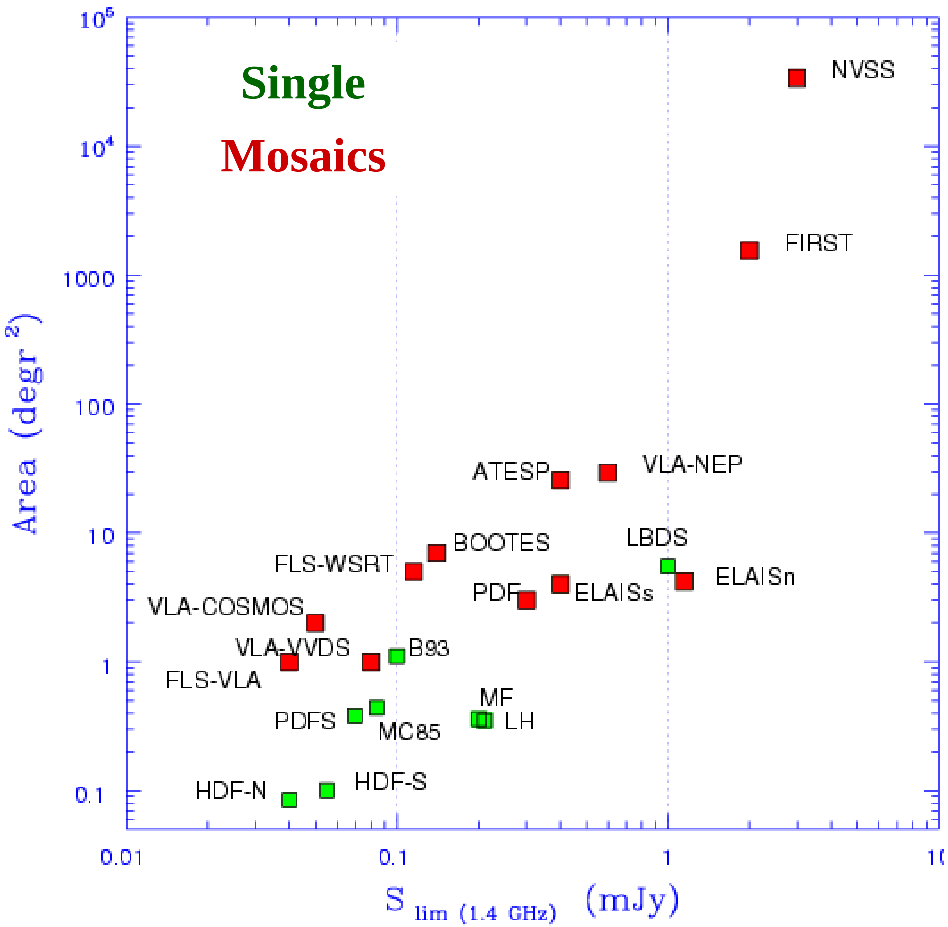
Radio faint population (sub-mJy)

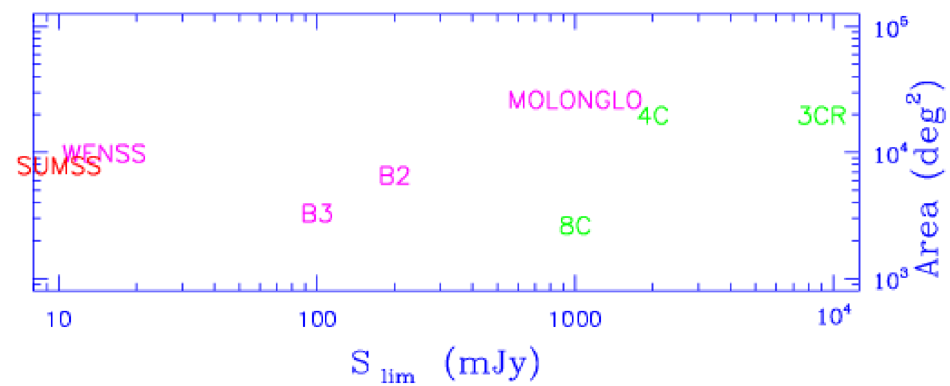
- Observational Technique
- Composition
- Caracteristics: optical, radio, etc.

Low Freq. Surveys/1.4 GHz Mosaics

Deep Fields/Mosaics @ 1.4 GHz



151/178 MHz 325/408 MHz 800 MHz



Low Freq. All Sky Surveys

Deep Fields:

1.4 GHz → best compromise between <u>FOV</u> ($\theta_B \propto \lambda/D$ ~30') and <u>resolution</u> ($\theta_S \propto \lambda/b_{max}$ ~1")

Mosaicing Technique

•Each pointing centre must contain <u>some degree of overlap</u>

Surveys for point sources

Serpens 3 mm continuum:

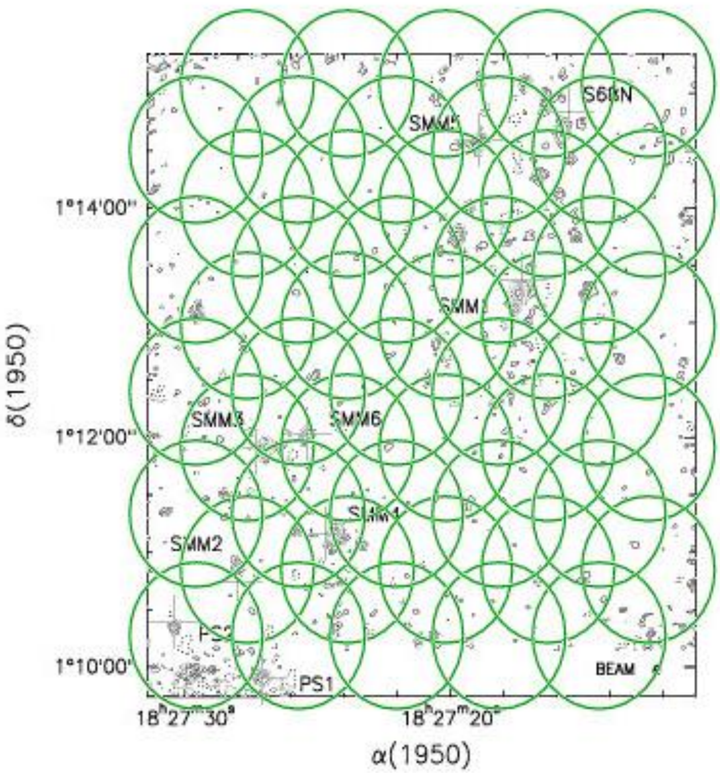
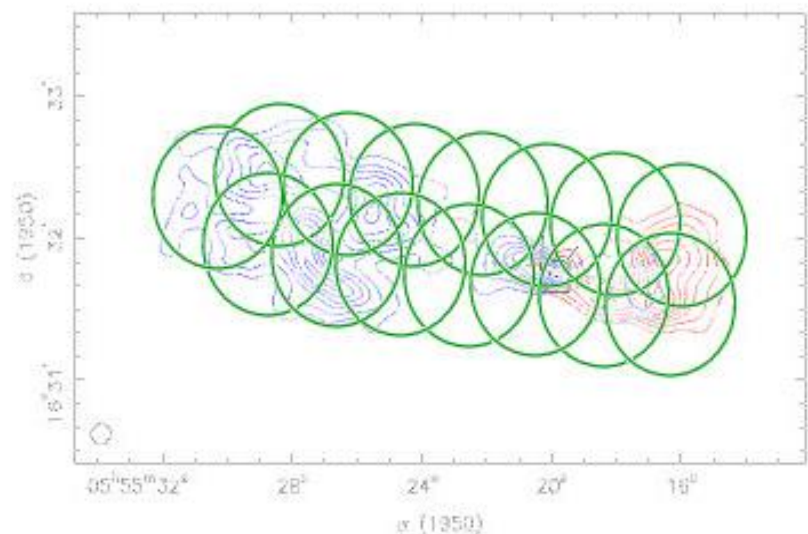


Image extended emission

G192.16 CO(J=1-0) outflow:



Mosaicing: Examples

Point source survey

VLA-COSMOS (1.4 GHz)

- 15 VLA pointings
- Area = 2.0 deg^2
- 3600 sources with S>50 μJy/beam
- Average rms noise ~10 μJy/beam.

