Cosmological Evolution of Gamma-ray and Fast Radio Bursts and their relation to Star Formation Rate and Gravitational Waves

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Transient Sources

Gamma-Ray Bursts (GRBs) were first transients, after Solar flares, Novae and Supernovae, discovered accidentally about 60 years ago. Fast Radio Bursts (FRBs) are more recent additions. The importance of transient has led to development of many dedicated instruments in the last two decades.

1. Most readily observed data are the light curves and spectra giving information about size, emission (and possibly particle acceleration) mechanisms and redshift.

2. Localization and discovery of progenitors are more difficult. However, determination of the cosmological evolution can provide indirect information. This will be the topic of my talk.

OUTLINE

I. General Remarks on Cosmology

The Roles of GRBs

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

C. Fast Radio Bursts

I. General Remarks

Cosmology with GRBs

1. GRBs as "Standard Candles?"

There has been many attempts but not very promising because of insufficient data

2. GRBs as Probes of the Early Universe

Through detailed description of the of the luminosity function and its cosmological evolution

Assumed Cosmological Model

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:

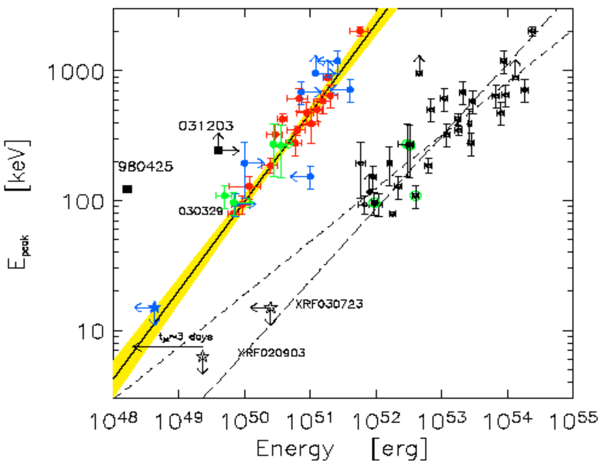
A. Cepheids: *Luminosity-Period*

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

GRB Correlations

Examples of Correlations

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.)

II. The Luminosity Function and its Evolution

Cosmology with Discrete Sources

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

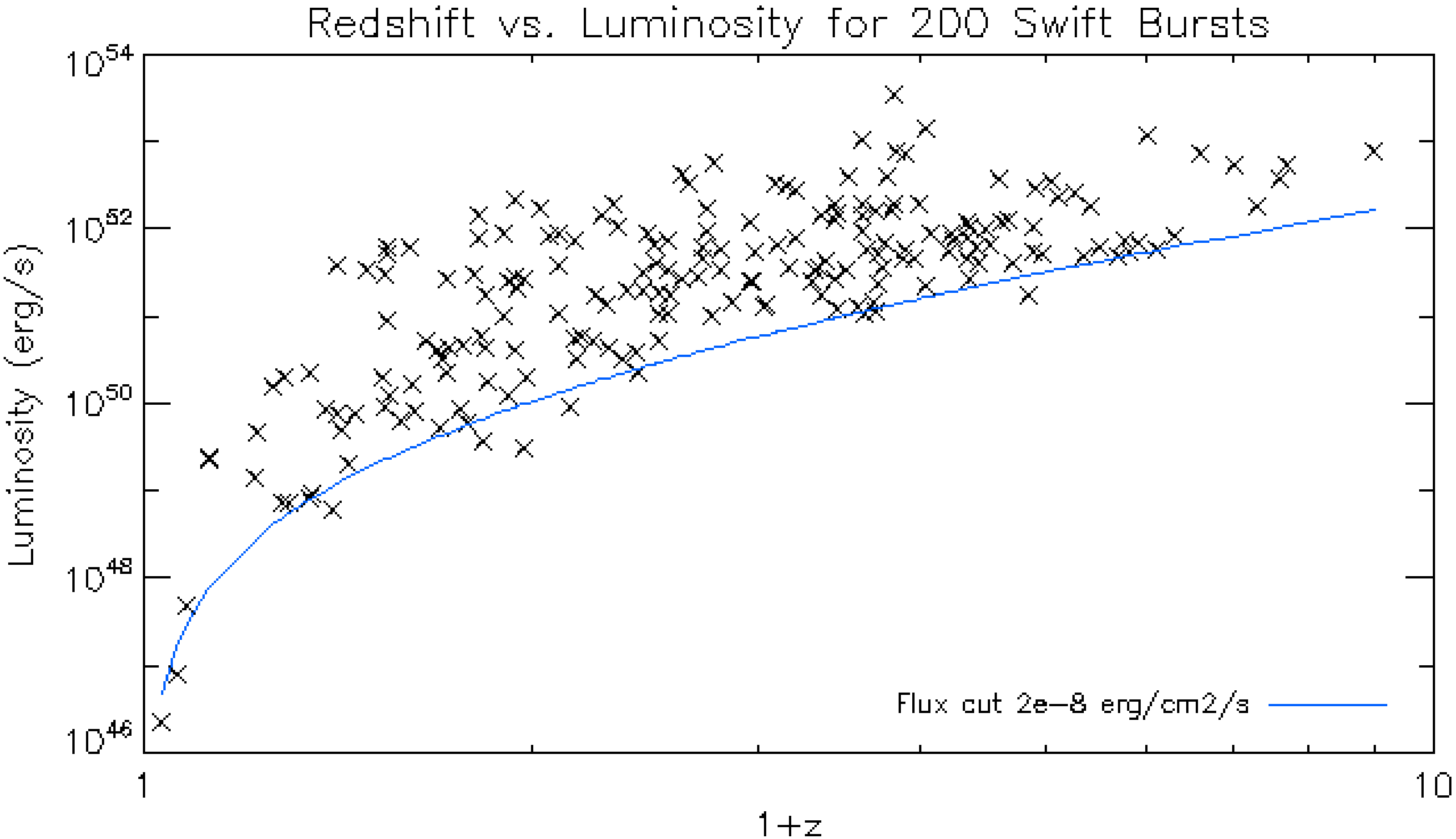
$g(z)$ Is the Luminosity Evolution

Redshift dependent luminosity function

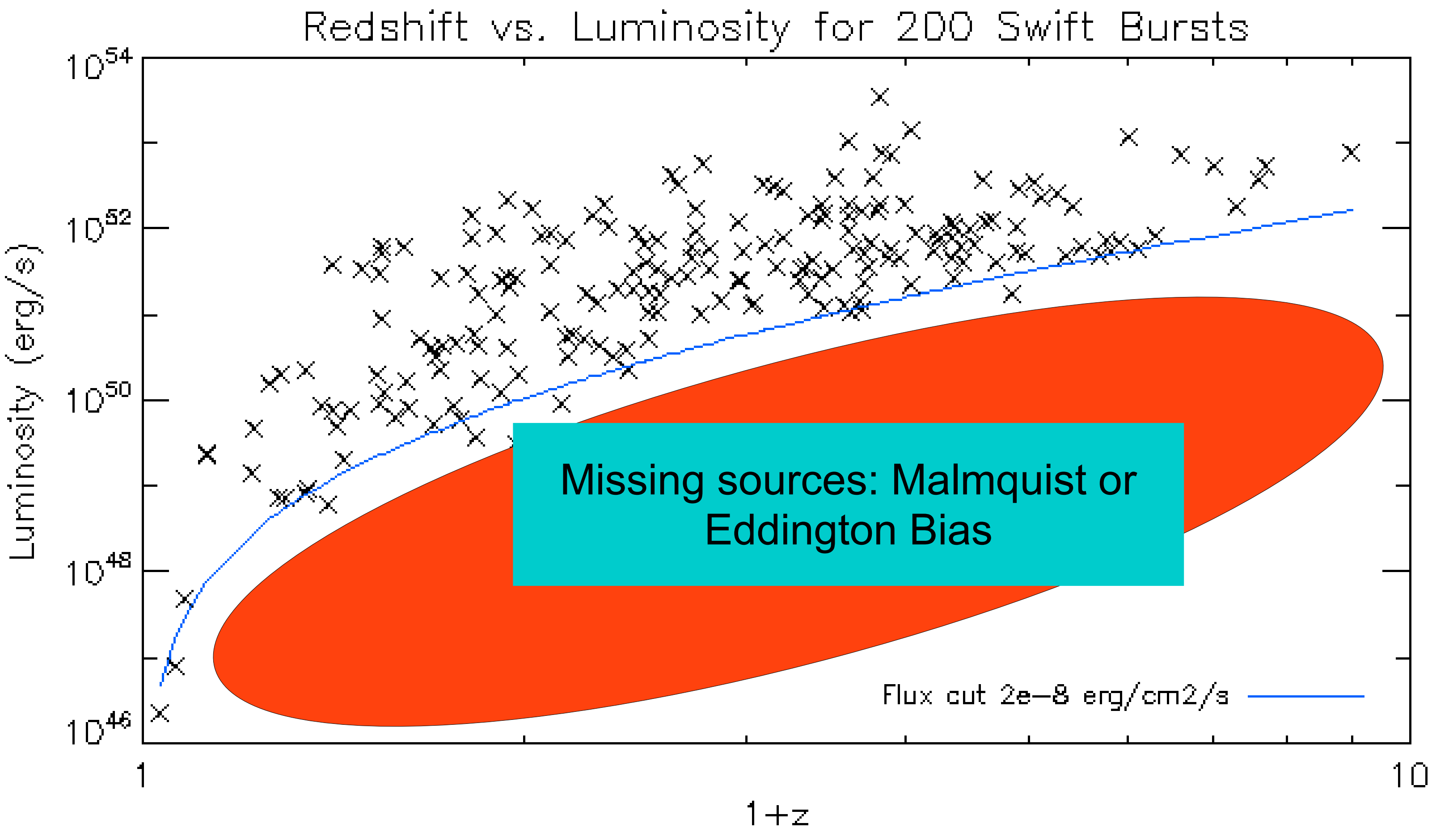
Alternative Approach

Luminosity dependent density evolution

The required data: Bivariate *L-z* distribution



Bi-variate Luminosity-redshift Distribution



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

Density Evolution $\rho(z)$

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

Difficulty: *Involves many functions each with several parameters*

Needs to minimize ChiSq or maximize likelihood in multi-dimensional space raising question of uniqueness

Procedures: 2. Non-parametric

Some past successful non-parametric methods

1. Schmidt (1968) V/V_{max}

2. Lynden-Bell (1973) *C-* methods

These however **assume** that Luminosity and Redshift are

Uncorrelated or are Independent variables

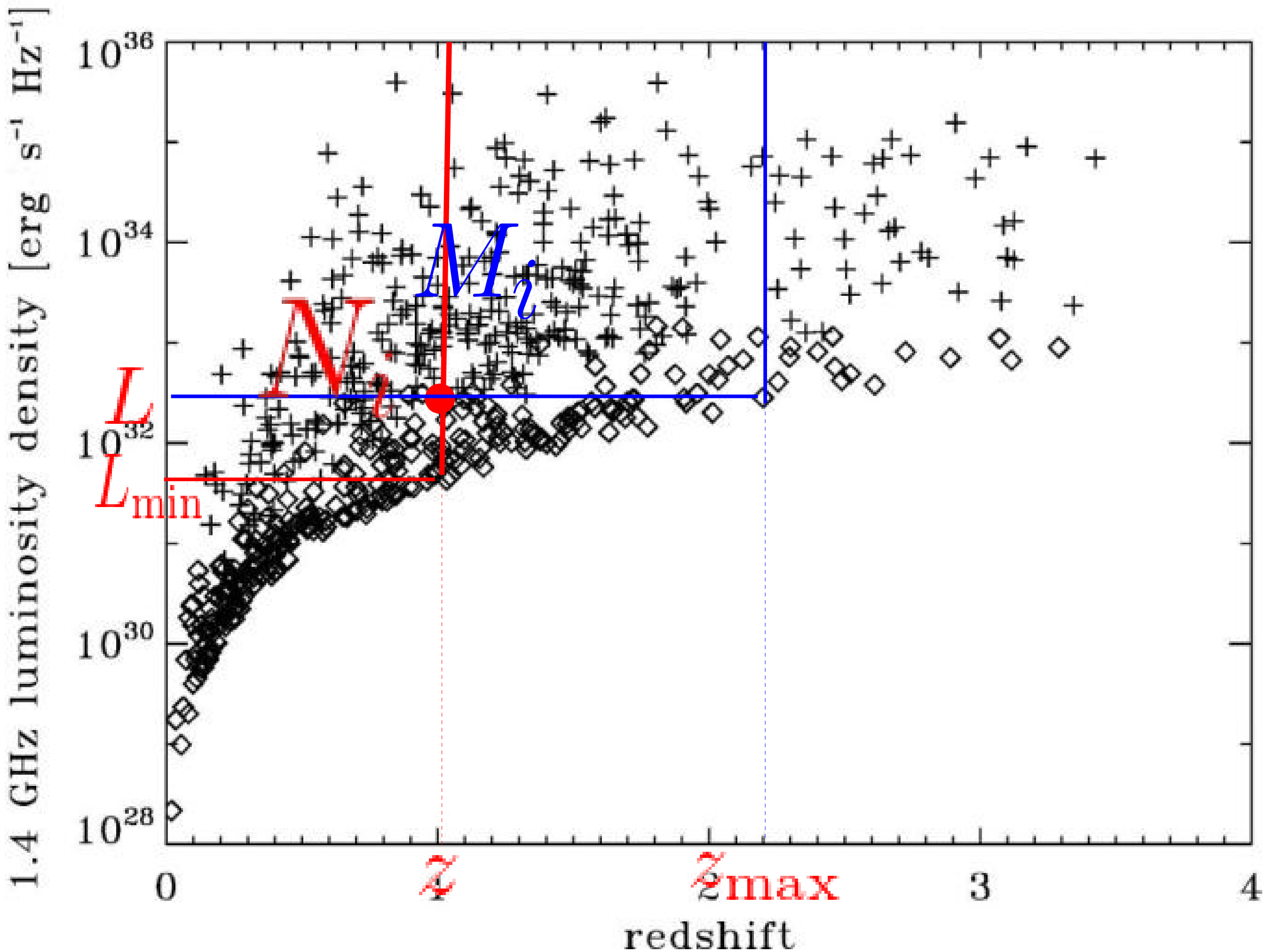
Petrosian, 1993

3. Efron-Petrosian (1992-99): Test of Independence

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

Test of Independence *Truncated Data*

Rank each source in its *associated sets* containing *Ni and Mi* sources

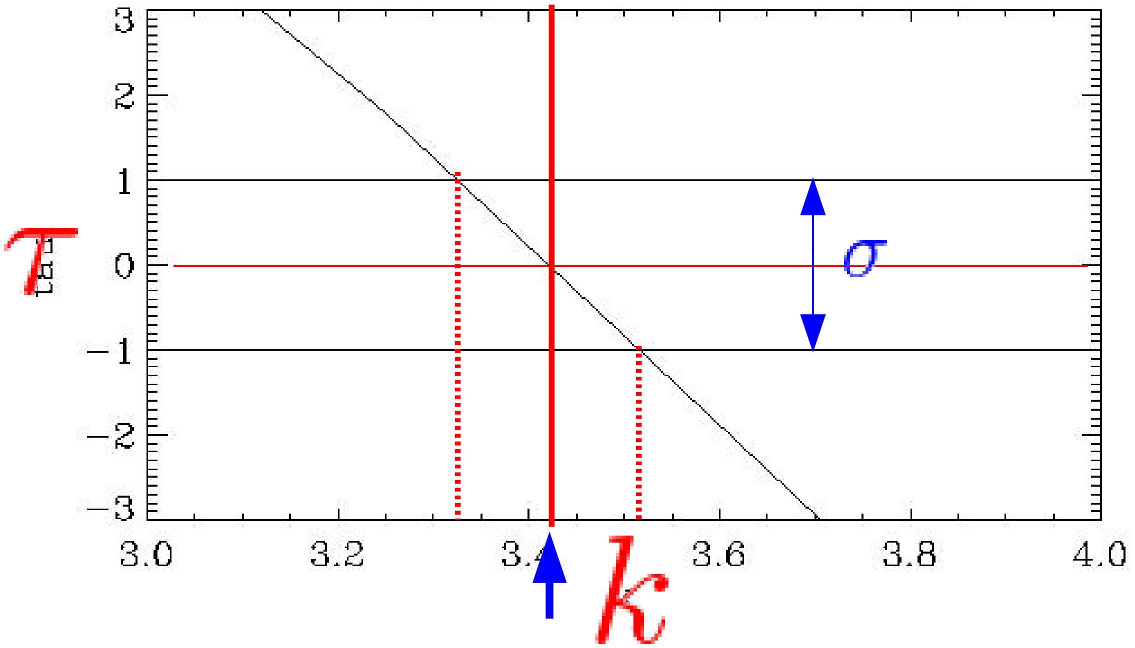
- 

Test of Independence

Remove the correlation by a variable transformation e.g.

