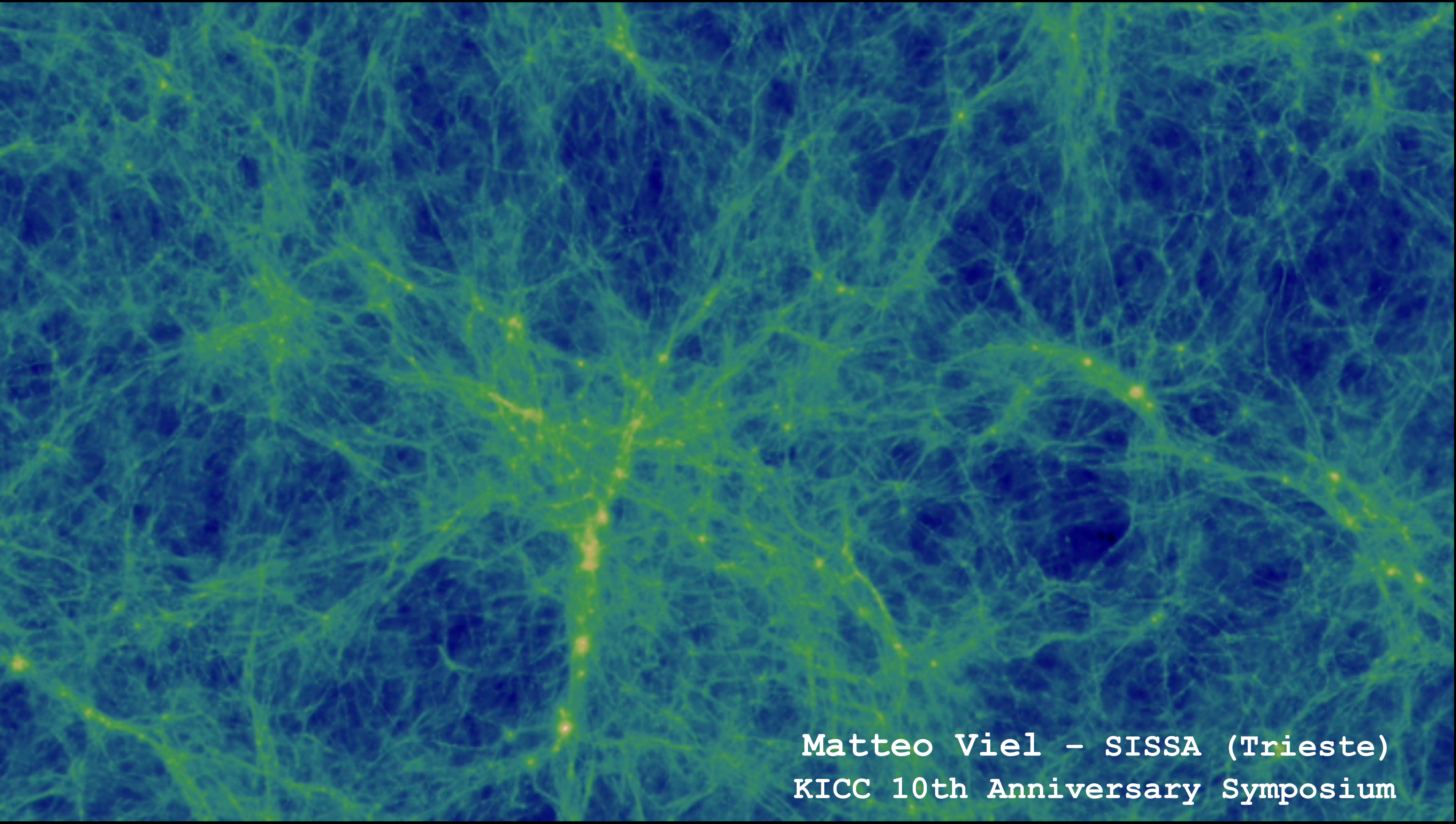
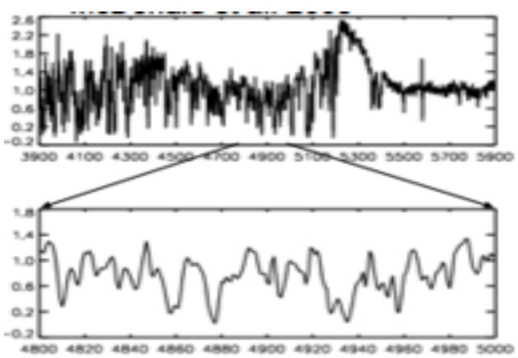
The intergalactic medium as a cosmological probe



Bolton+17, Sherwood simulation suite (PRACE call: 15 CPU Mhrs)
Puchwen+19, New simulations (PRACE call: 23 CPU Mhrs)

COSMOLOGY WITH QSOs

BOSS/SDSS-III



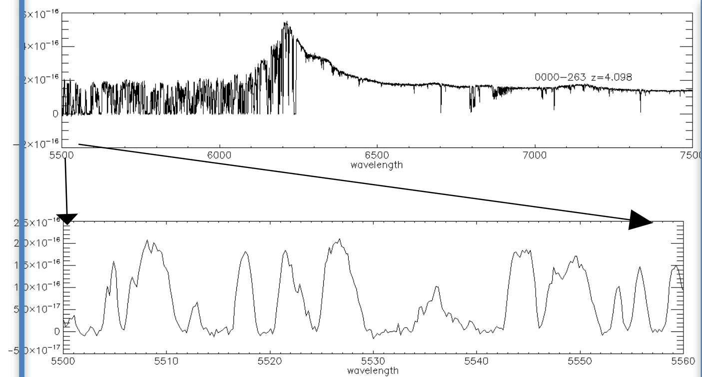
Low resolution BOSS and SDSS-III spectra S/N~2-3 - 160,000 spectra

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, McDonald+05
Seljak+06, Baur+16, Yeche+17 etc.

XQ-100



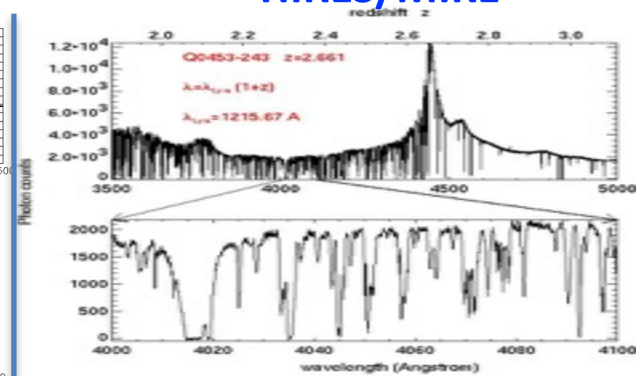
Medium resolution X-Shooter VLT spectra S/N ~ 30

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

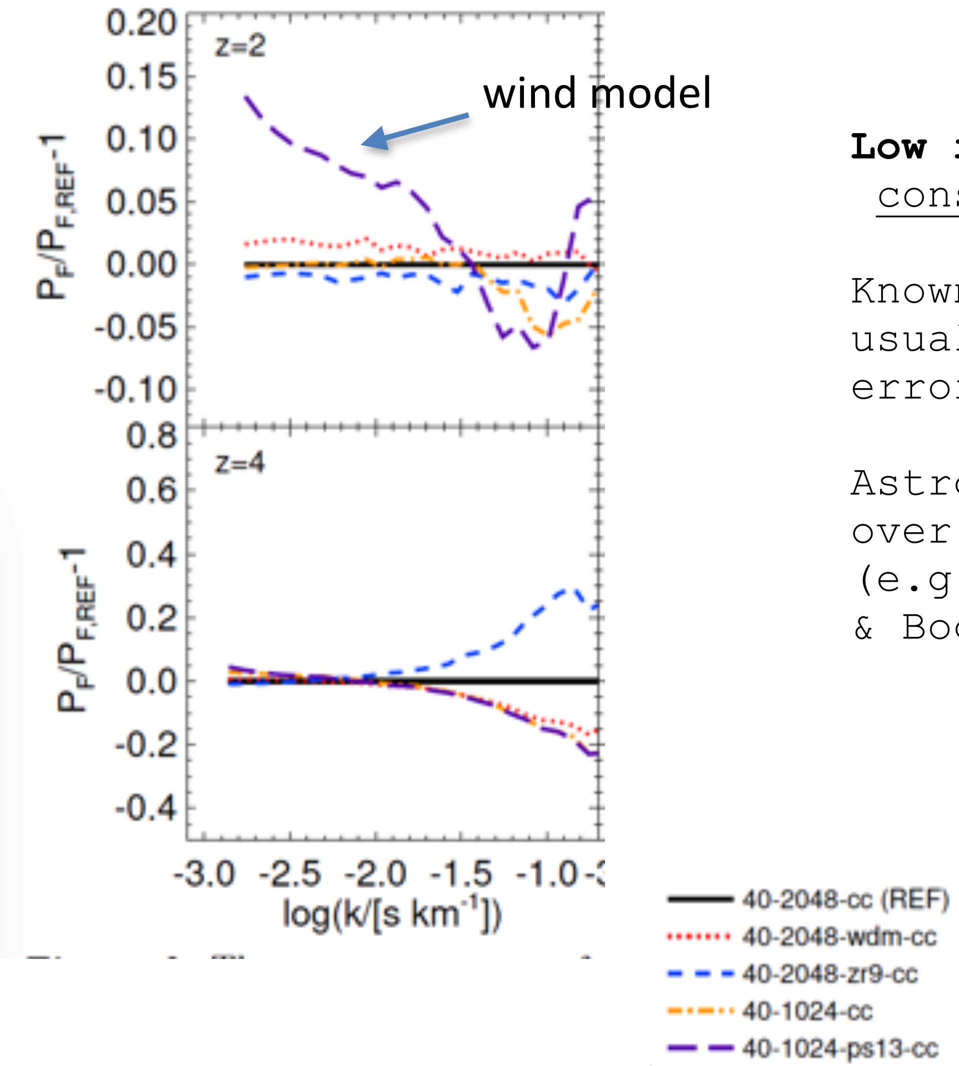


High resolution VLT or Keck spectra S/N ~100 - ~hundreds of spectra

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

MV, Haehnelt & Springel 04
MV+05,08,13, Becker+11
Yeche+17, Garzilli+18 ,
Bosman+18, Boera+19

Low-z Lyman-alpha flux power

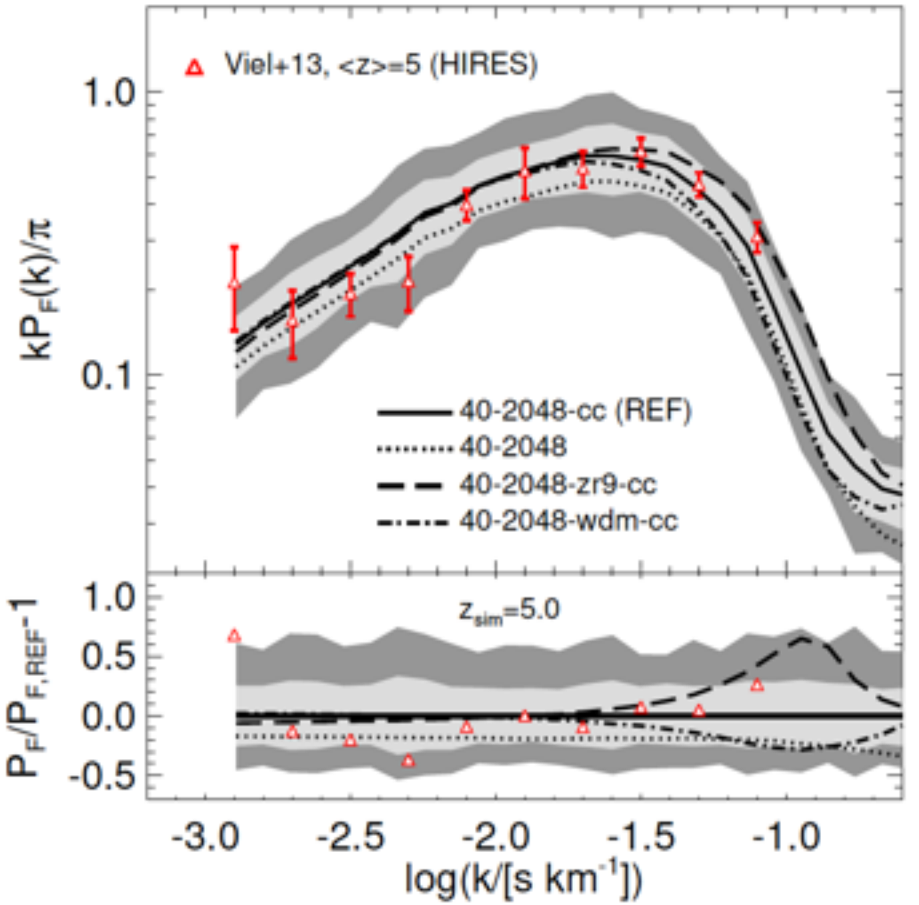


Low redshift:
constraining feedback, HeII reio.

