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Measurement of the small-scale 3D Lyman-α forest power spectrum
arXiv: 2310.09116

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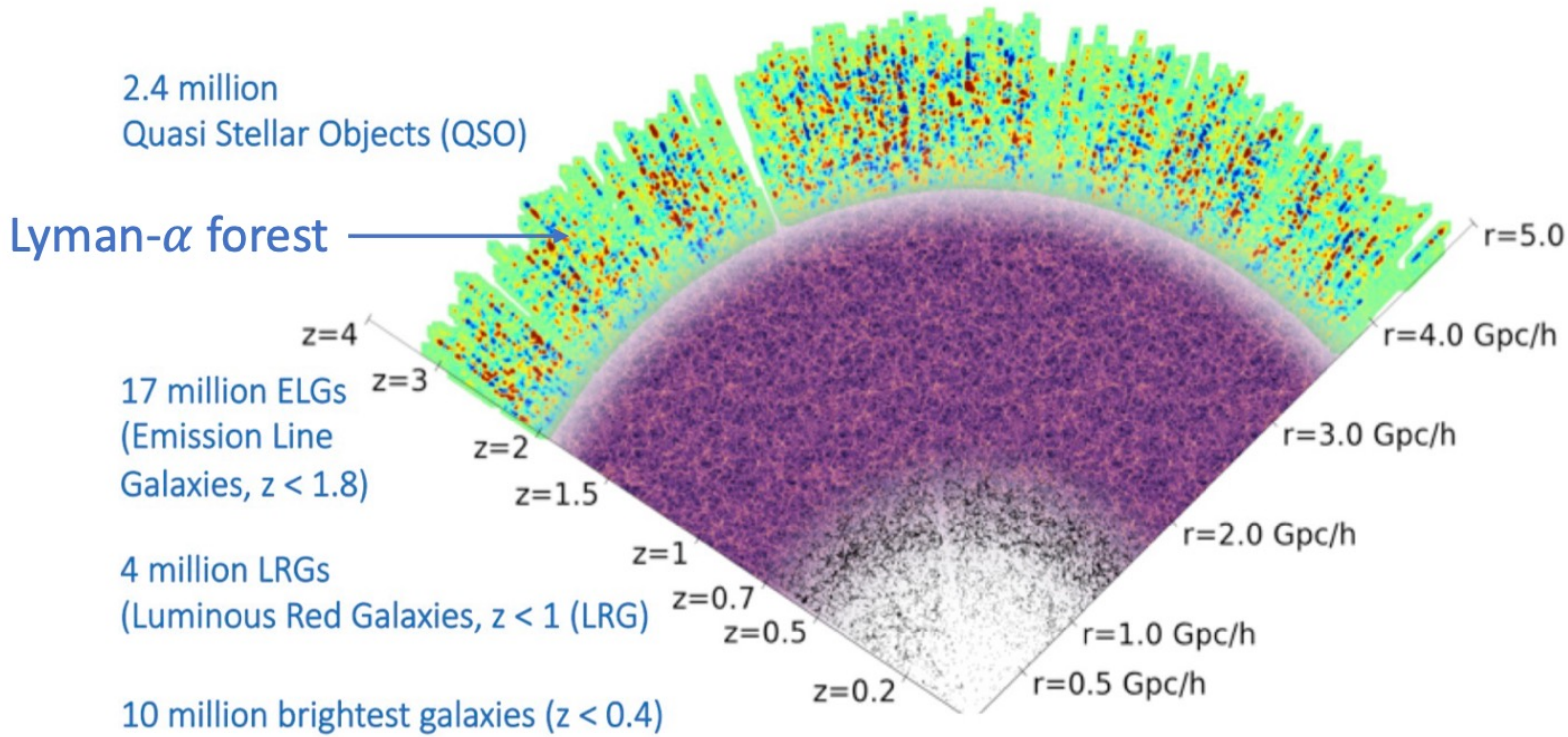
Action Dark Energy - 7th edition
7 November 2023 - Annecy

With Eric Armengaud, Guillaume Mention

DESI tracers of matter: Lyman-α forest



- Tracer of interest: Lyman-α forest (Lyα)
- Best tracer of the matter distribution in the universe at $z > 2$

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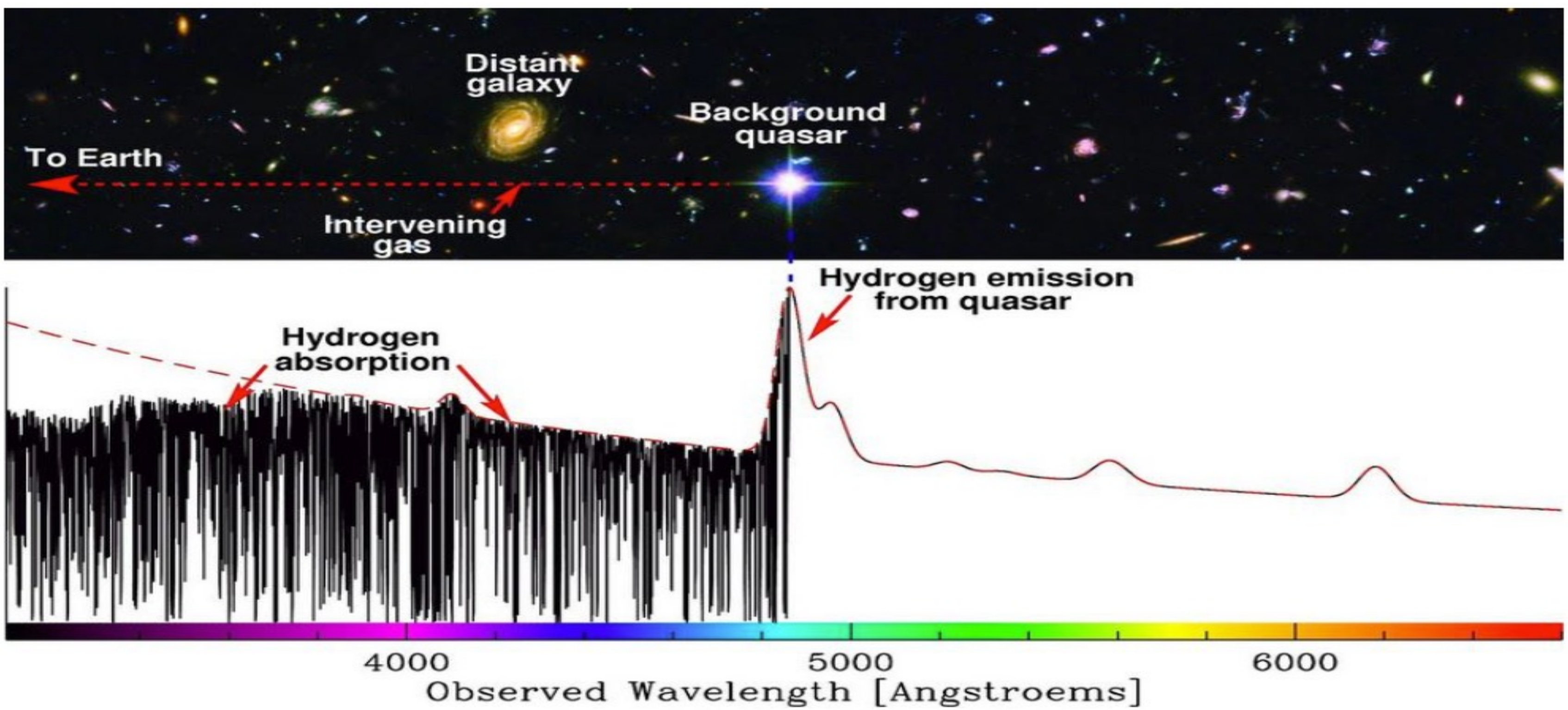
Lyα forest

