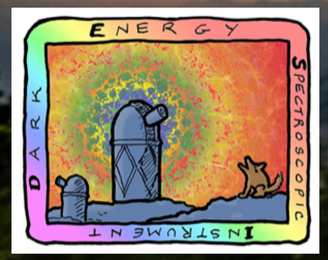
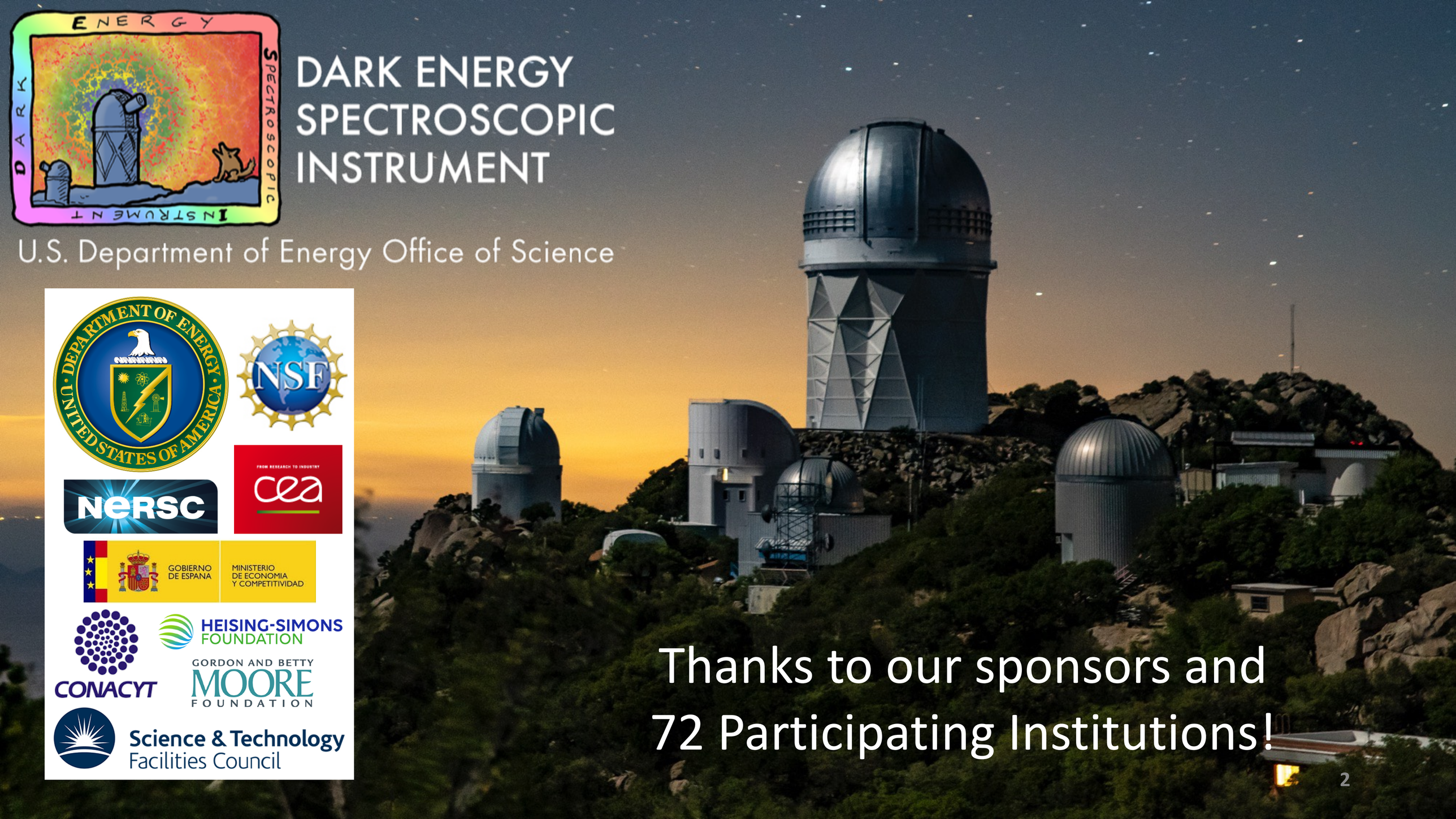
DESI Lyman-alpha forest:

BAO, growth of structure, etc.
synergies with high-z galaxies

E. Armengaud (CEA Saclay)




DARK ENERGY SPECTROSCOPIC INSTRUMENT
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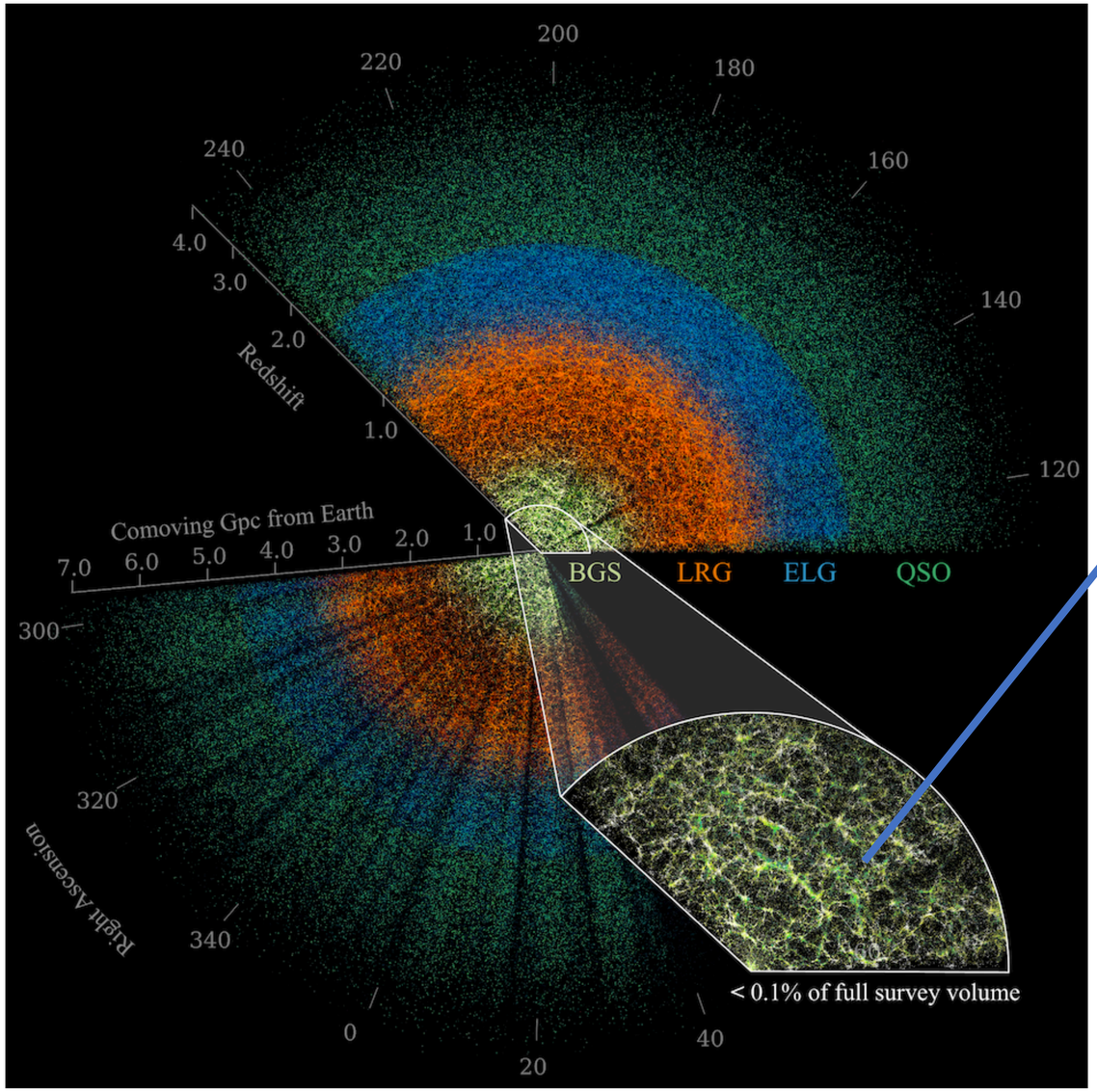
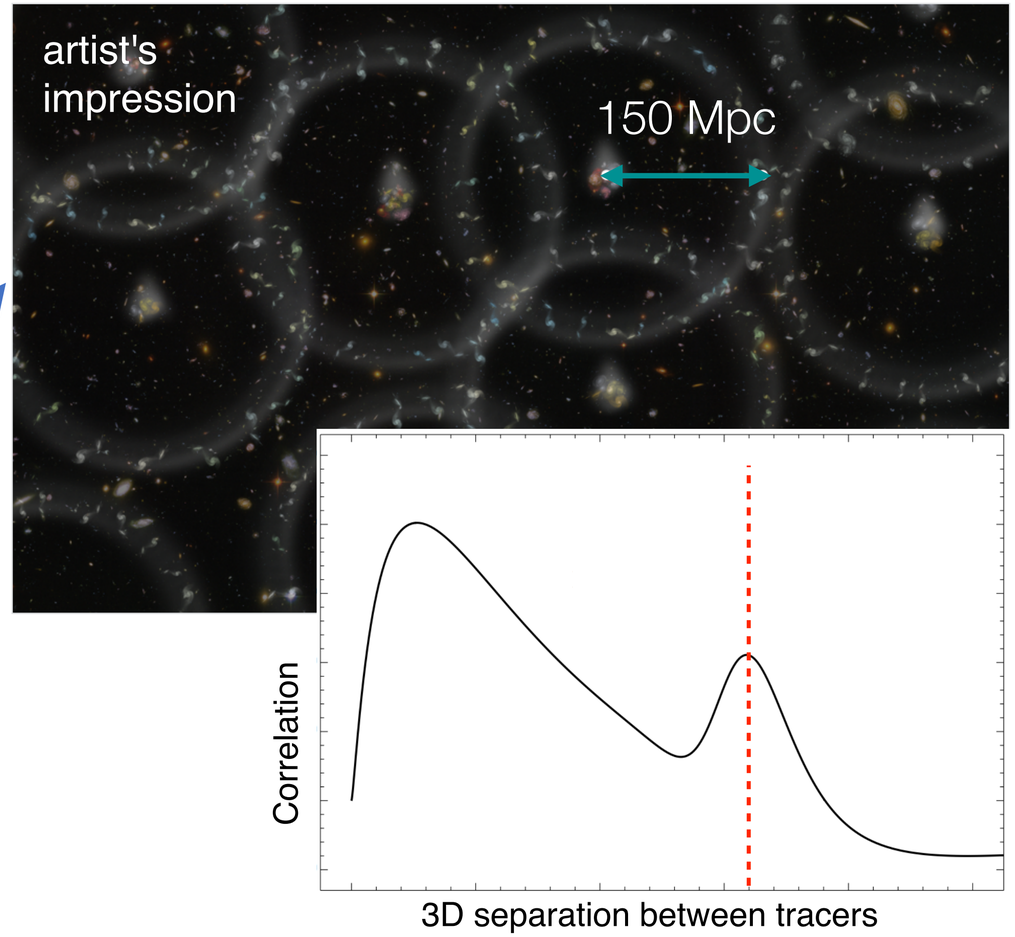
Measuring the BAO with DESI



BAO scale: standard ruler



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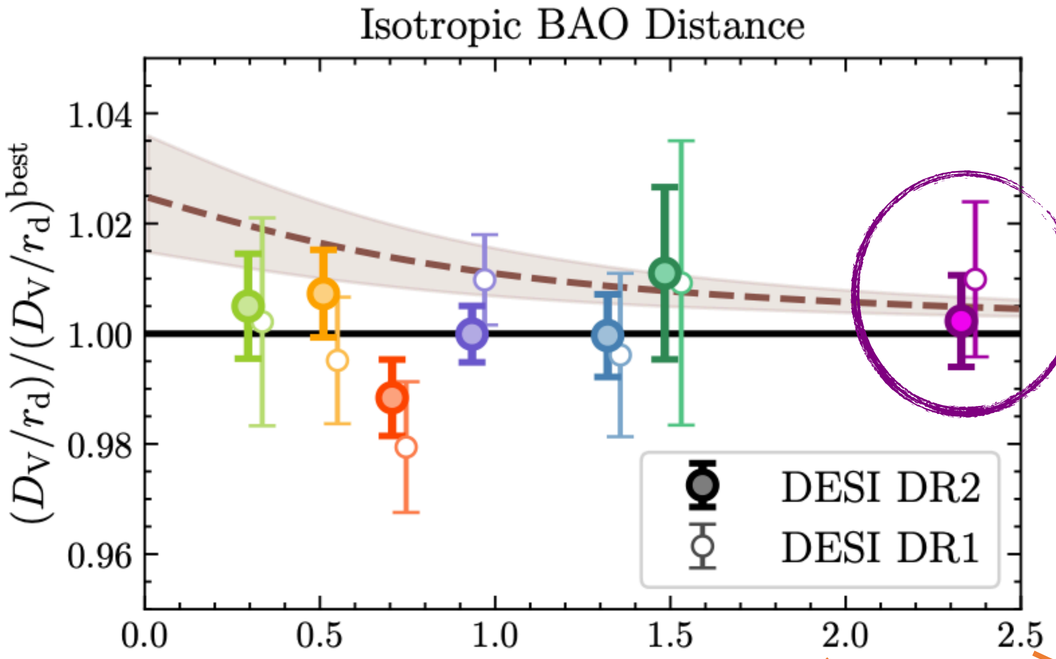
DESI DR2 BAO measurement

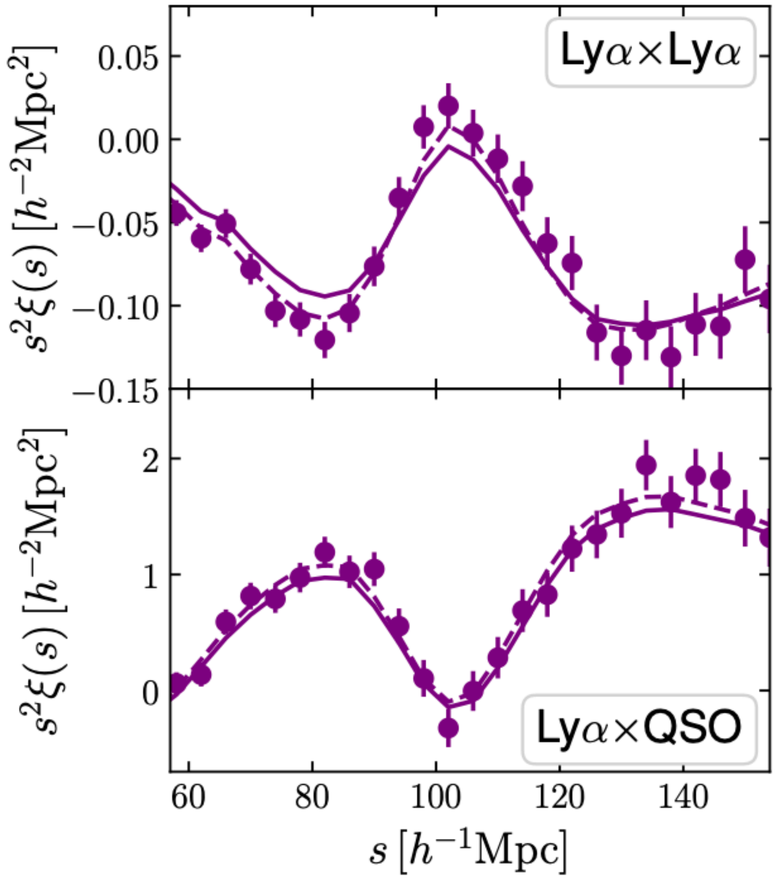


Abdul-Karim+ arXiv:2503.14738

z>2: cosmology in EdS regime (expansion, growth), more linear
⇒ **Lyα forest**

DESI DR2 Results I: ***Baryon Acoustic Oscillations from the Lyman Alpha Forest***

