Detection of Baryon Acoustic Oscillations using Lyman-α Forests in eBOSS/DESI

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Outline

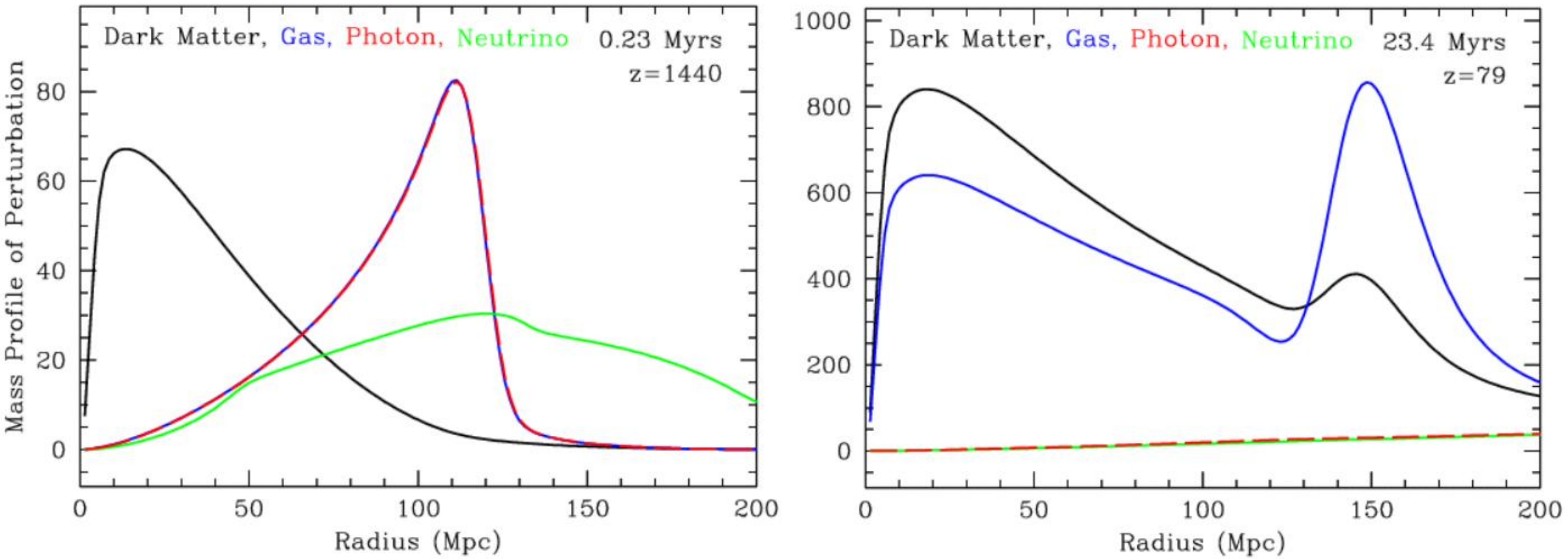
1. Introduction to BAO/Lyman-α forests

2. Modeling of HCDs

3. Summary

1. Introduction to BAO/Ly-α forests

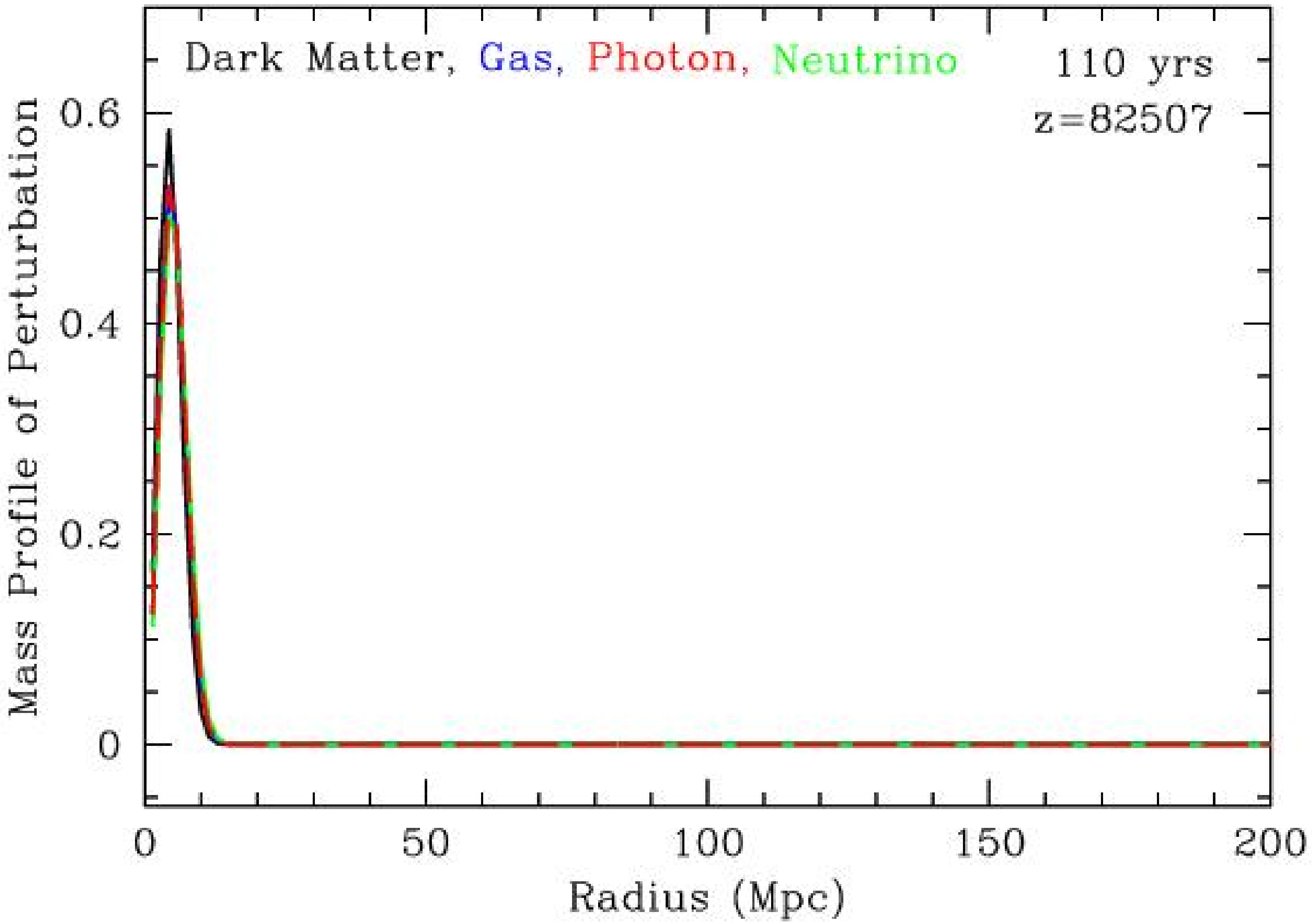
Baryon Acoustic Oscillations (BAO)



The BAO is used as the standard ruler to measure the expansion of the universe, and furthermore, constraint dark energy models.

The measurement of BAO:
A peak in the two point correlation function (2PCF) of matter tracers, such as Lyman-alpha forests.

Baryon Acoustic Oscillations (BAO)



Animation credit: [Daniel Eisenstein]

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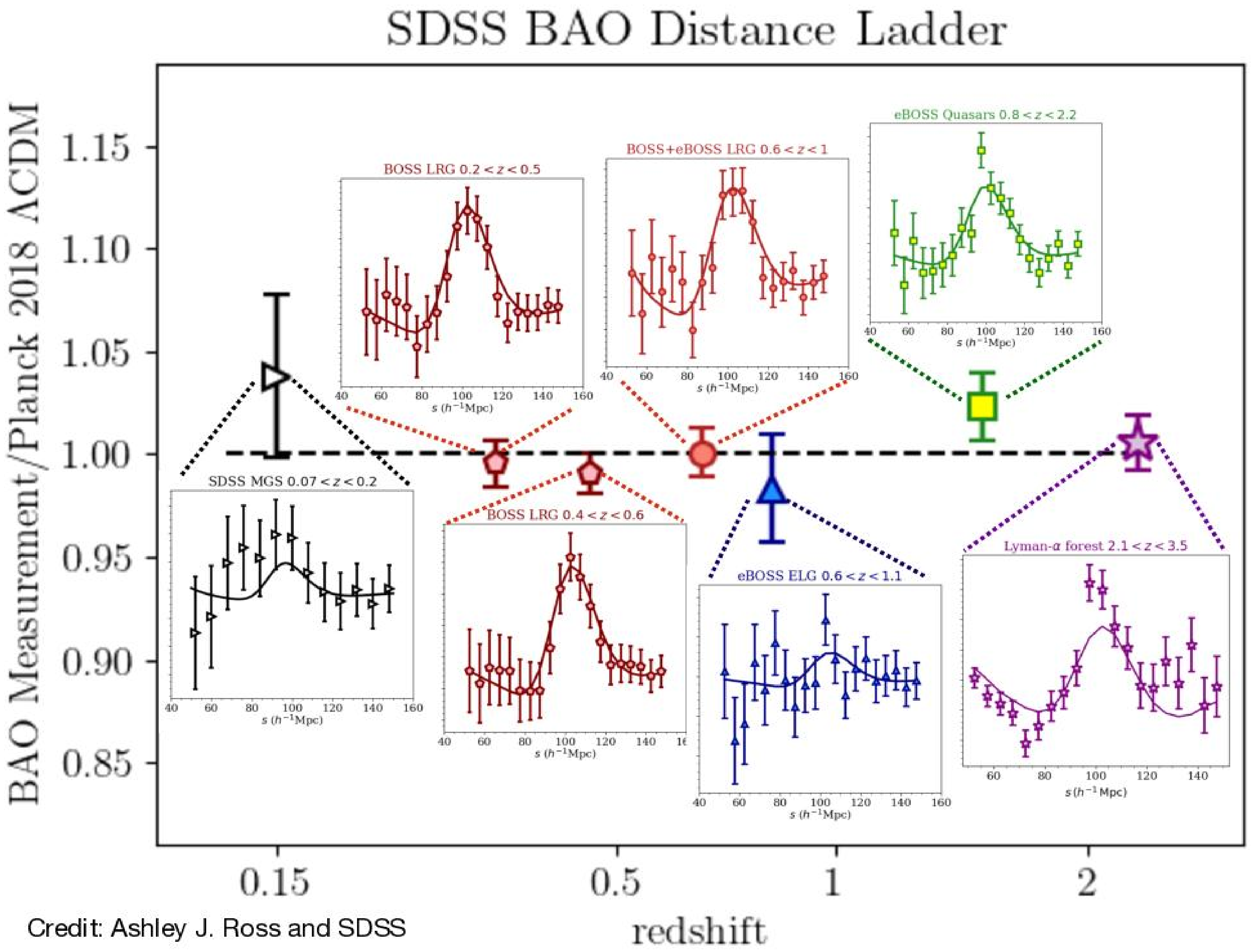


