

Mapping the young Universe

Joan Doria Ribera

Supervised by Laura Casas and Carles Sánchez, Observational Cosmology Group

IFAE Summer Fellow

Oct 14, 2026



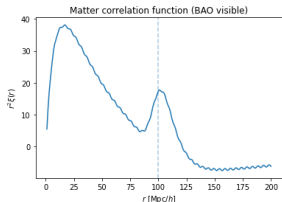
- ① Cosmology
- ② CMB lensing
- ③ Lyman- α forest
- ④ Cross-correlation
- ⑤ CoLoRe

Correlation function

- A correlation function describes the spatial distribution of a given class of objects throughout the Universe.

$$\begin{aligned}\xi(r) &= \langle \delta(x) \delta(x+r) \rangle_x \\ &= \frac{1}{V} \int \delta(x) \delta(x+r) d^3x\end{aligned}$$

- It gives the excess probability of finding two galaxies separated by a distance r compared with the probability expected if galaxies were distributed randomly with a uniform probability.



Power spectrum

- Fourier's theorem: any periodic function may be expanded into wave functions,

$$f(x) = \sum_k a_k e^{ikx},$$

where $|a_k|$ describes the amplitude of the mode.

- The **power spectrum**, $P(k) = |a_k|^2$, gives the amplitude of the fluctuations as a function of scale
- In a sphere, we use spherical harmonics, $e^{ikx} \longleftrightarrow Y_{l,m}(\theta, \phi)$.
- The **angular power spectrum** measures amplitude as a function of wavelength:

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2$$

Our cosmological model

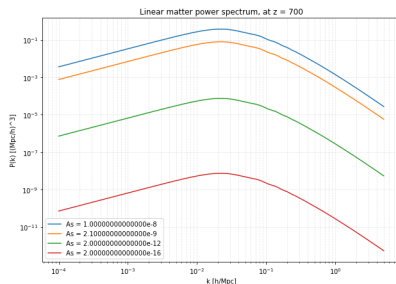
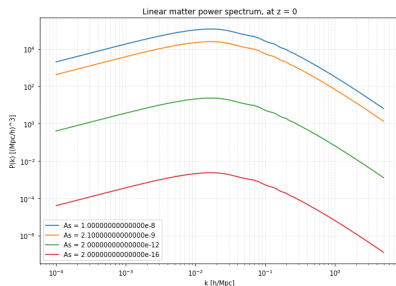
Λ CDM, Lambda Cold Dark Matter

The currently accepted standard cosmological model. It's based on the Big Bang Theory and it assumes a flat Universe.

It's described by six parameters that characterize our Universe

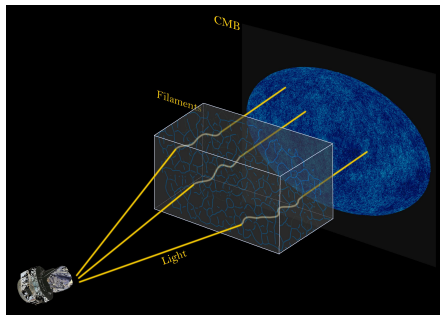
- Ω_m : matter density parameter (barions + dark matter).
- Ω_r : radiation density parameter.
- Ω_Λ : dark energy density parameter.
- H_0 : the Hubble constant.
- A_s : the amplitude of primordial scalar fluctuations (density fluctuations in the very early Universe).
- n_s : the scalar spectral index (how the amplitude of primordial density fluctuations varies with scale during inflation).

Variation of A_s , at $z = 0$ and $z = 700$.



Cosmic Microwave Background

The CMB is the microwave radiation that fills all the observable space, and it's the cooled remnant of the first light that was able to propagate freely through the Universe.



Source: Berkeley

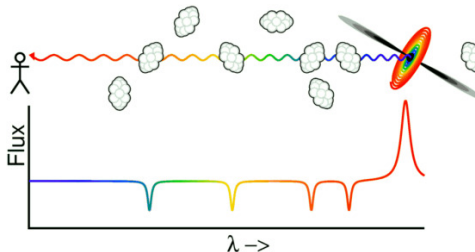
CMB Lensing

Gravity bends light. As CMB photons travel towards us from $z \approx 1100$, their paths are slightly deflected by the gravity of large structures (Dark Matter and galaxies) along the way.

