Marginalization approach in Baryonic Acoustic Oscilations - what we have learned so far?

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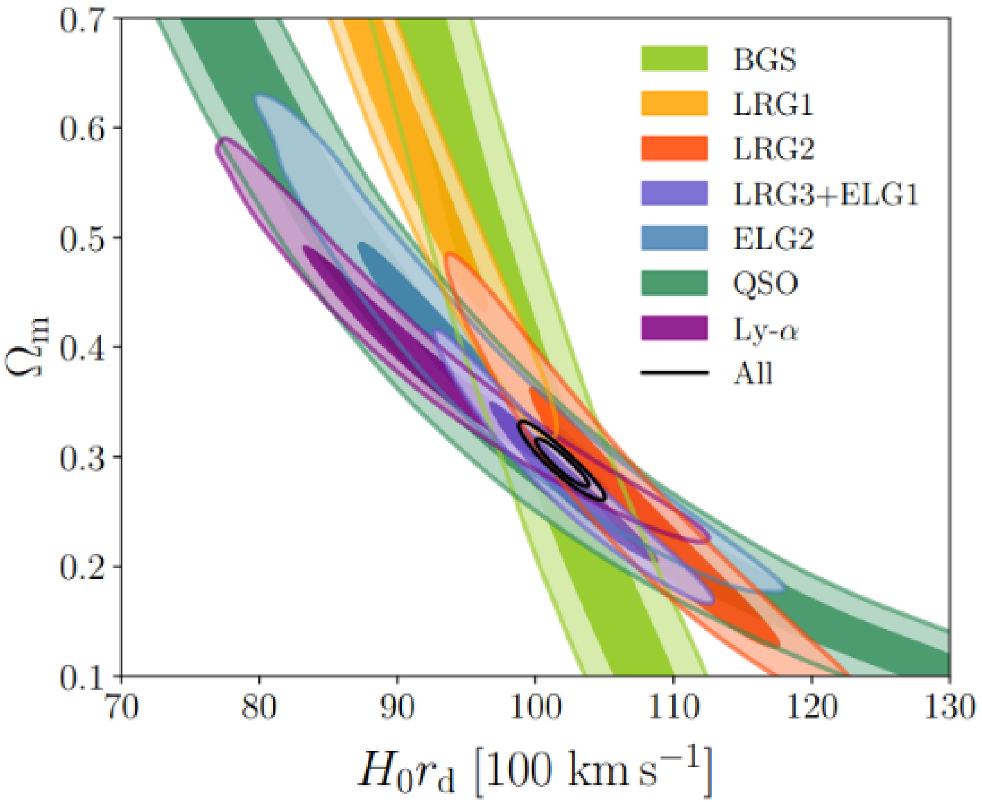
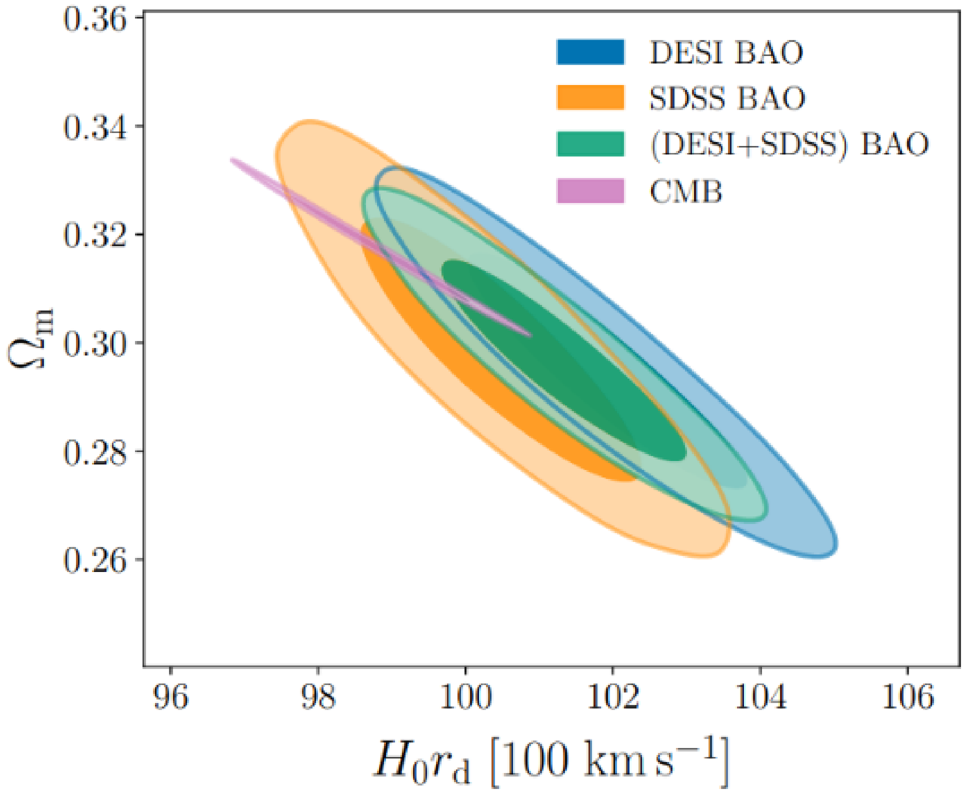
ИЯИЯЕ INRNE

