Baryon Acoustic Oscillations measurement and Expansion of the Universe

Cosmology at the summit

BS in Physics at Paul Sabatier (UT3), Intern at IRAP

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Academic Year 2023/2024

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- DESI measurements of the BAO
- Cosmological background
- Cosmological constraints in the ΛCDM model
  - Methods
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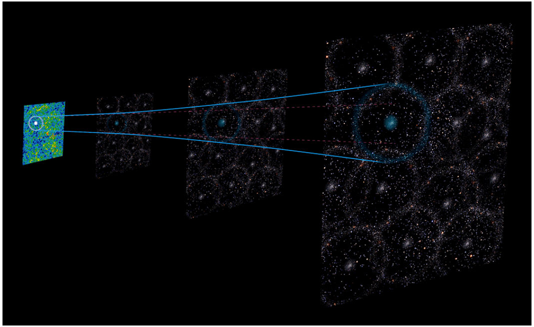
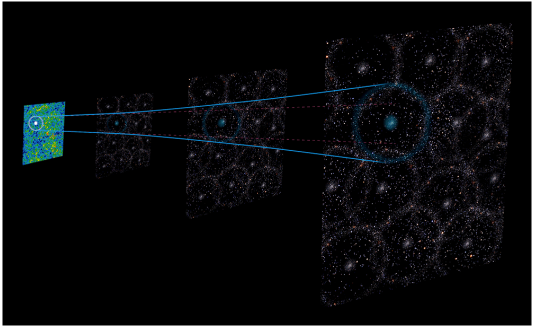
What are the Baryon Acoustic Oscillations (BAO) ?

- **Gravitation + Photon-matter interaction $\Longrightarrow$ Oscillations**



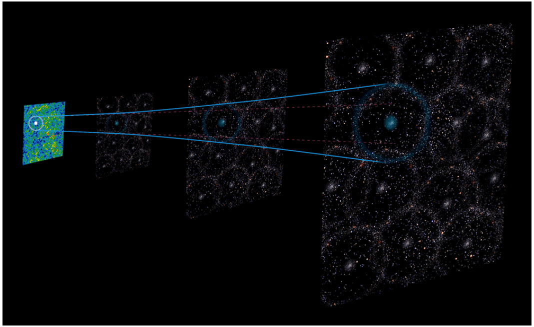
What are the Baryon Acoustic Oscillations (BAO) ?

- **Gravitation** + **Photon-matter interaction** $\Longrightarrow$ **Oscillations**
- That phenomenon ended ≈380 000 years after the Big Bang



What are the Baryon Acoustic Oscillations (BAO) ?

- **Gravitation** + **Photon-matter interaction** $\Longrightarrow$ **Oscillations**
- That phenomenon ended ≈380 000 years after the Big Bang
- It leaved an imprint on the **matter distribution**



- Matter distribution freezed : only evoluating with the expansion

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- Maximal distance the acoustic wave could travel in the primordial plasma : **sound horizon** r_d

$$r_d \approx 150 \text{ Mpc}$$

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- Matter distribution freezed : only evoluating with the expansion
- Maximal distance the acoustic wave could travel in the primordial plasma : **sound horizon r_d**

$$r_d \approx 150 \text{ Mpc}$$

- Observations of matter distribution at different redshifts $\Longrightarrow$ **Evolution of the universe and estimation the value of cosmological parameters**

The universe is like a giant sponge with holes of a caracteristic size r_d.

Probability density of finding a galaxy at the distance r

$$dP = ndV(1+\xi(r))$$

BOSS DR10 CMASS sample

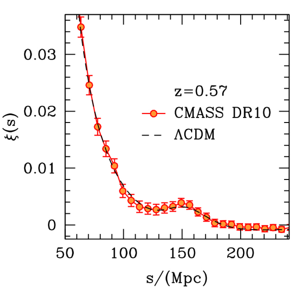

Figure: Credit: Ariel G. Sánchez and SDSS collaboration

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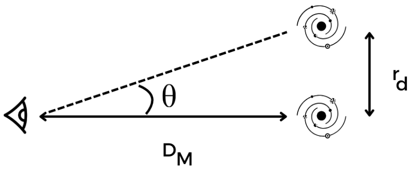
DESI covers 6 differents types of tracers :

