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SNe Ia, BAO and GRB cosmology to tackle the Hubble constant tension

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The Hubble constant and its tension

$\boldsymbol{H_0}$ TENSION due to its evolution or evolution of its parameters or new physics

$$v = H_0 \cdot D$$

HUBBLE'S LAW

M. G. Dainotti, De Simone, Schiavone, Montani, Rinaldi et al., 2021, ApJ, 912, 150.

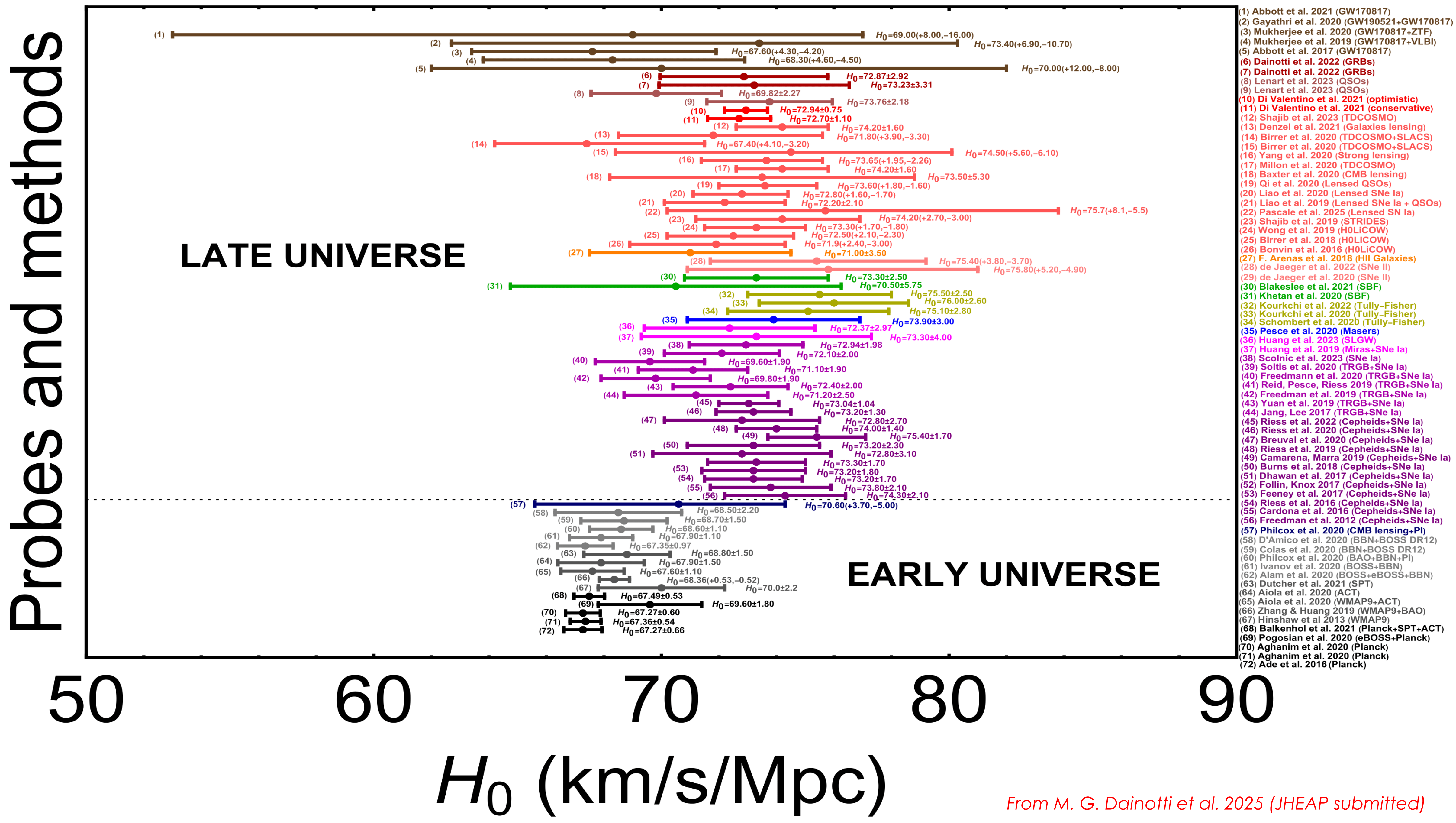
M. G. Dainotti, De Simone, Schiavone, Montani, Rinaldi et al.,, Galaxies, vol. 10, issue 1, 24.

~ 500 citations listed in top 1% papers in web of Science)

Montani, Carlevaro, Dainotti, PDU, 44, 2024, 101486

Montani, Carlevaro, Dainotti, PDU, 480, 1847M

- [2501.11772] A New Master Supernovae Ia sample and the investigation of the H_0 tension **(Dainotti**, De Simone, Mondal, Kohri, Kazunori, do Espírito Santo Pedreira,Bashyal, Angel; Dejrah, Nagataki, Shigehiro; et al. JHEAP submitted



Probes and methods
LATE UNIVERSE
EARLY UNIVERSE
H_0 (km/s/Mpc)
50
60
70
80
90
(1) H_0=69.00(+8.00,−16.00)
(2) H_0=73.40(+6.90,−10.70)
(3) H_0=67.60(+4.30,−4.20)
(4) H_0=68.30(+4.60,−4.50)
(5) H_0=70.00(+12.00,−8.00)
(6) H_0=72.87±2.92
(7) H_0=73.23±3.31
(8) H_0=69.82±2.27
(9) H_0=73.76±2.18
(10) H_0=72.94±0.75
(11) H_0=72.70±1.10
(12) H_0=74.20±1.60
(13) H_0=71.80(+3.90,−3.30)
(14) H_0=67.40(+4.10,−3.20)
(15) H_0=74.50(+5.60,−6.10)
(16) H_0=73.65(+1.95,−2.26)
(17) H_0=74.20±1.60
(18) H_0=73.50±5.30
(19) H_0=73.60(+1.80,−1.60)
(20) H_0=72.80(+1.60,−1.70)
(21) H_0=72.20±2.10
(22) H_0=75.7(+8.1,−5.5)
(23) H_0=74.20(+2.70,−3.00)
(24) H_0=73.30(+1.70,−1.80)
(25) H_0=72.50(+2.10,−2.30)
(26) H_0=71.9(+2.40,−3.00)
(27) H_0=71.00±3.50
(28) H_0=75.40(+3.80,−3.70)
H_0=75.80(+5.20,−4.90)
(30) H_0=73.30±2.50
(31) H_0=70.50±5.75
(32) H_0=75.50±2.50
(33) H_0=76.00±2.60
(34) H_0=75.10±2.80
(35) H_0=73.90±3.00
(36) H_0=72.37±2.97
(37) H_0=73.30±4.00
(38) H_0=72.94±1.98
(39) H_0=72.10±2.00
(40) H_0=69.60±1.90
(41) H_0=71.10±1.90
(42) H_0=69.80±1.90
(43) H_0=72.40±2.00
(44) H_0=71.20±2.50
(45) H_0=73.04±1.04
(46) H_0=73.20±1.30
(47) H_0=72.80±2.70
(48) H_0=74.00±1.40
(49) H_0=75.40±1.70
(50) H_0=73.20±2.30
(51) H_0=72.80±3.10
H_0=73.30±1.70
(53) H_0=73.20±1.80
(54) H_0=73.20±1.70
(55) H_0=73.80±2.10
(56) H_0=74.30±2.10
(57) H_0=70.60(+3.70,−5.00)
(58) H_0=68.50±2.20
(59) H_0=68.70±1.50
(60) H_0=68.60±1.10
(61) H_0=67.90±1.10
(62) H_0=67.35±0.97
(63) H_0=68.80±1.50
(64) H_0=67.90±1.50
(65) H_0=67.60±1.10
(66) H_0=68.36(+0.53,−0.52)
(67) H_0=70.0±2.2
(68) H_0=67.49±0.53
(69) H_0=69.60±1.80
(70) H_0=67.27±0.60
(71) H_0=67.36±0.54
(72) H_0=67.27±0.66
(1) Abbott et al. 2021 (GW170817)
(2) Gayathri et al. 2020 (GW190521+GW170817)
(3) Mukherjee et al. 2020 (GW170817+ZTF)
(4) Mukherjee et al. 2019 (GW170817+VLBI)
(5) Abbott et al. 2017 (GW170817)
(6) Dainotti et al. 2022 (GRBs)
(7) Dainotti et al. 2022 (GRBs)
(8) Lenart et al. 2023 (QSOs)
(9) Lenart et al. 2023 (QSOs)
(10) Di Valentino et al. 2021 (optimistic)
(11) Di Valentino et al. 2021 (conservative)
(12) Shajib et al. 2023 (TDCOSMO)
(13) Denzel et al. 2021 (Galaxies lensing)
(14) Birrer et al. 2020 (TDCOSMO+SLACS)
(15) Birrer et al. 2020 (TDCOSMO+SLACS)
(16) Yang et al. 2020 (Strong lensing)
(17) Millon et al. 2020 (TDCOSMO)
(18) Baxter et al. 2020 (CMB lensing)
(19) Qi et al. 2020 (Lensed QSOs)
(20) Liao et al. 2020 (Lensed SNe Ia)
(21) Liao et al. 2019 (Lensed SNe Ia + QSOs)
(22) Pascale et al. 2025 (Lensed SN Ia)
(23) Shajib et al. 2019 (STRIDES)
(24) Wong et al. 2019 (H0LiCOW)
(25) Birrer et al. 2018 (H0LiCOW)
(26) Bonvin et al. 2016 (H0LiCOW)
(27) F. Arenas et al. 2018 (HII Galaxies)
(28) de Jaeger et al. 2022 (SNe II)
(29) de Jaeger et al. 2020 (SNe II)
(30) Blakeslee et al. 2021 (SBF)
(31) Khetan et al. 2020 (SBF)
(32) Kourkchi et al. 2022 (Tully-Fisher)
(33) Kourkchi et al. 2020 (Tully-Fisher)
(34) Schombert et al. 2020 (Tully-Fisher)
(35) Pesce et al. 2020 (Masers)
(36) Huang et al. 2023 (SLGW)
(37) Huang et al. 2019 (Miras+SNe Ia)
(38) Scolnic et al. 2023 (SNe Ia)
(39) Soltis et al. 2020 (TRGB+SNe Ia)
(40) Freedmann et al. 2020 (TRGB+SNe Ia)
(41) Reid, Pesce, Riess 2019 (TRGB+SNe Ia)
(42) Freedman et al. 2019 (TRGB+SNe Ia)
(43) Yuan et al. 2019 (TRGB+SNe Ia)
(44) Jang, Lee 2017 (TRGB+SNe Ia)
(45) Riess et al. 2022 (Cepheids+SNe Ia)
(46) Riess et al. 2020 (Cepheids+SNe Ia)
(47) Breuval et al. 2020 (Cepheids+SNe Ia)
(48) Riess et al. 2019 (Cepheids+SNe Ia)
(49) Camarena, Marra 2019 (Cepheids+SNe Ia)
(50) Burns et al. 2018 (Cepheids+SNe Ia)
(51) Dhawan et al. 2017 (Cepheids+SNe Ia)
(52) Follin, Knox 2017 (Cepheids+SNe Ia)
(53) Feeney et al. 2017 (Cepheids+SNe Ia)
(54) Riess et al. 2016 (Cepheids+SNe Ia)
(55) Cardona et al. 2016 (Cepheids+SNe Ia)
(56) Freedman et al. 2012 (Cepheids+SNe Ia)
(57) Philcox et al. 2020 (CMB lensing+Pl)
(58) D'Amico et al. 2020 (BBN+BOSS DR12)
(59) Colas et al. 2020 (BBN+BOSS DR12)
(60) Philcox et al. 2020 (BAO+BBN+Pl)
(61) Ivanov et al. 2020 (BOSS+BBN)
(62) Alam et al. 2020 (BOSS+eBOSS+BBN)
(63) Dutcher et al. 2021 (SPT)
(64) Aiola et al. 2020 (ACT)
(65) Aiola et al. 2020 (WMAP9+ACT)
(66) Zhang & Huang 2019 (WMAP9+BAO)
(67) Hinshaw et al 2013 (WMAP9)
(68) Balkenhol et al. 2021 (Planck+SPT+ACT)
(69) Pogosian et al. 2020 (eBOSS+Planck)
(70) Aghanim et al. 2020 (Planck)
(71) Aghanim et al. 2020 (Planck)
(72) Ade et al. 2016 (Planck)
From M. G. Dainotti et al. 2025 (JHEAP submitted)