БЪЛГАРСКА АКАДЕМИЯ на НАУКИТЕ 1869

The state of the Hubble tension





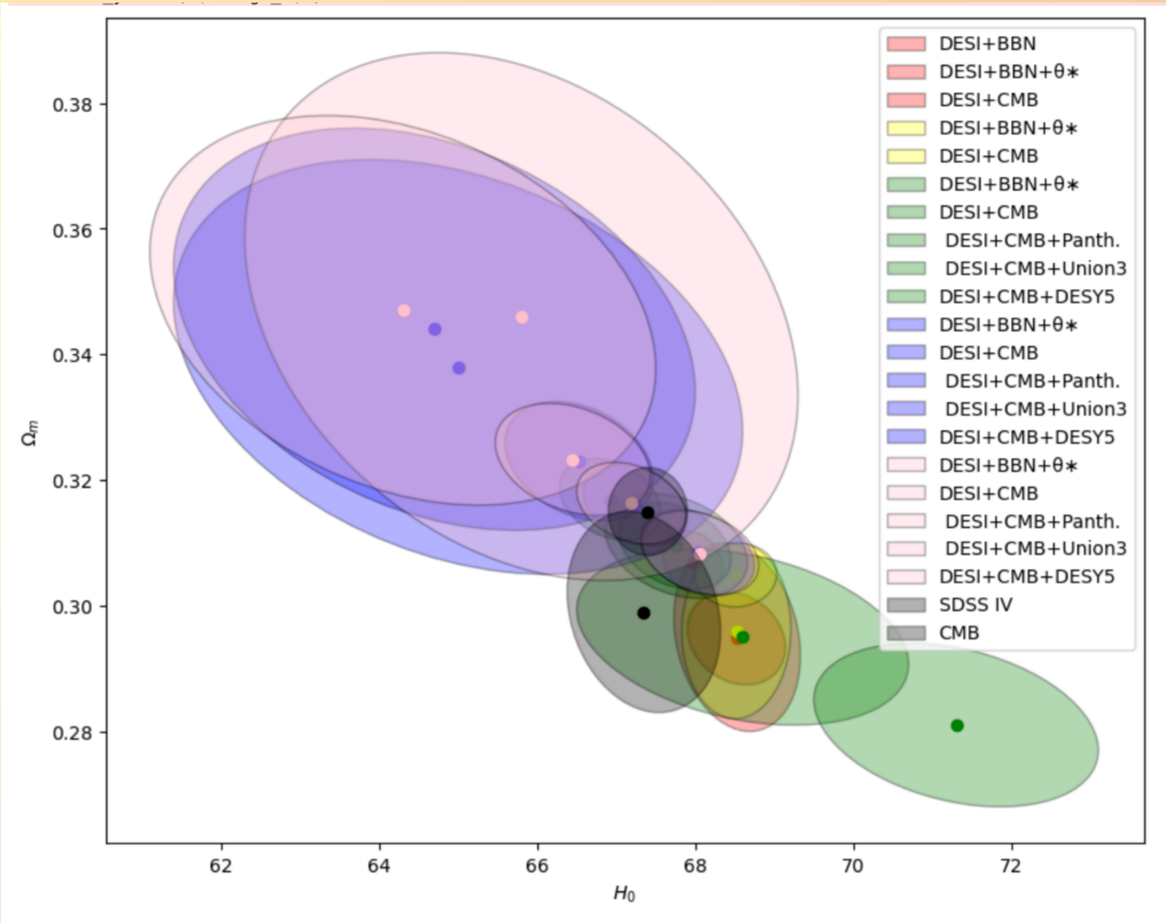
The Hubble tensions is at 5.3σ as of 2023! 3.4σ from DESI+BBN
The novelty: 2.5σ-3.9σ evidences for wwaCDM!

DESI collab., 2404.03002

Aghanim et al. , Astron. Astrophys. 641, 2020

Riess, A. G. et al. ApJL 934 (2022) L7

The covariance between Ω_m and H_0 for different models



3d BAO

$$\frac{D_H}{r_d} = \frac{c}{H_0 r_d} \frac{1}{E(z)},$$

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

2d BAO

$$\theta_{BAO}(z) = \frac{r_d}{(1+z)\, D_A(z)}$$

Data from:
DESI collab., 2404.03002

- Illustration (not posteriors)

The marginalization approach – BAO

- The χ^2 for data with covariance is

$$\chi^2 = \sum_i [\boldsymbol{v}_{obs} - \boldsymbol{v}_{model}]^T C_{ij}^{-1} [\boldsymbol{v}_{obs} - \boldsymbol{v}_{model}]$$

- We can marginalize by using Bayes theorem

$$p(D, M) = \frac{1}{p(D|M)} \int \exp\left[-\frac{1}{2}\chi^2\right] d\frac{c}{H_0 r_d},$$

- Finally by using

$$\tilde{\chi}^2_{BAO} = -2 \ln p(D, M)$$

- we get the same final χ^2 for 2d BAO and 3d BAO:

No dependence on H_0 or r_d left in χ^2

$$\chi^2 = \left(\frac{c}{H_0 r_d}\right)^2 A - 2B\left(\frac{c}{H_0 r_d}\right) + C,$$