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

$$g(z) = \frac{Z^k}{1 + (Z/Z_c)^k} \quad Z = 1 + z$$



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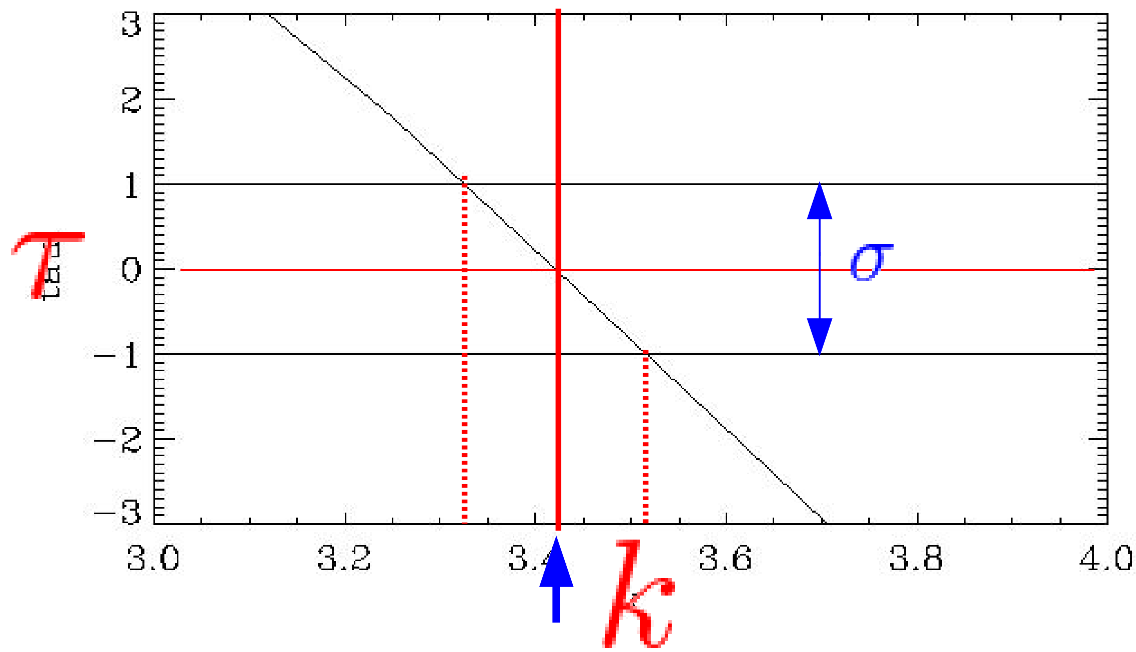

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$$L'_i = L_i / g_i(z)$$

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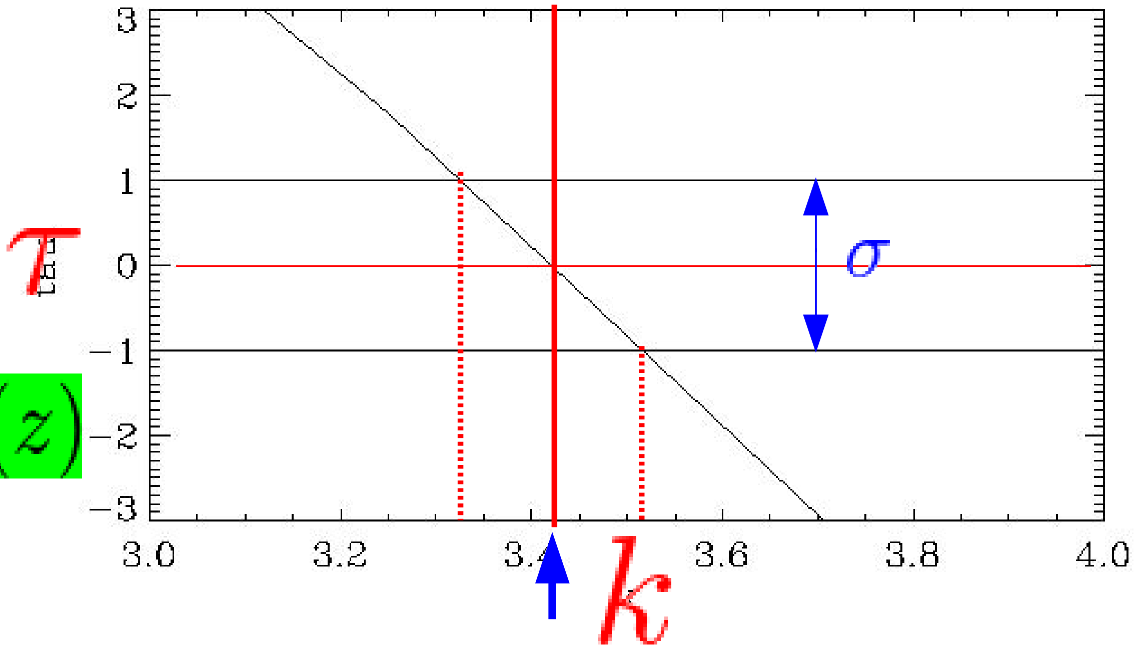
$$\Psi(L', z) = \psi(L')\rho(z)$$



The single variable distributions

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

Non-parametrically and with no binning

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

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

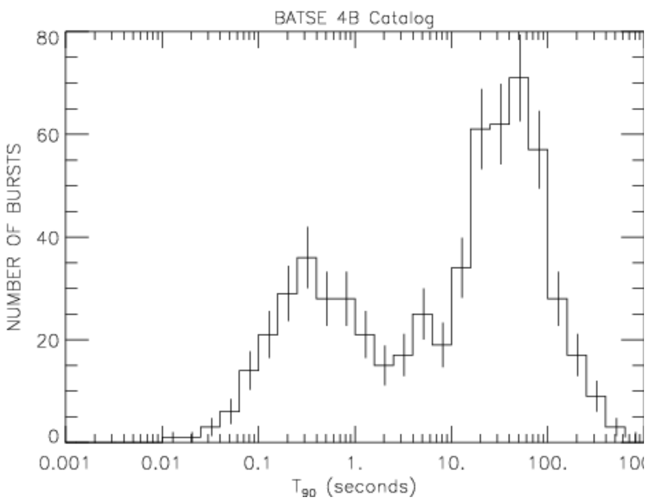
From these we get the sought differential distributions

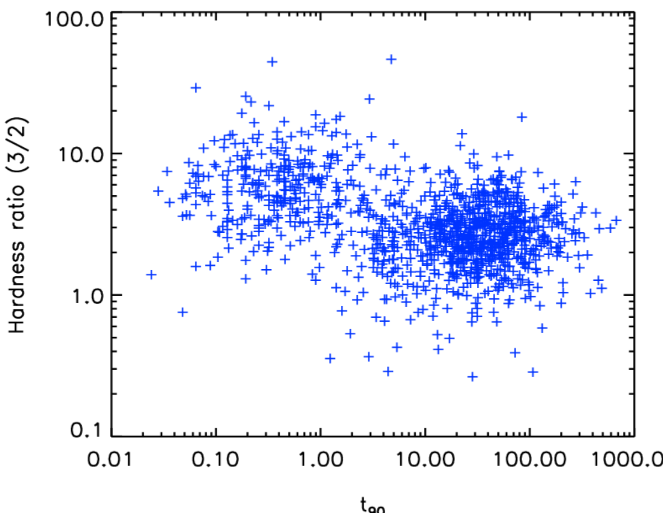
$$\Psi(L) \quad \text{and} \quad \rho(z)$$

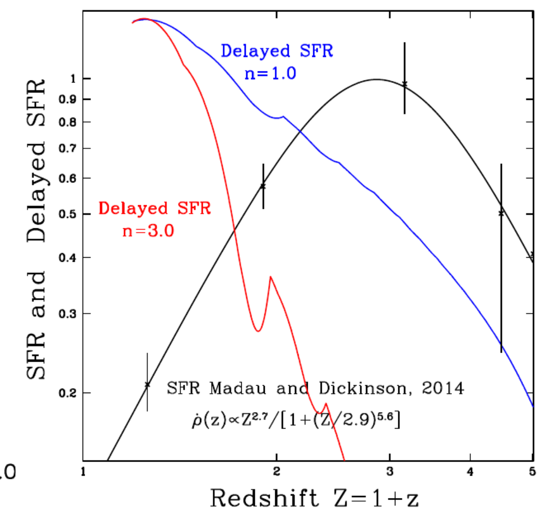
IV. Application to Swift Long and Short GRBs

