Plan

Matteo Viel

- Lecture 1: Cosmological effects of neutrinos in linear perturbation theory
- Lecture 2: Non-linear regime
- Lecture 3: Neutrinos in Intergalactic space
- Lecture 4: New ways of probing neutrino masses

Some thoughts

- Neutrinos do not cluster much
- Non-linearities produce features in the massive neutrino Matter power spectrum but… non-linear scales are difficult to model (expensive N-body) and on top of that affected by baryonic processes (lecture #4)
- Maybe we should look at them in the high-z Universe, after CMB but before structures become too non-linear

IDEAL place: the intergalactic medium

Bibliography

References:

1) MODEL BUILDING:

Bi & Davidsen 1997,
"Evolution of Structure in the Intergalactic Medium and the Nature of the Lyα Forest", ApJ, 479, 523

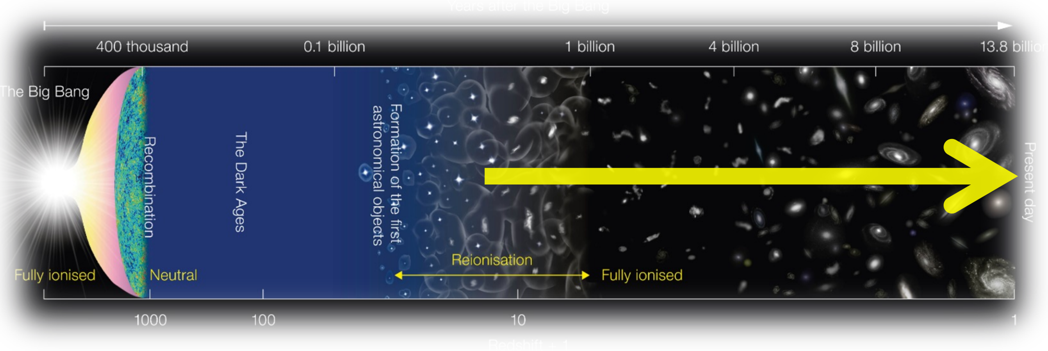
2) MORE ON OBSERVATIONS:

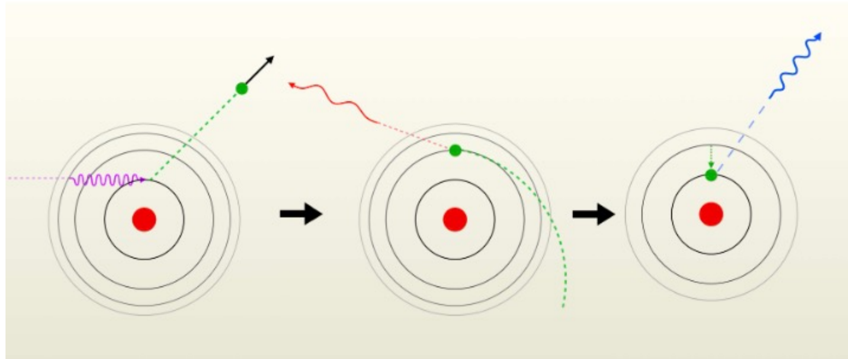
Rauch, 1998, "The Lyman-alpha forest in the spectra of QSOs", ARA&A, 32, 267

3) RECENT REVIEWS (include sims and recent data sets):

Meiksin, 2009, "The Physics of the IGM", Progress Reports, 81, 1405 McQuinn, 2016, "The Evolution of the Intergalactic Medium", ARA&A, 54,313

Intergalactic Medium





<u>Post-reionization Universe</u>

- 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

Intergalactic Medium

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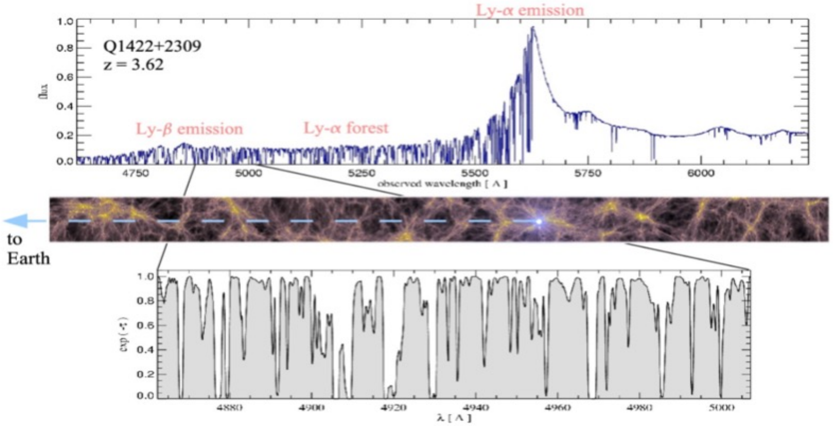
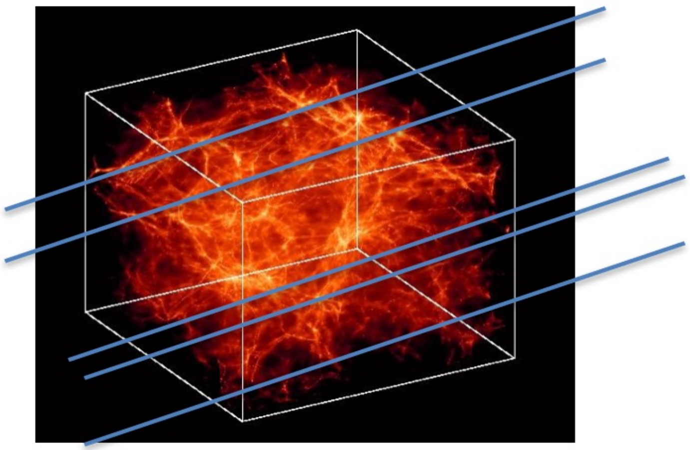
The Lyman-alpha forest





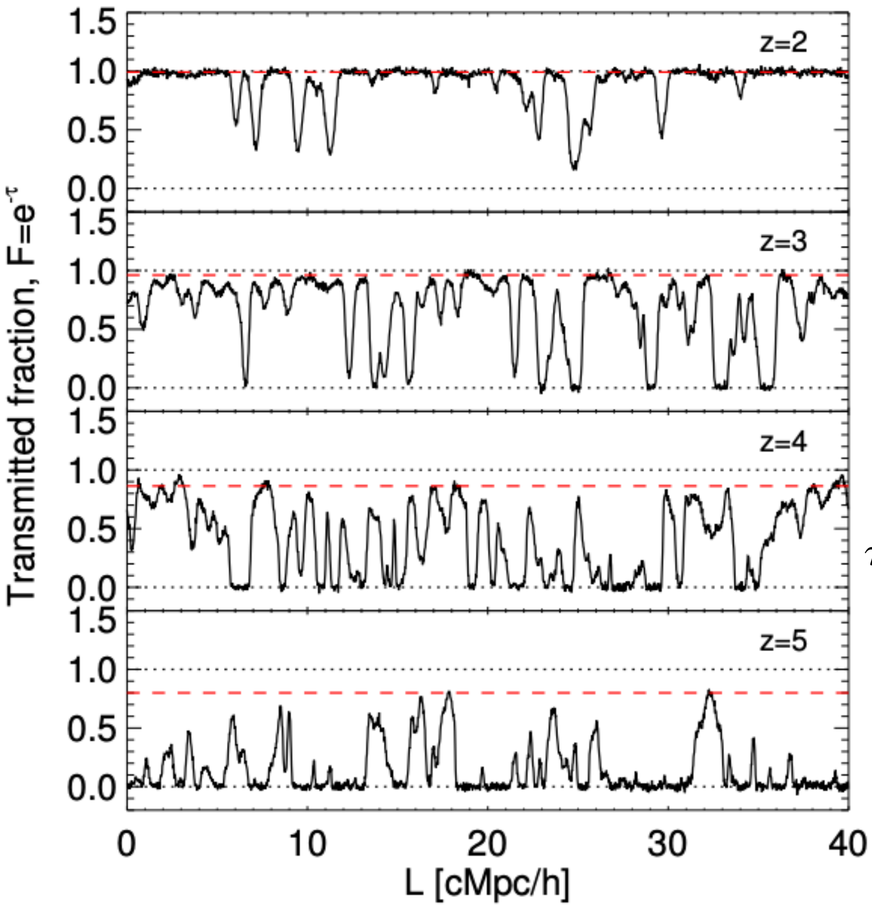
- **Intergalactic medium:** filaments at low density (outside galaxies) – distances spanned 0.1-100 Mpc/h

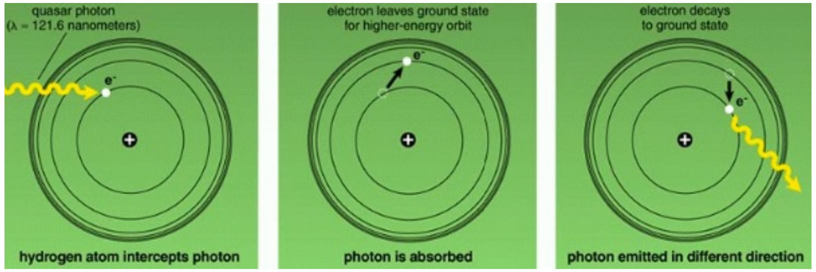
- Lyman-alpha forest its the main manifestation of the IGM

- High redshift observable, 1D projected power (but also 3D)

Physics of the Lyα forest

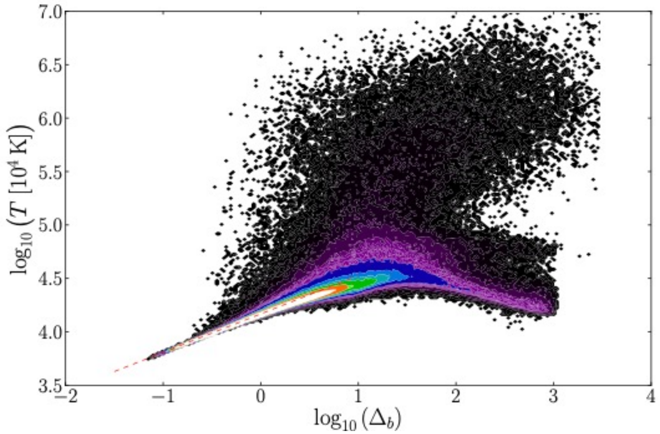
High-z (2<z<6) cosmic web





Shape of the lines determined by HI abundance, IGM thermal state, etc.

$$\tau_{\rm HI} \propto \Delta_b \, x_{\rm HI} \propto \Delta_b^2 \, T^{-0.7}/\Gamma_{\rm HI}$$



Physics of the Lyman-a forest

(Bi 1993, Bi & Davidsen 1997, Hui & Gnedin 1998, Matarrese & Mohayaee 2002)

$$k_J^{-1}(z) \equiv H_0^{-1}\left[\frac{2\gamma k_B T_m(z)}{3\mu m_p \Omega_{0m}(1+z)}\right]^{1/2}$$ Jeans length

$$\delta_0^{\rm IGM}(\mathbf{k},z) = \frac{\delta_0^{\rm DM}(\mathbf{k},z)}{1+k^2/k_J^2(z)} \equiv W_{\rm IGM}(k,z)D_+(z)\delta_0^{\rm DM}(\mathbf{k})$$ Filtering of linear DM density field

$$\mathbf{v}^{\rm IGM}(\mathbf{k},z) = E_+(z)\frac{i\mathbf{k}}{k^2}W_{\rm IGM}(k,z)\delta_0^{\rm DM}(\mathbf{k})$$ Peculiar velocity

$$n_{\rm IGM}(\mathbf{x},z) = \bar{n}_{\rm IGM}(z)\exp\left[\delta_0^{\rm IGM}(\mathbf{x},z) - \frac{\langle(\delta_0^{\rm IGM})^2\rangle D_+^2(z)}{2}\right]$$ Non linear density field

$$T(\mathbf{x},z) = T_0(z)\,(1+\delta^{\rm IGM}(\mathbf{x},z))^{\gamma(z)-1}$$ 'Equation-of-state'

$$\alpha(z,T(z))\,n_p n_e = J(z) n_{\rm HI}\ ,$$ Neutral hydrogen ionization equilibrium equation

$$\tau(u) = \frac{\sigma_{0,\alpha}\,c}{H(z)}\int_{-\infty}^{\infty} dy\, n_{\rm HI}(y)\,\mathcal{V}\left[u-y-v_{\parallel}^{\rm IGM}(y),\, b(y)\right]$$ Optical depth

Density Velocity Temperature

Linear fields: density, velocity

Non linear fields + Temperature

Spectra: Flux=exp(-τ)

MV, Matarrese S., Mo HJ., Haehnelt M., Theuns T., 2002a, MNRAS, 329, 848

More recent milestones

DATA: early 90s: advent of high res spectroscopy (UVES, Keck)

[1998-2002] Croft, Weinberg+: first quantitative use of the Lyman-alpha forest for cosmology.

[1998-2004] better understanding of physics of the IGM (Hui, Gnedin, Meiksin, White).

[2004] Viel+: usage of UVES to complement Croft's work with better sims to cover the parameter space.

[2005-06] SDSS-II results (McDonald, Seljak…): excellent synergy with CMB abd other probes demonstrated (constraints on inflation and neutrinos).

[2007-now] systematic use of QSO spectra for DM nature at small scales (Viel+).

[2013] BAO detected in the Lyman-alpha forest 3D correlation by BOSS (SDSS-III) from low resolution.

Modelling the observables

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Modelling 3D flux power

Arino-i-Prats, Miralda-Escude', MV, Cen (2015) - McDonald (2003)

$$\delta_F = \frac{F}{\bar{F}(z)} - 1 \qquad \eta = -\frac{1}{aH}\frac{\partial v_p}{\partial x_p}$$

$$\beta = \frac{b_{F\eta}\, f(\Omega)}{b_{F\delta}} \qquad b_{F\delta} = \frac{\partial \delta_F}{\partial \delta} \qquad b_{F\eta} = \frac{\partial \delta_F}{\partial \eta}$$

$$\delta_F = b_{F\delta}\delta + b_{F\eta}\eta$$

3D flux power

$$P_F(k,\mu) = b^2_{F\delta}\,(1+\beta\mu^2)^2\; P_L(k)\, D(k,\mu)$$

$$D\,(k,\mu) = \exp\left\{\left[q_1\Delta^2(k) + q_2\Delta^4(k)\right]\left[1 - \left(\frac{k}{k_v}\right)^{a_v}\mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2\right\}$$

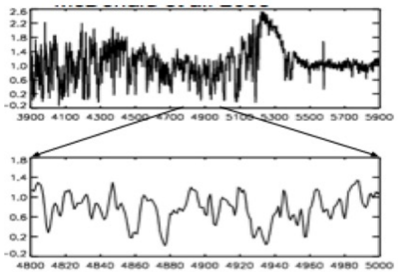
non-linear matter power | thermal broadening | pressure smoothing

1D flux power

$$P_{1D}(k_\parallel, z) = \frac{1}{2\pi}\int_{k_\parallel} P_F(k, k_\parallel, z)\, k\, dk$$

Data

BOSS/SDSS-III



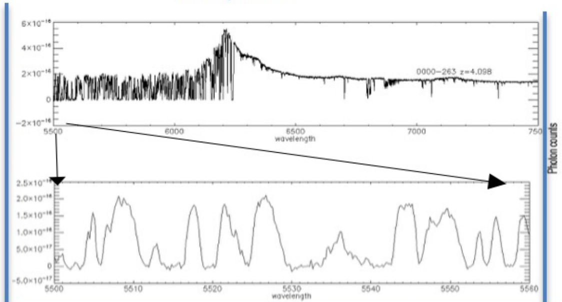
Low resolution BOSS and SDSS-III spectra S/N~2-3 - 160,000 spectra

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



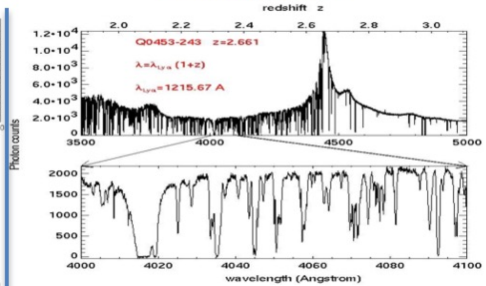
Medium resolution X-Shooter VLT spectra
S/N ~ 30

