Constraining dark matter properties with structure formation

Matteo Viel - SISSA (Trieste, Italy)

Colloquium - University of Genova
10/04/24

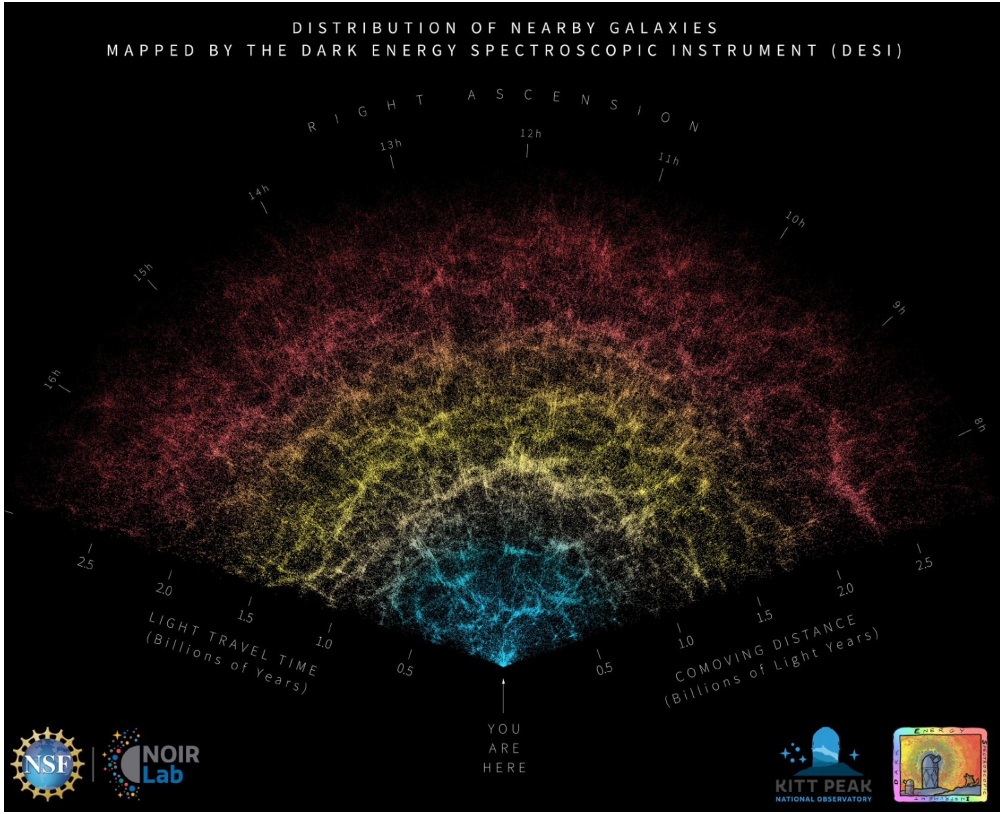
Galaxies

DESI - map of galaxies – April 2024

Matteo Viel

$$\delta(\mathbf{x}) = \frac{n_{\rm gal}(\mathbf{x}) - \overline{n}_{\rm gal}}{\overline{n}_{\rm gal}}$$

$$P(k) =< |\delta_{\mathbf{k}}|^2 >$$



$$\delta \sim 1$$

Galaxies

Webb's First Deep Field (NIRCam Image)

Matteo Viel

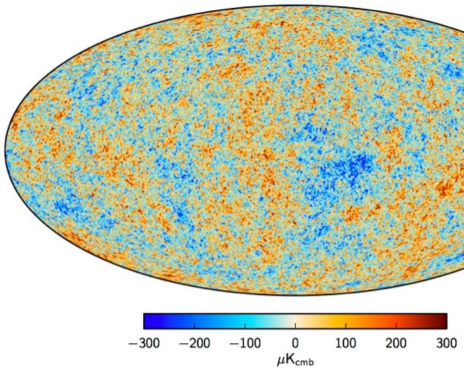
$$\delta \sim 10^6$$

Structure Formation

Matteo Viel

$\delta T/T \sim 10^{-5}$

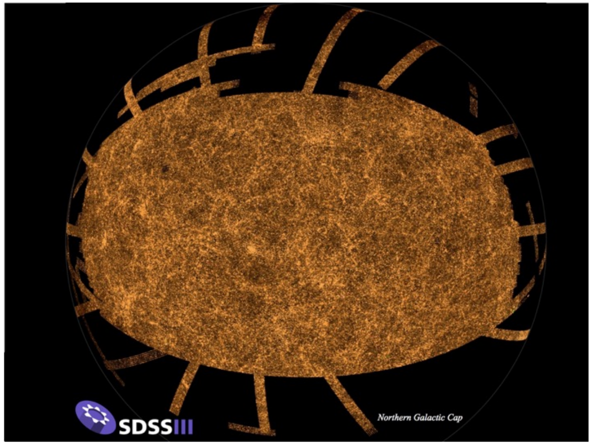
Initial Conditions



13 Gyrs later

Under the influence of gravity
and astrophysical processes....

Non-linear Universe



ΛCDM model:

- ➢ DM required at >50σ from CMB data alone
- ➢ Support for hierarchical structure formation
- ➢ Quantitative understanding in terms of linear (Jeans) theory

\+ perturbation theories
\+ hydrodynamic simulations

Peebles 1982

THE ASTROPHYSICAL JOURNAL, **263**:L1–L5, 1982 December 1

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

Subject headings: cosmic background radiation — cosmology — galaxies: formation

DM key ingredient in cosmic structure evolution
DM perturbations can grow before decoupling
(while baryon/radiation fluid oscillates)

Dark Matter Free Streaming

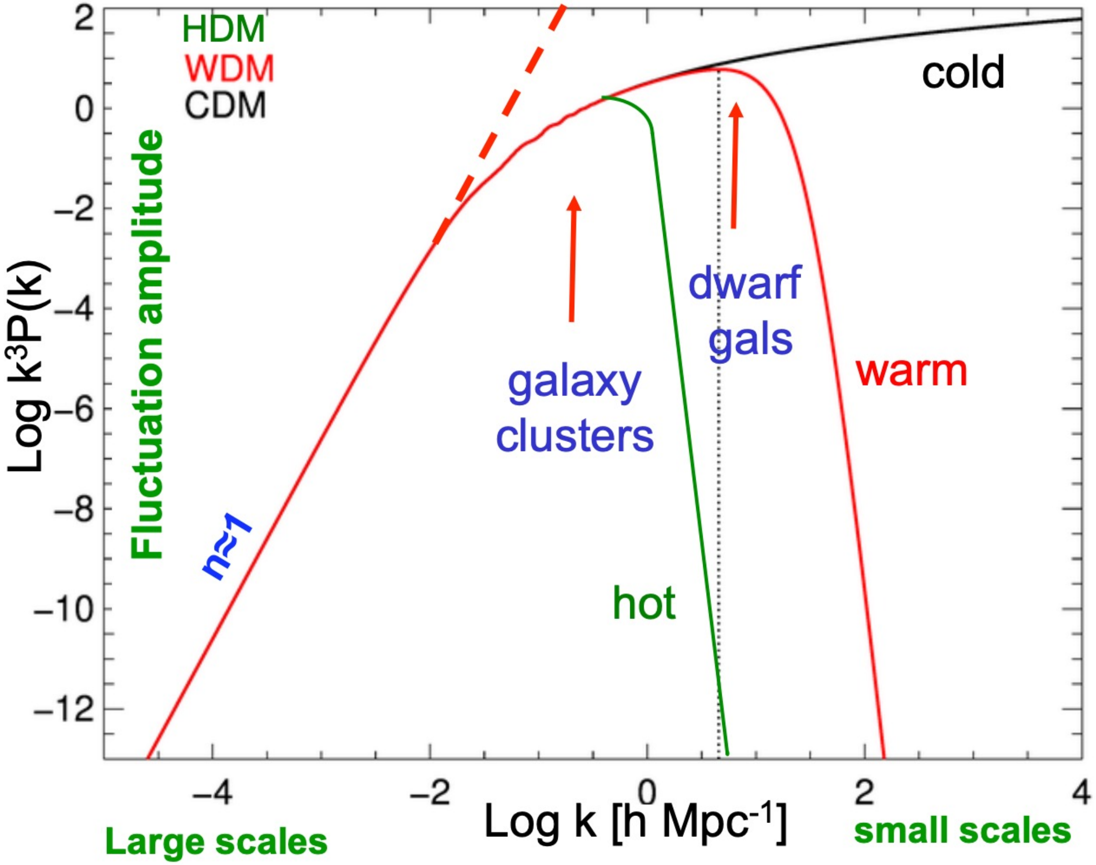
Matteo Viel

$$\lambda_{\rm FS} \propto m_{\rm DM}^{-1}$$

- M_{CDM} ~ 100 GeV
  SUSY – cutoff 10^{-6} $M_\odot$

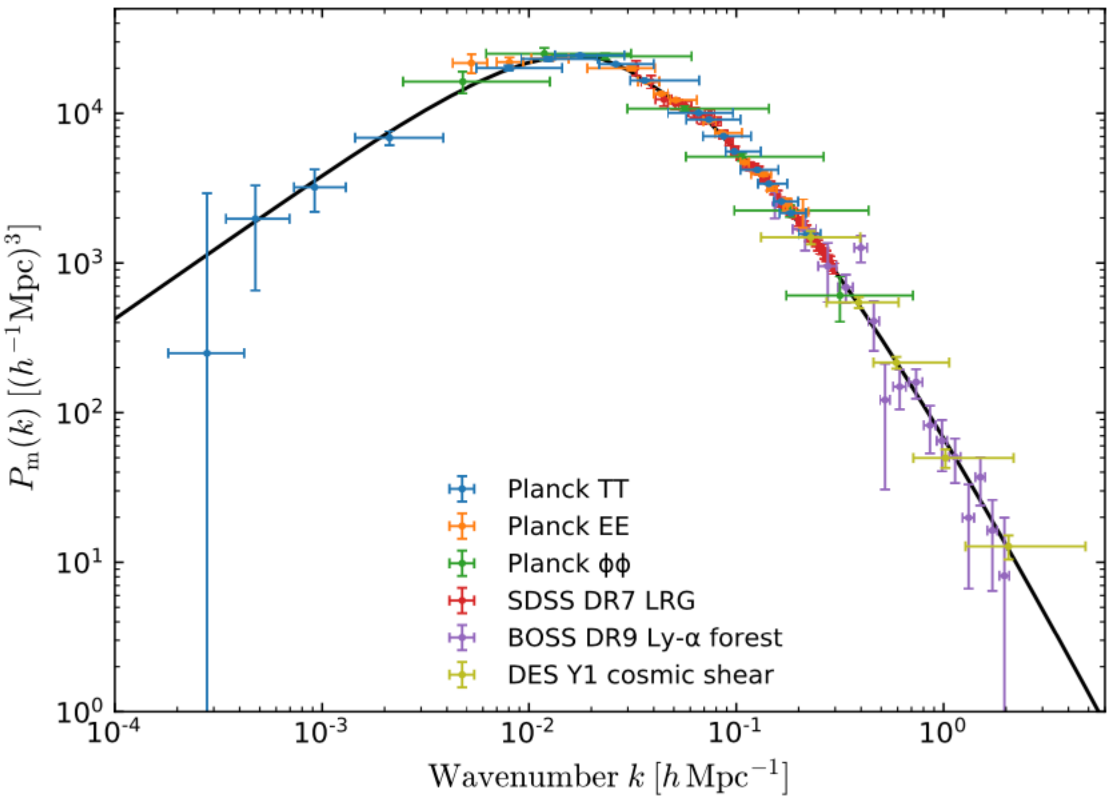
- M_{WDM} ~ few keV
  sterile ν – cutoff 10^{9} $M_\odot$

- M_{HDM} ~ few eV
  neutrinos – cutoff 10^{15} $M_\odot$



The linear matter power spectrum P(k)

- Fluctuations are now measured from a variety of observables
- Spanning a wide range of scales and redshifts
- Important tests for fundamental physics and structure formation processes



Crisis of (cold) dark matter at small scales?

- Missing satellite problem: more Milky Way subhaloes than there are observed satellites

- Cusp-core problem: simulations tend to predict cuspy DM profiles while in some cases cored profile seemed to be preferred

- Too-big-to fail problem: DM sims have ~10 massive subhaloes with Vmax > 10 km/s but only ~3 are observed

- The satellite-disk problem: a plane of corotating dwarf galaxies orbiting Andromeda

Crisis of (cold) dark matter at small scales?

