Title: Searching for the fundamental nature of dark matter in the cosmic large-scale structure

Speakers: Keir Rogers

Series: Cosmology & Gravitation

Date: April 17, 2023 - 11:00 AM

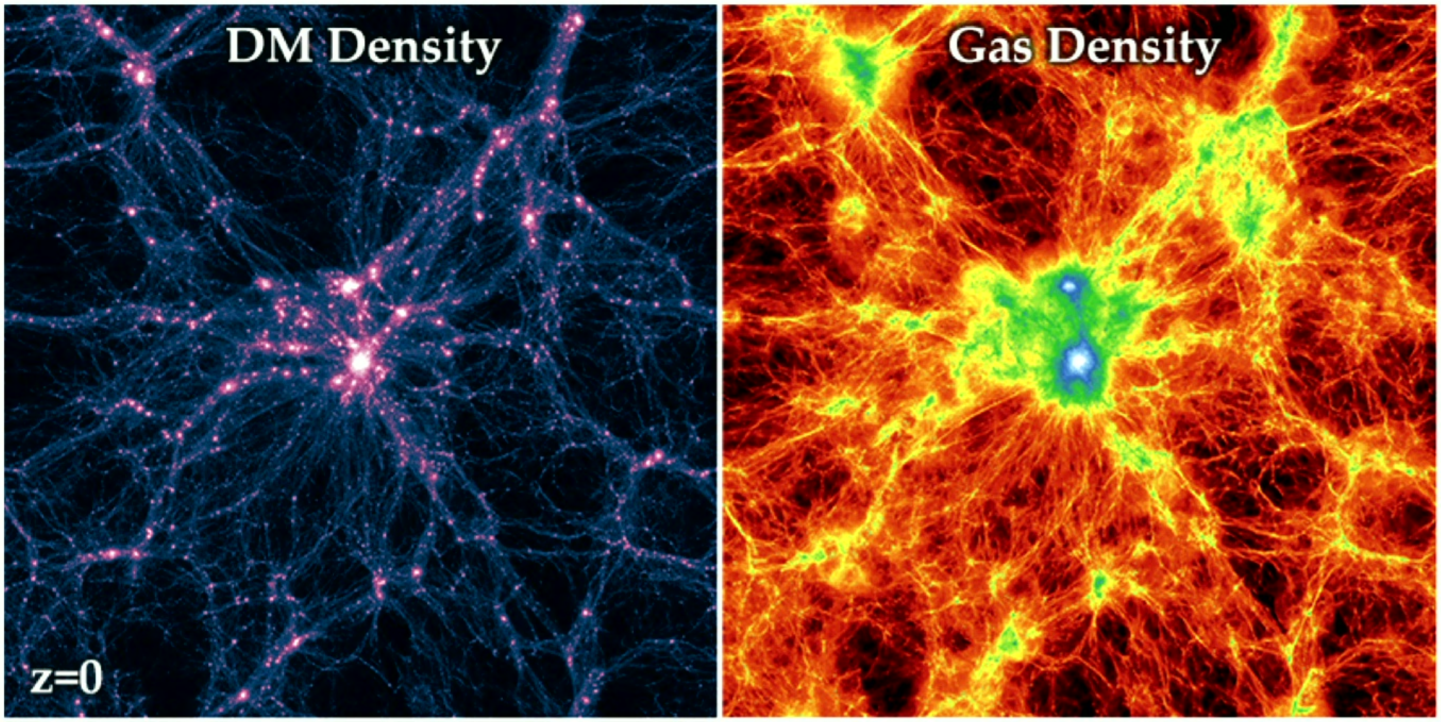
URL: https://pirsa.org/23040158

Abstract: The fundamental nature of dark matter (DM) so far eludes direct detection experiments, but it has left its imprint in the large-scale structure (LSS) of the Universe. I will present a search using cosmic microwave background (CMB) and galaxy surveys for ultra-light DM particle candidates called axions that are well motivated from high energy theory. In combining these datasets, I will discuss how the presence of axions can improve consistency between these probes and, in particular, help alleviate the S_8 cosmological parameter tension (the discrepancy in the amplitude of density fluctuations as inferred from CMB and galaxy data). I will then present complementary searches for ultra-light and light (sub-GeV) DM using a LSS probe called the Lyman-alpha forest. By combining complementary large- and small-scale structure probes, I will demonstrate how current and forthcoming cosmological data will systematically test the nature of DM. In order to model novel DM physics accurately and efficiently in CMB and LSS probes, I will present new machine learning approaches using neural network "emulators" to accelerate DM parameter inference from days to seconds and active learning to reduce massively the computational expense.

Zoom Link: TBD


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



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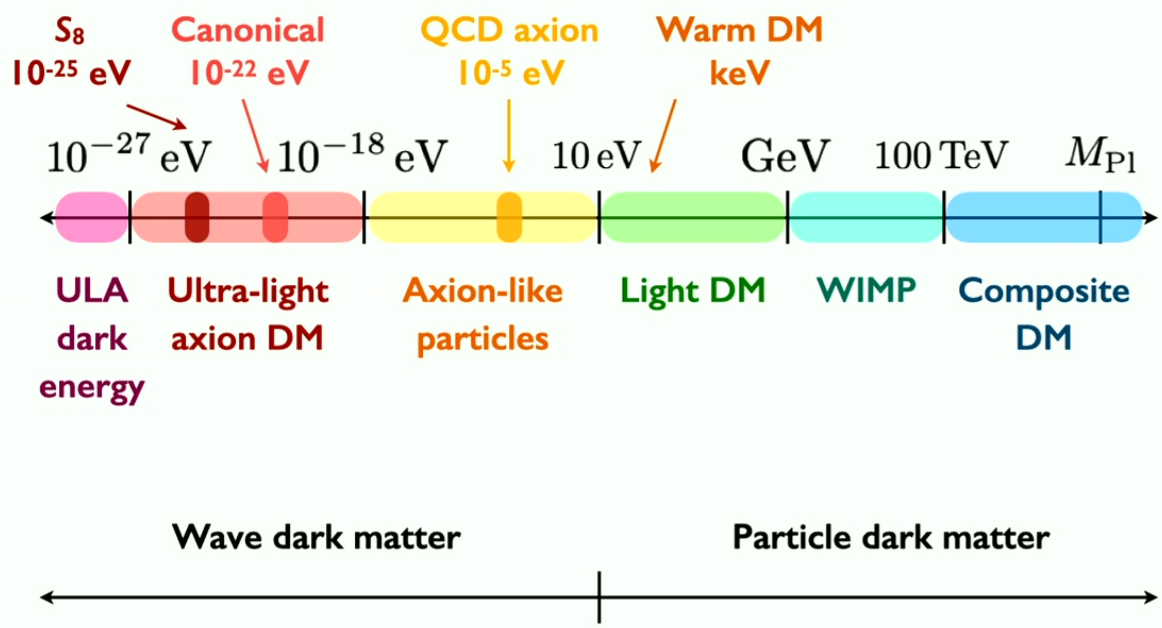
Illustris simulation

Beyond the WIMP: dark matter model space



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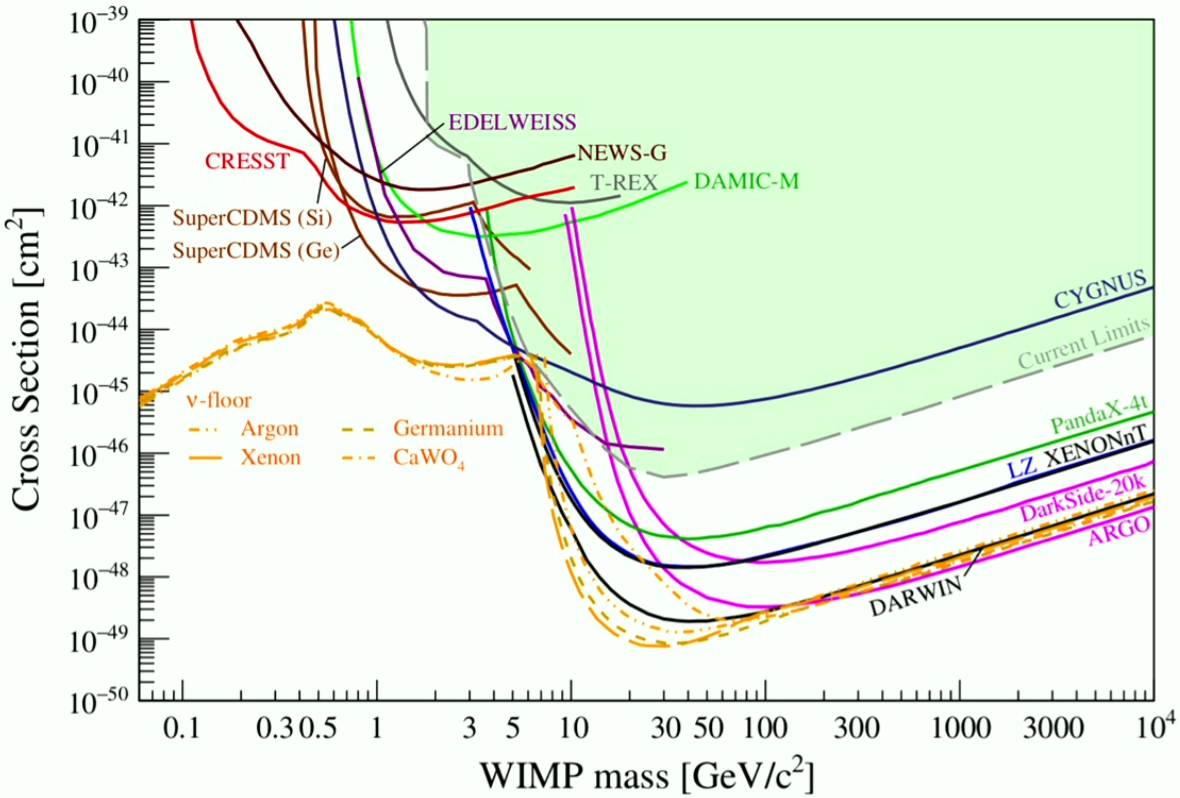
Not to scale

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



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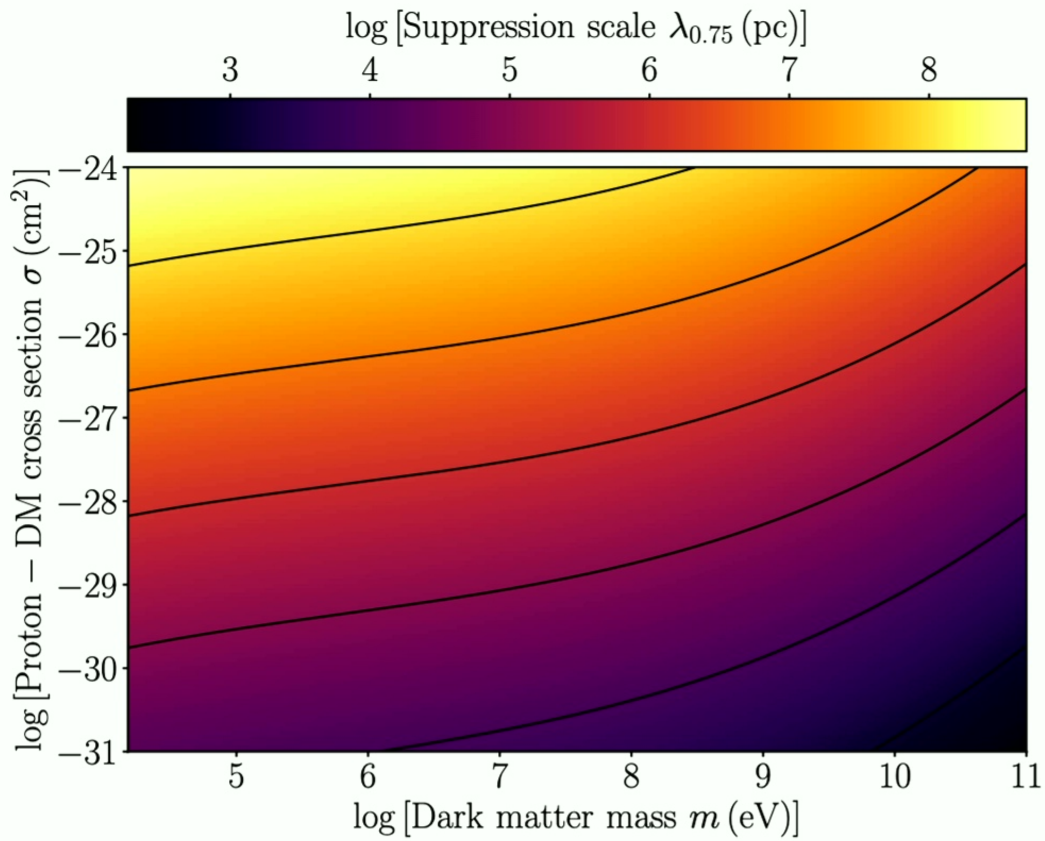
APPEC committee report (2021)