Credit: Ashley J. Ross and SDSS

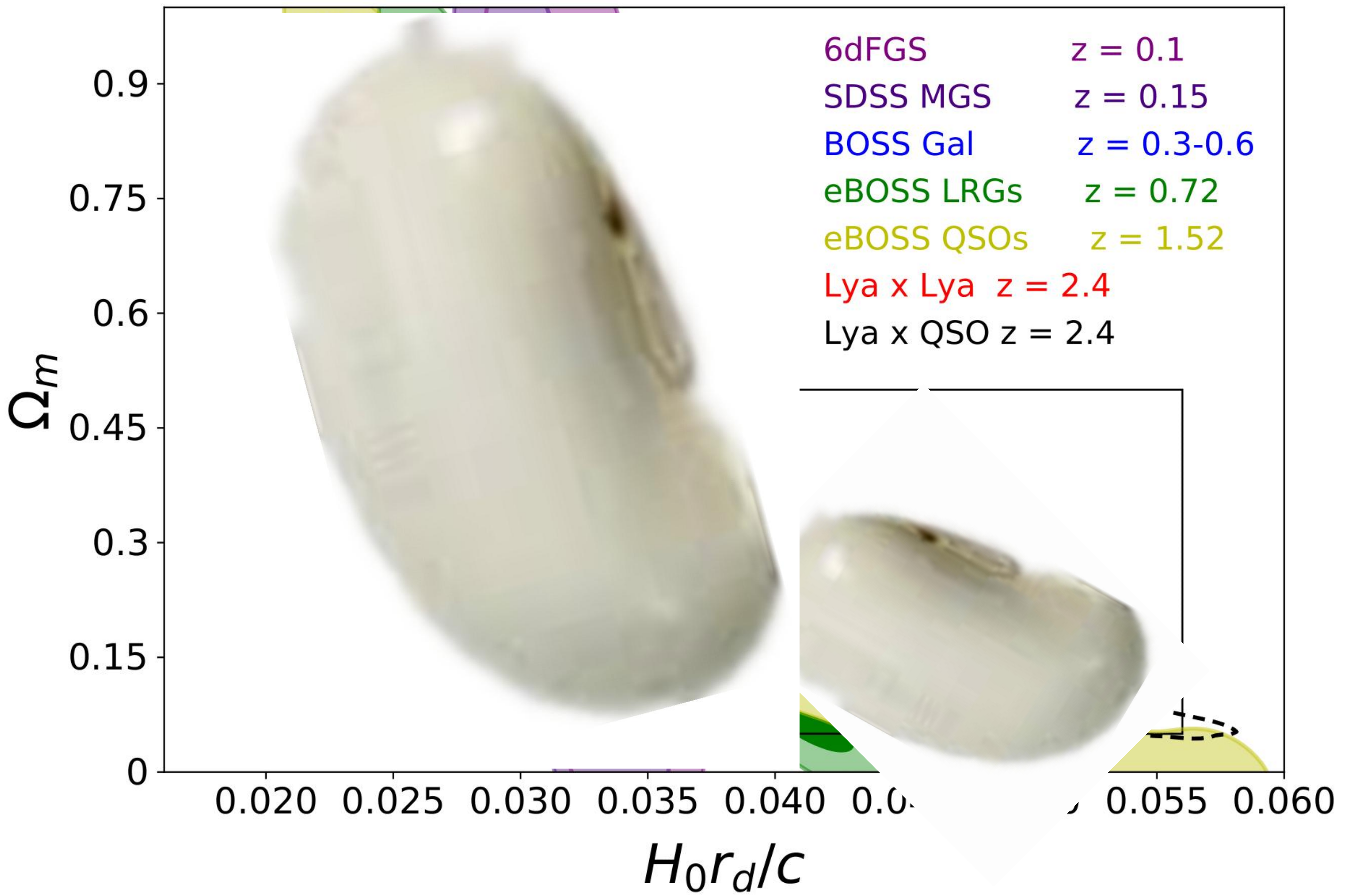
Baryon Acoustic Oscillations (BAO)

$$\xi(r_\perp, r_{||}) = \langle \delta_F(\lambda), \delta_{F'}(\lambda') \rangle |_{r_\perp, r_{||}}$$

$$r_d = [r_\perp^2 + r_{||}^2]^{\frac{1}{2}} = [D_M(z)^2 \Delta\theta^2 + D_H(z)^2 \Delta z^2]^{\frac{1}{2}}$$

$D_M(z)$ = angular diameter distance
$H(z) = c/D_M(z)$ = expansion rate

BAO peak determines $D_M(z)/r_d$ and $D_H(z)/r_d$



From Cuceu et al 2019 (arxiv:1906.11628)

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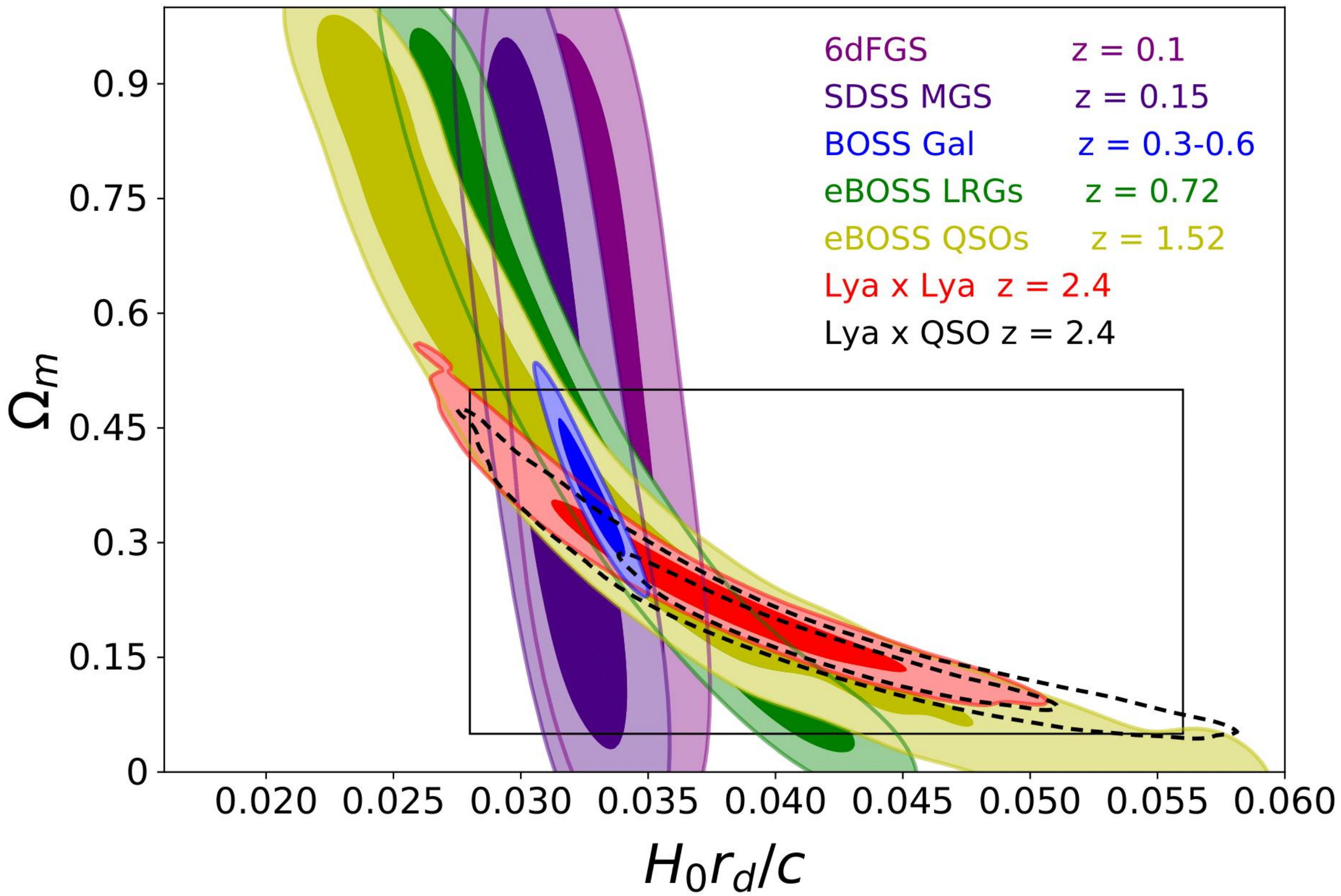

