A view of the sub-mJy radio population

Radio/optical properties, modeling and perspectives for future deep surveys

I. Prandoni[1]

A. Mignano[1,2], H.R. De Ruiter[3,1], L. Gregorini[1,2], P. Parma[1], M.H. Wieringa[4], G. Vettolani[5,1], R.D. Ekers[4]

[1] INAF - IRA, Bologna, Italy [2] University of Bologna, Bologna, Italy

[3] INAF - OABo, Bologna, Italy [4] CSIRO ATNF, Epping, Australia

[5] INAF, Roma, Italy

I – 1.4 GHz source counts

EMERGENCE OF NEW POPULATION(S)

Classical RG: ~ 99% @ S > 60 mJy)

NATURE/EVOLUTION

Low L/high z AGN, SB, Ell.

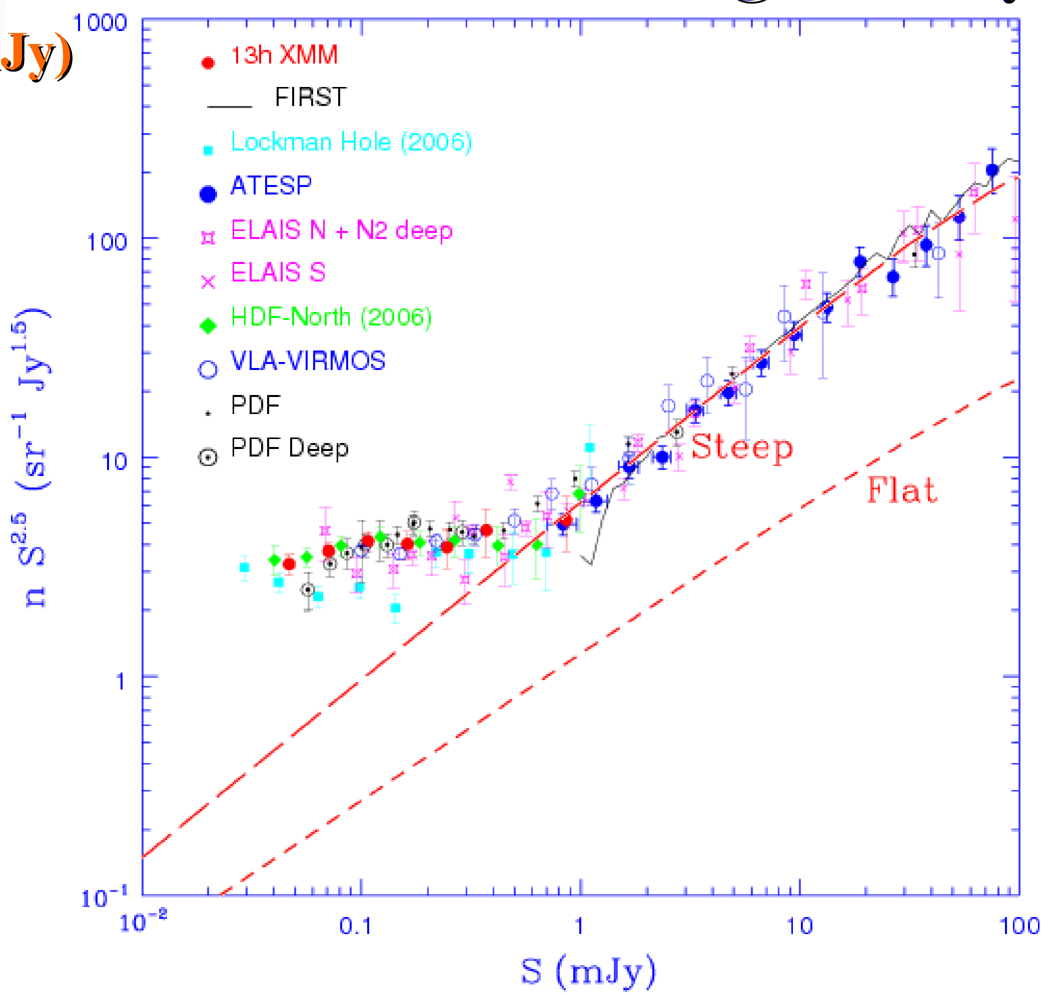
F(L) ? N(z) ?

SF dominates at μJy fluxes

ETS important at sub-mJy/mJy fluxes

e.g. *Richards et al. 99, Gruppioni et al. 99, Haarsma et al. 00, Prandoni et al. 01b, 02, Gruppioni et al. 03, Sullivan et al. 04, Ciliegi et al. 05, Fomalont et al. 06*

SHARP STEEPENING @ S<1 mJy



I – Scientific Drivers

SF galaxies:

→ SF History (z>2)
(Dust-enshrouded obj)

AGN: → Phys. Properties (FRI vs. RQ-QSO)
Faint end of RLF (F(L,z))
LDDE (Type II AGNs)

Connection between SFH & MBH accretion

II – The ATESP-DEEP1 Sample

1.4 GHz ATESP Survey:

- 26x1 sq. deg. at $\delta = -40°$
- 16 radio mosaics with uniform rms flux ~ 80 μJy
- 2967 sources with S > 0.4 mJy

  Spatial resolution: ~ 10"

(Prandoni et al. 2000a,b; 2001)

5 GHz follow-up:

- 2x0.5 sq. deg. at $\delta = -40°$
- 2 radio mosaics with uniform rms flux ~ 70 μJy
- 111 sources with S > 0.4 mJy
- Spatial resolutions:

  ~ 10" → radio spectra

  ~ 2" → radio morphology

(Prandoni et al. 2006)

UBVRIJK imaging from DPS

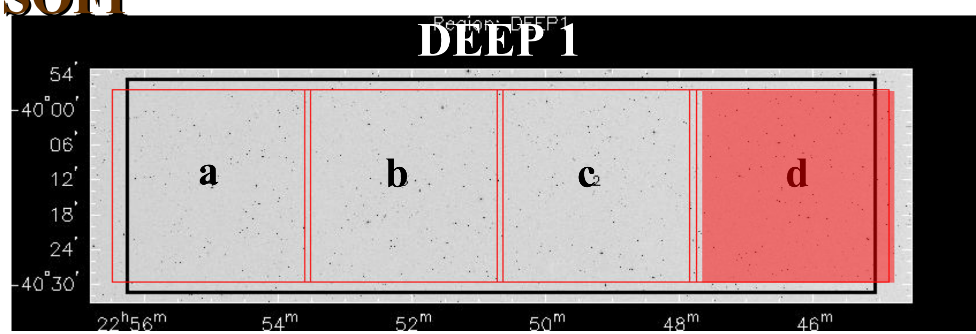
- 2x0.5 sq. deg. at $\delta = -40°$
- 4 WFI fields (DEEP1a,b,c,d) + SOFI

$U_{AB} \sim 25.7$, $B_{AB} \sim 25.5$, $V_{AB} \sim 25.2$,

$R_{AB} \sim 24.8$, $I_{AB} \sim 24.1$

$J_{AB} \leq 23.4$ and $21.3 < K_{s\,AB} \leq 22.7$

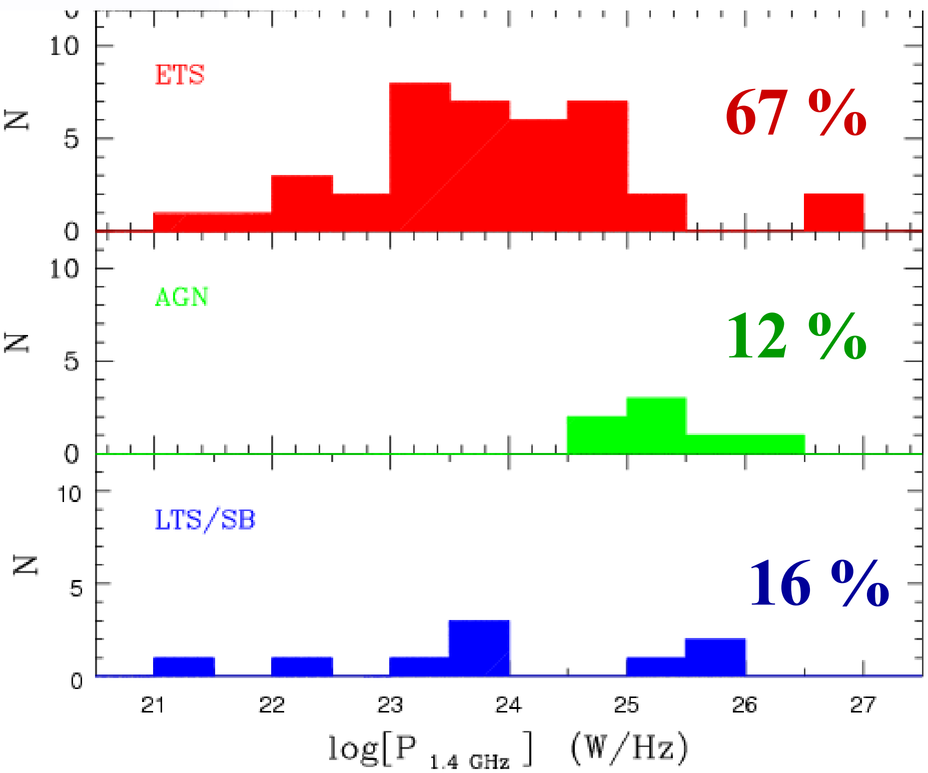
Mignano et al. 2006, Olsen et al 2006



II – ATESP-DEEP1 RS Properties

Redshift Distribution: (DEEP1abc)

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



Radio Power Distribution: (DEEP1abc)

- ETS → $10^{23\text{-}25}$ W Hz^{-1} (triggered by low-intermediate luminosity AGNs)
- QSO → P < $10^{25\text{-}26}$ WHz^{-1} RI-QSOs

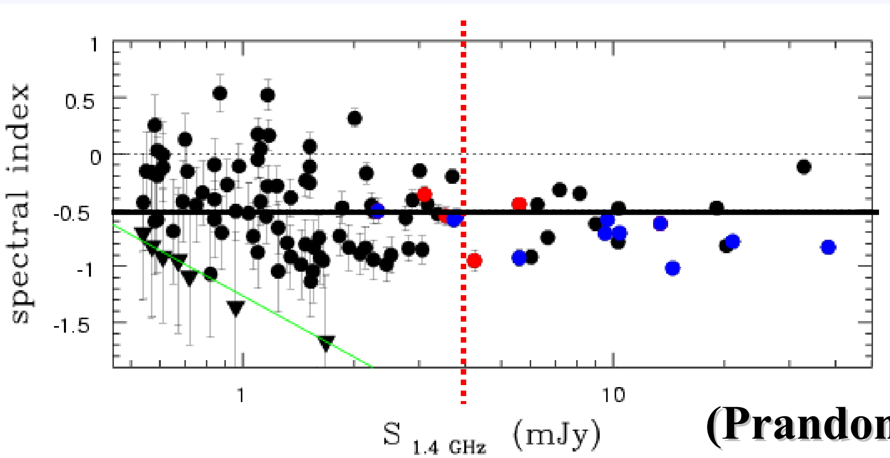
lower than usually found for classical radio-loud QSOs

- LTS → 2/3 P < 10^{24} W Hz^{-1} (SF)

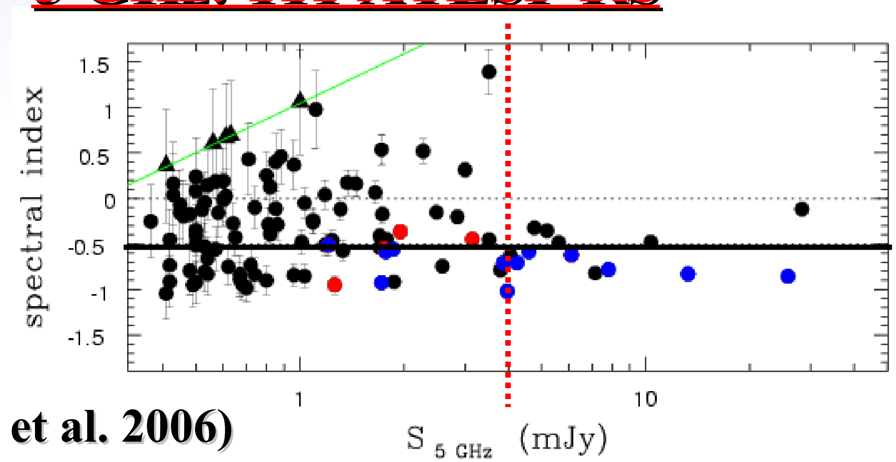
→**Sample largely dominated (78%) by AGN activity**

II – 1.4-5 GHz spectral index analysis

1.4 GHz: 109 ATESP RS



5 GHz: 111 ATESP RS



(Prandoni et al. 2006)

SIGNIFICANT FLATTENING WITH DECREASING FLUX

S > 4 mJy → **steep spectrum (α_{med} ~ -0.7, S ~ν^{α})**

NB: double/ext RS

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

63% at 5 GHz [α_{med}~-0.29]

+ significant # of inverted spectra (α >0) **29% at 5 GHz**

NB → expected flattening of 5 GHz counts at S ~ 0.5 mJy

II – ATESP-DEEP1: Radio Spectra Analysis

Radio spectral index vs R (DEEP1abc+d)

- most $\alpha > -0.5$ sources → high R

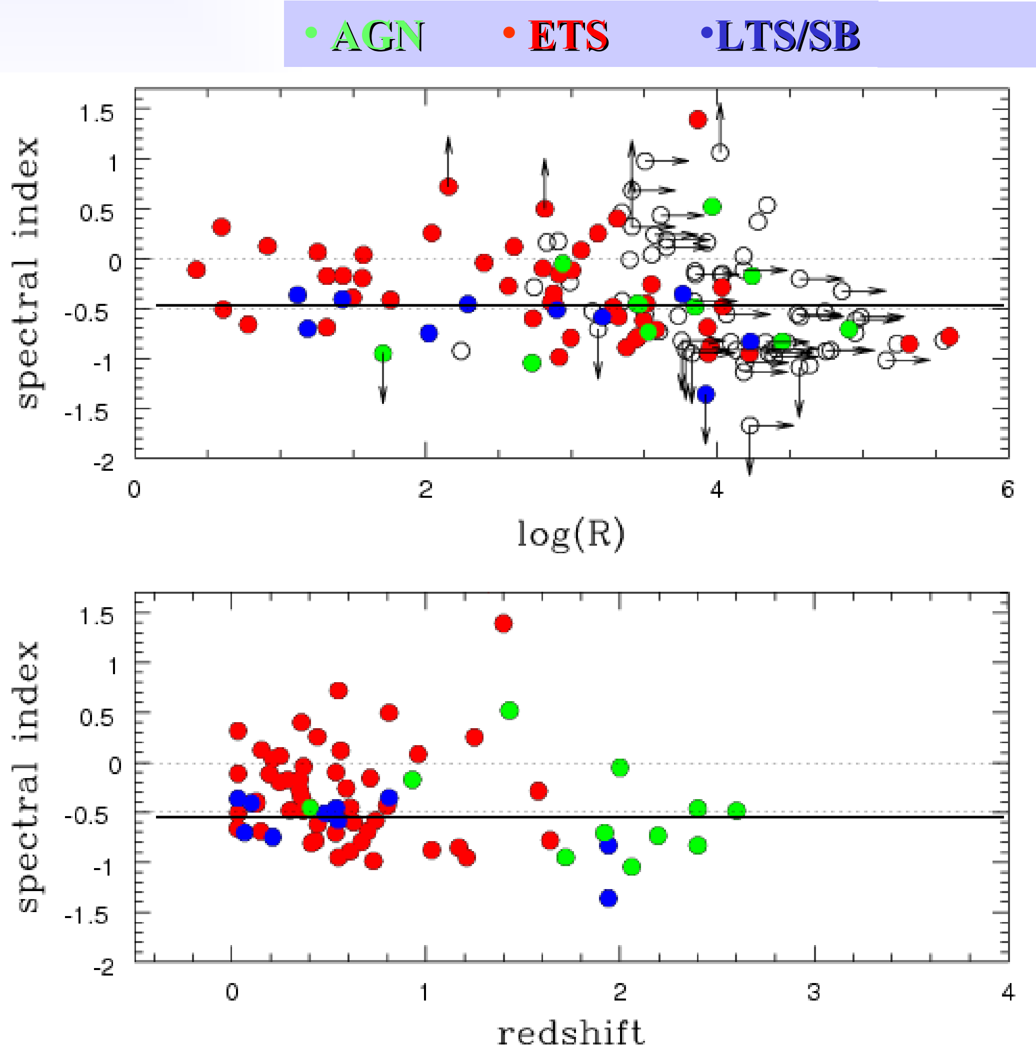
  [R>1000 → powerful RG and QS0]

- $\alpha > -0.5$ & low R → ETS

  [RS probably triggered by AGN]

- LTS/SB → steep sources

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

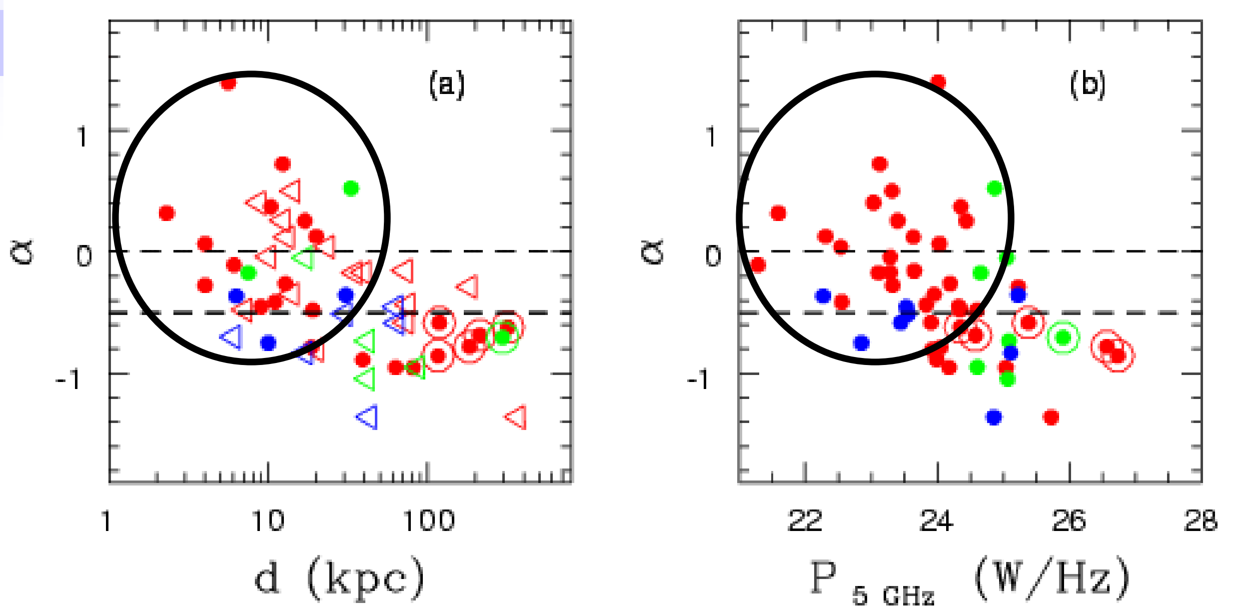


II – ATESP-DEEP1: Flat spectrum ETS

• AGN • ETS •LTS/SB

◁ Upper limits

⊙ Double/Extended RS



DEEP1abc:

39 ETS → 24 with flat/inverted spectra

- **Typically compact (<10-20 kpc)**
- **$P_{5\,GHz} \sim 10^{22-24}$ W Hz^{-1} (+ ETS spectra) → FRI class?**

BUT: FRI larger and steep

II – ATESP-DEEP1: Flat spectrum ETS

compactness + flat/inverted spectrum

→ Sinchrotron/free-free self-absorption

- similar to so-called Low Power Compact (LPC) RS?

  ($P_{408\ MHz} < 10^{25.5}$ W Hz^{-1}, see Giroletti et al. 2005)

  composite sub-class of FRI: Low-P BL Lac; jet instability; frustration

- young sources? But GPS → $P_{1.4\ GHz} > 10^{25}$ W Hz^{-1}

- low accretion/radiative efficiency (ADAF/ADIOS) LLAGN?

But typically $P_{5\ GHz} < 10^{21}$ W Hz^{-1} (eg. *Doi et al. 05)*

unless ADAF+jet → *higher P and still flat/inverted spectra*

(eg. Falcke & Biermann 99) → *further analysis needed*

I – Modeling the sub-mJy sources

A - Classical RL-AGNs → pure lum. ev.

→steep/flat *(e.g. Dunlop & Peacock 80)*
→FRI/FRII *(e.g. Willott et al. 01, Clewley & Jarvis 04, Sadler et al. 06)*

B - SF gals. → pure lum. ev.

