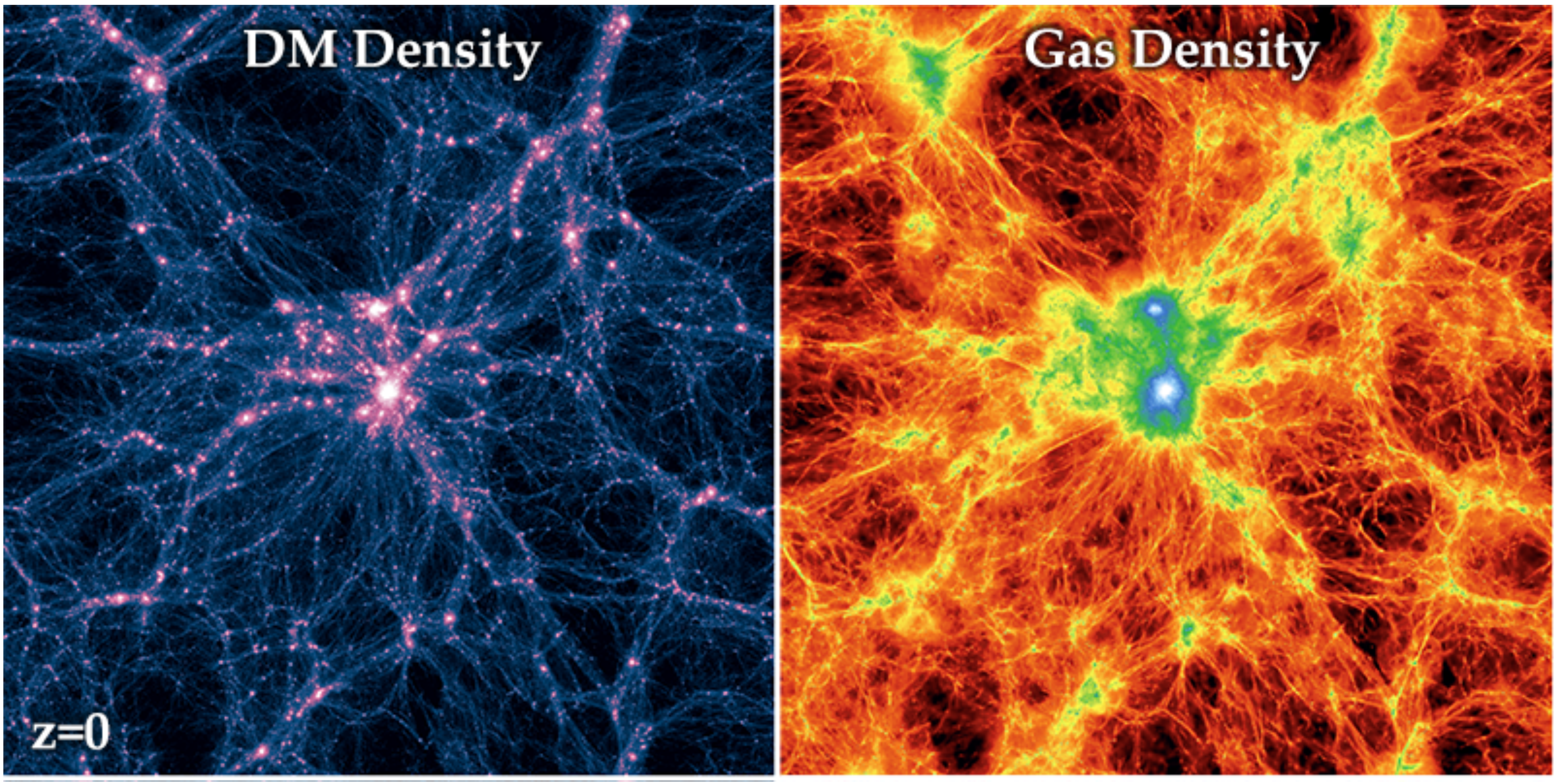
SEARCHING FOR THE FUNDAMENTAL NATURE OF DARK MATTER IN THE COSMIC LARGE-SCALE STRUCTURE

