<delta(k)delta(k’)>

Baryon acoustic oscillations in a non-flat universe

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Trabajo de Fin de Grado

Código FS22-17-FSC

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Contents

Current Section

Resumen

En este trabajo de fin de grado se hace uso de herramientas de computación de alto rendimiento y análisis de datos para estudiar los efectos de ligeras variaciones en el **modelo cosmológico estándar** ΛCDM. Este modelo asume un universo **espacialmente plano**, si bien las observaciones son compatibles con una curvatura no nula.

Este trabajo se basa en las **oscilaciones acústicas de bariones**, un fenómeno que nos permite estudiar el comportamiento del universo en sus etapas más tempranas.

Después de analizar el catálogo de galaxias del cartografiado **eBOSS**, obtenemos los siguientes resultados: $D_H/r_d = 18.66 \pm 0.72$ y $D_M/r_d = 18.28 \pm 0.53$ para un universo plano, en concordancia con los resultados para otros valores no nulos del **parámetro de curvatura** Ω_k, y lo que es más importante, con resultados anteriores en el campo.

The Baryon Acoustic Oscillations

1. **Early Universe**: Primordial density perturbations are created due to quantum fluctuations during inflation.
2. **Primordial plasma**: The high temperatures tightly bind photons and baryons in a plasma.
3. **Acoustic Oscillations**: Perturbations in the equilibrium between gravitational attraction and thermal radiation pressure cause pure acoustic waves to propagate through the plasma (BAO).
4. **Recombination**: As the universe expands and cools, the Thomson Scattering mechanism stops being effective and baryons decouple from the plasma, ‘turning off’ the interaction and freezing the Acoustic Waves.

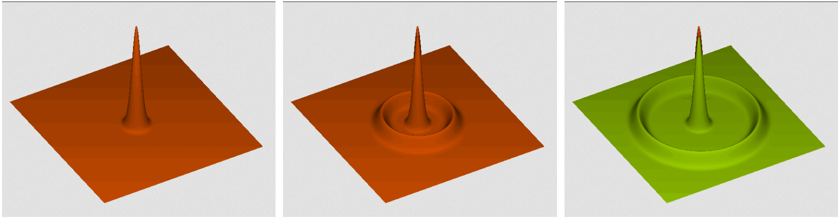
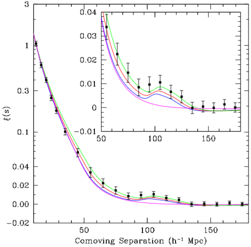


Figure 1: Different time evolution stages of the Baryon Acoustic Oscillations

The BAO analysis

Considering the distribution of the distances at which two galaxies are found of one another, we finde the correlation function $\xi(r)$ and its Fourier Transform, the power spectrum $P(k)$.



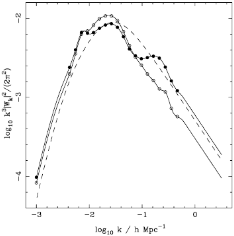


Figure 2: First BAO observations by the SDSS and the 2dF collaborations.

The ΛCDM model

Parameter	Parameter Name	Fiducial Value
Ω_b	Baryon Density Parameter	0.0481
Ω_c	Dark Matter Density Parameter	0.2604
H_0	Hubble Constant	67.6 $\mathrm{kms^{-1}Mpc^{-1}}$
τ_{reio}	Reionization Optical Depth	0.09
A_s	Scalar Perturbation Amplitude	2.0403×10^{-9}
n_s	Scalar Spectral Index	0.97
Ω_k	Curvature Parameter	$[-0.20, 0.20]$
r_d	Sound Horizon at Recombination	147.784 Mpc
D_H/r_d	Hubble distance	18.7
D_M/r_d	Angular diamater distance	18.3
Ω_Λ	Dark Energy Density Parameter	[0.49, 0.89]
Ω_m	Matter Density Parameter	0.31

Current Section

Objectives

1. Review the theoretical background of **BAO observables**, including their physical origin and mathematical formulation, and become familiar with the software tools for data analysis and visualization.
2. Learn to use these **software tools** for data preprocessing, analysis, and visualization of BAO-related cosmological data sets.
3. Investigate the impact of **different values of the curvature parameter** Ω_k on the behavior of BAO observables.
4. Analyze the most recent observational data on BAO observables, obtained from the **eBOSS experiment**, and compare the results with theoretical predictions for different values of Ω_k.
5. Make use of **high performance computing** to solve Physics problems.
6. Specific **data analysis** software development.
7. Learn to control computer clusters via **SSH** (Secure Shell).

