Theseus GRB population models

WG4
Coordinators:
G. Ghirlanda, R. Salvaterra, E. Bozzo

In collaboration with **S. Mereghetti**

INAF-Oss. Astr. Brera
INAF-IASF Milano
ISDC - Geneve

WG4: Population synthesis models

Coordinators: G. Ghirlanda, R. Salvaterra, E. Bozzo

Aims: generate synthetic populations of long and short GRBs calibrated with the largest constraints of multi-mission GRB samples to be used for the investigation of the detection rates and GRB parameter space accessible by Theseus.

Past activities:

- Construction of Long and Short GRB populations (based on actualised version of GRB populations published in GG2014 and GG2016, respectively);
- Development of detection criteria for SXI and XGIS (S. Mereghetti);
- Study of GRB detection rate and contribution to Mission Proposal;
- Participation to the optimisation for the science goals;
- Delivery of GRB population (short & long) to ESA for MOS I and II;
- Delivery of a long GRB afterglow library in the optical/NIR bands.

Studying the GRB populations

$$N(P_1 < P < P_2) = \frac{\Delta\Omega}{4\pi} \int_0^{\infty} dz \frac{dV(z)}{dz} \frac{\Psi(z)}{1+z} \int_{L(P_1,z)}^{L(P_2,z)} \phi(L) dL$$

$$\Psi(z) = \int_z^{\infty} \psi(z') P[t(z) - t(z')] \frac{dt}{dz'} dz'$$

GRB formation rate (GRBFR)

$$\phi(L) \propto \begin{cases} (L/L_b)^{-\alpha_1} & L < L_b \\ (L/L_b)^{-\alpha_2} & L \geq L_b \end{cases}$$

luminosity function (LF)

short GRBs:
NS-NS merger
(delay with respect to SFR)

long GRBs:
associated to SNIb/c
(prop. to SFR but see next)

model assumptions
[GRBFR + LF]

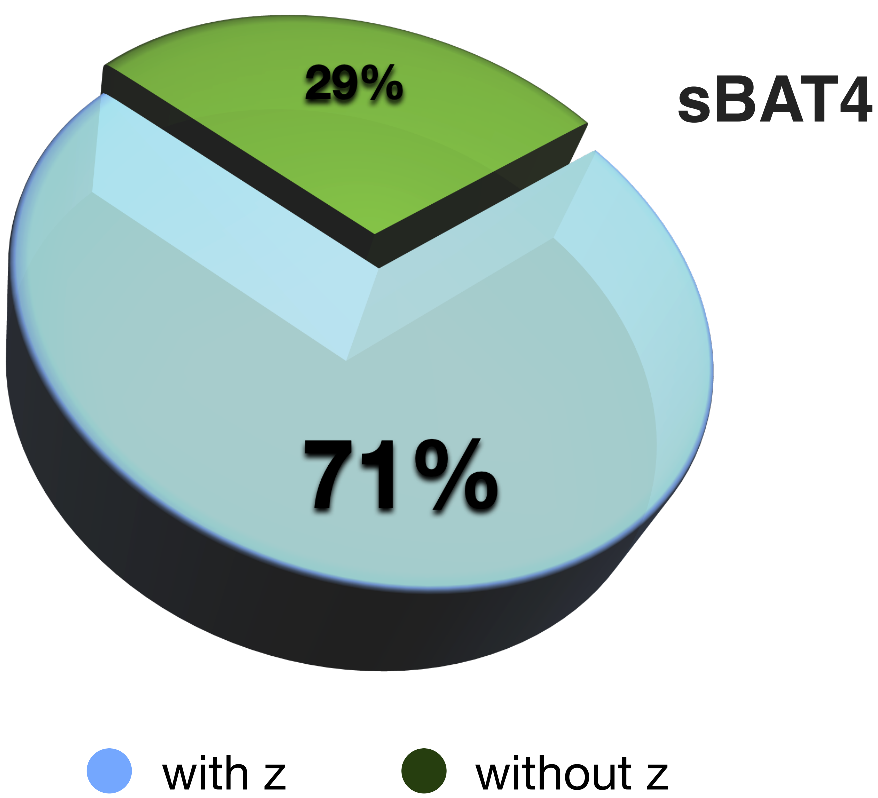
instrument and z-det
[biases]

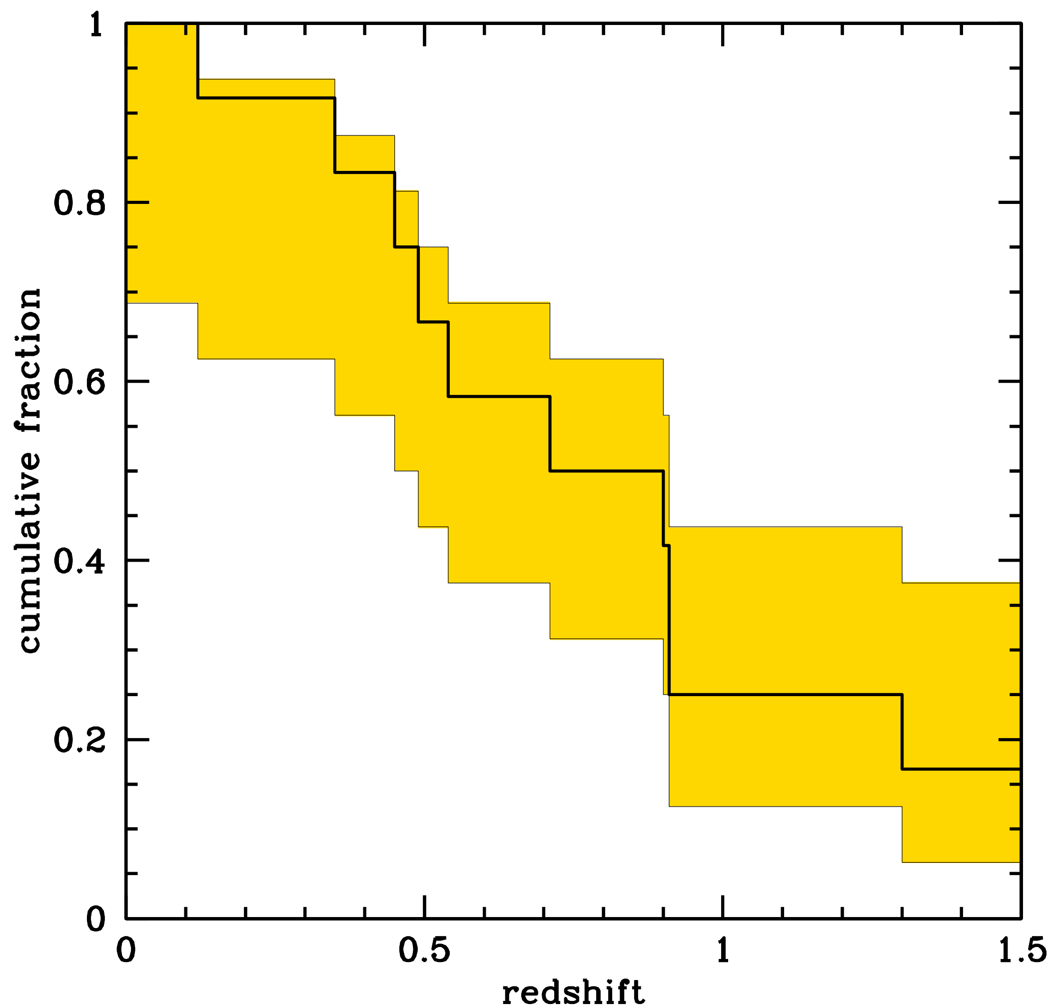
DATA
sub-samples
[BATSE/Fermi, Swift]

Short GRB: the sBAT4 sample

D'Avanzo et al. (2014) constructed a flux limited sample of 16 short GRBs with 70% of redshift measurements

1. promptly repointed by Swift/XRT
2. low Galactic extinction
3. away from Sun
4. **64ms peak flux larger than 3.5 ph s^{-1} cm^{-2}**





the median (average) redshift is 0.72 (0.85) higher than incomplete sample (~0.5; Fong et al. 2013)

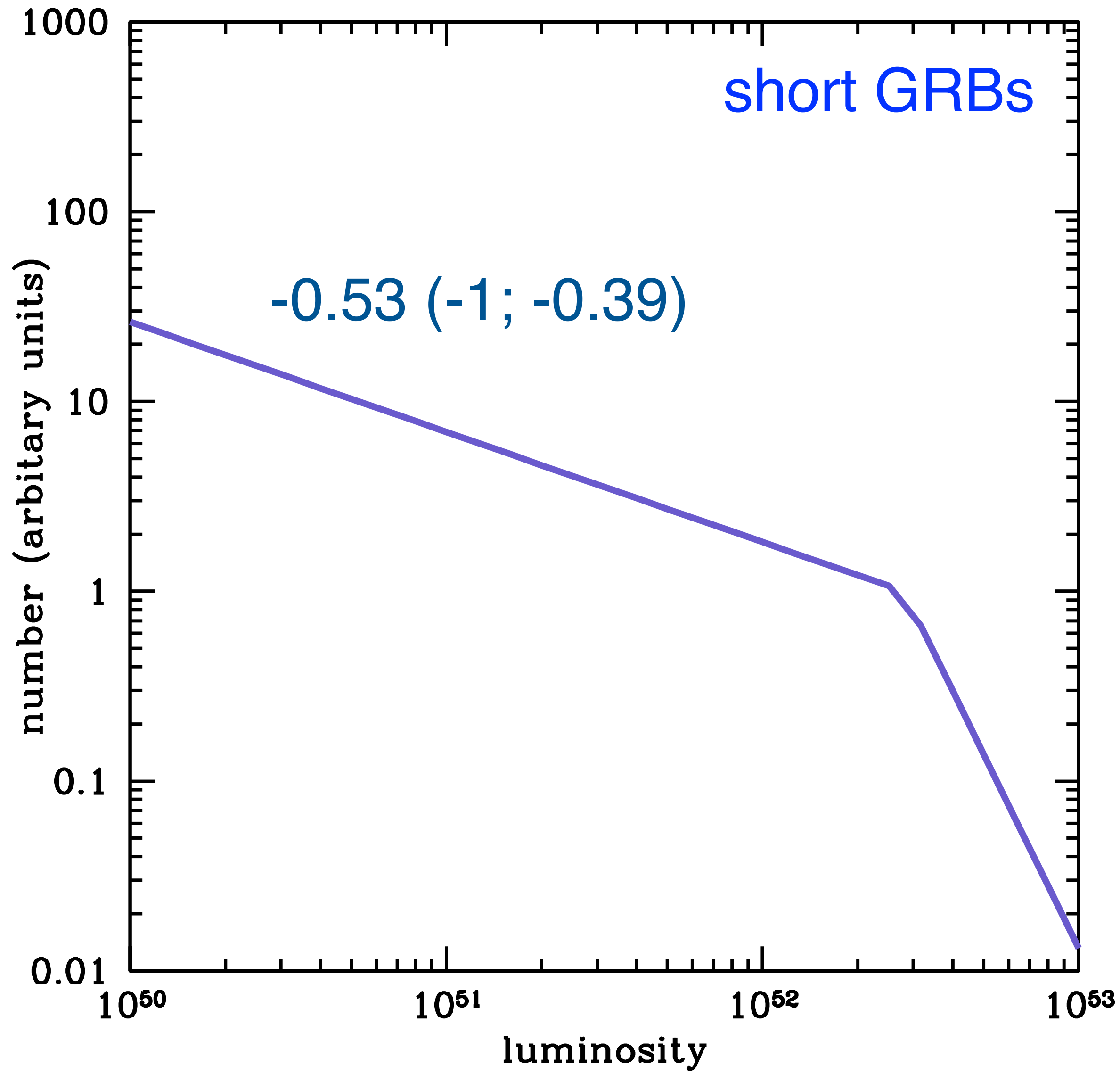
D'Avanzo et al. 2014

Short GRB: the sBAT4 sample

Ghirlanda et al (2016) obtained the short GRBFR and LF using the sBAT4 and Fermi data

Case (a): assuming correlations between Ep and Eiso/Liso

α_1	0.53	0.88	(0.39, 1.0)
α_2	3.4	2.2	(1.7, 3.7)
L_b	2.8	2.1	(0.91, 3.4)

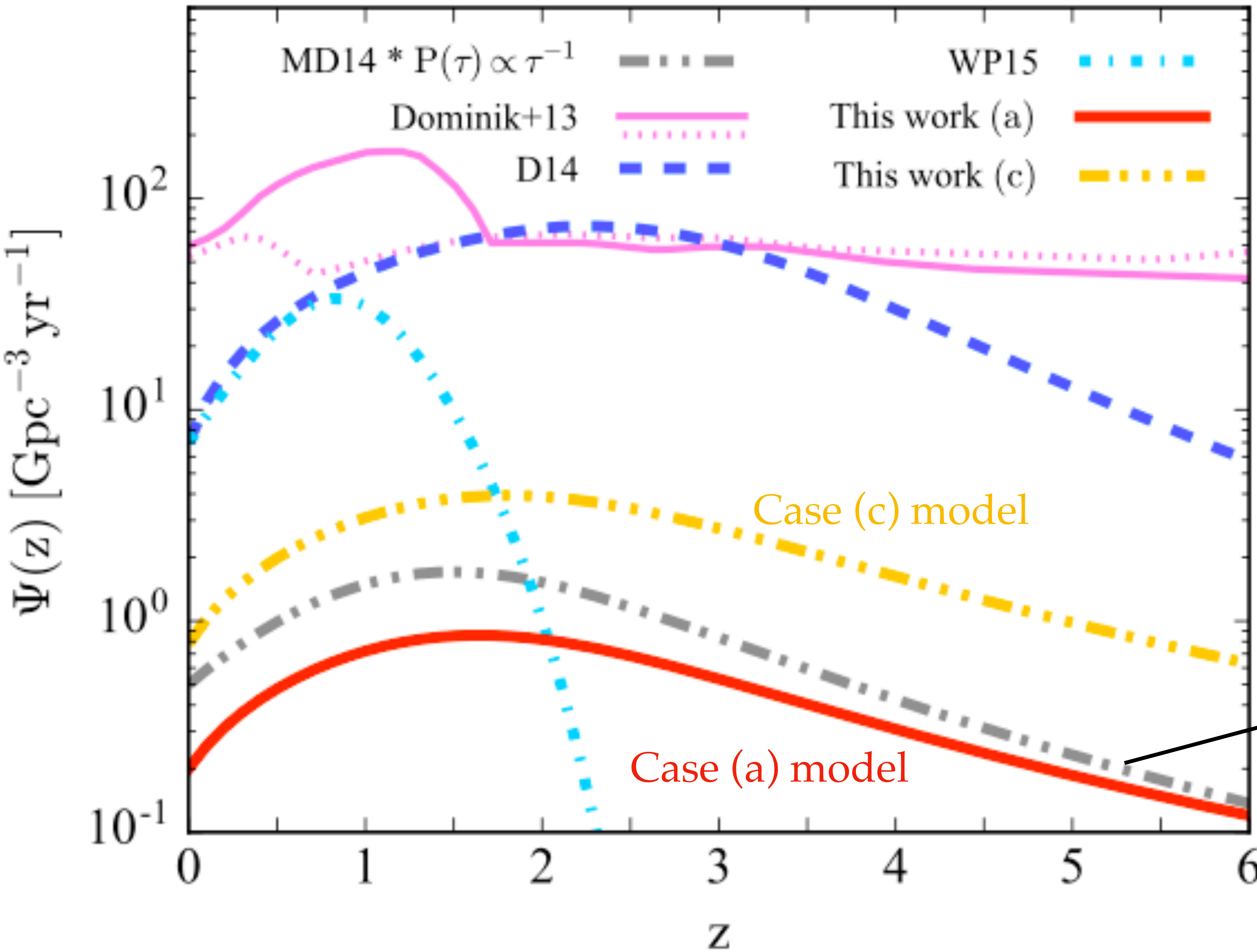


LF is a broken power law
but parameters only poorly determined and dependent on the assumptions

Ghirlanda et al. 2016

Short GRB: the sBAT4 sample

the derived intrinsic z-distribution (red line) is consistent with a τ^{-1} delay time distribution



