Maria Giovanna Dainotti

SNe Ia, the Gaussianity assumption and their use together with other high-z cosmological probes

06/05/2024, Thessaloniki

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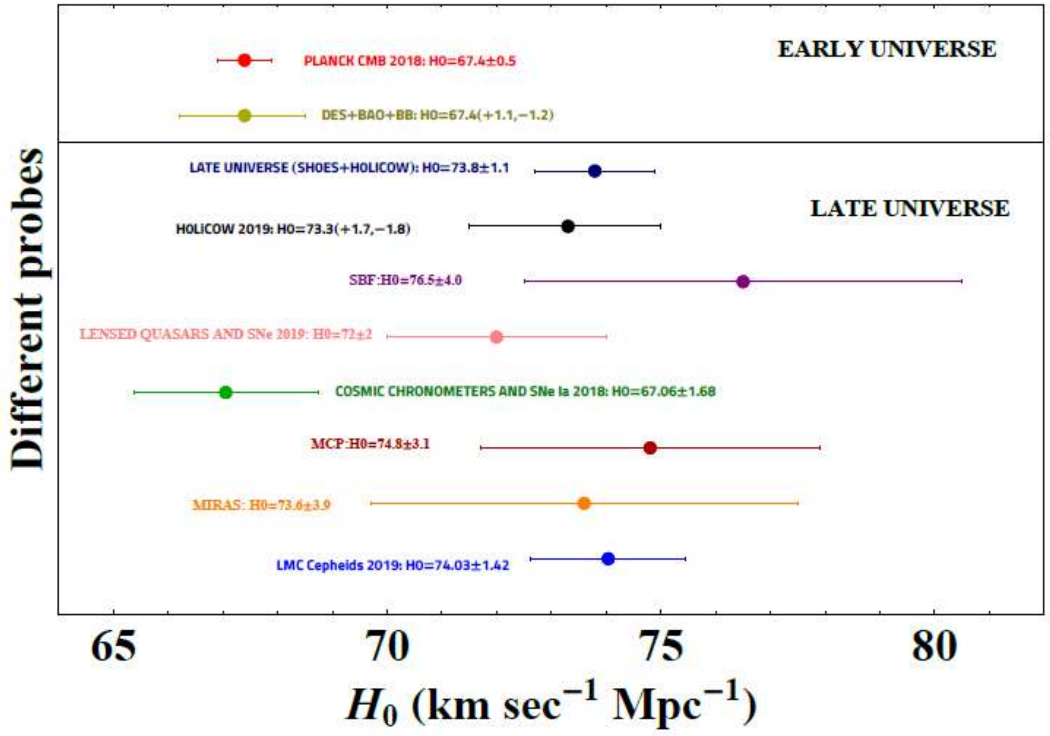
The Hubble constant and its tension

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

HUBBLE'S LAW



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

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.

Schiavove, Montani, Bompacigno, MNRASL

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

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, see talk of Leandros

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

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

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

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

Rs= sound horizon

Degeneracy between rs Ho and E(z), For more details see talk of Leandros

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

COSMOLOGICAL MODELS Adopted

The cosmological models

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

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

Radiation is neglected

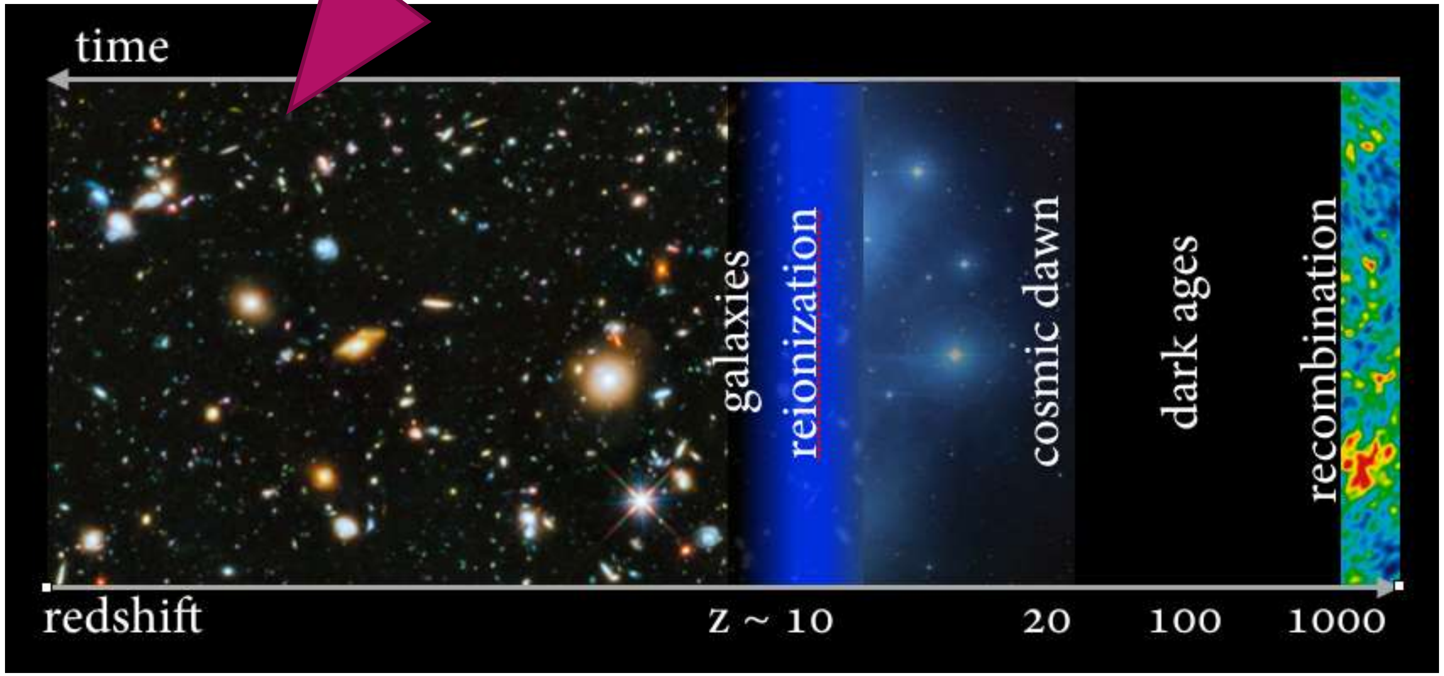
Curvature is neglected

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

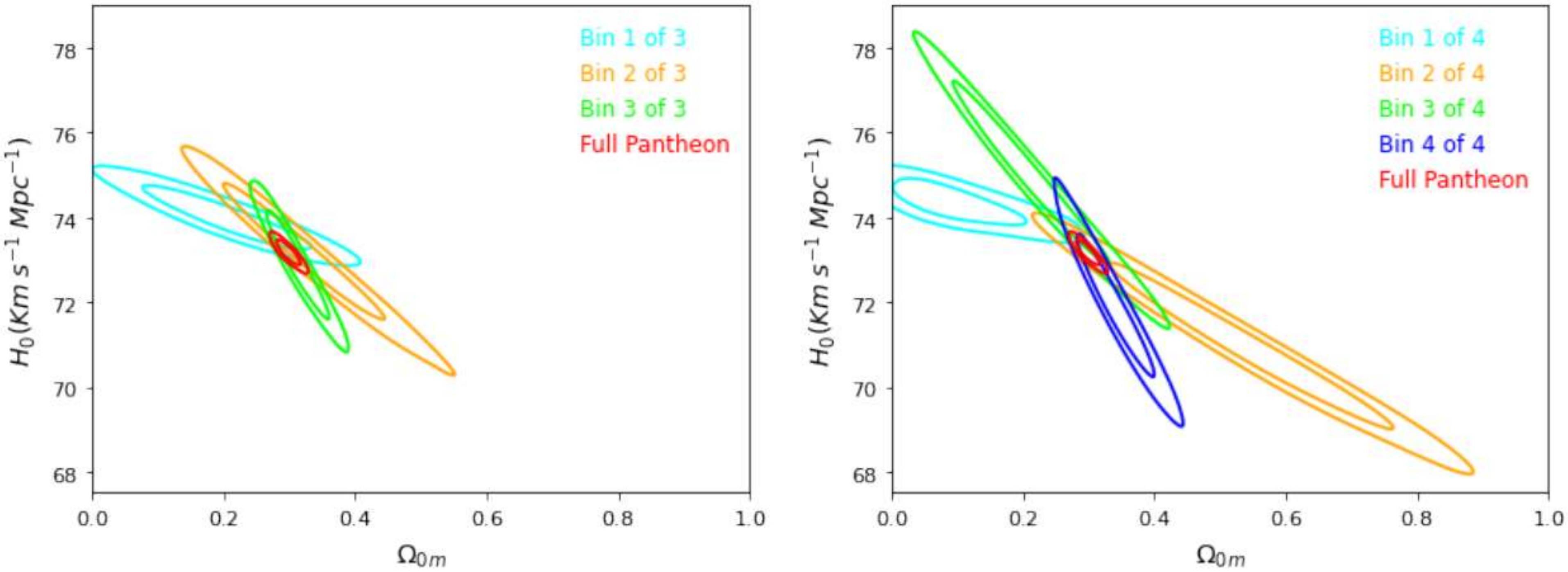
After we obtain several Ho values, we fit those with

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

α = evolution parameter

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

Criteria for the selection of bins



Preliminary 2D (H_0, Ω_{0m}) MCMC analysis considering the ΛCDM model

- Scolnic et al. (2018) suggest that it is important to have a number of SNe per bin in the hundreds so that the systematic uncertainties effect is properly taken into account

- 3 bins -> closure of contours in the parameter space and each bin contours is compatible in 1 σ with the total Pantheon
- 4 bins -> comparison with Kazantzidis & Perivolaropoulos (2020a)
- 20, 40 bins -> to test the independence of the results on the binning choice

Pantheon sample bins cosmology

THE ANALYSIS PERFORMED IS THE χ^2 REDUCTION FOLLOWED BY THE MARKOV CHAIN MONTE-CARLO WITH THE D'AGOSTINI METHOD IN ORDER TO ESTIMATE THE PARAMETERS AND TO OBTAIN CONTOURS AT 1σ AND 2σ CONFIDENCE LEVELS

$\chi^2 = \Delta\mu^T C^{-1} \Delta\mu$ WHERE $\Delta\mu = \mu_{obs}^{(SN)} - \mu_{th}$ AND $C = D_{stat} + C_{sys}$

THE FULL COVARIANCE MATRIX THAT INCLUDES BOTH STATISTICAL AND SYSTEMATIC UNCERTAINTIES

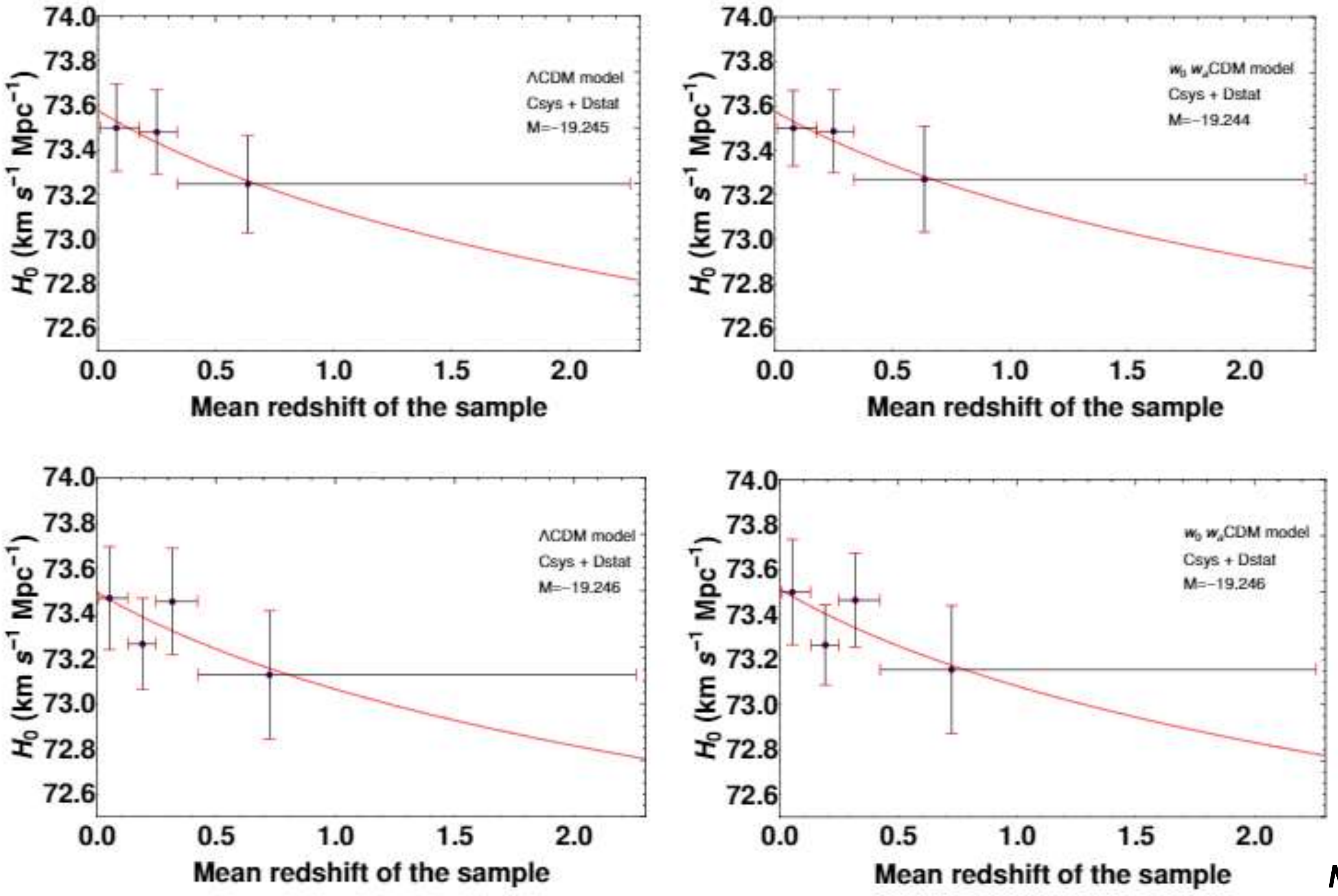
↓

FIRST OF ALL WE MUST DISCUSS THE SELECTION CRITERIA FOR THE BINS. IN SCOLNIC 2018 IT IS SUGGESTED TO MAINTAIN THE BINS IN THE ORDER OF THE HUNDREDS OF SNe SO THAT THE SYSTEMATIC EFFECTS CAN BE PROPERLY HIGHLIGHTED

↓

WE DECIDED TO EXPLORE THE FIRST Two CHOICES IN BINS: 3 BINS, 4 BINS

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

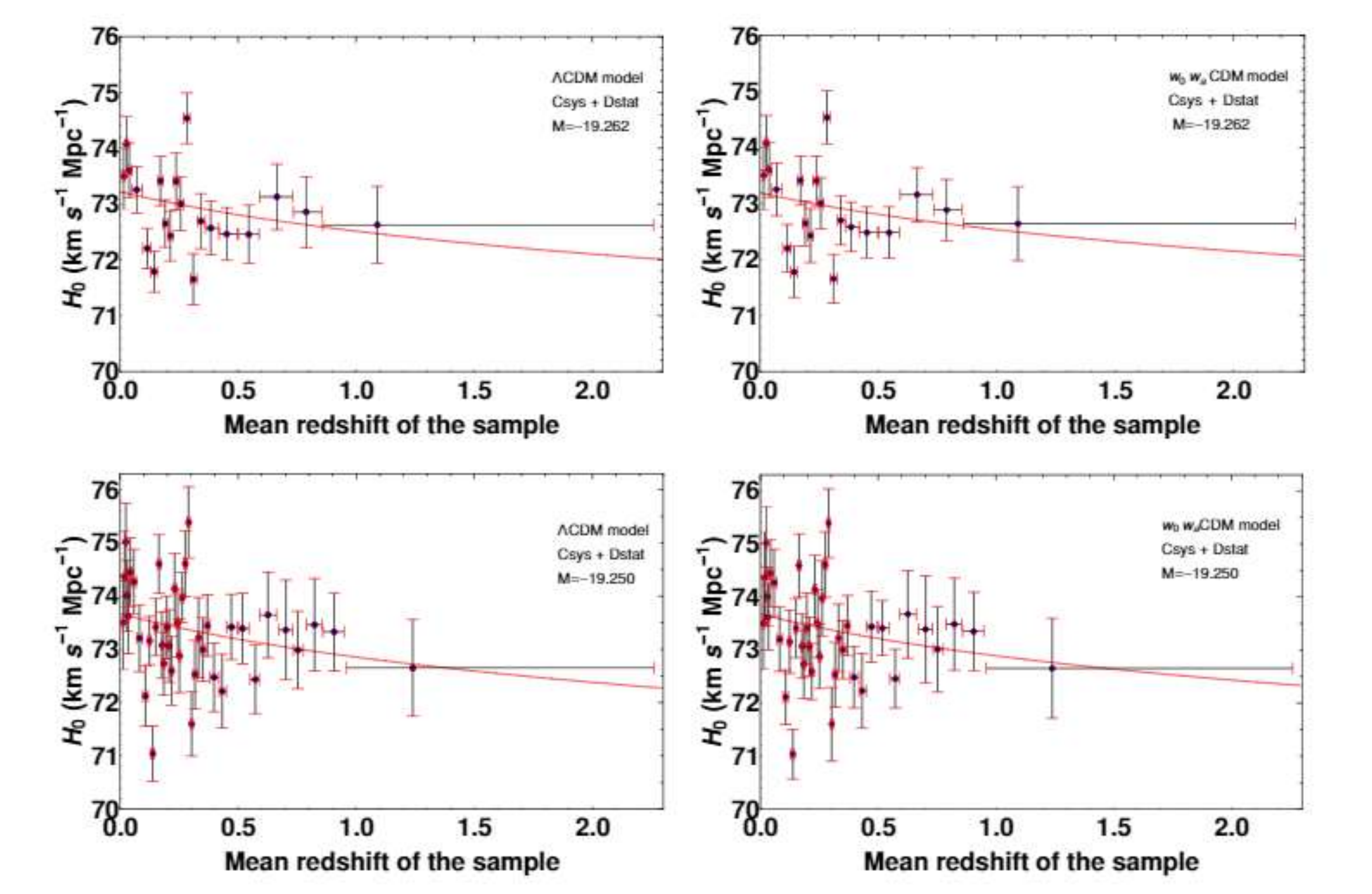


The w_0w_a**CDM** model results are compatible with the ΛCDM ones

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

Results for ΛCDM and w0waCDM models (20, 40 bins)



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

Extrapolation at z=1100
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.

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	$\tilde{H}_0$ (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	73.576 ± 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%

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

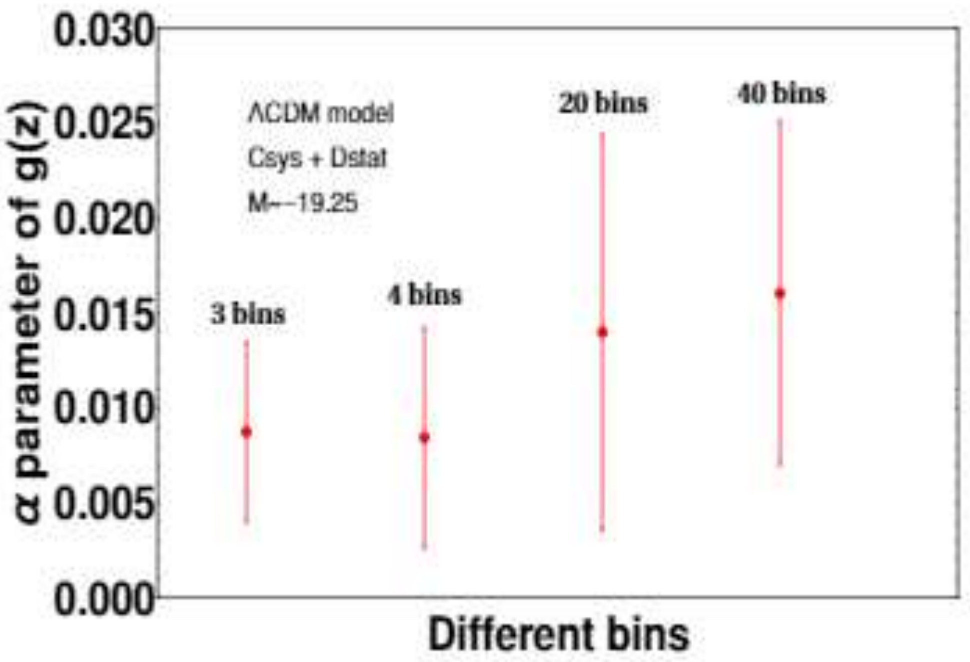
$$x_f = \frac{\tilde{H}_0(z = 0) - H_0(z = 1100)}{\sqrt{\sigma^2_{\tilde{H}_0(z=0)} + \sigma^2_{H_0(z=1100)}}}$$

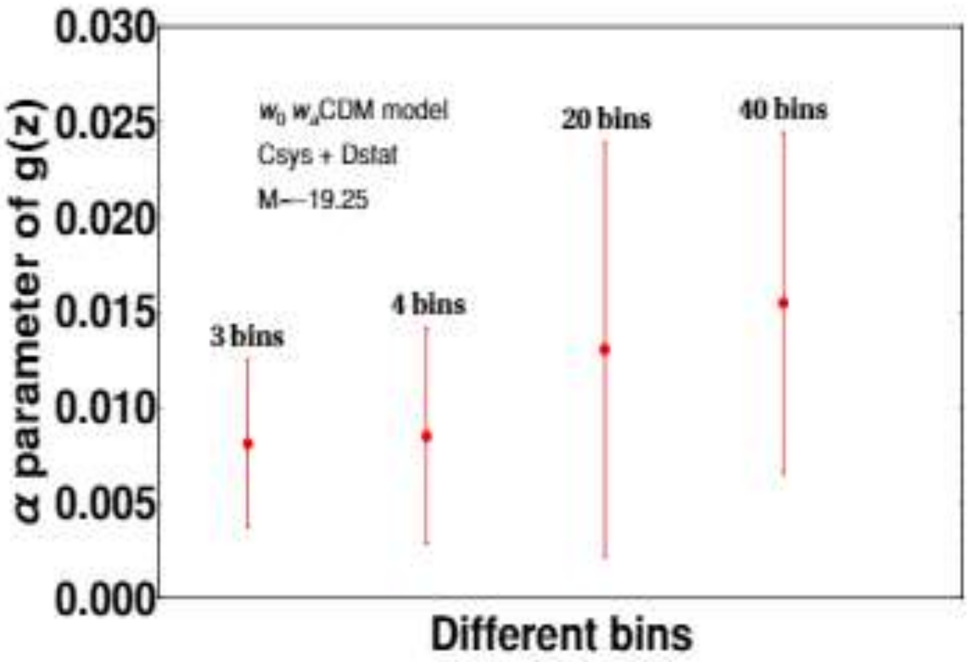
$$\%\mathrm{Diff} = 1 - x_f/x_i$$

On the Hubble constant tension in the SNe Ia Pantheon sample

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

The trend of the alpha parameter

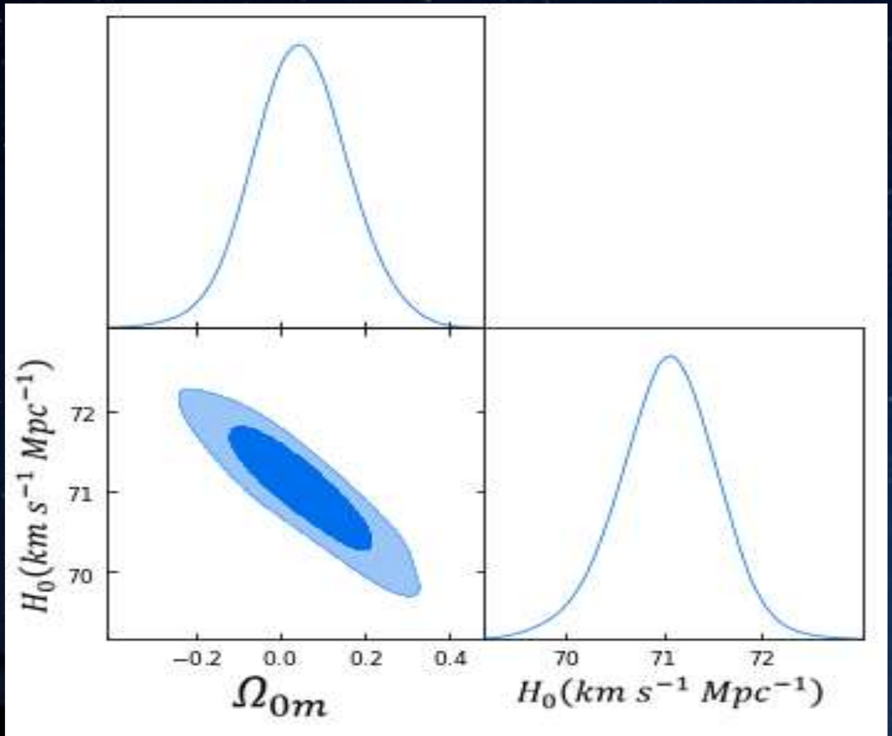




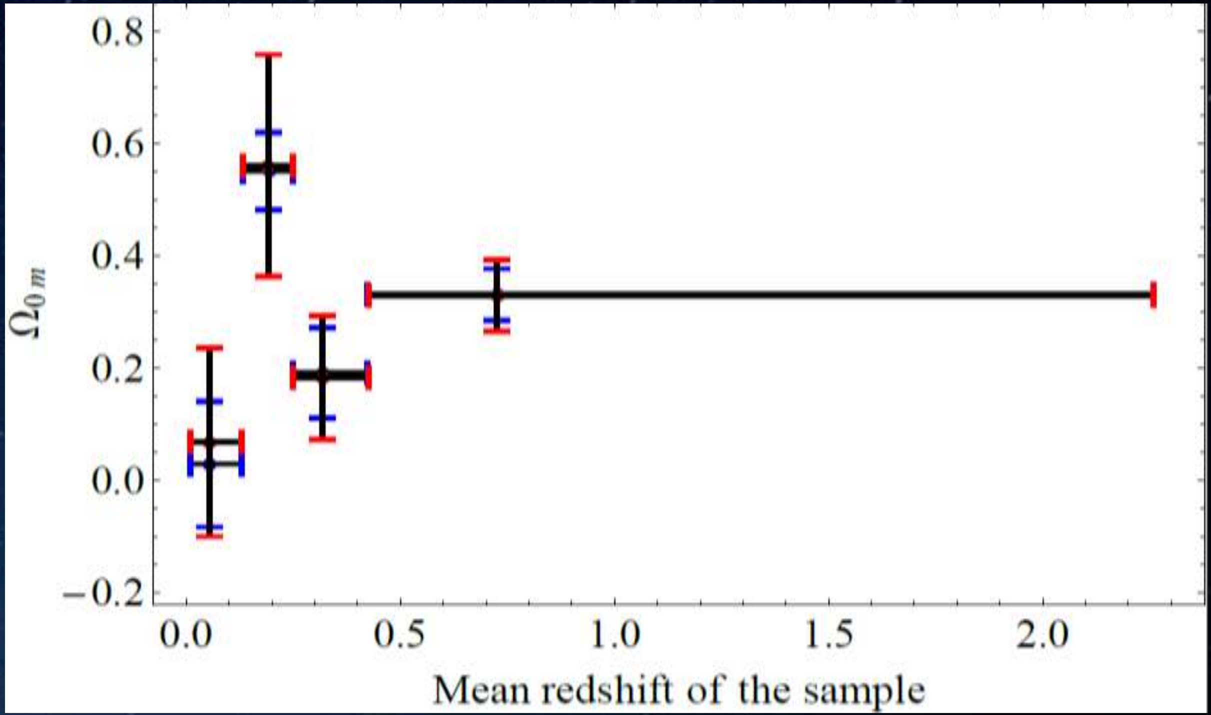
M. G. Dainotti, et al., 2021, ApJ, 912, 150