Current Section

Mathematics, software and hardware

1. **Mathematics** The Fast Fourier Transform algorithm
2. **Software**
   - **RUSTICO** Measures the power spectrum of a given galaxy catalog[1] as the Fourier Transform of the correlation function

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}') \rangle \text{, with } \delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}} \tag{1}$$

   - **CLASS** The theoretical power spectrum for a given cosmology.
   - **BRASS** Returns the best-fit parameters in the line-of-sight ($\alpha_{\parallel}$) and in the transverse ($\alpha_{\perp}$) direction of the theoretical power spectrum to the measured one, along with their standard deviations.
3. **Hardware** The clusters from the *FQM-378* research group in the Universidad de Córdoba.

[1] In our case, the Luminous Red Galaxies of the extended Baryon Oscillation Spectroscopy Survey (LRG eBOSS)

Pipeline

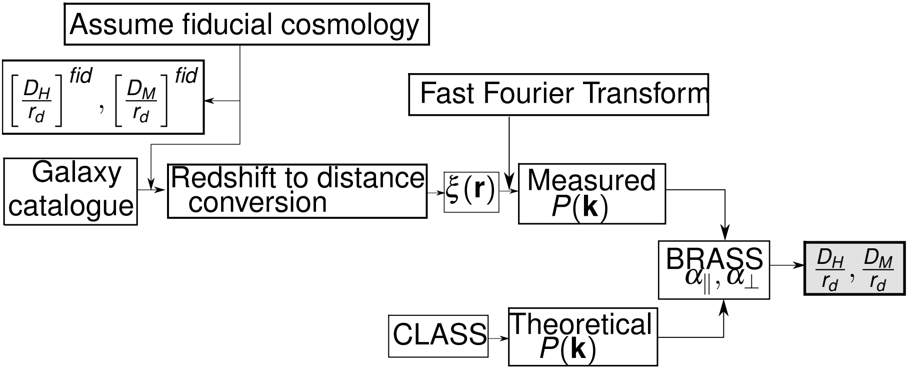


Figure 3: The pipeline used to measure the desired cosmological distances

Current Section

Procedure

Using the mentioned pipeline, we followed the following procedure to obtain the desired results

- A single **fixed flat cosmology** template is generated using CLASS
- For Ω_k in the range $[-0.20, 0.20]$ in steps of 0.05, nine different power spectrums are **measured** from the eBOSS galaxy catalog.
- Using BRASS, we fit the template to **each power spectrum**, obtaining $\alpha_{\|}$, $\alpha_{\perp}$. Each calculation is done three times iteratively, to assure better results.
- Having measured $\alpha_{\|}$ and $\alpha_{\perp}$ and calculated the fiducial values of the cosmological distances we are interested in, we obtain the **measured distances**.

$$\frac{D_H}{r_d} = \alpha_{\|} \left[\frac{D_H}{r_d} \right]^{\text{fiducial}}, \frac{D_M}{r_d} = \alpha_{\perp} \left[\frac{D_M}{r_d} \right]^{\text{fiducial}} \tag{2}$$

Results

Ω_k	D_H/r_d	D_M/r_d
-0.20	19.57 ± 0.85	17.85 ± 0.51
-0.15	19.25 ± 0.84	17.85 ± 0.54
-0.10	19.00 ± 0.80	17.96 ± 0.59
-0.05	18.82 ± 0.77	18.13 ± 0.59
0.00	18.66 ± 0.72	18.28 ± 0.53
0.05	18.61 ± 0.65	18.25 ± 0.47
0.10	18.57 ± 0.61	18.24 ± 0.43
0.15	18.50 ± 0.56	18.23 ± 0.41
0.20	18.36 ± 0.53	18.34 ± 0.39

Table 1: Distance measurements to eBOSS galaxies for different assumed values of the curvature parameter Ω_k.