From the Philipp's relation to the 3-parameter relation

The observed distance moduli of SNe Ia can be expressed through the modified Tripp formula (Scolnic et al. 2018):

Peak magnitude (B-band)

Absolute magnitude (B-band)

Stretch

Color

Host galaxy mass correction

$$\mu_{\rm obs} = m_B - M + \alpha x_1 - \beta c + \Delta M + \Delta B$$

Bias correction

M is the absolute magnitude of a reference SN (in B band) with stretch = 0 and color = 0

M is degenerate with H0

Theory vs. Data

FOR EACH BIN OF SUPERNOVAE Ia, A χ^2 TEST IS PERFORMED IN ORDER TO FIND THE BEST VALUE FOR H_0

$$\mu_{obs}^{(SN)} = m_B - M + \alpha x_1 - \beta c + \Delta M + \Delta B$$

$$\mu_{th}^{(SN)}(z, H_0, \dots) = 5 * \log_{10}\left(\frac{d_L(z.H_0, \dots)}{10pc}\right) + 25$$

$$\chi^2 = \sum_i \frac{(\mu_{obs}^i - \mu_{th}^i)^2}{{\varepsilon_{\mu obs}^i}^2}$$

THIS IS THE GENERALIZATION WITH THE COVARIANCE MATRIX C, WHICH INCLUDES STATISTICAL UNCERTAINTIES (DIAGONAL PART) AND SYSTEMATIC CONTRIBUTIONS (OFF-DIAGONAL)

$$\chi_{SNe}^2 = \Delta\mu^T C^{-1} \Delta\mu$$

$$\Delta\mu = \mu_{obs}^{(SN)} - \mu_{th}^{(SN)}$$

The BAO contribution

The total χ^2

$$\chi^2 = \chi^2_{SNe} + \chi^2_{BAOs}$$

$$\chi^2_{BAO} = \Delta d^T \cdot \mathcal{M}^{-1} \cdot \Delta d,$$

$$\Delta d = d_z^{obs}(z_i) - d_z^{theo}(z_i)$$

Rs= sound horizon

Degeneracy between rs Ho and E(z)

$$D_V(z) = \left[\frac{czd_L^2(z)}{(1+z)^2 H(z)}\right]^{1/3}, \qquad d_z(z) = \frac{r_s(z_d)}{D_V(z)}.$$

COSMOLOGICAL MODELS Adopted

The cosmological models

$$d_L(z.H_0, \ldots) = c(1+z)\int_0^{z'} \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_{0m}\,(1+z)^3 + \cancel{\Omega_{0r}\,(1+z)^4} + \Omega_{0\Lambda} + \cancel{\Omega_{0k}\,(1+z)^2}} \qquad (\Lambda CDM)$$

Radiation is neglected

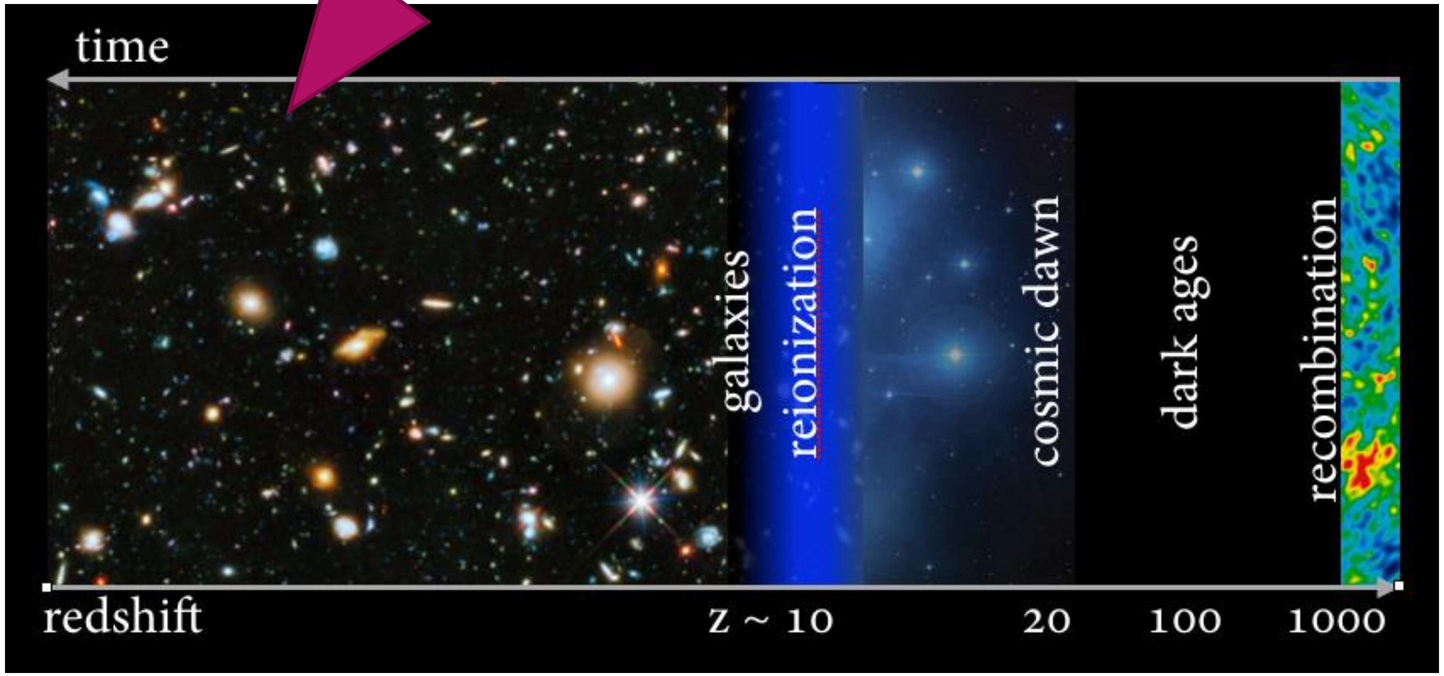
Curvature is neglected

Ω_{0DE}= dark energy density in the $w_0 w_a CDM$

$$(w_0 w_a CDM) \qquad H(z) = H_0\sqrt{\Omega_{0m}\,(1+z)^3 + \Omega_{0DE}\,(1+z)^{3\,(1+w_0+w_a)}\;e^{-3\,w_a\,\frac{z}{1+z}}}$$

Our work on the Hubble constant tension

We divide the **Pantheon sample** (1048 SNe Ia with $0 < z < 2.26$, Scolnic et al. 2018)
Bins (3,4,20,40) ordered in redshift + Baryon Acoustic Oscillations