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)

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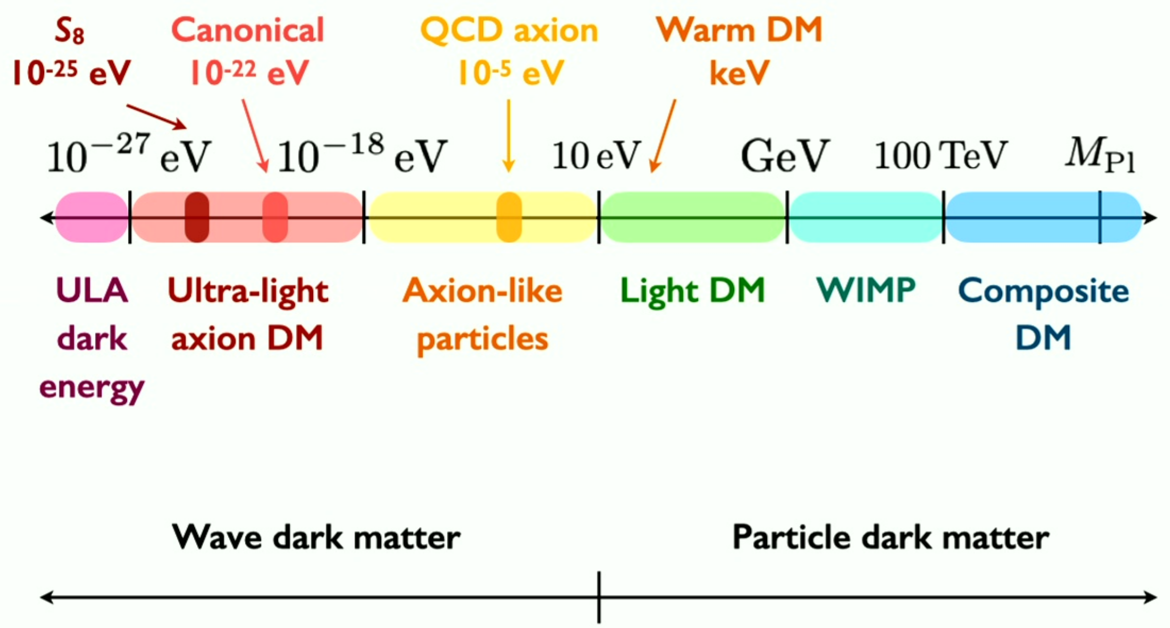
Beyond the WIMP: dark matter model space



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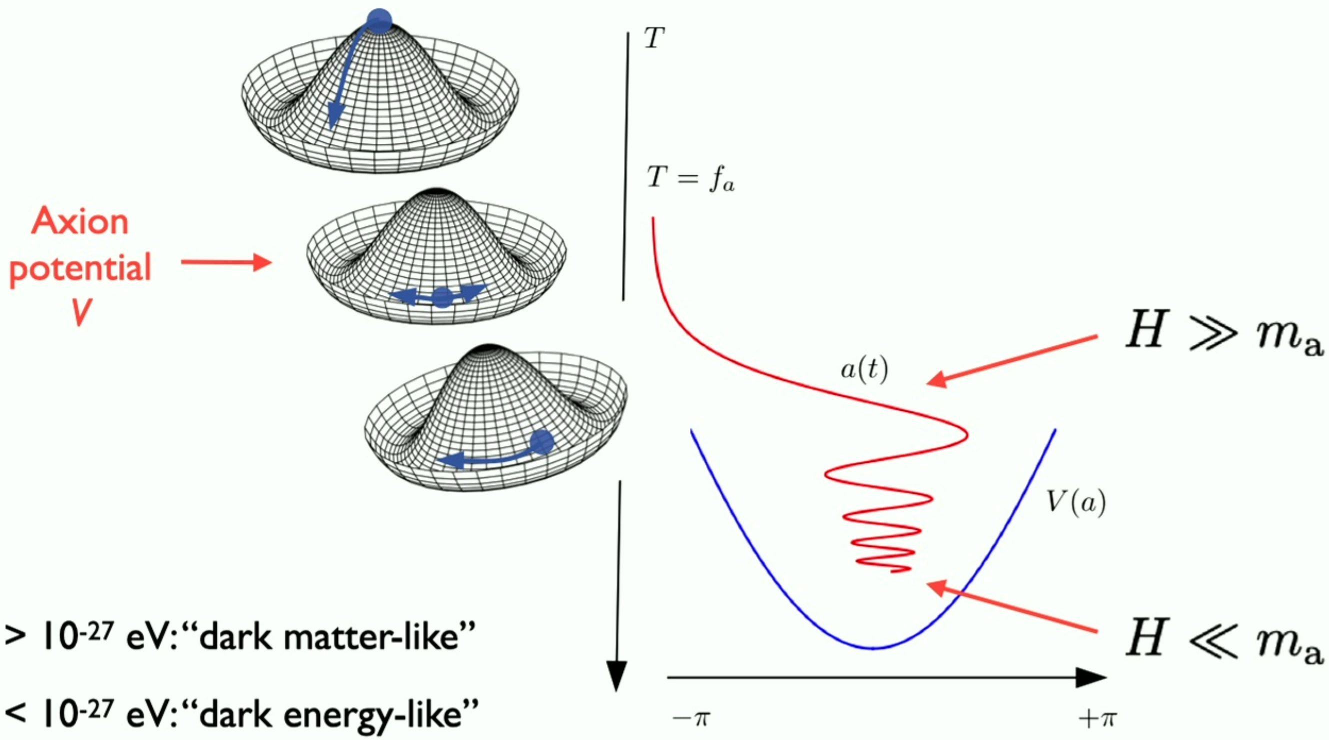
Not to scale

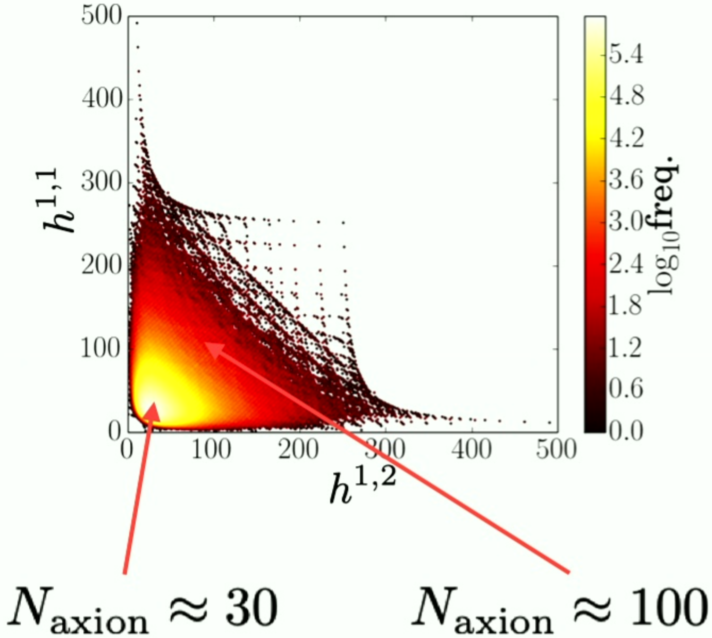
Axions are dark energy and dark matter candidates



- $m_a > 10^{-27}$ 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
- Axiverse of different mass axions from spacetime compactification
- One/more string axions can be DM

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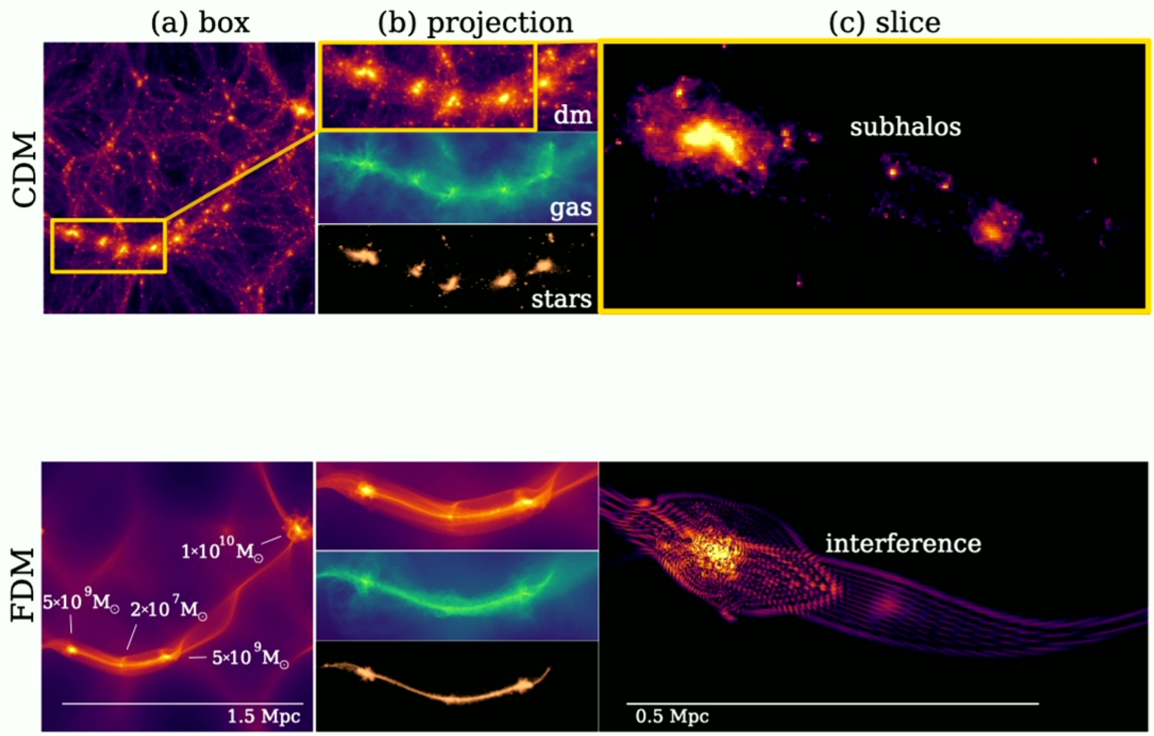
Figure credit: Marsh (2016)

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"

