The Lyman-alpha probe of large scale structures

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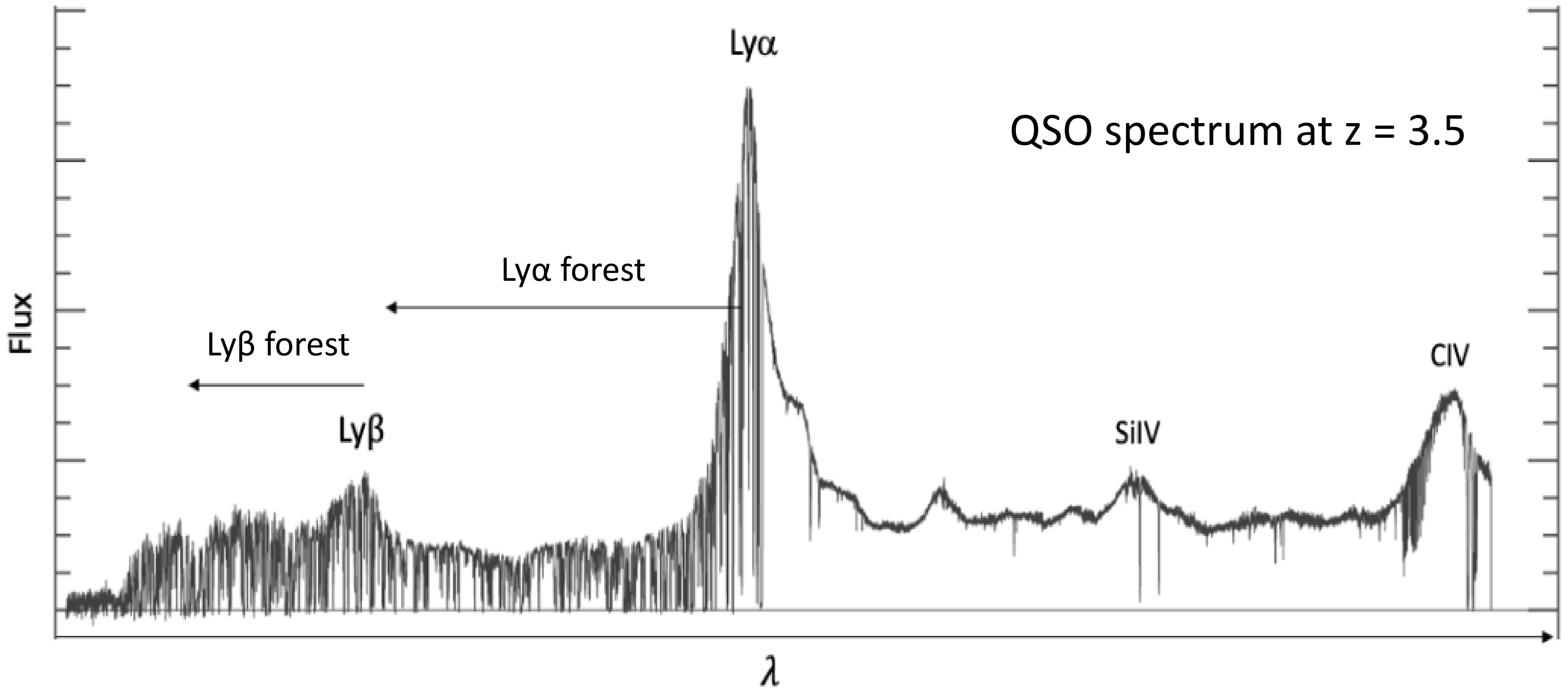
Physics of the Lyman-alpha forest

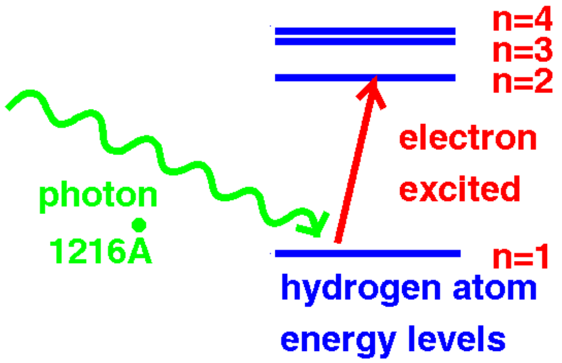
Lyman-alpha forest

- Lyman-alpha: transition of neutral Hydrogen at 1215.67 Å
- Lines on the QSO spectra at $\lambda_{\mathrm{obs}} = (1 + z_{abs})\lambda_{\mathrm{Ly}\alpha}$ caused by absorber at z_{abs}



Lyman-alpha forest

- Optical depth: $\tau_\lambda = \int n_{HI}(r)\,\sigma_\alpha(\lambda)dr$
- Lyman-alpha flux: $f_\lambda = \exp(-\tau_\lambda)$



- Photo-ionization equilibrium + Large scale:

$$\tau_\lambda \sim \tau(z) \propto \Omega_b^2 \frac{(1+z)^6 \bar{T}(z)^{-0,7}}{H(z)J_\gamma(z)} \frac{\left(1+\delta(z)\right)^\beta}{\left(1+\eta(z)\right)}$$

- $x_{HI} \sim 10^{-4}$, $\tau_\lambda \sim 1$ → Lyman-alpha observable

Lyman-alpha forest = Non-linear tracer of the neutral Hydrogen in the IGM

Observational statistics for large scale structures

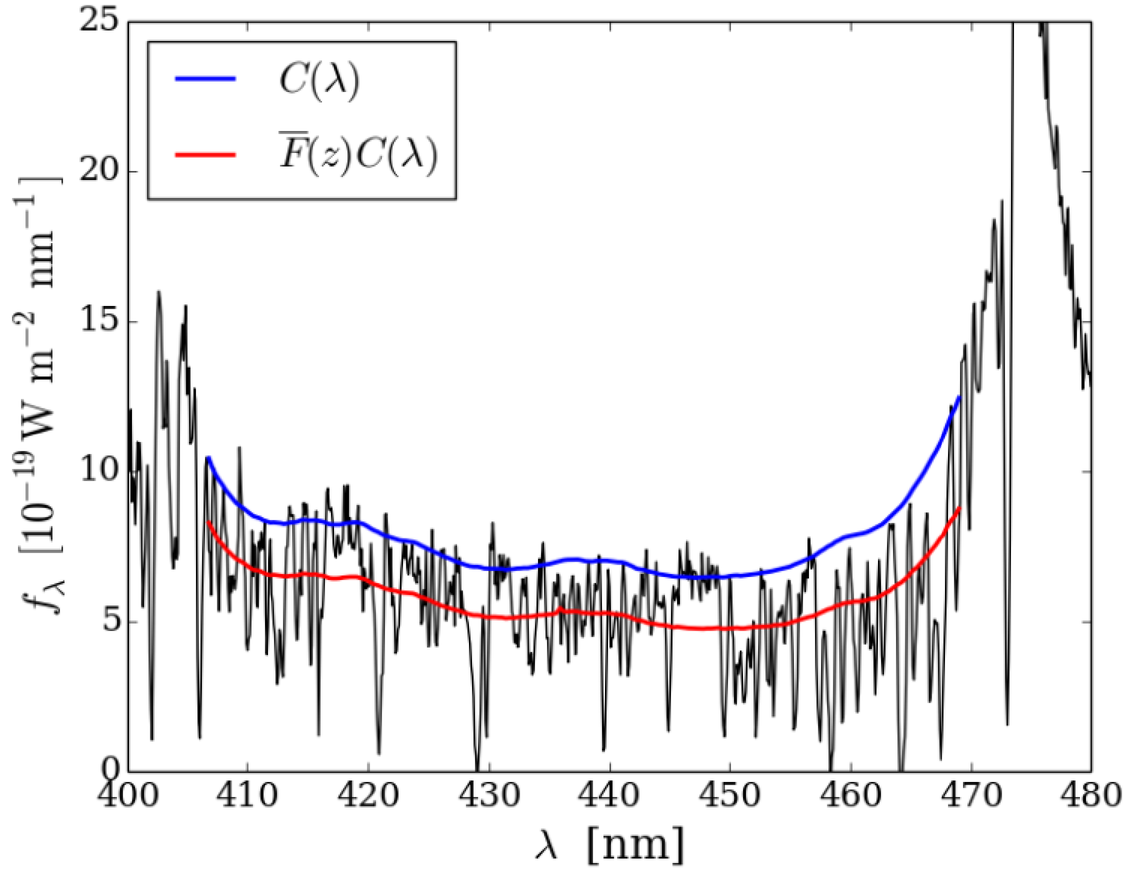
- Flux contrast:

$$\delta_F(\lambda) = \frac{f_q(\lambda)}{\overline{F}(\lambda)C_q(\lambda_{\mathrm{RF}})} - 1$$

- Correlation function and power spectrum:

$$\xi_F(\vec{r}) = < \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r}) >_x$$

