Maria Giovanna Dainotti

The Tension on the Hubble constant with new statistical assumptions

09/13/2024, The Dark Side of the Universe - DSU2024

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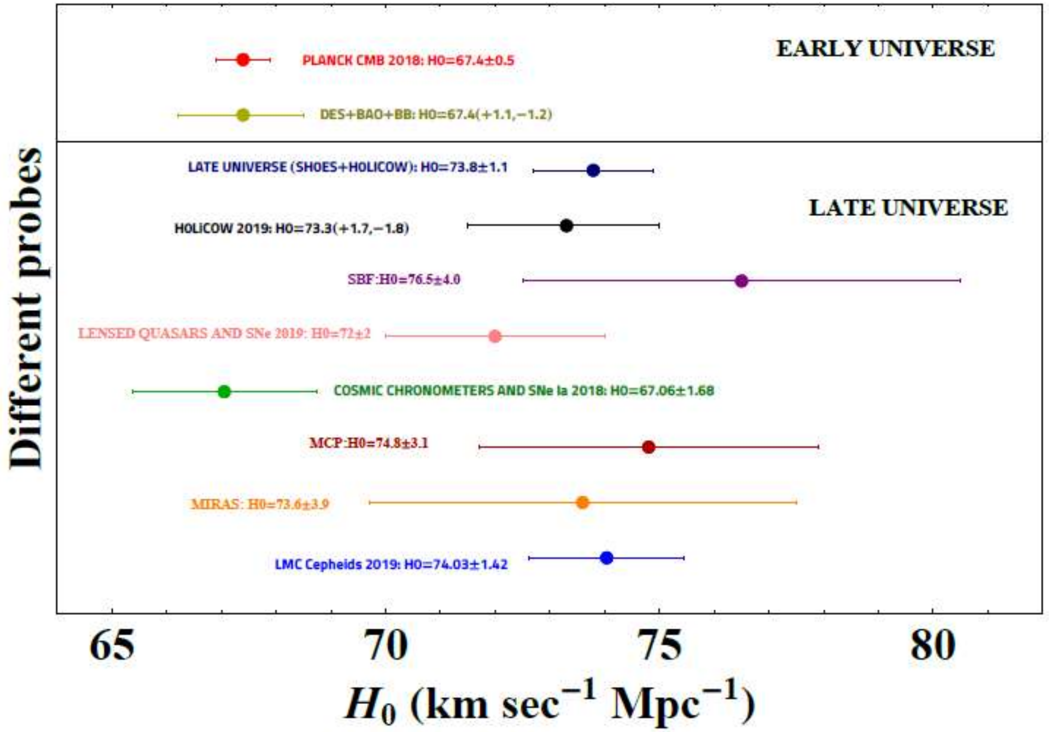
The Hubble constant and its tension

$H_0 \stackrel{\text{def}}{=} \frac{R'(t_0)}{R(t_0)}$, $R(t_0)$ = SCALE FACTOR COMPUTED IN THE PRESENT (t_0) → $v = H_0 \cdot D$

HUBBLE'S LAW



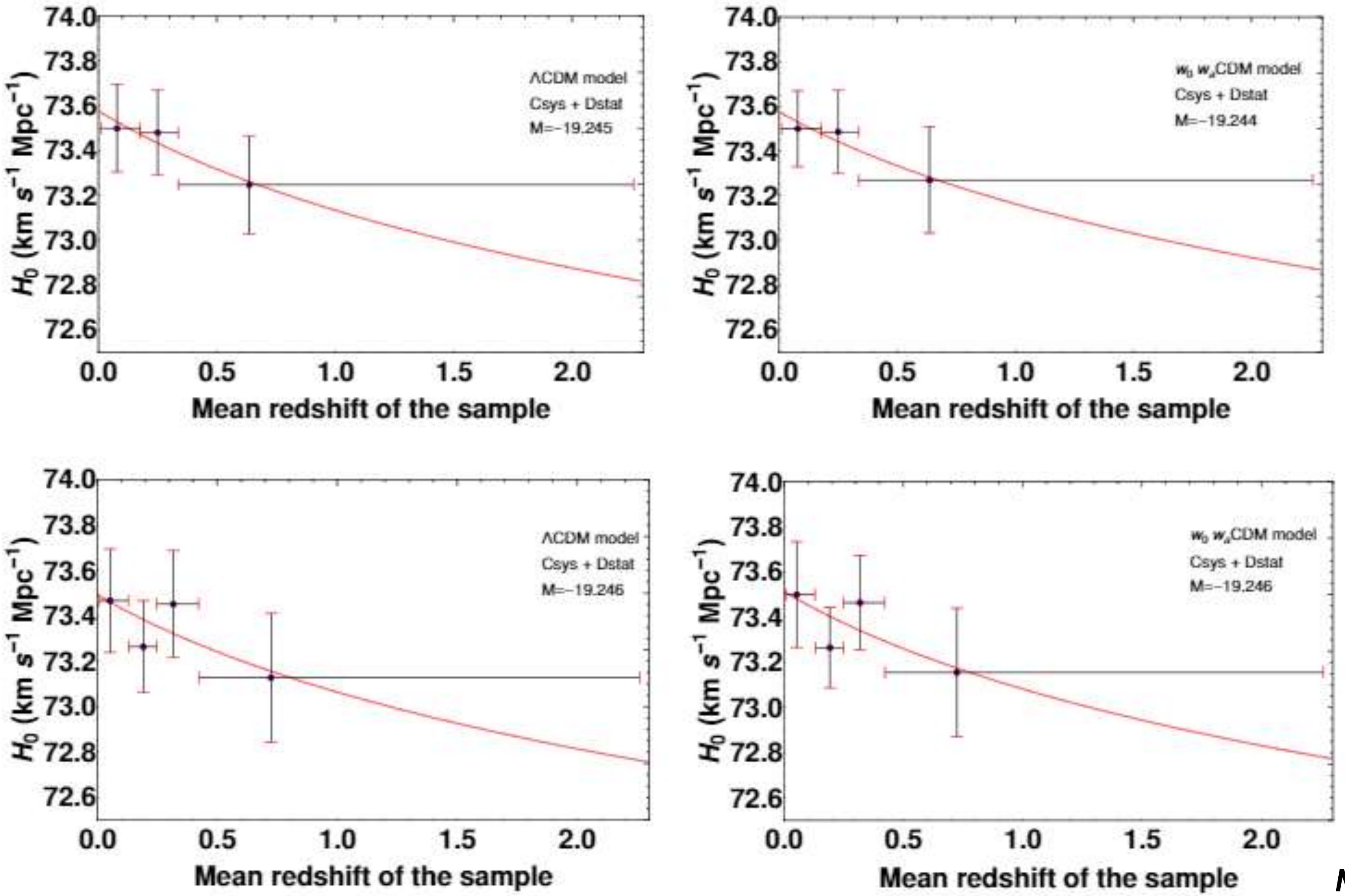
H_0 TENSION possibly due to its evolution or evolution of its parameters and its theoretical explanations

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

Dainotti et al. 2023, Galaxies, vol. 10, issue 1, 24.

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

Results for ΛCDM model (3, 4 bins)



The $\boldsymbol{w_0 w_a}$**CDM** model results are compatible with the ΛCDM ones (omitted for brevity)

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

Results for ΛCDM model (3, 4 bins)

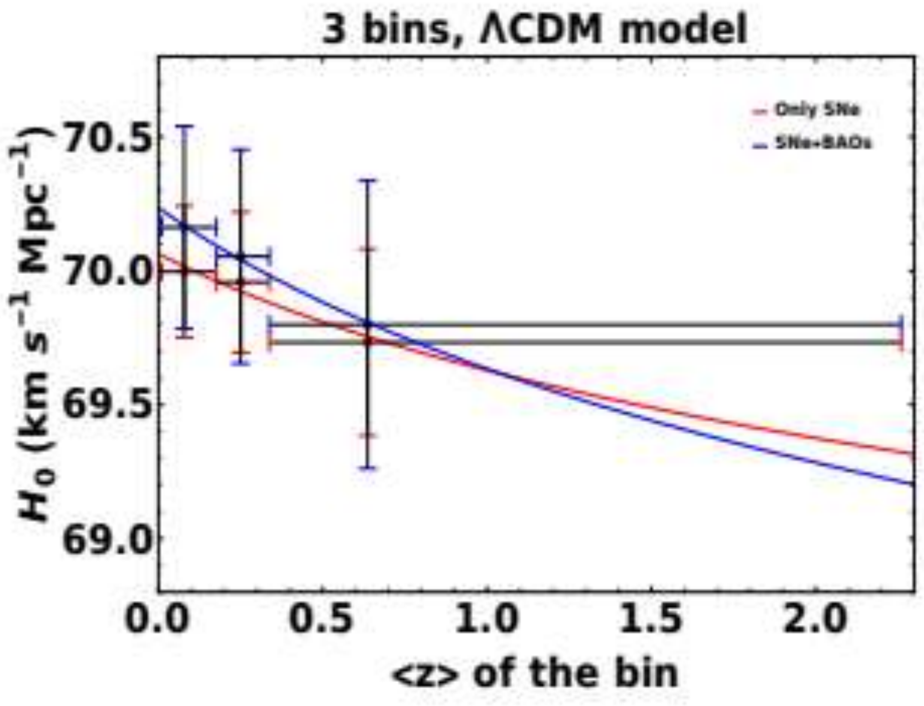
Flat ΛCDM Model, Fixed Ω_{0m}, with Full Covariance Submatrices C							
Bins	$\tilde{H}_0$ ($\mathrm{km\ s^{-1}\,Mpc^{-1}}$)	α	$\frac{\alpha}{\sigma_\alpha}$	M	$H_0\,(z = 11.09)$ ($\mathrm{km\ s^{-1}\,Mpc^{-1}}$)	$H_0\,(z = 1100)$ ($\mathrm{km\ s^{-1}\,Mpc^{-1}}$)	% Tension Reduction
3	73.577 ± 0.106	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%

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

Extrapolating H_0 at the redshift of the Last Scattering Surface ($z = 1100$) we obtained a value of H_0 compatible in 1 σ with the H_0 CMB measurement.

$H_0(z)$ fitting (3 bins ΛCDM) + BAOs

Varying H_0 and Ω_{0m}



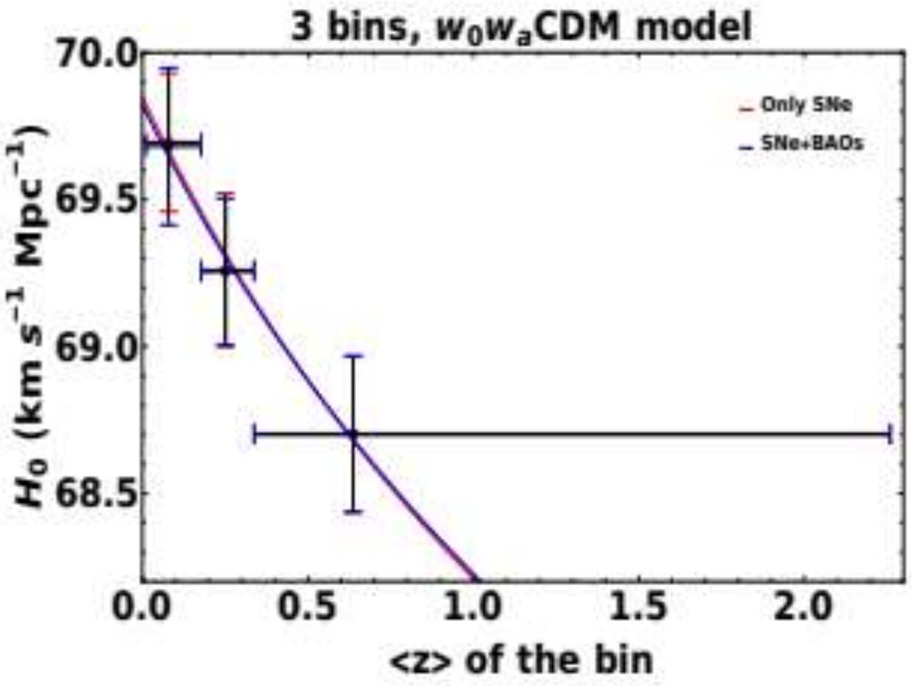
Flat ΛCDM model, without BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.093 ± 0.102	0.009 ± 0.004	2.0
Flat ΛCDM model, including BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.084 ± 0.148	0.008 ± 0.006	1.2

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

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

$H_0(z)$ fitting (3 bins $w_0 w_a CDM$) + BAOs

Varying H_0 and w_a



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

Flat $w_0 w_a$CDM 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 $w_0 w_a$CDM 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

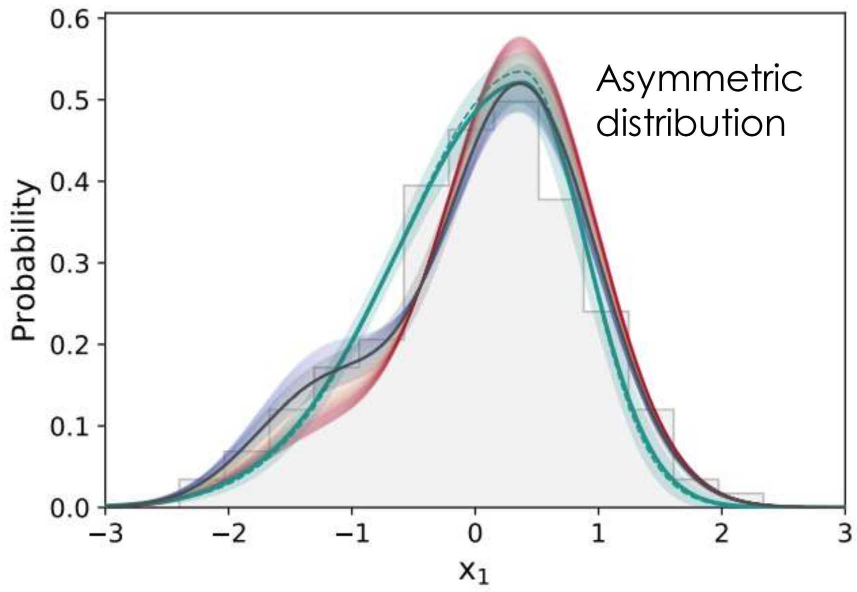
Discussion of the results

SNe Ia ANALYSIS: POSSIBLE ASTROPHYSICAL EFFECTS and Theory of modified gravity

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

- NICOLAS ET AL. 2021 SHOWS THAT THE STRETCH
- FACTOR EVOLVES WITH REDSHIFT.

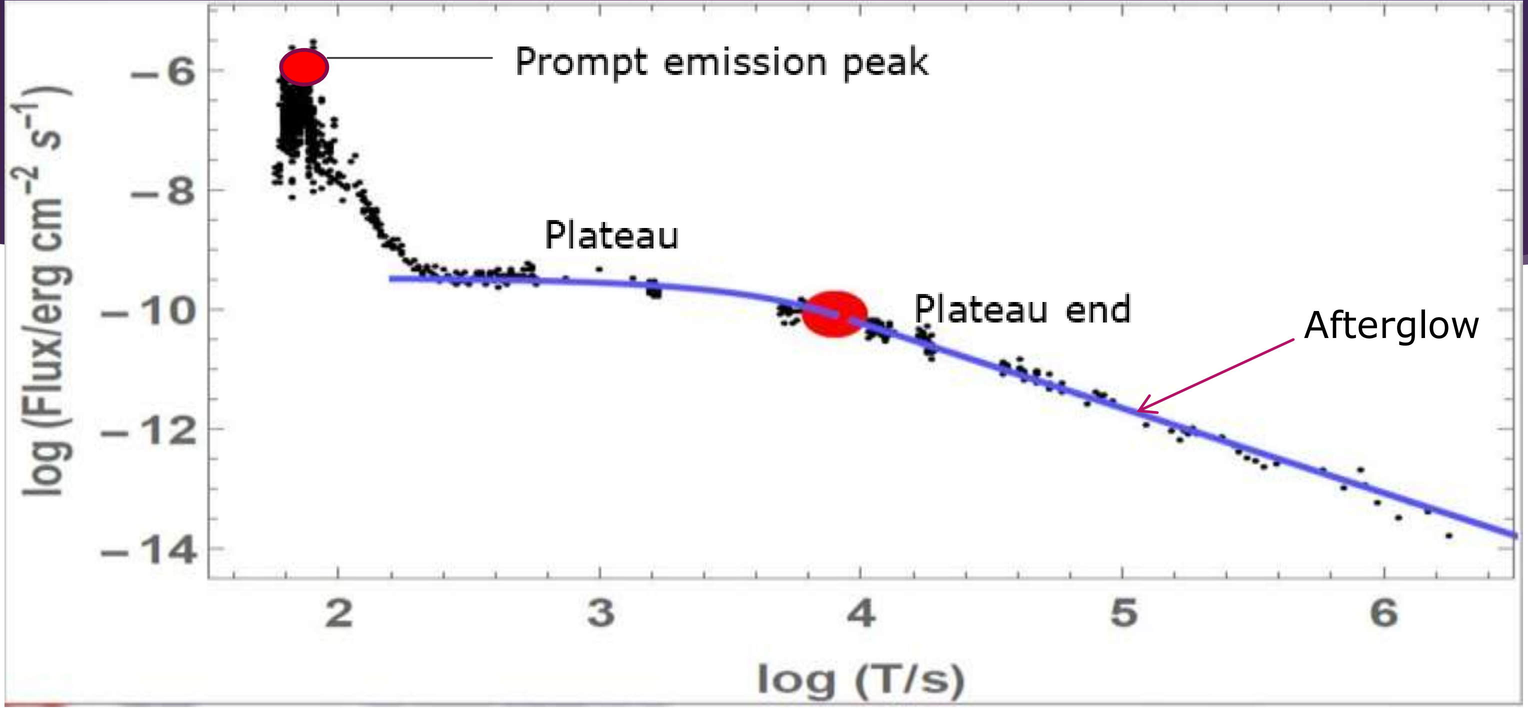
- NEW DATA ARE NEEDED TO FURTHER EXPLORE
- OUR RESULTS (E.G. PANTHEON+ or other statistical
- assumptions)



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

Let’s investigate the intermediate regions of redshift between SNe Ia and CMB

GRB standard plateau features



Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing).
The blue line is the phenomenological Willingale model (R. Willingale et al. 2007)

Standard is good!

- The less varied properties of the plateau compared to the prompt favor afterglow relation for cosmological applications.
- What is the standard set of the GRBs to be used?

For GRB standardization, possible reliable candidates are the Ta-La and Lpeak-La correlations

An important feature observed in the 60% of Swift satellite GRBs is the plateau emission, namely a flattening of the afterglow LC.
The work of Srinivasaragavan, Dainotti et al. 2020 has been updated with Dainotti et al. in preparation: 255 GRBs with known redshift from 01.2005-02-2024

Dainotti 2D and Oates relation
LaX - T*aX & LaX-LpX confirming the reliability after bias correction

Dainotti 3D relation
(Lax - T*ax - Lpx)
(reliable after bias correction)

Dainotti 2D and 3D relation in radio and optical
(probing these to be unbiased relation)

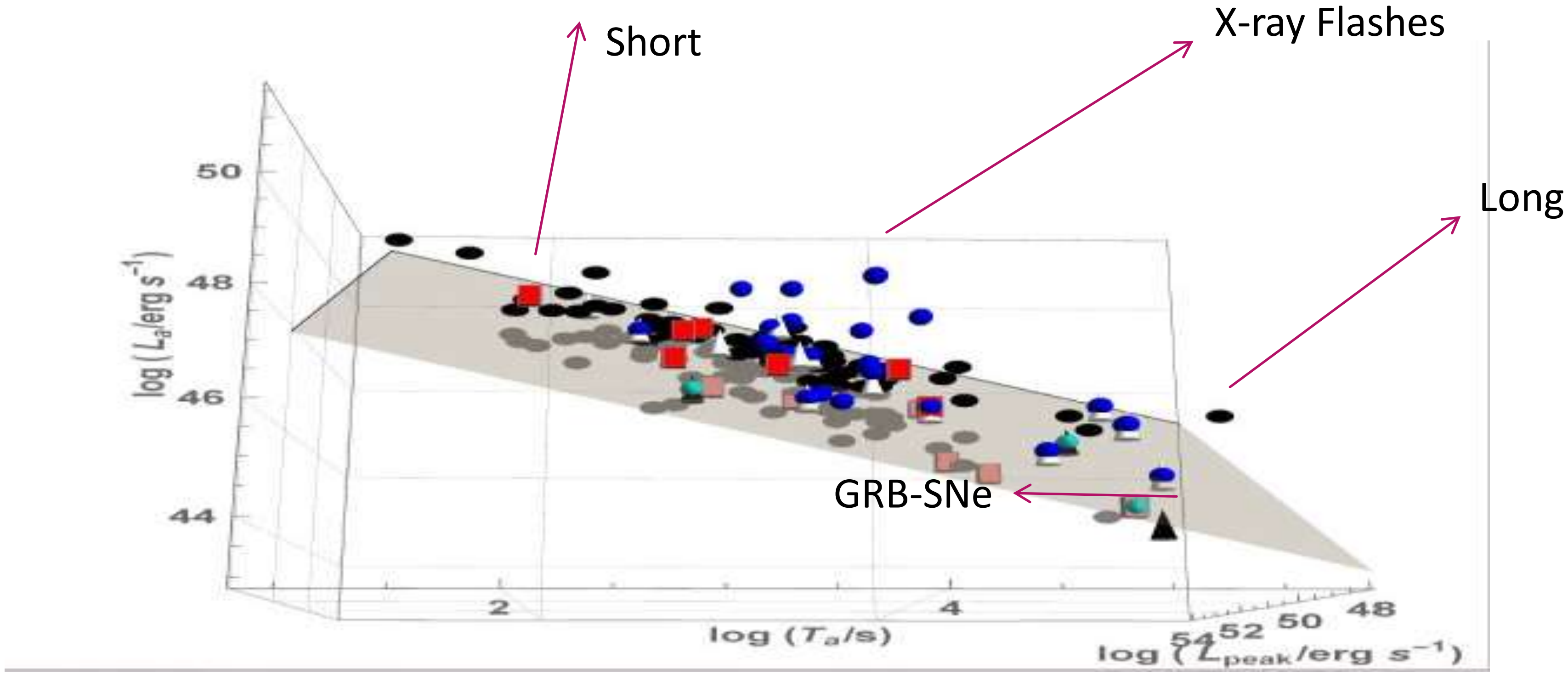
2008 2010 2011 2015 | 2016 2017 | 2020 2021 2022

THE EXTENSION OF THE LX-TA AND LX-LPEAK CORRELATIONS GIVEN THEIR INTRINSIC NATURE

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, σ_{int} of 24 %.



What are the solutions to allow for an independent calibration?

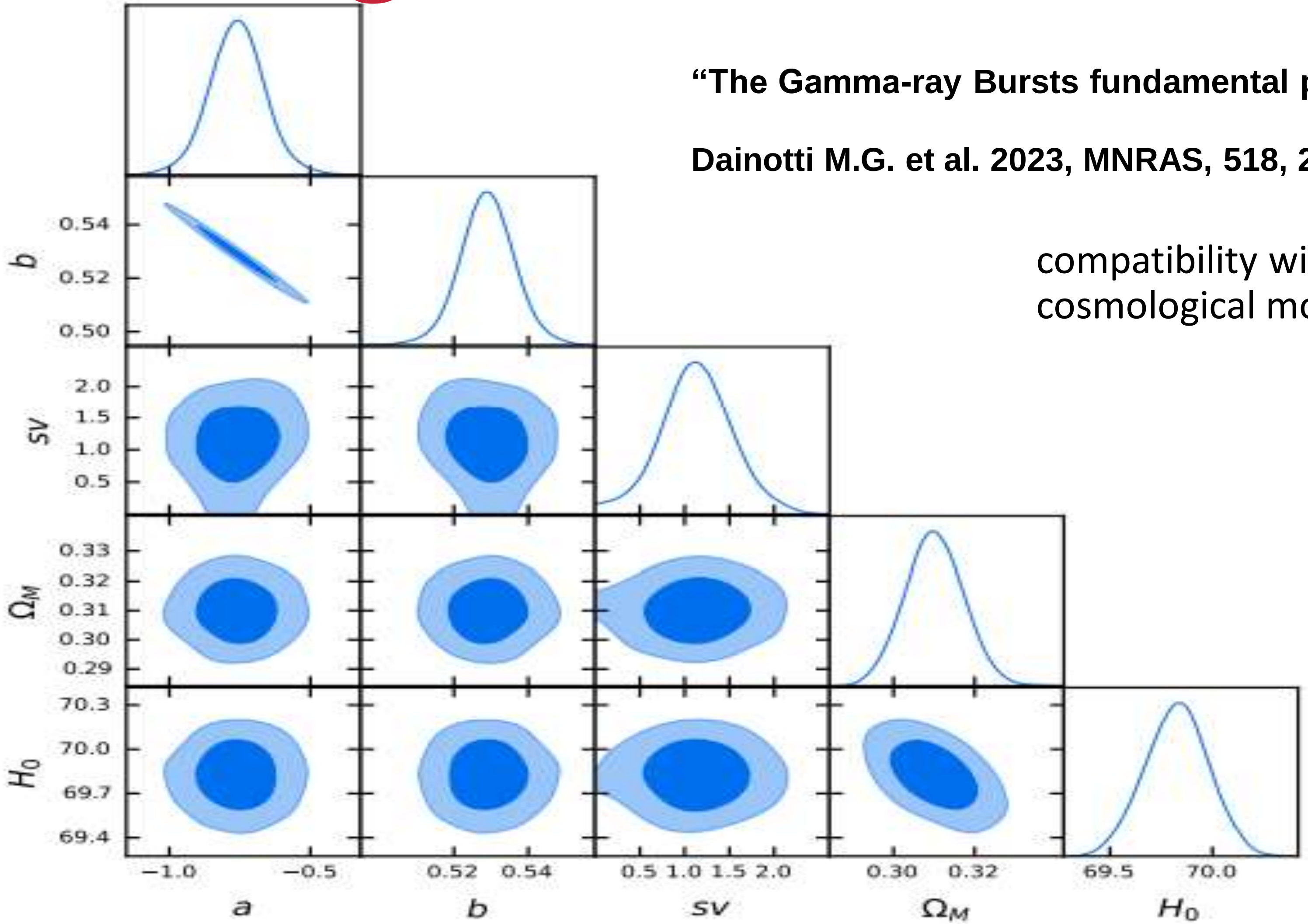
- Two solutions

- **Simultaneous fitting**: fit simultaneously the correlation parameters and the parameters of a cosmological model of interest from GRB observations.

- **Calibration with low-redshift probes (e.g., Cosmic Chronometers)**, given that objects at the same redshift should have the same luminosity distance regardless of the underlying cosmology

Let’s start with the simultaneous fitting

Combining GRBs + SNe Ia + BAO

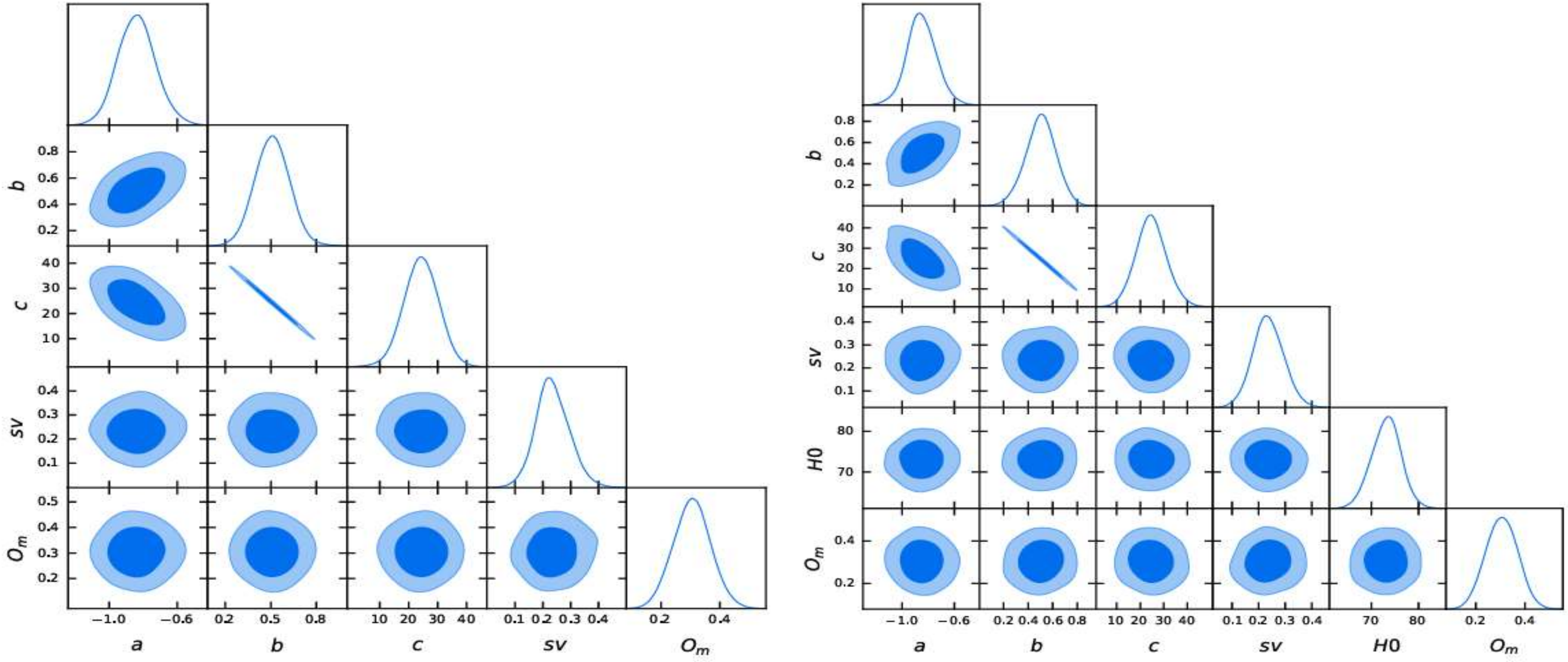


“The Gamma-ray Bursts fundamental plane correlation as a cosmological tool”,

Dainotti M.G. et al. 2023, MNRAS, 518, 2, 2201-2240.

compatibility with standard cosmological model

GRBs alone with evolution with Gaussian priors

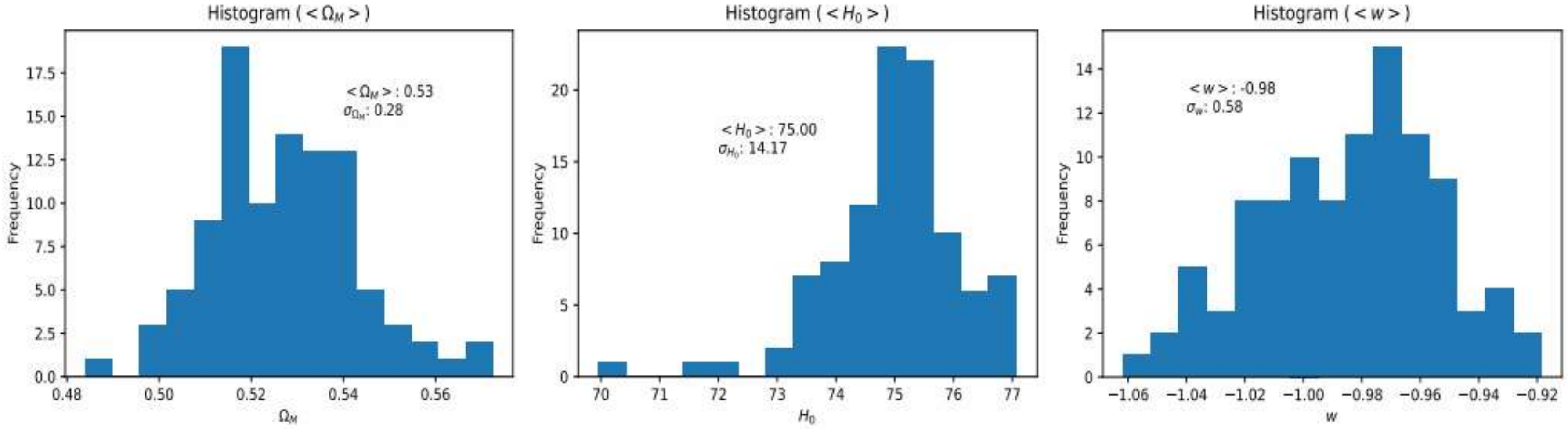


(a) Varying only Ω_M with evolutionary function

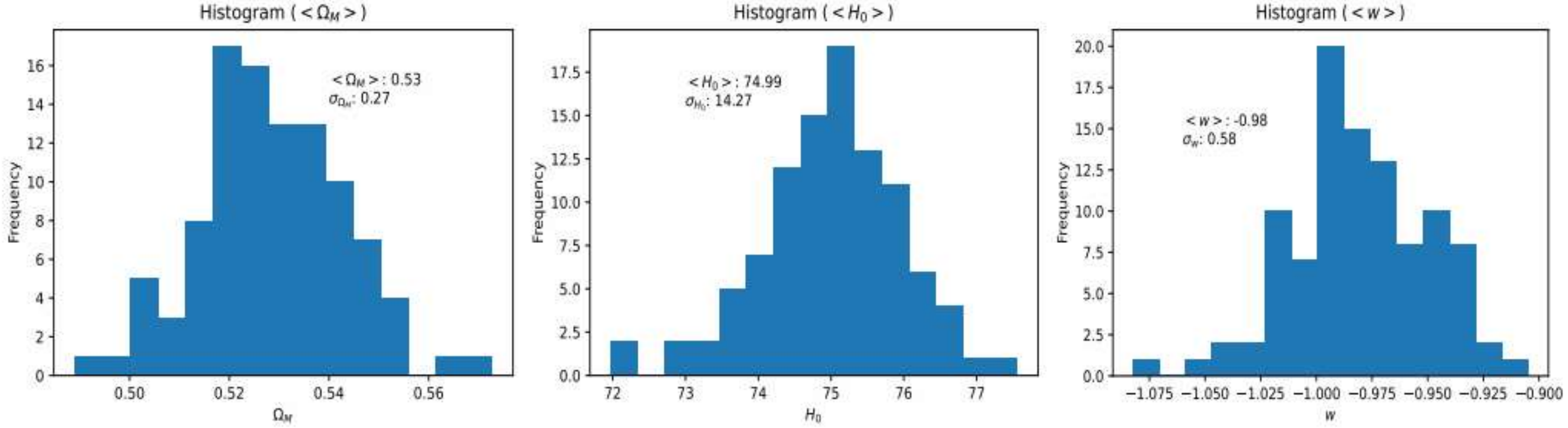
(b) Varying both Ω_M and H_0 with evolutionary function

Figure 10. Cosmological results for the GRBs alone (with no calibration) with Fundamental Plane using evolutionary functions and the assumptions of 3 σ Gaussian priors on the cosmological parameters investigated following Scolnic et al. (2018). Panels a) and b) show the contours from case (iii) for the case of Ω_M and the case of Ω_M and H_0 together, respectively.