Known systematic errors usually larger than statistical errors.

Astro parameters are marginalized over via template fitting (e.g. McDonald+06, Viel, Schaye & Booth 2012).

High-z Lyman-alpha flux power



High redshift:
constraining reionization

Statistical error usually comparable or larger than known systematic errors

Main systematics: **patchy reionization** (unlikely to be a small scale effect, Onorbe+18; Puchwein, Keating's talks).

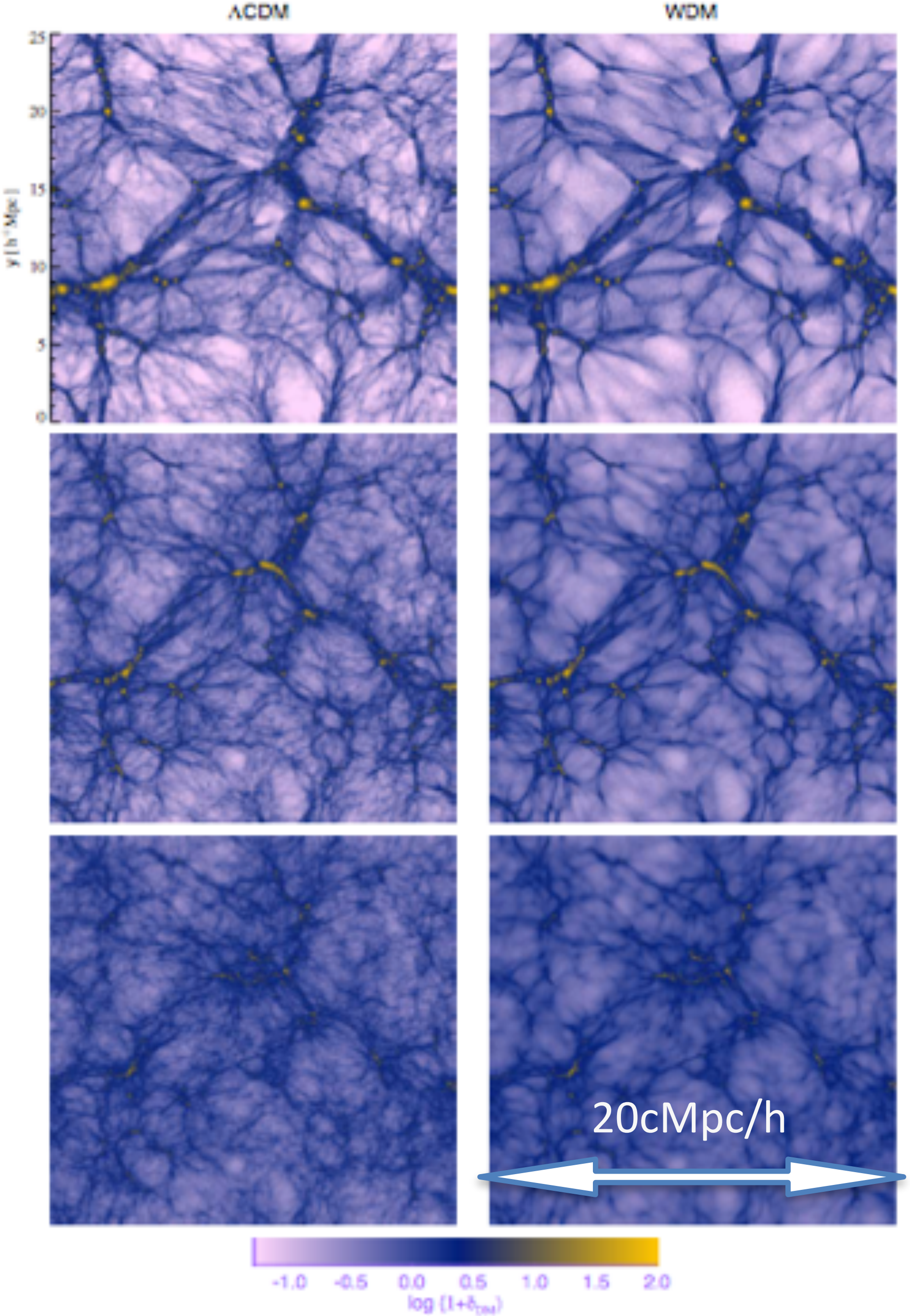
Boera+19 constraints on tau from ~20 QSOs are comparable (and in agreement) to those obtained by Planck CMB.

Two key *unique* aspects

$$P_{1D}(k) = \frac{1}{2\pi}\int_k^\infty P_{3D}(x)\,x\,dx$$

High redshift (and small scales):
possibly closer to linear behaviour

THE COSMIC WEB in WDM/LCDM scenarios



z=0

$$\frac{T_x}{T_\nu} = \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} < 1$$

$$k_{\mathrm{FS}} = \frac{2\pi}{\lambda_{\mathrm{FS}}} \sim 5\,\mathrm{Mpc}^{-1}\left(\frac{m_x}{1\,\mathrm{keV}}\right)\left(\frac{T_\nu}{T_x}\right)$$