→

$$\tilde{\chi}^2 = C - \frac{B^2}{A} + \log\left(\frac{A}{2\pi}\right),$$

Similar marginalizations for SN and Cosmic Chronometers

- SN measure the distance modulus:

$$\mu_B(z) - M_B = 5\log_{10}[d_L(z)] + 25\,,$$

- Marginalized χ^2:

$$\tilde{\chi}^2_{SN} = D - \frac{E^2}{F} + \ln\frac{F}{2\pi},$$

- For Cosmic Chronometers:

$$\chi^2_{CC} = \frac{(H_0E(z) - H_{obs}(z))^2}{\sigma^2} \rightarrow \chi^2_{CC} = -\left(G - \frac{B^2}{A} + log\left(\frac{A}{2\pi}\right)\right)$$

Application in dynamical dark energy

- 2d and 3d BAO datasets + Pantheon dataset
- We tested different DDE models (CPL parametrization) and pEDE/gEDE
- Approach by Lazkoz et al. (2005); Basilakos & Nesseris (2016); Anagnostopoulos & Basilakos (2018); Camarena & Marra (2021) Di Pietro & Claeskens (2003); Nesseris & Perivolaropoulos (2004); Perivolaropoulos (2005);

How removing H_0 and r_d will affect the preferred models?

$$E(z)^2 = \Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda(z),$$

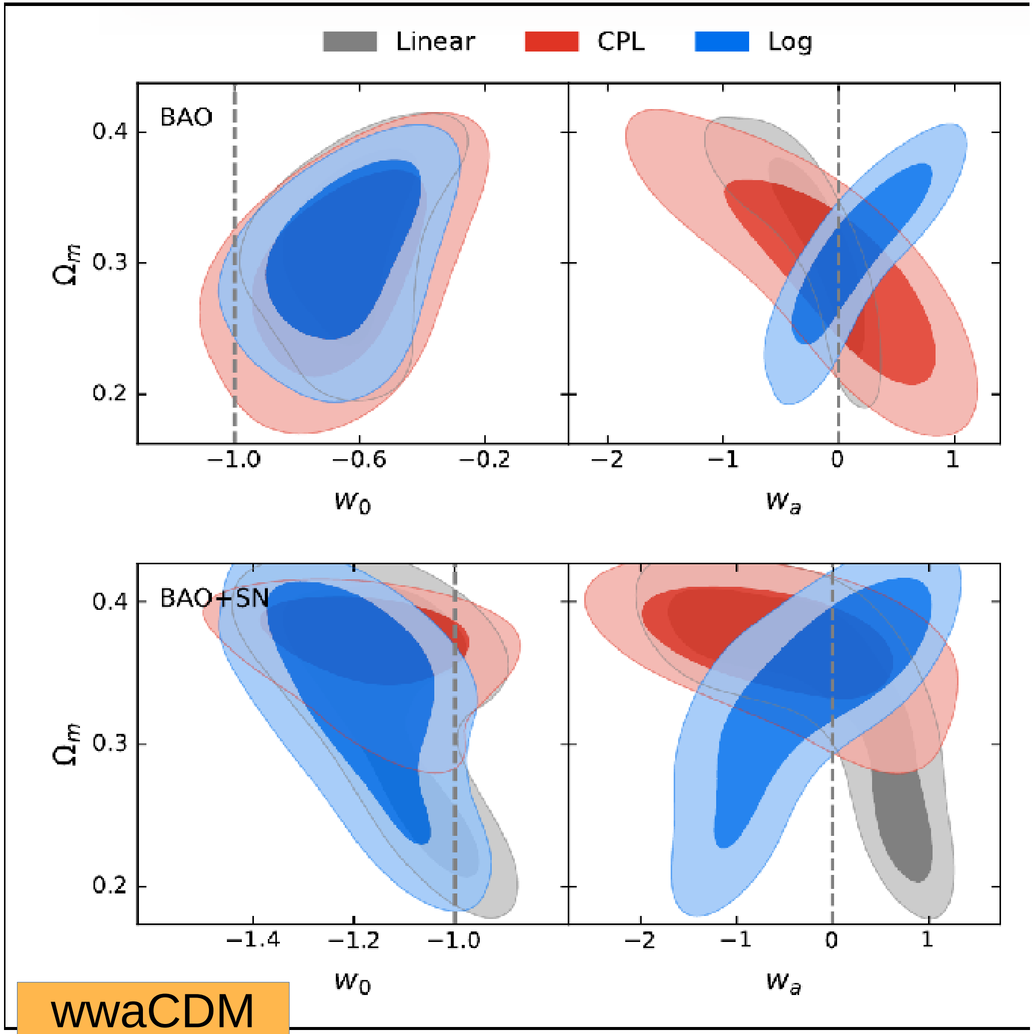
$$\Omega_\Lambda(z) = \Omega_\Lambda^{(0)} \exp\left[\int_0^z \frac{3(1+w(z'))dz'}{1+z'}\right]$$

$$w(z) = \begin{cases} w_0 + w_a z & \text{Linear} \\ w_0 + w_a \frac{z}{z+1} & \text{CPL} \\ w_0 - w_a \log(z+1) & \text{Log} \end{cases}$$