4 bins, ΛCDM model, comparison

4 BINS (262 SNe PER BIN), LIKE KAZANTZIDIS & PERIVOLAROPOULOS 2020a Phys. Rev. D **102**, 023520



OUR FIRST BIN



OUR VALUES: BLUE BARS, K&P VALUES: RED BARS

The advantage of our approach is that we use the full covariance matrix

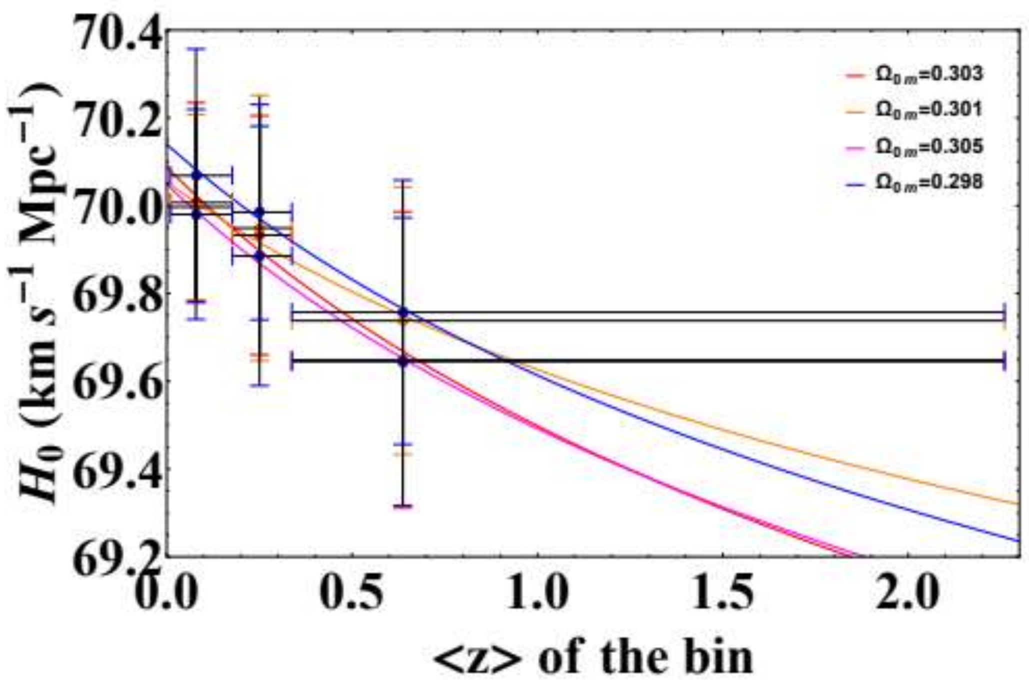
Testing the Hu-Sawicki model

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

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

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

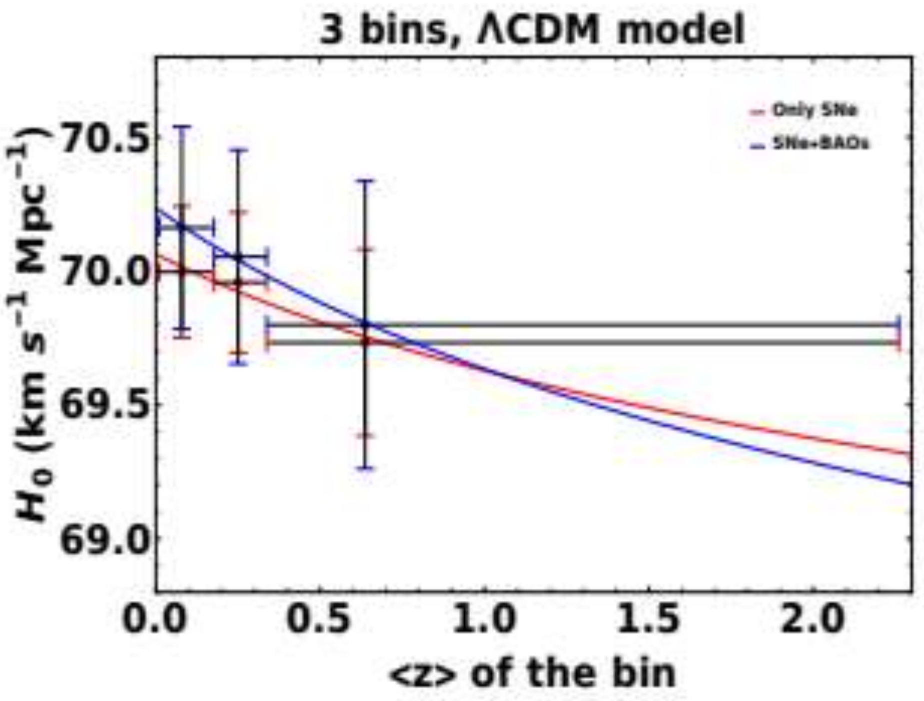
In the case of $F_{R0} = -10^{-7}$
(value of the field at the present time)



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

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

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



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

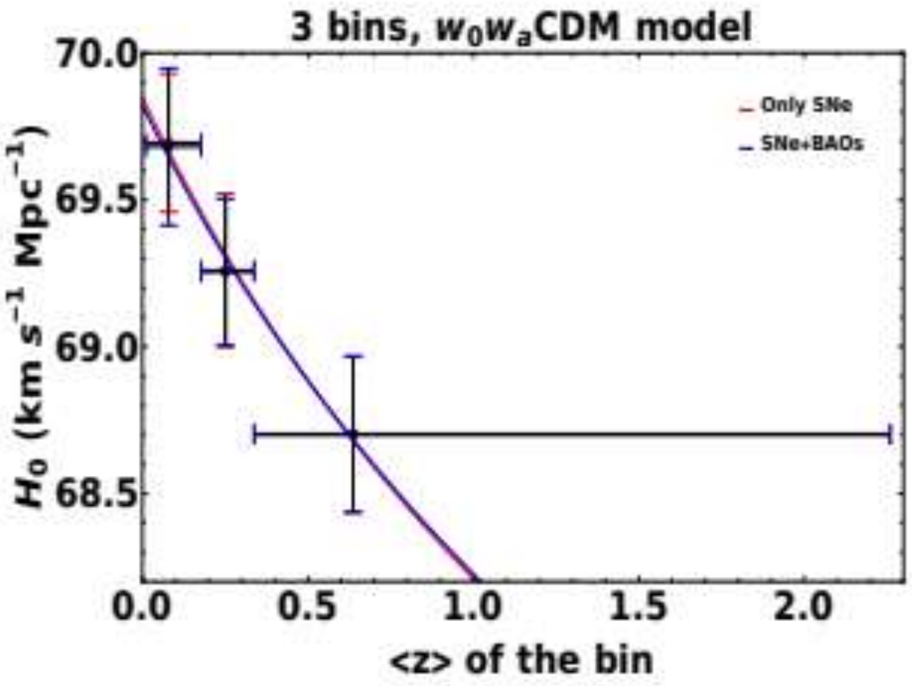
Flat ΛCDM model, without BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.093 ± 0.102	0.009 ± 0.004	2.0
Flat ΛCDM model, including BAOs, varying H_0 and Ω_{0m}			
Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
3	70.084 ± 0.148	0.008 ± 0.006	1.2

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

Varying H_0 and Ω_{0m}

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

Varying H_0 and w_a



Bins	$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
Flat w_0w_aCDM model, without BAOs, varying H_0 and w_a			
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

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

Discussion of the results

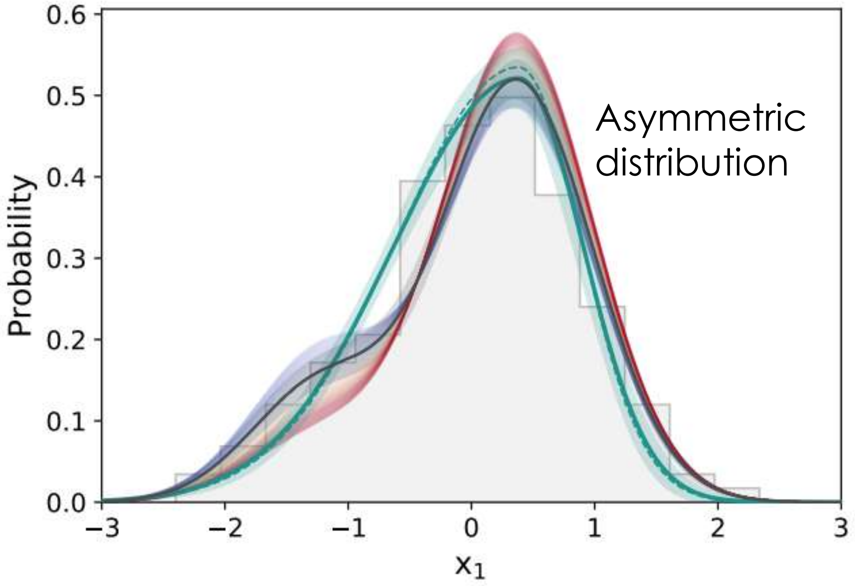
SNe Ia ANALYSIS: POSSIBLE ASTROPHYSICAL EFFECTS

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.

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

- 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

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
- New Theories are needed: slow rolling?

Slow-rolling scalar dynamics to alleviate the Hubble tension

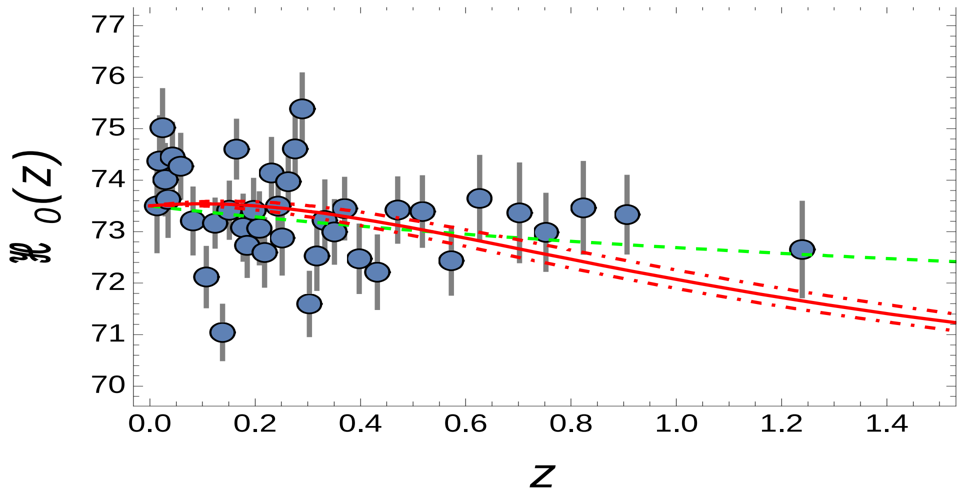
- Minimally coupled with Gravity scalar field, slow-rolling (denoted with sr) dynamics yields:
-

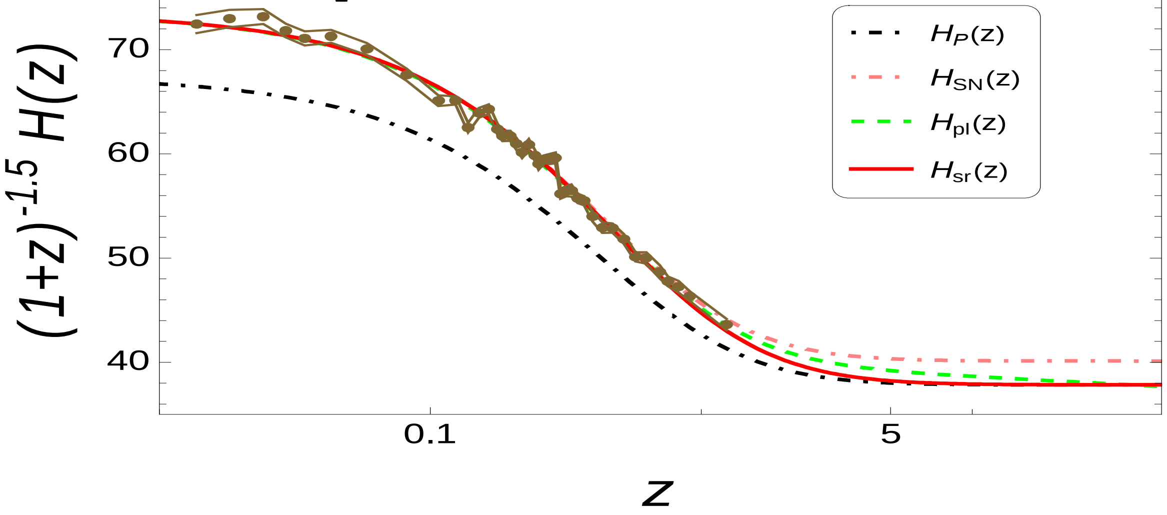
$$H_{\rm sr}(z) = \mathcal{H}_0(z)\ \sqrt{\Omega_{0m}^{\rm SN}(1+z)^3 + (1-\Omega_{0m}^{\rm SN})} \qquad \mathcal{H}_0(z) = H_{0\rm P}\sqrt{\frac{\Omega_{0m}^{\rm P}(1+z)^3 + (1-\Omega_{0m}^{\rm P}) + \Omega_{0\phi}(1+z)^{-3\beta}}{\Omega_{0m}^{\rm SN}(1+z)^3 + (1-\Omega_{0m}^{\rm SN})}}$$

$$H_{0\rm P} = 67.4 \qquad \Omega_{0m}^{\rm P} = 0.315$$

$$H_{0\rm SN} = 73.5 \qquad \Omega_{0m}^{\rm SN} = 0.298$$

- P=Planck;PL=power law. The quantity $\Omega_{0\phi}$is set in order to have $H_{sr}(0) = \mathcal{H}_0(0) = 73.5 \quad \Rightarrow \quad \Omega_{0\phi} = 0.189$
- Parameter β is determined by the fitting procedure of $\mathcal{H}_0(z)$ with the 40 bins distribution of the H_0 values in `Dainotti et al. 2021, ApJ, 912, 150.` $\beta = -0.285 \pm 0.026$
- For $z \gtrsim 5$, $H_{sr}(z)$ overlaps the flat ΛCDM model associated to the Planck data (a similar behavior is obtained by the power-law model in `Dainotti et al. 2021, ApJ, 912, 150.`





Montani, Carlevaro, Dainotti, PDU, 44, May 2024,

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

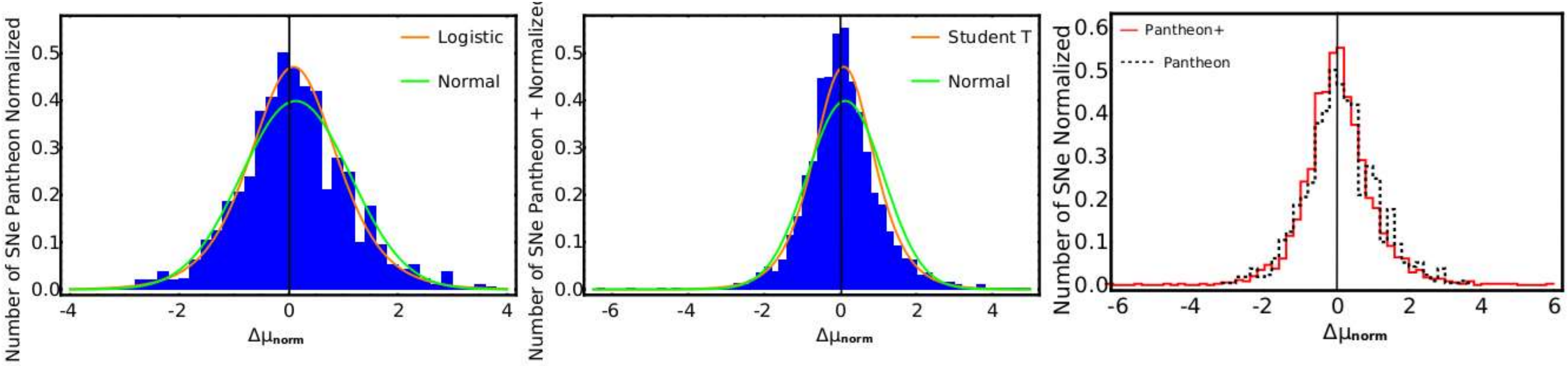


Figure 1: Normalized $\Delta\mu_{norm}$ histogram, defined as $\Delta\mu_{norm} = C^{-1/2}\,\Delta\mu$, for the 1048 SNe Ia in *Pantheon* (left panel) and the 1701 SNe Ia in *Pantheon* + (middle panel). The green curve is the best-fit Gaussian distribution, while the orange curves are the best-fit logistic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

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 $\sigma^2 = (s^2\ \pi^2)/3$

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

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

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

The two different Cosmological analysis

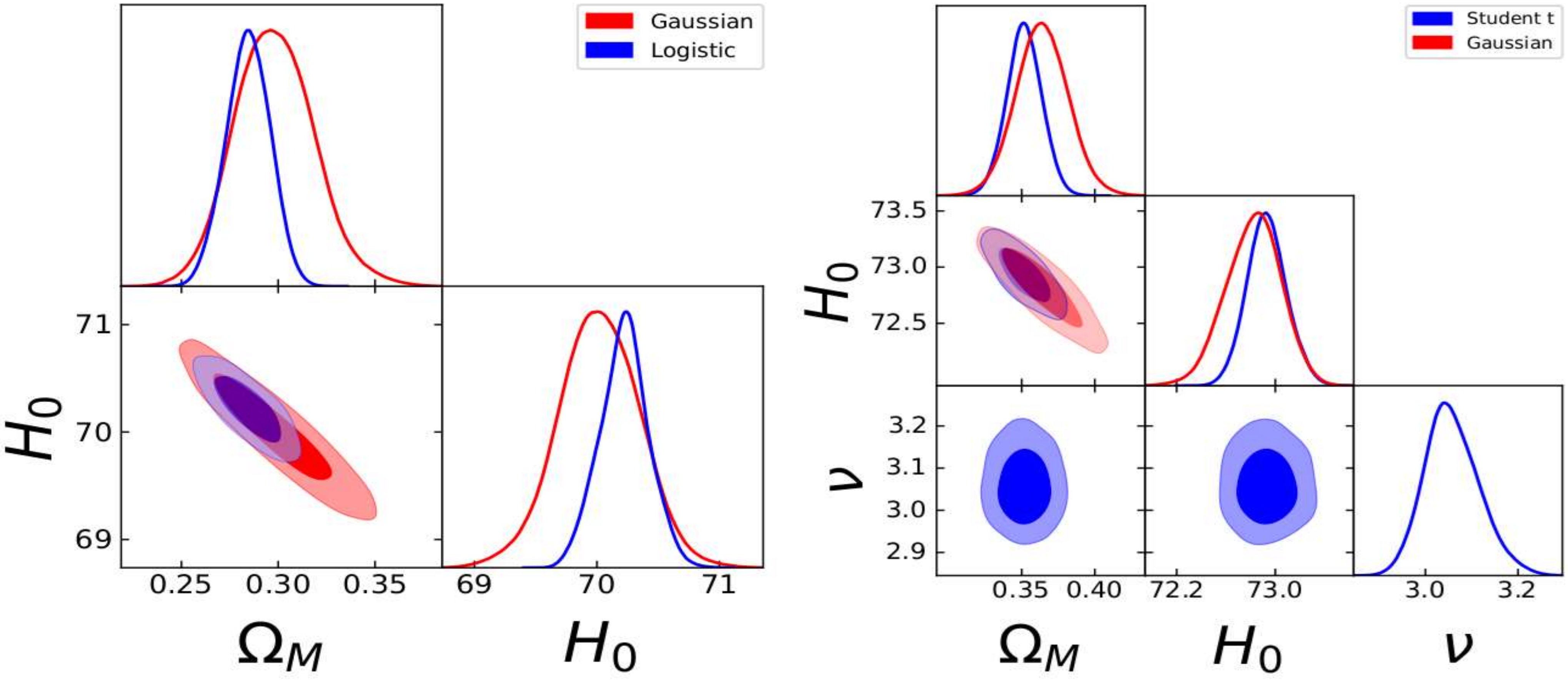


Figure 2: Fit of the flat ΛCDM model with Ω_M and H_0 free parameters. Left panel shows the results for *Pantheon* SNe Ia with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{logistic}$ as in the legend. Right panel shows the contours for the *Pantheon* + sample with both $\mathcal{L}_{Gauss}$ and $\mathcal{L}_{Student}$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

GRB cosmology:
What are the solutions to allow for an independent calibration?

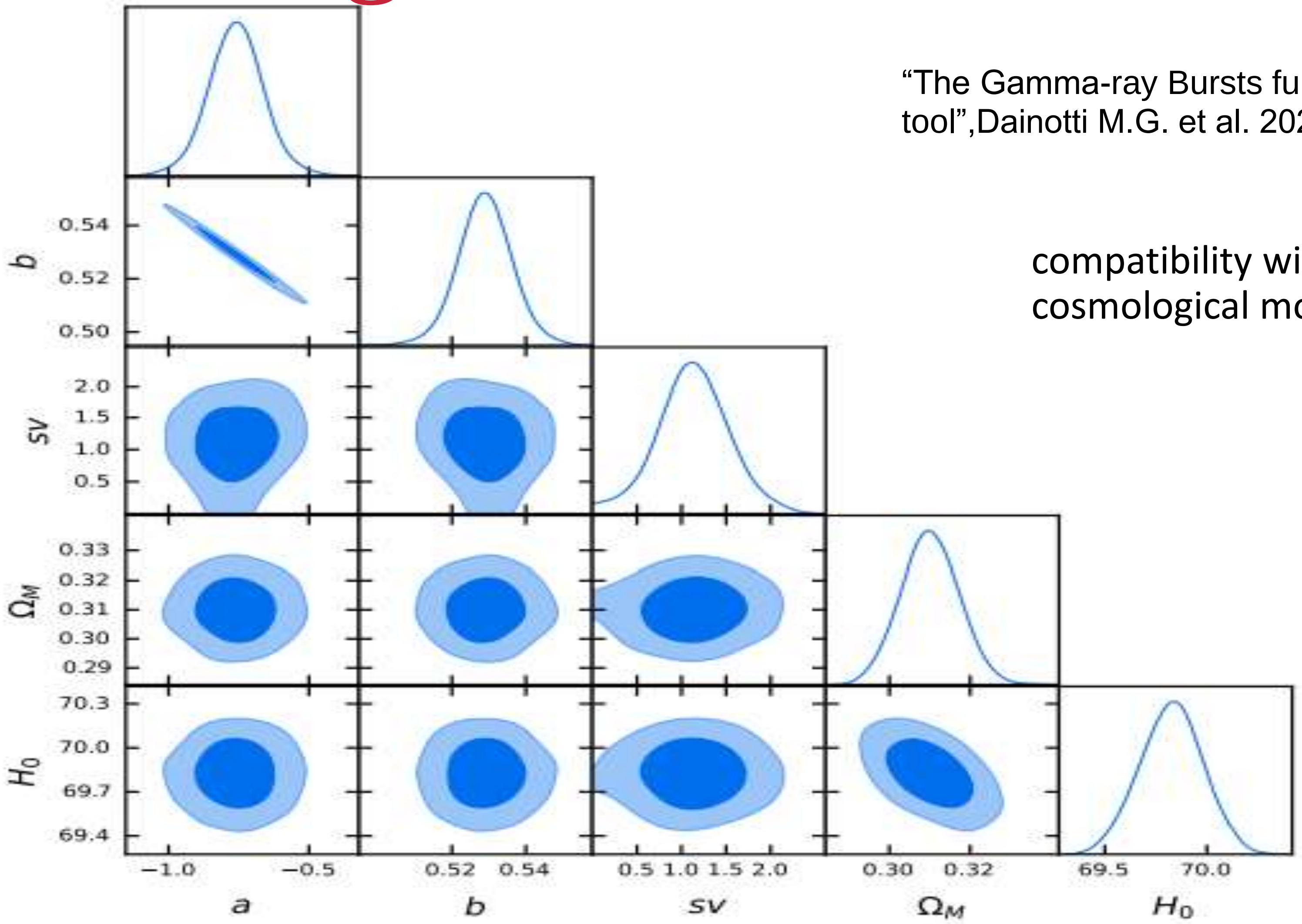
▶Two solutions

- **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 contemporaneous fitting

Combining GRBs + SNe Ia + BAO



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

compatibility with standard cosmological model

Simultaneous fitting

What else can we do?

Results for the Flat and non-flat models

Dainotti et al. 2023, … Nagataki, B. Zhang, N. Fraija, ApJS, 2023arXiv230510030, press release from NAOJ

$\mathcal{L}_{\mathcal{G}}$ likelihoods:	Non-flat ΛCDM			flat *w*CDM		
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 *w*CDM		
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 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!

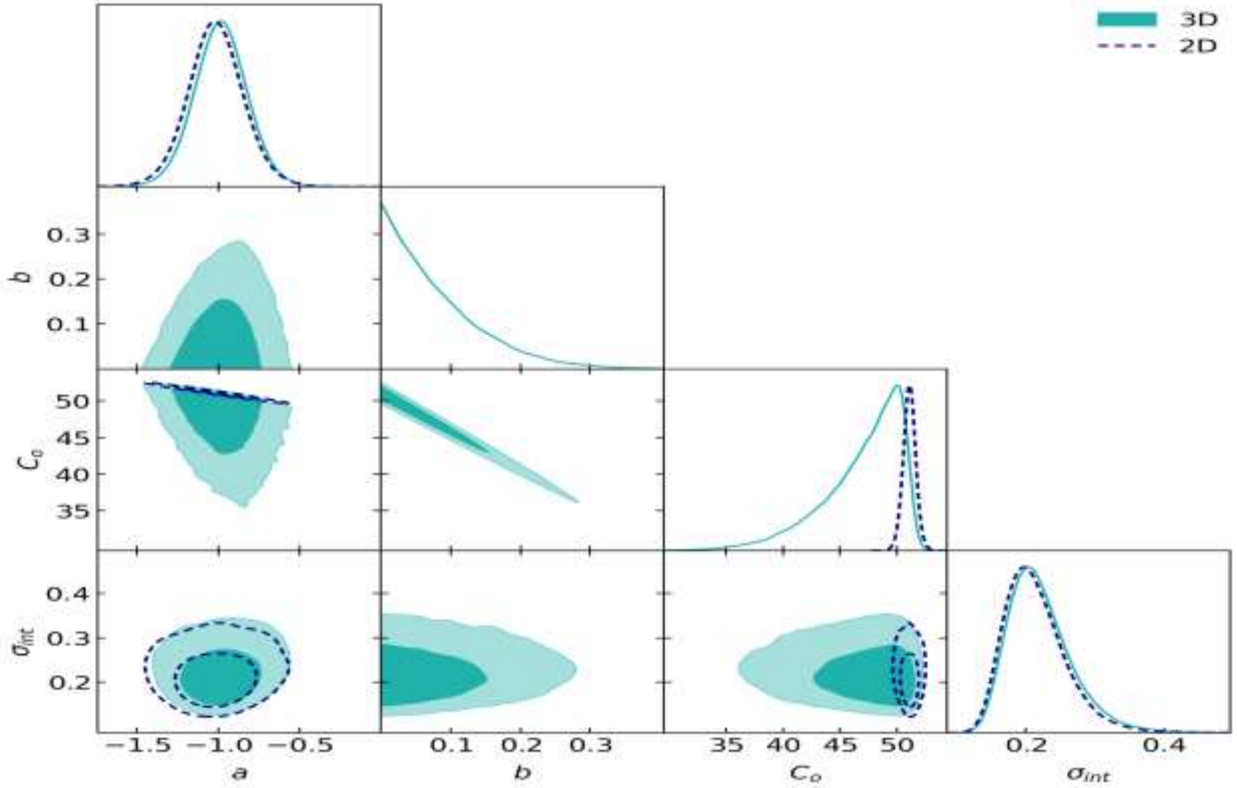
Dainotti et al. 2023 2303.06974.pdf (arxiv.org)

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

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

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 σ=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?

With machine learning

For redshift inference, regression:

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

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

3) Gibson, Narendra, Dainotti, et al. 2022, Frontiers, 9, 836215

4) Dainotti, ApJS, 267, 2, id 42, Lightcurve Reconstruction,

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, Cosmic Leap: NASA Swift Satellite and AI Unravel the Distance of the Farthest Gamma-Ray Bursts | University of Nevada, Las Vegas (unlv.edu); (20+) Facebook

7) Dainotti, et al. 2022, MNRAS, 514, 2, 1828-1856 (forecasts for GRB cosmology)

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

When?

How?

67 → Conley et al. 2011 precision $\sigma\Omega_M = 0.10$ → 2022

134 → Betoule et al. 2014 precision $\sigma\Omega_M = 0.042$ → 2026

390 → Scolnic et al. 2018 precision $\sigma\Omega_M = 0.022$ → 2042

With Machine learning (ML), errors on the parameters halved (n=2), and Lightcurve reconstruction (LCR)

Forecast including Swift, SVOM and Theseus (Einstein Probe data yet to be added)

So, we should not wait 18 years!

