Baryonic Acoustic Oscillations in SDSS and DESI using the intergalactic medium absorption

Hélion du Mas des Bourboux

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II/ Data and simulations: catalogs and dark matter tracer analysis

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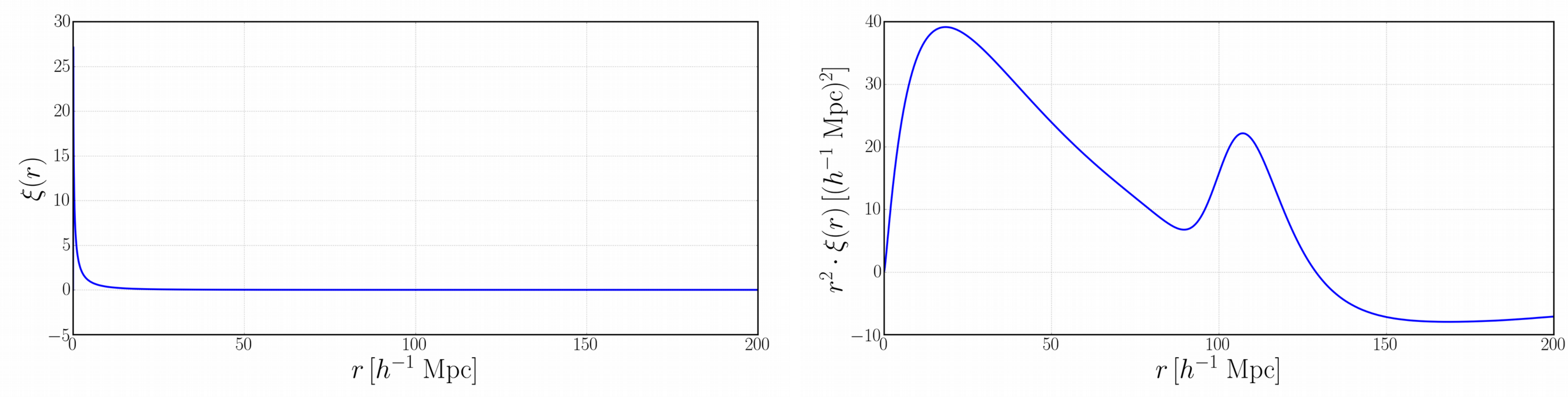
The correlation function

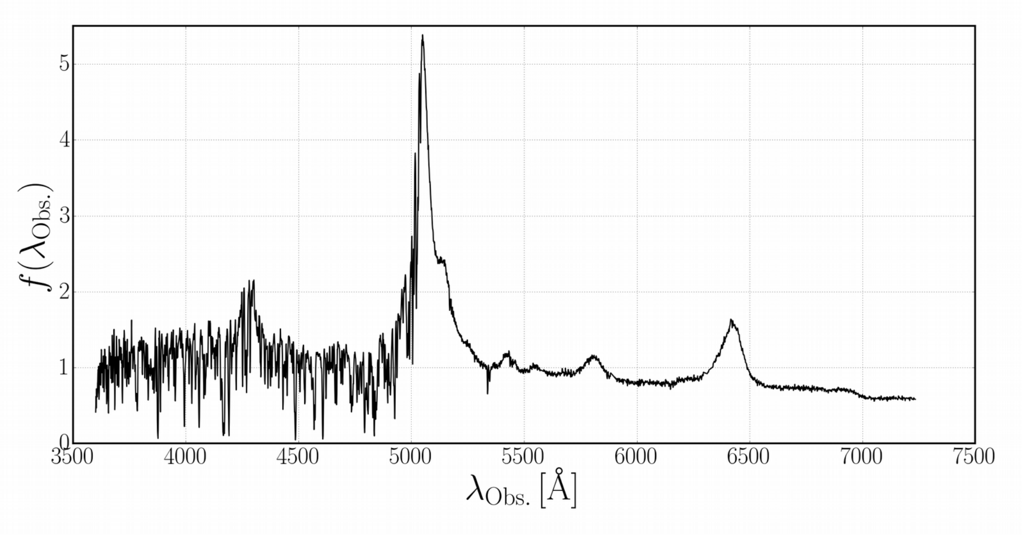
$\xi(\vec{r})$ is the matter correlation function.

It gives the correlation between two points in the Universe



Tracer: the quasars

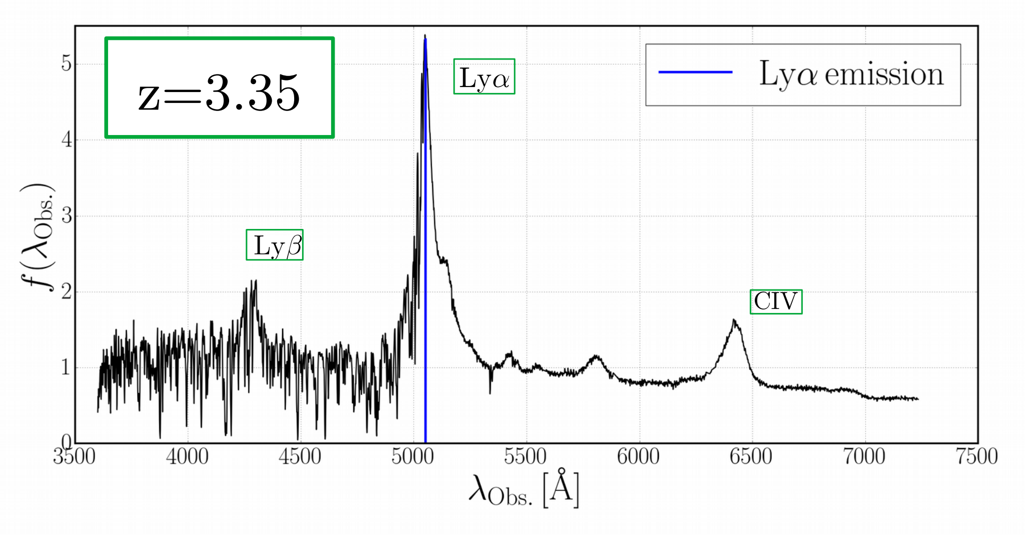
- Quasar = galaxy + supermassive black hole



- Spectrum of a BOSS quasar, the Universe was only 2 billion years old when the flux was emitted

Tracer: the quasars

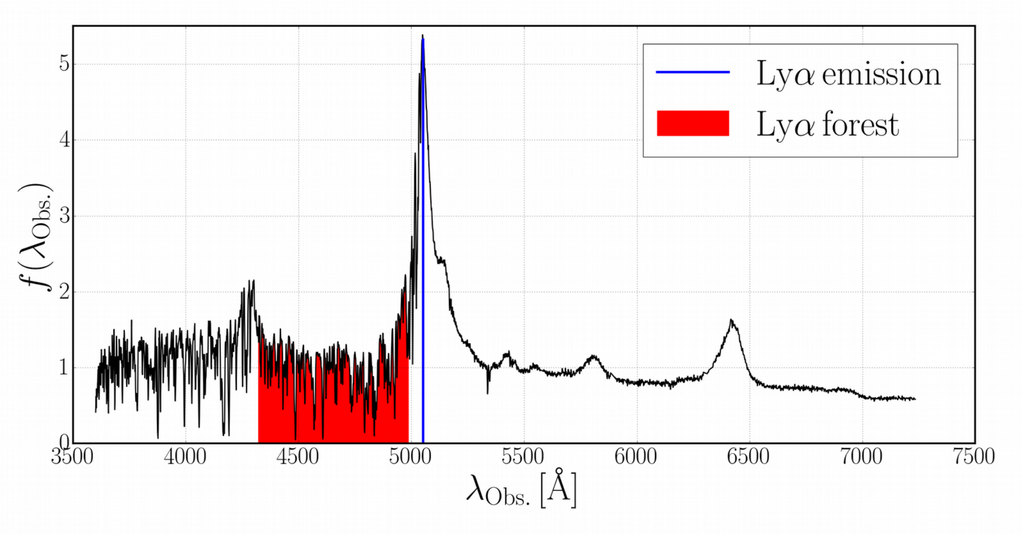
- Get the redshift from the different emission lines



- A quasar is a boolean tracer of matter density fluctuations.

Traceurs : les forêts Lyα

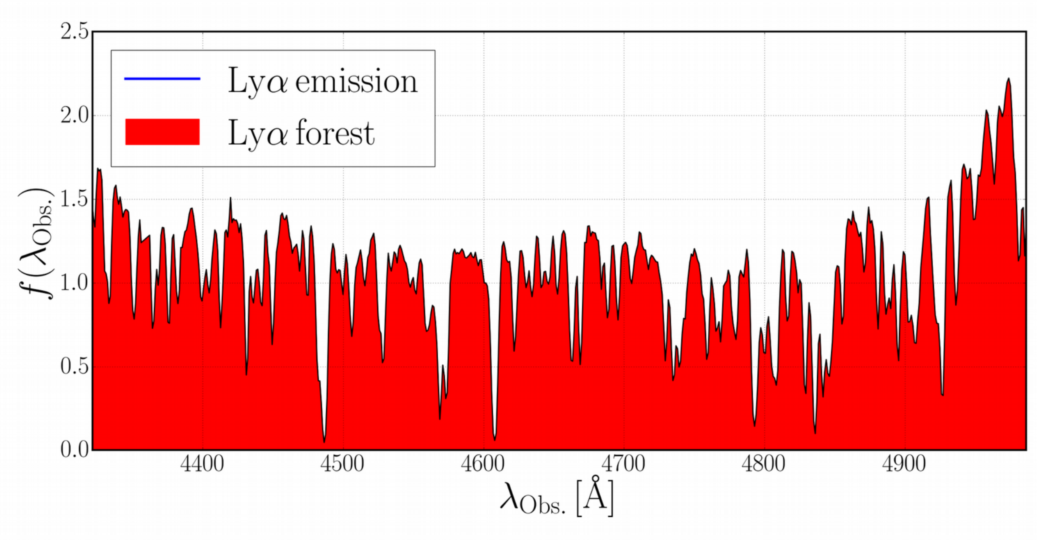
- Absorption continuum from neutral hydrogen in the intergalactic medium (IGM) along the line-of-sight.



$$z + 1 = \frac{\lambda_{\mathrm{Obs.}}}{1215.67}$$

- Lyα absorption: from electron shell n=1 to n=2.

Traceurs : les forêts Lyα



- A pixel of the Lyα forest gives a continuous tracer of matter density fluctuations.

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Data analysis

- This work is published in A&A

Baryon acoustic oscillations from the complete SDSS-III Lyα-quasar cross-correlation function at $z = 2.4$

Hélion du Mas des Bourboux[1], Jean-Marc Le Goff[1], Michael Blomqvist[2], Nicolás G. Busca[3], Julien Guy[4], James Rich[1], Christophe Yèche[1,5], Julian E. Bautista[6], Étienne Burtin[1], Kyle S. Dawson[6], Daniel J. Eisenstein[7], Andreu Font-Ribera[5,8], David Kirkby[9], Jordi Miralda-Escudé[10,11], Pasquier Noterdaeme[12], Isabelle Pâris[2], Patrick Petitjean[12], Ignasi Pérez-Ràfols[11], Matthew M. Pieri[2], Nicholas P. Ross[13], David J. Schlegel[5], Donald P. Schneider[14,15], Anže Slosar[16], David H. Weinberg[17], Pauline Zarrouk[1]

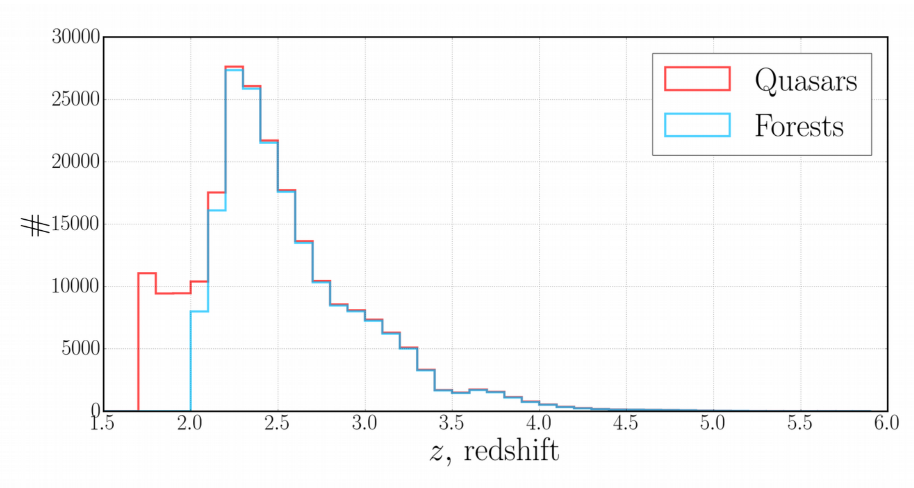
ABSTRACT

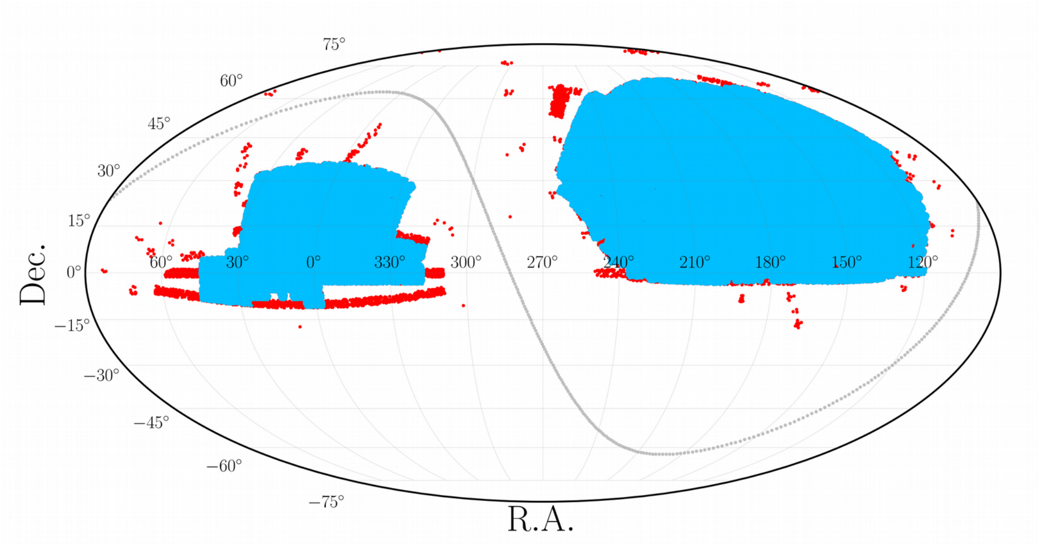
We present a measurement of baryon acoustic oscillations (BAO) in the cross-correlation of quasars with the Lyα-forest flux-transmission at a mean redshift $z = 2.40$. The measurement uses the complete SDSS-III data sample: 168,889 forests and 234,367 quasars from the SDSS Data Release DR12. In addition to the statistical improvement on our previous study using DR11, we have implemented numerous improvements at the analysis level allowing a more accurate measurement of this cross-correlation. We also developed the first simulations of the cross-correlation allowing us to test different aspects of our data analysis and to search for potential systematic errors in the determination of the BAO peak position. We measure the two ratios $D_H(z = 2.40)/r_d = 9.01 \pm 0.36$ and $D_M(z = 2.40)/r_d = 35.7 \pm 1.7$, where the errors include marginalization over the non-linear velocity of quasars and the metal - quasar cross-correlation contribution, among other effects. These results are within 1.8σ of the prediction of the flat-ΛCDM model describing the observed CMB anisotropies. We combine this study with the Lyα-forest auto-correlation function (Bautista et al. 2017), yielding $D_H(z = 2.40)/r_d = 8.94 \pm 0.22$ and $D_M(z = 2.40)/r_d = 36.6 \pm 1.2$, within 2.3σ of the same flat-ΛCDM model.

Key words. cosmology, dark energy, baryon acoustic oscillations, BAO, quasar, Lyα-forest, large scale structure

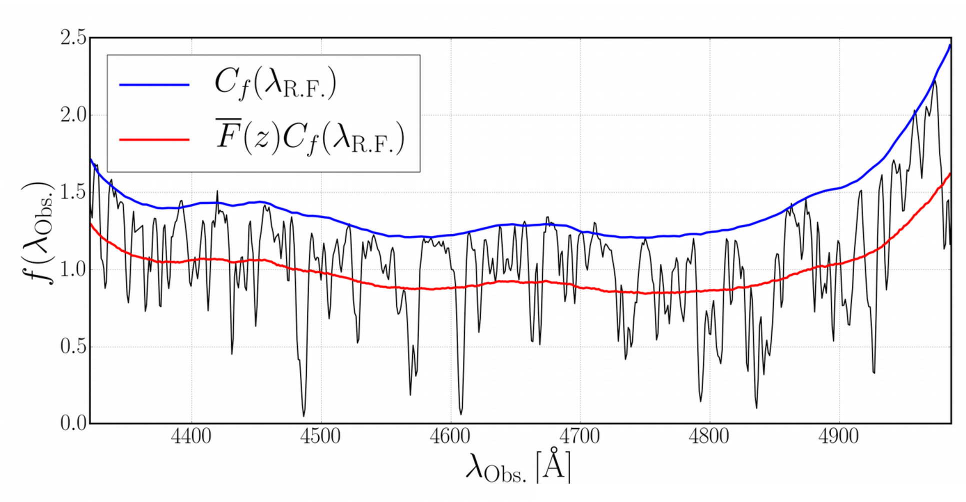
Quasars

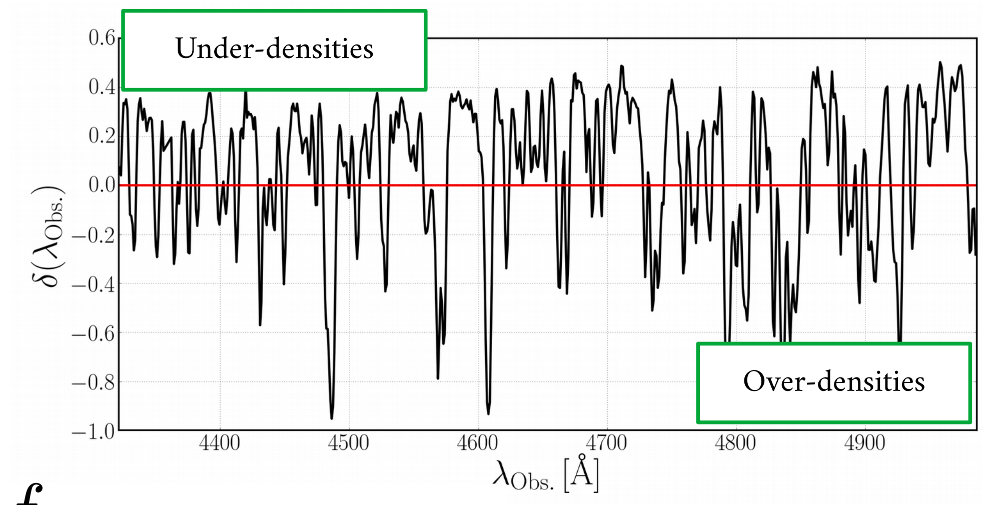
- We take quasars from DR7Q of SDSS-II and DR12Q of SDSS-III
- Redshift range of pixels $z \in [1.96, 4.96]$ impose a selection on quasar redshift: $z \in [1.7, 5.8]$.
- After all cuts, we have 234,367 quasars (164,017 in previous studies).





Transmitted flux fraction





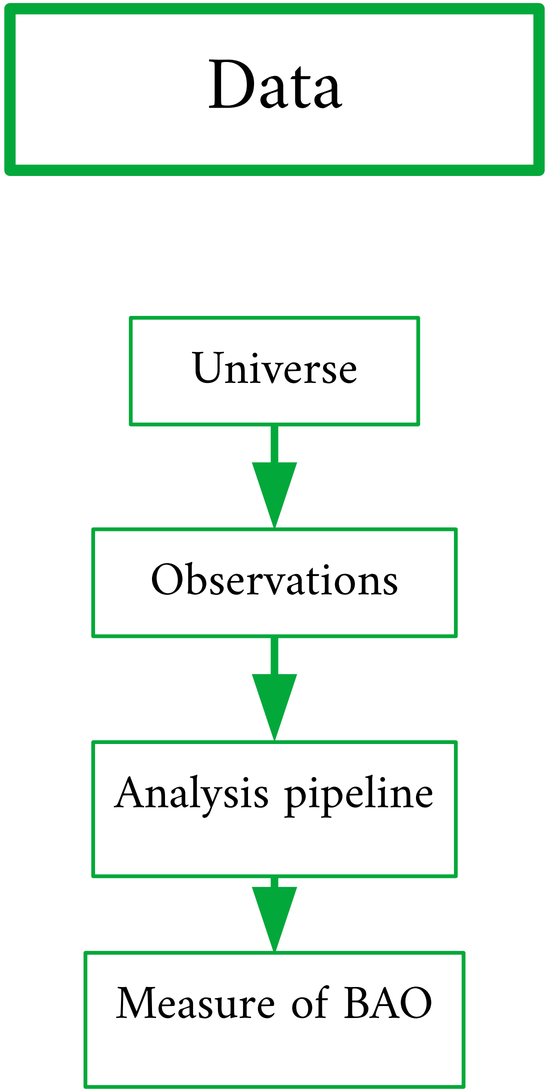
$$\delta_i = \frac{f_i}{\overline{F}(\lambda_{Obs.,i})C_f(\lambda_{R.F.,i})} - 1$$

$$C_f(\lambda_{R.F.,i}) = \overline{C}(\lambda_{R.F.,i})\left(A_{f,1} + A_{f,2}(\lambda_{R.F.,i} - \overline{\lambda_{R.F.,f}})\right)$$

- We fit all ~170,000 forests.
- This fit allows to get ~83M tracers of Lyα fluctuations.

