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POTENTIAL USE OF FERMI-LAT GRBS AS COSMOLOGICAL STANDARD CANDLES

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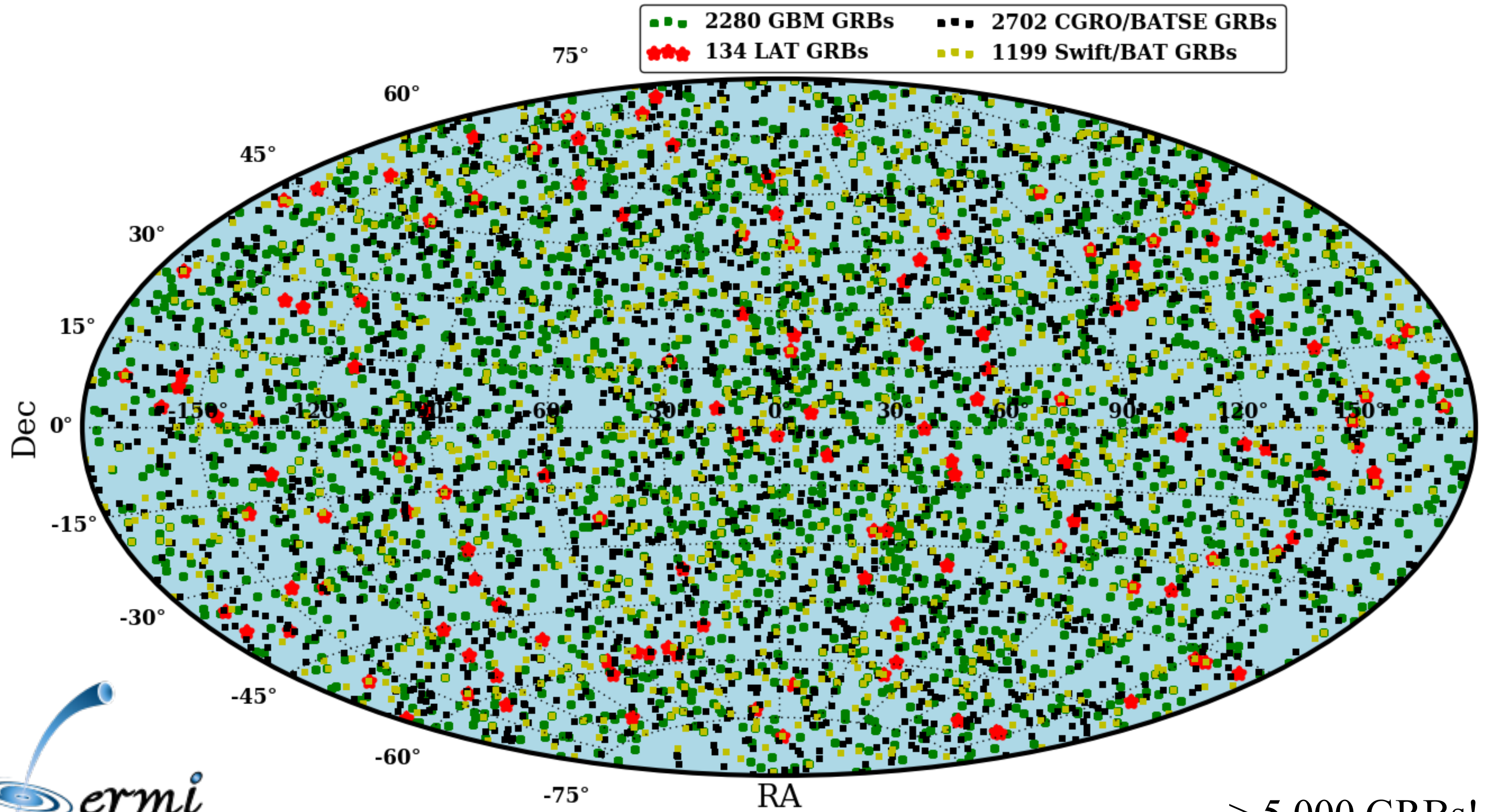
Sky map of *Compton*, *Swift* and *Fermi* GRBs

Until March 23, 2018



> 5,000 GRBs!

Gamma-ray Space Telescope

GRBs as cosmological standard candles

- No physical basis
- (unknown emission mechanism)
- Only phenomenological studies

Light curve

Phenomenological spectra

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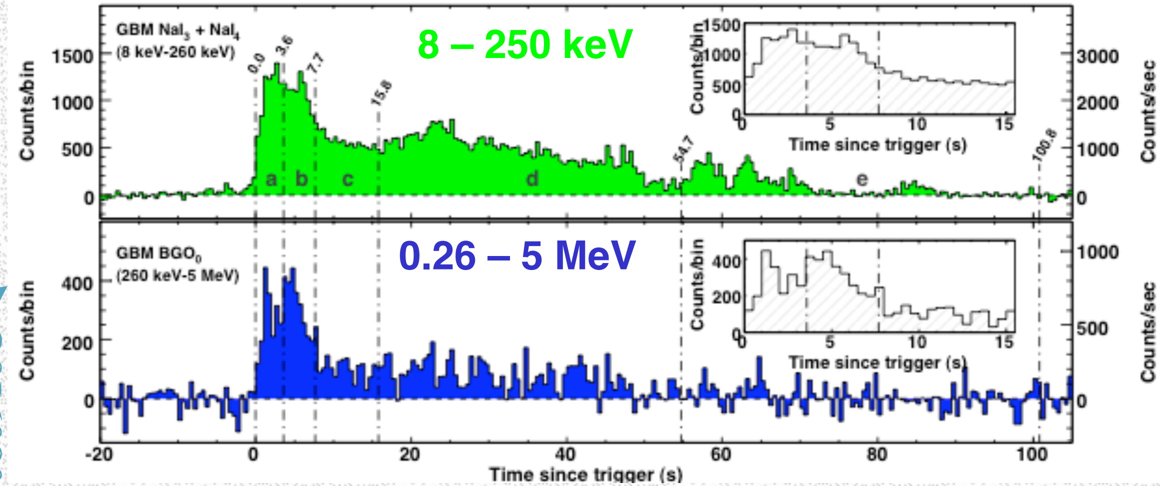
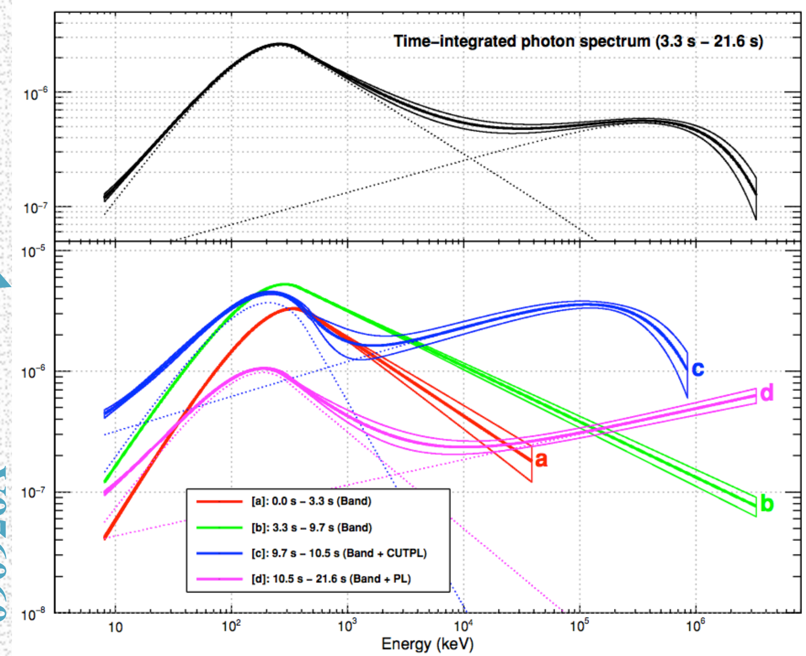


