

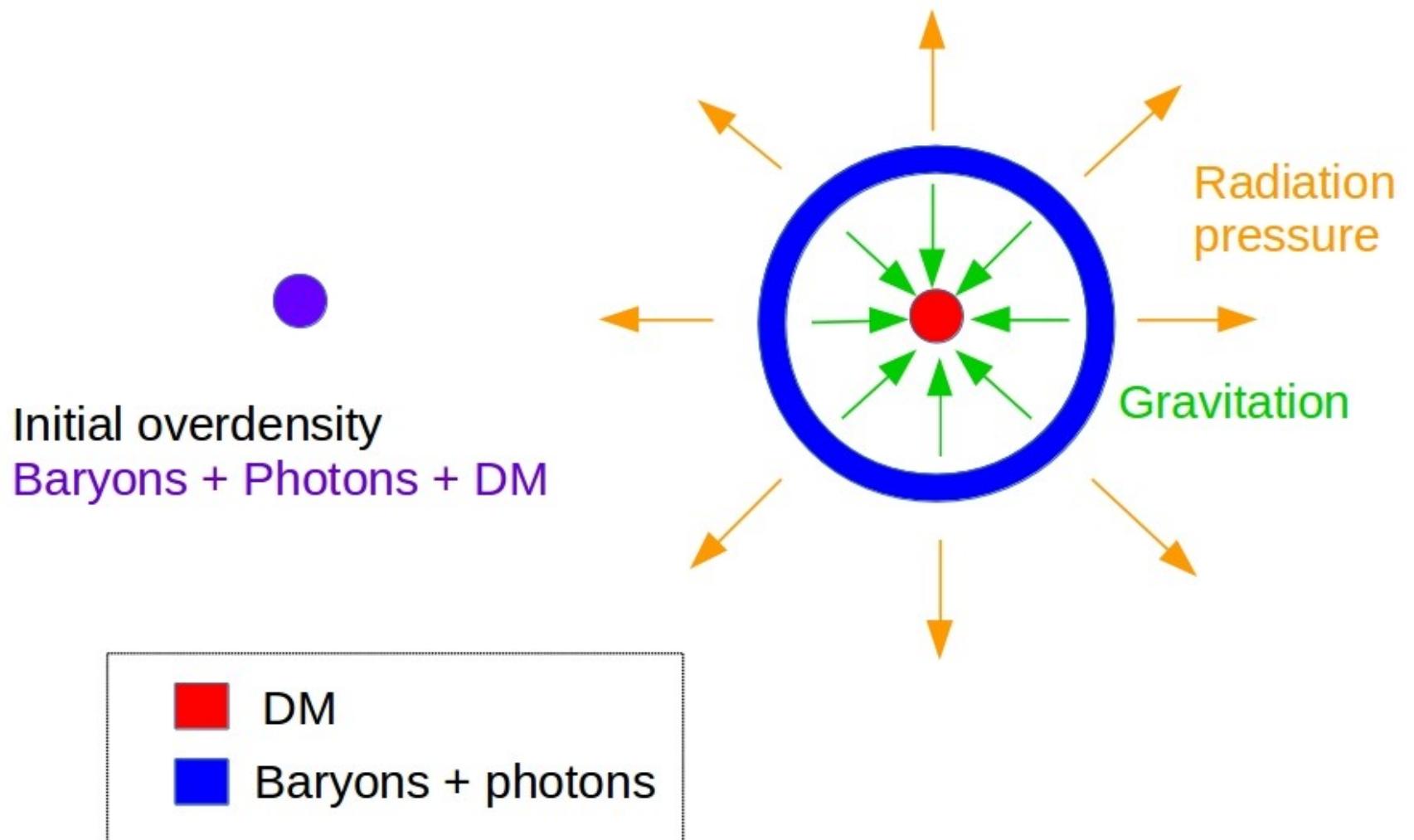
# Measuring the BAO peak using extended forests in the eBOSS – SDSS IV quasars

Victoria de Sainte Agathe  
LPNHE



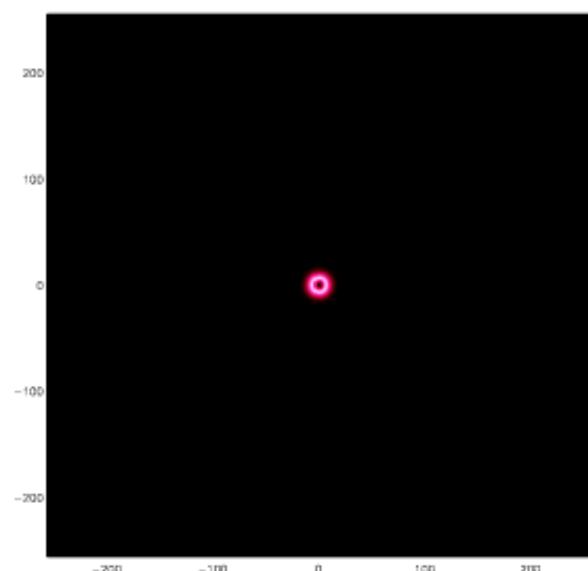
- 1) Introduction, definitions
- 2) The experiment : eBOSS
- 3) Ly forest as mass tracers
- 4) Computing the correlation functions
- 5) Fitting the correlation functions

# What is BAO ?

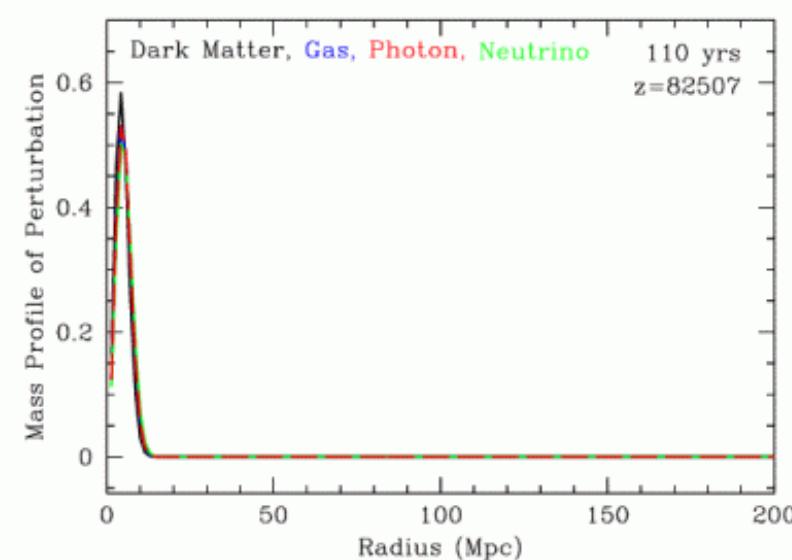
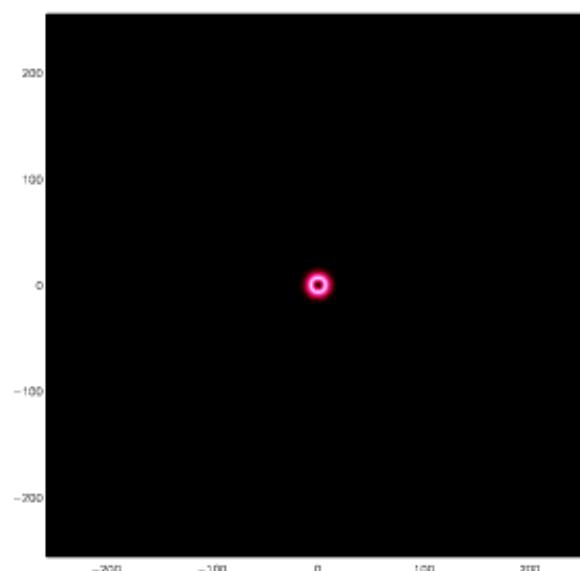


Initially : Universe homogenous with small overdensities  
**(Baryons, Photons, dark matter)**

Baryons

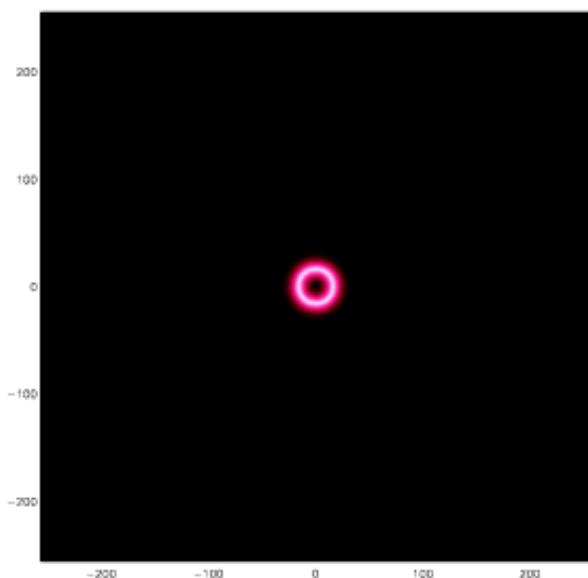


Photons

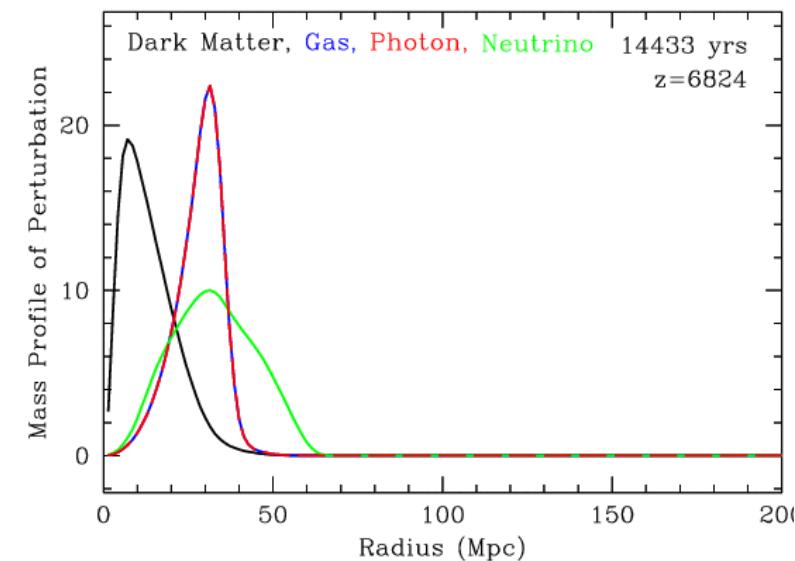
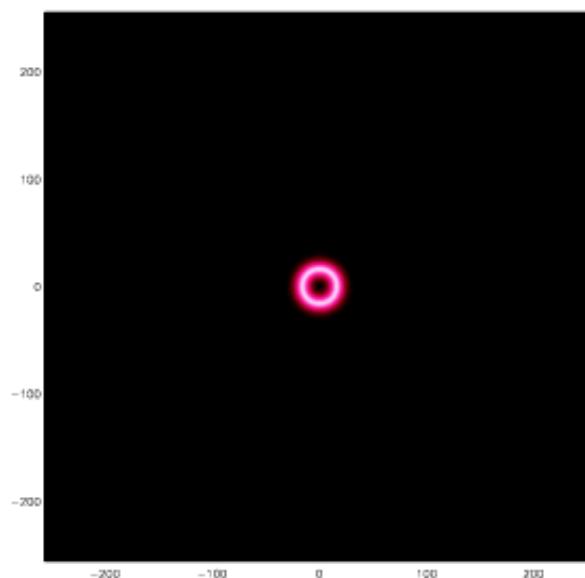


Baryons and photons are coupled and move outward  
While the dark matter stays at the center of the shell

Baryons



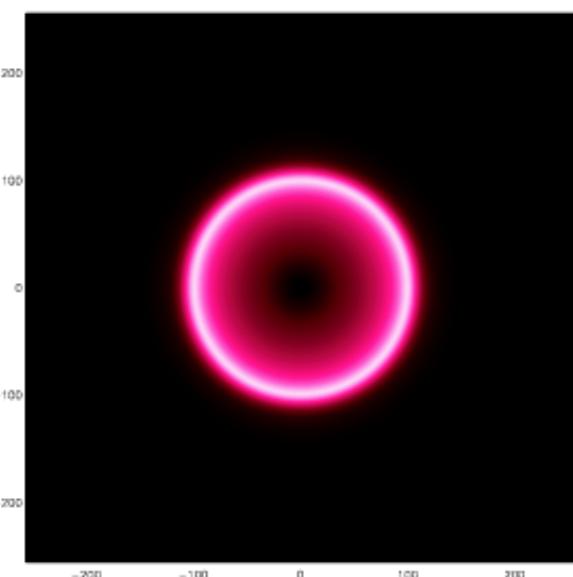
Photons



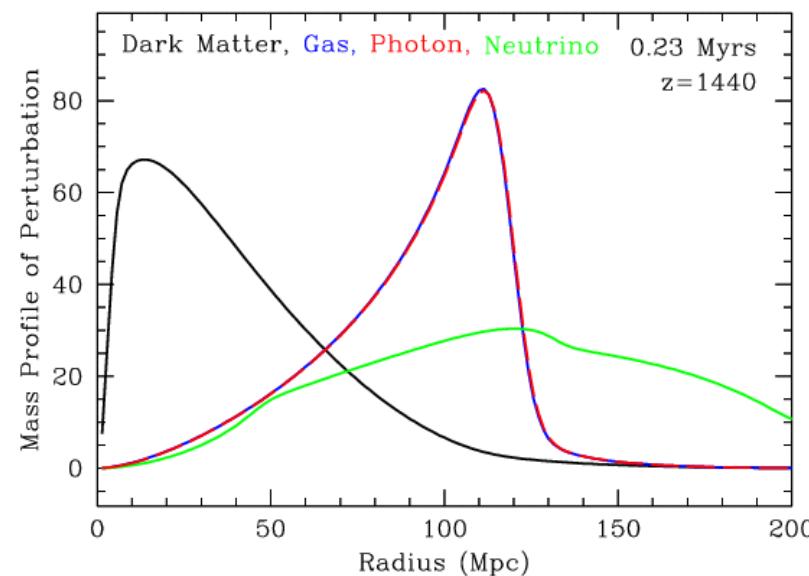
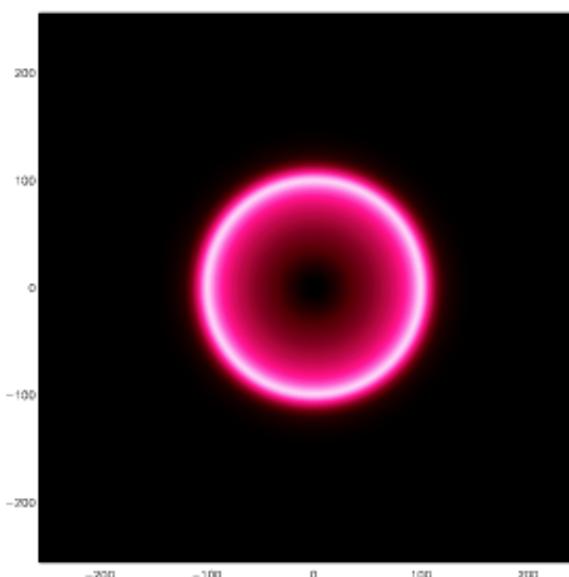
The **baryons+photons** fluid travels at the sound speed  $c_s$

