COSMOLOGY WITH DISCRETE SOURCES

Evolution of general luminosity function

Vahe' Petrosian

Stanford University

With

Jack Singal, Brad Efron and Ellie Kitanidis

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. GRBs

B. 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. Try to 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*

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?*

II. The Luminosity Function and its Evolution

Cosmology with Discrete Sources

First Step

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

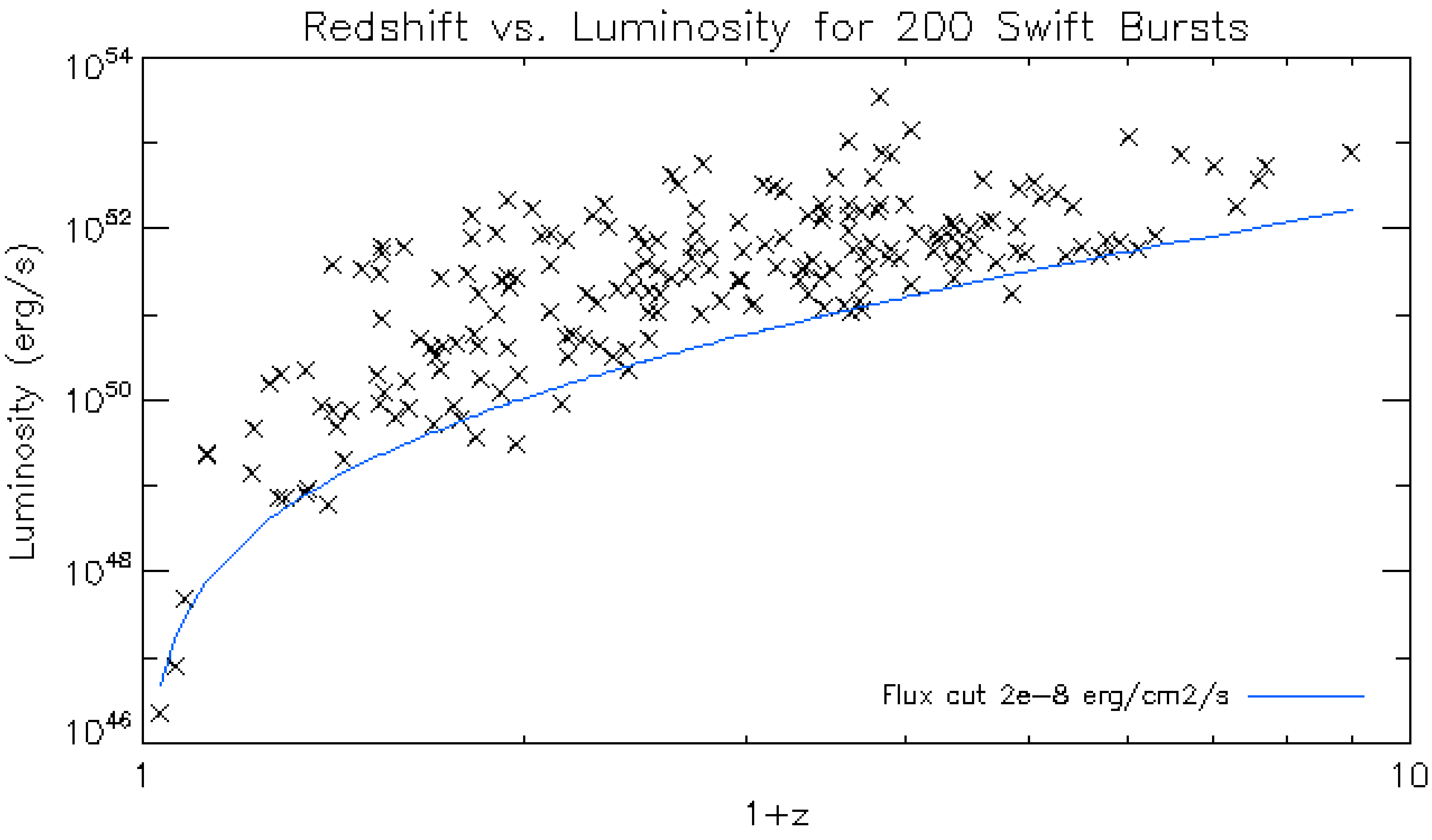
Without loss of generality we can write

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

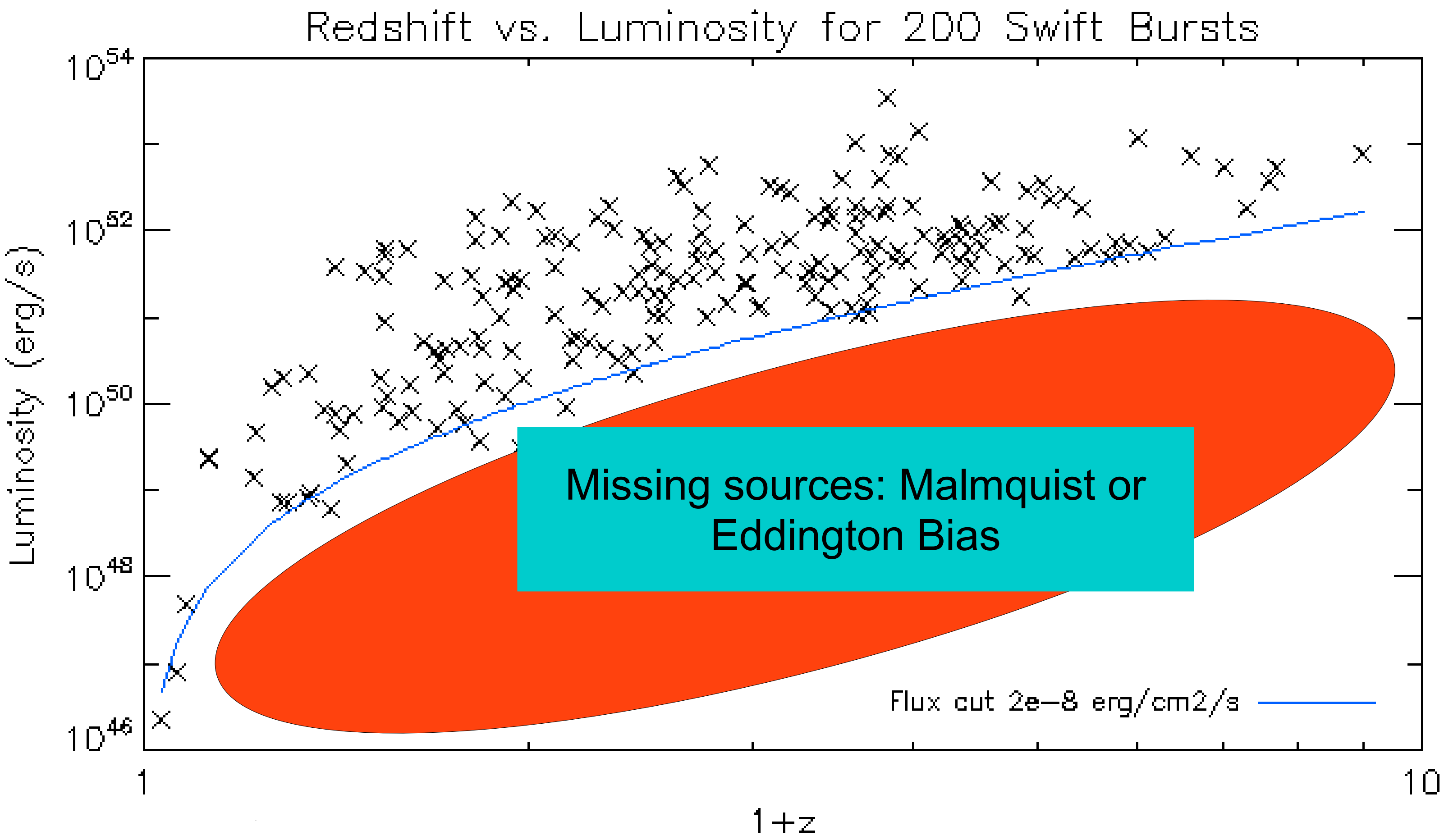
$\rho(z)$ Is the (co-moving) Density Evolution

$g(z)$ Is the Luminosity Evolution

The required data; Bivariate *L-z* distrbution



Bi-variate Luminosity-redshift Distribution



III. Procedures

Forward Fitting

vs

Non-parametric methods

Efron and Petrosian ApJ 1992

Procedures: 1. Forward Fitting

The common practice is to assume parametric forms for

"Luminosity" Function $\psi(L,z)$

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

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 "well-known" 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:

i.e. There is no luminosity evolution

g(z)=Constant

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

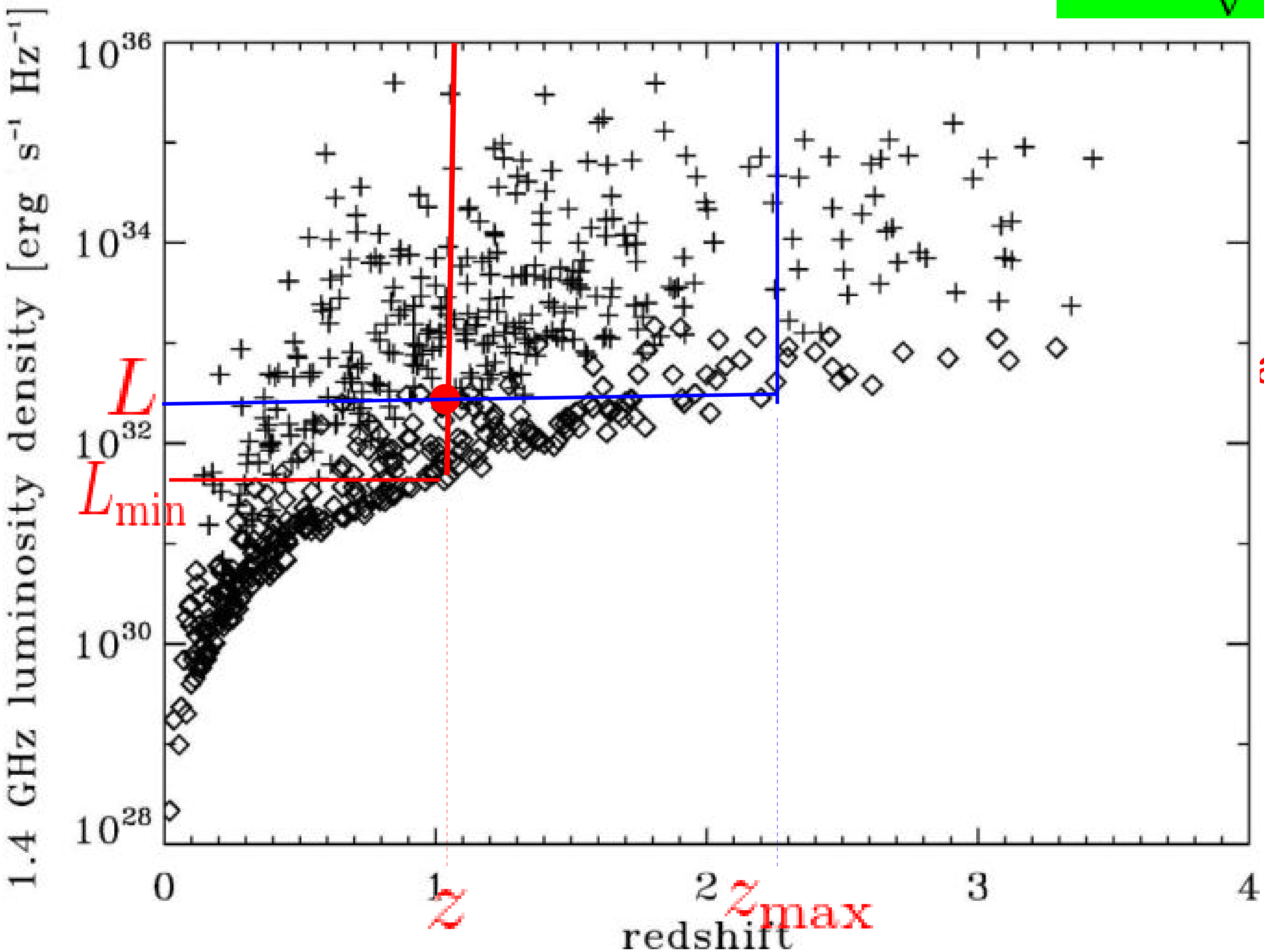
Determination the bi-varaiate distributions non-parametrically and directly from the data with very few assumptions or prescribed functional forms

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

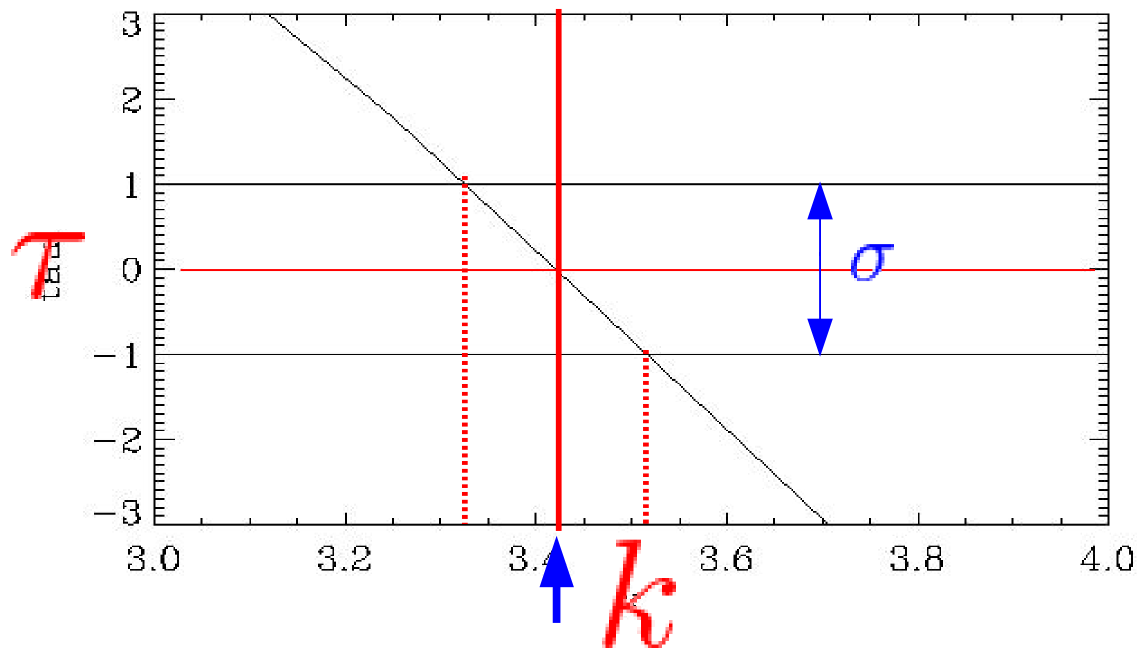
Sources in the sets

Test of Independence

Remove the correlation by a variable transformation e.g.