Ackermann+2009

090926A



Time-integrated spectra

Time-resolved spectra

Ackermann+2011

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Amati relation between $E_{i,p}$ and E_{iso}

$$E_{i,p} = E_p(1+z)$$ Intrinsic peak energy of time-integrated energy spectrum

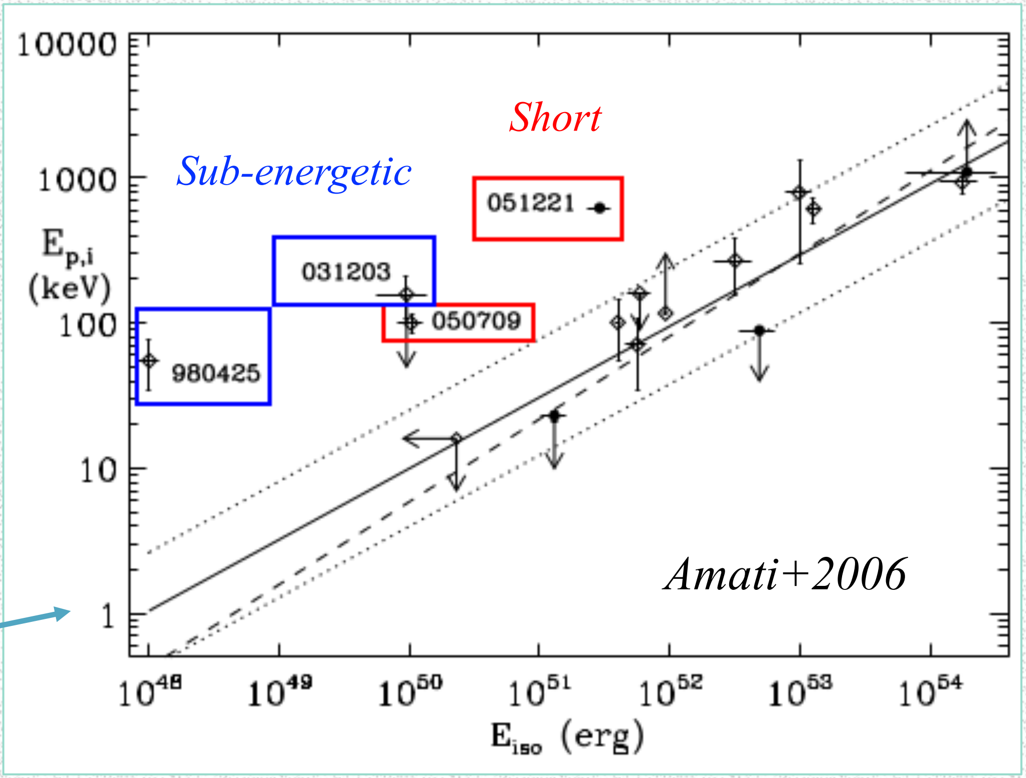
$$E_{iso} = \frac{4\pi d_L^2}{1+z} T_{90} \int_{\frac{1\,\mathrm{keV}}{1+z}}^{\frac{10^4\,\mathrm{keV}}{1+z}} E N(E) dE$$ Isotropic energy release over T_{90} in 1 keV – 10 MeV

Amati relation

$$E_{i,p} = k(E_{iso})^m$$

Amati+2002

Long GRBs



Fermi Gamma-ray Space Telescope

Amati relation between $E_{i,p}$ and E_{iso}

Evolving GRB samples and fits

References–linear fit	N	ρ	m	k	χ^2_ν
Amati et al. (2002)	9	0.92	0.52 ± 0.06	2.02 ± 1.04	3.9
Amati (2003)	20	0.92	0.35 ± 0.06	2.07 ± 0.95	6.1
Ghirlanda et al. (2004c)	27	0.80	0.40 ± 0.05	1.98 ± 0.85	6.2
Friedman & Bloom (2005)	29	0.88	0.50 ± 0.04	1.95 ± 0.90	9.5
Nava et al. (2006)	18	0.82	0.57 ± 0.02	1.85 ± 0.30	5.2
Amati (2006)	39	0.89	0.57 ± 0.02	1.90 ± 0.60	7.2
Amati (2006) (XRFs 020903 and 050416)	41	0.89	0.57 ± 0.02	1.91 ± 0.30	6.9
Amati (2006) (with sample variance)	41	0.89	$0.49^{+0.06}_{-0.05}$	$1.98^{1.04}_{-0.95}$	0.98
Amati et al. 2008 (A2008)	70	0.87	0.57 ± 0.01	1.97 ± 0.30	6.0
F. Dirirsa and S. Razzaque (2016)	5	0.90	0.56 ± 0.02	0.79 ± 0.30	6.69

References – likelihood method	N	ρ	m	k	σ_{ext}
Amati et al. 2008	70	0.87	0.54 ± 0.03	1.99 ± 0.85	0.17 ± 0.02
Demianski et al. 2016 (D2016)	162	-	-	~ 0.58	~ 0.24
Wang et al. 2016 (W2016)	151	-	-	1.42 ± 0.11	0.34 ± 0.03

Potential for cosmological application – Standard candles (?)

Amati relation with Fermi-LAT GRBs

- **Dedicated analysis of a uniform sample from a single spacecraft**
  - Fermi-GBM and LAT data
- **Detailed modeling of time-integrated spectra**
  - Multiple components required for fitting GBM+LAT data for some GRBs
  - More reliable Ep and Eiso measurements
  - Extension of Eiso calculation to 100 MeV

- **Test Amati relation for GRBs emitting at >100 MeV**
- **Compare Fermi-LAT sample of GRBs with other GRB sample: Revised *Wang+2016* sample**
  - 94 GRBs from BATSE, BeppoSAX, HETE-2, Swift-BAT, Konus Wind, Suzaku-WAM, Fermi-GBM (without Fermi-LAT bursts)
  - Updated Eiso calculation

Fermi-LAT GRBs with known redshift

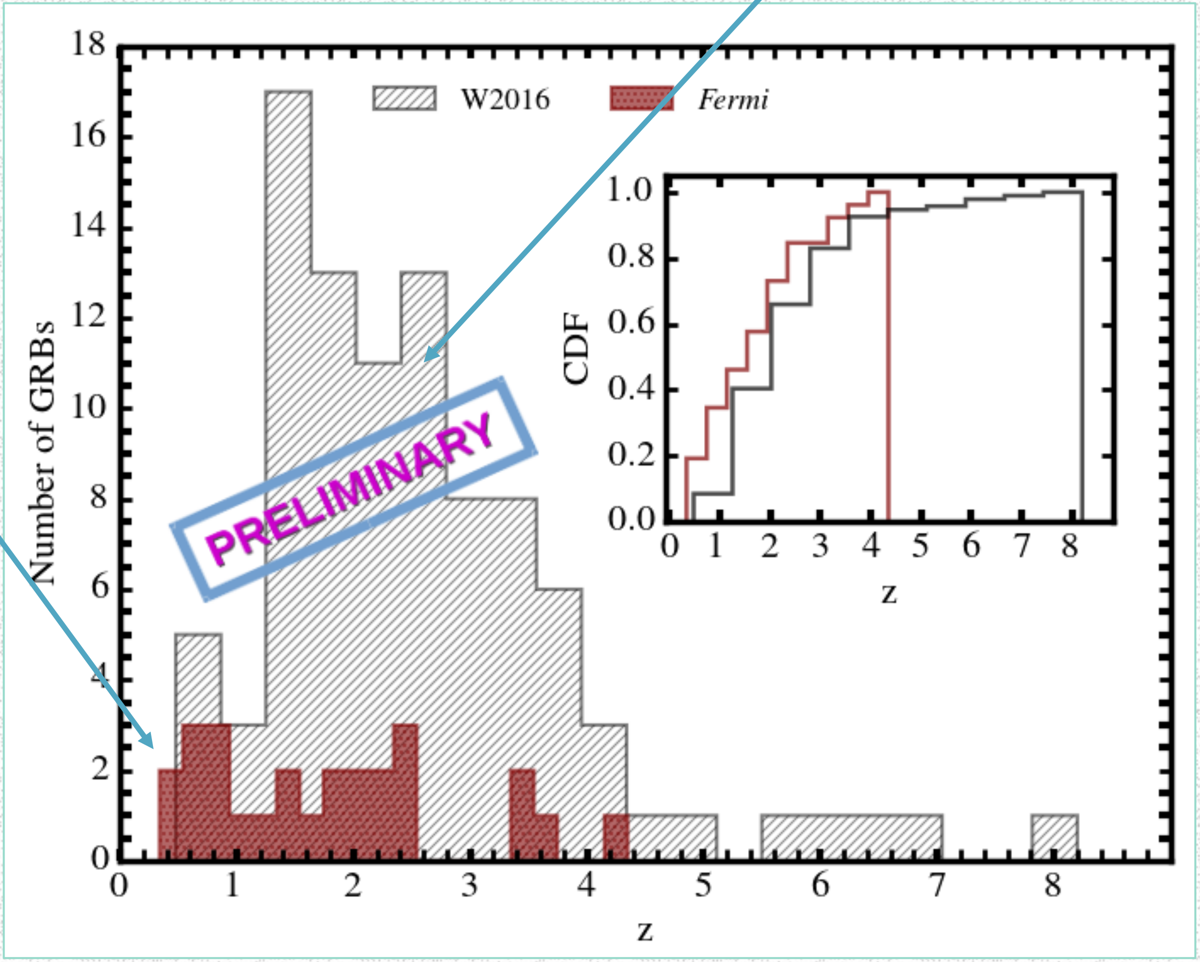
~ 115 GBM GRBs with known z (~1 GRB/month)