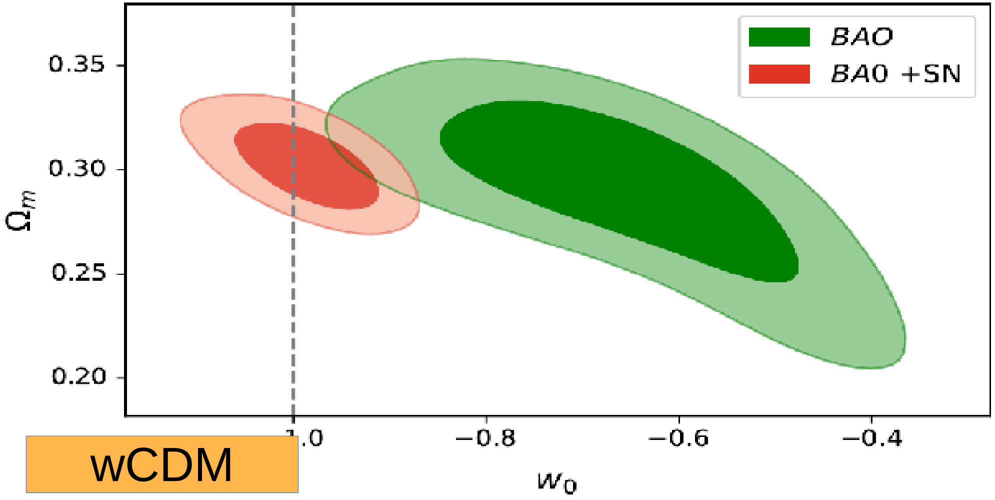
$$\Omega_{DE}(z) = \Omega_\Lambda \frac{1 - \tanh(\bar{\Delta} \log_{10}(\frac{1+z}{1+z_t}))}{1 + \tanh(\bar{\Delta} \log_{10}(1+z_t))}$$

The DE results

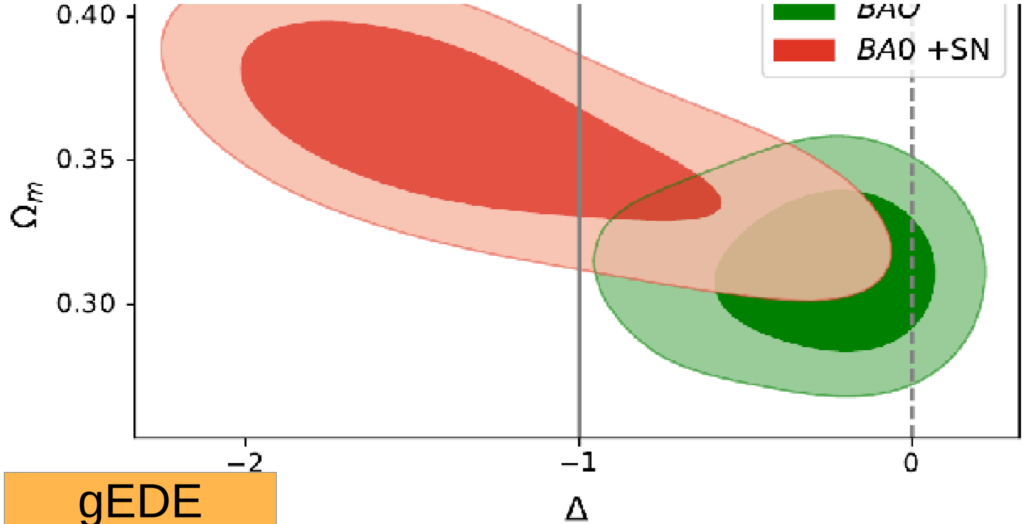
D.S., Benisty, A&A 668, A135 (2022)