$$\omega_x = \Omega_x h^2 = \beta\left(\frac{m_x}{94\,\mathrm{eV}}\right)$$

$$\beta = (T_x/T_\nu)^3$$

z=2

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

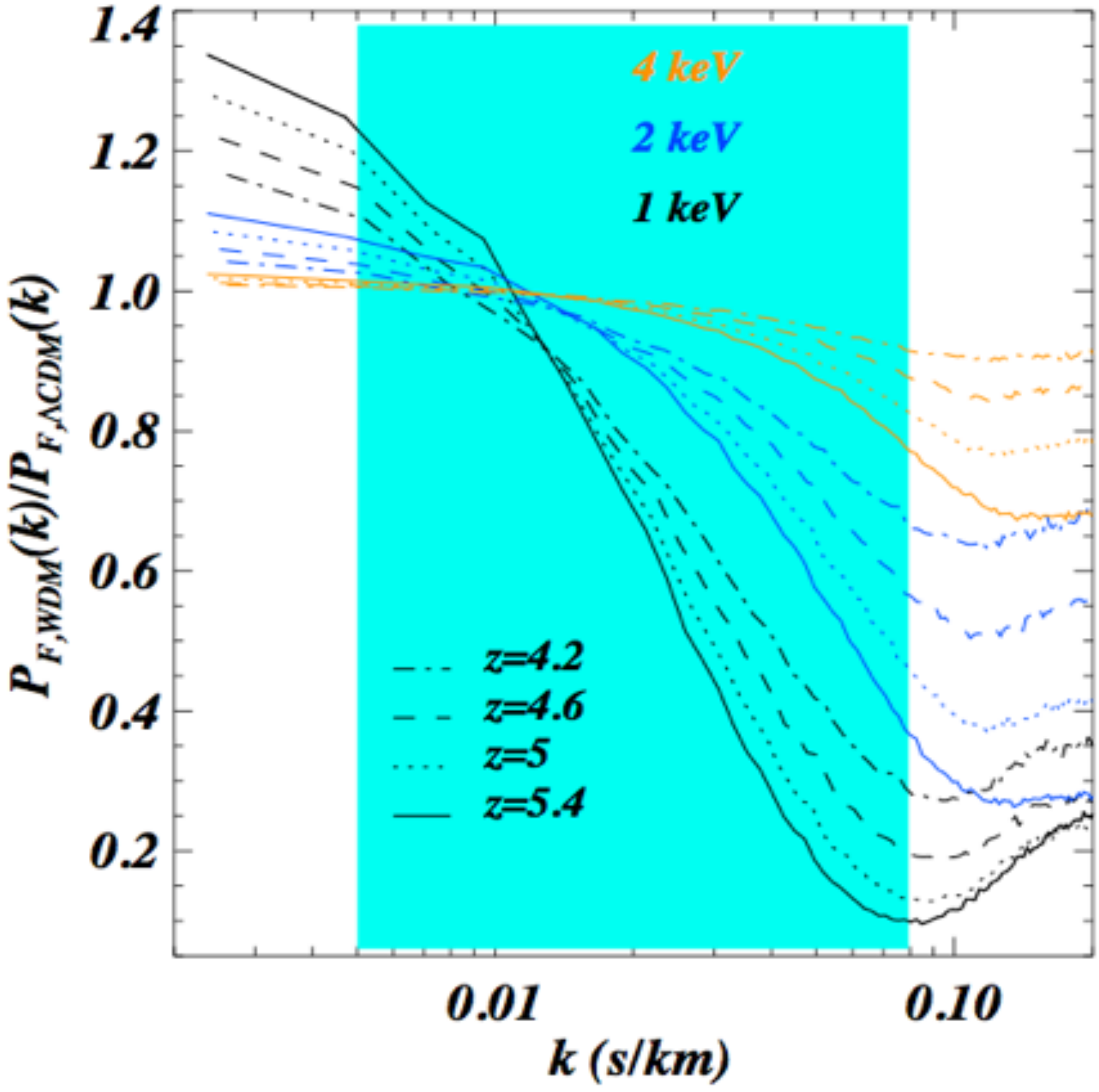
z=5

MV, Markovic, Baldi & Weller 2013

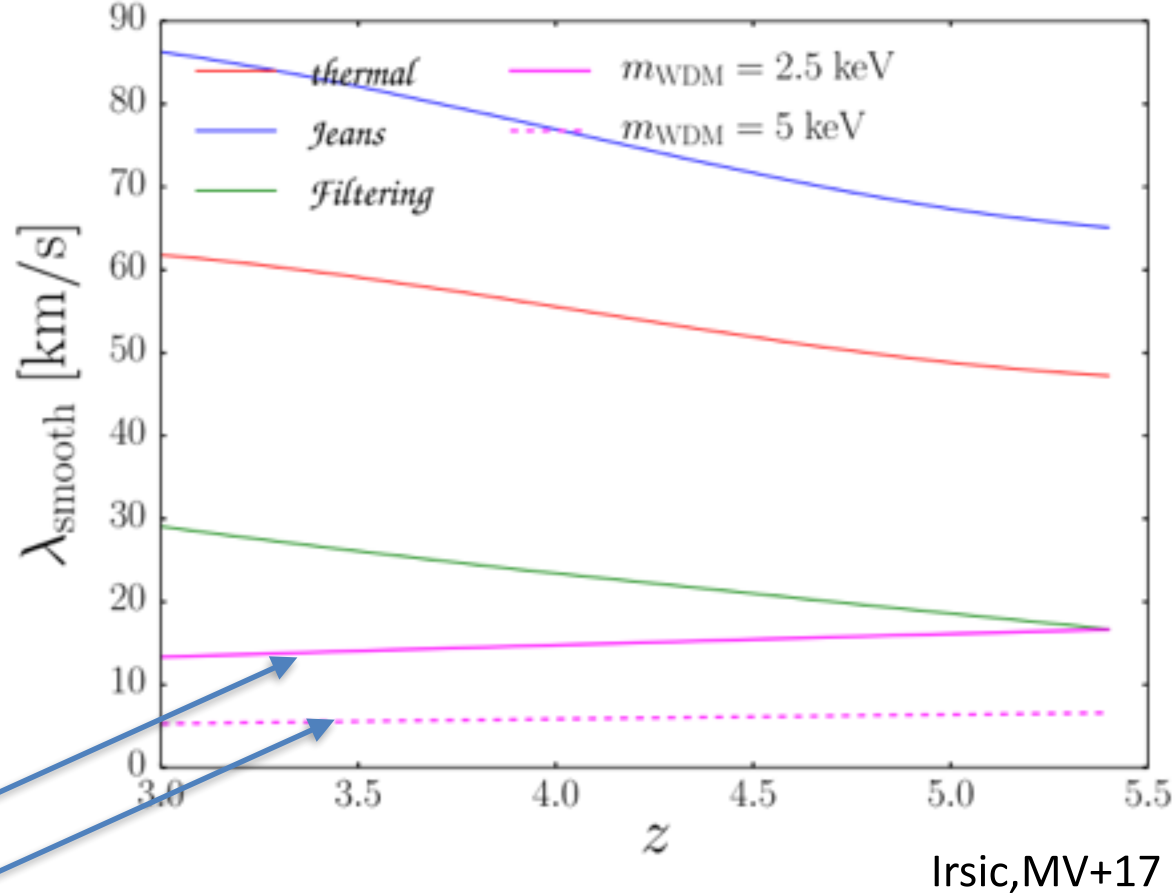
Markovic & MV, 2014

THE HIGH REDSHIFT WDM CUTOFF

$\delta_F = F/\langle F\rangle - 1$



Smoothing scales

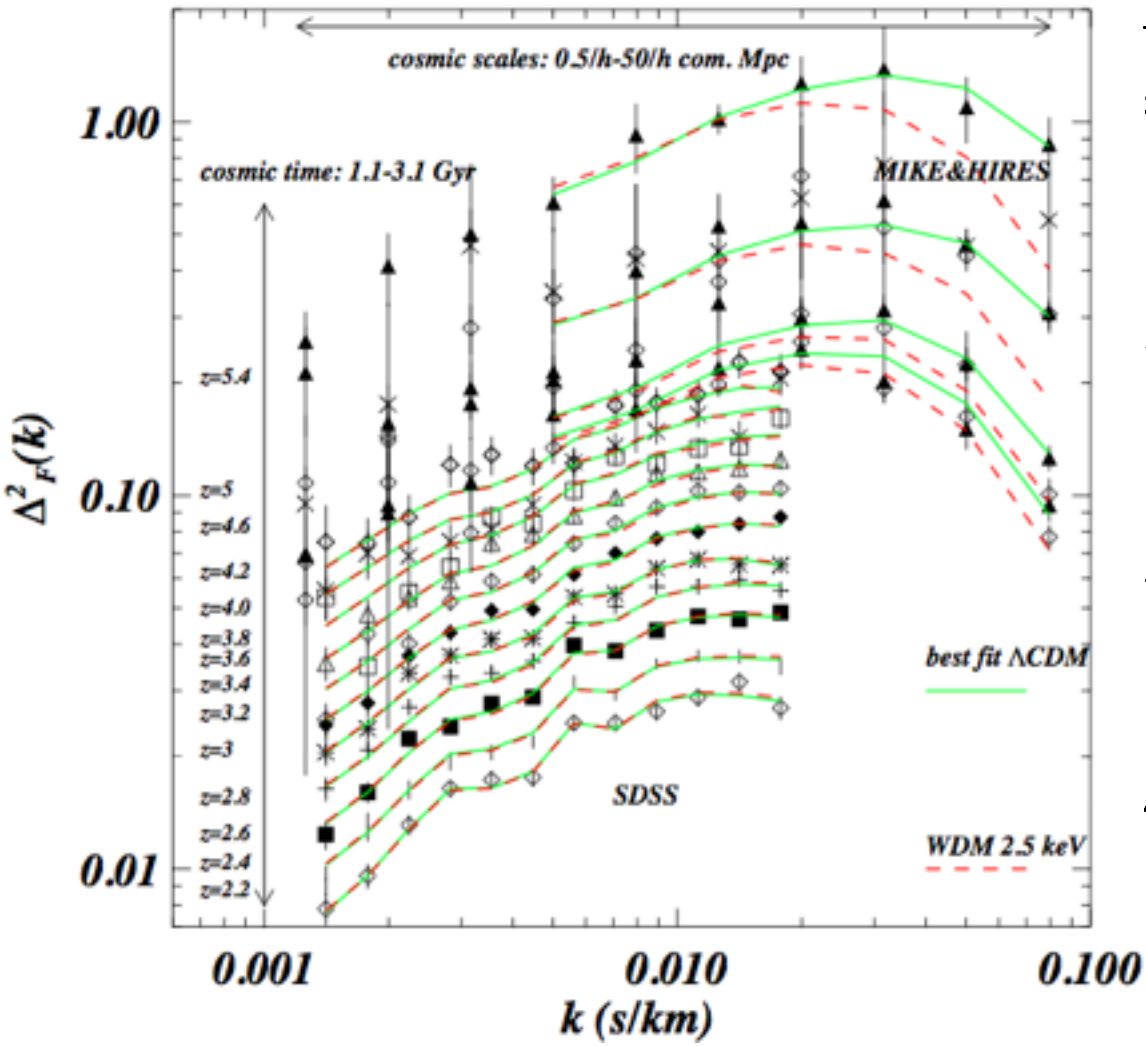


Irsic,MV+17

WARM DARK MATTER FREE STREAMING SCALE

STATUS in 2013

M $_{\text{thermal WDM}}$ > 3.3 keV (2σ C.L.)



This lower limit is derived under some assumptions

1) Bayesian analysis

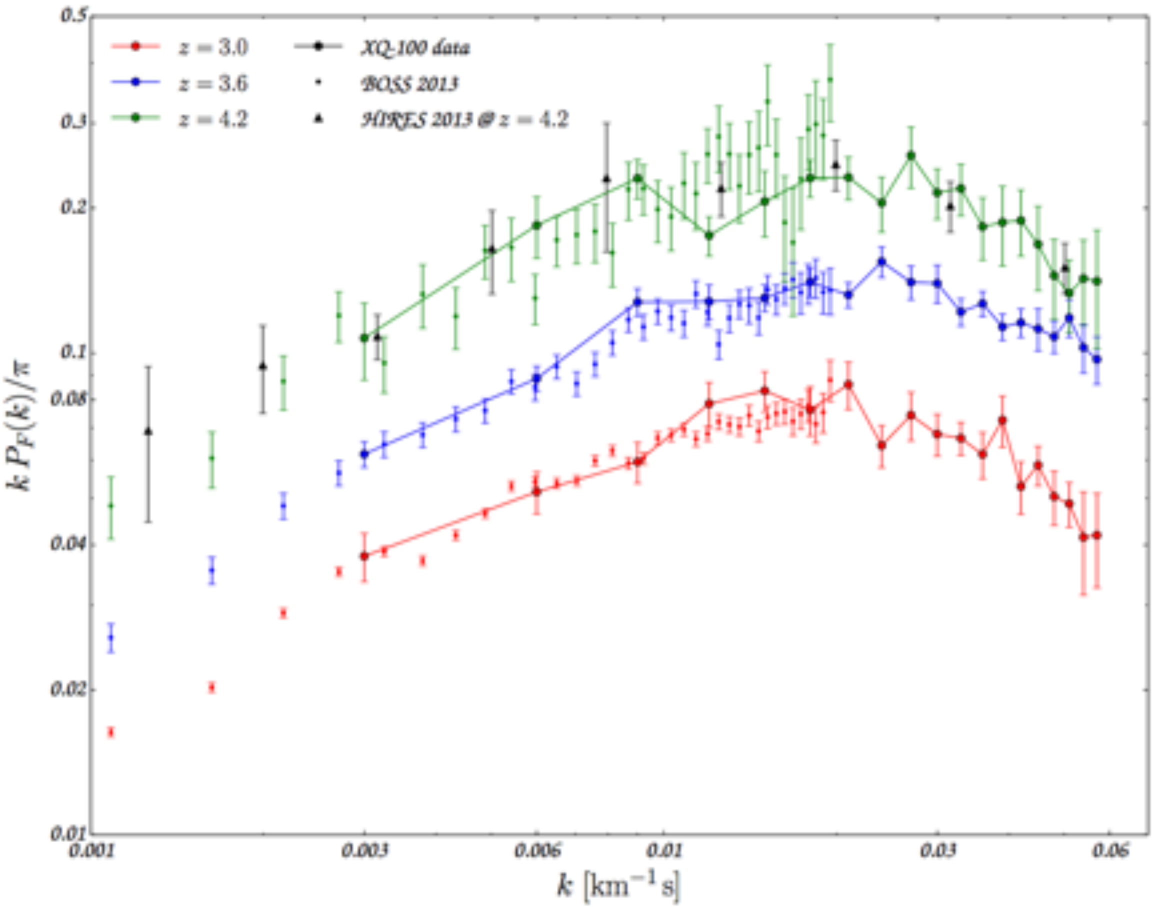
2) Bootstrap-derived covariance matrix from mock QSO sample with entries multiplied by 1.3

3) resolution corrections performed and particularly important at high-z & small-scales

4) limited exploration of redshift of reionization - Jeans smoothing

X-Shooter sample: bridging the gap between low-res and high-res

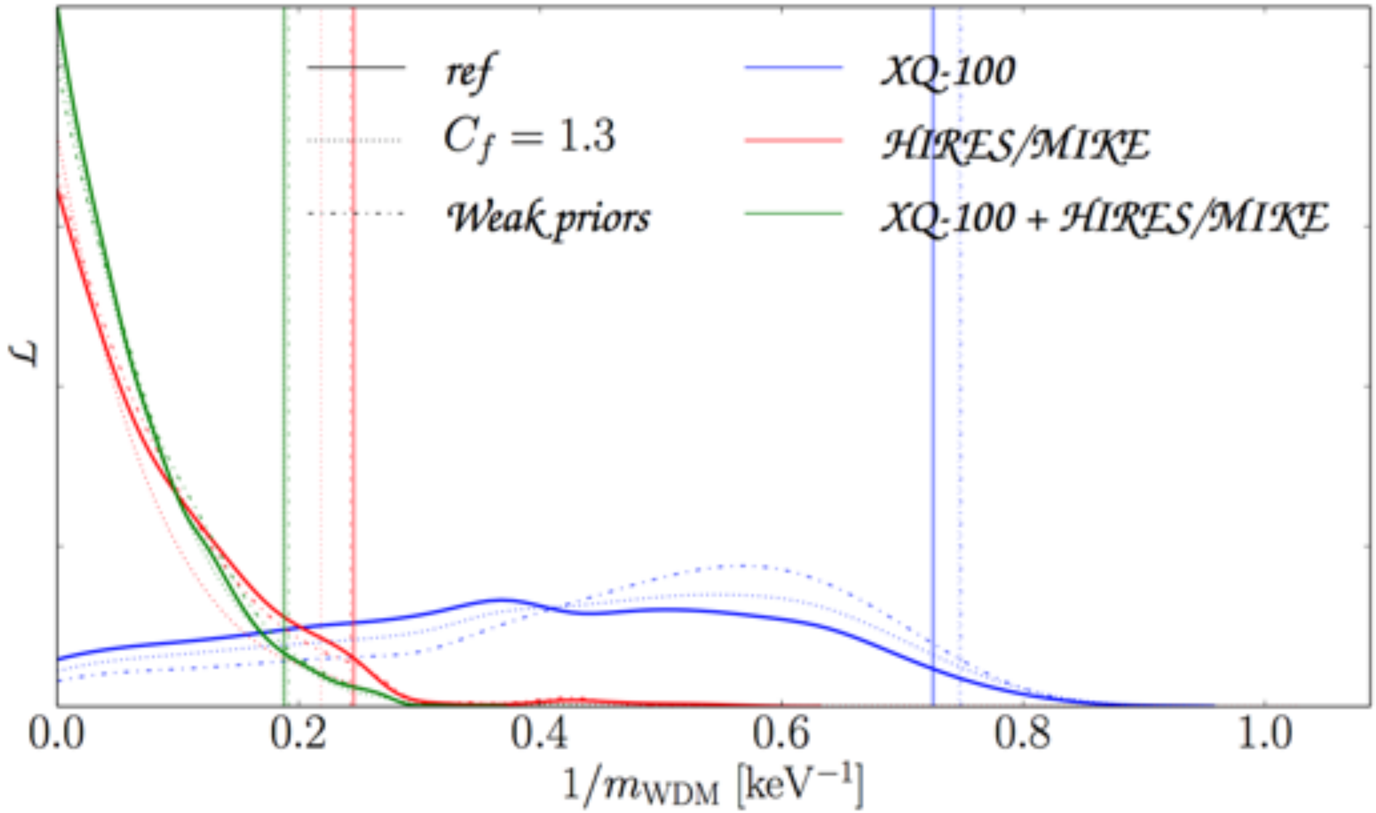
Irsic, MV+, 2017a, MNRAS, 466, 4332



- Sample of 100 QSOs at z>3.5 (**ESO Large Programme**, PI: Lopez).
- Medium resolution 30-50: different systematics involved.
- Down to relatively small scales 0.06 s/km —> 5-10 com. Mpc/h.
- Power spectrum extraction tested on mock spectra built using PRACE simulations.
- Sample is not very constraining by itself but becomes constraining when complemented by other redshifts (like SDSS or HIRES).

