

# Cosmological Distributions and Evolution of Gamma ray Bursts and their relation to Star Formation Rate and Gravitational Waves

## *GAMMA-RAY BURSTS AND COSMOLOGY*



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*With*

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# OUTLINE

- I. Some Historical Notes and GRB characteristics
- II. Cosmology With Discrete Sources
- III. GRBs as Standard Candles  
*and* Cosmological Probes
- IV. Procedures
- V. Results of Application to *Swift* Data

# I. Some General Features and Models

## *Major Stepping Stones*

1. Discovered by *Vela* satellites (4) 1969

*First GRB conference at Stanford 1984*

2. *BATSE* on *C-GRO* discovery of several 1000

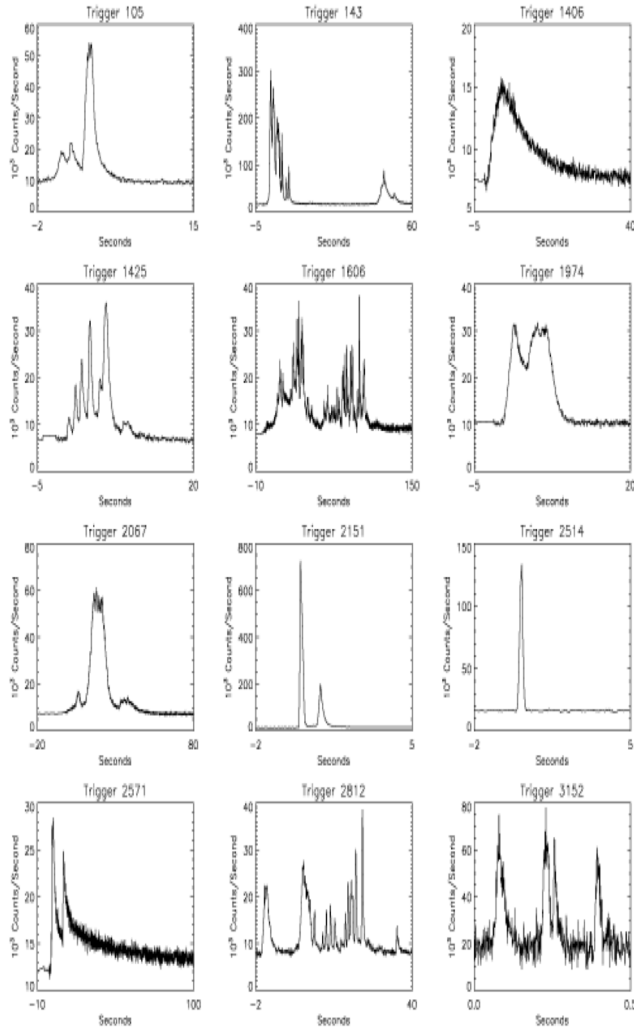
3. Cosmological Origin Established 1997 by *Beppo-Sax*

4. Accurate positions of several 100s by *Swift*

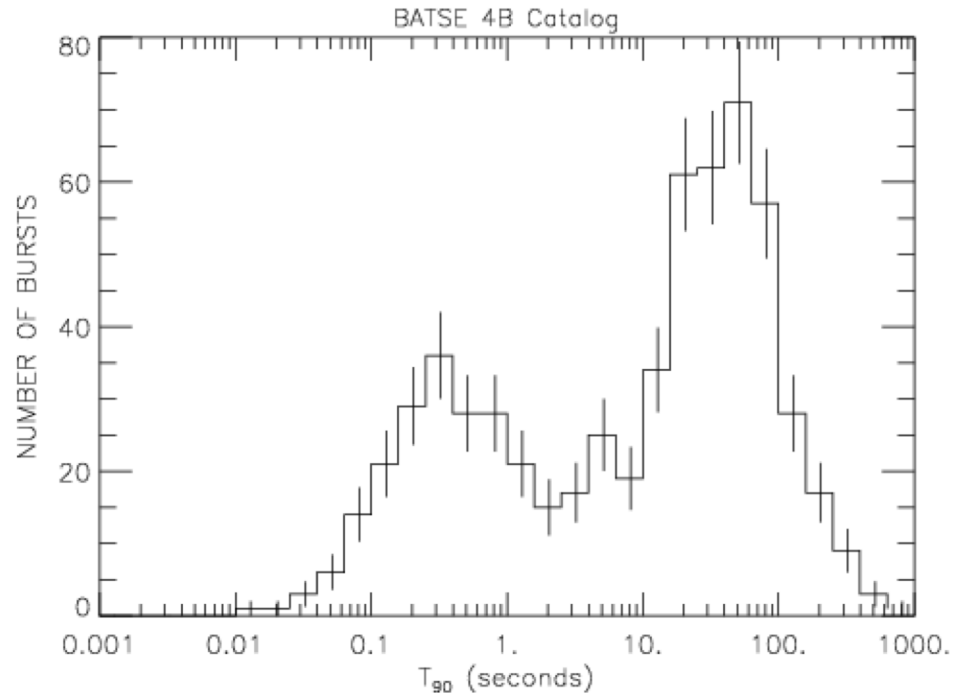
5. More ongoing detection by *Fermi-GBM* and *Fermi-LAT*

6. Recent discovery of *Gravitational Wave* source and GRB

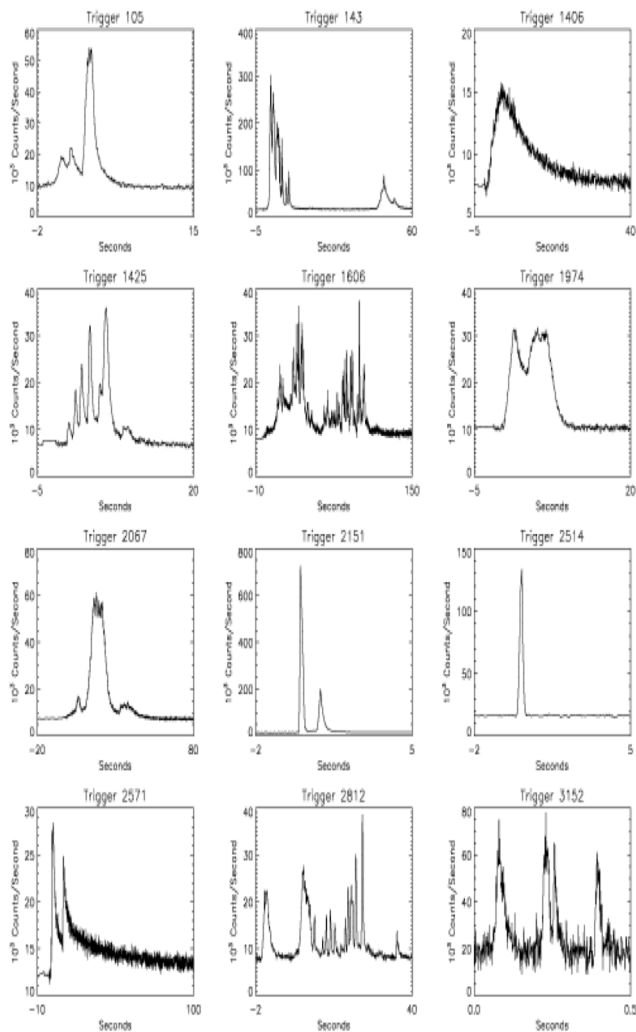
# GRB Light Curves: *Prompt and Afterglow*



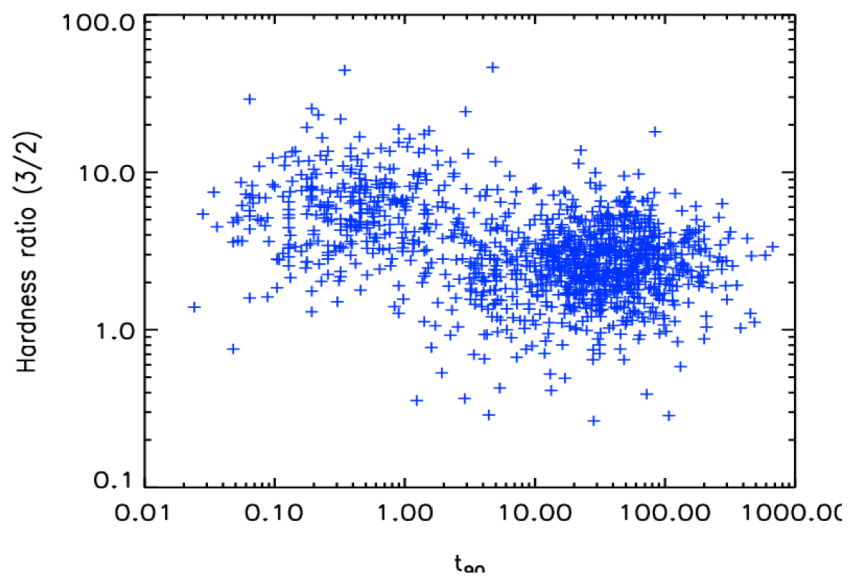
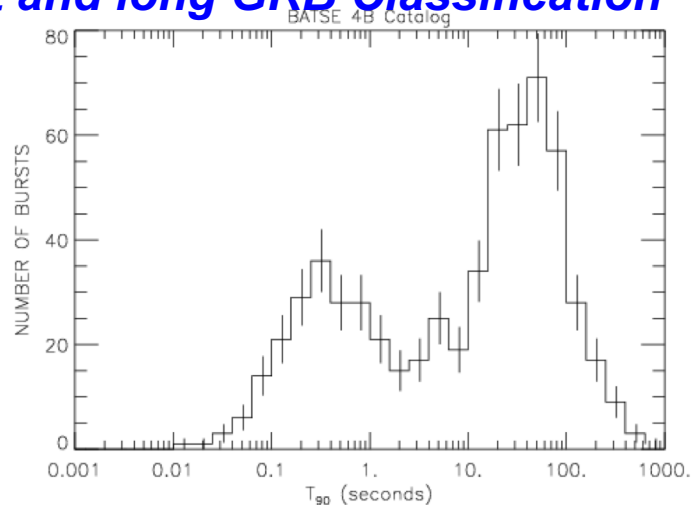
**Short and long**  
**GRB Classification**



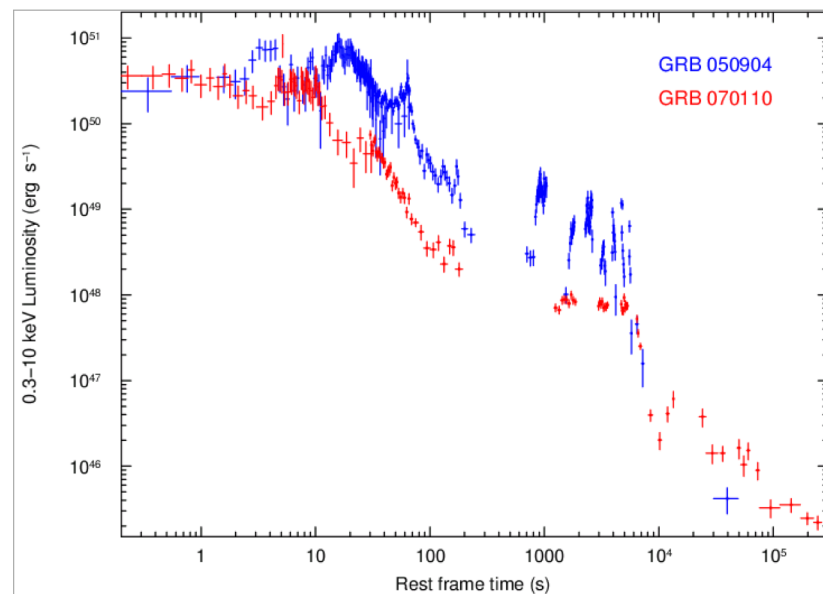
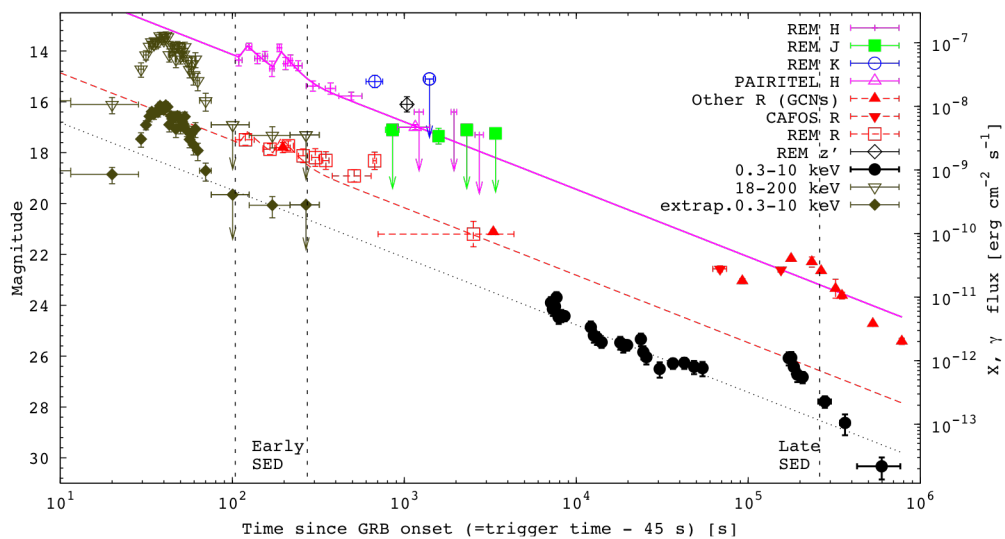
# GRB Light Curves: *Prompt and Afterglow*