Keir K. Rogers

Dunlap Fellow, Dunlap Institute for Astronomy & Astrophysics,

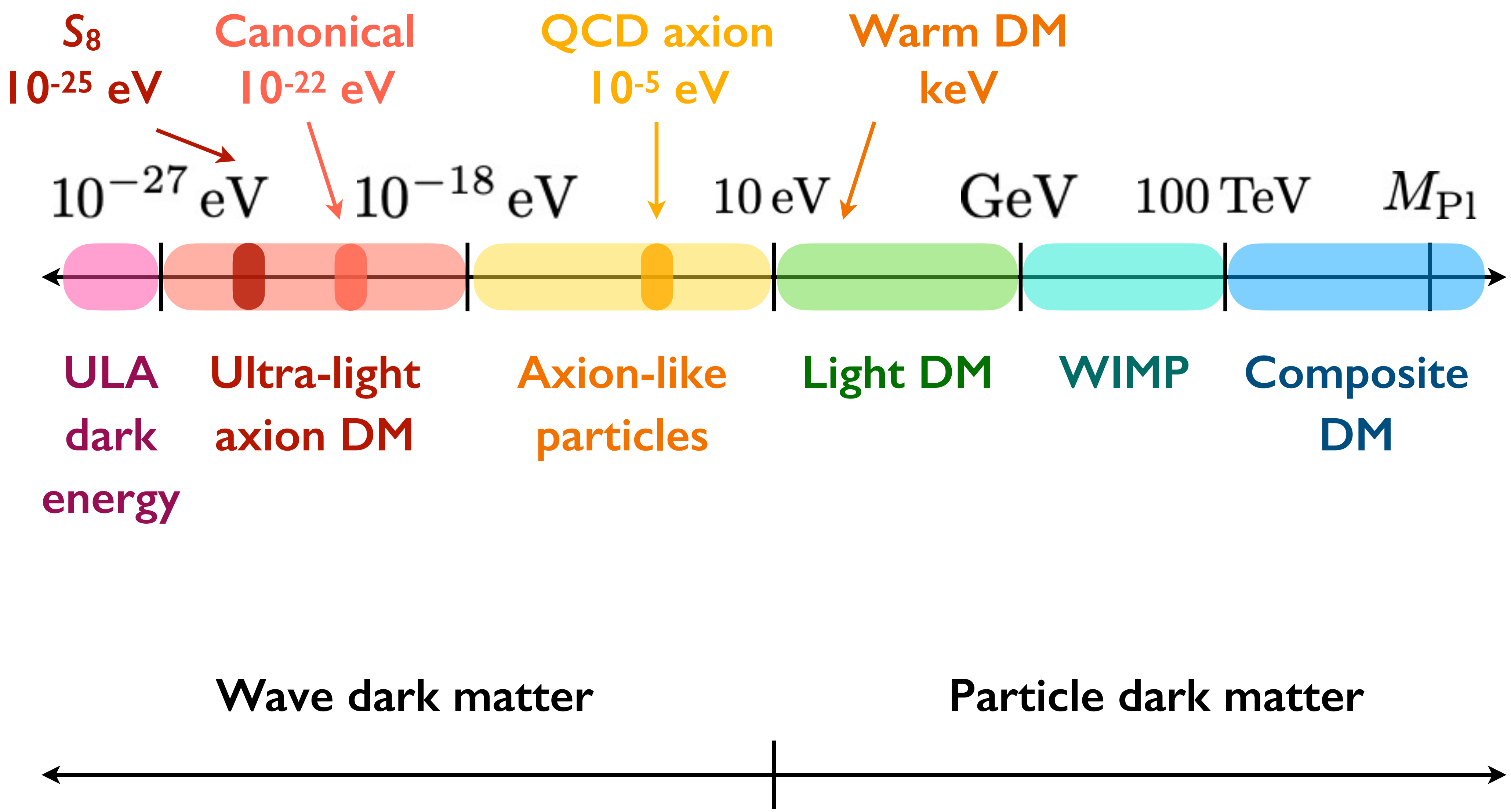
University of Toronto

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



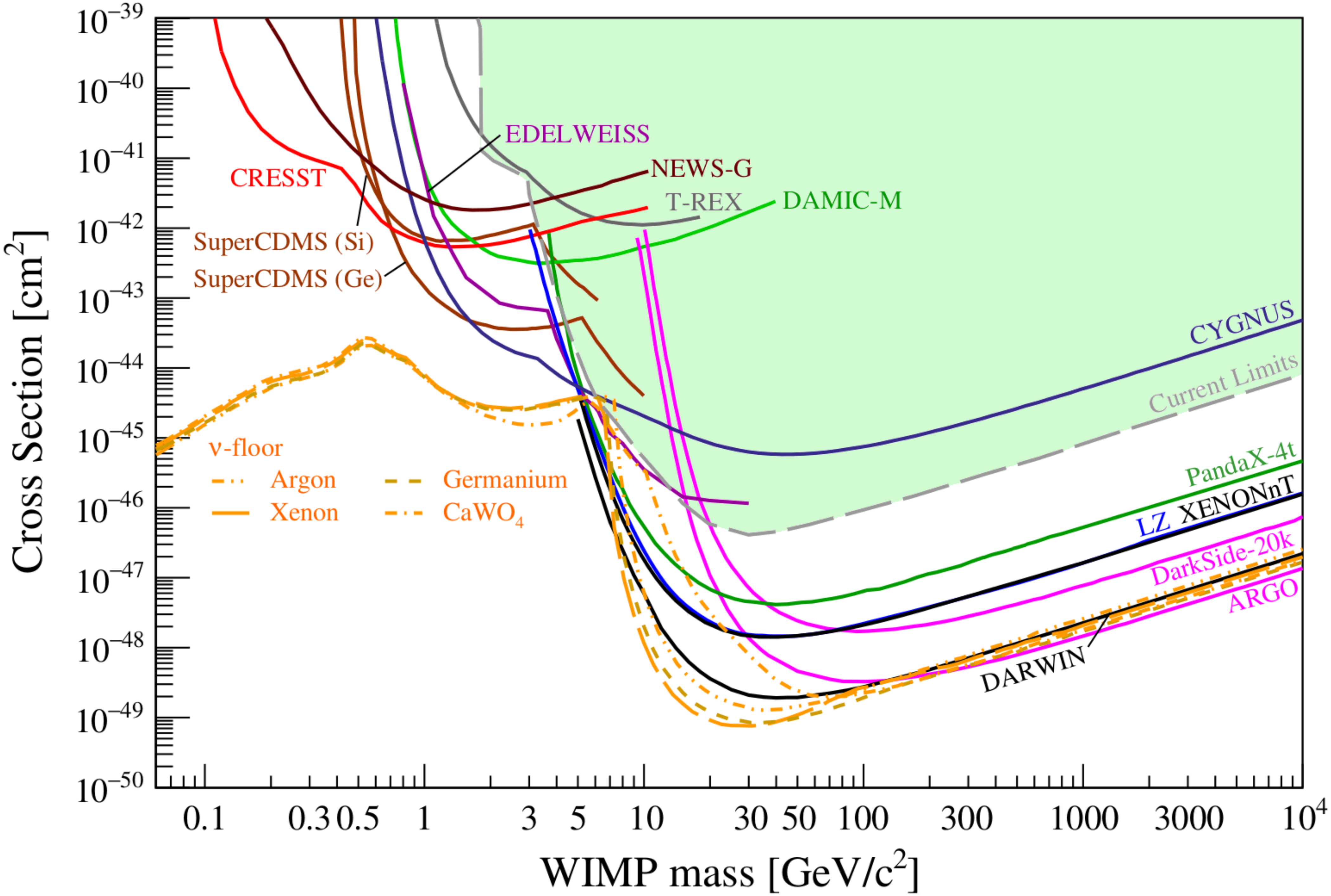
Illustris simulation

Beyond the WIMP: dark matter model space



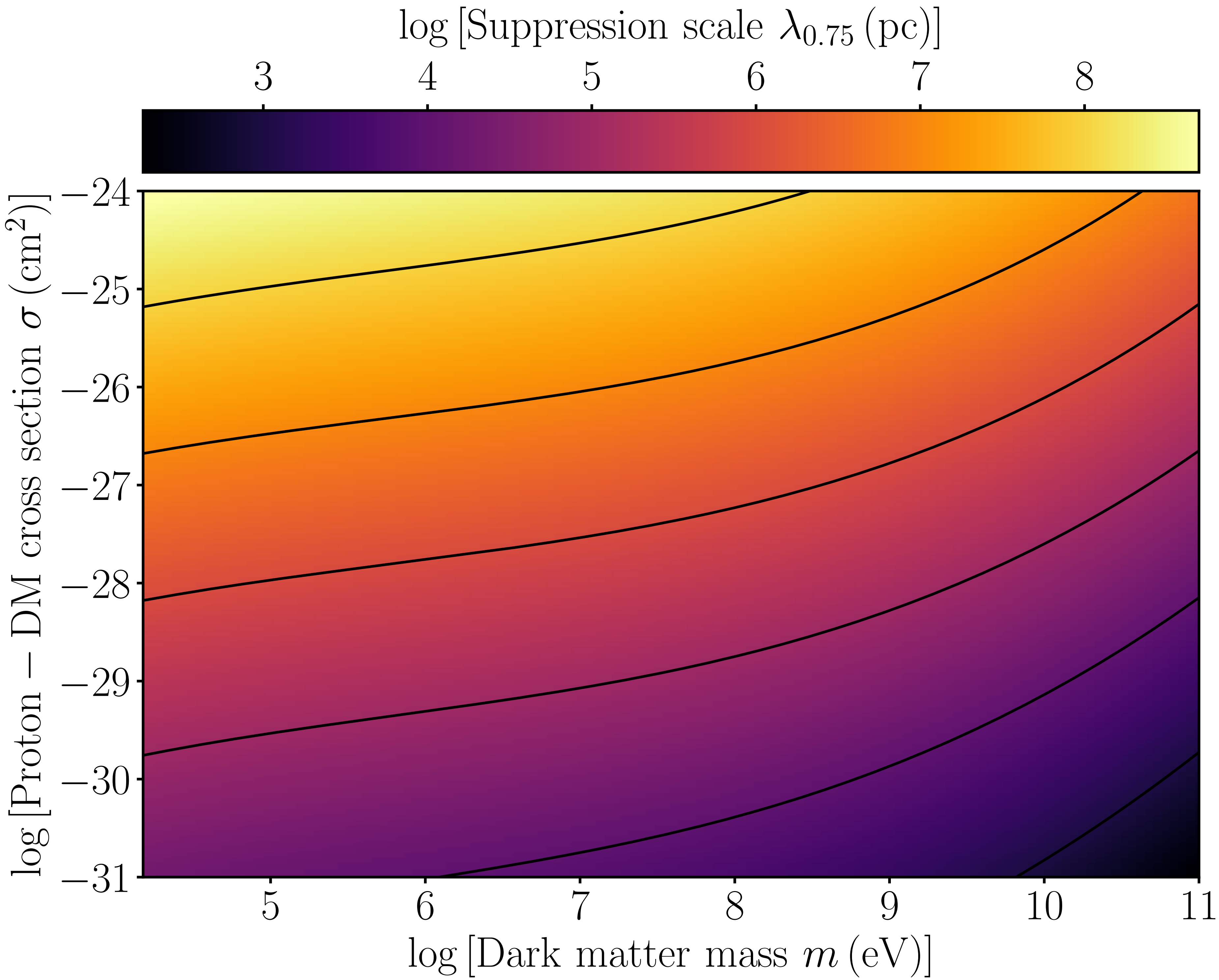
Not to scale

The technological frontier in dark matter direct detection is sub-GeV



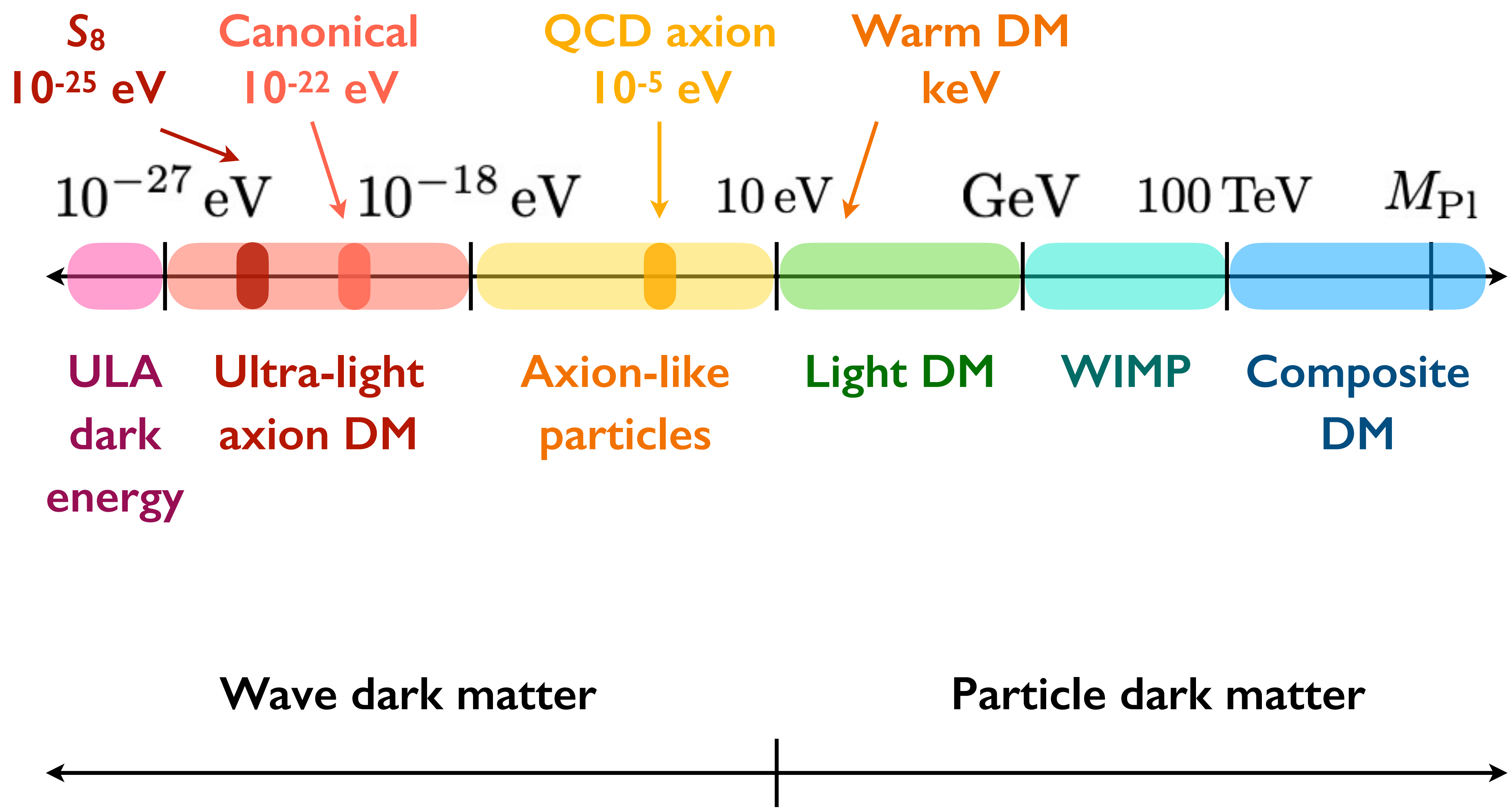
APPEC committee report (2021)

Light (sub-GeV) particle dark matter collisionally dampens growth of small-scale structure



Chen et al. (2002); Dvorkin et al. (2014); Rogers et al. (Phys. Rev. Lett., 2022)

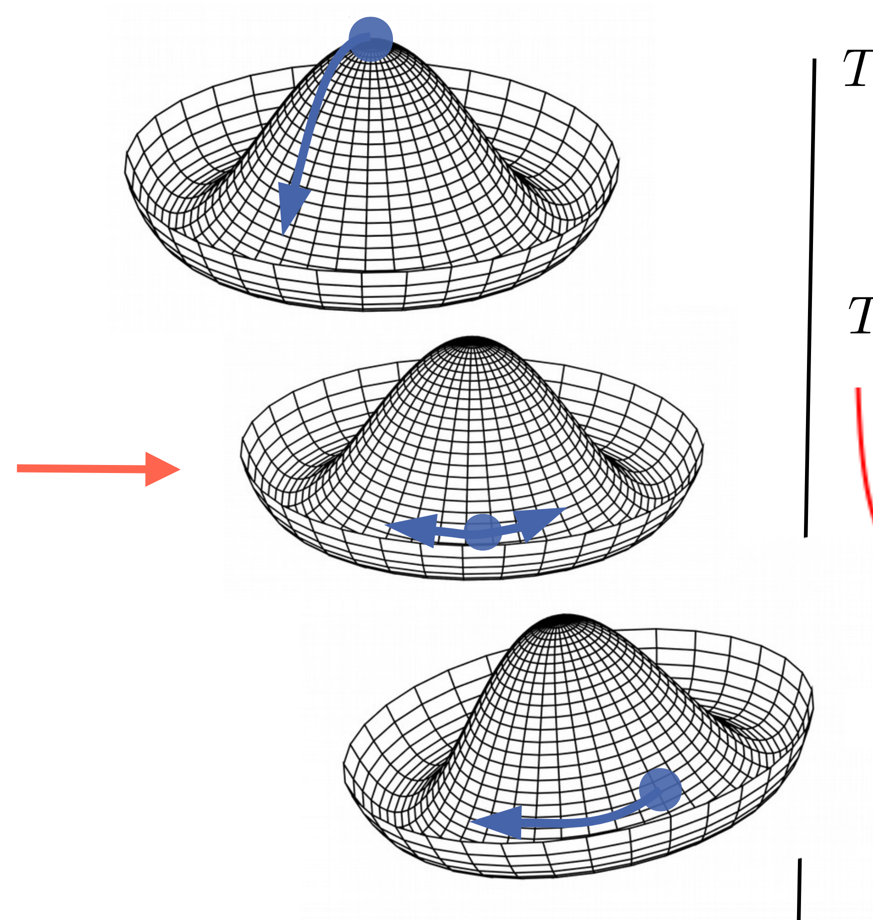
Beyond the WIMP: dark matter model space

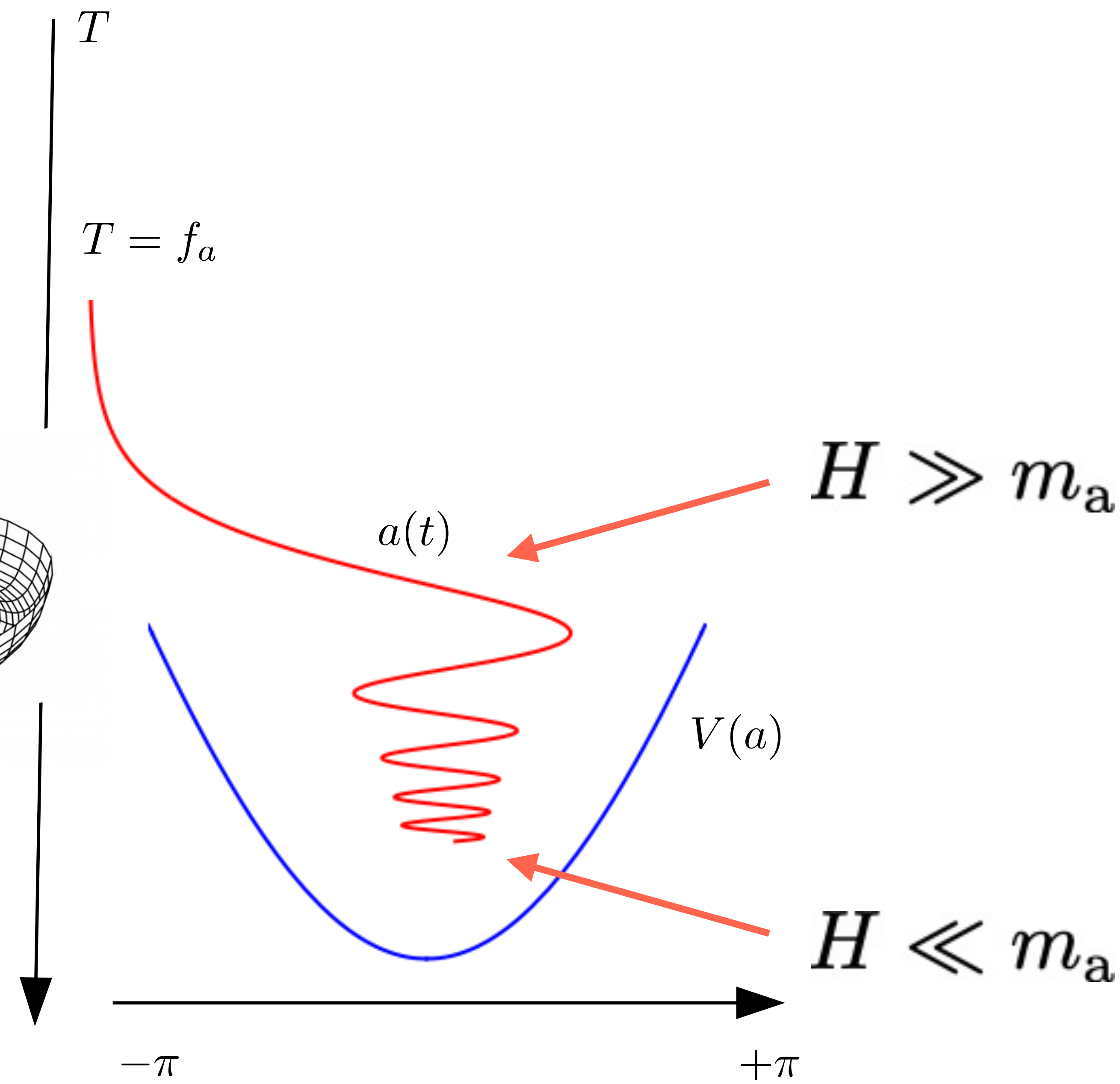


Not to scale

Axions are dark energy and dark matter candidates

Axion potential V

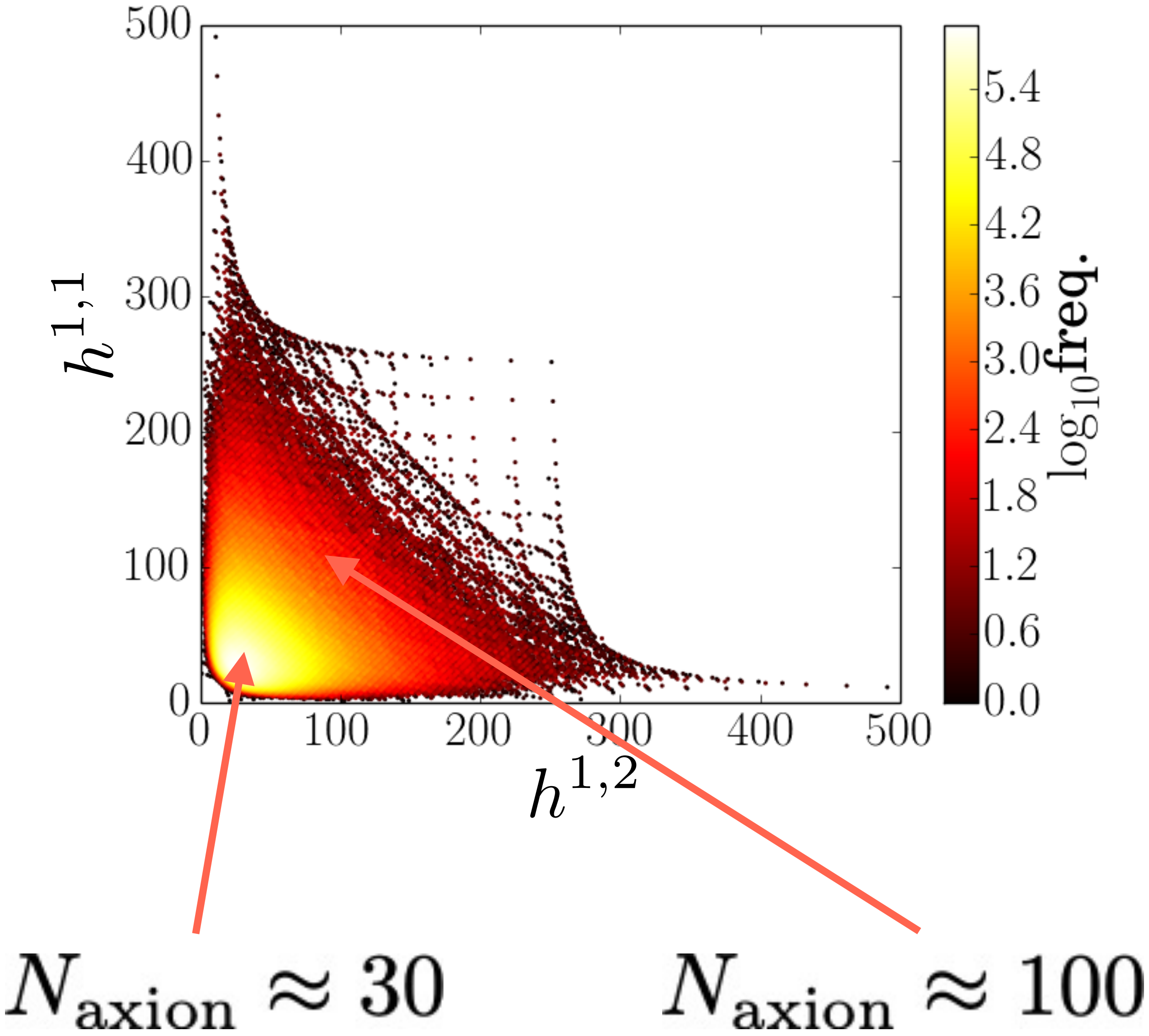




- $m_a > 10^{-27}$ eV: "dark matter-like"
- $m_a < 10^{-27}$ eV: "dark energy-like"
- $m_a = 10^{-33}$ eV: cosmological constant