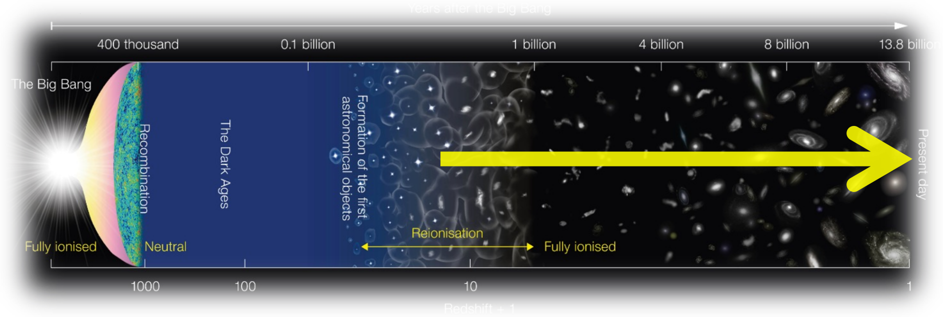
- Missing satellite problem: more Milky Way subhaloes than there are observed satellites
  Solution: more satellites have been observed and then most of the subhaloes do not form stars due to reionization

- Cusp-core problem: simulations tend to predict cuspy DM profiles while in some cases cored profile seemed to be preferred
  Solution: physics of star formation can alter the profile

- Too-big-to fail problem: DM sims have ~10 massive subhaloes with Vmax > 10 km/s but only ~3 are observed
  Solution: physics of galaxy formation can reduce circular velocity in subjaloes

- The satellite-disk problem: a plane of corotating dwarf galaxies orbiting Andromeda
  Solution: statistical ensemble of simulated Andromeda-like galaxies reduce the fine-tuning

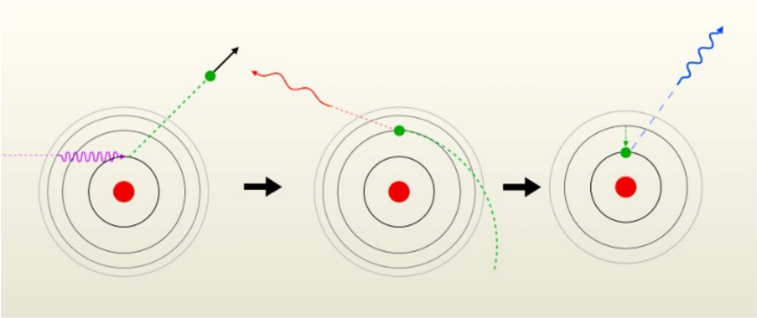
Intergalactic Medium



Post-reionization Universe

- Complementary to Cosmic Microwave Background (CMB) and local probes
- More linear Universe (simpler physics?)
- High-z galaxies are cold gas (HI) dominated
- Large **uncharted** volume: JWST, LSST, Euclid, DESI, Intensity Mapping (IM) experiments

HI



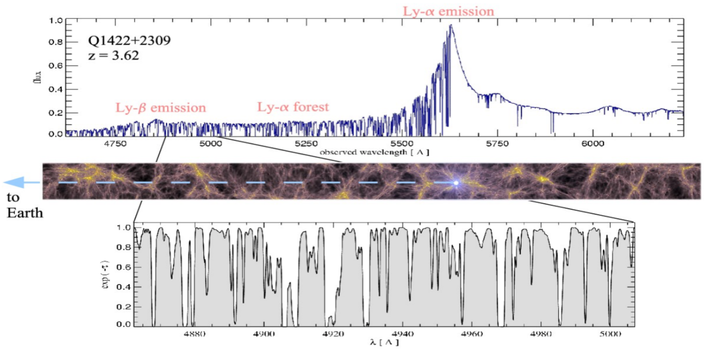
$$\lambda = \lambda_0(1+z)$$

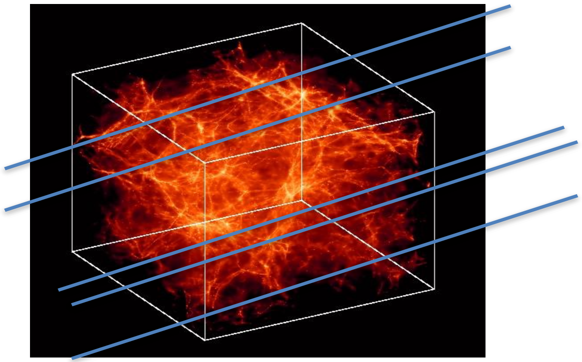
$$\lambda_0 = 1215.67\,\text{Å}$$

Intergalactic Medium

Matteo Viel

The Lyman-alpha forest

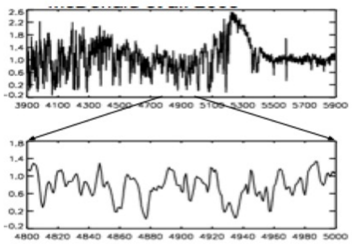




- **Intergalactic medium:** filaments at low density (outside galaxies) – distances spanned 0.1-100 Mpc/h
- Lyman-alpha forest its the main manifestation of the IGM
- High redshift observable, 1D projected power (but also 3D)

Data

BOSS/SDSS-III



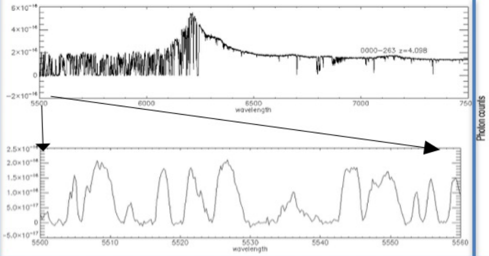
Low resolution BOSS and SDSS-III spectra S/N~2-3 – 160,000 spectra

Used to detect BAOs at z=2.3 and correlations in the transverse direction

Used to place stringent constraints on neutrino masses <0.12 eV

Busca+13, Slosar+14, Font-Ribera+14
Palanque-Delabrouille+15
Seljak+06, Baur+16, Yeche+17 etc.

XQ-100



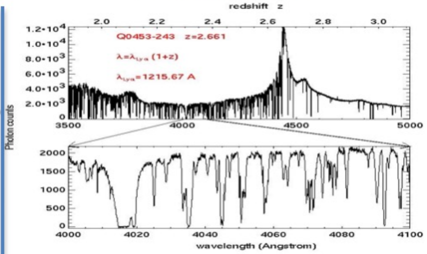
Medium resolution X-Shooter VLT spectra S/N ~ 30

100 spectra at z>3.5

Used to place stringent constraints on Warm Dark Matter in combination with high res. spectra

Irsic, MV+ 17a,17b
Lopez+16, Irsic+16

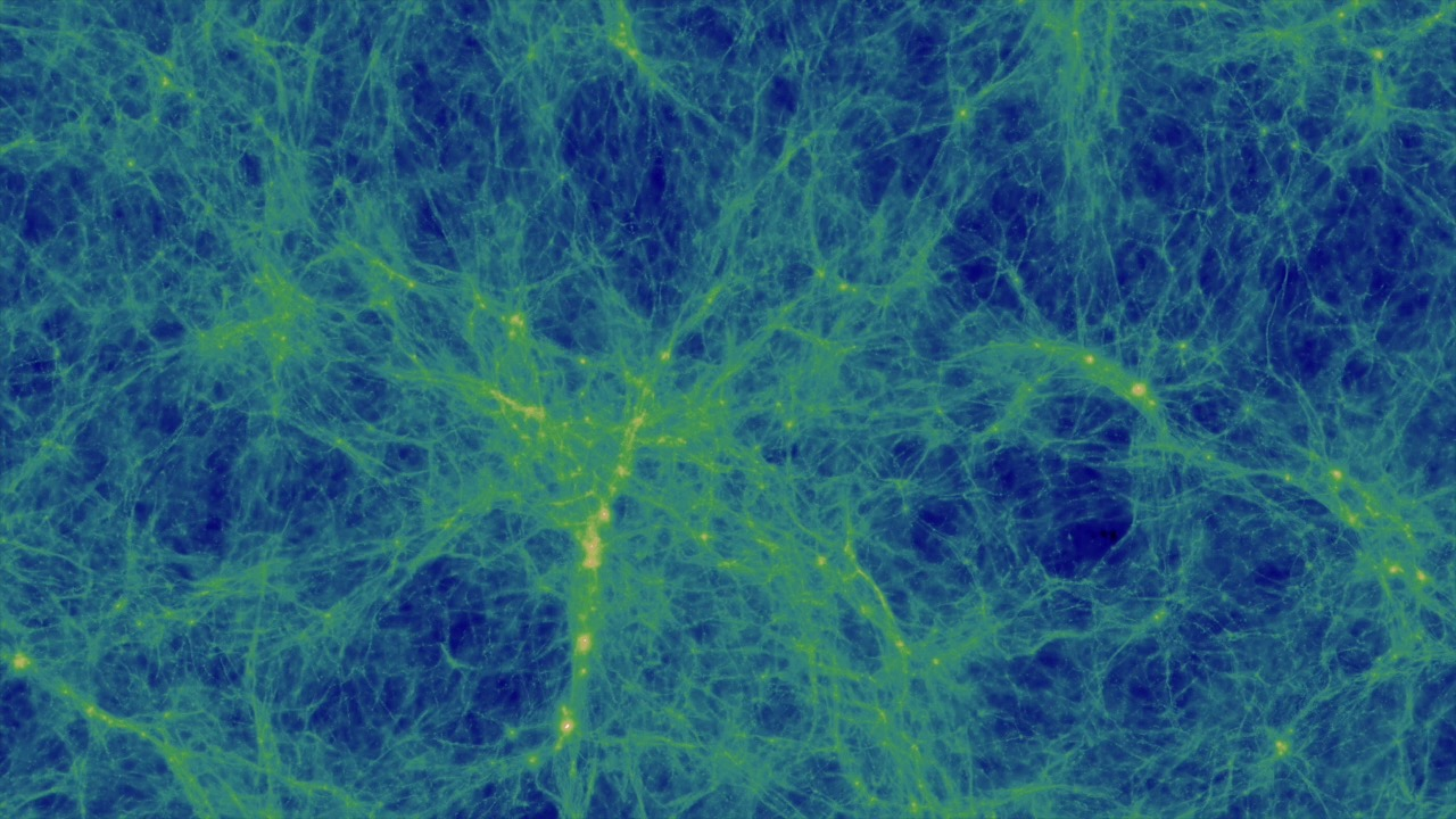
HIRES/MIKE

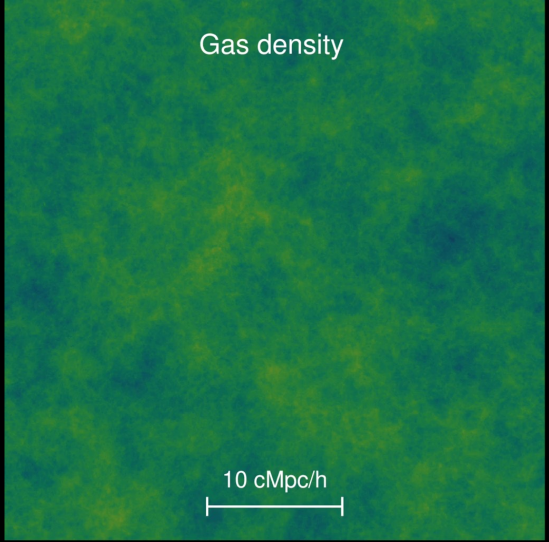


High resolution VLT or Keck spectra S/N ~100 – ~hundreds of spectra

Used for WDM, astrophysics of the IGM and galaxy formation, variation of fundamental constants

*MV+05,08,13, **Becker**+11*
Yeche+17, Garzilli+18 ,
Bosman+18





Gas temperature $z=20.0$

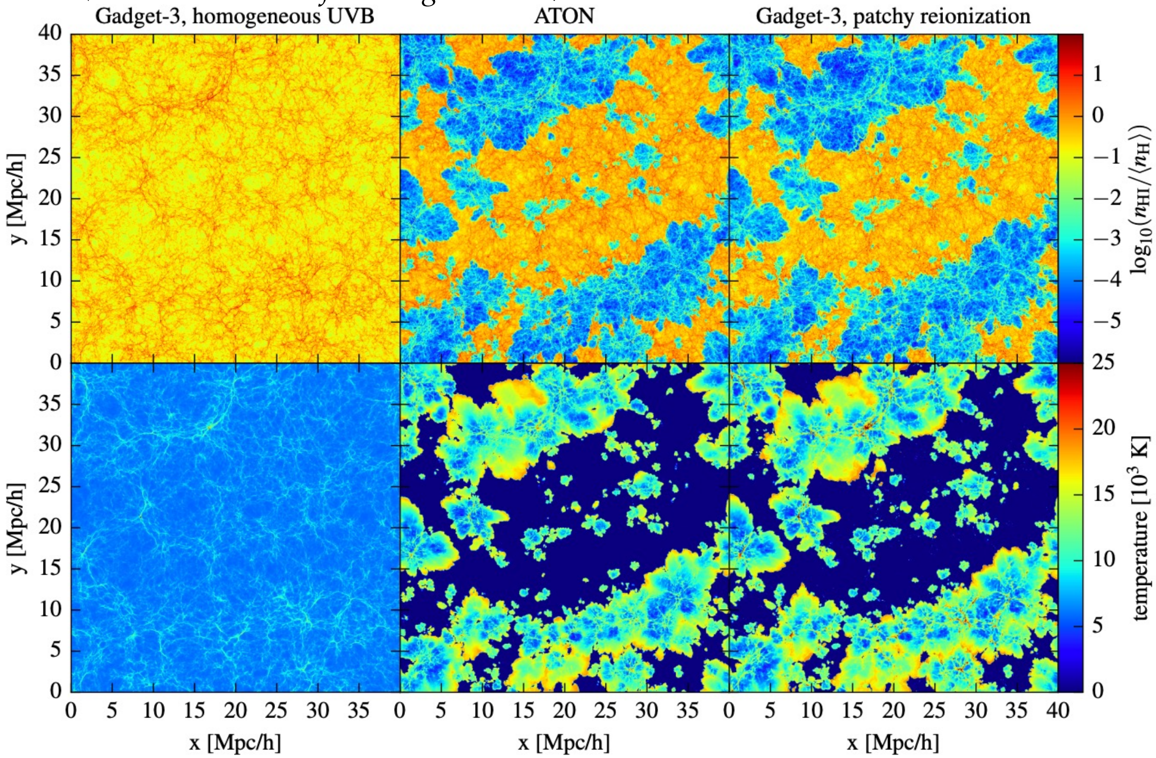
HI fraction

HI photoionisation rate

The simulations - I

https://www.nottingham.ac.uk/astronomy/sherwood/

z=7 (with reionization finishing at z=5.3)