LGRB progenitor: Collapsars

SGRB progenitor: NS-NS or NS-BH Merger







Density (rate) Evolution vs Star Formation Rate

VP, Kitanidis and Kocveski ApJ 2015

VP, Dainotti et al, 2021, 2024

Caveats: *Selection Effects and Truncations*

1. Gamma-ray trigger

    Peak count or flux threshold

2. Localization

    X-ray flux threshold

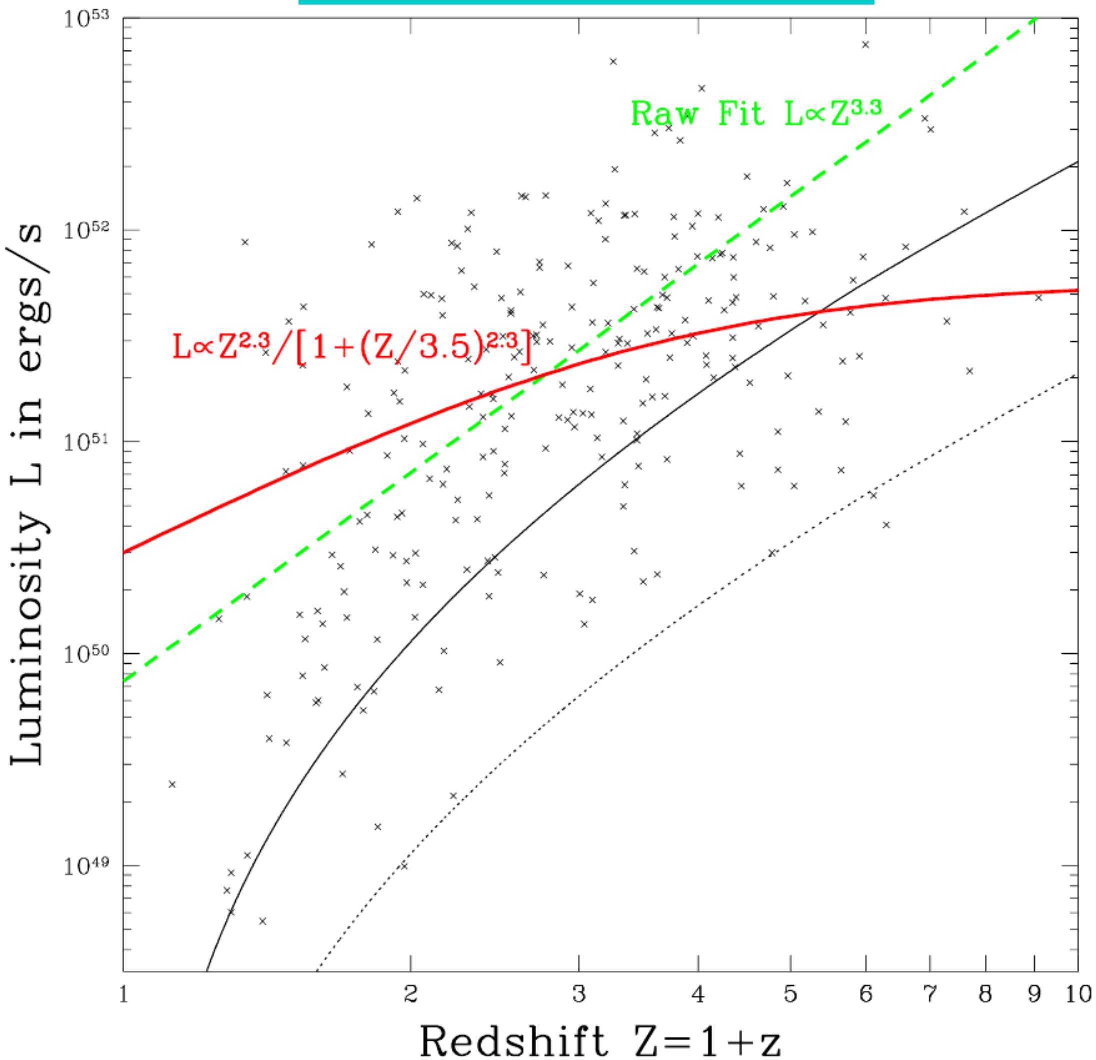
3. Optical follow-up and *Redshift*

    Optical Magnitude etc

1. Swift Long GRB Data

Truncated Luminosity vs Redshift

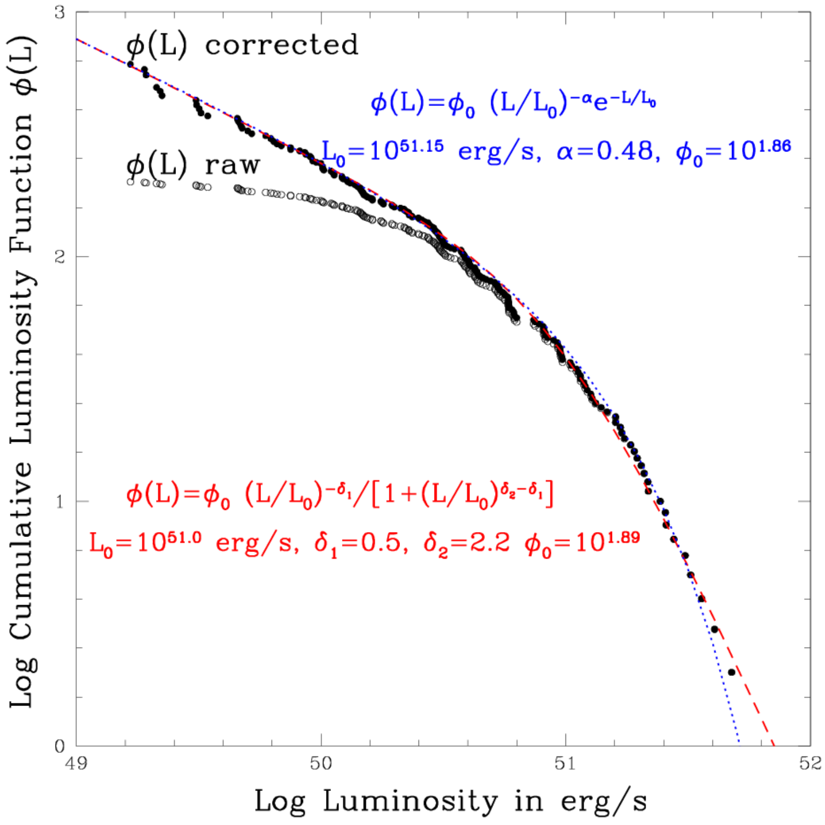
VP, Kitanidis, Kocevski, 2015



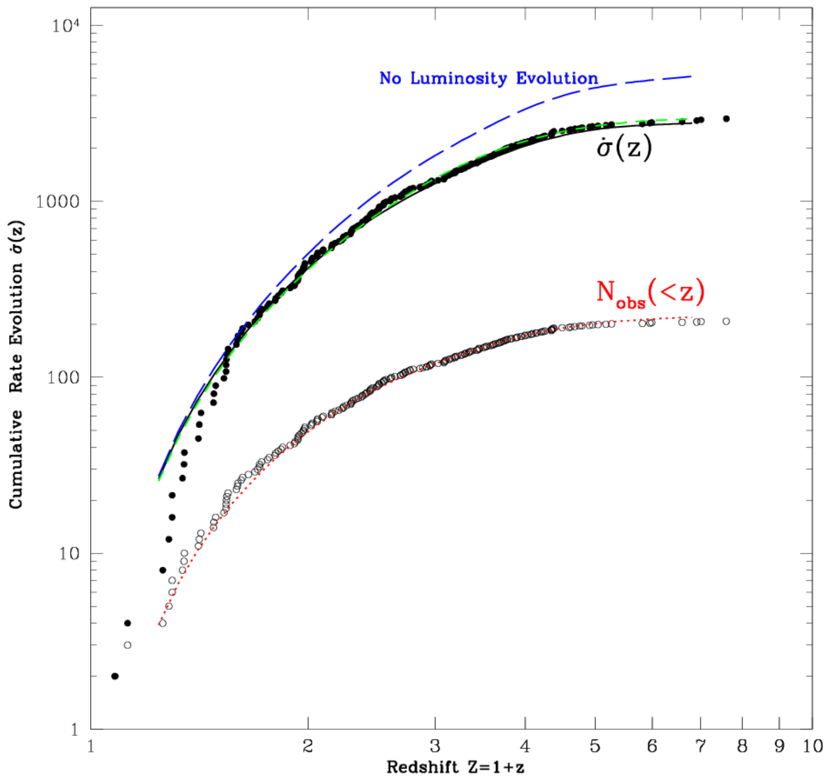
Cumulative Distributions

VP, Kitanidis, Kocevski, 2015

Luminosity Function

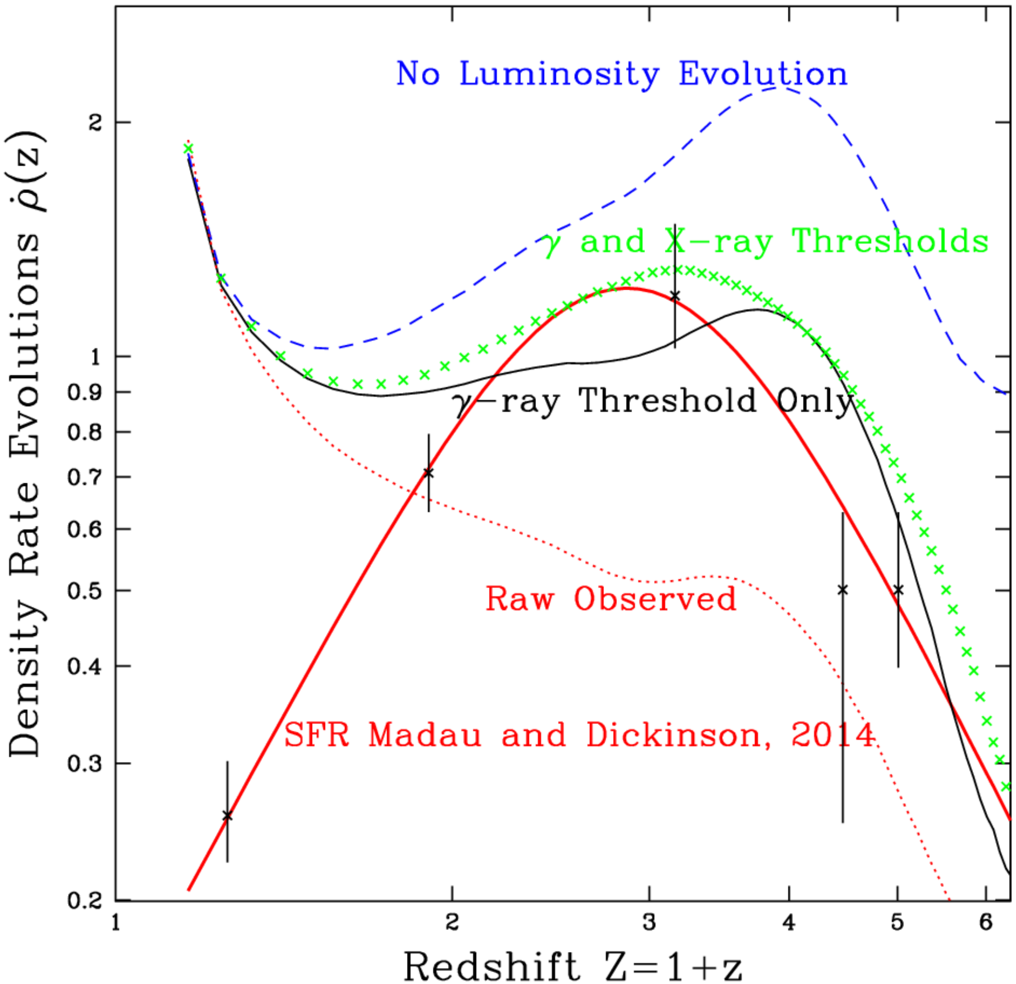


Rate Density Evolution



LGRBs and Star Formation Rates

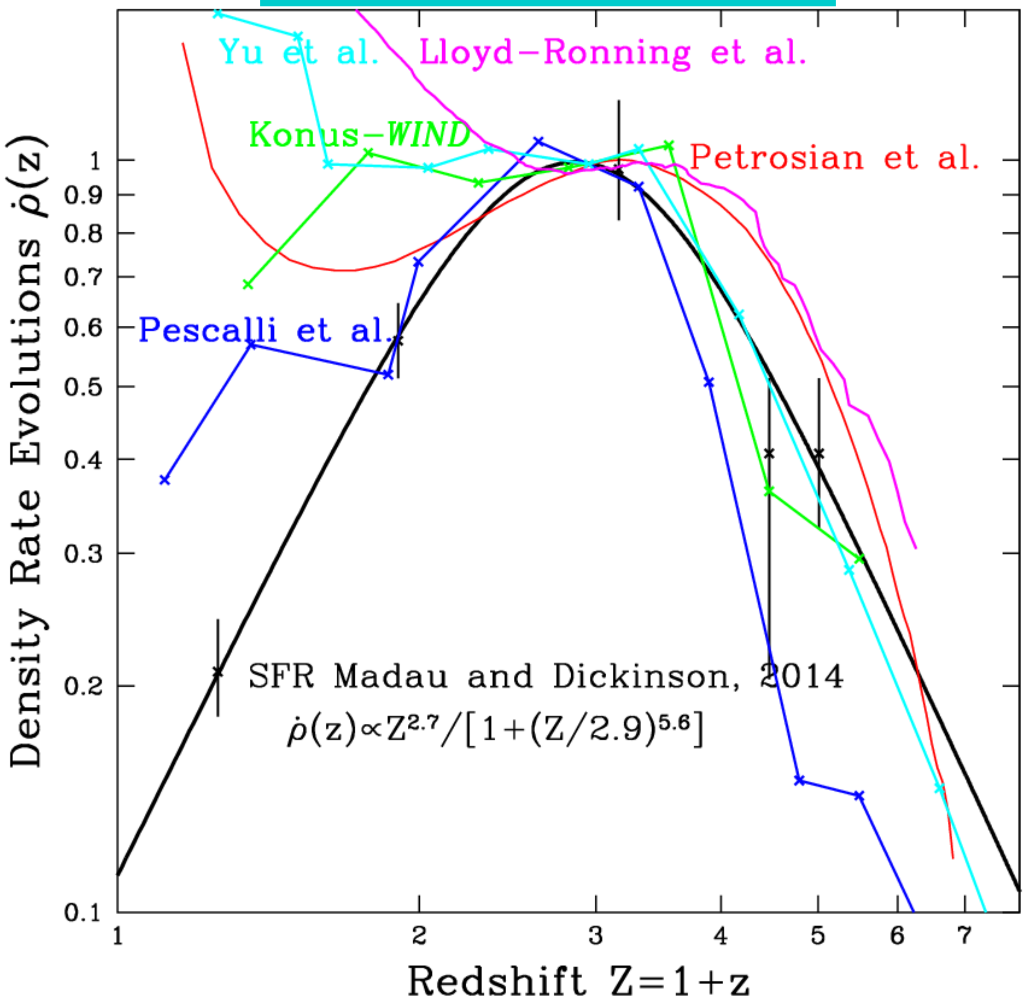
VP, Kitanidis, Kocevski, 2015



LGRBs and Star Formation Rates

Other results using LEP method

VP, Dainotti, 2024



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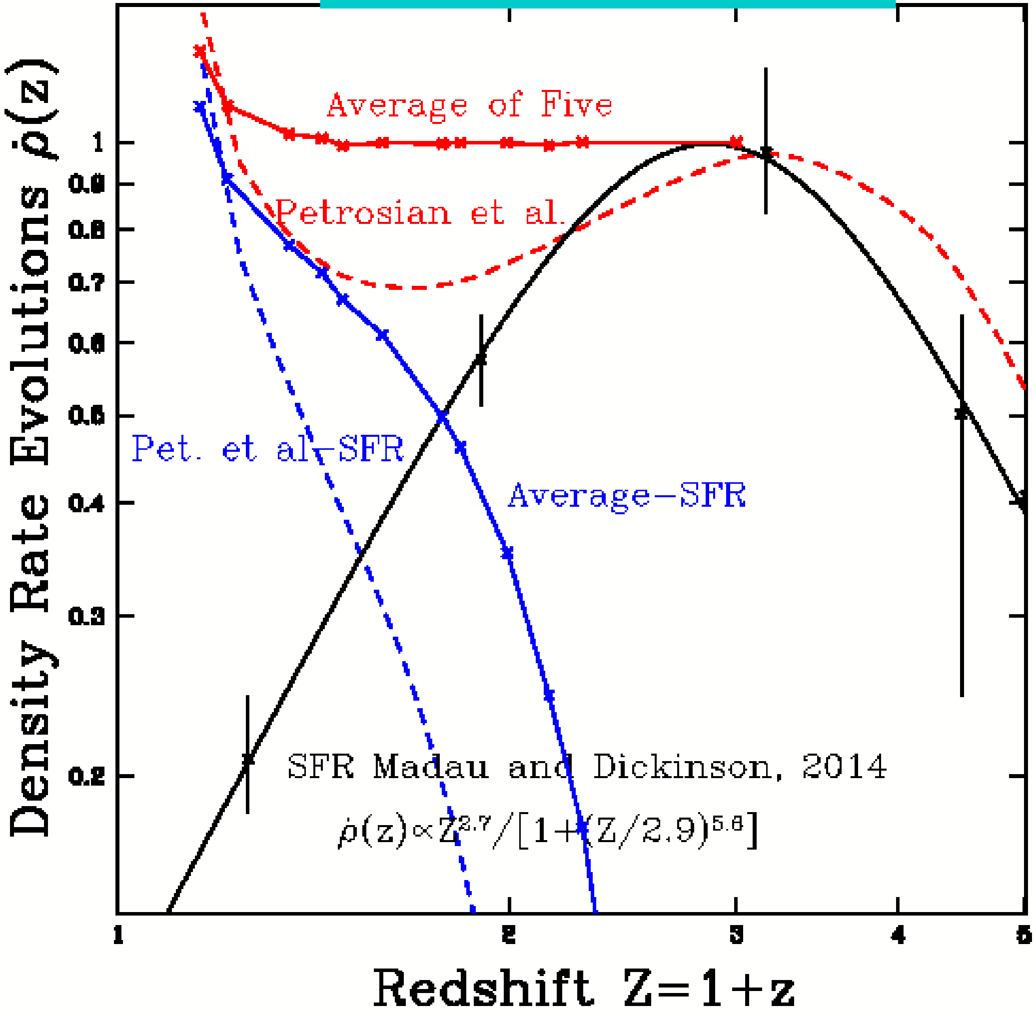
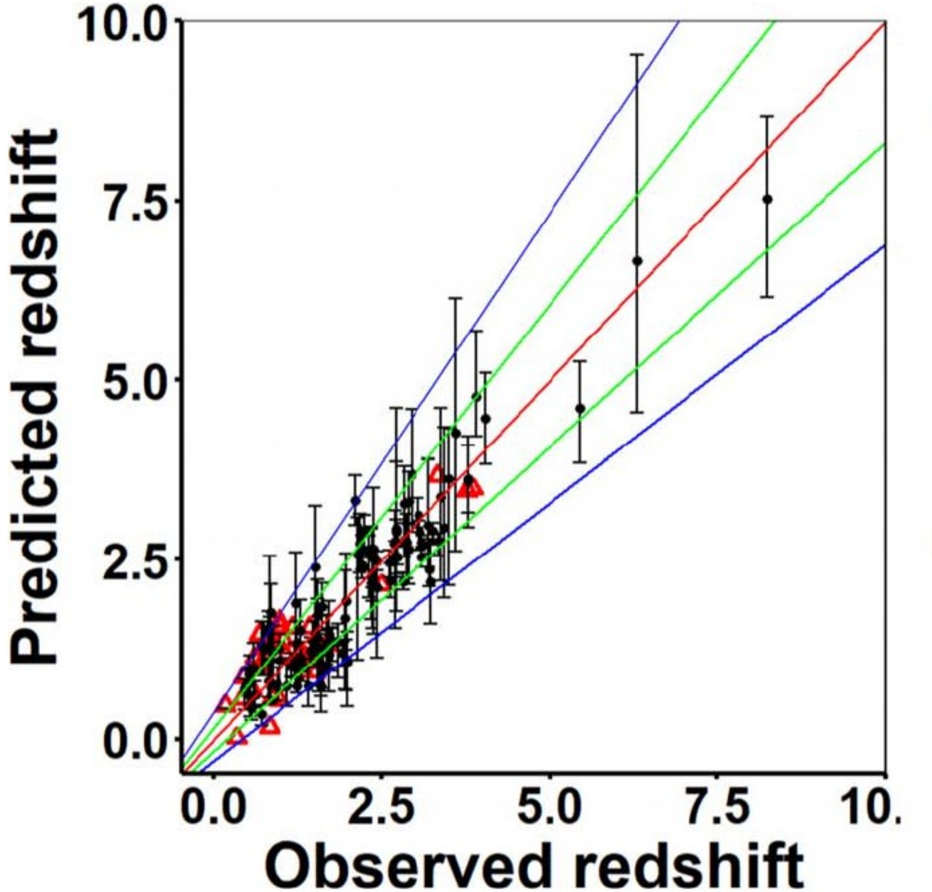