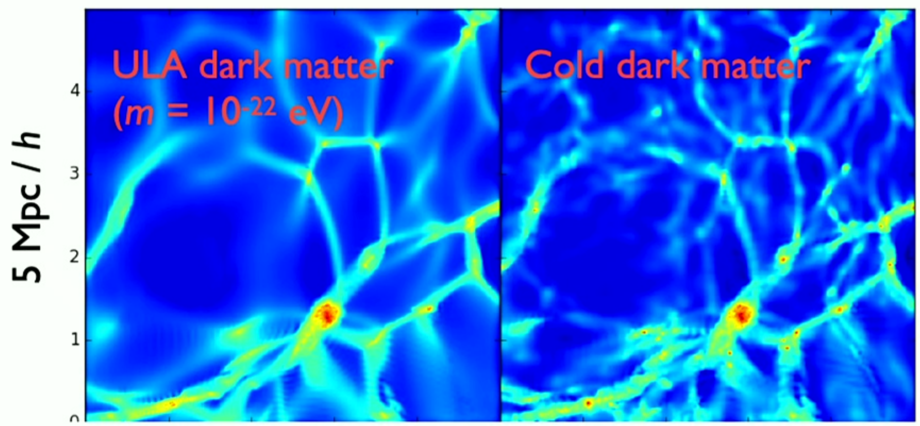
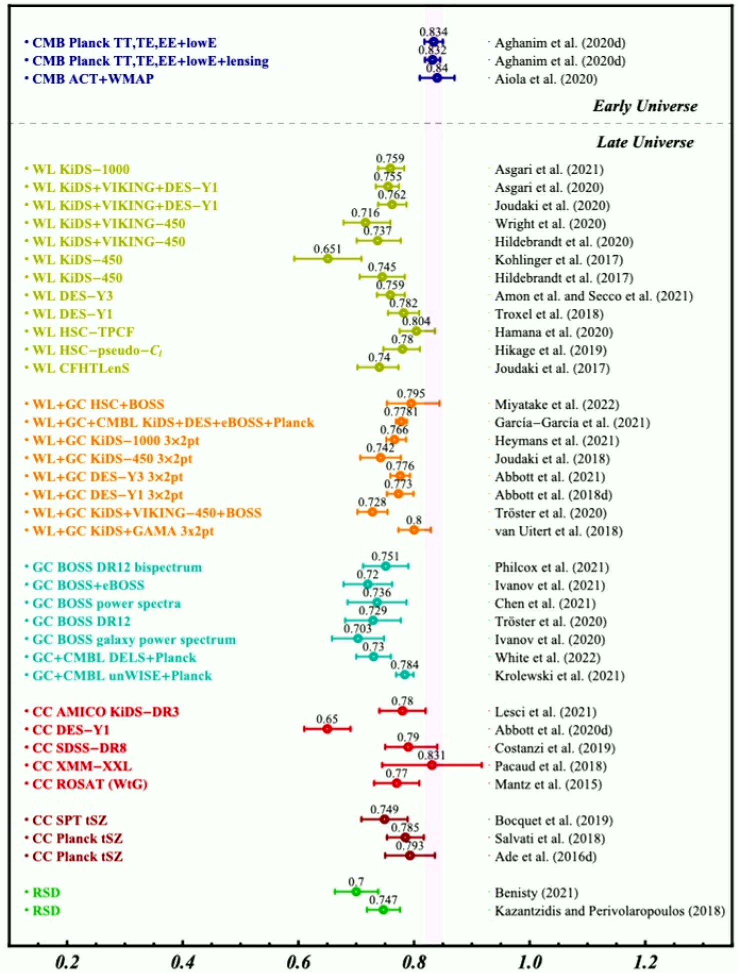


Figure credit: Armengaud et al. (2017); Hu et al. (2000)

Larger scales



S_8 tension

Smaller scales

S_8 ~ amplitude of density fluctuations at 8 Mpc/h

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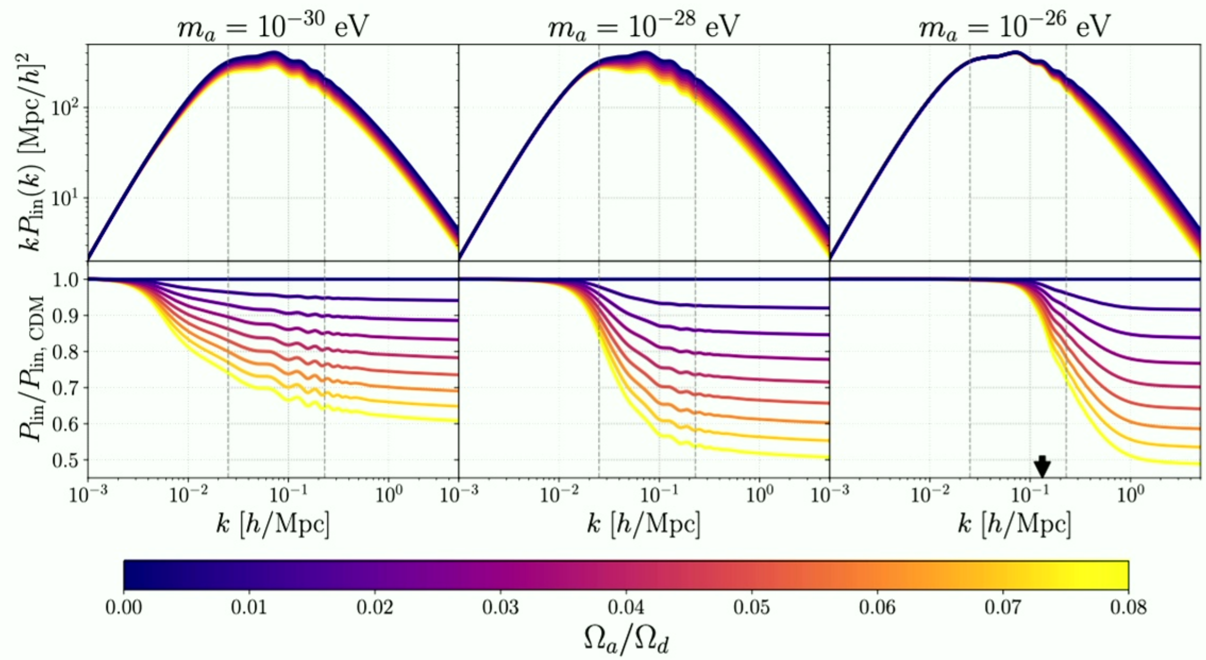
Abdalla et al. (Snowmass 2022)

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

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



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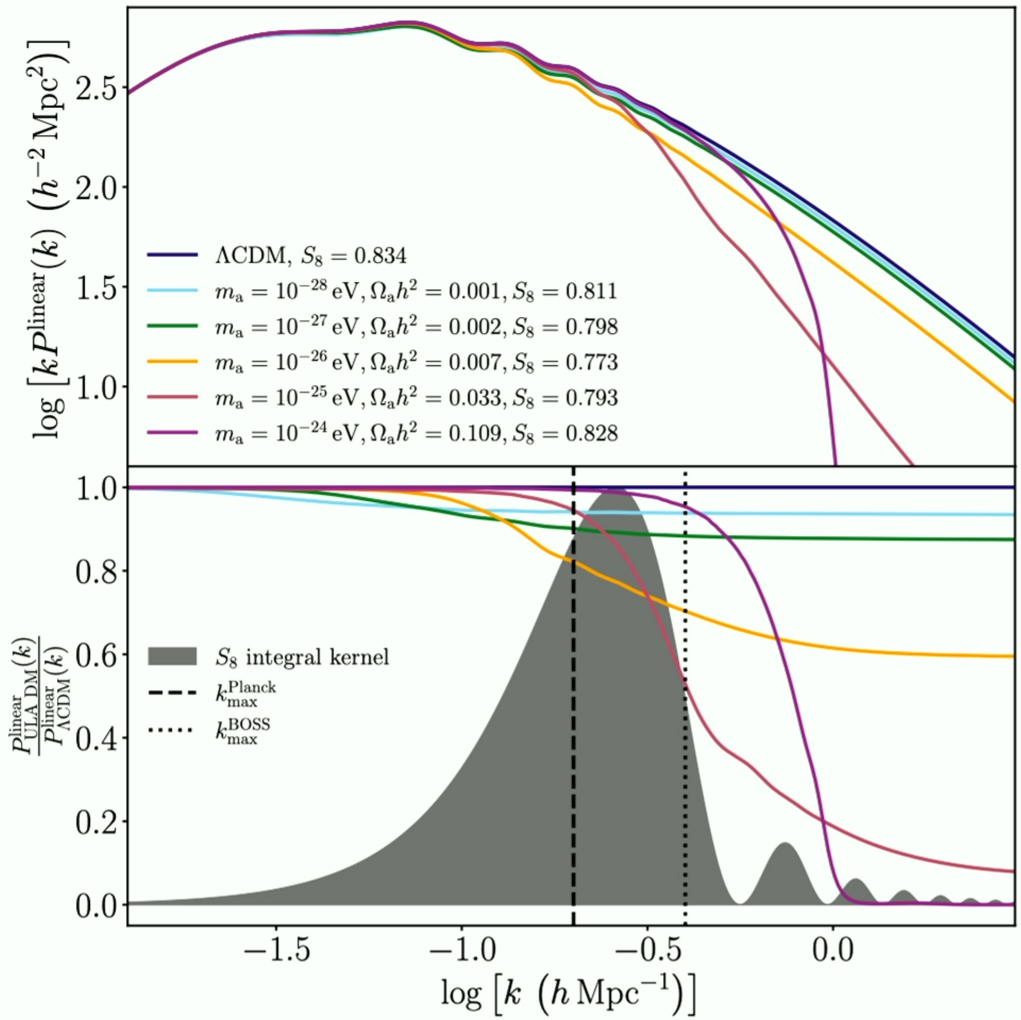
Laguë, Bond, Hložek, Rogers, Marsh, Grin (JCAP, 2022)



Axions lower S_8

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

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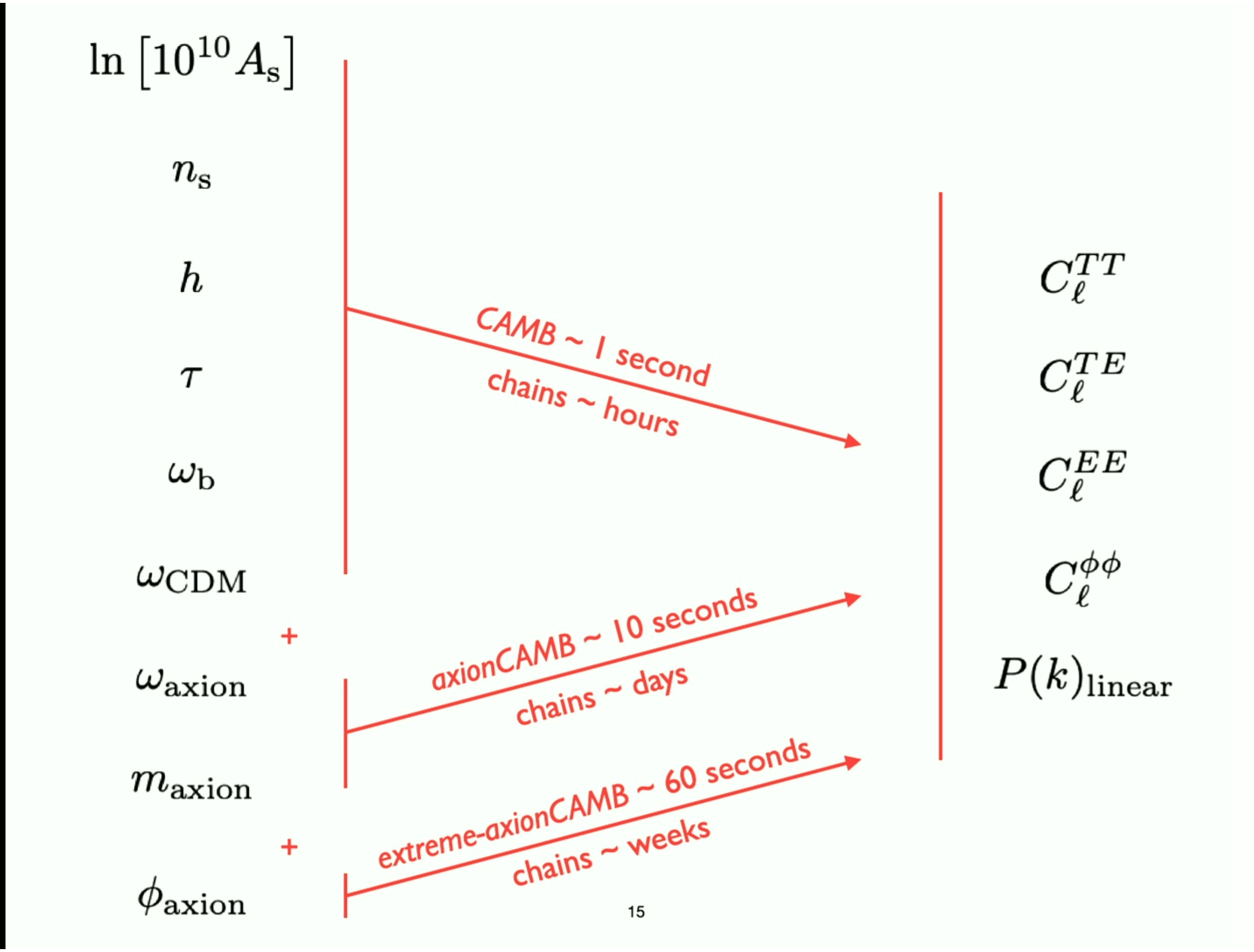
AXIONEMU:
NEURAL NETWORK EMULATOR OF AXION POWER SPECTRA