- Lyα transition between ground state n=1 and first excited state n=2 of HI ($\lambda_{\mathrm{Ly\alpha}} = 1215.17$ Å)
- Absorption by neutral hydrogen HI at $\lambda_{\mathrm{absorption}} = \lambda_{\mathrm{Ly\alpha}}(1 + z_{\mathrm{HI}})$
- Measurement along the quasar's line-of-sight (LOS)
- Lyα forest encodes the density fluctuations of matter ⟶ δ_F: density contrast



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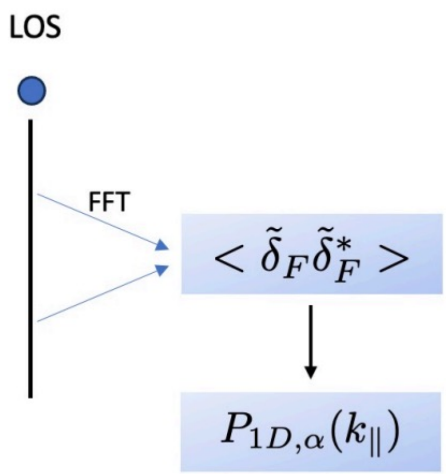
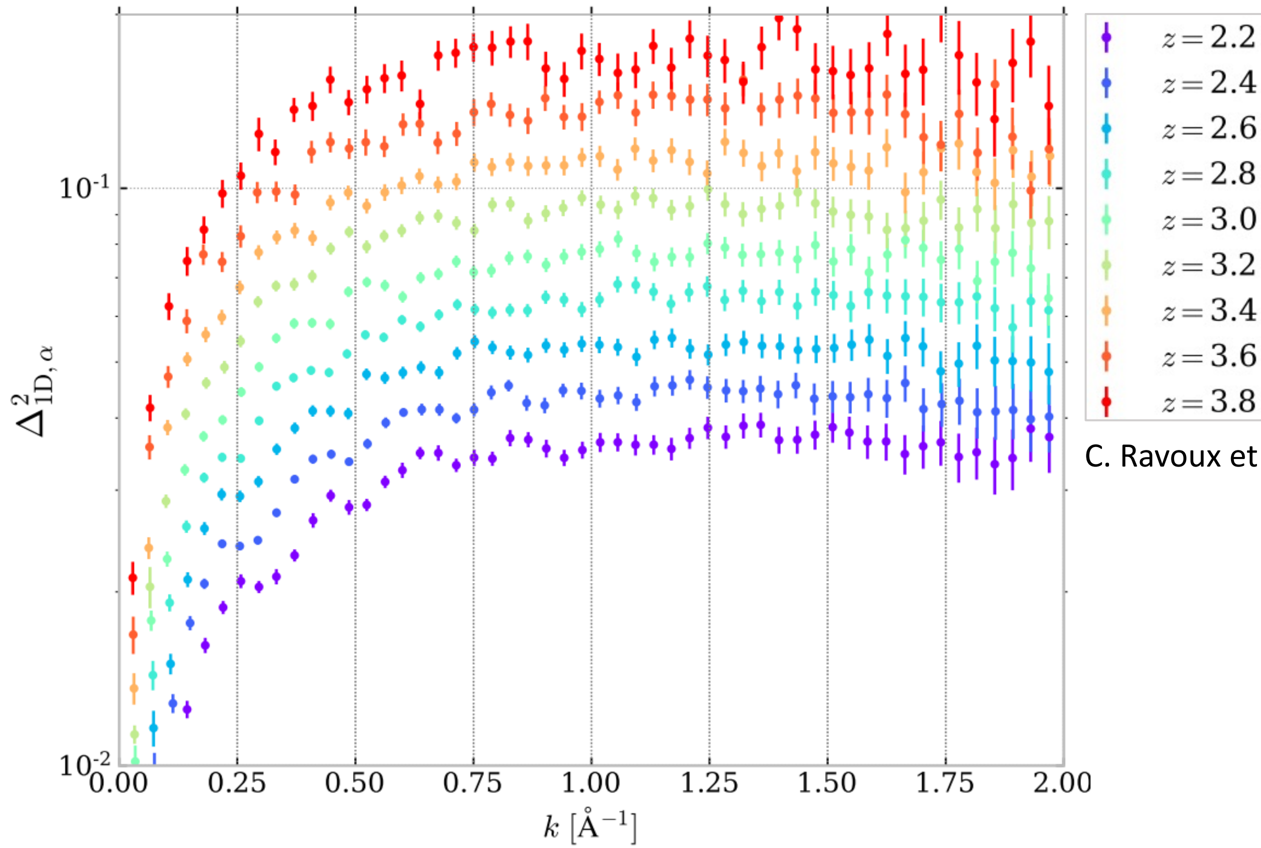
1D Power Spectrum: first DESI samples

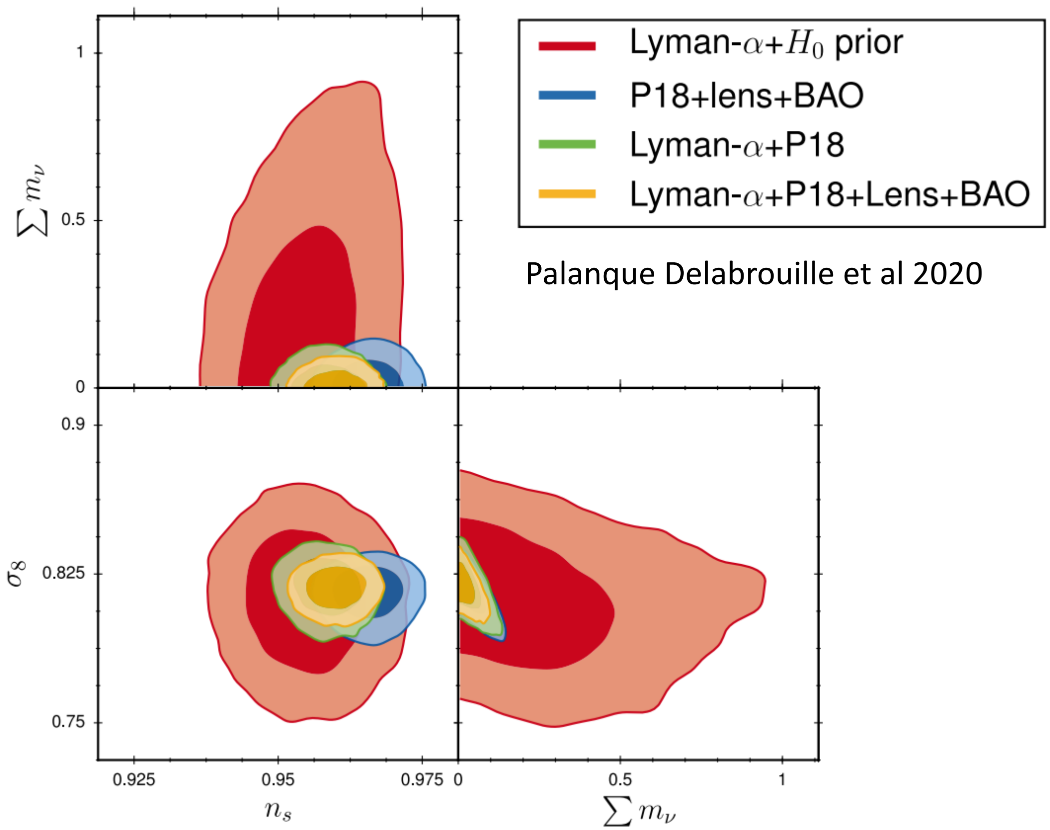




C. Ravoux et al 2023

- Cosmological observable: Lyα forest power spectrum at **small scales**
- P_{1D}: measurement of power spectrum along the quasar's LOS
- Measured P_{1D} for the first DESI Lyα forest sample (EDR) with the Fast Fourier Transform method

Cosmological constraints with P_{1D} (eBOSS)



