Title: Probing the String Axiverse with Galaxy Surveys

Speakers: Alex Lague

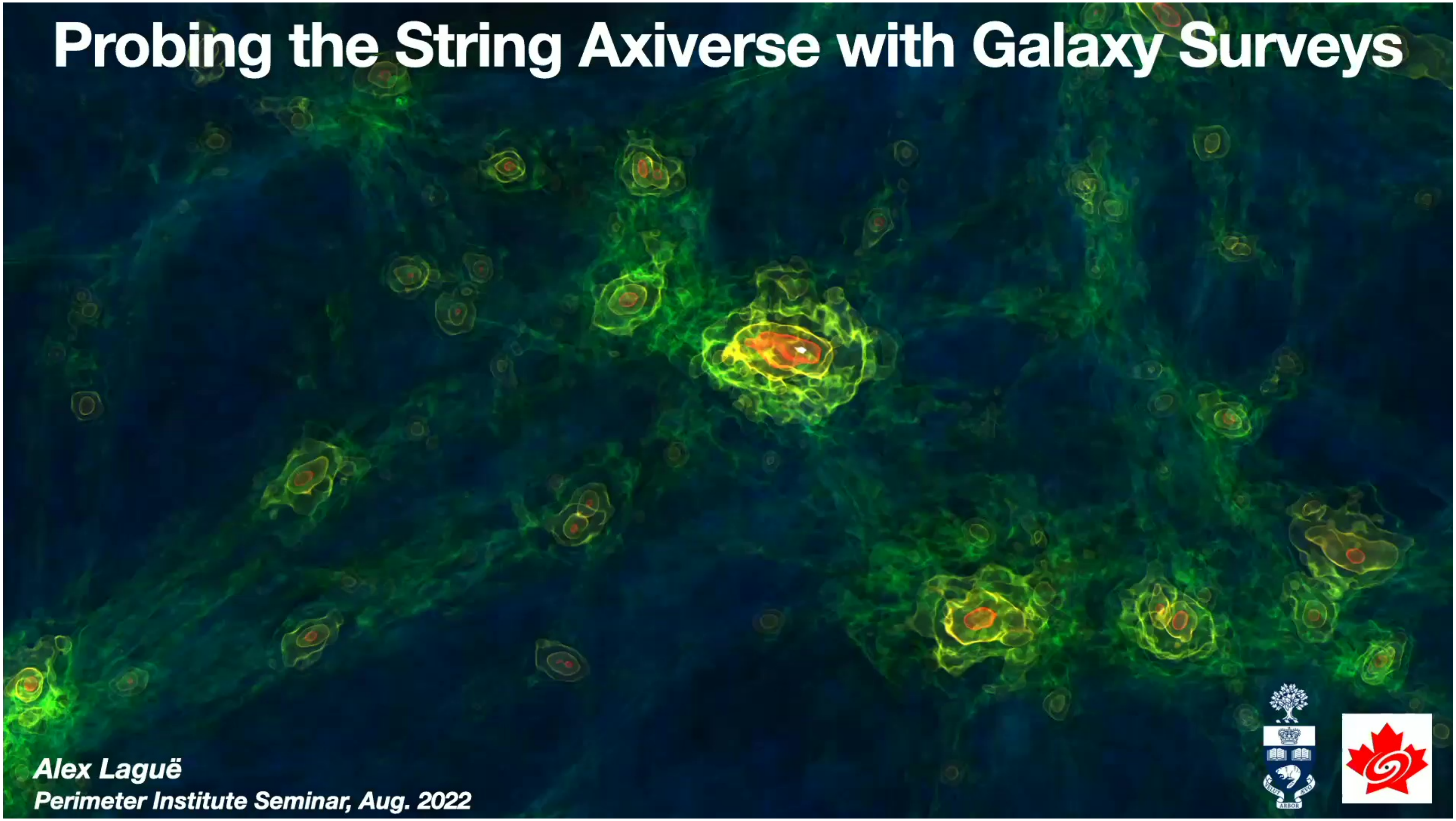
Series: Cosmology & Gravitation

Date: August 02, 2022 - 11:00 AM

URL: https://pirsa.org/22080001

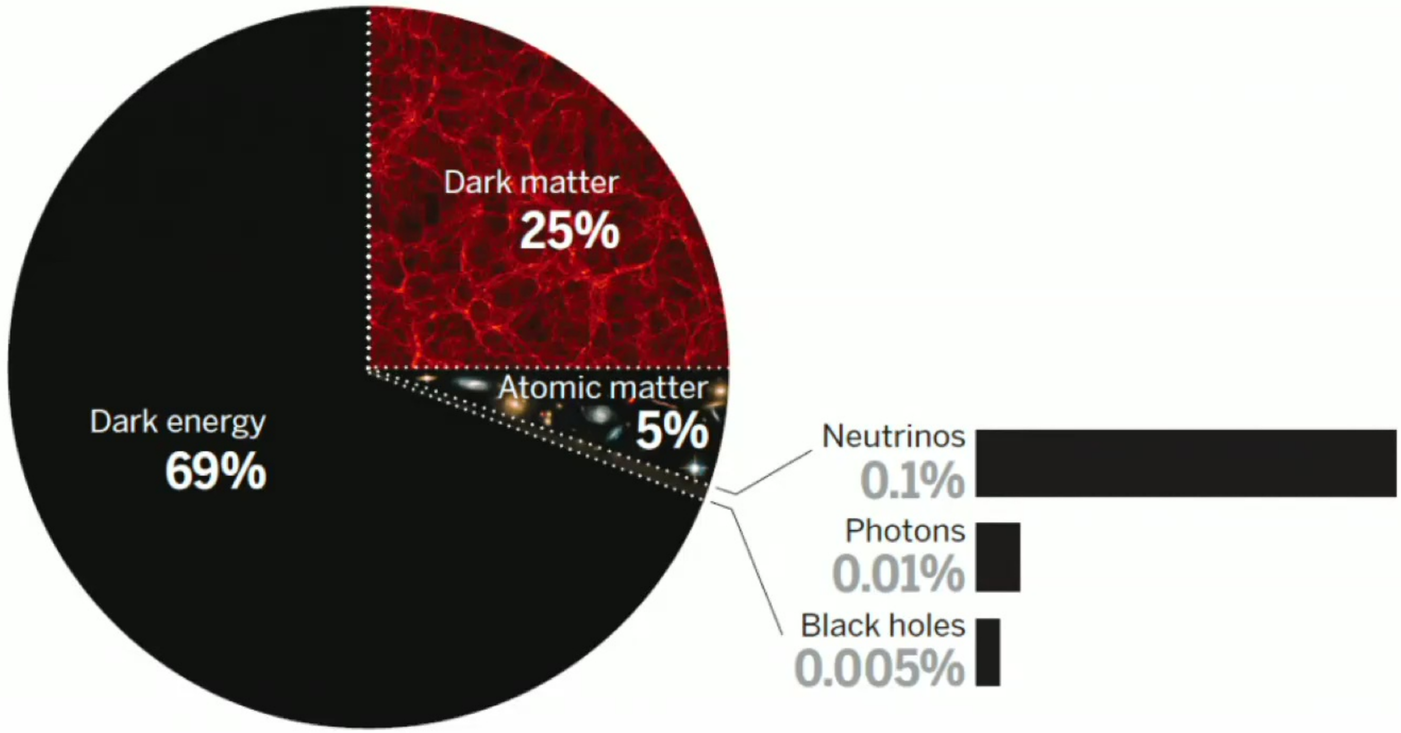
Abstract: String theory suggests the existence of multiple axion species forming what is known as an "axiverse". The axions in this model are thought to have logarithmically-distributed masses extending far below 10^{-21} eV, leading to the presence of ultralight axions. The latter have astrophysical de Broglie wavelength and affect the cosmic structures in which they cluster by erasing small-scale features. In contrast to other ultralight or fuzzy dark matter models, the string axiverse allows for a mixed dark sector with a subdominant ultralight component. Trace amounts of ultralight axions have been shown alleviate some observational discrepancies in cosmology such as the missing satellite problem and the Hubble-S8 tensions. Using an effective field theory approach and data from the Baryon Oscillation Spectroscopic Survey, we reach the strongest constraints on the axion relic density for axions with masses below 10^{-25} eV. To study heavier axions, we develop a new algorithm capable of simulating the formation of large-scale structure in the presence of more than one axion species. Making use of this code, we isolate new observational features in the cosmic web which may help us detect the presence of a plenitude of axions with weak lensing surveys.

Zoom Link: https://pitp.zoom.us/j/95089179013?pwd=NTBIeitScFRhYnBBSnlrcnoyVEhydz09


Probing the String Axiverse with Galaxy Surveys
Alex Laguë
Perimeter Institute Seminar, Aug. 2022

The multiple components that compose our universe

Current composition (as the fractions evolve with time)



Science/AAAS

The multiple components that compose our universe

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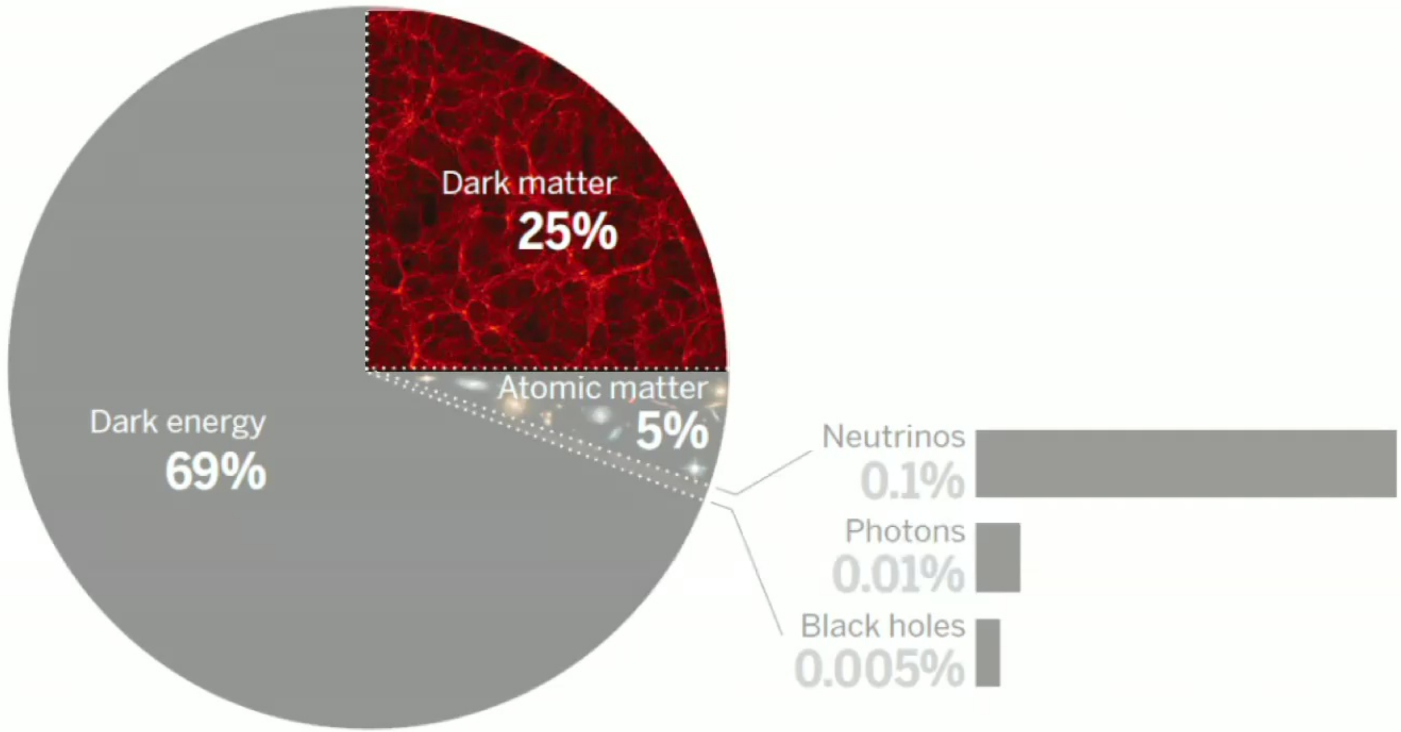
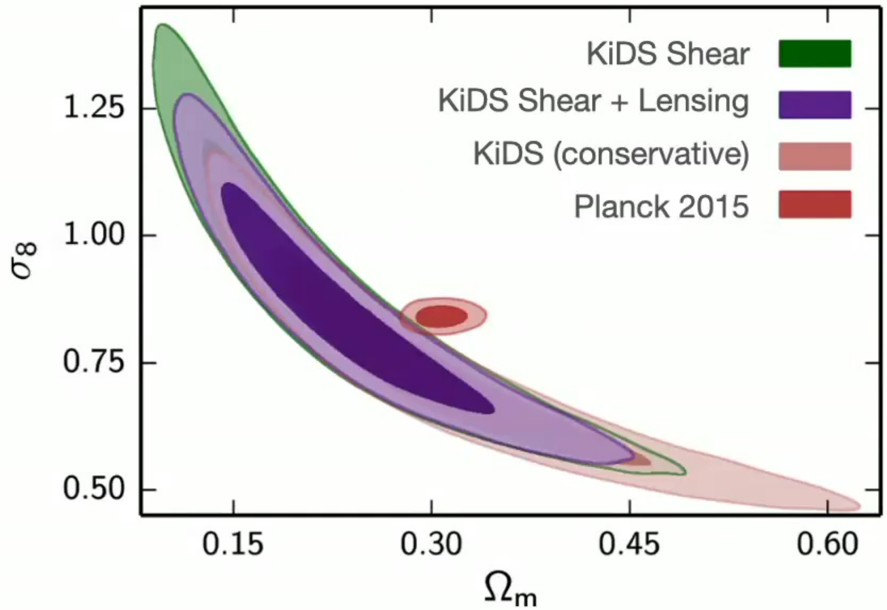
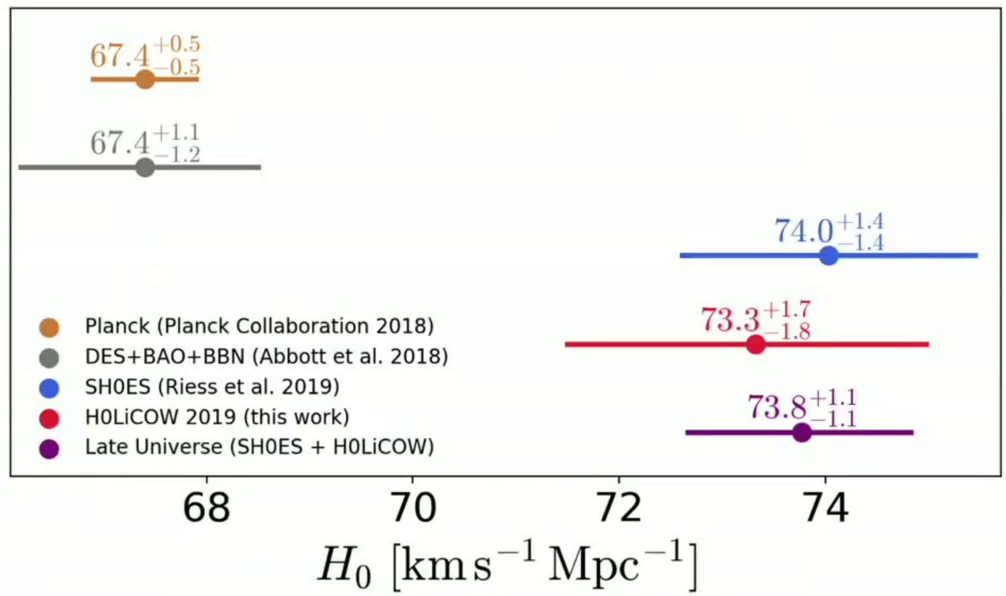


Science/AAAS

ΛCDM Tensions

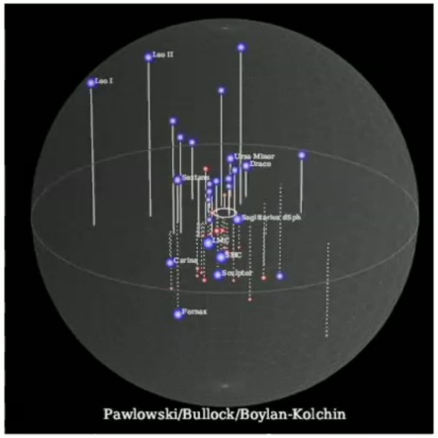


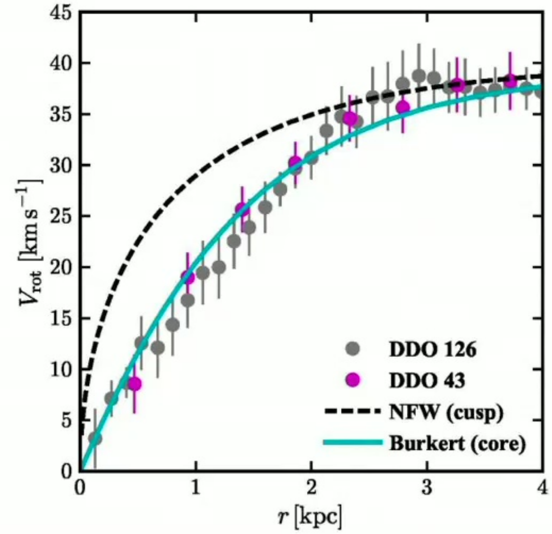
Joudaki *et al.*

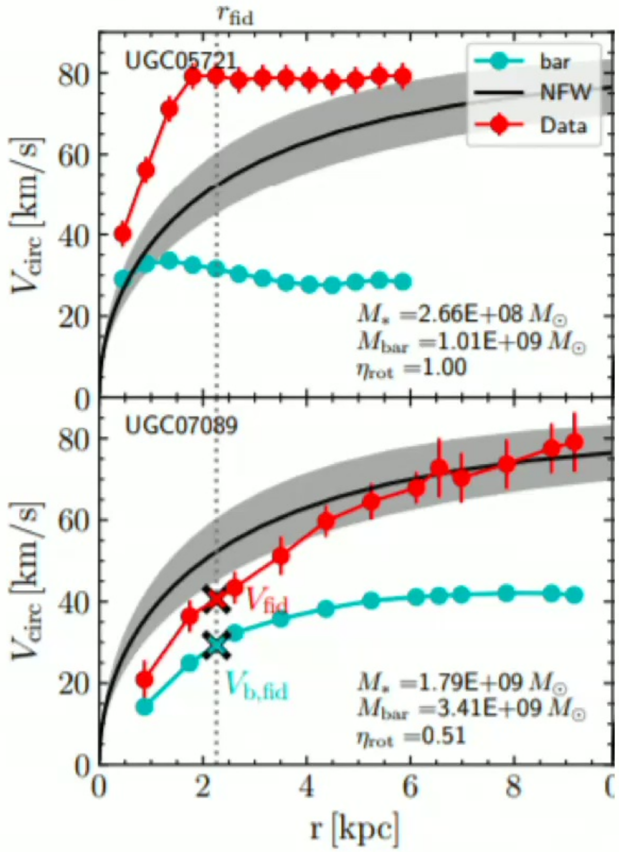


H0LiCOW Collaboration

Small-Scale Tensions





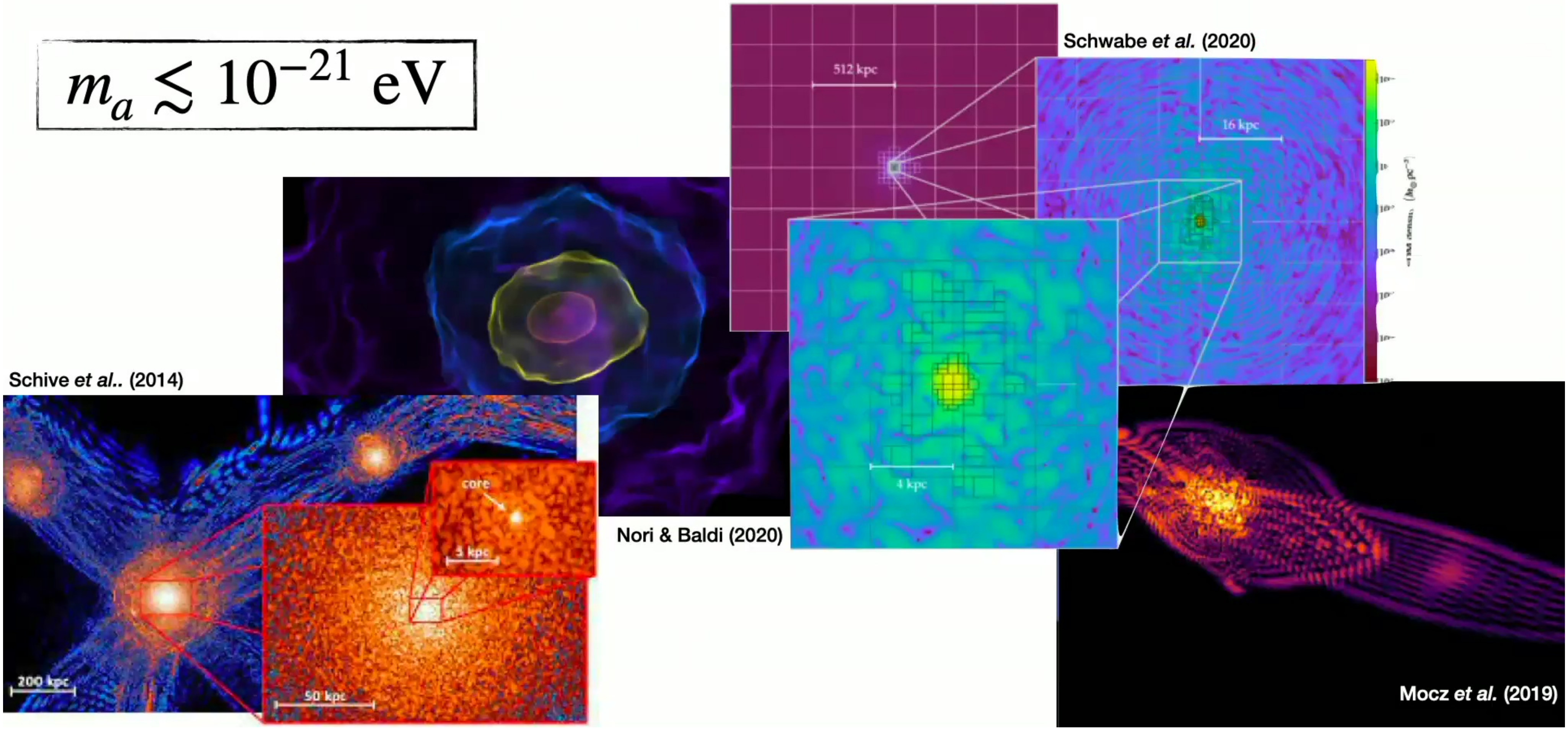


Bullock *et al.*

Santos-Santos *et al.*

Ultralight Axions, Fuzzy Dark Matter, ULDM, Wave DM, ψDM…

$$\boxed{m_a \lesssim 10^{-21}\ \mathrm{eV}}$$



Schwabe *et al.* (2020)

