Baryon Acoustic Oscillations datasets in cosmology

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Based on works with D. Benisty, J. Mifsud, J. Levi Said

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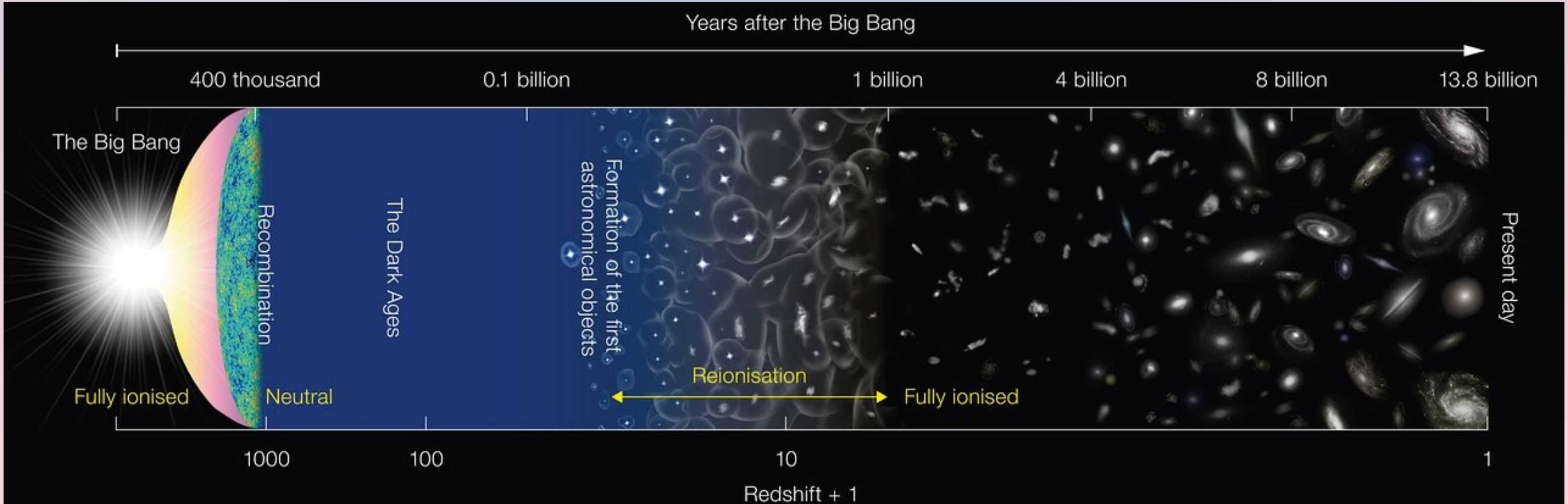
ИЯИЯЕ INRNE

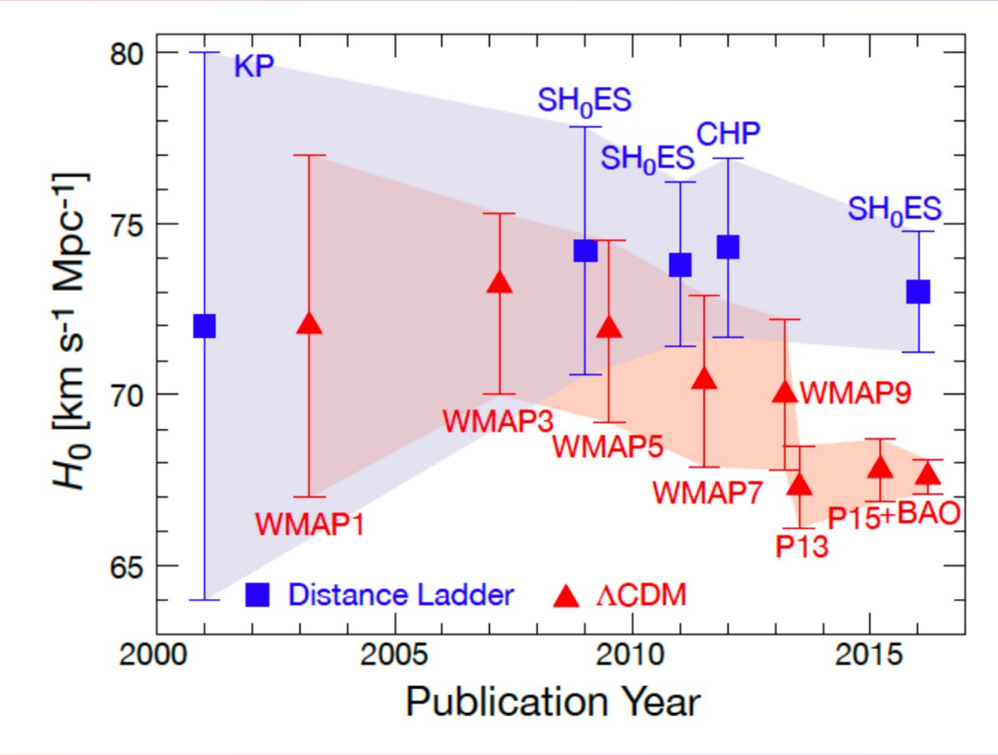
БЪЛГАРСКА АКАДЕМИЯ на НАУКИТЕ 1869

How it all began?

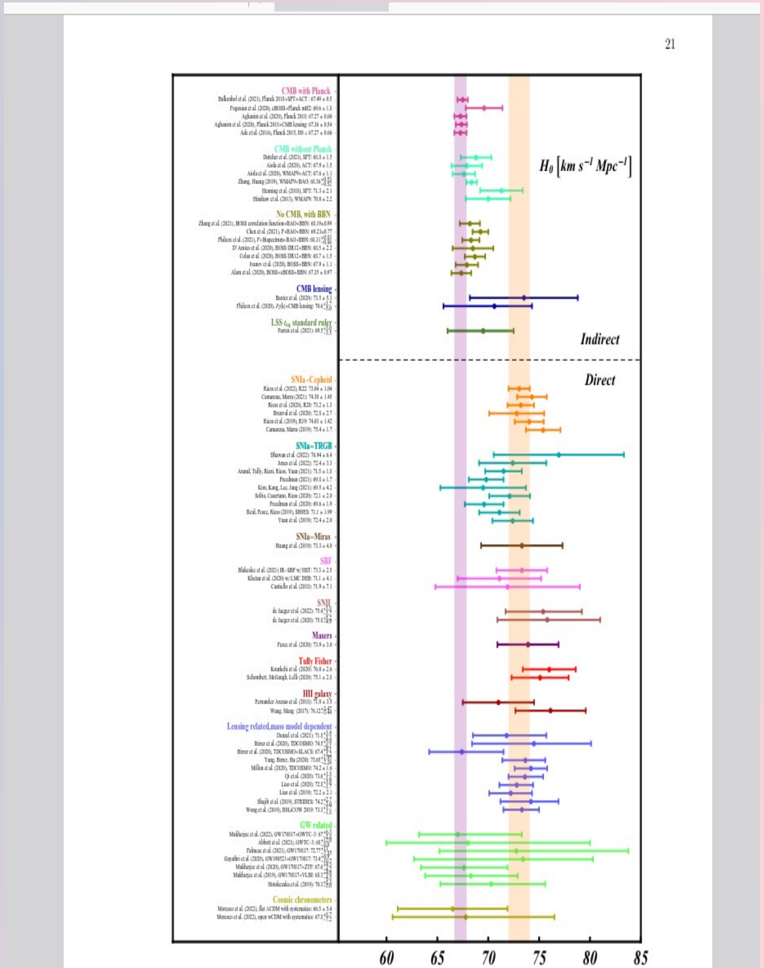
- Current paradigm – the LCDM model
- Different energy components depend differently on the redshift
- Composition – DE (~73%), DM (~23%), baryons, neutrinos, photons (~4%)
- From the local universe we observe accelerated expansion – measured by H_0
- Known epochs – inflation, radiation domination, dark matter domination, dark energy domination