GRBs calibrated on SNe Ia with uniform priors



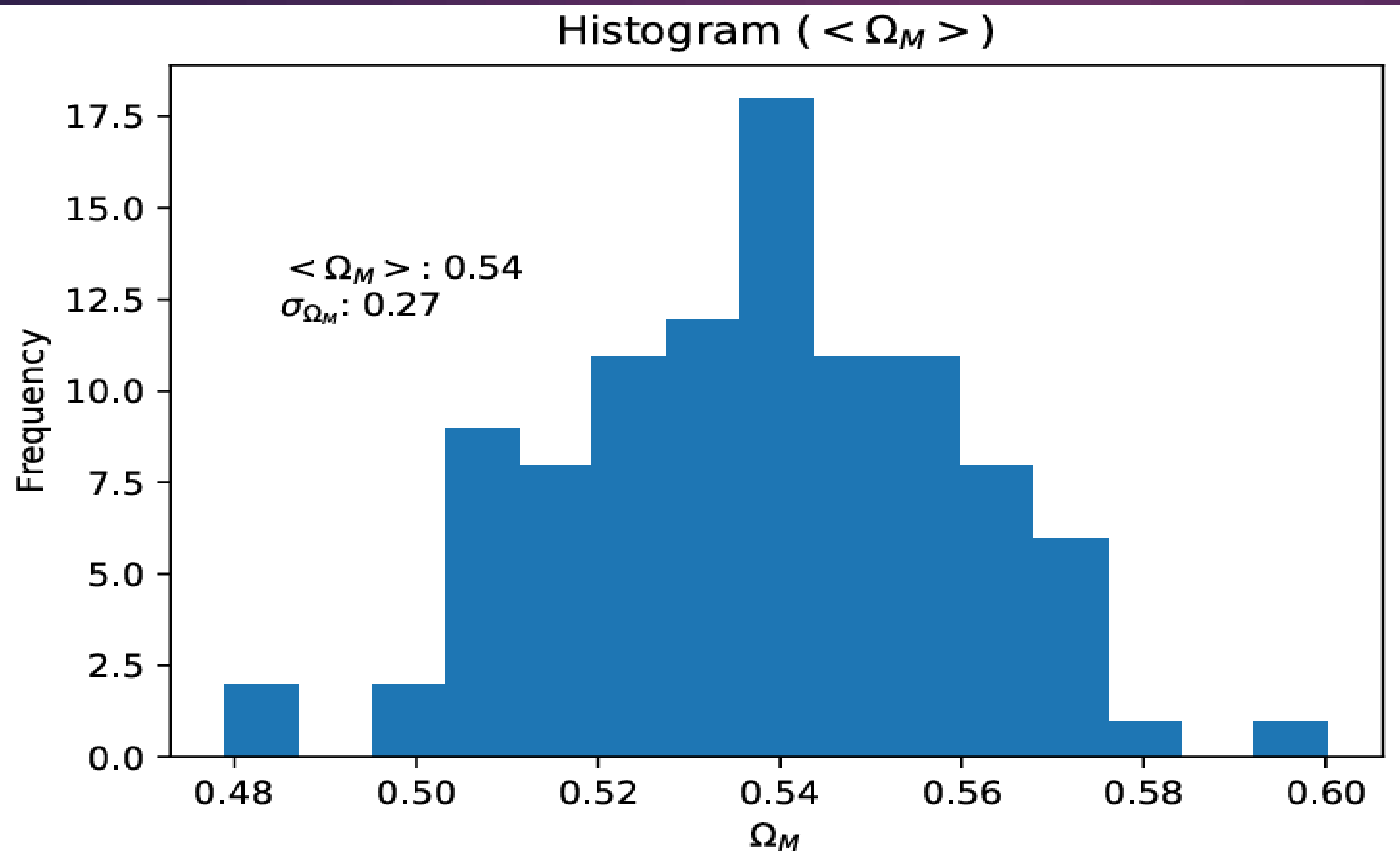
(a) Varying only Ω_M without evolution (b) Varying only H_0 without evolution (c) Varying only w without evolution



(d) Varying only Ω_M with fixed evolution (e) Varying only H_0 with fixed evolution (f) Varying only w with fixed evolution

M. G. Dainotti, A. Lenart, et al., 2022, MNRAS, 518, 2, 2201-2240
(tension increases, but errorbars are larger) Closer to the SNe Ia values

GRBs only by changing also the evolution together with the other parameters

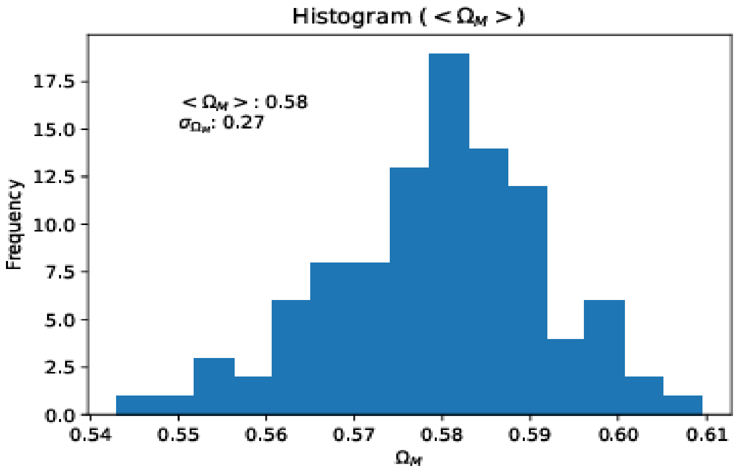


(g) Varying only Ω_M with evolutionary function

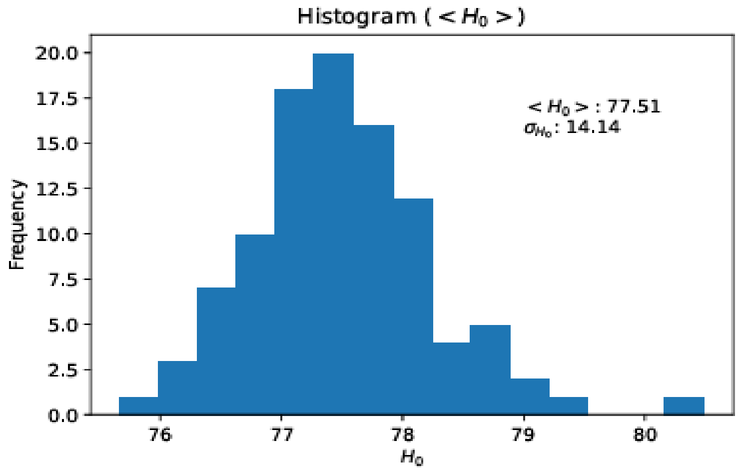
The priors here are uniform with 0<ΩM<1 starting with almost de-Sitter Universe to an universe filled with matter only

In future we will limit the ΩM to values with 5 σ to the current values in the literature

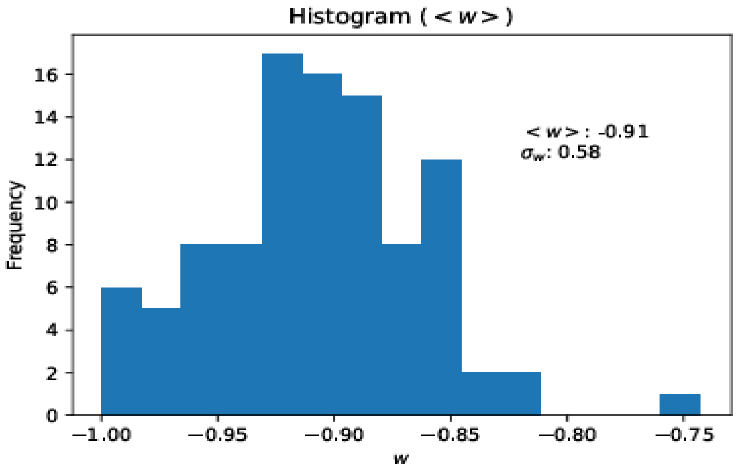
No calibration and uniform priors



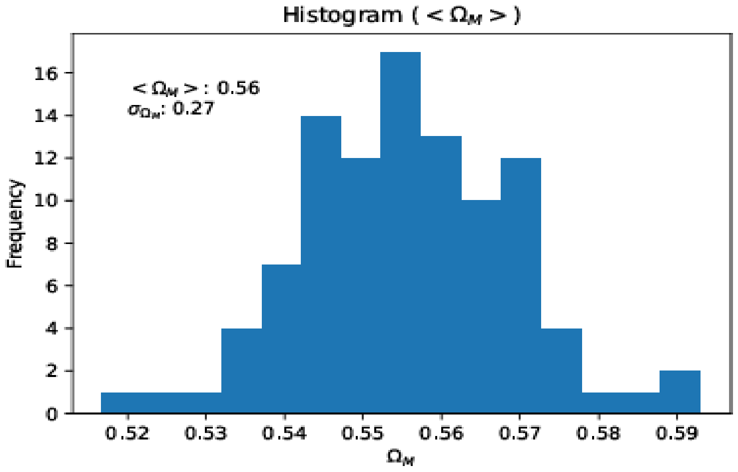
(a) Varying only Ω_M without evolution



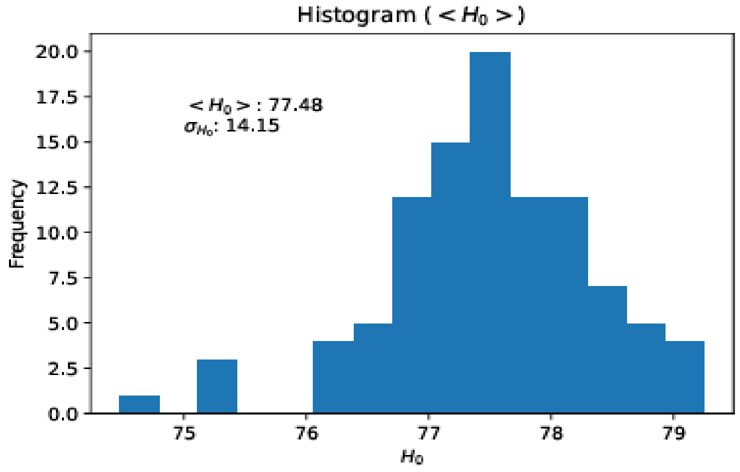
(b) Varying only H_0 without evolution



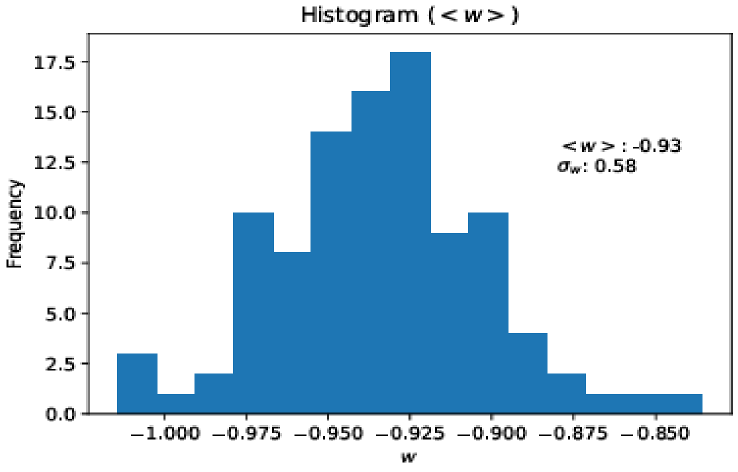
(c) Varying only w without evolution



(d) Varying only Ω_M with fixed evolution

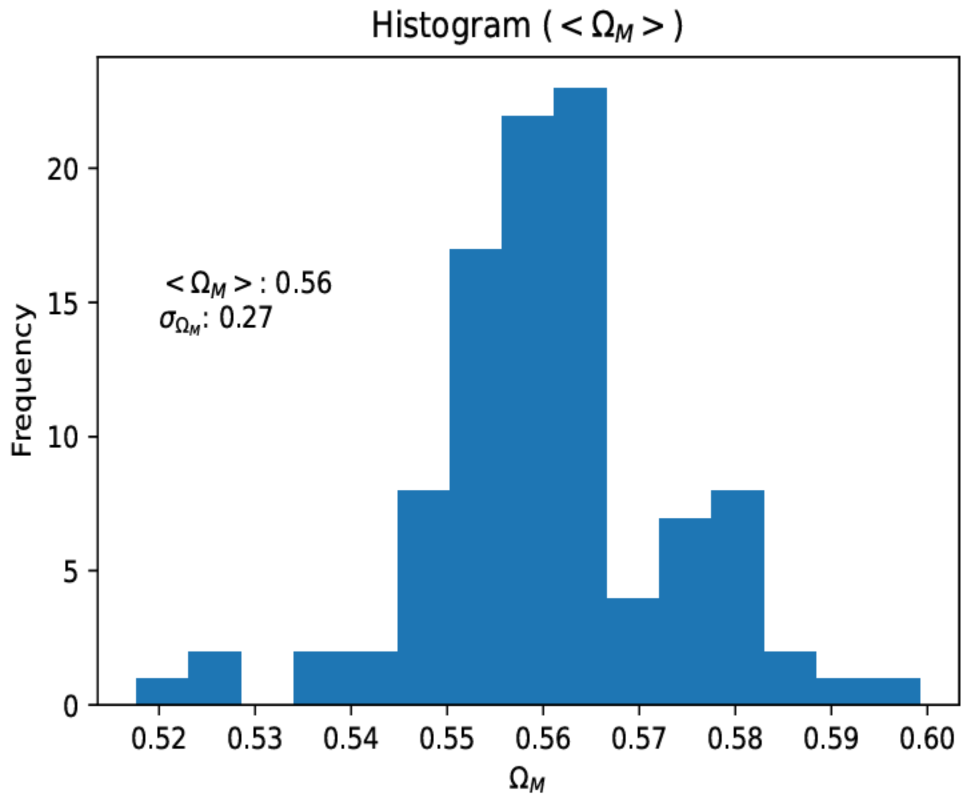


(e) Varying only H_0 with fixed evolution



(f) Varying only w with fixed evolution

Varying the evolution and the cosmological parameters



What else can we do?

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 QSQs do not fulfill. Only GRBs fulfil the Gaussianity assumptions the Gaussian likelihoods. Starting with SNe Ia

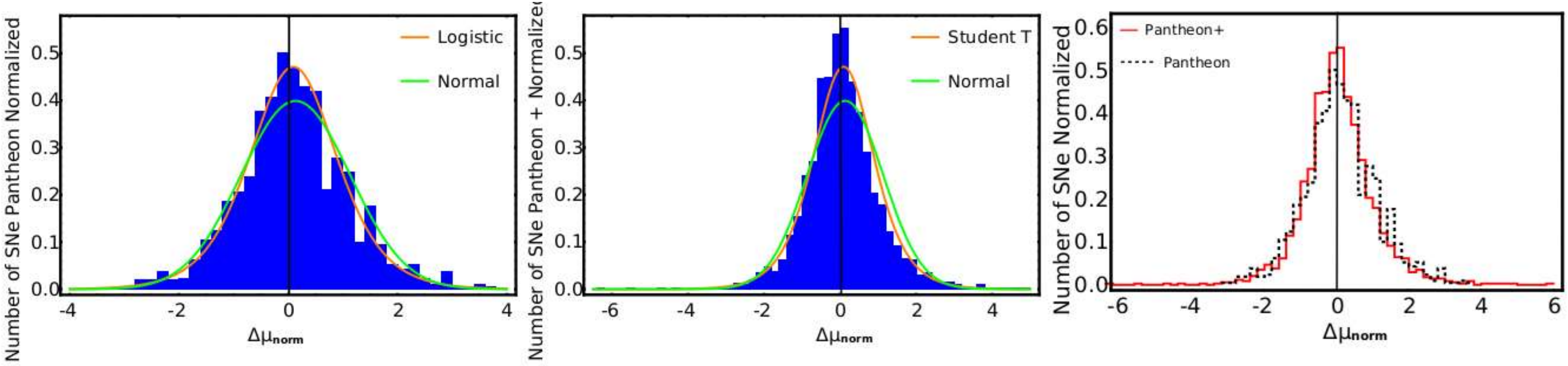


Figure 1: Normalized $\Delta\mu_{norm}$ histogram, defined as $\Delta\mu_{norm} = C^{-1/2}\,\Delta\mu$, for the 1048 SNe Ia in *Pantheon* (left panel) and the 1701 SNe Ia in *Pantheon* + (middle panel). The green curve is the best-fit Gaussian distribution, while the orange curves are the best-fit logistic (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.

Let's define the Logistic and the T-student

$$\mathrm{PDF}_{\mathrm{logistic}} = \frac{e^{-\frac{(x-\hat{x})}{s}}}{s\left(1+e^{\frac{-(x-\hat{x})}{s}}\right)^2}$$

$$\mathrm{PDF}_{\mathrm{student}} = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\nu\,\pi}\,s\,\Gamma\left(\frac{\nu}{2}\right)}\left[1+\frac{((x-\hat{x})/s)^2}{\nu}\right]^{-\frac{\nu+1}{2}}$$

s is scale and the variance $\sigma^2 = (s^2\ \pi^2)/3$

$\sigma\mu$, of the logistic with $\hat{x}$ = −0.004 and s = 0.08 (orange) and the Gaussian with $\hat{x}$ = 0.0007 and σ = 0.14 (green)

Γ is the gamma function, ν are the degrees of freedom, and $\sigma^2 = (s^2\ \nu)/(\nu - 2)$

The variance of the relation weights more than the number of sources used

Results for the Flat and non-flat models

$\mathcal{L}_G$ 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 $\mathcal{L}_N$ 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

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 H_0.

The two different Cosmological analysis

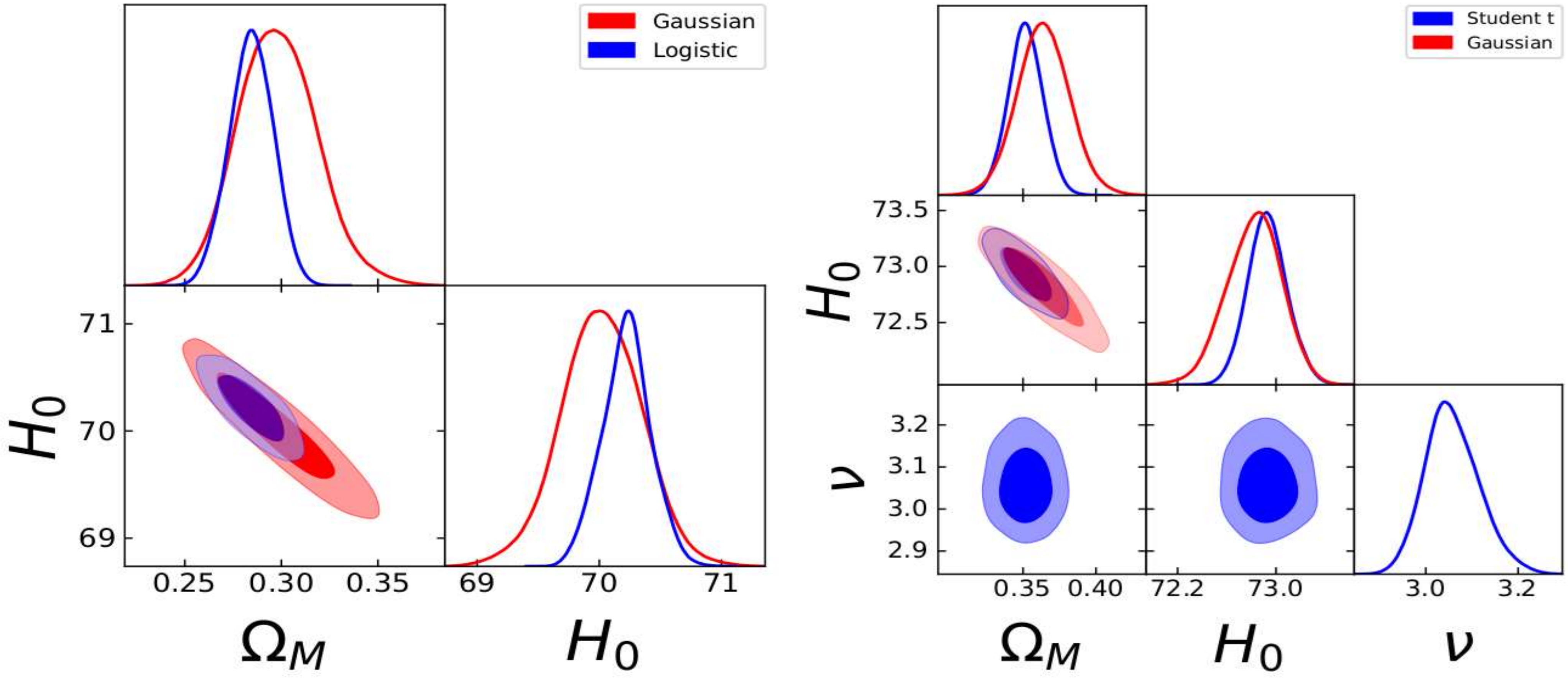
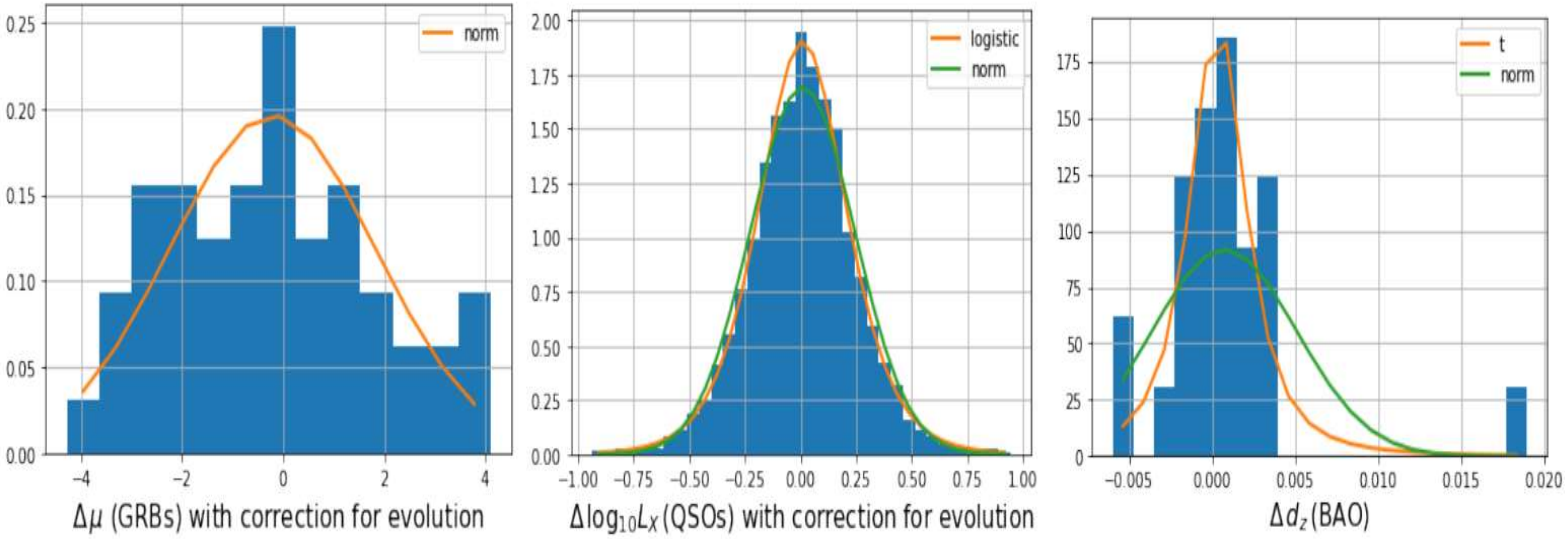


Figure 2: Fit of the flat ΛCDM model with Ω_M and H_0 free parameters. Left panel shows the results for *Pantheon* SNe Ia with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{logistic}$ as in the legend. Right panel shows the contours for the *Pantheon* + sample with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{Student}$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

Can high-z probe cast light on the Ho tension?

Let’s consider GRBs observed up to z=9.4
What’s the catch?

The best likelihood of the BAO, QSQs and GRBs



Bargiacchi, G., Dainotti, M.G., Nagataki, S. and Capozziello, S. MNRAS, 521(3), pp.3909-3924 (2023), ArXiv:2303.07076

GRBs are used with the Dainotti relations in X-rays and optical for long GRBs with plateaus

New statistics: Non-Gaussianity likelihoods for SNe Ia and QSQs -> 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 thus we are closer to the SNe Ia Pantheon sample values!

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

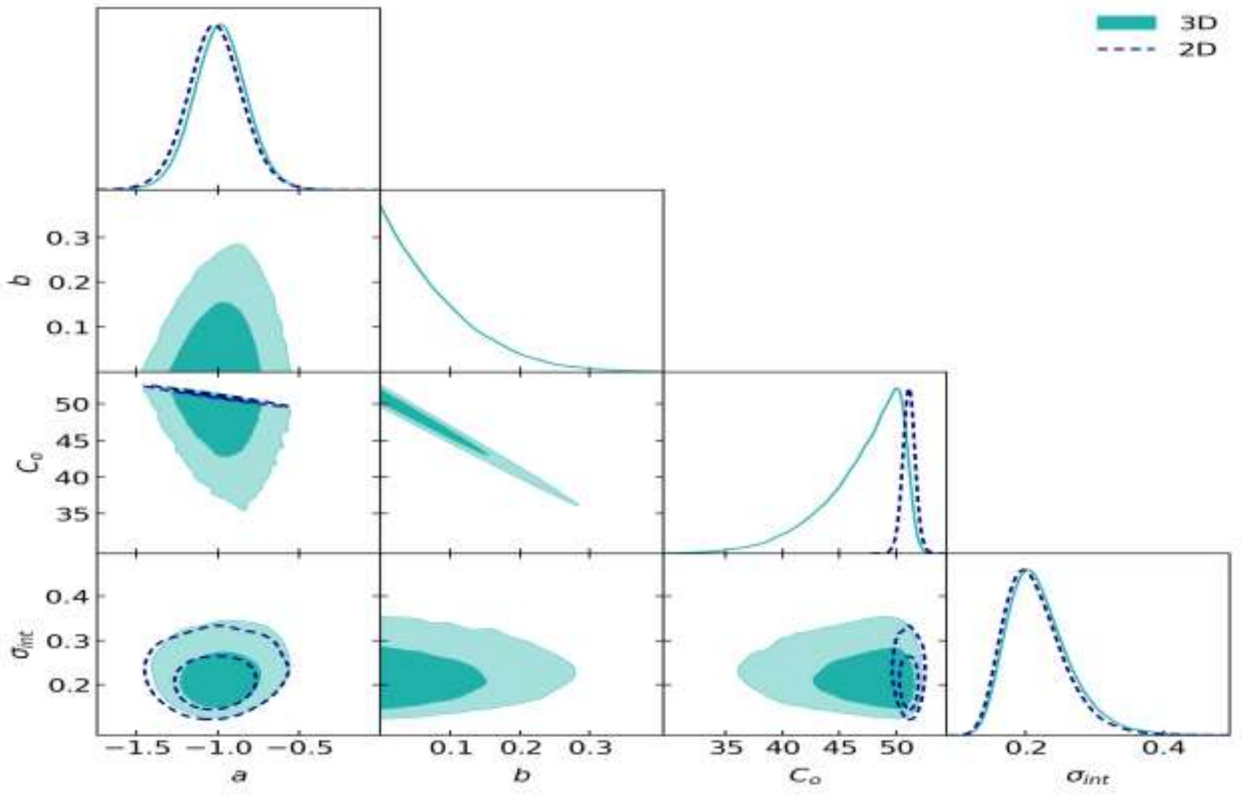
Bargiacchi, Dainotti et al. 2023, MNRAS, 521, 3909

Dainotti et al. 2023, including B. Zhang, N. Fraija, accepted in ApJS,

2023arXiv230510030D, press release

Besides the simultaneous fitting, we use the CCH as calibrators for the fundamental plane correlations

Favale, Dainotti, Gomez, Migliaccio , A&A submitted



		a	b	C_o	$\sigma_{\rm int}$
3D relation	Mode values	-0.97	< 0.21	50.11	0.21
	Mean	-0.98 ± 0.16	< 0.21	$46.96^{+4.25}_{-1.38}$	$0.22^{+0.03}_{-0.05}$
2D relation	Mode values	-1.00		51.00	0.19
	Mean	$-1.01^{+0.17}_{-0.16}$		51.11 ± 0.54	$0.21^{+0.03}_{-0.05}$

With evolutionary effects we have

$$\sigma_{int} = 0.20^{+0.03}_{-0.05}$$

This is comparable with the fundamental plane relation sigma=0.18 +/0.09

Currently the Epeak-Eiso correlation has a scatter of 0.20 (Amati et al. 2022), but depending on the sample size reaches 0.55 (Liu et al. 2022, Liang et al. 2022, Li et al. 2023)

Thus, we have consistently reached the smallest scatter for the GRB relations in the literature with this sample

What else do we need for GRB cosmology?