Schive *et al.*. (2014)

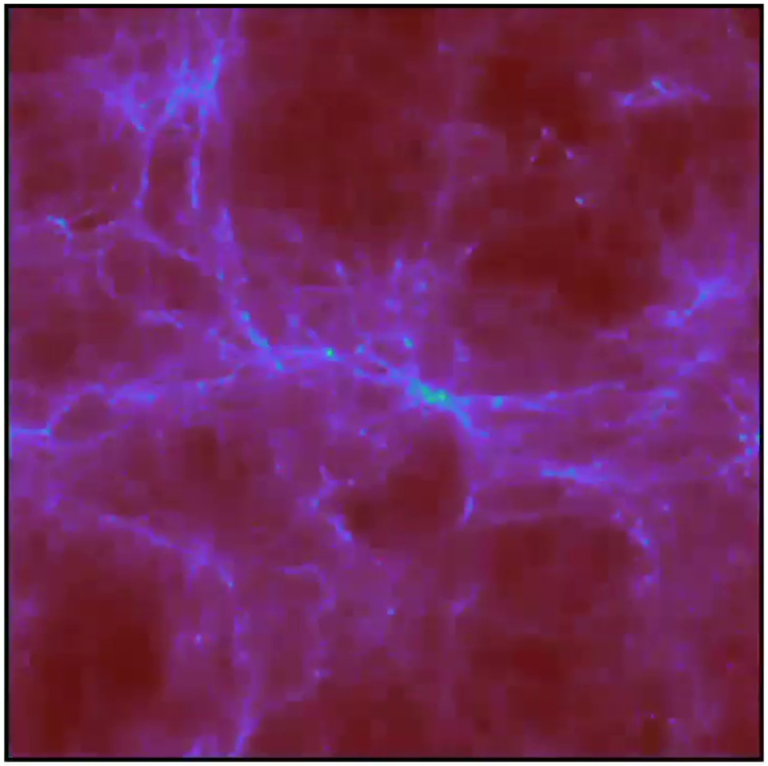
Nori & Baldi (2020)

Mocz *et al.* (2019)

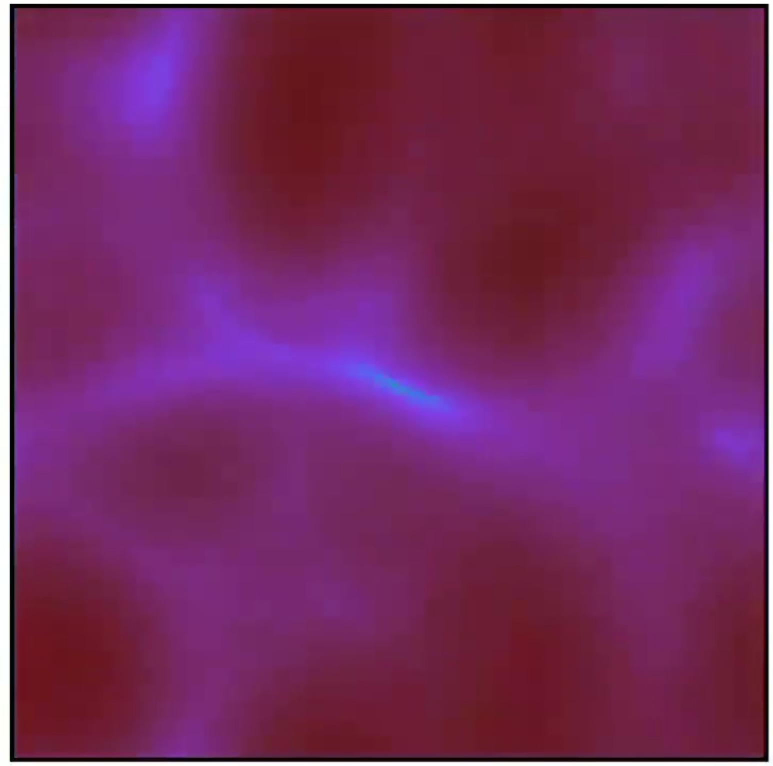
$$m \sim 10^{-22}\ \mathrm{eV}$$

$$\lambda_{\mathrm{dB}} = \frac{h}{mv} \sim 1\ \mathrm{kpc}$$

CDM



FDM



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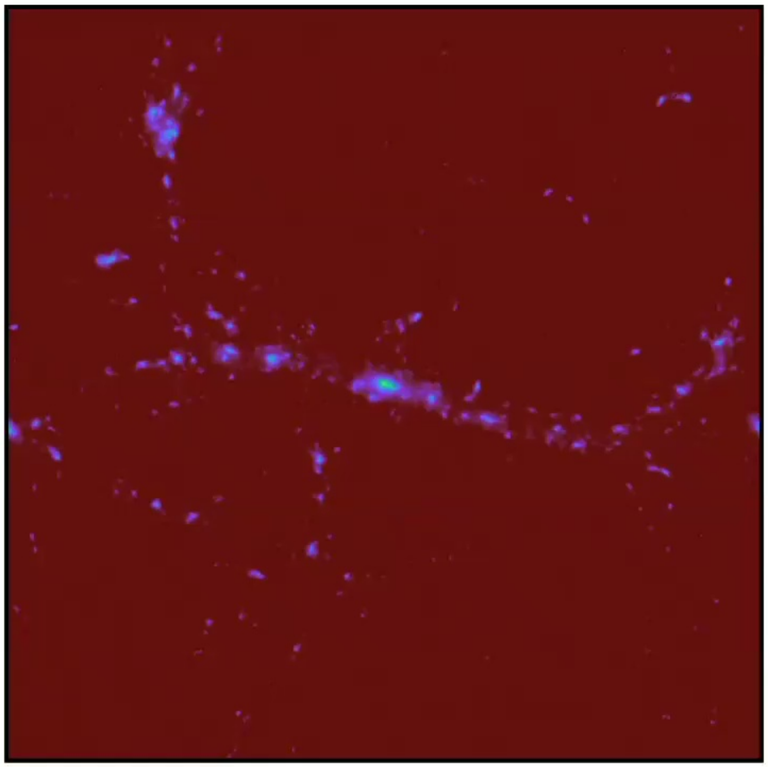
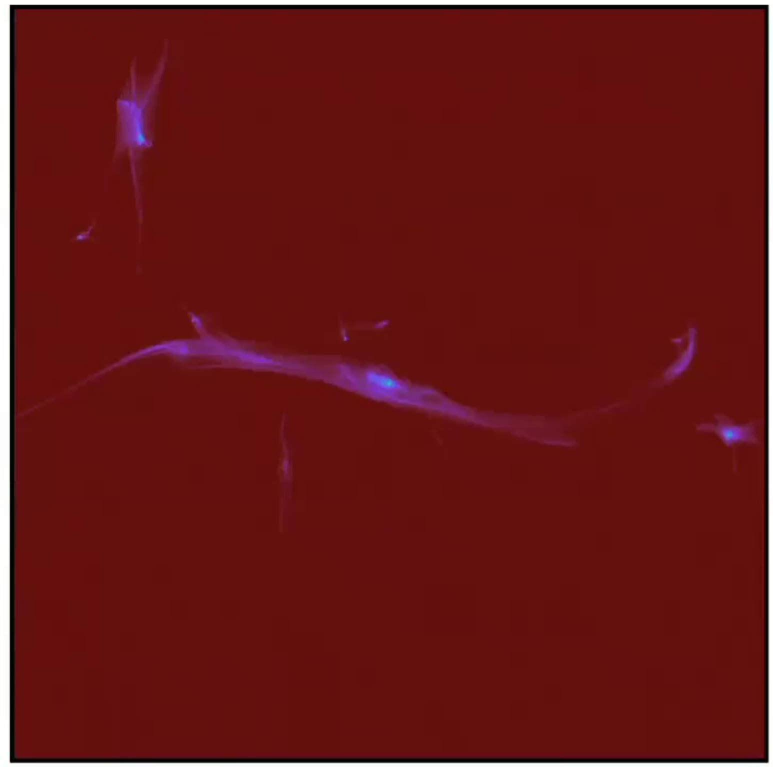
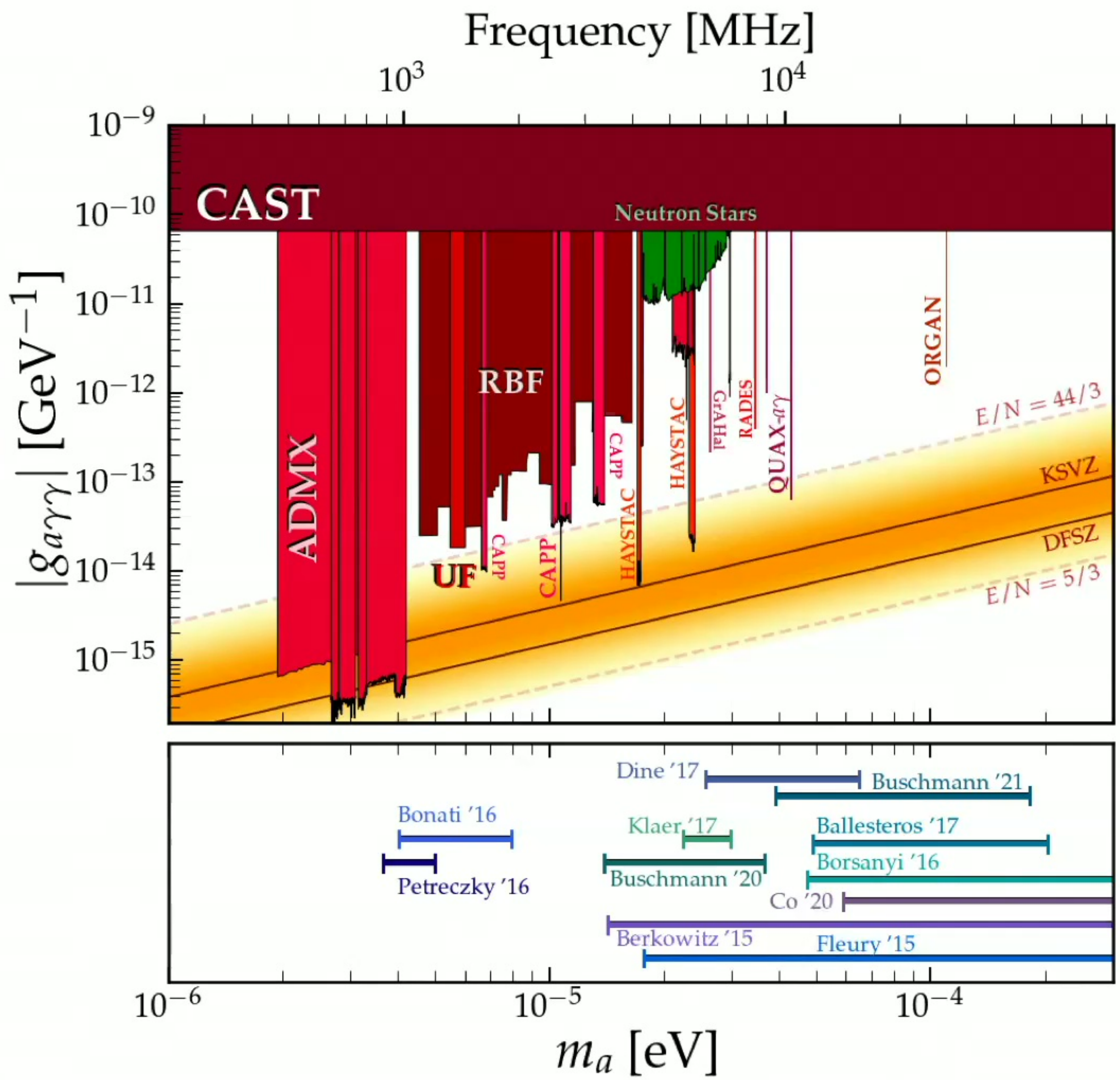


FDM



The QCD Axion

$$m_{a,\mathrm{QCD}} \gtrsim 10^{-6}\ \mathrm{eV}$$



Source: https://cajohare.github.io/AxionLimits/docs/am.html

The String Theory Axion

Axions In String Theory

Peter Svrček

Department of Physics and SLAC, Stanford University, Stanford CA 94305/94309 USA

and

Edward Witten

Institute For Advanced Study, Princeton NJ 08540 USA

String Axiverse

Asimina Arvanitaki[a,b], Savas Dimopoulos[c], Sergei Dubovsky[c,d], Nemanja Kaloper[e], and John March-Russell[f]

Multiple-axion framework

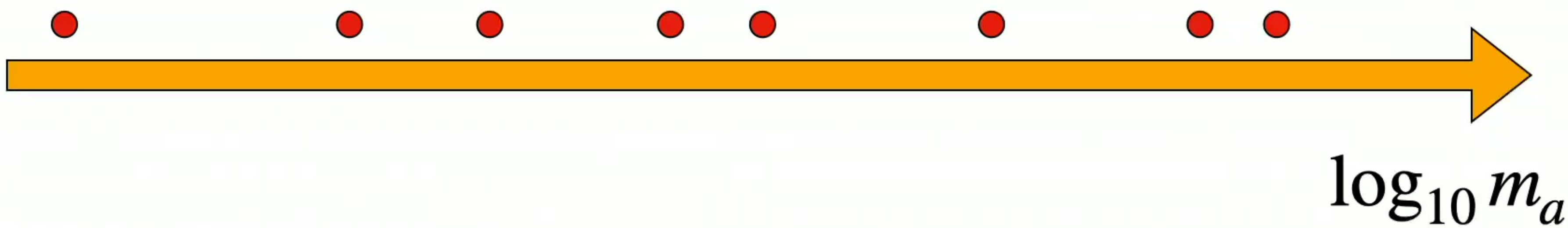
Thomas C. Bachlechner,[1] Kate Eckerle,[1] Oliver Janssen,[2,3] and Matthew Kleban[2,3]

Axionic Band Structure of the Cosmological Constant

Thomas C. Bachlechner

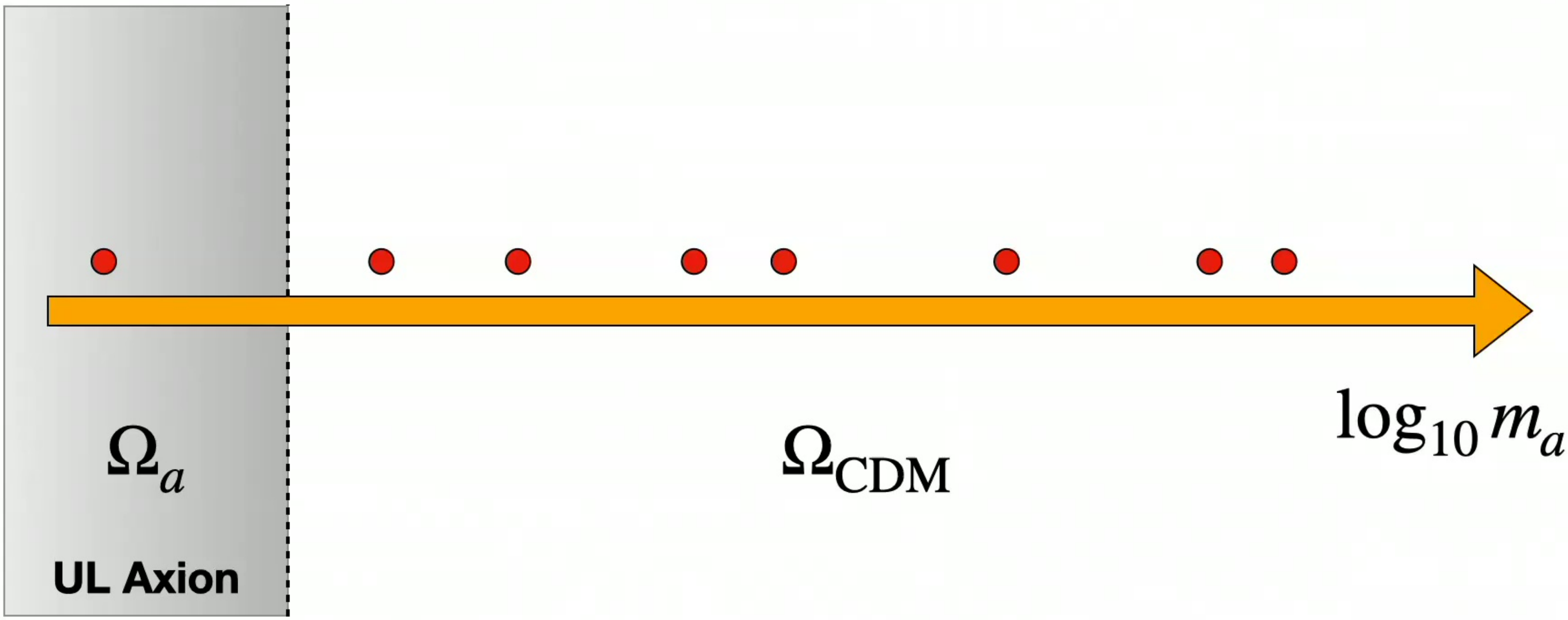
$$N_{\text{ax}} = \mathcal{O}(10) - \mathcal{O}(100)$$

The String Axiverse

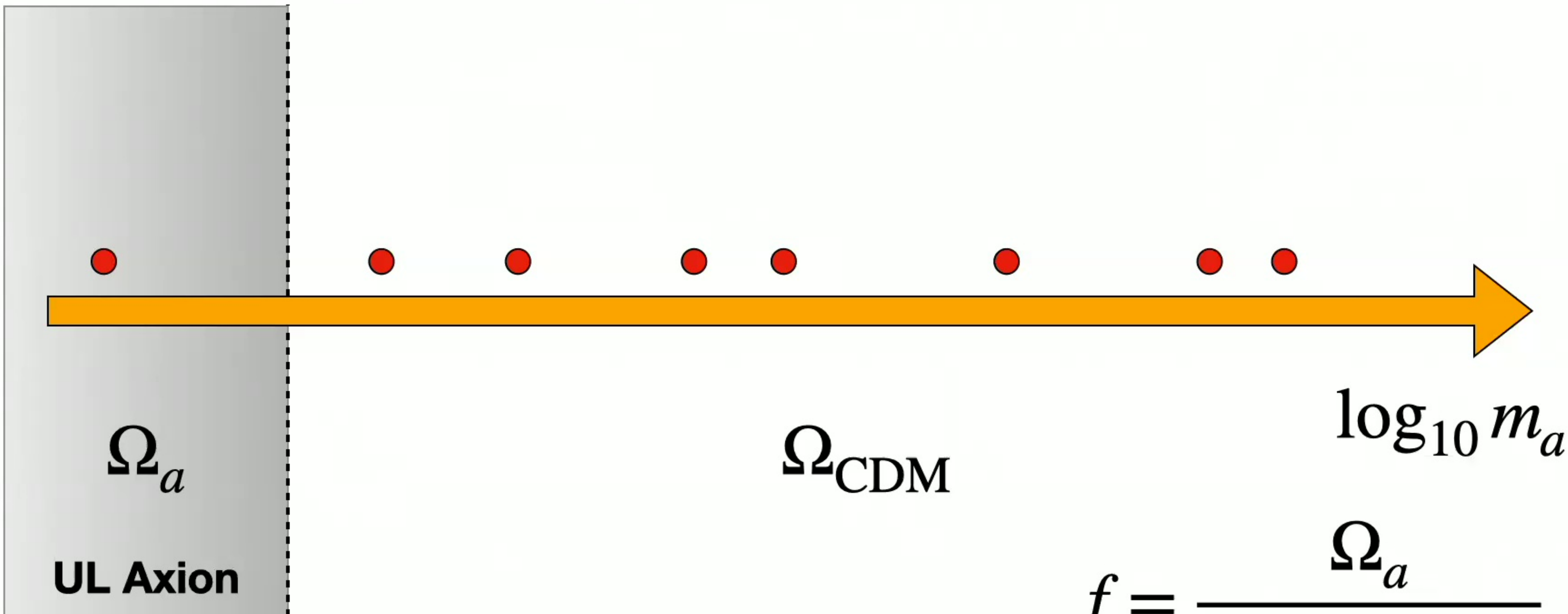


$$\boxed{\Omega_{a_i} \ll \Omega_{\mathrm{DM}}}$$

The String Axiverse (simplified)



