One-dimensional power spectrum from first DESI Lyman-α forest samples

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Colloque Action Dark Energy
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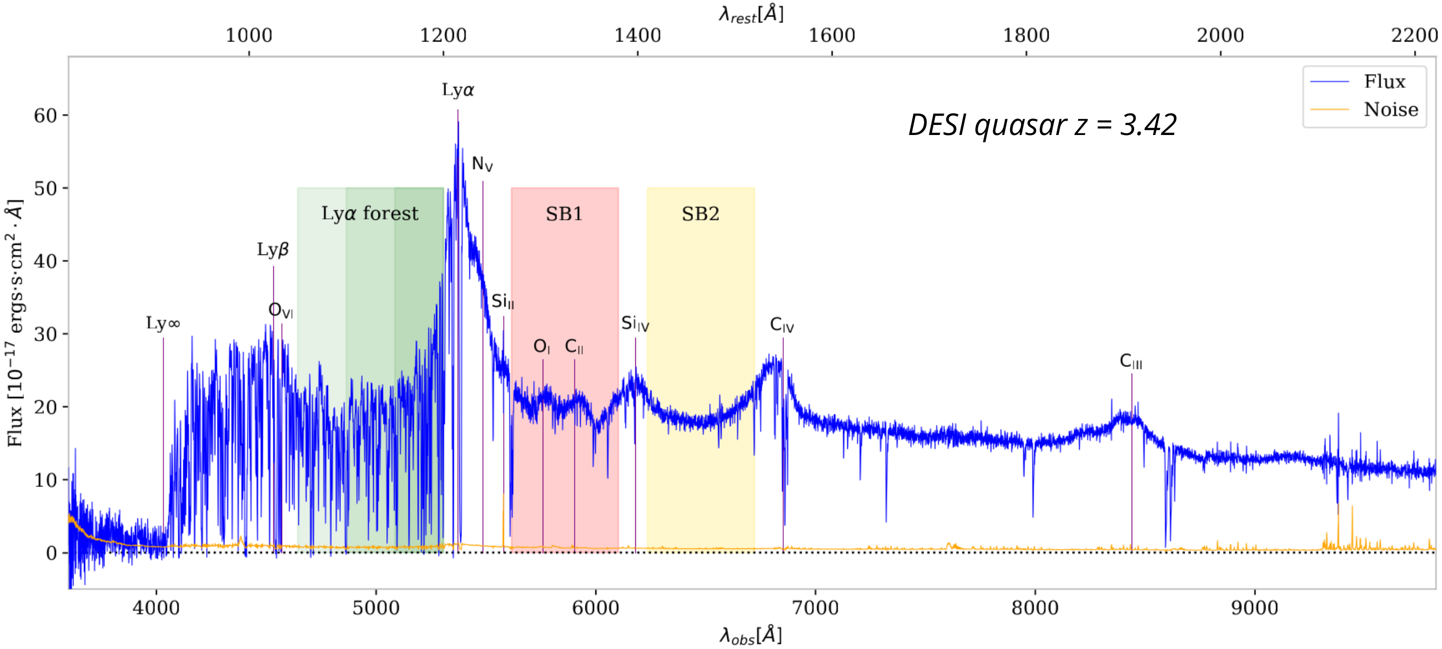
The Lyman-α forest

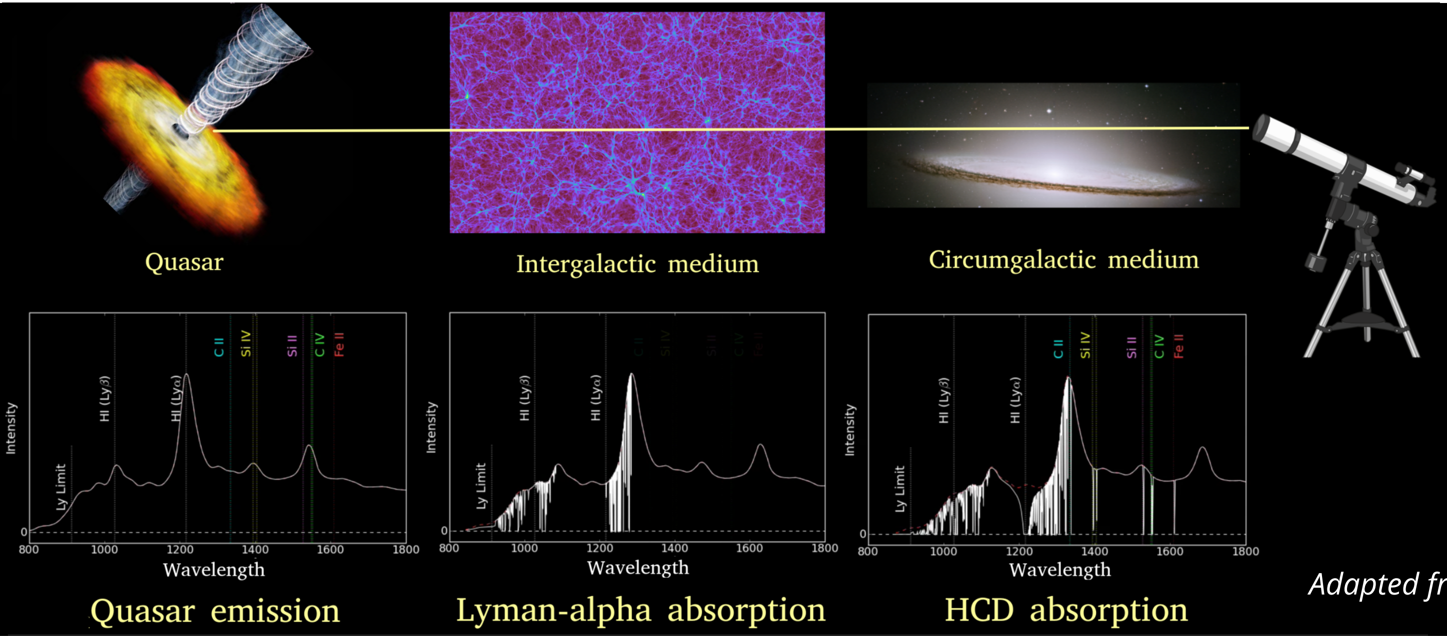
- Lyman-α = transition of neutral Hydrogen to first excited state
- Lines in quasar spectra at $\lambda_{\rm obs} = (1 + z_{\rm abs})\lambda_\alpha$ caused by absorbers in the intergalactic medium (IGM) at $z_{\rm abs}$



Lyman-α forest = non-linear tracer of neutral hydrogen in the IGM

Contaminants

- Near the quasar:
  - Intrinsic continuum
  - Broad absorption line quasars (BAL)
- Along the line-of-sight:
  - Metal absorptions in the IGM
  - Damped Lyman-α systems (DLA)
- Near the telescope:
  - Atmospheric absorption and emission
  - Instrument noise
  - Spectrograph resolution