NS-NS primordial binary merger expectations SFR*τ^{-1}

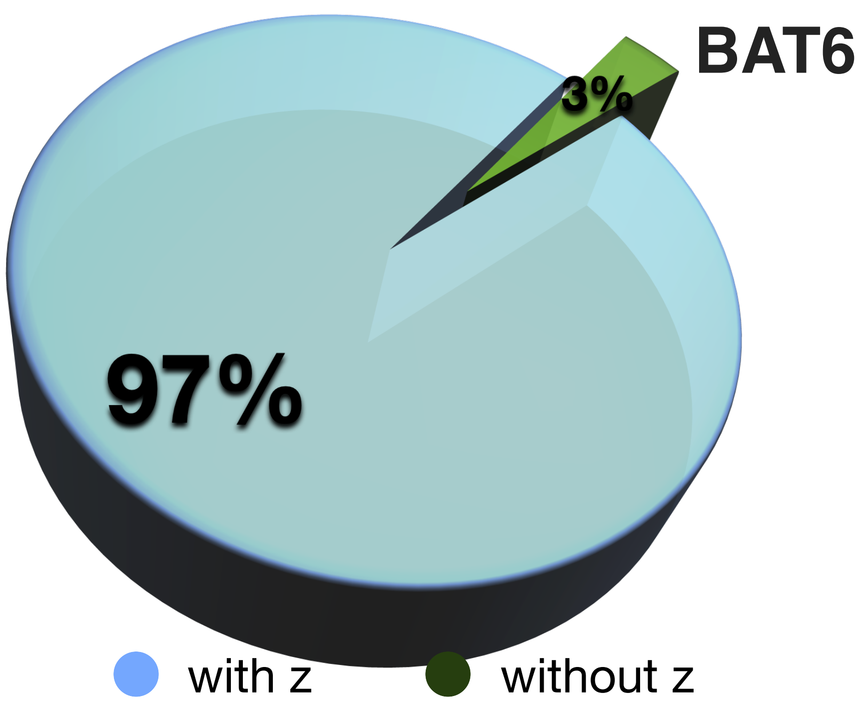
primordial NS-NS binary merger distributions provides a good description of the sGRB population

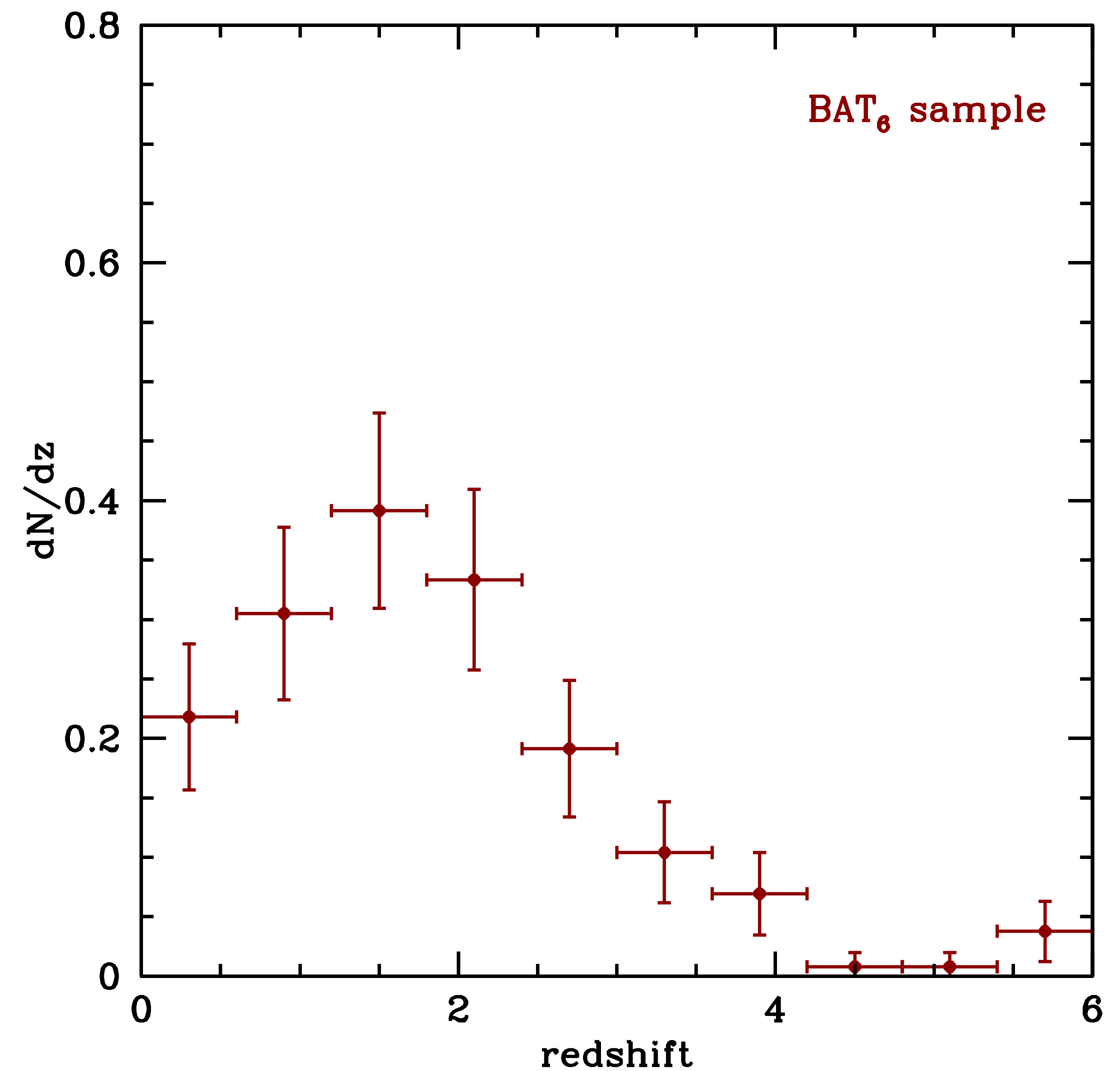
Ghirlanda et al. 2016

Long GRB: the BAT6 sample

BAT$_6$ is a complete, flux limited sample of 58 long GRBs
(extended to 100 bursts with slightly lower redshift completeness by Pescalli+15)

1. promptly repointed by Swift/XRT
2. low Galactic extinction
3. away from Sun
4. **peak flux larger than 2.6 ph s^{-1} cm^{-2}**



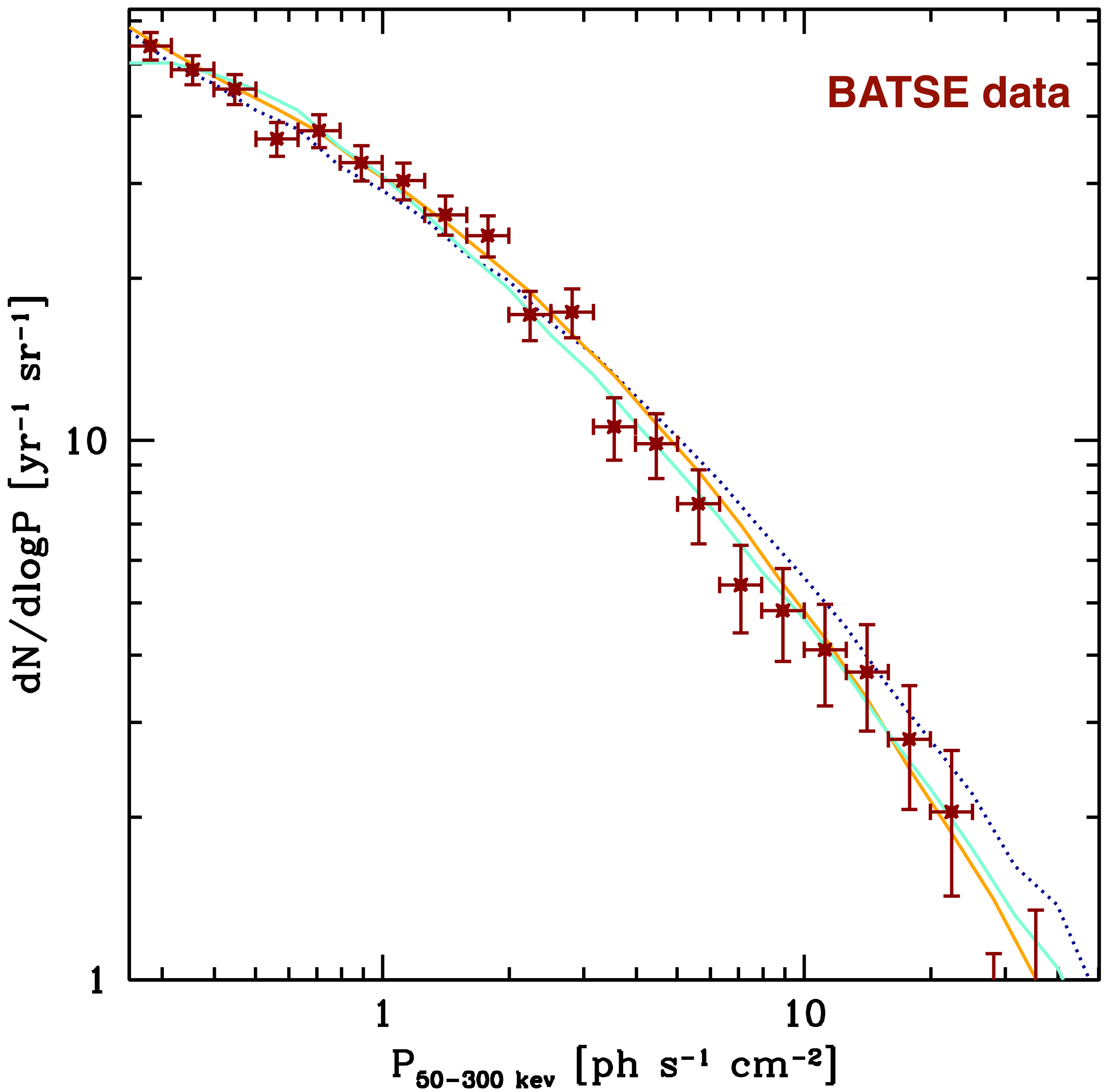


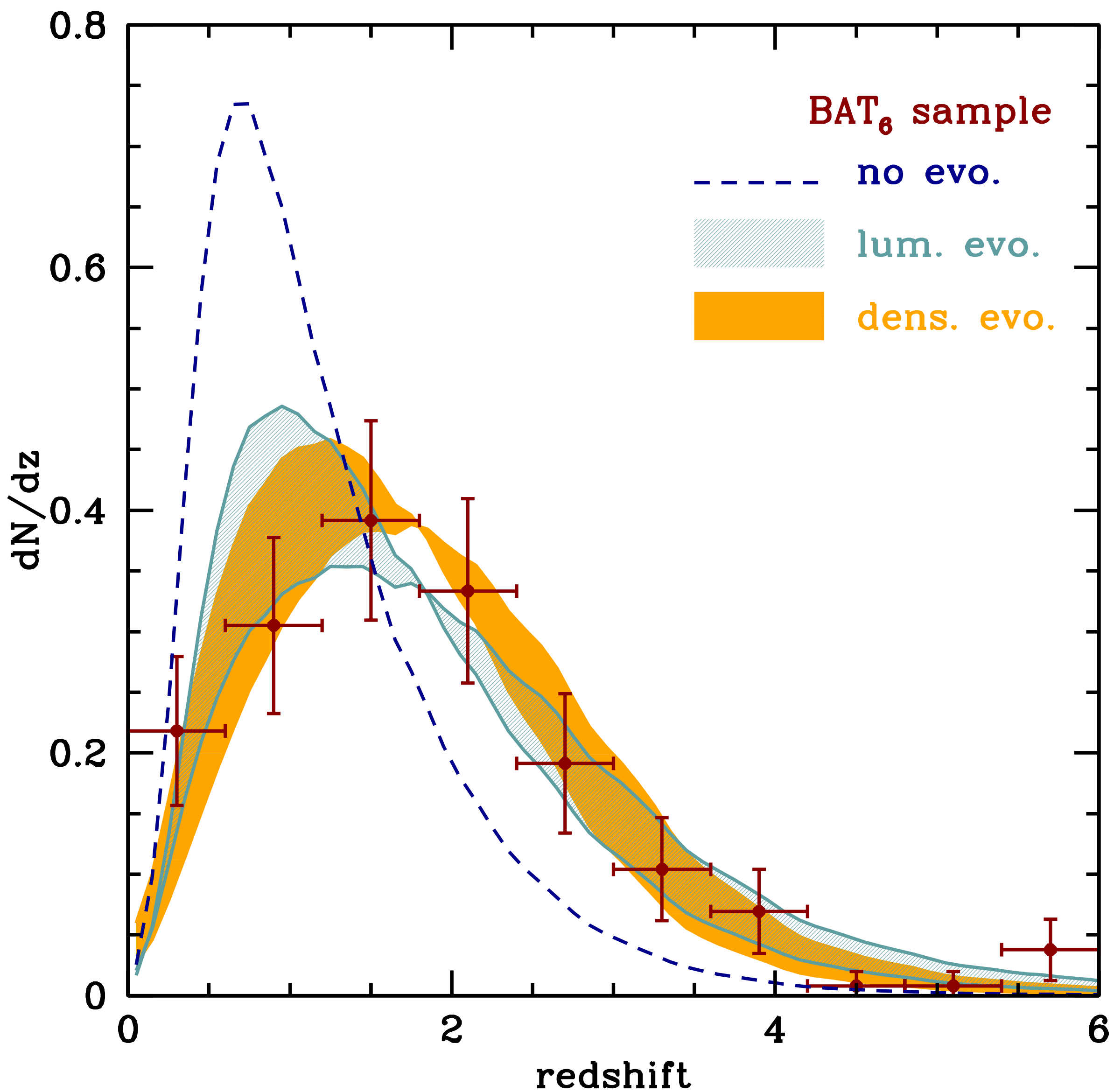
in spite of the severe cut in photon flux the mean (median) redshift is 1.80±0.14 (1.64±0.08) and the distribution extend at least up to z=5.47

Salvaterra et al. 2012

Long GRB: the BAT6 sample

GRB LF and z-distribution can be obtained by jointly fitting the BATSE logN-logP distribution and the BAT6 observed redshift distribution



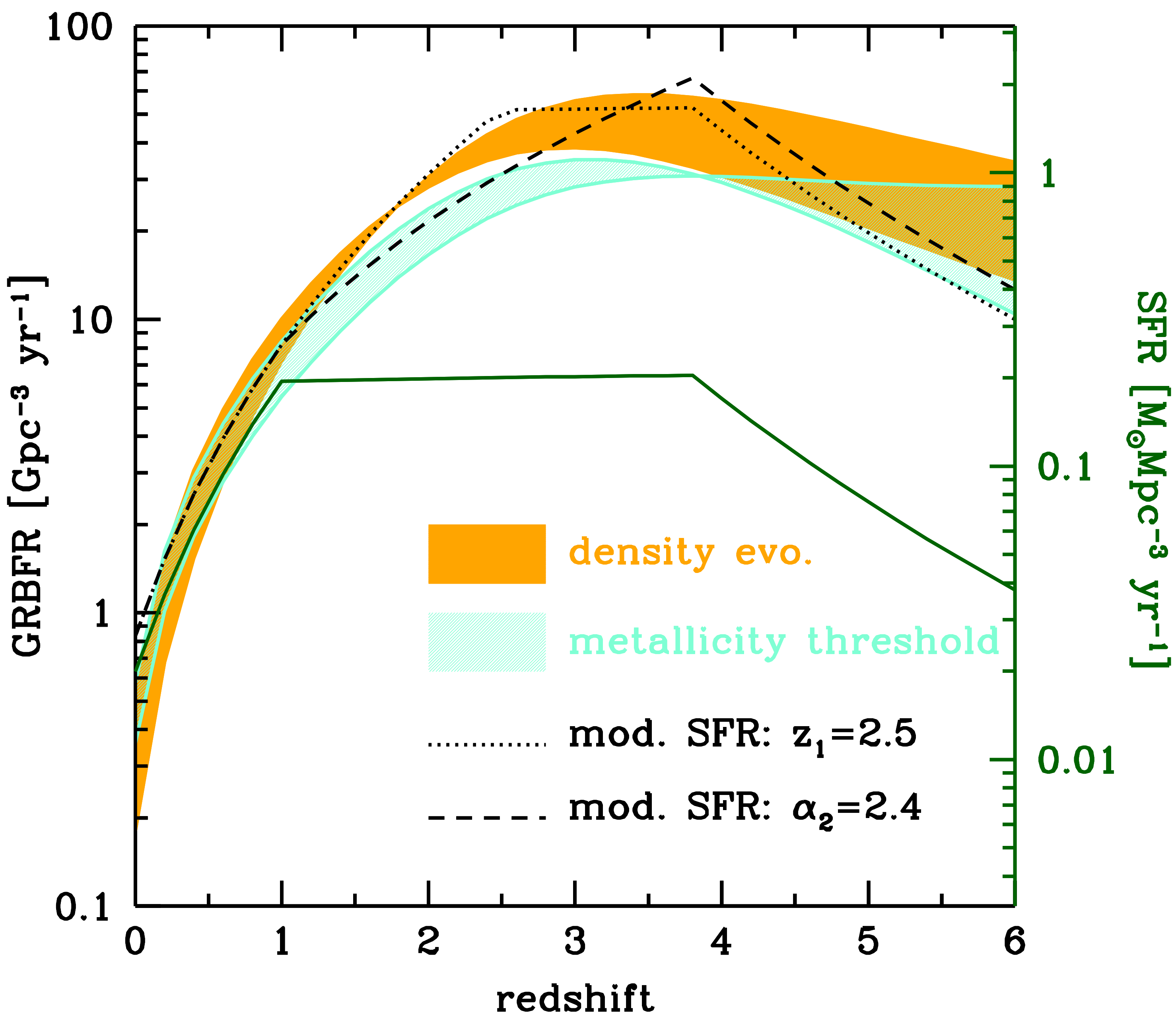


some evolution with redshift is required by the observed BAT6 redshift distribution

