Cosmology with the Lyman-α forest: from BAO to reionization

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05 June 2026

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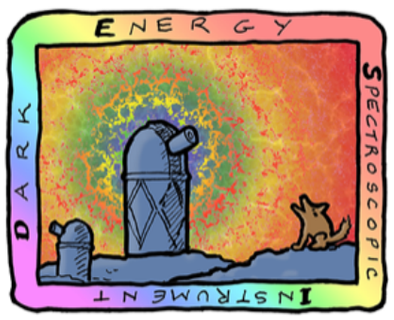
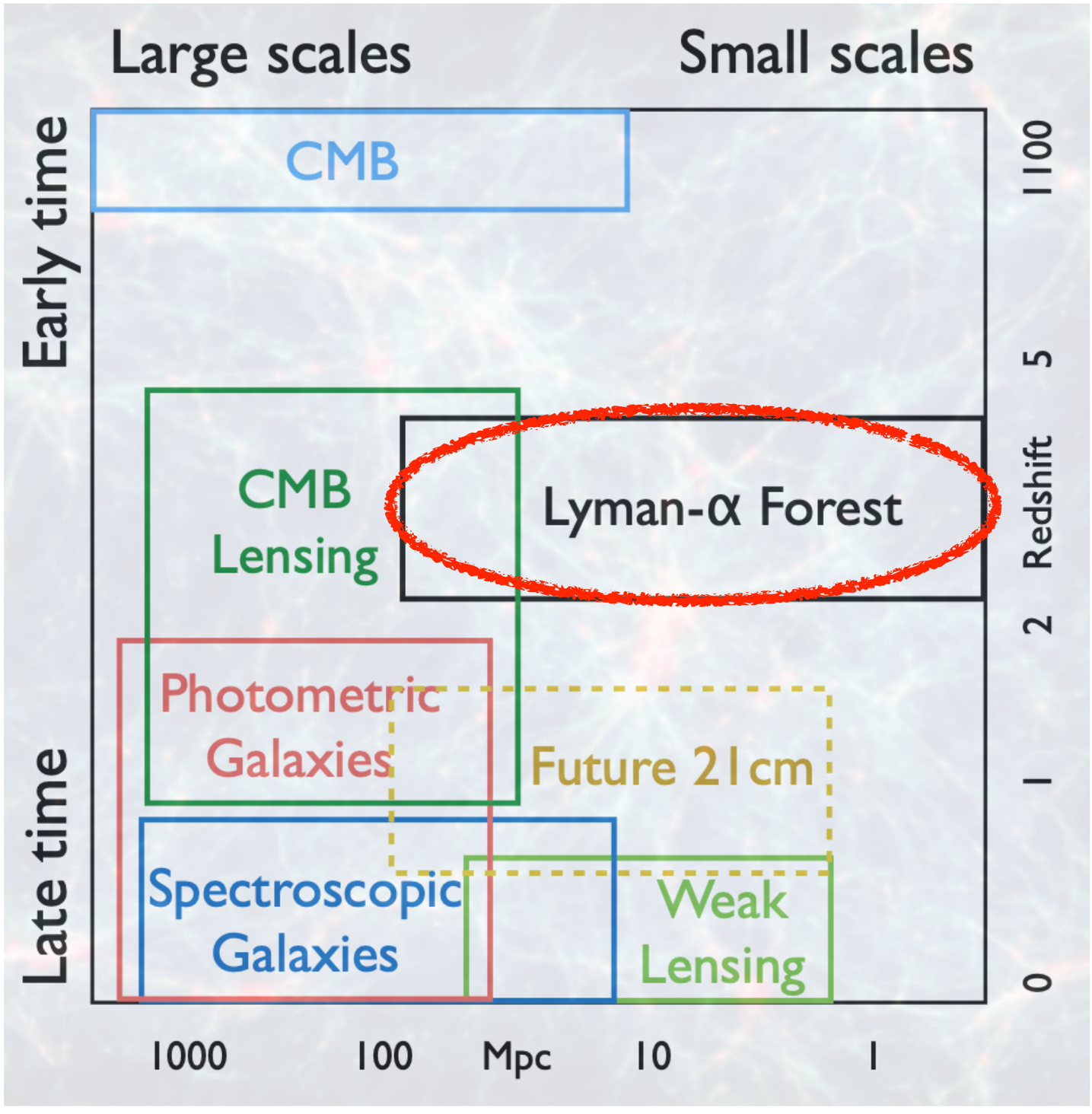


Probes of the cosmic large-scale structure (LSS)

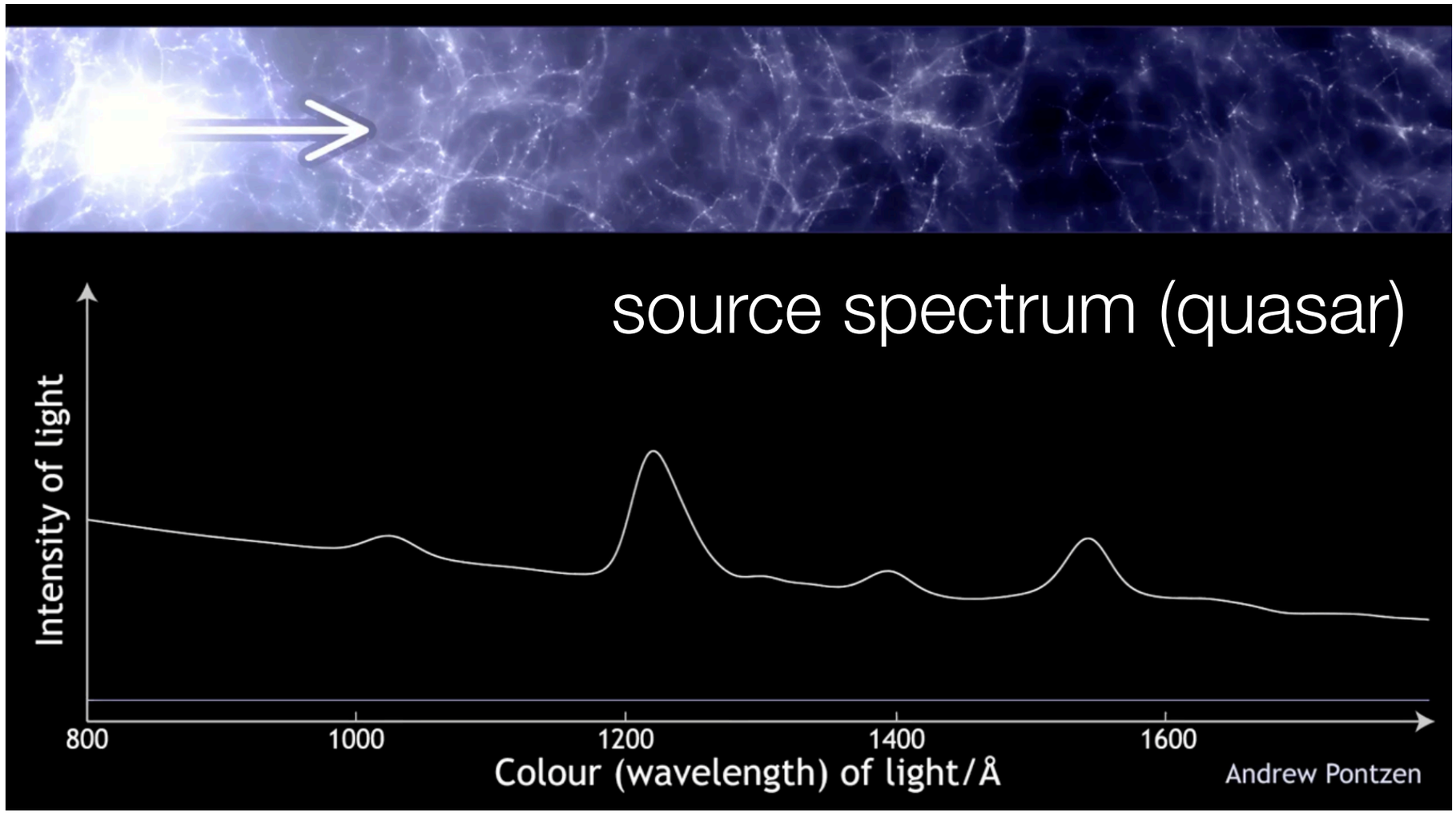


The Lyman-alpha forest is unique:

- **LSS at high redshift**: z>2

- probe the quasi linear regime down to **"small" scales** ~ Mpc

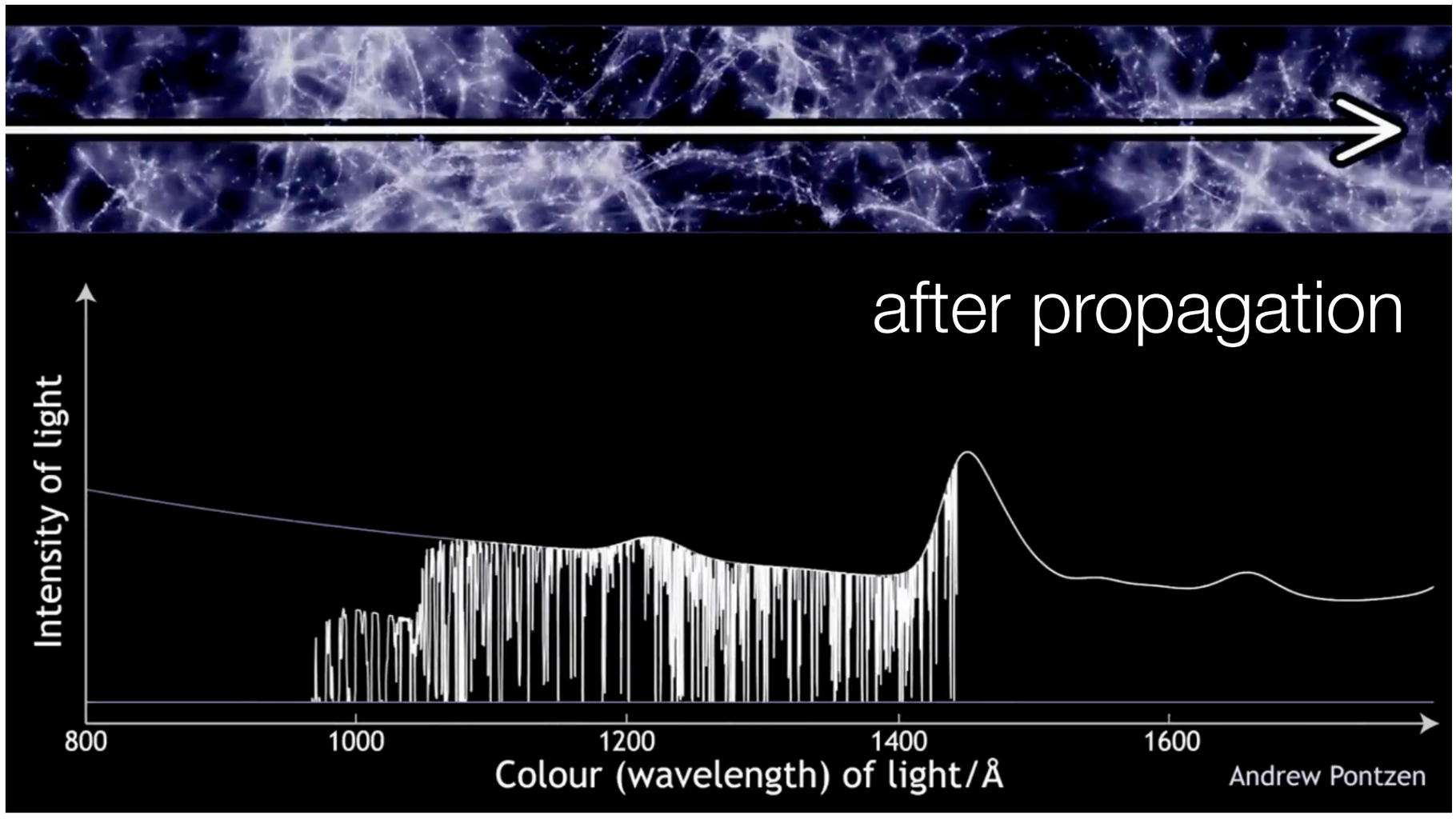
The Lyman-α forest



Resonant absorption of light by neutral hydrogen HI in the intergalactic medium (IGM)

- background source: usually quasars (bright)