Bolton+17
Puchwein, Bolton+23

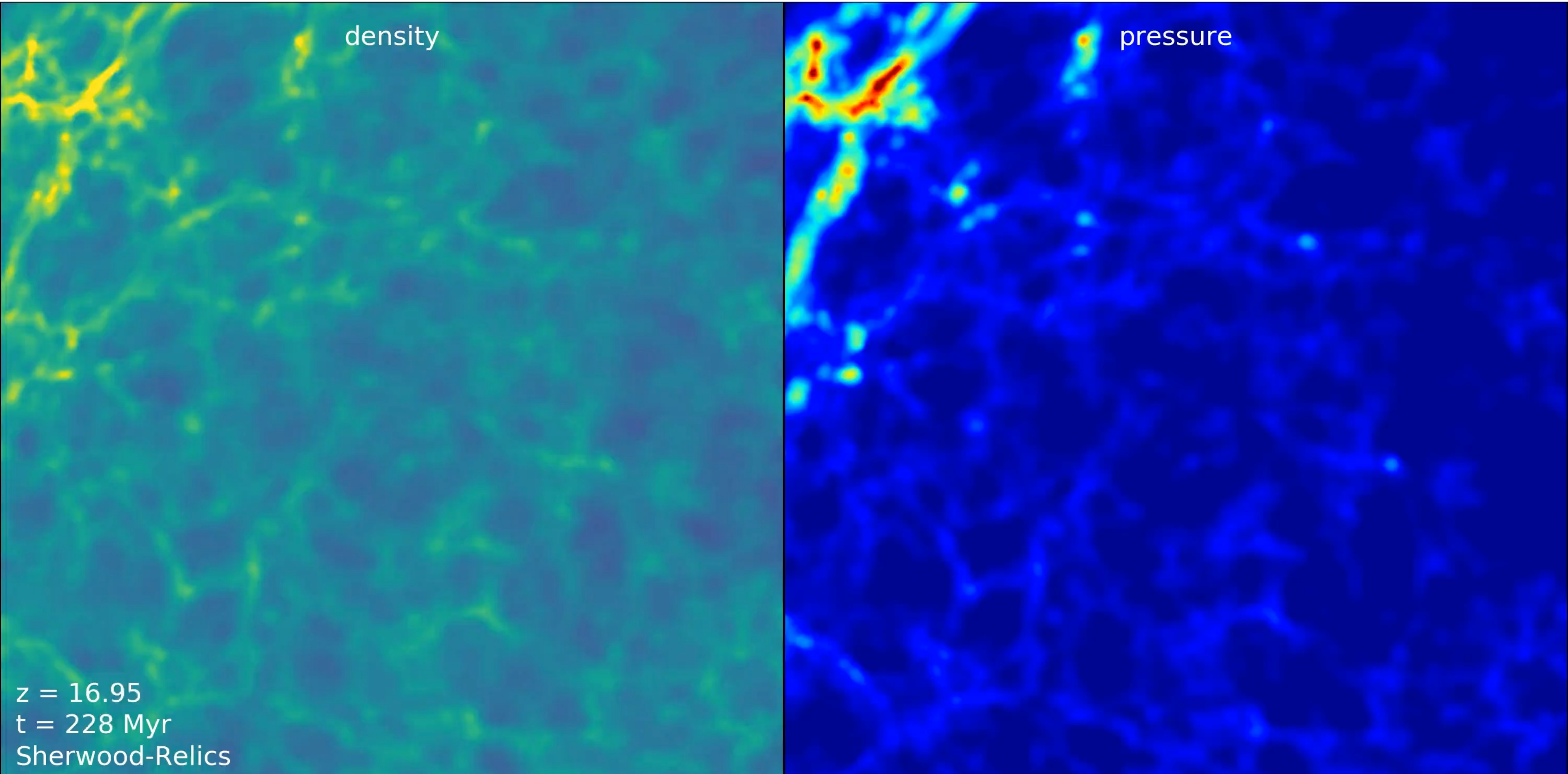
J. Bolton

E. Puchwein

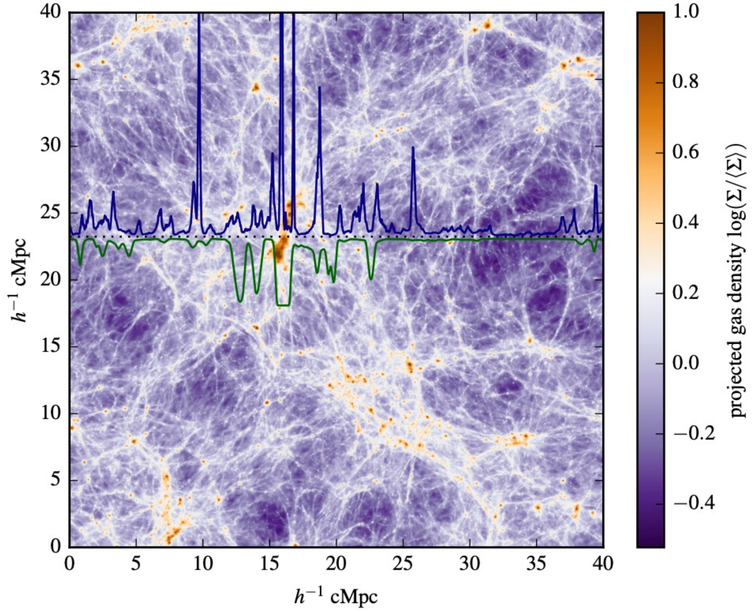
- **Sherwood-Relics suite** (>200 simulations: boxes 5-160 cMpc/h; M_{gas}=3.7e3-6.4e6 $M_{\odot}$) – about 75 Million CPU hrs (2017-now)
- G3 code + ATON to perform radiative transfer for patchy reionization
- Focus (and model calibration) on the high-z (z>4) forest

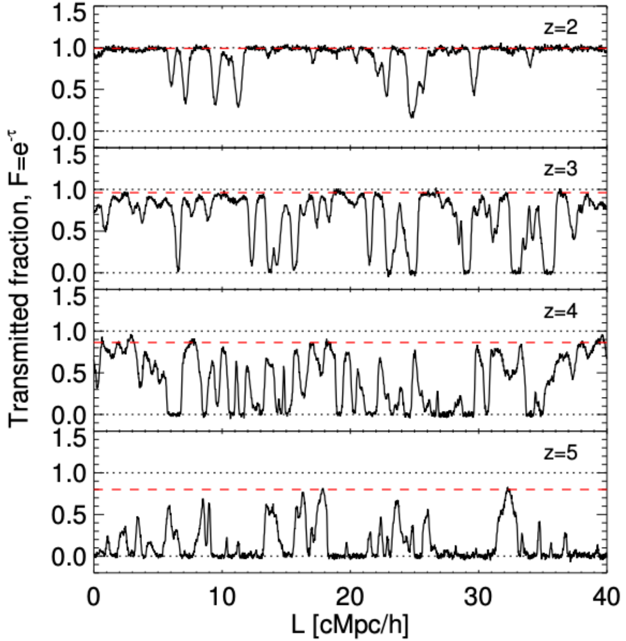
The simulations - II

Matteo Viel



The simulations - III



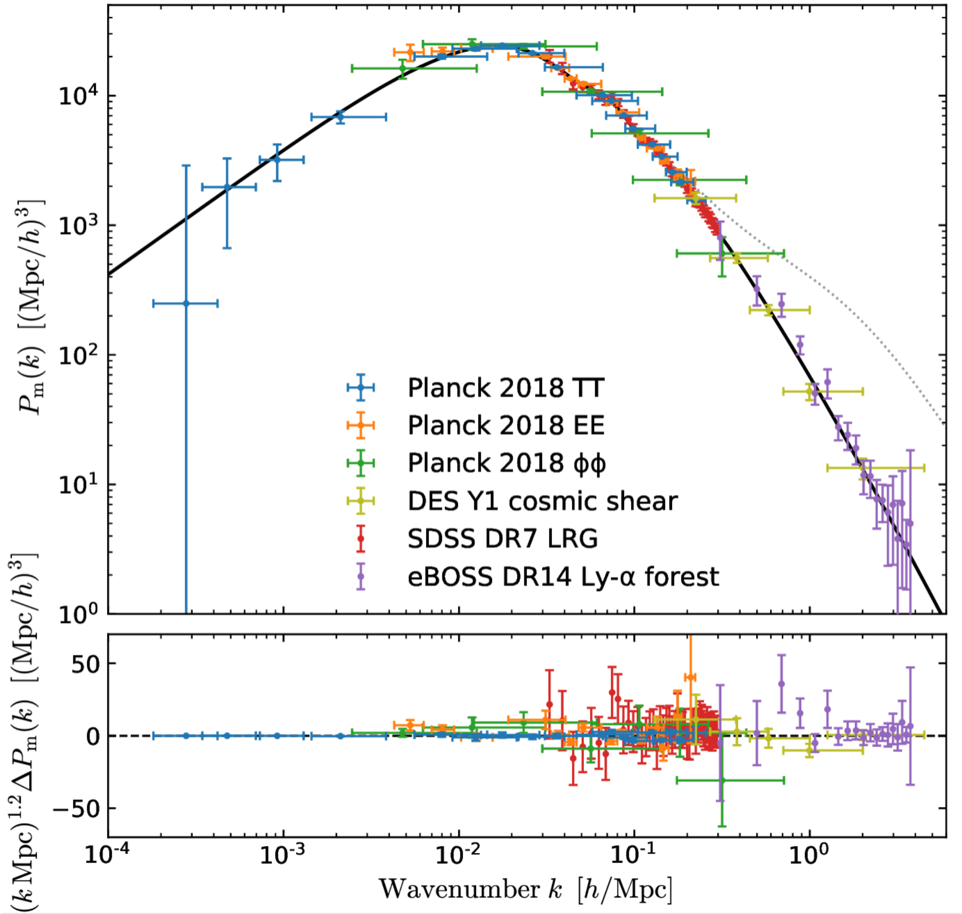


- Most of the flux statistics are in agreement with ΛCDM – 216,000 flux models fed into MCMC analysis

Increasing z → increasing HI → more absorption

Long lever arm of the linear power spectrum

Chabanier+19



Two reasons for why Lyα is so constraining:

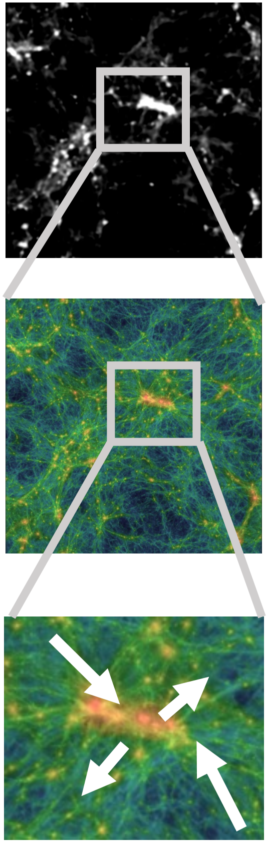
1) 1D is projected power.
2) We are at high-z possibly closer to linear regime.

Physical Scales

Intensity Mapping

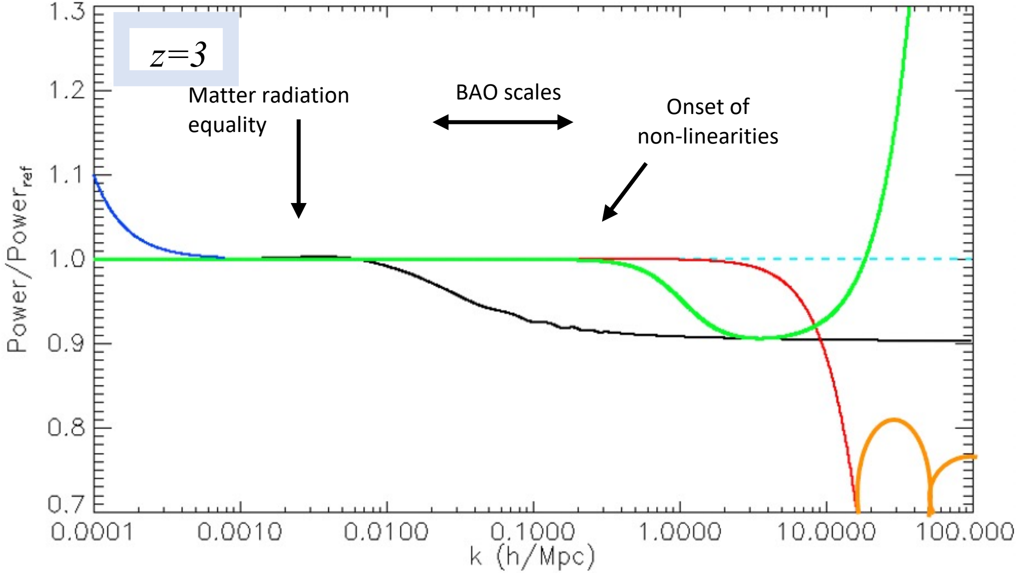
Intergalactic Medium

Circumgalactic Medium



Accretion and outflows

BARYON FEEDBACK and STAR FORMATION



LARGE SCALES with IM (Rel. effects or Non-Gaussianities)

REFERENCE MODEL

NEUTRINOS

DARK MATTER Interacting with baryons

WARM DARK MATTER (thermal)

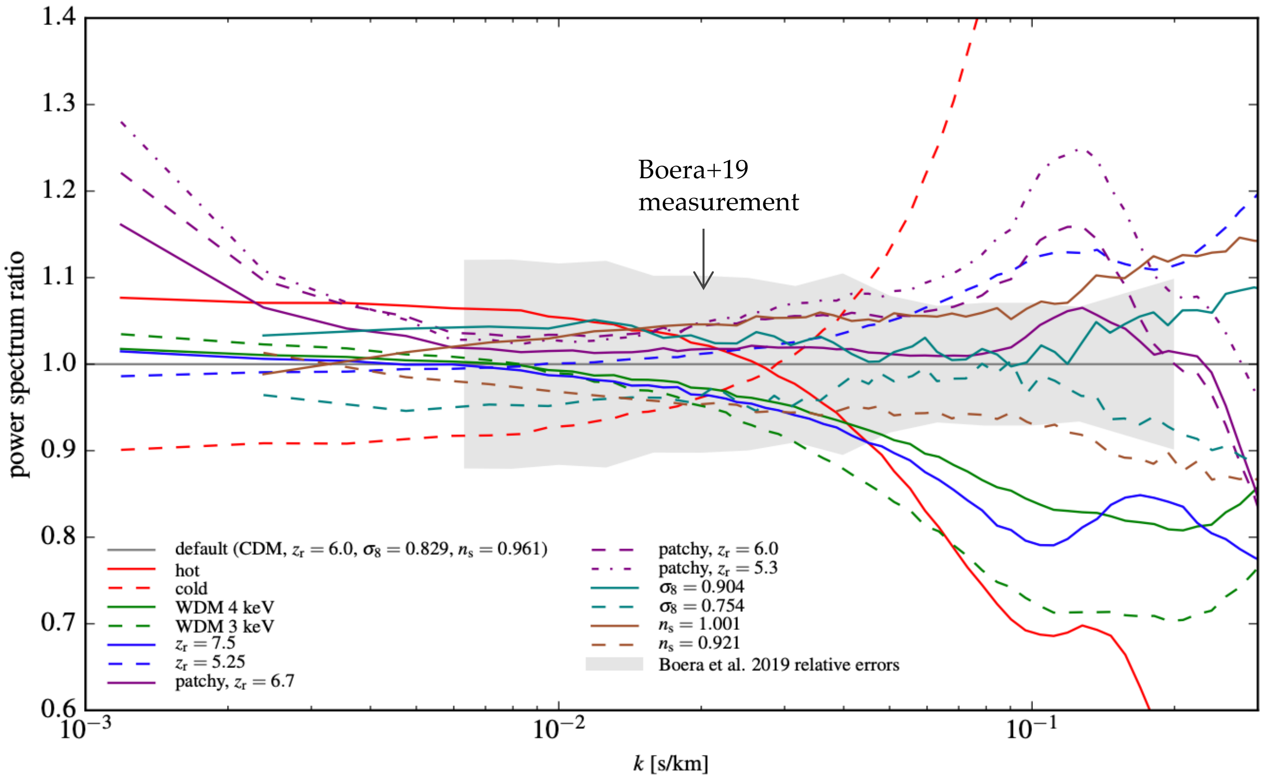
Large scales

Small scales

HI measures density perturbations in a matter dominated regime!

