LOW RADIO FREQUENCY SPECTRAL PROPERTIES OF milliJansky RADIO SOURCES

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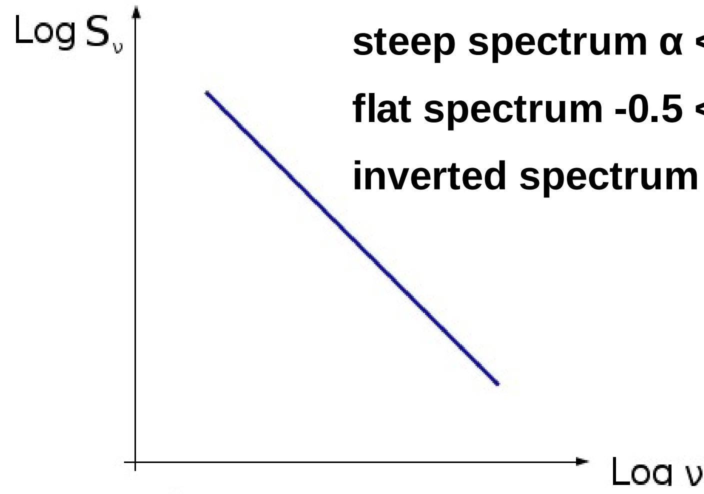
Outline

- **RADIO SPECTRA**
- **WEAK RADIO SOURCES**
- **WSRT DATA of a deep sky field at 325, 341, 375 MHz**
- **NOISE ANALYSIS**
- **CATALOGS EXTRACTION**
- **SOURCE COUNTS**
- **SPECTRAL INDEX**

Radio spectra

- **Continuum radio emission from galaxies can be due to synchrotron radiation, emitted by high-energy electrons accelerated in a magnetic field**
- **Synchrotron radiation from a high number of electrons has a <u>power law spectrum</u>**
- **Synchrotron emission can be produced in black holes magnetic fields (AGNs) or by SNe explosions in star forming regions (SFGs)**
- **Radio spectra → power law**

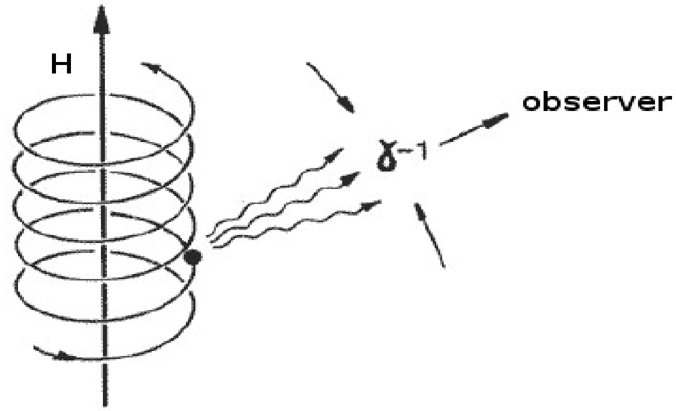
  $S_\nu \propto \nu^\alpha$, **α spectral index**