Abdul-Karim+ arXiv:2503.14739



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The Lyman-α forest

Resonant absorption of QSO's light by neutral hydrogen HI in the intergalactic medium

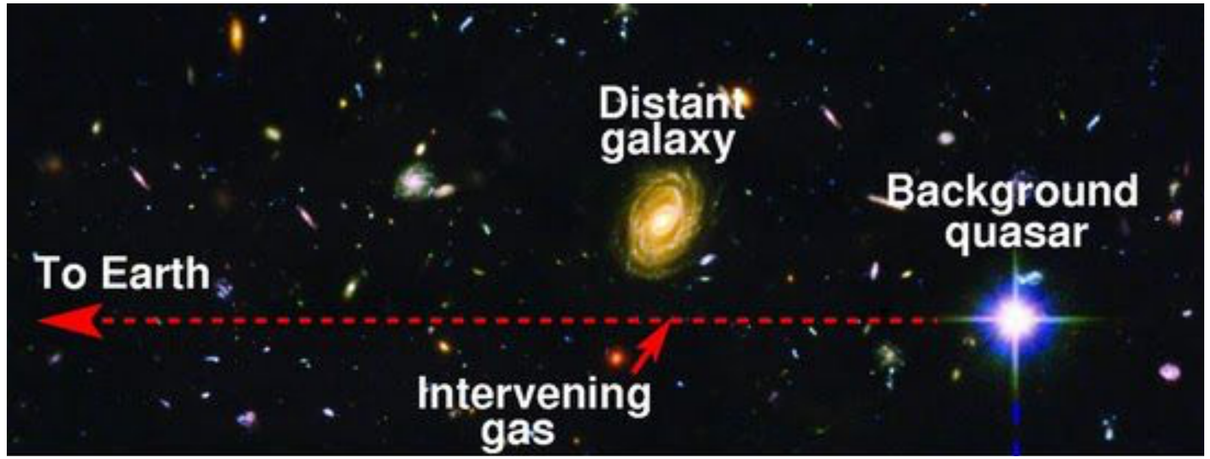
Transmission: $F = e^{-\tau}$

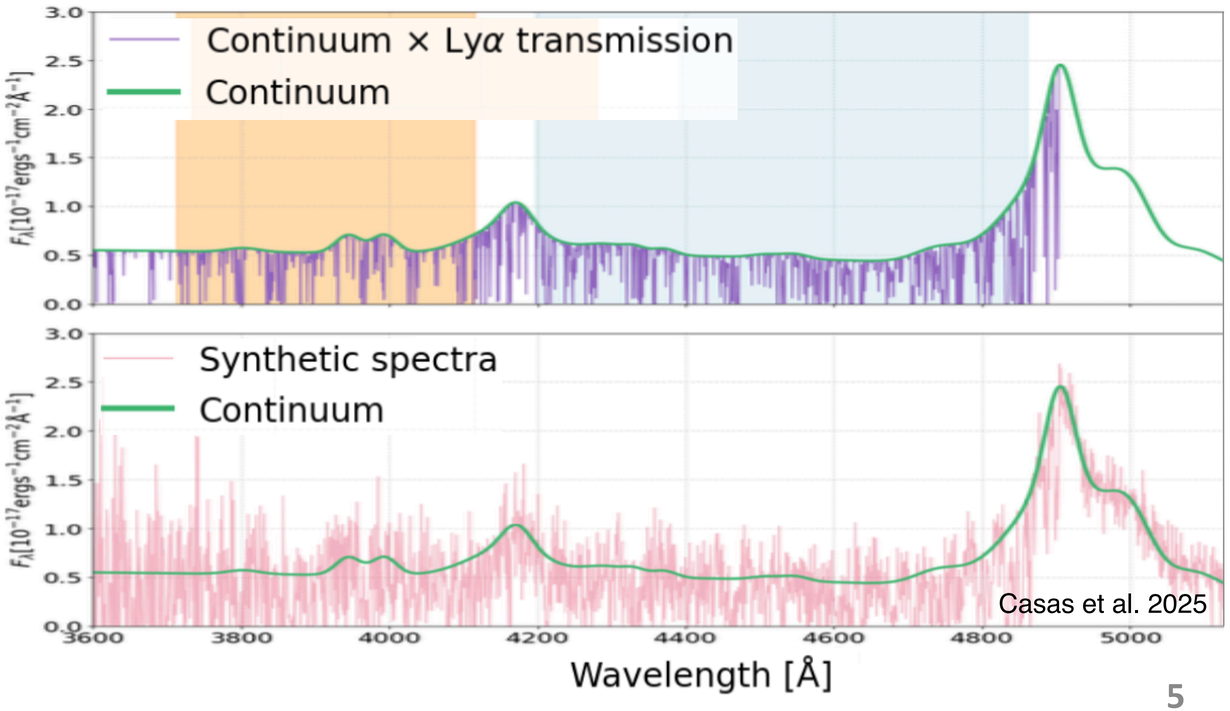
$$\tau \propto n_{\rm HI} \ \text{ on large scales}$$

Excellent tracer of matter density fluctuations at z>2

DESI Lyα:

- large footprint + density of lines-of-sight
- relatively low SNR





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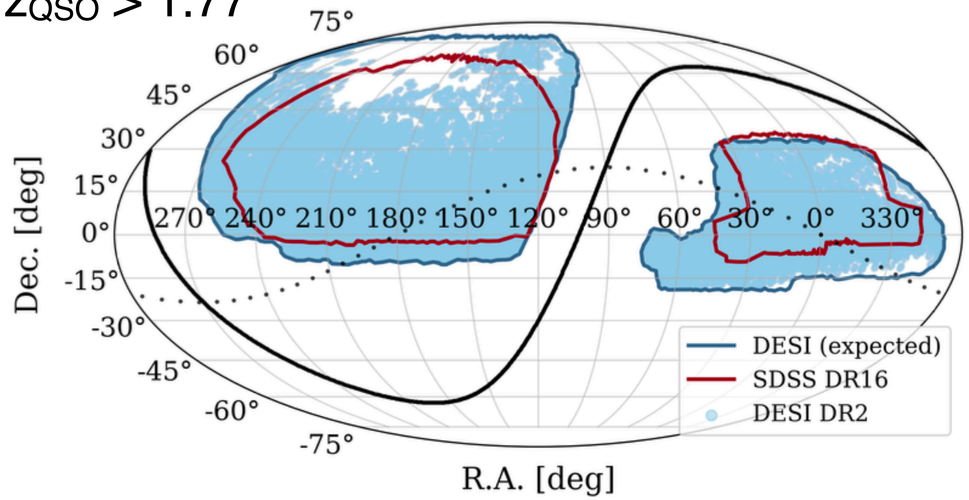
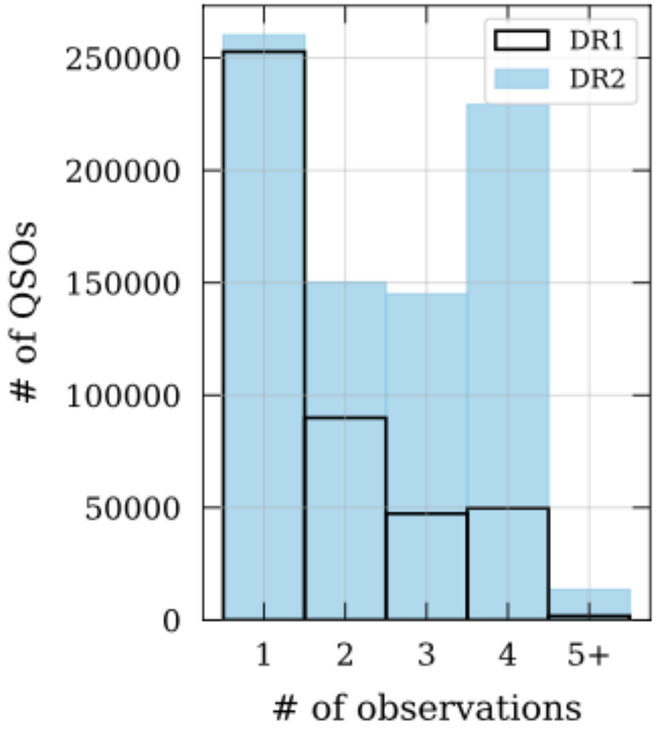
DESI DR2 Lyman-α sample

820,000 Lyα spectra (z_{QSO}>2.1)

1.2 million tracer QSOs with z_{QSO} > 1.77

z_{eff} = 2.33





Ancillary catalogs:

- BAL QSOs (20% for 1.77<z_{QSO}<3.8)
- DLA systems: new catalog for DR2 based on 3 algorithms, including a new template-based method

Brodzeller+ arXiv:2503.14740

Lyα spectra are re-observed with high priority up to 4 observations

⇒ SNR increased wrt DR1

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Measuring Lyman-α correlations

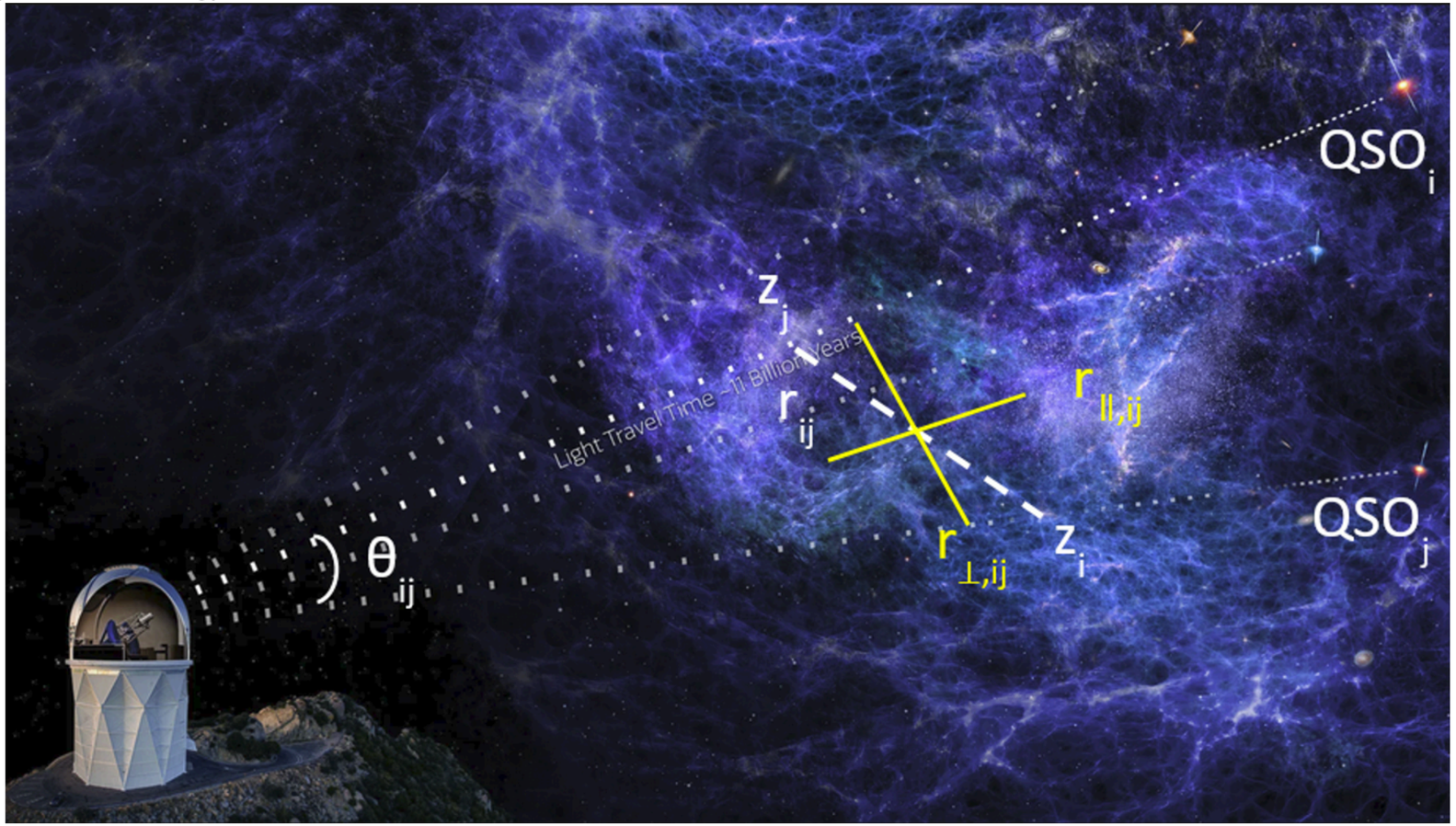
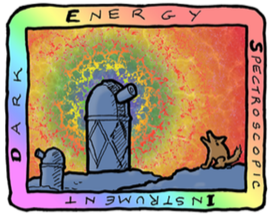


Image Credit: NOIRLab/NSF/AURA/P. Marenfeld and DESI Collaboration

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

4 correlations measured from: - autocorrelation **Lyα x Lyα**

- cross-correlation **Lyα x QSO's positions**



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Modelling the Lyα x Lyα correlation

