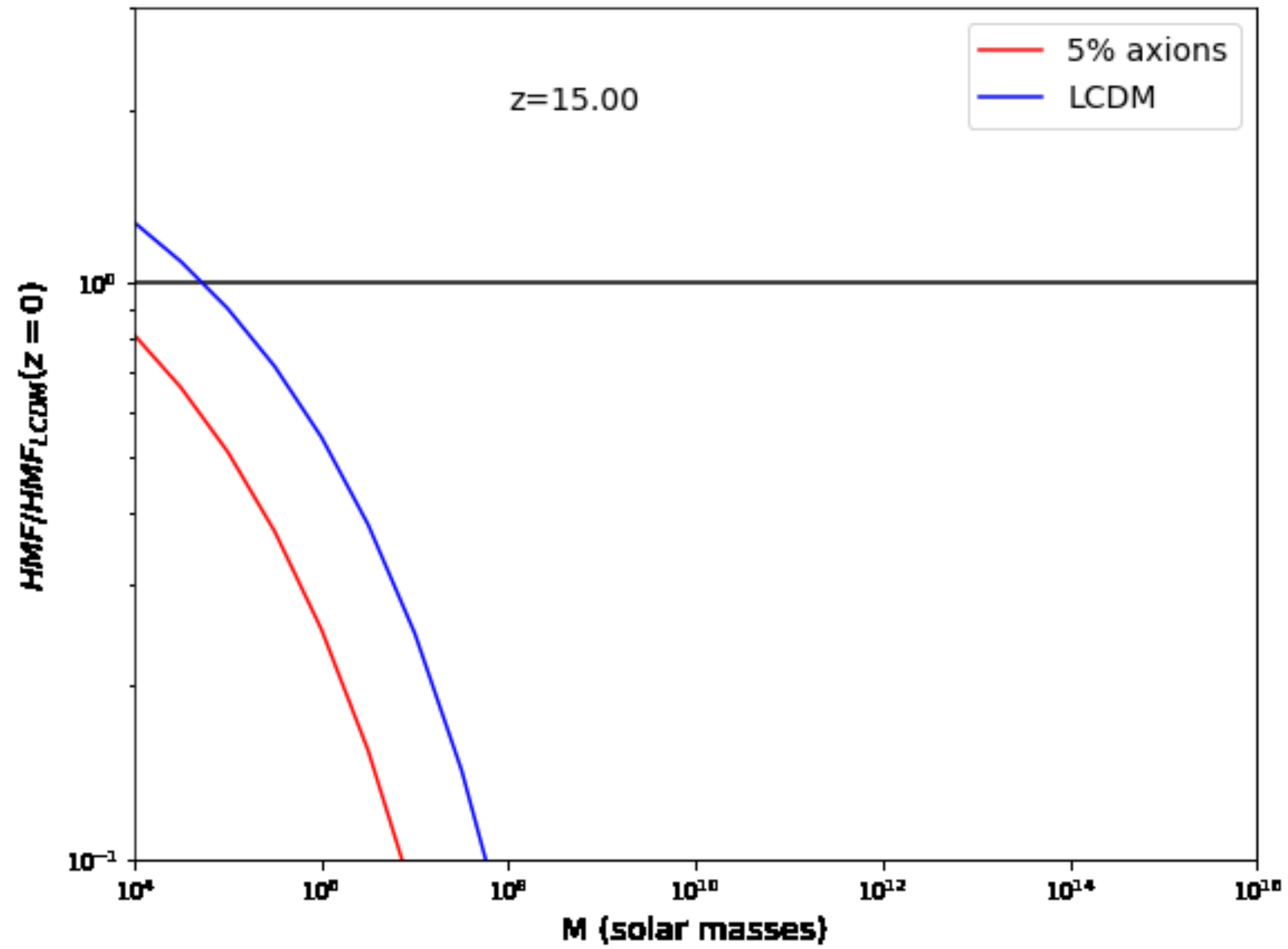
Dentler, Marsh, Hložek, Laguë, Rogers, Grin (MNRAS, 2022); Winch & Rogers (2023, in prep.)

Joint CMB & galaxy weak lensing limits using axion halo model



Dentler, Marsh, Hložek, Laguë, Rogers, Grin (MNRAS, 2022)