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

What are the next step?

And the party still continues…

- **Use data from Einstein Probe**
- 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
- **Continue Combine GRBs with other probes which are treated similarly as GRBs and look for a standard set of QSOs to tighten the existing relations**
- **We already did in..**

"Quasars: Standard Candles up to z= 7.5 with the Precision of Supernovae Ia" by Dainotti et al. ApJ, 950(1), id.45, 8 pp. (2023), ArXiv:2305.19668

- **The scavenger hunt for Quasar samples to be used as cosmological tools**

Dainotti, M.G., et al. Galaxies, 12, (1), id.4 (2024), ArXiv:2401.11998

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

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

Some tension in Ω_M also in QSOs?

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. σ-clipping technique reduces iteratively the scatter of the relation removing the outliers.

- Results:

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

–Ω_M = 0.268 ± 0.022 (The same precision reached in Scolnic et al. 2018)

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

“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, δ_F = 0.22 vs δ_F = 0.29 (24% less), than the original sample. This sample enables us to determine Ω_M =** 0.256 ± 0.089 **with a precision of 0.09 by using QSOs as standalone probes.**

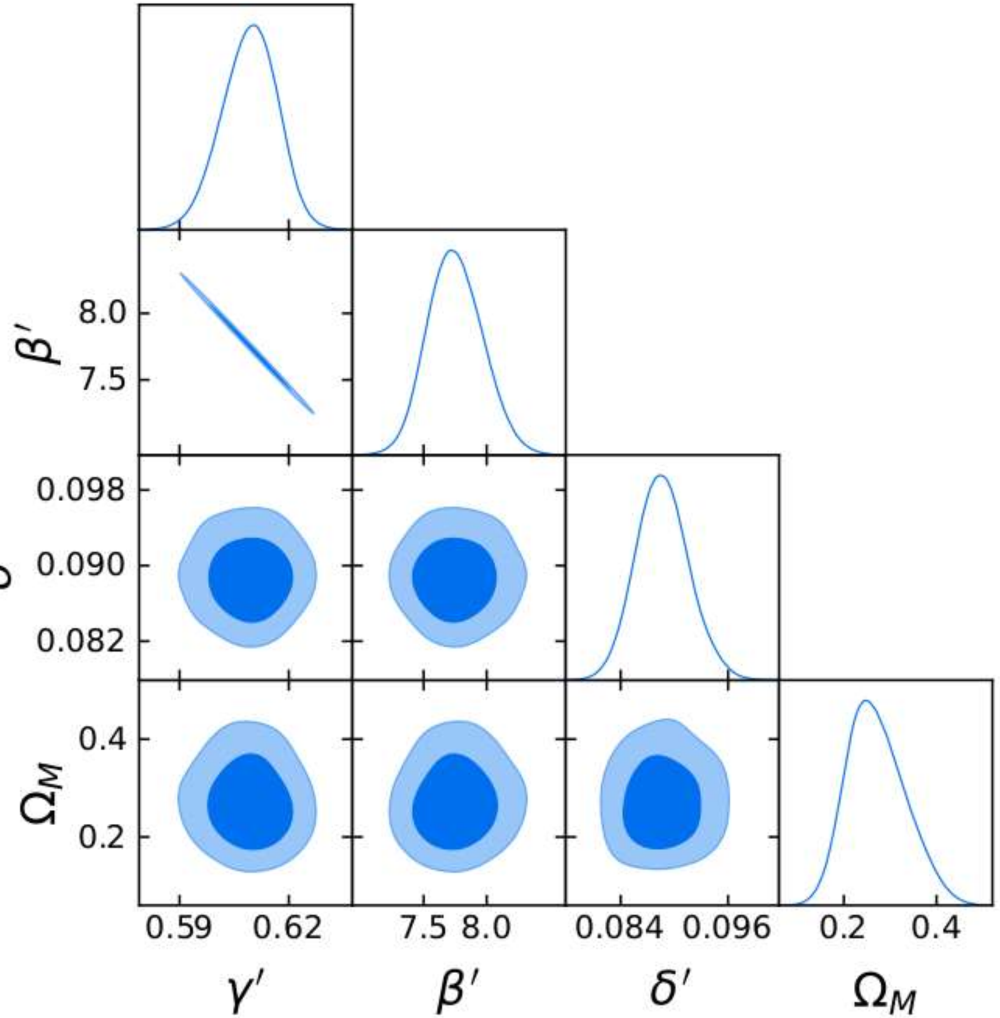


Figure 11. Results obtained from the gold sample of 1132 QSOs from the cosmological fit of the flat ΛCDM model with γ', β', and δ' of the RL relation, corrected for redshift evolution in the luminosities and Ω_M left as free parameter together with the ones of the relation. H_0 is fixed to $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ 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:** $\Omega_M=0.240\pm0.064$

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.

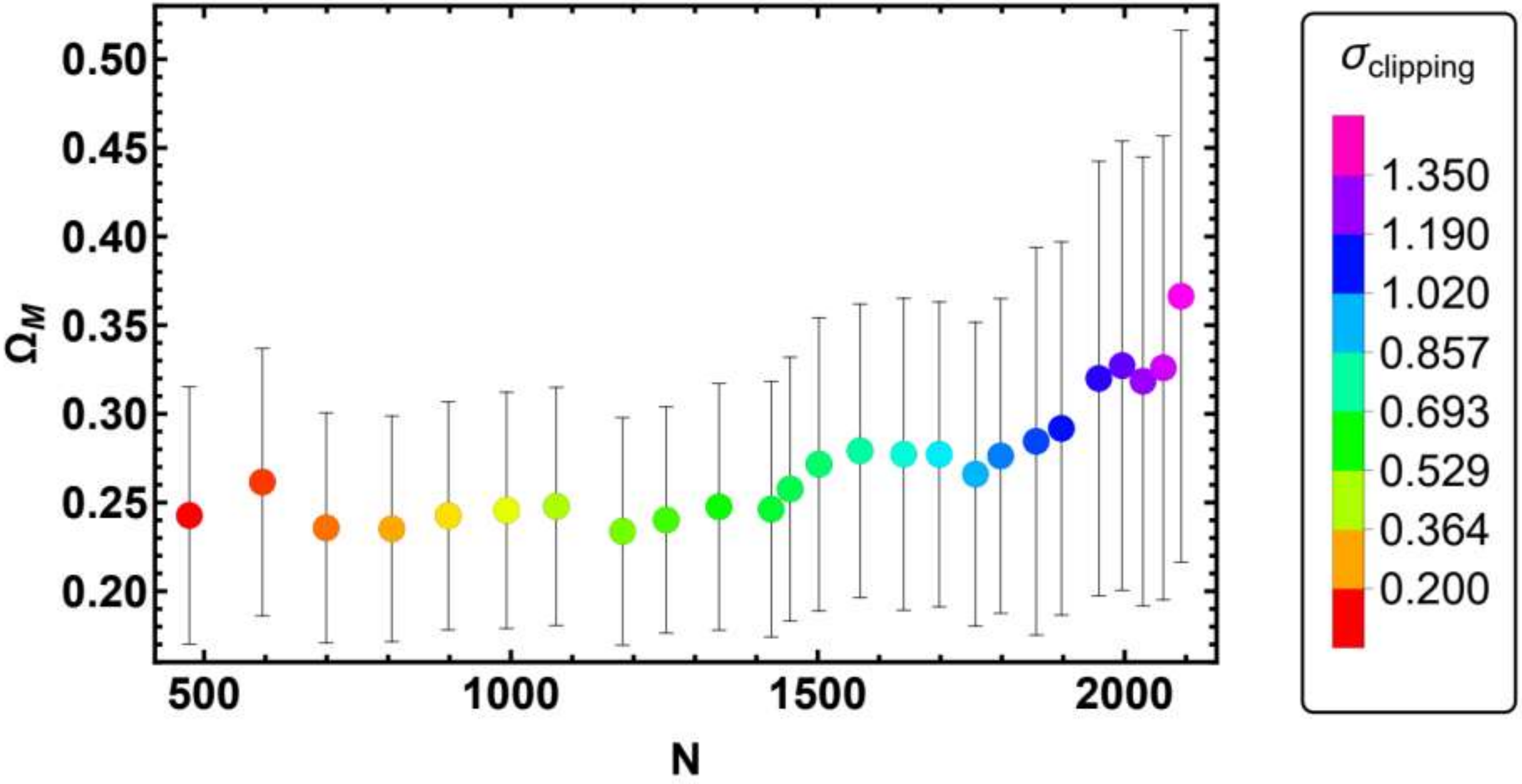
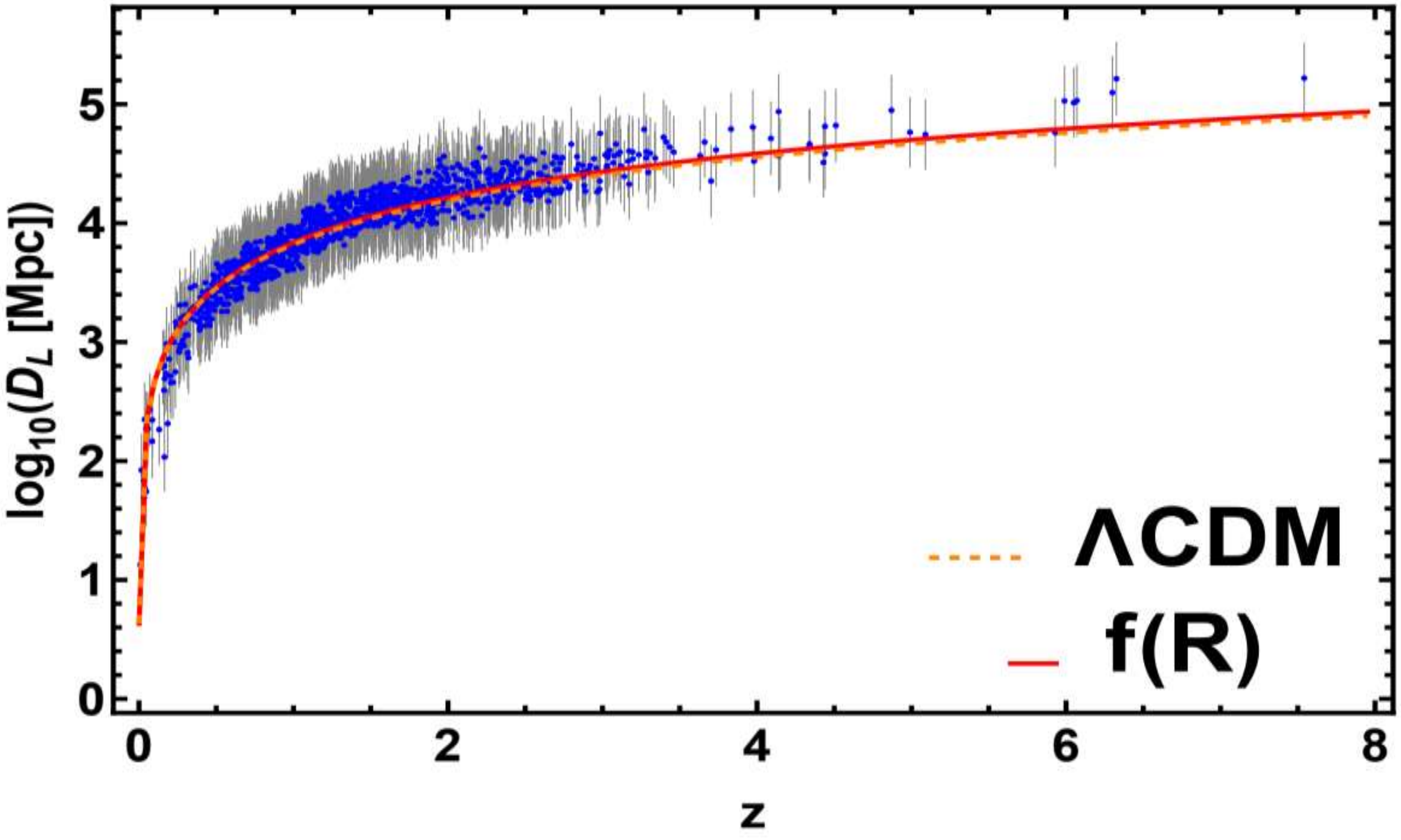


FIG. 8: The matter density parameter, Ω_M, computed for each sub-sample obtained in the σ clipping process, is shown as a function of the size of these subsets. The colour scheme indicates the interval chosen in the σ-clipping algorithm. The error bars represent 1 σ uncertainties.



$$H^2 = H_0^2 \left(\frac{\Omega_M}{\phi} (1+z)^3 + \Omega_\Lambda \right)$$

and

$$6H\dot{\phi} = G(\phi) \, .$$

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

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

- **check the decreasing trend of H0 SNE Ia Pantheon and Pantheon + with the new likelihoods**
- Analyzing the impact of the BAO from DESI Collaboration
- Leveraging the constraints from the SH0ES SNe Ia (Riess et al. 2022)
- **For the GRB sample increase we built the largest optical catalog to date (Dainotti et al., MNRAS submitted 53 coauthors)**
- **We continue to improve the GRB redshift prediction and LC reconstruction with Machine learning to reduce the number of years (ask me if you need data from reconstructed lightcurves)**
- **We continue the theoretical discussion: a given subset of GRBs fulfilling the magnetars can be standardizable candle.**

Announcements

- **MG 17 (parallel session on GRB correlations, their interpretation and cosmology)**
- **Parallel session on Machine Learning and AI on GRBs**

If you are interested, please submit a talk by 10th June. The Organizers just let me know that online talks are also possible

Call for abstract in Galaxies for the special issue:

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

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

Deadline for submission: 30th of September 2024.

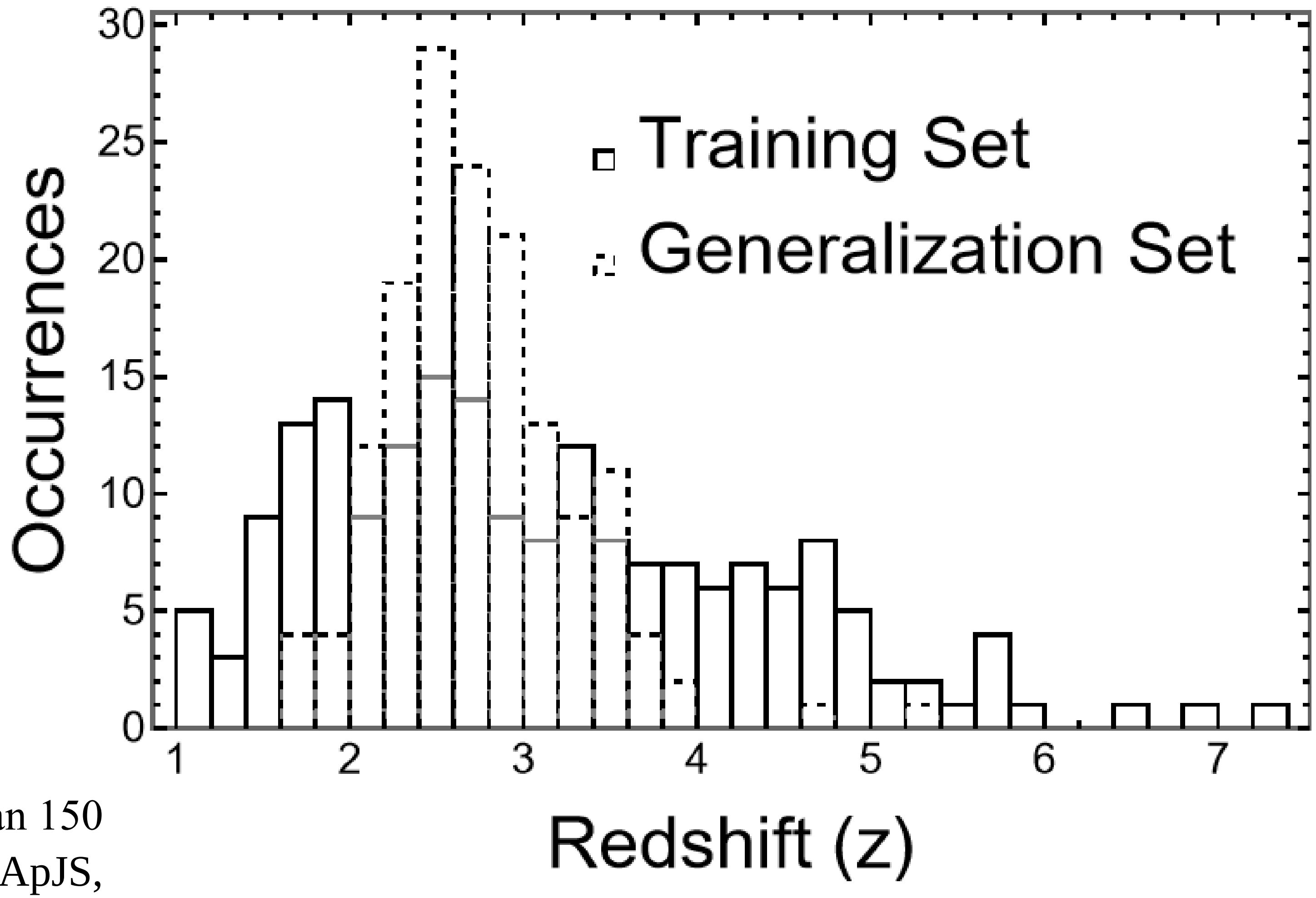
If you are interested, please contact me.

Calls for JSPS for postdoc for two years. Internal deadline from NAOJ side is the 1th of August.

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.

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?

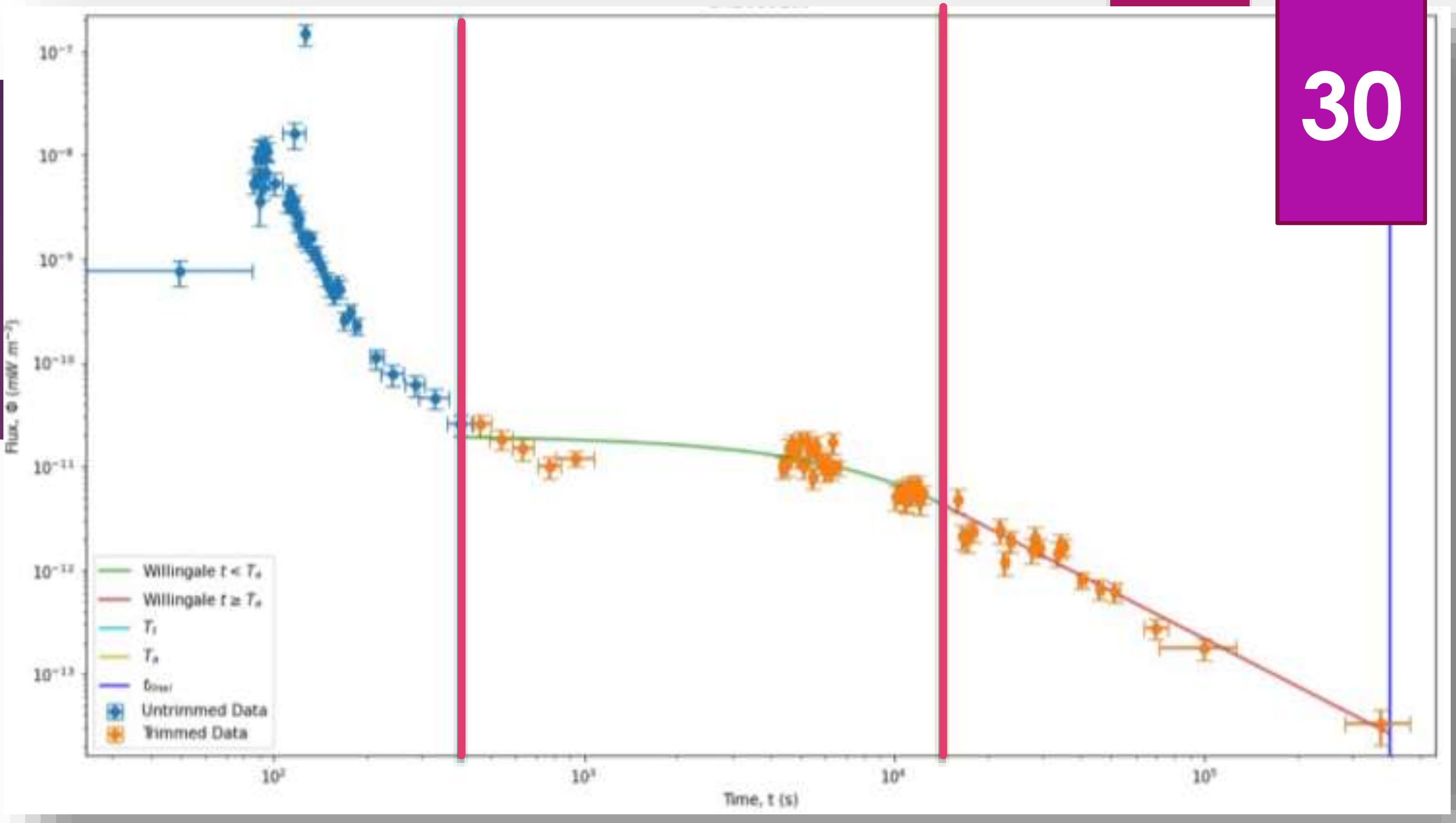
- We are training a supervised machine learning model on optical photometric GRB properties to reliably predict the redshift.

  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:

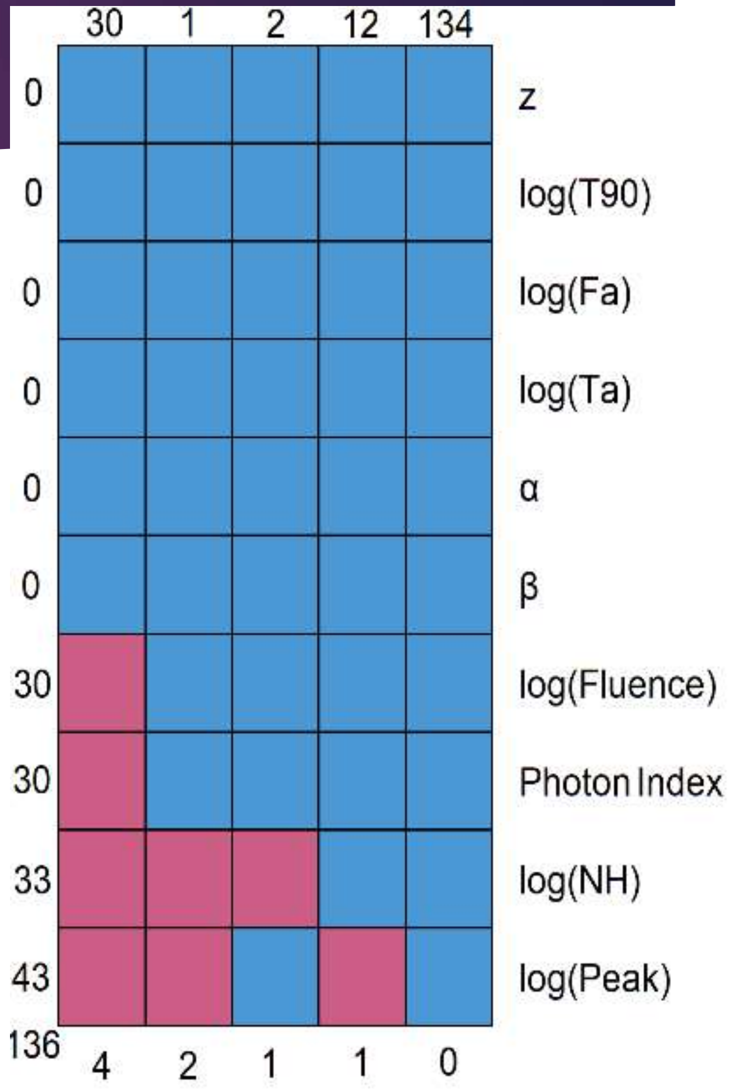
- 4 features from the prompt emission:
  Fluence,
  T90,
  Peak flux,
  Photon Index

- 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

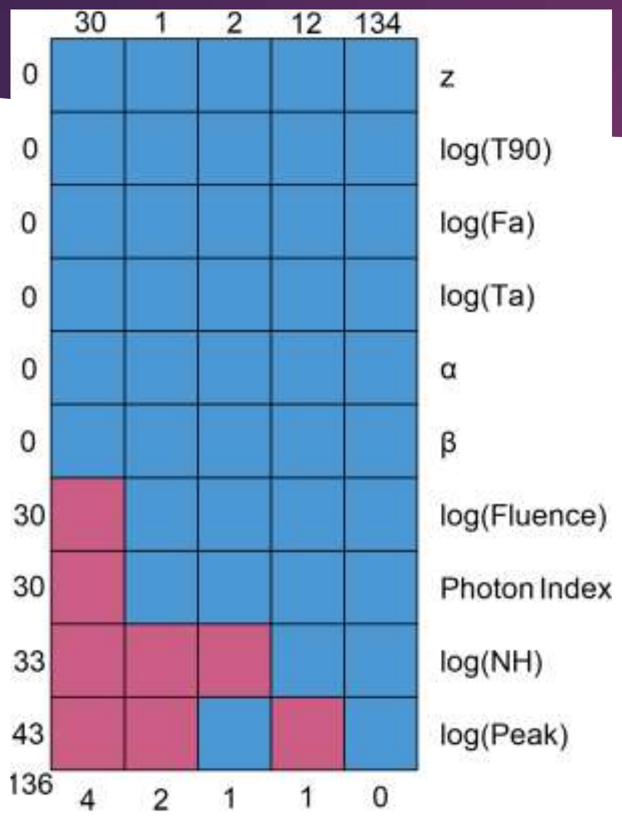
Multivariate Imputation by Chained Equations (MICE)

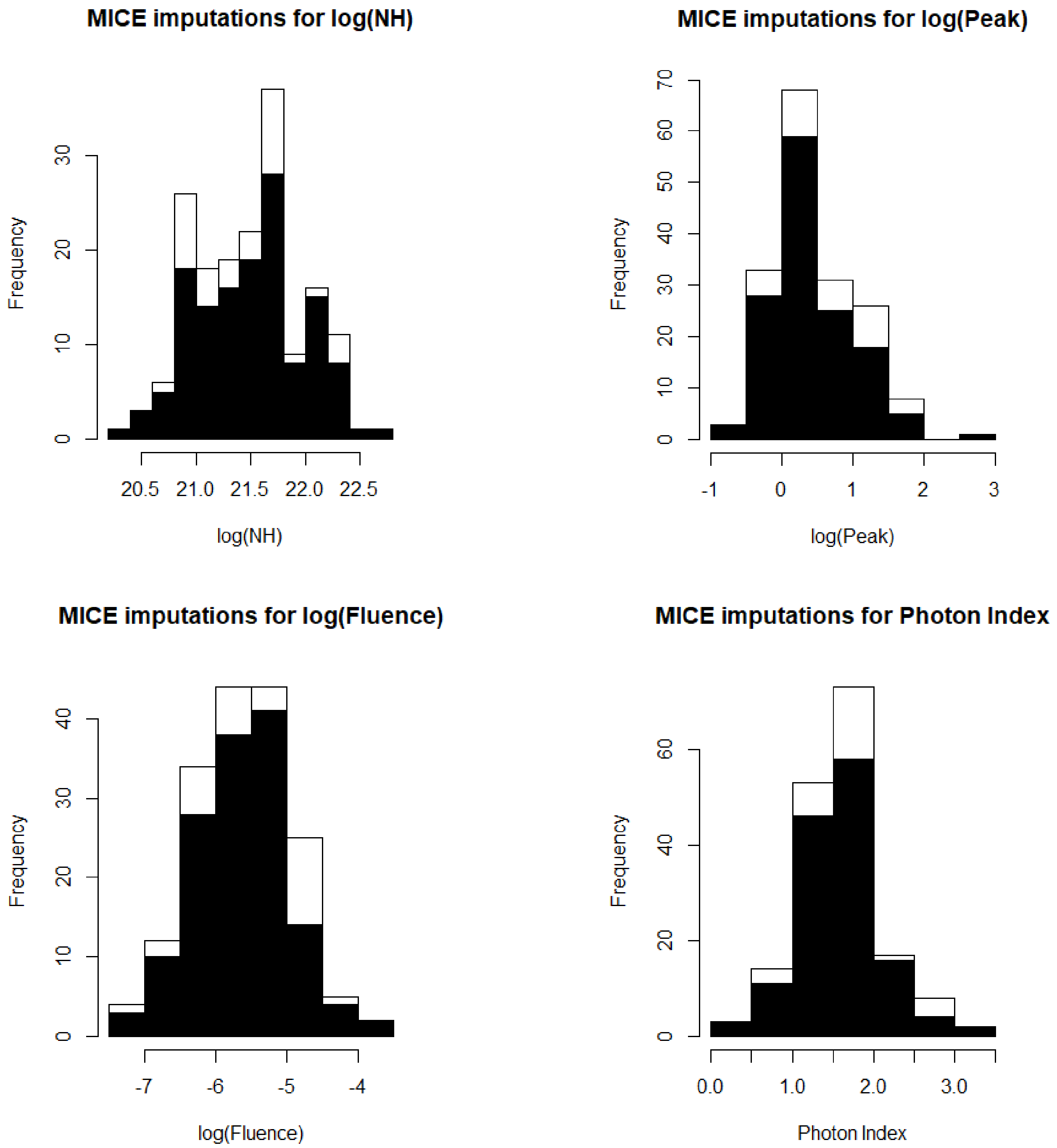
- <u>30 GRBs</u> have missing data in log(Fluence), Photon Index, log(NH) and log(Peak).
- There is <u>one GRB</u> that has missing data in log(NH) and log(Peak) and <u>2 GRBs</u> with missing log(NH).
- Finally there are <u>12 GRBs</u> with missing log(Peak).
- We use Multivariate Imputation by Chained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



