Evolution of the quasar radio luminosity function below 1mJy

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20 July 2017

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SKA AFRICA
SQUARE KILOMETRE ARRAY

Tools to beat noise

- **Long observations** ($\sqrt{t}$) but systematics and confusion!
- **New telescopes** with long baselines
- **P(D) analysis** (Scheuer 1957):a blind analysis of the probability distribution of a flux in a map to measure total noise contribution from faint sources below the confusion limit.
- **Stacking:** Select population in a deeper catalogue and use their positions to find their counterparts in radio map even if source is not detected. Then get the average

Below the detection threshold

- Source counts

  With redshift and stellar masses

- Luminosity functions
- (Specific) Star formation rates
- Far-infrared–radio correlation
- Spectral indices as function of flux
- Polarization fraction as function of flux
- Two-point correlation function
- HI mass function + evolution...

A wealth of science to be done with data below the detection threshold

Get more than a statistic

- Lots of science has being done with stacking. However, it gives a single average.

- ‘Beyond stacking’ (Mitchell-Wynne+ 2014)
- ‘Bayesian likelihood analysis’ (Vernstrom+ 2014)
- ‘Parametric stacking’ (Roseboom & Best 2014)
- ‘Far beyond stacking’ (Zwart, Santos & Jarvis 2015)
- ‘Evolution of the quasar radio luminosity function below the detection threshold’ (Malefahlo + in prep)

- Need a parametric model for observed binned flux-count , use Bayes theorm with a Poisson likelihood function.

Bayes theorem

$$\mathcal{P}\left(\mathbf{\Theta}|\mathbf{D},H\right) = \frac{\mathcal{L}\left(\mathbf{D}|\mathbf{\Theta},H\right) \mathit{\Pi}\left(\mathbf{\Theta}|H\right)}{\mathcal{Z}\left(\mathbf{D}|H\right)}.$$

$\mathcal{P}$: posterior distribution
Θ : parameters
D : Data
H : model
Π : Prior
$\mathcal{Z}$: Bayesian evidence

The measured flux $S_m = S + n$, where the noise n follows a Gaussian with σ. Assuming that the number of sources in the flux bin [S_{mi} ,S_mi+ Δs_{mi}] follows a Poisson distribution then the likelihood is,

$$\mathcal{L}_i\left(k_i|\boldsymbol{\theta}\right) = \frac{I_i^{k_i}\mathrm{e}^{-I_i}}{k_i!},$$

k_i : no: of sources
I_i : mean no: of sources in bin

$$I_i = \int_{S_{min}}^{S_{max}} \mathrm{d}S \frac{\mathrm{d}N(S)}{\mathrm{d}S} \int_{S_{m_i}}^{S_{m_i}+\Delta S_{m_i}} \mathrm{d}S_m \frac{1}{\sigma_n\sqrt{2\pi}} \mathrm{e}^{-\frac{(S-S_m)^2}{2\sigma_n^2}}.$$

S *:* Flux
S_m *:* Noisy Flux
dN/dS : Source counts
σ : Noise rms

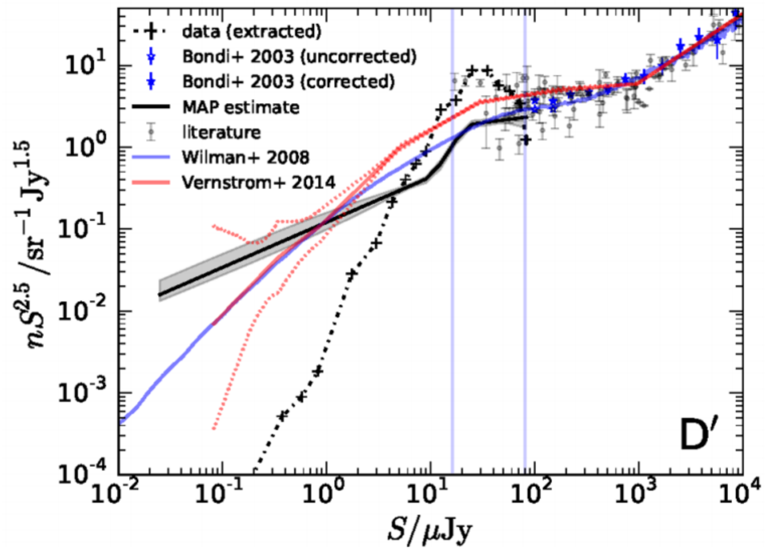
Mitchell-Wynne+ 2014

Bayestack

Bayestack

Zwart, Santos & Jarvis 2015:
Very Large Array (VLA) data stacked at the positions of sources from the VISTA Infra-red Deep Extragalactic Observations (VIDEO) survey.