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}
$C_\ell^{\phi\phi}$
$P(k)_{linear}$
15

Anran Xu

$\ln\left[10^{10} A_s\right]$

n_s

h

τ

ω_b

ω_{CDM}

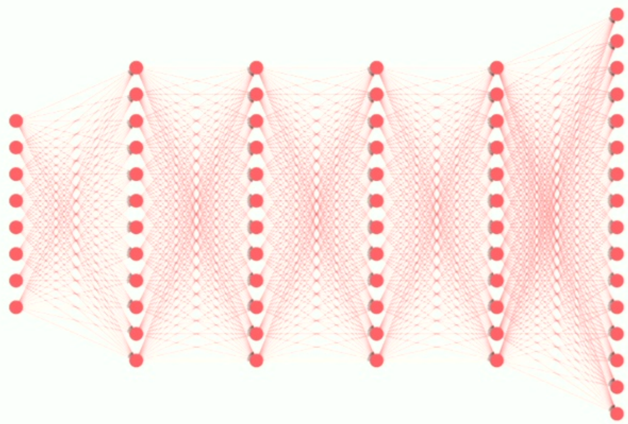
+

ω_{axion}

m_{axion}

+

ϕ_{axion}



axionEmu neural networks

~ 10^{-4} seconds

C_ℓ^{TT}

C_ℓ^{TE}

C_ℓ^{EE}

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

$P(k)_{linear}$

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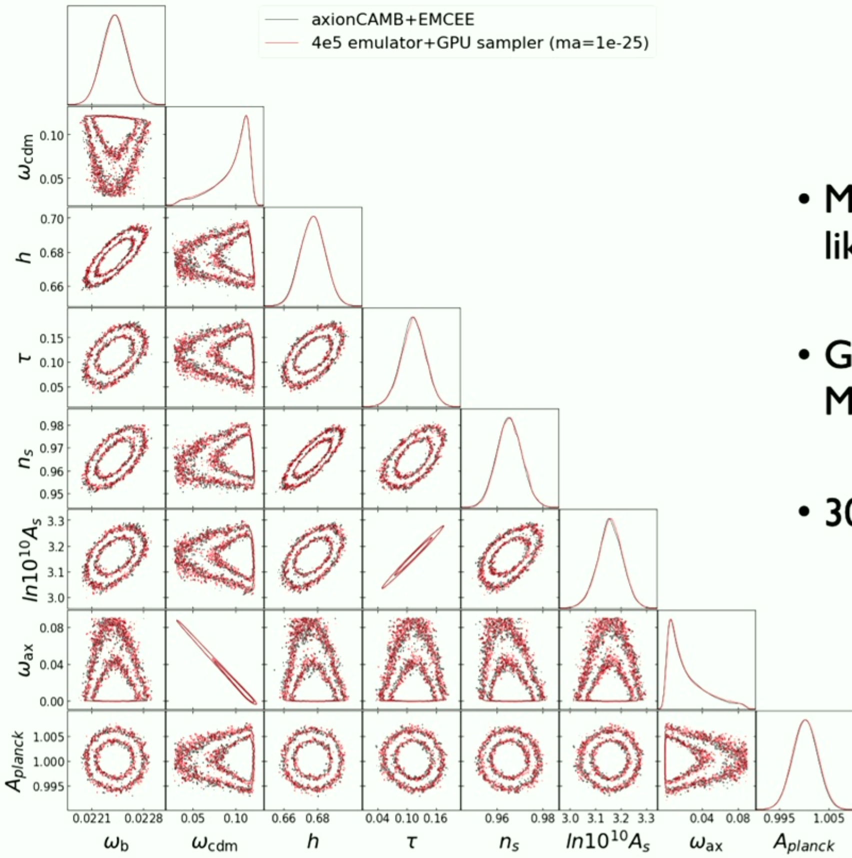
CosmoPower: Mancini+ (2022); *axionEmu*: Xu & Rogers (2023)

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

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Anran Xu & Keir Rogers (in prep, 2023)

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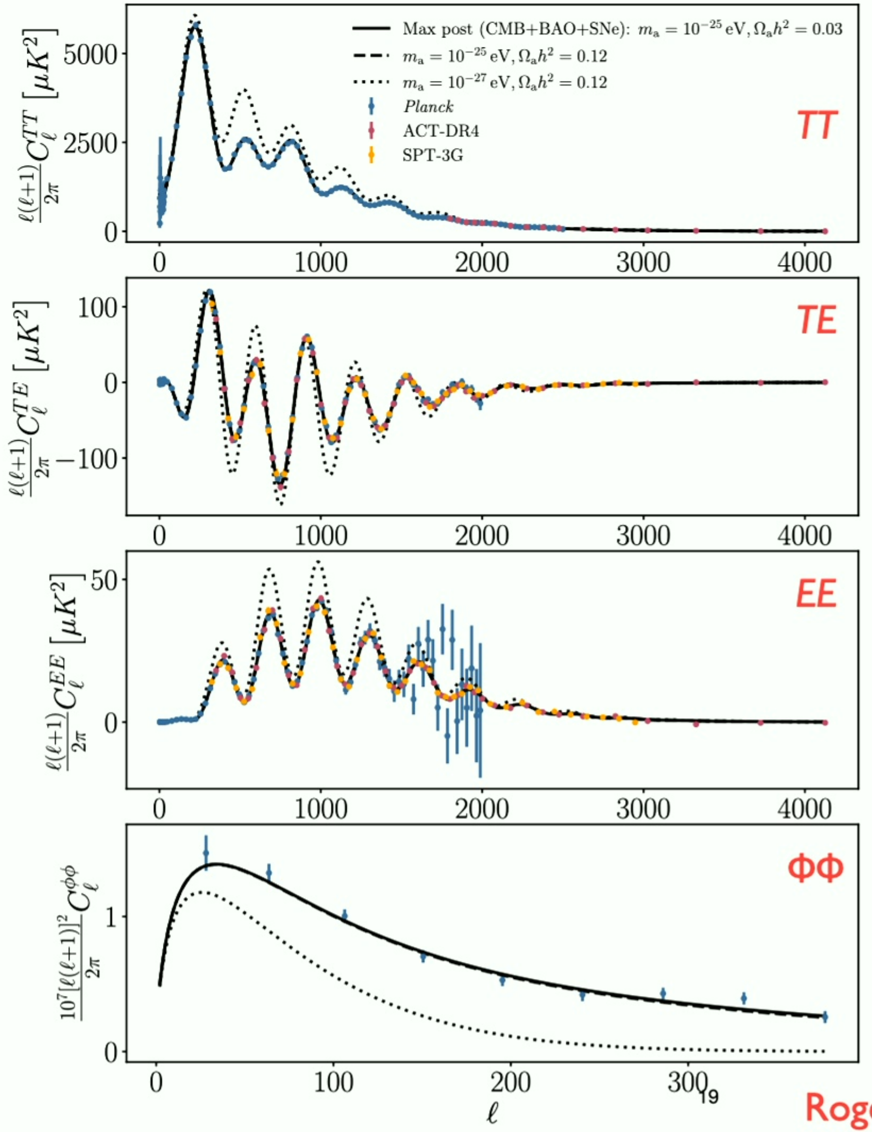
JOINT CONSTRAINTS ON ULTRA-LIGHT AXIONS FROM CMB & GALAXY SURVEYS

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



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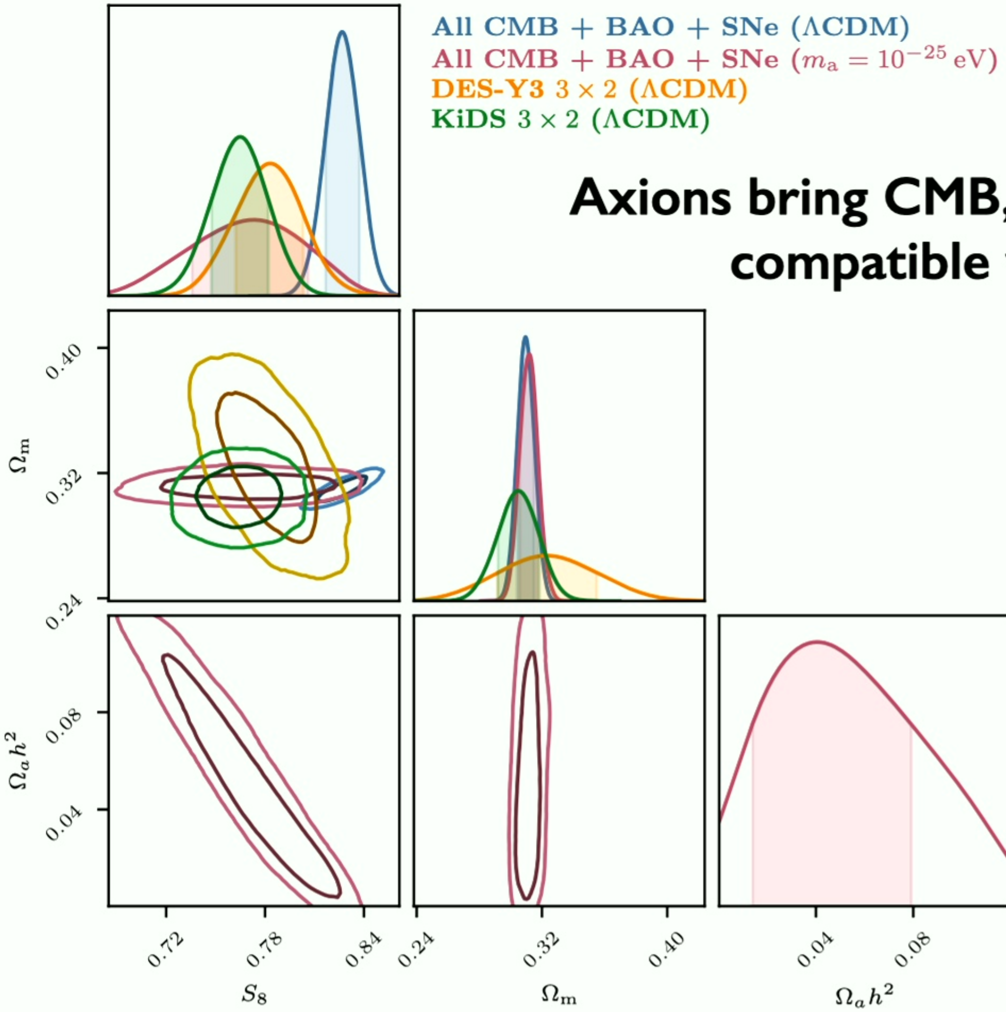
DE-like axions constrained by CMB acoustic oscillations & lensing potential