→ local F(L) + L ~ $(1+z)^p$ p~3
(*e.g. Condon 89, Saunders et al. 90, Machalski & Godlowski 00, Yun et. Al 01, Sadler et al. 02*)

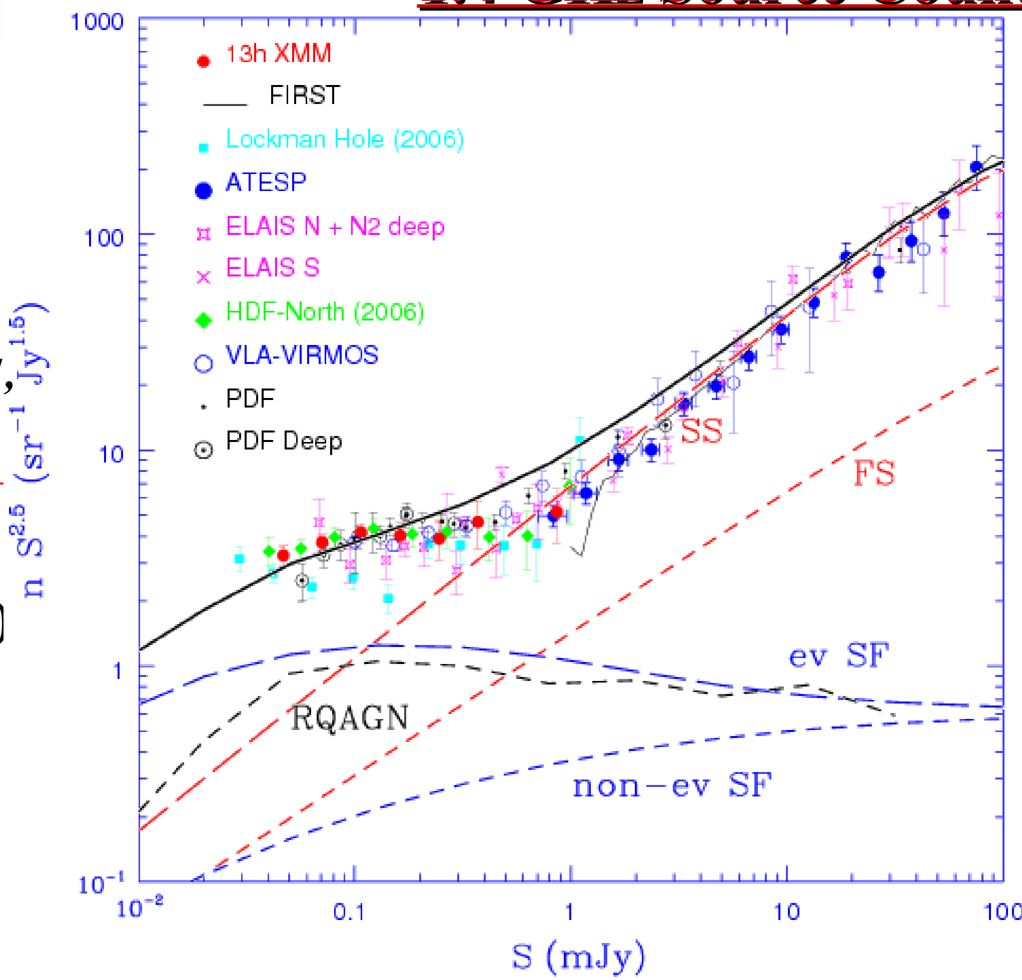
RQQSO: (*see Kukula et al. 1998*)

RS →compact & steep (<<10 kpc)
22< $\log(L_{1.4GHz})$<24

host galaxy → disk/spheroidal
(em. line spectrum)

LDDE (*Jarvis & Rawlings 2004*):
→ largest component at z<1

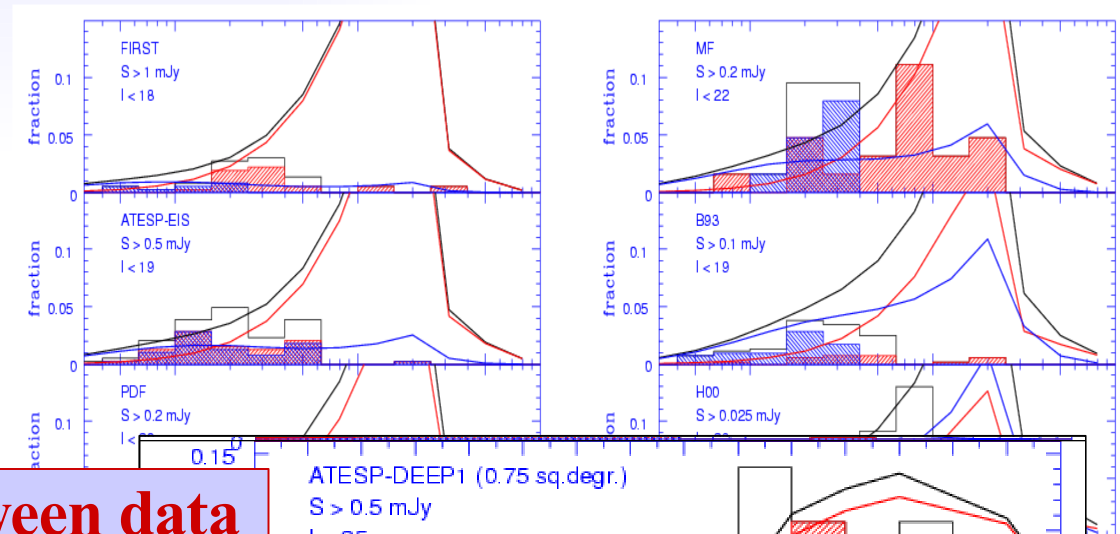
1.4 GHz Source Counts



III – Comparison with models

Models (Both Radio & Optical):

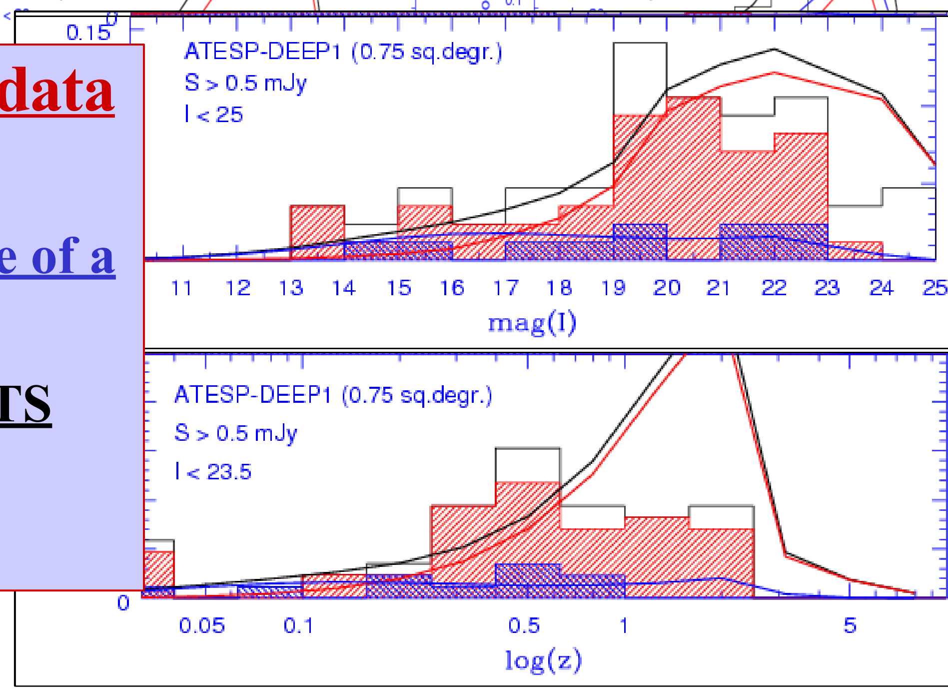
- **Radio Galaxies & QSO (Steep + Flat)**
- **Ev. (post-)SB & normal Spirals**



General agreement between data and models

At S>0.4 mJy & I<23.5 no evidence of a RQAGN component

Component of flat-spectrum ETS deserve further analysis



III – Implications for Deep LOFAR Surveys

Why LOFAR?

- **Large FoV (1.5 sq. degr/station @ 240 MHz)**

  → large statistics to better constrain models:
  a) ev. of SFGs at high z (>2)

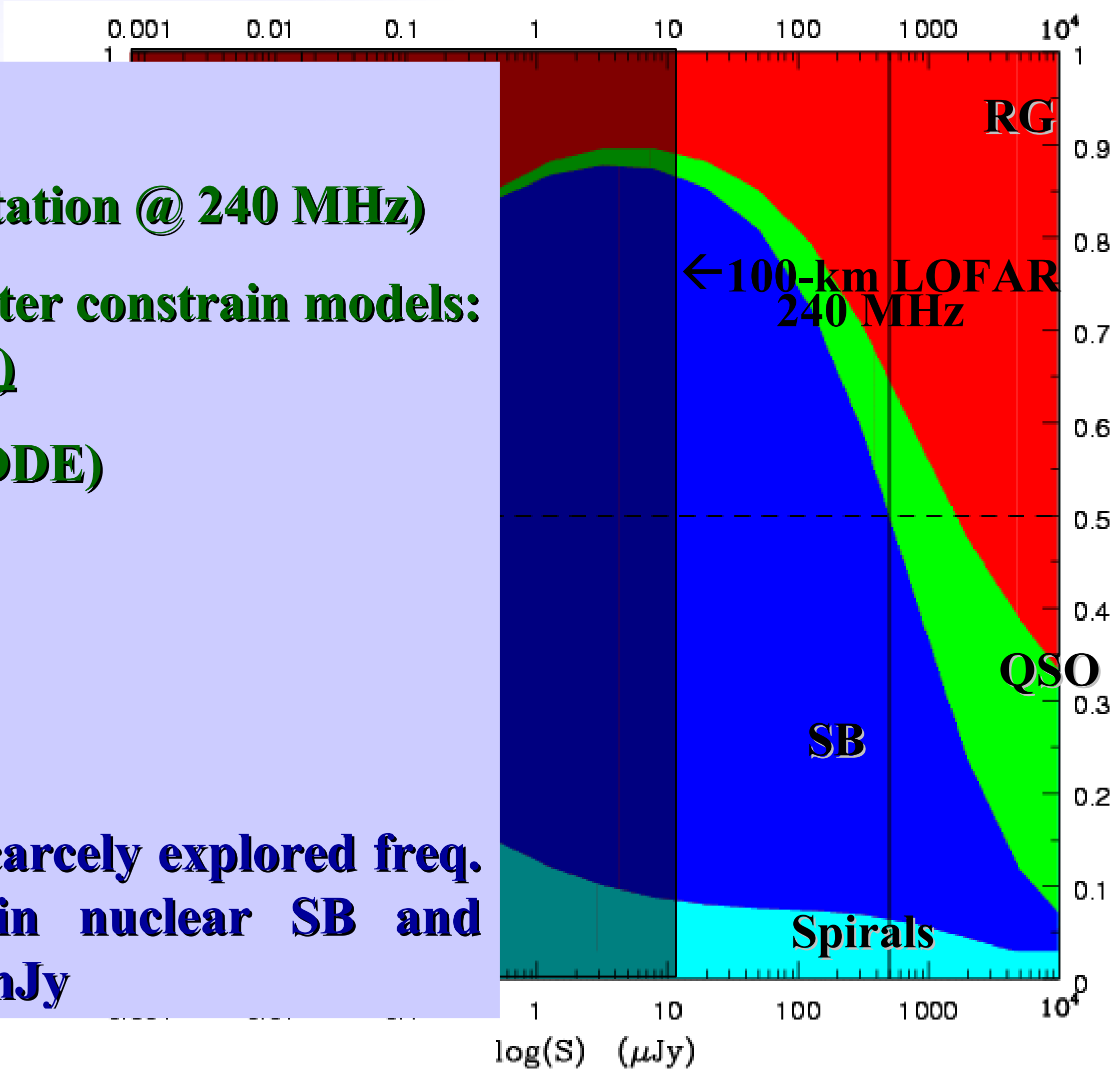
  b) ev. of AGNs (LDDE)

- **Low freq. Selection**

  → steep sources (SB)

- **Low freq. coverage**

  → radio spectra in a scarcely explored freq. range (effects of ff-abs in nuclear SB and flattening of AGNs at S<1 mJy



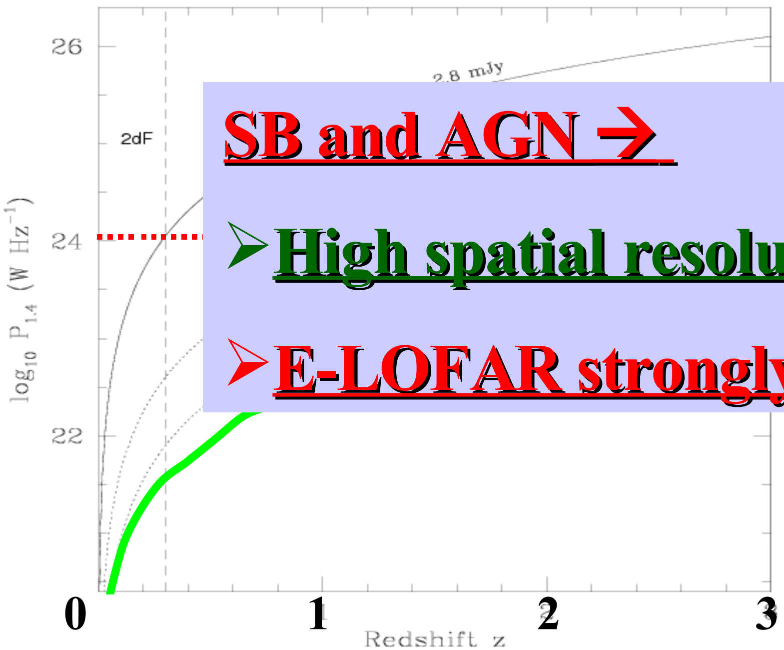
III – Model Predictions for Deep LOFAR Surveys

In 1.5 sq.deg. (Pr. Beam @ 240 MHz) → 2 10^4 RS (100-km LOFAR conf. Limit)

4000 SB @ z>2 400 SB @ z>4

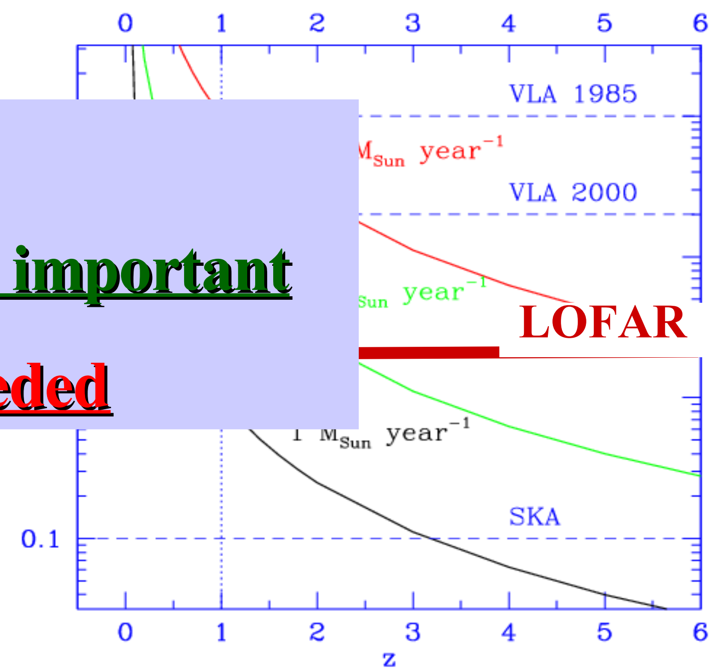
3000 AGN @ z>2 40 AGN @ z>4

➔ Deep optical-follow up feasible!



SB and AGN →

- **High spatial resolution important**
- **E-LOFAR strongly needed**



III – Comparison with models

Evolution of both radio and optical properties modeled (Prandoni et al. 04):

AGN: 1) Radio Galaxies associated to Early Type Galaxies:

RLF from DP90 (PLE model for Steep sources, smooth decline at z_{max} ~2.4)

Passive optical evolution for Ellipticals from Poggianti (1997)

2) Flat AGNs showing Sy1 or QSO optical spectra:

Optical LF for QSO objs (PLE model of Boyle et al. 1988,1991, z_{max} ~2)

RLF from the Ψ(R) function assuming 5% of Radio-Loud (Schmidt et al. 1995)

SFG: 1) Late Type Galaxies (normal spirals) &

2) Starburst and Post-Starburst Galaxies:

Local RLF (Sadler et al. 2002): 1/2 for (post-)SB and 1/2 for Spirals

+ PLE ➔ $L \sim (1+z)^{3.1}$ (z_{max} ~2, see Hopkins et al . 99) for (post-)SB

+ No Evolution for Spirals

Passive optical evolution from Poggianti (1997): Sc for (post-)SB, Sa for Spirals

III – Composition o

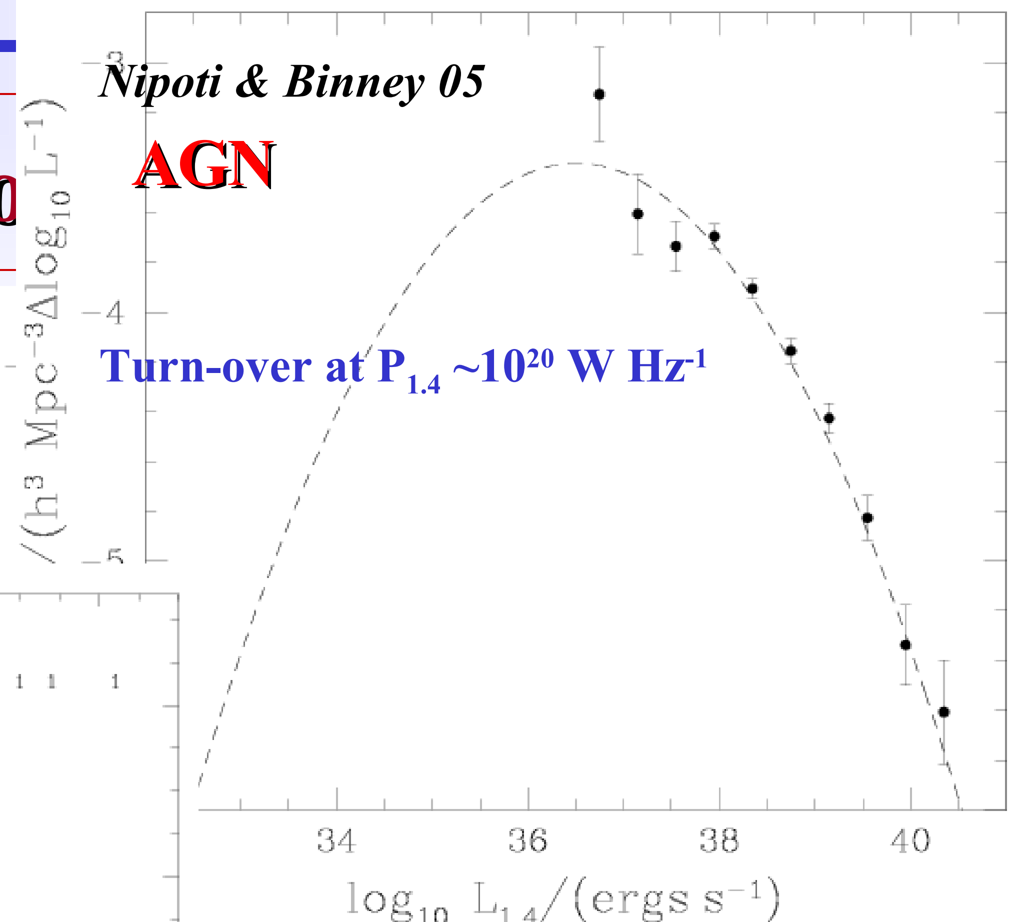
Critical Issues:

- ev. of Low-Lum AGNs
- extrapolation of Local LF

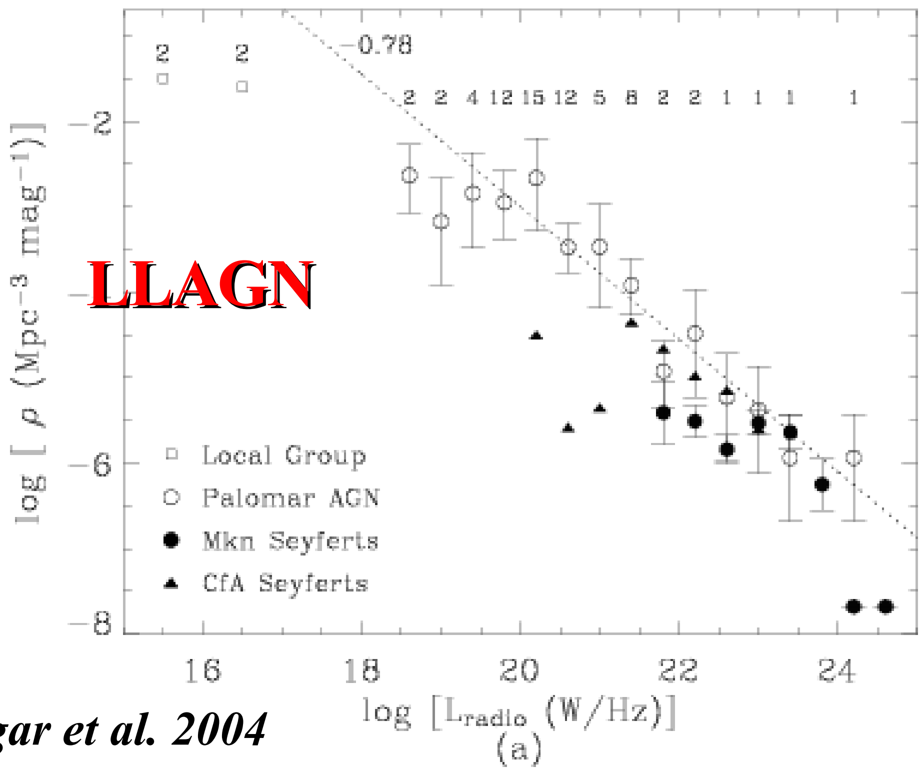
Nipoti & Binney 05

AGN

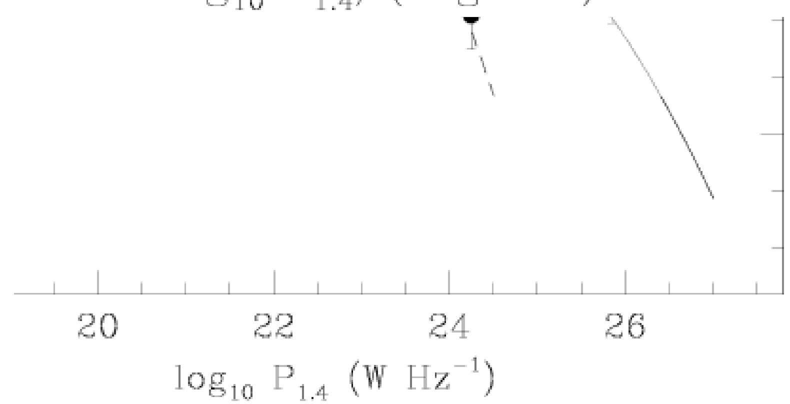
Turn-over at $P_{1.4} \sim 10^{20}$ W Hz^{-1}



LLAGN



Nagar et al. 2004



Sadler et al. 2002

III – Composition of the Faint Radio Sky

NanoJy Radio Counts

- **A)** AGN LF abruptly truncated at:

  $P_{1.4} \sim 10^{20}$ W Hz^{-1}

- **B)** AGN LF does not flatten down to:

  $P_{1.4} \sim 10^{18}$ W Hz^{-1}

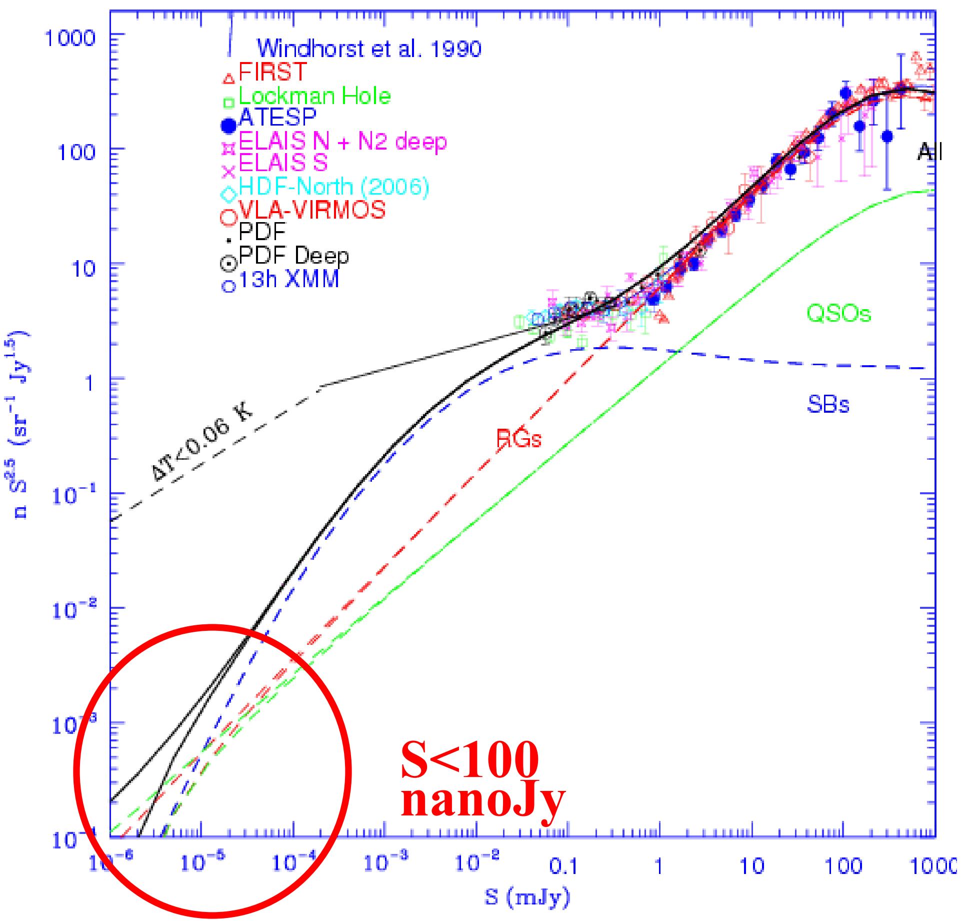


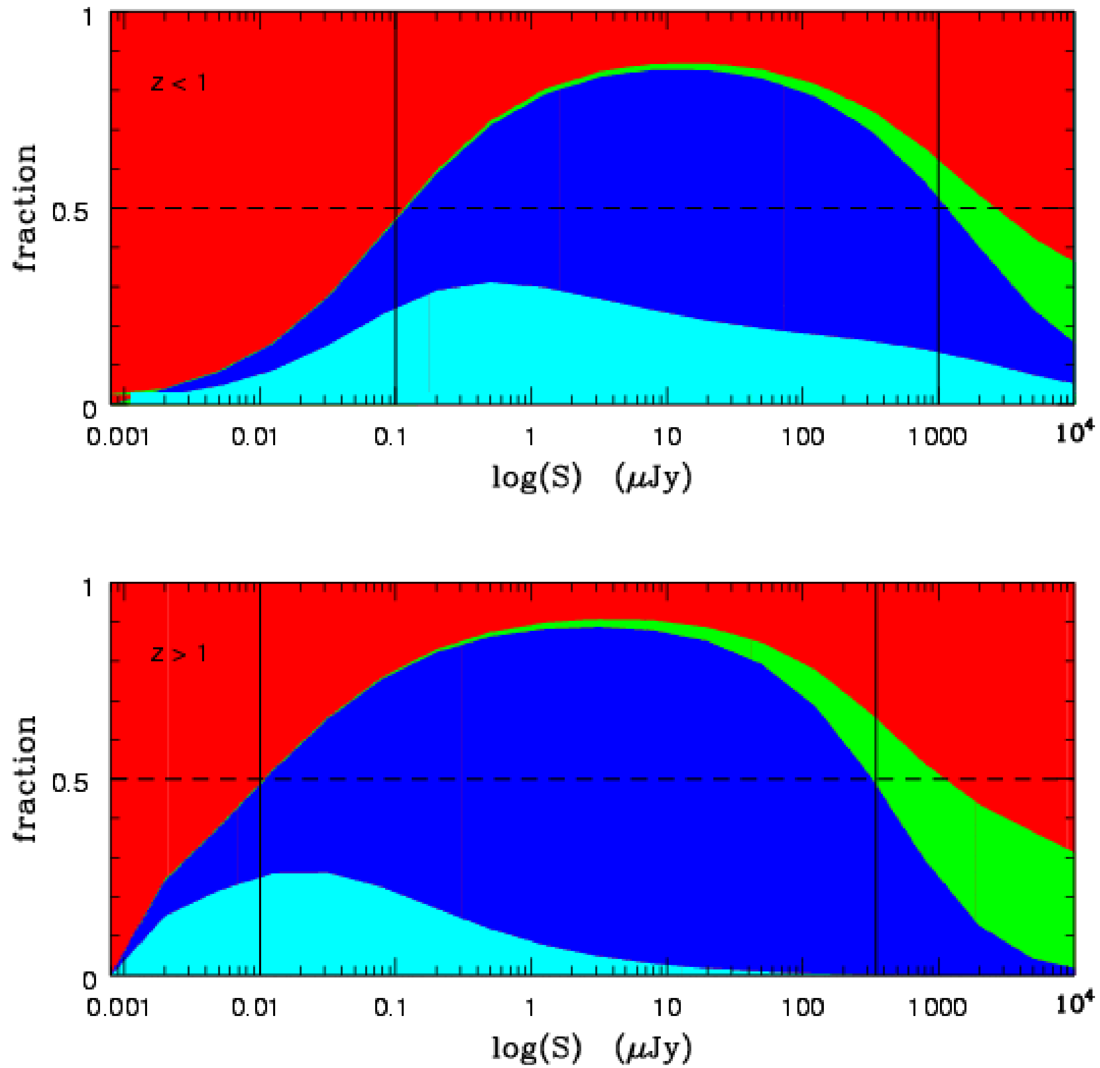
Figure 6:

Simulated Composition of the Faint Radio Source Population as a function of flux

Two redshift ranges:

a) z<1

b) z>1



Models:

Radio Galaxies

AGNs (Sy1 & Sy2)

Non evolving Spirals

Starburst and post-SB

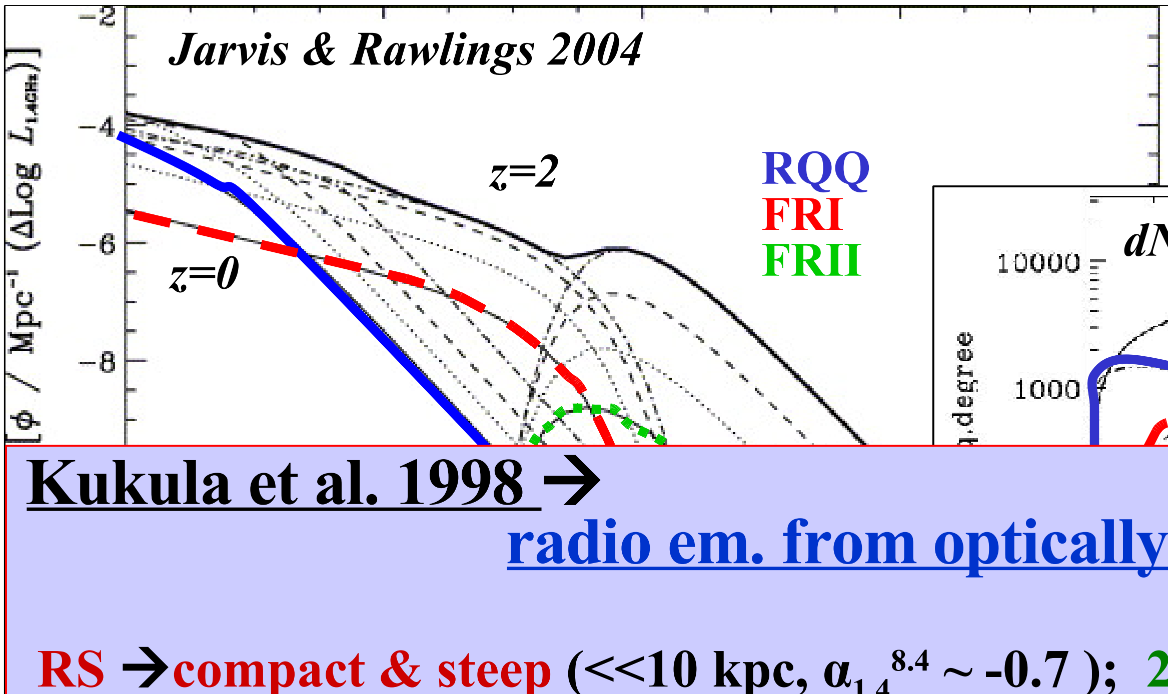
I – A Radio Quiet Component

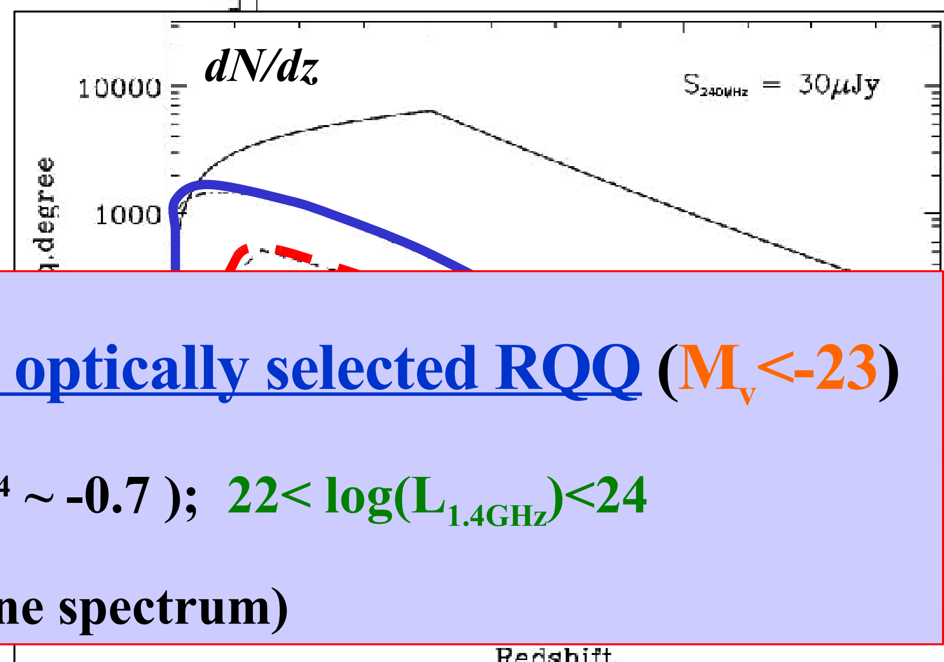
hard X-ray LDDE LF Ueda et al 2003

$\log(L_x) = -4.57 + 1.012 \log(L_{1.4GHz})$

Brinkmann et al. 2000

RQQ Radio 1.4 GHz LF





Kukula et al. 1998 →

radio em. from optically selected RQQ (M_v<-23)

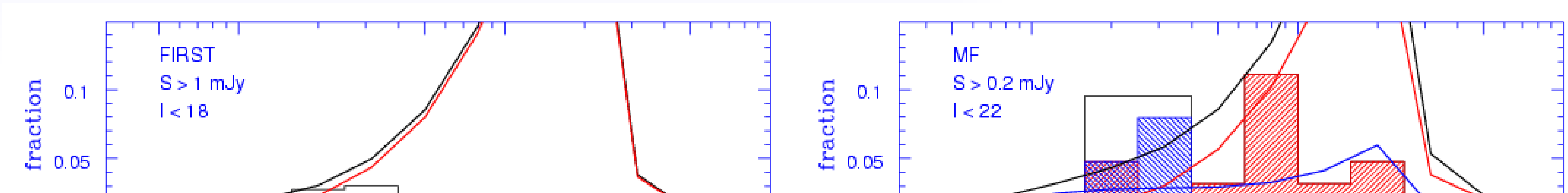
RS → compact & steep (<<10 kpc, $\alpha_{1.4}^{8.4} \sim -0.7$); $22 < \log(L_{1.4GHz}) < 24$

host galaxy → disk/spheroidal (em. line spectrum)

I – Optical follow-up

Sub-mJy population very ELUSIVE!

Updated to 2003



… but in the last years, evolving picture:

- **developement of photometric techniques**
- **deep spectroscopy surveys**
- **coordinated multi-λ observational efforts**

(e.g. PDS, VVDS, COSMOS, DPS, etc.)

Prandoni et al. 2004

INCOMPLETE OPT. ID. (tipically 50-60%)

More severe for OPT. SPECTROSCOPY

II – Opt. Identifications & Redshifts

Opt. Identification & Phot-z Derivation:

In DEEP1abc → 85 RS catalogued at 1.4 and/or 5 GHz

→ 66 identified to I~24 (77.6%)

→ 58 with I < 23 → mag-limited complete sample

→ 55 of 58 → redshift determination (95% success rate)

14 spectroscopic + 28 photometric

39 ETS (Ell, S0, Sa)	→	67 ± 11 %
9 LTS (Sp, SB)	→	16 ± 5 %
7 AGN (QSO, Sy1)	→	12 ± 5 %
3 UNCL	→	5 ± 3 %

I – Aims of present work

Observational characterization of mJy/sub-mJy population

We exploit deep multi-band optical data (UBVRIJK images + spectroscopy) & multi-frequency radio observations (ATESP 1.4 & 5GHz)

ATESP RS: 0.4<S<4 mJy → ideal to study the low-luminosity AGN component and infer its physical properties & evolution:

- low/high accretion rates? (FRI vs. RQQ)
- lower L AGNs peak at lower z?

  [NB: LDDE recently found for opt/X-ray AGNs Bongiorno et al. 07; Ueda et al. 03; Hasinger et al. 05] see also Vigotti et al. 03; Cirasuolo et al. 06 for radio AGNs

Future Work

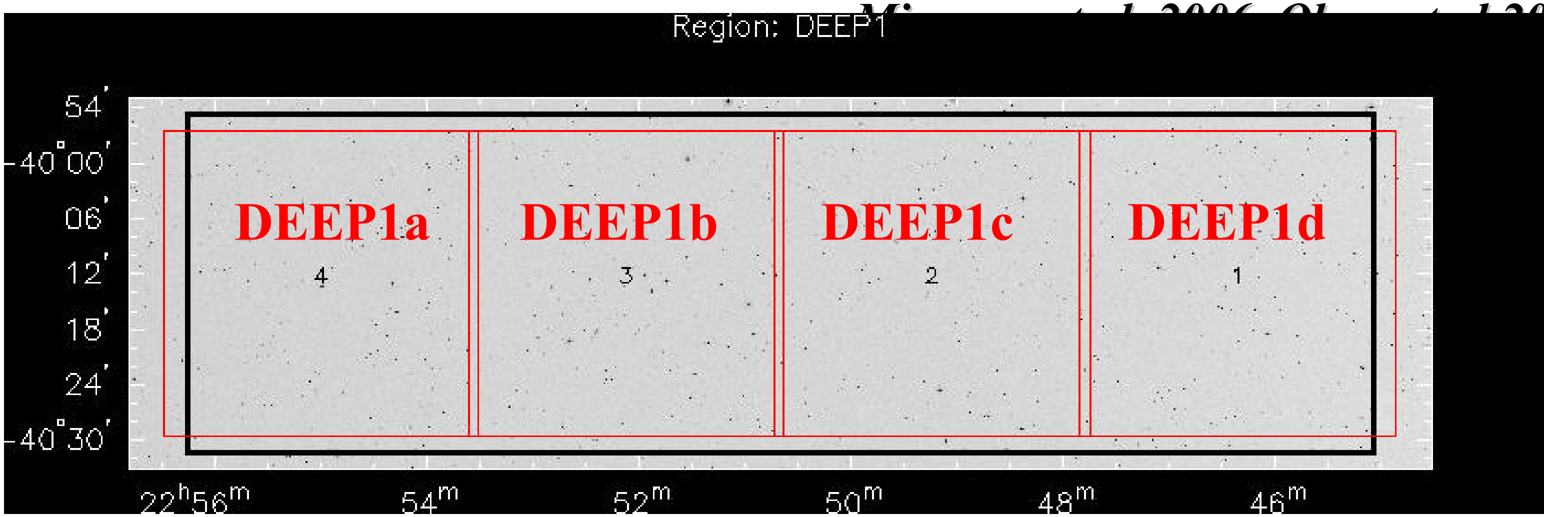
- **Set other observational constraints:**
  - R/O ratio, opt. Colors, radio spectral index, radio sky Tb, etc.
- **Update Models:**
  - new QSO LFs (2dF, SDSS, FIRST, etc.)
  - new optical models with particular respect to SBs (e.g. GALAXEV)
- **Introduce new Classes of objects that could be important at nJy levels:**
  - radio-quiet QSO
  - transient sky → e.g. single SN events
- **Check Robustness of Results by respect to Models**
- **Simulate images with resolution effects, dynamic range effects, etc.**