X-Shooter sample: results for WDM (thermal)

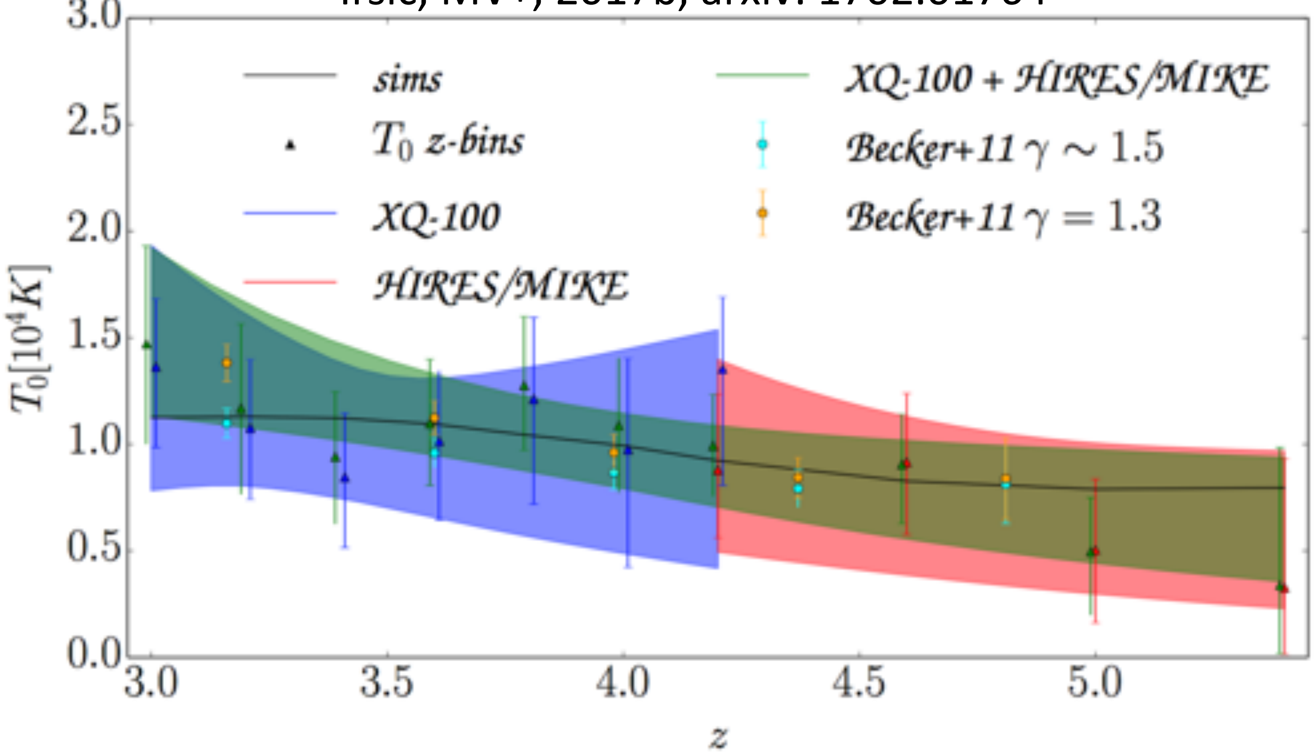
Irsic, MV+, 2017b, arxiv: 1702.01764



- Likelihood greatly improves (shrinks) when combined with HIRES, pushing towards LCDM (cold).
- **Increasing covariance matrix by 1.3 (for XQ-100) or applying weak priors on cosmo parameters does not impact**
- Limits are then: > 1.4, > 4.1, > 5.3 keV for the reference cases for XQ-100 (medium res.), HIRES/Keck (high res.) and combined, respectively.

X-Shooter sample: IGM thermal priors

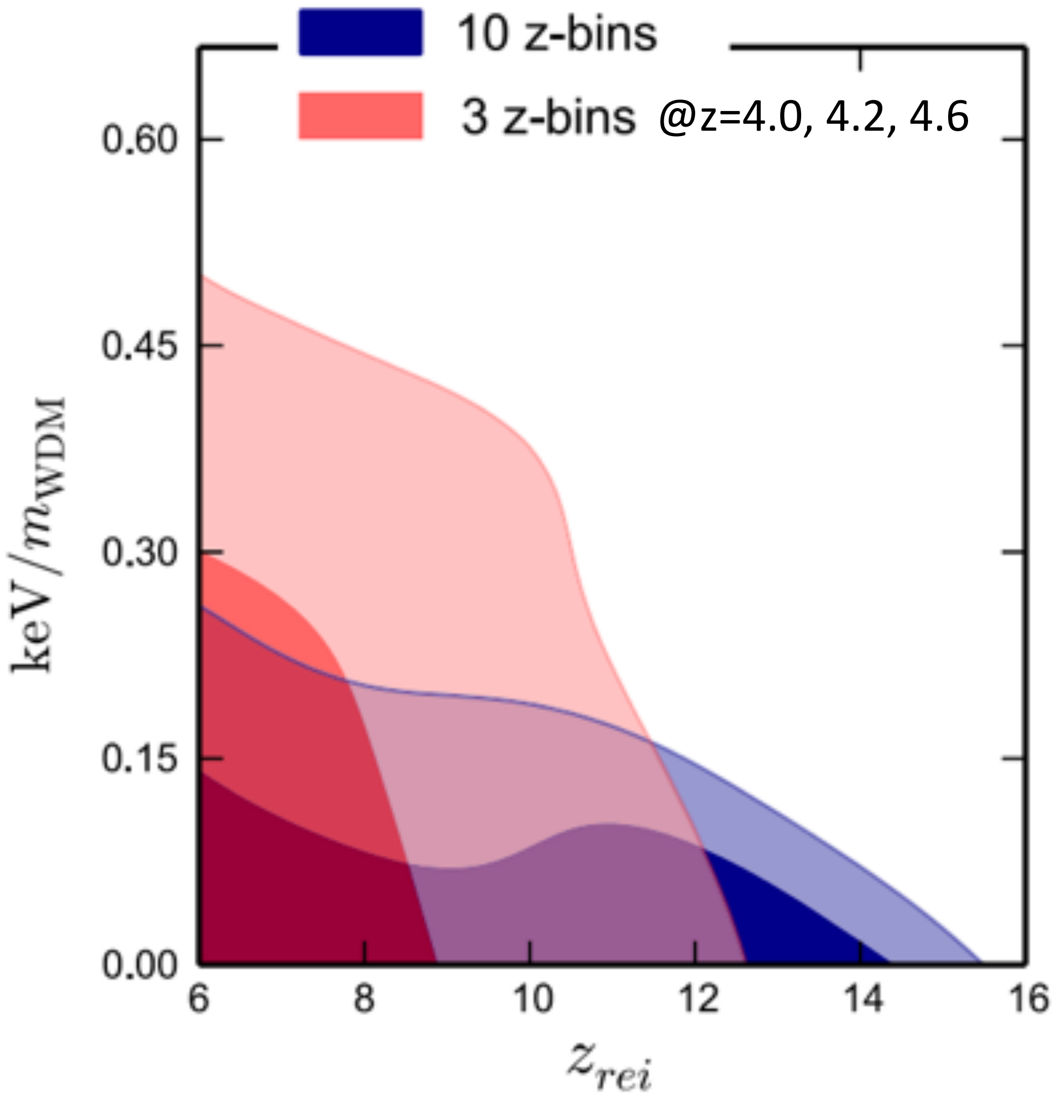
Irsic, MV+, 2017b, arxiv: 1702.01764



- Thermal history is the main nuisance. It is marginalized over but still quite sensitive to priors.
- For reference case $T_{IGM}(z)$ assumed to be a power-law (motivated by IGM physics), having this assumption lifted weakens the combined constrained to 3.5 keV.
- Key-aspect here: **wide redshift range** that allows to break degeneracies between WDM cutoff, Jeans pressure, filtering scale (all suppress power but differently in z).

Redshift coverage is important

Since it allows to break degeneracies



Irsic,MV+17

Non-cold Dark Matter at small scales - I: a new and more general approach

Standard approach

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu} \quad \Rightarrow$$

Applies to thermal WDM
(Fermi Dirac distribution)

$$\nu = 1.12\,;$$

$$\alpha = 0.049\left(\frac{m_x}{1\ \mathrm{keV}}\right)^{-1.11}\left(\frac{\Omega_x}{0.25}\right)^{0.11}\left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

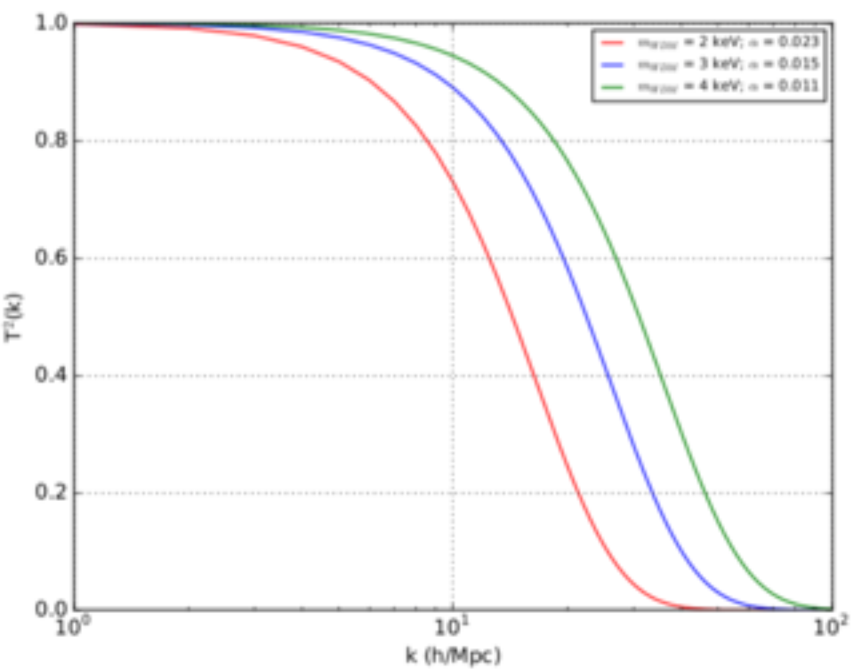
New general approach

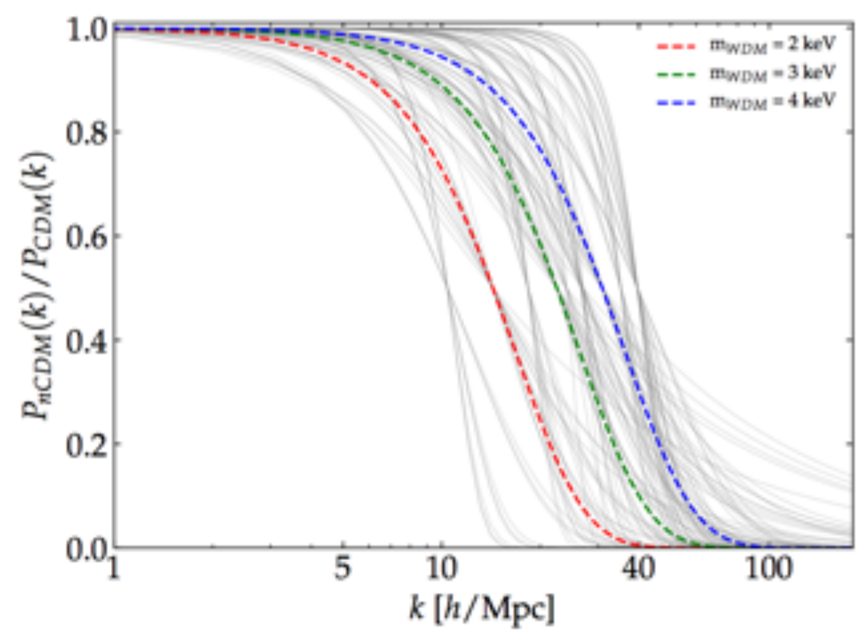
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

Applies to ?