EACH H_0 IS ESTIMATED IN ONE BIN

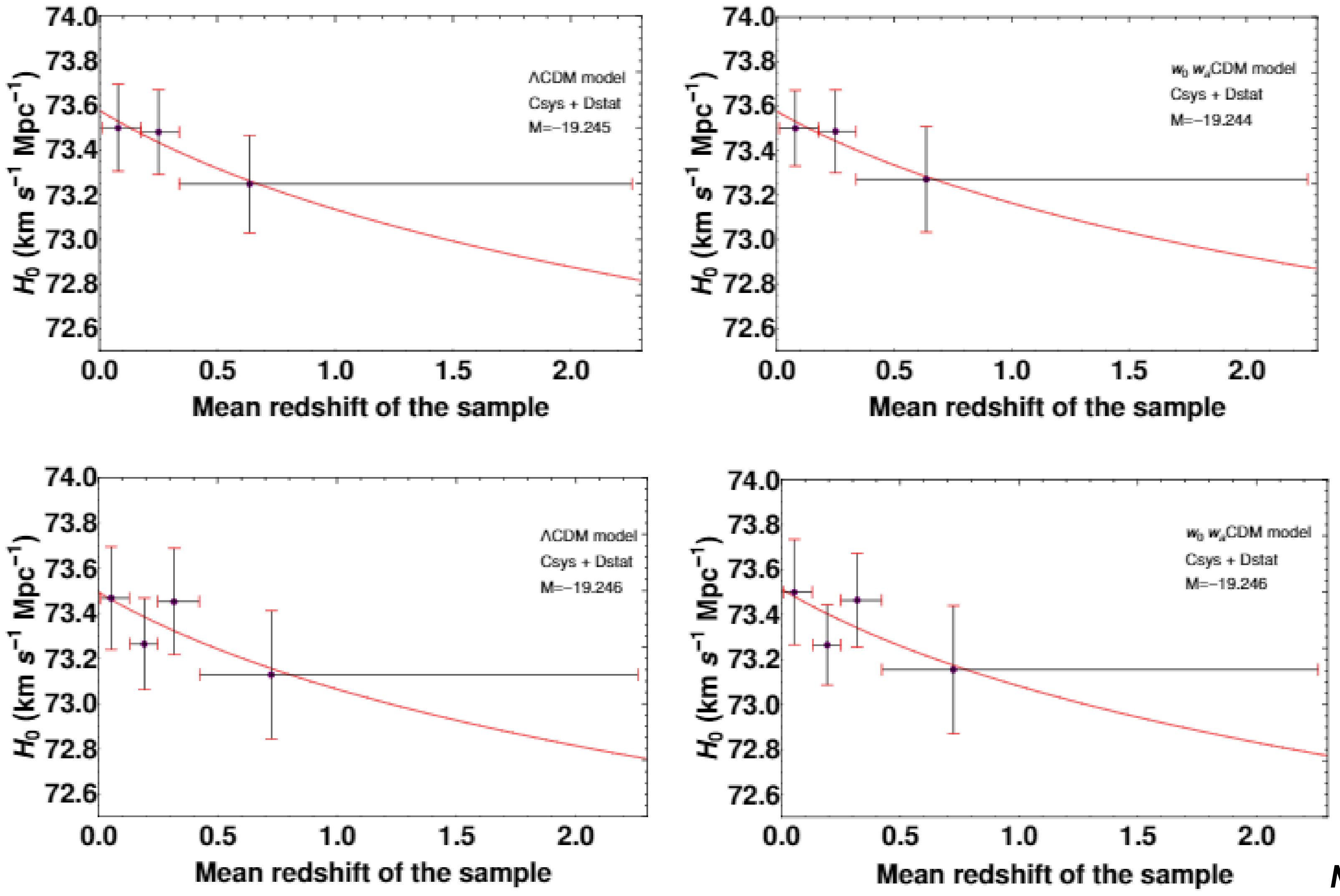
After we obtain several Ho values, we fit those with

$$g(z) = \frac{\tilde{H}_0}{(1+z)^{\alpha}}$$

α = evolution parameter

$\tilde{H}_0 = H_0(z=0)$

Results for ΛCDM and wowaCDM model (3, 4 bins)

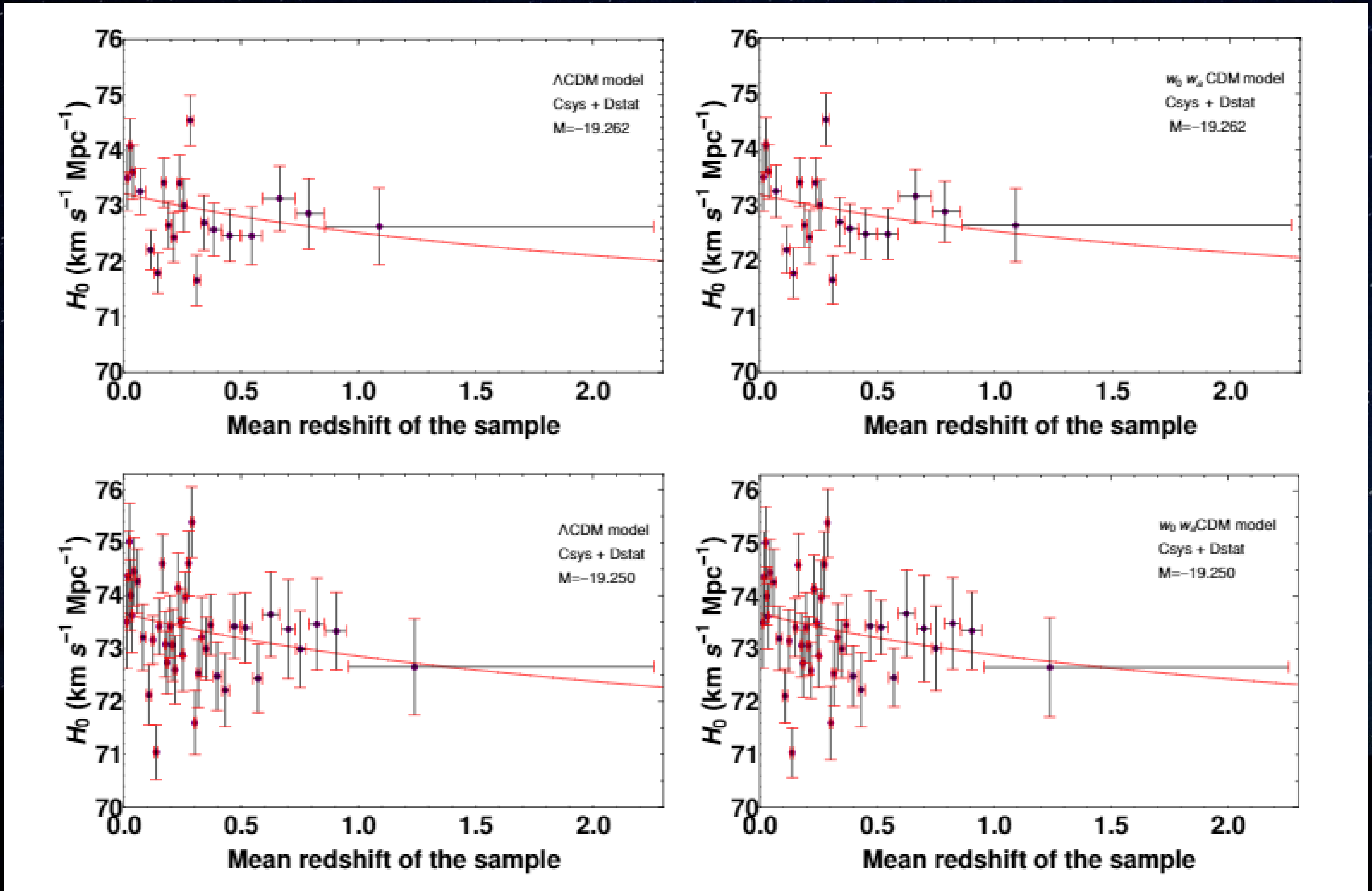


The $w_0 w_a$**CDM** model results are compatible with the ΛCDM ones

The evolution of the Ho is similar to the evolution of the MB parameter (Kazantzidis & Perivopalaropolous 2021)

M. G. Dainotti, et al., 2021, ApJ, 912, 150

ΛCDM and w0waCDM models (20, 40 bins)



M. G. Dainotti *et*

Extrapolation at z=1100
Results for ΛCDM model (3, 4 20, 40 bins)

Dainotti, et al., 2021, ApJ, 912, 150

Flat ΛCDM Model, Fixed Ω_{0m}, with Full Covariance Submatrices $\mathcal{C}$							
Bins	$\tilde{H}_0$ (km s^{-1} Mpc^{-1})	α	$\frac{\alpha}{\sigma_\alpha}$	M	$H_0\,(z=11.09)$ (km s^{-1} Mpc^{-1})	$H_0\,(z=1100)$ (km s^{-1} Mpc^{-1})	% Tension Reduction
3	73.577 ± 0.106	0.009 ± 0.004	2.0	-19.245 ± 0.006	72.000 ± 0.805	69.219 ± 2.159	54%
4	73.493 ± 0.144	0.008 ± 0.006	1.5	-19.246 ± 0.008	71.962 ± 1.049	69.271 ± 2.815	66%
20	73.222 ± 0.262	0.014 ± 0.010	1.3	-19.262 ± 0.014	70.712 ± 1.851	66.386 ± 4.843	68%
40	73.669 ± 0.223	0.016 ± 0.009	1.8	-19.250 ± 0.021	70.778 ± 1.609	65.830 ± 4.170	57%