## Short and long GRB Classification



# GRB Light Curves: *Prompt and Afterglow*

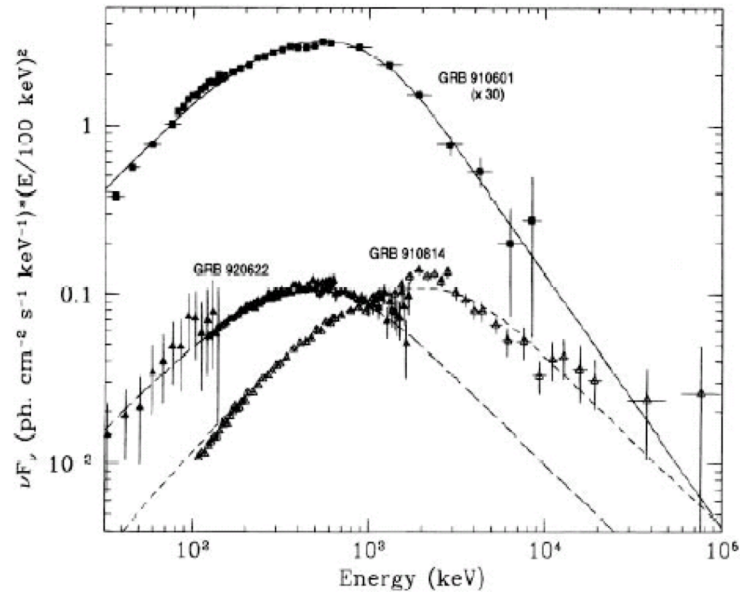


# GRB Spectra: *Prompt*

Early Prompt Spectra

Broken Power Law

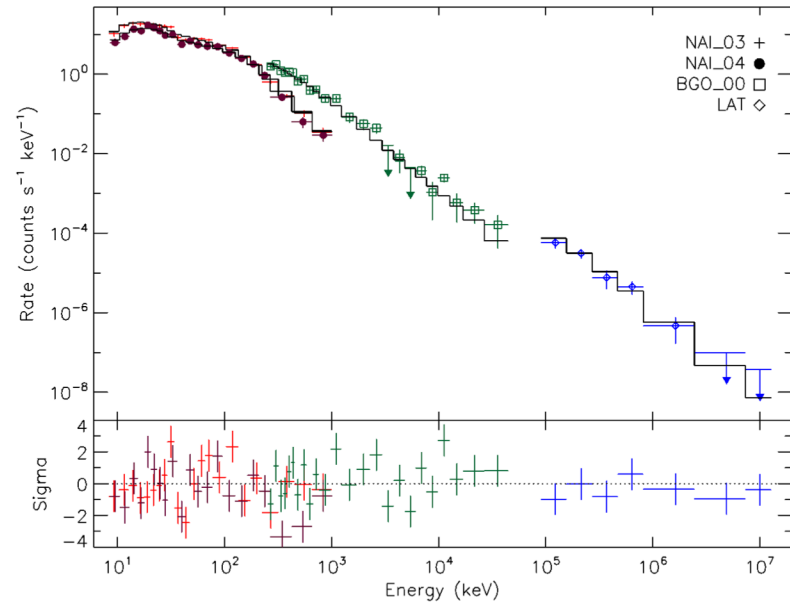
*Band model*



Fermi: GBM and LAT

GRB080916C

*Band model*



# GRB Spectra: *Prompt*

Early Prompt Spectra

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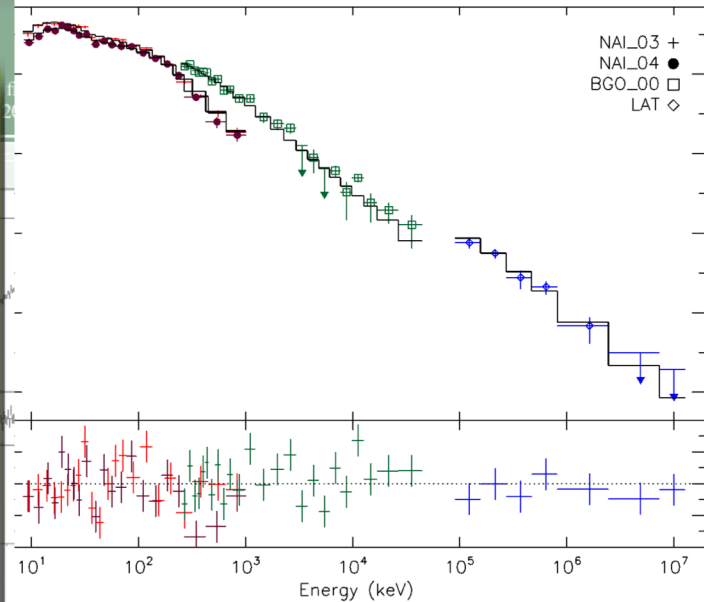
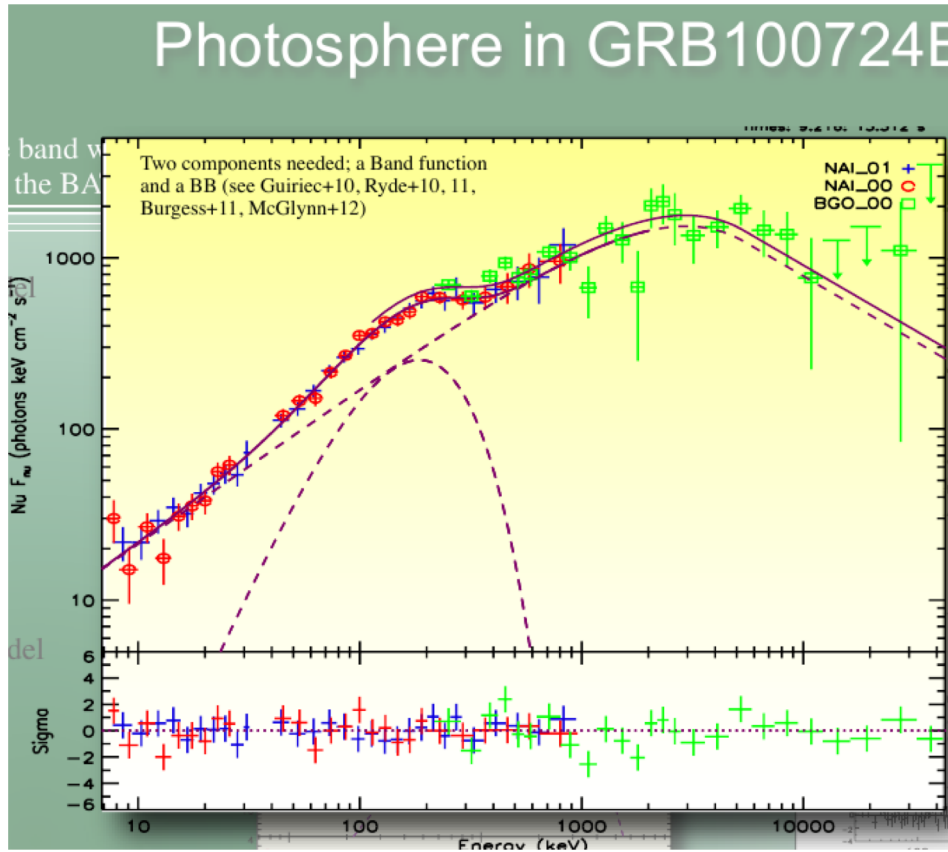
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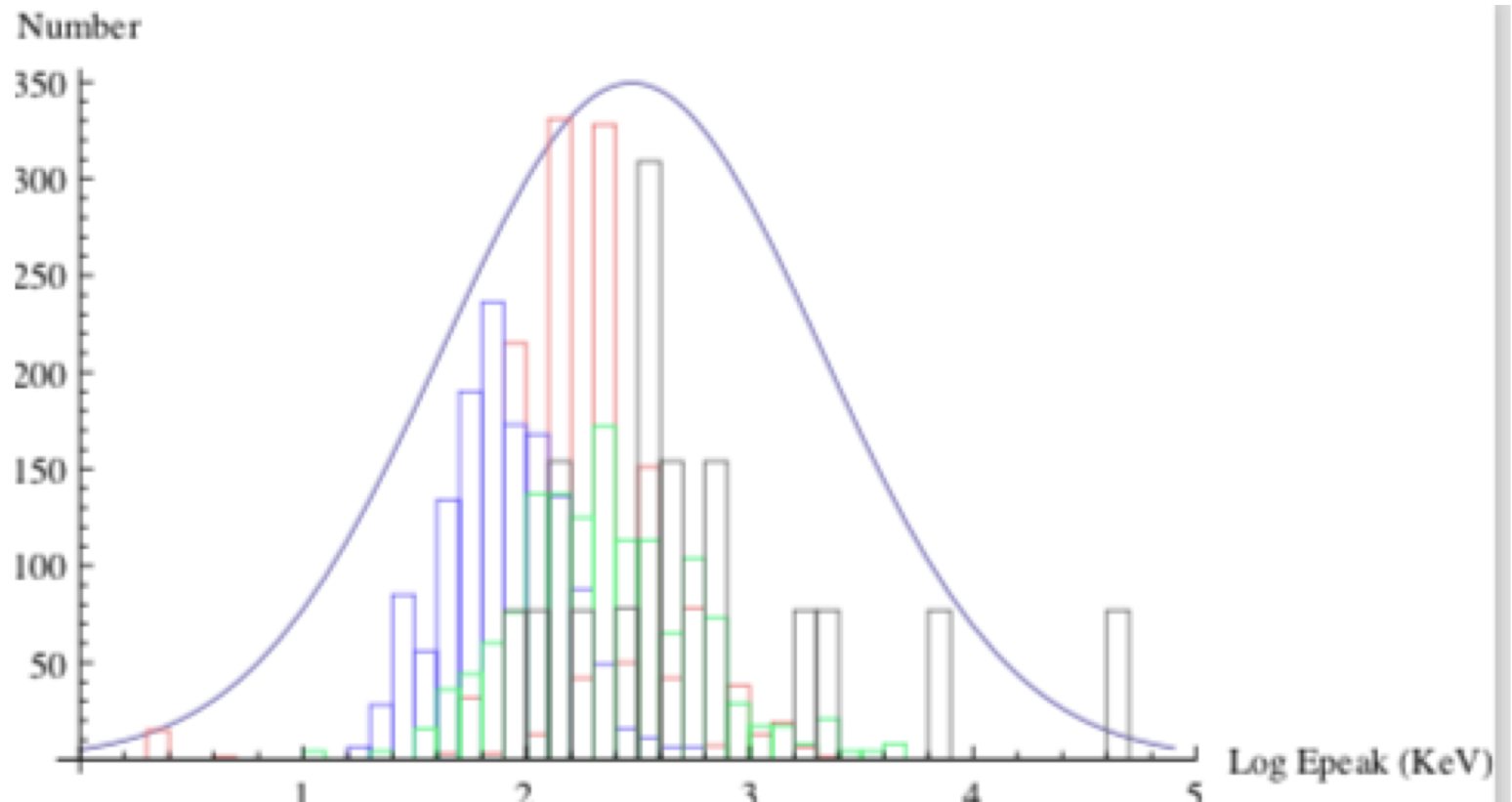
*Band*