A) Radio source counts

Survey → catalogue of sources → source counts vs.S (or mag)

logN – logS or logN – log m

- Integral counts N(>S): num. of sources per area unit (sr or deg2) with flux >S
- Differential counts N(S): num. of sources per area unit with flux between S and S+dS

Source counts → simplest cosmological tool to constrain

- a) source cosmological evolution;
- b) contribution of different galaxy types to global population;
- c) Universe geometry (in principle)

Comparison between Observed & Modeled source counts

A) Radio source counts

Simplest source count model → non-ev. static Euclidean Universe

$$N(>S) \propto S^{-1.5}$$

Integral counts

$$N(S) \propto S^{-2.5}$$

Differential counts

L → N(>S) = rho(L) V   rho(L)= uniform volume density of sources with luminosity L

(rho(L)dL=luminosity function)

V= 4/3 pd^3 = volume inside which sources have flux >S

S=L/(4pd^2)

NB: d=d(L)

$$N(L,<S) = \rho \frac{4\pi}{3} d^3 \propto \rho(L) L^{3/2} S^{-3/2}$$

Summing over L:

$$N_{tot}(<S) \propto (\sum_L \rho(L) L^{3/2}) S^{-3/2}$$

$$N_{tot}(S) = dN_{tot}(>S)/dS \propto S^{-5/2}$$

Radio source counts: Beyond Local Universe → relativistic expanding Universe

expansion: d_{max} luminosity distance d_L

In a E-dS, $\Lambda = 0, \Omega = 1 \rightarrow d_L = d_c(1+z)$ [d_c =comoving distance]

$$S = \frac{L}{4\pi d_c^2 (1+z)^2}$$

For a given S and L → d_c^2 <static Eucl.

geometry: curved space-time (Robertson-Walker metric)

$dV_{sr} = r^2\, dr \,/\, [(1-kr^2)]^{1/2}$ where $k = 0,1,-1$

NB: only when k=0 (flat Universe) → V=sphere (Euclidean case)

For any standard cosmological models:

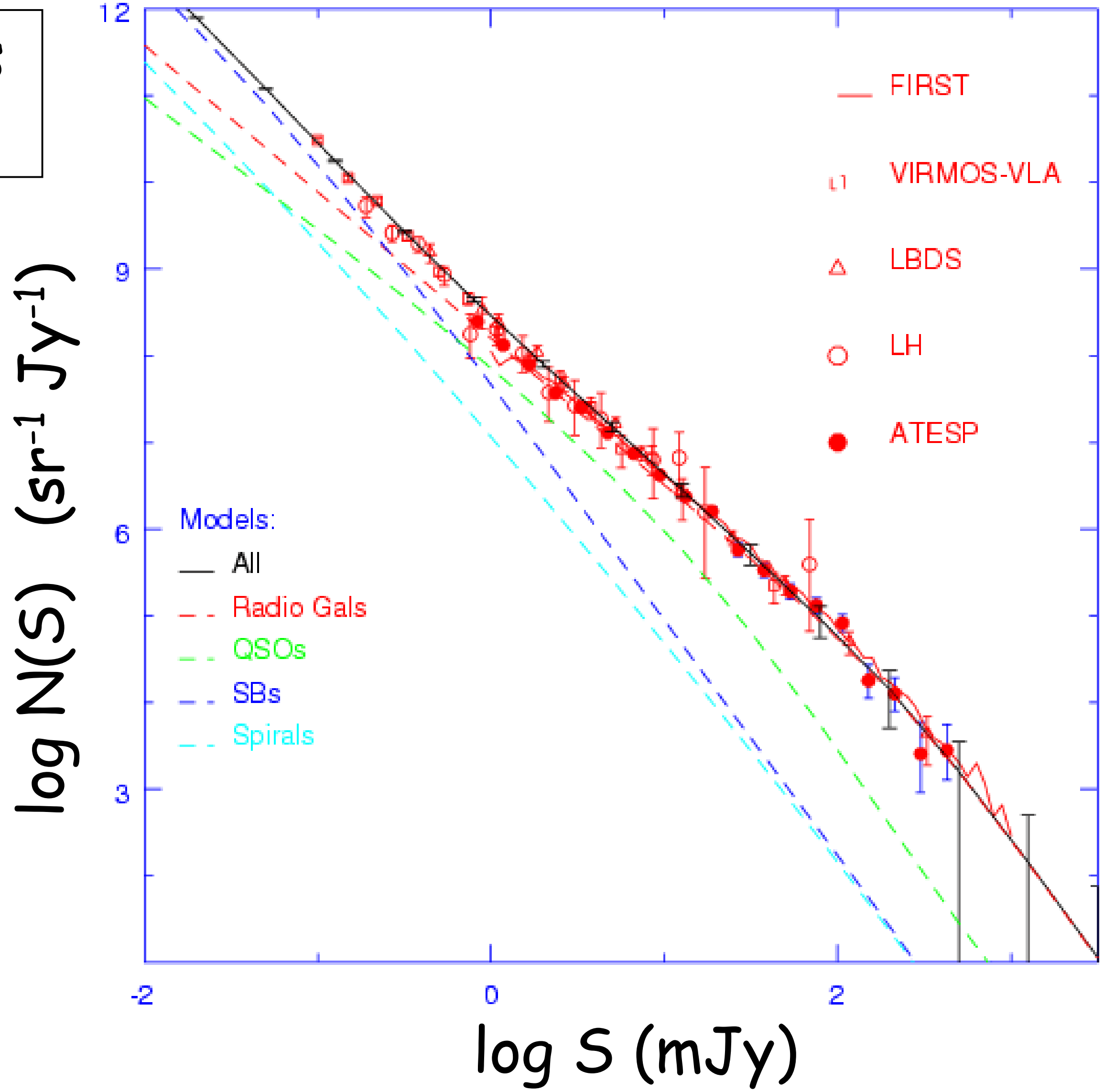
$$N(>S) \propto S^{-\alpha(S)}$$

where alpha<1.5 and →1.5 for S→infinite

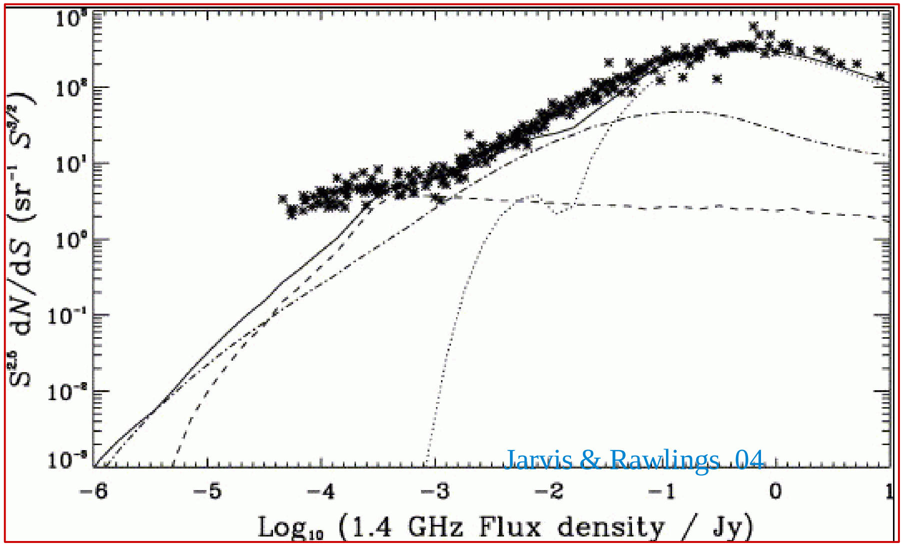
If **evolution** dominates the counts shape, Universe geometry cannot be determined.