steep spectrum α < -0.5

flat spectrum -0.5 < α < 0

inverted spectrum α > 0



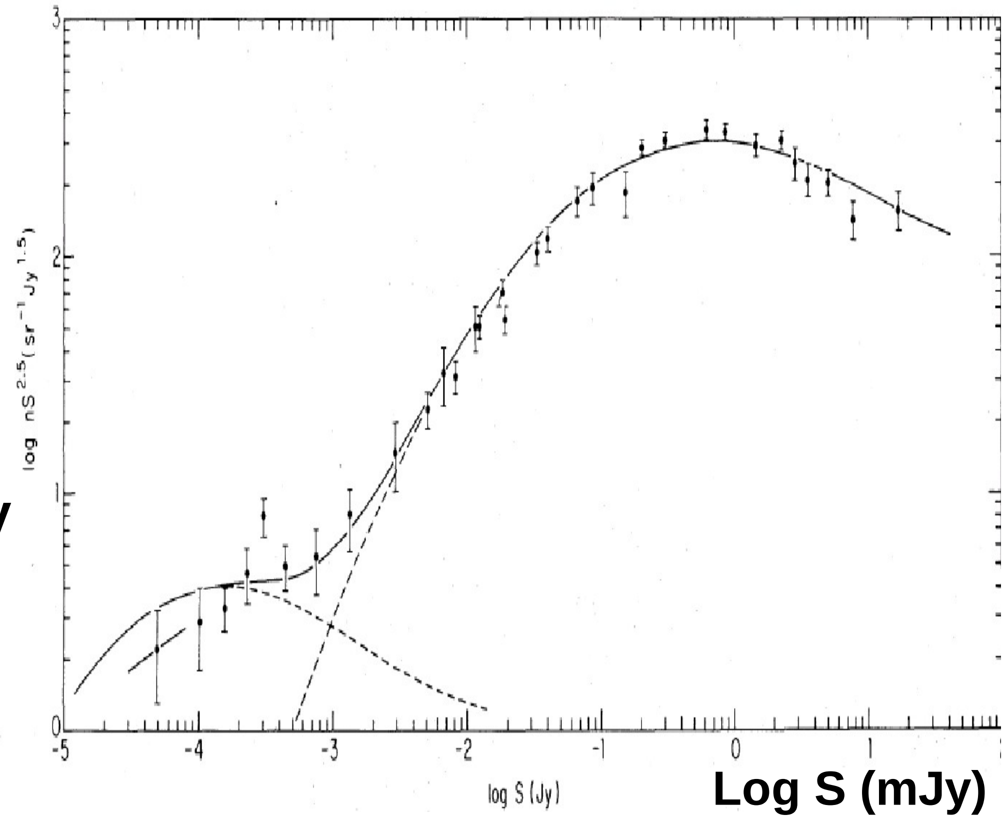
α~-0.1 → thermal emission

α~-0.7 → synchrotron

Sub-milliJansky radio sources (1)

- **Source counts → number of radio sources per unit solid angle with flux density between S and S+dS**
- **Flattening of source counts at ν=1.4GHz showed an excess of sources at low flux density (S~1-10mJy)**
- **This is due to a new population of radio sources which does not show up at higher flux density**

Log $nS^{2.5}$ (sr^{-1} $Jy^{1.5}$)



Log S (mJy)

ν=1.4GHz - Condon 1984

Sub-milliJansky radio sources (2)

- S>20 mJy sources have steep spectra
- S<20 mJy mixed inverted/flat spectra (Flat spectra due to compact objects – no jets)
- Spectral index studies of weak radio sources between 5 GHz and 1.4GHz, between 1.4GHz and 610MHz
- At S < 10 mJy and ν < 1.4 GHz spectral properties of sub-mJy population are not well known
- Studing such properties is very useful for future LOFAR surveys at very low frequencies

AIM of this work

To study spectral properties of radio weak population at lower frequencies (325MHz, 341MHz, 375MHz) than in the past

Sub-milliJansky radio sources (3)

- <u>Composition</u> → optical counterparts of radio sources
- Low identification rate, no agreement in composition before 2001
- <u>Radio to Optical ratio</u> → selection effect on sources detected by a survey, depending on radio&optical sensitivity of observations (Prandoni et al. 2001)
- Recent studies (Prandoni et al. 2010) → Mainly radio quiet AGNs and Star Forming Galaxies ($\nu \geq 1.4$GHz)