Lyman Alpha Forest

Ly α

The Lyman- α forest is a collection of absorption features observed in the spectra of distant quasars, produced by neutral hydrogen in the intergalactic medium (IGM).



Source: UCLA

Fluctuation transmission field

$$\delta_{\lambda} = \frac{f_{\lambda} - C_{\lambda} \bar{F}(\lambda)}{C_{\lambda} \bar{F}(\lambda)}$$

where f_{λ} is the observed quasar flux and $C_{\lambda} \bar{F}(\lambda)$ is a smooth component. C_{λ} is the intrinsic quasar continuum and $\bar{F}(\lambda)$ is the mean transmitted flux at redshift $z = \frac{\lambda}{\lambda_{\alpha}} - 1$, where $\lambda_{\alpha} = 1215.67 \text{ \AA}$.

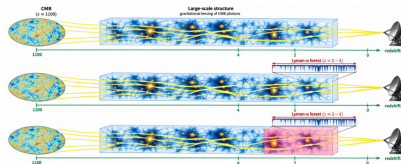
Cross-Correlation: Concept & Application

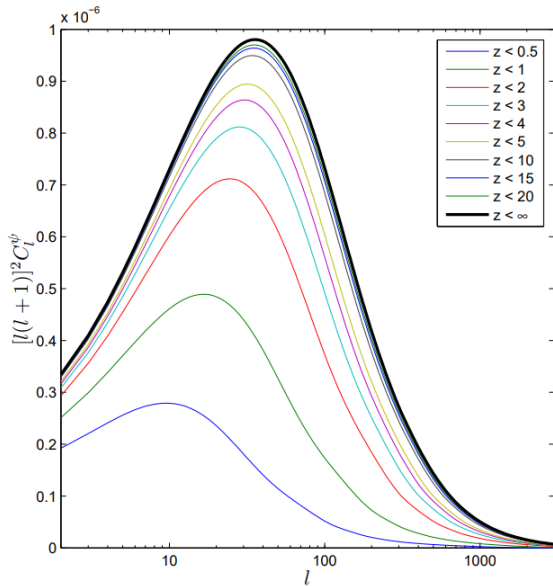
What is a Cross-Correlation?

A statistical tool that measures how strongly two tracers, A and B, respond to the same underlying structure.

- Compute the cross-power spectrum: $\tilde{C}_\ell^{AB} = \langle a_{\ell m}^A (a_{\ell m}^B)^* \rangle$.
- Useful to break degeneracy in coefficients, like with σ_8 .

- CMB lensing $\rightarrow$ Very sensitive to distortions in low-redshift scales.
- Ly α Forest $\rightarrow$ Gives information about the matter in low-redshift scales.





Source: Lewis, A., & Challinor, A.

What is CoLoRe?

CoLoRe (*Code for Large-Scale Structure Simulations*) is a fast semi-analytical tool used to generate mock cosmological datasets:

- Synthetic **Ly α** spectra.
- Synthetic **CMB lensing maps**.

Idealized Conditions

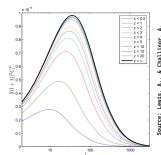
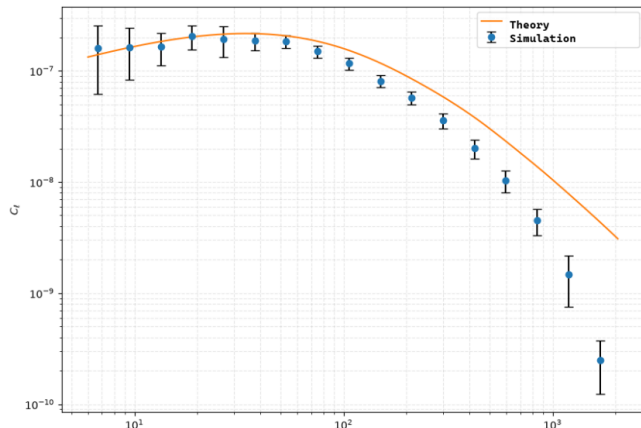
- Full-sky coverage.
- Idealized simulation framework.
- No instrumental noise.
- Free of foreground contaminants.

Fitting the simulation

Main idea: The theoretical C_l 's using CAMB should match approximately our CoLoRe simulation.

