The radio spectral index of sub-mJy sources and physical processes associated

A. Mignano[1,2], I. Prandoni[1], L. Gregorini[1,3], P. Parma[1], M.H. Wieringa[4], H.R. De Ruiter[5,1], G. Vettolani[6,1], R.D. Ekers[4]

[1] INAF - Istituto di Radioastronomia, Via Gobetti 101, I-40129, Bologna, Italy

[2] Dipartimento di Astronomia, Università di Bologna, Via Ranzani 1, I-40126, Bologna, Italy

[3] Dipartimento di Fisica, Università di Bologna, Via Irnerio 46, I-40126, Bologna, Italy

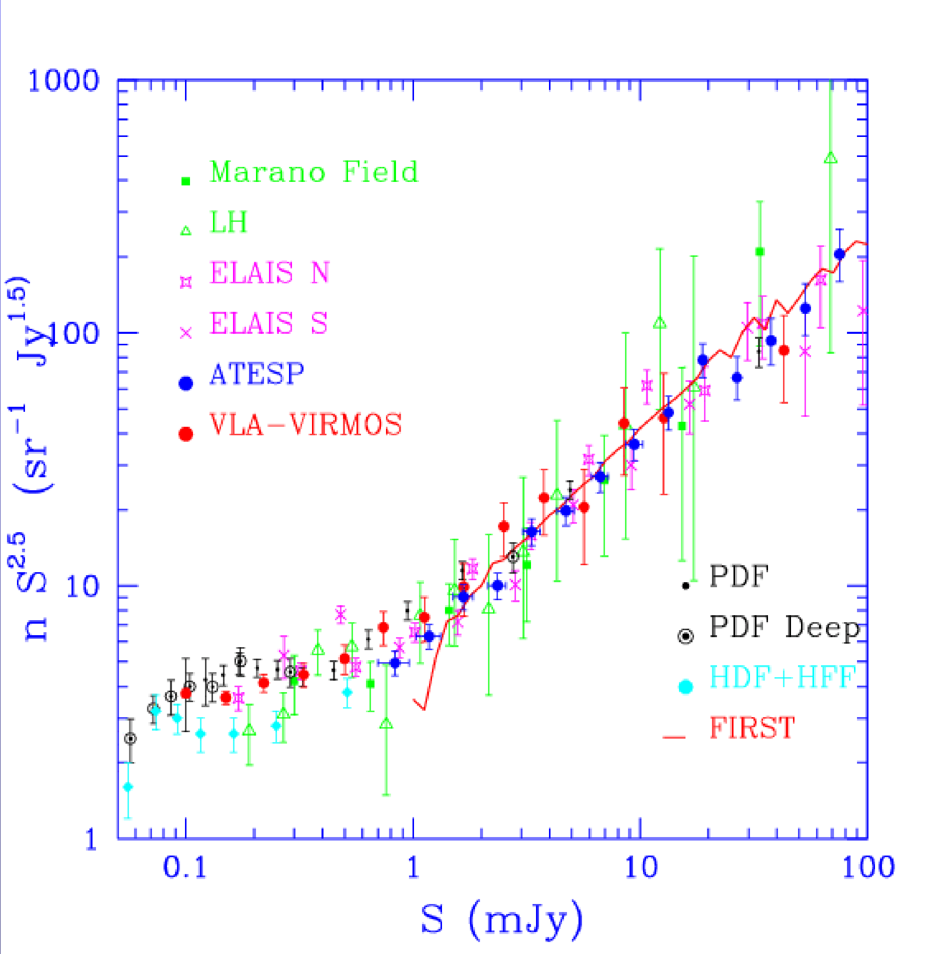
[4] CSIRO Australia Telescope National Facility, P.O. Box 76, Epping, NSW2121, Australia

[5] INAF - Osservatorio Astronomico di Bologna, Via Ranzani 46, I-40126, Bologna, Italy

[6] INAF - Viale del Parco Mellini 84, I-00136, Roma, Italy

Background sub-mJy radio population

- Flattening of normalized source counts from deep 1.4 GHz survey (e.g. *Windhorst et al. 1990*)
- New radio population
- Mixture of different classes of objects:
  - S.F. galaxies dominate at µJy fluxes → (e.g. *Richards et al. 1999*, *Sullivan et al. 2004*, *Ciliegi et al. 2005*)
  - ETS gal. more important at sub-mJy and mJy fluxes (e.g. *Gruppioni et al. 1999*, *Prandoni et al. 2001b*, *Sullivan et al. 2004*, *Ciliegi et al. 2005*)
- Problems:
  - Incomplete identification (at most 70-80%).
  - More severe incompleteness in spectral information.



SFH & AGN Evolution

- mJy/sub-mJy samples: Study of the radio emitting AGN evolution:
  - Evidence of increase of comoving number density of AGN up to z ~ 2-3 followed by a possible decline at higher z (e.g. *Boyle et al. 2000*). Redshift cut-off dependent on Luminosity Class (e.g. *Vigotti et al. 2003*)
  - *Waddington et al. (2000)* is the only study of a deep radio sample aimed at deriving the AGN RLF → evidence of decline in RLF at z > 2-3. Indication for lower luminosity AGN to peak at lower z.
  - Limitation of this work: only 72 objects in the sample.

… but in the last years, evolving picture:

➢ coordinate observational efforts

➢ development of photometric techniques (e.g. Phoenix Deep Survey, VLA-VIRMOS, COSMOS)

… multi-frequency radio observations: crucial to determine the nature of mJy and sub-mJy population (origin of radio emission).

Why this project?