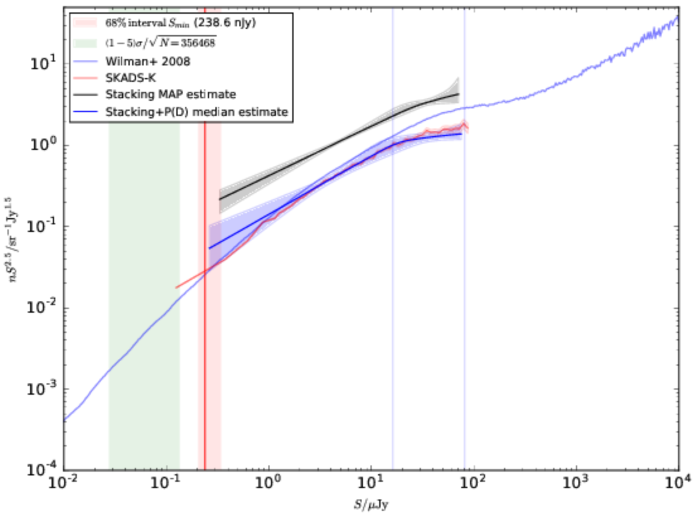
- Zwart et.al 2015



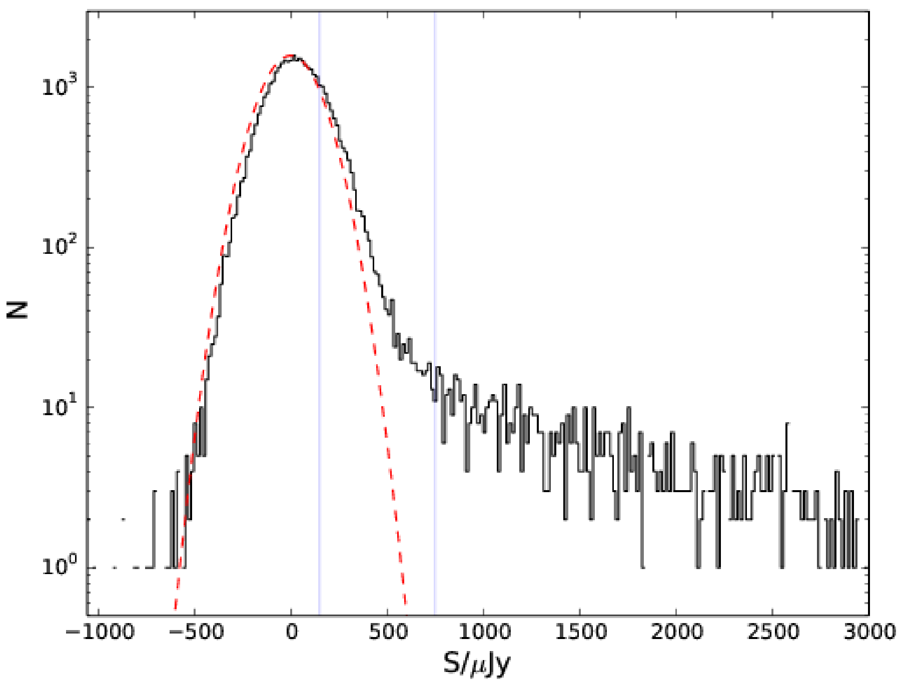
P(D) analysis + Stacking

Song Chen, Zwart, Sanotos, Jarvis:
combined stacking with P(D) analysis to account for confusion.