New or tighter Reliable correlations

Increase the sample size, having a cosmology independent approach via low-z probes

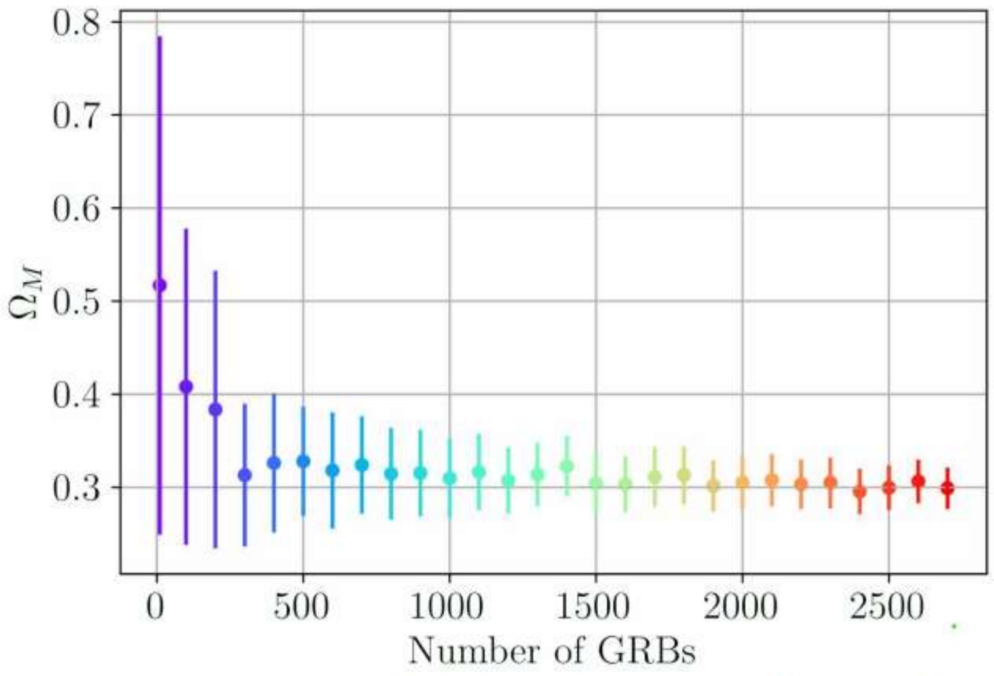
Physical interpretation, connection with theory In the quest for the standard set

How?

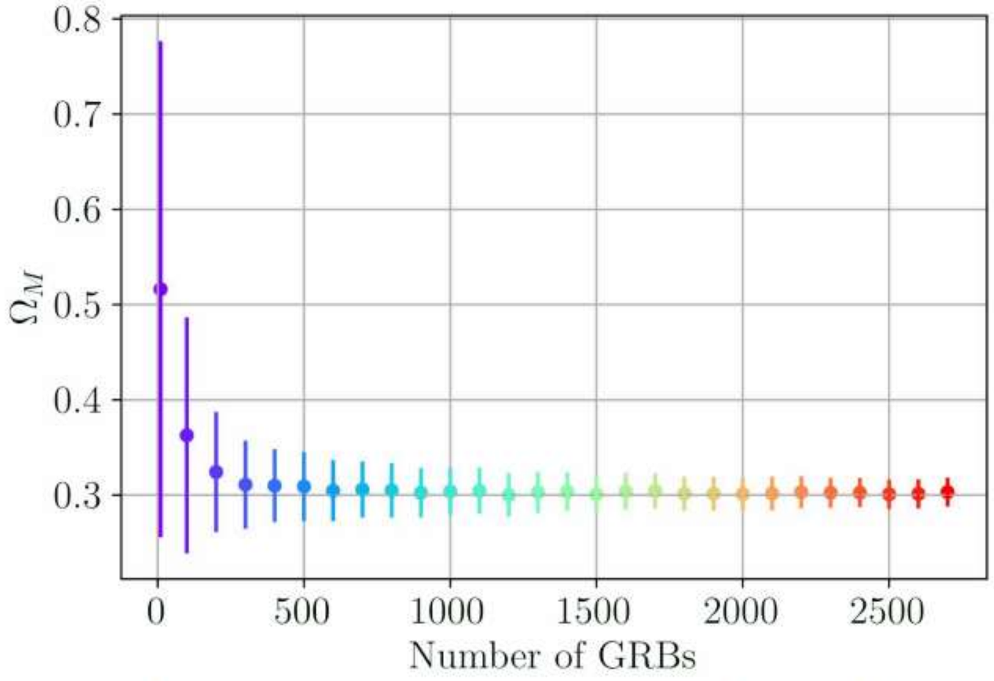
FORECASTS: THE PRECISION ON Ω_M WITH GRBs

WITH THE 3D OPTICAL RELATION

M. G. Dainotti, et al. 2022, MNRAS, 514, 2, 1828-1856



(a) OPTICAL | Simulation Results for the Full OPT Base with Undivided Errors



(b) OPTICAL | Simulation Results for the Full OPT Base with Halved Errors

How many GRBs with optical plateaus are needed to achieve the SNe Ia precision?

GRBs	Precision	When?	How?
67	Conley et al. 2011 precision $\sigma\Omega_M$ =0.10	Now	With Machine learning (ML), errors on the parameters halved (n=2), and Lightcurve reconstruction (LCR)
134	Betoule et al. 2014 precision $\sigma\Omega_M$ =0.042	2026	
390	Scolnic et al. 2018 precision $\sigma\Omega_M$ =0.022	2042	

M. G. Dainotti, et al. 2022, MNRAS, 514, 2, 1828-1856

Worry not: we should not wait 18 years!

The largest optical catalog to date!

- Press release from MNRAS
- Huge gamma-ray burst collection 'rivals 250-year-old Messier catalogue' | The Royal Astronomical Society (ras.ac.uk)
- Dainotti et al., 2024, MNRAS, tmp,1527D.

What’s the next step?

- To extend the distance ladder with CCH which entails a model independent approach at high-z possibly with the use of GRBs for which the redshift is inferred
- **We can combine GRBs with other probes which are treated similarly as GRBs and look for a standard set of QSOs to tighten the existing relations**
- **And we did! in..**

“Quasars: Standard Candles up to z= 7.5 with the Precision of Supernovae Ia” by

Dainotti, M.G., Bargiacchi, G., Lenart, A.L., Nagataki, S. and Capozziello, S. ApJ, 950(1), id.45, 8 pp. (2023), ArXiv:2305.19668

What else can we do?

- We can change the strategy/methodology to achieve the standard set and compare the differences
- And we did even with multiple methods in
- The scavenger hunt for Quasar samples to be used as cosmological tools

Dainotti, M.G., Bargiacchi, G., Lenart A.L. and Capozziello, S. Galaxies, 12, (1), id.4 (2024), ArXiv:2401.11998

- "A new binning method to choose a standard set of Quasars",

Dainotti, Lenart et al. Physics of the Dark Universe, Vol. 44, 101428, doi.org/10.1016/j.dark.2024.101428,https://arxiv.org/abs/2401.12847.

The story of GRB cosmology does not end here, it is just the beginning…

- For the sample increase we built the largest optical catalog to date

(Dainotti et al., MNRAS, 2024, tmp 1527D, 50 coauthors)

- We continue to improve prediction and LC reconstruction with Machine learning to reduce the number of years
- We continue the theoretical discussions: maybe given magnetars can be standardizable candle.

Special issue in Galaxies: free waivers for invited submission

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

- Deadline for submission: 15th of December 2024
- Impact factor: 3.2
- Fast peer reviewed process
- I am Guest Editor and recently an Editor.

Postdoctoral position open in my group at NAOJ

- Deadline is 25th of September, noon Japan time.
- The fellow will receive annual research funds of 500,000 JPY.
- The project description is in 33.
- The fellow is free to do their own project for the 50%.
- Project Research Fellow (General) | NAOJ: National Astronomical Observatory of Japan – English


Thank you for your attention!
maria.dainotti@nao.ac.jp
mariagiovannadainotti@yahoo.it

Inferring the unknown *z*

Finally, we inferred the *z* of 151 GRBs (generalization set).

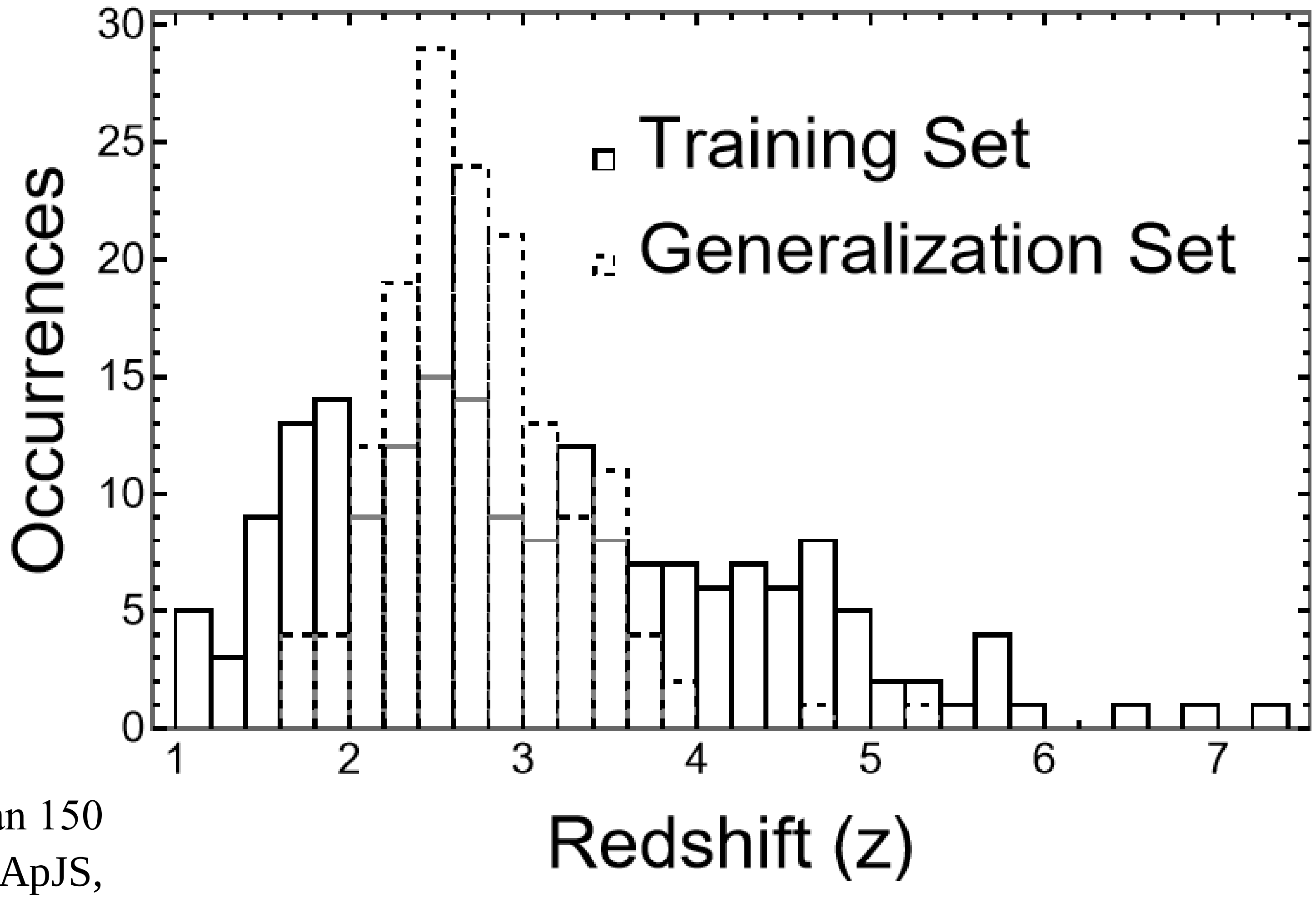


Figure 3. Histogram comparing the distributions of the training set $z_{observed}$ and the $z_{prediction}$ of the generalization set.

Dainotti et al. (2024)

Dainotti et al. 2024, "Inferring the redshift of more than 150 GRBs with a machine learning ensamble", accepted in ApJS, https://arxiv.org/abs/2401.03589.

Data Sample and results

- Data set: sample of 2421 Quasars (QSOs)
- Methods:

–**σ-clipping technique applied both in luminosity and flux to select a QSO sub-sample composed of sources that better follow the X-UV QSO relation**

- Results:

–**We have defined a sample of 983 Quasars up to z = 7.54 with reduced intrinsic dispersion δ = 0.007 which determines the matter density parameter Ω_M with the same precision of *Pantheon Type* Ia supernovae:**

–**$\Omega_M = 0.268 \pm 0.022$**

–**This is the first time that QSOs as standalone cosmological probes yield such tight constraints on Ω_M**

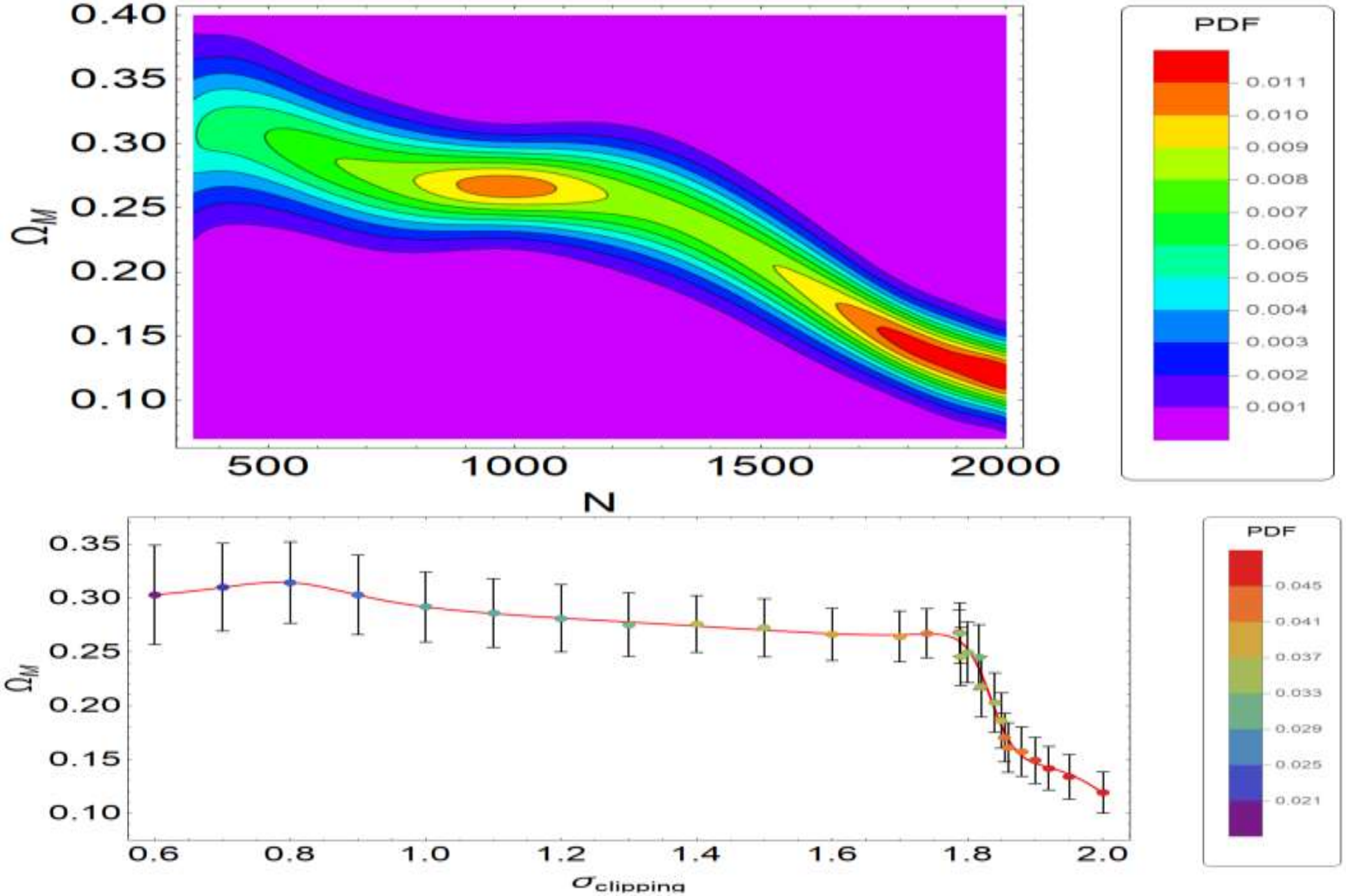


Figure 3. Upper panel: The values of Ω_M and their associated uncertainties vs. the number of Quasars. The color bar on the right shows the normalized probability density, indicating for each sample size the most probable value of Ω_M, thus the smallest uncertainty on Ω_M. This Fig. indicates that the smallest error bar on Ω_M (the red contour) is achieved for $N \approx 2000$, which yields $\Omega_M = 0.119 \pm 0.019$. This is obtained for our golden sample assuming a flat ΛCDM model. Bottom panel: Values of Ω_M with corresponding 1 σ uncertianities as a function of the σ-clipping threshold and the probability distribution function (PDF) showed with the colour bar on the right side. The red line is the best-fit of Ω_M points.

"The scavenger hunt for Quasar samples to be used as cosmological tools"
Dainotti, M.G., Bargiacchi, G., Lenart A.L. and Capozziello, S.
Galaxies, 12(1), id.4 (2024), ArXiv:2401.11998

- Data set: sample of 2421 Quasars (QSOs)
- Methods:

–**Huber regressor technique applied in redshift bins of the flux space to select a QSO sub-sample of sources that follow a tighter X-UV QSO relation**

- Results:

–**We discovered a sample of 1132 QSOs up to z = 7.54 exhibiting a reduced intrinsic dispersion, $\delta_F = 0.22$ vs $\delta_F = 0.29$ (24% less), than the original sample. This sample enables us to determine the matter density parameter Ω_M with a precision of 0.09 by using QSOs as standalone probes.**

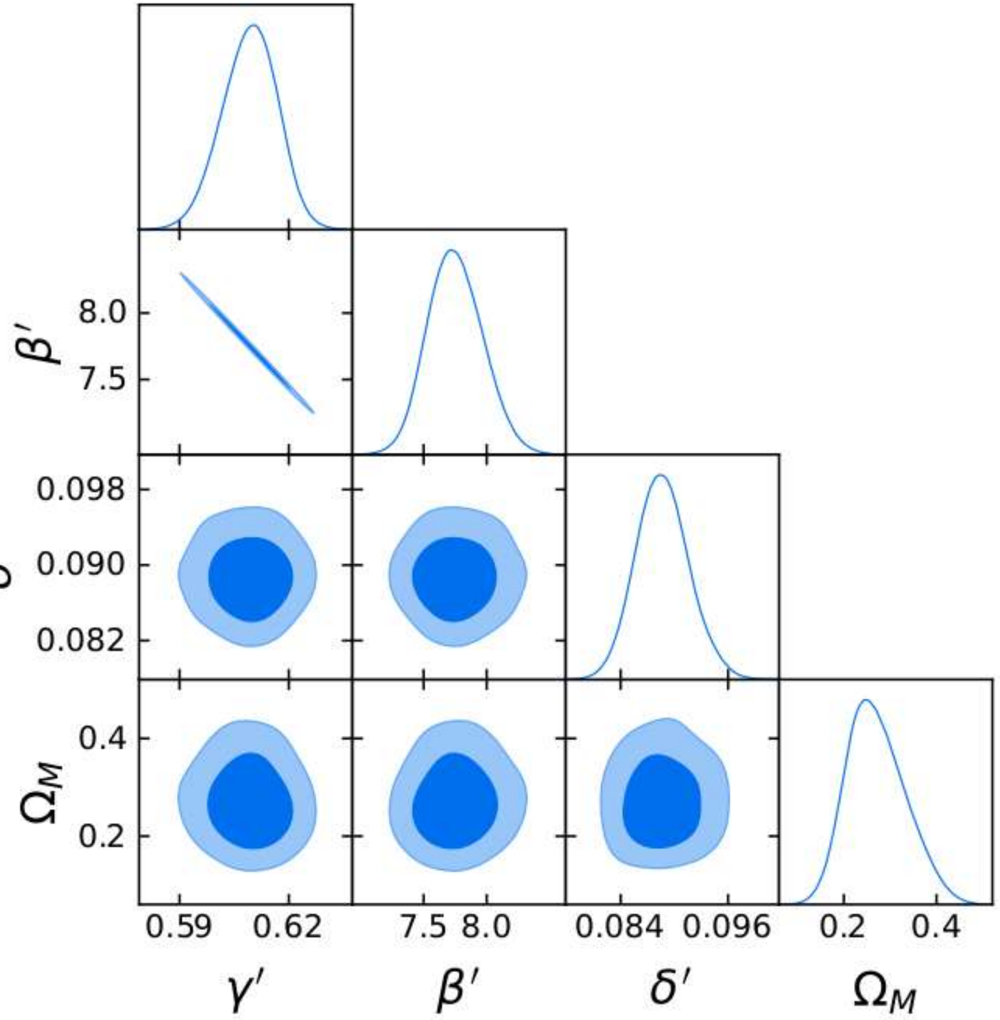


Figure 11. Results obtained from the gold sample of 1132 QSOs from the cosmological fit of the flat ΛCDM model with γ', β', and δ' of the RL relation, corrected for redshift evolution in the luminosities and Ω_M left as free parameter together with the ones of the relation. H_0 is fixed to $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with best-fit values with 1σ uncertainties: $\gamma' = 0.61 \pm 0.01$, $\beta' = 7.8 \pm 0.2$, $\delta' = 0.084 \pm 0.003$, and $\Omega_M = 0.256 \pm 0.089$. The dark region shows the 68% of probability of the parameters at play, while the lighter blue region the 95%.

"A new binning method to choose a standard set of Quasars"

Dainotti, M.G., Lenart A.L., Ghodsi, Chakraborty, Di Valentino, Montani 2024, Physics of the Dark Universe, 44, 101428, doi.org/10.1016/j.dark.2024.101428, arXiv:2401.12847.

- Data set: sample of 2421 Quasars (QSOs)
- Methods:

–bin-size maximization technique which enables an enhanced bin division

–Theil-Sen regressor technique applied in redshift bins of the flux space to select a QSO sub-sample composed of sources that better follow the X-UV QSO relation

- Results:

–A sample of 1253 QSOs up to $z = 7.54$ with an intrinsic dispersion, $\delta_F = 0.096$ vs $\delta_F = 0.29$ (68% less), than the original sample. We determine Ω_M with a precision of 0.064 by using QSOs as standalone probes.

We aim to have the largest numer of sources possible to enable enough statistical power, but we discard outliers. This provides us with a high precision cosmological measurements. The optimal sample has 1253 sources.

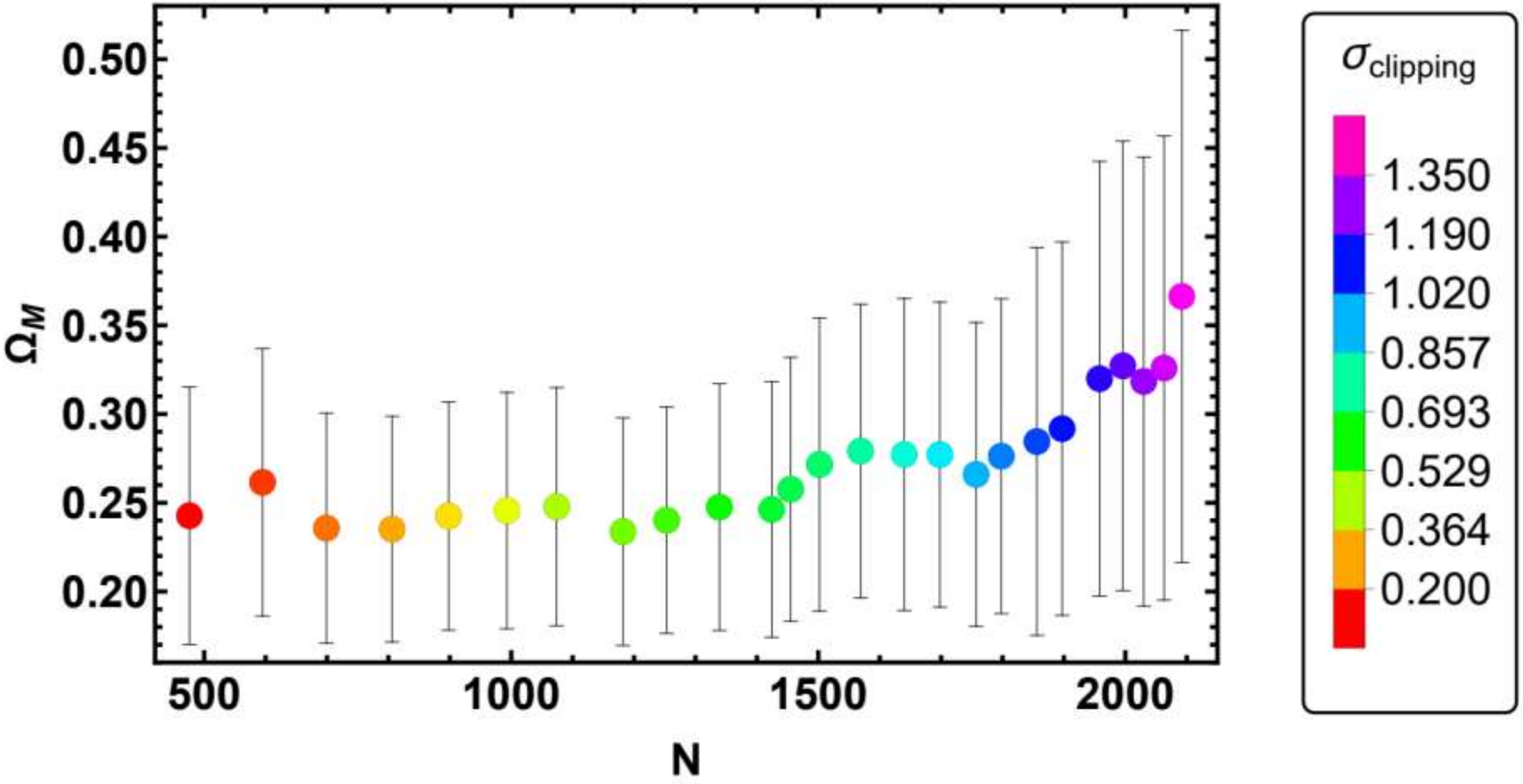


FIG. 8: The matter density parameter, Ω_M, computed for each sub-sample obtained in the σ clipping process, is shown as a function of the size of these subsets. The colour scheme indicates the interval chosen in the σ-clipping algorithm. The error bars represent 1 σ uncertainties.

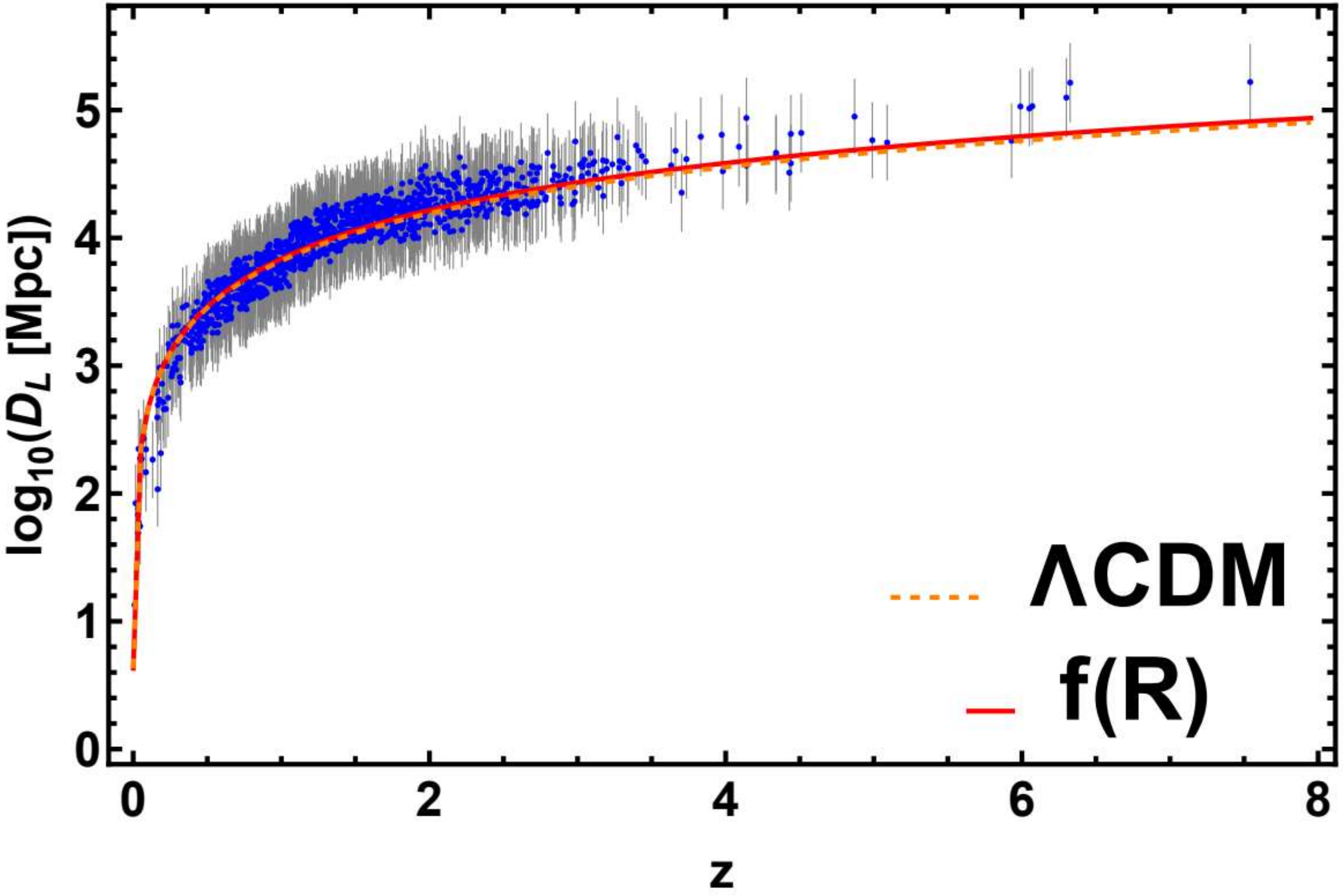


FIG. 12: The distance luminosity in the ΛCDM and induced by the f(R) modified theory of gravity for Ω_M=0.3 are shown in dashed orange and continuous red, respectively, with the total QSO sample in grey and the 'gold' sample in blue.

We investigate if the smaller value of Ω_M obtained for the golden sample can be explained by the f(R) gravity model.

For this purpose we compute numerically the function DL.

The f(R) model succesfully explains the difference between Ω_M observed at the low-z with SNe Ia and smaller value obtained by QSOs at higher z

Stay tuned: the story continues

- Next step is to use all these standard candles improved and extended subset to cast light on the new precision on cosmological parameters.

Overview of the redshifts

- THE PROBLEM

- Currently, the SWIFT GRB catalog only has **26% of GRBs** (~400) with measured redshift.

- Redshift measurements are crucial for the cosmological application of GRBs.
- Thus, a larger sample of GRBs with redshift can help address many outstanding cosmological mysteries.

- People have been trying for a GRB redshift estimator for 23 years with limited success.
- Finally, after two decades this method is promising!

WHAT ARE WE TRYING TO DO?