Wang+2016 sample

25 long + 1 short GRB detected by LAT with known redshift

***Fermi* sample**

11 June 2008 – 30 April 2017



Fermi Gamma-ray Space Telescope

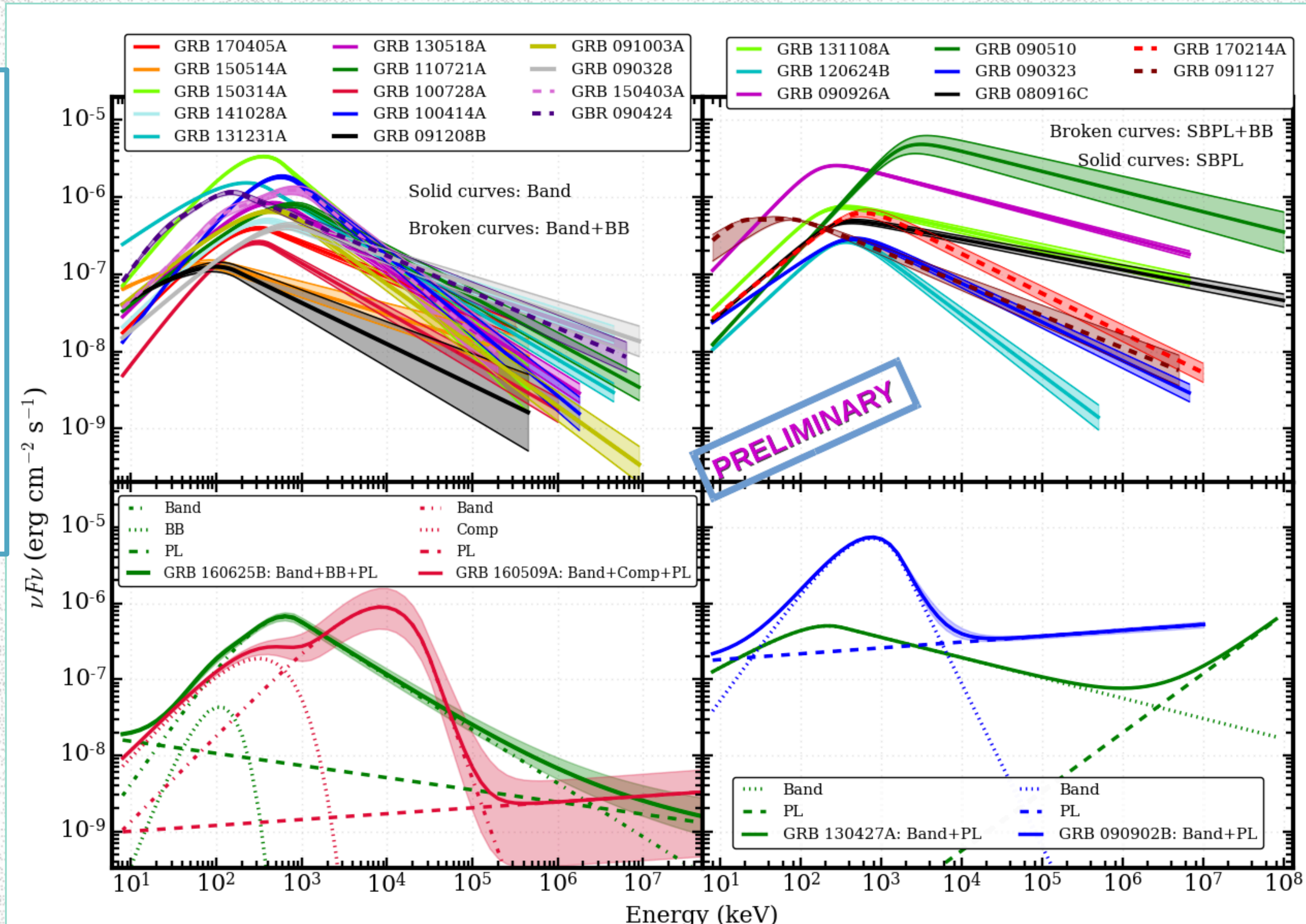
Fermi data analysis

- **GBM (8 keV - 40 MeV energy range)**
  - 2 BGO detectors: b0 (210 keV-40 MeV) and b1 (220 keV-40 MeV)
  - 12 NaI detectors: (8-900 keV)
  - GBM TTE data with 2 μs precision in 128 energy channels
- **LAT (30 MeV - 300 GeV energy range)**
  - Pass 8 Transient 20E data with correct energy dispersion
  - 12^{o} Radius Of Interest (ROI)
  - Binned likelihood analysis
- **RMFIT package for spectral analysis**
  - Band, Smoothly-broken power law, Power law, Compton, Blackbody and combinations

Time-integrated spectra of 25 LGRBs and 1 SGRB

Band, Smoothly-broken power law, Power law, Compton, Blackbody and combinations

12 : Band
5 : SBPL
3 : Band+BB
2 : SBPL+BB
2 : Band+PL
1 : Band+BB +PL
1 : Band+Comp +PL



