UNIVERSITY OF JOHANNESBURG

CAPP
Centre for Astro-Particle Physics

Fermi Gamma-ray Space Telescope

Constraints on Cosmological Parameters Using a Large Sample of Gamma-Ray Bursts with their redshift derived by Machine Learning

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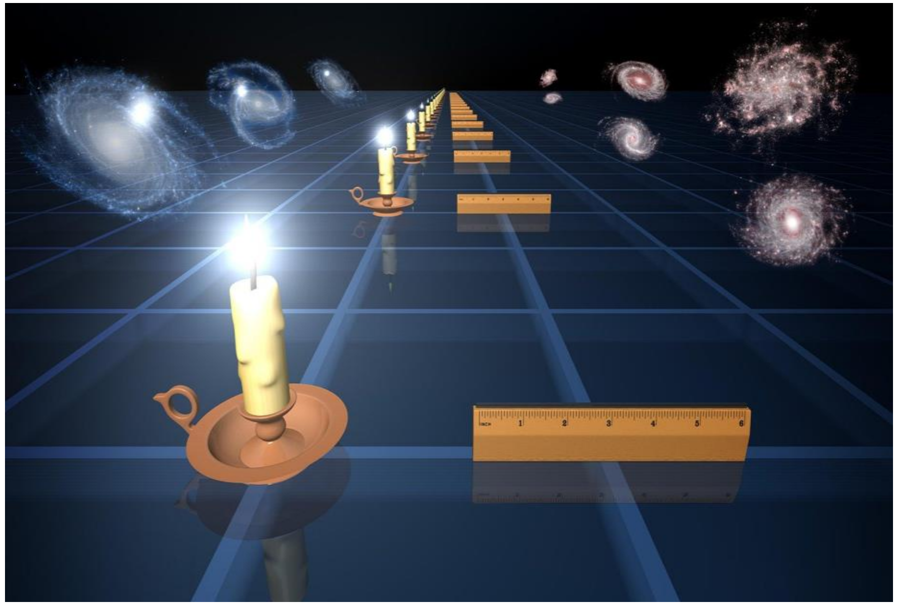
Outline

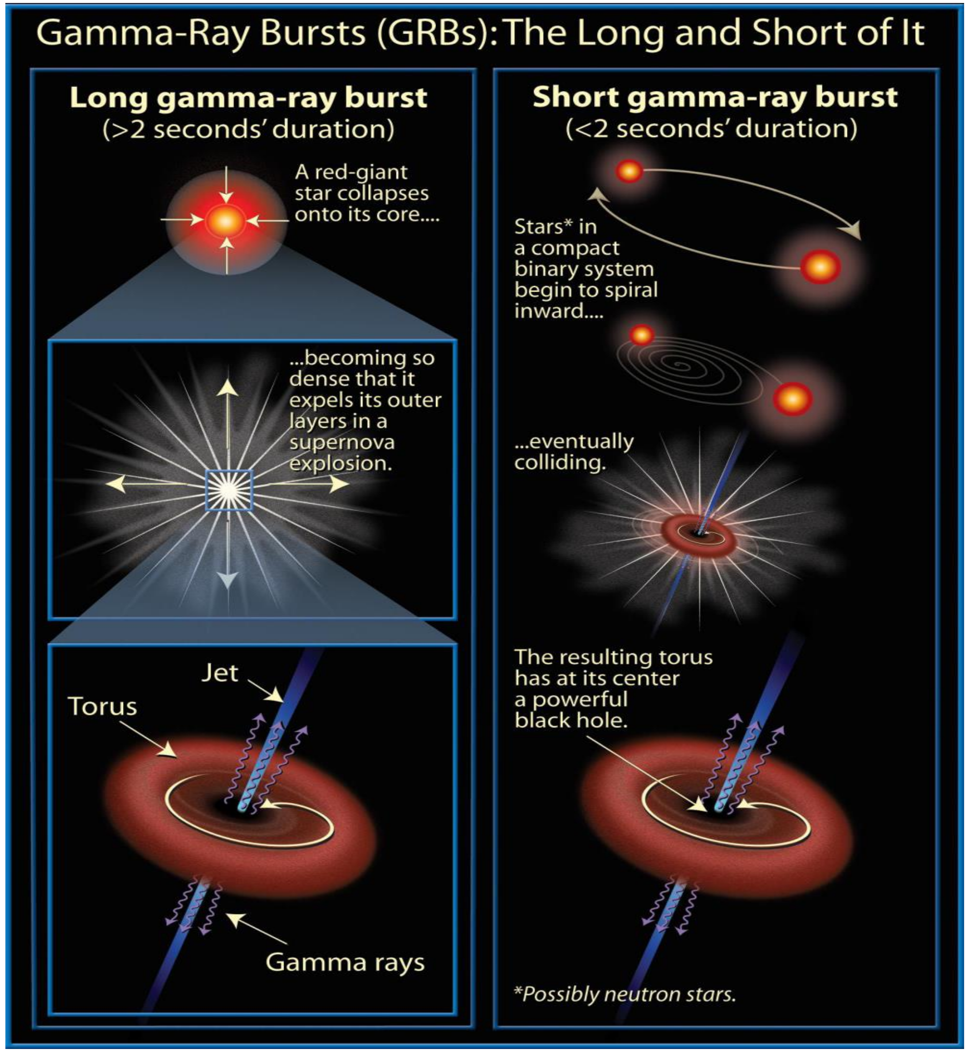
Introduction

- Gamma-ray Bursts (GRBs) are the most powerful explosions in electromagnetic wavebands ever discovered.
- Emitting in high energy range (keV to GeV) in gamma-ray within durations less than 1 second to few minutes.
- Detected at high redshift up to ~ 9.4.
- GRBs can be visible at a very large distance, because of their high luminosities ($L_{iso} \sim 10^{52}\ erg\ s^{-1}$).
- Are extremely bright and release an enormous isotropic equivalent radiated energy ($E_{iso} \sim 10^{54}\ erg$) in a few hundreds of seconds.