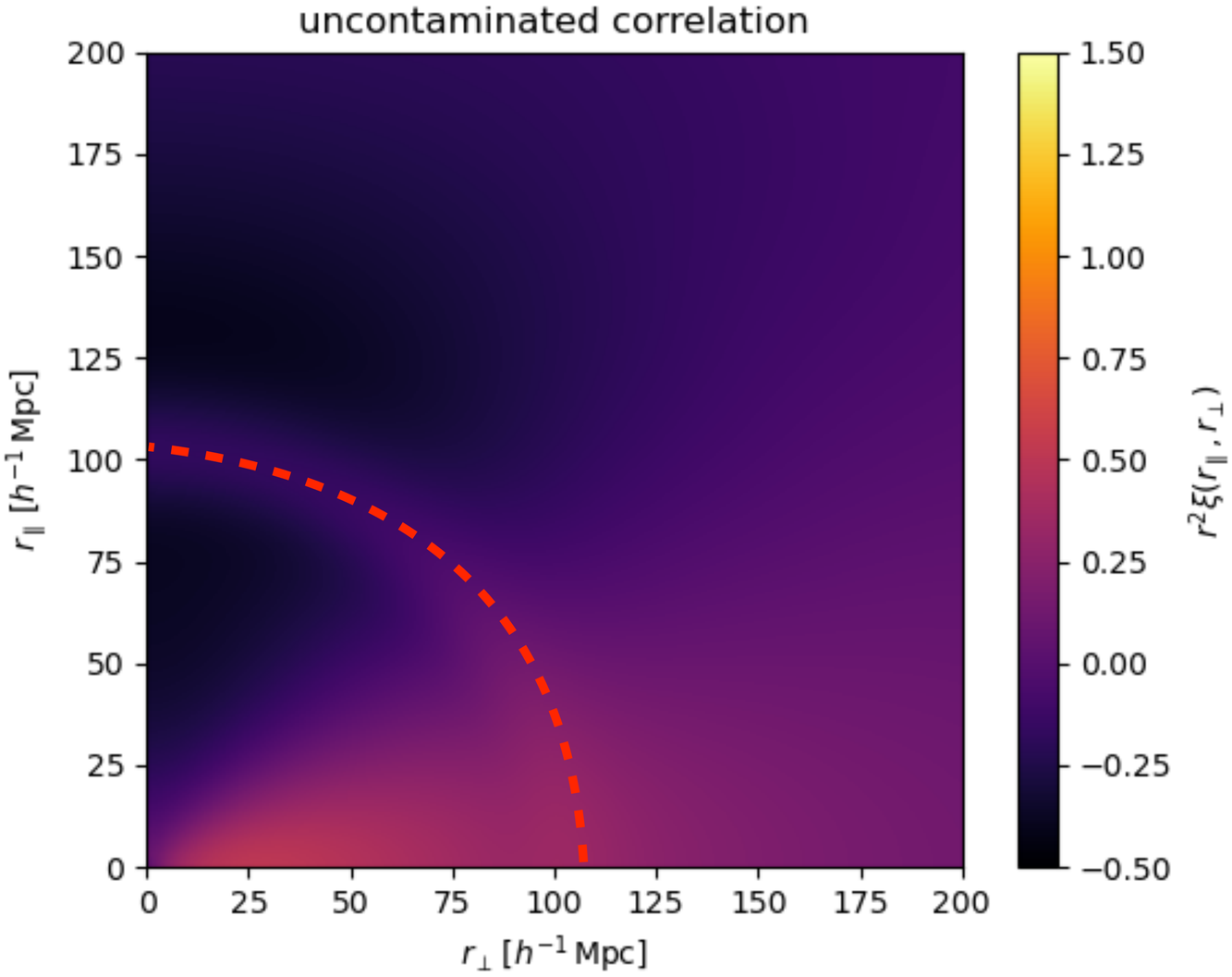
Correlation = Fourier [power spectrum]

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

includes BAO distance scale:
2 main fit parameters

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

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



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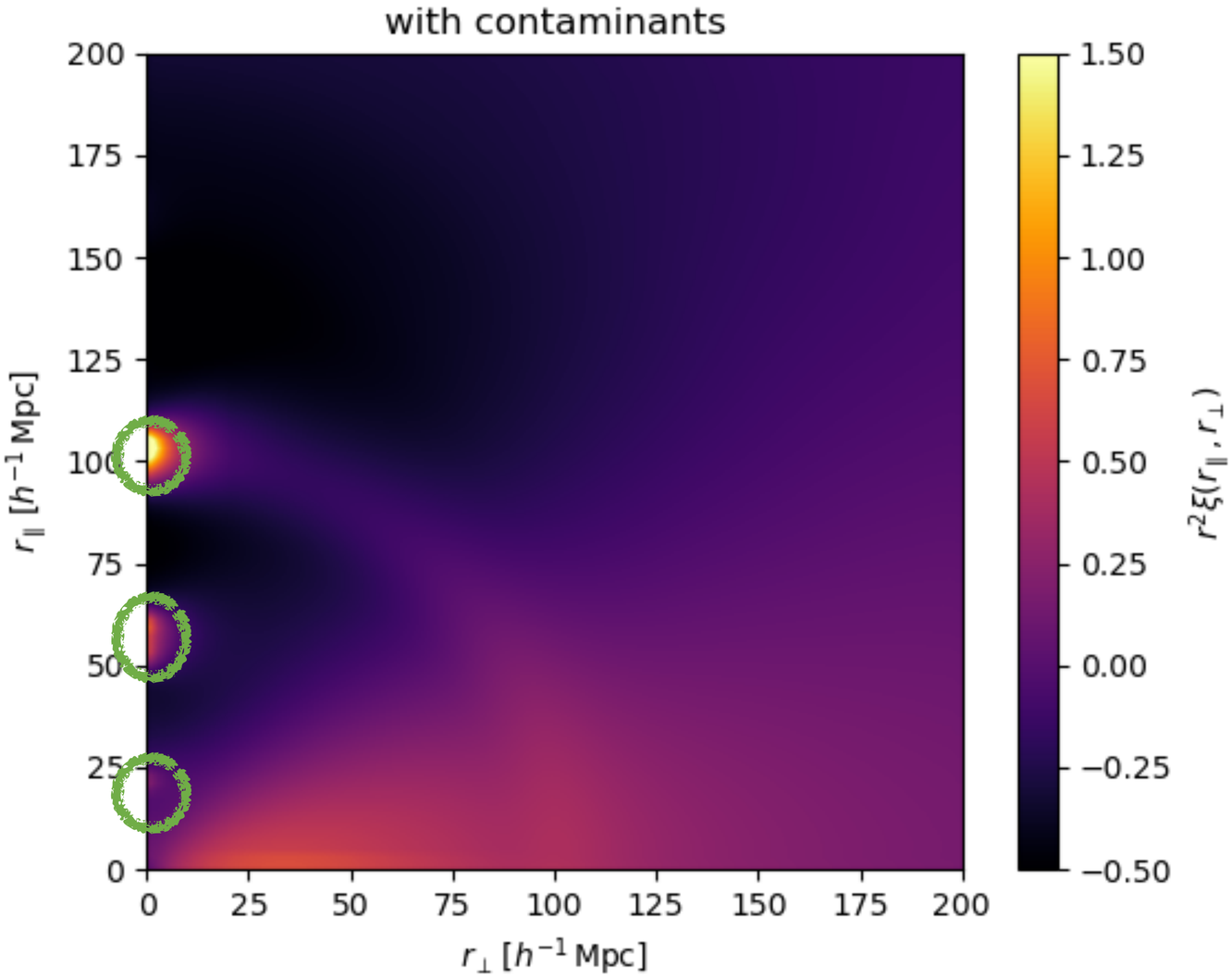
Modelling the Lyα x Lyα correlation

Contaminants:

- High column density absorbers

- Metals:
Si III (1207Å), Si II (1190Å, 1193Å, 1260Å):
spurious peaks
Modelled with a "metal matrix"

- Correlated noise
Guy et al., JCAP 01 (2025) 140



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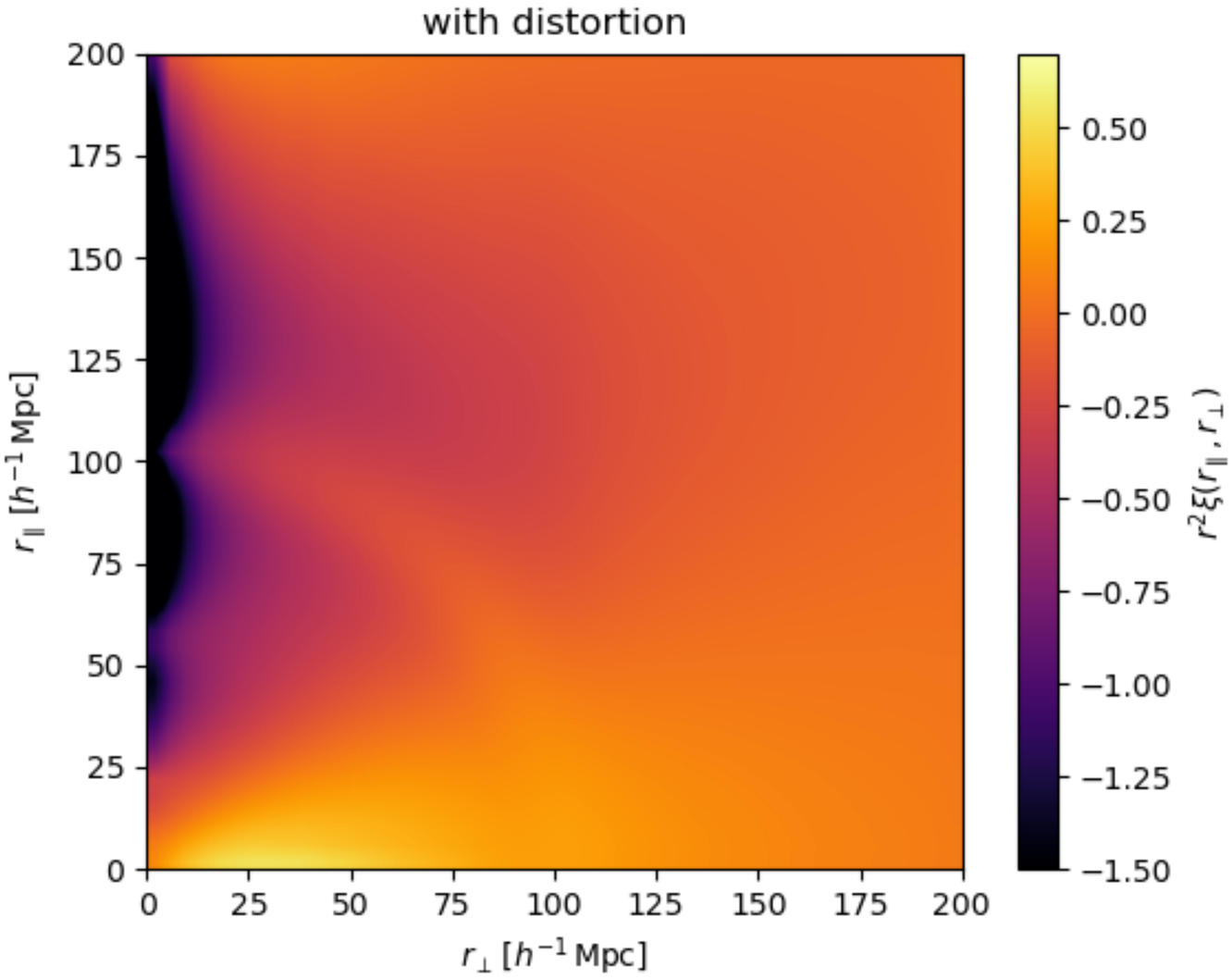
Modelling the Lyα x Lyα correlation

QSO's continuum fitting

Extract δ_F from measured spectra, taking into account the QSO's unabsorbed continuum

Effect on the measured correlations: distortion matrix D_{MN}

Matrix can be precisely computed from the survey



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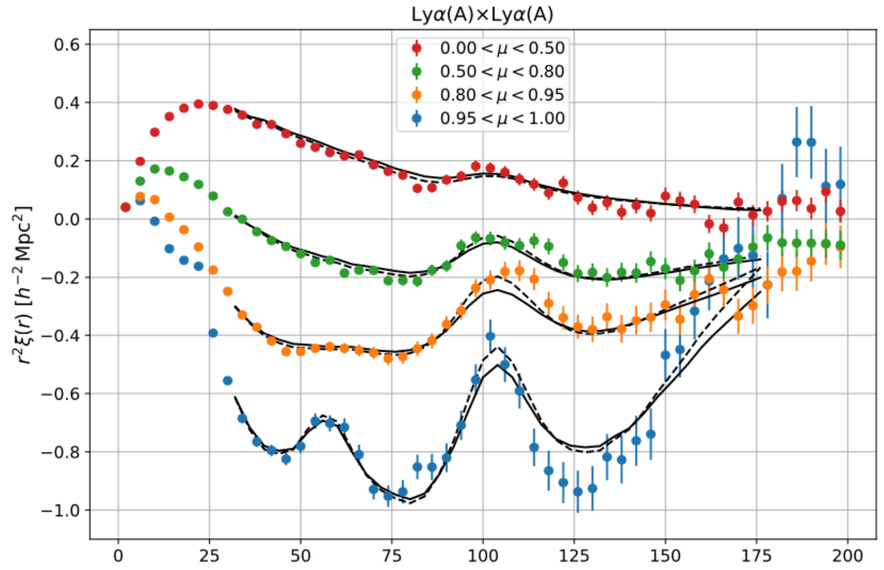
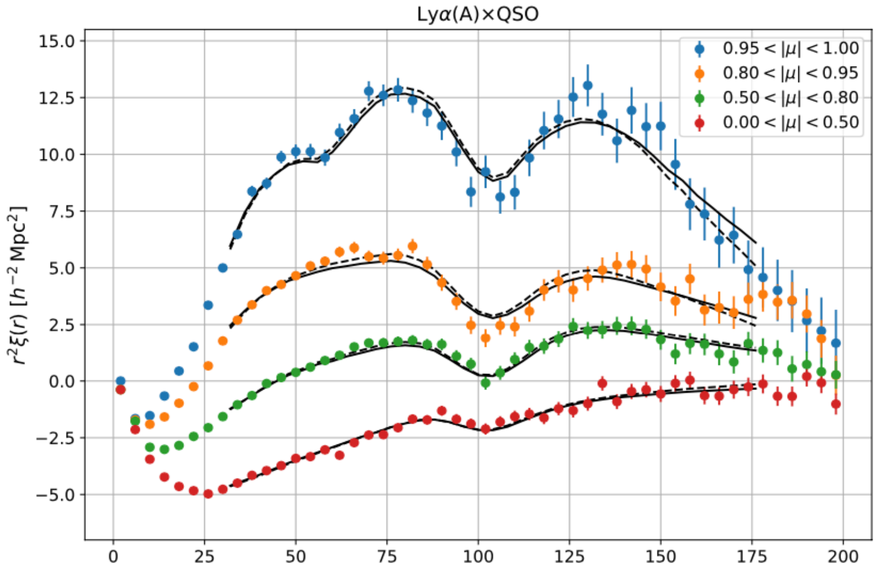
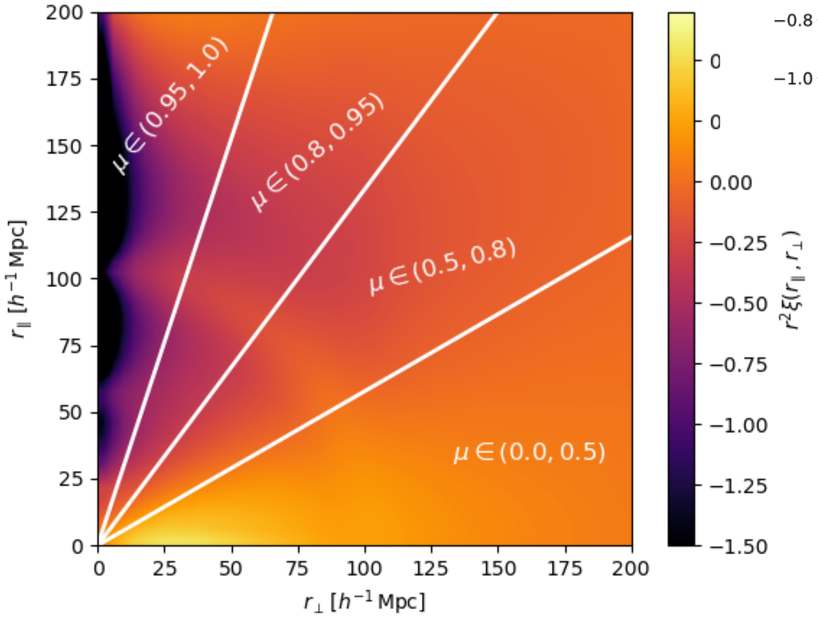
Correlation measurement and DR2 BAO fit





wedge plots: 4 μ-bins, for visualisation only

best-fit model (LyαxLyα)