Gamma-ray Space Telescope

Fluence, Ep and Eiso distributions of LAT GRBs

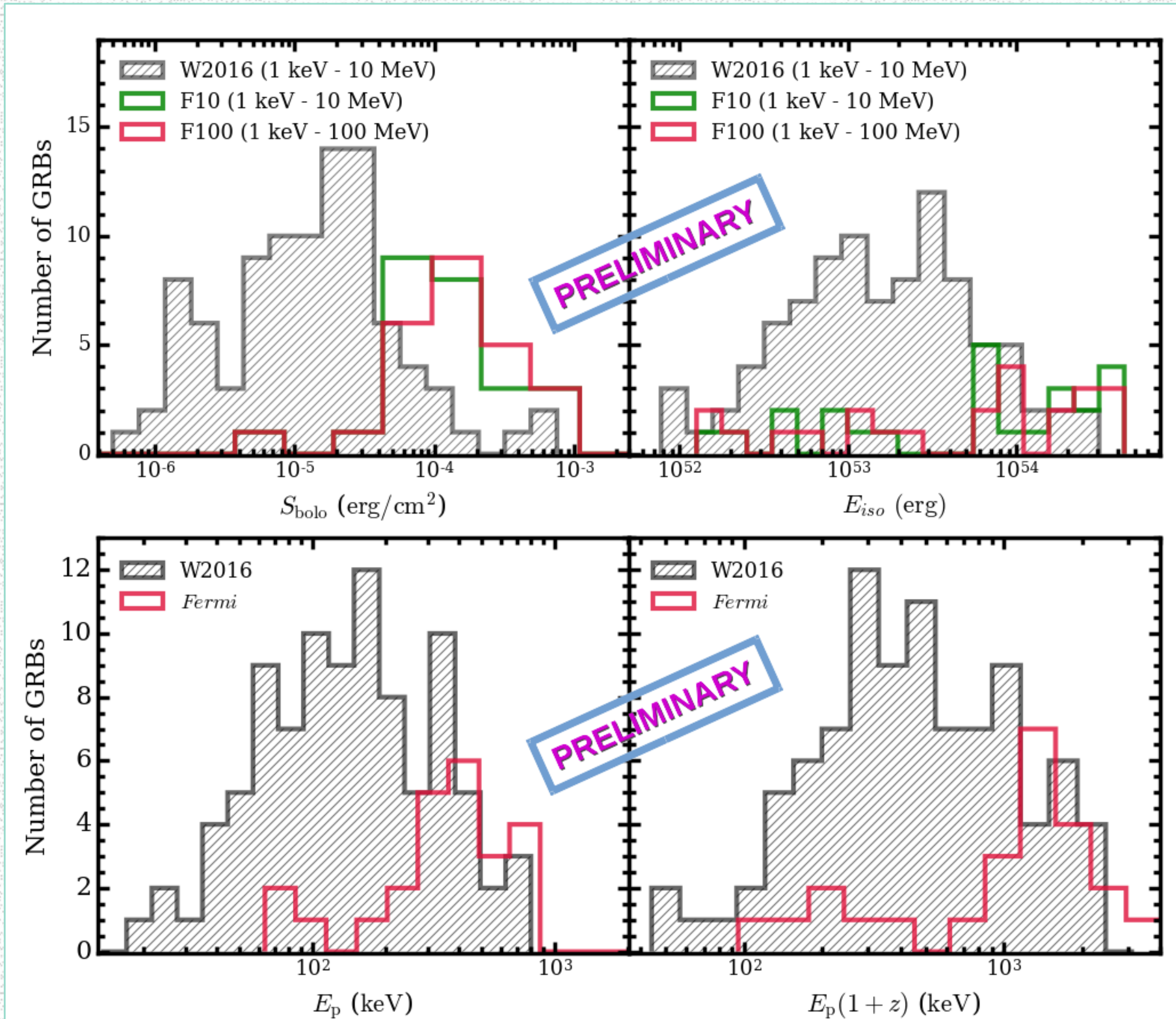
Fermi samples of 25 long GRBs

<u>F10 sample</u>
1 keV – 10 MeV

<u>F100 sample</u>
1 keV – 100 MeV

W2016 sample of 94 long GRBs

1 keV – 10 MeV



Fermi Gamma-ray Space Telescope

Amati relation for Fermi-LAT GRBs with known z

Linearized relation:

$$y = mx + k \; ; \; y \equiv \log_{10} \frac{E_{\rm iso}}{E_{\rm 0,iso}} \; , \; x \equiv \log_{10} \frac{E_{\rm i,p}}{E_0}$$

Likelihood fit: *D'Agostinit 2005*

Extrinsic systematics

$$L(m, k, \sigma_{\rm ext}) = \frac{1}{2} \sum_i^N \ln(\sigma_{\rm ext}^2 + \sigma_{y_{\rm i}}^2 + m^2 \sigma_{x_{\rm i}}^2) + \frac{1}{2} \sum_i^N \frac{(y_{\rm i} - m x_{\rm i} - k)^2}{(\sigma_{\rm ext}^2 + \sigma_{\rm y_i}^2 + m^2 \sigma_{x_{\rm i}}^2)}$$

Errors on parameters: *Demianski+Piedipalumbo 2011*

$$\int_{q_{\rm i,min}}^{q_{\rm i,med}} \mathcal{L}_{\rm i}(q_{\rm i}) dq_{\rm i} = \frac{1}{2} \int_{q_{\rm i,min}}^{q_{\rm i,max}} \mathcal{L}_{\rm i}(q_{\rm i}) dq_{\rm i}$$

$$\int_{q_{\rm i,l}}^{q_{\rm i,med}} \mathcal{L}_{\rm i}(q_{\rm i}) dq_{\rm i} = (1 - \eta) \int_{q_{\rm i,min}}^{q_{\rm i,med}} \mathcal{L}_{\rm i}(q_{\rm i}) dq_{\rm i}$$

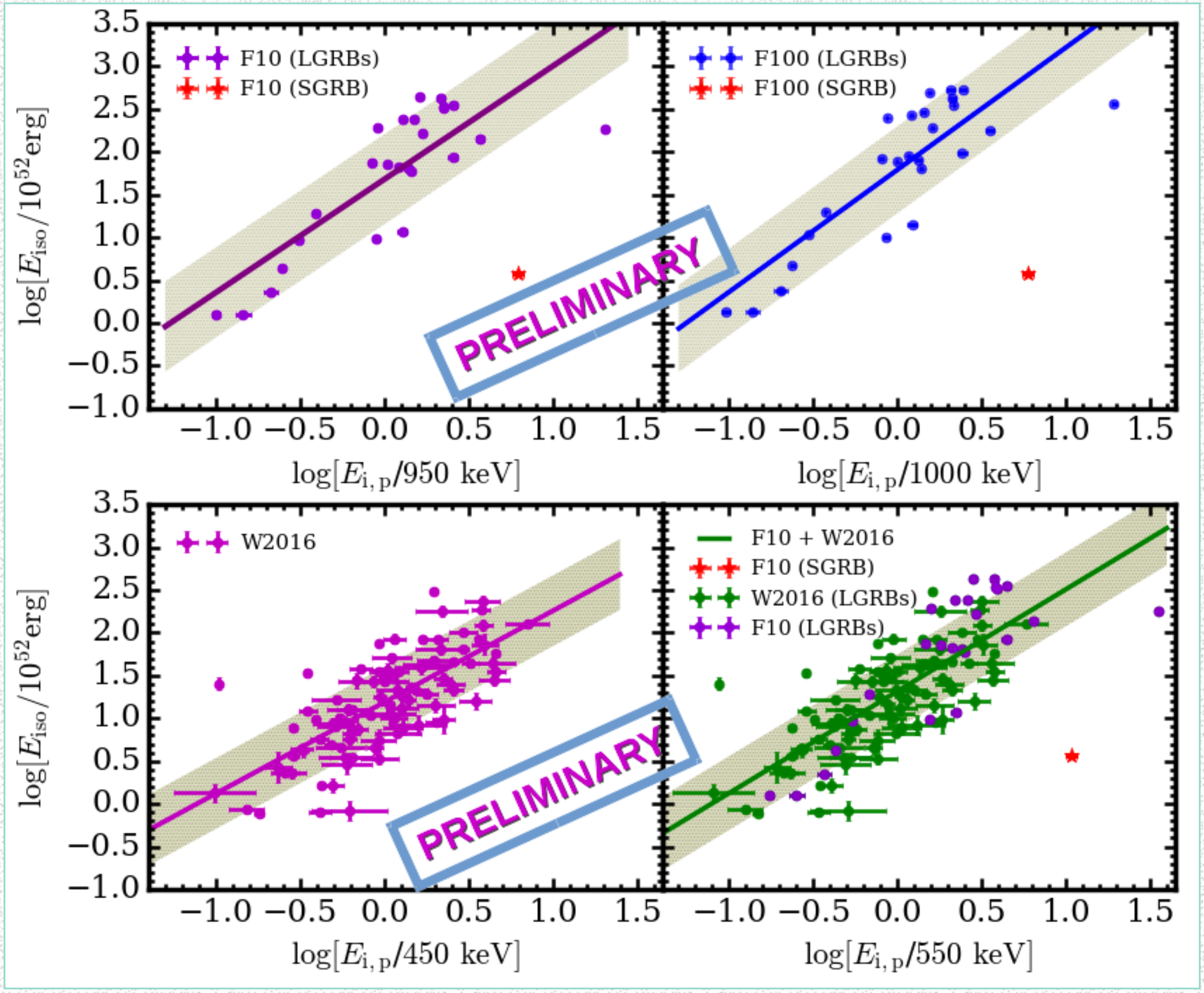
$$\sigma_{\rm y} = \sqrt{\sigma_k^2 + m^2 \sigma_x^2 + \sigma_m^2 x^2 + \sigma_{\rm ext}^2}$$

Wang+2016; Demianski+2017

Amati relation for Fermi-LAT GRBs with known z

Fits with 1σ scatter for separate and combined samples for

F10
F100
W2016
F10+W2016



Gamma-ray Space Telescope

Amati relation for Fermi-LAT GRBs with known z

Best fit:

$$\frac{E_{\rm iso}}{10^{52}\ {\rm erg}} = 10^{1.68\pm0.18}\left(\frac{E_{\rm i,pk}}{950\ {\rm keV}}\right)^{1.32\pm0.38}$$

F10 sample
(1 keV – 10 MeV)