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

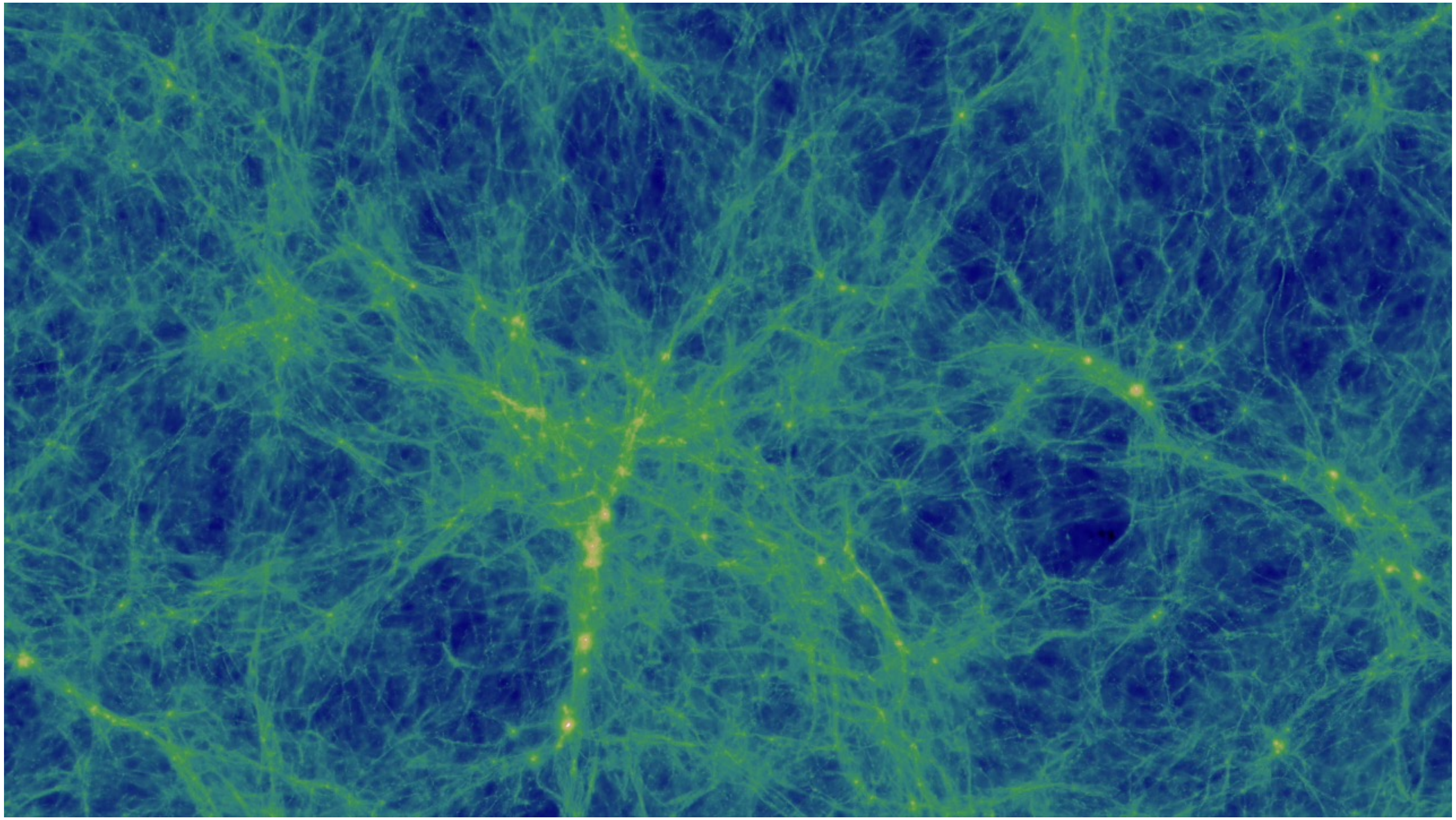


High resolution VLT or Keck spectra S/N ~100 - ~hundreds of spectra

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

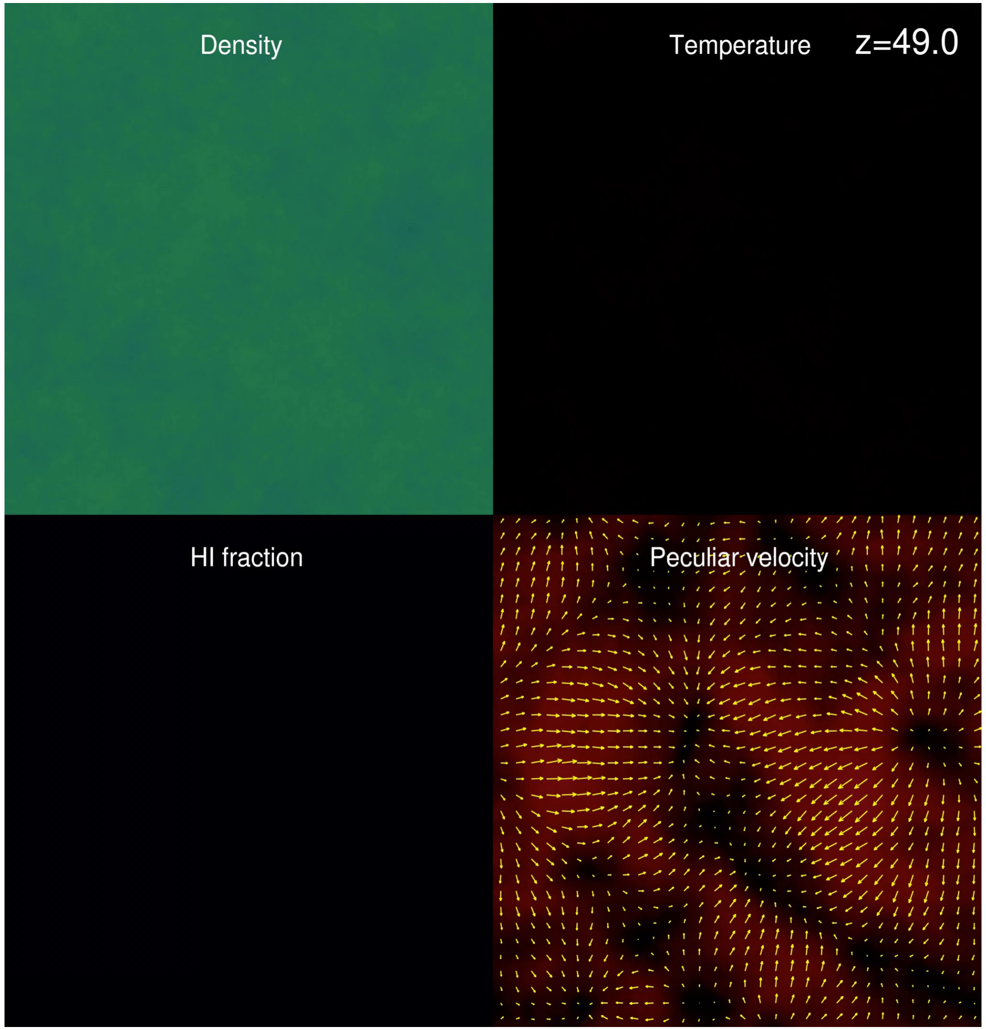
*MV+05,08,13, **Becker**+11*
Yeche+17, Garzilli+18 ,
Bosman+18

Movie nr. 1



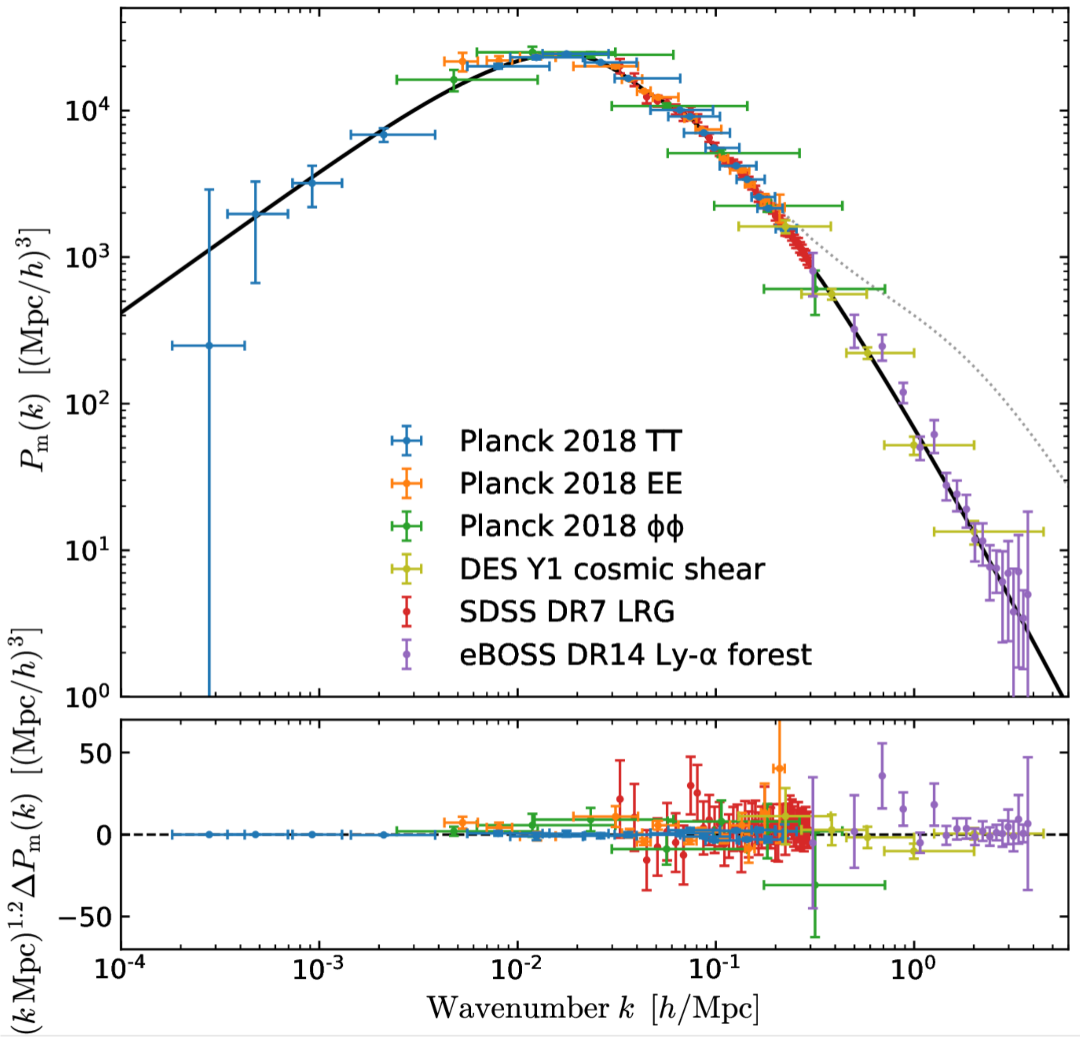
Bolton+17, Sherwood simulation suite (PRACE call: 15 CPU Mhrs)
Puchwen+19,+22, Sherwood relics (PRACE+Dirac call: 60 CPU Mhrs

Movie nr. 2



Long lever arm of the linear power spectrum

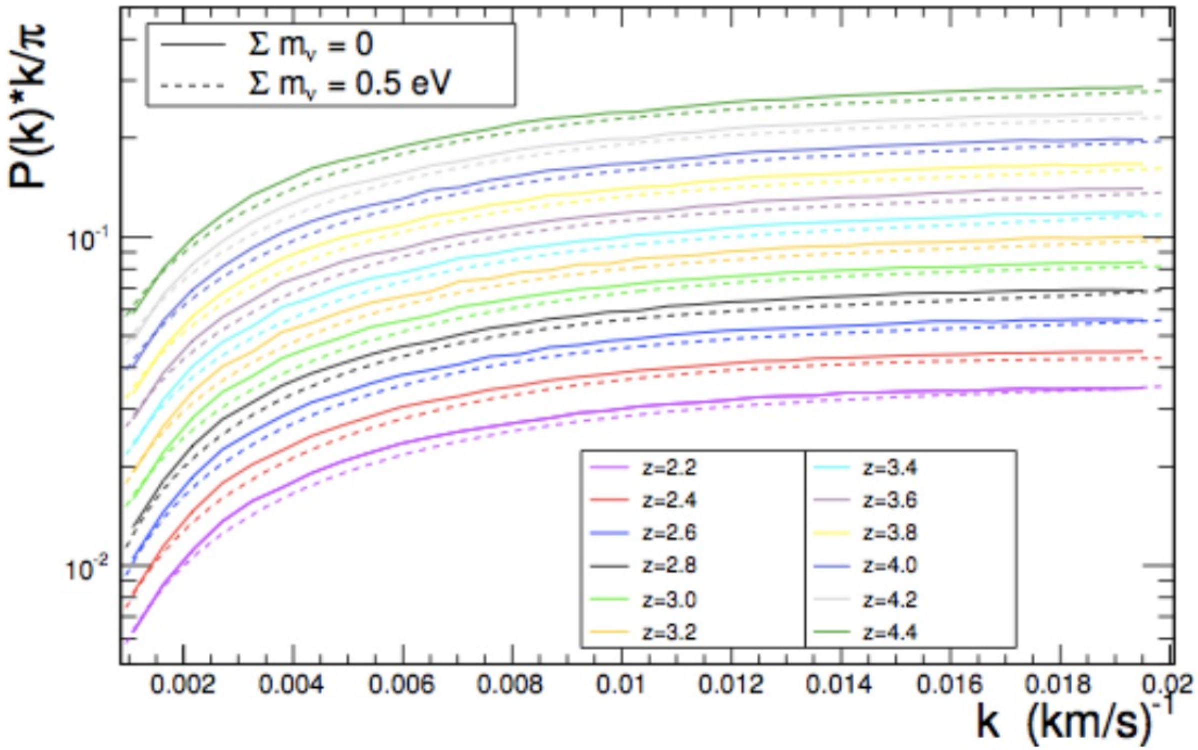
Chabanier+19



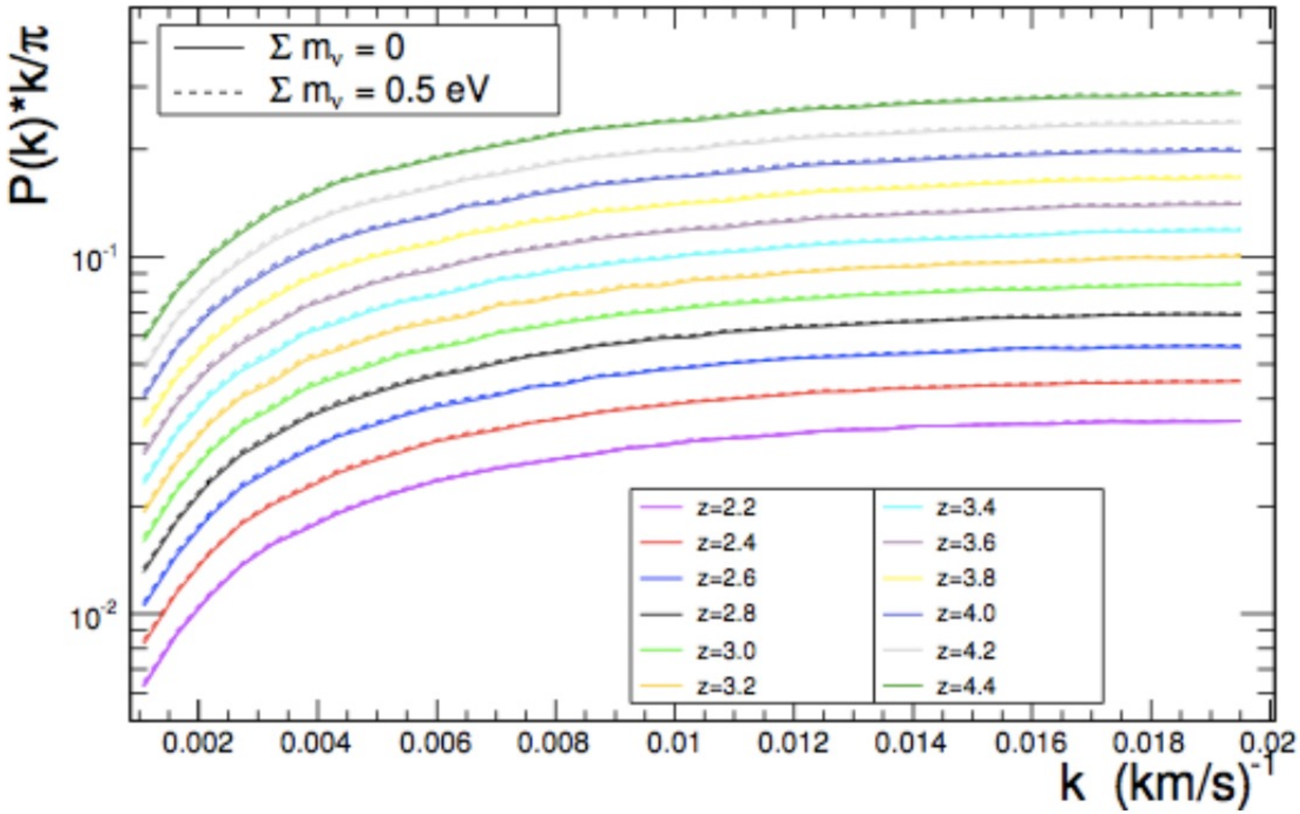
Two reasons for why Lyα is so constraining:

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

Neutrino impact - I



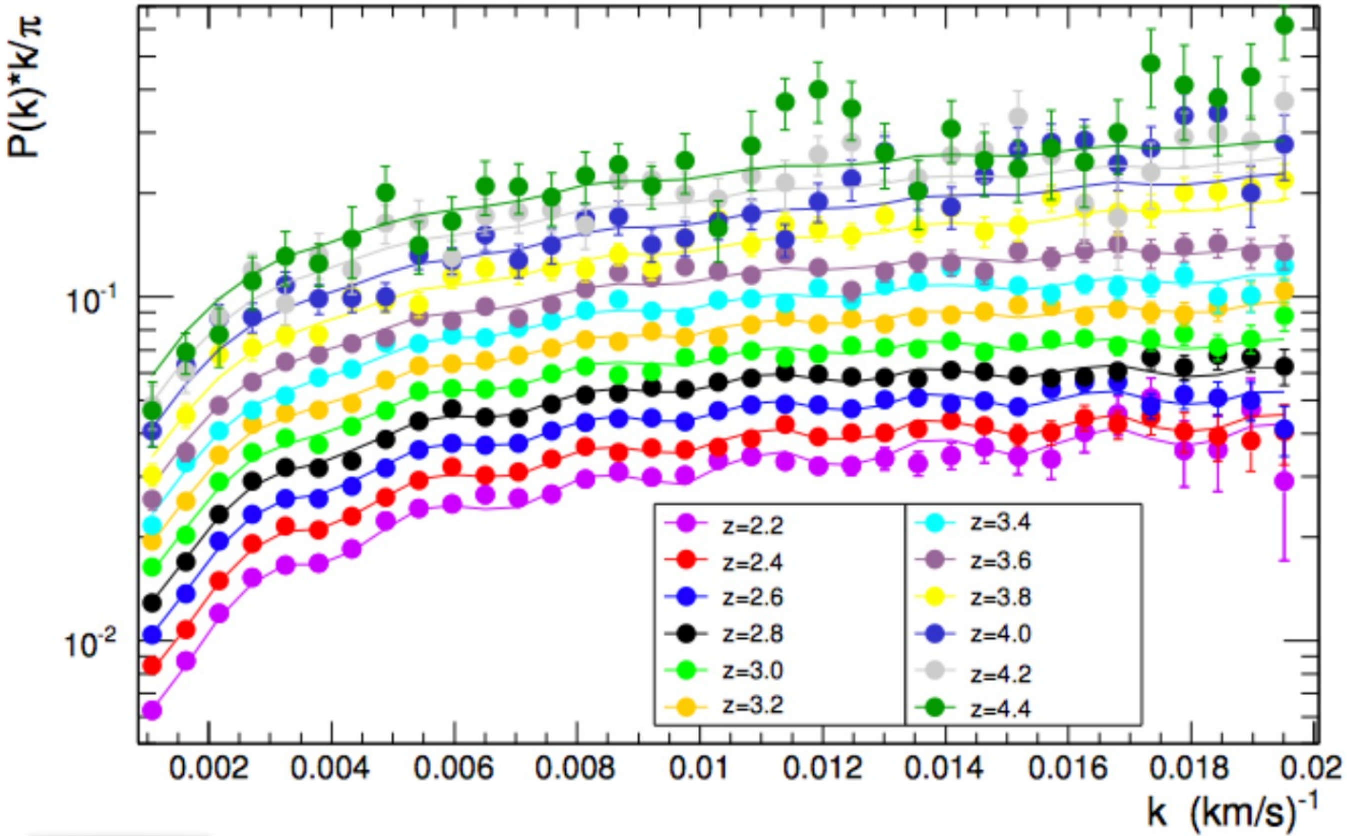
Neutrino impact - II



Neutrino impact - III

1D Flux power spectrum evolution

Nathalie Palanque-Delabrouille,[a,b] Christophe Yèche,[a] Julien Lesgourgues,[c,d,e] Graziano Rossi,[a,f] Arnaud Borde,[a] Matteo Viel,[g,h] Eric Aubourg,[i] David Kirkby,[j] Jean-Marc LeGoff,[a] James Rich,[a] Natalie Roe,[b] Nicholas P. Ross,[k] Donald P. Schneider,[l,m] David Weinberg[n]

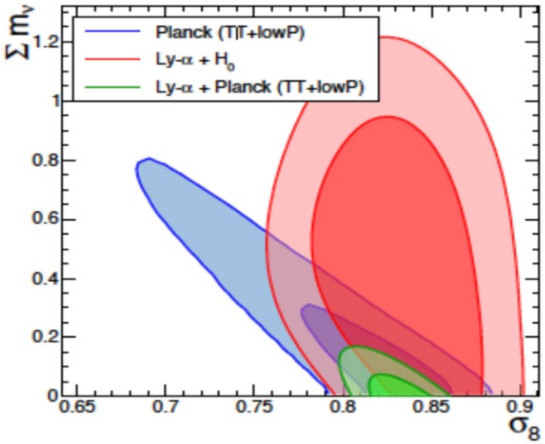


Neutrino impact - IV

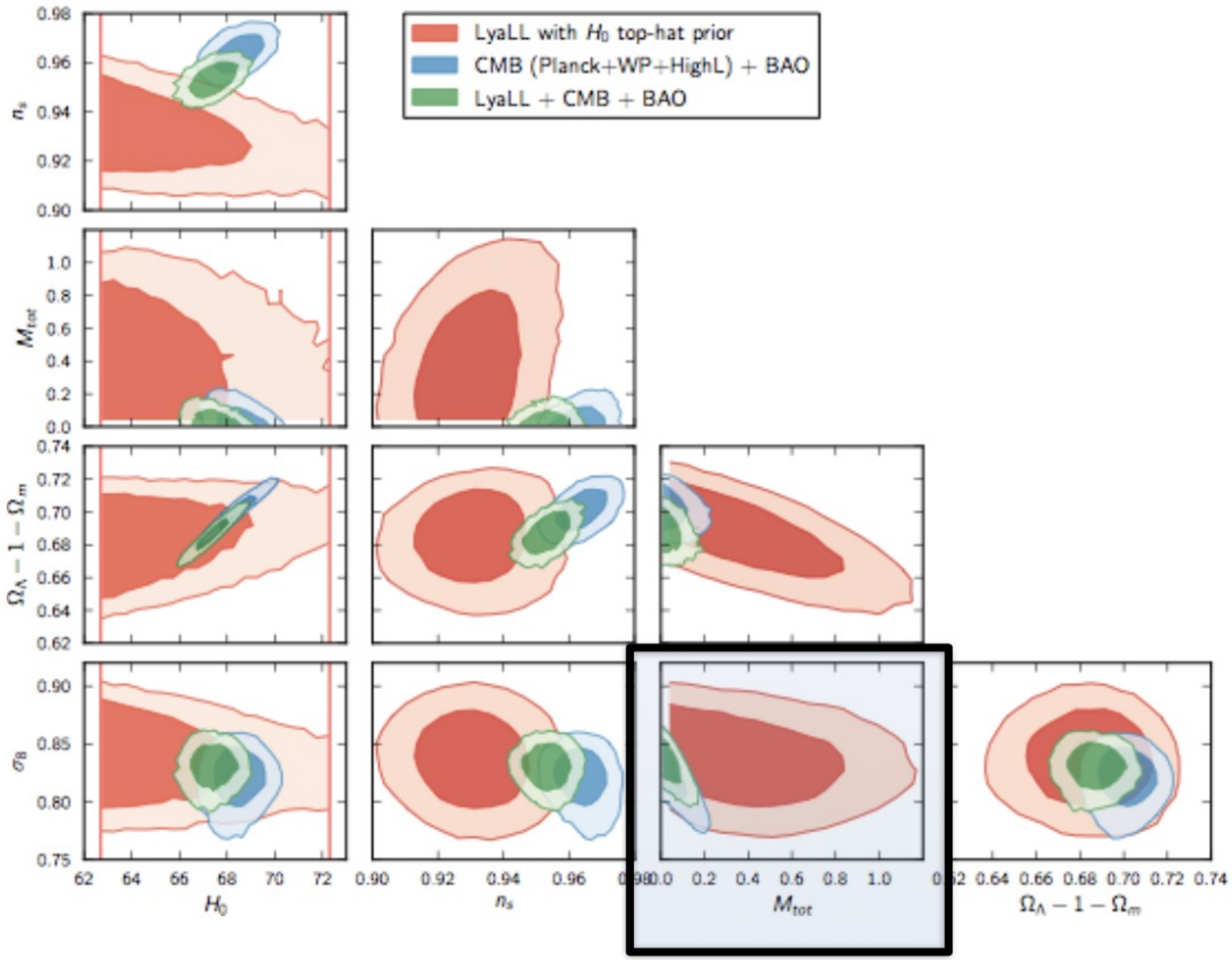
UPDATE using Planck 15

Palanque-Delabrouille+ 2015

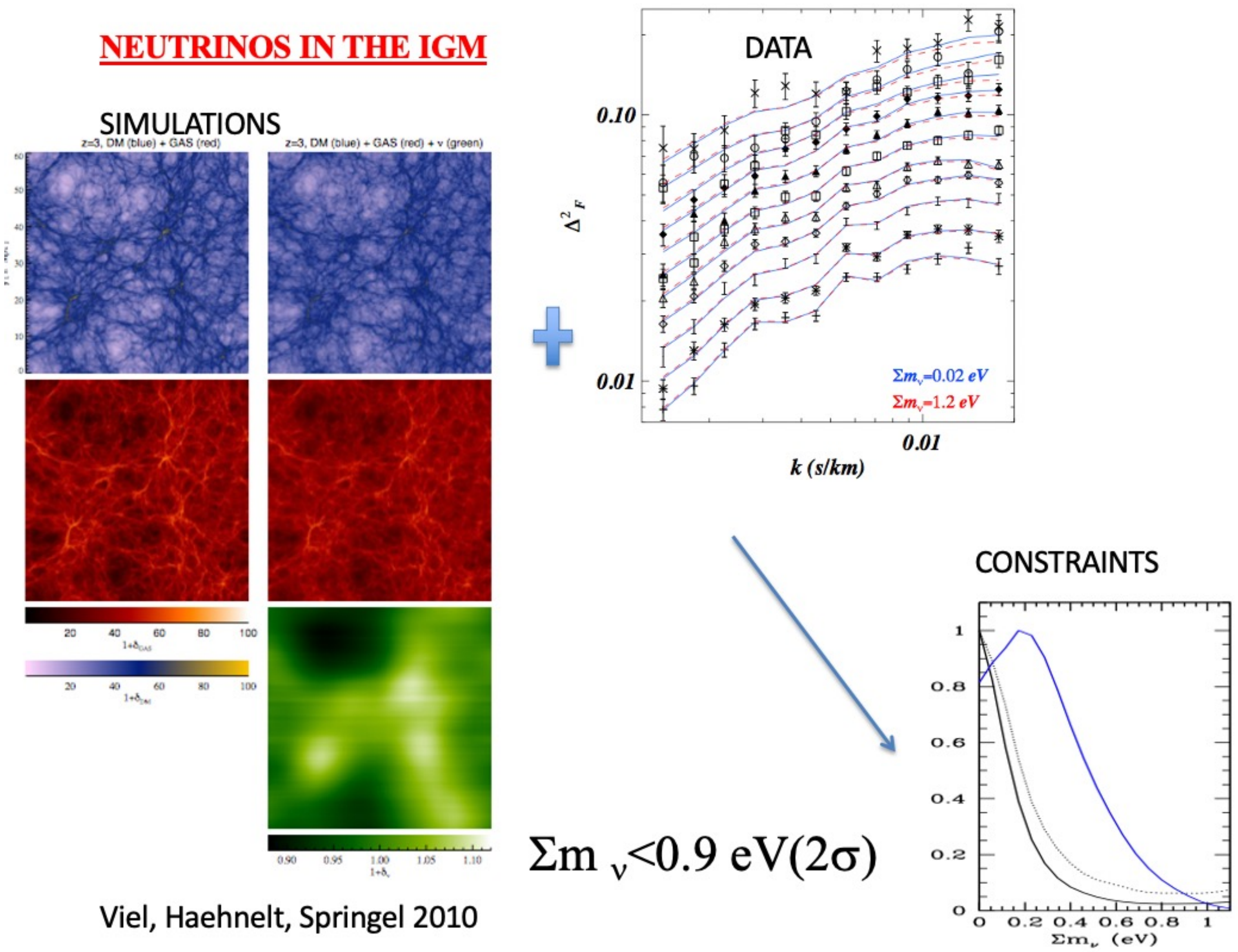
Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