Photosphere in GRB100724B

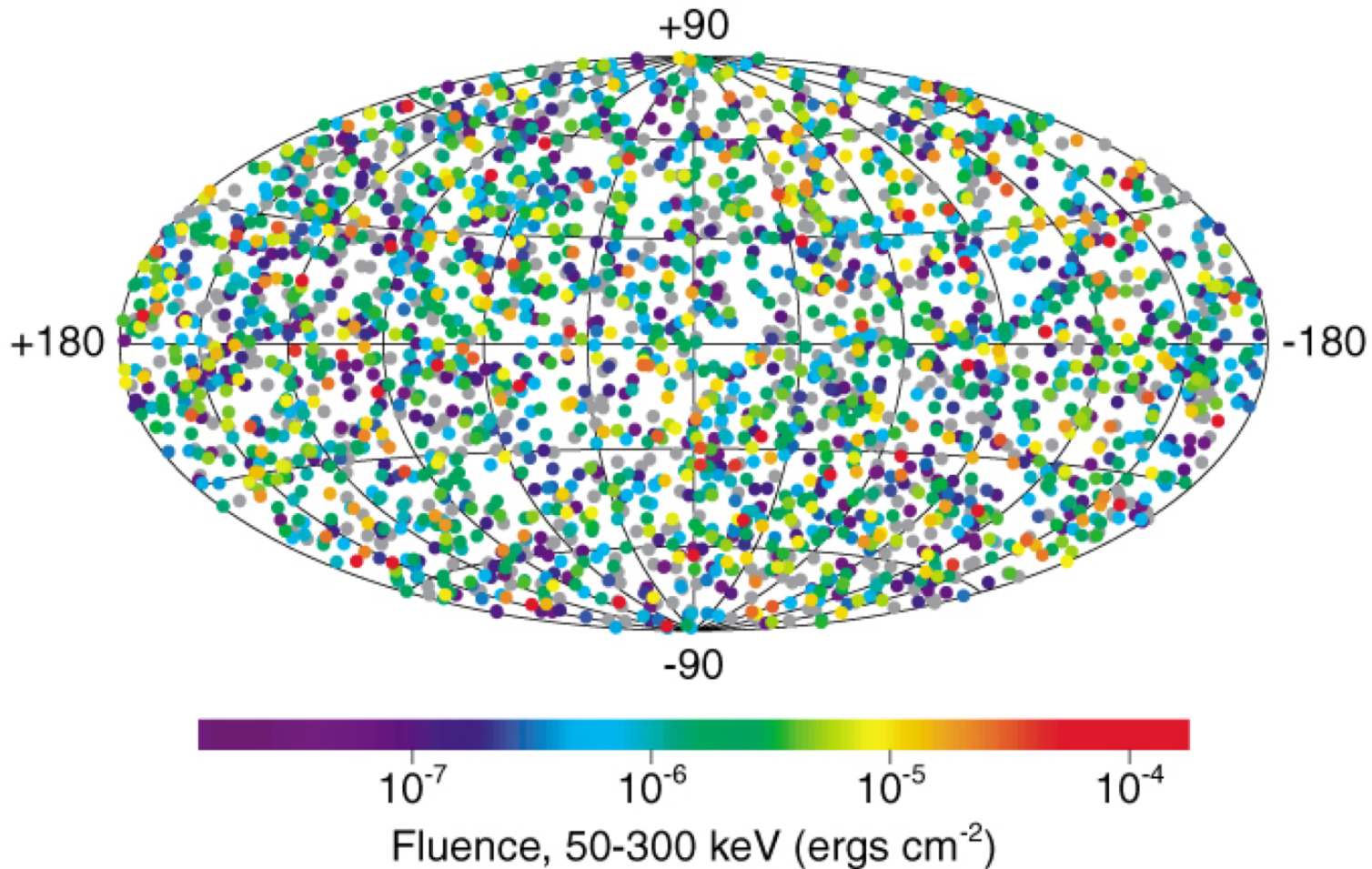
*model*



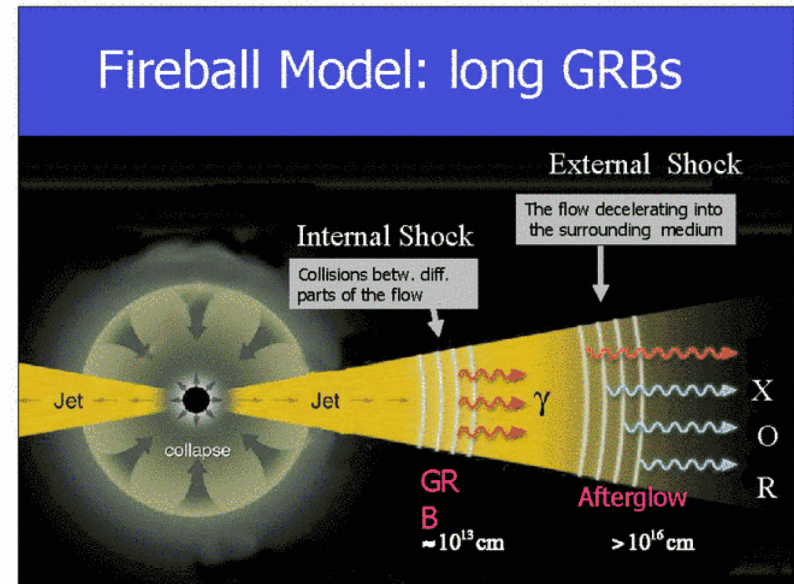
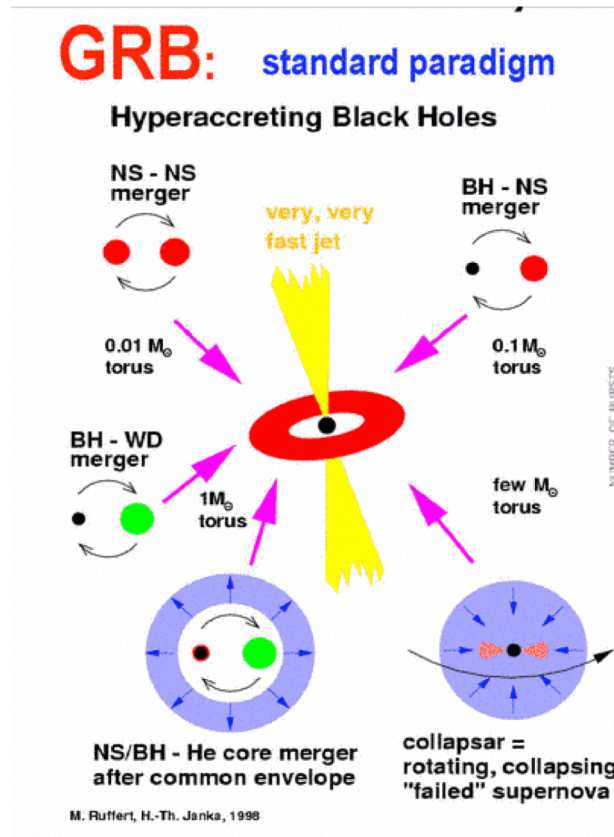
# GRB Epeak Distribution: *Prompt*



# GRB Angular Distribution



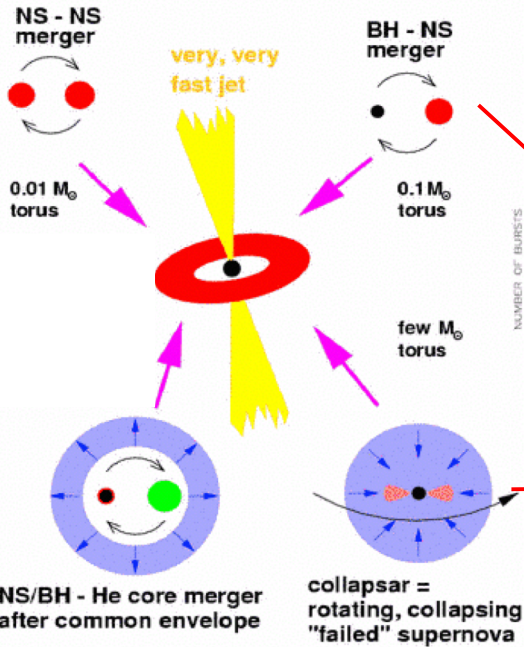
# GRB Progenitors and Models



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## GRB: standard paradigm

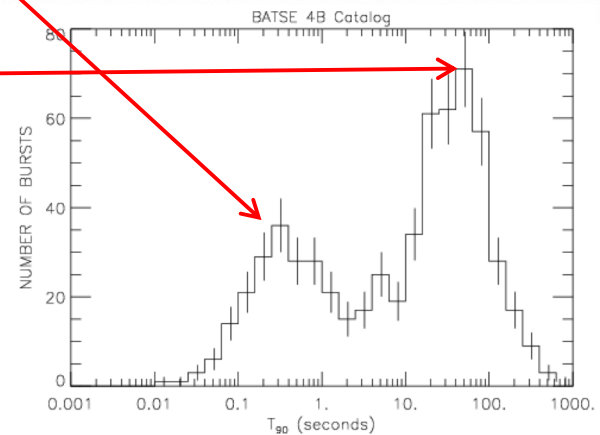
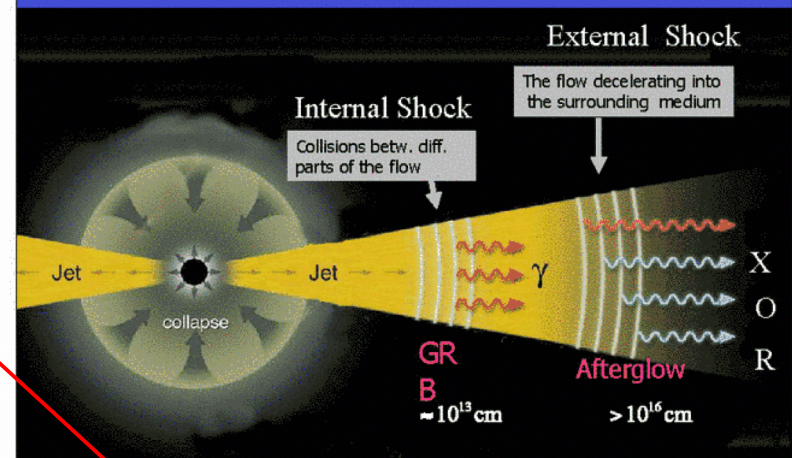
### Hyperaccreting Black Holes



Short  
GRBs

Long  
GRBs

## Fireball Model: long GRBs



## *II. Cosmology*

*With Discrete Sources*

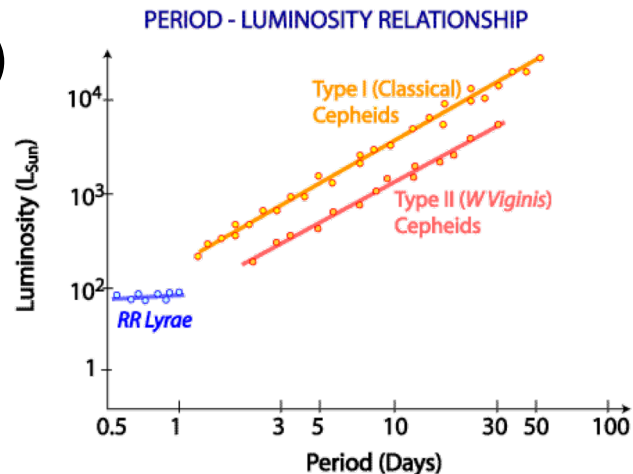
# Standard “Candles?”

A 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

(Cepheids )



# Discrete Sources

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

*Galaxies least understood astrophysical sources*

2. Type Ia Supernovae: *Standard Candle and better understood*

*BUT Low z*

3. GRBs: *High z and not well understood yet*

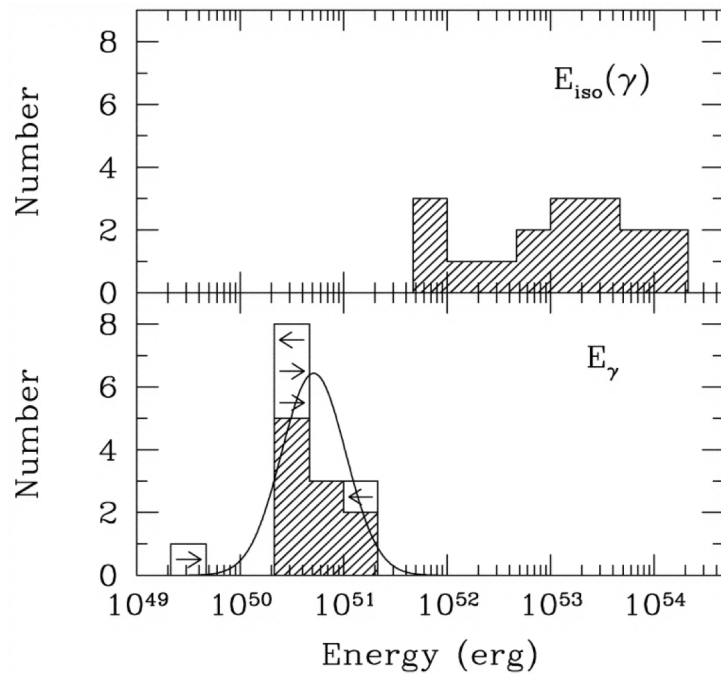
Question: *SN-like or Galaxy-like?*

# *III. GRBs as Standard Candles*

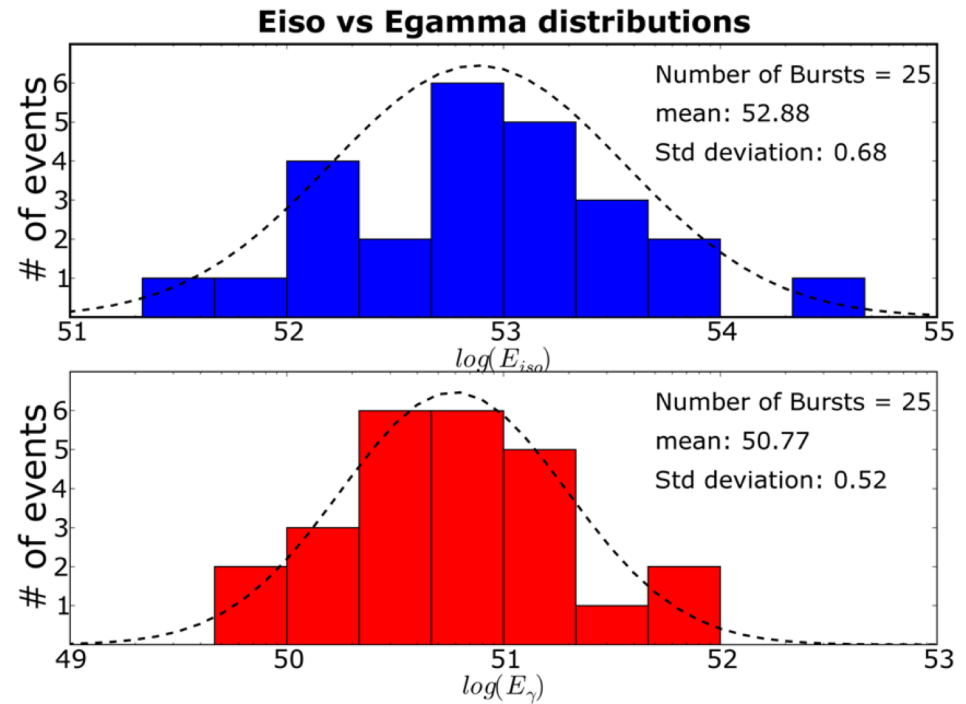
## *Cosmological Probes*

# A. GRBs: Standard Candles?

*Frail et al. 2001*



*Petrosian, Bouvier & Ryde 2009*



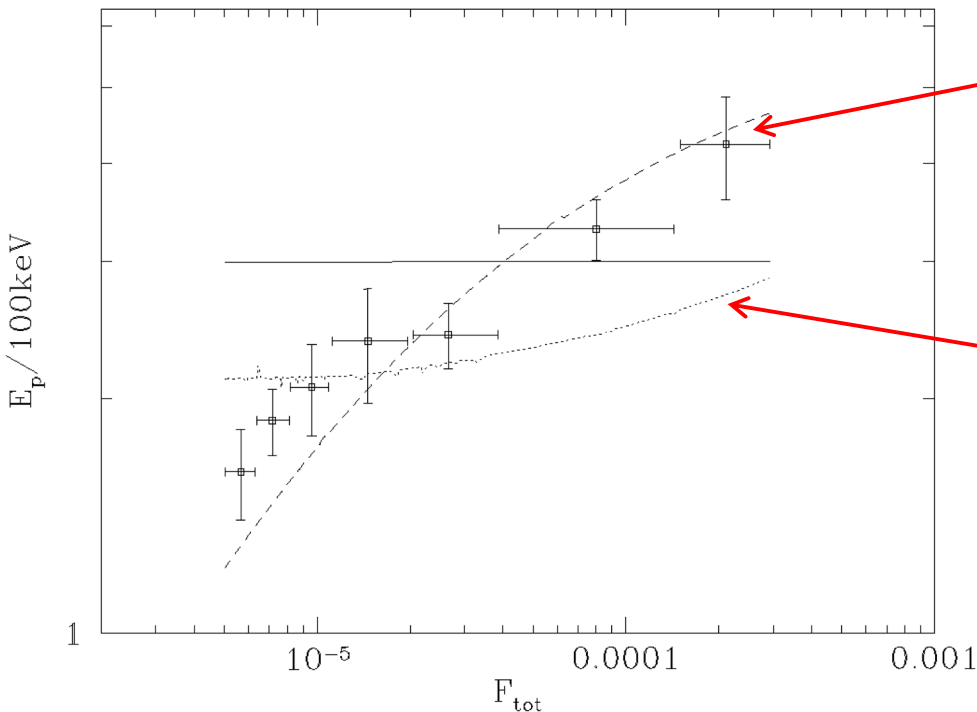
# A. GRB Correlations as SC?