$$c_s = \frac{c}{\sqrt{3(1 + \frac{3\rho_b}{4\rho_\gamma})}}$$

Baryons

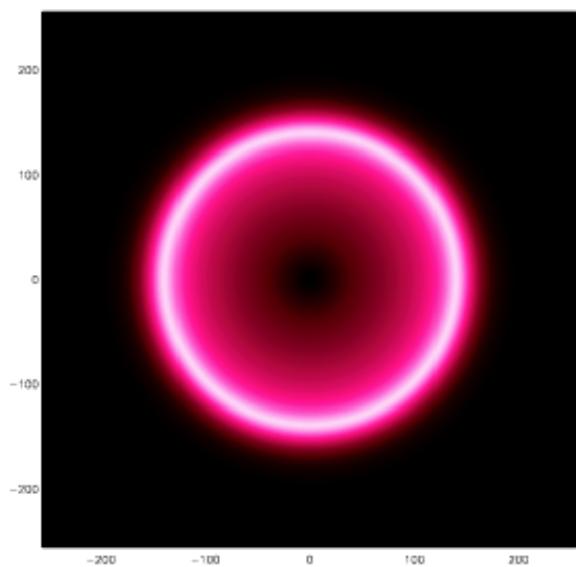


Photons

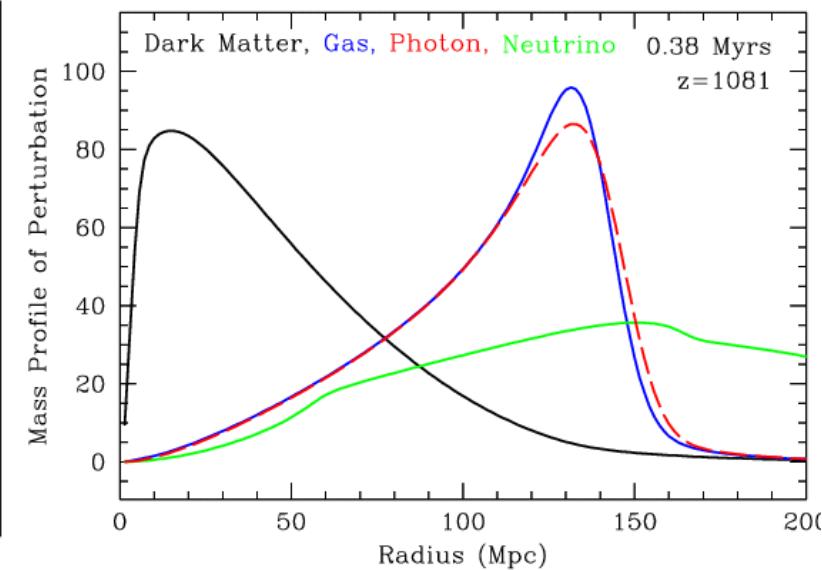
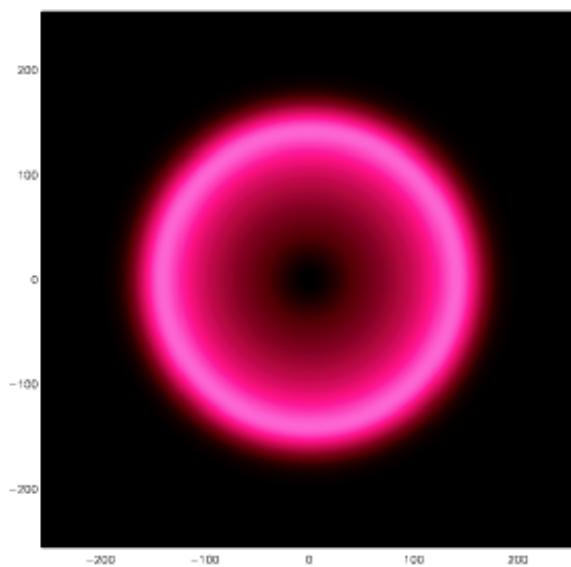


# Recombination : the **baryons** decouple from the **photons**

Baryons

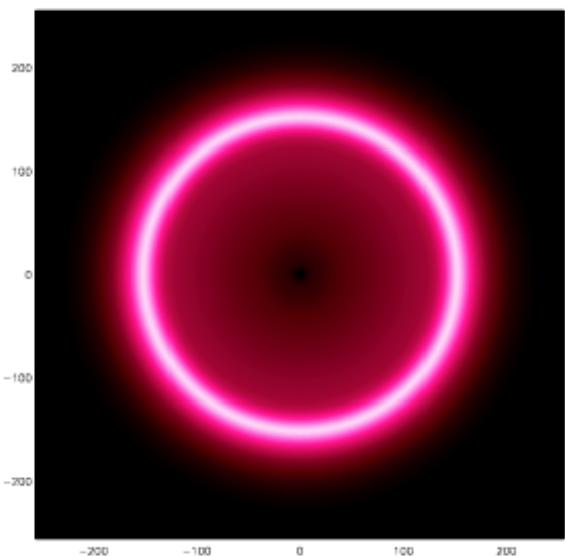


Photons

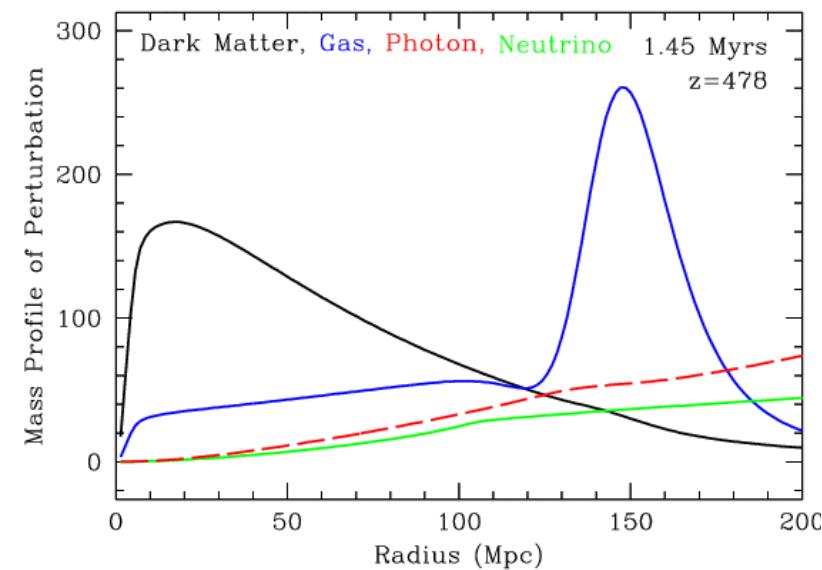
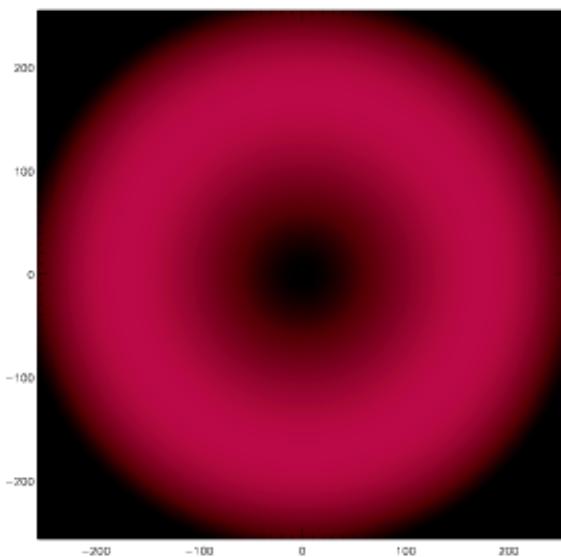


The **photons** goes away while the **baryons** interact with the **DM** in the center of the shell

Baryons

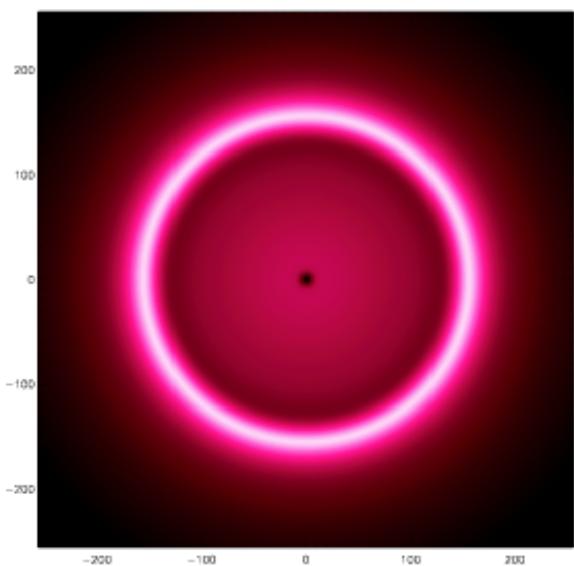


Photons

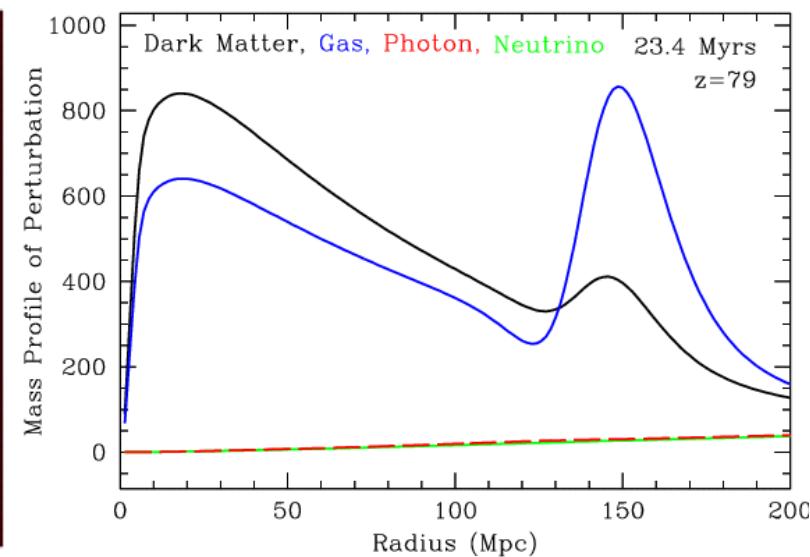
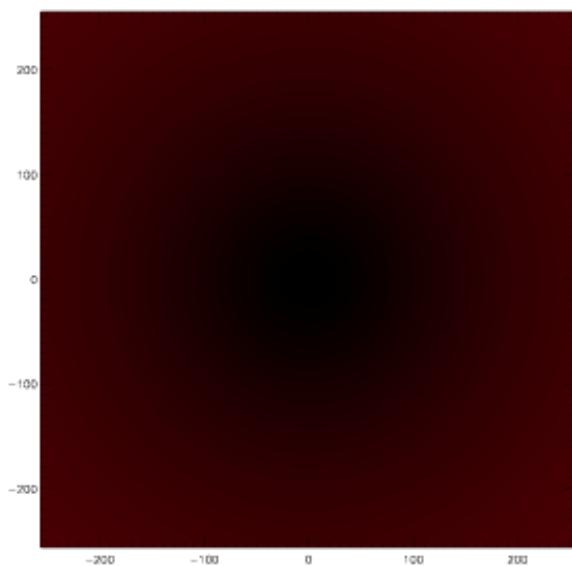


The **photons** goes away while the **baryons** interact with the **DM** in the center of the shell

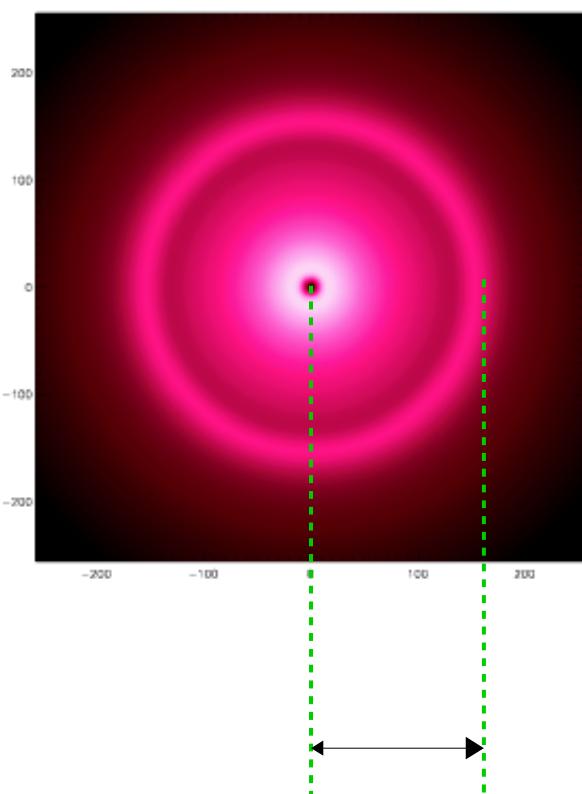
Baryons



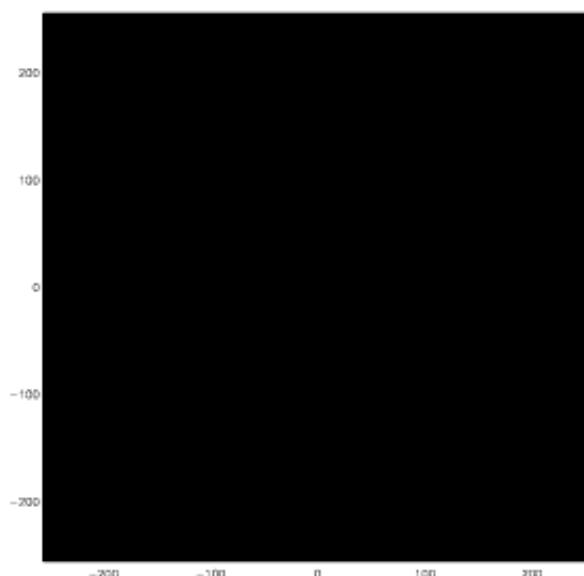
Photons



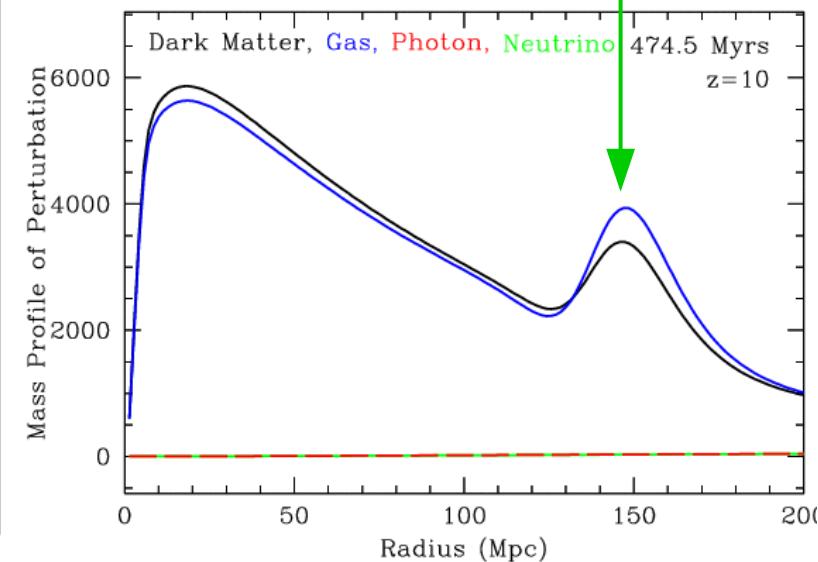
Baryons



Photons

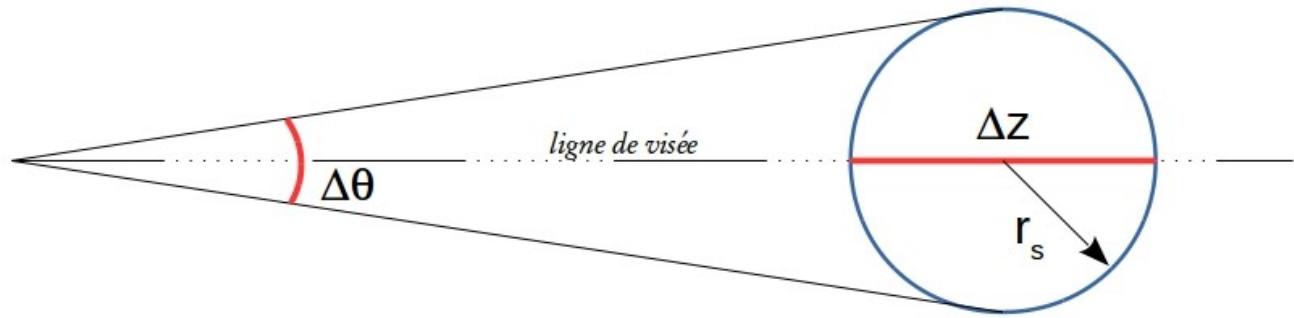
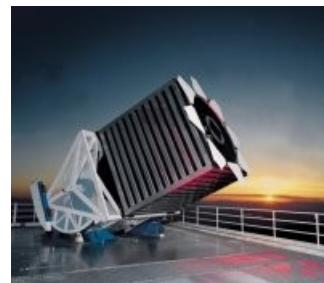