- The sample: 131 radiosources over 1 sq. deg. covered at 1.4 and 5 GHz down to 0.4 mJy (ATESP survey) and by U B V R I J K_s multicolor imaging down to R_{lim} ~ 25 (DPS Survey)
- Scopes: statistical study of faint radio population (80% id rate) → composition, z distrubution, radio spectra analysis
- → study the RLF of AGNs at low $L_{1.4GHz}$ doubling the Waddington sample

Radio & Optical DATA

Radio Data

The 1.4 GHz ATESP survey (*Prandoni et al. 2000a, b*), covering 26 square degrees, was carried out with the Australia Telescope Compact Array (ATCA). A region of 1 square degree was also imaged at 5 GHz (*Prandoni et al. 2006*).

1.4 GHz ATESP Survey:

- **26 square degrees at $\delta = -40°$**
- **16 radio mosaics with uniform rms flux ~ 80 μJy**
- **2967 sources catalogued down to ~ 0.4 mJy (109 in 5GHz region)**
- **Spatial resolution: ~ 10"**

5 GHz ATESP Survey:

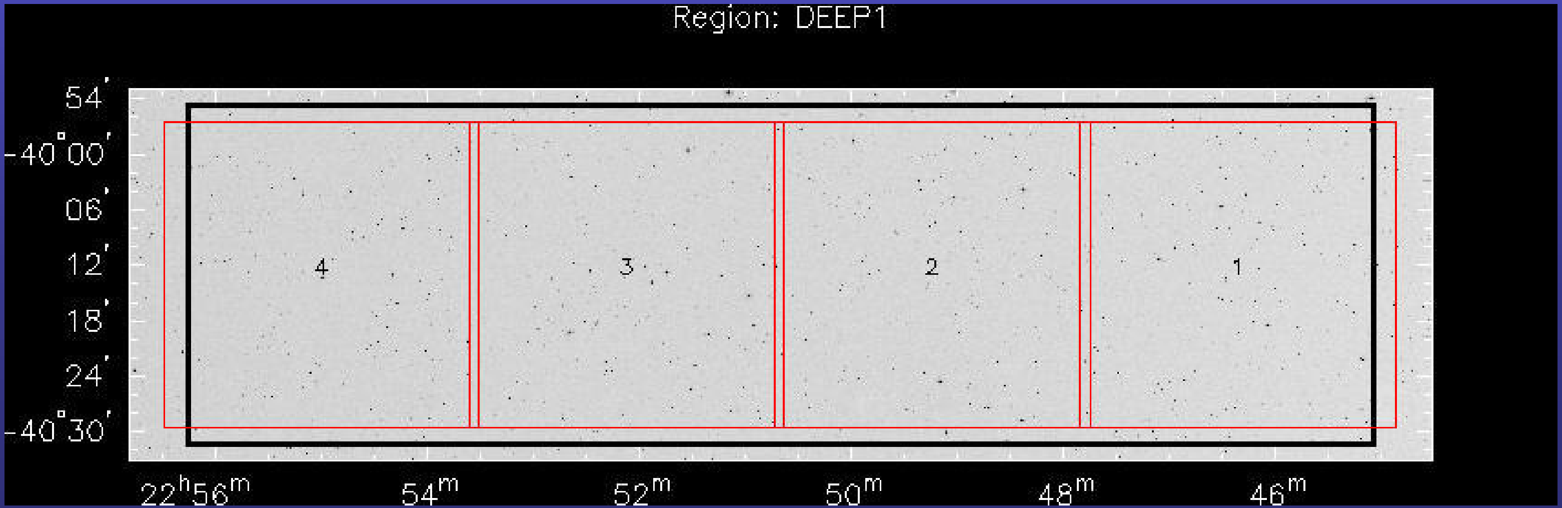
- **1 square degree at $\delta = -40°$**
- **2 radio mosaics with uniform rms flux ~ 70 μJy**
- **111 sources catalogued down to ~ 0.4 mJy**
- **Spatial resolutions:**
  - **~ 10" → radio spectra**
  - **~ 2" → radio morphology**