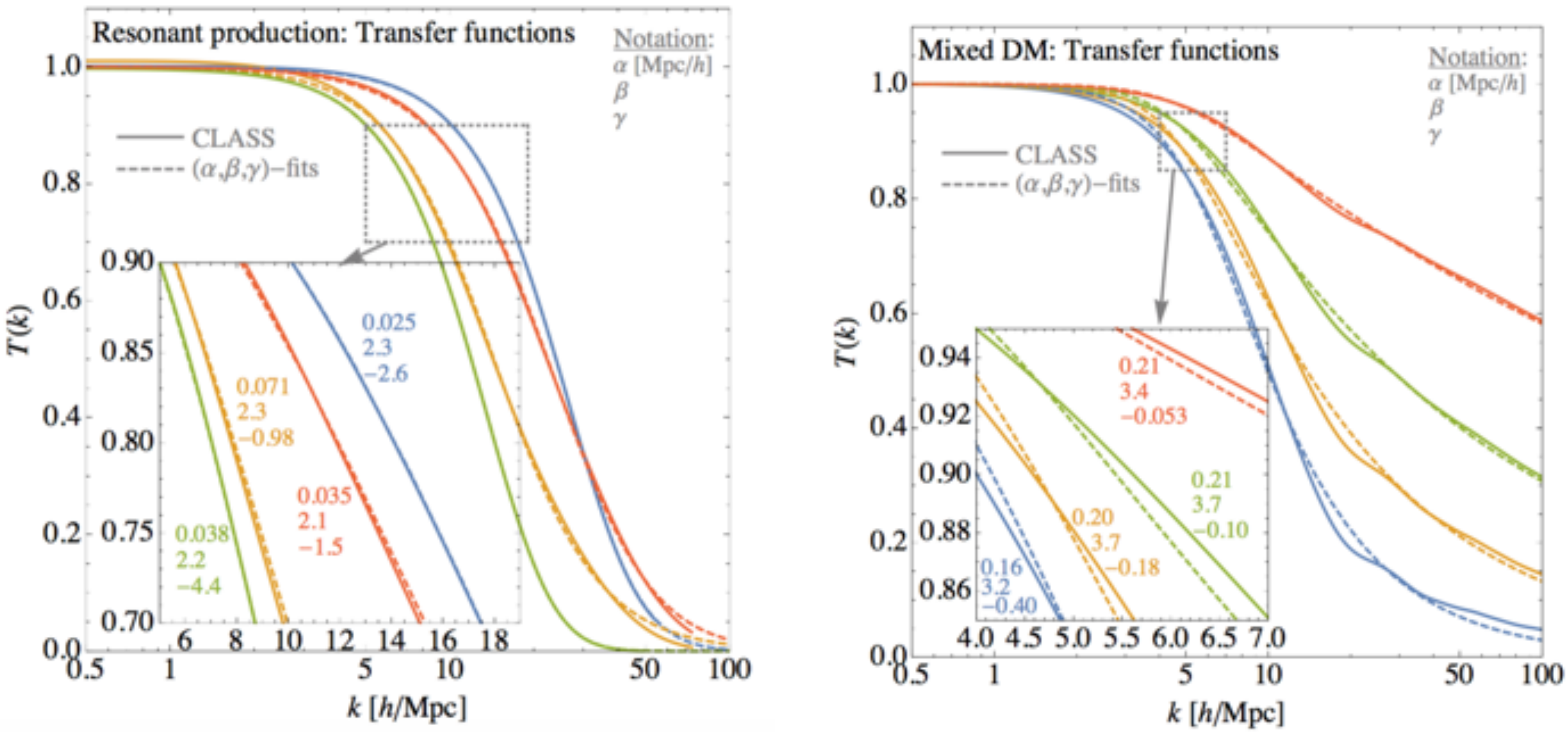
The larger is beta, the flatter is the shape for k < $k_{1/2}$; the larger is gamma, the steeper is the small-scale cutoff
.

Murgia, Merle, MV +17





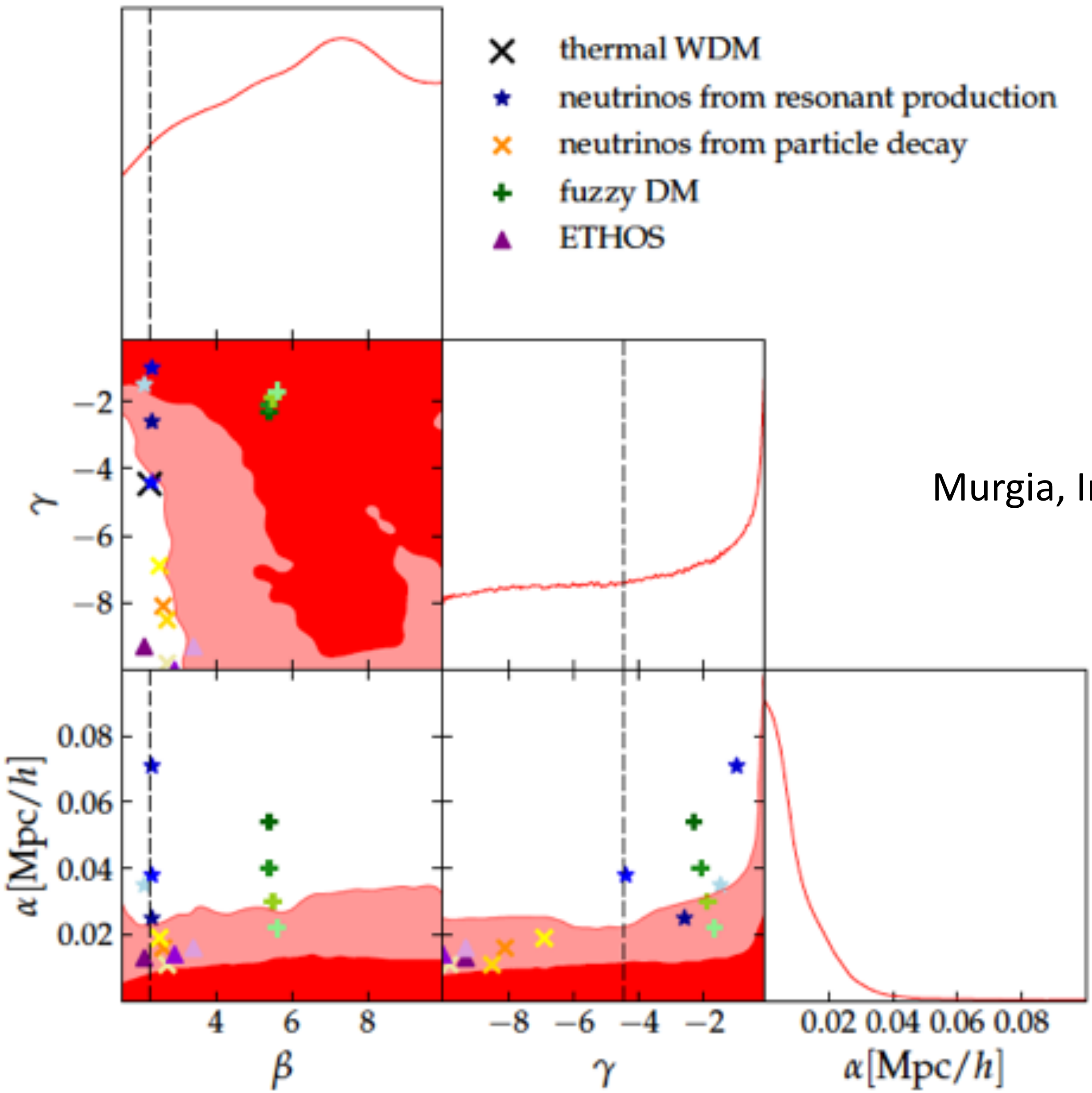
Non-cold Dark Matter at small scales - II: particle physics models



Simple parametrization proposed works well for:

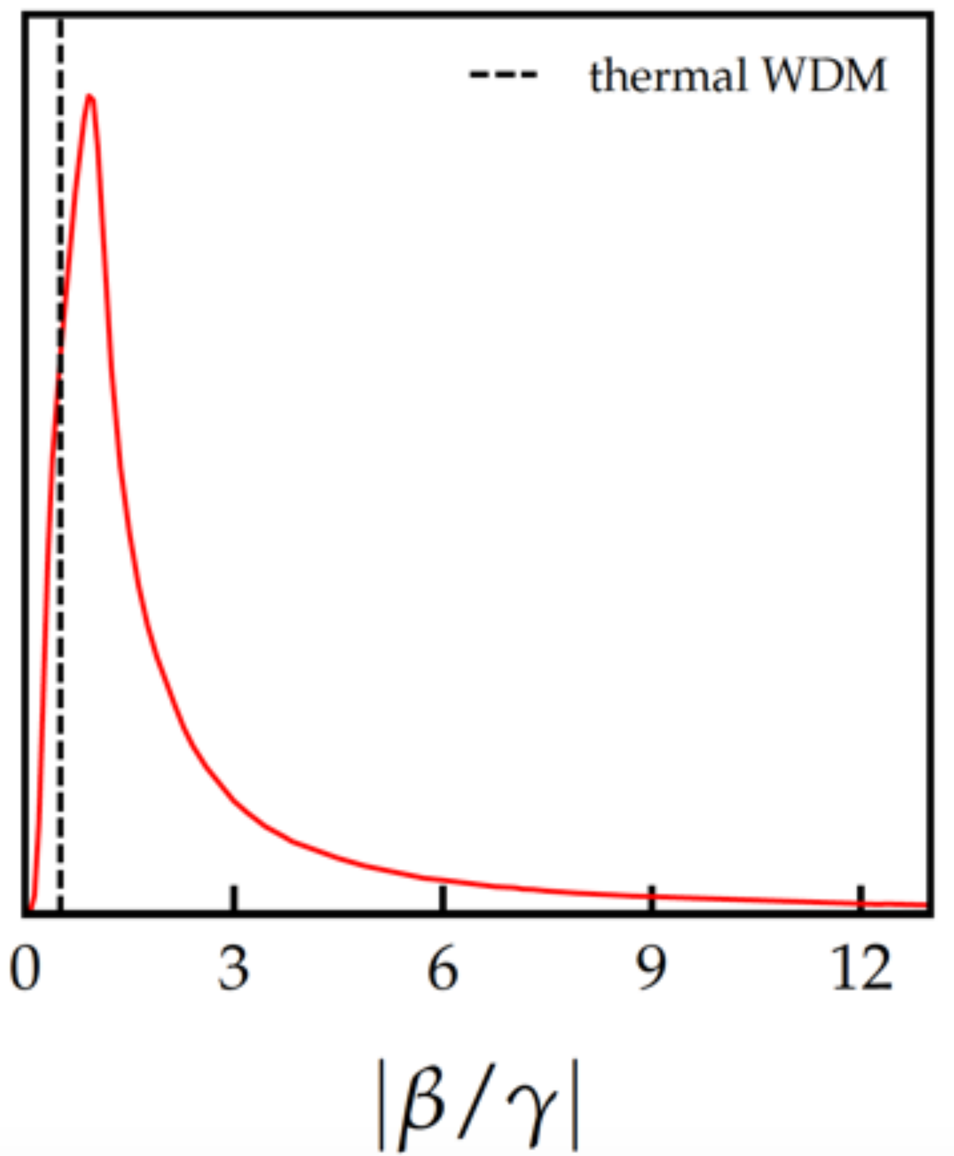
- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixed models
- fuzzy dark matter
- ETHOS models