Reason to build simulations

- 1st simulations of the cross-correlation function
- Build in association with Jean-Marc Le Goff
- Goals:
  - Qualitatively reproduce the data
  - Test different elements of the analysis pipeline
  - Consequences on the BAO measurement:
    - Systematical biais
    - Estimation of the precision



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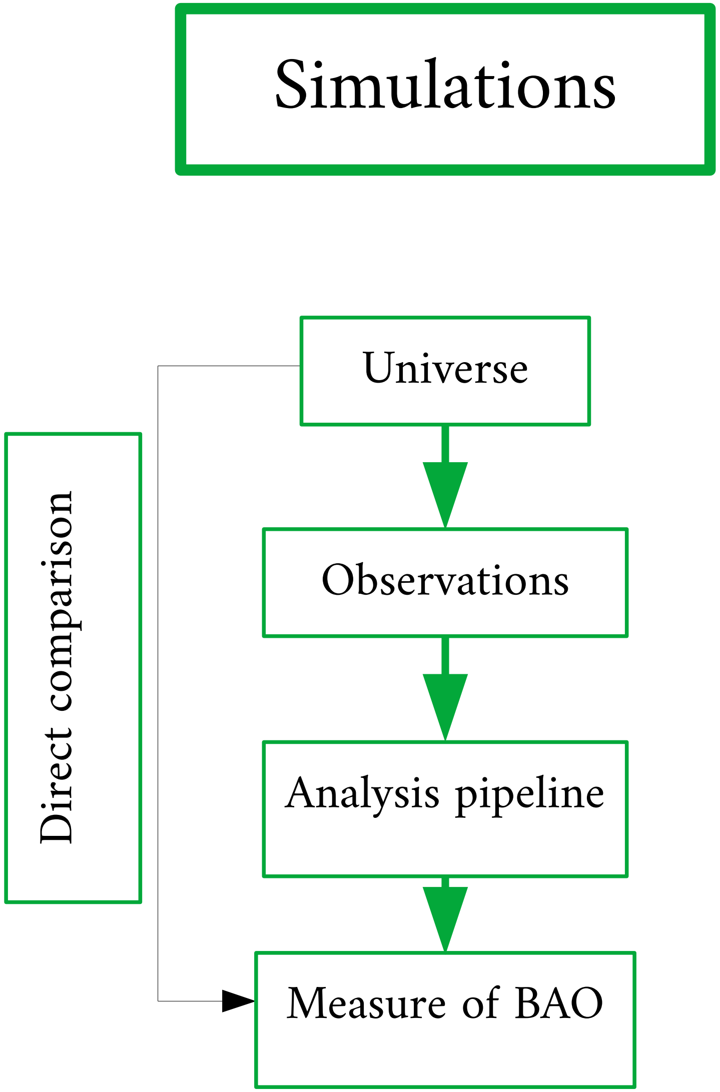
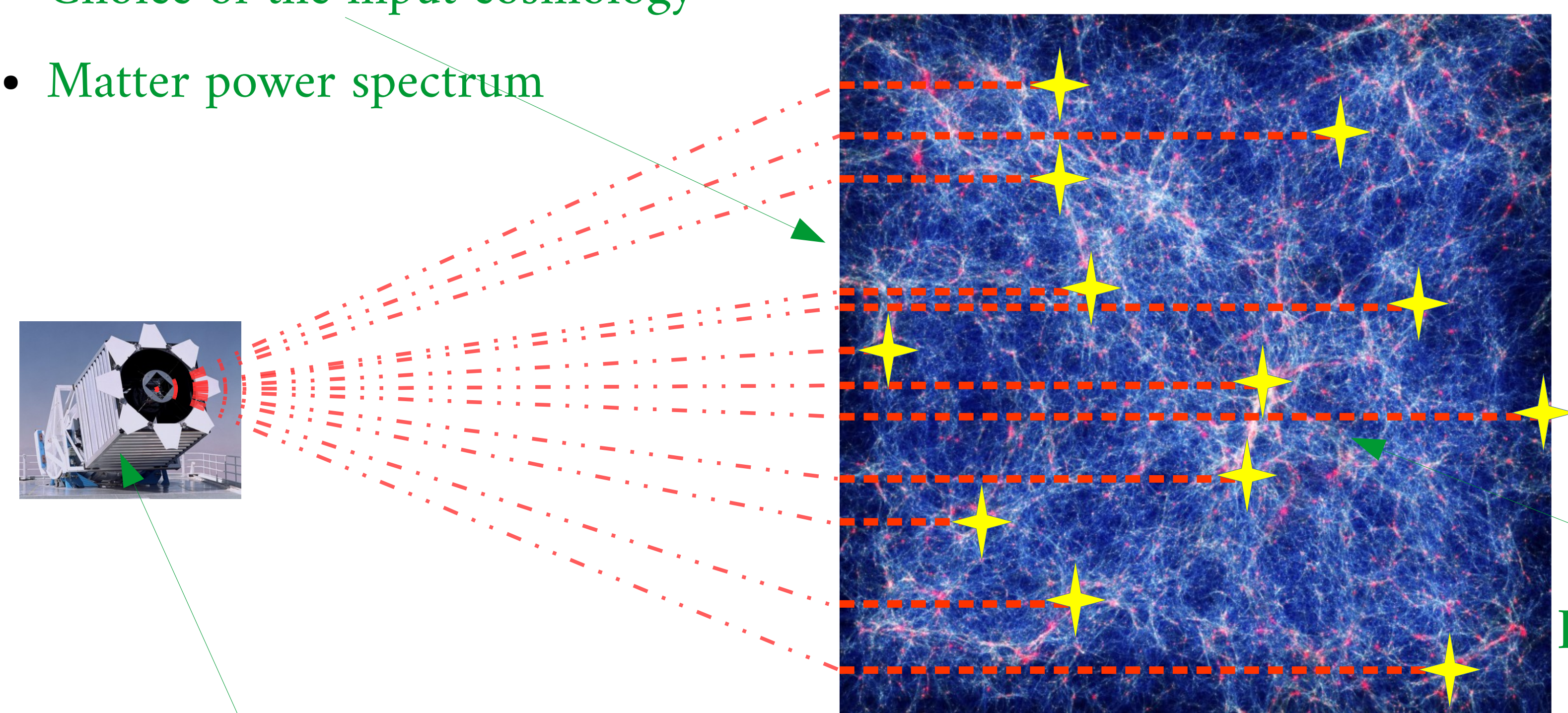


Principle

- 3D box
- Gaussian random field
- Choice of the input cosmology
- Matter power spectrum

Quasar set on big over-densities



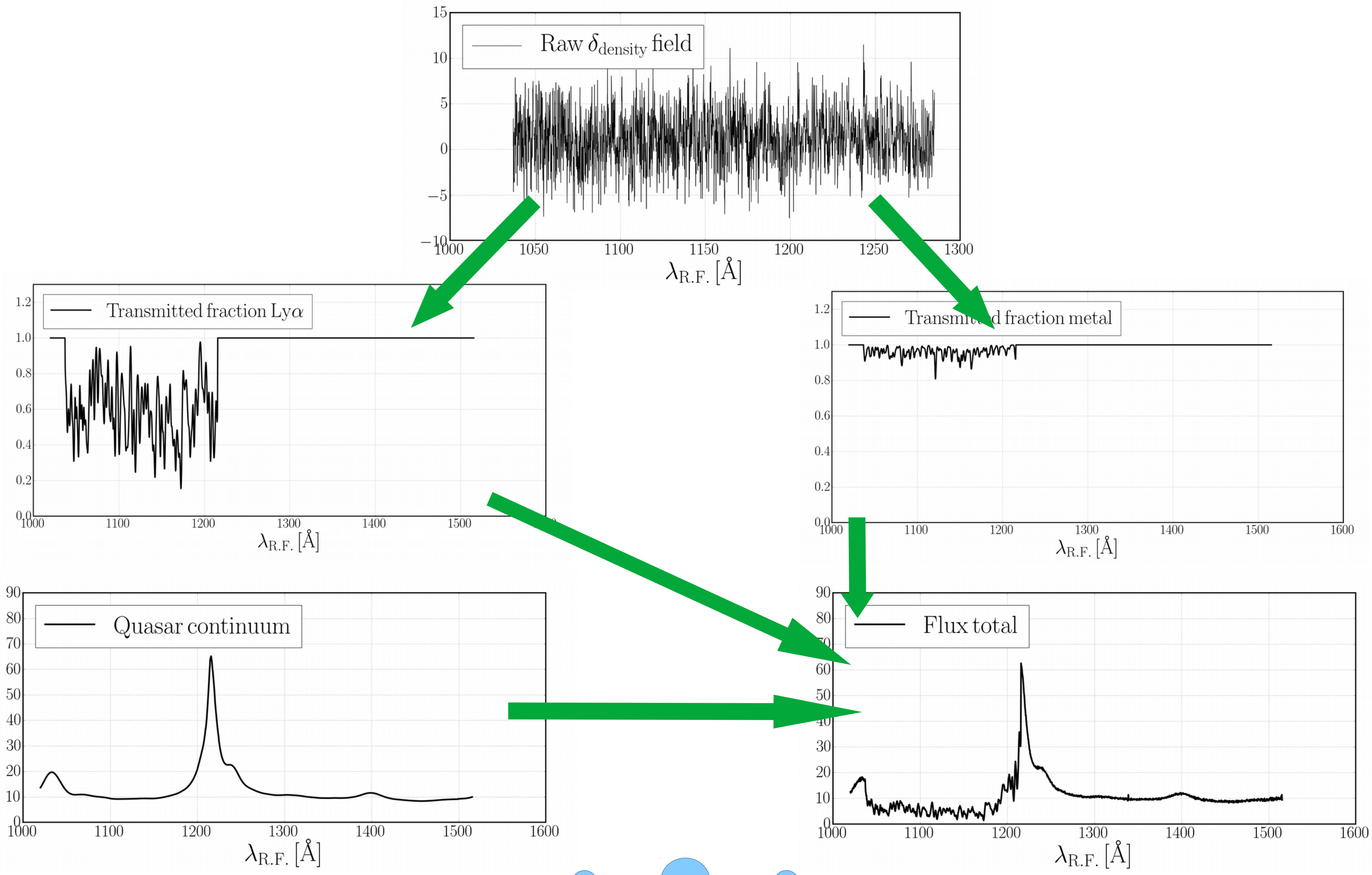
Telescope properties

IGM simulation from Julien Baur

Lyα forests along the line-of-sight

Principle

From Gaussian random field to a mocked spectrum of SDSS-III.



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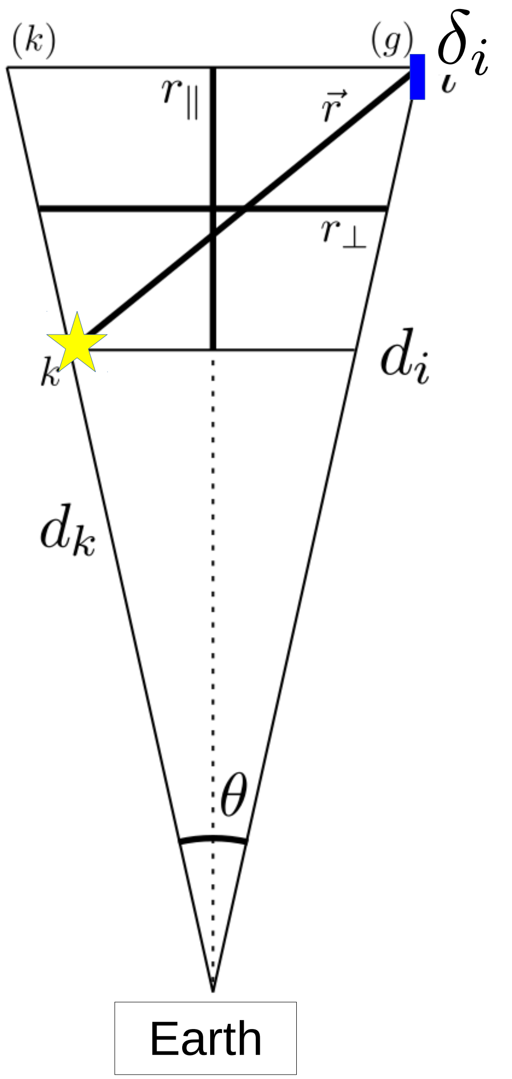
Measure

- We measure the 2-point cross-correlation function on 5000 squares of size $4\,h^{-1}\mathrm{Mpc}$ for $r_{\parallel} \in [-200, 200]$ and $r_{\perp} \in [0, 200]$
- Distance are computed using a reference cosmology (Planck2015)
- With:
  - 230k quasars
  - 83M pixels (170k forests)

→ 1.8G pairs in the BAO region

$$\xi_A^{qf} = \frac{\sum\limits_{(i,k)\in A} w_i \delta_i}{\sum\limits_{(i,k)\in A} w_i}$$



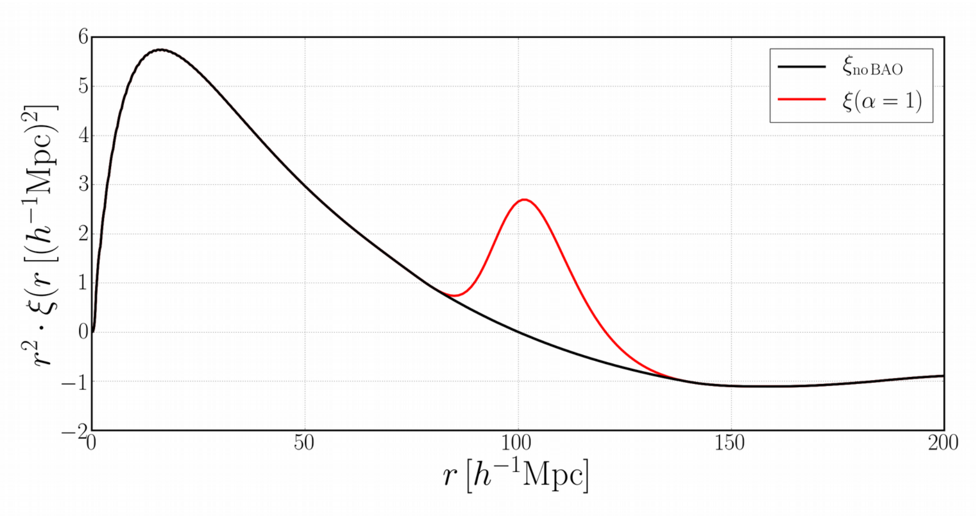
Fit of the BAO pic

- Fit by minimization of chi2:

$$\chi^2 = \left(\xi^{qf}_{measured} - \xi^{qf}_{model}\right)^{\top} C^{-1} \left(\xi^{qf}_{measured} - \xi^{qf}_{model}\right)$$

- Divide the pic from the broadband in the correlation function:

$$\xi^{qf}(r_\perp, r_\parallel, \alpha_\perp, \alpha_\parallel) = \xi_{\mathrm{smooth}}(r_\perp, r_\parallel) + \xi_{\mathrm{peak}}(r_\perp \alpha_\perp, r_\parallel \alpha_\parallel)$$



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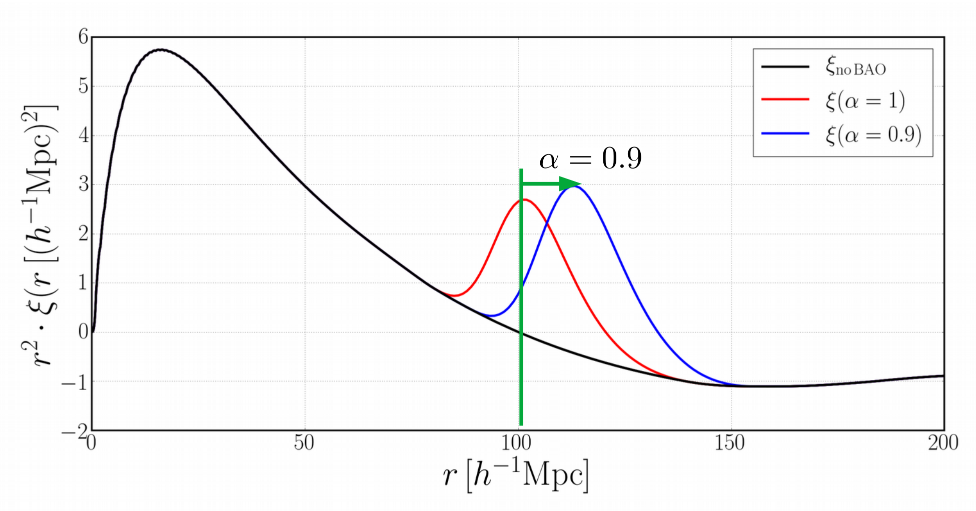

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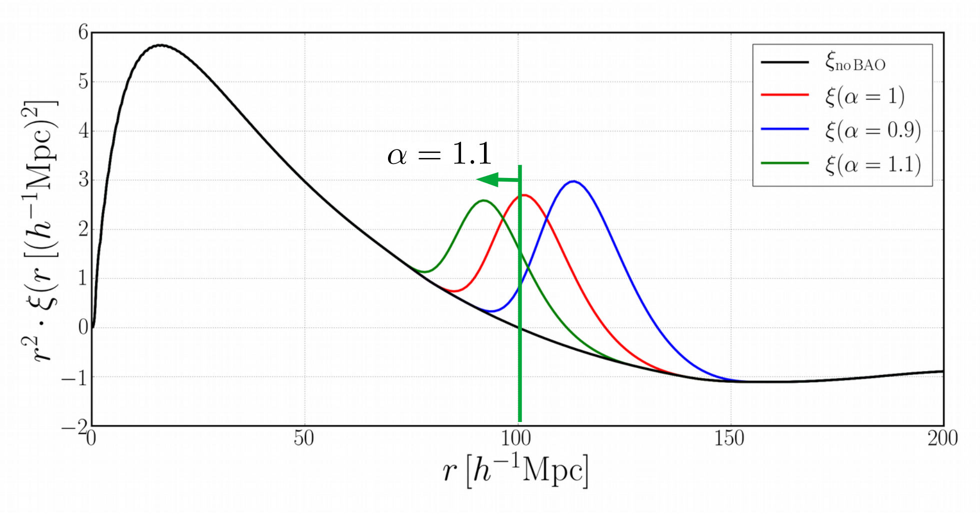
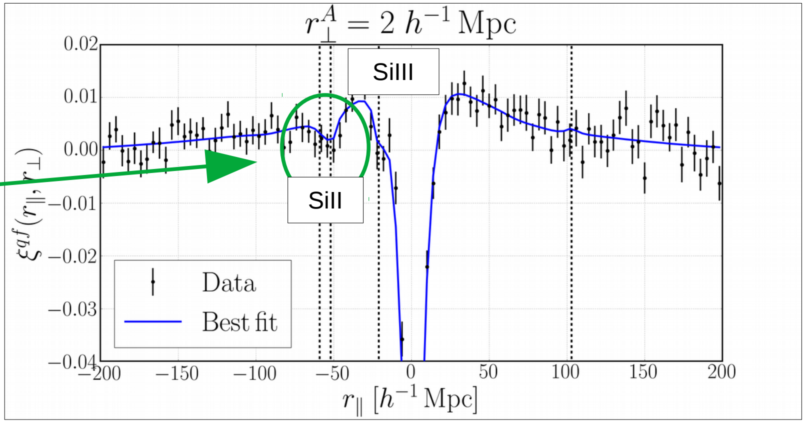


Full model

- The physical model is composed of different ingredients:
  - Tracers bias
  - Distortion matrix
  - Metals in the IGM
  - DLA and LLS
  - UV fluctuations
  - Systematical errors in the measure of quasar redshift
  - Proper motion of quasars and precision of quasar redshift measurement
  - UV photon from the quasar on the IGM

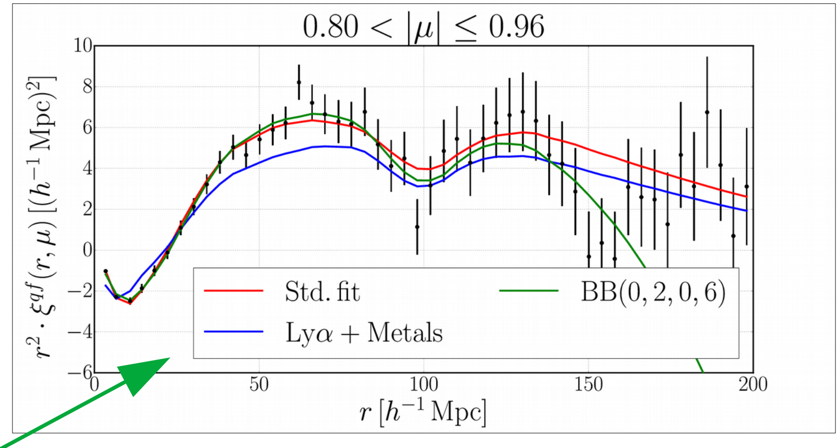


→ Full model has 15 parameters

→ It has a better χ^2 but doesn't change BAO measurement

Tests

- We proceed to different tests:
  - Based on data:
    - Split the data in two sets
    - Change the model fit to the data



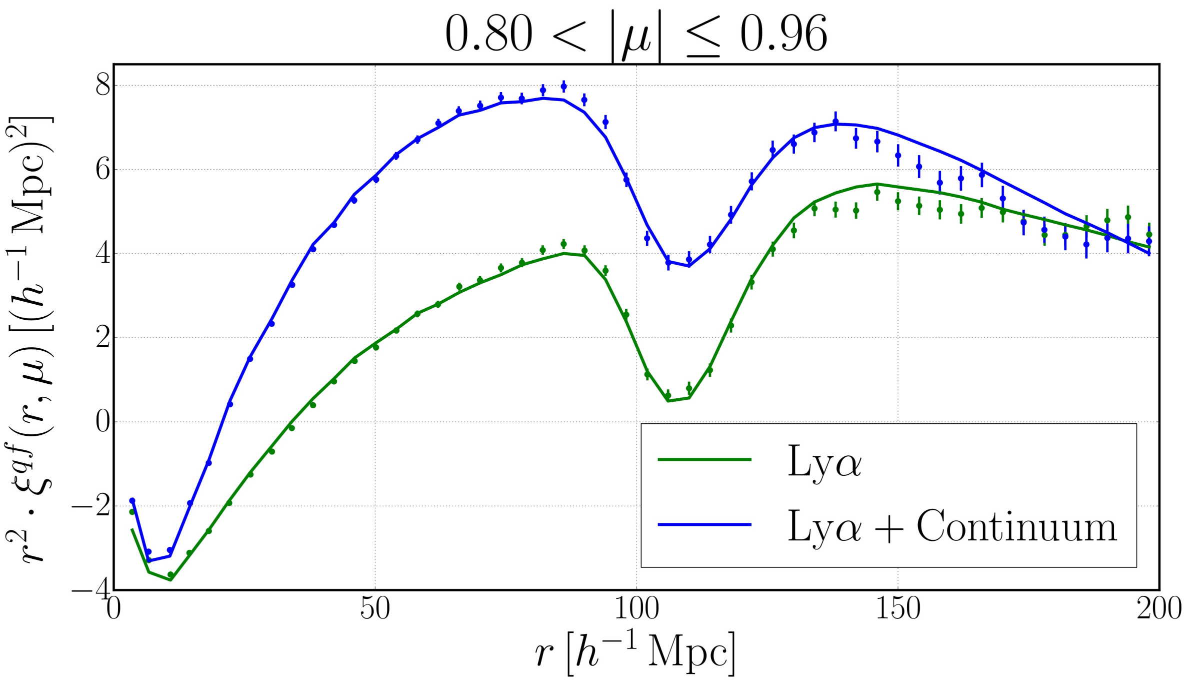
  - Based on simulations

→ The bias is smaller than the statistical error

→ The interpretation for the $\Delta\chi^2$ is near standard.

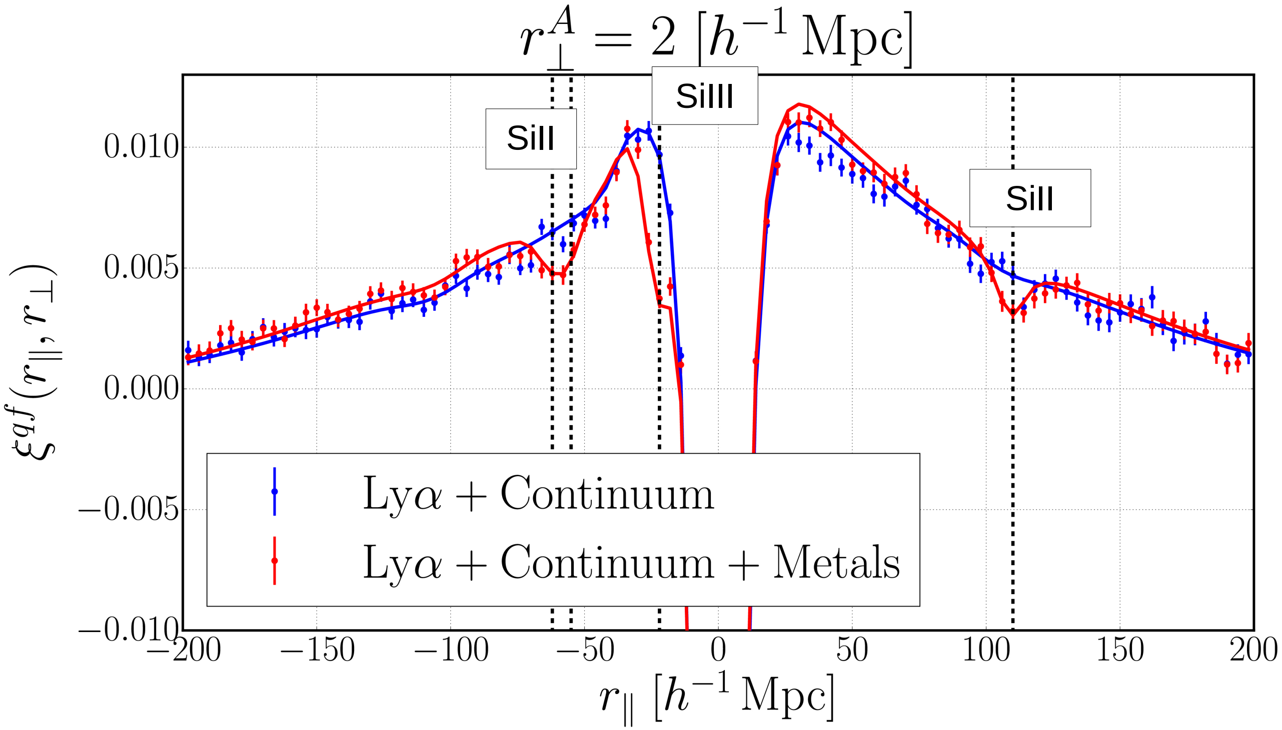
Tests: distortion matrix (simulation)

- The fit of the quasar continuum produces a distortion in the shape of the correlation function
- This distortion is well taken into account in the analysis as it is shown in the mocks.



Tests: Metals in the IGM (simulation)

- The IGM is composed of other elements than hydrogen
- This contribution is well taken into account in the analysis as it is shown in the mocks.