Neutrino impact - IV

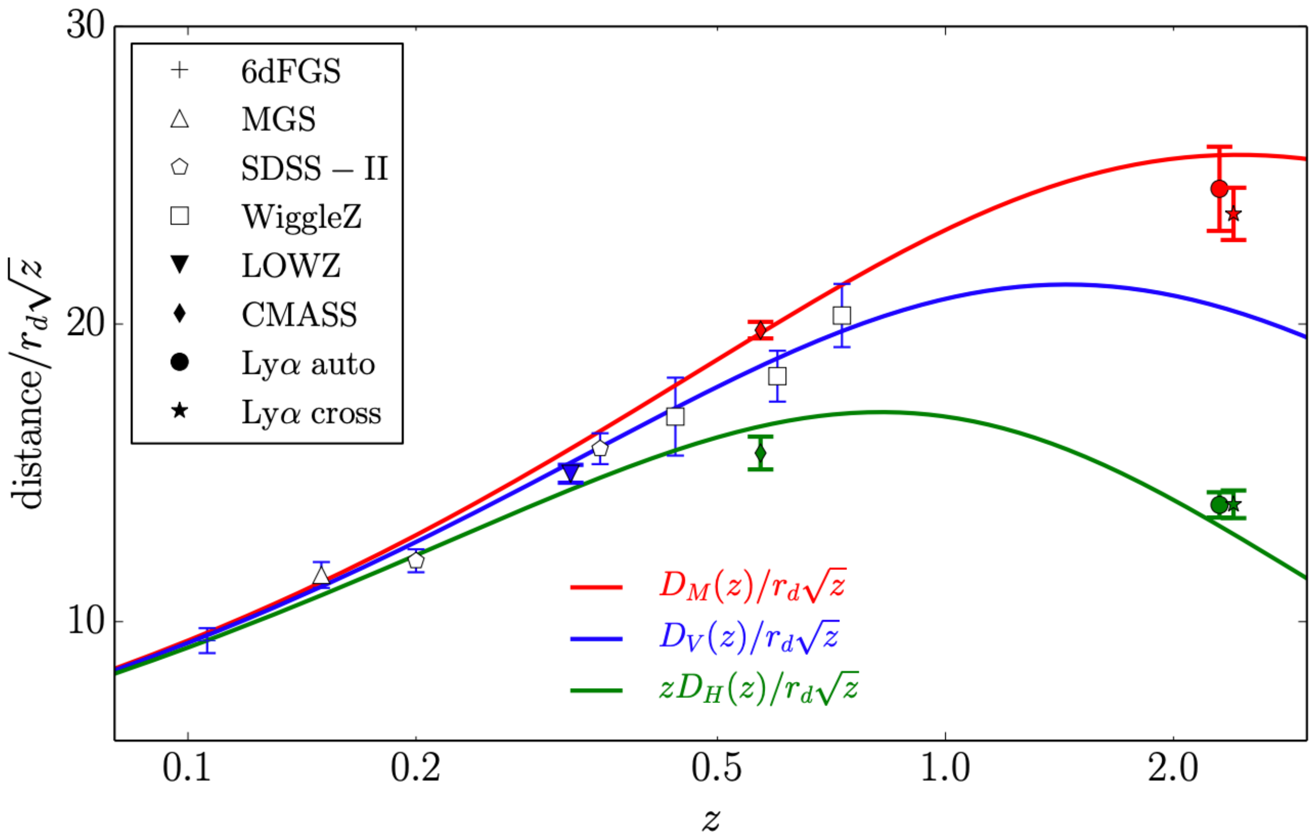


IGM and neutrinos



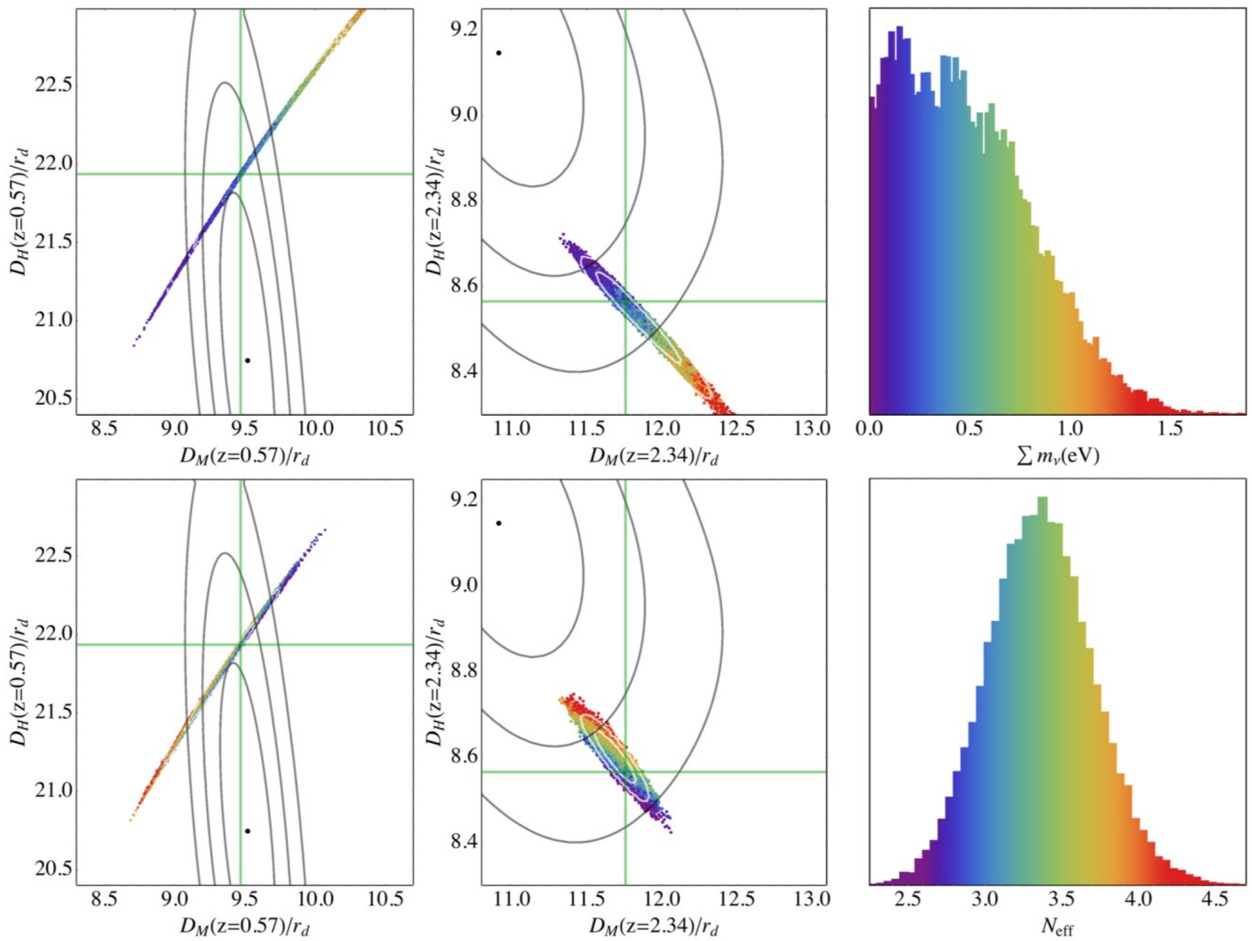
Neutrinos and BAOs

Aubourg+14



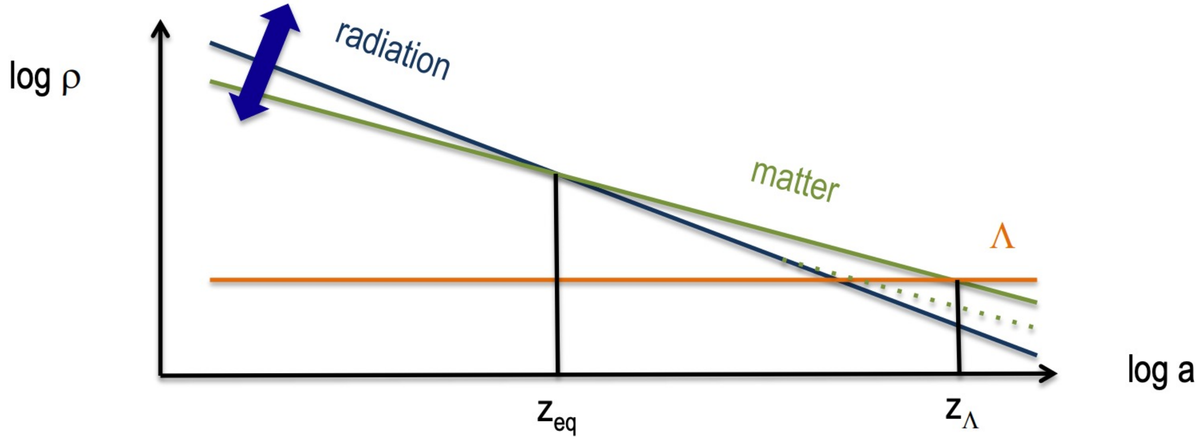
Neutrinos and BAOs

Aubourg+14

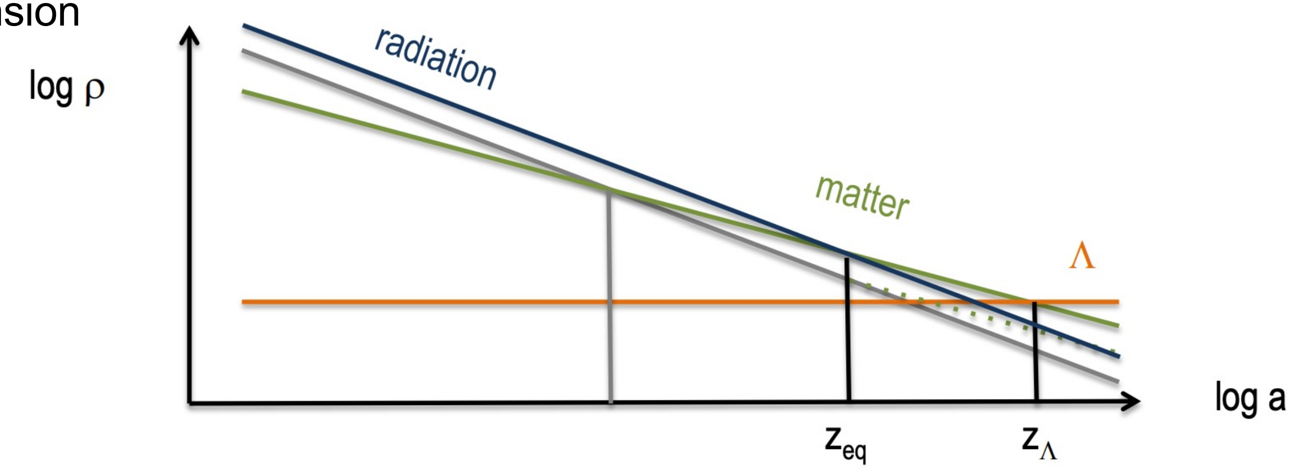


Neutrinos and BAOs

CMB
Constraints
Wcb independently
Of Wn



But late time expansion
And distances are
Affected by total
matter

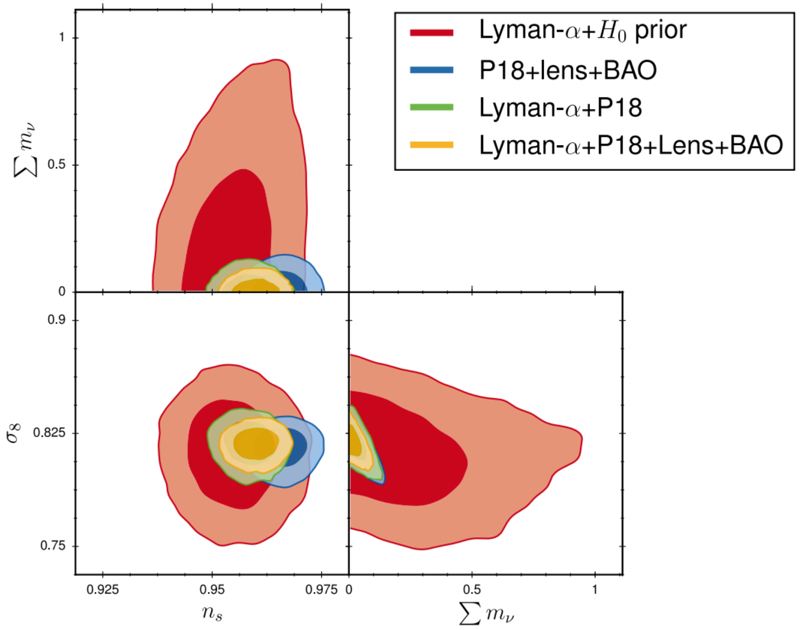


eBOSS data

	Frequentist		Bayesian	
	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO
T_0 (z=3) (10^3K)	9.7 ± 1.7	9.8 ± 2.0	9.5 ± 1.8	9.5 ± 1.8
γ	0.69 ± 0.10	0.68 ± 0.11	0.71 ± 0.10	0.71 ± 0.10
σ_8	0.825 ± 0.006	0.819 ± 0.008	0.818 ± 0.010	0.818 ± 0.007
n_s	0.958 ± 0.003	0.961 ± 0.003	0.959 ± 0.004	0.960 ± 0.003
Ω_m	0.311 ± 0.006	0.308 ± 0.006	0.316 ± 0.009	0.310 ± 0.006
$\sum m_\nu$ (eV , 95% CL)	< 0.099	< 0.089	< 0.099	< 0.074

Table 6. Preferred astrophysical and cosmological parameter values (68.3% confidence level) for the ΛCDM + m_ν model, for combined Lyman-α, CMB and BAO data.

Palanque-Delabrouille+20



What to expect from DESI?

DESI and other Dark Energy experiments in the era of neutrino mass measurements

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(Dated: May 16, 2014)

We present Fisher matrix projections for future cosmological parameter measurements, including neutrino masses, Dark Energy, curvature, modified gravity, the inflationary perturbation spectrum, non-Gaussianity, and dark radiation. We focus on DESI and generally redshift surveys (BOSS, HETDEX, eBOSS, Euclid, and WFIRST), but also include CMB (Planck) and weak gravitational lensing (DES and LSST) constraints. The goal is to present a consistent set of projections, for concrete experiments, which are otherwise scattered throughout many papers and proposals. We include neutrino mass as a free parameter in most projections, as it will inevitably be relevant – DESI and other experiments can measure the sum of neutrino masses to ~ 0.02 eV or better, while the minimum possible sum is ~ 0.06 eV. We note that constraints on Dark Energy are significantly degraded by the presence of neutrino mass uncertainty, especially when using galaxy clustering only as a probe of the BAO distance scale (because this introduces additional uncertainty in the background evolution after the CMB epoch). Using broadband galaxy power becomes relatively more powerful, and bigger gains are achieved by combining lensing survey constraints with redshift survey constraints. We do not try to be especially innovative, e.g., with complex treatments of potential systematic errors – these projections are intended as a straightforward baseline for comparison to more detailed analyses.

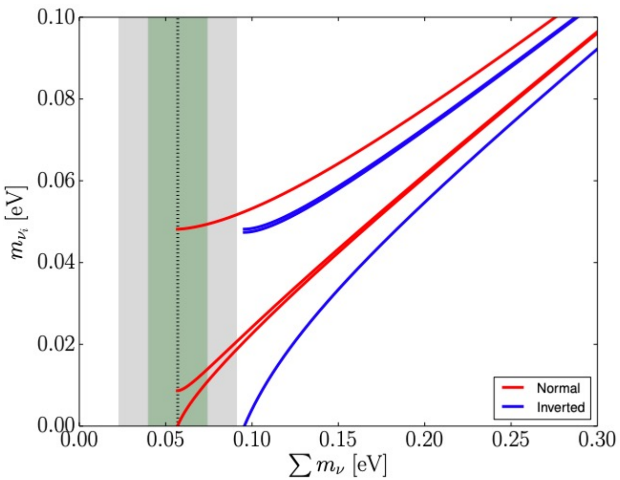


TABLE IX. Neutrino mass and other basic parameter projections. See Table VIII for experiment codes

	ω_m	ω_b	θ_s	Σm_ν	$\log_{10}(A)$	n_s	τ
value	0.141	0.0221	0.597	0.0600	−8.66	0.961	0.0920
P	0.0037	0.00015	0.00035	0.35	0.0039	0.0038	0.0045
$P + BgB + BlB$	0.00074	0.00015	0.00014	0.10	0.0038	0.0038	0.0044
$P + BgA0.1 + BlB$	0.00070	0.00013	0.00014	0.068	0.0037	0.0031	0.0044
$P + BgA0.2 + BlB$	0.00071	0.00012	0.00015	0.046	0.0037	0.0028	0.0043
$P + DES$	0.0013	0.00013	0.00017	0.041	0.0036	0.0032	0.0043
$P + BgB + BlB + DES$	0.00069	0.00011	0.00014	0.030	0.0035	0.0027	0.0043
$P + BgA0.1 + BlB + DES$	0.00067	0.00011	0.00014	0.029	0.0035	0.0027	0.0042
$P + BgA0.1 + BlB + ebA0.1$	0.00064	0.00012	0.00014	0.052	0.0037	0.0029	0.0043
$P + BgA0.2 + BlB + ebA0.2$	0.00064	0.00011	0.00014	0.036	0.0037	0.0027	0.0043
$P + BgA0.1 + BlB + ebA0.1 + DES$	0.00062	0.00011	0.00014	0.028	0.0035	0.0026	0.0042
$P + hdB + BgB$	0.00074	0.00015	0.00014	0.099	0.0038	0.0038	0.0044
$P + hdA0.1 + BgA0.1$	0.00069	0.00012	0.00014	0.061	0.0037	0.0030	0.0044
$P + hdA0.2 + BgA0.2$	0.00068	0.00011	0.00014	0.039	0.0037	0.0027	0.0043
$P + BBgB$	0.00055	0.00015	0.00014	0.090	0.0038	0.0038	0.0044
$P + BBgB + BlB$	0.00055	0.00015	0.00014	0.090	0.0038	0.0038	0.0044
$P + BBlB + BgB$	0.00072	0.00015	0.00014	0.098	0.0038	0.0038	0.0044
$P + BBgB + BBlB$	0.00055	0.00015	0.00014	0.090	0.0038	0.0038	0.0044
$P + BBgB + BBlB + DES$	0.00045	0.00011	0.00014	0.027	0.0035	0.0025	0.0043
$P + BBgA0.1$	0.00044	0.00011	0.00014	0.024	0.0036	0.0024	0.0043
$P + BBgA0.1 + BBlB$	0.00044	0.00011	0.00014	0.024	0.0036	0.0024	0.0043
$P + BBgA0.1 + BBlB + DES$	0.00043	0.00011	0.00014	0.021	0.0034	0.0024	0.0041
$P + BBgA0.2 + BBlB$	0.00042	0.00010	0.00014	0.017	0.0035	0.0022	0.0043
$P + BBgA0.2 + BBlB + DES$	0.00042	0.00010	0.00014	0.017	0.0033	0.0022	0.0040
$P + BB24gB + BB24lB$	0.00052	0.00015	0.00014	0.088	0.0038	0.0037	0.0044
$P + BB24gA0.1 + BB24lB$	0.00039	0.00011	0.00014	0.020	0.0035	0.0023	0.0043
$P + BB24gA0.1 + BB24lB + DES$	0.00038	0.00011	0.00013	0.019	0.0033	0.0023	0.0040
$P + BB24gA0.2 + BB24lB$	0.00037	$9.9e-05$	0.00014	0.015	0.0035	0.0020	0.0042
$P + BB24gA0.2 + BB24lB + DES$	0.00037	$9.9e-05$	0.00013	0.015	0.0032	0.0020	0.0040
$P + BgB + BlB + euB$	0.00054	0.00015	0.00014	0.090	0.0038	0.0038	0.0044
$P + BgA0.1 + BlB + euA0.1$	0.00043	0.00011	0.00014	0.021	0.0036	0.0024	0.0043
$P + BgA0.1 + BlB + euA0.1 + DES$	0.00043	0.00011	0.00014	0.019	0.0034	0.0023	0.0041
$P + BgA0.2 + BlB + euA0.2$	0.00042	0.00010	0.00014	0.015	0.0035	0.0021	0.0042
$P + BgA0.2 + BlB + euA0.2 + DES$	0.00041	0.00010	0.00014	0.015	0.0033	0.0021	0.0040
$P + BB24gA0.1 + BB24lB + euA0.1$	0.00036	0.00010	0.00013	0.017	0.0035	0.0022	0.0042
$P + BB24gA0.1 + BB24lB + euA0.1 + DES$	0.00036	0.00010	0.00013	0.016	0.0032	0.0022	0.0040
$P + BB24gA0.2 + BB24lB + euA0.2$	0.00034	$9.6e-05$	0.00013	0.014	0.0034	0.0018	0.0041
$P + BB24gA0.2 + BB24lB + euA0.2 + DES$	0.00034	$9.6e-05$	0.00013	0.013	0.0032	0.0018	0.0039
$P + LSST$	0.00080	0.00011	0.00015	0.020	0.0030	0.0029	0.0036
$P + BgB + BlB + LSST$	0.00060	0.00011	0.00014	0.018	0.0030	0.0025	0.0036
$P + BBgB + BBlB + LSST$	0.00044	0.00011	0.00013	0.016	0.0030	0.0022	0.0036
$P + BBgA0.1 + BBlB + LSST$	0.00042	0.00010	0.00013	0.015	0.0028	0.0021	0.0034
$P + BBgA0.2 + BBlB + LSST$	0.00041	0.00010	0.00013	0.014	0.0026	0.0020	0.0032
$P + BB24gA0.1 + BB24lB + LSST$	0.00038	0.00010	0.00013	0.015	0.0027	0.0020	0.0033
$P + BB24gA0.2 + BB24lB + LSST$	0.00036	$9.8e-05$	0.00013	0.013	0.0025	0.0018	0.0031
$P + BB24gA0.1 + BB24lB + euA0.1 + LSST$	0.00035	0.00010	0.00013	0.014	0.0026	0.0019	0.0032
$P + BB24gA0.2 + BB24lB + euA0.2 + LSST$	0.00033	$9.5e-05$	0.00013	0.011	0.0024	0.0016	0.0030
$P + wfB + BgB$	0.00064	0.00015	0.00014	0.095	0.0038	0.0038	0.0044
$P + wfA0.1 + BgA0.1$	0.00058	0.00011	0.00014	0.037	0.0037	0.0027	0.0043
$P + wfA0.2 + BgA0.2$	0.00056	0.00011	0.00014	0.021	0.0036	0.0025	0.0043
$P + BgB + BlA + l1D$	0.00066	0.00011	0.00014	0.053	0.0037	0.0032	0.0044
$P + BgA0.1 + BlA + l1D$	0.00065	0.00011	0.00014	0.048	0.0037	0.0030	0.0043
$P + BgA0.2 + BlA + l1D$	0.00066	0.00011	0.00014	0.040	0.0037	0.0027	0.0043
$P + BBgB + BBlA + l1D$	0.00041	0.00010	0.00014	0.039	0.0037	0.0029	0.0043
$P + BBgA0.1 + BBlA + l1D$	0.00039	0.00010	0.00014	0.023	0.0035	0.0021	0.0043
$P + BBgA0.2 + BBlA + l1D$	0.00038	0.00010	0.00014	0.017	0.0035	0.0019	0.0042
$P + BB24gB + BB24lA + l1D$	0.00036	0.00010	0.00014	0.034	0.0036	0.0028	0.0043
$P + BB24gA0.1 + BB24lA + l1D$	0.00035	0.00010	0.00013	0.019	0.0035	0.0019	0.0042
$P + BB24gA0.2 + BB24lA + l1D$	0.00034	$9.8e-05$	0.00014	0.015	0.0034	0.0016	0.0041
$P + BB24gA0.2 + BB24lA + l1D + euA0.2$	0.00032	$9.5e-05$	0.00013	0.013	0.0033	0.0015	0.0040
$P + BB24gA0.2 + BB24lA + l1D + LSST$	0.00033	$9.7e-05$	0.00013	0.012	0.0025	0.0015	0.0031
$P + BB24gA0.2 + BB24lA + l1D + euA0.2 + LSST$	0.00032	$9.5e-05$	0.00013	0.011	0.0024	0.0014	0.0030