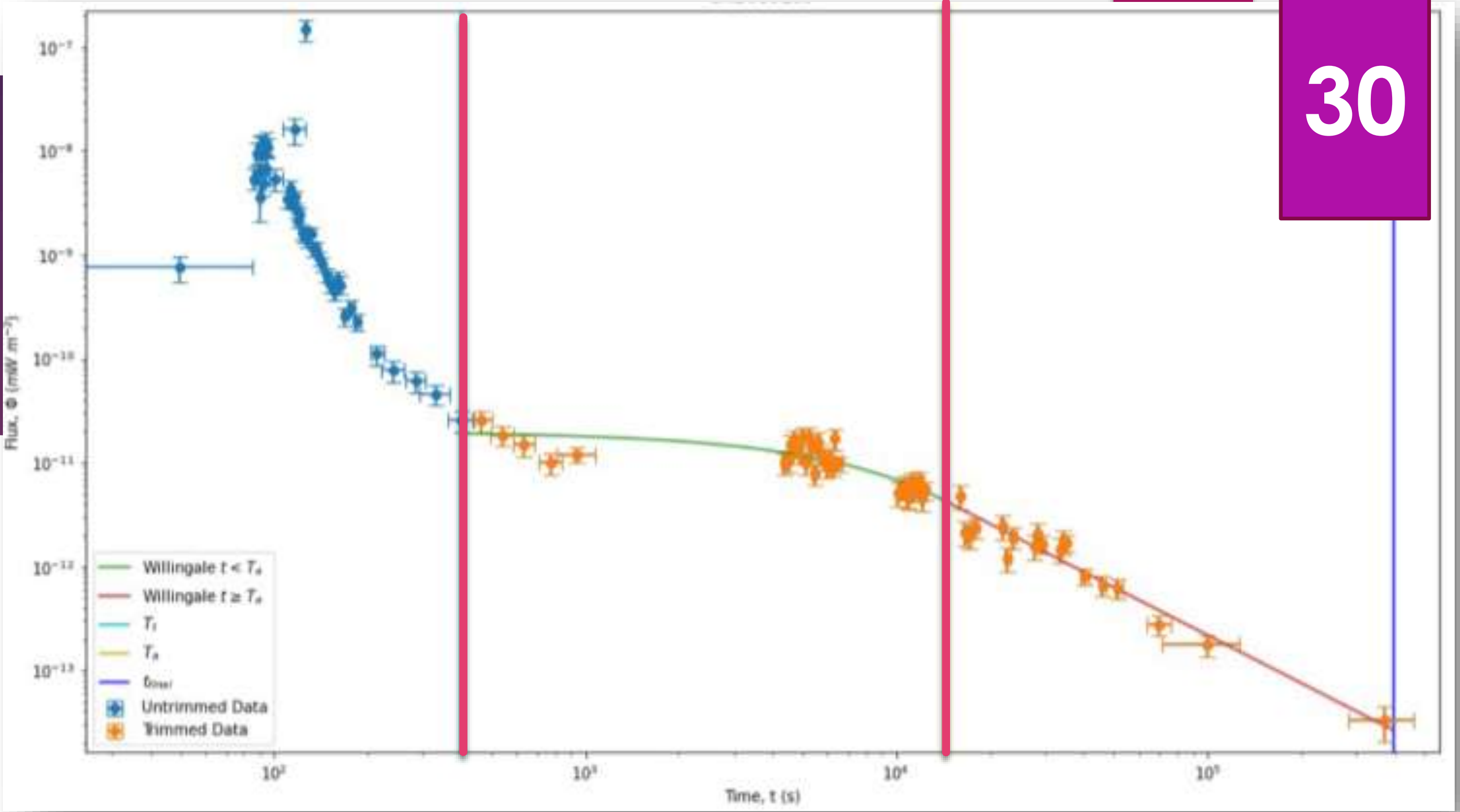
- We are training a supervised machine learning model on optical photometric GRB properties to reliably predict the redshift.
  Using this model, we will estimate the unknown redshift of GRBs.

HOW ARE WE GOING DO IT?

- We are applying the SuperLearner (an ensamble model) machine learning (ML) model to GRBs.
- We use MICE to impute missing data
- Applying Bias correction techniques to correct for bias in the prediction.
- For the first time, using plateau properties for GRB redshift estimation.

Data Sample

- We are using 179 GRBs which show the optical plateau in the lightcurve.
- These are taken from *"The Optical Two- and Three-dimensional Fundamental Plane Correlations for Nearly 180 Gamma-Ray Burst Afterglows with Swift/UVOT, RATIR, and the Subaru Telescope"* (Dainotti et al. 2022d)



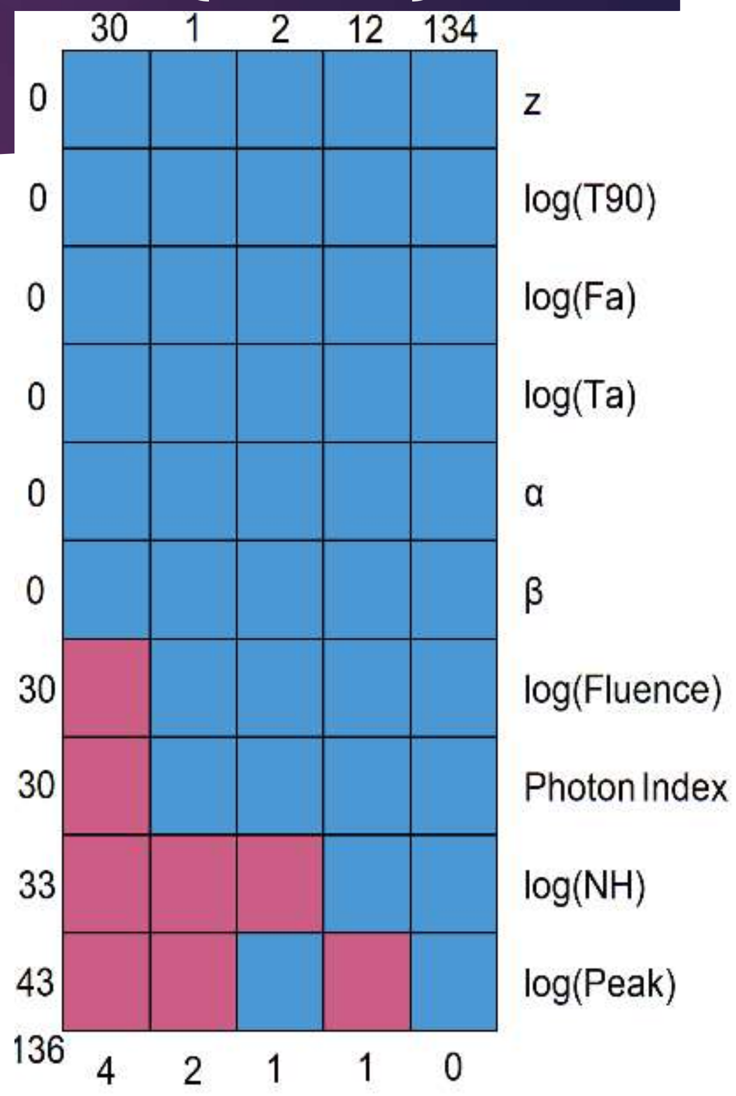
- The dataset contains GRBs from several telescopes and satellites Swift/UVOT, RATIR and the Subaru. We use 9 features in this analysis:

- 4 features from the prompt emission:
  Fluence,
  T90,
  Peak flux,
  Photon Index

- 5 features from the plateau emission:
  Time (Ta), Flux (Fa),
  Temporal index (α), Spectral index (β) at the end of plateau &
  Hydrogen column density (NH)

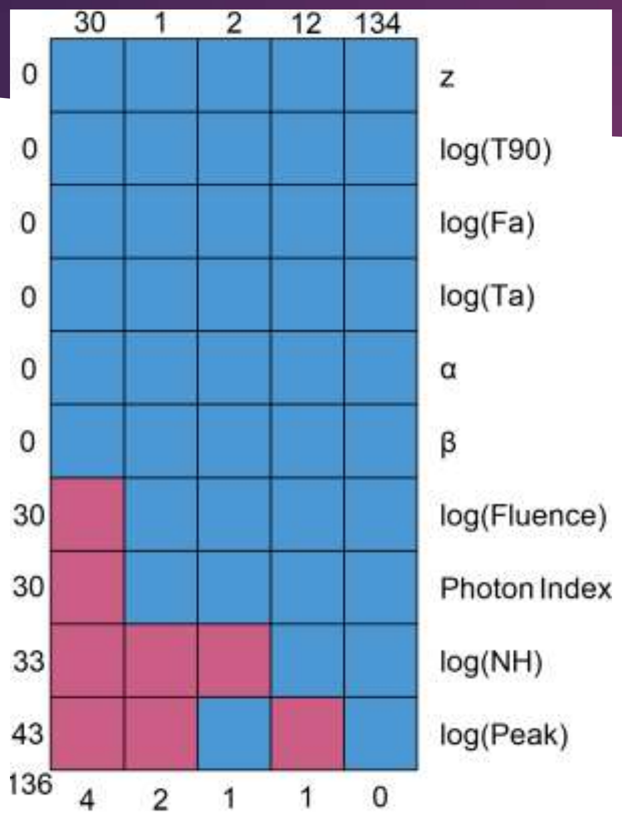
Missing data imputation
Multivariate Imputation by Chained Equations (MICE)

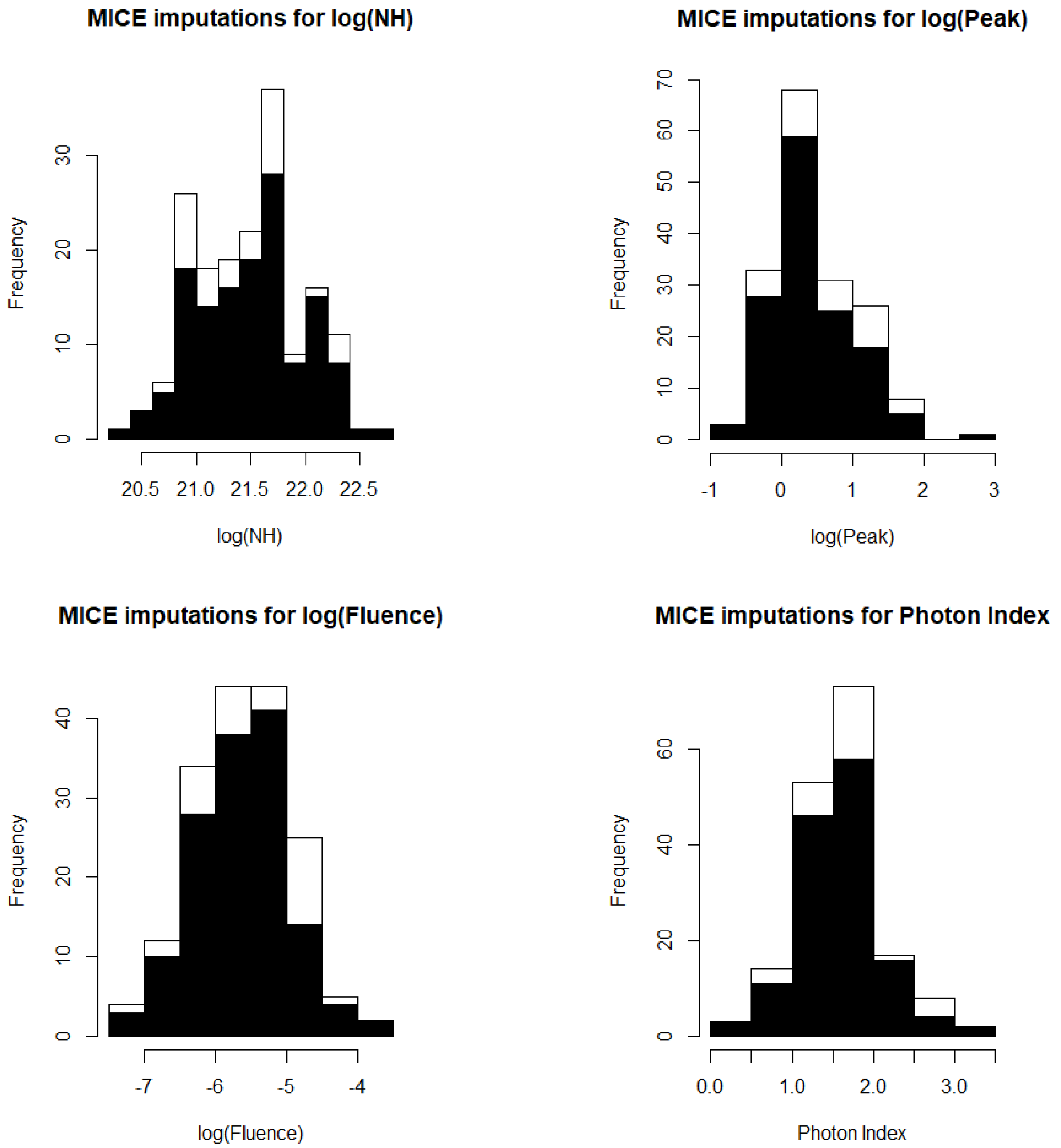
- 30 GRBs have missing data in log(Fluence), Photon Index, log(NH) and log(Peak).
- There is one GRB that has missing data in log(NH) and log(Peak) and 2 GRBs with missing log(NH).
- Finally there are 12 GRBs with missing log(Peak).
- We use Multivariate Imputation by Chained Equation (MICE) technique to impute 43 GRBs with missing data.
- Increases our training sample by 24% !
- Predictive mean-matching method known as “midastouch



Data Sample

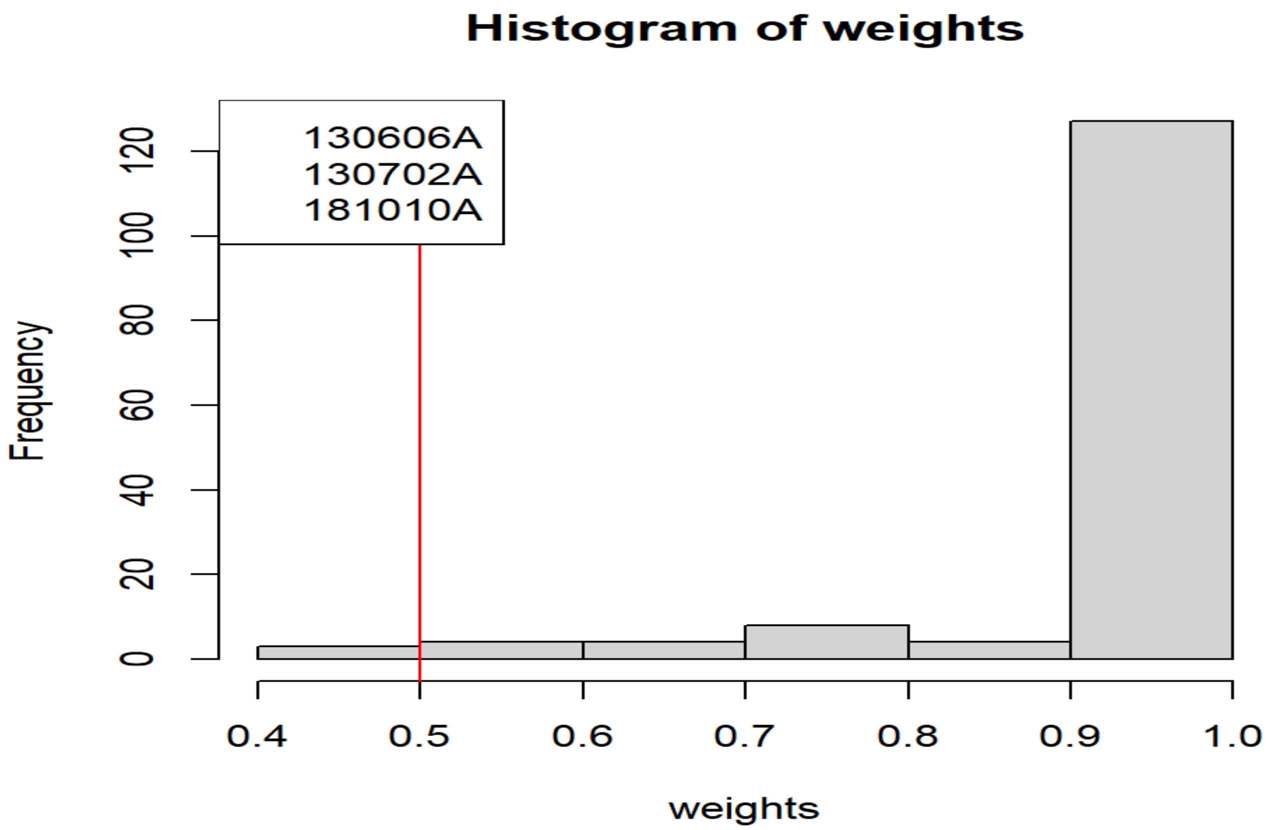
- This sample contains missing data as well





- We impute with MICE 34 GRBs
- We further impute with MICE 10 GRBs

The M-estimator→removing outliers



Methodology

- We developed an analytical formula using the 9 GRB properties
- Combine the 9 features to give good estimate for **log(z+1)**
- Many formulae were generated using a formula generator
- We tested them in the Generalized Additive Model (GAM) framework and picked the best

$$\log(z+1) = (\log(NH) + \log(T90) + PhotonIndex + \log(Fa))^2 + \log(Ta) + \alpha + \beta + \log(Fluence) + \log(Peakflux)$$

Methodology

$$\log(z+1) = (\log(NH) + \log(T90) + PhotonIndex + \log(Fa))^2 + \log(Ta) + \alpha + \beta + \log(Fluence) + \log(Peakflux)$$

1. Generalized Linear Model (GLM)
2. Bayesian GLM
3. GAM
4. StepAIC

SuperLearner!

- We did test many other ML models, but these 4 obtained the highest weights by SuperLearner consistently
- For the results we perform ten-fold cross validation 100 times

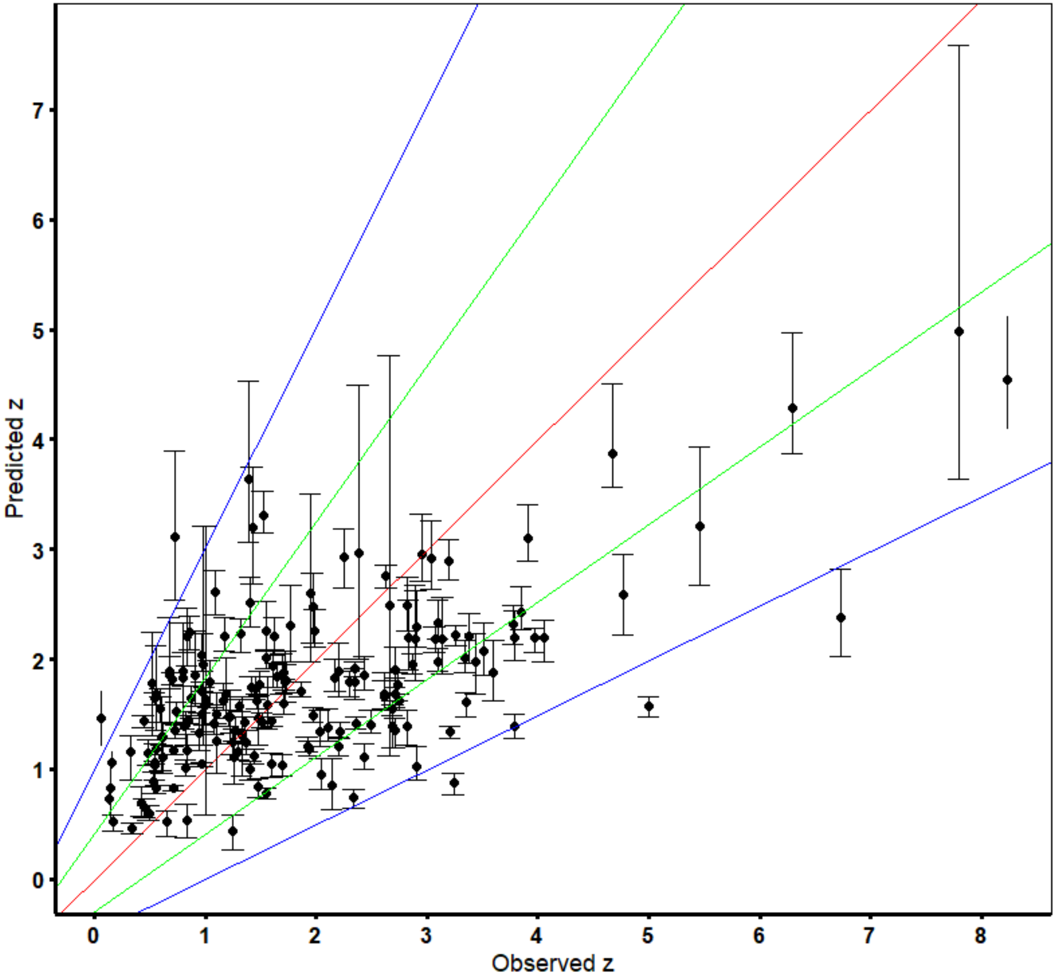
Results From Superlearner:

RMSE=SQRT((1/N)*Sum((zobs(i)-zpred(i)^2))

NMAD =(1/N) Median(|zi − z̄pred|),

Samplesize = 176 | In 2sigma = 171 (97%) | In sigma =114 (65%)

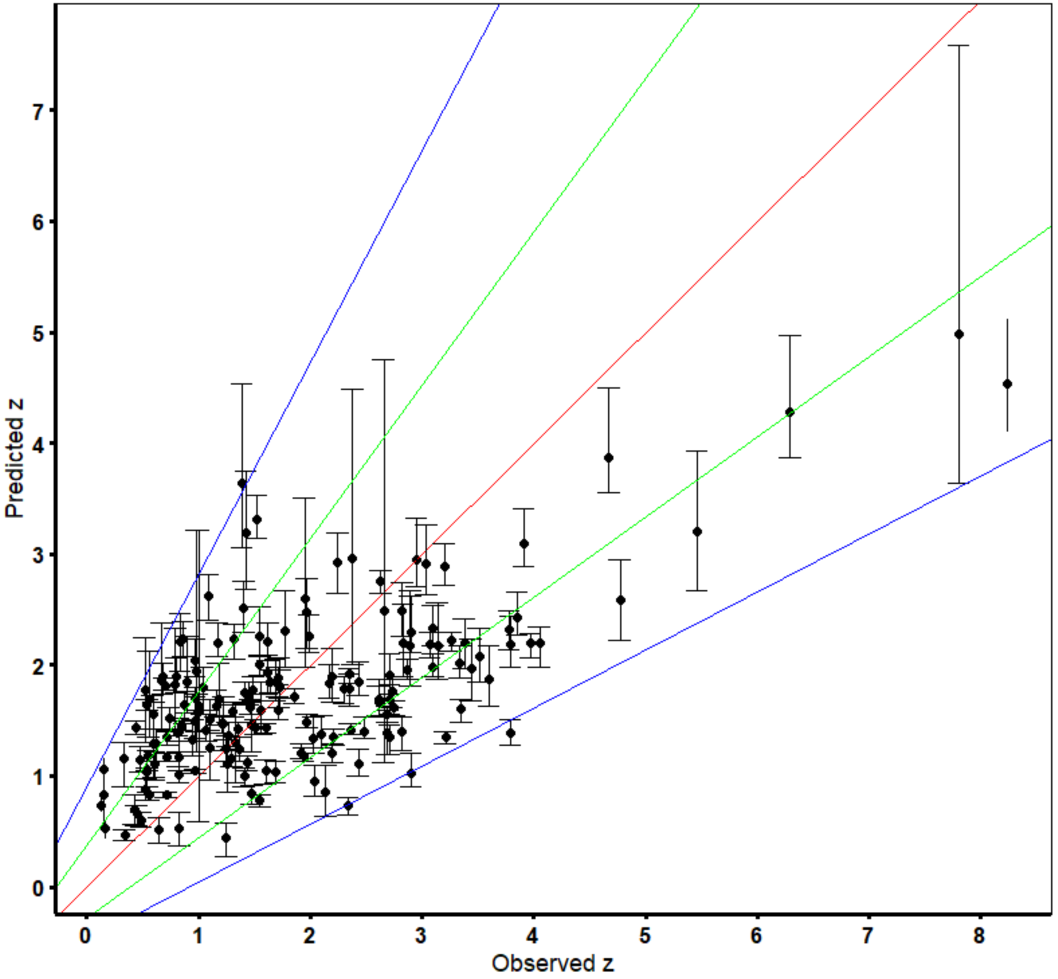
r = 0.621 | Sigma = 1.07 | RMS = 1.1 | Bias = 0.17 | NMAD = 1.47



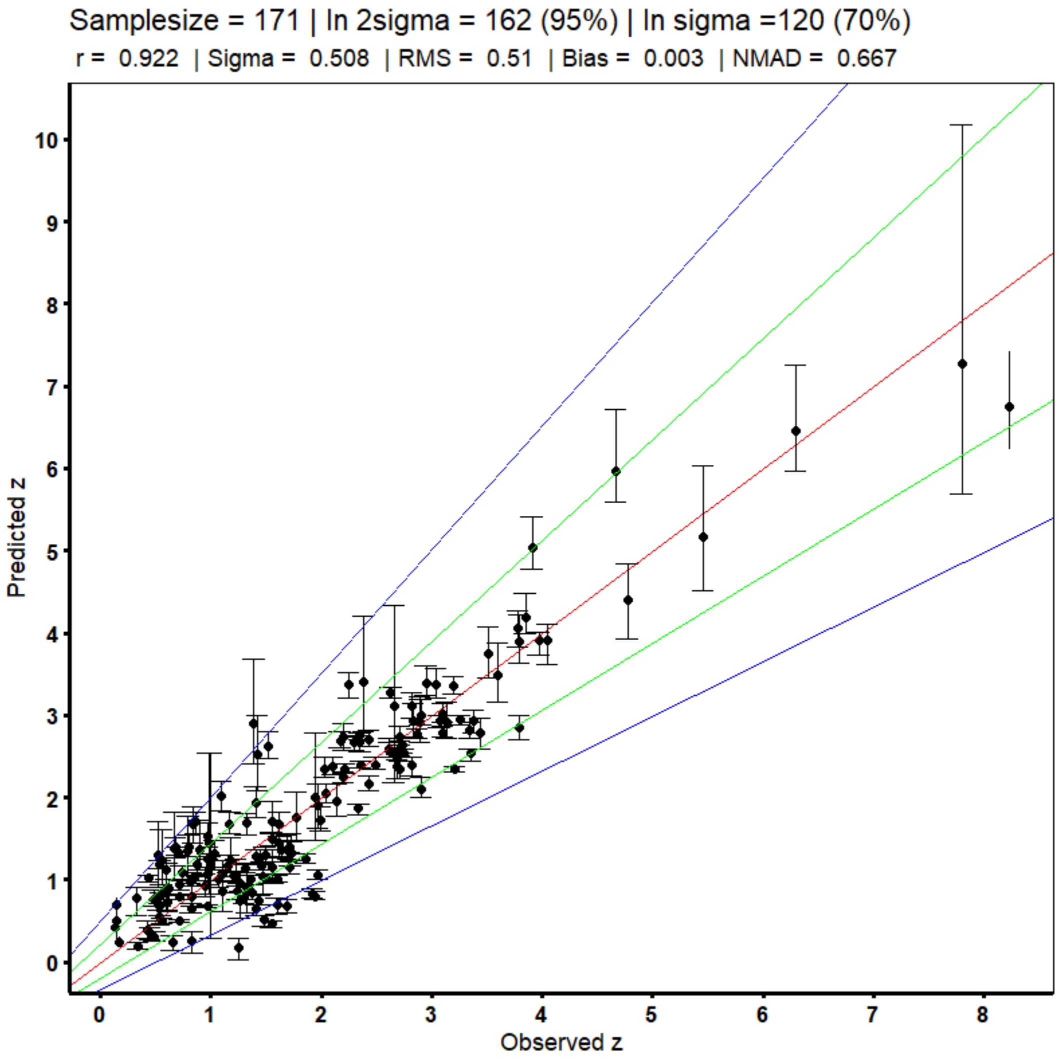
Remove outlier

Samplesize = 171 | In 2sigma = 167 (98%) | In sigma =108 (63%)

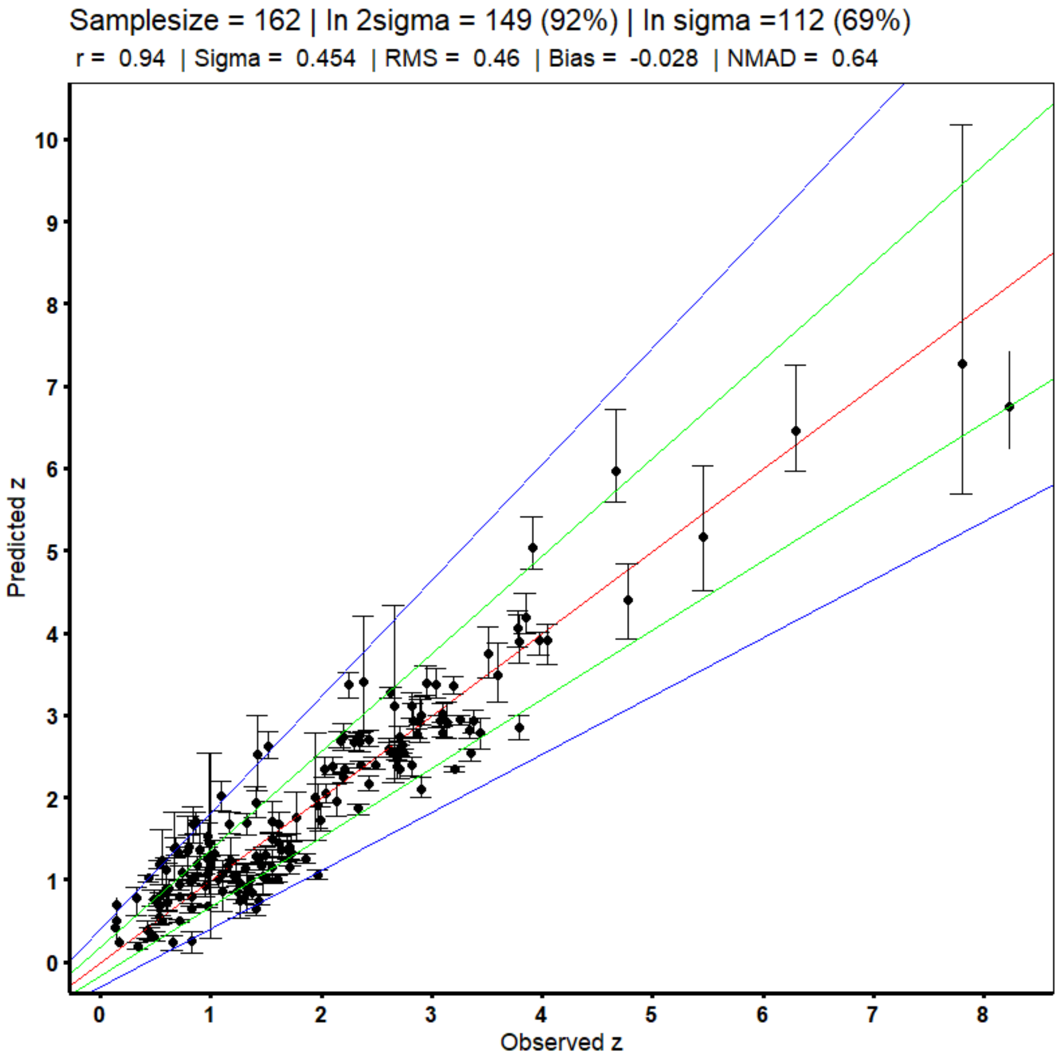
r = 0.672 | Sigma = 0.971 | RMS = 0.98 | Bias = 0.14 | NMAD = 1.39