Data Sample

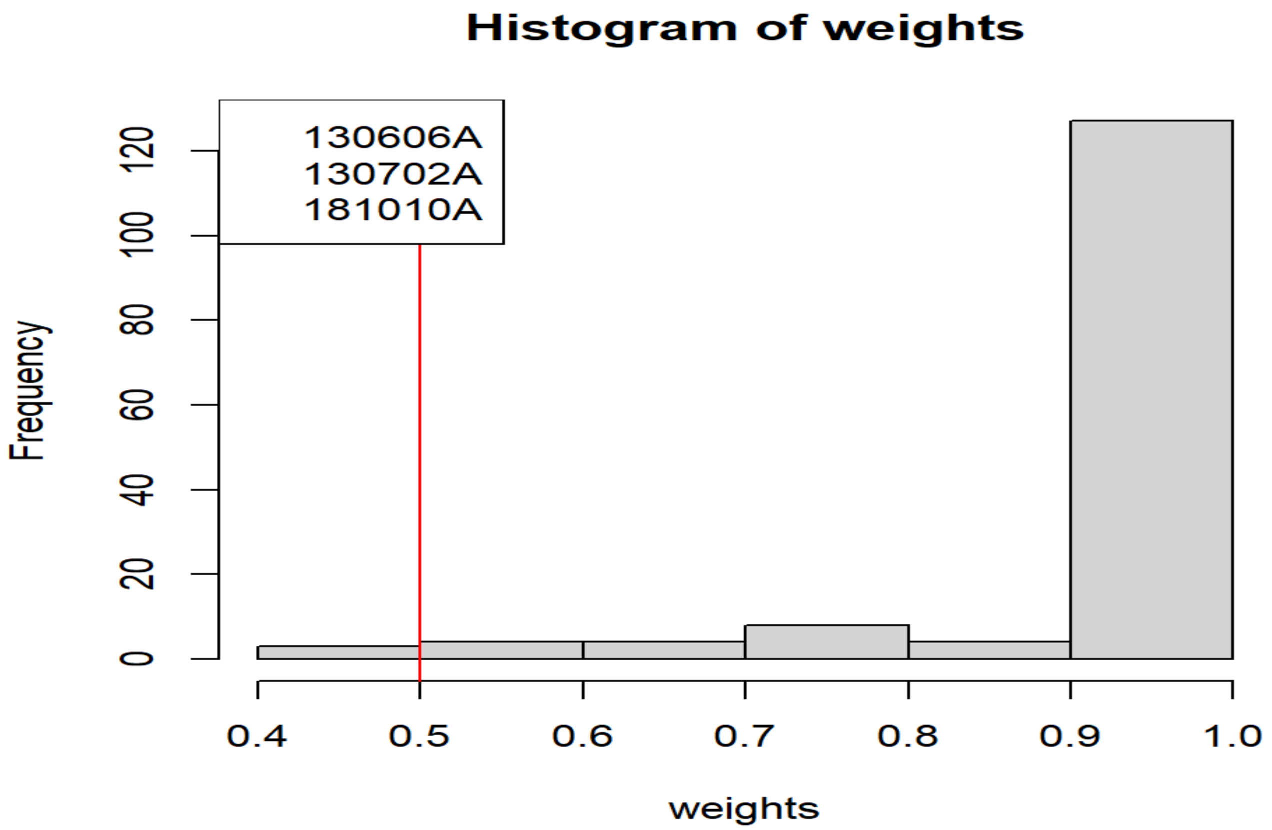
- This sample contains missing data as well





- 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!

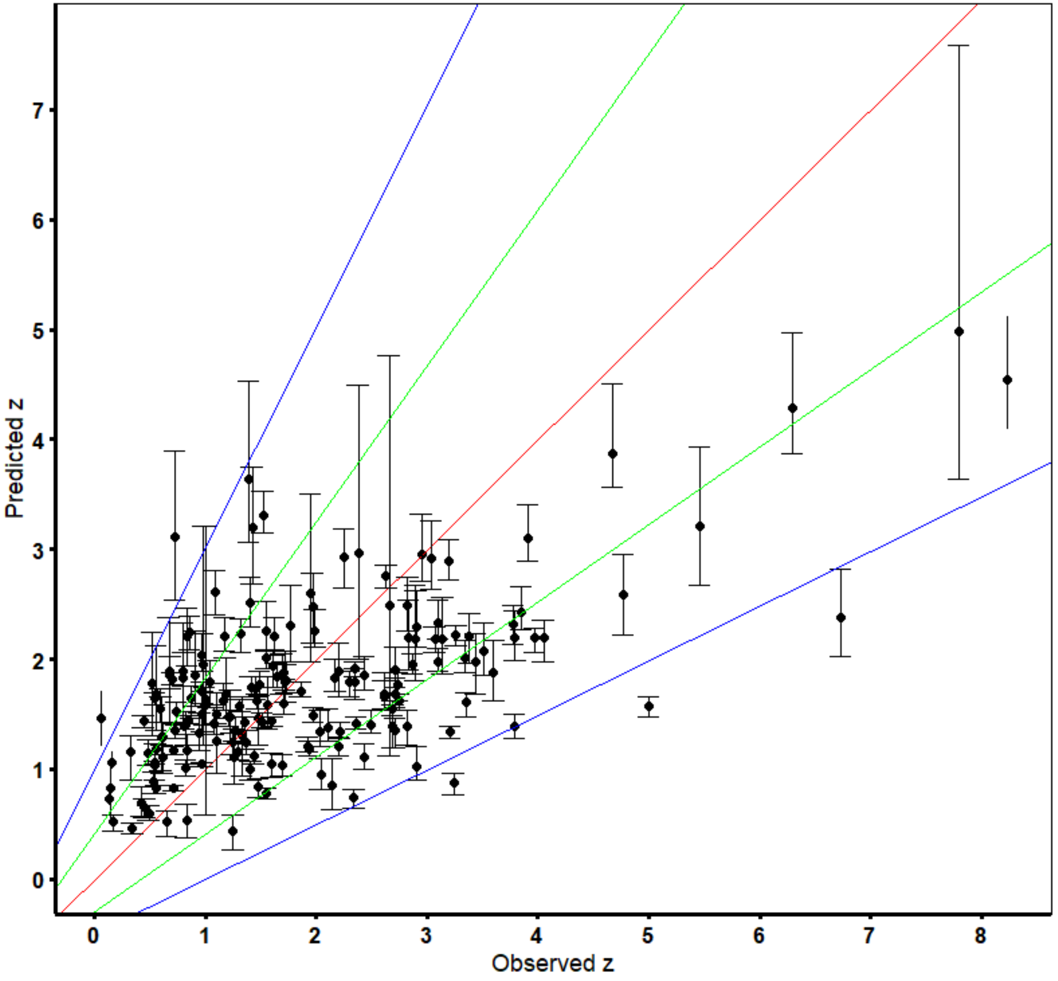
- We did test many other ML models, but these 4 obtained the highest weights by SuperLearner consistently
- For the results we perform ten-fold cross validation 100 times

Results From Superlearner:

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

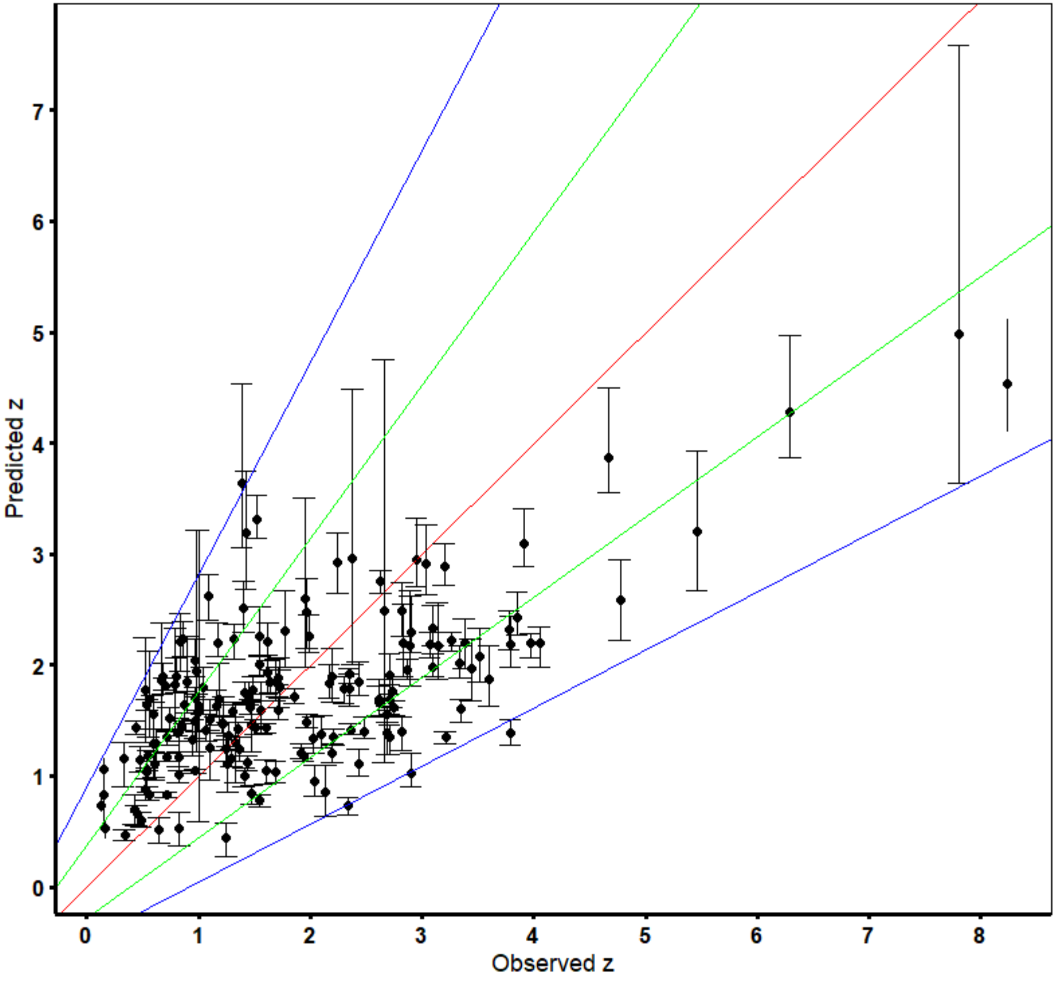
NMAD =(1/N) Median(|zi − z̄pred|),

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

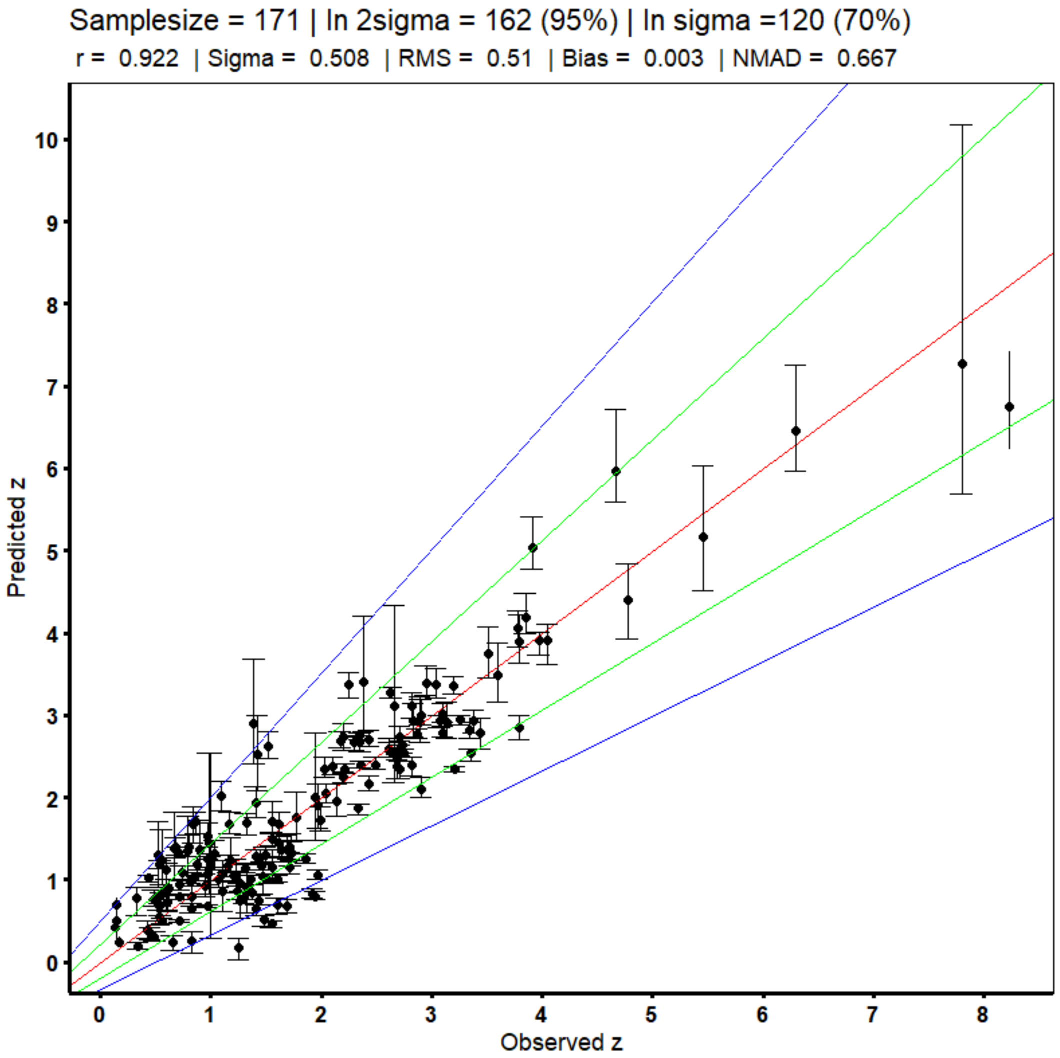


Remove outlier

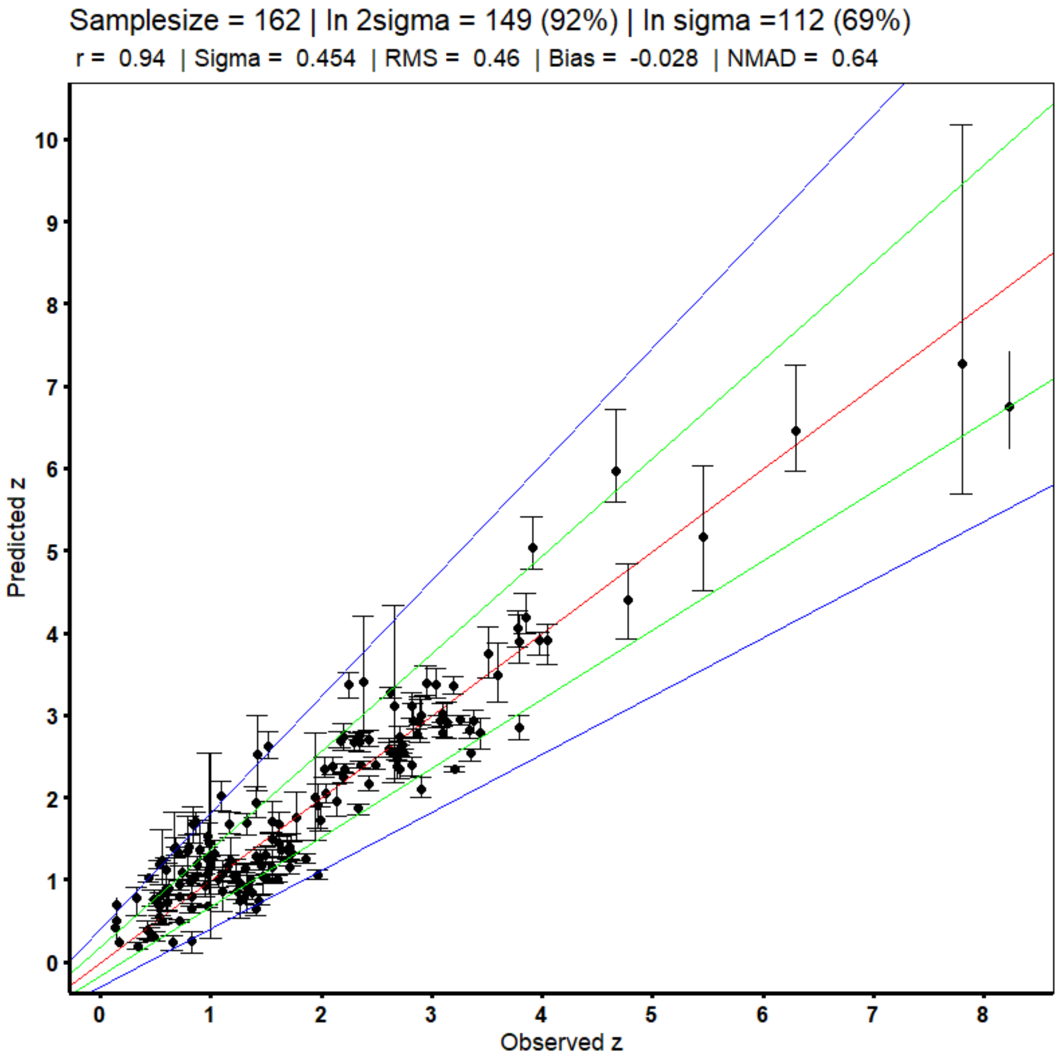
Samplesize = 171 | In 2sigma = 167 (98%) | In sigma =108 (63%)
r = 0.672 | Sigma = 0.971 | RMS = 0.98 | Bias = 0.14 | NMAD = 1.39



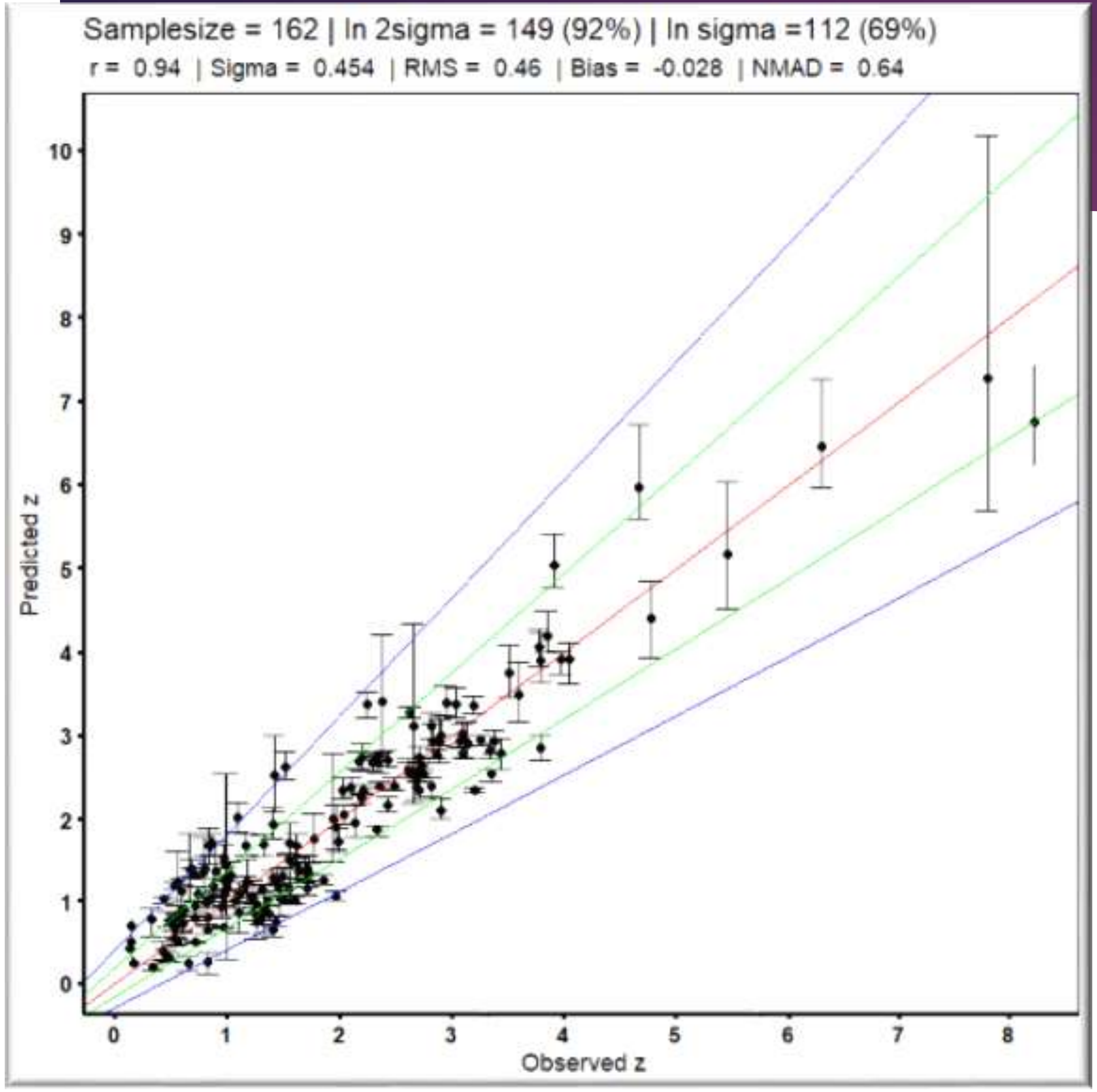
Results After Optimal Transport Bias Correction: to correct for biases



Remove outlier



Results After Optimal Transport Bias Correction:



For 162 GRBs:

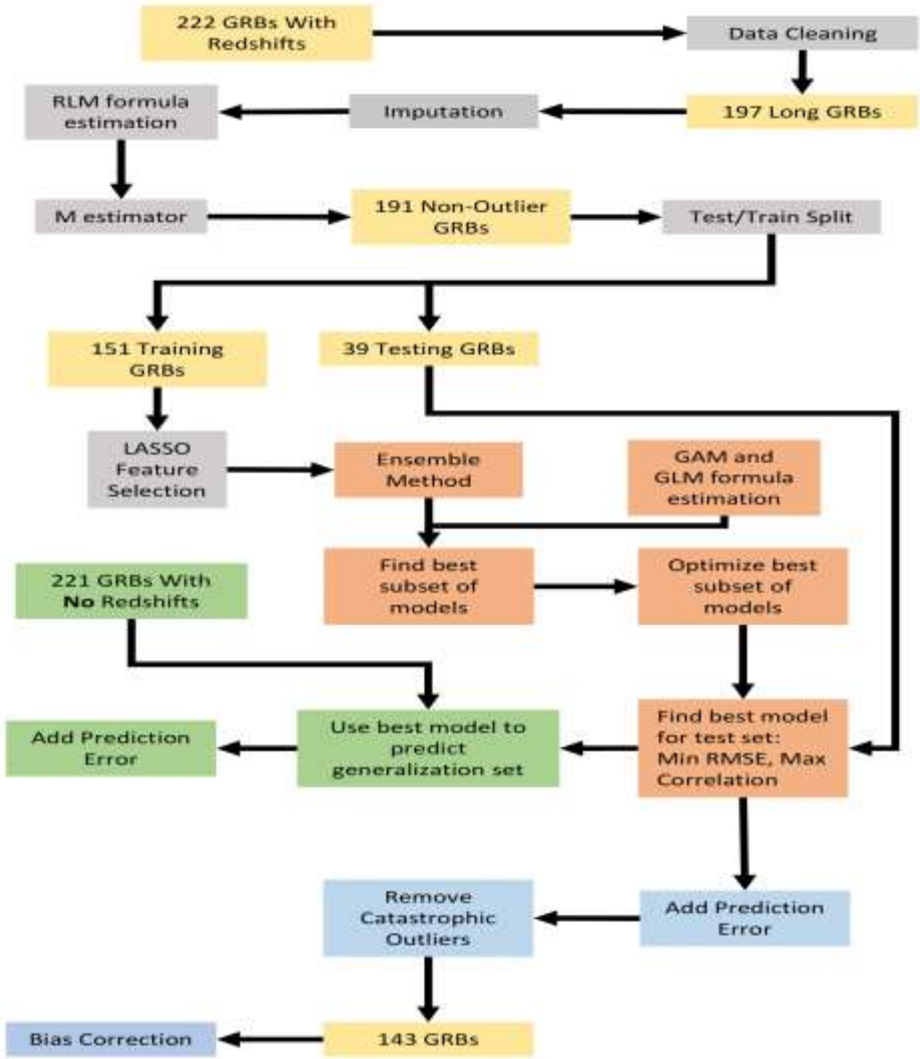
Pearson correlation= **0.94**

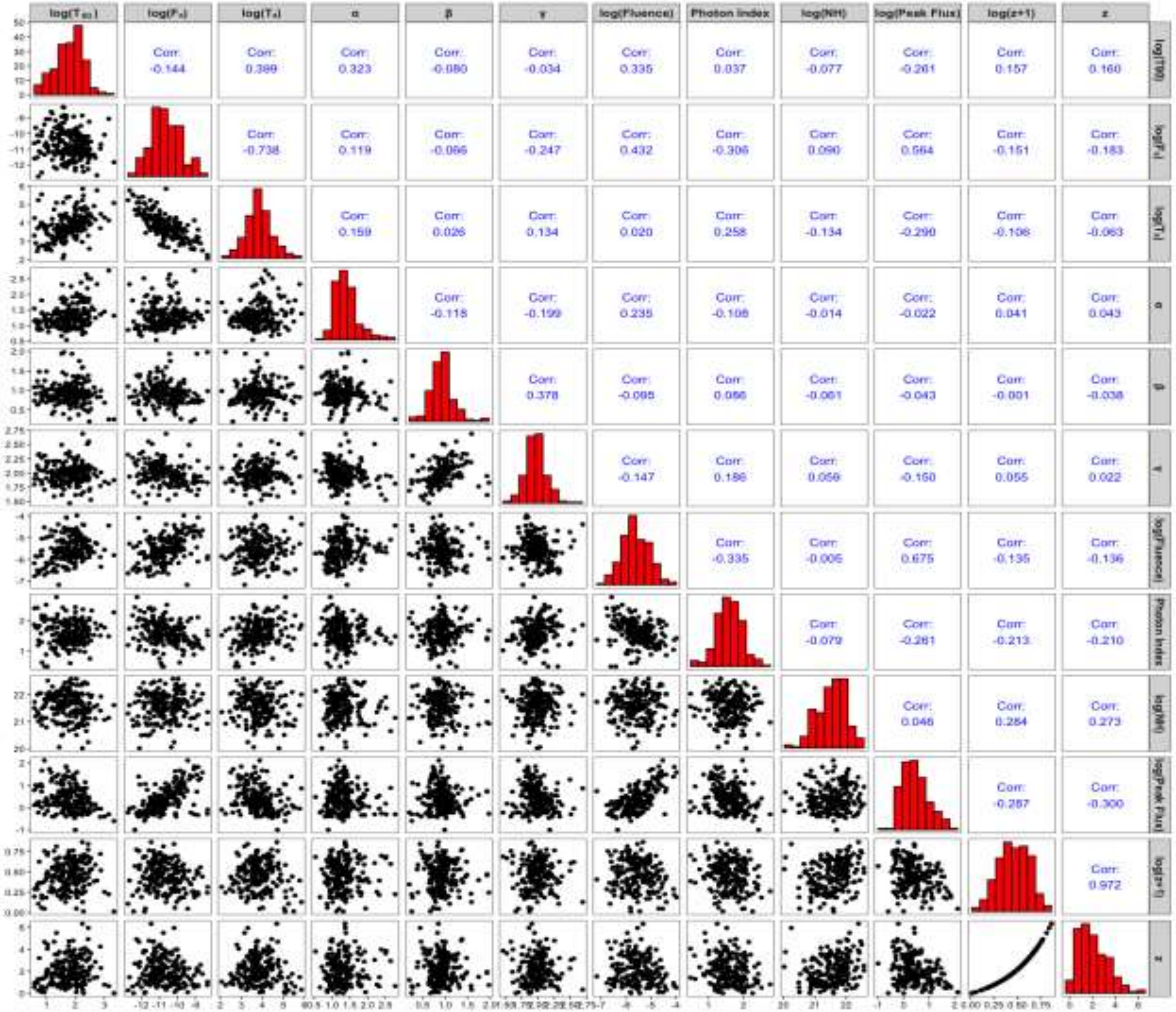
RMSE = **0.46**

Bias = **0.03**

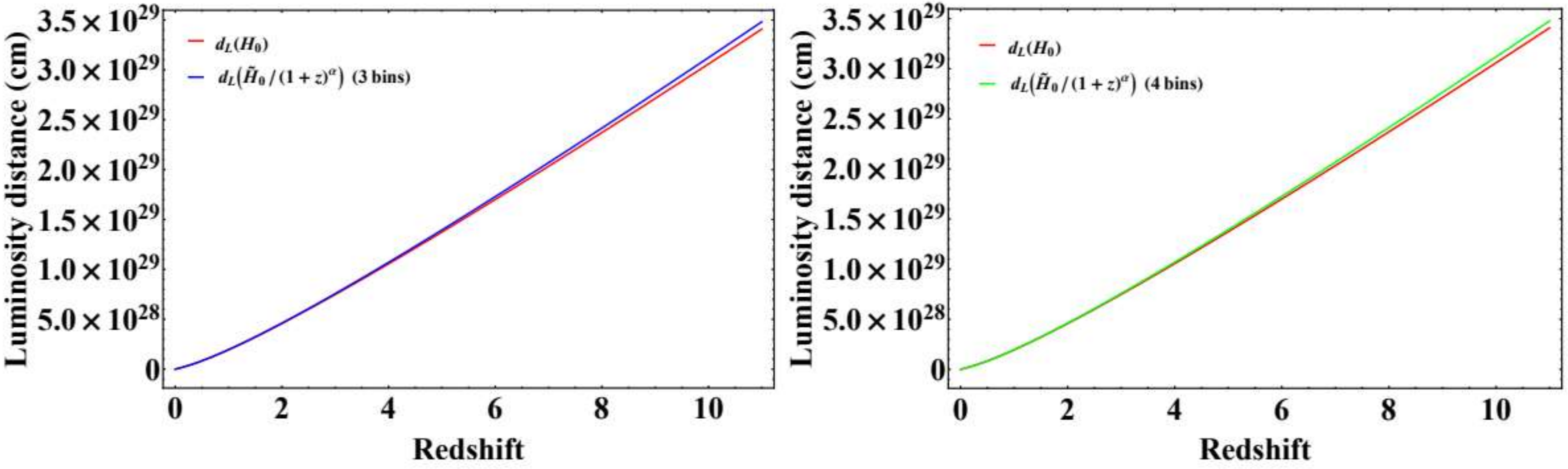
Comparing with Ukwatta et al. 2016, this is a **56% increase in Pearson correlation**