Matter power spectrum and WDM

2 well studied examples:
Particles becoming NR in RD era → free streaming scale is constant between zNR and zEQ but Free streaming horizon grows!
1) thermal WDM with FD distribution and unknown Tx temperature
2) non-thermal relic with rescaled FD distribution and Tx=Tν and some unkonw rescaling factor χ
Like Dodelson&Widrow (94) sterile non-resonantly produced neutrinos

$$(m_{th}, T_{th}) = (\chi^{1/4} m_X, \chi^{1/4} T_\nu)$$

$$P_{\Lambda WDM}(\eta, k) = P_{\Lambda CDM}(\eta, k) T(\eta, k)^2$$

Sterile neutrinos — Early decoupled thermal relics

$$\omega_X = \chi (T_\nu / T_\nu^a)^3 \frac{m_X}{94.1 eV} = (T_{th}/T_\nu^a)^3 \frac{m_{th}}{94.1 eV}$$

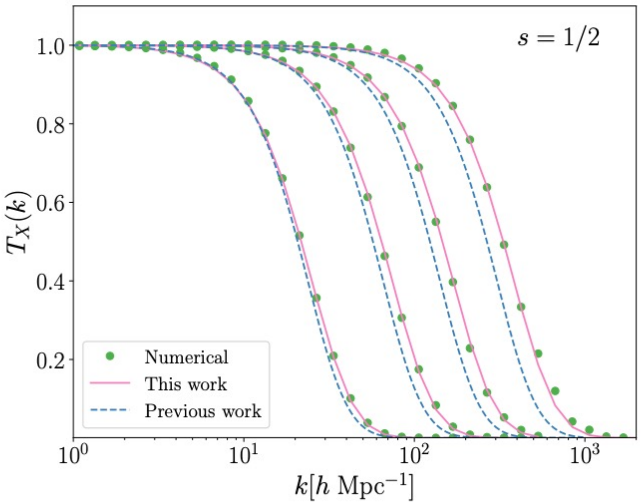
$$m_X = 4.43\, keV (T_\nu / T_\nu^a)(0.25 \times 0.7^2 / \omega_X)^{1/3} \left(\frac{m_{th}}{1 keV} \right)^{4/3}$$

Matter power spectrum and WDM

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

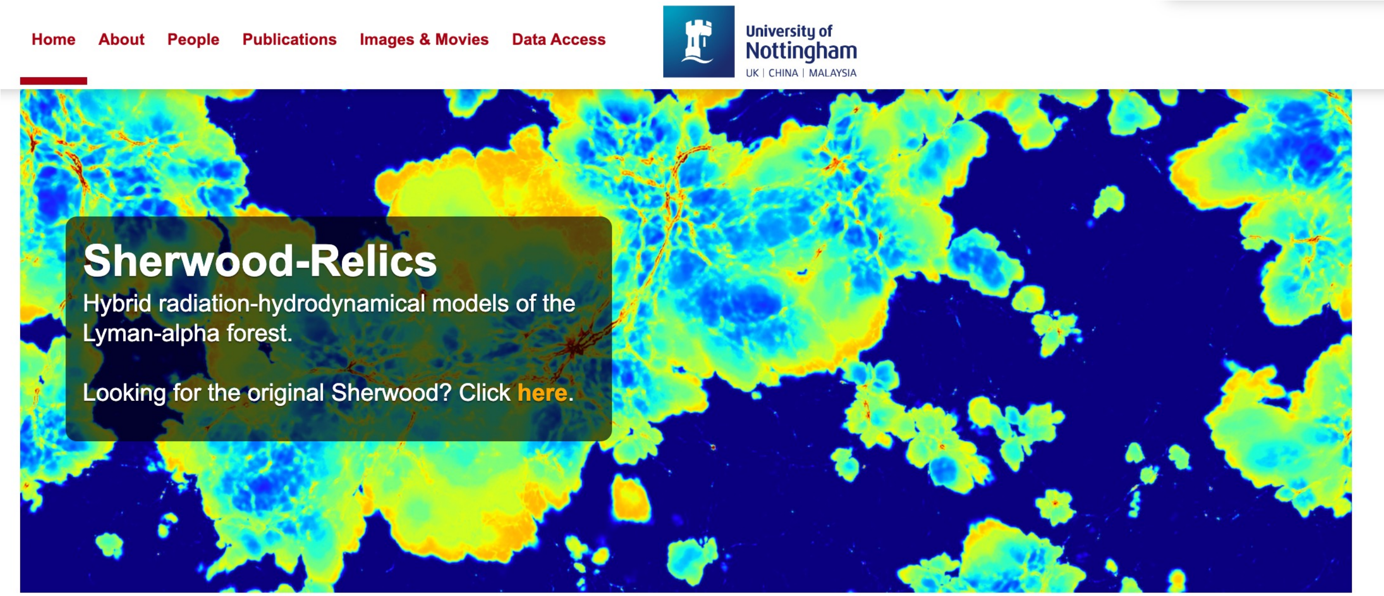
$$k_{break} = \frac{1}{0.24} X^{0.83} \left(\frac{\omega_X}{0.25 \times 0.7^2} \right)^{0.16} Mpc^{-1} \quad with\, X \equiv \frac{m_X/T_X}{1\, keV} T_\nu^a$$

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

Sherwood-Relics Collaboration



People

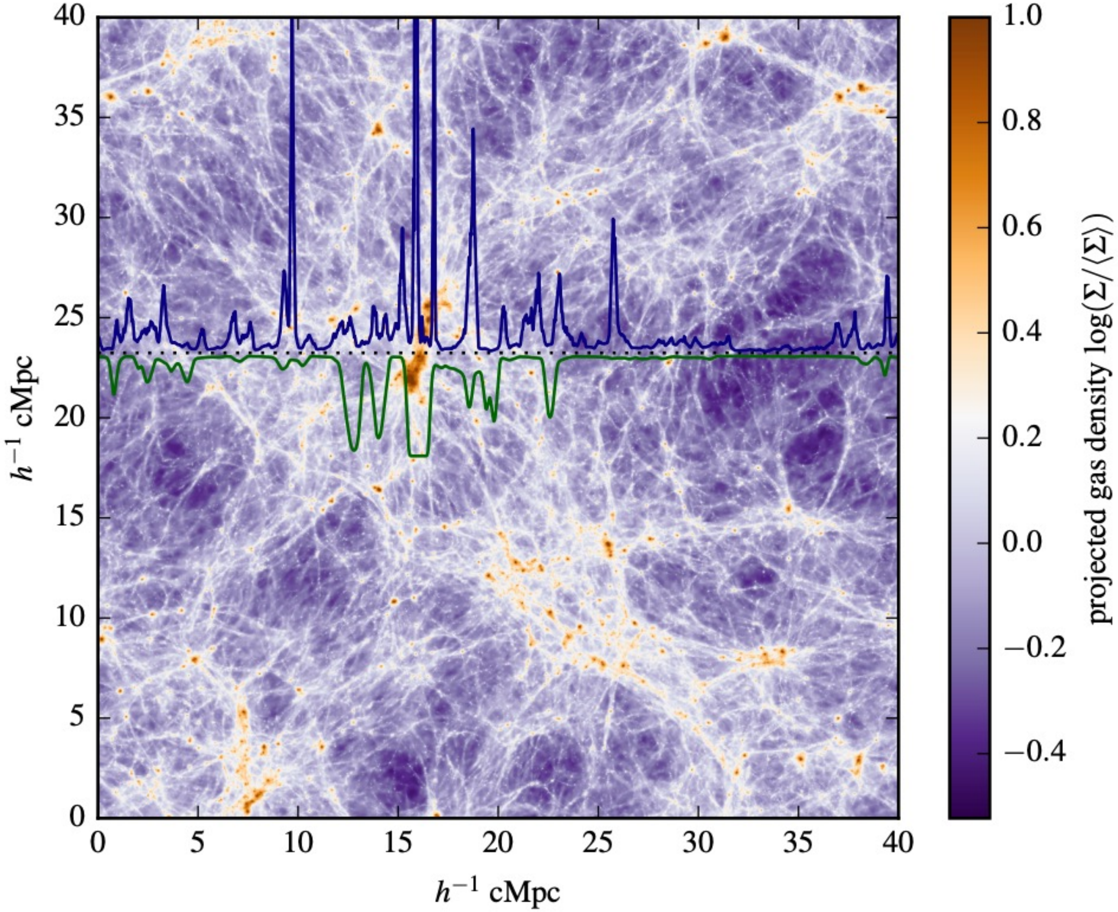
- Shikhar Asthana
- James Bolton
- Emma Chapman
- Prakash Gaikwad
- Martin Haehnelt
- Vid Irsic
- Laura Keating
- Girish Kulkarni
- Ewald Puchwein (PI)
- Tomáš Šoltinský
- Matteo Viel

Physics of the Lyα forest - I

High-z (2<z<6) cosmic web
Sherwood simulation suite – Bolton+17

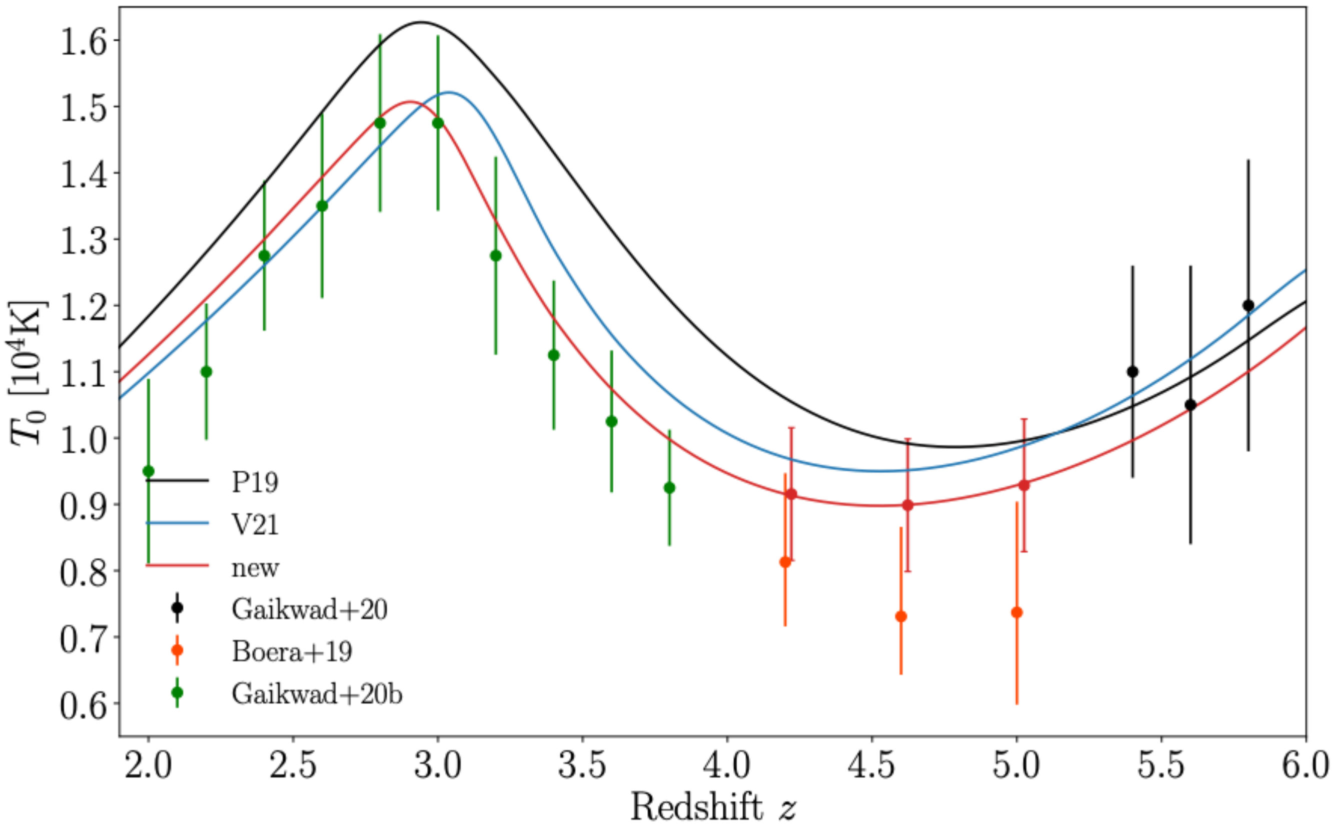
Relatively "simple" physics

- Gravity
- Cooling/Heating processes
- Few runs with feedback (winds/AGN)
- Radiative transfers due to patchy reionization included



Gadget-III + ATON code
About 400 simulations
Post-process to provide >60,000 flux 1D power models (varying also cosmology trough slope and amplitude of linear matter power)
About 75 Million CPU hrs
Boxes 5-160 Mpc/h
Resolutions 10^3-10^6 Msun/h per gas
Reference sims have 40 Mpc/h
and 10^5 Msun/h per gas