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

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

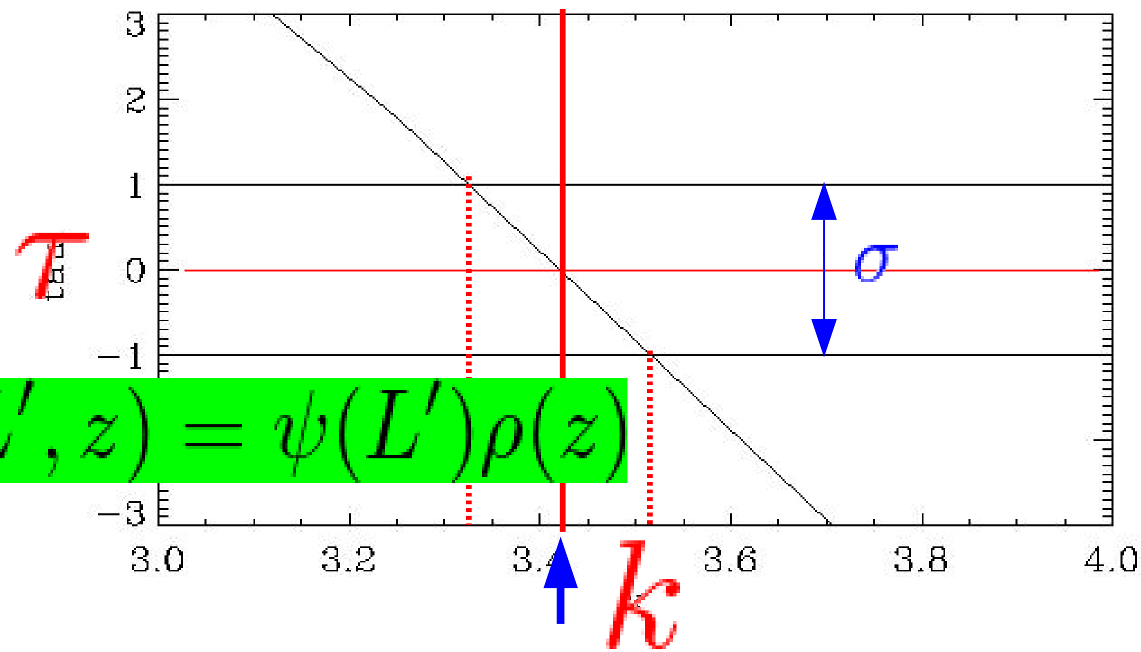


Test of Independence

Remove the correlation by a variable transformation e.g.

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

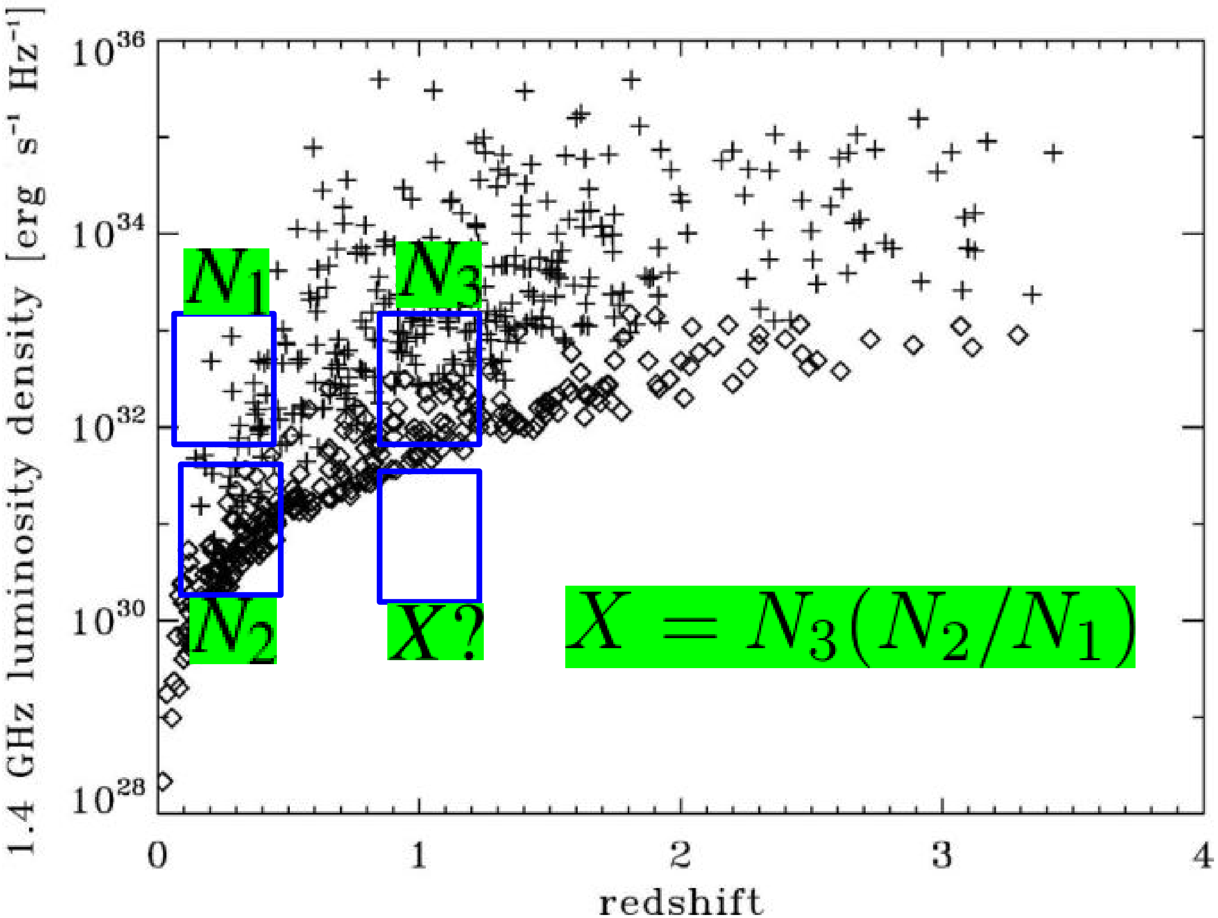
$$g(z) = (1+z)^k$$



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

Given uncorrelated or independent variables

Can account for truncation



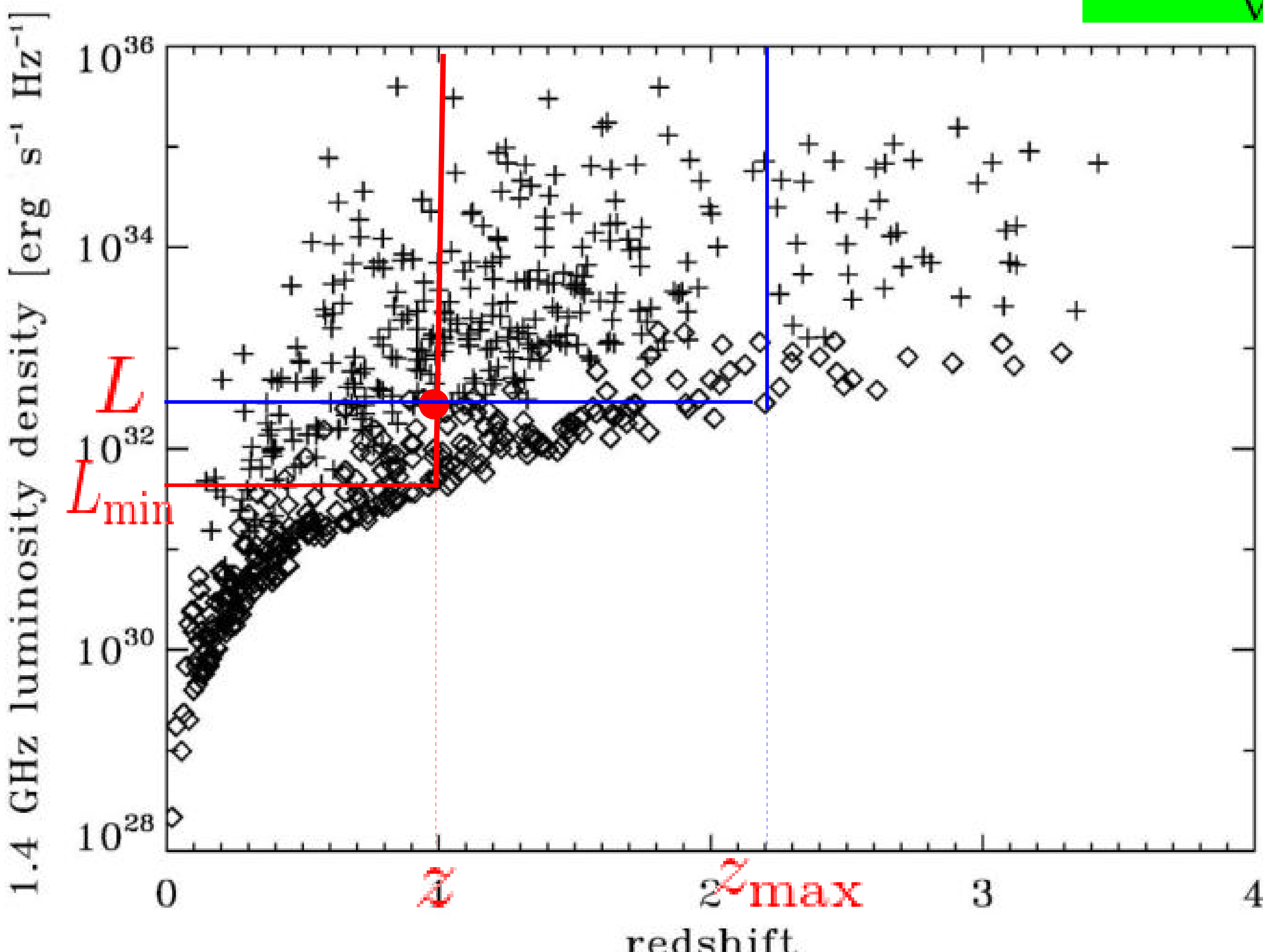
Petrosian, 1993

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

The single variable distributions

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

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

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

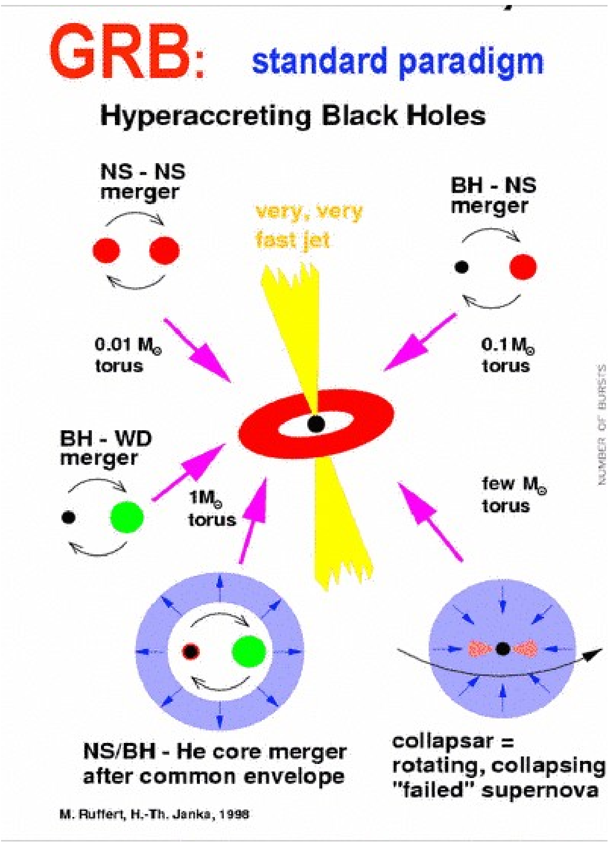
From these we get the sought differential distributions

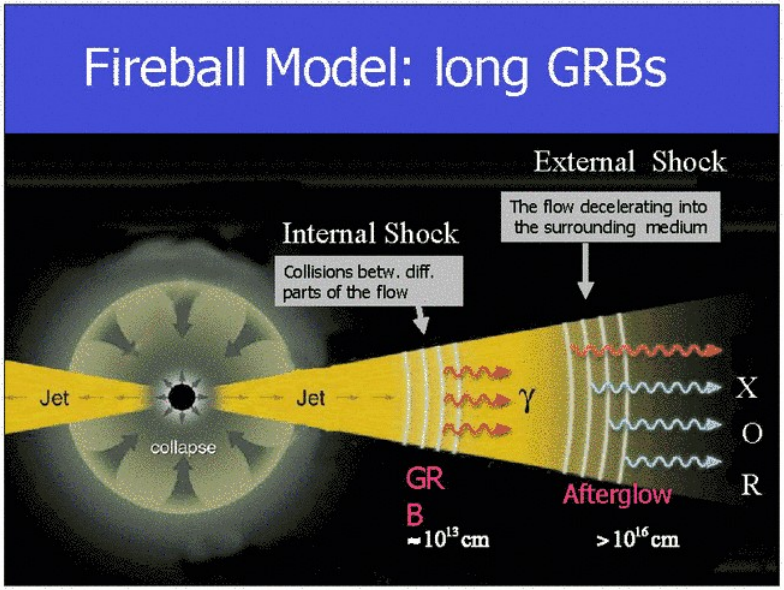
$$\Psi(L) \quad \text{and} \quad \rho(z)$$