II – The DPS: opt/NIR imaging

- The ATESP 5 GHz region imaged in several optical/NIR passbands as part of ESO *Deep Public Survey* (DPS) ATESP → DEEP1
- DPS → three 2x0.5 sq. deg. regions (DEEP1, 2, 3) in southern sky
- DPS optical (UBVRI) → WFI camera at the 2.2mt ESO telscope
- The DPS in the near-IR (J, K_s) → SOFI camera at NTT
- Typical depths → $U_{AB} \sim 25.7$, $B_{AB} \sim 25.5$, $V_{AB} \sim 25.2$, $R_{AB} \sim 24.8$, $I_{AB} \sim 24.1$

  $J_{AB} \lesssim 23.4$ and $21.3 < K_{s\ AB} \lesssim 22.7$

Mi... t al. 2006, Ol... t al 2006



II – The DPS: near-IR imaging

- The DPS in the near-IR (J, K_s) → SOFI camera at NTT
- Observations in K_s-band ($K_{s\ AB} \leq 21.3$) for ~ 1/2 the area covered by the optical survey (eg DEEP1a+b)
- For more limited region →

  $J_{AB} \leq 23.4$ and $K_{s\ AB} \leq 22.7$ NIR images available

  (eg. central regions of DEEP1a+b)

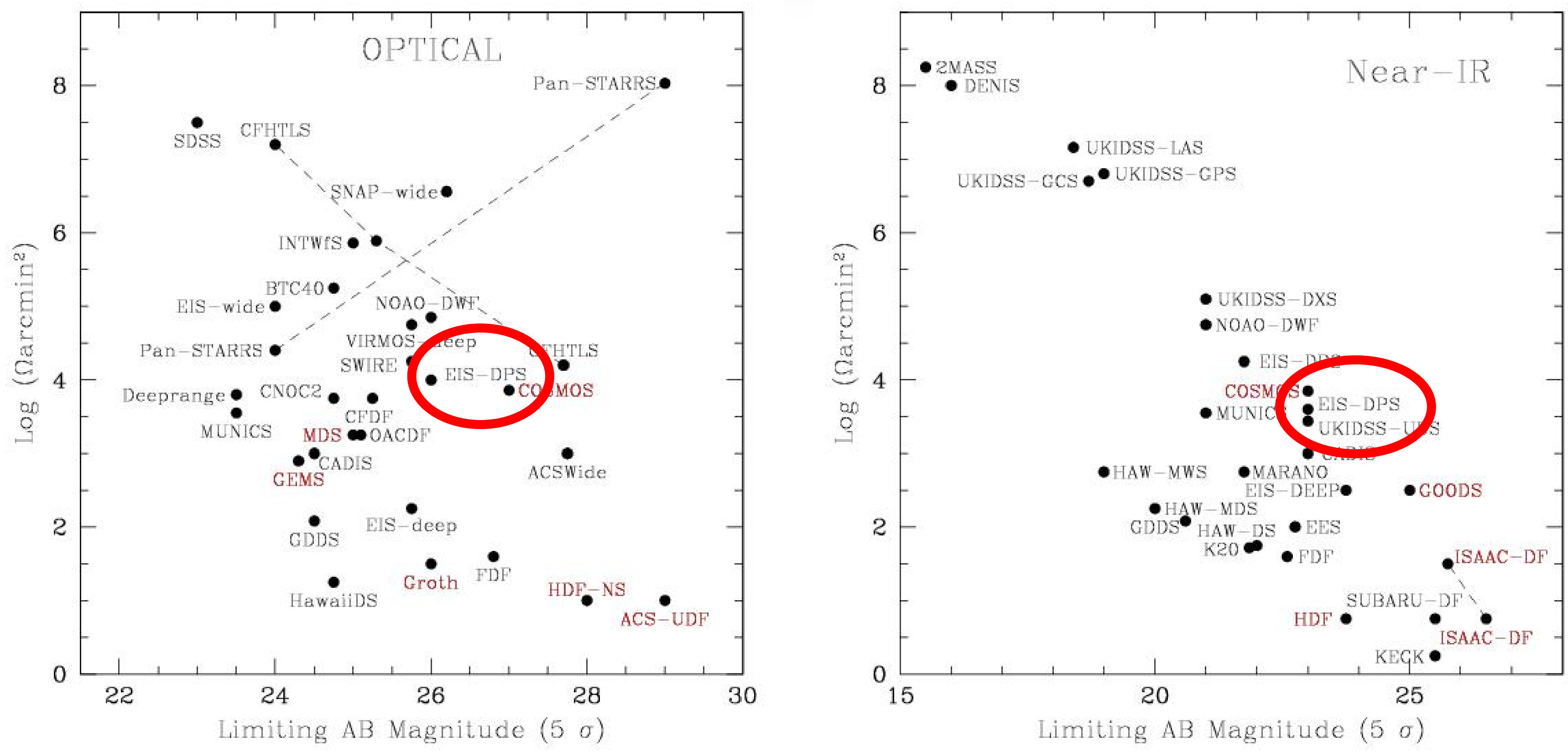
Olsen et al. 2006

Summary & Open Issues

- AGN component largely dominates at S>0.4 mJy
- We find a flat-spectrum RS component associated to ETS, which deserve further analysis
- If such component is AGN-driven → more plausibly related to FRI class (low efficiency) than to a RQ component (high efficiency)
- We find general agreement between data and models (RL-AGN + SFGs) but statistics still limited

- Larger statistics needed to better constrain models:
  - a) ev. of SFGs at high z (>2)
  - b) ev. of LLAGNs

II – Overview of opt/NIR surveys



Salvato 2005 - www.mpe.mpg.de/~mara/surveys

II – UBVRIJK Data Completeness

FIELD	PASSBAND	SEEING	m_{lim}
DEEP1a	U	1.4	25.3
	B	1.4	25.9
	V	1.0	25.8
	R	0.9	25.7
	I	0.9	23.8
	J	~0.7	~22.2
	K_{deep}	~0.7	~20.1
	$K_{shallow}$	~1.3	~19.6
DEEP1c	U	1.1	25.1
	B	1.3	26.6
	V	1.3	25.4
	R	1.3	25.3
	I	1.0	24.2
	J		
	$K_{shallow}$		

FIELD	PASSBAND	SEEING	m_{lim}
DEEP1b	U	1.2	24.6
	B	1.4	25.7
	V	1.3	25.4
	R	1.3	25.3
	I	1.0	24.2
	J	~0.7	~22.1
	K_{deep}	~0.9	~20.2
	$K_{shallow}$	~0.9	~19.4
DEEP1d	I		22.5

...tary data (Mignano PhD Thesis)

EIS-WIDE imaging data

Data reduction in progress

III – Open Issues

Conclusions:

- AGN component largely dominates at S>0.4 mJy
- large fraction of RS associated to ETS show flat/inverted radio spectra

  → most plausibly low efficiency accretion systems, but further analysis needed
- No evidence of RQAGN component at S>0.4 mJy
- Standard models of RL-AGN + SFGs fit data reasonably well

Open Issues:

- Larger statistics needed to better constrain models & derive AGN F(L,z)
- Largest model uncertainties due to a) ev. of SFGs at high z (>2)

  b) ev. of LLAGNs

III – Implications for Deep LOFAR Surveys

- **According to current observations and models:**

Ideal survey to study SFGs and their radio evolution (SFH a z>>1) should have a limiting flux of ~0.1 – 1 μJy @ 1.4 GHz

Why LOFAR?

→ Large FoV (1 sq. degr @ 240 MHz → several thousands RS)

→ Low freq. selection would clean the sample from flat-spectrum AGN component (note spectral flattening at S<1 mJy)

Feasibility:

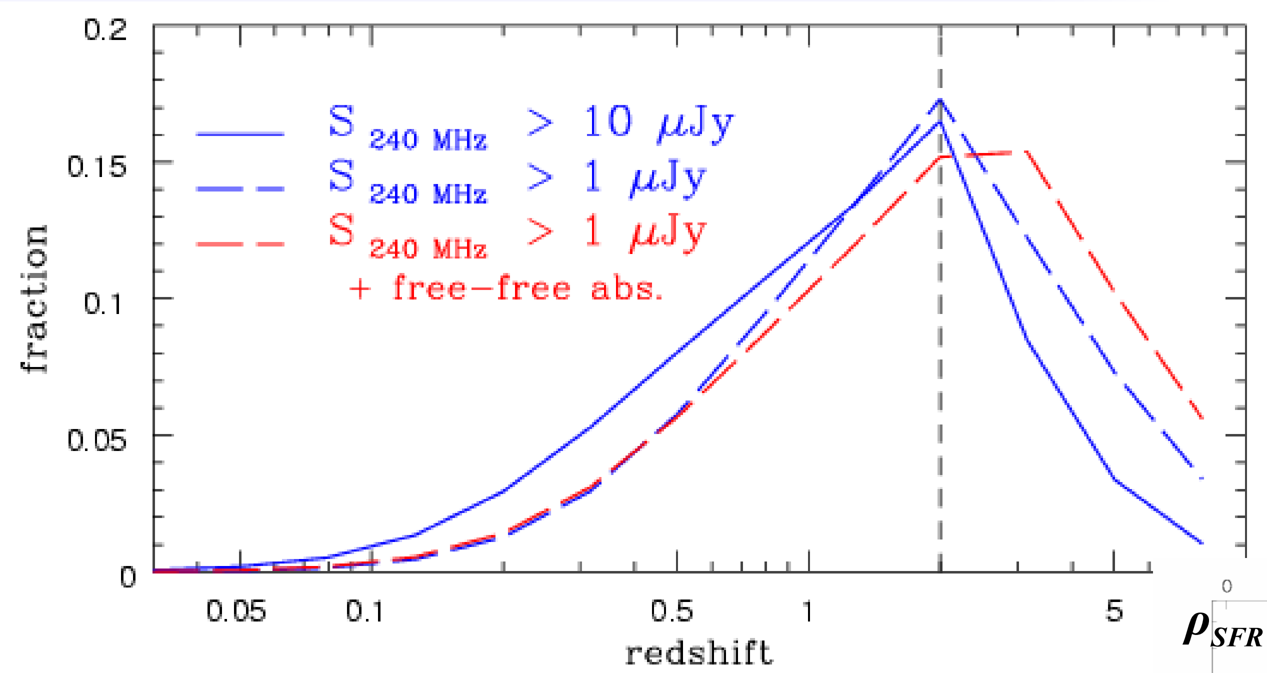
@ 240 MHz → S_{lim}~0.4 – 4 μJy (thanks to step spectrum of SFGs)

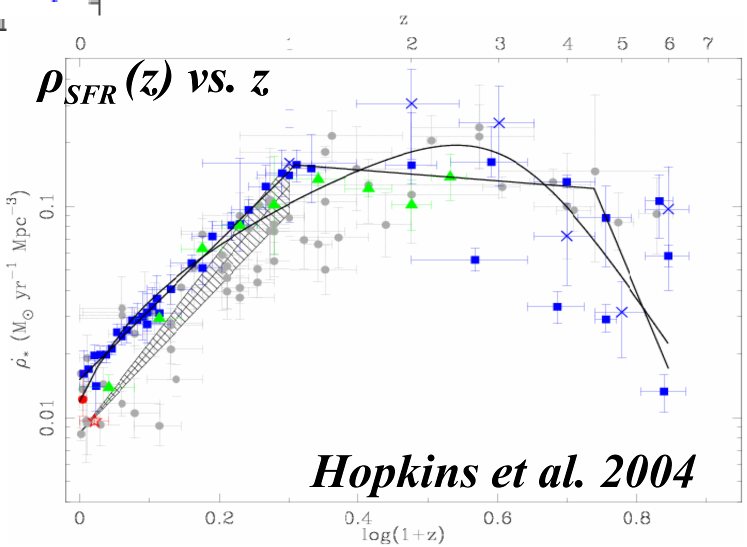
not feasible with 100-km LOFAR (confusion limited)

but feasible with E-LOFAR: 400-km LOFAR → S_{conf}~5 μJy @ 240 MHz

or 1000-km LOFAR → S_{conf}~1 μJy @ 240 MHz (sensitivity limited?)

III – Implications for Deep LOFAR Surveys





NB: also sub-mJy AGN component would benefit of high (sub-arcsec) spatial resolution

II – Optical spectroscopy

- ESP redshift survey (*Vettolani et al. 1998*):

complete spectroscopy for galaxies with $b_j < 19.4$

- DEEP1c and d (overlap with EIS-WIDE, Patch A, *Nonino et al. 99*):

complete spectroscopy for galaxies with I<19

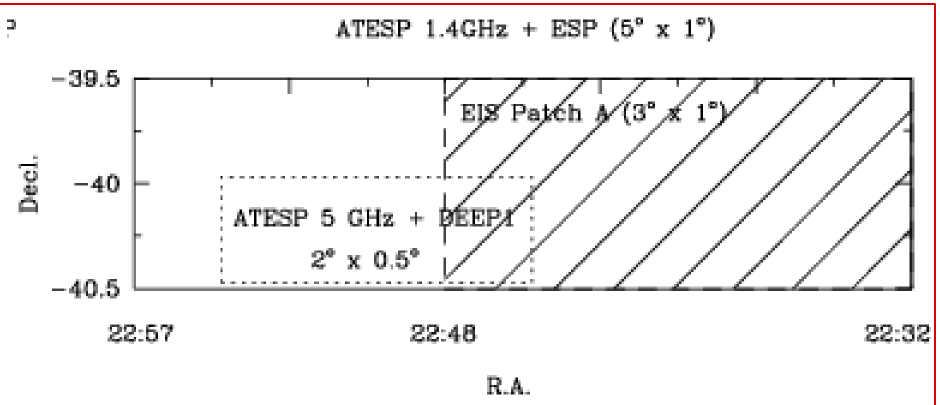
Prandoni et al. 2001b

+ sparse NTT/VLT spectroscopy for gals with 19<I<22.5

The ATESP-EIS Sample:

- 219/386 RS identified (57%) to I = 22.5
- 70 Spectra for all optical id with I < 19.0

+ 28 spectra at 19 < I < 22.5



II – ATESP-DEEP1 Sample Composition

Composition of the ATESP-DEEP1(abc) complete sample:

I<23.5 → 58 RS

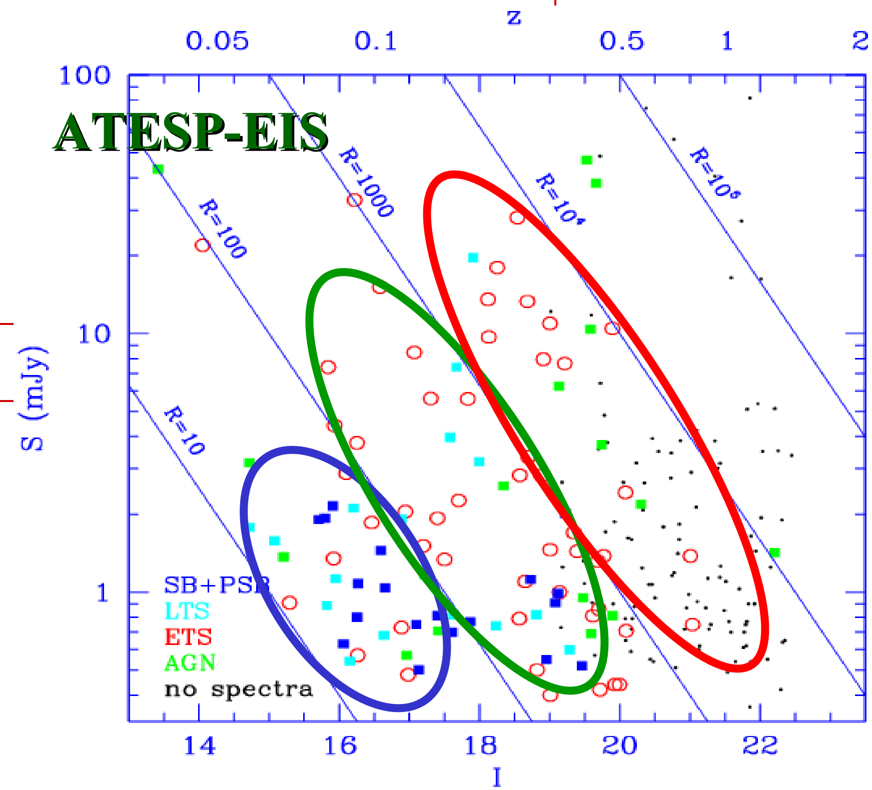
39 ETS (Ell, S0, Sa) → 67 ± 11 %

7 AGN (QSO, Sy1) → 12 ± 5 %

9 LTS (Sp, SB) → 16 ± 5 %

3 UNCL → 5 ± 3 %

Prandoni et al. 01b



Comparison with ATESP-EIS:

I<19 → 70 RS

49 ± 8% ETS

9 ± 3 % QSO

43 ± 8 % LTS

- UNCL

AGN/ETS dominate @ high R

II – ATESP-DEEP1: Flat spectrum ETS

Caveats: a) α from non-simultaneous obs. → variability effects

b) only 2 freq. available

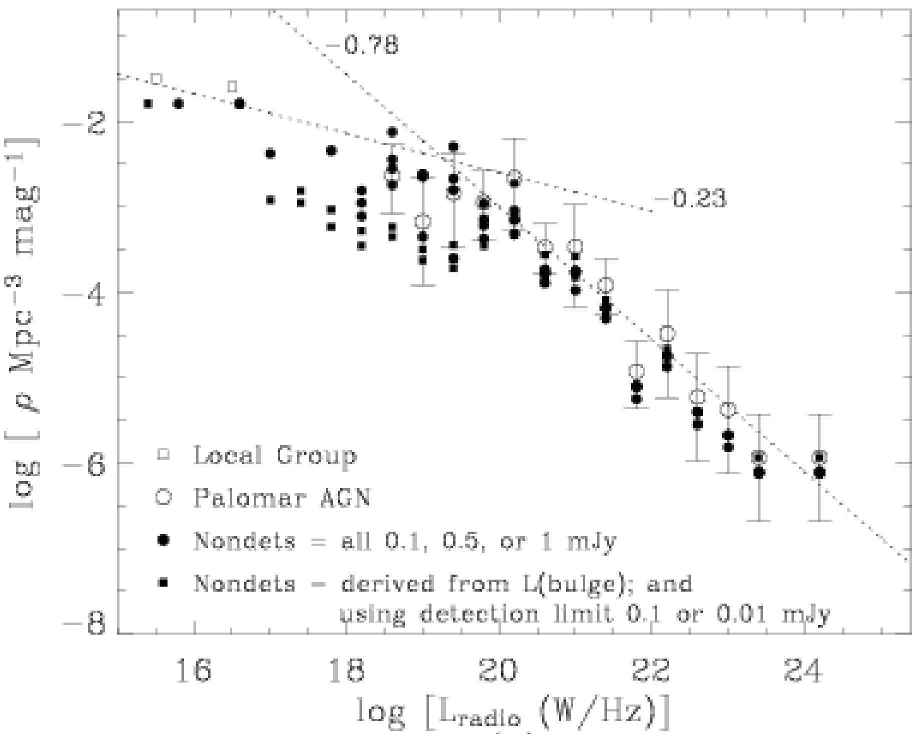
→ **Multi-freq simultaneous obs. needed to confirm spectra**

NB: high freq. data (>10 GHz) needed to discriminate ADAF from more conventional accretion schemes

→ **A flux-limited sub-sample of 15 ATESP-DEEP1 ETS with S>0.6 mJy has been proposed for 20/13, 6/3 cm and 12 mm quasi-simultaneous obs at ATCA**

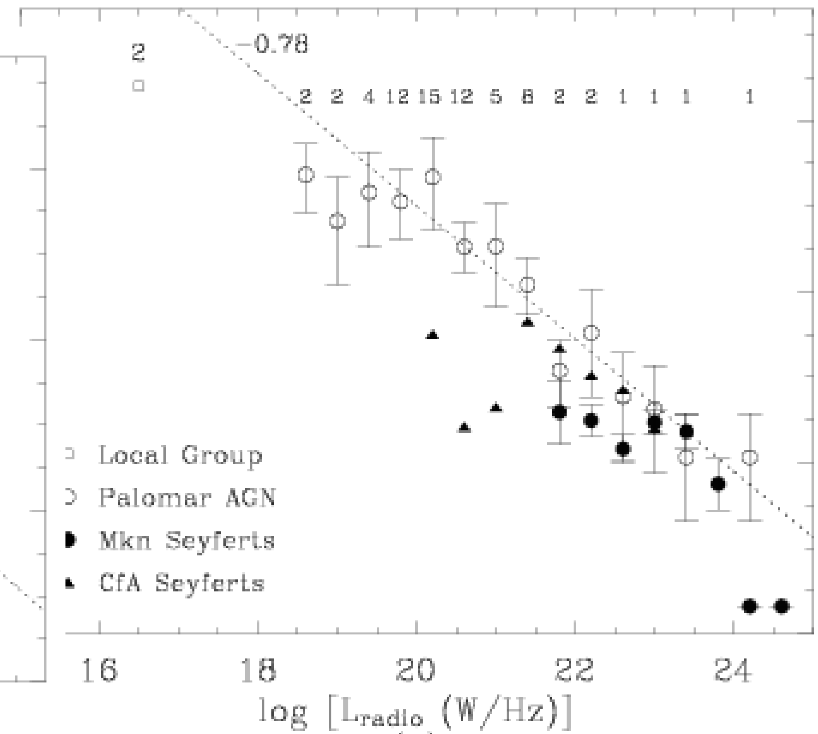
In May 2007 time allocated for 6/3 cm and 12mm obs.