The tensions in cosmology

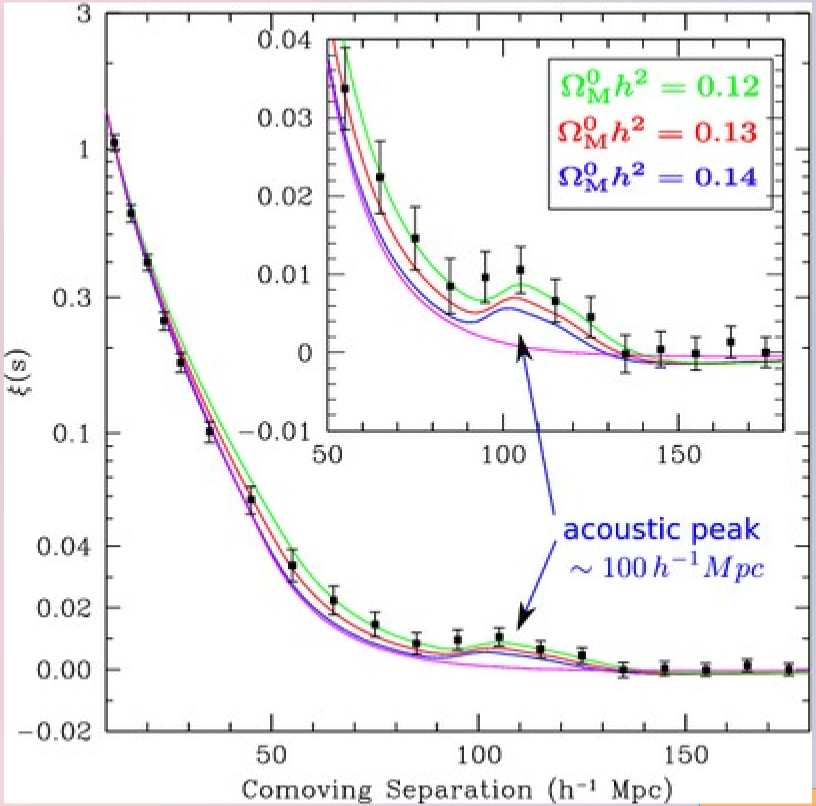


Freedman W., Nature Astronomy, 1, 0169 (2017), arXiv:1706.02739 [astro-ph.CO]



Abdalla et all. J. High En. Astrophys. 2204, 002 (2022) , arXiv: 2203.06142

BAO – „standard ruler“ in cosmology



- Baryonic acoustic oscilations are regular, periodic fluctuations in the density of the visible baryonic matter of the universe.
- Created by the intrerplay of gravity, radiative pressure and the expansion of the universe
- The distance at which plasma waves induced by radiation pressure froze at recombination the sound horizon, r_d
- Measured by looking at the large scale structure of matter

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$c_s(z) = \frac{c}{\sqrt{3\left(1 + \frac{3\Omega_b}{4\Omega_\gamma}\frac{1}{1+z}\right)}}$$

Planck 2018:

r_d=147.5 Mpc,
z_d=1059, z_*=1100.

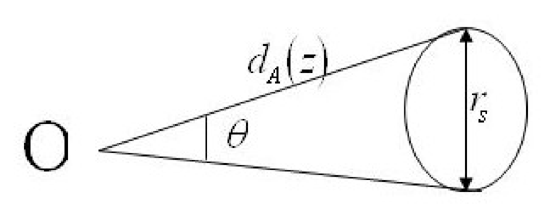
Credit: Eisenstein et al., 2005; Cole et al., 2005

Inferring cosmological parameters from BAO:

We measure the projections:

$$\Delta z = r_d H(z)/c$$

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)}$$



Both quantities ~ $r_d H_0/c$!

And we calculate the distances:

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

$$D_A = D_M/(1+z)$$

with

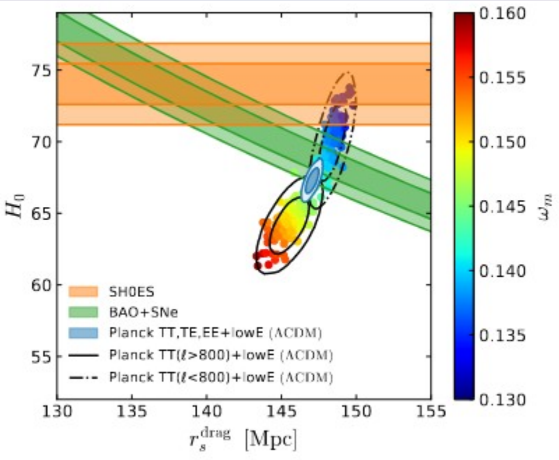
$$S_k(x) = \begin{cases} \frac{1}{\sqrt{\Omega_k}}\sinh\left(\sqrt{\Omega_k}x\right) & \text{if} \quad \Omega_k > 0 \\ x & \text{if} \quad \Omega_k = 0 \\ \frac{1}{\sqrt{-\Omega_k}}\sin\left(\sqrt{-\Omega_k}x\right) & \text{if} \quad \Omega_k < 0. \end{cases}$$

To get the parameters, we solve the Friedmann equations:

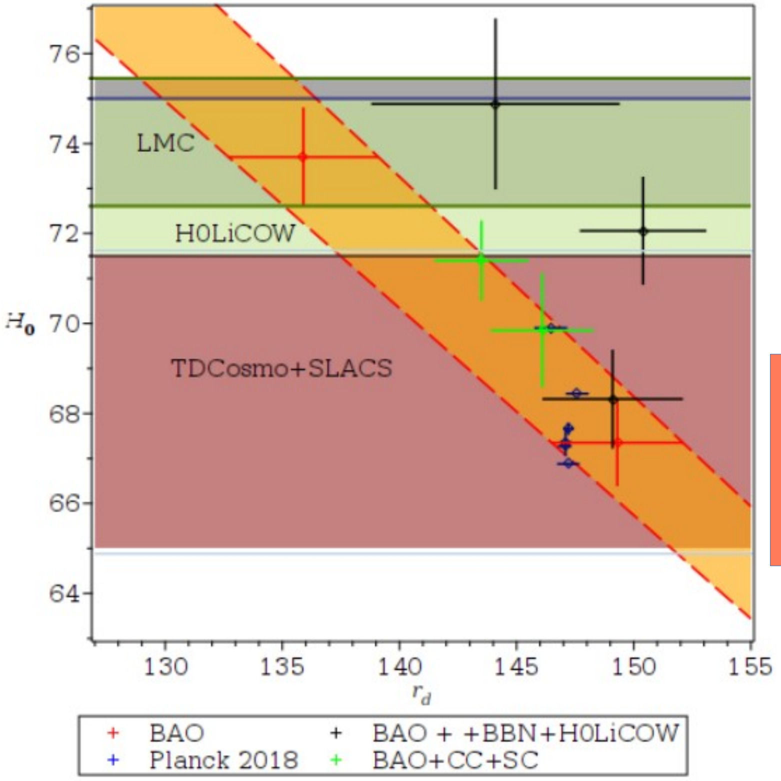
$$H(z)/H_0 = E(z)$$

$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda$$

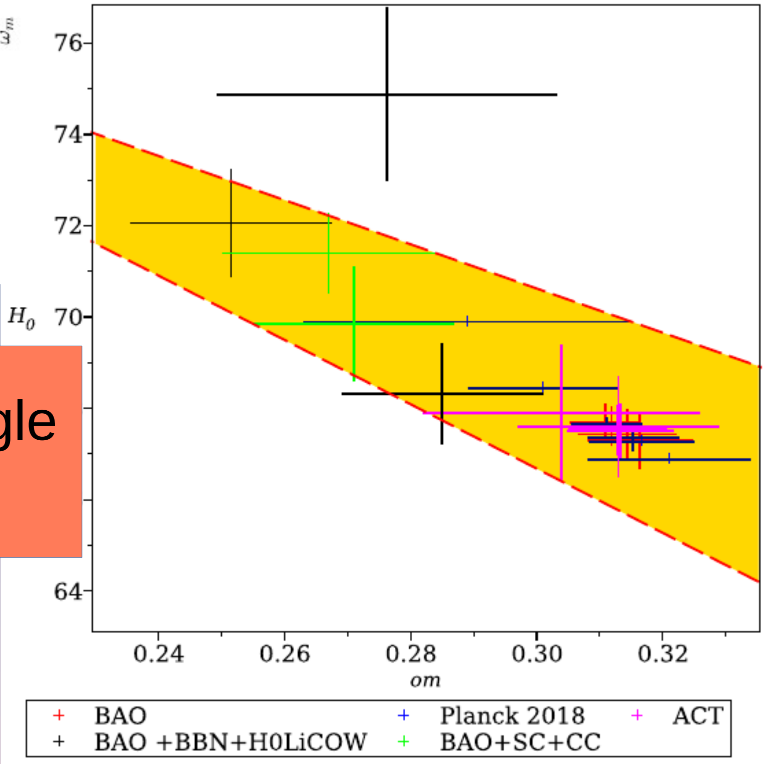
The problem: r_d, H_0 and Ω_m are coupled!