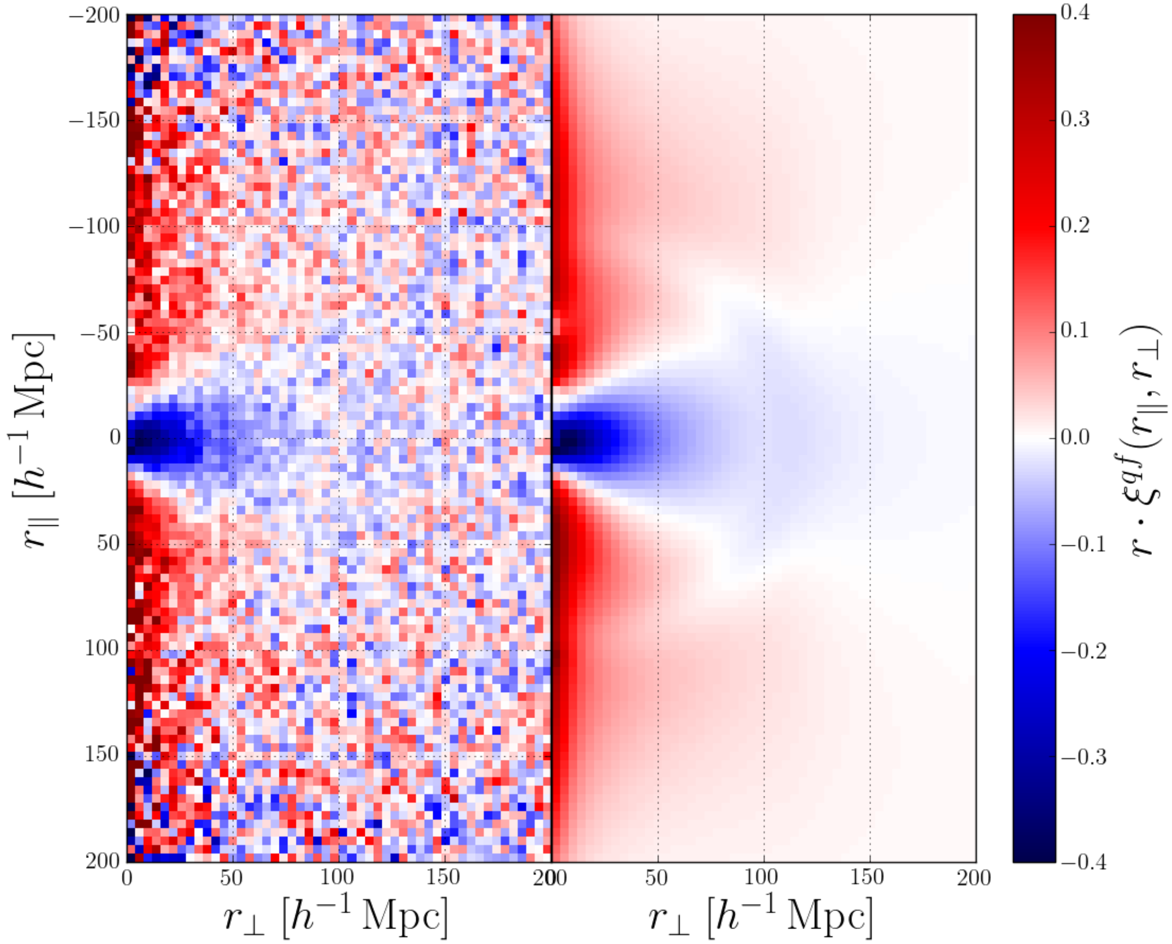


Tests: Systematical errors (simulation)

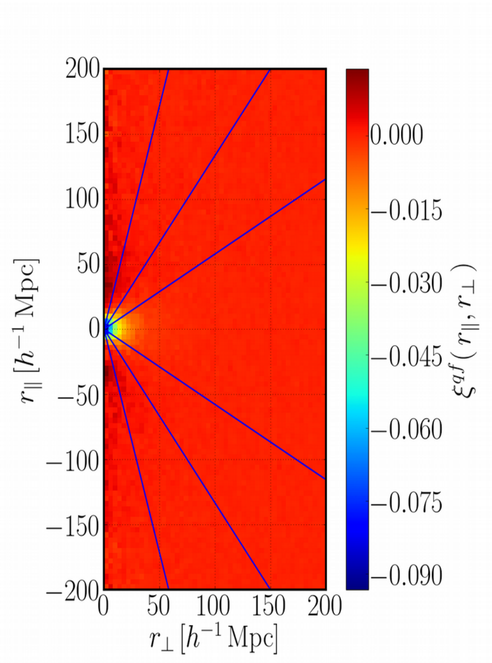
- Production of mocks with increasing realism
- Allows to understand the contribution of the different elements
- The bias on the BAO parameters is negligible compared to the statistical error.

Analyse	$\overline{\alpha_{\parallel}}$ $(\overline{\sigma})$	$\overline{\alpha_{\perp}}$ $(\overline{\sigma})$
Lyα	0.994 (0.025)	1.002 (0.028)
+Continuum	0.990 (0.038)	0.994 (0.050)
+Metals	0.988 (0.039)	1.003 (0.050)

Visualization: in 2D



Visualization: in wedges



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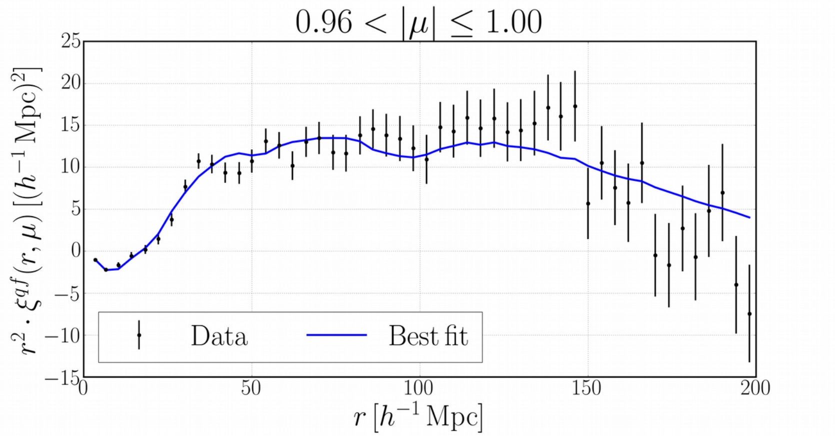

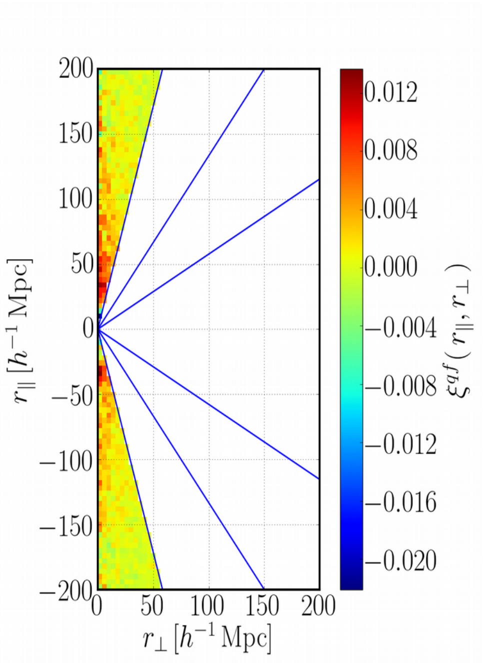

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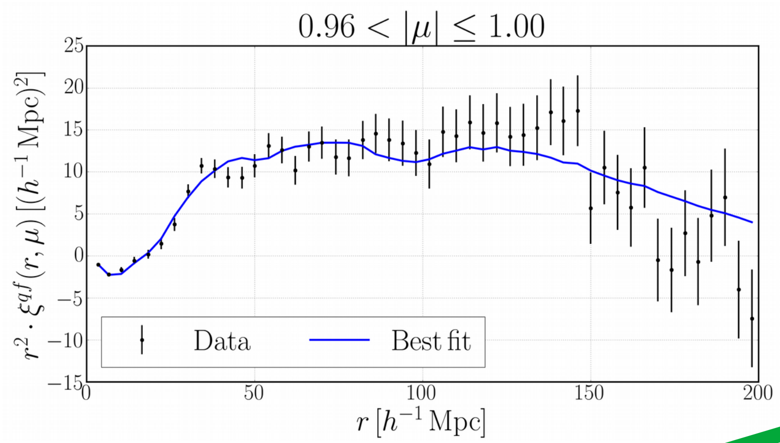
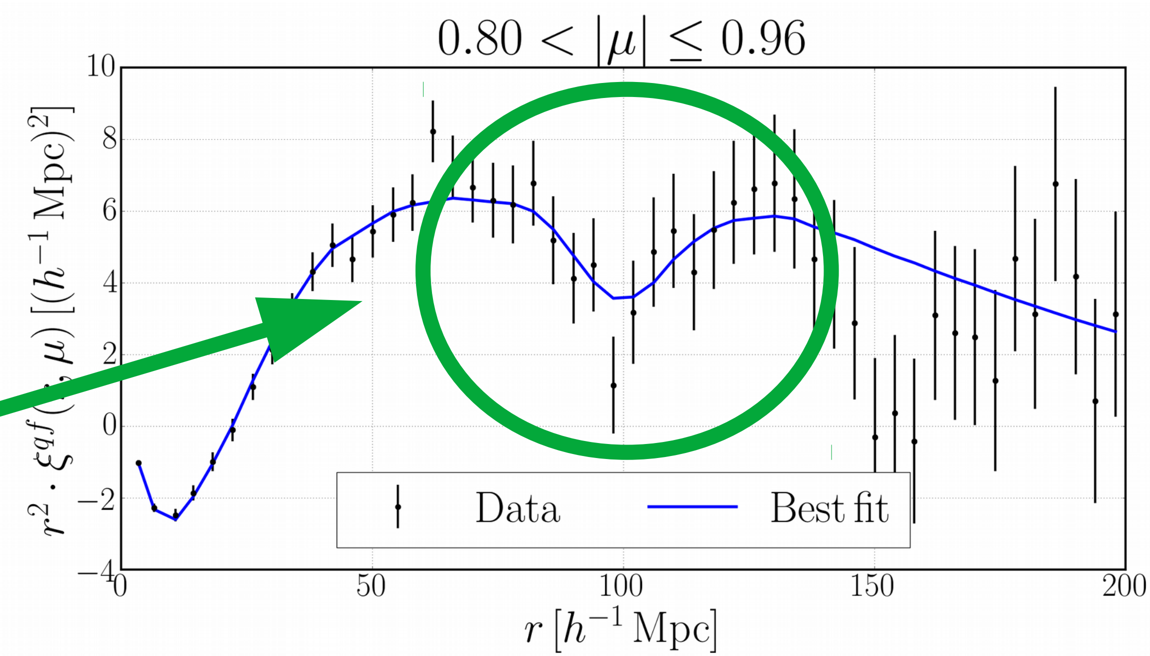
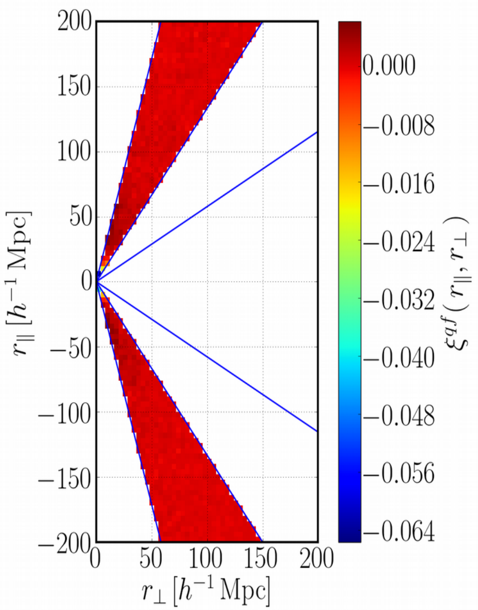
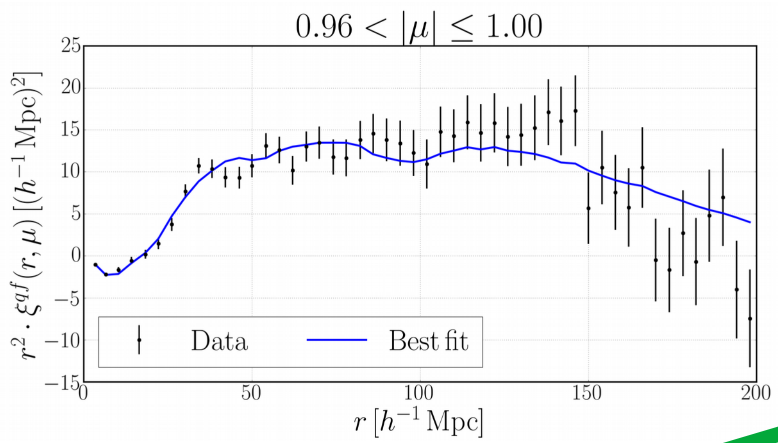


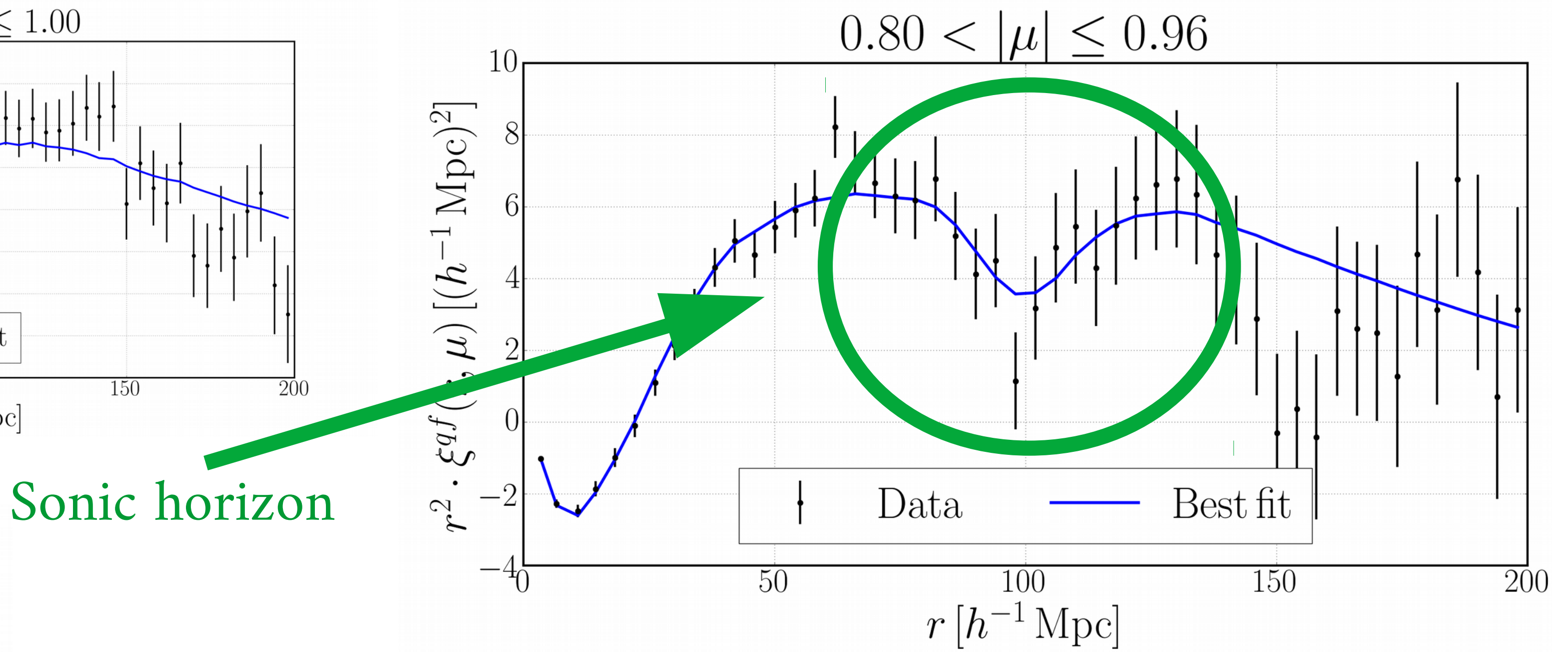


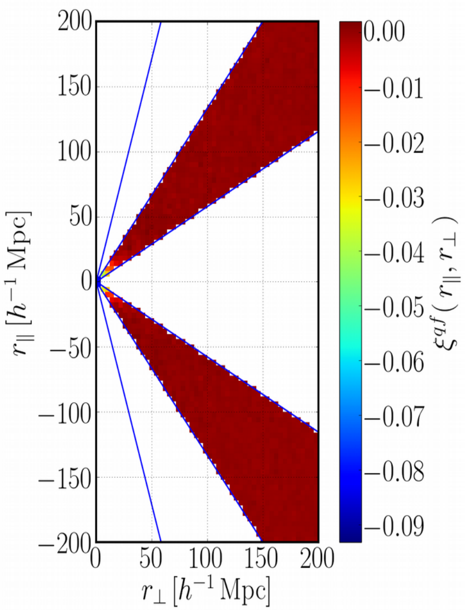
Sonic horizon

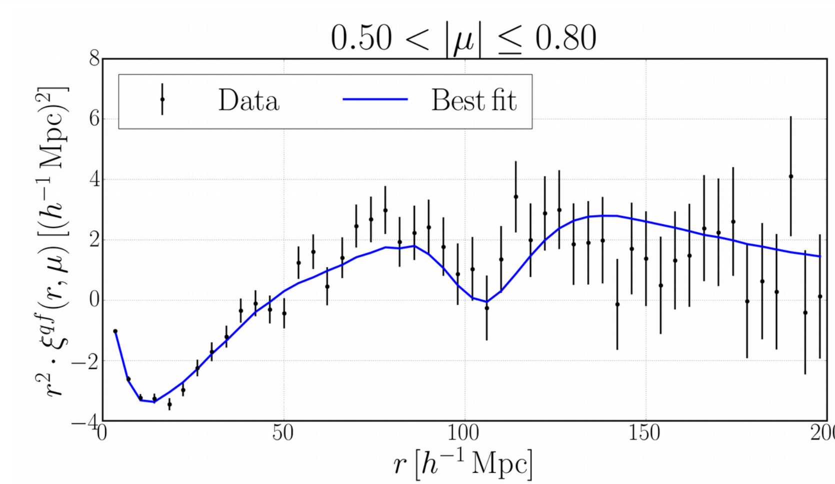


Visualization: in wedges









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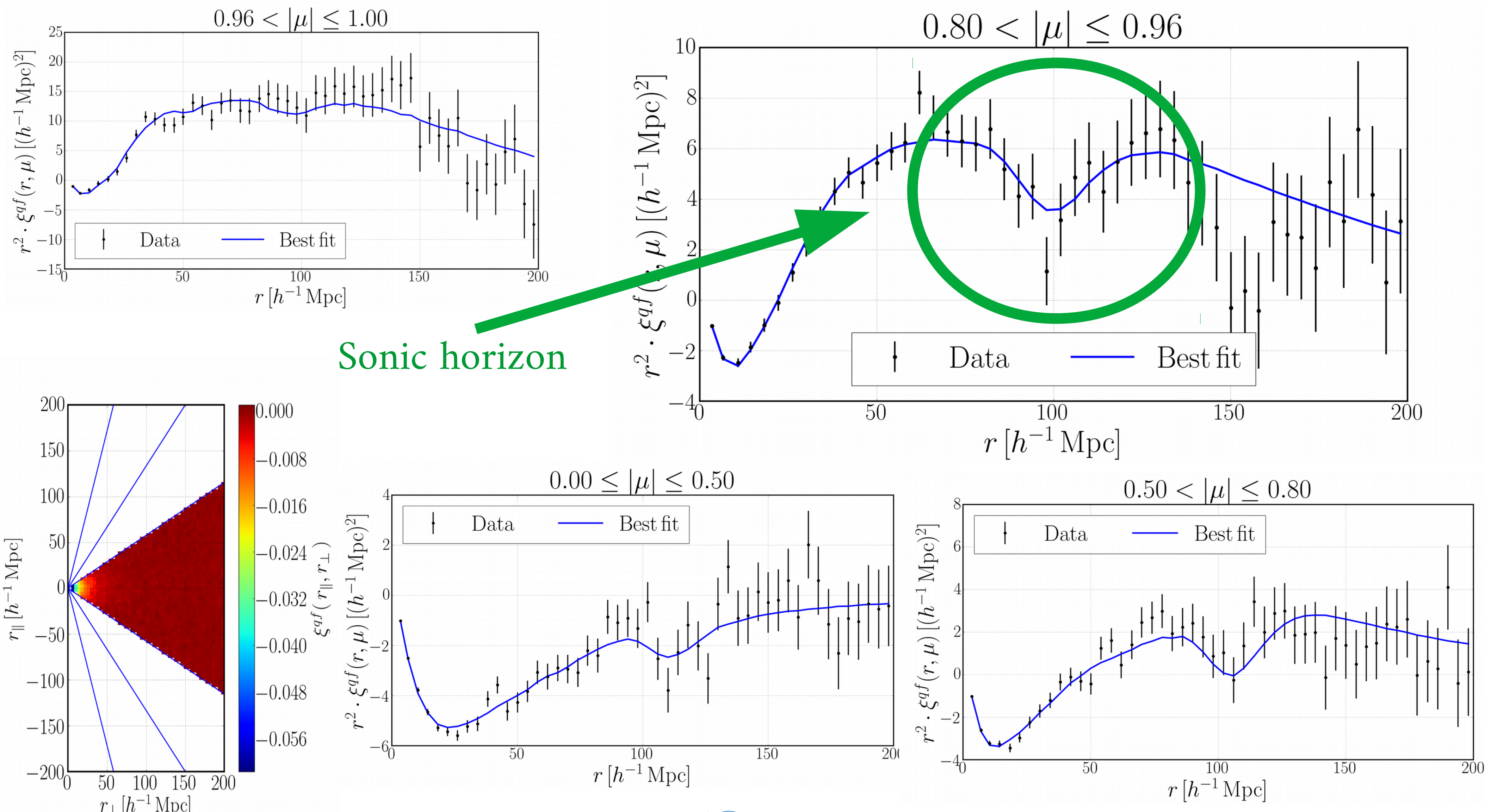

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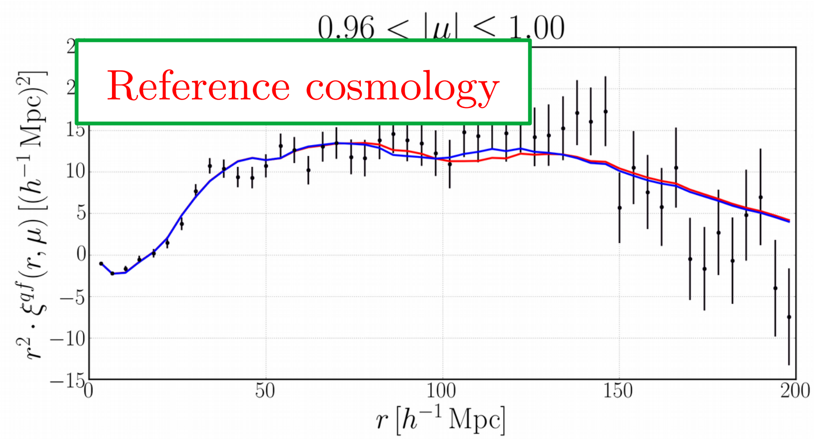