Impact on 1D flux power

Simulated 1D flux power @ z=4.6



More power

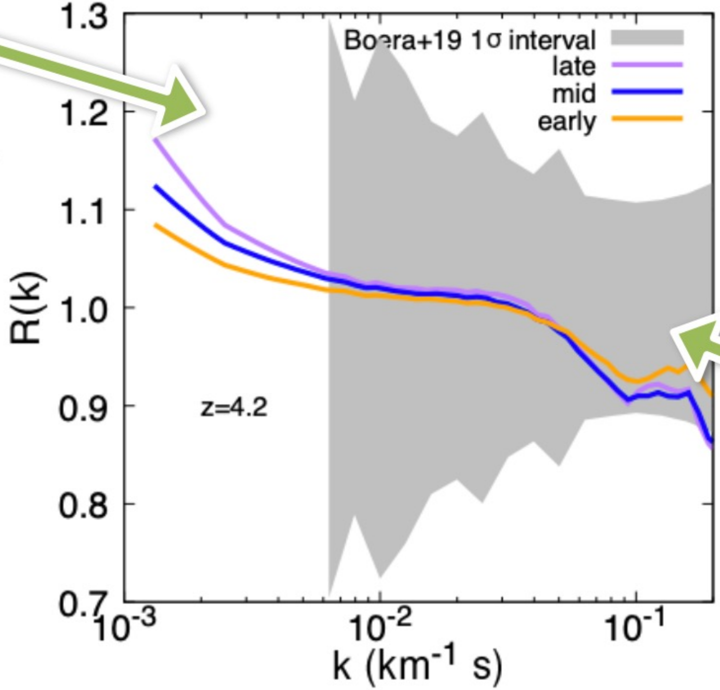
Less power

Large scales

Small scales

Patchy Reionization

Boost
due to variation in neutral fraction from large scale temperature fluctuations



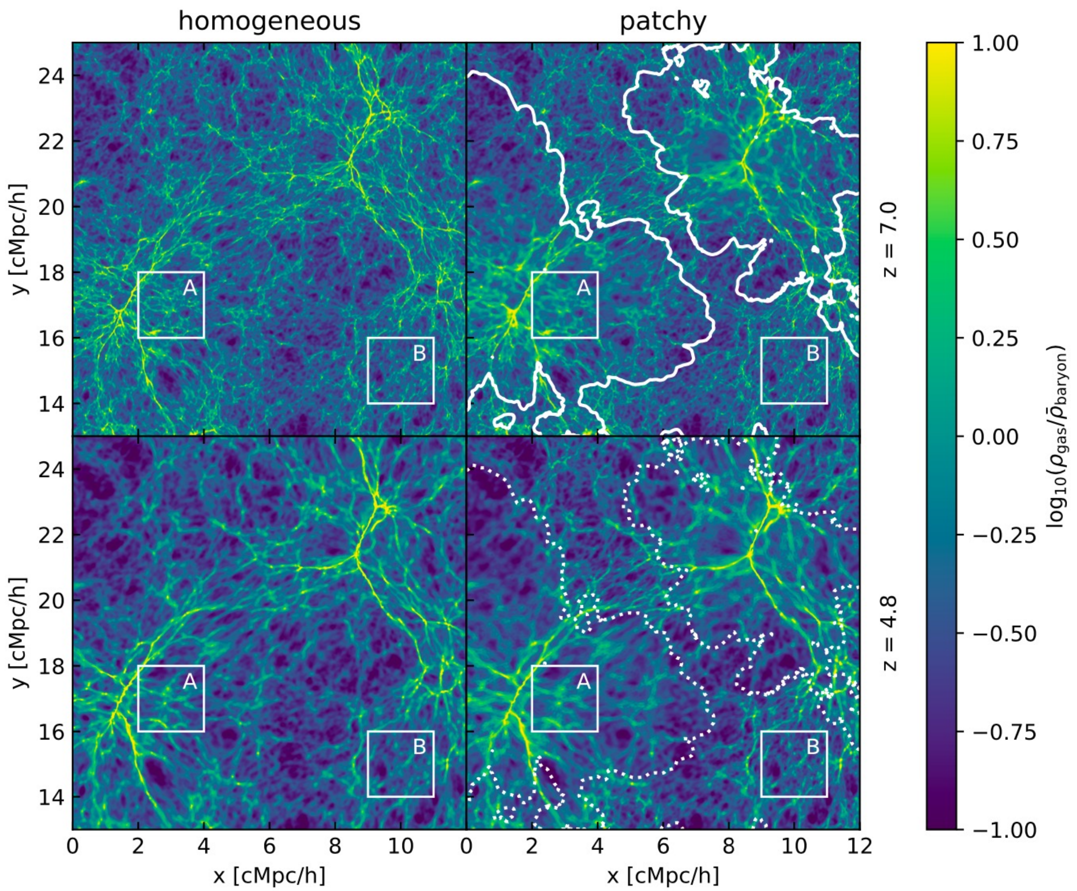
Molaro+23
"Detected" this
increase of power at 2.7σ
from KODIAQ, SQUAD,
XQ100 sample of 538 QSOs

Suppression
due to thermal broadening of recently ionised regions

Molaro, Bolton, Irsic,… MV 2021&2023

Patchy Reionization - II

Puchwein+23



During reionization

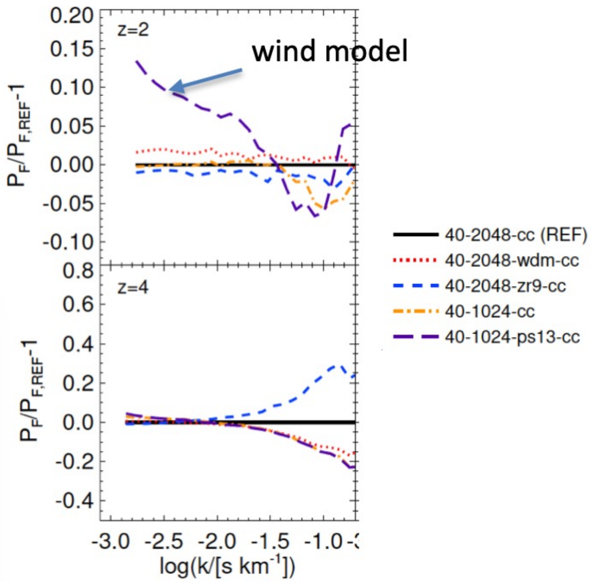
Note: Reionization ends at z =5.4

After reionization is complete

Galactic Feedback

Low redshift:
constraining feedback

Known systematic errors usually larger than statistical errors



Temperature density
low density relation for the IGM
is largely unaffected by feedback,
while the amount of hot collisionaly
Ionized gas changes

Viel+12
Bolton+17
Chabanier+23

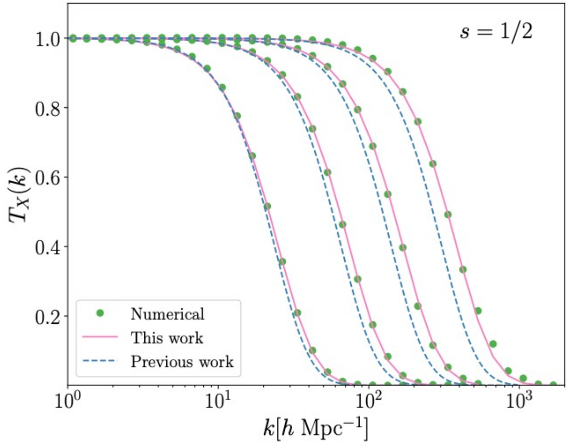
Matter power spectrum and WDM

Matteo Viel

$$T(k) \equiv [1 + (k/k_{break})^p]^{-10/p} \quad with\, p = 2.24$$

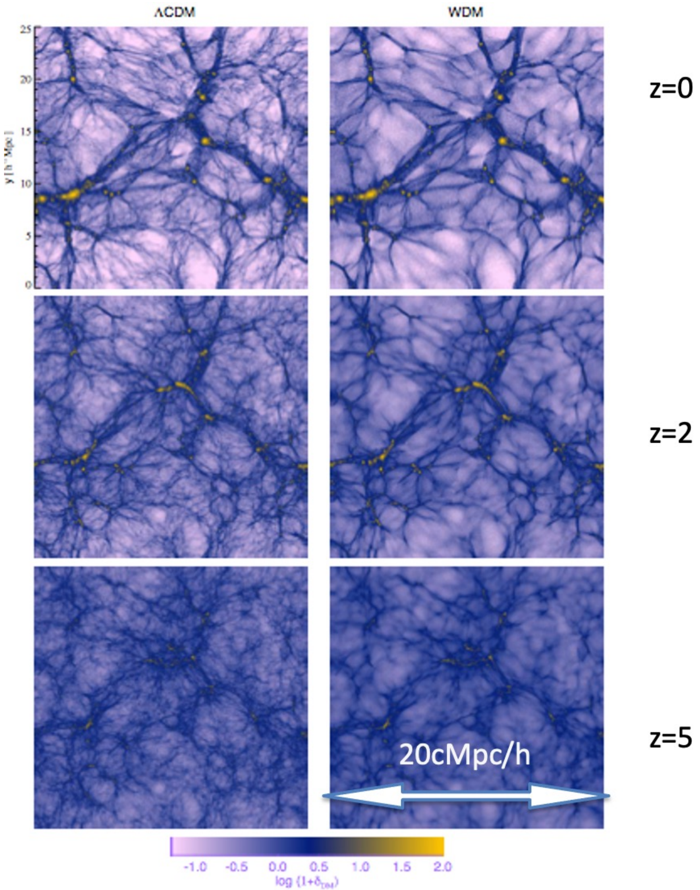
$$k_{break} = \frac{1}{0.24} X^{0.83} \left(\frac{\omega_X}{0.25 \times 0.7^2} \right)^{0.16} Mpc^{-1} \quad with\, X \equiv \frac{m_X/T_X}{1\, keV} T_\nu^a$$

Important: unlike active neutrinos this depends on both DM density and X
Because free streaming horizon depends on those



Viel+05;
Vogel&Abazajian https://arxiv.org/abs/2210.10753

A warm cosmic web?



$$k_{\rm FS} \sim 15.6 \frac{h}{\rm Mpc} \left(\frac{m_{\rm WDM}}{\rm 1keV}\right)^{4/3} \left(\frac{0.12}{\Omega_{DM} h^2}\right)^{1/3}$$

Free streaming scale of thermal warm dark matter

Viel et al 2005

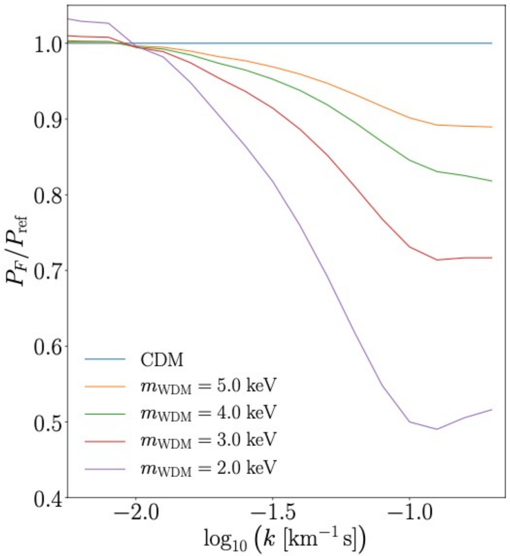
The smoothing scales

Vid Irsic

Unveiling Dark Matter free-streaming at the smallest scales with high redshift Lyman-alpha forest

Vid Iršič[1,2], Matteo Viel[3,4,5,6,7], Martin G. Haehnelt[1,8], James S. Bolton[9], Margherita Molaro[9], Ewald Puchwein[10], Elisa Boera[5,6], George D. Becker[11], Prakash Gaikwad[12], Laura C. Keating[13], Girish Kulkarni[14]
[1]Kavli Institute for Cosmology, University of Cambridge

WDM free streaming



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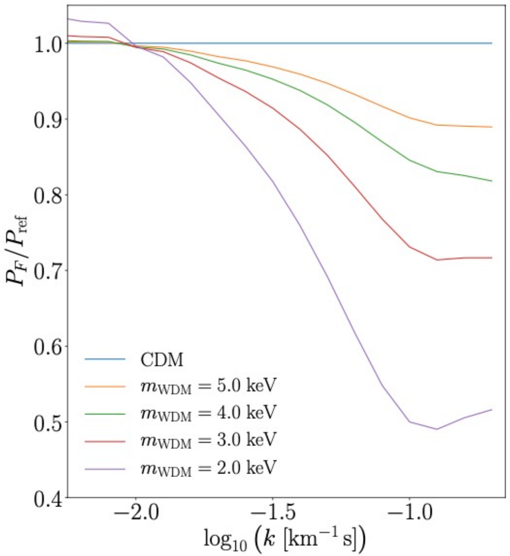
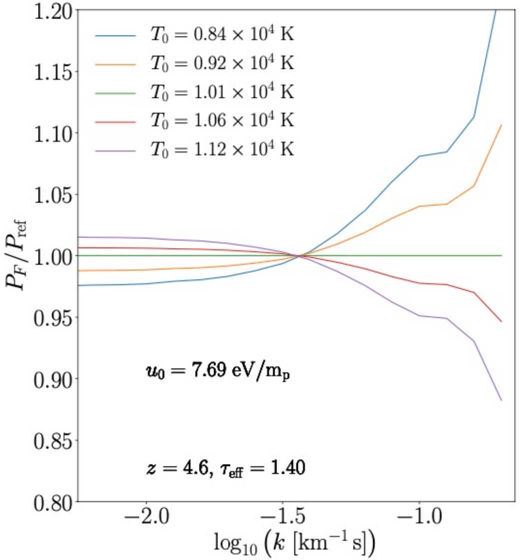