Knox & Millea (2020)
PRD 101, 043533



We need to disentangle them somehow!



D.S., MG-16 proc, arXiv:2111.07907

Where + and + are from D.B&D.S. A&A 647, A38 (2021)

So we marginalise over $H_0 r_d$

- We redefine the χ^2 to integrate over $H_0 r_d$
- We take two BAO datasets:

  - uncorrelated angular BAO

  - a mix of radial + angular BAO + covariances
- To which we add the Pantheon binned SN with the covariances $\tilde{\chi}^2 = \tilde{\chi}^2_{BAO} + \tilde{\chi}^2_{SN}.$
- We use them to constrain DE models (CPL, pEDE, gEDE)

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

where

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

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

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

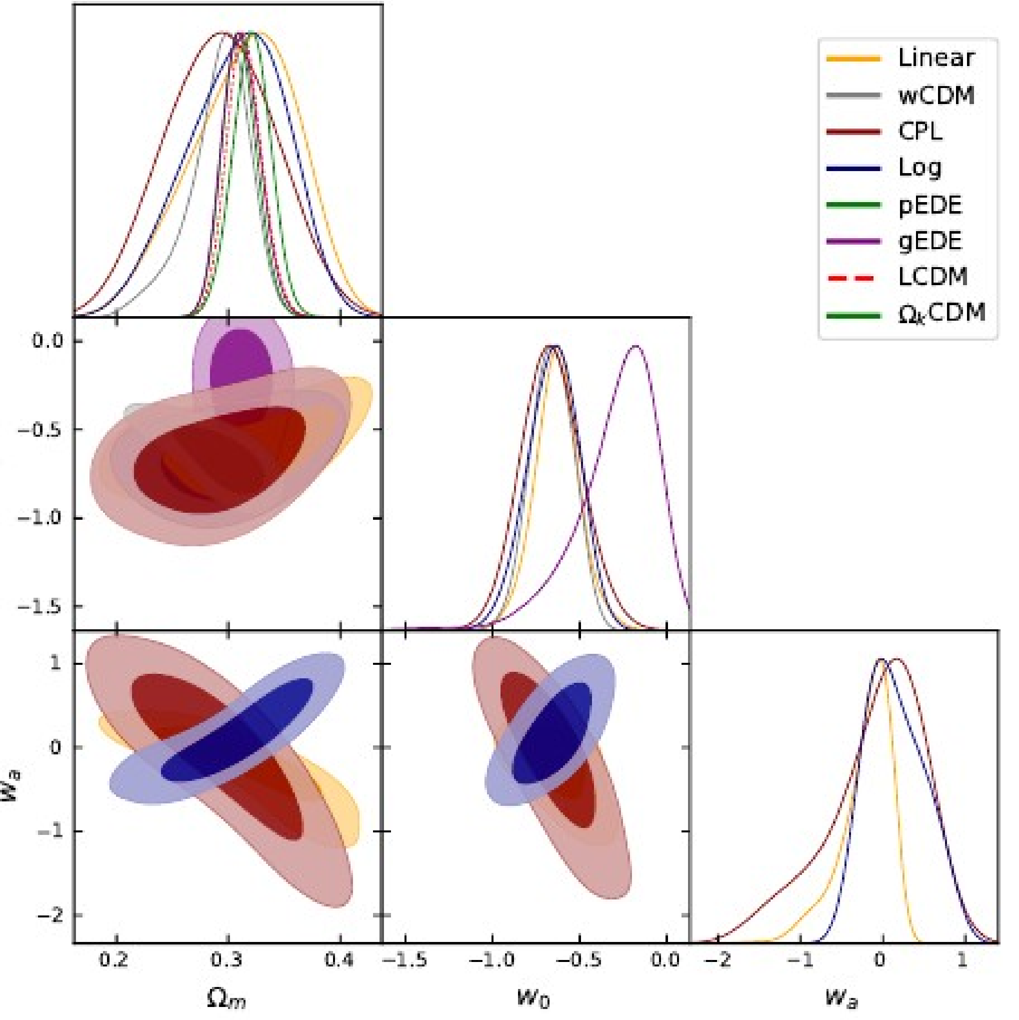
and

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

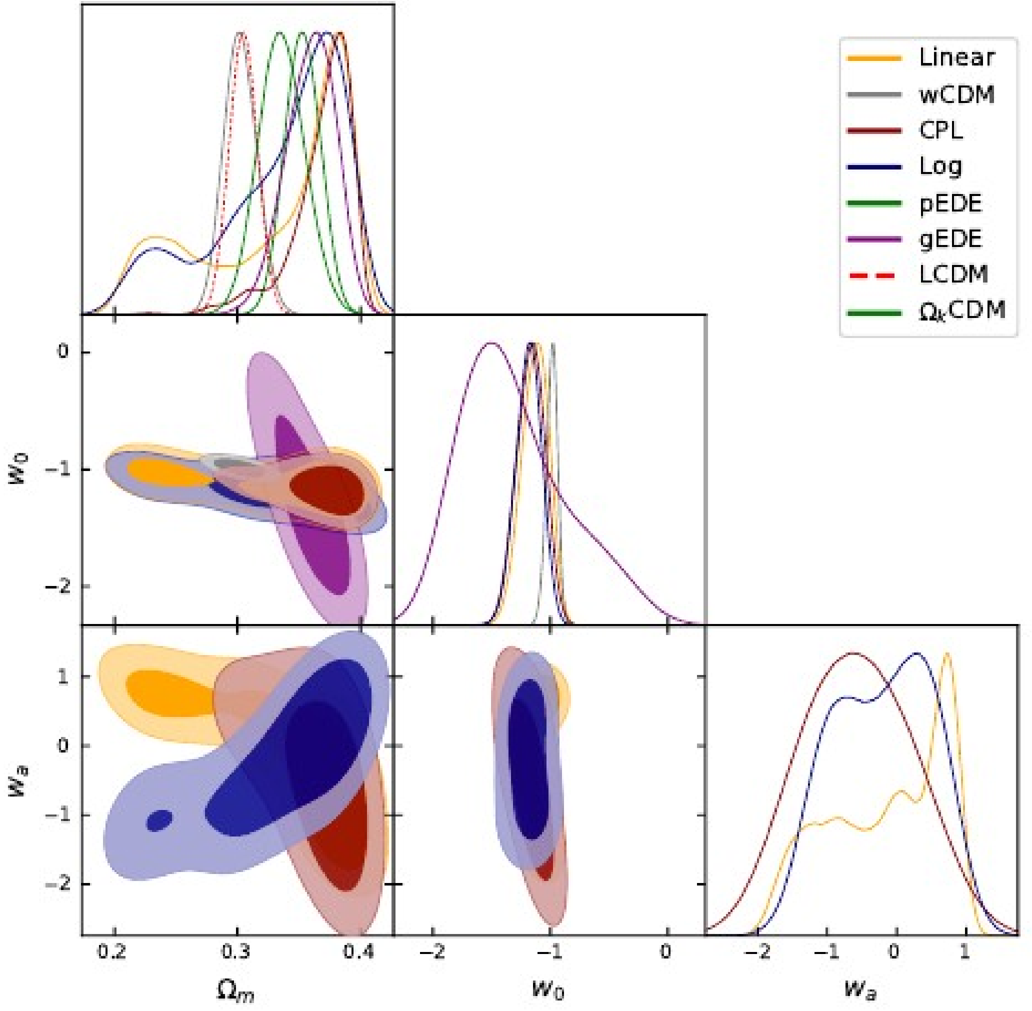
$$\Omega_{DE}(z) = \Omega_\Lambda \frac{1 - \tanh(\Delta \log_{10}(\frac{1+z}{1+z_t}))}{1 + \tanh(\Delta \log_{10}(1+z_t))}$$

$$f(z) = \frac{1}{(1+z)\sqrt{|\Omega_K|}} \mathrm{sinn}\left[|\Omega_K|^{1/2} \int \frac{dz'}{E(z')}\right].$$