BAO peak



The sound horizon  $r_s = 150\text{Mpc}$

# What can we measure with the BAO ?



$$\begin{cases} \Delta\theta \\ \Delta z \end{cases} \longrightarrow \begin{cases} D_M(z) = r_s \Delta\theta \\ D_H(z) = r_s \Delta z \end{cases}$$

$$D_M(z) = c \int_0^z dz' \frac{1}{H(z')}$$

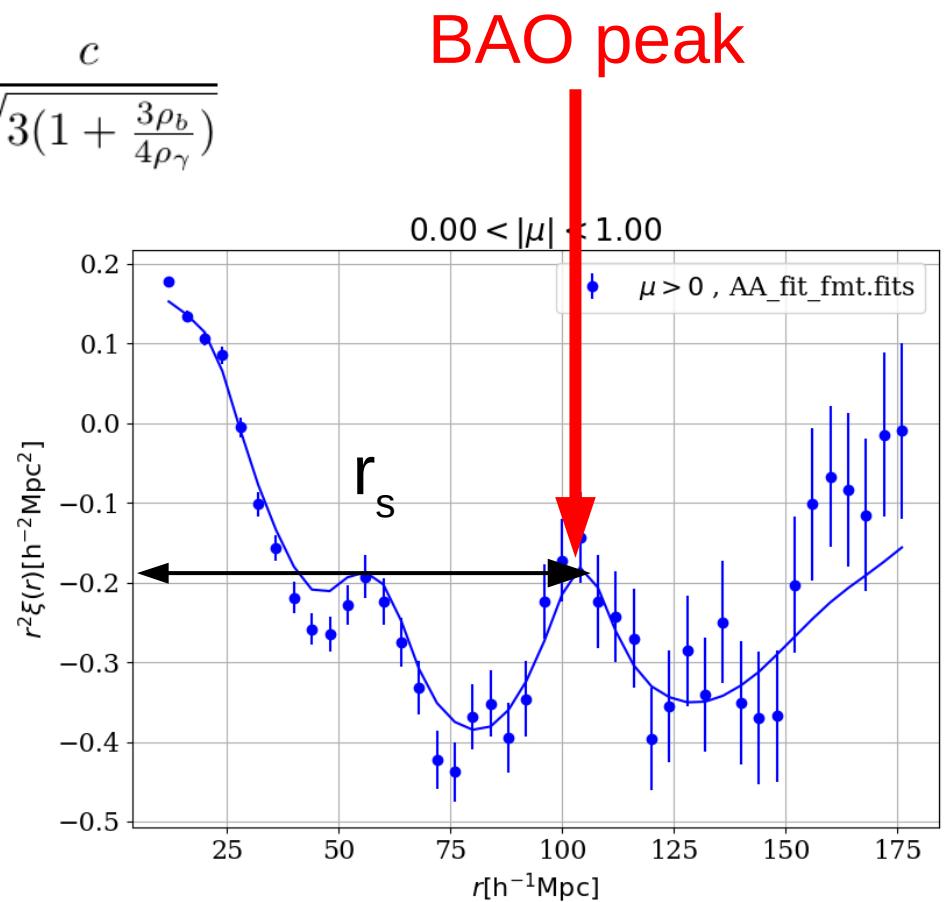
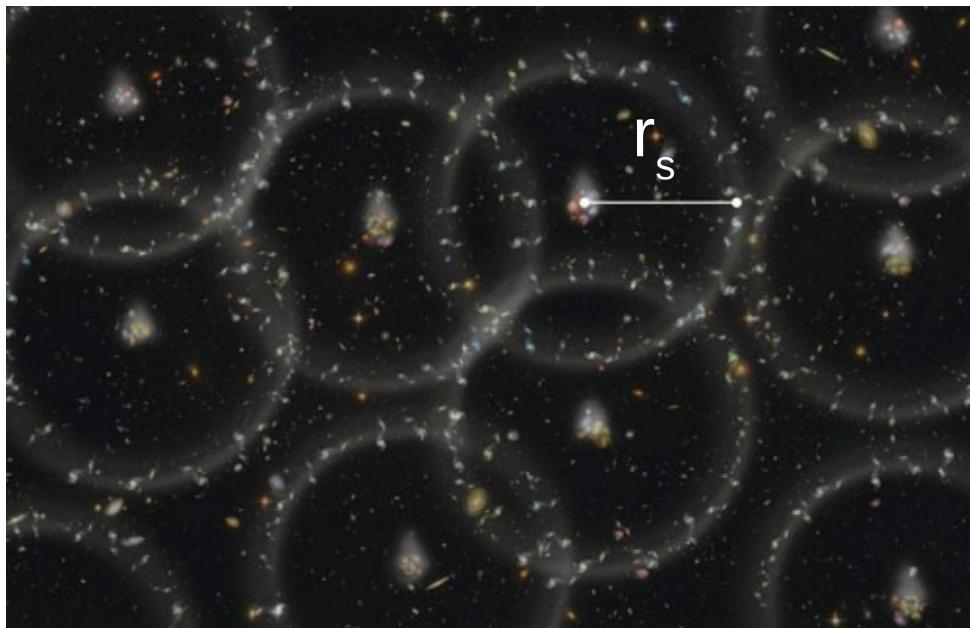
$$D_H(z) = \frac{c}{H(z)}$$

- Measure of  $D_M$  and  $D_H$  at redshift  $z$
- Since  $D_M$  and  $D_H$  depend on the cosmological parameters, this gives constraints on cosmological parameters

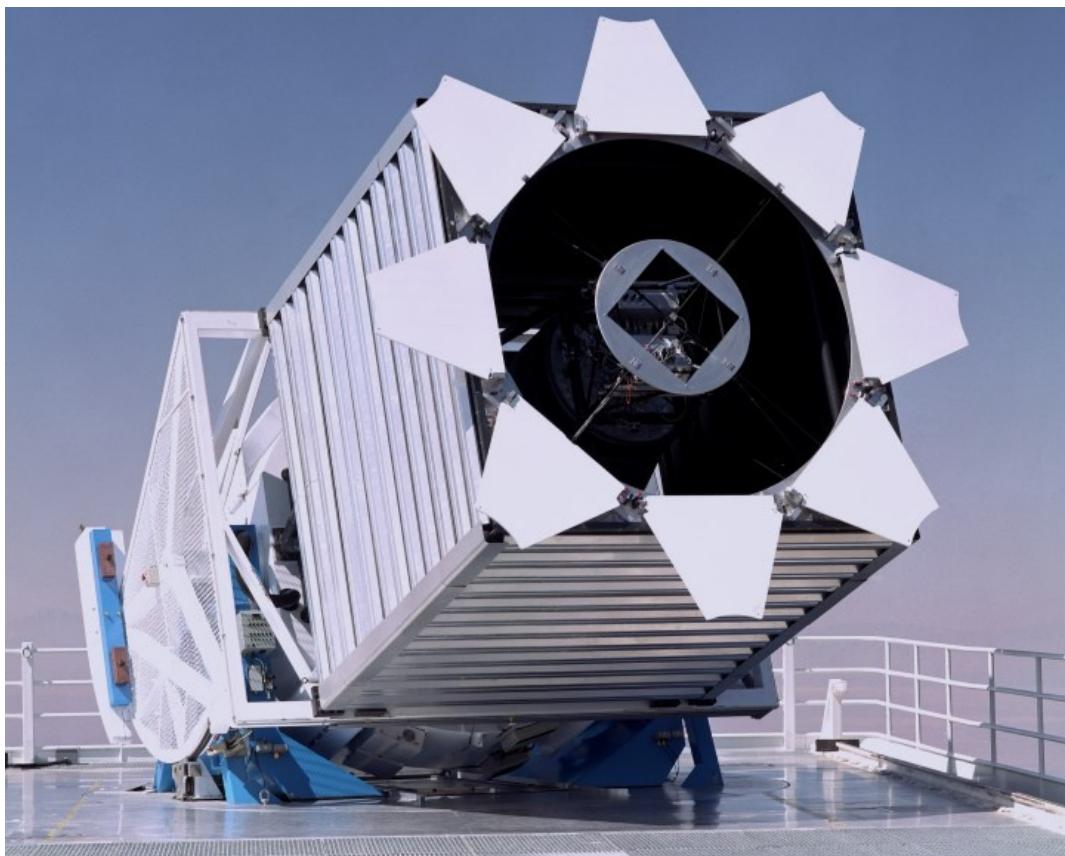
# How to measure the BAO ?

- Measure the separation distance between structures (galaxies, qsos, clouds ..) and compute the 2-point correlation function between matter density field
- The signal is weak : large amount of data

$$r_s = \int_0^{z_{dec}} \frac{dz}{H(z)} \frac{c}{\sqrt{3(1 + \frac{3\rho_b}{4\rho_\gamma})}}$$

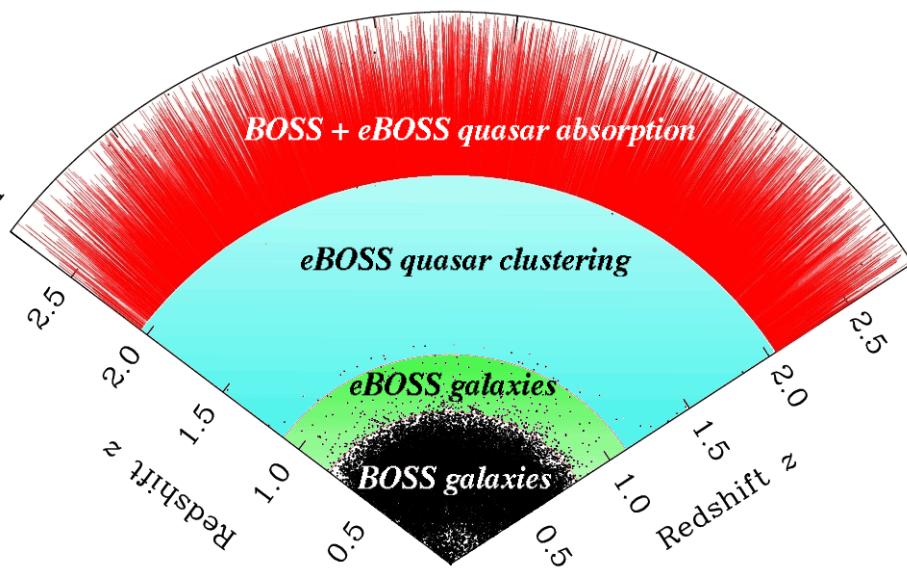


# The SDSS survey



- Most detailed 3d maps of the Universe ever made
- 2.5m Telescope at Apache Point Observatory
- 4 experiments :  
**BOSS/eBOSS**  
APOGEE  
MaNGA  
MARVELS

# The eBOSS experiment



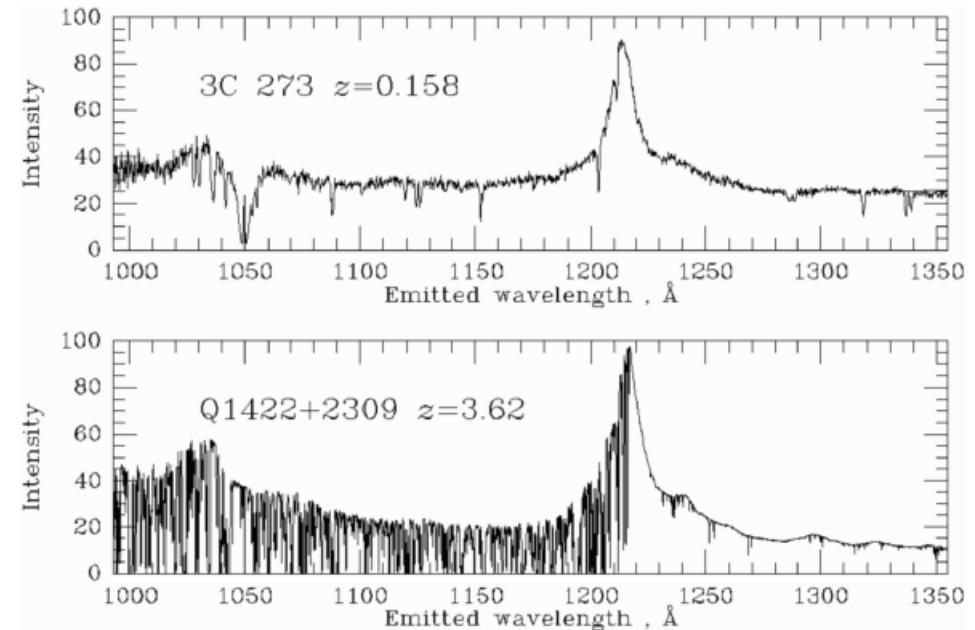
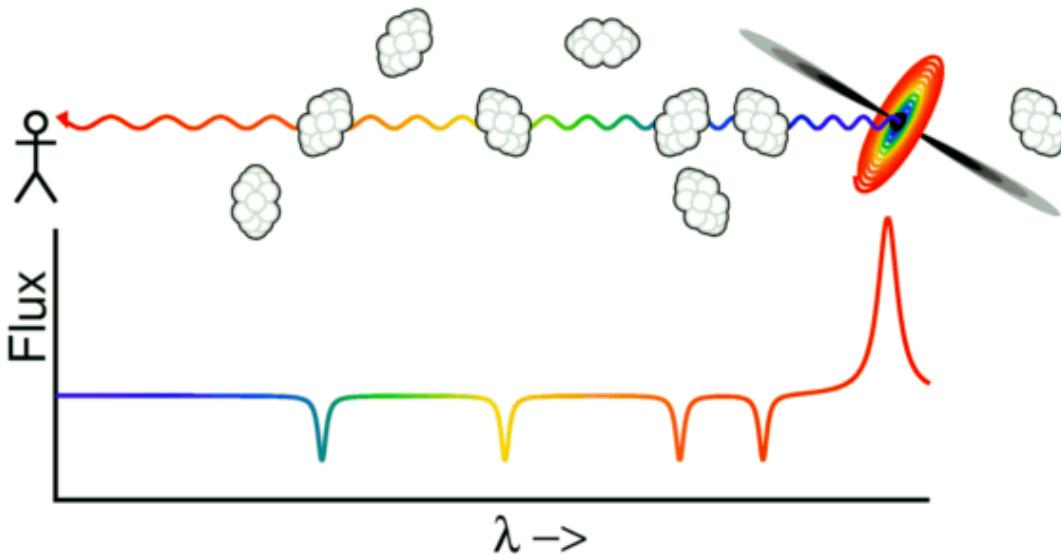
- 2014 – 2020

DR14 :

~ 200 000 high redshift  
quasars ( $2 < z < 4$ )

→ Measuring the BAO peaks with different mass tracers  
(galaxies, quasars, absorbers ...)