Salvaterra et al. 2012

Long GRB: the BAT6 sample

GRBs are biased tracer of cosmic SFR
either peaking at higher z or declining much rapidly at low-z

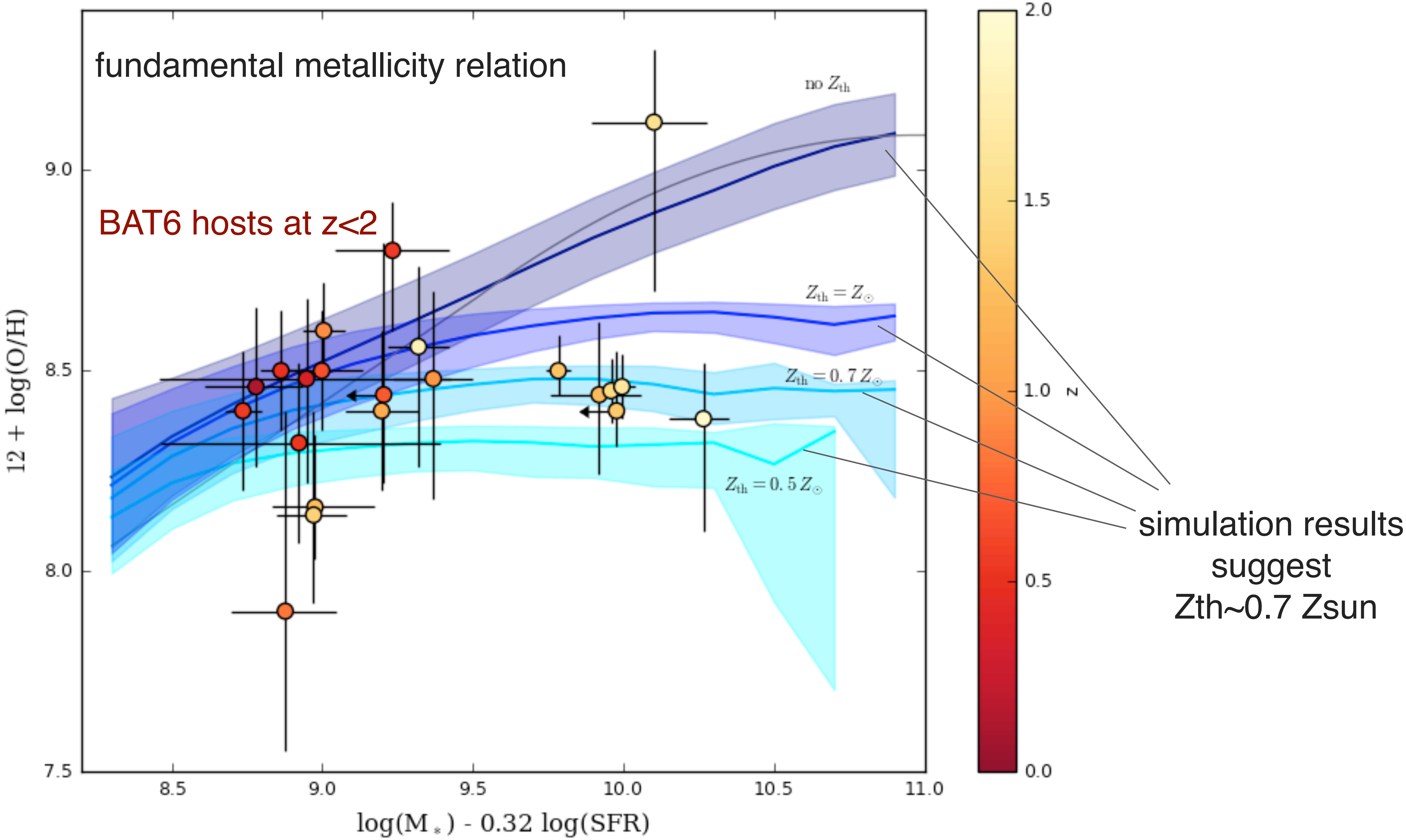


GRB ∝ SFR * $(1+z)^{\delta}$
δ=1.7 ± 0.5
main uncertainty factor

this can be explained assuming that GRBs form preferentially in low-metallicity environments

Salvaterra et al. 2012

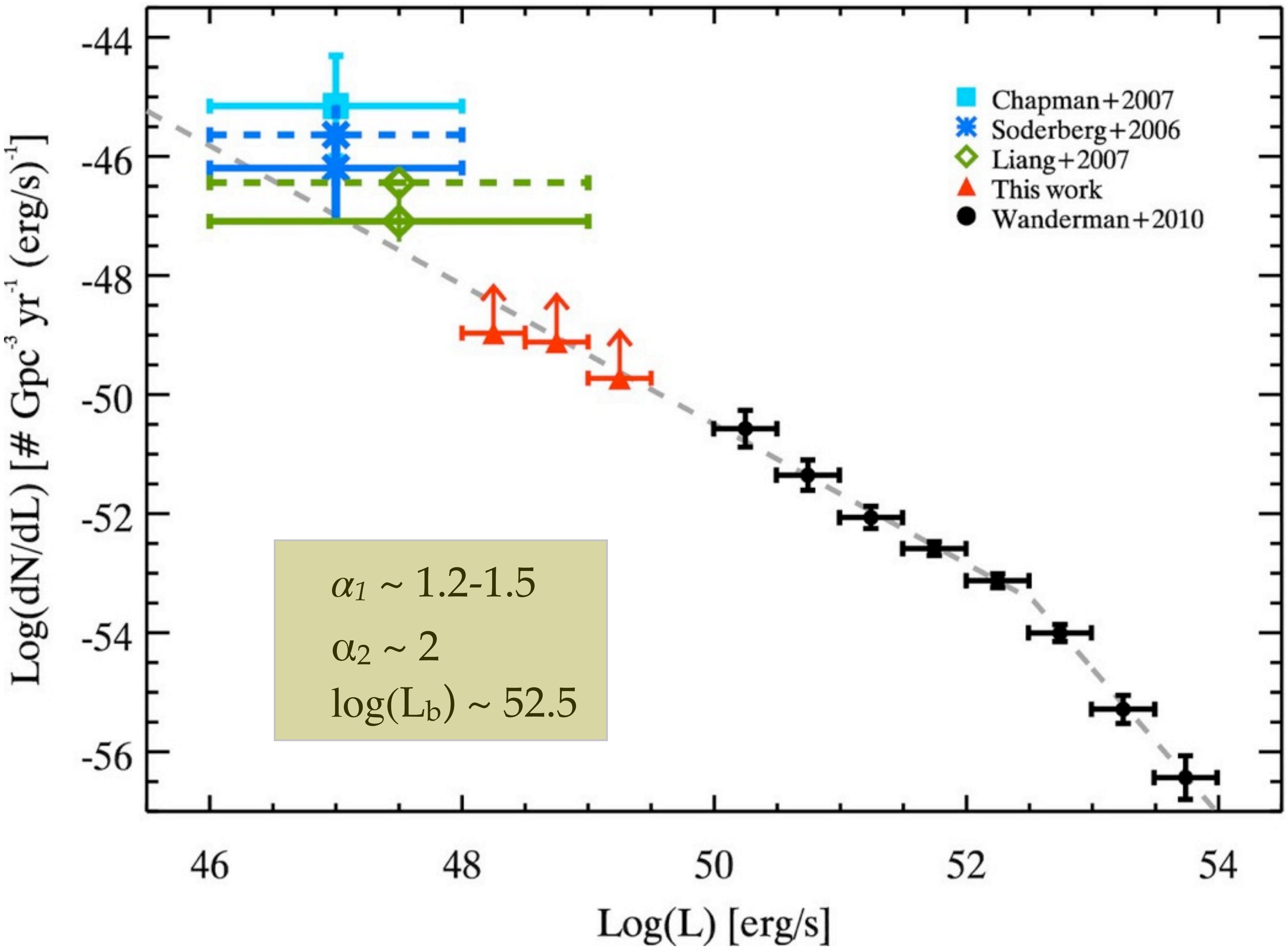
Long GRB: the BAT6 sample



Vergani et al. 2016, Vergani et al 2015, Japelj et al. 2016, Palmerio et al.

Long GRB: the BAT6 sample

LF is well described by a broken power-law down to 10^{46} erg s^{-1} consistent with the one derived using direct methods (Wanderman & Piran 2010, Pescalli et al. 2016)

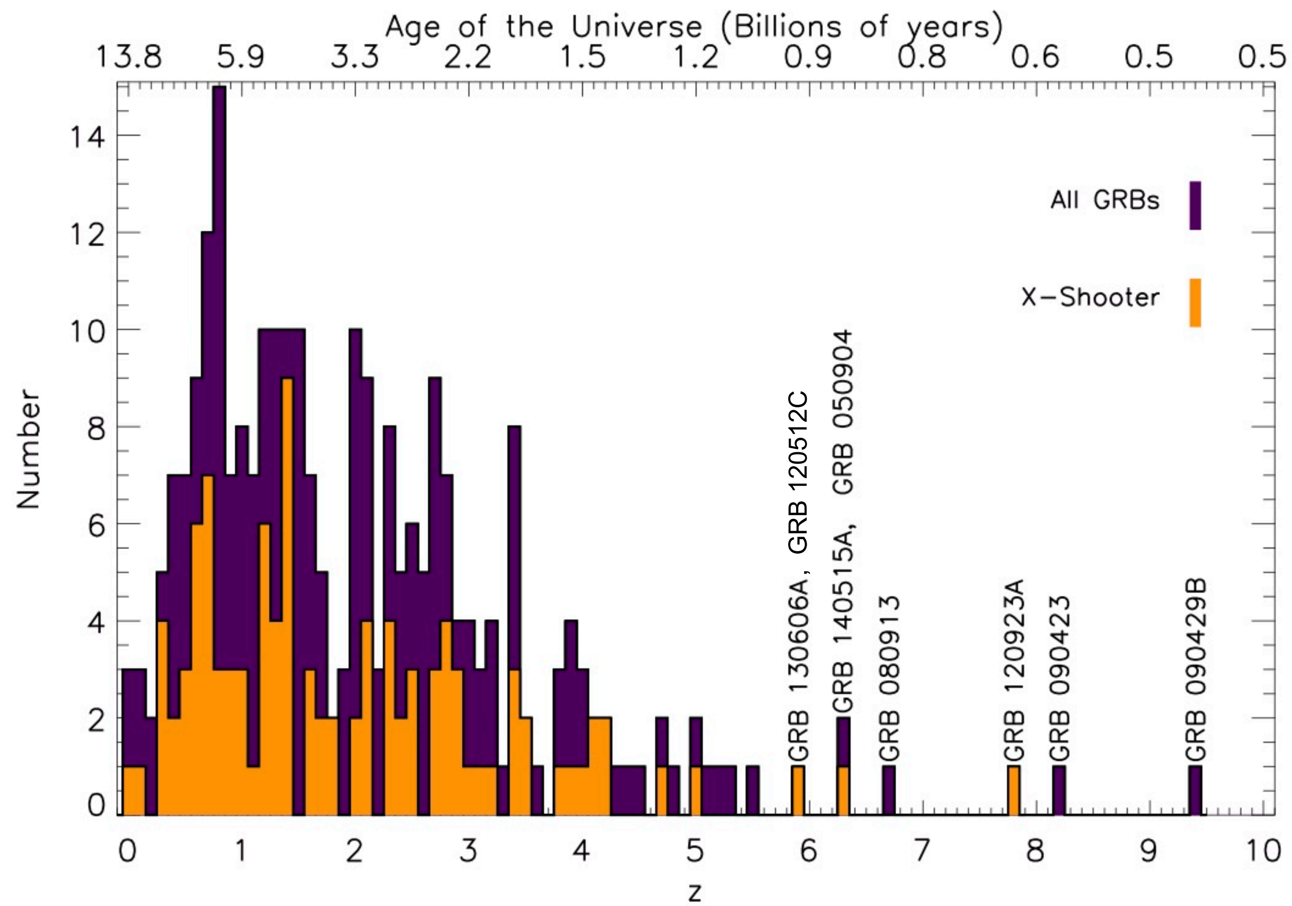


sub-luminous and intermediate bursts are on the extrapolation of the faint end

Pescalli et al. 2014

The high-z GRB population

- In 15 yrs of operations Swift localised (at least) 8 GRB at z>6
- This small sample already shows the potentiality of GRBs in providing new clues on the early Universe
- These bursts represent the tip of the iceberg of the much larger high-z GRB population

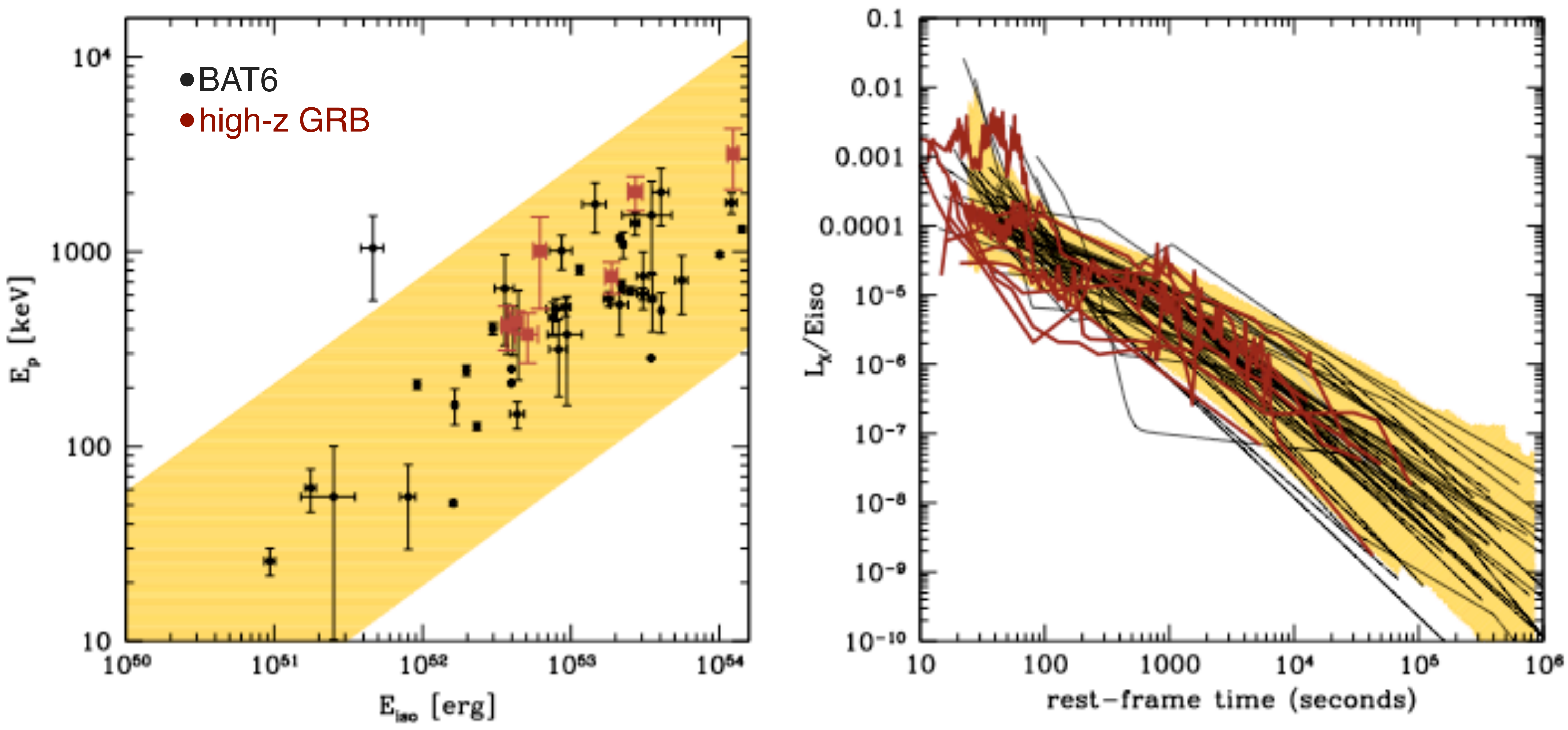


GRB	z	E_p [erg]	E_{iso} [erg]	$\log(N_{HI})$ [cm^{-2}]	$\log(N_{H,X})$ [10^{21} cm^{-2}]	Z [$Z_\odot$]	A_V	$M_{UV,host}$ [AB]	SFR_{host} [$M_\odot$ yr^{-1}]
050904	6.3	3178	1.24×10^{54}	21.6	63^{+34}_{-29}	-1.6 ± 0.3	0.15 ± 0.07	> -19.95	< 4.1
080913	6.7	1008	7×10^{52}	19.84	95^{+89}_{-77}	–	0.12 ± 0.03	> -19.00	< 1.3
090423	8.2	746	1.88×10^{53}	–	102^{+49}_{-54}	–	< 0.1	> -16.95	< 0.38
130606A	5.9	2028	2.7×10^{53}	19.93	< 30	-1.35 ± 0.15	< 0.05	–	–
140515A	6.3	376	5.1×10^{52}	18.62	< 226	< -0.8	0.11 ± 0.02	–	–
090429B	9.4	437	4.31×10^{52}	–	140 ± 10	–	0.10 ± 0.02	> -19.65	< 2.4
120521C	6.0	–	1.9×10^{53}	–	< 60	–	< 0.05	–	–
120923A	8.5	376	5.1×10^{52}	–	< 720	–	–	–	–