Palanque Delabrouille et al 2020

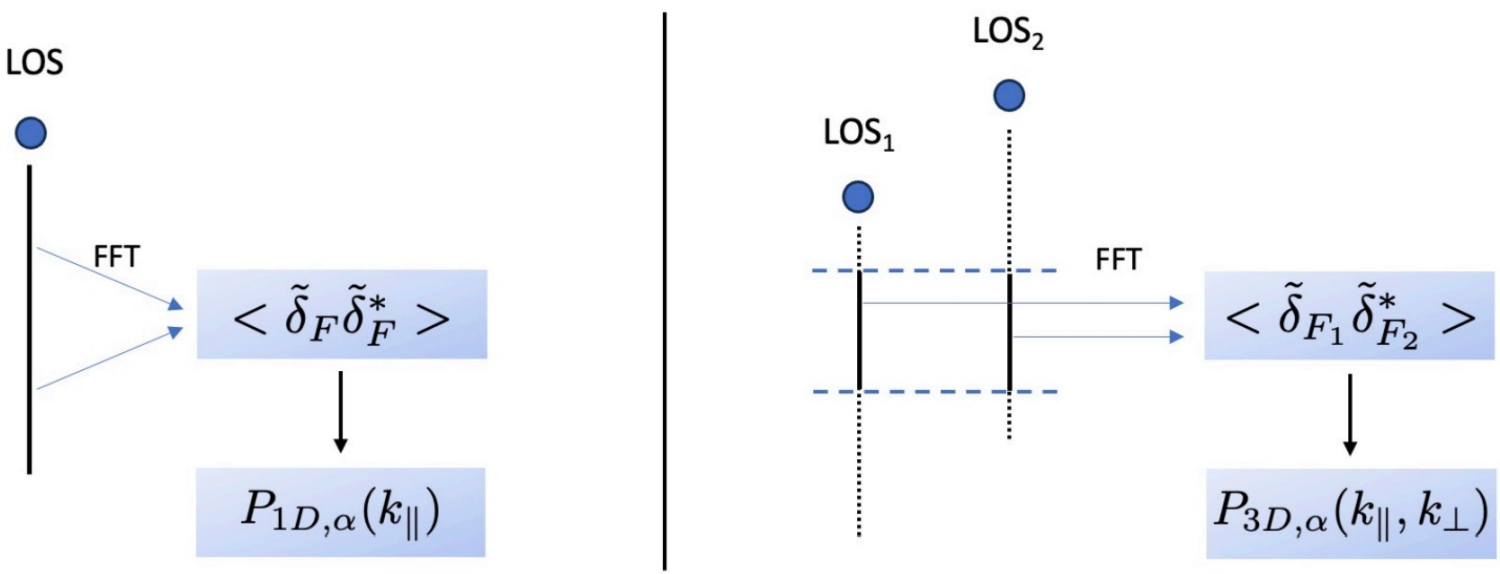
- Fit P_{1D} with a model from hydrodynamical simulations
- Main cosmological observables: (Amplitude, Slope) of the linear matter power spectrum $P_L(k)$ at $k_{Ly\alpha}$ and $z_{Ly\alpha}$ => Constraints on σ_8, n_s – See plot (eBOSS P_{1D} in agreement with Planck)
  => Constraints on neutrino properties: $\sum m_\upsilon$
- Also: DM properties (small scale cut-off in $P_L(k)$)

3D Power Spectrum: Extending P_{1D}

- P_{1D} : Correlating δ_F in independent LOS separately
- P_{3D} : Correlating δ_F across different LOS
- High density of quasars with eBOSS and DESI ⟶ P_{3D}

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

$$P_{3D}(z, k_\perp, k_\parallel) \equiv \int d^2\theta \, e^{i\boldsymbol{\theta}\cdot\boldsymbol{k}_\perp} \int d\Delta\lambda \, e^{i\Delta\lambda k_\parallel} \, \xi_{3D}(z, \theta, \Delta\lambda)$$



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A fast and simple estimator for $P_\times$ and P_{3D}

- $P_\times$: cross-spectrum, a hybrid quantity between real and Fourier space :

$$P_\times(z,\theta,k_\parallel) \equiv \int d\Delta\lambda \, e^{i\Delta\lambda k_\parallel} \, \xi_{3D}(z,\theta,\Delta\lambda)$$
$$= \int \frac{d^2 k_\perp}{(2\pi)^2} \, e^{i\boldsymbol{\theta}\cdot\mathbf{k}_\perp} \, P_{3D}(z,k_\perp,k_\parallel)$$

Font-Ribera+ 2018
Lam Hui+ 1998

- P_{1D} is a special case of $P_\times$: $P_{1D}(z,k_\parallel) = P_\times(z,\theta=0,k_\parallel)$

- A fast and simple estimator for $P_\times$: $\delta_{i:LOS}(\lambda) \xrightarrow{\text{FFT}} \delta_{i:LOS}(k_\parallel)$

Computation of angular separation for all possible pairs of LOS ij

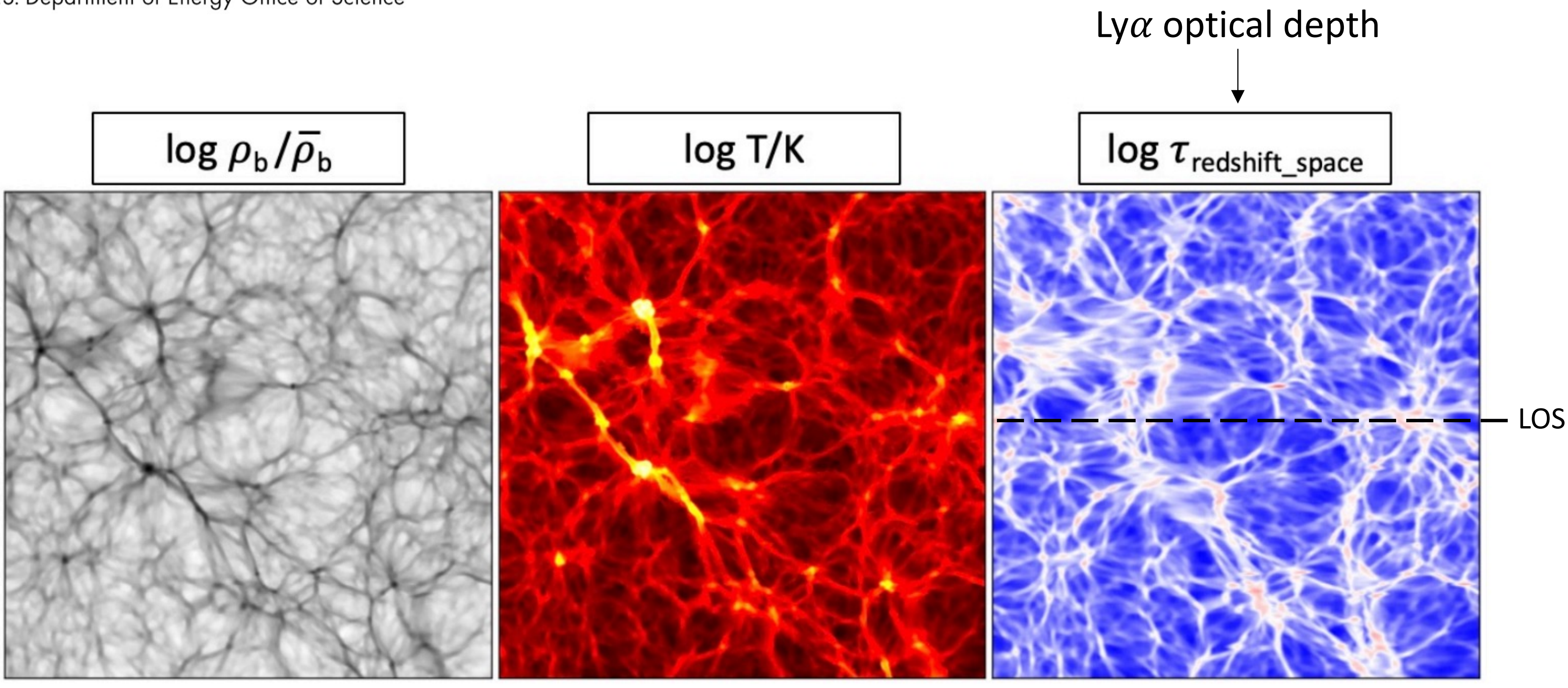
⇩

Estimator: $P_\times(\theta,k_\parallel) = \left\langle \Re\left(\tilde{\delta}_i(k_\parallel)\,\tilde{\delta}_j^*(k_\parallel)\right)\right\rangle$