Non-Cold Dark Matter and constraints on the SHAPE of the cutoff



Murgia, Irsic, MV, 2018

Non-Cold Dark Matter and constraints on the SHAPE of the cutoff - II



$$\alpha < 0.03\ \mathrm{Mpc}/h\ (2\sigma)$$

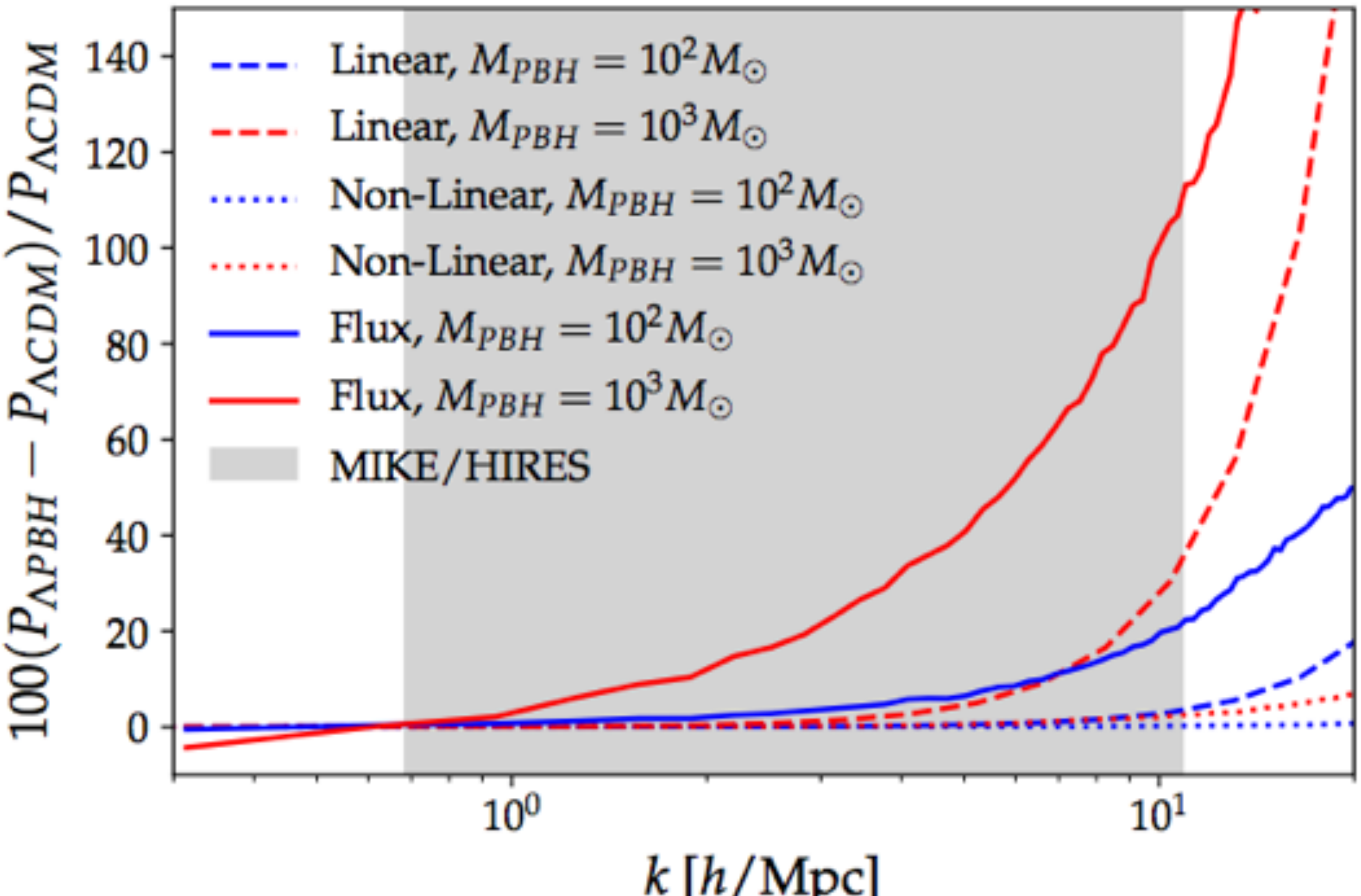
$$|\beta/\gamma| < 14$$

Murgia, Irsic, MV, 2018

Primordial Black Holes and the Lyman-alpha forest

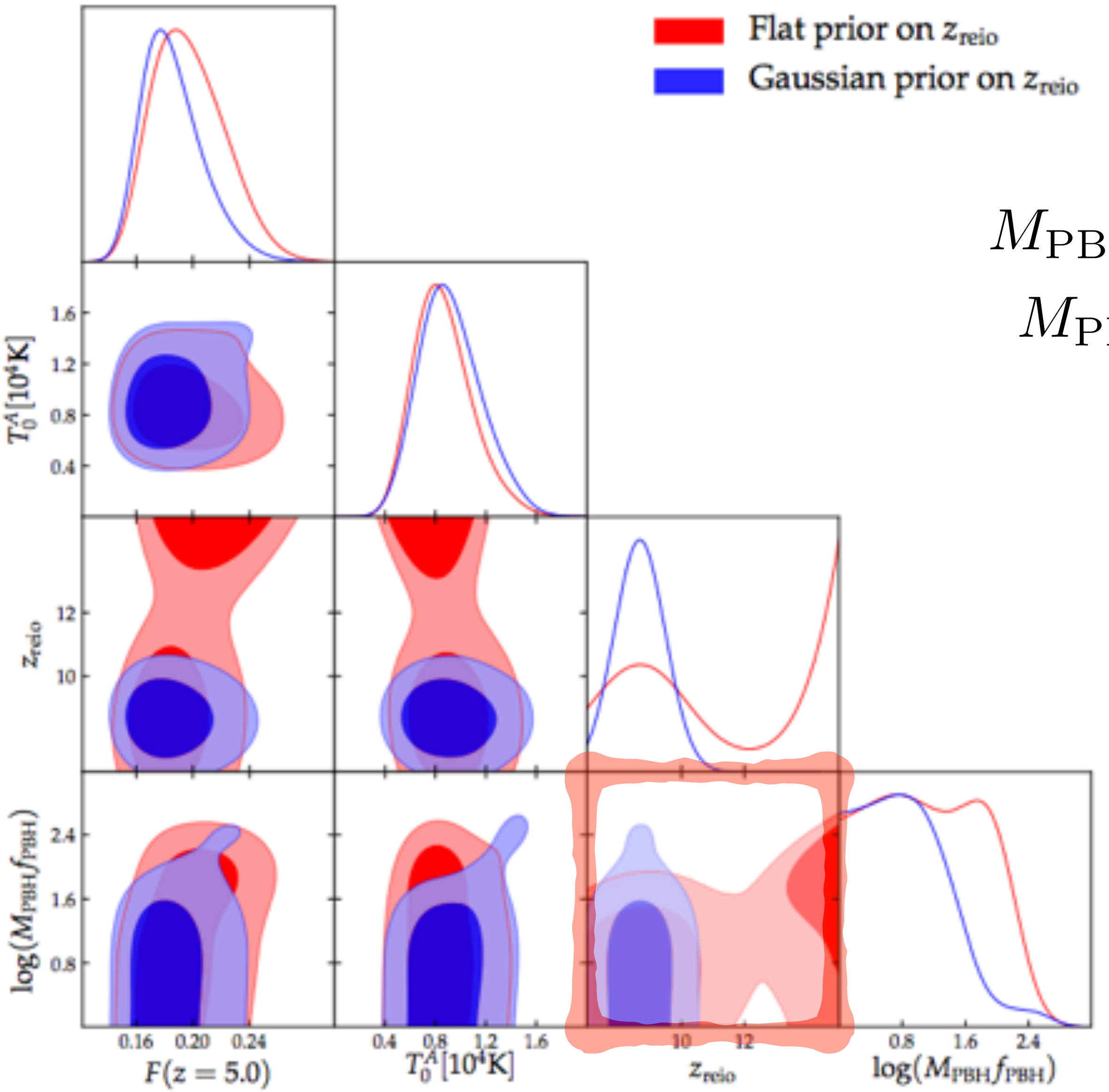
$$P_{\mathrm{CDM}}(k,z) = D^2(z)\left(T_{\mathrm{ad}}^2(k)P_{\mathrm{ad}} + T_{\mathrm{iso}}^2(k)P_{\mathrm{iso}}\right)$$

Afshordi, McDonald, Spergel 03



Murgia, Scelfo, MV, Raccanelli 2019

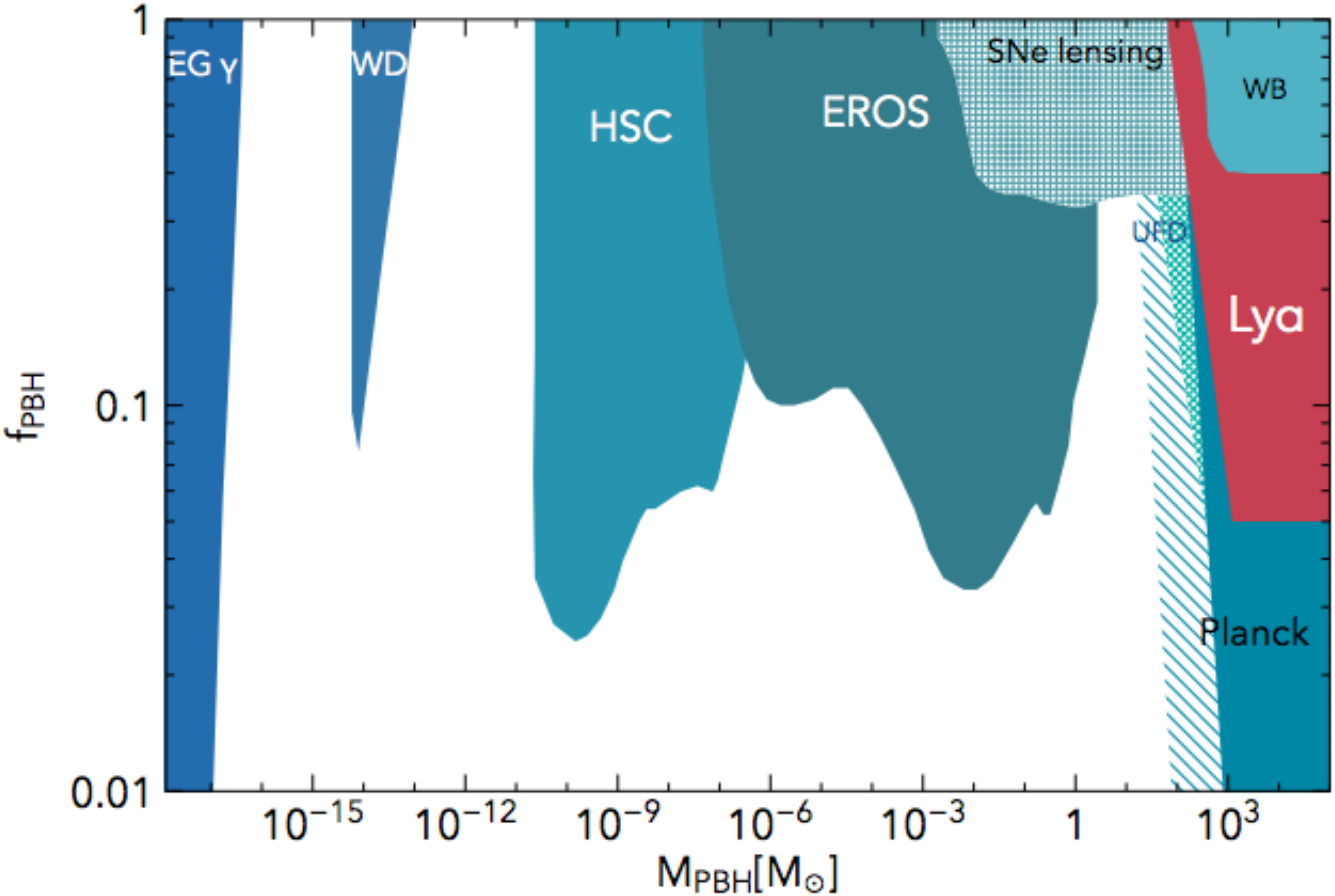
Primordial Black Holes - II



$$M_{\rm PBH} < 170 M_\odot$$

$$M_{\rm PBH} < 60 M_\odot$$

Primordial Black Holes - III

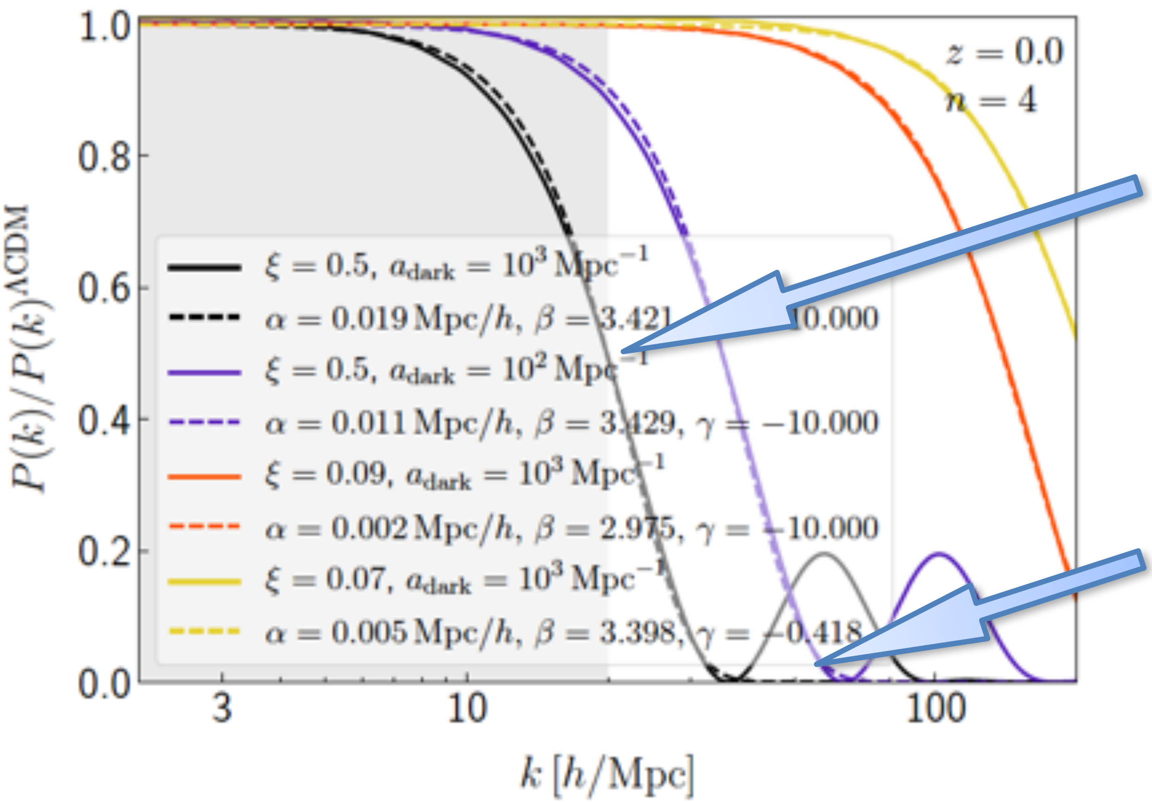


Non-Cold Dark Matter: DM-Dark radiation interactions

Non relativistic DM scattering off (extra) relativistic radiation n=0,2,4 are the models usually explored