Salvaterra 2015

The high-z GRB population

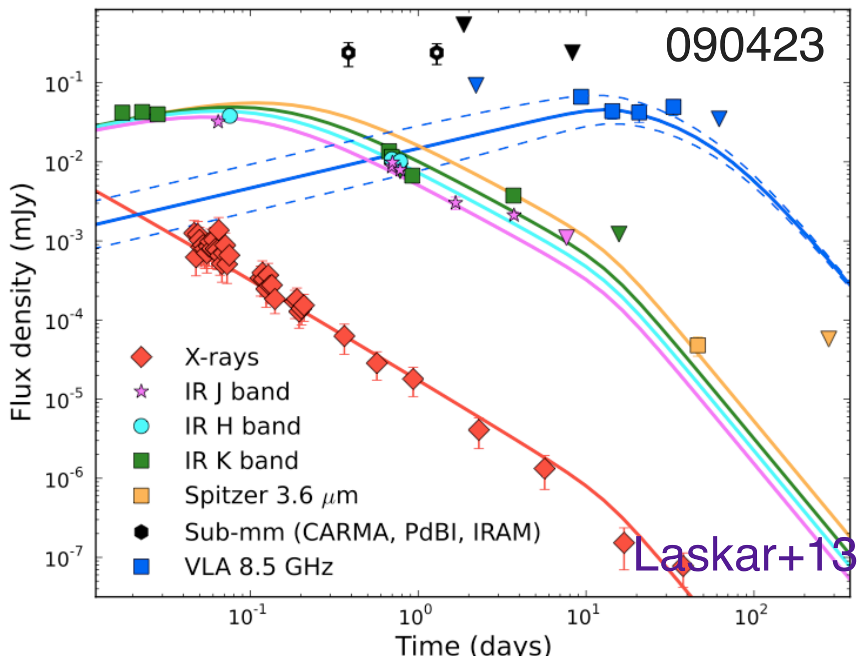
high-z GRBs are similar to low- and intermediate-z GRB ones

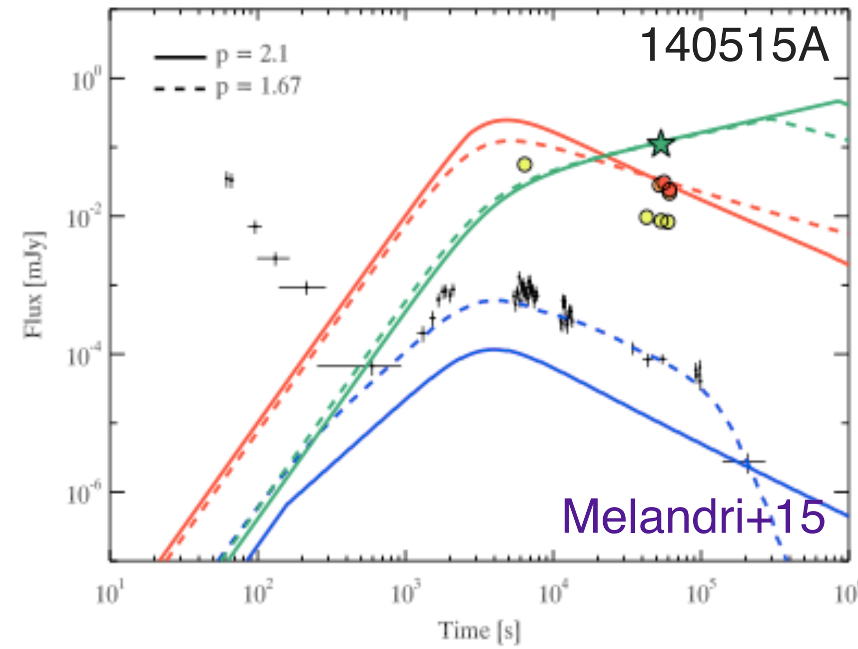


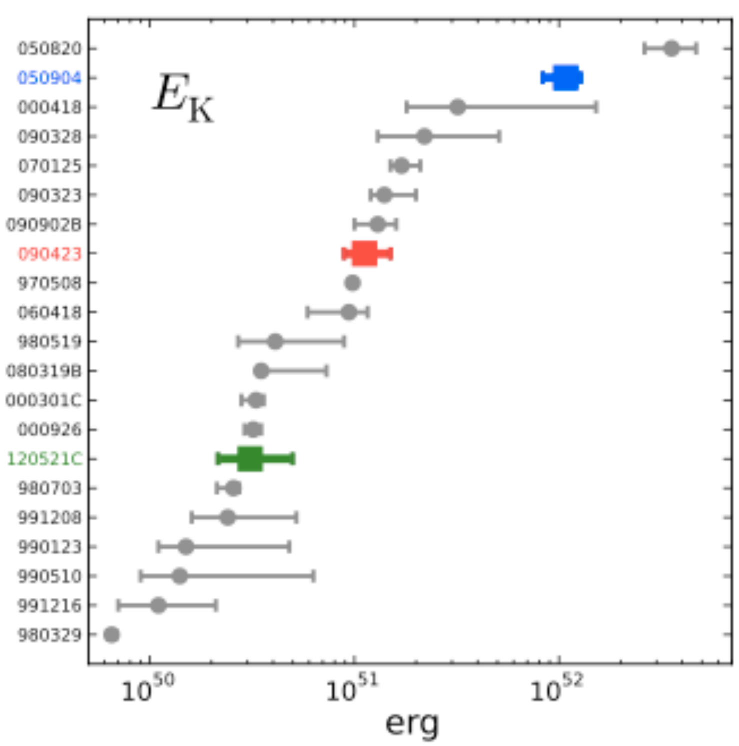
Salvaterra 2015

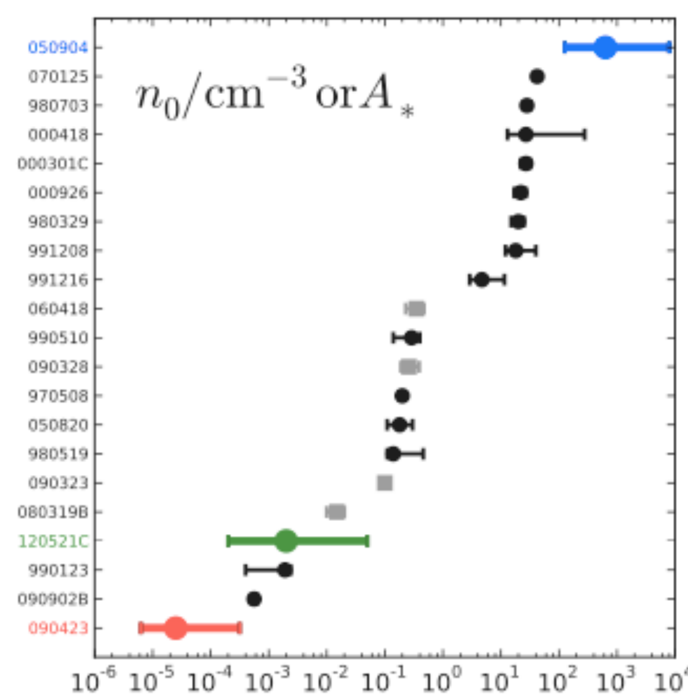
The high-z GRB population

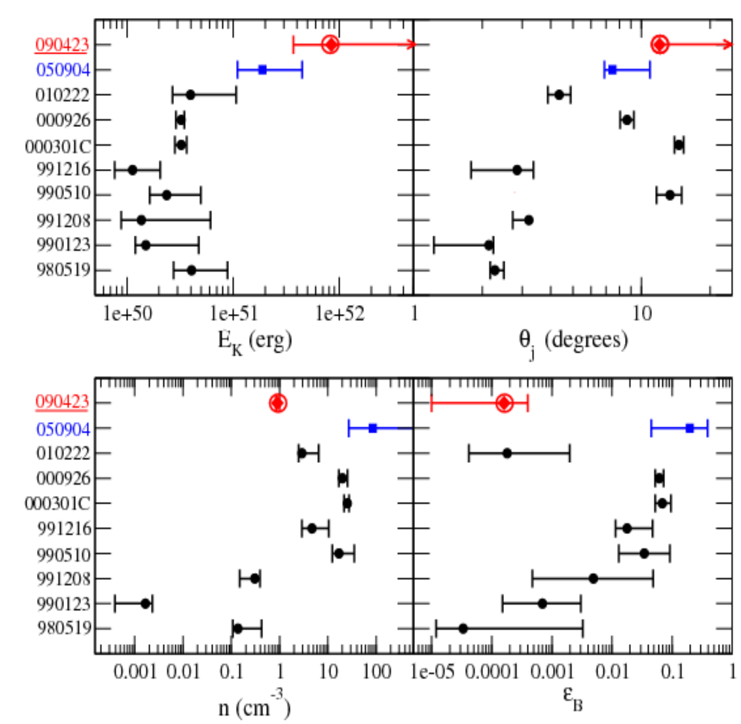
similar results from broad band afterglow modelling (including radio obs)







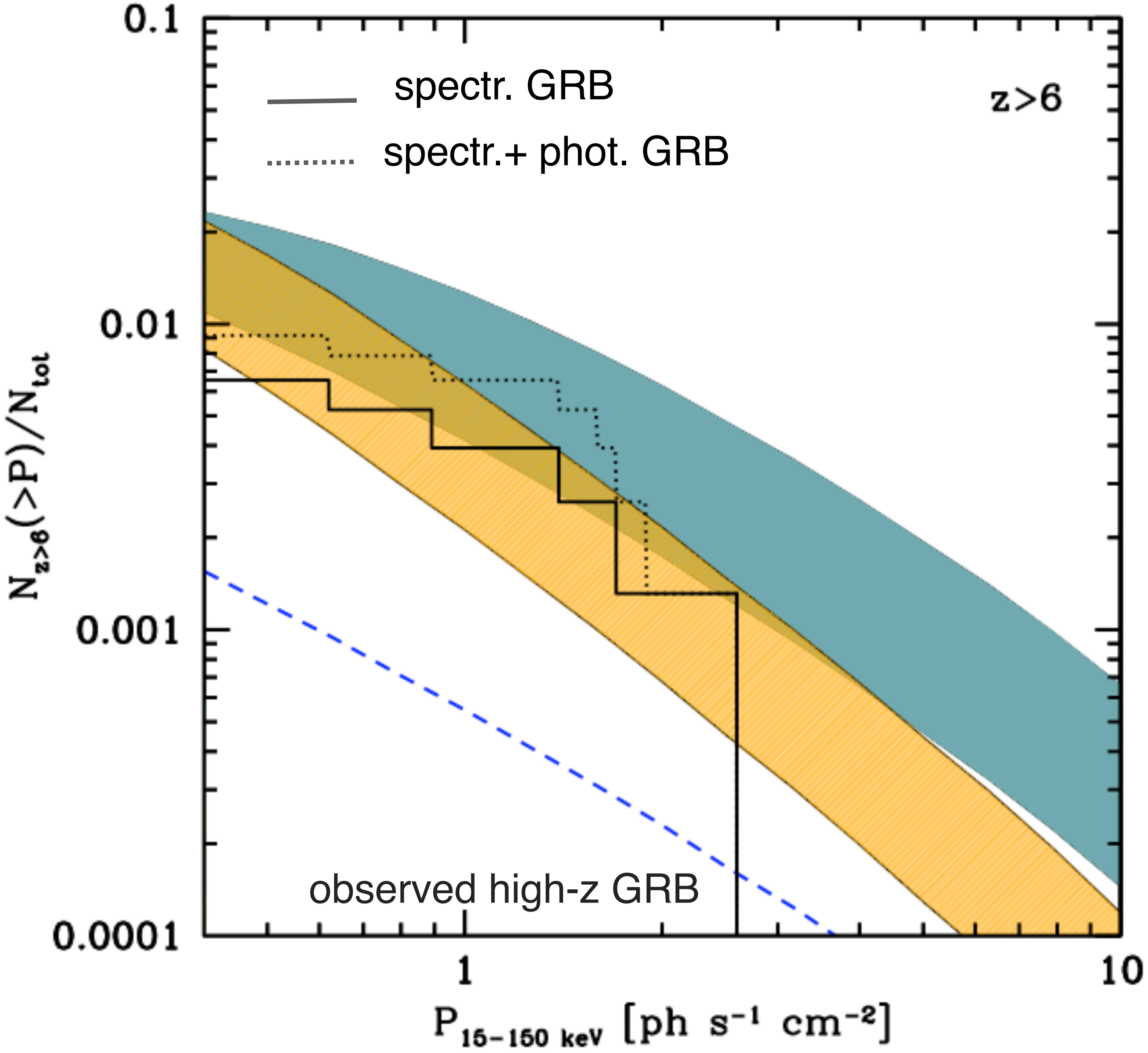




Chandra et al 2009, Laskar et al 2013, Melandri et al 2015

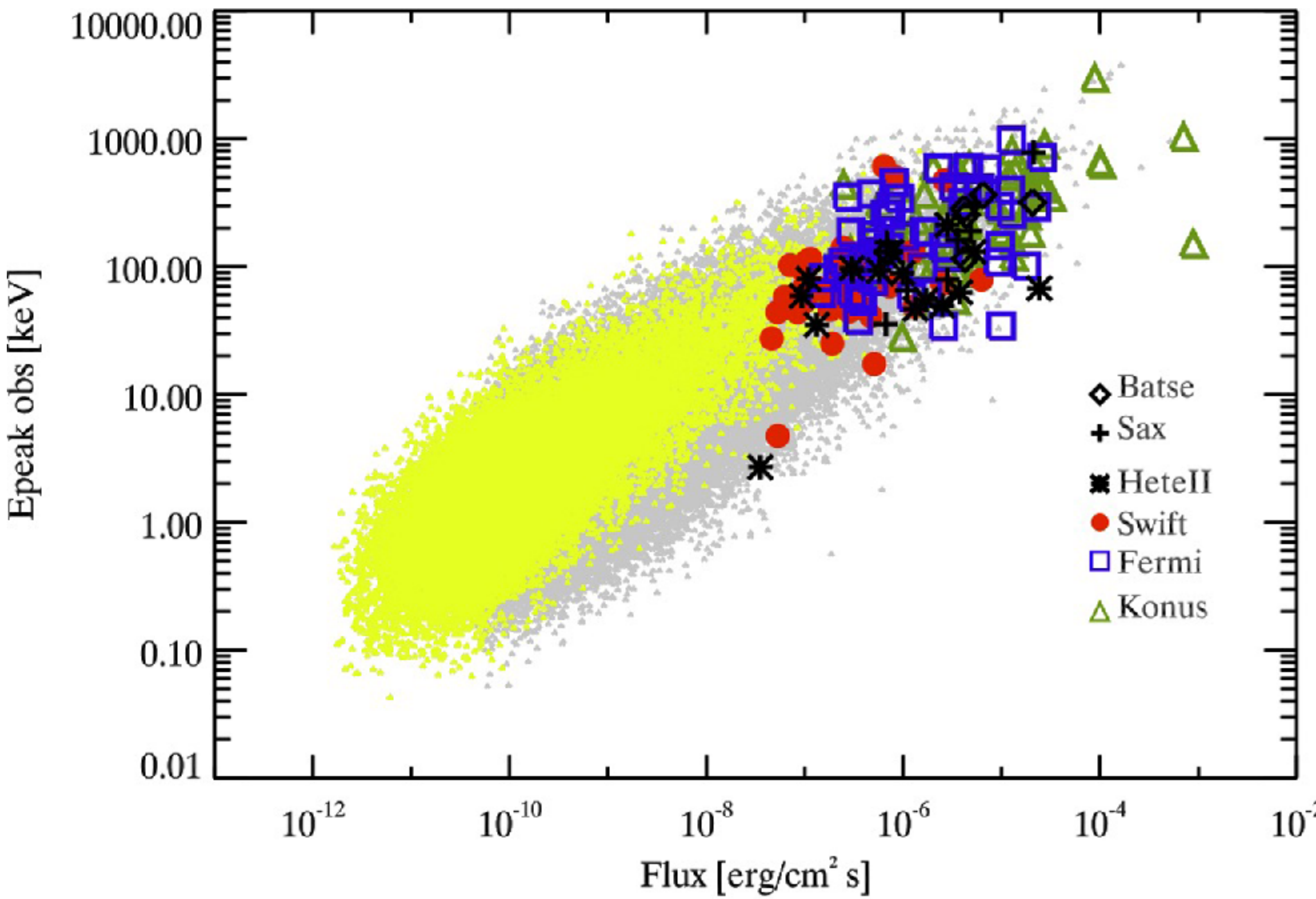
The high-z GRB population

high-z GRBs are 1-2% of the Swift GRBs but ~10% of the entire population



models are calibrated on z-distribution of a complete sample of bright GRBs (BAT6)

