AGN Population Studies

Luminosity Functions, Cosmological Evolutions, Correlations

Radio Loudness and Jet-Disk Connection

Multi-wavelength Observations

Vahe' Petrosian

Stanford University

With

Jack Singal and Lukasz Stawartz

Krakow Jets 2015

April 24 1915-2015

Day of rememberence of the

Genocide of Armenians by the Ottoman Empire

Recognized as the first genocide of modern history by many nations and recently by the Vatican and European Union

But shamefully not by USA

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Outline

I. Introduction

Why bother? And what to do

II. A bit of History

Malmquist, Eddington ……

III. Non-parametric Methods

Correlations and Distributions

IV. Applications to SDSSXFIRST and FermiXFIRST

Distribution of Radio Loudness

Luminosity-luminosity Correlation

I. Introduction

Population Studies:

1. Why is it important?

Studies of few brightest sources:

Not good representative of the population

Not useful for determination of

Distributions, Cosmological Evolutions and Correlations

For this purpose need a multi-variate description

At least two: one intrinsic, one spatial (or temporal) e.g. $\Psi(L, z)$

More for Multiwavelength AGN studies: e.g. $\Psi(L_{\mathrm{opt}}, L_{\mathrm{rad}}, z)$

I. Introduction

Population Studies:

2. Difficulties

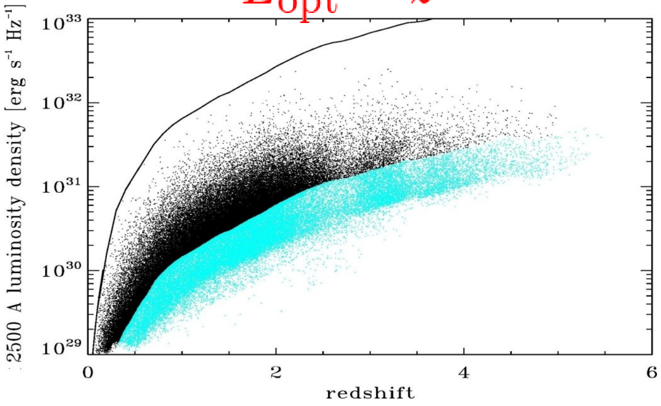
Many observational effects that introduce

Biases, Truncations, Censoring

Simplest case; *Flux limited samples*

But could be complicated: *Upper and lower limits; Subsamples with different limits*

$L_{\mathrm{opt}} - z$



II. Accounting For Biases and Truncations

(A Bit of History)

II. History

1. Forward Fitting to assumed parametric forms

Use, *e.g. Chi-squares,* to find best fit parameters

Malmquist 1925, Eddington 1940

Trumpler and Weaver 1953, Neymann and Scott 1959

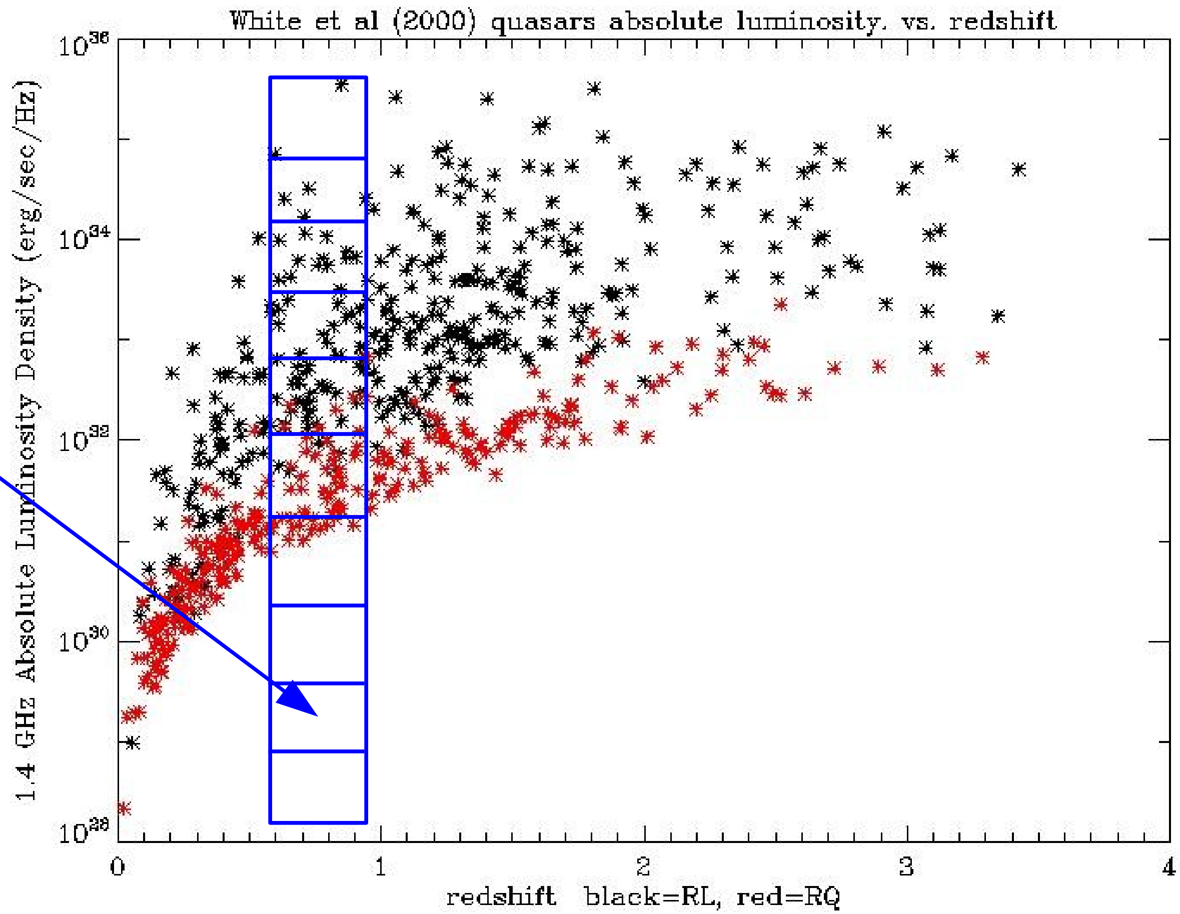
Not unique

(especially when more than few parameters)

II. History

2. Binning:

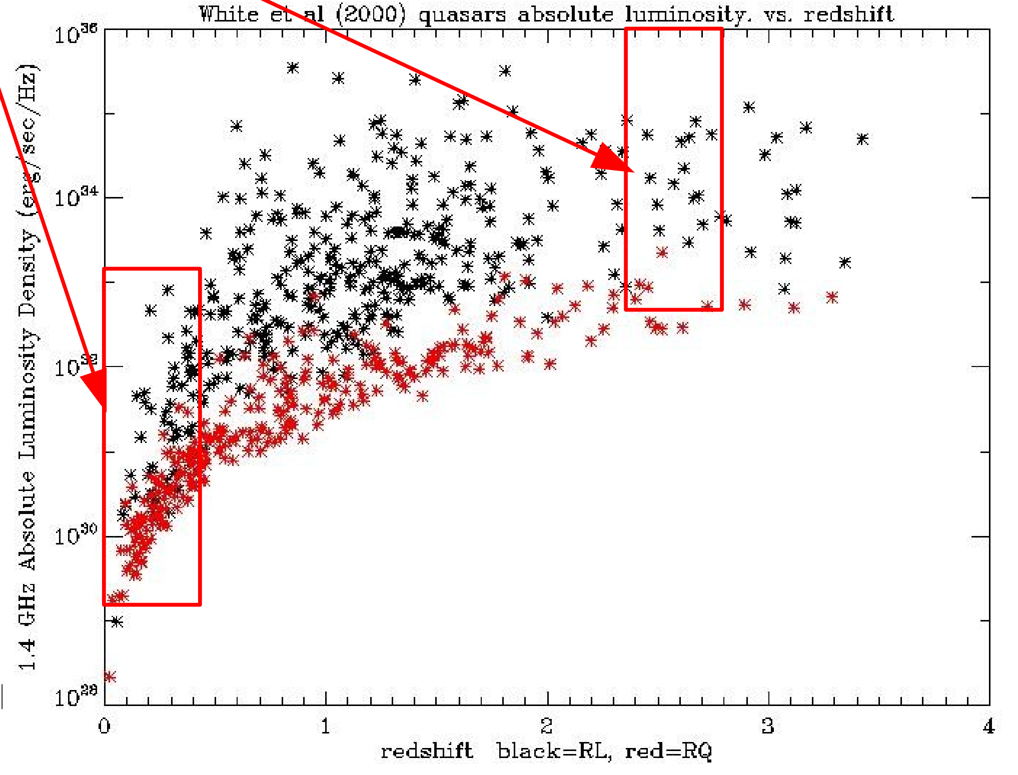
Many Empty Bins



II. History

2. Binning

With Little Overlap



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II. History

1. Forward Fitting

Malmquist 1925, Eddington 1940

2. Binning

3. Semi-parametric

$V/V_{\max}$ Kafka 1967, Schmidt 1968, VP 1973

4. Non-parametric

C^- Lynden-Bell 1971, Jackson 1972 (see review VP 1992)

II. History

1. Forward Fitting

Malmquist 1925, Eddington 1940

2. Binning

3. Semi-parametric

$V/V_{\max}$ Kafka 1967, Schmidt 1968, VP 1973

4. Non-parametric

C^- Lynden-Bell 1971, Jackson 1972 (see review VP 1992)

