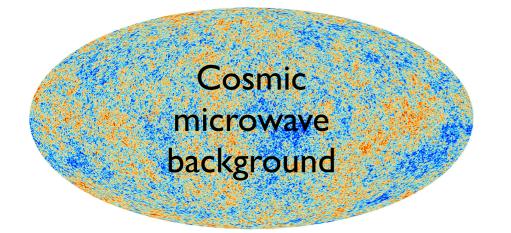
## IDENTIFYING THE FUNDAMENTAL NATURE OF DARK MATTER USING COSMOLOGICAL DATA

## Keir K. Rogers

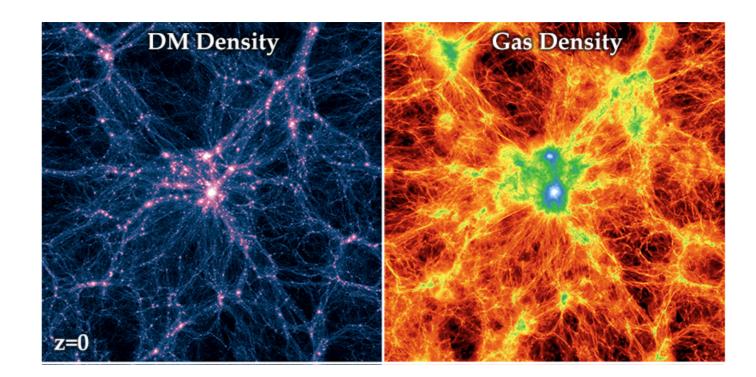
Dunlap Fellow, Dunlap Institute for Astronomy & Astrophysics, University of Toronto

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



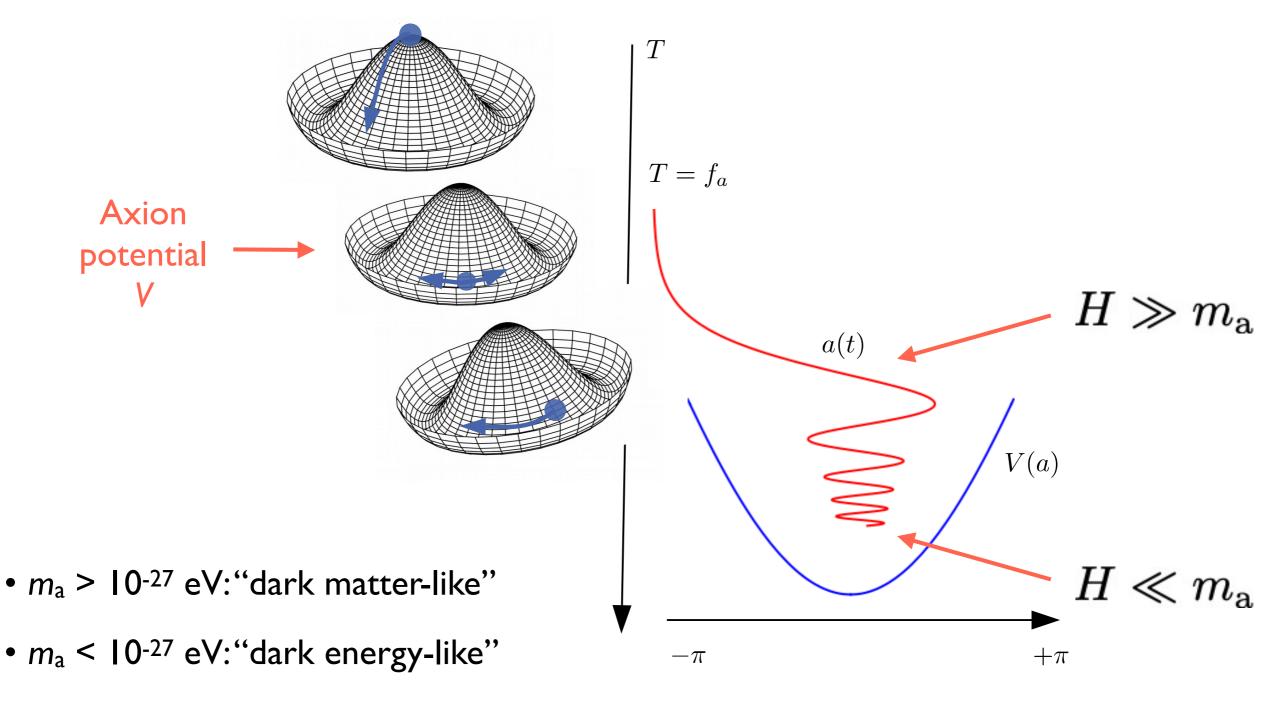
# How improve consistency between CMB and LSS?

2



Planck Collaboration; Illustris simulation

### Axions are dark energy and dark matter candidates



•  $m_a = 10^{-33} \text{ eV}$ : cosmological constant

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



## 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

• CMB Planck TT, TE, EE+lowE · Aghanim et al. (2020d) • CMB Planck TT, TE, EE+lowE+lensing · Aghanim et al. (2020d) • CMB ACT+WMAP · Aiola et al. (2020) Early Universe Late Universe • WL KiDS-1000 Asgari et al. (2021) • WL KiDS+VIKING+DES-Y1 Asgari et al. (2020) Joudaki et al. (2020) • WL KiDS+VIKING+DES-Y1 • WL KiDS+VIKING-450 Wright et al. (2020) Hildebrandt et al. (2020) • WL KiDS+VIKING-450 0.651 • WL KiDS-450 Kohlinger et al. (2017) • WL KiDS-450 Hildebrandt et al. (2017) • WL DES-Y3 Amon et al. and Secco et al. (2021) • WL DES-Y1 Troxel et al. (2018) • WL HSC-TPCF Hamana et al. (2020) • WL HSC-pseudo-Cl Hikage et al. (2019) • WL CFHTLenS Joudaki et al. (2017) • WL+GC HSC+BOSS Miyatake et al. (2022) 0.7781 • WL+GC+CMBL KiDS+DES+eBOSS+Planck García-García et al. (2021) 0.766 • WL+GC KiDS-1000 3×2pt Heymans et al. (2021) 0.742 • WL+GC KiDS-450 3×2pt Joudaki et al. (2018) • WL+GC DES-Y3 3×2pt Abbott et al. (2021) • WL+GC DES-Y1 3×2pt Abbott et al. (2018d) • WL+GC KiDS+VIKING-450+BOSS Tröster et al. (2020) • WL+GC KiDS+GAMA 3x2pt van Uitert et al. (2018) Philcox et al. (2021) • GC BOSS DR12 bispectrum GC BOSS+eBOSS Ivanov et al. (2021) • GC BOSS power spectra Chen et al. (2021) • GC BOSS DR12 Tröster et al. (2020) • GC BOSS galaxy power spectrum Ivanov et al. (2020) • GC+CMBL DELS+Planck White et al. (2022) • GC+CMBL unWISE+Planck Krolewski et al. (2021) CC AMICO KiDS–DR3 · Lesci et al. (2021) • CC DES-Y1 Abbott et al. (2020d) CC SDSS–DR8 Costanzi et al. (2019) • CC XMM-XXL Pacaud et al. (2018) • CC ROSAT (WtG) Mantz et al. (2015) • CC SPT tSZ Bocquet et al. (2019) • CC Planck tSZ Salvati et al. (2018) • CC Planck tSZ · Ade et al. (2016d) • RSD <sup>•</sup> Benisty (2021) • RSD Kazantzidis and Perivolaropoulos (2018) 1.2 0.4 0.8 1.0 0.2 0.6