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

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



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

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

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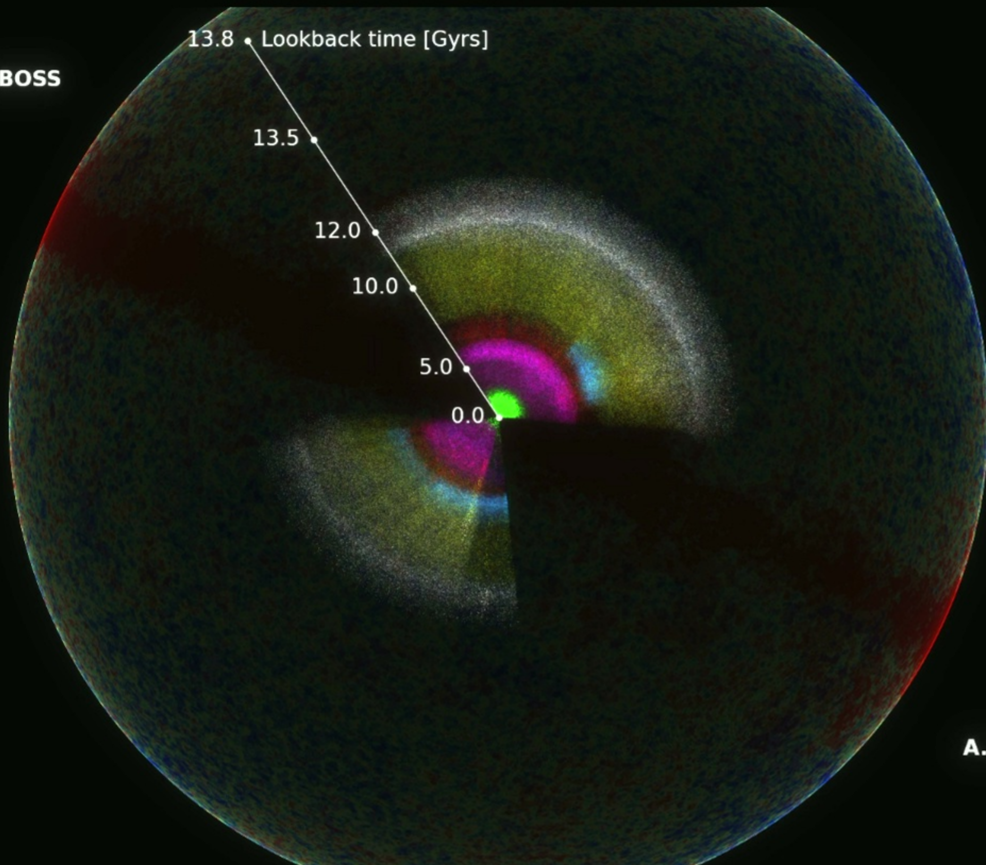
Rogers, Hložek, et al. (arXiv:2301.08361)

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

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

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

+ Infrared resummation
+ Alcock-Paczynski distortion

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

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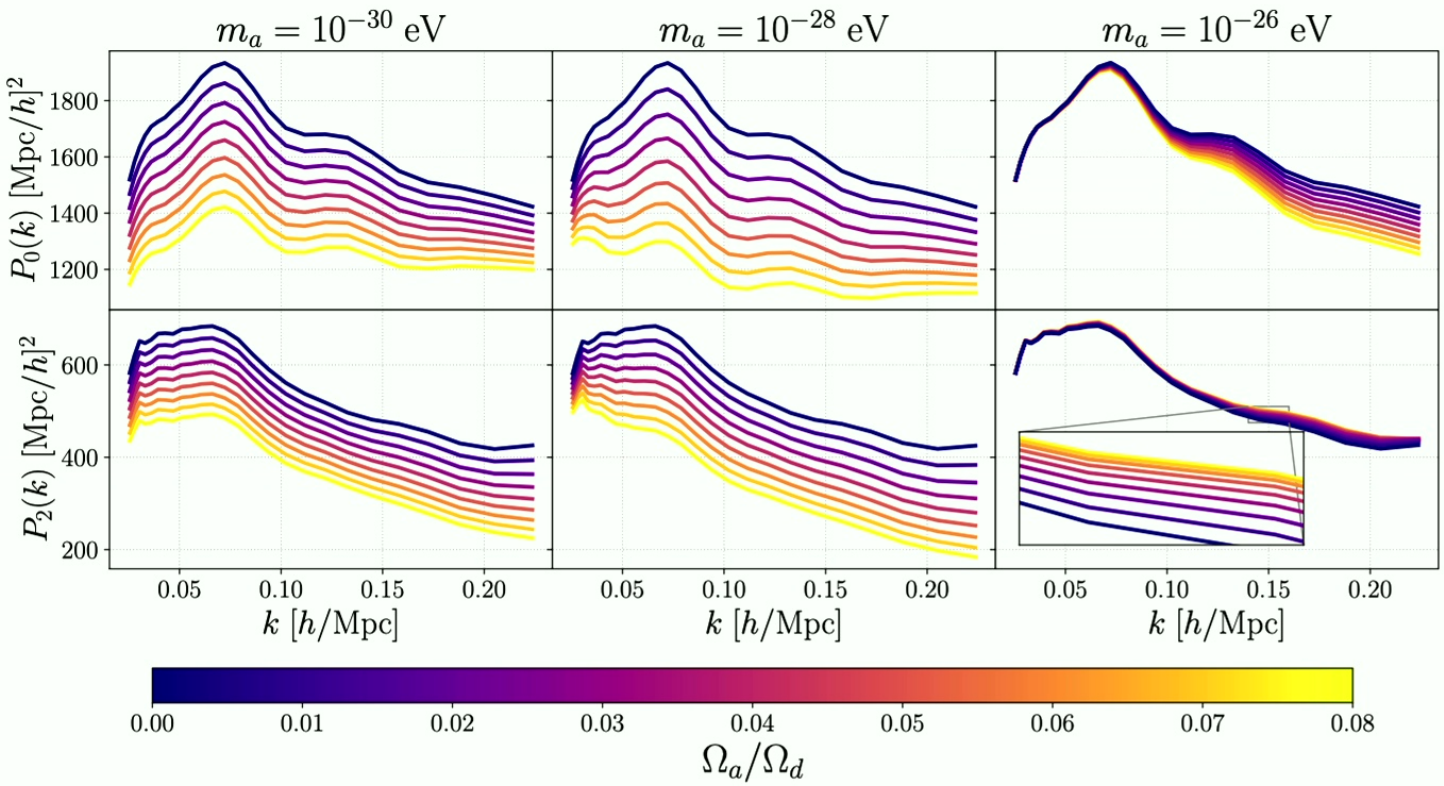
Galaxy clustering traces dark matter clustering — revealing signature of ultra-light axions



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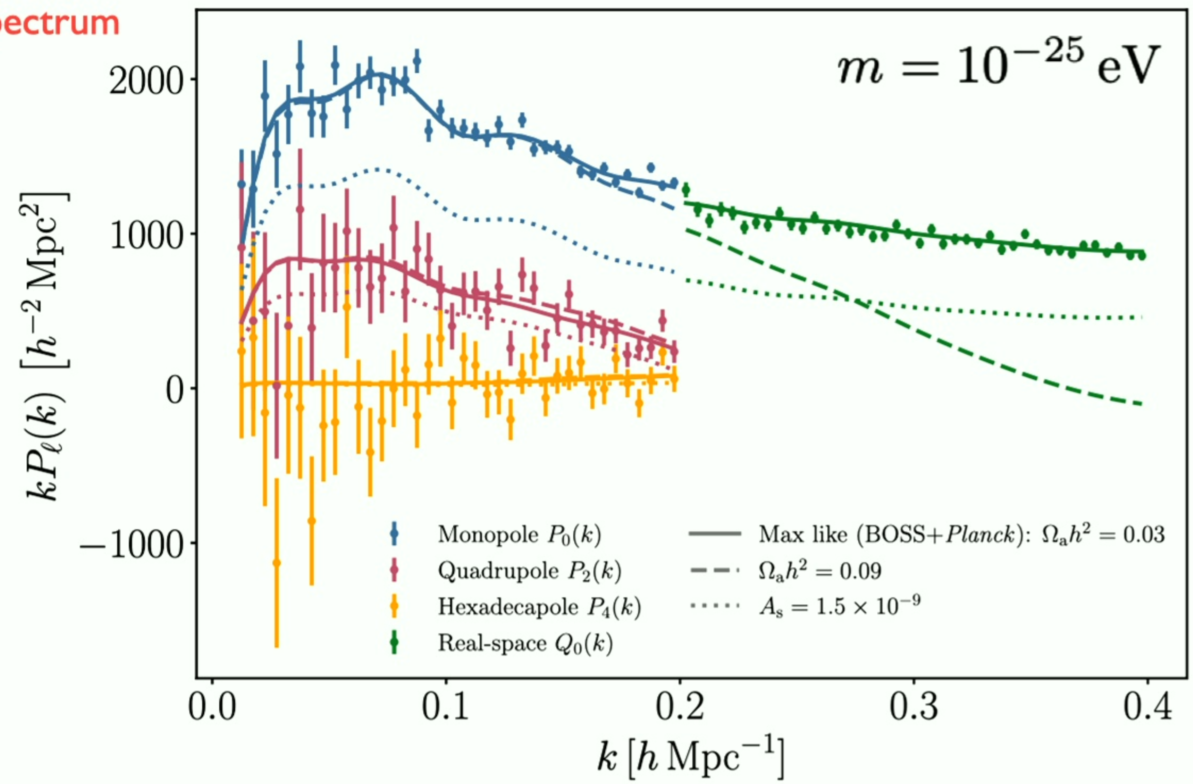
Laguë, Bond, Hložek, Rogers, Marsh, Grin (JCAP, 2022)

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

Power spectrum



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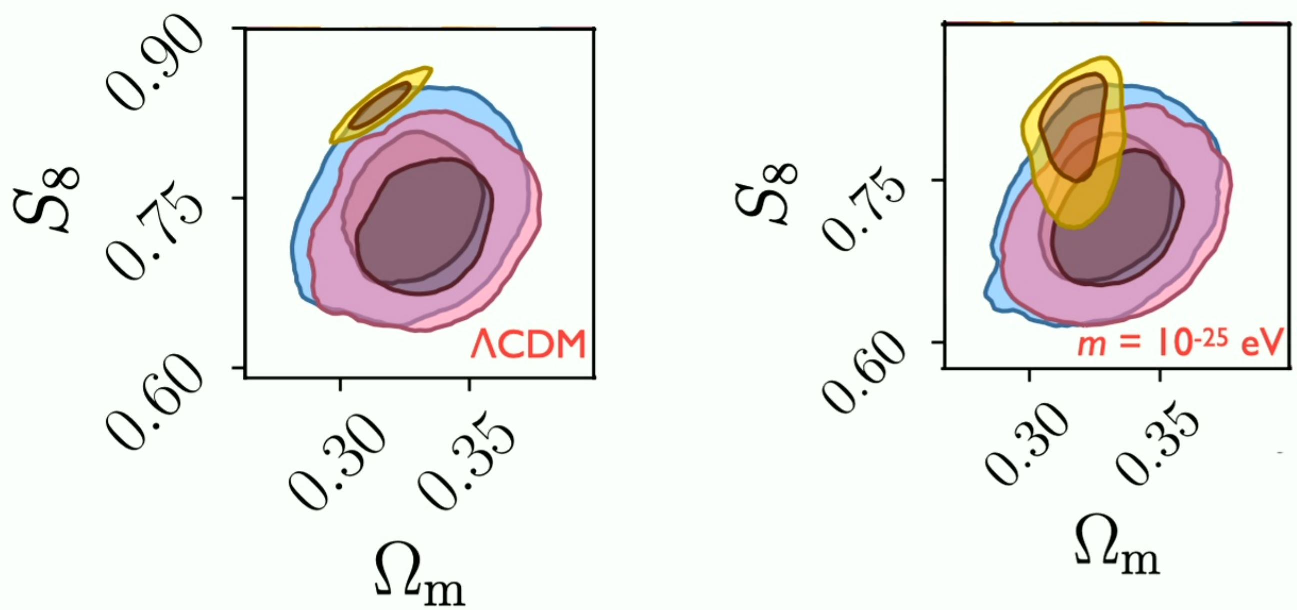
Rogers, Hložek, et al. (arXiv:2301.08361)