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

Axion-like particles abundantly produced in high-energy theory



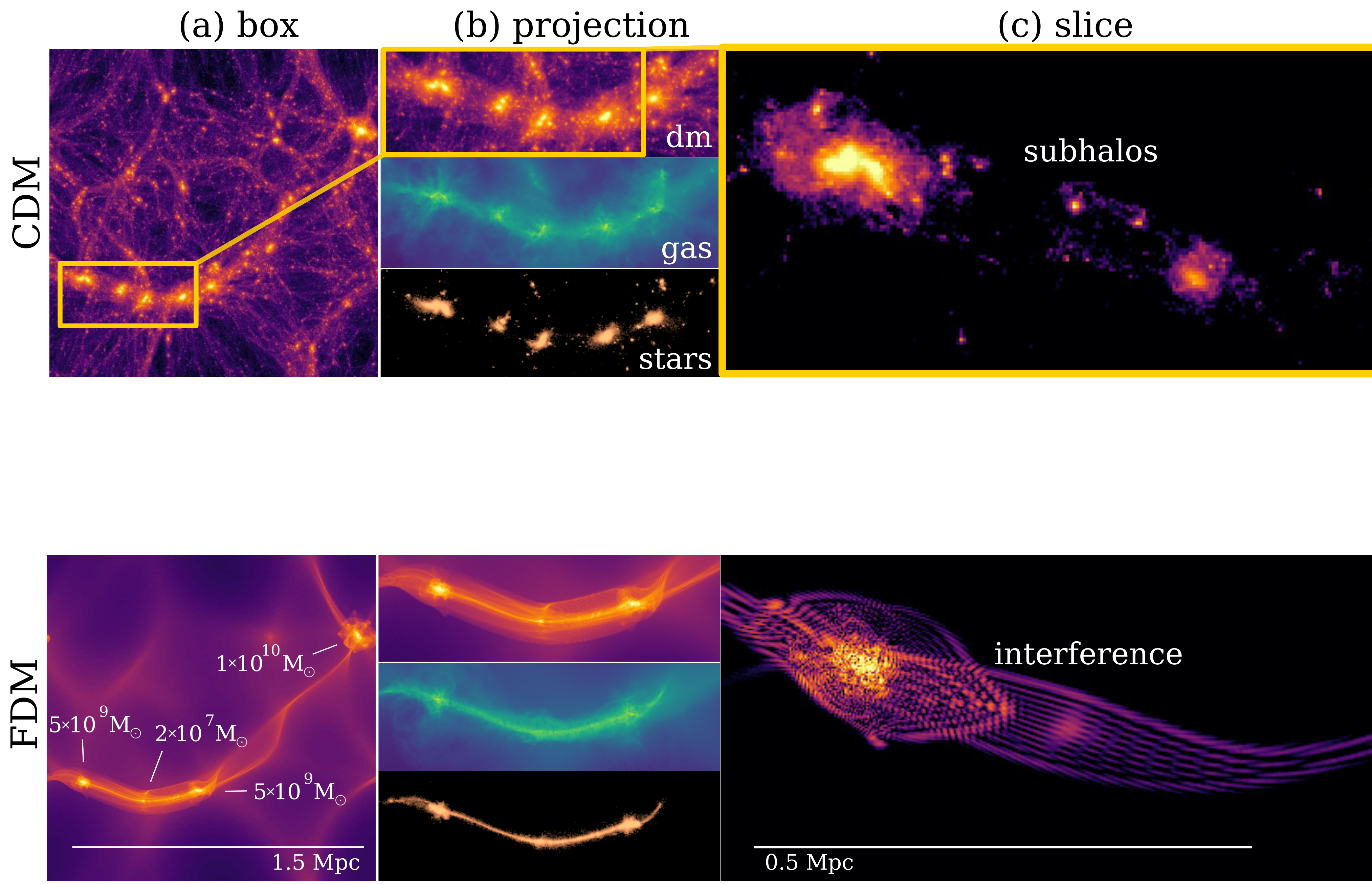
- Axion-like particles widely formed in BSM theories, inc. string models
- Axiverse of different mass axions from spacetime compactification
- One/more string axions can be DM

Figure credit: Marsh (2016)

Wave vs particle dark matter

Cold (massive particle) DM

Fuzzy (wave) DM ($m < 10^{-18}$ eV)



Mocz et al. (2019)

Ultra-light axions are invoked to resolve so-called cold dark matter "small-scale crisis"

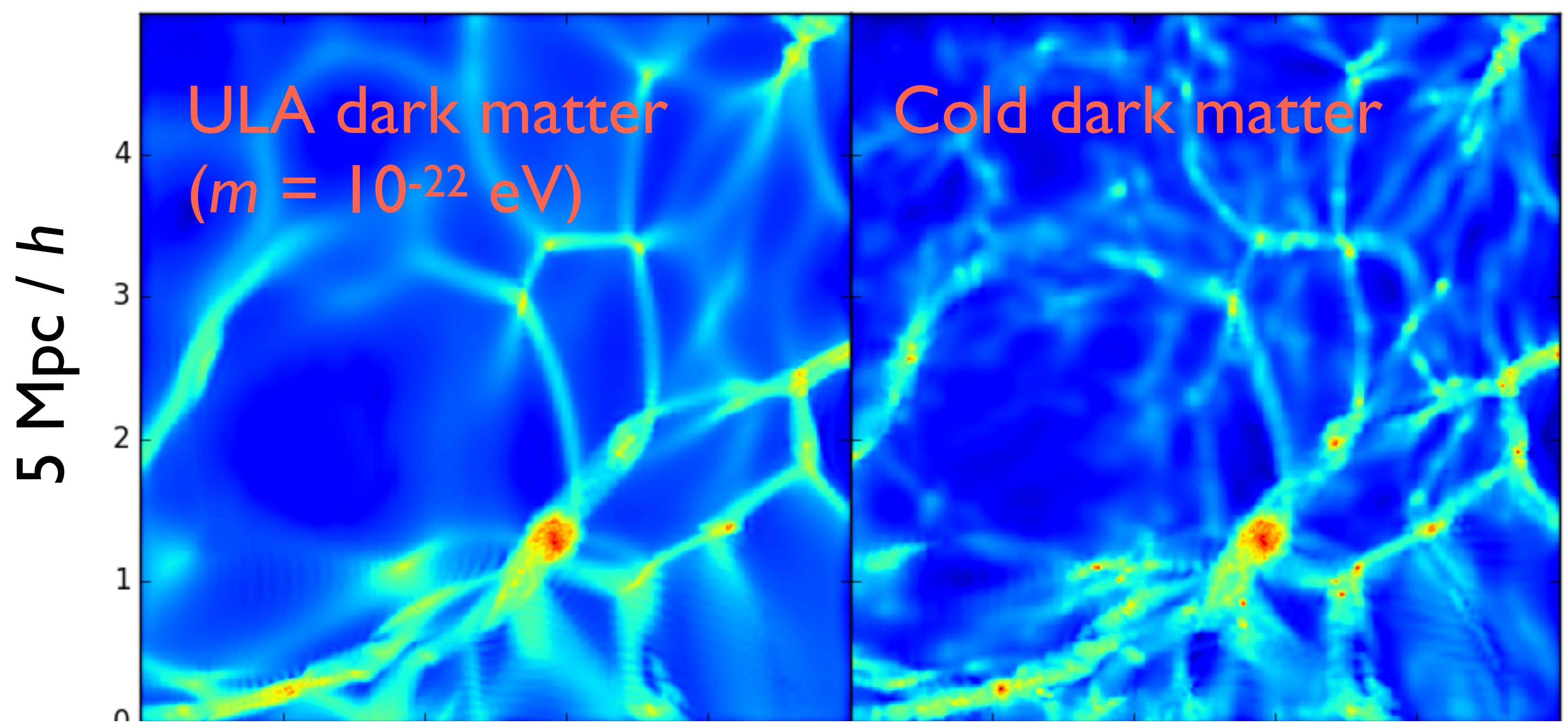
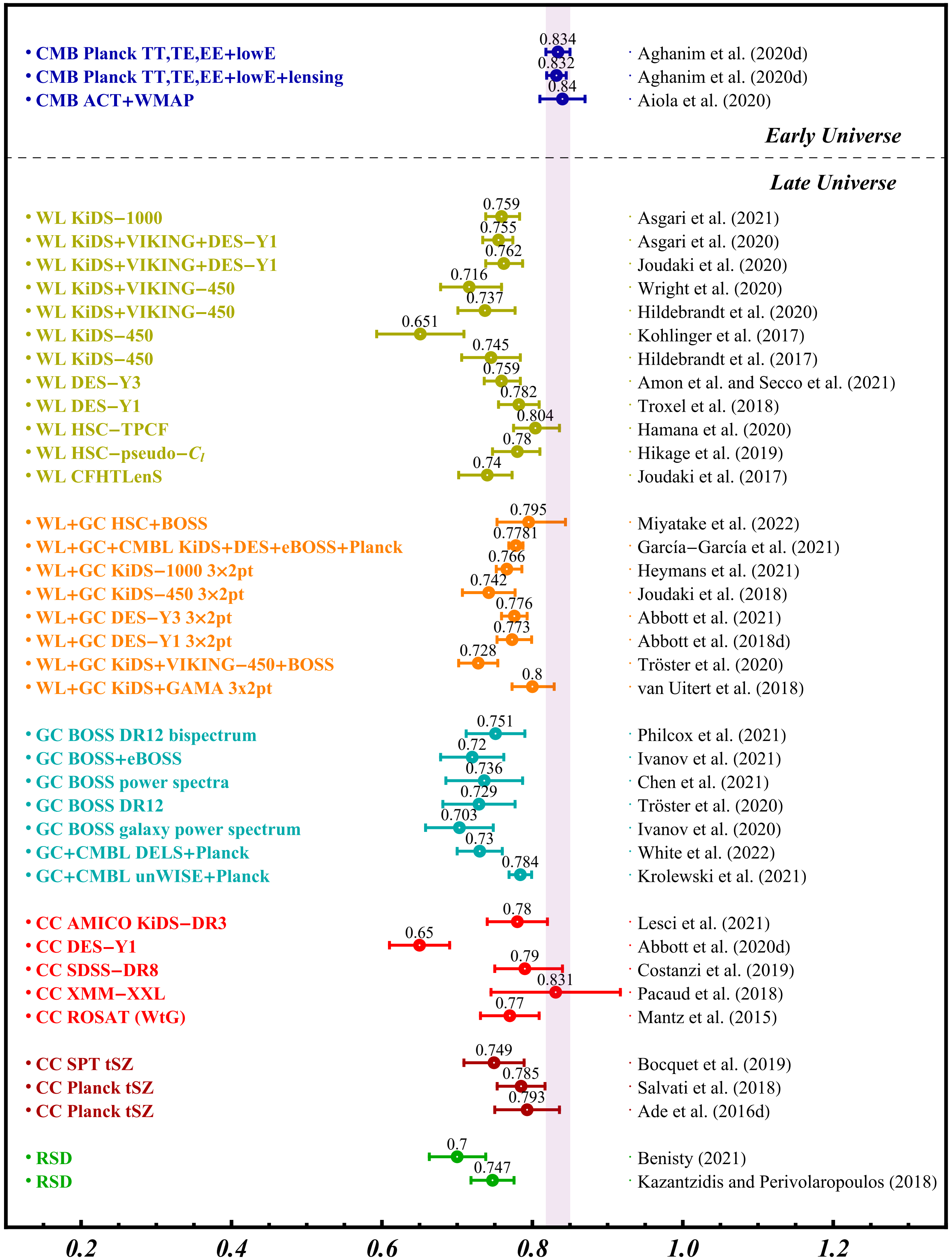


Figure credit: Armengaud et al. (2017); Hu et al. (2000)

Larger scales

Smaller scales



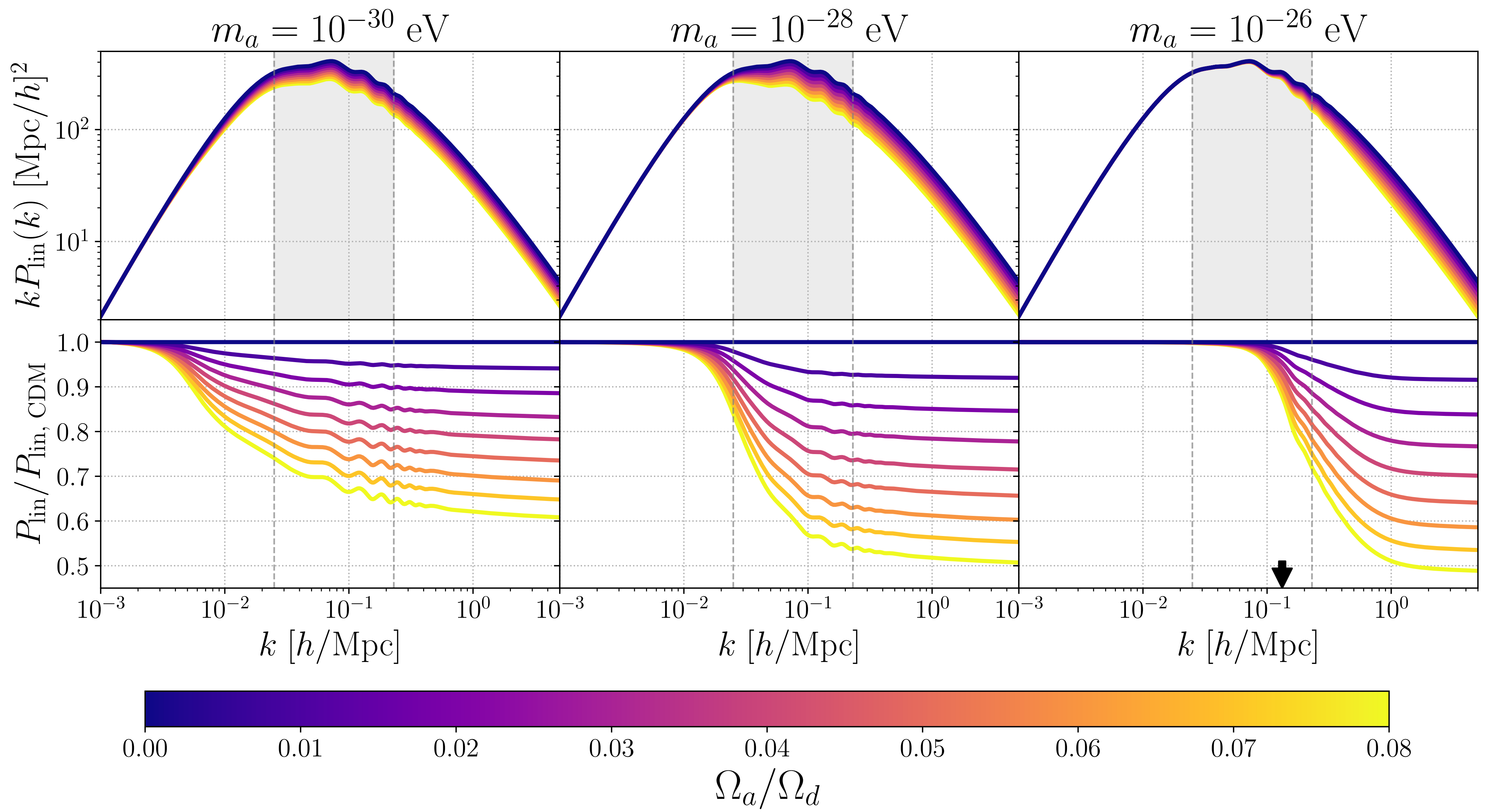
S_8 tension

S_8 ~ amplitude of density fluctuations at 8 Mpc/h

Abdalla et al. (Snowmass 2022)

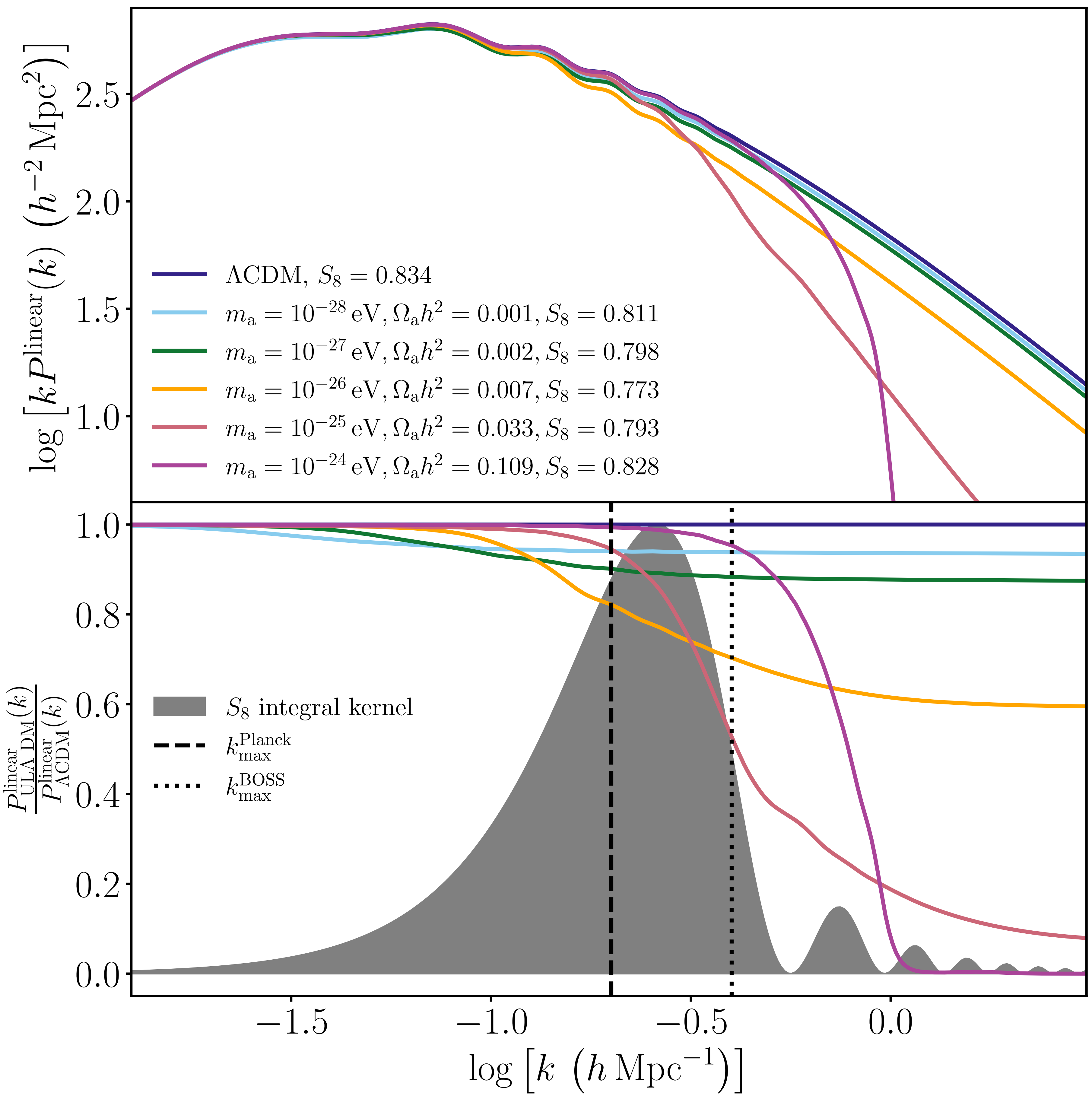
Ultra-light axion dark matter causes scale-dependent suppression in matter clustering