Chen + in prep



SDSS II&III quasars – FIRST



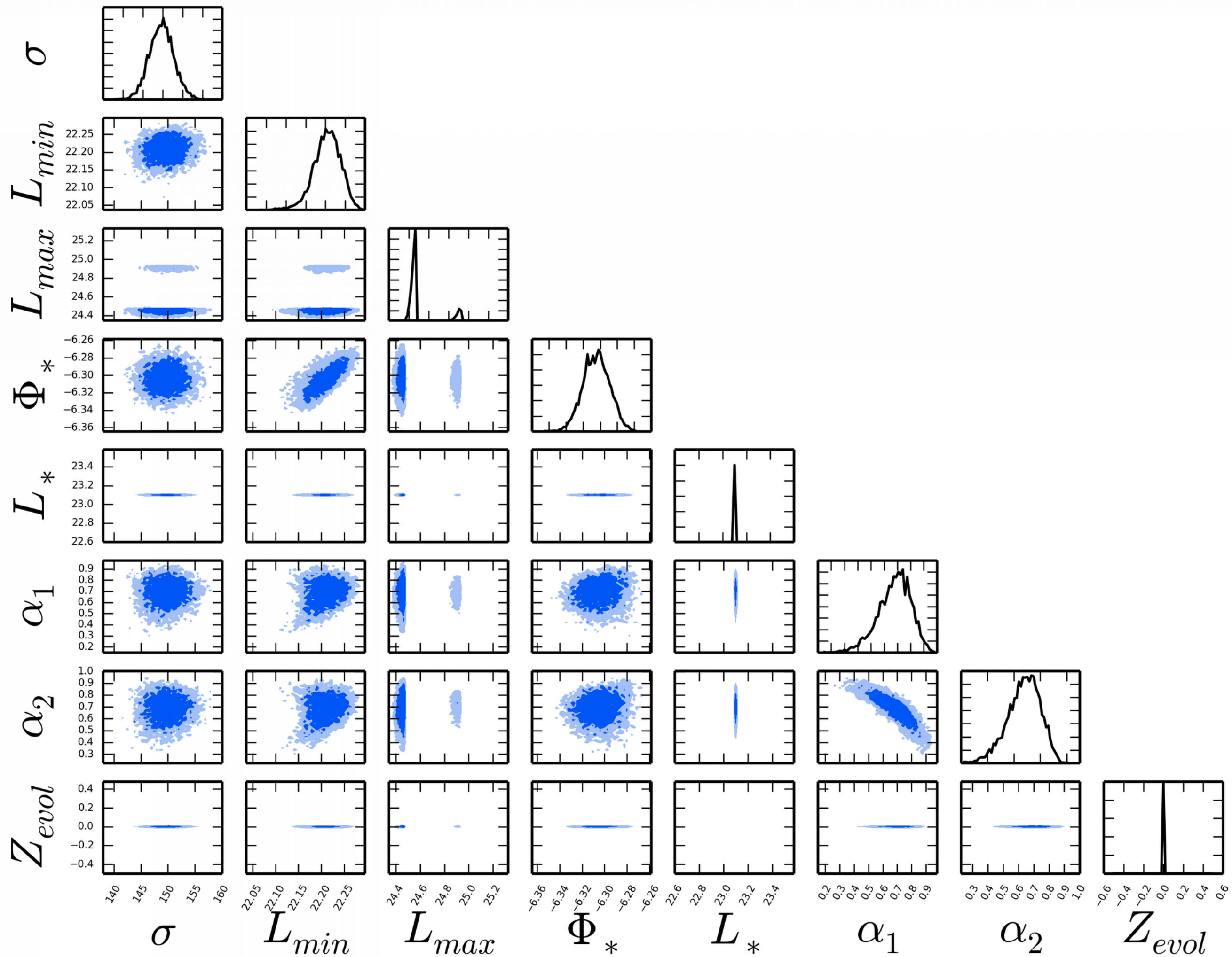
$$\frac{dN}{dS} = \frac{dN}{dL}\frac{dL}{dS} = \Phi(L) V_M 4\pi D^2 (1+z)^{1-\alpha}$$