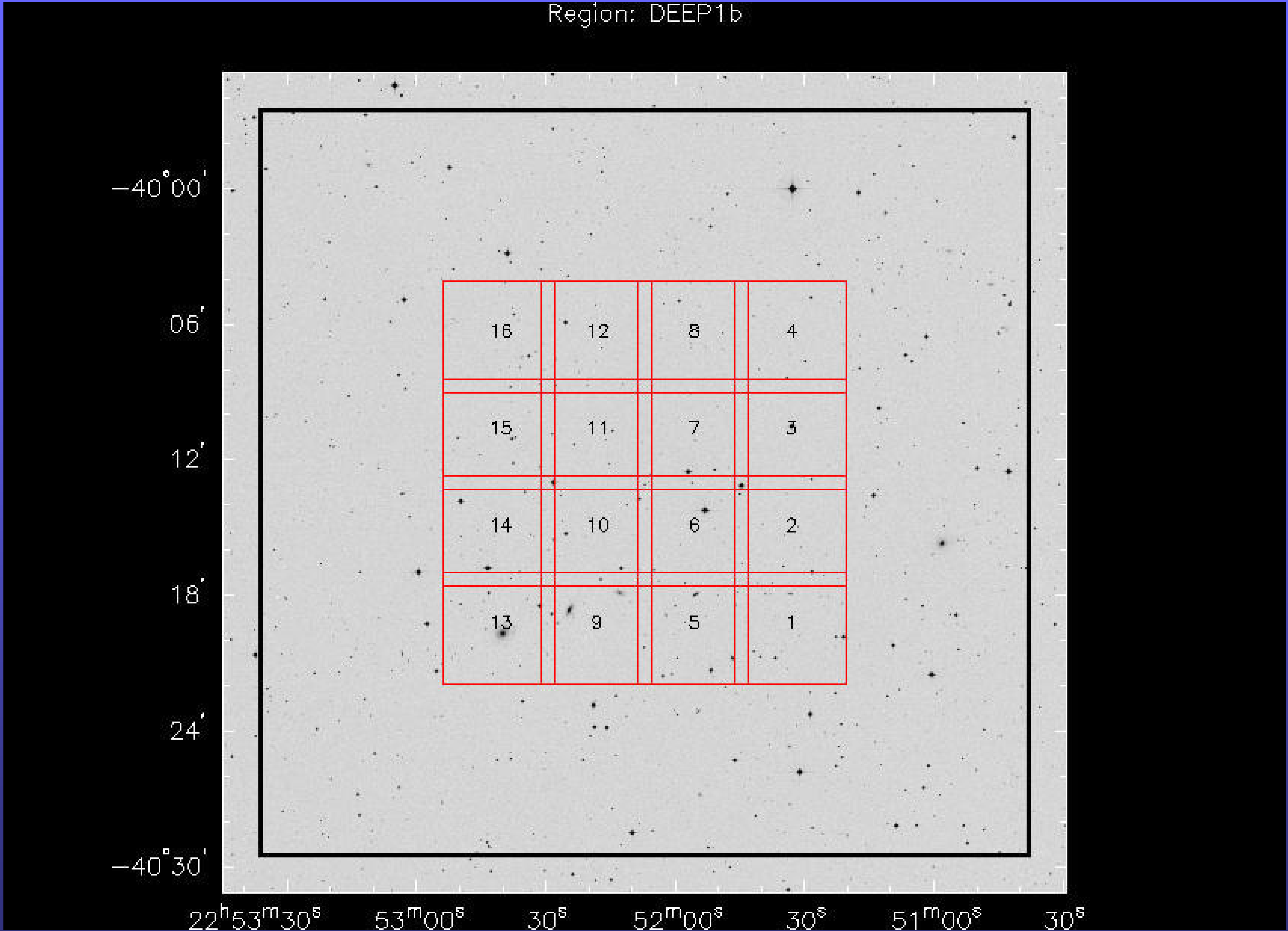
Optical Data - DPS optical

• The ATESP 5 GHz region was imaged in several optical and infrared passbands in the framework of the ESO ***Deep Public Survey*** (DPS), which comprises three 1 square degree regions (DEEP1, 2, 3) in the southern sky.

• The DPS was carried out in the optical (U, B, V, R, I), using the WFI (Wide Field Imager) camera mounted at the 2.2mt ESO telscope.

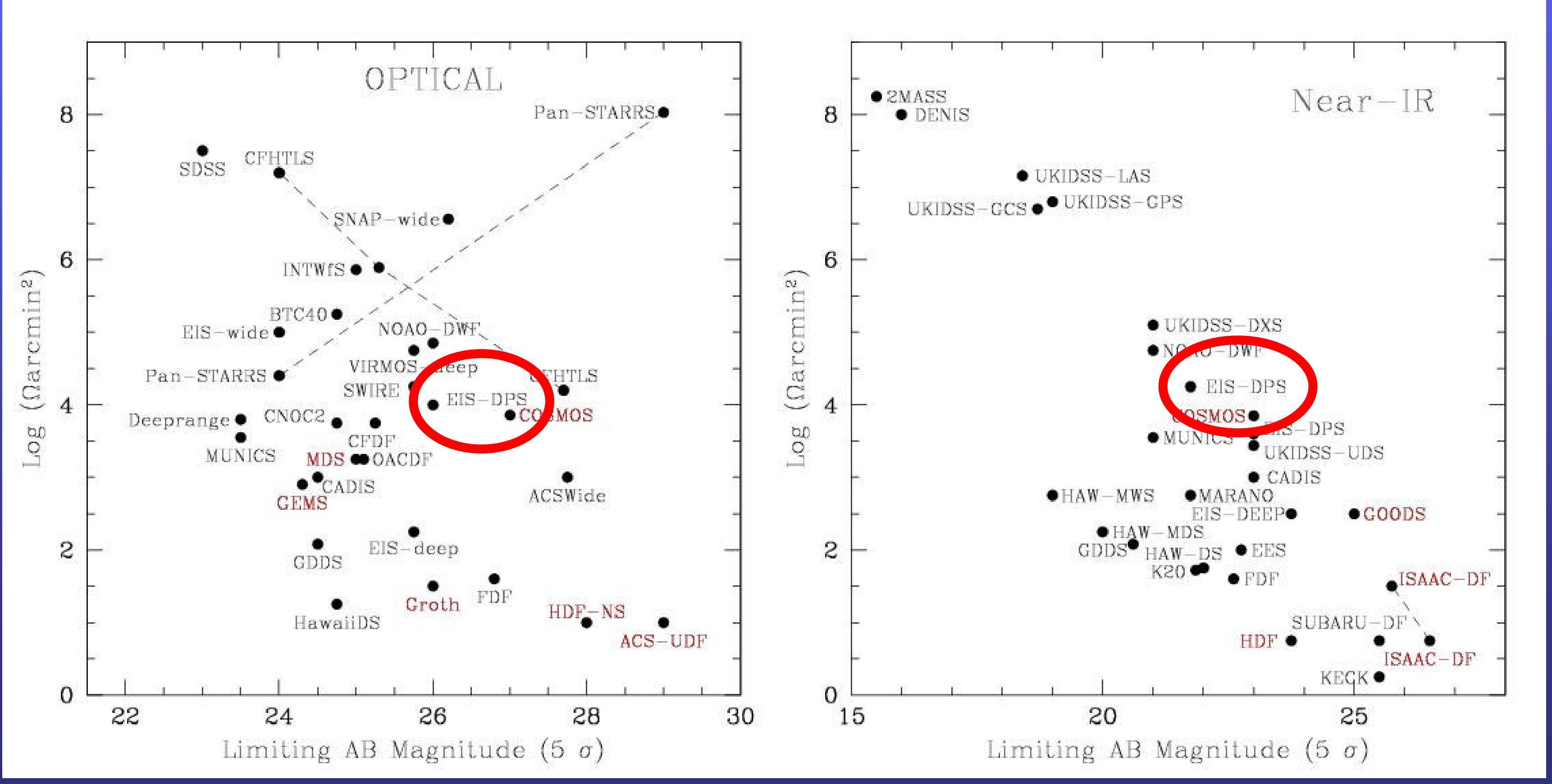
• The DEEP1 (the DPS region which overlaps with the ATESP) has typical depths of U_{AB} ~ 25.7, B_{AB} ~ 25.5, V_{AB} ~ 25.2, R_{AB} ~ 24.8, I_{AB} ~ 24.1 (*Mignano et al. 2006*).