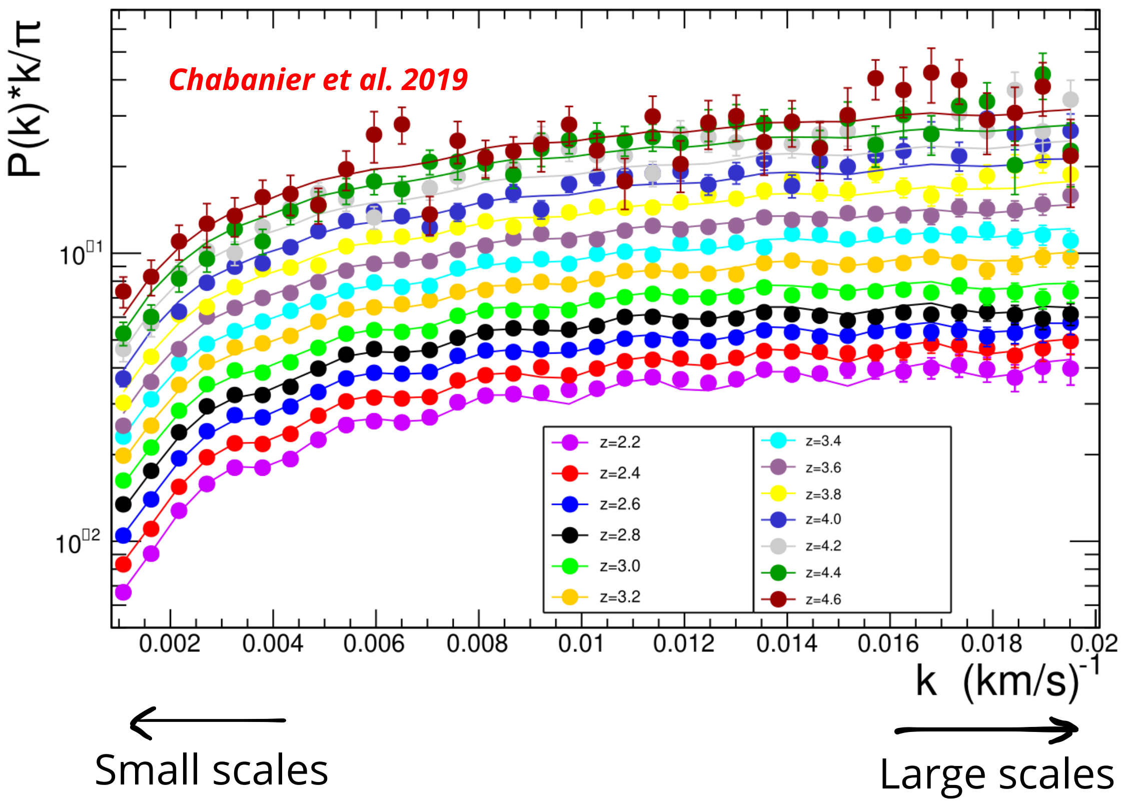
Adapted from A. Pontzen video

One dimensional power spectrum

- One dimensional power spectrum (P1D) measures correlations along individual lines-of-sight
- Sensitive to small-scale matter clustering and IGM thermal state
- **Can probe the small-scale matter power spectrum**

$$\Omega_{\rm m}, \sigma_8, n_{\rm s}$$

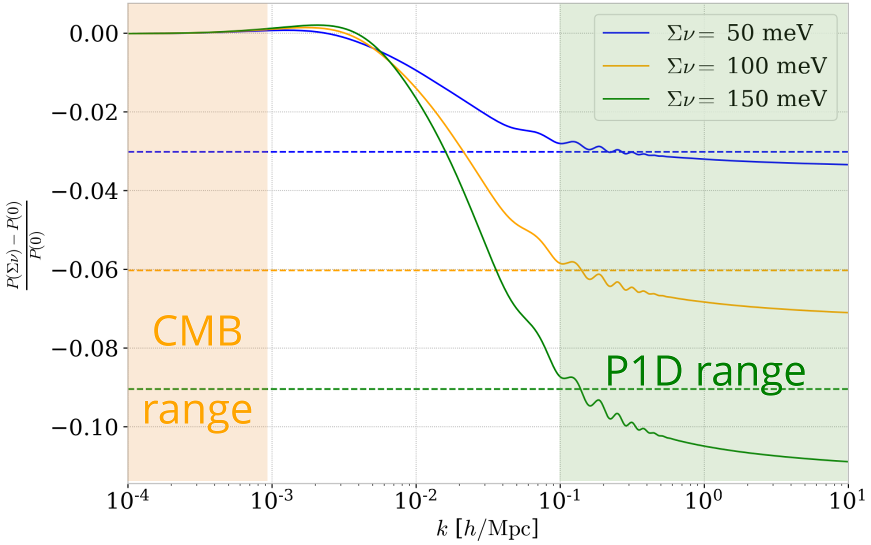
Latest eBOSS measurement

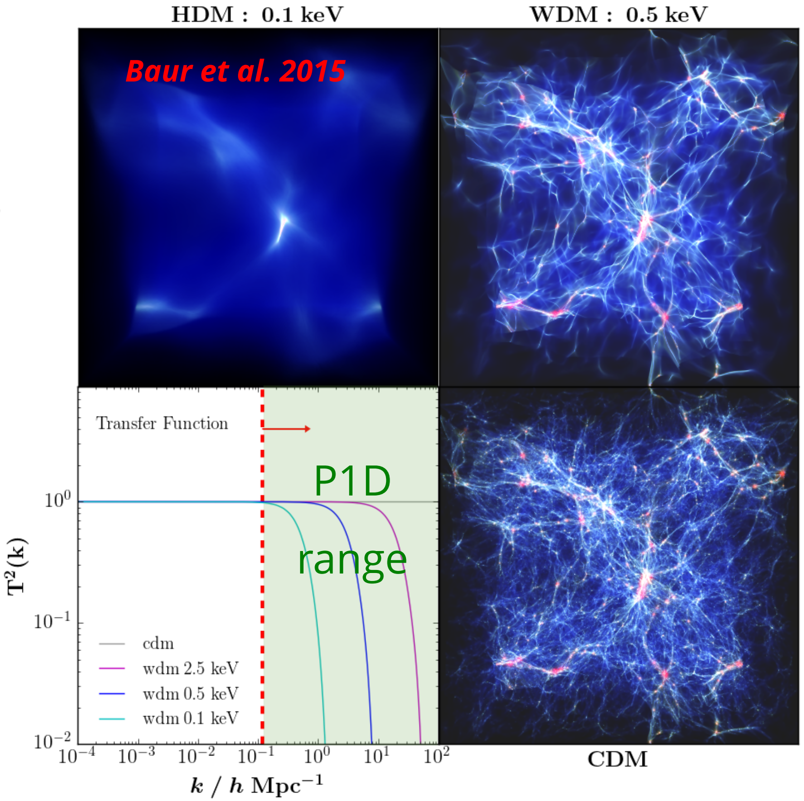


Neutrino masses and dark matter models

- Matter power spectrum impacted by:
  - Sum of neutrino masses $\sum m_\nu$
  - Dark matter model (e.g. warm dark matter)

P1D unique probe to constrain neutrino masses and dark matter properties





Latests cosmological constraints: eBOSS

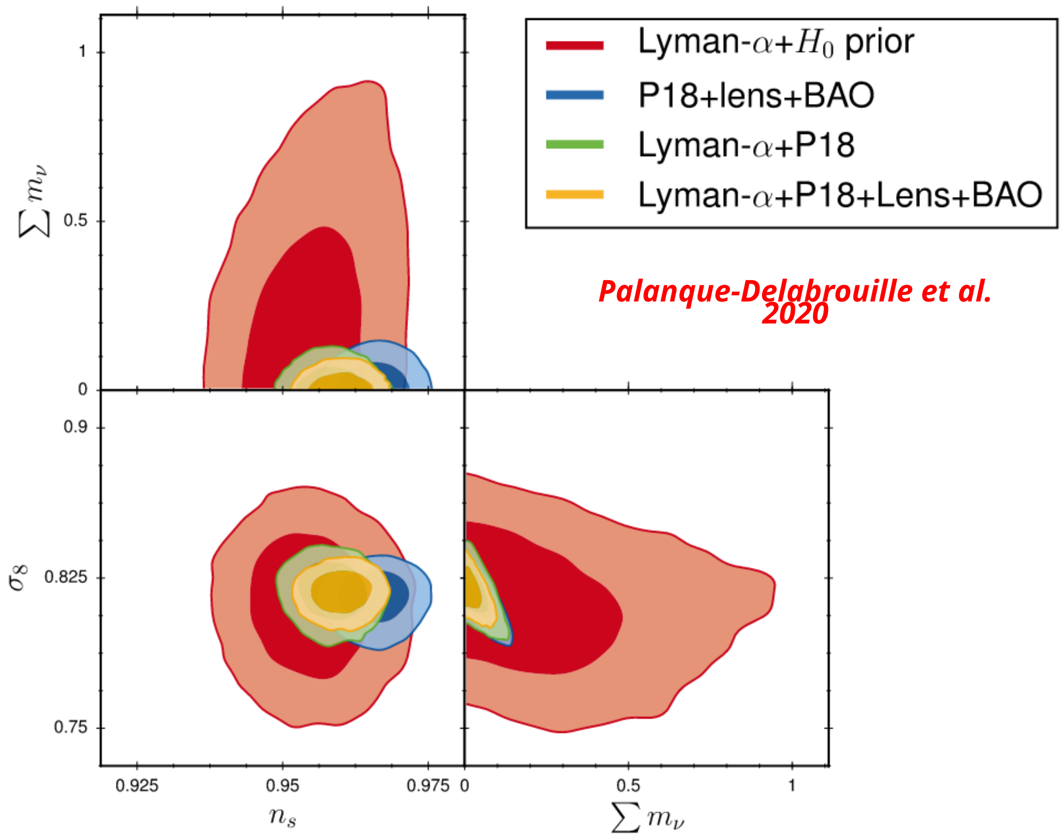
- Neutrino mass (P1D +CMB):

$$\sum m_\nu < 0.11\ \mathrm{eV}$$ at 95% C.L.