BUT There is a major shortcoming in these and most others methods

They assume independence of variables $\Psi(L,z) = \psi(L)\rho(z)$

II. History

It is therefore important to establish the dependencies

5. In a series of papers Efron and Petrosian

Describe non-parametric maximum likelyhood methods to

Test for independence

Determine the nature of correlation

Correct for its effects

Determine distributions

From data subject to complex truncations *(not just flux limited)*

That can be generalized to multi-variate distributions

See: www.inside-r.org/node/99623

cran.r-project.org/web/packages/DTDA/DTDA.pdf

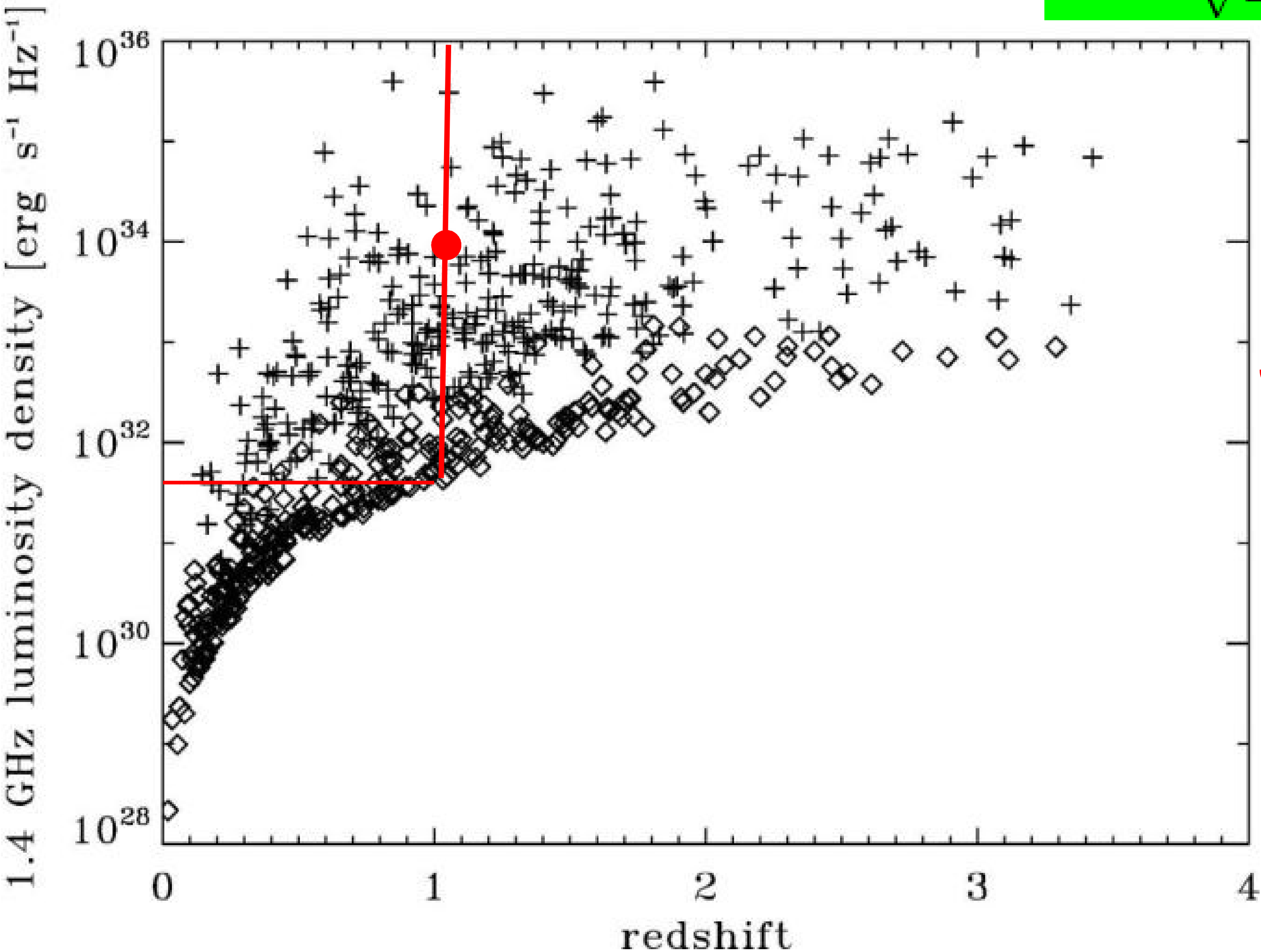
III. Non-parametric Maximum Likelyhood Method

Minimal assumptions about the forms of distributions
No binning
Accounts for contribution of each data point individually

Test of Independence or Correlation

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 set Ni sources

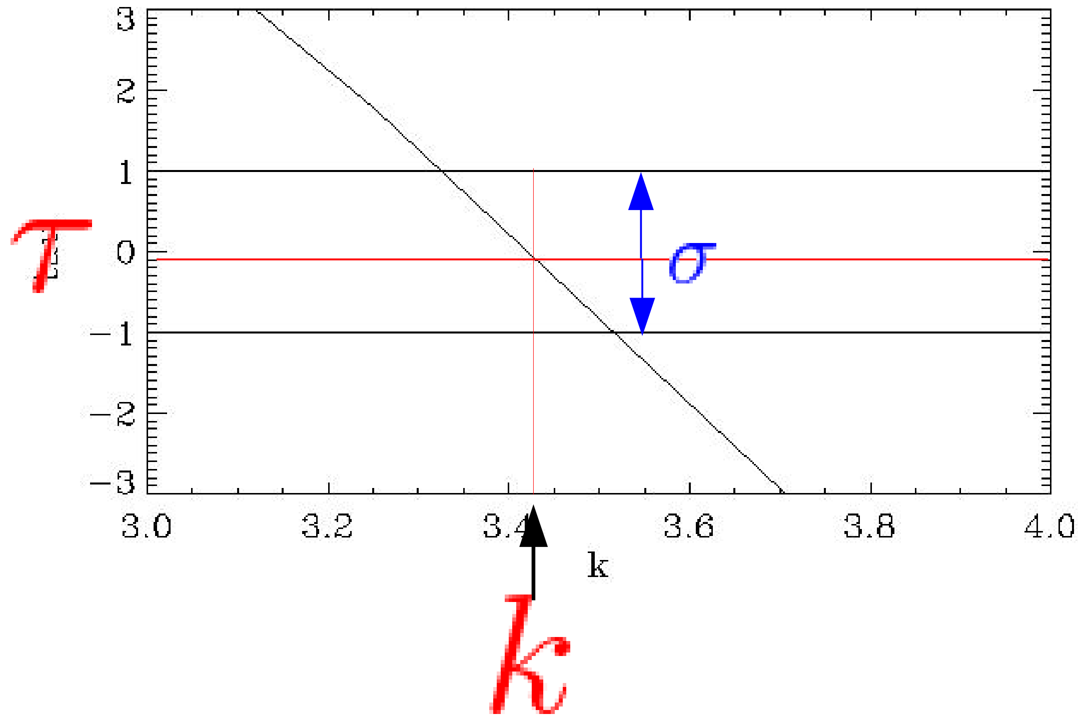
Krakow Jet2015

Luminosity Function and Evolutions

1. Test for independence of two (or more) variables in a bi-(or multi)-variate truncated data
2. Remove the correlation by a variable transformation e.g.

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

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



Luminosity Function and Evolutions

1. Test for independence of two (or more) variables in a bi-(or multi)-variate truncated data
2. Remove the correlation by a variable transformation
3. Determine the mono-variate distributions of now the independent variables $\psi(L') \quad \text{and} \quad \rho(z)$

$$\psi(L_i) = \phi(L_1)\frac{\prod_{j=2}^{i}(1+1/N_j)}{(L_{i-1}-L_i)\times(N_i+1)}$$

Luminosity Function and Evolutions

1. Test for independence of two (or more) variables in a bi-(or multi)-variate truncated data
2. Remove the correlation by a variable transformation
3. Determine the mono-variate distributions of now the independent variables $\psi(L') \quad \text{and} \quad \rho(z)$
4. Transfer back to obtain the distribution