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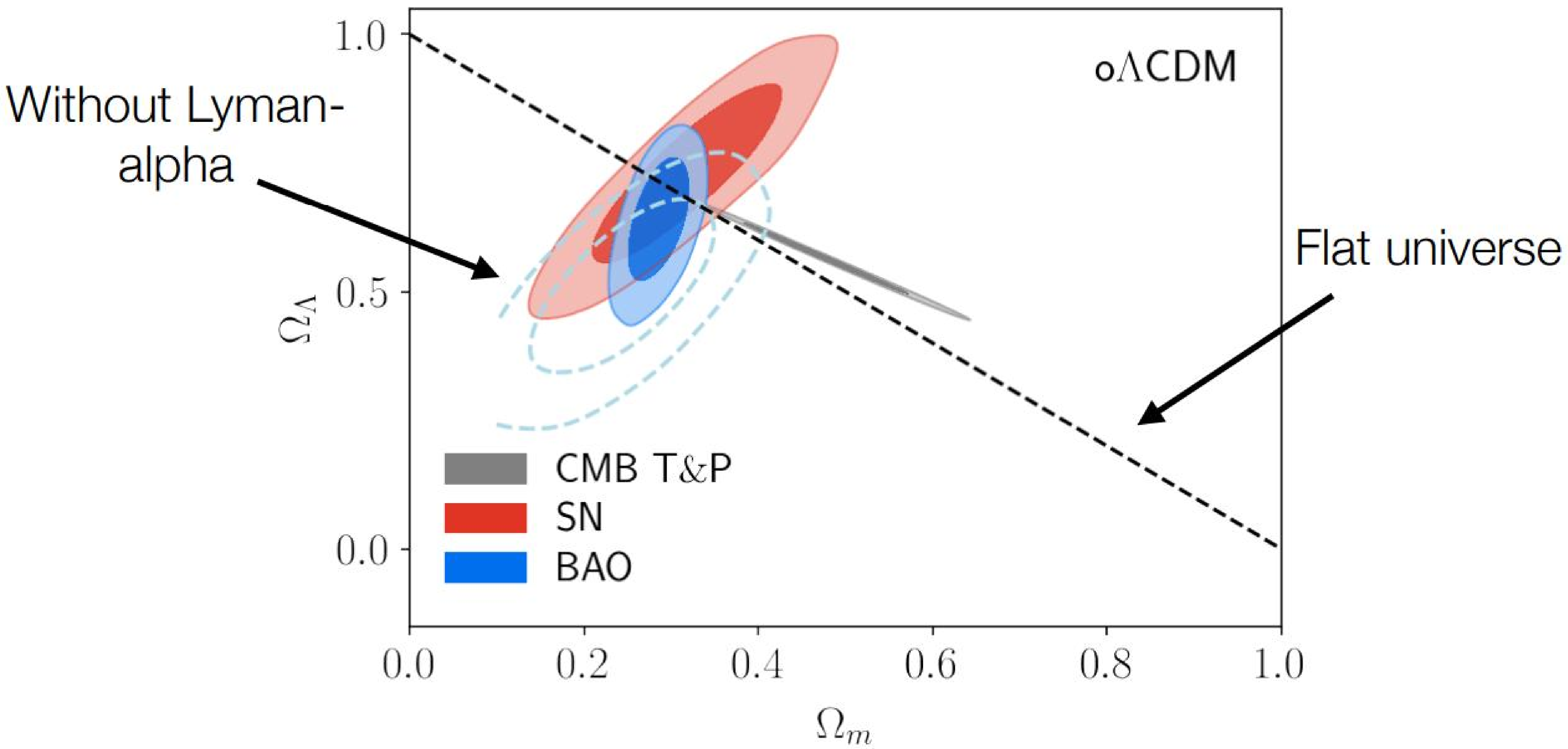
Dark Energy with BAO

(eBOSS Collaboration, 2020)

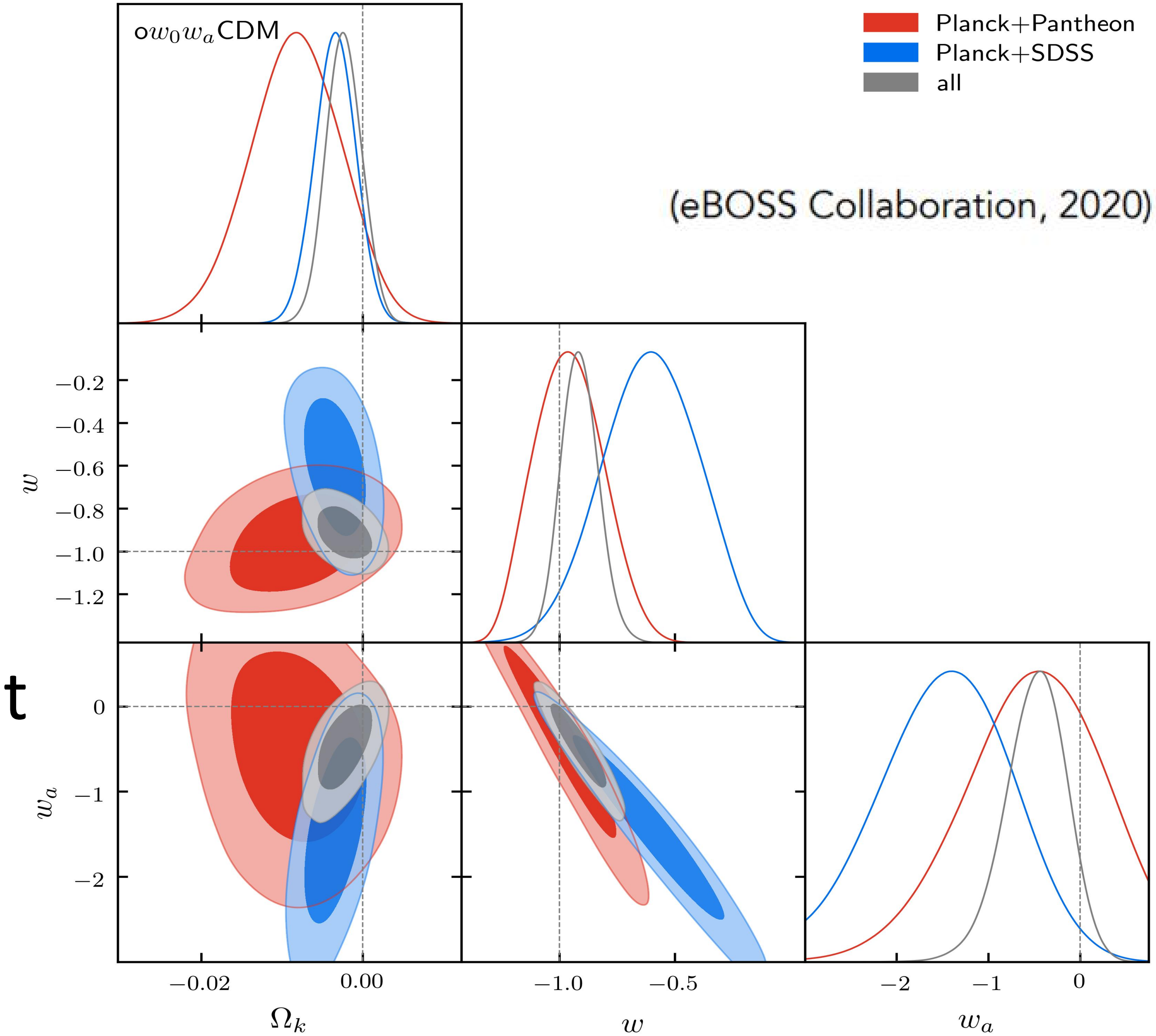


Dark Energy with BAO

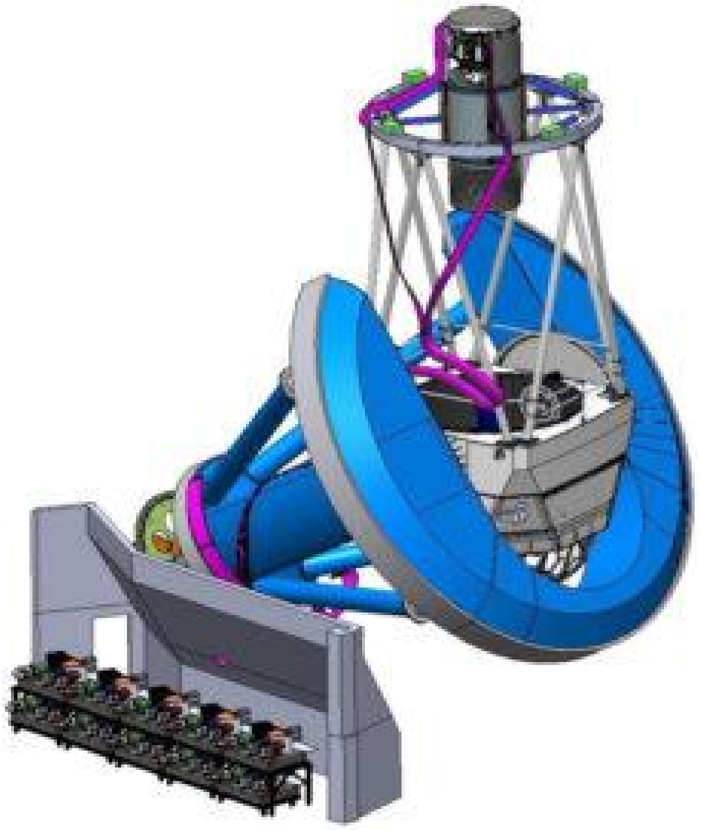
wCDM model:

$$w(a) = w_0 + w_a(1 - a)$$

- Agrees with ΛCDM model
- Consistent with cosmological constant



Dark Energy Spectroscopic Instrument



30 million galaxies and quasars

14,000 square degrees

5,000 robotic positioners.

Mayall 4m Telescope Kitt Peak (Tucson, AZ)

04/2021 ~ 1%survey

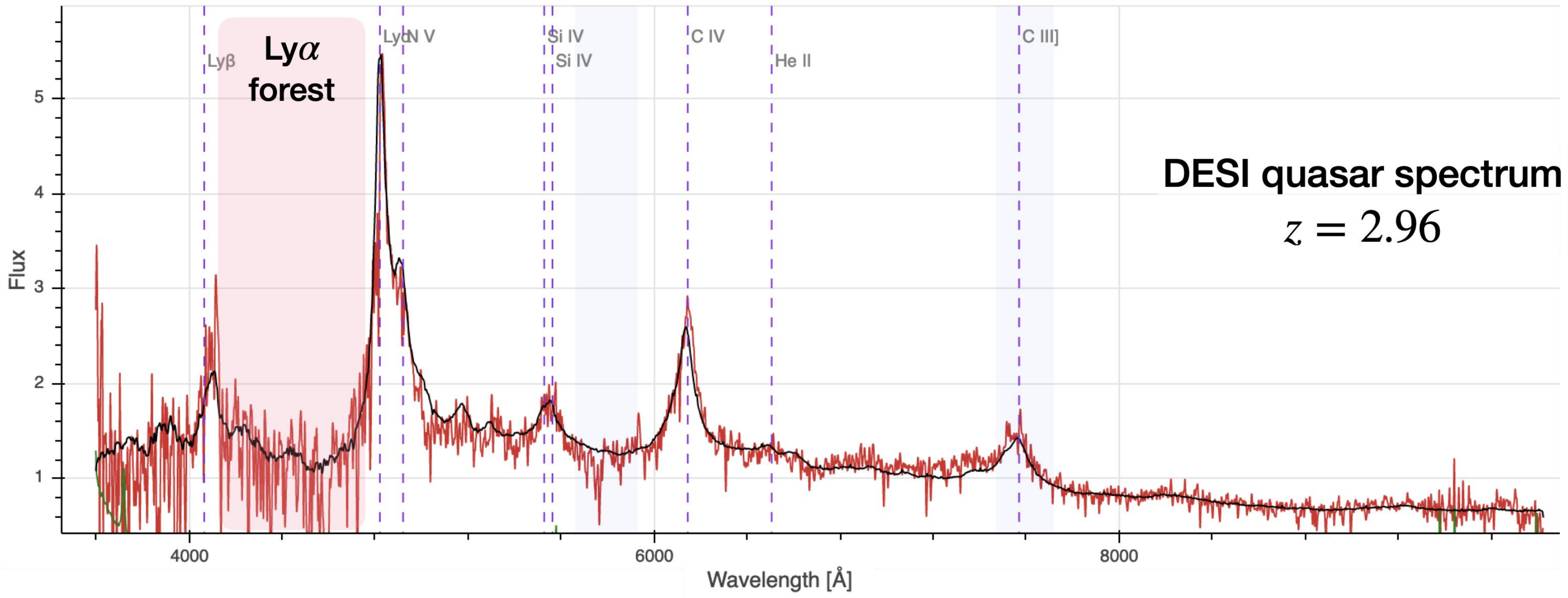
17/05/2021 ~ Start of the 5 year science survey