Fiducial Cosmological Parameters

$$\{\Omega_M = 0.3147, \Omega_\Lambda = 0.6853, \Omega_B = 0.04904, h = 0.6731, n_s = 0.9655, \sigma_8 = 0.8135\}$$

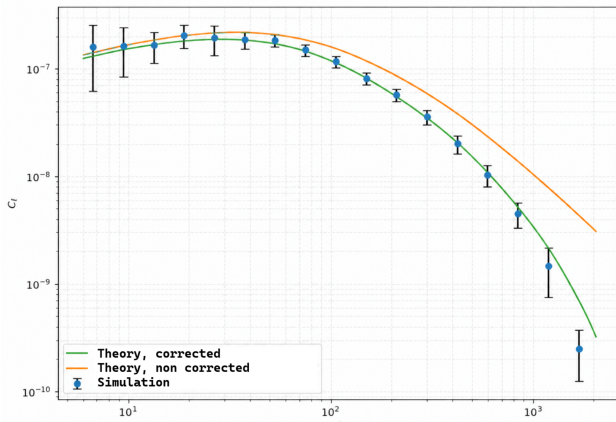


Fitting the simulation

Main idea: The theoretical C_l 's using CAMB should match approximately our CoLoRe simulation.

Fiducial Cosmological Parameters

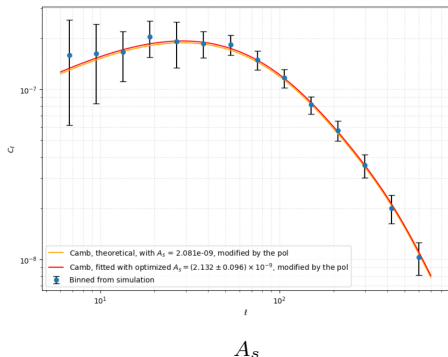
$\{\Omega_M = 0.3147, \Omega_\Lambda = 0.6853, \Omega_B = 0.04904, h = 0.6731, n_s = 0.9655, \sigma_8 = 0.8135\}$



Fitting

We create a function that takes only one of the cosmological parameters and then calculates χ^2 as

$$\chi^2 = \sum_{i=1}^N \left(\frac{D_i - M_i}{\sigma_i} \right)^2, \quad D_i = \text{interp} \left(L_i, \frac{1}{4} l^2 (l+1)^2 C_l^{\phi\phi} f_l \right)$$

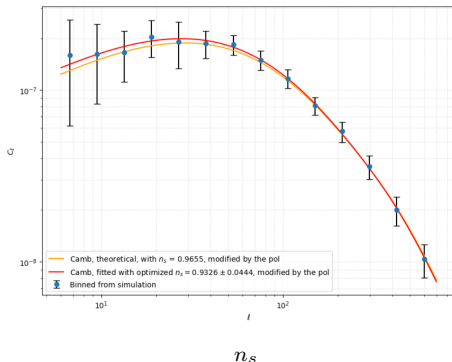


Fiducial A_s	2.081×10^{-9}
Optimized A_s	$(2.132 \pm 0.096) \times 10^{-9}$

Fitting

We create a function that takes only one of the cosmological parameters and then calculates χ^2 as

$$\chi^2 = \sum_{i=1}^N \left(\frac{D_i - M_i}{\sigma_i} \right)^2, \quad D_i = \text{interp} \left(L_i, \frac{1}{4} l^2 (l+1)^2 C_l^{\phi\phi} f_l \right)$$

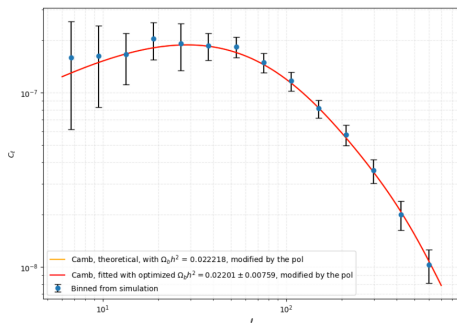


Fiducial n_s	0.9655
Optimized n_s	0.933 ± 0.044

Fitting

We create a function that takes only one of the cosmological parameters and then calculates χ^2 as

$$\chi^2 = \sum_{i=1}^N \left(\frac{D_i - M_i}{\sigma_i} \right)^2, \quad D_i = \text{interp} \left(L_i, \frac{1}{4} l^2 (l+1)^2 C_l^{\phi\phi} f_l \right)$$