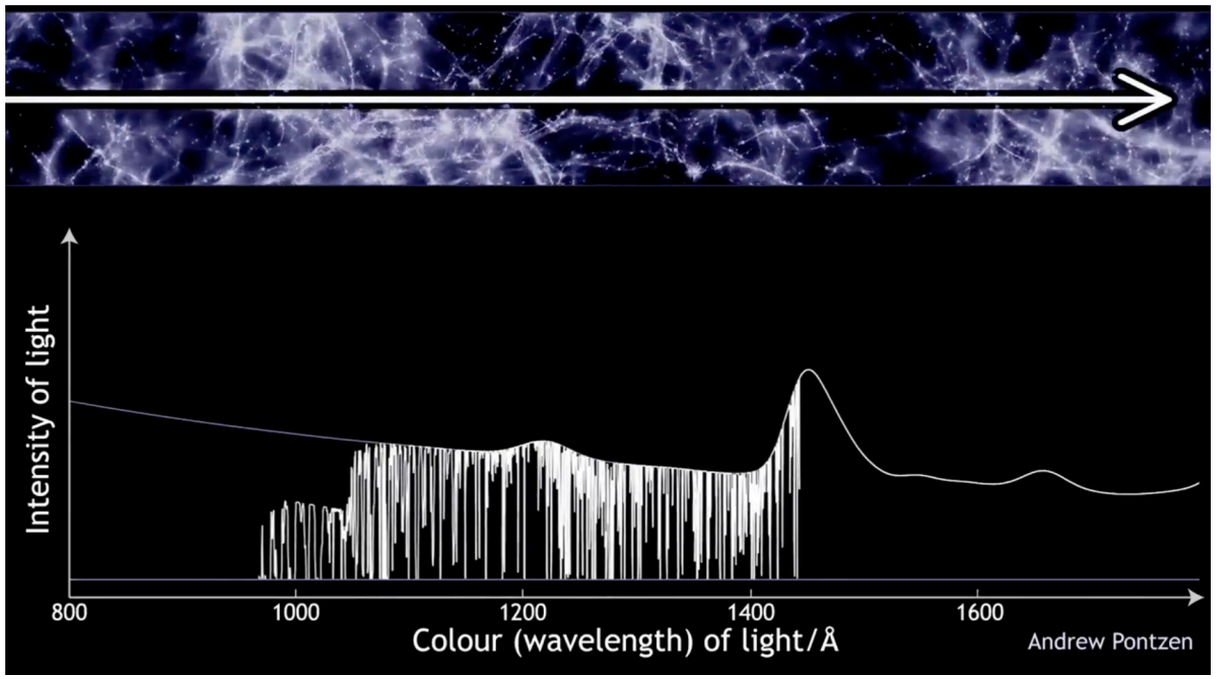
The Lyman-α forest



Resonant absorption of light by neutral hydrogen HI in the intergalactic medium (IGM)

- background source: usually quasars (bright)
- λ_{rest} = 1215 Å $\Rightarrow$ redshifted absorption in optical waves for z ~ 2 - 5

The Lyman-α forest



$$F(\lambda) = e^{-\tau_{\rm IGM}(z)} \in [0,1]$$

$\tau \sim 0$ at low redshift (IGM dilution)

$\tau \gg 1$ near reionization time

$\tau \sim 1$ @ $z \sim 2$ - 4 ($x_{HI} \sim 10^{-4}$)

$\Rightarrow$ Tracer of mild (nearly-linear) matter density fluctuations at z ~ 2 - 4

The Lyman-α forest

Original discovery in the early 70s (Lynds 71)
Interpretation: neutral HI "clouds" along line-of-sight

Revolution in the 90's: cosmological hydro simulations

- the Lya signal mostly originates from the dilute, photoionized IGM, and it can be computed (Hernquist+ 96)
- spatial correlations of the Lya forest are related to the matter power spectrum

  ⇒ first cosmology measurements with SDSS (McDonald+ 2004)

Limitations at that time

- simulations not accurate enough
- lack of data to map 3D Lya absorptions fluctuations

Computing the Lyα forest signal

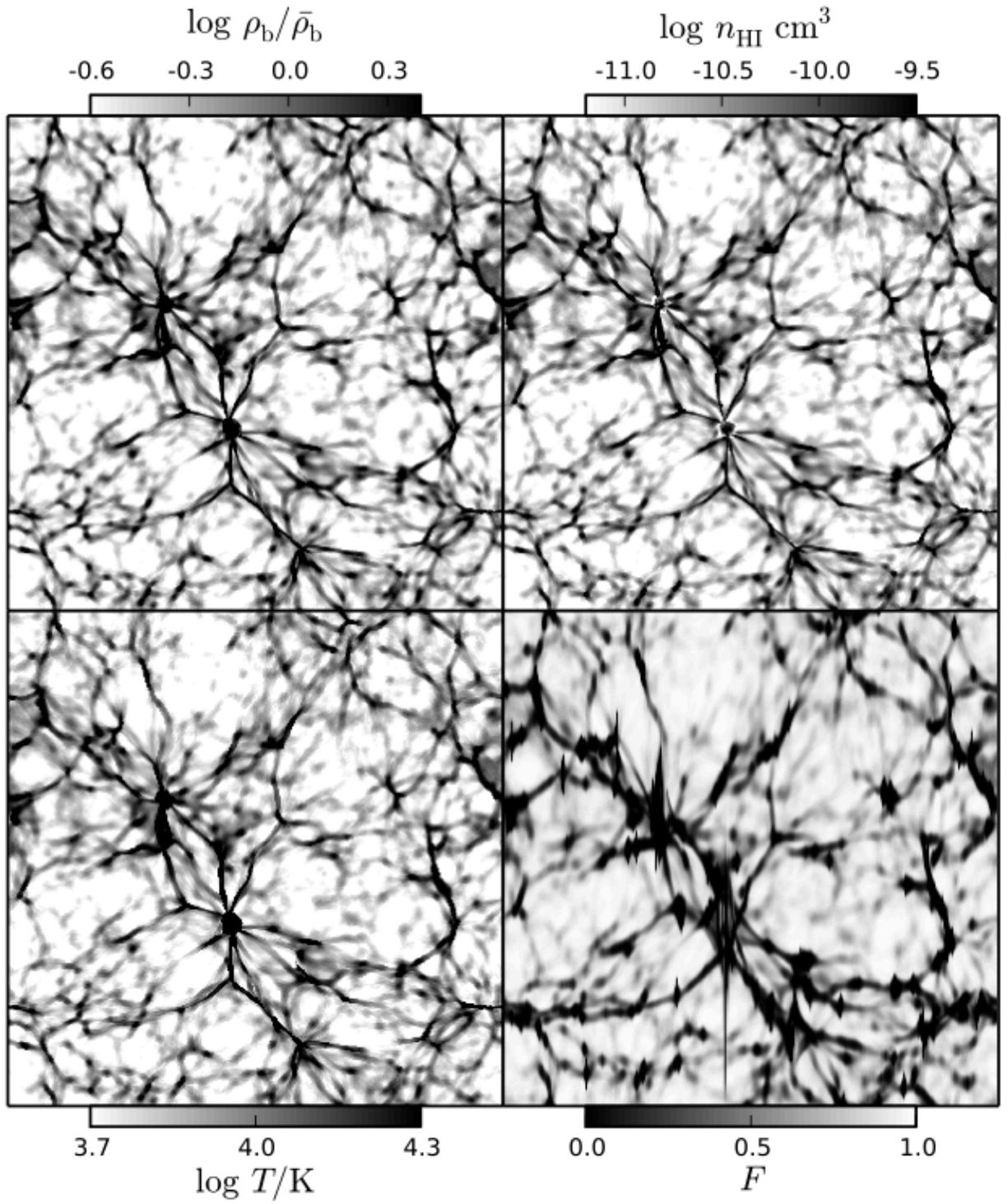
Non-linear gravitational evolution + hydrodynamics

cosmo-hydro simulation (GADGET, NYX, Ramses...)

gaz from SPH or grid method

- explicit model for gaz heating (UV radiation)
- compute temperature, HI density
- Do NOT need to model galaxy formation!

Lukic+ 1406.6361



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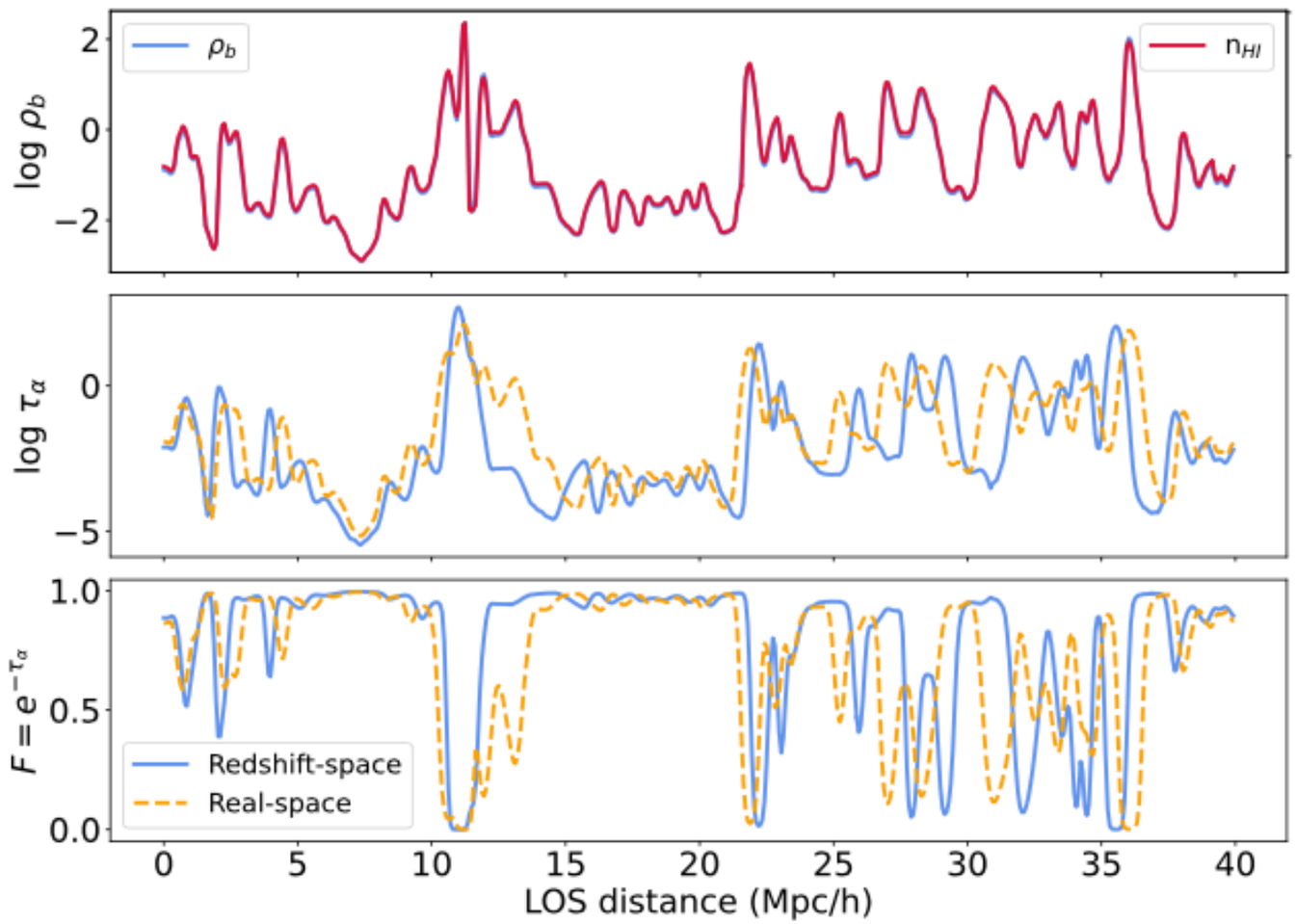


⇒ 3D field (anisotropic): $\delta_F = \frac{F}{\overline{F}} - 1$

δ_F is the measurable Lya "density contrast"