Axions improve consistency between *Planck* and BOSS



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

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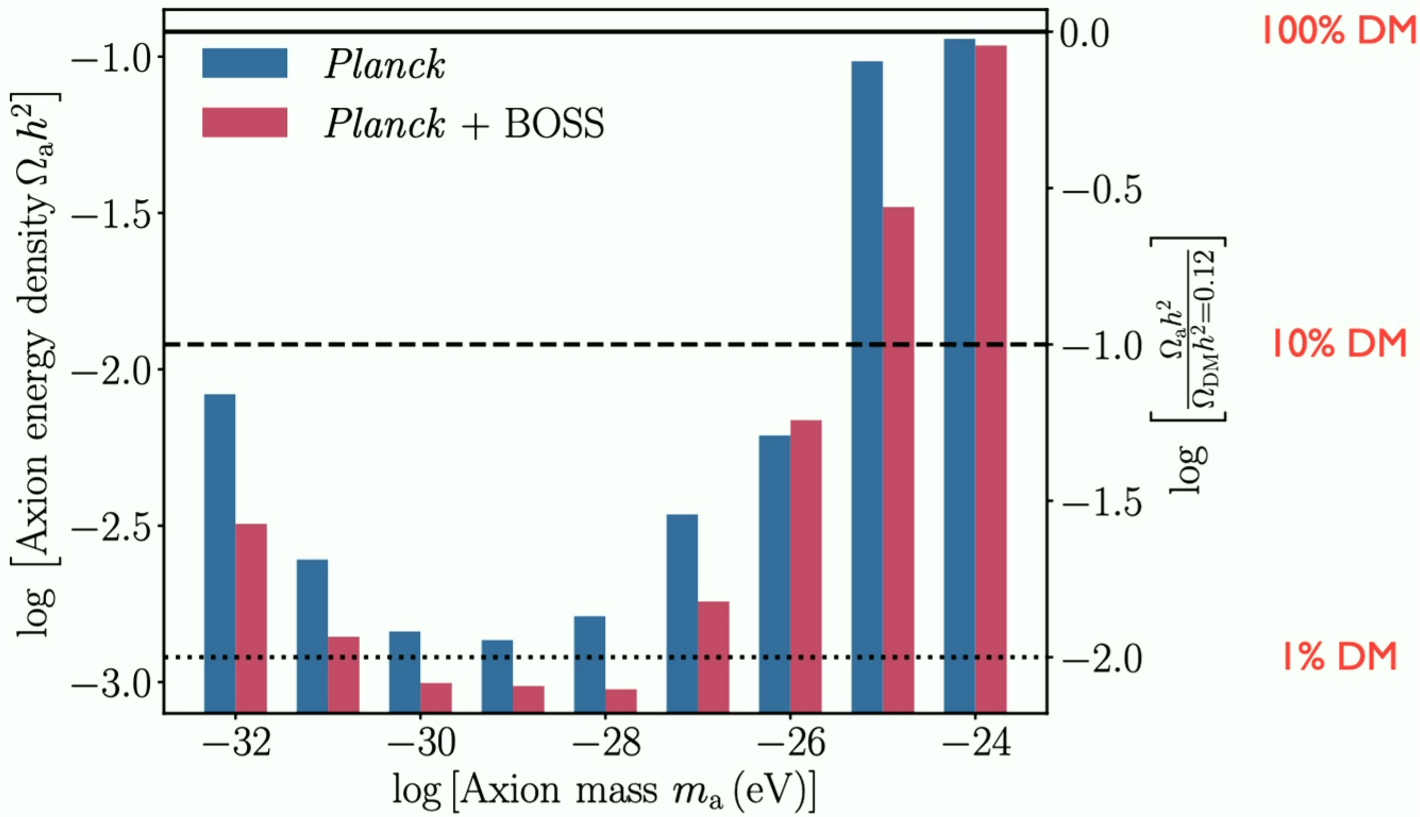
Rogers, Hložek, et al. (arXiv:2301.08361)

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



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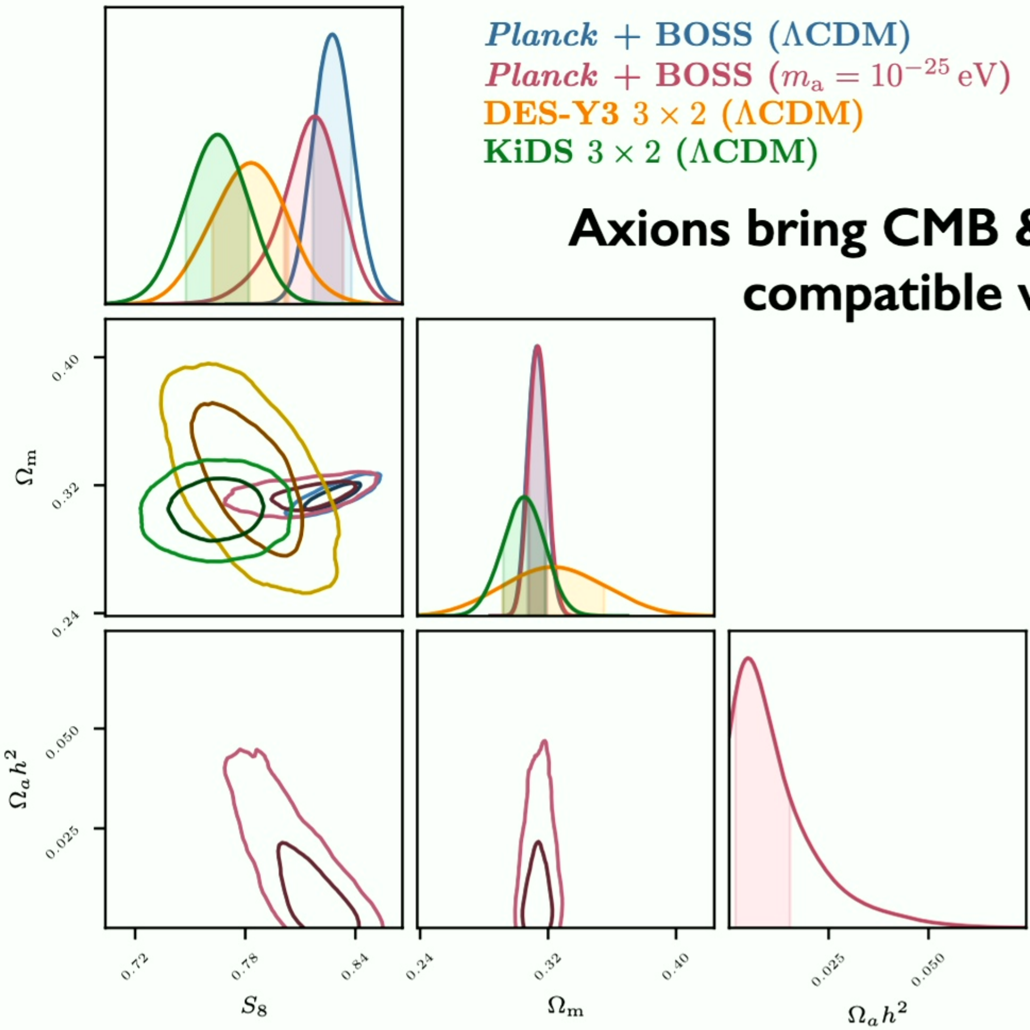
Rogers, Hložek, et al. (arXiv:2301.08361)



Axions bring CMB & galaxy clustering compatible with low S_8

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

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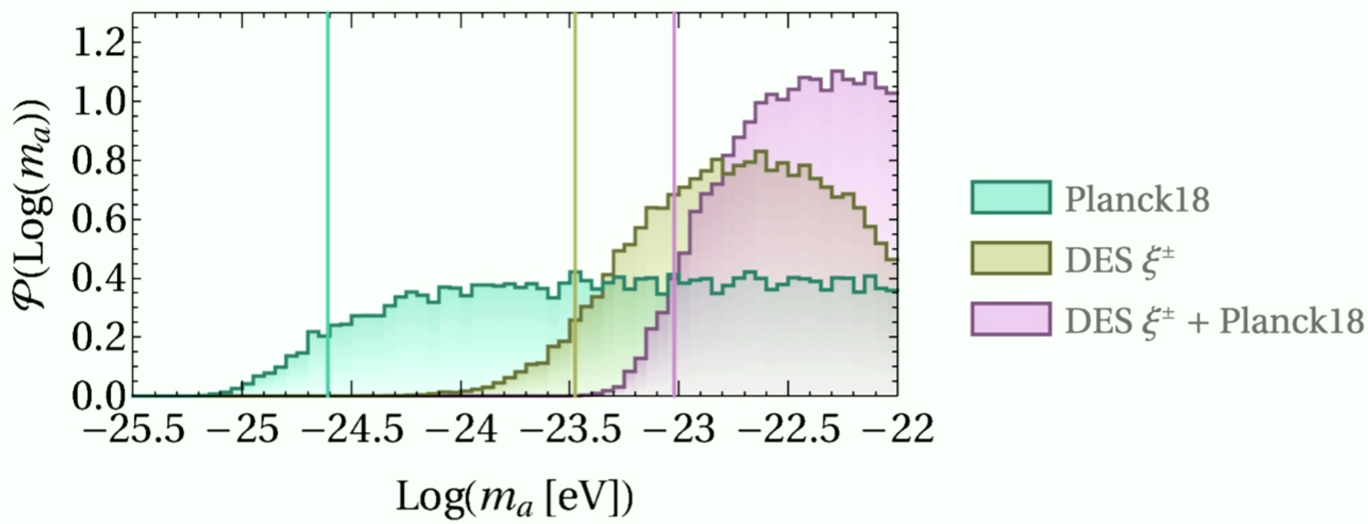
Rogers, Hložek, et al. (arXiv:2301.08361)