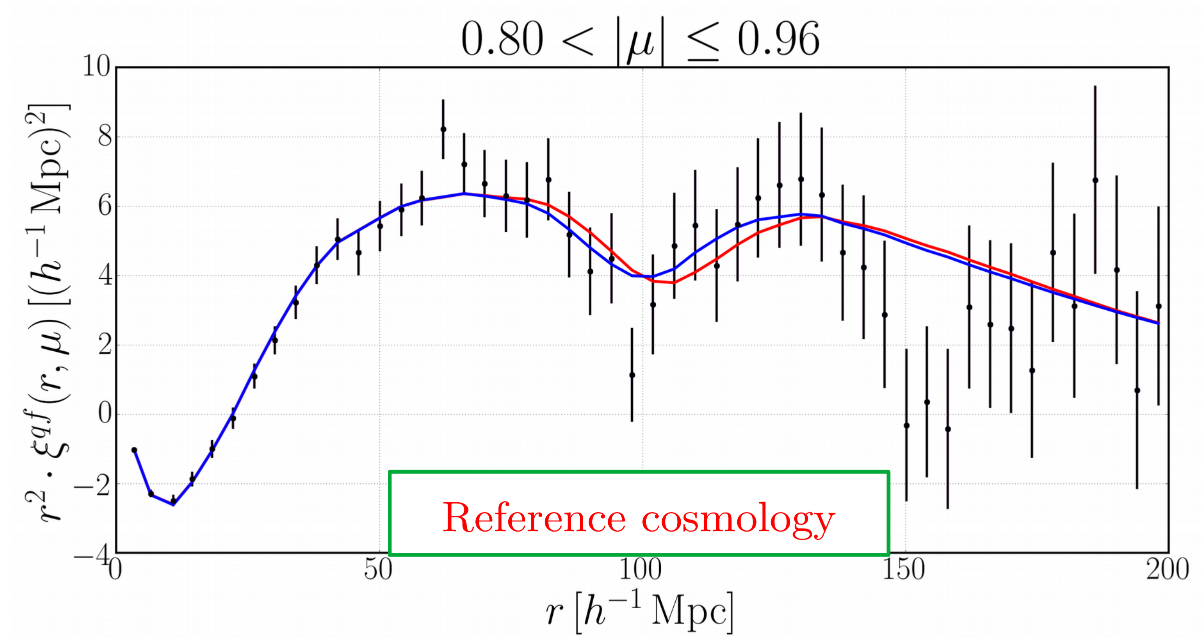

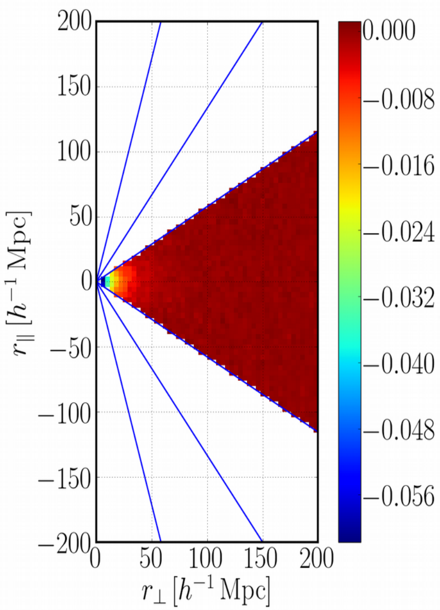

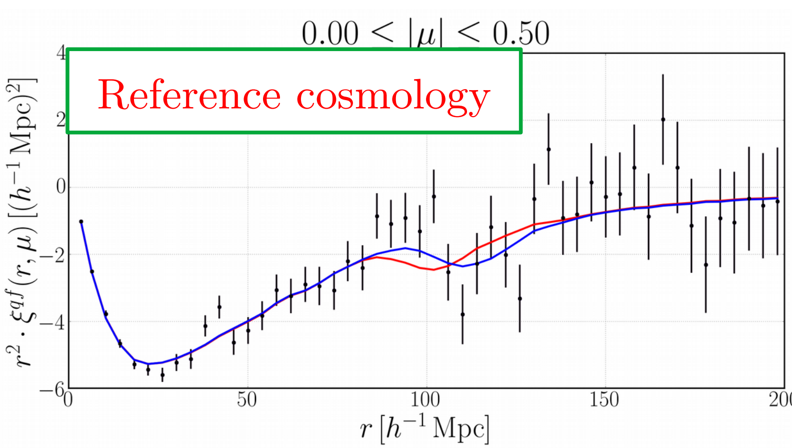

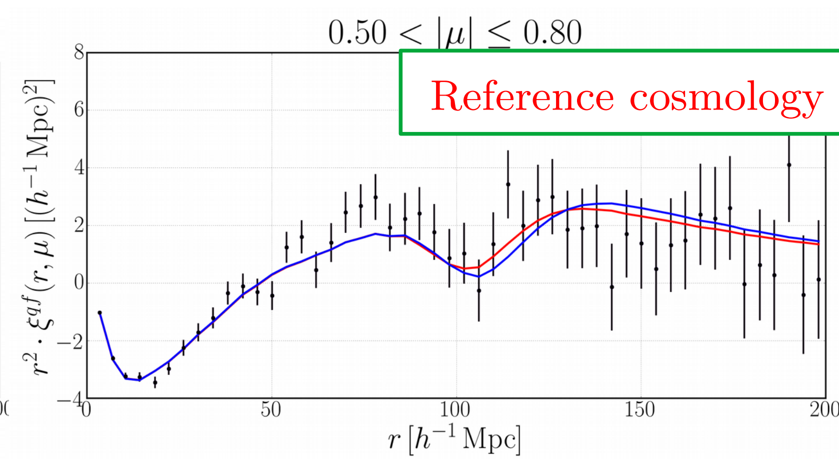

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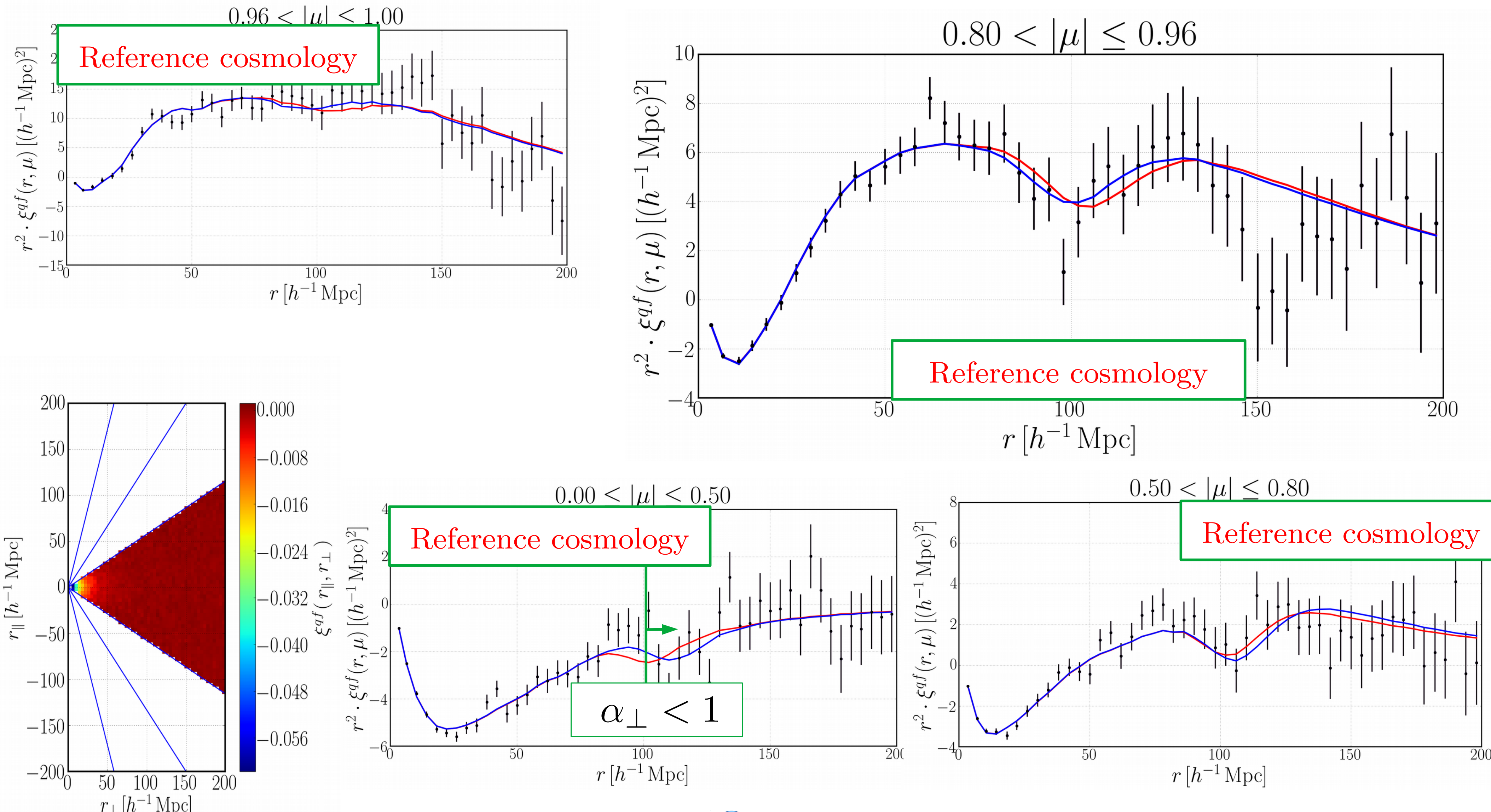

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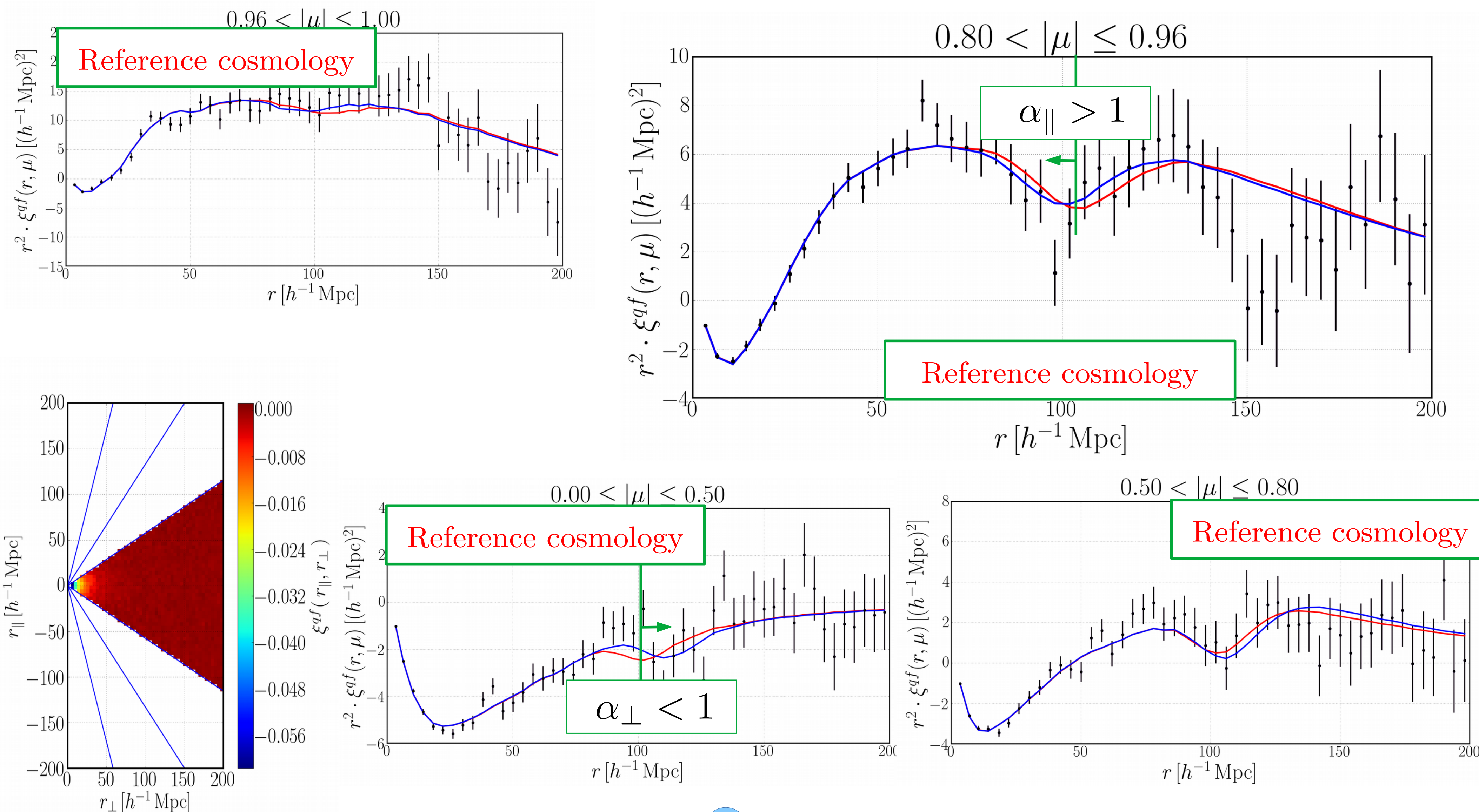
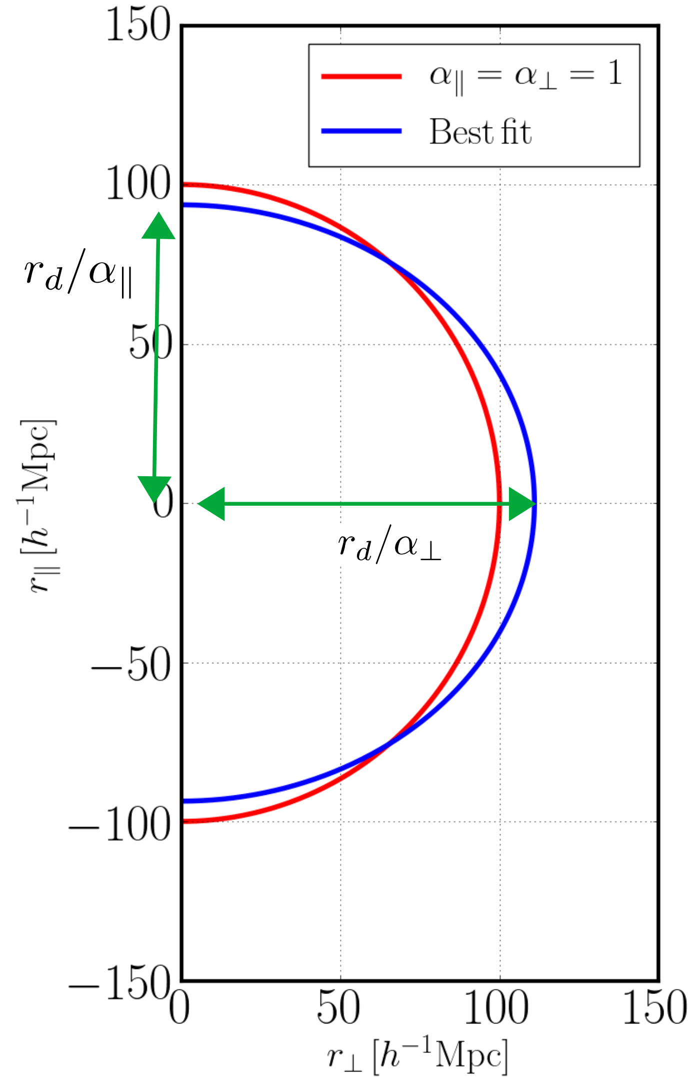


Mesure of BAO

- The result of this fit is a measurement of the two BAO parameters at a redshift of z=2.40:

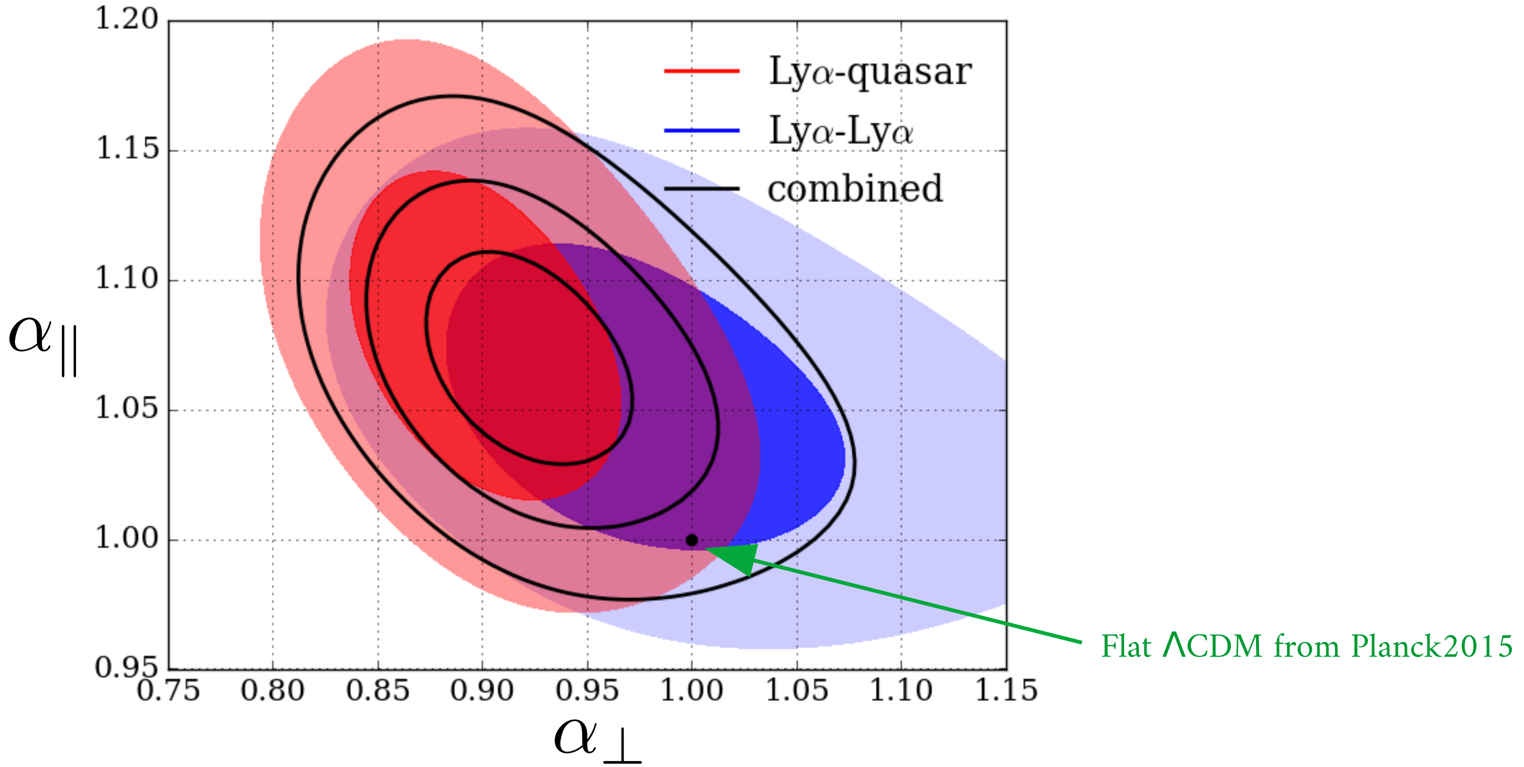
$$\alpha_\perp = 0.898\ (1\ \sigma)^{+0.043}_{-0.041}\ (2\ \sigma)^{+0.098}_{-0.084}$$
$$\alpha_\parallel = 1.077\ (1\ \sigma)^{+0.043}_{-0.041}\ (2\ \sigma)^{+0.090}_{-0.084}$$

- These two parameters describe the transformation of the BAO circle into an ellipsis by the error on the reference cosmology



Measure of BAO

- The cross-correlation is at 2.3σ from the flat ΛCDM of Planck 2015
- Combining with the auto-correlation we are at 1.8σ



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Flat ΛCDM

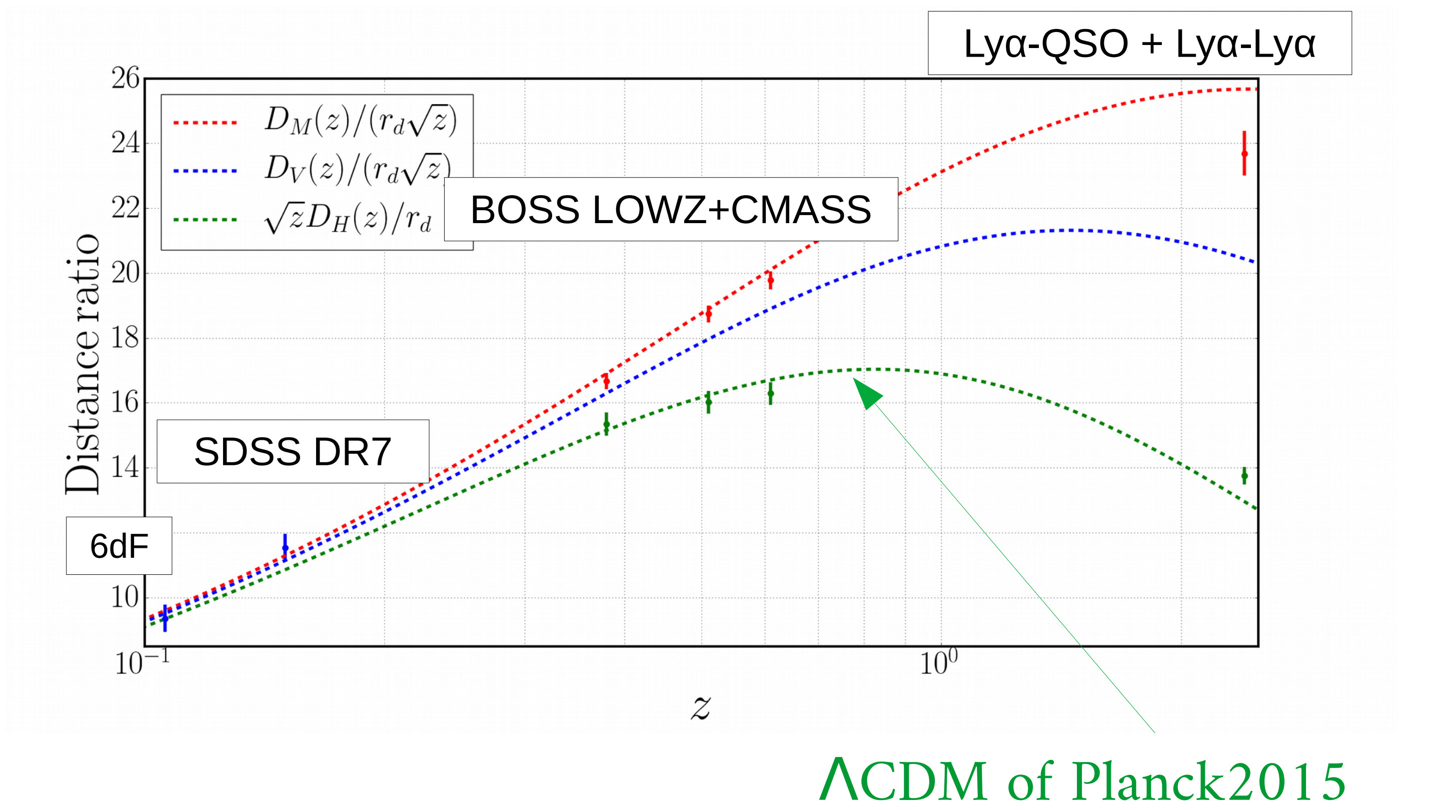
- Our measure of the BAO scale allows to asses parameters of the ΛCDM cosmological model.
- With only BAO, we only have two free parameters: $(\Omega_m, r_d h)$
- Other parameters are either not measured or derived from these two free parameters:
  - $\Omega_k = 0$
  - $\Omega_\Lambda = 1 - \Omega_m$

Flat ΛCDM

- The measure of BAO is linked to the divers cosmological distances.

$$\alpha_{\parallel} = \frac{[D_H(z)/r_d]_{\mathrm{meas.}}}{[D_H(z)/r_d]_{\mathrm{fid.}}}$$

$$\alpha_{\perp} = \frac{[D_A(z)/r_d]_{\mathrm{meas.}}}{[D_A(z)/r_d]_{\mathrm{fid.}}}$$



Flat ΛCDM

- Fit of ΛCDM with three different data set: all BAO (not our measure), all BAO, only CMB.
- The different results are compatible. All the BAO gives a measurement similar to the CMB.