The Lyα 3D power spectrum

3D δ_F field = a biased LSS tracer, like galaxies

⇒ Compute its **3D power spectrum**:

$$P_{\rm 3D}(k_{\parallel}, k_{\perp}) = \left\langle \left|\tilde{\delta}_F(k_{\parallel}, k_{\perp})\right|^2 \right\rangle$$

$$P(k,\mu) \sim b^2(1+\beta\mu^2)^2 P_{\rm lin}(k) F_{\rm NL}(k,\mu)$$

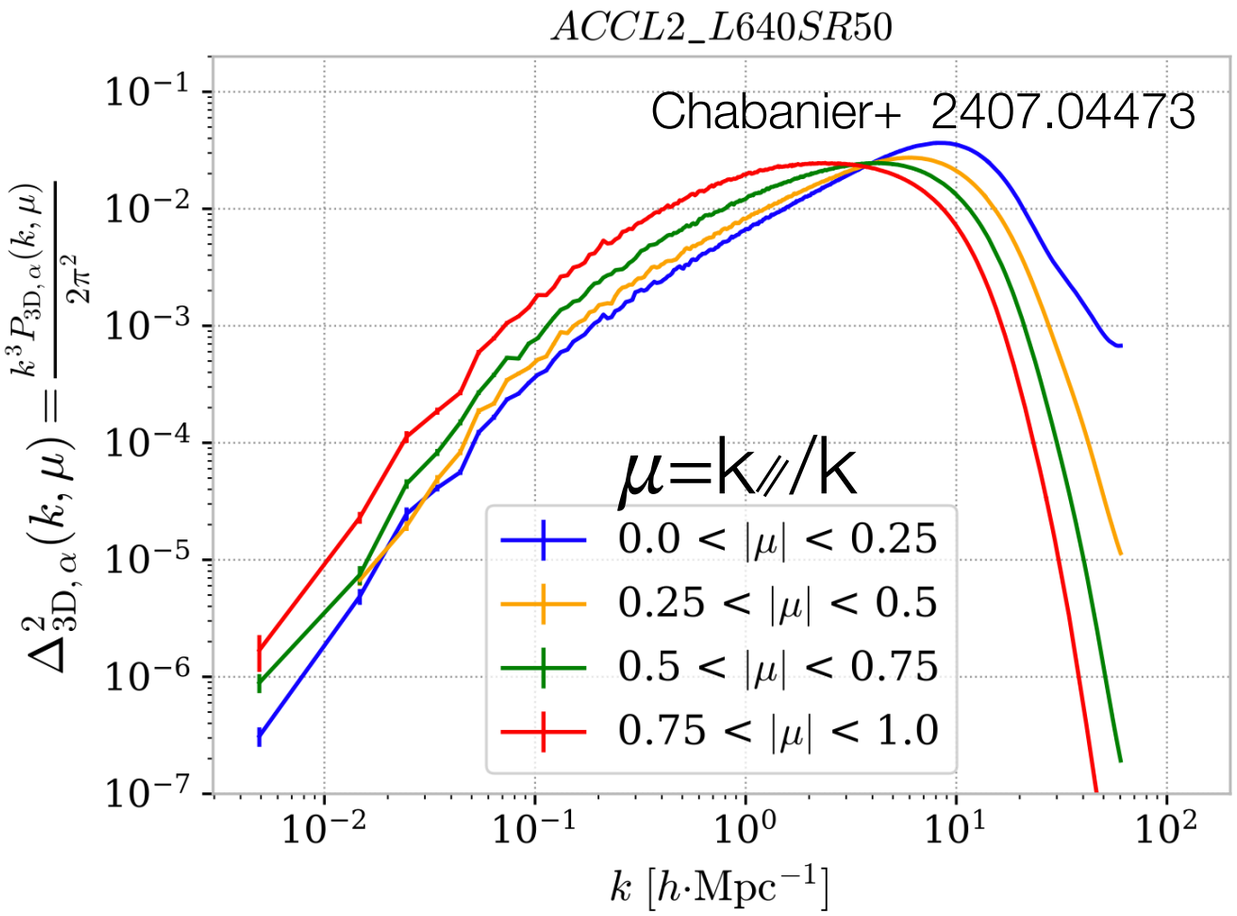
Kaiser: linear bias + RSD

non-linear effects

Non-linearities are relatively small for k<1 Mpc

Physical effects well-understood:

- Non-linear gravitational growth
- Thermal line broadening
- Jeans smoothing of the gas

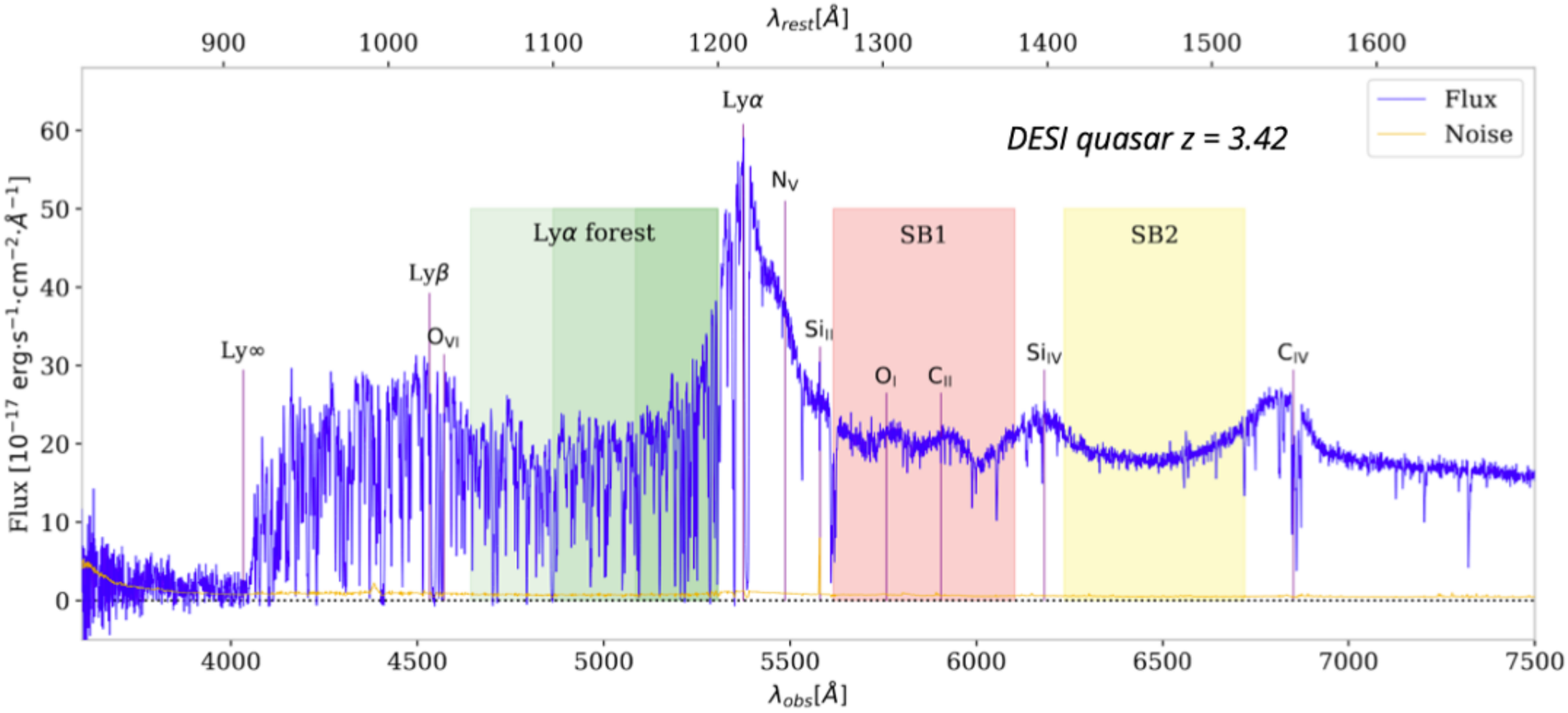


The DESI survey

3D spectroscopic map of LSS

Main goal: BAO (standard ruler to measure the Universe expansion)

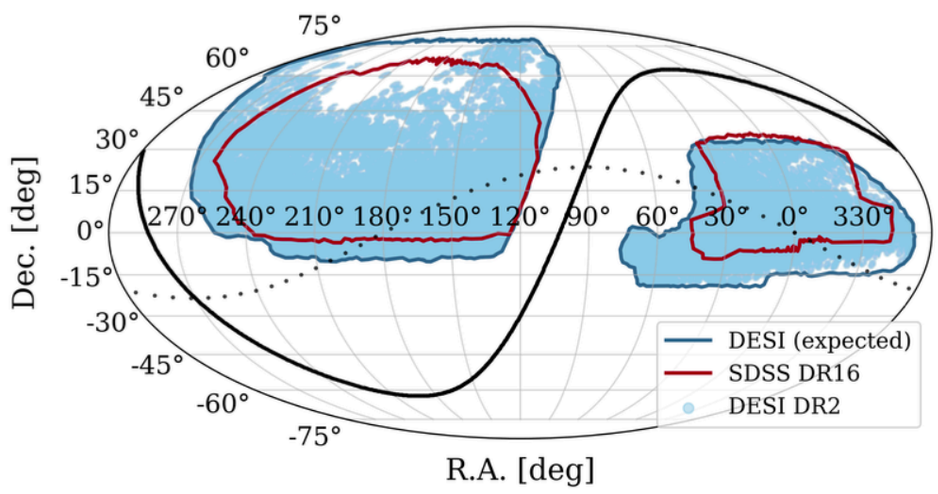
DESI Lyman-α forest sample



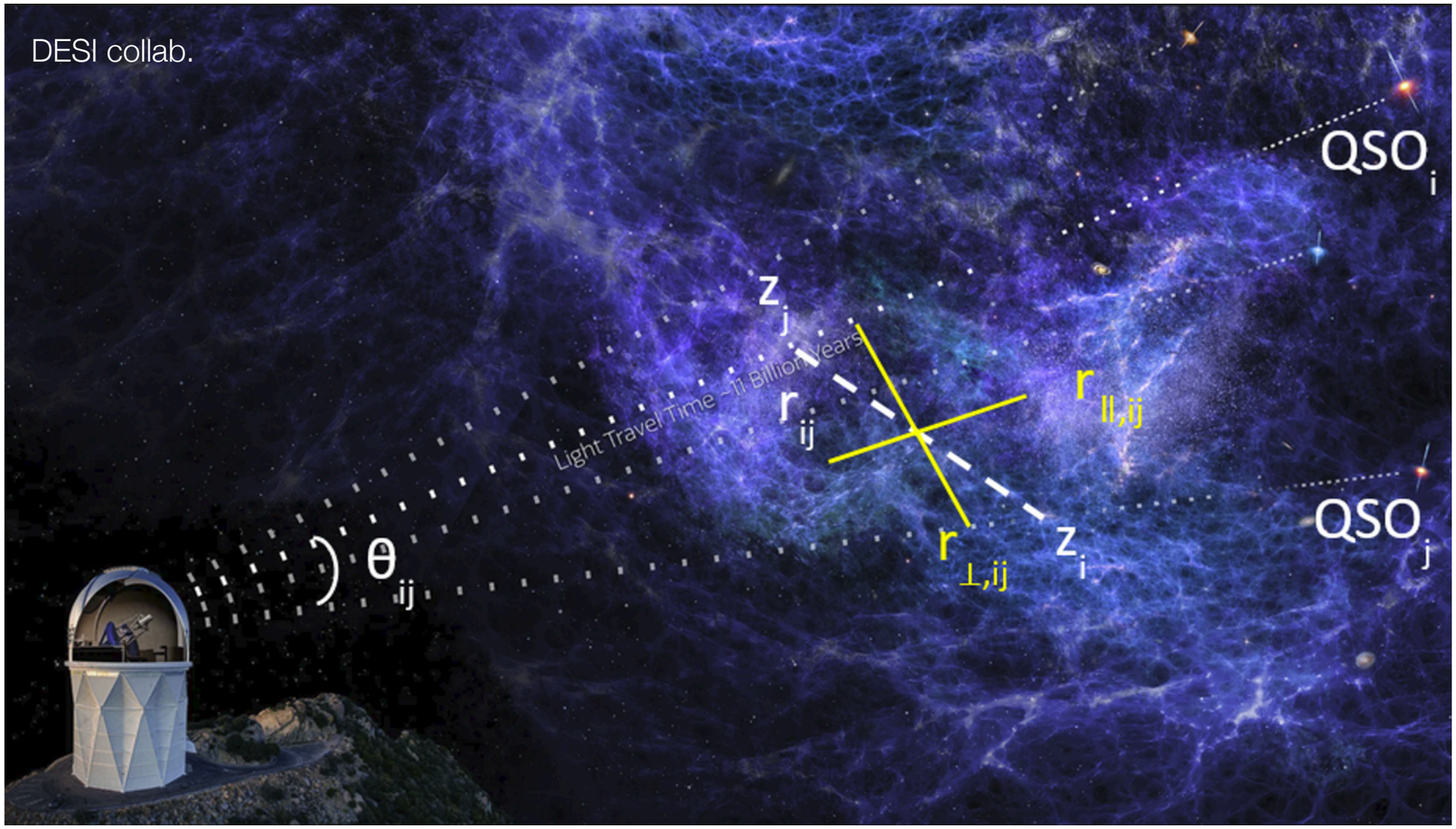
DESI DR2 sample:

820,000 Lyα spectra (z_{QSO}>2.1) @ z_{eff} = 2.33

60 spectra / deg^2



Measuring Lyα correlations: large scales



3D correlations: $\xi(r_{\parallel}, r_{\perp}) = \langle \delta_F(\vec{x}) \delta_F(\vec{x} + \vec{r}) \rangle$

also the 3D cross-correlation with QSO positions

The Lyα x Lyα correlation signal

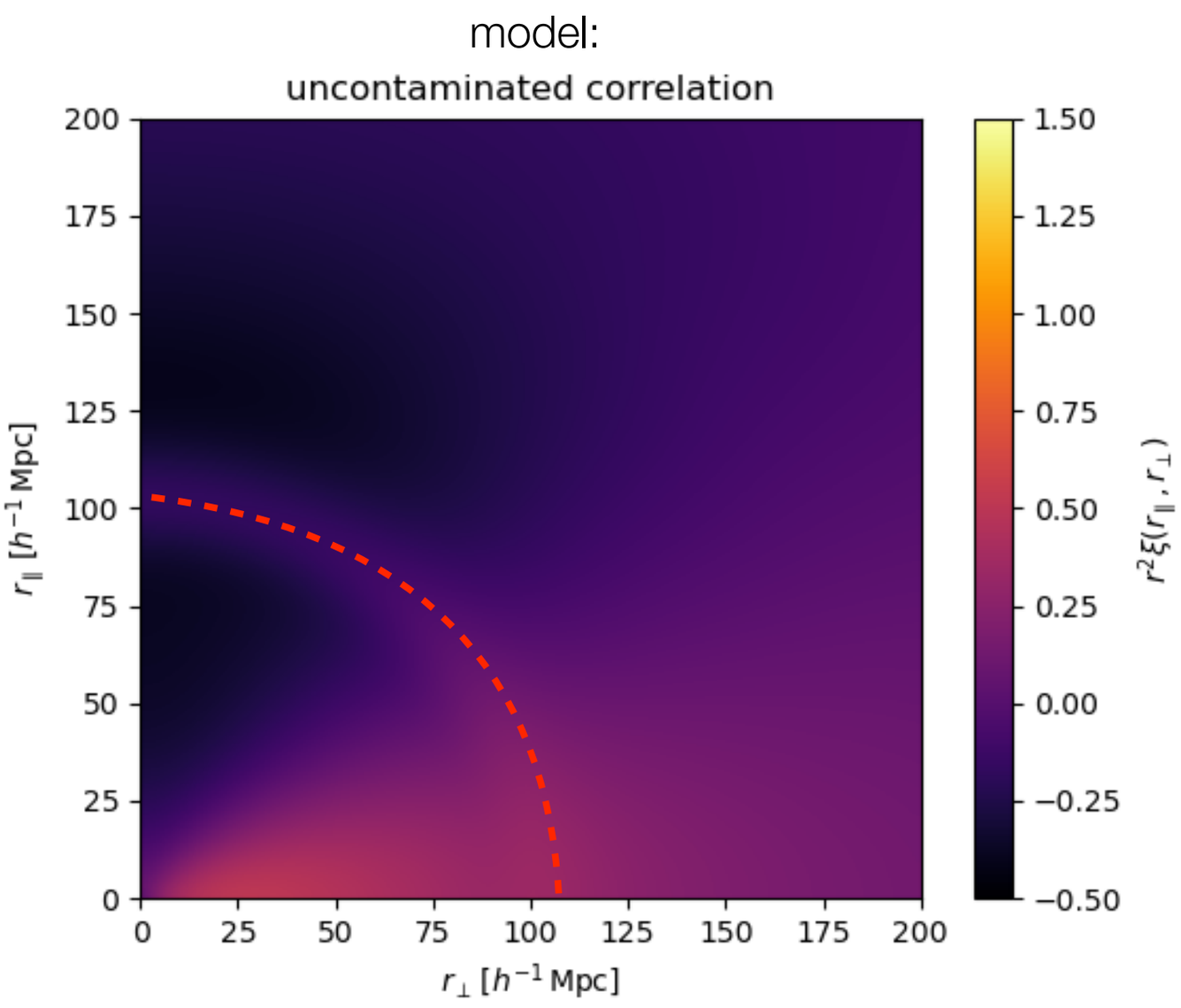
Correlation = Fourier [power spectrum]

$$P(k,\mu) \sim b^2(1+\beta\mu^2)^2 P_{\rm lin}(k) F_{\rm NL}(k,\mu)$$

includes BAO distance scale:
2 main fit parameters

$$\alpha_\parallel = \frac{D_H(z_{\rm eff})/r_d}{[D_H(z_{\rm eff})/r_d]_{\rm fid}}$$

$$\alpha_\perp = \frac{D_M(z_{\rm eff})/r_d}{[D_M(z_{\rm eff})/r_d]_{\rm fid}}$$

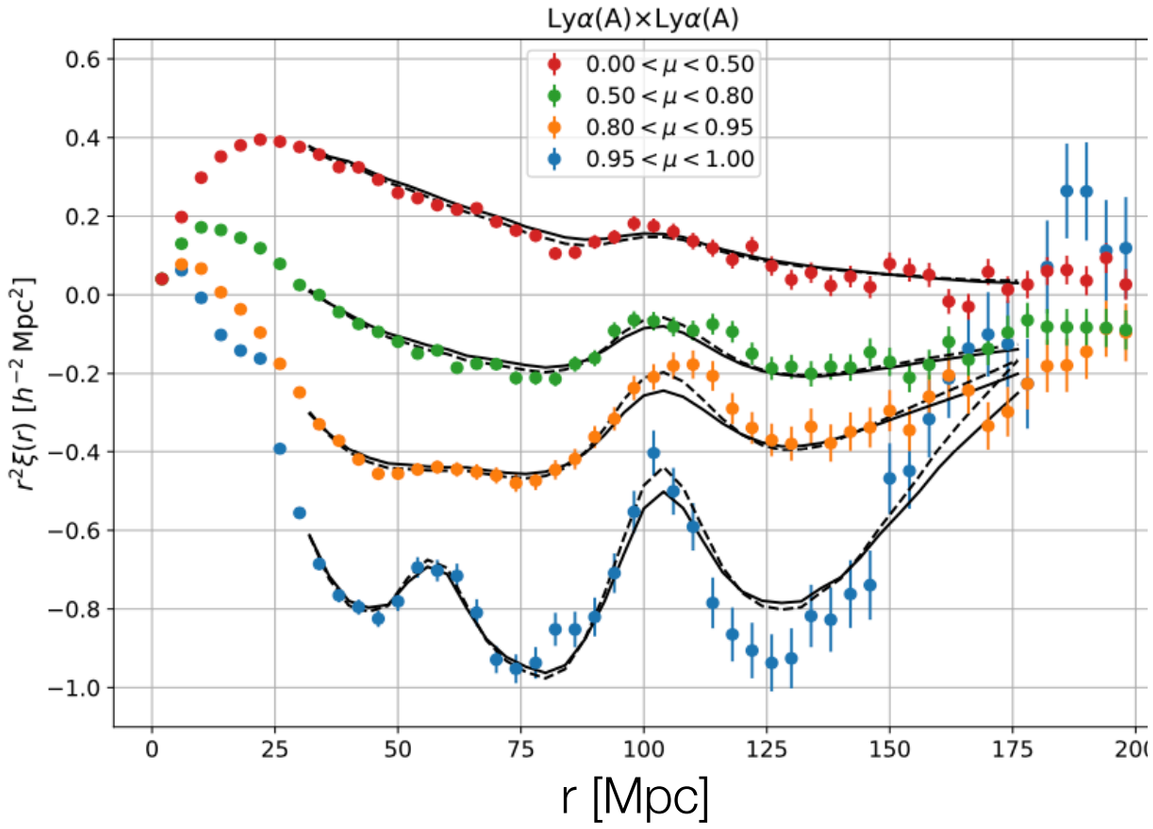


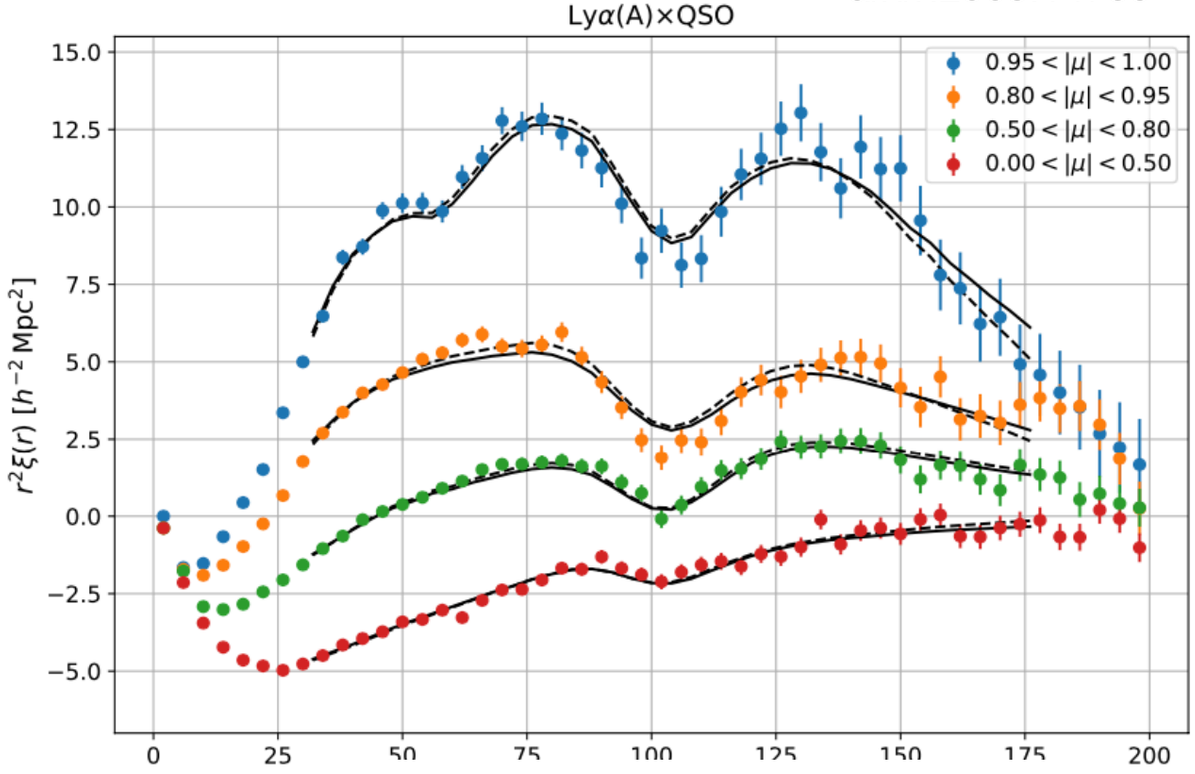
Real-life complications:

- metals
- quasar's continuum
- strong absorbers (circumgalactic medium)

Correlation measurement and DR2 BAO fit

arxiv:2503.14739



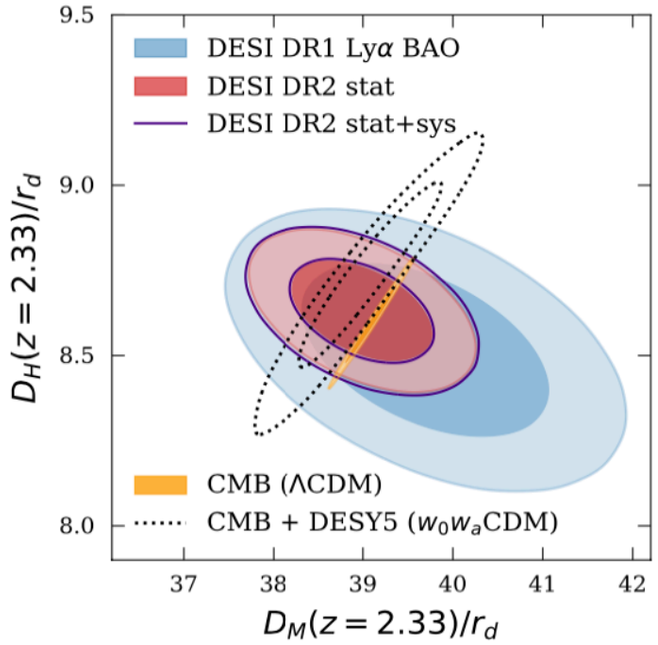


Fit 4 correlations with 2 main parameters ($\alpha_\parallel$, $\alpha_\perp$)

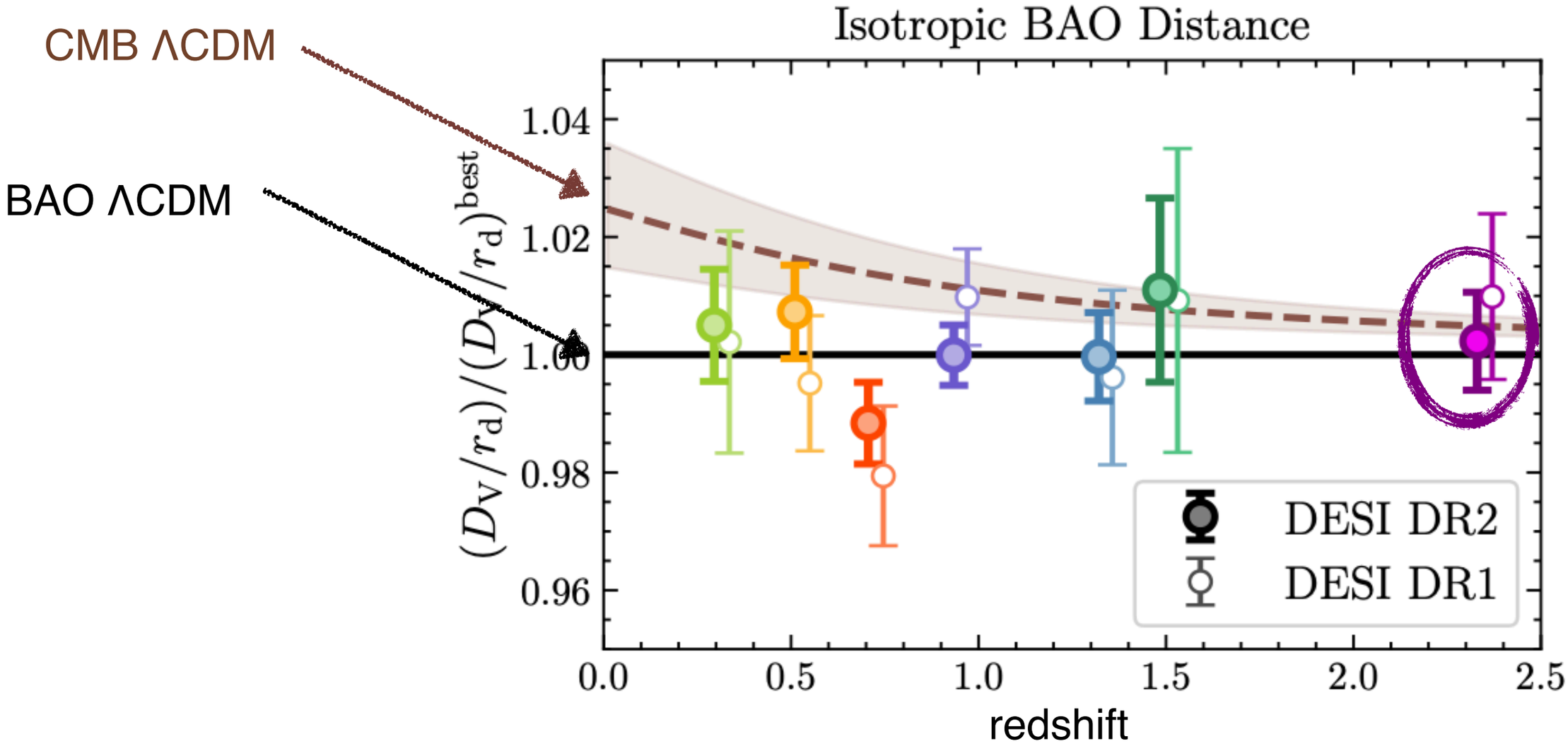
+ 15 nuisances

Chi2/dof = 9304.5/(9306−17) = 1.002 [PTE 45%]