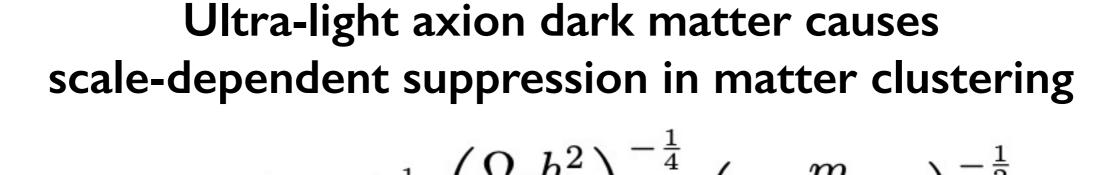
 $S_8 \sim \text{amplitude of density fluctuations at 8 Mpc/h}$ 

#### Smaller scales

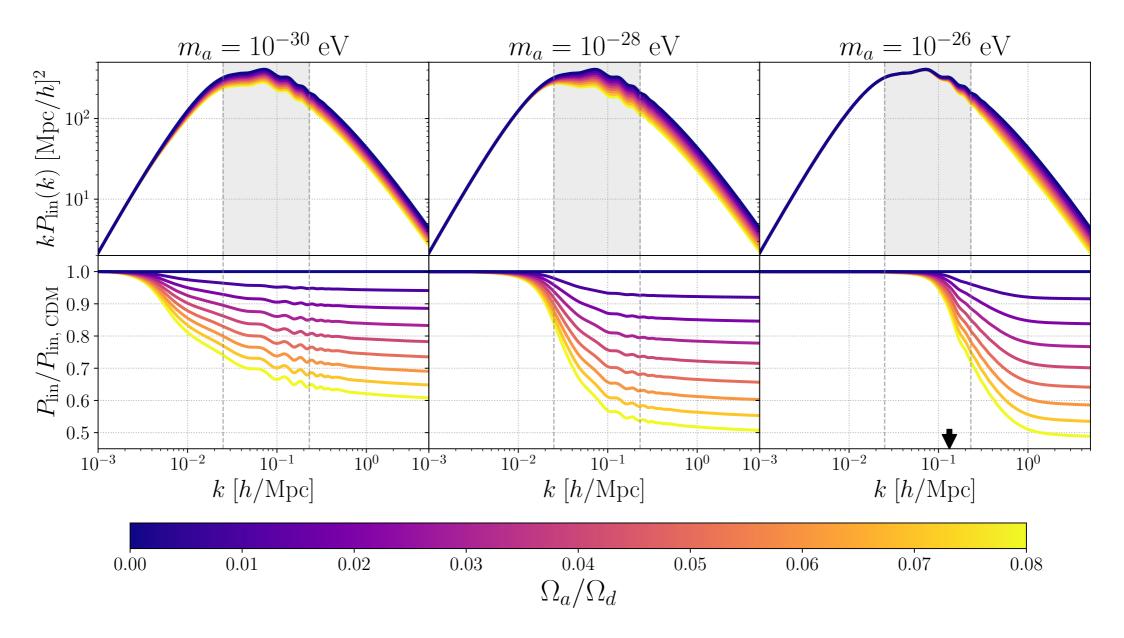
### Abdalla et al. (Snowmass 2022)