Angular BAO

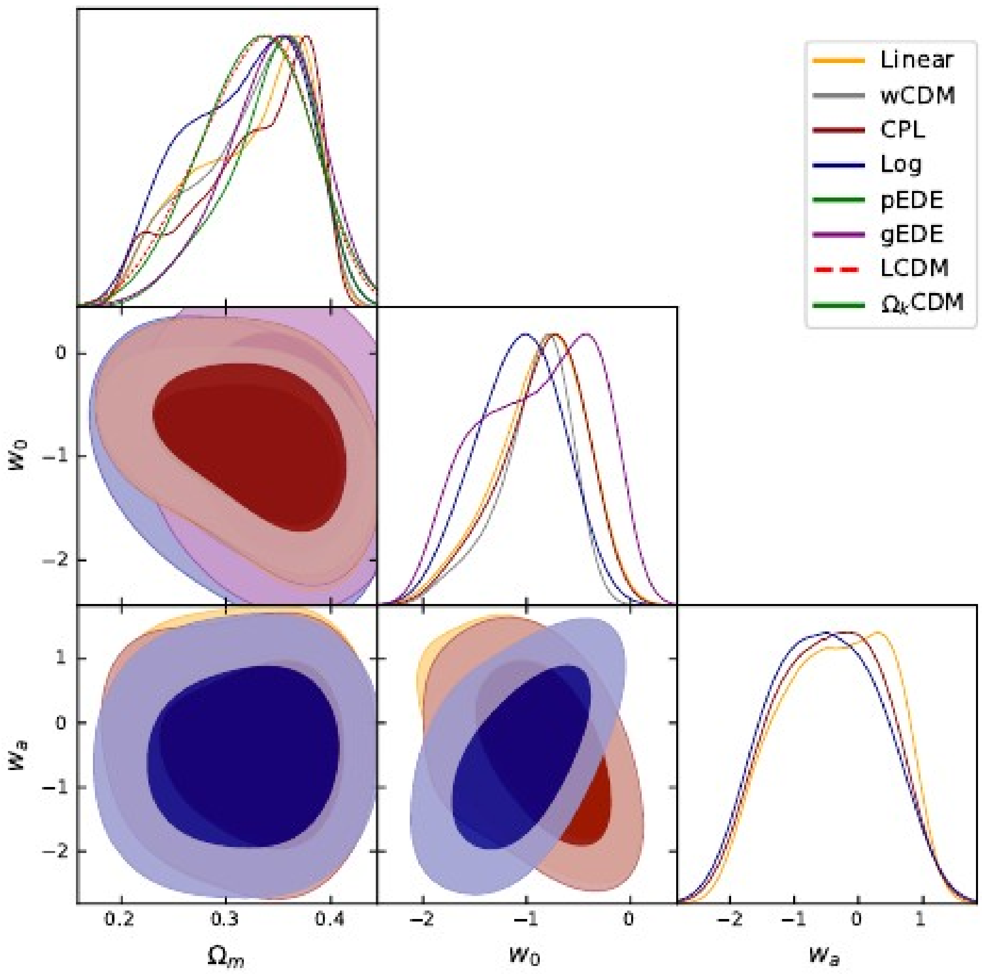


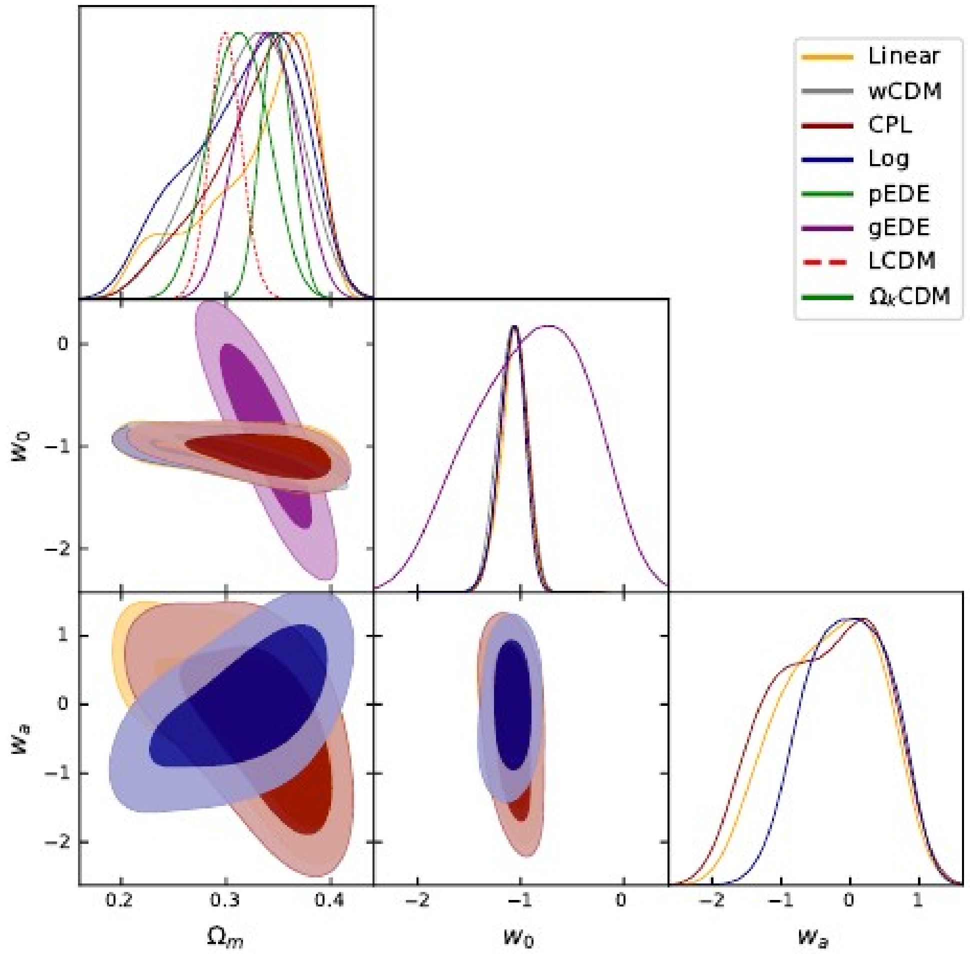
Angular BAO+SN



BAO

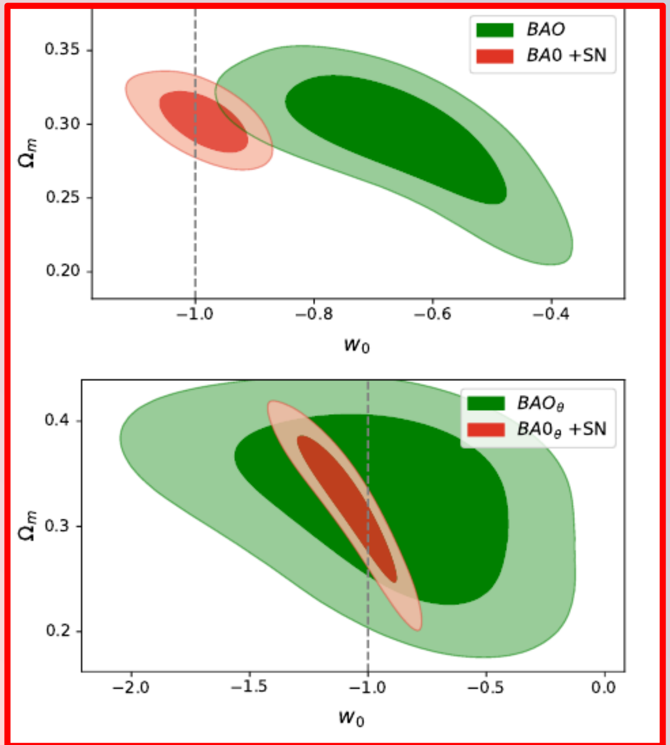
BAO+SN


Linear
wCDM
CPL
Log
pEDE
gEDE
LCDM
Ω_kCDM
w_0
w_a
Ω_m

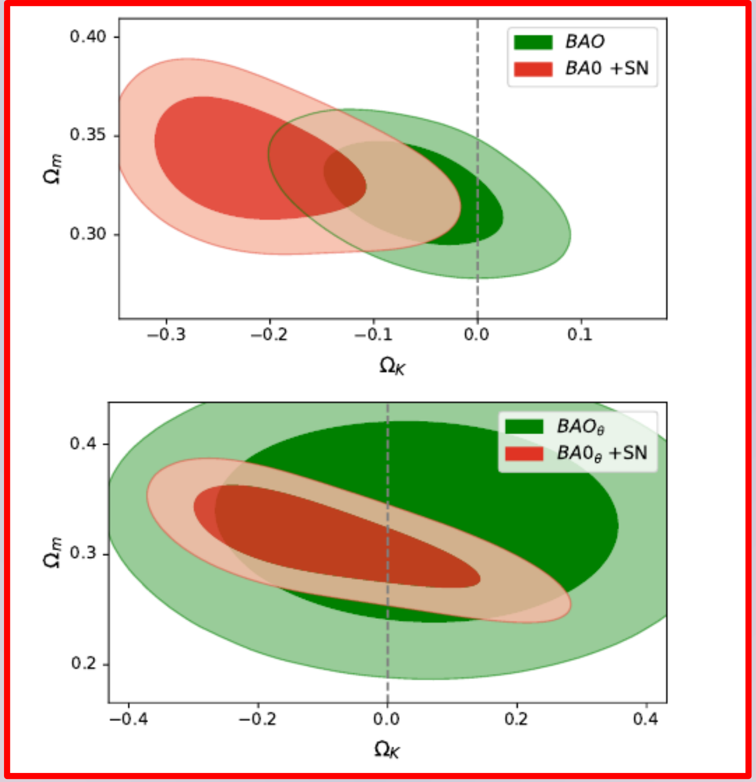

Linear
wCDM
CPL
Log
pEDE
gEDE
LCDM
Ω_kCDM
w_0
w_a
Ω_m

Different datasets, different models

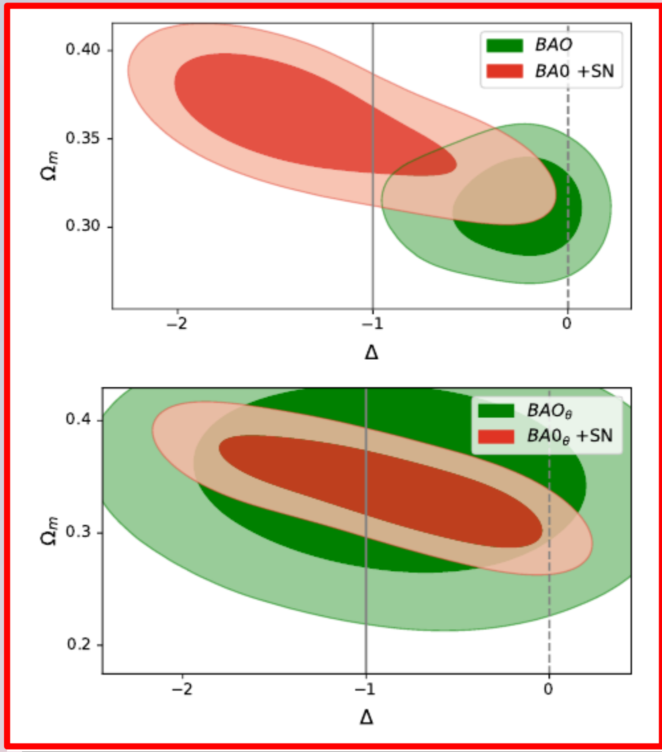
wCDM



OkLCDM

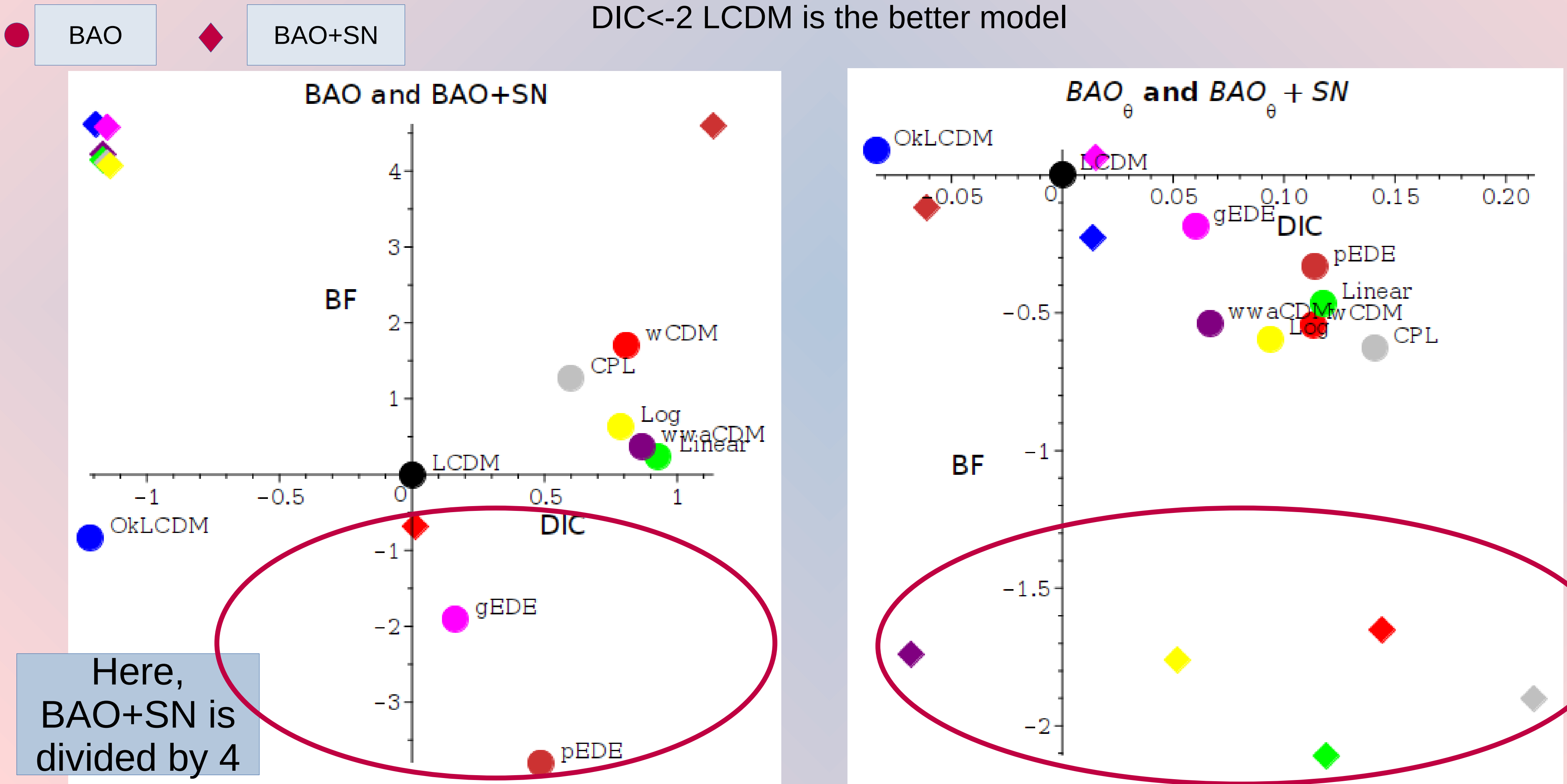


gEDE



Model comparison:

BF>2 LCDM is the better model
DIC<-2 LCDM is the better model



Here, BAO+SN is divided by 4

Conclusions:

- BAO alone are not able to constrain DE models
- Adding SN decreases the errors significantly
- The **angular** BAO dataset and the **mixed one** do not favor the same models (wCDM vs LCDM)
- The marginalization is able to produce interesting results on the cost of bigger error

Numbers are compatible with earlier results:

- BAO + SN:
- $w=-0.986 \pm 0.045$
- $w_0=-1.18\pm0.139$, $w_a=-0.367\pm 0.672$
- BAO_θ+SN
- $w=-1.08 \pm0.14$
- $w_0=-1.09\pm0.09$, $w_a=-0.31\pm0.74$
- **BAO + SN prefers a closed universe ($\Omega_k=-0.21\pm0.07$)**
- **BAO_θ+SN prefers a flat one ($\Omega_k=-0.09\pm0.15$)**

Constraining the dark energy models using the BAO data:
An approach independent of $H_0 \cdot r_d$
Staicova, Benisty
A&A 668, A135 (2022), arXiv:2107.14129 [astro-ph.CO]