Extrapolating H_0 at $z = 1100$ H_0 is compatible in 1 σ with the H_0 CMB measurement.

$$x_i = \frac{H_0^{(Cepheids)}(z\sim 0) - H_0^{(CMB)}(z\sim 1100)}{\sqrt{\sigma^2_{H_0^{(Cepheids)}(z\sim 0)} + \sigma^2_{H_0^{(CMB)}(z\sim 1100)}}}$$

$$x_f = \frac{\tilde{H}_0(z=0) - H_0(z=1100)}{\sqrt{\sigma^2_{\tilde{H}_0(z=0)} + \sigma^2_{H_0(z=1100)}}}$$

$$\%\mathrm{Diff} = 1 - x_f/x_i$$

By accounting for this evolution, we have 1.88 sigma tension < 2 sigma

w0waCDM model results (3, 4 20, 40 bins)

Calibrating the M value of μ_{obs} such that locally (namely, in the first bin) $H_0 = 73.5\ km/s/Mpc$

Values compatible in 1 σ with the Planck CMB value

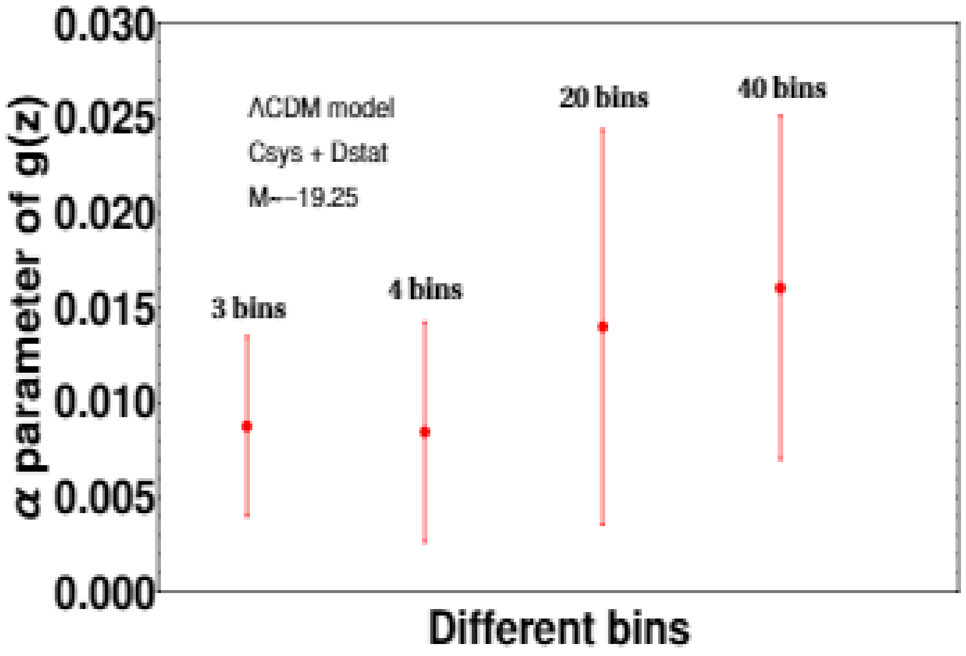
↑

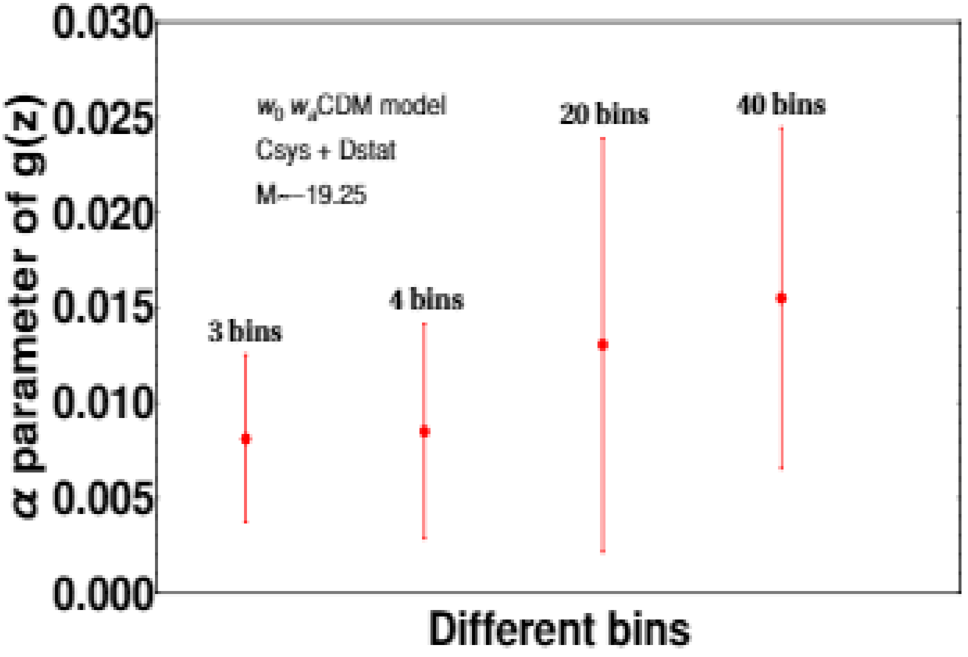
Flat $w_0 w_a$CDM Model, Fixed Ω_{0m}, with Full Covariance Submatrices $\mathcal{C}$							
Bins	$\tilde{H}_0$ $(\mathrm{km\ s^{-1}\ Mpc^{-1}})$	α	$\frac{\alpha}{\sigma_\alpha}$	M	$H_0\,(z=11.09)$ $(\mathrm{km\ s^{-1}\ Mpc^{-1}})$	$H_0\,(z=1100)$ $(\mathrm{km\ s^{-1}\ Mpc^{-1}})$	% Tension Reduction
3	73.576 ± 0.105	0.008 ± 0.004	1.9	-19.244 ± 0.005	72.104 ± 0.766	69.516 ± 2.060	55%
4	73.513 ± 0.142	0.008 ± 0.006	1.2	-19.246 ± 0.004	71.975 ± 1.020	69.272 ± 2.737	65%
20	73.192 ± 0.265	0.013 ± 0.011	1.9	-19.262 ± 0.018	70.852 ± 1.937	66.804 ± 5.093	72%
40	73.678 ± 0.223	0.015 ± 0.009	1.7	-19.250 ± 0.022	70.887 ± 1.595	66.103 ± 4.148	59%

M. G. Dainotti, et al., 2021, ApJ, 912, 150

On the Hubble constant tension in the SNe Ia Pantheon sample

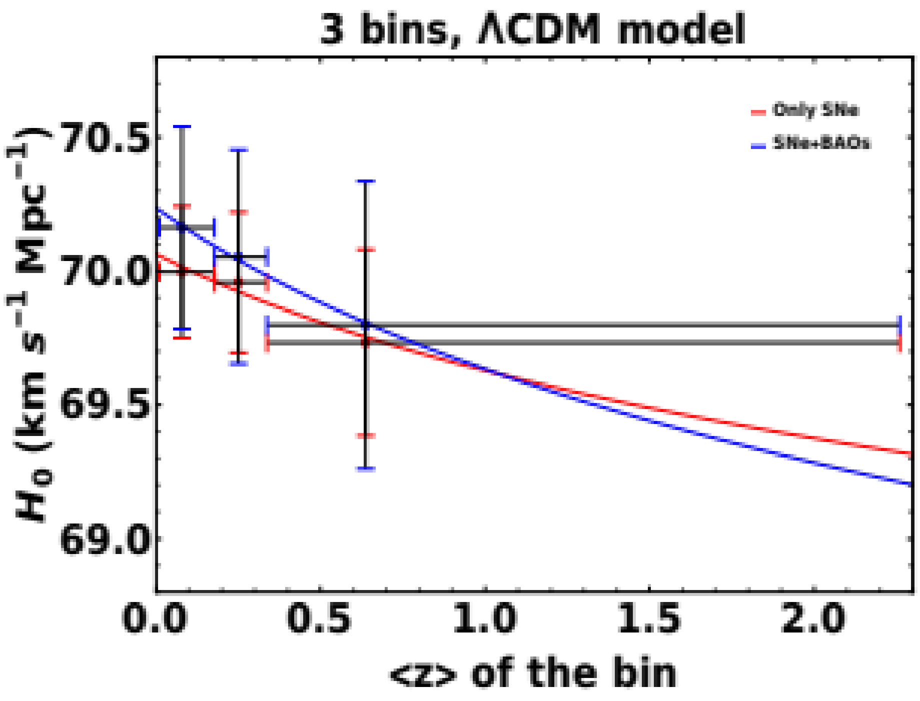
The trend of the alpha parameter





M. G. Dainotti, et al., 2021, ApJ, 912, 150

Continuing with BAOs
$H_0(z)$ fitting (3 bins ΛCDM) + BAOs



Flat ΛCDM model, without BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.093 ± 0.102	0.009 ± 0.004	2.0
Flat ΛCDM model, including BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.084 ± 0.148	0.008 ± 0.006	1.2