Fit 4 correlations with 2 main parameters ($\alpha_\parallel$, $\alpha_\perp$) + 15 nuisances

For DR2 BAO:

- fit range $30 < r < 180\,h^{-1}\,\mathrm{Mpc}$
- priors on some nuisance parameters

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

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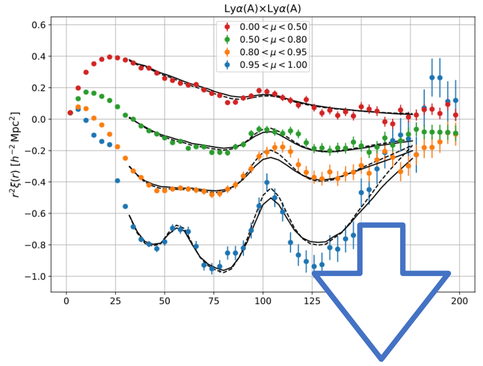
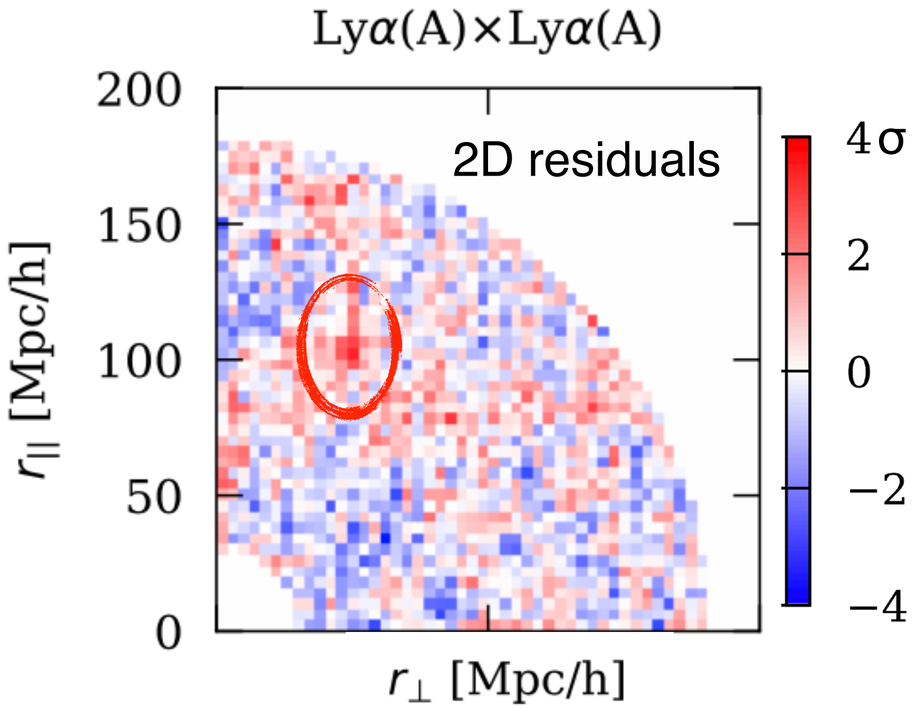
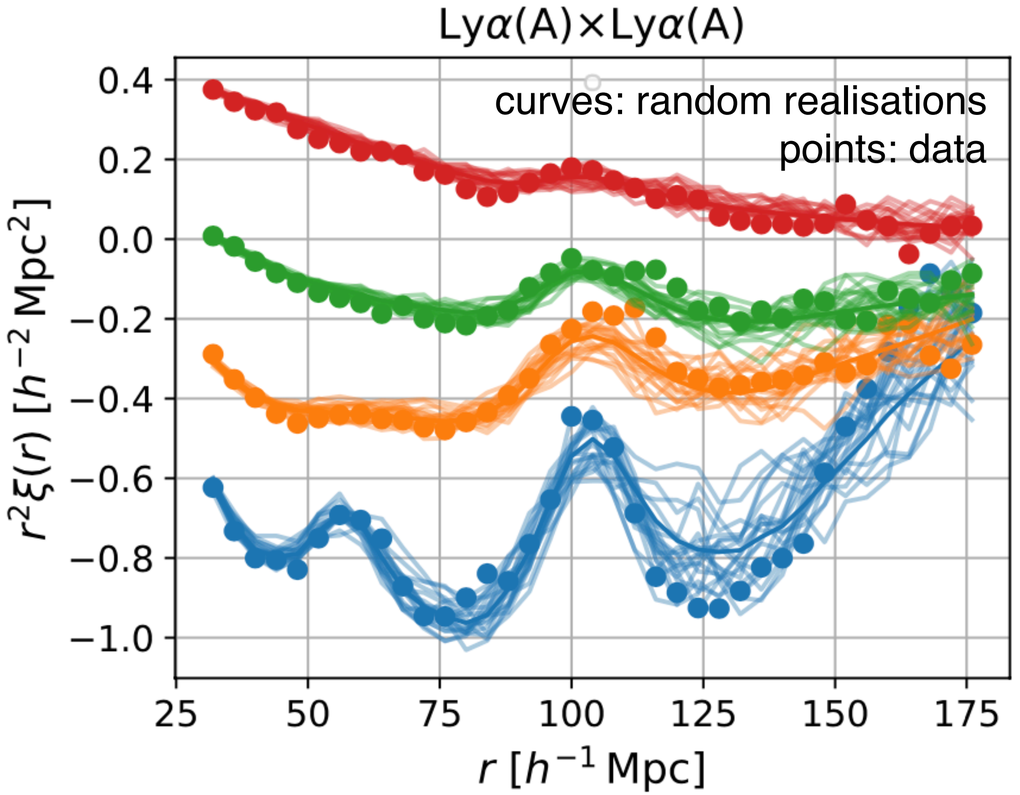
Goodness of fit



Tested largest "outliers" with random (bootstrap) realizations
Worse outlier found in 15% of cases
⇒ no significant disagreement between data and best fit





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Validation of the DR2 BAO measurement

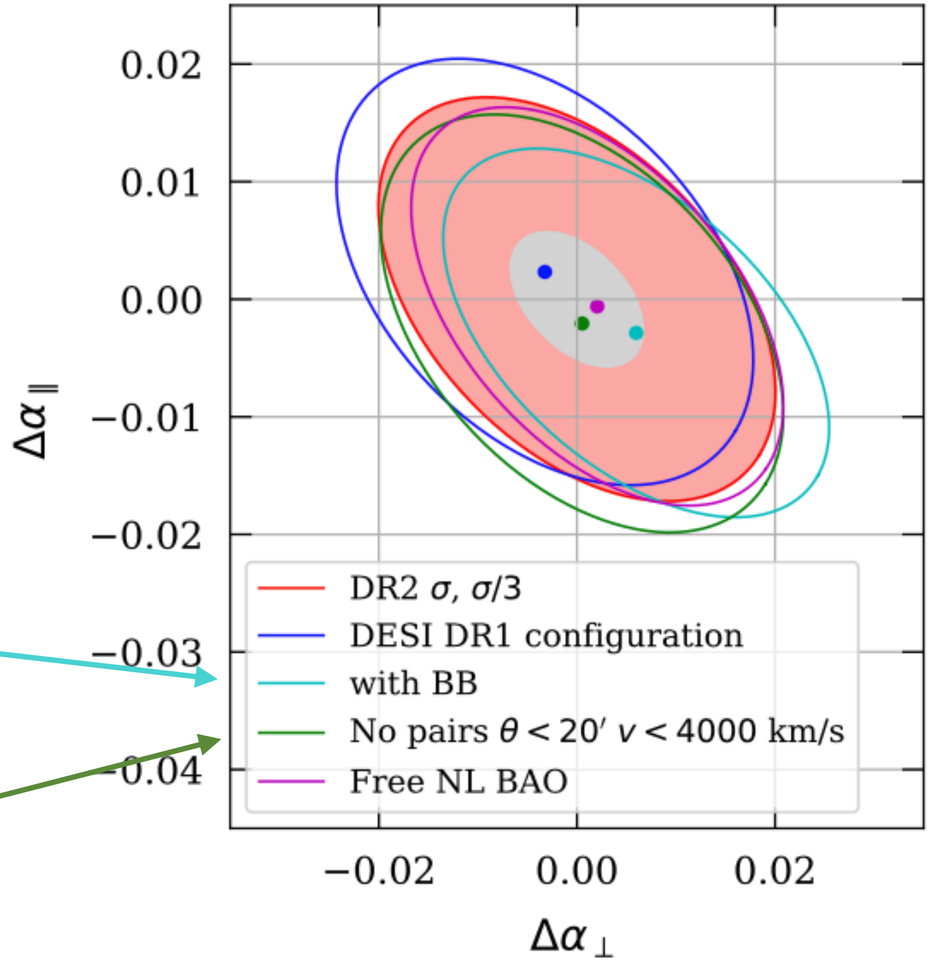
- Blind analysis
- Validation with mocks: Casas et al. arXiv:2503.14741

300 new ColoRe-QL mocks + 100 Saclay mocks

Check statistical errors, effects of all major contaminants

add broadband polynomials

mitigating QSO redshift errors
(see L. Casas et al. 2025)



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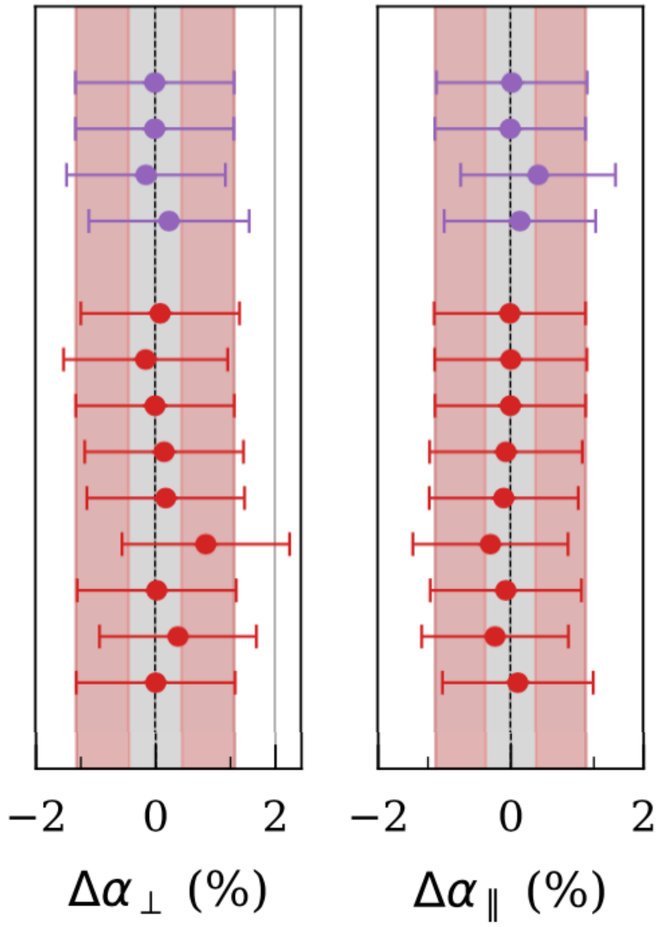
Other variations

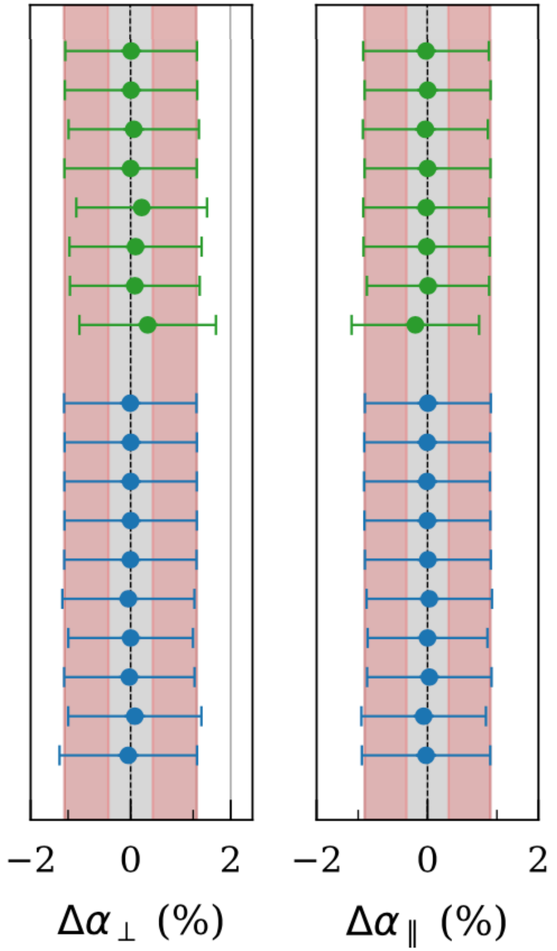


continuum fitting

no calibration
$\eta_{pip} = 1$
$\eta_{LSS} = 3.5$
$\Delta\lambda = 2.4\,Å$

dataset

$\lambda_{obs} < 5500\,Å$
$\lambda_{obs} > 3650\,Å$
$\lambda_{RF} < 1200\,Å$
$z_Q < 3.78$
> 50 pixels in forest
only quasar targets
mask DLAs with SNR_RED > 3
weak BALs
no sharp lines mask



correlations/covariance

dmat $r_\parallel < 200$ Mpc/h
dmat 2%
dmat model 4 Mpc/h
dmat model z-indep
$\Delta\lambda = 3.2\,Å$
$\Delta\lambda = 1.6\,Å$
nside = 32
$\Delta r = 5$ Mpc/h