$$\Psi(L, z)$$

IV. AGN Jet Accretion Disk Relation

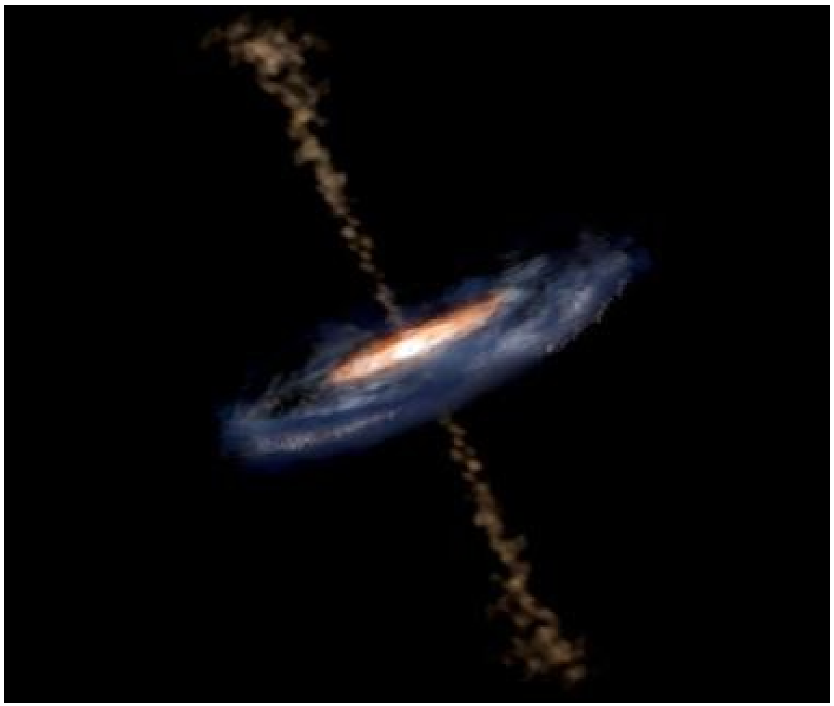
1. Radio LoudnessDistribution

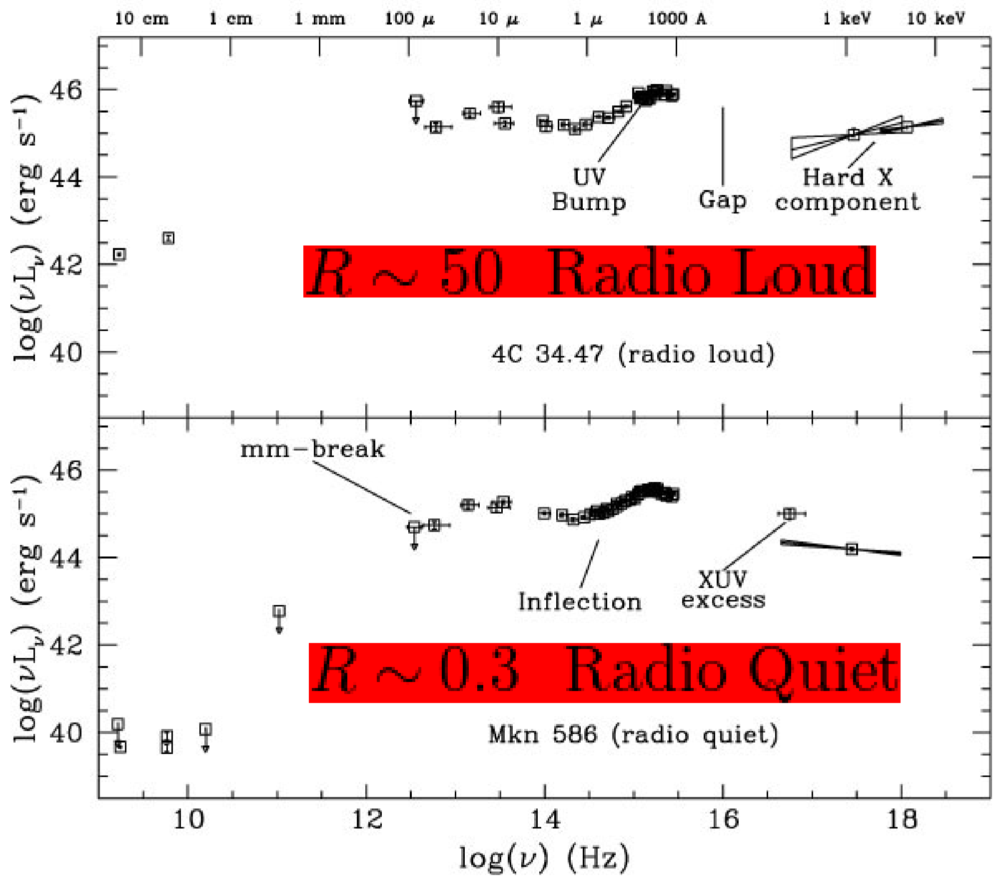
SDSSxFIRST

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

AGN Jets and Accretion Disks Relation

1. Distribution of Radio Loudness





Radio Loudness Parameter

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

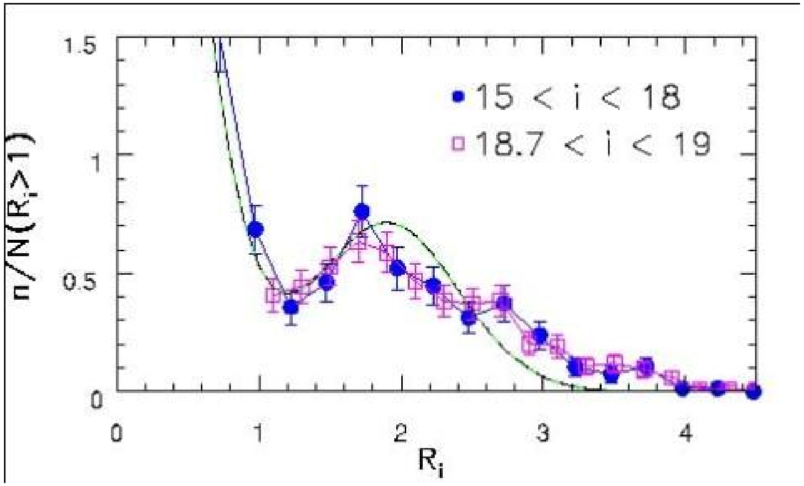
$R > 10$ Radio loud; $R < 10$ Radioquiet

Questions ?

1. Are there two distinct AGN classes?

   Jet vs Accretion Disk dominated AGNs?

   Is the distribution of *R* bimodal?



$$G(R, z)$$

From Ivezic et al. (2004)

2. Does distribution *G(R, z)* evolve ?

   Relative evolutions of optical and radio luminosity functions?

The Answer

1. Requires Determination of
    a. Radio and Optical Luminosity Functions and Evolution
    b. Correlation between the Luminosities
    c. Co-moving Density Evolution

RESULTS

2. Luminosity Evolution

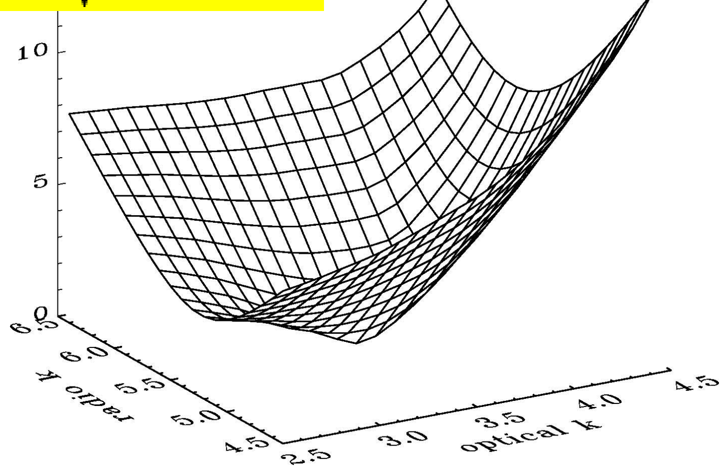
$$L_i' = L_i / g_i(z)$$

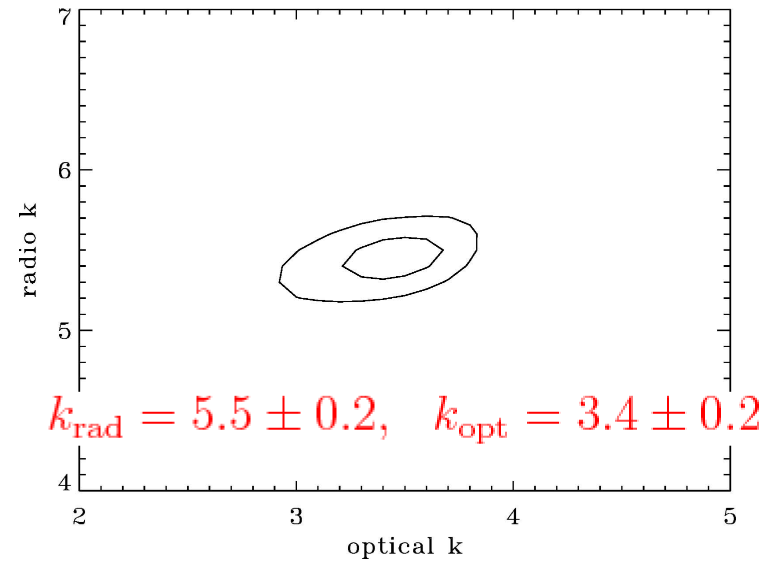
$$g(z) = (1+z)^k \ \text{ or } \ g(z) = \frac{(1+z)^k}{1 + \left(\frac{1+z}{1+z_c}\right)^k}$$

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

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

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





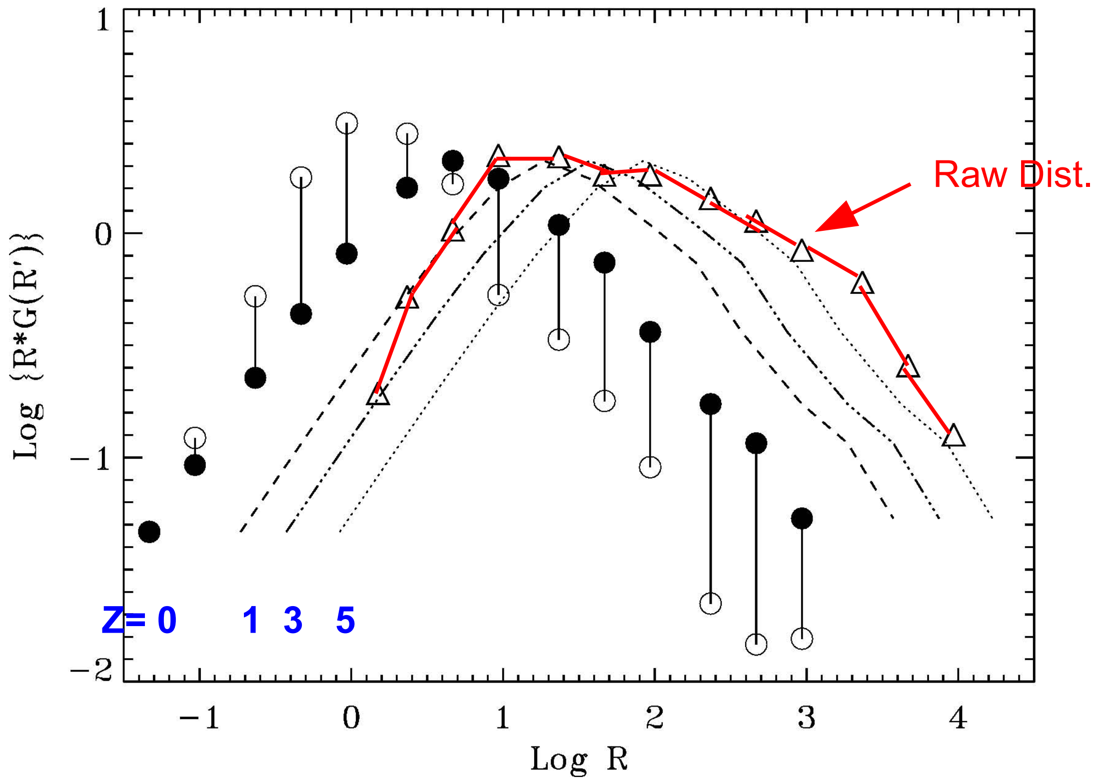
$$k_{\rm rad} = 5.5 \pm 0.2, \quad k_{\rm opt} = 3.4 \pm 0.2$$

RESULTS

5. Radio Loudness Distribution and Evolution

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

RG(R)



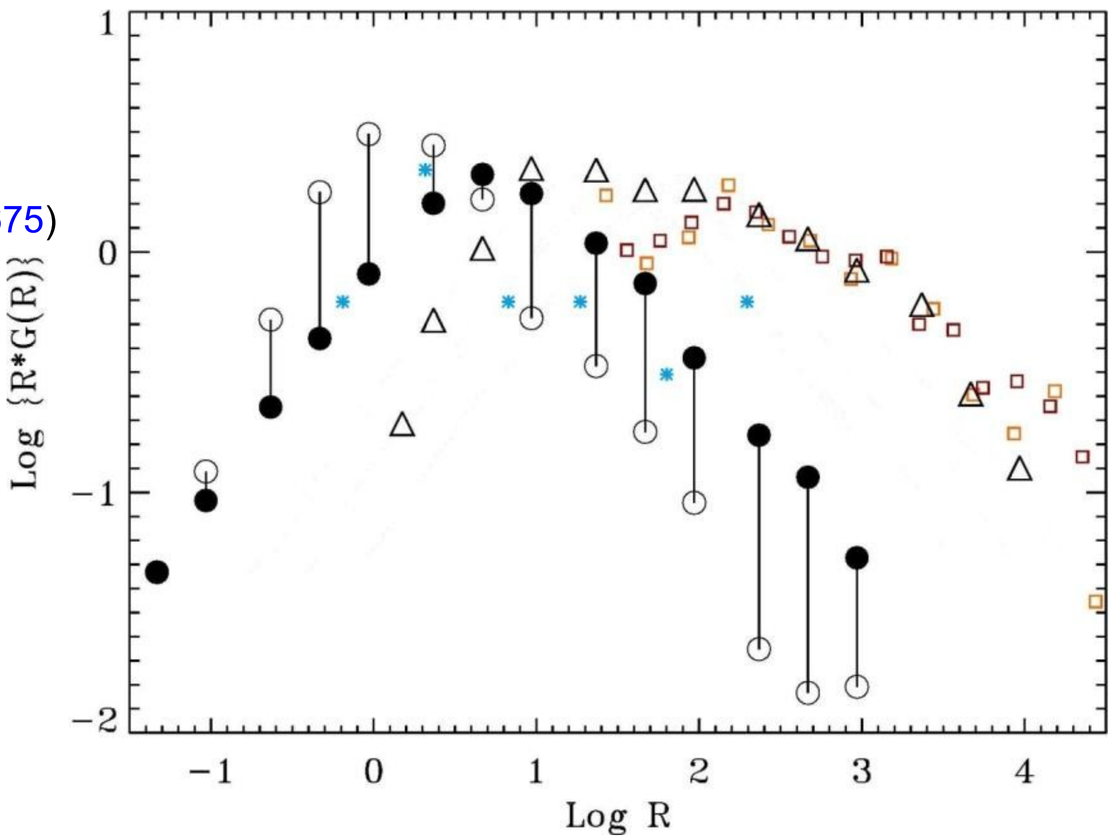
RESULTS

5. Radio Loudness Distribution and Evolution

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

Brown squares:
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.