## *Examples of Correlations*

### 1. Correlation between $E_{\text{peak}} - \mathcal{E}_{\text{iso}}$

*Predicted Before Redshifts*

*Lloyd, Petrosian & Mallozzi, 2000*



Observed correlation

Implies

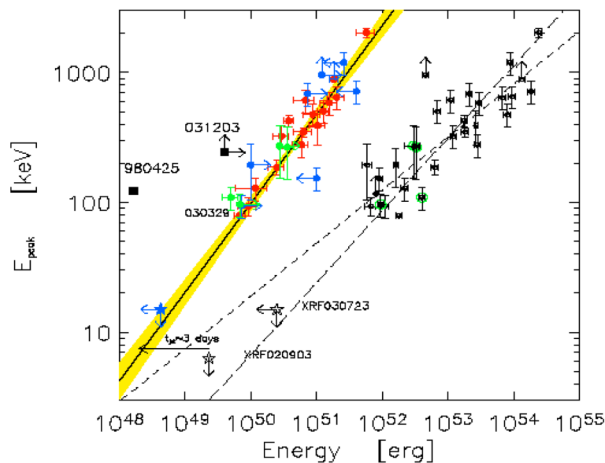
$$E_{\text{peak}} \propto \mathcal{E}_{\text{iso}}^{0.7-0.4}$$

Expected If independent

# A. GRB Correlations as SC?

## Examples of Other Correlations *After Few Redshifts*

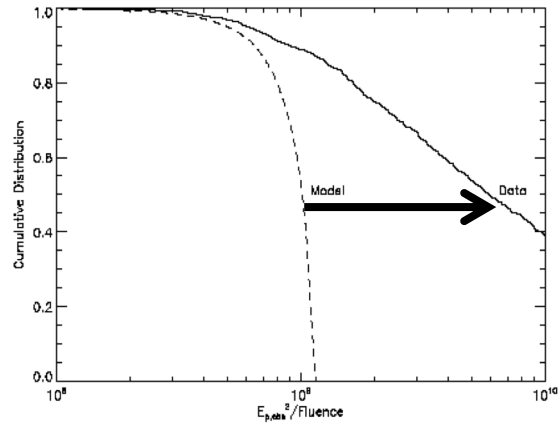
1. Variability-Luminosity (*Reichart et al. 2001*)
2. Lag-Luminosity (*Norris, Maeani & Bonnell 2000*)
3.  $E_{\text{peak}} - \epsilon_{\text{iso}}$  or  $E_{\text{peak}} - \epsilon_{\gamma}$  (*Amati; Ghirlanda et al.*)



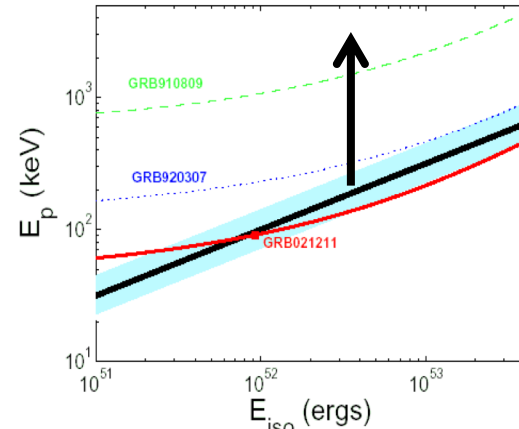
4. And Several Variations  
(*see Schaeffer et al.*)

# Problems With These Correlations

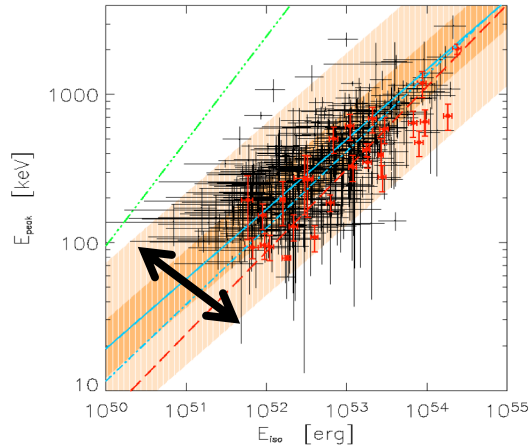
*in particular with*  $E_{\text{peak}} - \epsilon_{\text{iso}}$  or  $E_{\text{peak}} - \epsilon_{\gamma}$



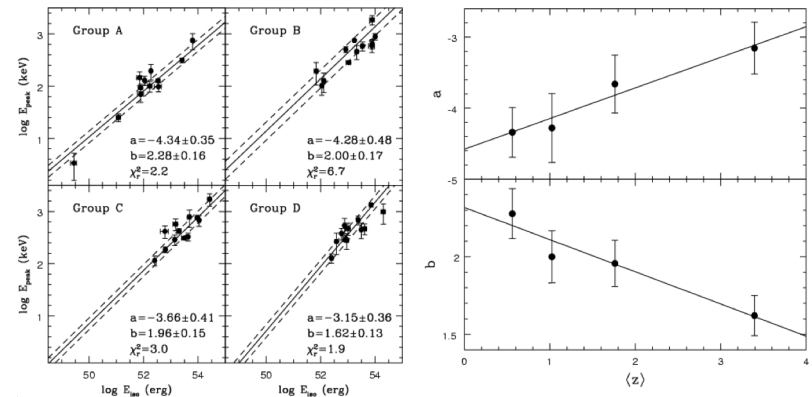
*Band and Preece*



*Nakar and Piran*



*Pseudo-Redshifts (Ghirlanda et al)*



*Li et al.*

# SOME RELEVANT EQUATIONS

## 1. “Luminosity Function” and Correlation

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

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

## 2. COSMOLOGY

$$\mathcal{E}_{\text{iso}} = 4\pi d_m^2 (1+z) F_{\text{tot}}, \quad \text{Define } \mathcal{E}_0 = 4\pi (c/H_0)^2 F_{\text{tot}}$$

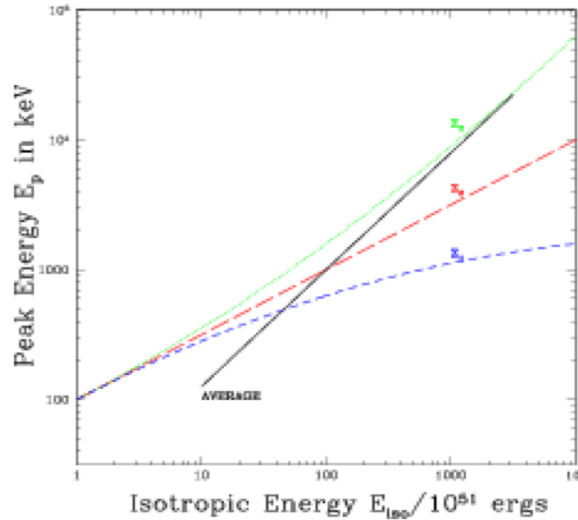
$$d_m = (c/H_0) \int_0^z dz / \sqrt{\Omega(z)}, \quad \text{with } \Omega = \rho/\rho_0$$

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

# POSSIBLE EVOLUTIONS

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

SHAPE



SPECTRAL and ENERGY

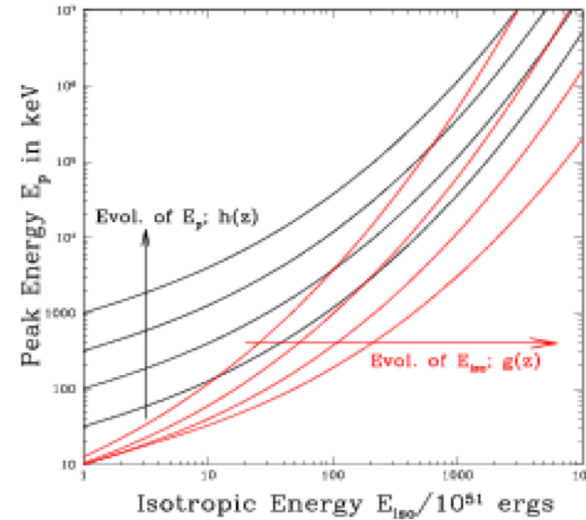


Figure 1: Schematic shape (left), spectral (right, red) and energy (right, black) Evolutions.

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

# B. GRBs: As Cosmological Probes

GRBs not appropriate yet for “precision” cosmology

*BUT*

Can be useful probes for study of the early universe  
*Reionization, Star Formation Rate, Metallicity 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*

# *IV. Procedures*

*1. Parametric: Forward Fitting*

*2. Non-parametric* Efron and Petrosian  
1992, 1994, 1999

Codes using this method can be found in

[www.inside-r.org/node/99623](http://www.inside-r.org/node/99623)

[cran.r-project.org/web/packages/DTDA/DTDA.pdf](http://cran.r-project.org/web/packages/DTDA/DTDA.pdf)

# Procedures: 1. Forward Fitting

The common practice is to assume forms for the GRB

“Luminosity” Function  $\psi(L, z); L = \text{peak lum. or } \epsilon_{\text{iso}}$

Rate (density) Evolution  $\dot{\rho}(z) \propto SFR(z), \text{ Metallicity}$

Energy Spectrum  $\text{Band or Broken power law}$

*(Porciani & Madau 2001; Guetta et al. 2005; Natarajan et al. 2005; Daigne et al. 2006; Salvaterra et al. 2007 and 2009; and others)*

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***Problems: Too many parameters and not unique results***

# Procedures: 2. Non-parametric

A. From Redshifts, Fluxes (and Flux Limits)

Calculate Luminosities (and Luminosity Limits)

to obtain the bi-variate ( $L$ - $z$ ) distribution  $\Psi(L, z)$

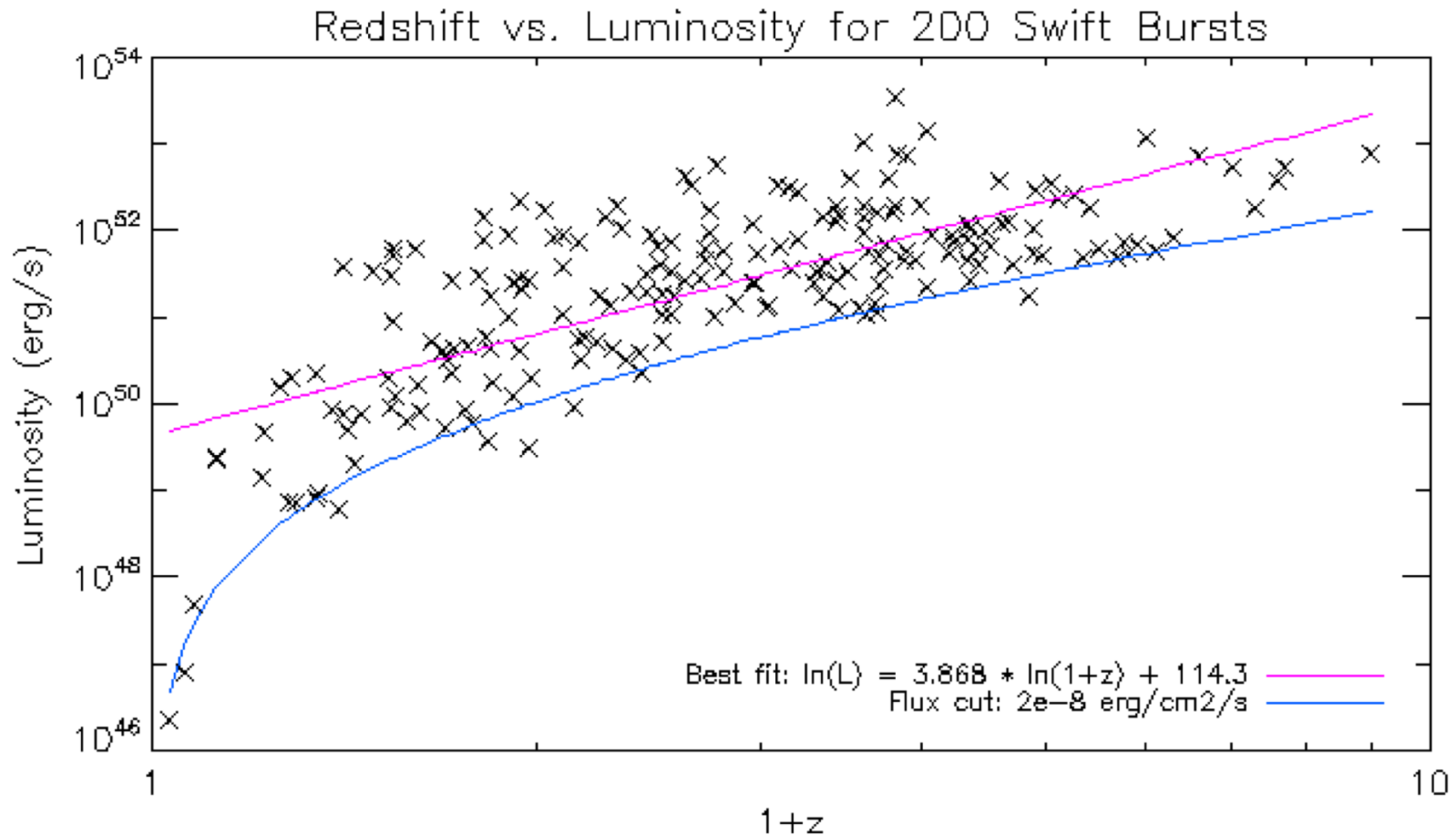
B. Attempt to obtain the basic distributions; e.g.