IV-A. Application to Swift Gamma-ray Bursts

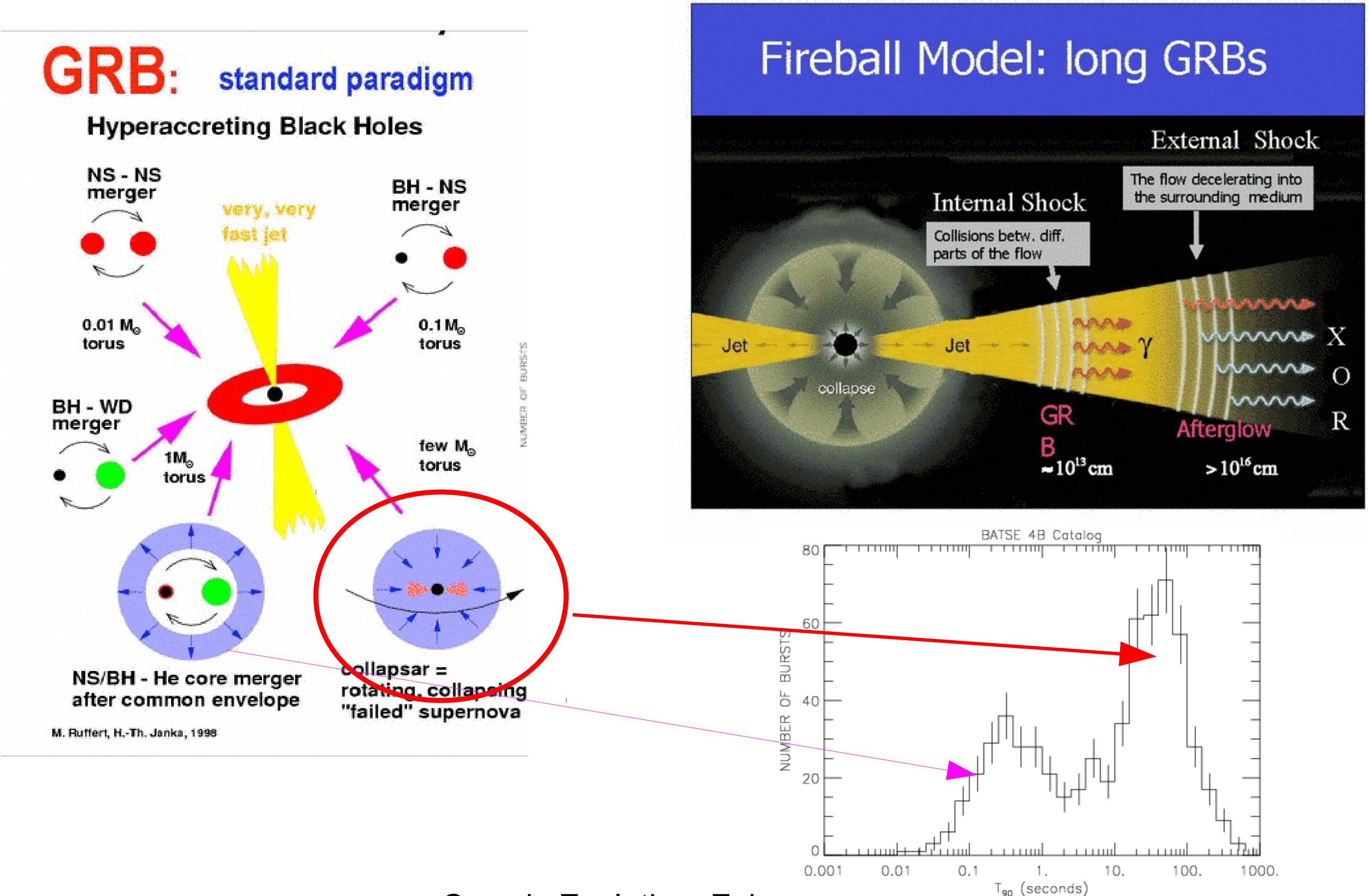
Density (rate) Evolution vs Star Formation Rate

II. GRBs as Standard Candles
Progenitors and Models



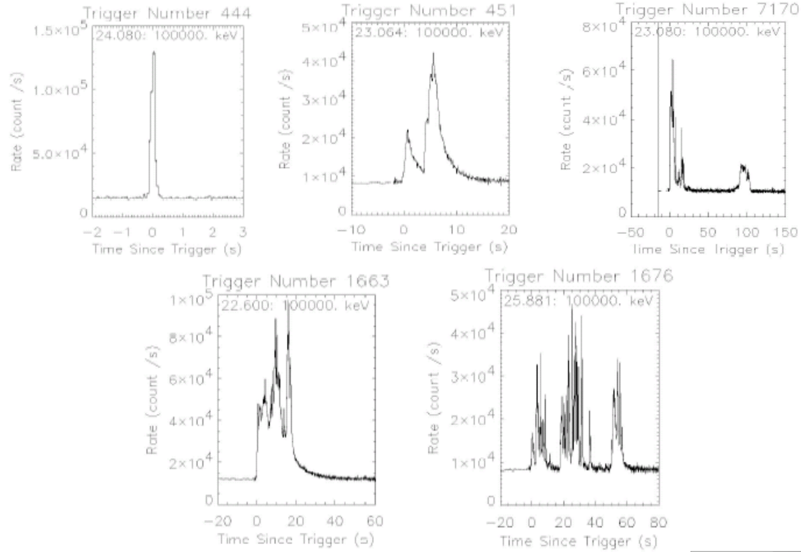


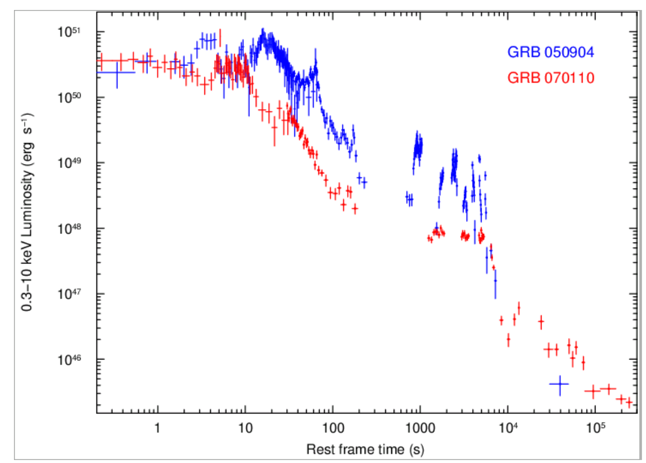
1. GRBs as Standard Candles
Progenitors and Models



GRB Light Curves: *Prompt and Afterglow*

Diversity of GRB Profiles



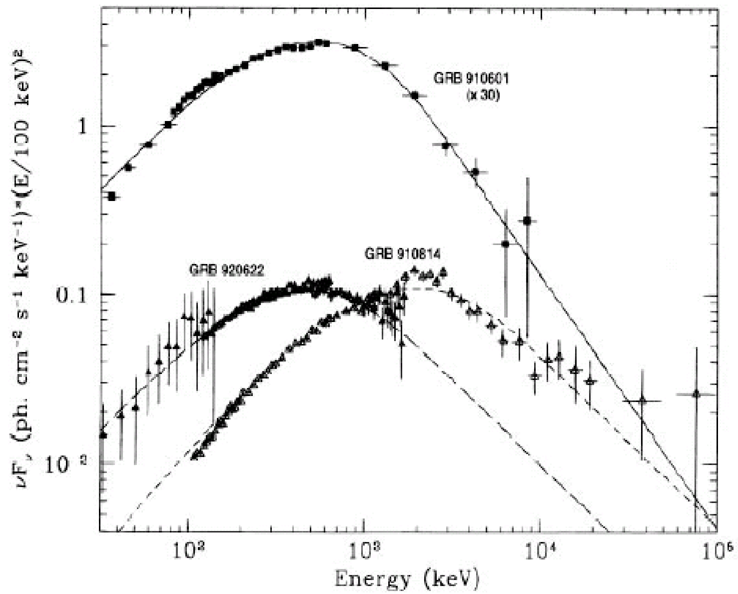


GRB Spectra: *Prompt*

Early Prompt Spectra

Broken Power Law

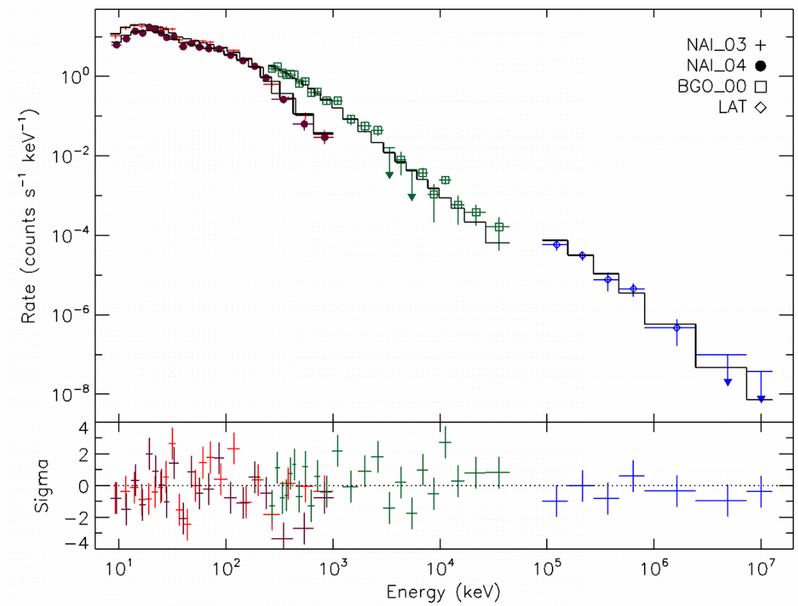
Band model



Fermi: GBM and LAT

GRB080916C

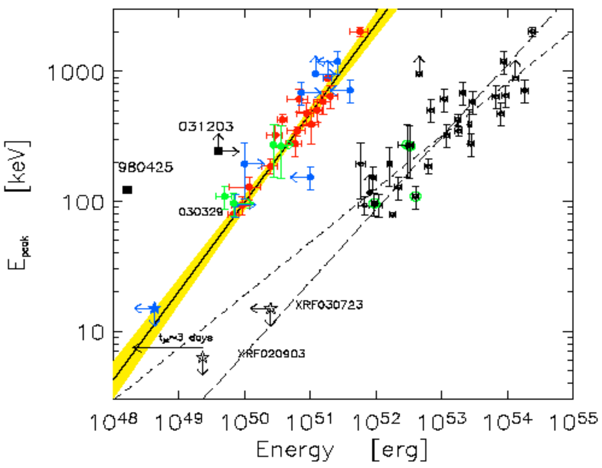
Band model



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.)*

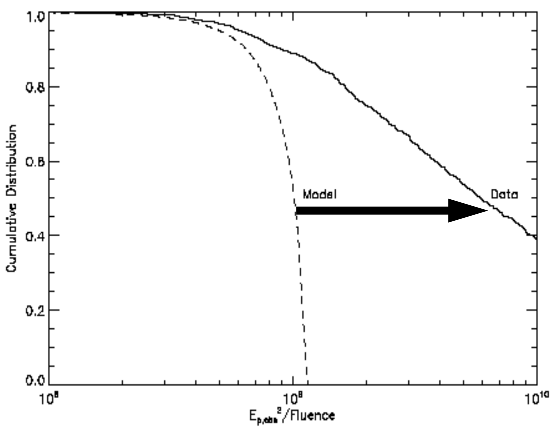


4. And Several Variations on These

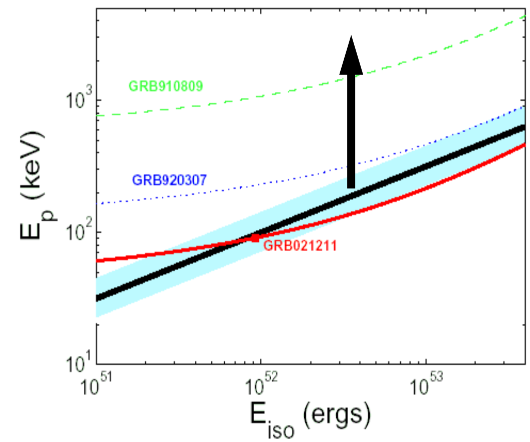
(see Schaeffer et al.)

Problems With These Correlations

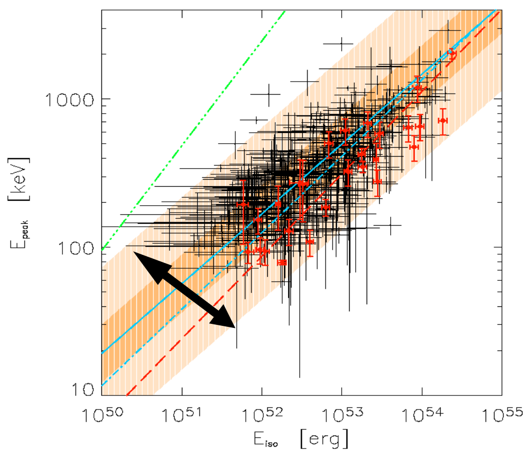
in particular with $E_{\mathrm{peak}} - \varepsilon_{\mathrm{iso}}$ or $E_{\mathrm{peak}} - \varepsilon_{\gamma}$



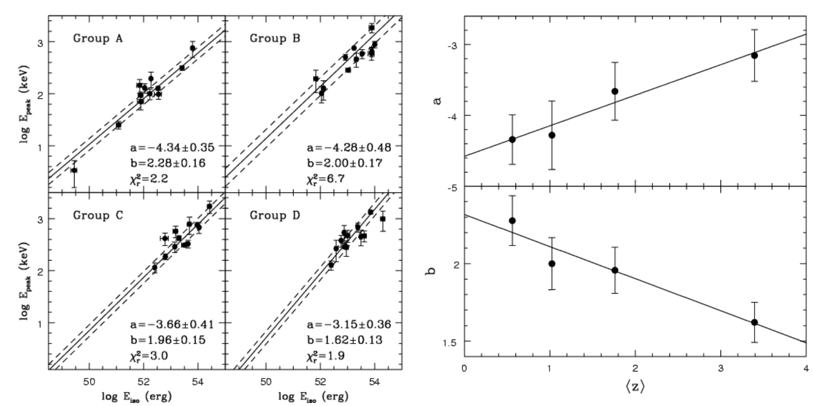
Band and Preece



Nakar and Piran



Pseudo-Redshifts (Ghirlanda et al)



Li et al.