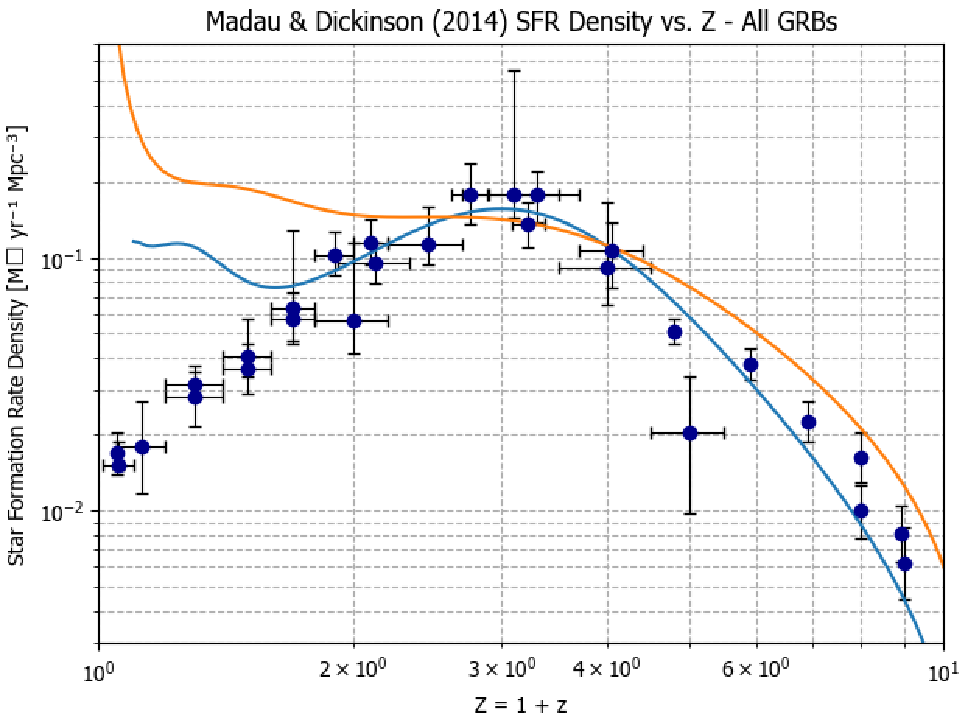
LGRB Redshifts Using Machine Learning

Dainotti et al.: Several papers



LGRB Redshifts Using Machine Learning

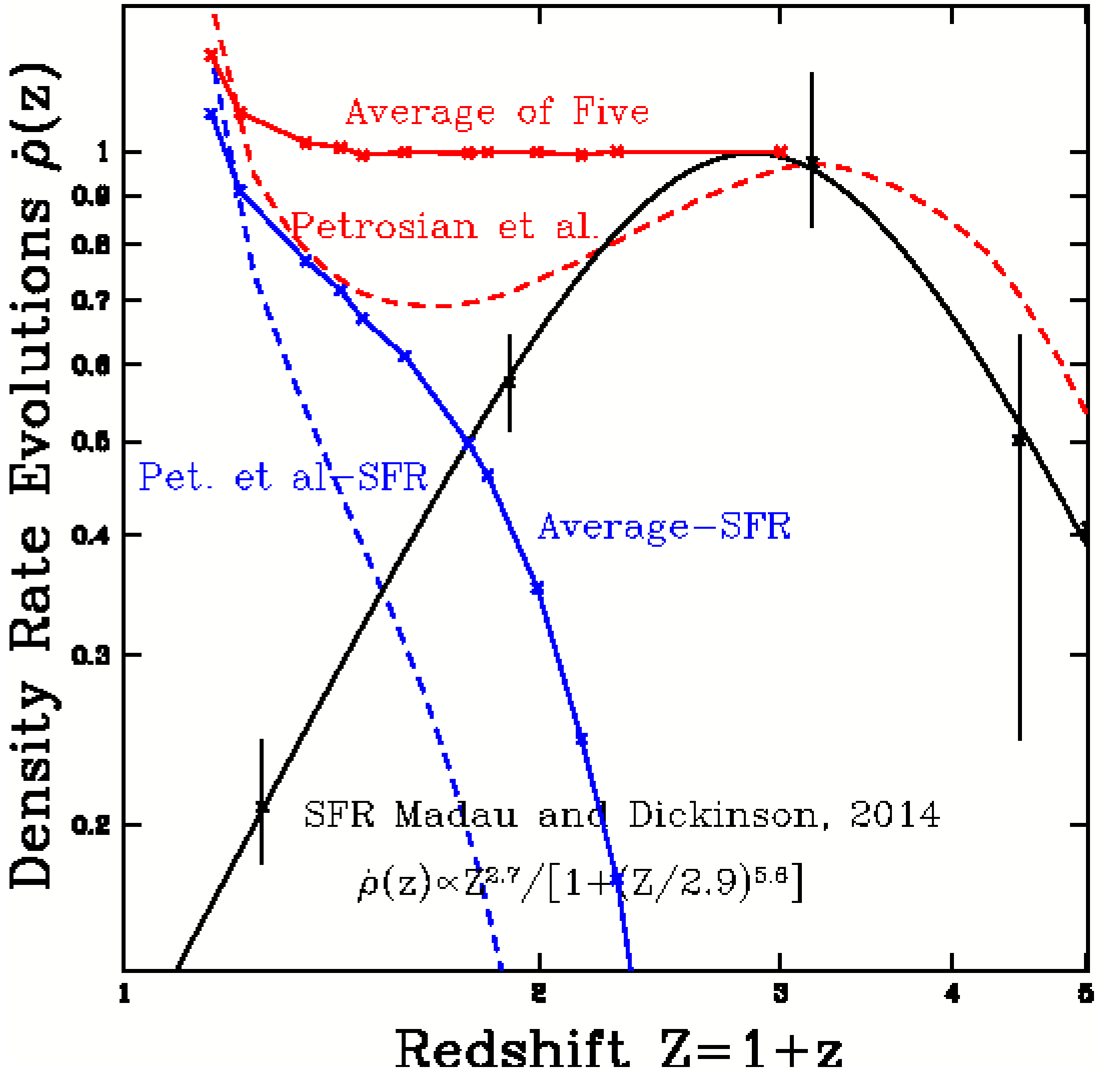
Chimpati, VP and Dainotti, 2026



Yerevan, HEAstro 2026

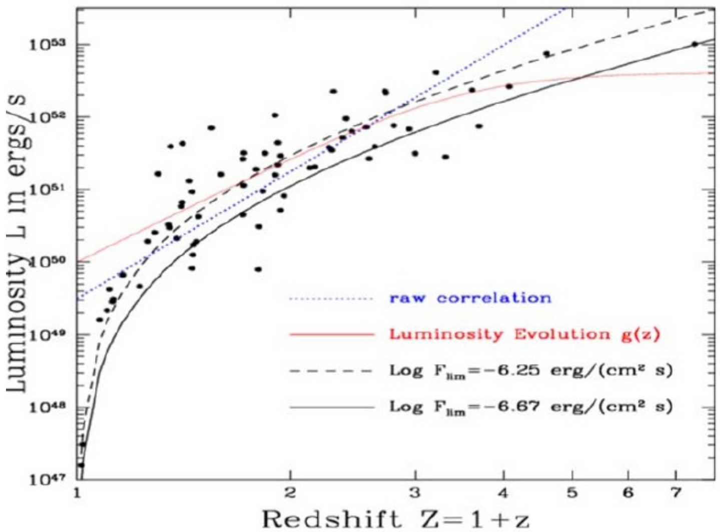
LGRB and Star Formation Rates

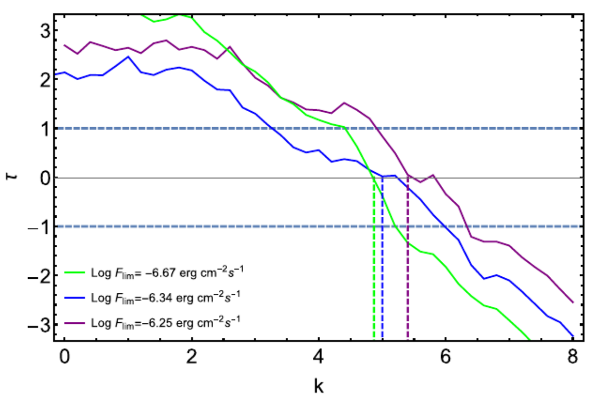
Five independent results (VP & Dainotti APJL 2023)

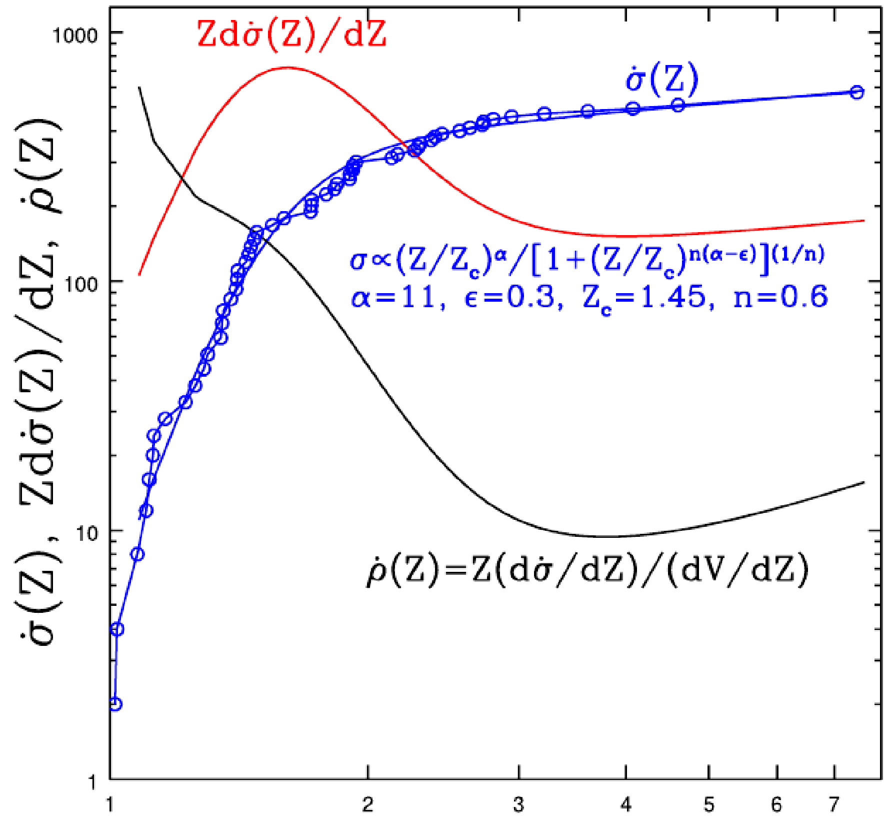


SGRBs: Data and Results

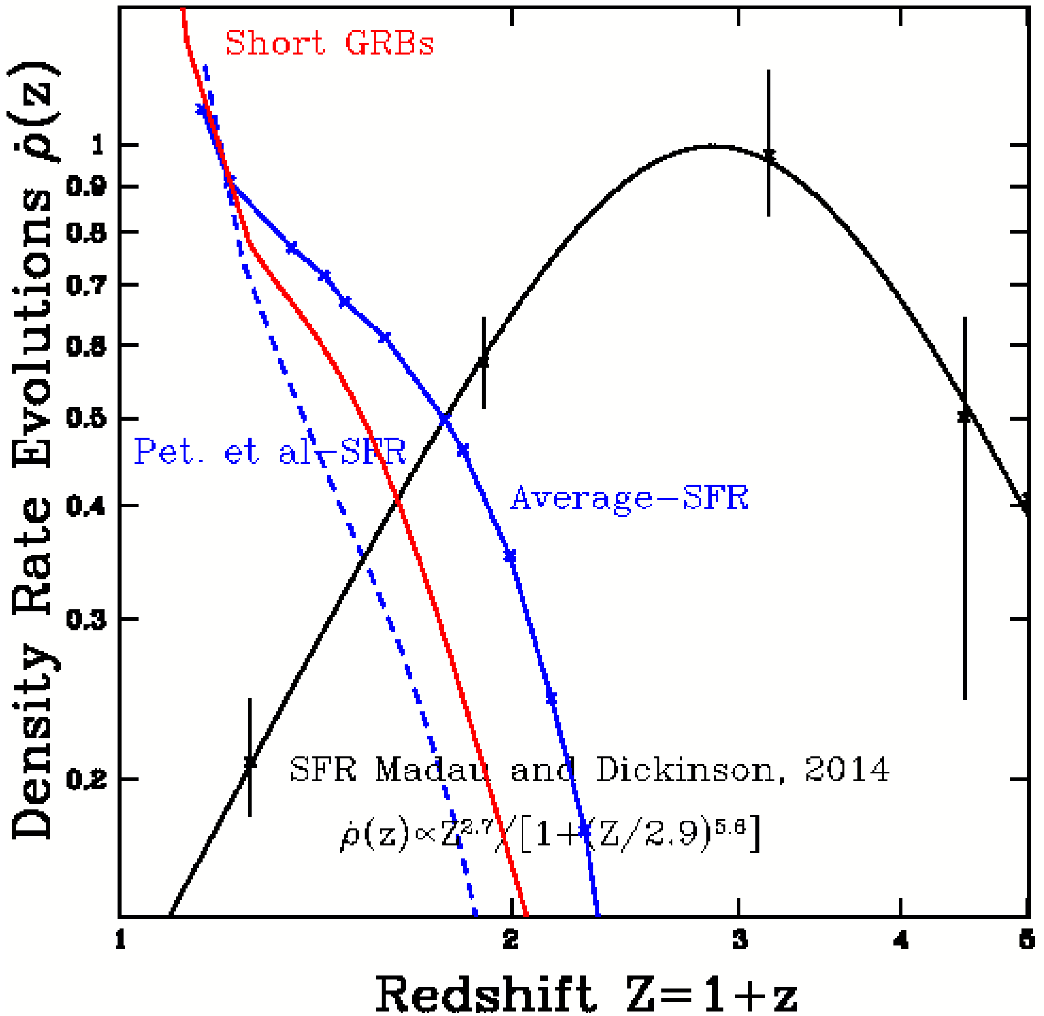
Dainotti, VP APJL 2023)