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



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

Axions lower S_8



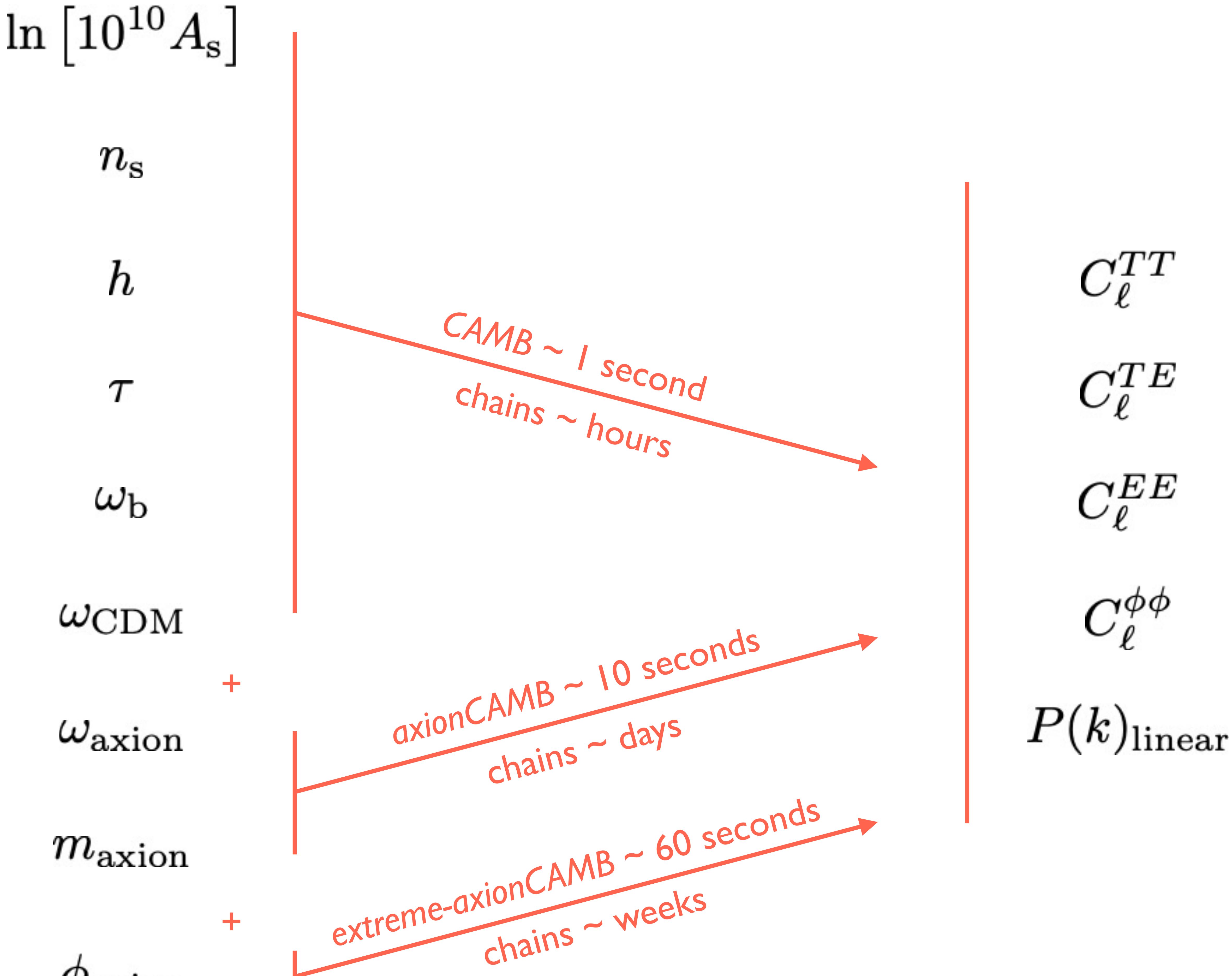
Rogers, Hložek, et al. (arXiv:2301.08361)

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

AXIONEMU: NEURAL NETWORK EMULATOR OF AXION POWER SPECTRA

with Anran Xu

https://github.com/keirkwame/axionEmu


$\ln\left[10^{10}A_s\right]$
n_s
h
τ
ω_b
ω_{CDM}
+
ω_{axion}
m_{axion}
+
ϕ_{axion}
CAMB ~ 1 second
chains ~ hours
axionCAMB ~ 10 seconds
chains ~ days
extreme-axionCAMB ~ 60 seconds
chains ~ weeks
C_ℓ^{TT}
C_ℓ^{TE}
C_ℓ^{EE}
$C_\ell^{\phi\phi}$
$P(k)_{linear}$

Anran Xu

$\ln\left[10^{10} A_\mathrm{s}\right]$

n_s

h

τ

ω_b

ω_CDM

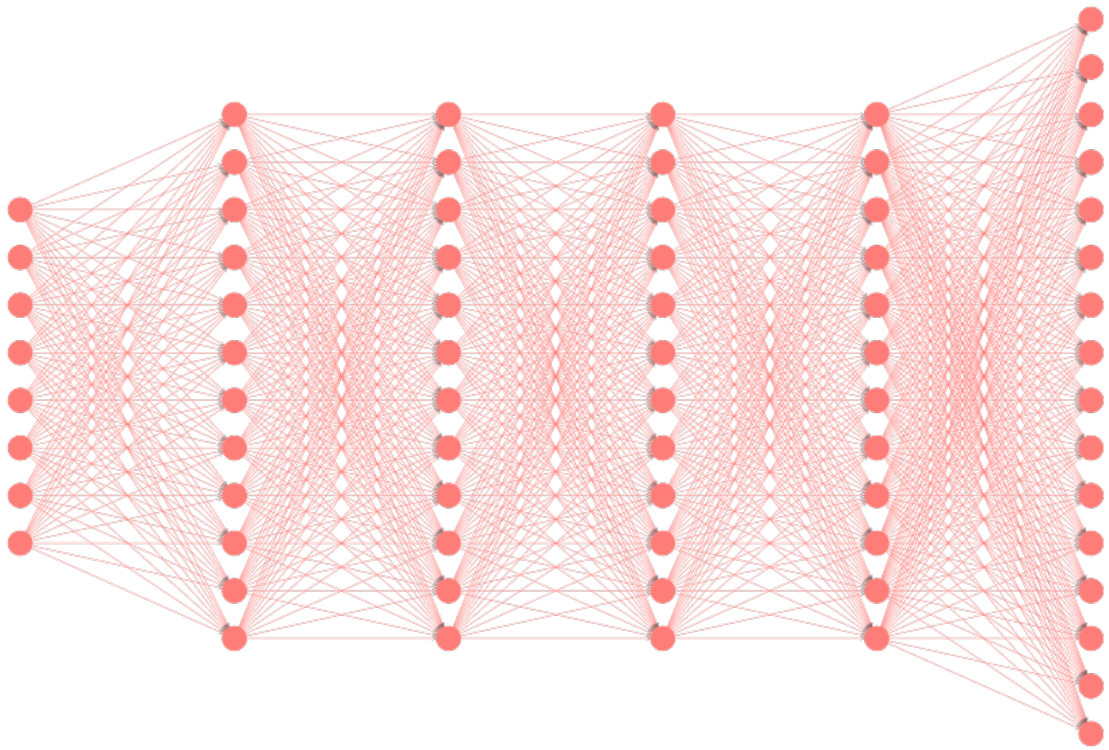
+

ω_axion

m_axion

+

ϕ_axion



axionEmu neural networks

~ 10^{-4} seconds

C_ℓ^{TT}

C_ℓ^{TE}

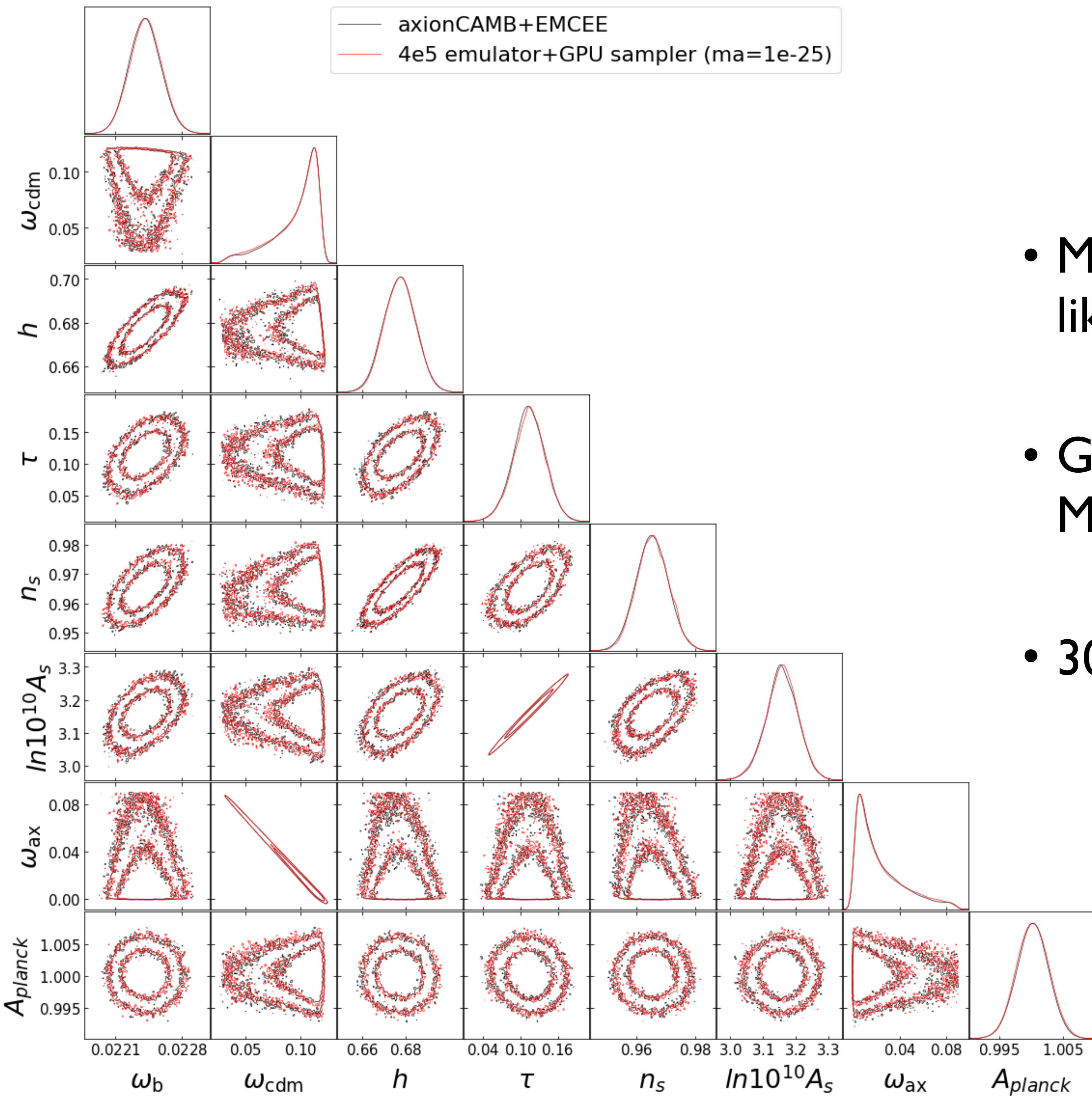
C_ℓ^{EE}

$C_\ell^{\phi\phi}$

$P(k)_\mathrm{linear}$

CosmoPower: Mancini+ (2022); *axionEmu*: Xu & Rogers (2023)

Neural net emulators will accelerate next-generation data analyses in GPU-heavy computing landscape



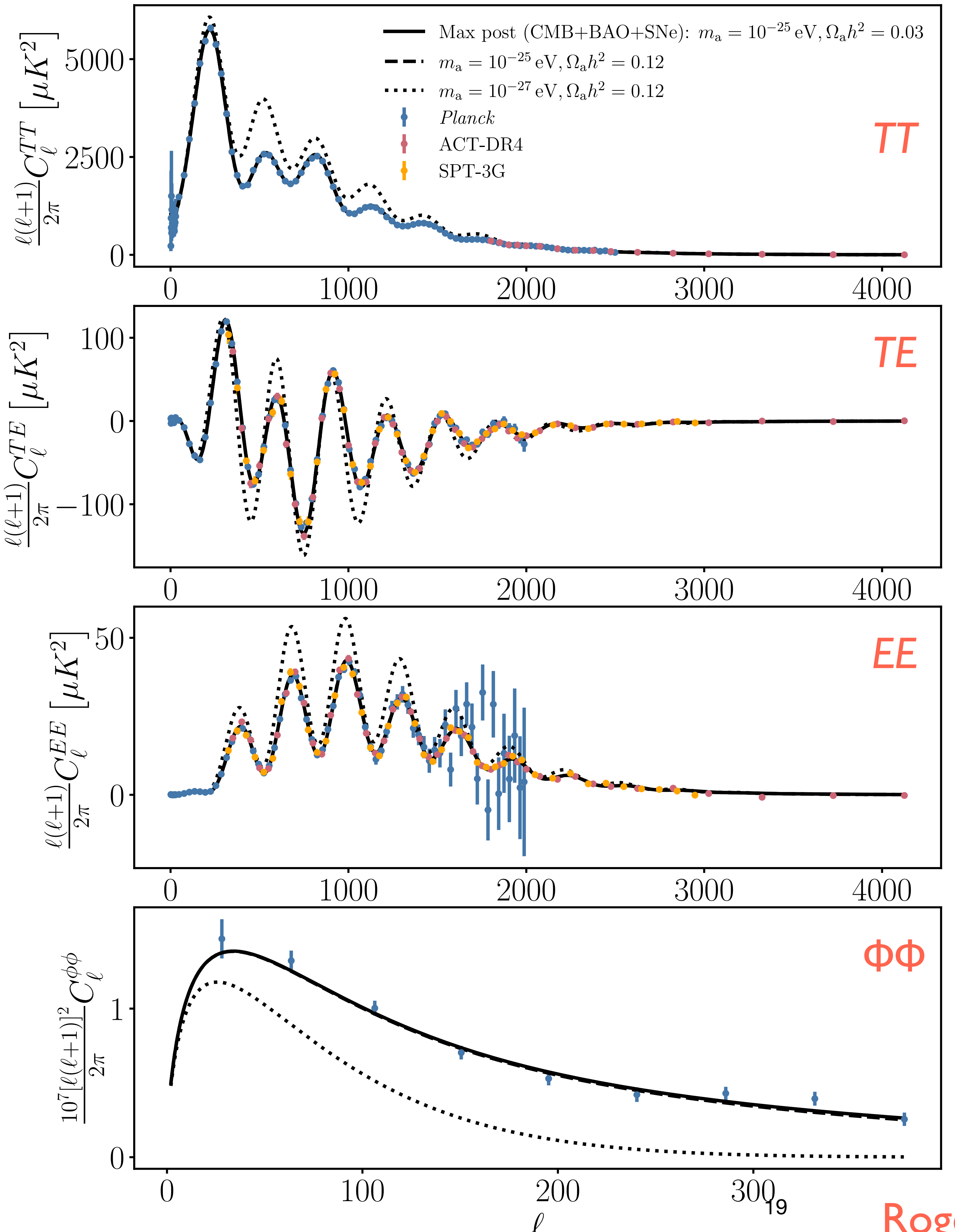
- Modified TensorFlow *Planck* CMB likelihood code
- GPU-accelerated Markov chain Monte Carlo sampling
- 30 hours → 10 seconds