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

Efron-Petrosian Method

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

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

Caveats: *Other Selection Effects and Truncation*

1. Gamma-ray trigger

   Peak count or flux threshold

2. Localization

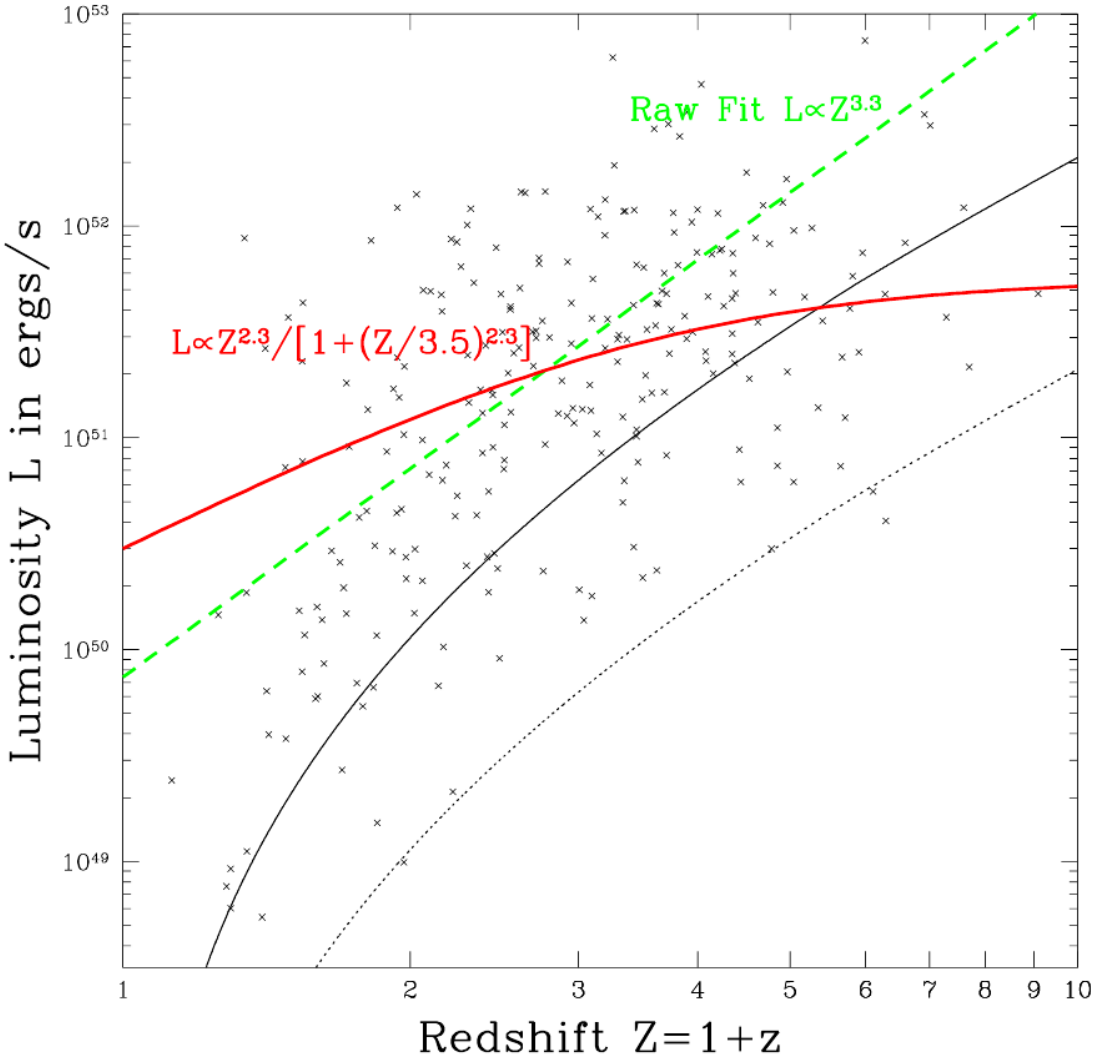
   X-ray flux threshold

3. Optical follow-up and *Redshift*

   Optical Magnitude etc

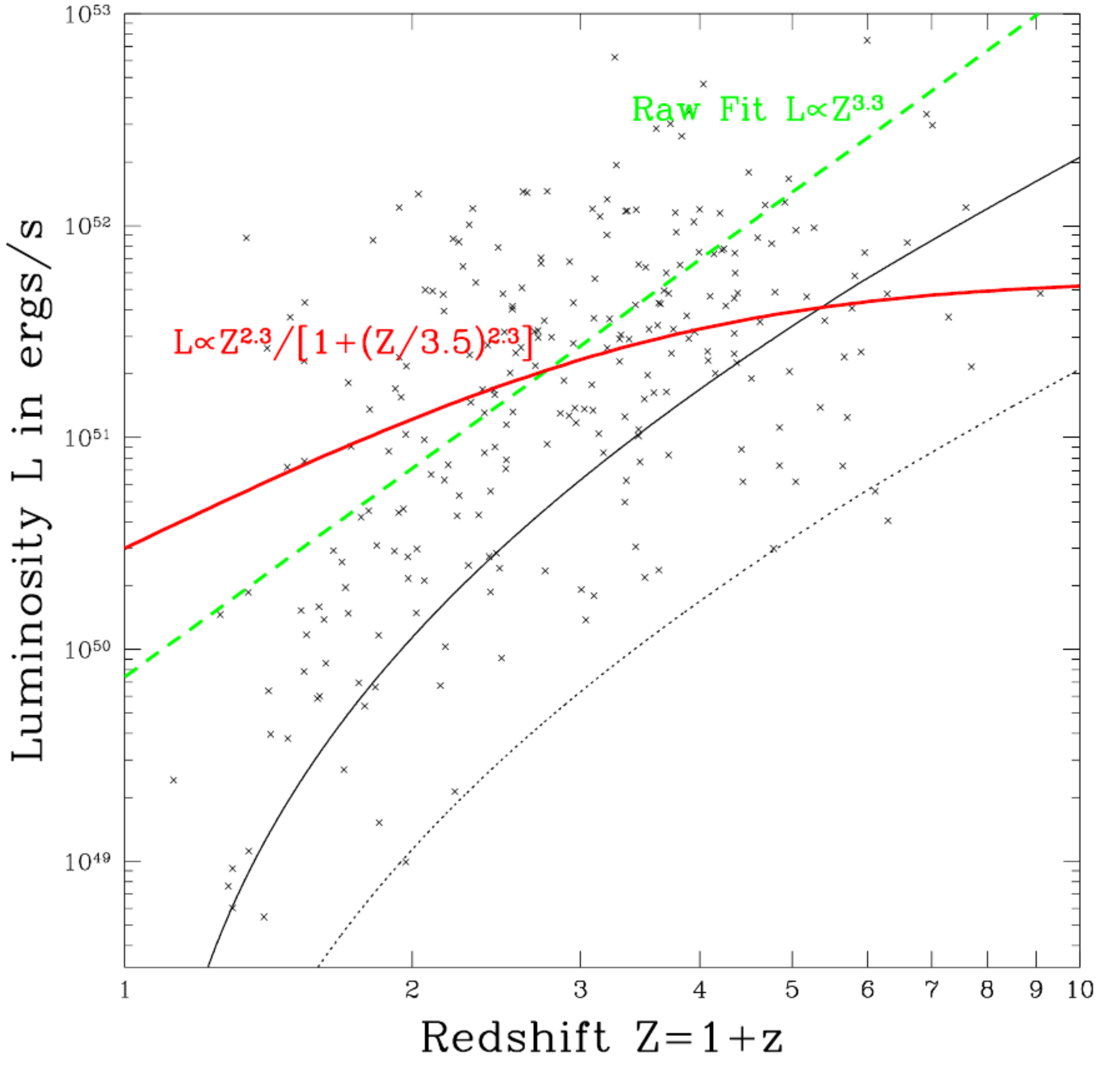
1. Test of independence

Luminosity evolution



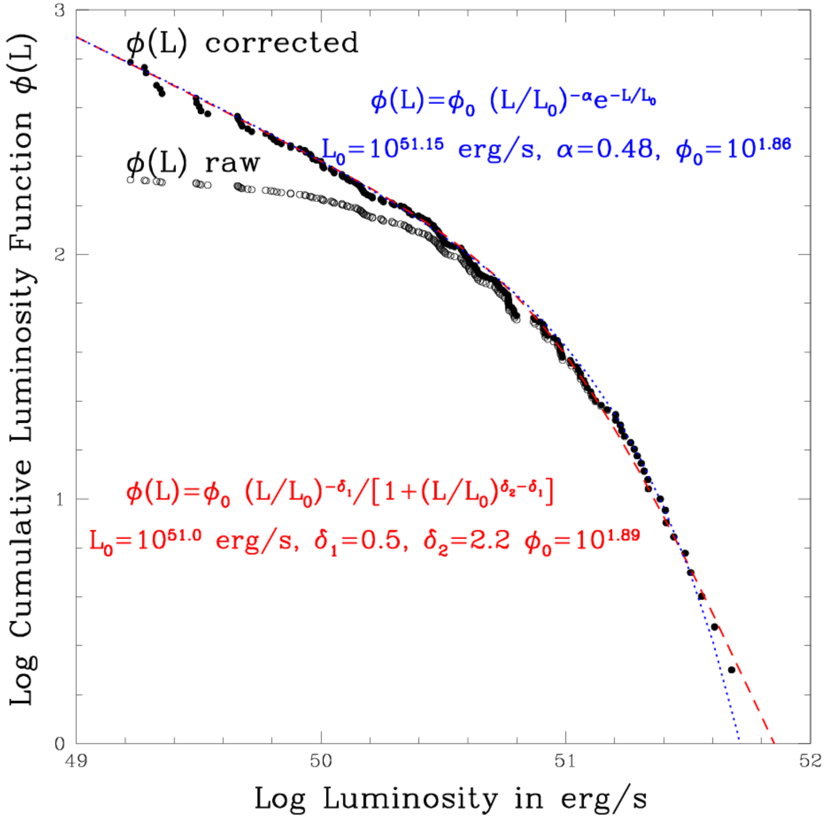
1. Test of independence

Luminosity evolution

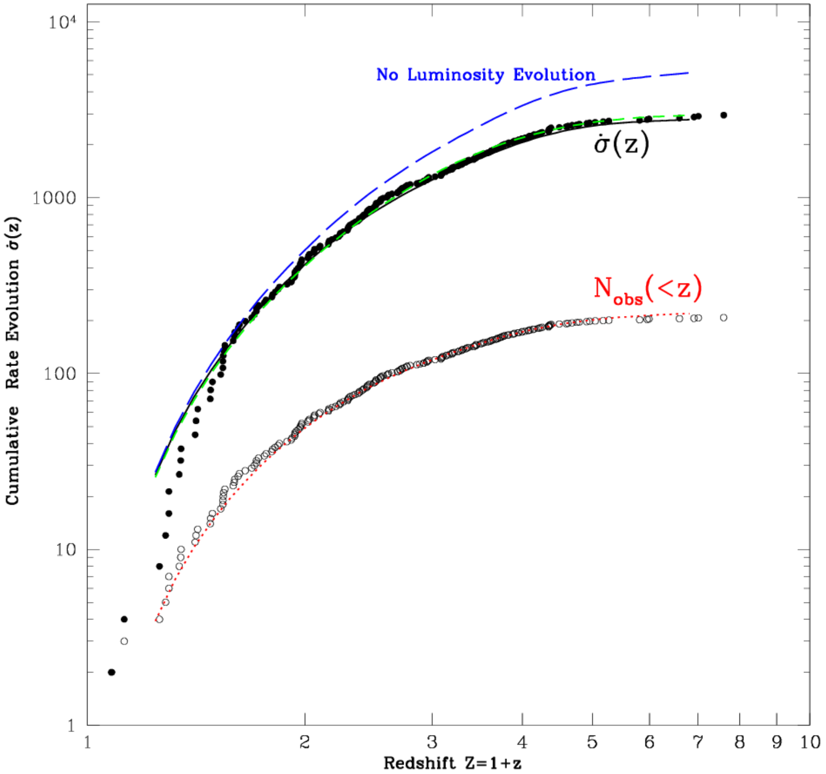


Cumulative Distributions

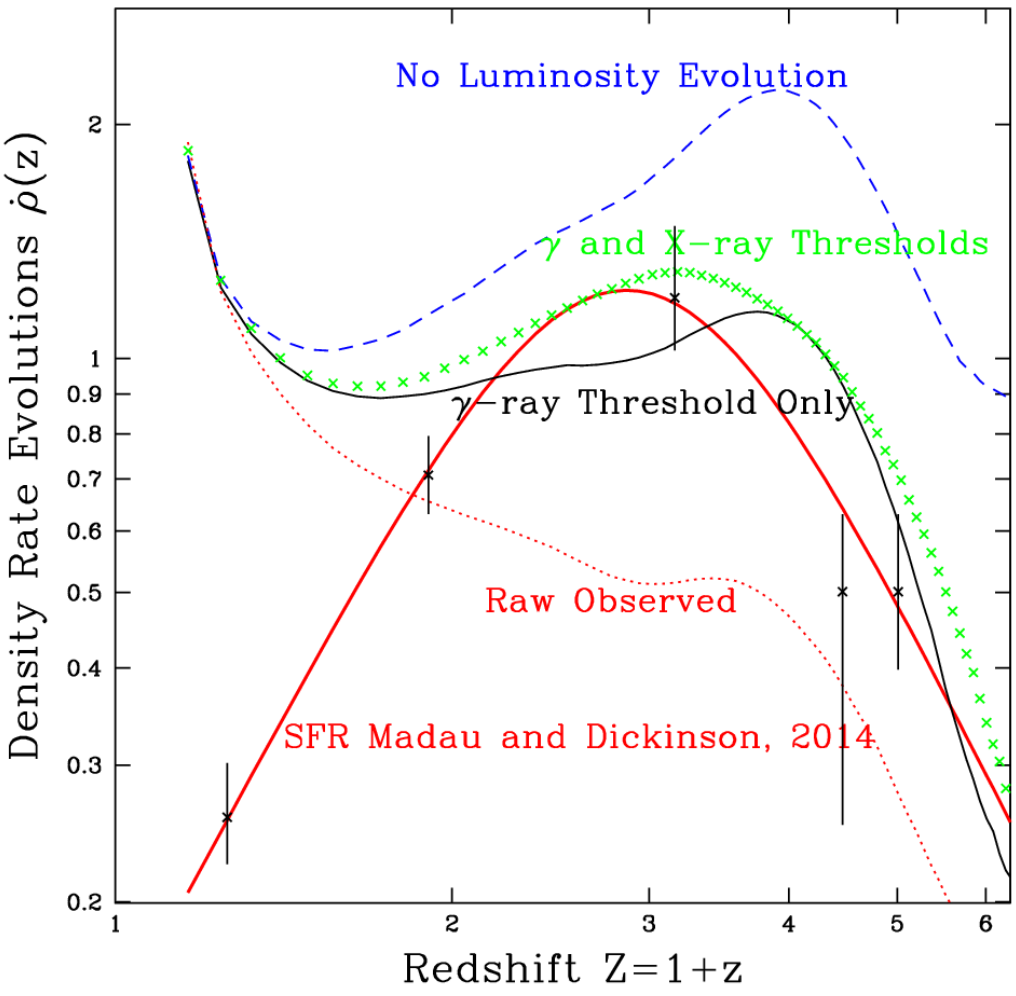
Luminosity Function



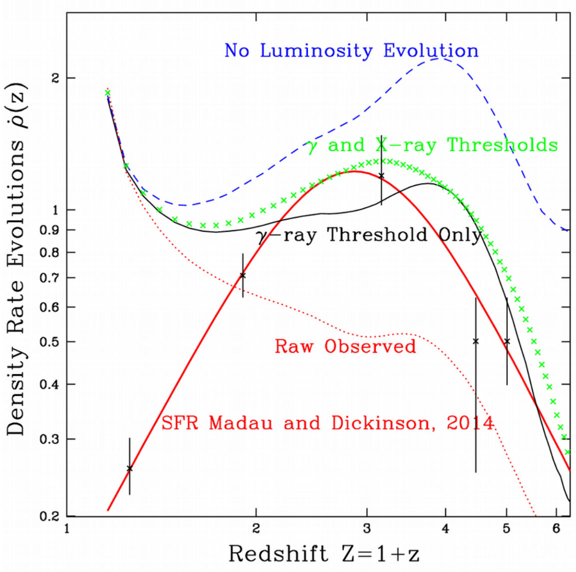
Rate Density Evolution



GRB and Star Formation Rates



GRB and Star Formation Rates