- The computation of $P_\times$ enables P_{3D} inference:

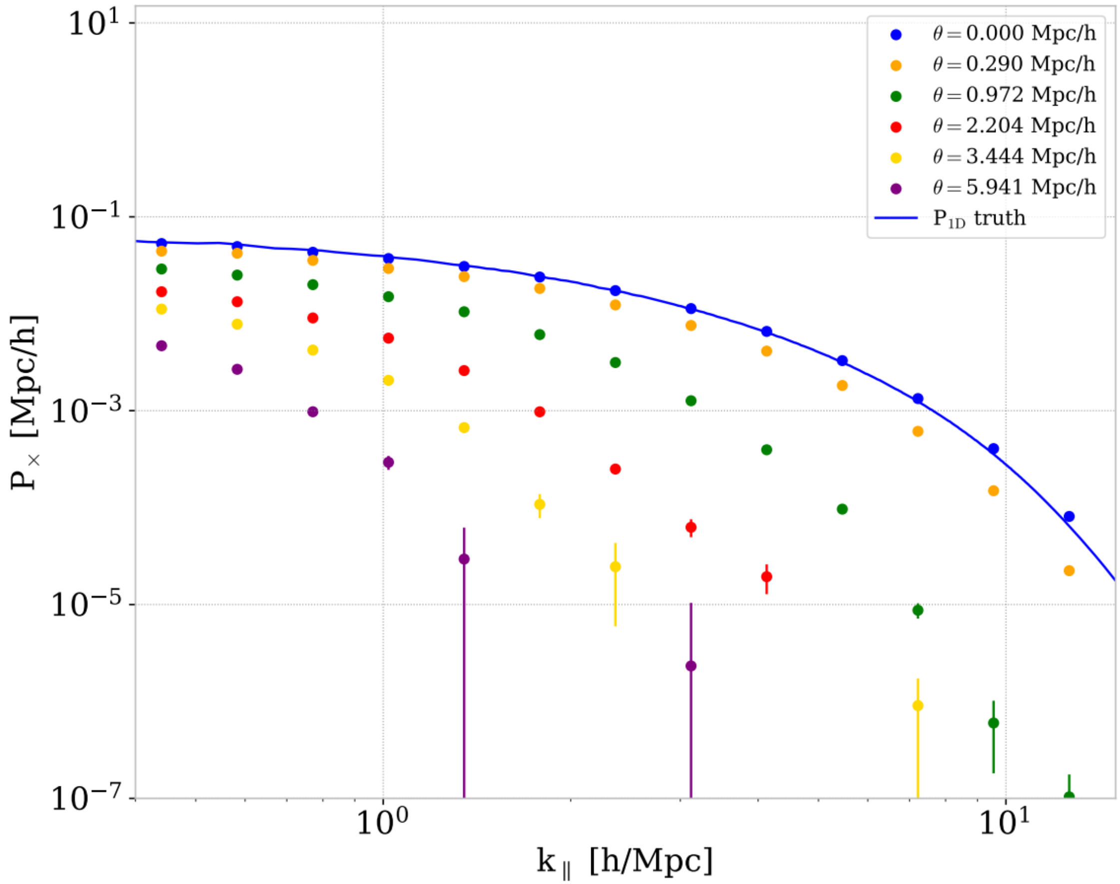
$$P_{3D}(z,k_\perp,k_\parallel) = 2\pi \int_0^\infty d\theta \, J_0(k_\perp\theta)\,\theta\,P_\times(z,\theta,k_\parallel)$$

Validation with hydrodynamical simulations



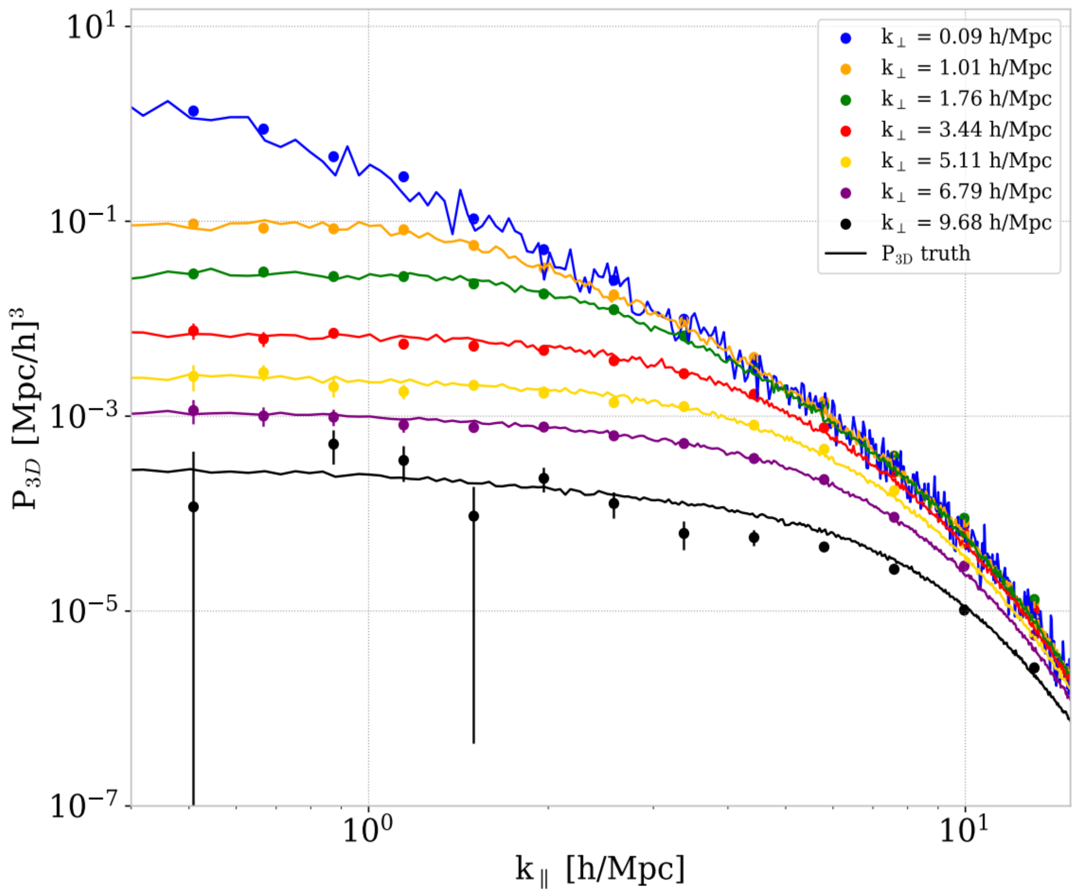
- Nyx: cosmological simulation code solving the evolution of the baryonic gas coupled to dark matter in the expanding Universe.
- Nyx snapshots at z = 2.0: 1536^3 cells, 150 $\mathrm{h^{-1}}$ Mpc, $\Delta\lambda$ = 98 $\mathrm{h^{-1}}$ kpc
- P_{3D} truth computed using gimlet: FFT 3D of the field

Results with reference, high density and noiseless mock: $P_x(k_\parallel,\theta)$