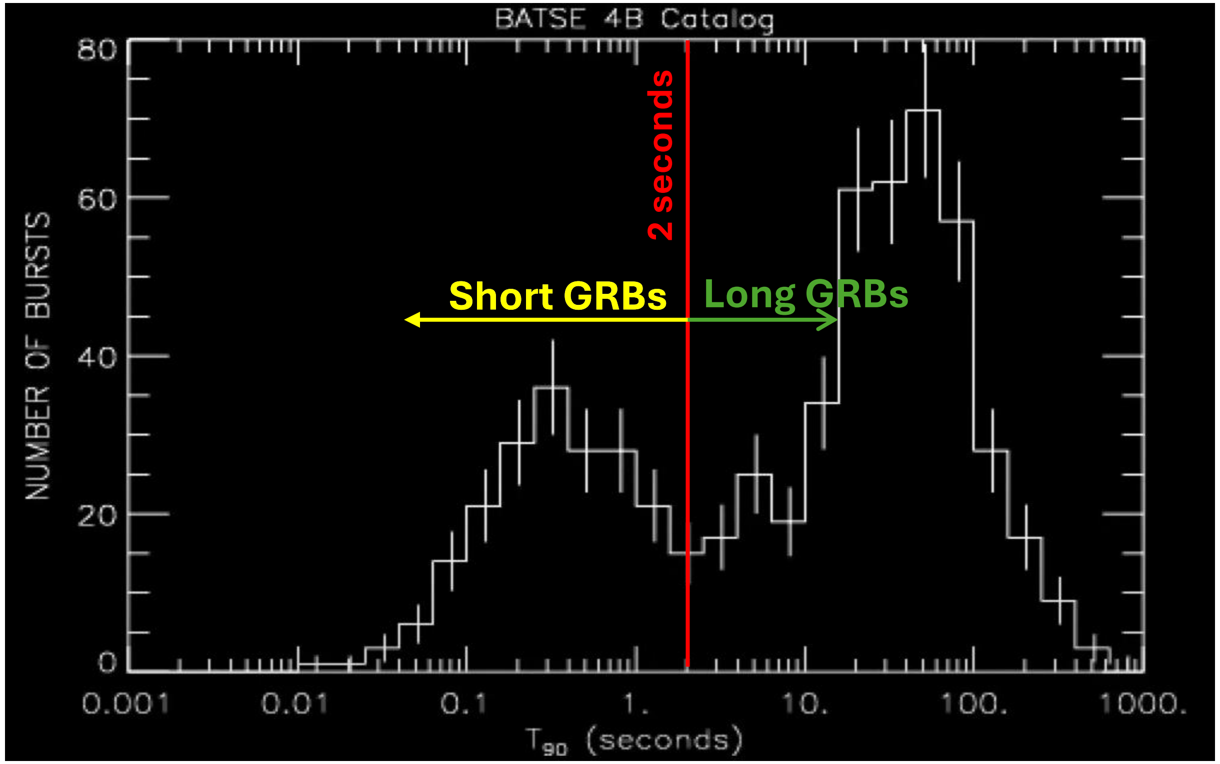
They have the potential to be used as cosmological standard candles.



Introduction

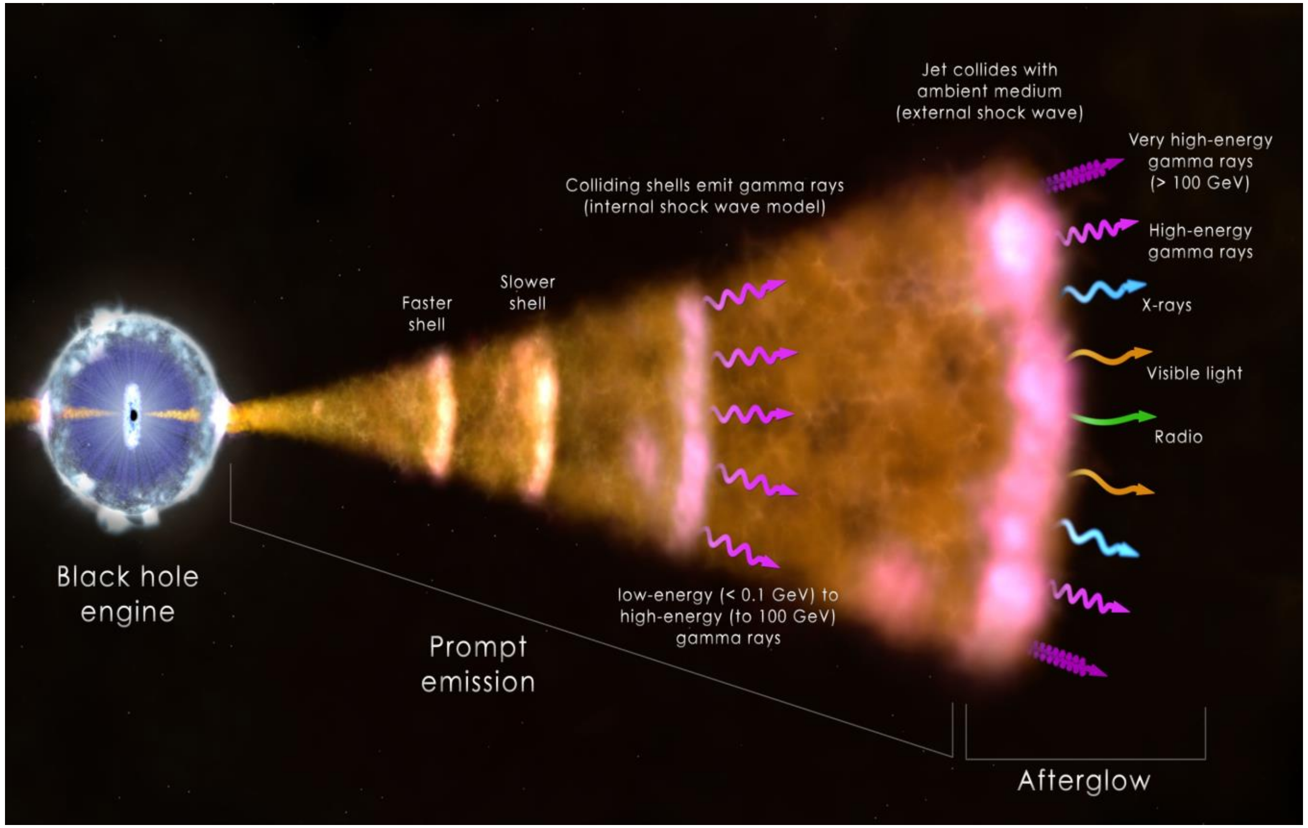


Credit: NASA and A. Feild (STScI)



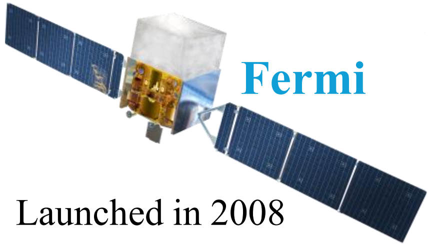
https://gammaray.nsstc.nasa.gov/batse/grb/duration/

Introduction



High Energy Stereoscopic System (H.E.S.S)

Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC)



Fermi

Launched in 2008

Konus-wind

Launched in 1994

Swift

Launched in 2004

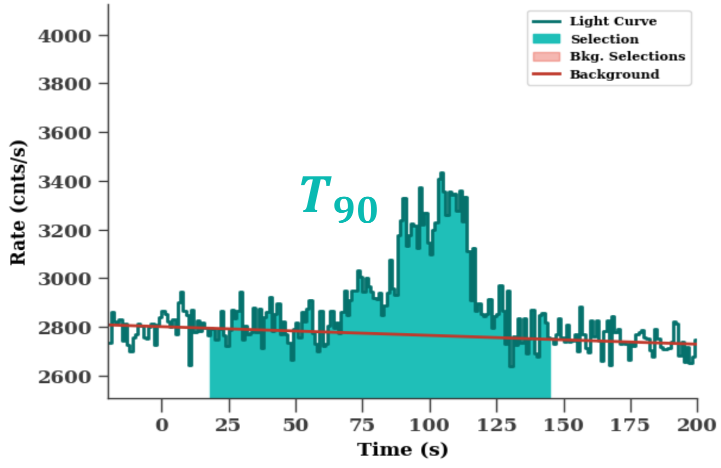
Phenomenological Correlations

❖ **Amati (2002):** (LGRBs - *$T_{90} > 2\ s$)

$$\frac{E_{iso}}{10^{52}\ erg} = 10^k \left(\frac{E_{i,peak}}{E_o\ keV}\right)^m$$