The String Axiverse (simplified)



$$f = \frac{\Omega_a}{\Omega_a + \Omega_{\mathrm{CDM}}}$$

Partially Ultralight DM

- $10\,\%$ of 10^{-25} eV for H_0 tension *(Blum & Teodori, 2021)*
- $6\,\%$ of 10^{-26} eV for $H_0 + S_8$ tensions (with EDE) *(Ye et al. 2021)*
- $5\,\%$ of 10^{-26} eV for $H_0 + S_8$ tensions (with DDE) *(Allali et al. 2022)*
- $1\,\%$ of 10^{-27} eV for $H_0 + S_8$ tensions (with KMIX) *(Alexander et al. 2022)*

Parameter	$m_a \simeq 10^{-28}\,\mathrm{eV}$	$m_a \simeq 10^{-27}\,\mathrm{eV}$	$m_a \simeq 10^{-26}\,\mathrm{eV}$	$m_a \simeq 4\times10^{-26}\,\mathrm{eV}$
H_0 [km/s/Mpc]	$70.7\ (70.2)^{+1.0}_{-1.0}$	$71.2\ (71.4)^{+1.1}_{-1.1}$	$71.56\ (70.99)^{+0.99}_{-0.98}$	$71.0\ (70.9)^{+1.1}_{-1.1}$
S_8	$0.812\ (0.812)^{+0.010}_{-0.010}$	$0.804\ (0.797)^{+0.013}_{-0.013}$	$0.784\ (0.789)^{+0.014}_{-0.014}$	$0.792\ (0.783)^{+0.017}_{-0.014}$
Tension with SH$_0$ES	$1.9\,\sigma$	$1.6\,\sigma$	$1.4\,\sigma$	$1.7\,\sigma$
Tension with S$_8$	$2.6\,\sigma$	$2.1\,\sigma$	$1.2\,\sigma$	$1.6\,\sigma$
$\chi^2_{DS} - \chi^2_{\Lambda CDM}$	-6.9	-9.7	-17.9	-11.7

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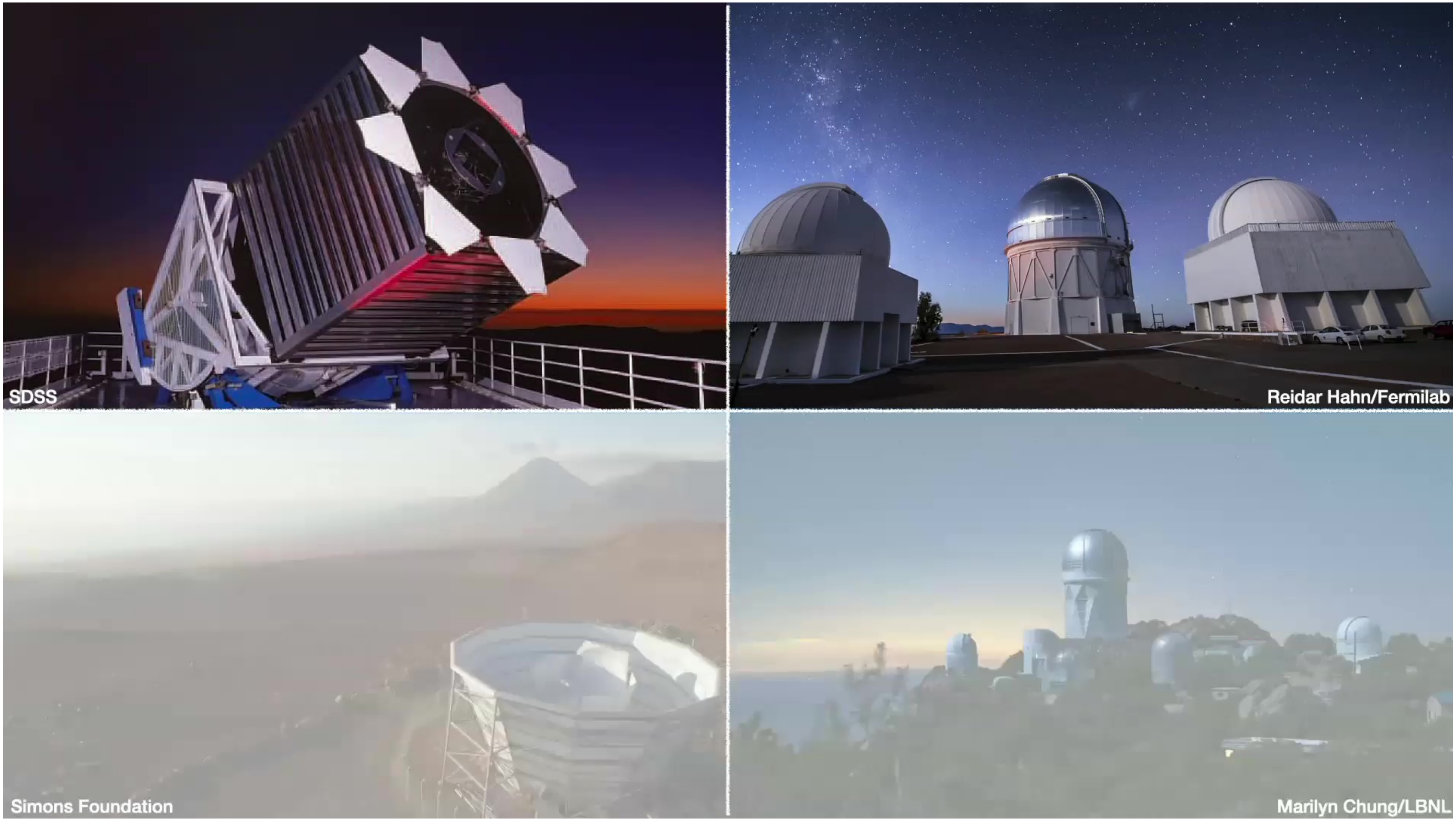
How to Deal with Larger Parameter Space?


SDSS
Reidar Hahn/Fermilab
Simons Foundation
Marilyn Chung/LBNL


SDSS
Reidar Hahn/Fermilab
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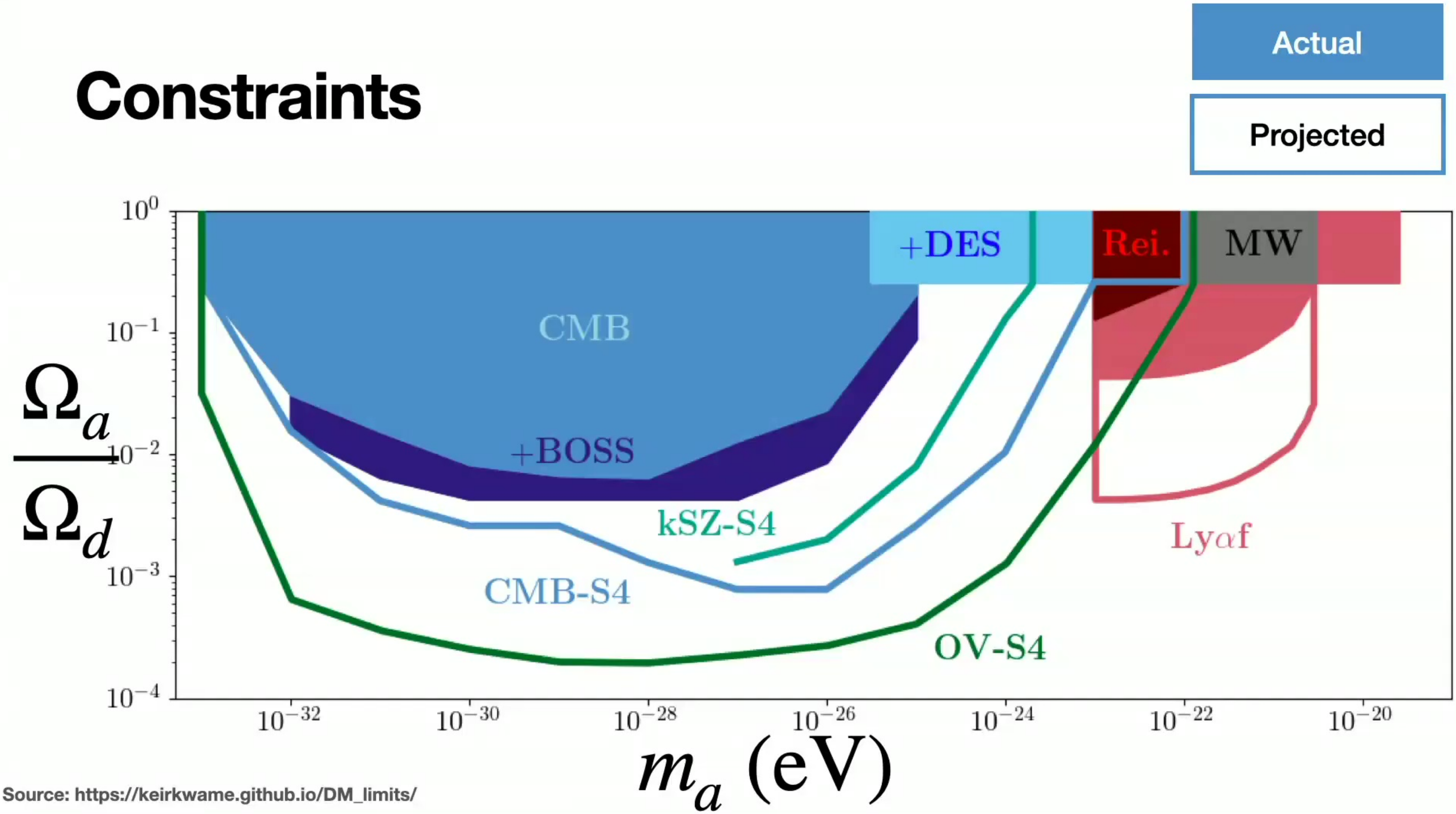
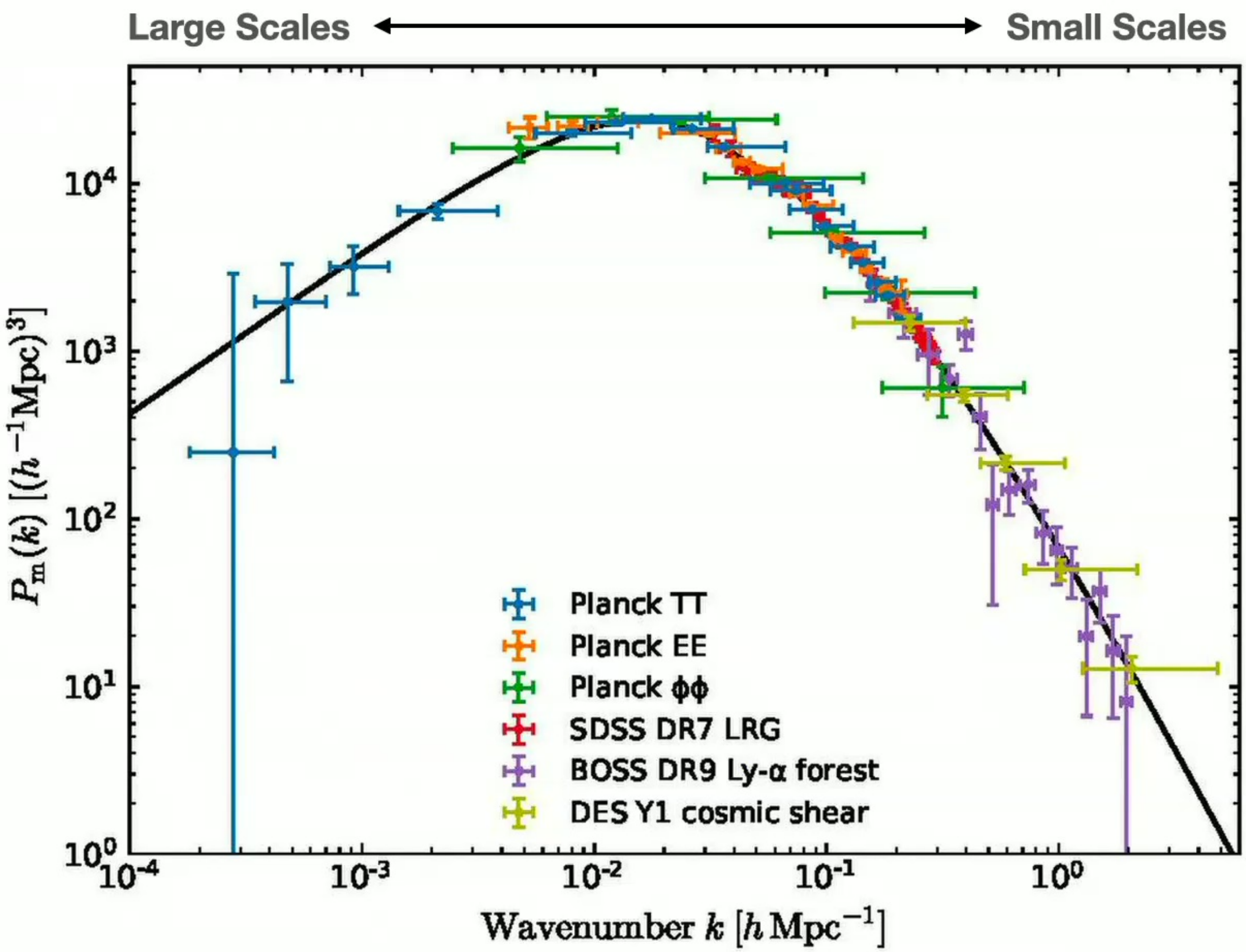
Constraints



Source: https://keirkwame.github.io/DM_limits/



$$\delta = \rho/\bar{\rho} - 1$$

$$P(k) \sim \left\langle \delta^2 \right\rangle$$

ESA and the Planck Collaboration

CDM

$$\frac{\partial^2\delta}{\partial t^2} + 2H\frac{\partial\delta}{\partial t} = 4\pi G\bar{\rho}\delta_{\text{tot}}$$

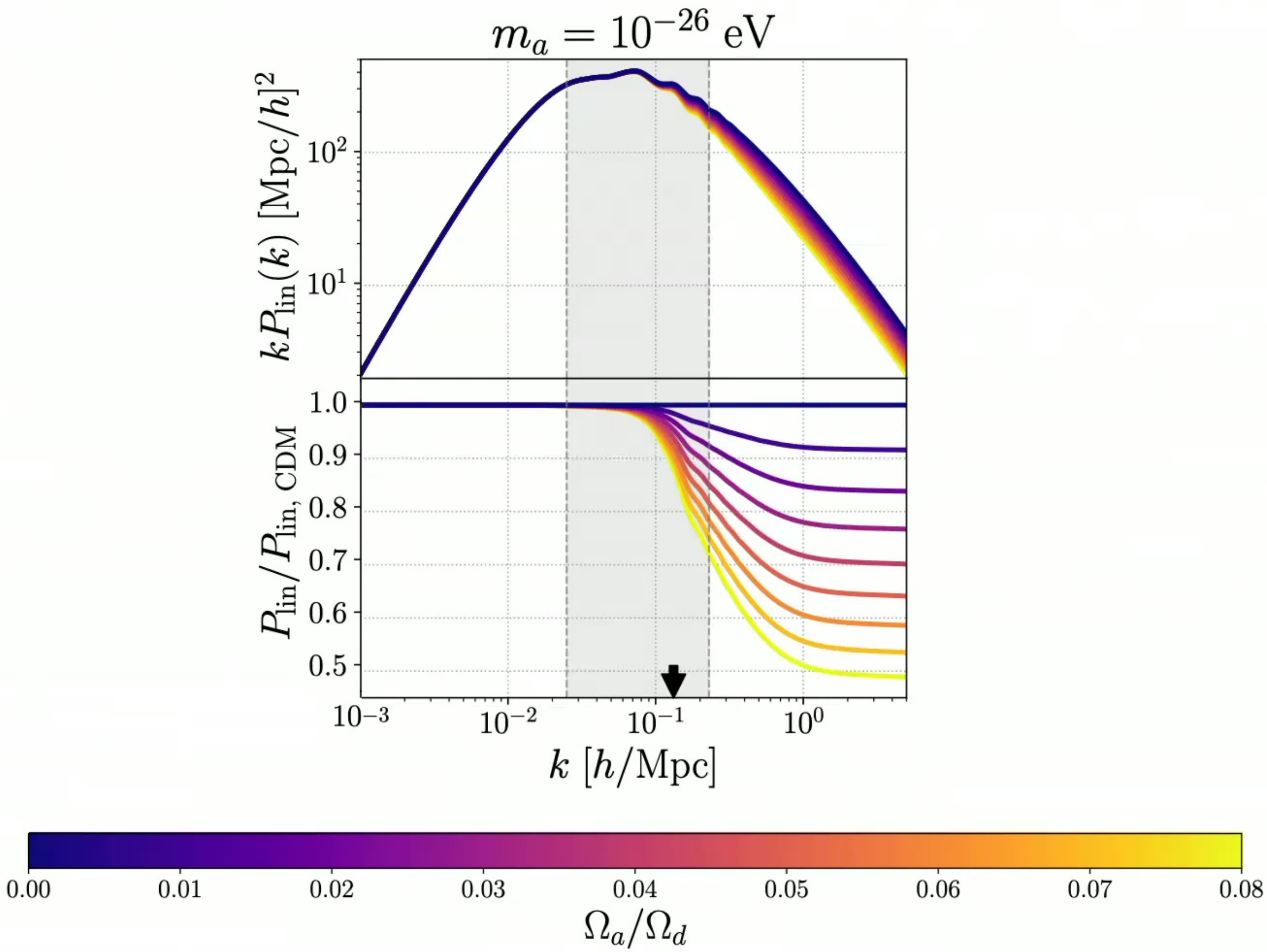
Total Density

Ultralight Axions

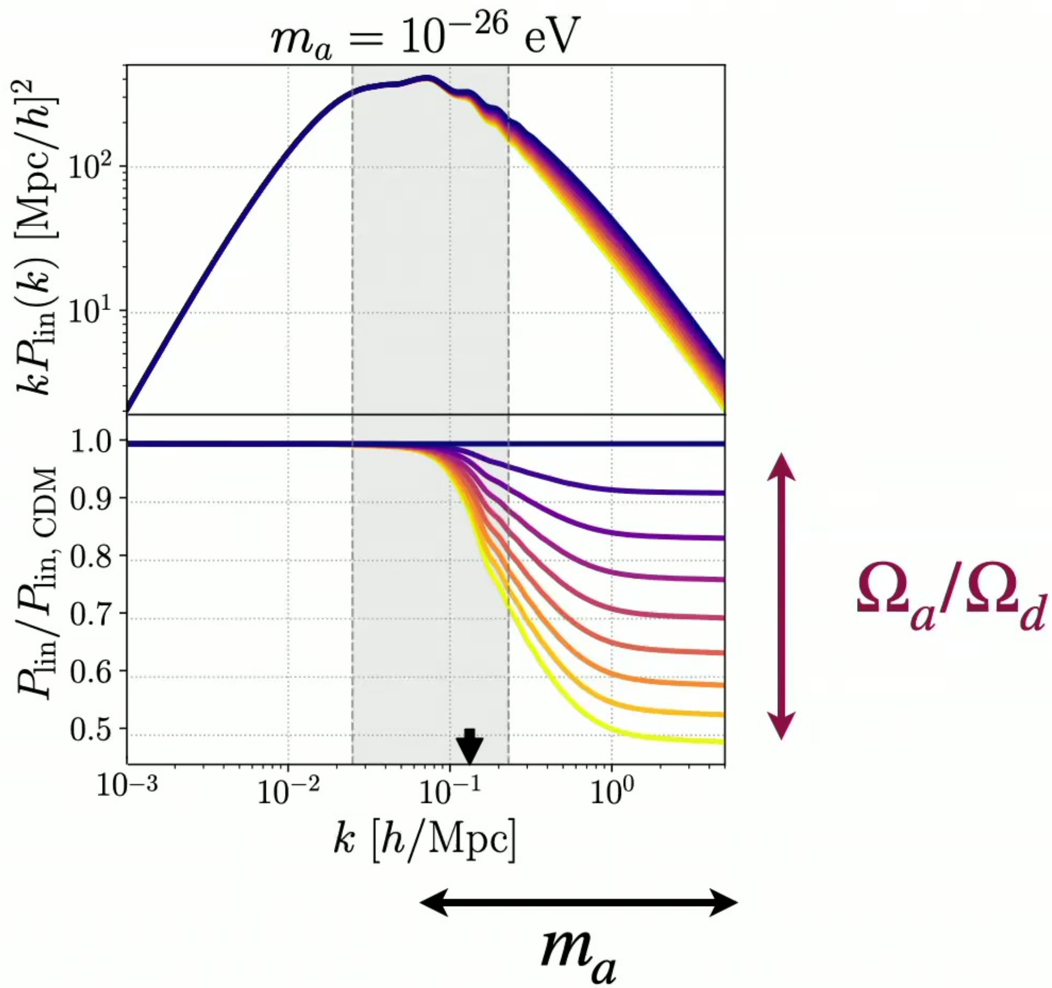
$$\frac{\partial^2 \delta_a}{\partial t^2} + 2H\frac{\partial \delta_a}{\partial t} = 4\pi G\bar{\rho}\delta_{\mathrm{tot}} - \frac{\hbar^2 k^4}{4m^2 a^4}\delta_a$$