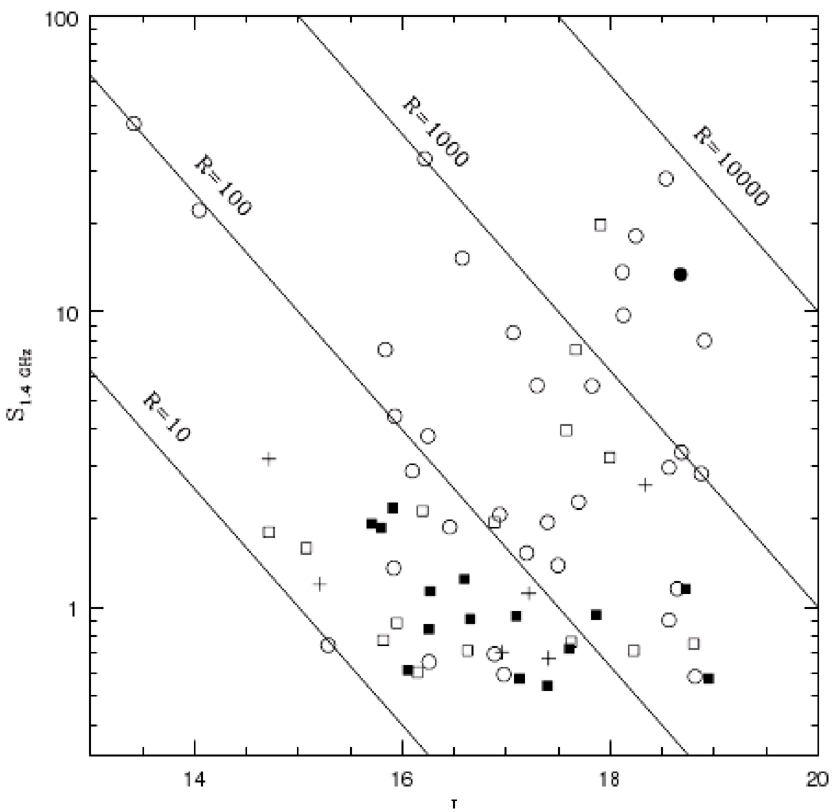


Fig. 4. 1.4 GHz flux density (in mJy) versus I magnitude; lines represent constant values of the radio to optical ratio R. Symbols represent different spectral classes: Early Type Spectrum + Liner (empty circles), Late Type Spectrum (empty squares), Starburst + post-SB (filled squares) and AGN (crosses). Also drawn is the single object for which spectroscopy is not available (filled circle).

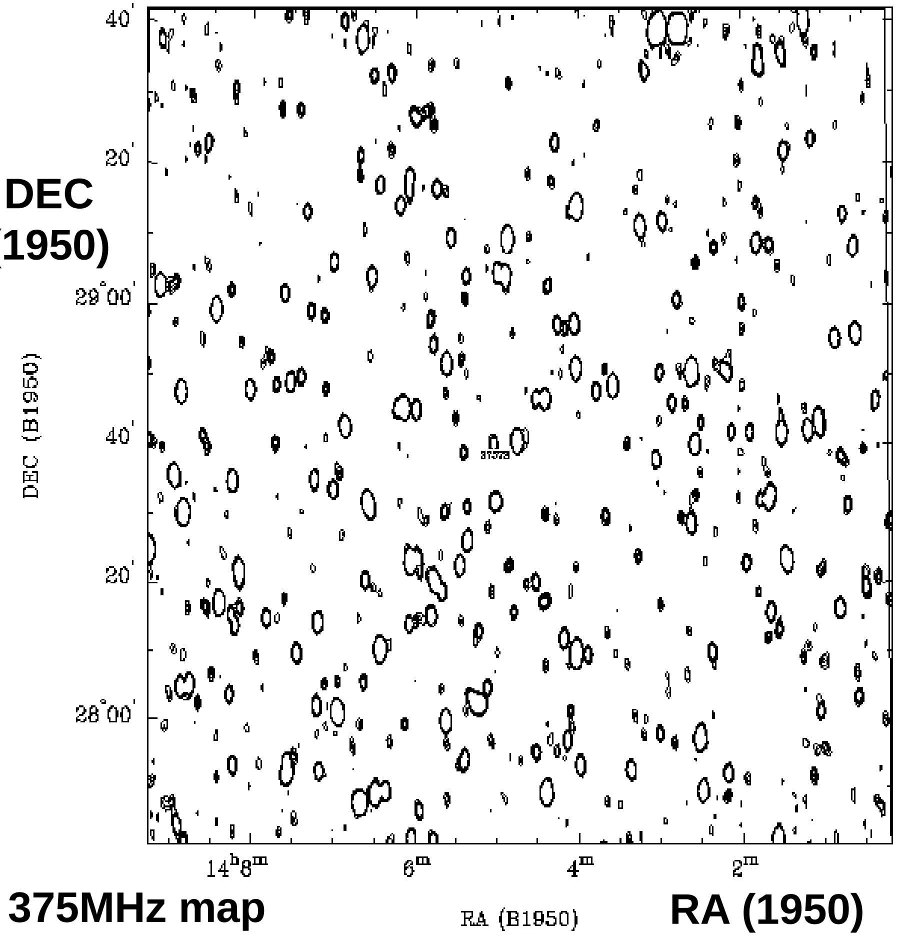
A. Di Vincenzo

Data

- **Westerbork (WSRT)**
  deep sky field observed at
  325, 341, 375 MHz
- **3 maps, 6x6 deg² each,**
  field F1404
- **Field center is**
  14:04:45.60 +28:41:29.004
- **Beam size**

ν	Major axis b (arcsec)	Minor axis a (arcsec)
325MHz	108,00	52,00
341MHz	102,80	49,50
375MHz	93,60	45,10

DEC (1950)