12/2021 ~ 15% survey

Quasars

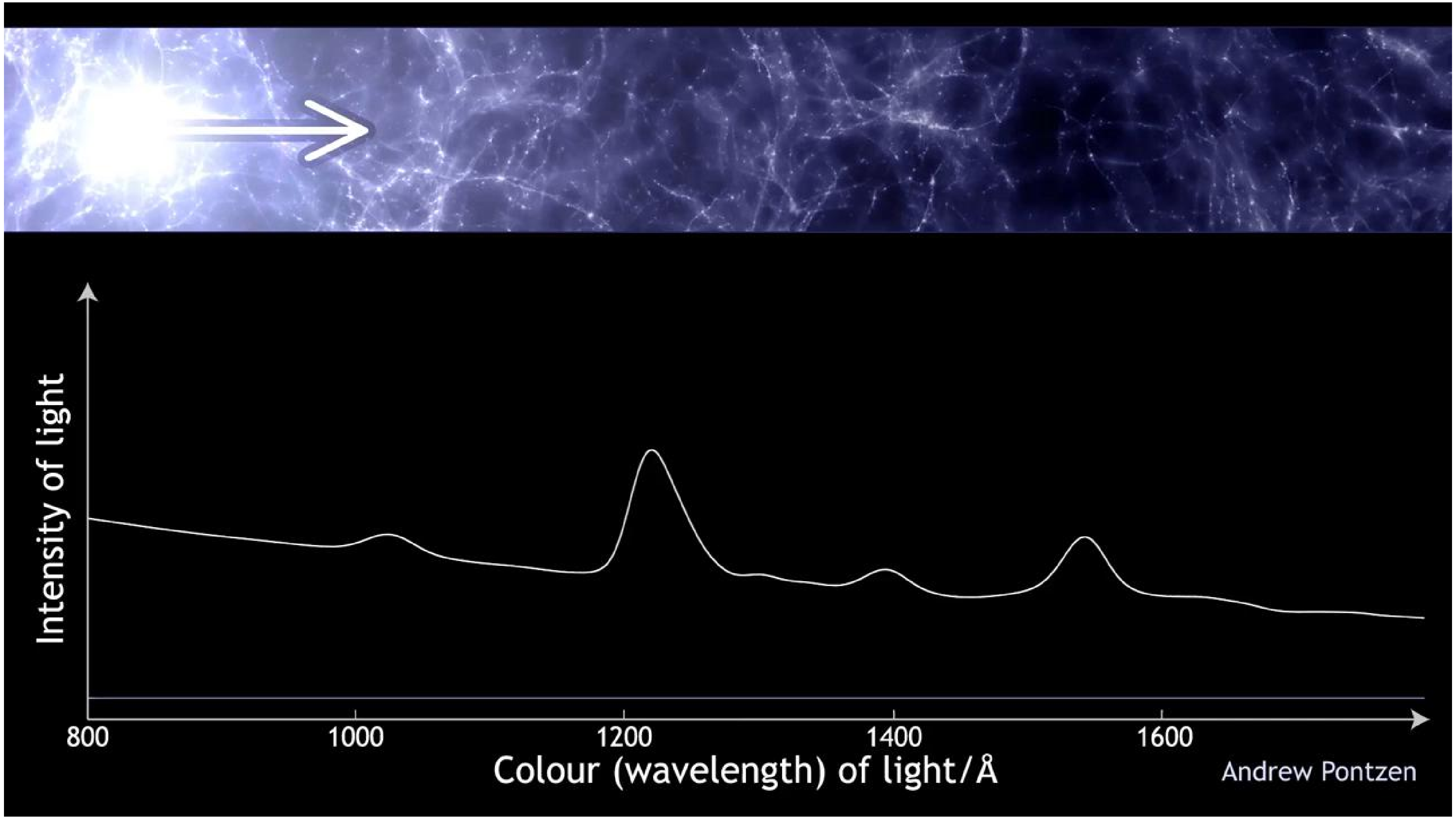
- The most luminous objects in the universe
- Supermassive black holes
- Accretion disks of matter

$$\lambda_{RF,\ Ly\alpha} = 1216\ \text{Å}$$



Quasar spectrum from DESI.

The Lyman-alpha forest

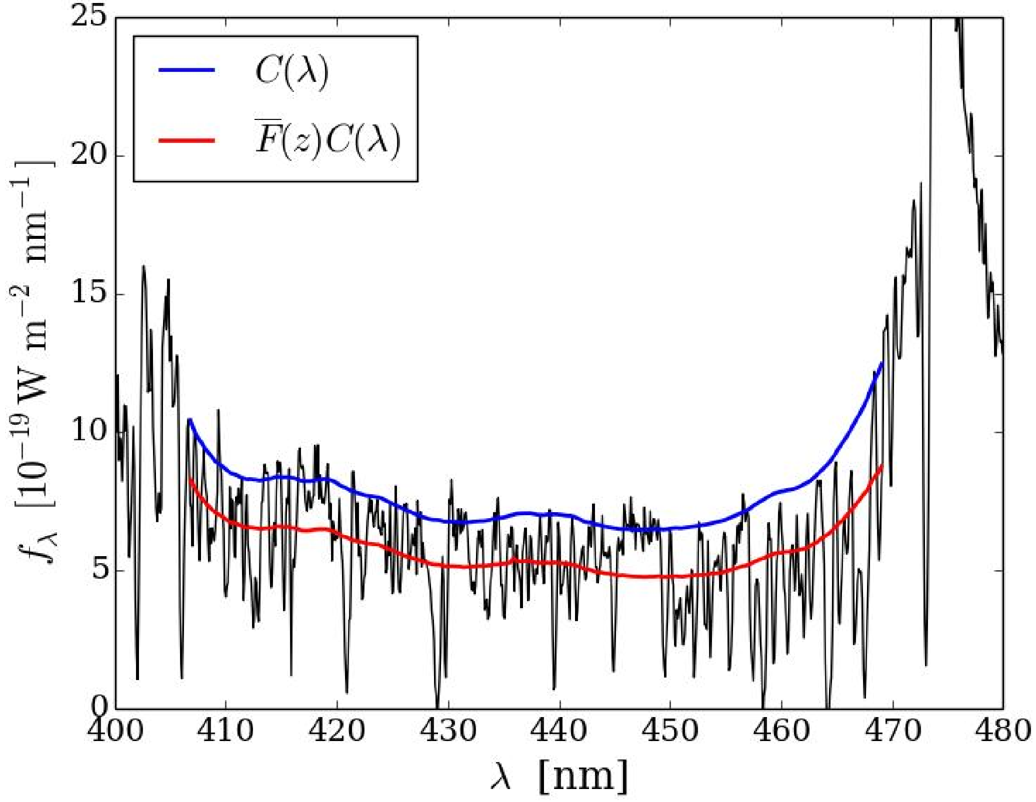


Video credit: [Andrew Pontzen]

The Lyman-alpha forest

The Lyman-alpha forest :

- QSO continuum: unabsorbed spectrum.
- Transmitted flux field: flux/continuum.
- Trace the density fluctuations and velocity-gradient fluctuations.



Thesis: Julianna Stermer

Transmitted flux fraction:

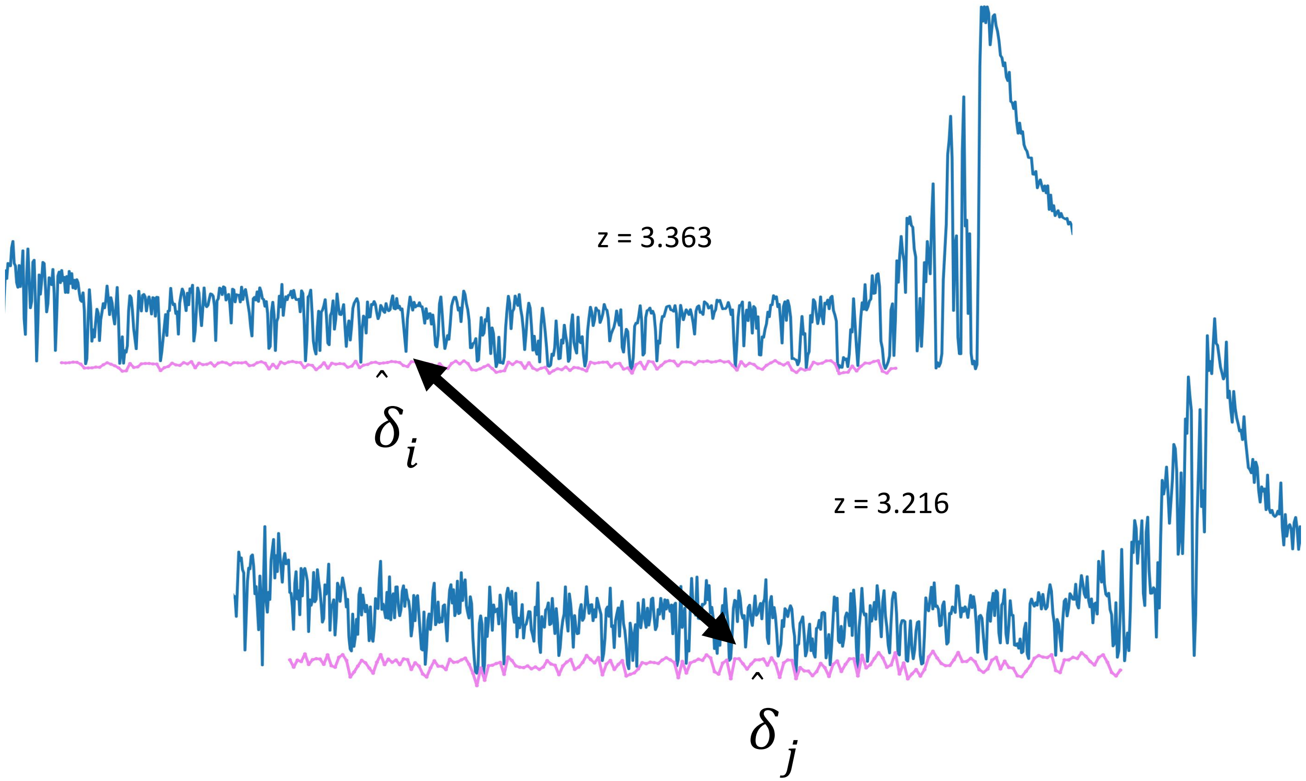
$$F_q(\lambda) = \frac{f_q(\lambda)}{C_q(\lambda)}$$