A modified halo model for mixed axion structure formation

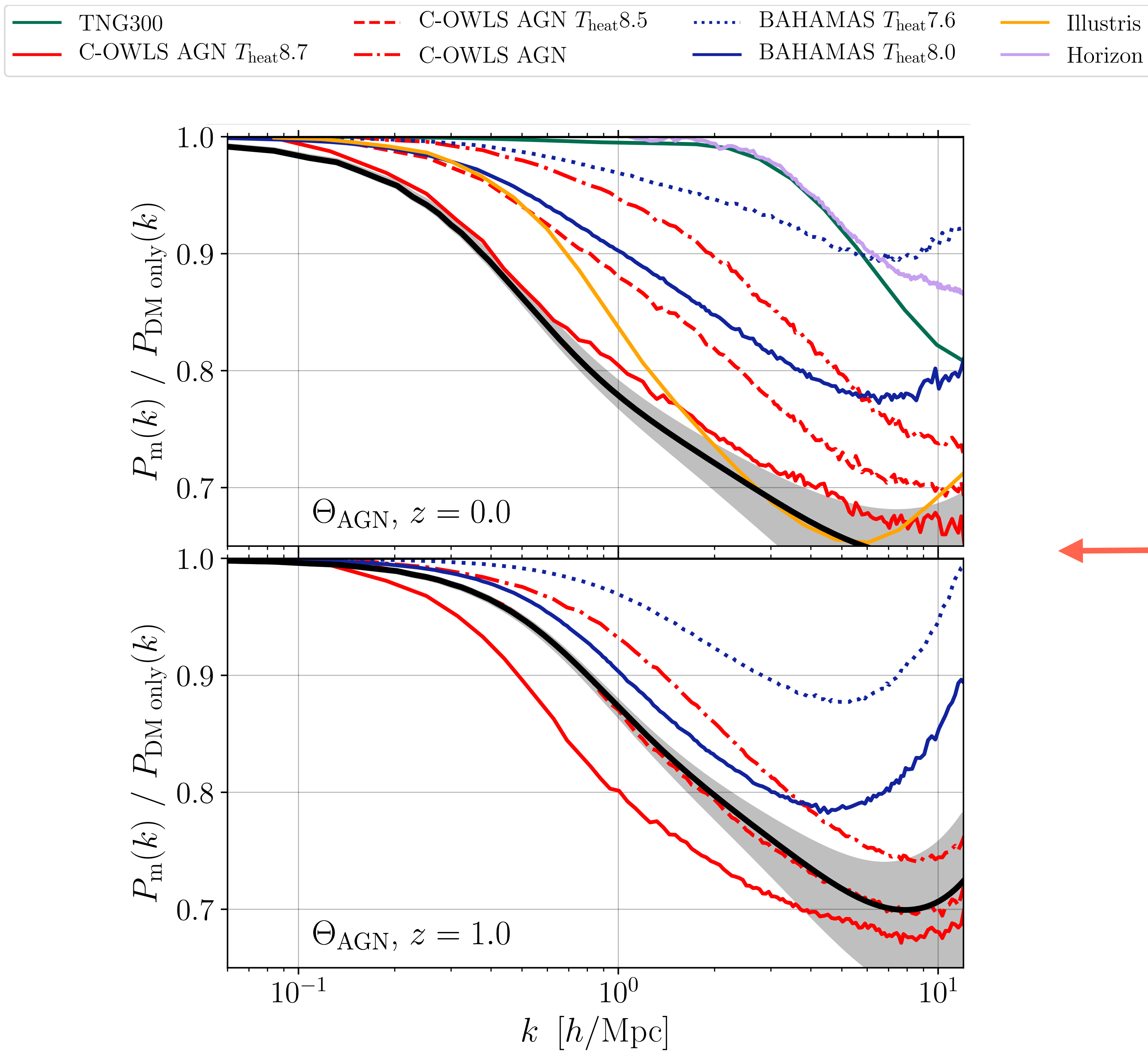


$$m_a = 10^{-24}\,\mathrm{eV}$$

- Axions do not cluster below de Broglie wavelength
- Suppressed halo population at Jeans scale
- Structure formation delayed leading to small-scale enhancement

Vogt et al. (2023); Harrison Winch & Keir Rogers (2023, in prep.)

Precision weak lensing analysis must account for baryonic feedback



Need feedback 100 - 1000 × stronger?

Amon & Efstathiou (2022)

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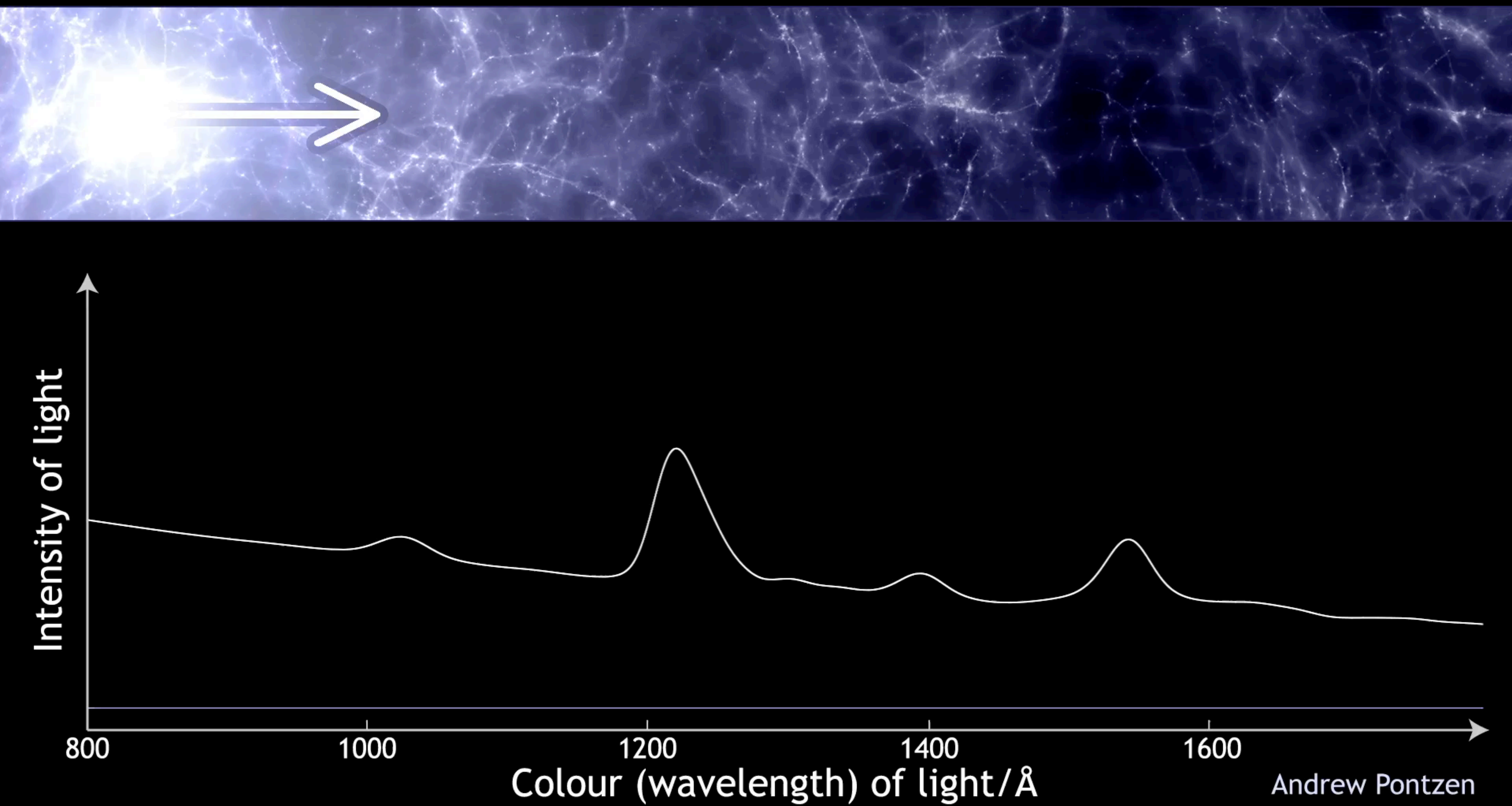
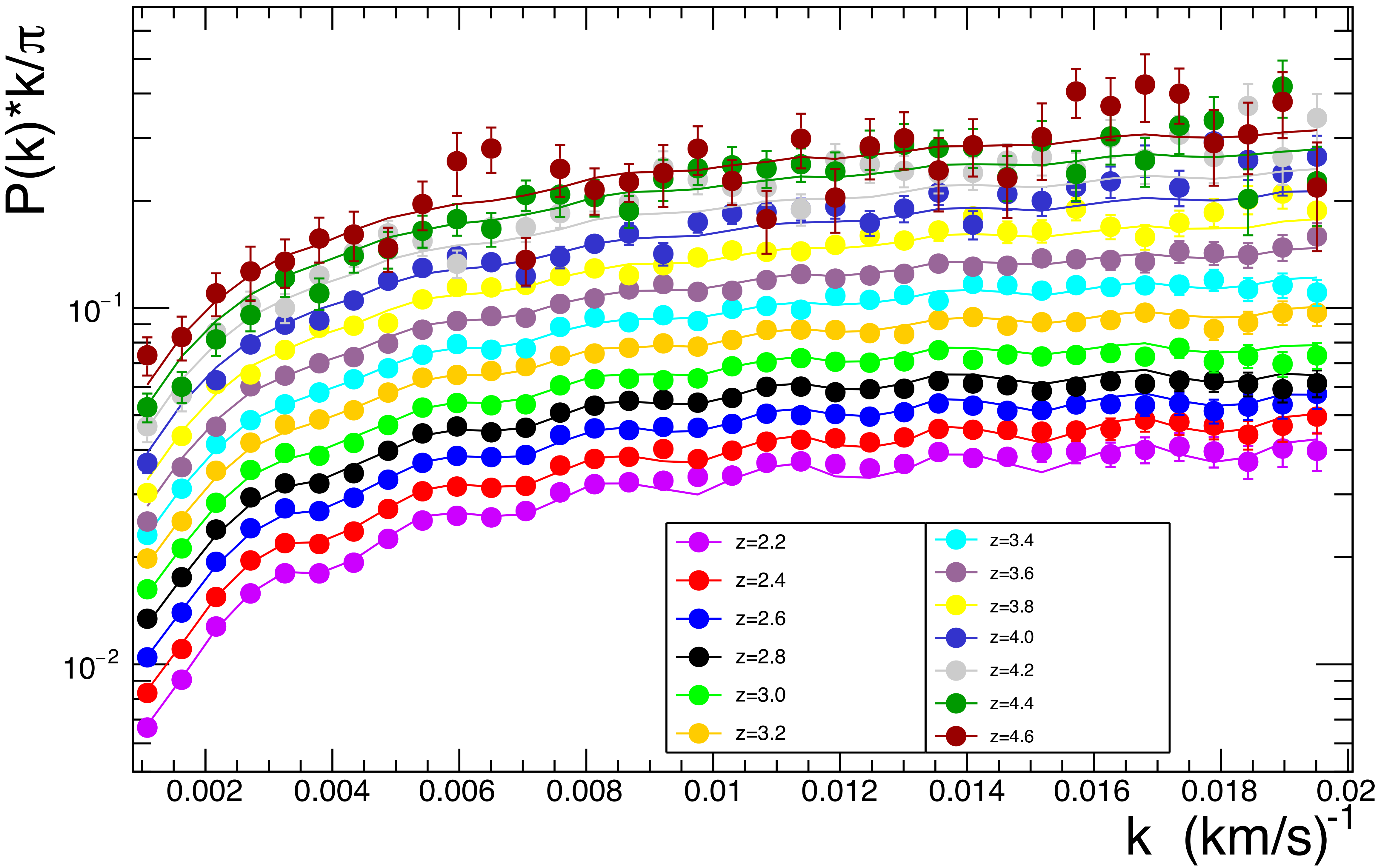
A resolution of the 5σ tension between *Planck* CMB and eBOSS Lyman-α forest