Données	Ω_m	Ω_k	$r_d h$
Tous BAO sauf Lyα	0.339 ± 0.044	0	99.3 ± 1.9
Tous BAO	0.292 ± 0.016	0	101.3 ± 1.4
Planck 2015 (TT+lowP)	0.315 ± 0.013	0	99.2 ± 1.5

Open ΛCDM

- We can also test extensions to the standard ΛCDM model.
- We give here the example of the open ΛCDM, where the Universe curvature is let free. We then have three free parameters:

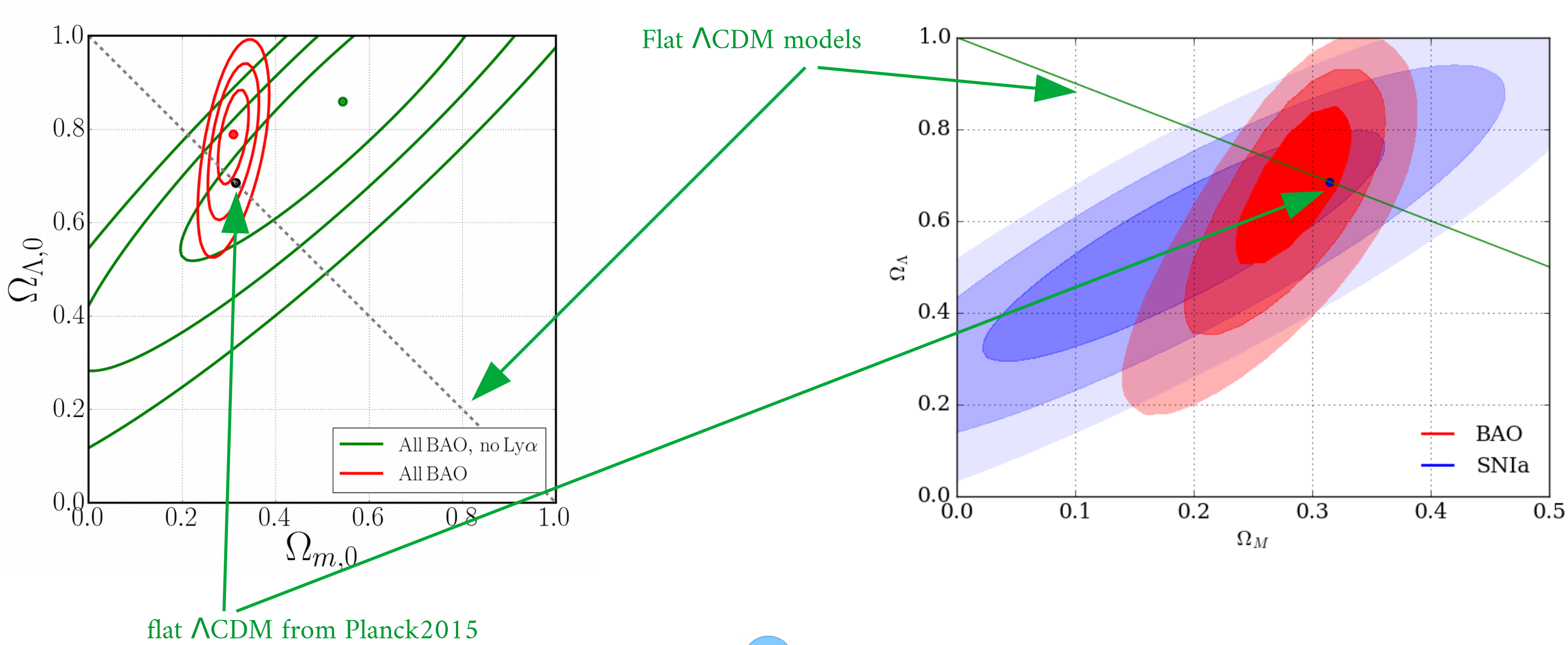
$$(\Omega_m, \Omega_k, r_d h)$$

- Ω_k is compatible with 0

Données	Ω_m	Ω_k	$r_d h$
Tous BAO sauf Lyα	0.54 ± 0.22	-0.40 ± 0.43	99.0 ± 1.9
Tous BAO	0.309 ± 0.022	-0.098 ± 0.081	102.3 ± 1.6
Planck 2015 (TT+lowP)	$0.510^{+0.073}_{-0.12}$	$-0.052^{+0.032}_{-0.018}$	78.5 ± 7.5
Planck 2015 (TT+lowP+BAO sauf Lyα)	0.3102 ± 0.0078	-0.0002 ± 0.0027	99.7 ± 1.1

Open ΛCDM

- Our measure of BAO is at high redshift. It constrains strongly the parameters of the open ΛCDM model.



Plan

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IV/ Fit and measure of BAO parameters

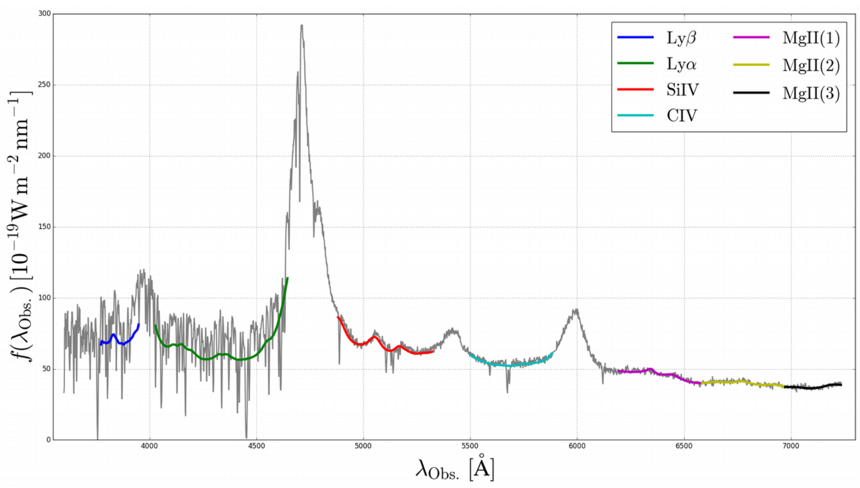
V/ Cosmological consequences

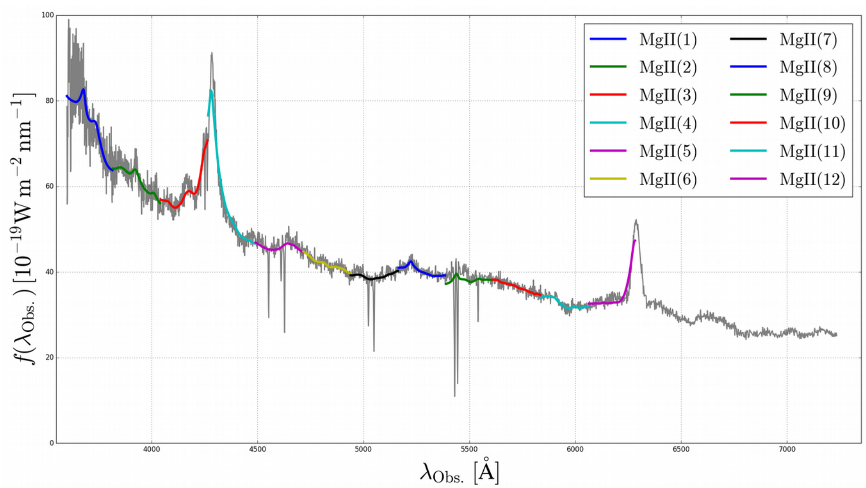
VI/ Future in eBOSS

VII/ Future in DESI

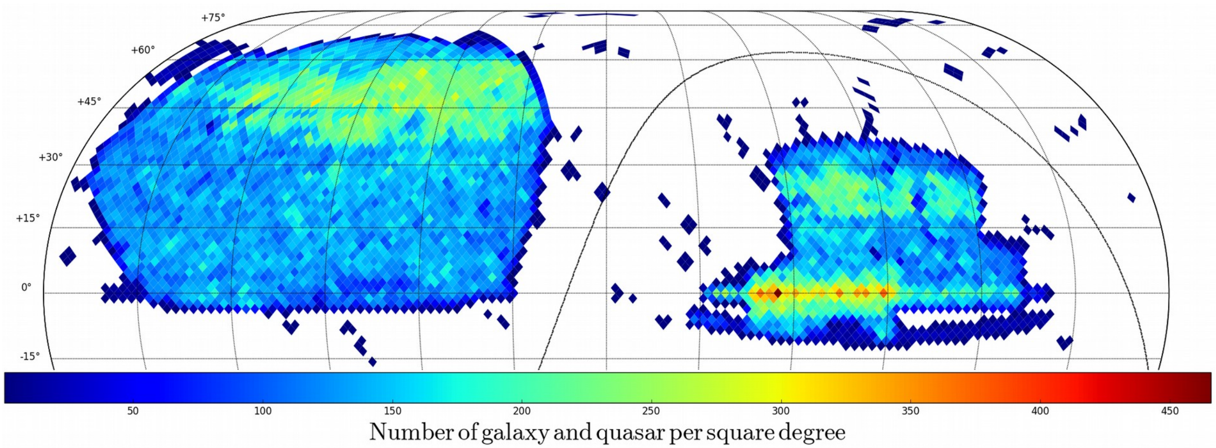
MgII x {QSO,Galaxy} correlation

- Use MgII absorption in Quasar spectra to trace matter density fluctuations
- Similar technique than in Lyman-alpha, but using 16 different forests
- Very different regime:
  - low bias
  - Not continuous tracer

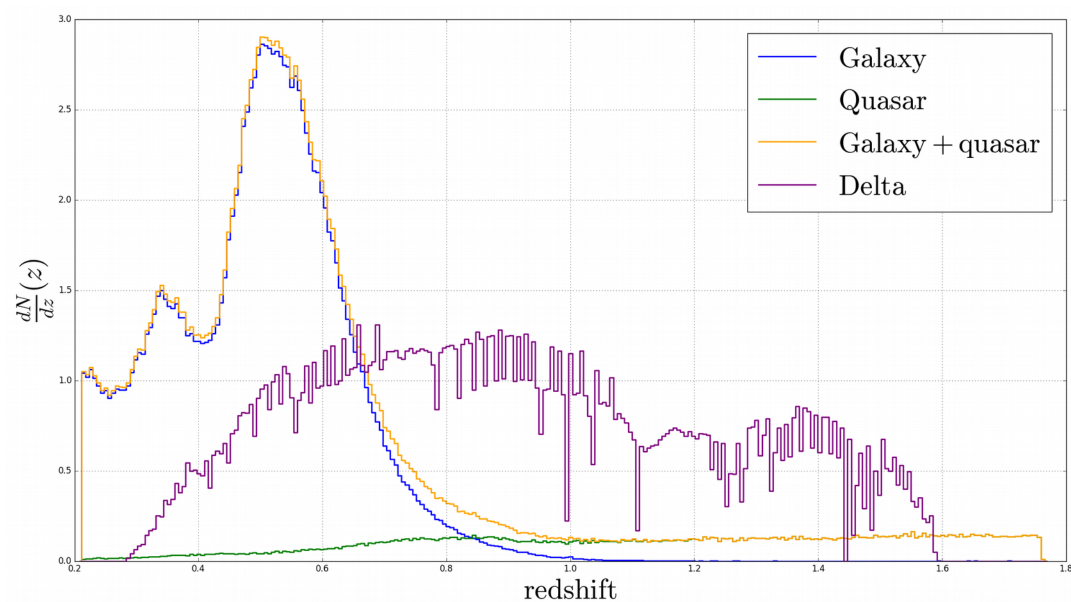




Distribution of tracers

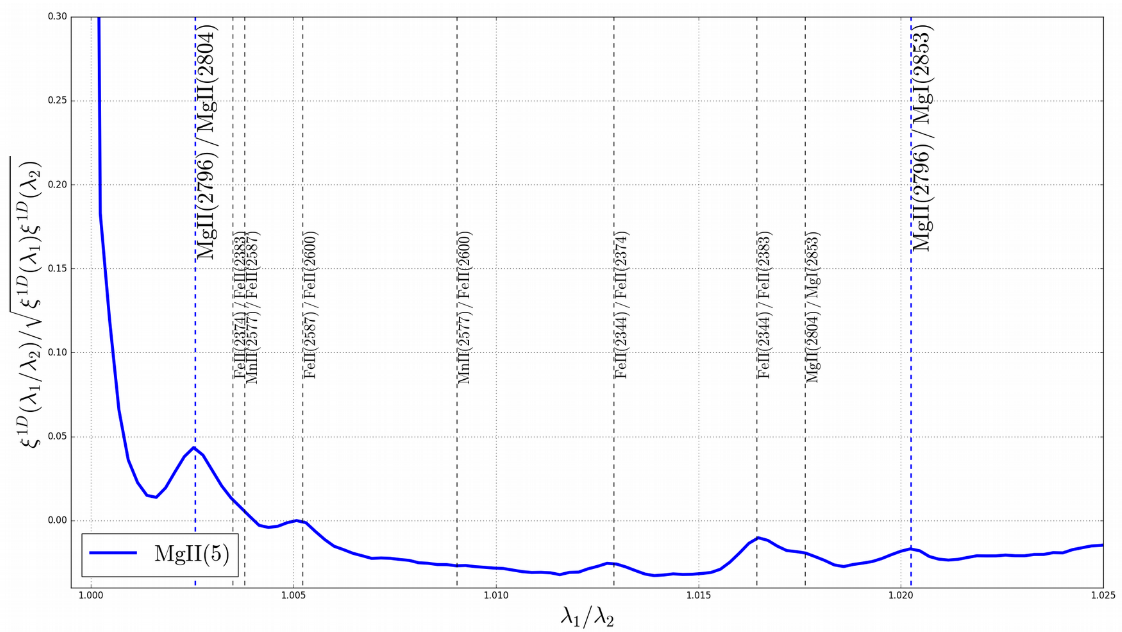


- Analysis in DR14
- Will improve by the end of eBOSS and DESI from low redshift quasars as tracers and forests



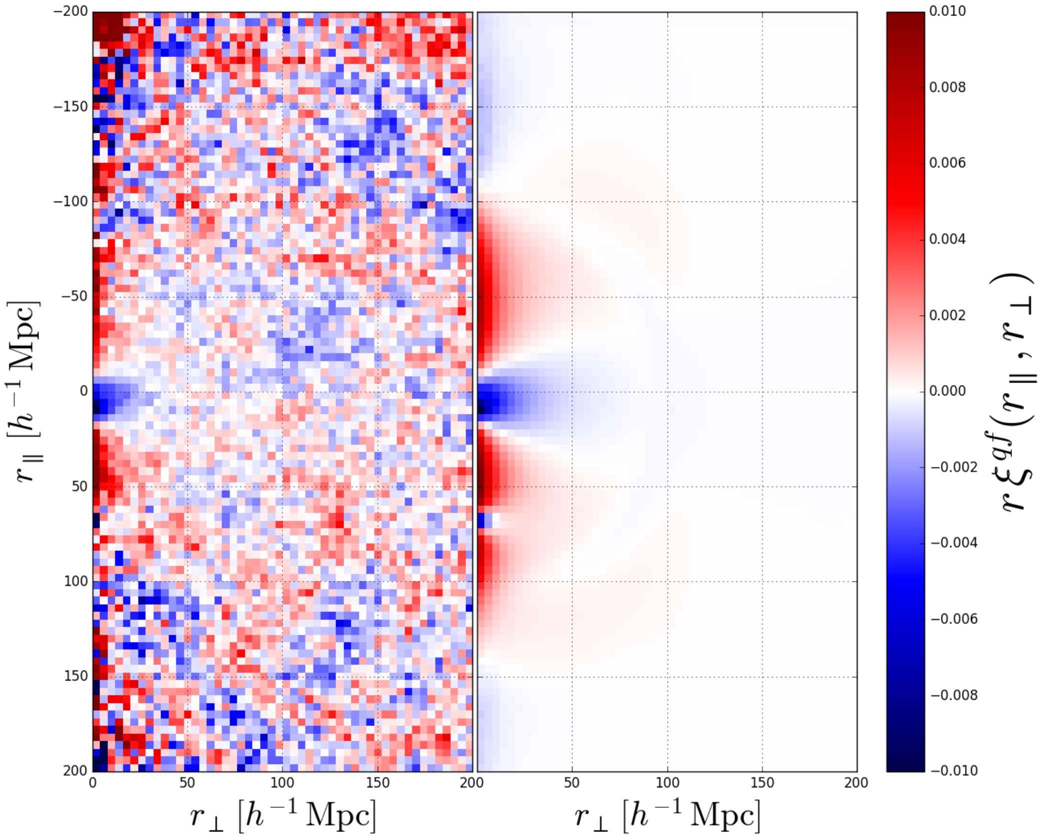
MgII 1d correlation function

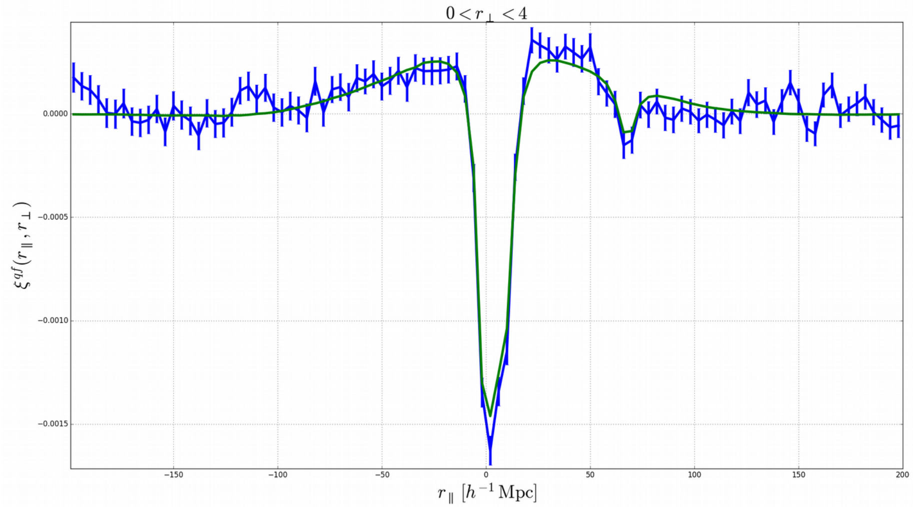
- Normalized correlation between two pixels from a MgII forest.
- Show the presence of other metals absorber in the IGM
- Only the two blue lines are contaminants



Correlation function

- Measurement of MgII doublet and MgI bias and their evolution with redshift
- ~ 7% measurement of the BAO parameters





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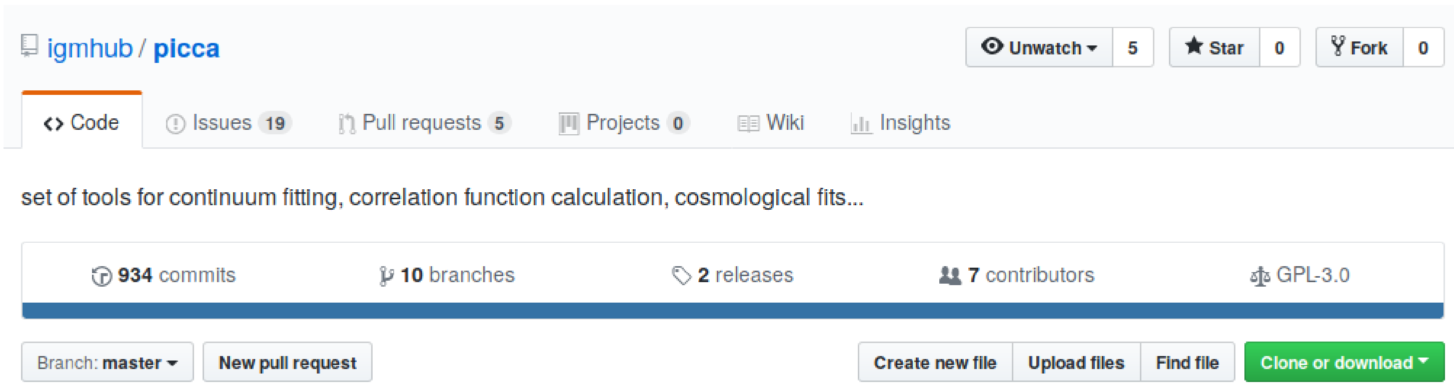
Prepare Lya analysis in DESI



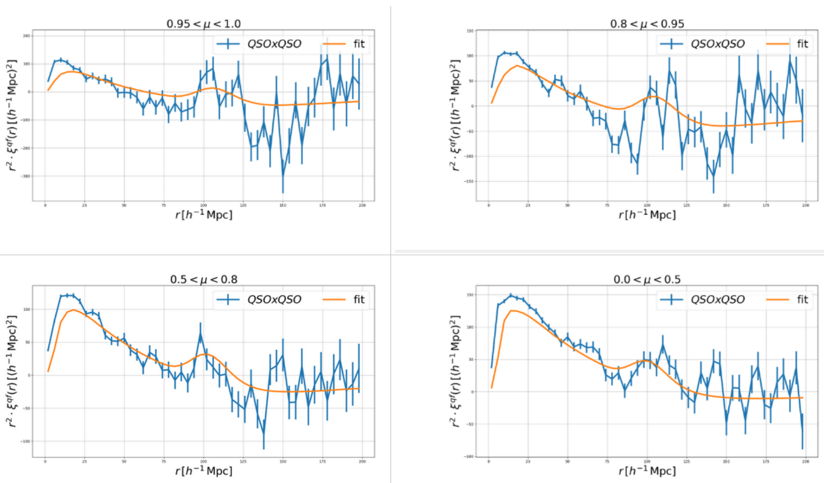
- Development of a Python tool to analyze IGM absorption for eBOSS and DESI
- Created by Nicolas Busca et al
- Already some publication using the code: Blomqvist et al 2018
- More are coming…

Lyman-alpha mocks in DESI

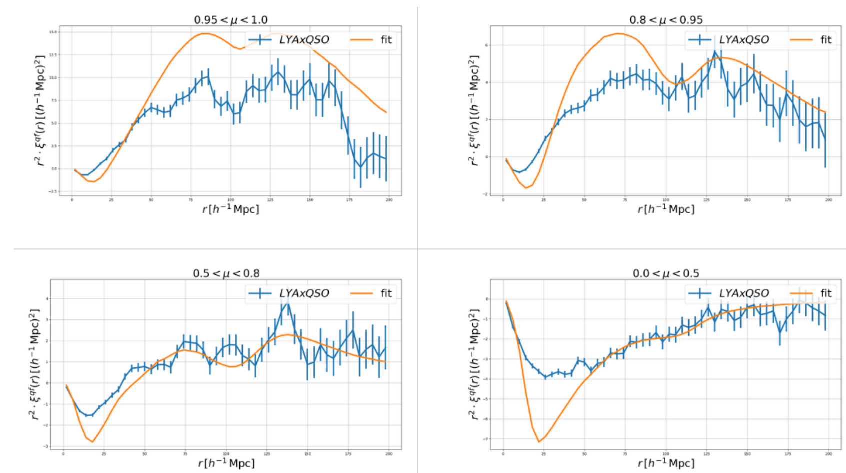
- Gaussian Random Field mock from Jean-Marc Le Goff and Thomas Etourneau
- The mock goes through "quickquasar" from Julien Guy do add quasar continua and be in a desi data format
- Wrote a tutorial on how to run picca on these mocks https://desi.lbl.gov/trac/wiki/IGMAnalysis

Lyman-alpha mocks in DESI

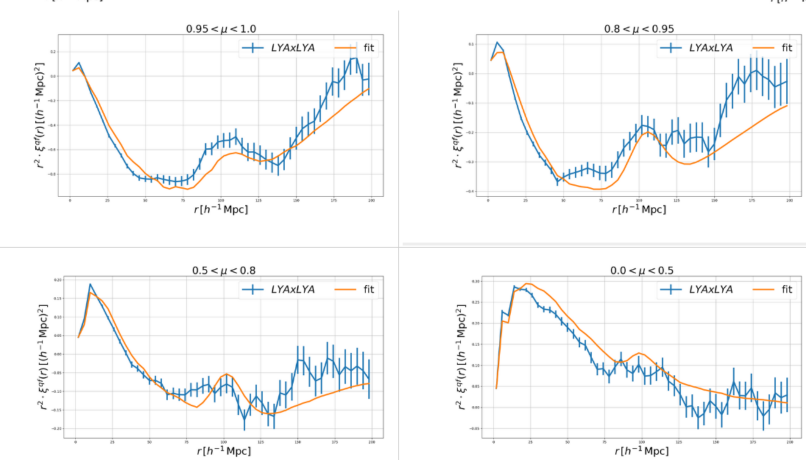
zeff	\alpha_{\parallel}	\alpha_{\perp}	\beta_{\mathrm{Ly}\alpha}	\beta_{\mathrm{QSO}}	(b\beta)_{\mathrm{Ly\alpha}}/f	f	\Delta r_{\parallel}	chi2 / (nbBin-nbPar)
2.55	0.968 +/- 0.017	1.037 +/- 0.023	0.906 +/- 0.016	0.171 +/- 0.011	-0.209 +/- 0.013	0.787 +/- 0.049	-1.02 +/- 0.098	9247.06 / (5008-13), p = 0



QSO auto-correlation



QSOxLya cross-correlation



Lya auto-correlation

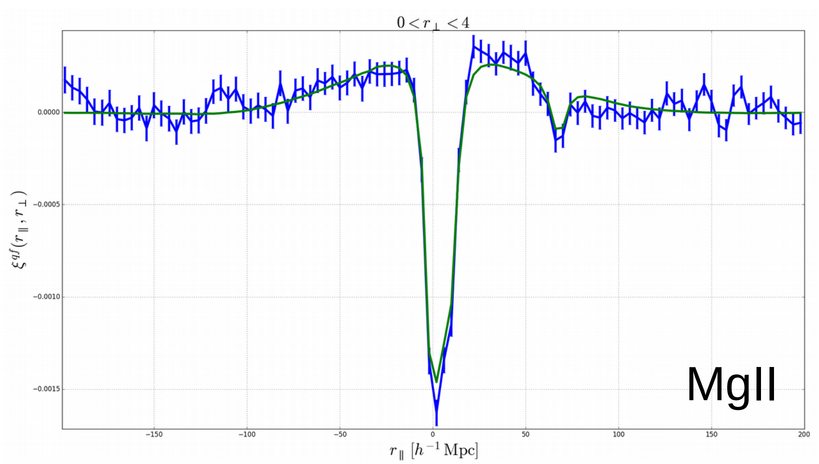
Conclusion

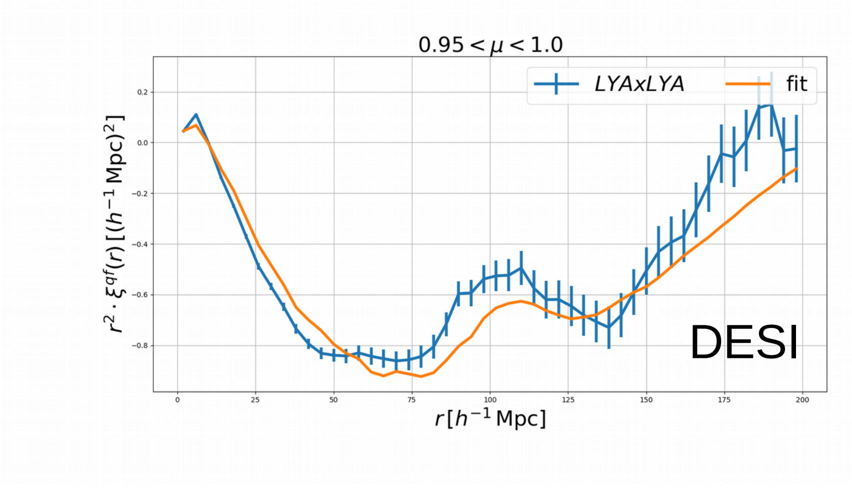
Conclusion

- Final measure of BAO with BOSS data in the cross-correlation of Lyα and quasars.
- Bias negligible compare to statistical error
- All the BAO measurement gives a measure of Ω_m as good as the CMB for flat ΛCDM, complementary for open ΛCDM.
- Three major improvements:
  - Physical fit of the correlation function
  - Development of simulations
  - Estimation of the covariance matrix with different technique

Conclusion-II

- MgII in eBOSS:
  - MgII x {QSO,Galaxy} correlation is measured and give a 7% measurement of BAO
  - Brings a IGM based measurement at a low redshift
- DESI:
  - DESI mocks are being build and already look very good
  - More work still need to be done: bad chi2, systematic velocity shift, add metals, ...