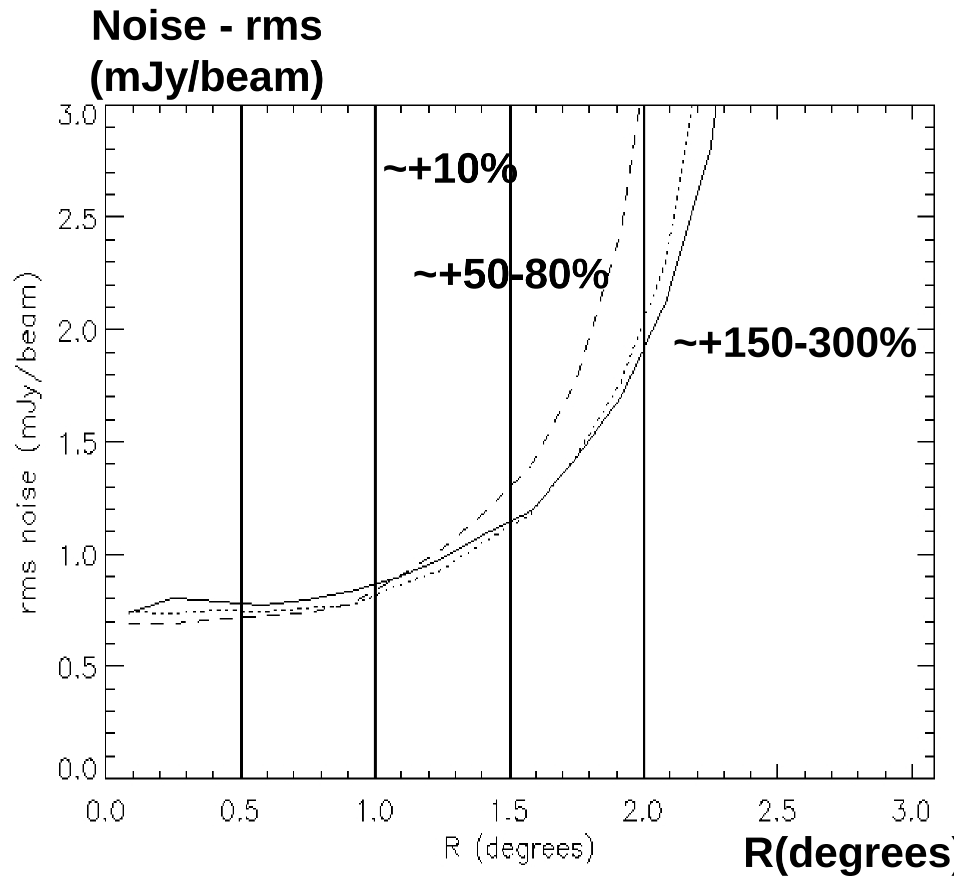
375MHz map **RA (1950)**

contours at 3, 6, 9, 12 σ

Noise Analysis

- **In radio observations noise level increases from center towards periphery**
- **Different methods have been used to compute noise analysis on field F1404**
- **Noise reference value at R=0°.5; R=1°→~+10%; R=2°→~+50-80%**
- **Noise is uniform till R=1°**

  (rms~0.7mJy)
- **Expected noise ~0.3mJy**



________ 325MHz
.............341MHz
------------375MHz

Catalogs

- **Task IMSAD (IMage Search And Destroy) from data reduction software package MIRIAD (Sault et al. 1995)**
- **IMSAD detects flux density islands and fits them with a two-dimensional gaussian function**
- **3 catalogs, limiting flux density of 4.5σ ~ 2.6mJy**

  - 339 sources at 325MHz

  - 339 sources at 341MHz

  - 345 sources at 375MHz

Flux density comparison

- **Steep spectrum expected (α ~-0.8, $S \propto \nu^{\alpha}$) for sources with S>50mJy at low frequencies**
- **<u>Expected:</u>**