- Warm dark matter model (P1D + High resolution):

$$m_\mathrm{X} > 5.3\ \mathrm{keV}$$ at 95% C.L.

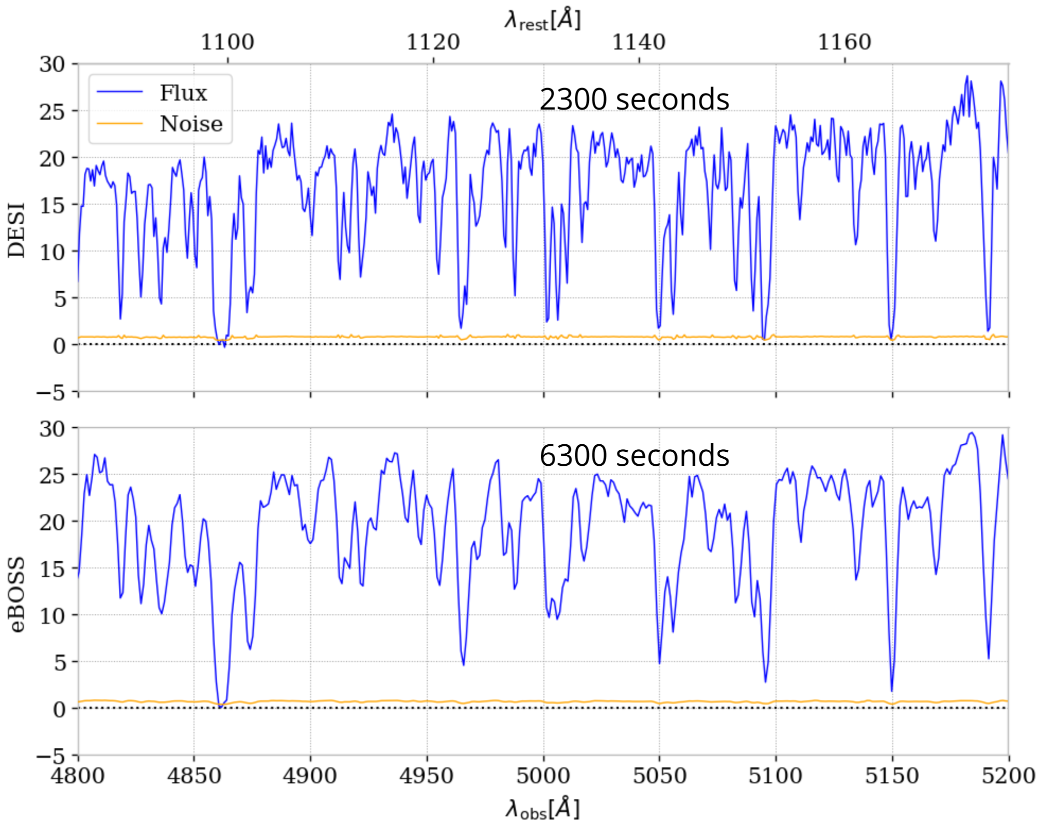
- Other constraints: Fuzzy dark matter, sterile neutrinos, running of the primordial power spectrum



Palanque-Delabrouille et al. 2020

Dark Energy Spectroscopic Instrument

- DESI:
  - Automated targeting, 5000 spectra per observation, improved resolution compared to eBOSS (R ~ 3000 - 5000)
- Survey validation:
  - Early 2021
  - ~ 30,000 Lyman-α forests
- Main survey:
  - Started in May 2021
  - Nearly 1 million Lyman-α forests



P1D model and corrections

- P1D measured using Fast Fourrier Transform estimator

$$P_{1\mathrm{D},\alpha}(k) = \left\langle P_{\mathrm{raw}}(k) \right\rangle$$

Without correction, Fourrier transform in the Lyman-α region

P1D model and corrections

- P1D measured using Fast Fourrier Transform estimator

Correction of the DESI pipeline noise estimation

Spectroscopic resolution correction adapted to DESI pipeline

$$P_{1\mathrm{D},\alpha}(k) = \left\langle \left[P_{\mathrm{raw}}(k) - P_{\mathrm{pipeline}}(k) - \alpha\right] \cdot R^{-2}(k) \cdot \mathrm{sinc}^2\left(\frac{k\Delta\lambda_{\mathrm{pix}}}{2}\right) \right\rangle$$

P1D model and corrections

- P1D measured using Fast Fourrier Transform estimator

Correction of the DESI pipeline noise estimation

Spectroscopic resolution correction adapted to DESI pipeline

Measurement of absorption from other IGM elements

$$P_{1\mathrm{D},\alpha}(k) = \left(\left\langle \left[P_{\mathrm{raw}}(k) - P_{\mathrm{pipeline}}(k) - \alpha \right] \cdot R^{-2}(k) \cdot \mathrm{sinc}^2 \left(\frac{k \Delta \lambda_{\mathrm{pix}}}{2} \right) \right\rangle - P_{\mathrm{SB1,m}}(k) \right)$$

P1D model and corrections

- P1D measured using Fast Fourrier Transform estimator

$$P_{1D,\alpha}(k) = \left(\left\langle \left[P_{raw}(k) - P_{pipeline}(k) - \alpha \right] \cdot R^{-2}(k) \cdot \mathrm{sinc}^2\left(\frac{k\Delta\lambda_{pix}}{2} \right) \right\rangle - P_{SB1,m}(k) \right)$$

$$\cdot A_{line}(z,k) \cdot A_{hcd}(z,k) \cdot A_{cf}(z,k)$$

Correction of the DESI pipeline noise estimation ($P_{pipeline}(k) - \alpha$)

Spectroscopic resolution correction adapted to DESI pipeline ($R^{-2}(k) \cdot \mathrm{sinc}^2\left(\frac{k\Delta\lambda_{pix}}{2} \right)$)

Measurement of absorption from other IGM elements ($P_{SB1,m}(k)$)

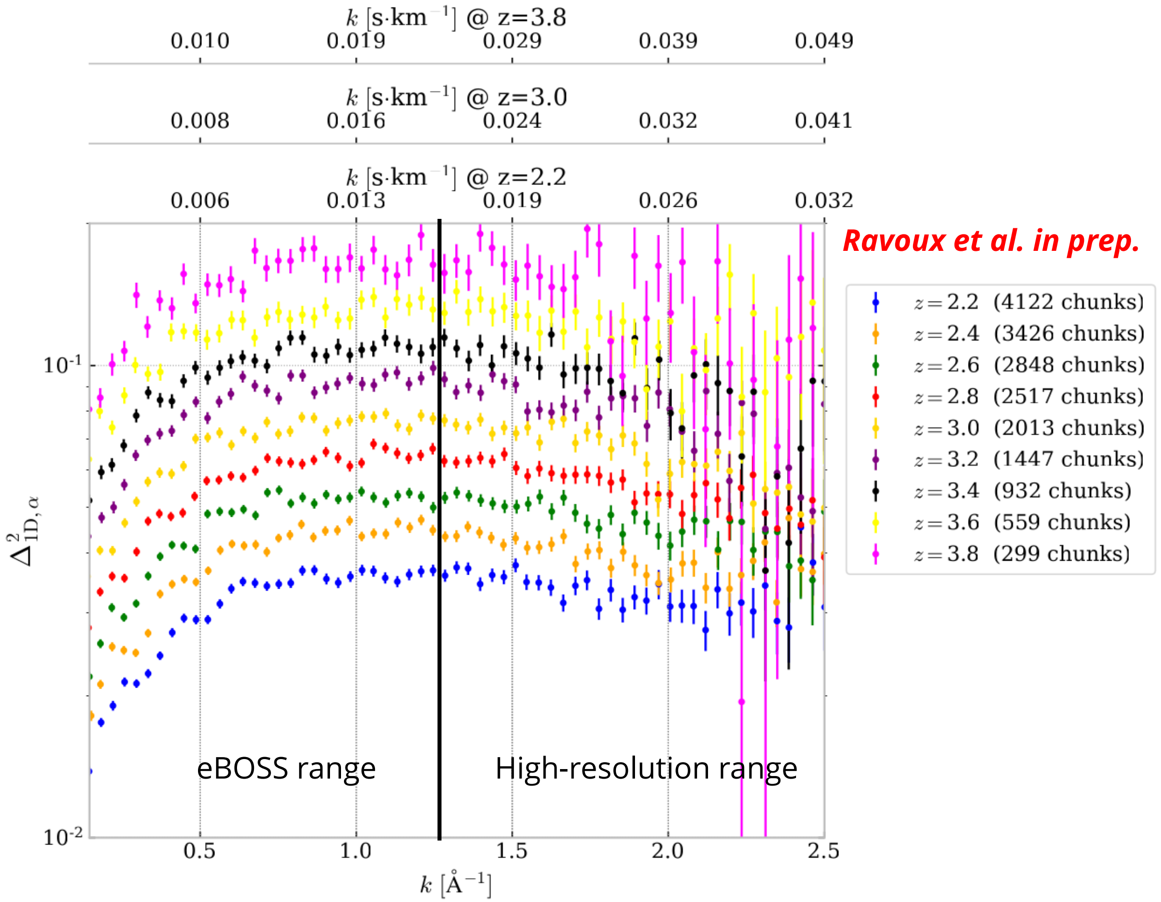
Masking of atmospheric lines ($A_{line}(z,k)$)