Thermal broadening



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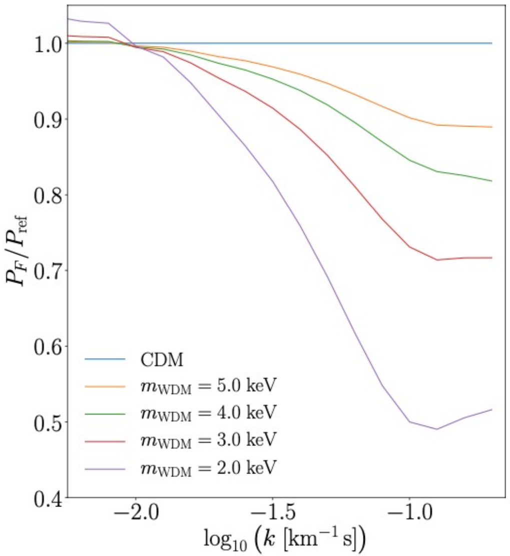
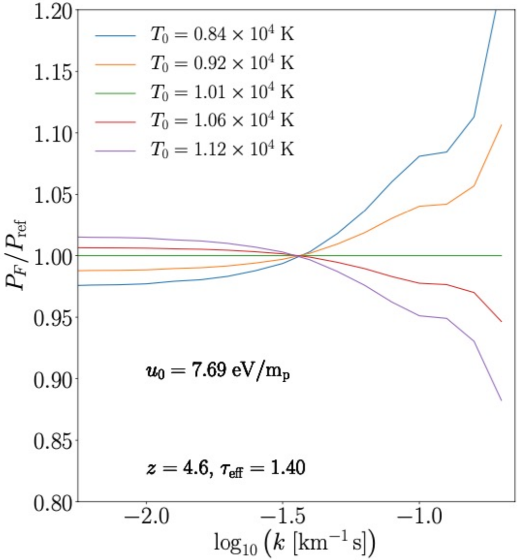
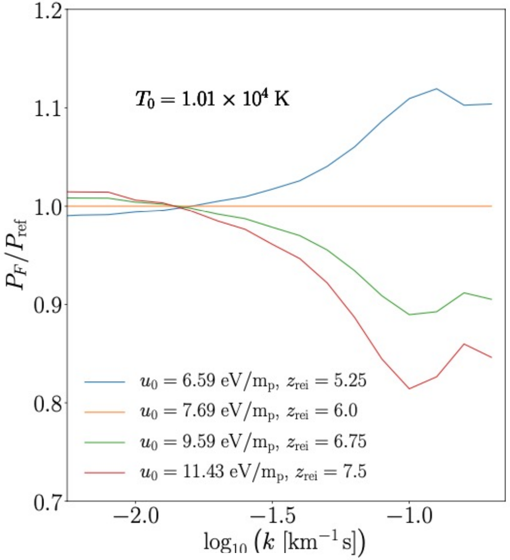


Thermal broadening



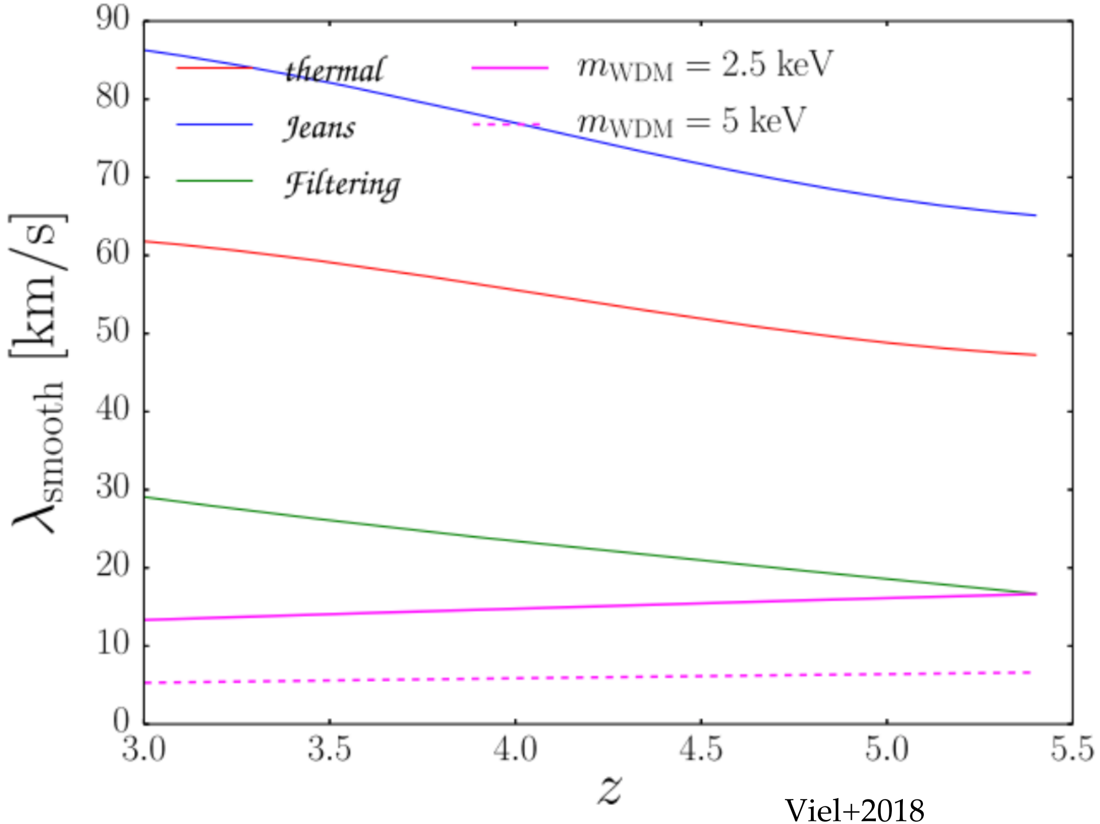
Gas pressure



$$u_0(t) = \int_0^t dt \frac{\mathcal{H}}{\bar{\rho}_m} \frac{3k_B}{2\mu}$$

$\mathcal{H}$ is heating rate

The smoothing scales - II

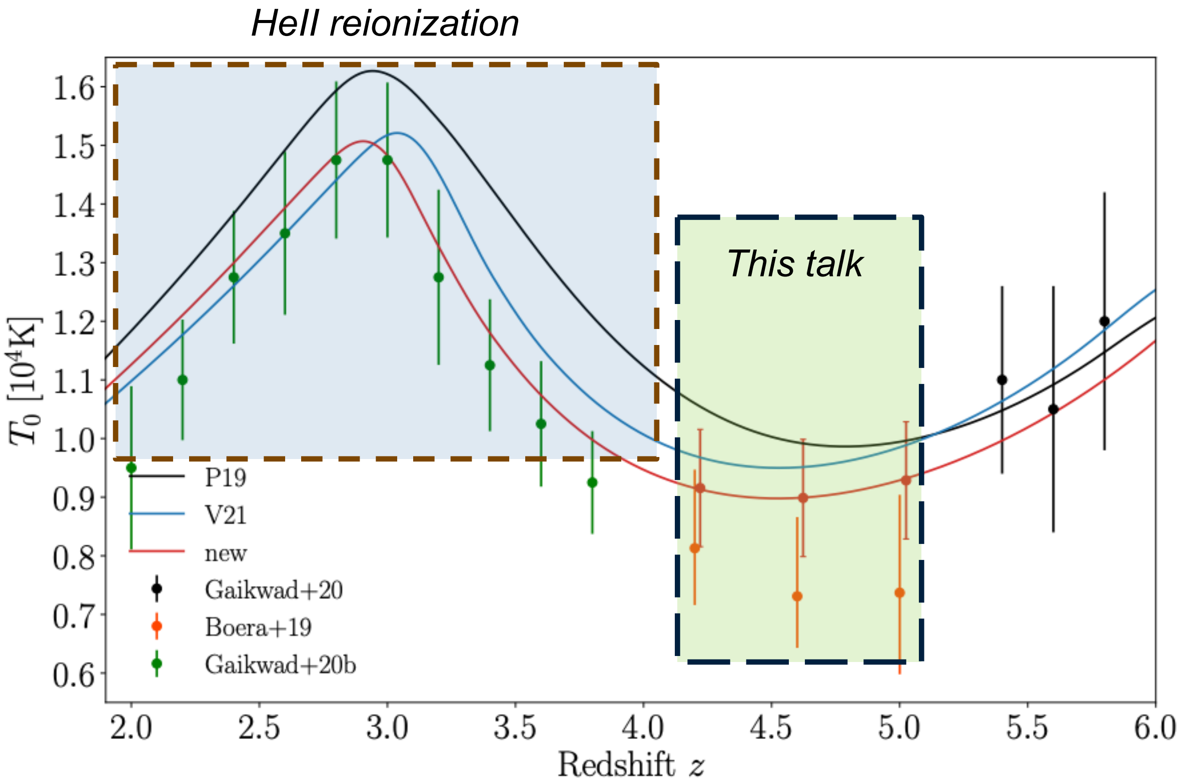


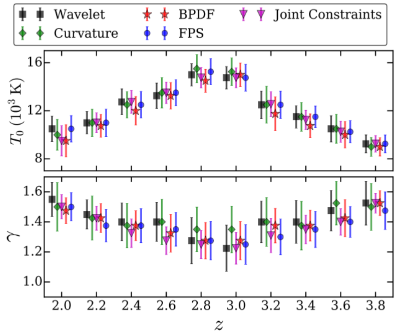
Viel+2018

Different physical scales (on top of instrumental resolution) affect the power spectrum cutoff:

- thermal: instataneous temperature at that redshift;
- filtering scale: depends on all the past thermal history – related to Jeans scale;
- WDM cutoffs are basically redshift independent

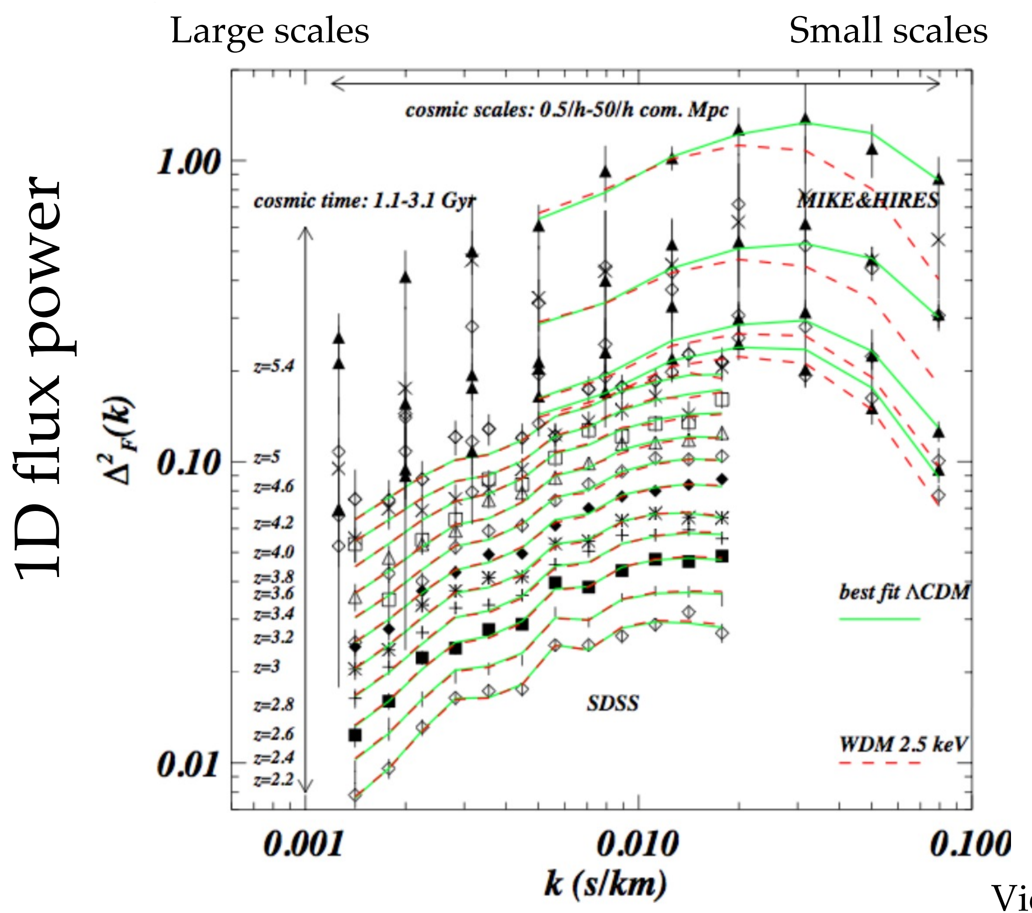
The IGM thermal state





- Constraints obtained with a variety of data and methods
- Sensitive to lines rather than the lines' clustering
- HeII bump quite well detected