S<sub>8</sub>

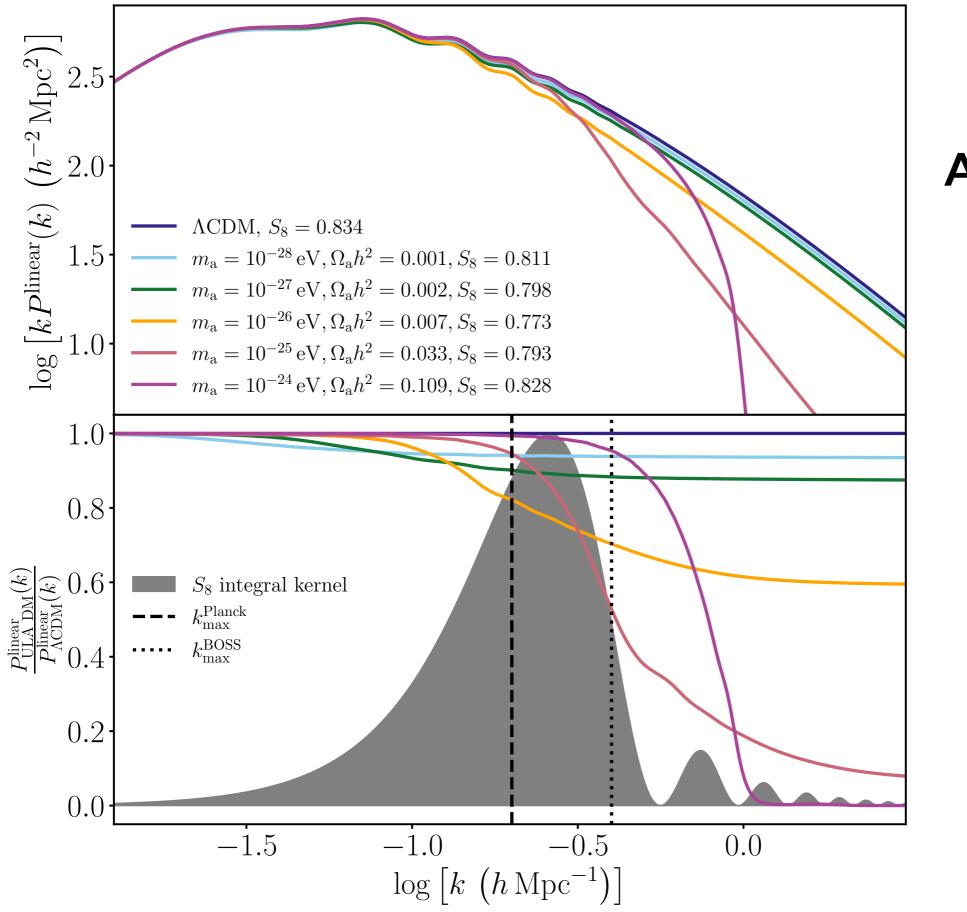
tension



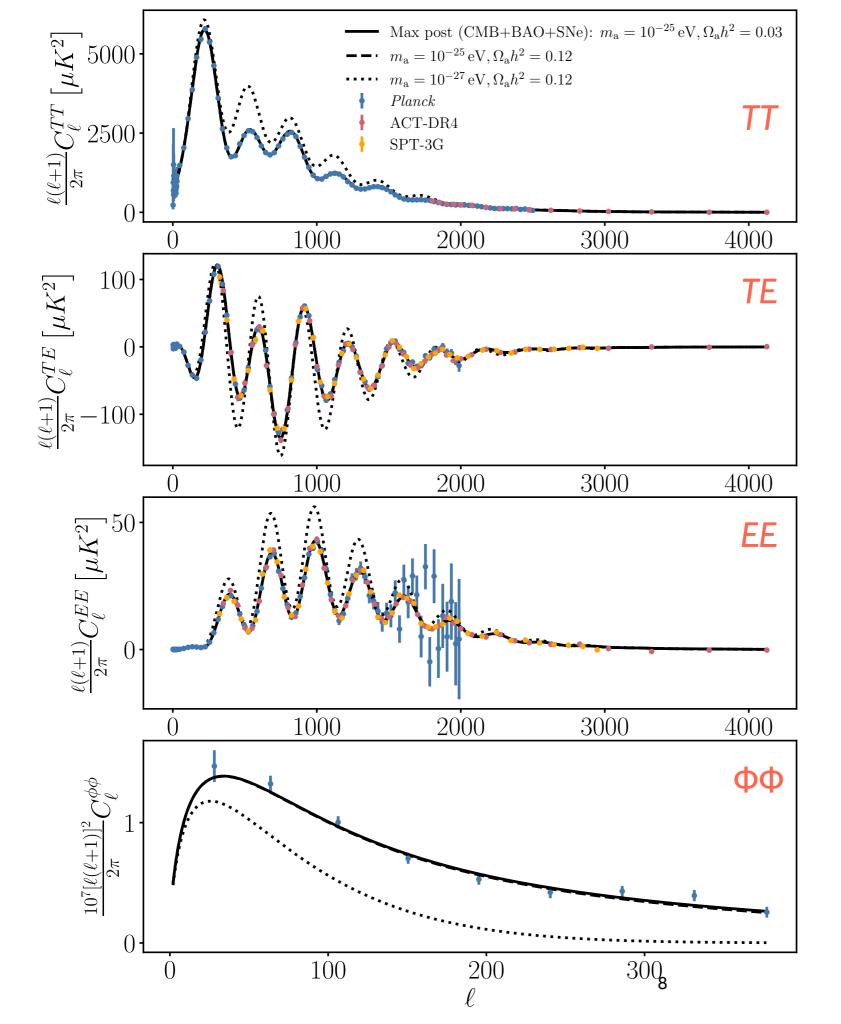
$$\lambda_{\text{Jeans}} = 9.4 \,(1+z)^{\frac{1}{4}} \,\left(\frac{M_{\text{a}}n}{0.12}\right) \quad \left(\frac{m}{10^{-26} \,\text{eV}}\right)^{-2} \,\text{Mpc}$$