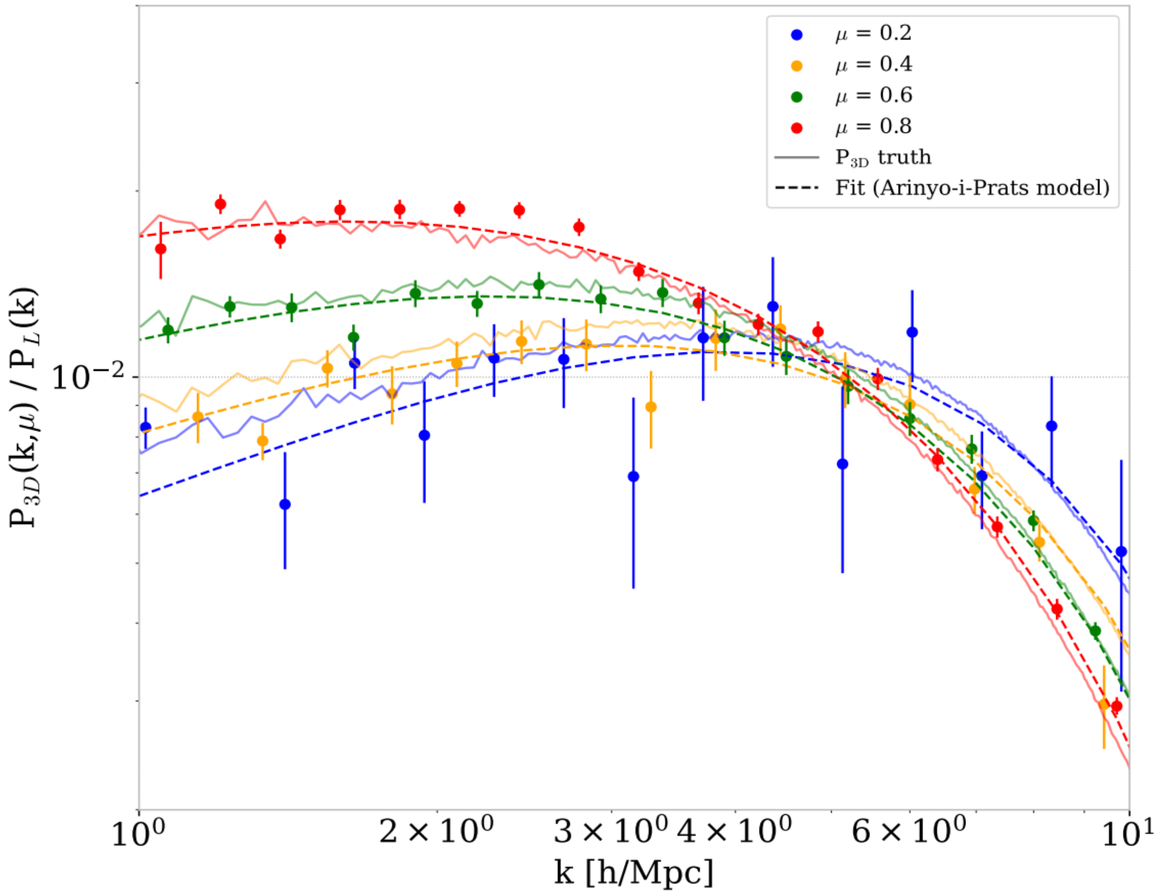
- Reference mock: 10^4 LOS drawn from Nyx box (very high density) without noise
- Overall power decreasing as function of θ
- Small-scale cut off at lower $k_\parallel$ as θ increases

Results with reference, high density and noiseless mock: $P_{3D}(k_{\parallel},k_{\perp})$



- P_{3D} in cartesian coordinates infered from P_x with $N_{LOS} = 10^4$: good agreement with truth
- $k_{\perp,max}$ = 10 h Mpc^{-1} $\propto 1 / \theta_{min}$

Results with reference, high density and noiseless mock: $P_{3D}(k,\mu)$



- Same measurement but in polar coordinates: $k = \sqrt{k_\perp^2 + k_\parallel^2}, \mu = k_\parallel / k$
- Fit: $$\frac{P_{3D}(k,\mu)}{P_L(k)} = b^2\,(1+\beta\mu^2)^2\,\exp\left(\left(q_1\Delta^2(k) + q_2\Delta^4(k)\right)\left[1 - \left(\frac{k}{k_v}\right)^{a_v}\mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2\right)$$

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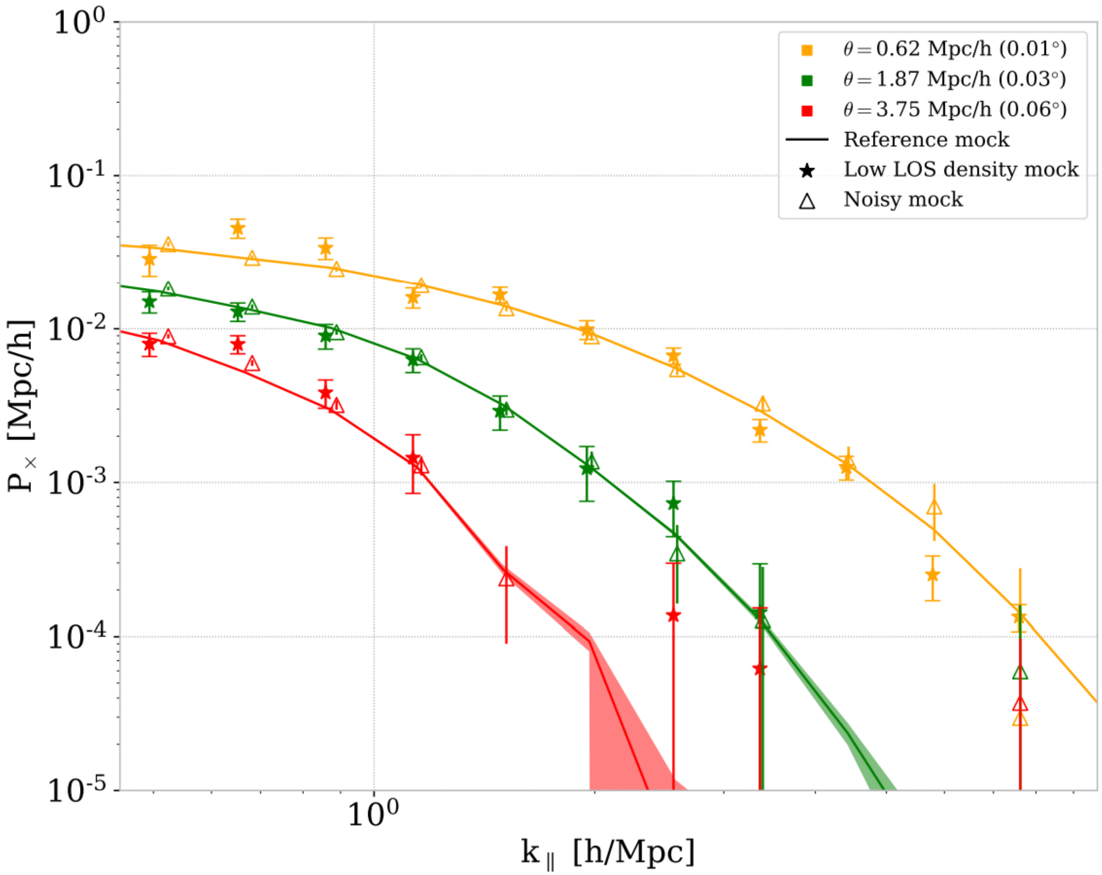
Results with realistic mocks



- Low LOS density mock: N_{LOS} = 500 ~ eBOSS pair statistics
- Noisy mock: adding realistic noise with σ_Δ= 0.5 for 1 Å (N_{LOS} = 10^4) ~ eBOSS
- Increase of statistical uncertainties in the measurement