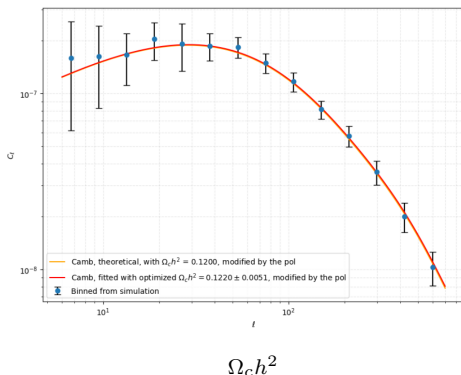
Fiducial $\Omega_b h^2$	0.0222
Optimized $\Omega_b h^2$	0.0220 ± 0.0076

$\Omega_b h^2$

Fitting

We create a function that takes only one of the cosmological parameters and then calculates χ^2 as

$$\chi^2 = \sum_{i=1}^N \left(\frac{D_i - M_i}{\sigma_i} \right)^2, \quad D_i = \text{interp} \left(L_i, \frac{1}{4} l^2 (l+1)^2 C_l^{\phi\phi} f_l \right)$$

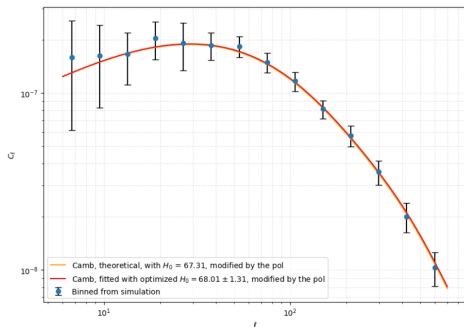


Fiducial $\Omega_c h^2$	0.1200
Optimized $\Omega_c h^2$	0.1220 ± 0.0051

Fitting

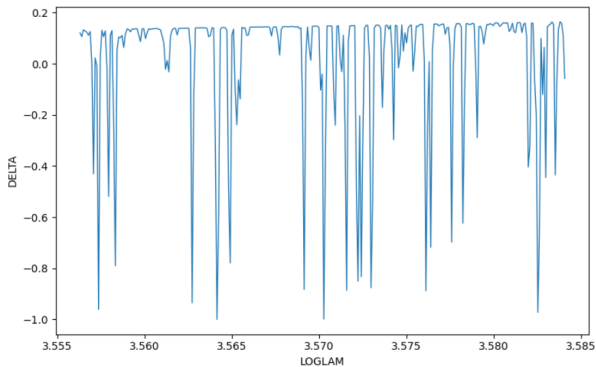
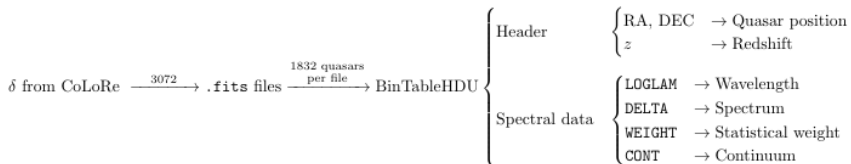
We create a function that takes only one of the cosmological parameters and then calculates χ^2 as

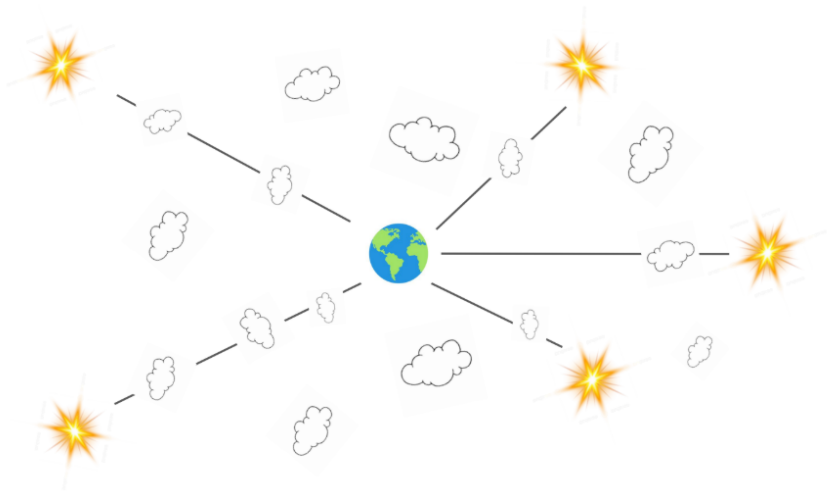
$$\chi^2 = \sum_{i=1}^N \left(\frac{D_i - M_i}{\sigma_i} \right)^2, \quad D_i = \text{interp} \left(L_i, \frac{1}{4} l^2 (l+1)^2 C_l^{\phi\phi} f_l \right)$$