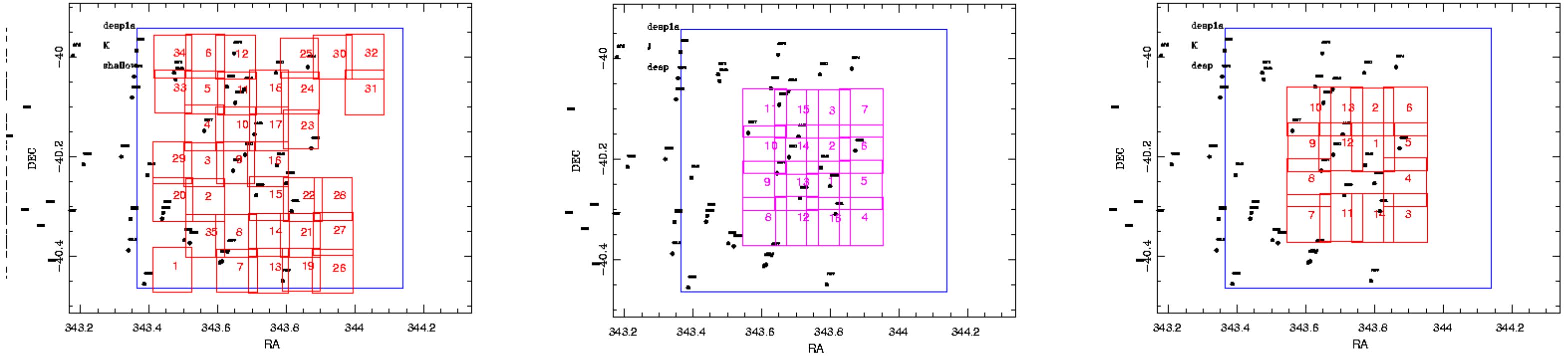



Region: DEEP1b
16
12
8
4
15
11
7
3
14
10
6
2
13
9
5
1
−40°00′
06′
12′
18′
24′
−40°30′
22h53m30s
53m00s
30s
52m00s
30s
51m00s
30s

Overview of Optical/NIR Surveys

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



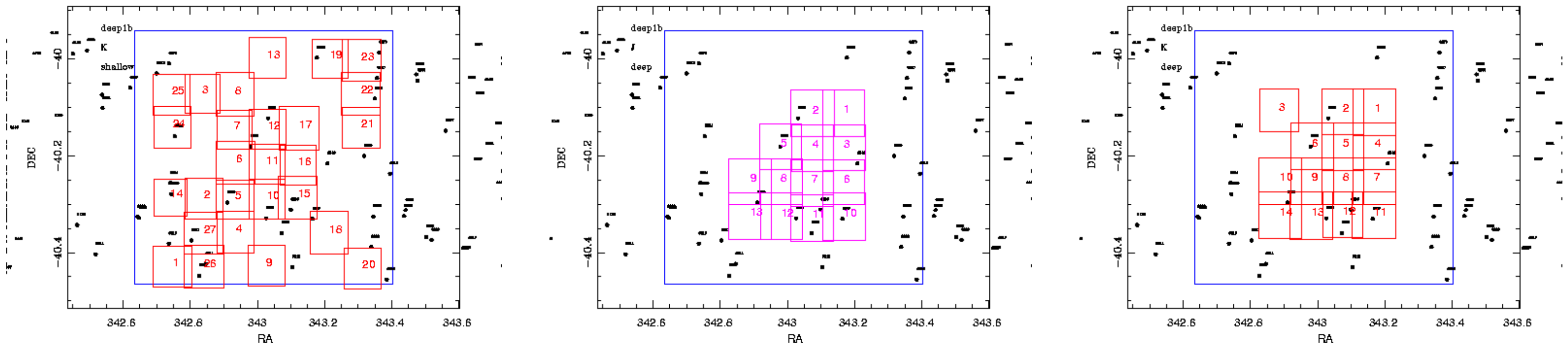


o

Deep1a →

id

I	0.97	1	24.19
J	0.073 ± 0.238	13	22.14 ± 0.23



Deep1b →

Radio Optical Analysis

Identification

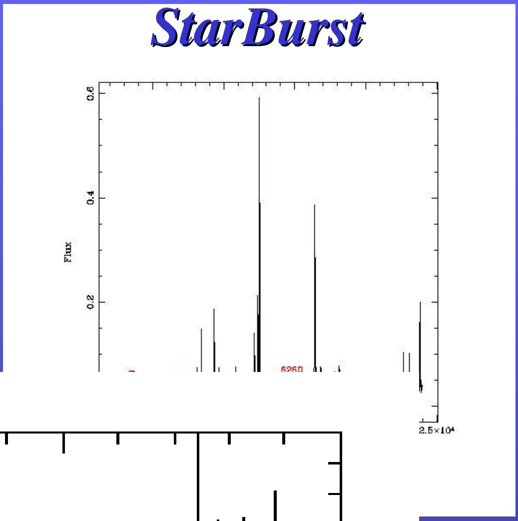
- 85 ATESP Radiosources searched for id with color catalogs (deep1a, b, c) with the Likelihood Ratio technique.

