Cosmological Distributions and Evolution of Gamma-ray Bursts and their relations to Star Formation Rate and Gravitational Waves

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OUTLINE

I. General Remarks

Correlations and standard candles

II. The Luminosity Function and its evolution

III. Procedures:

Forward Fitting vs Non-parametric methods

IV. Results of Applications

A. Long GRBs

B. Short AGNs

I. General Remarks

Cosmology with discrete sources

Cosmology with Standard “Candles?”

Method For Measuring Cosmological Distance

$$d_m(z) = (c/H_0)\int_0^z dz'/\sqrt{\Omega(z')}$$

1. Standard Candle: *Constant Luminosity* $d_m(z)(1+z) = [L/(4\pi f)]^{1/2}$
2. Standard Yardstick: *Constant Diameter* $d_m(z)/(1+z) = D/\theta$
3. OR: Find a **tight** relation between a

distance *dependent* and a **distance** *independent* parameter

Well known examples:

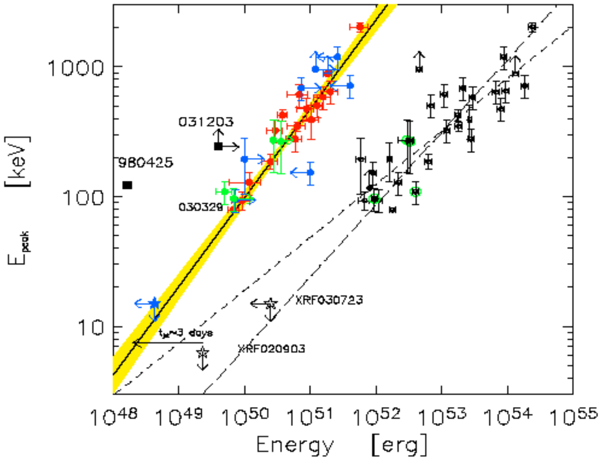
A. Cepheids: *Luminosity-Period relation*

B. Type Ia Supernovae: *Peak luminosity-Light profile width*

GRB Correlations as SC?

Examples of Correlations *After Few Redshifts*

1. Variability-Luminosity *(Reichart et al. 2001)*
2. Lag-Luminosity *(Norris, Maeani & Bonnell 2000)*
3. $E_{\rm peak} - \varepsilon_{\rm iso}$ or $E_{\rm peak} - \varepsilon_{\gamma}$ *(Amati; Ghirlanda et al.)*



4. And Several Variations on These

(see Schaeffer et al.)

SOME RELEVANT EQUATIONS

1. “Luminosity Function” and Correlation

$$\psi(\mathcal{E}_{iso}, E_p) = \phi(\mathcal{E}_{iso}[E_p])\zeta(E_p)$$

$$\phi(\mathcal{E}_{iso}) \propto \delta[(\mathcal{E}_{iso} - \mathcal{E}_0 f(E_p/E_0)], \quad \text{e.g.} \quad f(x) = x^\eta$$

2. COSMOLOGY

$$\mathcal{E}_{iso} = 4\pi d_m^2 (1+z) F_{tot}, \ \text{Define } F_0 = 4\pi (c/H_0)^2 F_{tot}$$

$$d_m = (c/H_0) \int_0^z dz/\sqrt{\Omega(z)}, \quad \text{with} \quad \Omega = \rho/\rho_0$$

$$\int_0^z dz'/\sqrt{\Omega(z')} = \left(\frac{f[E_p^{obs}(1+z)/E_0]}{(1+z)F_{tot}/F_0} \right)^{1/2}$$

POSSIBLE EVOLUTIONS

$$\mathcal{E}_{iso} = \mathcal{E}_0 \times g(z) f\left(z, \frac{E_p}{E_0 \times h(z)}\right)$$

SHAPE **SPECTRAL and ENERGY**

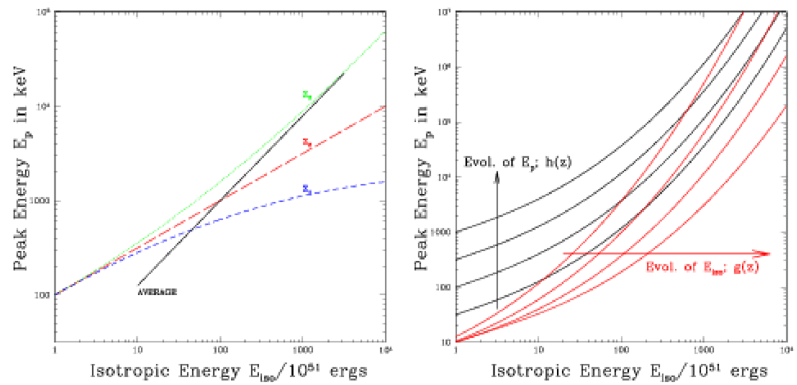
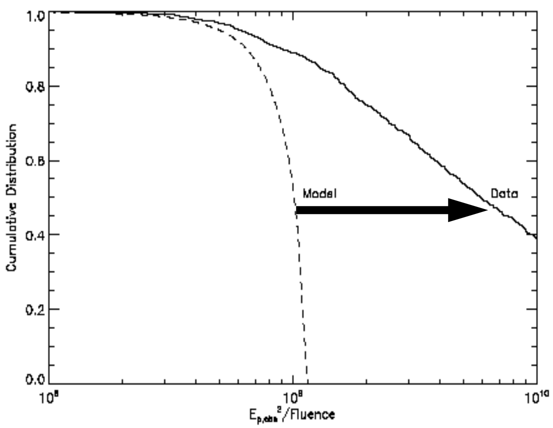


Figure 1: Scheamatic shape (left), spectral (right, red) and energy (right, black) Evolutions.

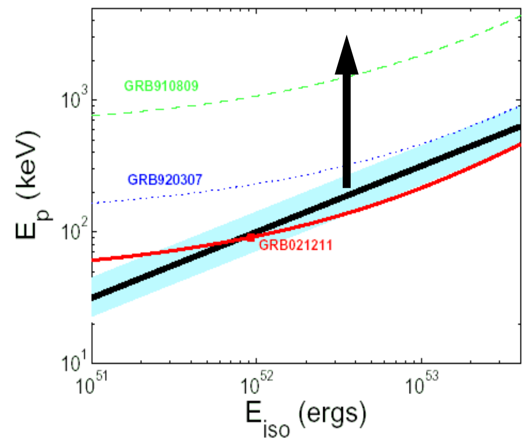
$$\left(\int_0^z \frac{dz'}{\sqrt{\Omega(z')}} \right)^2 = f\left(\frac{E_p^{obs}(1+z)}{E_0 h(z)} \right) \frac{F_0 g(z)}{(1+z)F_{tot}}$$

Problems With These Correlations

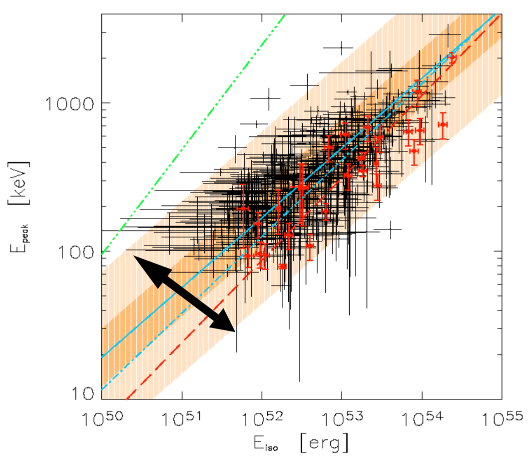
in particular with $E_{\rm peak} - \varepsilon_{\rm iso}$ or $E_{\rm peak} - \varepsilon_{\gamma}$



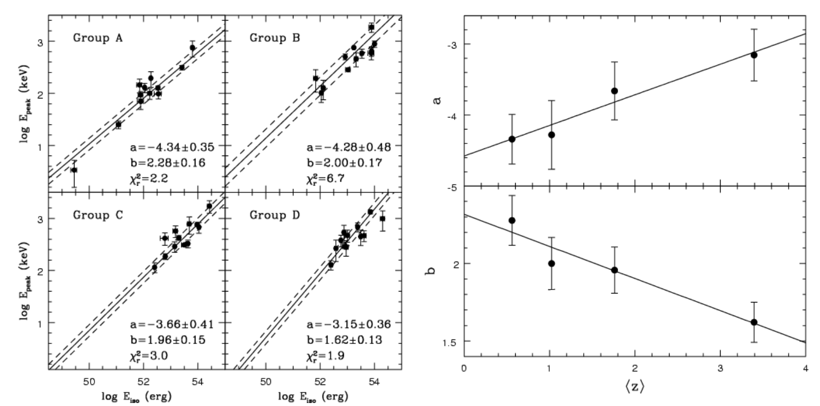
Band and Preece



Nakar and Piran



Pseudo-Redshifts (Ghirlanda et al)



Li et al.