Salvaterra et al. 2012, Ghirlanda et al. 2015 a softer energy band is more efficient only if coupled with a better sensitivity



Ghirlanda et al. 2015

WG4: Population synthesis models

Lessons from previous studies:

- Importance to use all possible observational constraints derived from previous missions
- Calibrate models using well defined, flux limited sub-sample (redshift complete)
- **Short GRBs:**
    - LF: described by a broken power-law but the faint-end is very uncertain and assumption dependent
    - GRBFR: SFR + delay time distribution as expected for NS-NS mergers
- **Long GRBs:**
    - LF: well described by a broken power-law extended down to L_{min}~10^{46} erg s^{-1}
    - GRBFR: SFR + density evolution as $(1+z)^{1.7 \pm 0.5}$
- **High-z GRBs:**
    - ~1-2% of the Swift GRBs: tip of the iceberg
    - Observed high-z GRBs are similar to low- / intermediate-z ones

PS: Population Scheme

Long GRBs		Short GRBs
GG+2015; Salvaterra+2012; Pescalli+2016	$\Phi(L) \propto \begin{cases} L^{-a_1} & L_{\rm min} < L < L_{\rm beak} \\ L^{-a_2} & L \geq L_{\rm beak} \end{cases}$	GG+2016
$\Psi(z) \propto (1+z)^{\delta}\ \mathrm{CSFR}_{\rm MD14}$ Madau & Dickinson 2014; Salvaterra+2012		$\Psi(z, \mathrm{sGRB})$ GG+2016
Kaneko+2006; Gruber+2010; Nava+2010	$f_{\rm Band}(\alpha, \beta, E_{\rm p})$	GG+2004; 2009; Yu+2018
Nava+2013	$E_{\rm p} \propto \begin{cases} E_{\rm iso} & \text{Amati+2002} \\ L_{\rm iso} & \text{Yonetok+2004} \end{cases}$	D'Avanzo+2015
	$\mathrm{N_h}$ Grupe+2007	

Reducing bias impact: complete GRB samples

>1000 GRBs detected by Swift (since 2005)

Definition of samples with favourable observing conditions for ground-based observations (then redshift measure)

> 60% of Swift GRBs are missing a redshift measure.

BAT6 sample

Salvaterra+12

- 58 **long** GRB (up to May 2011)
- peak flux > 2.6 photons/s/cm^2
- 97% with redshift (wrt 35% whole Swift sample)

SBAT4 sample

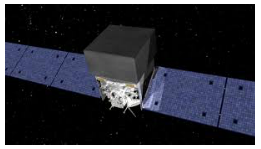
D'Avanzo+14

- 16 **short** GRB (up to June 2013)
- peak flux > 3.5 photons/s/cm^2
- 69% with redshift (wrt 25% whole Swift sample)

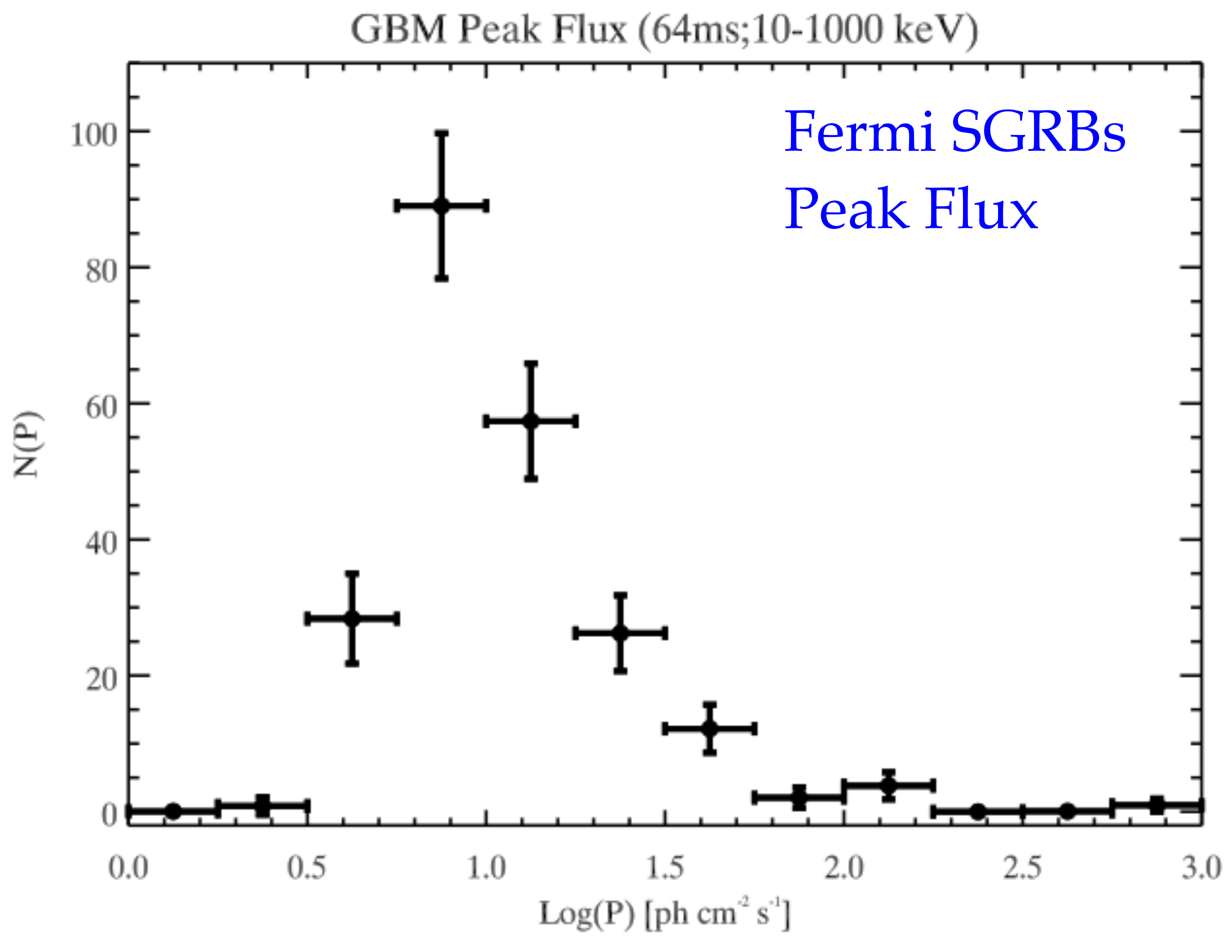
These samples are complete in flux (flux-limited) and have a high completeness in redshift

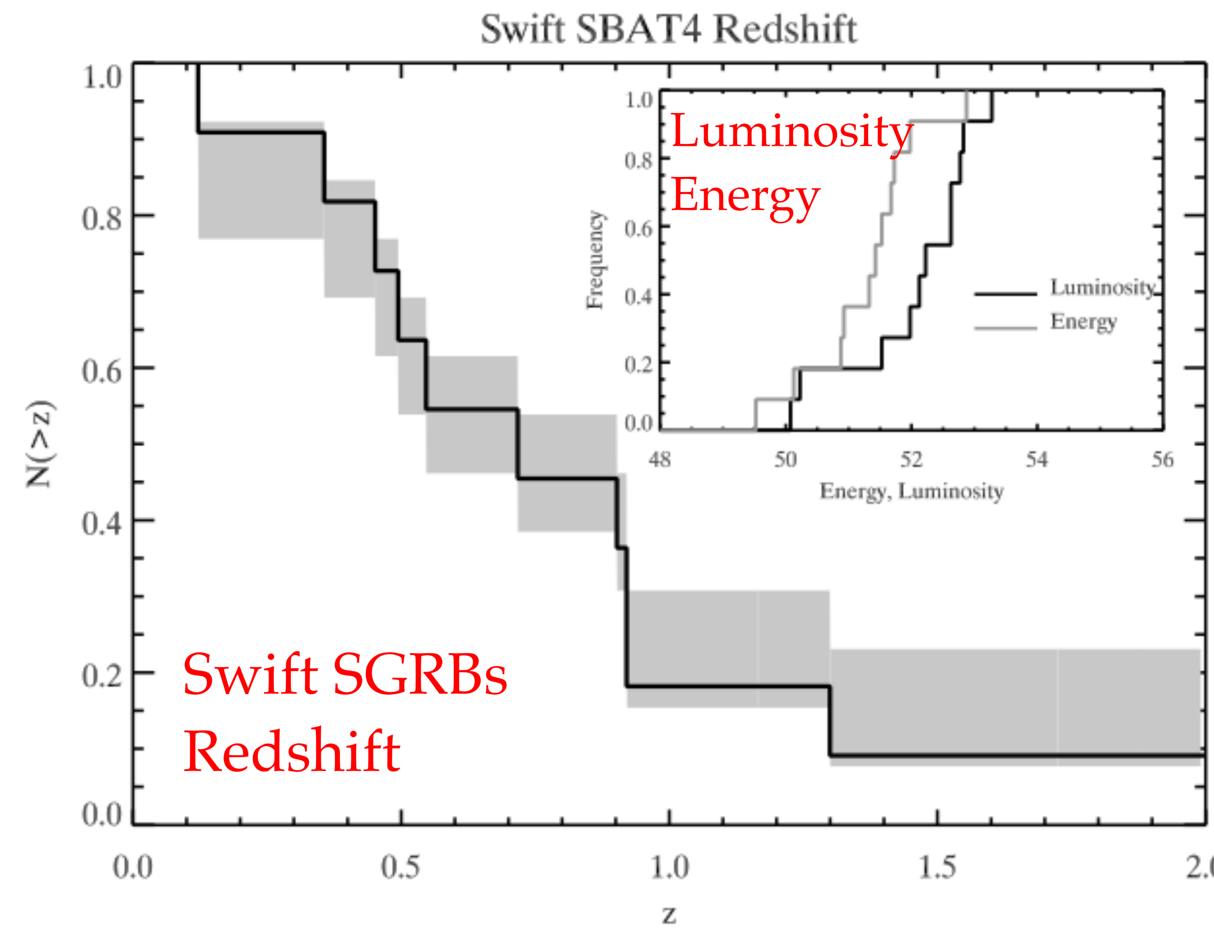
Provide both prompt and afterglow constraints

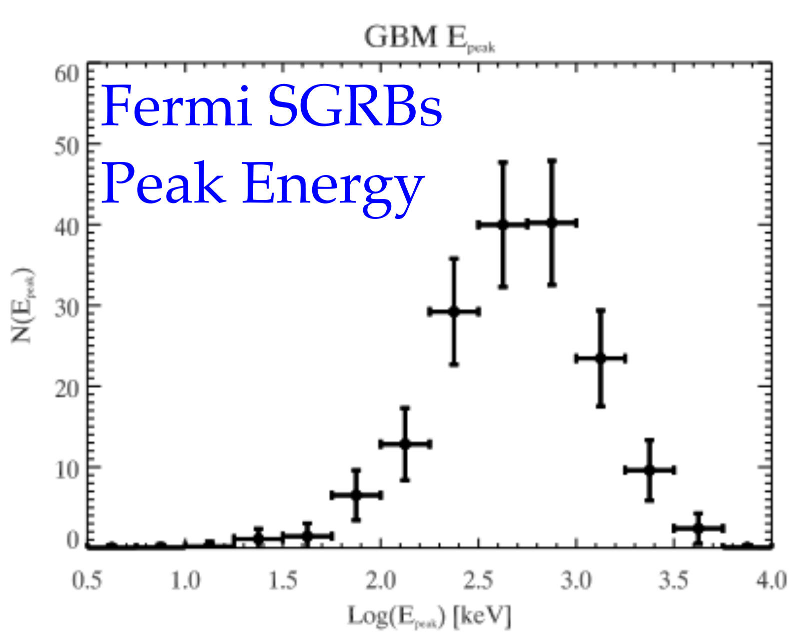
Additional Observables: extending the number of constraints