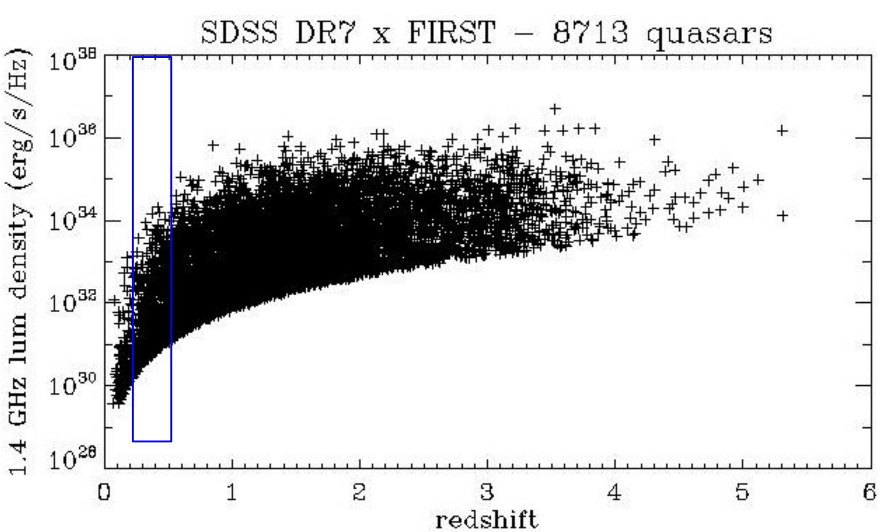
- Broderick & Fender (2011, *MNRAS*, 417,184
  Also find no bi-modality in X-ray loudness R_X.

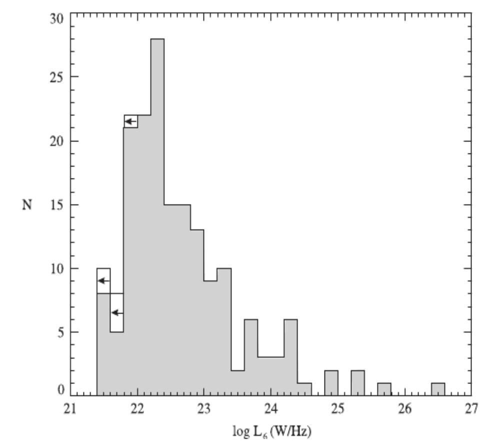
- Kimball et al. (2011, *ApJL*, 739, L29)
  In a deep (20 μJy at 6GHz) survey detect almost every SDSS quasar in a small field. They find very few sources with $R<0.1$ and find no sign of bi-modality.

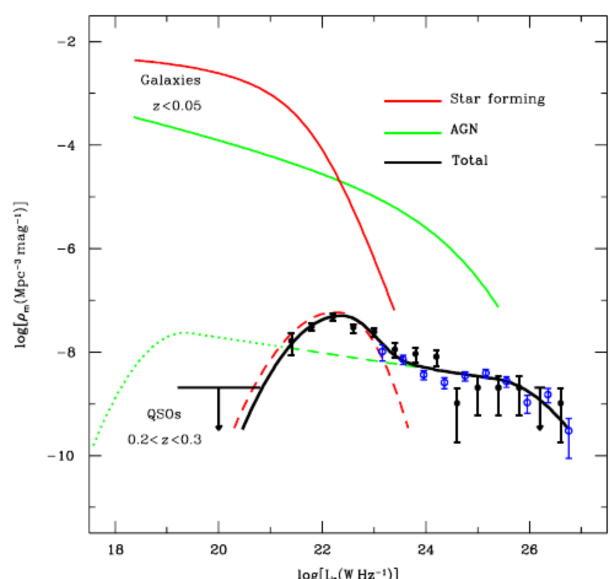
RESULTS

5. Radio Loudness Distribution and Evolution

Deep radio survey; Kimball et al. ApJ, 2011, 739, L29



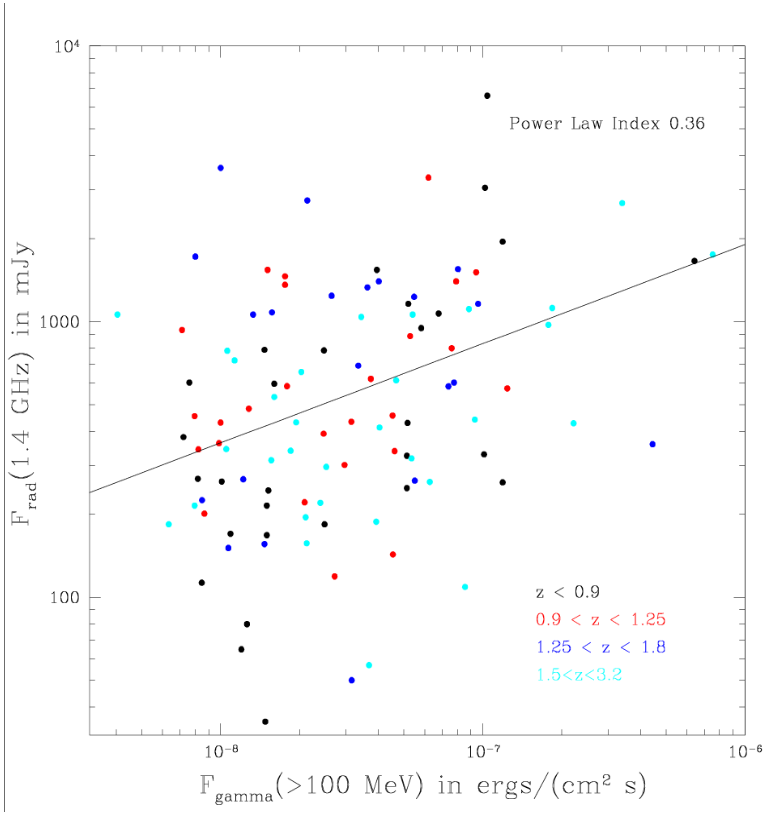




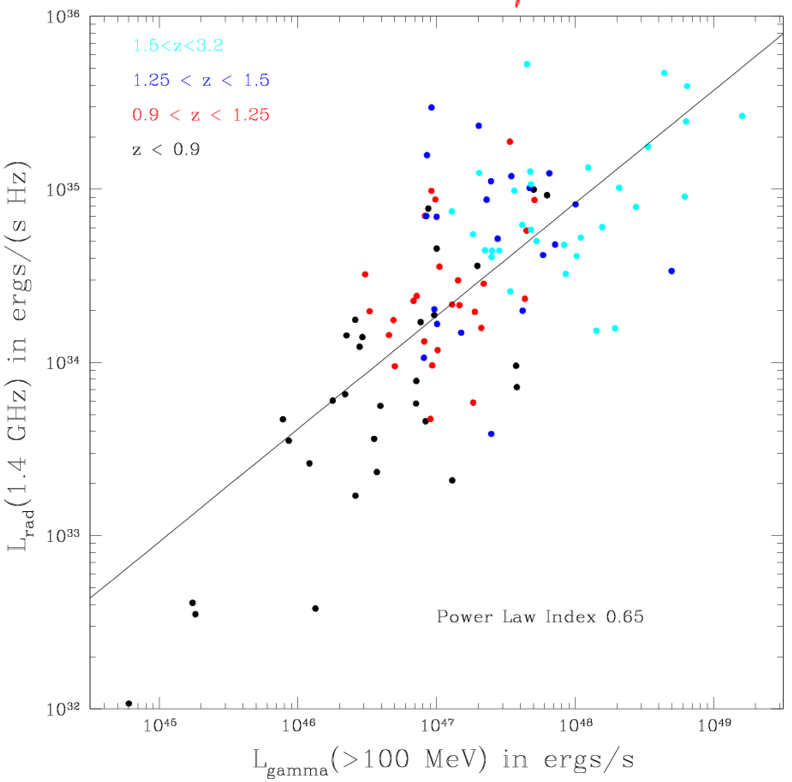
Krakow Jet2015

General Remarks

Often flux-flux correlation are used as proxy



$$L_{\rm rad} \propto L_\gamma^{0.62}$$



General Remarks

Mutual dependence on redshift or distance induces false correlation

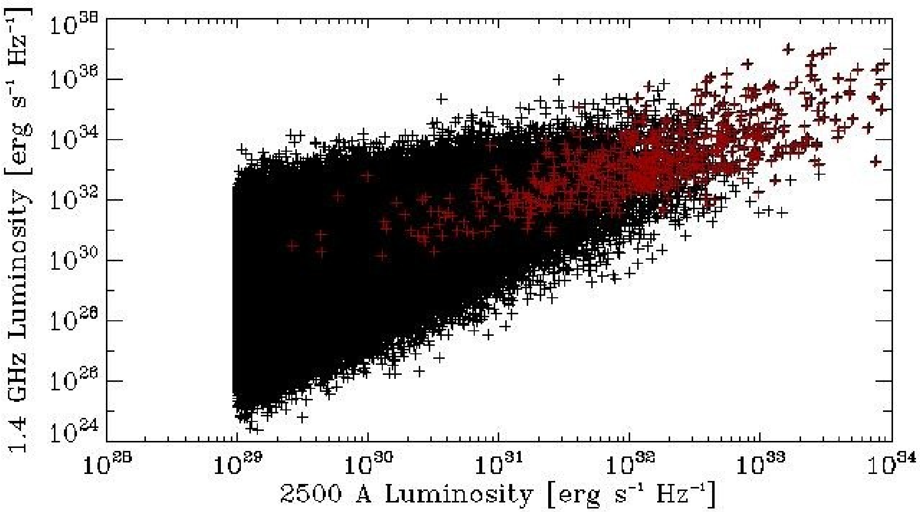
$$\Psi(L_o, L_r, z) = \psi_o(L_o)\psi_r(L_r)\rho(z)$$

$$< Log(L_r) > (L_o) = \frac{\int_0^{f(L_o)} \rho(z)(dV/dz)dz \int_{4\pi d_L^2 f_{lim}}^{\infty} Log(L_r)\psi(l_r)dL_r}{\int_0^{f(L_o)} \rho(z)(dV/dz)dz \int_{4\pi d_L^2 f_{lim}}^{\infty} \psi(l_r)dL_r}$$