wwaCDM

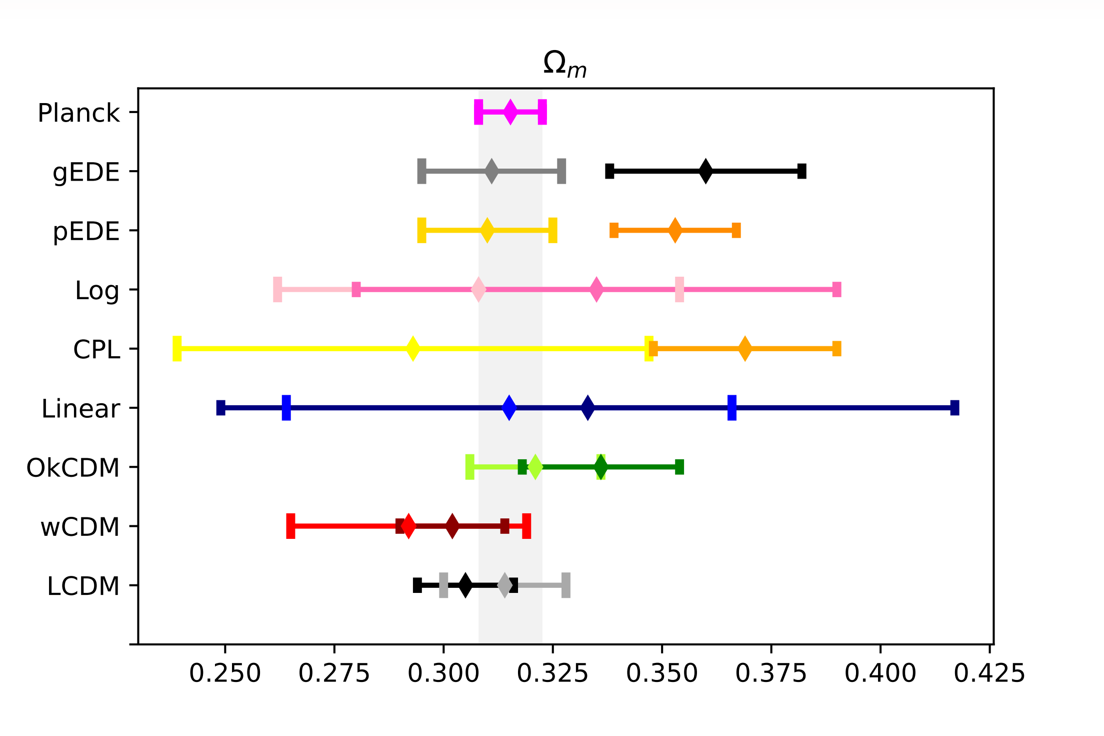


wCDM



gEDE

Tesions in the matter density Ω_m

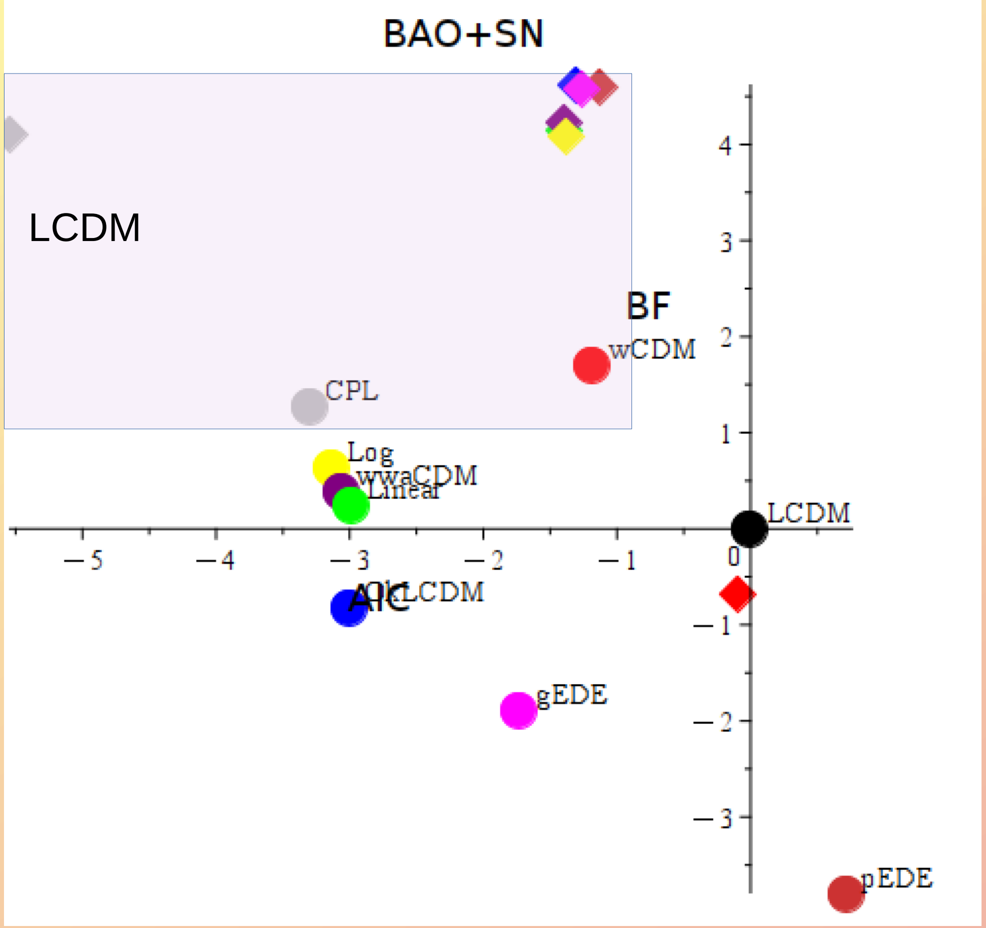


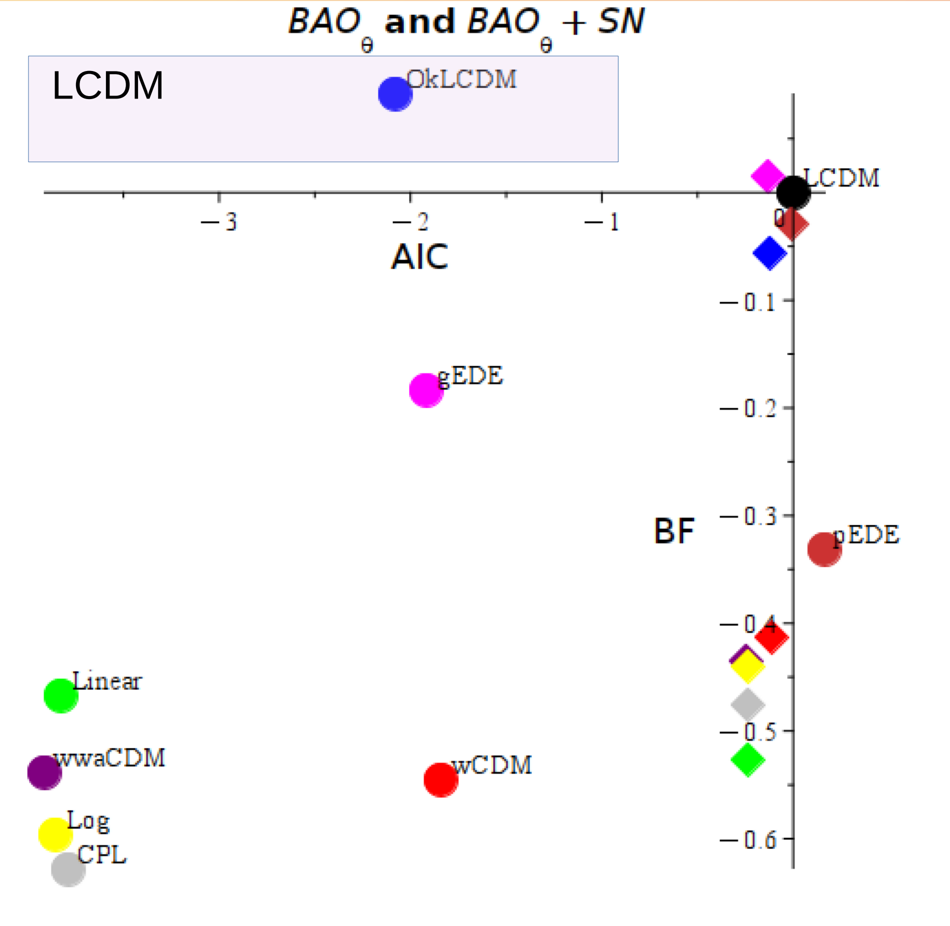
The lighter colors are BAO, the darker ones are the BAO+SN

3d BAO and BAO+SN

SDSS IV → Ω_m~0.25 - 0.31

Comparing the two datasets statistically





Main results:

- 2d and 3d BAO infer different cosmological parameters
- They prefer different cosmological models
- SN have strong effect but not sufficient to change this preference
- Indications of a preference for DDE in some cases
- Statistical measures do not agree over model preferences
- pEDE stands out, even with SN
- Despite marginalizing over H_0 and r_d, Ω_m feels the tension

Constraining the dark energy models using baryon acoustic oscillations: An approach independent of H0 · rd,

Denitsa Staicova, David Benisty , Astron.Astrophys. 668 (2022) A135, Astron.Astrophys. 668

Application to interacting dark energy (IDE) models

- This form of the model studied in Wang et al. (2016); Di Valentino et al. (2017, 2020a); Yang et al. (2020)
- We assume a model in which DE and DM interact
- The direction of the energy flow is governed by the sign of ξ
- The final eq. for E(z):

$$\rho_b + \rho_{CDM} + \rho_{DE} = \left(\frac{3}{8\pi G}\right) H^2,$$

$$\begin{cases} \dot{\rho}_{CDM} + 3H\rho_{CDM} & = & -Q(t) \\ \dot{\rho}_{DE} + 3H(1+w)\rho_{DE} & = & Q(t), \end{cases}$$

$$Q = 3H\xi\rho_{DE},$$

$$E(z)^2 = \Omega_{m,0}(1+z)^3 + \Omega_{DE,0}(1+z)^{3(1+w-\xi)} + \frac{\xi\Omega_{DE,0}}{\xi - w}\left((1+z)^3 - (1+z)^{3(1+w-\xi)}\right),$$

Are there evidence of energy flow between DM and DE if remove H_0 and r_d?