with Vivian Poulin

Lyman-alpha forest traces intergalactic medium around mean cosmic density

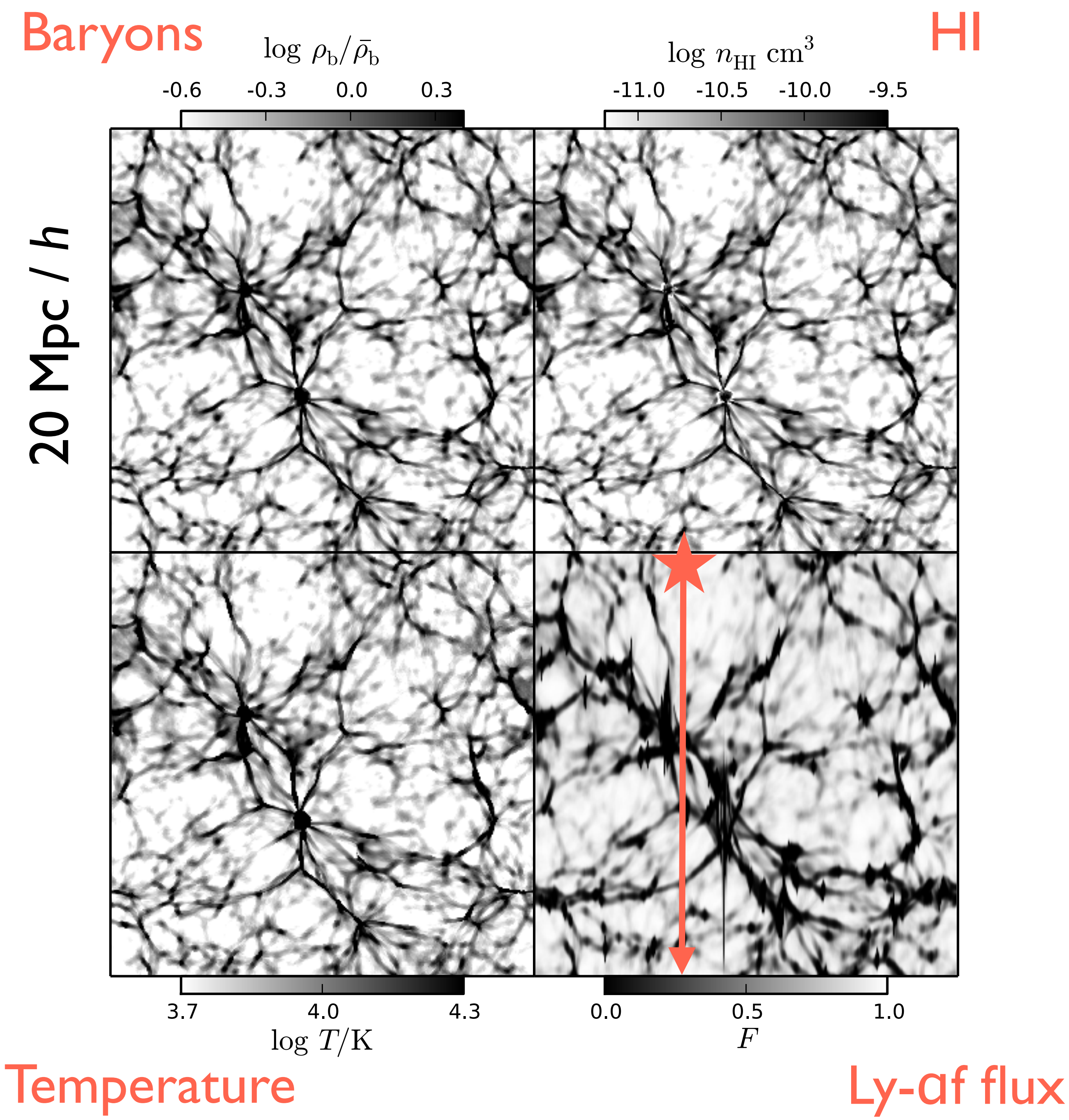


eBOSS measures Lyman-α forest flux power spectrum for quasi-linear modes in matter epoch