Field	N_{rad}	$N_{id} \geq LR_{thresh}$	C	(1−R)	Mult.	NIR	N_{id}^{tot}	(%)
DEEP1a	27	18	98.6	7.4	2	2	22	77.8
DEEP1b	26	19	99.1	6.8	1	0	20	76.9
DEEP1c	32	21	99.0	6.3	0	0	21	65.6
ATESP–DEEP1	**85**	**58**	**98.9**	**6.8**	**3**	**2**	**63**	**74.1**

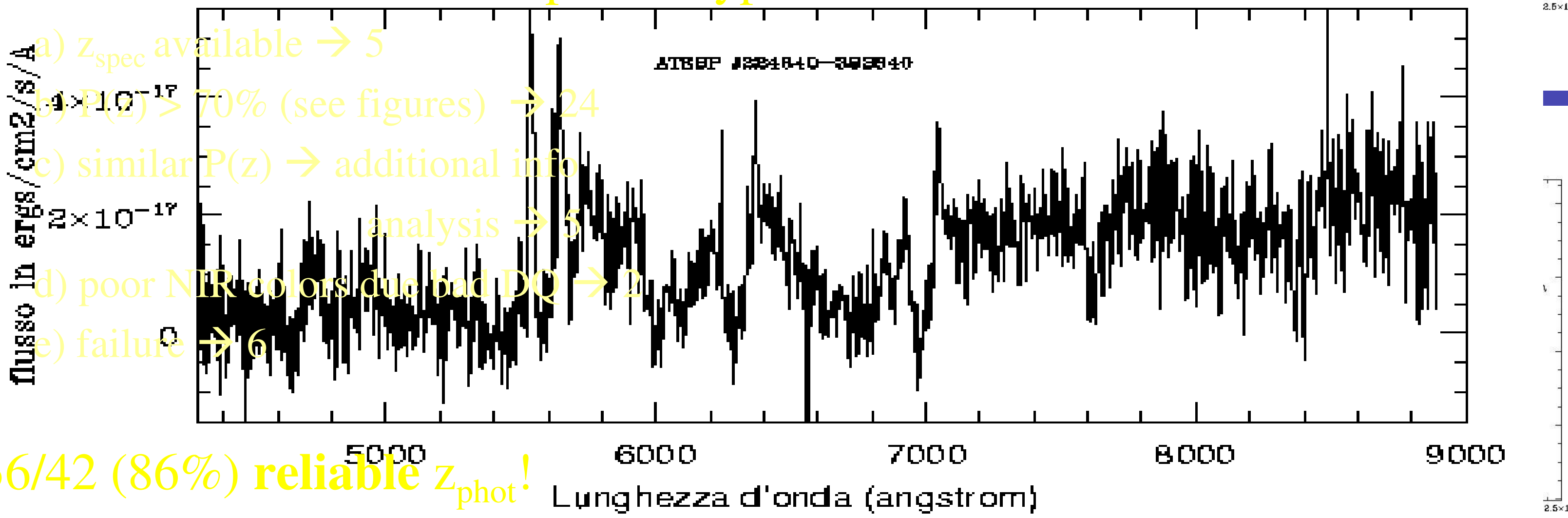
Survey	S_{lim} (mJy)	(N_{rad})	area (sq.degr.)	I_{lim}	$\%_{id}$
VVDS–VLA	0.08	1054	1	25	74.0
Phoenix	0.1	839	3	25	79.0
VLA–LH	0.05	63	0.03	24.5	92.0
ATESP–EIS	0.4	386	3	22.5	57.3
ATESP–DEEP1	**0.4**	**85**	**0.5**	**25**	**74.1**

Photometric Spectra of Radio-Sources

- 42 ATESP radiosources in the 0.5 sq. deg. with extensive color information analyzed with Hyperz
- Used default SEDs (from normal galaxies to quasars).
- In addition, some peculiar quasar SEDs (Red and BAL QSO) directly downloaded from the SDSS web pages.



- Choice between different Spectral types:
  - a) z_{spec} available → 5
  - b) P(z) > 70% (see figures) → 24
  - c) similar P(z) → additional info analysis → 5
  - d) poor NIR colors due bad DQ → 2
  - e) failure → 6



- 36/42 (86%) **reliable** z_{phot}!

From ATESP-EIS to ATESP-DPS Faint Radiosource Composition

Composition: out of 42 identified ATESP radiosources:

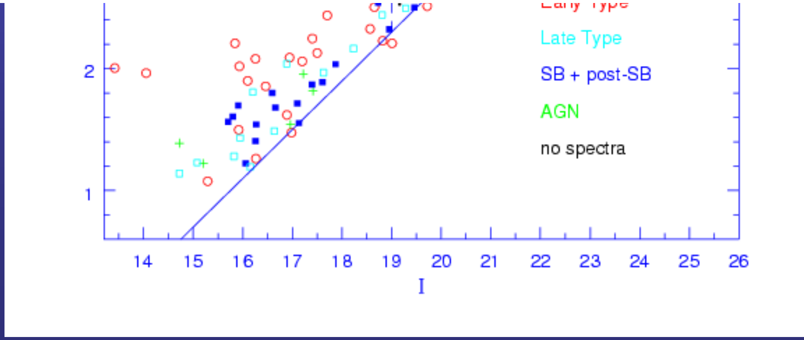
- 24 (57%) ETS (Elliptical, S0)
- 6 (14%) QSO
- 6 (14%) LTS (Spirals and starburst galaxies)
- 6 (14%) UNCL.