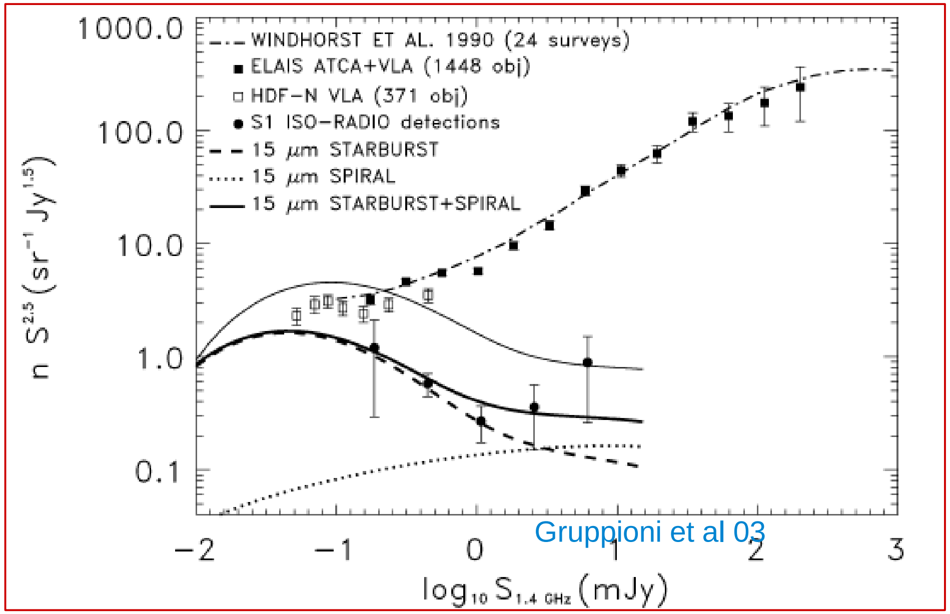
Observed Radio Source Counts

Differential Counts
@ 1.4 GHz



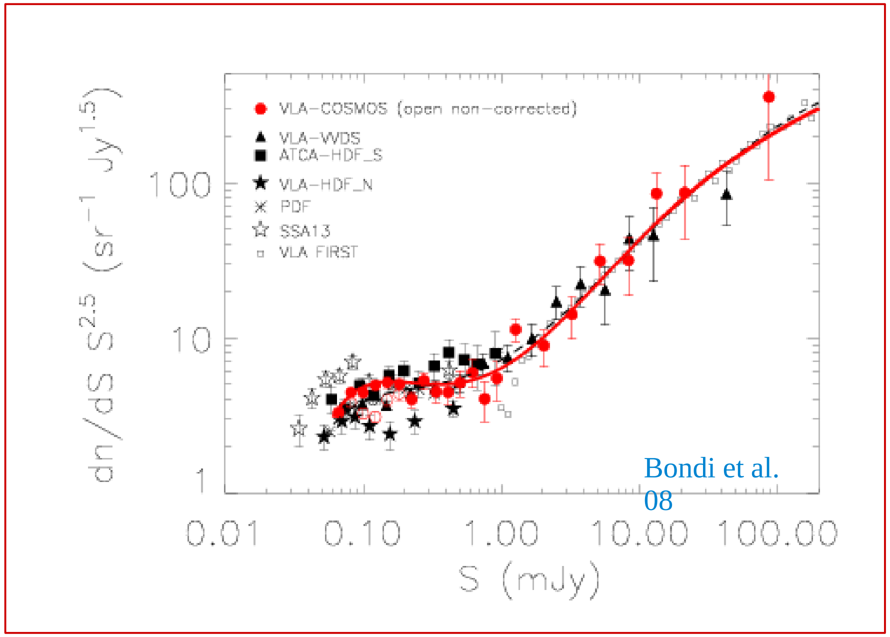
Results: Radio Source Counts

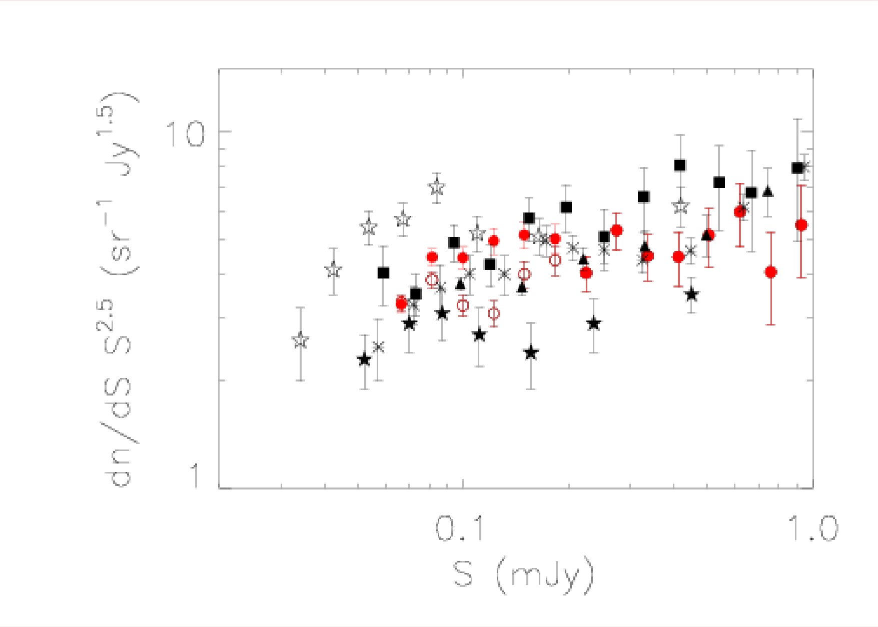




First interpretation of change in the slope of sub-mJy counts was an evolving population of starbursts.