Anran Xu & Keir Rogers (in prep, 2023)

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

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

arXiv: 2301.08361
JCAP, 01, 049, 2022
MNRAS, 515, 5646, 2022
with Hložek, Laguë, Ivanov, Philcox, Cabass, Akitsu, Marsh, Bond, Dentler, Grin

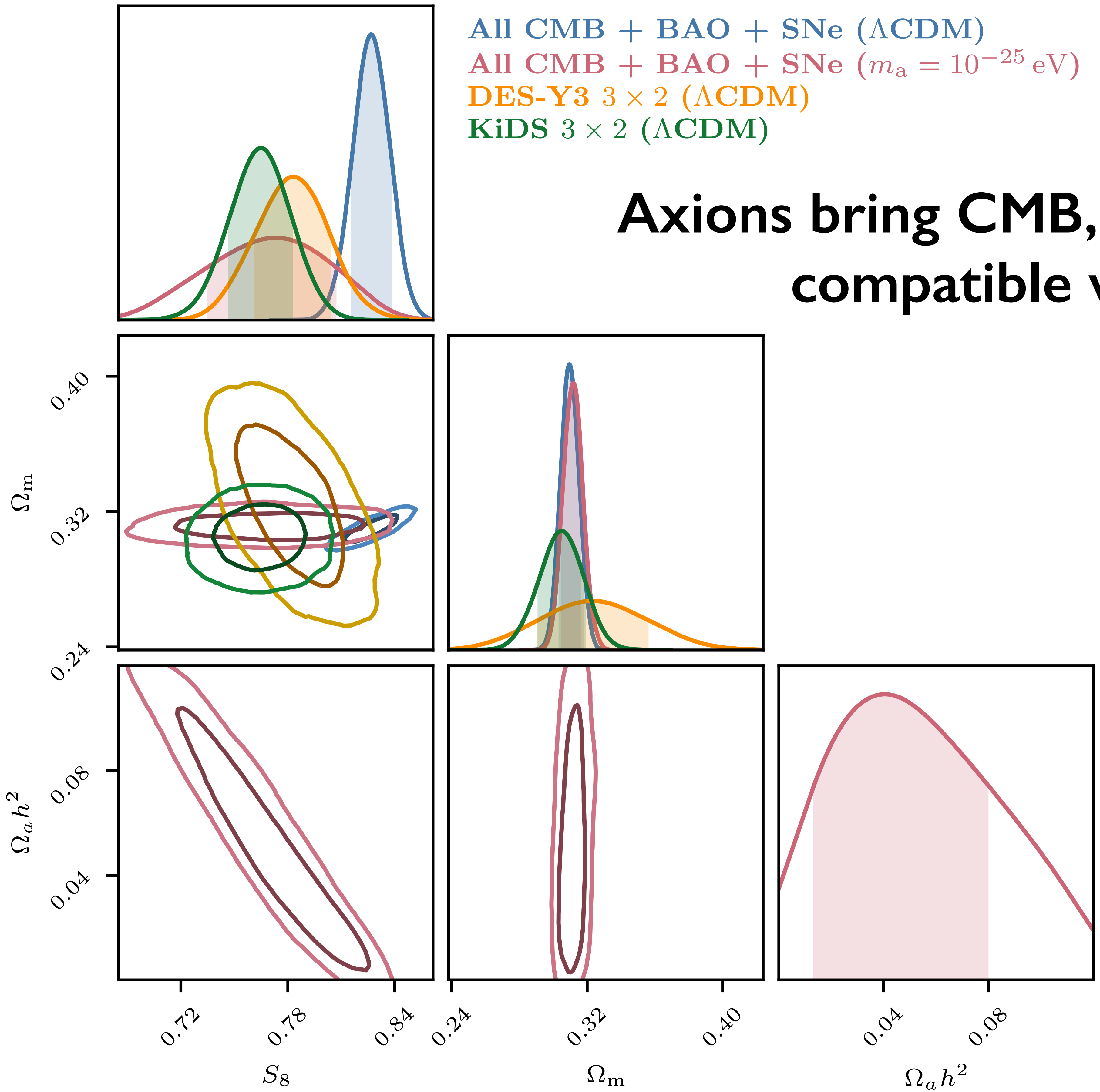


DE-like axions constrained by CMB acoustic oscillations & lensing potential

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

Rogers, Hložek, et al. (arXiv:2301.08361)

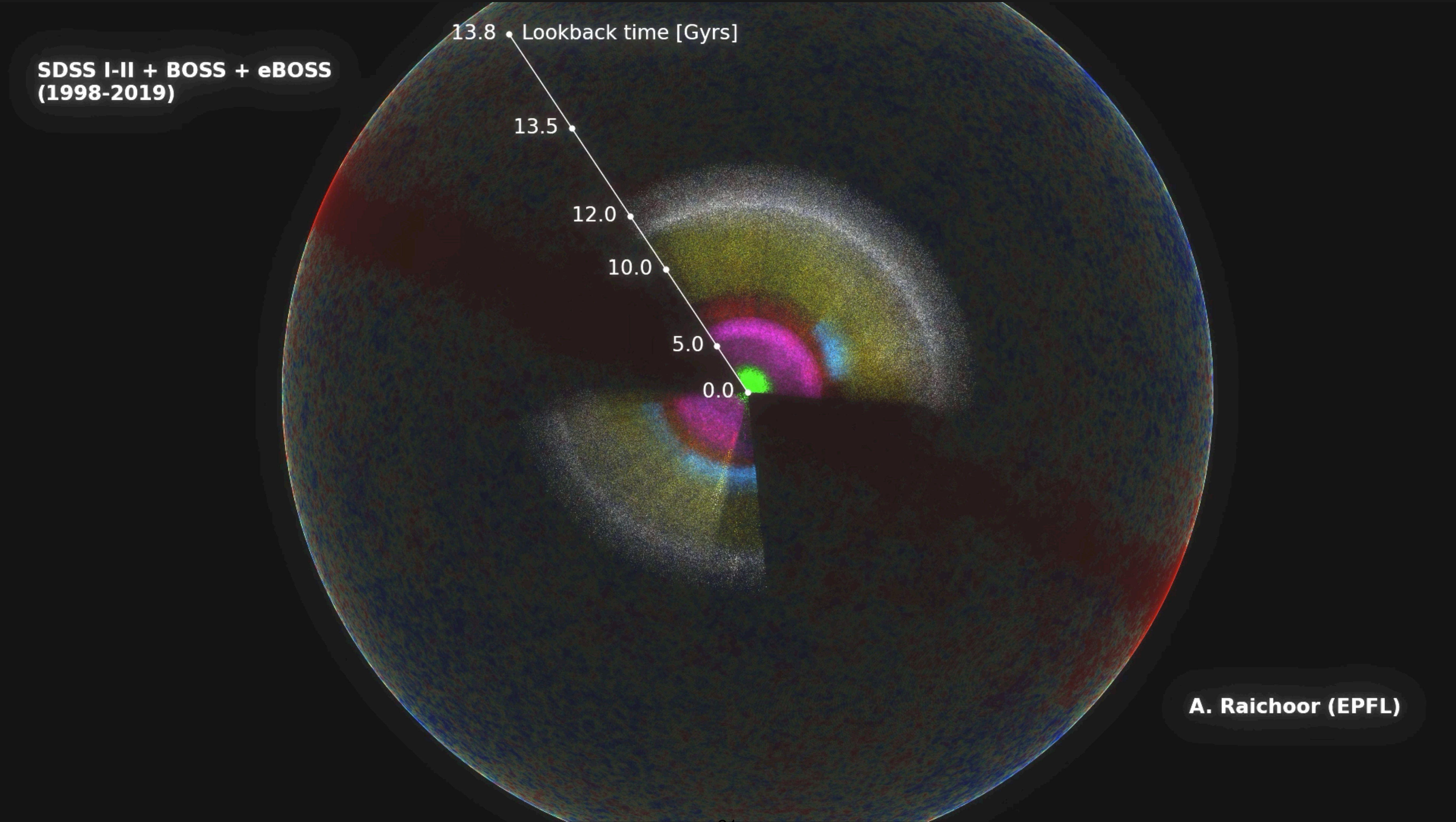
Axions bring CMB, BAO & SNe data compatible with low S_8



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

Rogers, Hložek, et al. (arXiv:2301.08361)

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

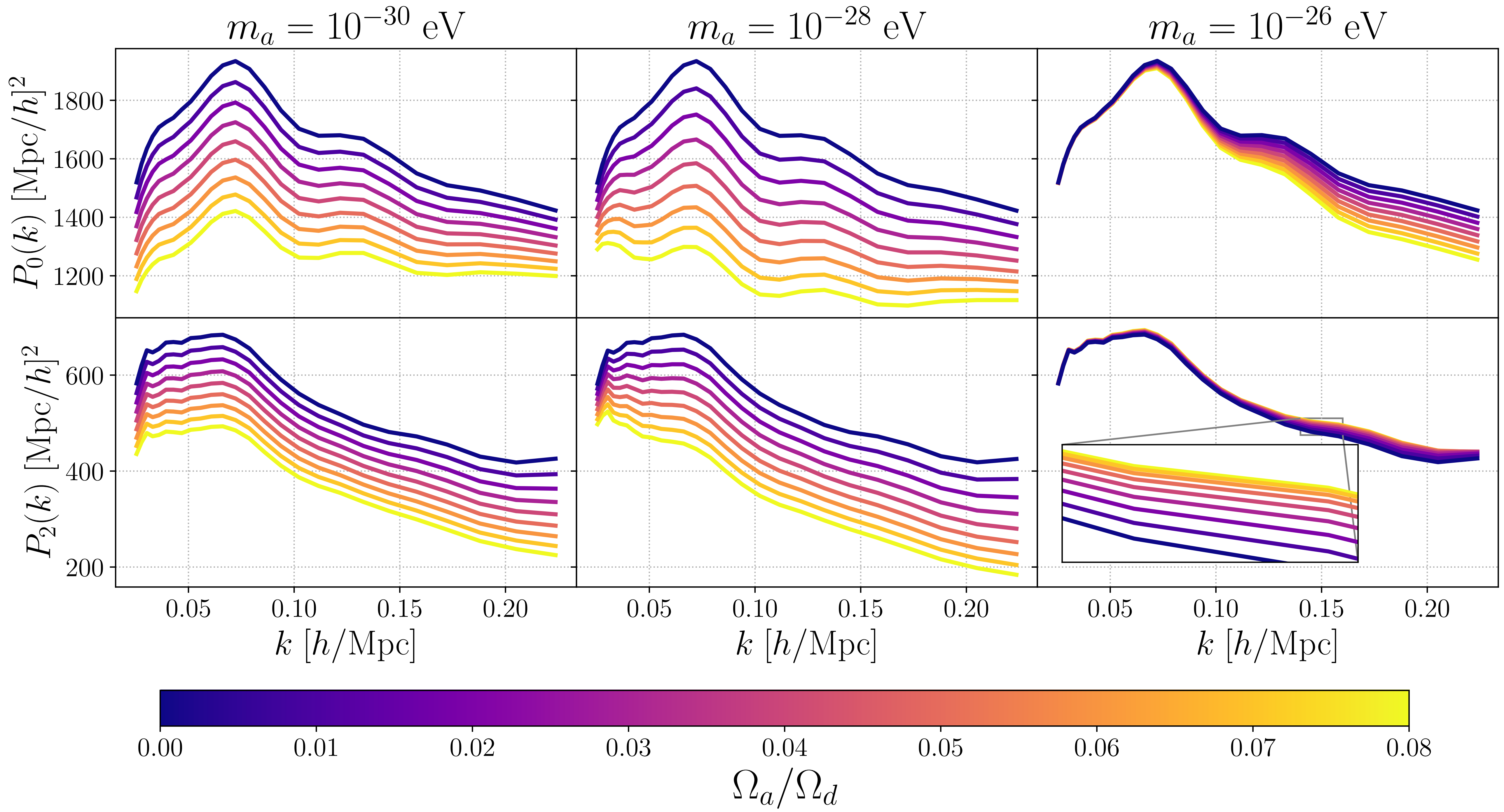
$$P_\ell(k) = P_\ell^{\rm Tree}(k) + P_\ell^{1-\rm loop}(k) + P_\ell^{\rm Counter}(k) + P_\ell^{\rm Stoch}(k)$$

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

+ Infrared resummation
+ Alcock-Paczynski distortion

Rogers, Hložek, et al. (arXiv:2301.08361); Baumann et al. (2012); Chudaykin et al. (2020)

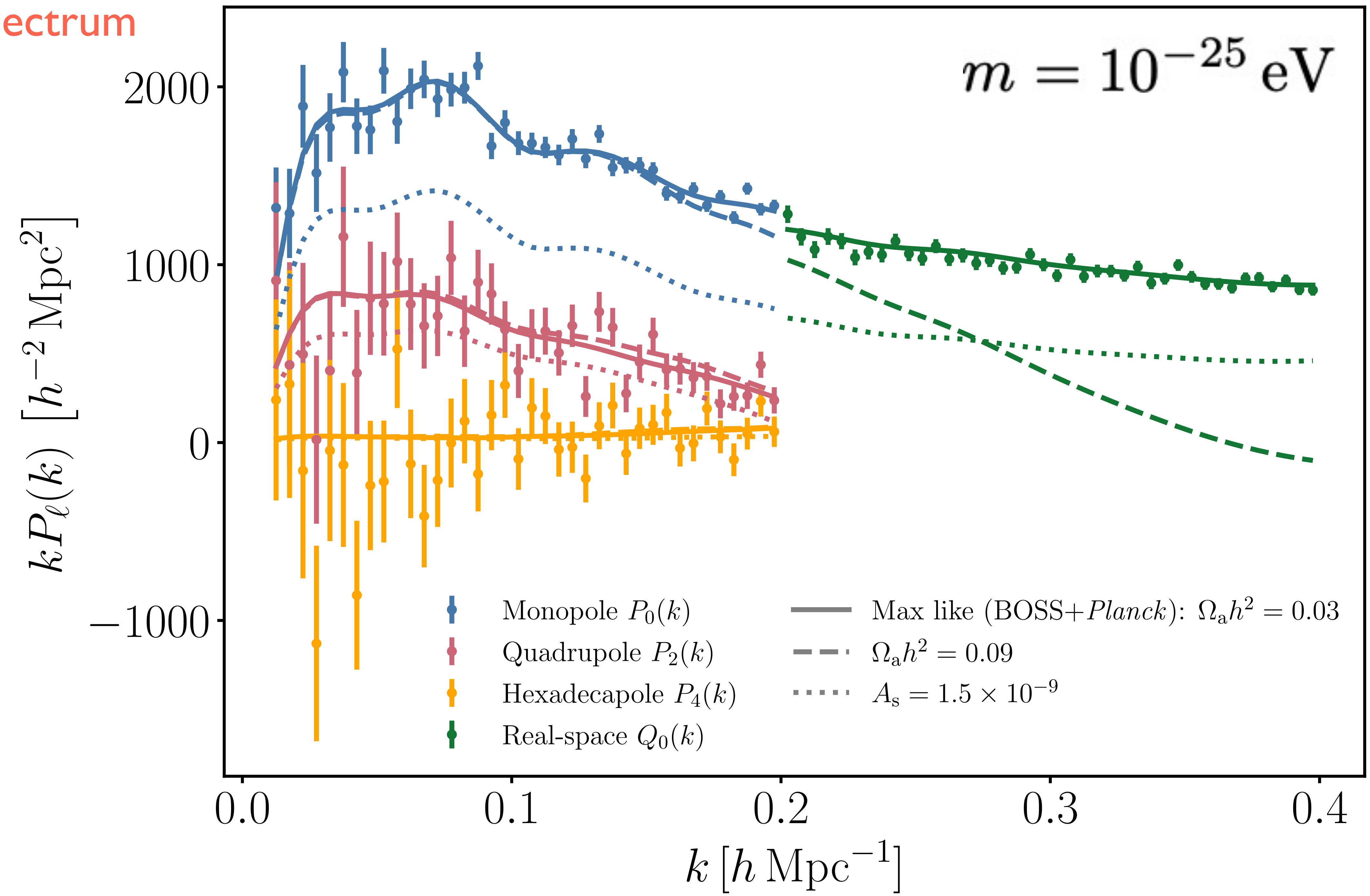
Galaxy clustering traces dark matter clustering — revealing signature of ultra-light axions