$$P_F(\vec{k}) = \mathrm{TF}[\xi_F(\vec{r})]$$



eBOSS DR16 results

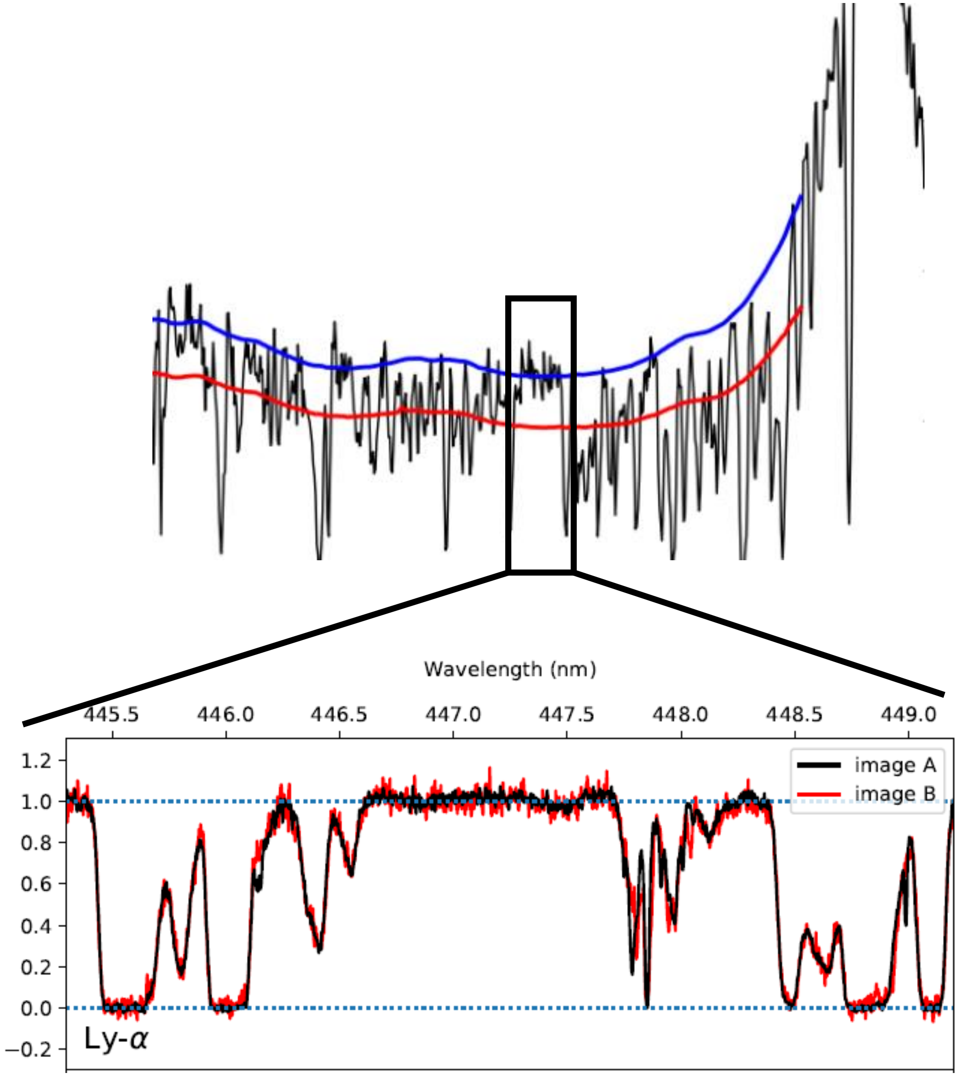
Lyman-alpha observations

- Moderate resolution QSO surveys:
  - SDSS/eBOSS
  - DESI
  - (WEAVE-QSO)
- High resolution QSO observations: UVES, HIRES, XSHOOTER, ESPRESSO, 4MOST, COS
- Other target: Lyman-alpha forest from Lyman-Break Galaxies (e.g.: CLAMATO)

High resolution observations

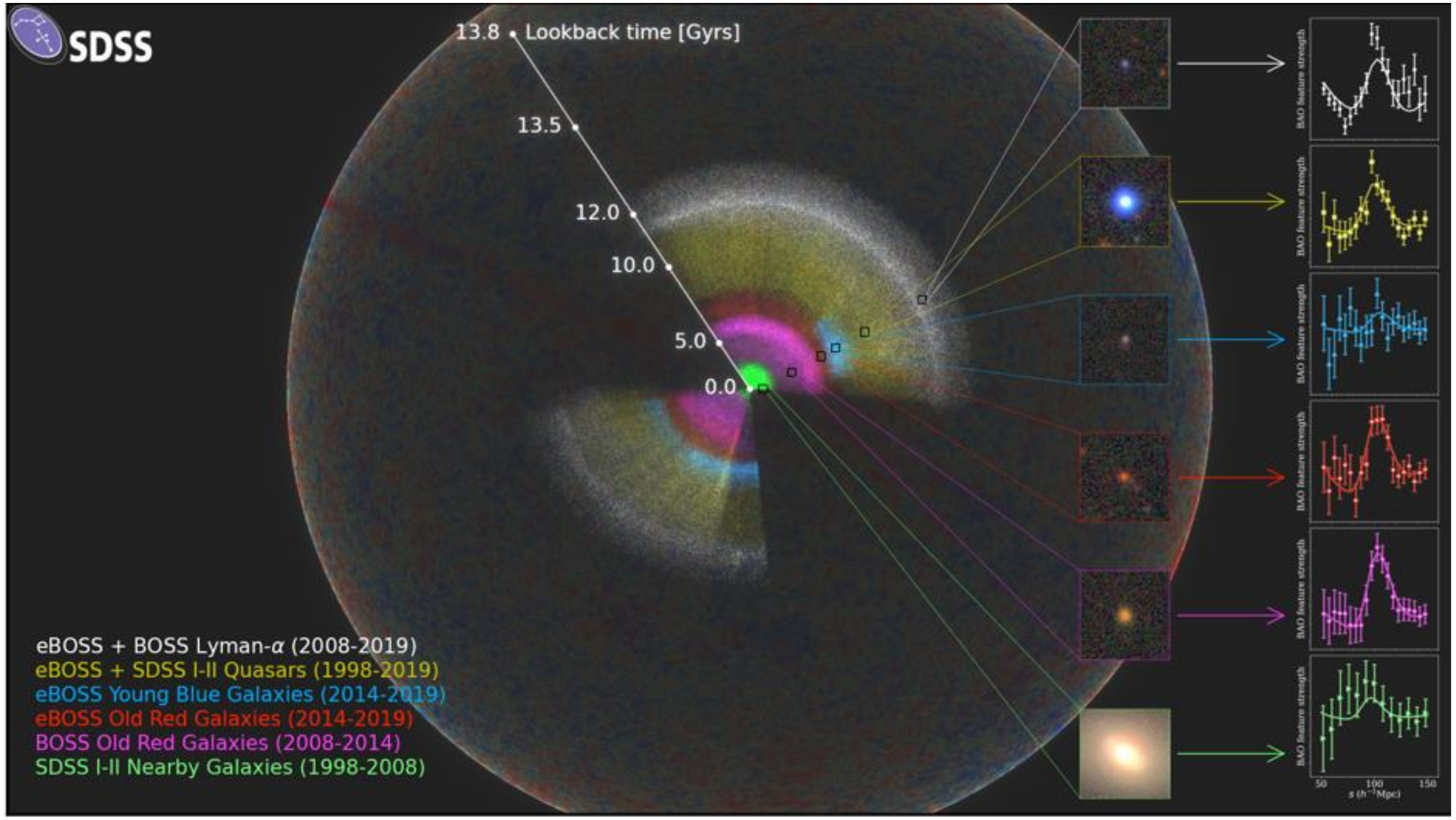
- <u>Currently</u> : R = 30 000 – 100 000, mean SNR per pixel ~ 20
  - SQUAD survey (UVES,VLT), Murphy et al. 2019, 467 QSO
  - KODIAQ survey (HIRES,Keck), O'Meara et al. 2017, 300 QSO
  - COS instrument (HST), Danforth et al. 2016, 87 QSO

- <u>Future experiments</u>:
  - ESPRESSO instrument (VLT)
  - 4MOST Cosmology redshift survey (VISTA)



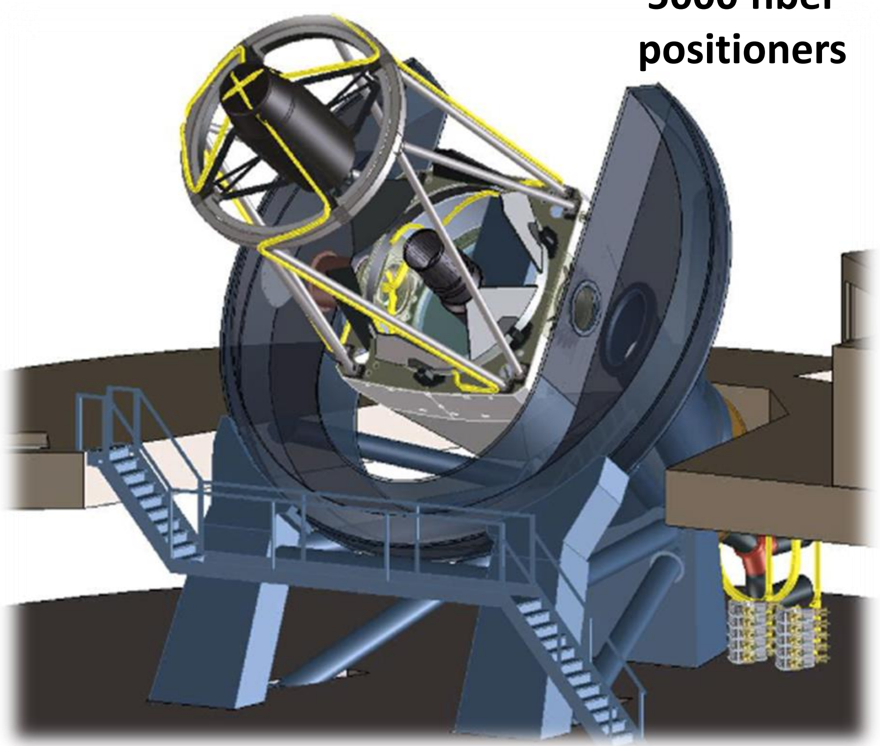
eBOSS for Lyman-alpha

- <u>SDSS/eBOSS</u>: 10 000 deg², 210 000 spectra, R = 2000, $\lambda \sim [360, 1000] nm$, mean SNR per pixel ~ 2



DESI

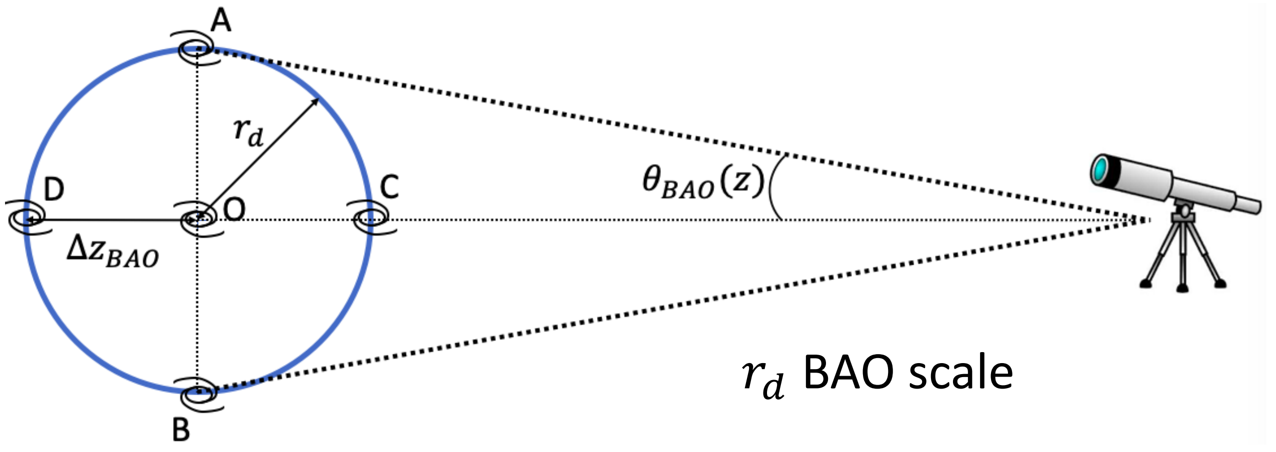
- <u>DESI</u>: 700k Lyman-alpha spectra, R ~ 3000 - 5000, higher SNR for the same exposure time, 14 000 deg^2



BAO measurement

Baryonic Acoustic Oscillations

- Standard ruler for distance measurement : 100 Mpc/h comoving
- Cf. Eric Aubourg talk (15 years of baryonic oscillations)