Masking of Damped Lyman-α systems ($A_{hcd}(z,k)$)

Correction of continuum fitting error ($A_{cf}(z,k)$)

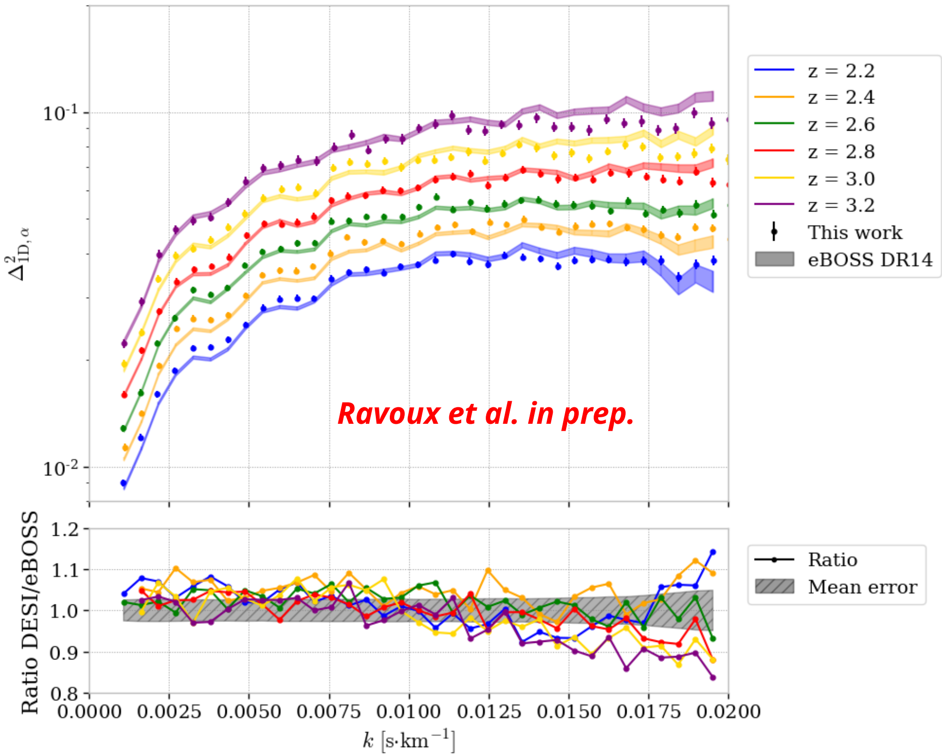
P1D measurement

- Data set: Survey validation + first two months of DESI
- ~7000 Lyman-α forests (SNR quality cut)
- Systematics and statistical error bars
- Other estimation of P1D with quadratic estimator in parallel (*Karacayli et al. in prep*)

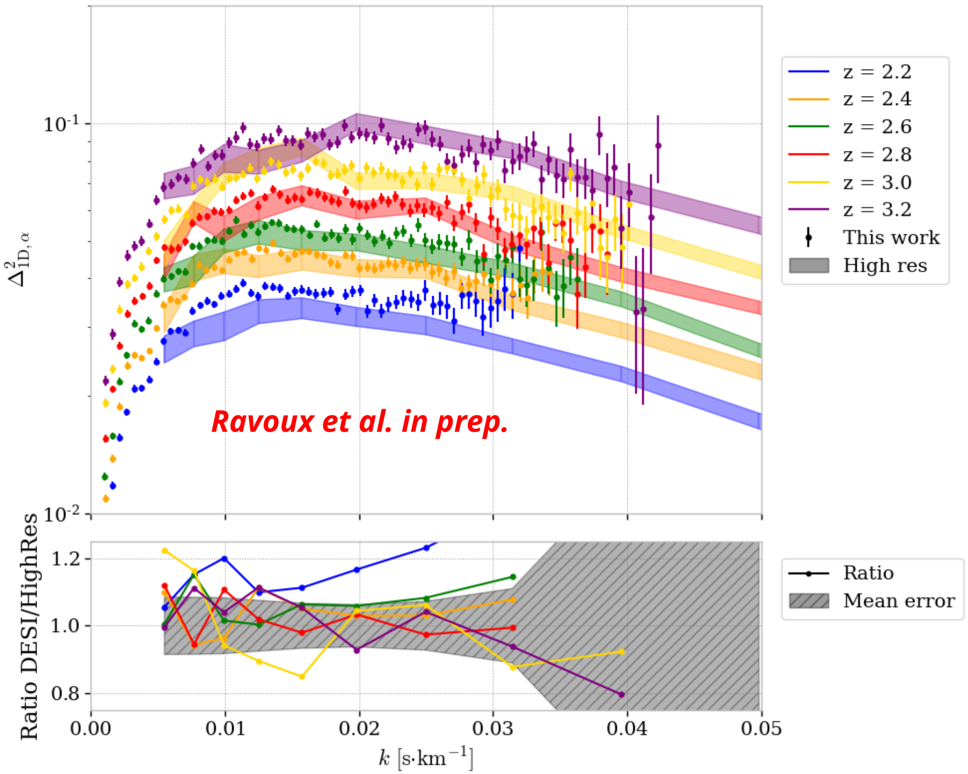


Comparison with previous measurements

eBOSS DR14 measurement ***Chabanier et al. 2019***



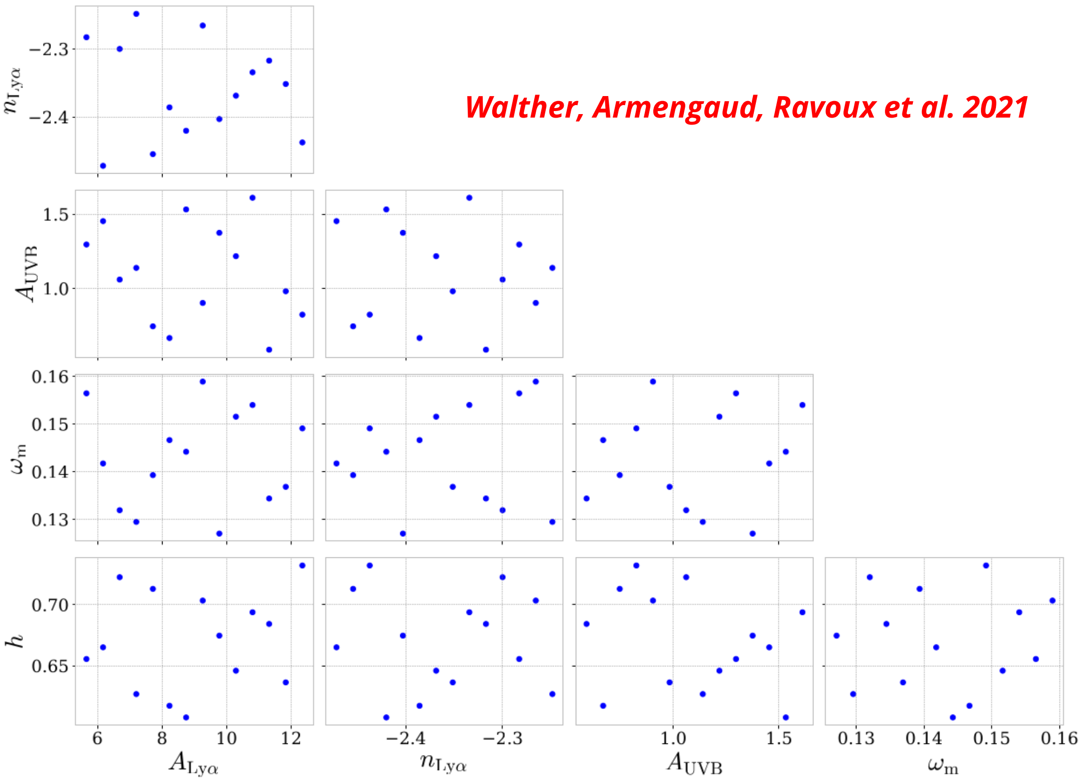
High resolution measurement ***Karacayli et al. 2022***