- Low z galaxies of the bright galaxy survey (BGS) $(0.1 < z < 0.4)$
- Luminous red galaxies (LRG1 & LRG2) $(0.4 < z < 0.6)$ & $(0.6 < z < 0.8)$
- Emission line galaxies (ELG) $(1.1 < z < 1.6)$
- Quasars (QSO) $(0.8 < z < 2.1)$
- Lyman-α forest quasars (Lyα) $(1.77 < z < 4.16)$

DESI measures **angle separation θ and difference of redshift Δz** between pairs of galaxies in each tracer.



$$\boxed{\theta = \frac{r_d}{D_M}}$$

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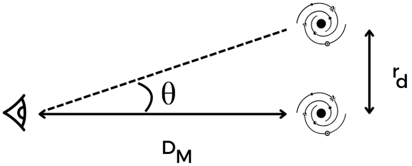

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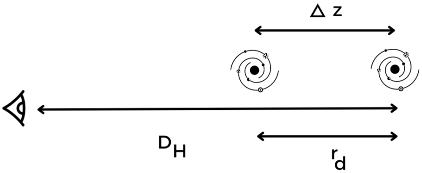

$$\boxed{\Delta z = \frac{r_d}{D_H}}$$

DESI data

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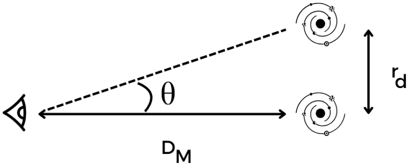

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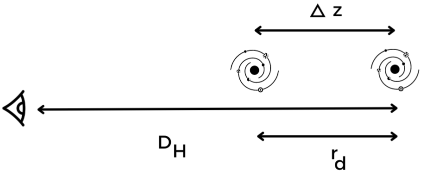

$$\boxed{\Delta z = \frac{r_d}{D_H}}$$

Angle average distance : $D_V(z) = (zD_M(z)^2 D_H(z))^{1/3}$

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Flat ΛCDM model

Curve density Ω_K :

$$\Omega_K = 0 = 1 - \Omega_m - \Omega_\Lambda \quad \text{(Flat)}$$

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$$H(z) = H_0 E(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)^{3(1+\omega)}}$$

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Comoving angular distance $D_M(z)$:

$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{E(z')}$$

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Comoving angular distance $D_M(z)$:

$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{E(z')}$$

Comoving distance along the line-of-sight $D_H(z)$:

$$D_H(z) = \frac{c}{H_0 E(z)}$$

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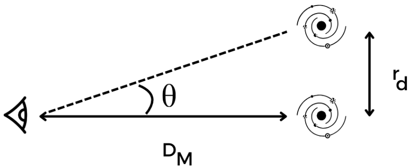
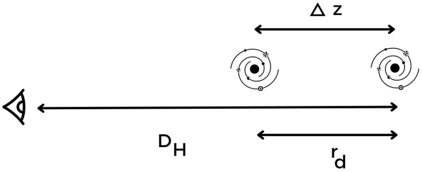
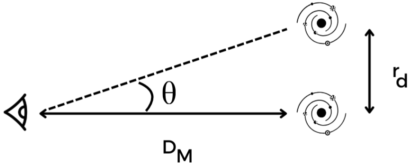
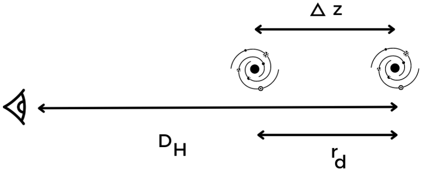




Cosmological framework

$$E(z) = \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)^{3(1+\omega)}}$$