Statistics-dominated measurement for BAO parameters



BAO measurements: Lyα vs galaxies



DESI DR2: **0.7% (stat+syst) precision** on isotropic BAO @ z=2.3

a high-redshift "anchor point" for cosmology

Lyα 3D correlations: beyond BAO

- **Large-scale Lyα correlations: essentially BAO, Alcock-Paczynski (AP), linear growth of structure**

- Template-based model for fit:

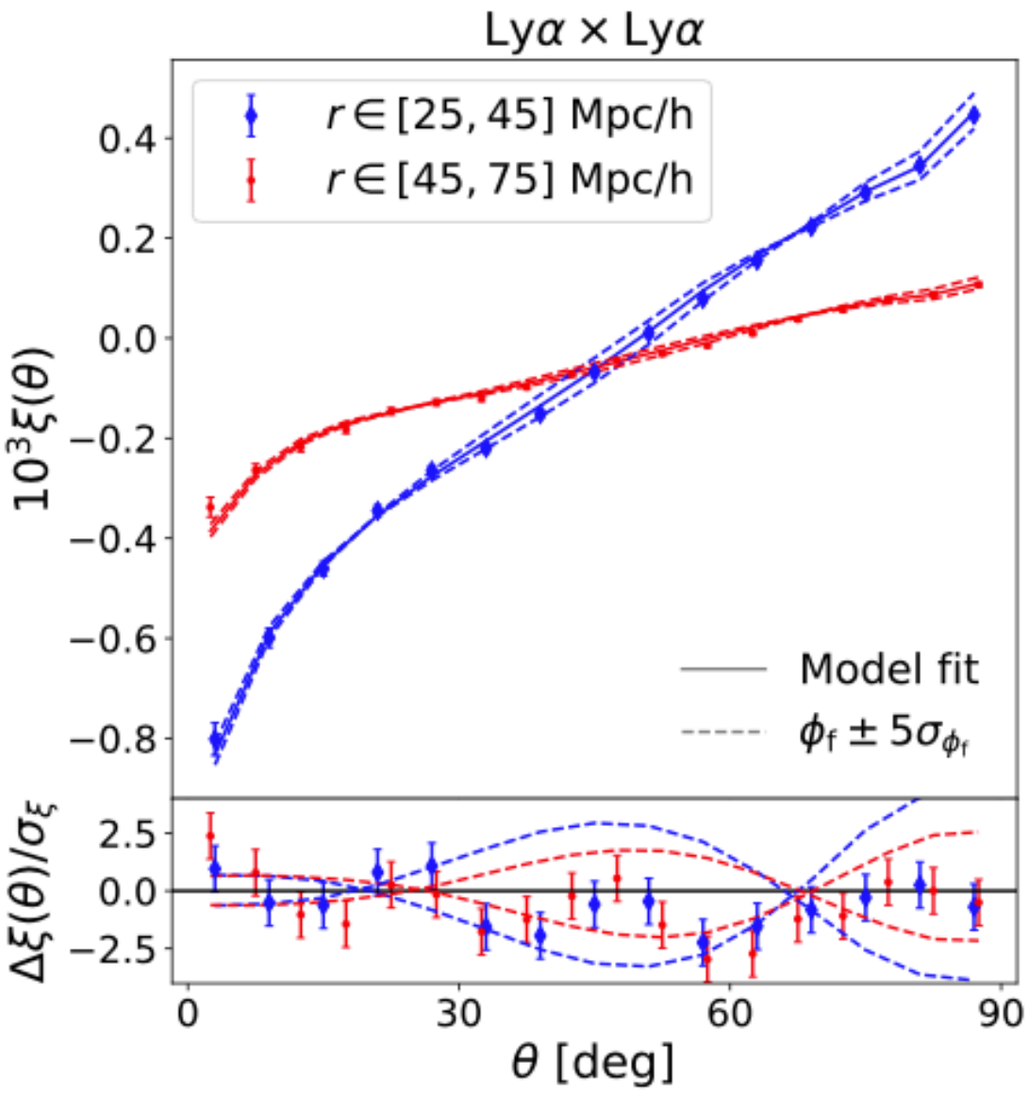
$$\xi(r_\parallel, r_\perp) = \xi_s(q^s_\parallel r_\parallel, q^s_\perp r_\perp) + \xi_p(q^p_\parallel r_\parallel, q^p_\perp r_\perp)$$

broadband **BAO**

- Focus on $\phi_s = \dfrac{q^s_\perp}{q^s_\parallel}$:

Alcock-Paczynski (D_M/D_H) from the broadband robustly measured

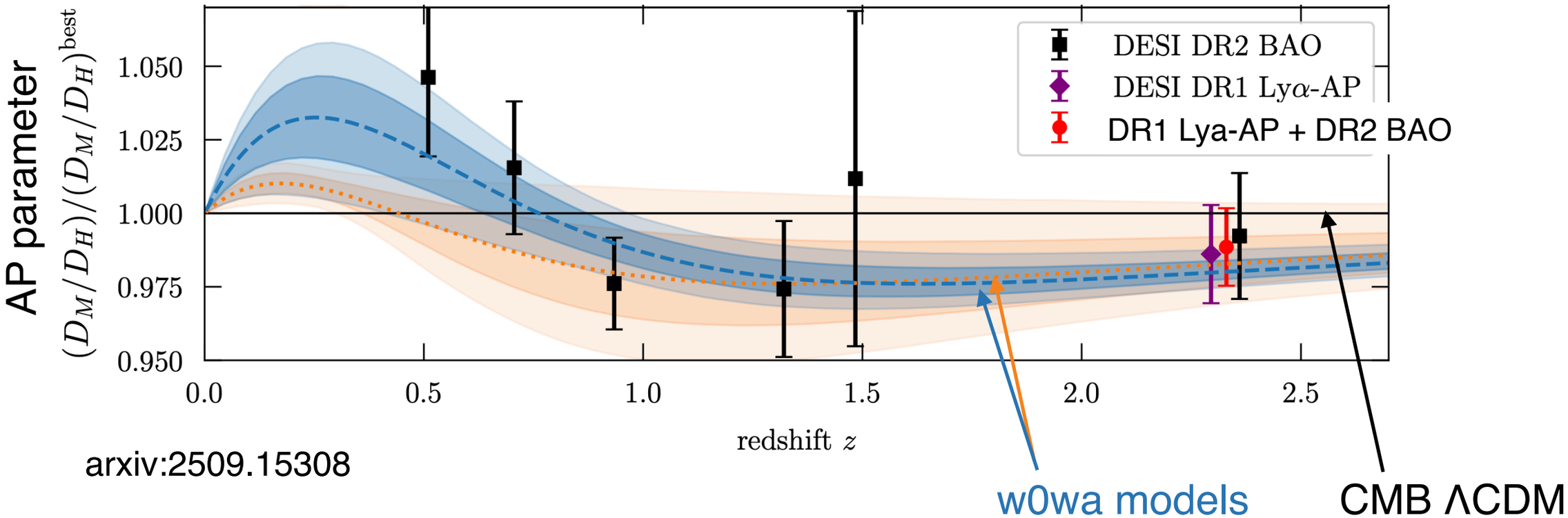
DESI DR1: $\phi_s = 0.987 \pm 0.017$



arxiv:2509.15308

High-redshift AP measurement: impact on cosmology

1.6% measurement of AP: factor of 2.4 improvement wrt DR1 BAO

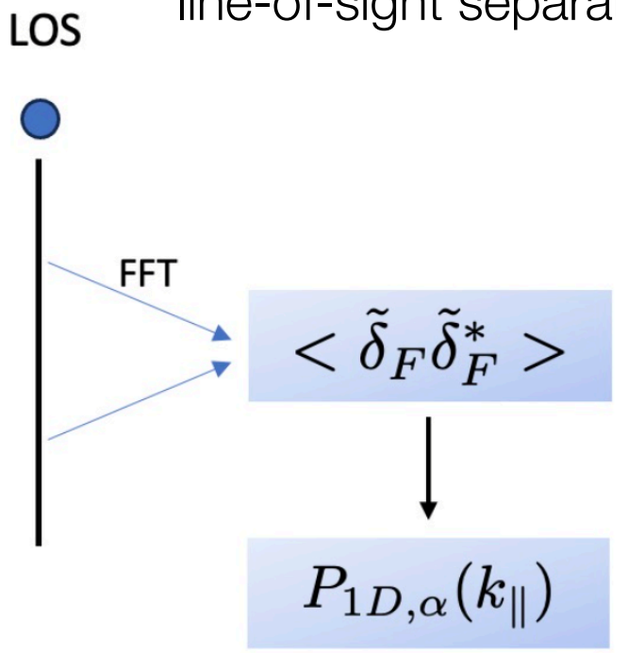


arxiv:2509.15308

- Although this is z~2.3, the AP parameter is sensitive to Dark Energy!
- DR2 measurement in prep.

Small scale Lyα correlations: P1D

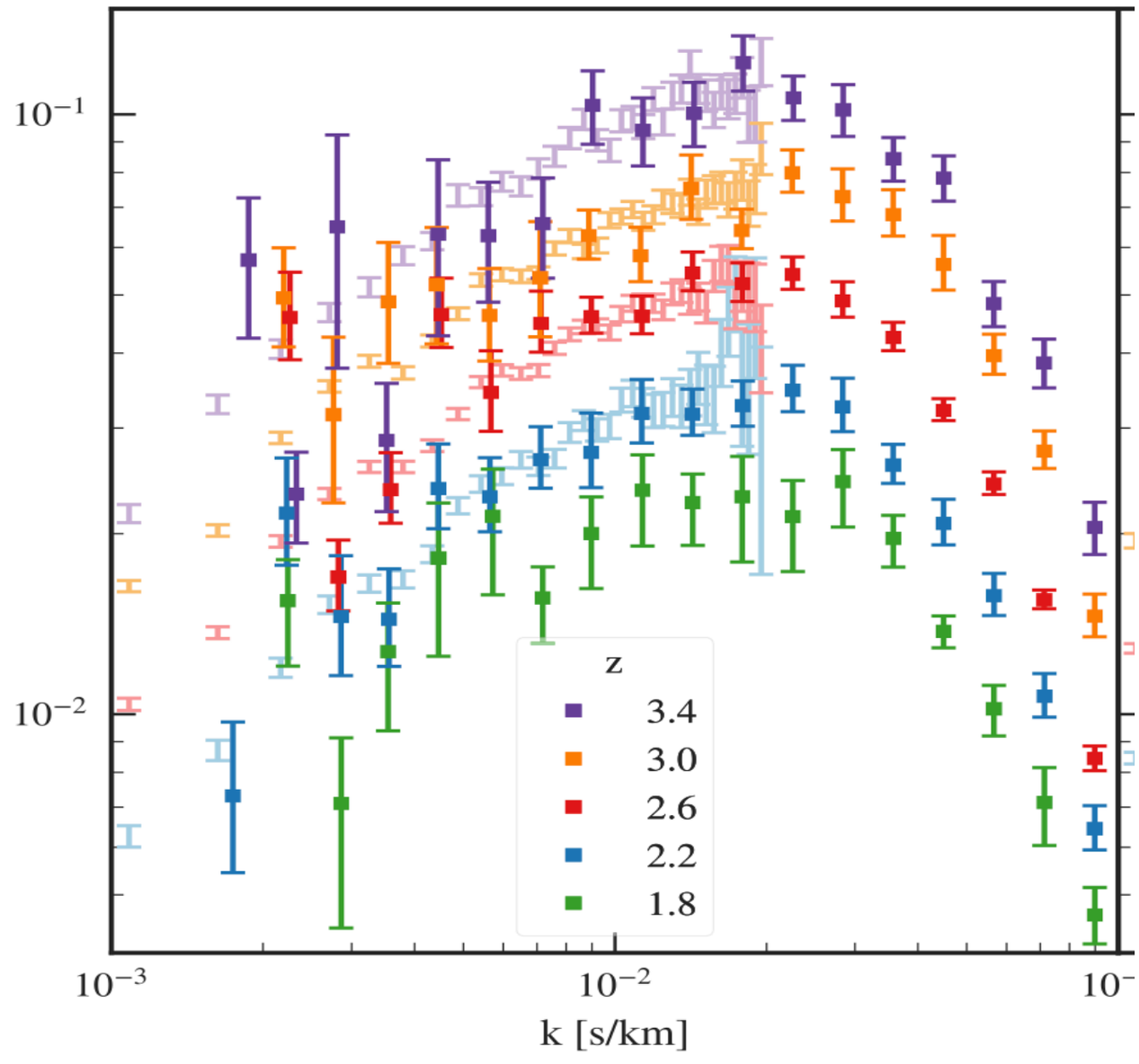
line-of-sight separation >> wavelength separation