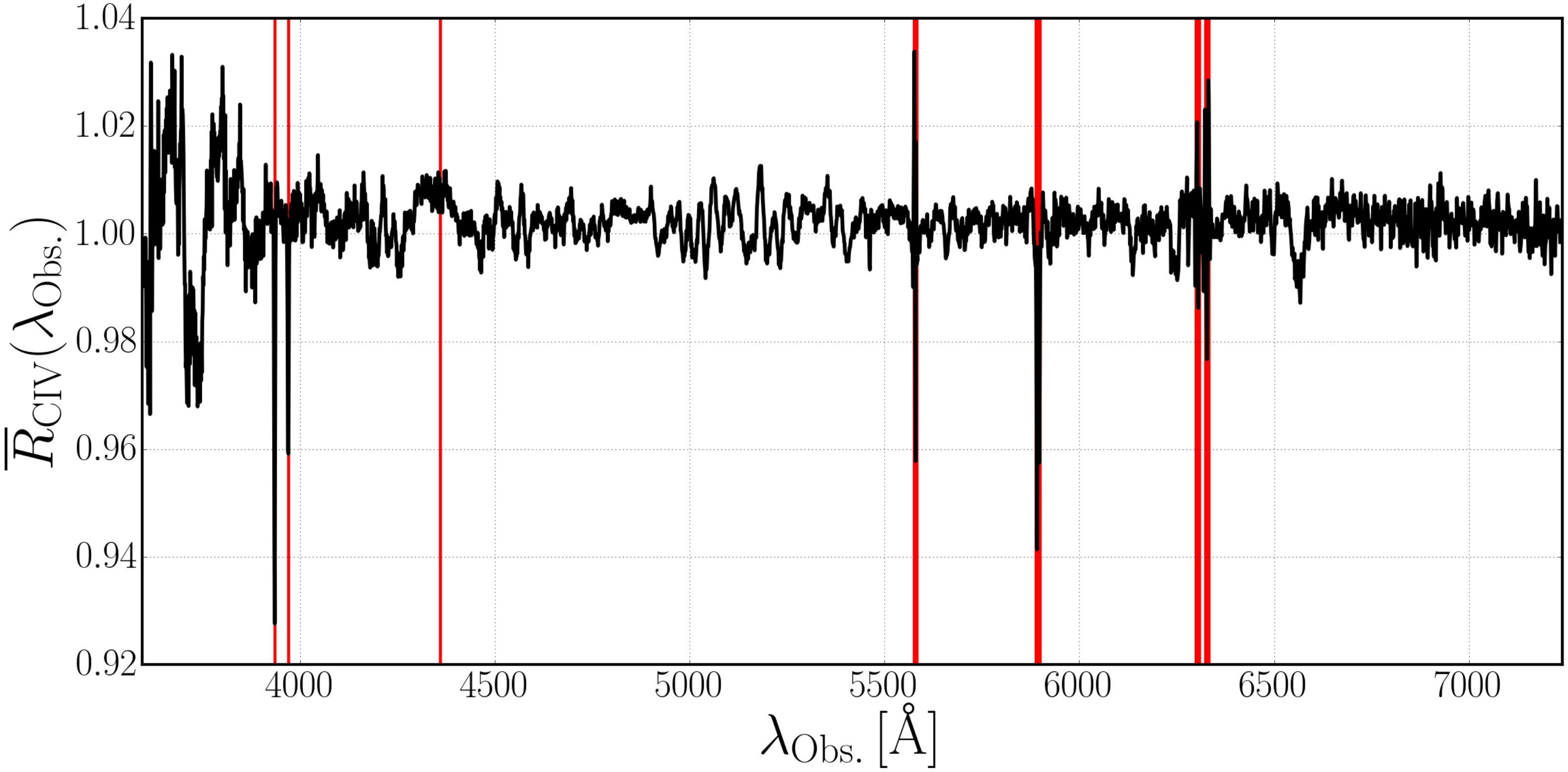




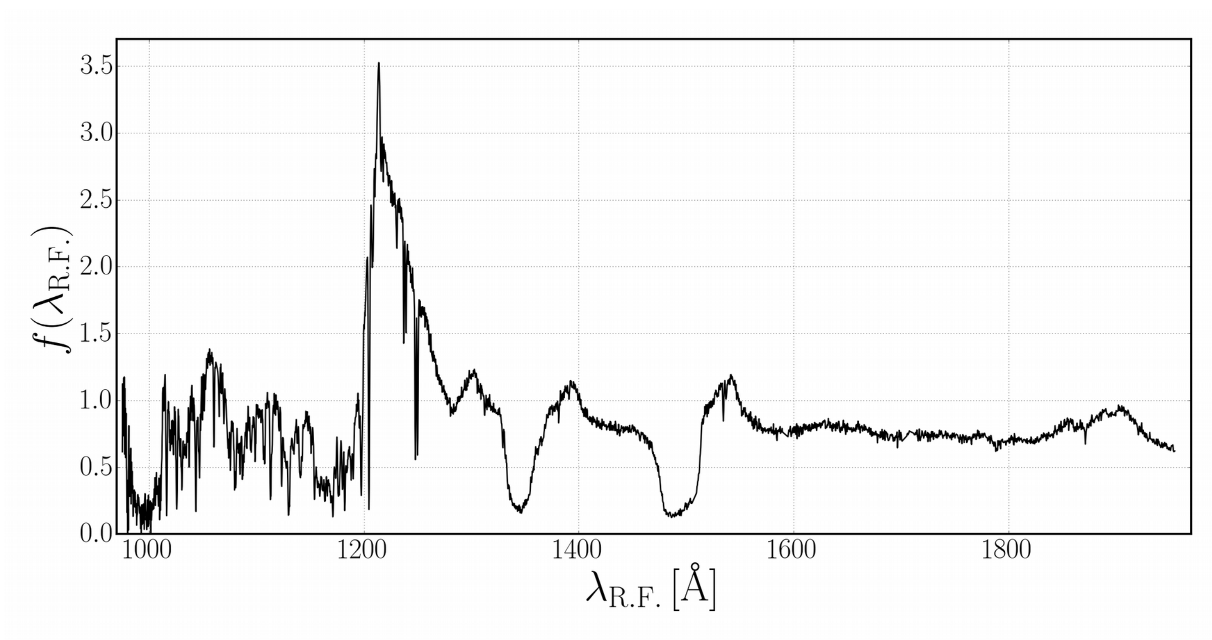
Thank you for your time

Diapos supplémentaires

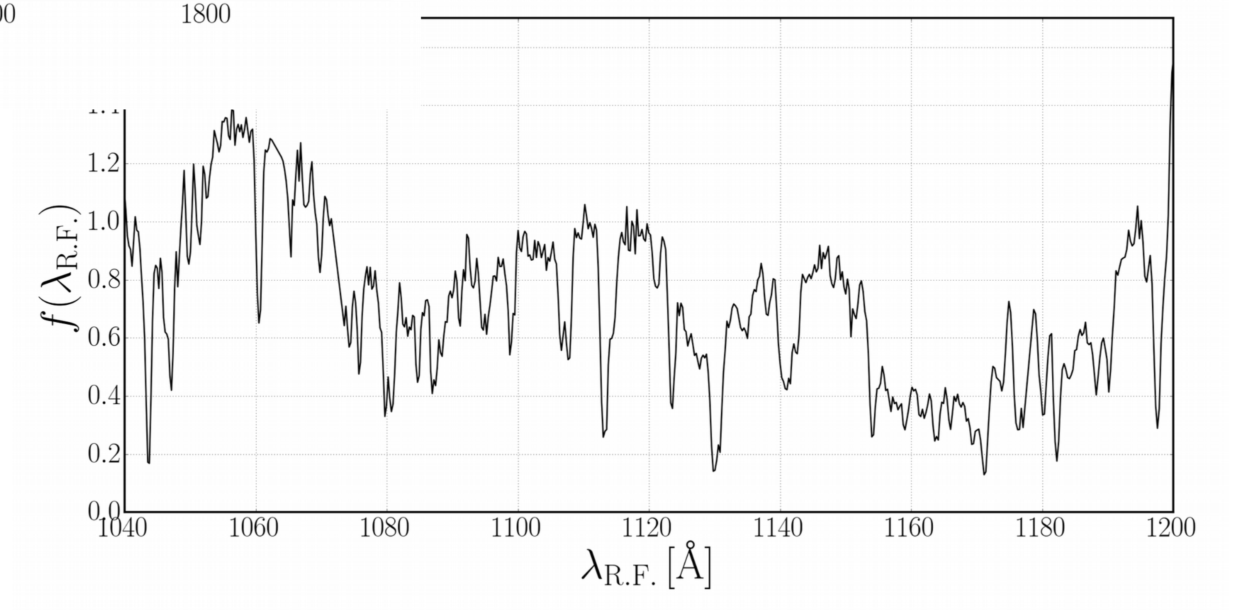
Raies du ciel et erreurs de calibration



BAL

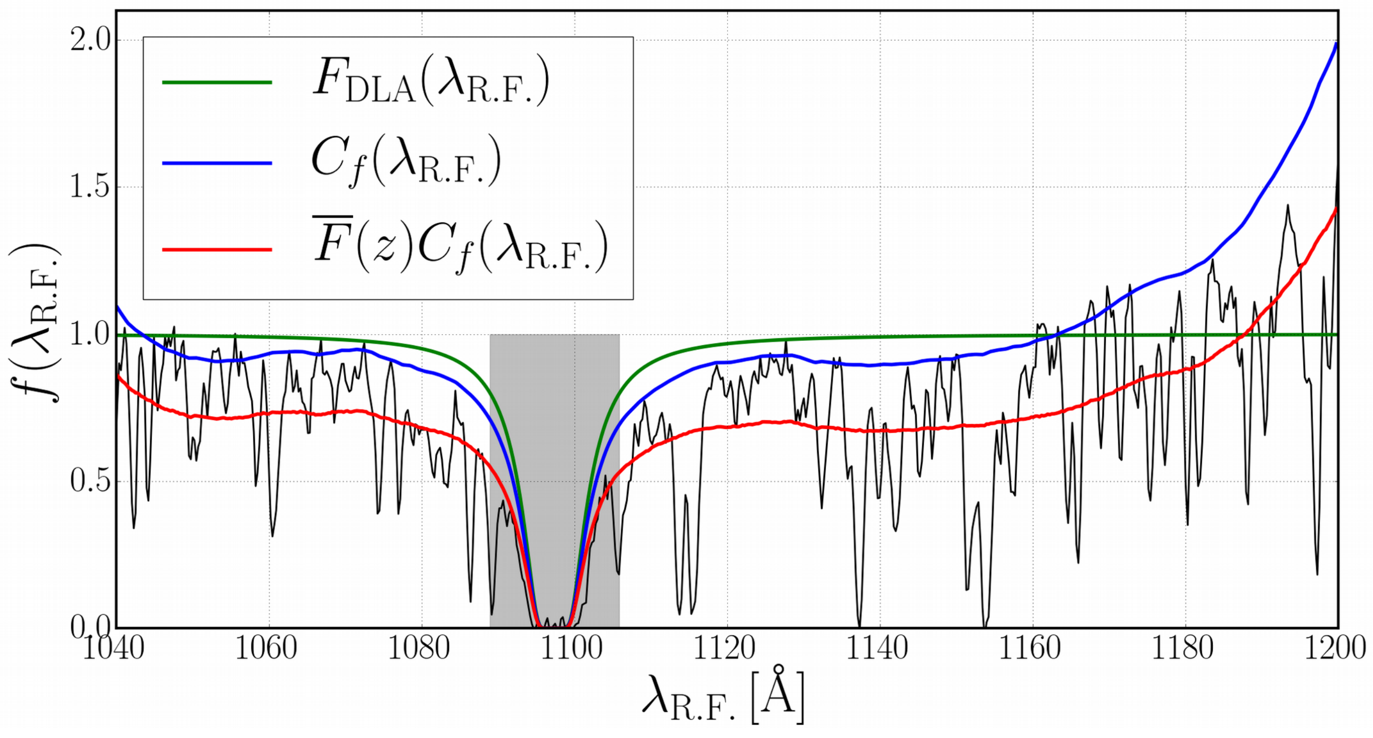


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1000
1200
1400
1600
1800
$f(\lambda_{R.F.})$
$\lambda_{R.F.}$ [Å]



1.2
1.0
0.8
0.6
0.4
0.2
0.0
1040
1060
1080
1100
1120
1140
1160
1180
1200
$f(\lambda_{R.F.})$
$\lambda_{R.F.}$ [Å]

DLA



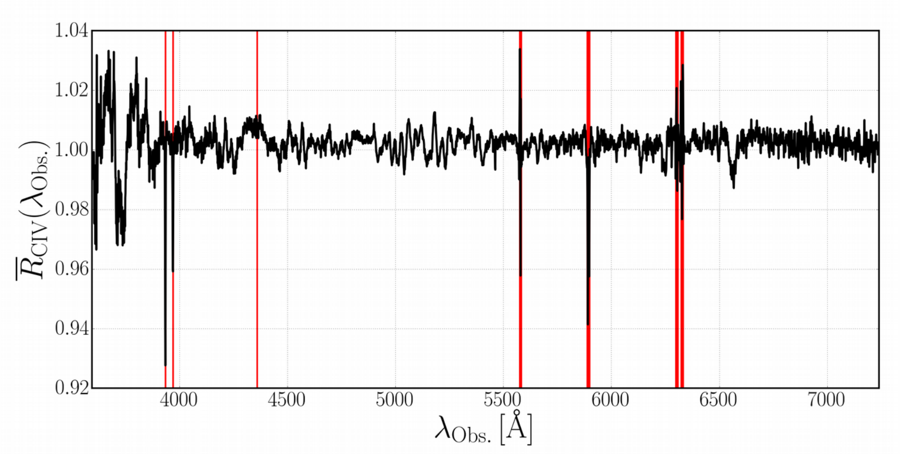
$F_{\mathrm{DLA}}(\lambda_{\mathrm{R.F.}})$
$C_f(\lambda_{\mathrm{R.F.}})$
$\overline{F}(z)C_f(\lambda_{\mathrm{R.F.}})$
2.0
1.5
1.0
0.5
0.0
1040
1060
1080
1100
1120
1140
1160
1180
1200
$f(\lambda_{\mathrm{R.F.}})$
$\lambda_{\mathrm{R.F.}}$ [Å]

Champ de transmission de flux

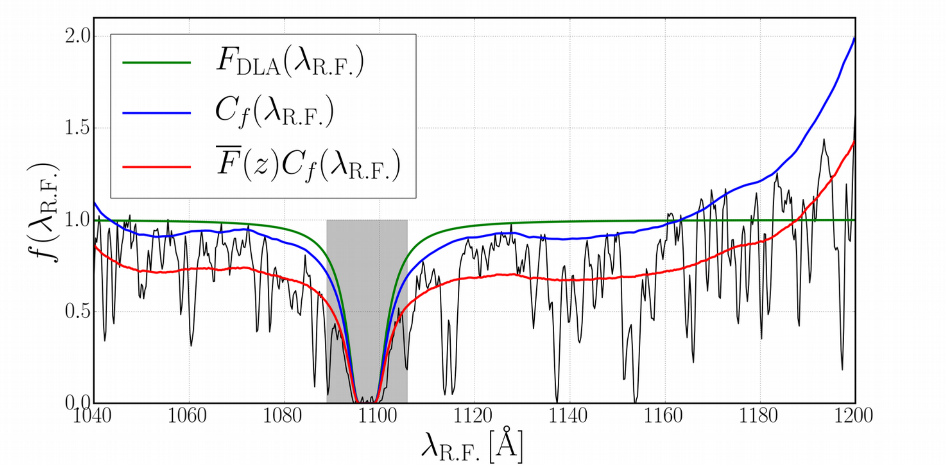
- Nous voulons extraire des spectres la fluctuation de transmission de flux :

$$\vec{\delta_i} = (\mathrm{R.A.}, \mathrm{Dec.}, r, \delta, w)_i$$

- Les spectres sont composés du flux d'émission des quasars, de l'absorption par la Voie Lactée et de l'atmosphère, de l'absorption des DLA...

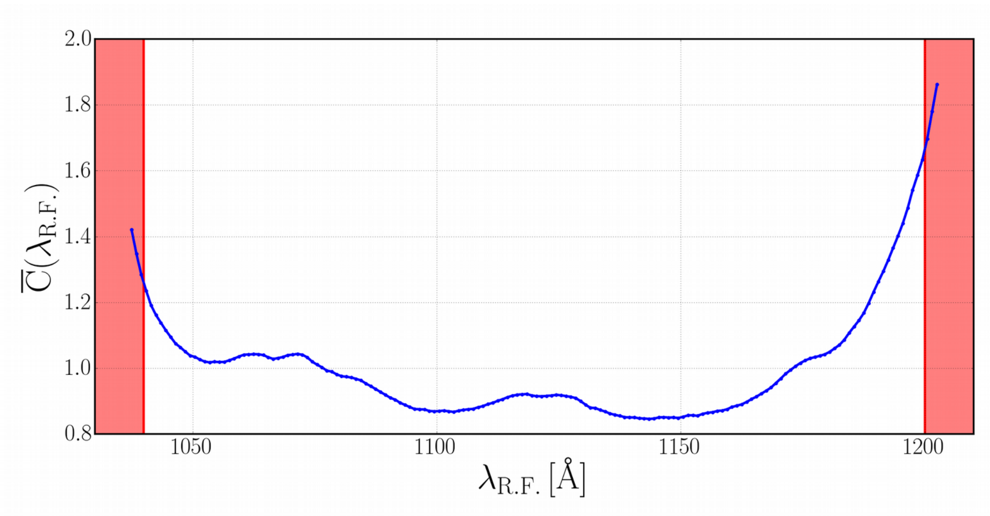


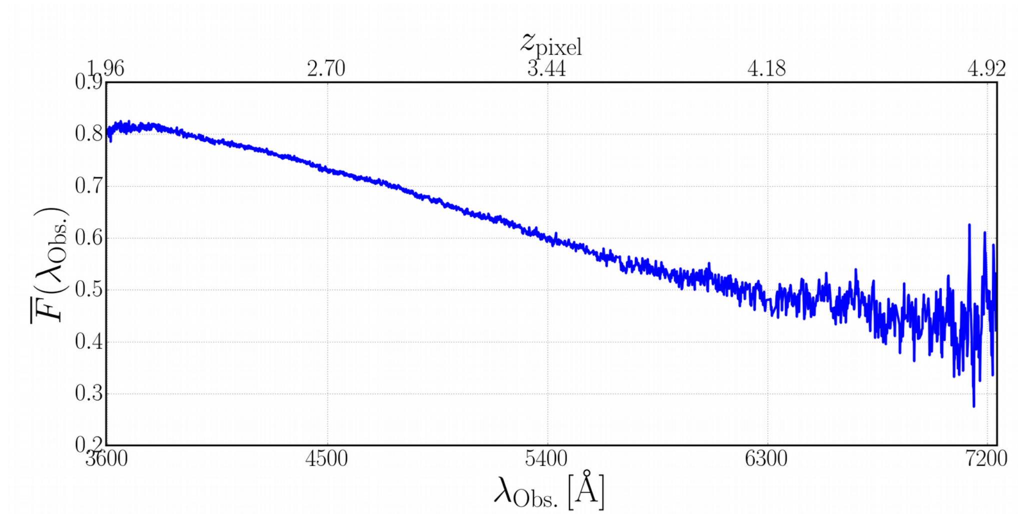
Calibration et raies du ciel

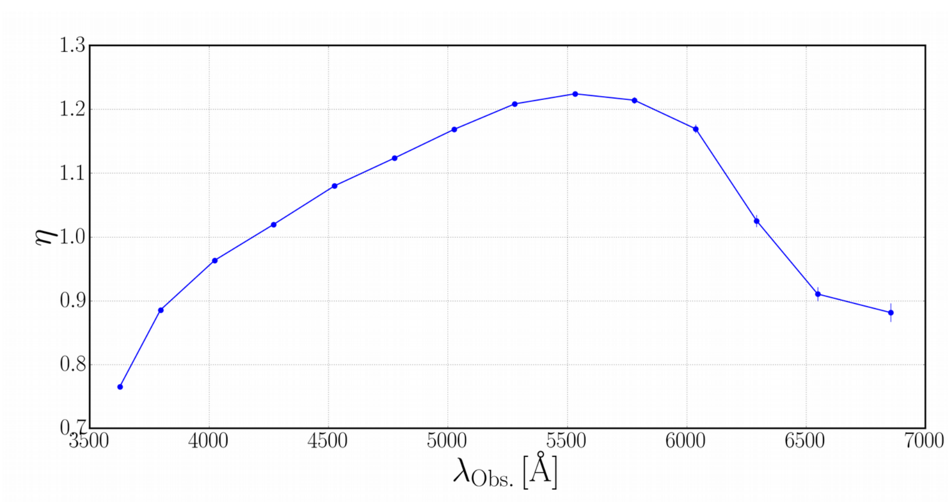


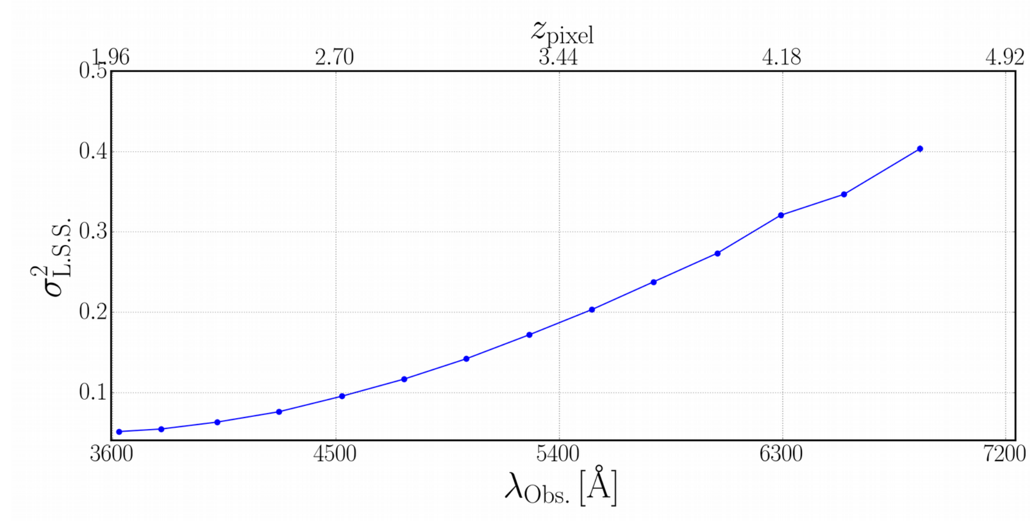
Exemple de DLA

Résultat de la définition des pixels







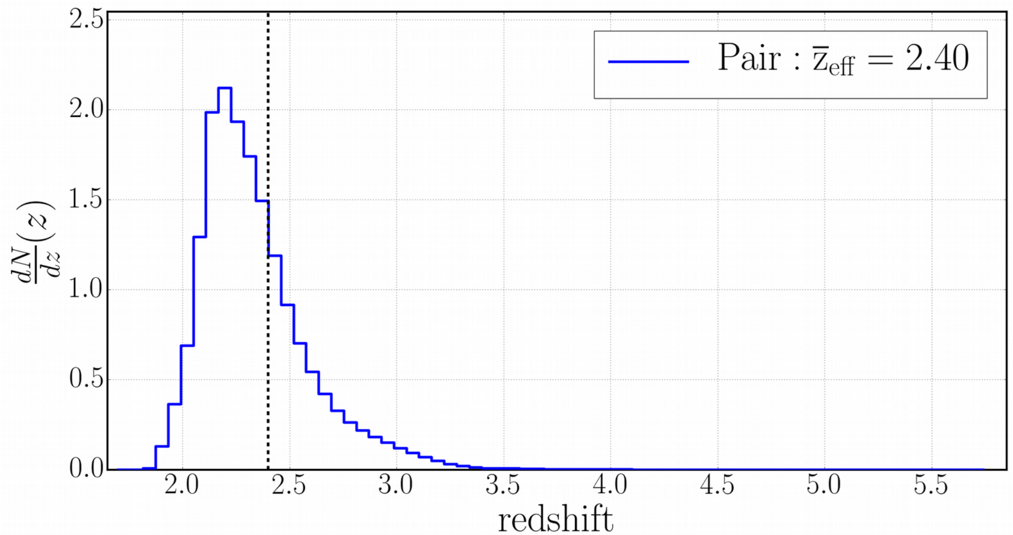


Redshift de la mesure

- Le redshift de la mesure est défini comme le redshift moyen des paires pixel-qso situées dans le pic BAO. L'erreur est estimée à partir des sous-échantillons.

$$z_{\mathrm{eff}} = 2.3962 \pm 0.0017$$

- Distribution pondérée du redshift des paires pixels-quasars.