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





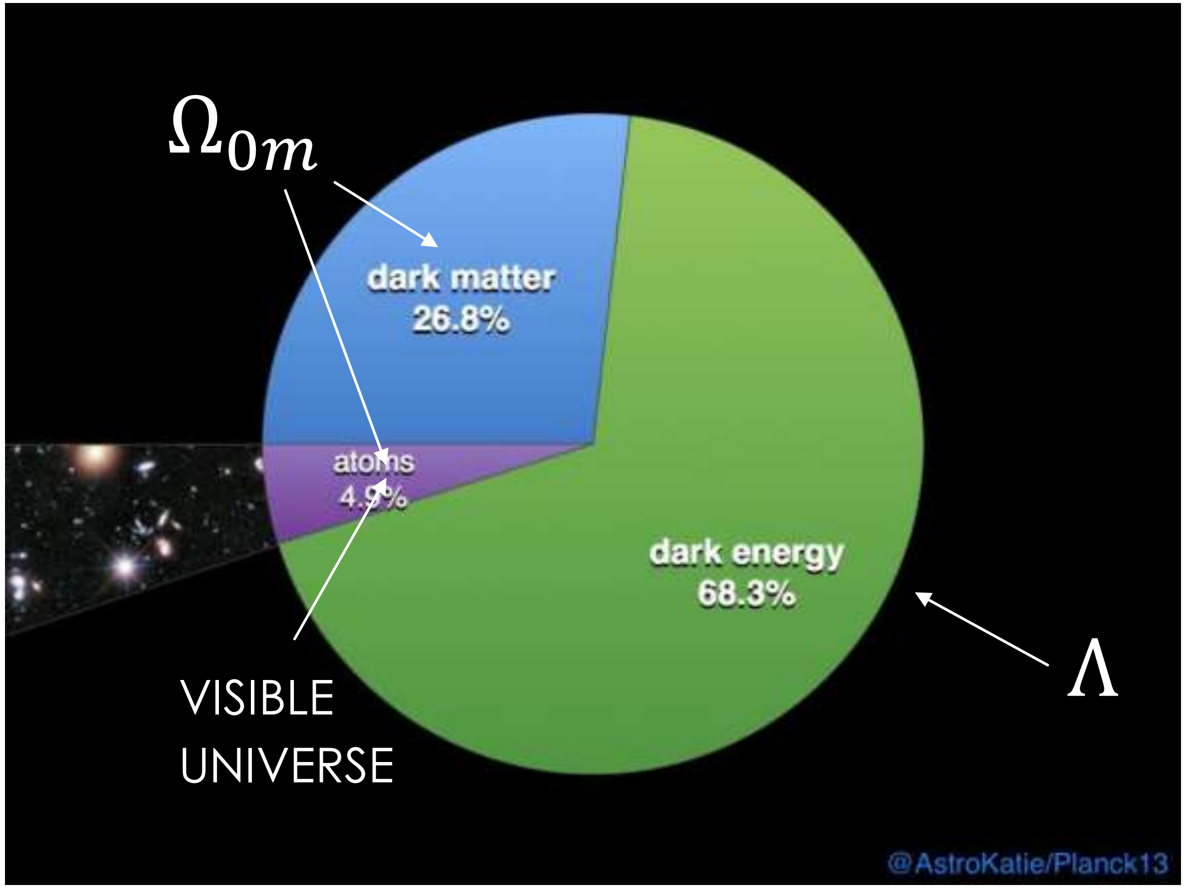
The correction to the luminosity distance



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?

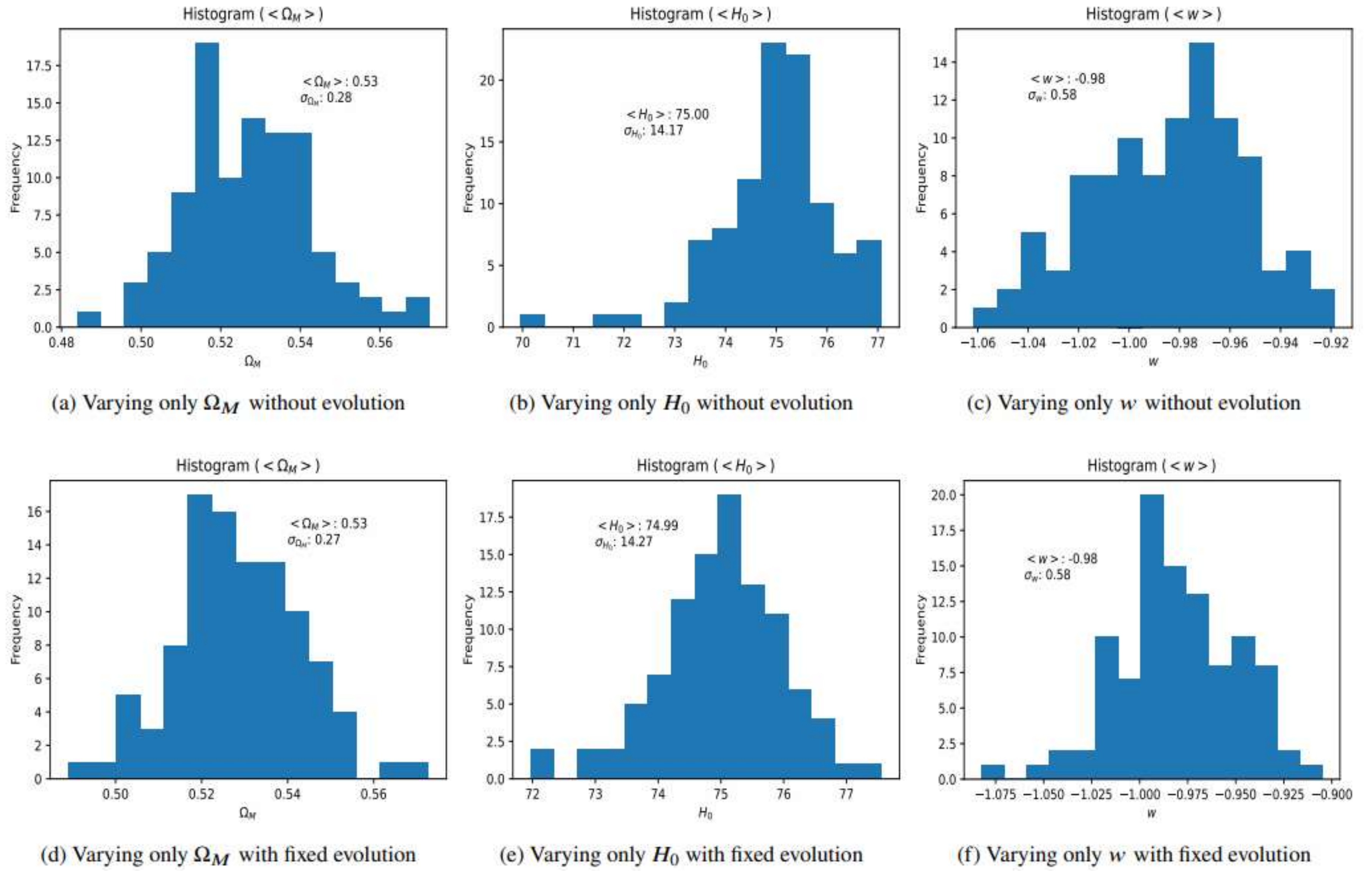
What can we investigate with GRBs, SNe Ia, Quasars and BAO?



Open problems: the so-called Hubble tension

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

The 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

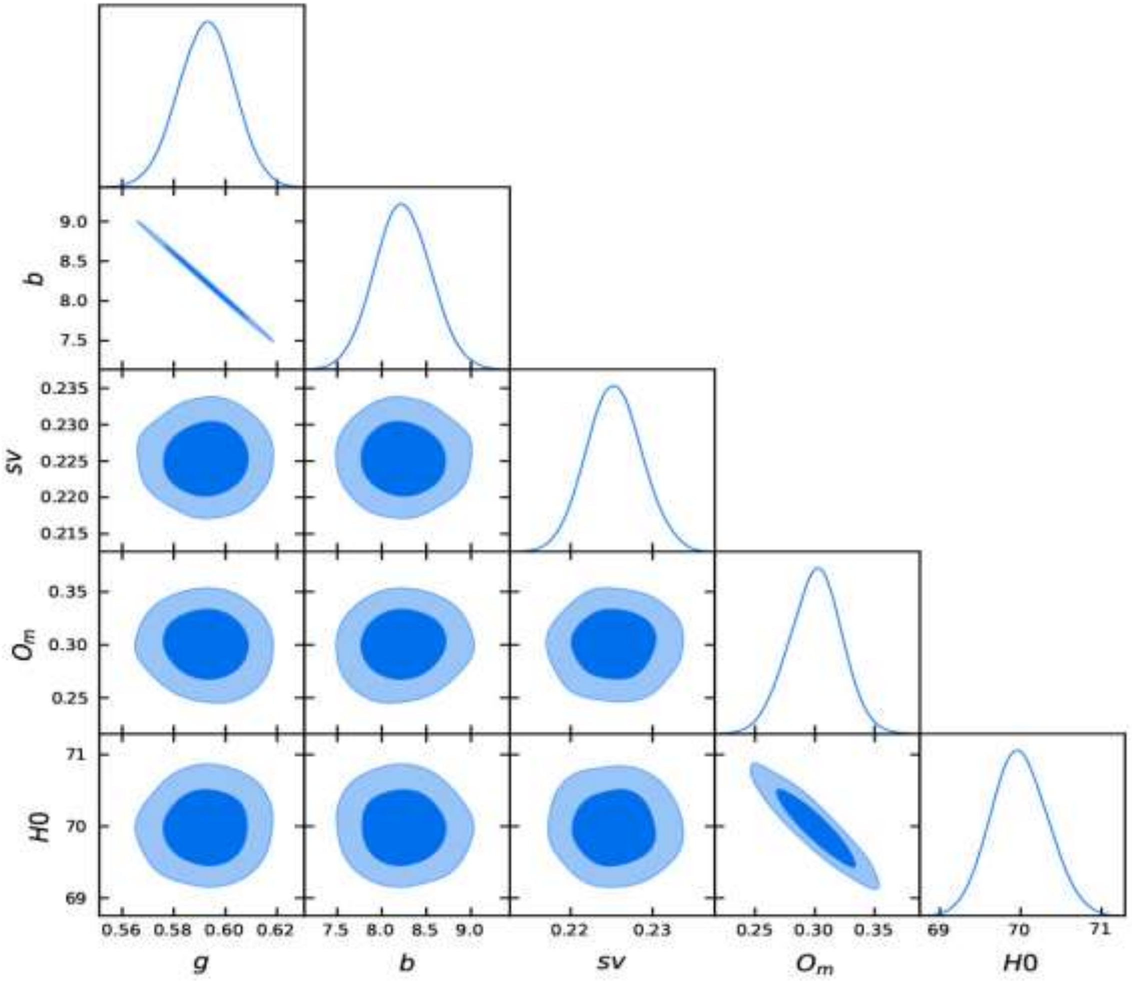
(e) Varying only H_0 with fixed evolution

(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



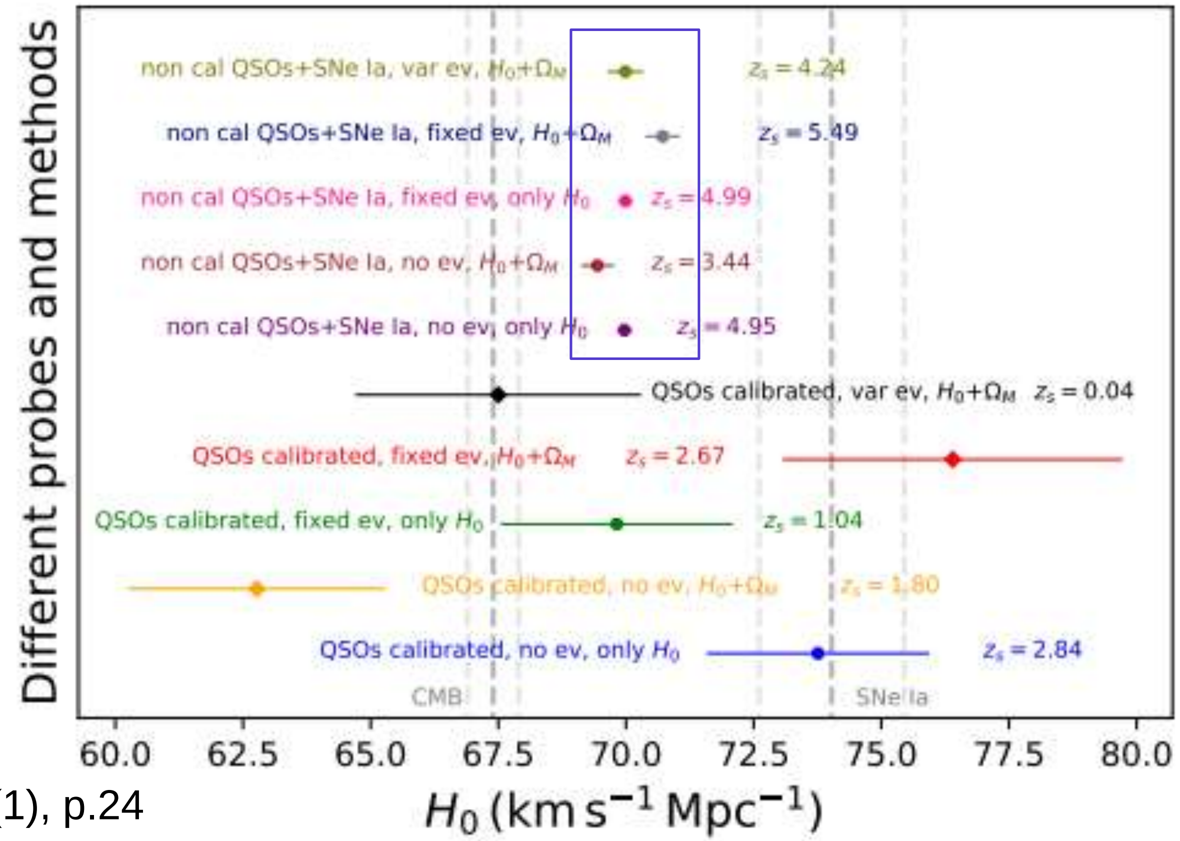
What happens to the tension?

“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

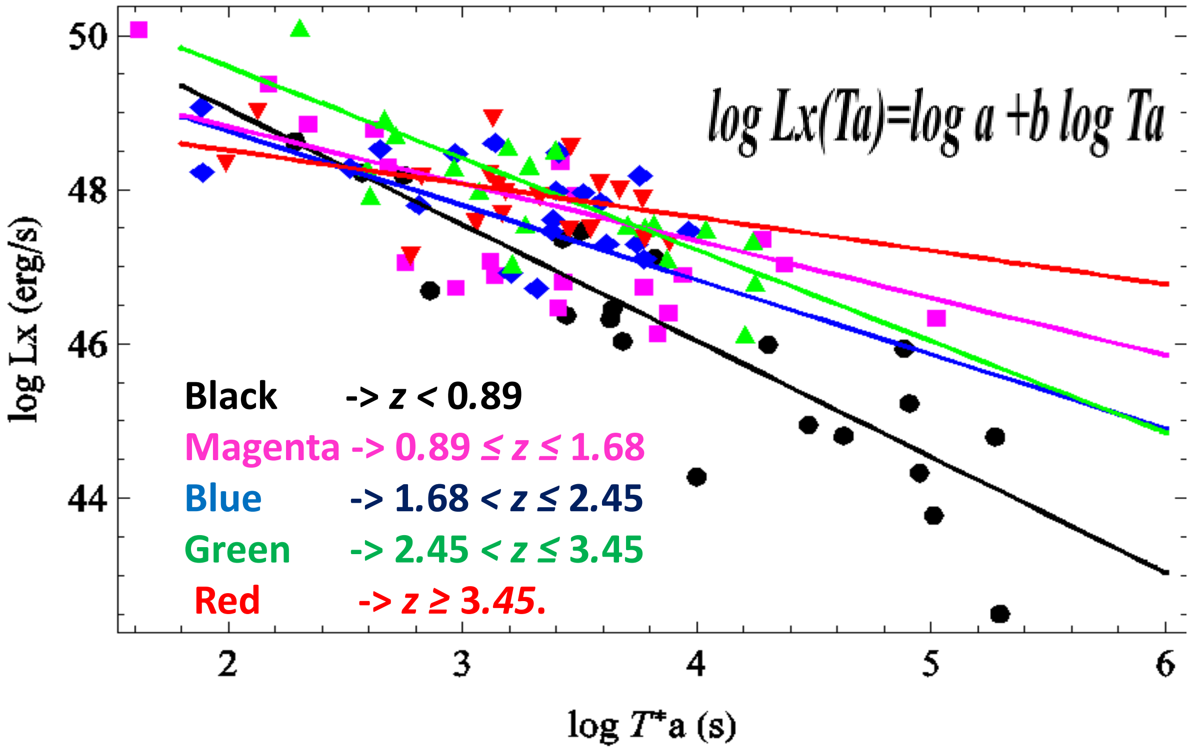
Tension due to an evolution of H_0 with redshift or a constant value that stands between the one of SNe and CMB?

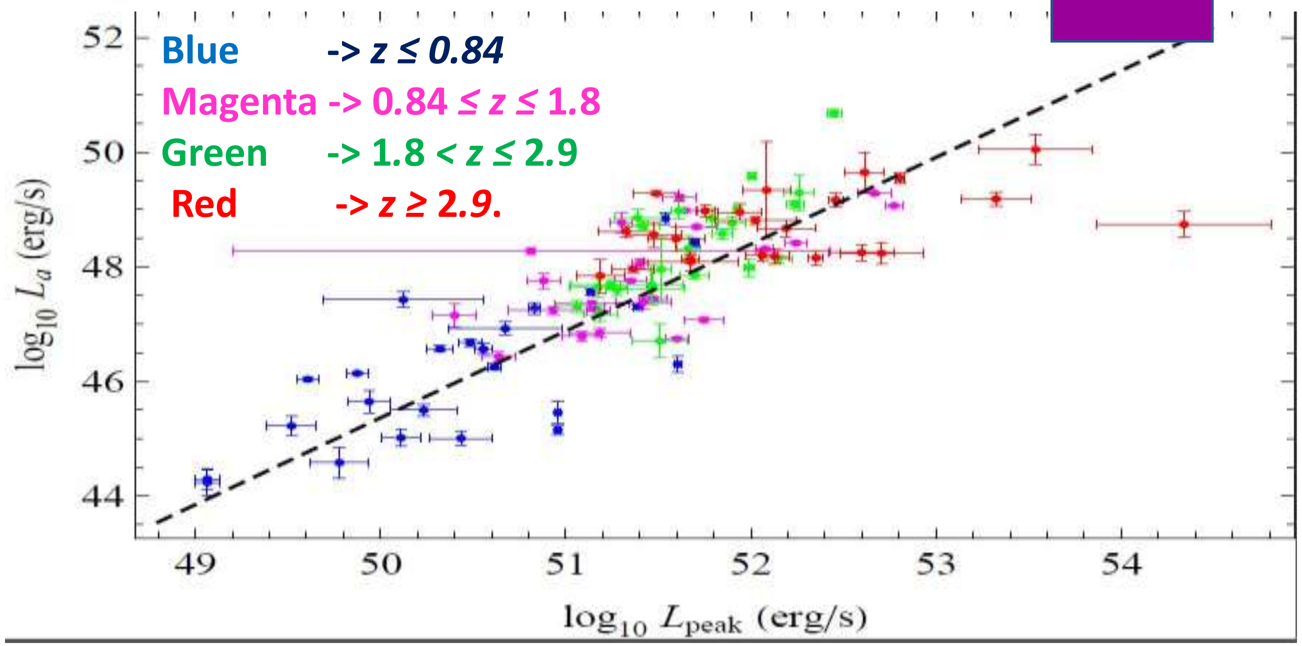


See:
"On the evolution of the Hubble constant with the SNe Ia Pantheon sample and baryon acoustic oscillations: a feasibility study for GRB-cosmology in 2030", Dainotti, M.G. et al. 2022, Galaxies 10(1), p.24