# Ly forests as mass tracers

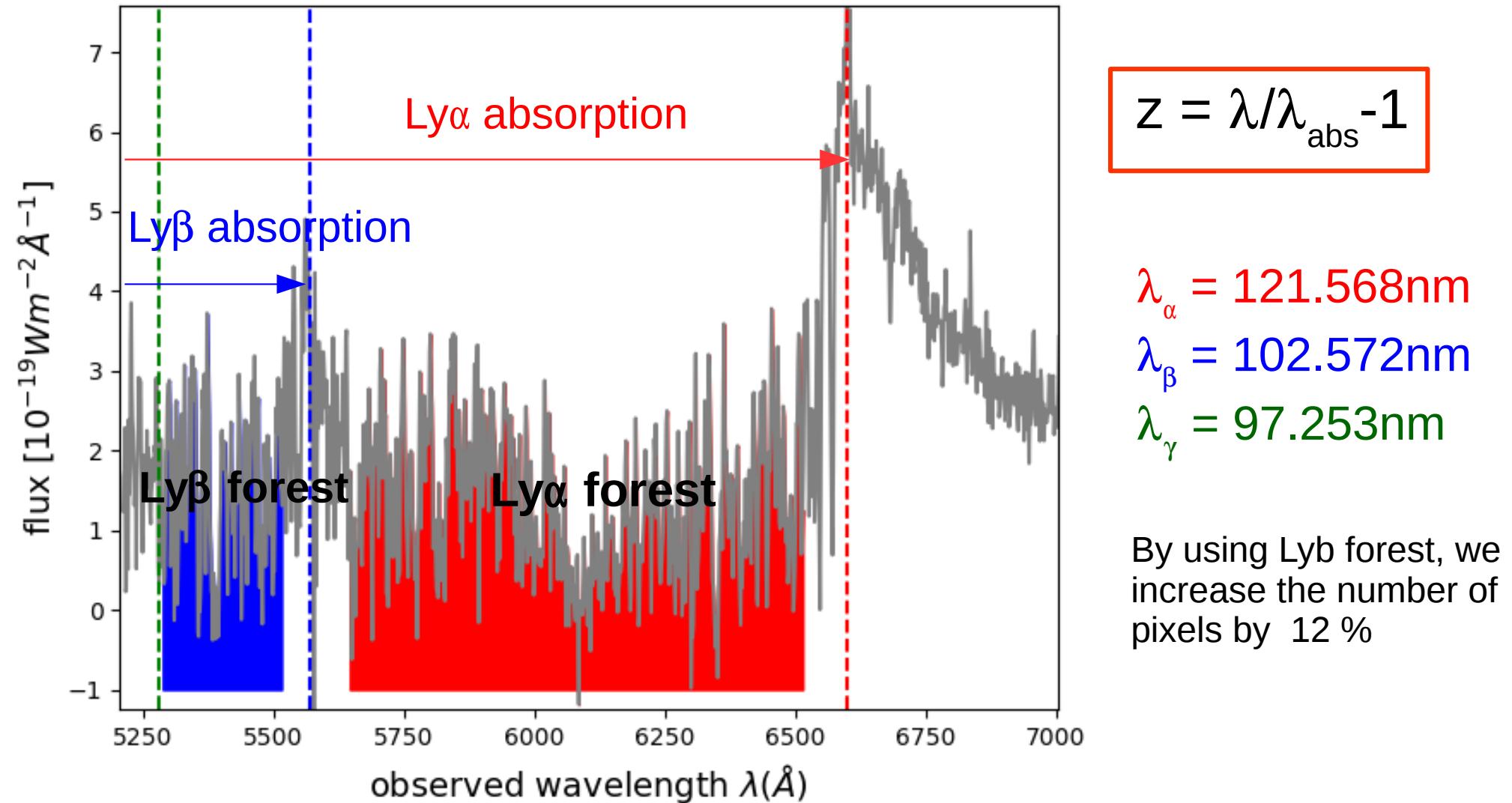


If wavelength  $\lambda_{\text{abs}}$  is absorbed in a cloud at redshift  $z$ , the absorption is redshifted and observed at  $\lambda = \lambda_{\text{abs}}/(1+z)$

→ the cloud redshift is :

$$z = \lambda/\lambda_{\text{abs}} - 1$$

# Spectrum of a quasar at $z = 3.29$



- Hydrogen is the most common element in the Universe
- The light emitted by the quasar passes through lots of H clouds : absorption line = cloud

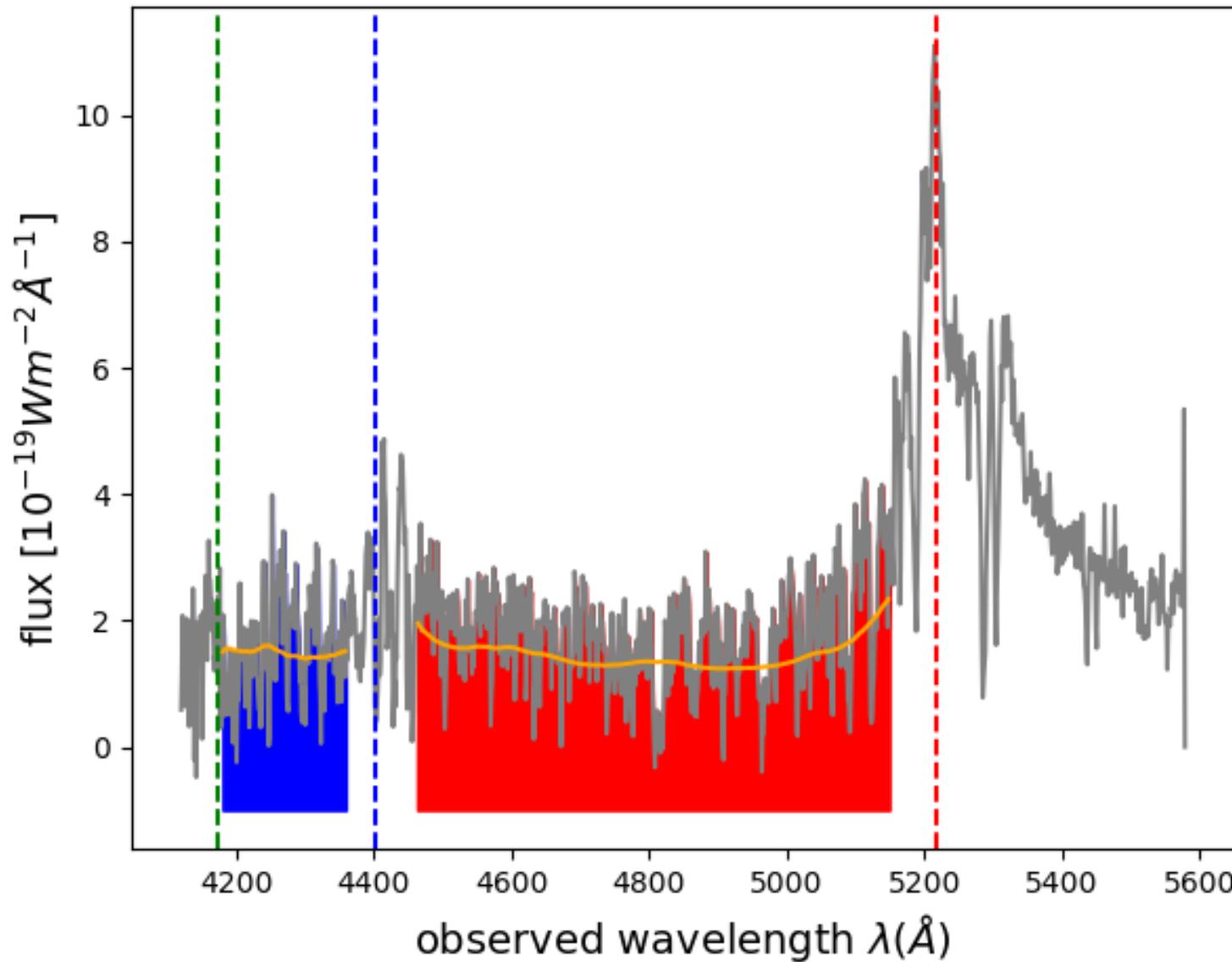
# 4) Compute the correlation function

3 steps :

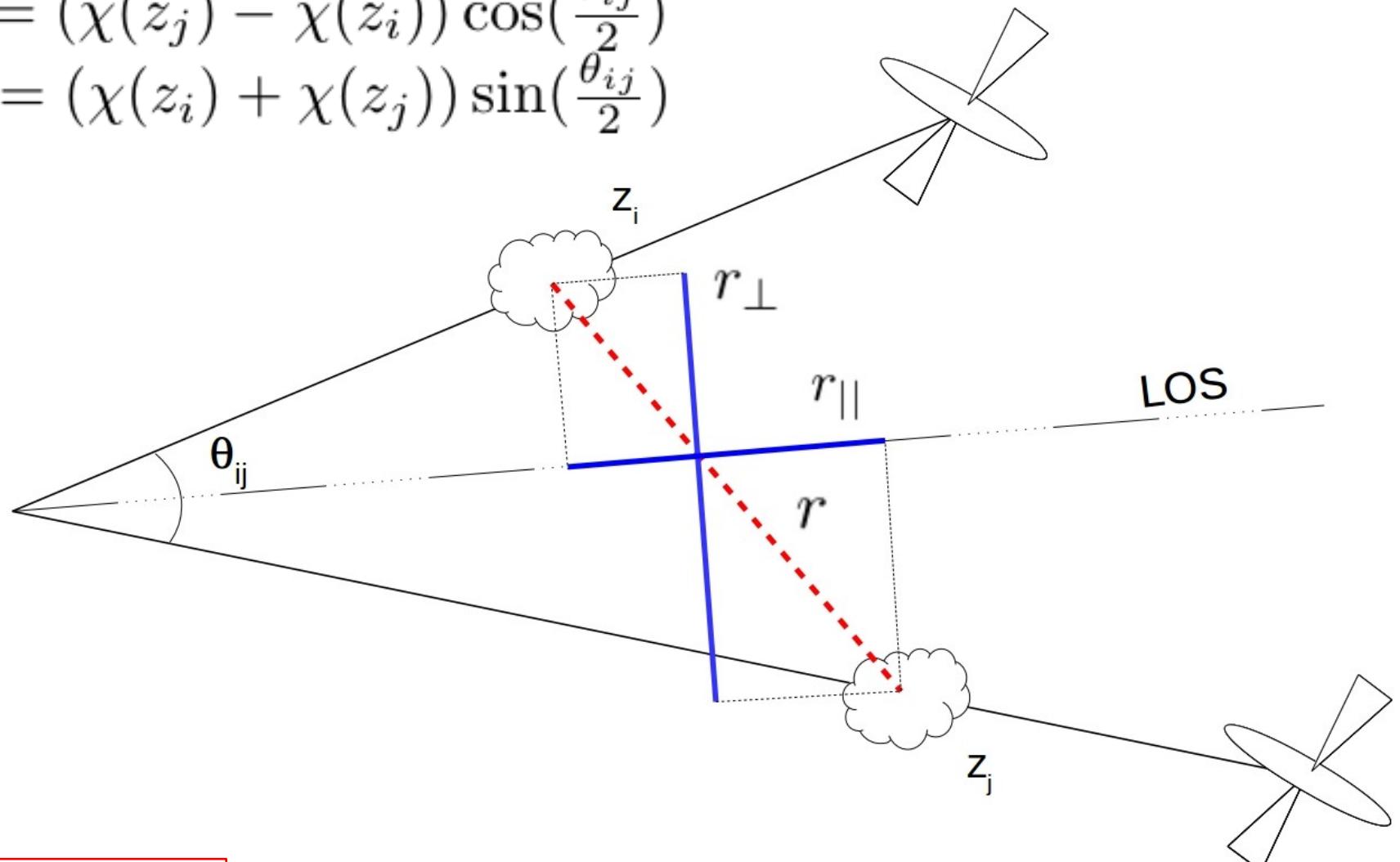
1. Extract the absorption field  $\delta_q(\lambda)$  of every forest
2. Define the separation distances
3. Compute the correlation function

# 1. Extract the density field $\delta_q(\lambda)$ of every forest

$$f_q(\lambda) = \boxed{C_q(\lambda)}(1 + \delta_q(\lambda)).$$



$$\begin{cases} r_{||} = (\chi(z_j) - \chi(z_i)) \cos\left(\frac{\theta_{ij}}{2}\right) \\ r_{\perp} = (\chi(z_i) + \chi(z_j)) \sin\left(\frac{\theta_{ij}}{2}\right) \end{cases}$$