Fits for various other samples and combinations

Full LGRB samples	No. of GRBs	ρ	$E_{0,\rm dec}$ (keV)	m	k	$\sigma_{\rm ext}$
F10	25	0.72	950	1.32 ± 0.38	1.68 ± 0.18	0.46 ± 0.13
F100	25	0.76	1000	1.43 ± 0.37	1.79 ± 0.18	0.44 ± 0.13
W2016	94	0.71	450	1.07 ± 0.20	1.19 ± 0.08	0.38 ± 0.06
F10+W2016	119	0.77	550	1.19 ± 0.16	1.32 ± 0.07	0.41 ± 0.05
$z > 1.414$ samples						
F10	14	0.18	1300	0.70 ± 0.63	2.16 ± 0.13	0.26 ± 0.09
W2016	84	0.71	500	1.02 ± 0.17	1.22 ± 0.07	0.37 ± 0.05
F10+W2016	98	0.77	550	1.18 ± 0.18	1.34 ± 0.07	0.38 ± 0.06

- Slight difference in parameters between F10 and F100 samples
- Noticeable difference with other samples in some cases
- Error is dominated by unknown systematics in all cases

Constraints on Cosmological parameters

ΛCDM flat cosmology: $\Omega_m + \Omega_\Lambda = 1$

Distance modulus: $$\mu(z) = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25$$

From Amati relation

Calculate for each GRB in the sample:

$$d_L = \left[\frac{1+z}{4\pi}\frac{E_{0,\mathrm{iso}}}{S_{\mathrm{bolo}}}10^k\left(\frac{E_{\mathrm{i,p}}}{E_{0,\mathrm{dec}}}\right)^m\right]^{1/2}$$

$$\sigma_\mu(z) = \left[\left(\frac{5}{2}\sigma_{\log E_{\mathrm{iso}}}\right)^2 + \left(\frac{5}{2\ln 10}\frac{\sigma_{S_{\mathrm{bolo}}}}{S_{\mathrm{bolo}}}\right)^2\right]^{1/2}$$

$$\sigma^2_{\log E_{\mathrm{iso}}} = \left(\sigma_m \log\frac{E_{\mathrm{i,p}}}{E_{0,\mathrm{dec}}}\right)^2 + \left(\frac{m}{\ln 10}\frac{\sigma_{E_{\mathrm{i,p}}}}{E_{\mathrm{i,p}}}\right)^2 + \sigma_k^2 + \sigma_{\mathrm{ext}}^2.$$

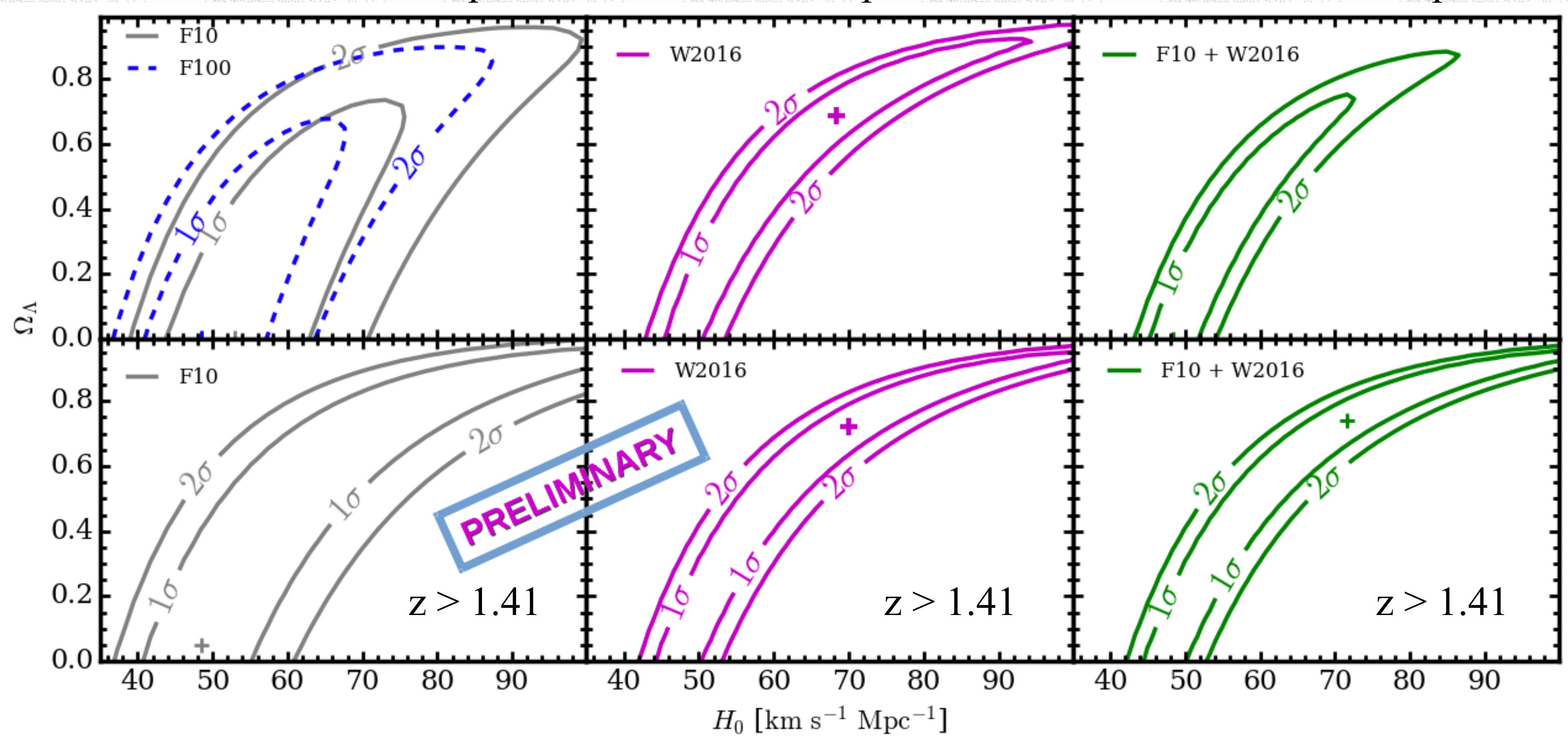
$$\chi^2(H_0,\Omega_\Lambda) = \sum_{i=0}^{N}\frac{\left(\mu(z_i) - \mu^{\mathrm{pred}}(z_i; H_0, \Omega_\Lambda)\right)^2}{\sigma^2_{\mu(z_i)}}$$

H_0 and Ω_Λ free

Gamma-ray Space Telescope

Constraints on Cosmological parameters

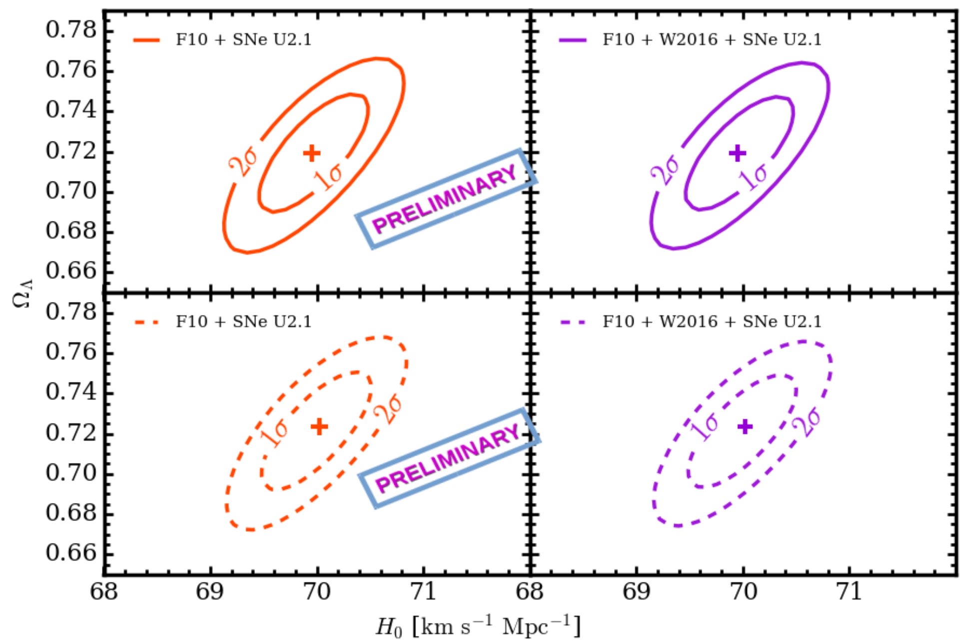
F10 / F100 sample W2016 sample F10+W2016 sample