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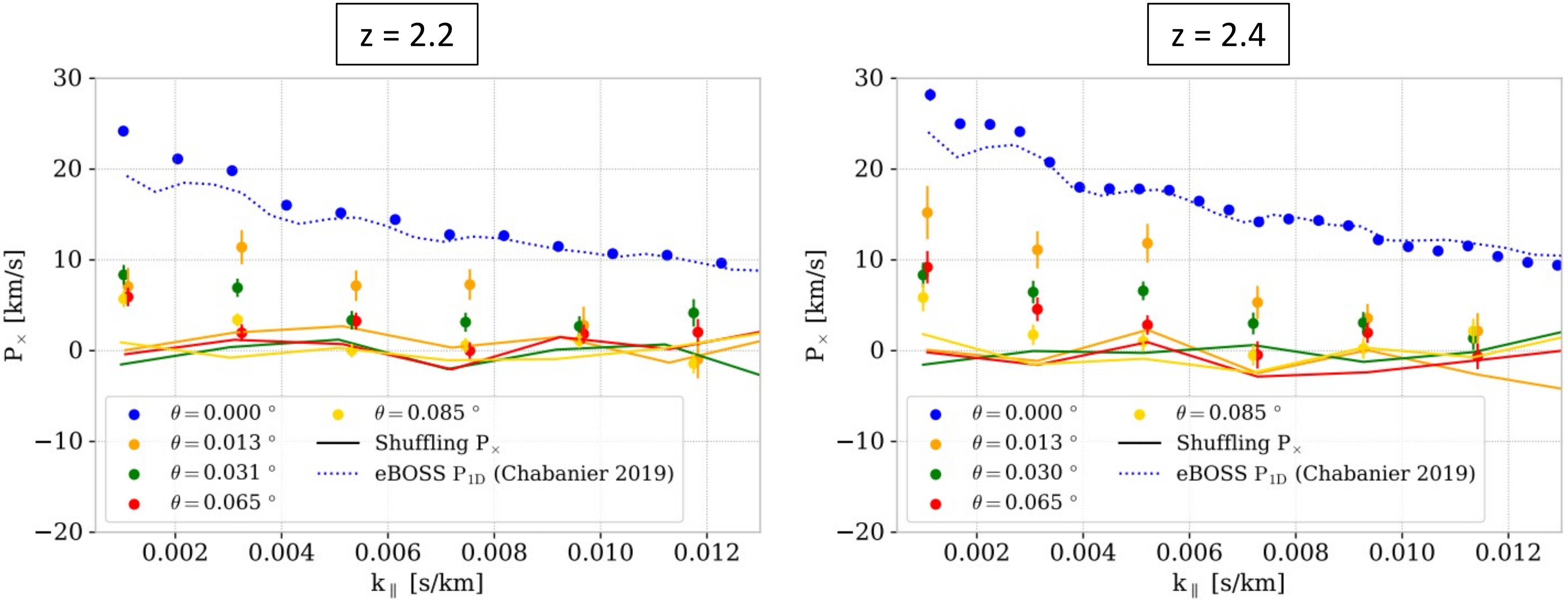
Proof-of-principle: Application to SDSS quasar spectra



- Use public eBOSS DR16Q catalog
- Reprocess Lya forest sample: - Select corresponding wavelength ranges (z bins)
  - Apply dedicated cuts (SNR, Resolution)
- Pair statistics:

$\langle\theta\rangle(°)$	0	0.013	0.03	0.065	0.085
$N(z=2.2)$	6848	105	329	342	440
$N(z=2.4)$	3438	28	89	78	104

- Shuffling (null test): cross-correlate LOS with random angular separations

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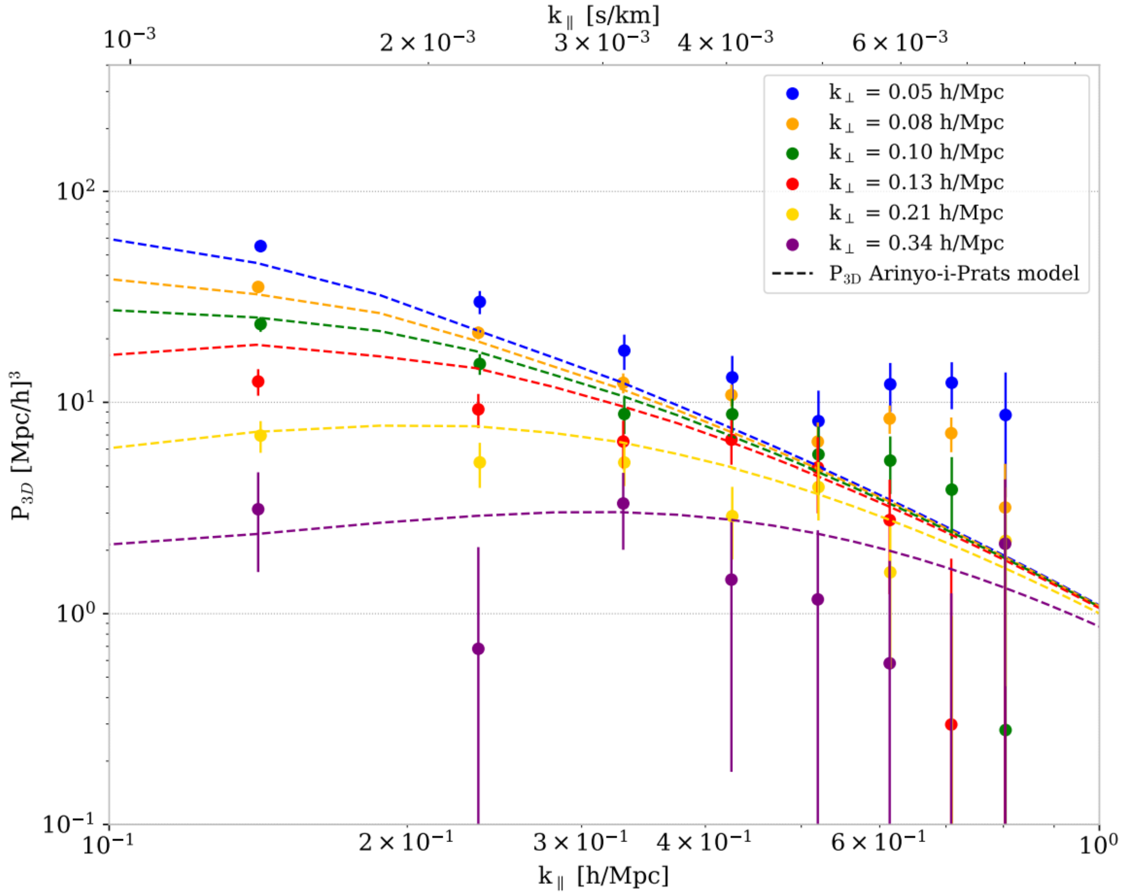
Proof-of-principle: Application to SDSS quasar spectra

z ≃ 2.3



- P_{3D} computed from the statistical combination of $P_x(z = 2.2)$ and $P_x(z = 2.4)$
- For an illustrative purpose: P_{3D} model from Arinyo-i-Prats

Conclusion and prospects

Summary

- Small-scale correlations of Lya forest are a powerful cosmological tool
- P1D measurement (BOSS/DESI EDR): longitudinal correlations only
- P3D measurement: more challenging, yet to be made
- Fast and simple method to compute P_x and P_{3D}
- Validation on Nyx hydrodynamical simulations
- Proof-of-principle measurement on real data: eBOSS DR16Q

Prospects

- Towards DESI Y1 measurement:
  - Full systematics study on P_{3D} required for DESI ~ expected to be similar to P_{1D}
  - Better pair statistics with DESI Y1
  - Cosmological interpretation

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Thank you !