Chabanier et al. (2019)

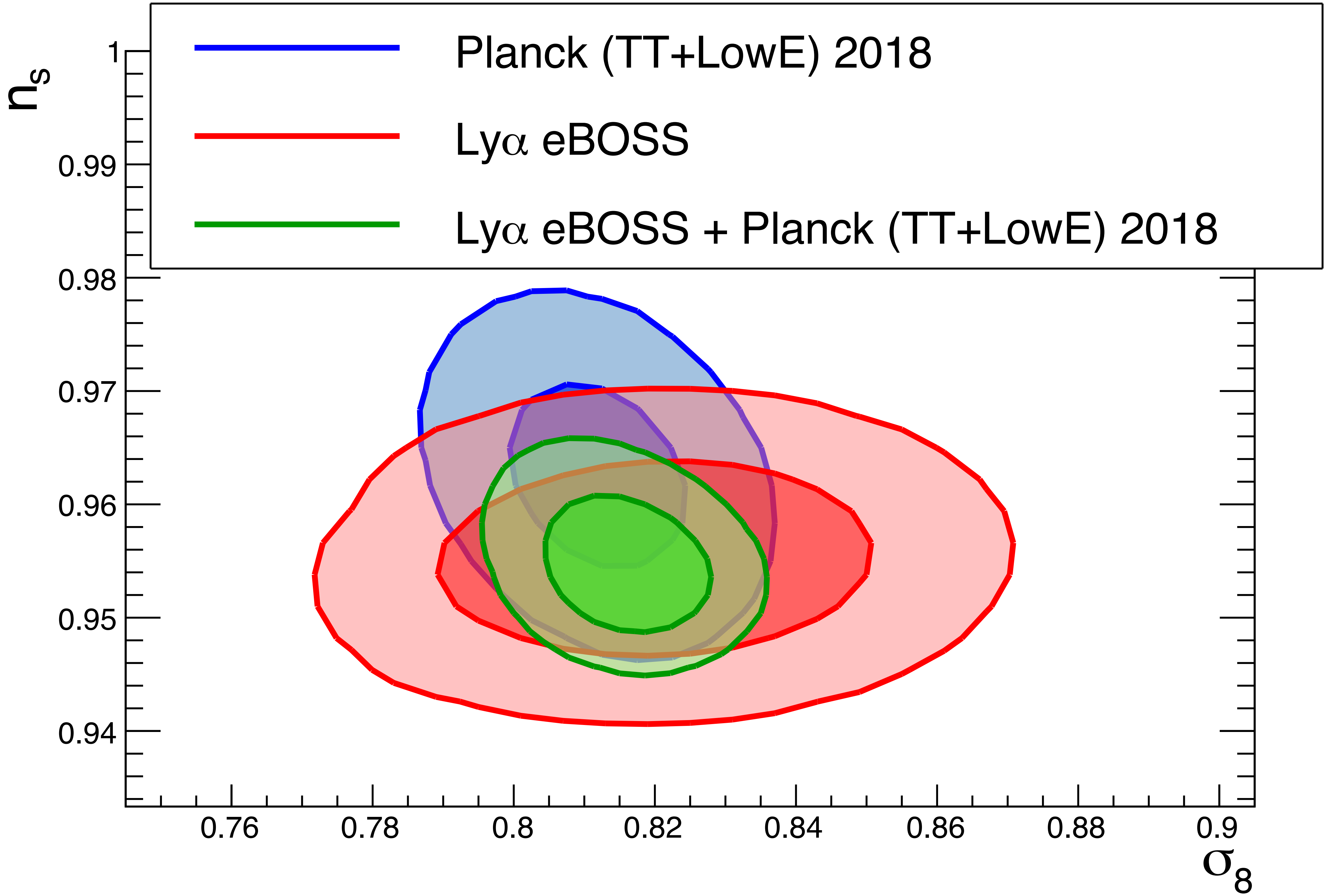
Lyman-alpha forest probes smallest cosmic scales — robustly account for range of astrophysical states



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

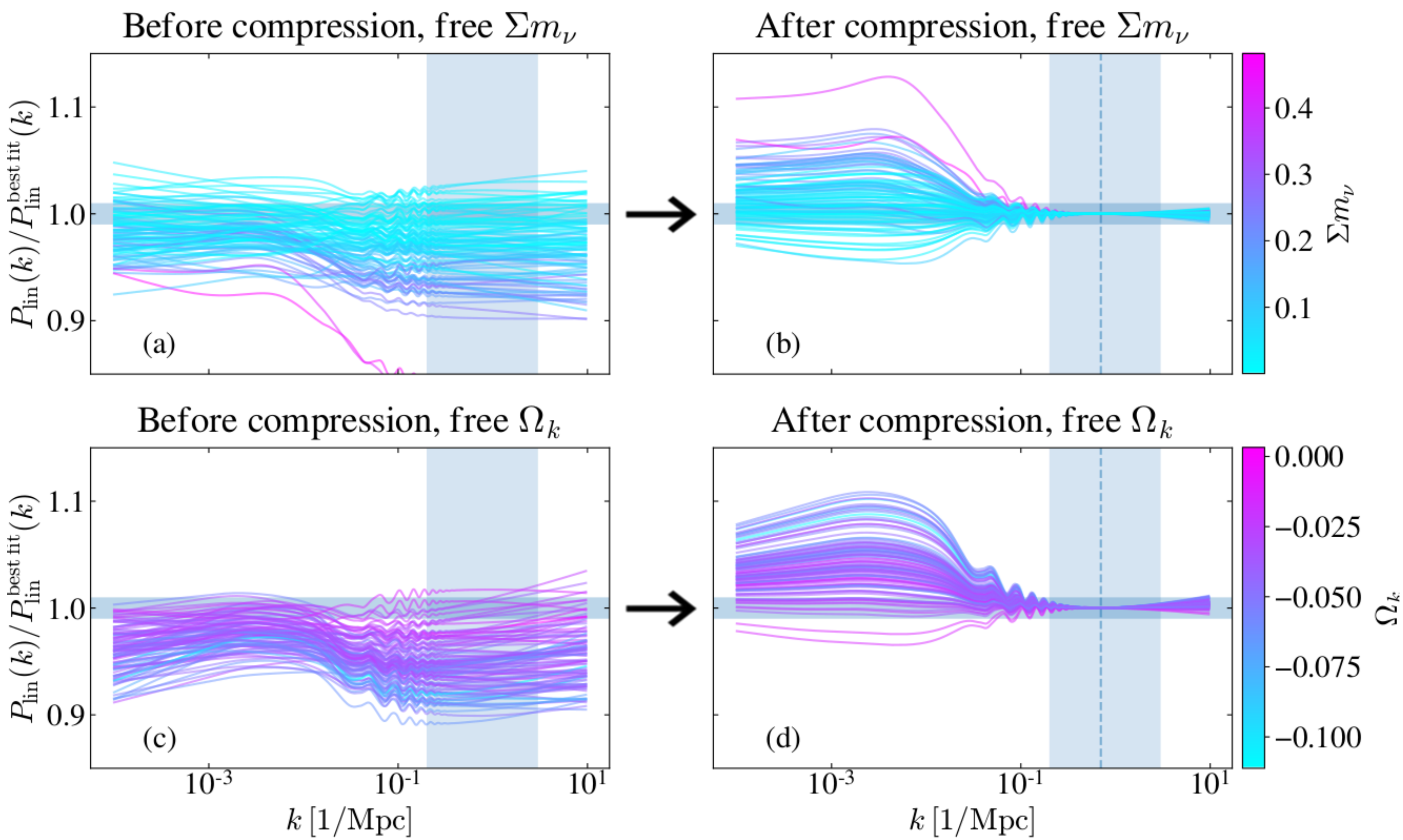
Lukić et al. (2015); Rogers et al. (JCAP, 2019); Rogers & Peiris (Phys. Rev. D, 2021)