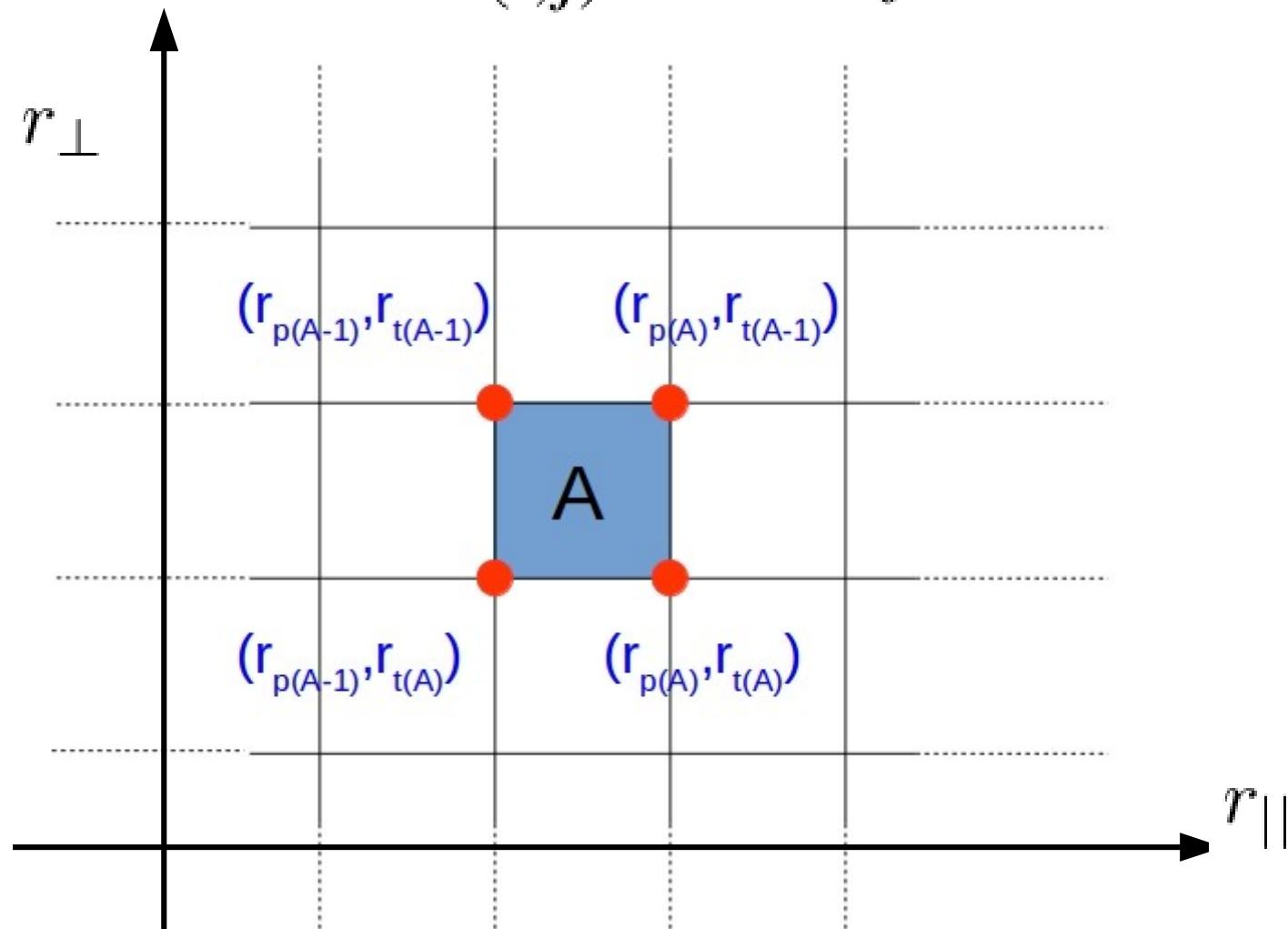


$$z = \lambda / \lambda_{\text{abs}} - 1$$

20

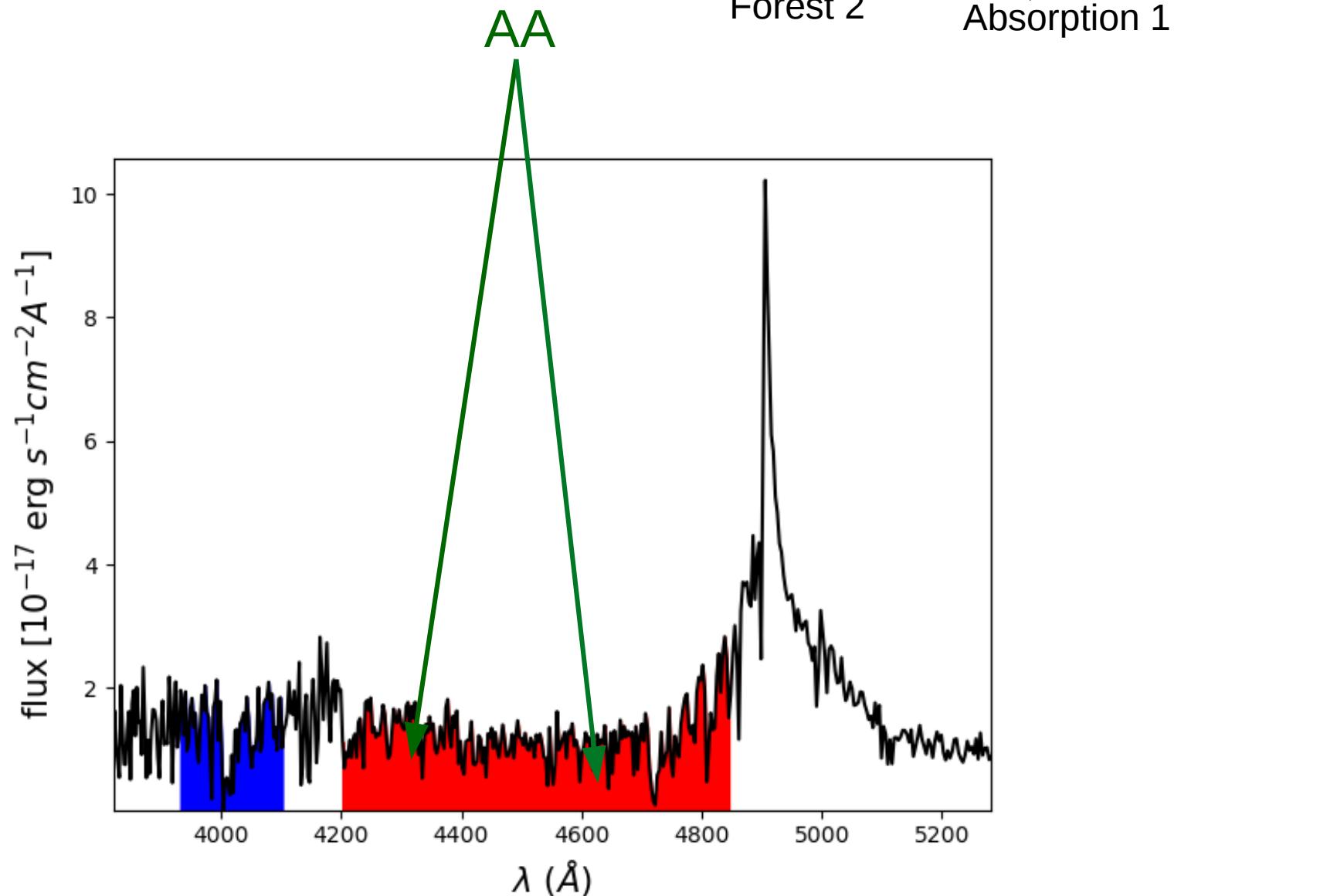
### 3. The correlation function

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

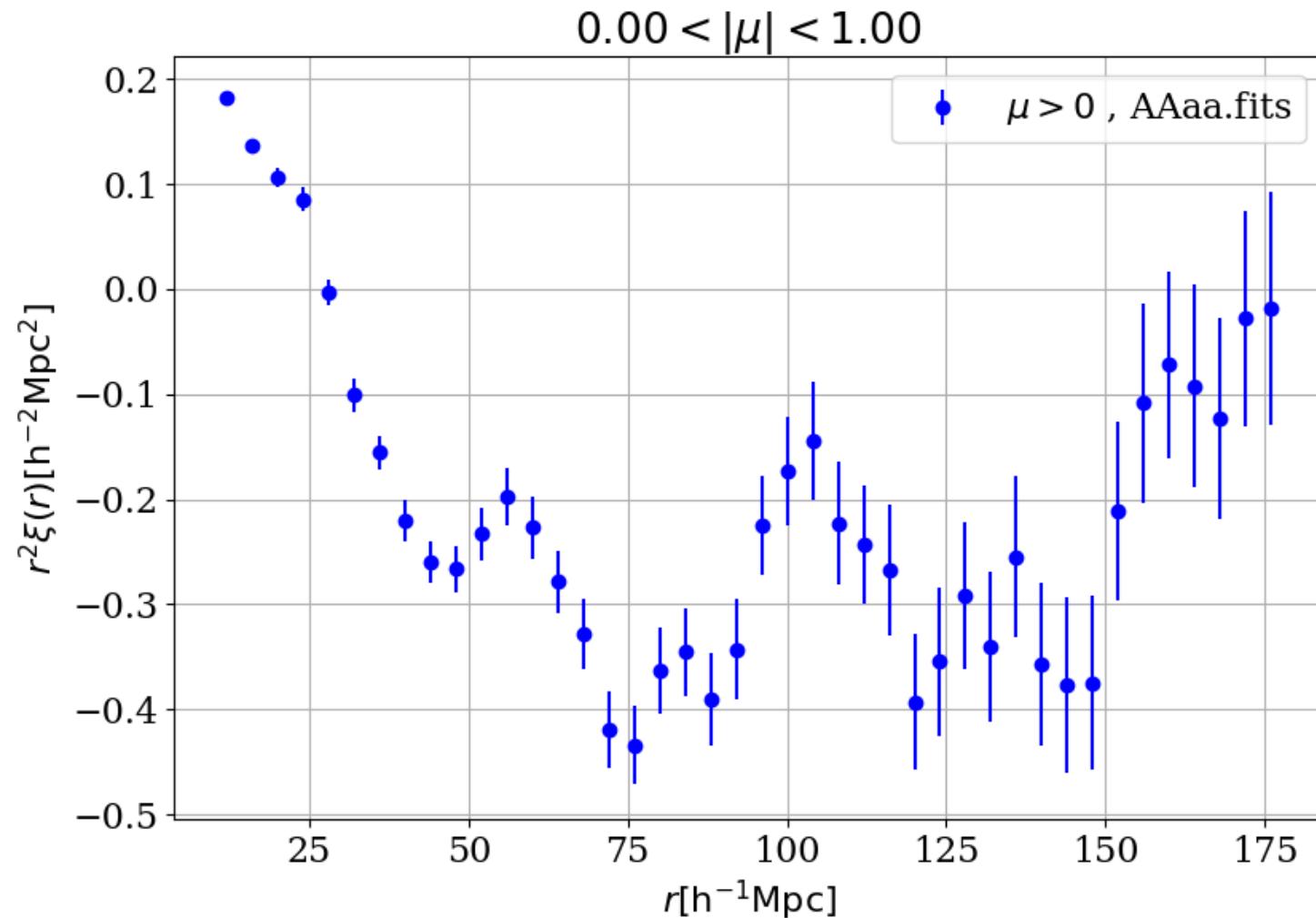


# Ly $\alpha$ autocorrelation function AA(aa)

e.g. : Bautista et al., 2017

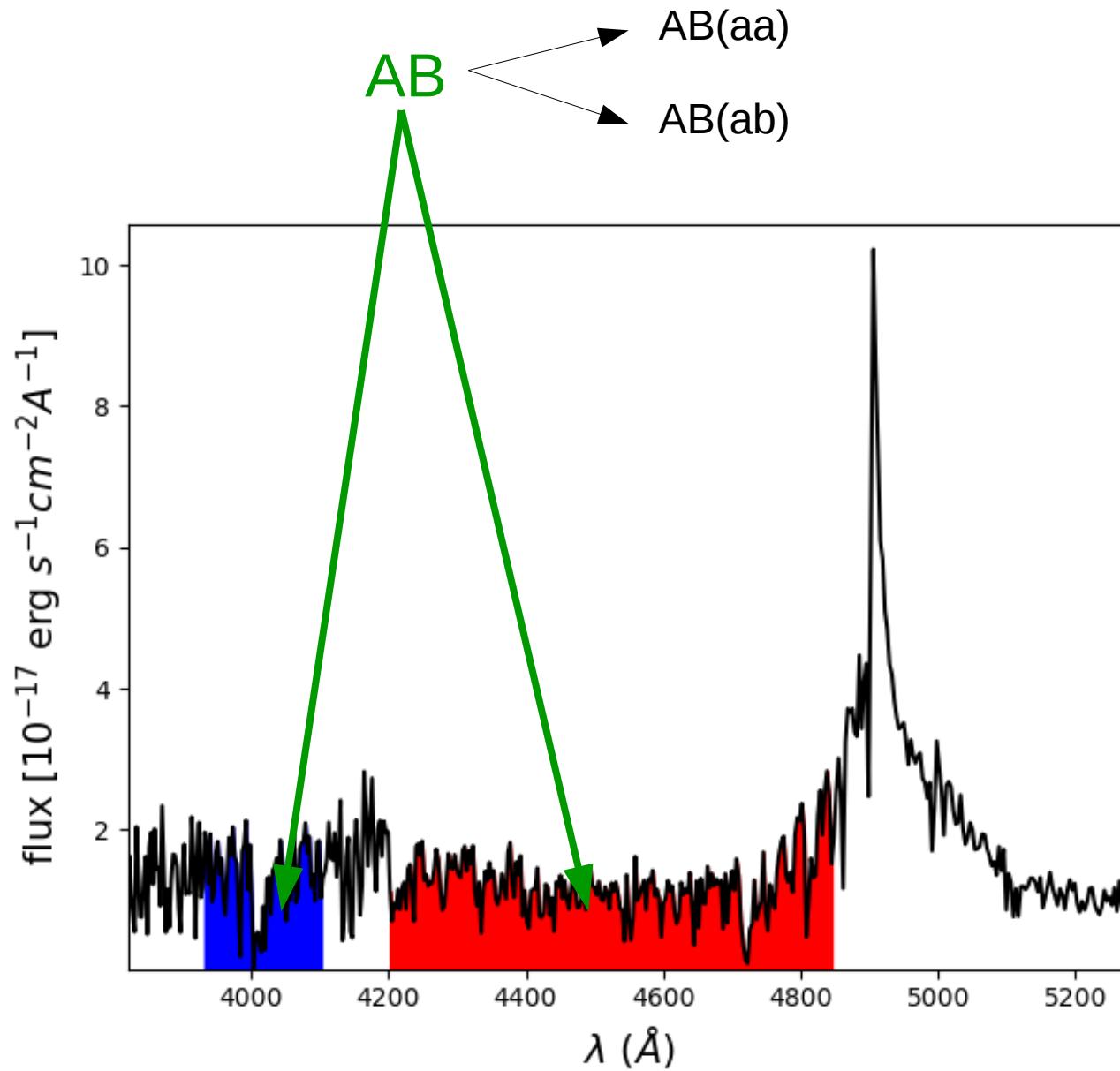


# Lya auto-correlation function



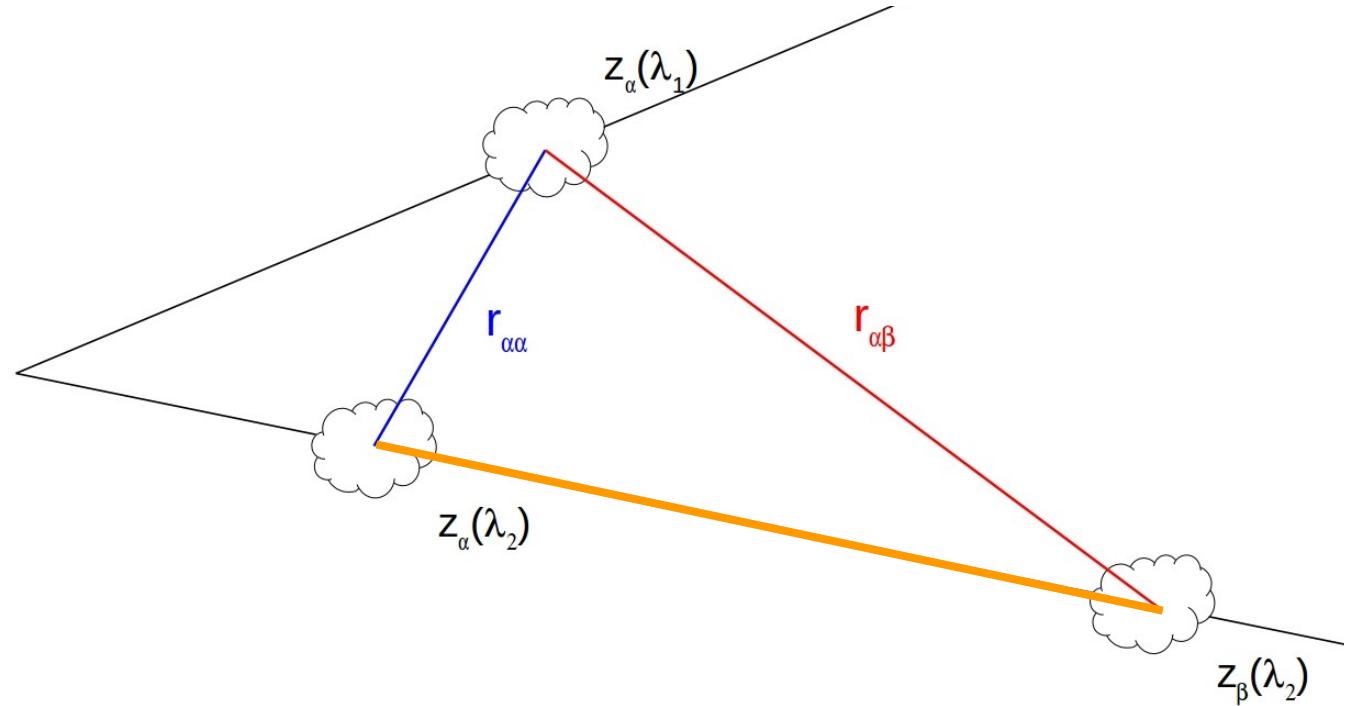
# Ly $\alpha$ -Ly $\beta$ correlation function AB(aa) and AB(ab)