- Observed quantities:

$$\Delta\theta_{BAO} = r_d/D_M$$
$$\Delta z_{BAO} = r_d/D_H$$

- Deviation measurement (Alcock-Paczynski test):

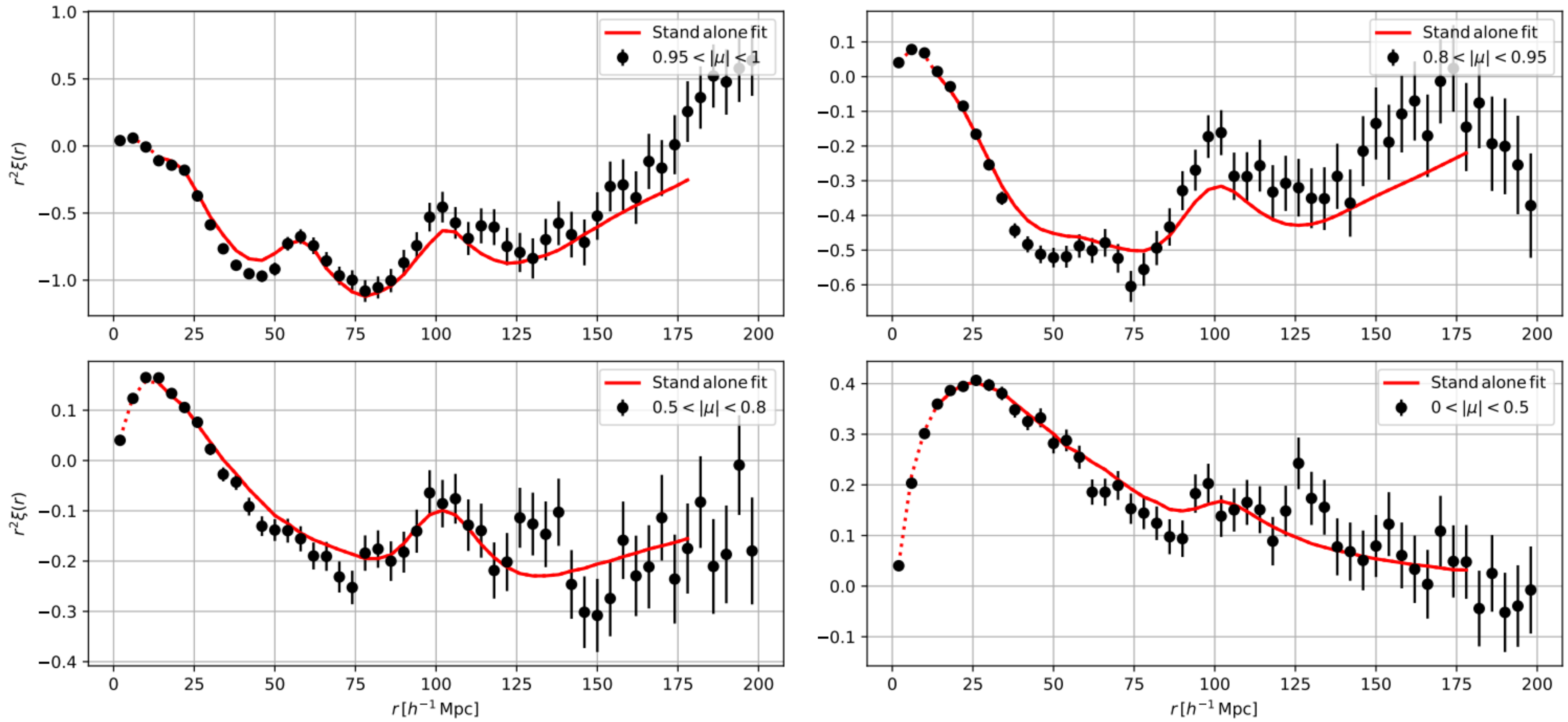
$$\alpha_{\parallel} = \frac{D_H/r_d}{(D_H/r_d)_{fiducial}}$$
$$\alpha_{\perp} = \frac{D_M/r_d}{(D_M/r_d)_{fiducial}}$$

Autocorrelation results

- Main statistics:

$$\hat{\xi}_A = \frac{\sum_{(i,j)\in A} w_i w_j \delta_i \delta_j}{\sum_{(i,j)\in A} w_i w_j}$$

- Other observables: QSO-Lya, DLA-Lya cross-correlations
- Contaminants: HCD metals, continuum fitting…



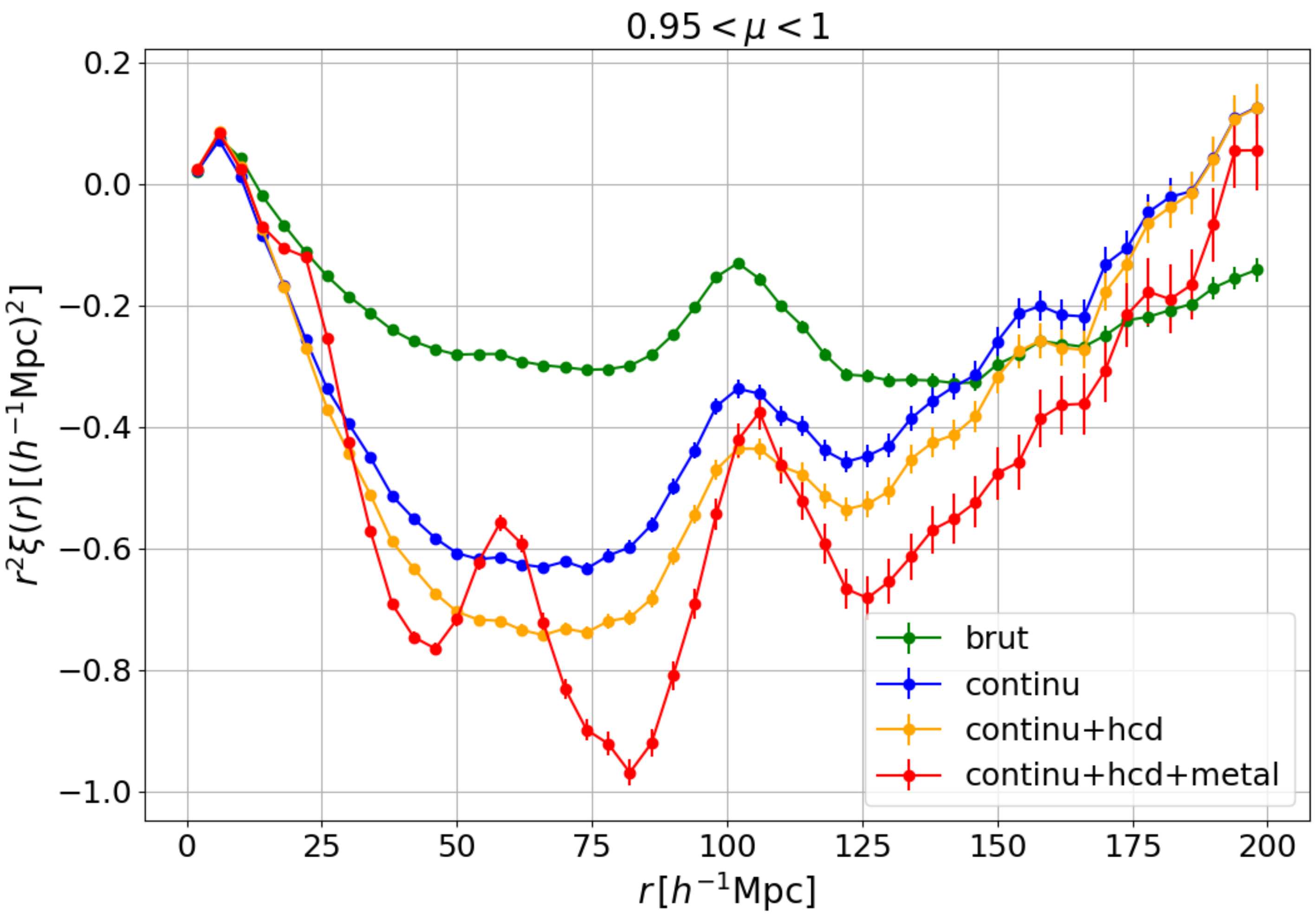
du Mas des Bourboux et al. 2020

Synthetic data

- Understand theoretical and observational systematics thanks to synthetic data

- At these scales, Hydrodynamic simulations not achievable → Log-normal mocks (Etourneau et al. in prep., Farr et al. 2020)

- Robust BAO peak position independent of broadband modeling

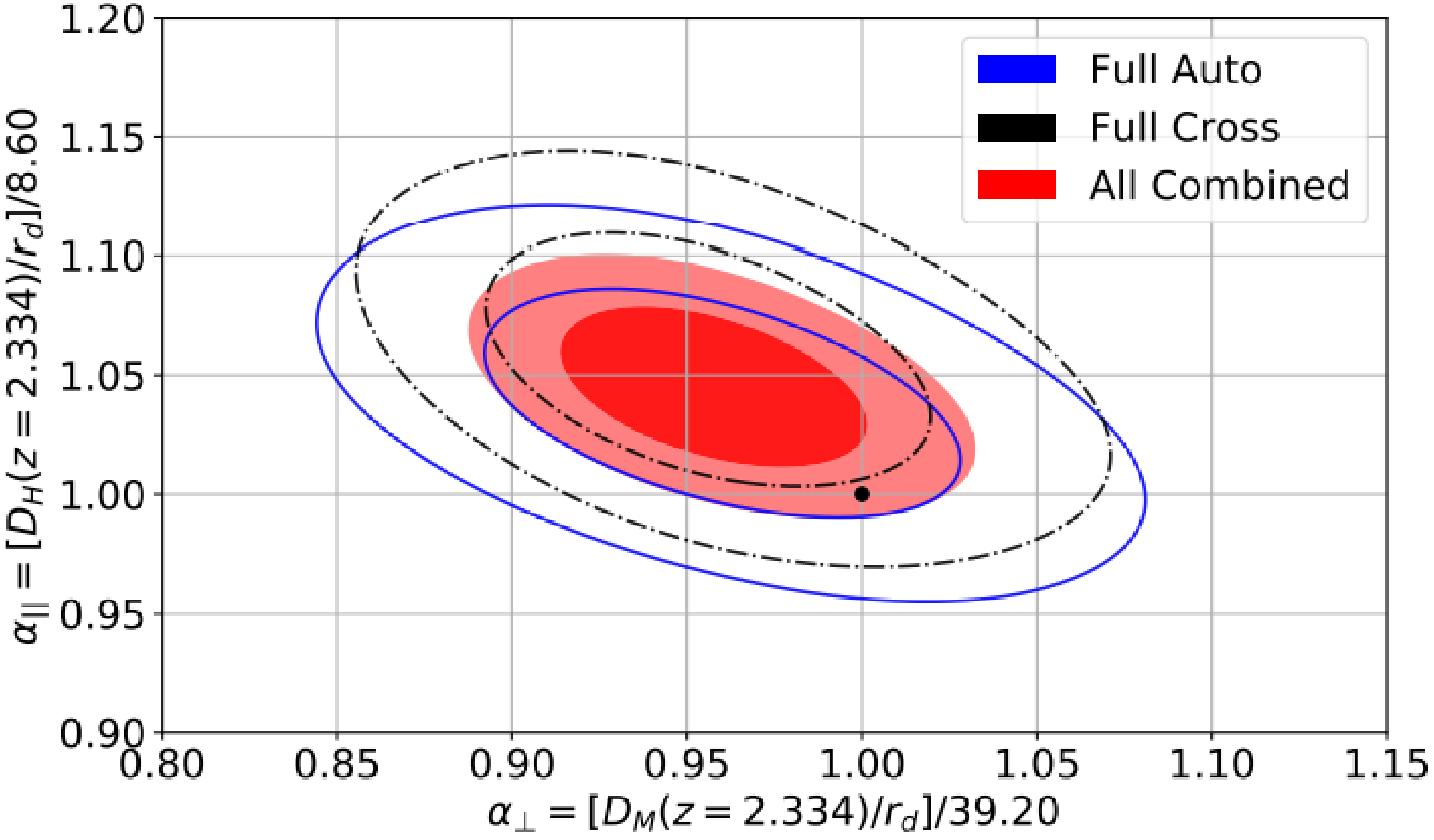


Etourneau et al. in prep.