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



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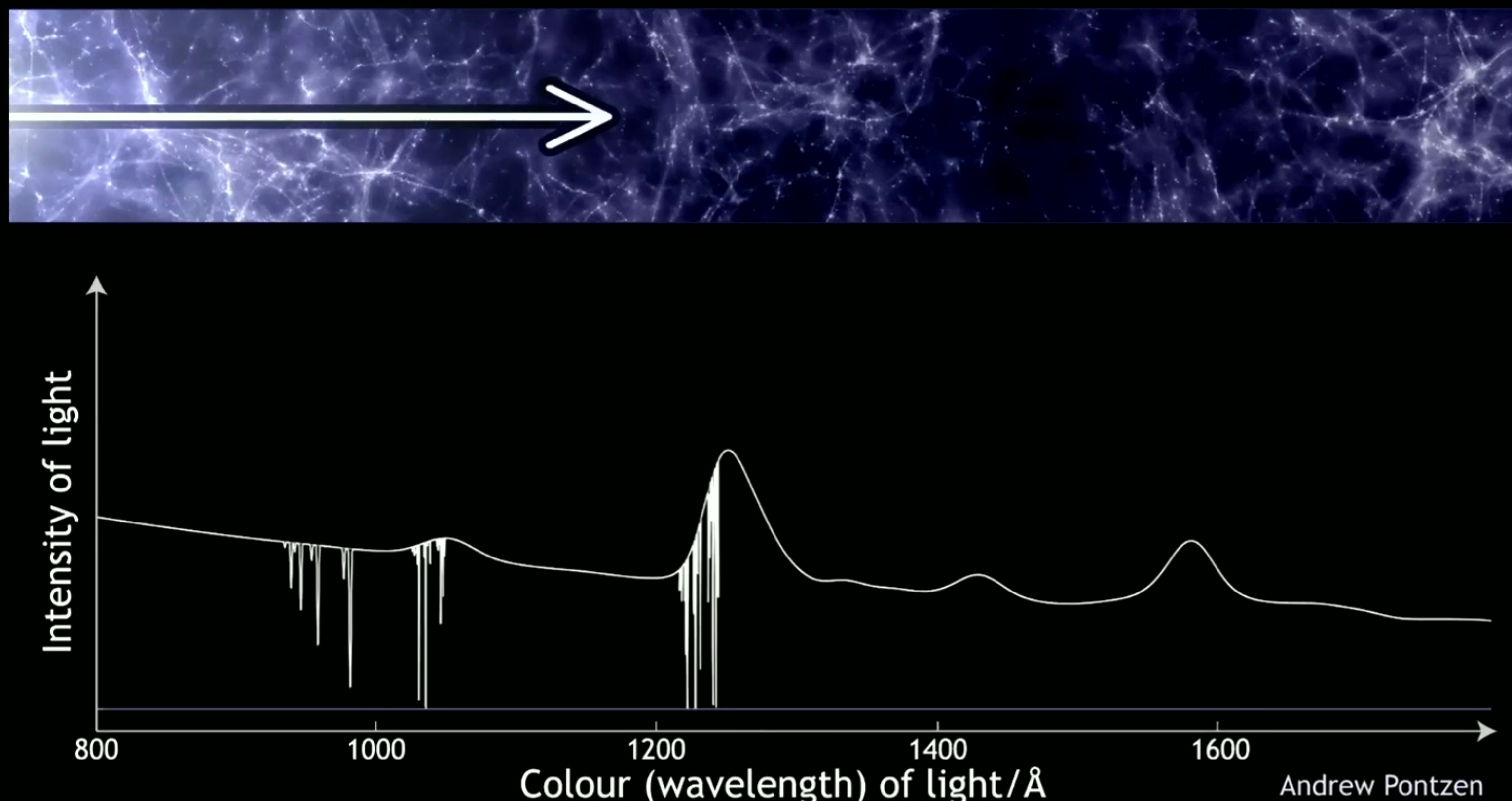
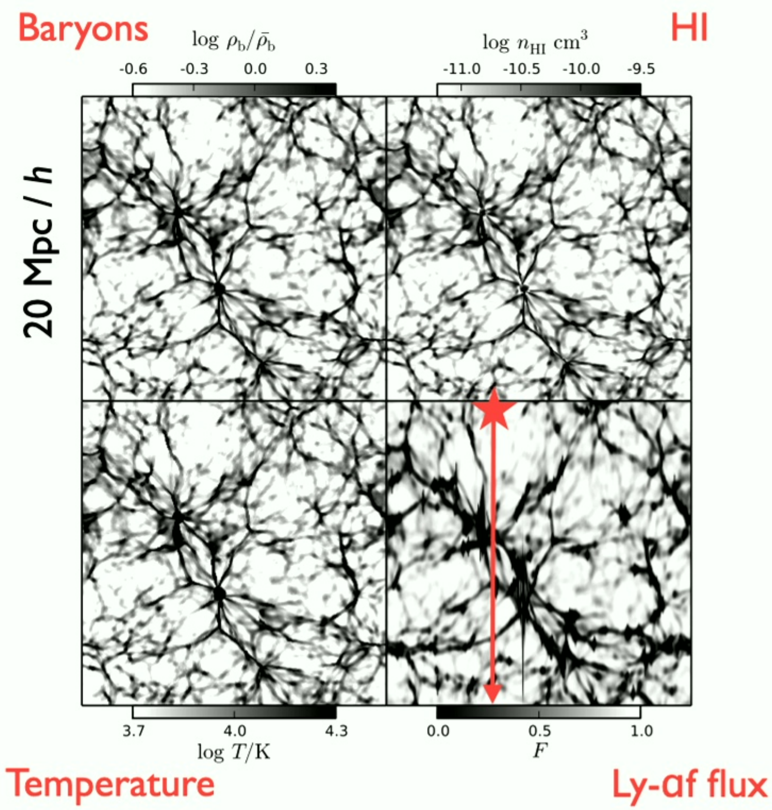
Dentler, Marsh, Hložek, Laguë, Rogers, Grin (MNRAS, 2022)

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

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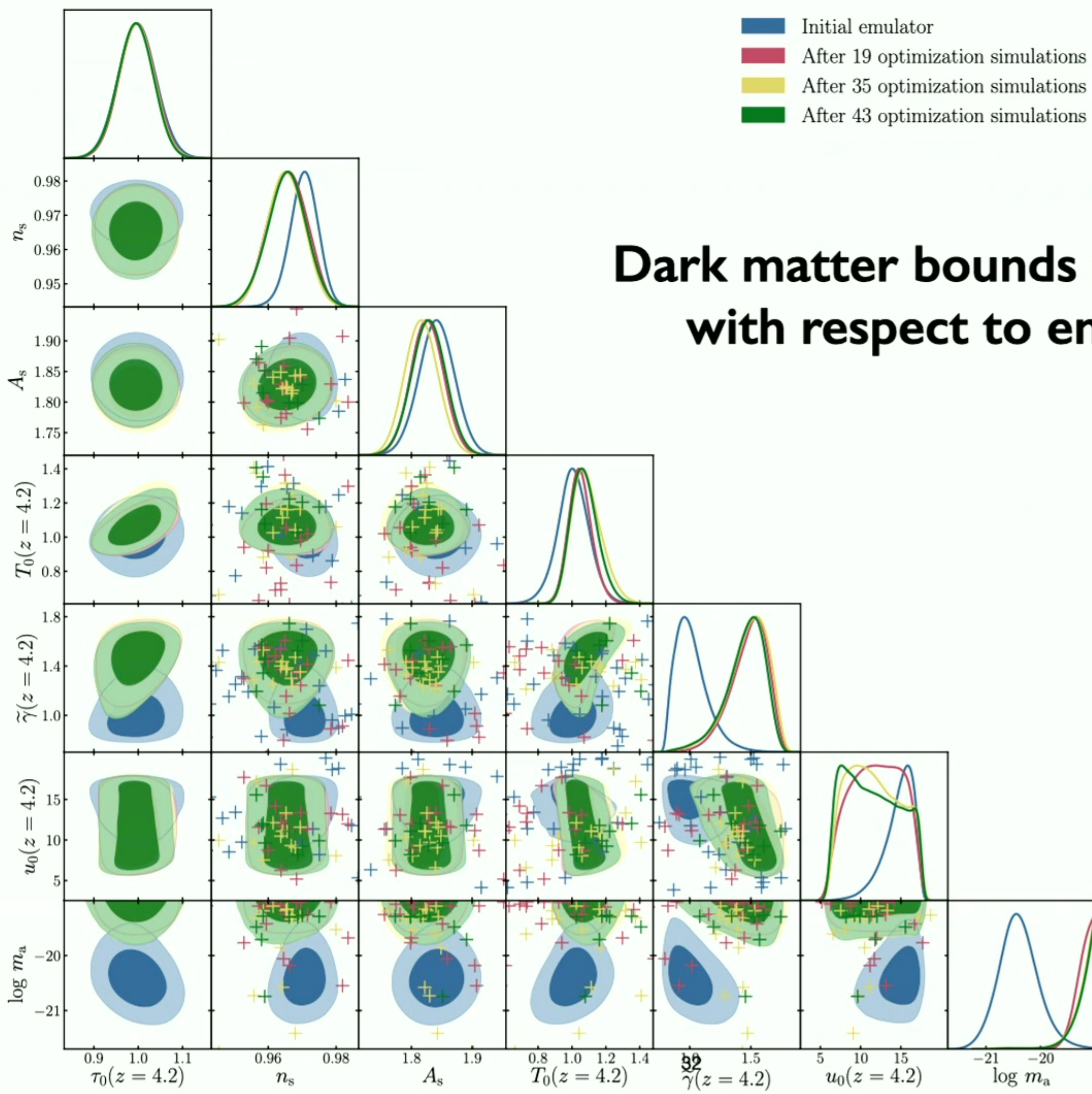
Lukić et al. (2015); Rogers et al. (JCAP, 2019); Rogers & Peiris (Phys. Rev. D, 2021)

Dark matter bounds converged with respect to emulator



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

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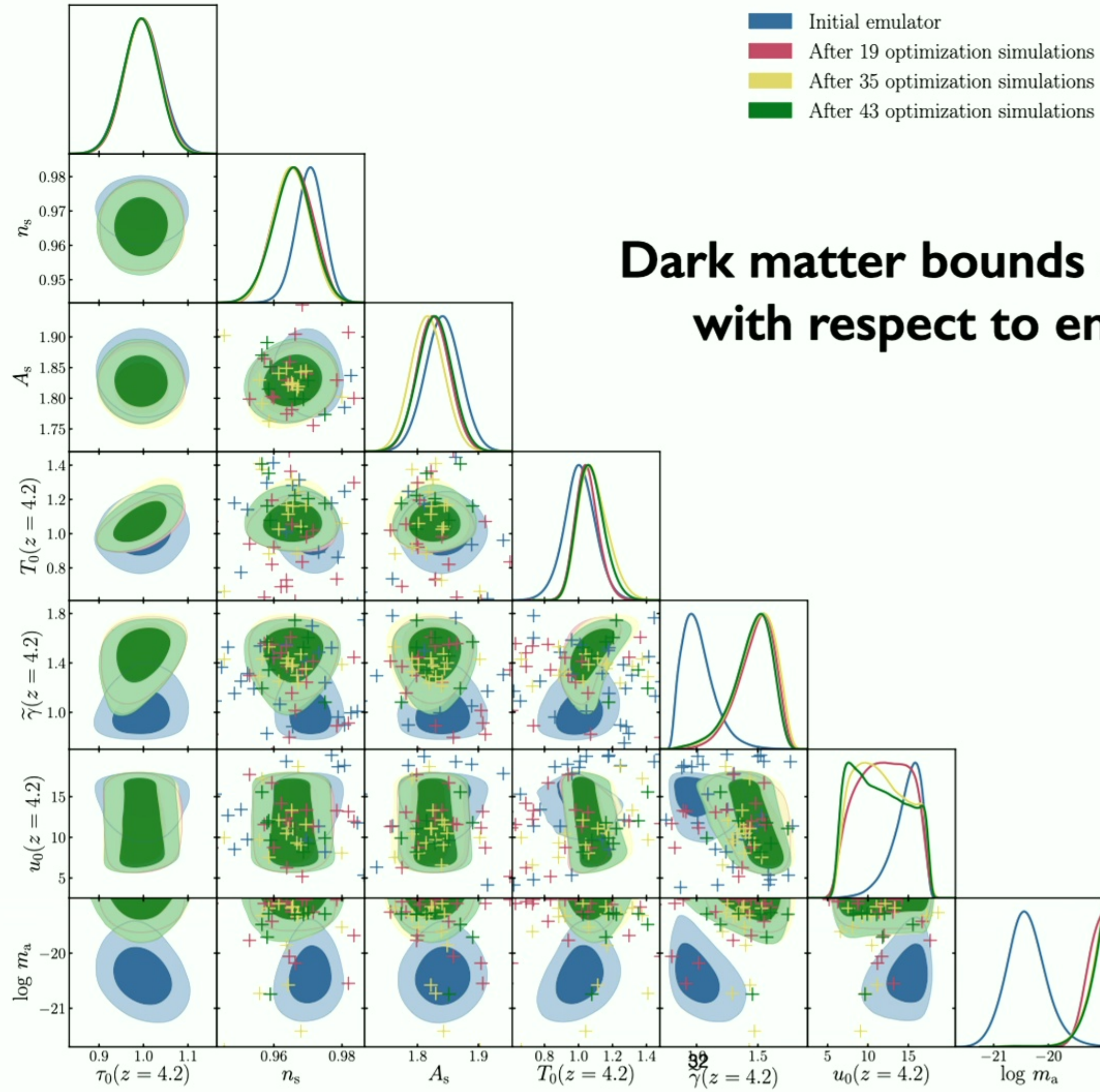
DARK MATTER EMULATOR WITH ACTIVE LEARNING