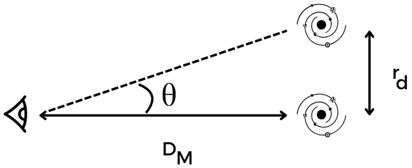


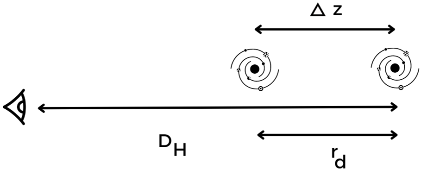
$$\theta = \frac{r_d}{D_M}$$

Cosmological framework

4 Cosmological constraints in the ΛCDM model

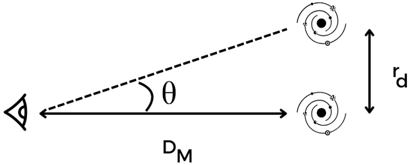
$$E(z) = \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)^{3(1+\omega)}}$$

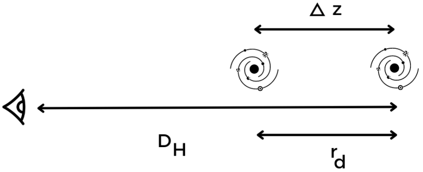




$$\theta = \frac{r_d}{D_M} = \frac{H_0 r_d}{c \int_0^z \frac{dz'}{E(z)}} = \frac{H_0 r_d}{f(z, \Omega_m, \omega)}$$

$$E(z) = \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)^{3(1+\omega)}}$$





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Cosmological framework

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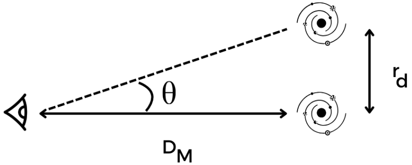

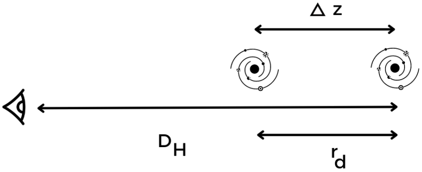

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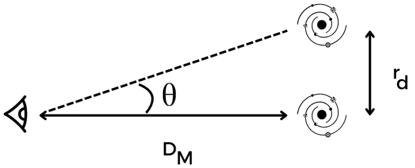

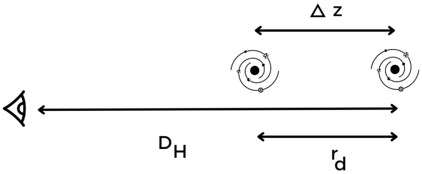

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3 free parameters : $(H_0 r_d, \Omega_m, \omega)$

Compare the model with experimental values

θ value

Data : θ_D

Model : $\theta_M = \frac{H_0 r_d}{c \int_0^z \frac{dz'}{E(z)}}$

$$\chi^2_\theta = \sum_{z_i} \left(\frac{\theta_D - \theta_M}{\sigma(\theta_D)} \right)^2$$

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Δz value

Data : Δz_D

Model : $\Delta z_M = \frac{H_0 r_d}{cE(z)}$

$$\chi^2_{\Delta z} = \sum_{z_i} \left(\frac{\Delta z_D - \Delta z_M}{\sigma(\Delta z_D)} \right)^2$$

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D_V value

Data : $D_{V,D}$

Model :

$$D_{V,M} = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$

$$\chi^2_{D_V} = \sum_{z_i} \left(\frac{D_{V,D} - D_{V,M}}{\sigma(D_{V,D})} \right)^2$$

Compare the model with experimental values

θ value

Data : θ_D

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Data : $D_{V,D}$

Model :

$$D_{V,M} = (zD_M(z)^2 D_H(z))^{1/3}$$

$$\chi^2_{D_V} = \sum_{z_i} \left(\frac{D_{V,D} - D_{V,M}}{\sigma(D_{V,D})}\right)^2$$

$$\chi^2 = \chi^2_\theta + \chi^2_{\Delta z} + \chi^2_{D_V}$$

θ value

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Model : $\theta_M = \frac{H_0 r_d}{c \int_0^z \frac{dz'}{E(z)}}$

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Δz value

Data : Δz_D

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D_V value

Data : $D_{V,D}$

Model :