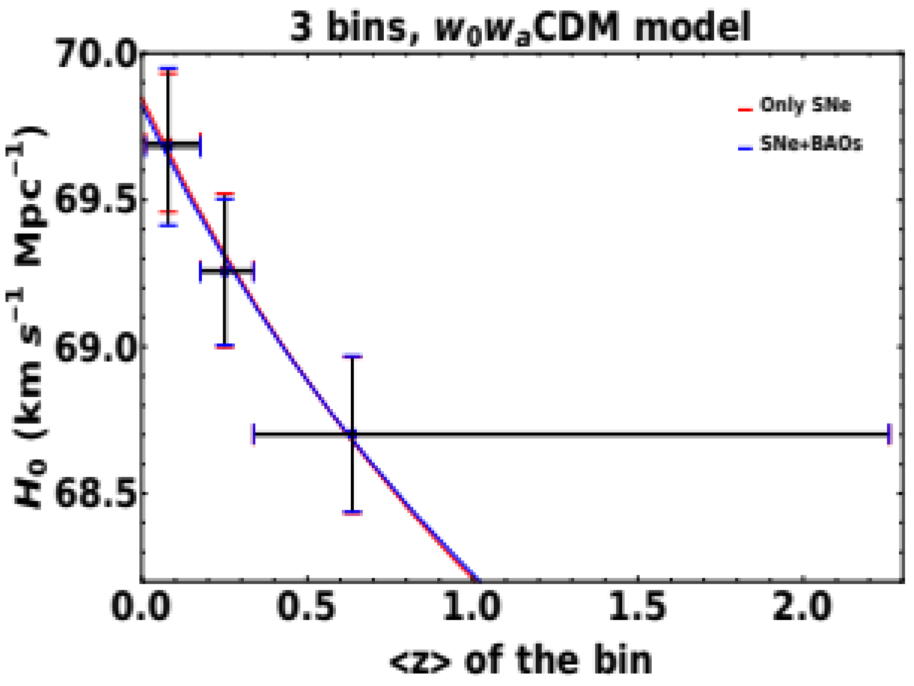
M.G. Dainotti, et al., 2022, Galaxies, 10, 1, 24

M.G. Dainotti, et al., 2022, Galaxies, 10, 1, 24

Varying H_0 and Ω_{0m}

$H_0(z)$ fitting (3 bins w_0w_aCDM) + BAOs

Varying H_0 and w_a



M.G. Dainotti, et al., 2022, Galaxies, 10, 1, 24

Flat w_0w_aCDM model, without BAOs, varying H_0 and w_a			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	69.847 ± 0.119	0.034 ± 0.006	5.7
Flat w_0w_aCDM model, including BAOs, varying H_0 and w_a			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	69.821 ± 0.126	0.033 ± 0.005	5.8

M.G. Dainotti, et al., 2022, Galaxies, 10, 1, 24

Results due to:

1) DIFFERENT THEORETICAL FRAMEWORKS
2) ASTROPHYSICAL BIASES OR SELECTION EFFECTS

- MODIFIED GRAVITY SCENARIO, $G = G(z)$ -> IN MODIFIED THEORIES THERE IS A VARIATION OF THE G CONSTANT (ex. $\mathrm{f}(R)$ THEORIES, HU-SAWICKI MODEL)

- THE HU-SAWICKI MODEL WITH VARYING Ω_{0m} is not an a successful model.
- New Theories are needed: slow rolling?

New Analysis with a combination of sample: The Master sample

Pantheon, PantheonPlus, JLA, and DES: **3789 SNe Ia**.

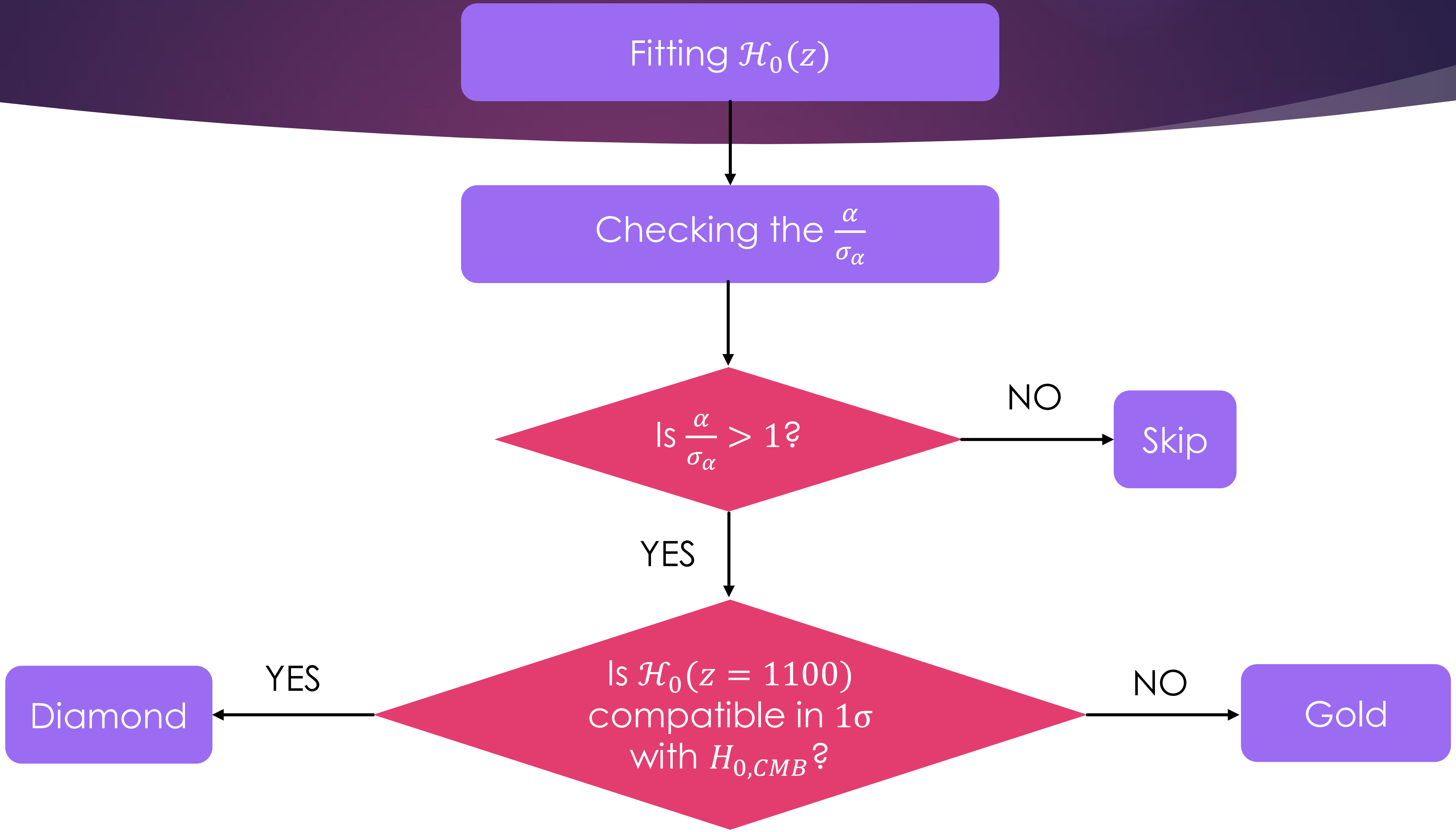
Duplicate entries removed by assigning priority to catalogs in the following order: Pantheon, JLA, DES, and PantheonPlus.

The order priority chosen for comparison with the Pantheon sample

Two binning techniques: equi-populated, equi-spacing

Upon publications, data will be publicly available in the Github Or upon request now

Results


Fitting $\mathcal{H}_0(z)$
Checking the $\frac{\alpha}{\sigma_\alpha}$
Is $\frac{\alpha}{\sigma_\alpha} > 1$?
NO
Skip
YES
Is $\mathcal{H}_0(z = 1100)$ compatible in 1σ with $H_{0,CMB}$?
YES
Diamond
NO
Gold

Samples with $\frac{\alpha}{\sigma_\alpha} \geq 3$

Summary table of the cases with $\alpha/\sigma_\alpha \geq 3$			
Equispacing in log z, Diamond Case, best Likelihood			
Sample	Bins	Model	α/σ_α
PantheonPlus (duplicates removed)	3	w_0w_aCDM	3.75
Equispacing in log z, Gold Cases, best Likelihood			
Sample	Bins	Model	α/σ_α
PantheonPlus (with duplicates)	3	w_0w_aCDM	4.75
JLA	12	ΛCDM	6.00
DES	12	ΛCDM	6.25
Equispacing in log z, Gold Cases, Marshall's Likelihood			
Sample	Bins	Model	α/σ_α
PantheonPlus (with duplicates)	3	w_0w_aCDM	3.14
PantheonPlus (with duplicates)	4	w_0w_aCDM	3.00
JLA	12	ΛCDM	5.56
Equispacing in log z, Gold Cases with high-z SNe Ia, Marshall's Likelihood			
Sample	Bins	Model	α/σ_α
PantheonPlus (with duplicates)	3	w_0w_aCDM	4.00
PantheonPlus (with duplicates)	4	w_0w_aCDM	3.14
Equispacing in log z, Gold Cases with SH0ES Constraints, Marshall's Likelihood			
Sample	Bins	Model	α/σ_α
PantheonPlus (with duplicates)	3	w_0w_aCDM	3.14
PantheonPlus (duplicates removed)	3	w_0w_aCDM	3.00

$\frac{\alpha}{\sigma_\alpha} \geq 3$ in the 34,4% of cases (11 out of 32)