Relatively good agreement in the respective wavenumber ranges

Emulator for cosmological interpretation

- Interpretation of P1D measurement with simulation:
  - High-resolution hydrodynamical simulations 4096^3 / 120 Mpc (2M CPU hours) with Nyx
- Gaussian processes emulator:
  - Covers cosmological parameter space
  - Reduce number of simulations



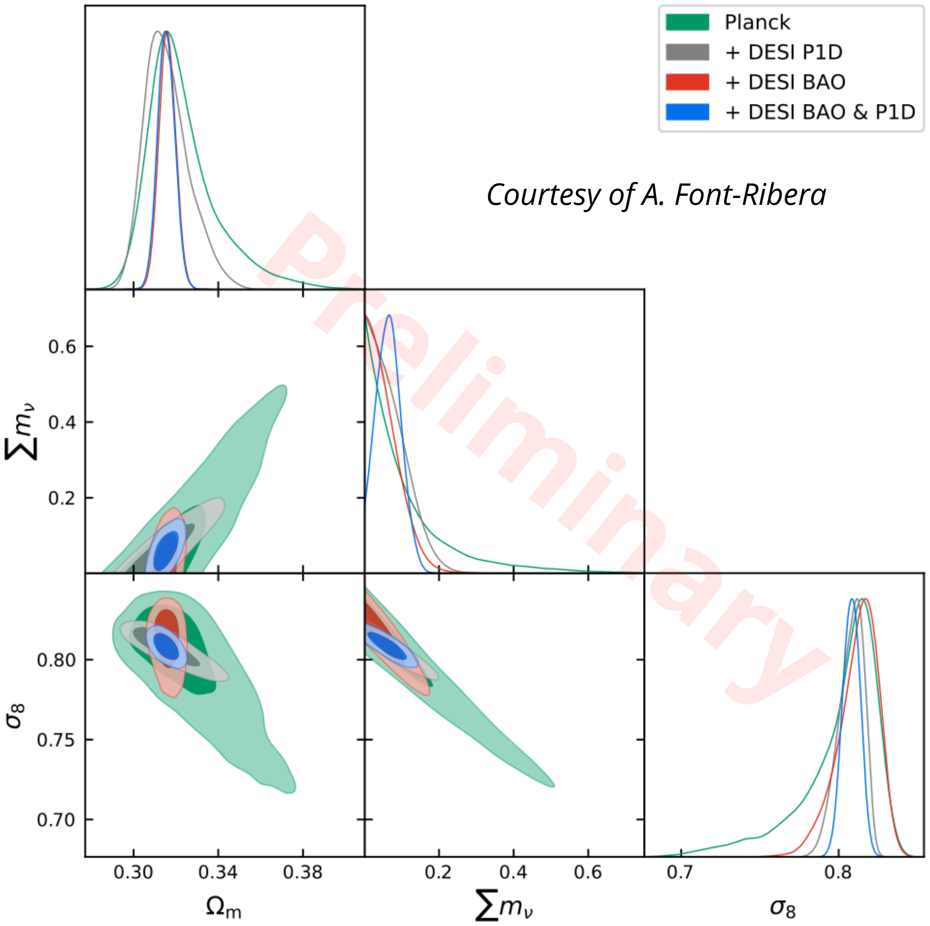
Walther, Armengaud, Ravoux et al. 2021

Forecast: full DESI survey

- Constraints on WDM improved by a factor 1.6 ***Valluri et al. 2022***
- IGM thermal parameters: factor 2.6
- Neutrino mass: in association with BAO and CMB, we expect a precise measurement

$$\sigma\left(\sum m_\nu\right) = 0.02\,\mathrm{eV}$$

DESI collaboration 2016



Courtesy of A. Font-Ribera

Conclusion

- First P1D measurement on DESI data soon available
- This measurement probes smaller scales than eBOSS
- Promising perspective for DESI cosmological constraints

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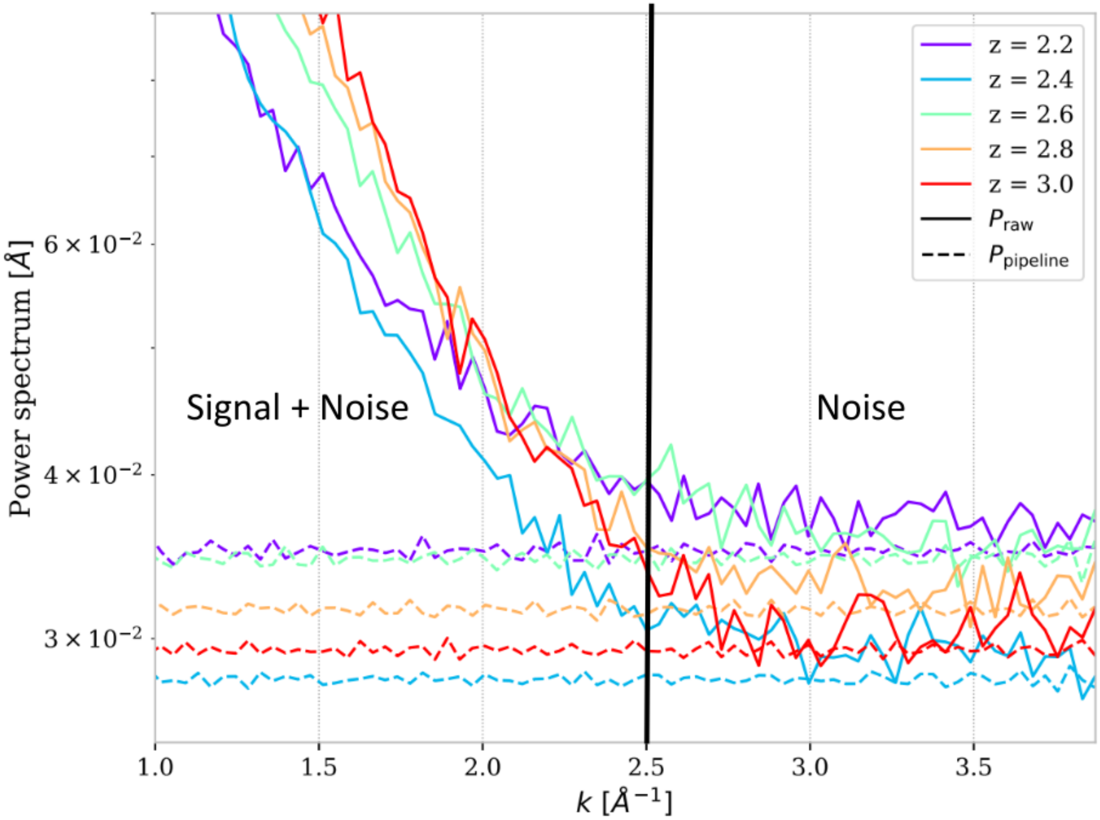
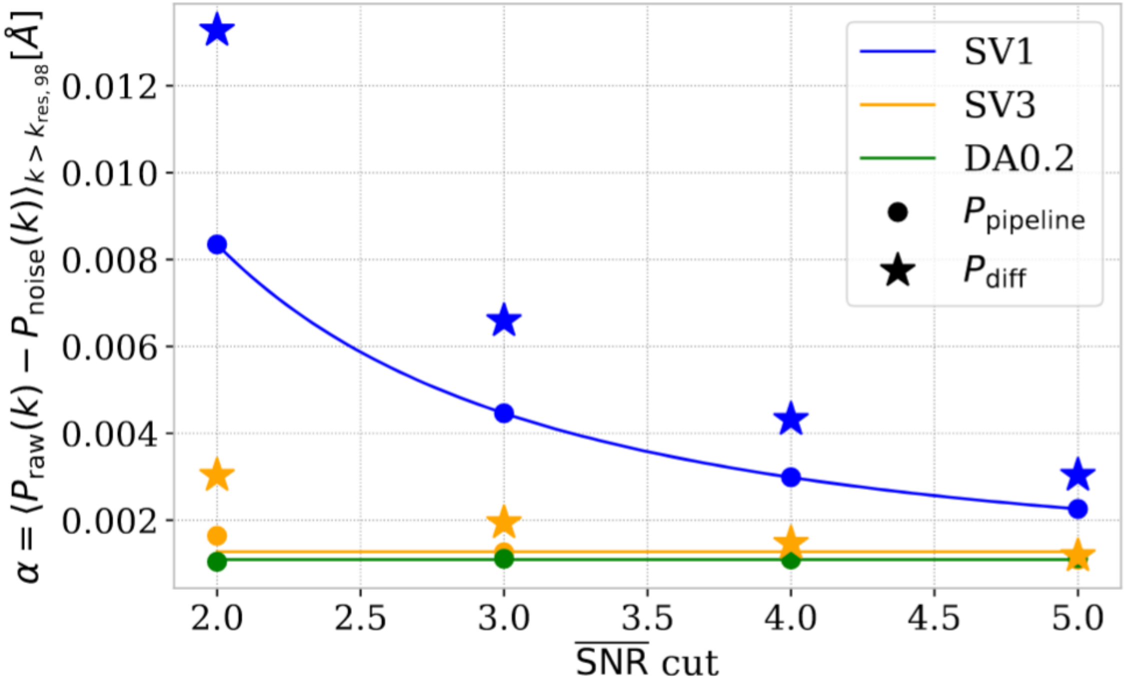
Noise estimation