$S_{325MHz} \rightarrow$ 5% greater than S_{341MHz}

$S_{341MHz} \rightarrow$ 10% greater than S_{375MHz}

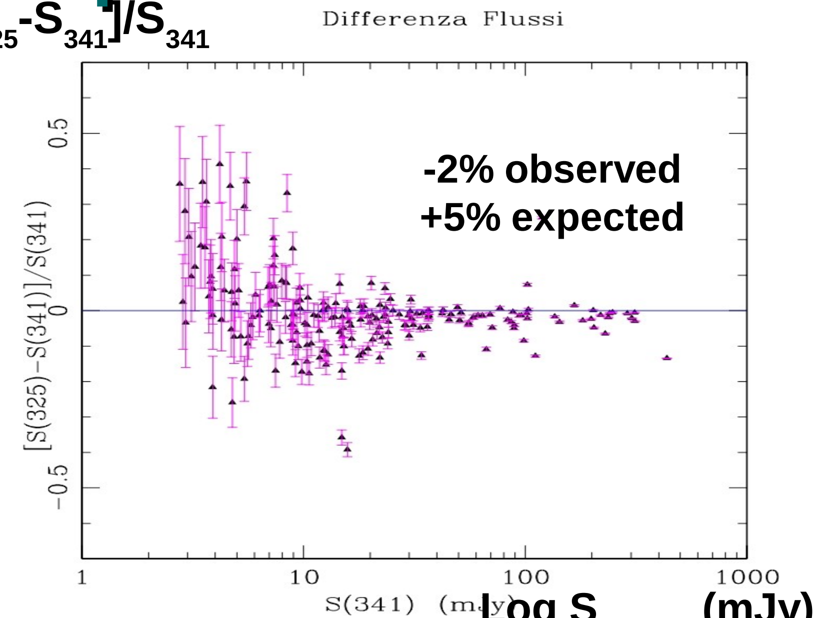
for sources with S>50 mJy

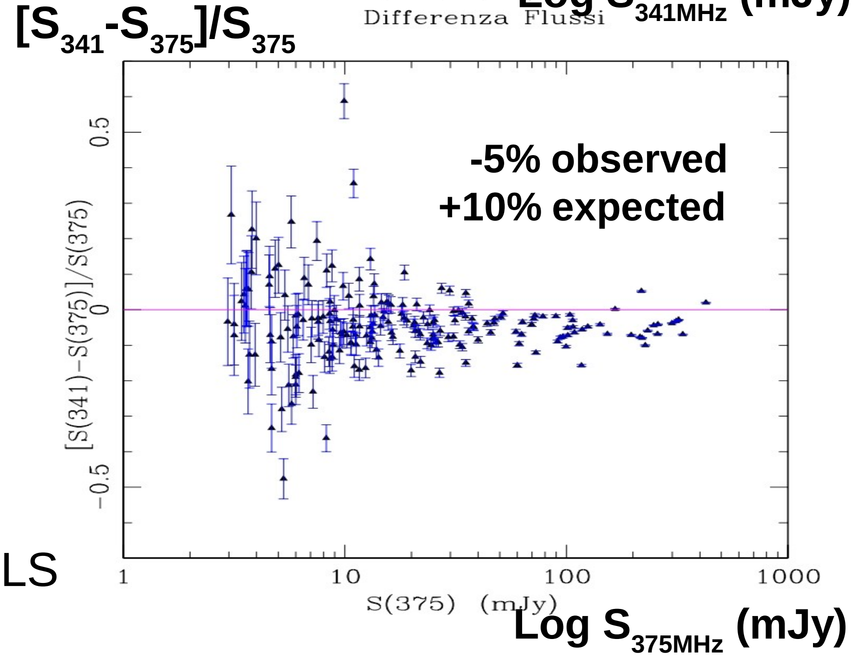
- **<u>Observed:</u>**

$S_{325MHz} \rightarrow$ 2% <u>less</u> than S_{341MHz}

$S_{341MHz} \rightarrow$ 5% <u>less</u> than S_{375MHz}

- **Perhaps flux density calibration inconsistency among frequencies**

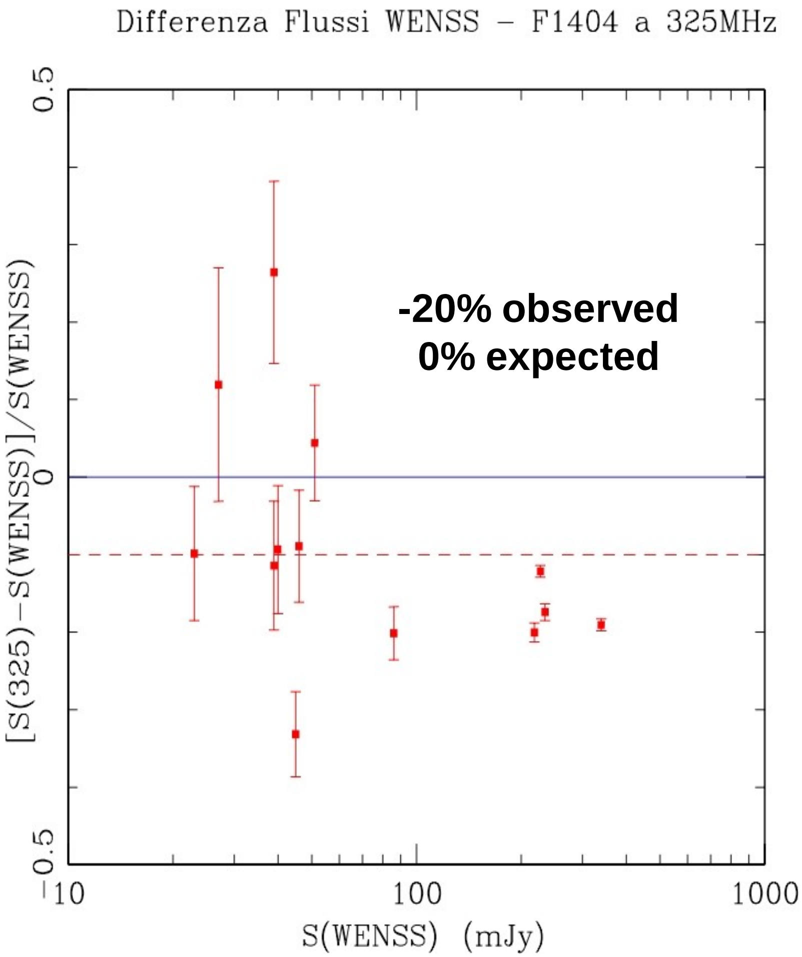




Comparison with WENSS survey

- **WENSS (Westerbork Northern Sky Survey), δ > 30° at ν=325MHz, limiting flux density ~18mJy**
- **F1404 limiting flux dens. ~2.6mJy**