Cosmology with Discrete Sources

Determination of Global Cosmological Parameters

1. Type Ia Supernovae: *Standard Candle and well understood*

BUT Low z

2. Galaxies and Quasars (AGNs): *High z but broad distributions*

Galaxies least understood astrophysical sources

3. Gamma-Ray Bursts: *High z and not well understood*

Question: *SN-like or Galaxy-like?*

Cosmology with Discrete Sources

First Step

Determination of the Luminosity Function $\Psi(L,z)$

Without loss of generality we can write

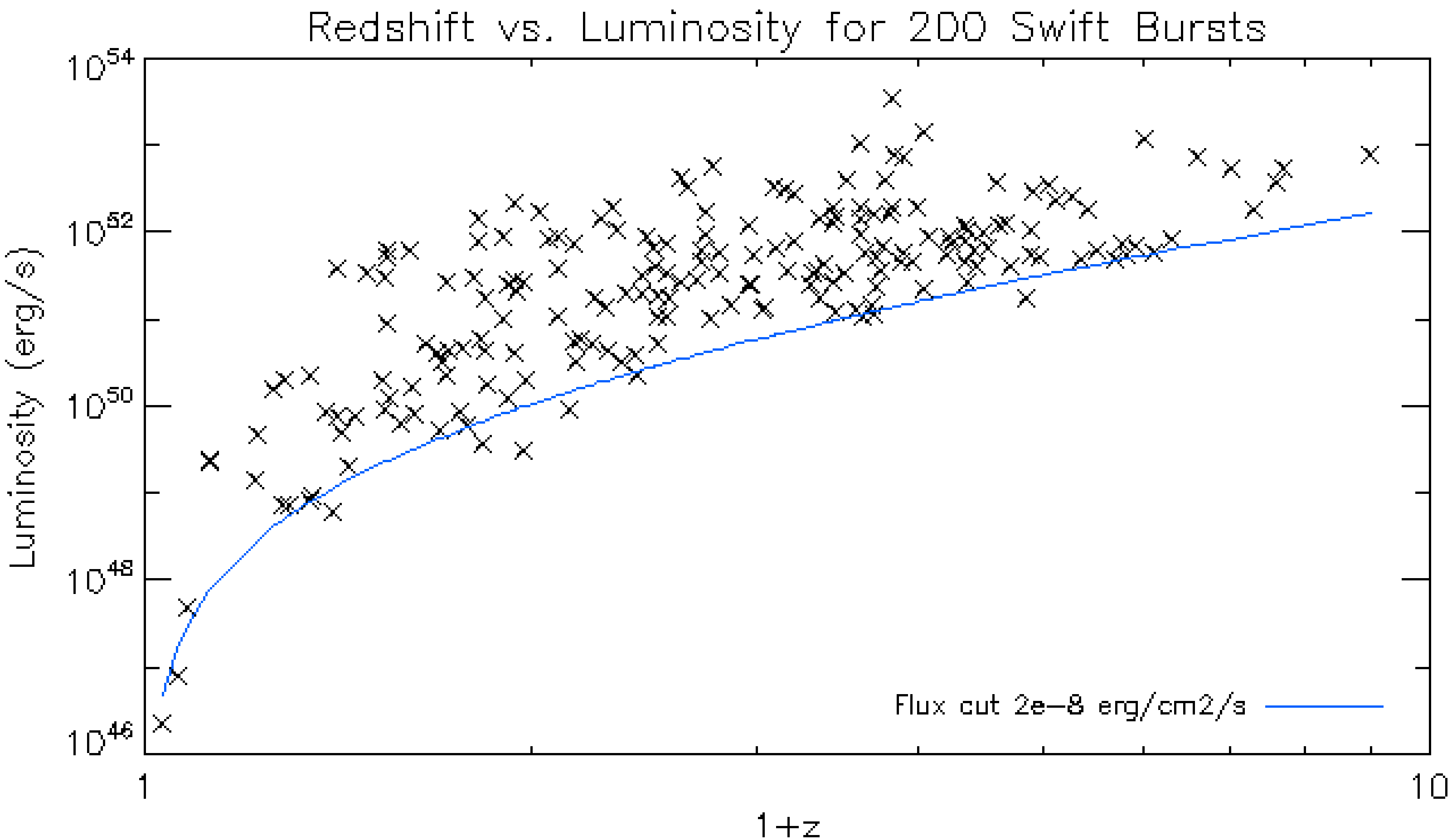
$$\Psi(L,z) = \rho(z)\psi(L/g(z))/g(z)$$

$\rho(z)$ Is the (co-moving) Density Evolution

$g(z)$ Is the Luminosity Evolution

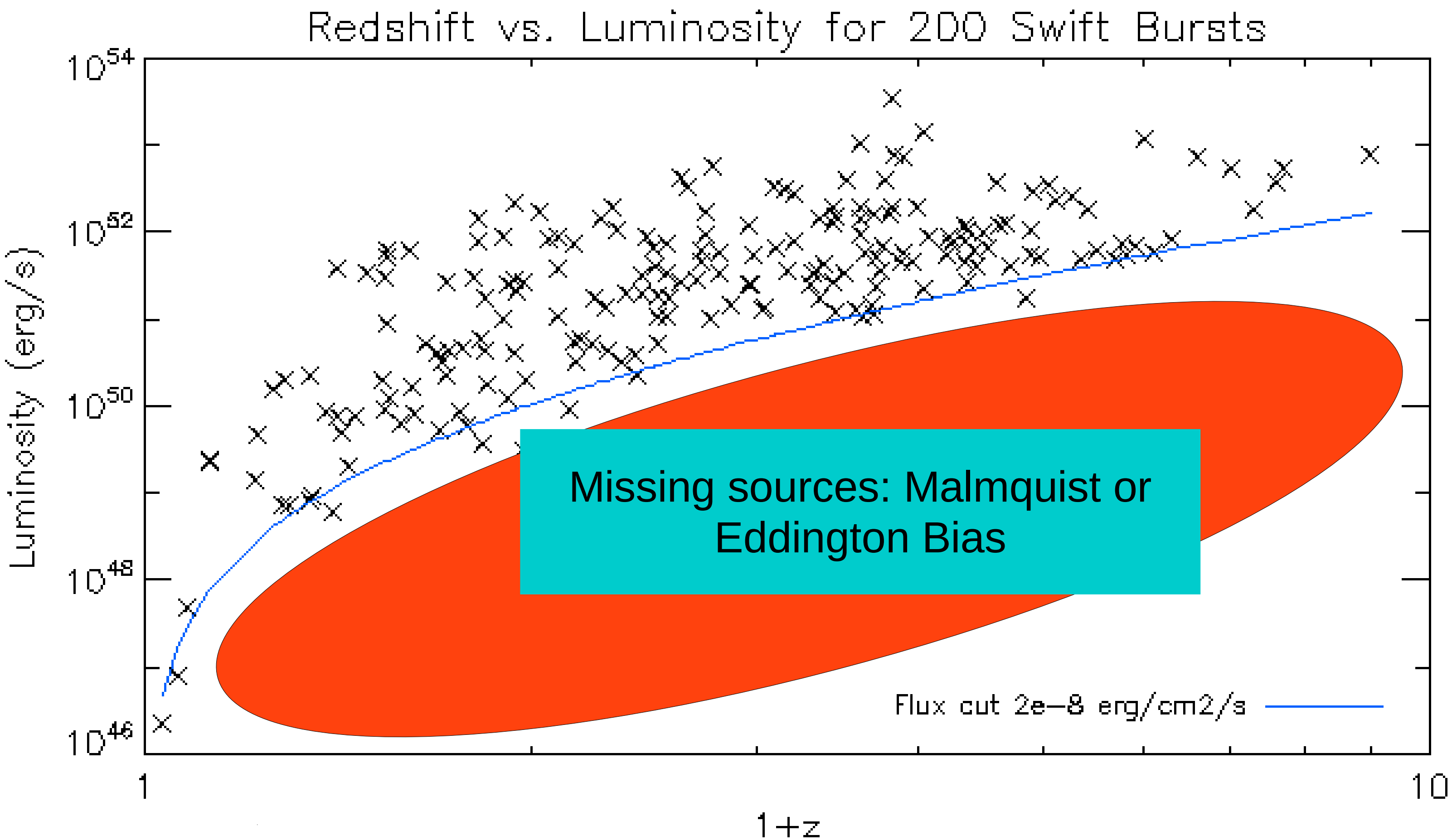
II. The Luminosity Function and its Evolution

The required data: Bivariate *L-z* distribution



Konus-WIND at 25

Bi-variate Luminosity-redshift Distribution



Konus-WIND at 25

III. Procedures

Forward Fitting
vs
*Non-parametric **EPL** Methods*

Efron and Petrosian ApJ 1992
Lynden-Bell 1973

Procedures: 1. Forward Fitting

The common practice is to assume forms for the GRB

"Luminosity" Function $\Psi(L,z) = \rho(z)\psi(L/g(z))/g(z)$

Luminosity Evolution $L(z) = L_o g(z); \quad g(z) = (1+z)^k$

Density Evolution $\rho(z)$

Energy Spectrum *Power-low, Broken Power-law, etc*

Difficulty: *Involves many functions each with several parameters*

Uniqueness??

Procedures: 2. Non-parametric

Some past non-parametric methods

Schmidt (1968) V/V_{max} or Lynden-Bell (1973) *C-* methods

These however assume that Luminosity and Redshift are

Uncorrelated or are Independent variables

Procedures: 2. Non-parametric

More recently (Efron and VP, 1992, 1999) have developed a method that first determines the *L-z* correlation; i.e. $g(z)$

Then remove this correlation by defining $L_o = L/g(z)$

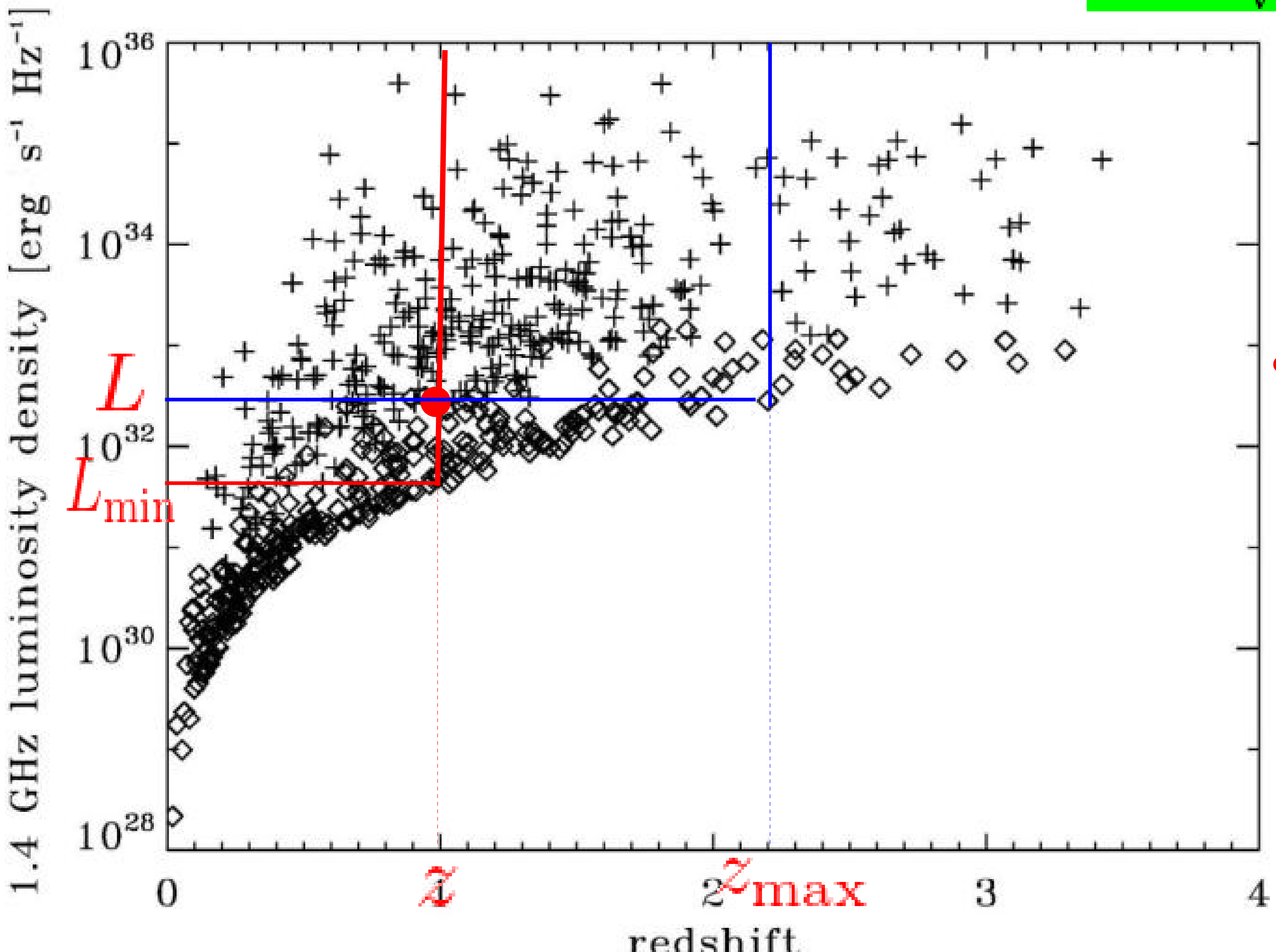
Which is now independent of redshift and allows