Fiducial H_0	67.31 km/s/Mpc
Optimized H_0	(68.0 ± 1.3) km/s/Mpc

H_0





C_ℓ 's from Data: What do we do with each quasar?

1. Quasar = Line of Sight (LOS)

- Each quasar provides a 1D Lyman- α spectrum at a position (RA, DEC).

2. Spectral Selection

- We select only pixels within a specific redshift range:

$$z \in [1.9, 3.6] \quad (\lambda_{\text{obs}} \in [3600, 5600] \text{ \AA})$$

3. Average Fluctuation per Quasar

- We collapse the 1D spectrum into a single weighted mean flux fluctuation $\bar{\delta}$:

$$\bar{\delta} = \frac{\sum w_i \delta_i}{\sum w_i}$$

Main Idea

We convert a 3D spectral dataset into a **2D catalog of points** on the sky:

$$\text{Quasar } q \rightarrow (\text{RA}_q, \text{DEC}_q, \bar{\delta}_q)$$

Pixelization (HEALPix $N_{\text{side}} = 64$)

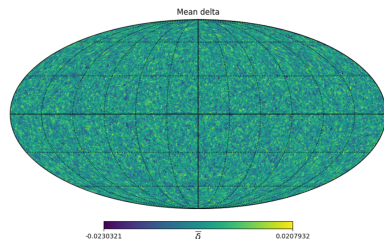
- Assign each quasar position (RA, DEC) to a sky pixel p .
- If multiple quasars fall in the same pixel, we average their $\bar{\delta}$ weighted by forest weight w_q :

$$\Delta_F(p) = \frac{\sum_{q \in p} w_q \bar{\delta}_q}{\sum_{q \in p} w_q}$$

Angular Mask $M(\hat{n})$

- Pixels without quasars contain no physical data. In that case (**NOT our case**), the observed sky is explicitly masked:

$$\Delta_F^{\text{obs}}(\hat{n}) = M(\hat{n}) \Delta_F(\hat{n})$$



HEALPix map $\Delta_F^{\text{obs}}(\hat{n})$ showing mean fluctuations.

Hit-Weighted Monopole Subtraction

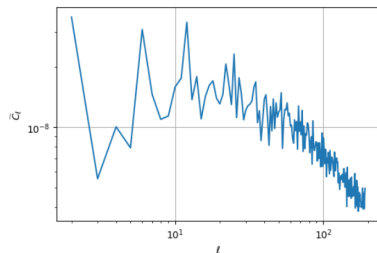
- Calculate global mean weighted by pixel hit count N_p :

$$\langle \delta \rangle = \frac{\sum_{p \in \text{obs}} N_p \Delta_F(p)}{\sum_{p \in \text{obs}} N_p}$$

- Center observed field:
 $\Delta(p) \leftarrow \Delta_F(p) - \langle \delta \rangle$.

Pseudo- C_ℓ Calculation

- Compute spectrum via `healpy.anafast` ($\ell_{\text{max}} = 191$).
- Direct output is a ****Pseudo- C_ℓ **** ($\tilde{C}_\ell \neq C_\ell$) due to mode-coupling caused by the sky mask $M(\hat{n})$.



C_ℓ 's Analysis: Resolution Sensitivity

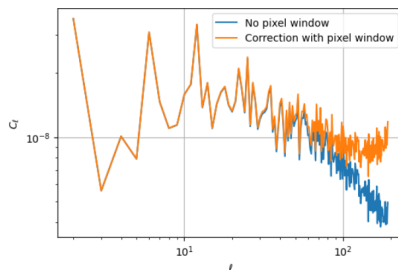
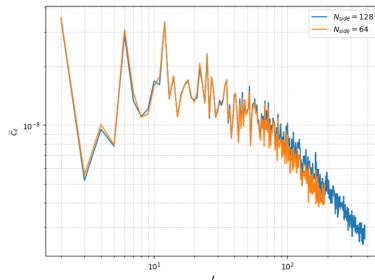
Comparing Pixel Resolutions

- Analyzed grid resolutions $N_{\text{side}} = 64$ and $N_{\text{side}} = 128$.
- Multipole reach extends from $\ell_{\text{max}} = 191$ to $\ell_{\text{max}} = 383$.