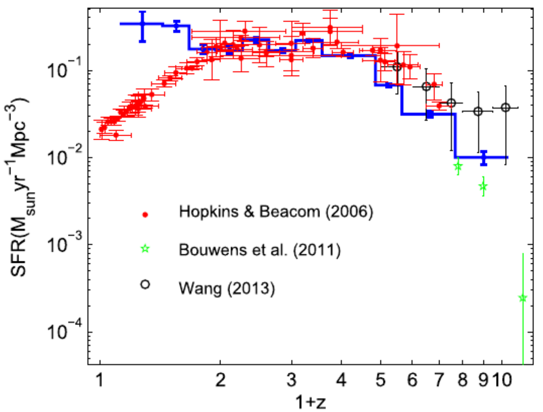
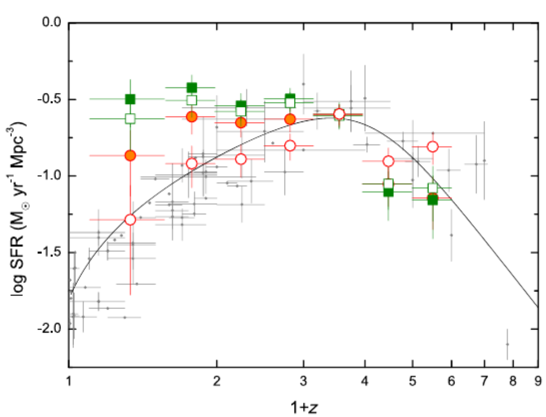
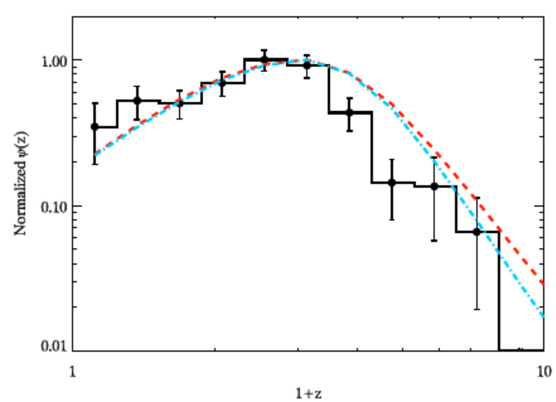


Figure 8. Comparison between GRB formation rate $\rho(z)$ (blue) and the observed SFR. The SFR data are taken from Hopkins & Beacon (2006), which are shown as red dots. The SFR data from Bouwens et al. (2011) (stars) and Wang (2013) (open circles) are also used. All error bars are 1σ errors.





Short GRBs and Gravitational Waves

More uncertain because fewer SGRBs

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

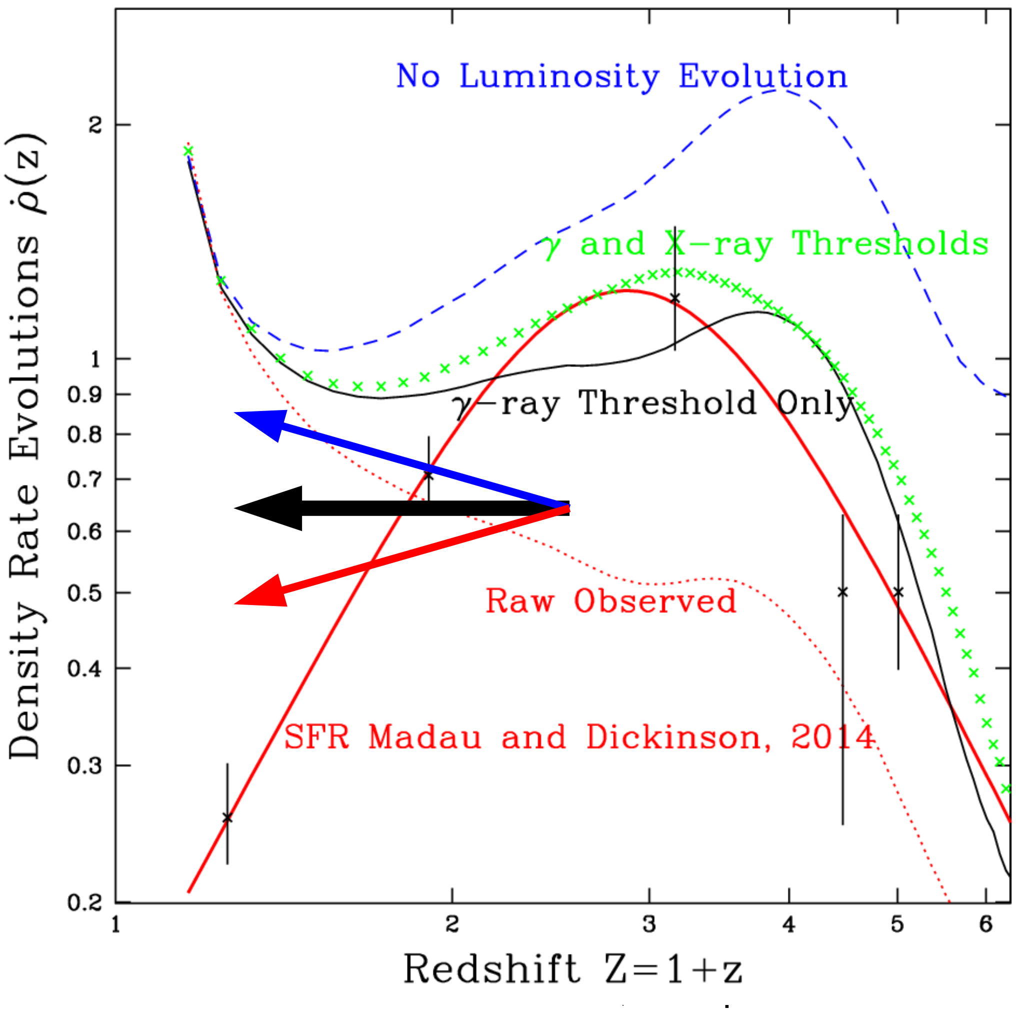
Different band width

Different Thresholds

But with EF method we

Can combine them

SGRB and Star Formation Rates



Short GRBs and Gravitational Waves

More uncertain because fewer SGRBs

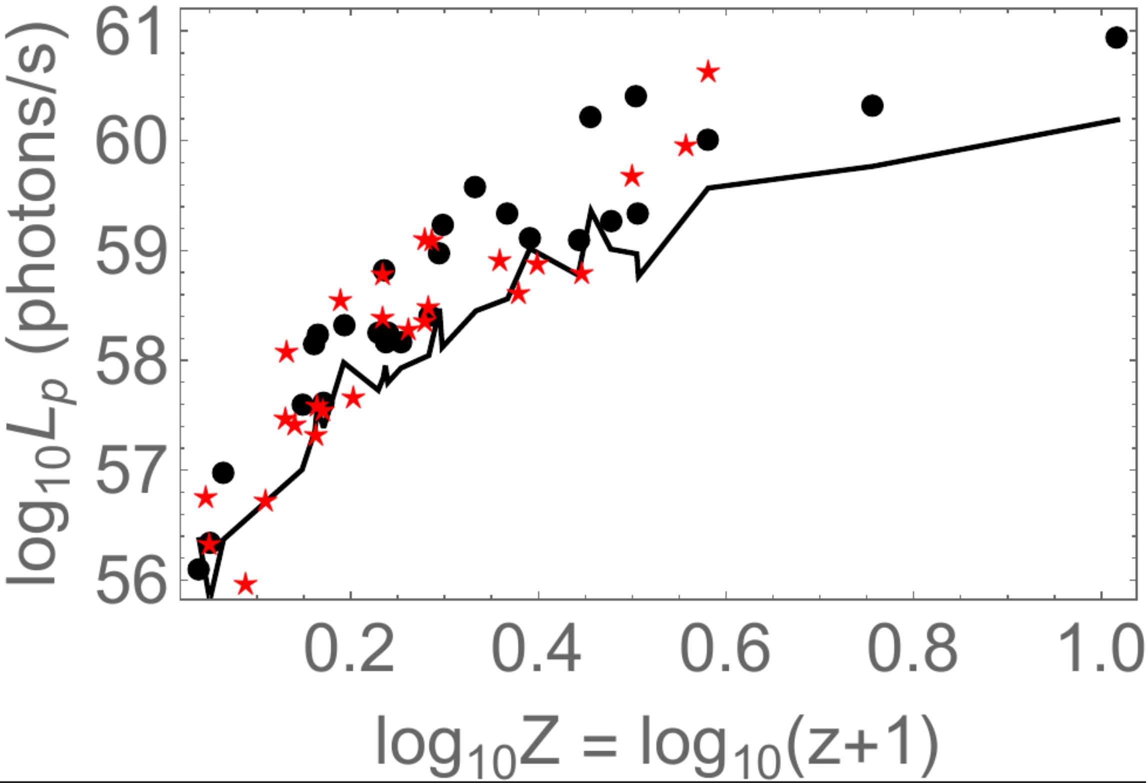
27-GBM, 33-*Swift* and 8-*Konus*-WIND with redshifts