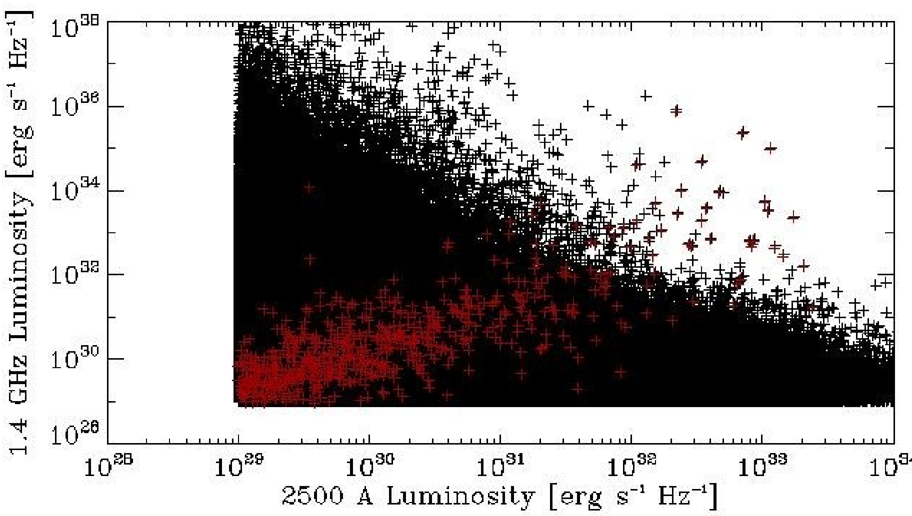
Simulation Results

Parent Populations

correlated $L_r \propto L_o$



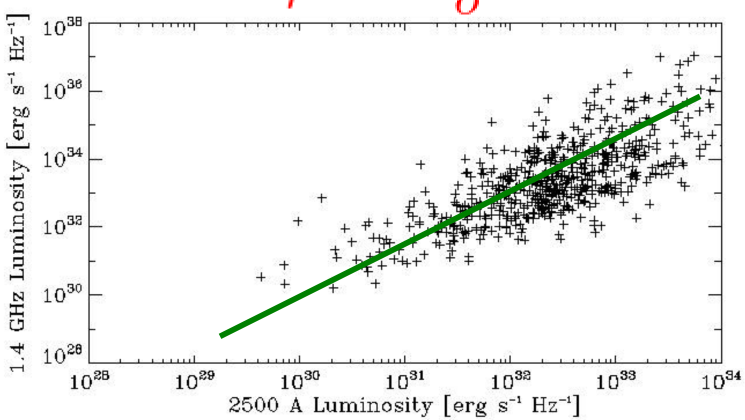
uncorrelated $L_r \propto L_o^{0.0}$



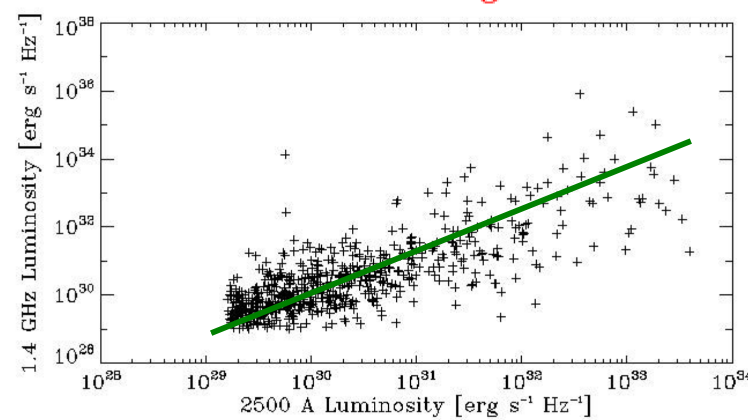
Luminosity-Luminosity Correlation

Measured Correlations

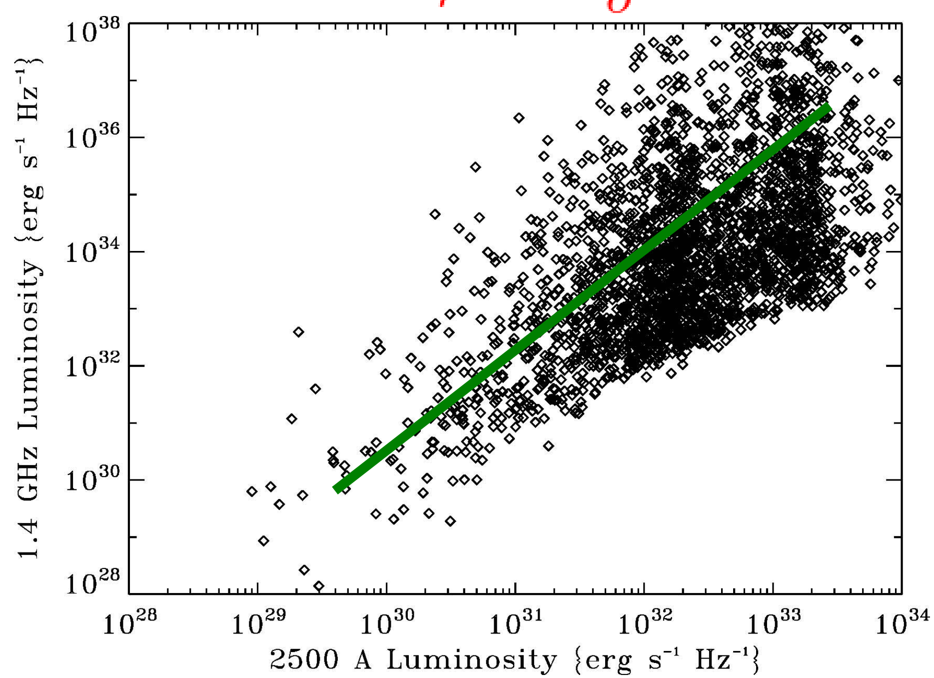
$$L_r \propto L_o^{1.3}$$



$$L_r \propto L_o^{0.8}$$

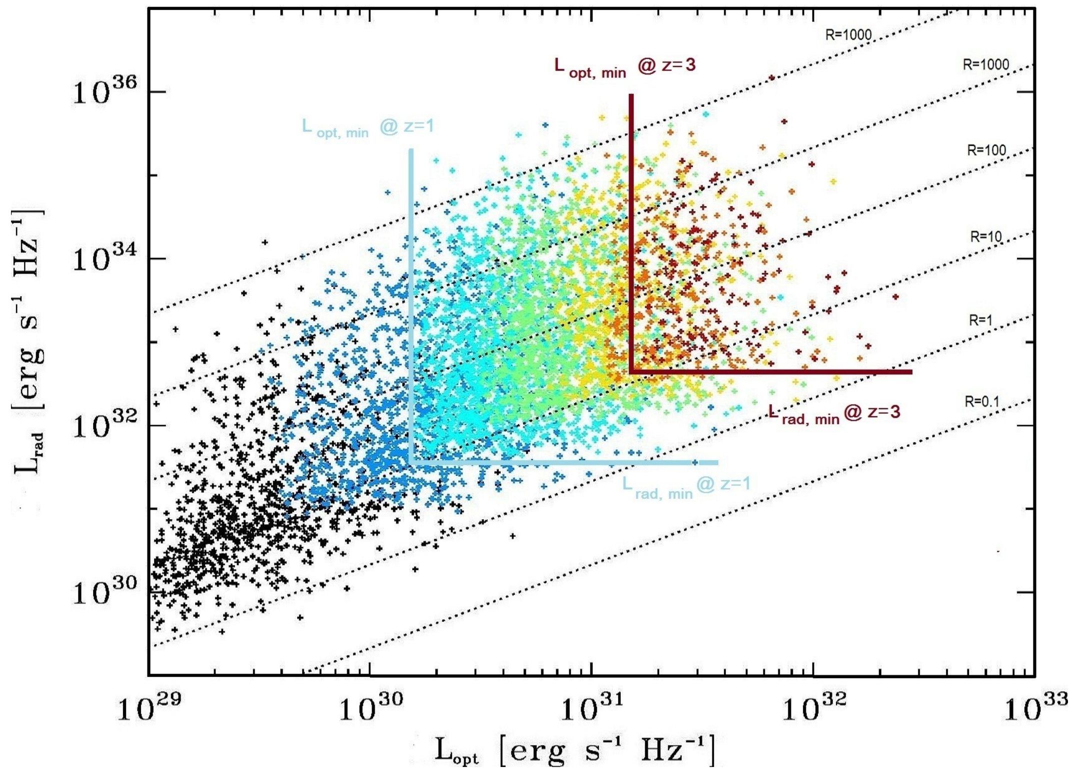


$$L_r \propto L_o^{1.2}$$



Luminosity-Luminosity Correlation

Distance or Redshift Effects

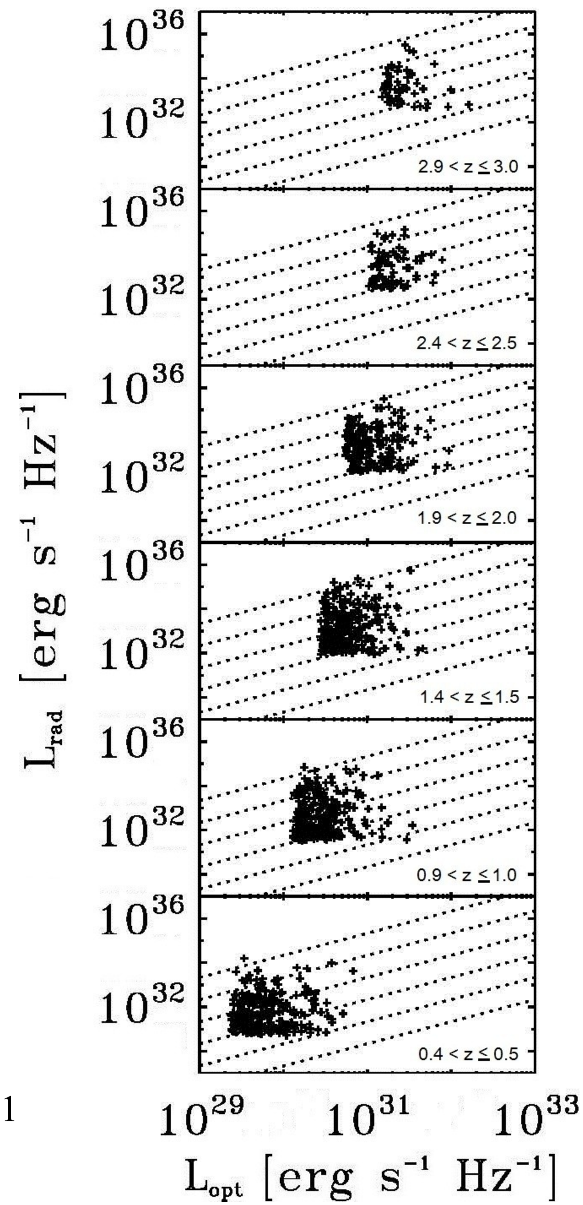


Whole Sample *Corr. Coef. ~0.74*

Partial Corr. Coef. = 0.11 *(Prob<0.01)*

$$r_{L_oL_r;z} = \frac{r_{L_oL_r} - r_{zL_o}r_{zL_r}}{(1-r^2_{zL_o})(1-r^2_{zL_r})}$$

Krakow Jet201



Correl. Coef.