Determination of all distributions non-parametrically and directly from the data with very few assumptions or prescribed functional forms

1. Test of Independence

Spearman Rank Order Test: Distribution of Ranks R_j

Kendall's tau Statistic $\tau = \frac{\Sigma_j (R_j - E_j)}{\sqrt{\Sigma_j V_j}}$



associated sets of

L_i, z_i

With

N_i and M_i

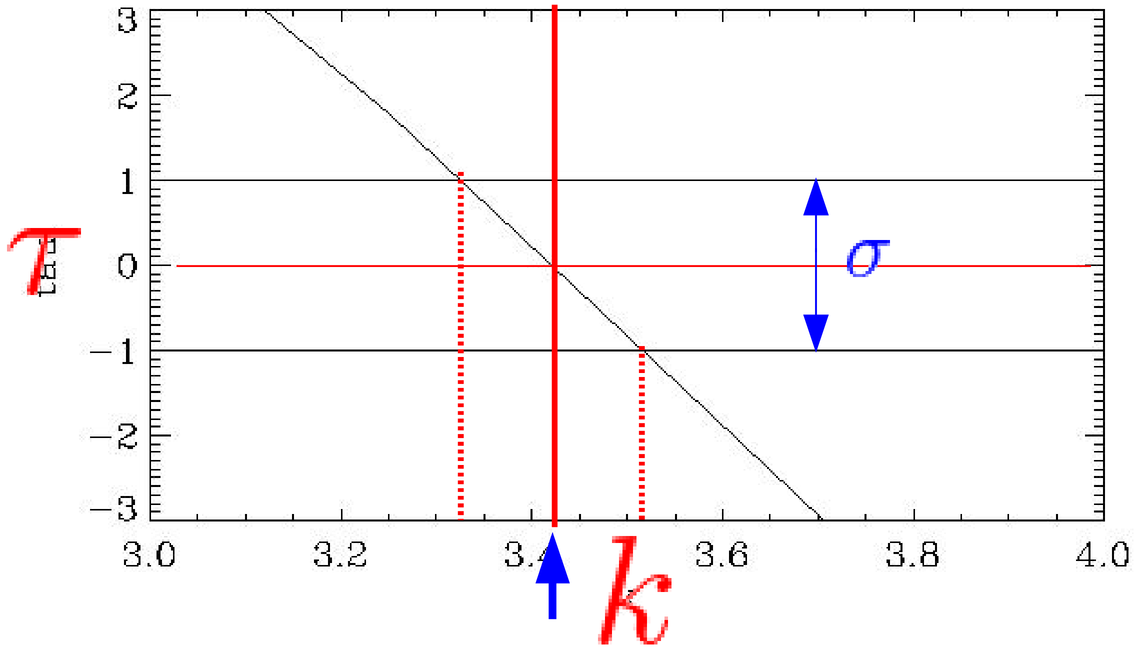
Sources in the sets

Test of Independence

Remove the correlation by a variable transformation e.g.

$$L_i' = L_i/g_i(z)$$

$$g(z) = (1+z)^k$$



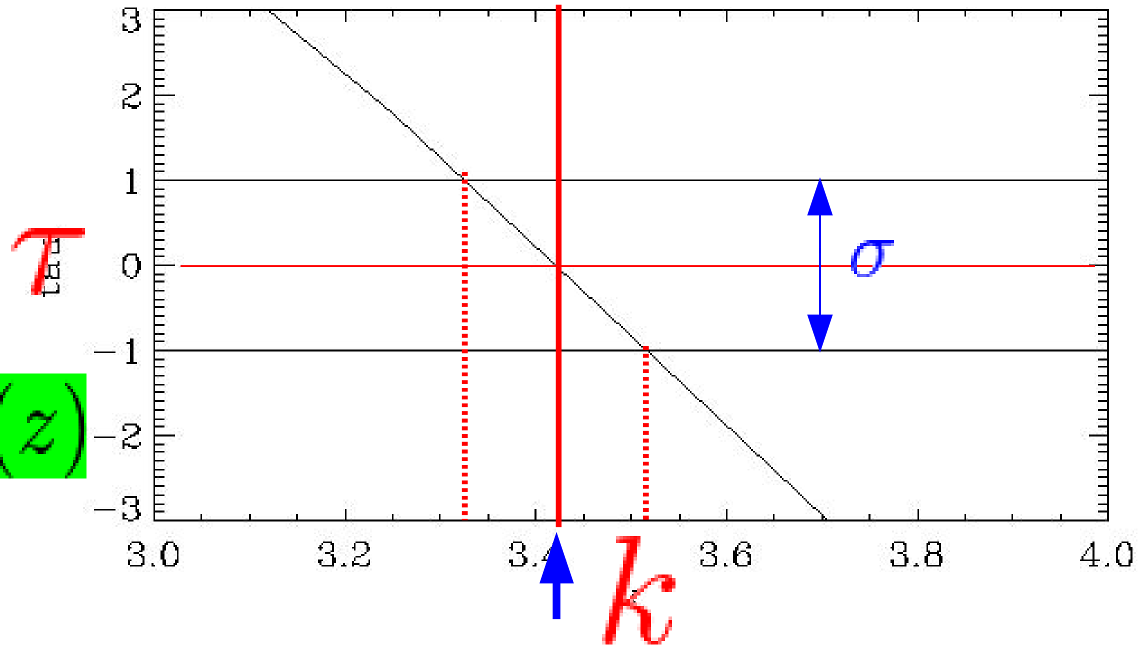
Test of Independence

Remove the correlation by a variable transformation e.g.