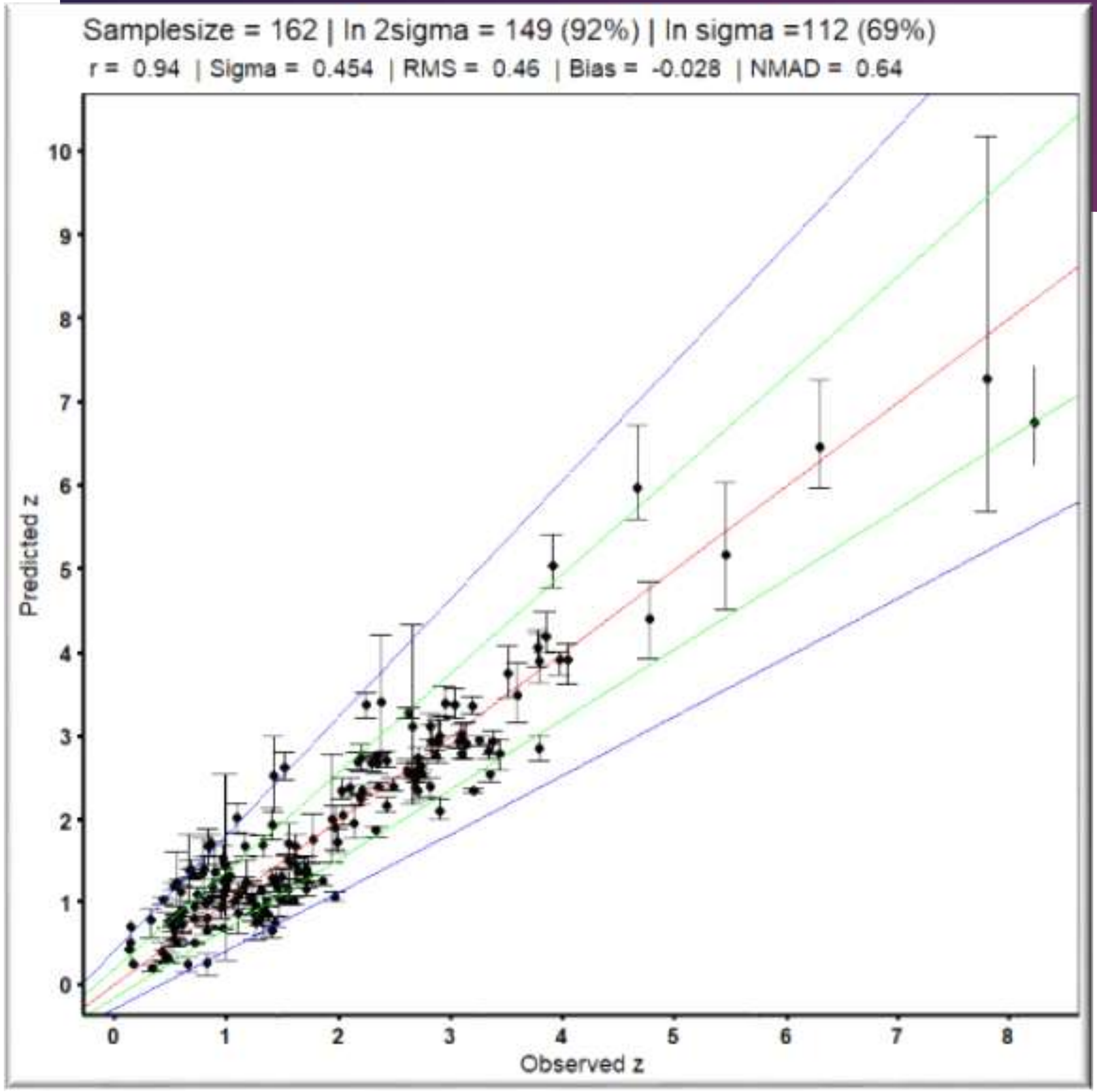
Results After Optimal Transport Bias Correction: to correct for biases



Remove outlier



Results After Optimal Transport Bias Correction:



For 162 GRBs:

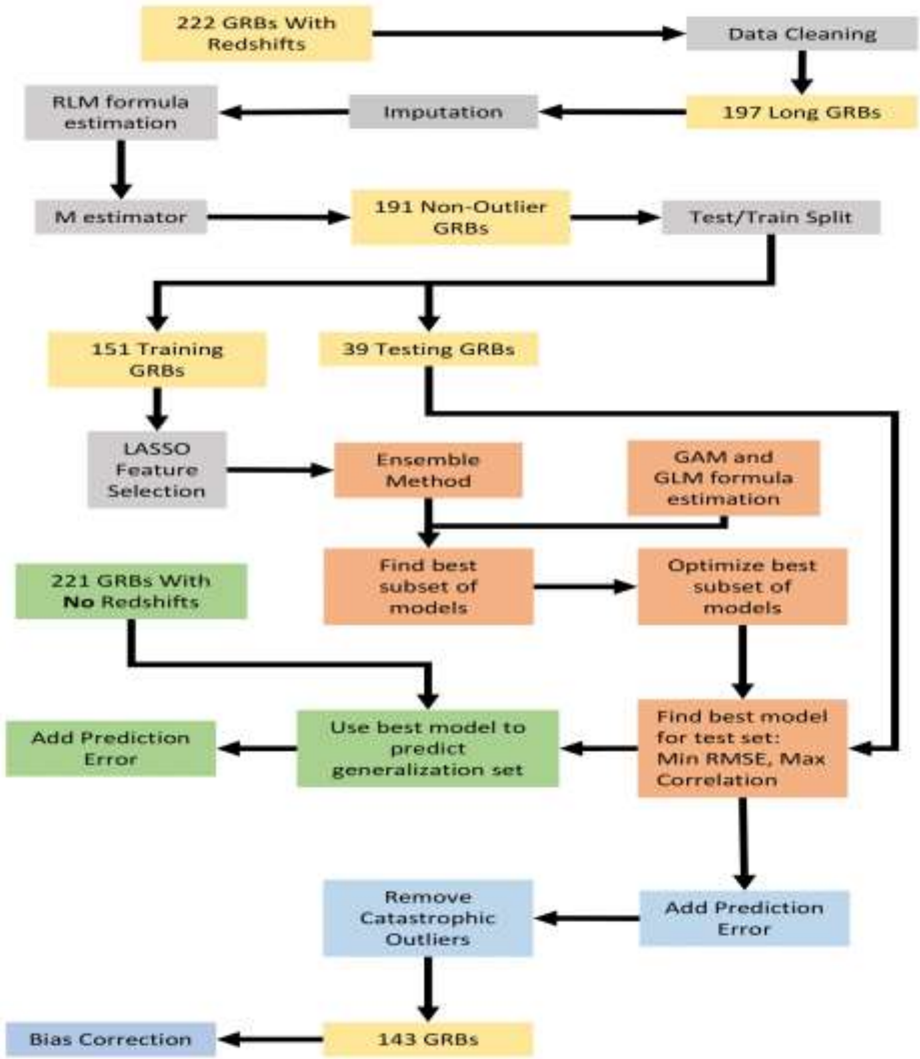
Pearson correlation= **0.94**

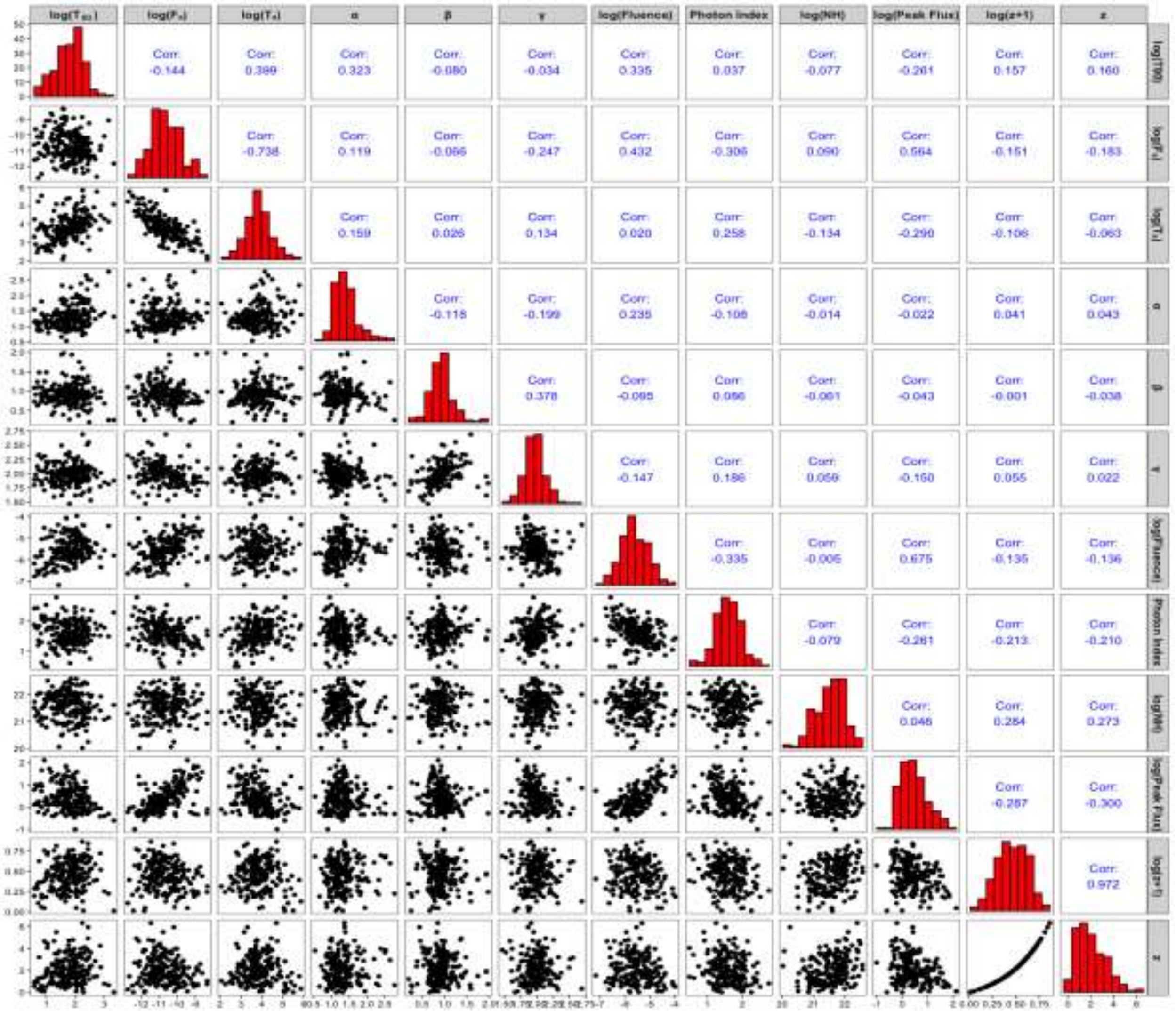
RMSE = **0.46**

Bias = **0.03**

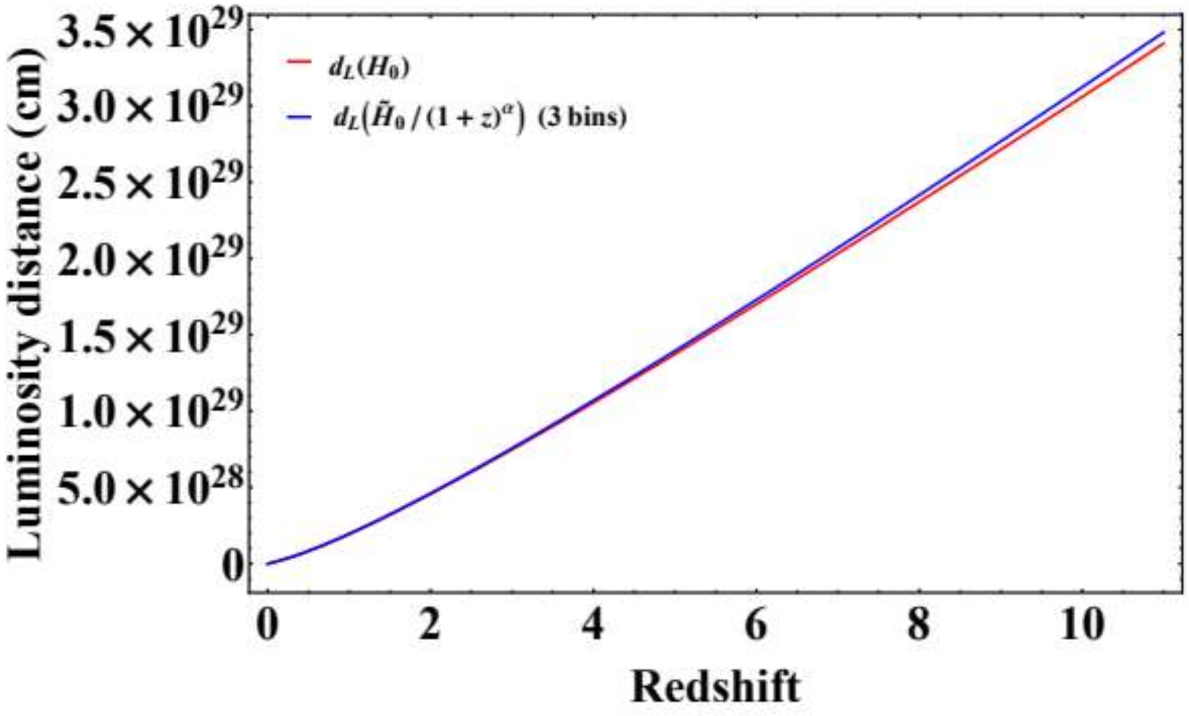
Comparing with Ukwatta et al. 2016, this is a **56% increase in Pearson correlation**

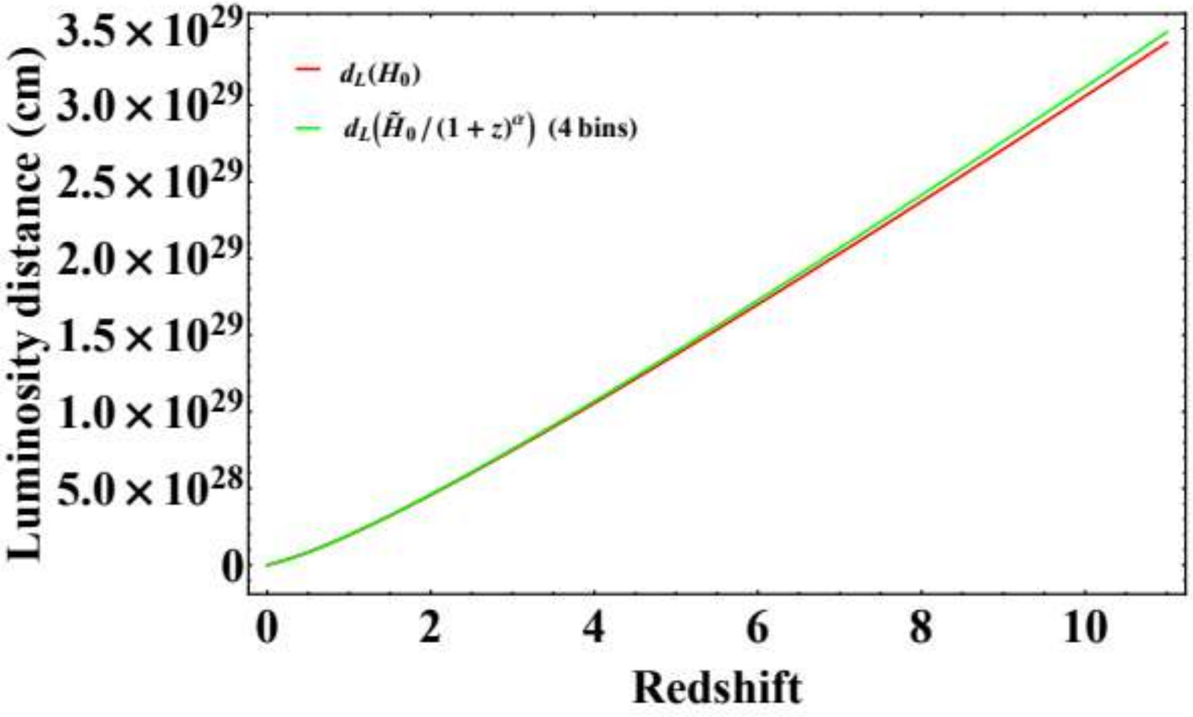
Continuing with X-rays
Dainotti et al. 2024,ApJS, 271, 1, id.22, 15.





The correction to the luminosity distance

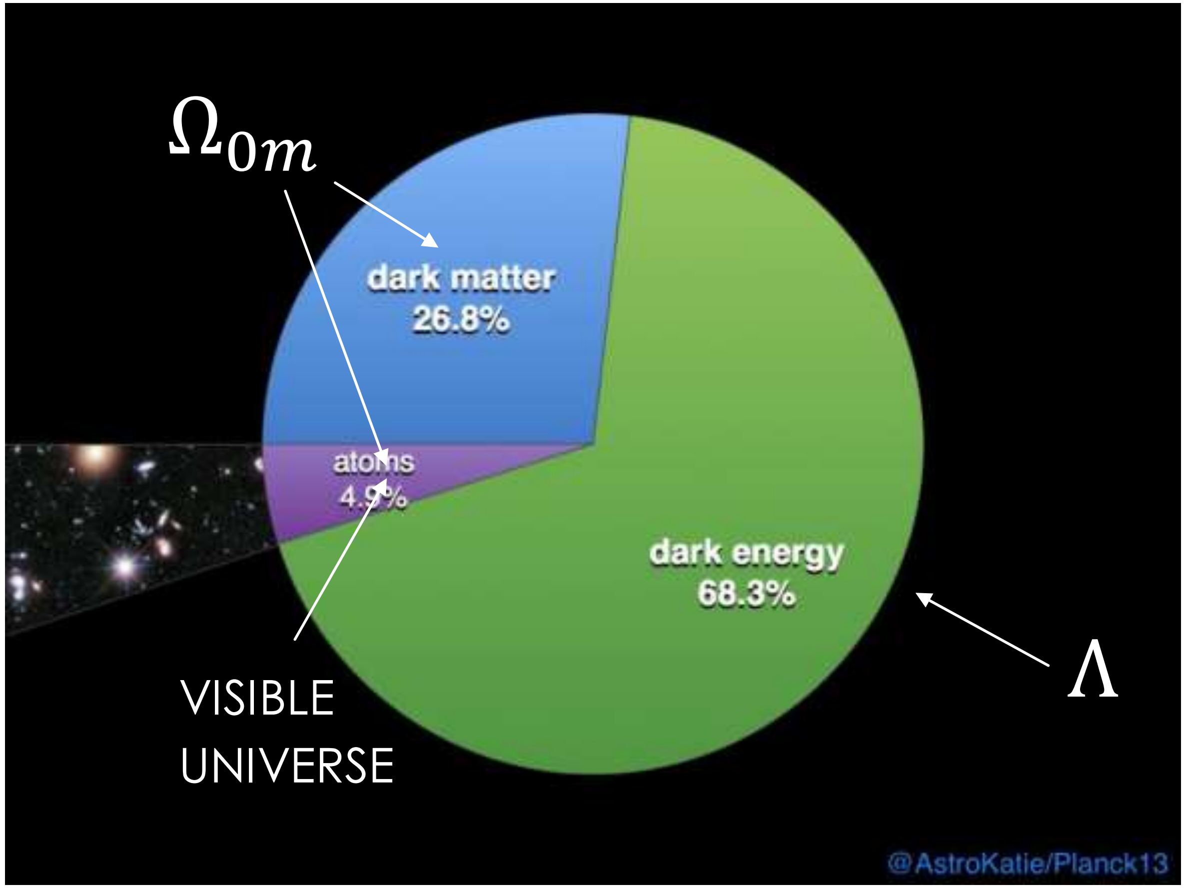




At redshift $z \cong 10$ the correction to the luminosity distance becomes in the order of $0.5 * 10^{29} cm$
1Mpc=3.0857E+24 cm, thus 16233 Mpc=16.23 Gpc. To have an idea Virgo cluster is only 16.5 Mpc away, so this distance is 1000 times larger

Now, are you ready for GRB-cosmology?

What can we investigate with GRBs, SNe Ia, Quasars and BAO?



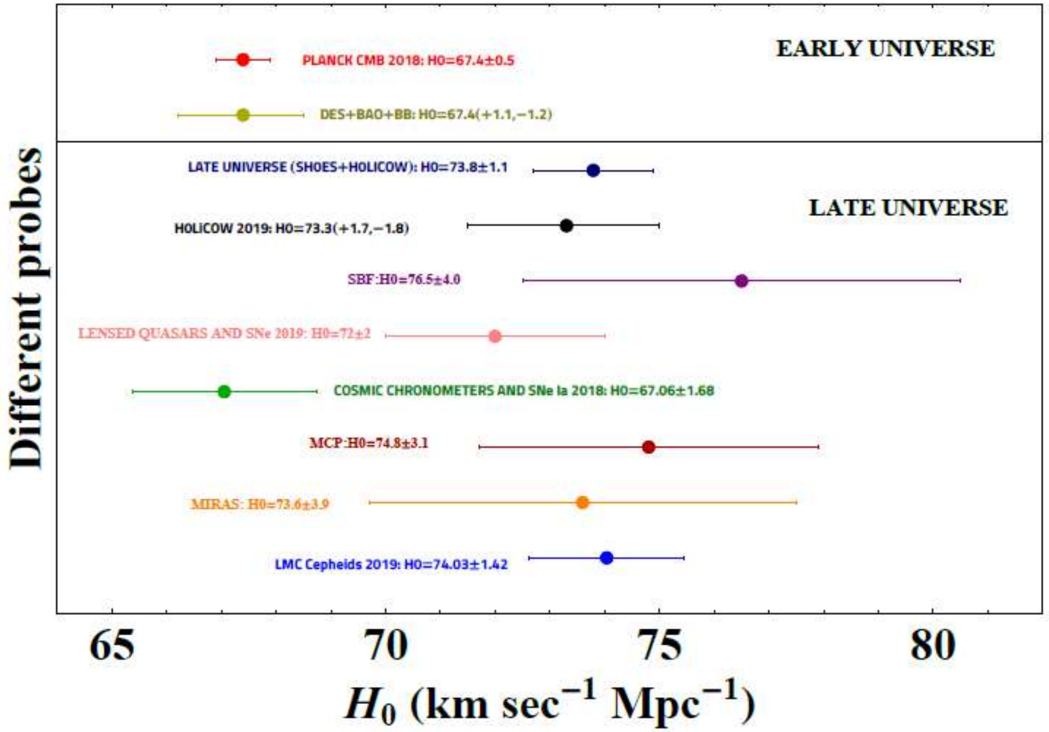
Open problems: the so-called Hubble tension

(Dainotti et al. ApJ, 2021-> **listed in top 1% paper in web of Science**)

The Hubble constant and its tension

$$H_0 \stackrel{\text{def}}{=} \frac{R'(t_0)}{R(t_0)}$$, $R(t_0)$ = SCALE FACTOR COMPUTED IN THE PRESENT (t_0) → $v = H_0 \cdot D$

HUBBLE'S LAW



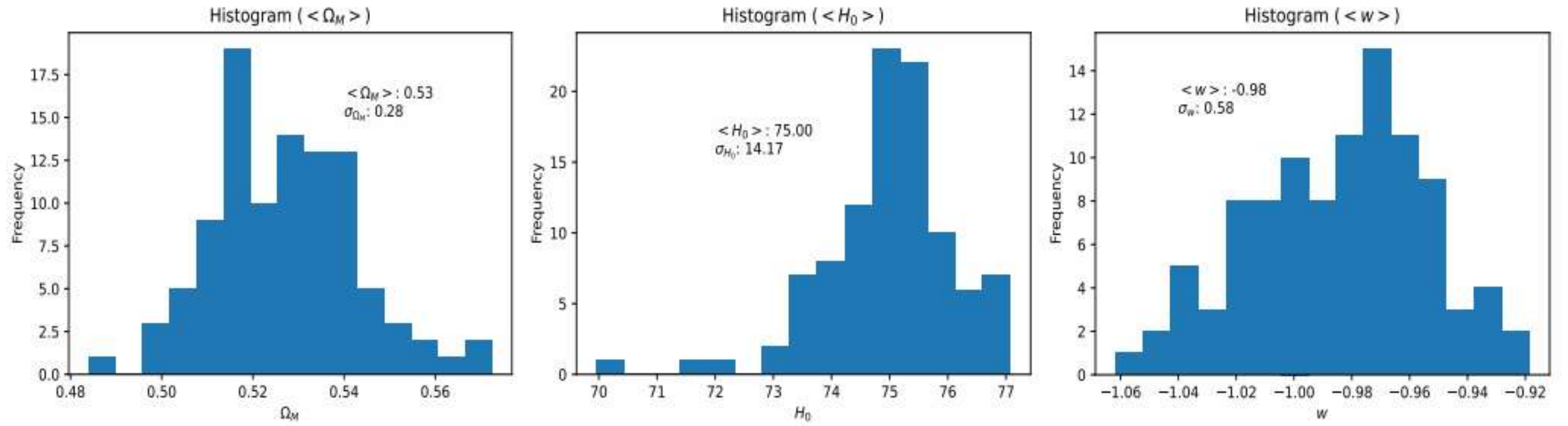
H_0 TENSION possibly due to its evolution or evolution of its parameters and its theoretical explanations

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

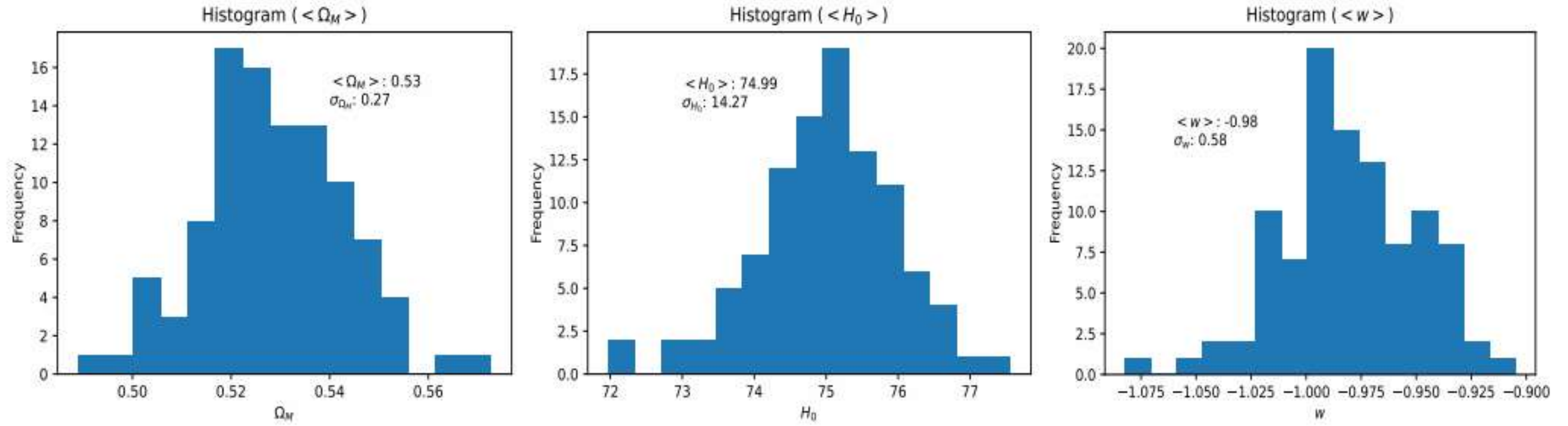
Dainotti et al. 2023, Galaxies, vol. 10, issue 1, 24.

Schiavone, Montani, Bombacini 2023, MNRASL

The latest cosmological results with GRBs only



(a) Varying only Ω_M without evolution (b) Varying only H_0 without evolution (c) Varying only w without evolution

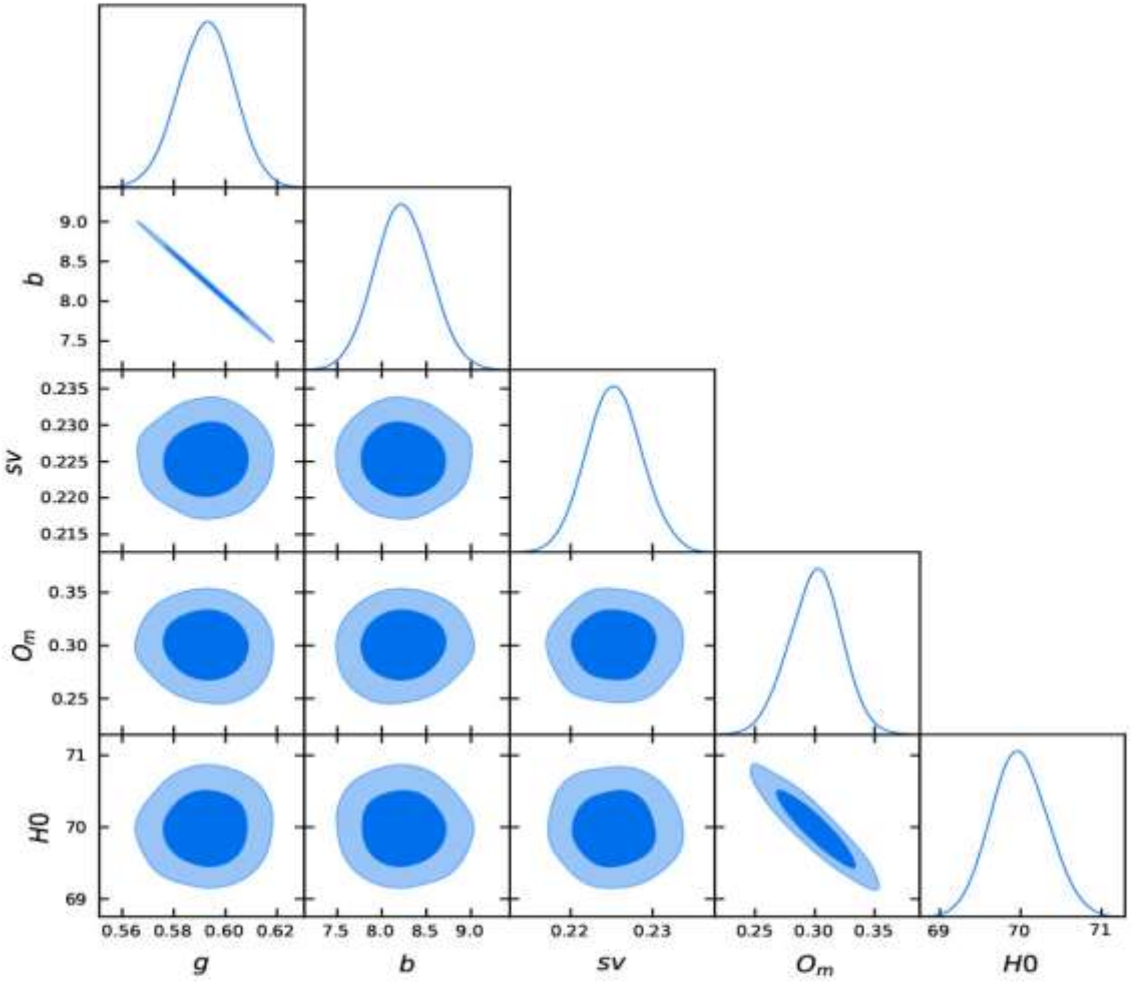


(d) Varying only Ω_M with fixed evolution (e) Varying only H_0 with fixed evolution (f) Varying only w with fixed evolution

M. G. Dainotti, A. Lenart, et al., 2022, MNRAS, 518, 2, 2201-2240
(tension increases, but errorbars are larger)

Results from QSO cosmology

- QSOs+SNe Ia: compatibility with standard cosmological model



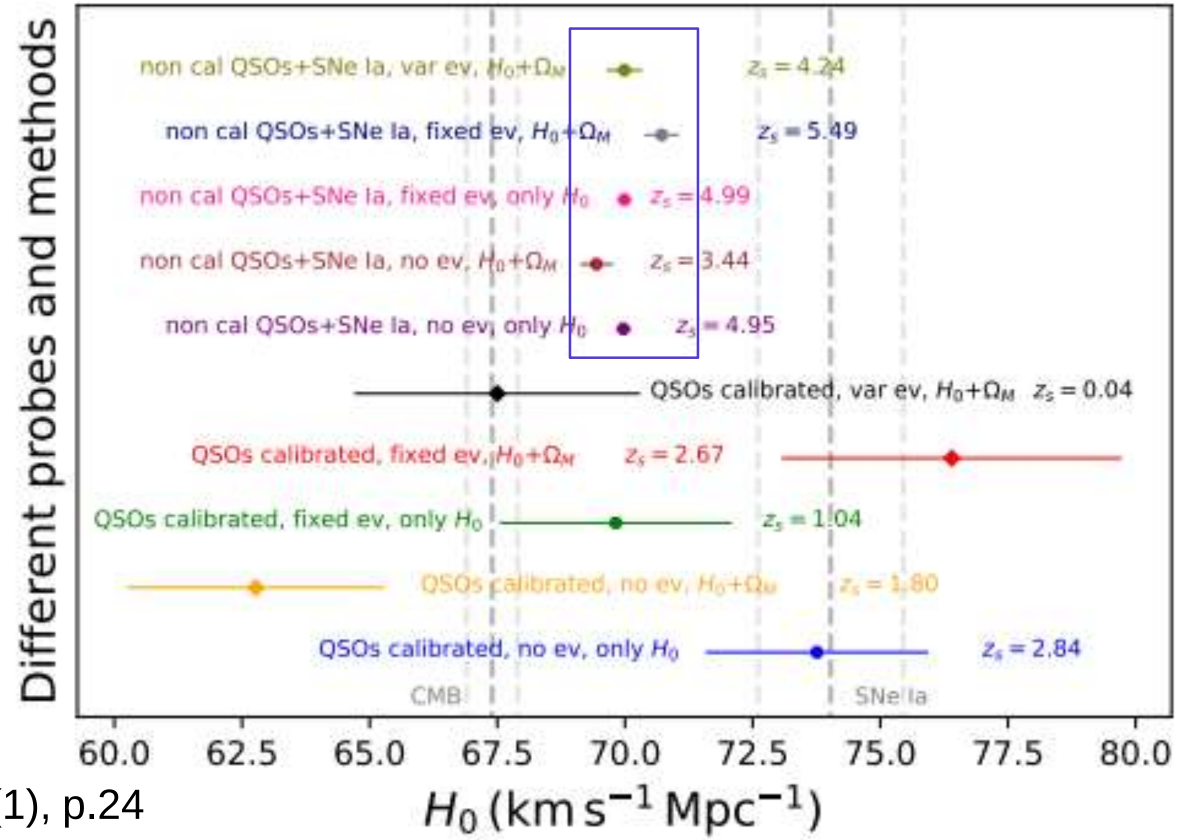
What happens to the tension?