Gaussian redshift errors
no prior on L0_HCD
no prior on beta_HCD
no prior on drp_QSO
no prior on bias_QSO
no prior on bias_CIV_eff
UV fluctuations
ignore small-scales correction
ignore modelling of sky residuals
ignore quasar radiation

modelling choices

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DESI DR2 Lyman-α BAO result

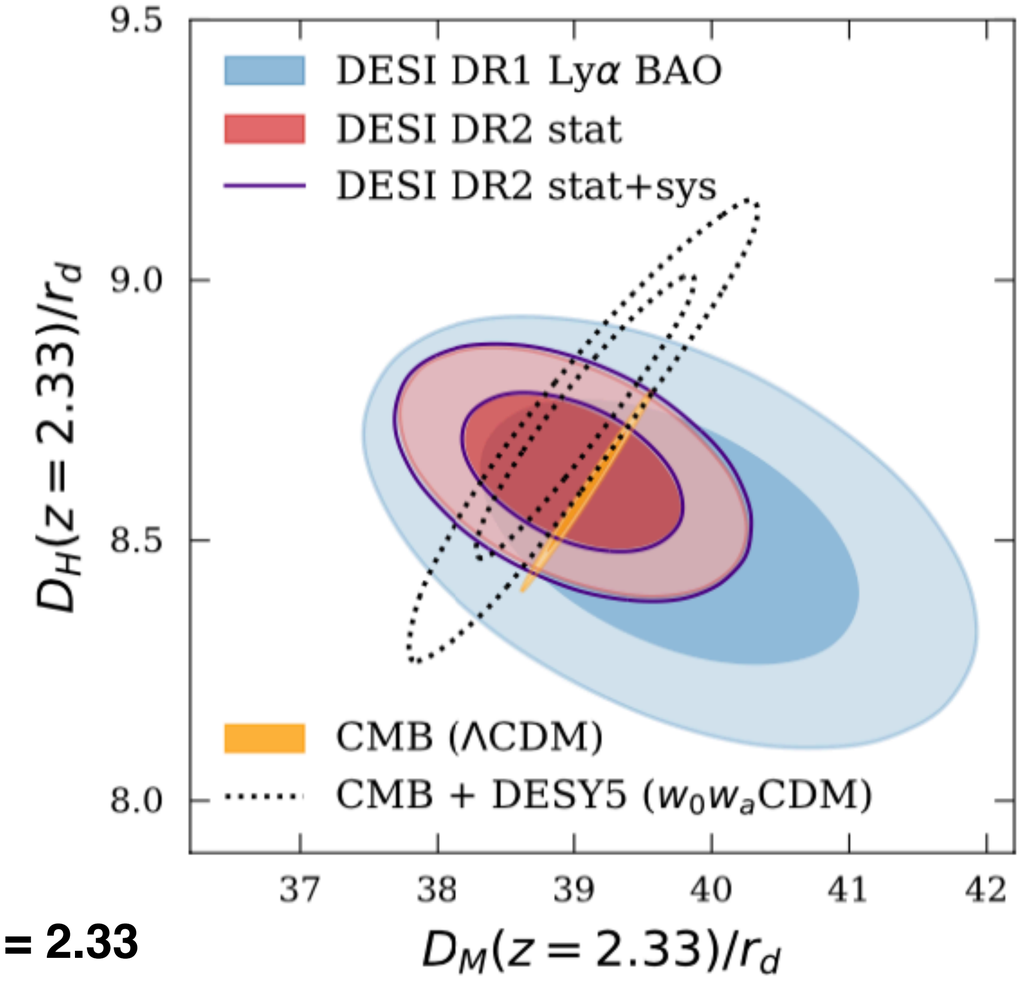
Best-fit unblinded BAO parameters:

$$\alpha_{\parallel} = 1.002 \pm 0.011 \qquad \alpha_{\perp} = 0.995 \pm 0.013$$

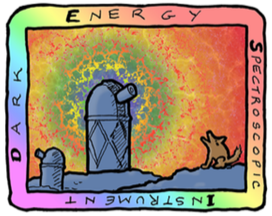
correlation: $\rho = -0.46$

Systematic error on the amplitude of the BAO shift due to non-linear evolution

- see F. Sinigaglia et al. ApJ 971, L22 (2024) ; R. de Belsunce et al. arXiv:2412.06892
- Added to the covariance: $\Delta\alpha_{\parallel} = \Delta\alpha_{\perp} = 0.3\%$



0.7% measurement (stat+sys.) of isotropic BAO at z_{eff} = 2.33



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DESI DR1 Lyα 3D Full-shape

Cuceu et al. arxiv:2509.15308

- **Linear cosmology from large-scale Lyα: essentially BAO, Alcock-Paczynski (AP), RSD**
- Template-based model:

$$\xi(r_\parallel, r_\perp) = \boxed{\xi_s(q_\parallel^s r_\parallel, q_\perp^s r_\perp)} + \boxed{\xi_p(q_\parallel^p r_\parallel, q_\perp^p r_\perp)} \quad \Rightarrow \quad \alpha = \sqrt{q_\perp\, q_\parallel}, \quad \phi = \frac{q_\perp}{q_\parallel}$$

broadband **BAO**

- ϕ_s ⇒ **AP from the broadband**: quite robust + factor of ~ 2 improvement over BAO
- α_s : not robust at this stage

- **Linear growth measurement**: from Lyα auto + cross-correlation with QSO
  (Lyα has two independent linear biases: $\beta \neq$ f/b)

- Measurement: similar to BAO, same sample & correlations,
  validation with mocks, data splits and variations

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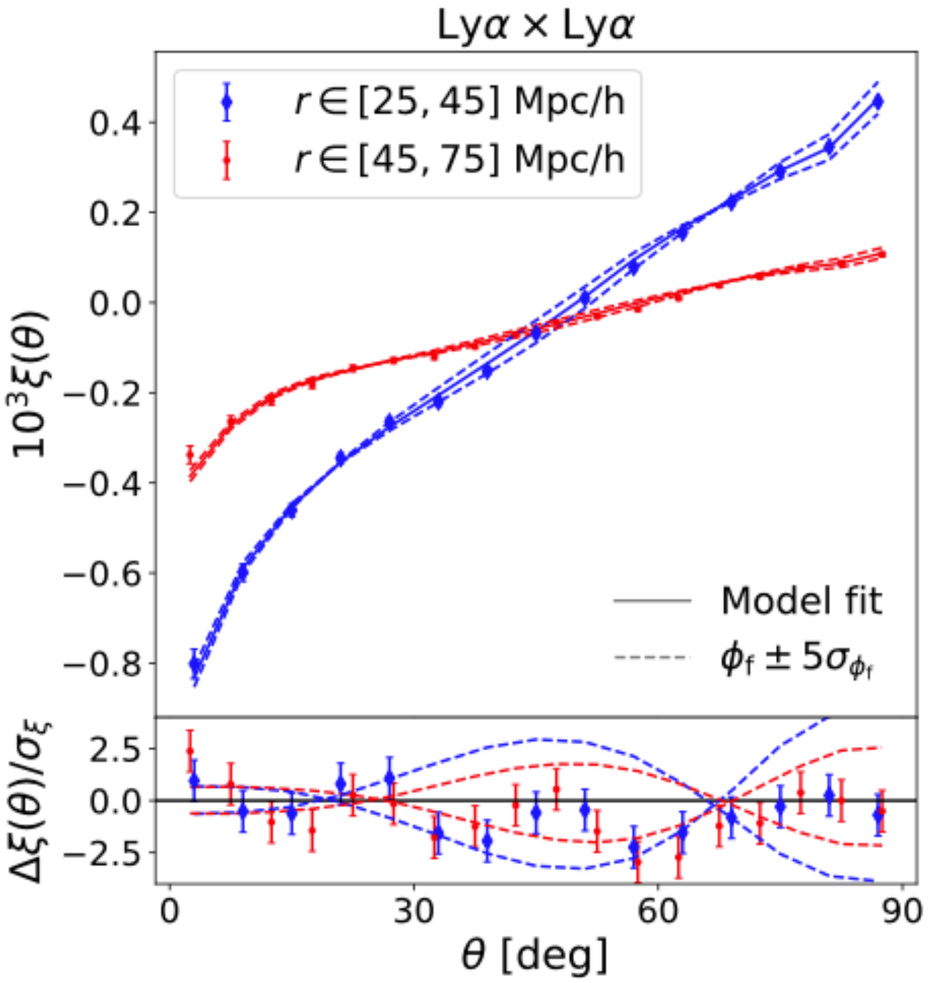
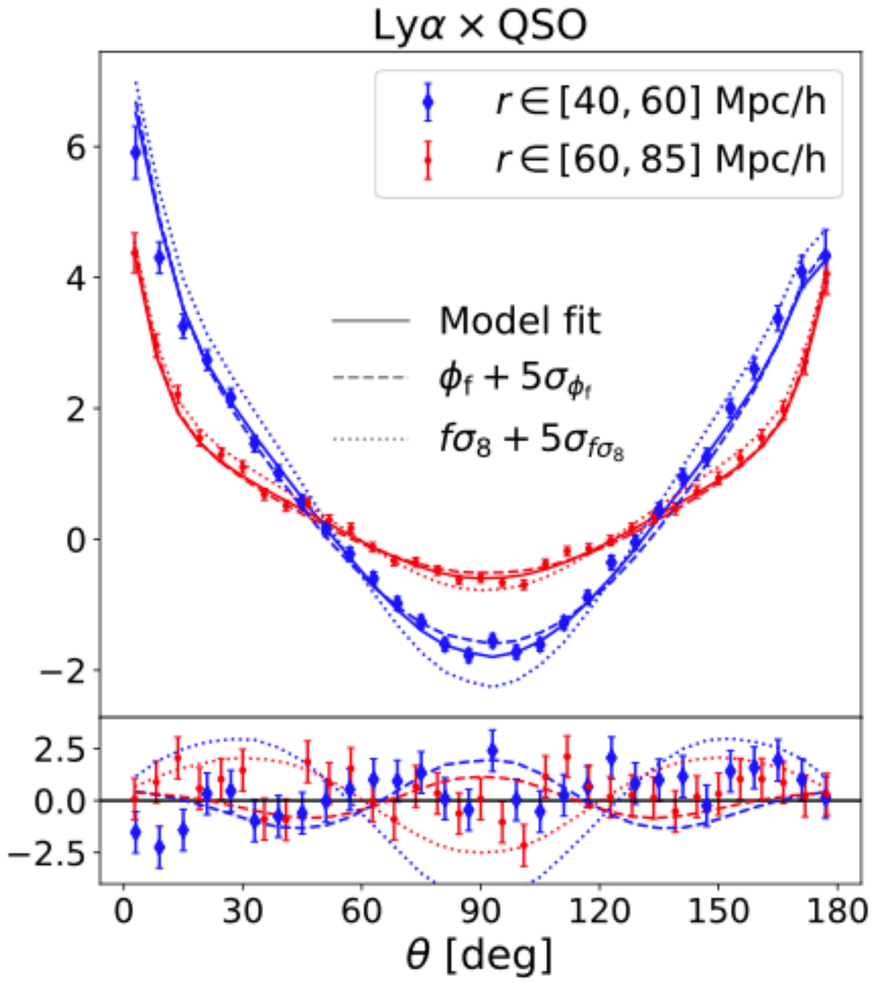
Alcock-Paczynski and growth signals





Fit :

r_min,auto = 25 Mpc/h
r_min,cross = 40 Mpc/h

chi2 = 9145.1/9163
(PTE 0.55)

shell plots: radial bins, for visualisation only

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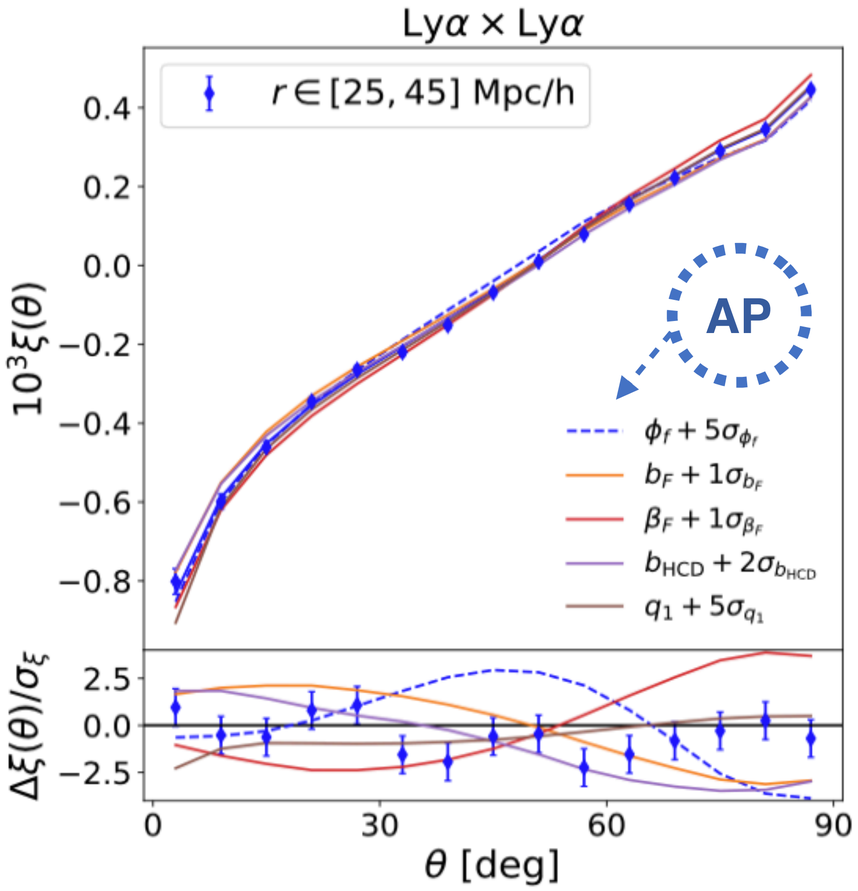
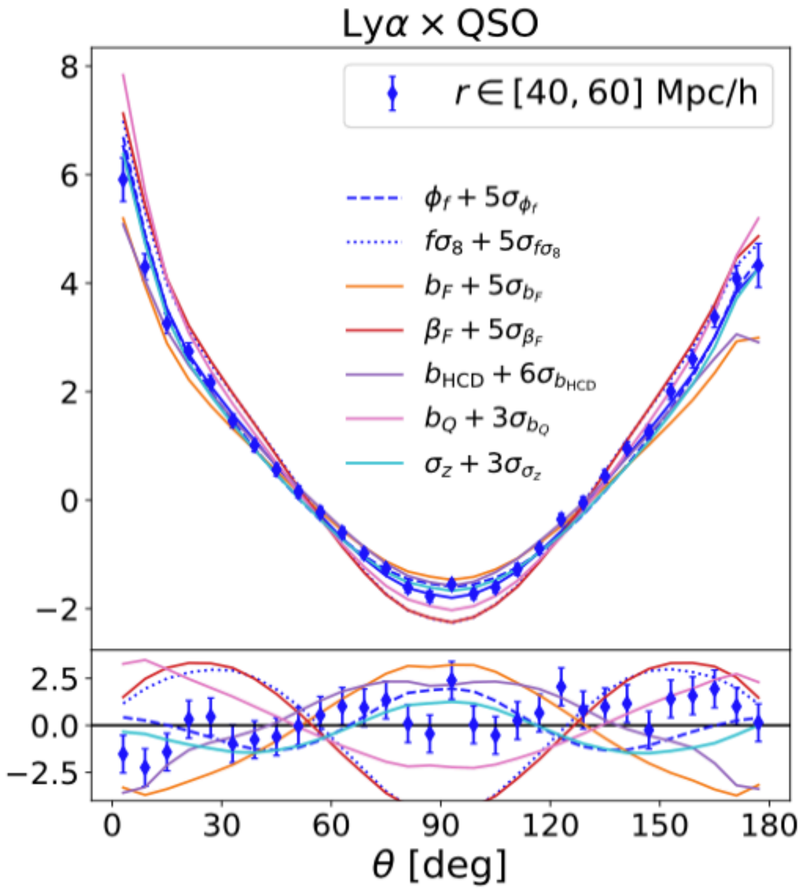
AP and growth vs "nuisances"