Formation Rates Short and Long GRBs



SUMMARY: GRBs

1. Progenitor Duration Relation May be more complex:

Some of low redshift LGRBs may be NS-NS, or NS-BH mergers

following a Formation Rate similar to SGRBs and delayed SFR

Two recent observations found association of LGRBs with Kilonovae

2. The low redshift component of LGRBs will have important consequence for gravitational wave detection rate.

3. Recent Machine Learning increase the number of LGRBs and show similar excess at Low redshifts.

V. Application to CHIME FRBs

Discovered by Lorimer et al (2007)

Now more than a 1000 by CHIME

Few repeaters, some identified as Soft GRBs

Progenitors Magnetars

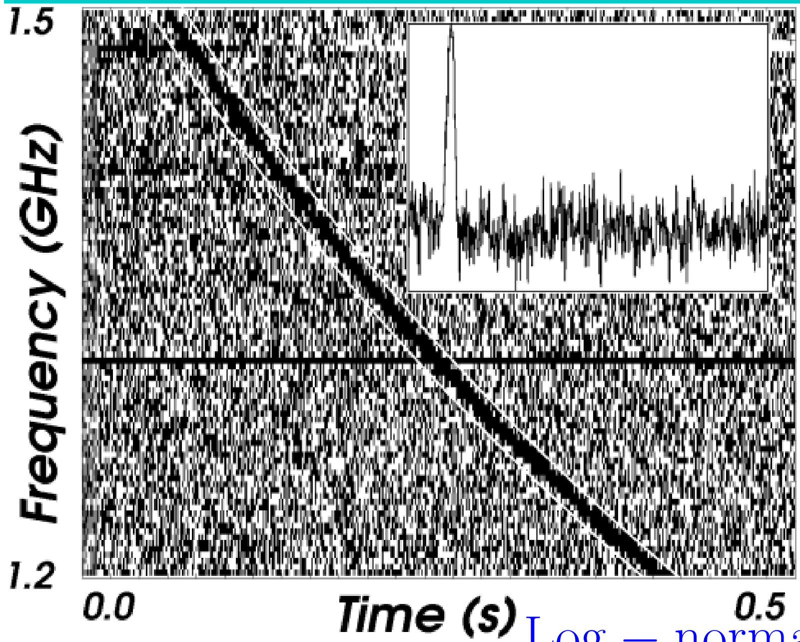
But mostly at cosmological distances up to *z~5*

Results on about 600 from

Chimpati, and VP 2025

General Features of FRBs

Distances (redshifts) obtained fro the Dispersion Measures



$$\Delta t_{\rm obs}(\nu) = Z\Delta t_Z \propto DM_{\rm obs}/\nu^2$$

$$DM_{\rm obs} = DM_{\rm Gal} + DM_{\rm IGM} + DM_{\rm Host}/Z$$

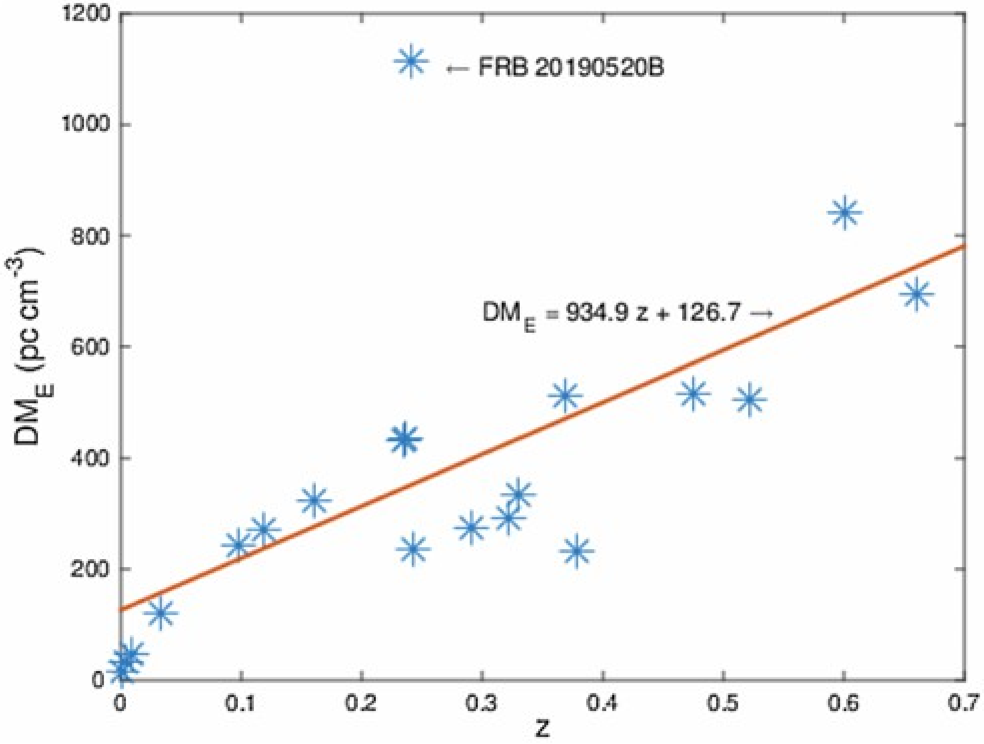
$$DM_{\rm Gal} = DM_{\rm MW} + DM_{\rm Halo}$$

$$\rm Log - normal\ dist.\ host;\ \ < DM_{host} >= 127; \sigma = 0.88$$

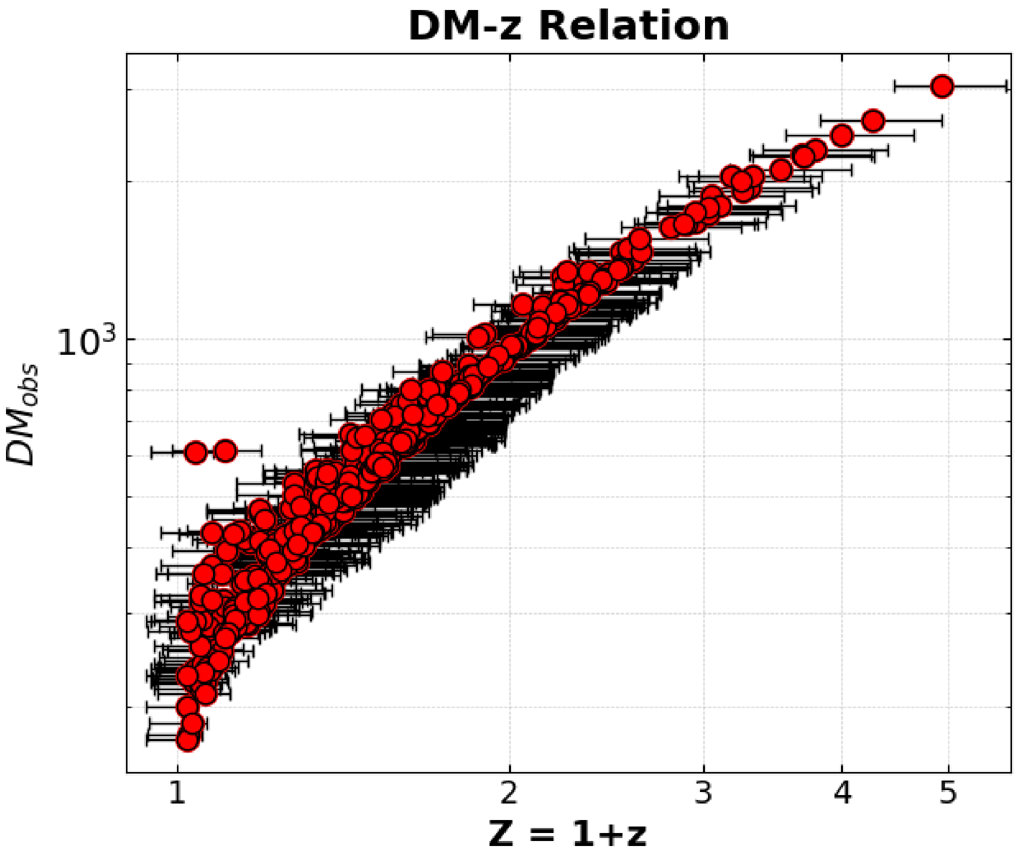
$$DM_{\rm IGM}(Z) = c\int_1^Z Zn_e(Z)dZ/[H_0\sqrt{\Omega_m Z^3 + 1 - \Omega_m}] \quad n_e = f_{\rm IGM}(\rho_b/m_p)(1-Y/2)$$

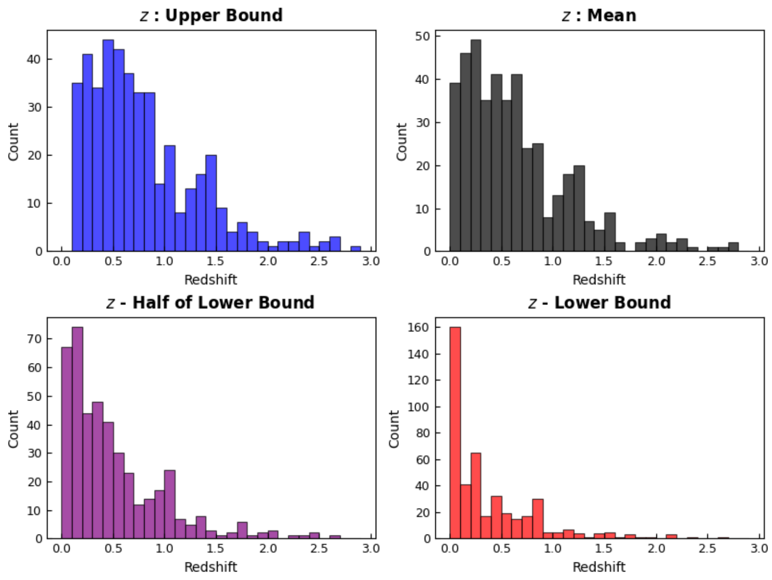
$$p_{\rm IGM}(\Delta) = A\Delta^{-\beta}\exp(-\frac{(\Delta^{-\alpha} - C_0)^2}{2\alpha^2\sigma^2_{\rm IGM}}),\ \Delta = DM_{\rm IGM}$$