-0.134

0.068

0.110

-0.003

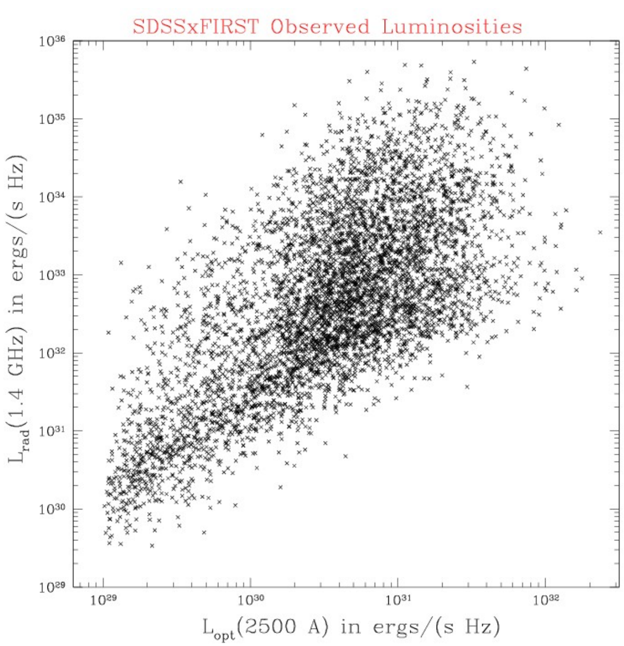
0.270

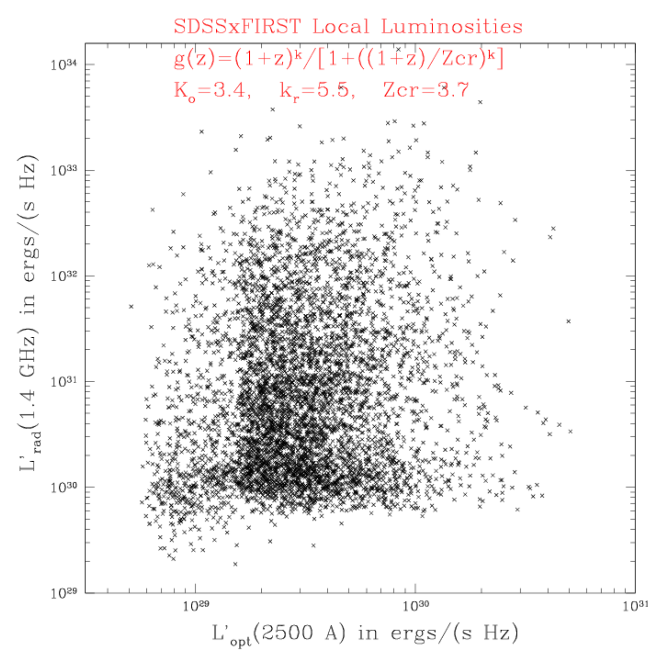
0.127

Luminosity-Luminosity Correlation

Observed vs Local Distributions

Since radio and optical luminosities evolve differently this will induce more correlation between luminosities.
Given the luminosity evolutions we can transform all luminosities to the local values $L_i' = L_i/g_i(z)$



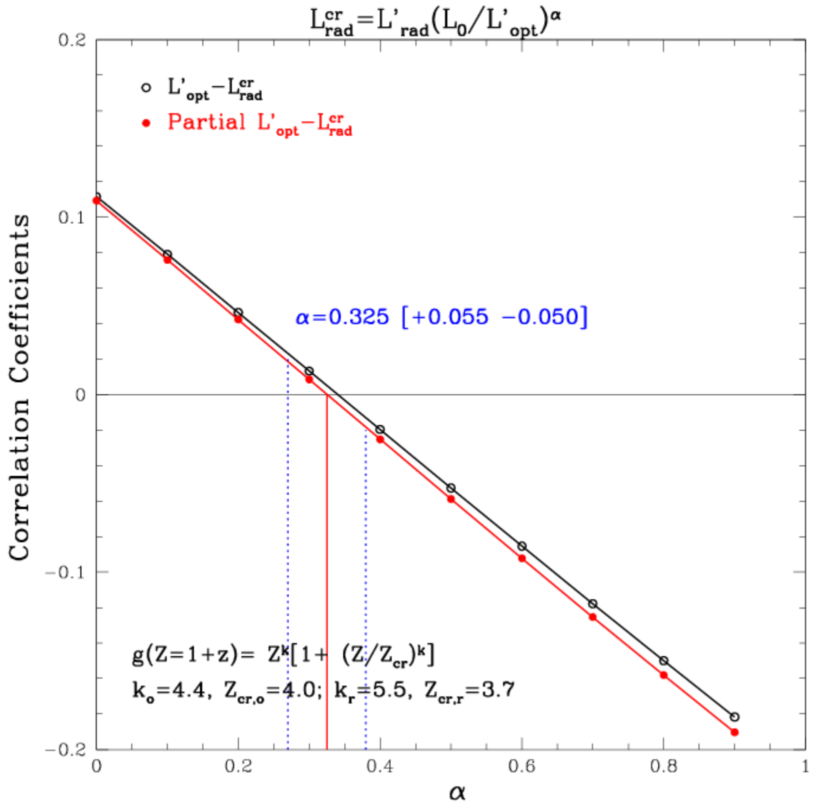


Luminosity-Luminosity Correlation
Of Local Luminosities

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

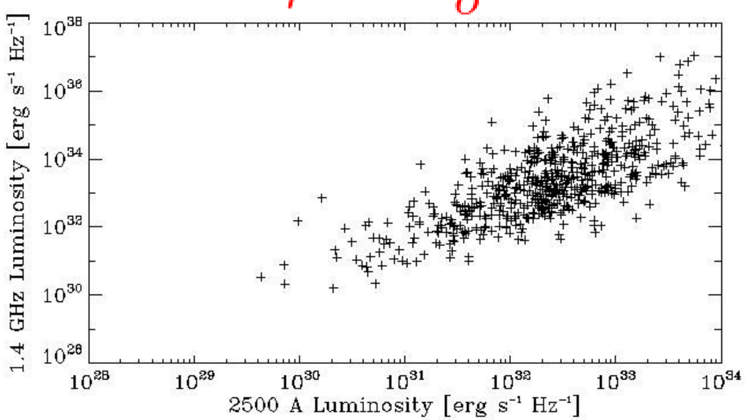
$$L'_{\rm rad} \propto {L'_{\rm opt}}^{0.325}$$