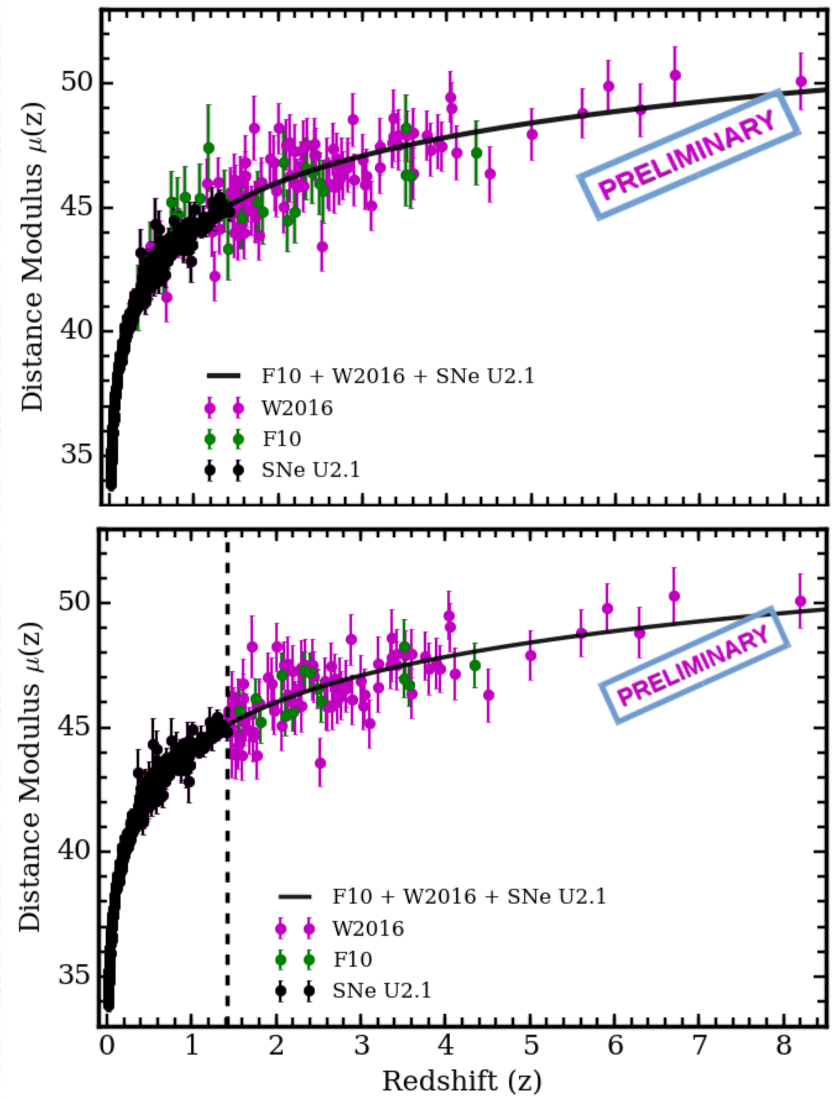


- Constraints on H_0 and Ω_Λ can be obtained for some cases
- Errors on parameters are rather large

Constraints on Cosmological parameters

Constraints with combination of type Ia SNe data





Type Ia SNe data:
U2.1 sample of 580 SNe
$0.015 < z < 1.414$

Suzuki+2012

UJ CAPP

Constraints on Cosmological parameters

Constraints for various samples and combinations

Reference (all sample)	H_0 [km s^{-1} Mpc^{-1}]	Ω_Λ	χ^2/dof
F10	53^{+23}_{-9}	0	15.6/23
F100	48^{+19}_{-7}	0	18.6/23
W2016	68^{+26}_{-23}	$0.69^{+0.2}_{-0.69}$	87.2/92
F10 + W2016	48^{+24}_{-3}	0	110.6/117
SNe U2.1	$69.95^{+0.58}_{-0.46}$	0.72 ± 0.03	562.3/578
F10 + SNe U2.1	$69.95^{+0.49}_{-0.56}$	0.72 ± 0.03	580.4/603
F10 + W2016 + SNe U2.1	$69.95^{+0.54}_{-0.48}$	0.72 ± 0.03	667.6/697
Sample with $z > 1.414$			
F10	48^{+51}_{-8}	$0.05^{+0.9}_{-0.1}$	8.3/12
W2016	69.95^{+30}_{-26}	$0.72^{+0.23}_{-0.72}$	78.4/82
F10 + W2016	71.61^{+28}_{-27}	$0.74^{+0.22}_{-0.74}$	93.1/96
F10 + SNe U2.1	$70.03^{+0.49}_{-0.55}$	0.72 ± 0.03	580.4/592
F10 + W2016 + SNe U2.1	$70.03^{+0.48}_{-0.54}$	0.72 ± 0.03	648.8/676

- Combined F10+W2016+SNe sample gives the best fit
- Dominated by type Ia SNe data

Take home points

- **Detailed spectral analysis of 26 Fermi GRBs detected both by LAT and GBM with known redshift in 9.5 years of data**
  - Multiple spectral components in a number of GRBs
  - Eiso calculation up to 100 MeV
- **Amati relation for Fermi-LAT GRBs is consistent with relation derived from other samples (e.g., *Wang+2016, Demianski+2017*) in literature**
  - Large scatter in fit parameters, dominated by unknown systematics
- **Constraints on flat ΛCDM cosmological model with 2 free parameters: H_0, Ω_Λ**
  - Fermi-LAT GRBs and/or another GRB sample can constrain parameters in some cases (including $z > 1.414$, beyond type Ia SNe redshift)
  - The errors on the parameters are too large at present

Increased GRB sample with known redshift in future can be interesting

Backup Slides

Details of Spectral fits

Fermi sample of 25 GRBs with selected detectors and results from the spectral model fits of time-integrated flux within T_{90}