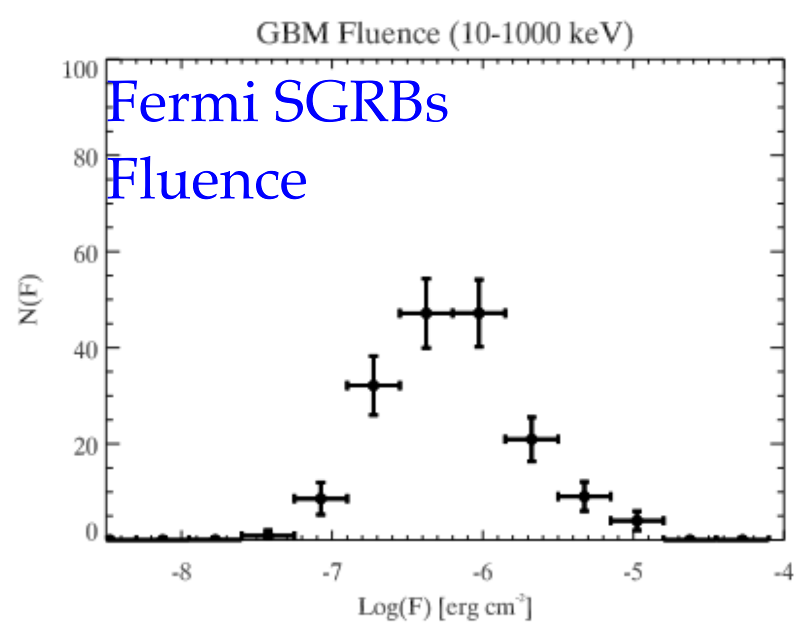
 +  = **7 Constraints**

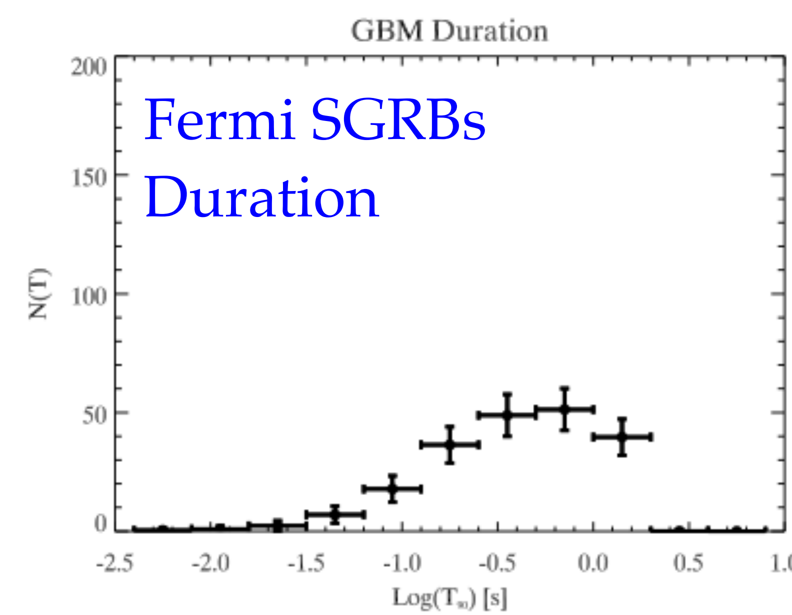
Short GRB population:
Ghirlanda+2016











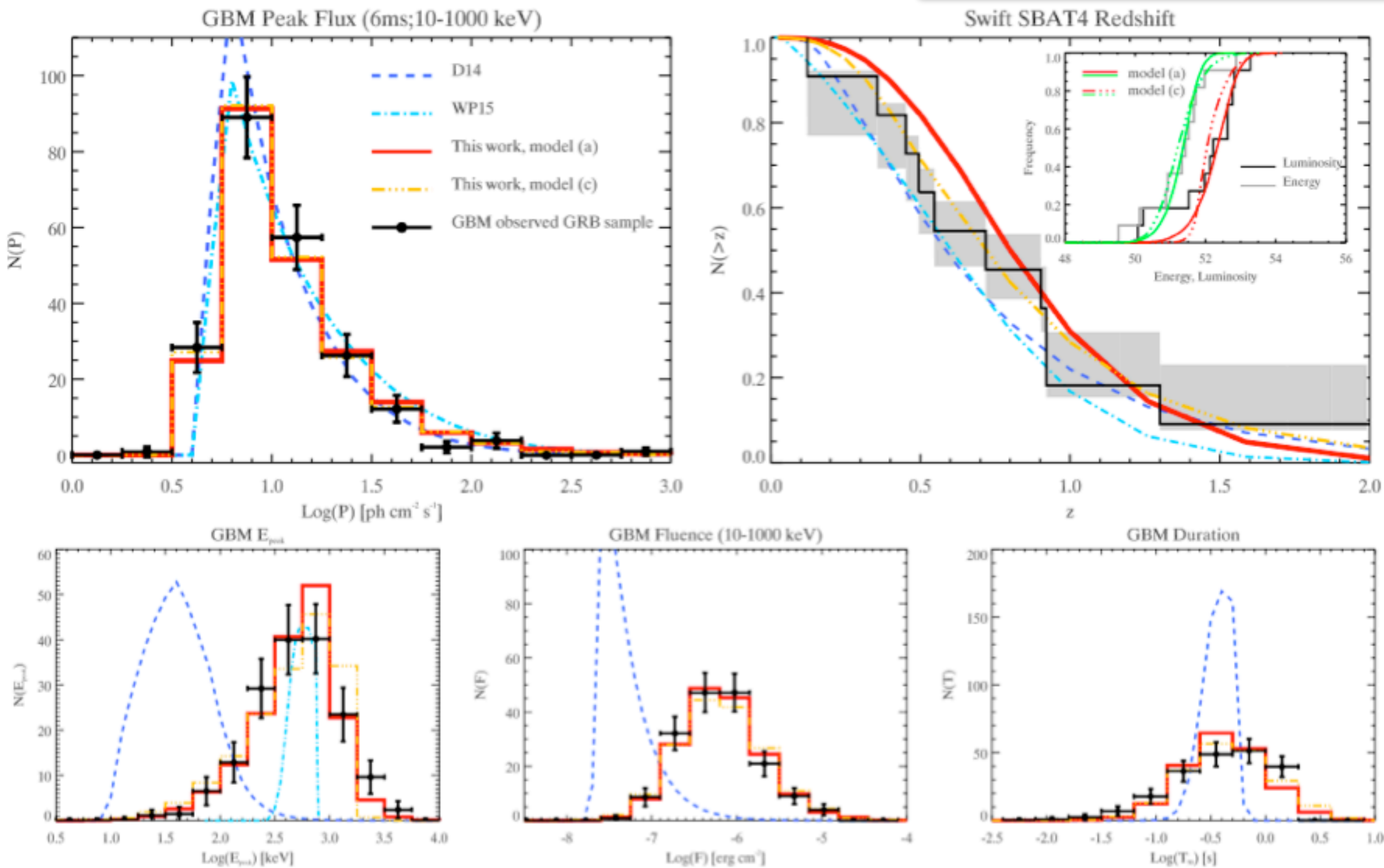
Short GRB population

(1) Delay independent constraints on z-dependent event rate

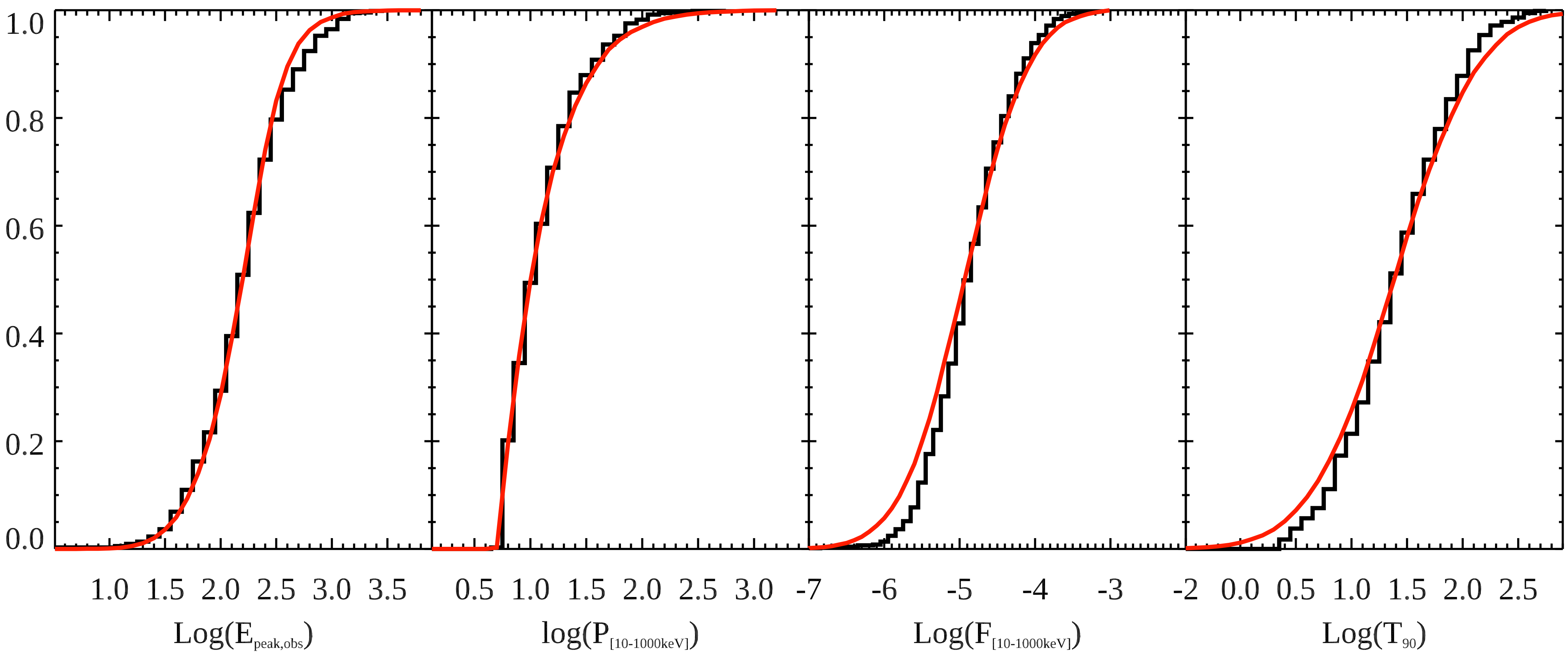
Ghirlanda et al. 2016

(2) Luminosity function

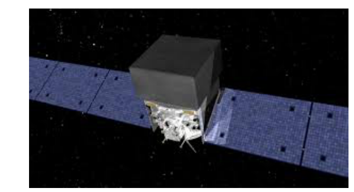
α_1	0.53	0.88	(0.39, 1.0)
α_2	3.4	2.2	(1.7, 3.7)
L_b	2.8	2.1	(0.91, 3.4)

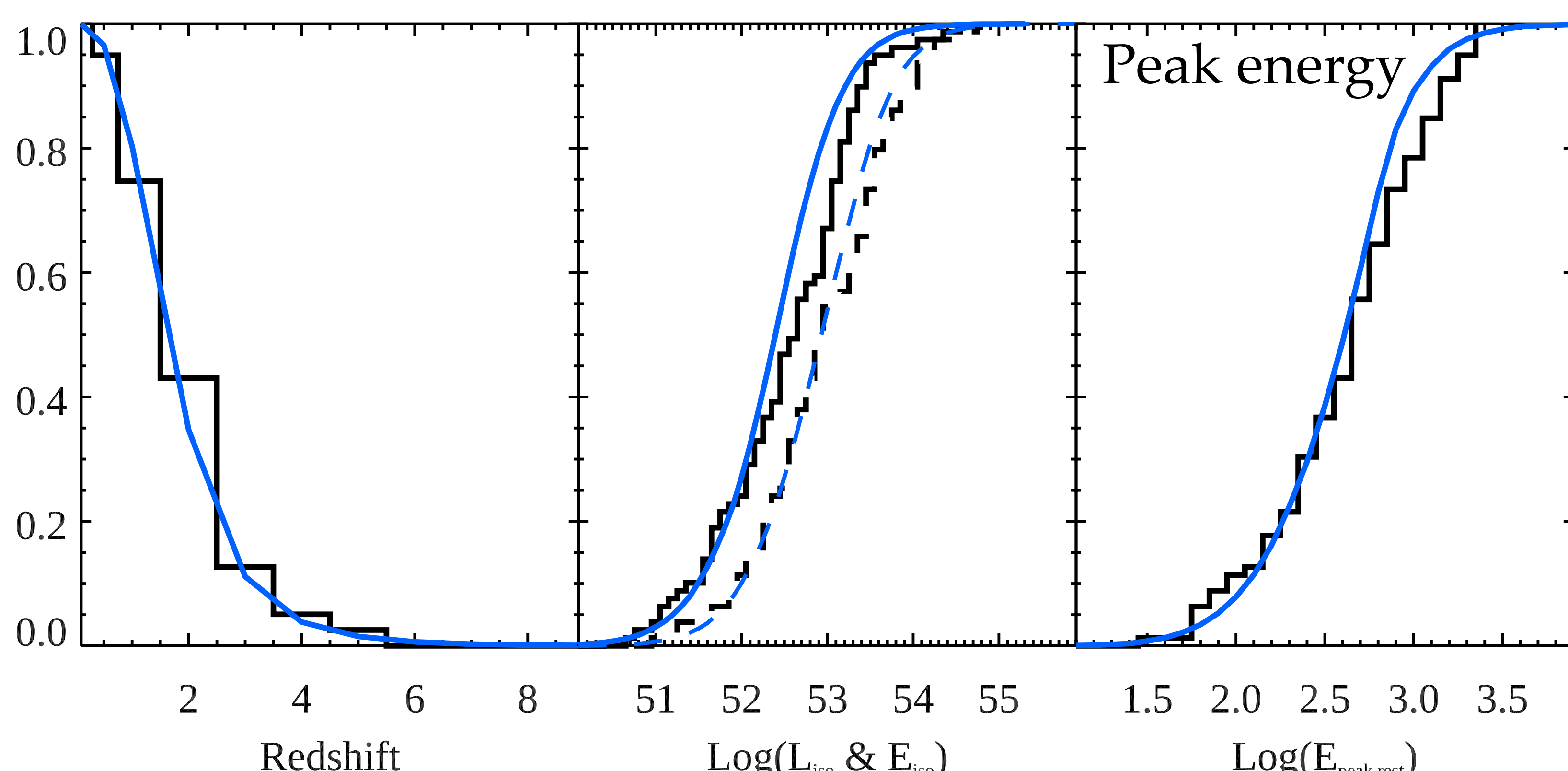


Long GRB population



Fermi / GBM Constraints





Swift constraints BAT6

GG et al., in preparation

Theseus Detection

(S. Mereghetti)

SXI

Instrumental setup

- total FoV
- energy range = 0.3-5 keV
- Duty cycle = 100% (MOS will provide the realistic estimate)
- Background count

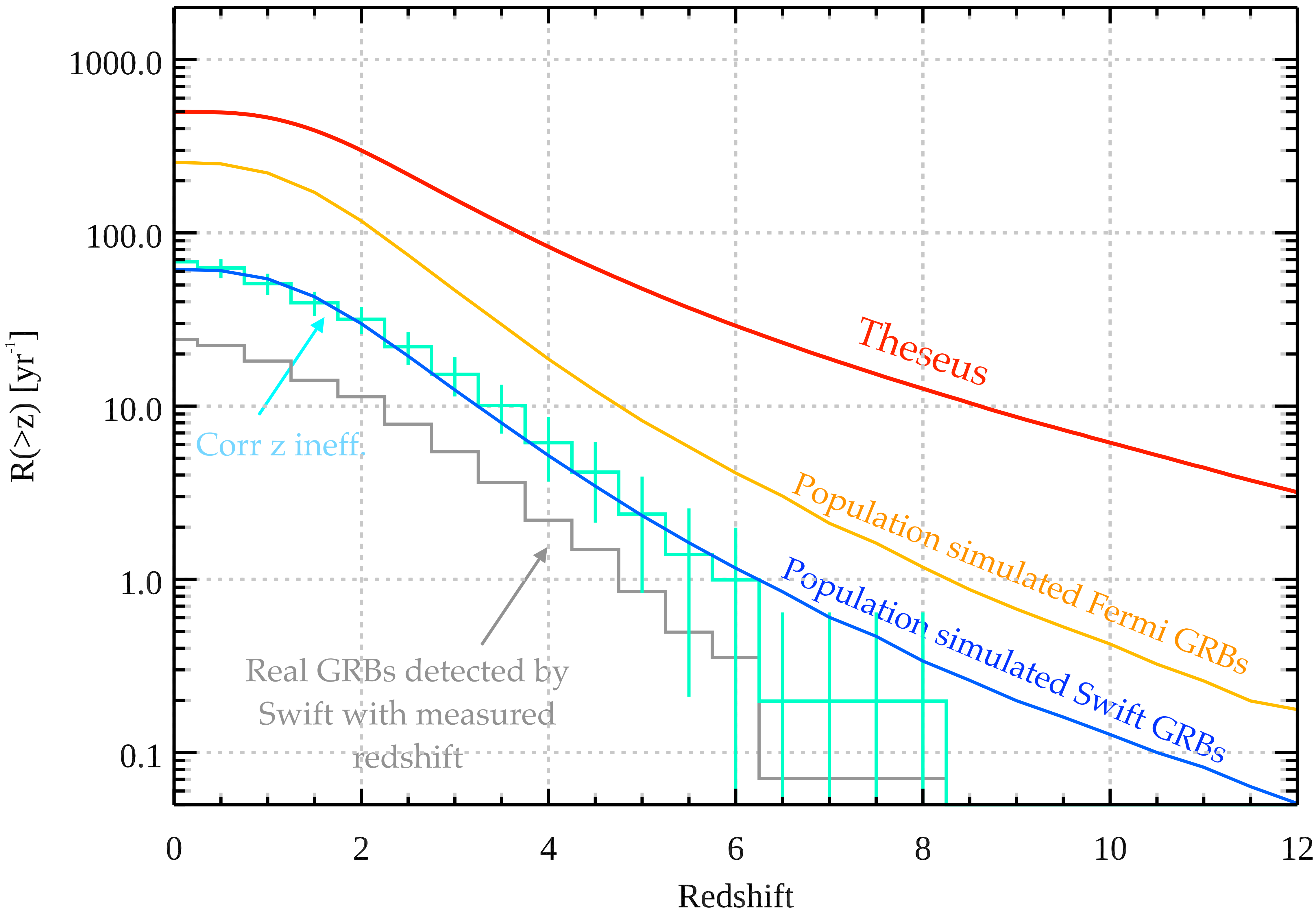
XGIS

Instrumental setup

- total FoV
- energy ranges = 2-30, 25-150 … keV
- Duty cycle = 100% (MOS will provide the realistic estimate)
- Background count rate
- Angular dependence of the detector response

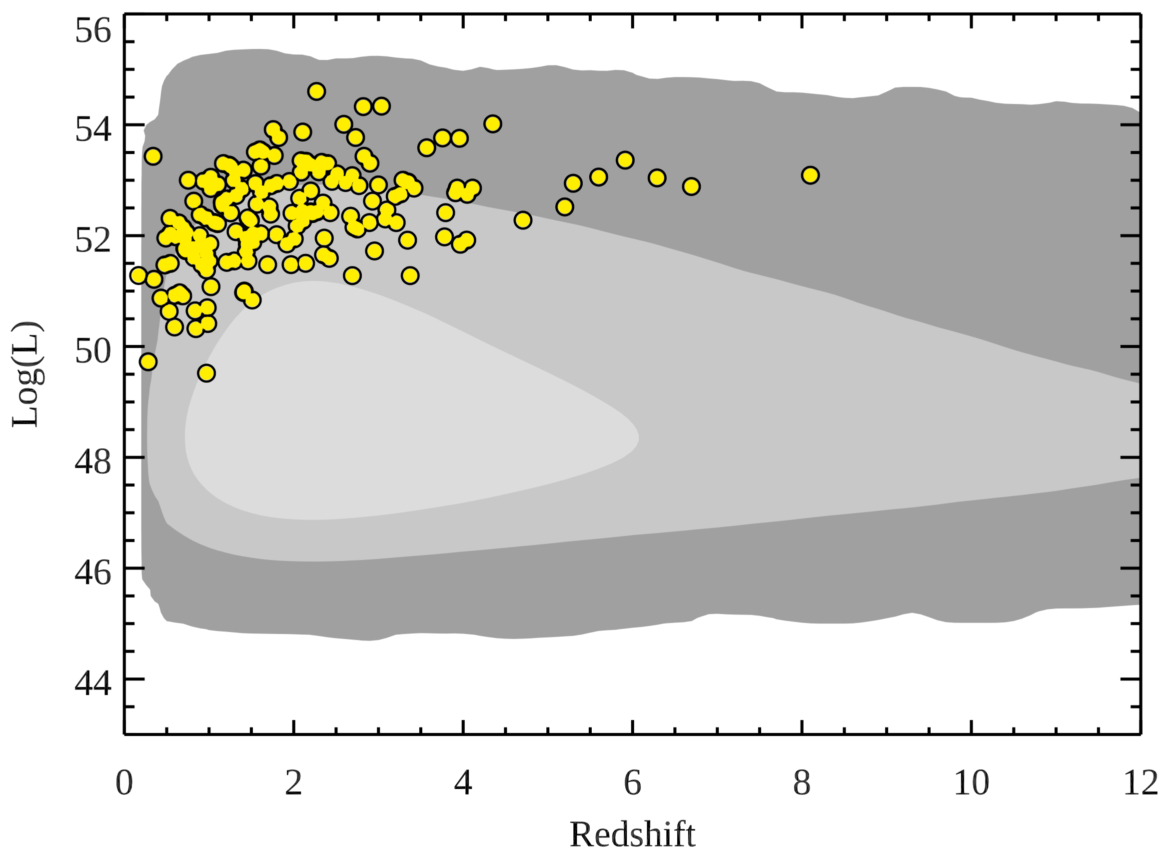
Detection condition: source counts wrt to background counts