eBOSS Collaboration found consistency with *Planck* CMB



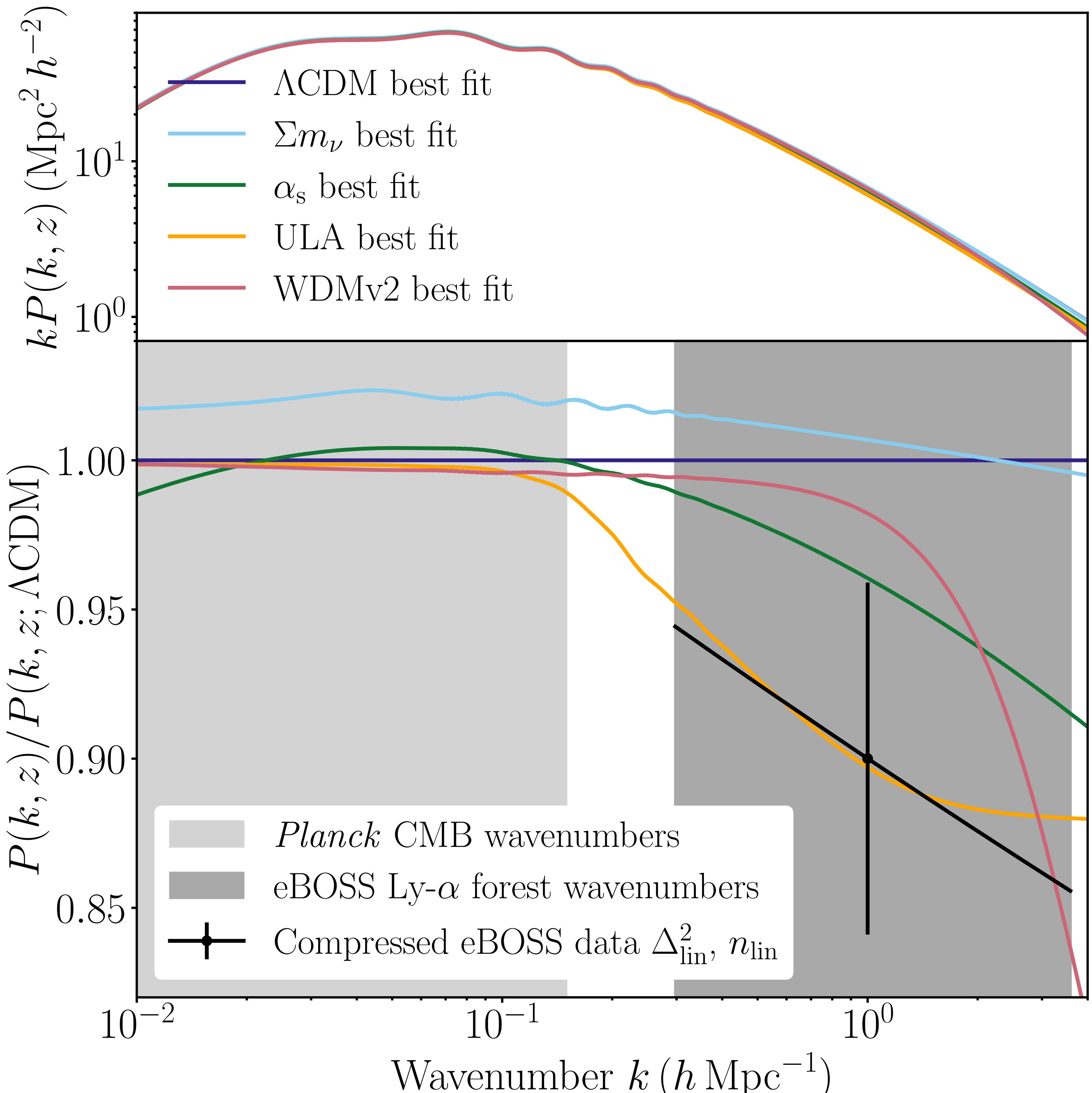
Chabanier et al. (2019); Palanque-Delabrouille et al. (2020)

All the cosmological information in the eBOSS Lyman-α forest compressed to two parameters



Rescaled to same amplitude and tilt at $k_{\rm pivot}$ = 1 h/Mpc, $z_{\rm pivot}$ = 3