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

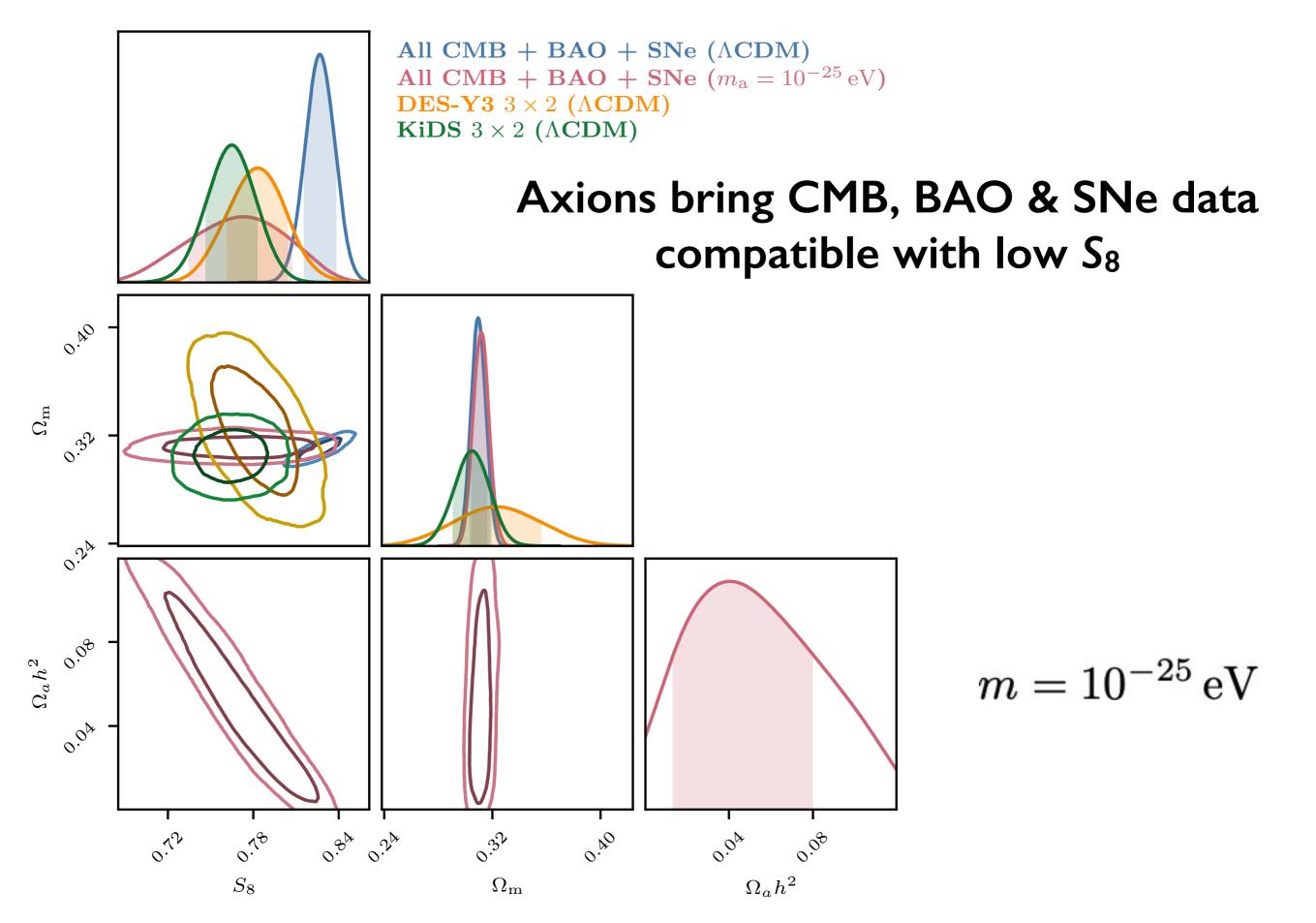


### Axions lower S<sub>8</sub>

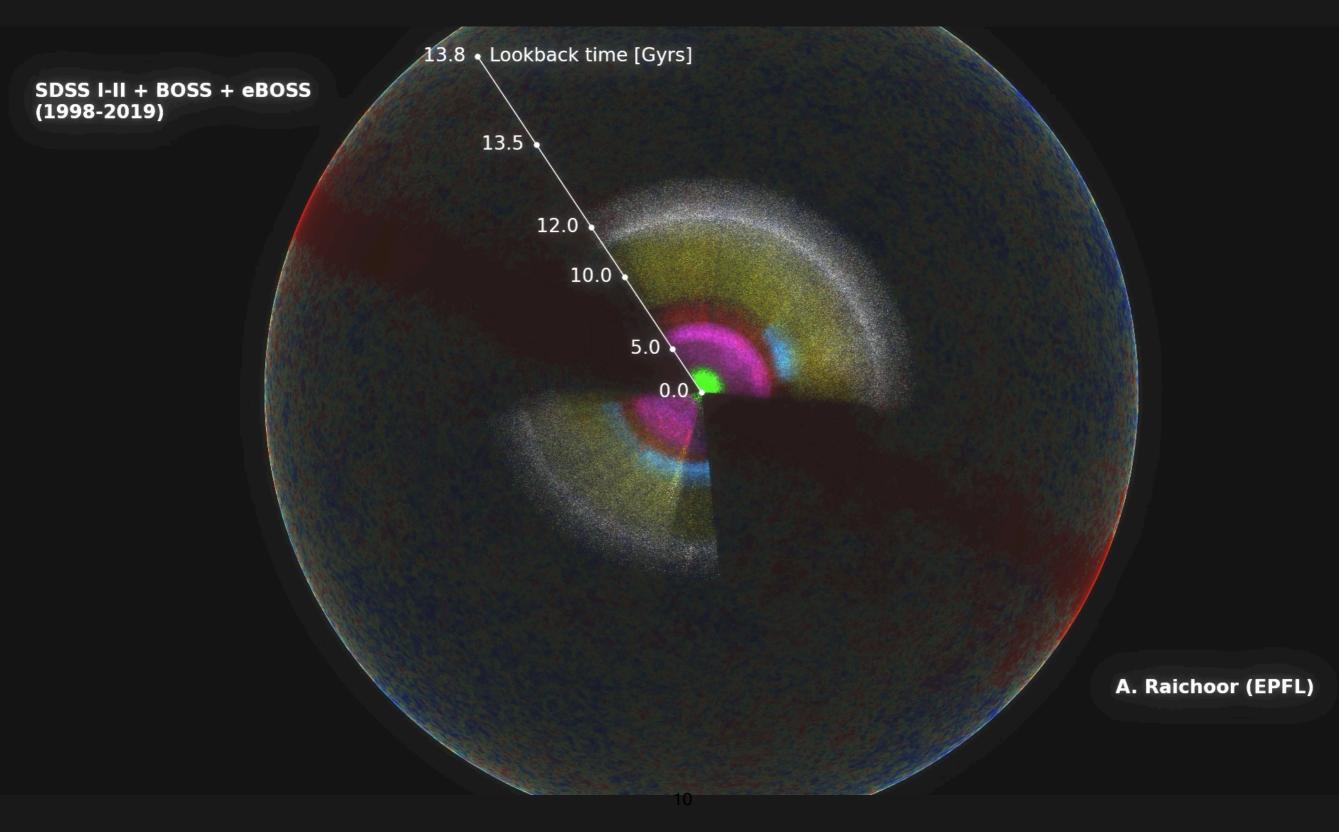


DE-like axions constrained by CMB acoustic oscillations & lensing potential

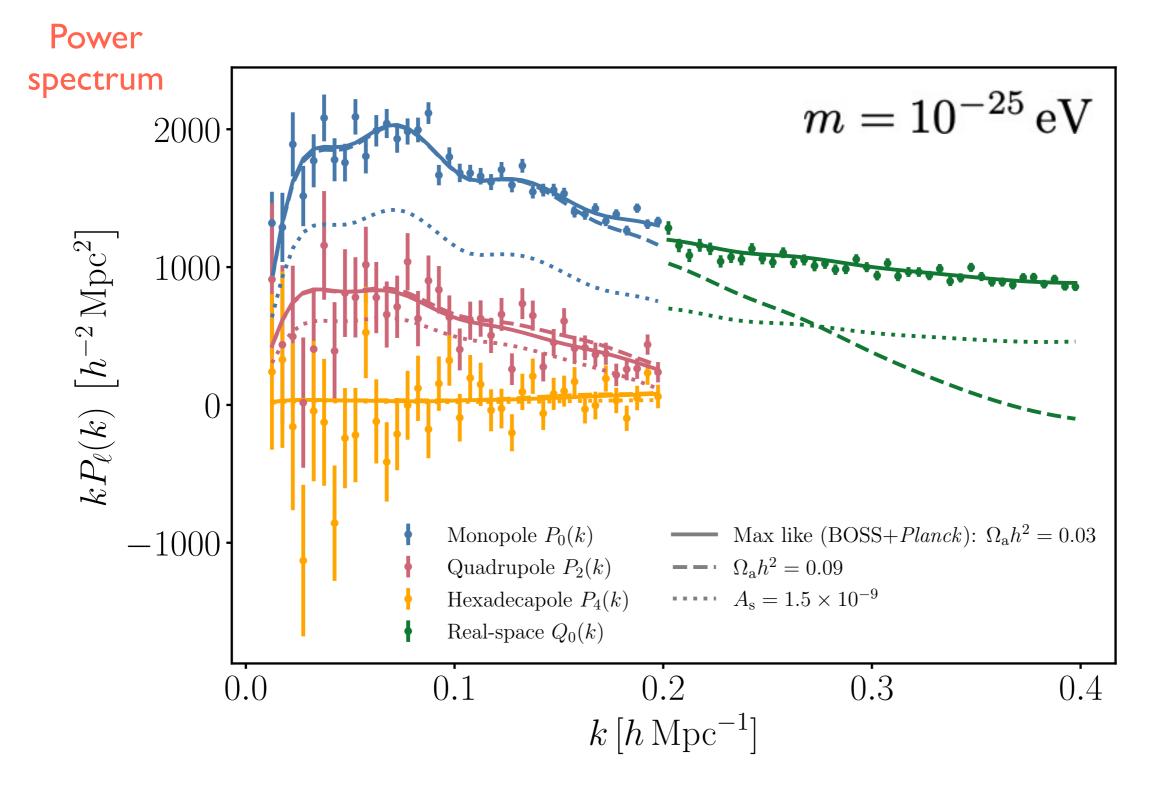
$$m_{\mathrm{a}} \leq 10^{-26} \, \mathrm{eV}$$