*Luminosity Function*  $\psi(L)$ ; *Rate (density) Evolution*  $\dot{\rho}(z)$

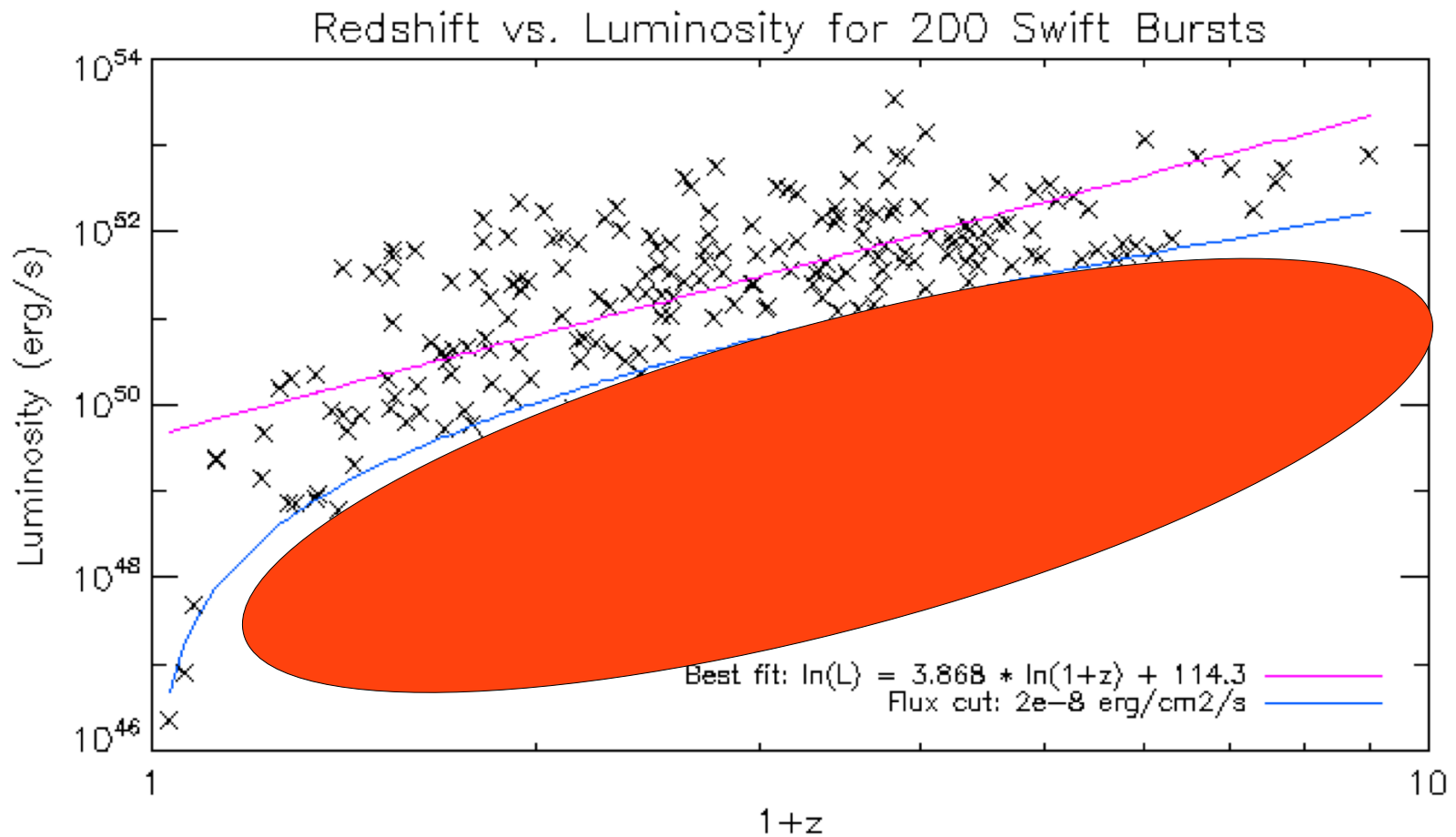
*Efron & Petrosian methods obtains these*

directly from the data and without prescribed functional forms (with essentially no a priori assumptions)

# Description of the EP methods for Bi-variate Luminosity-redshift Distribution $\psi(L, z)$



# Bi-variate Luminosity-redshift Distribution

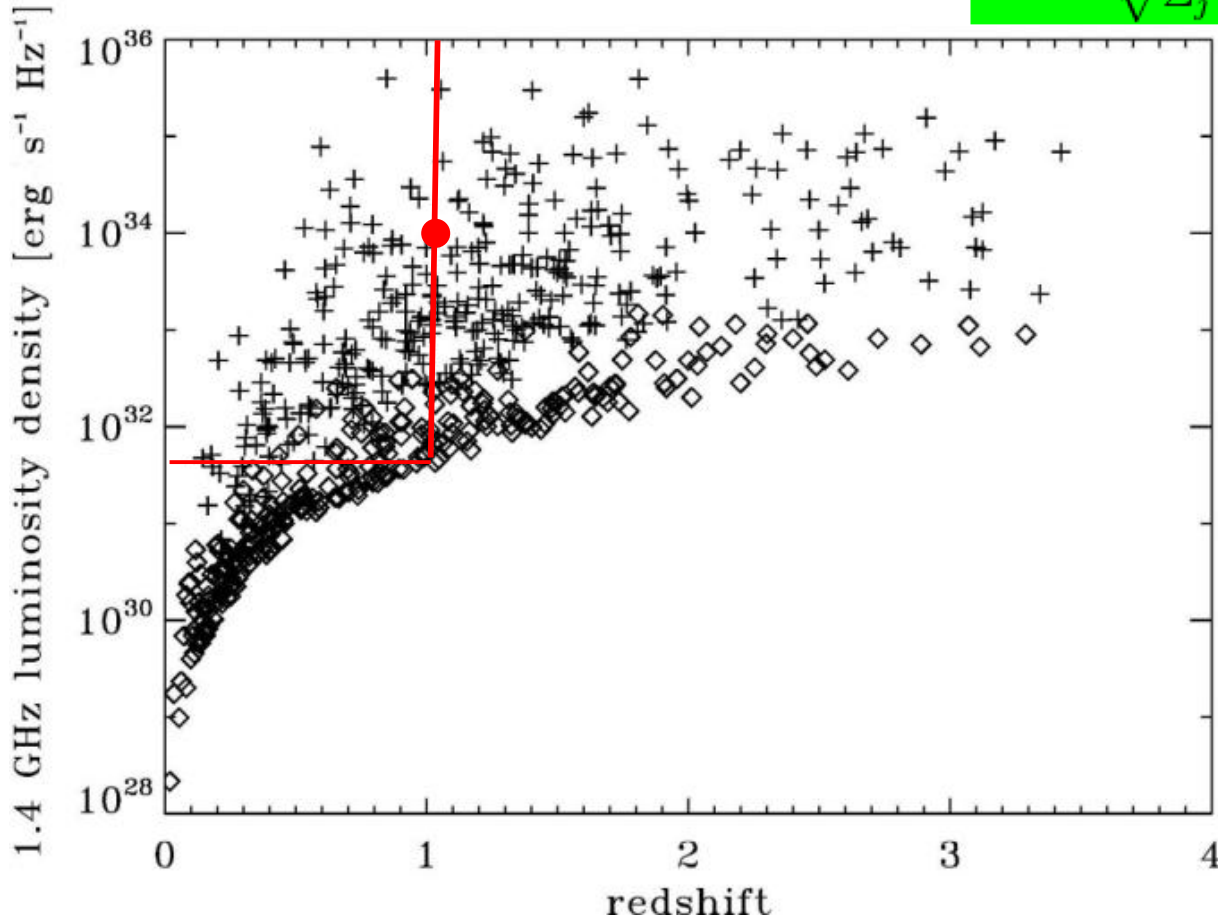


# Test of Independence

Spearman Rank Order Test: Distribution of Ranks  $R_j$

Kendall's tau Statistic

$$\tau = \frac{\sum_j (R_j - E_j)}{\sqrt{\sum_j V_j}}$$



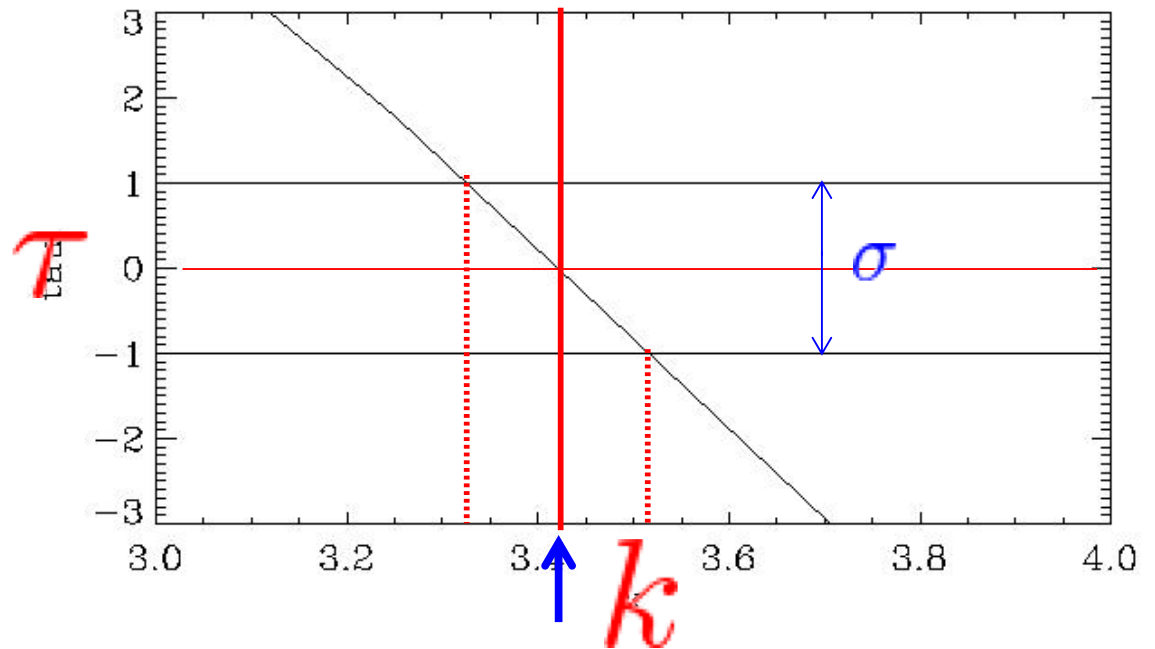
Associated  
Set

# Test of Independence

Remove the correlation by a variable transformation e.g.

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

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

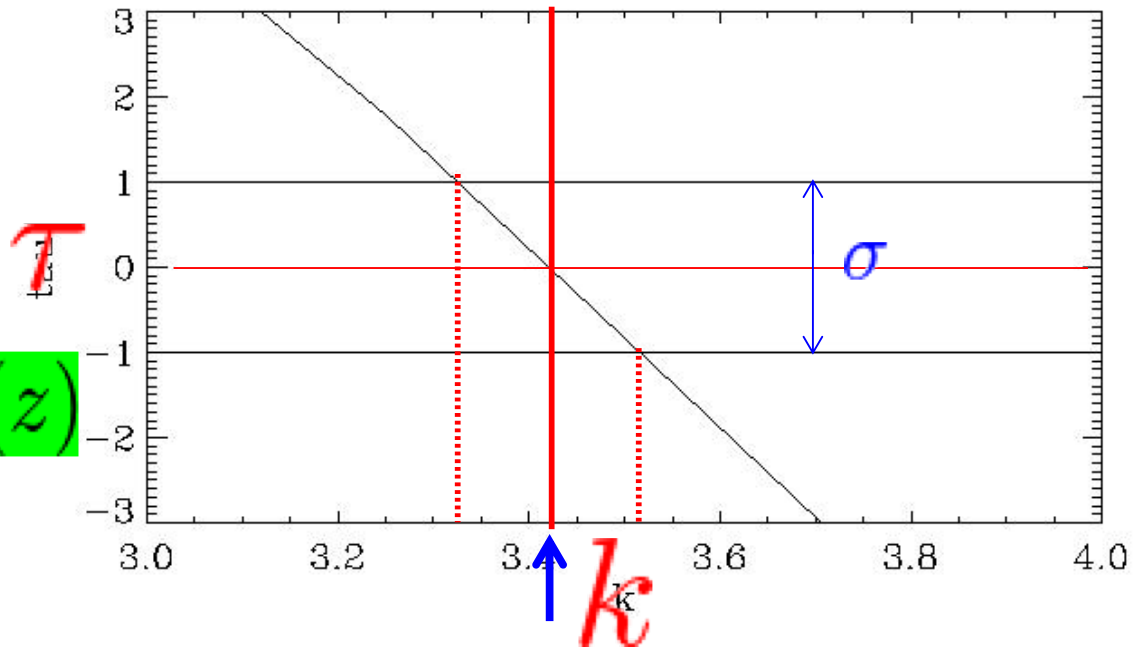


# Test of Independence

Remove the correlation by a variable transformation e.g.

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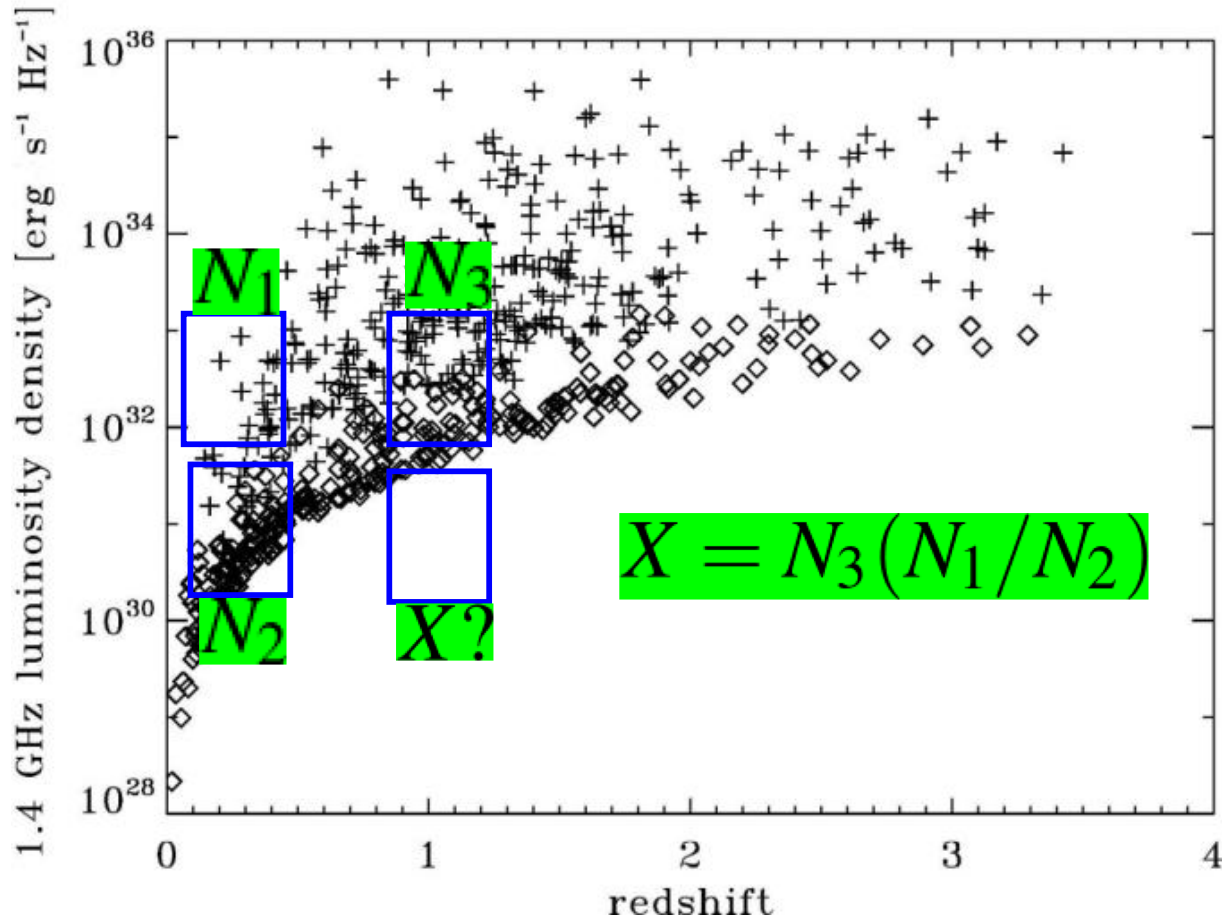
$$g(z) = (1 + z)^k$$