Total Density

Axion Effective Sound Speed



$m_a = 10^{-26}$ eV
$kP_{\rm lin}(k)$ [Mpc/h]^2
10^2
10^1
$P_{\rm lin}/P_{\rm lin,\,CDM}$
1.0
0.9
0.8
0.7
0.6
0.5
10^{-3}
10^{-2}
10^{-1}
10^0
k [h/Mpc]
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Ω_a/Ω_d

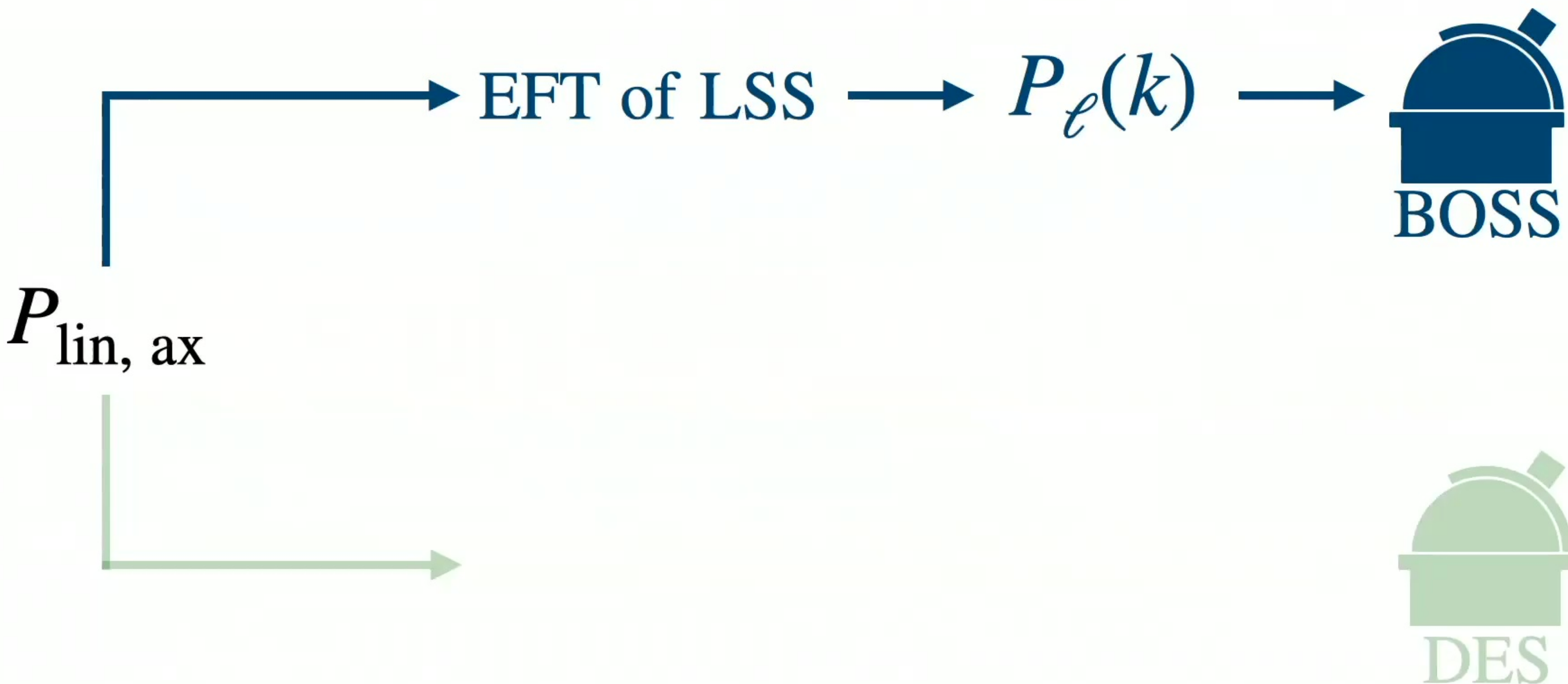


Scale-Mass Relation

$$\boxed{m_a \leftrightarrow k_J}$$

Theory to Data

Theory to Data



Galaxy Power Spectrum

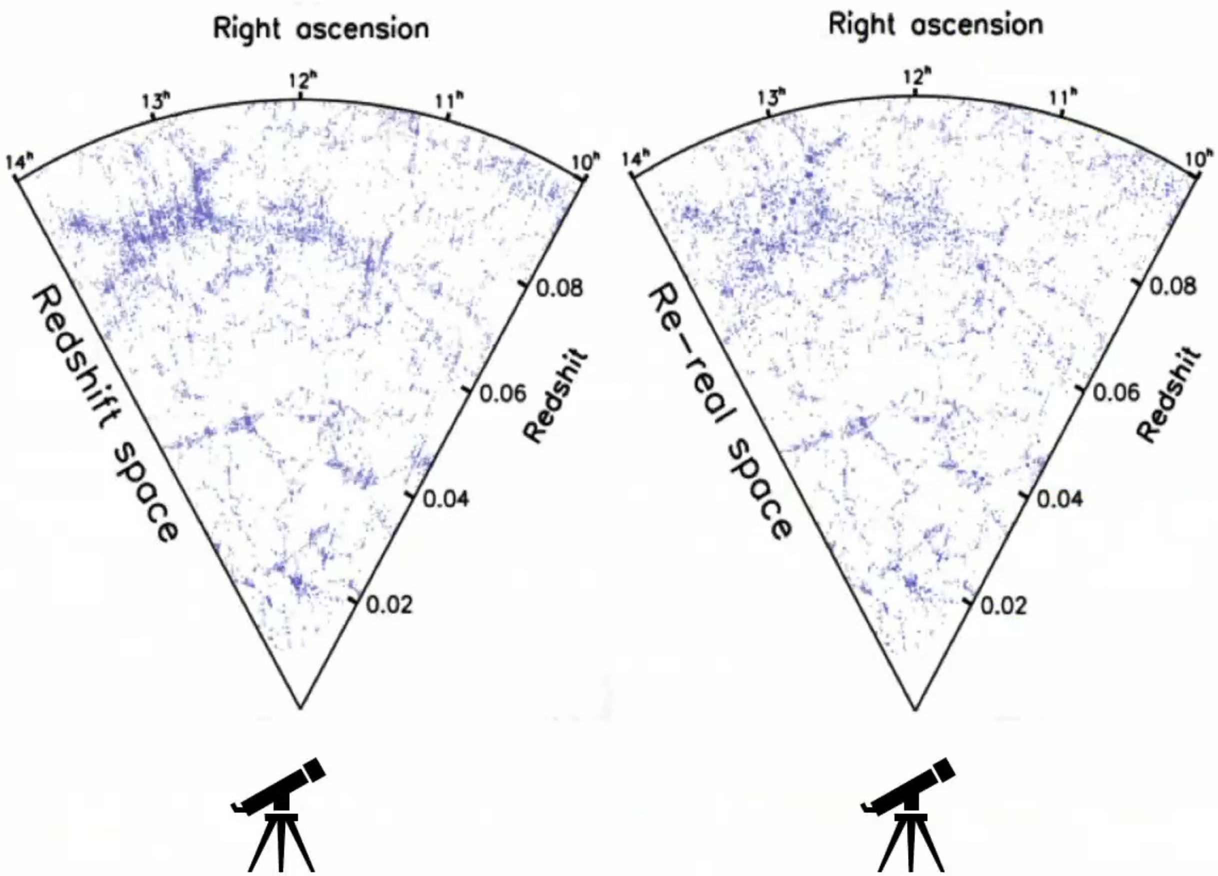
via EFT of LSS

$$P_g(\mathbf{k}) = b_1^2 P_{\rm lin}(k) + P_{1-{\rm loop}}(\mathbf{k}) + P_{\rm counter}(\mathbf{k}) + P_{\rm stoch}(k)$$

$$\mathbf{k} \to (k, \mu)$$

$$P_\ell(k) = \frac{2\ell + 1}{2} \int_{-1}^{+1} {\rm d}\mu \; P_g(k, \mu) \mathscr{P}_\ell(\mu)$$

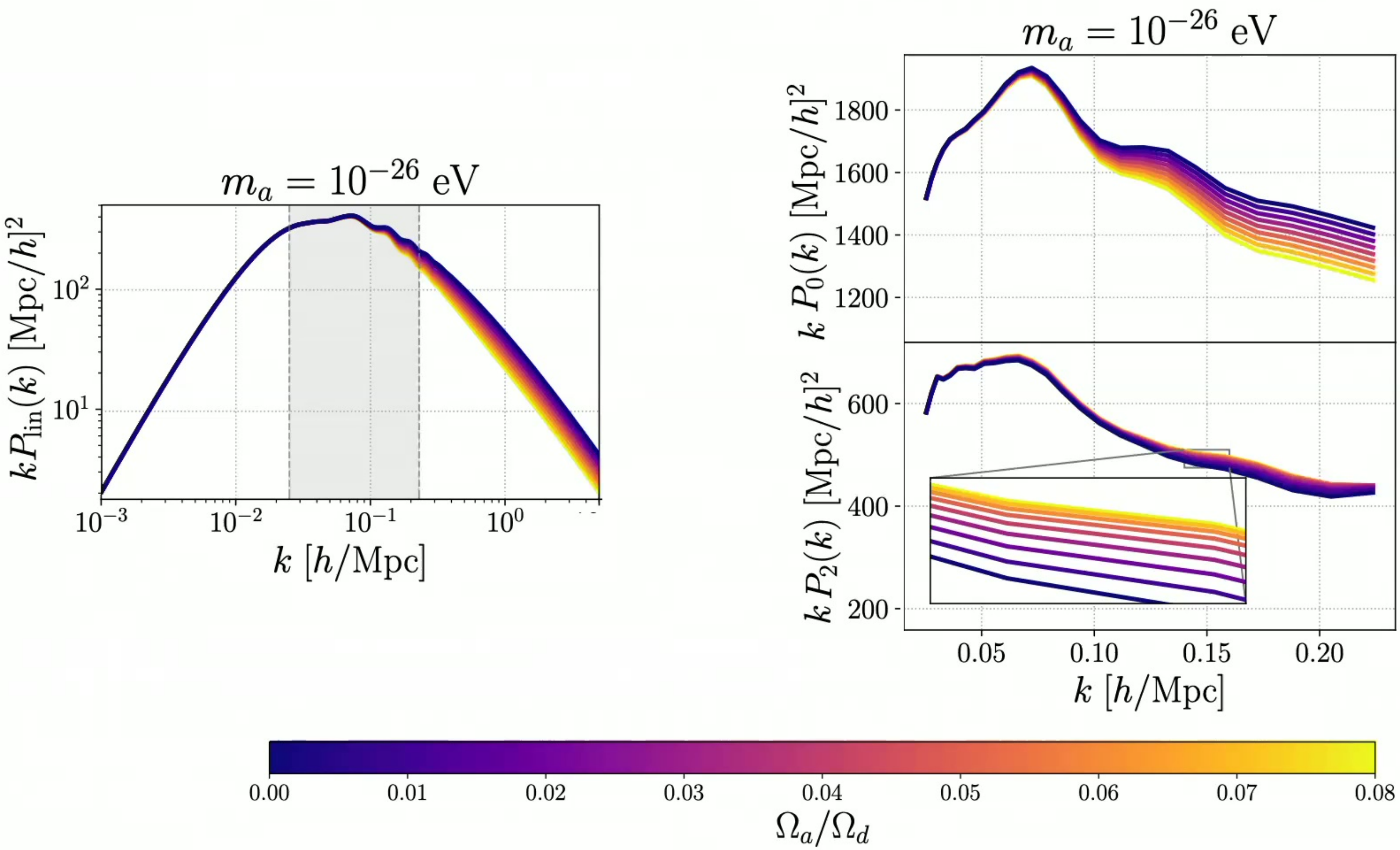
Galaxy Power Spectrum



SDSS

Matter

Galaxies



Laguë *et al.* (2022)

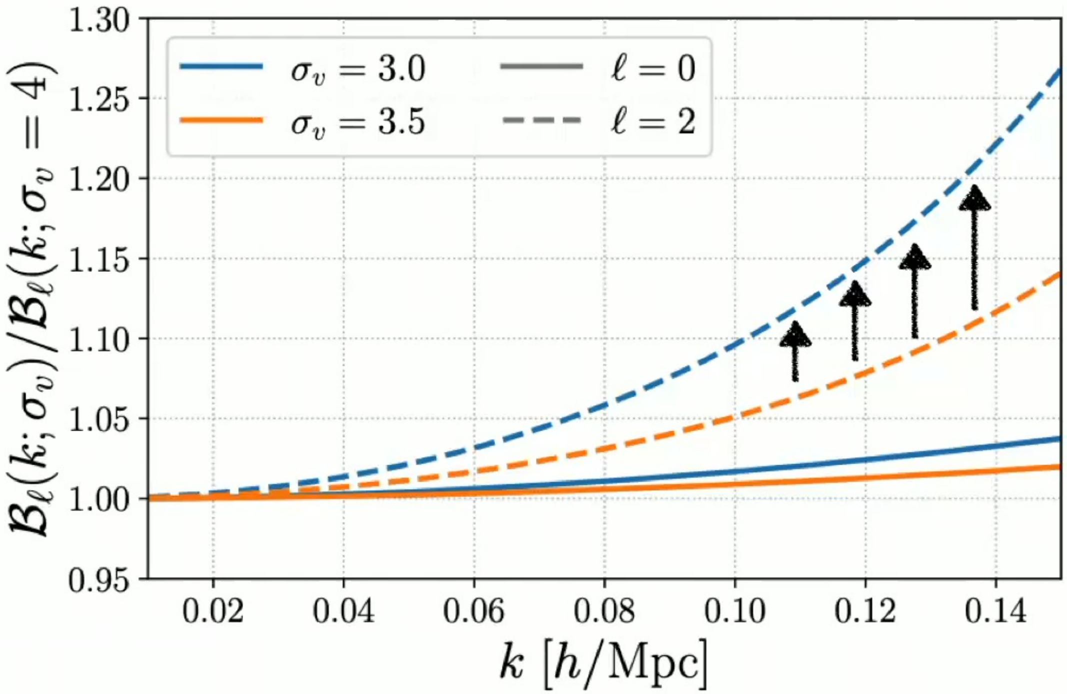
Simplified Model

$$P_\ell(k) = \frac{2\ell + 1}{2} b_g^2 P_{\rm lin}(k) \underbrace{\int_{-1}^{1} d\mu \; e^{-\left(k\mu f \sigma_v\right)^2} \left(1 + f\mu^2\right)^2 \mathscr{P}_\ell(\mu)}$$

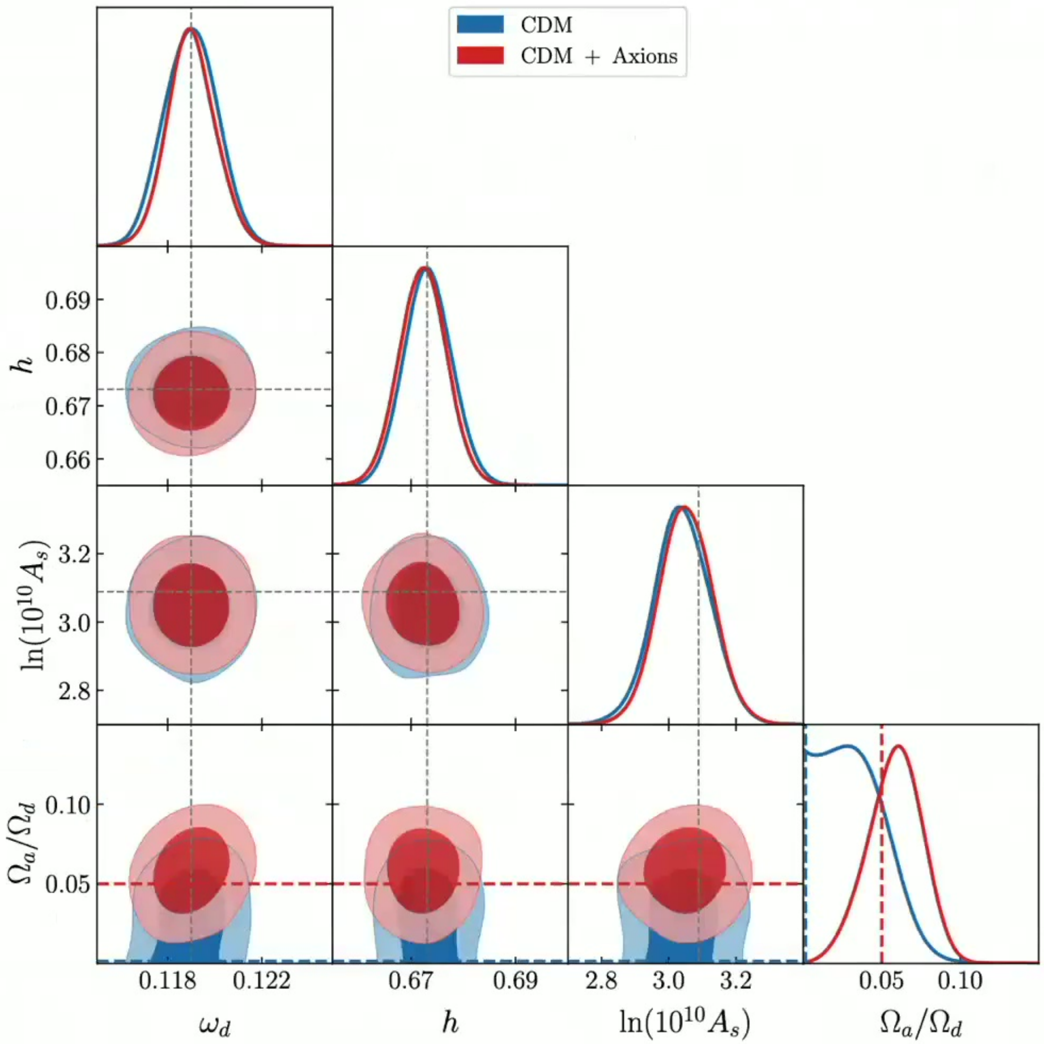
$$\mathscr{B}_\ell \equiv \int_{-1}^{1} d\mu \; e^{-\left(k\mu f \sigma_v\right)^2} \left(1 + f\mu^2\right)^2 \mathscr{P}_\ell(\mu)$$

Simplified Model

$$\mathscr{B}_\ell \equiv \int_{-1}^{1} d\mu\ e^{-(k\mu f\sigma_v)^2} \left(1 + f\mu^2\right)^2 \mathscr{P}_\ell(\mu)$$