Lyman-alpha BAO results

- Results for the α parameters

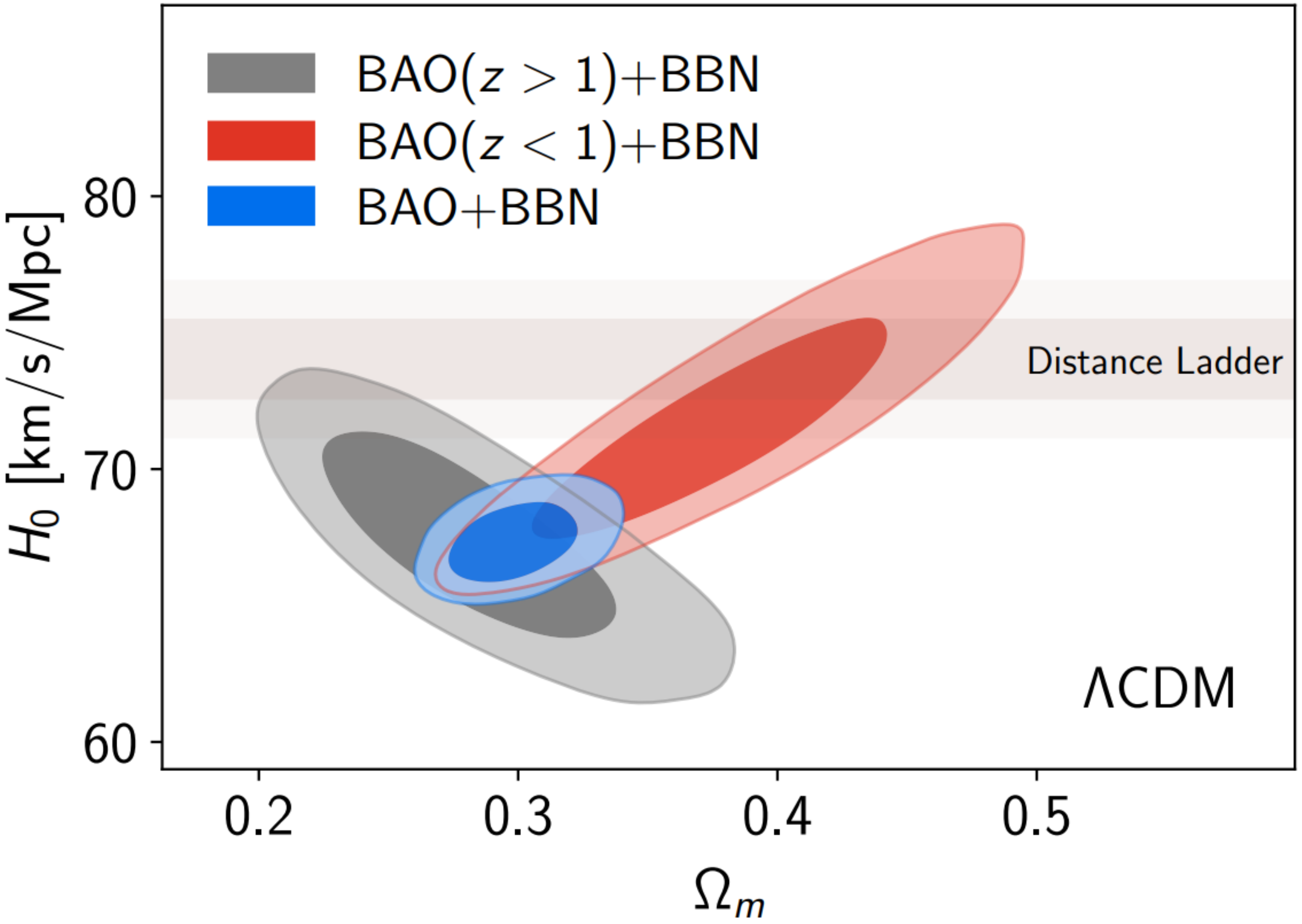
- Included in the main eBOSS cosmology paper



du Mas des Bourboux et al. 2020

Lyman-alpha BAO results

- High z measurements complementary to low z (H0)
- Cf. Jean-Paul Kneib talk for eBOSS final cosmology results
- Cf. Richard Neveux for QSO clustering analysis



eBOSS collaboration 2020

One dimensional power spectrum

One dimensional power spectrum

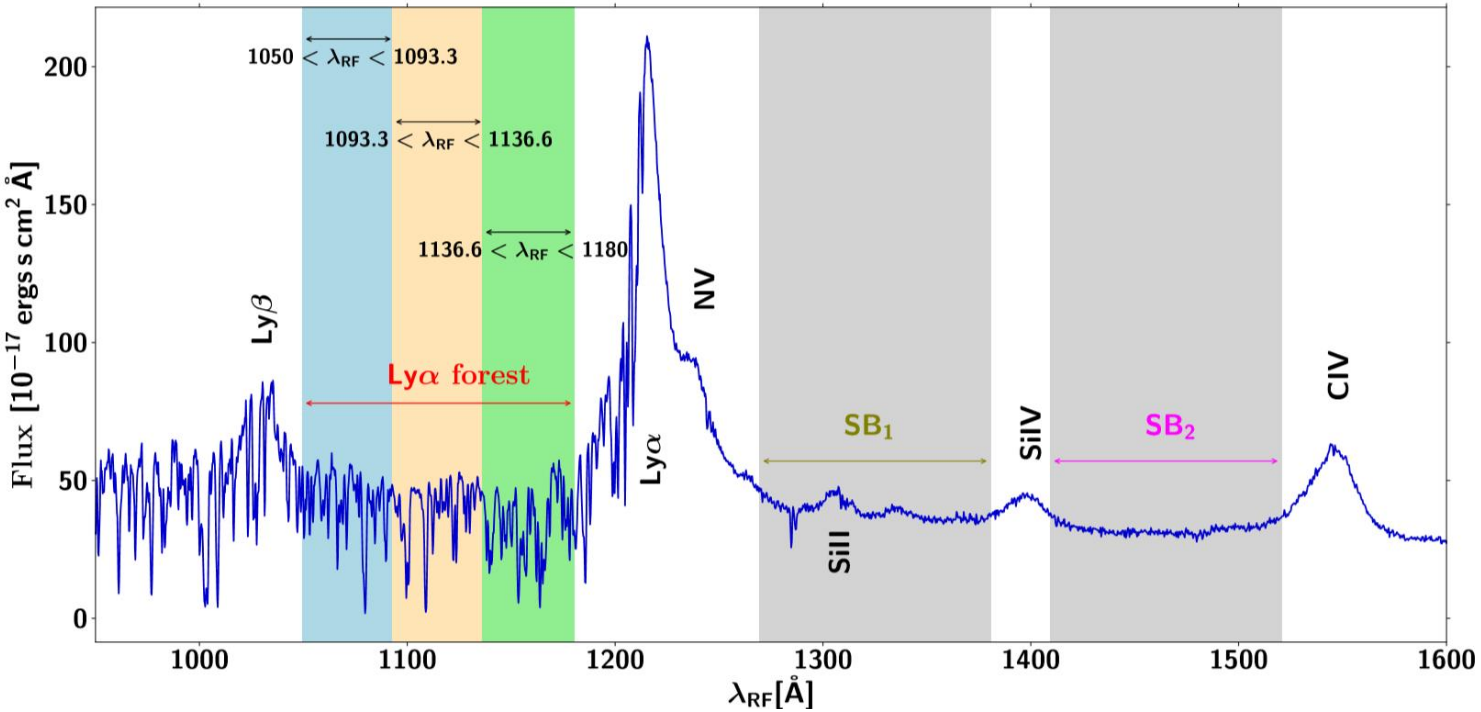
- <u>P1D definition</u>:

$$P_{1D}(z, k_{\parallel}) = \int \frac{d\boldsymbol{k}_{\perp}}{(2\pi)^2} P_{3D}(z, \boldsymbol{k}_{\perp}, k_{\parallel})$$