Strong outflows may shift the peak to cm λ (Quataert & Narayan 99)



−0.78
−0.23
−2
−4
−6
−8
log [ρ Mpc^{-3} mag^{-1}]
Local Group
Palomar AGN
Nondets = all 0.1, 0.5, or 1 mJy
Nondets − derived from L(bulge); and
using detection limit 0.1 or 0.01 mJy
16
18
20
22
24
log [L$_{radio}$ (W/Hz)]

(b)



−0.78
2
2 2 4 12 15 12 5 8 2 2 1 1 1 1
Local Group
Palomar AGN
Mkn Seyferts
CfA Seyferts
16
18
20
22
24
log [L$_{radio}$ (W/Hz)]

(a)

Figure 7:

Simulated Composition of the Faint Radio Source Population as a function of flux

Two magnitude ranges:

a) I<23

b) I>23

+ Dust effect

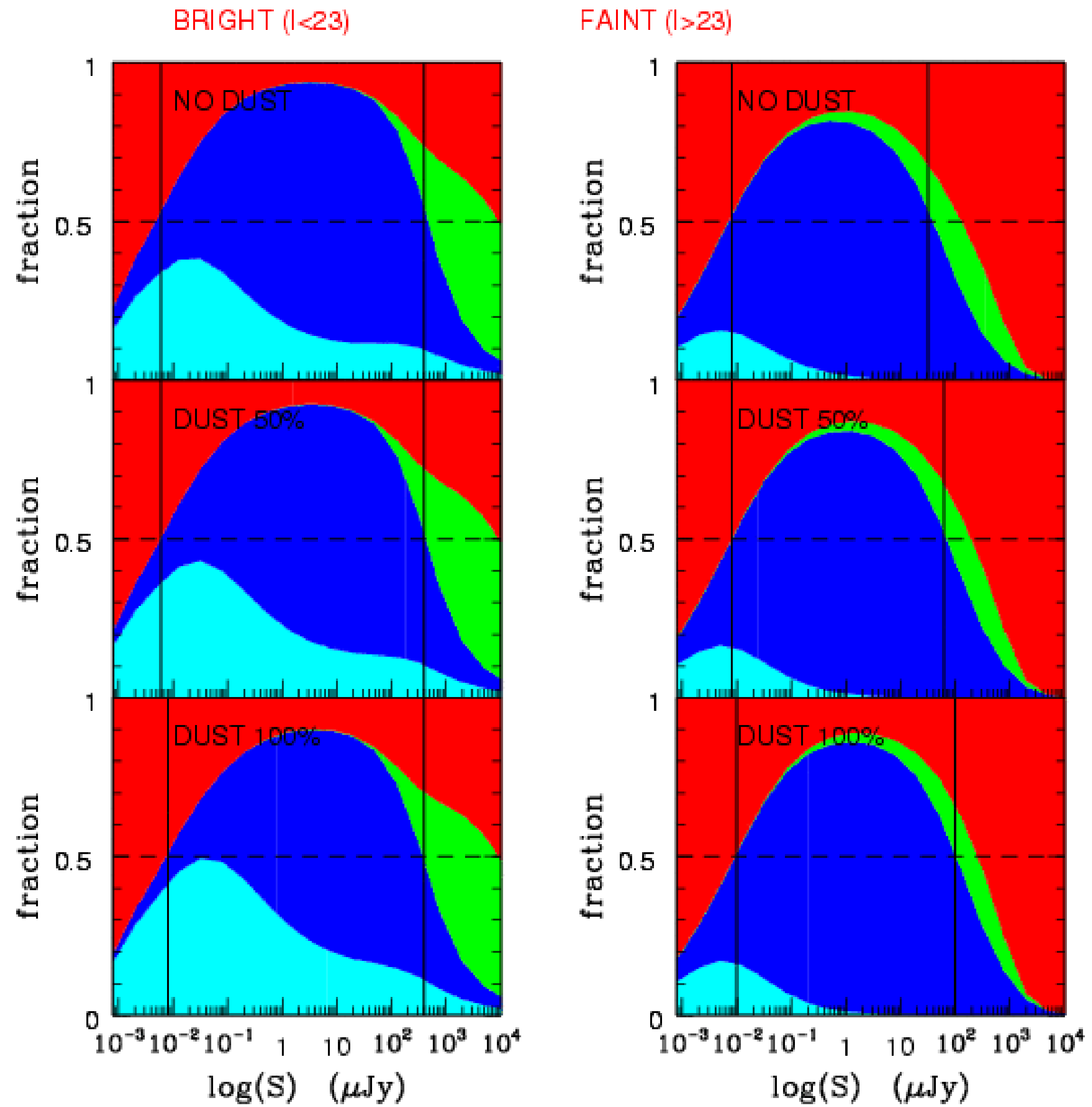
Models:

Radio Galaxies

AGNs (Sy1 & Sy2)

Non evolving Spirals

Starburst and post-SB



Comparison Samples

A number of surveys at the mJy, sub-mJy and μJy level have been performed, which can provide important boundary conditions to any modelling of the radio sky.

The radio counts are constrained by using all the samples available in the literature. We then focused on samples with optical spectroscopy follow-up to get constraints on the redshift and magnitude distributions of the sources. In particular we refer to the following samples: FIRST (Magliocchetti et al. 2000), ATESP-EIS (Prandoni et al. 2001b), PDF (Phoenix Deep Field, Georgakakis et al. 1999), MF (Marano Field, Gruppioni et al. 1999), B93 (sample collection studied by Benn et al. 1993), H00 (Collection studied by Haarsma et al. 2000). The relevant information for these samples is listed in Table 1. Radio fluxes refer to 1.4 GHz and optical magnitudes are given in I band.

Table 1 – Comparison Samples

Sample	FIRST	ATESP-EIS	PDF	MF	B93	H00
- S_{lim} (mJy)	~1	0.5	0.2	0.2	0.1	0.025
- Area (sq.degr)	6.3	3.0	3.0	0.36	1.1	0.044
- N_{tot}	386	365	938	63	523	77
- $mag(I)_{lim}$ (spectroscopy)	18	19	20	22	21	23
- N_{sp}	38	70	228	29	72	25
-N_{tot} (expected from models)	547	570	1311	157	1194	126
- $\%_{SF}$ (expected from models)	8	17	30	30	47	63
- $\%_{AGN}$ (expected from models)	92	83	70	70	53	37

NB: SF = Spirals + (post-)Starburst; AGN = Radio Gals + AGNs.

Observational Constraints

The models should be able to reproduce:

1) Radio Number Counts

The models can fit the observed number counts within a factor of 2 along the entire flux range spanned by the counts (40 μJy – 1 Jy).

2) The total number of sources in the given samples

The observed and modeled N_{tot} values agree within a factor of 2.

The larger values expected from the models are in part due, at least to incompleteness present in the real samples.

3) N(z) at different limiting fluxes

The models can trace with good accuracy the redshift distribution of the sources in the given samples. Unfortunately, the optical spectroscopy follow-up of faint radio samples is severely incomplete and therefore models can be constrained only at *low redshifts*.

4) N(m) at different limiting fluxes

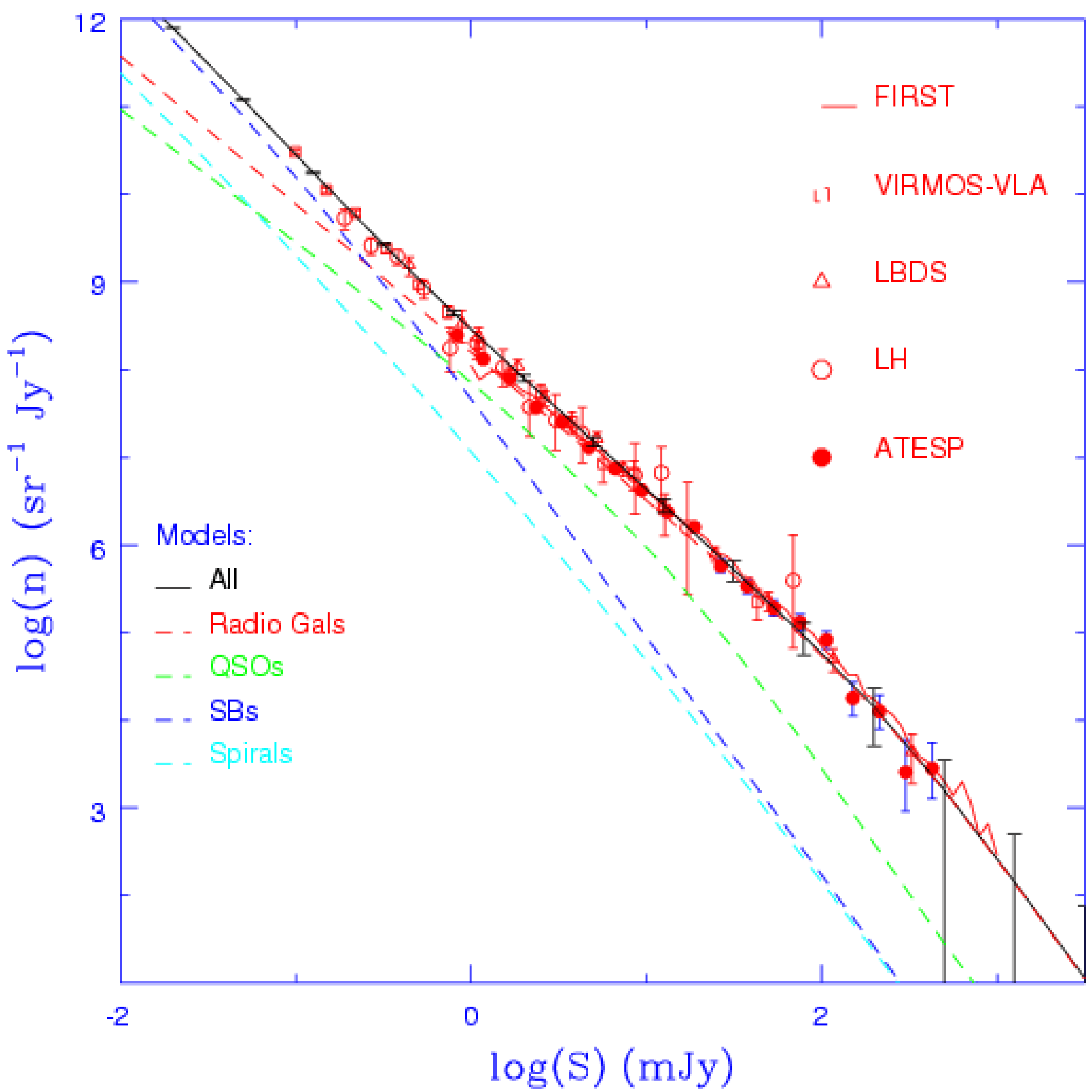
The models can trace with good accuracy the magnitude distribution of the sources in the given samples. Again, incompleteness in the optical follow-up allows us to probe our models only at *bright magnitudes.*

Figure 1:

Differential 1.4 GHz Number Counts

Models:

- Radio Galaxies
- AGNs (Sy1 & Sy2)
- Non evolving Spirals
- Starburst and post-SB
- All classes



II – Photometric z derivation

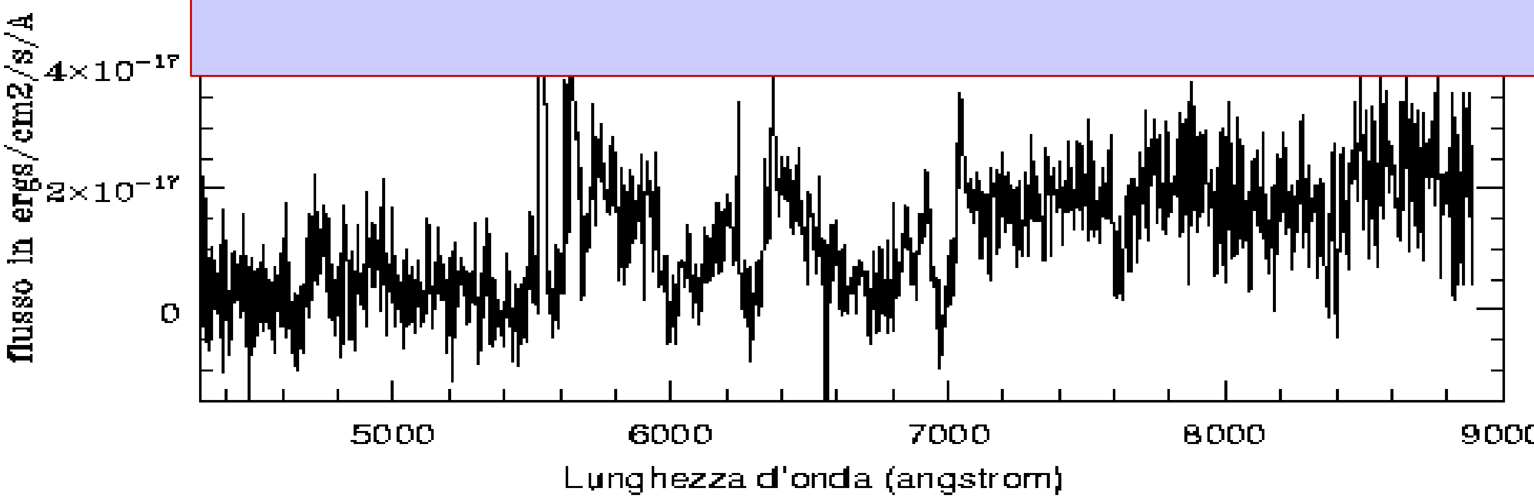
•66 identi

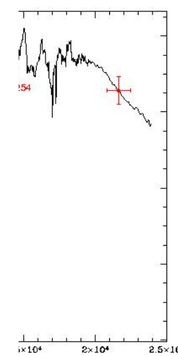
•Used Hy
types and

•Used def

•In additi
(Richards

- **Results:**
  - a) z_{spec} available → 14
  - b) high P(z) (or reduced χ^2 <1) → 28
  - c) low P(z) (or reduced χ^2 >1) → additional analysis → 13 (5 with no JK)
  - d) failed → 11 [typically faintest objects: 6 I>23.5 + 2 only NIR)]
    3 deblending troubles
- **55/66 (83%) → z_{phot}** NB: for DEEP1c only UBVRI
- **55/58 (95%) in magnitude-limited complete sample (I<23.5)**





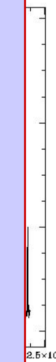


Figure 2: N(z) for the samples listed in Table 1

Models & Data: Radio Galaxies + AGN

Starburst, post-SB + Non evolving Spirals

All classes

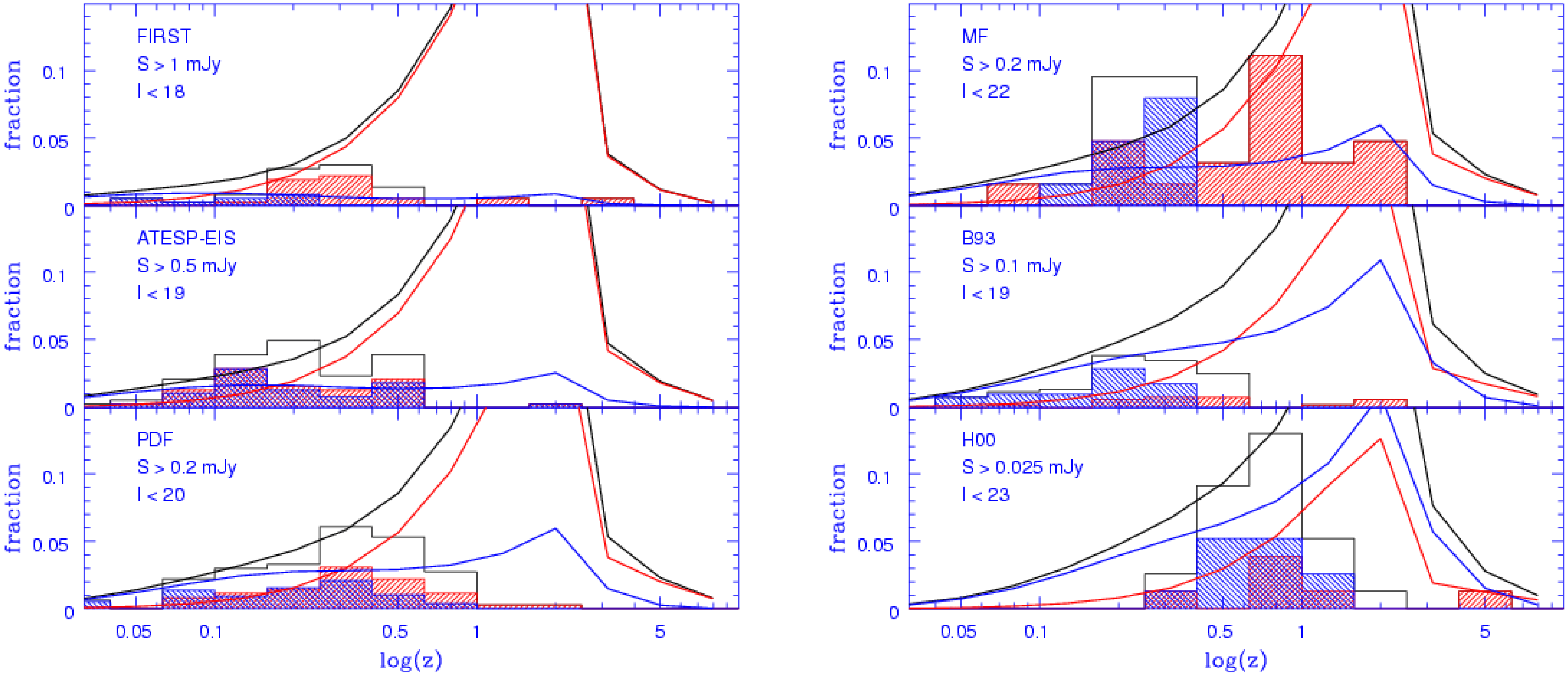


Figure 3: N(m) for the samples listed in Table 1

Models & Data: Radio Galaxies + AGN - SB, post-SB + Non evolving Sp - All classes

- Solid lines: No Dust
- Dashed lines: 50% of Dusty SB
- Dotted lines: 100% of Dusty SB

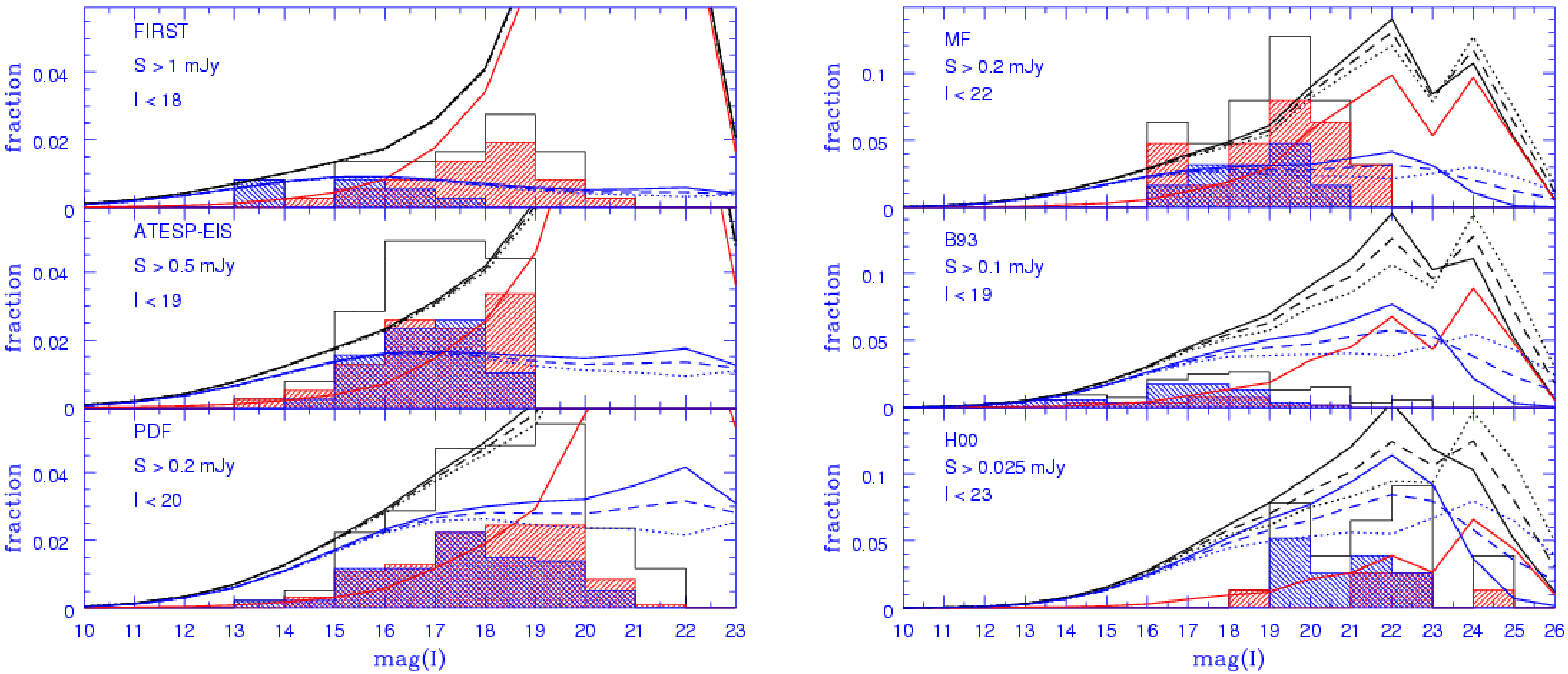


Figure 4: N(m) for the sample H00 (see Table 1)