Status in 2013

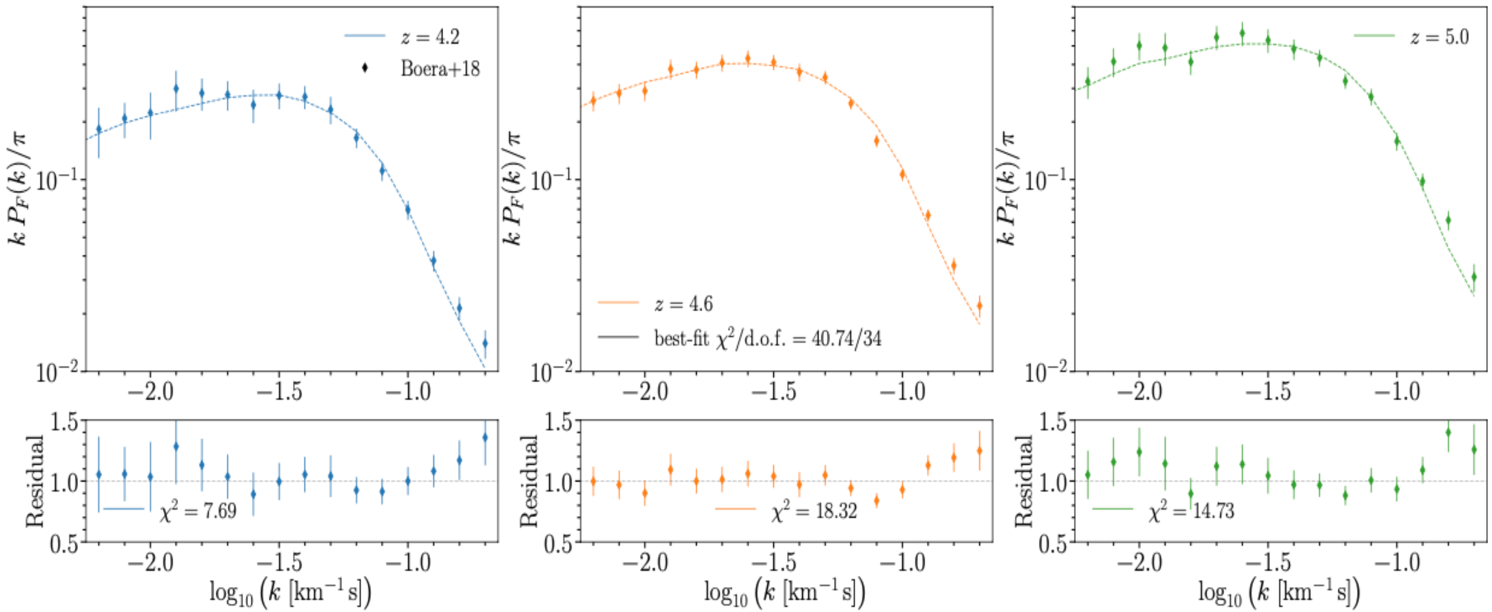


Viel+13

- Test of structure formation for a LCDM Universe in a **unique "pre-galactic" environment**
- $m_{WDM} > 3.3$ keV (2σ C.L.)

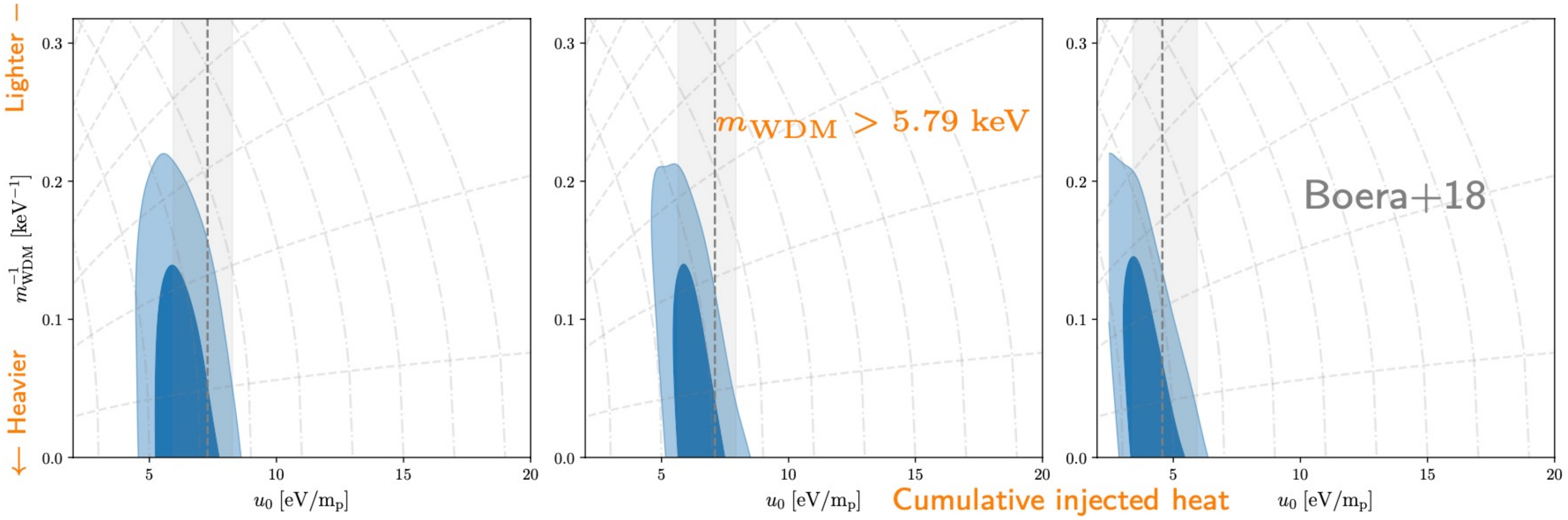
Note: 10 yrs later only a factor 2 more high-z QSOs

The data



Boera+19, Irsic+23

Thermal WDM

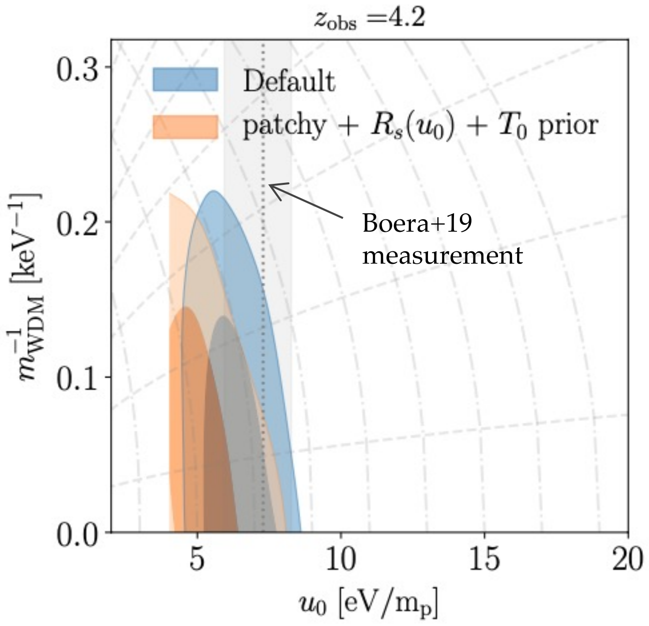


Irsic+23

Thermal WDM

Light WDM

Heavy WDM or LCDM



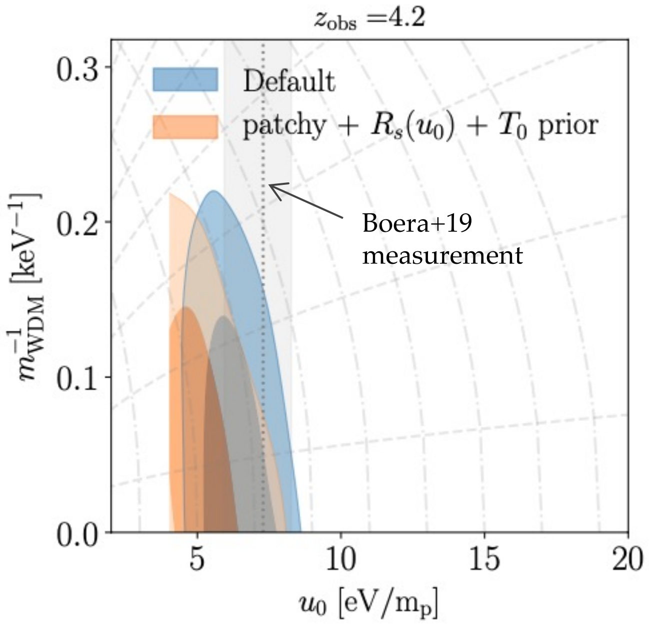
Injected heat

Irsic, MV +23

Thermal WDM - II

Light WDM

Heavy WDM or LCDM



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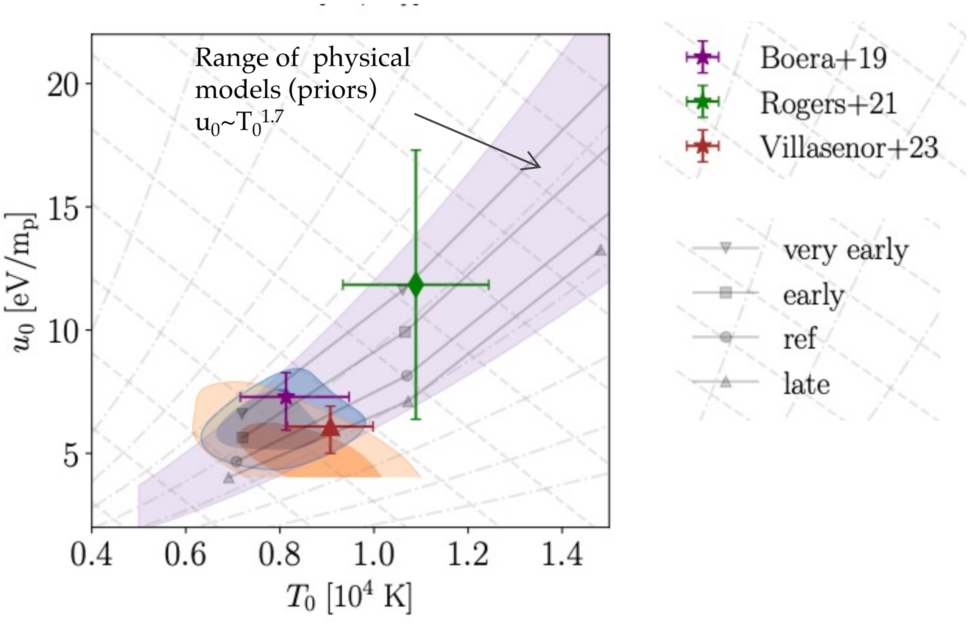
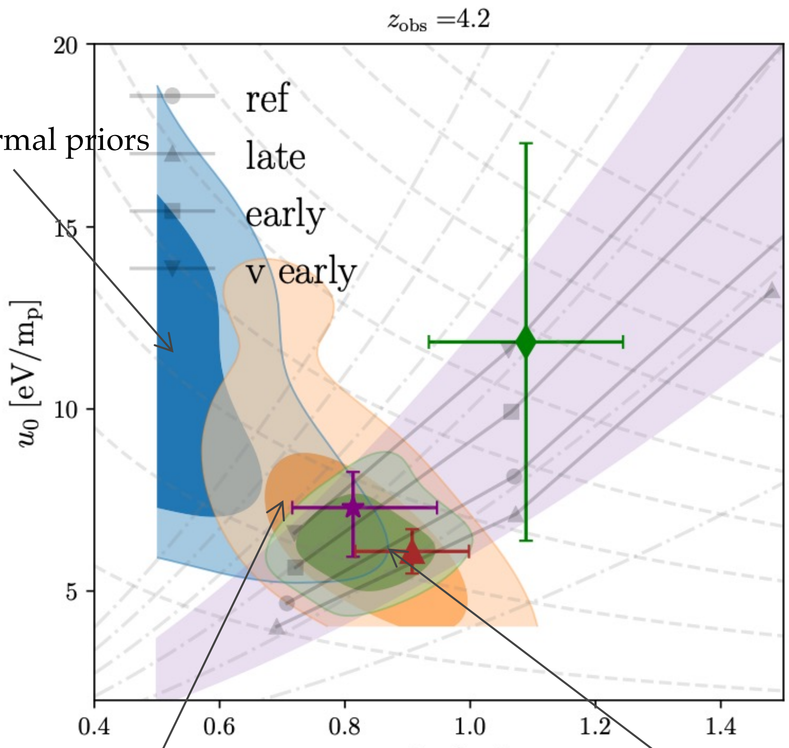