$$L'_i = L_i / g_i(z)$$

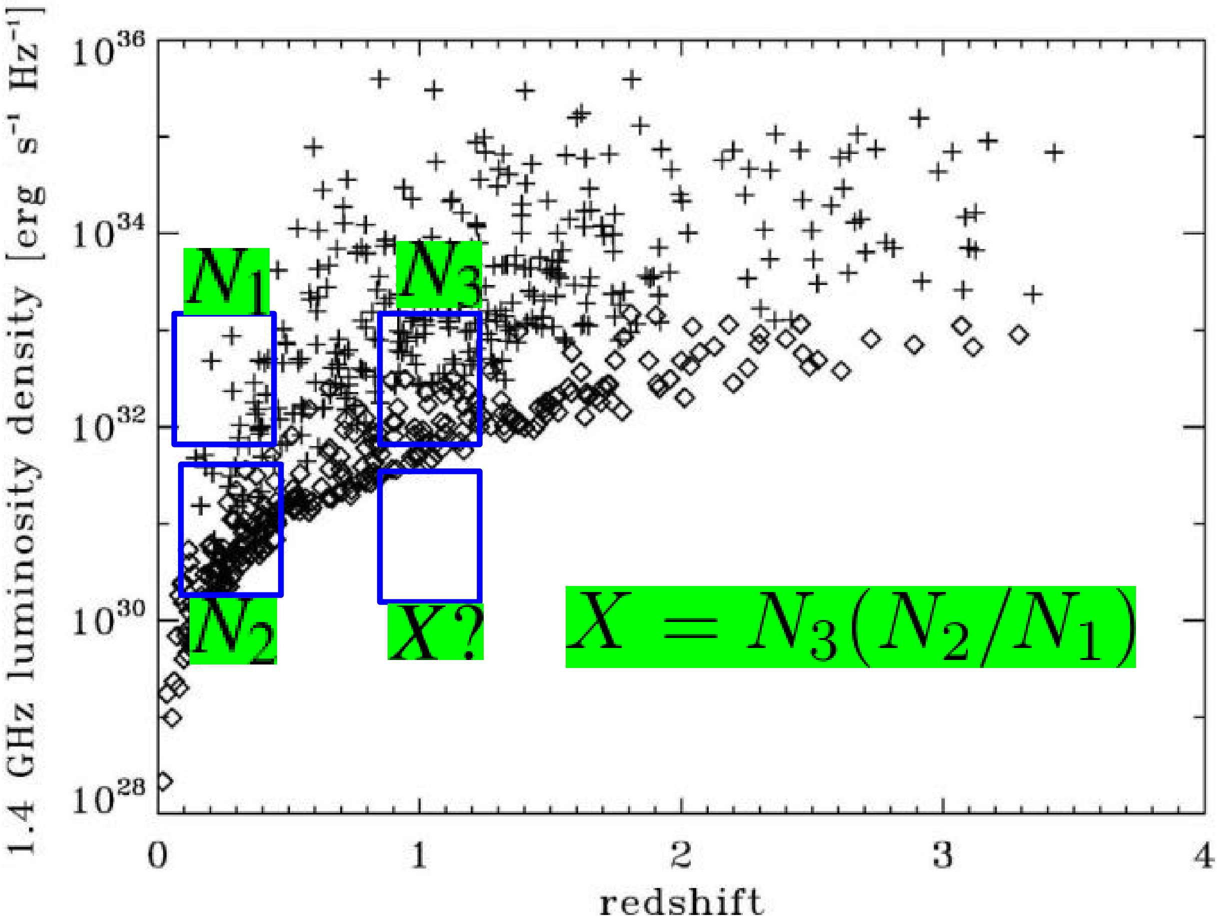
$$g(z) = (1+z)^k$$

$$\Psi(L', z) = \psi(L')\rho(z)$$



Given uncorrelated or independent variables

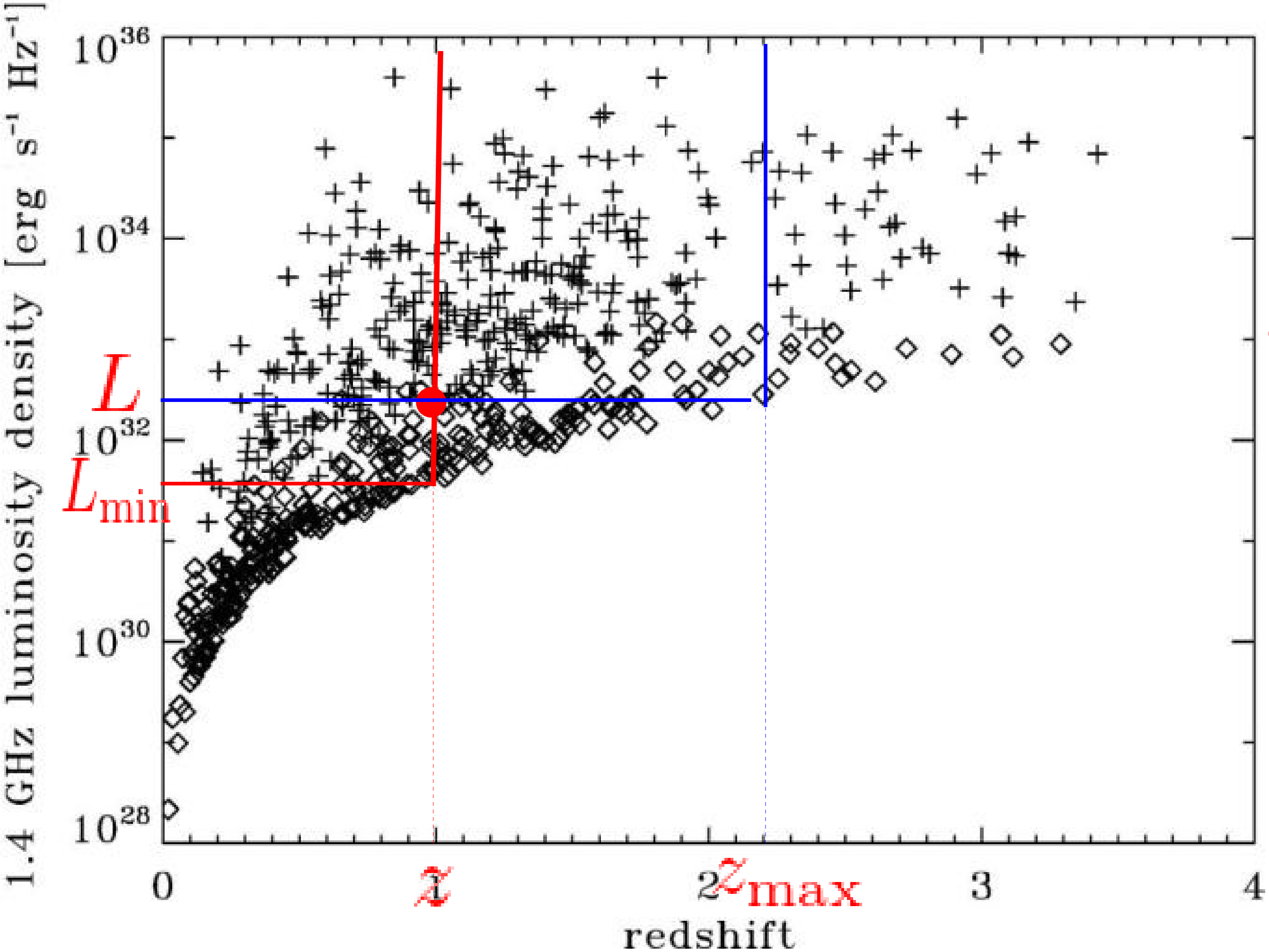
Can account for truncation



Petrosian, 1993

2. The Bivariate Distributions

Based on the associated sets



associated sets of

L_i, z_i

With

N_i and M_i

Sources in the sets

The single variable distributions

The method gives the cumulative *L* and *z* distributions

Non-parametrically and with no binning

$$\Phi(L_i) = \int_{L_i}^{\infty} \Psi(L) dL = \Pi_1^i (1 + 1/N_j)$$

$$\sigma(z_i) = \int_0^{z_i} \rho(z)(dV/dz) dz = \Pi_1^i (1 + 1/M_j)$$

From these we get the sought differential distributions

$$\Psi(L) \quad \text{and} \quad \rho(z)$$

IV. Application to Swift Long Gamma-ray Bursts

Density (rate) Evolution vs Star Formation Rate

Caveats: *Selection Effects and Truncations*

1. Gamma-ray trigger

   Peak count or flux threshold

2. Localization

   X-ray flux threshold

3. Optical follow-up and *Redshift*

   Optical Magnitude etc

2. Bias Due to X-ray Observations

Strong *Correlation* between

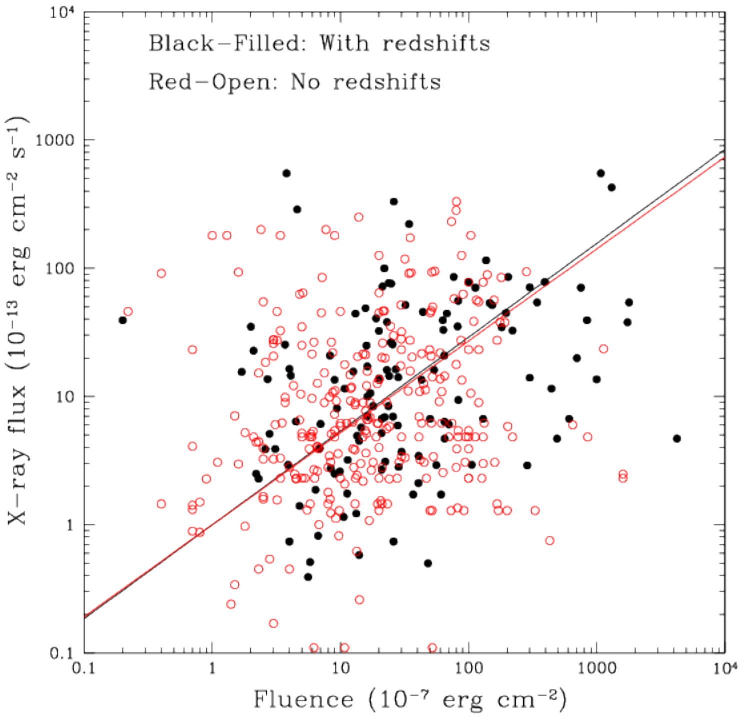
Gamma and X-rays

Same for GRBs with

or without redshift.

Thus, Small bias if any

(data from Nysewander et al. 2009)



3. Optical and Redshift Bias

There is no good criteria for redshift bias.

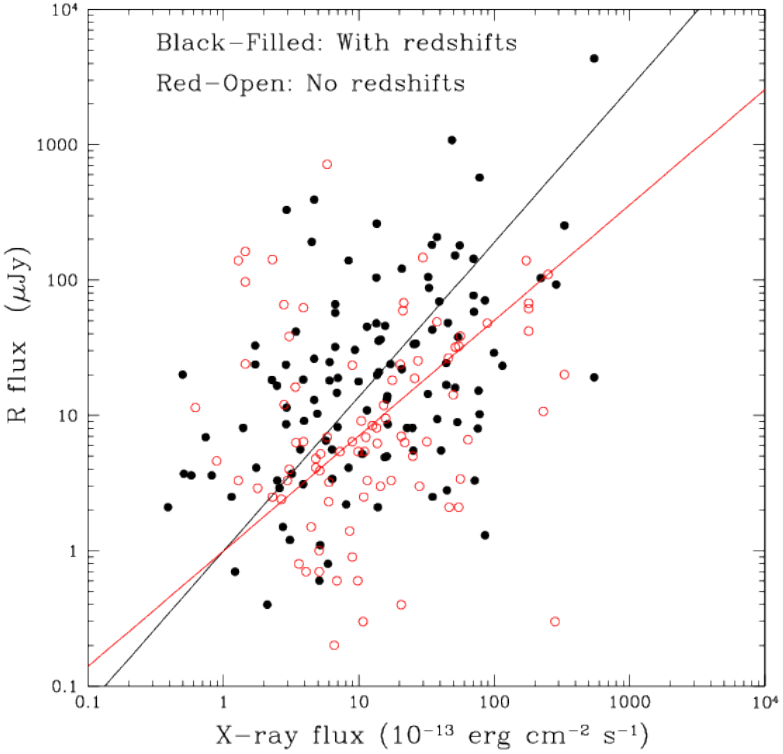
The *optical flux* can be used as indicator but there is no well defined limit.

Opt.-X-ray fluxes *correlated*

So *use X-ray threshold*

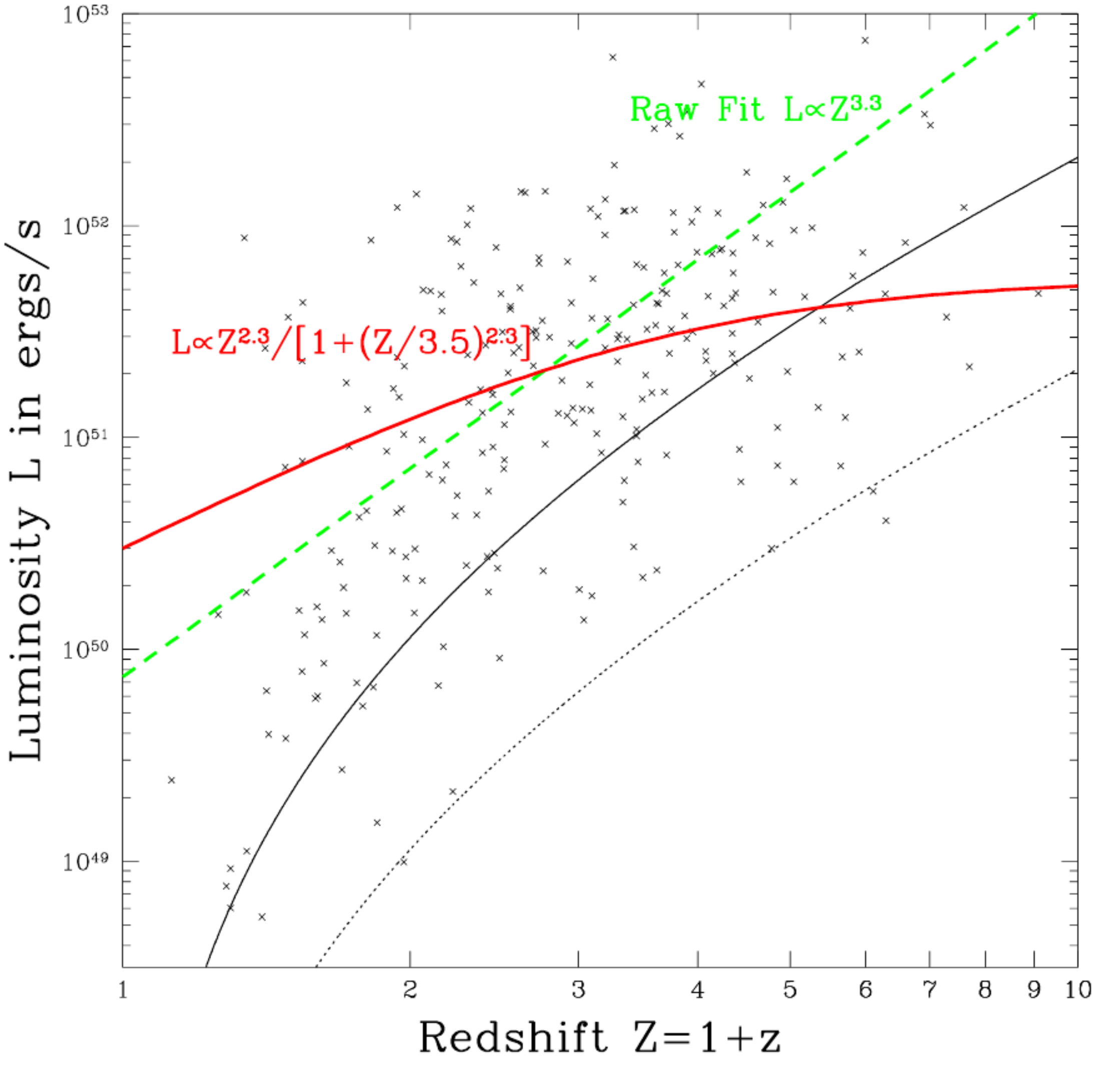
to correct for this bias

(data from Nysewander et al. 2009)