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

# Bi-variate Luminosity-redshift Distribution

If  $L$  and  $z$  are independent or uncorrelated



*Petrosian, 1993*

# Summary of EP Methods

1. Test for independence in a truncated data
2. Remove the dependence (or correlation) by a

transformation

$$L_0 = L/g(z); \text{ e.g. } g(z) = (1+z)^\alpha$$

3. Determine the distributions of

*now independent variables*  $L_0$  and  $z$

The method gives *point by point non-parametric*

estimate of the cumulative functions

$$\dot{\sigma}(z) = \int_0^z \dot{\rho}(z)(1+z)^{-1} [dV(z)/dz] dz \text{ and } \Phi(>L) = \int_L^\infty \psi(L) dL$$

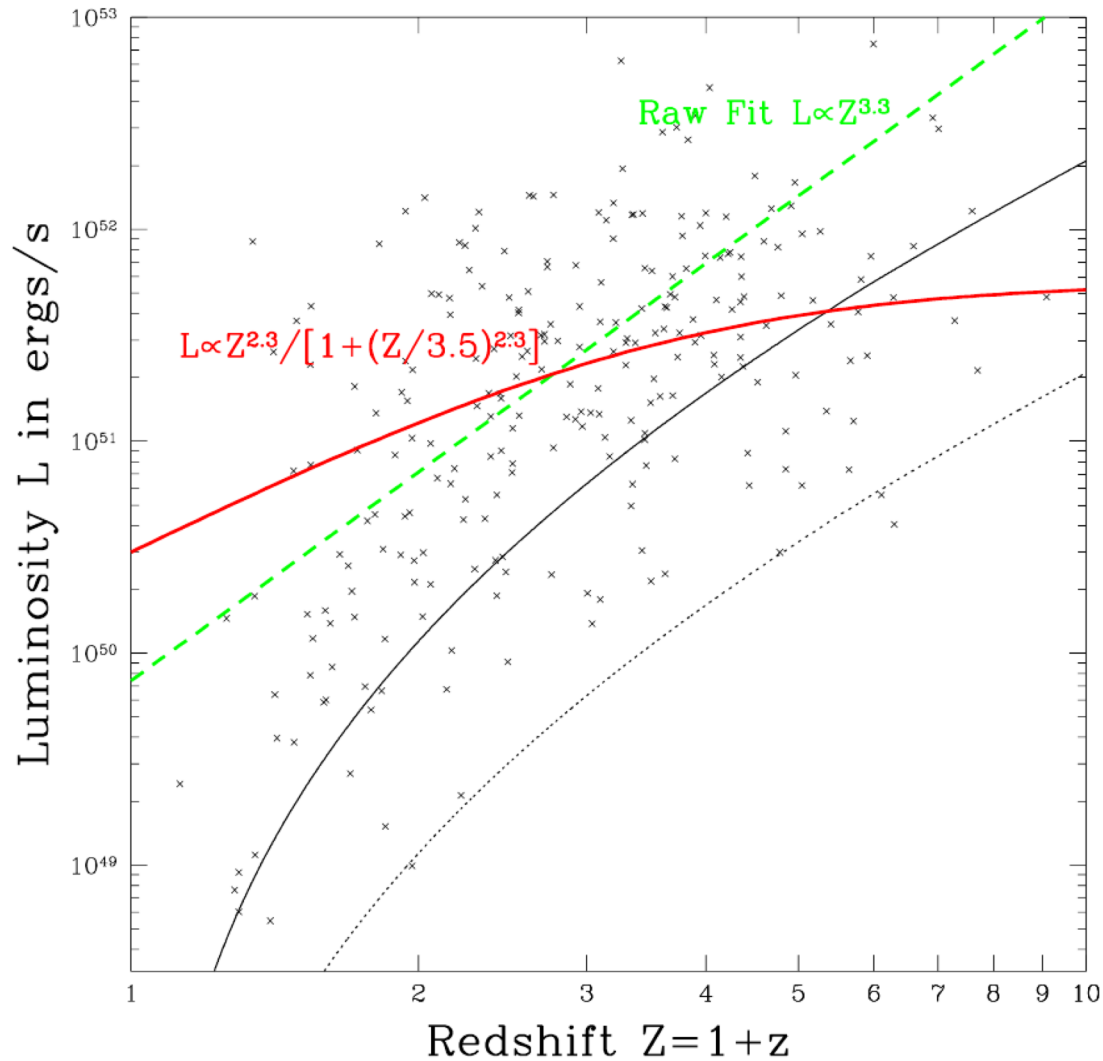
## *V. Results*

*From Application Of EP methods to*

*Swift Long GRB Data*

# 1. Test of independence

## *Luminosity evolution*



## Caveats: *Other Selection Effects and Truncation*

### 1. Gamma-ray trigger

*Peak count or flux threshold*

### 2. Localization

*X-ray flux threshold*

### 3. Optical follow-up and *Redshift*

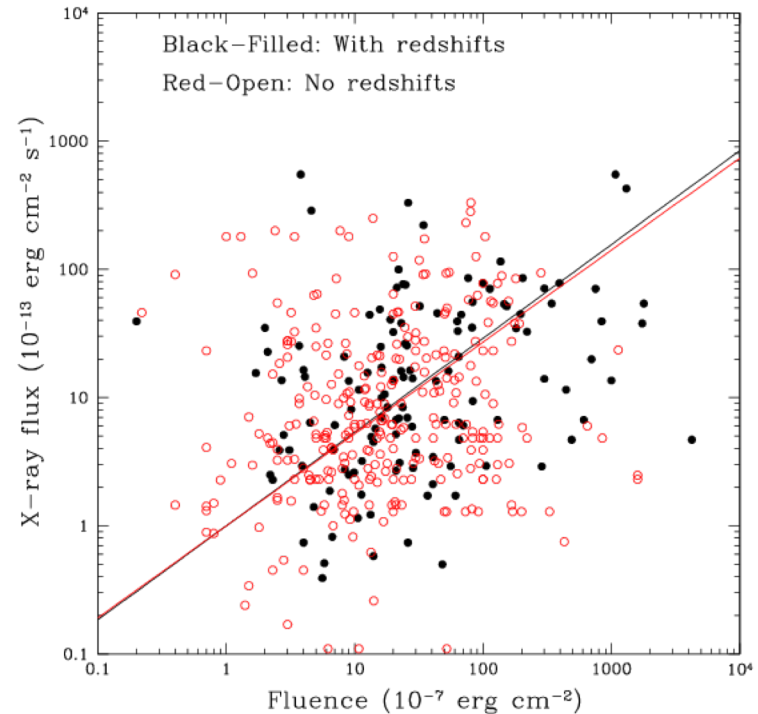
*Optical Magnitude etc*

## 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.

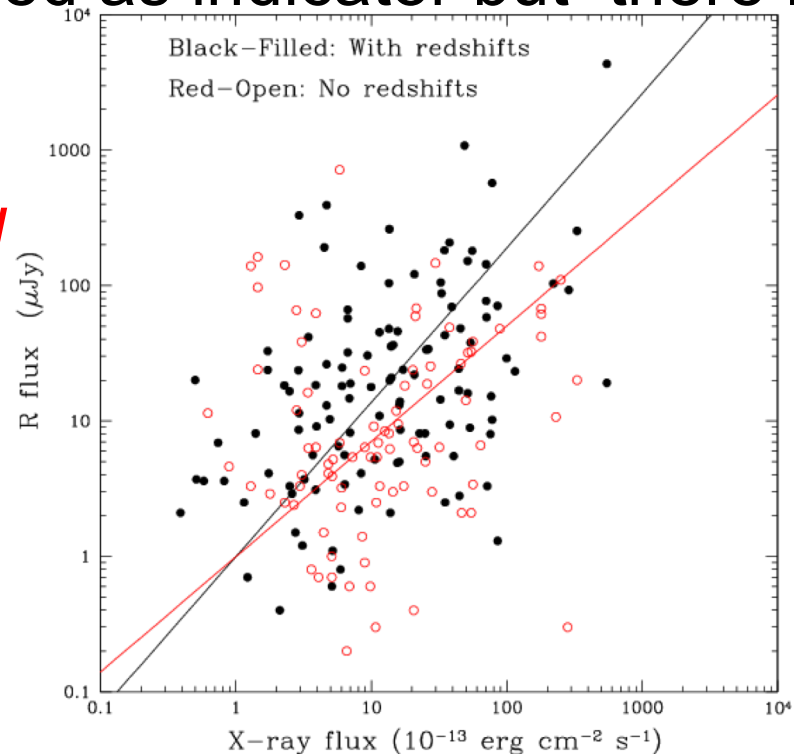
The *optical flux* can be used as indicator but there is no well defined limit.

Opt.-X-ray fluxes *correlated*

So *use X-ray threshold*

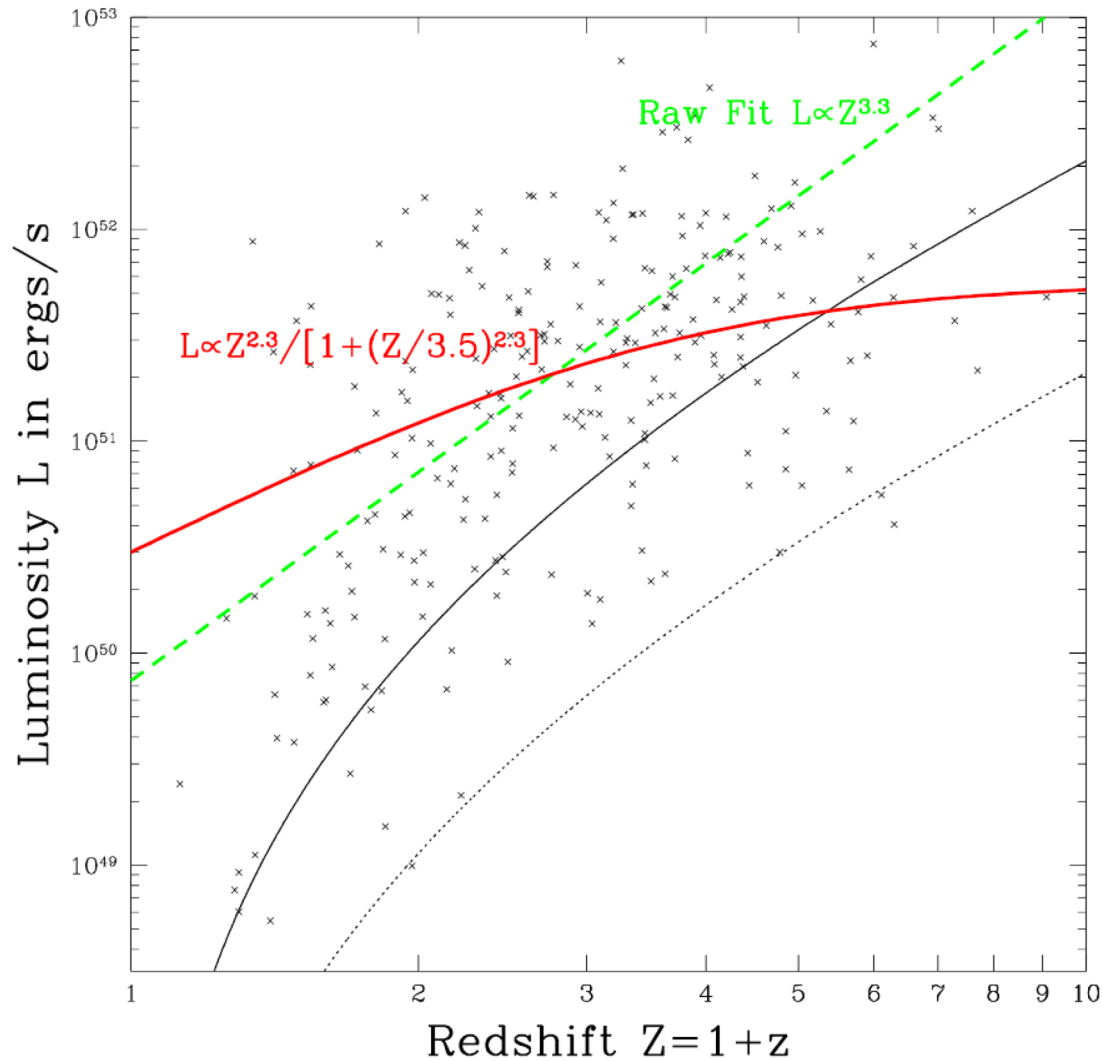
to correct for this bias

(data from Nysewander et al. 2009)