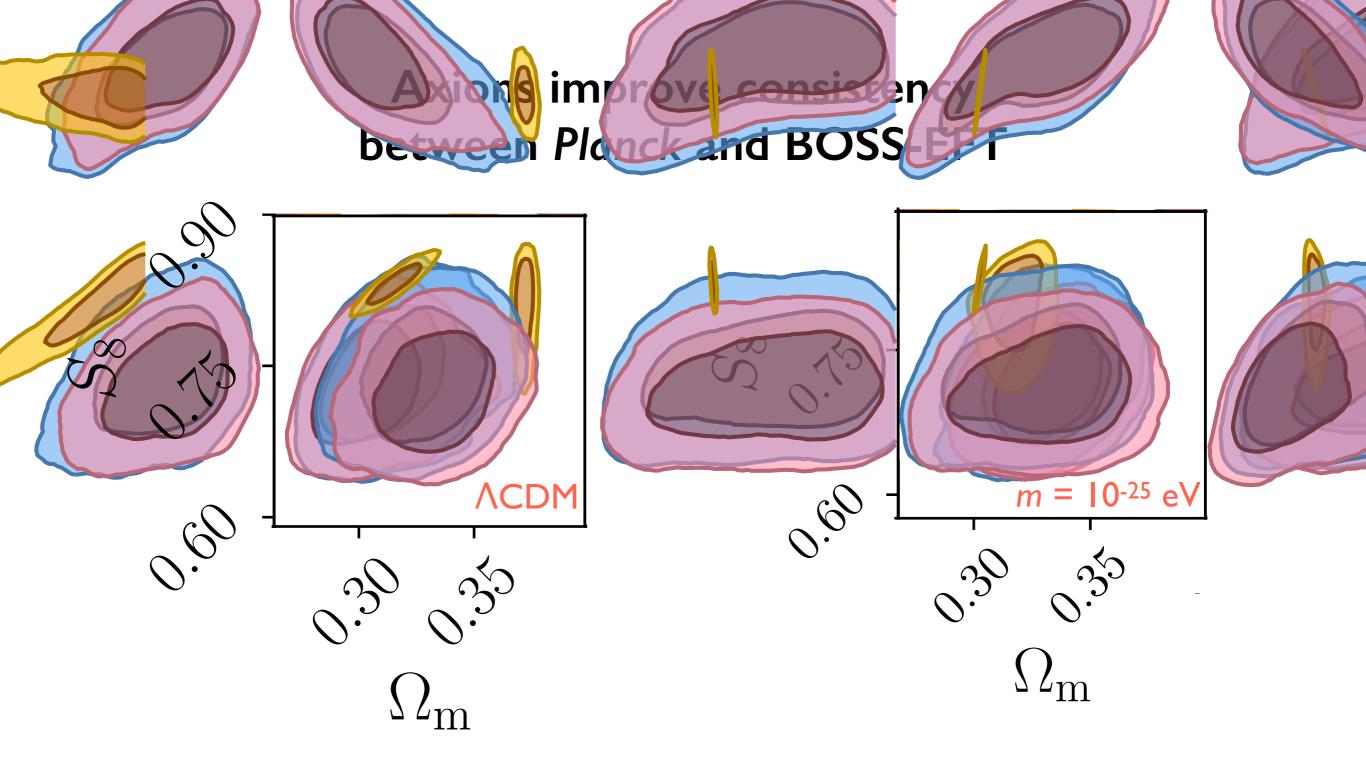


# Sloan Digital Sky Survey maps galaxies and intergalactic gas towards edge of observable Universe



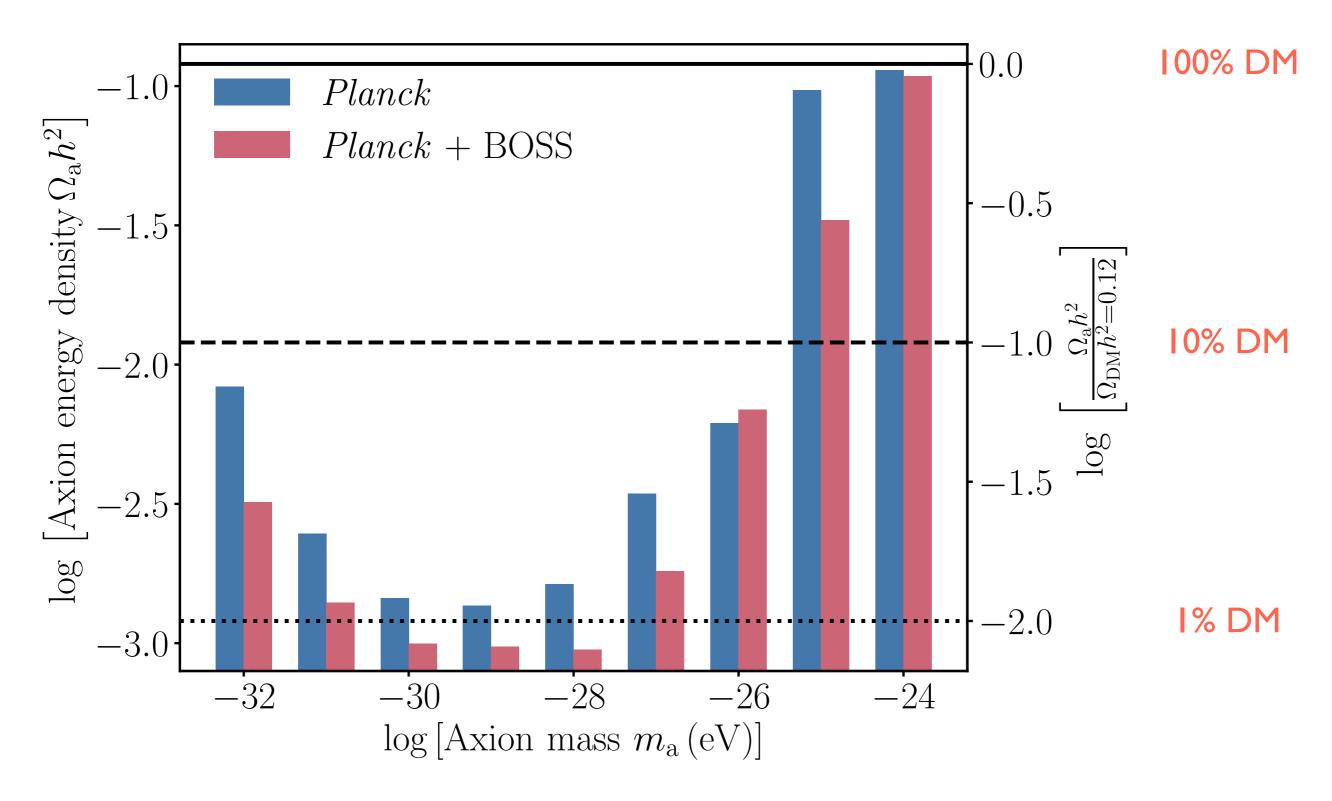
# Full-shape BOSS galaxy power spectrum increases sensitivity to ultra-light axions