$D_{V,M} = (z D_M(z)^2 D_H(z))^{1/3}$

$$\chi^2_{D_V} = \sum_{z_i} \left(\frac{D_{V,D} - D_{V,M}}{\sigma(D_{V,D})} \right)^2$$

$$\chi^2 = \chi^2_\theta + \chi^2_{\Delta z} + \chi^2_{D_V}$$

Method : Calculate χ^2 for different values of the parameters $(H_0 r_d, \Omega_m, \omega)$ and estimate the best fit to the data

My objective is to demonstrate the acceleration of the expansion : fit the data with the ΛCDM model

- Hubble constant : $H_0 = 67.97$ km.s^{-1}Mpc^{-1}
- Sound horizon : $r_d = 147.09$ Mpc
- Matter density: $\Omega_m = 0.3$
- State equation parameter : $\omega = -1$

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ω inference

Free parameter : ω

Fixed parameters : $H_0 r_d = 9997$ km.s^{-1}, $\Omega_m = 0.3$

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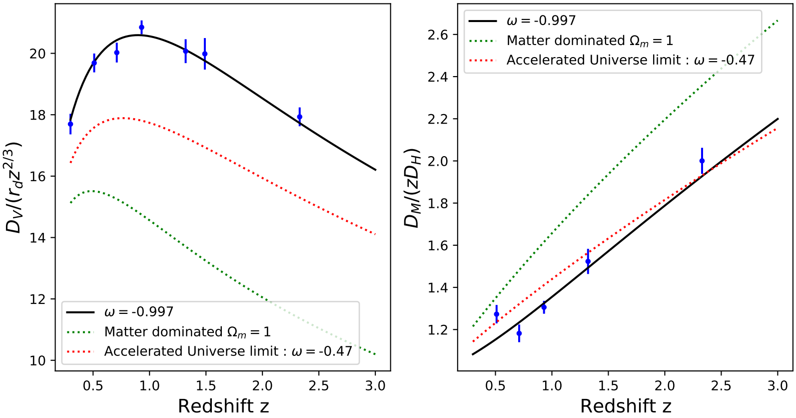

Results : $\omega = -1.00 \pm 0.02$ $\chi^2 = 13.8$

Ω_m, ω inference

Free parameters : ω, Ω_m

Fixed parameter : $H_0 r_d = 9997$ km.s^{-1}

Ω_m, ω inference

Free parameters : ω, Ω_m

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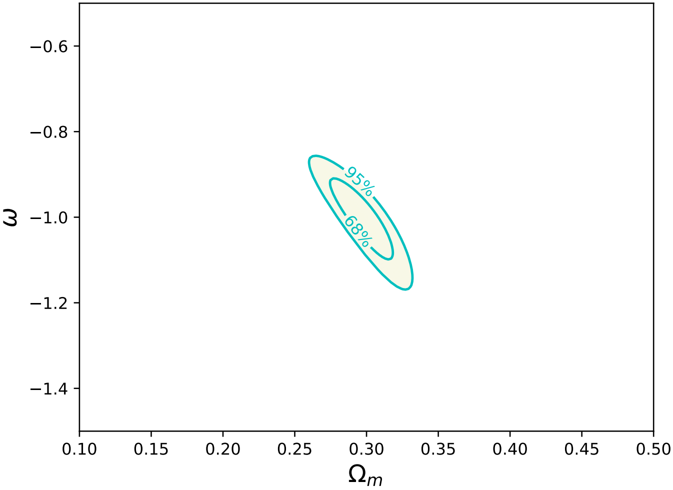

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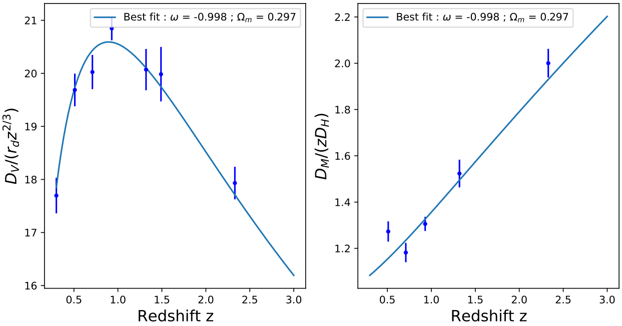