JLA and DES, 12 bins ΛCDM -> $\frac{\alpha}{\sigma_\alpha}$ from 5.56 to 6.25

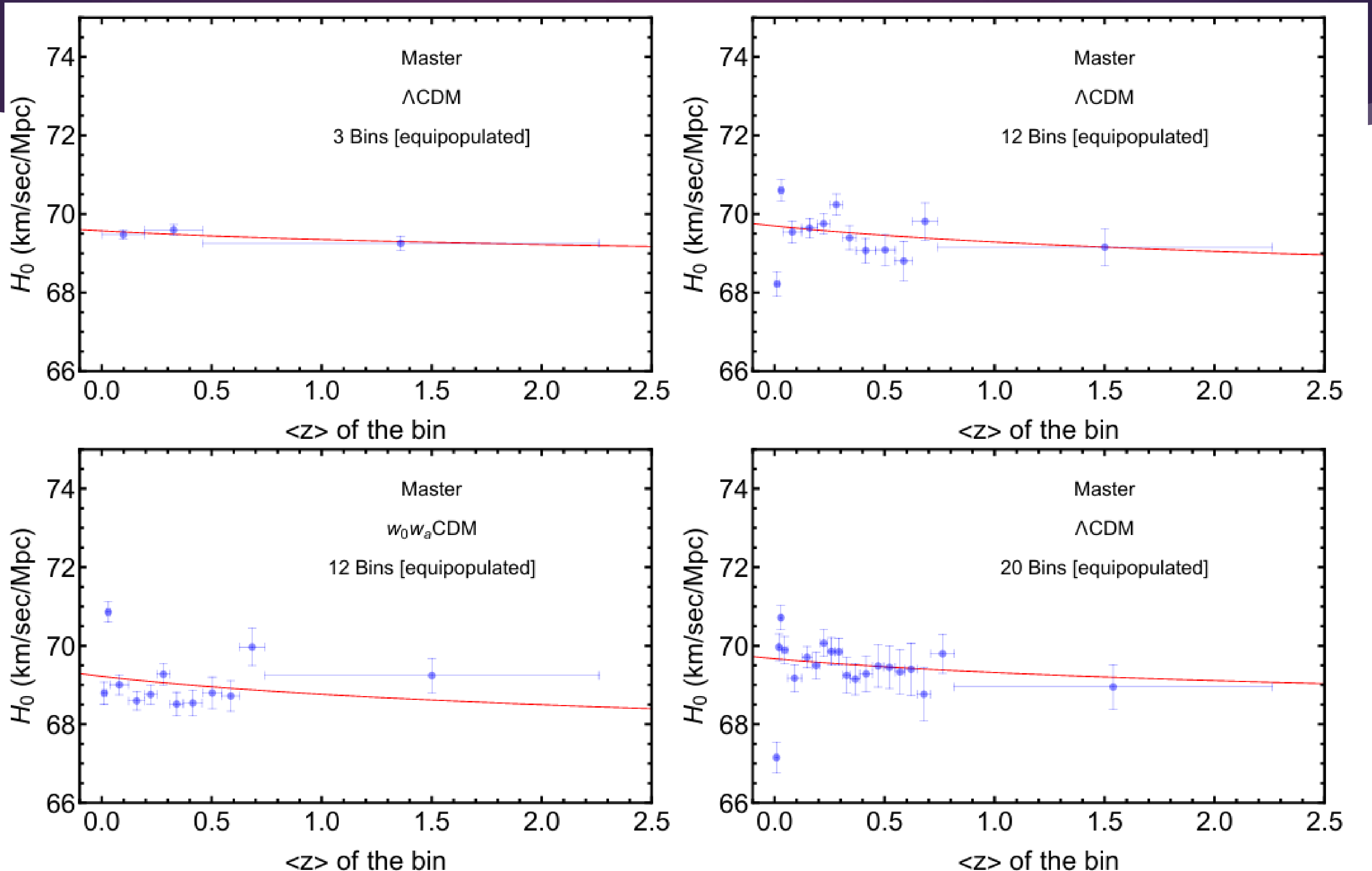
Master Sample shows only Diamond cases!

PantheonPlus with duplicates -> only Gold

Results: Master Sample

Equipopulation binning, Diamond cases, Master Sample $H_0 = 70$					
Bins	Model	$\tilde{H}_0$	α	α/σ_α	$\mathcal{H}_0(z = 1100)$
3	ΛCDM	69.57 ± 0.12	0.005 ± 0.004	1.25	67.18 ± 1.89
12	ΛCDM	69.70 ± 0.14	0.008 ± 0.007	1.14	65.90 ± 3.23
12	w_0w_aCDM	69.22 ± 0.13	0.010 ± 0.006	1.67	64.54 ± 2.71
20	ΛCDM	69.66 ± 0.13	0.007 ± 0.007	1.00	66.33 ± 3.25
20	w_0w_aCDM	69.23 ± 0.13	0.009 ± 0.007	1.29	65.00 ± 3.19
Equipopulation binning, Diamond case, Master Sample, $H_0 = 73.04$					
Bins	Model	$\tilde{H}_0$	α	α/σ_α	$\mathcal{H}_0(z = 1100)$
20	ΛCDM	72.78 ± 0.14	0.008 ± 0.007	1.14	68.81 ± 3.38

Results: Master Sample



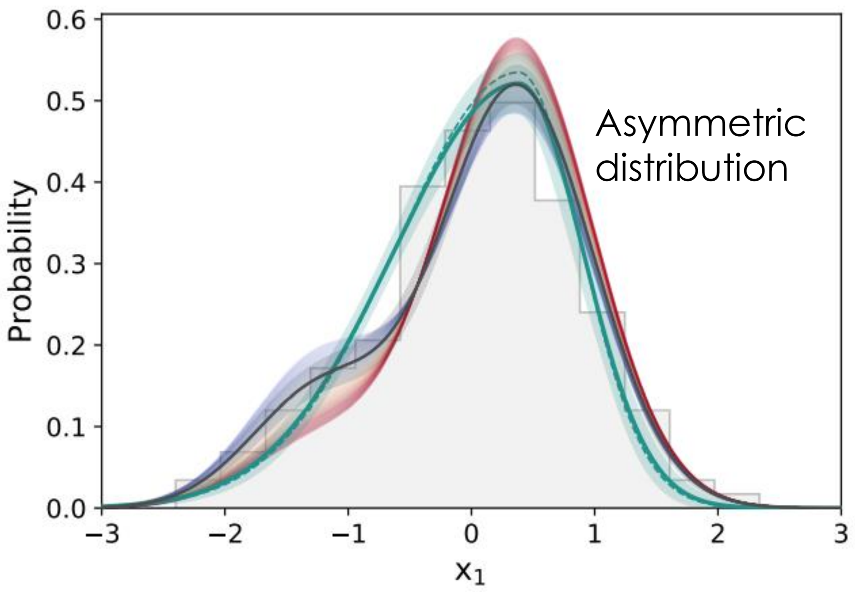
Discussion of the results

SNe Ia ANALYSIS: POSSIBLE ASTROPHYSICAL EFFECTS

POSSIBLE EVOLUTIONARY EFFECTS ON THE OBSERVABLES LIKE COLOR, STRETCH AND MASS CORRECTION OR STATISTICAL FLUCTUATIONS OR EVEN HIDDEN BIASES

- NICOLAS ET AL. 2021 SHOWED THAT THE STRETCH FACTOR EVOLVES WITH REDSHIFT AND THIS MAY EXPLAIN OUR OBSERVED TREND.

- NEW DATA confirms this trend
- Wojtak et al. 2023, MNRAS, 525, 4 → 2 populations regarding the stretch and a clear trend of Hubble residuals increasing with the colour parameter.



N. Nicolas, et al., 2021, A&A, 649, A74

Are you ready to look at the tension from another perspective?

We strive to reach precision cosmology

BUT

What about the assumptions of the likelihood?

Common assumption: Gaussian likelihood of the SNe Ia, BAO, Quasars and GRBs.

Are all this valid?

NO! SNe Ia, BAO and QSOs do not fulfill. Only GRBs fulfil the Gaussianity assumptions the Gaussian likelihoods. Starting with SNe Ia

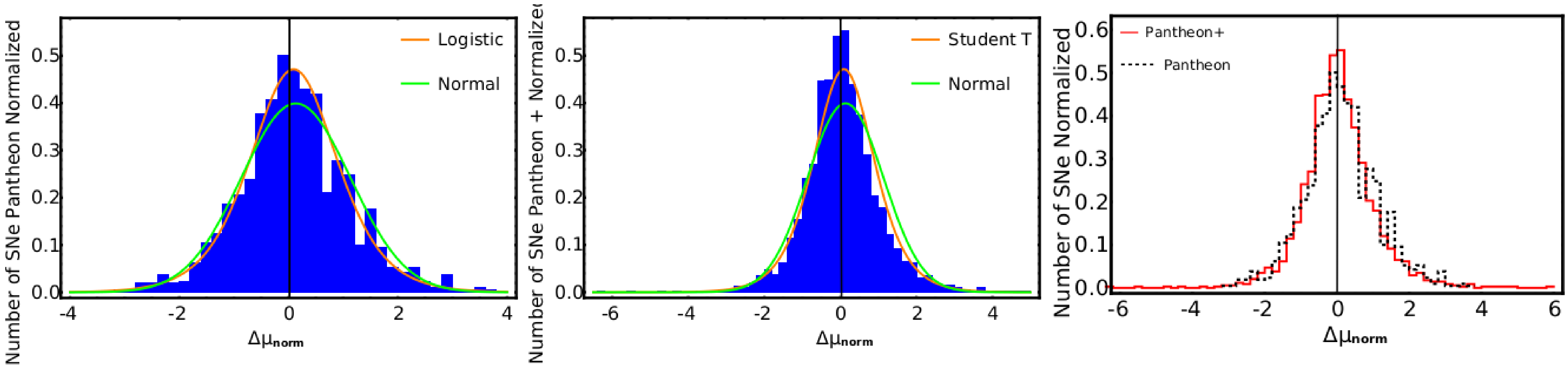


Figure 1: Normalized $\Delta\mu_{norm}$ histogram, defined as $\Delta\mu_{norm} = C^{-1/2}\,\Delta\mu$, for the 1048 SNe Ia in *Pantheon* (left panel) and the 1701 SNe Ia in *Pantheon* + (middle panel). The green curve is the best-fit Gaussian distribution, while the orange curves are the best-fit logistic (left panel) and Student's t (middle panel) distributions. Right panel shows the superimposition of the *Pantheon* and *Pantheon* + distributions. In all panels the vertical black line marks the zero line.