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

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



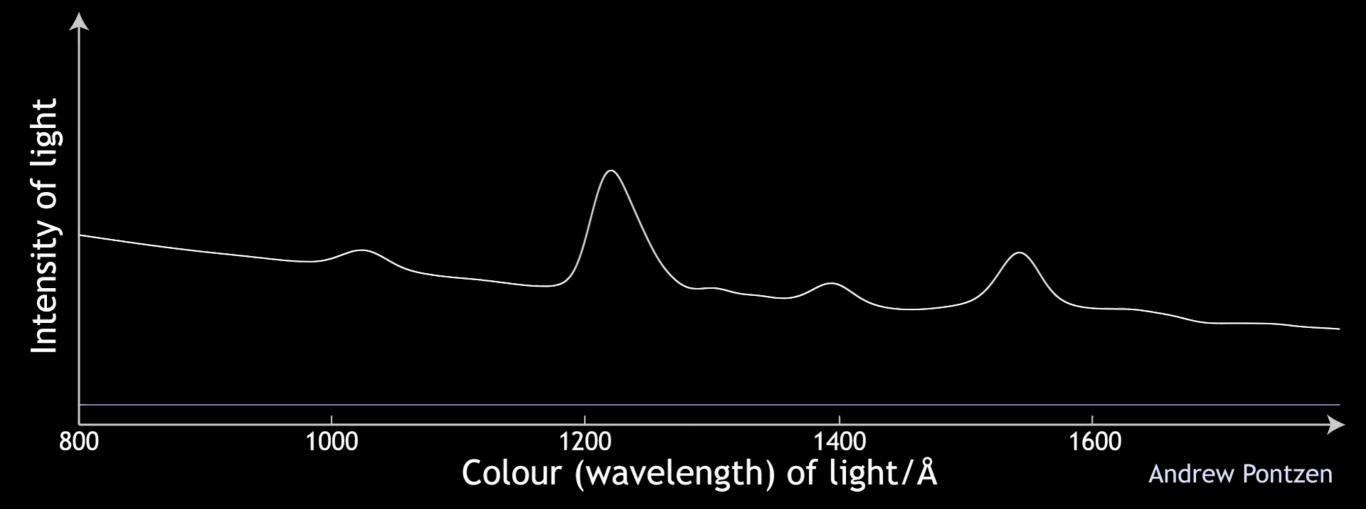


# 5σ TENSION BETWEEN PLANCK CMB AND EBOSS Lyman-α forest and Constraints on physics beyond ΛCDM

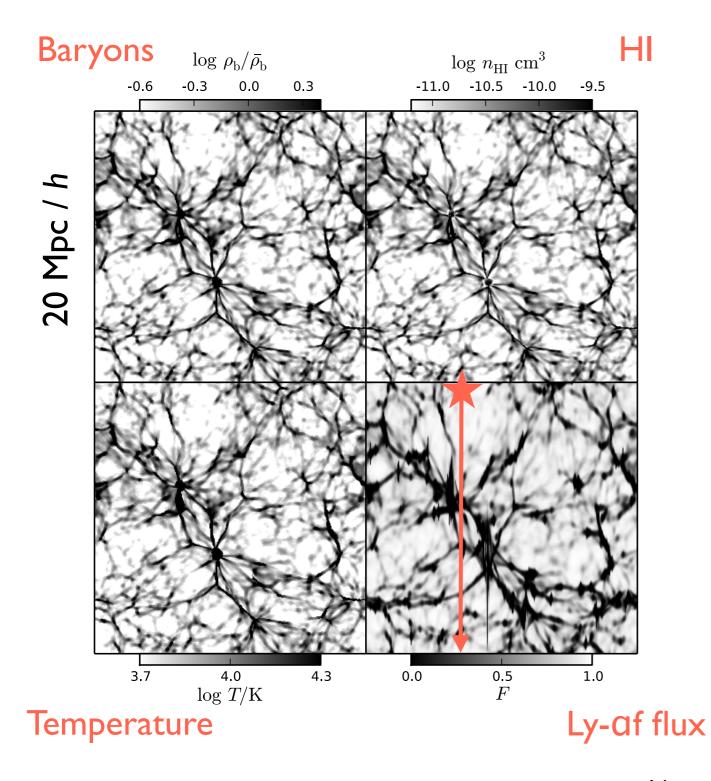
arXiv: 2311.16377 with Vivian Poulin

### Lyman-alpha forest traces intergalactic medium around mean cosmic density



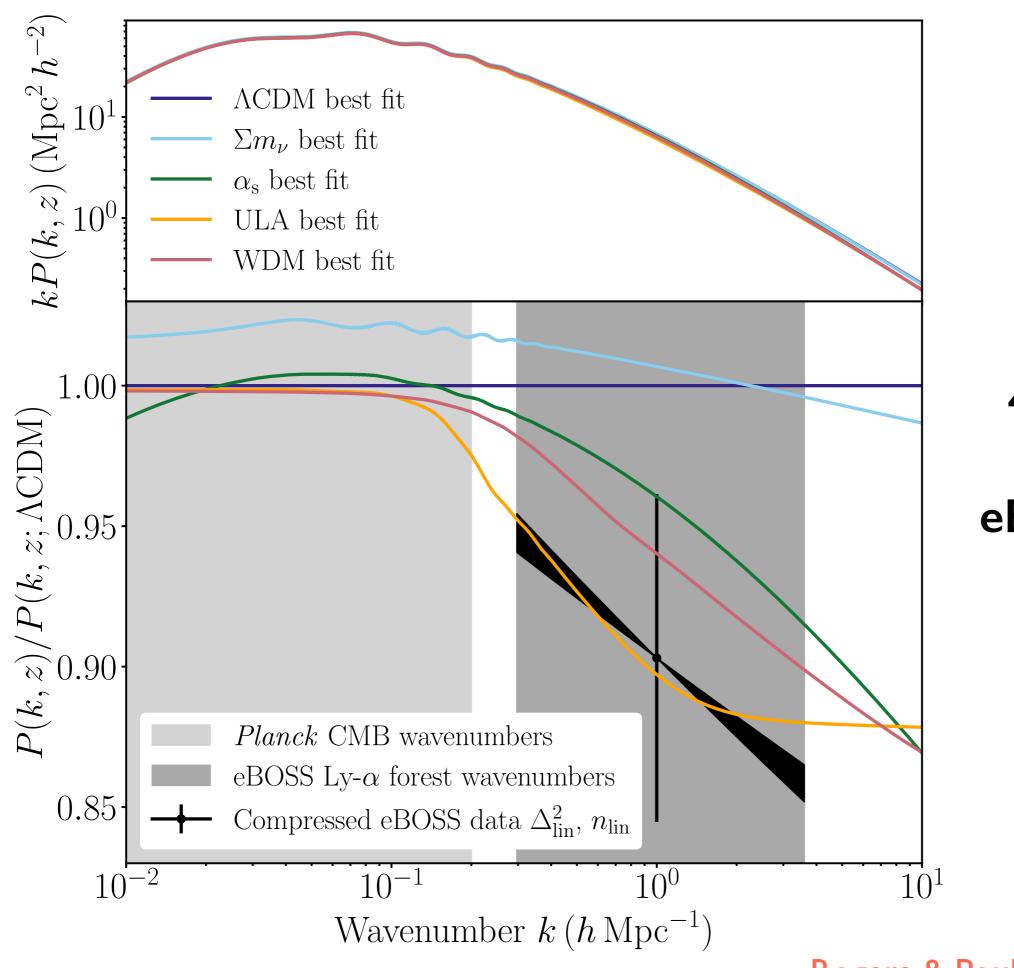