More DE models:

- Here we take the factor $H_0 r_d$ as one variable
- Datasets:

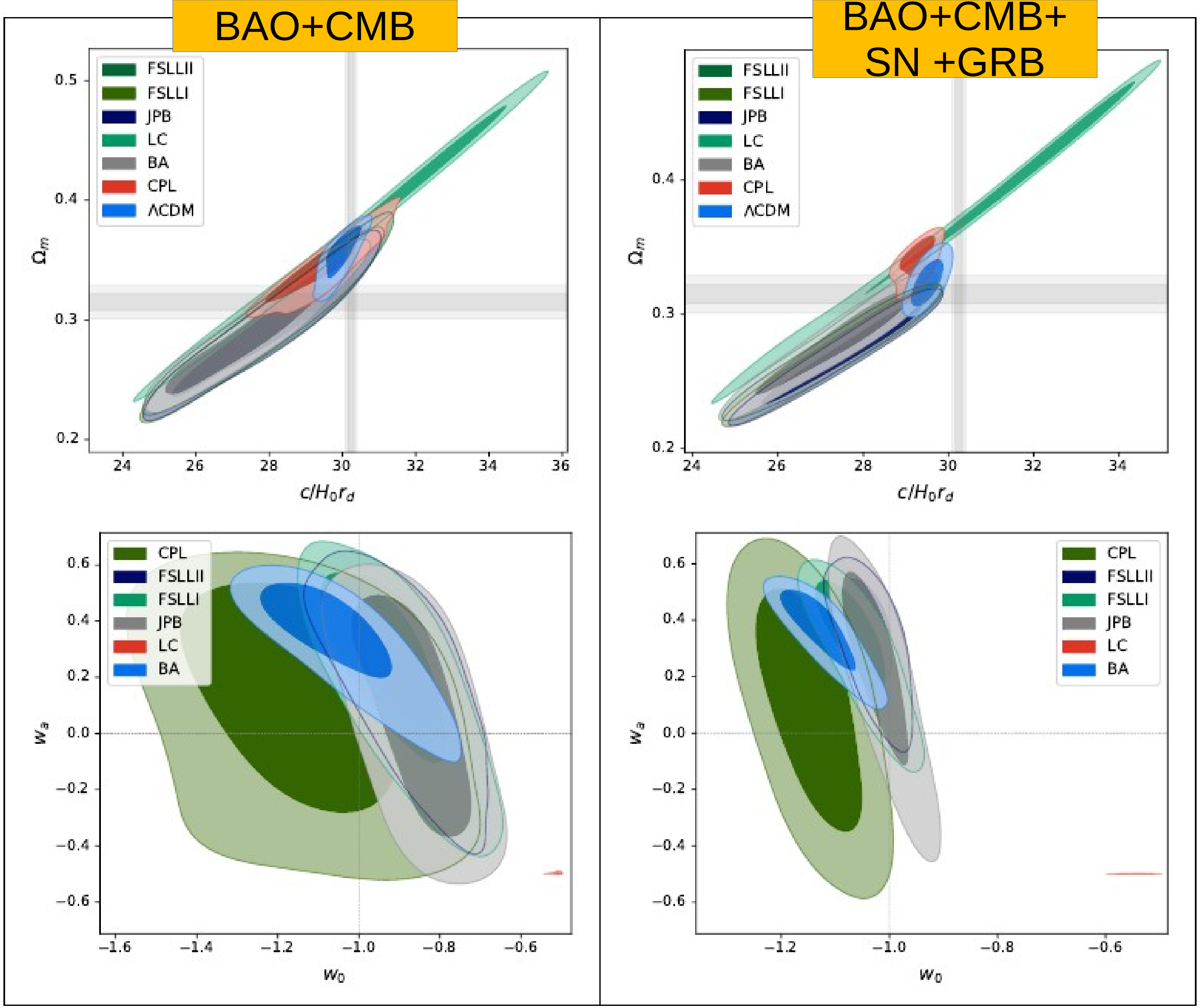
  -BAO+CMB

  -SN

  -GRB

	EOS
Chevalier-Polarski-Linder (CPL)	$\Omega_{DE}(z) = \Omega_\Lambda \exp\left[\int_0^z \frac{3(1+w(z'))dz'}{1+z'}\right]$
Barboza–Alcaniz (BA)	$\Omega_{DE} = \Omega_\Lambda (1+z)^{3(1+w_0)} (1+z^2)^{\frac{3w_1}{2}}$
Low correlation model (LC)	$\Omega_{DE} = \Omega_\Lambda (1+z)^{(3(1-2w_0+3wa))} e^{\frac{9(w_0-wa)z}{(1+z))}}$
Jassal–Bagla–Padmanabhan (JBP)	$\Omega_{DE} = \Omega_\Lambda (1+z)^{3(1+w_0)} e^{\frac{3w_1 z^2}{2(1+z)^2}}$
Feng–Shen–Li–Li (FSLL)	$\Omega^{\pm}_{DE} = \Omega_\Lambda (1+z)^{3(1+w_0)} e^{\pm\frac{3w_1}{2}\arctan(z)} (1+z^2)^{\frac{3w_1}{4}} (1+z)^{\mp\frac{3}{2}w_1}$

Universe 2022, 8(12), 631;arXiv:2211.08139


BAO+CMB
BAO+CMB+
SN +GRB
FSLLII
FSLLI
JPB
LC
BA
CPL
ΛCDM
Ω_m
c/H_0r_d
CPL
FSLLII
FSLLI
JPB
LC
BA
w_a
w_0

Or in terms of the Hubble tension:

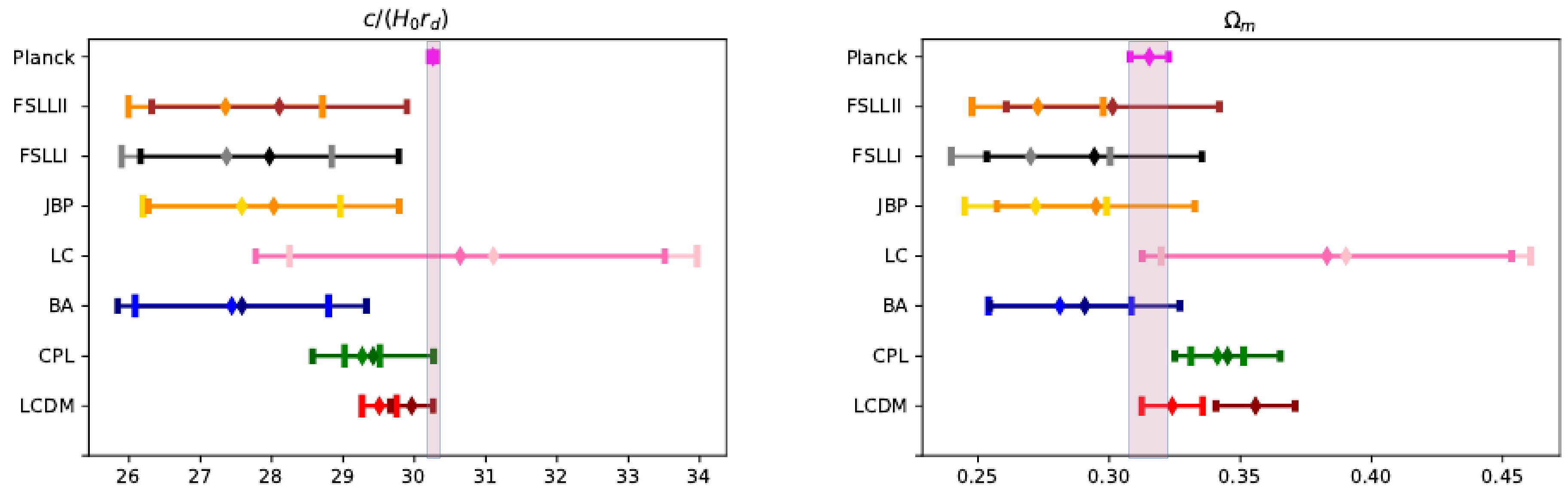
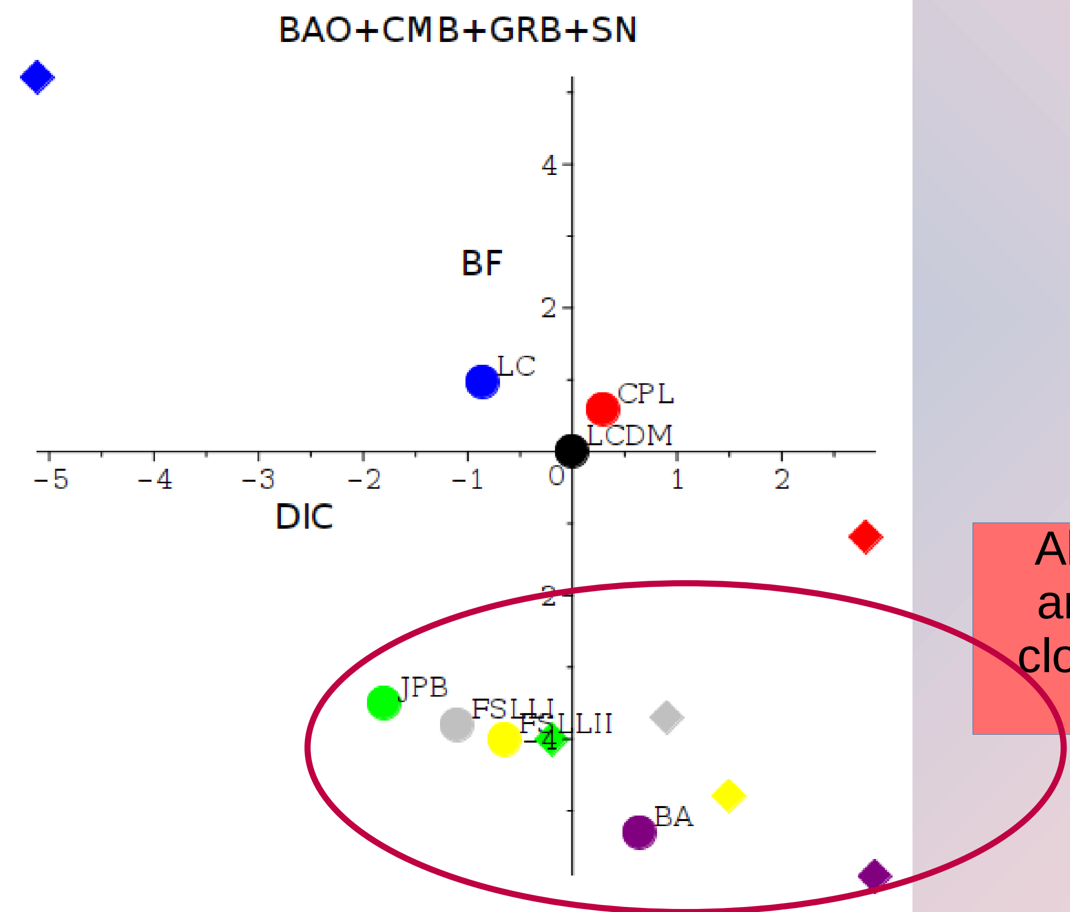


Figure 2. The final values of the $c/(H_0 r_d)$ from different DE models, compared to the values from Planck for the BAO+CMB+SN+GRB dataset. The smaller, darker, errorbox are for BAO+CMB, the lighter, bigger errorbox–for SN+GRB.

Comparison of the models

Here, LC is divided by 40 to fit the plot.



All models but LC and CPL are very close or better than LCDM

On the Robustness of the Constancy of the Supernova Absolute Magnitude:
Non-parametric Reconstruction & Bayesian approaches

D. Benisty, J. Mifsud, J. Levi Said, D. Staicova arXiv:2202.04677

- M_B from SN is considered a constant
- What will happen if we callibrate it with BAO measurements?
- Datasets: BAO + SN
- Methods: ANN, GP,

  MCMC

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

$$\mu_{Ia}(z) = 5\log_{10}\left[d_L(z)\right] + 25 + M_B(z)\,,$$

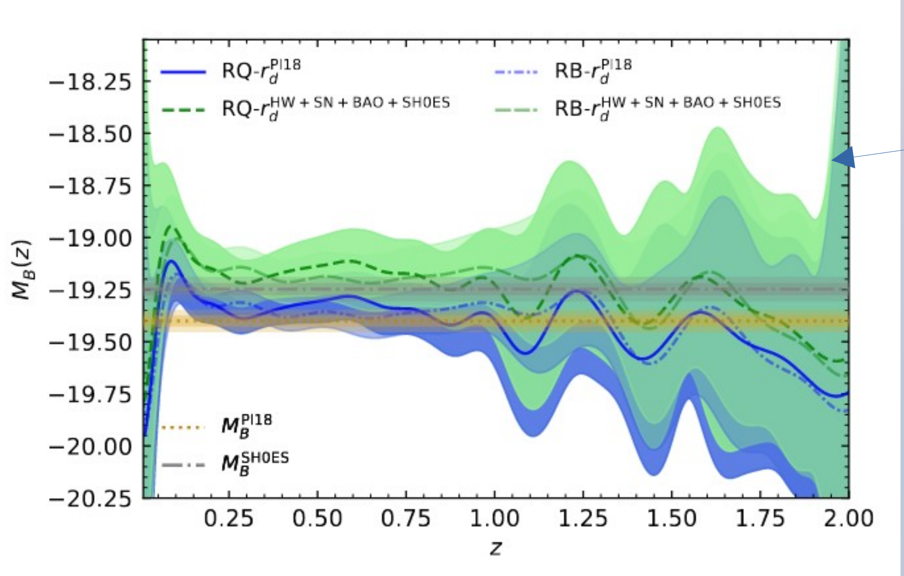
$$M_B = \mu_{Ia} - 5\log_{10}\left[(1+z)^2\left(\frac{D_A}{r_d}\right)_{\rm BAO}\cdot r_d\right] - 25\,, \quad (3a)$$

$$\Delta M_B = \Delta\mu_{Ia} + \frac{5}{\ln 10}\left[\frac{\Delta r_d}{r_d} + \frac{\Delta\left(D_A/r_d\right)_{BAO}}{\left(D_A/r_d\right)_{BAO}}\right]\,. \quad (3b)$$

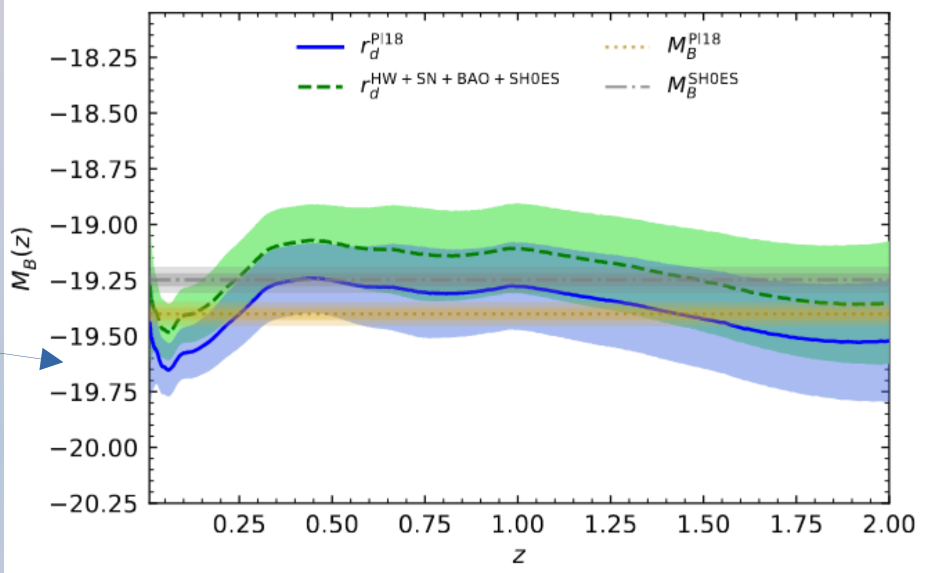
Distance Duality Relation?