Observed flux

Quasar continuum

Flux delta field: $\delta_F(\vec{x}) = \frac{F(\vec{x}) - \bar{F}}{\bar{F}} = \frac{f_q(\lambda)}{C_q(\lambda)\bar{F}} - 1$

The Lyman-α auto-Correlation function



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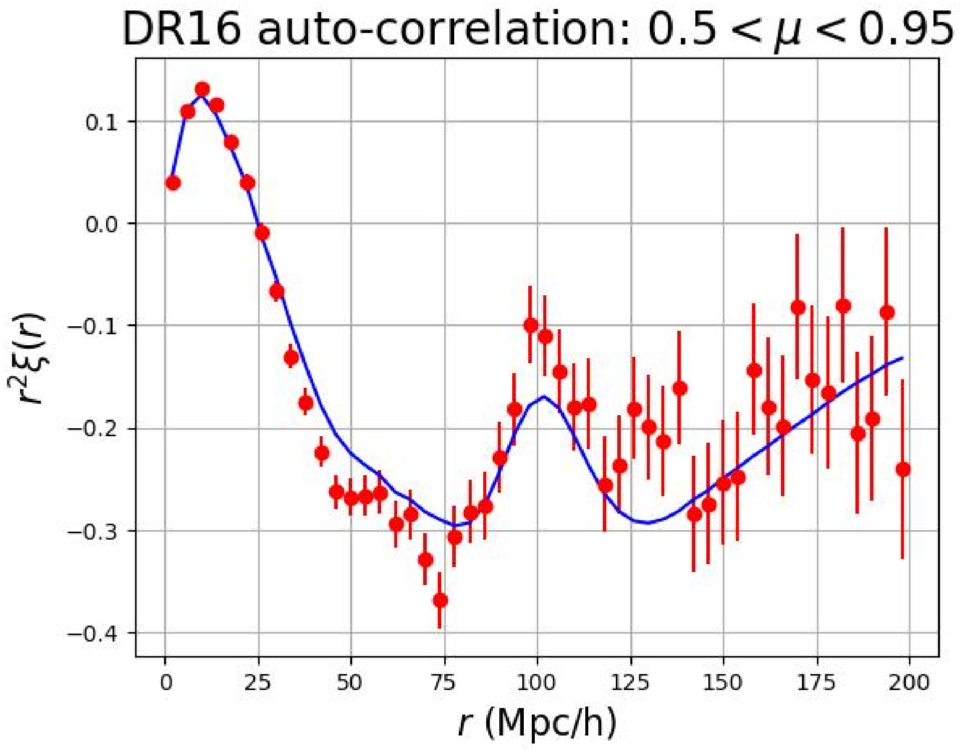
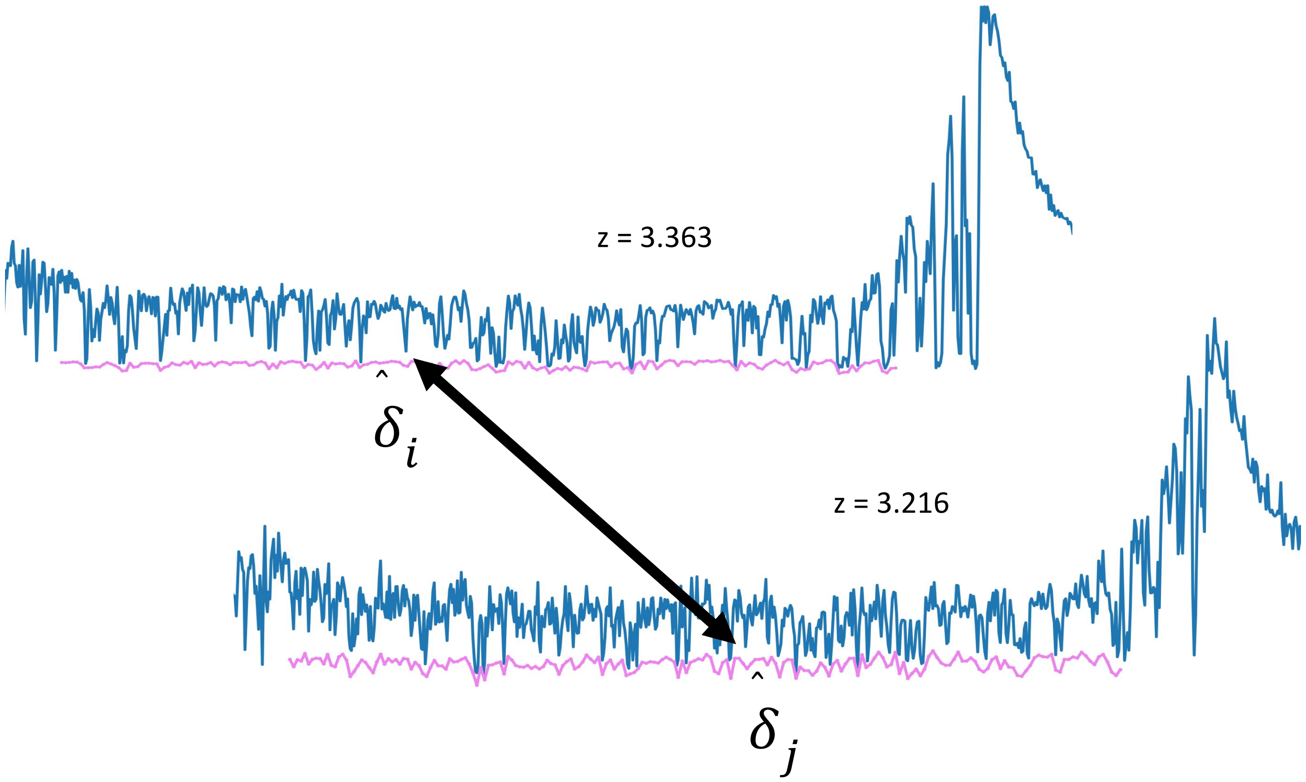


du Mas des Bourboux et al, arXiv:2007.08995

$$\xi_A = \frac{\sum_{(i,j)\in A} w_i w_j \delta_i \delta_j}{\sum_{(i,j)\in A} w_i w_j}.$$

The Lyman-α auto-Correlation function



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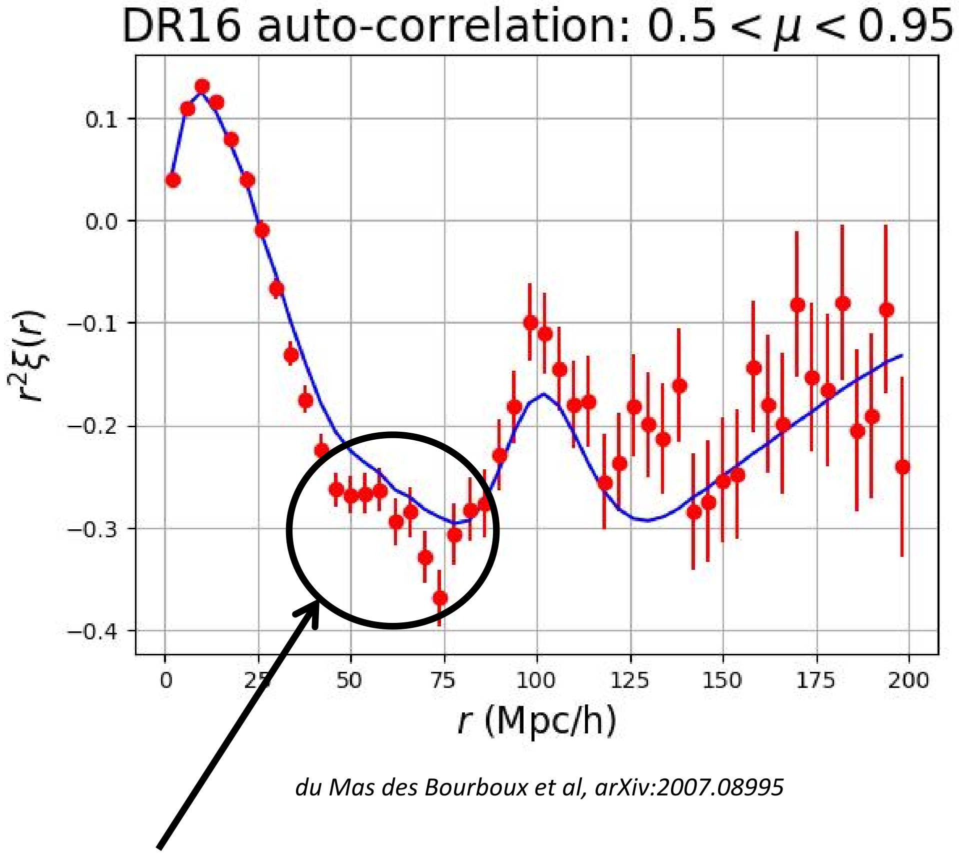


du Mas des Bourboux et al, arXiv:2007.08995

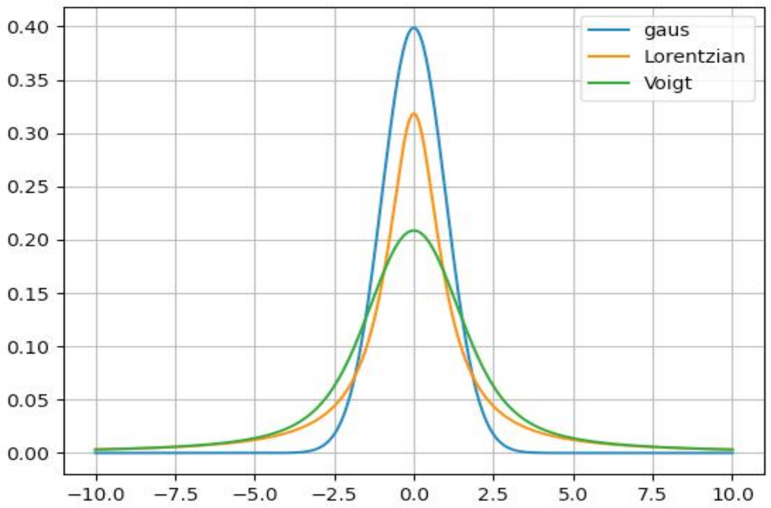
Bad fitting for 25<r<75: HCDs?