GRB name	detectors	model	$T_{05} - T_{95}$ (s)	α, γ	β	E_p, E_0 (keV)	kT (keV)	α_1	C-Stat/dof$^{(*)}$
GRB 170405A	n6+n7+n9+nb+b1+LAT	Band	7.36-86.08	-0.84 ± 0.01	-2.44 ± 0.02	315.8 ± 7.78			1544.1/588
GRB 170214A	n0+n1+n3+b0+LAT	SBPL+BB	12.54-135.49	-1.17 ± 0.02	-2.51 ± 0.01	507.7 ± 34.9	41.99 ± 1.28		1253.7/368
GRB 160625B	n7+n9+b1+LAT	Band+BB+PL	188.45-650.54	-0.40 ± 0.06	-2.70 ± 0.02	642.92 ± 15.48	27.94 ± 1.09	-2.16 ± 0.04	1462.9/354
GRB 160509A	n0+n1+n3+b0+LAT	Band+Comp+PL	7.68-379.4	-0.87 ± 0.08	-5.16 ± 0.49	8591.48 ± 68.27			
				-0.79 ± 0.04		317.14 ± 16.60		-1.76 ± 0.10	1741.9/474
GRB 150514A	n3+n6+n7+b0+LAT	Band	0.00-10.8	-1.45 ± 0.08	-2.33 ± 0.05	76.28 ± 8.26			590.57/472
GRB 150403A	n3+n4+b0+LLE	Band+BB	3.33-25.60	-1.02 ± 0.02	-2.95 ± 0.10	793.63 ± 52.55	33.30 ± 1.58		524.75/358
GRB 150314A	n0+na+n1+n9+b1+LAT	Band	0.6-11.29	-0.63 ± 0.01	-3.02 ± 0.10	357.38 ± 4.78			1333.0/588
GRB 141028A	n6+n7+n9+b1+LAT	Band	6.66-38.16	-0.91 ± 0.02	-2.37 ± 0.02	396.45 ± 15.29			691.79/473
GRB 131231A	n0+n3+n7+b0+LAT	Band	13.31-44.31	-1.23 ± 0.01	-2.65 ± 0.03	225.17 ± 3.02			1665.0/476
GRB 131108A	n0+n3+n6+n7+b0+b1+LAT	SBPL	0.32 - 19.32	-0.99 ± 0.02	-2.23 ± 0.01	205.32 ± 6.91			950.58/716
GRB 130518A	n3+n6+n7+b0+b1+LAT	Band	9.9-57.9	-0.89 ± 0.01	-2.71 ± 0.03	458.85 ± 9.22			1357.1/592
GRB 130427A	n6+n9+na+b1+LAT	Band+PL	11.23-142.34	-1.41 ± 0.01	-2.27 ± 0.01	219.61 ± 4.38		-1.22 ±0.21	2105.1/488
GRB 120624B	n1+n2+na+b0+b1+LAT	SBPL	-258.05-13.31	-1.04 ± 0.01	-2.78 ± 0.04	352.9 ± 11.4			2015.7/588
GRB 110721A	n6+n7+n9+b1+LAT	Band	0.45 - 24.9	-1.12 ± 0.01	-2.60 ± 0.03	780.87 ± 43.32			666.74/473
GRB 100728A	n0+n1+n2+n5+b0+LAT	Band	13.25-178.75	-0.52 ± 0.02	-2.63 ± 0.04	310.7 ± 7.06			3075.3/595
GRB 100414A	n7+n9+n11+b1+LAT	Band	2.0 - 28.4	-0.50 ± 0.02	-2.91 ± 0.06	578.89 ± 11.69			750.82/469
GRB 091208B	n10+n9+b1+LAT	Band	0.26 - 15.26	-1.29 ± 0.07	-2.53 ± 0.12	98.22 ± 9.74			422.09/351
GRB 091127	n6+n7+n9+b1+LAT	SBPL+BB	0.00-7.80	-1.40 ± 0.11	-2.42 ± 0.04	56.80 ± 7.38	4.44 ± 0.26		694.34/477
GRB 091003A	n0+n3+n6+b0+b1+LAT	Band	1.09 - 22.19	-1.08 ± 0.01	-2.79 ± 0.05	452.21 ± 17.44			674.54/600
GRB 090926A	n6+n7+n8+b1+LAT	SBPL	2.05-22.05	-0.90 ± 0.01	-2.27 ± 0.01	171.50 ± 2.36			945.02/478
GRB 090902B	n0+n2+n9+b0+b1+LAT	Band+PL	0-22	-0.53 ± 0.01	-4.14 ± 0.28	760.66 ± 7.69		-1.92 ± 0.01	1320.6/601
GRB 090510	**n3+n6+n7+n9+b0+b1+LAT**	**SPBL**	**0.002-1.744**	**-0.86 ± 0.03**	**-2.26 ± 0.03**	**1873.00 ± 212.70**			**788.82/720**
GRB 090424	n7+n8+nb+b1+LAT	Band+BB	0.448-14.720	-0.58 ± 0.06	-2.47 ± 0.04	153.3 ± 3.74	7.32 ± 0.37		811.17/472
GRB 090328	n7+n8+b1+LAT	Band	4.67-61.67	-1.04 ± 0.02	-2.37 ± 0.04	703.75 ± 47.16			769.08/360
GRB 090323	n6+n7+n9+n11+b1+LAT	SBPL	-1.0 - 173	-1.29 ± 0.01	-2.50 ± 0.02	399.44 ± 17.17			1558.6/597
GRB 080916C	n3+n4+b0+LAT	SBPL	0 - 66	-1.11 ± 0.01	-2.20 ± 0.01	270.46 ± 12.20			579.20/364

Notes: α and β are the lower and higher photon indices for the Band and SBPL functions, respectively. γ is the photon index of Comp model while α_1 is that of the PL. E_0 is the SBPL e-folding energy and E_p is the Band or Comp peak energy. kT is the BB temperature. The C-Stat/dof$^{(*)}$ is the ratio of the C-stat resulting from the fit and the associated degrees of freedom (dof). GRB 090510 is the only short GRB in the sample.

Details of Fluence and Eiso calculations

Intrinsic peak energy $E_{\rm i,p}$ and isotropic radiated energy $E_{\rm iso}$ for the *Fermi* GRB sample

GRB name	z	$E_{\rm i,p}$ (keV)	$E^{*}_{\rm iso}$ (10^{52} erg)	$S^{*}_{\rm bolo}$ (10^{-5} erg/cm^2)	$\mu \pm \sigma^{\dagger}_{\mu}$	$E^{**}_{\rm iso}$ (10^{52} erg)	$S^{**}_{\rm bolo}$ (10^{-5} erg/cm^2)	$\mu \pm \sigma^{\ddagger}_{\mu}$	References for redshift
GRB 170405A	3.51	1424.42 ± 35.24	240.00 ± 2.41	9.24 ± 0.09	46.30 ± 1.25	293.00 ± 4.87	11.28 ± 0.19	46.41 ± 1.20	de Ugarte Postigo et al. (2017)
GRB 170214A	2.53	2119.788 ± 119.06	338.00 ± 4.36	22.40 ± 0.29	45.65 ± 1.28	425.00 ± 6.10	28.22 ± 0.40	45.77 ± 1.20	Kruehler et al. (2017)
GRB 160625B	1.406	1546.86 ± 37.25	435.01 ± 6.06	83.54 ± 1.16	43.35 ± 1.25	494.13 ± 7.34	94.87 ± 1.42	43.55 ± 1.20	Xu et al. (2016)
GRB 160509A	1.17	19334.10 ± 652.25	182.68 ± 4.97	49.91 ± 1.36	47.42 ± 1.75	364.81 ± 13.81	99.73 ± 3.79	47.30 ± 1.27	Tanvir et al. (2016)
GRB 150514A	0.807	137.84 ± 14.93	1.26 ± 0.05	0.71 ± 0.03	44.74 ± 1.48	1.37 ± 0.07	0.78 ± 0.04	44.70 ± 1.24	de Ugarte Postigo et al. (2015a)
GRB 150403A	2.06	2428.51 ± 160.80	85.20 ± 1.81	8.10 ± 0.17	46.79 ± 1.30	95.30 ± 2.72	9.06 ± 0.27	47.06 ± 1.21	Pugliese et al. (2015)
GRB 150314A	1.758	985.66 ± 13.20	72.70 ± 0.96	9.20 ± 0.12	45.25 ± 1.24	76.00 ± 1.72	9.61 ± 0.22	45.49 ± 1.19	de Ugarte Postigo et al. (2015b)
GRB 141028A	2.33	1320.18 ± 50.90	64.00 ± 0.74	4.89 ± 0.06	46.56 ± 1.24	79.80 ± 1.24	6.10 ± 0.09	46.64 ± 1.20	Xu et al. (2014)
GRB 131231A	0.6439	370.15 ± 4.97	19.20 ± 0.13	17.42 ± 0.12	42.58 ± 1.30	20.10 ± 0.20	18.23 ± 0.18	42.71 ± 1.20	Cucchiara (2014)
GRB 131108A	2.40	1163.20 ± 28.54	66.80 ± 0.65	4.85 ± 0.05	46.41 ± 1.24	89.90 ± 1.19	6.53 ± 0.09	46.39 ± 1.19	de Ugarte Postigo et al. (2013a)
GRB 130518A	2.49	1601.40 ± 32.19	167.00 ± 1.53	11.40 ± 0.11	45.97 ± 1.26	189.00 ± 2.48	12.92 ± 0.17	46.18 ± 1.20	Sanchez-Ramirez et al. (2013)
GRB 130427A	0.3399	294.25 ± 5.86	9.29 ± 0.06	31.72 ± 0.20	41.38 ± 1.33	10.65 ± 0.12	36.34 ± 0.39	41.38 ± 1.21	Levan et al. (2013)
GRB 120624B	2.2	1214.47 ± 26.24	242.00 ± 2.95	20.49 ± 0.25	44.84 ± 1.24	267.00 ± 4.65	22.63 ± 0.39	45.04 ± 1.19	de Ugarte Postigo et al. (2013b)
GRB 110721A	3.512	3523.30 ± 195.47	139.00 ± 2.64	5.35 ± 0.10	48.20 ± 1.35	179.00 ± 4.40	6.89 ± 0.17	48.36 ± 1.21	Berger (2011)
GRB 100728A	1.567	797.62 ± 18.05	75.00 ± 1.06	11.74 ± 0.17	44.60 ± 1.24	82.50 ± 1.74	12.92 ± 0.27	44.76 ± 1.19	Kruehler et al. (2010)
GRB 100414A	1.368	1370.82 ± 27.68	58.70 ± 0.77	11.88 ± 0.16	45.28 ± 1.25	63.50 ± 1.24	12.86 ± 0.25	45.52 ± 1.19	Cucchiara (2010)
GRB 091208B	1.063	202.63 ± 20.10	2.26 ± 0.12	0.75 ± 0.04	45.39 ± 1.40	2.37 ± 0.17	0.78 ± 0.06	45.44 ± 1.23	Wiersema et al. (2009)
GRB 091127	0.49	94.87 ± 5.83	1.27 ± 0.06	2.03 ± 0.09	42.86 ± 1.56	1.35 ± 0.06	2.15 ± 0.10	42.82 ± 1.24	Cucchiara et al. (2009a)
GRB 091003A	0.8969	857.81 ± 33.08	9.58 ± 0.16	4.43 ± 0.08	45.43 ± 1.24	10.20 ± 0.21	4.70 ± 0.10	45.64 ± 1.19	Cucchiara et al. (2009b)
GRB 090926A	2.1062	861.41 ± 8.52	195.00 ± 0.92	17.83 ± 0.08	44.46 ± 1.24	250.00 ± 1.93	22.85 ± 0.17	44.47 ± 1.19	Malesani et al. (2009)
GRB 090902B	1.822	2146.57 ± 21.71	329.00 ± 1.87	39.05 ± 0.22	44.82 ± 1.28	349.00 ± 3.35	41.45 ± 0.40	45.13 ± 1.20	Cucchiara et al. (2009c)
GRB 090510	**0.903**	**5929.71 ± 460.76**	**3.69 ± 0.14**	**1.68 ± 0.07**	-	**6.75 ± 0.32**	**3.08 ± 0.15**	-	Rau et al. (2009)
GRB 090424	0.544	236.83 ± 5.81	4.30 ± 0.08	5.52 ± 0.1	43.12 ± 1.36	4.63 ± 0.12	5.95 ± 0.16	43.17 ± 1.21	Chornock et al. (2009b)
GRB 090328	0.736	1221.71 ± 81.87	11.60 ± 0.29	7.99 ± 0.20	45.20 ± 1.24	14.20 ± 0.45	9.82 ± 0.31	45.29 ± 1.20	Cenko et al. (2009)
GRB 090323	3.57	2060.09 ± 138.07	430.00 ± 10.40	15.76 ± 0.39	46.27 ± 1.28	535.00 ± 17.20	19.64 ± 0.62	46.40 ± 1.20	Chornock et al. (2009a)
GRB 080916C	4.35±0.15	2434.39 ± 106.87	357.00 ± 13.50	9.78 ± 0.15	47.20 ± 1.30	533.00 ± 18.50	14.60 ± 0.23	47.16 ± 1.20	Greiner et al. (2009)