Table 6.1: The ATESP–DEEP1 sample composition.

Survey	mag lim	ETS(%)	LTS+SB (%)	AGN (%)	UNCL (%)
EIS–Wide	< 19	49 ± 8	43 ± 8	9 ± 3	–
EIS–Wide	$19 < I < 22.5$	46 ± 13	11 ± 6	25 ± 9	18 ± 8
ATESP–DEEP1*	$I < 25$	60 ± 12	14 ± 6	14 ± 6	12 ± 5

*based on identified sources in regions DEEP1a and b

28 spectra at $19 < I < 22.5$



$$R = S_{1.4} * 10^{(m-12.5)}$$

- R < 100 → Star Formation
- R > 100 → Nuclear Activity

Redshift & Radio Power distribution

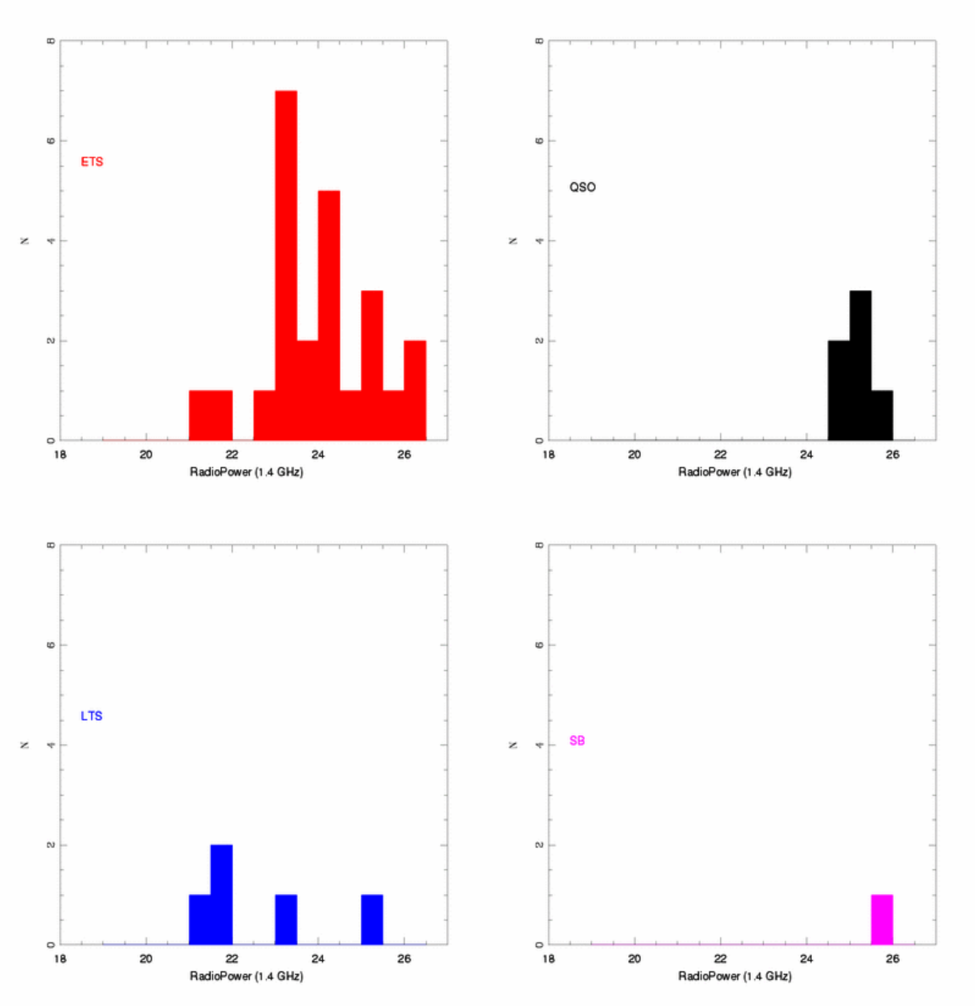
Redshift Distribution (see Figures):

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

Radio Power Distribution:

- ETS → 10^{23-25} W Hz^{-1} (triggered by low-intermediate luminosity AGNs)
- QSO → P = 10^{25-26} WHz^{-1}
- LTS 3/5 → P < 10^{22} WHz^{-1} (SF)

→ **Sample largely dominated (70%) by AGN activity**



Radio Spectra Analysis -Intro

- Spectral index α → $S \propto \nu^{\alpha}$
- $\alpha < -0.5$ → steep spectrum
  - Sinchrotron ($\alpha = -0.7$)
    - SF
    - AGN (useful info from radio morphology)
- $\alpha > -0.5$ → flat spectrum, ($\alpha > 0$) inverted
  - Thermal bremsstrahlung (SF on large scale)
  - Sinchrotron autoabsorbed (AGN)
  - ADAF ? (*Fiore 2000*)

→ mJy RS have $\alpha < -0.5$ → flattening of spectra at deeper fluxes (Donnelly 1987, Gruppioni 1997)