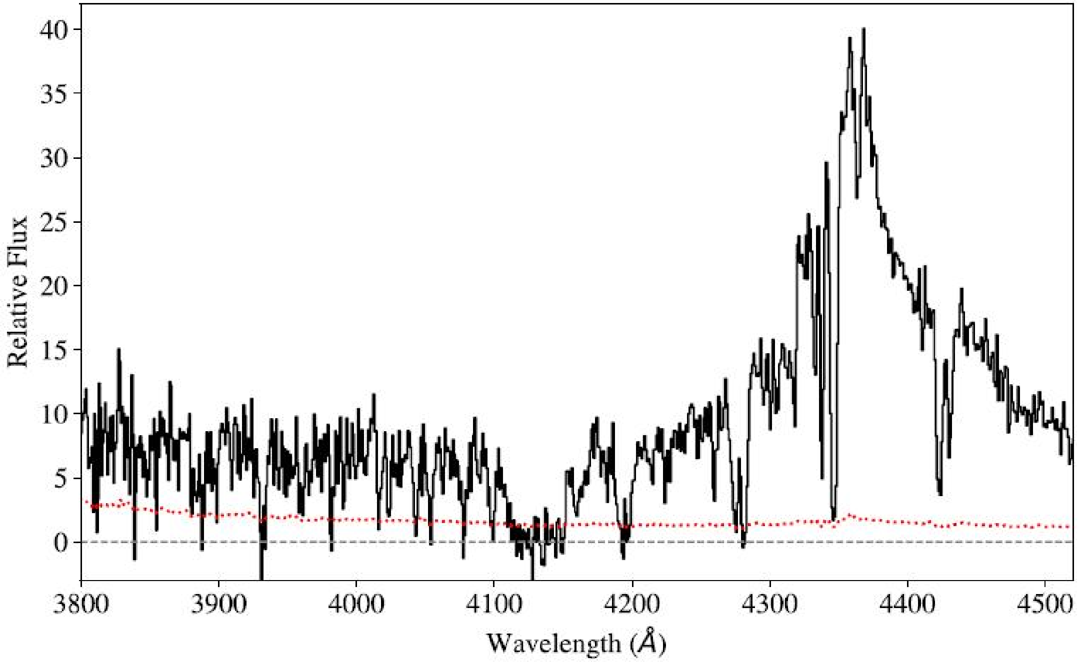
High Column Density Systems (HCDs)

- NHI column density of a gas concentration:
  High Column Density Systems (HCDs): $N \geq 10^{17}$ / cm^2
  Damped Lyman-α Systems (DLAs): $N \geq 10^{20}$ / cm^2

- HCD absorption parametrized with Voigt profile

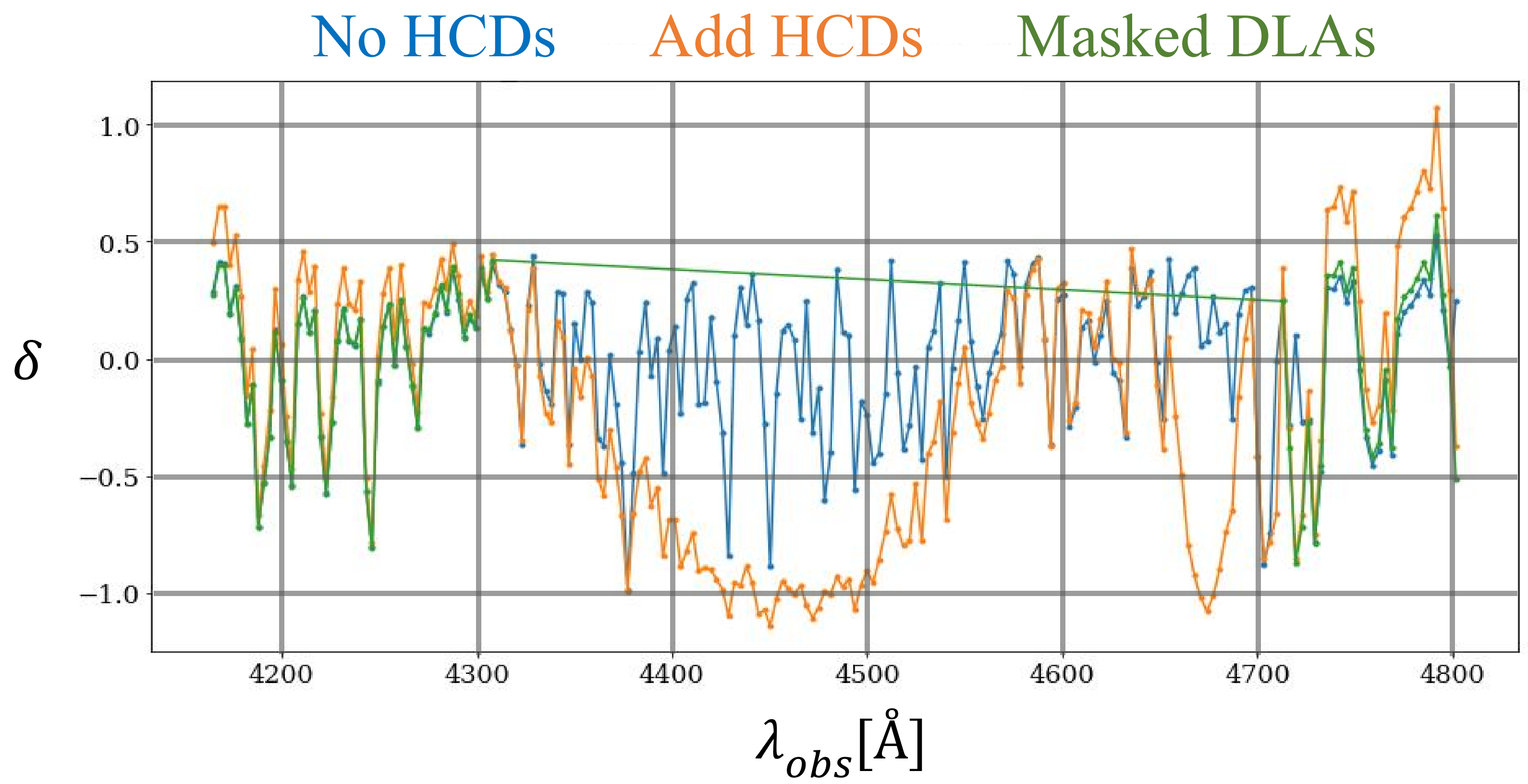
- Voigt profile = Gaussian ⊛ Lorentzian
  Gaussian: thermal Doppler broadening
  Lorentzian: cross-section





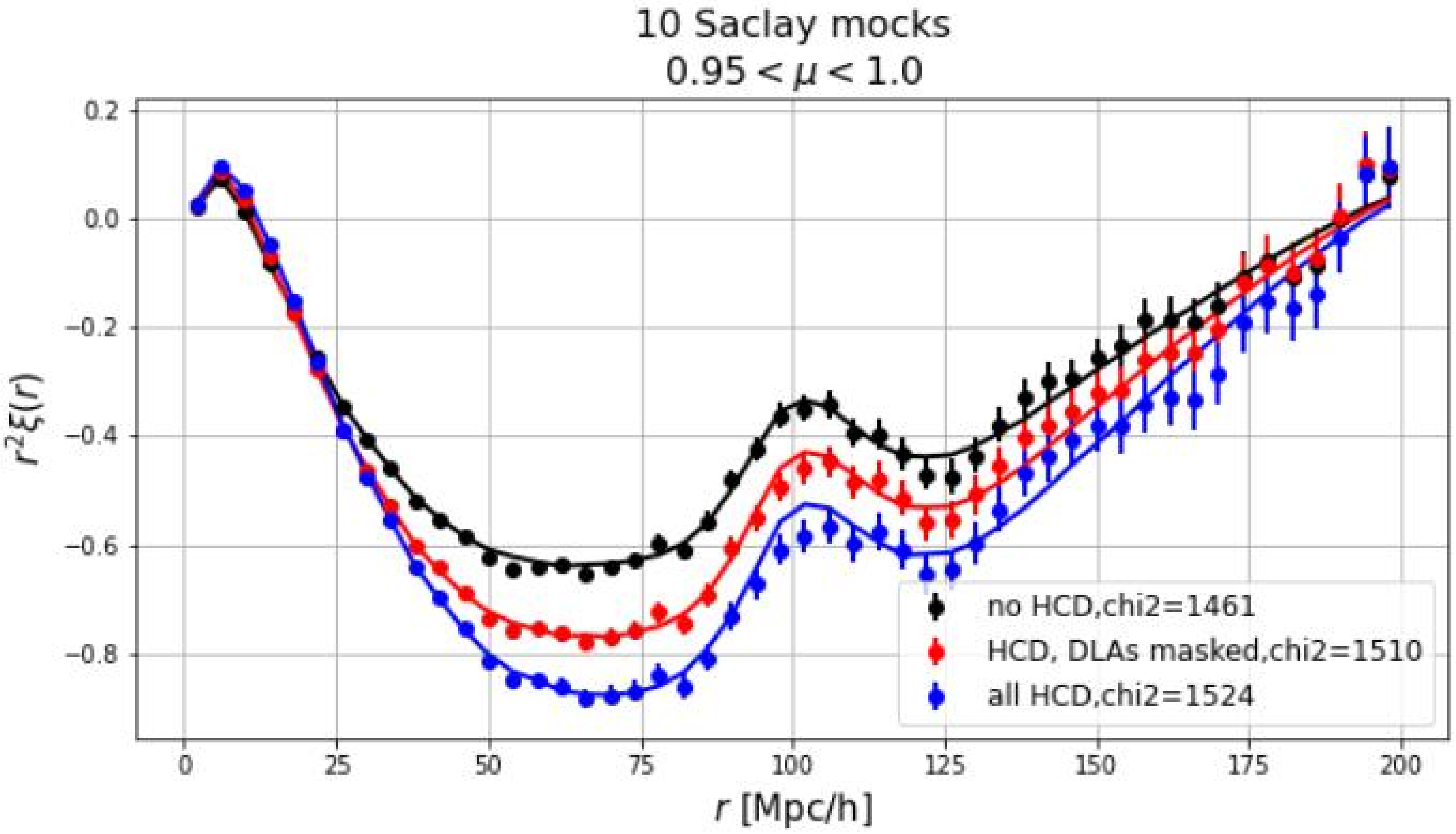
D. Parks et al. (2018)

HCD effect on the correlation function



- DLAs are detectable and can be masked.
- Smaller HCDs are not detectable but they still affect the correlation function.