Physics of the Lyα forest - III



IGM thermal state

Constraints obtained with a huge variety of data and methods

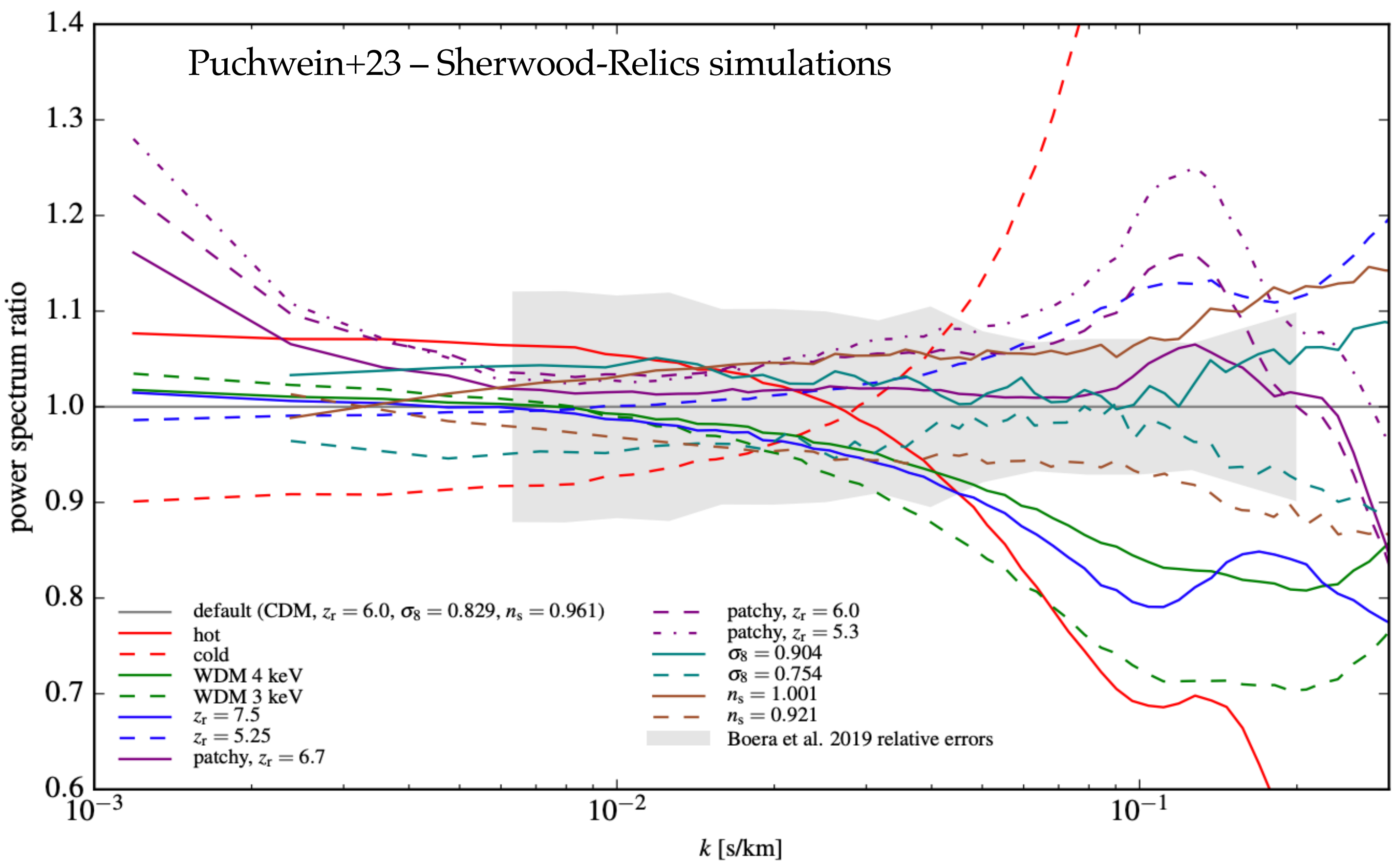
Sensitive to lines rather than the clustering of the lines

HeII bump quite well detected

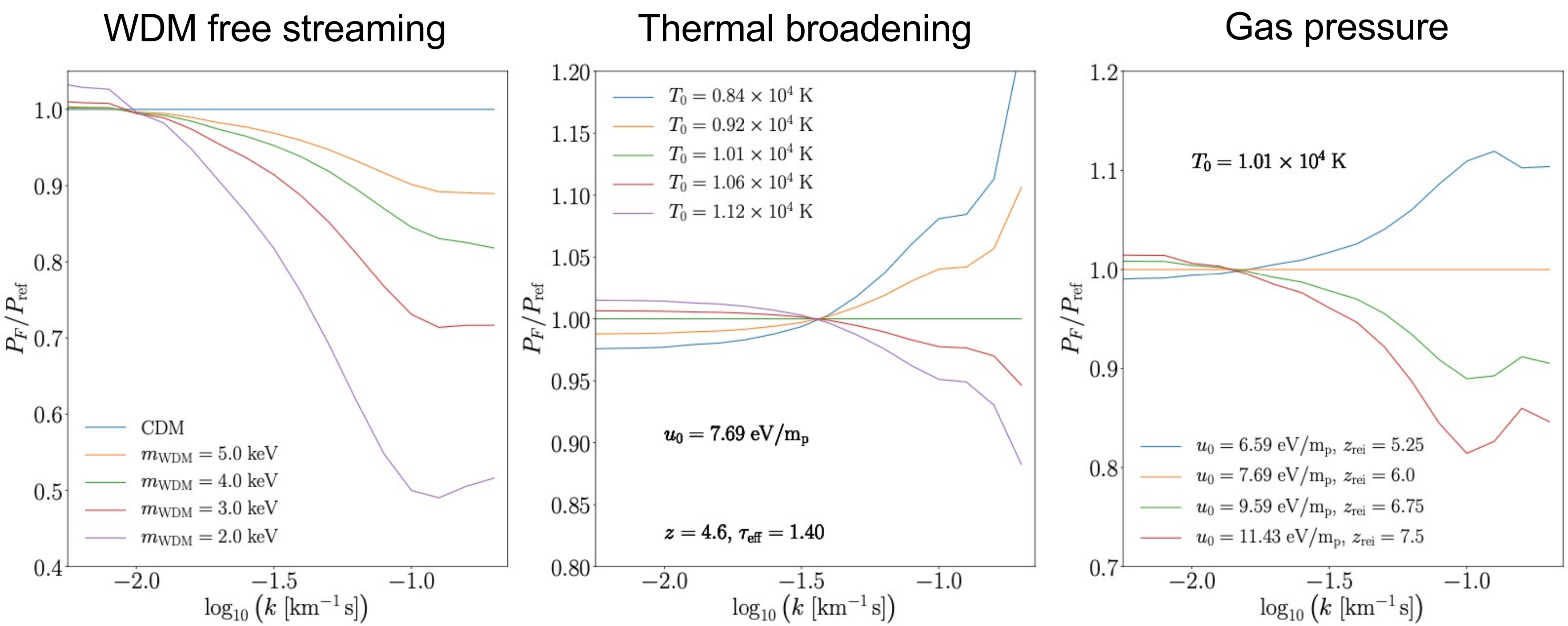
Physics of the Lyα forest - IV

- Large scale increase due to patchy reionization
- Small scale increase/decrease due to WDM/temperature
- Intermediate regime also quite constraining

Simulated 1D flux power @ z=4.6



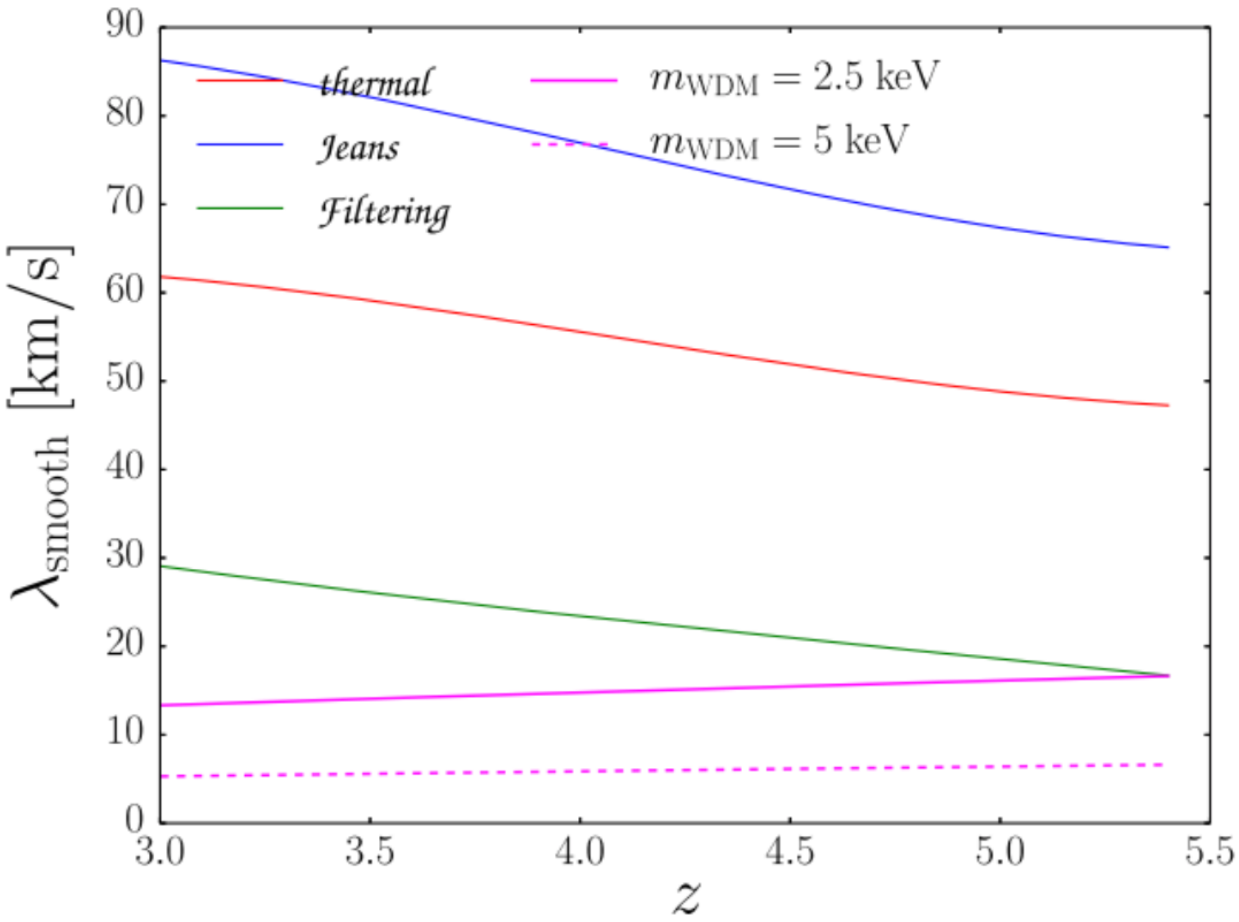
Physics of the Lyα forest - V



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

$\mathcal{H}$ is heating rate

Physics of the Lyα forest - VI



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

- thermal: instataneous temperature at that redshift;

- Jeans: scale due to gas pressure;

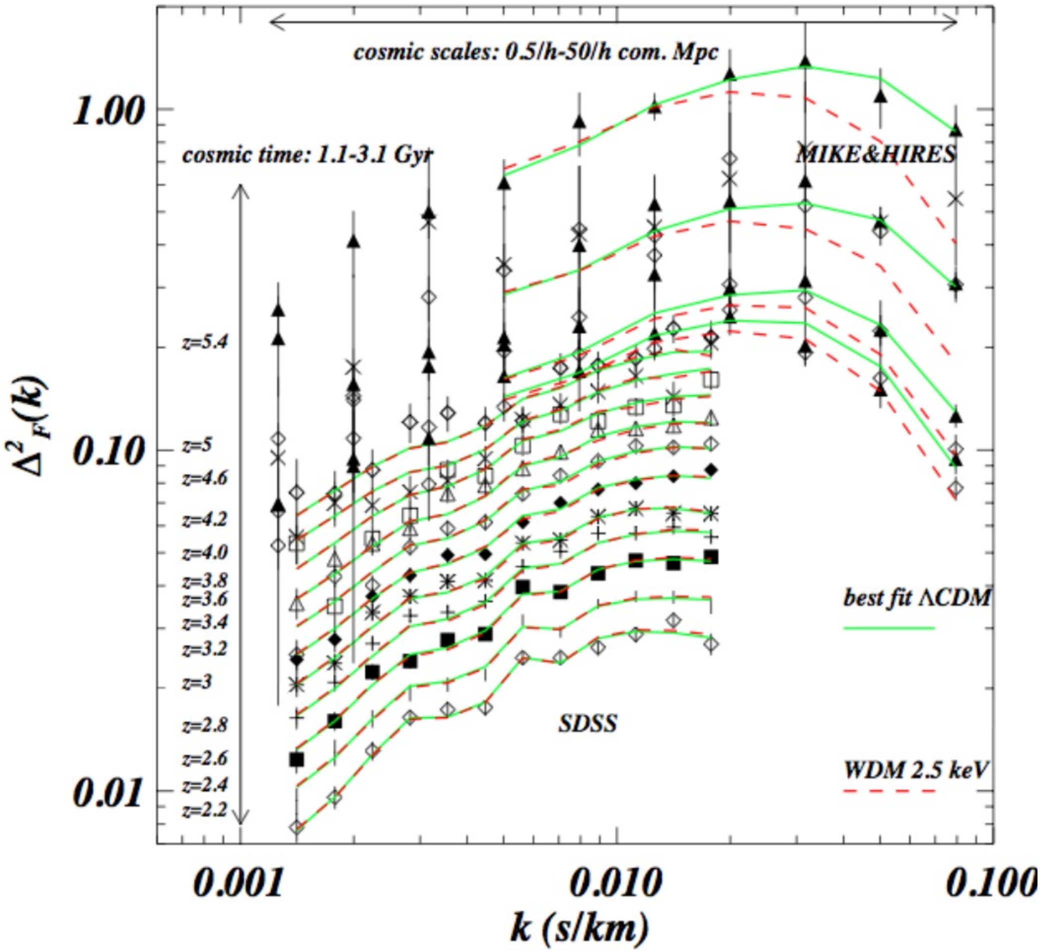
- filtering scale: depends on all the past thermal history;

- WDM cutoffs are basically redshift independent

- Constraints are obtained from **a full shape** of the 1D fux power.

Status in 2013

Viel+13

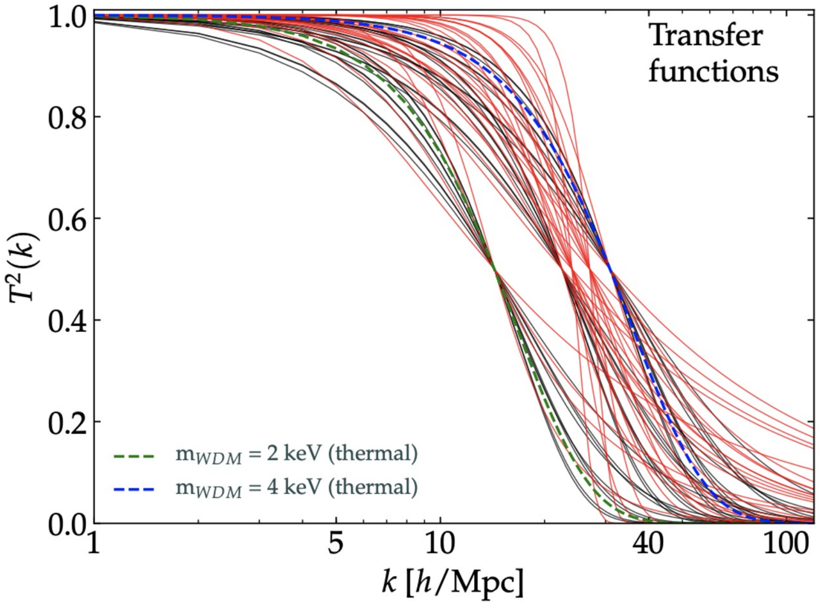


- Test of structure formation for a LCDM Universe in a **unique "pre-galactic" environment**

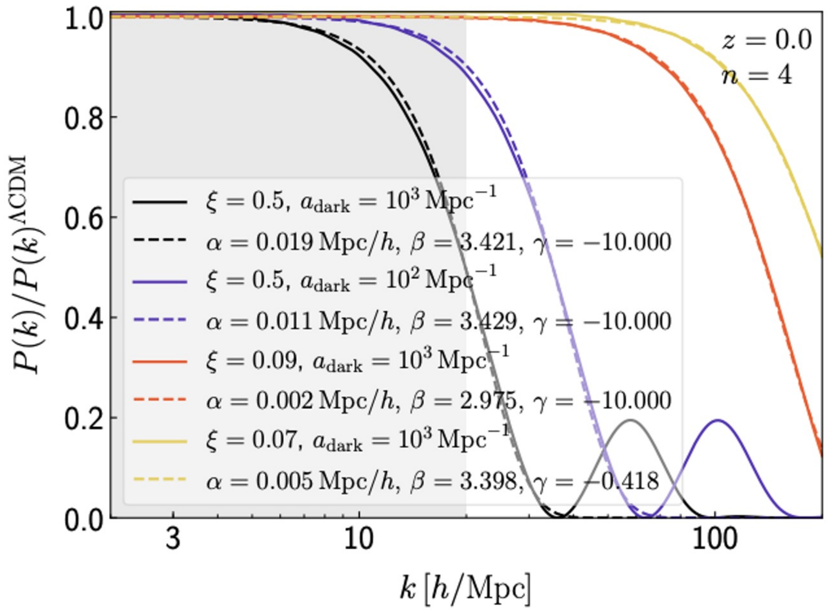
- $m_{WDM} > 3.3$ keV (2σ C.L.)