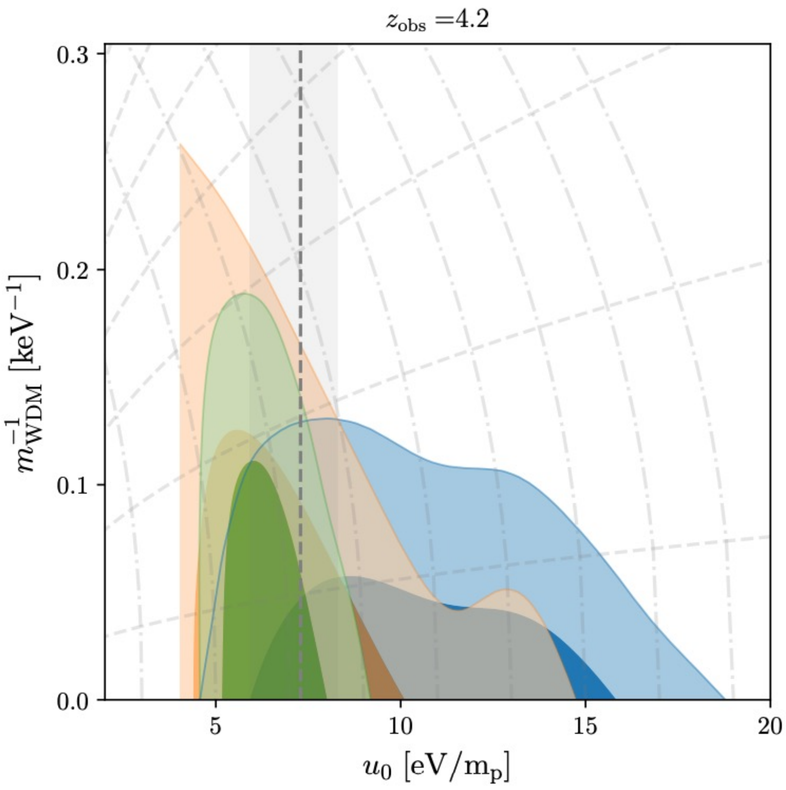
IGM temperature

Irsic, MV +23

Thermal WDM – the effect of thermal priors

Matteo Viel





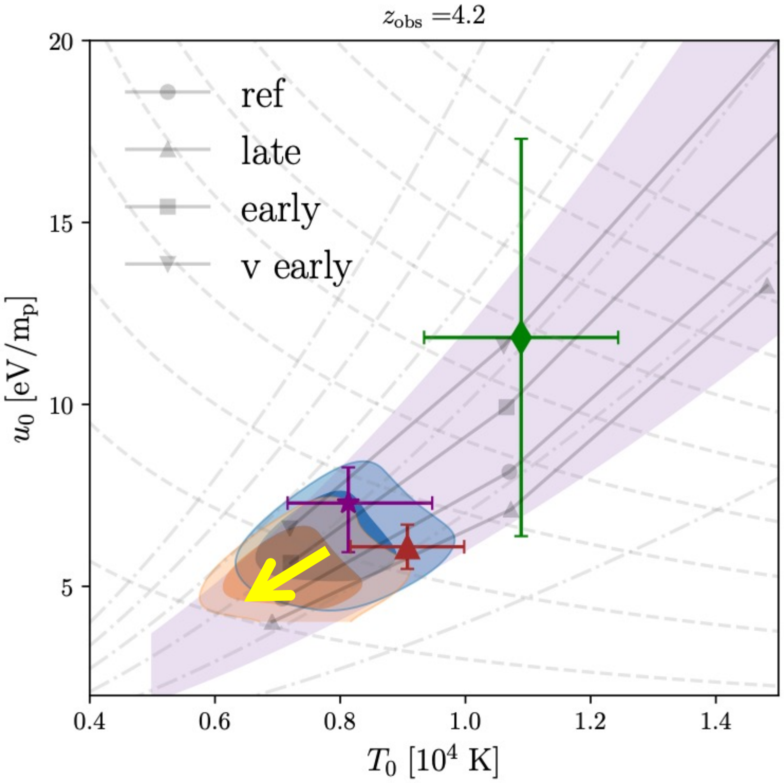
No thermal priors

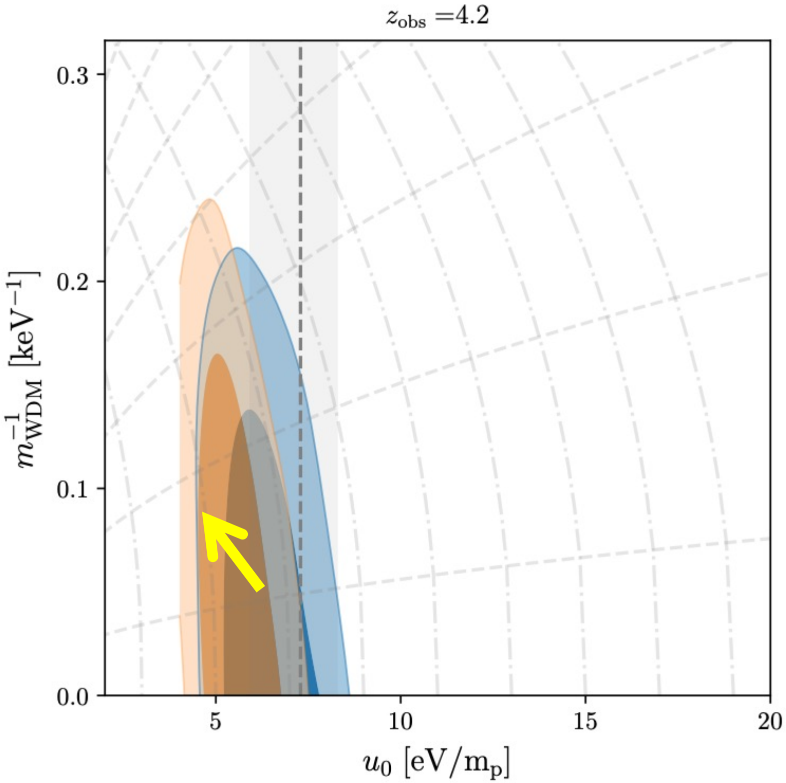
$T_0(z)$ prior

Reference prior along the envelope of physically motivated models

Irsic+23

Thermal WDM – inclusion of patchy correction

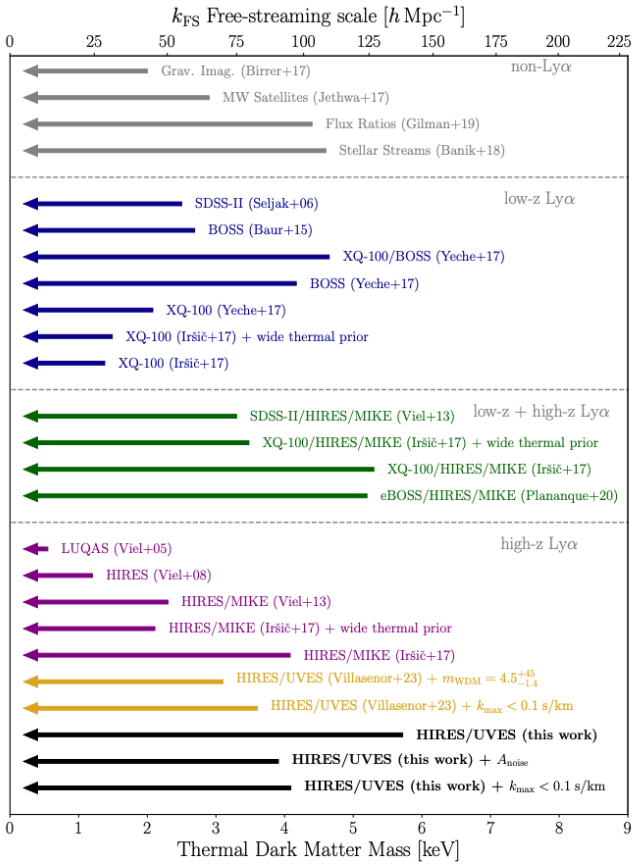




Irsic+23

Thermal WDM

Matteo Viel



Tests made:
Cut small scales
Marginalize over data noise
Assume/Remove T_0 priors
Correct for a model dependent resolution
Patchy reionization models

Name	m_{WDM} [keV] (2σ)	$\tau_{eff}(z=4.6)$	$T_0(z=4.6)$ [10^4 K]	$\gamma(z=4.6)$	$u_0(z=4.6)$ [eV/m$_p$]	$A_{noise}(z=4.6)$	χ^2/dof
Default	> 5.72	$1.502^{+0.061}_{-0.061}$	$0.743^{+0.041}_{-0.075}$	$1.35^{+0.24}_{-0.19}$	$6.19^{+0.68}_{-0.68}$	-	40.7/34
$k_{max} < 0.1$ km^{-1} s	> 4.10	$1.501^{+0.060}_{-0.074}$	$0.840^{+0.095}_{-0.340}$	$1.28^{+0.09}_{-0.28}$	$8.91^{+1.57}_{-5.26}$	-	10.2/20
A_{noise}	> 3.91	$1.458^{+0.053}_{-0.074}$	$0.966^{+0.156}_{-0.466}$	$1.23^{+0.06}_{-0.23}$	$5.93^{+0.38}_{-2.28}$	$1.12^{+0.49}_{-0.29}$	18.4/31
T_0 prior	> 5.85	$1.494^{+0.062}_{-0.077}$	$0.770^{+0.110}_{-0.120}$	$1.31^{+0.10}_{-0.31}$	$6.50^{+1.00}_{-1.60}$	-	47.6/34
$R_s(u_0)$ mass resolution	> 4.44	$1.531^{+0.073}_{-0.064}$	$0.617^{+0.007}_{-0.118}$	$1.38^{+0.28}_{-0.13}$	$7.90^{+1.70}_{-2.30}$	-	30.7/34
patchy reion.	> 5.10	$1.486^{+0.058}_{-0.068}$	$0.686^{+0.046}_{-0.080}$	$1.33^{+0.17}_{-0.26}$	$5.32^{+0.58}_{-0.52}$	-	41.0/34
$R_s(u_0) + T_0$ prior	> 4.24	$1.473^{+0.056}_{-0.076}$	$0.83^{+0.11}_{-0.11}$	$1.28^{+0.09}_{-0.28}$	$5.53^{+0.73}_{-1.2}$	-	39.4/34
patchy + $R_s(u_0) + T_0$ prior	> 5.90	$1.450^{+0.051}_{-0.070}$	$0.828^{+0.098}_{-0.098}$	$1.26^{+0.08}_{-0.26}$	$4.87^{+0.52}_{-0.71}$	-	40.8/34

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Scalar Dark Matter

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

KG and Einstein equations

$$T^{\phi}_{\mu\nu} = g_{\mu\nu}\left(-\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - \frac{1}{2}m^2\phi^2\right) + \partial_\mu\phi\partial_\nu\phi.$$

Energy momentum tensor for the scalar field

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)dx^2$$

Metric

$$\phi = \frac{1}{\sqrt{2m}}\left(\varphi e^{-imt} + \varphi^* e^{imt}\right)$$

Oscillating field

$$i\left(\dot{\varphi} + \frac{3}{2}H\varphi\right) = -\frac{\partial^2\varphi}{2a^2 m} + m\Phi\varphi,$$

Dropping higher order and averaging over one oscillating period: Schrodinger type eq.

$$\rho_\phi \equiv m\varphi\varphi^*, \quad v_i \equiv \frac{\partial_i\{\arg(\varphi)\}}{am} = -\frac{i}{2am}\left(\frac{\partial_i\varphi}{\varphi} - \frac{\partial_i\varphi^*}{\varphi^*}\right)$$

Defining density and velocities of the fluid

$$\dot{v}_i + Hv_i + \frac{v_j\partial_j v_i}{a} = -\frac{\partial_i\Phi}{a} + \frac{1}{2a^3m^2}\partial_i\left(\frac{\partial^2\sqrt{\rho_\phi}}{\sqrt{\rho_\phi}}\right)$$

Euler eq. NOTE the pressure term

$$\dot{\rho}_\phi + 3H\rho_\phi + \frac{\partial_i(\rho_\phi v_i)}{a} = 0.$$

Continuity

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15, Nori&Baldi 18

Scalar Dark Matter - II

Matteo Viel

$$\delta_{\rm m} = F\delta_\phi + (1-F)\delta_{\rm c}.$$

$$\ddot{\delta}_{\phi k} + 2H\dot{\delta}_{\phi k} + \frac{c_s^2 k^2}{a^2}\delta_{\phi k} - \frac{3}{2}H^2\delta_{{\rm m}k} = 0,$$

$$\ddot{\delta}_{{\rm c}k} + 2H\dot{\delta}_{{\rm c}k} - \frac{3}{2}H^2\delta_{{\rm m}k} = 0.$$

Linear perturbation theory in CDM+scalar field model

$$c_s^2 \equiv \frac{k^2}{4a^2m^2}. \qquad \frac{k_{\rm J}}{a} = \sqrt{Hm},$$

$$\frac{k_{\rm Jeq}}{a_0} = \frac{a_{\rm eq}}{a_0}\sqrt{H_{\rm eq}m} \approx 7\,{\rm Mpc}^{-1}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{1/2}$$

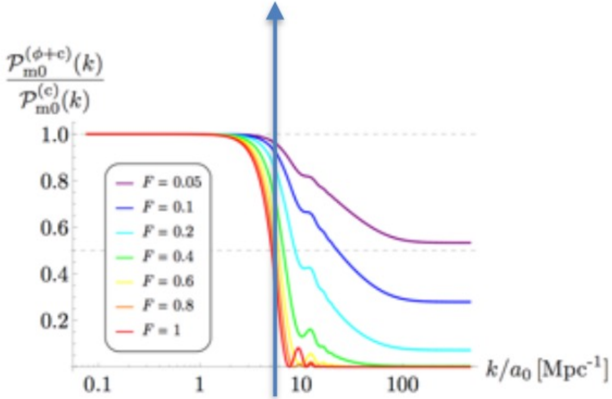
Sound speed of scalar DM and Jeans scale definition

At $k<k_J$ no pressure

At $k>k_J$ pressure and oscillations no growth

Comoving Jeans $k_J \sim a^{1/4}$ in MD

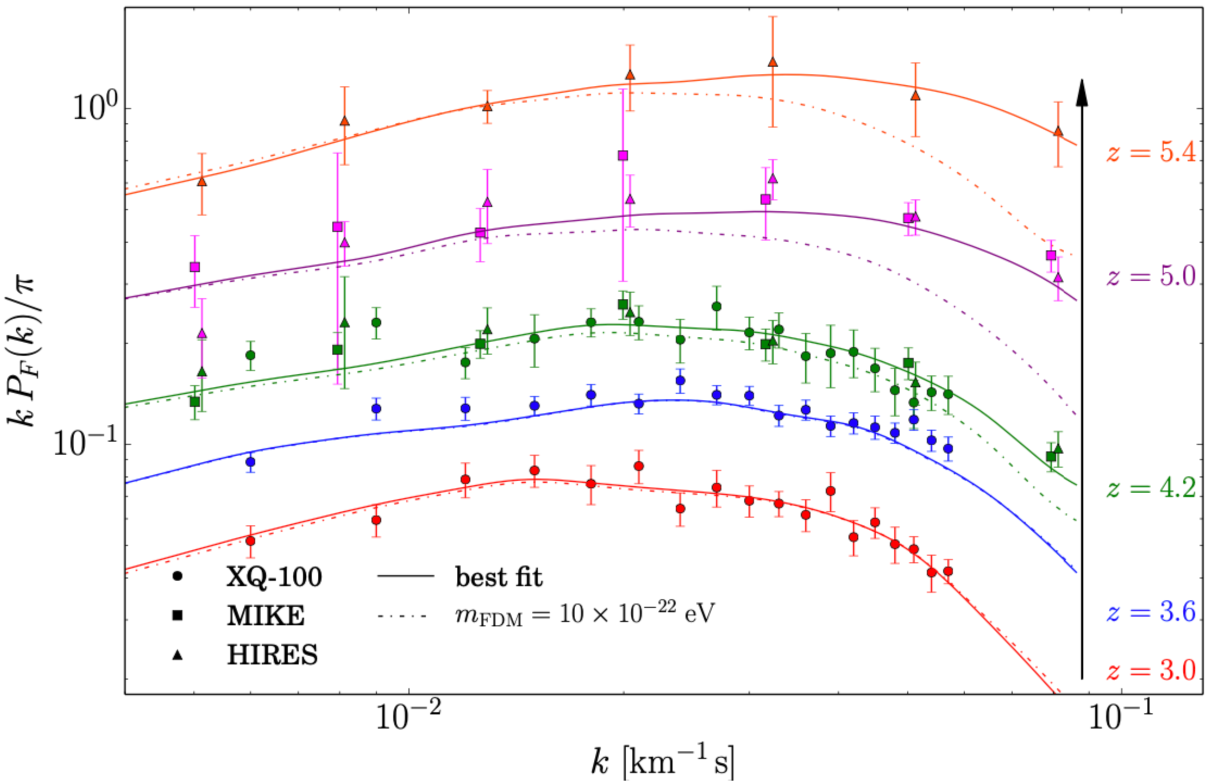
Important quantity is k_J at equival.