In Ly $\beta$  forest, we observe both the Ly $\alpha$  and Ly $\beta$  absorptions



$$r_{p,\alpha\alpha}(\lambda_1, \lambda_2) = (\chi(z_\alpha(\lambda_1)) - \chi(z_\alpha(\lambda_2))).$$

$$r_{p,\alpha\beta}(\lambda_1, \lambda_2) = r_{p,\alpha\alpha}(\lambda_1, \lambda_2) - (\chi(z_\beta(\lambda_2)) - \chi(z_\alpha(\lambda_2)))$$

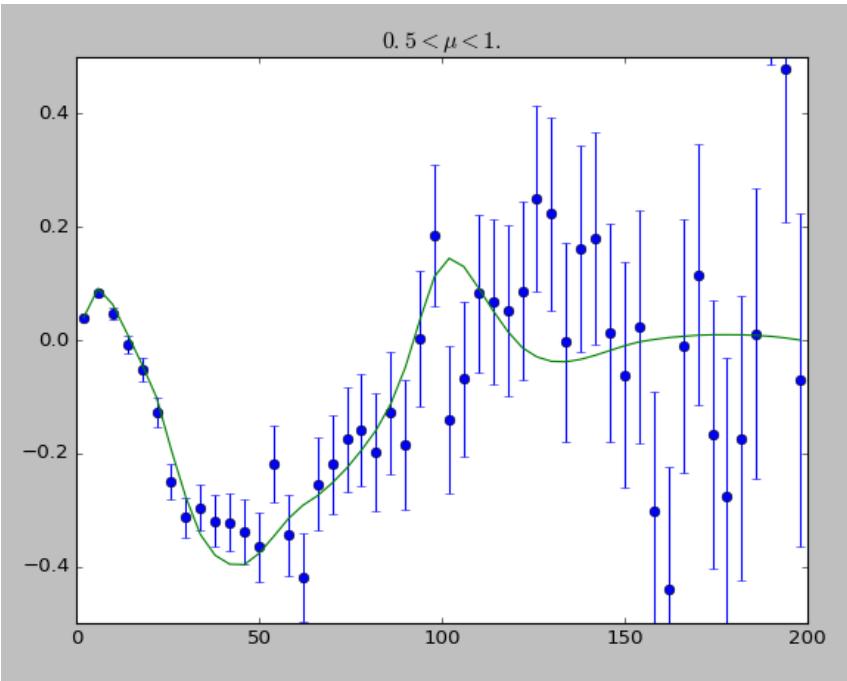
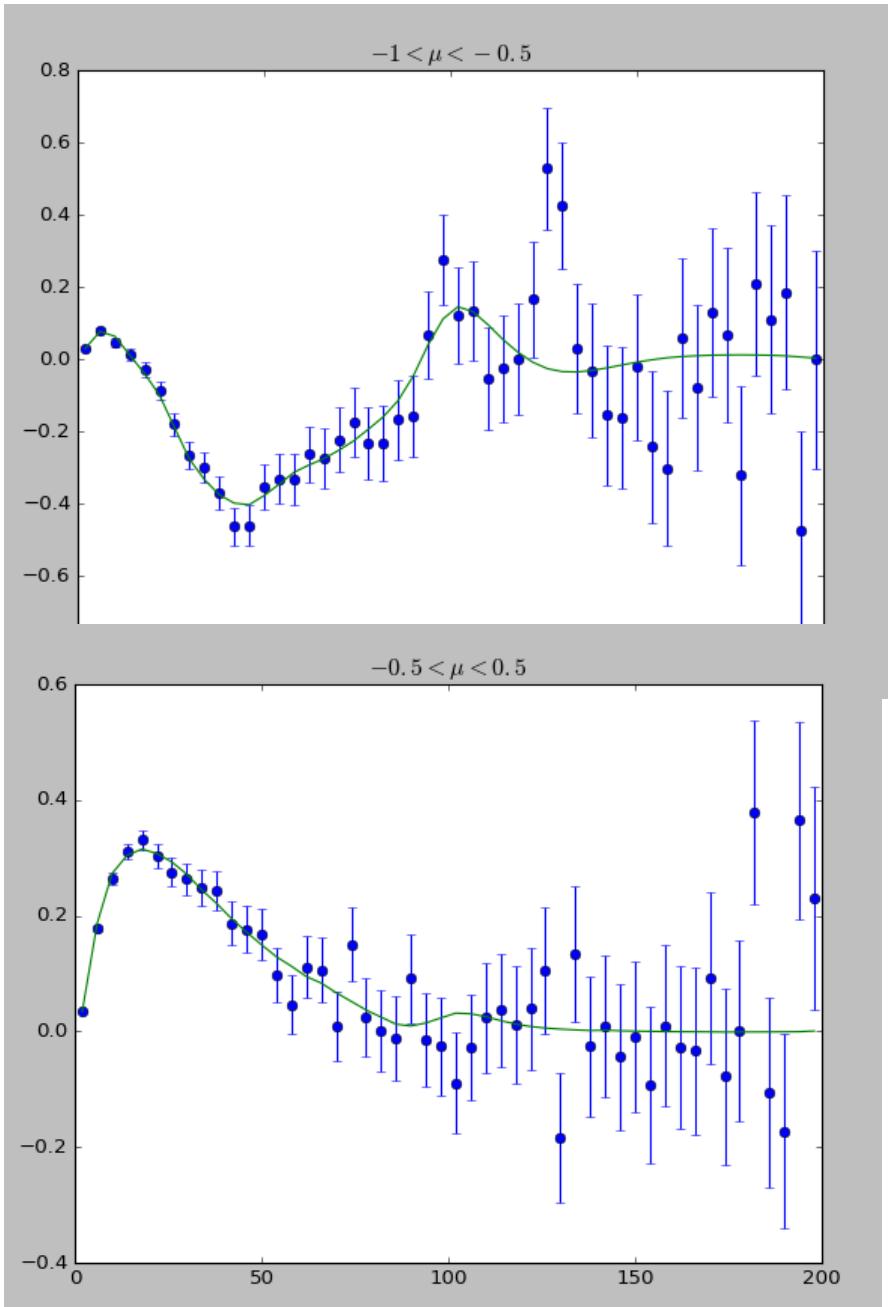


Study window :

$$r_p \text{ in } [-200h^{-1}\text{Mpc}, 200h^{-1}\text{Mpc}]$$

$$\left. \begin{aligned} & 430h^{-1}\text{Mpc} < \chi_\beta(\lambda) - \chi_\alpha(\lambda) < 525h^{-1}\text{Mpc} \\ & r_{p,\alpha\alpha}(\lambda_1, \lambda_2) \in [-200h^{-1}\text{Mpc}, 200h^{-1}\text{Mpc}] \end{aligned} \right\} \rightarrow -725h^{-1}\text{Mpc} < r_{p,\alpha\beta}(\lambda_1, \lambda_2) < -230h^{-1}\text{Mpc}.$$

# 25 Correlation between ly<sub>a</sub> in ly<sub>a</sub> forest and ly<sub>a</sub> in ly<sub>b</sub> forest AB(aa)



$$\mu = \frac{r_{||}}{r}$$

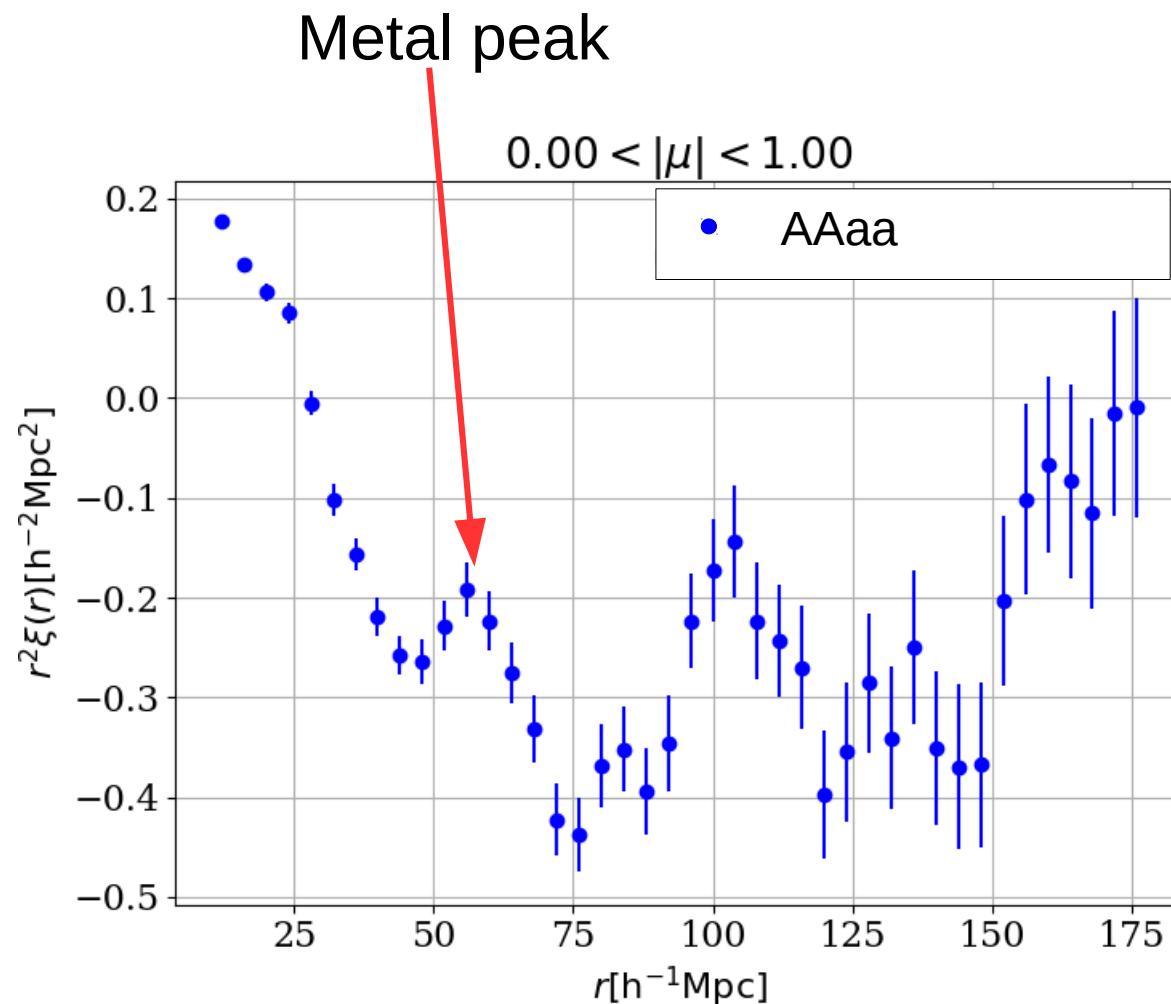
# Fitting the correlation functions

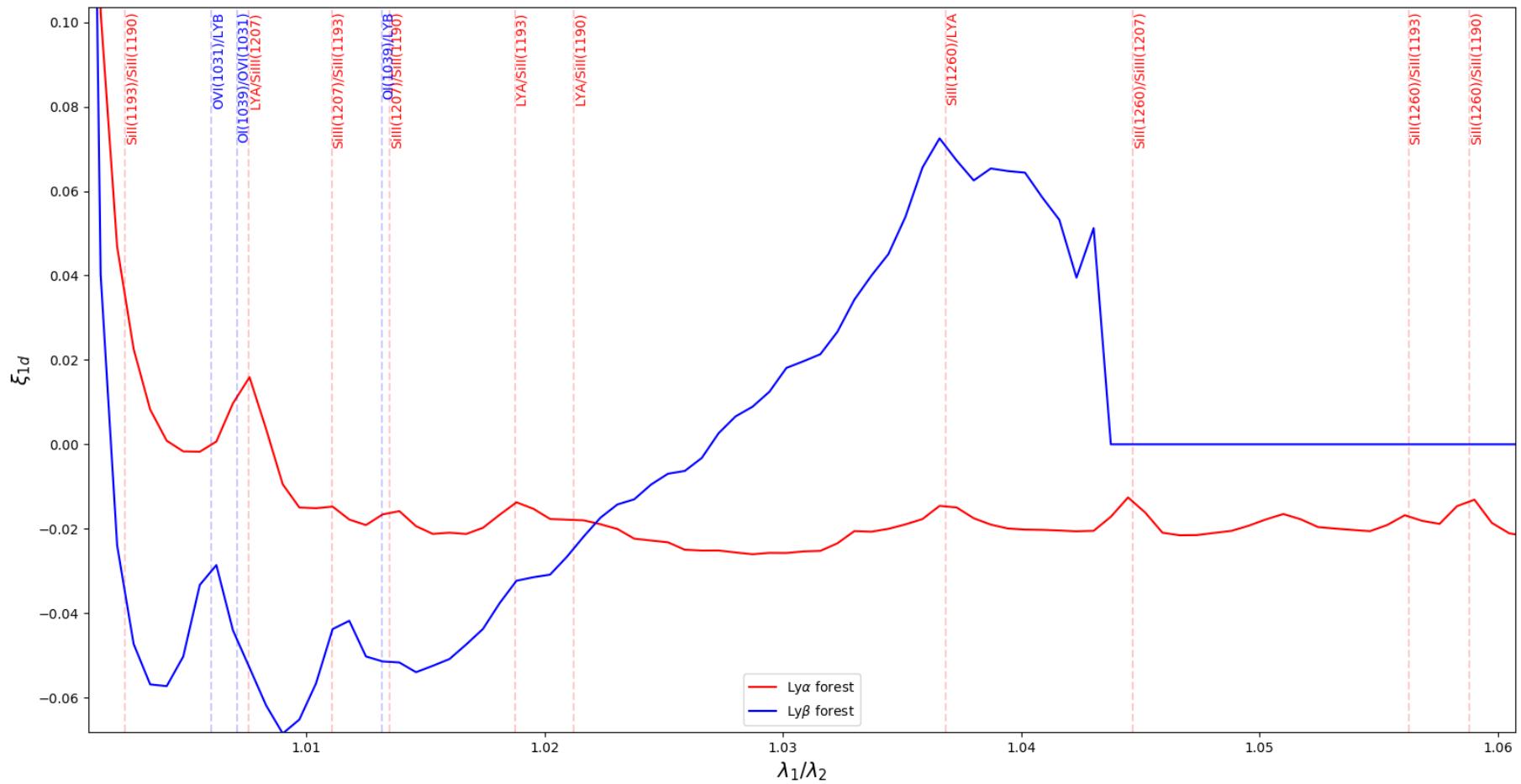
- Matter power spectrum extracted from the CMB
- $\Lambda$ CDM model with 6 parameters (Planck Collaboration, 2015)