$$E_{iso} = \frac{4\pi d_L^2}{1+z} S_{bolo}\ , \qquad E_{i,peak} = E_p(1+z)$$

$$S_{bolo}(E_1, E_2, z) = T_{90} \int_{E_1(1+z)}^{E_2(1+z)} EN(E)dE$$

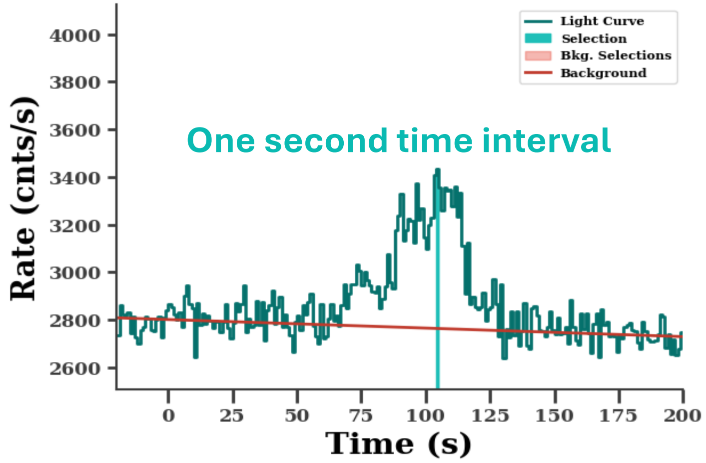


❖ **Yonetoku (2007):** (SGRBs - LGRBs)

$$\frac{L_{iso}}{10^{51}} = 10^k \left(\frac{E_{i,peak}}{E_o\ keV}\right)^m$$

$$L_{iso} = 4\pi d_L^2 P_{bolo}$$

$$P_{bolo}(E_1, E_2, z) = \int_{E_1/((1+z)}^{E_2/(1+z)} EN(E)dE$$



* T_{90} : the time to detect 90% of GRBs fluence.

Phenomenological Correlations

$$d_L = (1+z)\frac{c}{H_o}\int_0^z \frac{dz`}{\sqrt{(1-\Omega_\Lambda)(1+z)^3 + \Omega_\Lambda}}$$

$H_o = 67.3\ km\ s^{-1}\ Mpc^{-1}\ and\ \Omega_\Lambda = 0.685$ (Planck Collaboration et al., 2018)

From the H_o and Ω_Λ if one can predict $(E_{iso}\ ,\ L_{iso})$ by measuring the peak of spectra then it possible to use GRBs as standard candles because of this d_L.

Redshift

- The redshift of the GRBs can be obtained from the absorption or emission lines.
- GRB 970508 from the few absorption lines, the redshift was determined to be $z = 0.8$ Frail et al., 1997.
- Swift satellite is well studied the localization of GRBs, enabling Swift follow-up observations and facilitating timely redshift measurements Gehrels et al., 2009.
- From photometric and spectroscope, many GRBs have been identified and can be found in many GRBs catalogs such as Fermi-GBM von Kienlin et al., 2020, and Kouns-Wind Tsvetkova et al., 2021.
- The farthest GRB identified is GRB 090429B $z \approx 9.4$ Cucchiara et al., 2011.

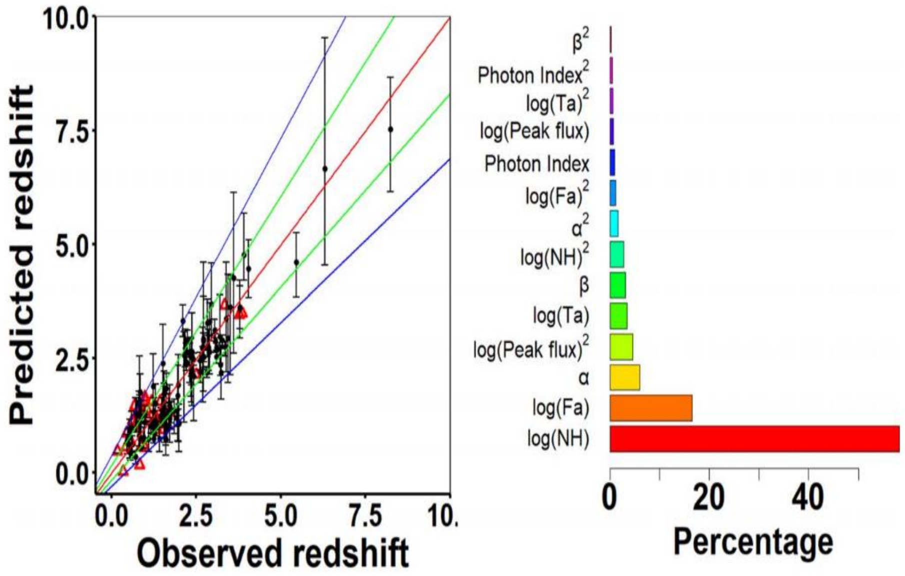
Machine Learning Models

Estimations of GRB Redshift

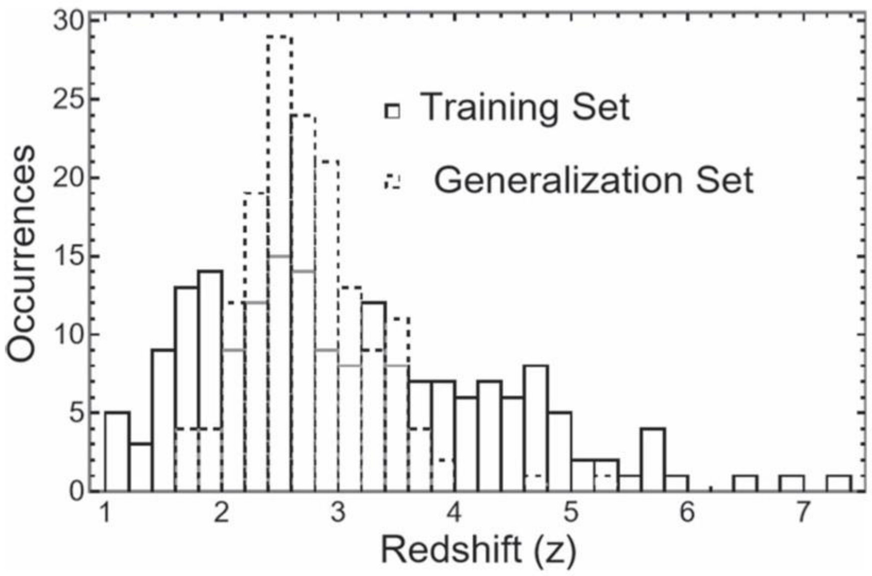
SuperLearner:
An ensemble learning technique that improves predictive accuracy by combining the outputs of multiple statistical models.

Trains various **supervised models**:
such as generalized additive models and random forests

Observed redshifts with predicted redshifts for 103 GRBs



Dainotti et al. 2024



Dainotti et al. 2024

- A sample of Swift GRBs based on their observed prompt and afterglow.

Machine Learning Models

- We used data **from Fermi Gamma-ray Monitor (Fermi-GBM)** von Kienlin et al., 2020 catalogue, **128 GRBs (2008-2018)** with known redshift.

- **Kouns-Wind** Tsvetkova et al., 2021 catalogue, **338 GRBs (2005-2018)** with known redshift.