$$\Gamma_{\rm DR-DM} \propto a_{\rm dark} T^n$$

$$\xi = T_{\rm DR}/T_\gamma$$



Late kinetic decoupling induced by DM-DR produces collisional damping (cutoff in P(k))

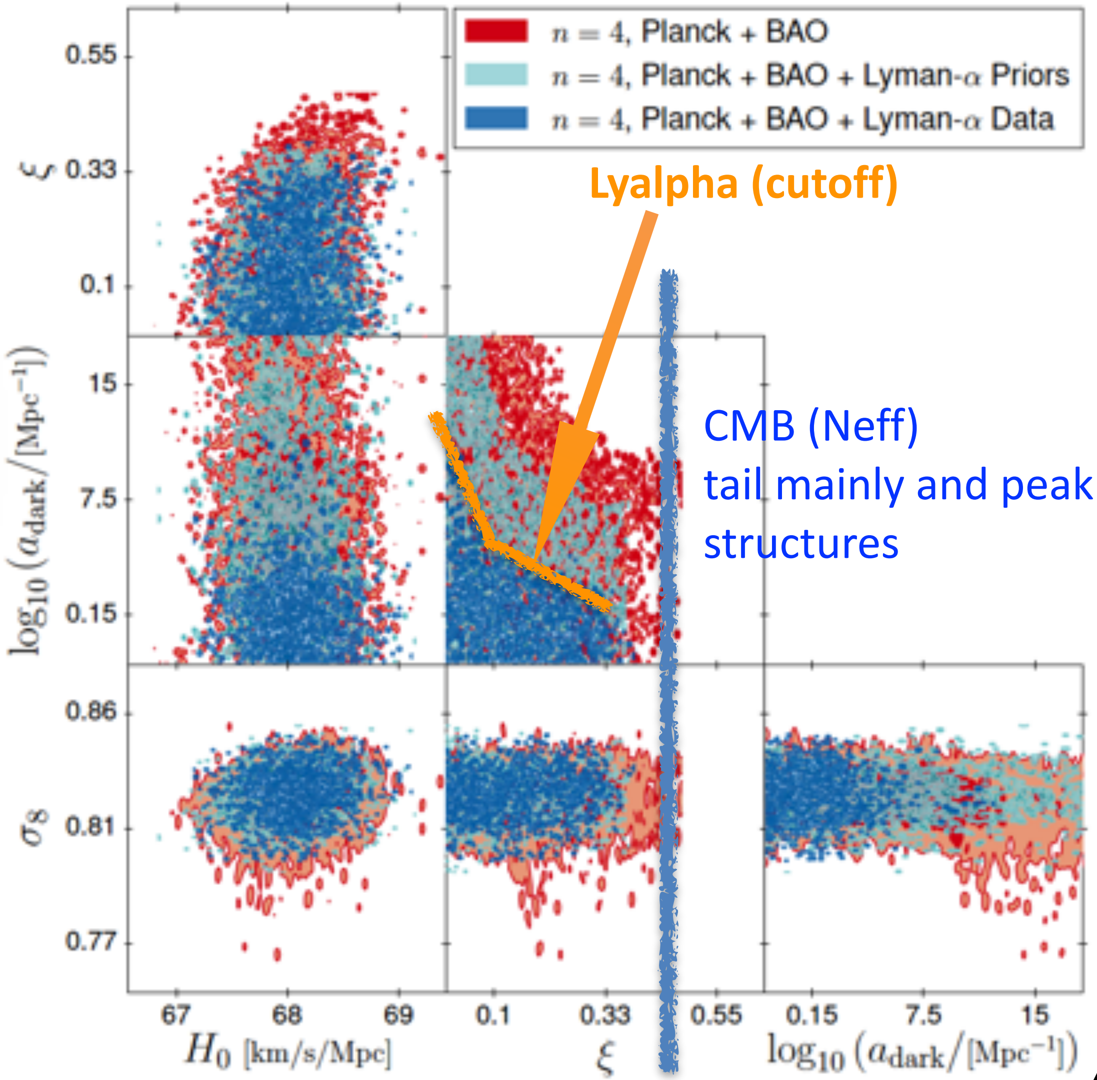
DM clustering and DR pressure produce DAOs at small scales

Constraining Dark Matter - Dark Radiation interactions with CMB, BAO, and Lyman-α

Maria Archidiacono[1,2], Deanna C. Hooper[1], Riccardo Murgia[3], Sebastian Bohr[1], Julien Lesgourgues[1], Matteo Viel[1,5]

Archidiacono, Hooper, Murgia, Bohr, Lesgourgues, MV 2019

Non-Cold Dark Matter: DM-Dark radiation interactions



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

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

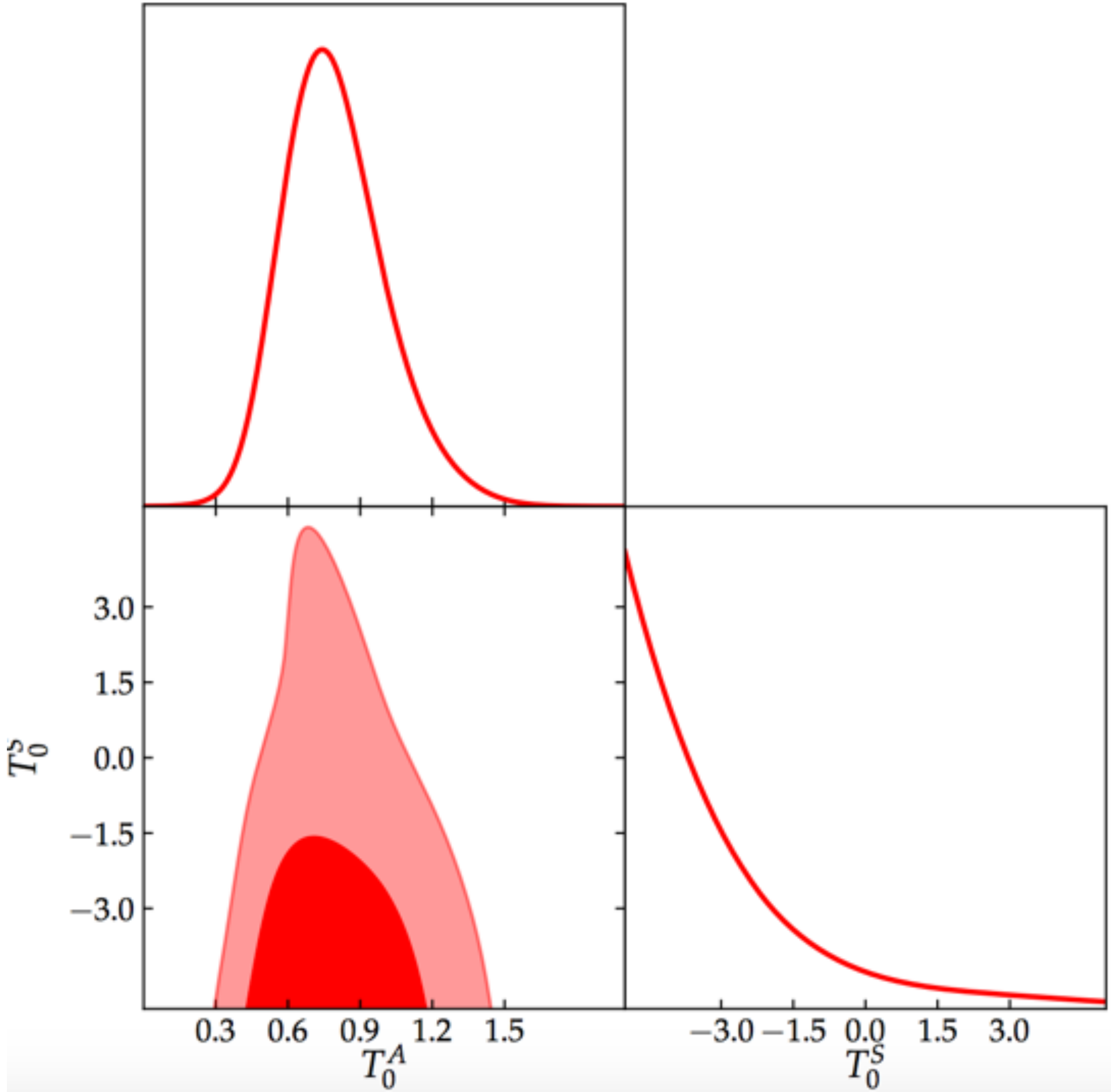
CONCLUSIONS - I

- WDM: consistency with cold dark matter **> 3.5 keV** relics 2σ C.L.

- More general simple model presented, in which for the first time some **constraints on the shape** are obtained.

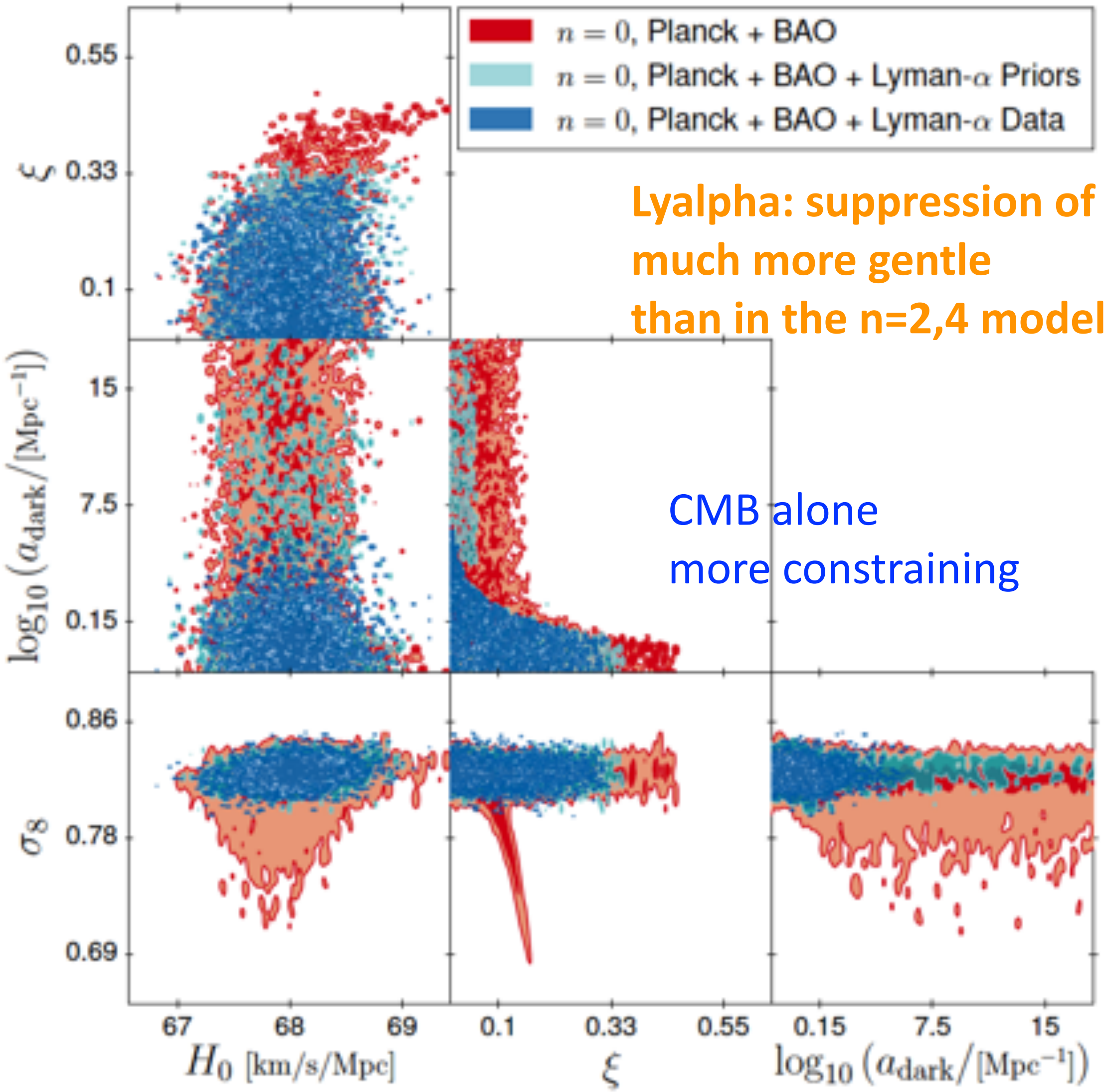
- Constraints placed by a isocurvature - Poisson term are prior dependent and range from **60-170 M_sun** window (already closed by Planck) is also closed by Lyman-alpha forest data.