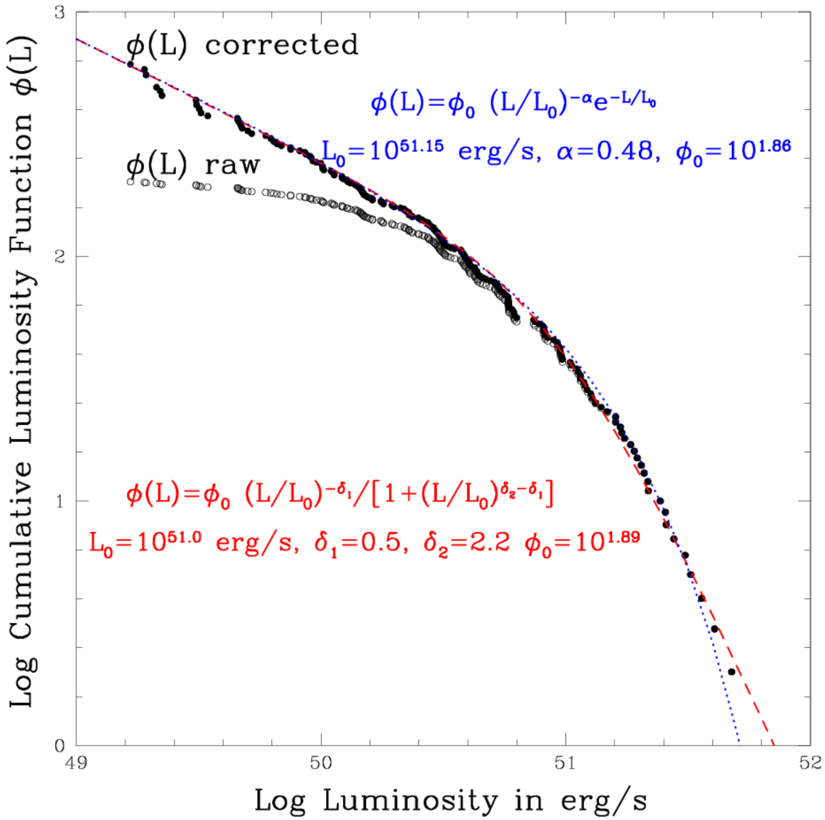
1. Test of independence

Luminosity evolution

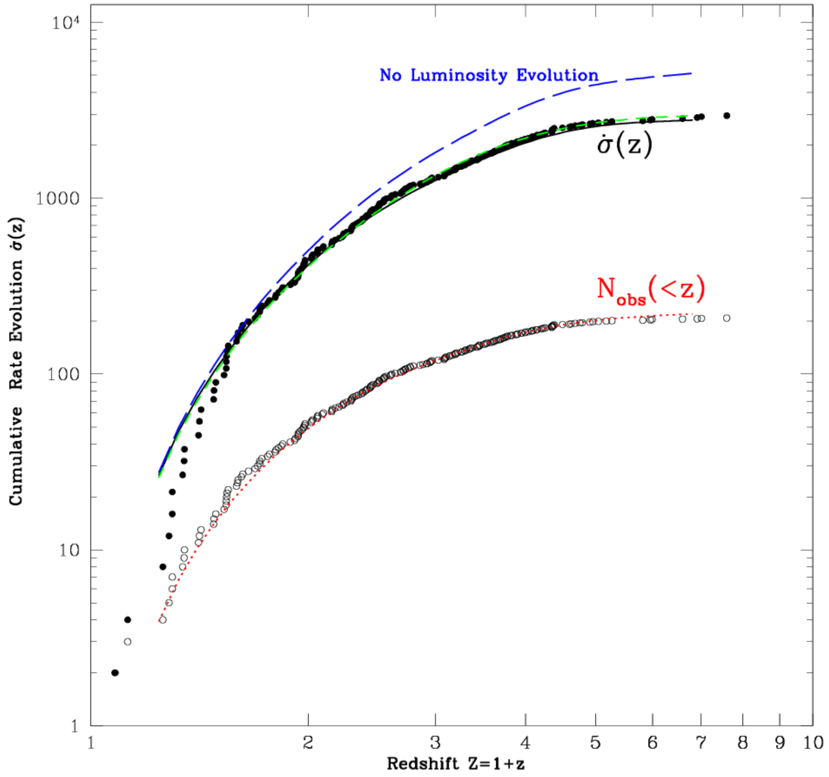


Cumulative Distributions

Luminosity Function

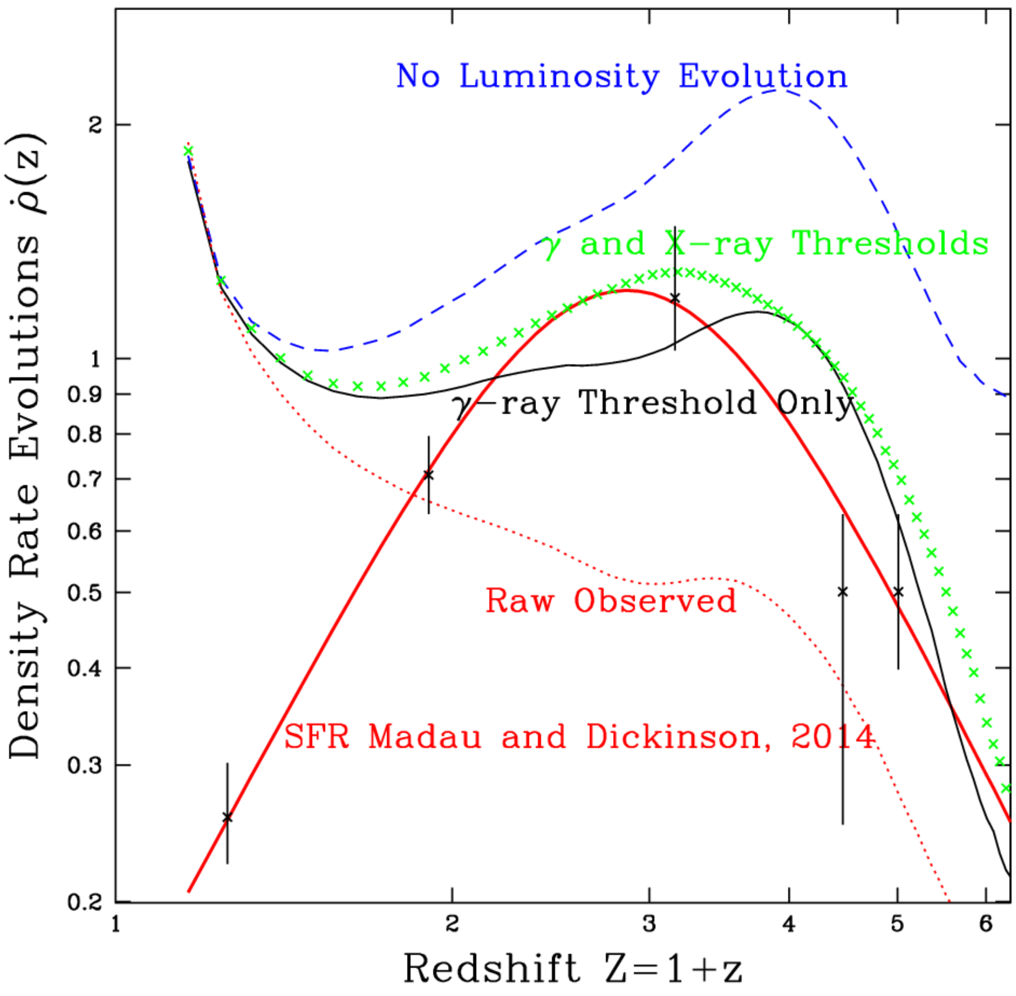


Rate Density Evolution



Konus-WIND at 25

GRB and Star Formation Rates



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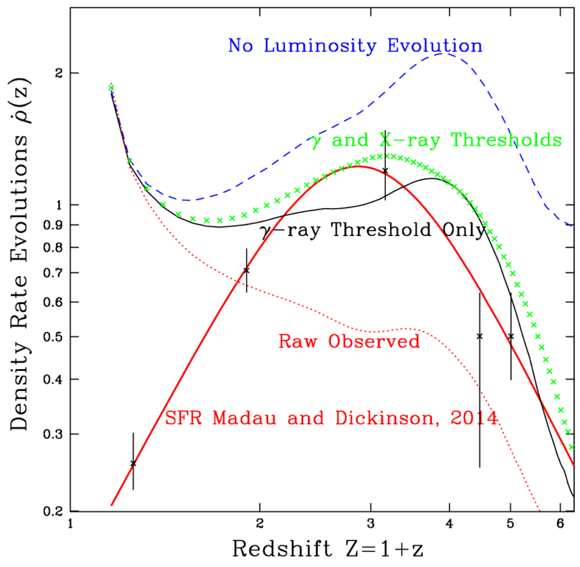


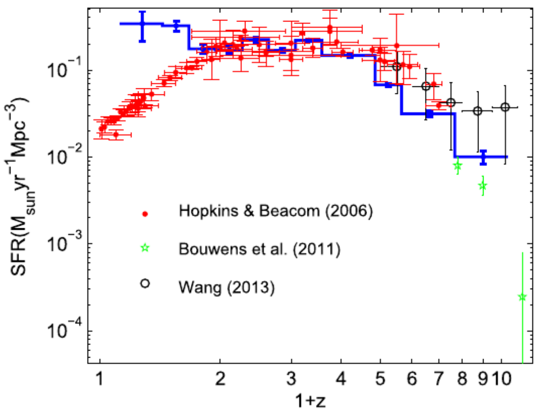
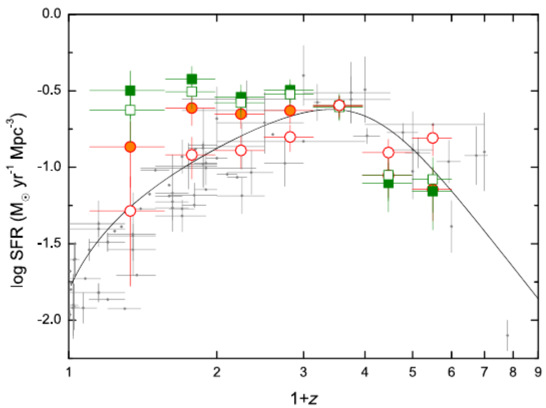
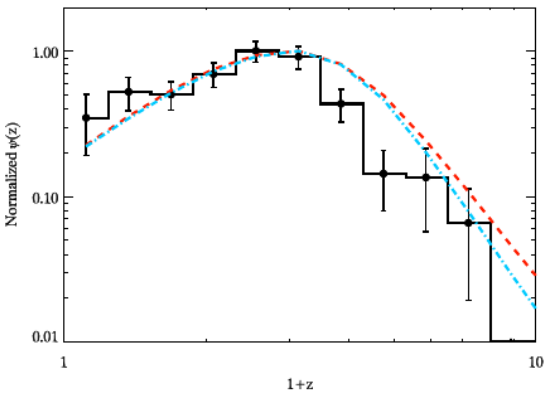


Figure 8. Comparison between GRB formation rate $\rho(z)$ (blue) and the observed SFR. The SFR data are taken from Hopkins & Beacon (2006), which are shown as red dots. The SFR data from Bouwens et al. (2011) (stars) and Wang (2013) (open circles) are also used. All error bars are 1σ errors.