Results: Radio Source Counts



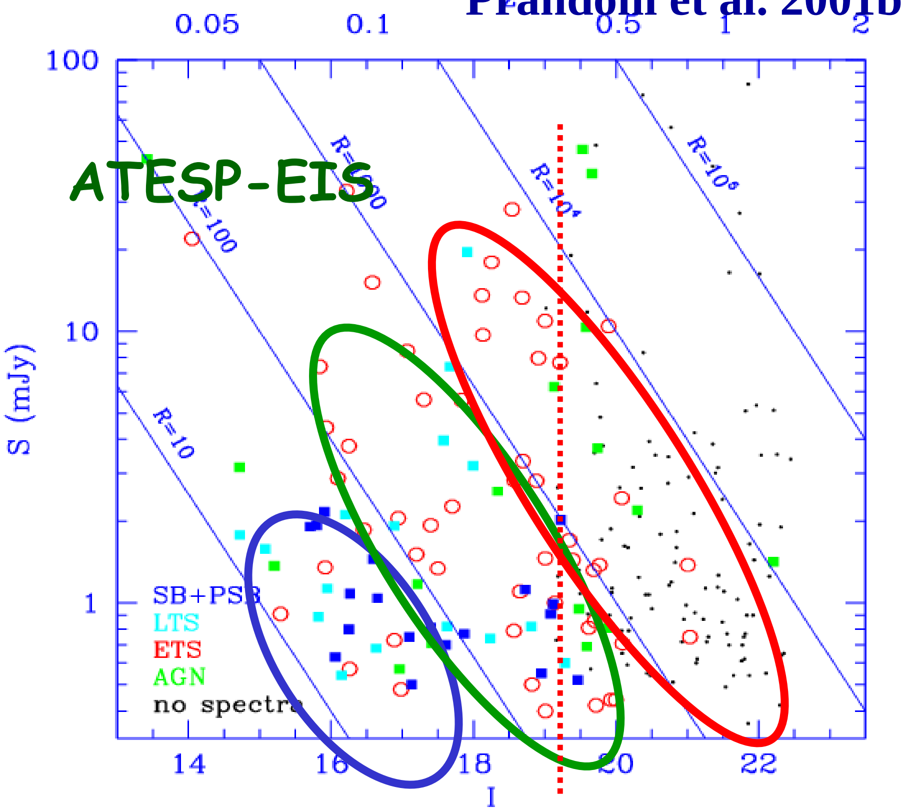


- Wide scatter of source counts below 1 mJy from different surveys (cosmic variance & incompleteness corrections)
- Optical classification of sub-mJy sources

Flux interval 1.4 GHz (μJy)	Early type	Late type	Starburst	Total
$S < 60$	29%	34%	37%	80%
$60 \leq S < 100$	34%	32%	34%	84%
$100 \leq S < 150$	42%	32%	26%	90%
$150 \leq S < 500$	48%	33%	19%	95%
$S \geq 500$	61%	20%	19%	95%

Composition of the sub-mJy population

Prandoni et al. 2001b



<u>Radio to Optical Ratio:</u>

$R = S \times 10^{0.4[mag-12.5]}$

(Condon 80)

R>100 → AGN/ETS
R<100 → SFGs

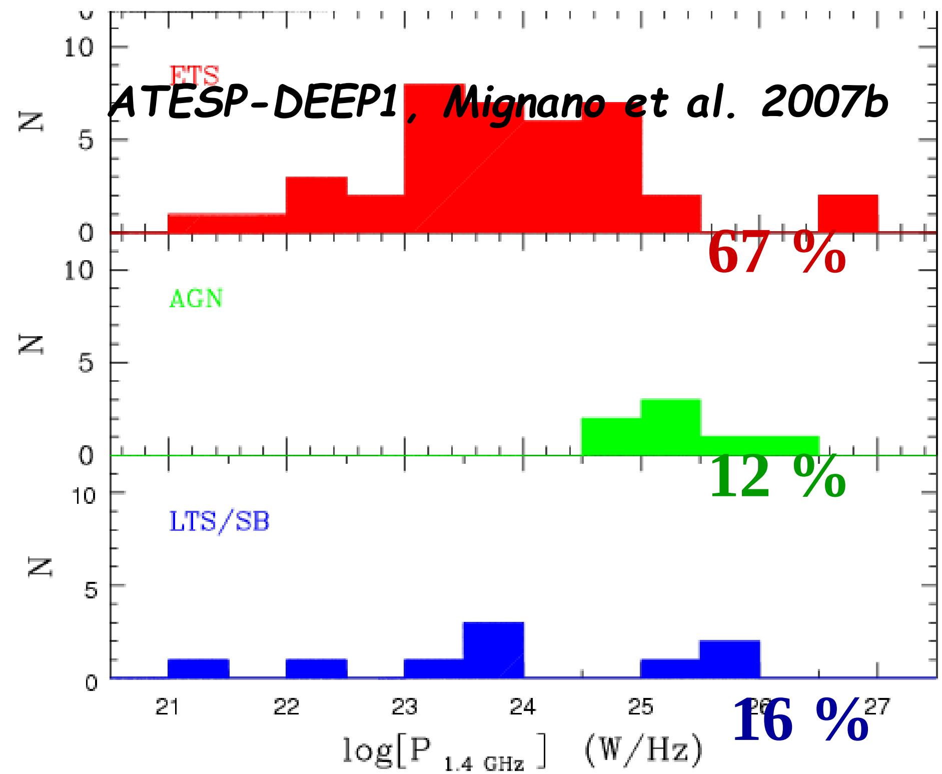
SF dominates @ low R
AGN/ETS dominate @ high R

→ Early-type gals important at sub-mJy fluxes
→ Selection effects explain discrepancies among sub-mJy samples

Assessing the Low-P AGN Component

Redshift Distribution:

- ETS up to z = 2 (peak at z = 0.5)
- QSO → $1.5<z<2.5$
- LTS → $z<1$



Radio Power Distribution:

- ETS → 10^{23-25} W Hz^{-1}

(triggered by low-intermediate luminosity AGNs)

- QSO → P ~ 10^{25-26} WHz^{-1}

RI-QSOs

lower than usually found for classical radio-loud QSOs

- LTS → 2/3 P < 10^{24} W Hz^{-1}

(SF)

➔ Sample largely dominated (78%) by AGN activity

Results: radio spectral properties

•Consistent results from other survey: evidences of different populations at sub-mJy levels

•SIGNIFICANT FLATTENING WITH DECREASING FLUX

S > 4 mJy → steep spectrum (α_{med} ~ -0.7)

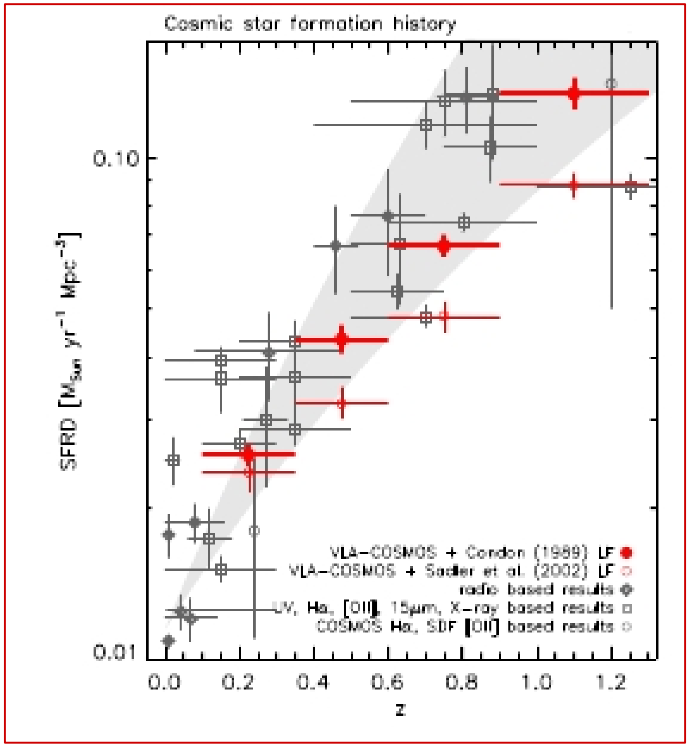
S < 4 mJy → large fraction of flat spectra (α > -0.5)