Matrice de covariance : mélange de la position angulaire

- L'idée est de créer un très grand nombre de réalisation de la fonction de corrélation en gardant la corrélation entre ses différents bins.

- Pour chaque réalisation « r » les forêts reçoivent la position angulaire d'une autre forêt.

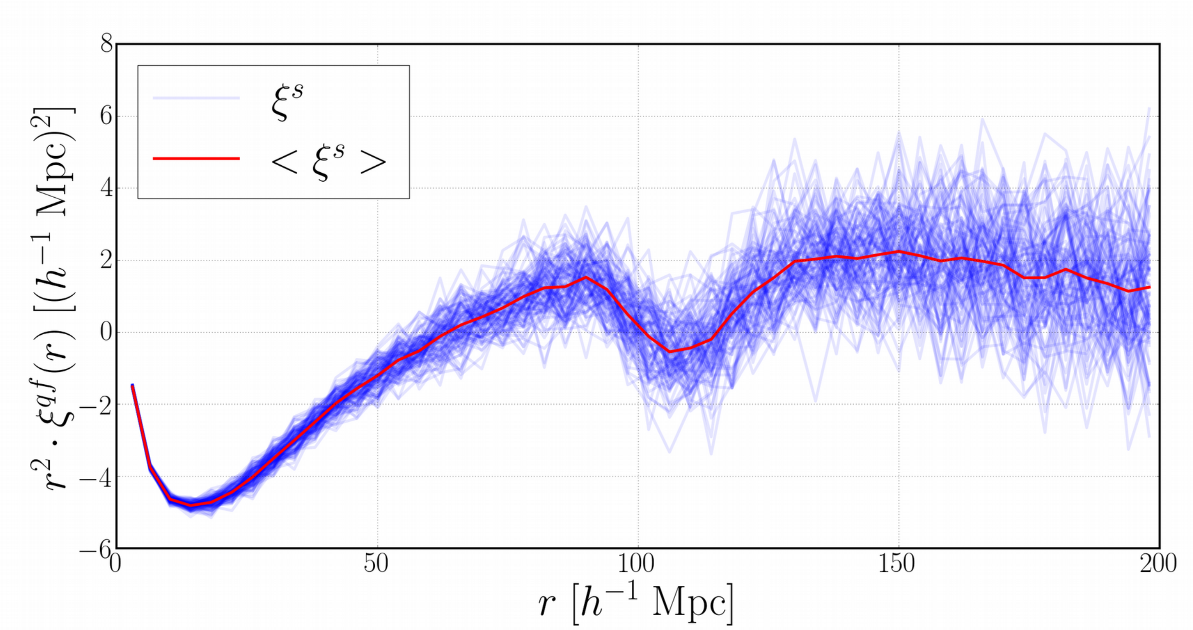
→ La corrélation entres pixels de mêmes forêts est conservée, mais

$$\mathbb{E}\left[\xi^{qf,r}\right] \approx 0 \quad \text{et} \quad \mathbb{E}\left[\xi^{ff,r}\right] \approx 0$$

Matrice de covariance : variance des mocks

- Méthode très similaire au sous-échantillonnage
- Pour chacun des 100 mocks, nous mesurons la fonction de corrélation.
- La matrice de covariance est alors :

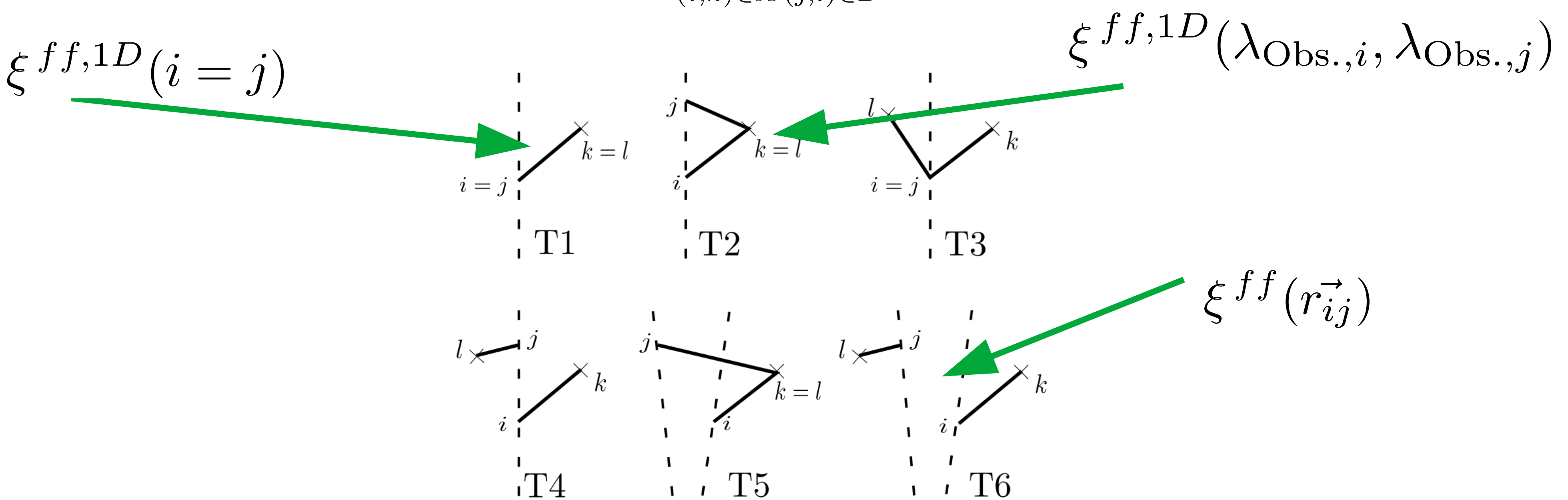
$$C_{AB} = \left\langle \xi_A^{qf} \xi_B^{qf} \right\rangle - \left\langle \xi_A^{qf} \right\rangle \left\langle \xi_B^{qf} \right\rangle$$



Matrice de covariance : décomposition en diagramme

- L'idée est de décomposer le calcul de la matrice de covariance en diagramme où la corrélation entre pixels est différente :

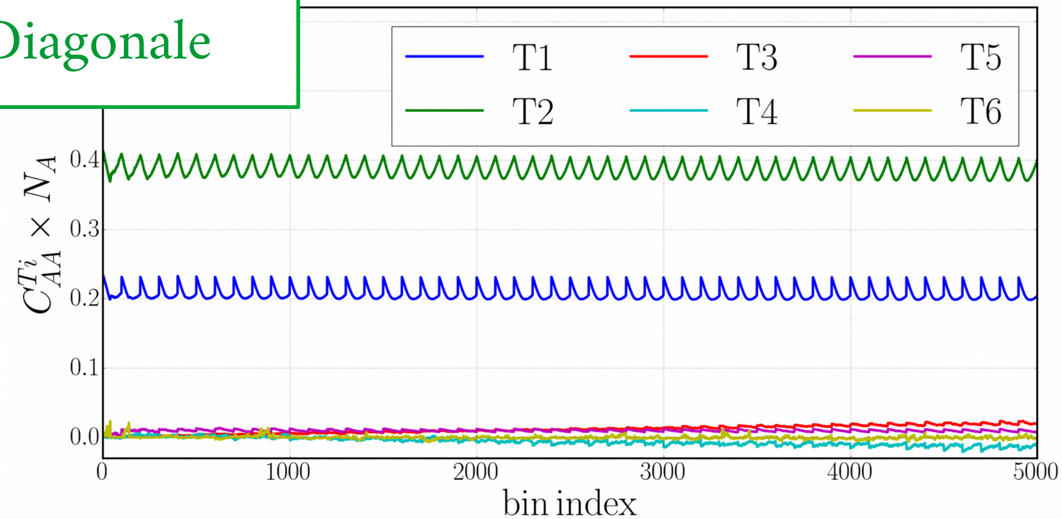
$$C_{AB} = \frac{1}{W_A W_B} \sum_{(i,k)\in A} \sum_{(j,l)\in B} w_i w_j \mathbb{E}\left[\delta_i \delta_j\right]$$



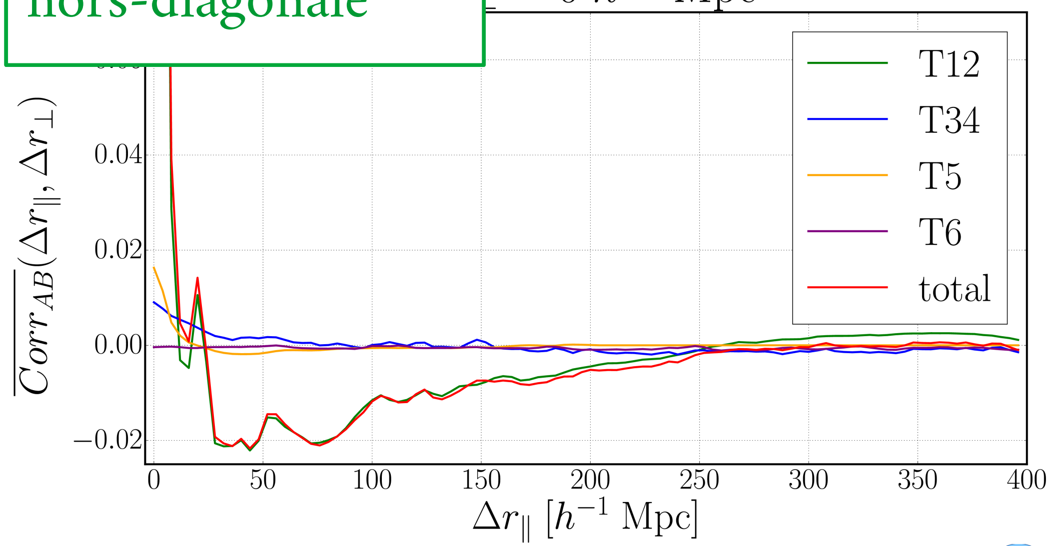
Matrice de covariance : décomposition en diagramme

- La matrice est dominée par la contribution de T1 et T2
- T3 et T4 s'annulent
- T5 joue un faible rôle et T6 est négligeable

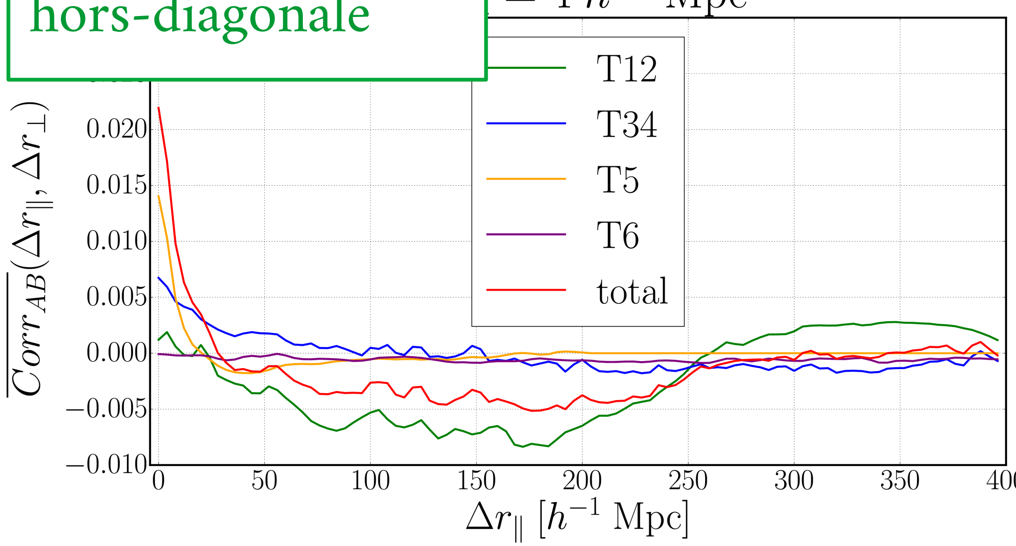
Diagonale



hors-diagonale



hors-diagonale

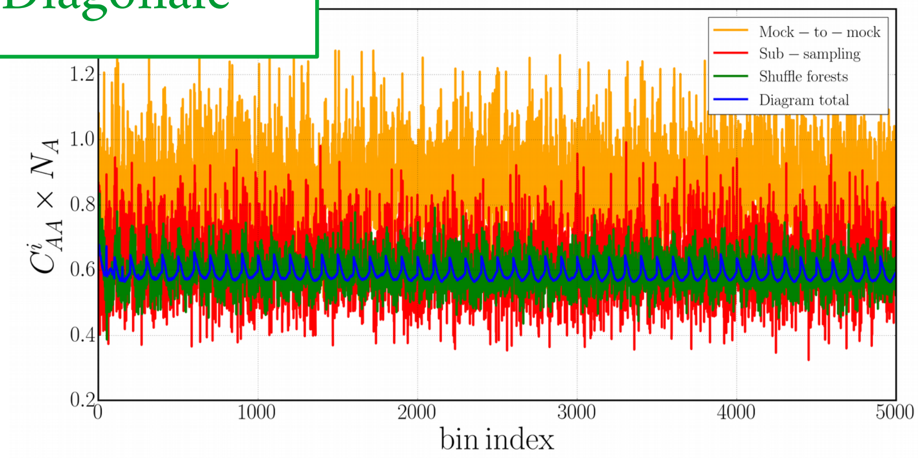


Matrice de covariance : bilan

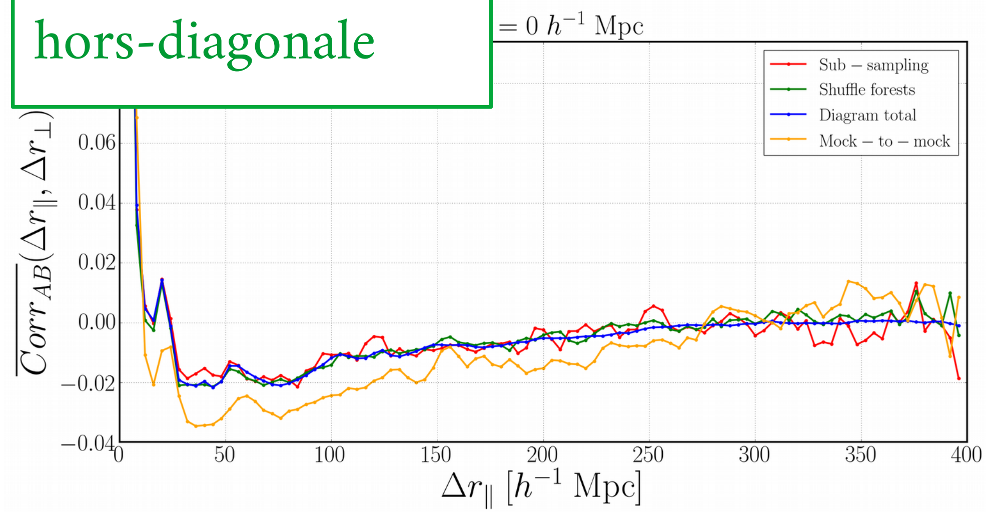
- Très bon accord des quatre techniques
- La variance est différente dans les simulations
- Décomposition en diagramme très précis mais très long
- Mélange des forêts manque une partie de la corrélation.

→ Analyse avec sous-échantillonnage + moyenne des termes

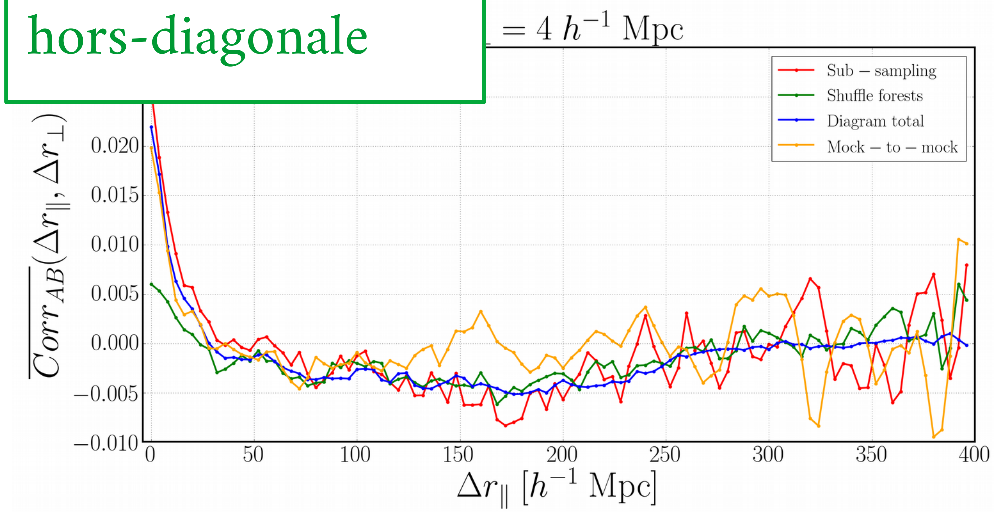
Diagonale



hors-diagonale



hors-diagonale

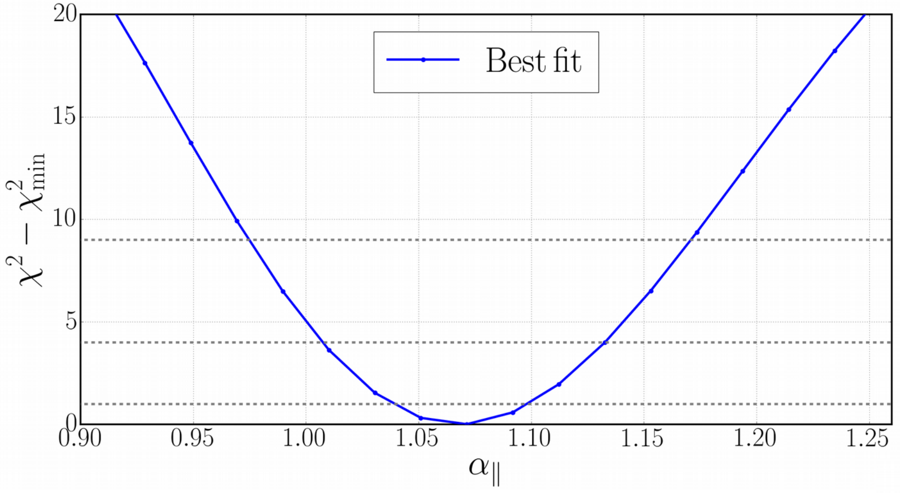


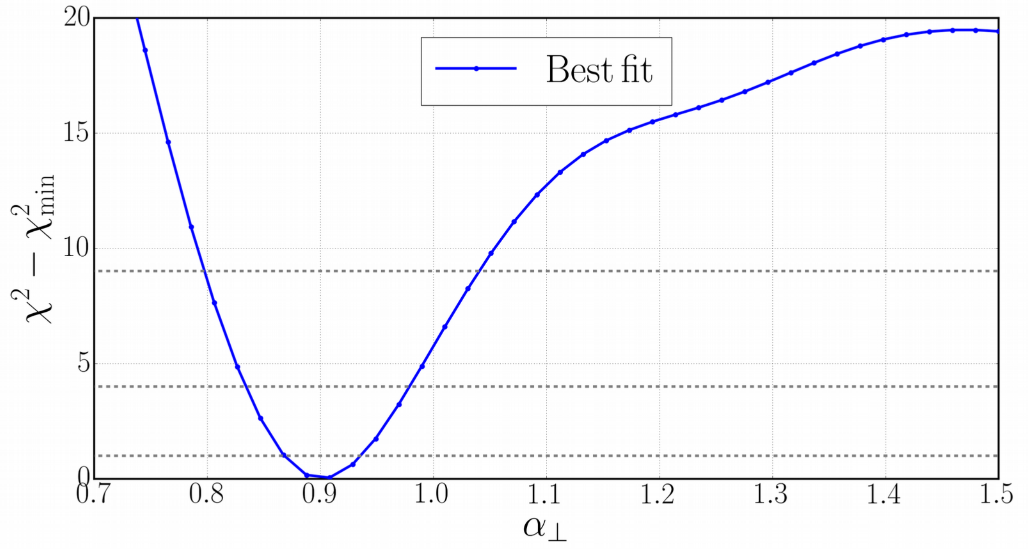
Significance du pic BAO

- Afin d'estimer la significance du pic BAO nous comparons deux ajustements :
  - L'ajustement standard où l'amplitude du pic BAO est fixe
  - Un ajustement sans pic BAO
- La significance est déduite de la différence de chi2 pour deux paramètres libres de différence :