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Bolometric	Peak Flux	Fluence
Band Model	$\alpha, \beta, E_p, P_{\rm bolo}$	$\alpha, \beta, E_p, S_{\rm bolo}$
Comptonized Model	$\alpha, E_p, P_{\rm bolo}$	$\alpha, E_p, S_{\rm bolo}$

We excluded:
- All SGRBs.
- GRBs with errors on spectral parameters exceeding 100% and those without Ep values across all spectral models were excluded.

- GRBs best-fitted with the Band model showing $\beta \geq -2$, indicating no peak, were also excluded.

- These applied to both GBM and KW data, regardless of redshift availability.

- **Band :** Band D. et al., 1993.
  with indices α, β, and spectral peak energy E_p in keV.

$$N_{Band}(E) = A_{Band} \begin{cases} \left(\frac{E}{100\ keV}\right)^{\alpha} exp\left[-\frac{E(2+\alpha)}{E_p}\right] & if\ E \leq E_b \\ \left(\frac{E}{100\ keV}\right)^{\beta} exp(\beta-\alpha) \left[-\frac{E_p}{100\ keV}\ \frac{\alpha-\beta}{2+\alpha}\right]^{\alpha-\beta} & if\ E > E_b, \end{cases}$$

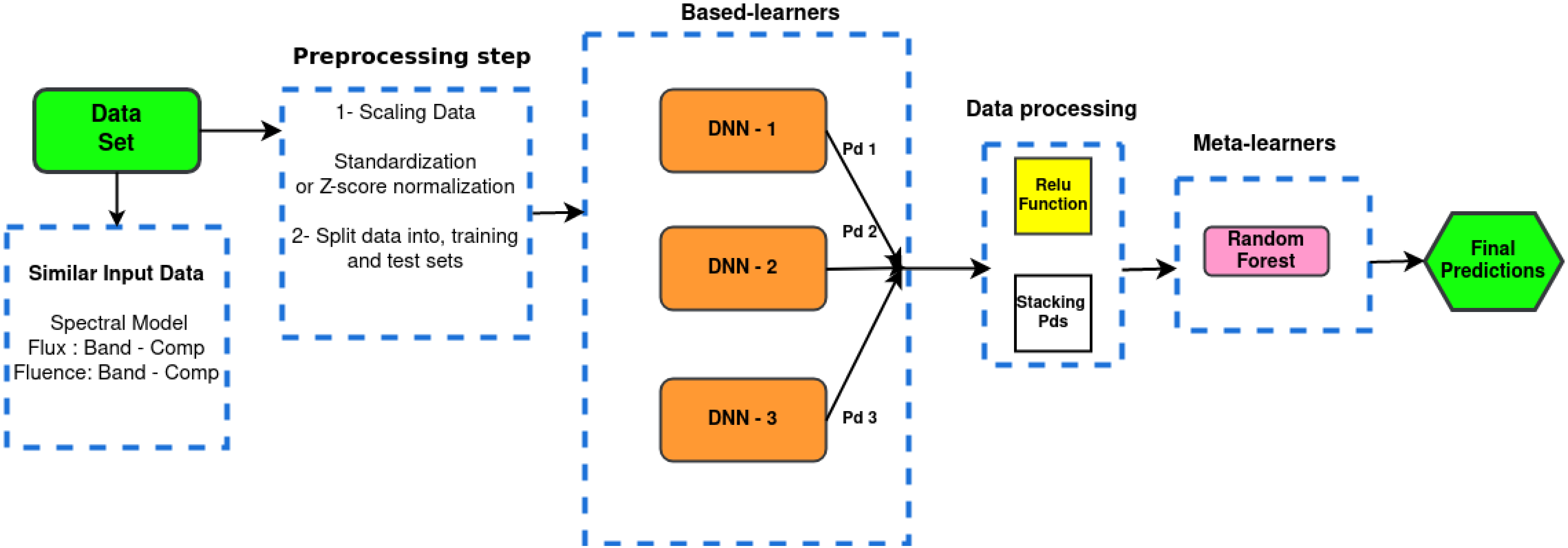
- **Comptonized :** Steiner J. F. et al., 2009.

The photon index γ, and the peak energy E_p.

$$N_{Comp}(E) = A_{Comp} \left(\frac{E}{100\ keV}\right)^{\gamma} \exp\left[-(2+\gamma)\frac{E}{E_p}\right]$$

Machine Learning Models

Ensemble Stacking



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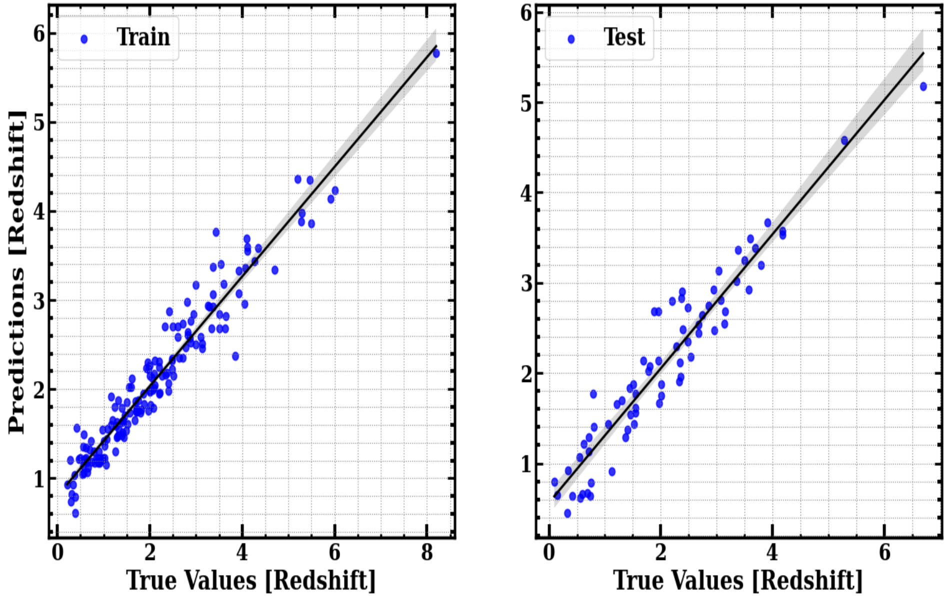
Estimations of GRB Redshift

❖ Results from ensemble model with true redshift

GBM data	Train	Test
	R^2 - MAE	R^2 - MAE
Band fluence	0.812 - 0.383	0.724 - 0.555
Band flux	0.819 - 0.450	0.798 - 0.290
Comp fluence	0.827 - 0.439	0.801 - 0.392
Comp flux	0.823 - 0.384	0.812 - 0.437
Band fluence and flux	0.844 - 0.370	0.821 - 0.498
Comp fluence and flux	0.831 - 0.424	**0.823 - 0.343**
KW-GBM data	**Train**	**Test**
	R^2 - MAE	R^2 - MAE
Band fluence	0.858 - 0.431	0.838 - 0.433
Band flux	0.846 - 0.430	0.839 - 0.413
Comp fluence	0.857 - 0.409	0.836 - 0.433
Comp flux	0.860 - 0.337	0.852 - 0.364
Band fluence and flux	0.851 - 0.418	0.838 - 0.406
Comp fluence and flux	0.861 - 0.369	**0.860 - 0.397**
KW data	**Train**	**Test**
	R^2 - MAE	R^2 - MAE
Band fluence	0.838 - 0.543	0.804 - 0.615
Band flux	0.827 - 0.503	0.766 - 0.457
Comp fluence	0.826 - 0.480	0.810 - 0.509
Comp flux	0.842 - 0.441	**0.831 - 0.361**
Band fluence and flux	0.846 - 0.463	0.812 - 0.551
Comp fluence and flux	0.838 - 0.406	0.829 - 0.512



Predicted redshift from the ensemble models (DNNs + Random Forest) vs. true redshift for train and test samples from the combined KW-GBM data with known redshift. The regression lines are shown with 95% CL.