- Noise computed within DESI spectroscopic pipeline
- Alternative noise estimation:
  - Resolution suppresses physical signal at small scales
  - Use asymptotic value of raw power spectrum
- Comparison with pipeline:
  - Done with successive data reductions
  - Helped to improve noise model in pipeline



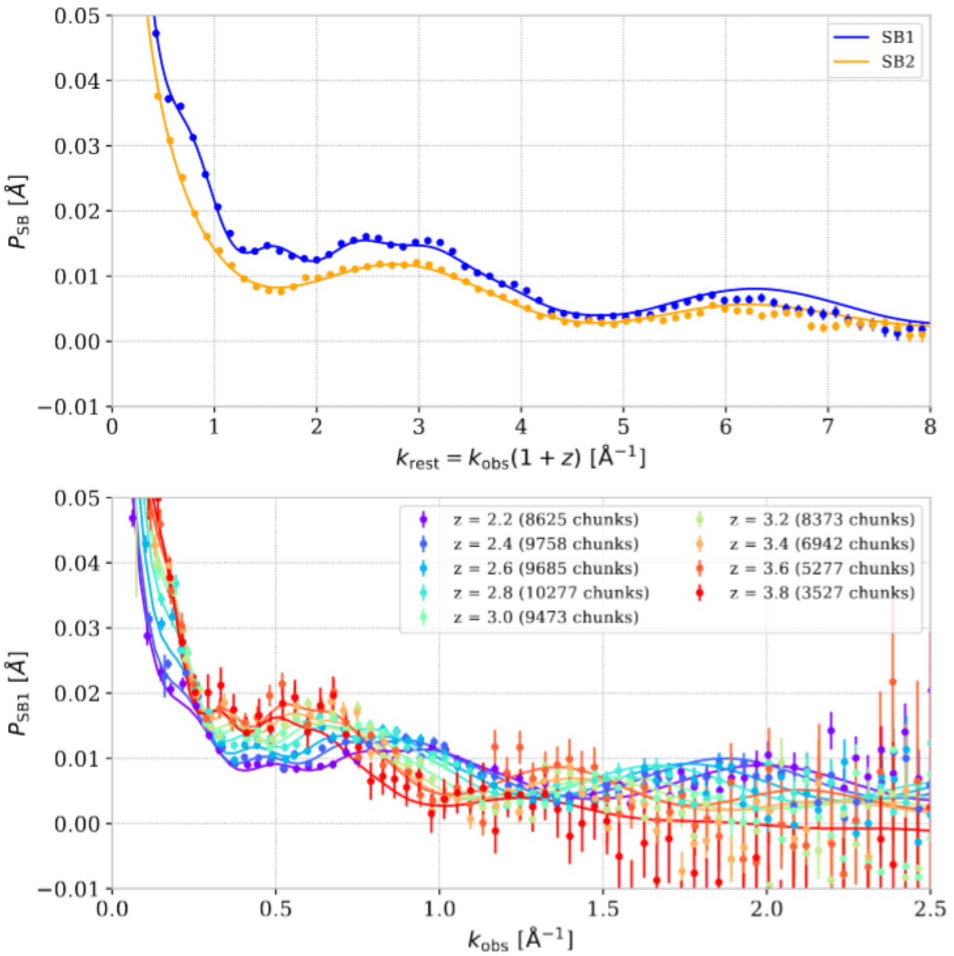
Noise correction

- For P1D measurement, use pipeline noise with additive correction.
- Different corrections for three DESI data sets with specific observation strategies (SV1, SV3, DA0.2)



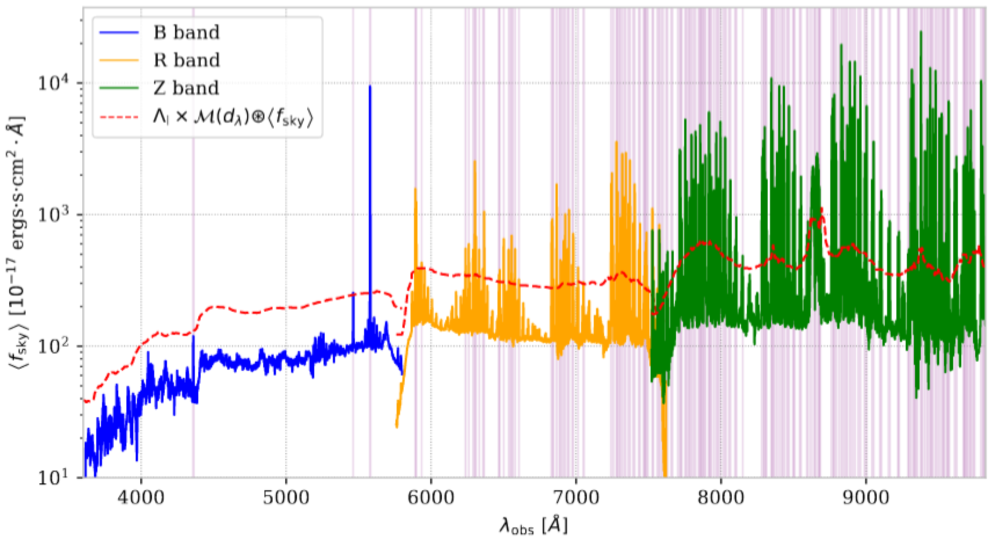
Metal power spectrum estimation

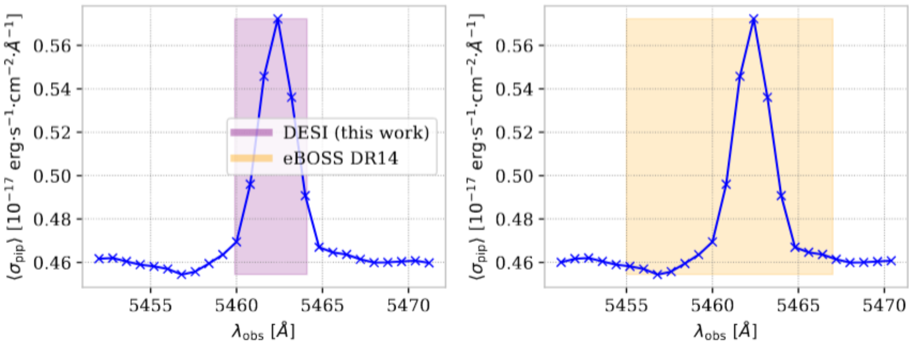
- Contribution from metal absorptions statistically computed using side bands
- Oscillations in side band power spectrum: CIV and SiIV doublets
- Physically motivated model to closely reproduce side band power spectrum
- Model subtracted to P1D measurement