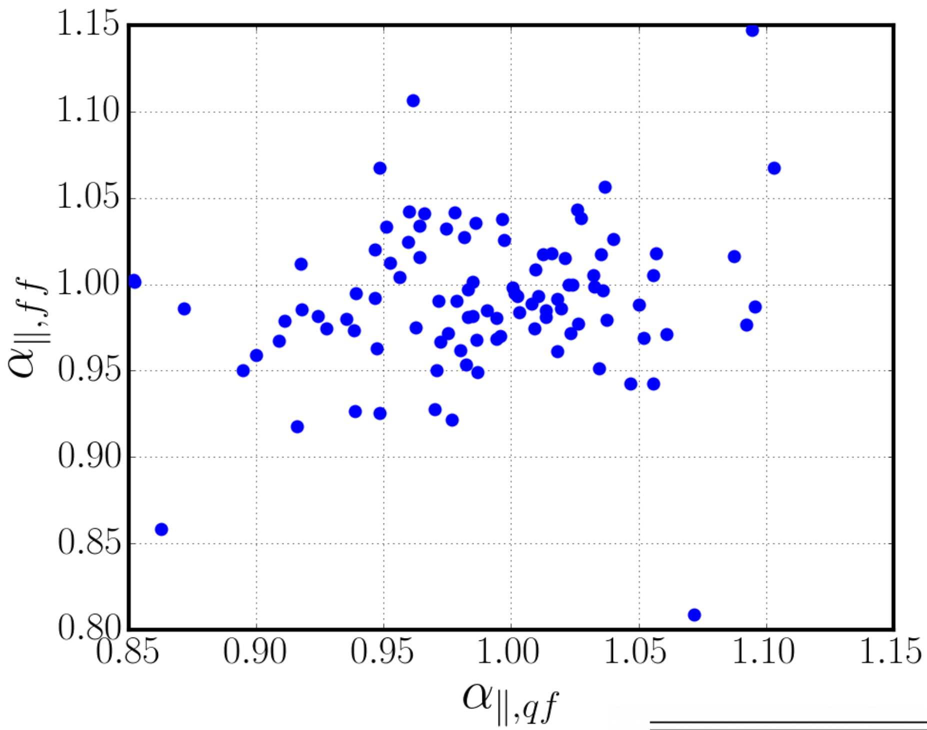
$$\Delta\chi^2_{\mathrm{min}} = 3.7\ \sigma$$

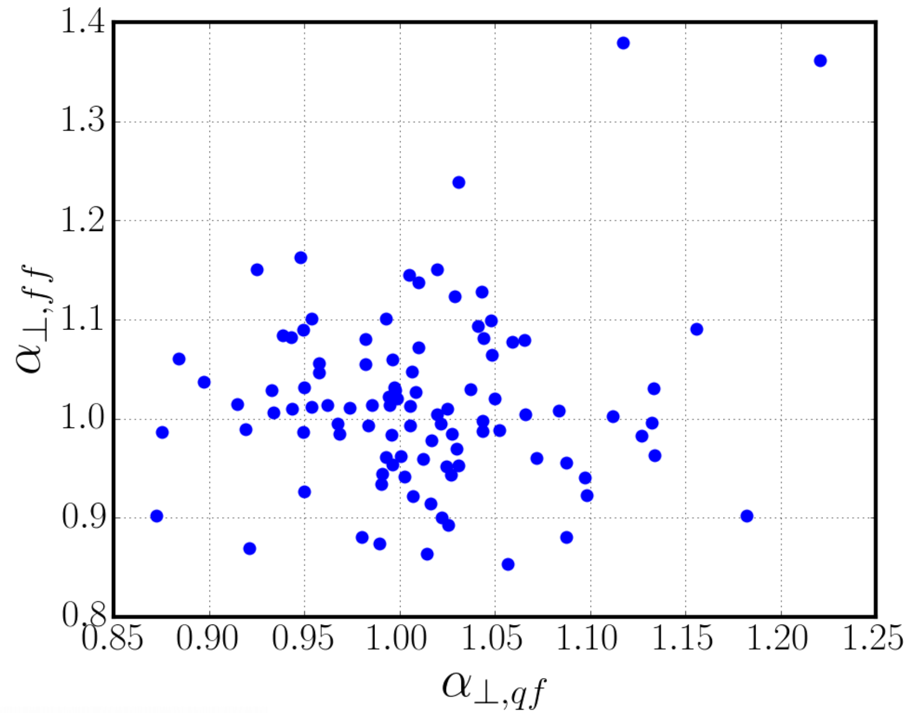
Mesure de l'échelle BAO





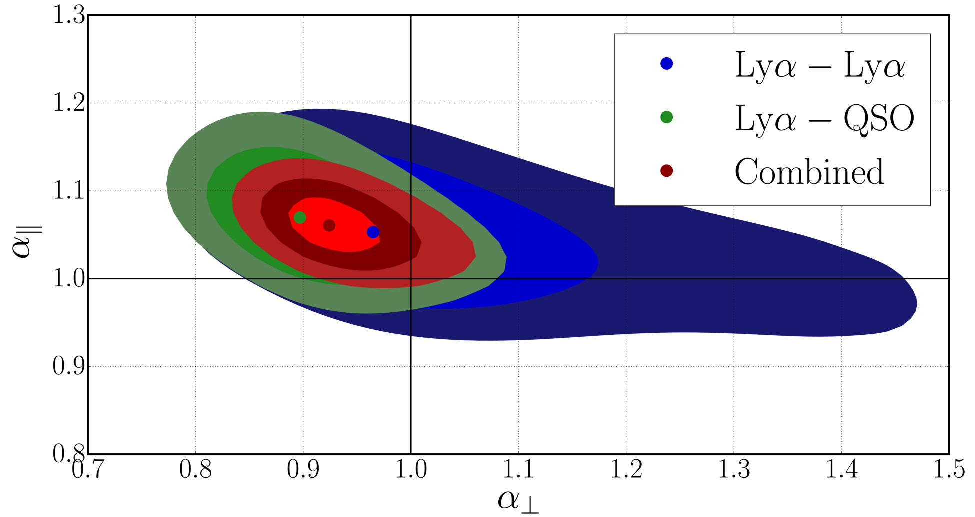
Combinaison





$\rho(\alpha_{\perp}^{\text{cross}}, \alpha_{\parallel}^{\text{cross}})$	-0.325 ± 0.087
$\rho(\alpha_{\perp}^{\text{auto}}, \alpha_{\parallel}^{\text{auto}})$	-0.428 ± 0.089
$\rho(\alpha_{\perp}^{\text{cross}}, \alpha_{\perp}^{\text{auto}})$	0.004 ± 0.096
$\rho(\alpha_{\parallel}^{\text{cross}}, \alpha_{\parallel}^{\text{auto}})$	0.11 ± 0.11
$\rho(\alpha_{\perp}^{\text{cross}}, \alpha_{\parallel}^{\text{auto}})$	-0.13 ± 0.12
$\rho(\alpha_{\parallel}^{\text{cross}}, \alpha_{\perp}^{\text{auto}})$	0.093 ± 0.09

Ajustement combiné : mesure de BAO

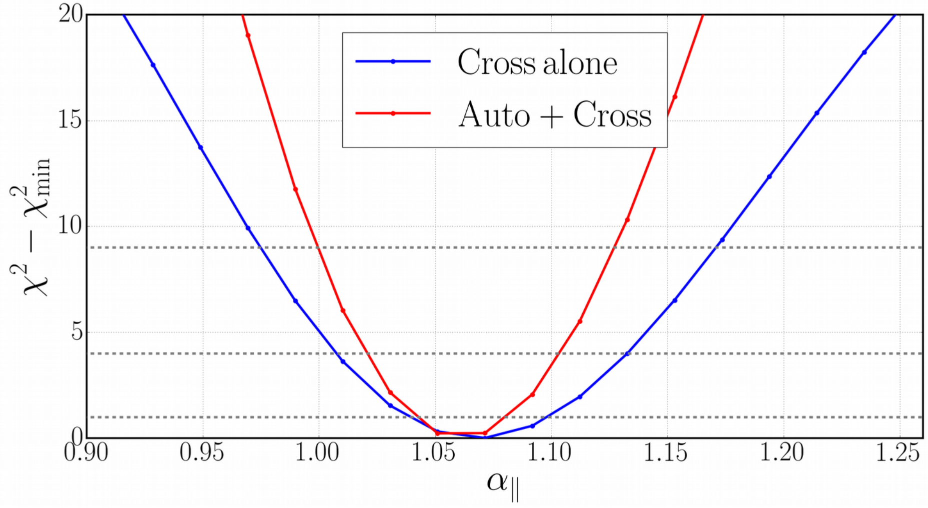


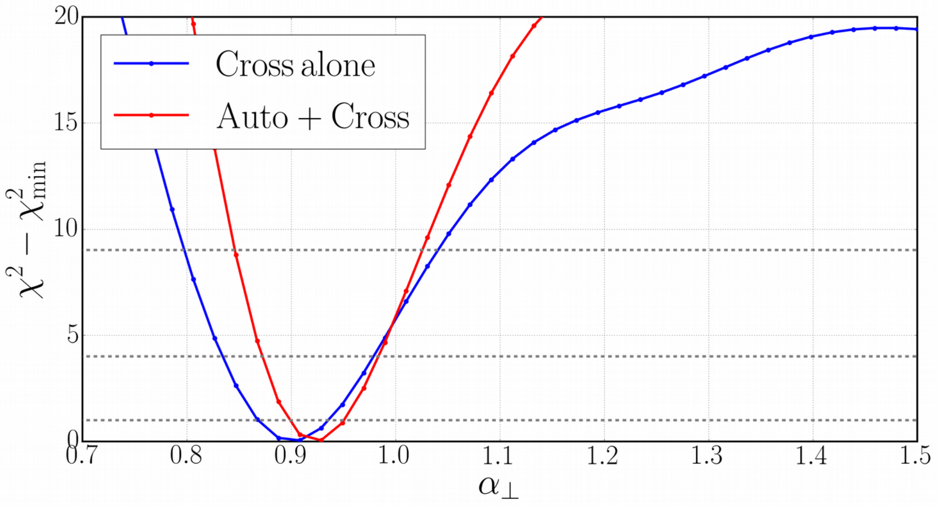
- Résultat : $$\alpha_{\parallel} = 1.061 \; (1\;\sigma)^{0.021}_{0.021} \; (2\;\sigma)^{0.043}_{0.041}$$ $$\alpha_{\perp} = 0.923 \; (1\;\sigma)^{0.028}_{0.026} \; (2\;\sigma)^{0.061}_{0.051}$$
- Par rapport à la cosmologie de Planck2015 :

$$\Delta\chi^2_{\mathrm{min}} = 3840.82 - 3830.69 = 10.13$$

$$\Delta\chi^2_{\mathrm{min}} = 2.7\;\sigma$$

Ajustement combiné : mesure de BAO





Ajustement combiné : significance du pic

- Différence de chi2 entre le modèle sans pic et avec pic :

$$\Delta\chi^2_{\text{min}} = 3876.41 - 3830.69 = 45.7$$

- Conversion en significance :

$$\Delta\chi^2_{\text{min}} = 6.4\ \sigma$$

Tests : changement de modèle (données)

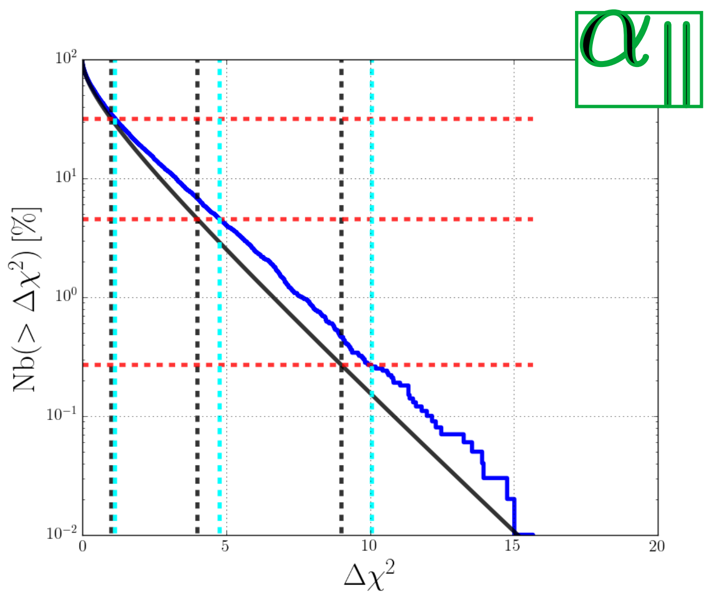
Analyse	$\alpha_{\parallel}$	$\alpha_{\perp}$	α_{opt}	$\chi^2_{\min}/(N_{bin} - N_{param})$, *proba*
Lyα	1.072 ± 0.029	0.899 ± 0.032	1.000 ± 0.017	$2827.93/(2504 - 5), p = 3.9\ 10^{-6}$
+Metaux	1.072 ± 0.029	0.899 ± 0.032	0.999 ± 0.017	$2787.46/(2504 - 9), p = 3.2\ 10^{-5}$
+Vitesse QSO	1.070 ± 0.031	0.897 ± 0.036	0.997 ± 0.019	$2583.54/(2504 - 10), p = 0.10$
+HCD	1.071 ± 0.032	0.899 ± 0.036	0.998 ± 0.019	$2577.03/(2504 - 13), p = 0.11$
+UV	1.069 ± 0.032	0.900 ± 0.036	0.998 ± 0.019	$2576.31/(2504 - 14), p = 0.11$
+Radiation	1.068 ± 0.030	0.901 ± 0.034	0.998 ± 0.018	$2573.54/(2504 - 15), p = 0.12$
prior b_q	1.068 ± 0.030	0.901 ± 0.034	0.998 ± 0.018	$2573.52/(2504 - 16), p = 0.11$
$(R_{\parallel}, R_{\perp})$	1.068 ± 0.030	0.901 ± 0.033	0.998 ± 0.018	$2572.18/(2504 - 17), p = 0.11$
$(\Sigma_{\parallel}, \Sigma_{\perp})$	1.068 ± 0.030	0.901 ± 0.034	0.998 ± 0.018	$2573.54/(2504 - 17), p = 0.11$
A_{peak}	1.069 ± 0.032	0.899 ± 0.036	0.997 ± 0.019	$2573.36/(2504 - 16), p = 0.11$
$A_{peak} = 0$	$---$	$---$	$---$	$2590.10/(2504 - 13), p = 0.081$
$\alpha_{\parallel} = \alpha_{\perp} = 1$	1	1	1	$2580.93/(2504 - 13), p = 0.10$
BB$(0, 2, 0, 6)$	1.076 ± 0.027	0.899 ± 0.031	1.001 ± 0.016	$2534.15/(2504 - 36), p = 0.17$
$r_{\min} = 40$	1.067 ± 0.025	0.904 ± 0.030	0.998 ± 0.015	$2403.86/(2354 - 15), p = 0.17$
$r_{\max} = 180$	1.069 ± 0.030	0.899 ± 0.034	0.998 ± 0.018	$3349.56/(3180 - 15), p = 0.011$
baofit	1.069 ± 0.031	0.898 ± 0.036	0.997 ± 0.019	$2580.07/(2504 - 10), p = 0.11$

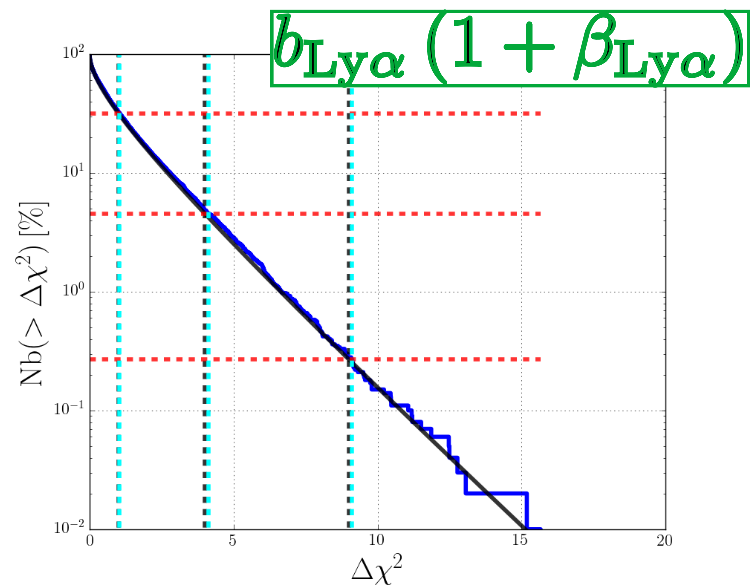
Tests : changement d'analyse (données)

Analyse	$\alpha_{\parallel}$	$\alpha_{\perp}$	α_{opt}	$\chi^2_{\min}/(N_{bin} - N_{param})$, *proba*
std.fit	1.068 ± 0.030	0.901 ± 0.034	0.998 ± 0.018	$2573.54/(2504 - 15), p = 0.12$
$r_{\parallel} < 0$	1.061 ± 0.050	0.918 ± 0.052	1.001 ± 0.029	$1213.31/(1252 - 15), p = 0.68$
$r_{\parallel} > 0$	1.075 ± 0.040	0.881 ± 0.049	0.993 ± 0.025	$1335.28/(1252 - 15), p = 0.026$
$z_{\rm pairs} < 2.3962$	1.071 ± 0.047	0.909 ± 0.045	1.003 ± 0.026	$2533.53/(2504 - 15), p = 0.26$
$z_{\rm pairs} \geq 2.3962$	1.063 ± 0.042	0.908 ± 0.052	0.998 ± 0.026	$2605.78/(2504 - 15), p = 0.051$
NGC	1.063 ± 0.033	0.921 ± 0.041	1.004 ± 0.020	$2614.82/(2504 - 15), p = 0.039$
SGC	1.103 ± 0.069	0.867 ± 0.056	1.002 ± 0.037	$2523.85/(2504 - 15), p = 0.31$
FiberId < 500	1.061 ± 0.045	0.907 ± 0.045	0.997 ± 0.026	$2447.31/(2504 - 15), p = 0.72$
FiberId ≥ 500	1.069 ± 0.043	0.904 ± 0.054	1.000 ± 0.027	$2634.39/(2504 - 15), p = 0.021$
$\mathrm{SNR}_{\mathrm{Ly}\alpha} < 3.2919$	1.014 ± 0.042	0.932 ± 0.043	0.980 ± 0.024	$2678.66/(2504 - 15), p = 0.0042$
$\mathrm{SNR}_{\mathrm{Ly}\alpha} \geq 3.2919$	1.103 ± 0.039	0.869 ± 0.045	1.002 ± 0.023	$2630.53/(2504 - 15), p = 0.024$
SNR_1700 < 5.16	1.062 ± 0.036	0.904 ± 0.039	0.996 ± 0.021	$2615.12/(2504 - 15), p = 0.039$
SNR_1700 ≥ 5.16	1.065 ± 0.048	0.908 ± 0.056	0.999 ± 0.029	$2698.02/(2504 - 15), p = 0.0019$
Amp. CIV < 7.36	1.075 ± 0.033	0.856 ± 0.042	0.981 ± 0.021	$2538.52/(2504 - 15), p = 0.24$
Amp. CIV ≥ 7.36	1.091 ± 0.066	0.912 ± 0.044	1.015 ± 0.035	$2550.05/(2504 - 15), p = 0.19$
$\mathrm{Mag}_{\mathrm{i}} < -25.4$	1.077 ± 0.037	0.884 ± 0.046	0.995 ± 0.023	$2595.37/(2504 - 15), p = 0.067$
$\mathrm{Mag}_{\mathrm{i}} \geq -25.4$	1.040 ± 0.045	0.922 ± 0.042	0.991 ± 0.025	$2551.92/(2504 - 15), p = 0.19$
CORE QSO	1.090 ± 0.042	0.873 ± 0.043	0.998 ± 0.024	$2590.52/(2504 - 15), p = 0.076$
not CORE QSO	1.048 ± 0.051	1.010 ± 0.097	1.033 ± 0.040	$2613.22/(2504 - 15), p = 0.041$
Add BAL forest	1.050 ± 0.029	0.940 ± 0.036	1.004 ± 0.018	$2535.86/(2504 - 15), p = 0.25$
No DLA correction	1.053 ± 0.034	0.910 ± 0.041	0.993 ± 0.021	$2586.06/(2504 - 15), p = 0.086$

Lien entre chi2 et précision

- Les simulations semblent montrer que l'erreur est sous-estimée de ~10 %
- La génération de 10,000 fastMC à partir du meilleur modèle apporte la même conclusion.
- Dans le cas ci-dessous pour :
  - Les paramètres BAO : $\sigma(1,2,3) \rightarrow \Delta\chi^2(1.14, 4.76, 10.05)$
  - Les autres paramètres : $\sigma(1,2,3) \rightarrow \Delta\chi^2(1.04, 4.13, 9.12)$





Lien entre chi2 et précision

CL	$\Delta\chi^2$: Lyα-only simulation 68.27%	95.45%	99.7%	$\Delta\chi^2$: Complete simulation 68.27%	95.45%	99.7%
Cross						
$\alpha_{\parallel}$	1.14 ± 0.02	4.76 ± 0.09	10.05 ± 0.53	1.17 ± 0.05	4.88 ± 0.17	11.73 ± 1.79
$\alpha_{\perp}$	1.18 ± 0.02	4.86 ± 0.08	10.59 ± 0.43	1.19 ± 0.05	4.73 ± 0.16	10.2 ± 0.71
$b(1+\beta)_{\mathrm{Ly}\alpha}$	1.04 ± 0.02	4.13 ± 0.09	9.12 ± 0.25	1.04 ± 0.06	4.07 ± 0.22	9.52 ± 1.55
$\beta_{\mathrm{Ly}\alpha}$	1.02 ± 0.01	4.07 ± 0.09	9.17 ± 0.27	0.91 ± 0.06	3.78 ± 0.33	10.5 ± 0.74
$(\alpha_{\parallel}, \alpha_{\perp})$	2.62 ± 0.03	7.25 ± 0.05	12.93 ± 0.32	2.61 ± 0.08	7.16 ± 0.19	14.15 ± 1.26
Auto						
$\alpha_{\parallel}$	1.14 ± 0.02	4.52 ± 0.1	10.68 ± 0.43	1.17 ± 0.03	4.67 ± 0.14	9.81 ± 0.88
$\alpha_{\perp}$	1.20 ± 0.01	4.85 ± 0.08	10.84 ± 0.59	1.19 ± 0.03	4.86 ± 0.13	10.23 ± 0.35
$b(1+\beta)_{\mathrm{Ly}\alpha}$	0.98 ± 0.02	4.09 ± 0.09	9.25 ± 0.4	0.93 ± 0.02	3.80 ± 0.11	8.31 ± 0.39
$\beta_{\mathrm{Ly}\alpha}$	0.99 ± 0.01	4.07 ± 0.07	9.48 ± 0.49	1.09 ± 0.02	4.40 ± 0.12	9.70 ± 0.54
$(\alpha_{\parallel}, \alpha_{\perp})$	2.63 ± 0.03	7.13 ± 0.11	14.22 ± 0.74	2.60 ± 0.05	7.05 ± 0.15	14.15 ± 0.97
Combined						
$\alpha_{\parallel}$	1.09 ± 0.02	4.20 ± 0.06	9.68 ± 0.43	1.07 ± 0.05	4.37 ± 0.26	10.26 ± 1.75
$\alpha_{\perp}$	1.09 ± 0.02	4.32 ± 0.13	10.17 ± 0.63	1.11 ± 0.07	4.19 ± 0.32	—
$b(1+\beta)_{\mathrm{Ly}\alpha}$	1.03 ± 0.02	4.06 ± 0.09	9.41 ± 0.9	0.93 ± 0.05	3.74 ± 0.17	8.45 ± 1.85
$\beta_{\mathrm{Ly}\alpha}$	0.97 ± 0.02	4.14 ± 0.11	9.27 ± 0.58	1.26 ± 0.06	4.75 ± 0.23	10.19 ± 1.72
$(\alpha_{\parallel}, \alpha_{\perp})$	2.46 ± 0.03	6.43 ± 0.1	13.25 ± 0.98	2.40 ± 0.11	6.33 ± 0.18	15.79 ± 1.66

Tests : précision de la mesure (simulation)

- Nombre de mocks à 1, 2 et 3 sigma de la valeur attendue trop important.
- L'étude des fast Monte-Carlo a prouvé cet effet de l'ordre de 10 %, et les erreurs sont corrigées dans l'article publié.

Type	Ajustement et données	$\Delta\chi^2 > 2.29$	$\Delta\chi^2 > 6.18$	$\Delta\chi^2 > 11.83$
Attendu		31.7	4.6	0.27
Lyα	croisée	46	10	1
	auto	39	4	1
	combinés	42	4	0
Lyα+Continu	croisée	40	7	0
	auto	42	4	1
	combinés	37	10	0
Lyα+Continu+Métaux	croisée	45	13	1
	auto	33	10	1
	combinés	31	13	0

Données et valeurs

Données	Redshift	D_H/r_d	D_M/r_d	D_V/r_d
6dF	0.106	–	–	3.047 ± 0.137
SDSS DR7	0.15	–	–	4.466 ± 0.168
BOSS LOWZ+CMASS	0.38	24.89 ± 0.58	10.27 ± 0.15	–
	0.51	22.43 ± 0.48	13.38 ± 0.18	–
	0.61	20.86 ± 0.45	15.45 ± 0.22	–
BOSS forêt-Lyα auto+cross	2.40	8.88 ± 0.18	36.7 ± 1.1	–