- Correlation within each line-of-sight

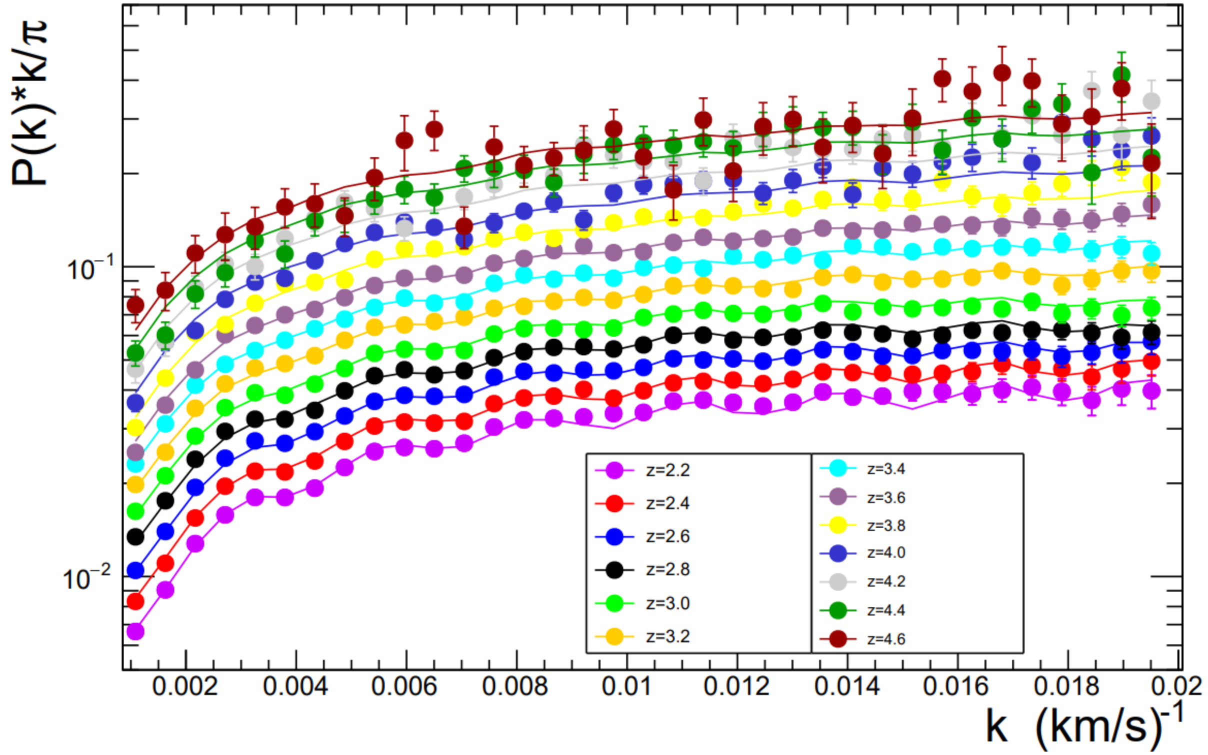
- Probe the matter power spectrum to small-scales (~ 1 Mpc)

- Constraints DM models which erase small-scale clustering



P1D computation on eBOSS data

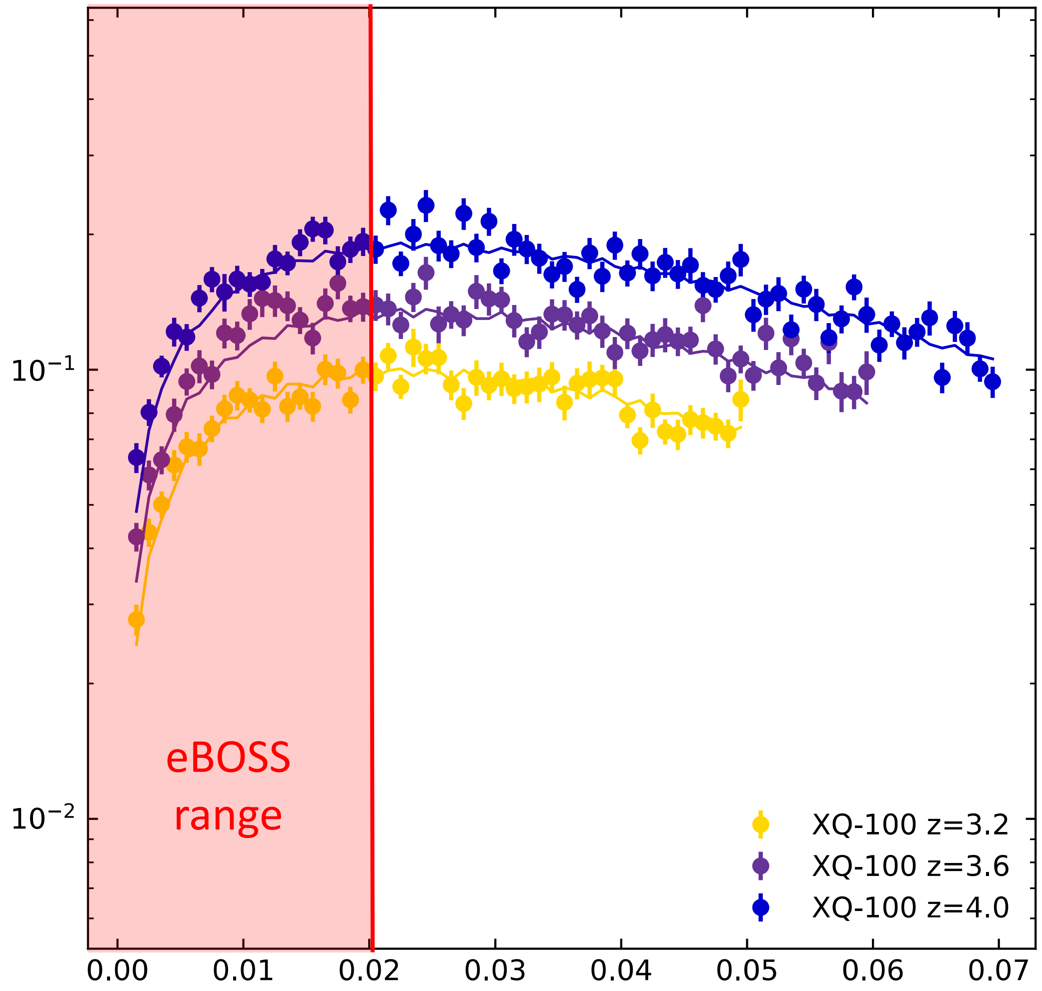
- Most precise measurement today (Chabanier et al. 2019)
- Improved systematics analysis (metals, HCD, …) compared to BOSS
- Model:



$$P^{raw}(k) = \left(P^{Ly\alpha}(k) + P^{Ly\alpha - SiIII/II}(k) + P^{metals}(k)\right) \times W^2(k, R, \Delta v) + P^{noise}(k)$$

P1D computation on XQ100 data

- High resolution P1D with XQ100 data
- Crucial to obtain high k information which are needed for DM models erasing small-scale clustering



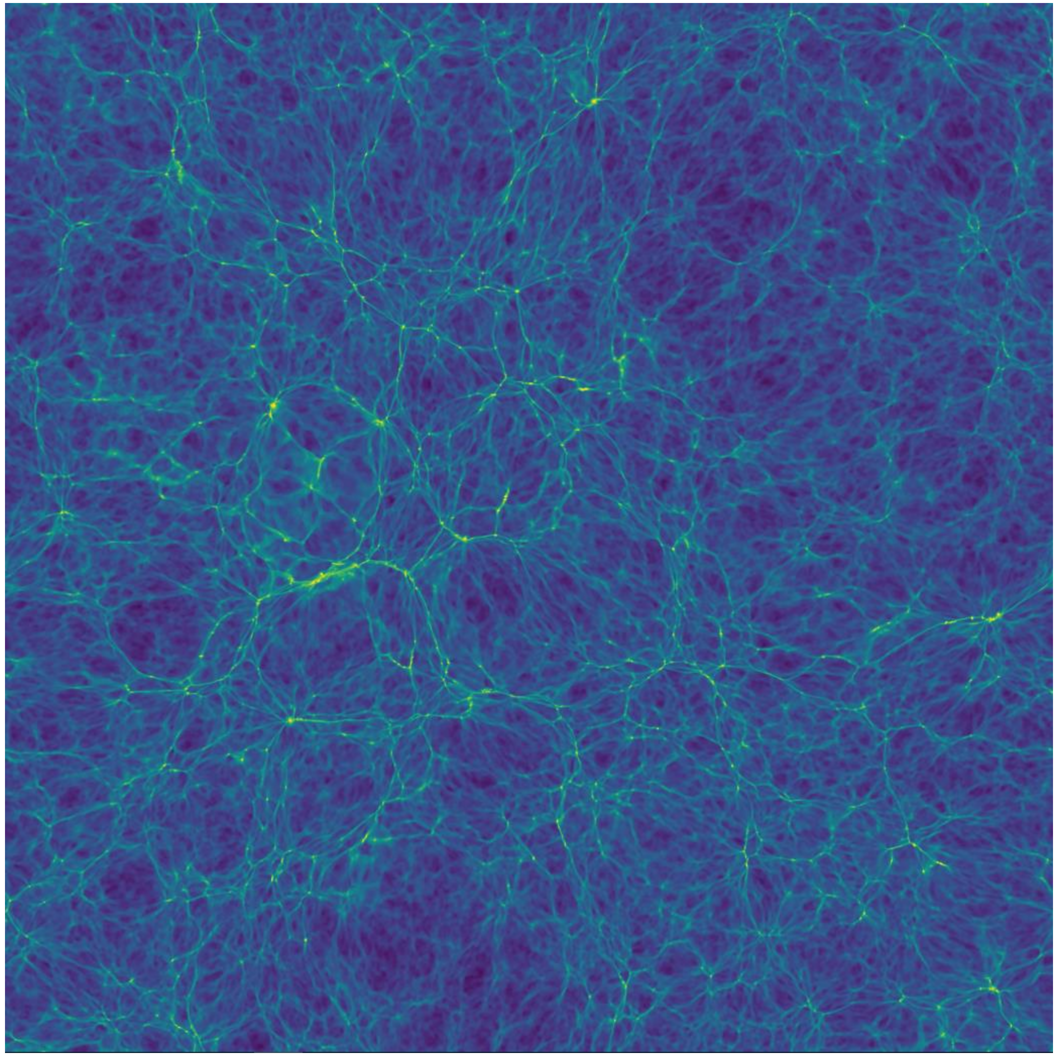
Yeche et al. 2017, Irsic et al. 2017

Hydrodynamic simulations

- At the small-scales considered, use of Hydrodynamic simulations (Baryons + DM fluids)

- High number of resolution elements:
  - Need to resolve the Jeans scale (~100 kpc)
  - Large scales to cover P1D k-range

- Cf. Solène Chabanier talk (What simulations bring to cosmology)



Walther et al. in prep.