# Fitting the correlation functions

1) Matter PS with Planck

2) Metals

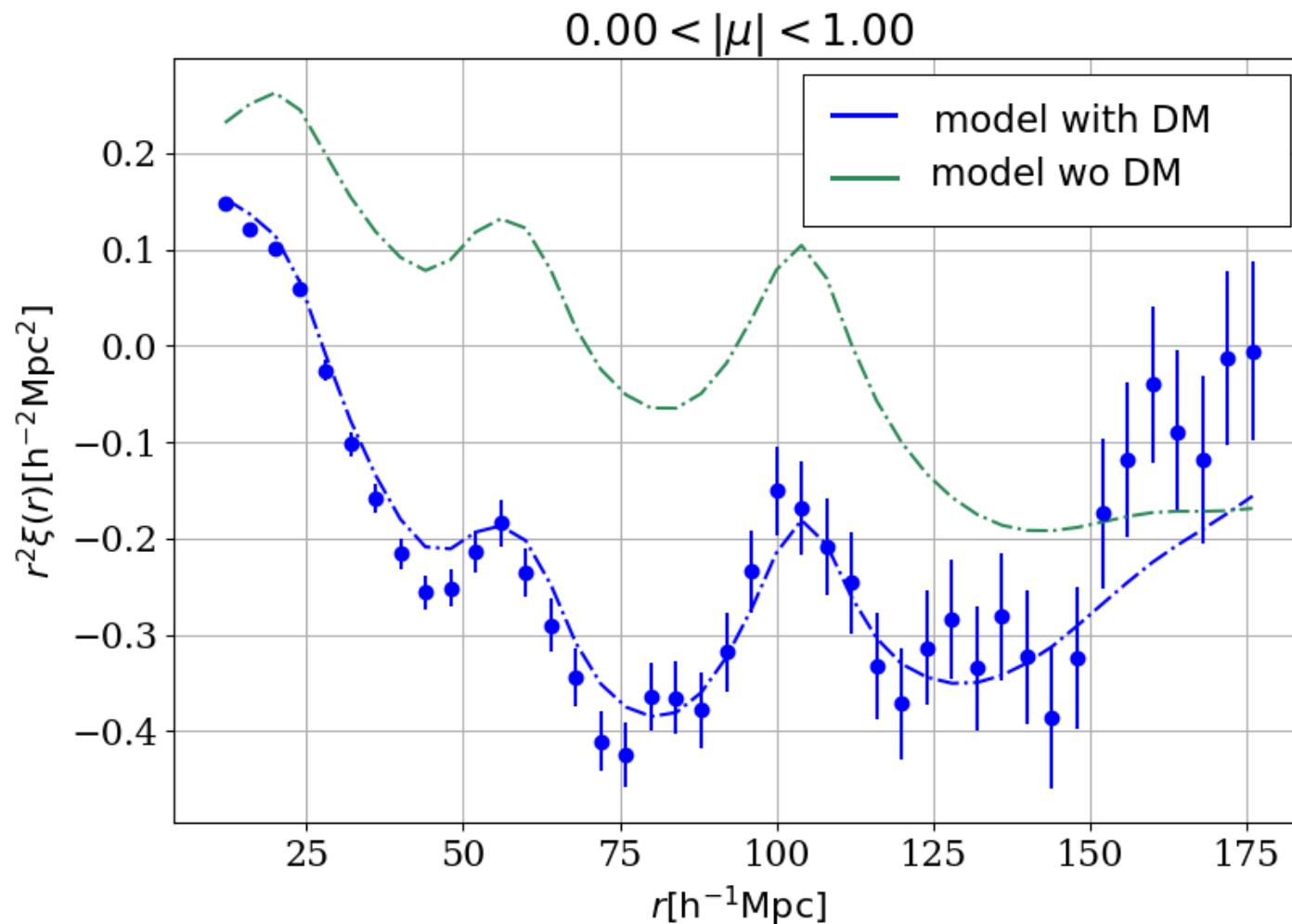




→ We compute the 1d CF to find the metals in every forest

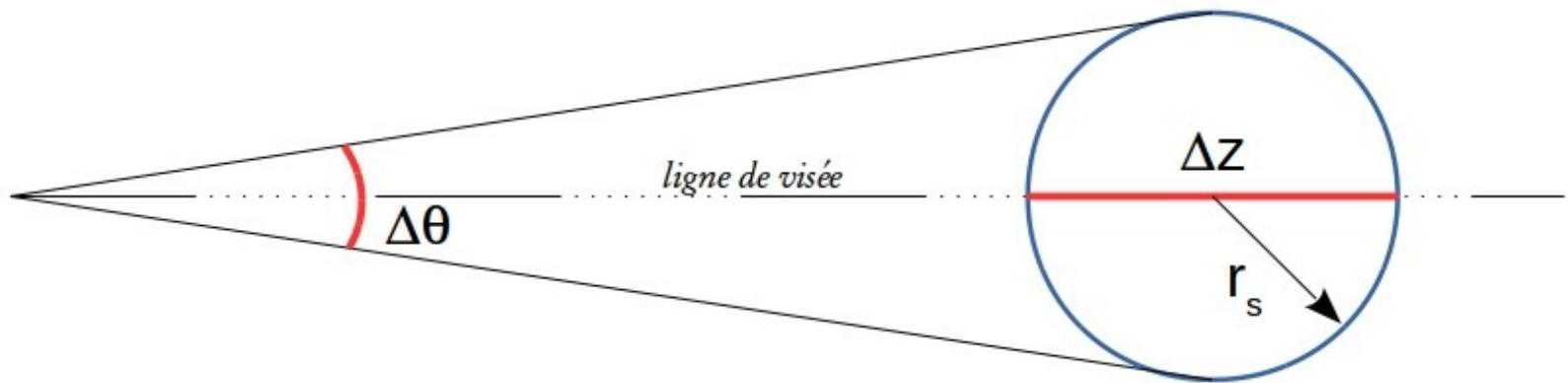
# Fitting the correlation functions

## 3) Effect due to the continuum fitting



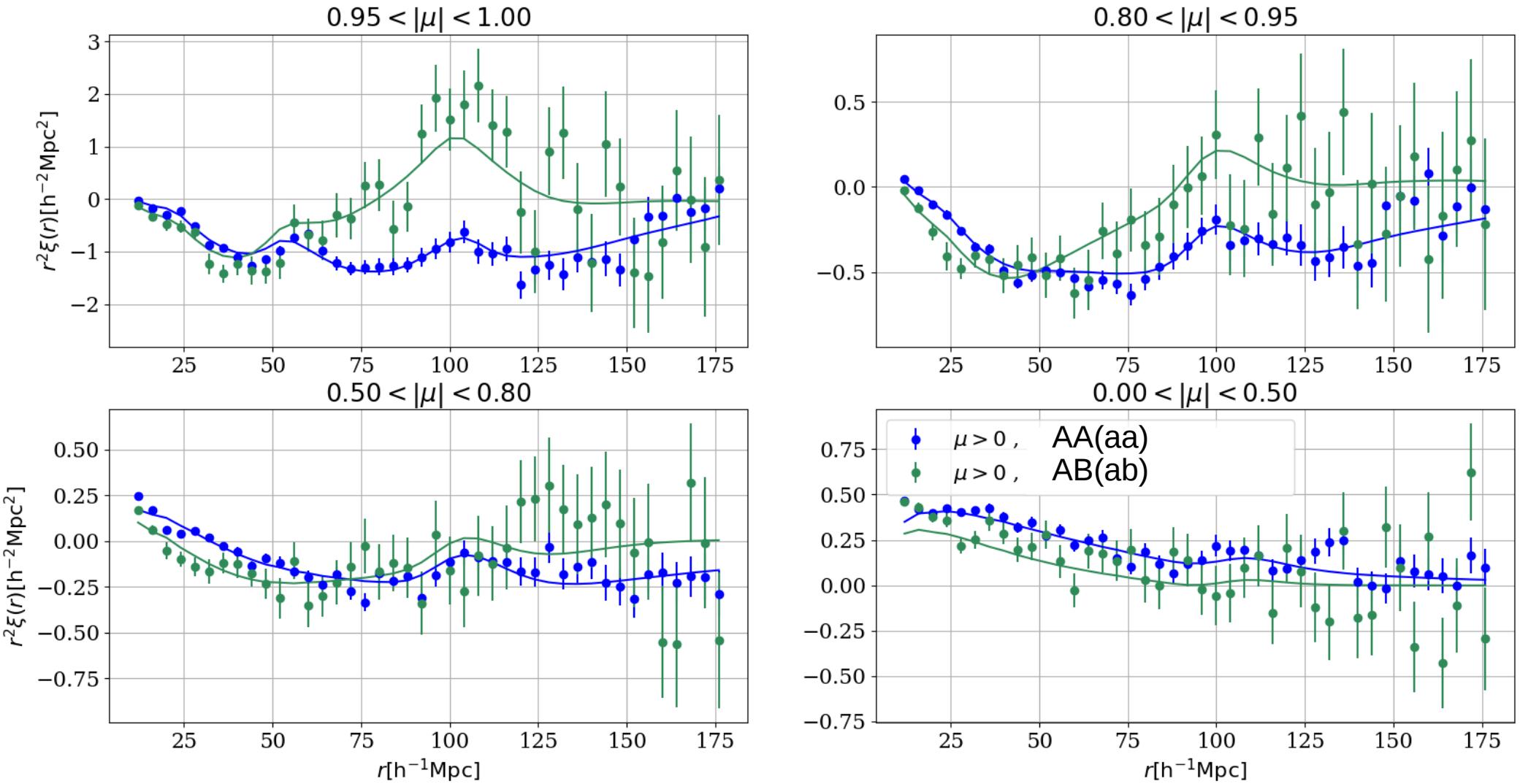
# Fitted parameters

→ 26 parameters for the ly $\alpha$  auto-correlation (bias, b, HCD parameters, UV parameters ...)



$$\left\{ \begin{array}{l} \alpha_p = \frac{[\Delta\theta(z)]_{measured}}{[\Delta\theta(z)]_{fiducial}} \\ \alpha_t = \frac{[\Delta z]_{measured}}{[\Delta z]_{fiducial}} \end{array} \right. \iff \left\{ \begin{array}{l} \alpha_p = \frac{[D_H(z)/r_s]_{measured}}{[D_H(z)/r_s]_{fiducial}} \\ \alpha_t = \frac{[D_M(z)/r_s]_{measured}}{[D_M(z)/r_s]_{fiducial}} \end{array} \right.$$

# Results for AA(aa) and AB(aa)



→ We use a combined fit with AA(aa) and AB(aa) data

# Comparaison

AA(aa) only

```

alpha_SiIII(1207) [ 1.  0.01]
ap [ 1.01374271  0.02745198]
beta_SiIII(1207) [ 0.5  0.01]
at [ 0.97965032  0.0408327 ]
beta_LYA [ 1.56875918  0.05927593]
bias_SiIII(1190) [-0.00145877  0.00030212]
L0_lls [ 14.34797611  0.49327832]
bias_SiIII(1207) [-0.00439474  0.00039056]
alpha_SiIII(1193) [ 1.  0.01]
beta_SiIII(1260) [ 0.5  0.01]
bias_lls [-0.0331132  0.00174303]
bias_gamma [ 0.10623863  0.05401143]
per_binsize_AAaa [ 4.  0.4]
alpha_SiIII(1260) [ 1.  0.01]
beta_SiIII(1193) [ 0.5  0.01]
growth_rate [ 0.962524  0.1      ]
lambda_uv [ 300.  10.]
alpha_LYA [ 2.9  0.1]
bias_LYA [-0.21159585  0.00391295]
```

```

fval 1569.63489318
ndata 1590
npar 26
```

AA(aa) + AB(aa)

```

alpha_SiIII(1207) [ 1.  0.01]
ap [ 1.01830712  0.02467502]
beta_SiIII(1207) [ 0.5  0.01]
at [ 0.98262227  0.04204928]
beta_LYA [ 1.56502825  0.12256053]
bias_SiIII(1190) [-0.00136422  0.0002727 ]
L0_lls [ 14.62048861  0.50862697]
bias_SiIII(1207) [-0.00424114  0.00035789]
alpha_SiIII(1193) [ 1.  0.01]
beta_SiIII(1260) [ 0.5  0.01]
bias_lls [-0.03056011  0.00646464]
bias_gamma [ 0.09778028  0.05379036]
per_binsize_AAaa [ 4.  0.4]
alpha_SiIII(1260) [ 1.  0.01]
beta_SiIII(1193) [ 0.5  0.01]
growth_rate [ 0.962524  0.1      ]
lambda_uv [ 300.  10.]
alpha_LYA [ 2.9  0.1]
bias_LYA [-0.21387743  0.00716951]
```