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)

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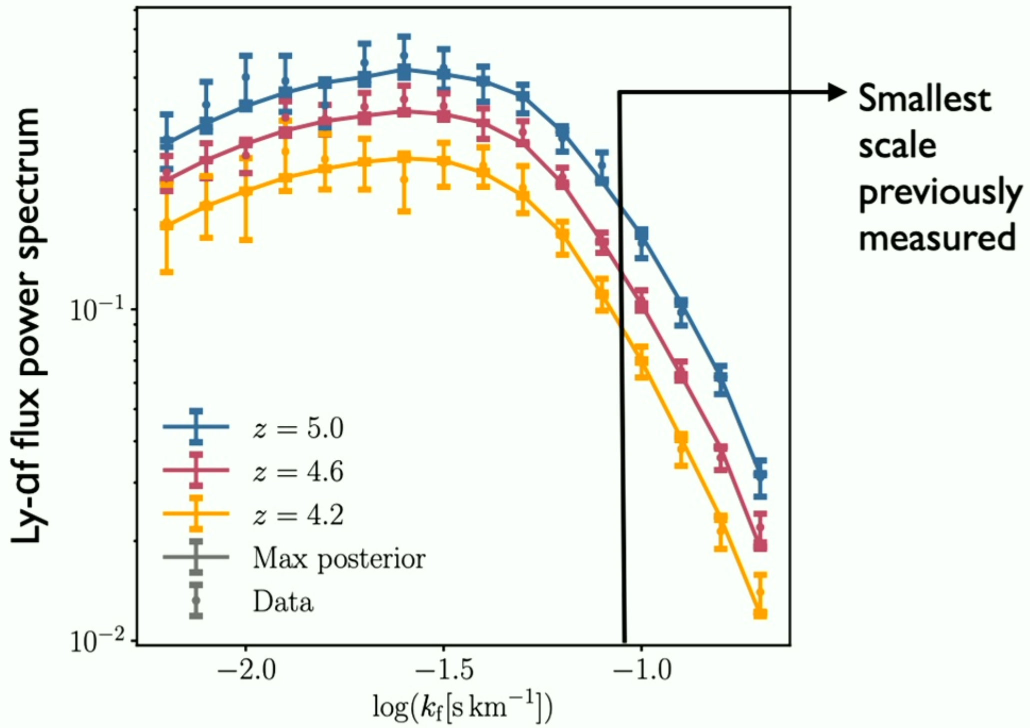
NEW LIMITS ON
DARK MATTER — PROTON INTERACTION

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)

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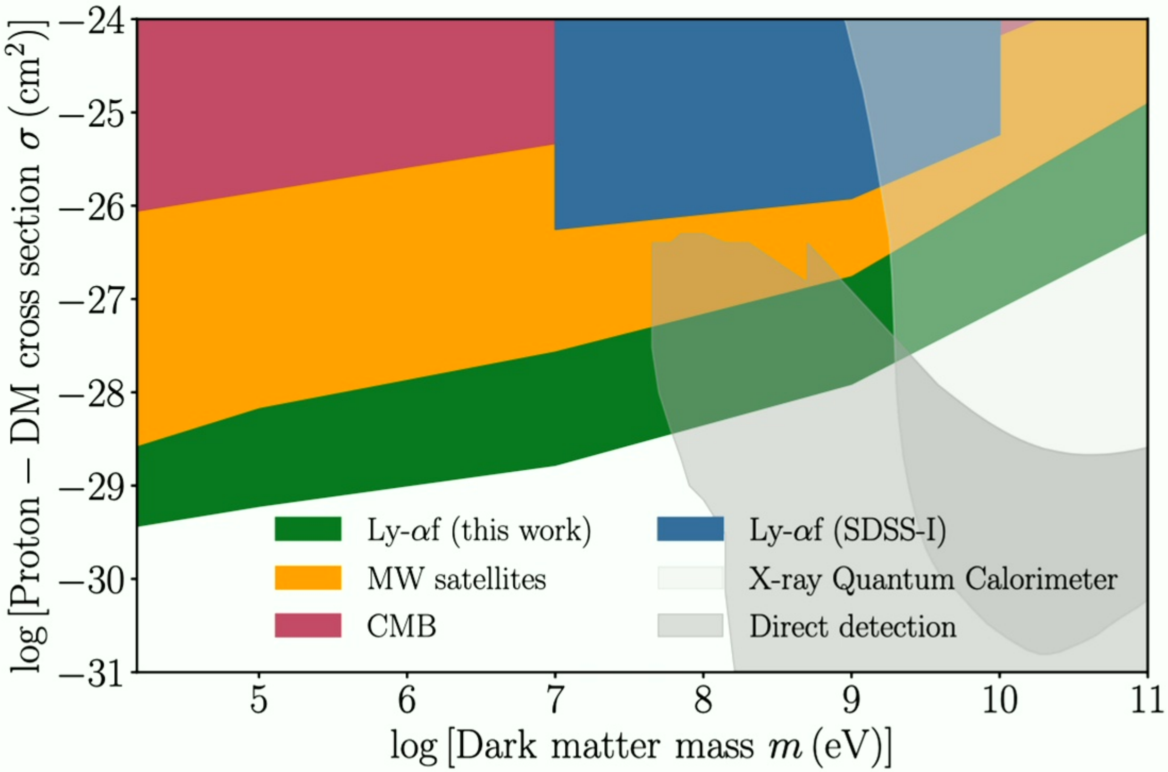
Rogers & Peiris (PRL, 2021); Rogers et al. (PRL, 2022)

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



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

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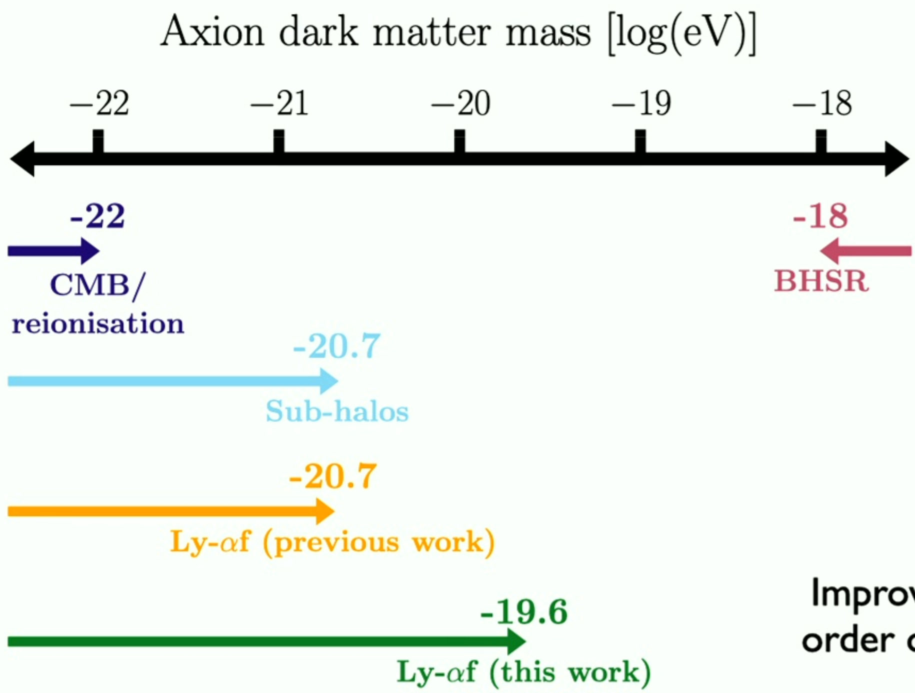
STRONG BOUND ON CANONICAL ULTRA-LIGHT AXION DARK MATTER

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

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

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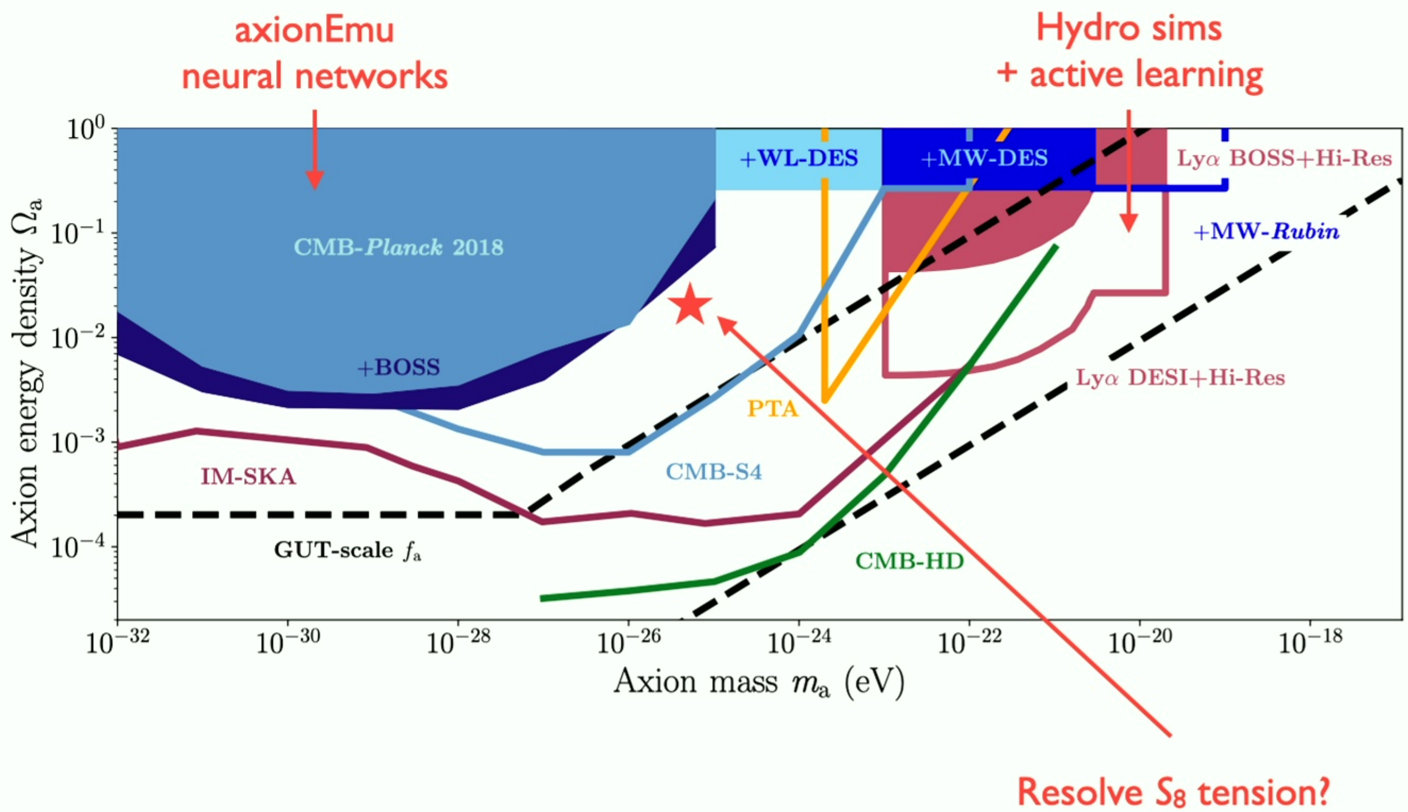
Rogers & Peiris (Phys. Rev. Lett., Phys. Rev. D, 2021ab)

Multi-probe approach to detect ultra-light axions



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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**