- **S_{325MHz} for F1404 turns out to be 20% less than S_{WENSS} (S>50 mJy)**
- **It is not a statistically significant sample, just 14 common sources**
- **It supports a possible flux density calibration inconsistency**
- **It has been chosen <u>not</u> to correct F1404 flux densities by comparison with WENSS ones**

$[S_{325MHz}-S_{WENSS}]/S_{WENSS}$



Log S_{WENSS} (mJy)

350MHz Catalog

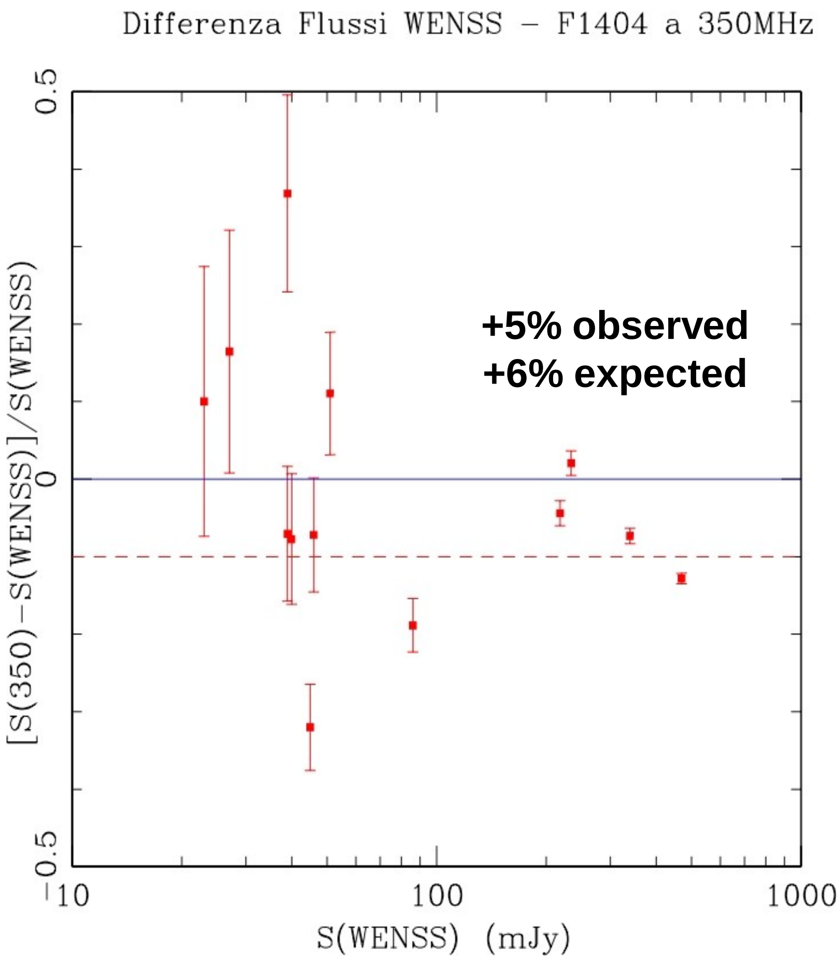
- **It has been decided to merge F1404 catalogs by cross-correlating them and averaging flux densities in a 350MHz catalog**
- **203 Common sources between 325, 341, 375MHz; 10” distance**
- **New comparison with WENSS survey**
- **Hypothesis → <u>α~-0.8</u>**