Models & Data: Radio Galaxies + AGN - SB, post-SB + Non evolving Sp – All classes

We show also sample objects with measured redshift but not clear classification:

Irregular/merging objects (green)

red (I-K>4) objects

We explore two scenarios:

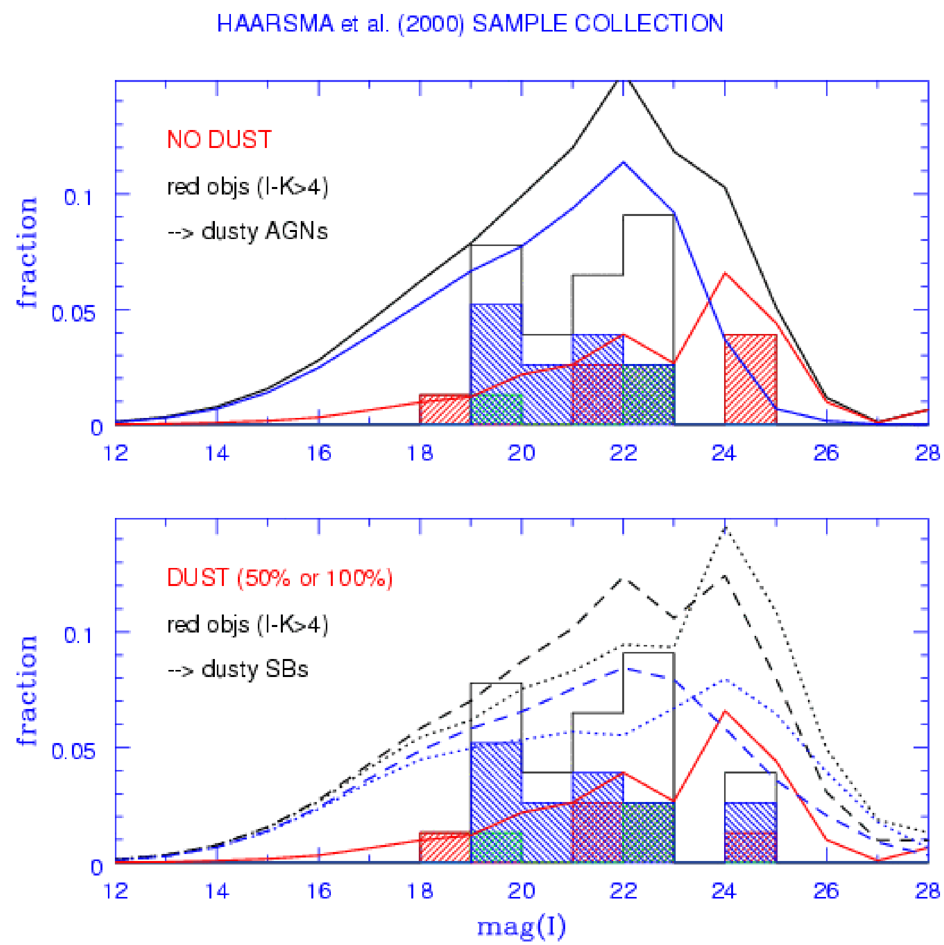
Top: No Dust & red objs summed to RGs and AGNs

Bottom: Dust present and red objs summed to SB,post-SB and Spirals

No Dust

50% of Dusty SB

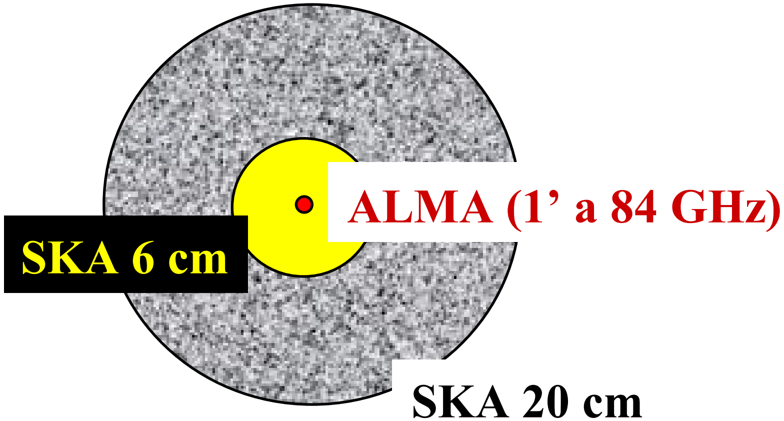
100% of Dusty SB

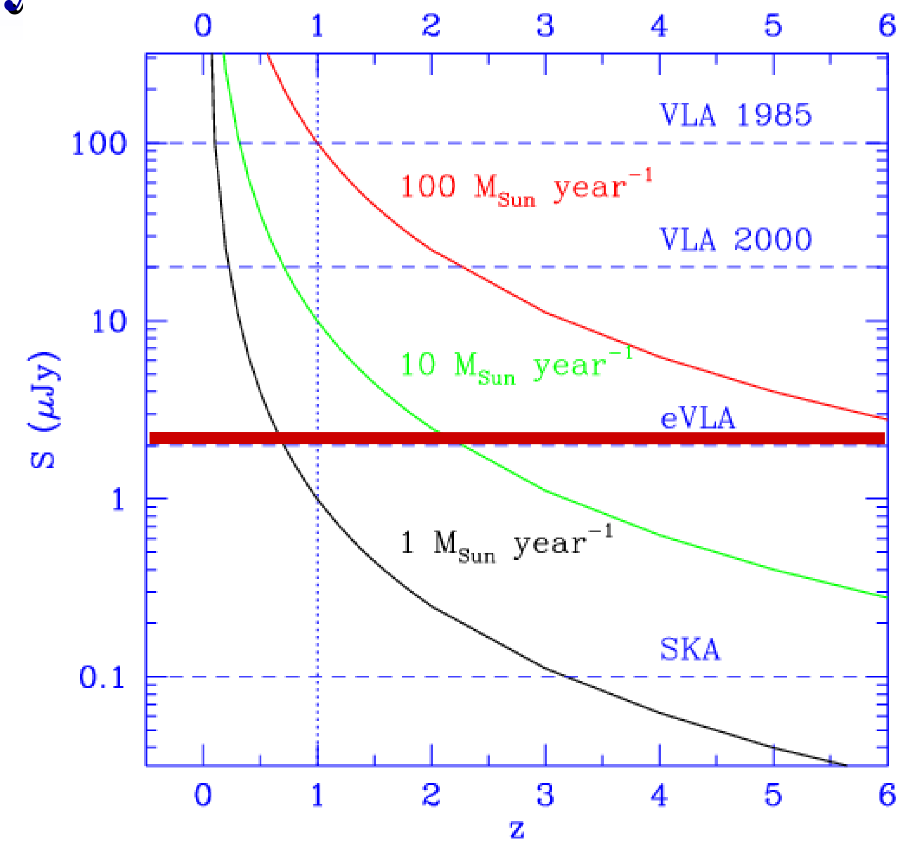


IL FUTURO DELLE SURVEY RADIO

2) SFH a z>> 1: → 100 nJ

1 deg² @ 1.4 GHz
0.1 arcsec risoluzione
1 RS/arcsec²





IL FUTURO DELLE SURVEY RADIO

1) Proprieta' fisiche ed evoluzione sorgenti sub-mJy e microJy

—

Follow-up ottico completo:

- Identificazioni: **I<22 ~50%**
  I<26 ~80%
- Spettri: **<50% a I_{lim} telescopio 4m**

Deep redshift surveys (VIRMOS)

Deep Multicolor Imaging → redshift fotometrici (ATESP5)

ALMA → z per SB distanti

→ <0.1" <=> <1 kpc a z>1

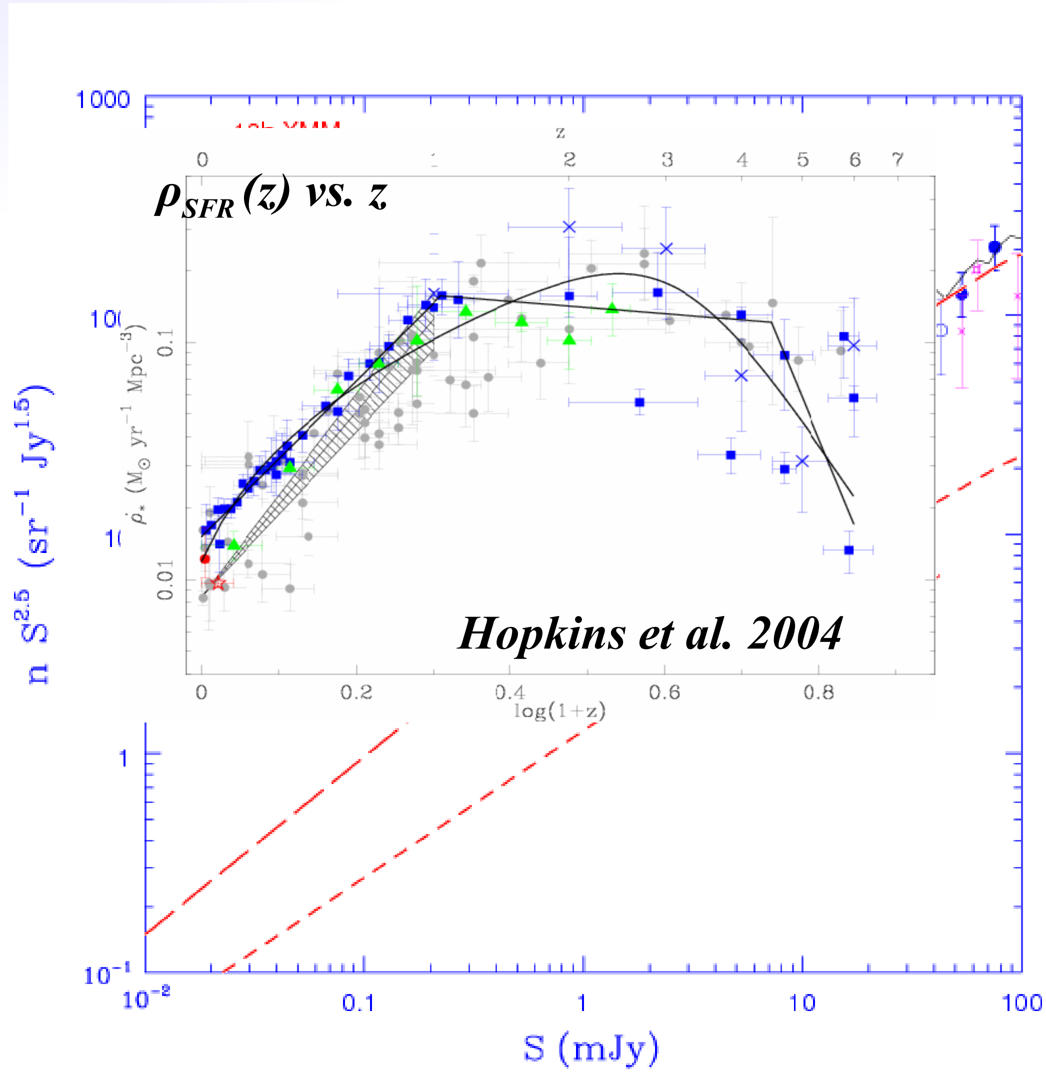
I – 1.4 GHz source counts

SHARP STEEPENING
@ S<1 mJy

EMERGENCE OF NEW POPULATION(S)
RL-AGN ~ 99% @ S > 60 mJy

strongly ev. SB?

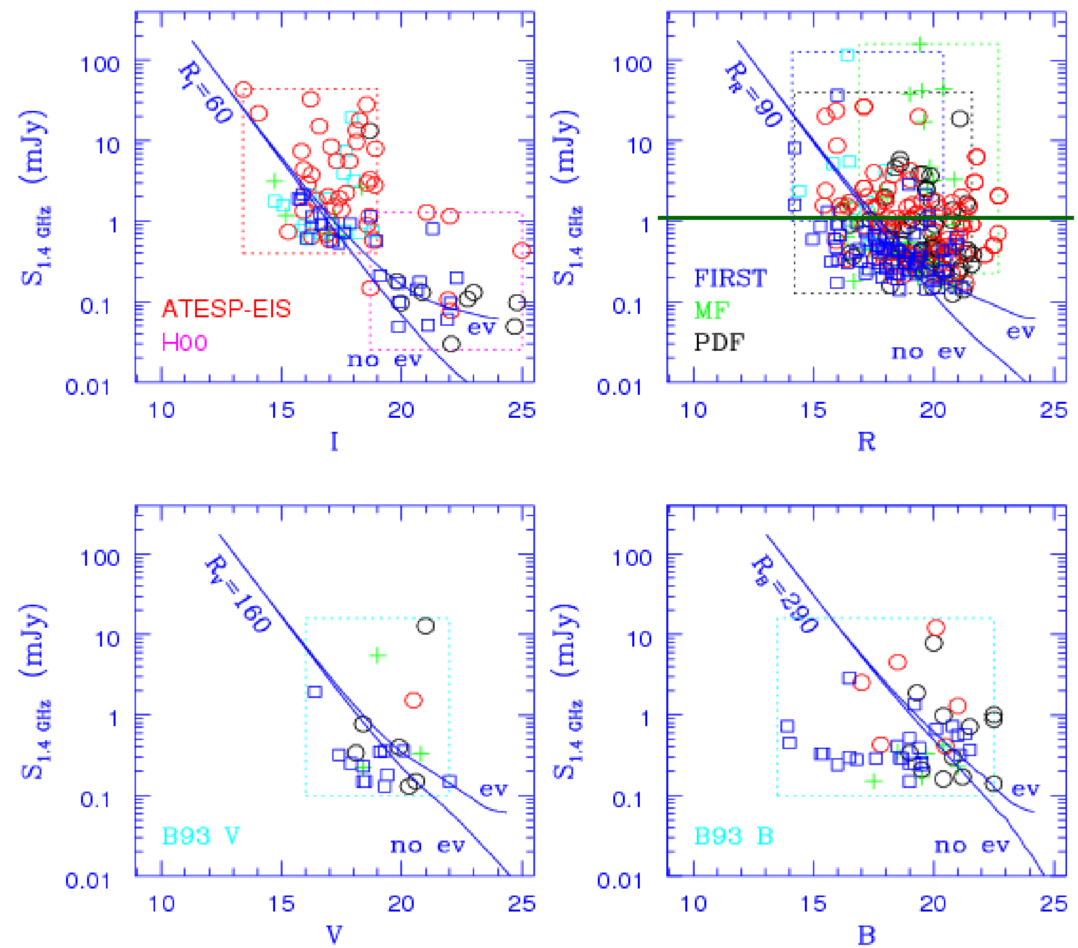
➔ **Early-type gals important at sub-mJy fluxes**



I – The sub-mJy Population

Prandoni et al. 2002

➔ **Early-type gals important at sub-mJy fluxes**



NATURE/EVOLUTION

[Low L/high z AGN, SB, Ell.]

F(L) ? N(z) ?

See e.g.

Richards et al. 99, Gruppioni et al. 99, Georgakakis et al. 99, Haarsma 00, Prandoni et al. 01b, 02, 04 Gruppioni et al. 03, Sullivan et al. 04, Ciliegi et al. 05, Fomalont et al. 06

R>R* ➔ AGN/ETS

R<R* ➔ SFGs

R* = R*(z)

I – The sub-mJy Population

SB+Sp CONTRIBUTION TO 1.4 GHz COUNTS

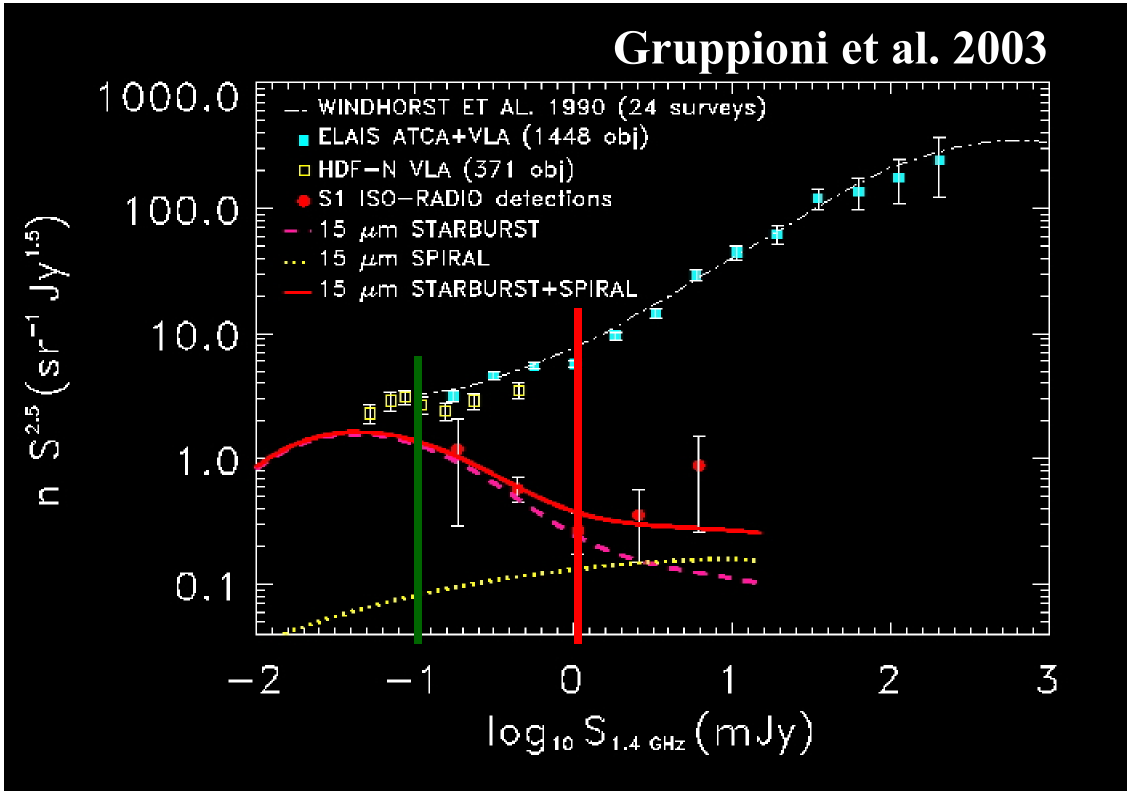
ELAIS S

SB + Spirals:

a) $L_{15\mu} \sim k\, L_{1.4\,GHz}$

b) mod. ev. per $n(S_{15\mu})$

→ $n(S_{15\mu})$ → $n(S_{1.4GHz})$



Contribution of MIR SB+Sp to $n(S_{1.4\,GHz})$:

~10% a S ~ 0.5-1 mJy

>60% a S < 0.05-0.1 mJy

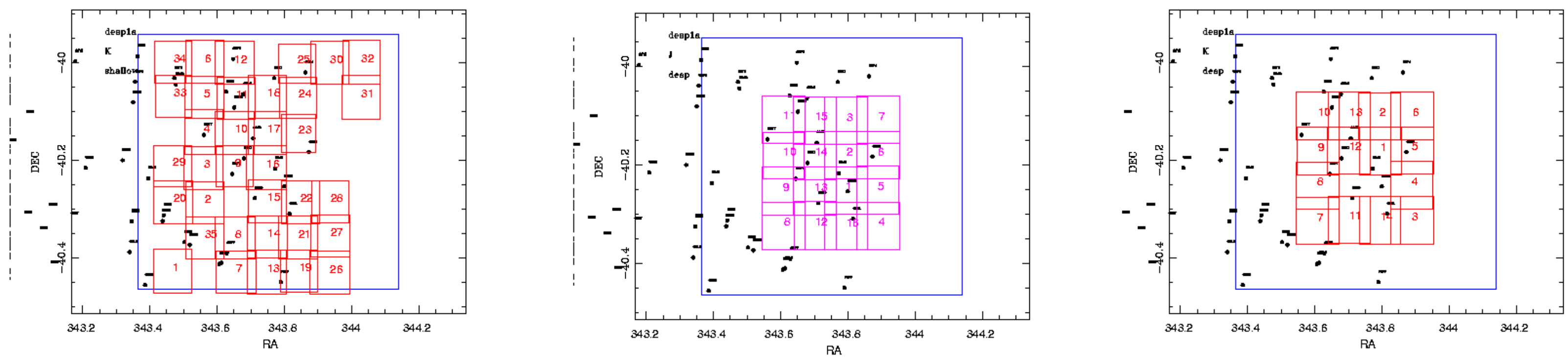
→Nuclear processes dominate @ S > 0.5 mJy?