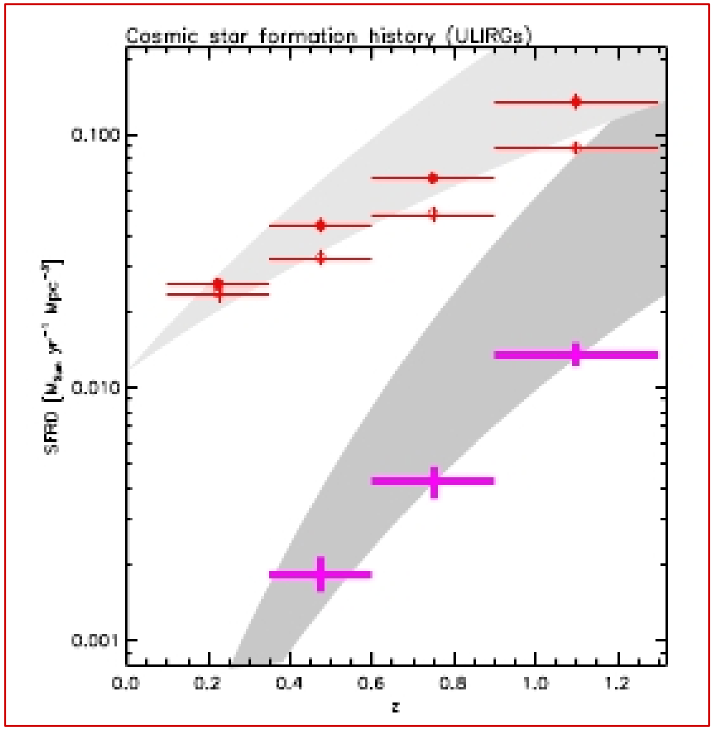
+ significant # of inverted spectra (α >0)

Optical Classification	Number of detection	Fraction of flat spectrum	Number of limits	Median α_{r_med}
Early	225	34%	65	-0.55 ± 0.04
Late	80	21%	21	-0.70 ± 0.04
Starburst	37	11%	8	-0.69 ± 0.10
Unidentified	263	34%	64	-0.59 ± 0.04

1.4 GHz Flux Interval (mJy)	Number of detection	Number of limits	Median α_{r_med}
$0.10 \leq S < 0.15$	171	110	-0.61 ± 0.04
$0.15 \leq S < 0.50$	304	69	-0.46 ± 0.03
$S \geq 0.50$	158	0	-0.67 ± 0.05

Results: cosmic SF history





Red= COSMOS, Violet=ULIRGs

- Largest sample of radio selected star forming galaxies from the VLA-COSMOS Survey (Smolcic et al. 2009)
- Radio data consistent with the dust-corrected ones obtained from optical-UV surveys
- Somewhat slower evolution for ULIRGs with respect to MIR data

Assessing the Low-P AGN Component

Radio spectral index vs R

- most α > -0.5 sources → high R

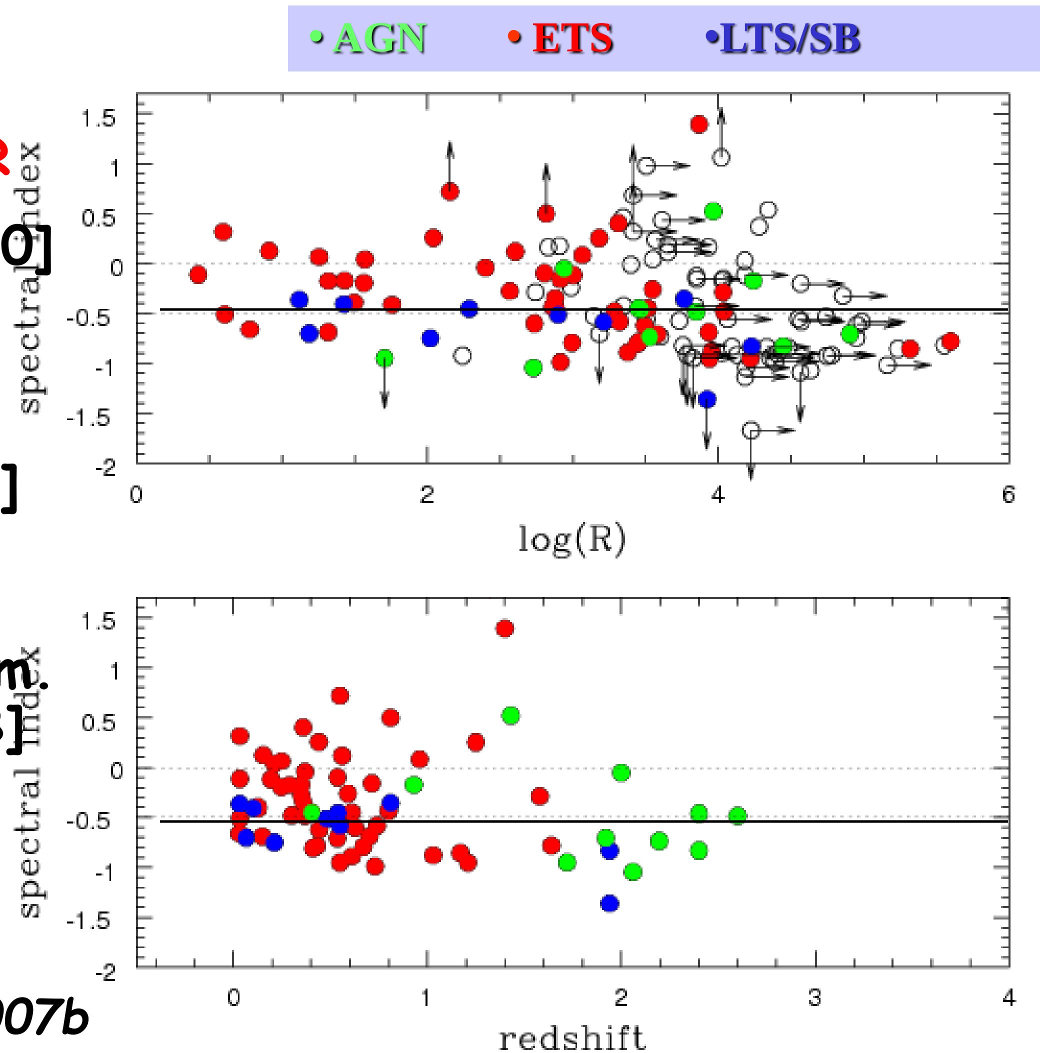
[R>1000 → powerful RG and QSO]

- α > -0.5 & low R → ETS

[RS probably triggered by AGN]

- LTS/SB → steep sources

[as expected for synchrotron em. in gal. disks or in nuclear SB]