Notes. The bolometric fluence $S^{*}_{\rm bolo}$ and isotropic energy $E^{*}_{\rm iso}$ are computed for the energy range 1-10^4 keV using equations (2) and (1). $S^{**}_{\rm bolo}$ and $E^{**}_{\rm iso}$ are computed for the energy range 1-10^5 keV. $E_{\rm i,p} = (1+z)E_0$ for the SBPL spectral fits, with e-folding energy E_0. $E_{\rm i,p} = (1+z)E_{\rm p}$ for the Band or Comp spectral fits, with peak energy $E_{\rm p}$.

Fermi Gamma-ray Space Telescope

Sensitivity to initial choice of H_0 and Ω_Λ

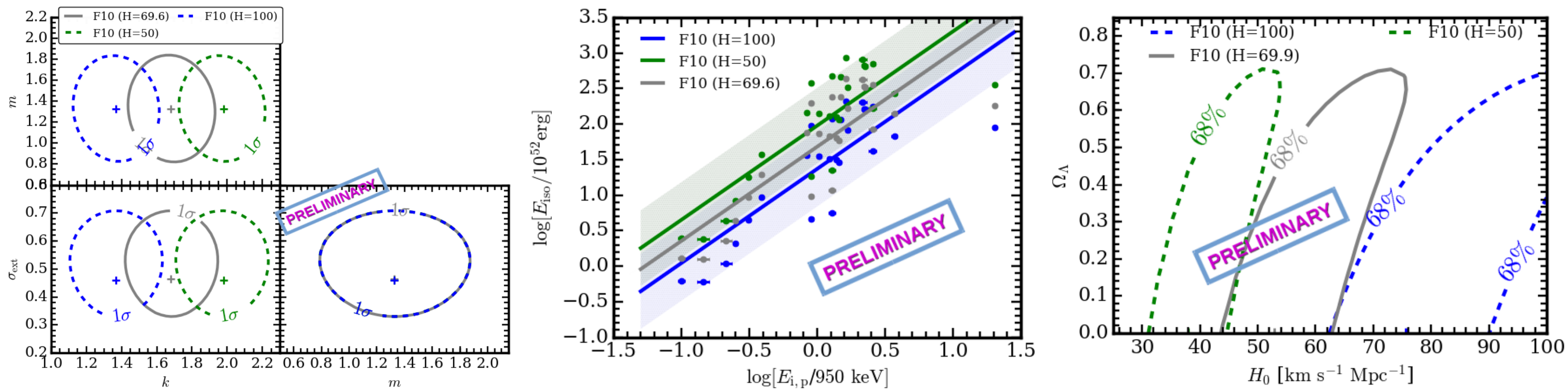


Figure 7. Results from the sensitivity study of the Amati relation and cosmological parameters on the initial choice of H_0 and Ω_Λ to calculate E_{iso}. The grey lines correspond to initial $H_0 = 69.6$ km s^{-1} Mpc^{-1} (default case). The blue and green lines correspond to initial values of $H_0 = 100$ and 50 km s^{-1} Mpc^{-1}, respectively. The initial value of $\Omega_\Lambda = 0.714$ (default case) is the same for all cases.

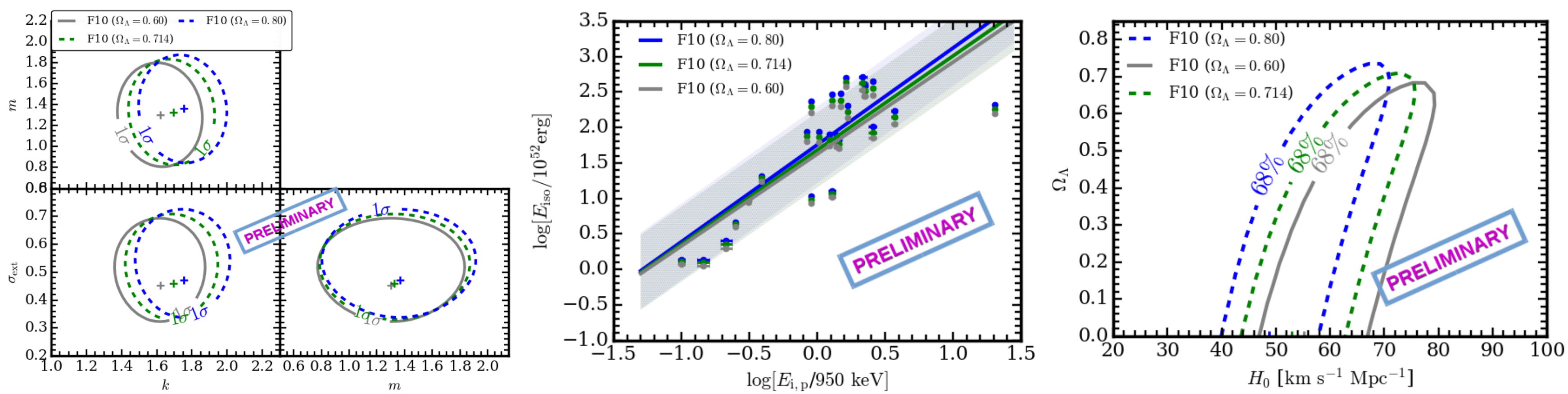


Figure 8. Results from the sensitivity study of the Amati relation and cosmological parameters on the initial choice of H_0 and Ω_Λ to calculate E_{iso}. The grey lines correspond to initial $\Omega_\Lambda = 0.714$ (default case). The blue and green lines correspond to initial values of $\Omega_\Lambda = 0.8$ and 0.6, respectively. The initial value of $H_0 = 69.6$ km s^{-1} Mpc^{-1} (default case) is the same for all cases.