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

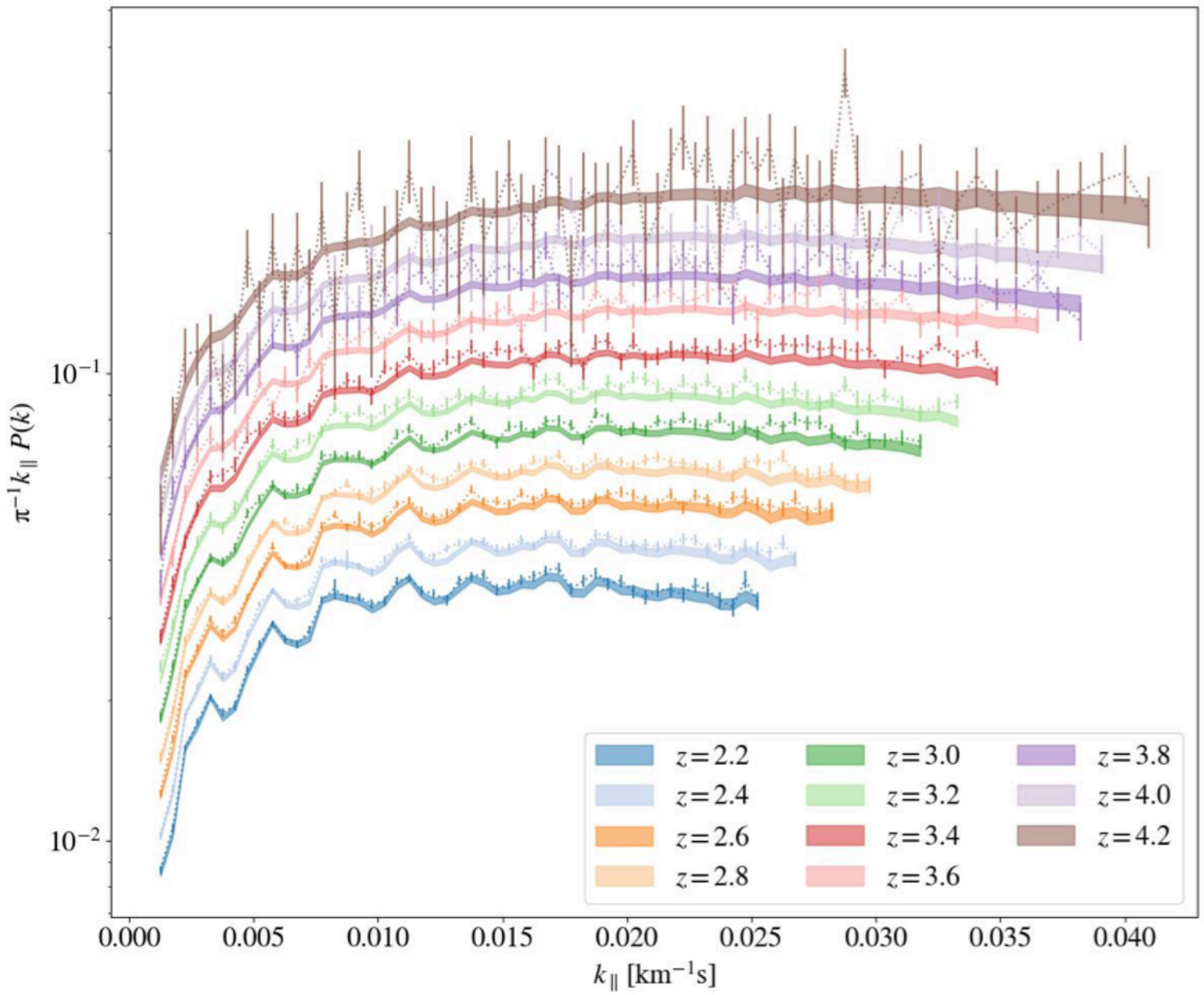
- "Historical" LSS probe, can be measured even with a few spectra
- Up to k ~ few Mpc^{-1}
- Now %-level precision

Walther+ 2018

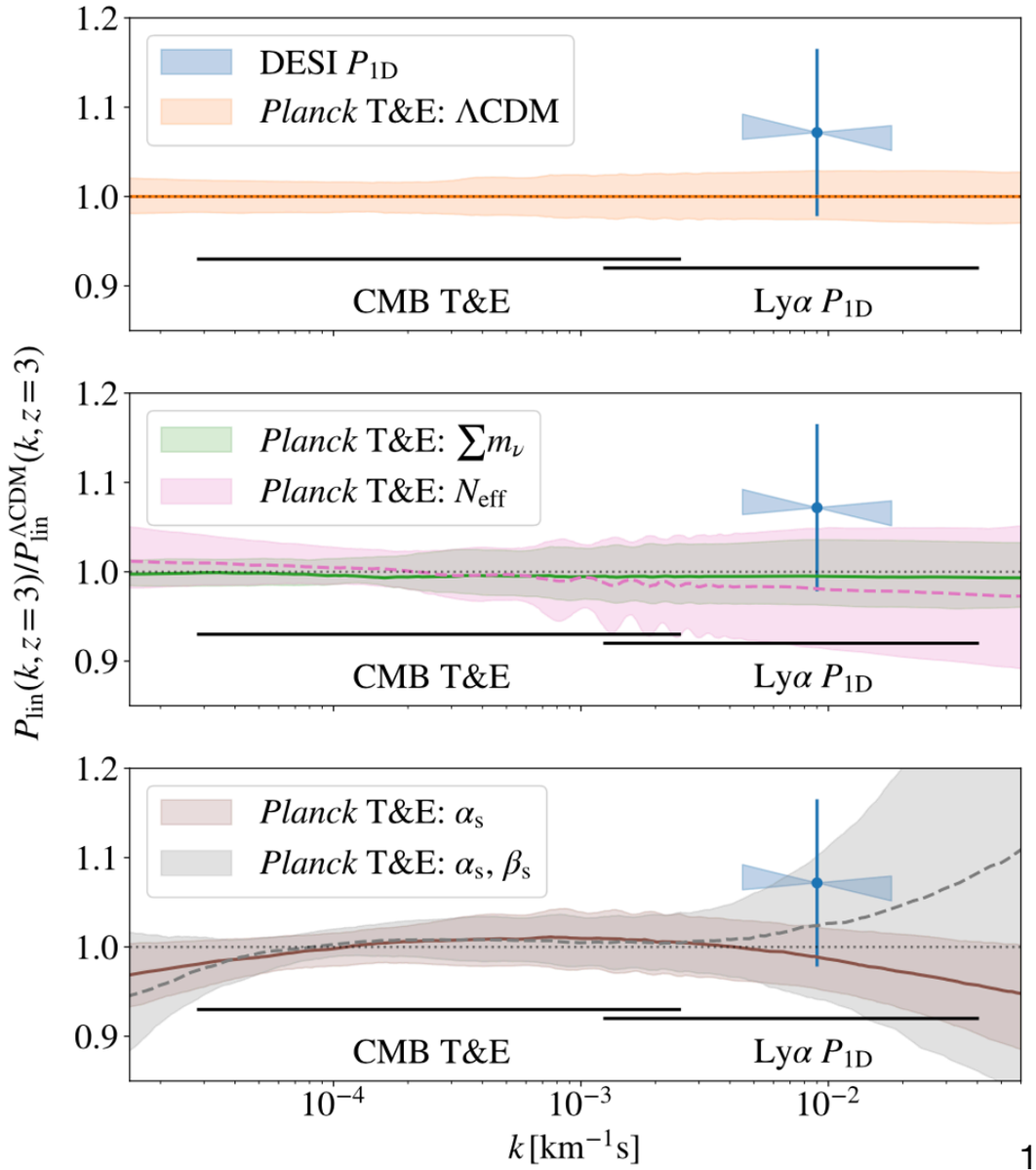


DESI DR1 Lyα small-scale P1D

$P_{1D}(k)$ measurements in 11 redshift bins
$2.2<z<4.2$ (arxiv:2505.09493)



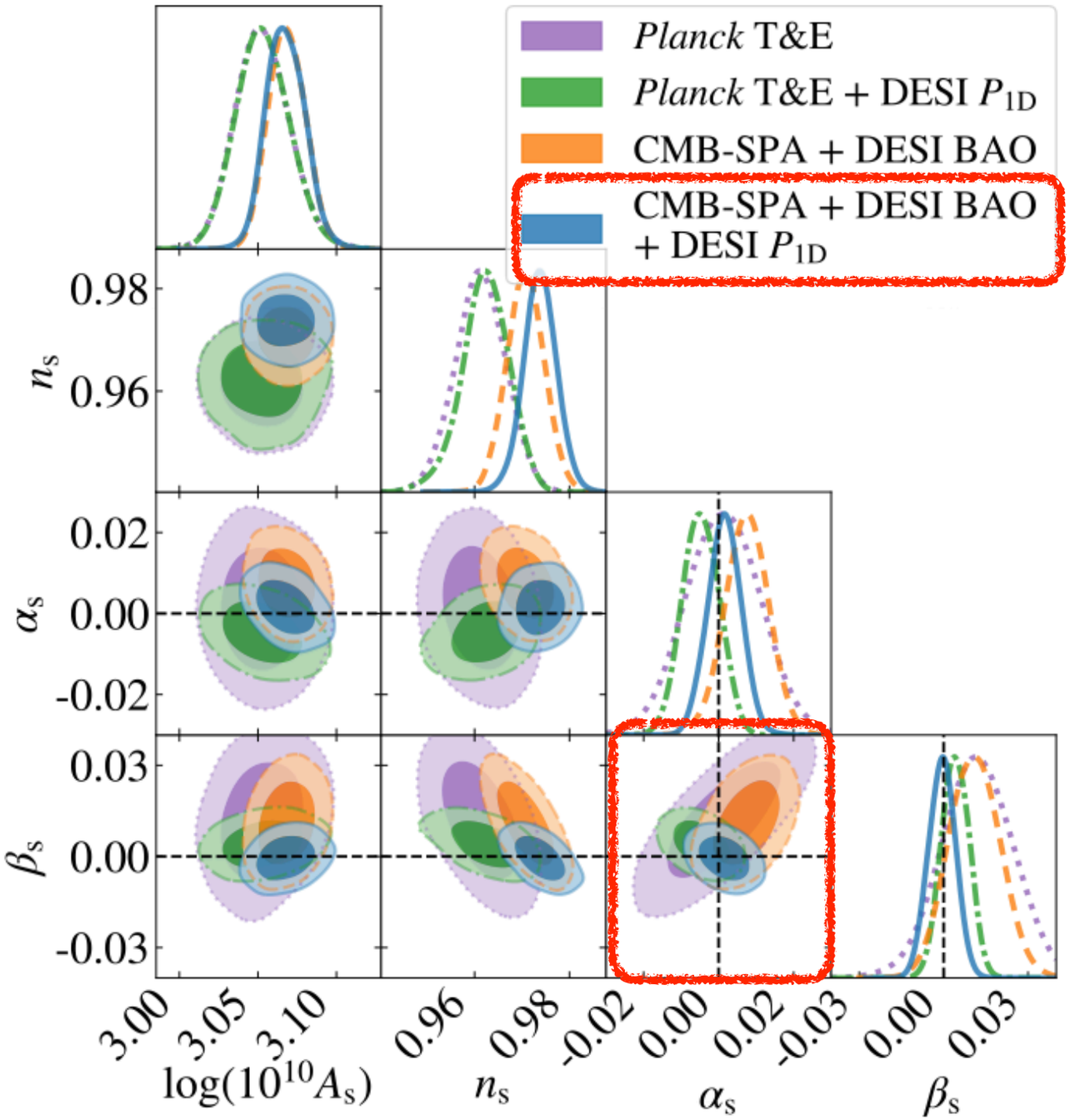
Model fit: sensitive to **(amplitude, slope) of linear matter power spectrum** at k~Mpc^{-1}