Atmospheric emission lines

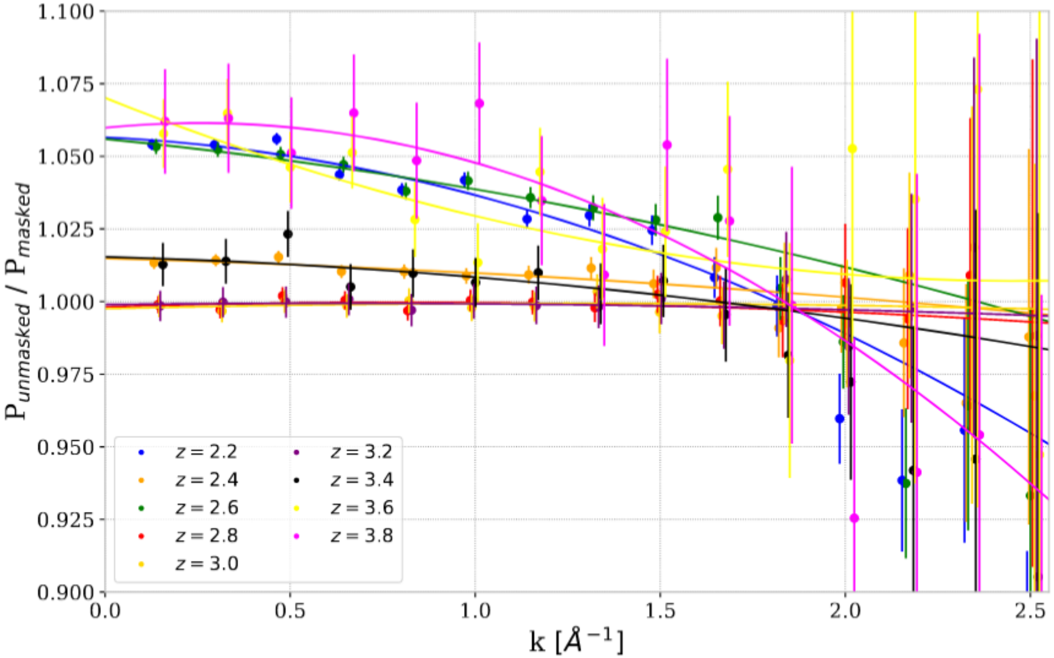
- Lines from atmosphere removed by pipeline but increase noise and impact P1D
- Build a new atmospheric line mask using DESI sky fibers
- Automated algorithm based on sky flux level
- Reduced masked length compared to eBOSS





Corrections with mocks

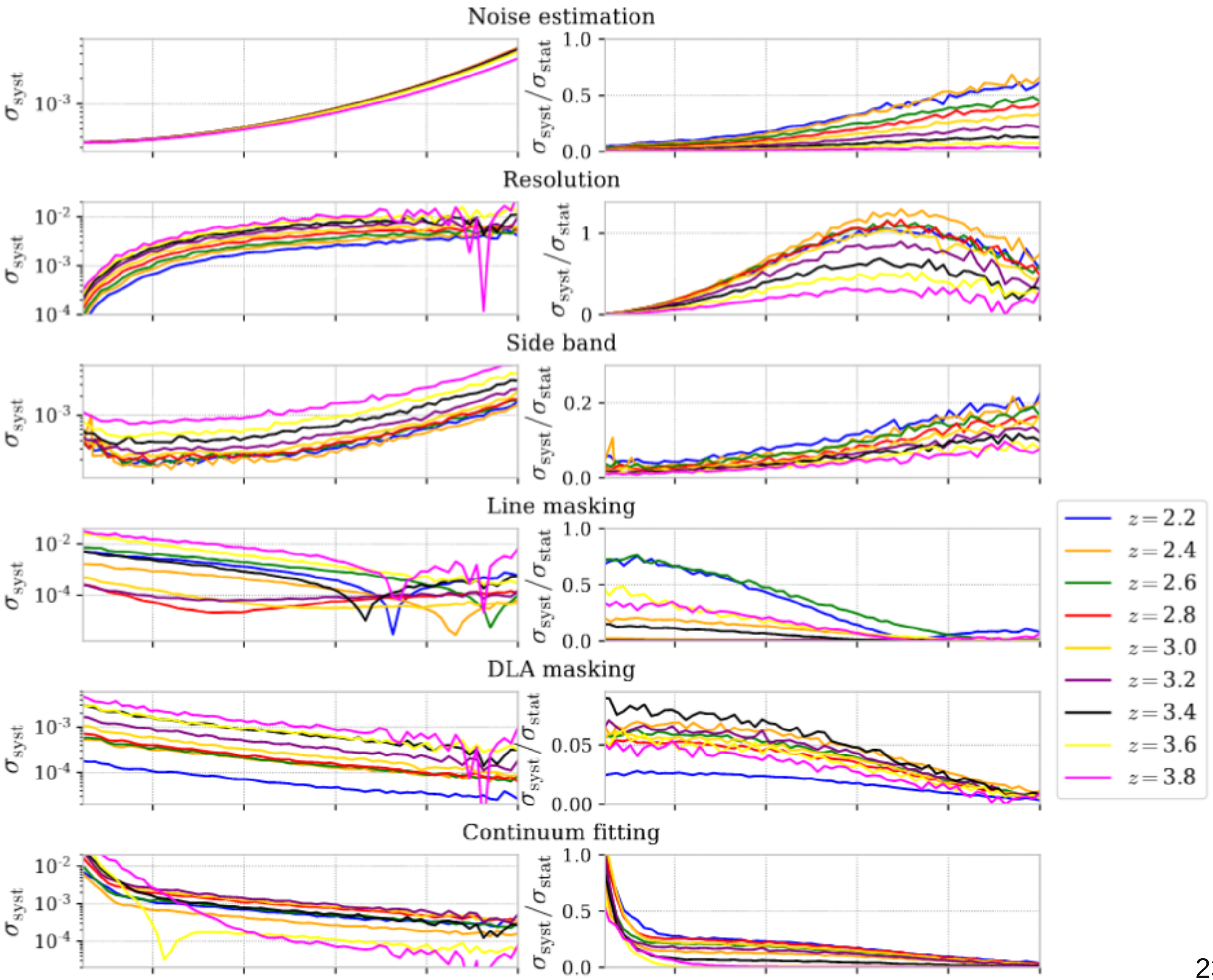
- Characterization of effects from
  - Masking atmospheric lines
  - Masking DLAs
  - Continuum fitting method
- Mocks with uncorrelated lines-of-sight and well-defined P1D (Ohio mocks)
  - Compare "truth" to measured P1D
- Correction applied on the P1D data measurement



Correction of atmospheric lines masking

Systematic and statistical uncertainties

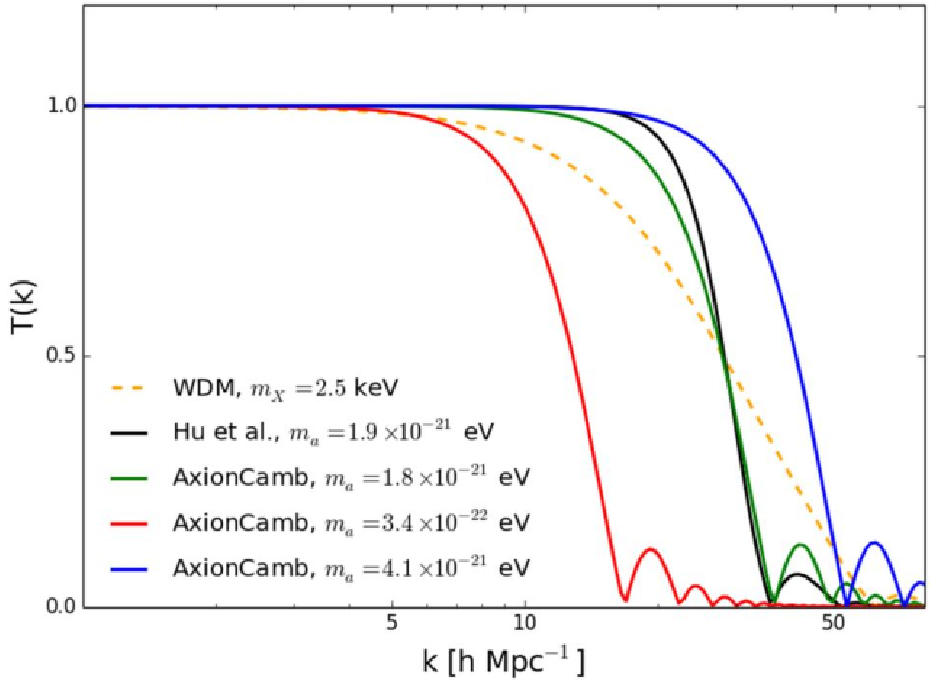
- Statistical uncertainties from FFT mode counting
- First estimation of systematic uncertainties similarly to eBOSS measurement:
  - Lower statistics with respect to eBOSS
  - Relatively good systematics/statistics ratio