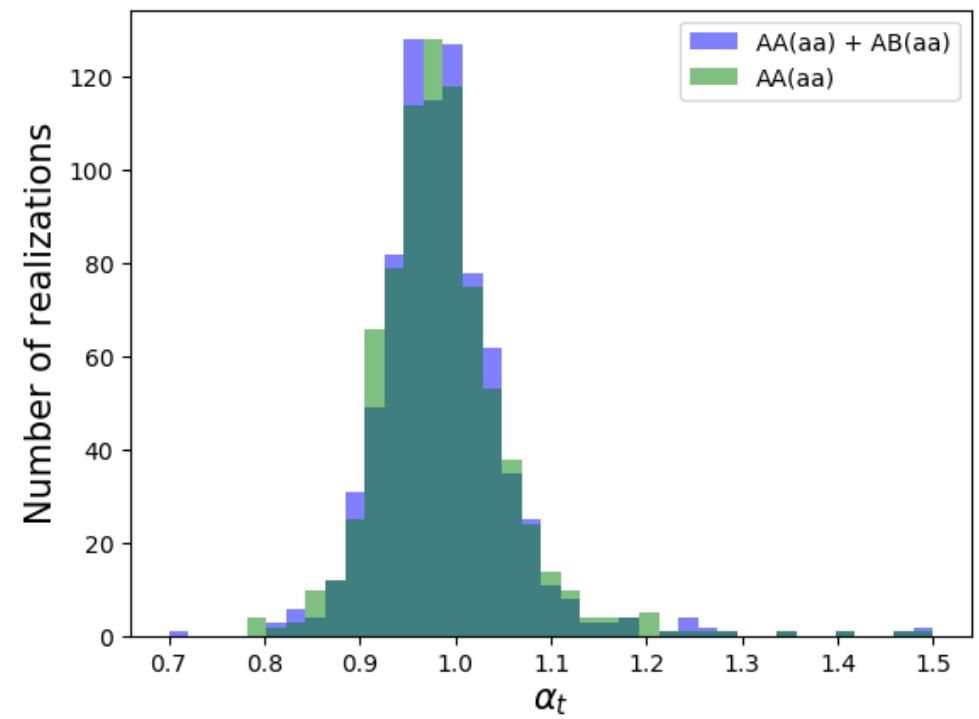
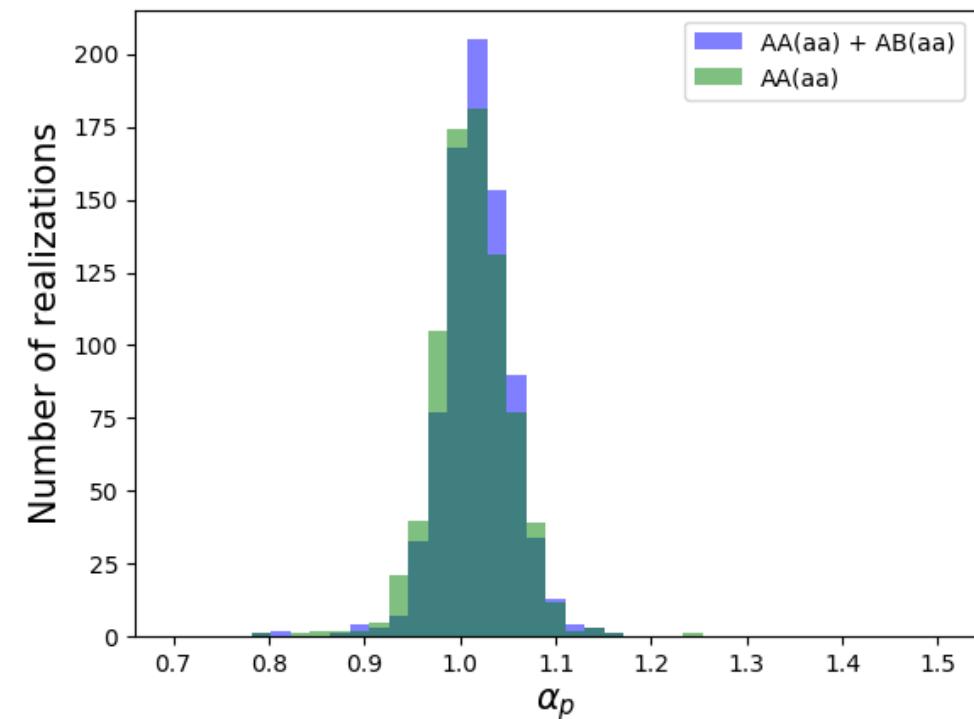
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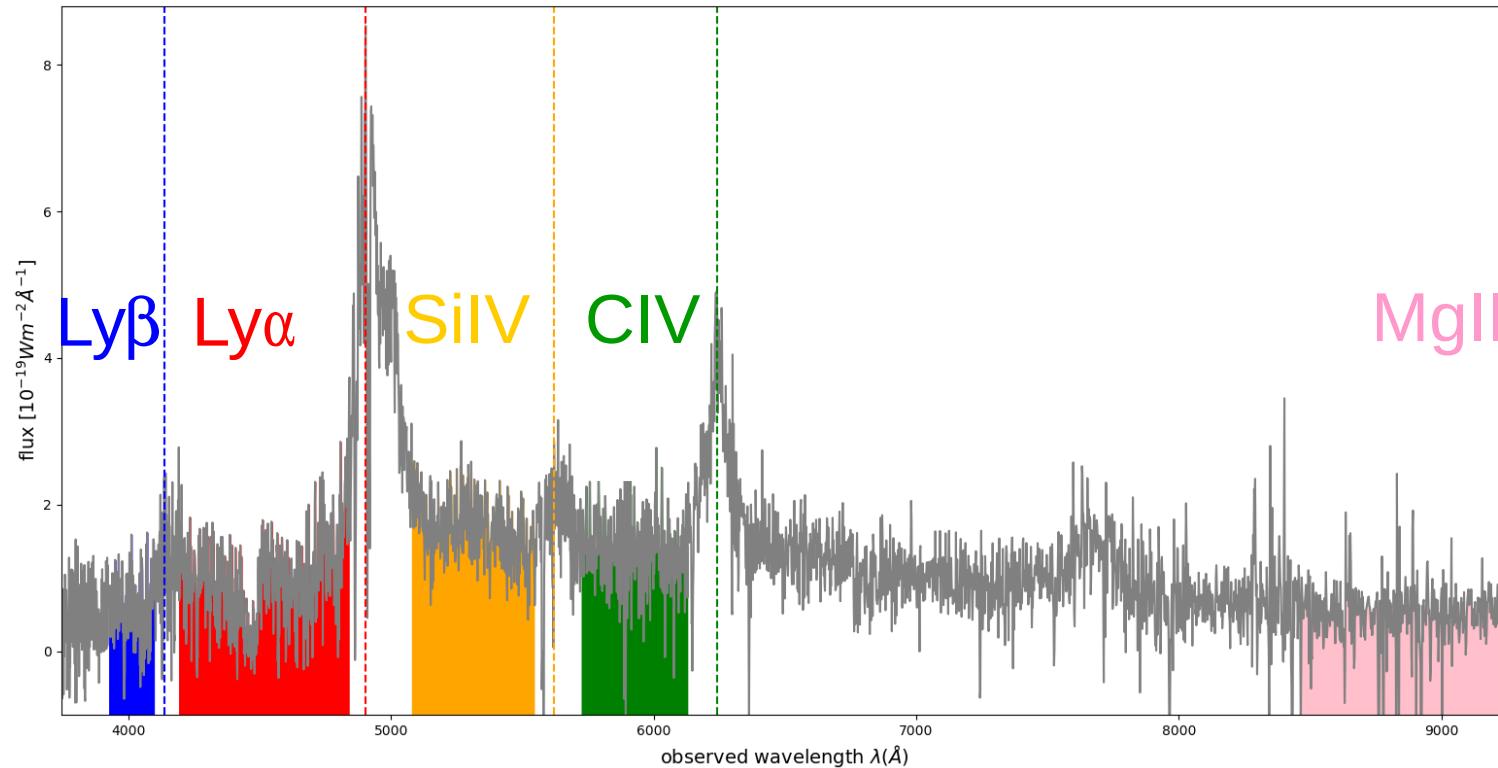
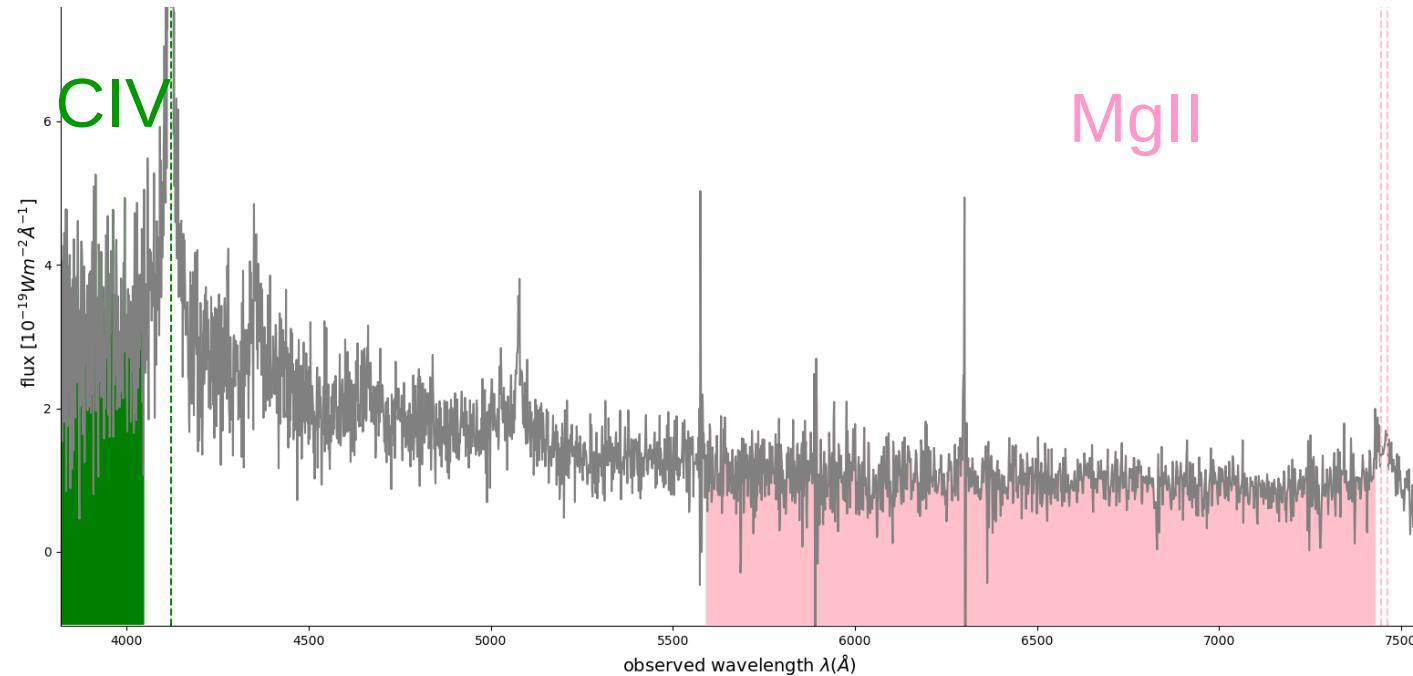
fval 4776.71772286
ndata 4770
npar 28
```

By using AB(aa) we have increased the number of pairs of pixels by 12 %

→ The error bar should have decrease by 6 %

# MC simulation



$Z = 3.03$  $Z = 1.66$ 

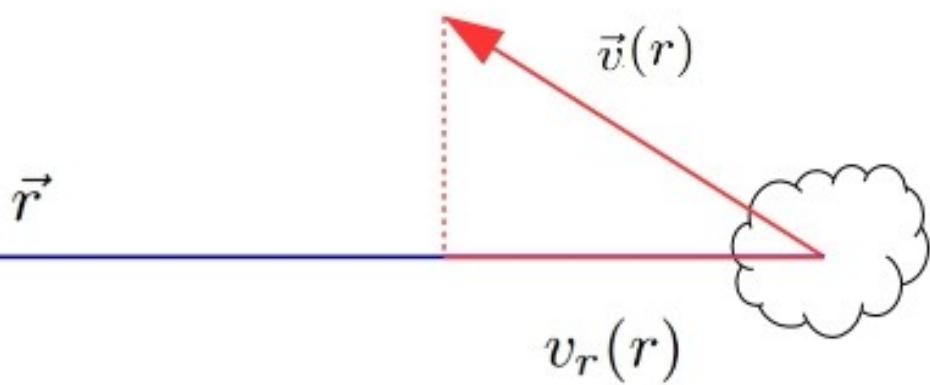
# Conclusion

- J'ai développé des codes capables de faire l'analyse complète des fonctions de corrélation entre les différentes forêts de quasars
- Il faut maintenant utiliser les autres forêts pour réaliser des fits combinés.

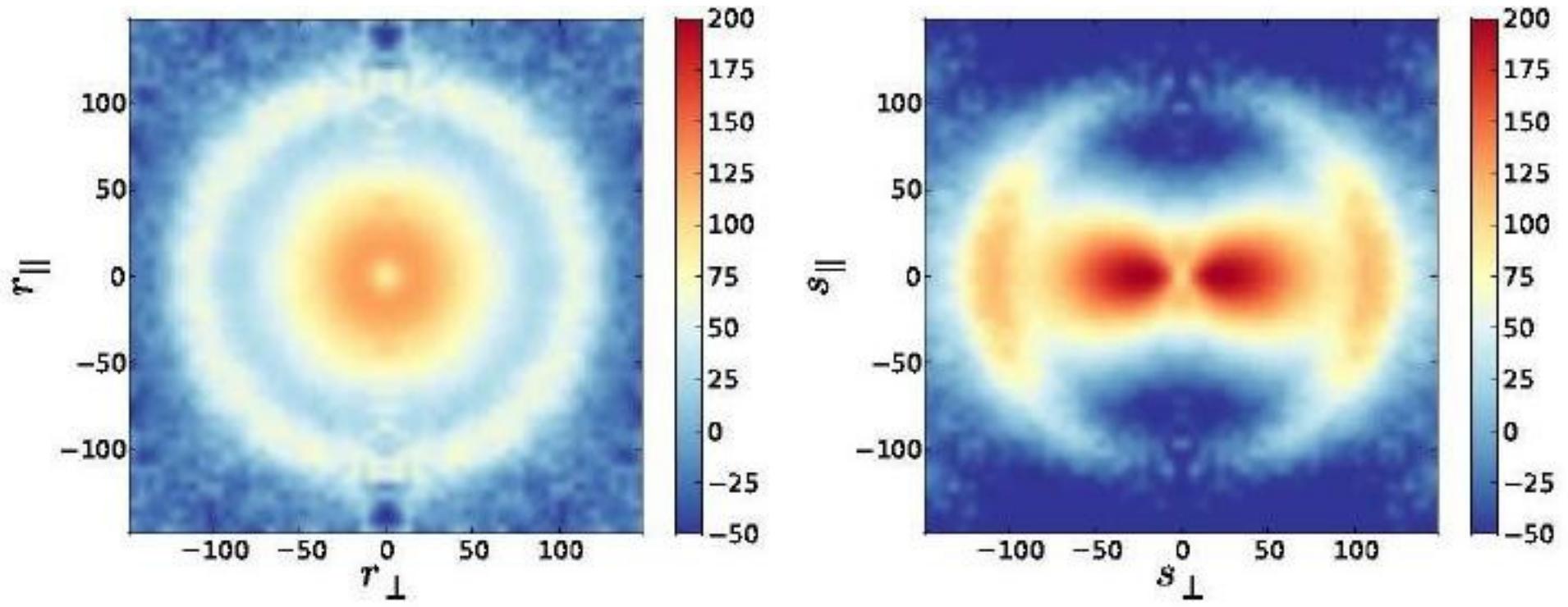
# Extra slides

## 2) Redshift space distortions : matter falls into potential wells

$$\vec{s}(r) = \vec{r} - v_r(r) \frac{\vec{r}}{r}$$



# RSD effects



Padmanabhan et al. (2012)

$$\delta^s = b(1 + \mu^2 \beta) \delta$$

$$P^s(k, \mu) = b_1 b_2 (1 + \beta_1 \mu^2) (1 + \beta_2 \mu^2) P^r(k)$$

$$\mu = \frac{r_{\parallel}}{r_{\perp}}$$