P1D: implication for inflation models

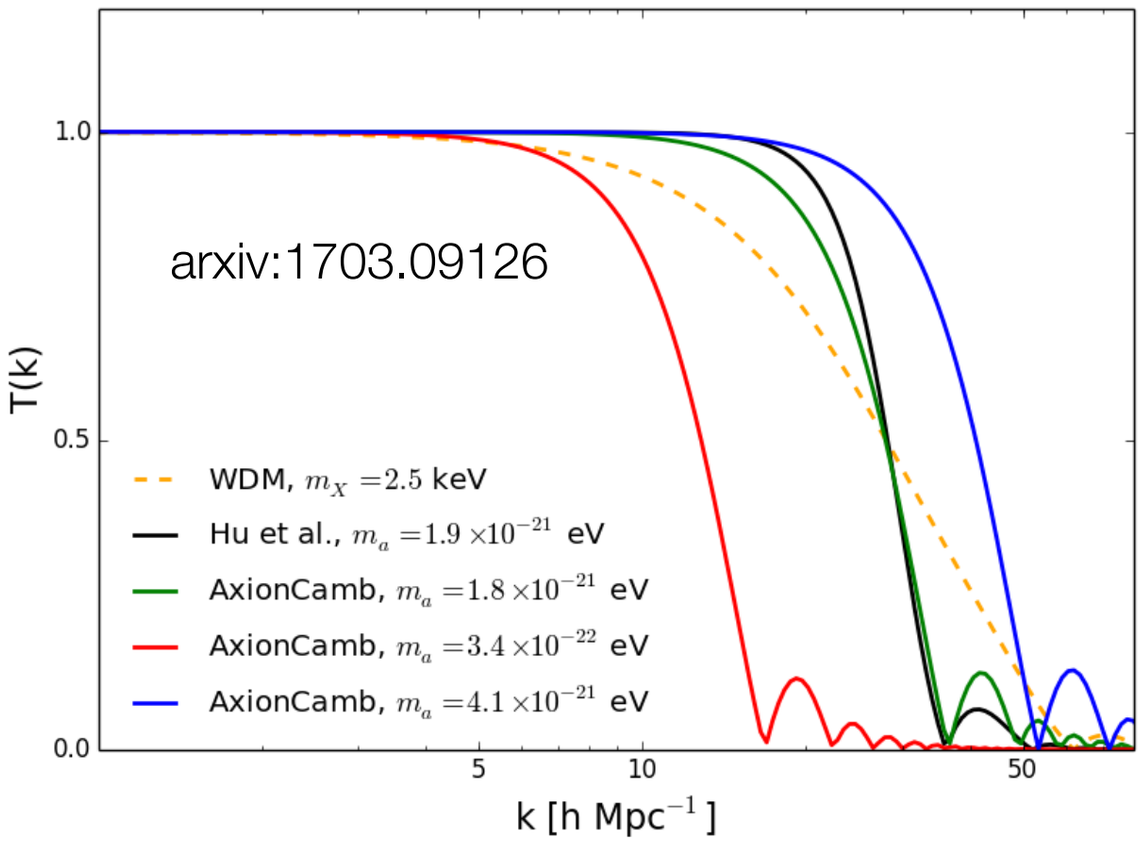
Running of the primordial power spectrum (α_s, β_s):

$$\log \Delta^2_{\mathcal{R}}(k) = \log A_s + (n_s - 1)\log(k/k_s) + \frac{\alpha_s}{2}\log(k/k_s)^2 + \frac{\beta_s}{6}\log(k/k_s)^3$$



arxiv:2601.21432

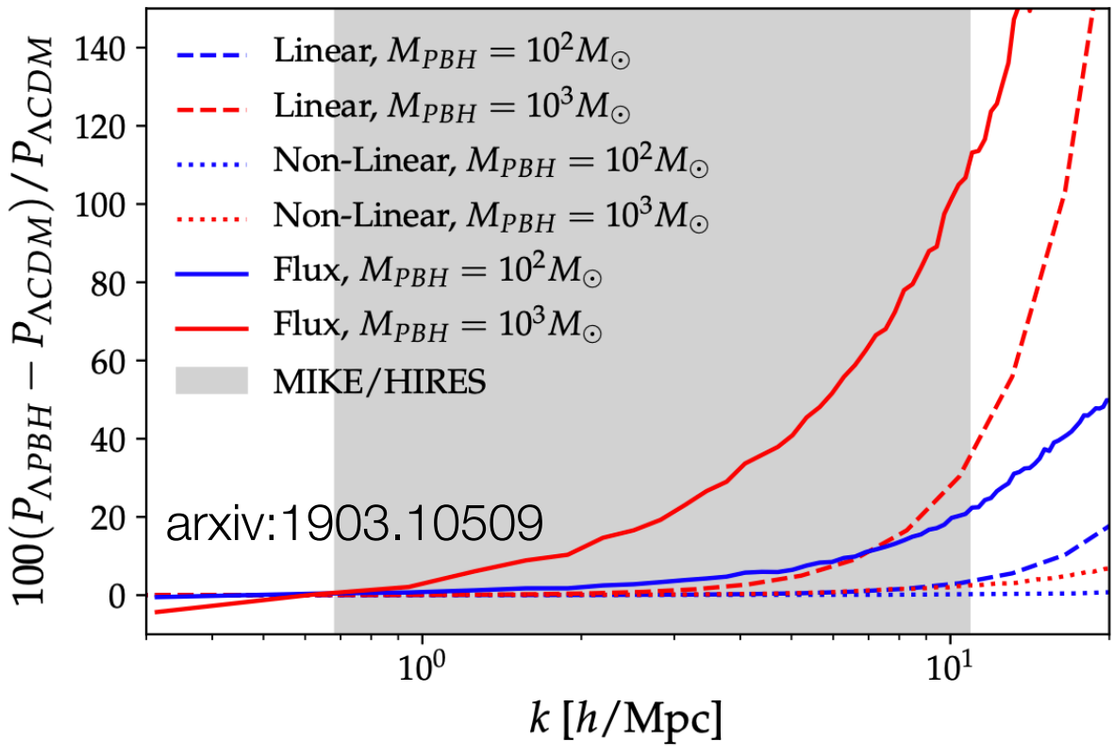
Lyman-α forest constraints on Dark matter models



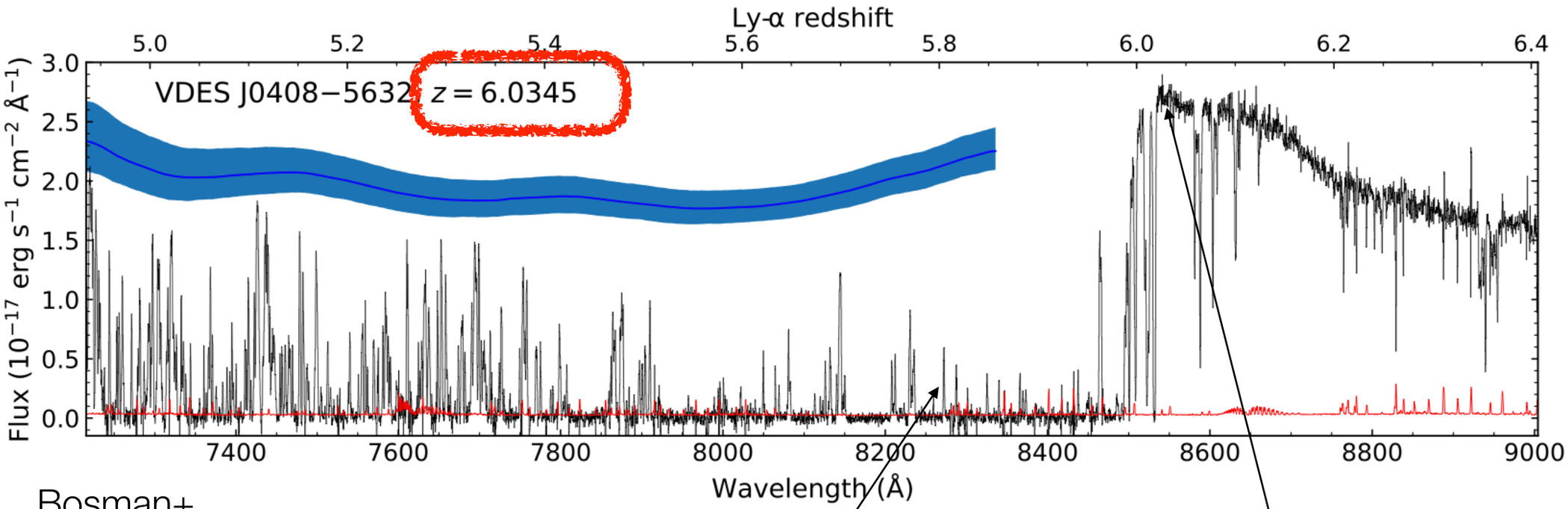
Several DM models predict a cutoff / a bump in P(k) at high k
⇒ Constrained by P1D. Eg.

- Fuzzy DM (lowest mass possible) m~10^{-21} eV
- keV-scale Warm DM

- Massive primordial black holes m~100 M_{sun}



Lyman-α ~~forest~~ absorption and reionization



Bosman+
arxiv:2108.03699

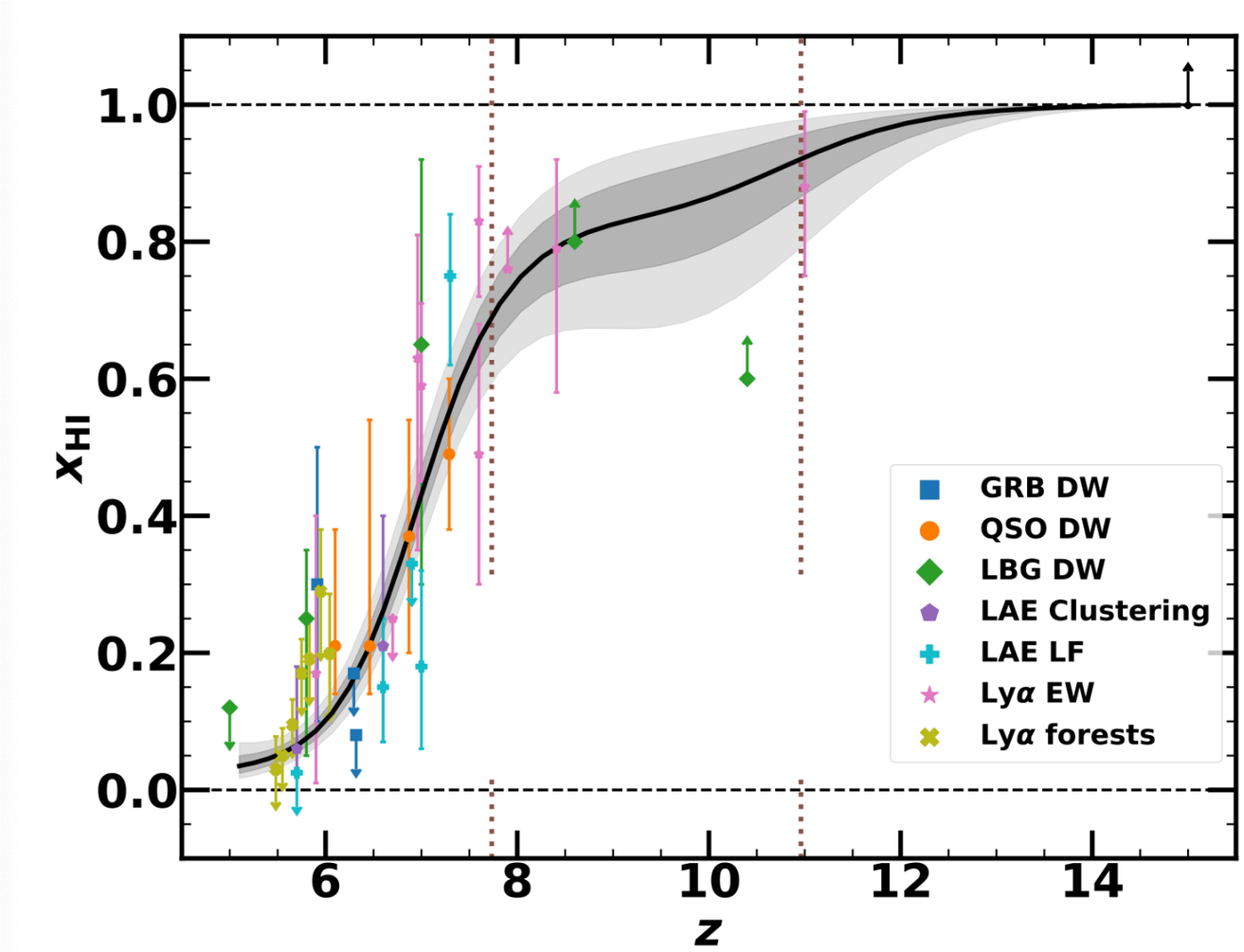
Lya transmission spikes

Lya damping wing

Lya absorption becomes nearly complete (F~0) for $z \sim z_{reio}$

The neutral Hydrogen fraction $\mathbf{x_{HI}}$ can be inferred from transmission spikes in QSO spectra (z~6) or Lya damping wings in JWST galaxies (z~9).