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

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





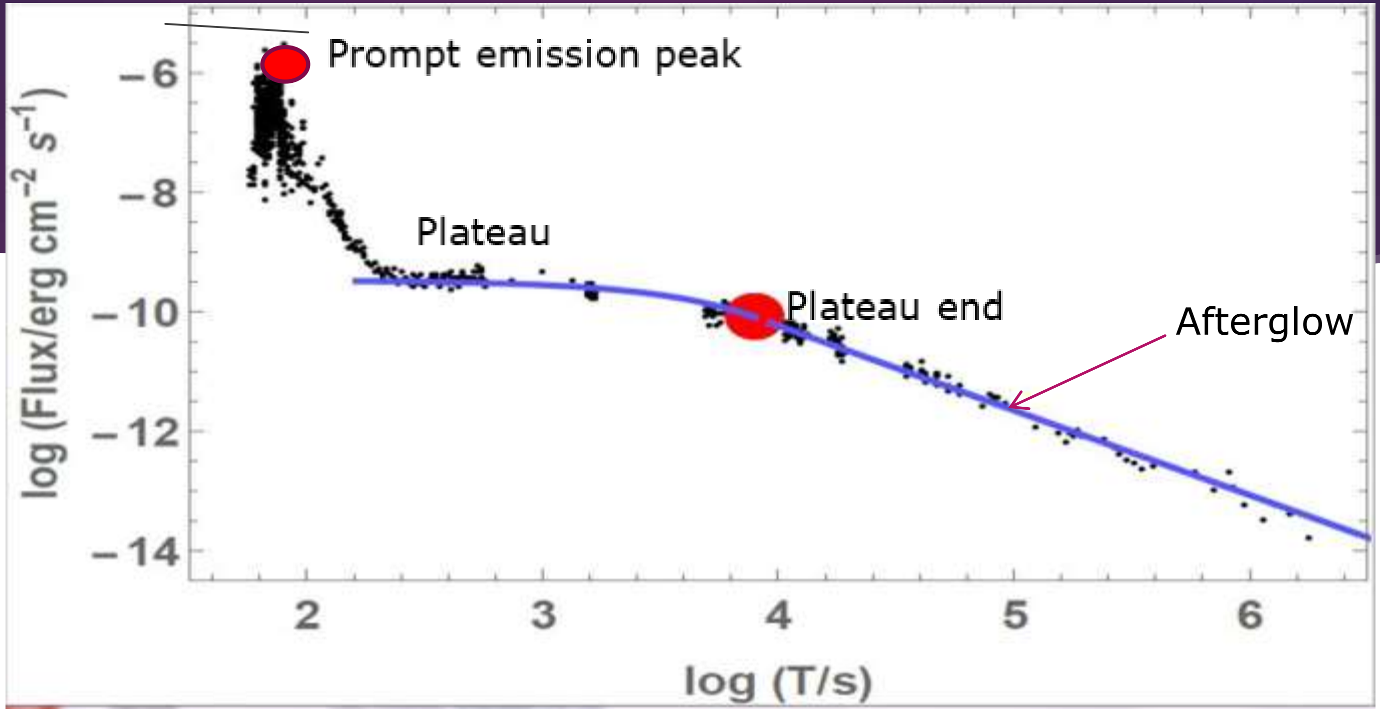
Log Lx(Ta)= log A +B log Lpeak

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.**

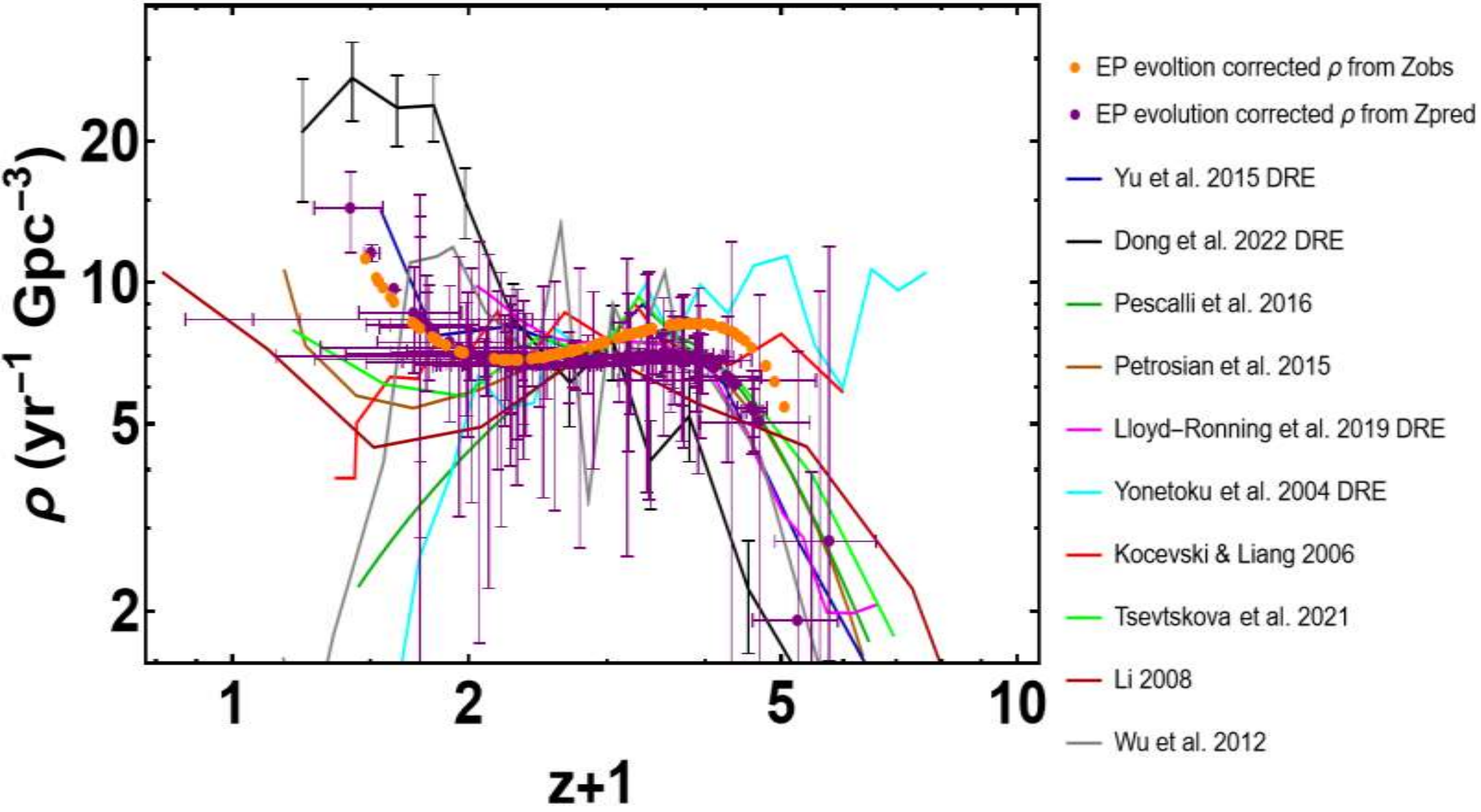
GRB phenomenology

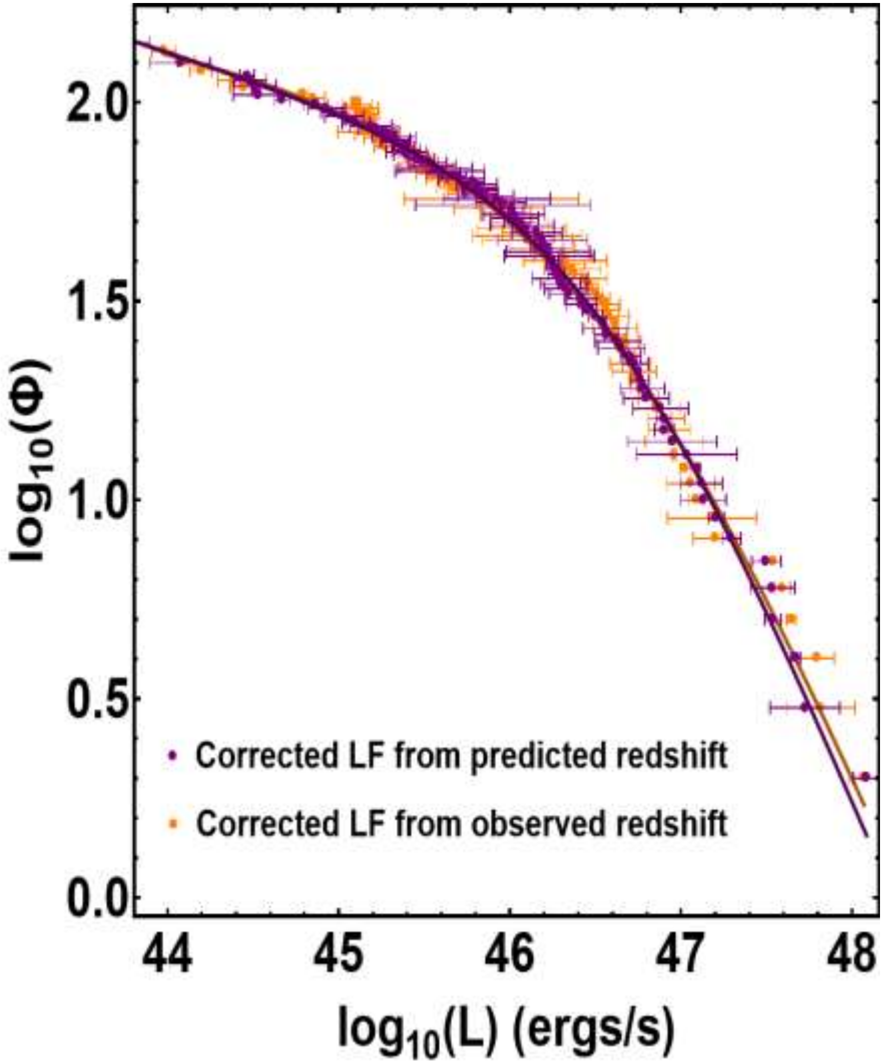


Important features of a well-sampled GRB light curve observed by Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing). The blue line is the phenomenological Willingale model (R. Willingale et al. 2007)

- **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.**

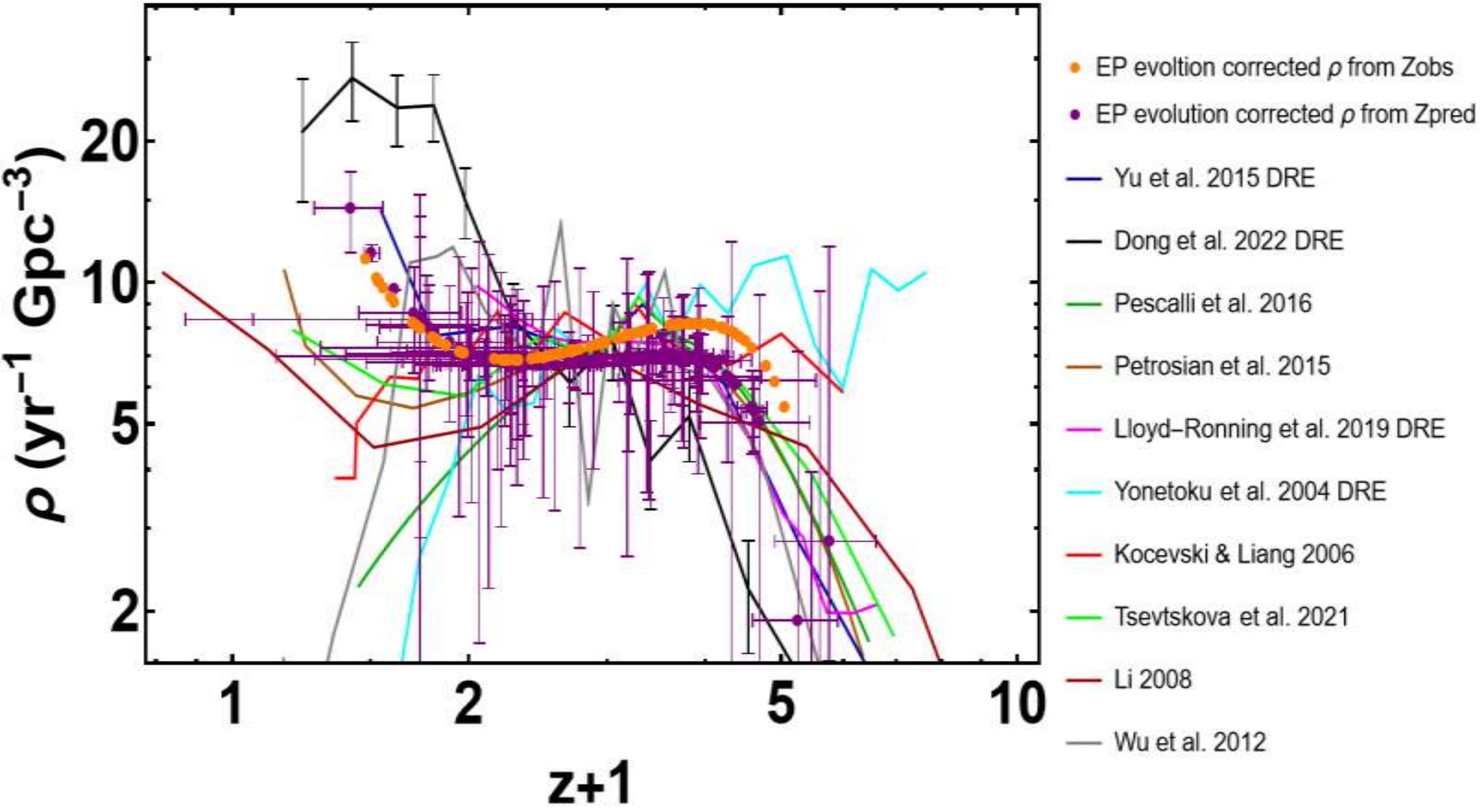
Density rate evolution and luminosity function:

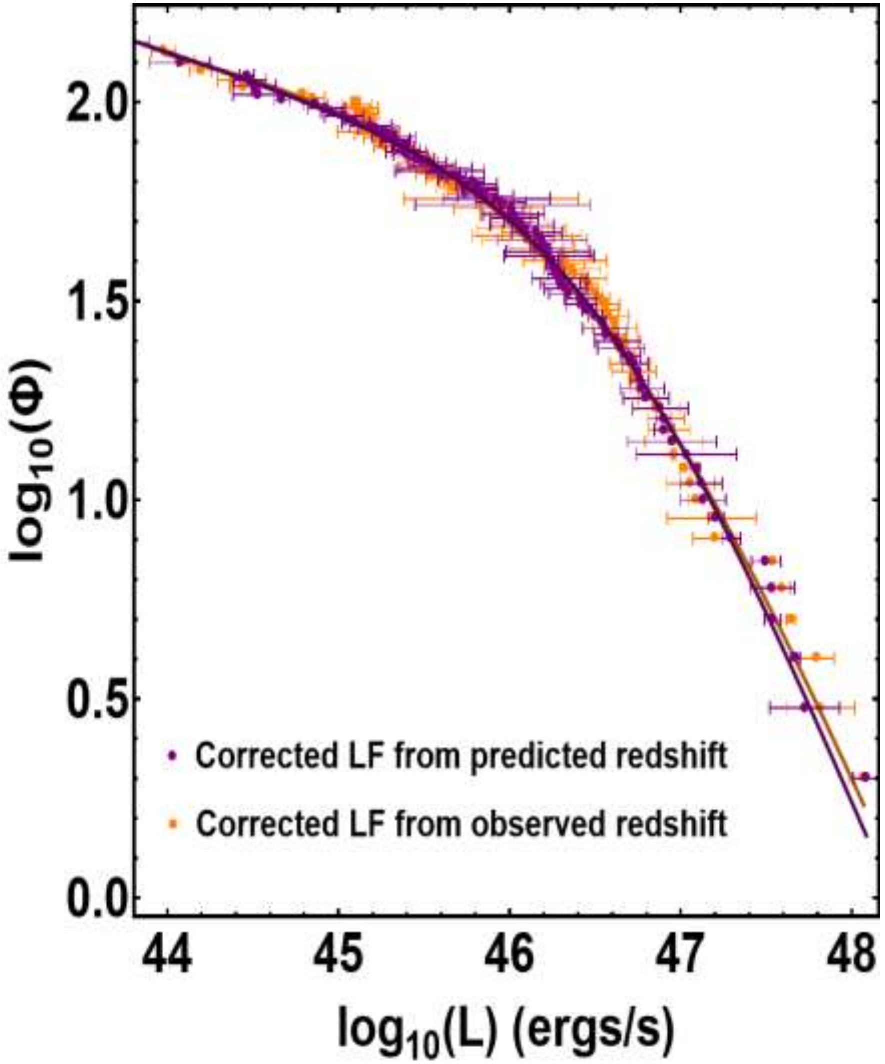




- The blue points in both pictures represent the LF and DRE derived using Zobs.
- The red points in both pictures represent the LF and DRE derived using Zpred.
- The orange and purple show the selection bias corrected density rate evolution for Zobs and Zpred respectively.

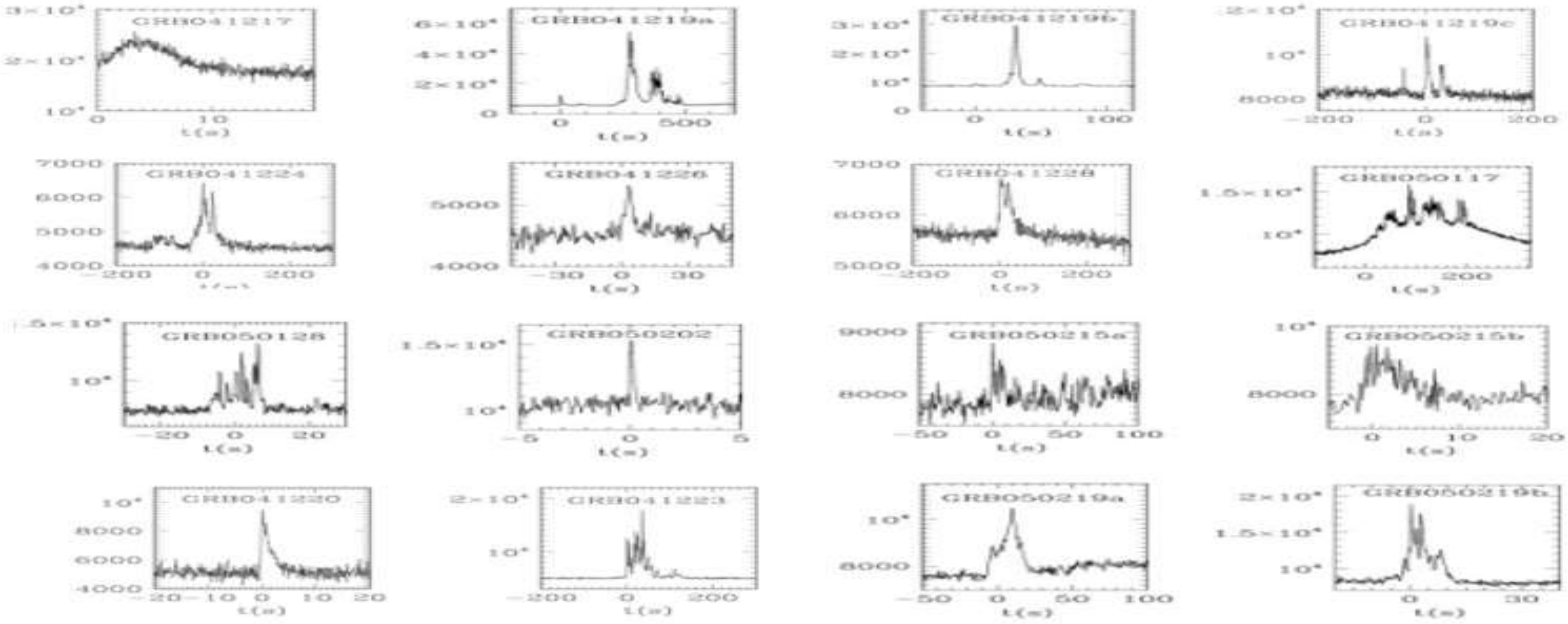
Density rate evolution and luminosity function:





- 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.

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?

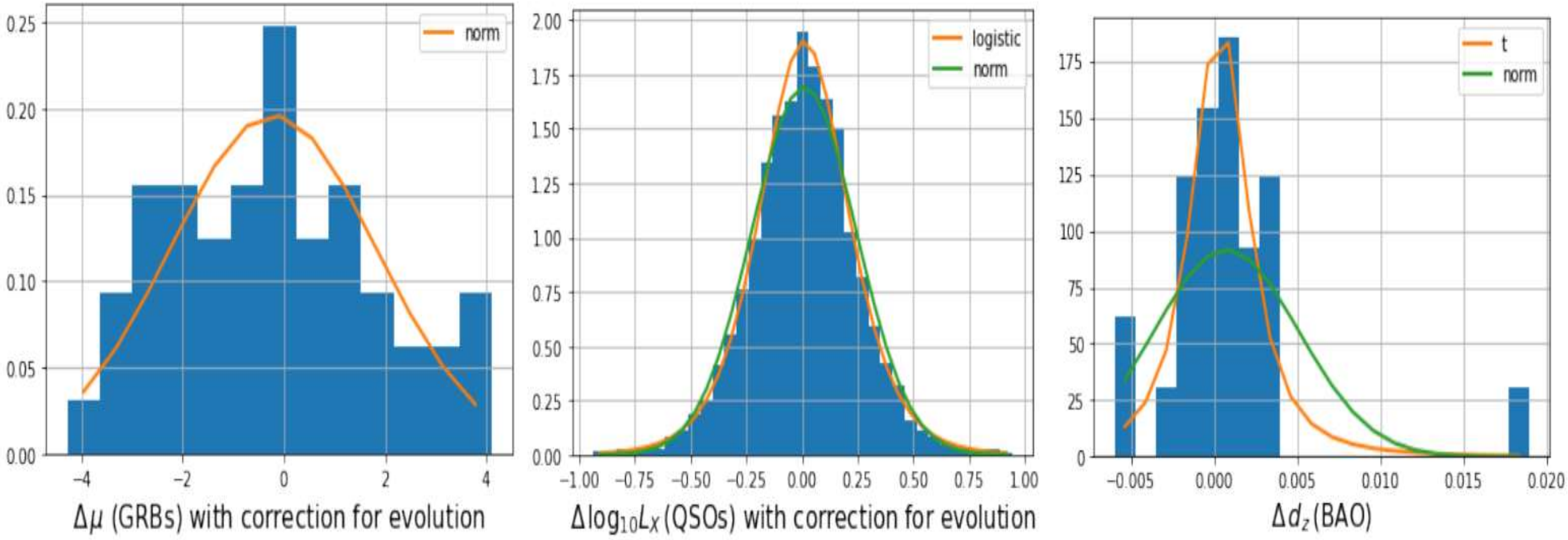
Because They…

- 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

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

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

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

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.

Thank you for your attention!

maria.dainotti@nao.ac.jp

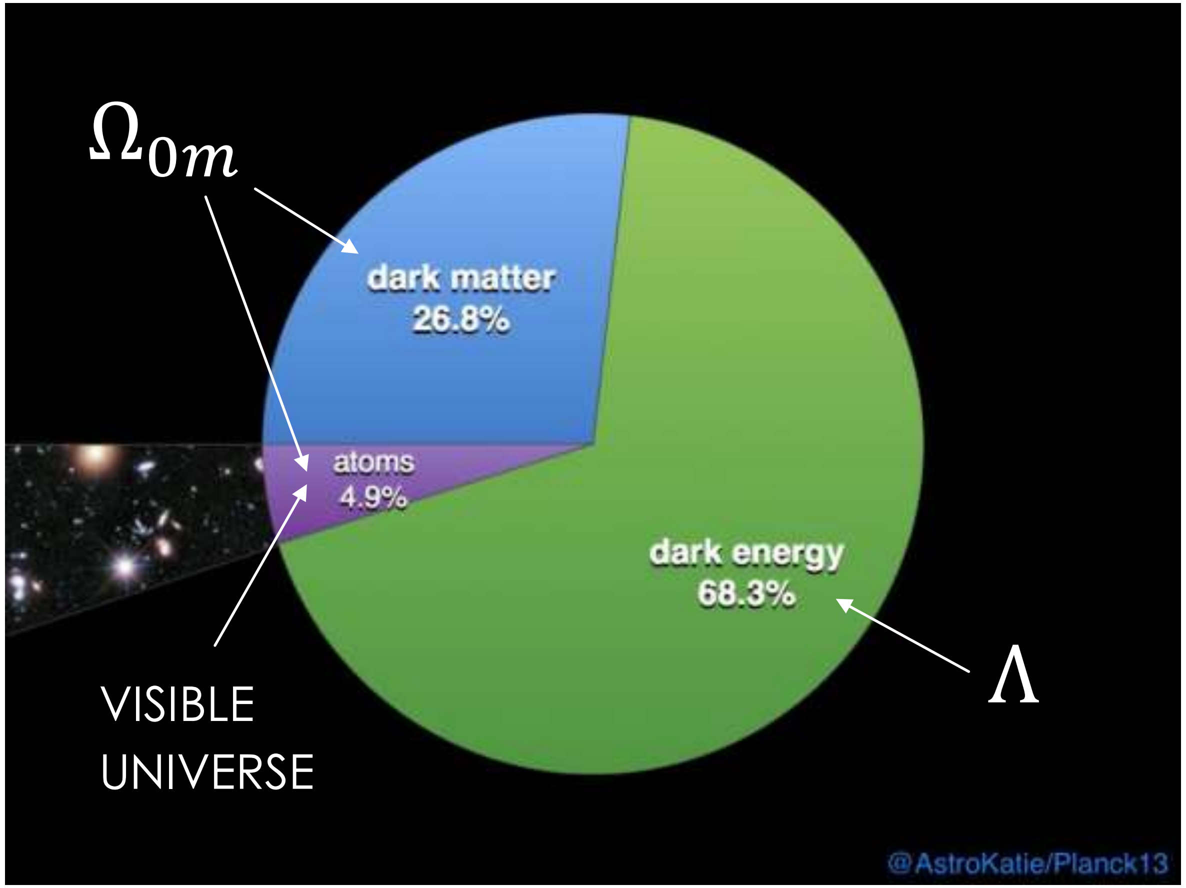
mariagiovannadainotti@yahoo.it

The motivation behind the plateau emission

- Magnetars, accretion onto black hole models (already mentioned in Van Eerten, Asaf, Mei etc)
- Additional references for the magnetar model (Stratta, Dainotti et al. 2018, Rowlinson, Dainotti et al. 2014, Rea et al. 2015)
- A low Γ, Husne-Dereli et al. 2022.
- Take away: "the Afterglow is easier" – Bing Zhang in the panel discussion
- Thus, more suited for standard candle!

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»

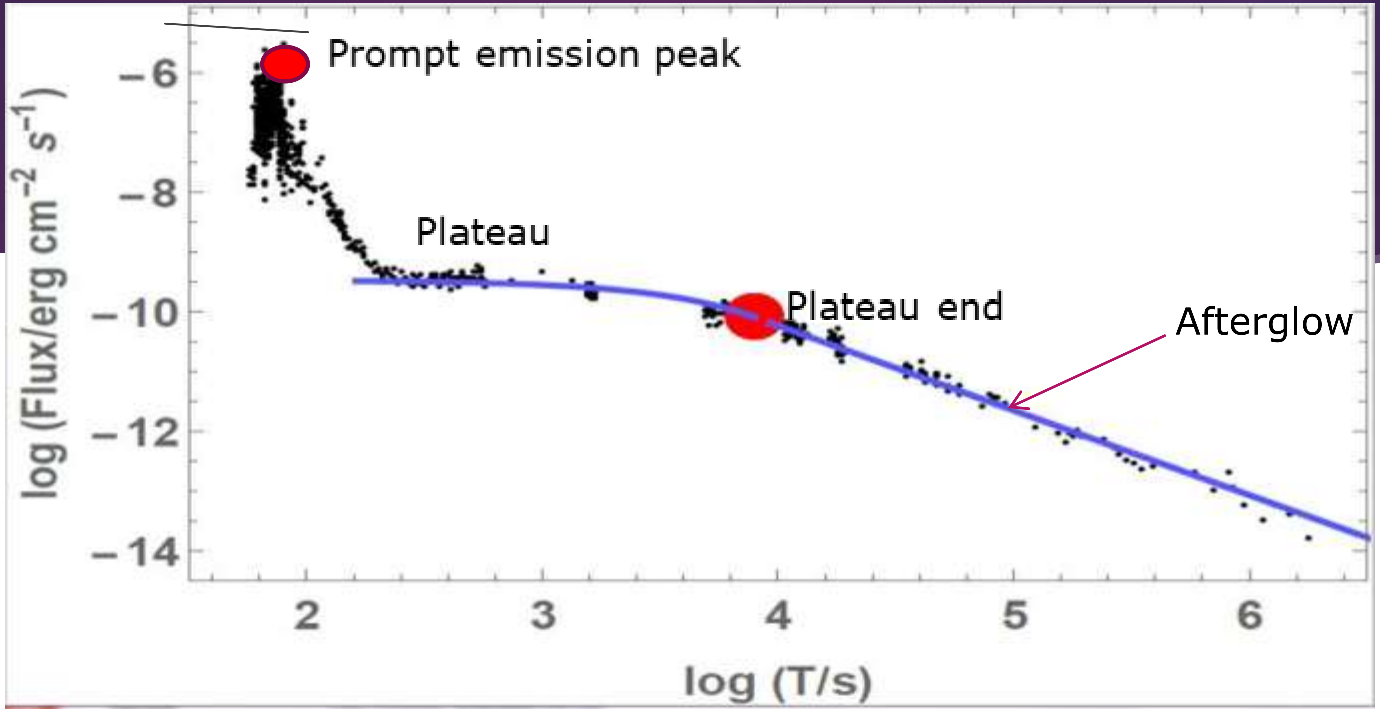
Ω_{0m} DESCRIBES THE TOTAL MATTER DENSITY (DARK MATTER + BARYONS) OF THE UNIVERSE

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

GRB phenomenology



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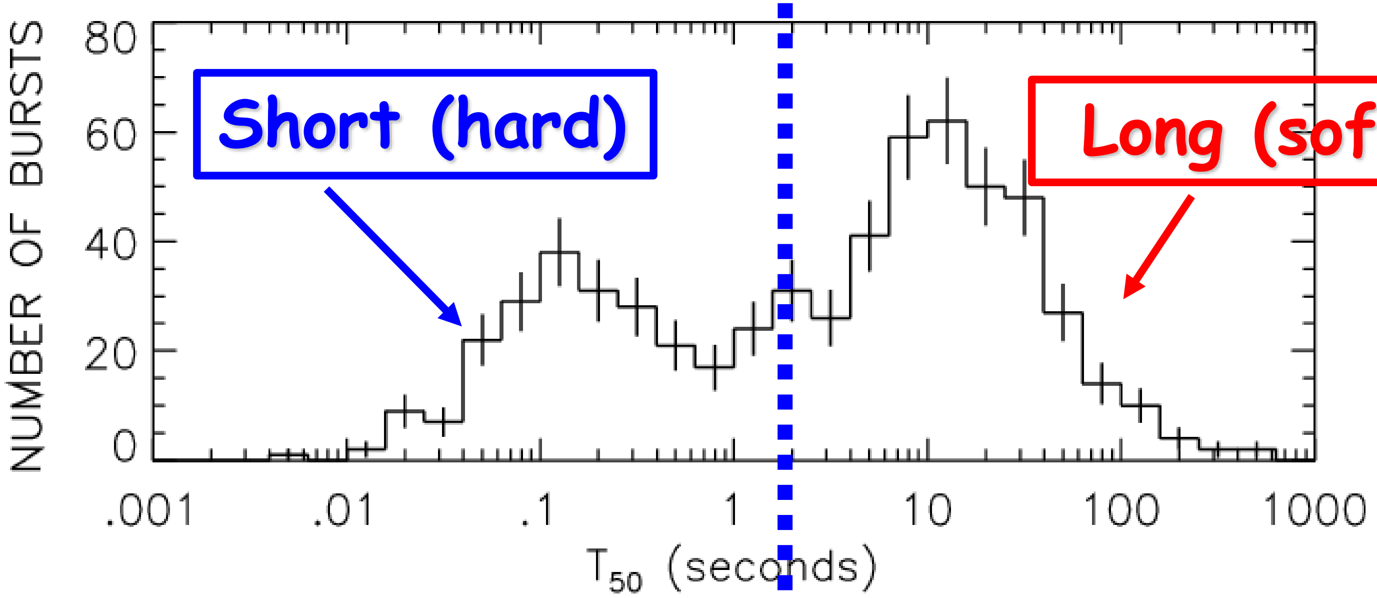
- X-rays, optical and radio observed after days/months (afterglows), distinct from the main γ-rays.

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?