Dainotti, M.G., Bargiacchi, G., Bogdan M., Capozziello, S. and Nagataki S, "*Reduced uncertainties up to 43% on the Hubble constant and the matter density with the SNe Ia with a new statistical analysis*", JHEAP, 41, 30-41.

The two different Cosmological analysis

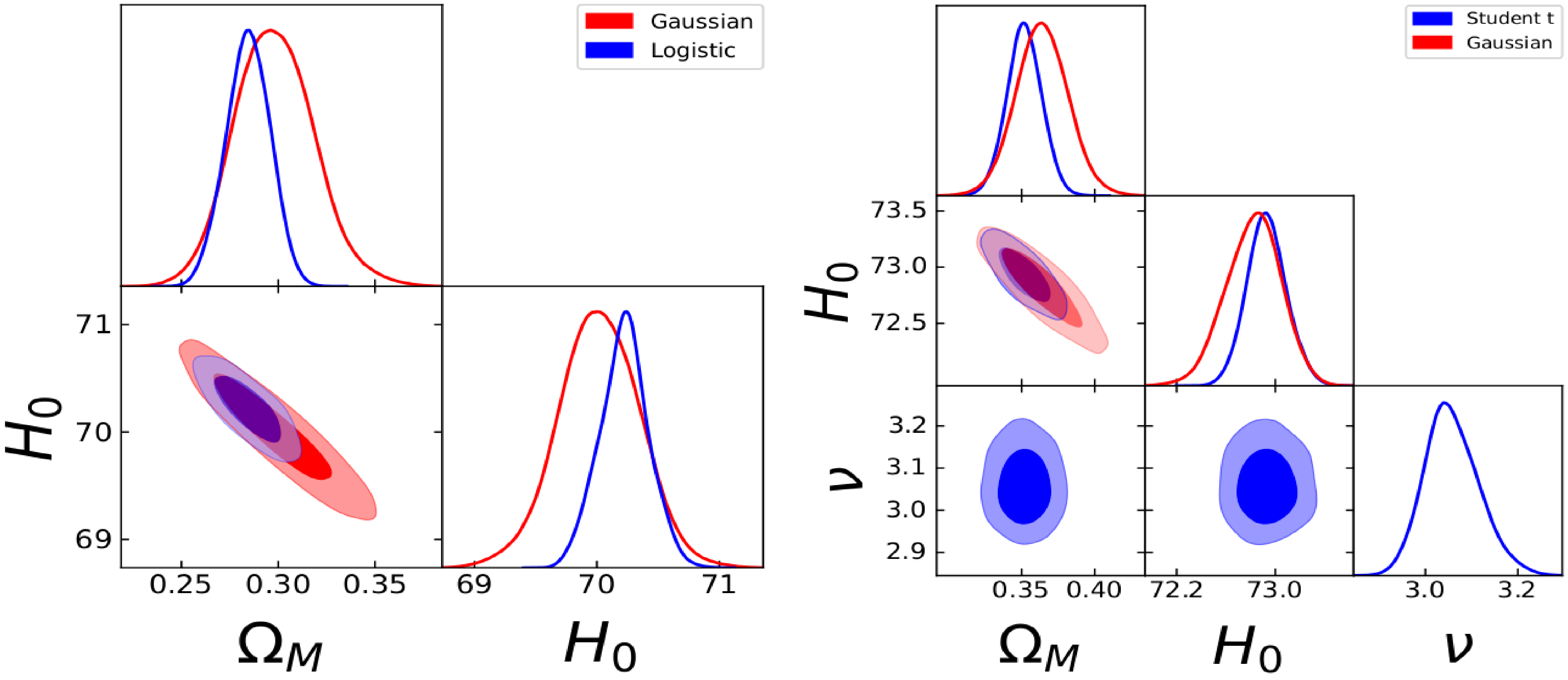


Figure 2: Fit of the flat ΛCDM model with Ω_M and H_0 free parameters. Left panel shows the results for *Pantheon* SNe Ia with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{logistic}$ as in the legend. Right panel shows the contours for the *Pantheon* + sample with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{Student}$ as illustrated in the legend.

Results on Ω_M and H_0 within a flat ΛCDM model

Both Ω_M and H_0 are free parameters,

The L*logistic* for the Pantheon

L*Student* for the Pantheon +

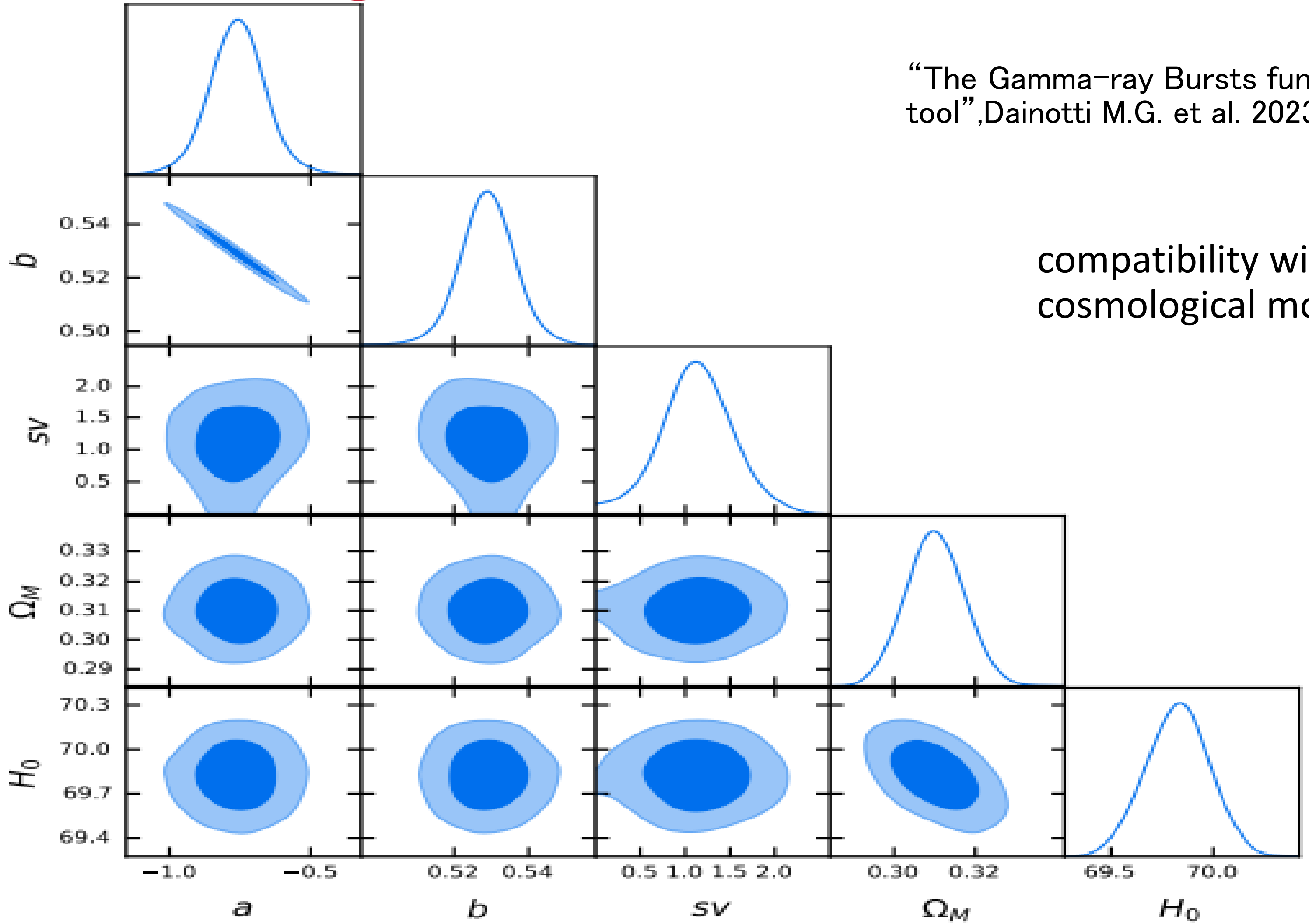
significantly reduce the uncertainties on both parameters.

L*logistic* on Ω_M by 43% (from 0.021 to 0.012) and 41% (from 0.34 to 0.20) for H_0, respectively,

L*Student* by 42% (from 0.019 to 0.011) for Ω_M and 33% (from 0.24 to 0.16) for H0.

Are you ready to look at the tension with high-z probes?