### Lyman-alpha forest probes smallest cosmic scales — robustly account for range of astrophysical states



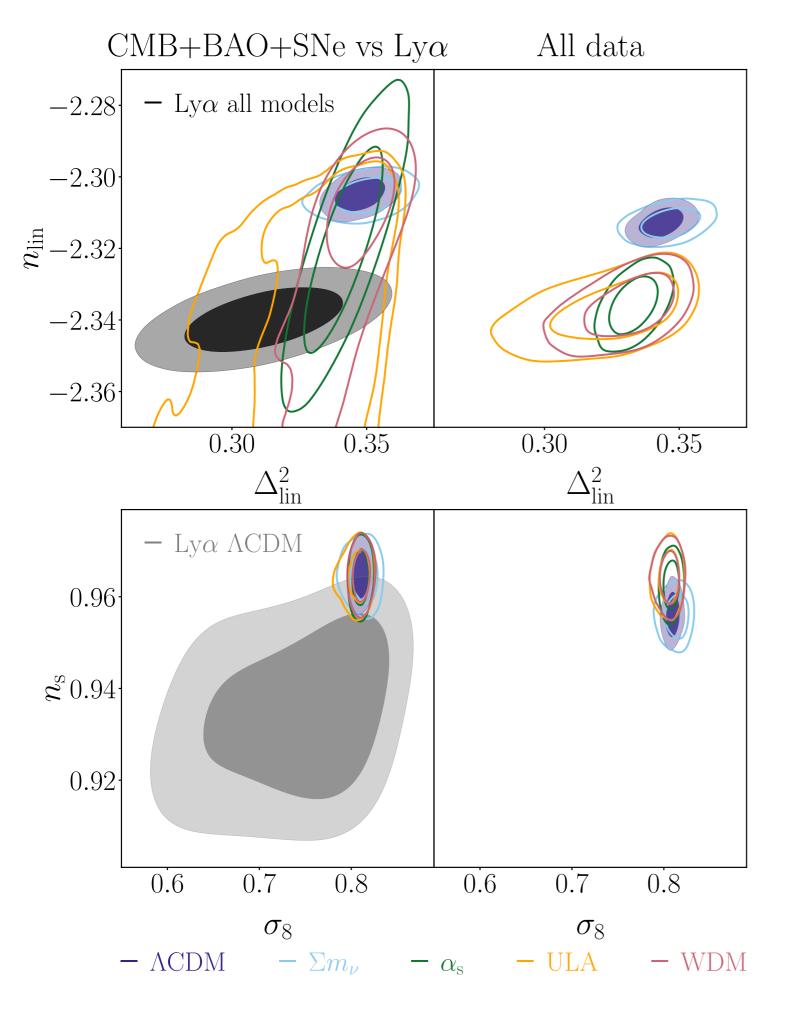
- Ly-alpha forest traces DM & intergalactic medium astrophysics
- ~ 3000 CPU-hours per simulation in I2-D parameter space
- $\Rightarrow$  need ML-accelerated emulator

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

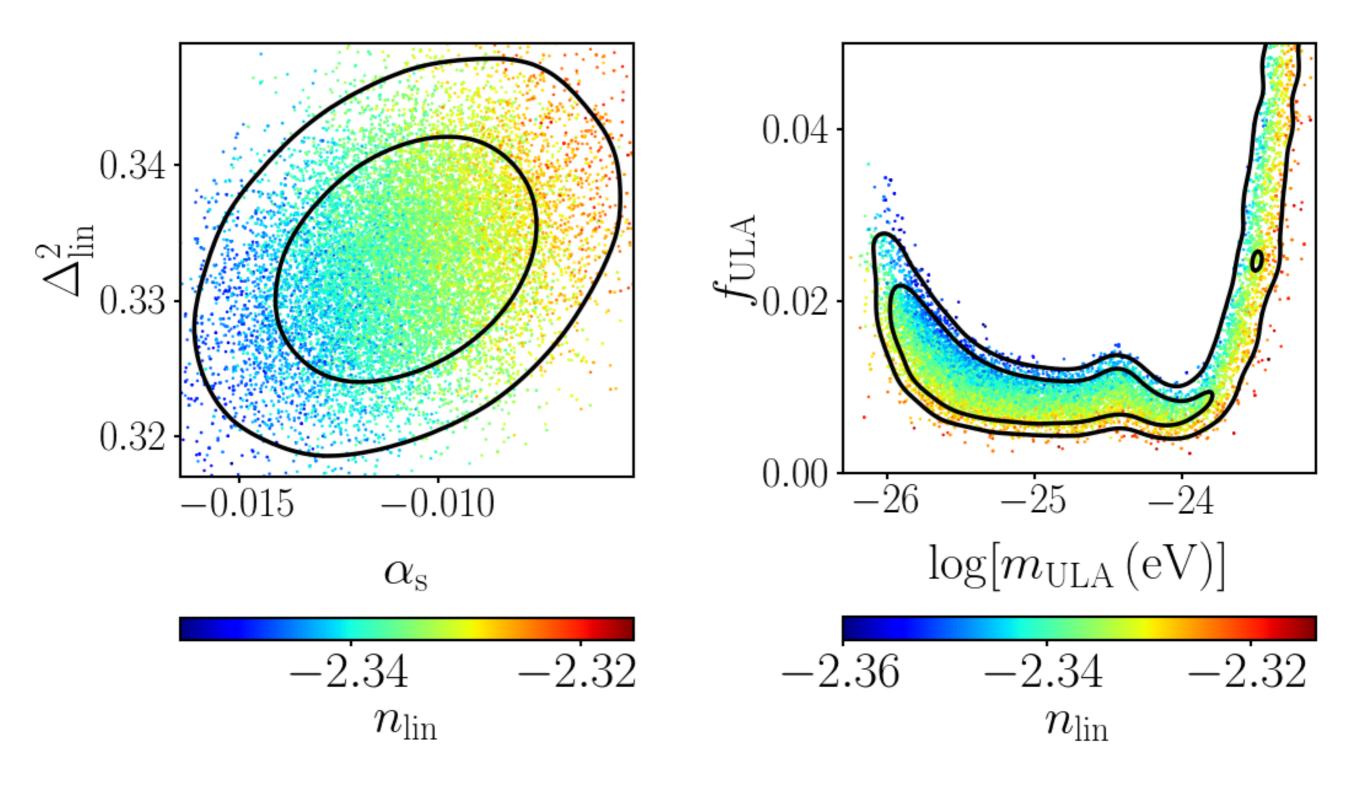
#### Rogers & Poulin (arXiv: 2311.16377)