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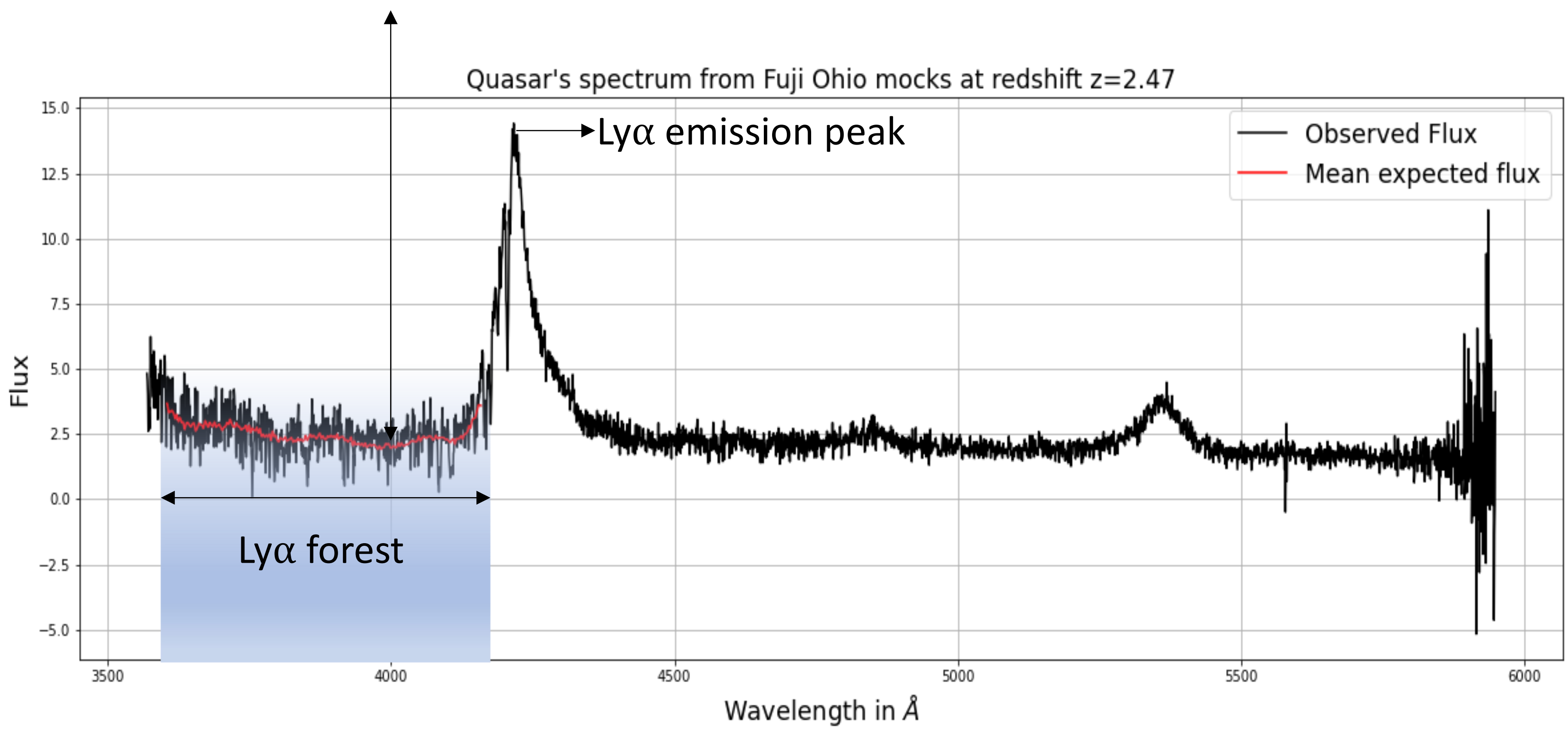
Quasar spectrum

- Lyα forest range: $1050 < \lambda < 1180$ Å

$$\delta(\lambda) = \frac{f_q(\lambda)}{\overline{F}(z)C_q(\lambda)} - 1 = \delta(\boldsymbol{\theta}, \lambda) = \frac{F(\boldsymbol{\theta}, \lambda)}{\overline{F}(\lambda)} - 1$$

: Represents the fluctuations around the mean expected flux



Noise and resolution

- For real data, noise and resolution effects must be accounted for:

$$P_{\times,\mathrm{Ly}\alpha}(\theta, k_{\|}) = \frac{P_{\times}(\theta, k_{\|}) - P_n(\theta, k_{\|})}{\left\langle \widetilde{W}_i(k_{\|})\, \widetilde{W}_j(k_{\|}) \right\rangle}$$

- With the assumption of uncorrelated noise between different LOS:

$$P_n(\theta, k_{\|}) = \begin{cases} \langle |\tilde{\delta}_{i,n}|^2 \rangle & \text{if } \theta = 0 \\ 0 & \text{if } \theta > 0 \end{cases}$$

From P_x to P_{3D}

- The computation of P_x enables P_{3D} inference:

$$P_{3\mathrm{D}}(z, k_\perp, k_\parallel) = \int d^2\theta \, e^{i\boldsymbol{\theta}\cdot\boldsymbol{k}_\perp} \, P_\times(z, \theta, k_\parallel)$$

- Moving to cylindrical coordinates, 2D → 1D integral:

$$P_{3\mathrm{D}}(z, k_\perp, k_\parallel) = 2\pi \int_0^\infty d\theta \, J_0(k_\perp \theta) \, \theta \, P_\times(z, \theta, k_\parallel)$$

- Units:
  - Simulations: P_x in $h^{-1}\ Mpc$ and P_{3D} in $[h^{-1}\ Mpc]^3$
  - eBOSS: P_x in $km\ s^{-1}$ and P_{3D} in $\mathrm{deg}^2\ km\ s^{-1}$
  - DESI: P_x in Å and P_{3D} in deg^2 Å

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P3D computation

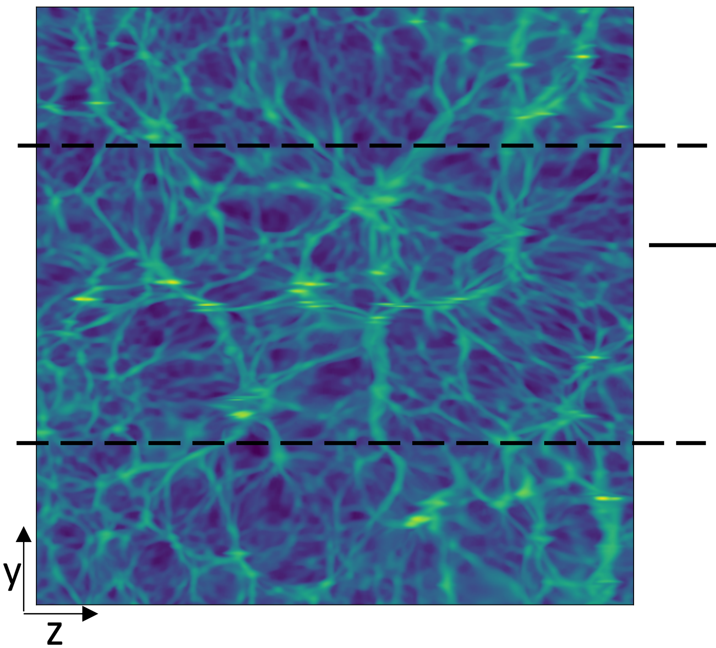
$$P_\times(z,\Delta\theta) \equiv \int d\Delta v \; e^{i\Delta v k_\parallel} \; \xi_{3D}(z,\Delta\theta,\Delta v) = \int \frac{d\mathbf{k}_\perp}{(2\pi^2)} \; e^{i\boldsymbol{\Delta}\theta\mathbf{k}_\perp} \; P_{3D}(z,k_\perp,k_\parallel)$$