Results :

$$\omega = -1.0 \pm 0.1 \qquad \Omega_m = 0.30 \pm 0.02$$

$$\chi^2 = 15.3$$

$H_0 r_d, \Omega_m$ inference

Free parameters : hr_d, Ω_m

Fixed parameter : $\omega = -1$

$H_0 r_d, \Omega_m$ inference

Free parameters : hr_d, Ω_m

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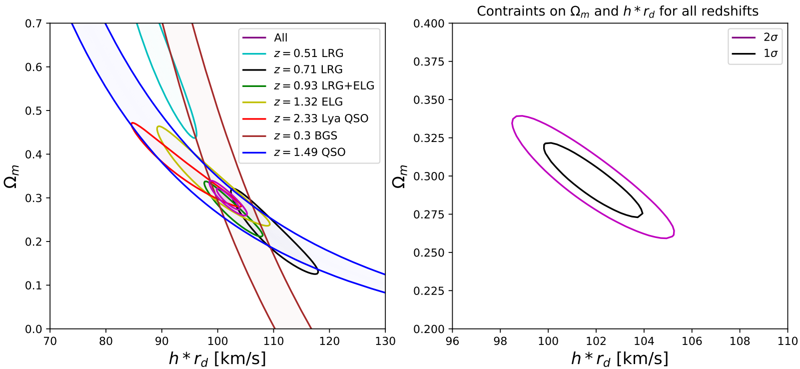


Results :

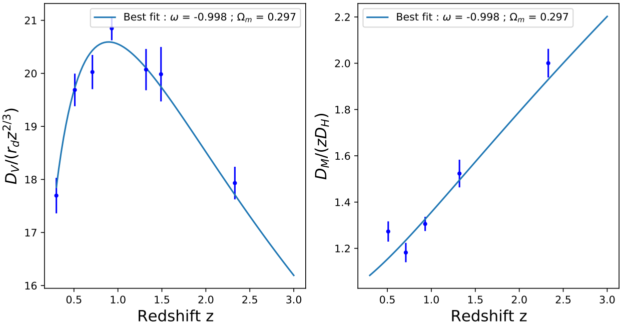
$$\Omega_m = 0.30 \pm 0.02 \qquad hr_d = (102 \pm 2)\ \text{km.s}^{-1}$$

$$\chi^2 = 15.4$$

Ω_m, ω inference

Free parameters : ω, Ω_m

Fixed parameter : $H_0 r_d = 9997$ km.s^{-1}



Results :

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$H_0 r_d, \Omega_m, \omega$ inference (Preliminary work)

Free parameters : hr_d, Ω_m, ω

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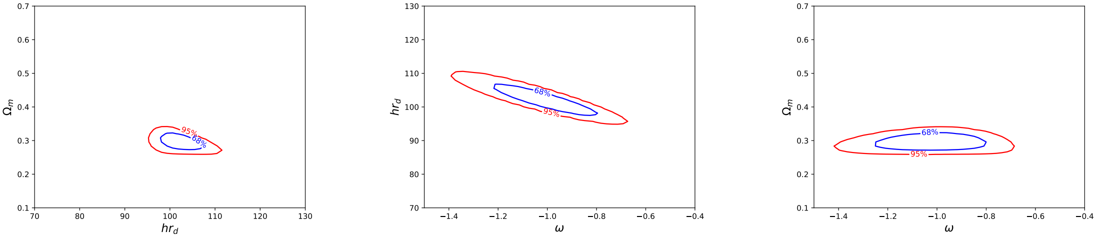

Preliminary results :

$$\Omega_m = 0.296 \qquad hr_d = 101.8 \text{ km.s}^{-1} \qquad \omega = -1$$

$$\chi^2 = 15.3$$

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A powerful cosmological probe

The BAO measurements is also a powerful cosmological probe for :

- Dynamics behind dark energy
- Curvature of the universe
- Sum of neutrinos masses and the Hubble constant value, in combination with others probes

Thank you for listening!
Any questions?