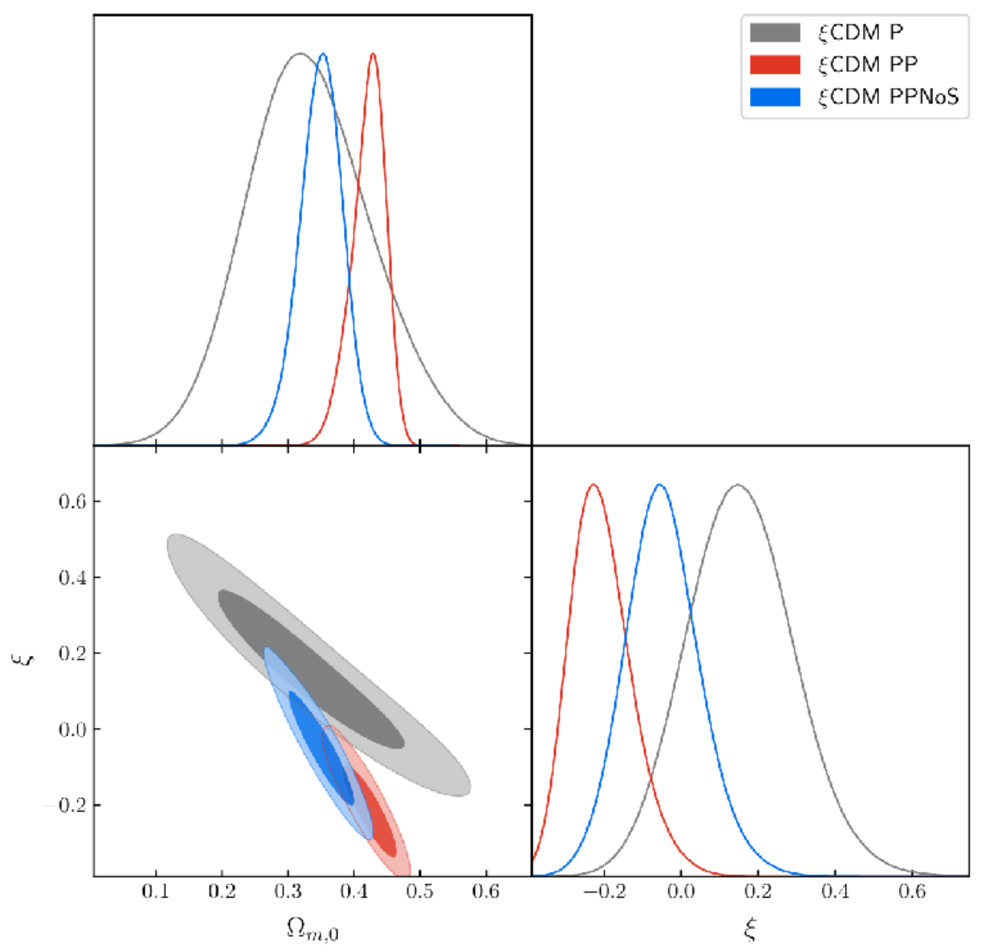
The datasets we use

- Pantheon + SN dataset

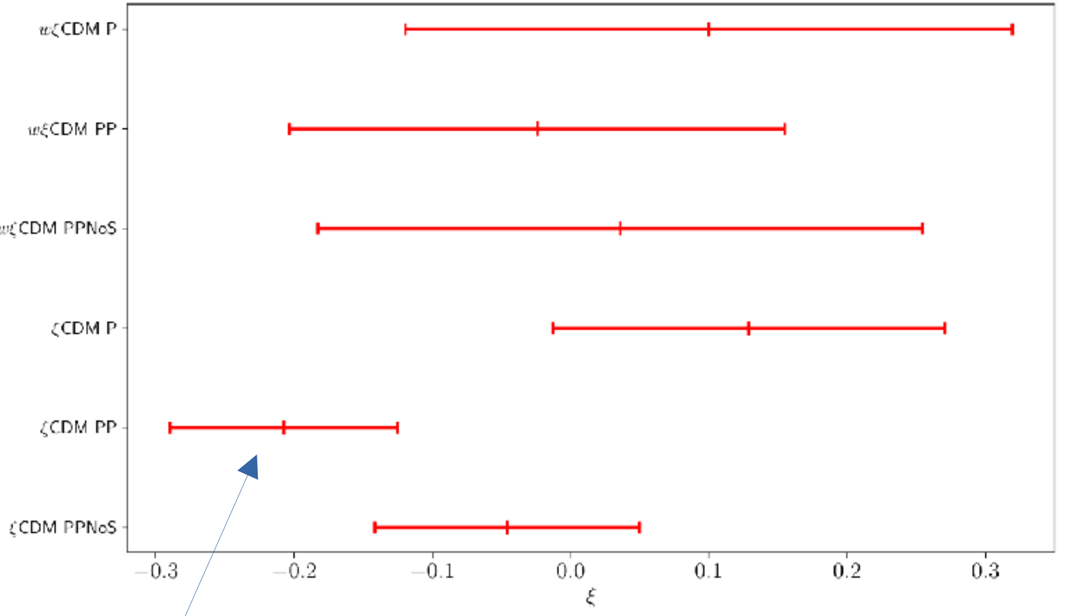
  -- calibrated with Cepheids (PP)

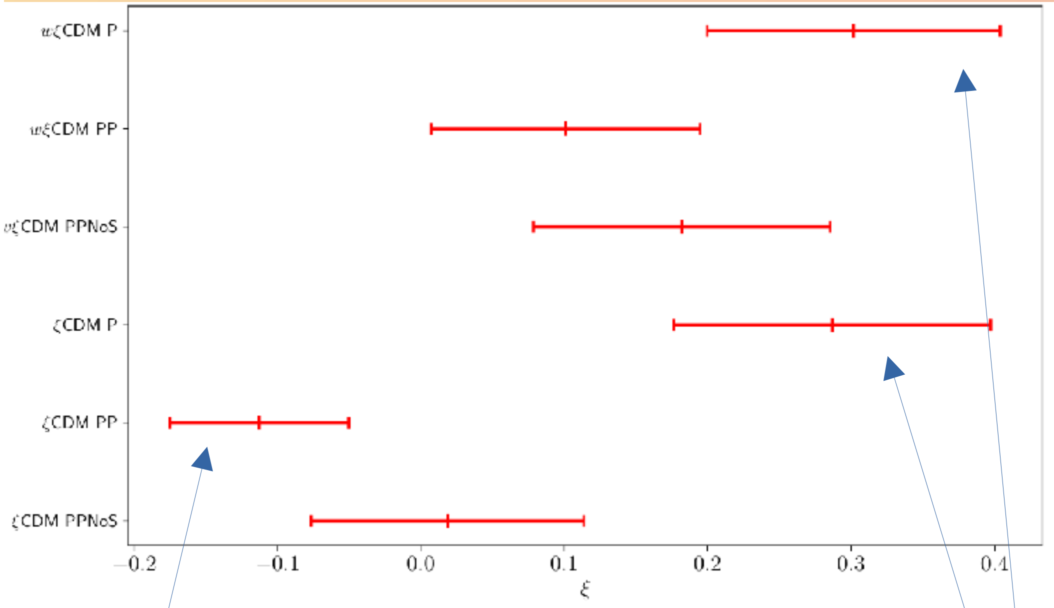
  -- non-calibrated (PPNoS)