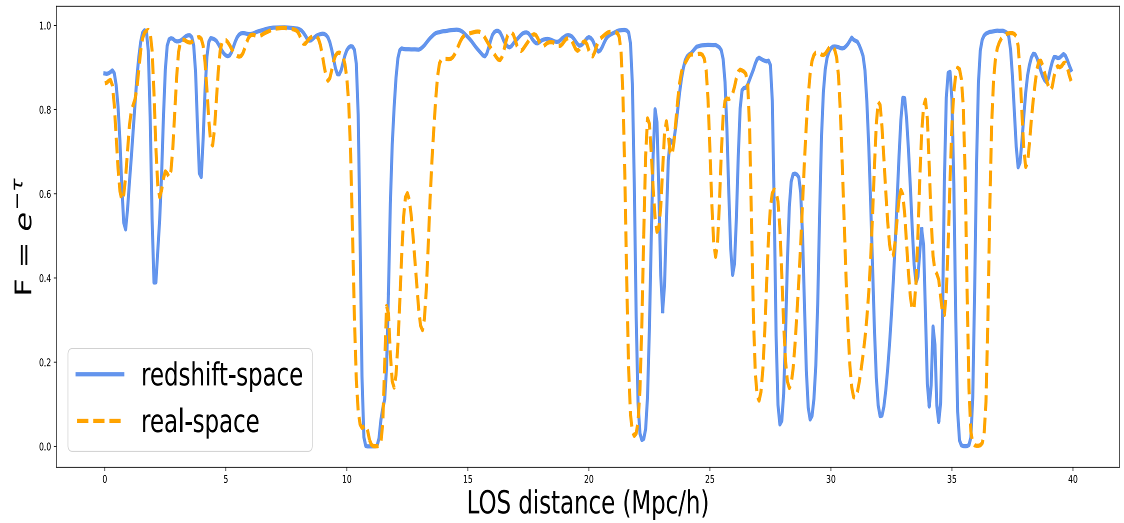
$$P_{3D}(k_\perp,k_\parallel) = 2\pi \int \Delta\theta \; J_0(\Delta\theta k_\perp) \; P_\times(z,\Delta\theta,k_\parallel) \; d\Delta\theta$$

- Choice of $k_\perp$ grid
- For each ($k_\perp$, $k_{/\!/}$) bin: interpolate $P_x(\Delta\theta, k_{/\!/})$ with spline
- Integrate interpolated $P_x(\Delta\theta, k_{/\!/})$ according to the above equation to get $P_{3D}(k_\perp, k_{/\!/})$

Validation on Nyx box: LOS drawing

$\log \tau_{\text{redshift\_space}}$





$$\delta_F = \frac{F}{\bar{F}} - 1$$

- Draw LOS from box
- Compute the transmitted flux fraction F and mean transmitted flux fraction $\bar{F}$
- Compute density contrast δ_F

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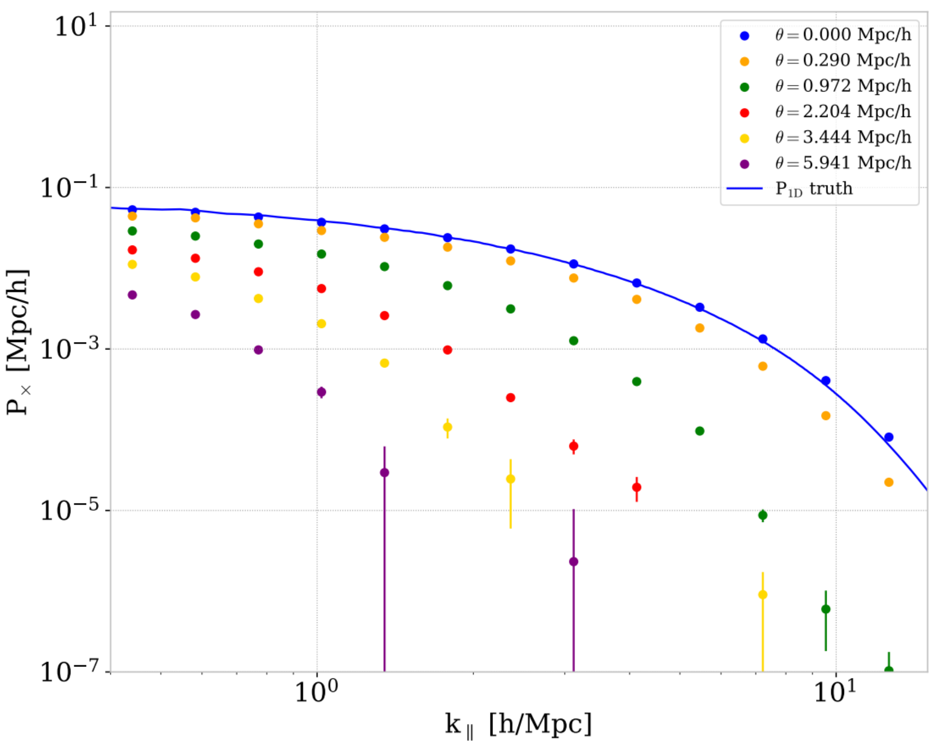
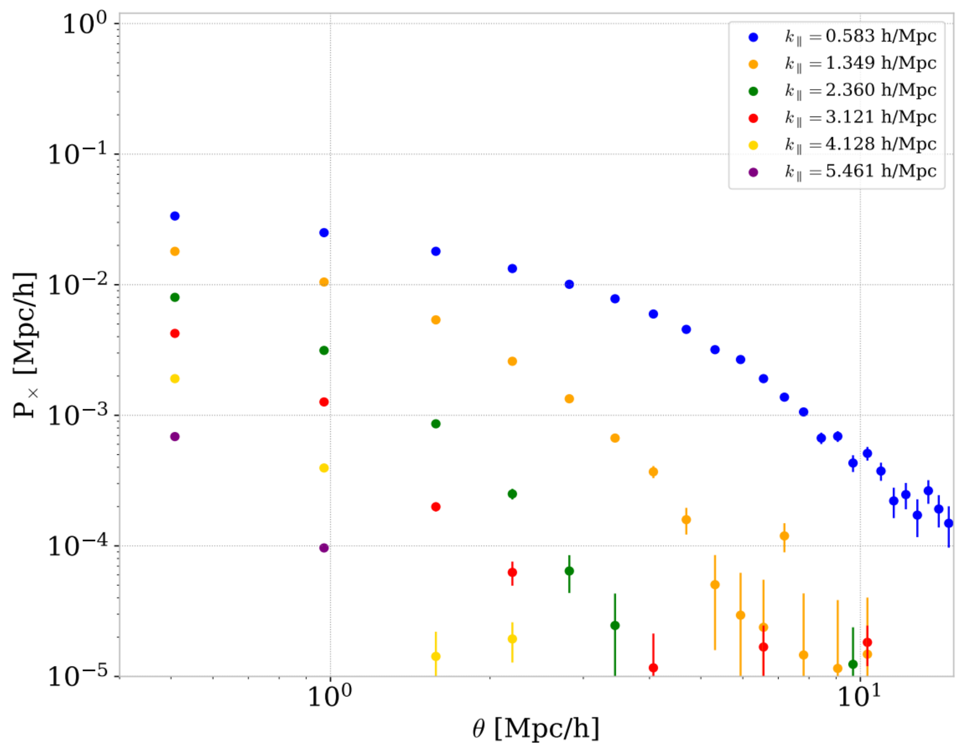
Results with reference, high density and noiseless mock: $P_\times$





- Reference mock: 10^4 LOS drawn from Nyx box (very high density) without noise
- Overall power decreasing as function of θ
- Small-scale cut off at lower $k_\parallel$ as θ increases
- The transverse correlations decrease faster as function of θ at larger $k_\parallel$

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Application to SDSS quasar spectra

- eBOSS DR16Q: z > 2.1 - no BAL - no DLA
- Computation of δ_F using the oublicly available pipeline picca
- Two samples:
  - z = 2.2: (λ_{min}, λ_{max}) = (3850, 3930) Å - including 38461 Lyα forests with 89 pixels each, spanning a comoving distance of ~ 59 h^{-1} Mpc
  - z = 2.4: (λ_{min}, λ_{max}) = (4056, 4210) Å - including 18653 Lyα forests with 162 pixels each, spanning a comoving distance of ~ 105 h^{-1} Mpc
- Same resolution correction W($k_{\parallel}$,R) as eBOSS – P_{1D}
- SNR cut:
  - $P_x(\theta = 0)$: $\overline{SNR}$ > 3.9 at z = 2.4 and > 4.1 at z = 2.2 as in eBOSS – P_{1D}
  - $P_x(\theta > 0)$: $\overline{SNR}$ > 1 for both z bins
- Resolution cut:
  - $P_x(\theta = 0)$: $\bar{R}$ > 85 $km\ s^{-1}$ as in eBOSS – P_{1D}