Fuzzy dark matter

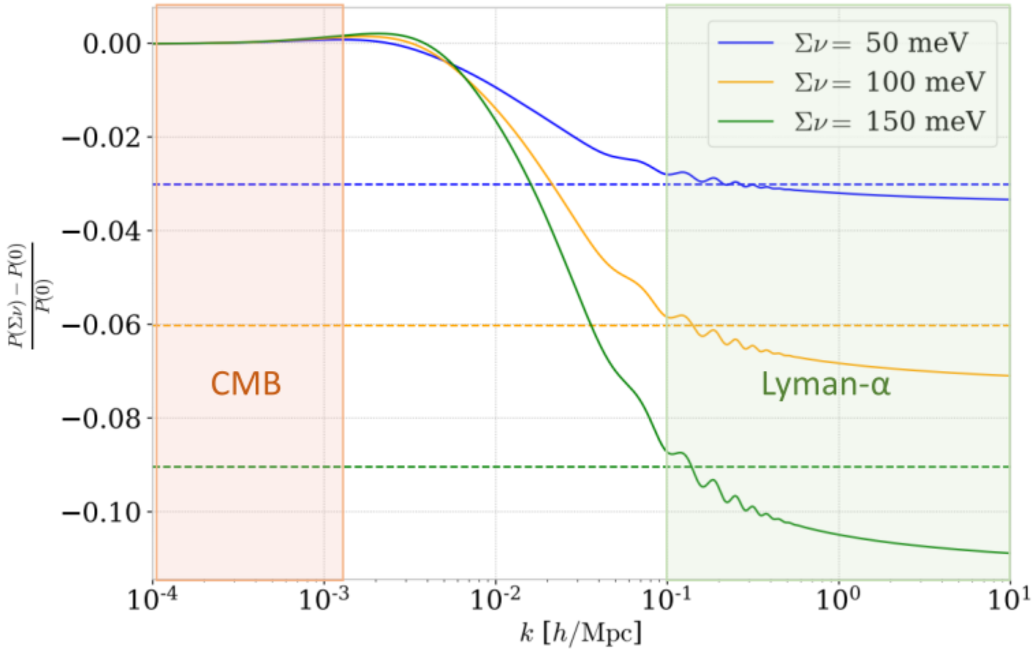
- Fuzzy Dark Matter (Armengaud et al. 2017, Irsic et al. 2017):
    - De Broglie length close to structure formation and DM halo dynamics
    - Smooth the density fluctuation by quantum wave effects
- Constraint by P1D:

$$m_\mathrm{a} > 2 \times 10^{-21}\ \mathrm{eV}$$



P1D simulations for eBOSS

- For BOSS/eBOSS:
  Taylor expanded grid



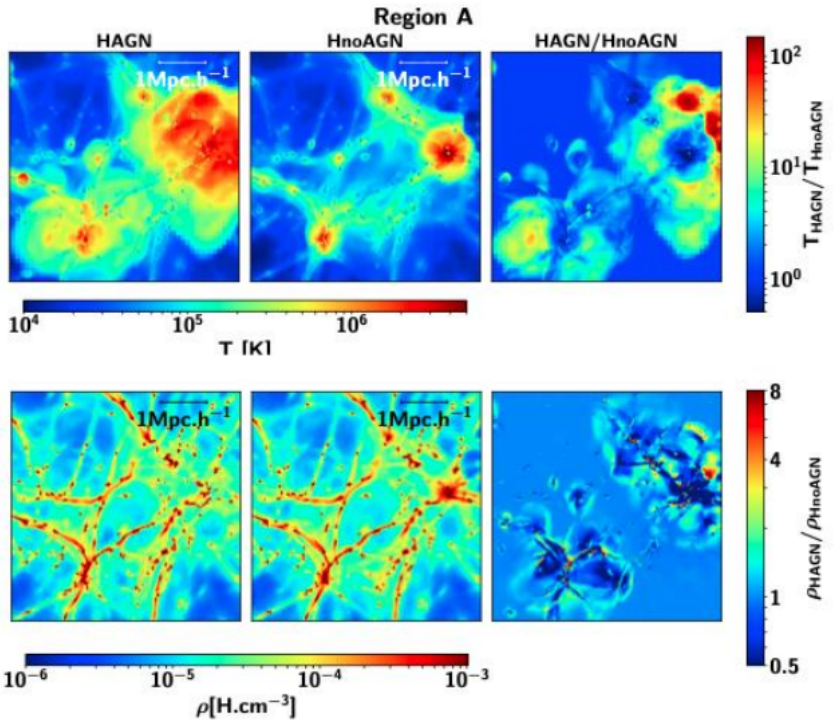
	parameter	*central*	*range*
Cosmology	keV / m_X	0.0	+0.2 +0.4
	$\Sigma m_\nu / eV$	0.0	+0.4 +0.8
	h	0.675	±0.05
	Ω_M	0.31	±0.05
	σ_8	0.83	±0.05
	n_s	0.96	±0.05
	$dn_s / d\ln k$	0.00	±0.04
	z_{reio}	12	±4
	N_{eff}	3.046	±1
Intergalactic Medium	$T_0^{z=3} / K$	14,000	±7,000
	$\gamma^{z=3}$	1.3	±0.3
Optical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

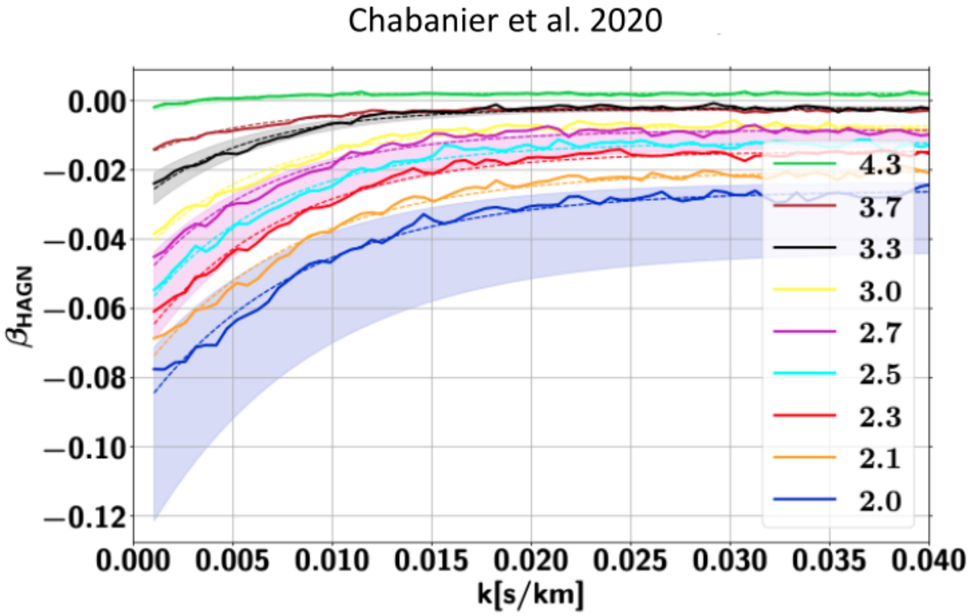
Nyx sub-grid physics

- Nyx = Hydrodynamical code on grid + Dark matter particles on PM scheme
  - Lyman-α forest not very sensitive to very dense IGM regions
  - AMR is not adapted
- Other physical processes modeled in Nyx:
  - Gas chemistry = fixed composition with H and He abundance
  - Inverse Compton + atomic collisional processes
- Effects not included:
  - Thermal feedback from AGN or supernovae
  - Inhomogeneous radiative background (UV)
- High redshifts: full reionization history (assumed homogeneous)
- **Choice**: No explicit simulation of these effects but taken into account as a nuisance at the fitting stage
- **Example**: AGN effect on P1D accounted for (Chabanier et al. 2020, Horizon-AGN simulation)
- More modeling effort needed to take into account other effects.

AGN feedback

- Physical effect = baryons and temperature redistribution in the IGM
- P1D correction, using different feedback parameters with HorizonAGN simulations





DESI forecasts

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\mathrm{max}} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\mathrm{max}} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\mathrm{max}} = 0.2$)	0.020	0.062