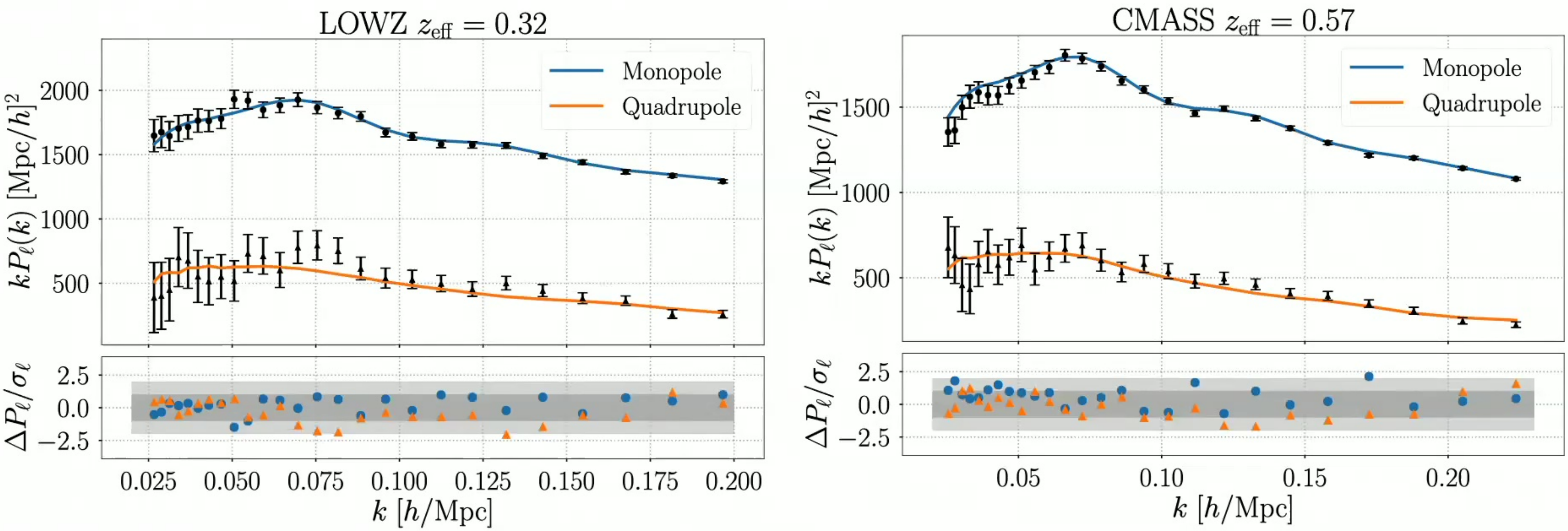
Validation



Laguë *et al.* (2021)

BOSS Data

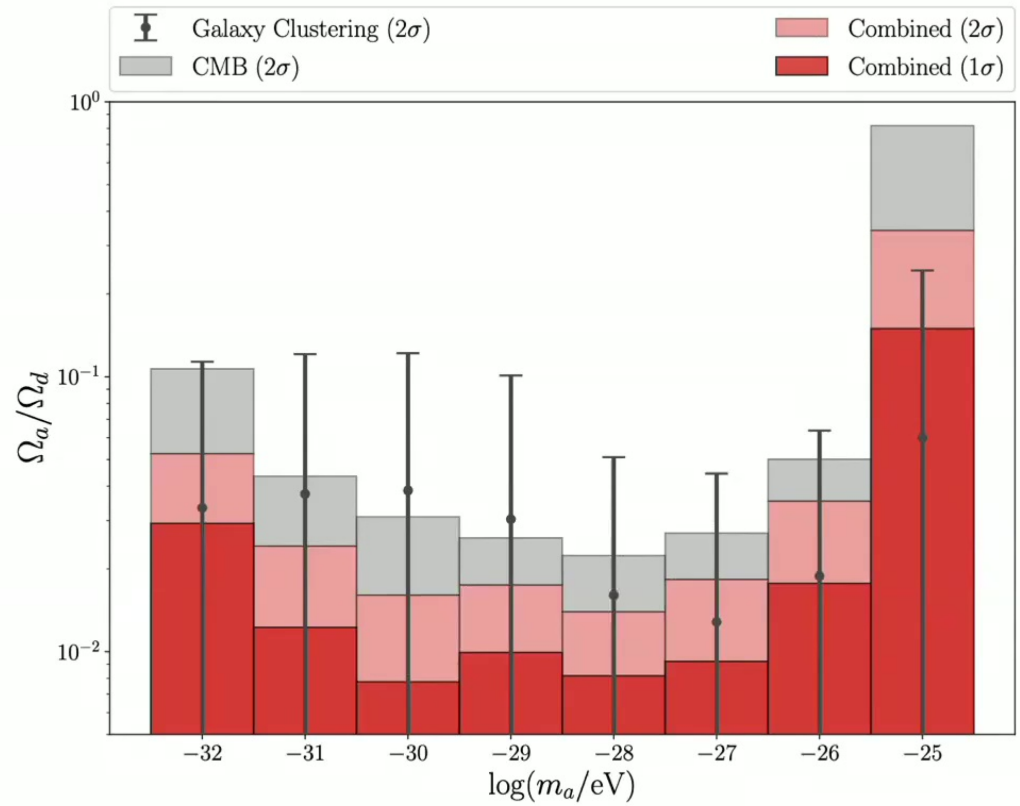
$m_a = 10^{-27}$ eV



Laguë *et al.* (2022)

Constraints

Fraction of DM



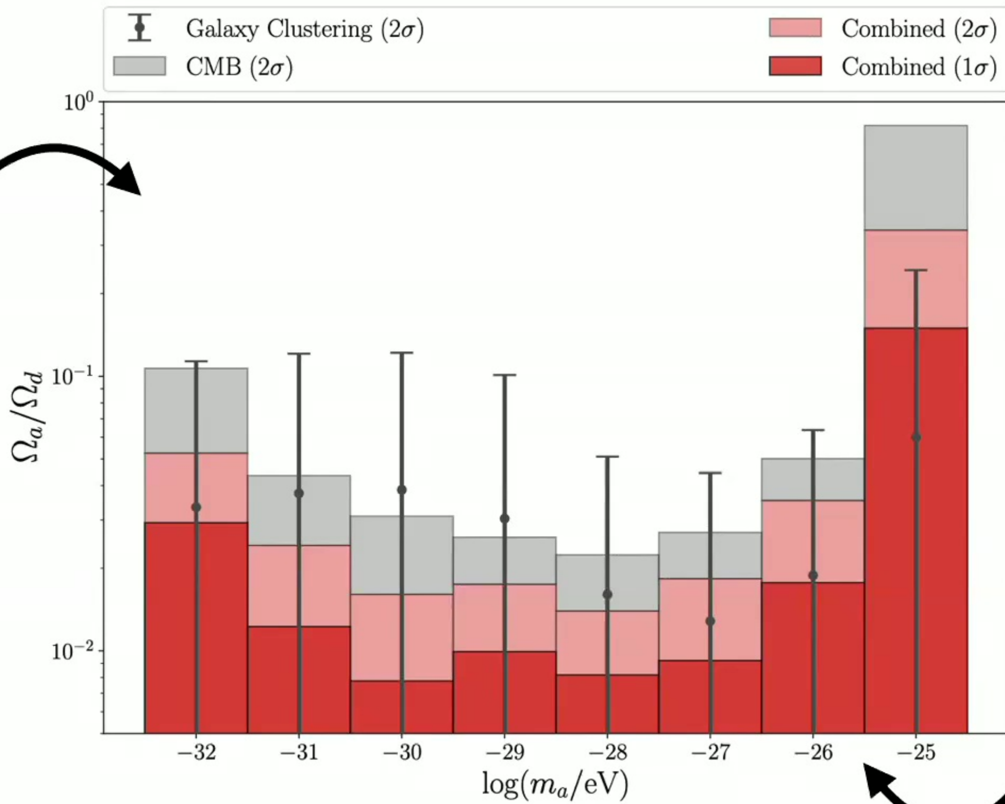
Axion Mass

Laguë *et al.* (2021)

Constraints

Disfavoured

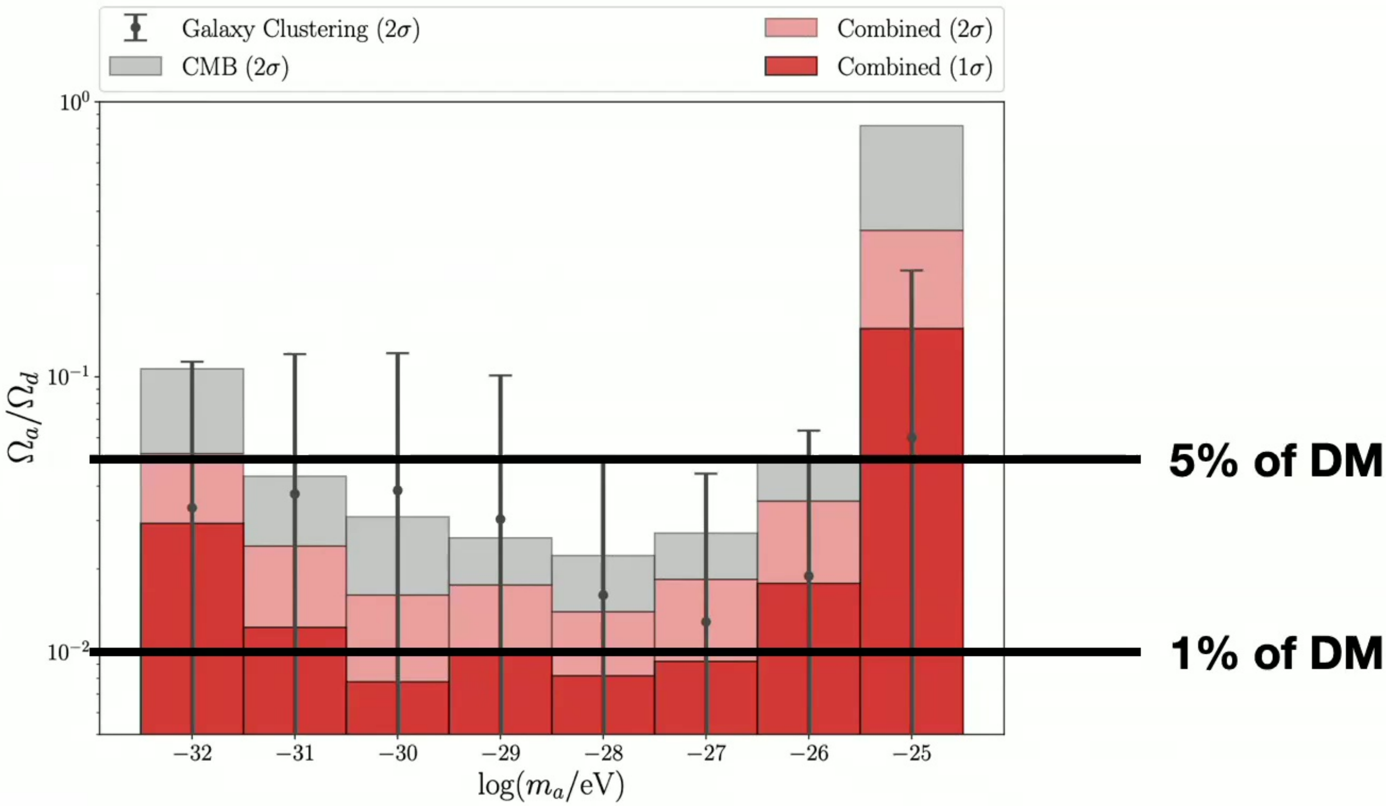
Fraction of DM



Allowed

Constraints

Fraction of DM



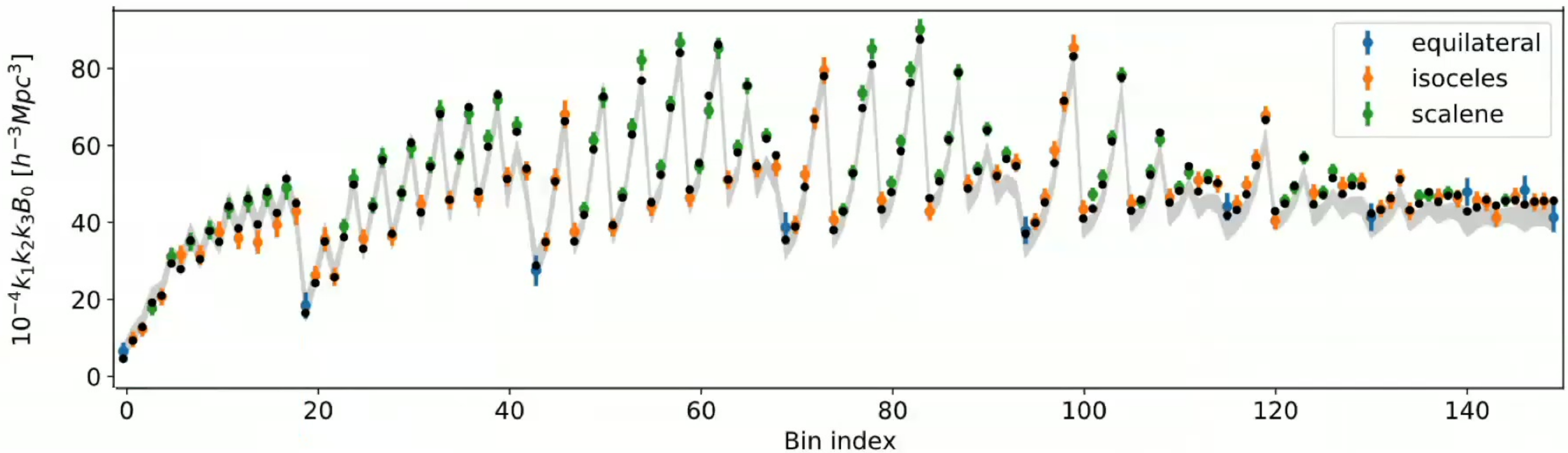
Axion Mass

Laguë *et al.* (2021)

Most scenarios: under 5% of DM

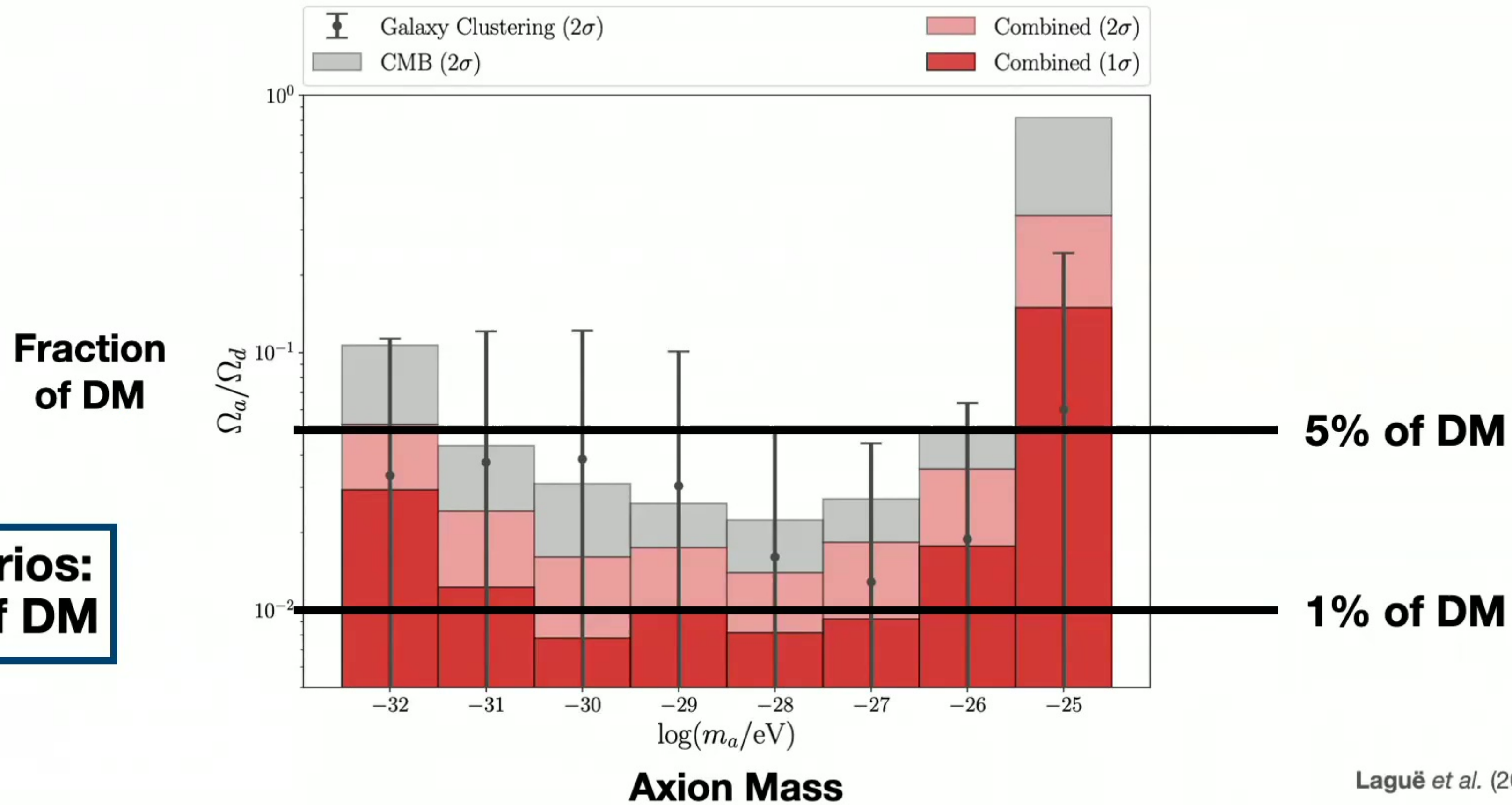
In prep.

Inclusion of P_4, B_0 & validation with CLASS – PT



D'Amico *et al.* (2022)

Constraints

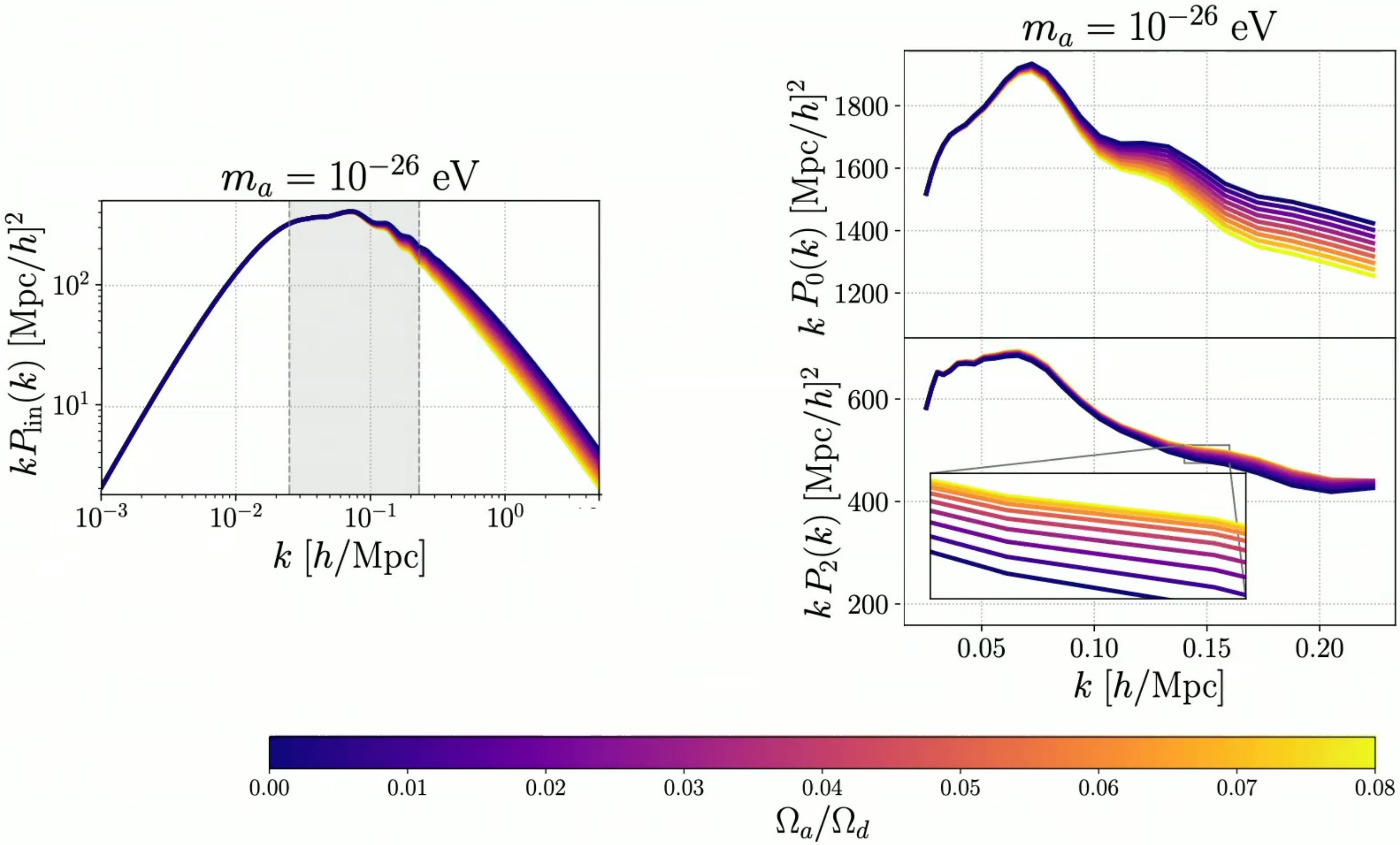


Laguë *et al.* (2021)