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

"New" non-cold Dark Matter models



Murgia+17



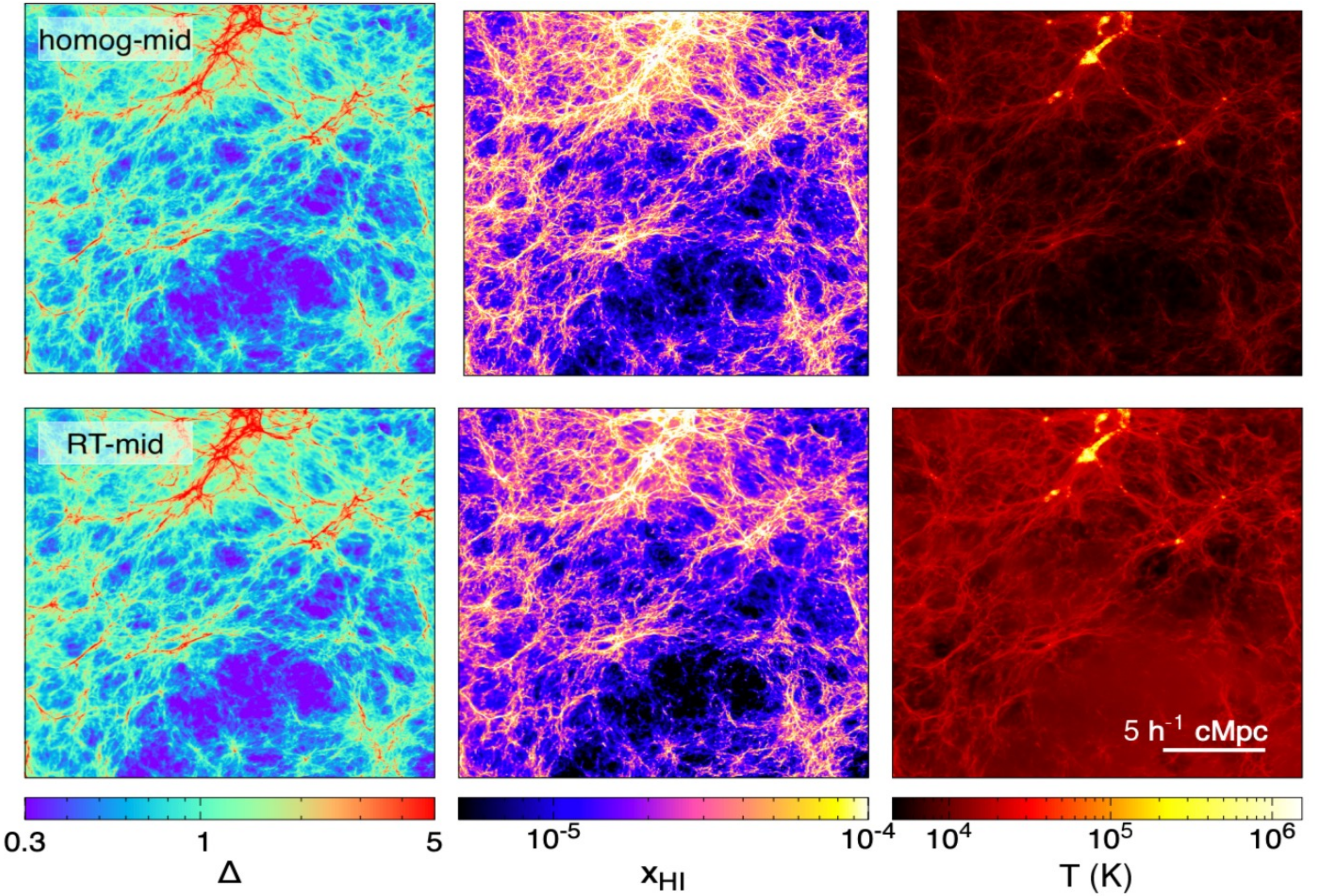
Archidiacono+19

Features to be constrained: shape (before and after $k_{1/2}$) - plateau - Oscillations/bumps in power

Patchy Reionization - I

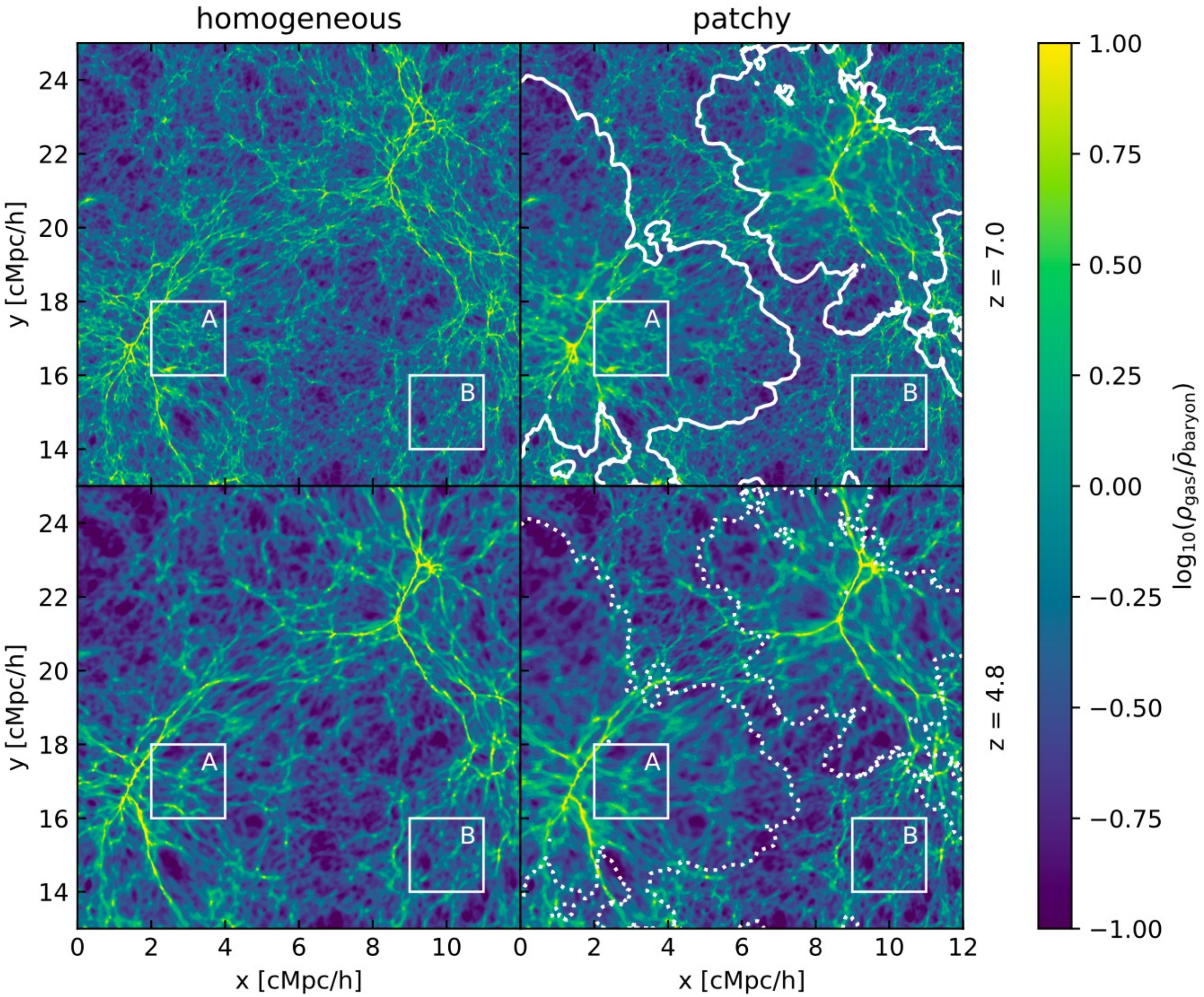
Molaro, Irsic+21, +23

z =5.4



Patchy Reionization - II

Puchwein+23



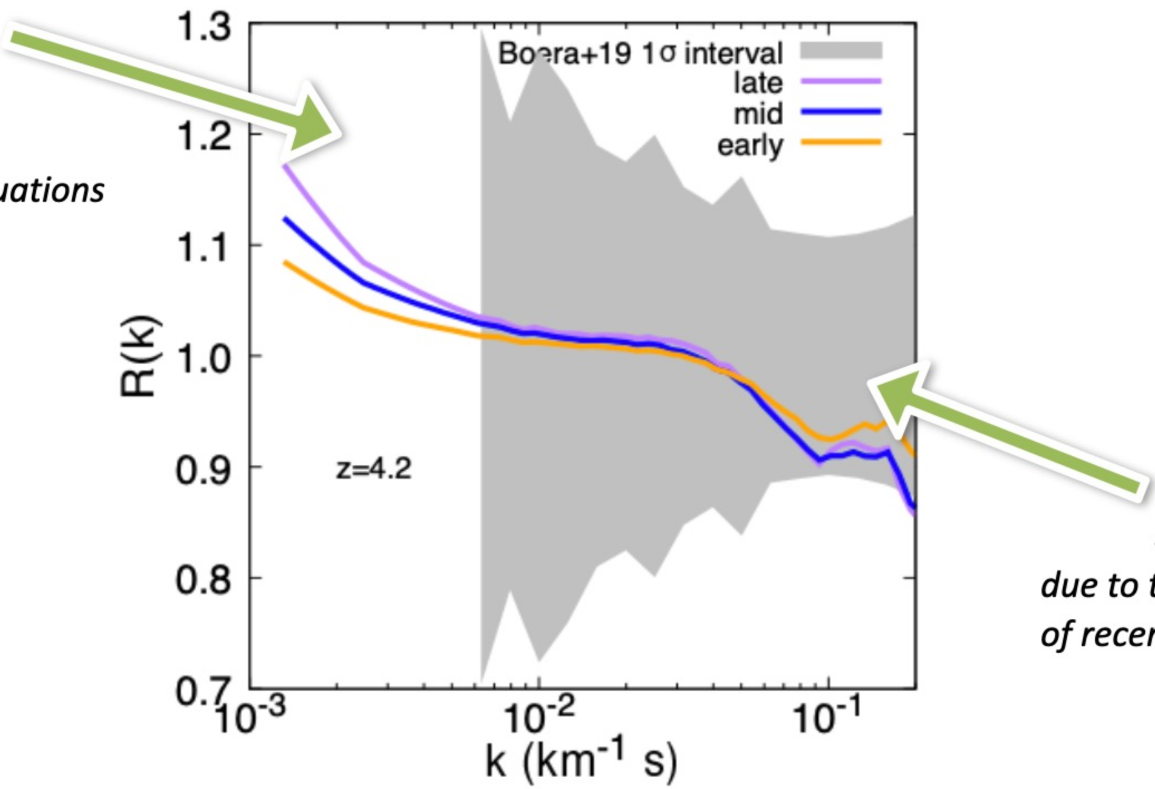
During reionization

Note:
Reionization ends at z =5.4

After reionization is complete

Patchy Reionization - III

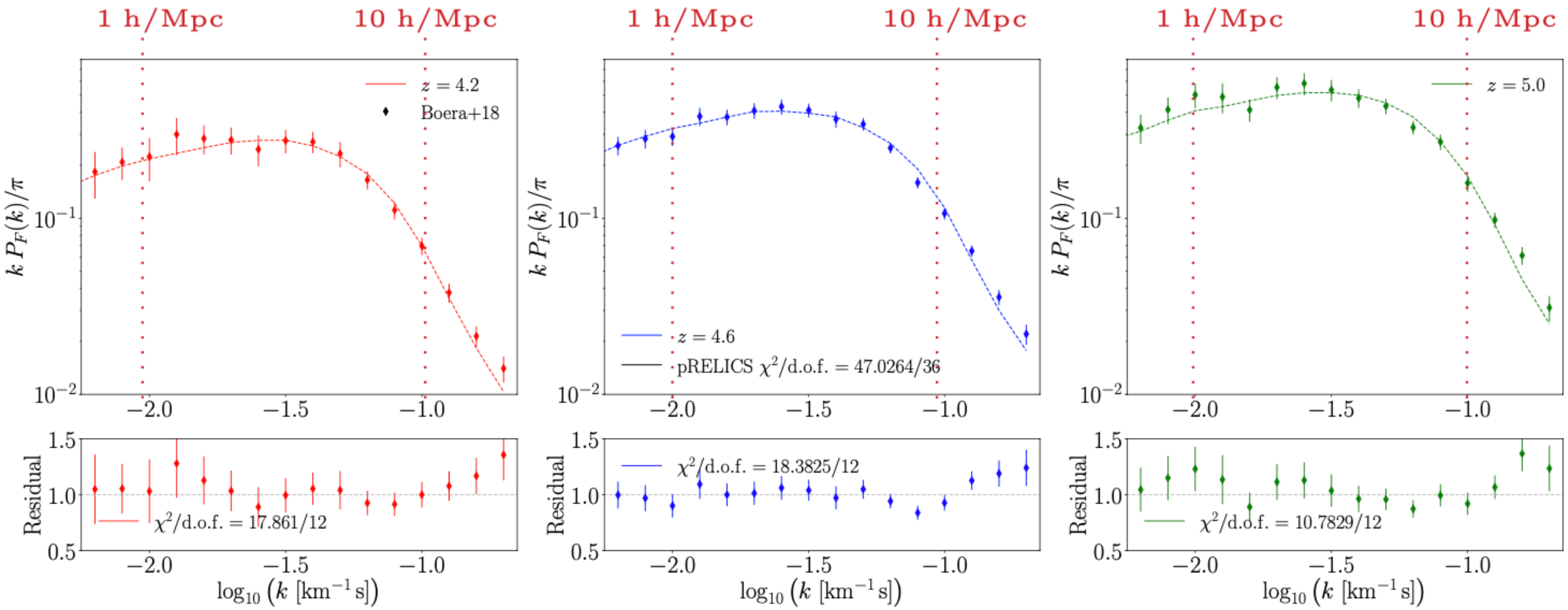
Boost
due to variation in neutral fraction from large scale temperature fluctuations