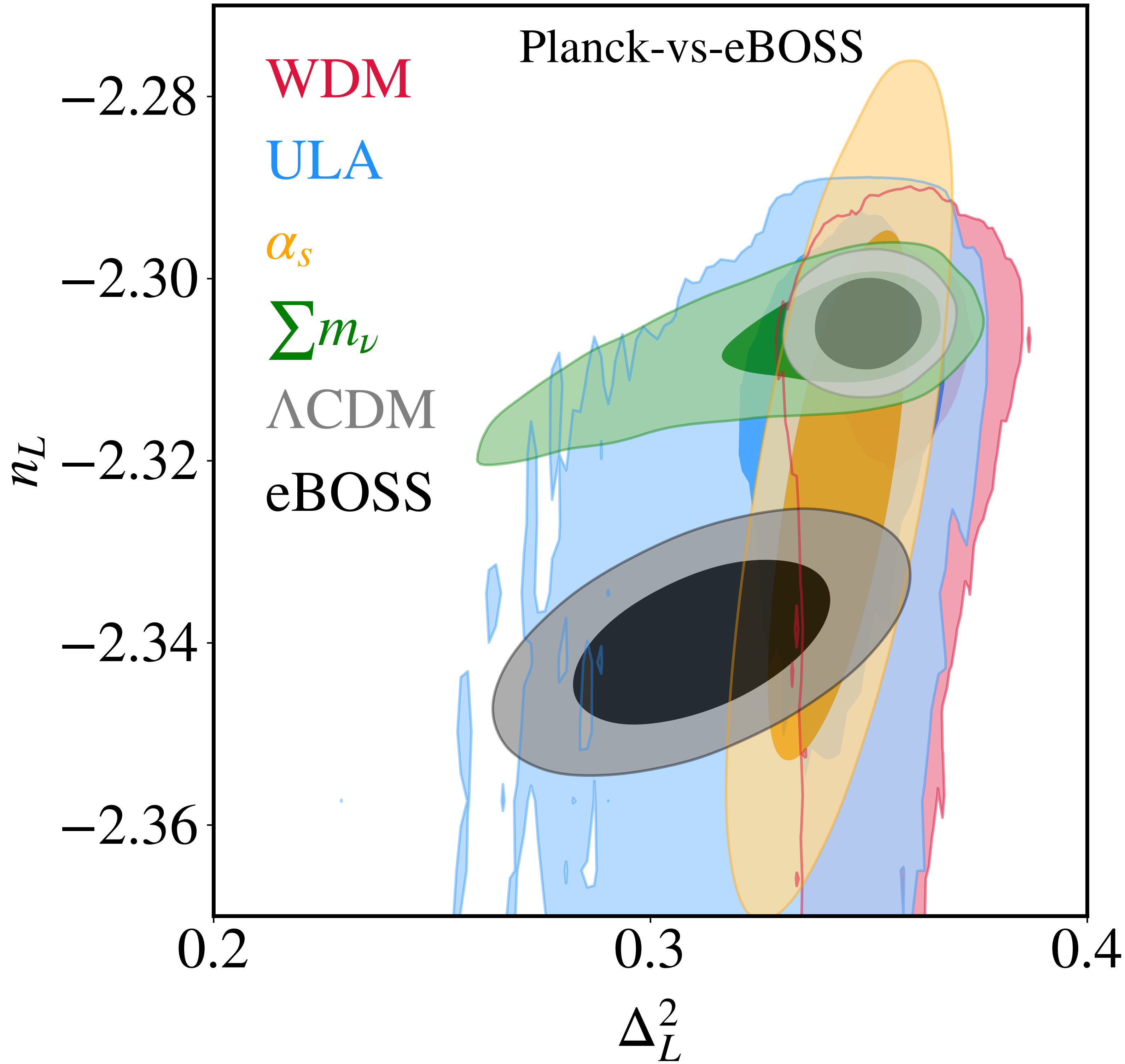
Pedersen, Font-Ribera, Rogers, et al. (JCAP, 2021)



4.8σ tension between eBOSS Ly-αf & *Planck* CMB

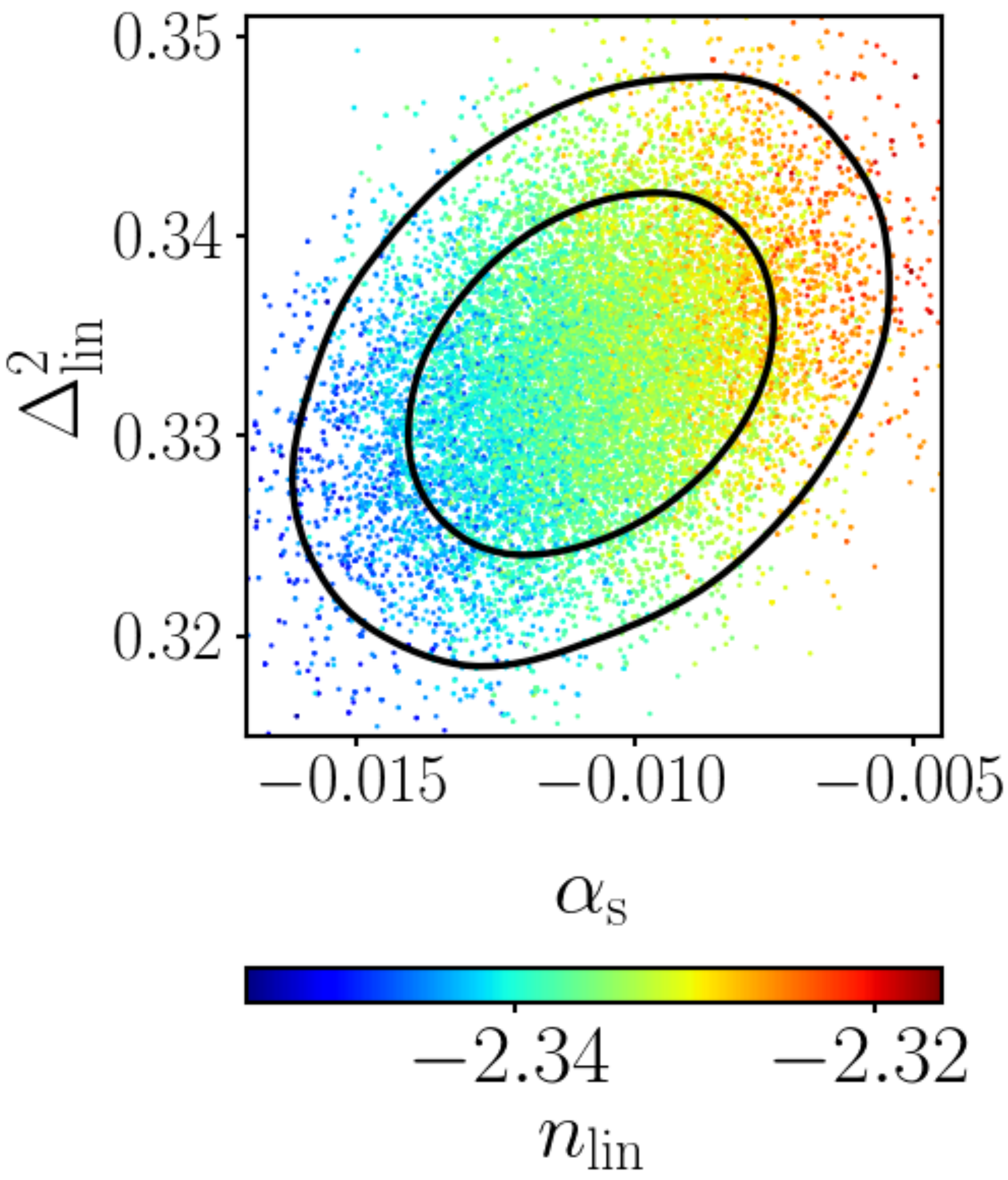
Rogers & Poulin (2023, in prep.)