Most scenarios: under 5% of DM

Matter

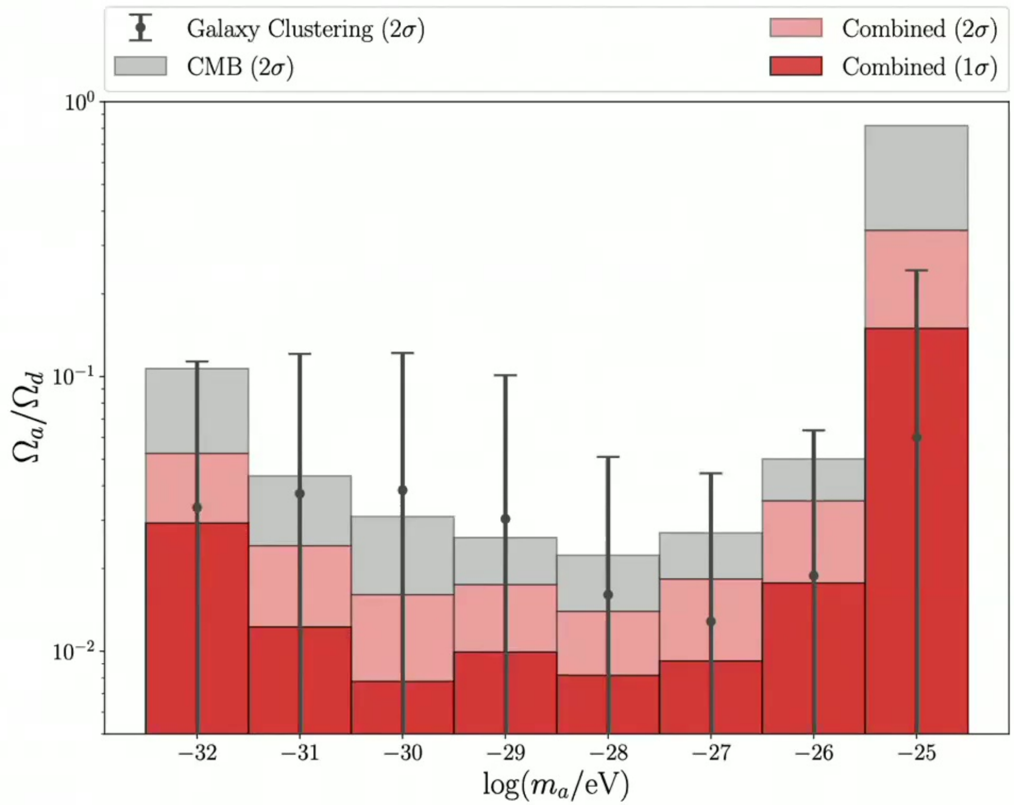
Galaxies



Laguë *et al.* (2022)

Constraints

Fraction of DM



Axion Mass

Laguë *et al.* (2021)

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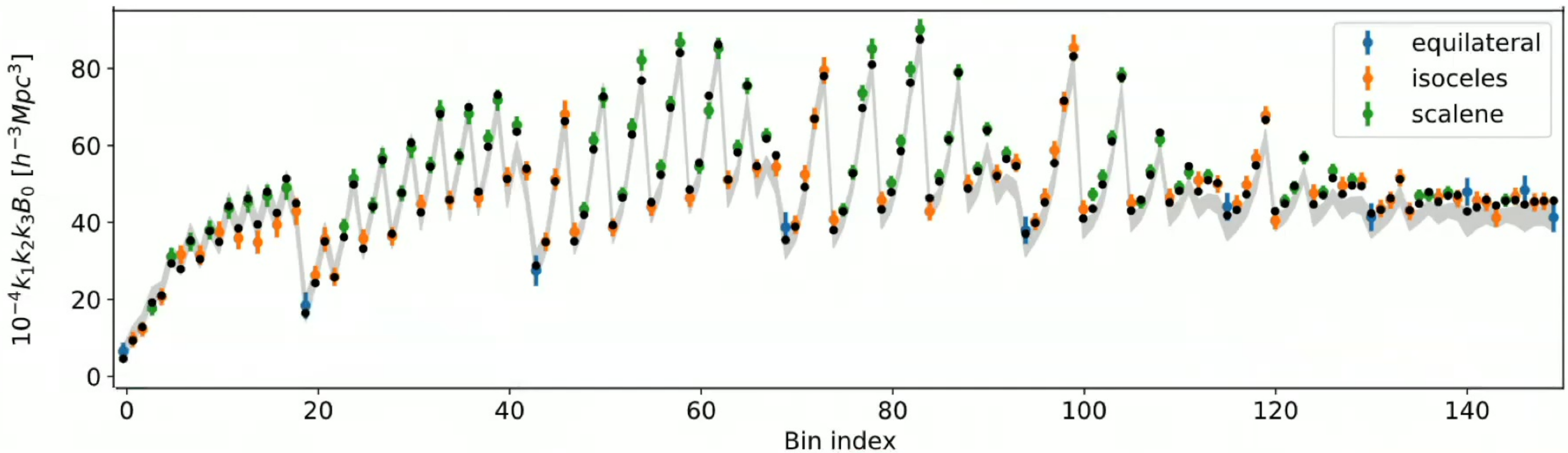


D'Amico *et al.* (2022)

Theory to Data

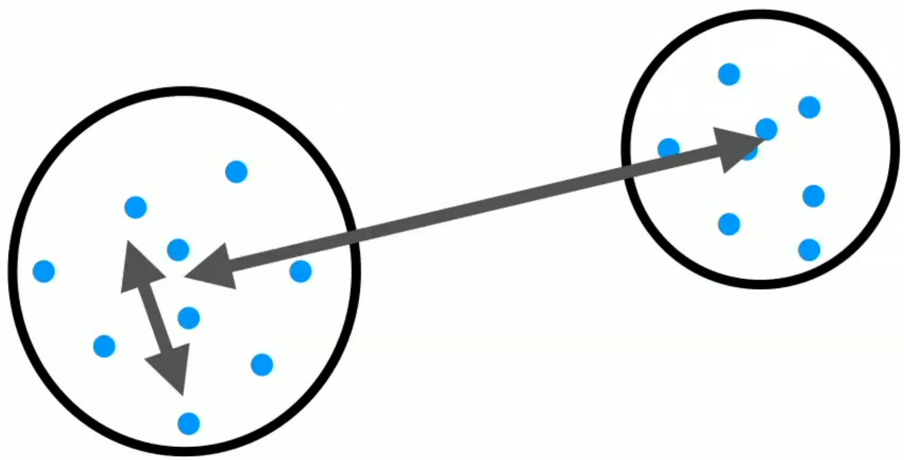
$\{m_a, \Omega_a/\Omega_d\}$

EFT of LSS $\longrightarrow P_\ell(k) \longrightarrow$ BOSS

Halo Model $\longrightarrow \xi_\pm(\theta) \longrightarrow$ DES

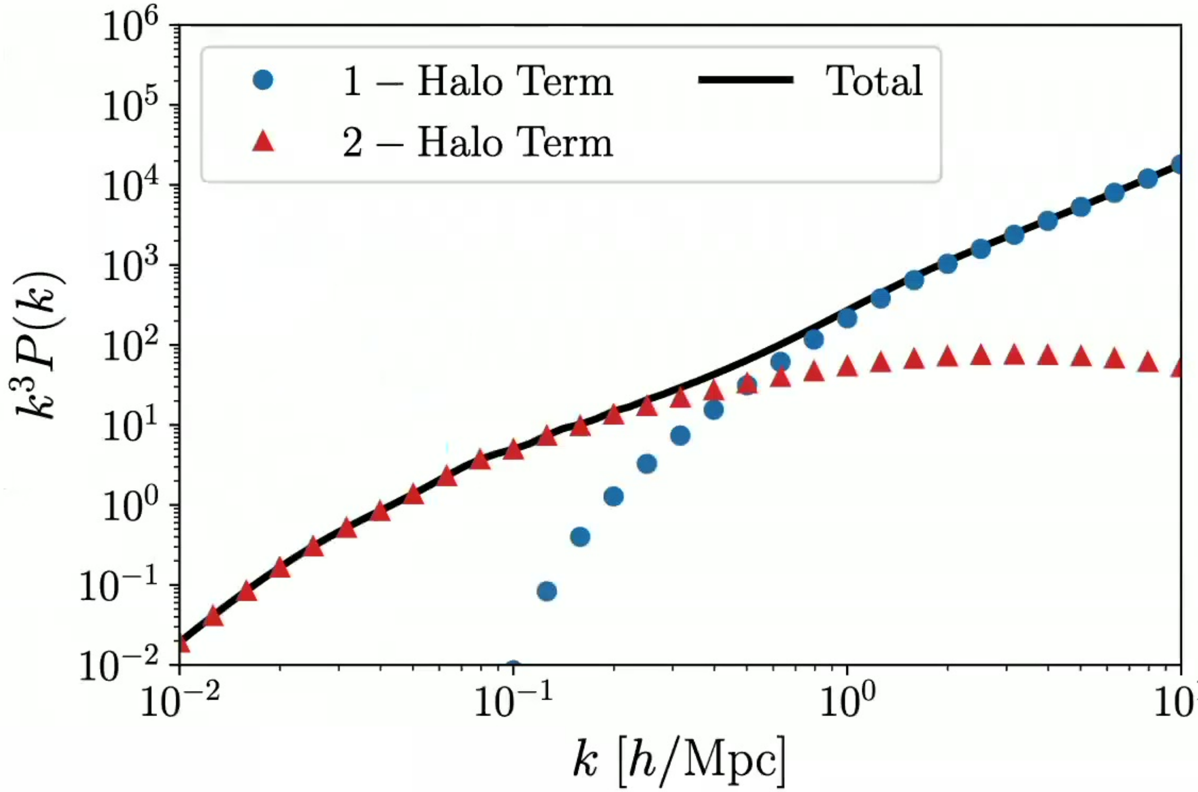
The Halo Model

$$P_{\mathrm{NL}} = P_{\mathrm{2h}} + P_{\mathrm{1h}}$$



The Halo Model

$$P_{\mathrm{NL}} = P_{2\mathrm{h}} + P_{1\mathrm{h}}$$



$$P_{\mathrm{NL}} = P_{2\mathrm{h}} + P_{1\mathrm{h}}$$

$$\approx P_{\mathrm{lin}}$$

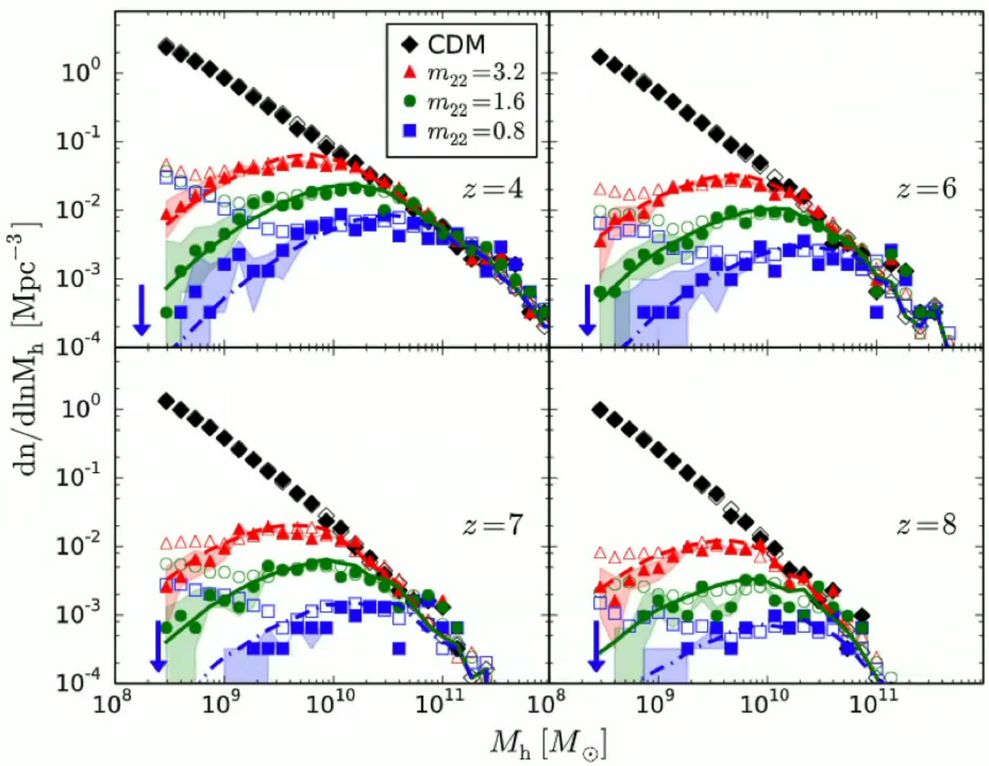
Halo Mass Function

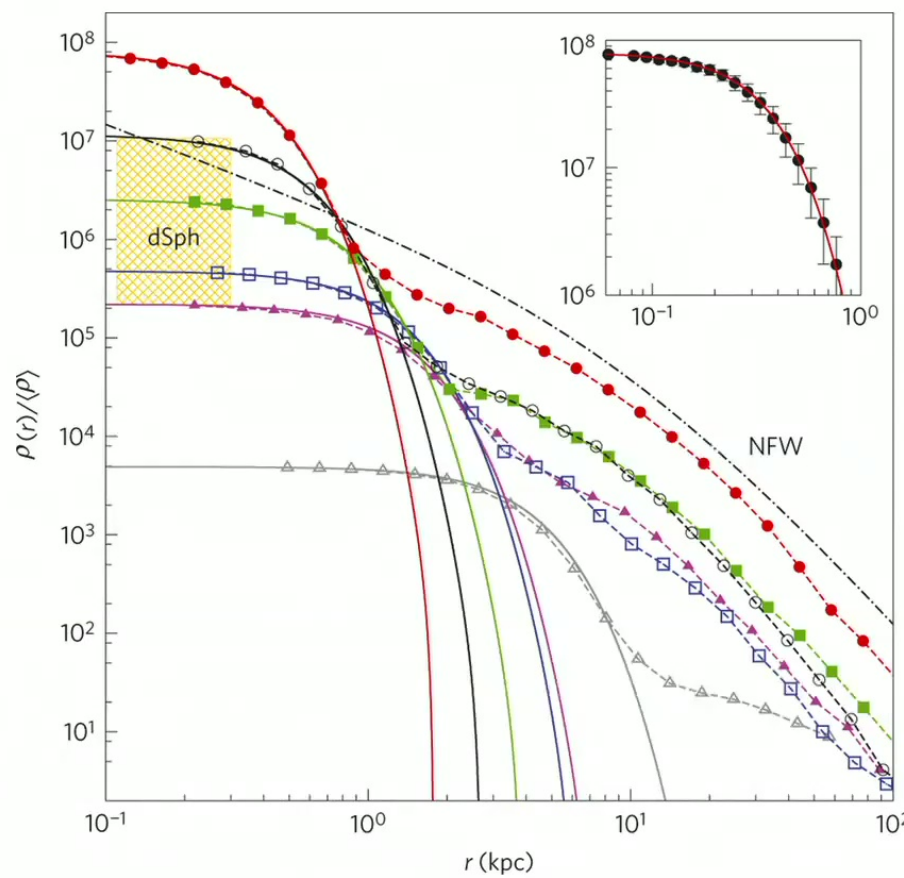
$$\propto \int_0^\infty M^2 W^2(k, M) F(M) \mathrm{d}M$$

$$= \frac{1}{M} \int_0^{r_\mathrm{v}} \frac{\sin(kr)}{kr} 4\pi r^2 \rho(r, M) \mathrm{d}r$$

Density Profile

The Halo Model with (100%) ULAs

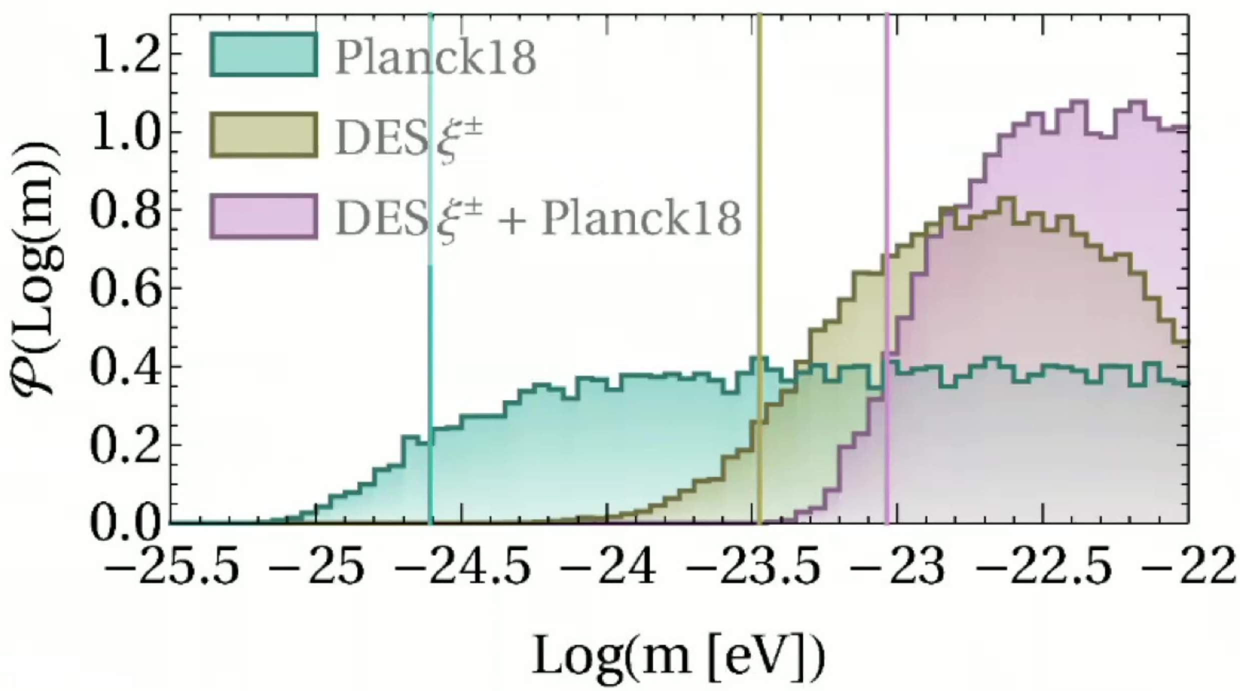




Schive *et al.* (2014/2015)

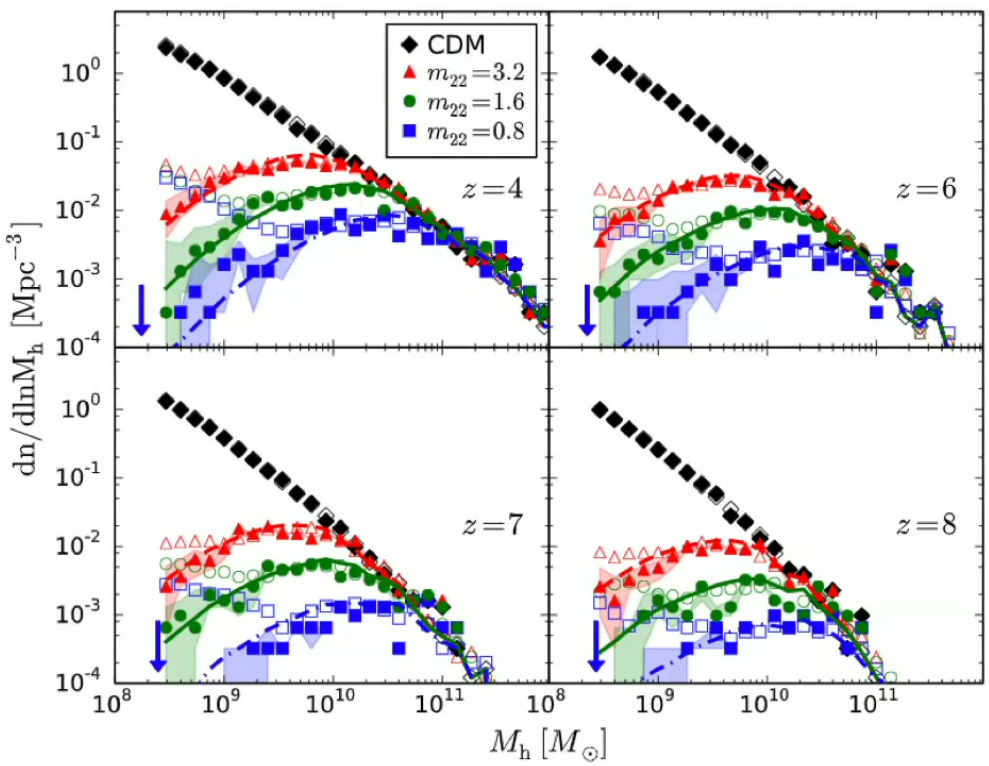
DES and Fuzzy Dark Matter

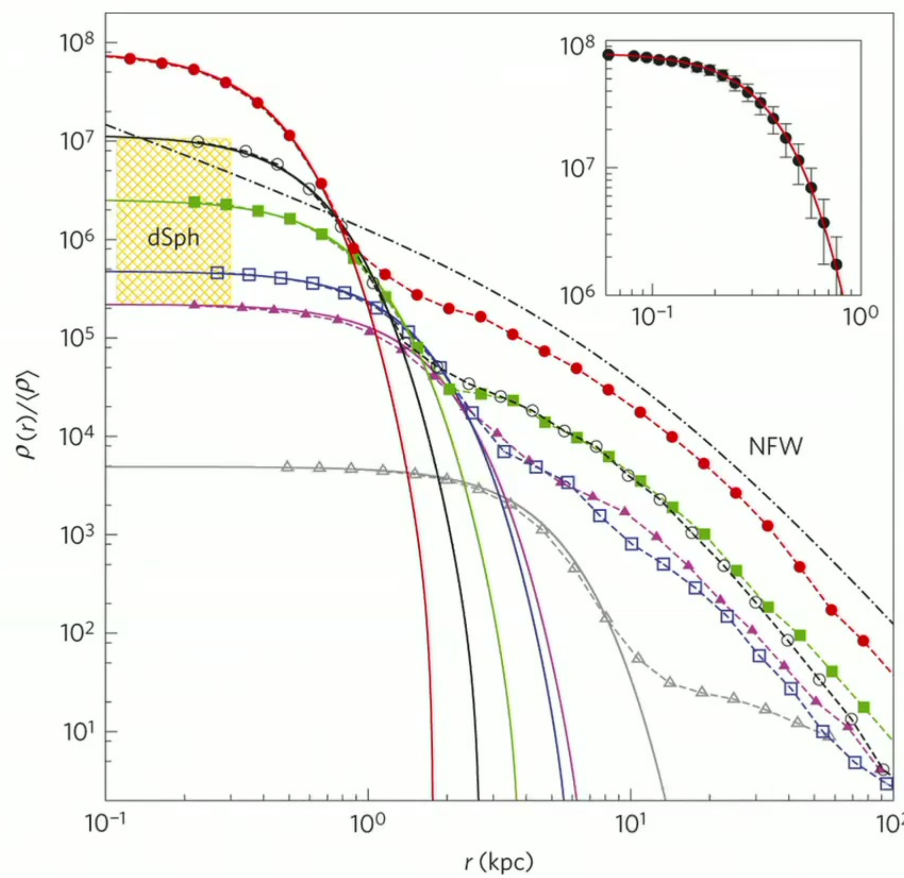
$$m > 10^{-23}\ \mathrm{eV} \quad (95\,\%\ \mathrm{C.L.})$$