Key Observations

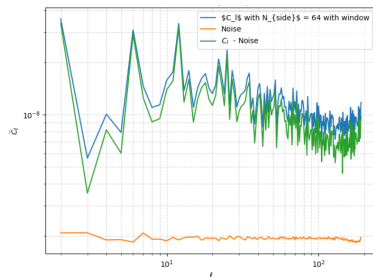
- Both curves coincide up to $\ell \approx 100$, diverging at higher multipoles due to the N_{side} resolution limit—a direct consequence of the **HEALPix pixel window effect**.

$$C_\ell^{\text{correct}} = \frac{\tilde{C}_\ell}{W_\ell^2(N_{\text{side}})}$$



ShotNoise Characterization

- **Physical Origin:** Finite quasar sampling per pixel creates variance in $\bar{\delta}$, producing a white noise floor N_ℓ at high ℓ .
- **Permutation Null Test:** Shuffled $\bar{\delta}$ values across positions ($N = 100$ realizations).
- Preserves pixel hit counts, geometry, and field distribution while destroying angular correlations.

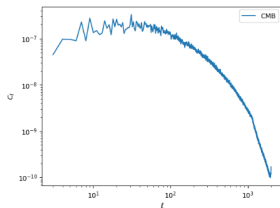


Signal Extraction & Range

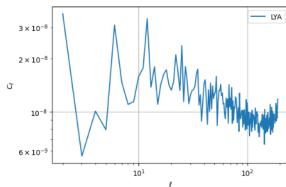
- **Noise Subtraction:**

$$C_\ell^{\text{signal}} = C_\ell^{\text{measured}} - N_\ell^{\text{perm}}$$

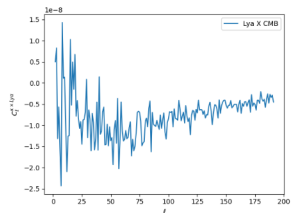
Recap



CMB lensing



Ly- α



Cross-correlation CMB $\times$ Ly- α

SUMMARY

- We computed the CMB lensing Cl' s and found the theoretical model by fitting.
- We computed the $\text{Ly}\alpha$ Cl' s.
- We cross-correlated $\text{Ly}\alpha$ X CMB lensing.
- **Future goals**
 - To work out the theoretical model for $\text{Ly}\alpha$.
 - To work out a theoretical model for the cross-correlated probes.

Thank you!

What is CMB Lensing?

The Basic Idea

Gravity bends light. As CMB photons travel towards us from $z \approx 1100$, their paths are slightly deflected by the gravity of large structures (Dark Matter and galaxies) along the way.

Why is it useful?

- The deflection is very small (a few arcminutes).
- By measuring how the pattern is distorted, we can reconstruct a map of the **invisible Dark Matter!**

CAMB $C_l^{\phi\phi}$

- ϕ : **Lensing potential** (the integrated gravitational pull along the line of sight).
- $C_l^{\phi\phi}$: **Power spectrum** of ϕ .
- Tells us **how strong** the lensing distortion is at each angular scale l .

Convergence of light

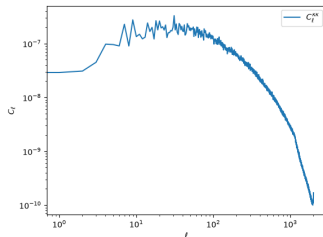
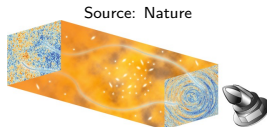
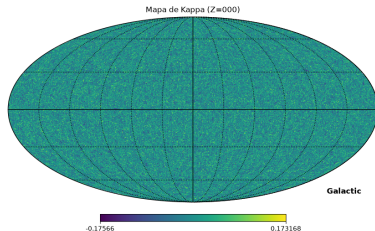
We will be interested in the convergence or divergence effect by the galaxies on the CMB light, but CAMB gives us a the "lens potential" power spectrum, so

$$C_l^{\kappa\kappa} = \frac{(l(l+1))^2}{4} C_l^{\phi\phi}.$$

In a .fits file from CoLoRe,

Filename: out_kappa_z000.fits

No.	Name	Ver	Type	Cards	Dimensions	Format
0	PRIMARY	1	PrimaryHDU	6	()	
1	BINTABLE	1	BinTableHDU	17	3145728R x 1C	[1E]



Cross-Correlation: Concept & Application

What is a Cross-Correlation?