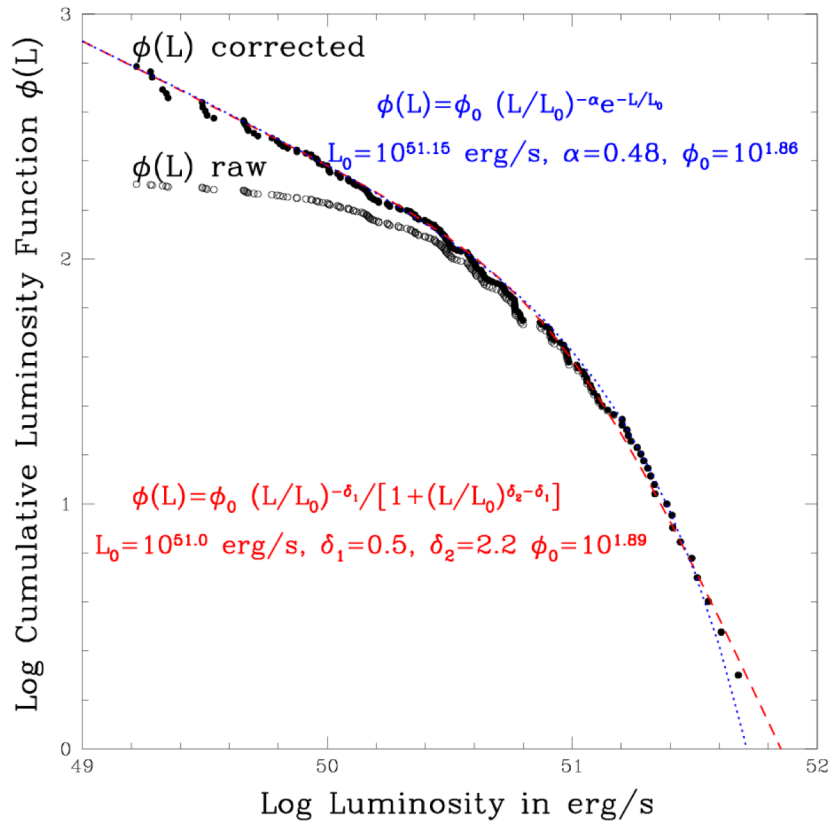
# 1. Test of independence

## *Luminosity evolution*

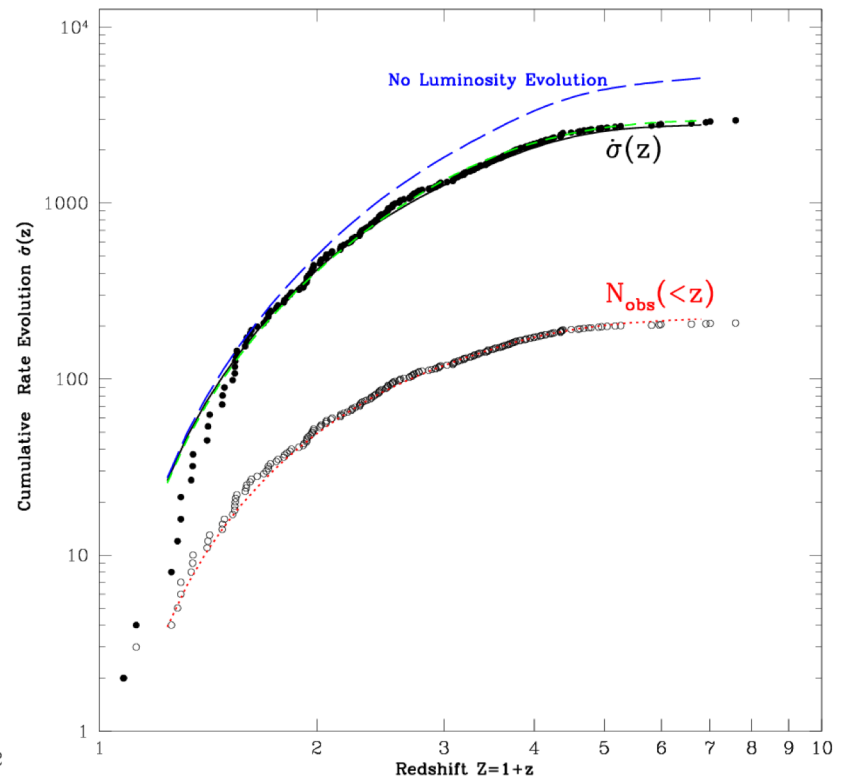


# Cumulative Distributions

## Luminosity Function

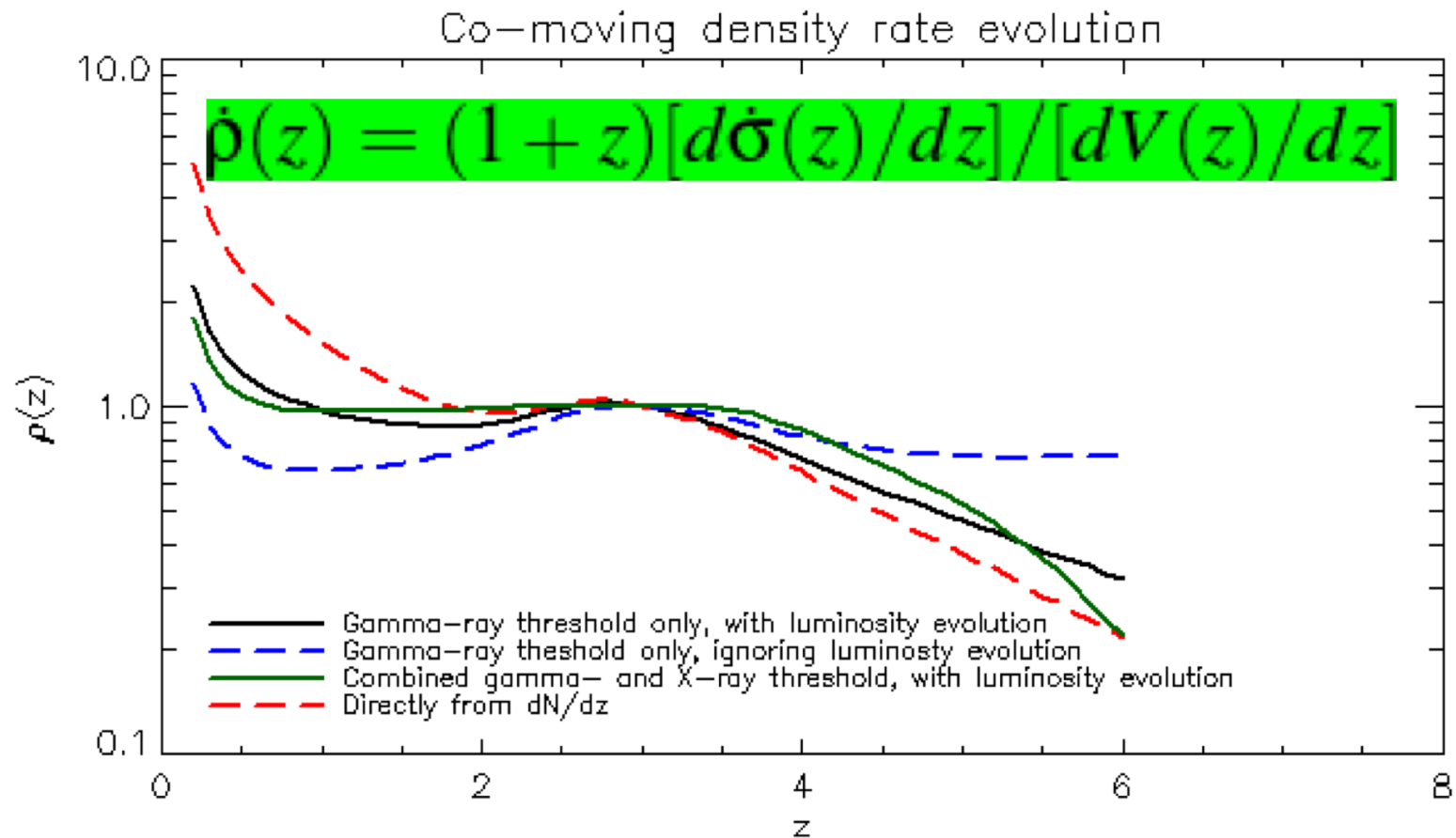


## Rate Density Evolution



# Density Rate Evolution

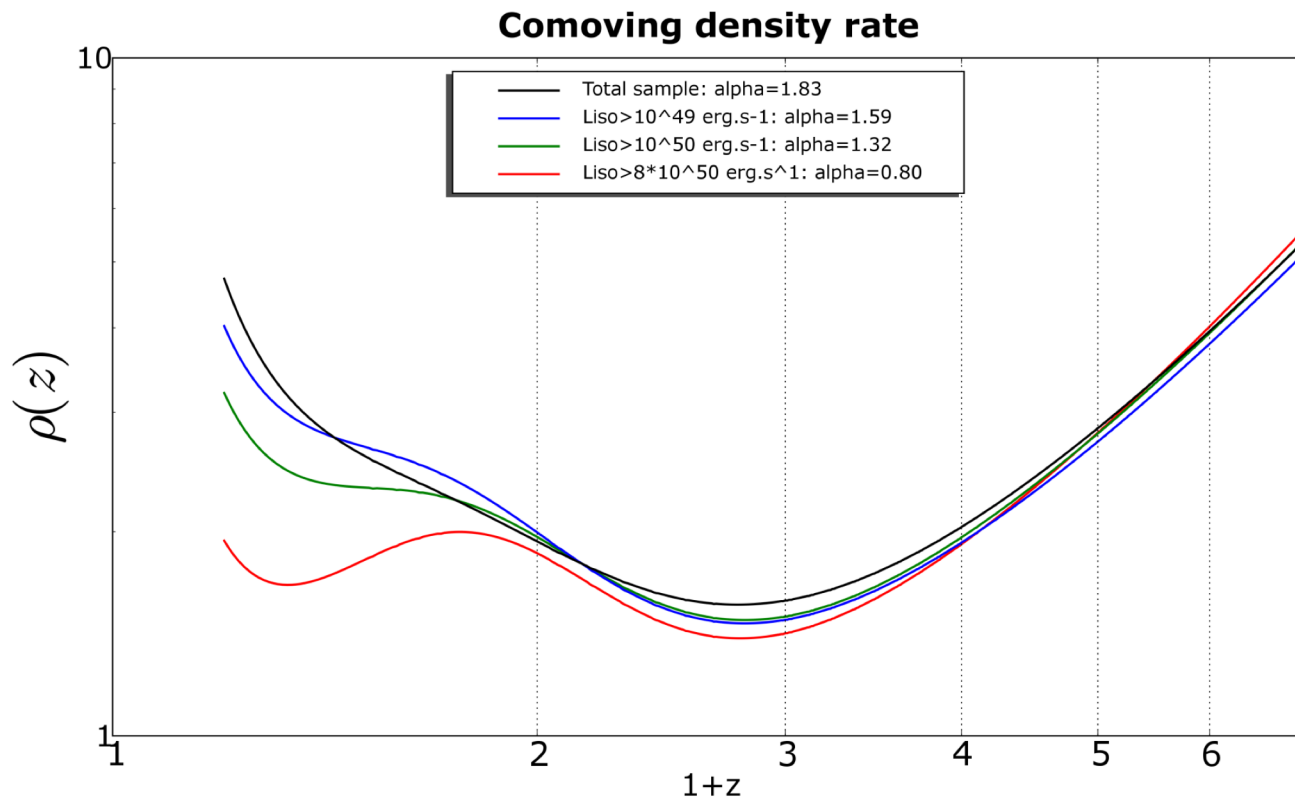
*Using different selection criteria*



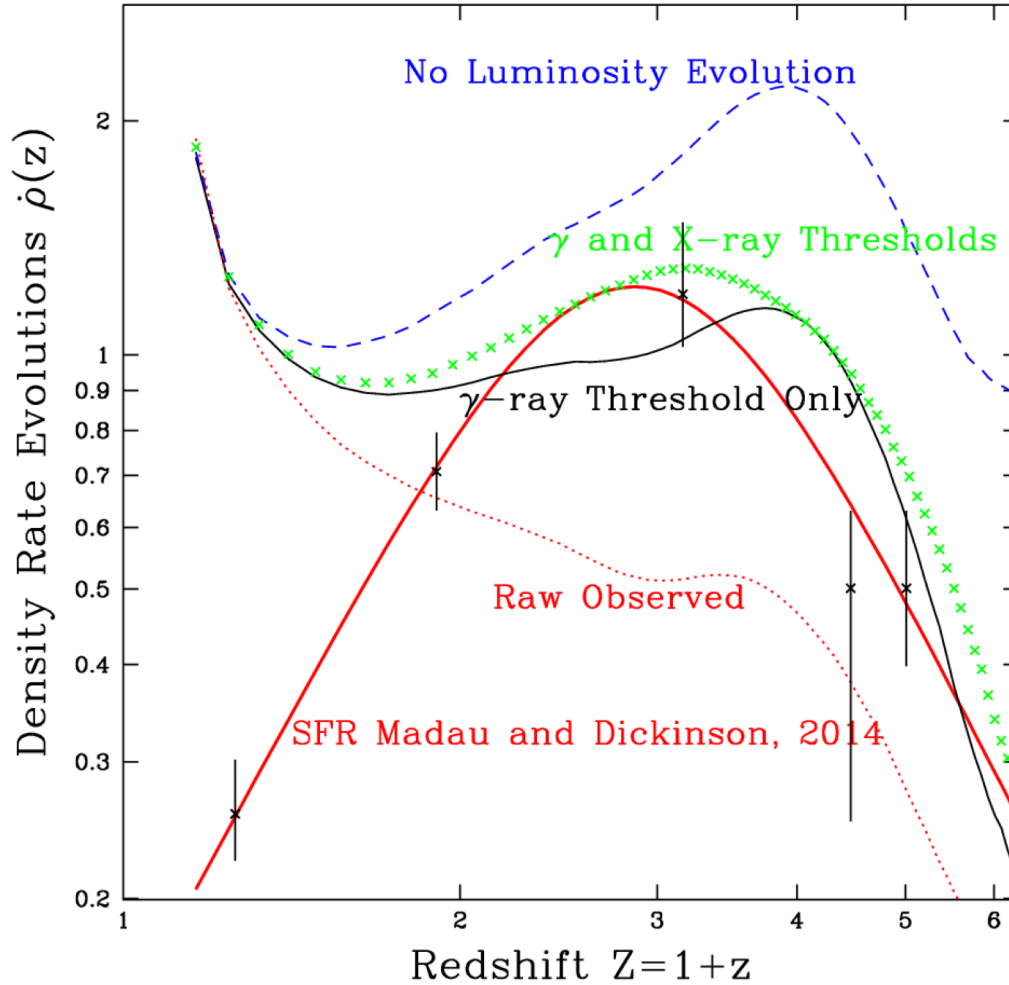
# Density Rate Evolution

*Using different Luminosity Ranges*

$$\dot{\rho}(z) = (1+z) [d\dot{\sigma}(z)/dz] / [dV(z)/dz]$$

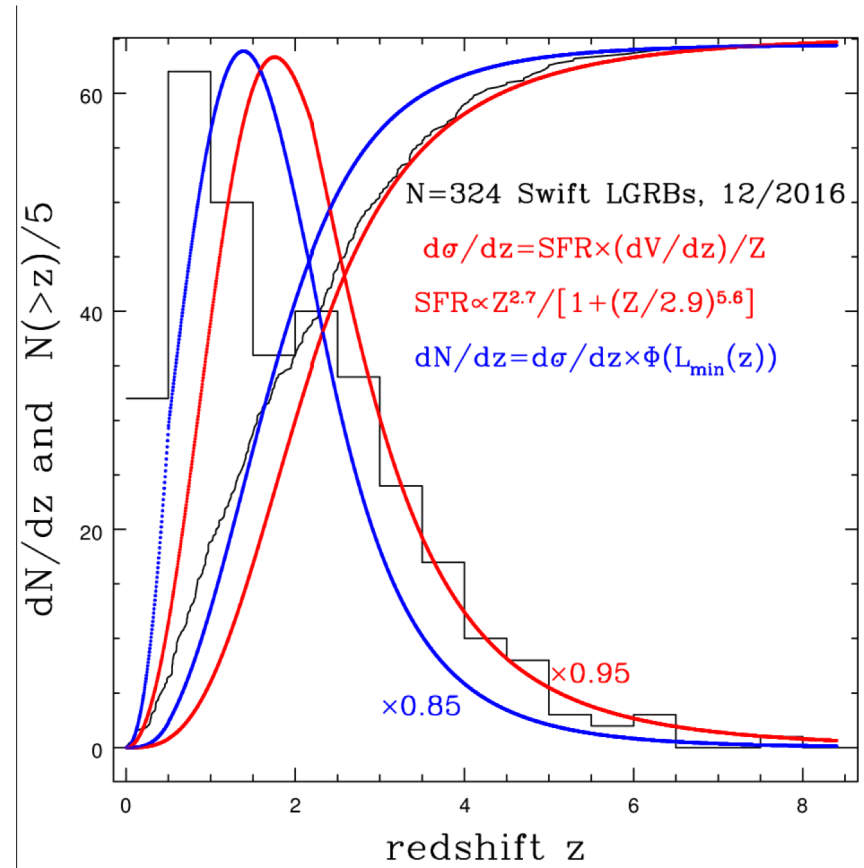
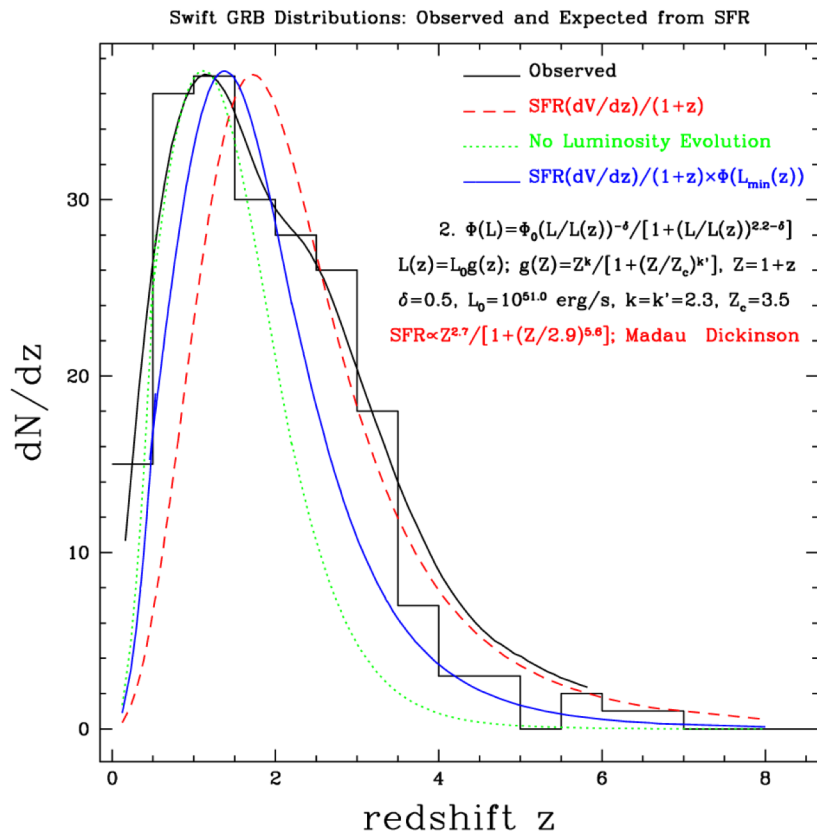


# GRB and Star Formation Rates



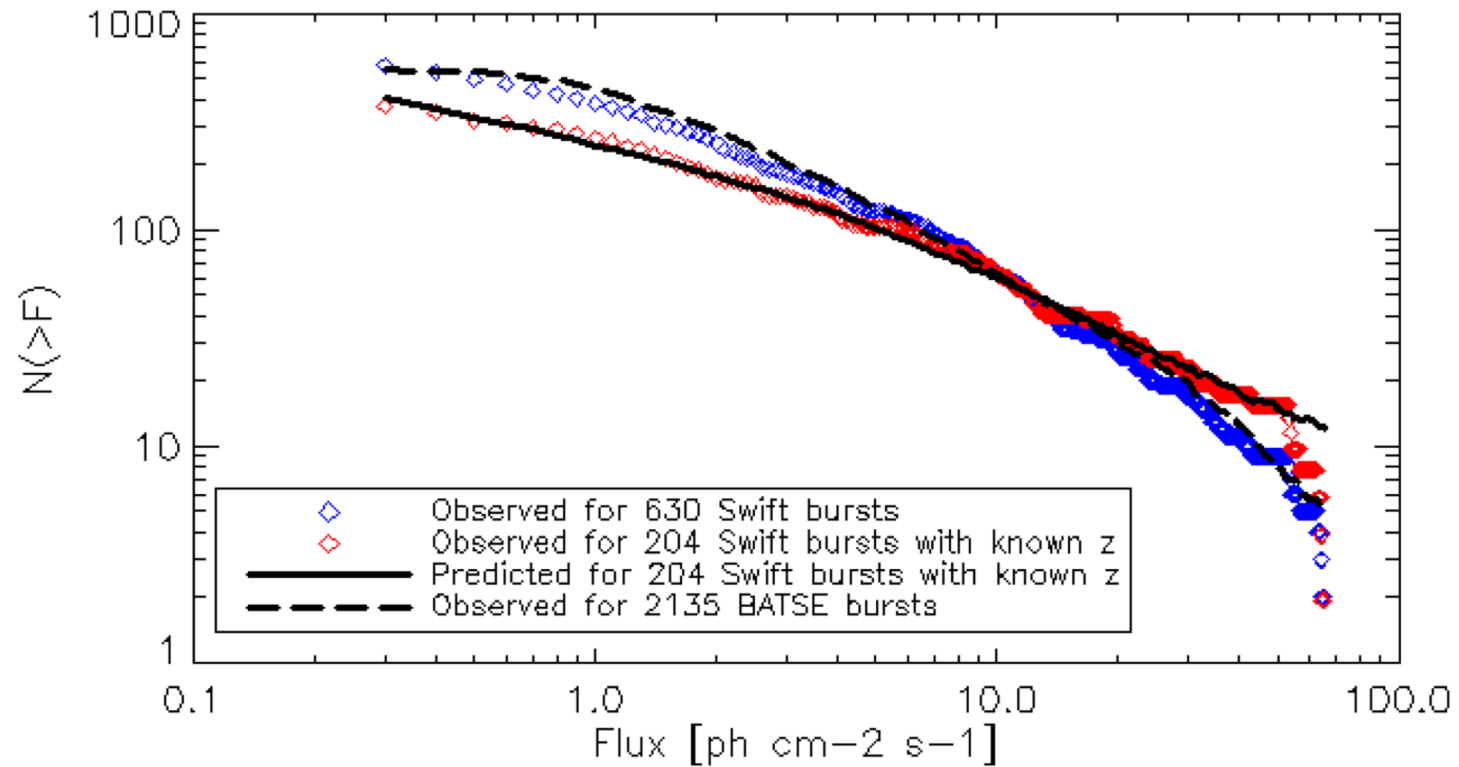
# Further Testing of the Results

*Assume GRB rate=SFR*