- Autocorrelation: no major degeneracy between AP and nuisances
- Cross-correlation: similarities between
  - Lyα RSD / growth ;
  - AP / quasar redshift error

AP (essentially from Lyα x Lyα) is more robust than growth (from Lyα x QSO)

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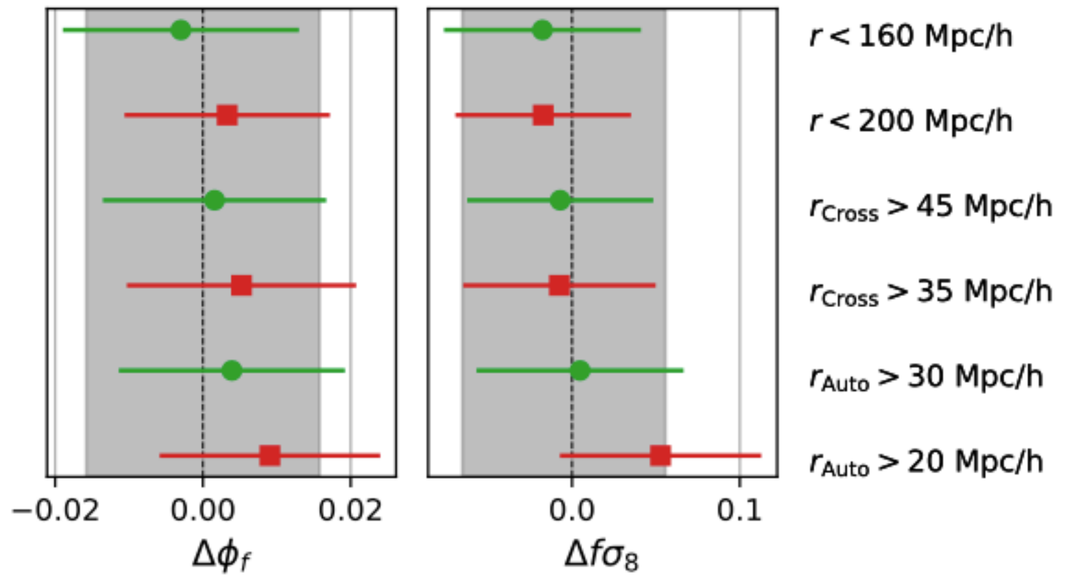
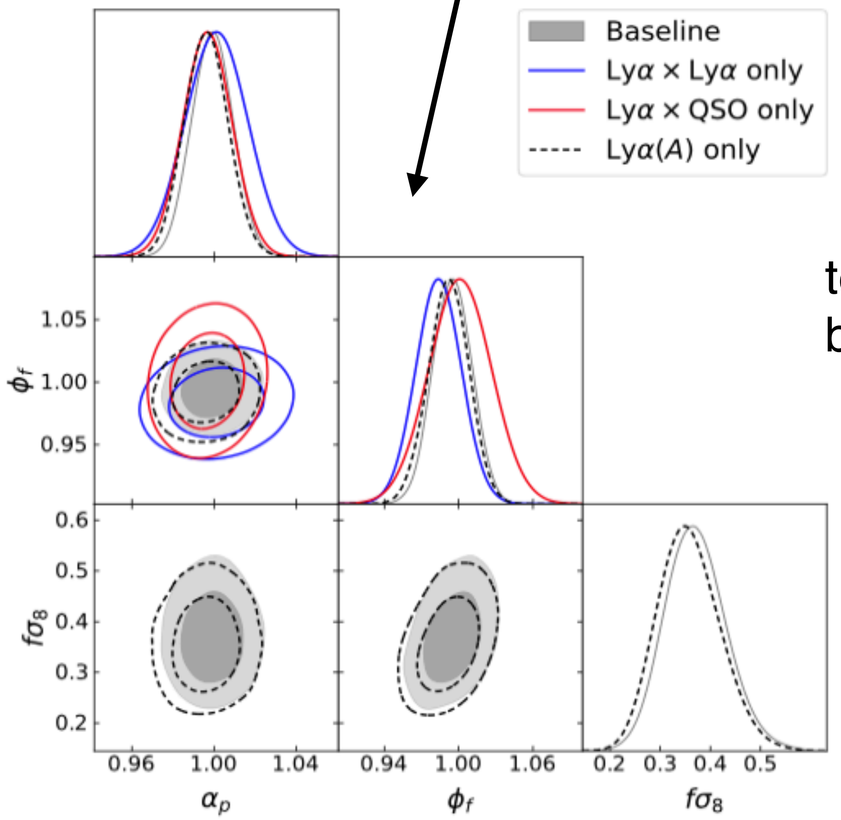
Validation of the DR1 FS measurement

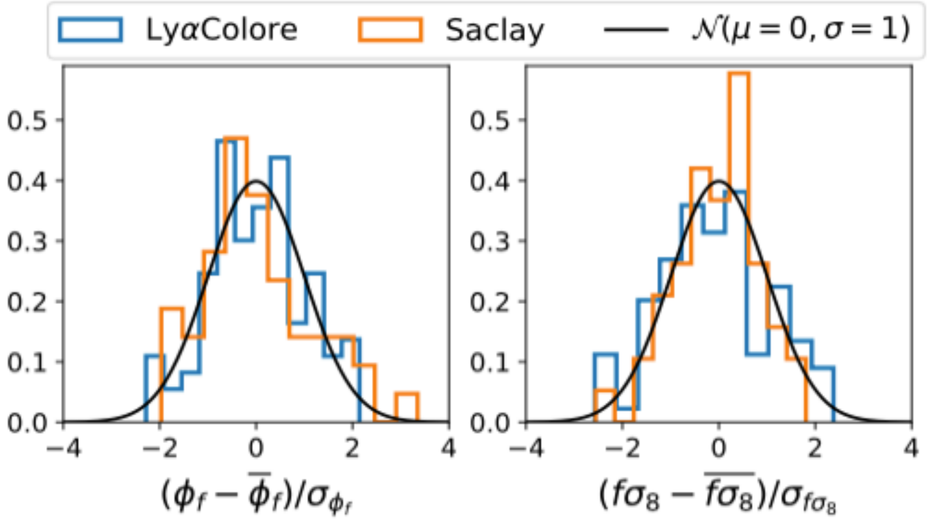
robustness vs scale cut



consistency auto/cross



test of statistical error bars from mocks



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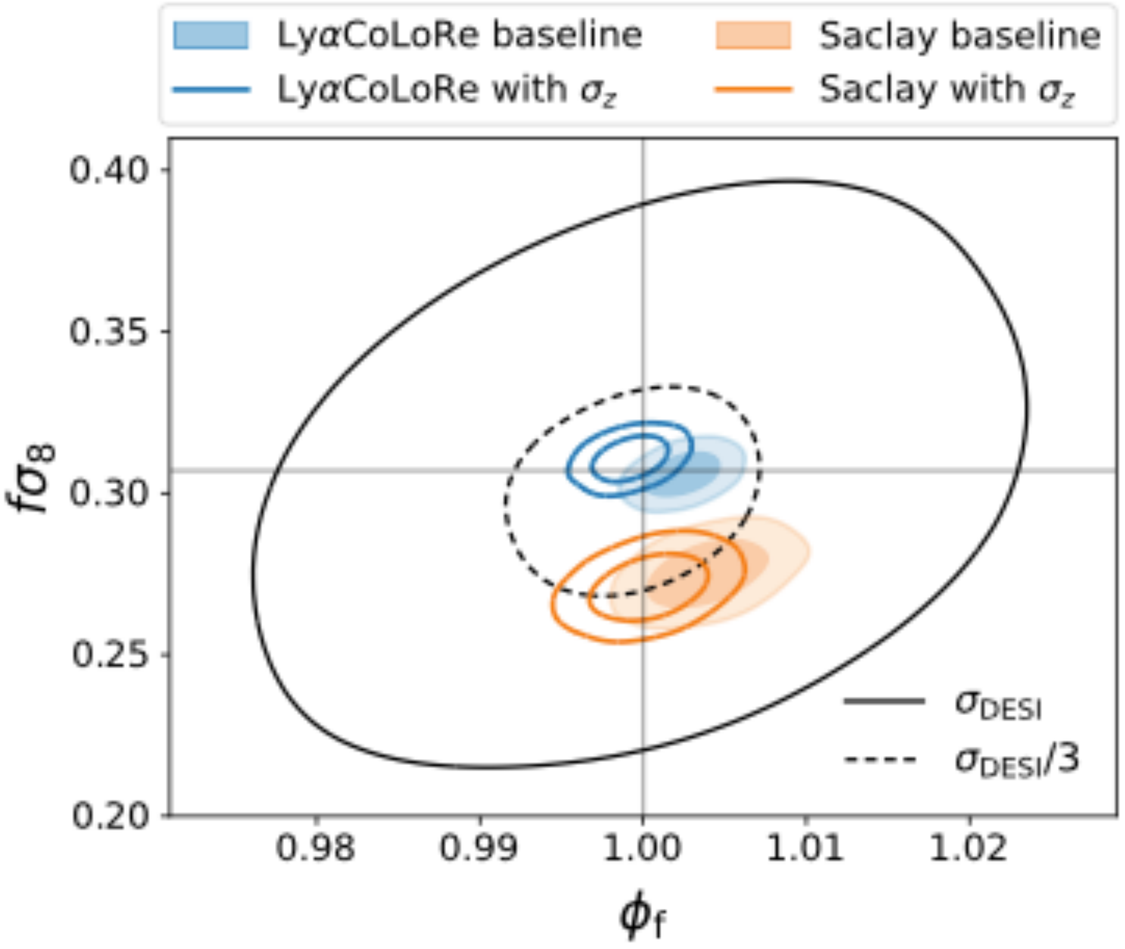
Validation on mocks

Measurement of parameter biases on stacks of mocks

- AP is unbiased in the presence of major Lya contaminants

- Linear growth: bias seen in one of the two stacks of mocks

Linear growth in DR1:
- 0.033 systematics added
- recommend not to use it in cosmology inference



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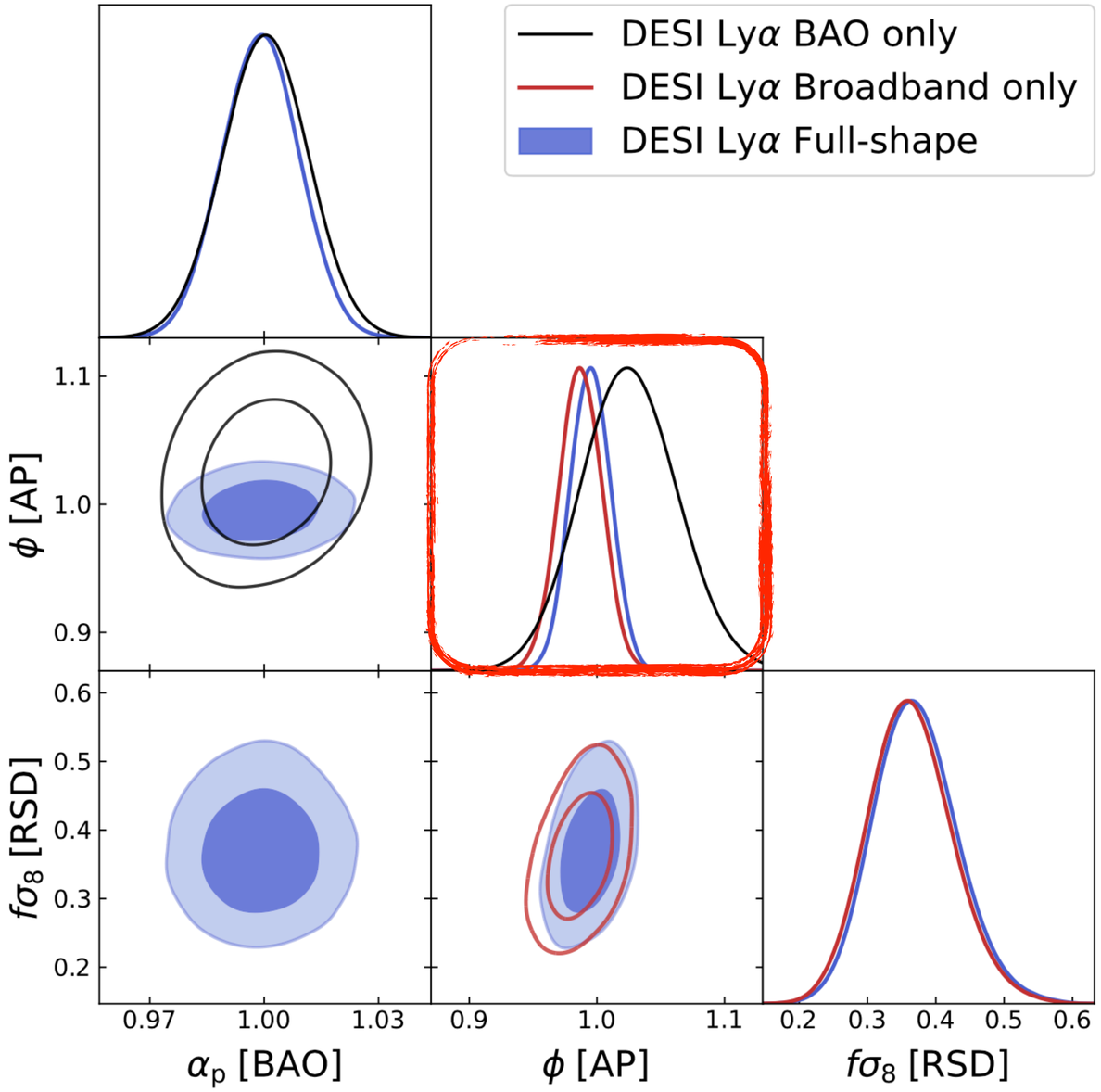
DR1 Lyα Full-Shape results