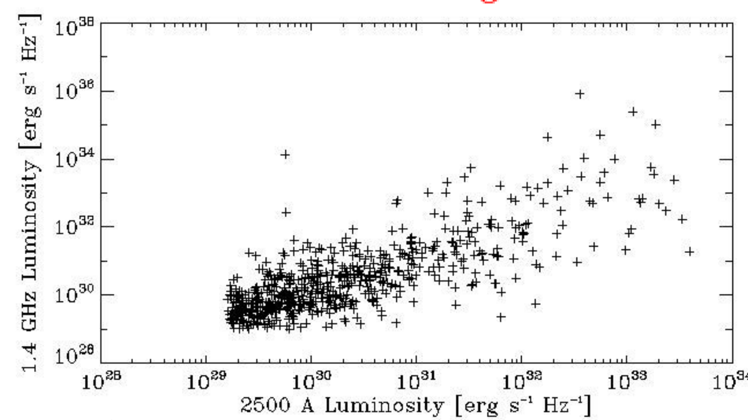
Luminosity-Luminosity Correlation

Measured Correlations

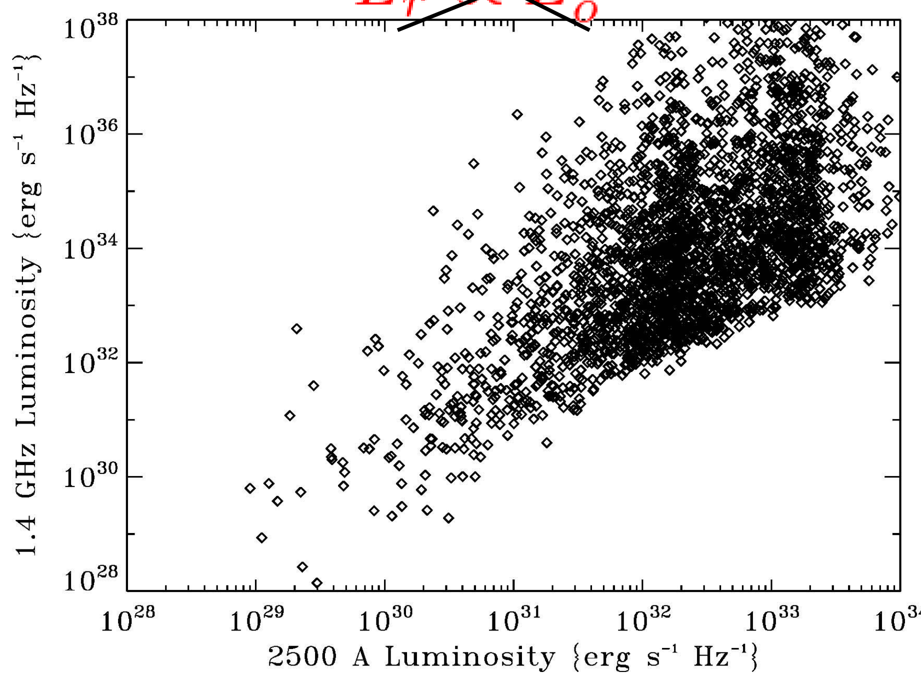
$L_r \propto L_o^{1.3}$



$L_r \propto L_o^{0.8}$



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

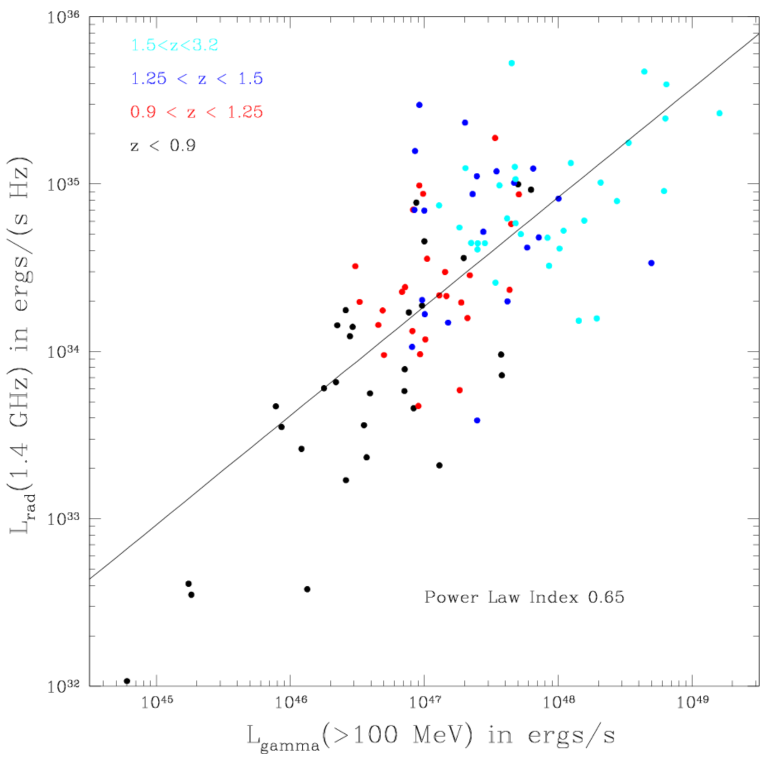


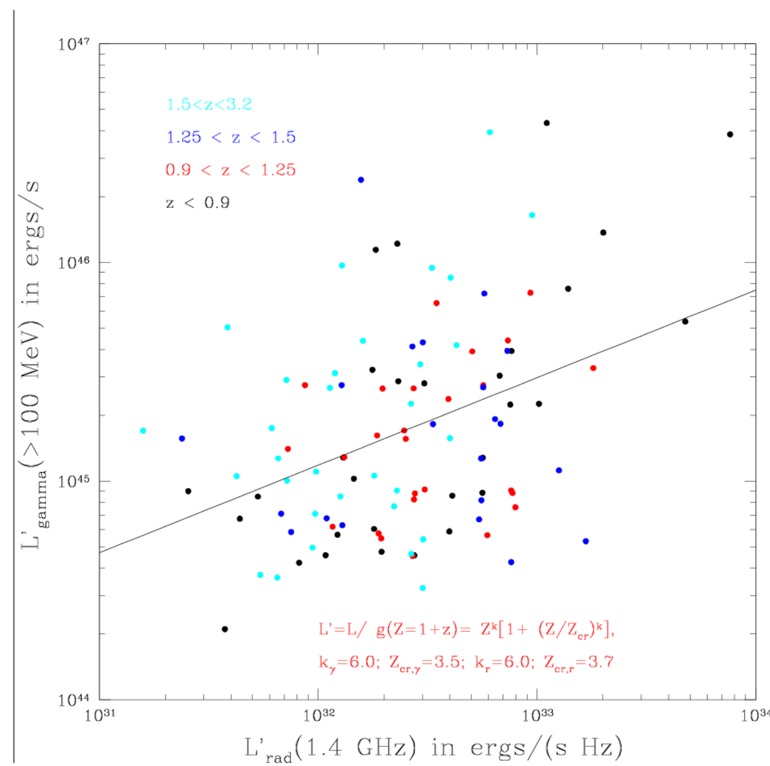
$L'_{\mathrm{rad}} \propto {L'_{\mathrm{opt}}}^{0.325}$

Luminosity-Luminosity Correlation

Radio Gamma-ray

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

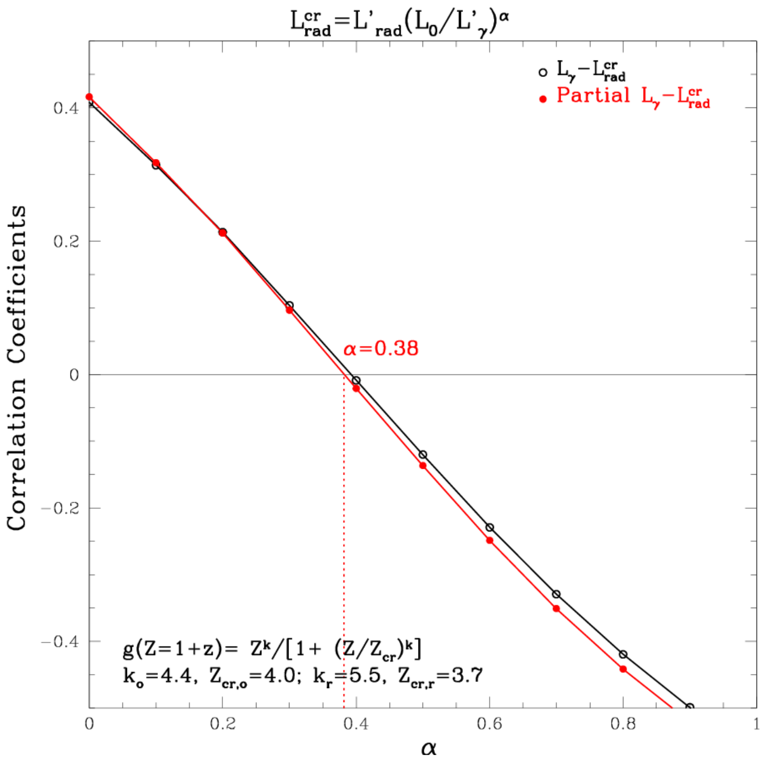


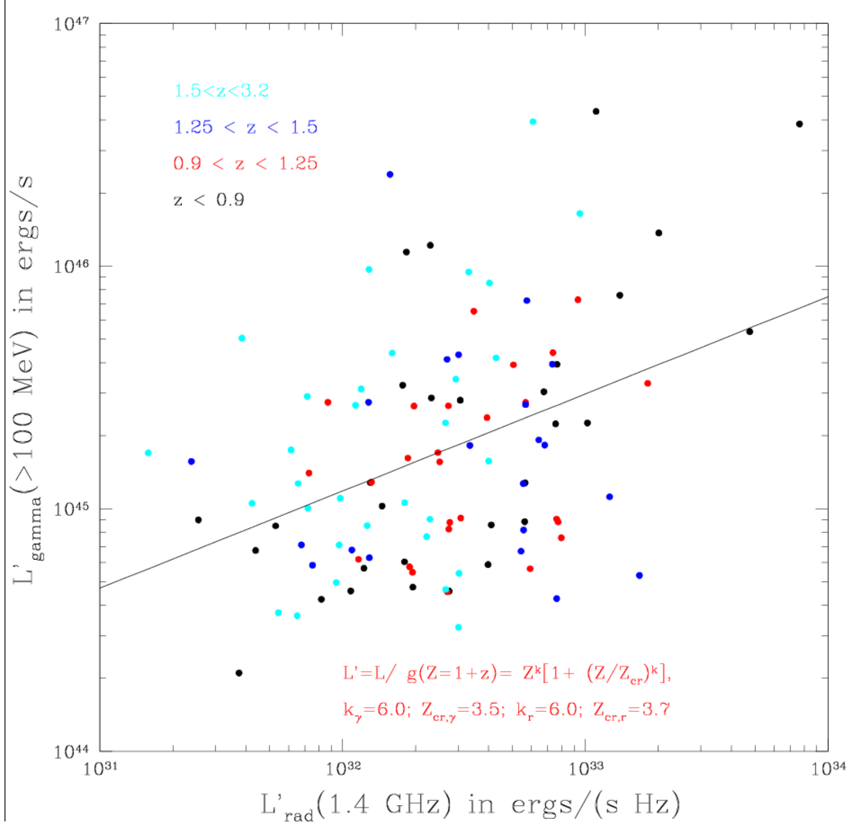


Luminosity-Luminosity Correlation

Radio Gamma-ray

$$L'_{\rm rad} \propto {L'_\gamma}^{0.4}$$





Summary and Conclusions

Radio Loudness Distribution

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.

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

Summary and Conclusions

Luminosity-Luminosity Correlations

In general the observed luminosities show strong correlations.

This is result of several factors

a. Observational selection biases

b. Distance dependence of luminosities (Partial Correlation)

c. Cosmological evolution of luminosities

We have shown that one can account for all these factors and find

the true intrinsic correlation

The intrinsic radio-optical correlation was found to be weaker but highly significant indicating a

relation between accretion disk and jet emissions

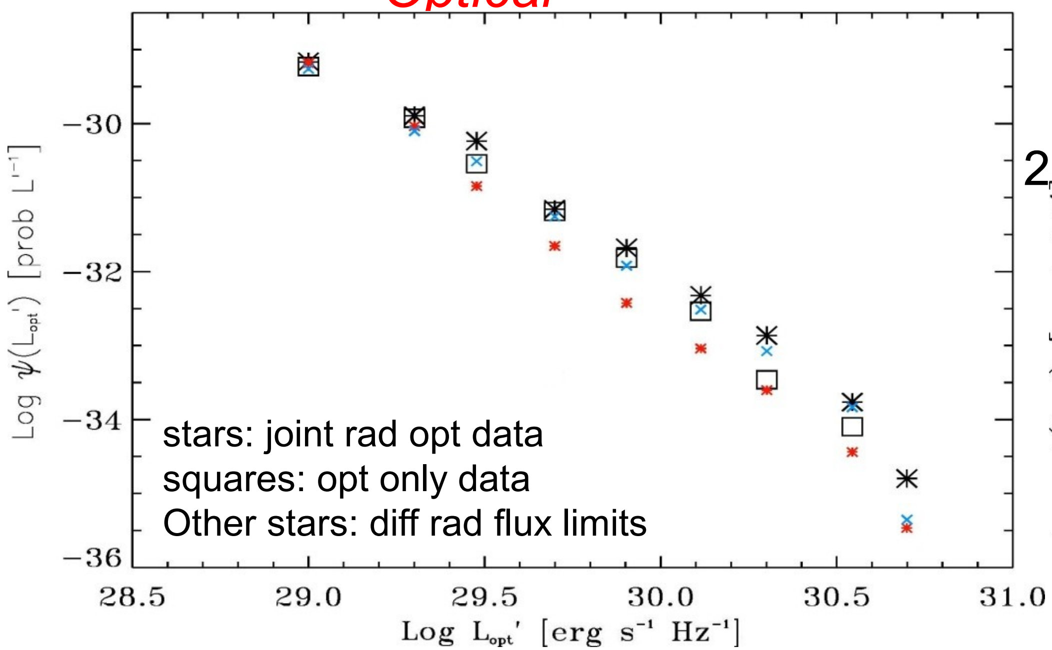
Preliminary analysis of radio-gamma-ray data shows similar luminosity evolution and a stronger L-L correlation indicating