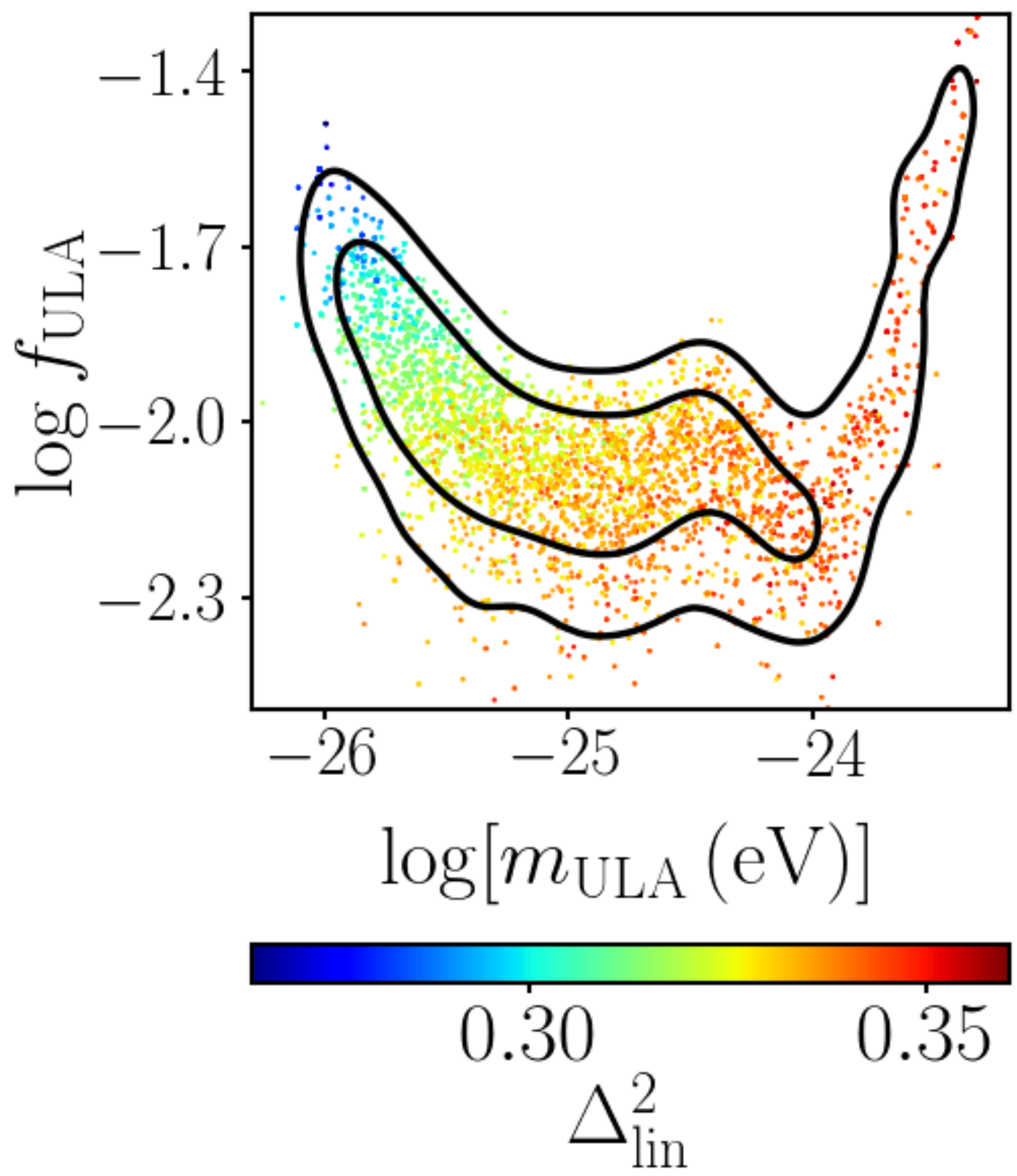
Power spectrum running reduces tension 4.8σ to 0.9σ; ultra-light axions to 0.4σ



Rogers & Poulin (2023, in prep.)