Dentler *et al. (incl. AL)* (2021)

The Halo Model with (100%) ULAs

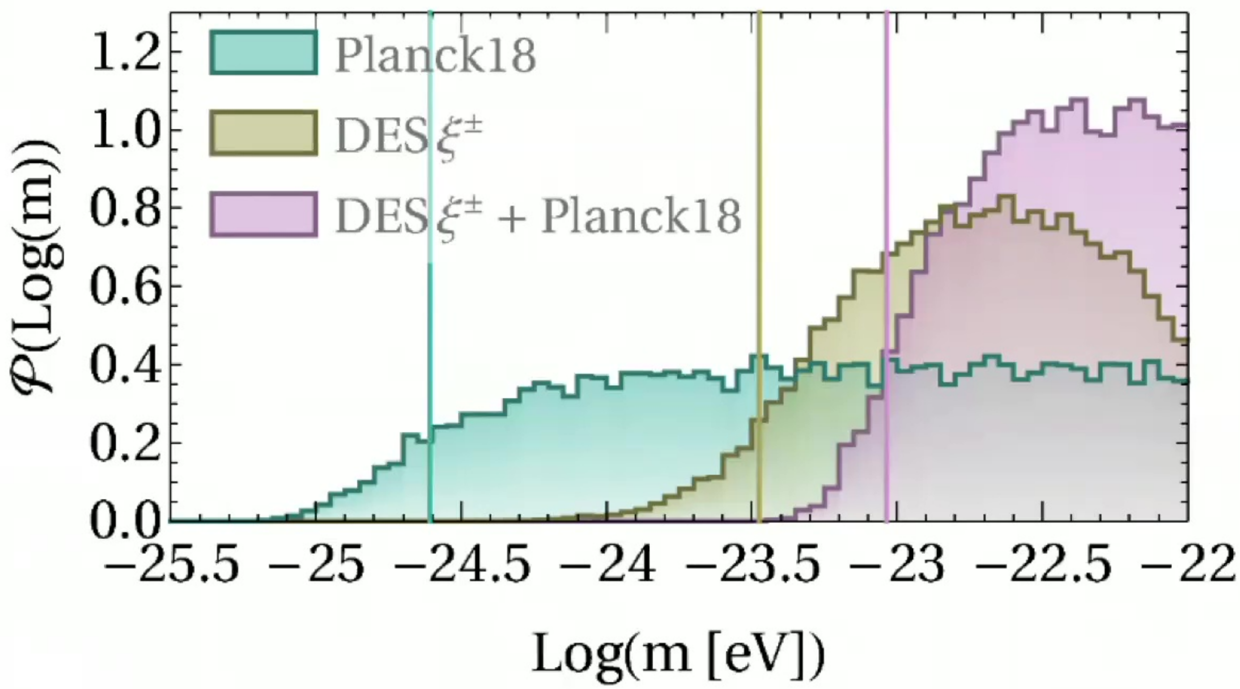




Schive *et al.* (2014/2015)

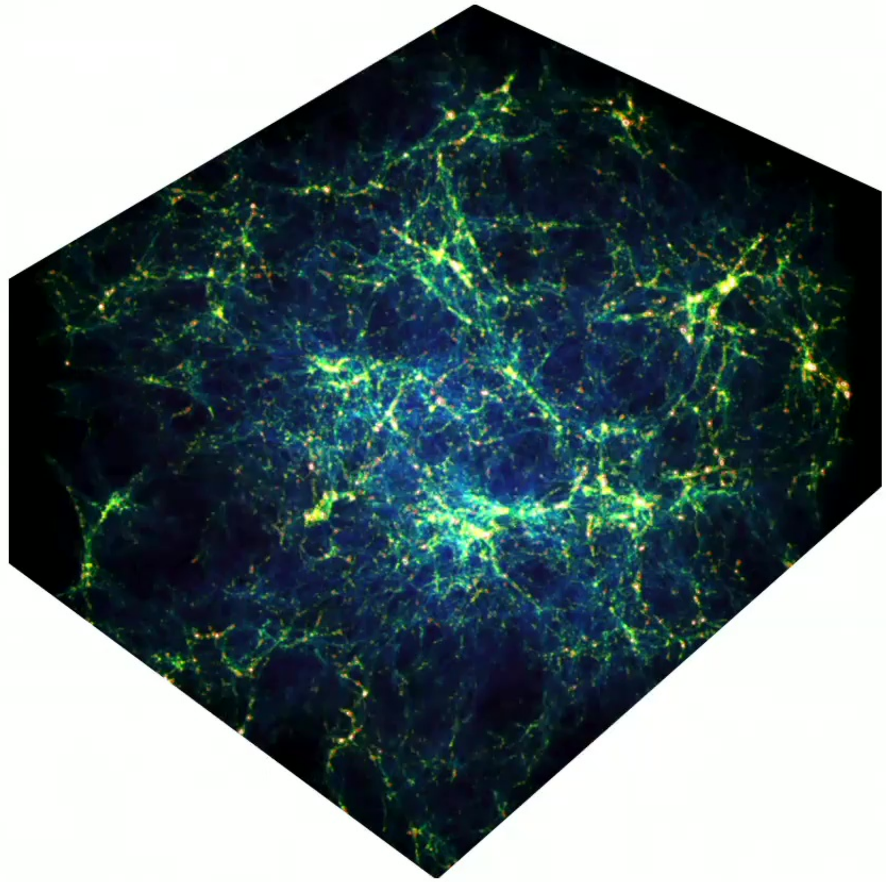
DES and Fuzzy Dark Matter

$$m > 10^{-23}\ \mathrm{eV}\quad (95\,\%\ \mathrm{C.L.})$$

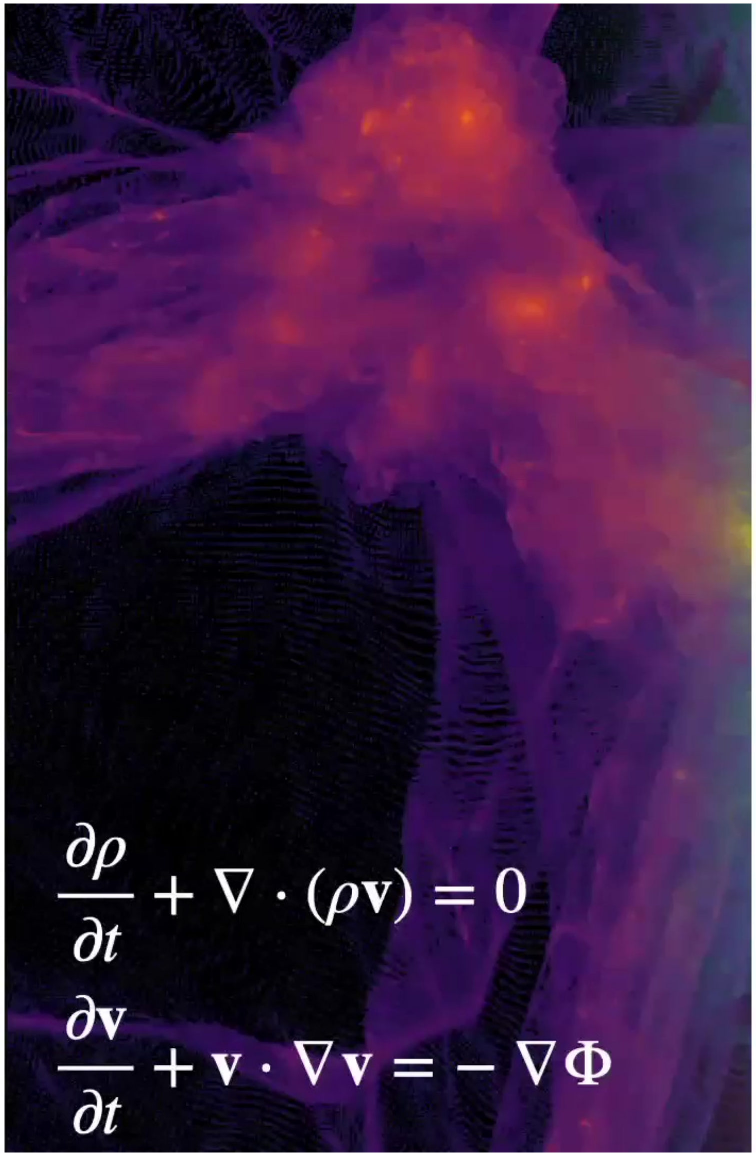


Dentler *et al. (incl. AL)* (2021)

Mixed Dark Matter Simulations



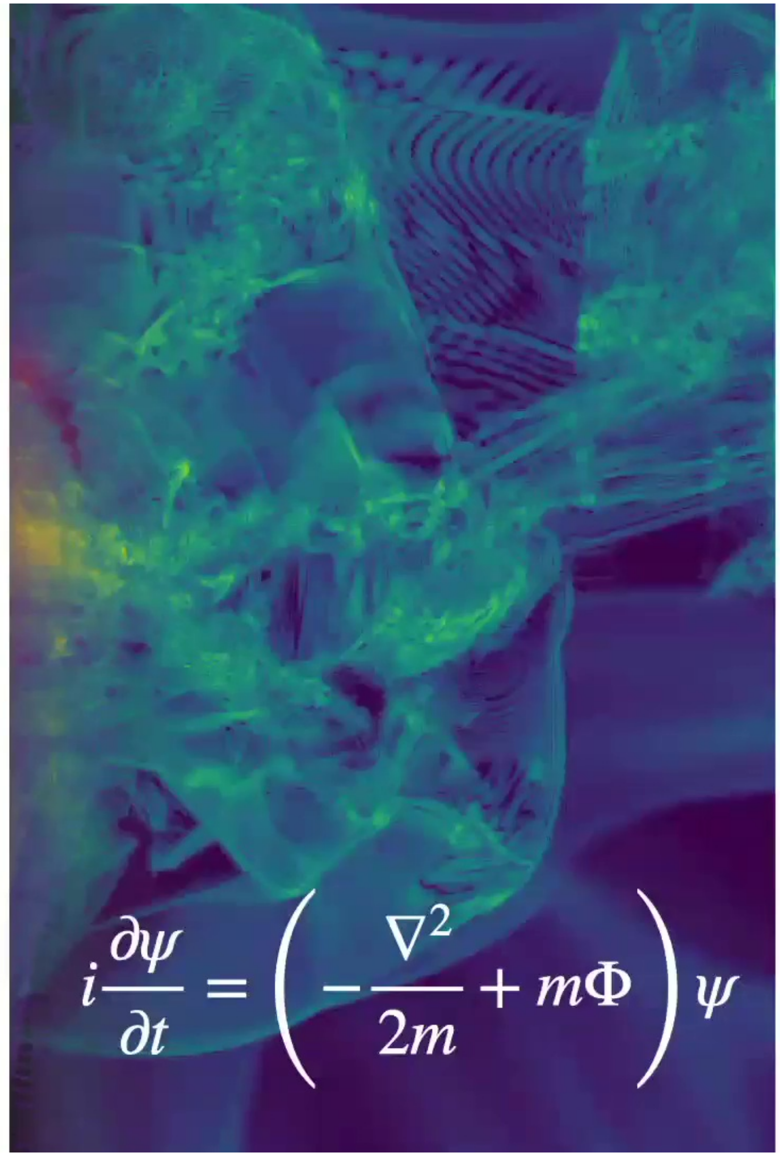
CDM



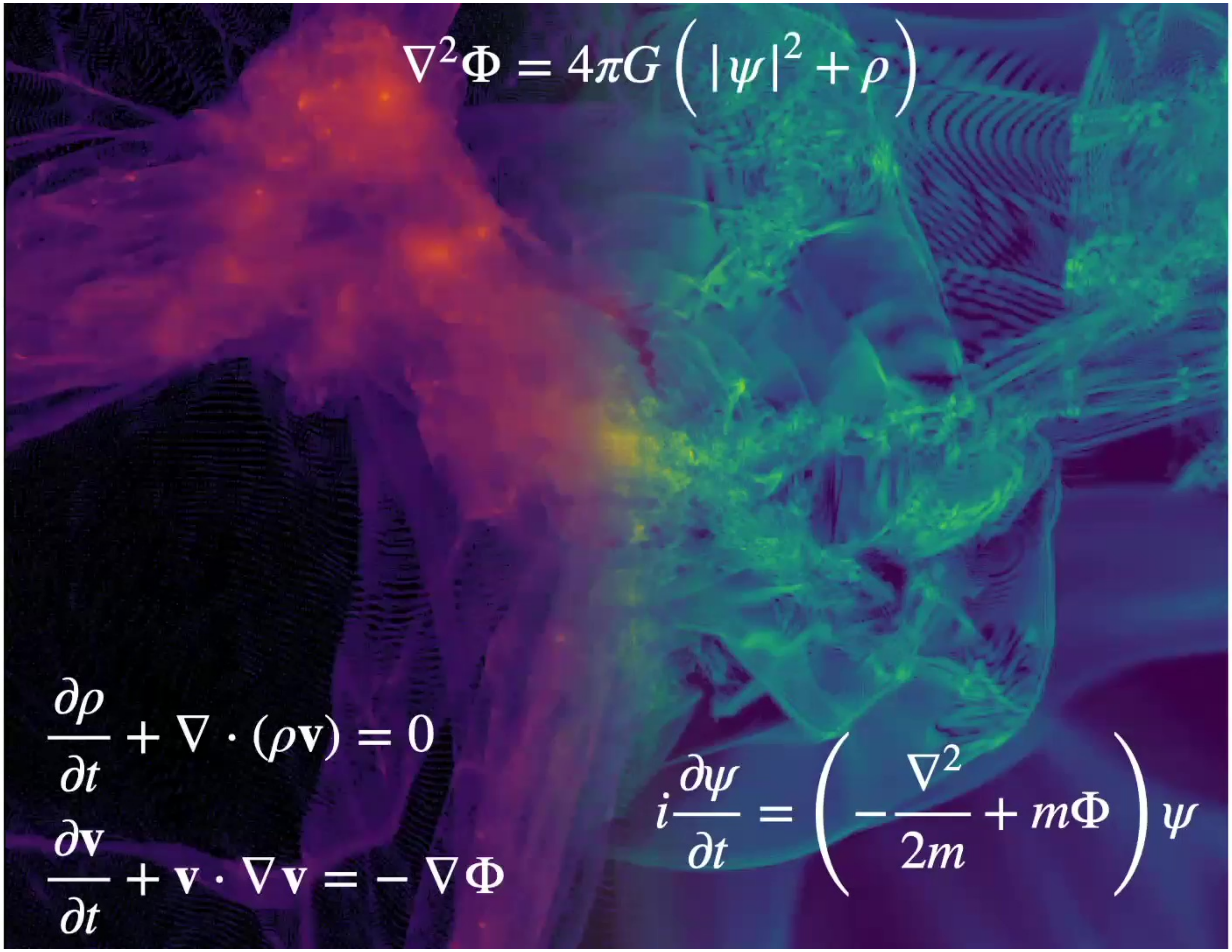
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = - \nabla \Phi$$

ULAs

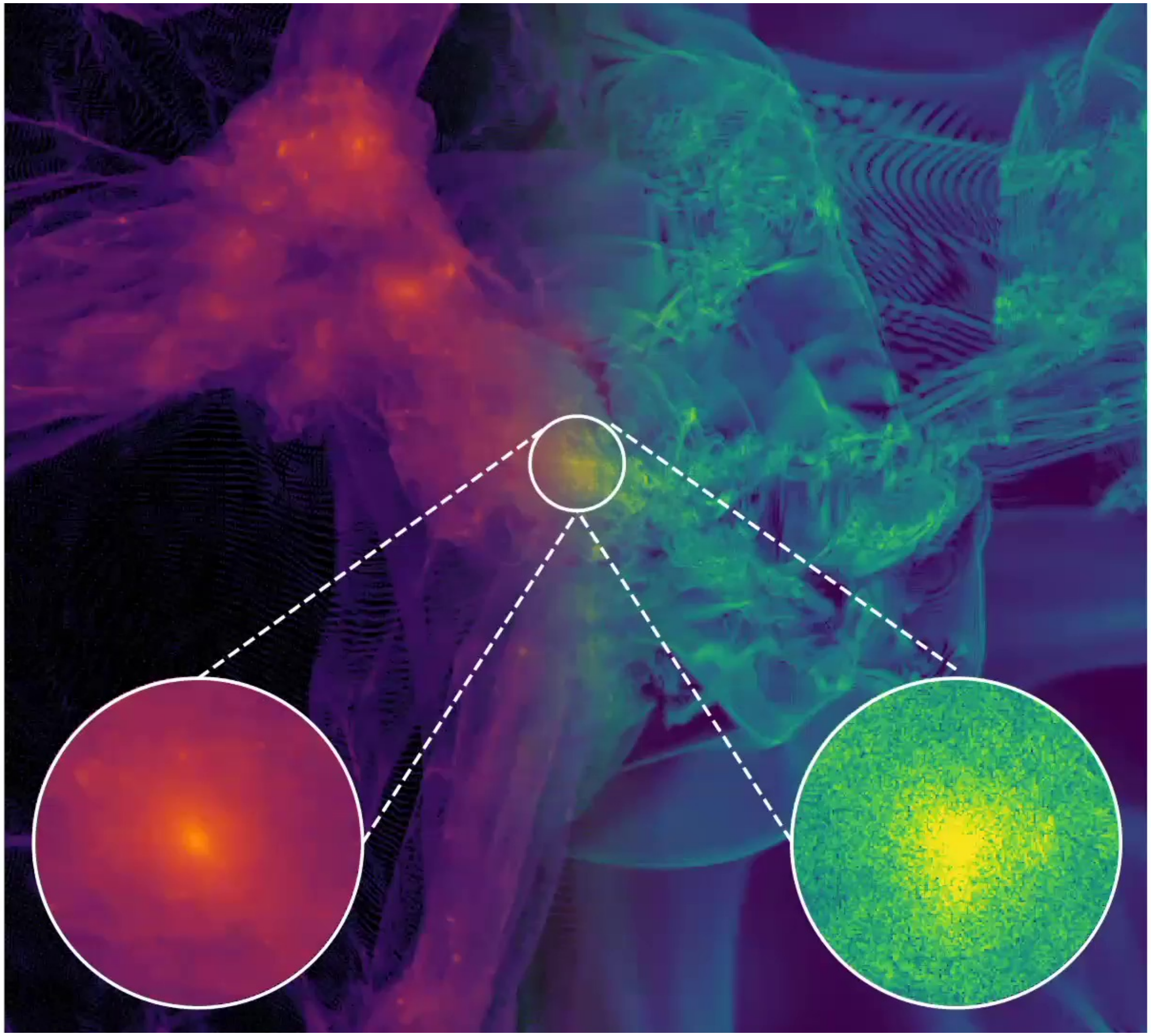

$i\frac{\partial\psi}{\partial t} = \left(-\frac{\nabla^2}{2m} + m\Phi\right)\psi$