  <u>expected</u> S_{WENSS} =+106% S_{350MHz}

  <u>observed</u> S_{WENSS} =+105% S_{350MHz}

- **Good agreement between S_{WENSS} and S_{350MHz} for F1404**

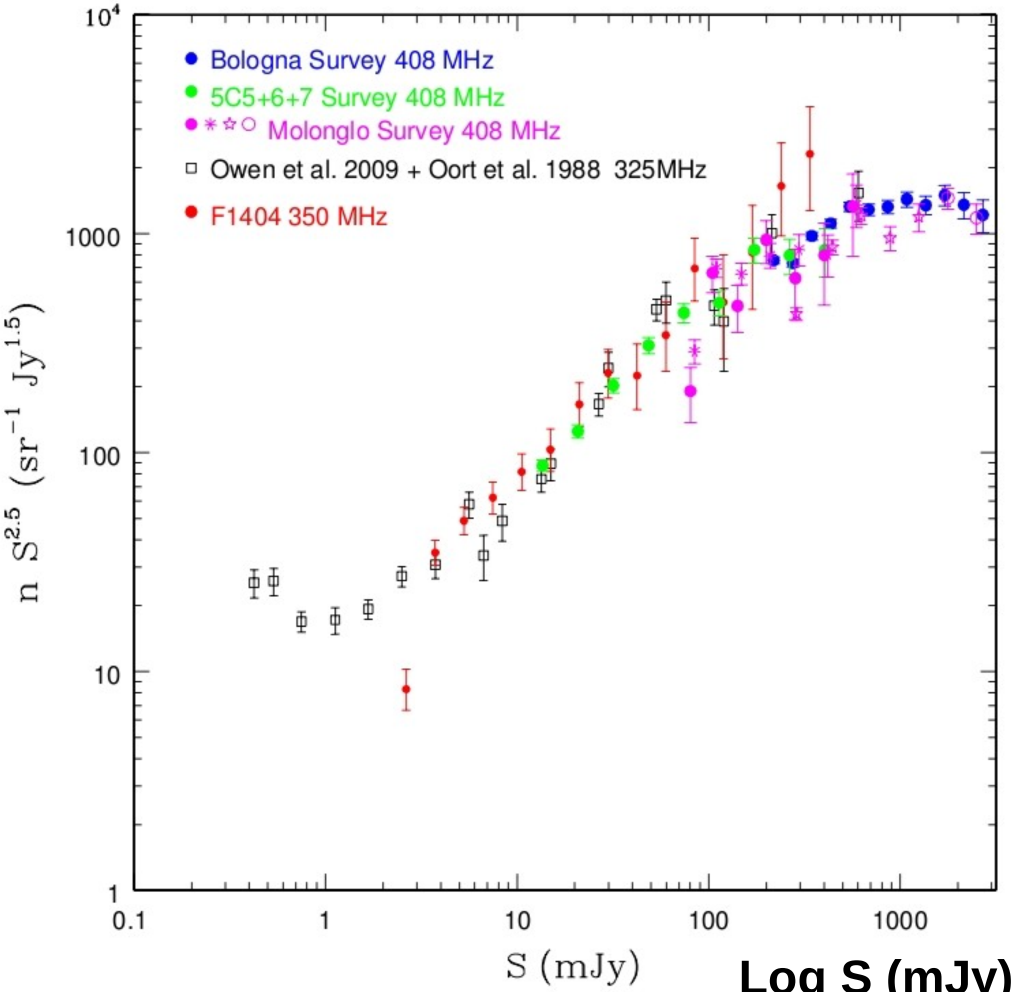
$[S_{350MHz}-S_{WENSS}]/S_{WENSS}$



Log S_{WENSS} (mJy)

Source counts results

Log nS$^{2.5}$ (sr^{-1} Jy$^{1.5}$)



Log S (mJy)

- **Red** source counts computed from 350MHz catalog (S>4.5σ) of this work
- Good agreement with source counts at 408MHz
- Lower flux (red) point → incompleteness of catalog
- Source counts computed in this work are the deepest available at ν<400MHz after Owen et al. 2009
- In source counts by Owen et al. (2009) there is a flattening at S~1mJy, as seen at higher frequencies

WSRT - F1404 (this work)
Colla et al. (1973)
Pearson et al. (1978)
Robertson et al. (1977)
Owen et al. (2009) + Oort et al. (1988)