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

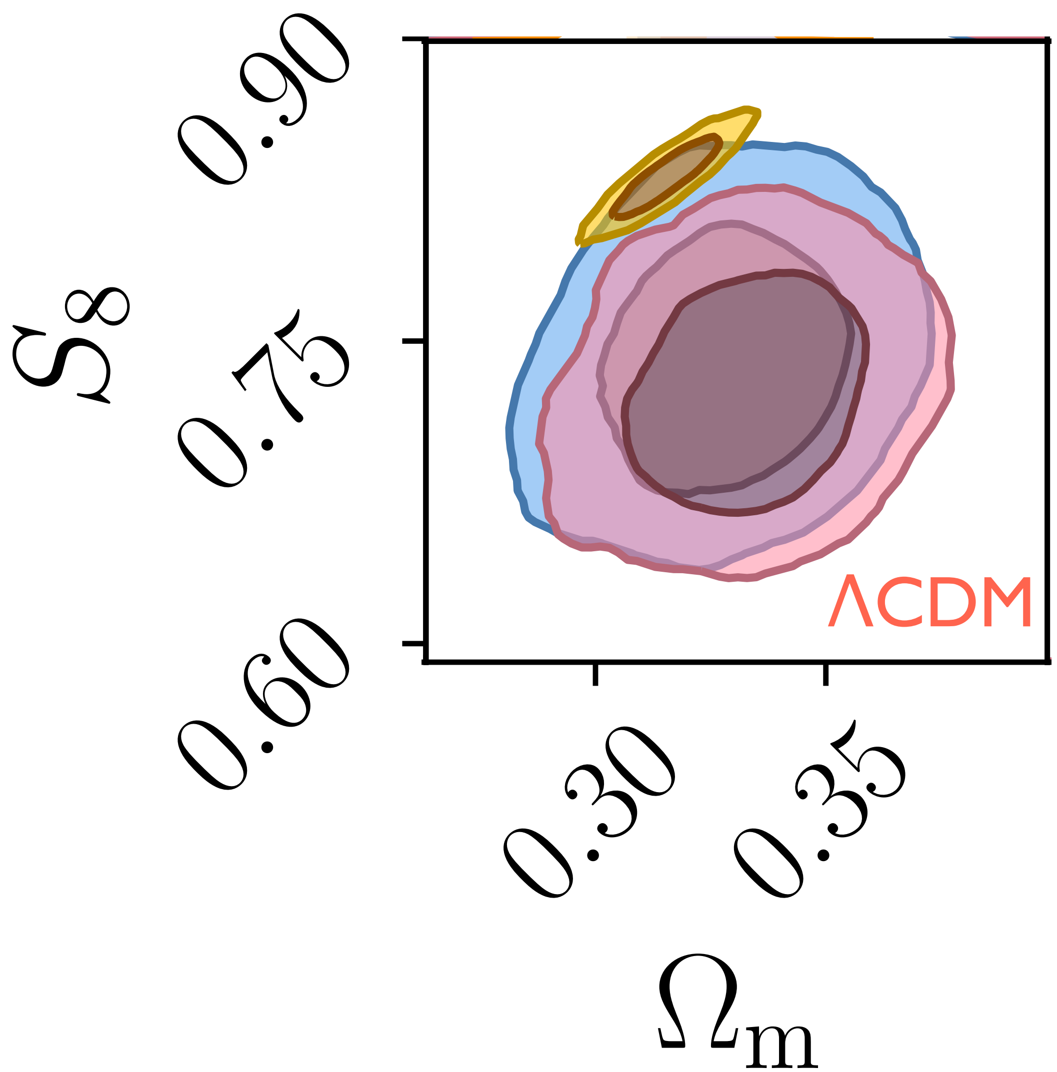
Full-shape BOSS galaxy power spectrum increases sensitivity to ultra-light axions

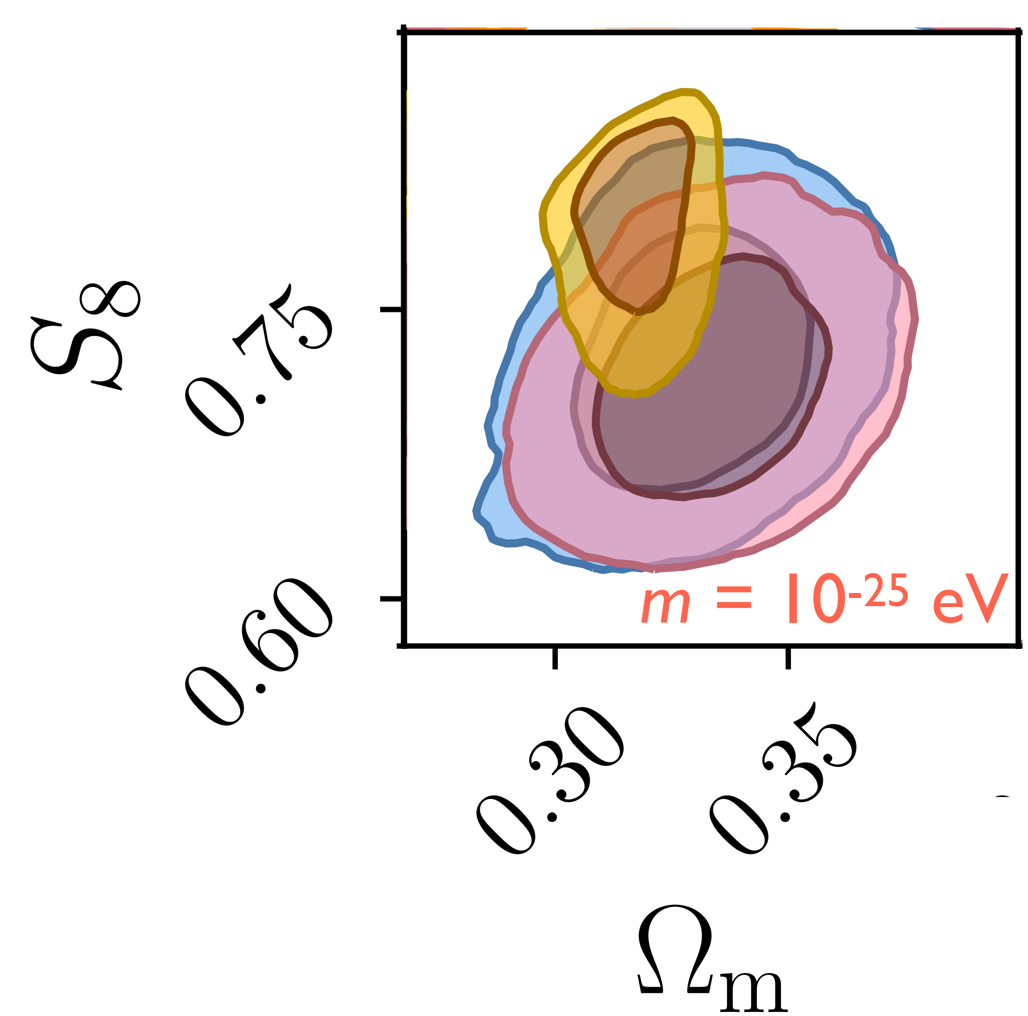
Power spectrum



Rogers, Hložek, et al. (arXiv:2301.08361)

Axions improve consistency between *Planck* and BOSS

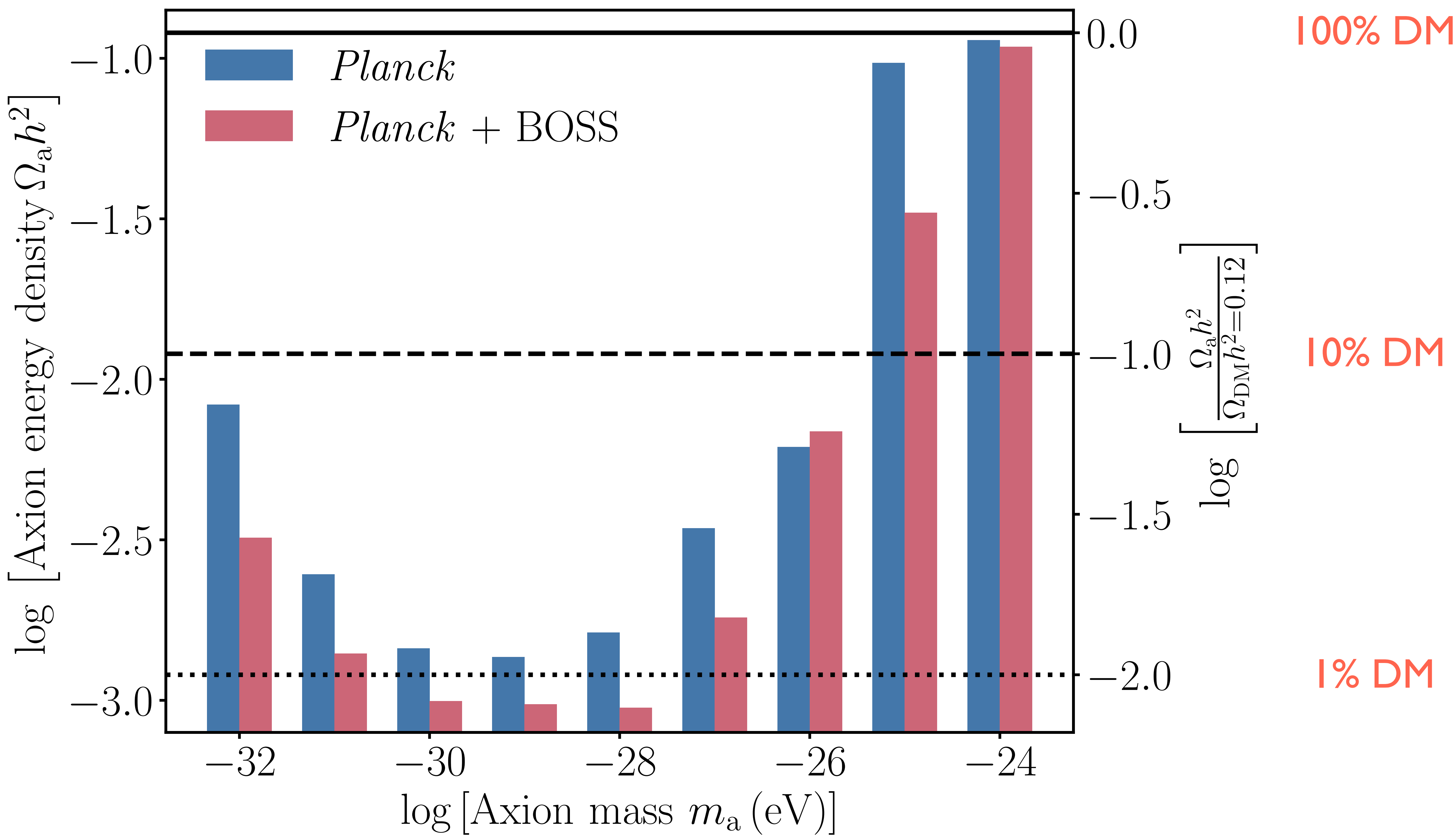




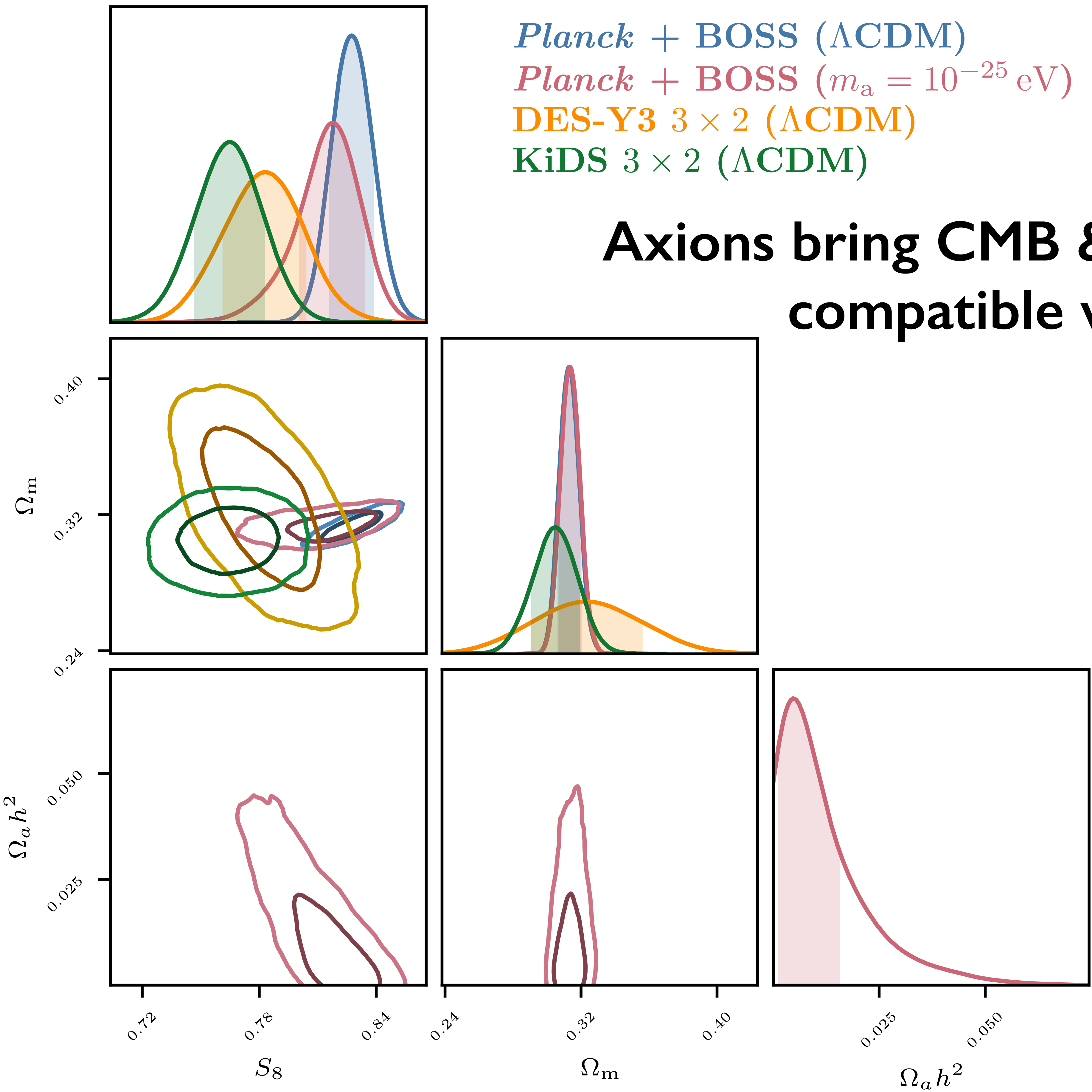
- *Planck* cosmic microwave background
- BOSS galaxy power spectrum
- BOSS galaxy power spectrum + bispectrum