more intimate relation between these emissions

RESULTS

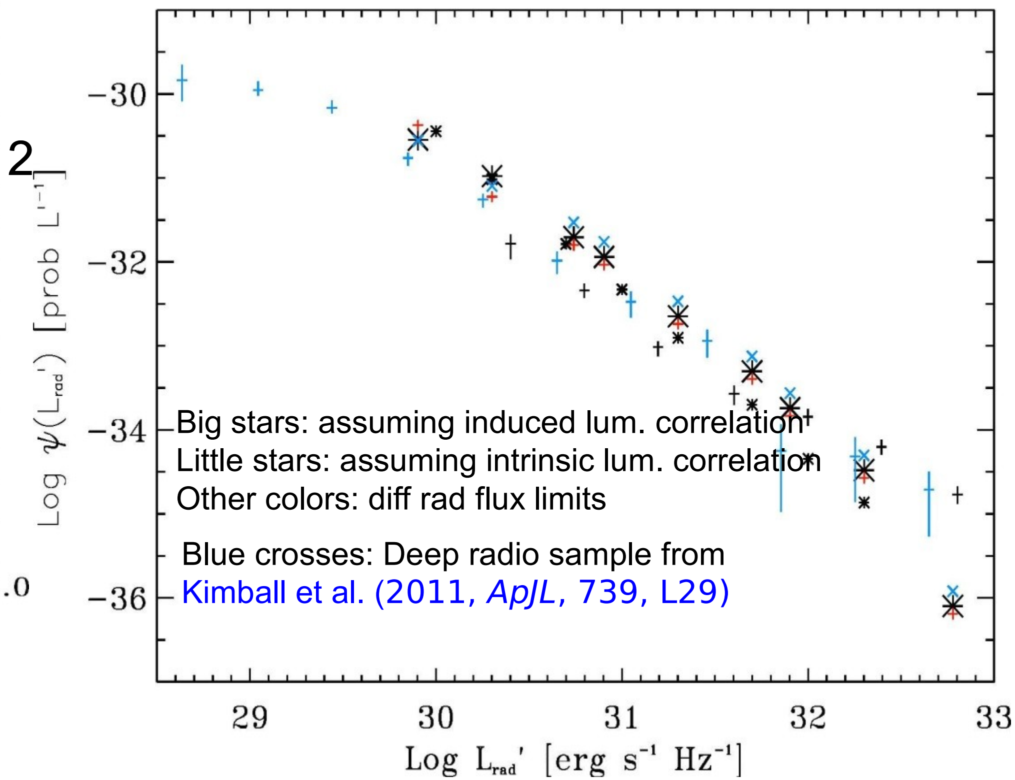
3. Local Luminosity Functions

Optical



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

Radio

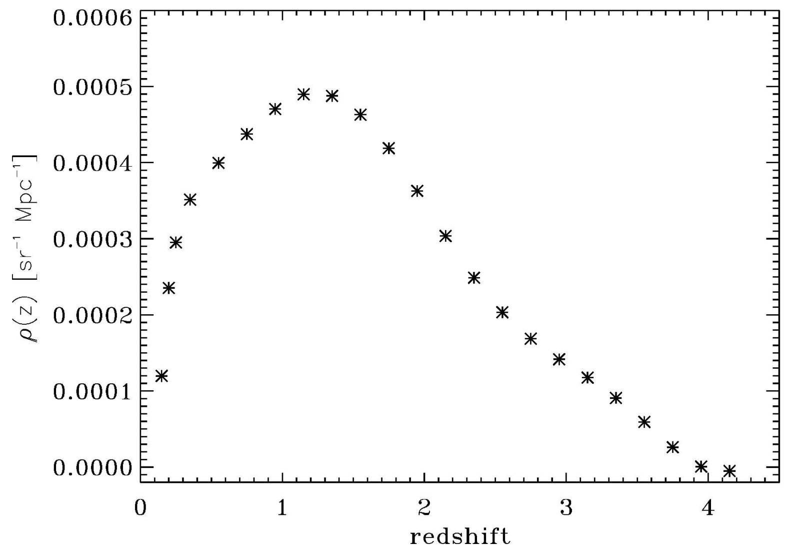


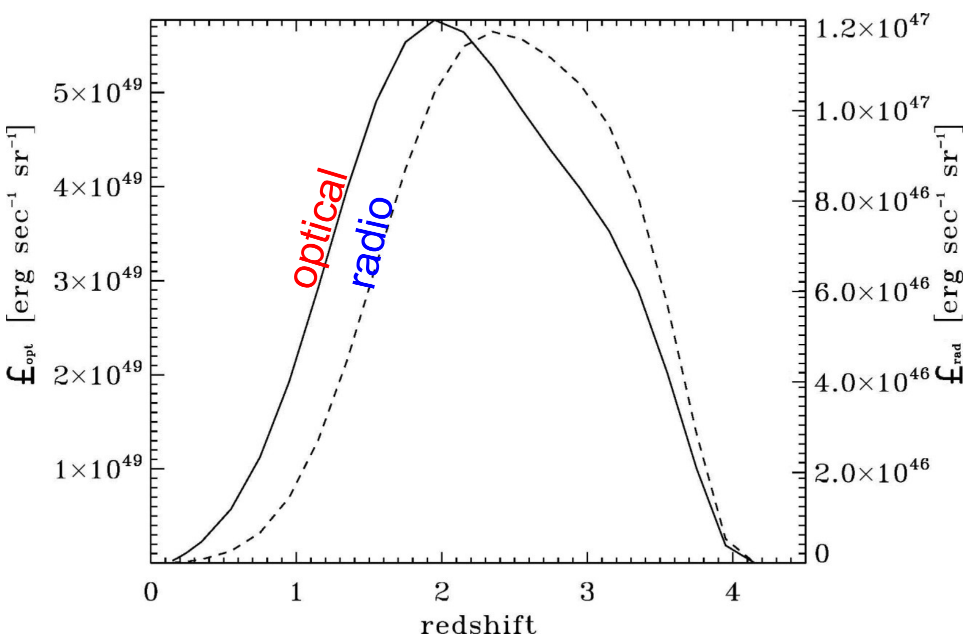
RESULTS

4. Co-moving Number Density and "Light" Evolution

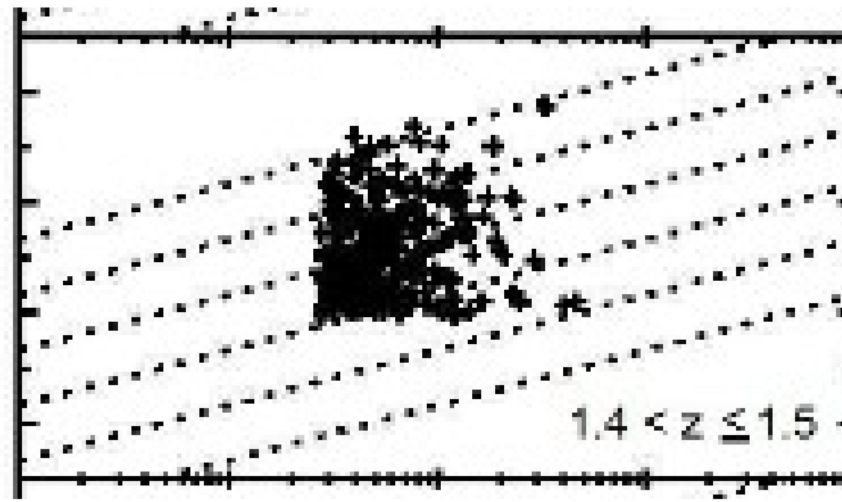
$$\rho(z)$$

$$\mathcal{L}(z) = \langle L \rangle g(z) \times \rho(z)(dV/dz)$$





Partial Correlation: *Some Caveats*



1. Effects of Truncation

Appears that we are seeing a corner of the distribution

Efron and Tibshirani 1996 Annals of Statistics

Log-normal distribution with the center outside the observed range

2. Distribution power-law
3. Requires Correlations between Luminosities and Redshift

$$r_{L_oL_r;z} = \frac{r_{L_oL_r} - r_{zL_o}r_{zL_r}}{(1 - r^2_{zL_o})(1 - r^2_{zL_r})}$$

4. Parson correlation is not robust and is affected by outliers

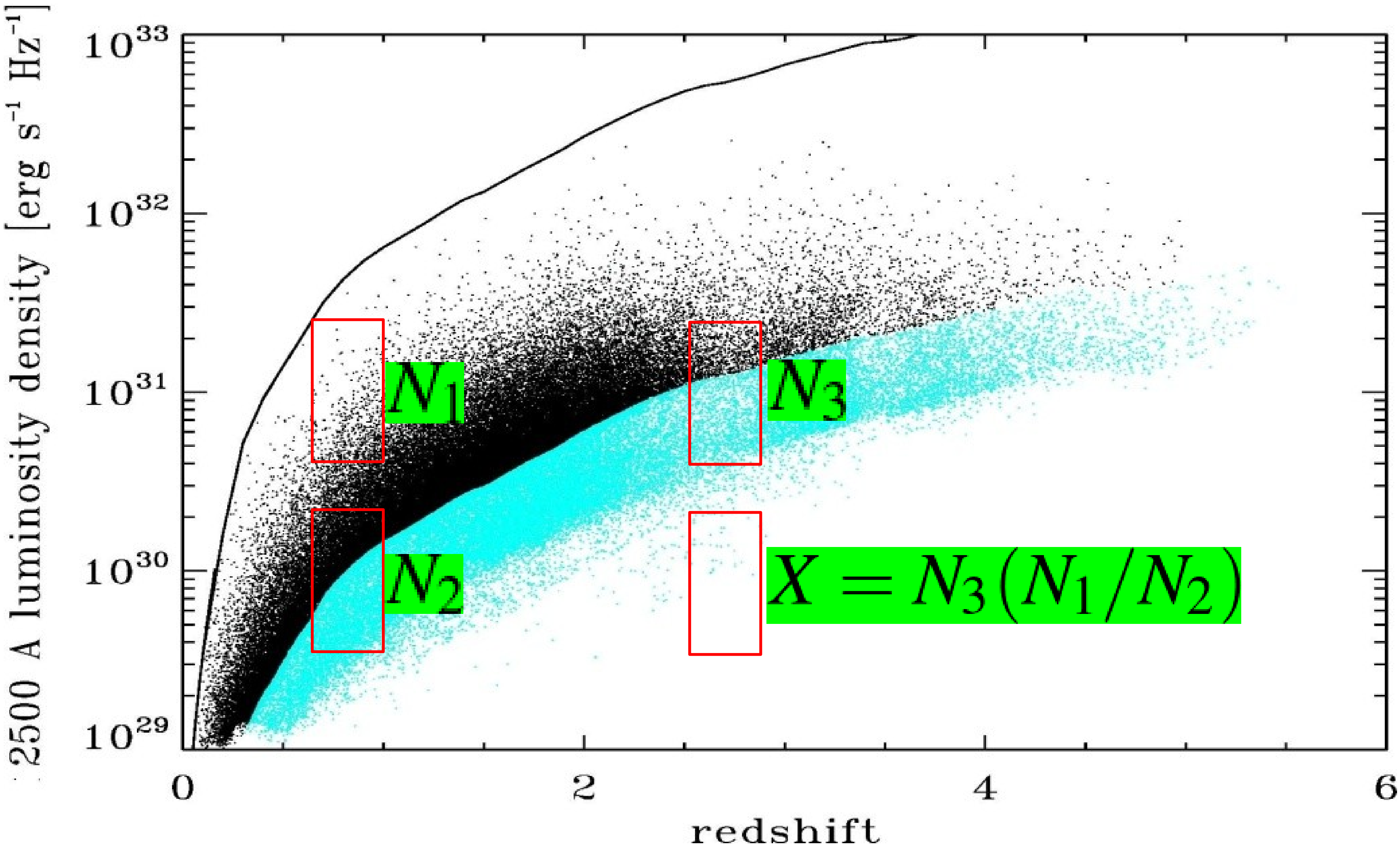
Luminosity Function and Evolutions

1. Test for independence of two (or more) variables in a bi-(or multi)-variate truncated data

2. Remove the correlation by a variable transformation e.g.

3. Determine the mono-variate distributions of now the independent variables $\psi(L')$ and $\rho(z)$

Distributions of Uncorrelated or Independent Variables



Distributions of Uncorrelated or Independent Variables