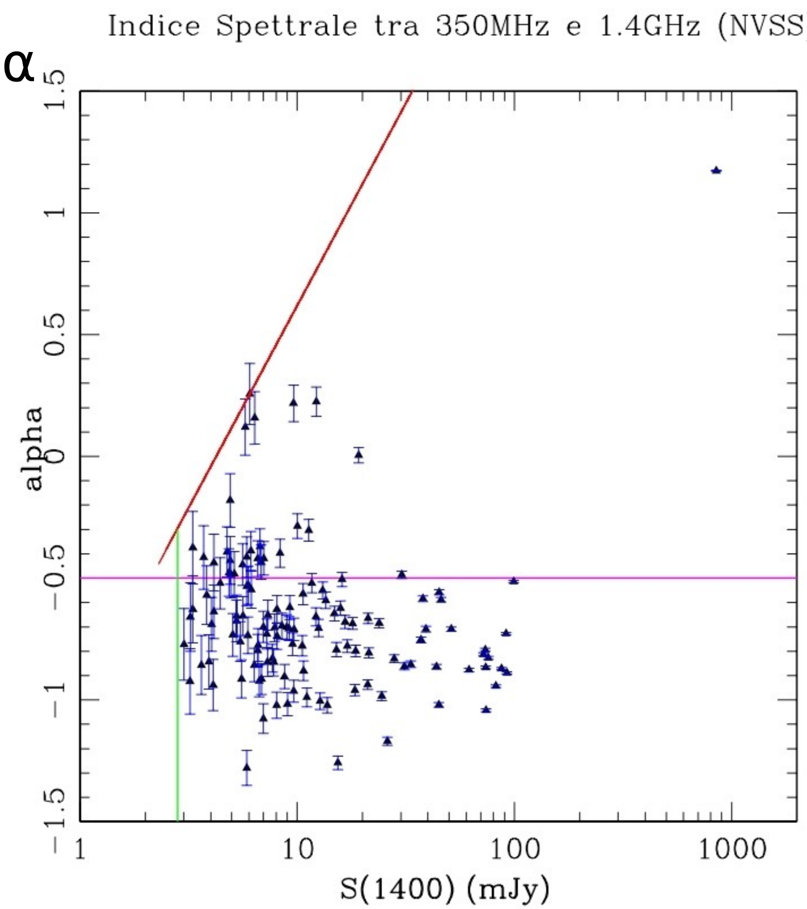
Cross-correlation with NVSS

- NVSS (NRAO VLA Sky Survey), ν=1.4GHz, δ >-40°, over 1.8 million sources (Condon et al. 1998)
- NVSS beam size=45”x45”, F1404 beam size ~50”x100”, consistent
- Cross-correlation between 1.4GHz & 350MHz sources; 10” distance
- 123 Common sources in F1404
- Spectral index computed for each common source

Spectral Index results

- There is a variable source at S~1 Jy MRK668, type 1.5 Seyfert (Veron-Cetty & Veron 2006)
- S>20mJy traditional steep spectrum population
- Evidence for a mixed spectrum population, with flat/inverted spectra, emerging at S<20mJy

α



Log S (1.4GHz) (mJy)

	S=5mJy	S=10mJy	S=20mJy	S=50mJy
MEDIA > S	-0.69 ± 0.29	-0.73 ± 0.26	-0.80 ± 0.16	-0.82 ± 0.13
MEDIA < S	-0.59 ± 0.21	-0.62 ± 0.29	-0.63 ± 0.30	-0.66 ± 0.29

Summary

- **3 Catalogs extracted from a WSRT deep sky field observed at 325, 341, 375MHz (~340 sources, limiting flux density ~2.6mJy)**
- **1 Merged catalog at 350MHz (~200 sources)**
- **Radio <u>source counts agree with past works</u> at higher frequencies, they are the deepest available after Owen et al. 2009**
- **Cross-correlation between NVSS and 350MHz catalog to compute spectral index**
- **<u>Spectral index</u> results:**

  S>20mJy → α=-0.8 **→ traditional <u>steep spectrum</u> population**

  S<20mJy → <u>flattening</u> of α **→ evidence for a population of flat/inverted spectrum sources**

Radio Source Counts

Source counts: **Number of objects per solid angle unit, with monochromatic flux density greater than S_ν (or between S_ν and $S_\nu+dS_\nu$). Plotted as Log S vs Log $nS^{2.5}$**

Hypothesis: The Universe has Euclidean geometry on large scale, so radio sources have a uniform distribution over space

Expected number of sources N_0 increases with volume as

$N_0(>S) \sim D^3$ **with** $S = \frac{P}{4\pi D^2}$ **hence** $D \sim S^{-\frac{1}{2}}$

so the expected number of sources is $N_0(>S) \sim S^{-\frac{3}{2}}$

Differentiating last equation, it becomes $n_0 = \frac{dN_0}{dS} \sim \frac{d}{dS} \cdot S^{-\frac{3}{2}} \sim S^{-\frac{5}{2}}$

Then observed source counts are normalized with respect to expected ones

$$\frac{n}{n_0} \sim \frac{n}{S^{-\frac{5}{2}}} = nS^{\frac{5}{2}}$$

If observed source counts are Euclidean, then $n/n_0 \sim 1$

Such a ratio is constant with increasing flux density

Thank you!