Plateau is set by FDM fraction

Cutoff scale set by FDM mass

Scalar Dark Matter - III



Irsic, Viel+ 2022 PRL

The IGM as a thermometer

- Dark Photon Dark Matter: simple extension of the SM of particle physics

$$\mathcal{L}_{\gamma A'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}$$

- Dark photon converts into standard photon when a resonance condition is met

$$E_{A'\to\gamma} \sim 2.5\,\mathrm{eV}\left(\frac{\epsilon_{-14}}{0.5}\right)^2 \left(\frac{3}{1+z_{\rm res}}\right)^{3/2} \left(\frac{m_{-13}}{0.8}\right)$$

Bolton, Caputo, Liu, MV, PRL, 2022

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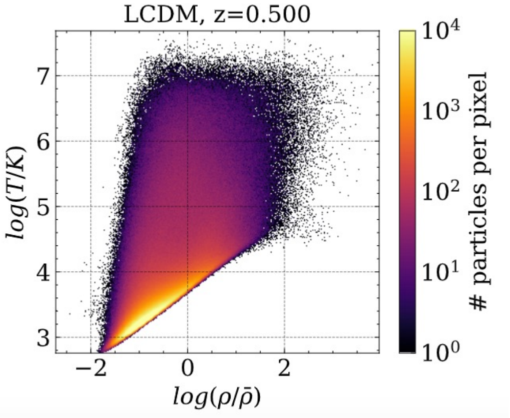
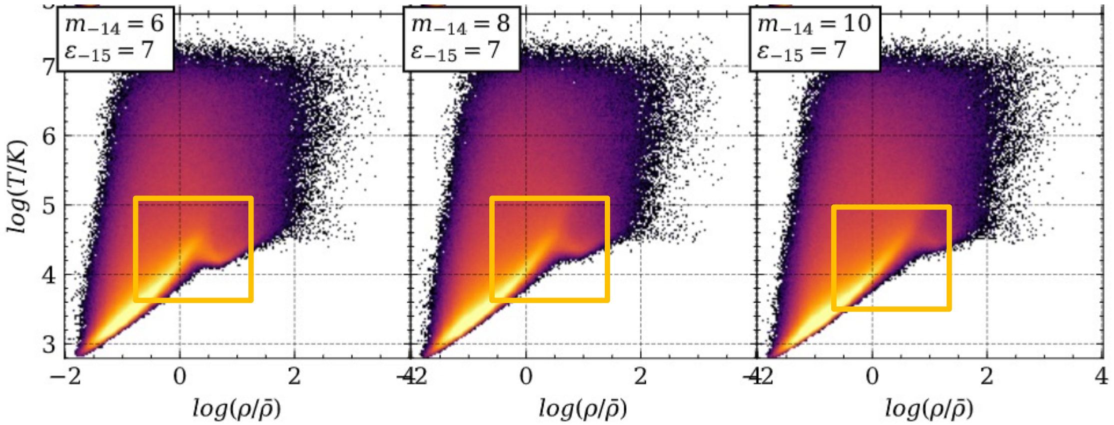
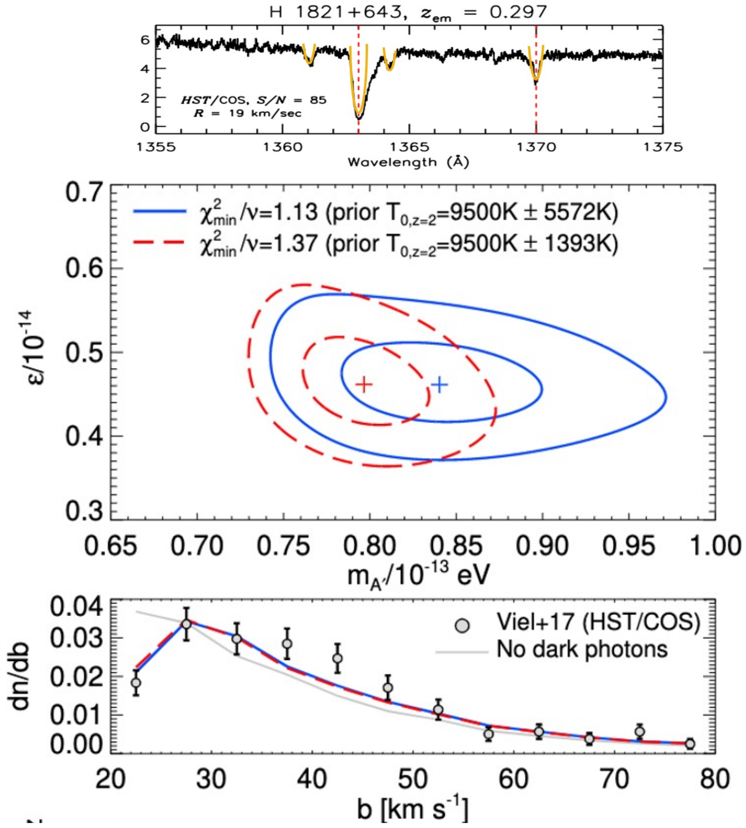




Bolton, Caputo, Liu, MV, PRL, 2022

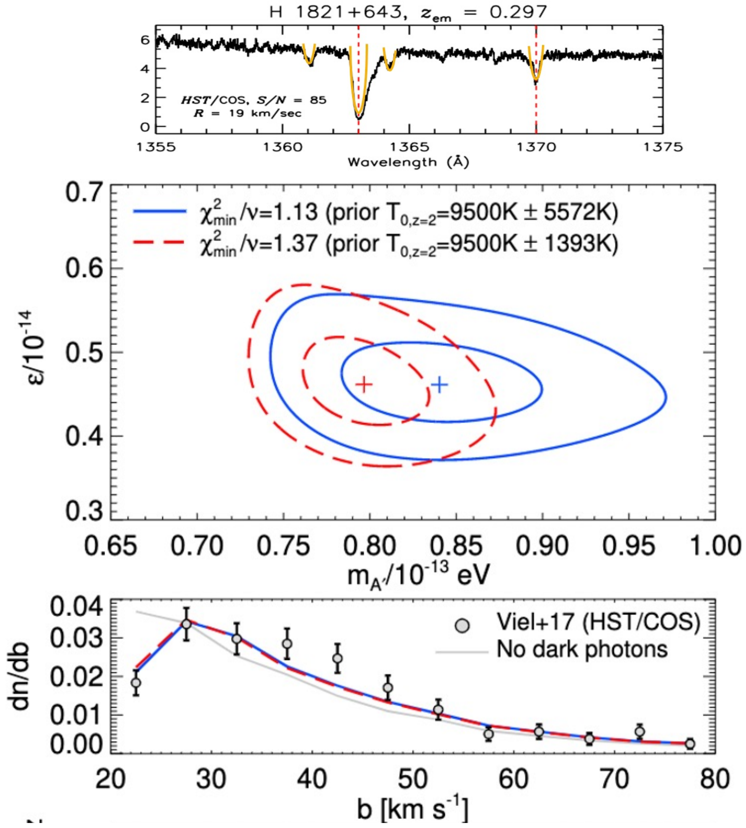
The IGM as a thermometer - II



- Effect is small but can be used to place constraints on extra-heating
- At z=0.1 COS/HST lines are broader than expected (feedback, turbulence?)

The IGM as a thermometer - II

Matteo Viel



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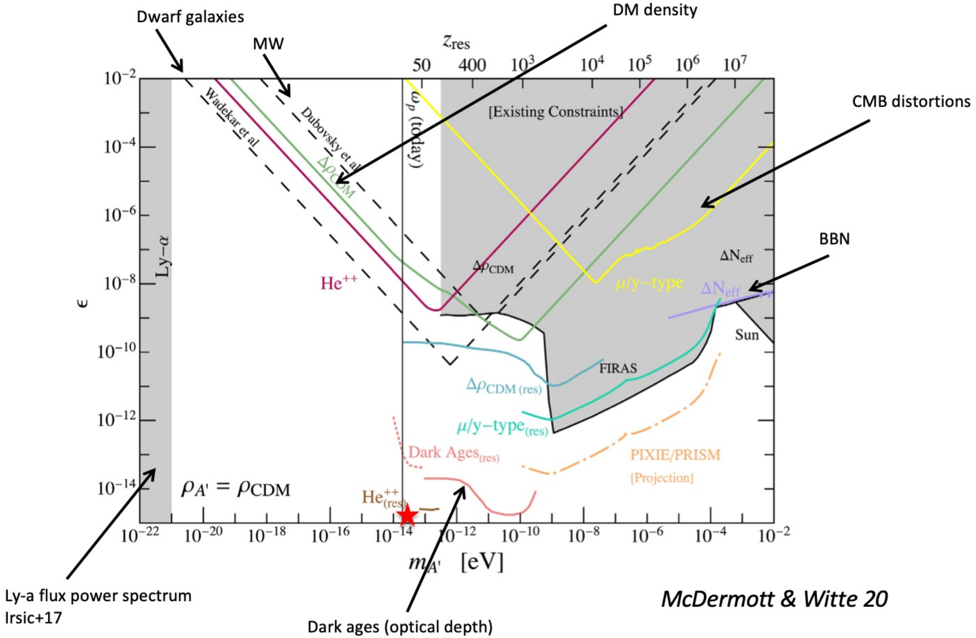
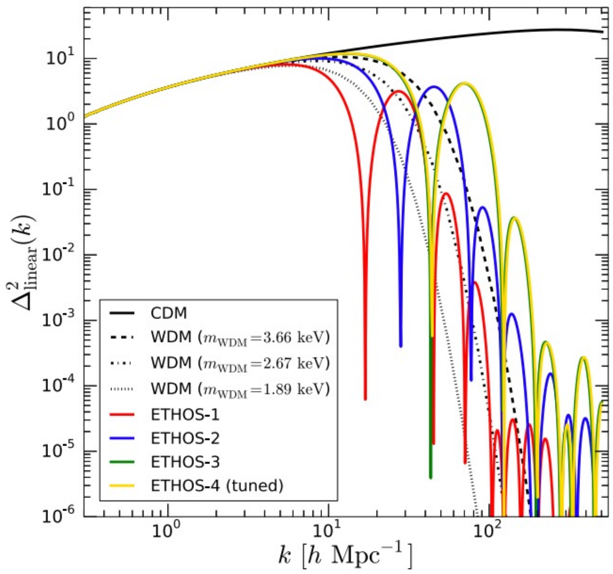


McDermott & Witte 20

Baryon-DM or Dark radiation-DM interactions

Vogelsberger+16



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- … but still the forest can provide competitive constraints (Archidiacono+19, Hooper+22, Iliev's talk….)

Baryon-DM or Dark radiation-DM interactions

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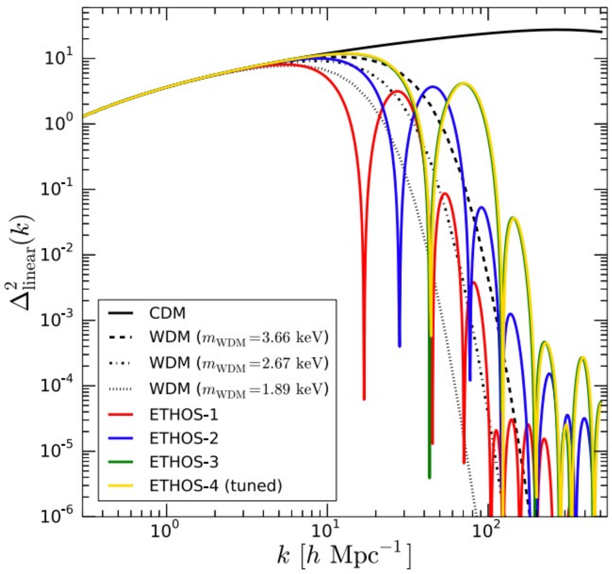

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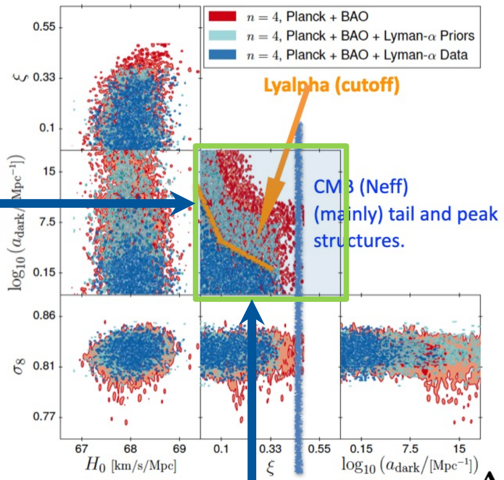
Strength of interaction



Particle Physics: fermionic relativistic DR (e.g. sterile neutrinos) interacting with DM through a new boson mediator of a new U(1) symmetry.

$$\Delta\chi^2 = -3.6$$

Amount of of Dark Radiation

Summary

- New data with new analysis: **5.7 keV** 2σ C.L. on WDM thermal mass

- Small scale regime of flux power is not easy to fit
if you stop at k<0.1 s/km then **4 keV** is a robust and conservative limit

- New features: **patchy reionization**, resolution corrections,
new set of physical models. Warning: our results are prior driven.

- Pushing to small scales is double and hitting the regime > 6keV is likely
to depend a lot on noise modelling….. But…. ESPRESSO, ANDES…

- Application to: inject heat in the IGM → Dark Photon

- Application to: non standard DM-b and DM-DR interactions