HCD effect on the correlation function



d.o.f=1574

More HCDs → Worse fitting → New model?

2. Modeling of HCDs

Model Introduction

Modeling of Ly-α power spectrum:

$$P_{Ly\alpha}(\mathbf{k}) = P_{QL}(\mathbf{k}) D_{NL}(\mathbf{k}) b_{Ly\alpha}^2 (1 + \beta_{Ly\alpha}\mu^2)^2$$

- $P_{QL}(\mathbf{k})$: Quasi-linear power spectrum
- $D_{NL}(\mathbf{k})$: Non-linear effect
- $b_{Ly\alpha}^2$: Amplitude
- $(1 + \beta_{Ly\alpha}\mu^2)^2$: Redshift space distortion

HCD model:

$$b'_{\mathrm{Ly}\alpha} = b_{\mathrm{Ly}\alpha} + b_{\mathrm{HCD}} F_{\mathrm{HCD}}(k_{||})$$

$$b'_{\mathrm{Ly}\alpha}\beta'_{\mathrm{Ly}\alpha} = b_{\mathrm{Ly}\alpha}\beta_{\mathrm{Ly}\alpha} + b_{\mathrm{HCD}}\beta_{\mathrm{HCD}} F_{\mathrm{HCD}}(k_{||})$$

$$F^{\mathtt{exp}}_{\mathtt{HCD}}(k_{||}) = \exp(-L_{\mathtt{HCD}} * k_{||})$$

No physical explanation for L_{HCD} and b_{HCD}!

Model Introduction

The cross-correlation function of HCDs × Ly-α:

$$\xi_\times(\Delta_j) = \sum_{j\in\mathrm{HCD}} \sum_{j_{\mathrm{HCD}}} \delta'(j+\Delta_j)\delta_{\mathrm{HCD}}(j_{\mathrm{HCD}})(\frac{V(j-j_{\mathrm{HCD}})}{\langle V\rangle} - 1)$$

$$= \sum_{j\in\mathrm{HCD}} \sum_{j_{\mathrm{HCD}}} \xi_\times(j+\Delta_j - j_{\mathrm{HCD}})(\frac{V(j-j_{\mathrm{HCD}})}{\langle V\rangle} - 1)$$

The cross power spectrum of HCDs × Ly-α:

$$P_\times(\vec{k}) = b_{\mathrm{LY}\alpha} b_{\mathrm{HCD}} (1+\beta_{\mathrm{LY}\alpha}\mu_k^2)(1+\beta_{\mathrm{HCD}}\mu_k^2) P_{\mathrm{L}}(\vec{k})\sqrt{D_{\mathrm{NL},\alpha}}(\vec{k}) F_{\mathrm{HCD}}(k_{||}d)$$

Amplitude — Redshift space distortion — Quasi-linear power spectrum

$$F_{\mathrm{HCD}}(k_{||}d) = (\widetilde{\frac{V}{\langle V\rangle} - 1})(k_{||}d)$$

Model Introduction

Lyα auto-power spectrum:

$$P_{\mathrm{F},\alpha}(\mathbf{k}) = b_\alpha^2(1+\beta_\alpha\mu_k^2)^2 P_\mathrm{L}(\mathbf{k}) D_{\mathrm{NL},\alpha}(\mathbf{k})$$

↓ Non-linear effects

HCD auto-power spectrum:

$$P_{\mathrm{F,H}}(\mathbf{k}) = b_\mathrm{H}^2(1+\beta_\mathrm{H}\mu_k^2)^2 P_\mathrm{L}(\mathbf{k}) F_\mathrm{H}^2(k_{||})$$

Total flux power spectrum:

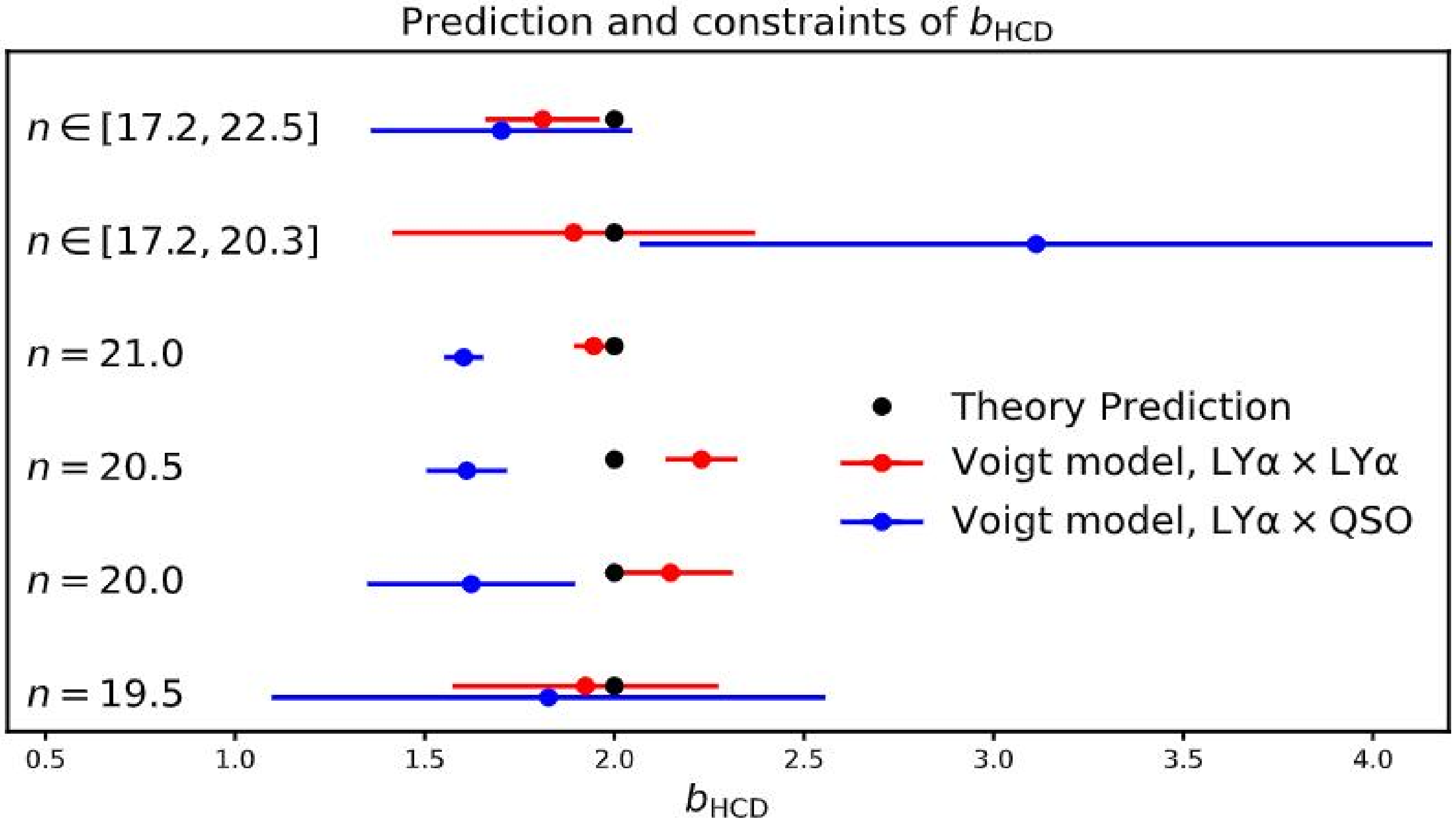
$$P_{\mathrm{F,Total}}(\mathbf{k}) = \frac{P_{\mathrm{F},\,\alpha} + 2P_{\mathrm{F},\,\alpha\mathrm{H}} + P_{\mathrm{F,H}}}{(1+C)^2} = b'^2(1+\beta'\mu_k^2)^2 P_\mathrm{L}(\mathbf{k})$$

$$b' = \frac{b_\alpha\sqrt{D_{\mathrm{NL},\alpha}}(\mathbf{k}) + b_\mathrm{H} F_\mathrm{H}(k_{||})}{1+C},\ \beta' = \frac{b_\alpha\beta_\alpha\sqrt{D_{\mathrm{NL},\alpha}}(\mathbf{k}) b_\mathrm{H}\beta_\mathrm{H}F_\mathrm{H}(k_{||})}{b_\alpha\sqrt{D_{\mathrm{NL},\alpha}}(\mathbf{k}) + b_\mathrm{H}F_\mathrm{H}(k_{||})}$$ and $C = \langle \delta_{\mathrm{F},\alpha}(\vec{r}), \delta_{\mathrm{F,H}}(\vec{r})\rangle$

Model Validation

Two types of 10-mocks, input b_{HCD}=2.0:

- HCDs with the same n=19.5, 20, 20.5, 21.
- A distribution of HCDs with/without the large DLAs (n>20.3).