- Pantheon SN dataset (P)
- Transversal BAO dataset (BAO)
- Cosmic Chronometers (CC)



Comparison between ξ for different priors





uniform prior

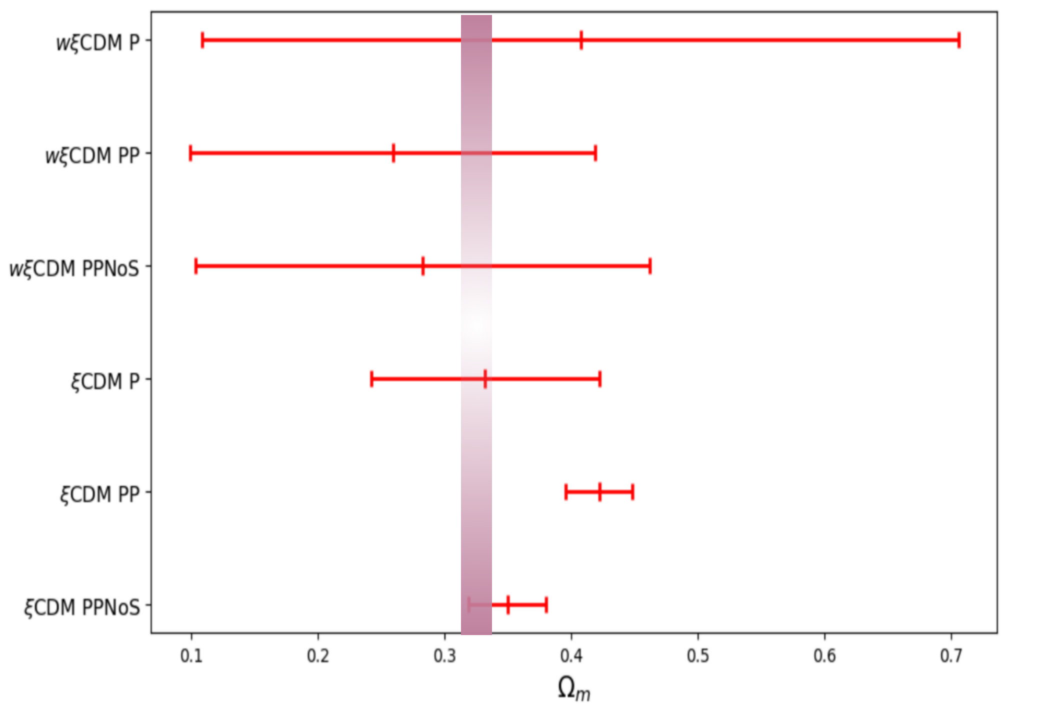
CMB prior

$\xi \in [-0.33, 1]$, $\Omega_{m,0} \in [0, 1]$,

$\Omega^{CMB}_{m,0} = 0.139 \pm 0.095$

Main results:

- The **calibrated** PP dataset gives 68% evidence of a flow from DE to DM with $\xi = -0.21 \pm 0.08$, for ξCDM but no evidence for wξCDM
- For P dataset: we get $\xi = 0.15 \pm 0.13$ at 68% CL for ξCDM and $\xi = 0.09 \pm 0.25$ for wξCDM
- The **uncalibrated** PP dataset finds no evidence of ξ for both ξCDM ($\xi = -0.05 \pm 0.1$) and ξCDM ($\xi = 0.02 \pm 0.24$)
- Different SN datasets prefer different ξ



Late-Time constraints on Interacting Dark Energy: Analysis independent of H0, rd and MB, David Benisty, Supriya Pan, Denitsa Staicova, Eleonora Di Valentino, Rafael C. Nunes, A&A 2024

Thank you for your attention!

Credits: NASA, ESA, CSA, STScI, Webb ERO Production Team

Where the coefficients are:

- 3d

$$A = f^j(z_i) C_{ij} f^i(z_i),$$

$$B = \frac{f^j(z_i) C_{ij} v^i_{model}(z_i) + v^j_{model}(z_i) C_{ij} f^i(z_i)}{2},$$

$$C = v_j^{model} C_{ij} v_i^{model}.$$

No dependence on H_0 or r_d left in χ^2

- 2d

$$A_\theta = \sum_{i=1}^{N} \frac{h(z_i)^2}{\sigma_i^2},$$

$$B_\theta = \sum_{i=1}^{N} \frac{\theta_D^i \, h(z_i)}{\sigma_i^2},$$

$$C_\theta = \sum_{i=1}^{N} \frac{\left(\theta_D^i\right)^2}{\sigma_i^2}.$$

- CC

$$G = \sum_i \left(H_i \, C_{cov}^{-1} \, H_i^T\right)$$

$$B = \sum_i \left(E_i \, C_{cov}^{-1} \, H_i\right)$$

$$A = \sum_i (E_i C_{cov}^{-1} E_i^T),$$

The posteriors for ξCDM and wξCDM