Combining GRBs + SNe Ia + BAO



"The Gamma-ray Bursts fundamental plane correlation as a cosmological tool",Dainotti M.G. et al. 2023, MNRAS, 518, 2.

compatibility with standard cosmological model

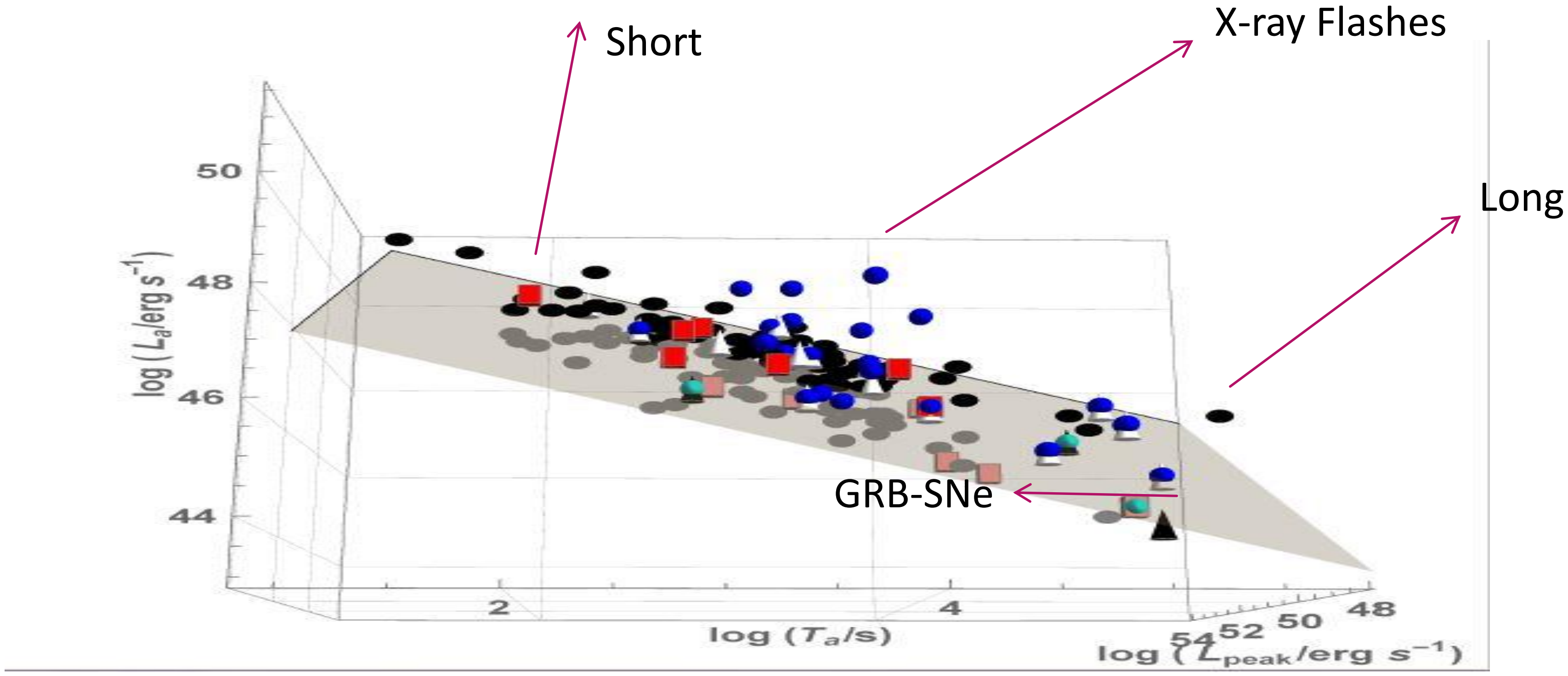
Simultaneous fitting

THE FUNDAMENTAL PLANE RELATION FOR COSMOLOGY

Press release by NASA and press conference at the AAS June 2016:
https://swift.gsfc.nasa.gov/news/2016/grbs_std_candles.html
Mention in Scientific American, Stanford highlight of 2016, INAF Blogs, UNAM gaceta, and many online newspapers took the news

M. G. Dainotti, S. Postnikov, X. Hernandez, M. Ostrowski, 2016, ApJL, 825L, 20

- the 3D Lpeak-Lx-Ta correlation **is intrinsic** and it has a reduced scatter, σint of 24 %.



Results for the Flat and non-flat models

Dainotti et al. 2023, Bargiacchi..Kazunari, B. Zhang, N. Fraija, ApJS,
2023arXiv230510030, 951, 63, press release from NAOJ
Bargiacchi, Dainotti, Nagataki, Capozziello, MNRAS, 521, 3909

$\mathcal{L}_{\mathcal{G}}$ likelihoods:	Non-flat ΛCDM			flat wCDM		
GRBs+QSOs+BAO+*Pantheon*	H_0	Ω_M	Ω_k	H_0	Ω_M	w
No Evolution	69.98 ± 0.32	0.310 ± 0.010	-0.018 ± 0.025	69.90 ± 0.40	0.312 ± 0.010	-1.012 ± 0.038
Fixed Evolution	70.20 ± 0.33	0.297 ± 0.009	-0.027 ± 0.025	70.45 ± 0.37	0.295 ± 0.009	-1.058 ± 0.035
Varying Evolution	70.10 ± 0.30	0.304 ± 0.010	-0.024 ± 0.024	70.12 ± 0.38	0.306 ± 0.010	-1.031 ± 0.036
GRBs+QSOs+BAO+*Pantheon* +	H_0	Ω_M	Ω_k	H_0	Ω_M	w
No Evolution	72.94 ± 0.23	0.366 ± 0.011	-0.023 ± 0.021	72.80 ± 0.24	0.371 ± 0.010	-1.011 ± 0.030
Fixed Evolution	73.02 ± 0.23	0.354 ± 0.010	-0.021 ± 0.021	73.07 ± 0.25	0.354 ± 0.010	-1.035 ± 0.029
Varying Evolution	72.94 ± 0.24	0.362 ± 0.011	-0.021 ± 0.022	72.91 ± 0.25	0.364 ± 0.010	-1.020 ± 0.030
The $\mathcal{L}_{\mathcal{N}}$ likelihoods:	Non-flat ΛCDM			flat wCDM		
GRBs+QSOs+BAO+*Pantheon*	H_0	Ω_M	Ω_k	H_0	Ω_M	w
No Evolution	70.34 ± 0.23	0.299 ± 0.008	-0.040 ± 0.022	70.31 ± 0.24	0.300 ± 0.008	-1.043 ± 0.028
Fixed Evolution	70.37 ± 0.22	0.287 ± 0.007	-0.027 ± 0.017	70.47 ± 0.24	0.289 ± 0.007	-1.046 ± 0.024
Varying Evolution	70.33 ± 0.23	0.294 ± 0.008	-0.033 ± 0.020	70.37 ± 0.25	0.295 ± 0.008	-1.046 ± 0.027
GRBs+QSOs+BAO+*Pantheon* +	H_0	Ω_M	Ω_k	H_0	Ω_M	w
No Evolution	72.99 ± 0.17	0.361 ± 0.009	-0.026 ± 0.017	72.93 ± 0.18	0.362 ± 0.010	-1.025 ± 0.026
Fixed Evolution	73.03 ± 0.17	0.347 ± 0.008	-0.011 ± 0.018	73.06 ± 0.19	0.348 ± 0.009	-1.019 ± 0.024
Varying Evolution	72.99 ± 0.17	0.356 ± 0.009	-0.019 ± 0.017	72.99 ± 0.18	0.357 ± 0.009	-1.023 ± 0.025

New statistics: Non-Gaussianity likelihoods for SNe Ia and QSOs -> reduced uncertainties

Table 2. Percentage difference of the uncertainties on the best-fit values of cosmological parameters obtained when using the $\mathcal{L}_N$ instead of the $\mathcal{L}_G$ likelihood.

	Non-flat ΛCDM			flat *w*CDM		
GRBs+QSOs+BAO+*Pantheon*	$\Delta_{\%}(H_0)$	$\Delta_{\%}(\Omega_M)$	$\Delta_{\%}(\Omega_k)$	$\Delta_{\%}(H_0)$	$\Delta_{\%}(\Omega_M)$	$\Delta_{\%}(w)$
No Evolution	-0.28	-0.20	-0.16	-0.34	-0.20	-0.26
Fixed Evolution	-0.30	-0.22	-0.32	-0.35	-0.22	-0.31
Varying Evolution	-0.23	-0.20	-0.17	-0.34	-0.20	-0.25
GRBs+QSOs+BAO+*Pantheon* +	$\Delta_{\%}(H_0)$	$\Delta_{\%}(\Omega_M)$	$\Delta_{\%}(\Omega_k)$	$\Delta_{\%}(H_0)$	$\Delta_{\%}(\Omega_M)$	$\Delta_{\%}(w)$
No Evolution	-0.26	-0.27	-0.19	-0.25	0	-0.13
Fixed Evolution	-0.26	-0.20	-0.14	-0.24	-0.10	-0.17
Varying Evolution	-0.29	-0.18	-0.23	-0.28	-0.10	-0.17

In All configurations we have reduction of the scatter on all parameters

H0 central values are higher when probes are combined together → 73!

Dainotti et al. 2023 2303.06974.pdf (arxiv.org)

Bargiacchi, Dainotti,..Nagataki.. et al. 2023, MNRAS, 521, 3909

Dainotti et al. 2023, .. B. Zhang, N. Fraija, ApJS, 2023arXiv230510030D, 951, 63, press release from NAOJ

Announcements

Call for abstract in Galaxies (Impact factor=3.2) for the special issue:

The aim is to gather mini-review on the topics above or any topic of interest on GRBs. There is no page limits and I have several waivers to allow the publication to be free of charge.

Deadline for submission: 15th of March 2024.

If you are interested, please contact me.

Special Issue "Gamma-Ray Bursts in Multiwavelength: Theory, Observational Correlations and GRB Cosmology"

Thank you very much for your attention