Results

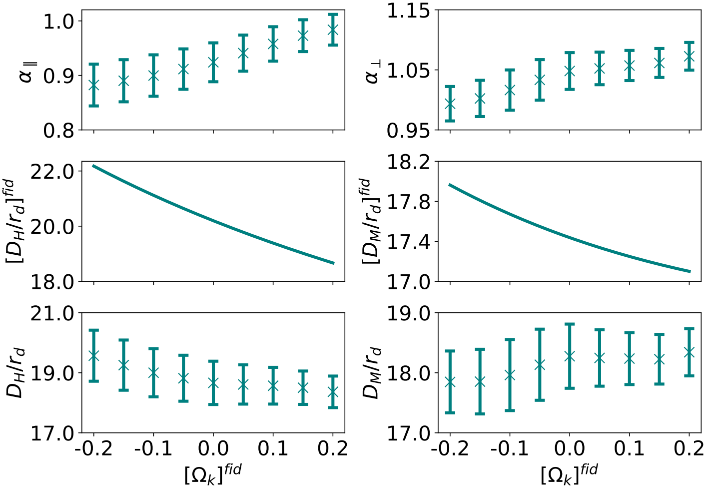


Figure 4: Derivation of cosmological distance measurements.

Current Section

Conclusiones

1. Hemos revisado e implementado la metodología BAO para **medir distancias cosmológicas** en el Universo, y la hemos aplicado a una muestra de galaxias del cartografiado eBOSS.
2. Hemos usado **computación** de alto rendimiento para calcular las posiciones de las características BAO de las **galaxias de eBOSS** junto con sus incertidumbres.
3. Hemos obtenido unas **mediciones de distancia** a las galaxias de eBOSS normalizadas a la escala del horizonte de sonido de $D_H/r_d = 18.66 \pm 0.72$ y $D_M/r_d = 18.28 \pm 0.53$.
4. Nuestro resultado principal es que **no hay dependencia significativa** de estas observables con respecto a cambios en el valor asumido del parámetro de curvatura Ω_k en el rango de estudio.

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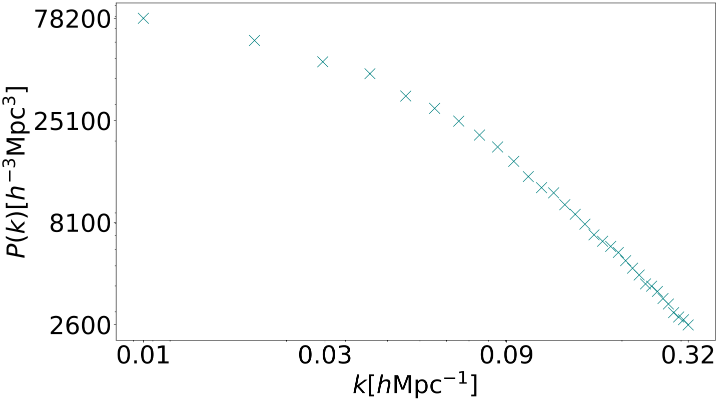

Figure 5: Power spectrum of the LRG eBOSS galaxies.

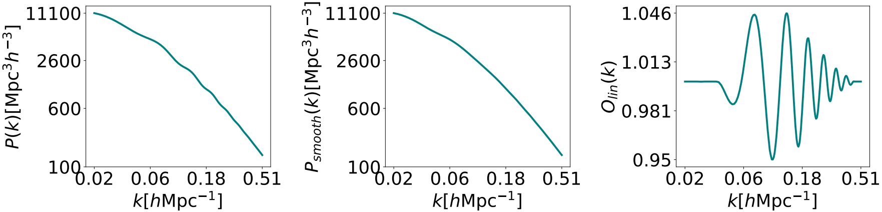

Figure 6: The template power spectrum and its smooth and the pure BAO components.