II. UBVRIJK Data Completeness

FIE

m

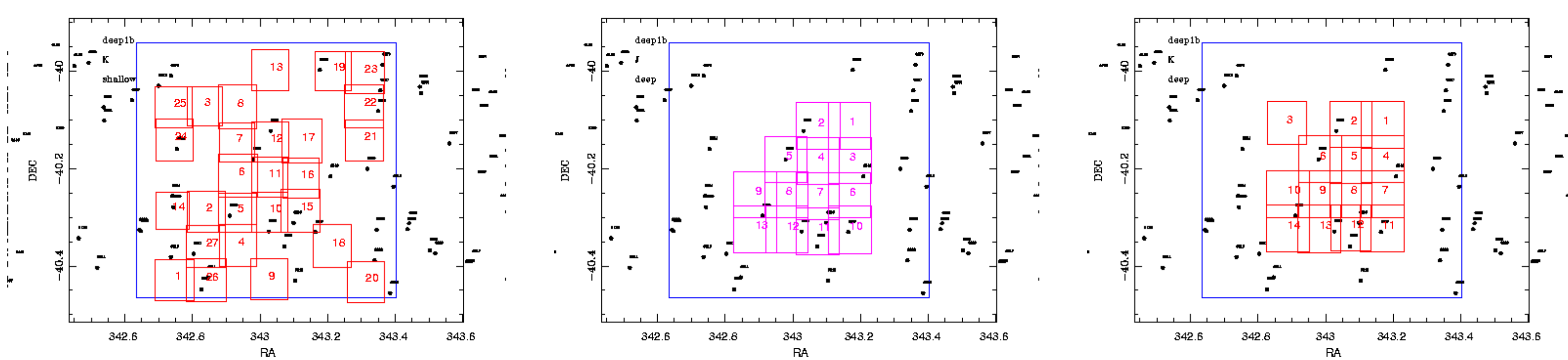
DEF



Deep1a →

DEE

5



Deep1b →

D

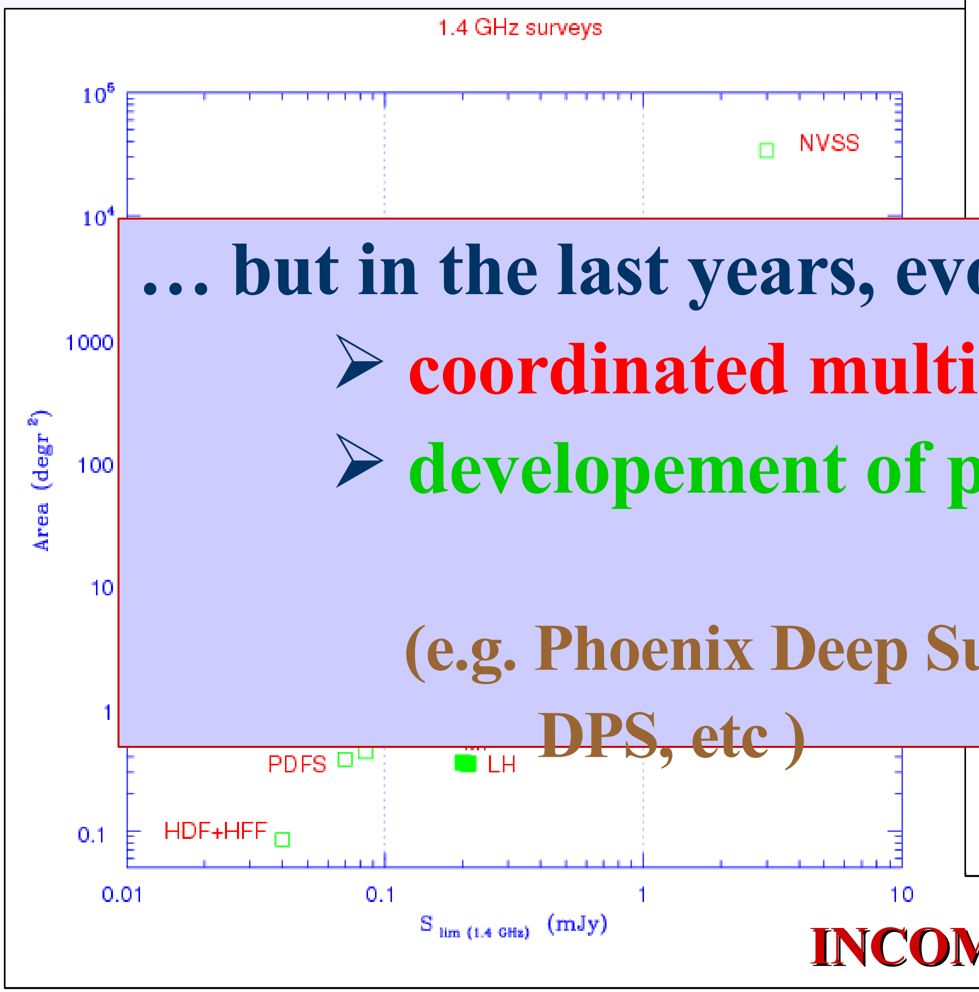
Thesis)

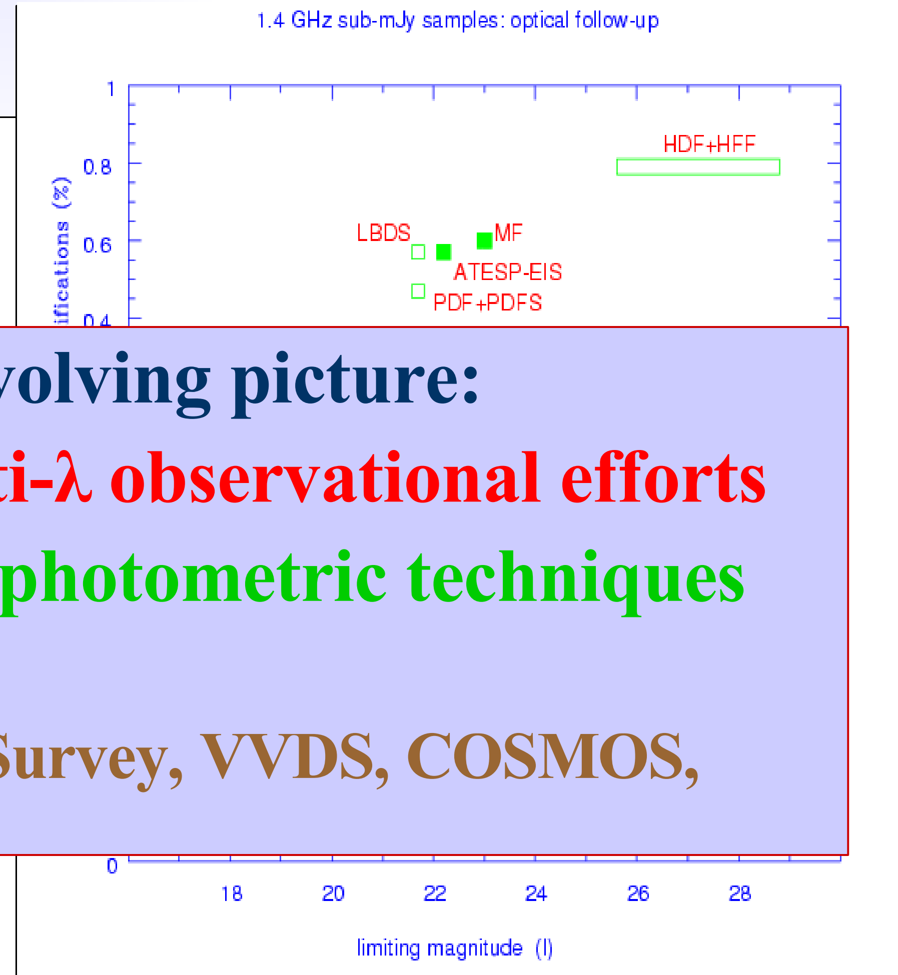
EIS-WIDE imaging data

Data reduction in progress

I – Optical follow-up

Updated to 2004





… but in the last years, evolving picture:

- **coordinated multi-λ observational efforts**
- **developement of photometric techniques**

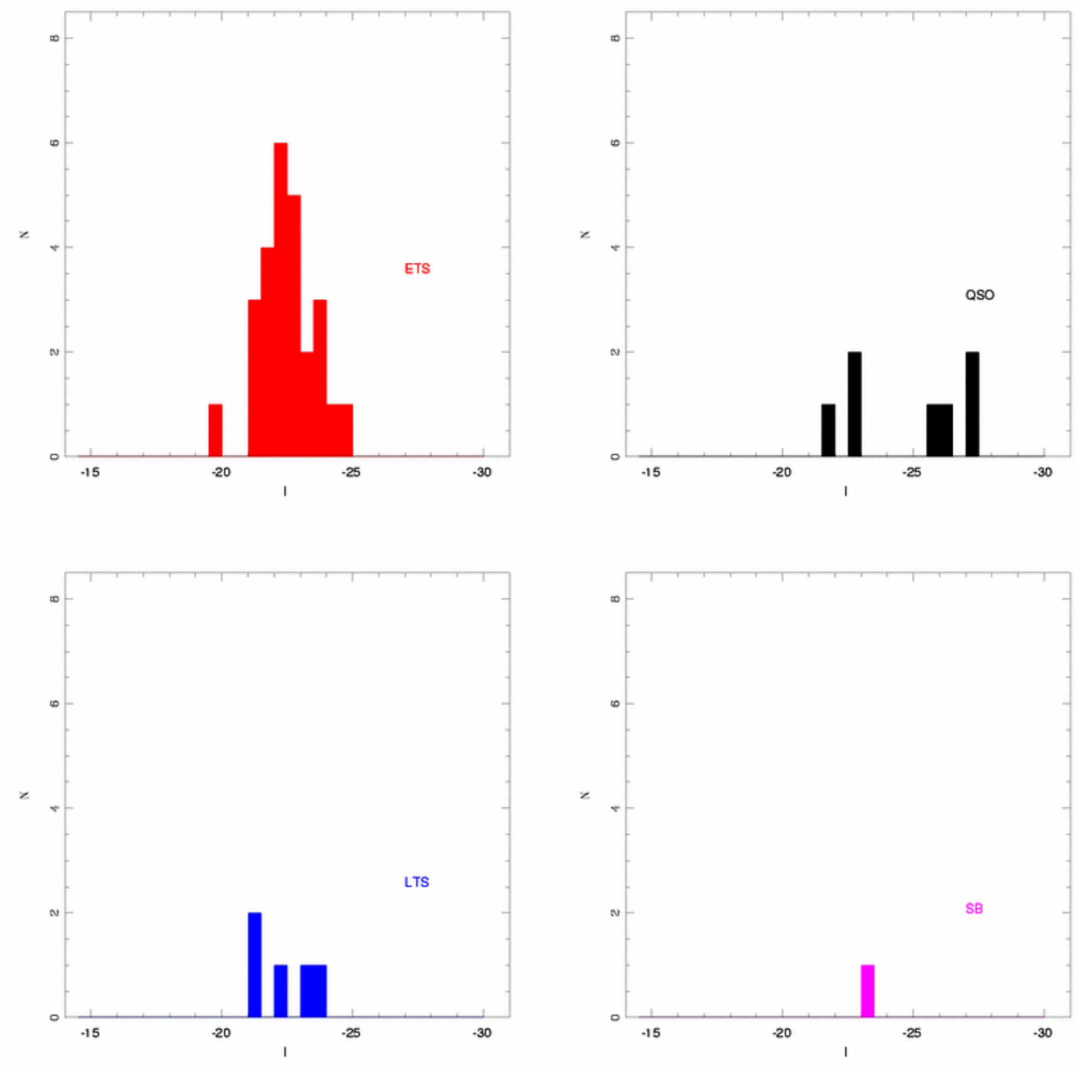
(e.g. Phoenix Deep Survey, VVDS, COSMOS, DPS, etc)

INCOMPLETE OPT. ID. (at most 70-80%)

MORE SEVERE for OPT. SPECTROSCOPY

Abs. Magnitude (I Band)

- **N vs Abs Mag (I)**



- ETS (typically red)
- QSO → brighter
- LTS → blue
- SB → blue

II – ATESP-DEEP1 RS Properties

Redshift Distribution: (DEEP1ab)

- ETS up to z = 2 (peak at z = 0.7)
- QSO up to z = 5
- LTS up to 0.5

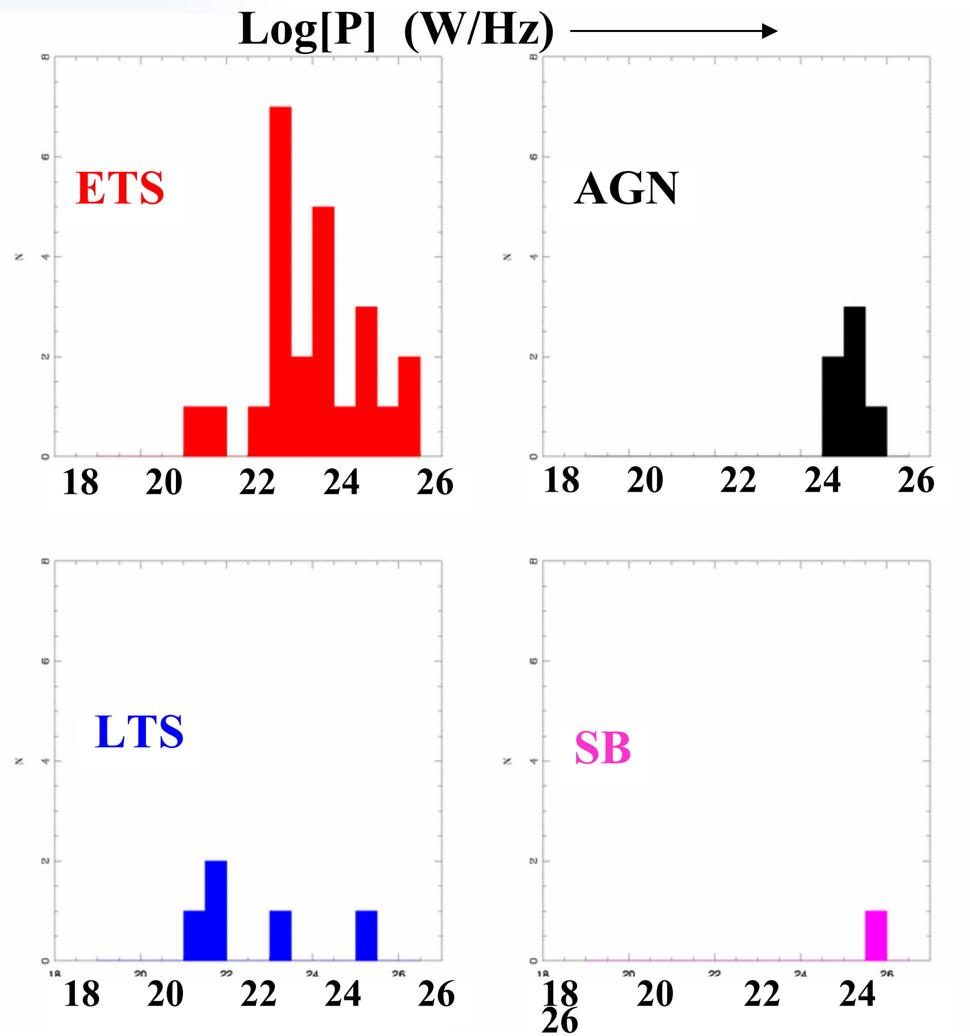
Radio Power Distribution: (DEEP1ab)

- ETS → 10^{23-25} W Hz^{-1} (triggered by low-intermediate luminosity AGNs)
- QSO → P < 10^{26} WHz^{-1}

lower than usually found for classical radio-loud QSOs

- LTS → 4/5 P < 10^{23} WHz^{-1} (SF)

→ **Sample largely dominated (78%) by AGN activity**

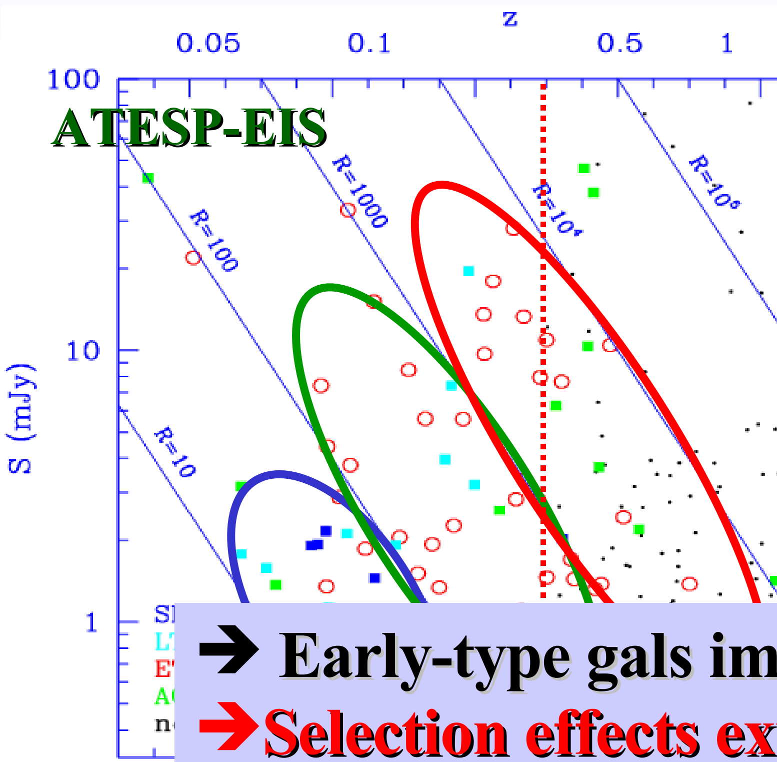


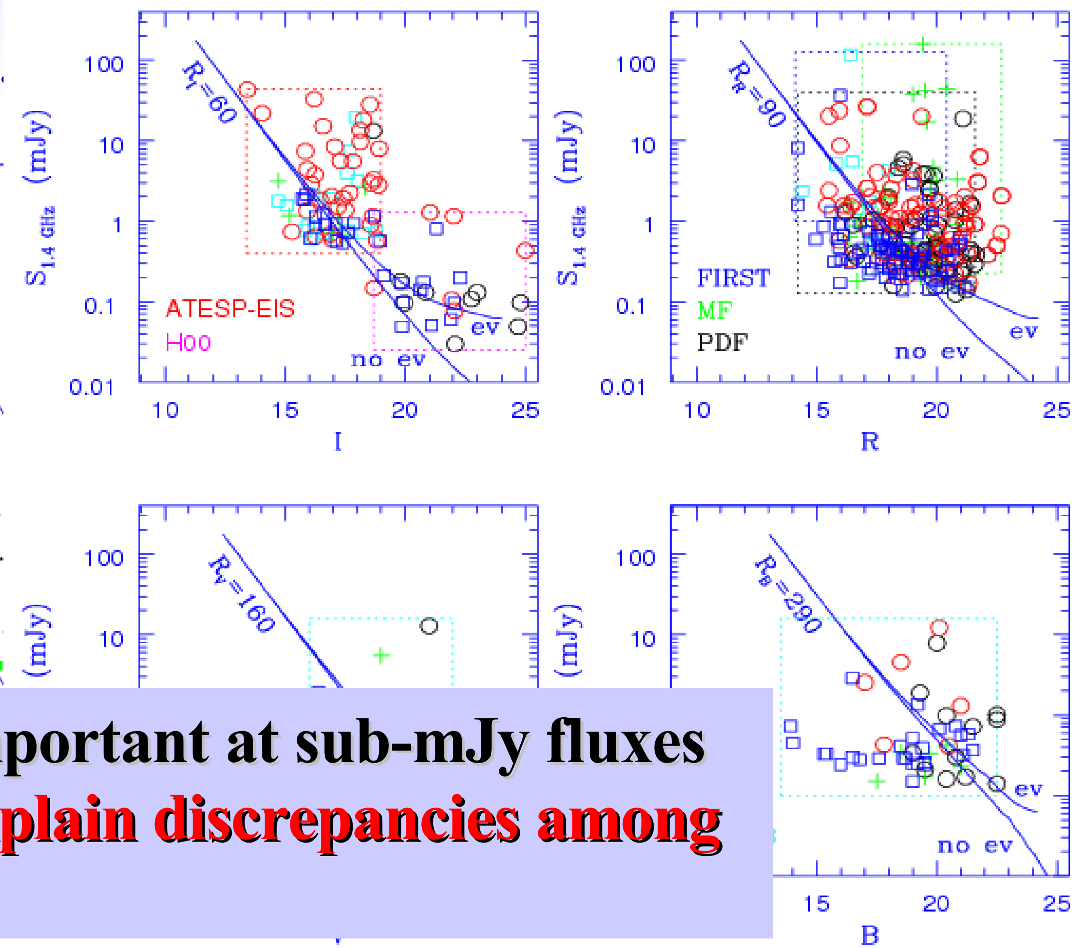
I – The sub-mJy Population

strongly ev. SB?