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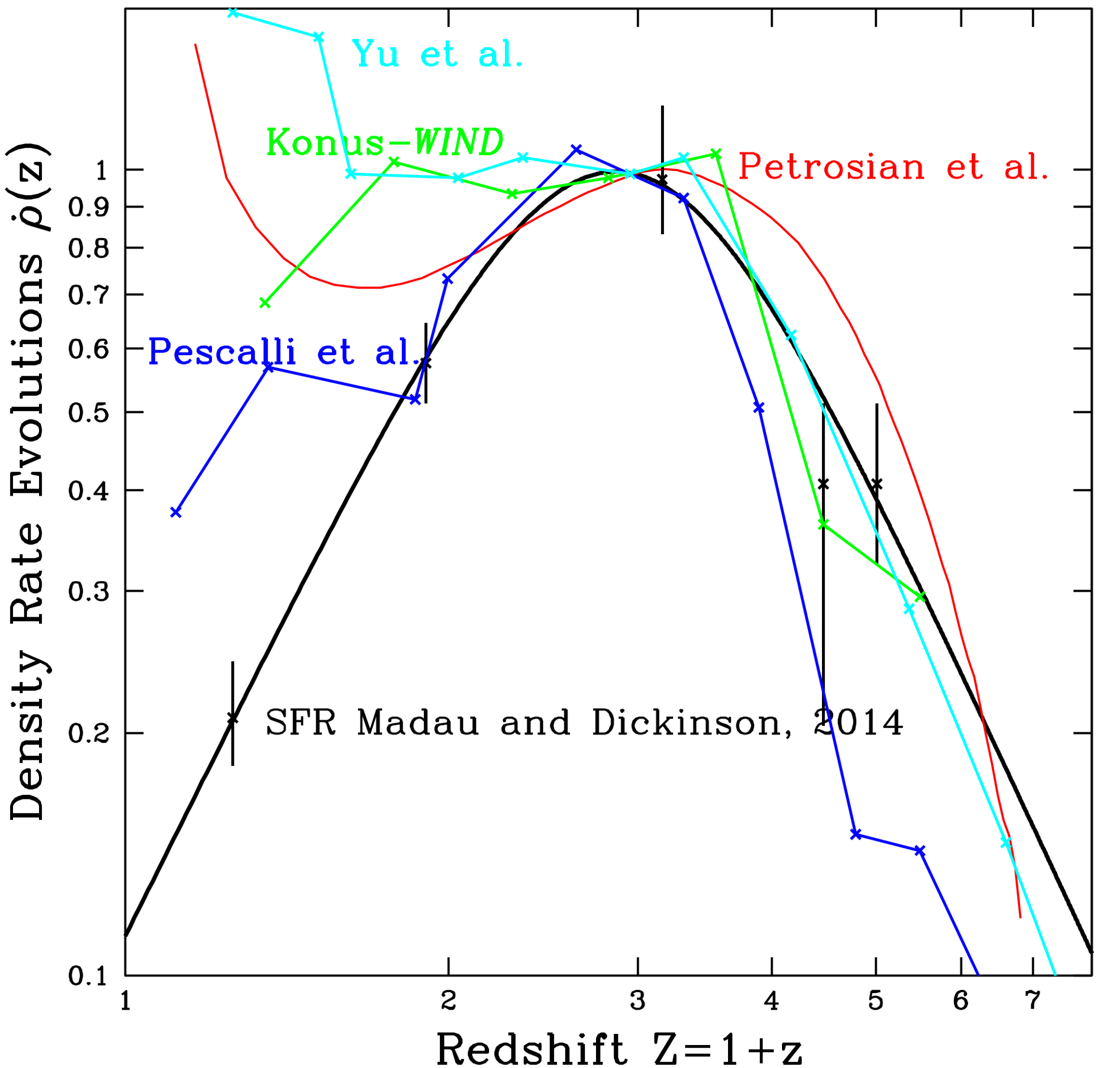


SUMMARY on Long GRBs

1. In order to use GRBs as Cosmological Tools we need a better understanding of the *distribution and evolution* of their characteristics.

2. We have emphasized the advantages of *non-parametric approach* and demonstrated how to determine luminosity and rate density evolutions.

GRB Formation Rate very different than the Star Formation Rate.

3. Further studies can improve our understanding of the phenomenon which will help in using them as tools to explore

The high redshift universe.

4. In the long run, GRBs may prove to be useful for

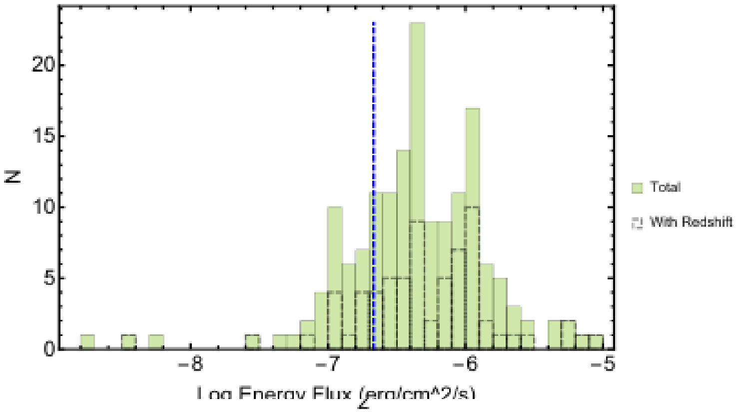
GLOBAL cosmological studies.

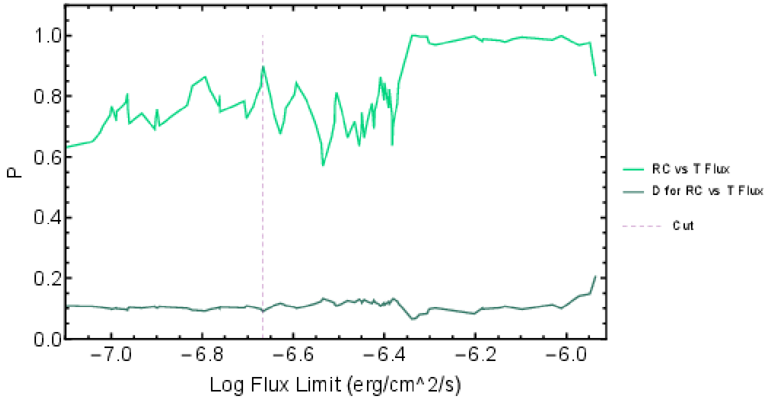
Short GRBs and Gravitational Waves

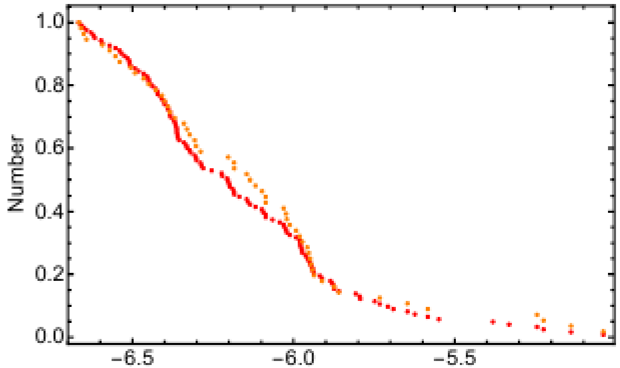
Preliminary results from a Swift sample of SGRB

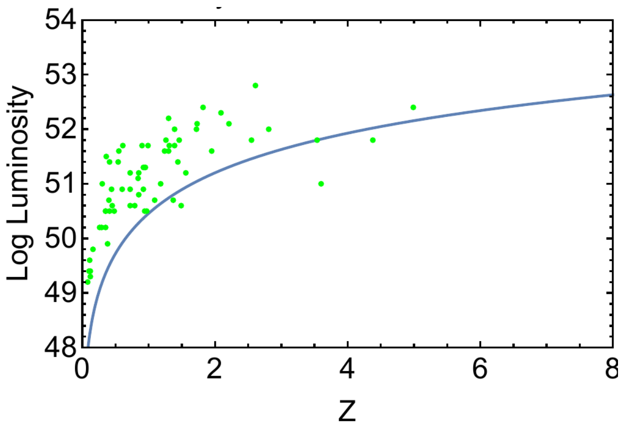
More uncertain because fewer SGRBs

1. Sample selection









Konus-WIND at 25

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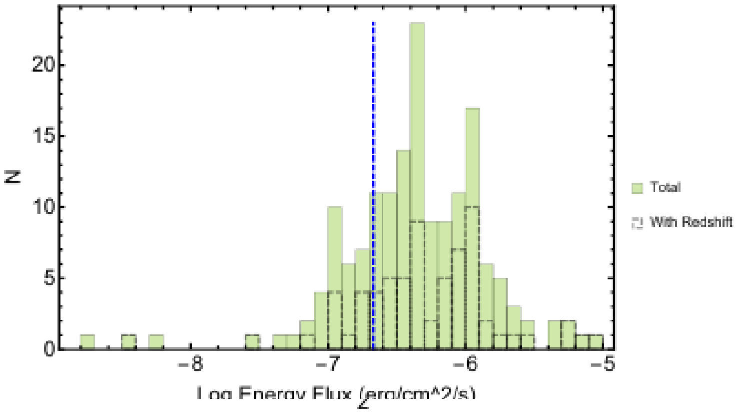
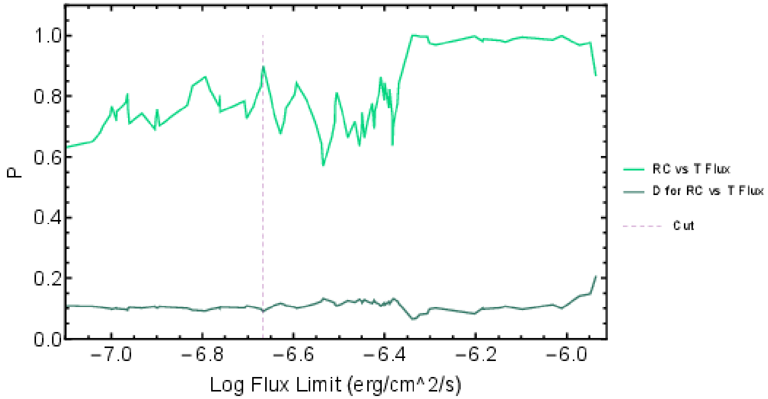
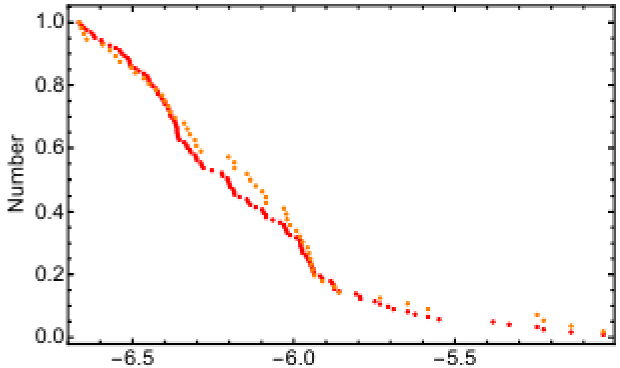
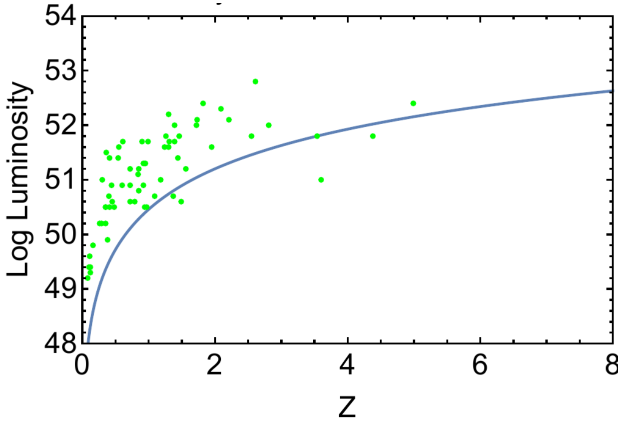