$$d_L(z) = (1+z)^2 d_A(z))$$

Phys.Dark Univ. 39 (2023) 101160, arXiv:2202.04677



GP



ANN

Radial Basis (RB)

$$k(z,\tilde{z}) = \sigma_f^2 \exp\left(-\frac{(z-\tilde{z})^2}{2l^2}\right),$$

GP

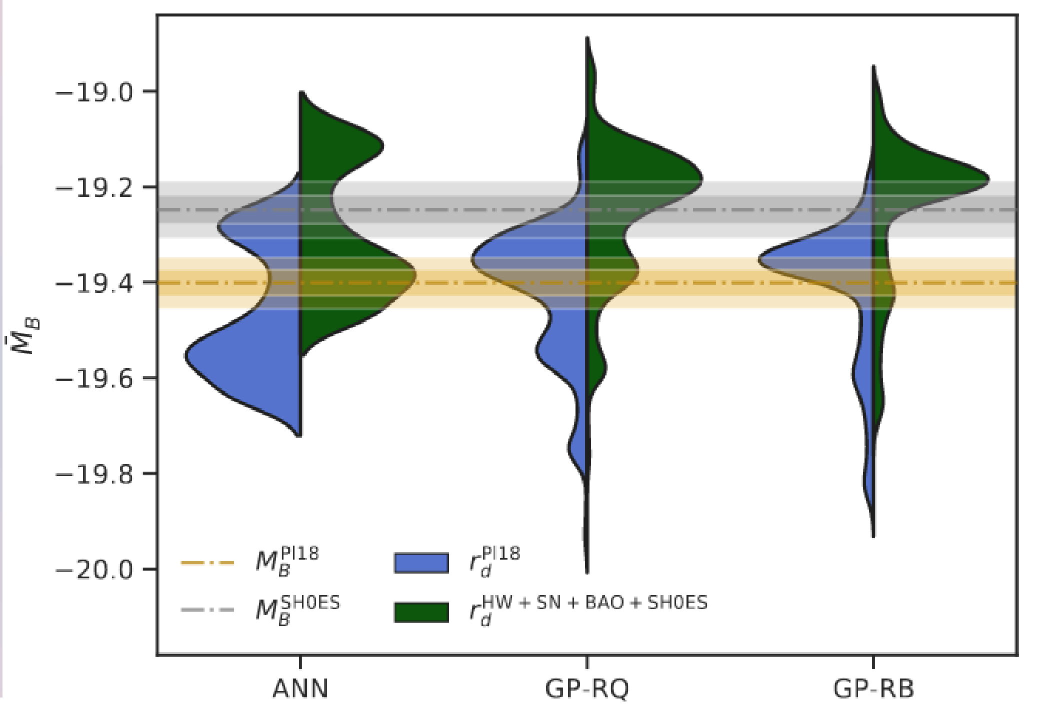
Rational Quadratic (RQ)

$$k(z,\tilde{z}) = \frac{\sigma_f^2}{\left(1+|z-z'|^2/2\alpha l^2\right)^{\alpha}}.$$

ANN

$$\begin{aligned}\text{risk} &= \sum_{i=1}^{N} \text{bias}_i^2 + \sum_{i=1}^{N} \text{variance}_i \\ &= \sum_{i=1}^{N} \left[\mu_{Ia}(z_i) - \bar{\mu}_{Ia}(z_i)\right]^2 + \sum_{i=1}^{N} \sigma_{Ia}^2\left(\mu_{Ia}(z_i)\right),\end{aligned}$$

Is it constant? Not 1 Gaussian!

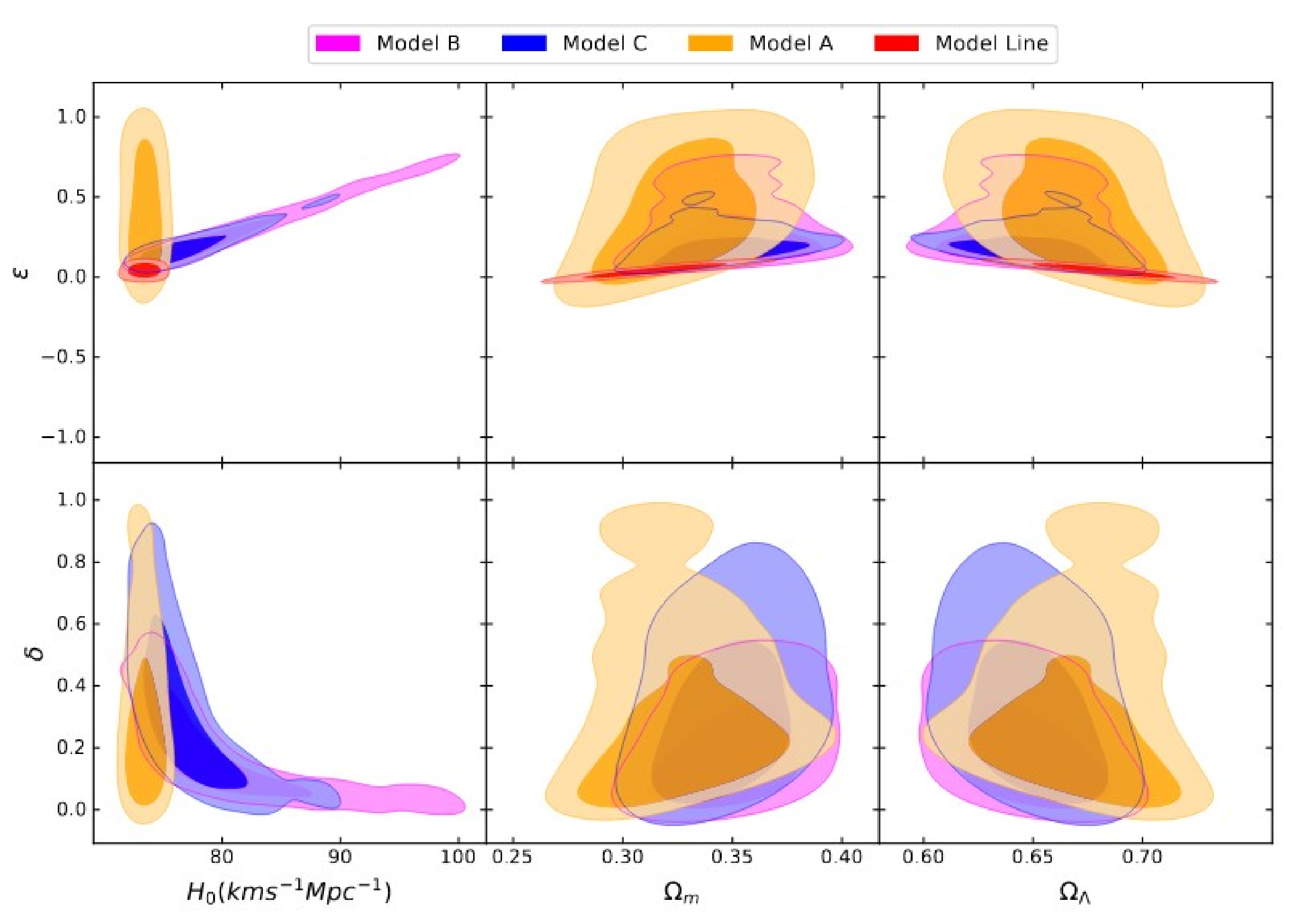


Technique	$r_{d,fit}^{\mathrm{Pl18}}$	$r_{d,fit}^{\mathrm{HW+SN+BAO+SH0ES}}$	$r_{d,full}^{\mathrm{Pl18}}$	$r_{d,full}^{\mathrm{HW+SN+BAO+SH0ES}}$
ANN	-19.58 ± 0.11 and -19.26 ± 0.04	-19.1 ± 0.04 and -19.42 ± 0.11	-19.38 ± 0.20	-19.22 ± 0.20
GP-RQ	-19.35 ± 0.03	-19.18 ± 0.03	-19.42 ± 0.35	-19.25 ± 0.39
GP-RB	-19.35 ± 0.07	-19.18 ± 0.07	-19.42 ± 0.29	-19.25 ± 0.33

We tested known models for the nuissance parameter

$$\mu_{obs} = m_B^* - (M_B - \alpha X_1 + \beta C),$$

$$\delta M_B(z) = \begin{cases} \epsilon z & \text{Model Line} \\ \epsilon\left[(1+z)^\delta - 1\right] & \text{Model A} \\ \epsilon z^\delta & \text{Model B} \\ \epsilon\left[\ln(1+z)\right]^\delta & \text{Model C} \ . \end{cases}$$



Conclusions:

- **The constancy of M_B is at level of 1σ.**
- The MCMC do not prefer any of the tested non-constant model significantly.
- **We exchange the tension in H_0-r_d with a tension in the M_B-r_d plane**

Thank you for your attention!