Prandoni et al. 2002

Prandoni et al.





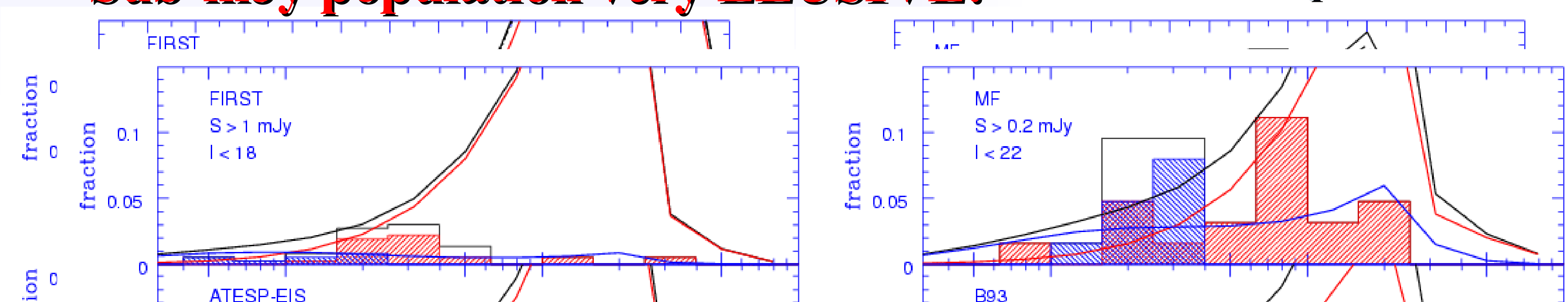
- ➔ Early-type gals important at sub-mJy fluxes
- ➔ Selection effects explain discrepancies among sub-mJy samples

SF dominates @ low R

I – Optical follow-up

Sub-mJy population very ELUSIVE!

Updated to 2003



… but in the last years, evolving picture:

- **developement of photometric techniques**
- **deep spectroscopy surveys**
- **coordinated multi-λ observational efforts**

(e.g. PDS, VVDS, COSMOS, DPS, etc)

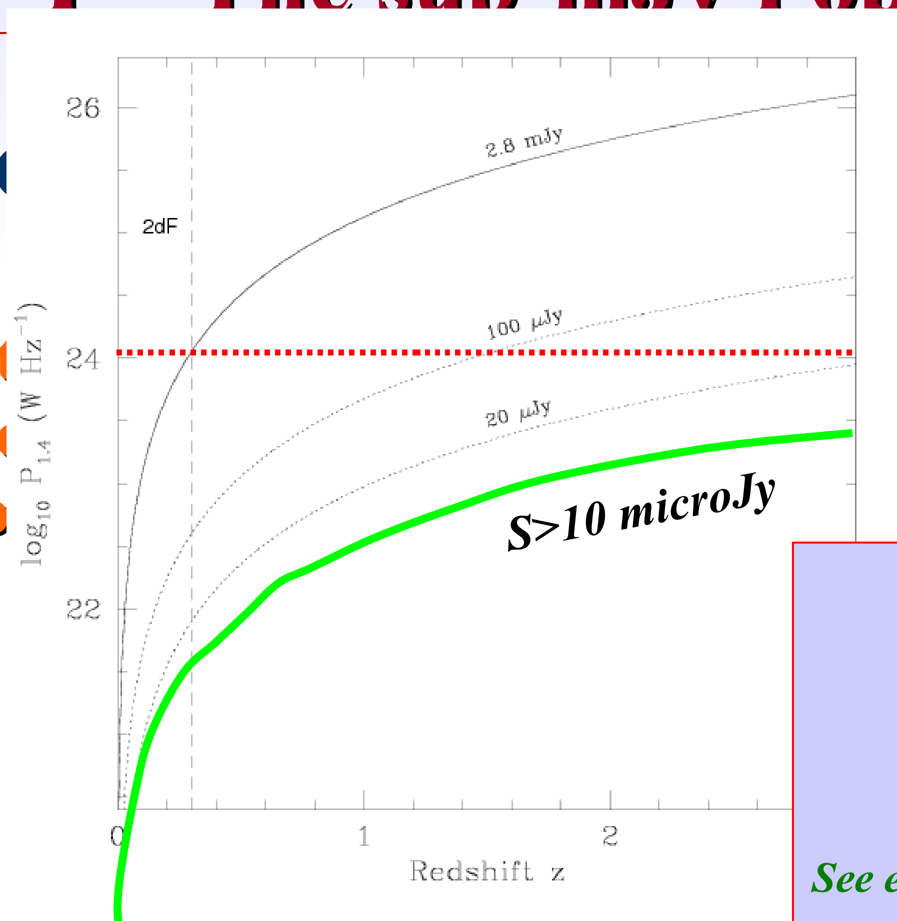
INCOMPLETE OPT. ID. (tipically 50-60%)

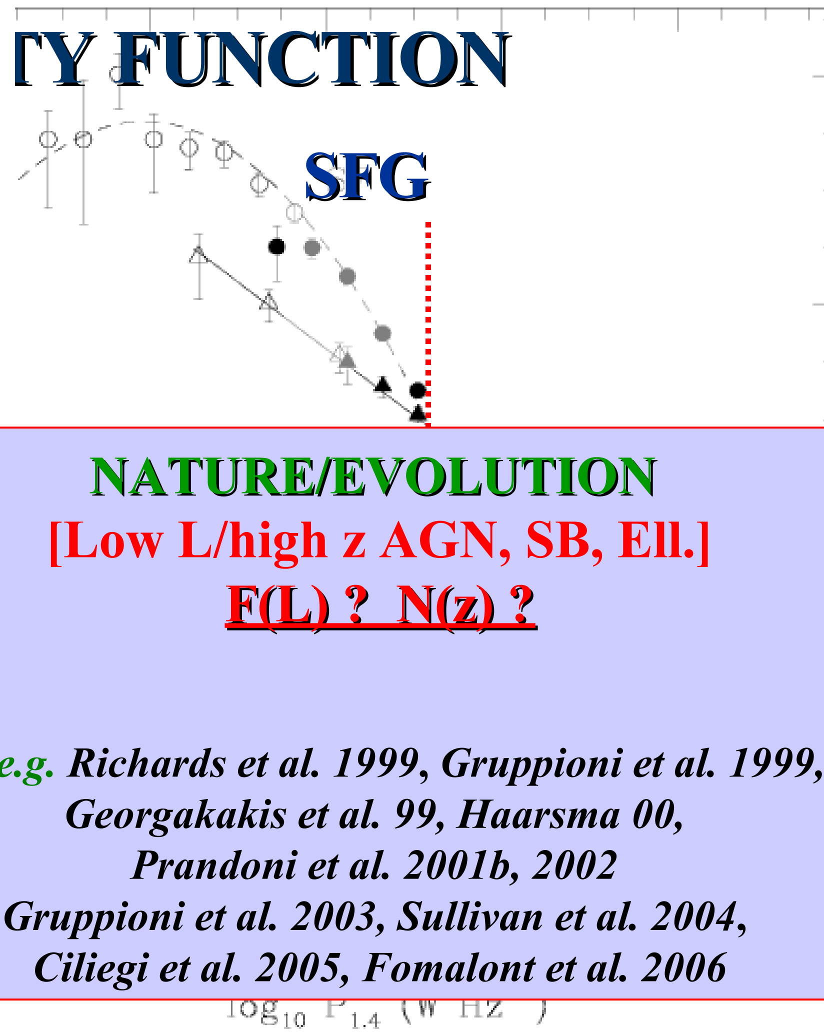
More severe for OPT. SPECTROSCOPY

I – The sub-mJy Population

L... TY FUNCTION

St...
d...
lo...





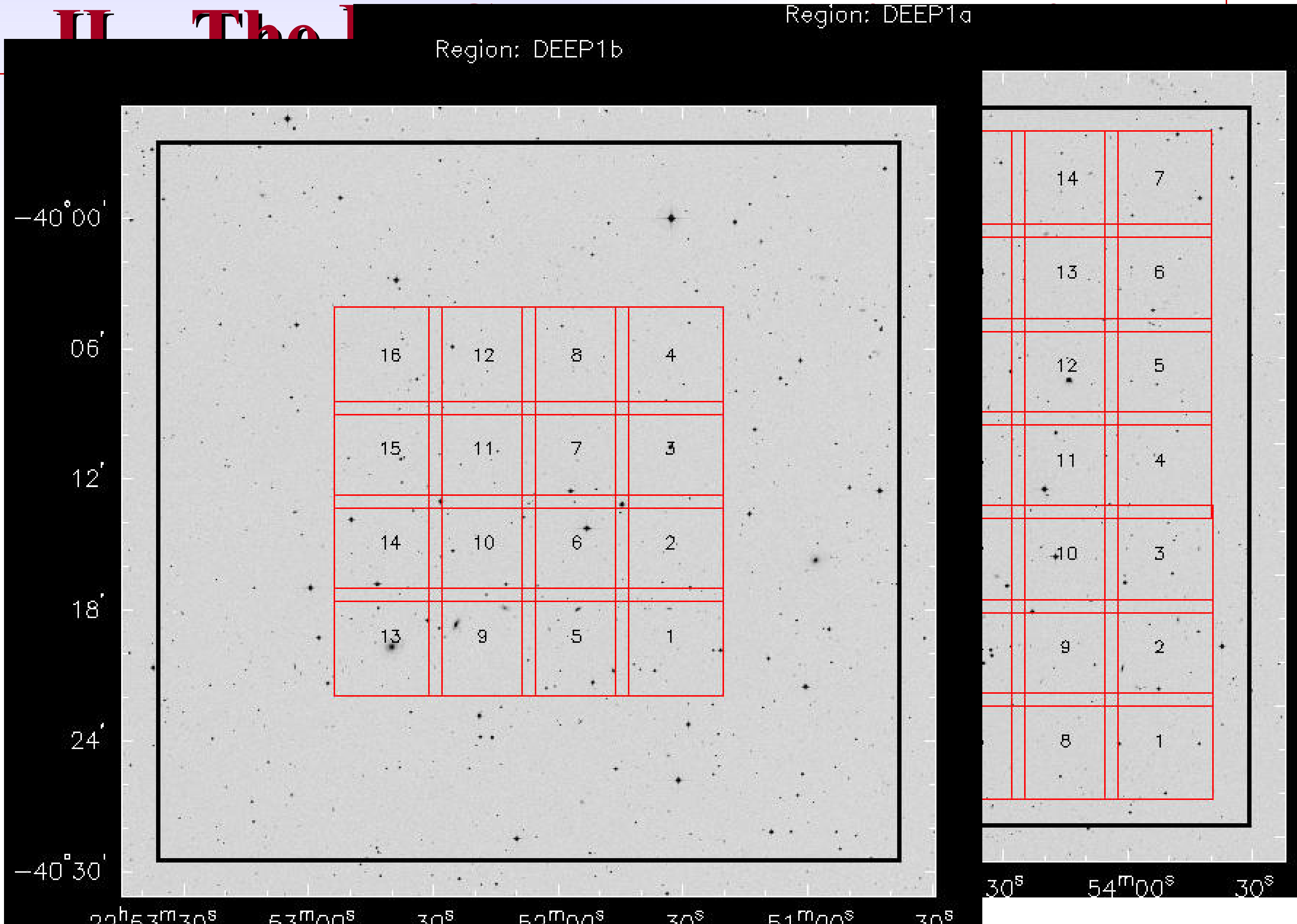
➔SFG dominate at S<< 10...
unless strongly ev.

NATURE/EVOLUTION
[Low L/high z AGN, SB, Ell.]
F(L) ? N(z) ?

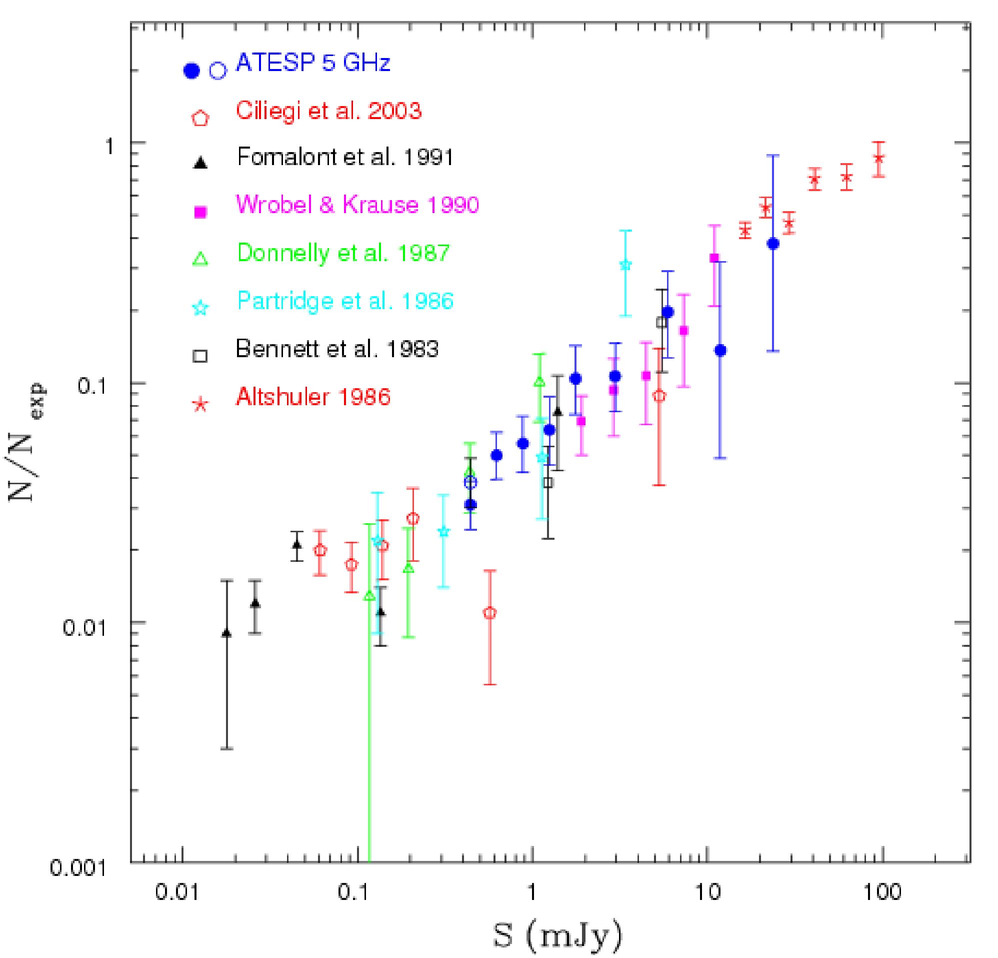
See e.g. ***Richards et al. 1999, Gruppioni et al. 1999, Georgakakis et al. 99, Haarsma 00, Prandoni et al. 2001b, 2002 Gruppioni et al. 2003, Sullivan et al. 2004, Ciliegi et al. 2005, Fomalont et al. 2006***

Sadler et al. 2002

II The


Region: DEEP1a
14 7
13 6
12 5
11 4
10 3
9 2
8 1
30s 54m00s 30s
Region: DEEP1b
16 12 8 4
15 11 7 3
14 10 6 2
13 9 5 1
−40°00′
06′
12′
18′
24′
−40°30′
22h53m30s 53m00s 30s 52m00s 30s 51m00s 30s

II – The ATESP SURVEY



5 GHz ATESP Survey:

- 2x0.5 sq. deg. at δ = –40°
- 2 radio mosaics with uniform rms flux ~ 70 μJy
- 111 sources with S > 0.4 mJy
- Spatial resolutions:

  ~ 10" → radio spectra

  ~ 2" → radio morphology

(Prandoni et al. 2006)

III – Comparison with models

OBSERVATIONAL CONSTRAINTS

The models should be able to reproduce at the same time:

1) Radio Number Counts

2) The total number of sources in the given samples

3) N(z) at different limiting fluxes

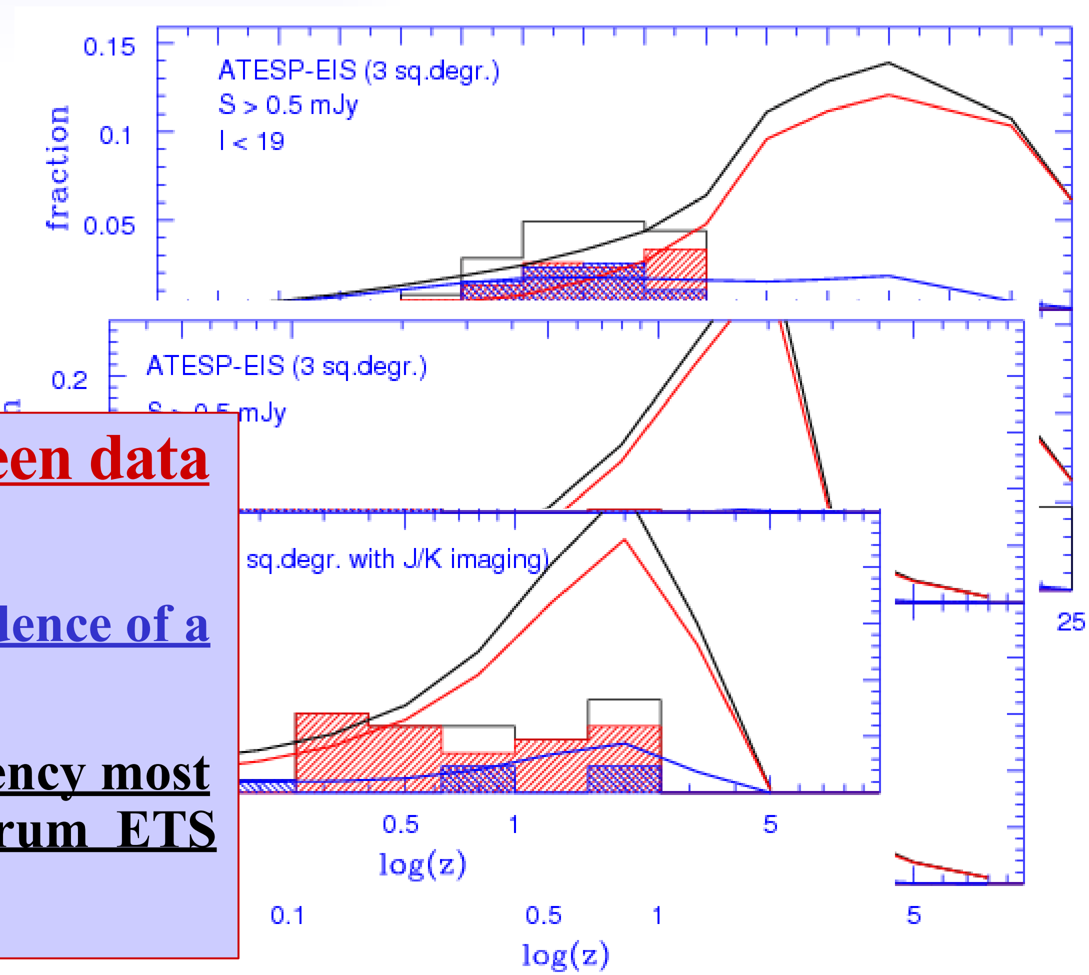
4) N(m) at different limiting fluxes

Also dust effects explored

III – Comparison with models

Models:

- **Radio Galaxies & QSO (Steep + Flat)**
- **Ev. (post-)SB & normal Spirals**



General agreement between data and models

At S>0.4 mJy & I<23.5 no evidence of a RQAGN component

Low-accretion/radiative efficiency most plausible scheme for flat-spectrum ETS

-

I – Aims of present work

Observational characterization of mJy/sub-mJy population

We exploit **deep multi-band optical data** (UBVRIJK images + spectroscopy) & **multi-frequency radio observations** (ATESP 1.4 & 5GHz)

ATESP RS: 0

component and

➢ low/high acc

➢ lower L AGN

[NB: LDD

Ueda et al. (

06 for radio

Waddington et al. (2000):

only study of sub-mJy radio sample aimed at deriving the ev. of AGN RLF

→Indication for lower L AGN to peak at lower z, but *poor statistics*