# Further Testing of the Results

## *Log N-Log S Test*



# 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

*More uncertain because fewer SGRBs*

27-GBM, 33-Swift and 8-Konus-WIND with redshifts

Different band width

Different Thresholds

But with EF method we

Can combine them



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*More uncertain because fewer SGRBs*

27-GBM, 33-Swift and 8-Konus-WIND with redshifts

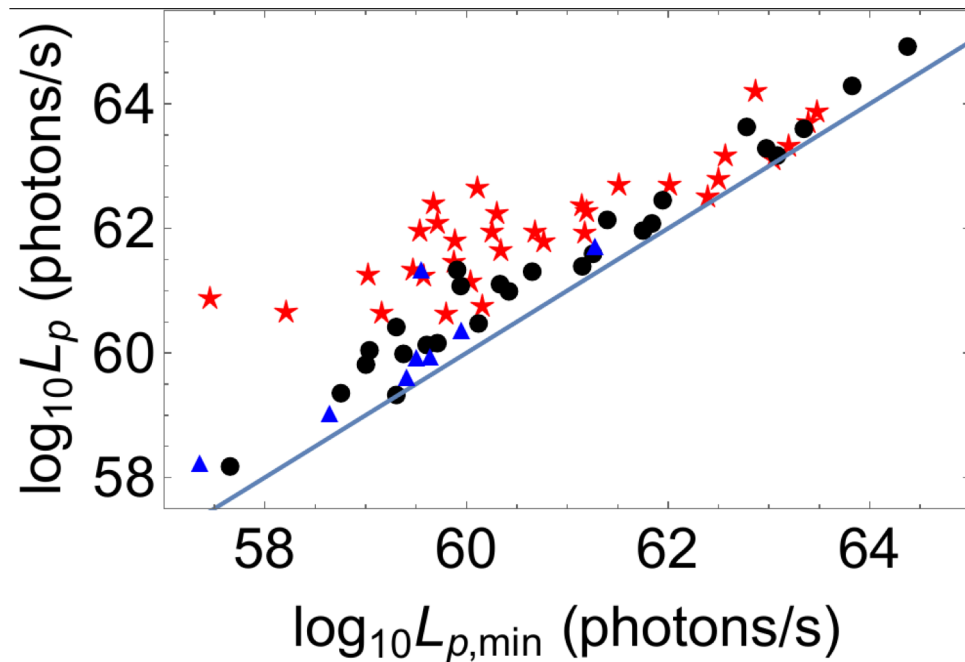
Different band width

Different Thresholds

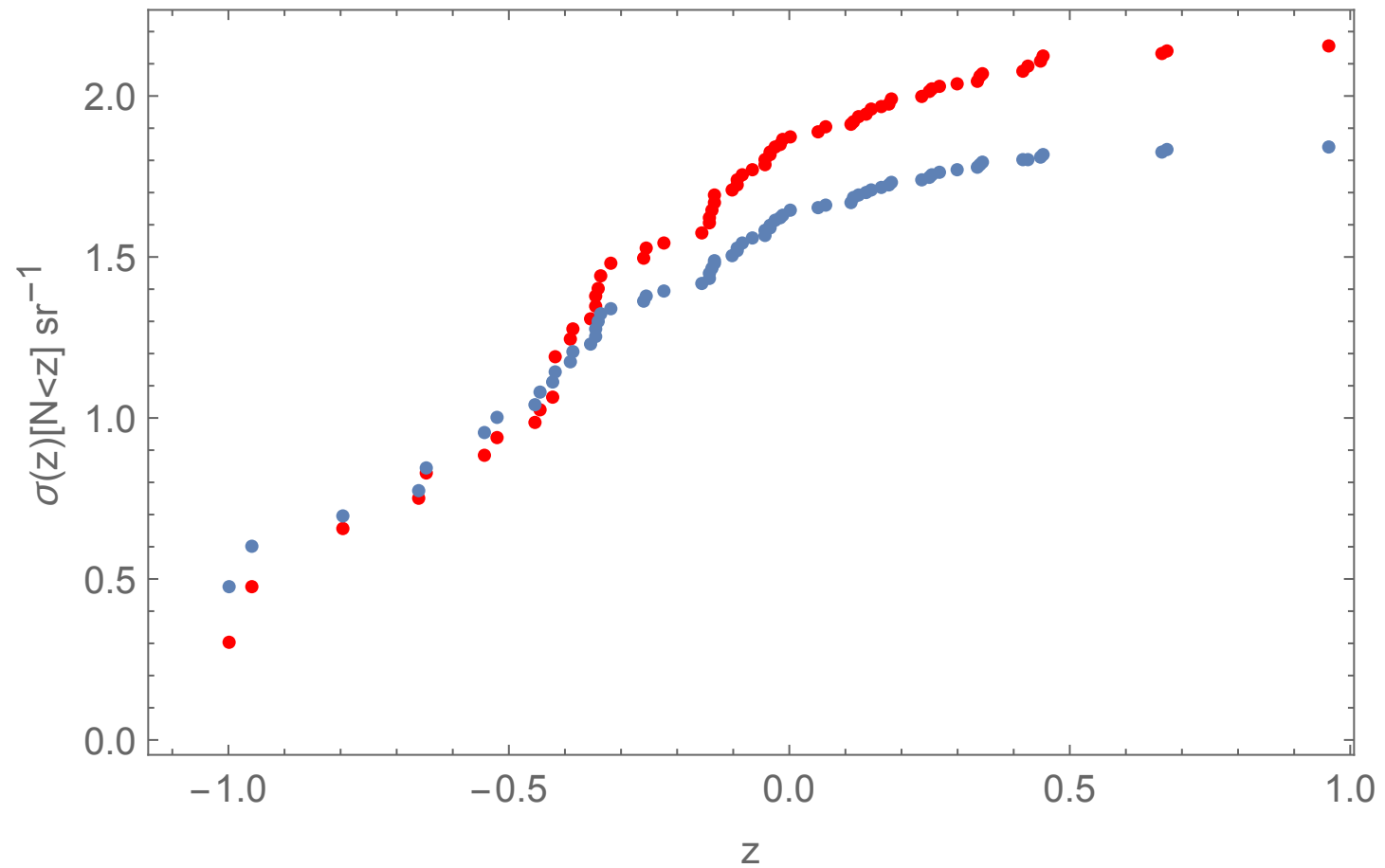
But with EF method

we can combine them

$$L_{\min}(z) = 4\pi d_L^2 F_{\lim}$$



# Short GRBs and Gravitational Waves



# SGRB and Star Formation Rates