“A bias-free cosmological analysis with quasars alleviating $H0$ tension”, Lenart A.L., Bargiacchi G. Dainotti, et al. 2022, ApJS, 264, 46, research highligh

"Bias-free cosmological computations involving Quasars", Lenart A.L. , Bargiacchi, Lenart et al. 2022, ApJS, 264, 46.

- H_0 tension:
  - 1σ errors on H_0 strongly decrease with non-calibrated QSOs + SNe
  - In these cases all H_0 values compatible within 2σ with each other pointing to the region intermediate between the one of CMB and SNe

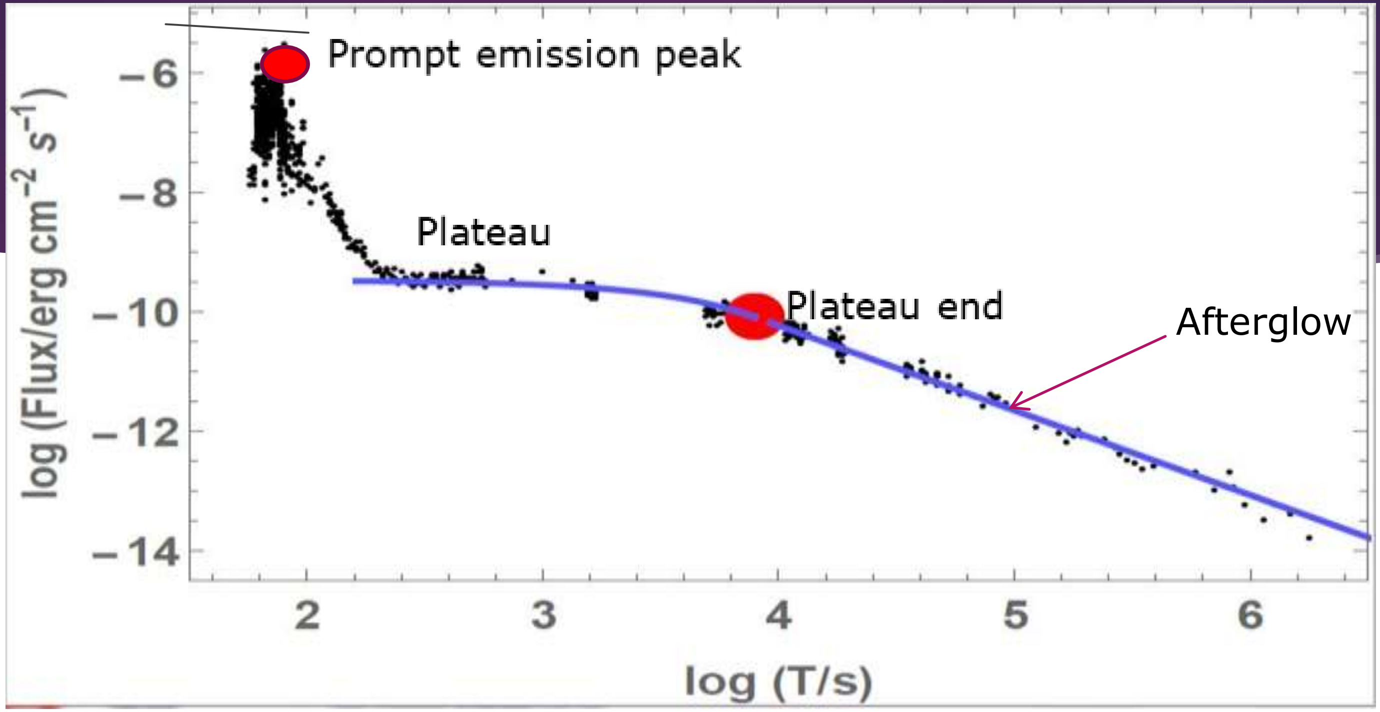
Tension due to an evolution of H_0 with redshift or a constant value that stands between the one of SNe and CMB?



See:
"On the evolution of the Hubble constant with the SNe Ia Pantheon sample and baryon acoustic oscillations: a feasibility study for GRB-cosmology in 2030", Dainotti, M.G. et al. 2022, Galaxies 10(1), p.24

"On the Hubble constant tension in the SNe Ia Pantheon sample.", Dainotti, M.G. et al. 2021, ApJ 912(2), p.150

GRB phenomenology



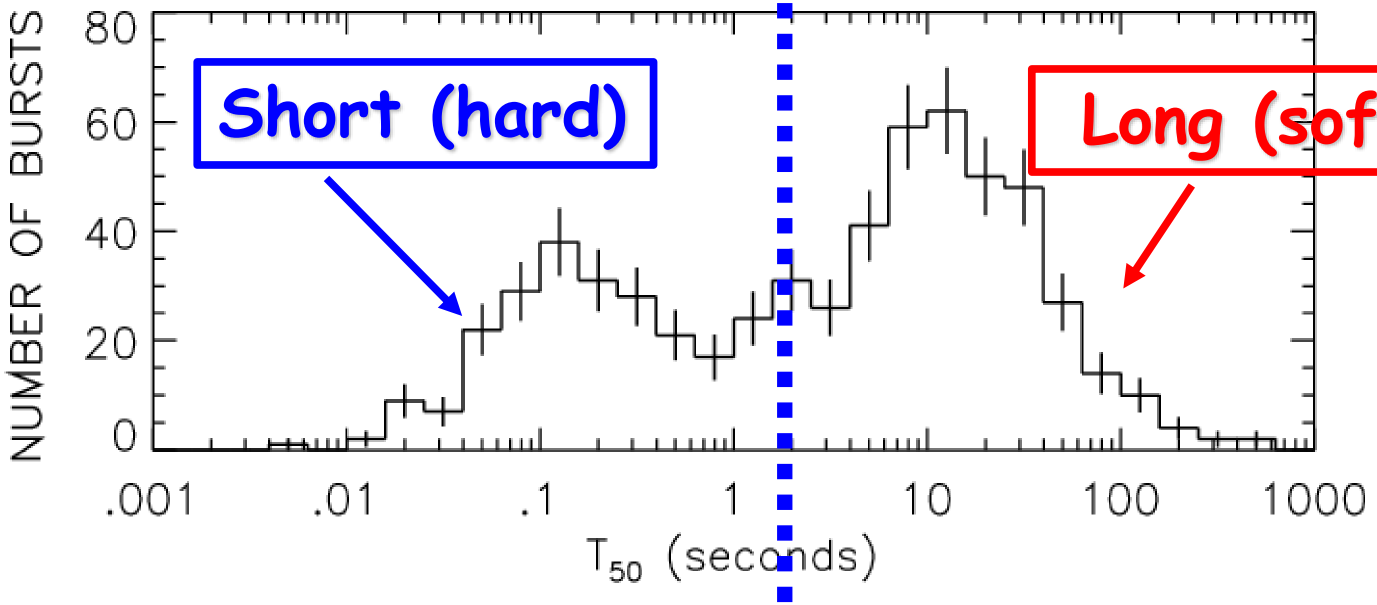
Important features of a well-sampled GRB light curve observed by Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing). The blue line is the phenomenological Willingale model (R. Willingale et al. 2007)

- **Flashes of high energy photons in the sky (typical duration is few seconds).**
- **Cosmological origin accepted (furthest GRBs observed z ~ 9.4).**
- **Extremely energetic and short: the greatest amount of energy released in a short time.**
- **X-rays, optical and radio observed after days/months (afterglows), distinct from the main γ-rays.**

Short vs Long GRBs

compact object mergers (NS-NS, NS-BH)

core collapse of massive stars ($M > 30\ M_{sun}$)



Short GRBs -> $T_{90}<2$ s

Long GRBs -> $T_{90}>2$ s

C. Kouveliotou et al., 1996, AIP Conf. Proc., 384, 42.
W. S. Paciesas et al., 1999, ApJS, 122, 465.

J. P. Norris & J. T. Bonnell 2006, intermediate class of GRBs with mixed properties.
O. Bromberg et al. 2013, ApJ, 764, 179 T_{90}=0.8s in Swift data

Why are GRBs potential cosmological tools?

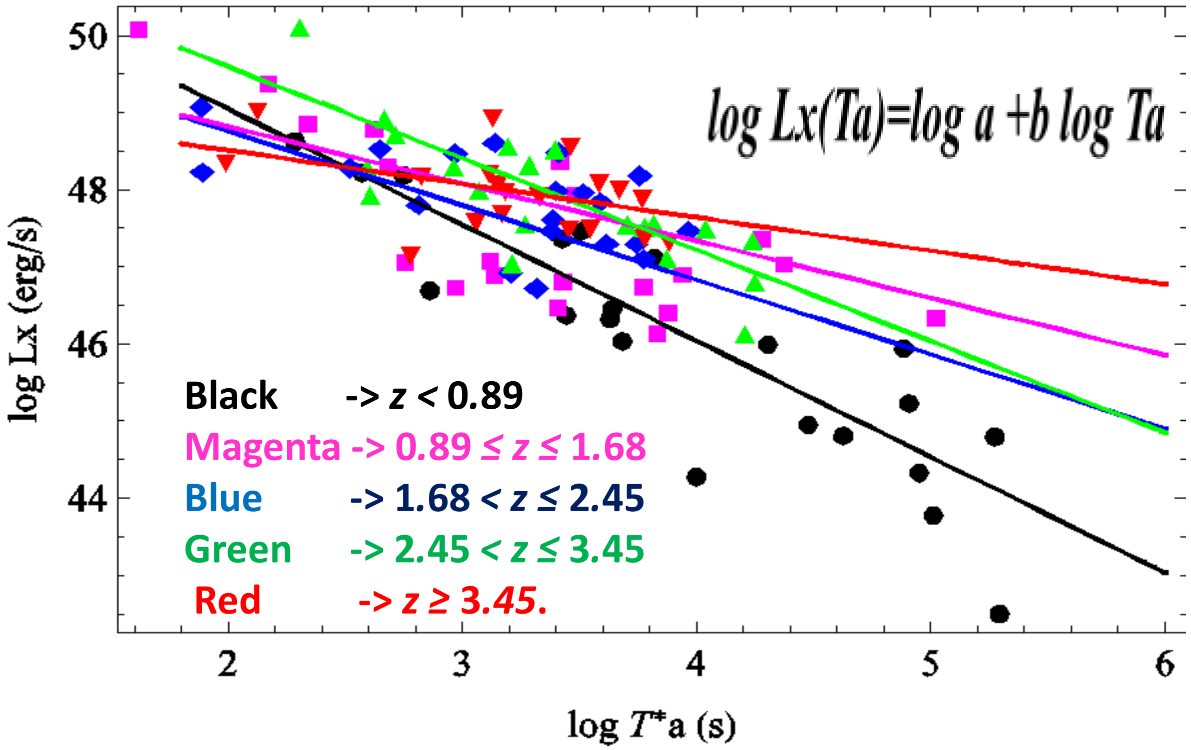
Because They…

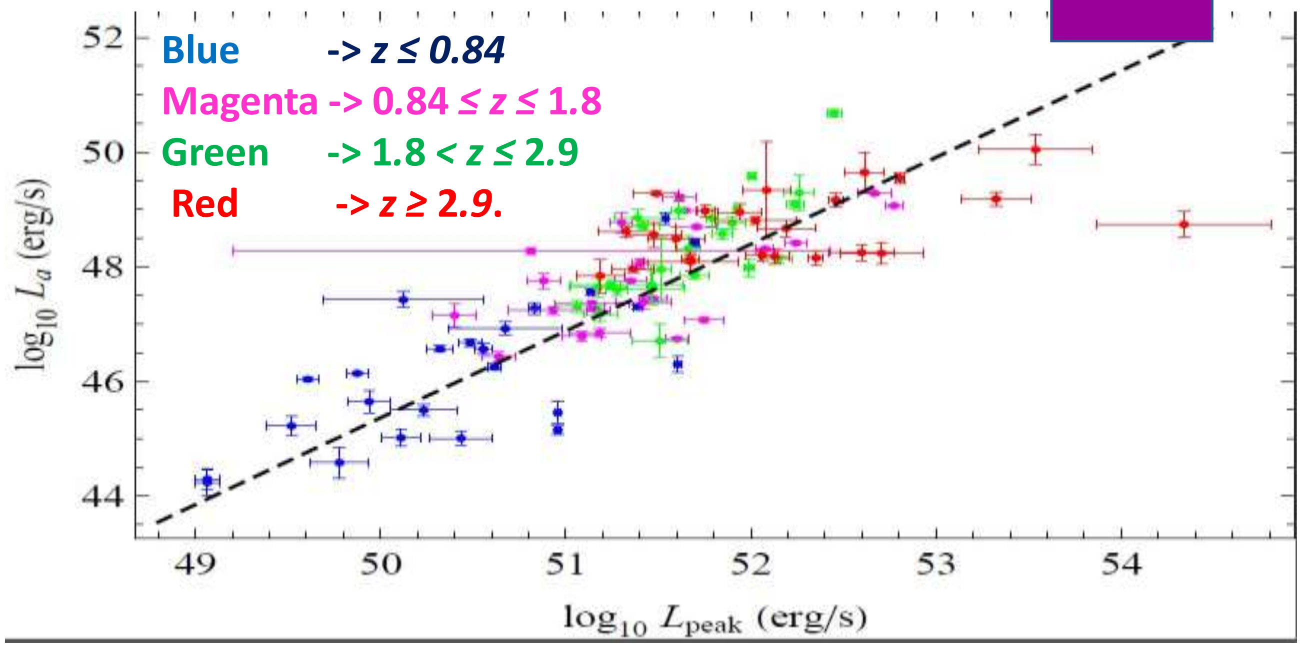
- Can be probes of the early evolution of the Universe.
- Are observed beyond the epoch of reionization.
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than SN Ia (z=2.26) and quasars (z=7.54).

But They…

- Don't seem to be standard candles with their isotropic prompt luminosities spanning over 8 order of magnitudes (this is a problem for the machine learning analysis too) and we have a few redshifts measured.

Possible reliable candidates are the $L_X - T^*_a$ and Lpeak-La correlations





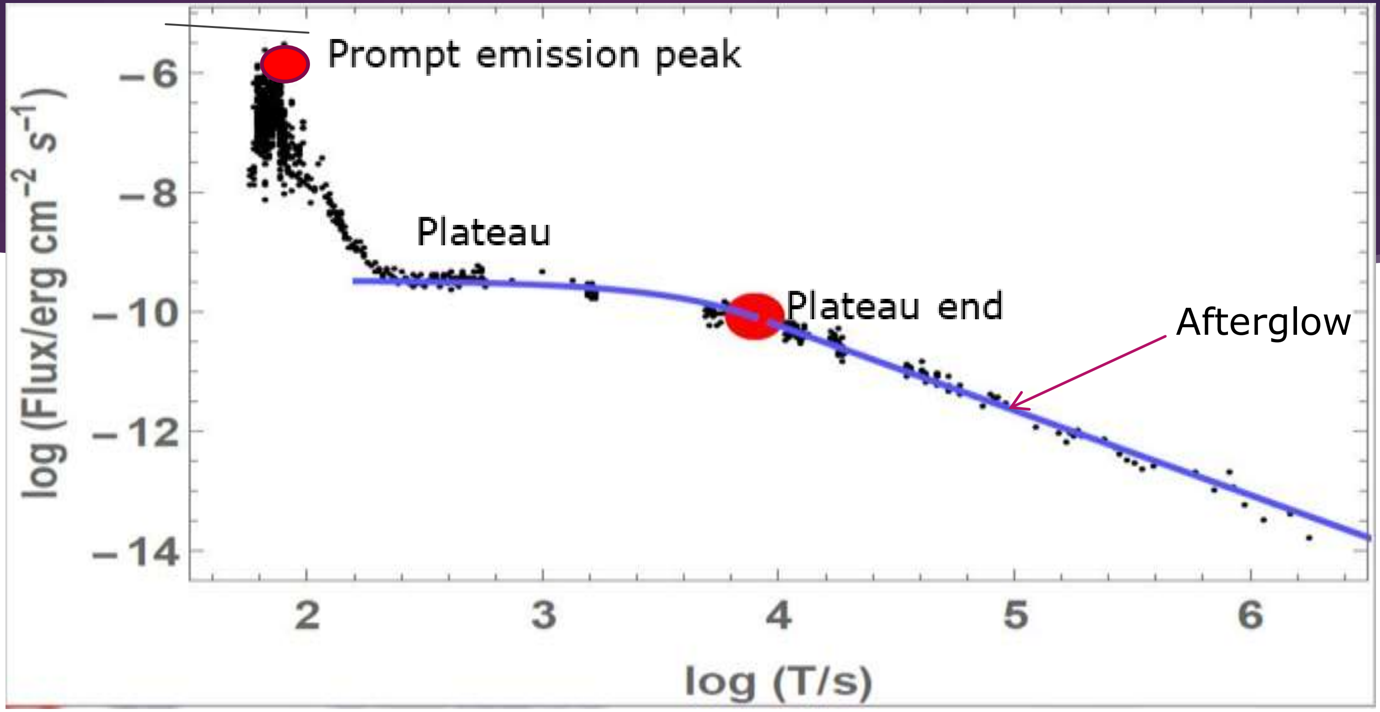
Log Lx(Ta)= log A +B log Lpeak

b=-1.0 -> Energy reservoir of the plateau is constant

La-Ta correlation first discovered by **Dainotti, et al. (2008), MNRAS, 391, L 79D**, later updated by **Dainotti et al. (2010), ApJL, 722, L 215; Dainotti et al. (2011a), ApJ, 730, 135; Dainotti et al. (2015a), ApJ, 800, 1, 31. The La-Lpeak first discovered by Dainotti et al., MNRAS, 2011b, 418, 2202.**

To account for selection biases **Dainotti et al. 2013, ApJ, 774, 157 and Dainotti et al. 2015b, MNRAS, 451, 4** showed that both **these correlations are intrinsic to GRB physics and not to selection biases.**

GRB phenomenology



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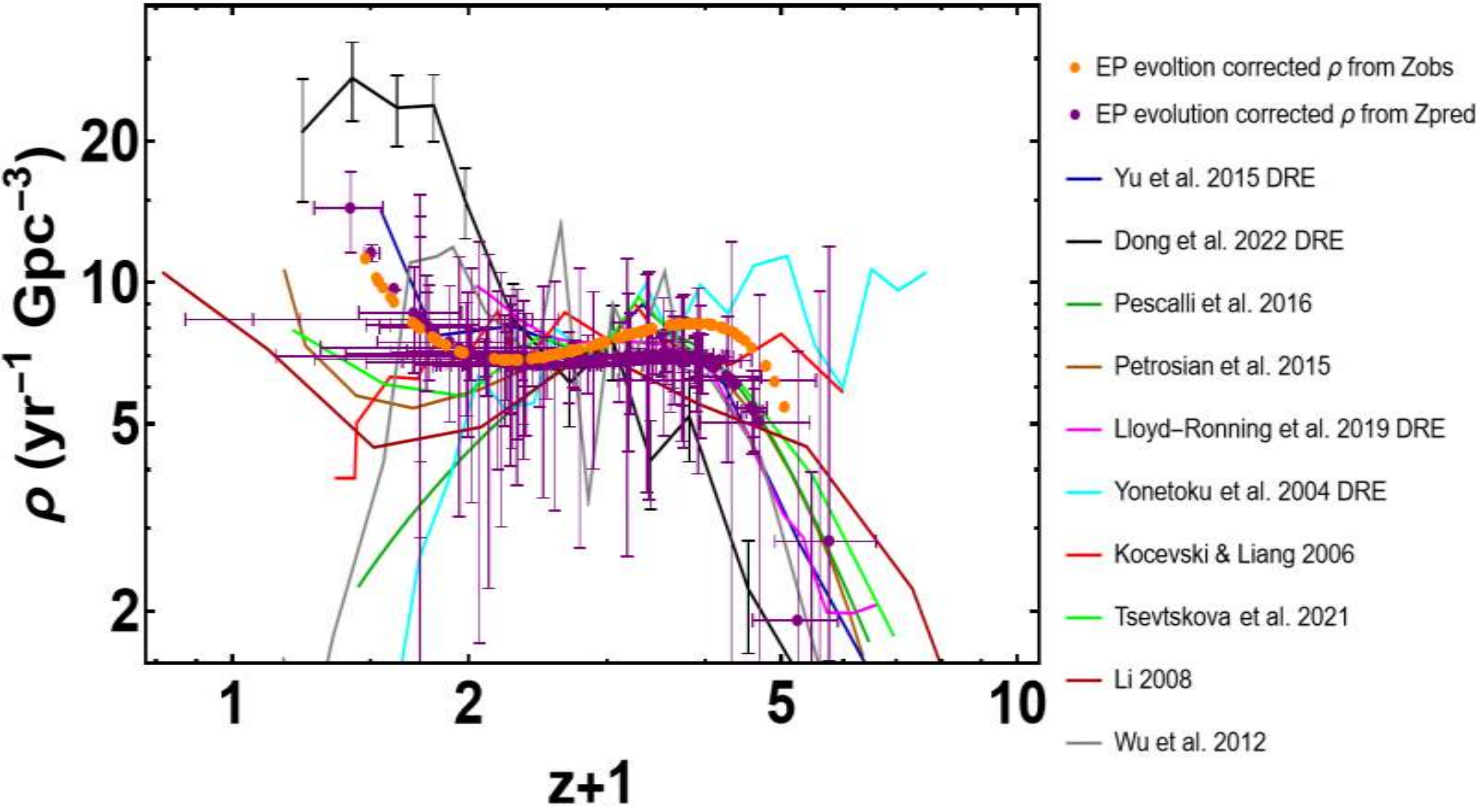
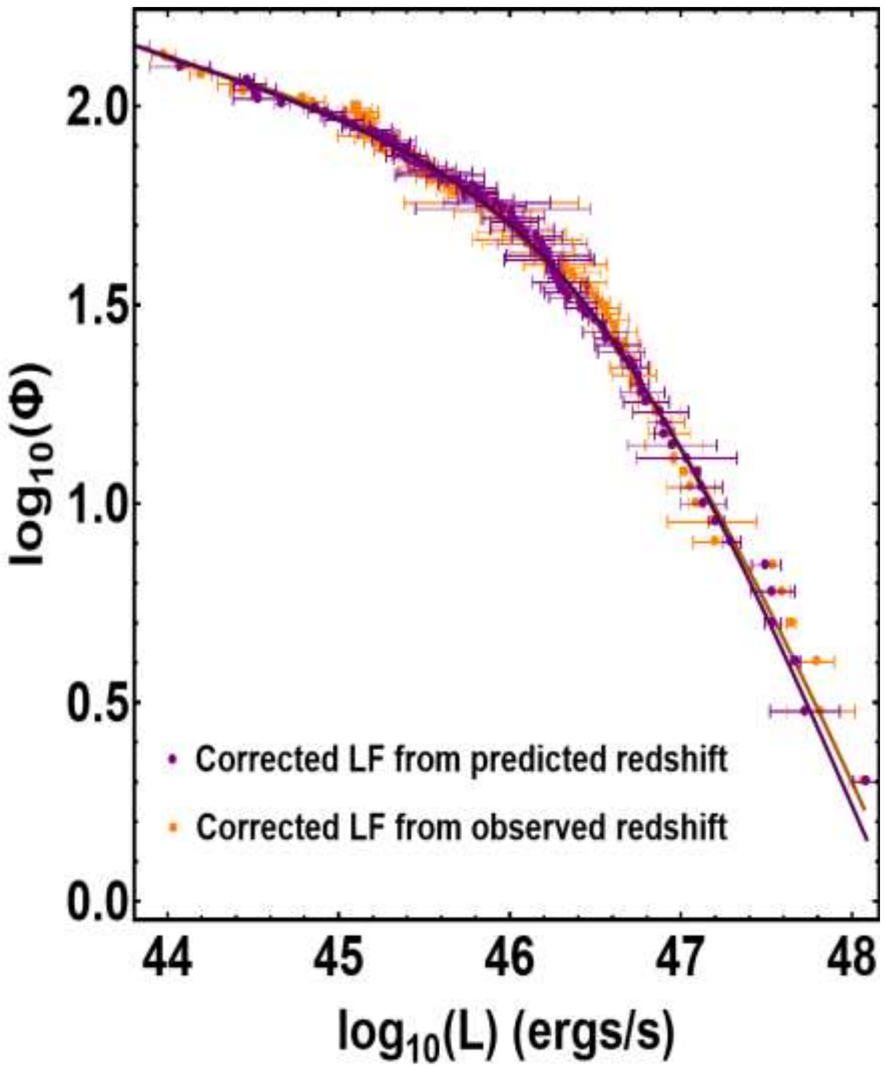
- **X-rays, optical and radio observed after days/months (afterglows), distinct from the main γ-rays.**

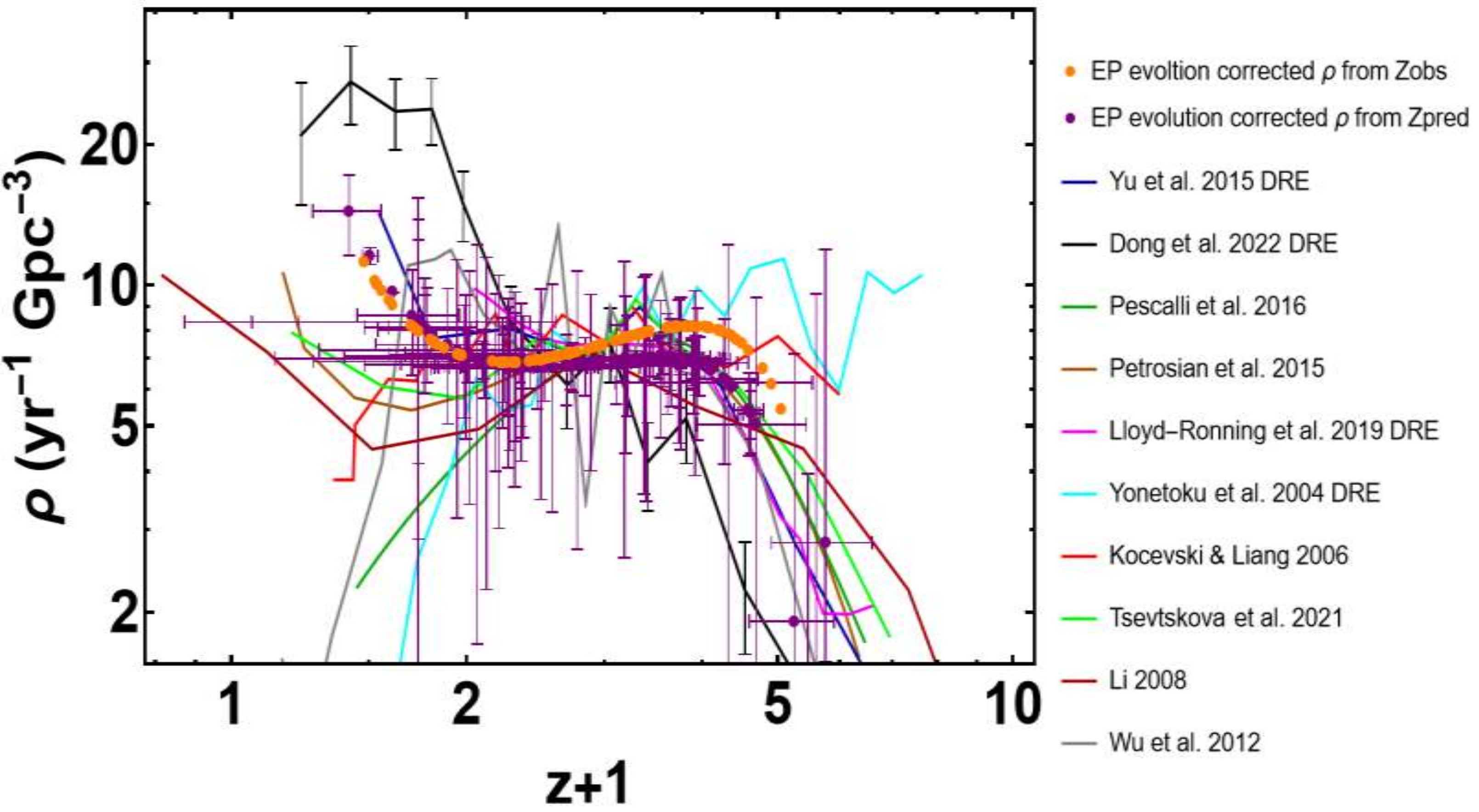
Density rate evolution and luminosity function:

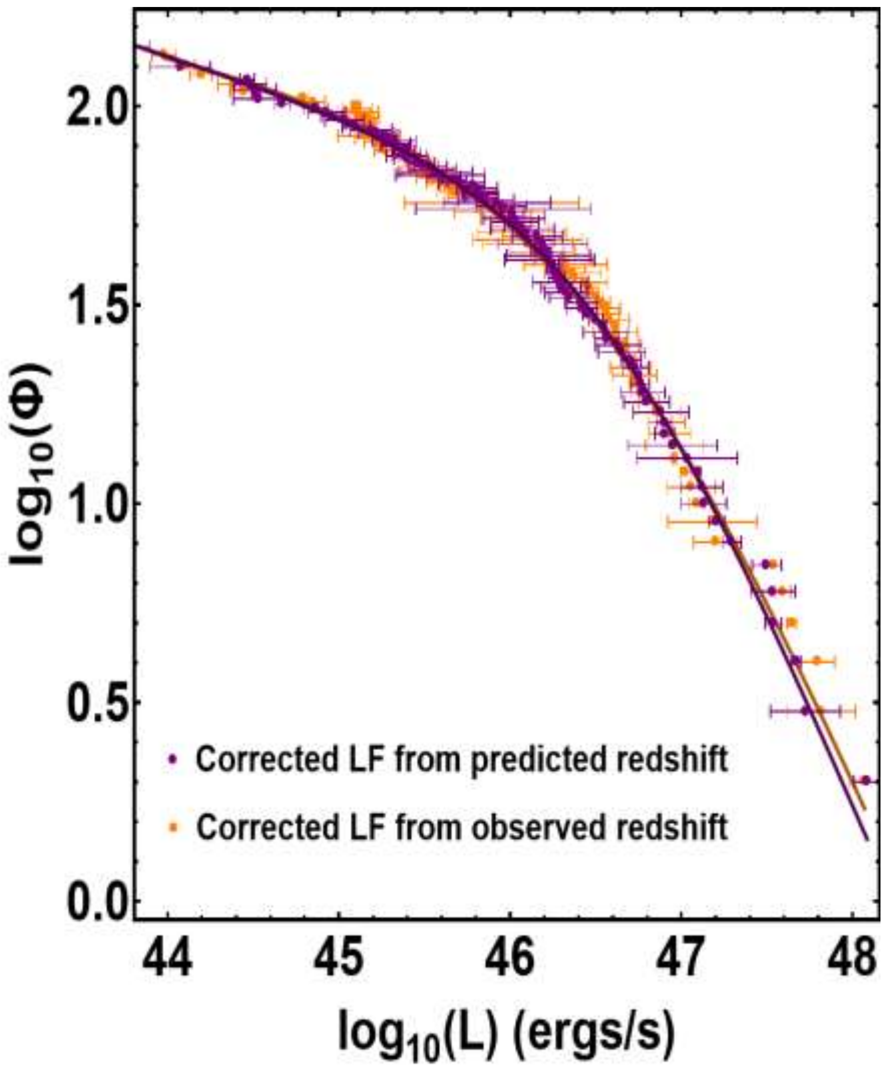




- The blue points in both pictures represent the LF and DRE derived using Zobs.
- The red points in both pictures represent the LF and DRE derived using Zpred.
- The orange and purple show the selection bias corrected density rate evolution for Zobs and Zpred respectively.