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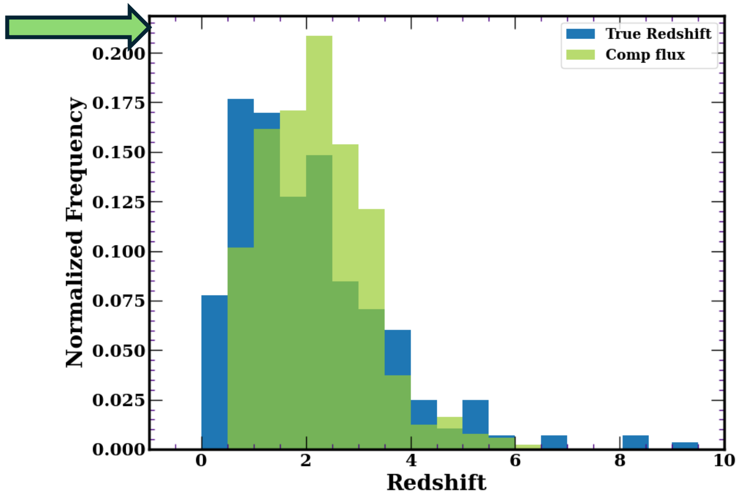
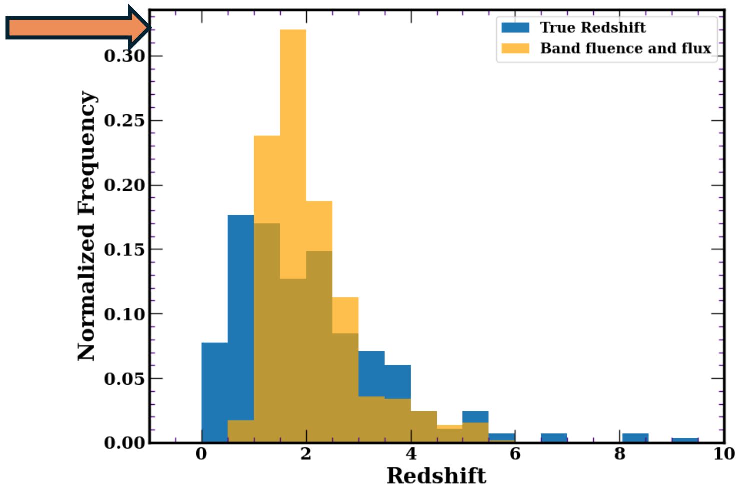
Estimations of GRB Redshift

Pseudo-redshifts compare with the samples of GRBs with true redshifts

GBM data	p-value
Band fluence	0.1532
Band flux	0.0681
Comp fluence	0.1531
Comp flux	**0.5713**
Band fluence and flux	0.1532
Comp fluence and flux	0.1531
KW-GBM data	**p-value**
Band fluence	0.0681
Band flux	0.0681
Comp fluence	0.0948
Comp flux	**0.8319**
Band fluence and flux	0.5713
Comp fluence and flux	0.1745





Kolmogorov-Smirnov (KS) *Hodges, 1958* test between the GRB samples with measured redshift and estimated pseudo redshift for GBM data without measured redshift.

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Estimations of GRB Redshift

Results of the Amati (Amati et al., 2002) and Yonetoku (Yonetoku et al., 2004) correlation fits applied to the KW-GBM samples of GRBs with true redshift and GBM sample of GRBs with pseudo redshift. To see if may help to constrain the cosmological parameters.

$$x = \log_{10}\left(\frac{E_{i,p}}{E_o}\right),\ y = \log_{10}\left(\frac{E_{iso}}{erg/s}\right)$$

Or $\log_{10}\left(\frac{L_{iso}}{erg/s}\right)$

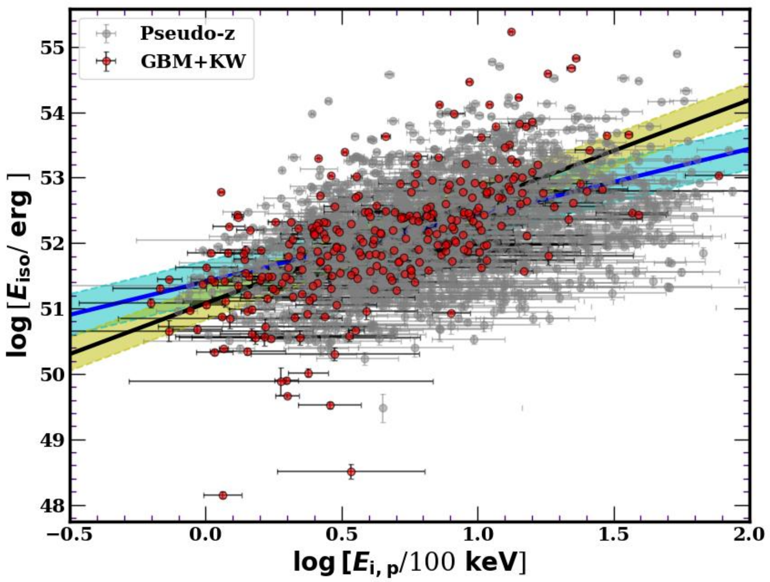
To get the error in y we followed:

$$\sigma_y = \sqrt{\sigma_k^2 + m^2\sigma_x^2 + \sigma_m^2 + \sigma_{ext}^2}$$

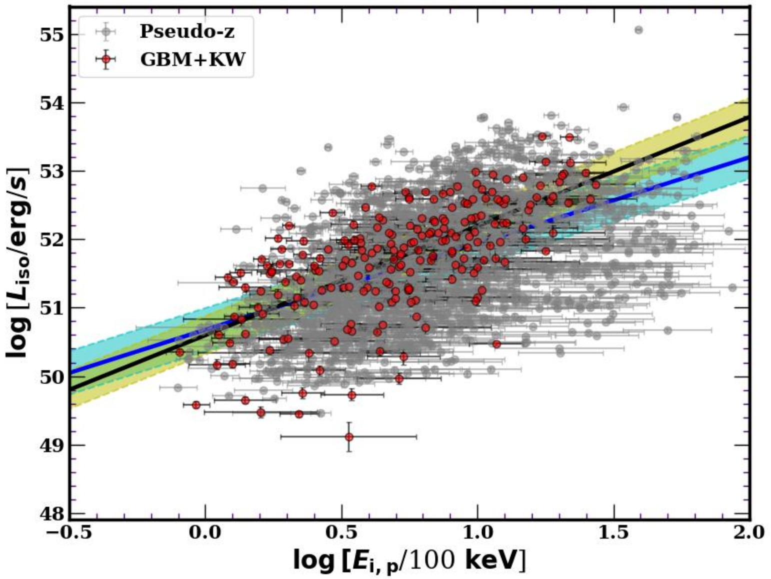
Max-likelihood function used to determine the parameters (k, m, σ_{ext})

$$L(m, k, \sigma_{ext}) = \frac{1}{2}\sum_i^N \ln(\sigma_{ext}^2 + \sigma_{yi} + m^2\sigma_{xi}) + \frac{1}{2}\sum_i^N \frac{(y_i - mx_i - k)^2}{(\sigma_{ext}^2 + \sigma_{yi} + m^2\sigma_{xi})}$$