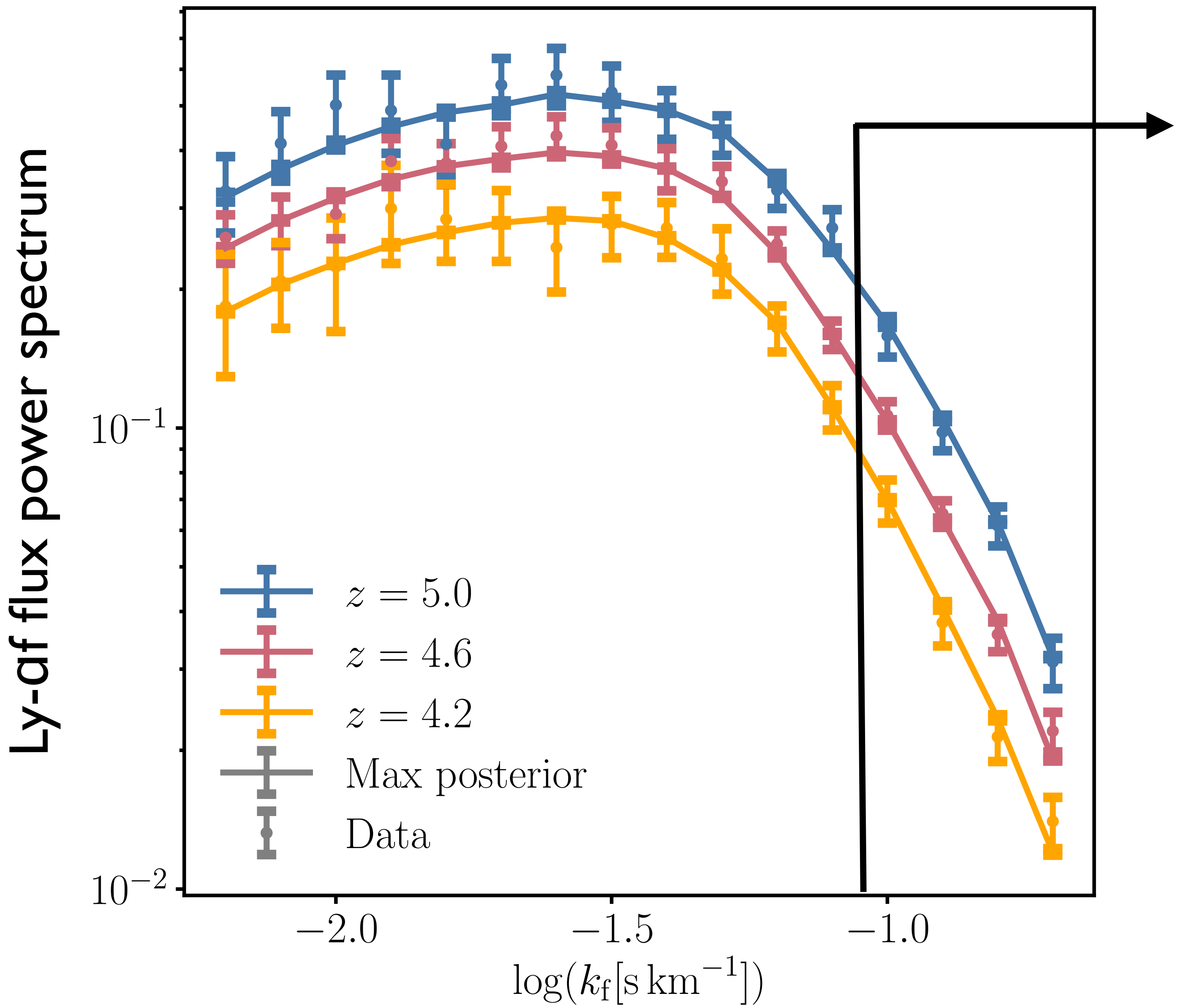
Planck CMB + BAO + SNe + eBOSS Ly-α forest constraints on running and ULA DM





Rogers & Poulin (2023, in prep.)

Dark matter limits driven by new small-scale data



Smallest scale previously measured

Data: Boera et al. (2019)

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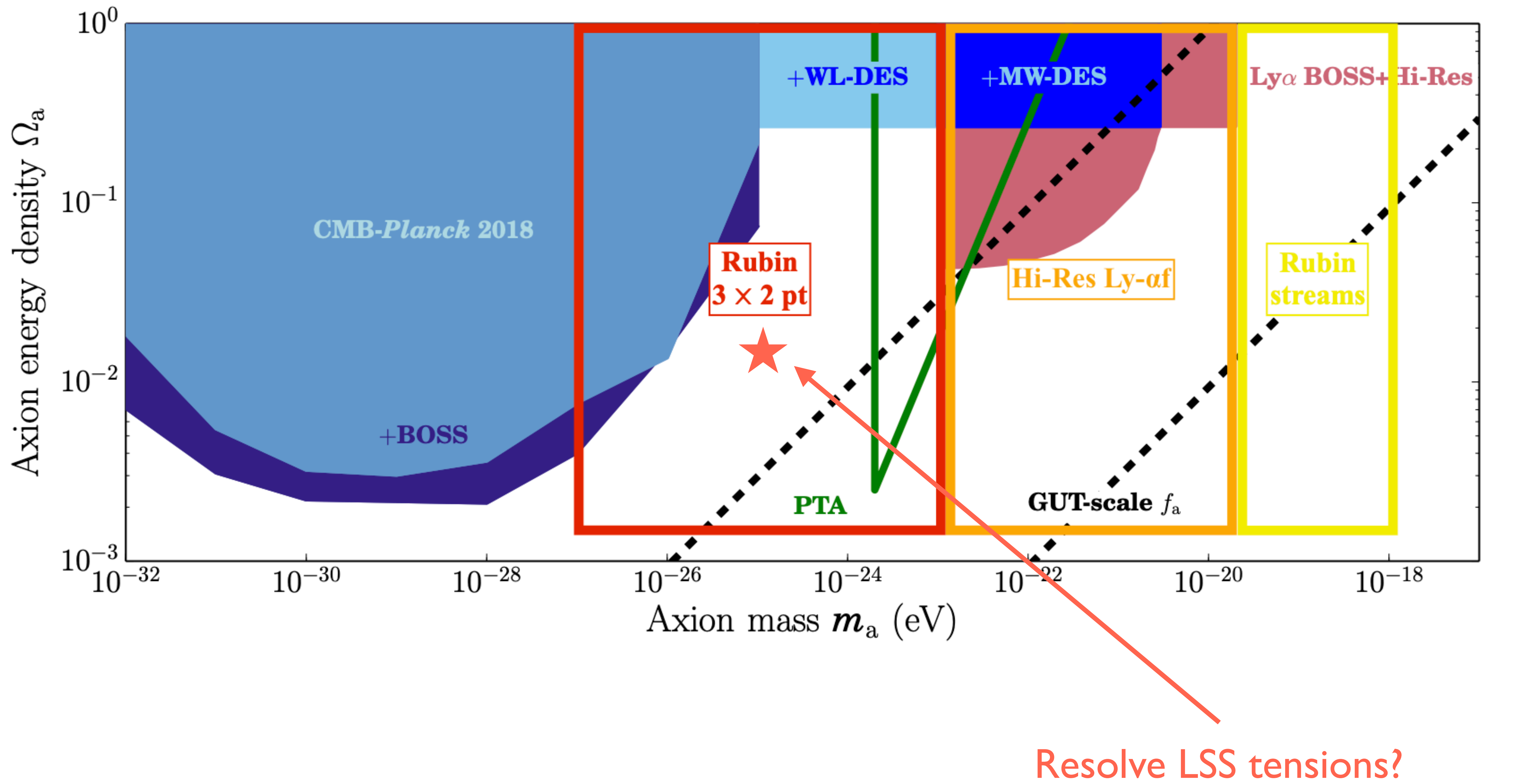
Stockholm University

Rogers & Peiris (PRL, 2021); Rogers et al. (PRL, 2022)

Multi-probe approach to detect ultra-light axions



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

Summary

- **New frontier in dark matter detection** is light & ultra-light dark matter
- **Ultra-light axions improve consistency** between CMB/large-scale structure
- *Rubin* and DESI data poised to **disentangle DM effects and astrophysics**