Density rate evolution and luminosity function:





- The blue points in both pictures represent the LF and DRE derived using Zobs.
- The red points in both pictures represent the LF and DRE derived using Zpred.
- The orange and purple show the selection bias corrected density rate evolution for Zobs and Zpred respectively.

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

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

Bias correction

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

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

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

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

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

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

COSMOLOGICAL MODELS Adopted

The cosmological models

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

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

Radiation is neglected

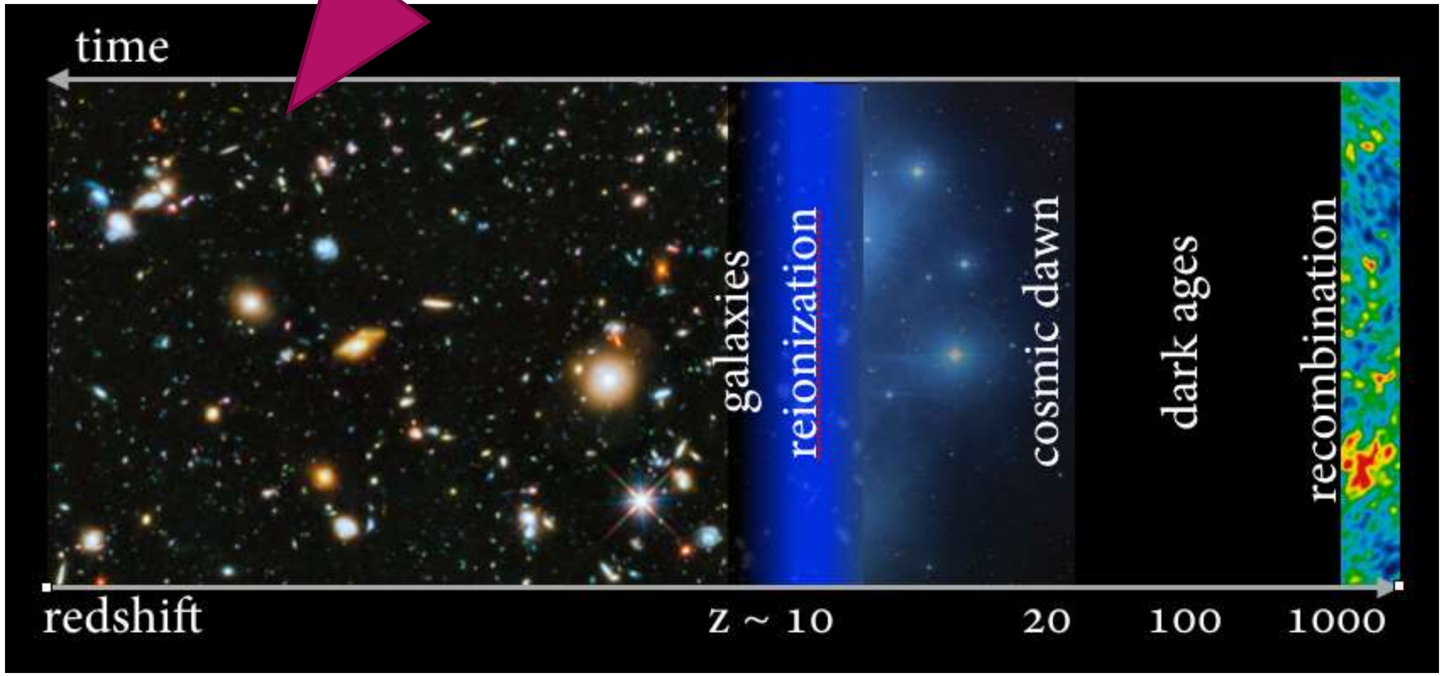
Curvature is neglected

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) in 3 and 4 bins ordered in redshift + 1 Baryon Acoustic Oscillations



EACH H_0 IS ESTIMATED IN ONE BIN

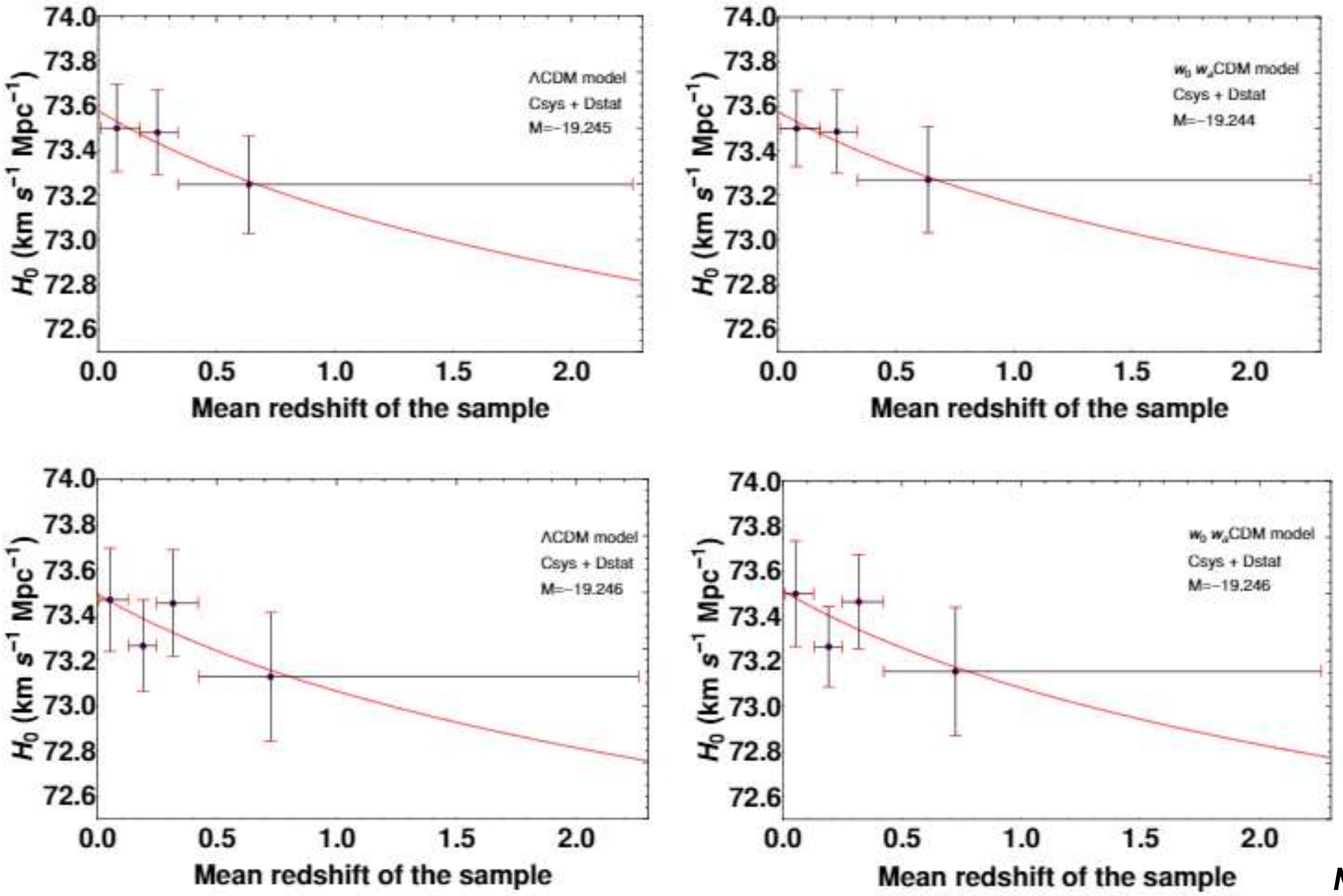
After we obtain several Ho values, we fit those with

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

α = evolution parameter

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

Results for ΛCDM model (3, 4 bins)



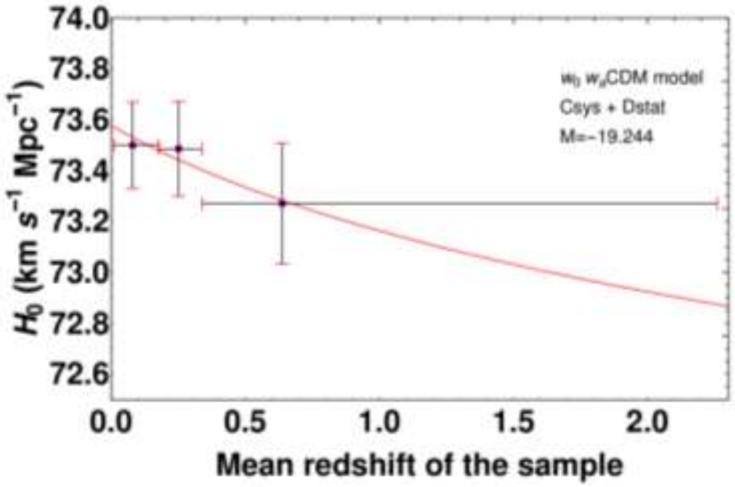
The w_0w_aCDM model results are compatible with the ΛCDM ones

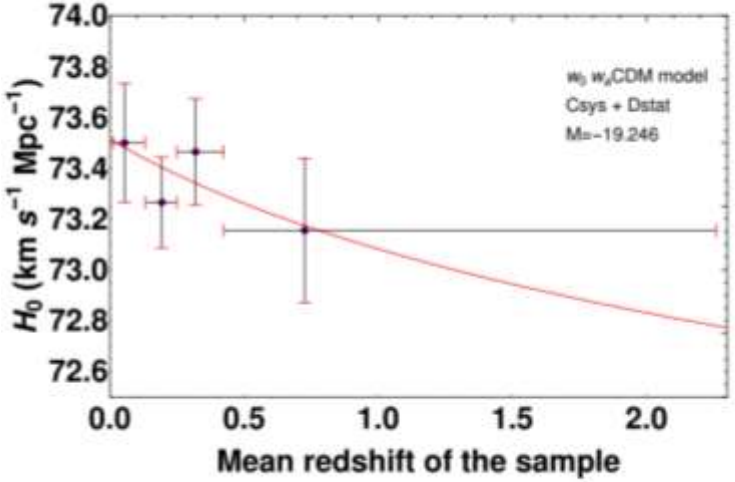
The evolution of the Ho is similar to the evolution of the MB parameter (L. Kazantzidis and L. Perivolaropoulos Phys. Rev. D **102**, 023520)

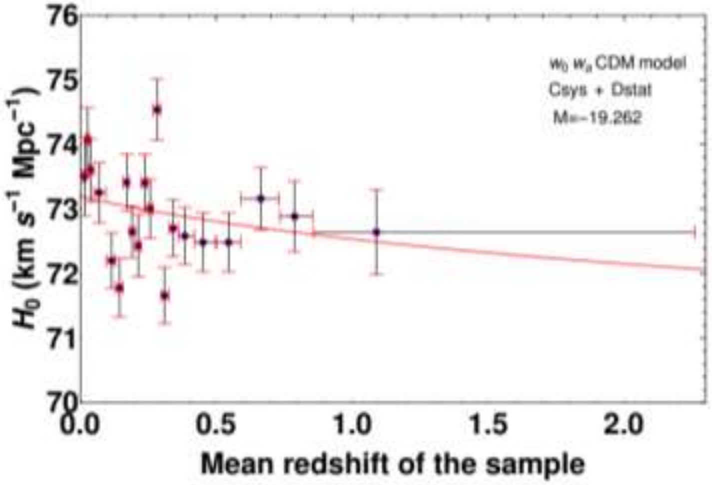
M. G. Dainotti, et al., 2021, ApJ, 912, 150

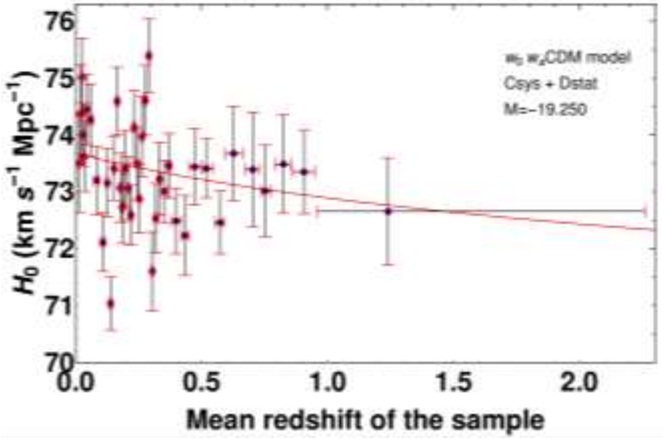
w0waCDM model results

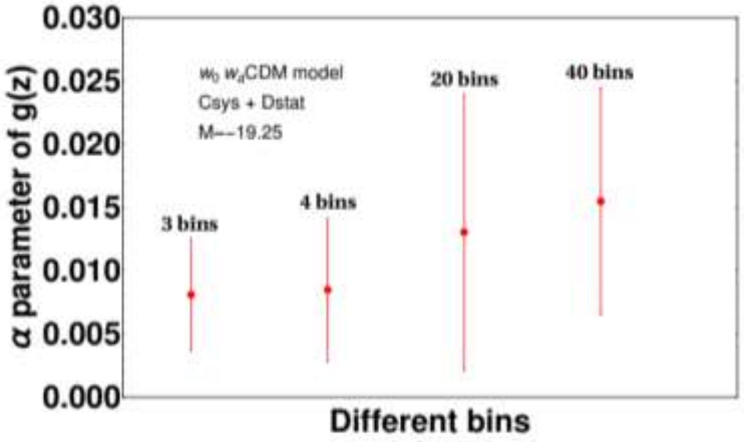
Calibrating the M value of μ_{obs} such that locally (namely, in the first bin) $H_0 = 73.5\ km/s/Mpc$











Results for ΛCDM model (3, 4 20, 40 bins)

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%

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

Extrapolating H_0 at the redshift of the Last Scattering Surface ($z = 1100$) we obtained a value of H_0 compatible in 1 σ with the H_0 CMB measurement.

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_0w_aCDM 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%

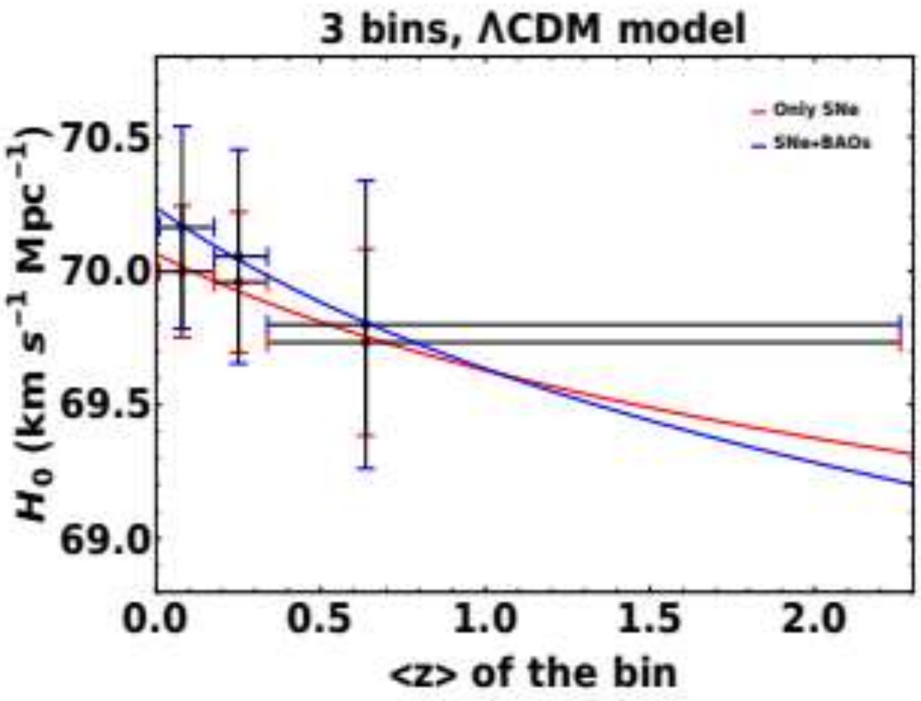
$$x_i = \frac{H_0^{(Cepheids)}(z \sim 0) - H_0^{(CMB)}(z \sim 1100)}{\sqrt{\sigma^2_{H_0^{(Cepheids)}(z\sim 0)} + \sigma^2_{H_0^{(CMB)}(z\sim 1100)}}}$$

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

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

$H_0(z)$ fitting (3 bins ΛCDM) + BAOs

Varying H_0 and Ω_{0m}



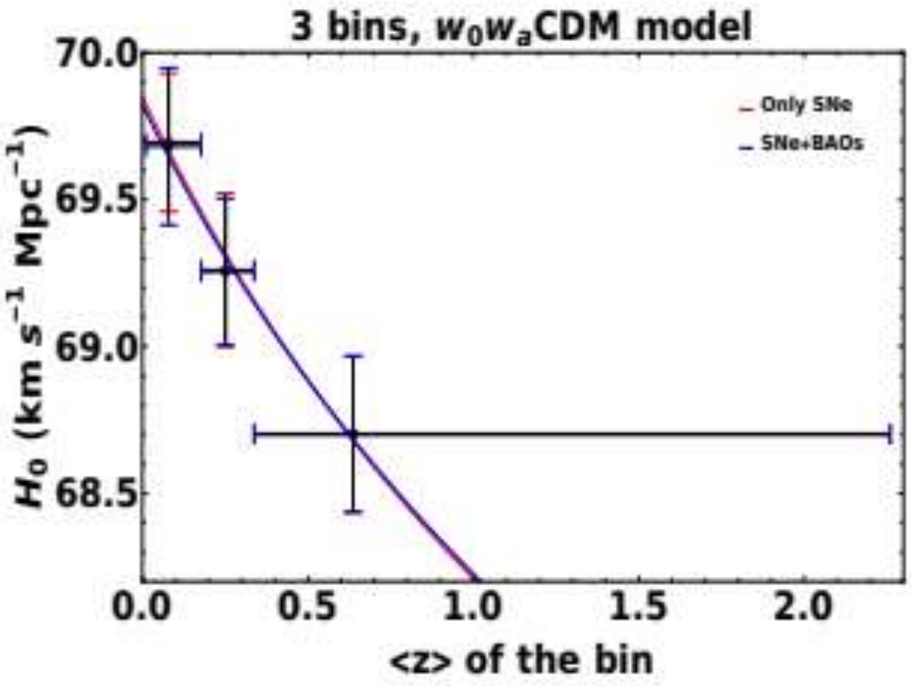
M.G. Dainotti, et al., 2022, Galaxies, 10, 1, 24

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

$H_0(z)$ fitting (3 bins $w_0 w_a CDM$) + BAOs

Varying H_0 and w_a



Flat $w_0 w_a$CDM 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 $w_0 w_a$CDM 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

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

FURTHER CONSIDERATIONS

In this case, the parameter space has been enlarged up to 2-dimensions.

1) In order to have a reliable statistical representation of the Pantheon sample, we focus our analysis on the case of 3 bins, ignoring the subsequent divisions of the Pantheon sample to avoid statistical fluctuations to dominate.

2) In the current analysis, it is important to consider the following constraint in the $w_0 w_a CDM$ case,

$$w(z) > -1 \quad \text{where} \quad w(z) = w_0 + w_a * \frac{z}{1+z}$$

is the CPL parametrization

However, also phantom models with w<-1 can be considered

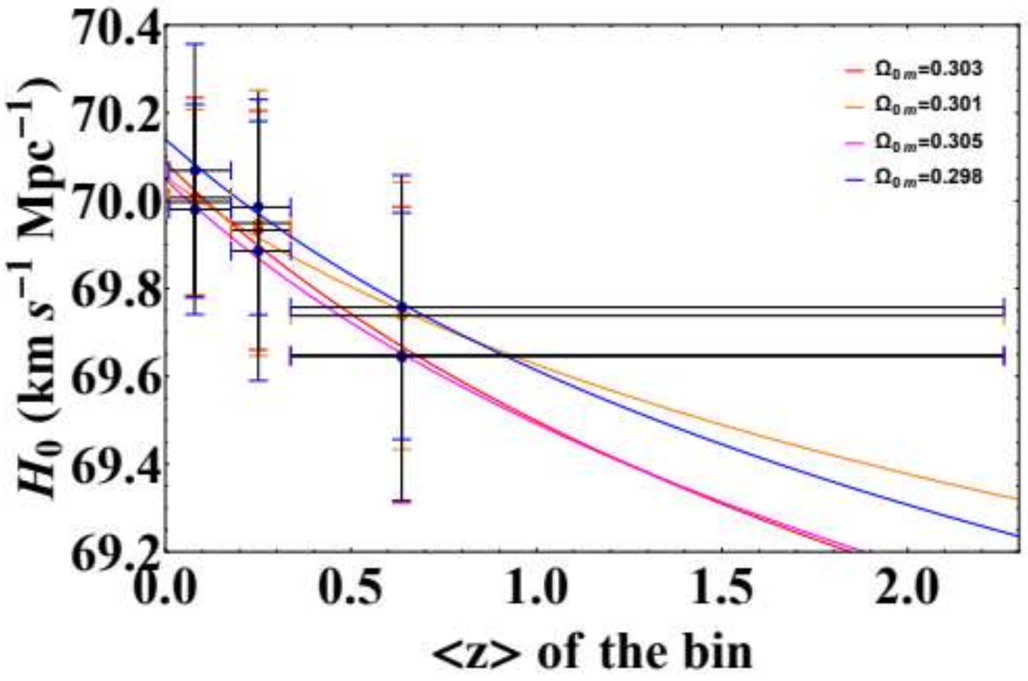
Testing the Hu-Sawicki model

$$S_g = -\frac{1}{2\chi}\int d^4x\sqrt{-g}f(R)$$

Testing the Hu & Sawicki (2007) model with $n = 1$

$$f(R) = R + F(R) = R - m^2 \frac{c_1 \left(R/m^2\right)^n}{c_2 \left(R/m^2\right)^n + 1}$$

In the case of $F_{R0} = -10^{-7}$
(value of the field at the present time)



Despite adopting this modified gravity model, such a decreasing trend is still visible

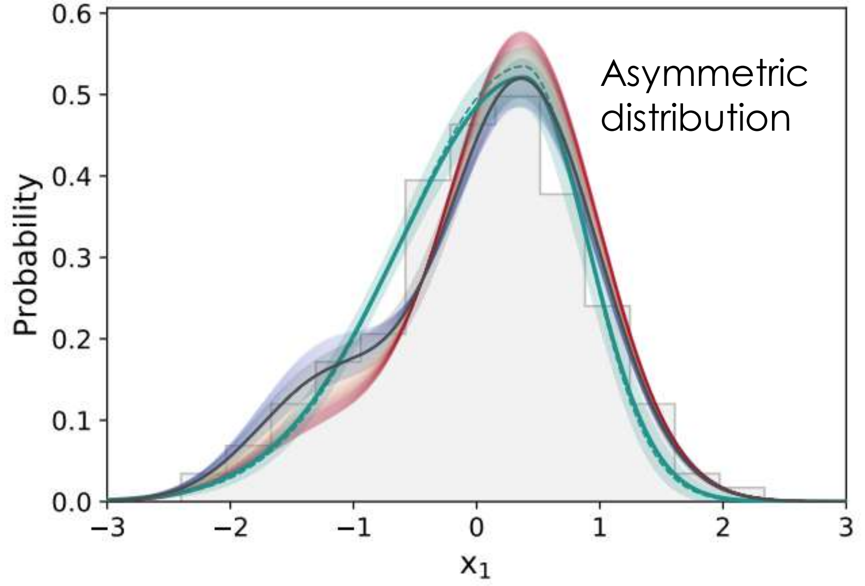
Discussion of the results

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

- IN ANOTHER PAPER, NICOLAS ET AL. 2021, IT IS SHOWN THAT THE STRETCH FACTOR (x_1) SHOWS AN EVOLUTIONARY TREND WITH REDSHIFT AND THIS MAY EXPLAIN OUR OBSERVED TREND.

- <u>NEW DATA ARE NEEDED TO FURTHER EXPLORE OUR RESULTS (E.G. PANTHEON+)</u>



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

Discussion of the results

SNe Ia ANALYSIS: POSSIBLE THEORETICAL MODELING

THIS RESULTS CAN BE EXPLAINED THANKS TO DIFFERENT THEORETICAL FRAMEWORKS

IF NOT DUE TO 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} HAS BEEN ANALYZED BUT THE HUBBLE CONSTANT DECREASING TREND WAS PROVEN TO HOLD ANYWAY

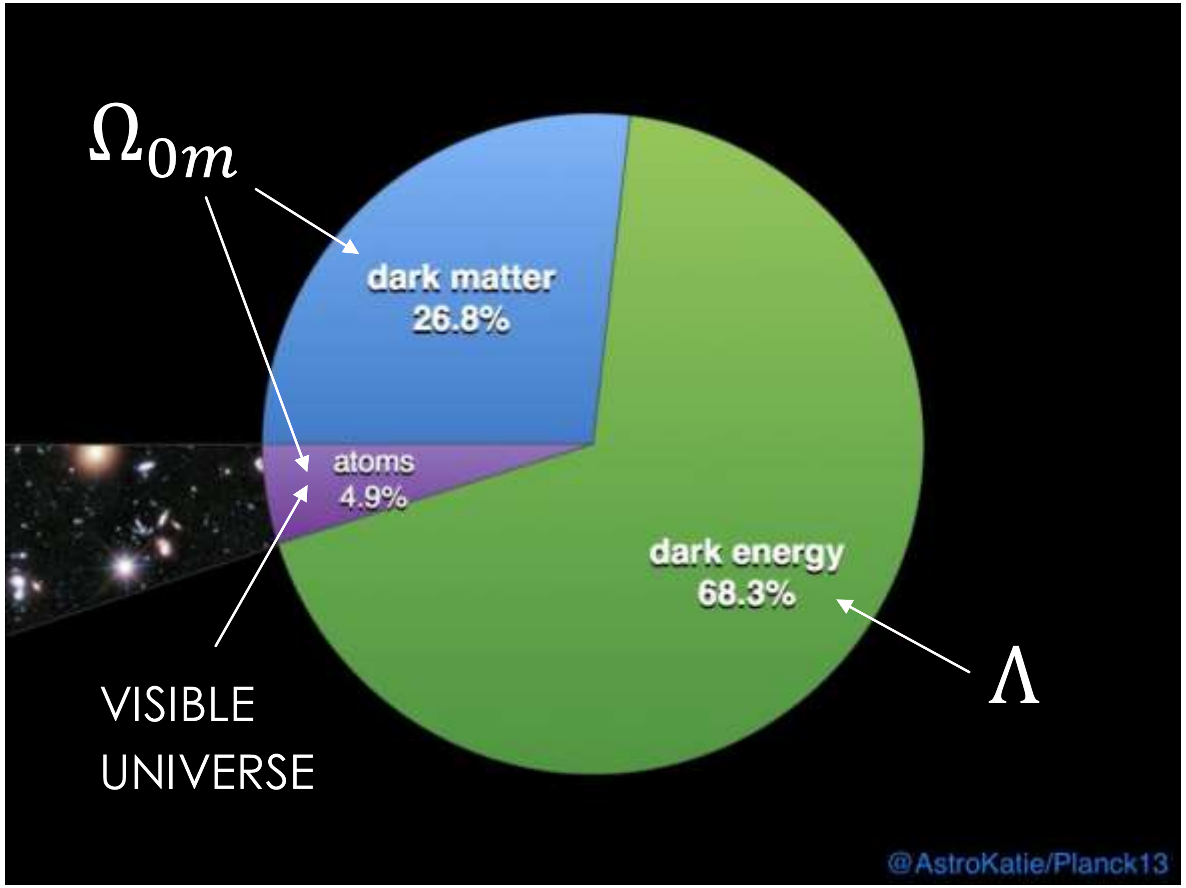
THIS «G» MAY NOT BE A CONSTANT, AFTER ALL...

$$F = \frac{G m_1 m_2}{d^2}$$

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

What are the fundamental cosmological parameters that we can infer with GRBs?

H_0 (Hubble constant), Ω_{0m} (total matter density), $\Omega_{0\Lambda}$ (dark energy density), w (equation of state parameter)



ΛCDM MODEL IS BASED ON THE PRESENCE OF THE «**COLD DARK MATTER**» (CDM, NOT DIRECTLY VISIBLE) AND THE «COSMOLOGICAL CONSTANT»

Ω_{0m} DESCRIBES THE TOTAL MATTER DENSITY (DARK MATTER + BARYONS) OF THE UNIVERSE

Λ IS THE COSMOLOGICAL CONSTANT THAT DESCRIBES RESPONSIBLE FOR THE EXPANSION OF THE UNIVERSE

w IS THE PARAMETER OF THE EQUATION OF STATE FOR THE UNIVERSE ($w = -1$ IN THE ΛCDM MODEL)

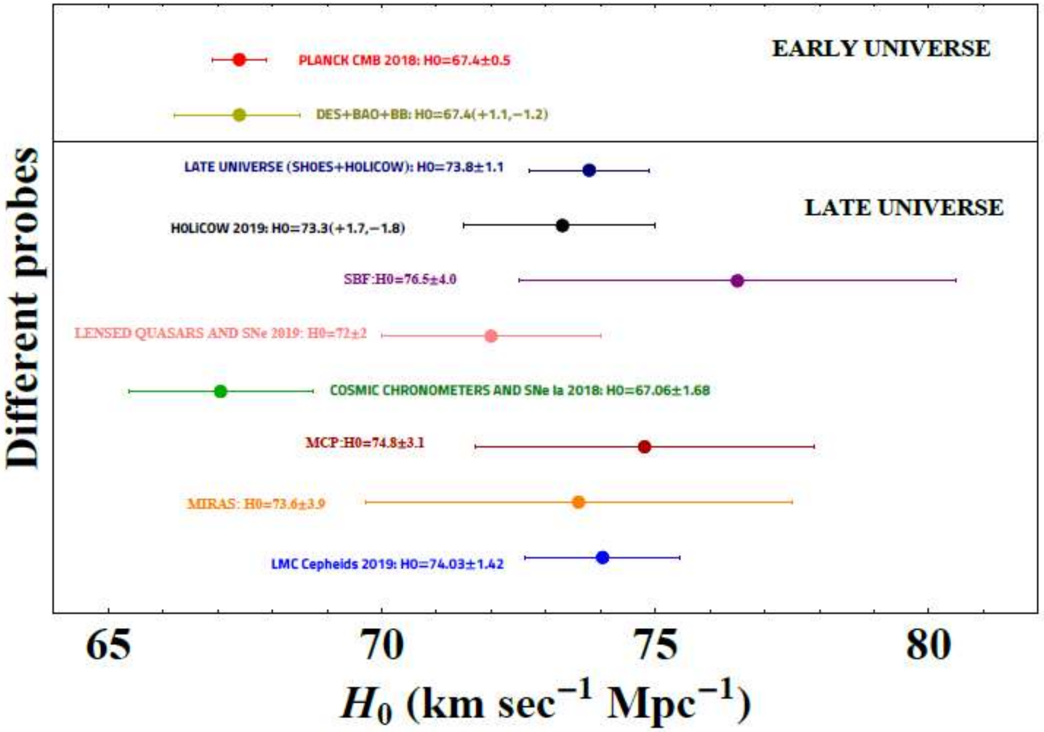
H_0 IS A CONSTANT THAT DESCRIBES THE UNIVERSE EXPANSION RATE

The Hubble constant and its tension

The Hubble constant tension ranges from 4.4 to 6 sigma according to the sample sizes and releases used.

$$v = H_0 \cdot D$$

HUBBLE'S LAW



H_0 TENSION possibly due to its evolution or evolution of its parameters and its theoretical explanations

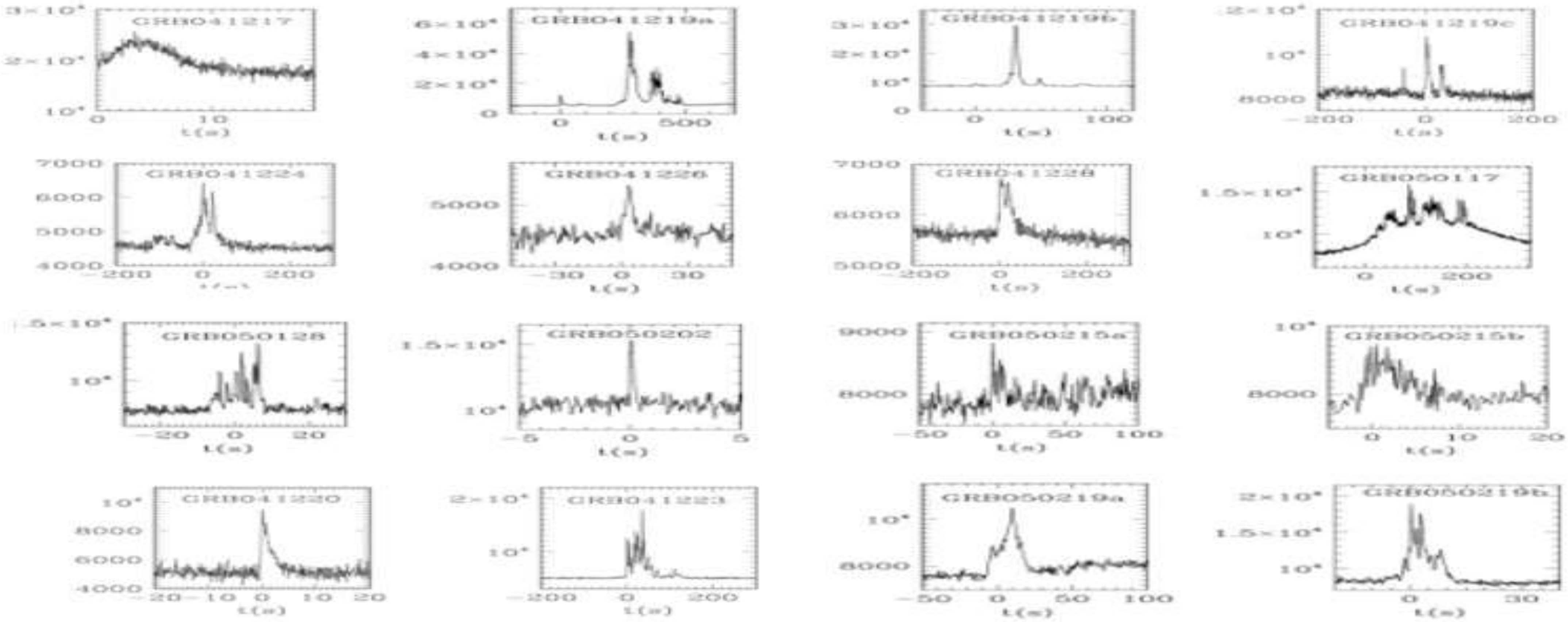
M. G. Dainotti, et al., 2021, ApJ, 912, 150.