D_L : luminosity distance
Z : redshift
V_m : (maximum) volume
$\Phi(L)$: luminosity function model

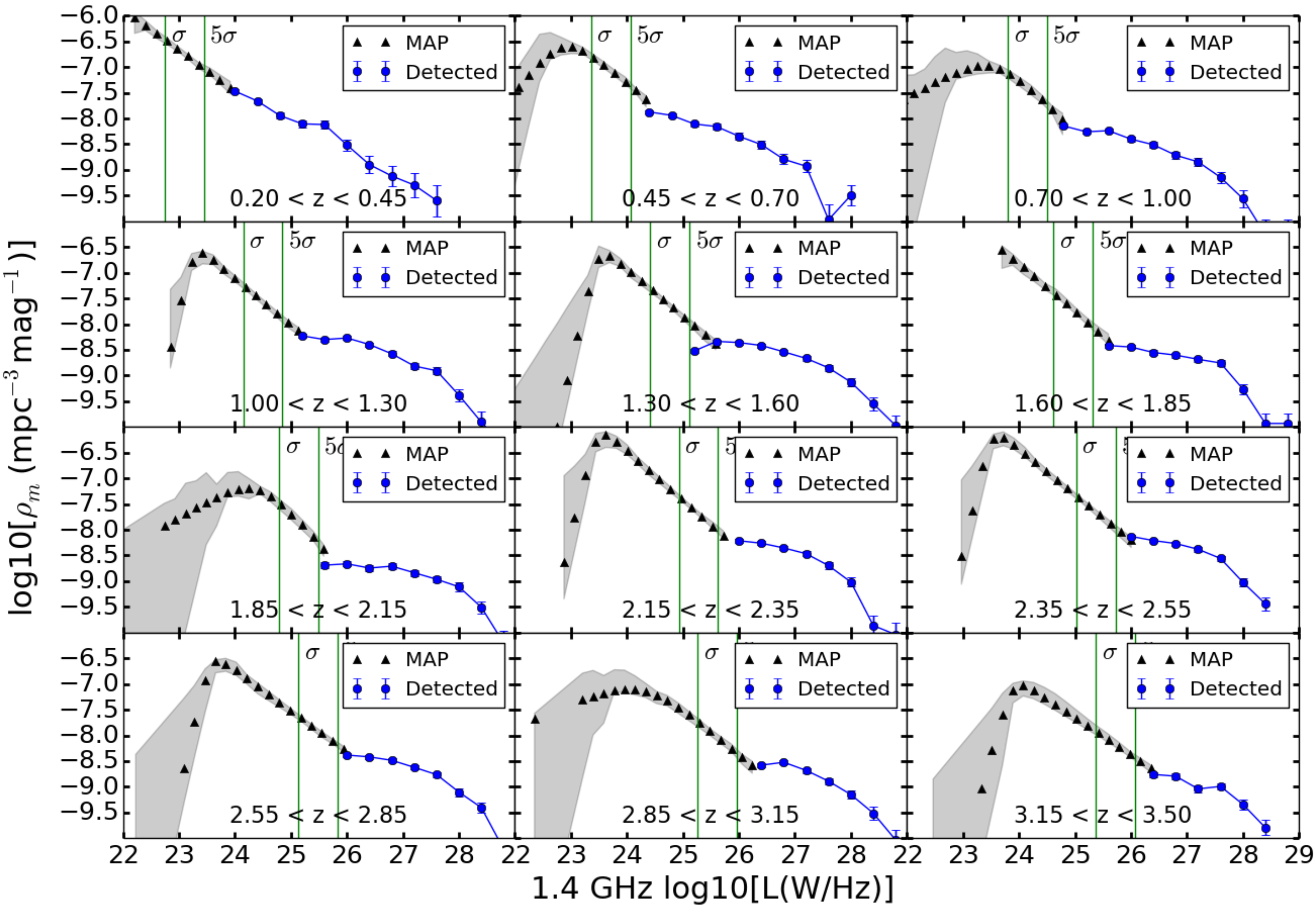
Fit luminosity function (LF) models to the noisy flux data using a Bayesian stacking technique (Zwart et al. 2015)