Sample of Observed DM-Redshift



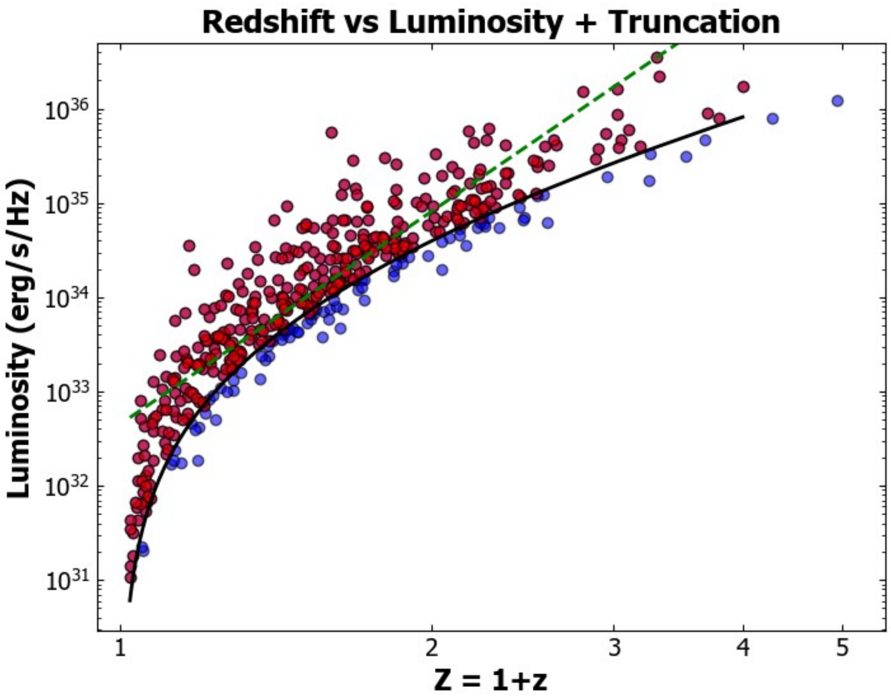
Luminosity Redshift From CHIME

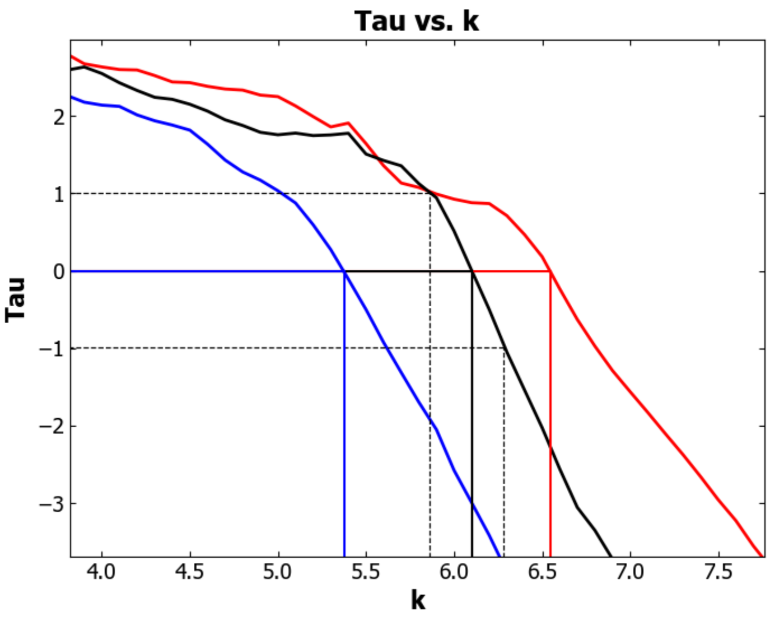




Luminosity-Redshift Scatter

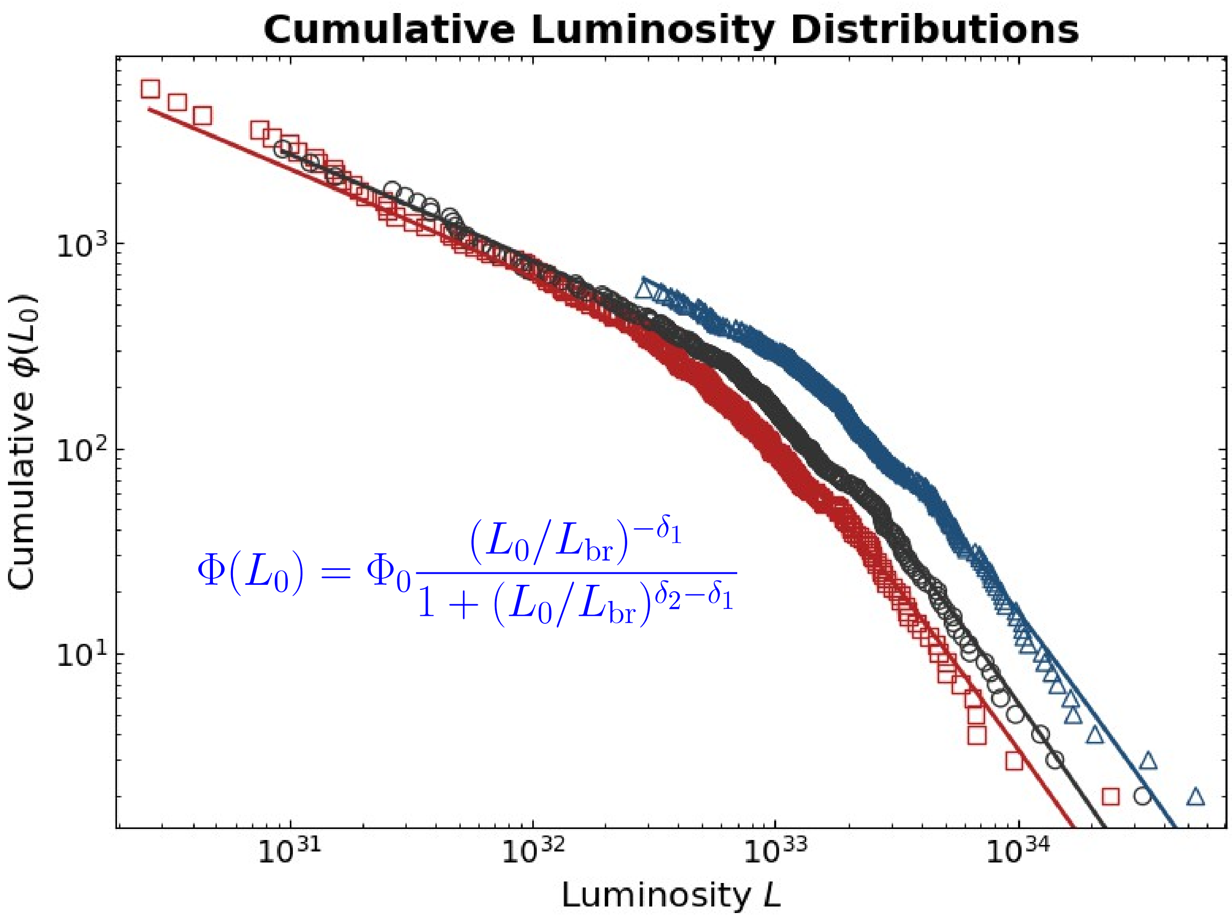
Luminosity Evolution



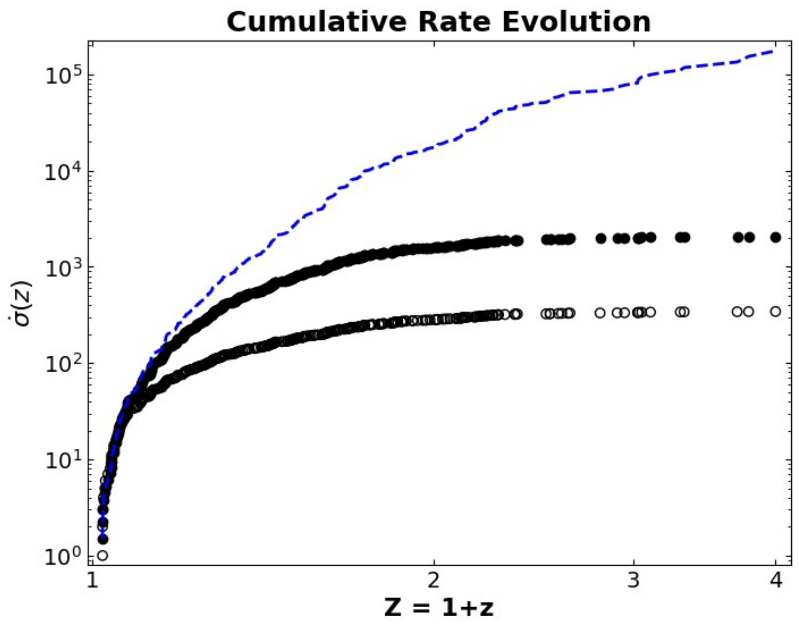


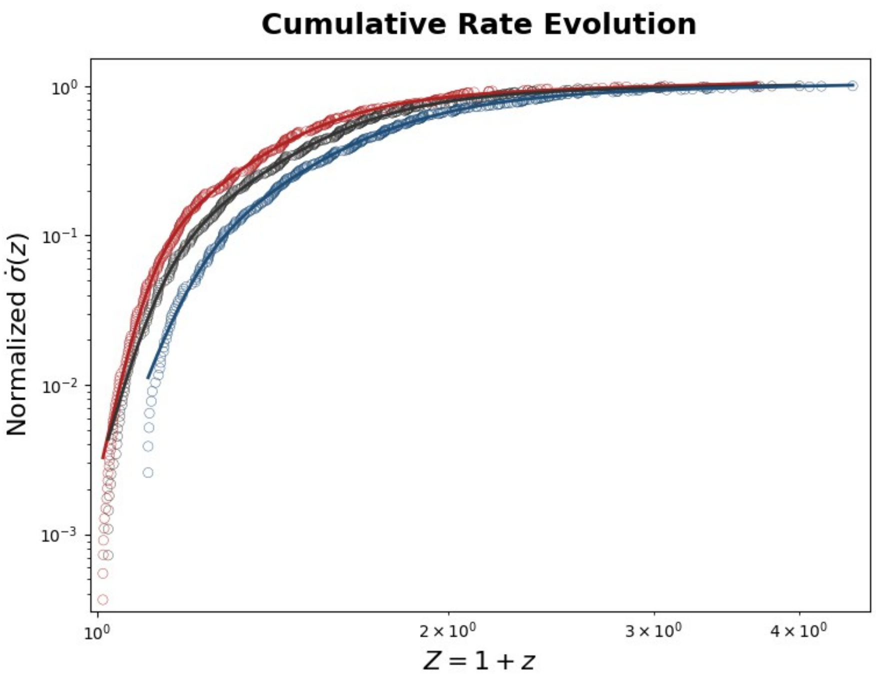
$$G(Z) = Z^k/(1+Z^k/Z_{cr}^k);\ Z = 1+z$$

Cumulative Local Luminosity Function



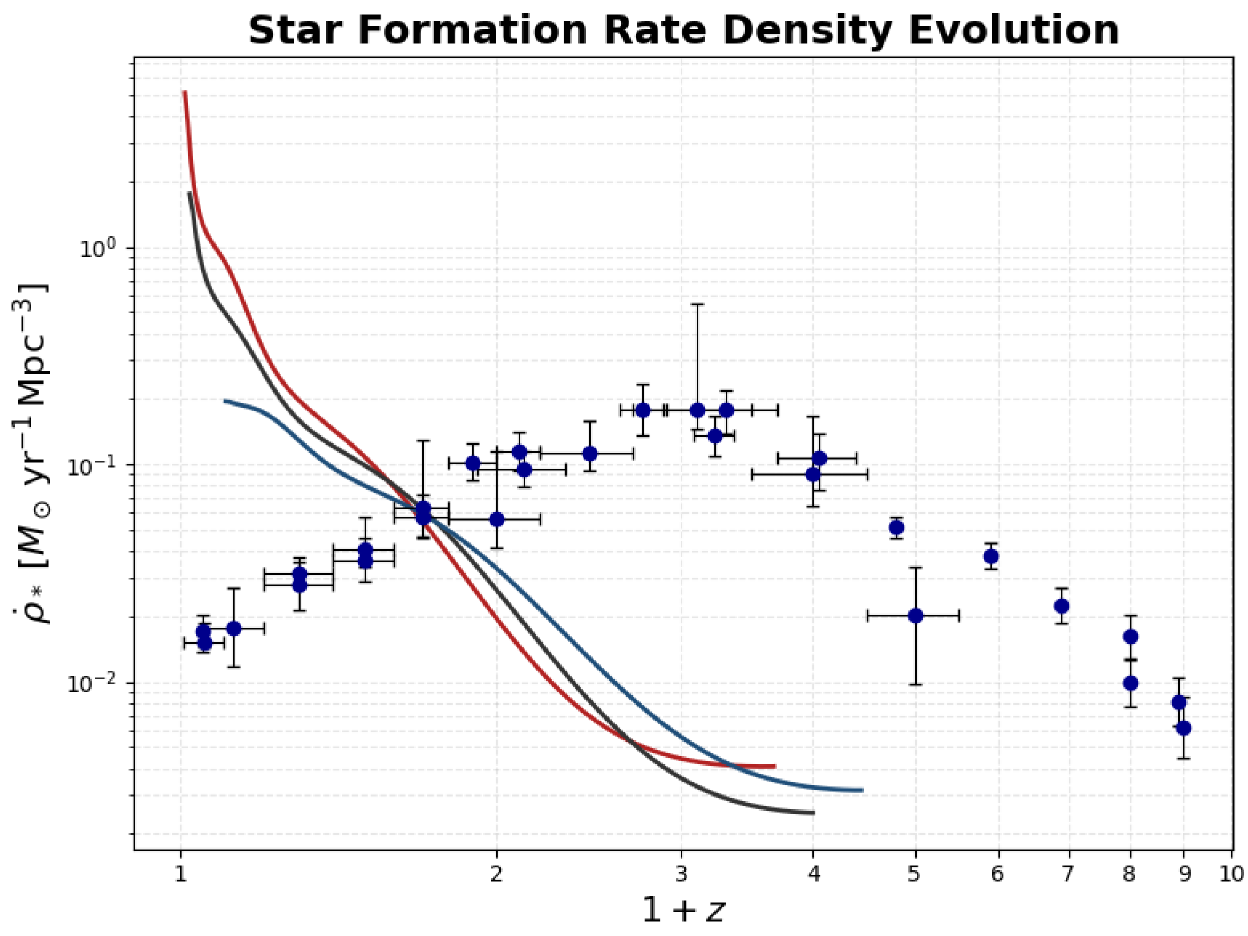
Cumulative Number Rate Evolution





$$\dot{\sigma}(Z) = \sigma_0 Z^{\alpha} \times [1 + (Z/Z_1)^{\alpha-\beta}]^{-1} \times [1 + (Z/Z_2)^{\beta-\epsilon}]^{-1}$$

Density Rate Evolution and SFR



SUMMARY: FRBs

1. More than 1000 FRBs with measured Dispersion measure

Can estimate redshifts correcting for Our and Host galaxy contribution.

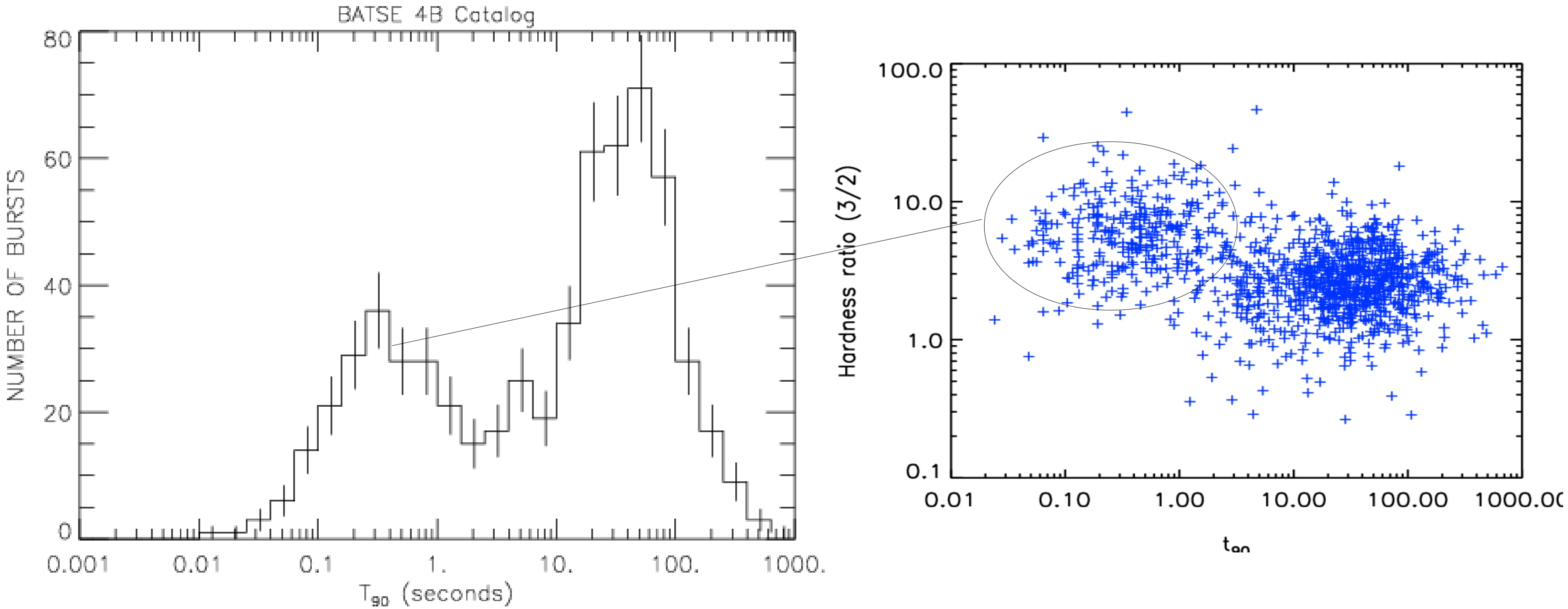
2. After accounting for the redshift uncertainty we find a Formation Rate similar to SGRBs and delayed SFR *expected for magnetars*