- Constraints on **DM-DR radiation models** presented. n=4,2 models can provide an equally good fit than LCDM (n=0 could ease S_8 and H_0 tensions slightly, by 1-2 sigmas).



3.0
1.5
0.0
−1.5
−3.0
T_0^S
0.3 0.6 0.9 1.2 1.5
T_0^A
−3.0 −1.5 0.0 1.5 3.0
T_0^S

Non-Cold Dark Matter: DM-Dark radiation interactions



Lyalpha: suppression of power much more gentle than in the n=2,4 models

CMB alone more constraining

Particle Physics: Non Abelian DM. DM charged under a dark non-abelian symmetry with dark gluons being the DR.

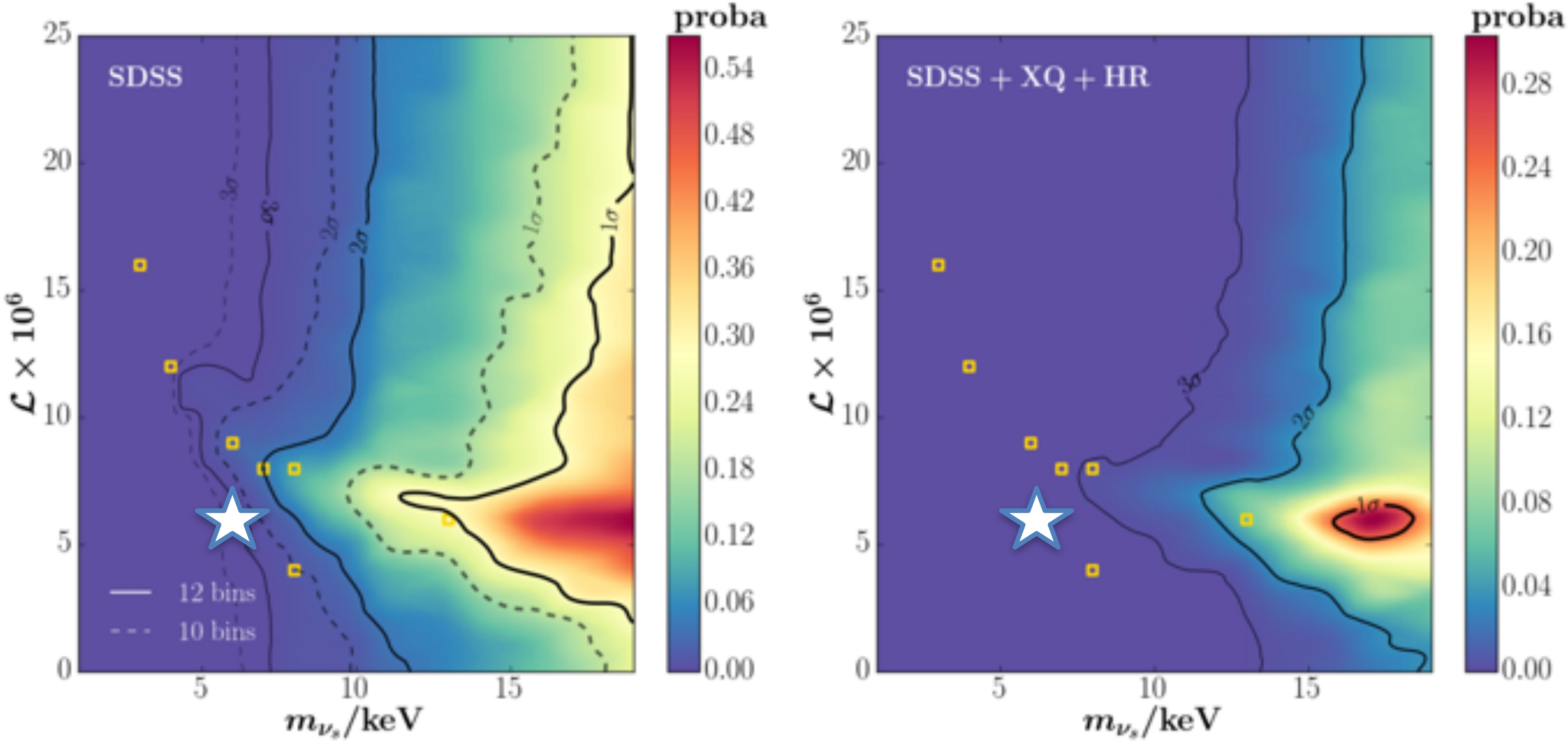
DR is a perfect fluid.

Parameter	Lyα BOSS + H_0^{Gaussian} (PY15) (1)	Lyα eBOSS + H_0^{Gaussian} (This work) (2)	Lyα eBOSS + Planck (TT+lowE) (3)	Lyα eBOSS + XQ-100 + Planck (TT+lowE) (4)
T_0 (z=3) (10^3K)	8.9 ± 3.9	10.3 ± 1.7	11.3 ± 1.6	13.7 ± 1.5
γ	0.9 ± 0.2	0.8 ± 0.1	0.7 ± 0.1	0.9 ± 0.1
σ_8	0.855 ± 0.025	0.820 ± 0.021	0.817 ± 0.007	0.804 ± 0.008
n_s	0.937 ± 0.009	0.955 ± 0.005	0.954 ± 0.004	0.961 ± 0.004
Ω_m	0.288 ± 0.012	0.269 ± 0.009	0.330 ± 0.009	0.309 ± 0.011
H_0 (km s^{-1} Mpc^{-1})	67.1 ± 1.0	67.1 ± 1.0	66.2 ± 0.6	67.6 ± 0.8

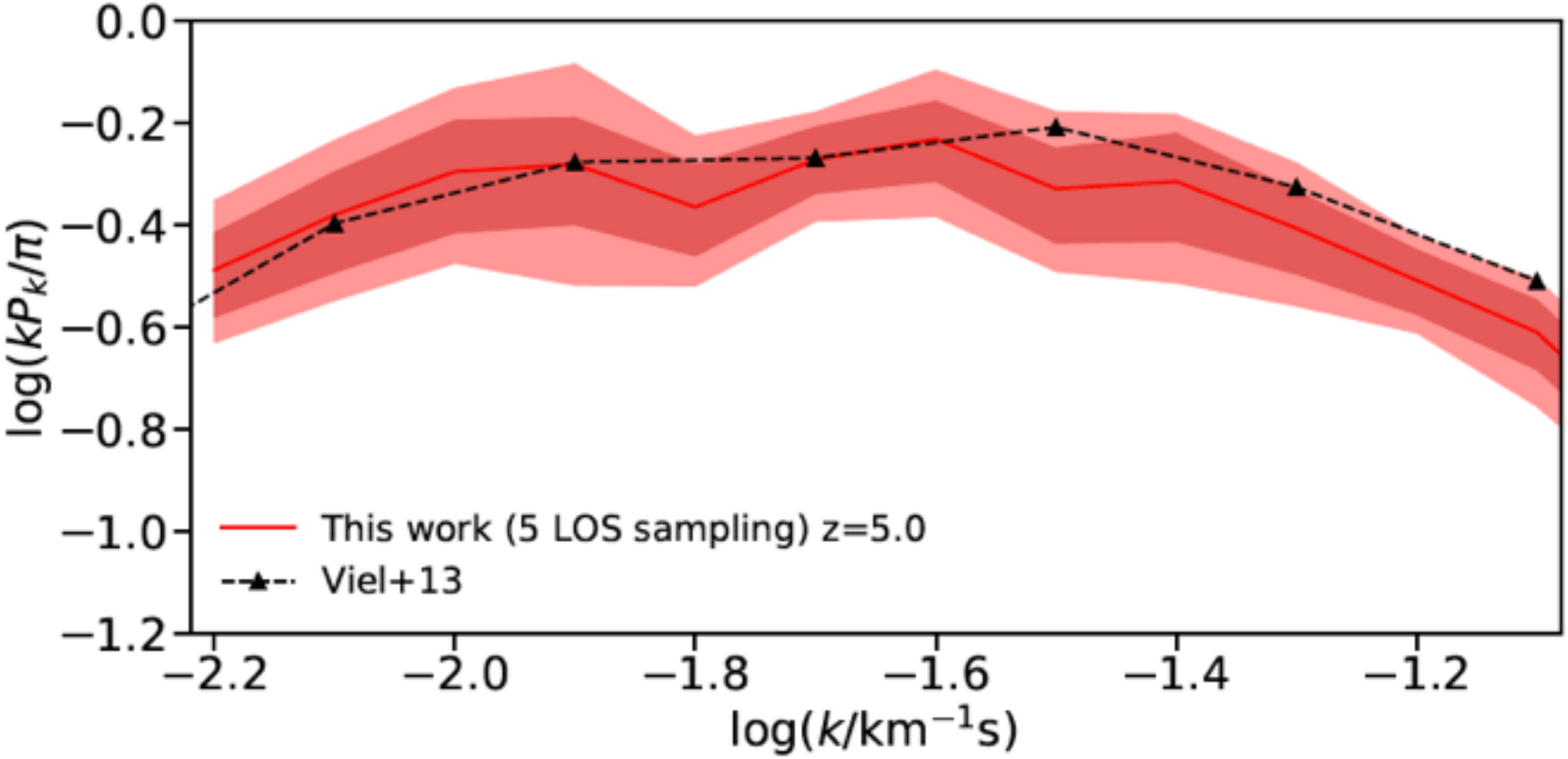
Chabanier + 19

TABLE III: The final summary of the marginalized estimates (1 and 2σ C.L.) and best fit values for $m_{\rm WDM}$. Planck priors on σ_8, $n_{\rm s}$ and $\Omega_{\rm m}$ have been applied. The REF. model refers to our reference conservative analysis; REF. w/o 30% refers to the case in which we do not add an extra 30% uncertainty on the data to account for underestimated bootstrap error bars; REF. w/o covmat refers to the case in which we use only the diagonal terms of the covariance matrix; REF+SDSS is the joint analysis of our reference model and SDSS flux power.

model	(1σ)	(2σ)	best fit	χ^2/d.o.f.
REF.	> 8.3 keV	> 3.3 keV	33 keV	34/37
REF. w/o 30%	> 11.1 keV	> 4.5 keV	100 keV	48/37
REF. w/o covmat	> 7.7 keV	> 3.1 keV	14.3 keV	33.2/37
REF. + SDSS	> 7.2 keV	> 3.3 keV	42 keV	183.3/170


proba
SDSS
12 bins
10 bins
m_{ν_s}/keV
$\mathcal{L} \times 10^6$
SDSS + XQ + HR

Baur+17



From Boera+18