$$\Phi(L) = \frac{\Phi_*/L_*}{(L/L_*)^\alpha + (L/L_*)^\beta}$$

Posterior distribution



Radio luminosity functions (RLF) of optically selected quasars



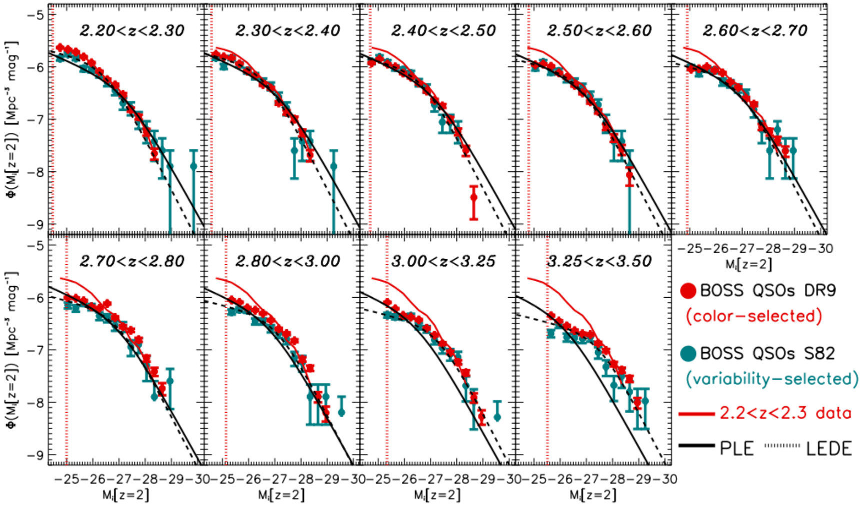
Optical selections

Problem

- Our RLF of optically selected quasars suffers from optical incompleteness due to:
- Optical selection functions (colour selection)
- Instrumental limitations (fiber collision)
- Bad data

Solution

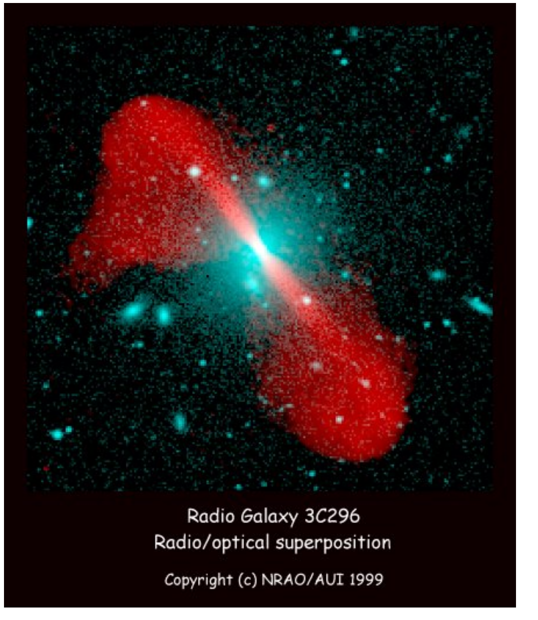
- Find SDSS luminosity function (corrected for these selection effects) in literature
- Use the optical – radio luminosity correlation to predict the true RLF of optically selected quasars