A statistical tool that measures the spatial alignment between two different fields/tracers A and B across the sky.

- Checks if overdensities in field A coincide with overdensities in field B .
- Compute the cross-power spectrum: $\tilde{C}_\ell^{AB} = \langle a_{\ell m}^A (a_{\ell m}^B)^* \rangle$.

Application: Ly α Forest $\times$ CMB Lensing

CMB lensing $\rightarrow$ Very sensitive to distortions in low-redshift scales.

Ly α Forest $\rightarrow$ Gives information about the mass in low-redshift scales.

- **What we obtain:** A direct measurement of how gas traces the dark matter distribution at low redshift.
- **Main goal:** To directly measure the growth of cosmic structure (σ_8) in the young Universe (low z), filling the critical gap between low-redshift galaxy surveys ($z < 1.5$) and the early CMB ($z \sim 1100$).

Why do we need a bias?

- Dark matter δ_m is invisible.
- We observe Ly α flux fluctuations:

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

- At large scales, flux and dark matter are linked via a linear bias relation:

$$\delta_F(\mathbf{x}, z) \approx b_F(z) \delta_m(\mathbf{x}, z)$$

Why is $b_F(z)$ negative?

- Higher matter density ($\delta_m > 0$) $\rightarrow$ More neutral hydrogen.
- More hydrogen $\rightarrow$ Higher Ly α absorption.
- Higher absorption $\rightarrow$ Lower flux ($\delta_F < 0$).

Empirical model:

$$b_F(z) = -0.1352 \left(\frac{1+z}{1+2.4} \right)^{2.9}$$

Cosmological Structure Growth

- The matter field grows over cosmic time: structures were less clustered in the past.
- The linear growth factor $D(z)$ scales the present-day matter field $\delta_0(\mathbf{x}) \equiv \delta_m(\mathbf{x}, z=0)$:

$$\delta_m(\mathbf{x}, z) = D(z) \delta_0(\mathbf{x})$$

- Normalized at $z=0$:
 $D(0) = 1 \implies D(z) < 1$ for $z > 0$.

3D Flux Fluctuation Model

- For a given line of sight $\hat{n}$ at comoving distance $\chi(z)$:

$$\mathbf{x}(z) = \chi(z)\hat{n}$$

- Combining bias and growth yields the 3D fluctuation at redshift z :

$$\delta_F(\chi(z)\hat{n}, z) \approx b_F(z)D(z) \delta_0(\chi(z)\hat{n})$$

Projecting 3D Space into a 2D Map

- The forest mean delta integrates 3D flux along line of sight $\hat{n}$ using selection window $W(z)$:

$$\Delta_F(\hat{n}) = \int_{z_{\min}}^{z_{\max}} dz W(z) \delta_F(\chi(z)\hat{n}, z)$$

Summary

- **Selection Window:**
 $W(z)$ describes how the pixels of the quasar forests are weighted as a function of redshift.
- **Normalization:**
 $W(z)$ is normalized such that
 $\int dz W(z) = 1.$

Redshift-Space Distortions (RSD)

- Gas and matter do not only follow the expansion of the Universe, but also possess peculiar velocities.
- These velocities cause Lyman- α absorption features to appear shifted in redshift compared to where they would be under pure cosmological expansion.
- Consequently, the observed redshift is not a perfect radial coordinate: it is distorted by gas velocities along the line of sight.

$$\Delta_F(\hat{n}) = \int_{z_{\min}}^{z_{\max}} dz W(z) b_F(z) D(z) \left[j_l(k_\chi(z)) - \beta_F(z) j_l''(k_\chi(z)) \right]$$

Projected Flux

$$\Delta_F(\hat{n}) = \int_{z_{\min}}^{z_{\max}} dz W(z) b_F(z) D(z) [j_l(k_\chi(z)) - \beta_F(z) j_l''(k_\chi(z))]$$