Amati correlation



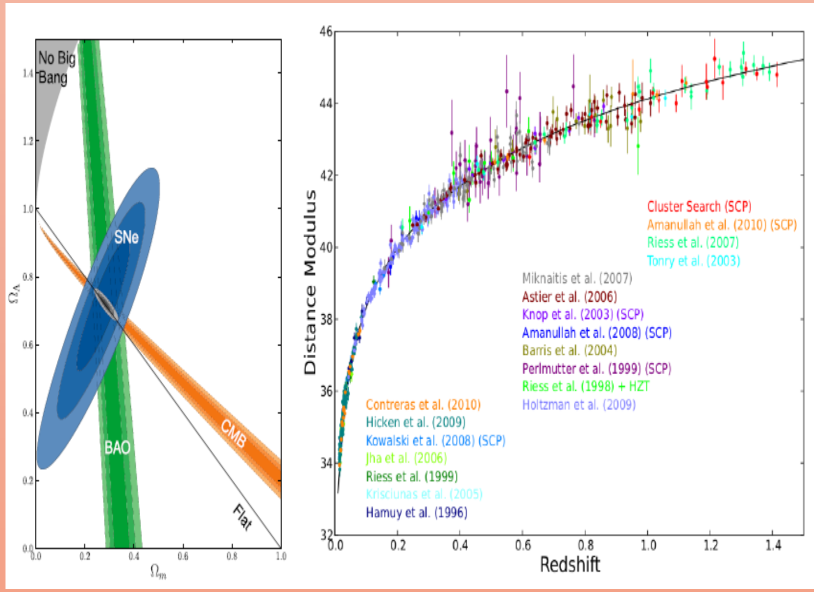
Yonetoku correlation



The ensemble model used for predicting pseudo redshift is "*Comp flux*" derived from KW-GBM true-redshift data (KS-test p-value: 0.8319).

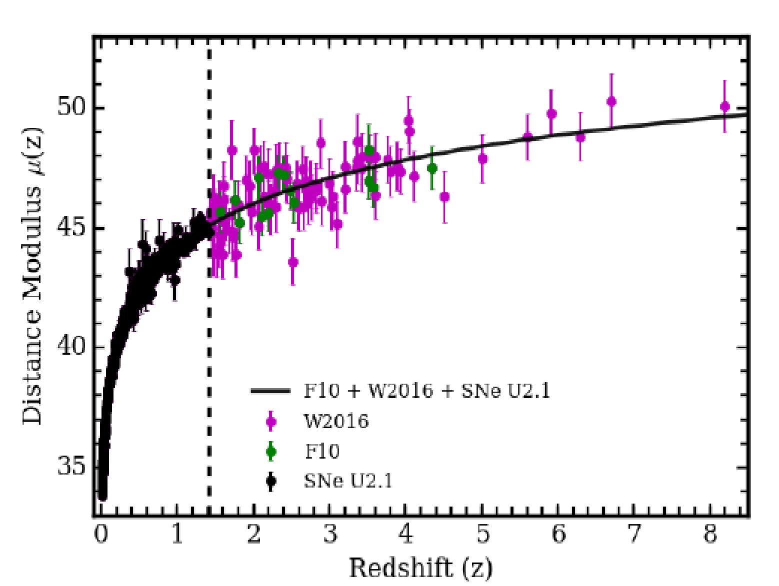
Constraints on cosmological parameters

Supernova Type Ia (SNe Ia):
Observed only up to z = 2



Suzuki et al., 2012

GRBs
Observed up to z = 8.2



Combined SNe and GRB Hubble diagram
Dirirsa, F.F, Razzaque, S. , and Piron, F. 2018, 2019

❖ Based on the best fit from the p-value shown in “Comp-flux," we have published pseudo-redshift dataset: is available on the Zenodo website.

https://doi.org/10.5281/zenodo.13695954

❖ Once the parameters are obtained by fitting the linearized Yonetoku relation, we can use the GBM data with pseudo-redshift to estimate the cosmological parameters.

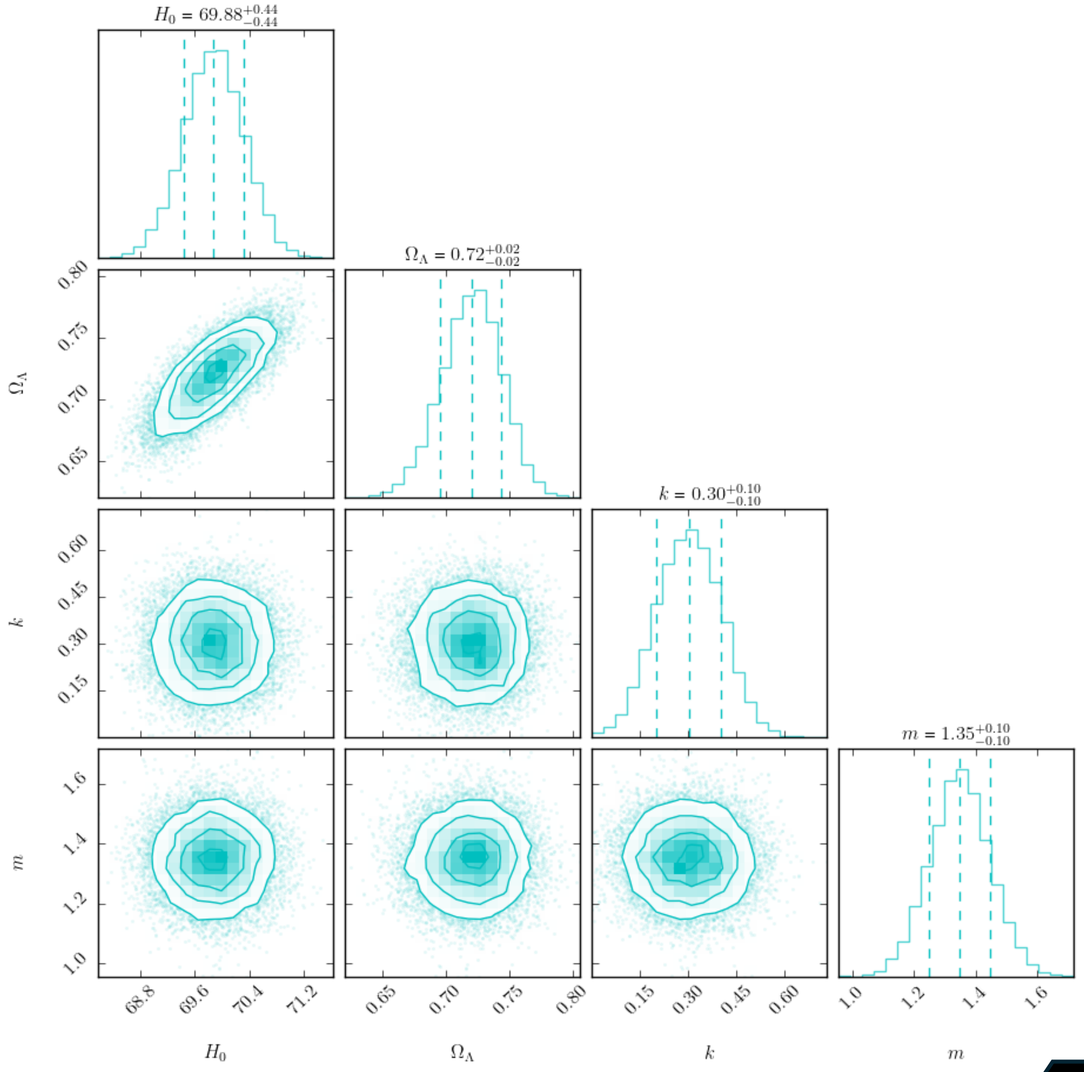
Preliminary results
Constraints on cosmological parameters