Konus-WIND at 25

Short GRBs and Gravitational Waves

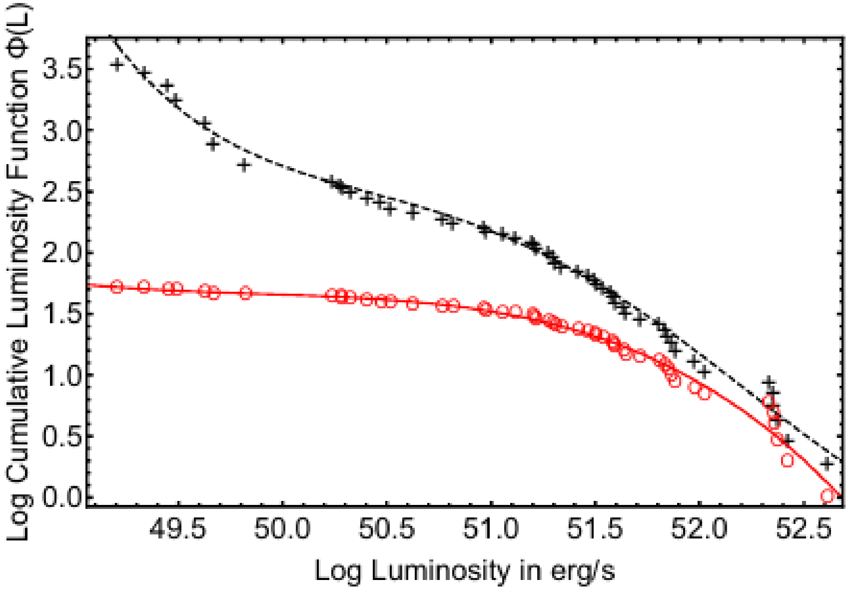
Preliminary results from a Swift sample of SGRB

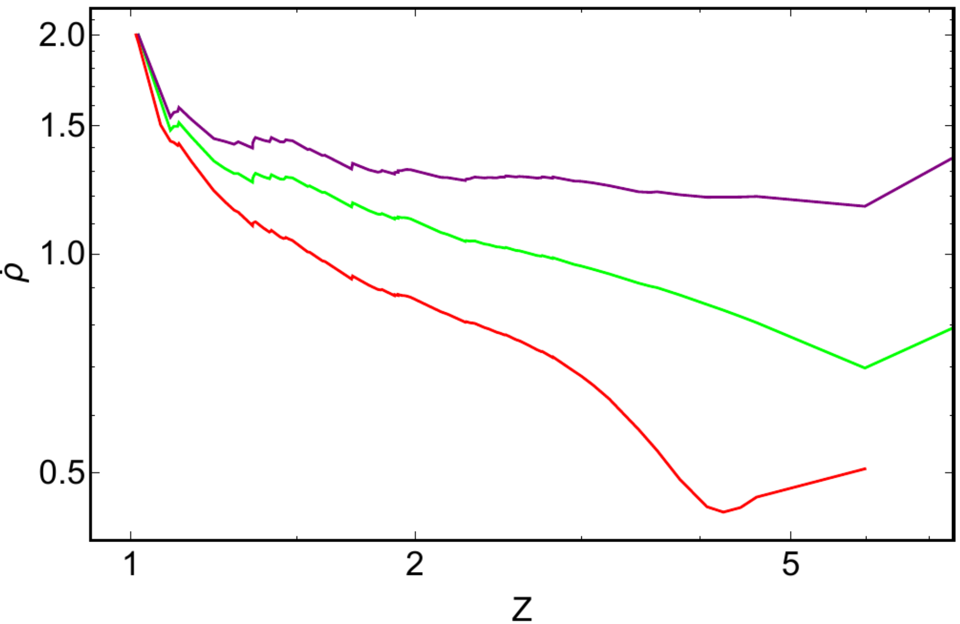
2. Results:

a. Luminosity Evolution $L(z) \propto Z^k/(1+Z/Z_c)^k; \ \ k=3.6$

b. Cumulative Luminosity Function $\Phi(L)$

c. Density Rate Evolution $\dot{\rho}(z)$





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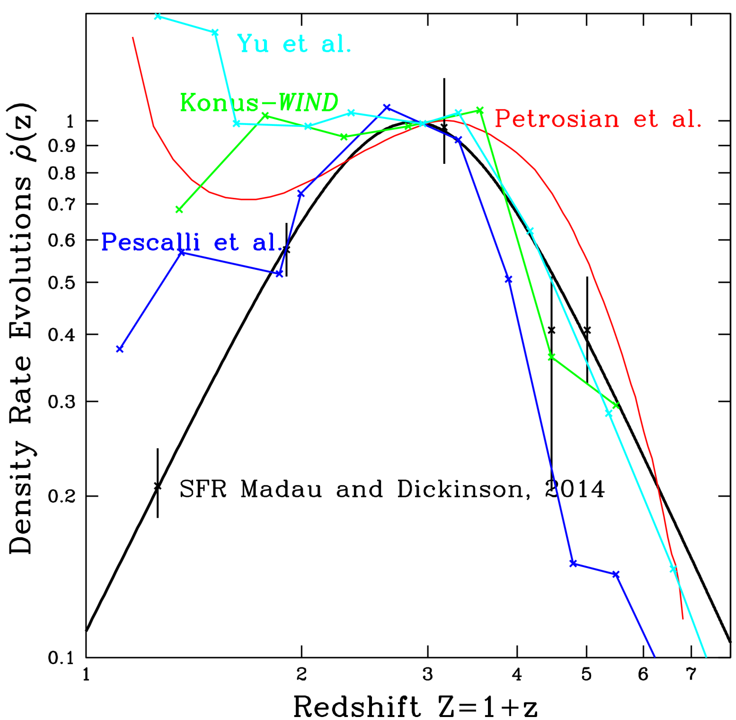

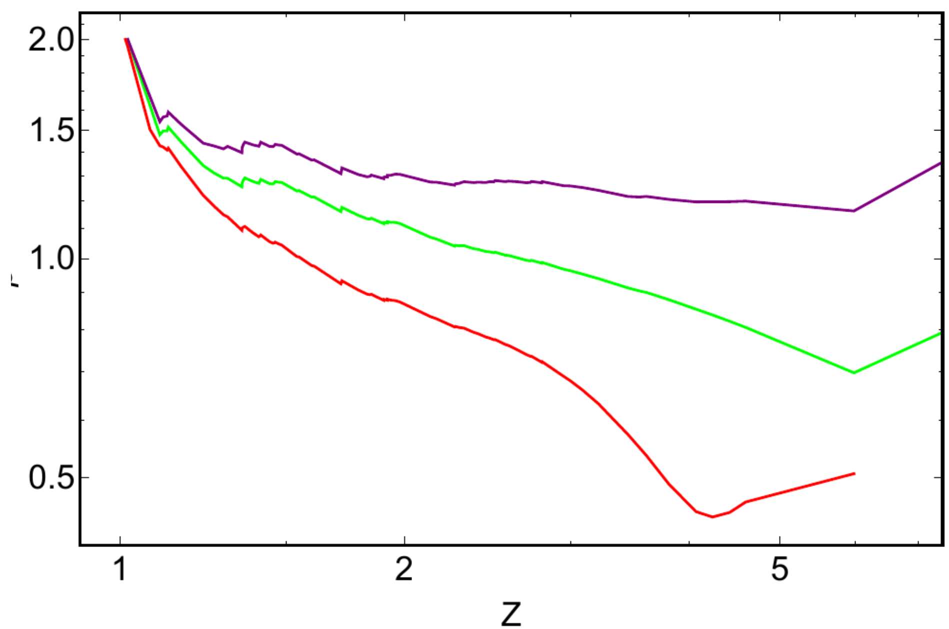

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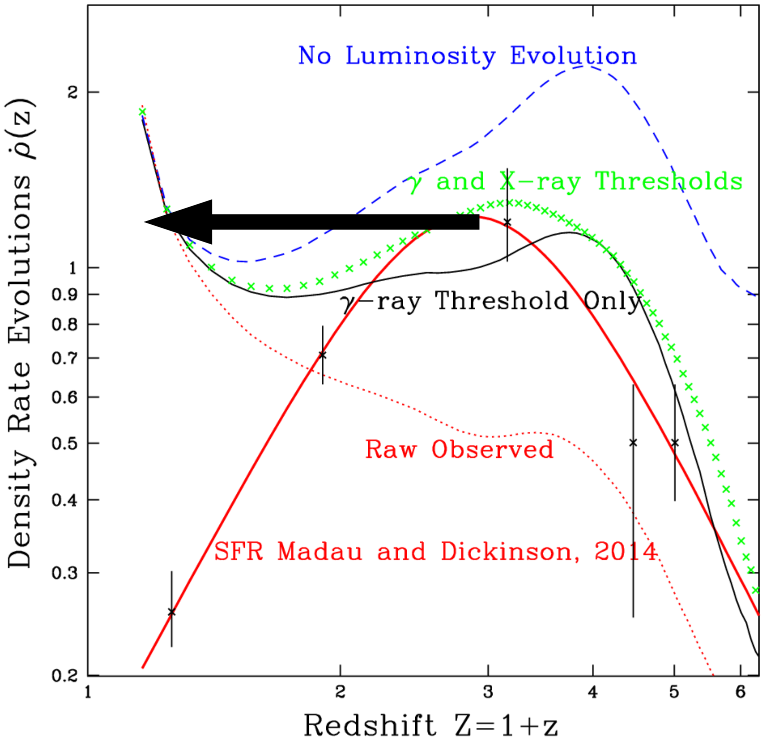
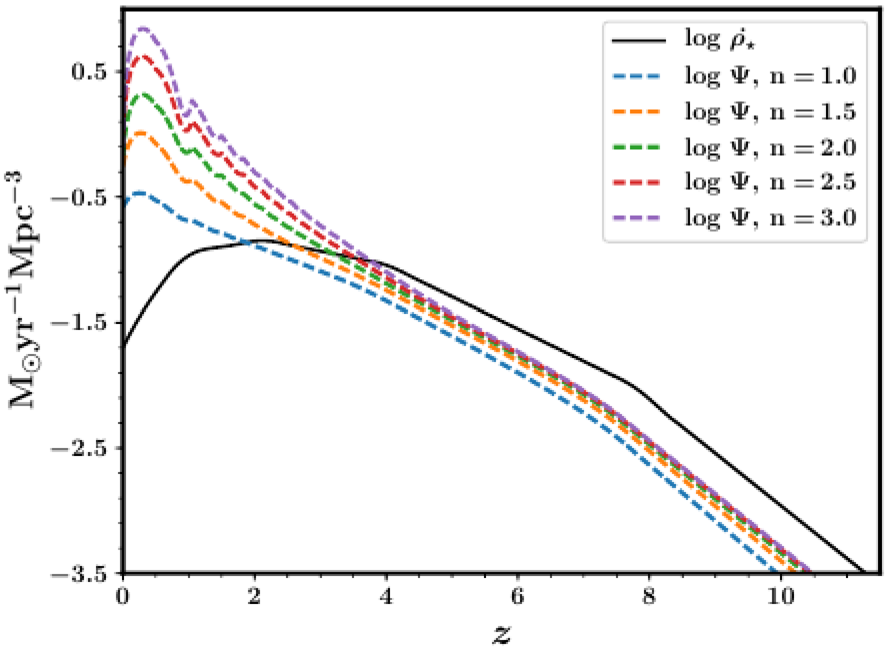
SGRB and Star Formation Rates