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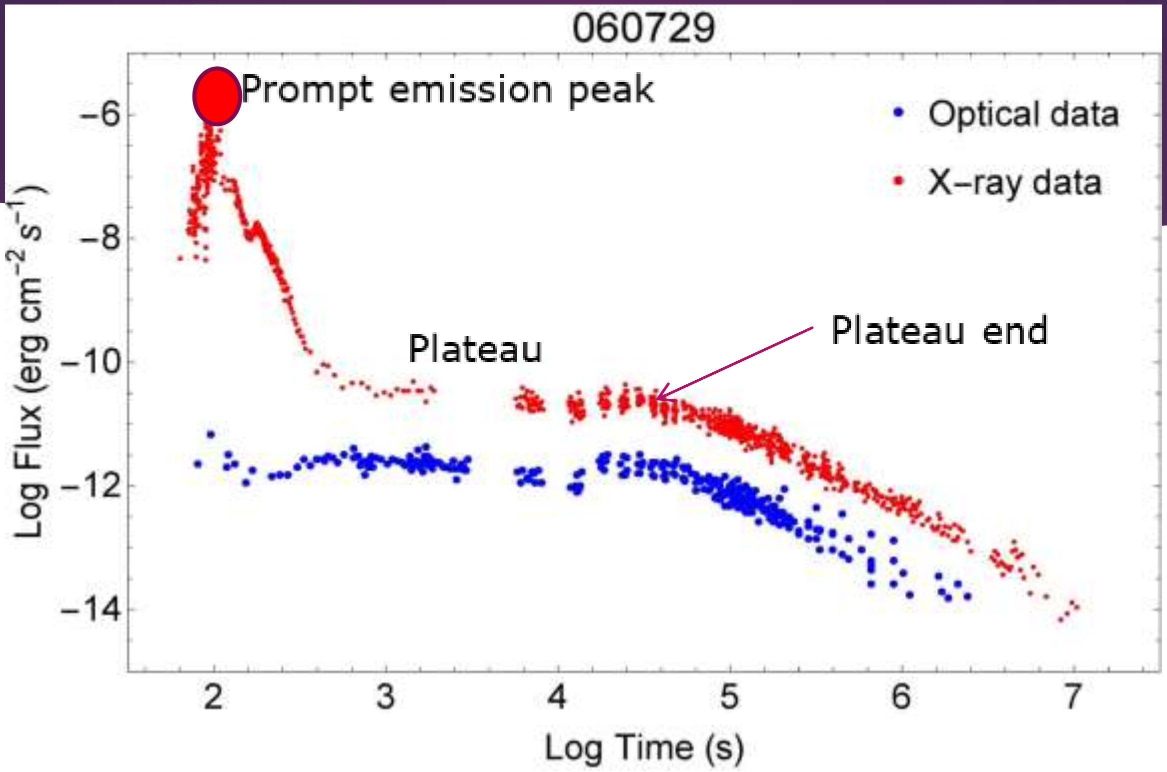
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than SN Ia (z=2.26) and quasars (z=7.54).

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.

GRB standard plateau features

Standard is good!



Burst Alert Telescope+ X-Ray Telescope+UVOT from Swift.

Dainotti, Livermore, Kann, Li, Oates, Yi, Zhang, Gendre, Cenko, Fraija 2020, ApJL, 905, 26.

- 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?

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

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

Update numbers compared to previous work in Srinivasaragavan, Dainotti et al. 2020 with Dainotti et al. in preparation: from 01.2005-02/2024: 255 GRBs with known redshift out of 427 (60%) and 299 with unknown redshifts from 01.2005-02/2024.

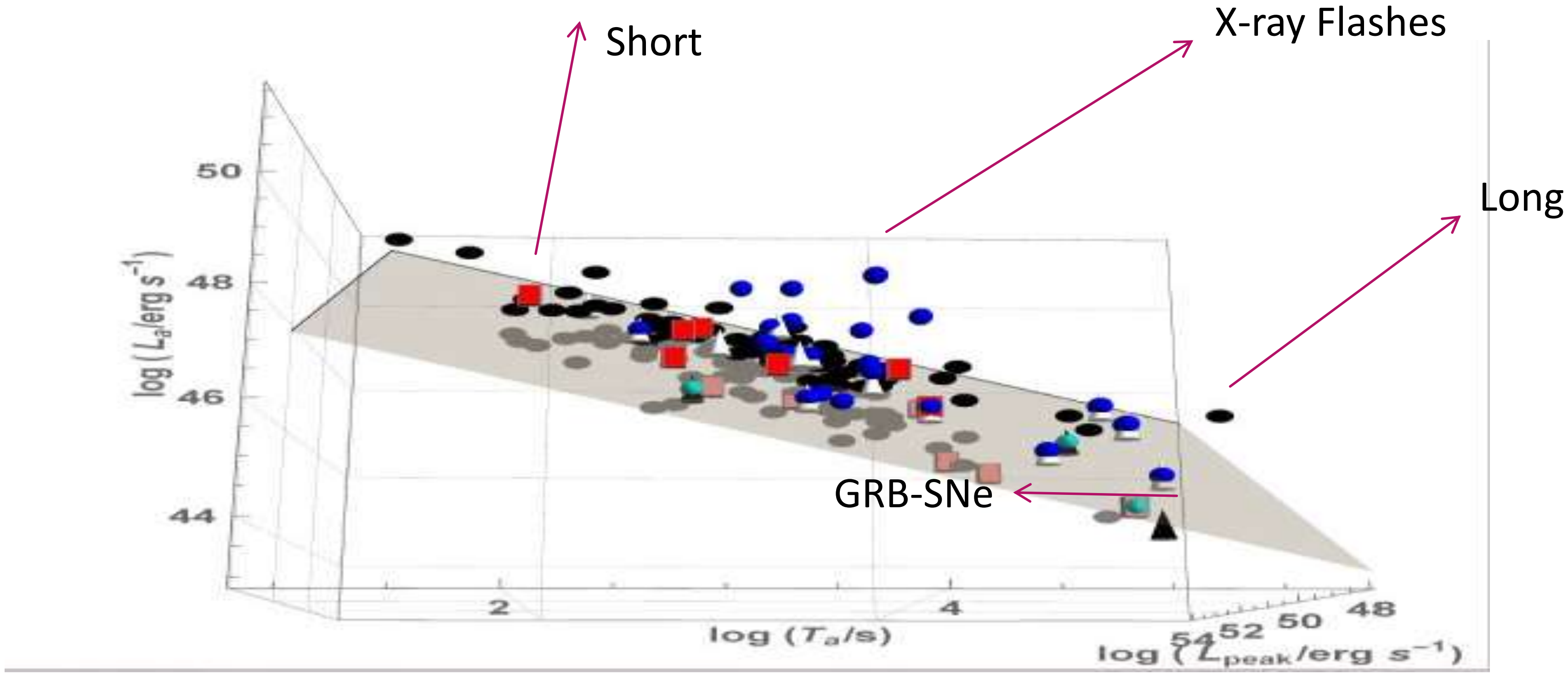
Dainotti 2D and Oates relation LaX - T*aX & LaX-LpX confirming the reliability after bias correction	Dainotti 3D relation (Lax - T*ax - Lpx) (reliable after bias correction)	Dainotti 2D and 3D relation in radio and optical (probing these to be unbiased relation)
2008 2010 2011 2015	2016 2017	2020 2021 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

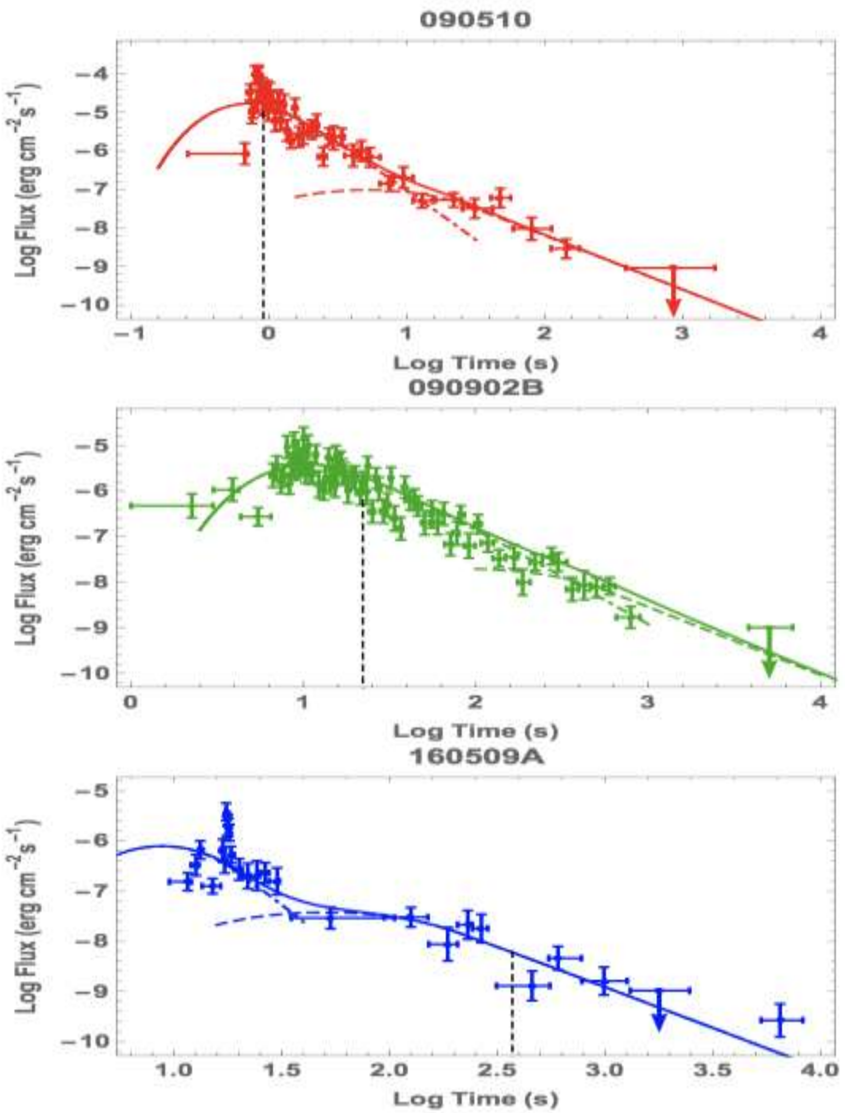
- the 3D Lpeak-Lx-Ta correlation **is intrinsic** and it has a reduced scatter, σ_{int} of 24 %.

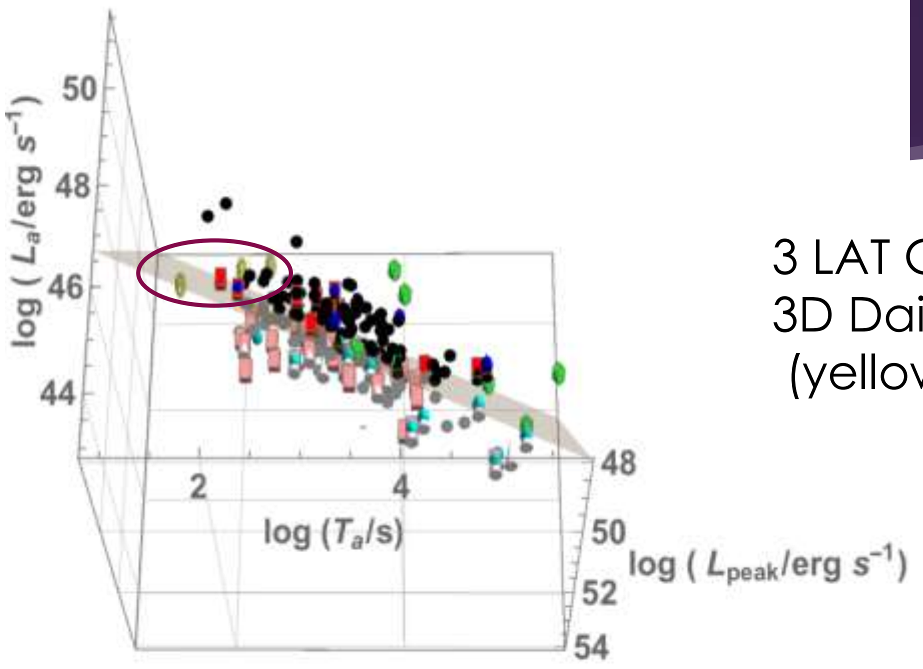


The plateau emission in γ-rays (CAT II)

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

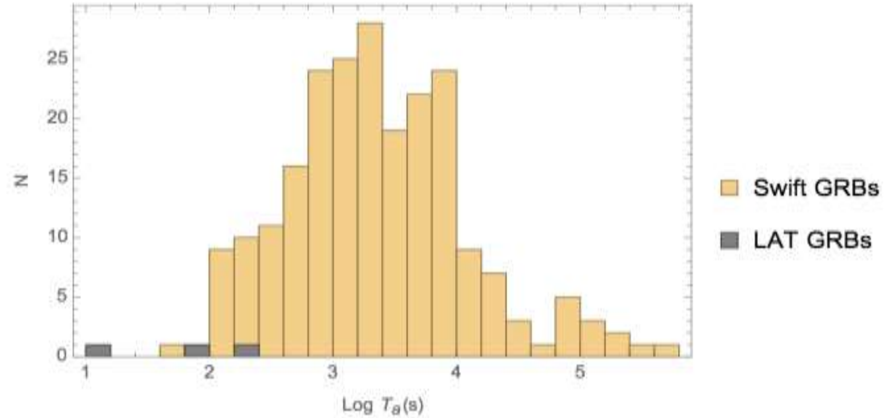
Spin-off paper of the work in the second GRB catalog





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

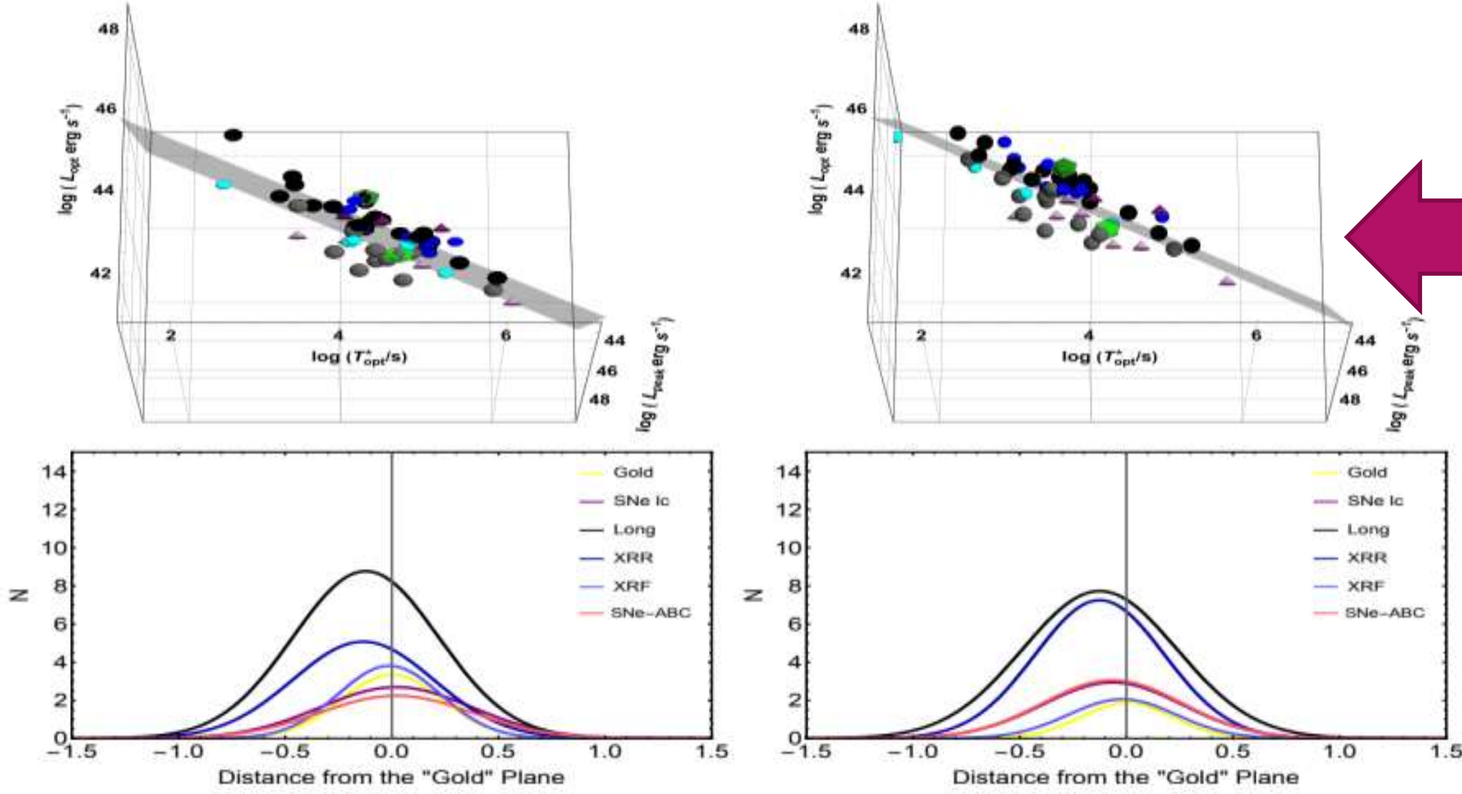


Figure 5. Upper panels: 58 GRBs in the $L_{opt}^{(\prime)} - T_{opt}^{(*/\prime)} - L_{opt}^{(\prime)}$ parameter space with the fitted plane parameters in Table 2, including LGRBs (black circles), SGRBs (red cuboids), GRB-SNe Ic (purple cones), XRFs and XRRs (blue spheres), and ULGRBs (green icosahedrons). 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

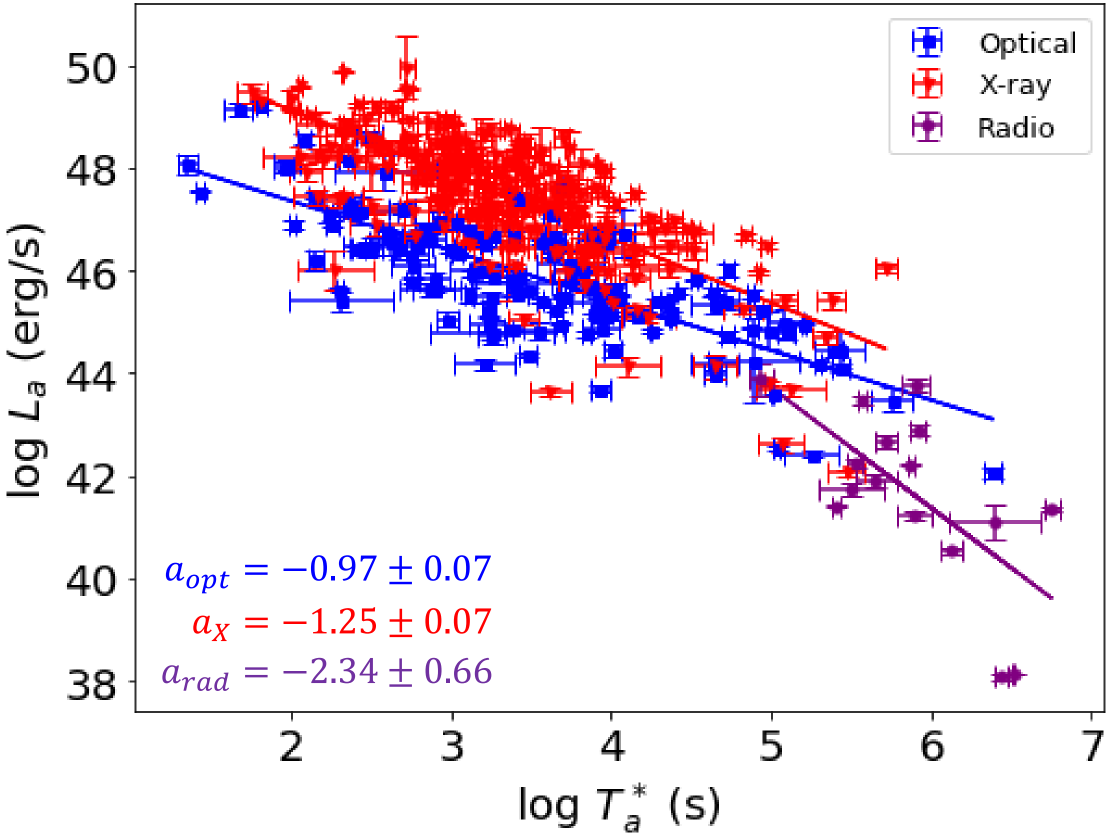
- **Long=31**
- **Gold→ 6**
- **XRF=4**
- **XRR=19**
- **GRB-SNe Ib/c-> 9**
- **SNe Ib/c (ABC)->7**

COMPARING CORRELATIONS IN WAVELENGTHS

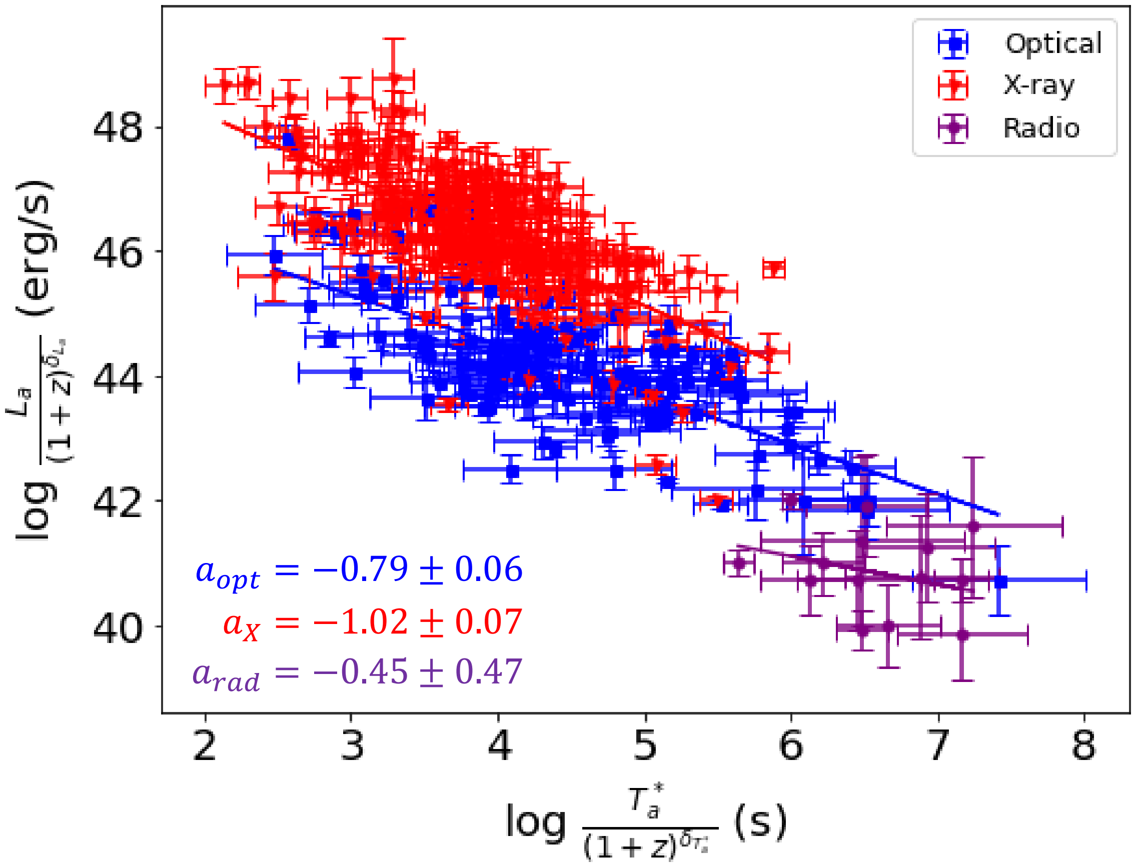
Levine, Dainotti et al. ApJL,925, 15, 2022

Dainotti et al. 2021, Galaxies,

NOT CORRECTED



CORRECTED



The fundamental plane relation for new classes: Ambushing the standard candle in its own nest

Dainotti, Lenart, Sarracino, Nagataki, Capozziello & Fraija 2020, ApJ, 904, issue 2, 97, 13

- **The platinum sample:** a subset of the gold sample obtained after removing gold GRBs with at least one of the following features:
  - Tx is inside a large gap of the data, and thus has a large uncertainty.
  - A small plateau duration <500 s with gaps after it. This could mean that the plateau phase is longer than the one observed.
  - Flares and bumps at the start and during the plateau phase.
  - It reduces the scatter of 31%.

Press release distributed by the AAS, issued by Jagiellonian, Space Science Institute, and by INAF (Italian National Astrophysics Institute) and interview by INAF.

The fundamental plane relation for new classes

Dainotti et al. 2020, ApJ, 904, issue 2, 97, 13

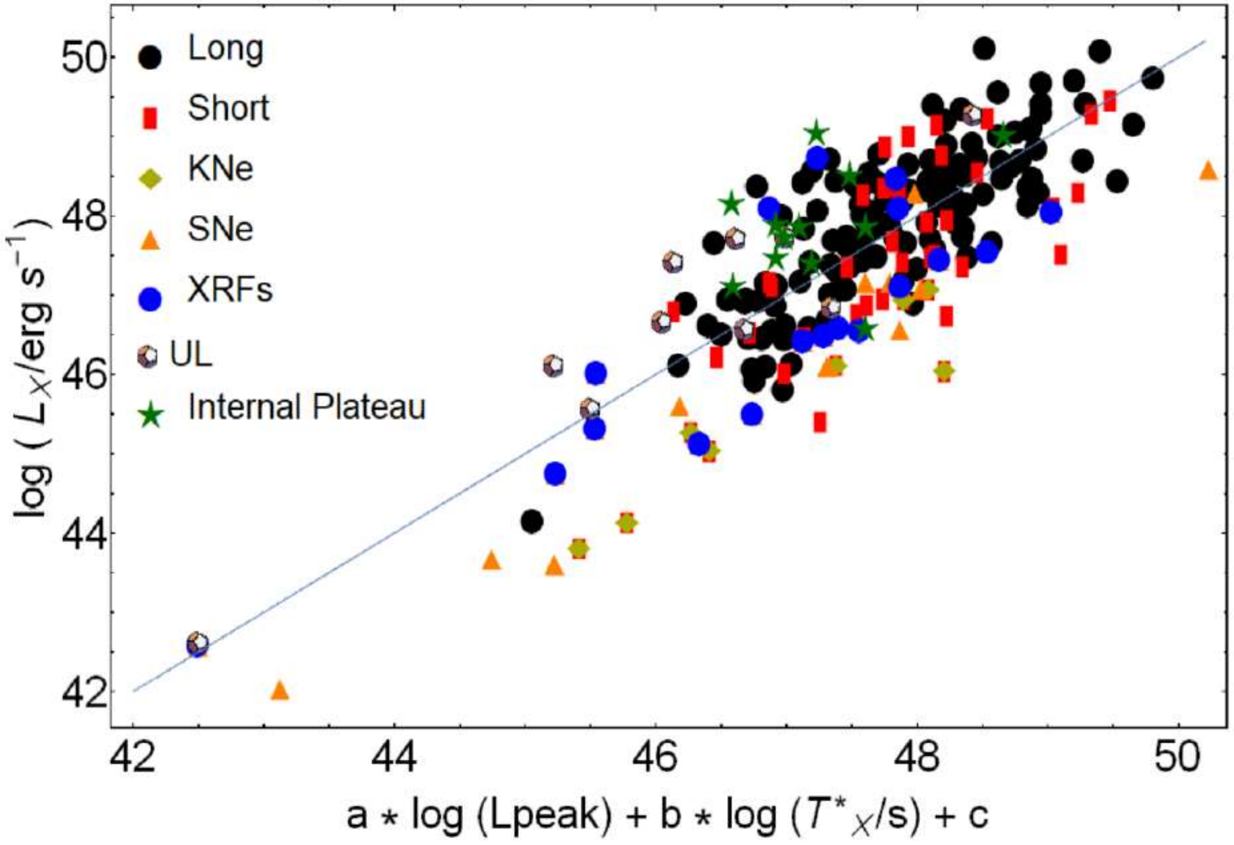


Figure 1. The 2D projection of the $L_X - T^*_X - L_{peak}$ relation for the 222 GRBs of our sample, with a plane fitted including LGRBs (black circles), SGRBs (red rectangles), KN-SGRBs (dark yellow rhombuses), SN-LGRBs (orange triangles), XRFs (blue circles), ULGRBs (dodecahedrons), and GRBs with internal plateaus (green stars).