Simulation Grid

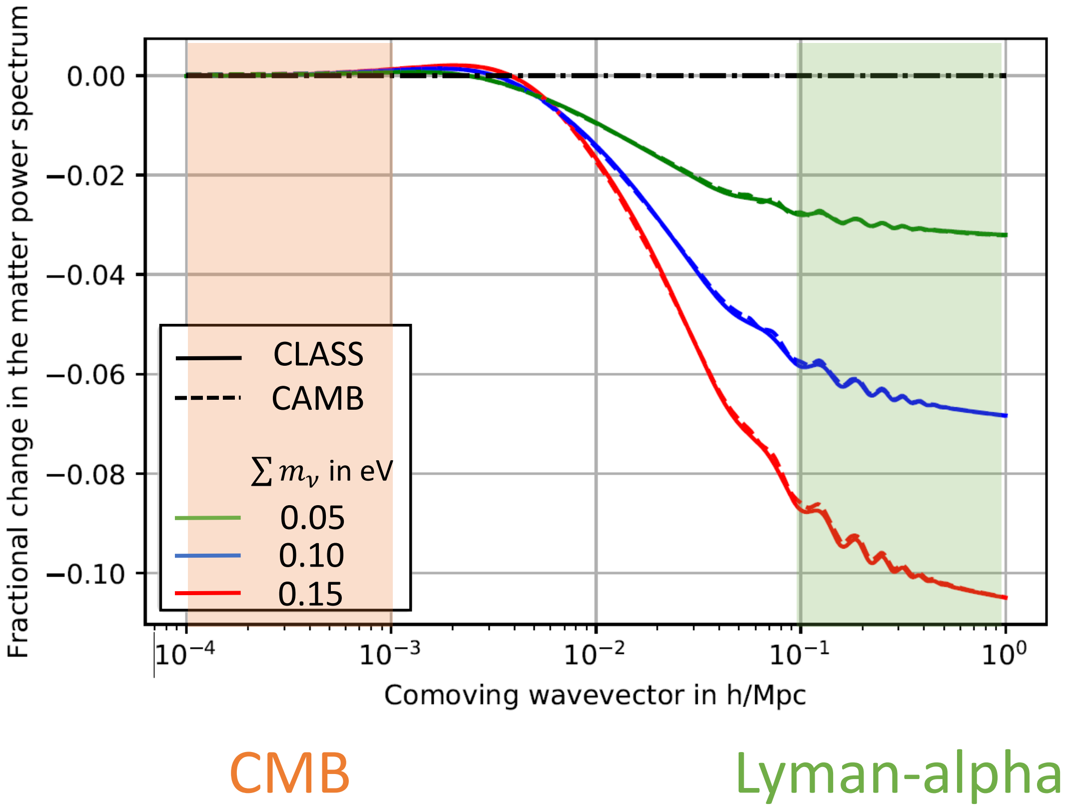
- For BOSS/eBOSS: Taylor expanded grid
- For DESI: Emulated simulation grid with Gaussian Processes (Walther et al. in prep)

TGCC

	parameter	central	range
Cosmology	keV / m_X	0.0	+0.2 +0.4
	$\Sigma m_\nu / eV$	0.0	+0.4 +0.8
	h	0.675	±0.05
	Ω_M	0.31	±0.05
	σ_8	0.83	±0.05
	n_s	0.96	±0.05
	$dn_s / d\ln k$	0.00	±0.04
	z_{reio}	12	±4
	N_{eff}	3.046	±1
Intergalactic Medium	$T_0^{z=3} / K$	14,000	±7,000
	$\gamma^{z=3}$	1.3	±0.3
Optical Depth	A^τ	0.0025	±0.0020
	η^τ	3.7	±0.4

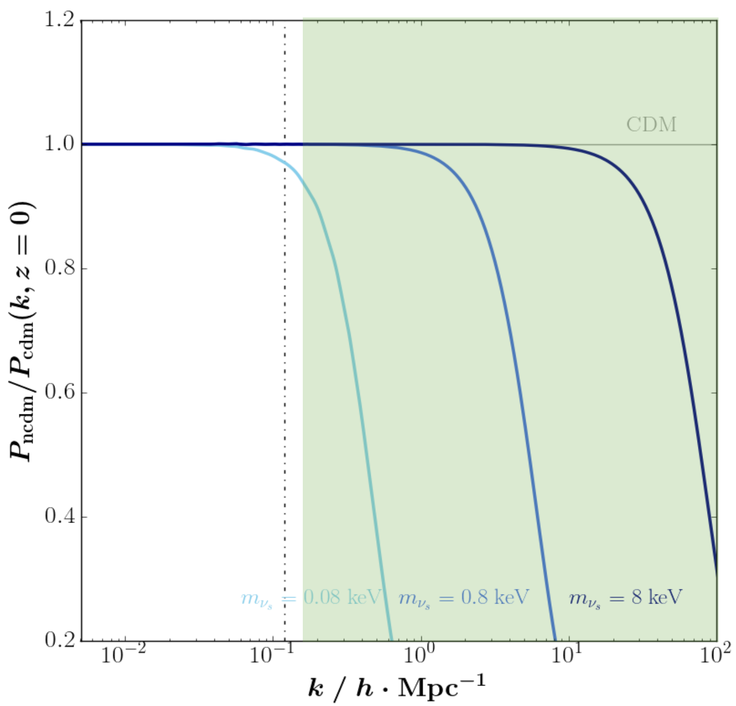
Neutrinos impact on LSS

- Particle physics: Constraint the mass differences
- Cosmology: Sum of neutrino mass $\sum m_\nu$ impact large-scale structure formation
  - Free streaming length: $\lambda_{FS} \sim \left(\frac{\pi v_{th}^2}{G\bar{\rho}}\right)^{1/2}$
  - Smoothing of small-scale clustering: Neutrinos escape Dark Matter potential wells smaller than λ_{FS}
  - Higher mass = Larger impact → Upper limit

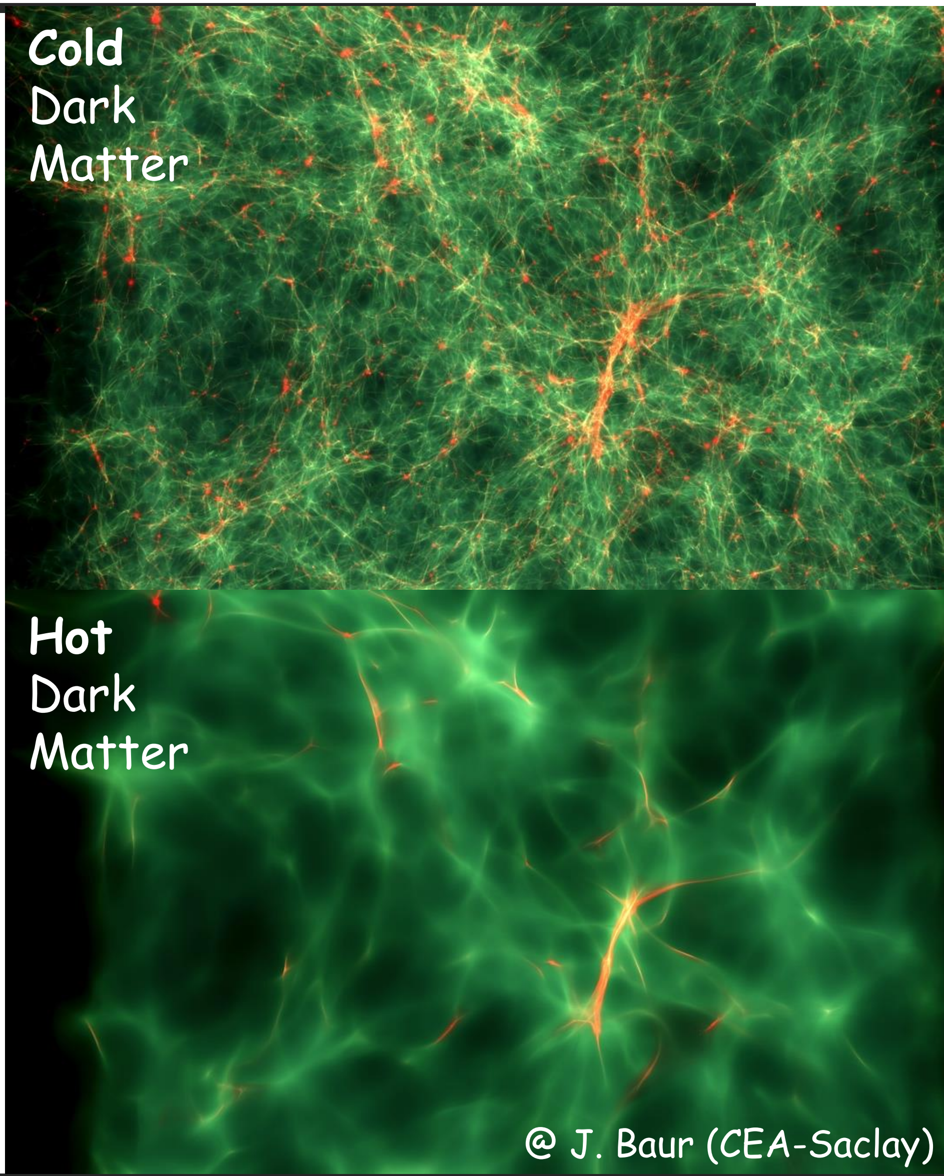


WDM impact

- Thermal relics from CMB
- Power cut-off on small-scale
- Lower mass = Higher impact → lower limit



Lyman-alpha

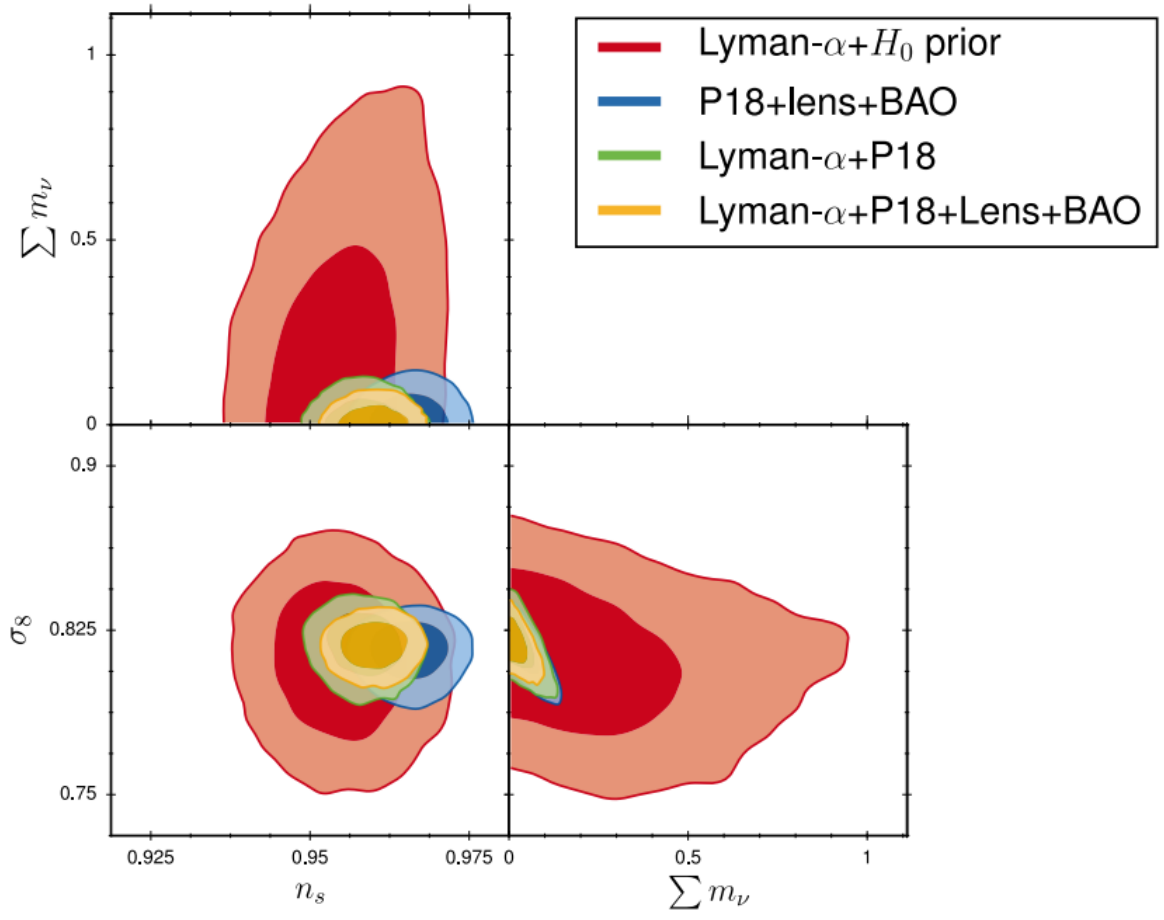


Neutrinos and WDM constraints

- Cosmological constraints using P1D computed on data and simulations (Palanque-Delabrouille et al. 2020)