- **GBM-GRB data**:
  True redshift: 116 GRBs, $0.0 < z < 8.2$
  Pseudo redshift: 1576 GRBs, $0.6 < z < 6.3$

- **SNe Ia data**:
  SNe U2.1 Suzuki et al. (2012) : 580, $0.0 < z < 1.4$
  Dark Energy Survey (DES) Abbottet al. 2019: 207, $0.02 < z < 0.85$

- Using the MCMC method for Fermi GRB samples with true and pseudo-redshift. The parameters k, and m, represent the phenomenological parameters of the Yonetoku relation.

$$\chi^2(H_0, \Omega_\Lambda, k, m) = \sum_{i=1}^{N} \left[\frac{\mu^{obs}(z_i, k, m) - \mu^{th}(z_i, H_0, \Omega_\Lambda, k, m)}{\sigma^2_{\mu\,(zi)}} \right]^2 + \left(\frac{k - k'}{\sigma_k} \right)^2 + \left(\frac{m - m'}{\sigma_m} \right)^2$$



Preliminary results
Constraints on cosmological parameters

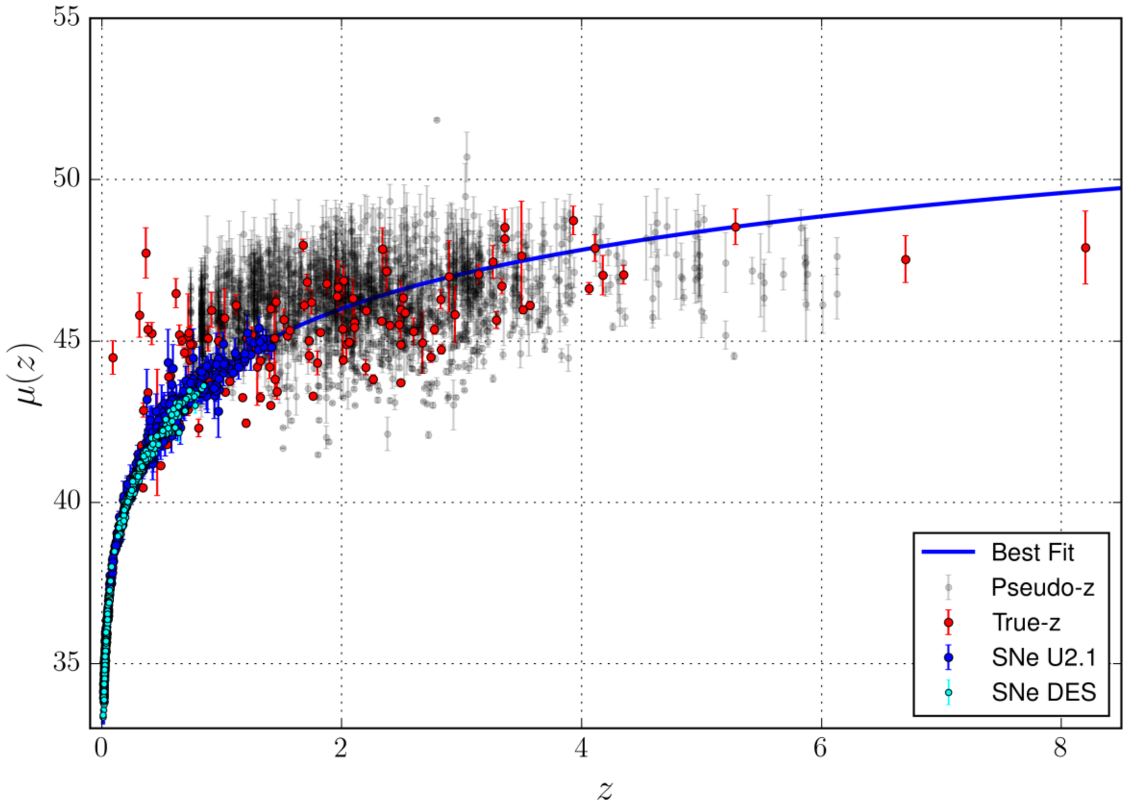
The Distance Modulus given as:

$$\mu = 5\log\frac{d_l}{Mpc} + 25$$

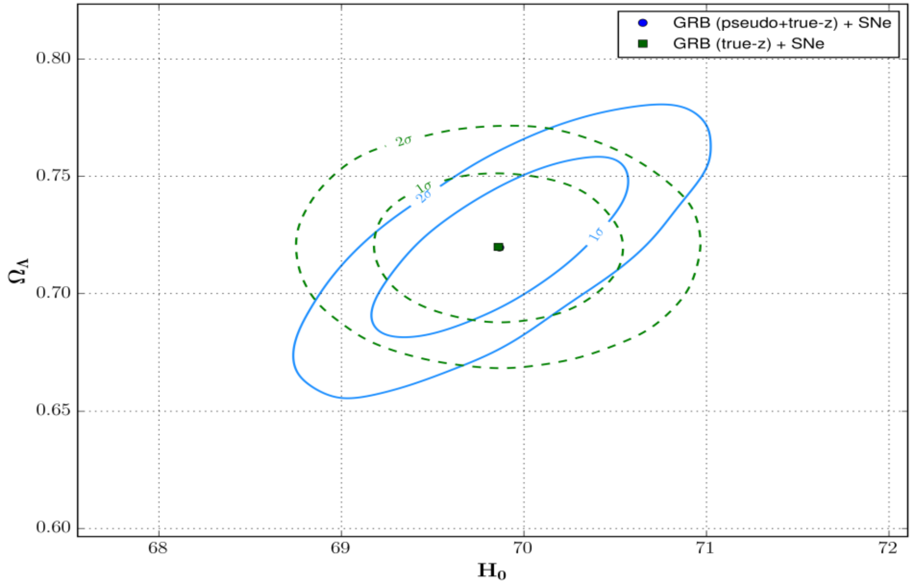
$$\mu(z) = \frac{5}{2}\log_{10}\left[\frac{1}{4\pi\, P_{bolo}}\left(\frac{E_{i,p}}{E_0}\right)^m\right] + \frac{5}{2}(k+51) - 5\log_{10}(1\ MPC) + 25$$