Theseus wrt to Swift & Fermi: long GRBs

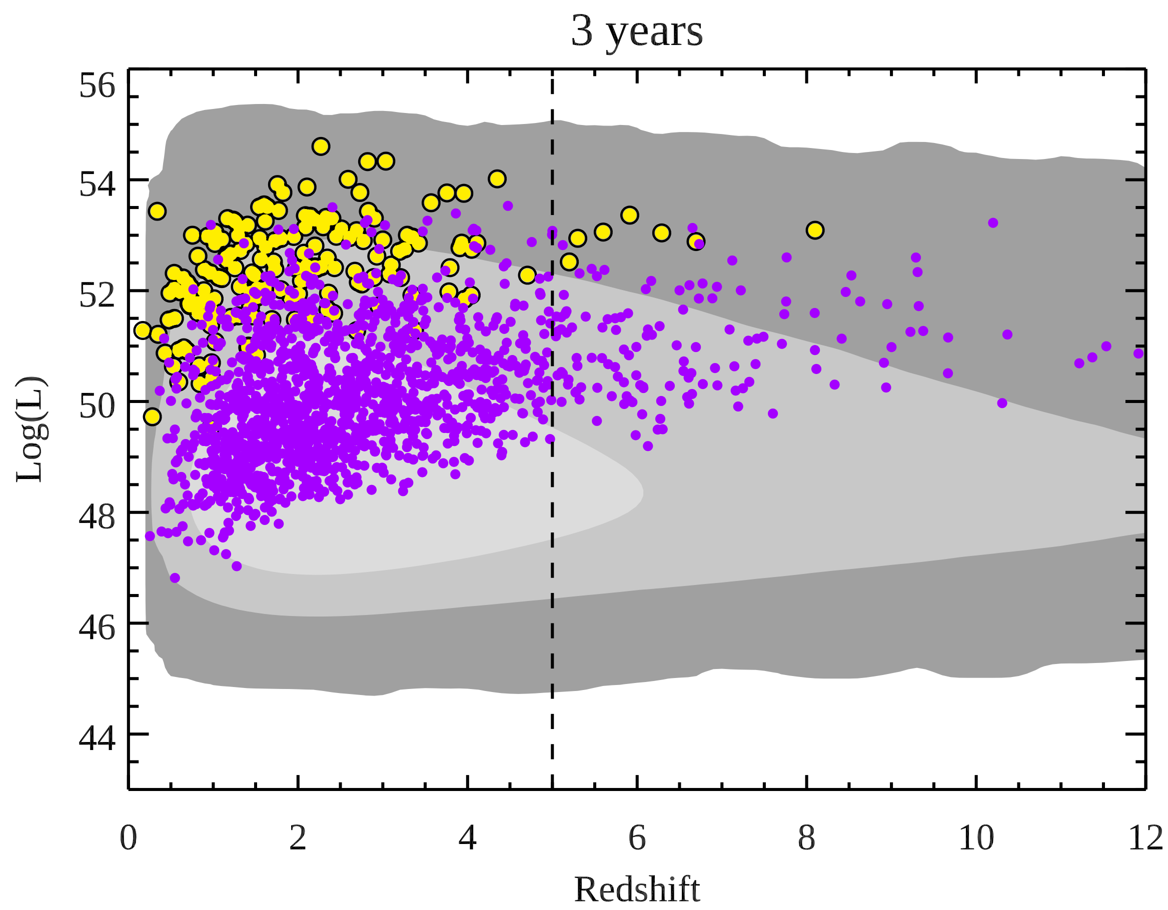


Theseus's Long GRB population

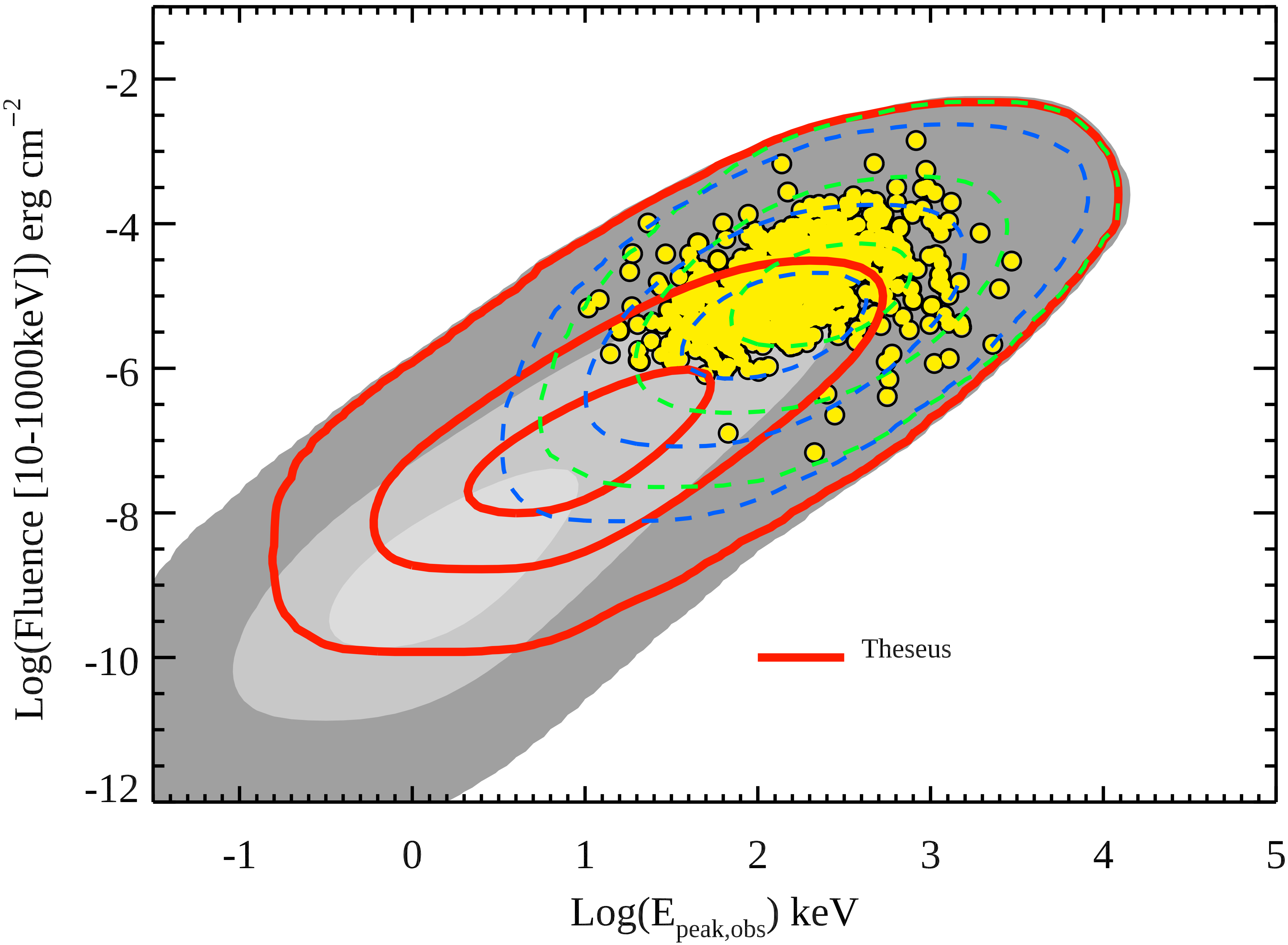
Current sample in >15 years



Theseus

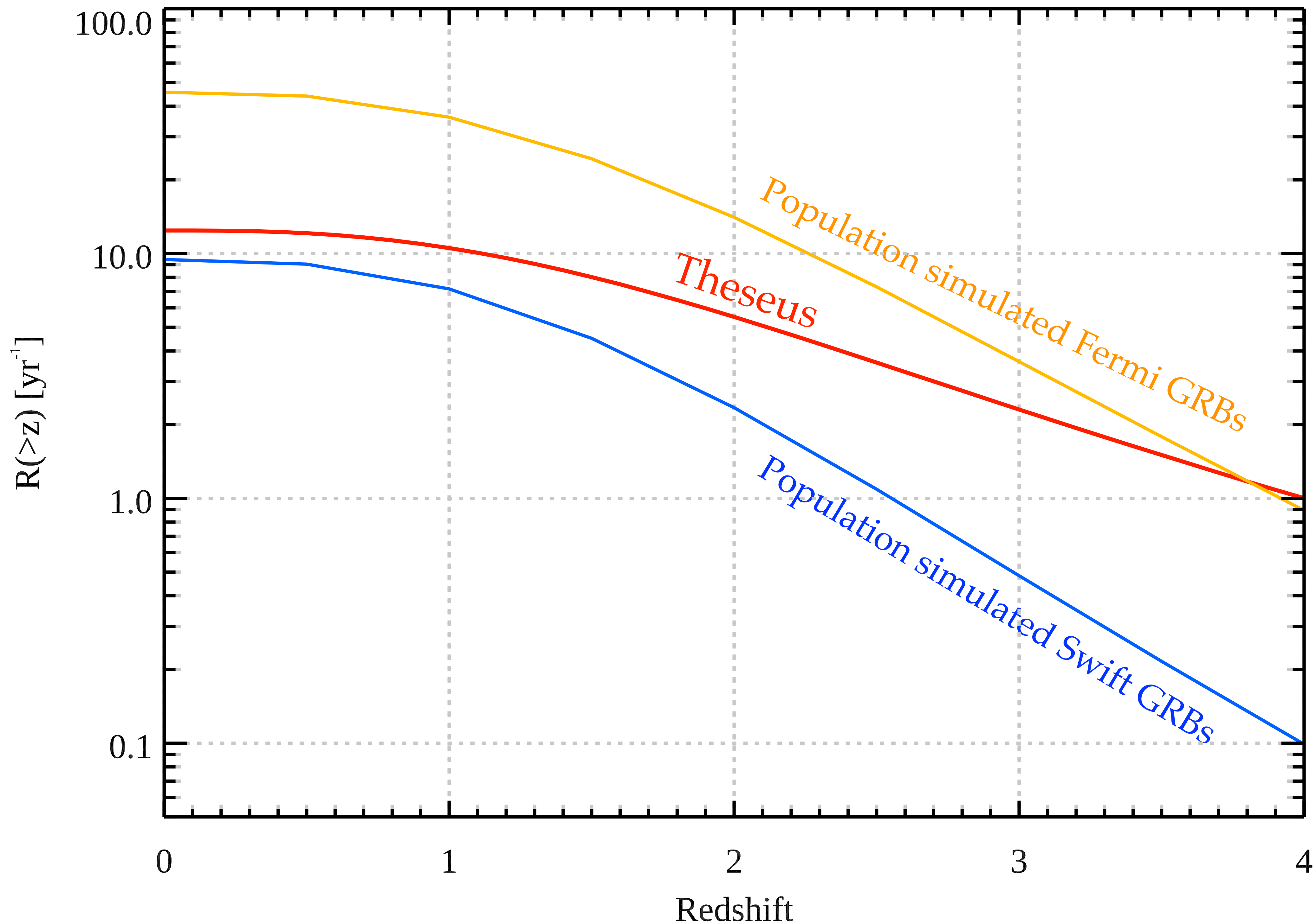


Theseus's Long GRB population

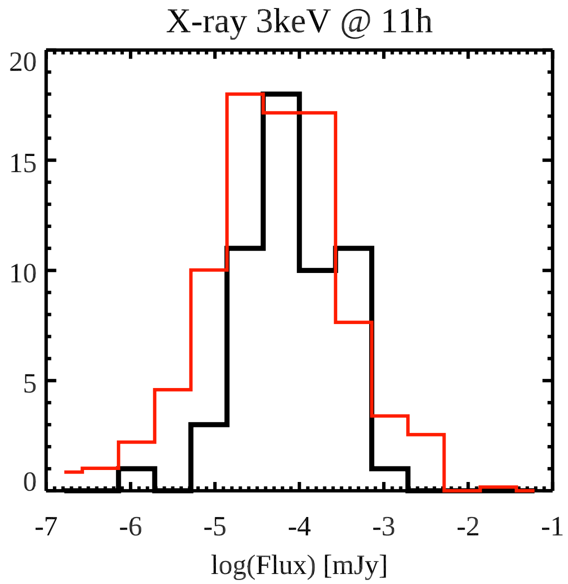


Theseus wrt to Swift & Fermi: short GRBs

Short GRBs mostly detected by XGIS



Afterglows

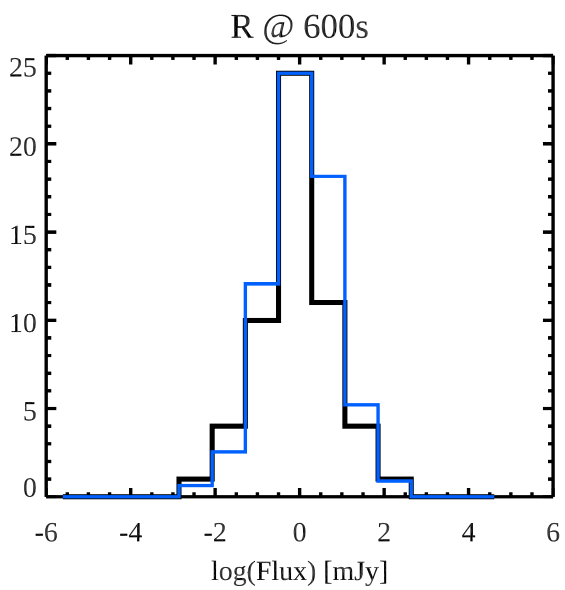


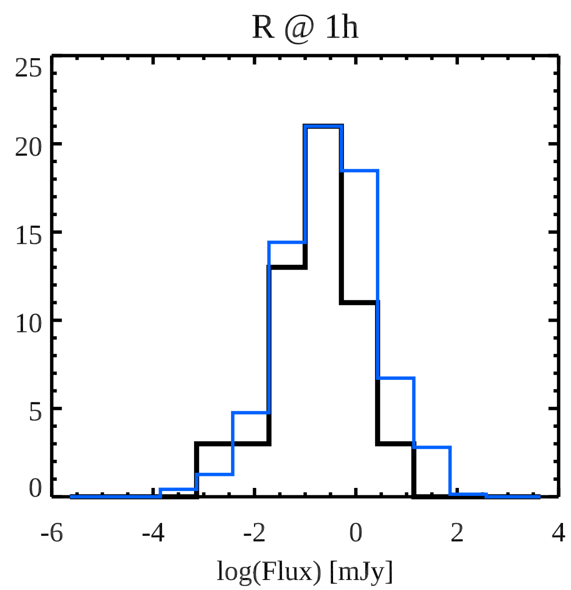
Standard Afterglow model

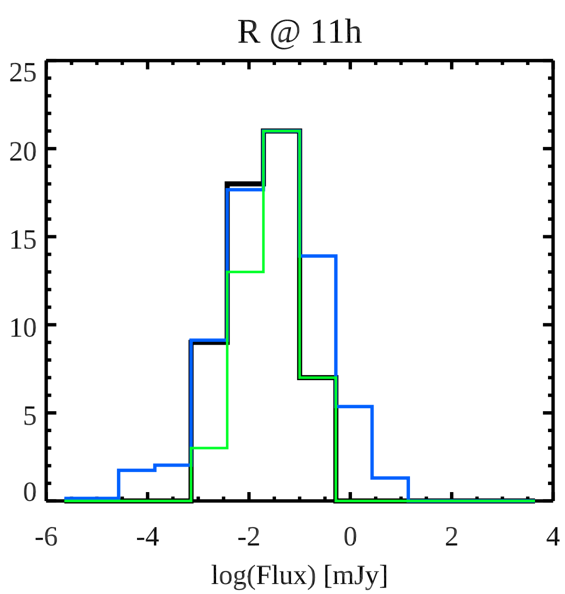
[e.g. Panaitescu & Kumar 2000; van Eerten 2012 …]

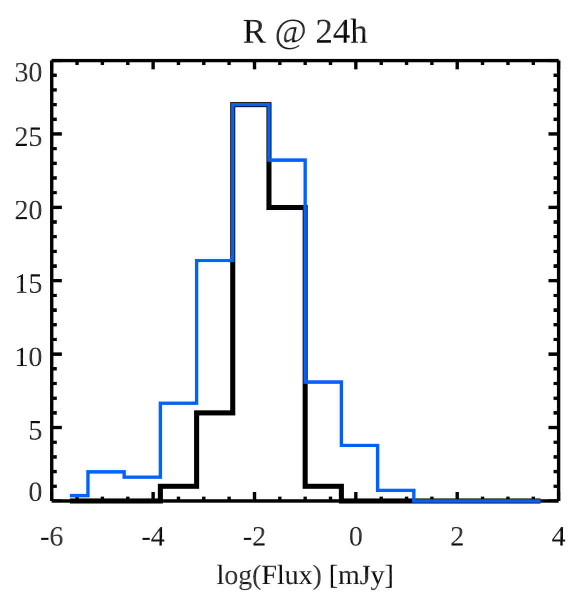
GG, RS + in prep.