- Loose constraint by Lyman-alpha only (Neutrinos simulated)
- Strong constraints combining with CMB data

- DESI: Emulated grid and higher data statistics will improve the precision of constraints



Neutrinos and WDM constraints

- Neutrino mass:

P1D	P1D + CMB	P1D + CMB + BAO + WL	
$\sum m_\nu < 0.58\ eV$	$\sum m_\nu < 0.11\ eV$	$\sum m_\nu < 0.09\ eV$	95 % CL

(Palanque-Delabrouille et al. 2020)

- WDM mass (eBOSS + XQ100):

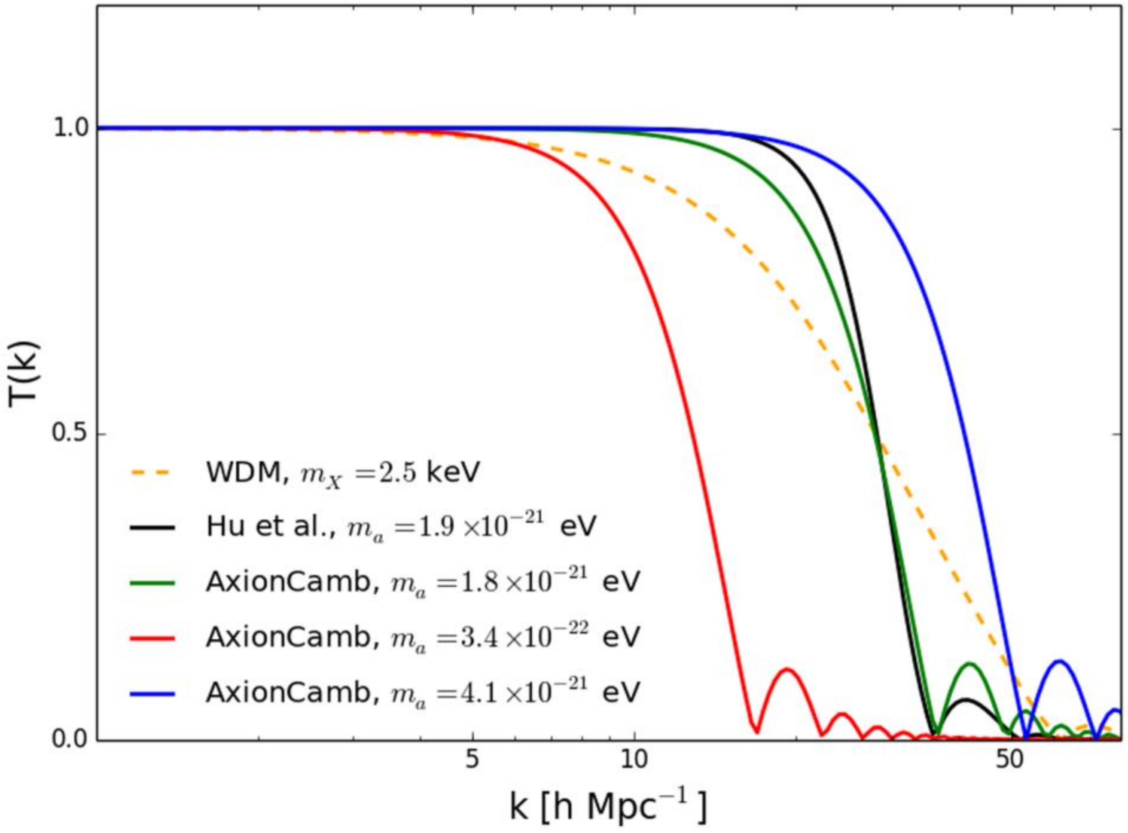
$m_X > 5.3\ keV$ 95 % CL

- Sterile neutrinos (Baur et al. 2016):
  - Equivalence relation with thermal relics mass (WDM)
  - P1D constraint: $m_s > 34\ keV$ (Non-resonantly produced)
  - X-ray signal at $m_s = 7\ keV$ → in strong tension

Fuzzy Dark Matter

- Fuzzy Dark Matter (Armengaud et al. 2017, Irsic et al. 2017):
  - De Broglie length close to structure formation and DM halo dynamics
    $$\frac{\lambda_{dB}}{2kpc} \sim \left(\frac{10^{-22}eV}{m}\right)\left(\frac{10\ km/s}{v}\right)$$
  - Smooth the density fluctuation by quantum wave effects
  - Constraint by P1D:

$$m_a > 2 - 3 \times 10^{-21}\ eV$$



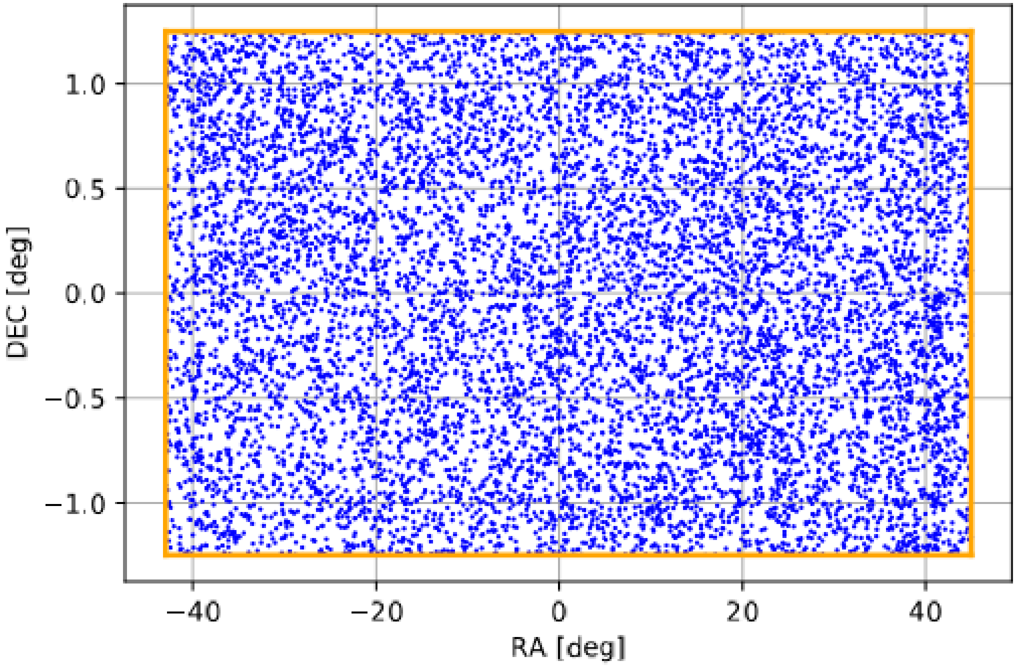
3D tomographic map

Lyman-alpha tomography

- Objective : Produce a high-redshift 3D map of matter distribution, large scales, large volume ($\sim Gpc^3.h^{-3}$).

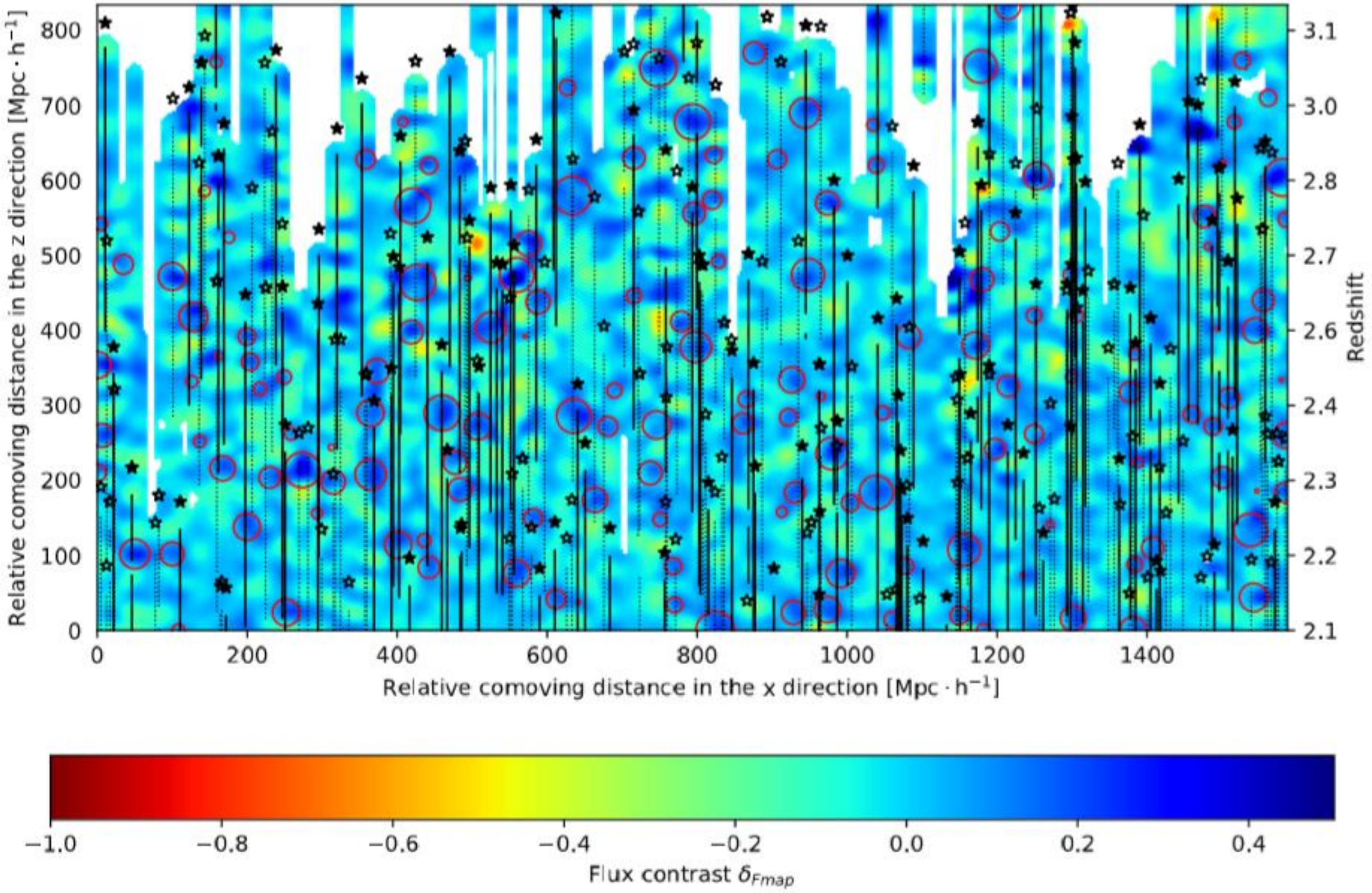
- Wiener filter is used ~ Noise-aware Gaussian interpolation of lines-of-sight (can be improved)