Back up Slides

GRBs as Standard Candles

GRB Classification

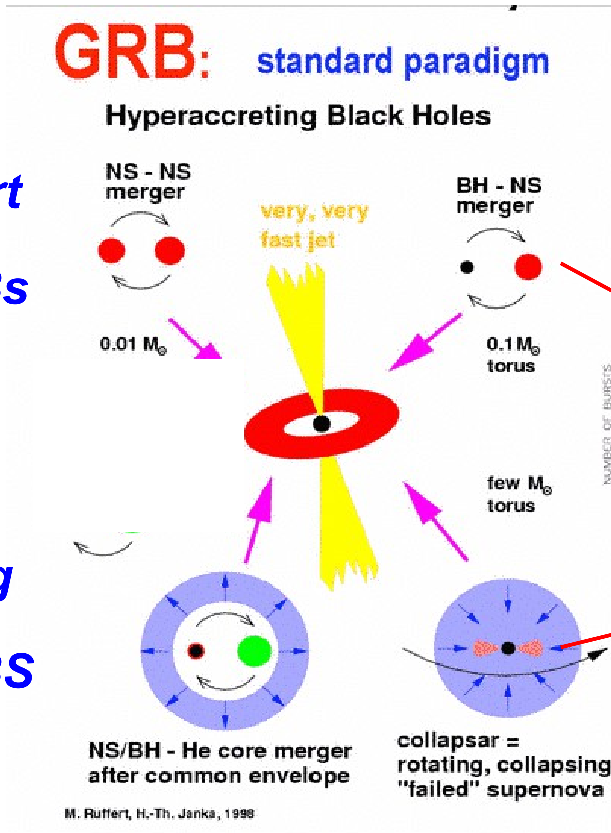
Short and Long

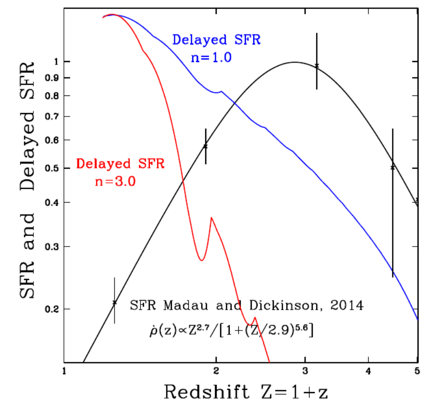


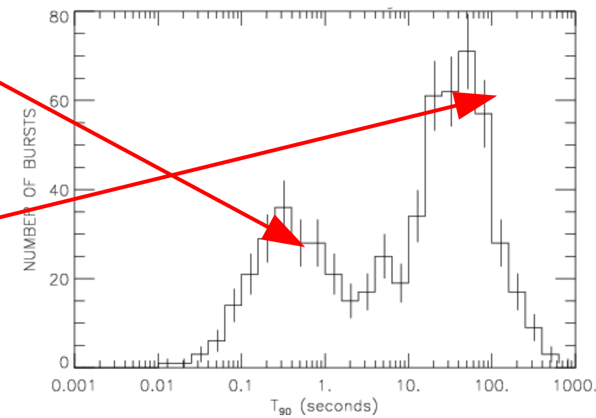
GRB Progenitors and Models

Short GRBs

Long GRBS



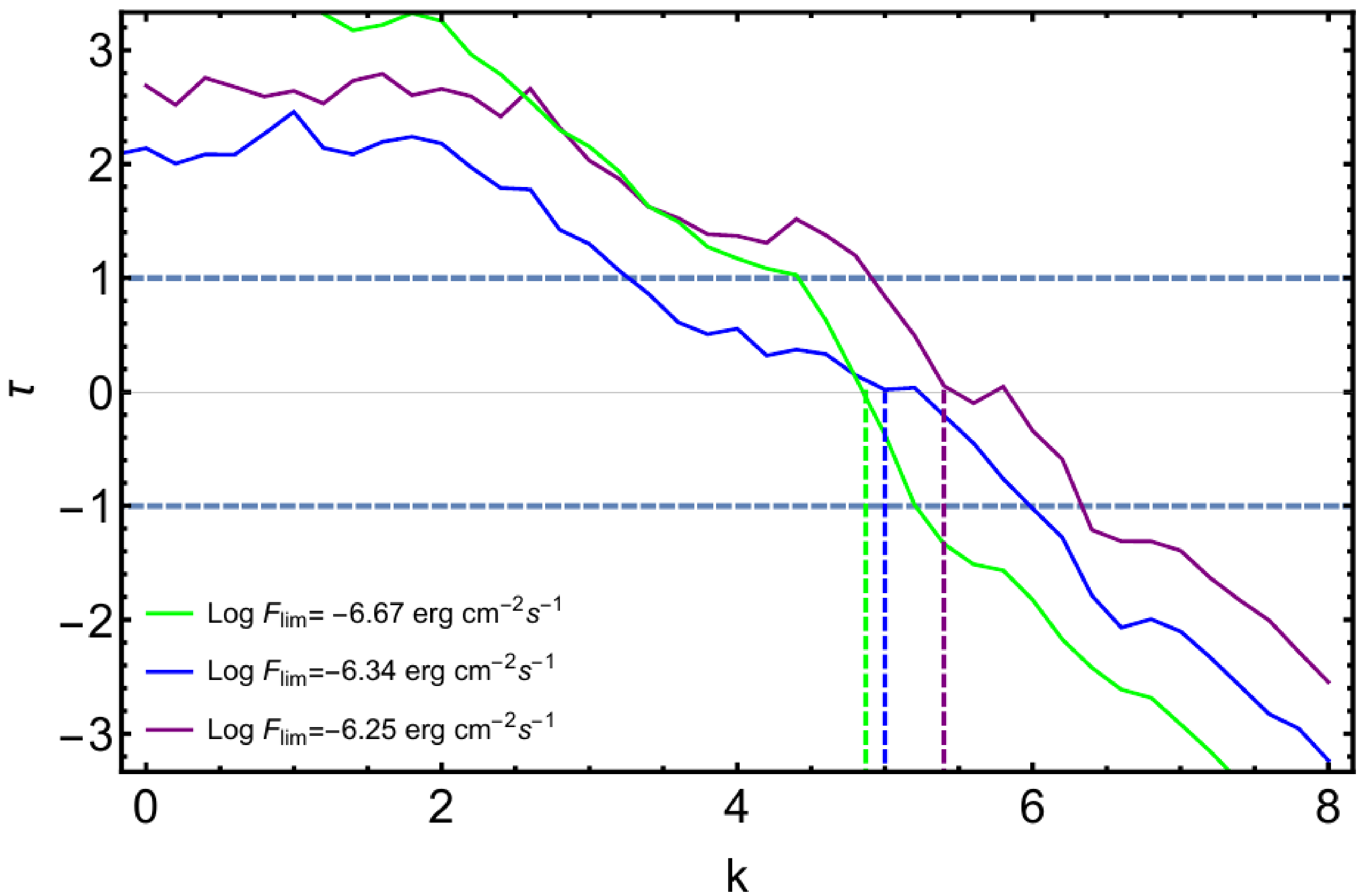




Luminosity Evolution of SGRB

Dainotti, VP, Bowden, 2021

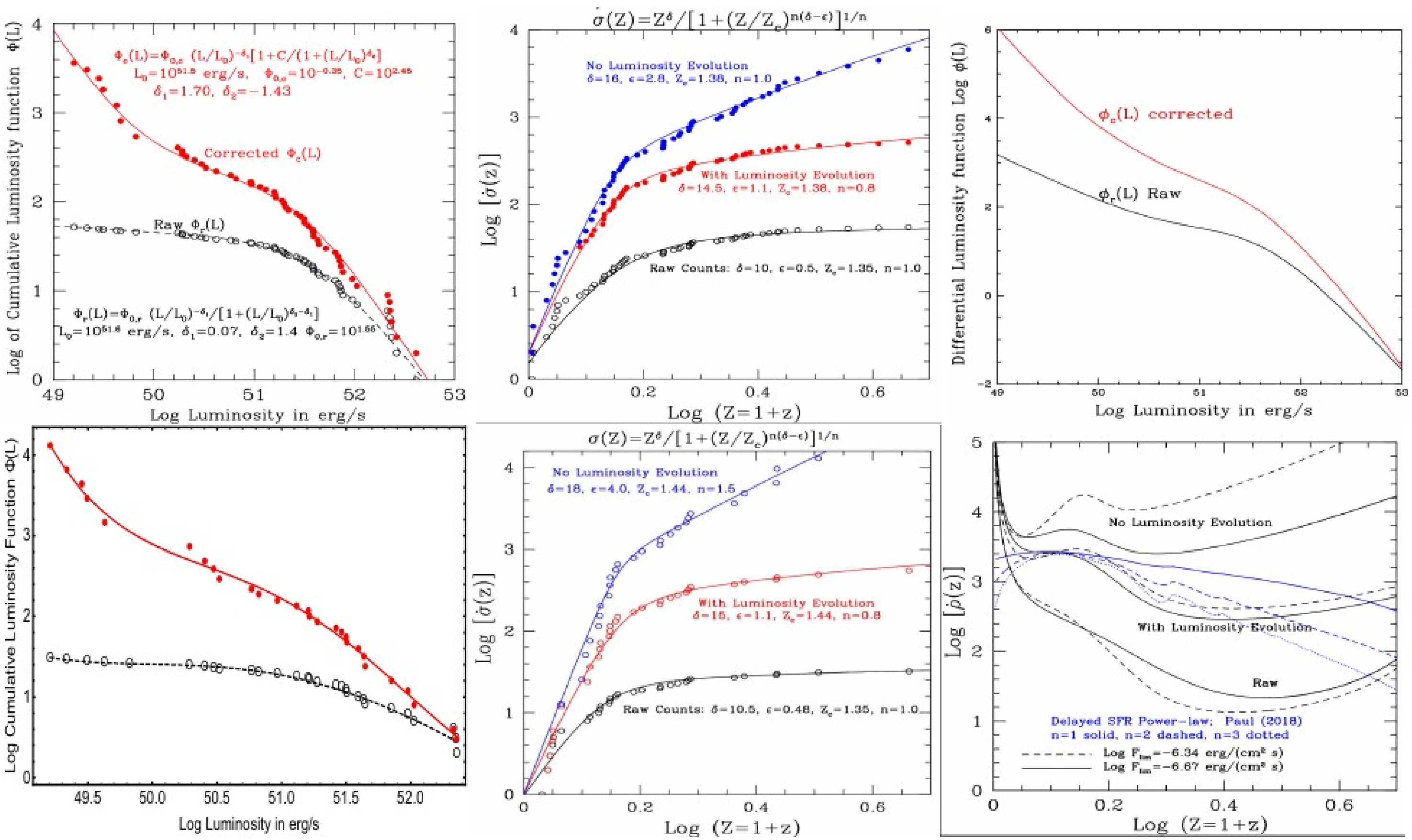
Luminosity Evolution $L(z) \propto Z /[1(Z/Z_c)], \quad k = 5.0\pm \sim 1 \quad Z = 1 + z,\ Z_c = 3.5$



Cumulative functions of SGRB

Dainotti, VP, Bowden, 2021

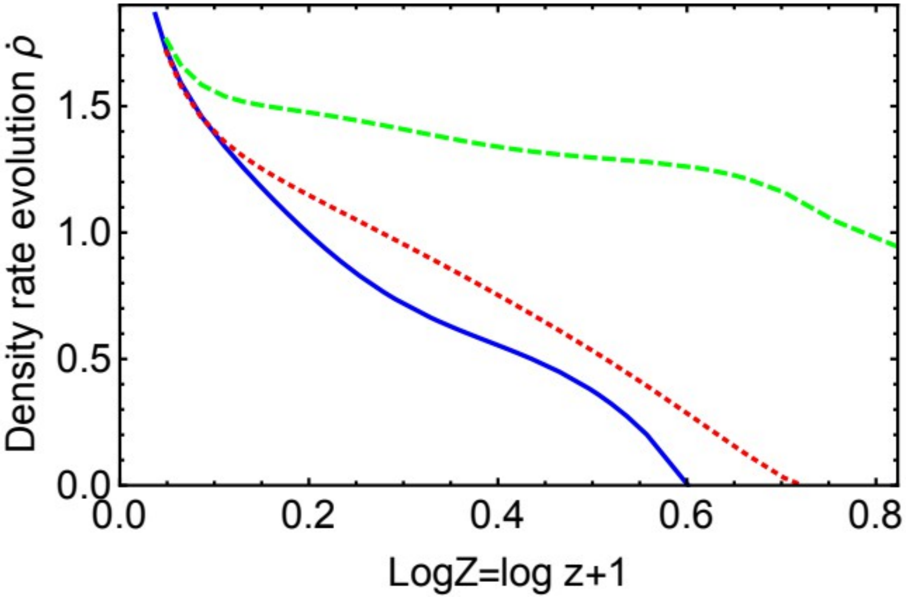
Cumulative Luminosity Function $\Phi(L)$ Density Rate Evolution $\dot{\rho}(z)$



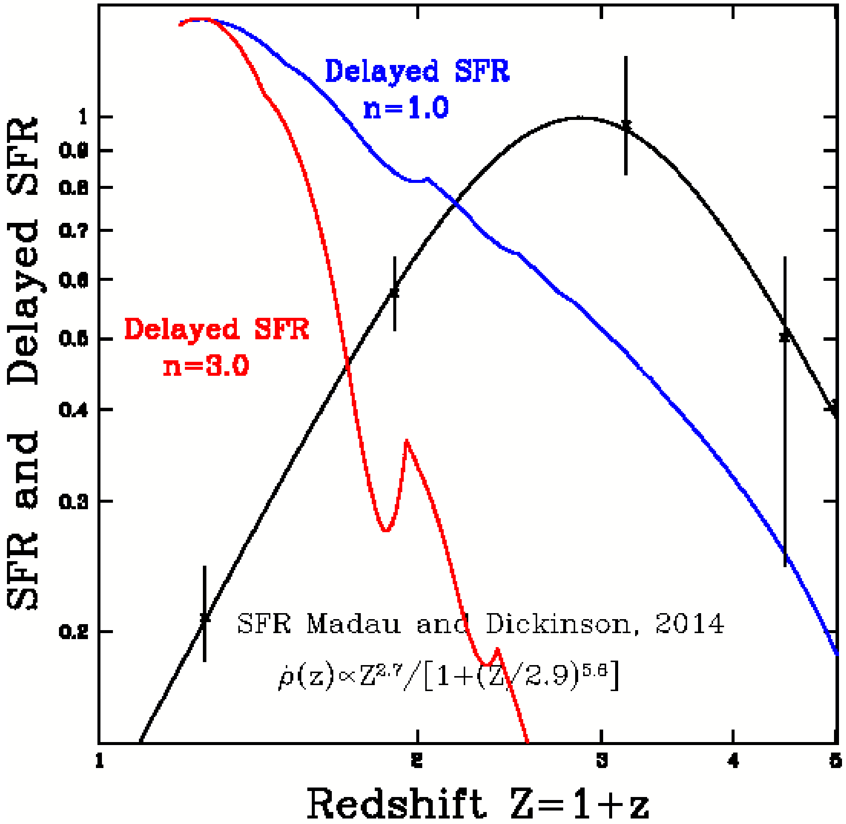
Yerevan, HEAstro 2026

SGRB and Delayed-Star Formation Rates

Dainotti, VP, Bowden, 2021



Pdainotti, VP and Bowden, 2021



Paul atXiv:1710.05620

Cosmology with Discrete Sources

Determination of Global Cosmological Parameters

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

   BUT Low z

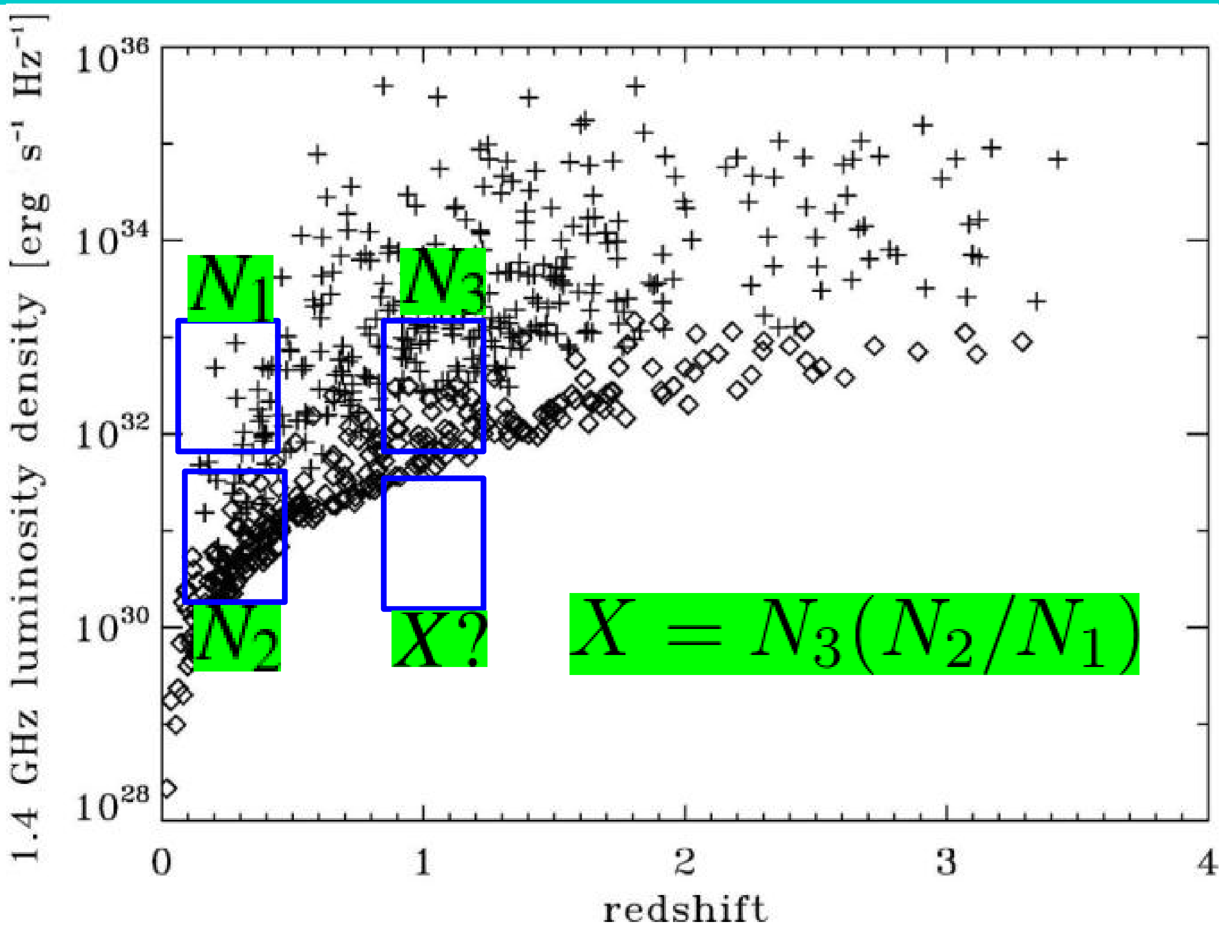
2. Galaxies and Quasars (AGNs): *High z but broad distributions*