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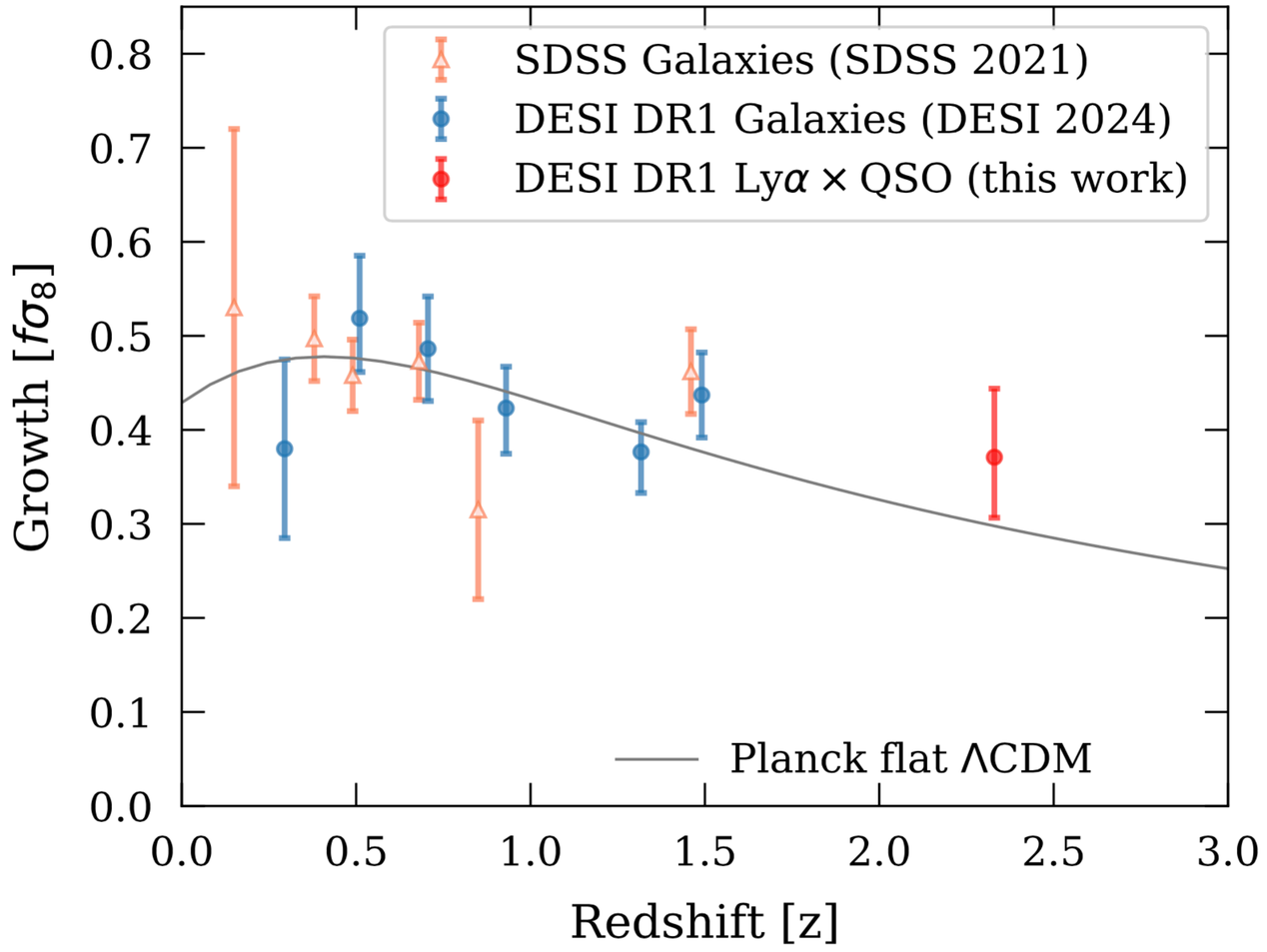
DR1 Lyα Full-Shape results

16% constraint on fσ_8, "recommend not for cosmology inference"



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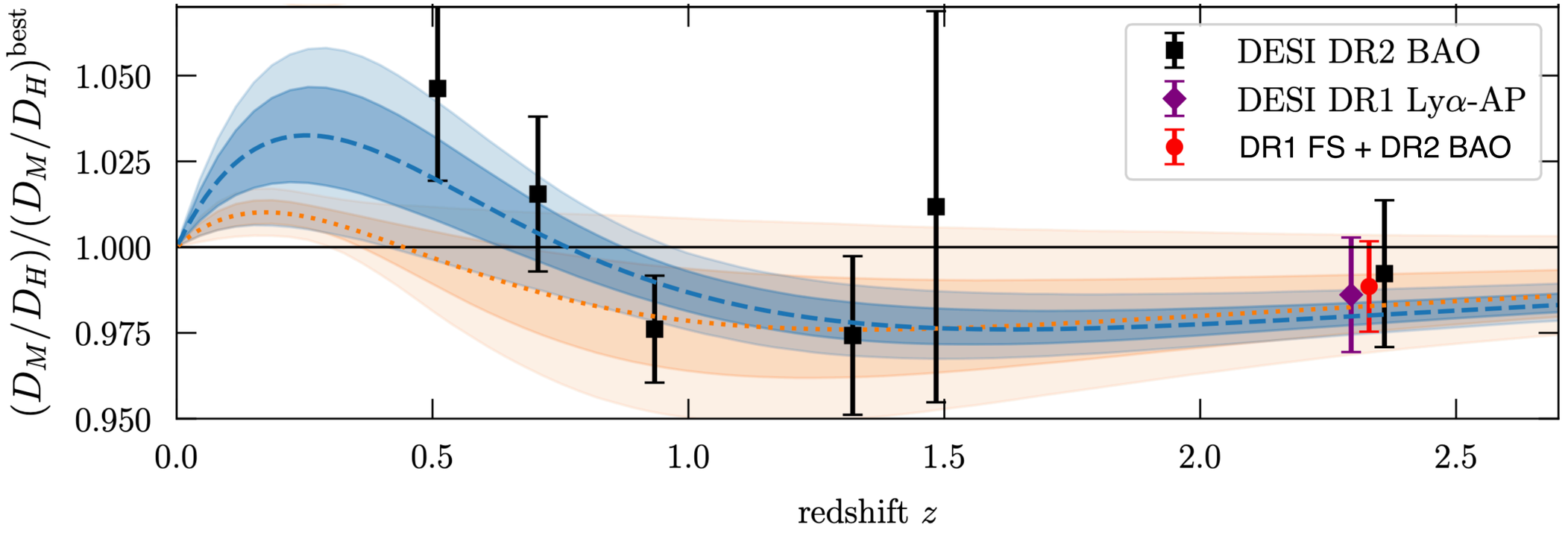
DR1 Lyα Full-Shape results

1.6% constraint on AP: factor of 2.4 improvement wrt DR1 BAO



- DR2 measurement ongoing (still blinded)
- Expect sub-% precision on AP using future DESI data
  ⇒ could play a key role on Dark Energy!

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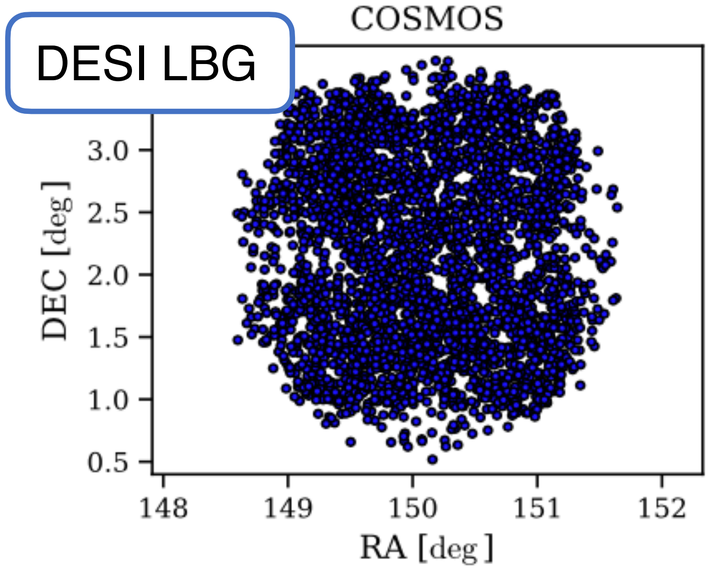
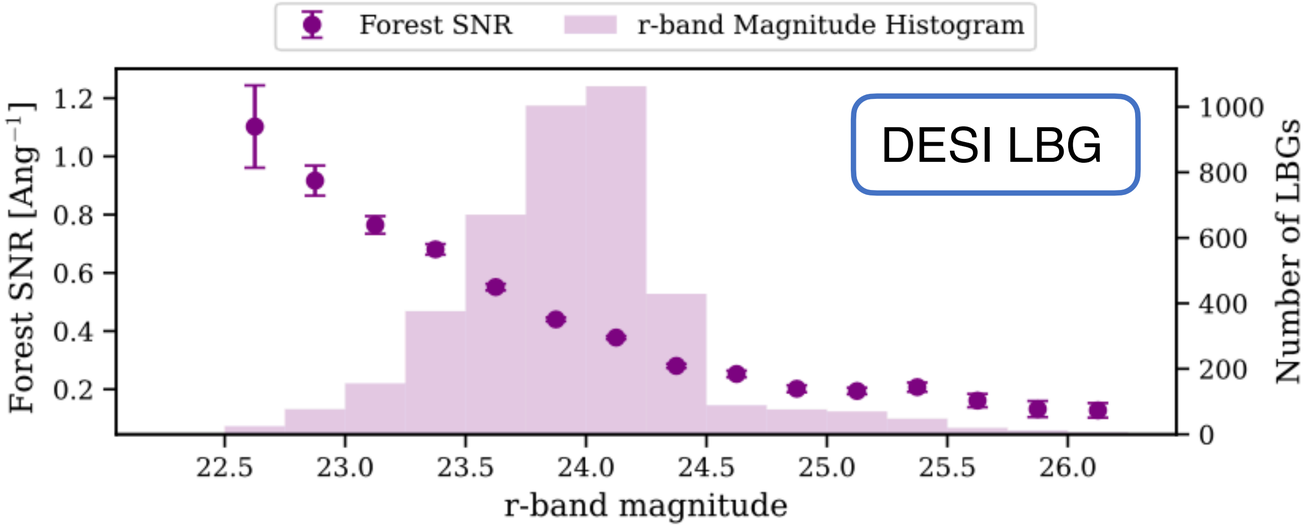
The Lyα forest from LBG spectra

- **Lya forest from quasars**: low density (DESI main survey: 60/deg2 for z>2.1)
- Future spectroscopic LSS surveys will target galaxies at z>2

- **Lyman-Break Galaxies**:
  - targeted with u-dropout selection
  - **spectra can be used for Lya forest**, low SNR compared to quasars

- DESI pilot surveys to prepare DESI-2 include LBG samples in the COSMOS and XMM fields





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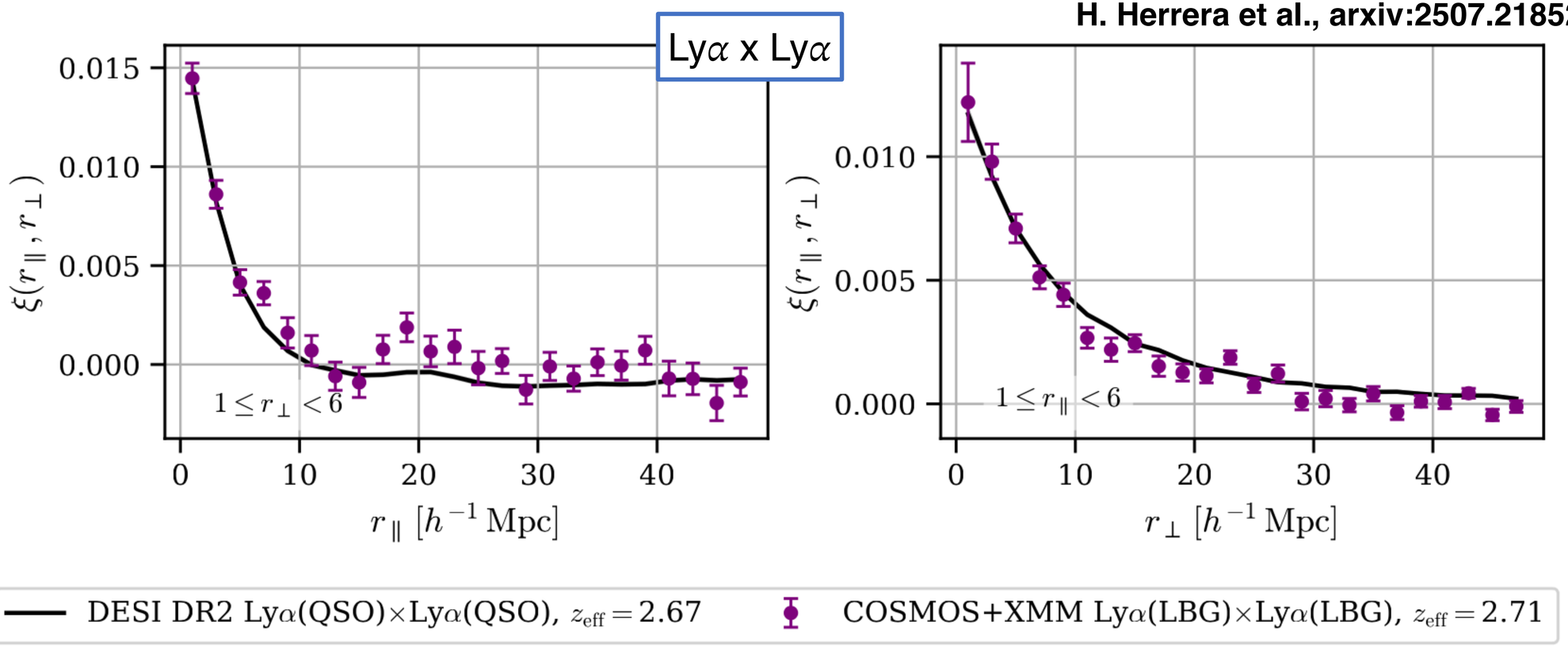
First measurement of the 3D Lyα correlations with DESI LBG spectra

H. Herrera et al., arxiv:2507.21852



- From 4,151 spectra in COSMOS and XMM-LSS fields
- Measured up to r = 48 Mpc/h
- Effective redshift **$z_{\rm eff}$ = 2.70** significantly larger than for quasar spectra