Dainotti et al. 2023, Galaxies, vol. 10, issue 1, 24.

Both 1% Top cited papers in web of Science

Montani, Carlevaro, Dainotti 2024, PDU, in press

For 20 years, we’ve been struggling: how to use GRBs as standard candles?
Challenge: Light curves vary widely - “if you've seen one GRB, you've seen one GRB”



Swift lightcurves taken from the Swift repository: this is the main disadvantage of the prompt

Why are GRBs potential cosmological tools?

Because They…

- Can be probes of the early evolution of the Universe.
- Are observed beyond the epoch of reionization.
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than SN Ia (z=2.26) and quasars (z=7.54).

But They…

- Don't seem to be standard candles with their isotropic prompt luminosities spanning over 8 order of magnitudes (this is a problem for the machine learning analysis too), different classes and unclear physics of the progenitor.
- **Good news**:More GRB redshifts with Machine learning and plateau emission thanks to Swift indirectly, so we can tick another bullet in the achievement of Swift (see Brad's talk)

GRBs as distance indicators: Drawbacks of forward fitting methods

Dainotti et al. 2011a, ApJ, 730, 2011

Each correlation carries its own scatter added to the the scatter of the variables and dependence of z is through dL. Previous attempts to employ GRB relations are the ones by Atteia et al. 2002, Yonetoku et al. 2004, Guiriec et al. 2005. **There is a circularity dependence**

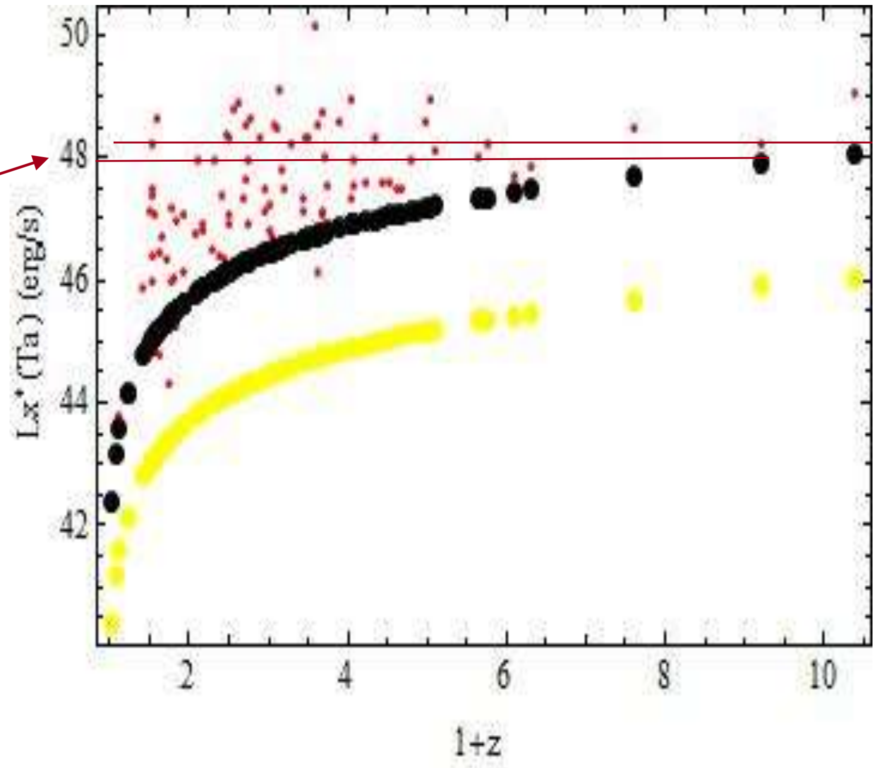
$\Phi(E) \propto E^{-\gamma_a} \propto E^{-(\beta_a+1)}$, where (β_a, γ_a) are the spectral and photon indices, respectively. It is worth stressing that the fit of

$$L_X^* = \frac{4\pi D_L^2(z) F_X}{(1+z)^{1-\beta_a}}, \quad (6)$$

where $F_X = F_a \exp(-T_p/T_a)$ is the observed flux at the time T_a.

$$\mu_{obs}(z) = 25 + \frac{5}{2}\log\left[\frac{L_X^*(T_a)}{4\pi f_a(T_a, T_p, F_a T_a)(1+z)^{(-1+\beta_a)}}\right]$$
$$= 25 + \frac{5}{2}\left\{a \log\left[\frac{T_a}{1+z}\right] + b\right\}$$
$$- \frac{5}{2}\log\left[4\pi f_a(T_a, T_p, F_a T_a)(1+z)^{(-1+\beta_a)}\right], \quad (15)$$

For small variation of luminosity→ Large variation in z



Physical interpretation: testing the standard fireball model→ standard candle?

The Closure Relations in γ-rays
Dainotti et al. 2023, Galaxies, 11, 1

The Closure Relations in X-rays
Dainotti et al. 2021, PASJ, 73, 4.

The Closure Relations in optical
Dainotti et al. 2022, ApJ, 940, 2, 169.

The scatter drawn by using the closure relationships is comparable with the current scatter

The Closure Relations in radio
Levine, Dainotti et al. 2023, MNRAS, 519, 3.

With machine learning

For redshift inference, regression:

1) Dainotti, Narendra, Pollo et al. 2021, ApJ,920, 2, 118.

2) Narendra, Gibson, Dainotti, Pollo et al. 2022, ApJS, 259, 2, 55.

3) Gibson, Narendra, Dainotti, Pollo et al. 2022, Frontiers in Astronomy and Space Science, 9, 836215

4) Lightcurve Reconstruction, Dainotti, including Narendra, Pollo et al. 2023, accepted in ApJS, 267, 2, id 42,

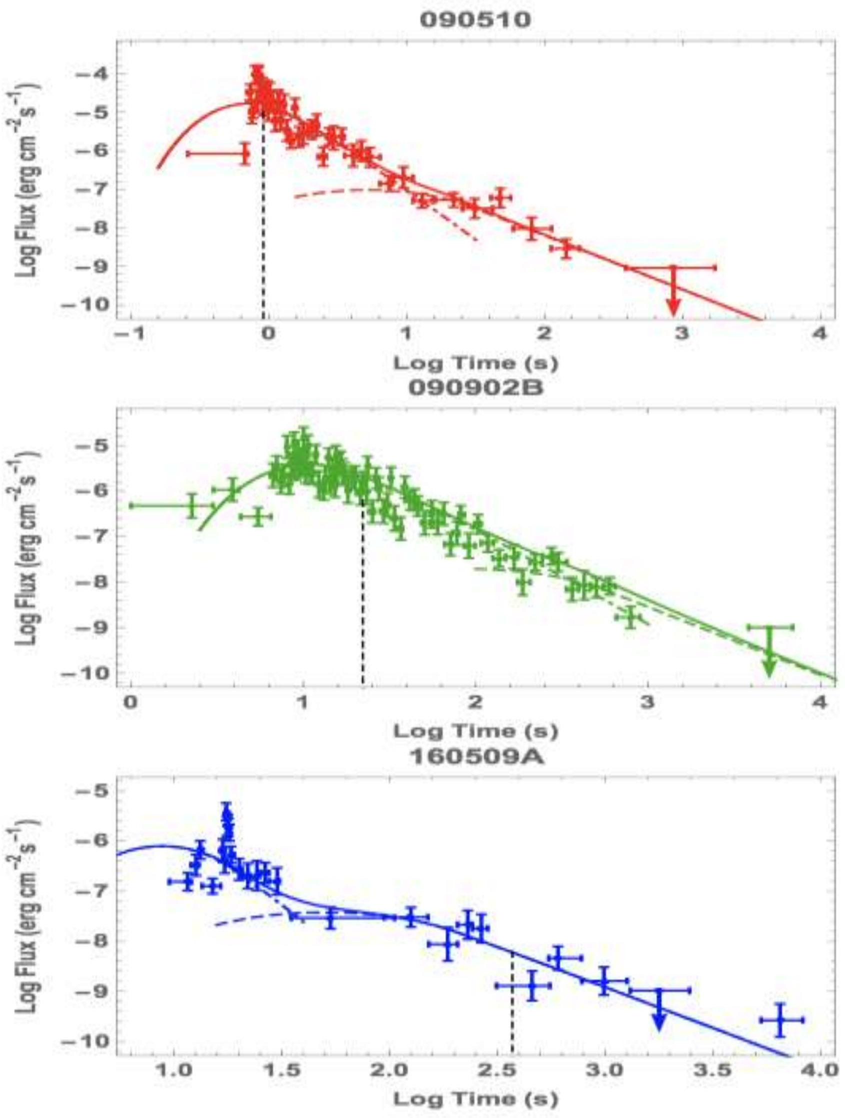
5) Dainotti et al. 2024, Inferring the Redshift of More than 150 GRBs with a Machine-learning Ensemble Model, **ApJS, 271, 1, id.22, 15.**

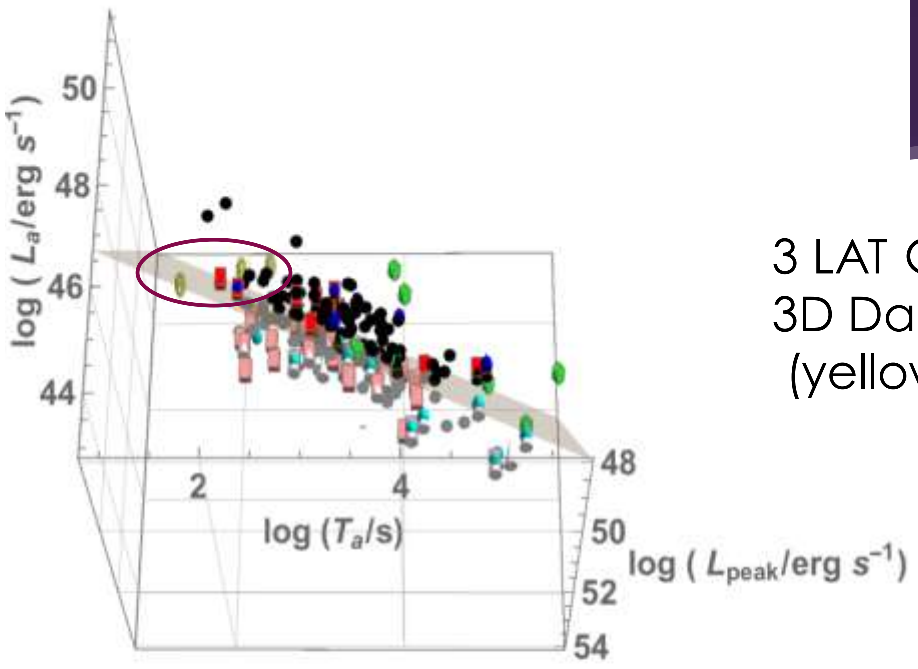
6) Dainotti, Narendra et al. 2024, ApJL, accepted, press from UNLV and Facebook post from Swift

The plateau emission in γ-rays (CAT II)

(Dainotti et al. 2021, in collaboration with the Fermi-LAT members ApJS 255, 13)

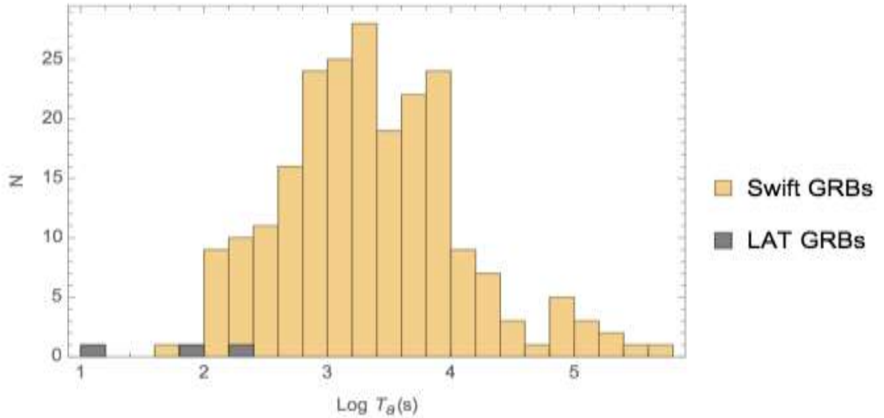
Spin-off paper of the work in the second GRB catalog





3 LAT GRBs follow the 3D Dainotti relation (yellow points)

The LAT GRBs have shorter plateaus compared to X-rays



The 3D correlation in optical exists for 58 GRBs !!!

M. G. Dainotti, et al., 2022c, ApJS, 261, 2, 25. Press release from NAOJ

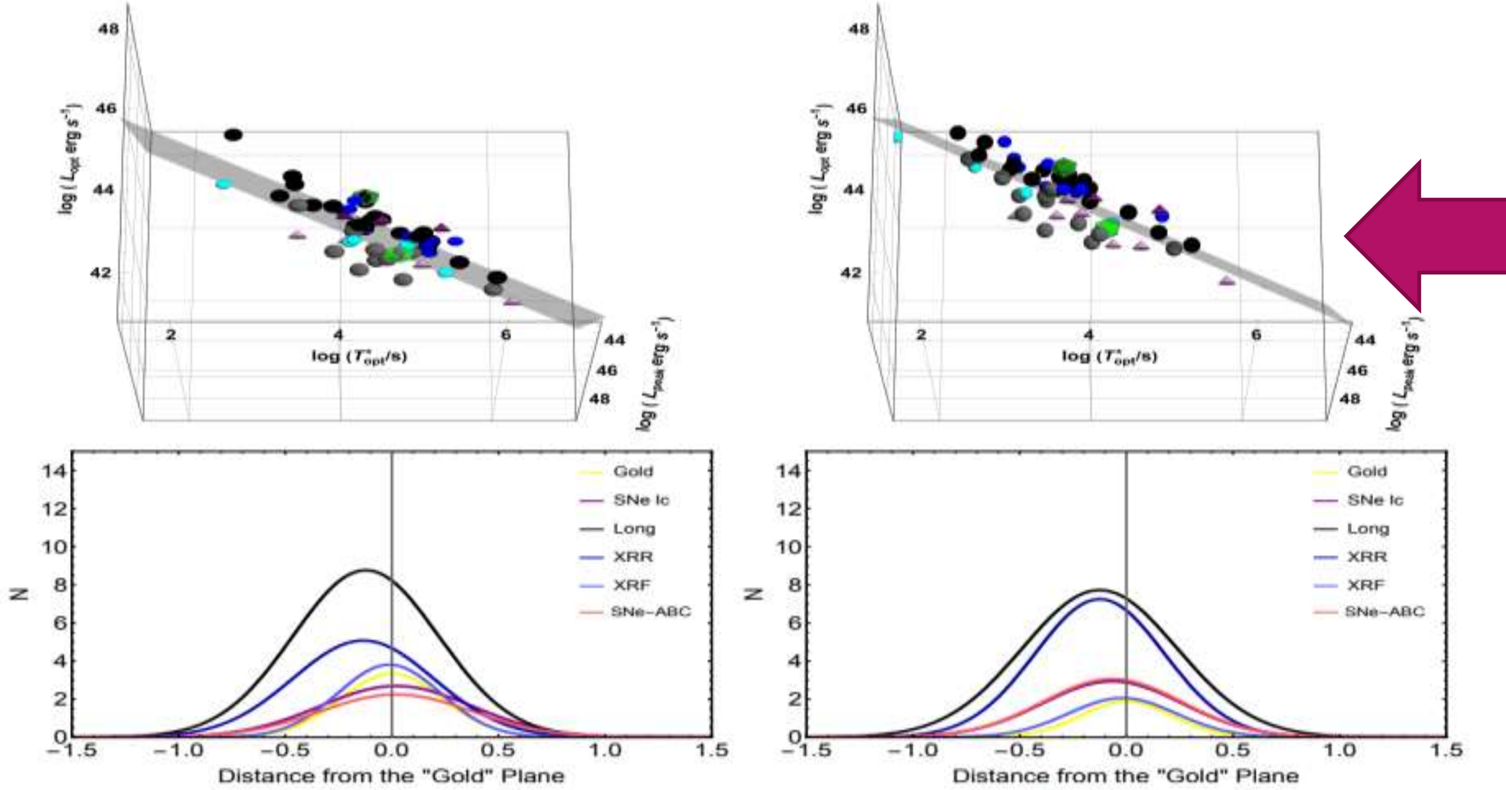
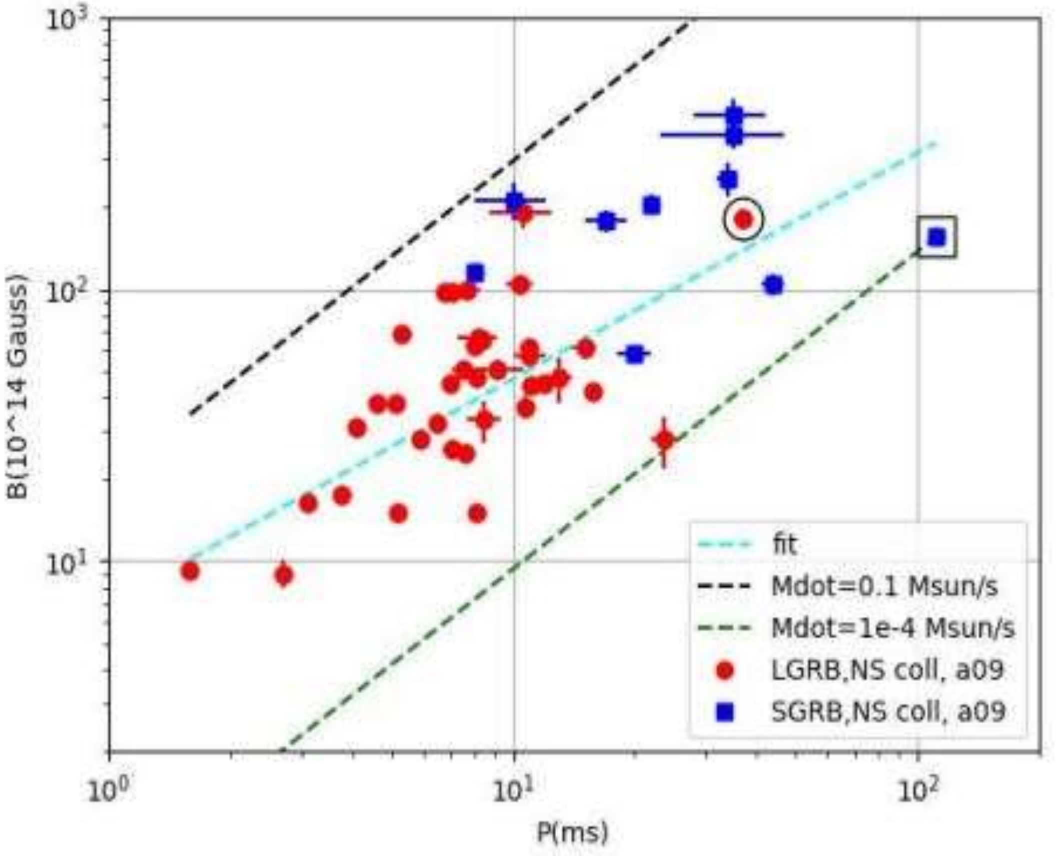


Figure 5. Upper panels: 58 GRBs in the $L^{(\prime)}_{opt} - T^{*(\prime)}_{opt} - L^{(\prime)}_{opt}$ parameter space with the fitted plane parameters in Table 2, including LGRBs (black circles), SGRBs (red cuboids), GRB-SNe Ic (purple cones), XRFs and XRRs (blue spheres), and ULGRBs (green icosahedrons). The left and right panels display the 3D correlation with and without any correction for both redshift evolution and selection biases, respectively. Lower panels: the distances of the GRB of each class indicated with different colors from the Gold fundamental plane, which is taken as a reference, with and without correction for redshift evolution and selection biases, respectively.

Correcting for evolution

- Long=31
- Gold→ 6
- XRF=4
- XRR=19
- GRB-SNe Ib/c-> 9
- SNe Ib/c (ABC)->7

Two different classes within the magnetar scenario



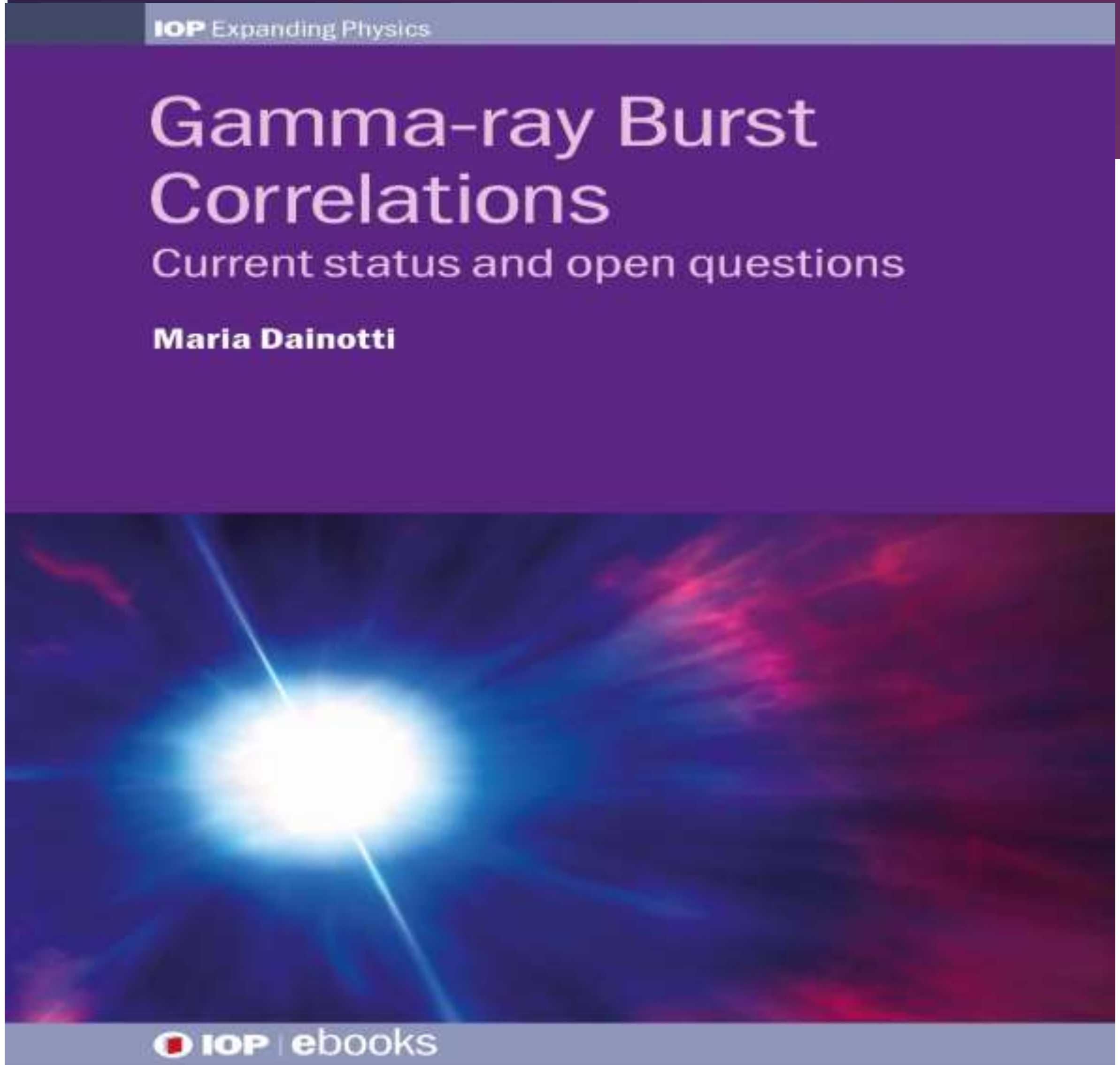
G. Stratta, M. G. Dainotti, S. Dall'Osso, X. Hernandez, G. De Cesare, 2018, ApJ, 869, 155

- The spin-down luminosity of the magnetar is entirely beamed within **Ɵjet** (=jet opening angle)
- The long GRB 070208 (circle) and the peculiar GRB 060614A (square).

- Previous literature:Zhang et al. 2013, **A. Rowlinson et al. 2014 including Dainotti, N. Rea et al. 2015 (including Dainotti)**, **P.** Beniamini et al. 2017, P. Beniamini & R. Mochkovitch 2017.

- Within the external shock model (G. Srinivasagaravan, M. G. **Dainotti et al. 2020**, et al. 2017).

For a more a complete review see



A series of review papers:

Dainotti, M.G., & del Vecchio, R., "Gamma Ray Burst afterglow and prompt-afterglow relations: An overview", NAREV, 77, 23 (2017).

Dainotti, M.G., del Vecchio, R. & Tarnopolski, M., "Gamma Ray Burst Prompt correlations" Advances in Astronomy, vol. 2018, id. 4969503.

Dainotti & Amati, "Gamma Ray Burst selection effects in prompt correlations: an overview", PASP, 30, 987, 051001 (2018b).

Dainotti 2019, IOP, expending Physics

GRB zoo

Which GRB class best works as a standard candle?

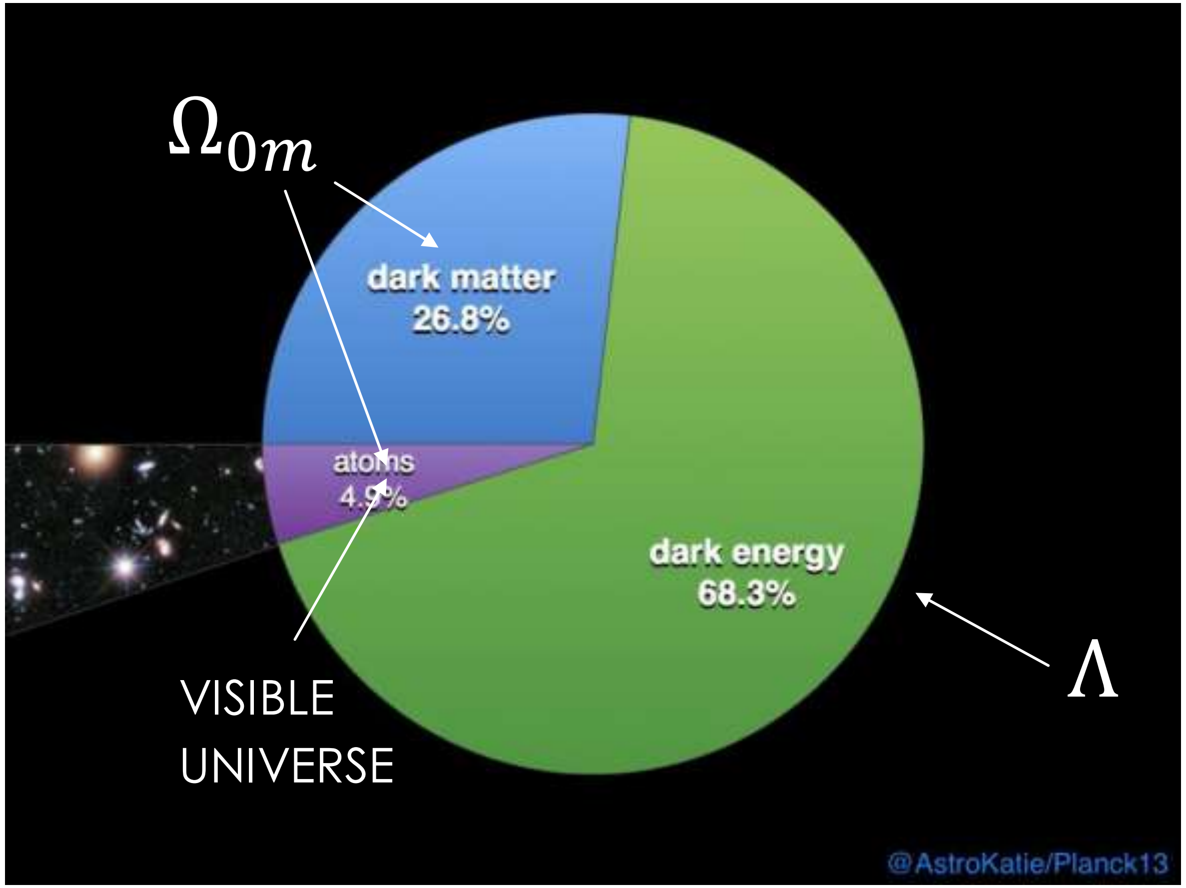
None of these classes are standard candles (but good news are coming!)

The drive is to standardize them.

Class	Duration of prompt emission	X-ray fluence/ γ-ray fluence	Presence of supernovae or optical bumps or other features
X-ray flashes	>2 s	>1	In some cases
GRB-SNe Ib/c	>2 s	<1	Yes
Short	<2 s	<1	No
Short Extended Emission (SEE)	<10 s	<1	Generally not
Long	>2 s	<1	No
Very Long	> 500s	< 1	Yes
Ultra Long	> 1000s	< 1	Yes
Type-I	<2s		No +low SFR+ natal kick
Type-II	>2s		Yes +high SFR+ no kick

Sakamoto et al. 2003
Woosley & Bloom 2006
Mazet et al. 1992, Kouveliotou et al. 1993
Norris & Bonnel 2006)
Levan et al. 2016
Piro et al. 2014,
Zhang et al. 2009, Beniamini et al. 2021

What can we investigate with GRBs, SNe Ia, Quasars and BAO?



Open problems: the so-called Hubble tension

(Dainotti et al. ApJ, 2021-> **listed in top 1% paper in web of Science**)