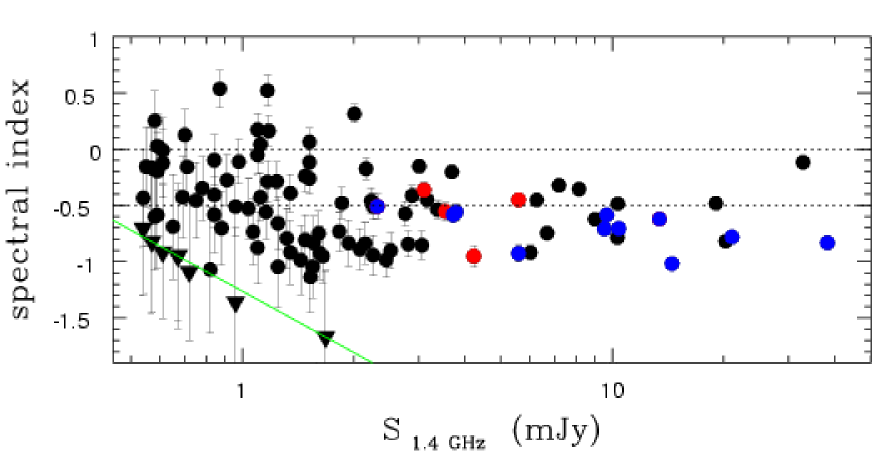
→ Multifrequency Data available for very small mJy & sub-mJy samples

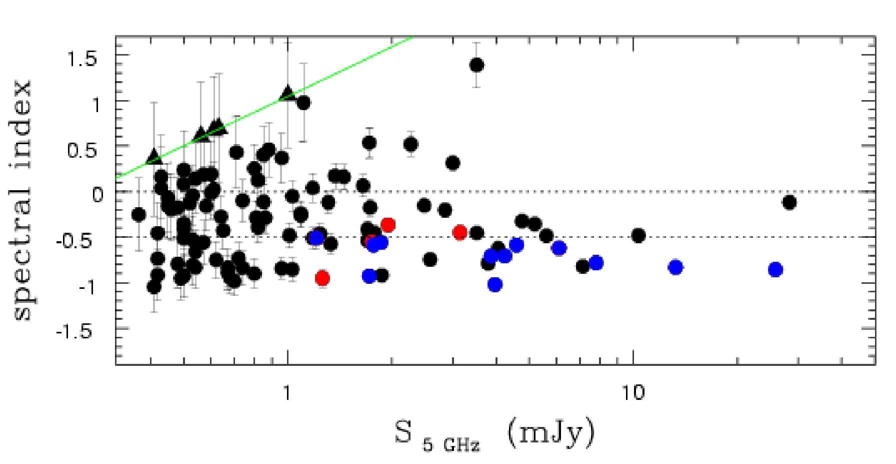
Radio Spectra analysis - I

- Analysis on the entire ATESP-DEEP1.
- Significant flattening with decreasing flux:

  S > 4 mJy → steep spectrum (α ~ 0.7) → synchrotron radio emission.

  S < 4 mJy → 46% (at 1.4 GHz), 63% (at 5 GHz) → flat spectra (α > -0.5) with significant fraction (29% at 5 GHz) of inverted spectra (α >0).
- General agreement with what found in literature (*Fomalont et al. 1991, Donnelly et al. 1987*).
- RS multiple/extended (typically AGN) → steep synchrotron radio spectra, mainly found at mJy flux densities. Unresolved multiple-component present also at lower fluxes, but poor deconvolution (*Prandoni et al. 2006*).





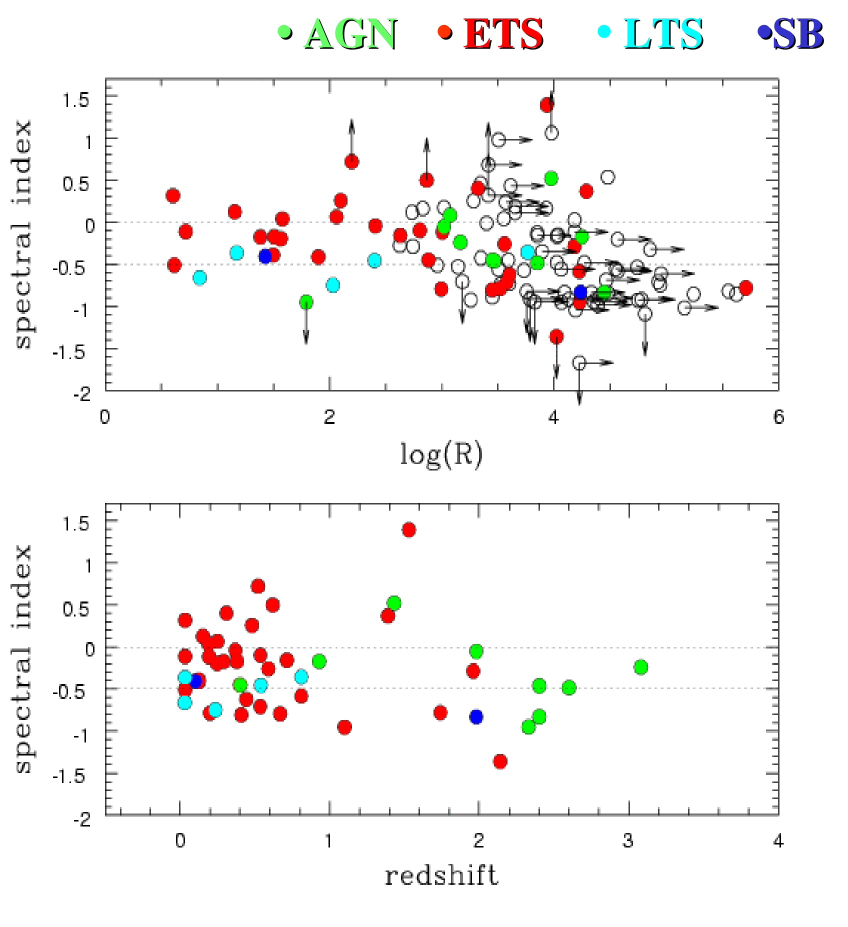
Radio Spectra analysis – II

Global analysis of the radio and optical properties of the ATESP-DEEP1 sample.