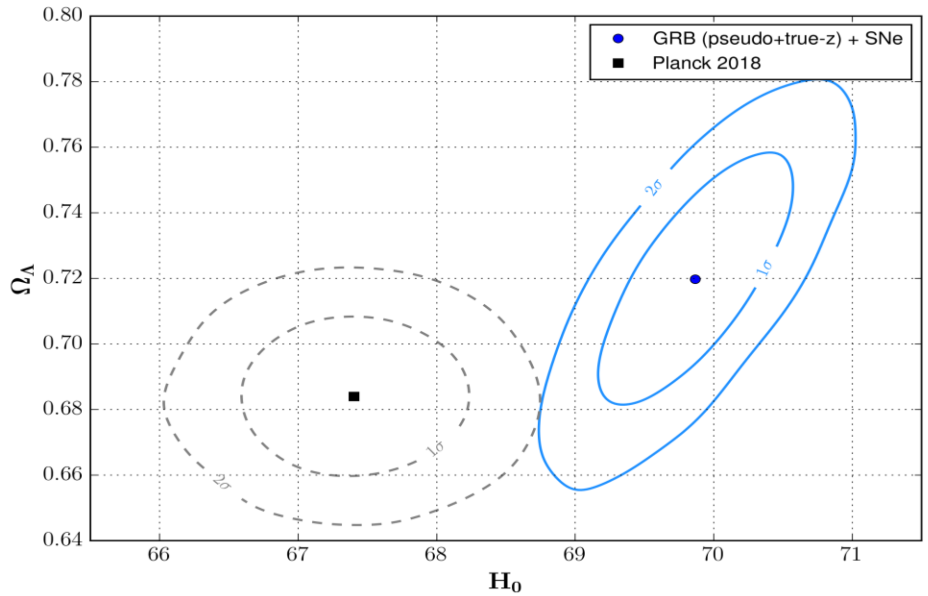
The uncertainty in Distance Modulus:

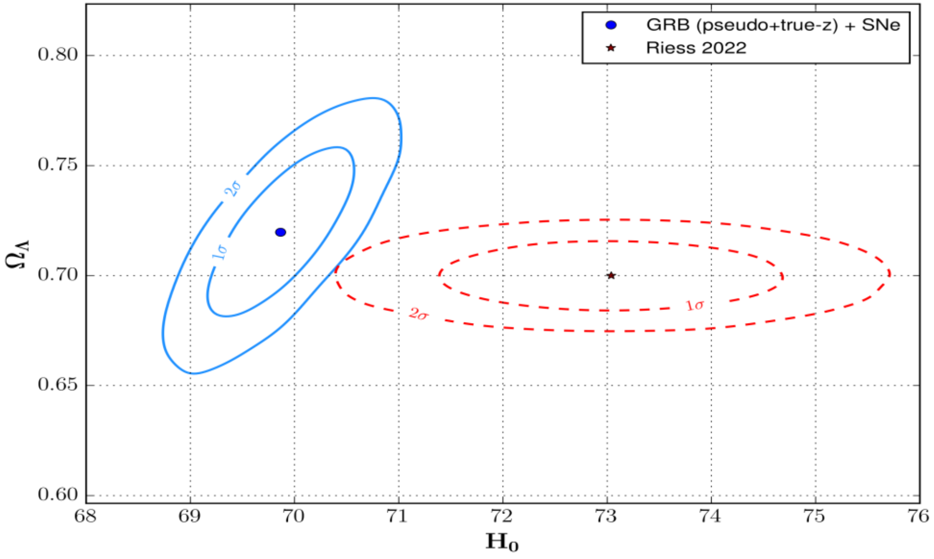
$$\sigma_{\mu(z)} = \frac{5}{2\ln 10}\left[\left(\frac{\sigma_{P_{bolo}}}{P_{bolo}}\right)^2 + \left(\frac{m\,\sigma_{E_{i,p}}}{E_{i,p}}\right)^2\right]^{1/2}$$

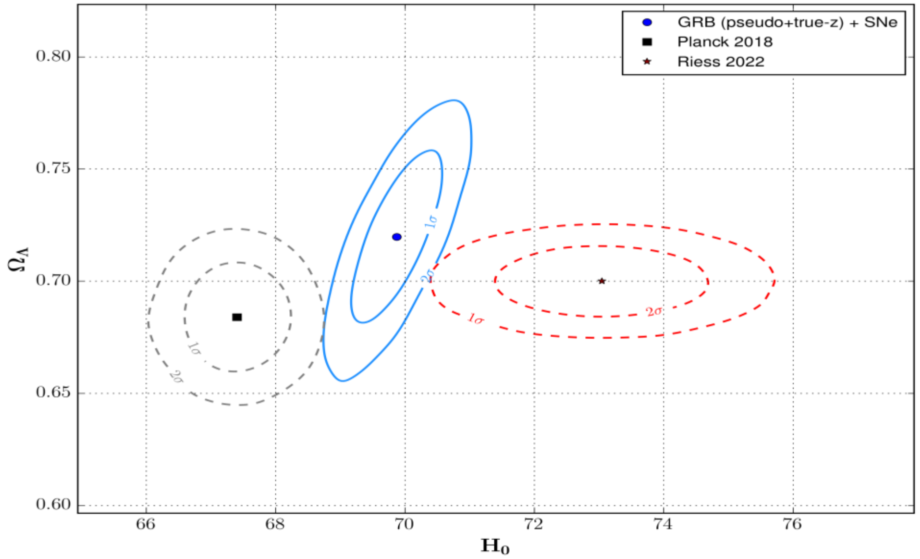


Preliminary results
Constraints on cosmological parameters









Summary

- We used a large sample of pseudo-redshifts predicted by our machine learning model, which is based on the Yonetoku correlation. This allowed us to explore how large number of GRBs can help constrain cosmological parameters.

- Specifically, we fit the Yonetoku parameters (k, m) simultaneously with the cosmological parameters (H_0, Ω_Λ).

- Our pseudo-redshift sample spans a wide redshift range from **z = 0.6 to 6.3**. To improve constraints at lower redshifts, we also included GRBs with known redshifts and combined them with SNe Ia data from **Suzuki et al. (2012)** and the **Dark Energy Survey (DES)**.

- We compared our best-fit values of H_0, Ω_Λ with results from other major studied:
  - Our H_0 value higher than Planck 2018, but lower than Riess 2022.
  - For Ω_Λ the all results are consistent within uncertainties.

Source	H_0 (km/s/Mpc)	Ω_Λ	Data	References
GBM pseudo+true z	69.88 ± 0.44	0.72 ± 0.02	GRB + SNe	-
GBM true z	69.86 ± 0.43	0.72 ± 0.02	GRB + SNe	-
WMAP 9	69.3 ± 0.8	0.721 ± 0.015	CMB	Bennett et al. (2013)
F10 + SNe	70 ± 0.6	0.72 ± 0.03	GRB + SNe	Dirirsa et al. (2019)
F10 W2016 + SNe	70 ± 0.5	0.72 ± 0.03	GRB + SNe	Dirirsa et al. (2019)
Planck 2018	67.4 ± 0.5	0.684 ± 0.0073	CMB	Planck Collaboration et al. (2020)
SDSS/BAO+SNe	68.5 ± 1.0	0.70 ± 0.02	BAO + SNe	Alam et al. (2021)
Riess 2022	73.04 ± 1.04	~ 0.70	Cepheids + SNe	Riess et al. (2022)
Cosmic Chronometers	69.0 ± 1.2	0.70 ± 0.02	Galaxy ages	Moresco (2024)

☺ Thank you