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

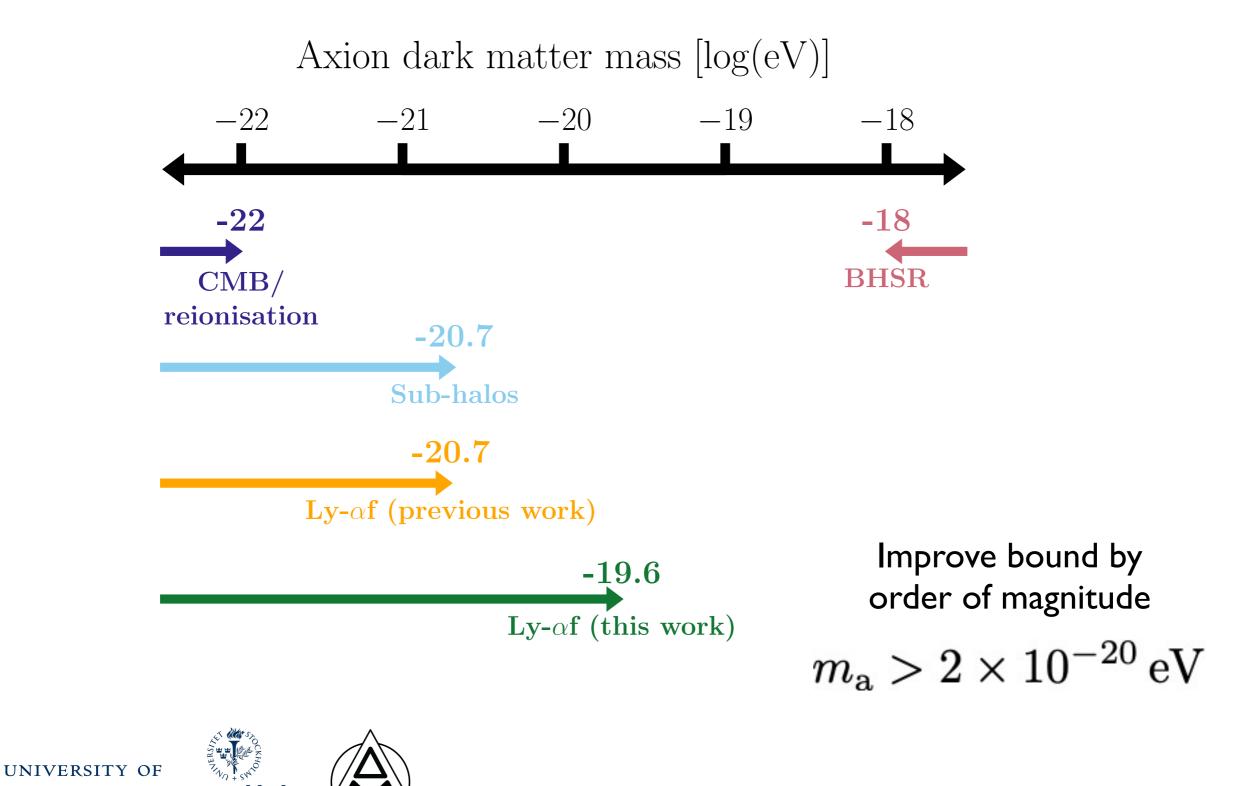
Rogers & Poulin (arXiv: 2311.16377)

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



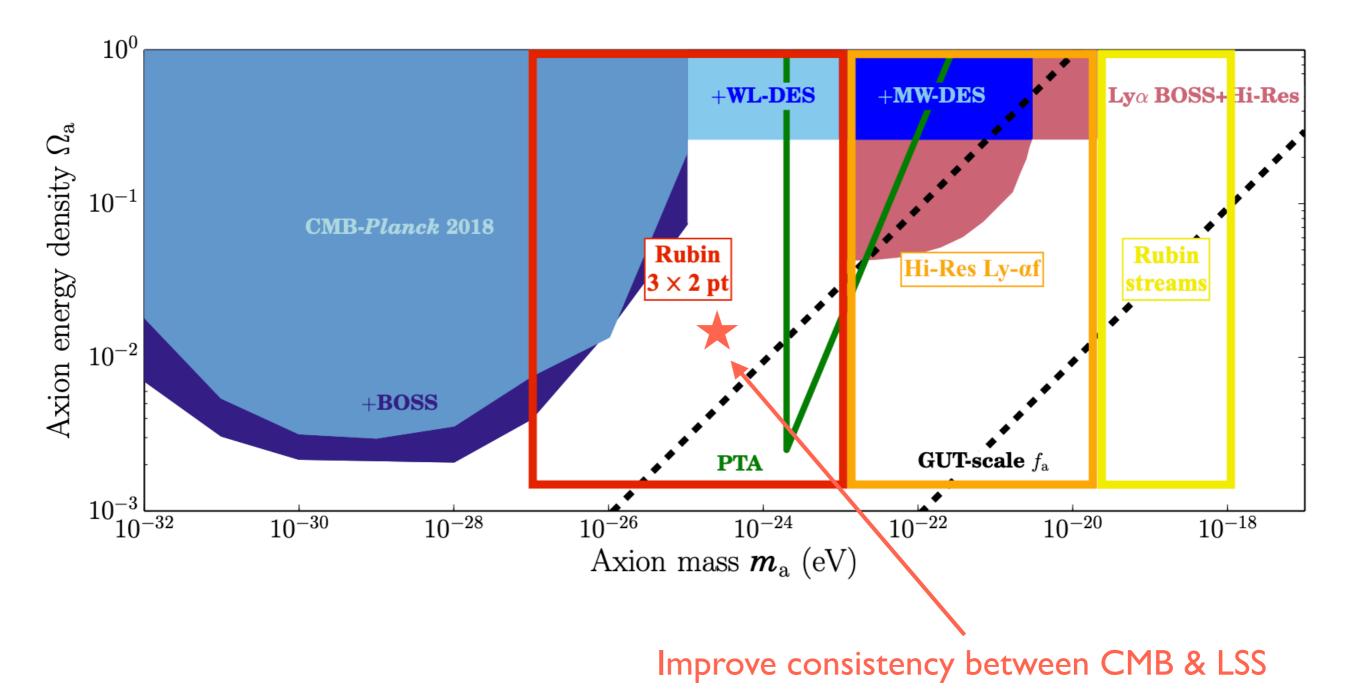
#### Rogers & Poulin (arXiv: 2311.16377)

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



Roger<sup>80</sup> & Peiris (Phys. Rev. Lett., Phys. Rev. D, 2021ab)

### 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

- Joint analysis of CMB & large-scale structure strengthens axion sensitivity
- 5 $\sigma$  tension between CMB & Ly- $\alpha$ f alleviated by small-scale suppression

• Rubin and DESI data poised to disentangle DM effects and astrophysics