- **Several KN have been associated with short GRBs.**
- **All cases are presented in Gompertz et al. 2019, Rossi et al. 2020.**

Intrinsic scatter after correction for biases
σ=0.18 +/0.09

- **The temporal power-law (PL) decay index of the plateau, α_i: a very steep decay, α_i ≥3 for Li et al. (2018) and α_i ≥4 for Lyons et al. (2010), indicates the internal origin of the plateau related to the magnetar.**

3D fundamental plane relations for different samples: the whole, GRBs associated with KNe and SGRB and KNe.

Dainotti et al. 2020, ApJ, 904, issue 2, 97, 13

All GRBs with plateaus

GRBs associated with KNe

SGRBs and SGRBs-KNe

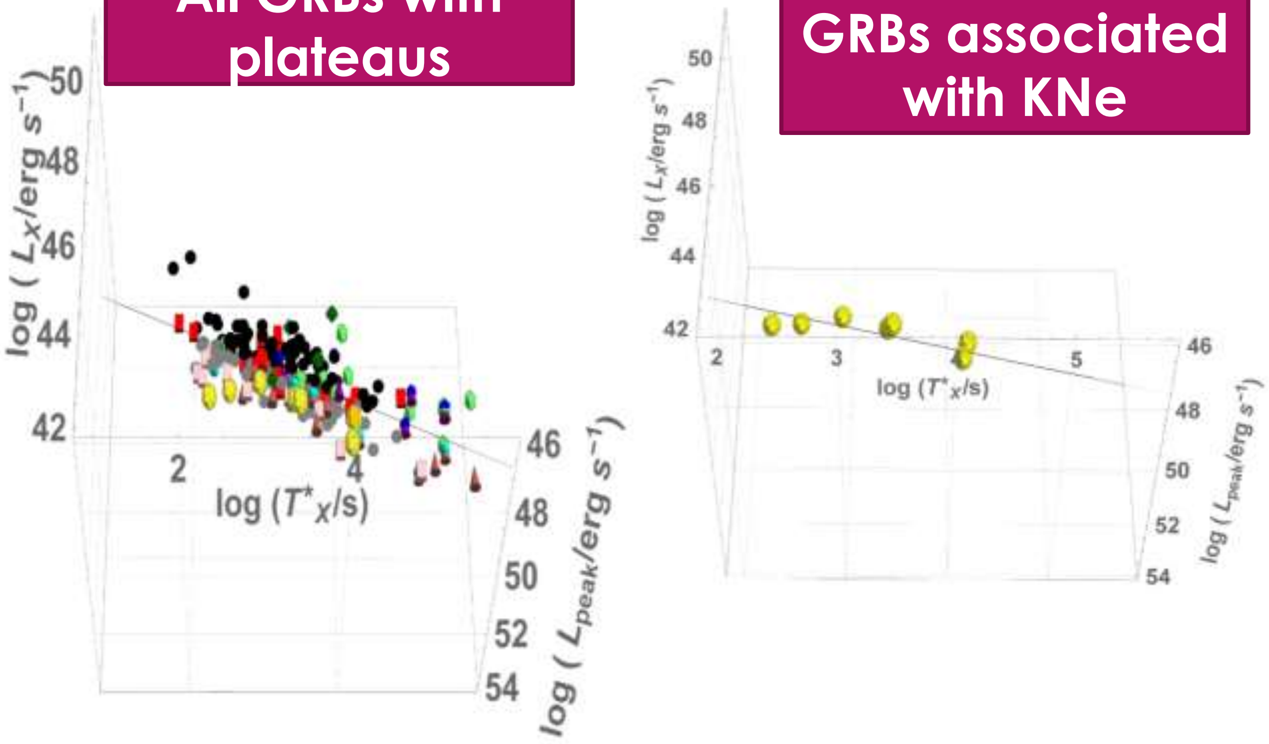


Figure 2. left panel: 222 GRBs in the $L_X - T^*_X - L_{peak}$ parameter space, with a fitted plane including SN-LGRBs (purple cones), XRFs (blue spheres), SGRBs (red cuboids), LGRBs (black circles), ULGRBs (green dodecahedrons), KN-SGRBs (yellow truncated icosahedrons) and GRBs with internal plateau (dark green diamonds). Darker colors indicate GRBs above the plane, while lighter colors GRBs below the plane. This figure shows the edge on projection. right panel shows the same fitting, but with only the KN-SGRB.

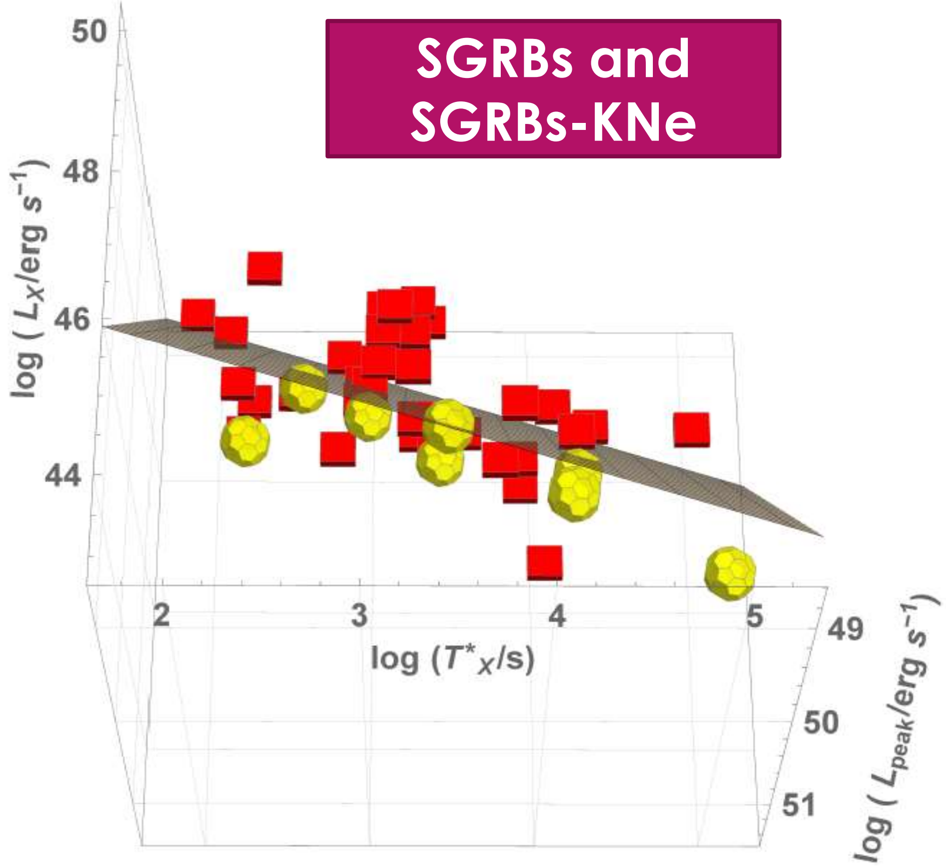
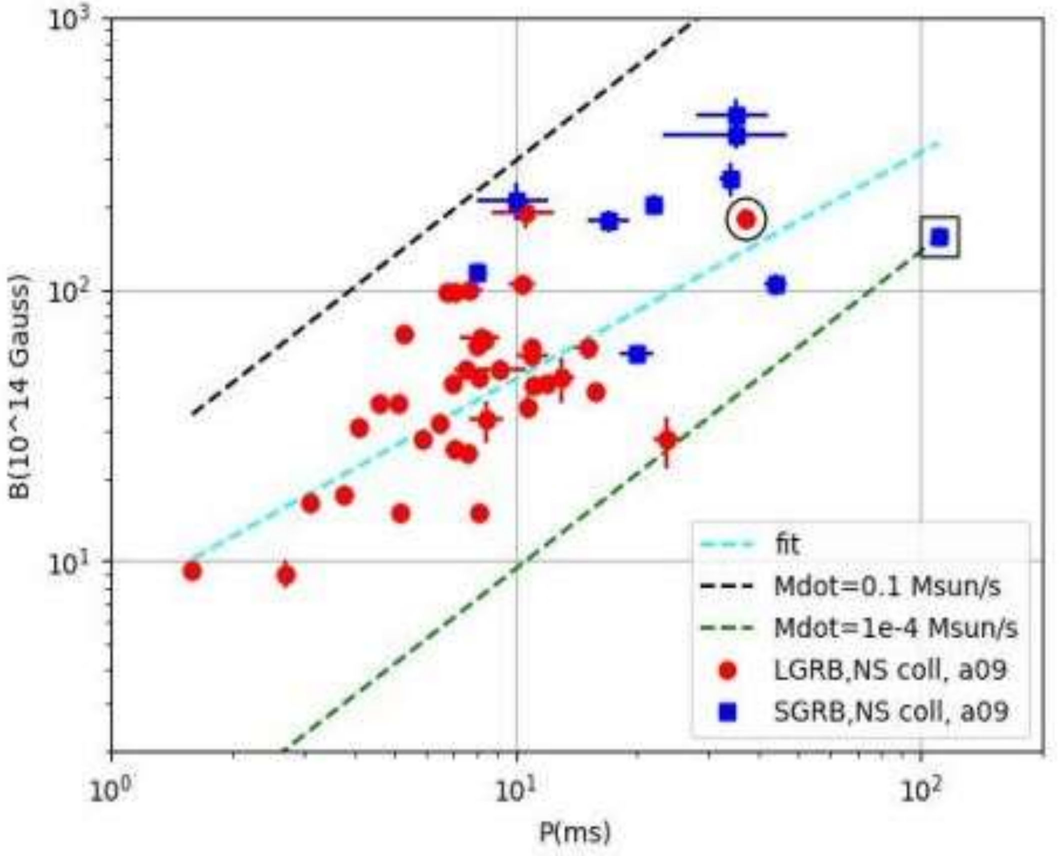


Figure 8. The $L_X - T^*_X - L_{peak}$ relation for the SGRB sample with separated KN-SGRB cases. We note here that all the KN-SGRBs fall below the best-fitting plane.

Two different classes within the magnetar scenario



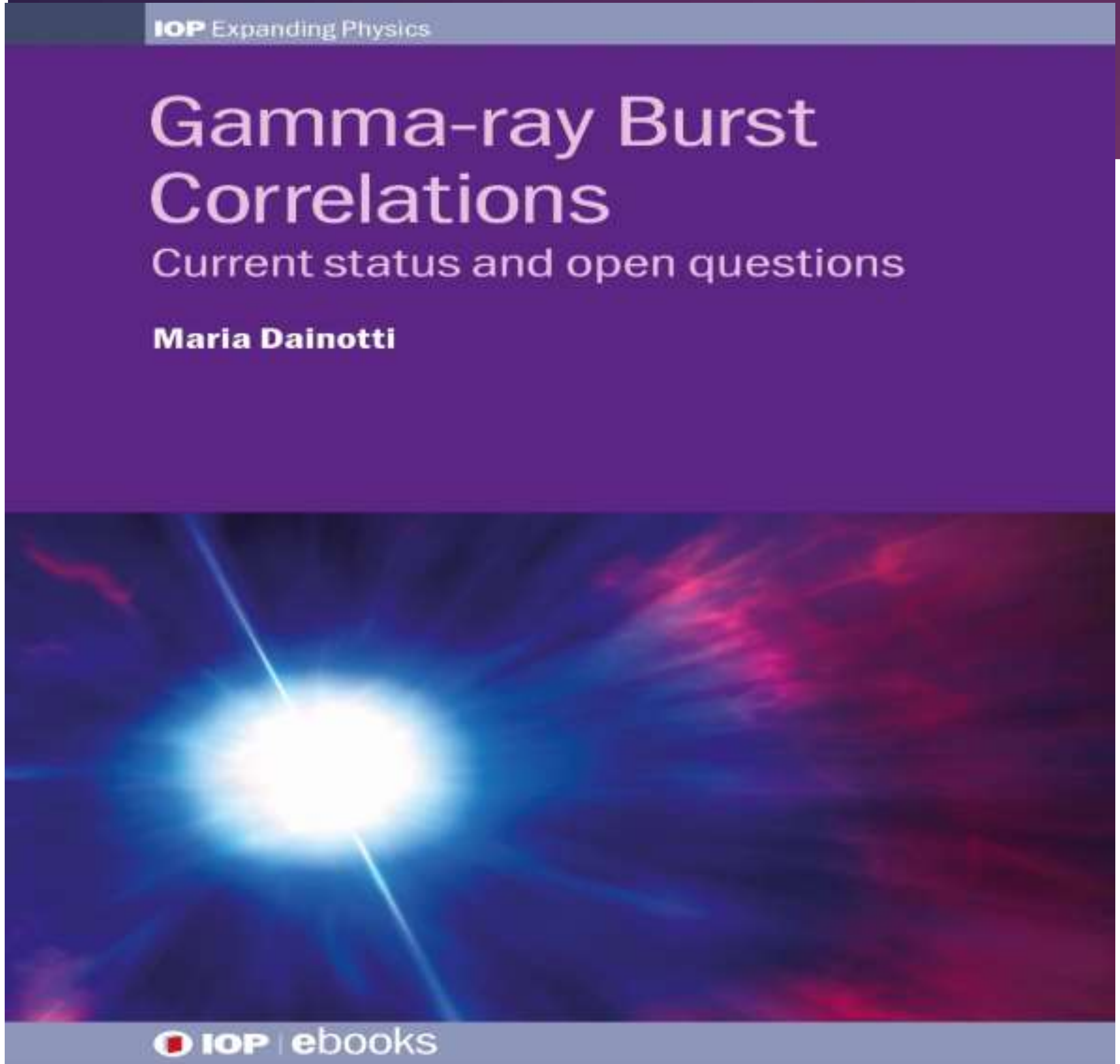
G. Stratta, M. G. Dainotti, S. Dall'Osso, X. Hernandez, G. De Cesare, 2018, ApJ, 869, 155

- The spin-down luminosity of the magnetar is entirely beamed within **Θjet** (=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. 2020).

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

Why should we use ML and not forward fitting method with the established relations?

What do we gain with Lightcurve Reconstruction?

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**

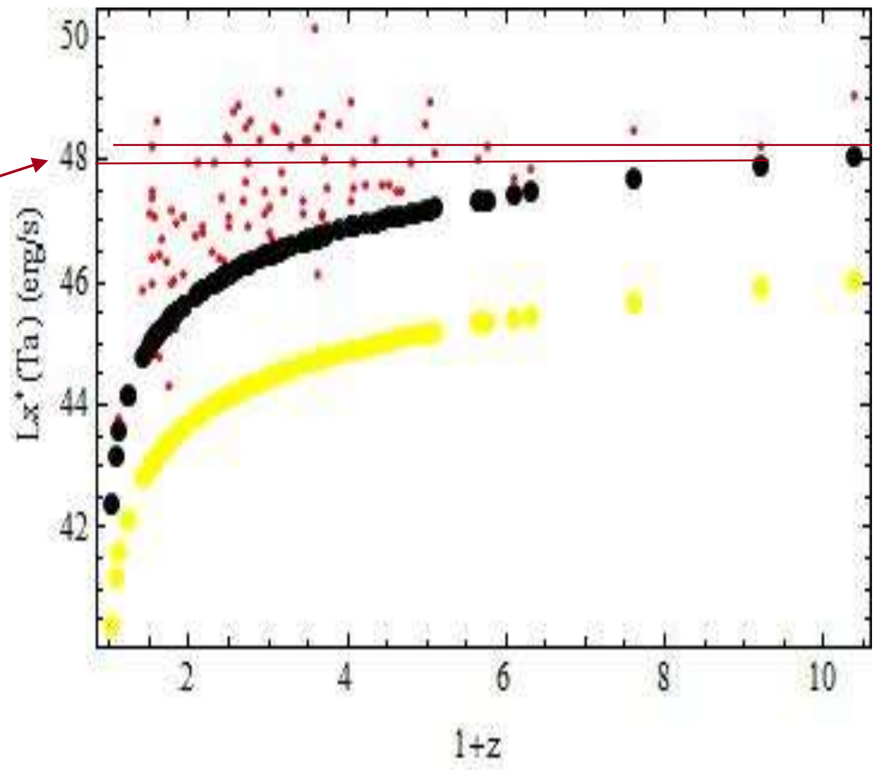
$\Phi(E) \propto E^{-\gamma_a} \propto E^{-(\beta_a+1)}$, where (β_a, γ_a) are the spectral and photon indices, respectively. It is worth stressing that the fit of

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

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



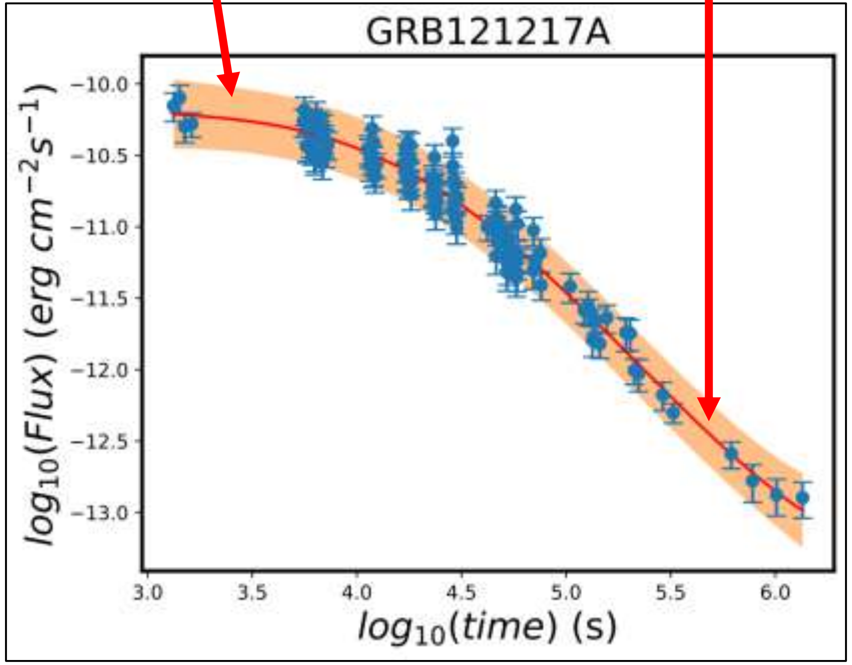
LC Reconstruction – Methodology

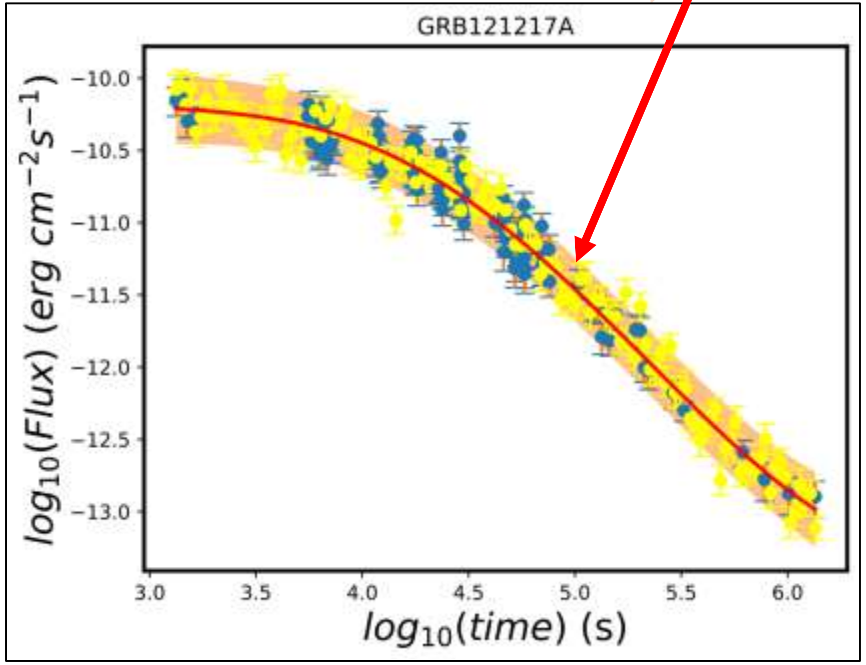
Fit the GP function (orange band)

Derive the best fit GP (red line)

Perform 100 MCMC simulation of the reconstructed LC

Pick one flux value at random at equal time intervals





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.

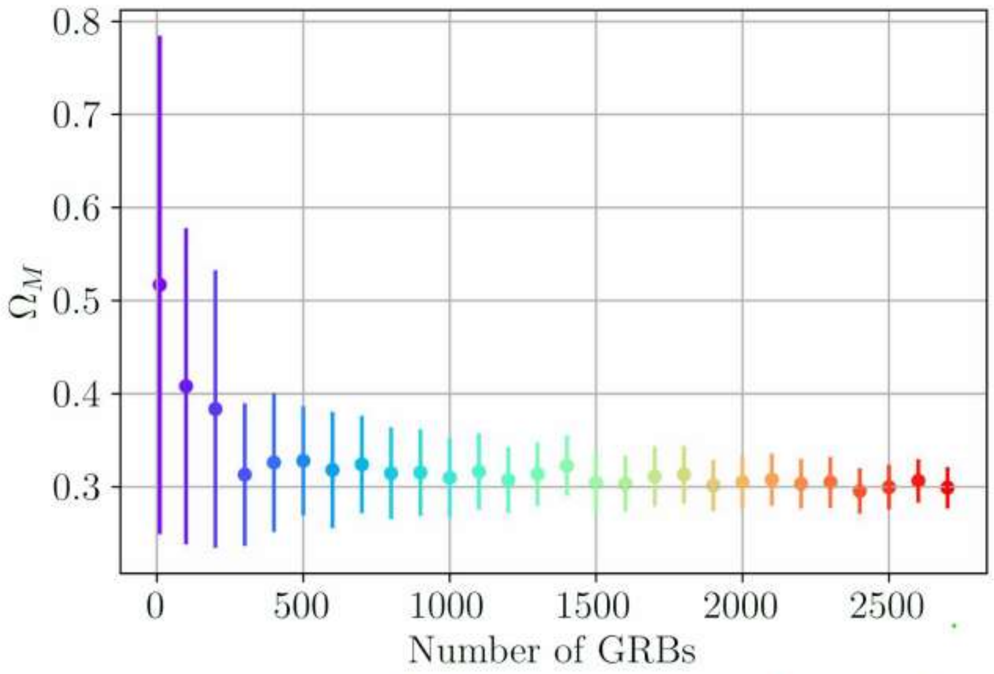
Stay tuned: the story continues

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

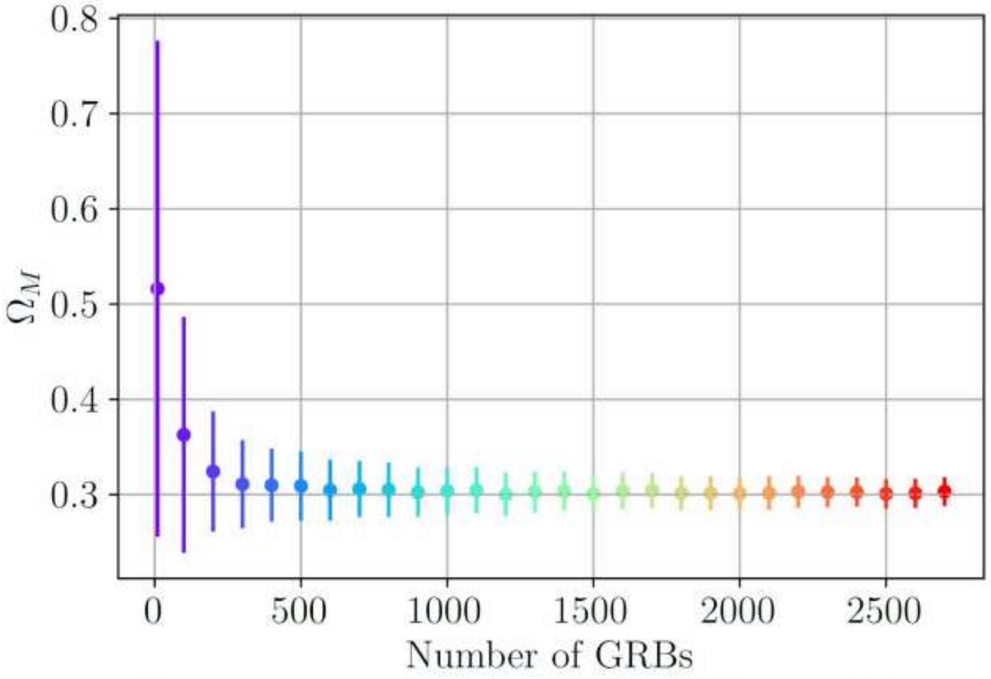
FORECASTS: THE PRECISION ON Ω_M WITH GRBs

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

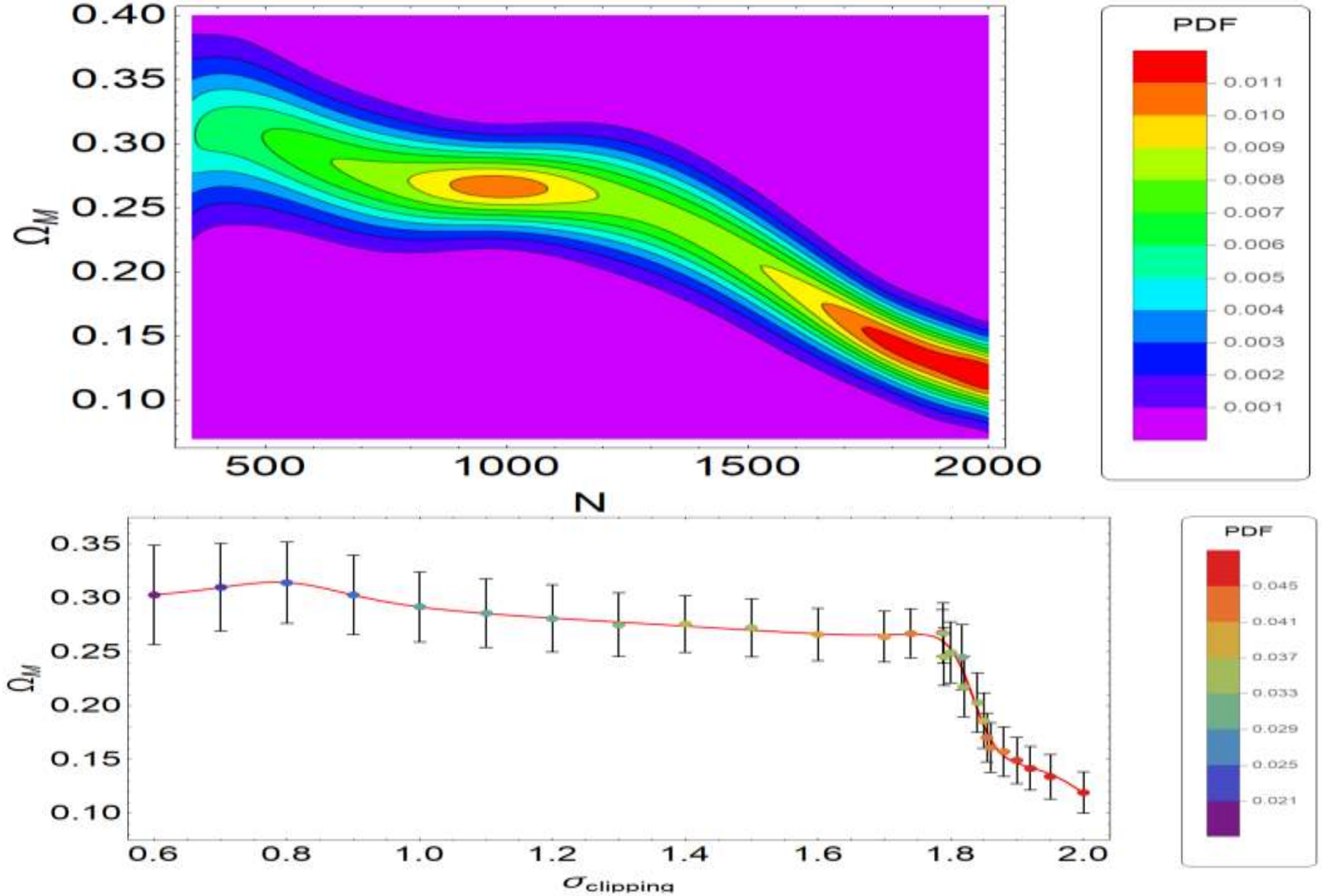


Figure 3. Upper panel: The values of Ω_M and their associated uncertainties vs. the number of Quasars. The color bar on the right shows the normalized probability density, indicating for each sample size the most probable value of Ω_M, thus the smallest uncertainty on Ω_M. This Fig. indicates that the 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.