Rogers, Hložek, et al. (arXiv:2301.08361)

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



Rogers, Hložek, et al. (arXiv:2301.08361)

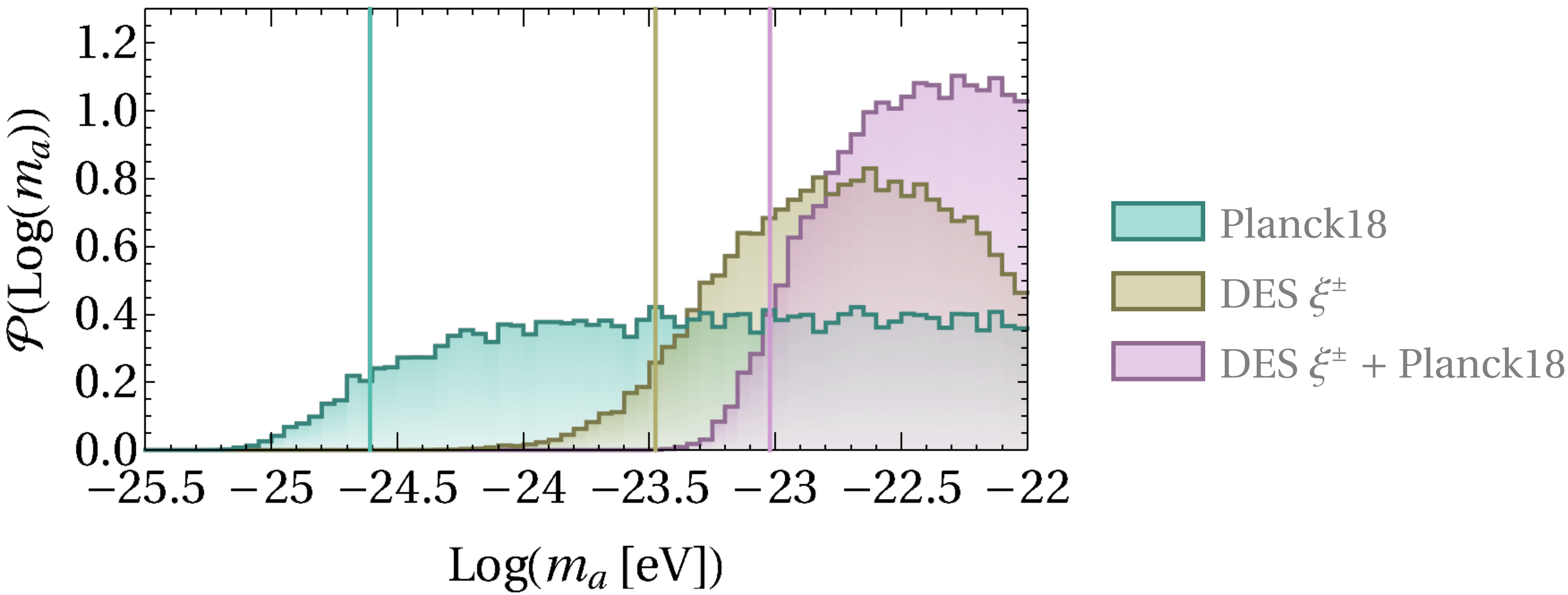


Axions bring CMB & galaxy clustering compatible with low S_8

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

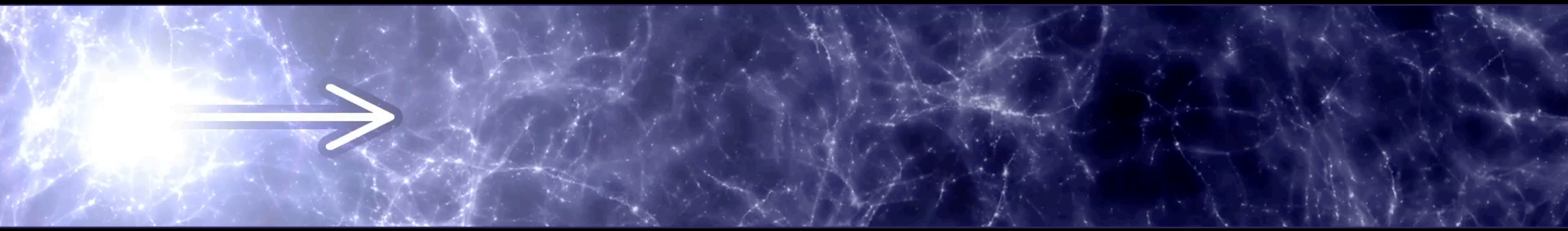
Rogers, Hložek, et al. (arXiv:2301.08361)

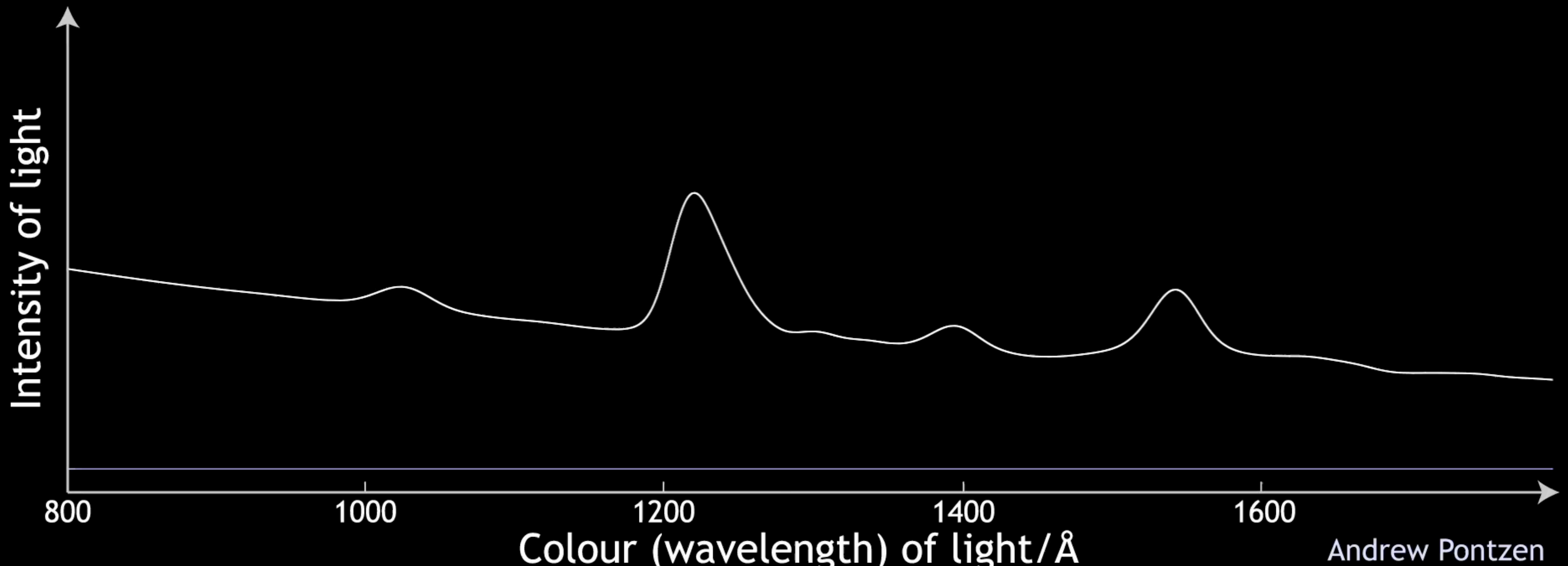
Joint CMB & galaxy weak lensing limits using axion dark matter halo model



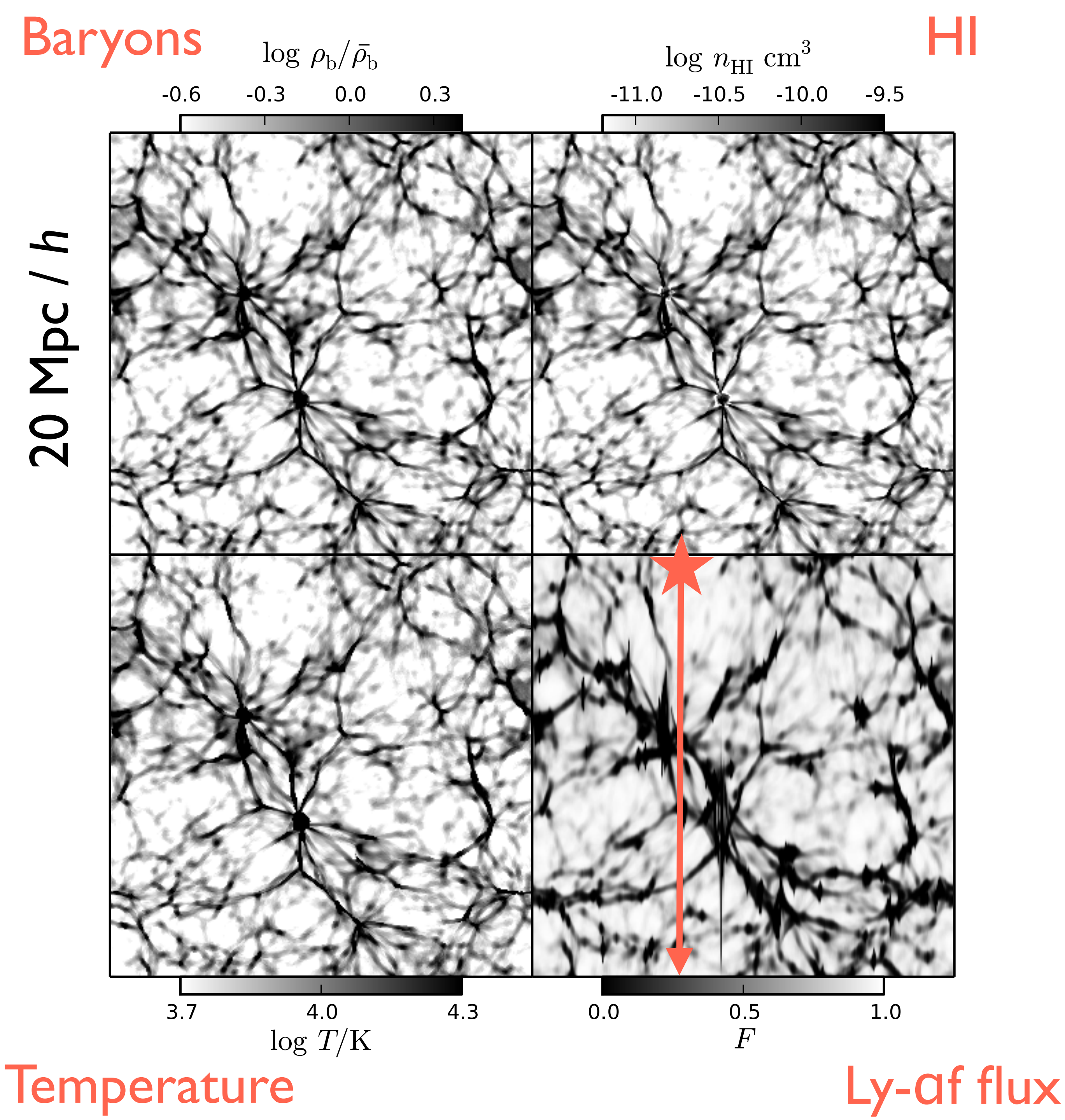
Dentler, Marsh, Hložek, Laguë, Rogers, Grin (MNRAS, 2022)

Lyman-alpha forest probes smallest cosmic scales





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



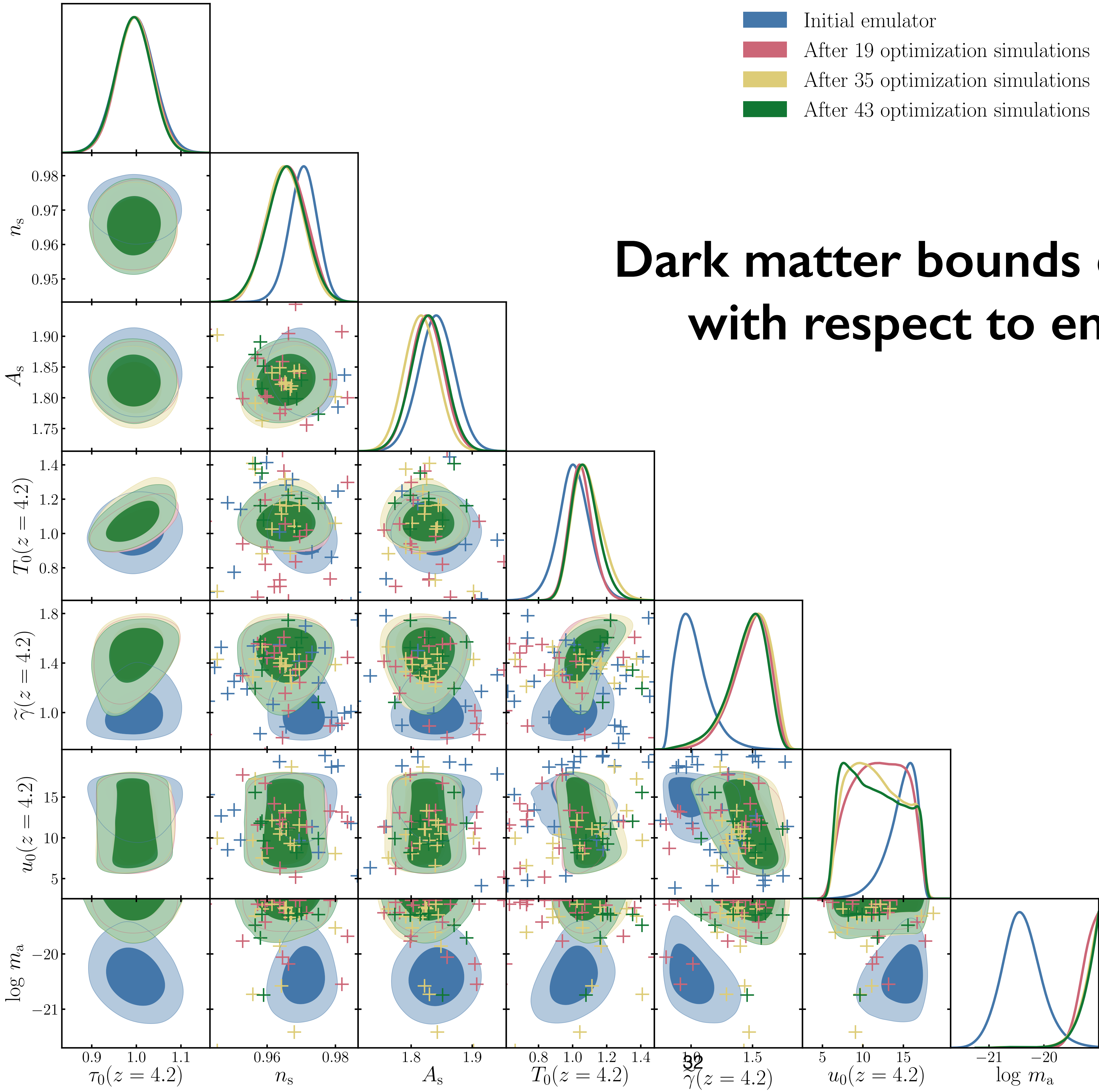
- Ly-alpha forest traces DM & intergalactic medium astrophysics
- ~ 3000 CPU-hours per simulation in 12-D parameter space
- ⇒ need ML-accelerated emulator

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

Dark matter emulator with active learning

JCAP, 02, 031, 2019
JCAP, 02, 050, 2019
Phys. Rev. D, 103, 043526, 2021
with Peiris, Bird, Pontzen, Verde, Font-Ribera