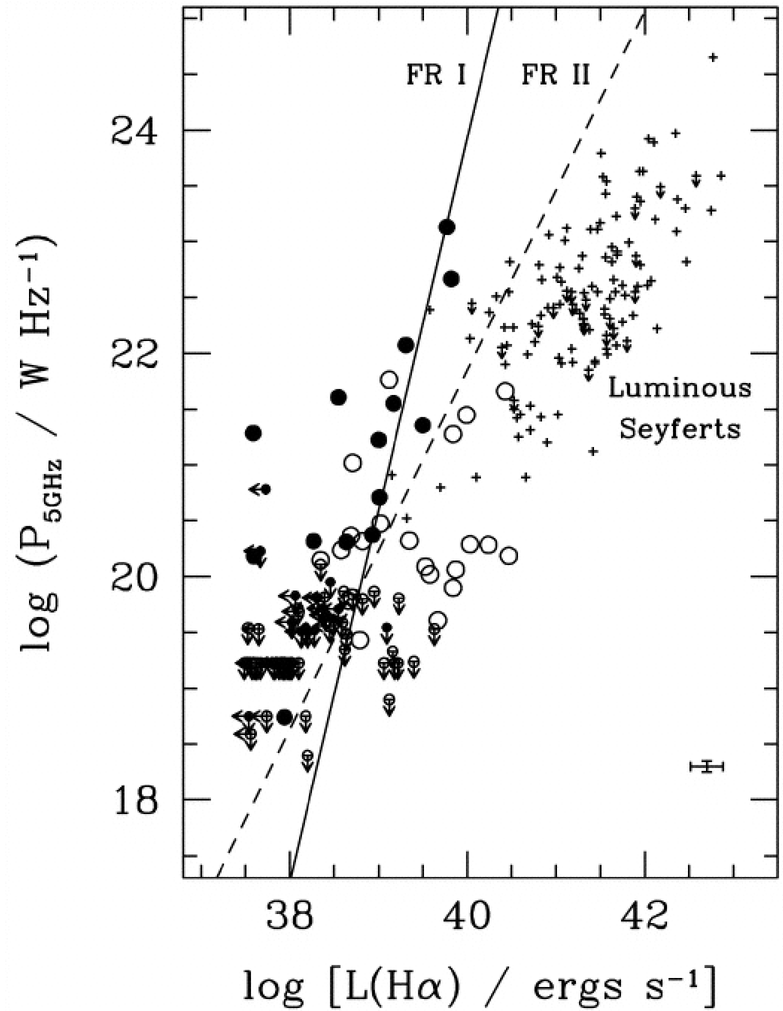


Mignano et al. 2007b

Compact radio emission in E and S0: AGN/SF

Optical spectroscopic information to interpret the nature of compact radio emission in a sample of 216 E and S0 galaxies (VLA data).

Radioemission on scales of several hundred pc or less and radio power →



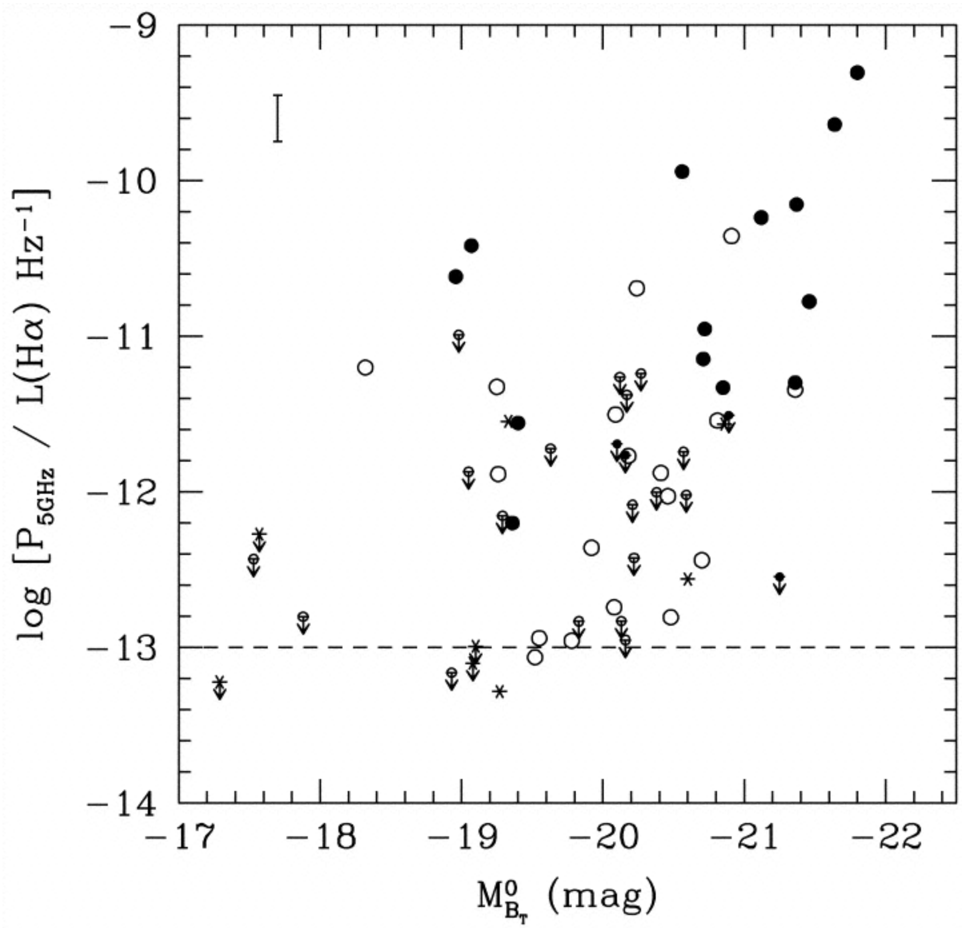
Filled synbols: E, open:S0 (Ho 1999)

The relation between radio power line emission is consistent with the low-luminosity extension of similar relations seen in classical radio galaxies and in Seyfert.

Compact radio emission in E and S0: AGN/SF

Ho 1999

The measured Halpha luminosities, 10^{38} – 10^{40} erg/s, imply the presence of 10^3 – 10^5 Msol of warm (10^4 K) ionized hydrogen. A purely thermal source with electron temperature of 10^4 K generates ~10^{-13} W/Hz of radio power at 5 GHz. The vast majority of the sources fall well above this threshold → most of the radio emission is therefore nonthermal.



Filled symbols: E, open: S0s classified as AGNs, asterisks: S0s as HII nuclei

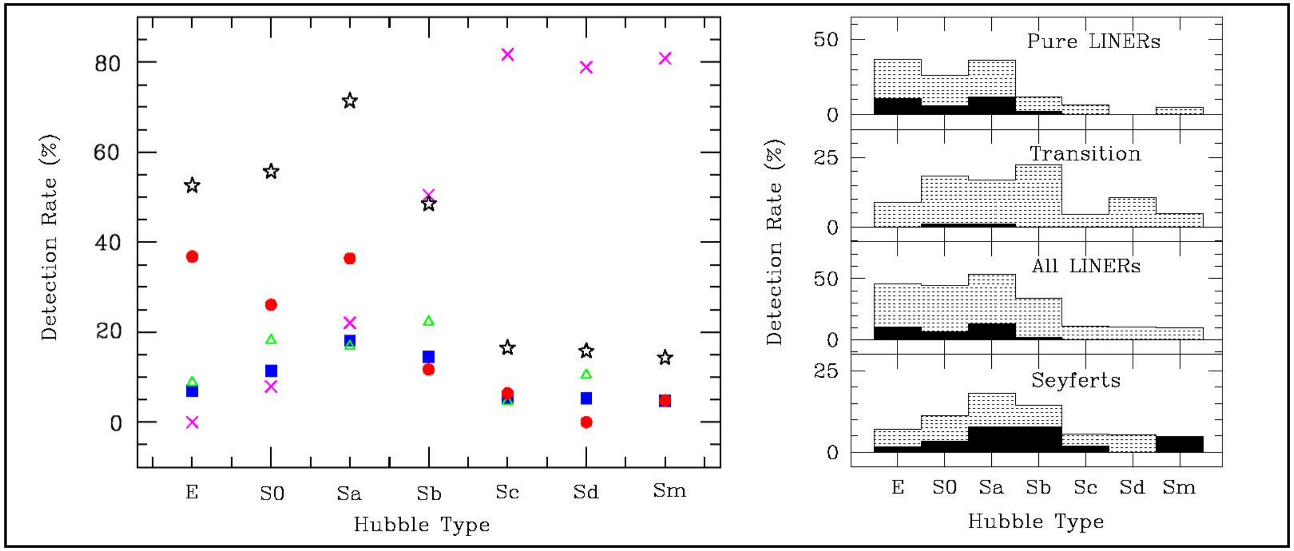
Optical Data: *Palomar Survey*

(*Ho 2008*)