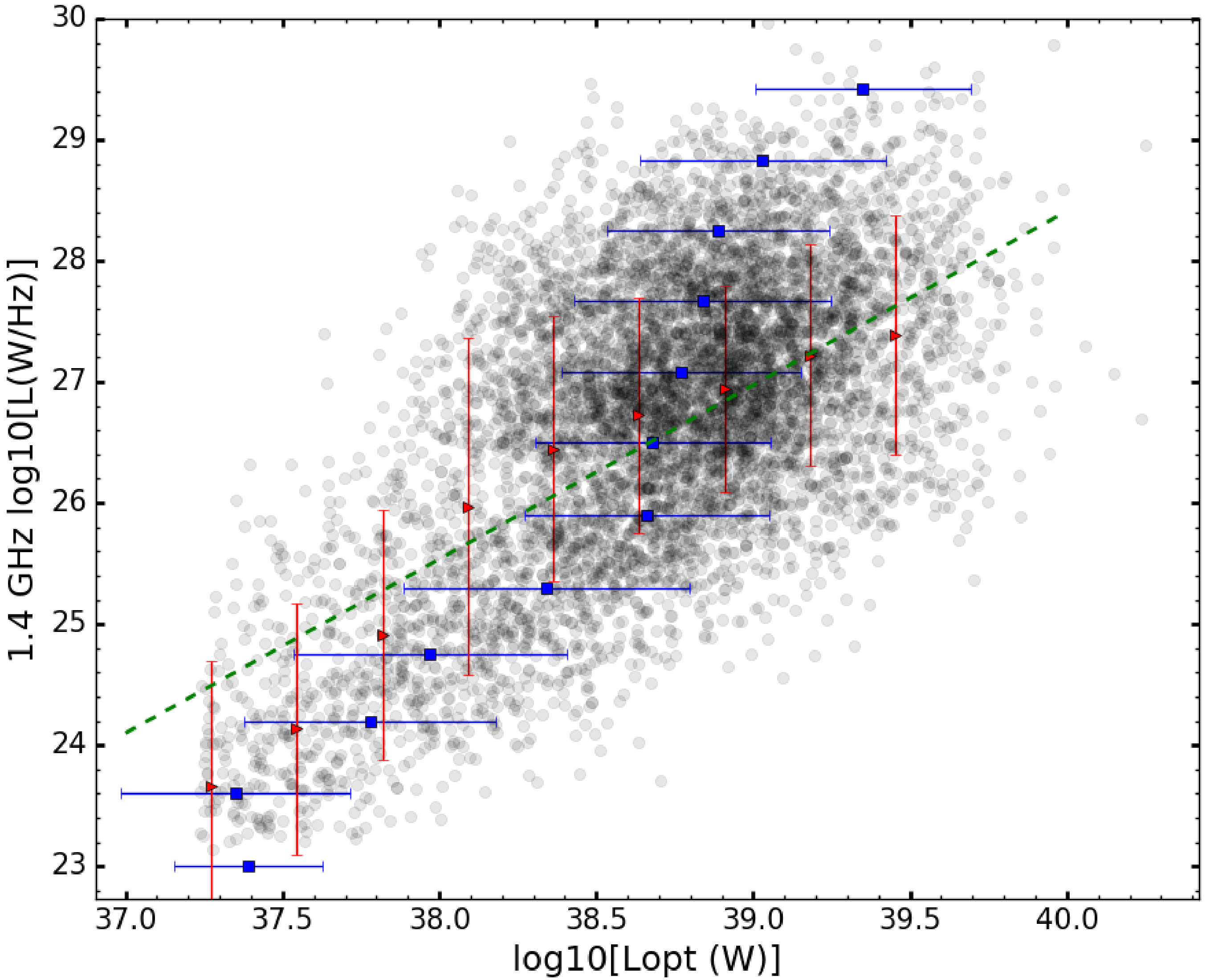
- Ross et. al 2013

Radio - optical correlation

- Optical emission in a quasar (AGN) comes from accretion of matter into the black hole
- Radio emission mainly comes from jets.
- A good correlation is expected if jets are linked to the accretion rate.