Dark matter bounds converged with respect to emulator



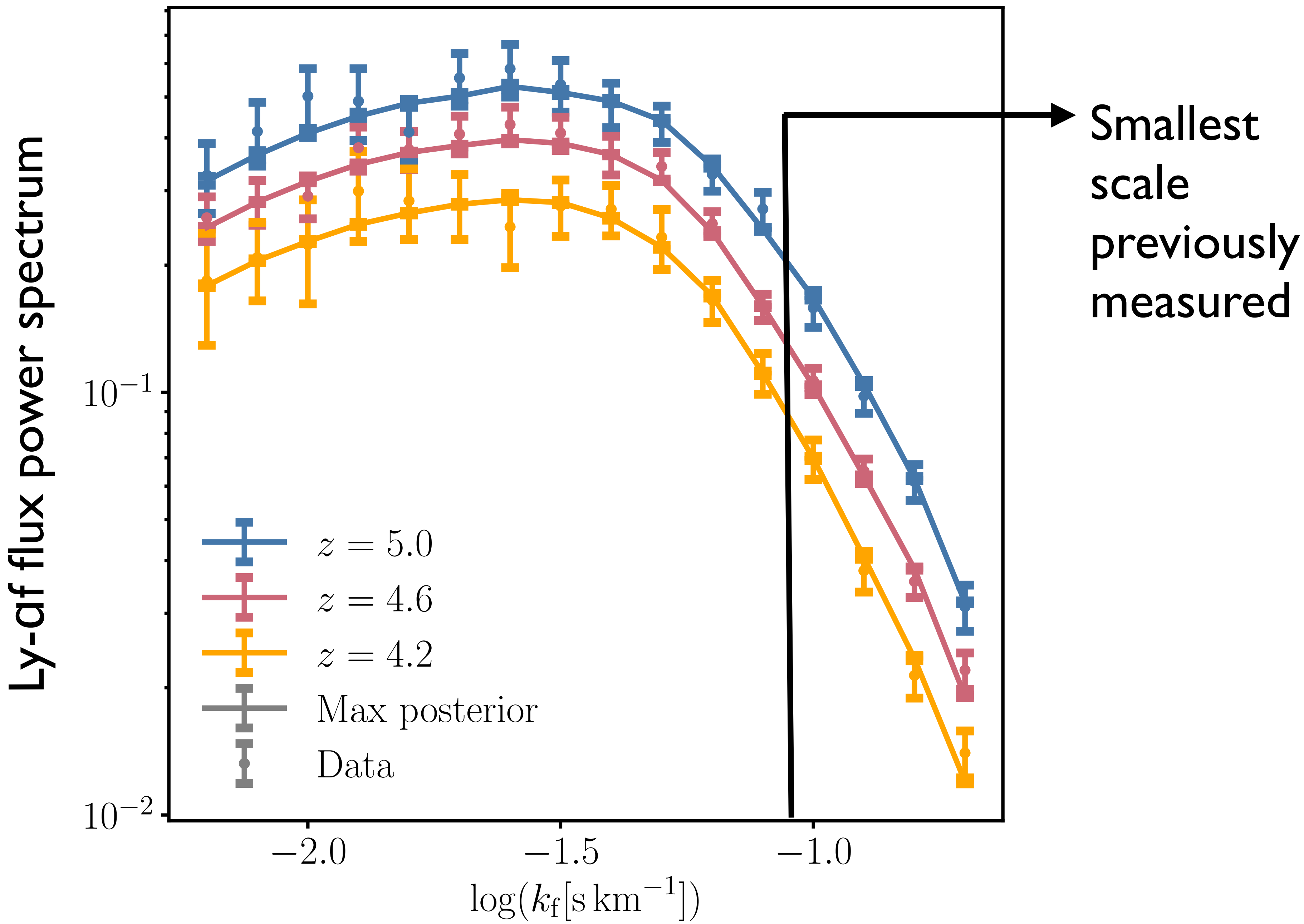
Rogers & Peiris (Phys. Rev. D, 2021)

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

NEW LIMITS ON DARK MATTER — PROTON INTERACTION

Phys. Rev. Lett., 128, 171301, 2022
Phys. Rev. D, 103, 043526, 2021
with Dvorkin, Peiris

Dark matter limits driven by new small-scale data



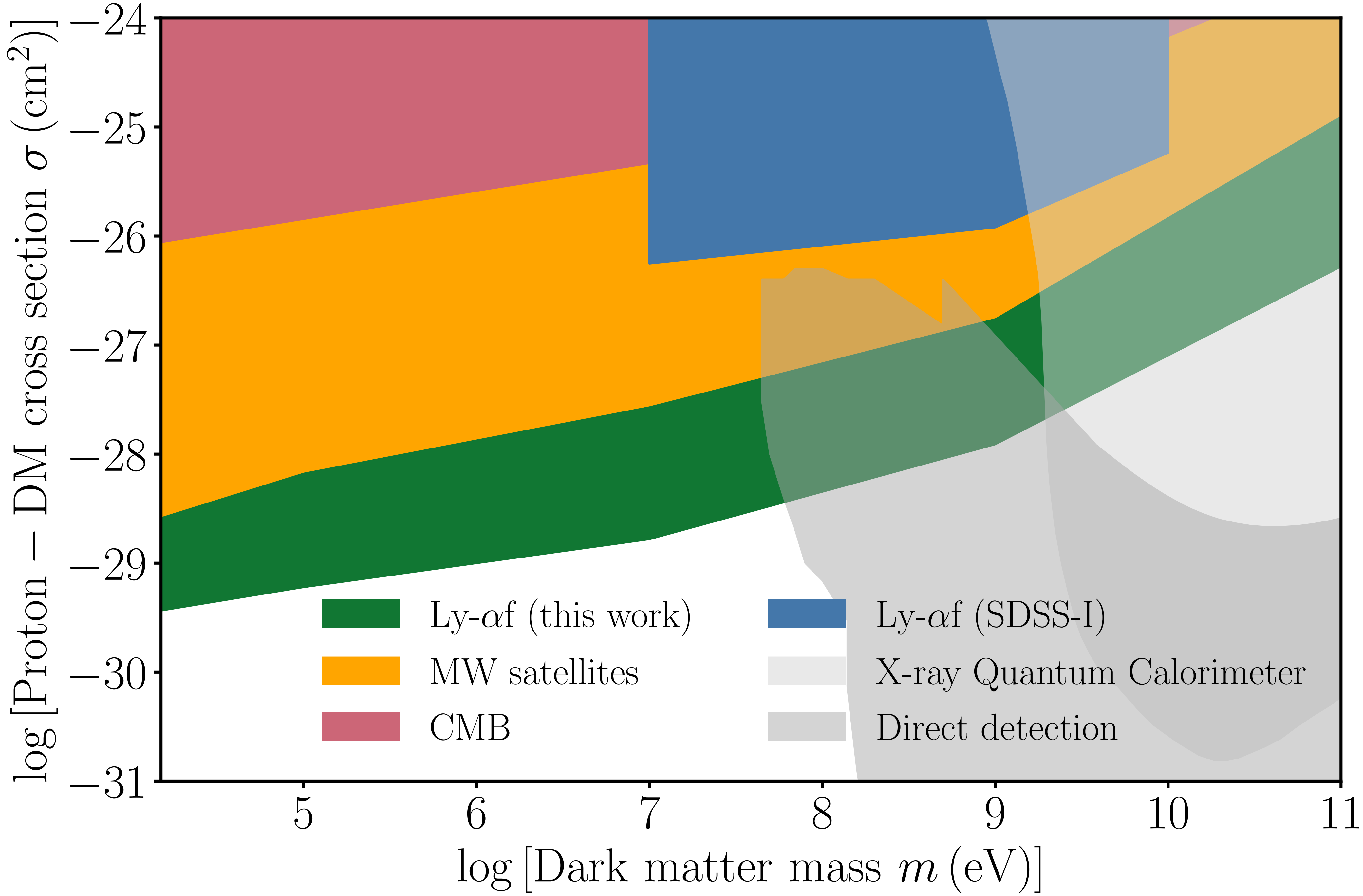
Data: Boera et al. (2019)

UNIVERSITY OF TORONTO

Stockholm University

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

Cosmological limits on light (sub-GeV) dark matter highly complementary to direct detection



UNIVERSITY OF TORONTO

Rogers et al. (Phys. Rev. Lett., 2022)

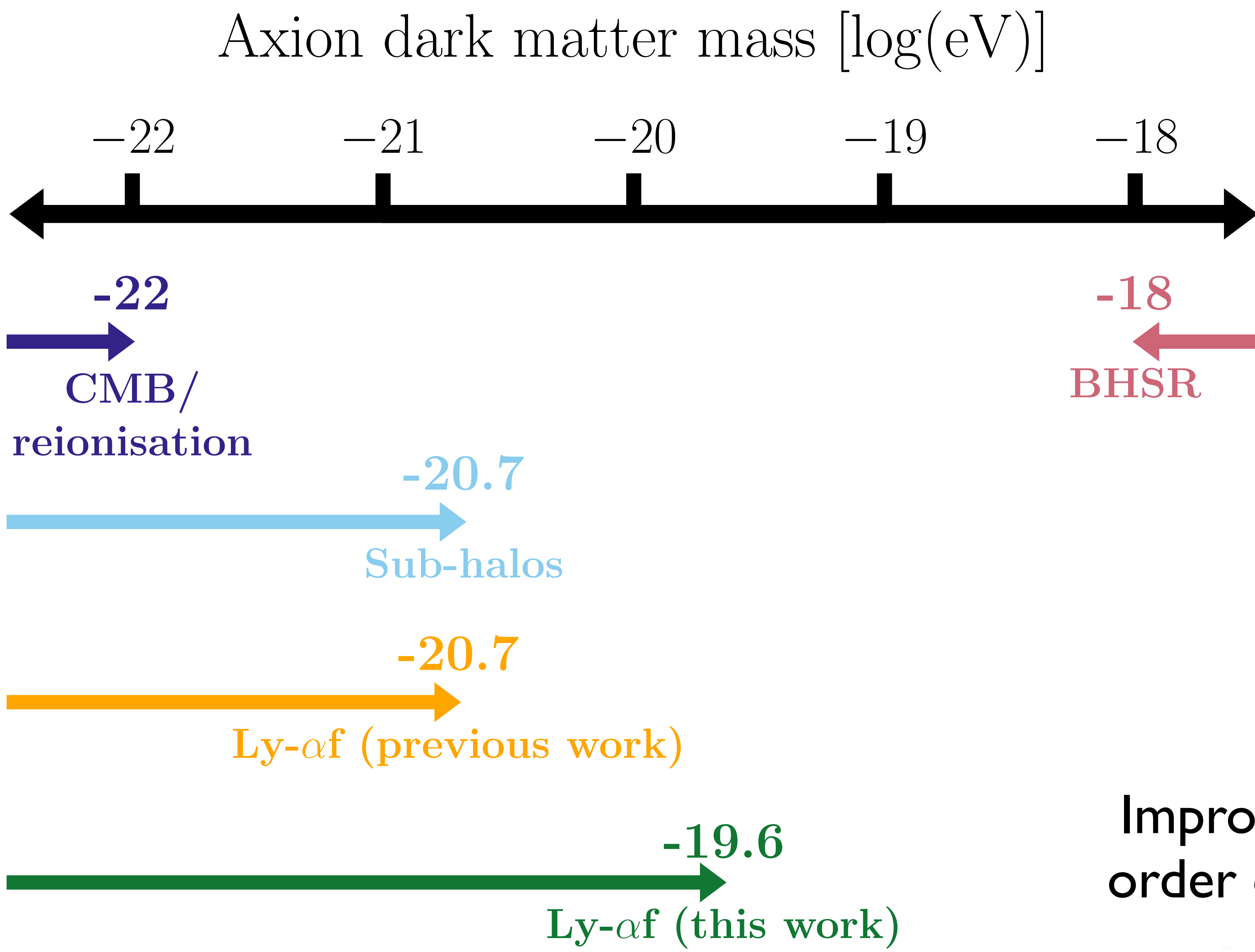
Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

Stockholm University

STRONG BOUND ON CANONICAL ULTRA-LIGHT AXION DARK MATTER

Phys. Rev. Lett., 126, 071302, 2021
with Peiris

"Canonical" 10^{-22} - 10^{-21} eV axion DM is ruled out



Improve bound by order of magnitude

$$m_a > 2 \times 10^{-20}\,\mathrm{eV}$$

UNIVERSITY OF TORONTO

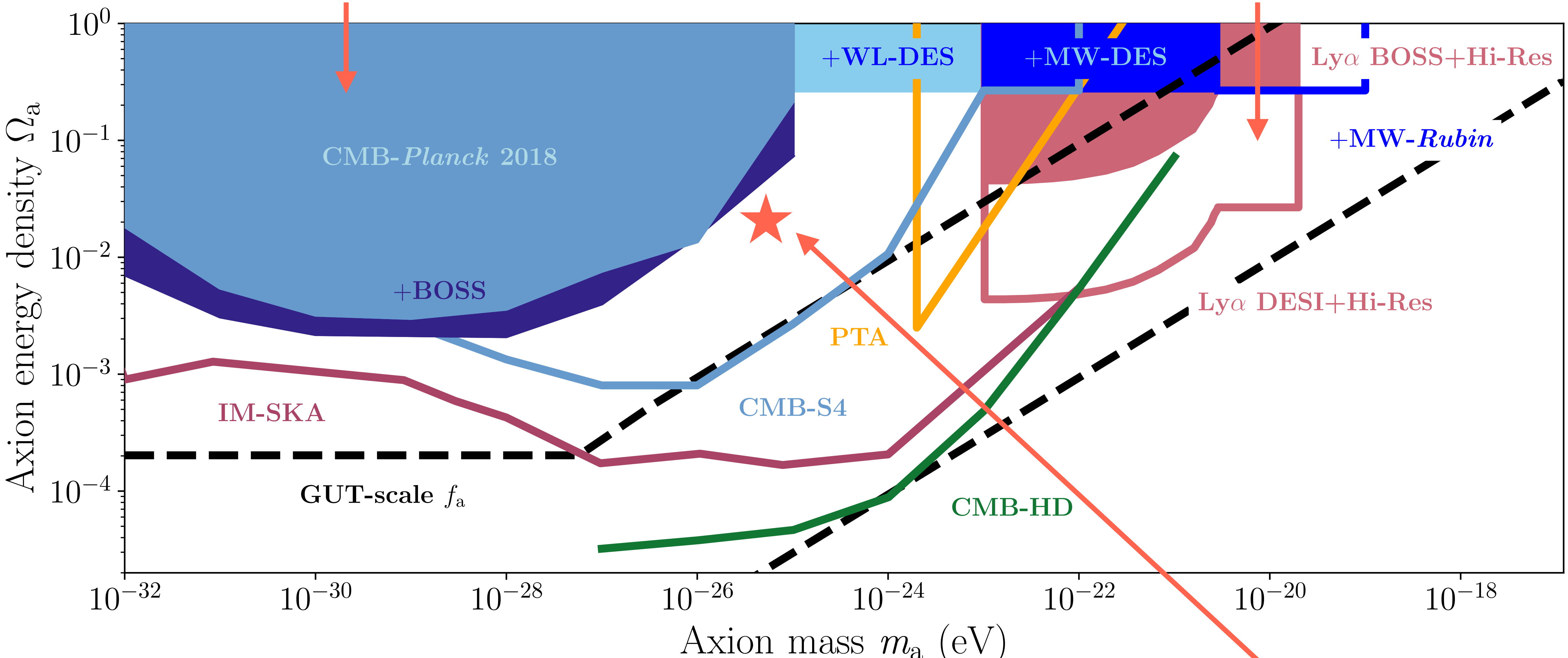
Stockholm University

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

Multi-probe approach to detect ultra-light axions

axionEmu
neural networks

Hydro sims
+ active learning



Resolve S_8 tension?

https://keirkwame.github.io/DM_limits

Summary

- **New frontier in dark matter detection** is light & ultra-light dark matter
- Rule out "small-scale crisis" axion; but axions could **resolve S_8 tension**
- Machine learning emulator approaches to **accelerate next-gen data analyses**