Different band width

Different Thresholds

But with EF method we

Can combine them



C

Short GRBs and Gravitational Waves

More uncertain because fewer SGRBs

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

Different band width

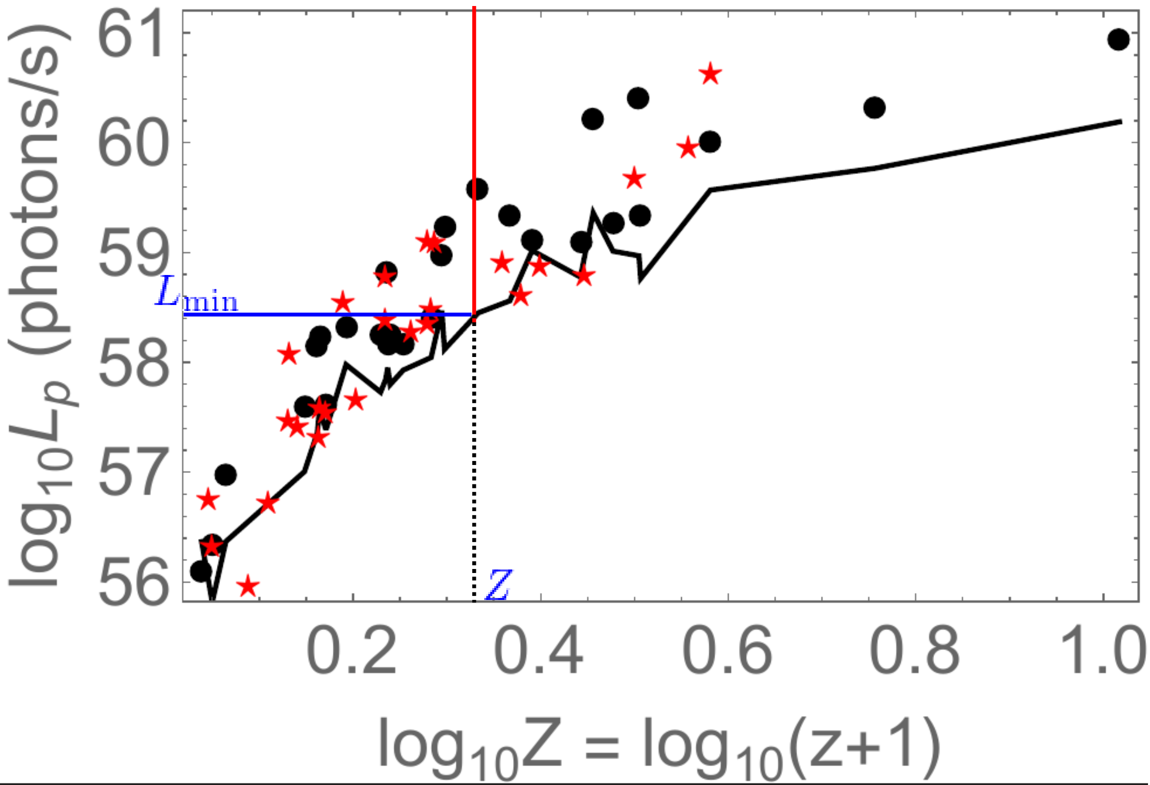
Different Thresholds

But with EF method

we can combine them

by defining

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



C

Short GRBs and Gravitational Waves

More uncertain because fewer SGRBs

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

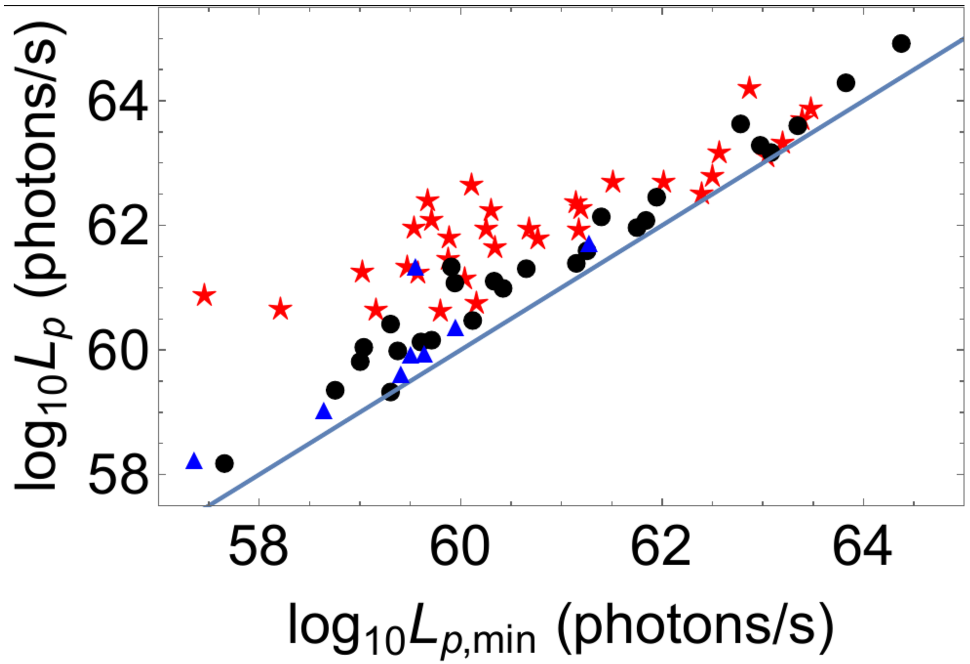
Different band width

Different Thresholds

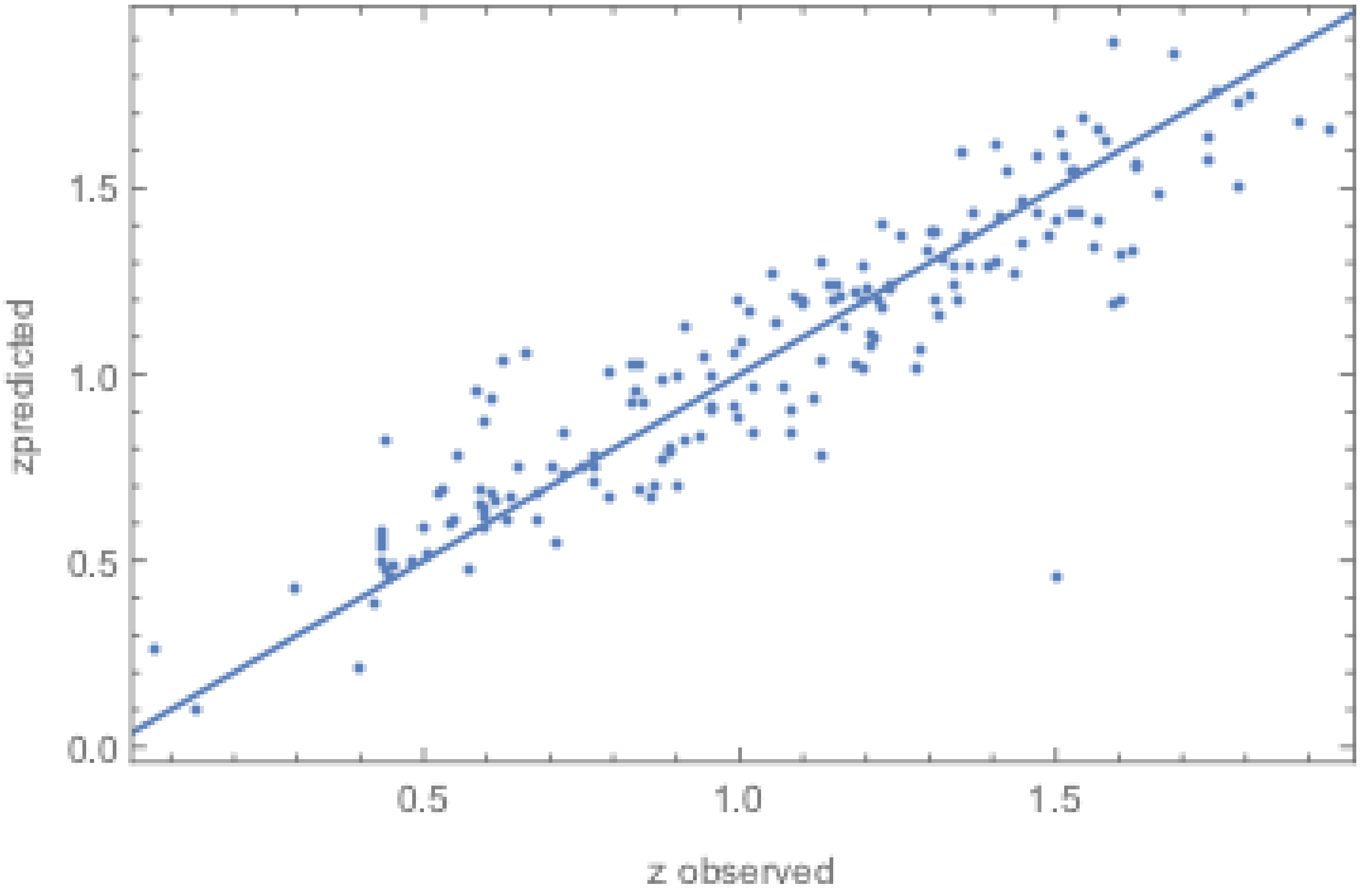
But with EF method

we can combine them

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



Use Machine Learning to estimate z



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. I 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.

IV-B. Application to SDSS X FIRST AGNs

Question of radio loud-radio quiet quasars

Schneider et al., 2010, *AJ*, 139, 2360 (i mag < 19.1; 65,000 quasars)
Becker et al. 1995, *ApJ*, 450, 559 (flux $_{1.4\ GHz}$>1 mJy; 300,000 objects)
Joint quasars 5,445

Outline

I. AGN Jet and Accretion Disk Emission

Radio Loudness

II. Data and Selection Biases

Optical and Radio Flux limited Samples

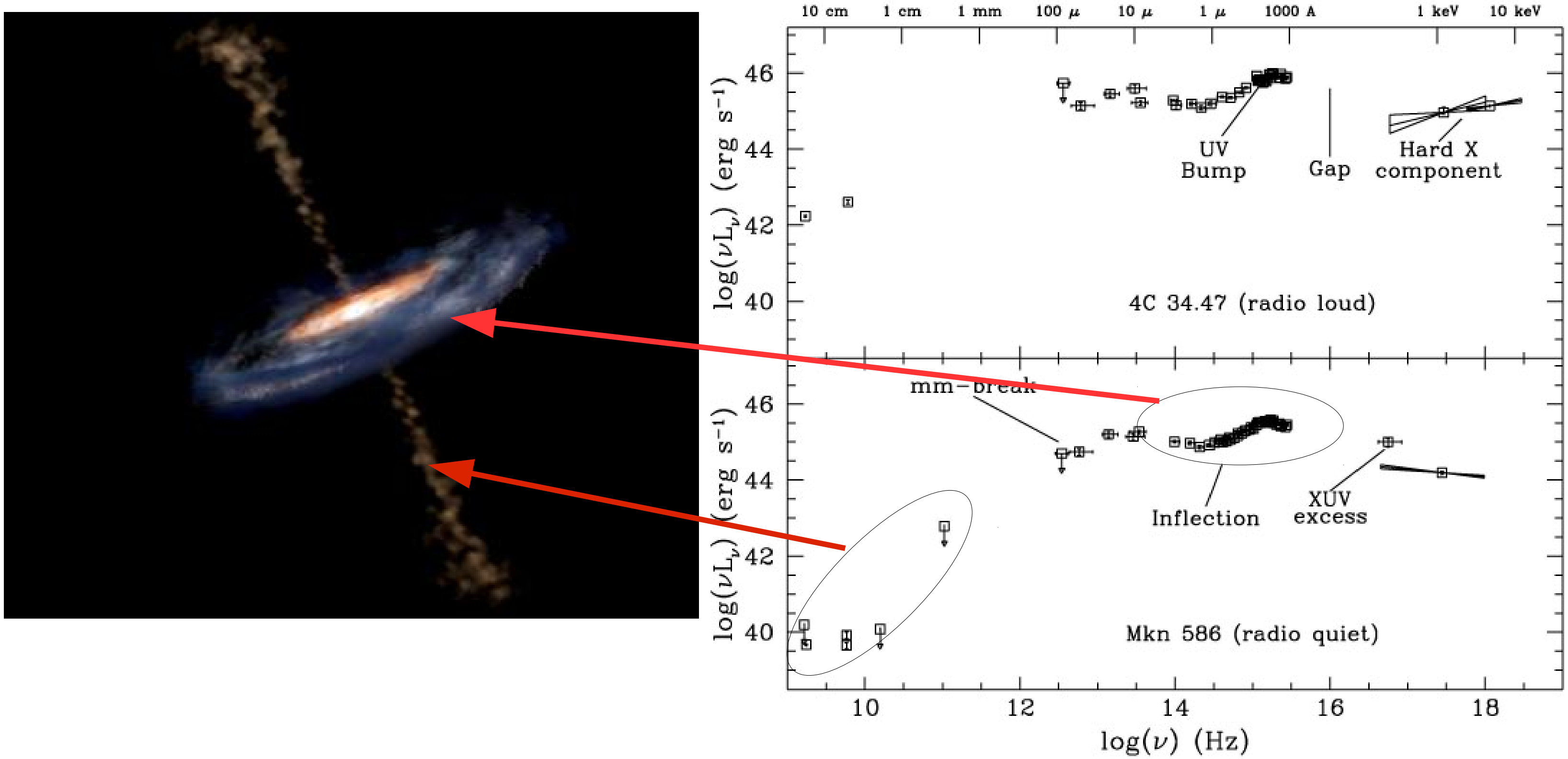
III. Data Analysis and Correlations

Non-parametric Methods

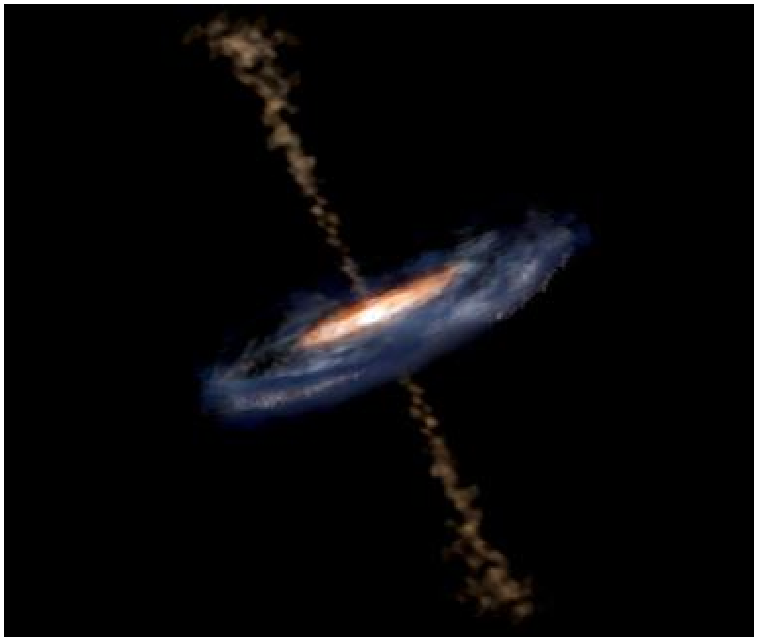
IV. Results from Application to SDSS and FIRST Quasars

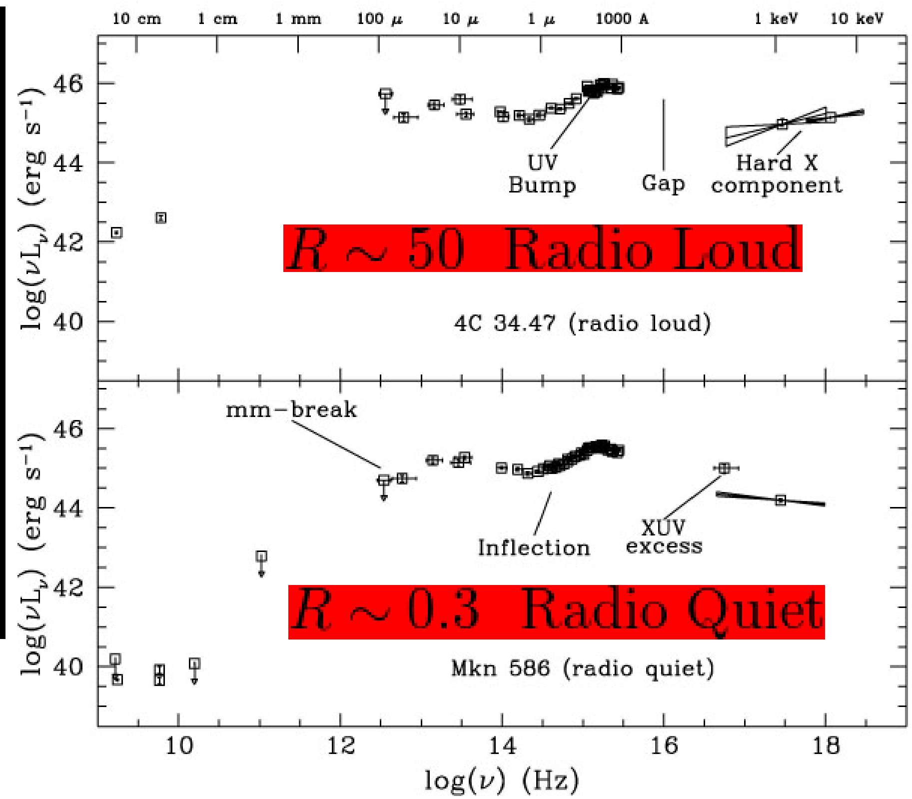
Distribution of Radio Loudness

I. AGN Jets and Accretion Disks



I. AGN Jets and Accretion Disks





$R > 10$ Radio loud; $R < 10$ Radioquiet

Radio Loudness Parameter

$$R = \frac{L_{rad}(5\mathrm{GHz})}{L_{opt}(2500\mathrm{A})}$$

The Answer

1. Requires Determination of

   a. Radio and Optical Luminosity Functions and Evolution

   b. Correlation between the Luminosities

   c. Co-moving Density Evolution

2. Need a Large Sample of Sources

   a. Cosmological Model Ω_i

   b. Redshifts *z*

   c. Optical and Radio Fluxes: *spectral indicies*

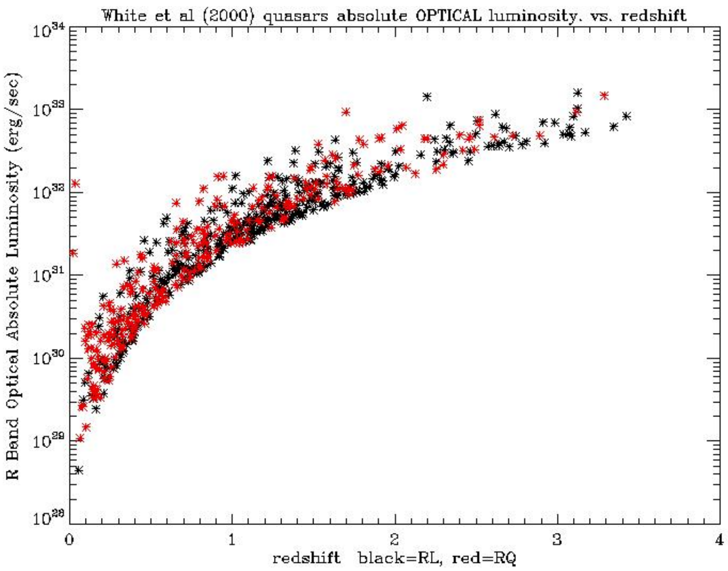
$$L = 4\pi d_L^2(\Omega_i, z) f / K(z)$$