   Galaxies least understood astrophysical sources

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

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

Given uncorrelated or independent variables Can account for truncation



Petrosian, 1993

2. Bias Due to X-ray Observations

Strong *Correlation* between

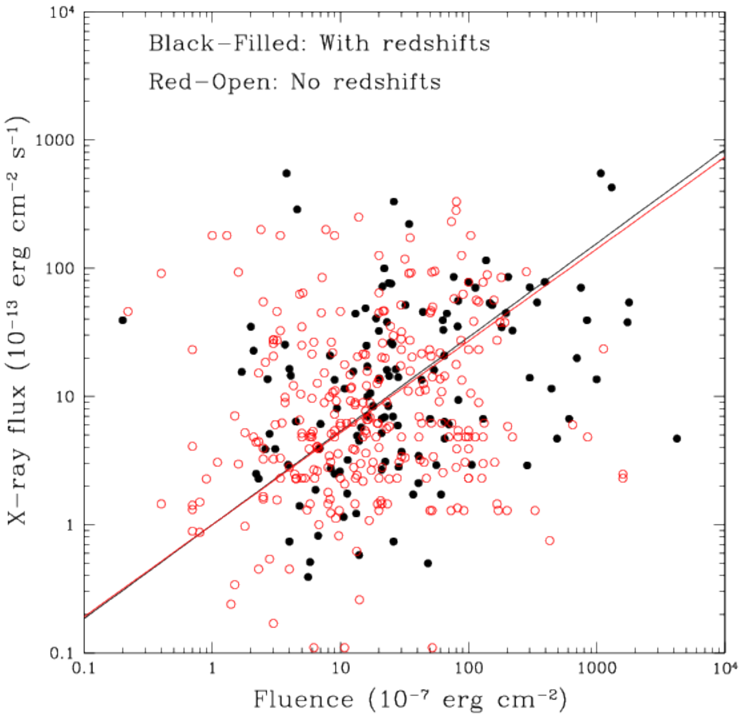
Gamma and X-rays

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.

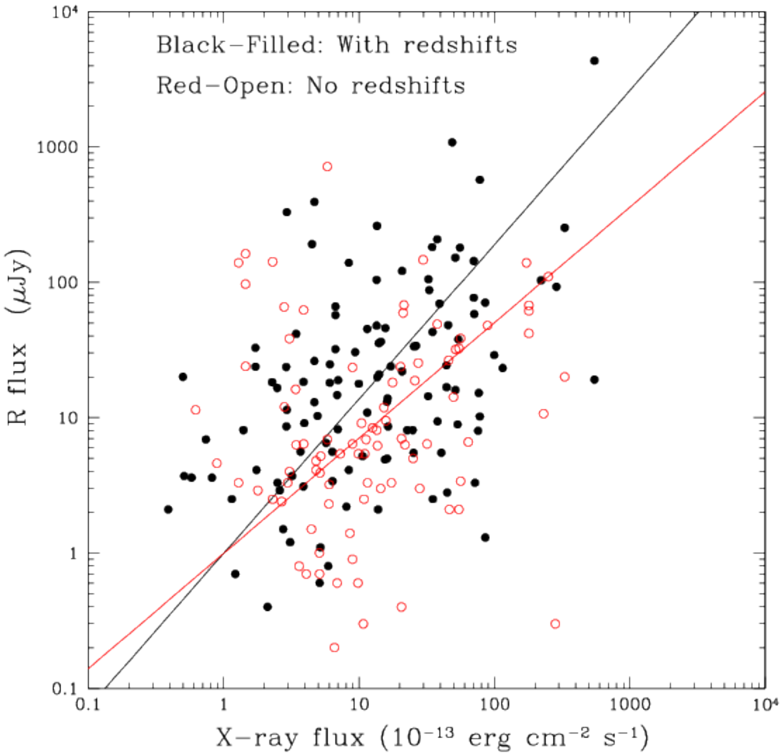
The *optical flux* can be used as indicator but there is no well defined limit.

Opt.-X-ray fluxes *correlated*

So *use X-ray threshold*

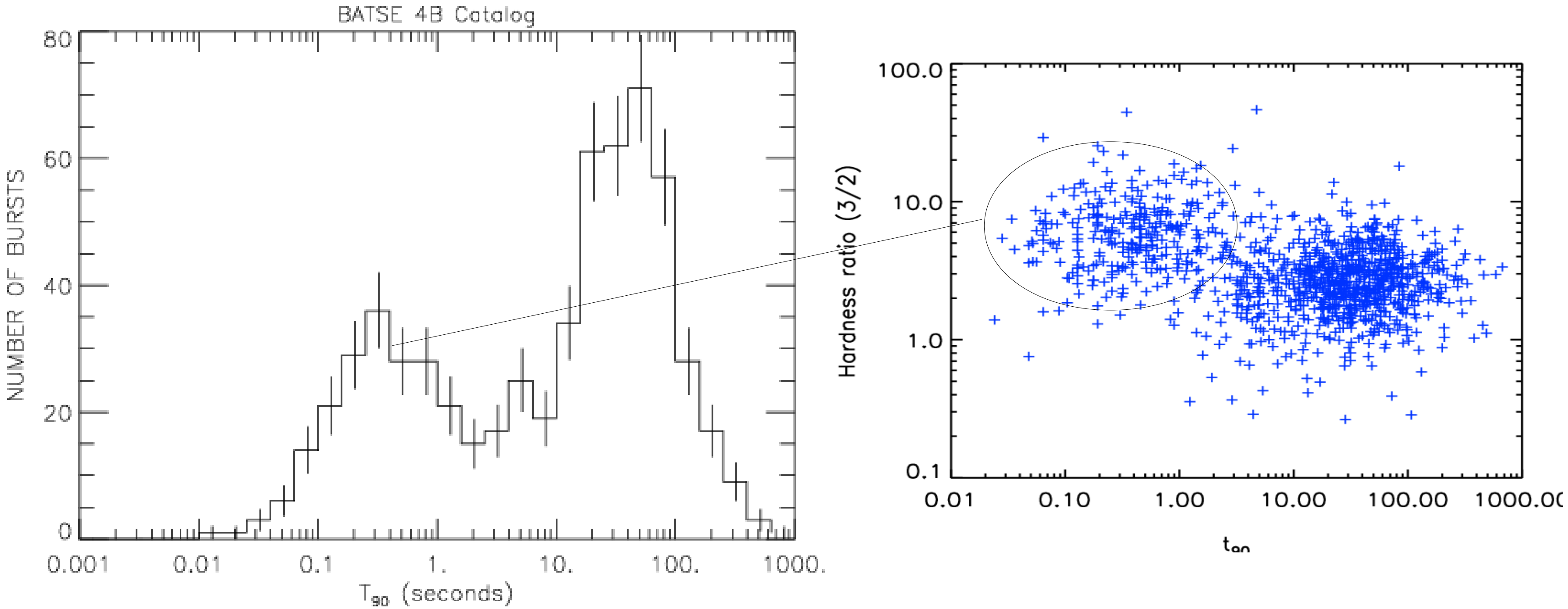
to correct for this bias

(data from Nysewander et al. 2009)



GRB Classification

Short and Long



Cosmology with Standard Candles?”

Method For Measuring Cosmological Distance

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

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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*

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

GRB Correlations

Examples of Correlations

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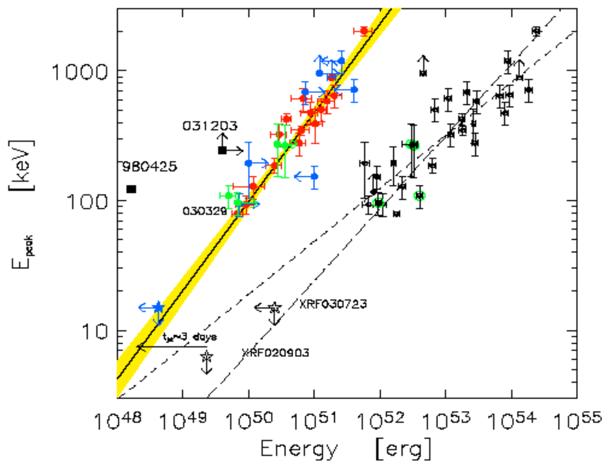
2. Lag-Luminosity *(Norris, Maeani & Bonnell 2000)*
3. $E_{\rm peak} - \varepsilon_{\rm iso}$ or $E_{\rm peak} - \varepsilon_{\gamma}$ *(Amati; Ghirlanda et al.)*



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**

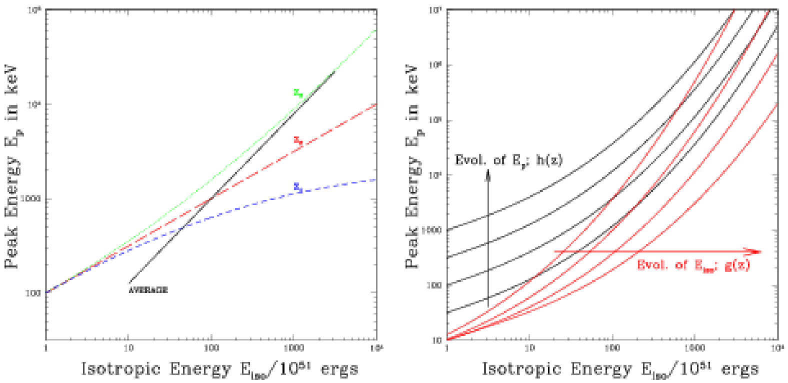
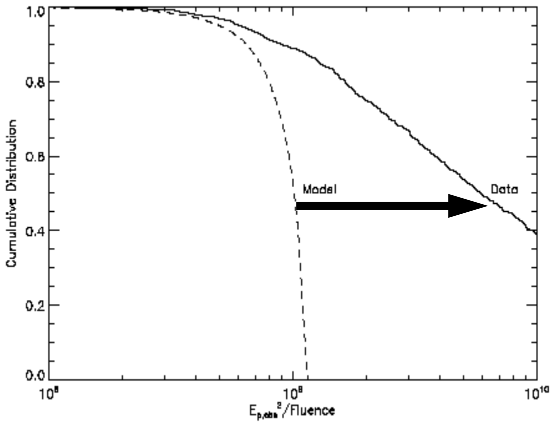


Figure 1: Scheamatic shape (left), spectral (right, red) and energy (right, black) Evolutions.

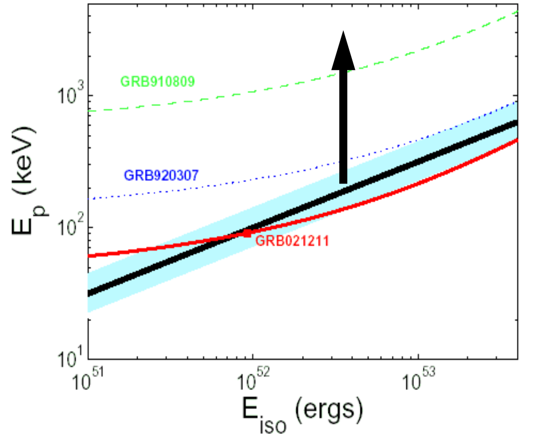
$$\left(\int_0^z \frac{dz'}{\sqrt{\Omega(z')}} \right)^2 = f\left(\frac{E_p^{obs}(1+z)}{E_0 h(z)} \right) \frac{F_0 g(z)}{(1+z)F_{tot}}$$

Problems With These Correlations

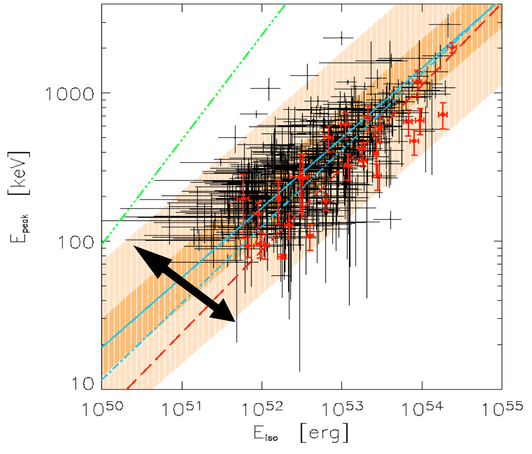
in particular with $E_{\mathrm{peak}} - \varepsilon_{\mathrm{iso}}$ or $E_{\mathrm{peak}} - \varepsilon_{\gamma}$



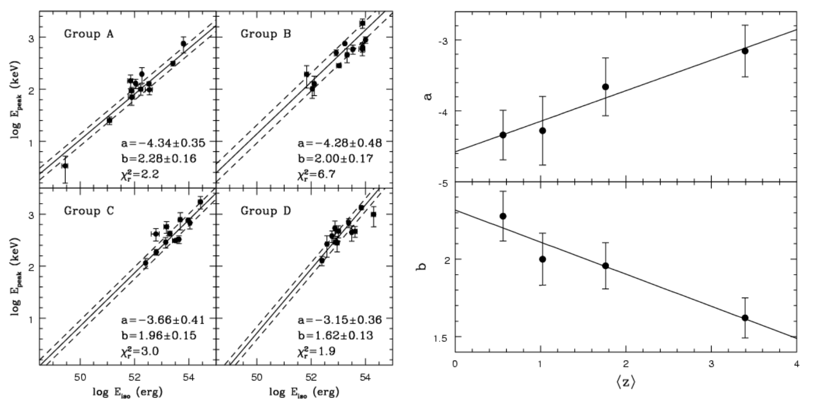
Band and Preece



Nakar and Piran



Pseudo-Redshifts (Ghirlanda et al)



Li et al.