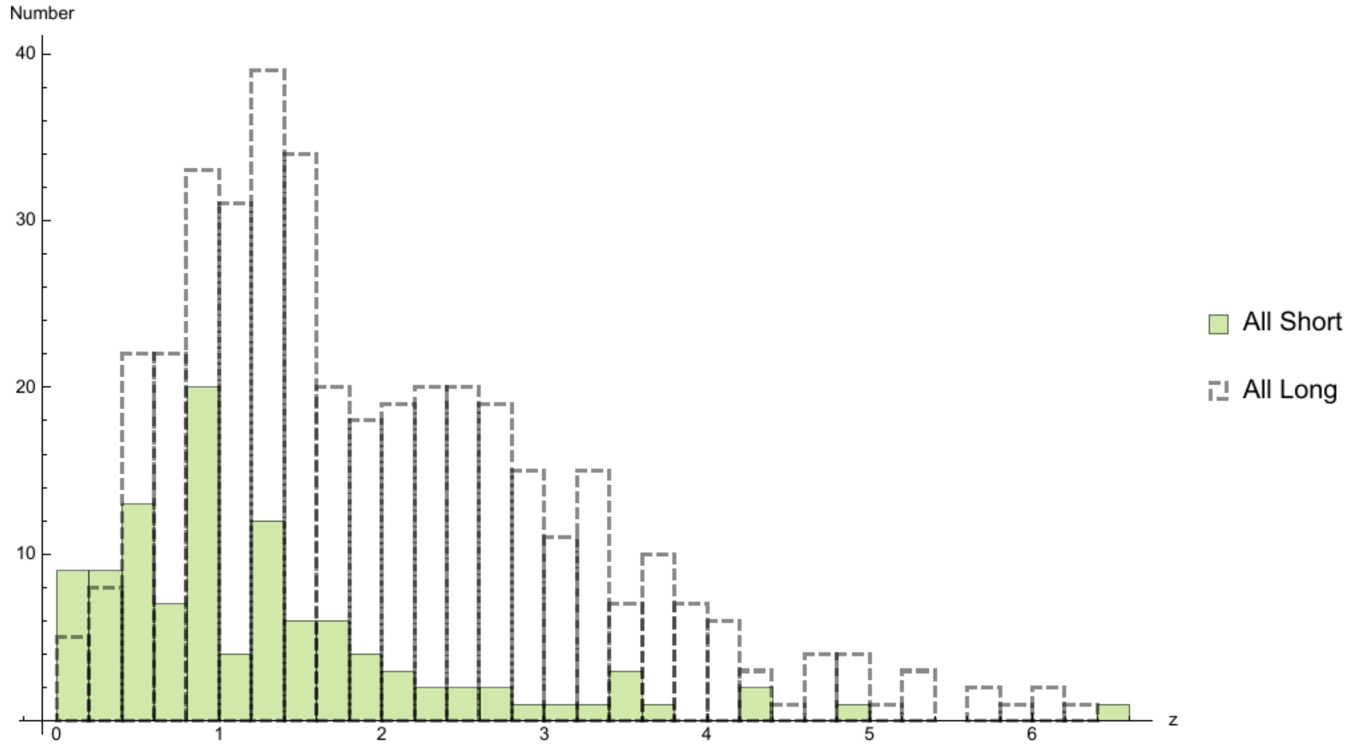




Paul atXiv:1710.05620

Comparison: Short and Long GRBs

Redshift distribution



Konus-WIND at 25

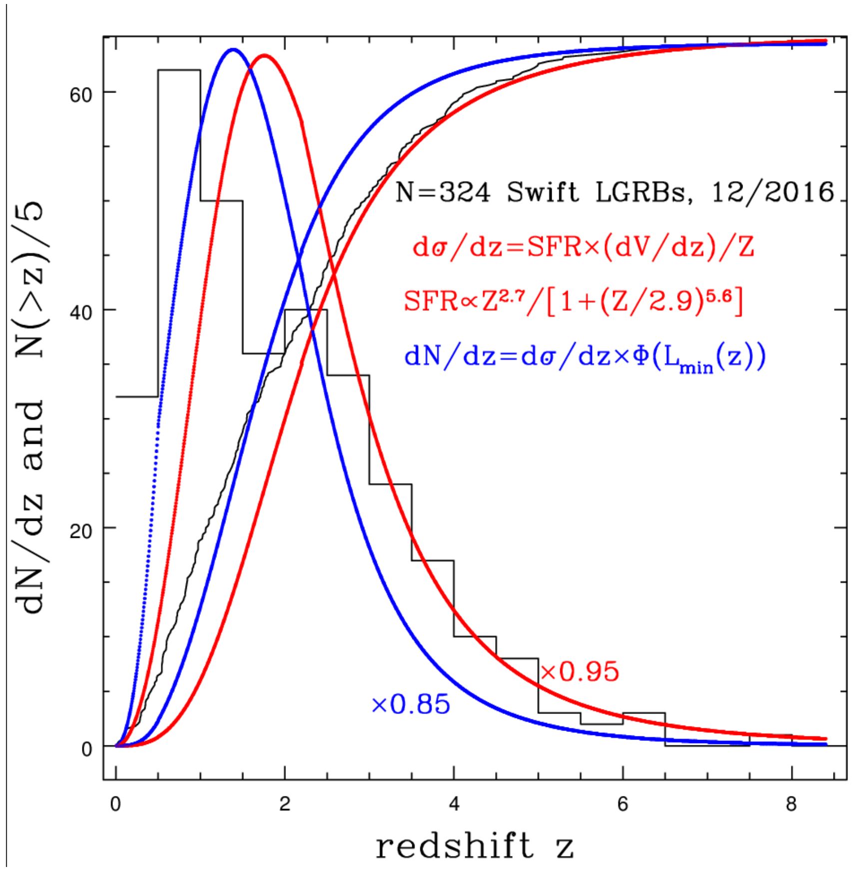
SUMMARY: Short GRBs

1. Small samples that can be considered “complete”
2. Preliminary results show
   a. *Similar luminosity evolution as Long GRBs*
   b. *Luminosity function steeper at low luminosities*
   c. *Rate evolution similar to the low redshift part of the LGRBs:*
      Perhaps delayed SFR
3. The high rates of both at low redshift will have important consequence for gravitational wave rate.

Backups

Further Testing of the Results

Assume GRB rate=SFR



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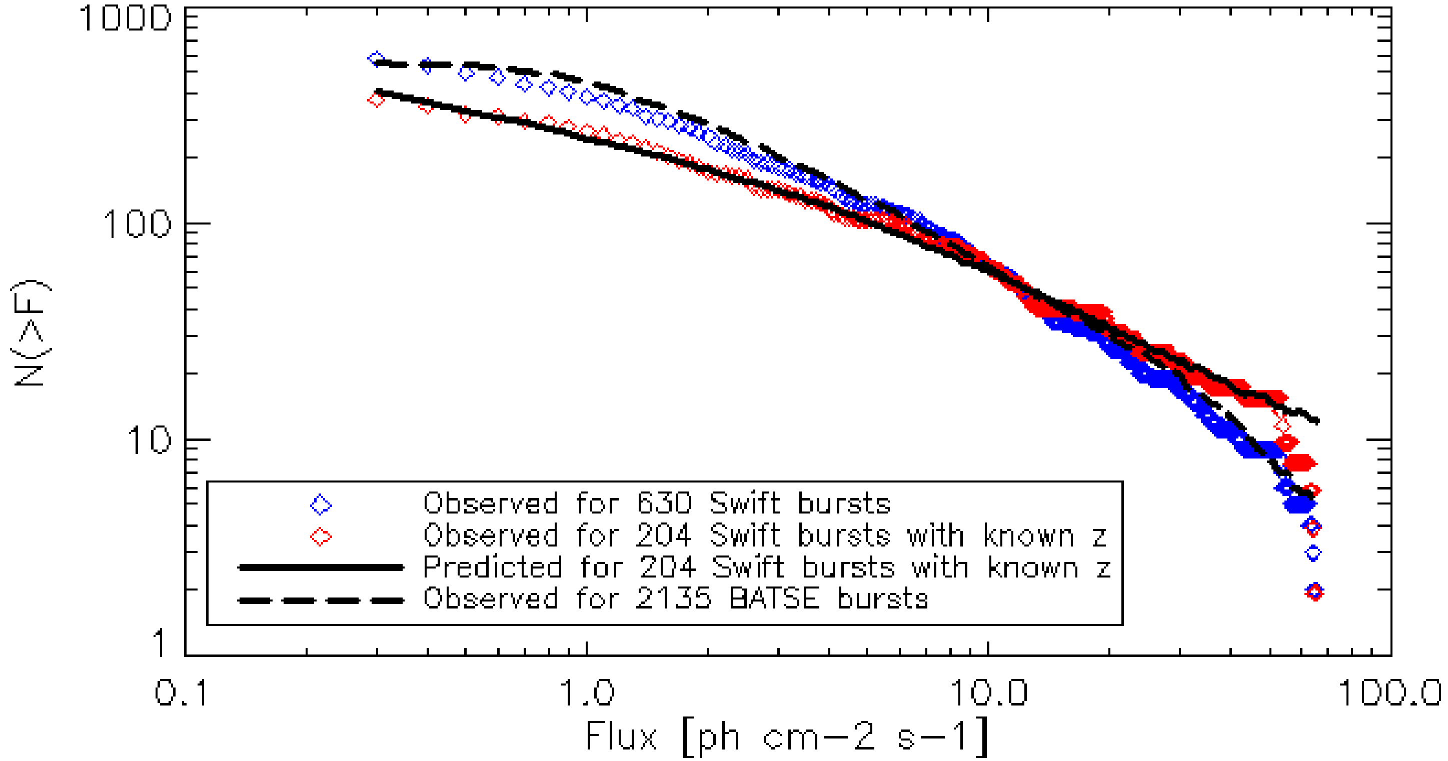
Further Testing of the Results

Log N-Log S Test



Konus-WIND at 25

GRBs: As Cosmological Probes

GRBs Can be useful probes for study of the early universe such as Reionization, Star Formation Rate, Metalicity Evolution

However

For this we need to determine the evolution of their characteristics (e.g. Formation Rate, Luminosity, ...)

*This requires a large sample with **redshifts** and well defined observational selection criteria and data truncation*