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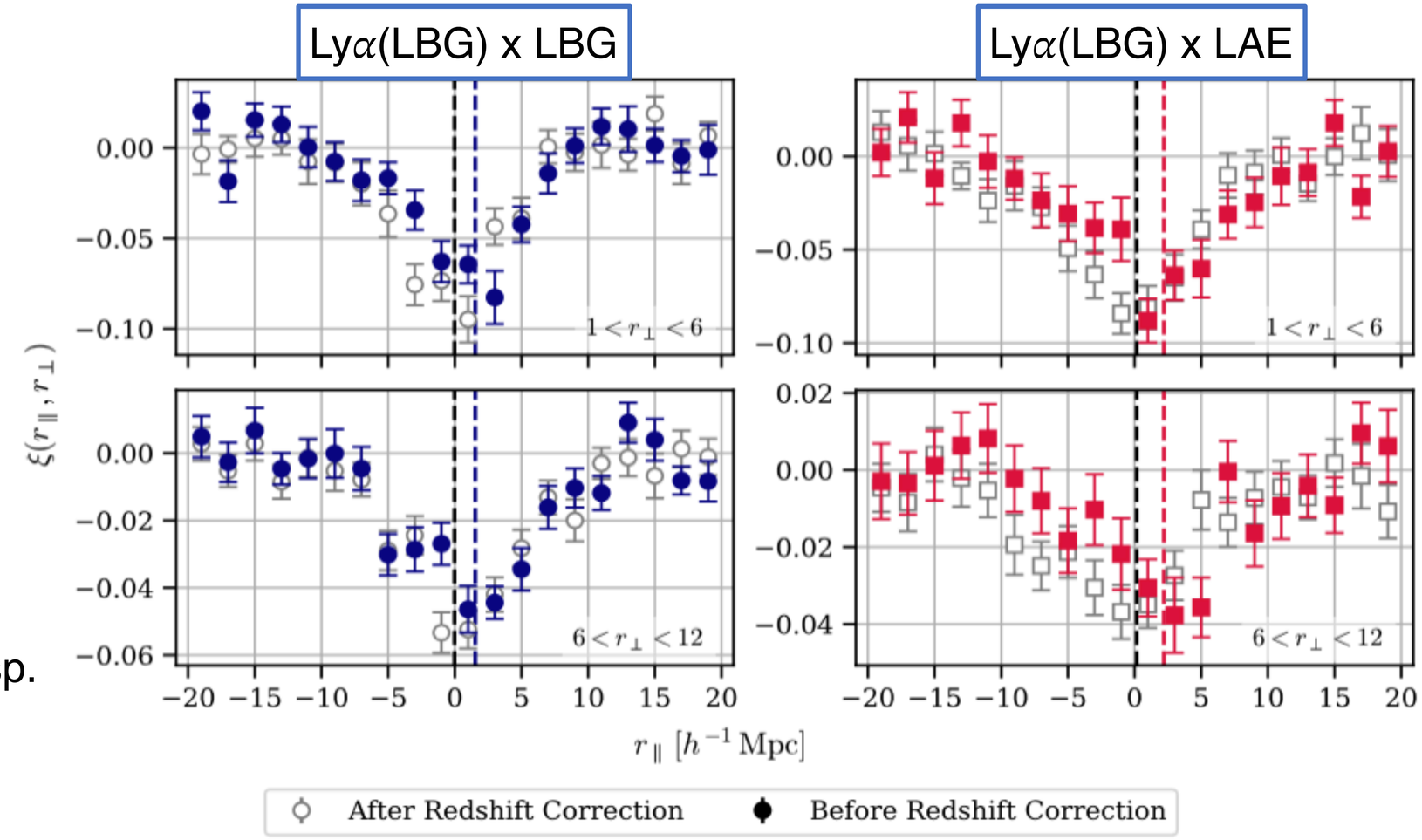
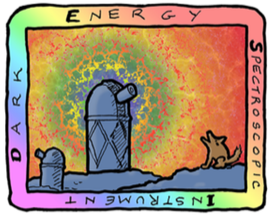
Lyα in LBG: Cross-correlation with galaxies

Cross-correlations measurements similar to Lyα(QSO) x QSO

Galaxy redshift correction: systematic offset Δv = -169 (resp. -241) km/s for LBG (resp. LAE)



⇒ Tool to assess the precision and improve the accuracy of galaxies' redshifts



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Lyα in LBG: forecast

Forecast for a future survey (eg. DESI-2) 5000 deg^2, 1000 LBG/deg^2

- Using both Fisher and a measurement on a dedicated LBG mock sample
- Both methods agree

- Expect precise BAO and Full-Shape AP measurement

Correlation	$\sigma_{\alpha_\parallel}$ (%)	$\sigma_{\alpha_\perp}$ (%)	$\sigma_{\alpha_{\rm ISO}}$ (%)	$\sigma_{\alpha_{\rm AP}}$ (%)	$\sigma^{\rm FS}_{\alpha_{\rm AP}}$ (%)
Mock-based Forecast					
Lyα(LBG)×Lyα(LBG)	1.08	1.13	0.57	1.90	0.67
Lyα(LBG)×LBG	1.10	0.95	0.55	1.71	1.00
Lyα(LBG)×Lyα(LBG)+Lyα(LBG)×LBG	0.83	0.72	0.42	1.29	0.57
Fisher Forecast					
Lyα(LBG)×Lyα(LBG)	1.11	1.00	0.57	1.80	–
Lyα(LBG)×LBG	1.26	0.86	0.62	1.82	–
Lyα(LBG)×Lyα(LBG)+Lyα(LBG)×LBG	0.87	0.68	0.44	1.34	–
Lyα(QSO)×LBG	1.78	1.38	0.89	2.72	–
LBG×LBG	1.04	0.59	0.51	1.41	–

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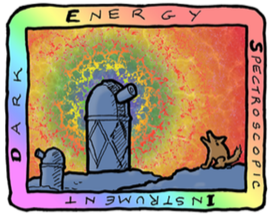

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Conclusion

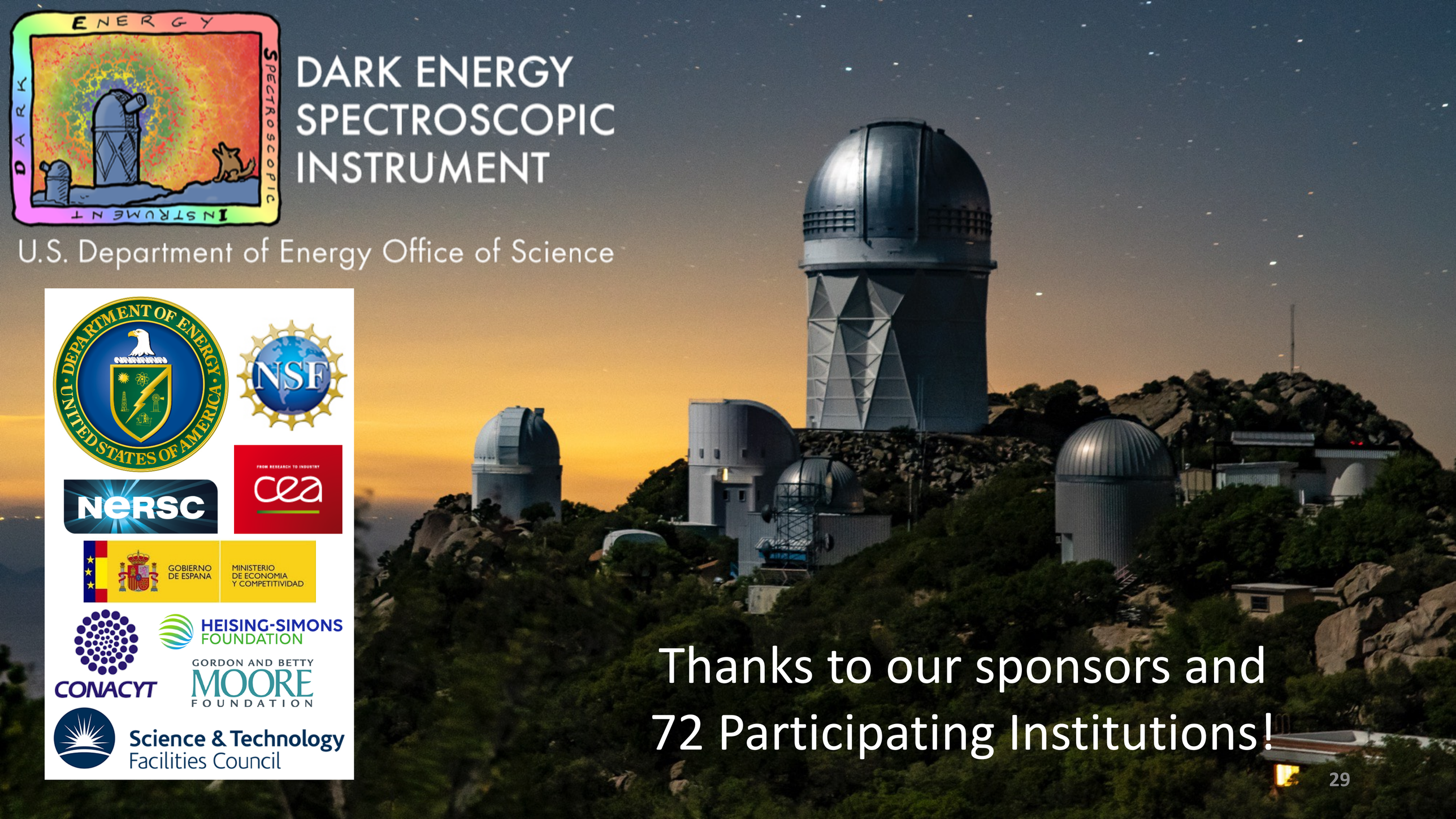
DESI Lyman-alpha results:

- DR2: 0.7% isotropic BAO measurement at z_{eff}=2.3
- DR1: 1.6% AP measurement + first measurement of $f\sigma_8$
- Coming up soon: DR1 P1D (running of n_s); DR2 3D full-shape

Outlook and <u>synergies:</u>

- sub-% AP from the Lya forest within reach, important test of DE models
- <u>Lyα is / will be very helpful for any other LSS probes at z>2:</u>

1) demonstrate cosmological signal, eg. (HI IM x Lyα) detection by CHIME
2) calibrate redshifts, spectro- or photo-z (eg. clustering redshift method for lensing)
3) cosmology with Nx2 correlations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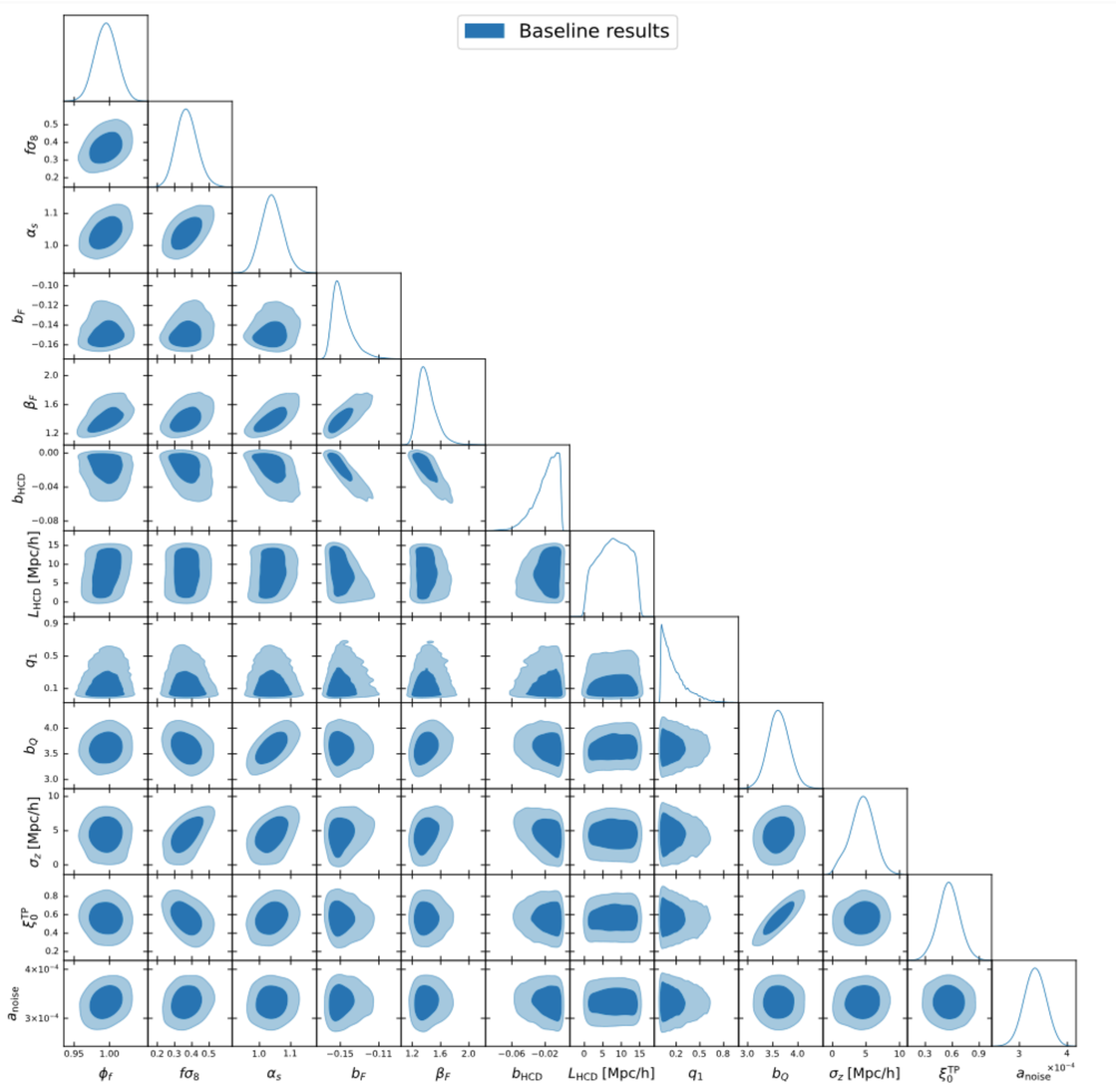
Parameters in FS fit

Parameter	Priors
$\{\alpha, \phi\}$	$\mathcal{U}[0.01, 2.00]$
f	$\mathcal{U}[0.00, 2.00]$
b_F	$\mathcal{U}[-2.00, 0.00]$
β_F	$\mathcal{U}[0.00, 5.00]$
b_Q	$\mathcal{U}[0.00, 10.00]$
b_{HCD}	$\mathcal{U}[-0.20, 0.00]$
β_{HCD}	$\mathcal{N}(0.500, 0.090)$
$L_{\rm HCD}(h^{-1}{\rm Mpc})$	$\mathcal{U}[0.00, 15.00]$
$10^3 b_{\rm SiII(1190)}$	$\mathcal{U}[-500.00, 0.00]$
$10^3 b_{\rm SiII(1193)}$	$\mathcal{U}[-500.00, 0.00]$
$10^3 b_{\rm SiII(1260)}$	$\mathcal{U}[-500.00, 0.00]$
$10^3 b_{\rm SiIII(1207)}$	$\mathcal{U}[-500.00, 0.00]$
$10^3 b_{\rm CIV(eff)}$	$\mathcal{N}(-24.3, 1.5)$
$\Delta r_{\parallel}(h^{-1}{\rm Mpc})$	$\mathcal{N}(0.0, 1.0)$
$\sigma_v(h^{-1}{\rm Mpc})$	$\mathcal{U}[0.00, 15.00]$
ξ_0^{TP}	$\mathcal{U}[0.00, 2.00]$
$10^4 a_{\rm noise}$	$\mathcal{U}[0.00, 100.00]$
q_1	$\mathcal{U}[0.00, 2.00]$
k_v	$\mathcal{U}[0.30, 2.00]$
a_v	$\mathcal{U}[0.10, 1.00]$
b_v	$\mathcal{U}[1.00, 2.00]$
k_p	$\mathcal{U}[5.00, 22.00]$



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LBG plots