- Use of DR16-Stripe 82 homogeneous field ($37\ deg^{-2}, < d_\perp > = 13\ Mpc.h^{-1}$)

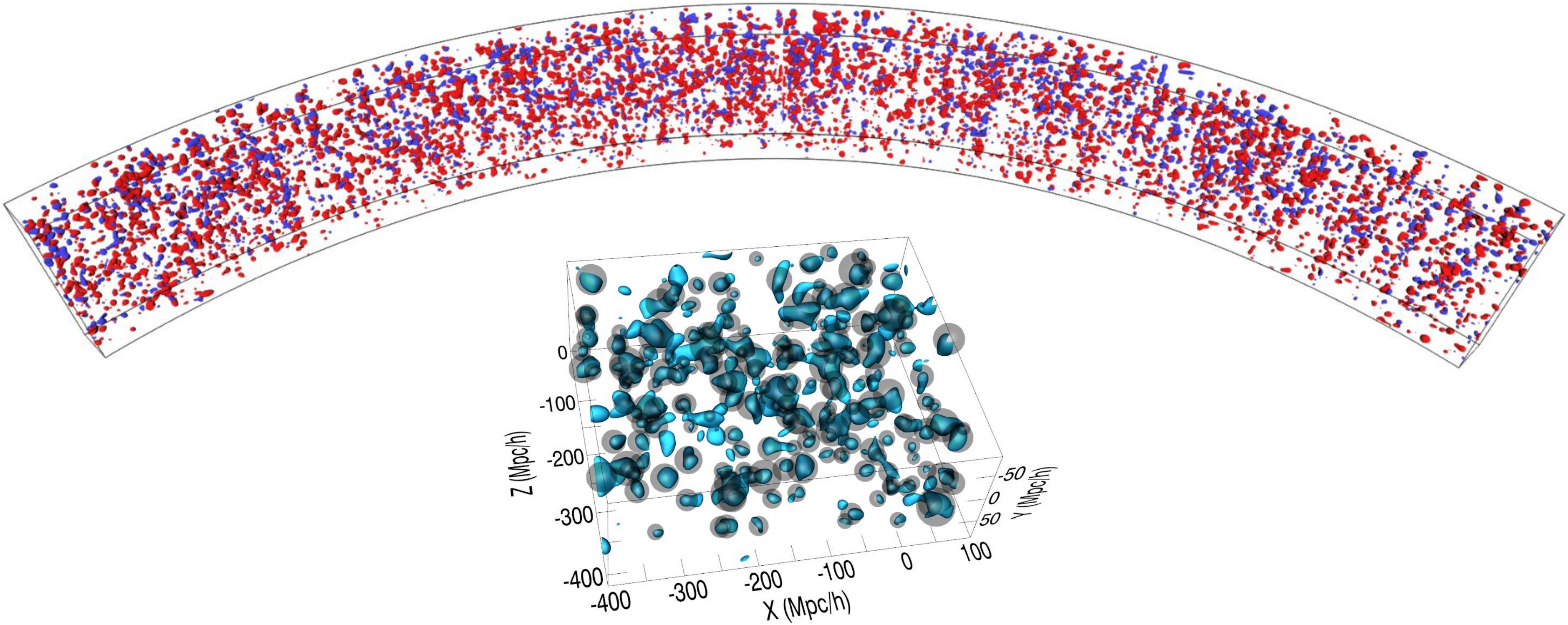


eBOSS Stripe82 results

- Results with a smoothing reconstruction length of 13 Mpc.h^{-1} (Ravoux et al. 2020)
- Spherical void finder over all Stripe
- Similar results obtained on mocks (synthetic data)
  - 34% correlation between map and underlying DM

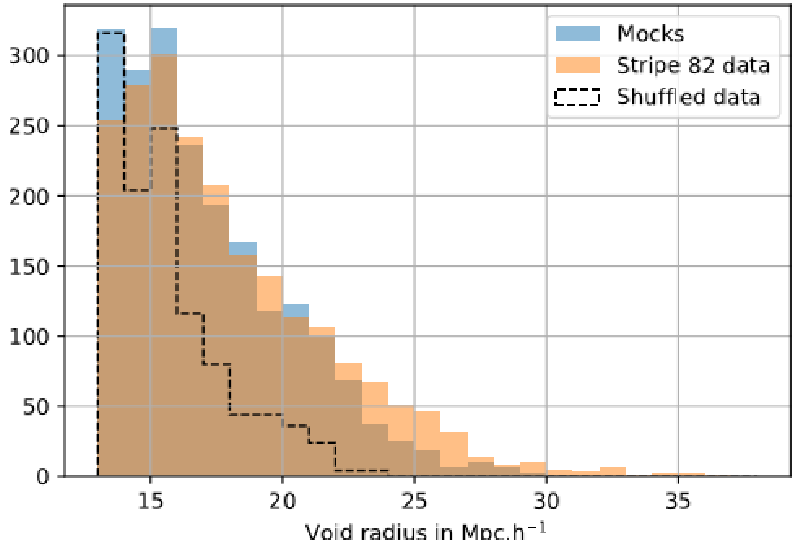


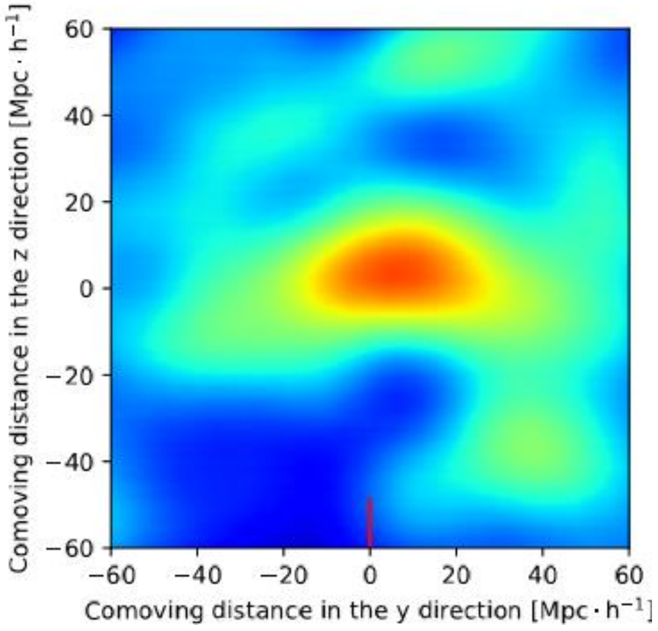
3D view



Applications

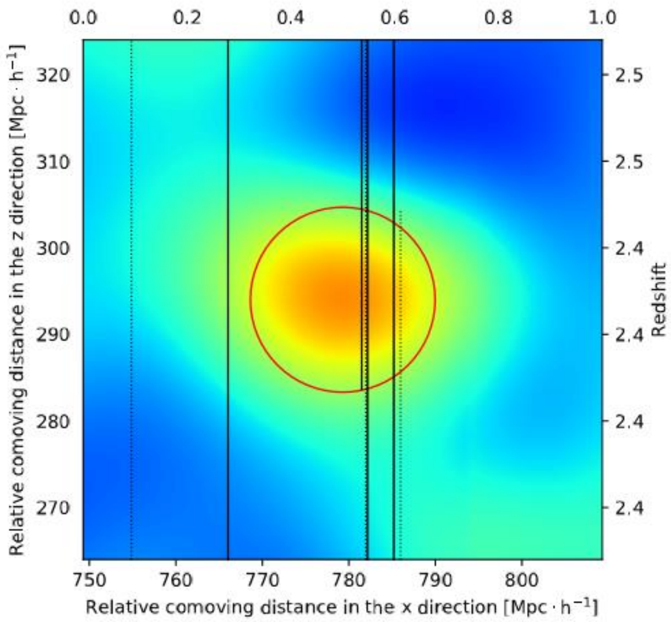
Void catalog at z > 2
(Large voids)





Tomographic map stacked over QSO position

Search for protoclusters



Conclusion

- Lyman-alpha forest = Unique tool for LSS at redshift z > 2
- Important constraints on cosmological parameters (BAO for distance measurement, P1D for small-scales properties)
- New potential applications (Tomographic maps)

Annexes

Annexe: FGPA model

$$\gamma + \mathrm{H_I} \leftrightarrow \mathrm{e^-} + \mathrm{p^+}$$

- photo-ionization equilibrium : $$n_\gamma n_{HI} \langle \sigma_{ioniz} c \rangle = n_p n_e \langle \sigma_{rec} v \rangle_T$$

$$n_{HI} = n_b^2 \frac{\langle \sigma_{rec} v \rangle_T}{n_\gamma \langle \sigma_{ioniz} c \rangle} \qquad \langle \sigma_{rec} v \rangle_T \propto T^{-0.7}$$

$$\rightarrow \qquad n_{HI} \propto \frac{(1+z)^6\, \Omega_b^2\, (1+\delta)^2\, T^{-0.7}}{\text{ionizing photon flux}}$$

with $T = \bar{T}(z)(1+\delta)^{\gamma(z)-1}$ and $\gamma(z \sim 3) \sim 1.6$

$$\tau(z) \propto \Omega_{\mathrm{B}}^2 \frac{(1+z)^6\, \bar{T}(z)^{-0.7}}{H(z) J_\gamma(z)} \frac{(1+\delta(z))^\beta}{(1+\eta(z))^1} \qquad \eta \equiv \frac{v_p'(z)}{H(z)}$$

$$\beta = 2 - 0.7(\gamma(z) - 1) \sim 1.6$$

Annexe: Other dark matter models

- DM models which affects the initial transfer function of the simulation

- Resonantly produced sterile neutrinos (Baur et al. 2016):
  - Modeled as a mix of CDM and WDM
  - Constraints with P1D

- Not possible when the simulation code needs modification (interacting DM, anihilation proceses...)