CDM



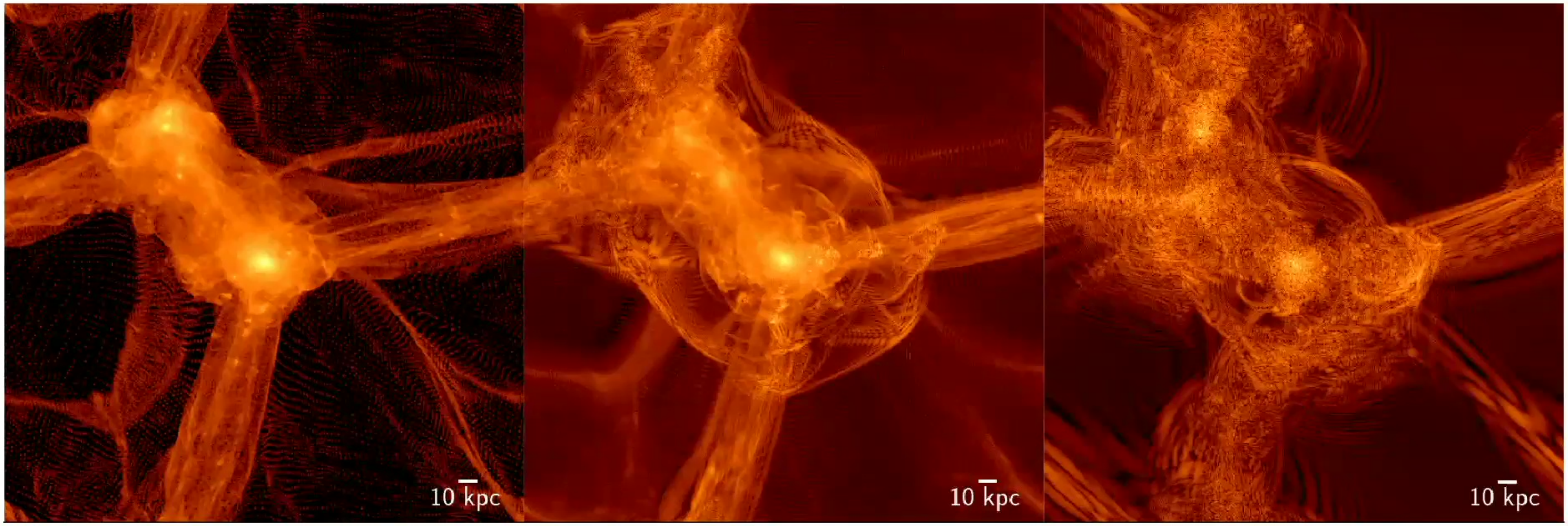
$$\nabla^2\Phi = 4\pi G\left(|\psi|^2 + \rho\right)$$
$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$
$$\frac{\partial\mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = -\nabla\Phi$$
$$i\frac{\partial\psi}{\partial t} = \left(-\frac{\nabla^2}{2m} + m\Phi\right)\psi$$

ULAs



Laguë *et al.* (in prep.)

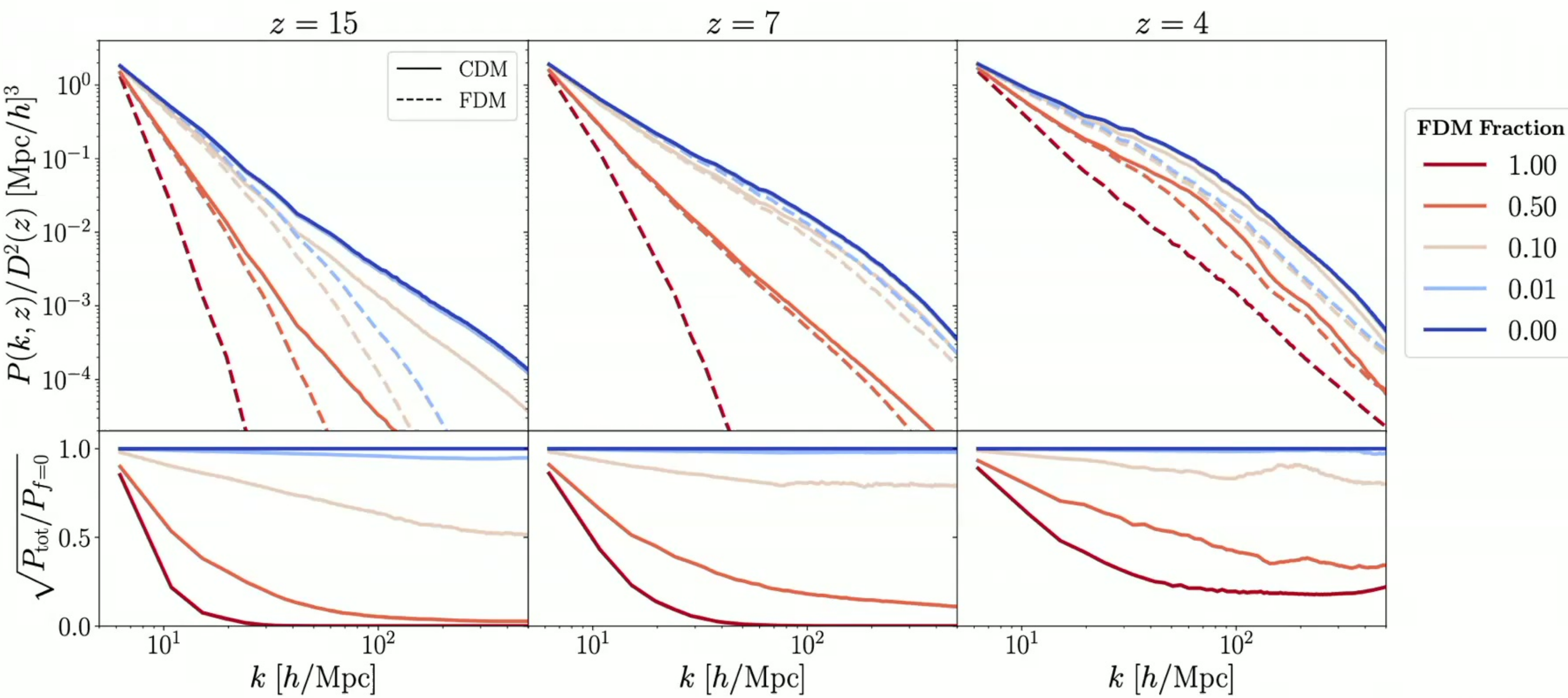
Mixed Dark Matter Simulations



100% CDM **50% - 50%** **100% ULA**

Laguë *et al.* (in prep.)

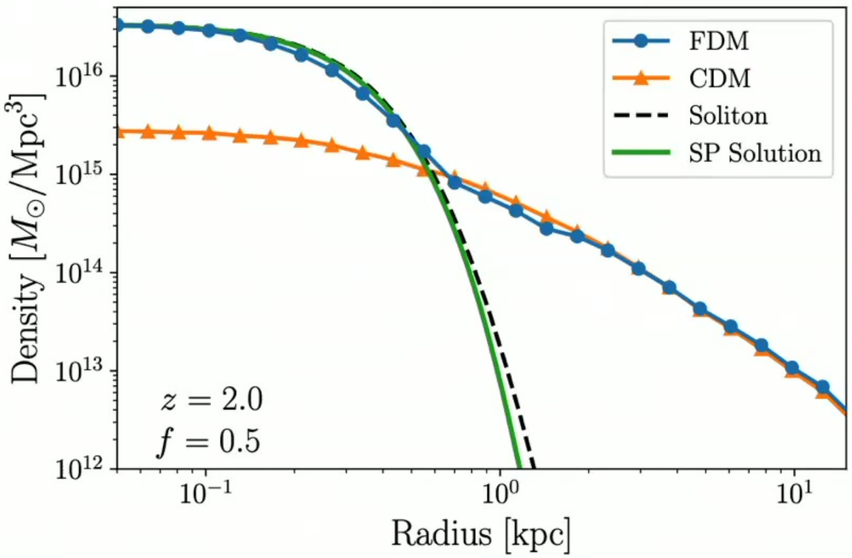
NL Power Spectra



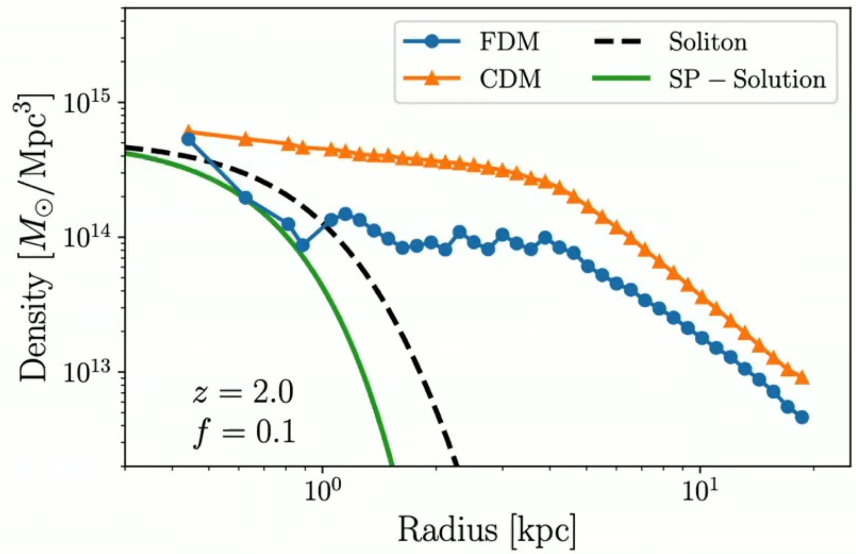
Laguë *et al.* (in prep.)

Halo Density Profiles

50% ULA



10% ULA

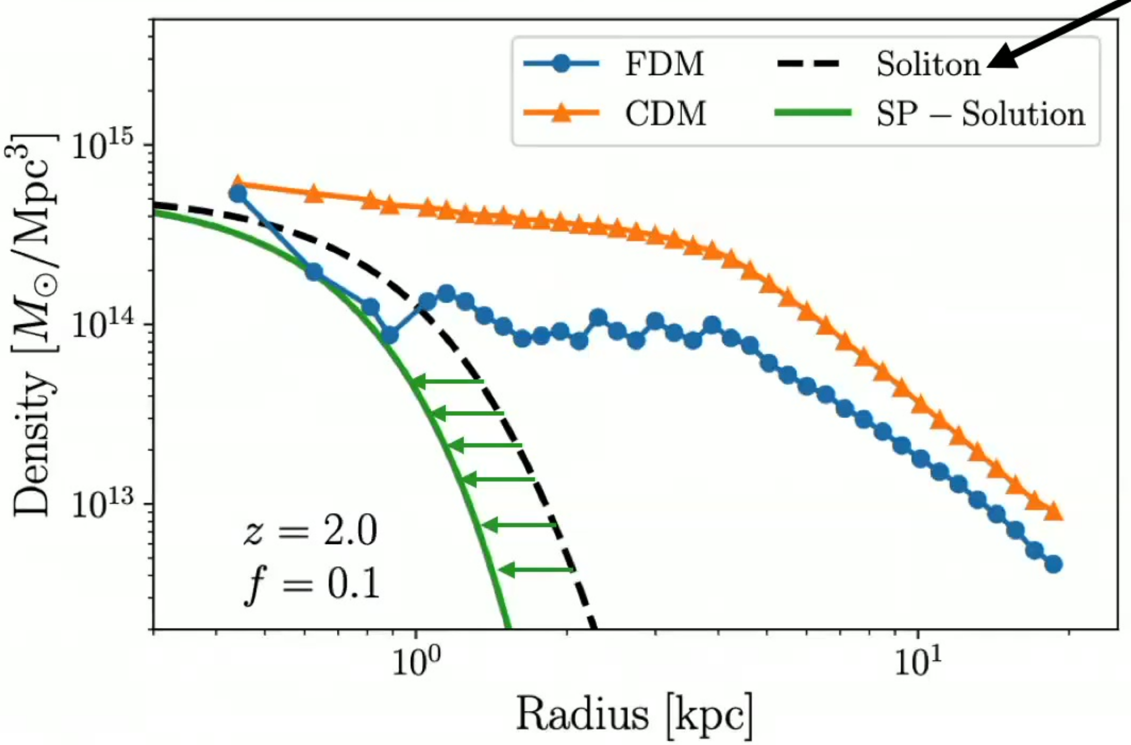


Laguë *et al.* (in prep.)

Halo Density Profiles

100% ULA density profile

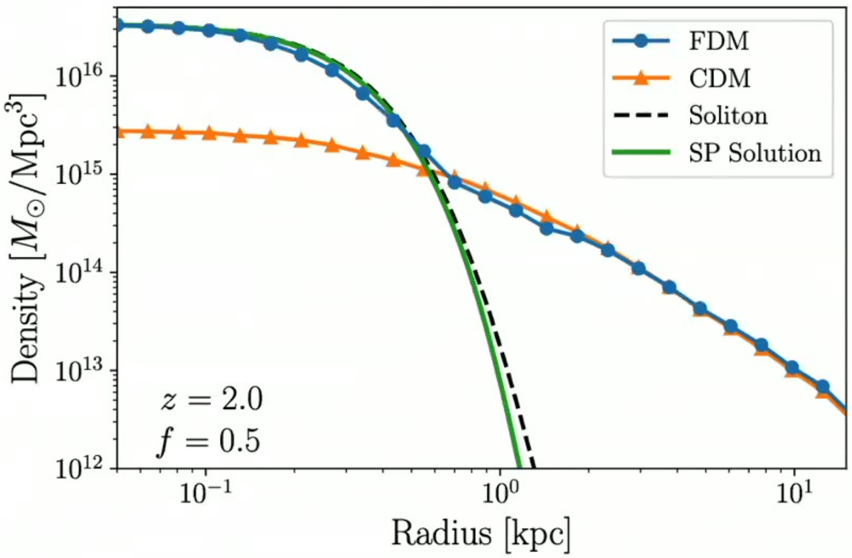
10% ULA



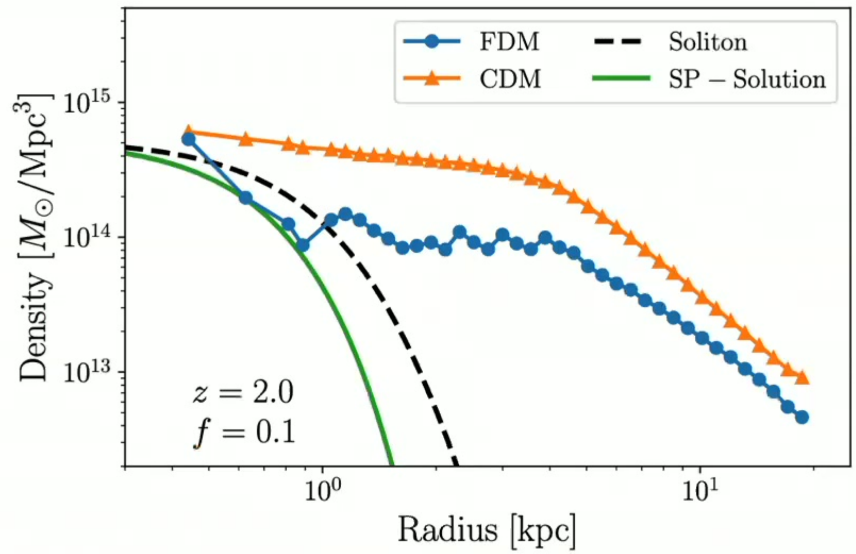
Laguë *et al.* (in prep.)

Halo Density Profiles

50% ULA



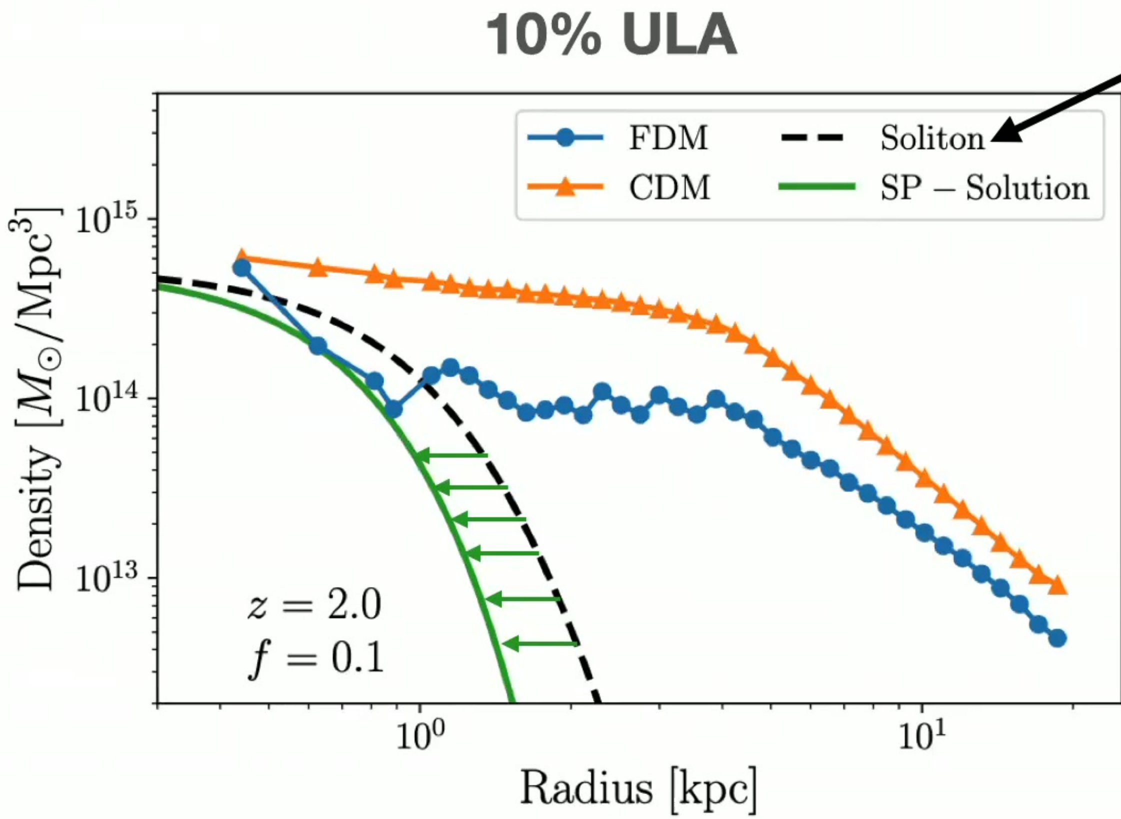
10% ULA



Laguë *et al.* (in prep.)

Halo Density Profiles

100% ULA density profile

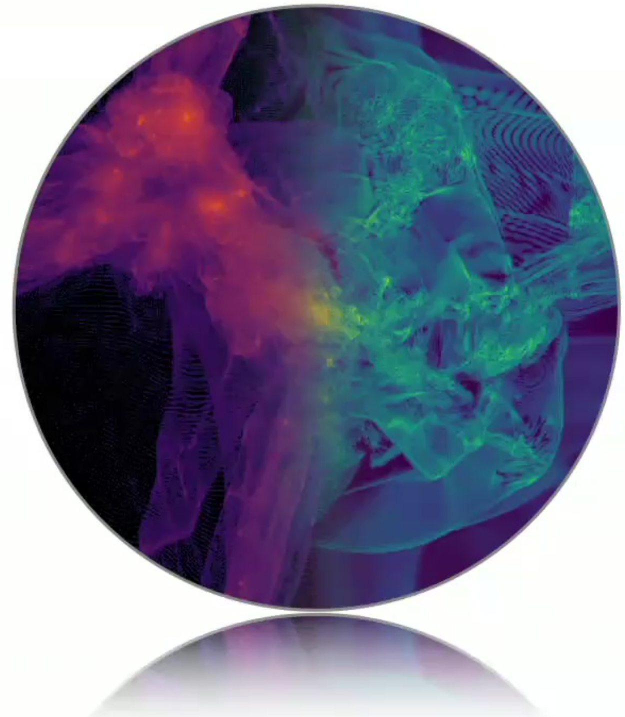


Laguë *et al.* (in prep.)

Small-Scale Tensions vs Mixed DM

Core-Cusp:	depends on fraction and baryons
Missing Satellites:	sub-halos suppressed at low fraction
Rotation Curve Diversity:	depends on distribution of ULAs

Summary



- The Axiverse and its many axions
- Sub-dominant ultralight DM
- Extra motivation from cosmological tensions
- Improved modelling on semi-linear scales
- Strong constraints from galaxy and lensing surveys
- New simulation tools