II. Data: Optical

Luminosity-redshift Distribution

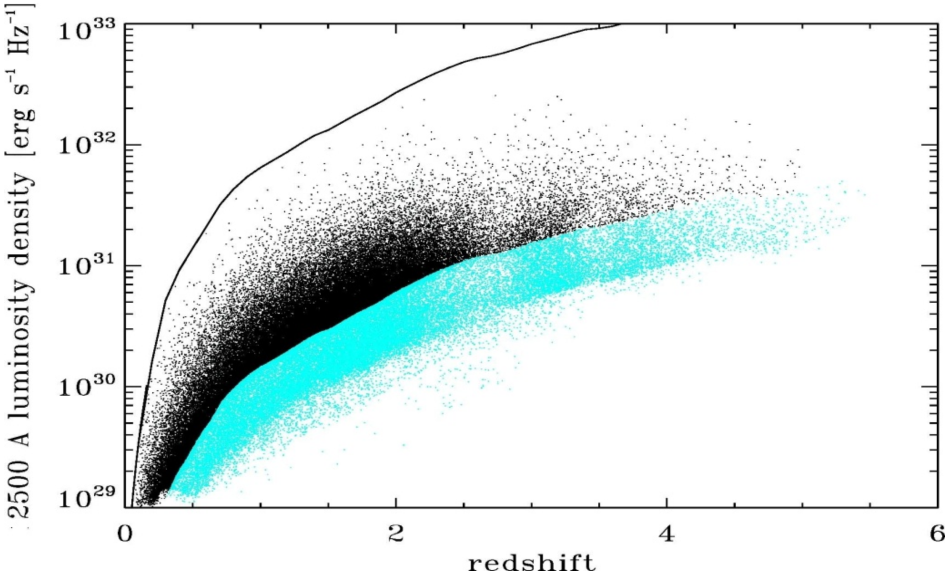
POSS-I (636 sources)

White et al. (2000)



SDSS DR-7 (105 ksources)

Abazajian et al. (2009)



Evolution of bi-Variate Luminosity Function

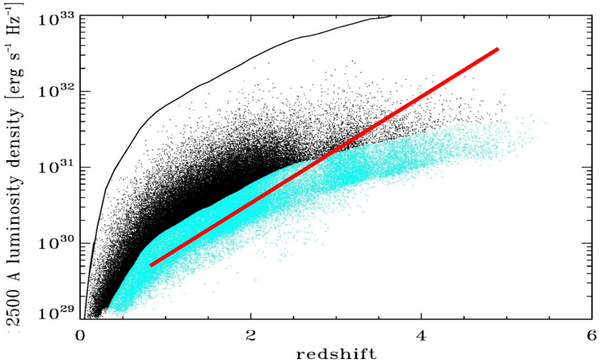
$$\Psi(L_{\rm opt}, L_{\rm rad}, z) \longrightarrow G(R, z)$$

Not difficult if variables are *uncorrelated or independent*

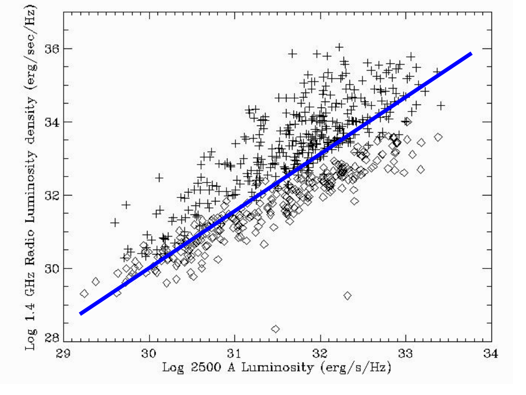
$$\Psi(L_o, L_r, z) = \psi_o(L_o)\psi_r(L_r)\rho(z)$$

But they seem correlated

$L_{\rm opt} - z$ Correlation



$L_{\rm rad} - L_{\rm opt}$ correlation



Bi-Variate Luminosity Function

•and its Evolution

$$\Psi(L_{\rm opt}, L_{\rm rad}, z) \longrightarrow G(R, z)$$

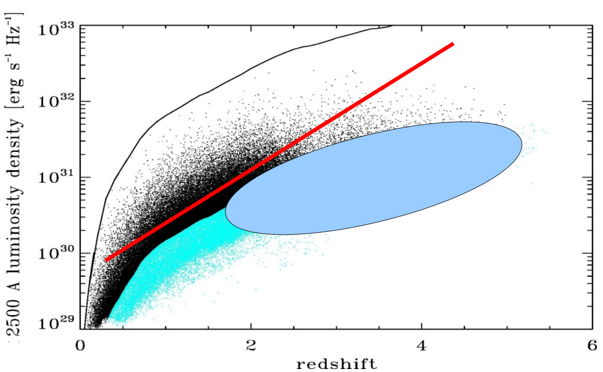
Not difficult if variables are *uncorrelated or independent*

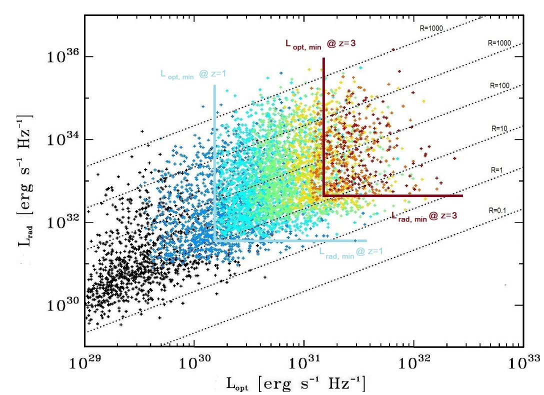
$$\Psi(L_o, L_r, z) = \psi_o(L_o)\psi_r(L_r)\rho(z)$$

But they seem correlated

$L_{\rm opt} - z$ correlation

$L_{\rm rad} - L_{\rm opt}$ correlation





Partially induced by the same *z* dependence of of both *Lo* and *Lr*

RESULTS

1. $L_{\rm rad} - L_{\rm opt}$ Correlation.

In our case, L_{opt} and L_{rad} are observed to be correlated.
Is this intrinsic or induced by redshift dependence?

a. Assume correlation to be intrinsic (not redshift induced)

Define $L' = L_{\rm crr} = L_{\rm rad} \times (L_{\rm opt}/L_0)^{-\alpha}$

And find $\alpha = 1.2 \pm 0.1$

b. Assume correlation is redshift induced

determine the individual luminosity evolutions

VI. RESULTS

2. Luminosity Evolution

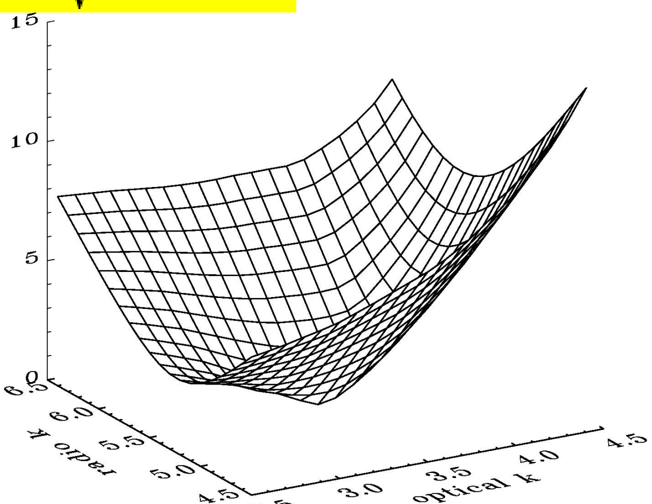
$$L' = L \times g(z)$$

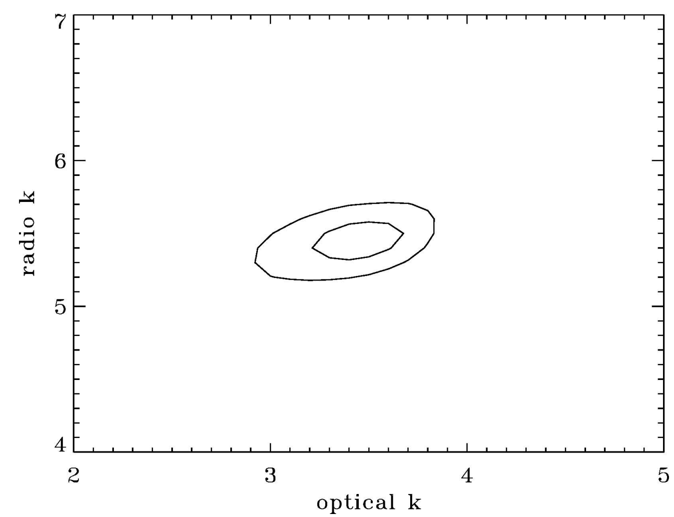
$$g(z) = (1+z)^k \quad \text{or} \quad g(z) = \frac{(1+z)^k}{1+\left(\frac{1+z}{1+z_c}\right)^k}$$

But we have tri-variate function $\Psi(L_{\rm opt}, L_{\rm rad}, z)$

And two evolutions parameters $k_{\rm rad}$ and $k_{\rm opt}$

$$\tau = \sqrt{\tau_{\rm rad}^2 + \tau_{\rm opt}^2}$$





Cosmic Ev $k_{\rm rad} = 5.5 \pm 0.2, \quad k_{\rm opt} = 3.4 \pm 0.2$

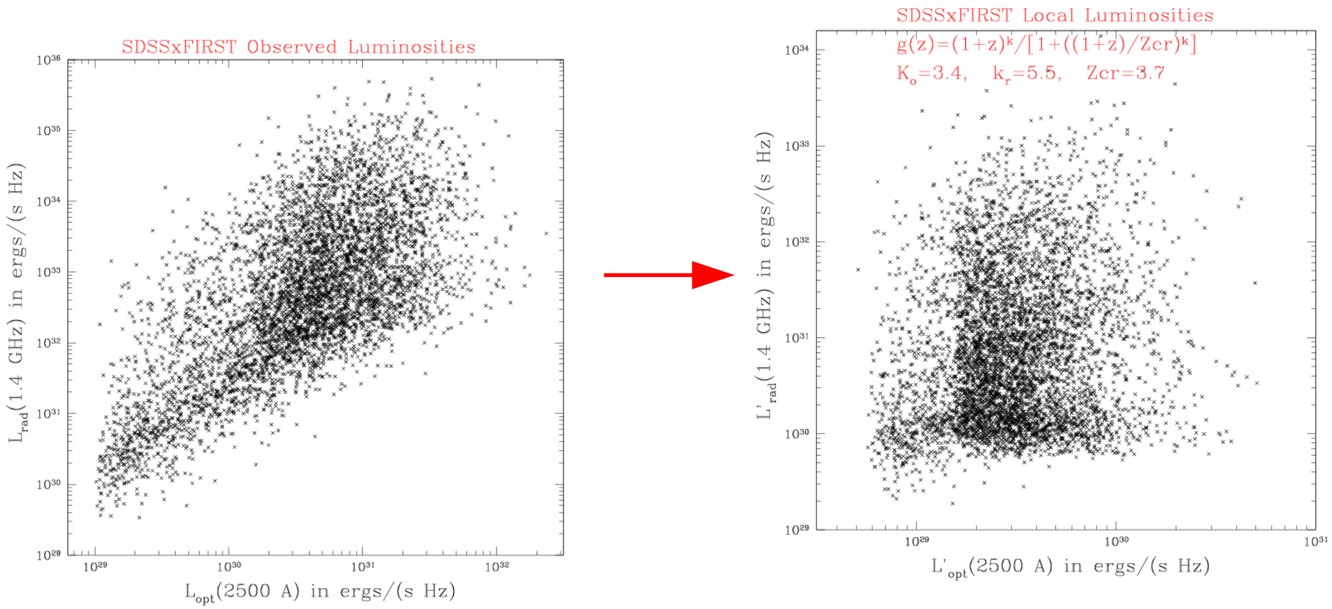
•

Luminosity-Luminosity Correlation

Observed vs Local

Since radio and optical luminosities evolve differently this will induce some correlation between luminosities.

Given the luminosity evolutions we can transform all luminosities to the local values $L_i' = L_i / g_i(z)$



Luminosity-Luminosity Correlation

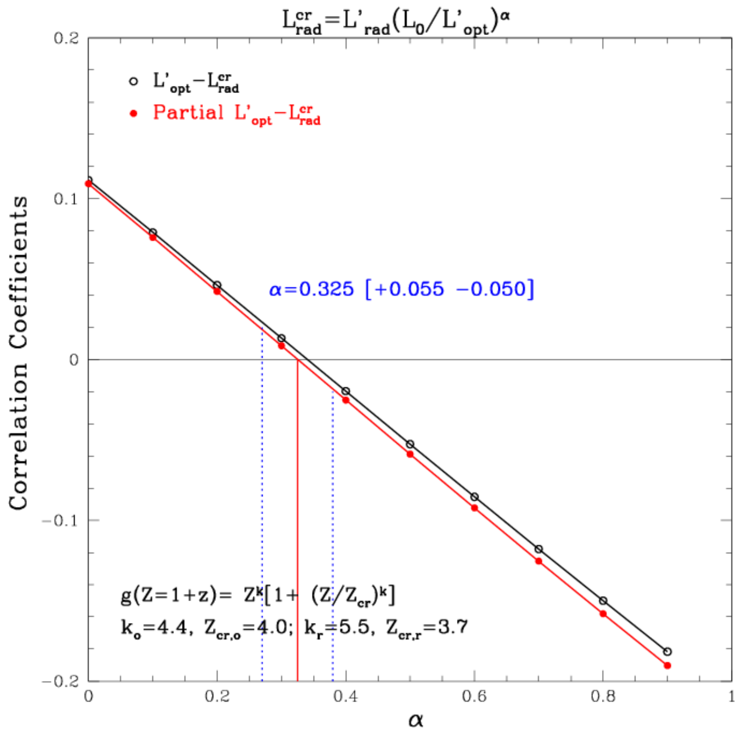
Of Local Luminosities

L-L Correlation Coefficient of *0.11* for *>5000* sources implies a probability that this is drawn a random *(uncorrelated)* sample is $P < 10^{-7}$