- Distribution of n_{ISM}
- Distribution of p ($N(\gamma) \propto \gamma^{-p}$)
- Fraction of shock energy ϵ_e
- Fraction of shock energy ϵ_B

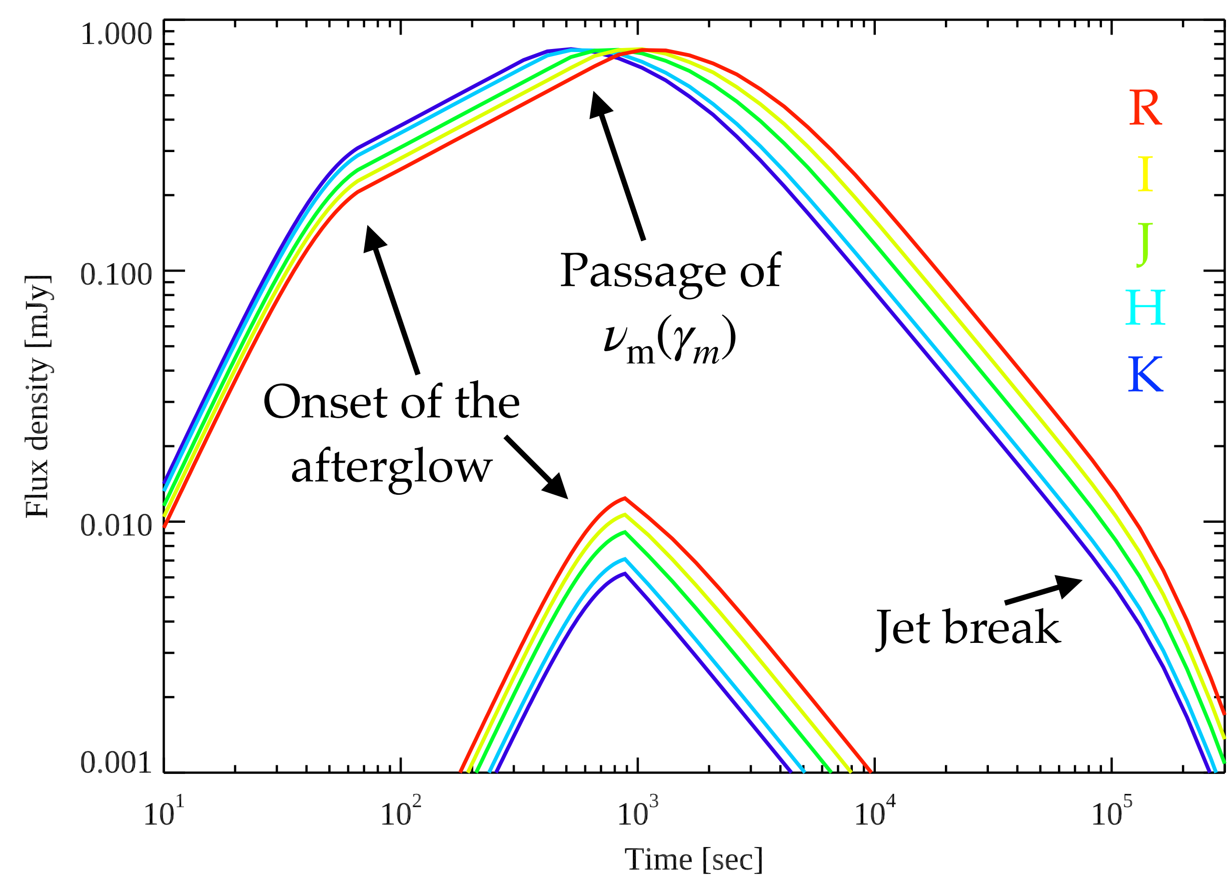








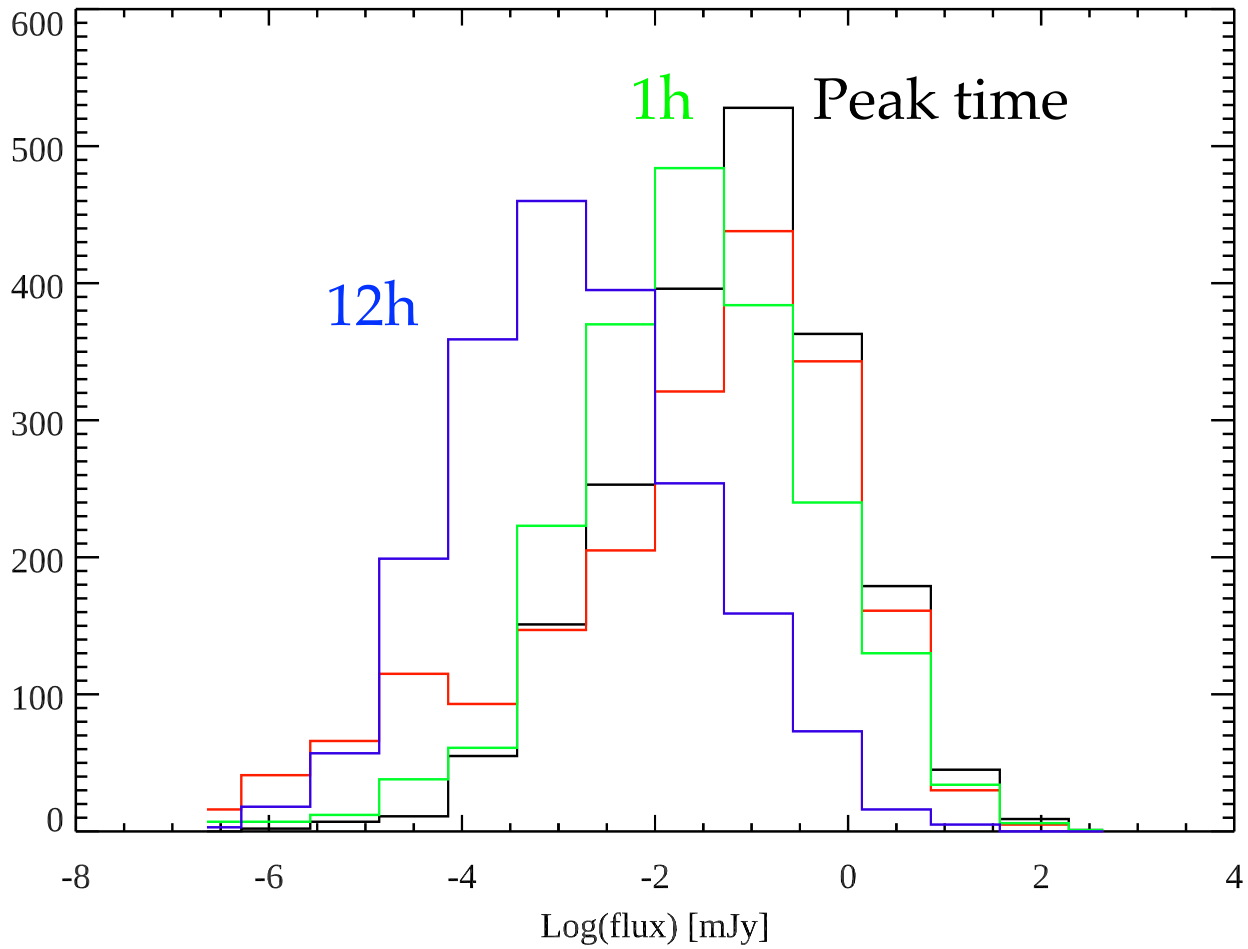
- Distribution of $\Gamma_0 \propto E_{\mathrm{iso}}$ (GG+2018)
- Distribution of θ_{jet} (GG+2007)



Afterglows

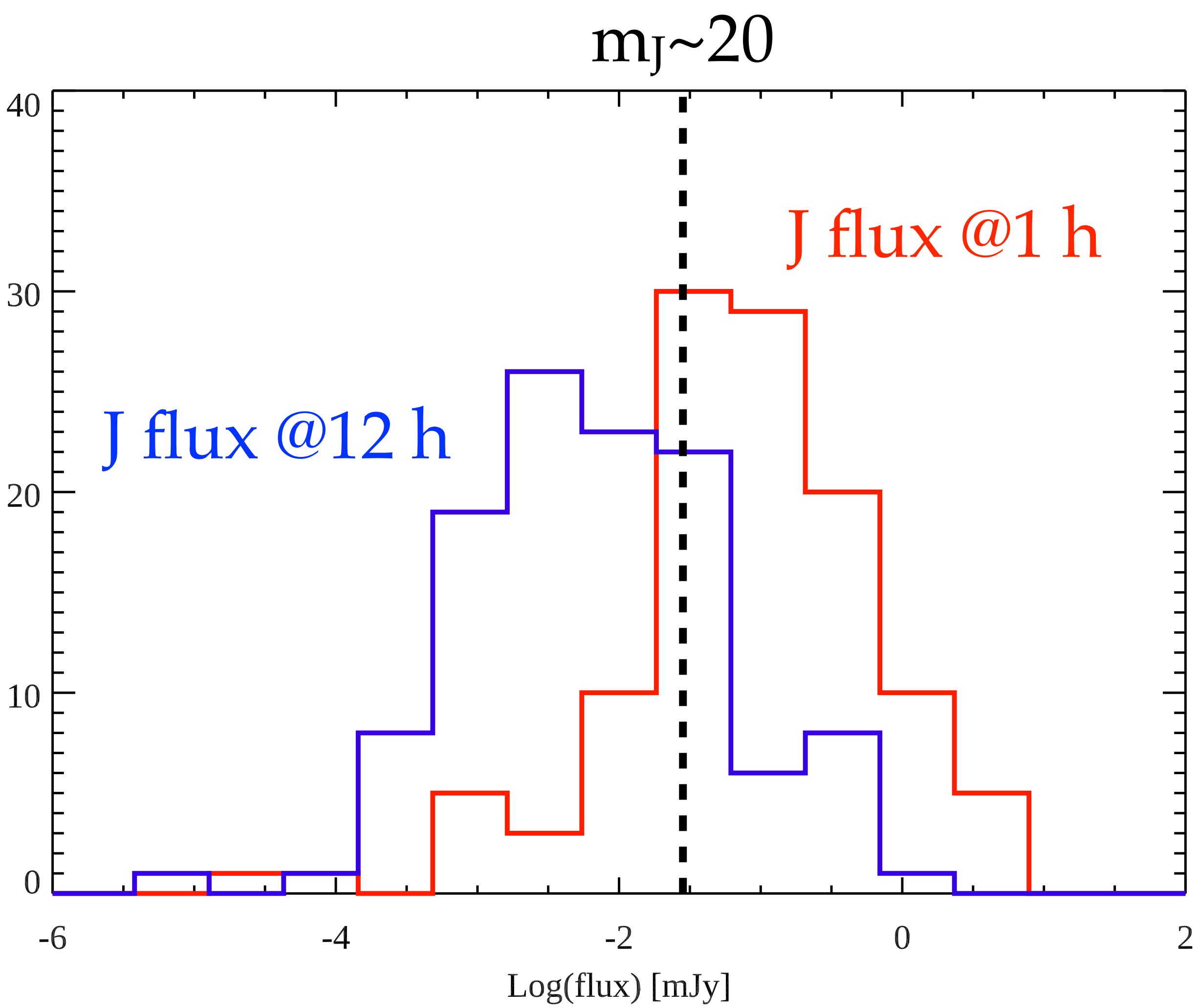
Theseus 2000 Long GRB afterglows

WG4 —> Library of .txt files delivered and available in the simulation tools



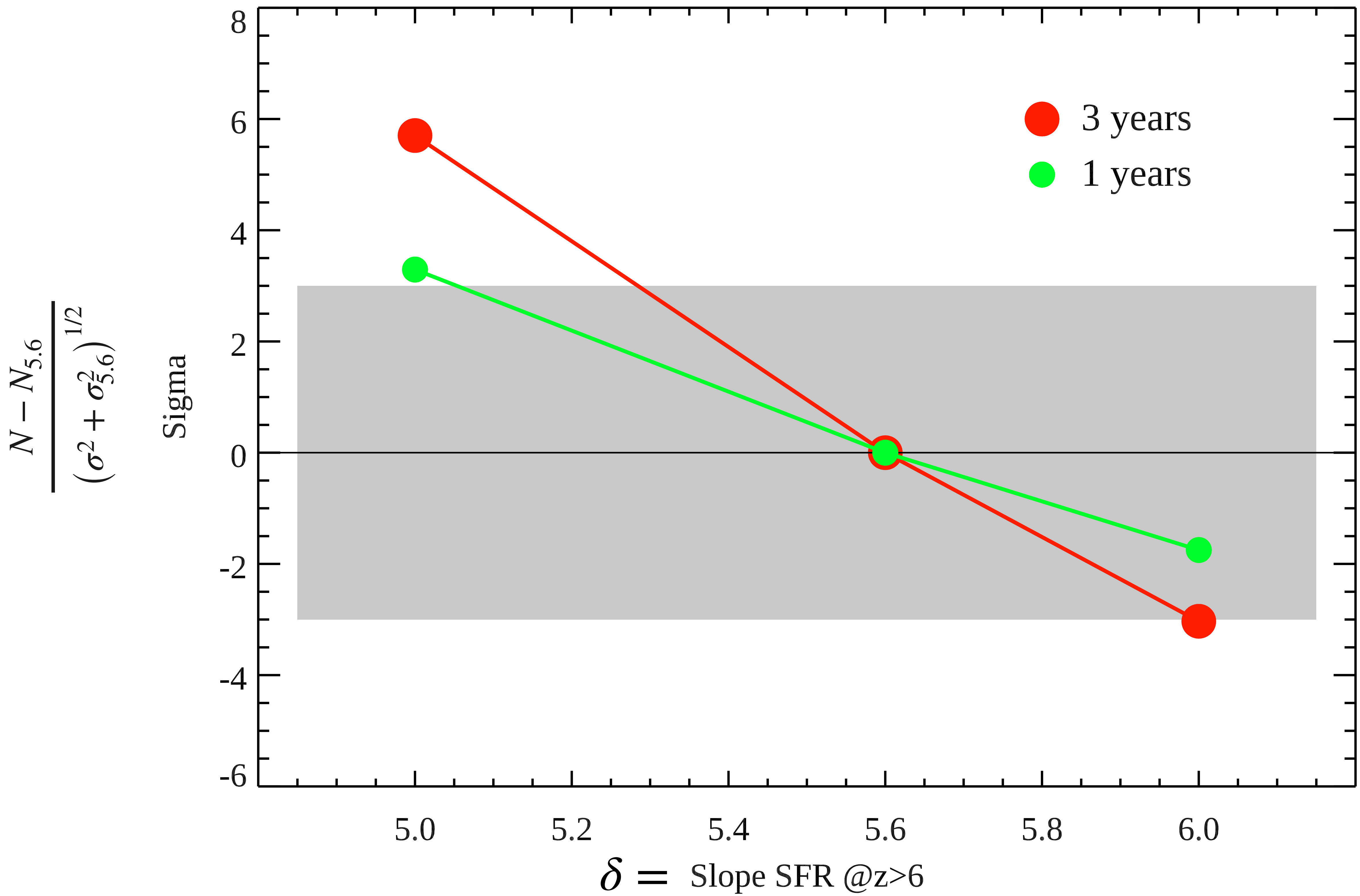
Similar library for Short GRBs is on the way (accounting for different environ.)

Long GRB afterglows @ z>6



No host extinction
No IGM absorption
No DLA

Constraints on the CSFR @ z>6



WG4: Population and rates

On-going activities:

1. Explore the properties of the detected GRB popoulation(s) (other WGs and YB plots proposals)
2. Implement viewing angle effects (off-beam bursts)
3. Short GRB afterglow library
4. Early X-ray afterglow detection through SXI

Future activities:

5. Document describing the population setup, results and relevant plots (useful for YB)
6. Study of the model uncertainties and their impact on the detection rate uncertainty
7. Study afterglow assumptions and their impact on redshift measurement
8. Implement Pop-III (need inputs from other WGs)

Thank you