- **Sample 486 galaxies**
- **Magnitude limit $B_T \leq 12.5$ mag**
- **Spectra with high resolution**

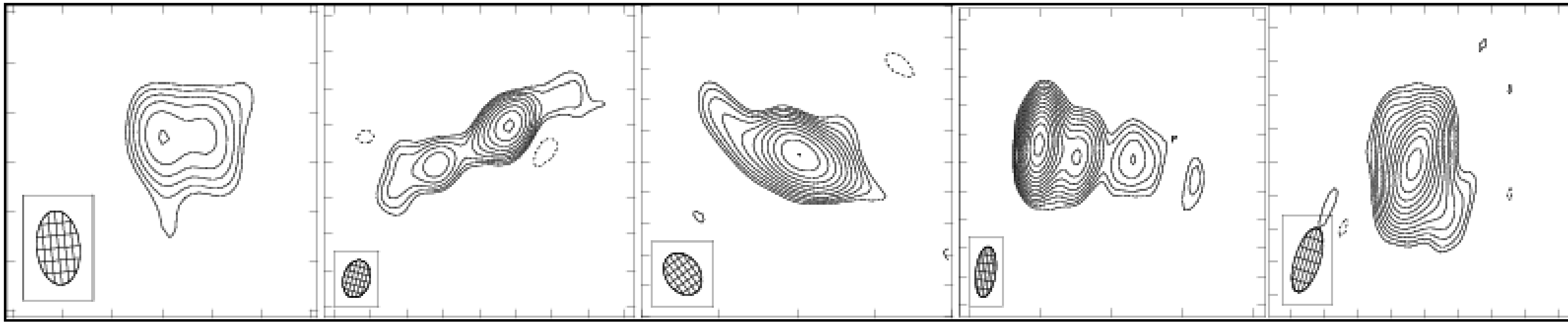
➡ **FWHM = 2.5 A between 6210 and 6860 A**

➡ **FWHM = 4 A between 4230 and 5110 A**



***Left:* Seyfert = blue, LINER = red, transition = green, Seyfert+LINER+Transizione = star, nuclei HII = cross.**

Radio Data



LLAGN at 5 GHz with VLBA. Images have scales of few mas, contours are multiple of 2σ (~ 0.3 mJy)

High rate radio emission both in *early-type galaxies* (30-40%) and in sia *late-lype galaxies* (44-47%)

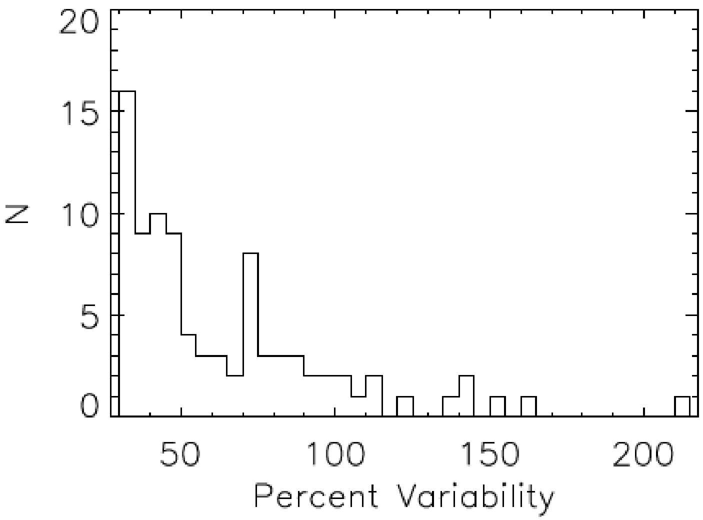
Radio structures have scales in the range arcsec-mas.

In the *Palomar sample*, Seyfert and LINER have similar percentage of detection.

Low percentage for transition nuclei.

Seyfert 1	LINER 1	Seyfert 2	LINER 2	Transizione
72%	63%	30%	38%	16%

Variability
(Hodge et al. 2013)



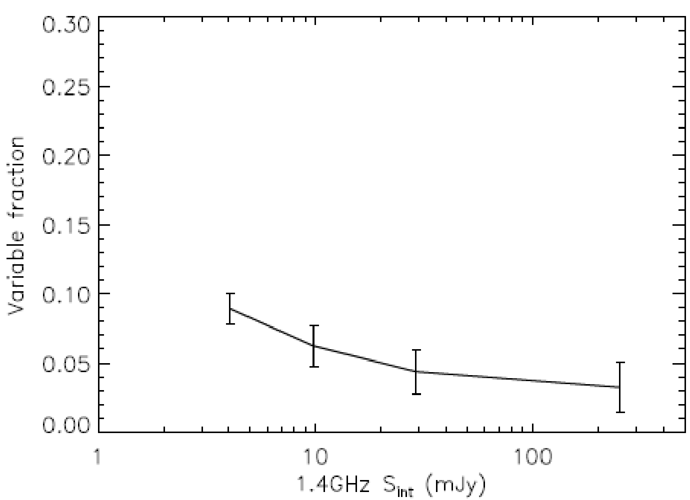


FIG. 6.— Variable fraction of radio sources as a function of flux density. The median flux density for each flux density bin is plotted.

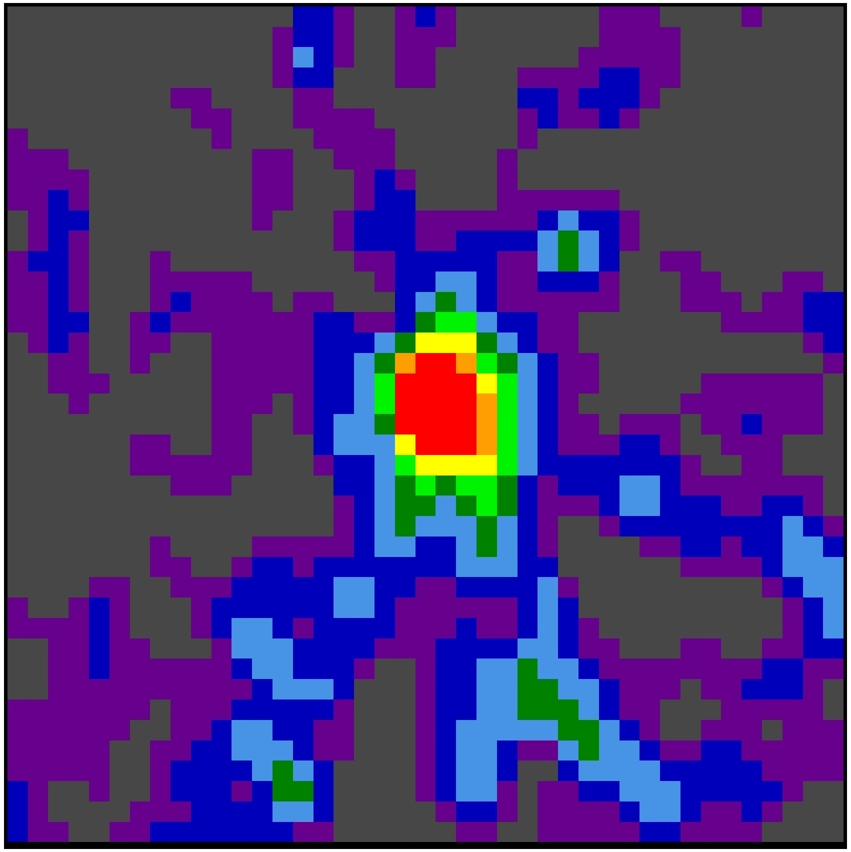
Blind survey for extragalactic radio variability that was carried out by comparing three epochs of data from the FIRST survey.