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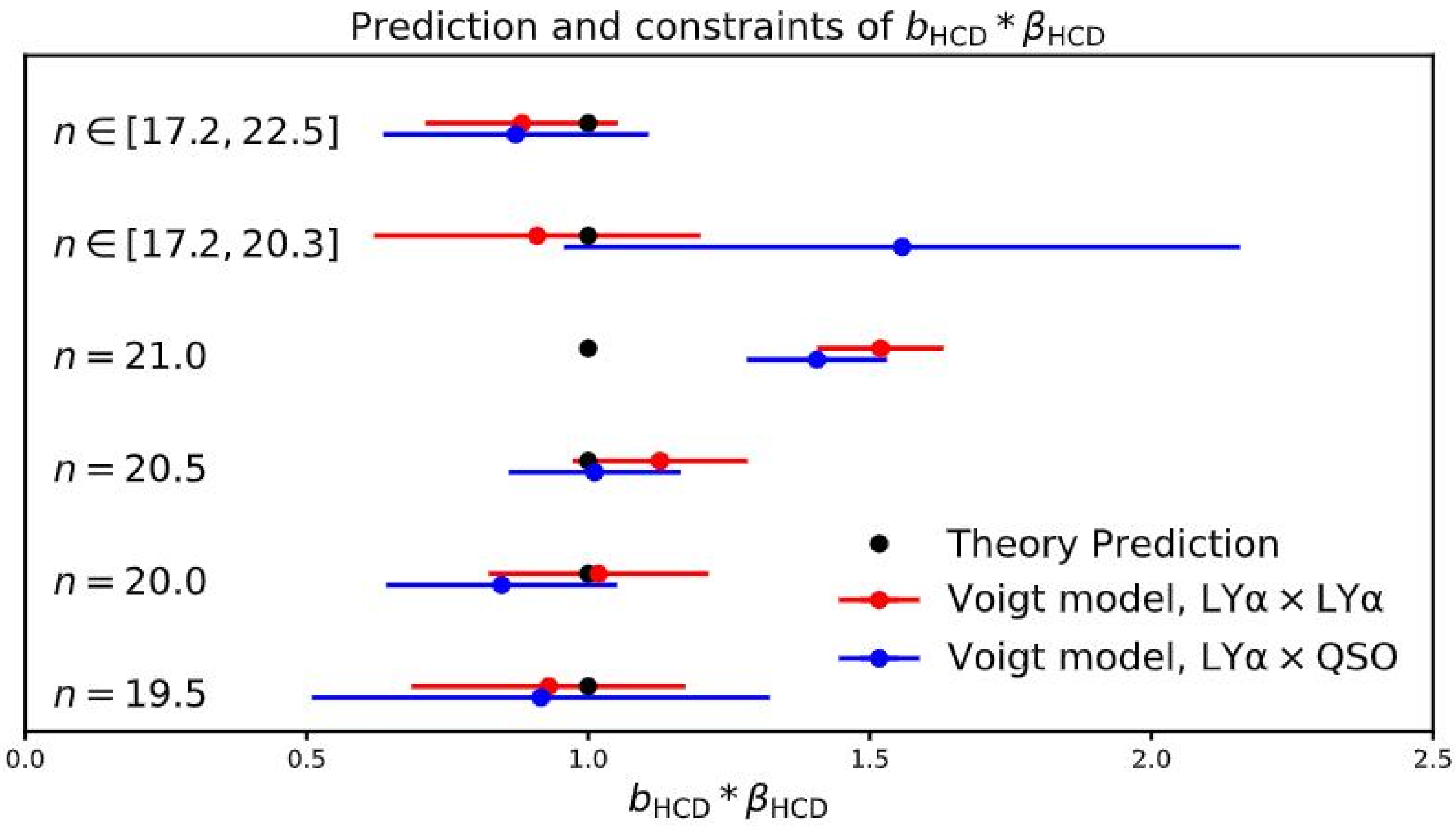
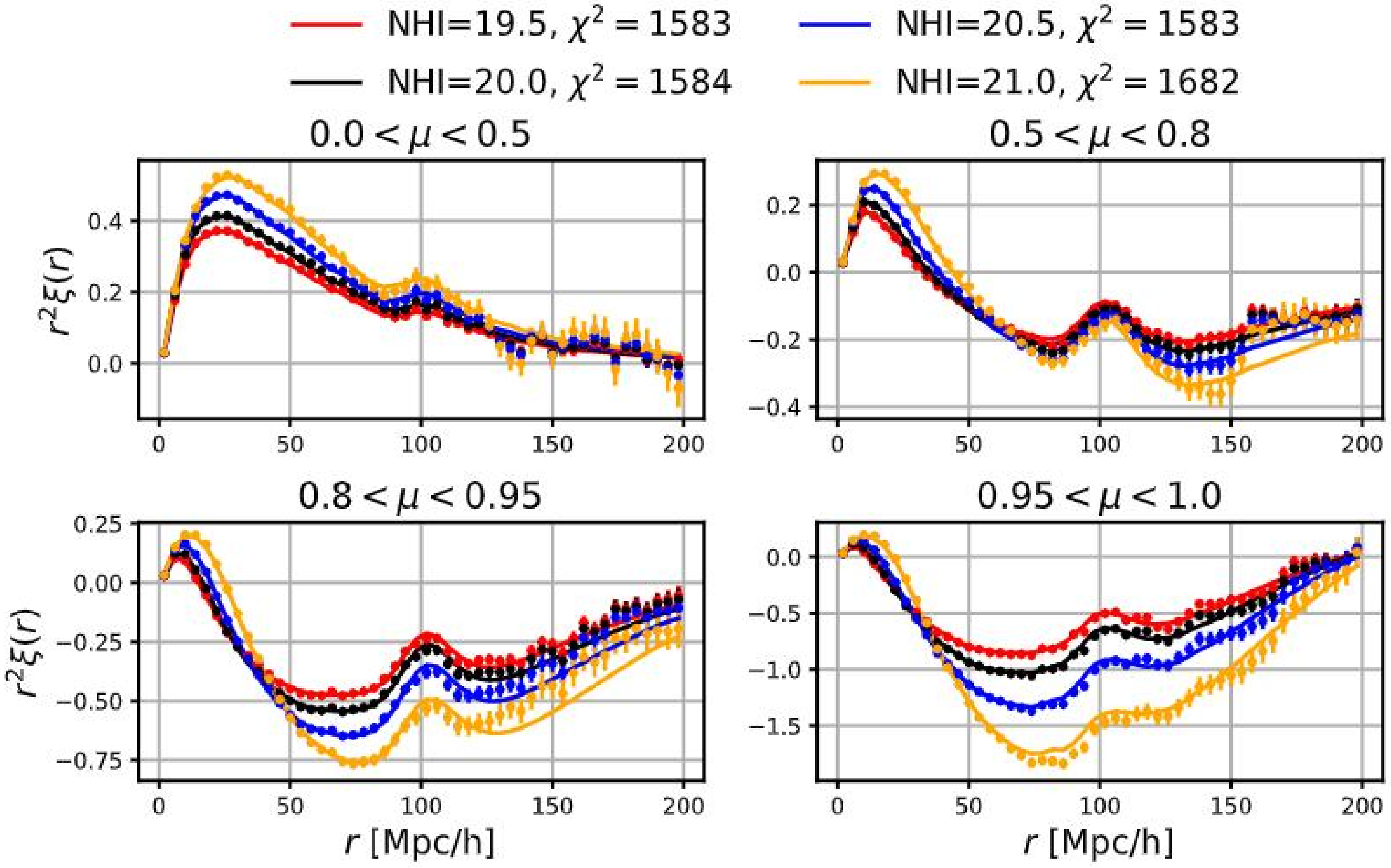


Model Validation

Fits for Lyα auto-correlation function:

- Voigt model gives good fitting for different mocks

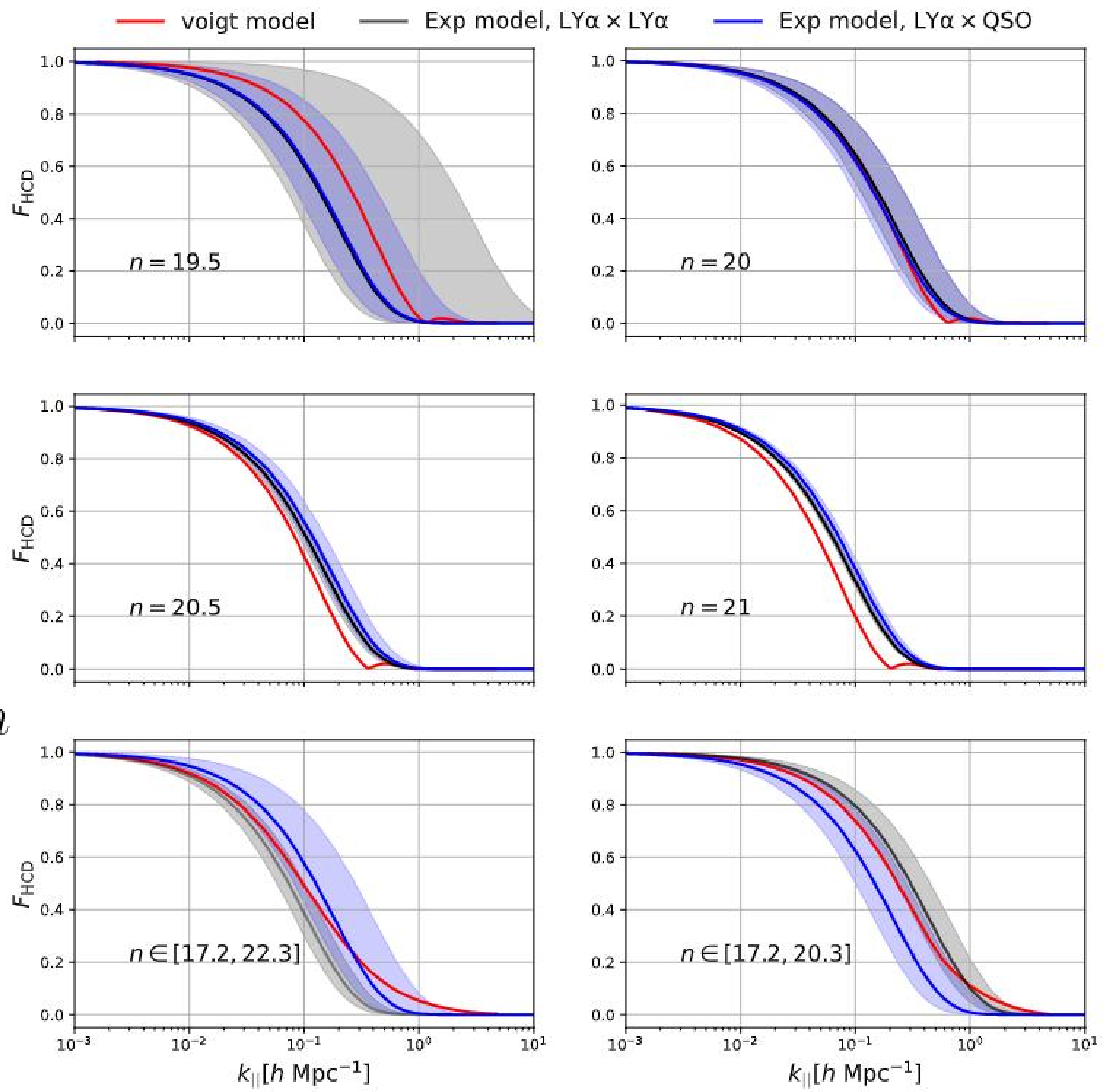


Model Comparison

$$F_{\mathrm{HCD}}^{\mathrm{exp}}(k_{||}) = \exp(-L_{\mathrm{HCD}} * k_{||})$$

- In DR16: L_{HCD}=10
- Best fit: L_{HCD}=3

$$F_{\mathrm{HCD}}^{\mathrm{voigt}}(k_{||}d) = \int (\widetilde{\frac{V}{\langle V \rangle} - 1})(k_{||}d, n) f(n) dn$$



Conclusion

Detection of BAO:

- Correlation function of different tracers.
- Constraints on Dark Energy models.

Modeling of HCDs:

- Voigt model gives accurate physical measurement of b_{HCD} and β_{HCD}.
- Voigt model gives good fitting for the Lyα correlation functions.

Thank you!