Suppression
due to thermal broadening of recently ionised regions

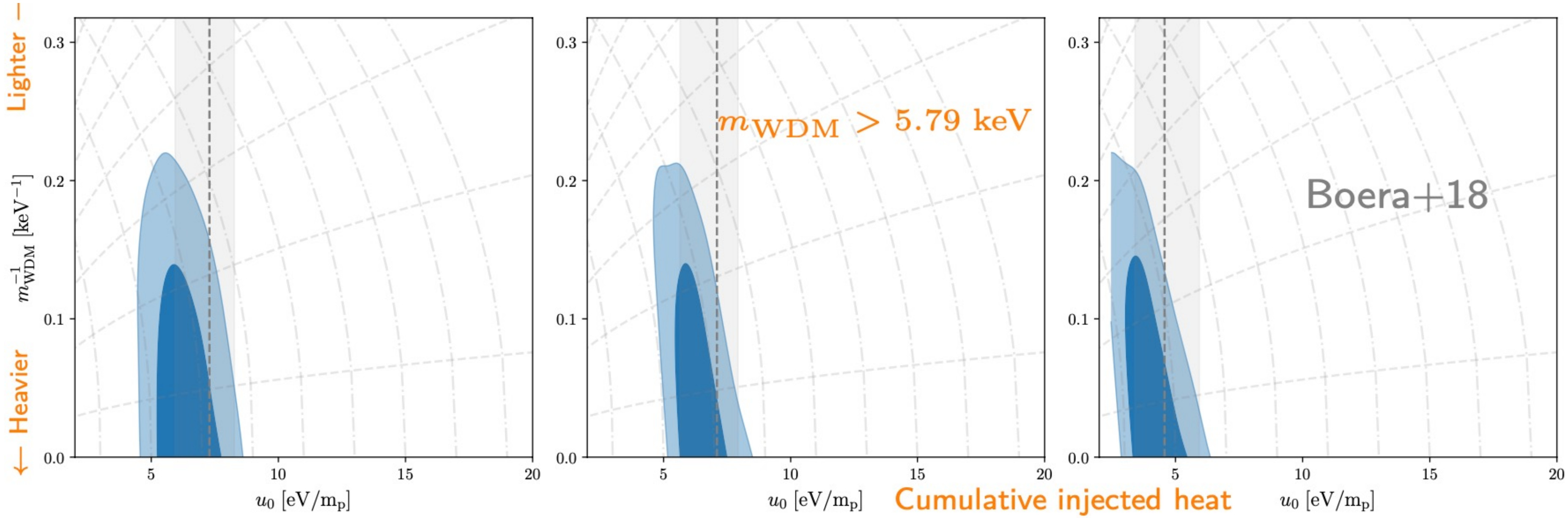
Molaro, Irsic+21, +23

Thermal WDM - III



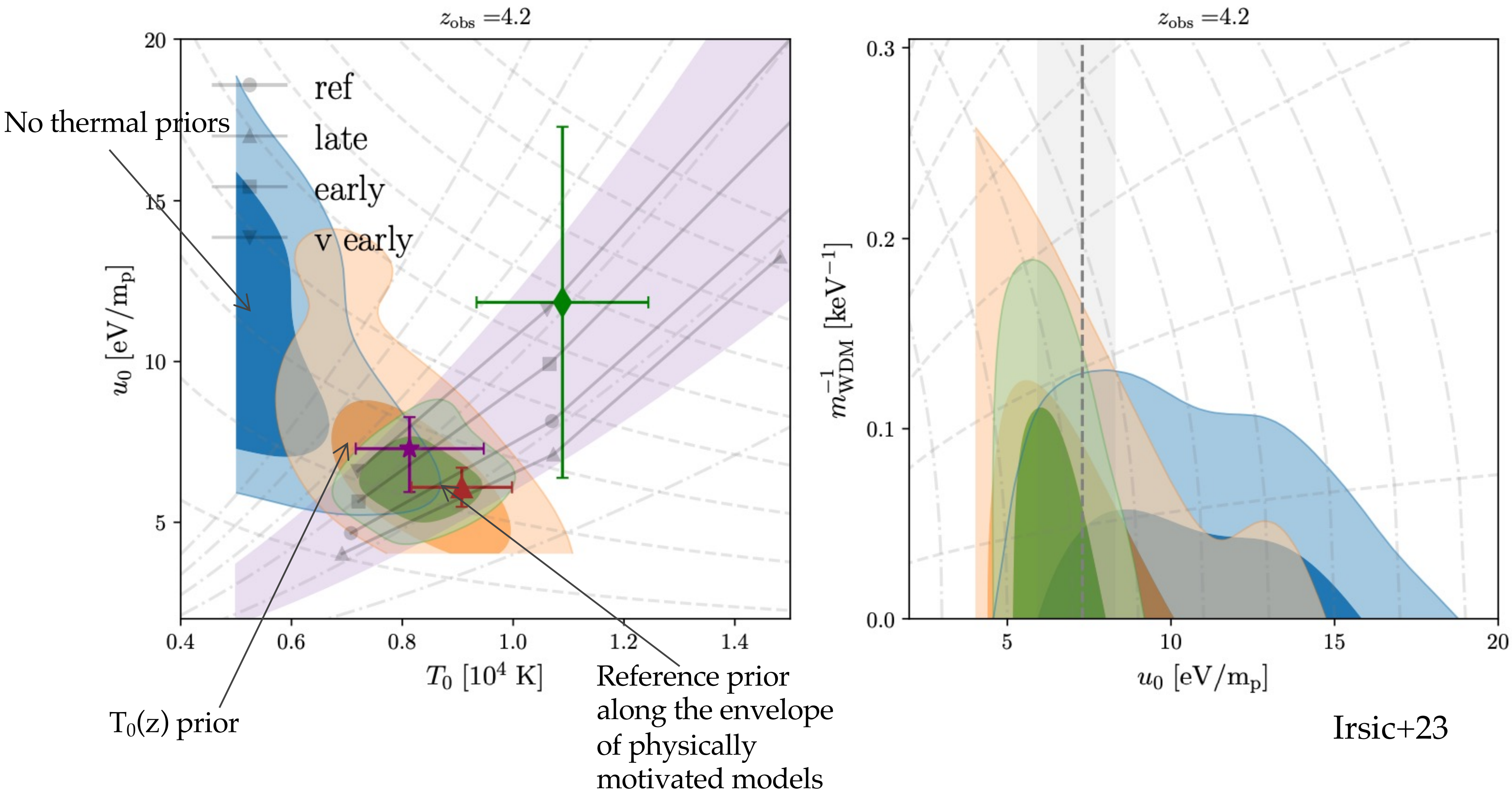
Irsic+23

Thermal WDM - III



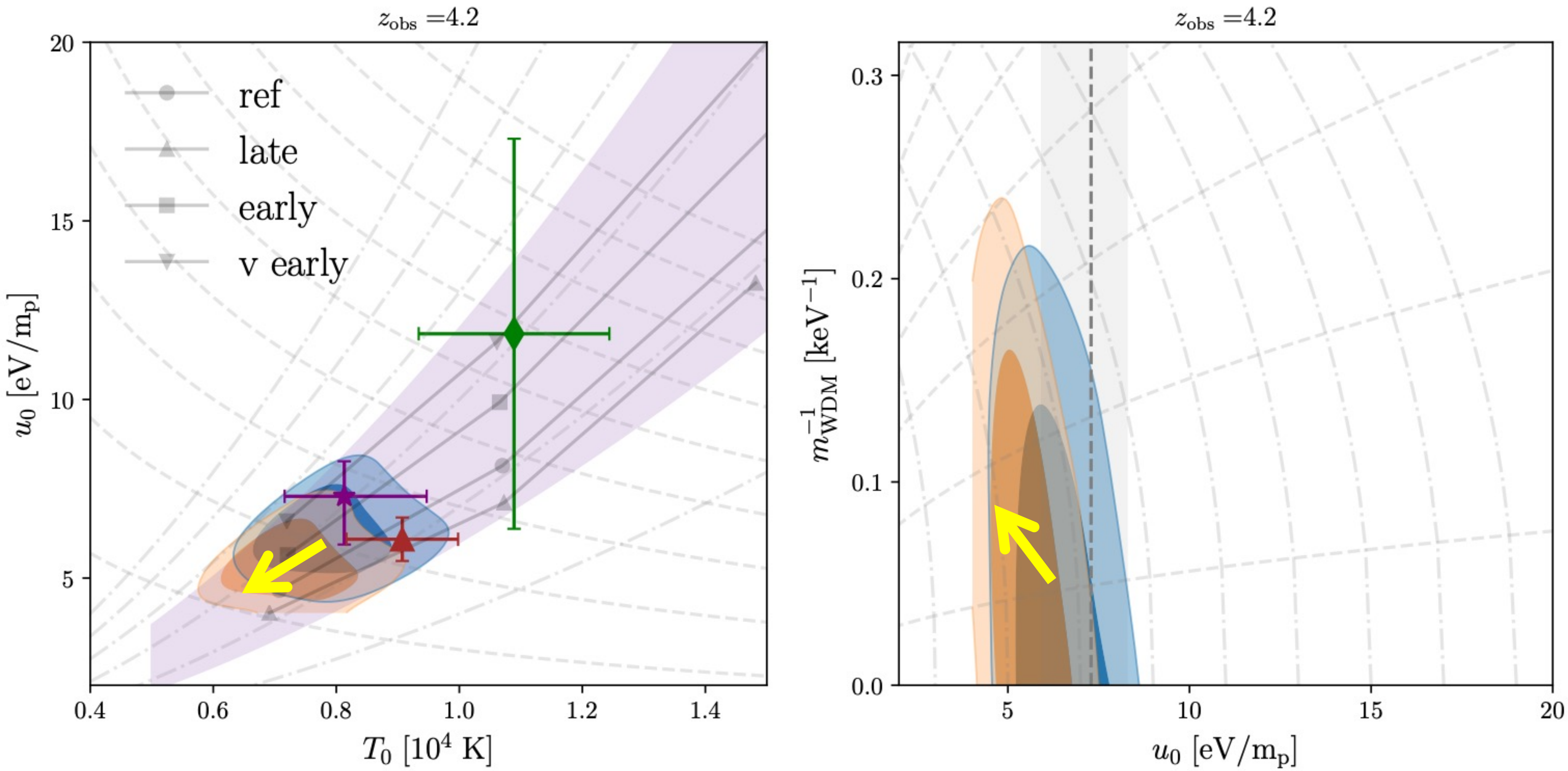
Irsic+23

Thermal WDM – the effect of thermal priors



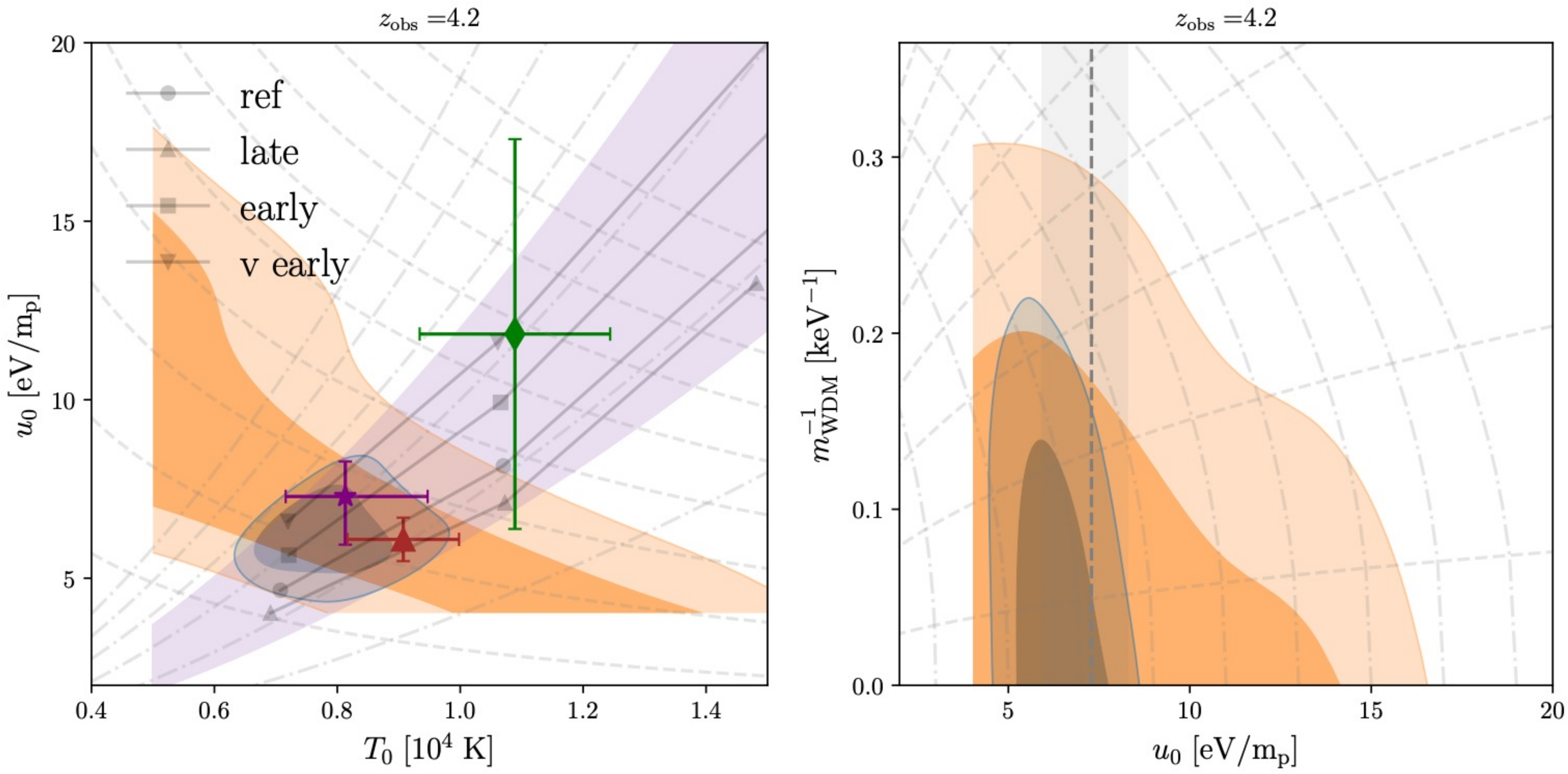
Irsic+23

Thermal WDM – inclusion of patchy correction



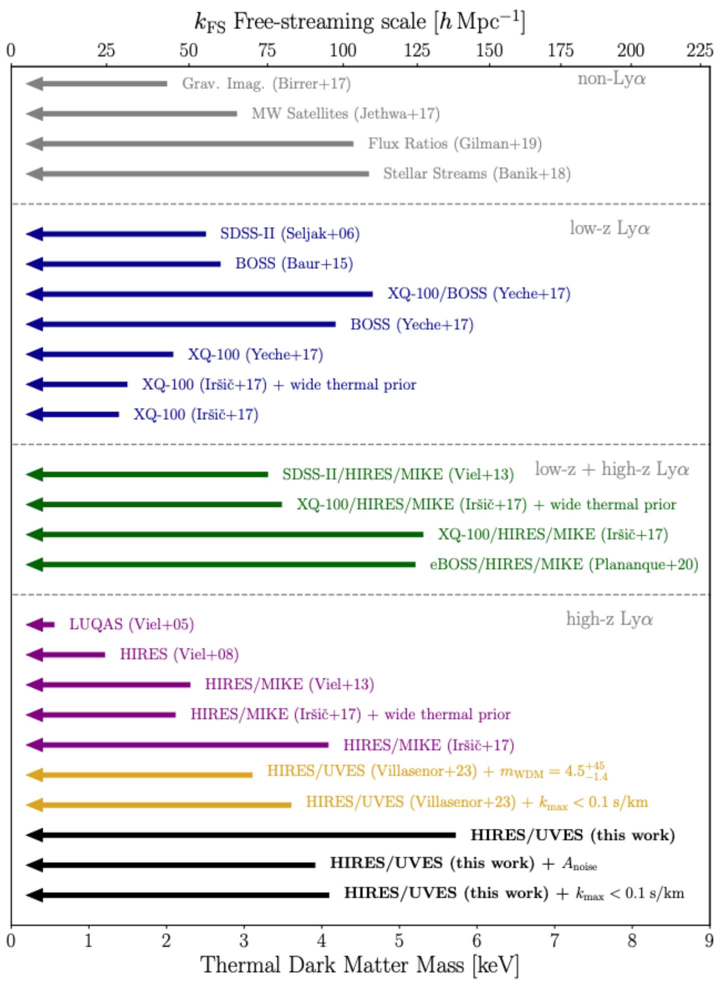
Irsic+23

Thermal WDM – noise correction



Irsic+23

Thermal WDM - III



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	$1.502^{+0.061}_{-0.061}$	$0.743^{+0.041}_{-0.075}$	$1.35^{+0.24}_{-0.19}$	$6.19^{+0.68}_{-0.68}$	-	48.9/34
$k_{max} < 0.1$ km^{-1} s	> 4.10	$1.501^{+0.060}_{-0.074}$	$0.840^{+0.095}_{-0.340}$	$1.28^{+0.09}_{-0.28}$	$8.91^{+1.57}_{-5.26}$	-	12.6/20
A_{noise}	> 3.91	$1.458^{+0.053}_{-0.074}$	$0.966^{+0.156}_{-0.466}$	$1.23^{+0.06}_{-0.23}$	$5.93^{+0.38}_{-2.28}$	$1.20^{+0.49}_{-0.29}$	23.8/31
$T_0(z)$ prior	> 5.85	$1.494^{+0.062}_{-0.077}$	$0.770^{+0.110}_{-0.120}$	$1.31^{+0.10}_{-0.31}$	$6.50^{+1.00}_{-1.60}$	-	65.6/34
$R_s(u_0)$ mass resolution	> 4.44	$1.531^{+0.073}_{-0.064}$	$0.617^{+0.007}_{-0.118}$	$1.38^{+0.28}_{-0.13}$	$7.90^{+1.70}_{-2.30}$	-	29.6/34
patchy reion.	> 5.10	$1.486^{+0.058}_{-0.068}$	$0.686^{+0.046}_{-0.080}$	$1.33^{+0.17}_{-0.26}$	$5.32^{+0.58}_{-0.52}$	-	55.3/34

Irsic+23