- The epochs are spaced seven years apart and have an overlapping area of 60 deg^2.
- 89 variable sources down to the millijansky level with variability amplitude > 30%
- No evidence for transient phenomena.
- The fraction of radio sources that are variable appears to remain constant down to the millijansky level, possibly even increasing slightly at low flux.
- The variable sample contains a larger fraction of quasars

Results: radio properties of non-radio detected objects

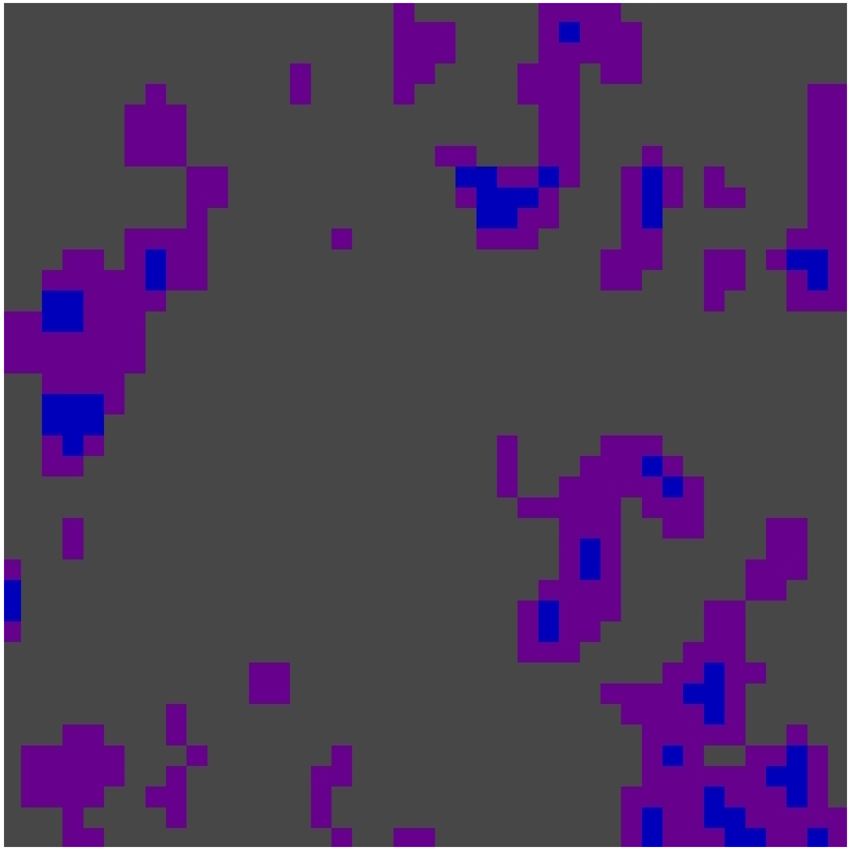
- Only a small fraction of optical galaxies are radio detected.
- Stacking techniques can be used to derive the average radio properties of a large population of sub-threshold objects selected in a different band (optical, IR, X-rays...).
- Stacking *N* objects the noise in the stacked image can decrease by square root of *N*.
- Applied to a sample of about 800 Extremely Red Objects in the VVDS survey

Stacking EROs



- Average of 740 fields centered on EROs with SNR<3, each field has an r.m.s = 17 μJy
  Peak = 8.4 μJy
  r.m.s. = 0.8 μJy
  SNR = 10

Stacking Empty Fields



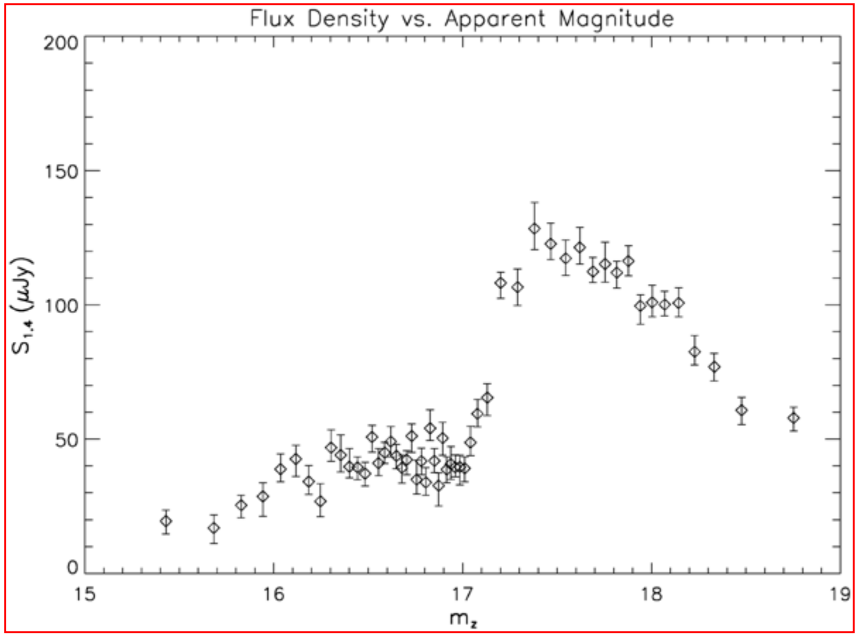
- Average of 740 fields centered on random position with SNR<3
  Peak = 1.4 μJy
  r.m.s. = 0.7 μJy
  SNR = 2

Radio detection of radio-quiet galaxies

(Hodge+ 2008)

Radio emission (FIRST survey) of a sample of ~ 185000 optically-selected quiescent galaxies from the SLOAN Digital Sky Survey.

Radio limit ~ 10s of microJy.



- Luminous Red Galaxies (~ 45% of the total sample) harbor AGN
- Nebulous results for the remaining sample

Dwarf Galaxy Harbors Supermassive Black Hole

Reines et al 2011 found a region near the center of the galaxy that strongly emits radio waves with characteristics of those emitted by super-fast "jets" of material spewed outward from areas close to a black hole.
They then searched images from the Chandra X-Ray Observatory that showed the same, radio-bright region to be strongly emitting energetic X-rays. This combination, they said, indicates an active, black-hole-powered, galactic nucleus

Composite image of the dwarf galaxy Henize 2-10. Hubble Space Telescope data is colored red, green and blue, Very Large Array data is yellow and the Chandra X-Ray Observatory data is purple

Future

- The e-MERLIN Galaxy Evolution Survey:
  - Proposed as a Legacy Survey will exploit new improved capabilities of e-MERLIN at 1.4 and 5 GHz
  - couples μJy sensitivity with sub-arcsec resolution to disentangle the relative contribution of AGN and starburst within individual galaxies.

- LOFAR All Sky Survey
  - Starting 2010
  - Will image the whole sky at 150 MHz with a sensitivity, scaled to 1.4 GHz, typical of the radio deep fields observed so far.