The Nature of this Calculation

Define $L_{\rm rad}^{cr} = L'_{\rm rad}(L_0/L'_{\rm opt})^{\alpha}$

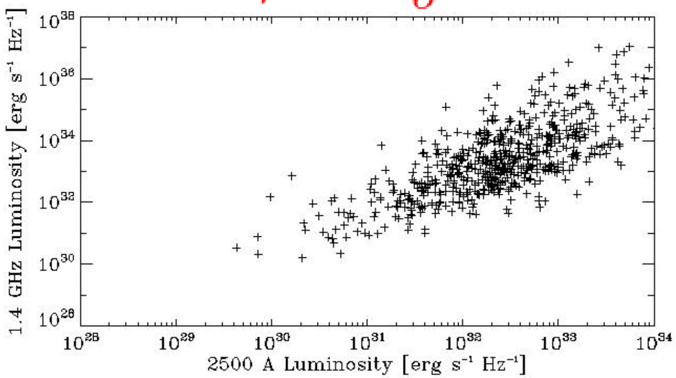
$$L'_{\rm rad} \propto {L'_{\rm opt}}^{0.325}$$



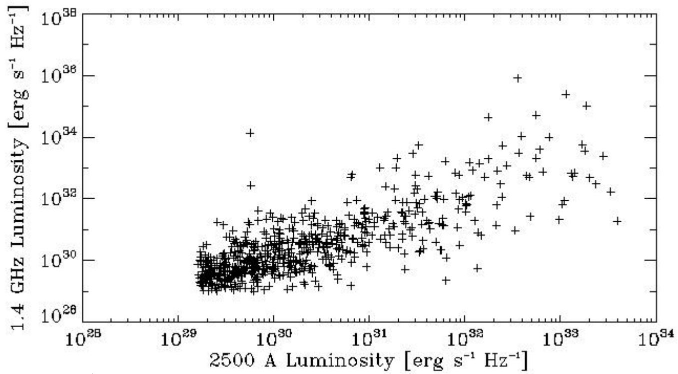
Luminosity-Luminosity Correlation

Measured Correlations

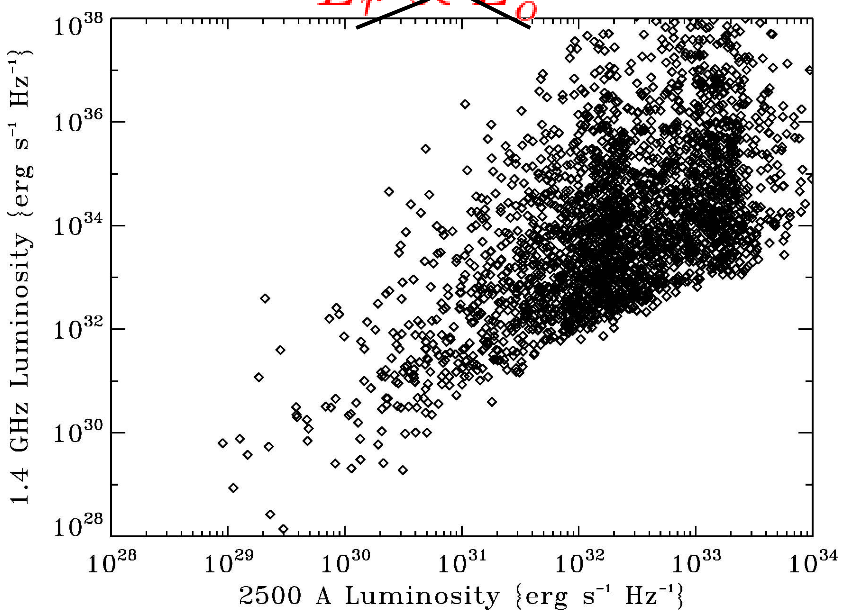
$L_r \propto L_o^{1.3}$



$L_r \propto L_o^{0.8}$



~~$L_r \propto L_o^{1.2}$~~

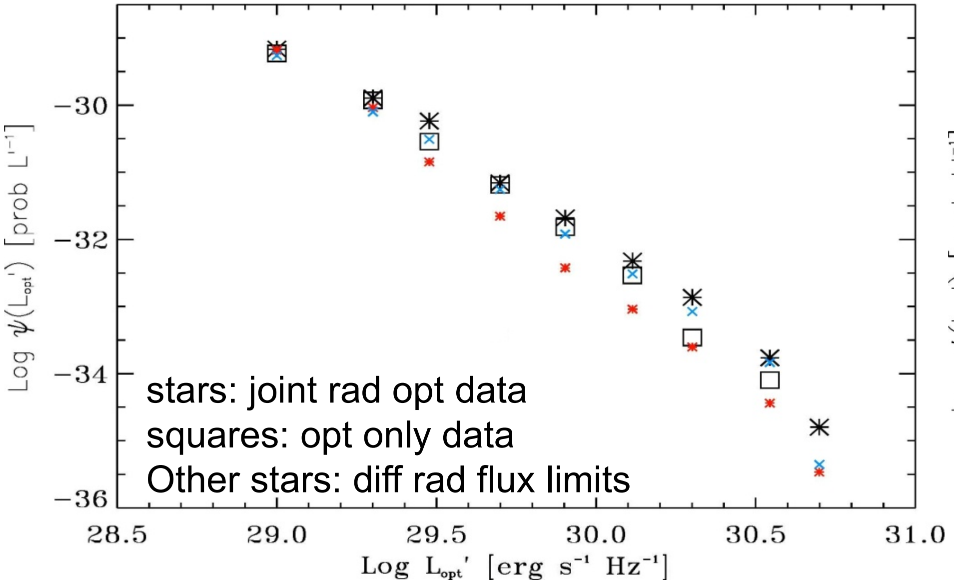


$L'_{\rm rad} \propto {L'_{\rm opt}}^{0.325}$

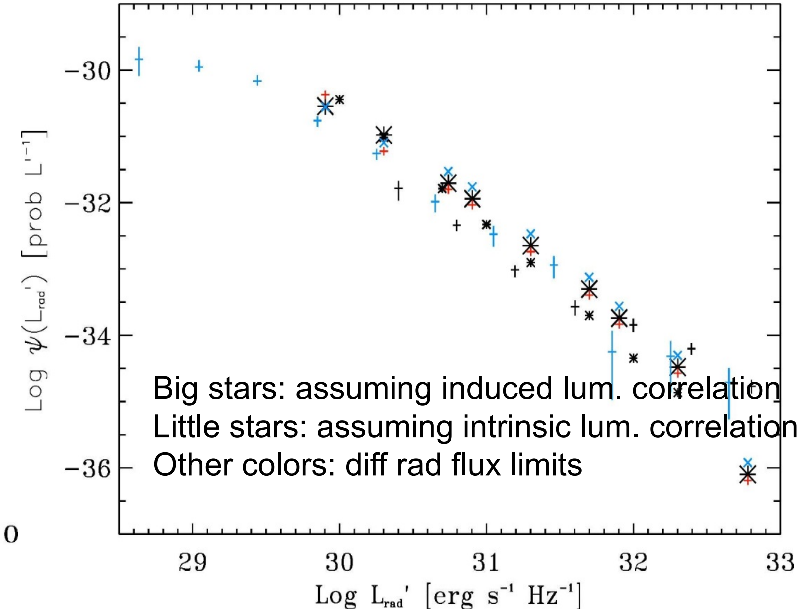
RESULTS

2. Local Luminosity Functions

Optical



Radio



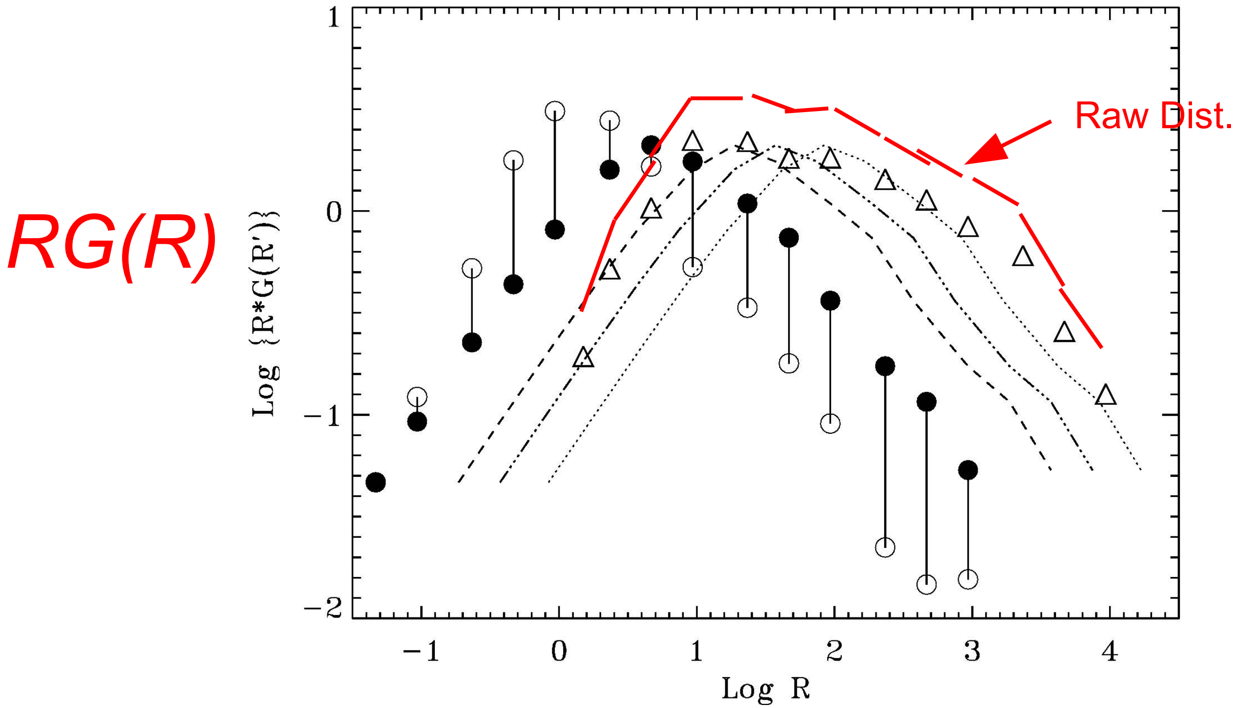
- Reasonable agreement with Boyle et al. 2000, *MNRAS*, 317, 1014
-

Blue crosses: Deep radio sample from Kimball et al. (2011, *ApJL*, 739, L29)

RESULTS

3. Radio Loudness Distribution and Evolution

$$G(R) = \int_0^\infty \Psi(L_{\rm opt}, R \times L_{\rm opt}, z) L_{\rm opt} dL_{\rm opt}$$



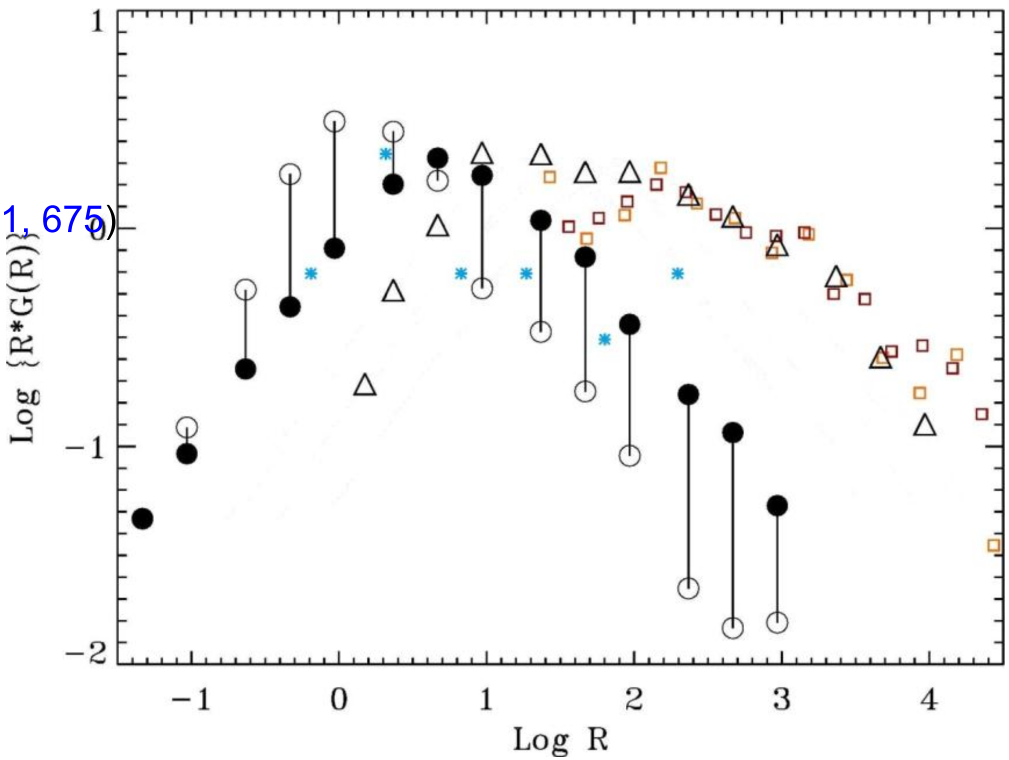
RESULTS

3. Radio Loudness Distribution and Evolution

$$G(R) = \int_0^\infty \Psi(L_{\rm opt}, R \times L_{\rm opt}, z) L_{\rm opt} dL_{\rm opt}$$

Red & Orange:
Ivezic et al. (2004, conf)

Blue:
Cirasuolo et al. (2006, *MNRAS*, 371, 675)



Other results on bi-modality

Mahoney et al. (2012, *ApJ*, 754, 12)   find no bi-modality
X-ray selected sample and radio flux down to 20 μJy.

Broderick & Fender (2011, *MNRAS*, 417,184
Also find no bi-modality in X-ray loudness R_X.

Kimball et al. (2011, *ApJL*, 739, L29)
In a deep (20 μJy at 6GHz) survey detect almost every SDSS quasar in a small field. They find very few sources with *R<0.1* and find no sign of bi-modality.
Using V/V_{max} method, they construct radio luminosity function and claim it is best fit by a two population model (AGN and Starburst?).

SUMMARY and CONCLUSIONS

We have used non-parametric methods to account for observational selection effects and determine the distributions and correlations of luminosities and redshift.

We find that the intrinsic radio loudness distribution shows no sign of bi-modality, indicating a continuum of Jet-accretion disk strength ratio.

There is strong positive luminosity evolution with redshift in both radio and optical, with radio evolution even stronger- quasars were more radio loud in the past.

This may indicate that jet production was more efficient for a given accretion power at higher redshifts.

Also , the contribution of quasar to the cosmic radio background will be somewhat higher than previously thought

J. Singal, V. Petrosian, A. Lawrence, & L. Stawarz, 2013, *ApJ*, 764, 43