Lyman-α ~~forest~~ absorption and reionization



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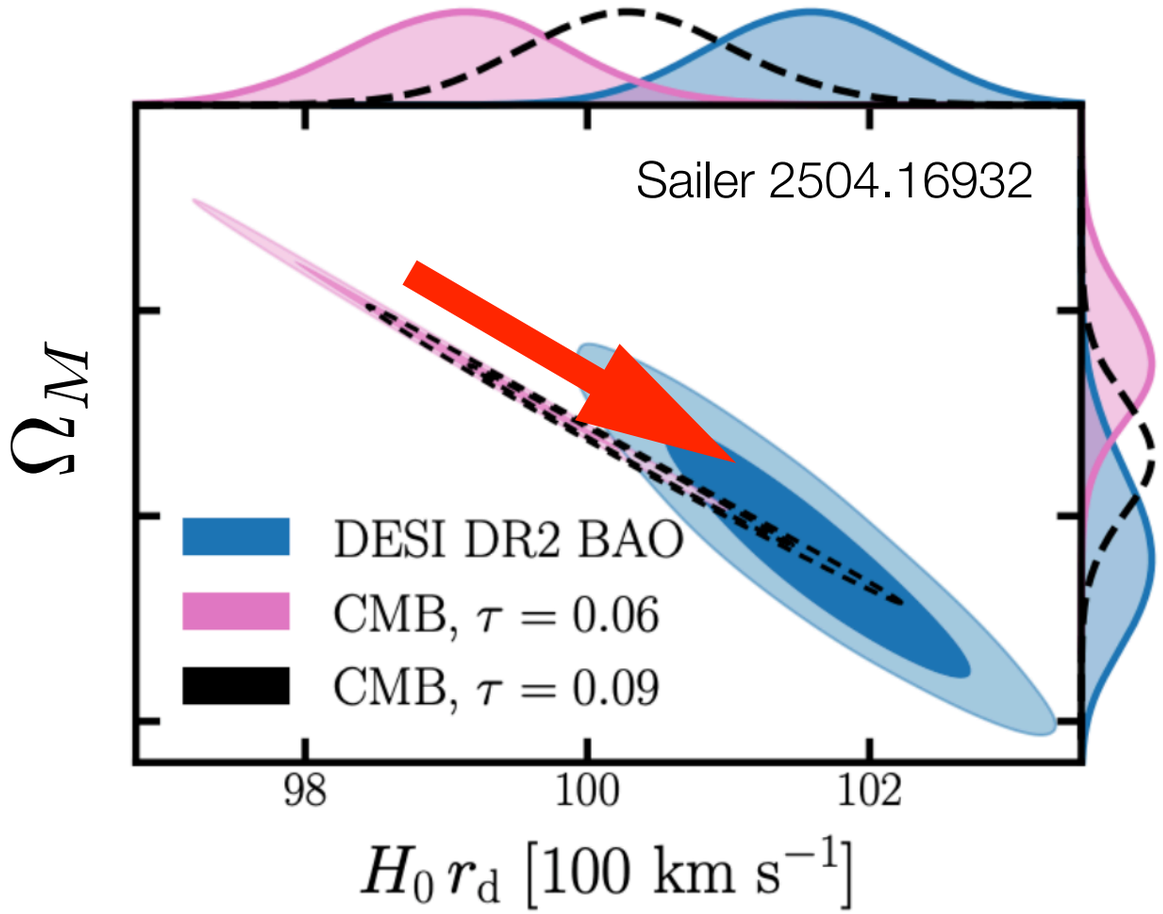
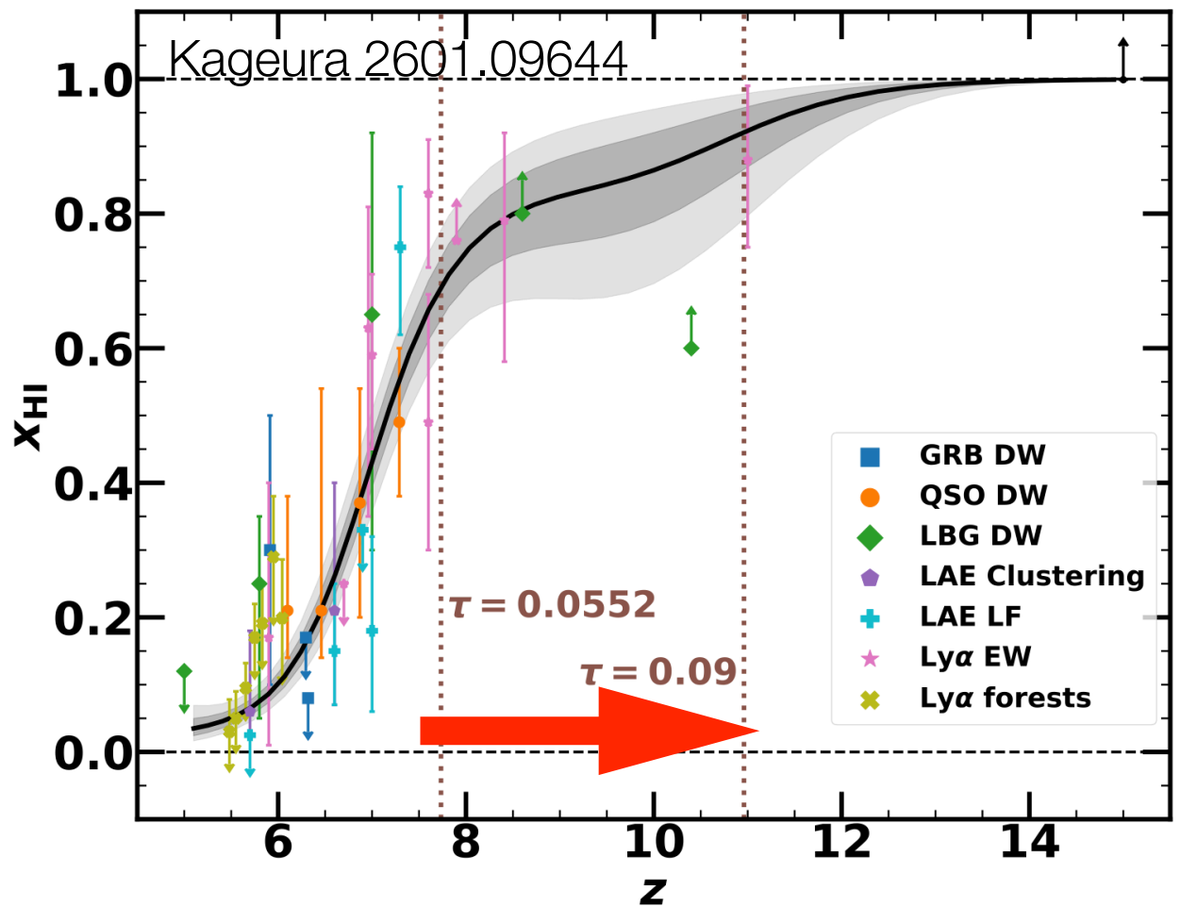
Reionization and cosmological tensions

BAO - CMB tension in LCDM
Can be alleviated by:
dynamical dark energy,
negative neutrino masses,...
or **arbitrarily changing τ in CMB**



$$\tau \sim \int_0^{1050} (1 - x_{\rm HI}) dz$$



⇒ This scenario is constrained by

Lya absorption measurements around $z_{\rm reio}$

Outlook

The Lyman-alpha forest is an "old" cosmological probe .. but its full potential is only starting to emerge

- Precise high-z cosmological distance scales
- Shape of the linear matter power spectrum (inflation, Dark Matter, ...)
- Epoch of reionization
- ...

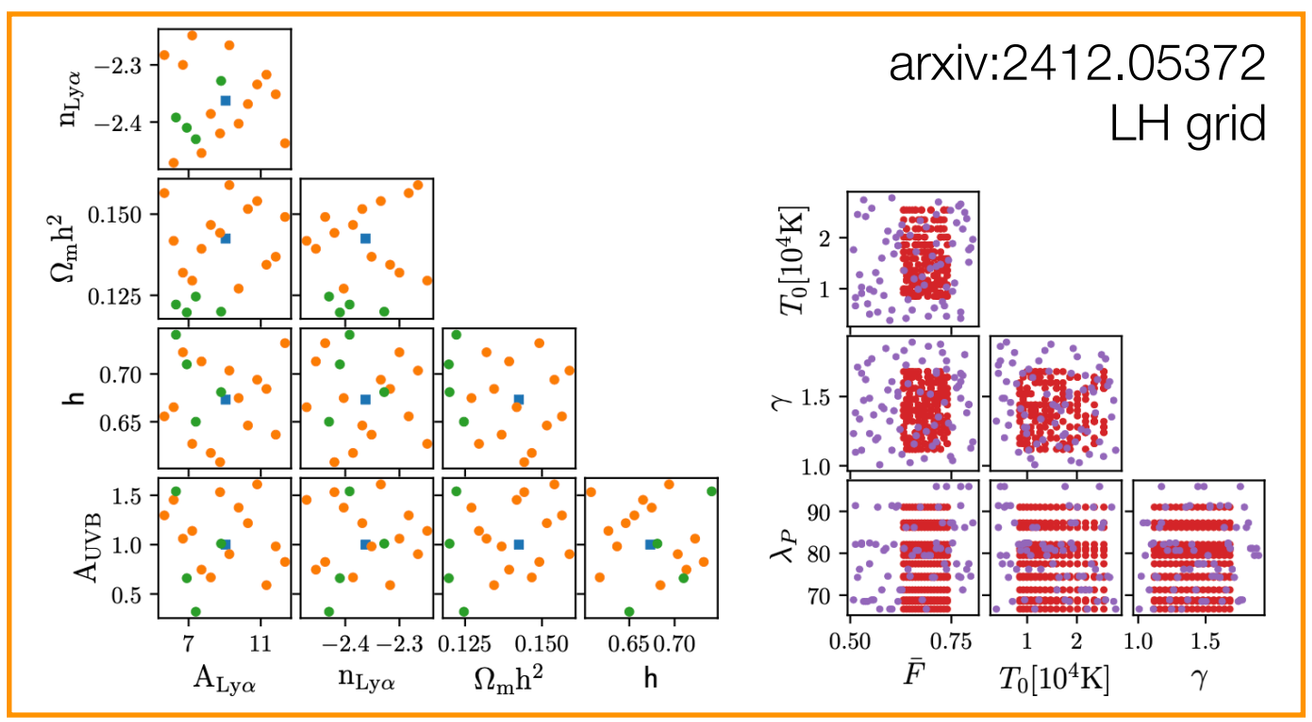
What's next?

- Many more DESI results to come
- Next surveys will use LBG spectra in addition to QSO: much more dense sampling of the cosmic web
- Obvious synergies with other upcoming high-z surveys (galaxies, 21cm, etc.)

Modelling and interpreting P1D data

- Need to rely on a finite set of hydro simulations
- Interpolation scheme (Taylor expansion; GP emulator, etc.)
- Include other nuisance parameters

Simulation suite	Box size		Resolution		Code
B13* [10]	25 Mpc/h	$\sim$37.0 Mpc	130.2 h^{-1} kpc	$\sim$193 kpc	GADGET-3
	100 Mpc/h	$\sim$148 Mpc	130.2 h^{-1} kpc	$\sim$193 kpc	
	100 Mpc/h	$\sim$148 Mpc	32.55 h^{-1} kpc	$\sim$48.2 kpc	
B19* [18]	40 Mpc/h	$\sim$57.1 Mpc	156.3 h^{-1} kpc	$\sim$223 kpc	MP-GADGET
THERMAL [19]	20 Mpc/h	$\sim$29.8 Mpc	19.5 h^{-1} kpc	$\sim$29.1 kpc	Nyx
P21* [20–22]	$\sim$47.3 Mpc/h	67.5 Mpc	$\sim$61.4 h^{-1} kpc	87.7 kpc	MP-GADGET
SHERWOOD$^+$ [23, 24]	40 Mpc/h	$\sim$59.0 Mpc	19.5 h^{-1} kpc	$\sim$28.8 kpc	P-Gadget3
PRIYA [11, 12]	120 Mpc/h	$\sim$171 Mpc	39.1 h^{-1} kpc	$\sim$55.9 kpc	MP-GADGET
	120 Mpc/h	$\sim$171 Mpc	78.1 h^{-1} kpc	$\sim$111 kpc	
Lyssa (this work)	$\sim$80.8 Mpc/h	120 Mpc	$\sim$19.7 h^{-1} kpc	29.3 kpc	Nyx



Borde+ 2013
"Taylor" grid

Parameter	Central value	Range
n_s	0.96	$\pm$0.05
σ_8	0.83	$\pm$0.05
Ω_m	0.31	$\pm$0.05
H_0	67.5	$\pm$5
$T_0(z=3)$	14000	$\pm$7000
$\gamma(z=3)$..	1.3	$\pm$0.3
A^τ	0.0025	$\pm$0.0020
η^τ	3.7	$\pm$0.4