FIRST - SDSS correlation

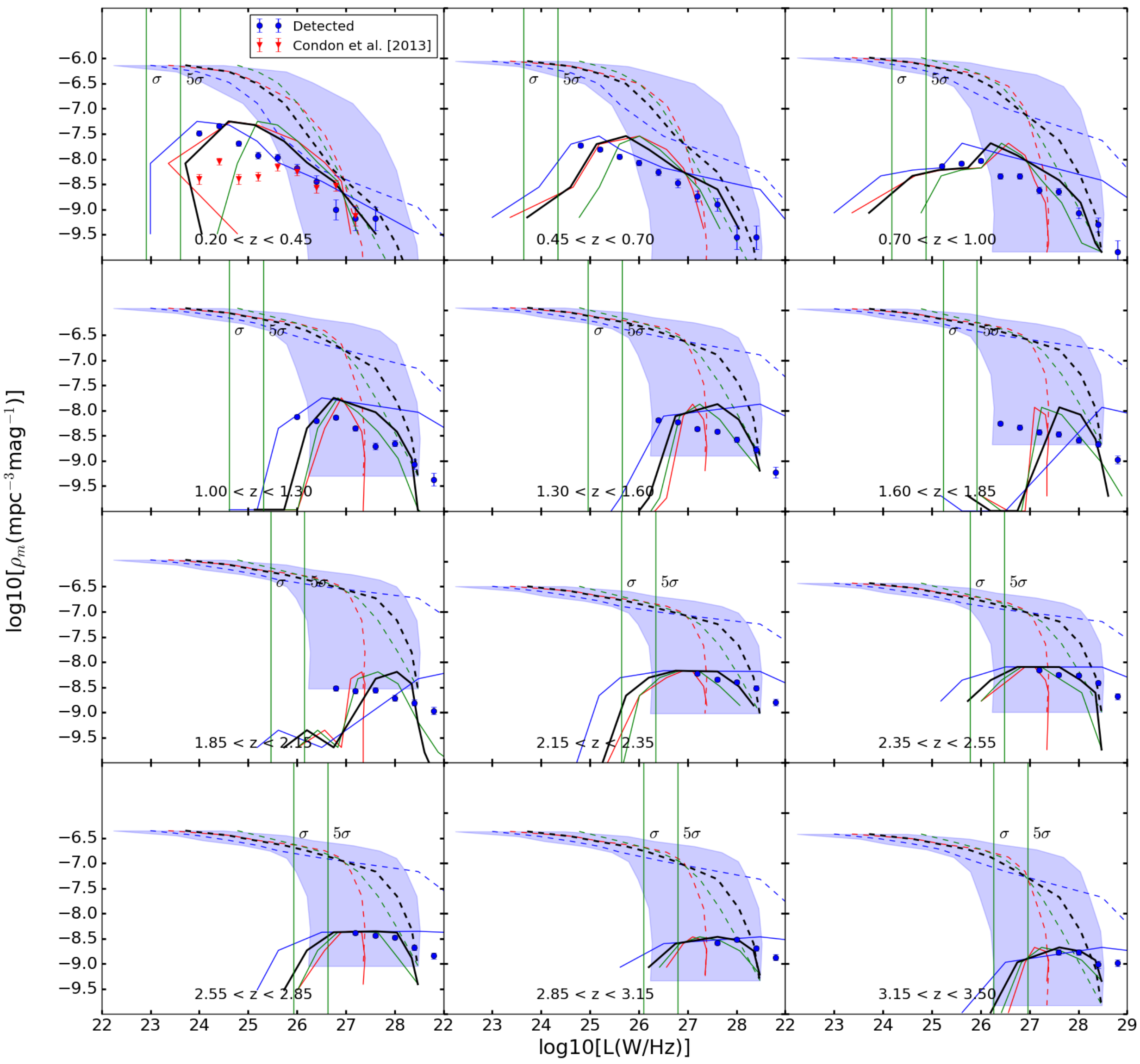


Correlation scatter?

- The radio luminosity is not a precise measure of the bulk power in the jets as it also depends on the gaseous environment of the radio source.
- The reddening of optical quasar light might contribute to the scatter.
- Optical variability may increase the scatter and may also depend on luminosity (0.2 mag in B band in the order of years).
- The sampling of the radio-optical planes strongly non-uniform.

Serjeant et al. 1998

True RLF of opitical quasar



Work in progress

Conclusions and future work

- No more median stack, Bayesian frame work below is well establish
- code is available `BAYESTACK` (jz@uwcastro.org)
- We used bayestack to push the RLF an order of magnitude below the detection threshold.
- general steepening of the RLF at low luminosities suggests another source of emission (increasing contribution from SF)
- Or a break down in the link between accretion rate and radio luminosity.
- Deeper data from the new generation of radio telescopes will allow fainter detections above the threshold but using stacking techniques such as the one presented in this project puts one a step ahead to much fainter radio luminosity function

To do:

- Include evolution in the model
- Fit other models, Schechter function, triple power-law
- Malefahlo 2017 in prep