Any existing optical information used. In particular from the EIS-WIDE survey

We found that:

1. most of the flat-spectrum sources → high R (> 1000), typically associated to classical powerful RG and QSO.
2. flat-spectrum sources (low R) preferentially identified with ETS → (radio emission probably triggered by low-luminosity AGNs).
3. SF galaxies typically associated to steep-spectrum sources, (synchrotron emission in galactic disks or in nuclear starbursts).



Summary

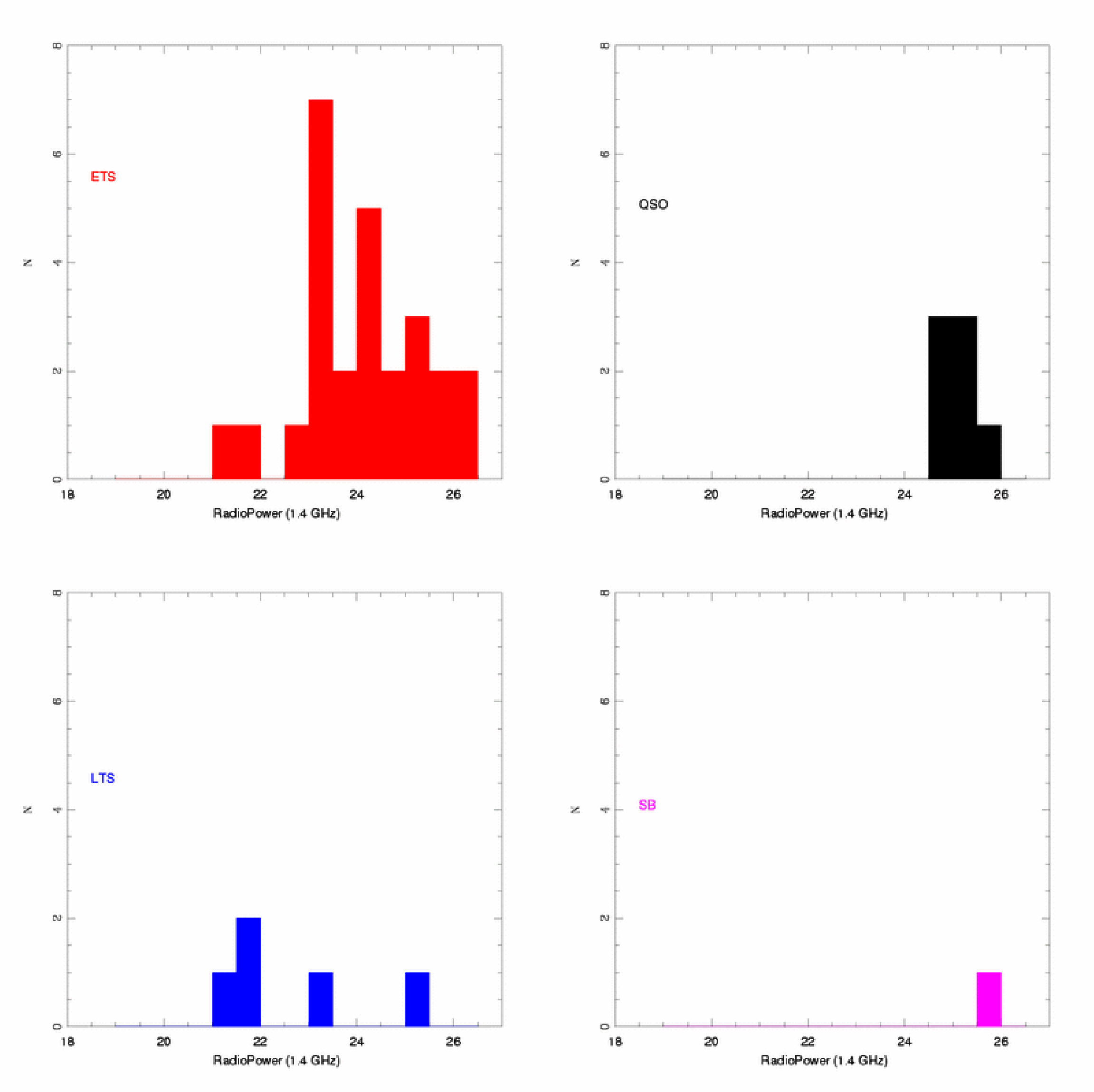
- ✓ Reduction of DPS
- ✓ Production of color catalog
- ✓ New technique for photometry check
- ✓ Identification with ATESP survey (74%)
- ✓ Composition of ATESP sample and distribution in L, P, z for each type → largely (70%) dominated by nuclear activity
- ✓ Flattening of radio spectra at sub-mJy fluxes
- ✓ Flat spectra → ETS/AGN (autoabsorbed AGN?, less efficient accretion?)

The future?

- Complete observation of Deep1 (→enlarge the sample) – ongoing observations & proposals
- …with a larger sample: study of AGN luminosity function with a complete sample of objects at low L
- Flat spectra ETS selected for detailed study

Analysis Plots (2)

- **N vs Radio Power**

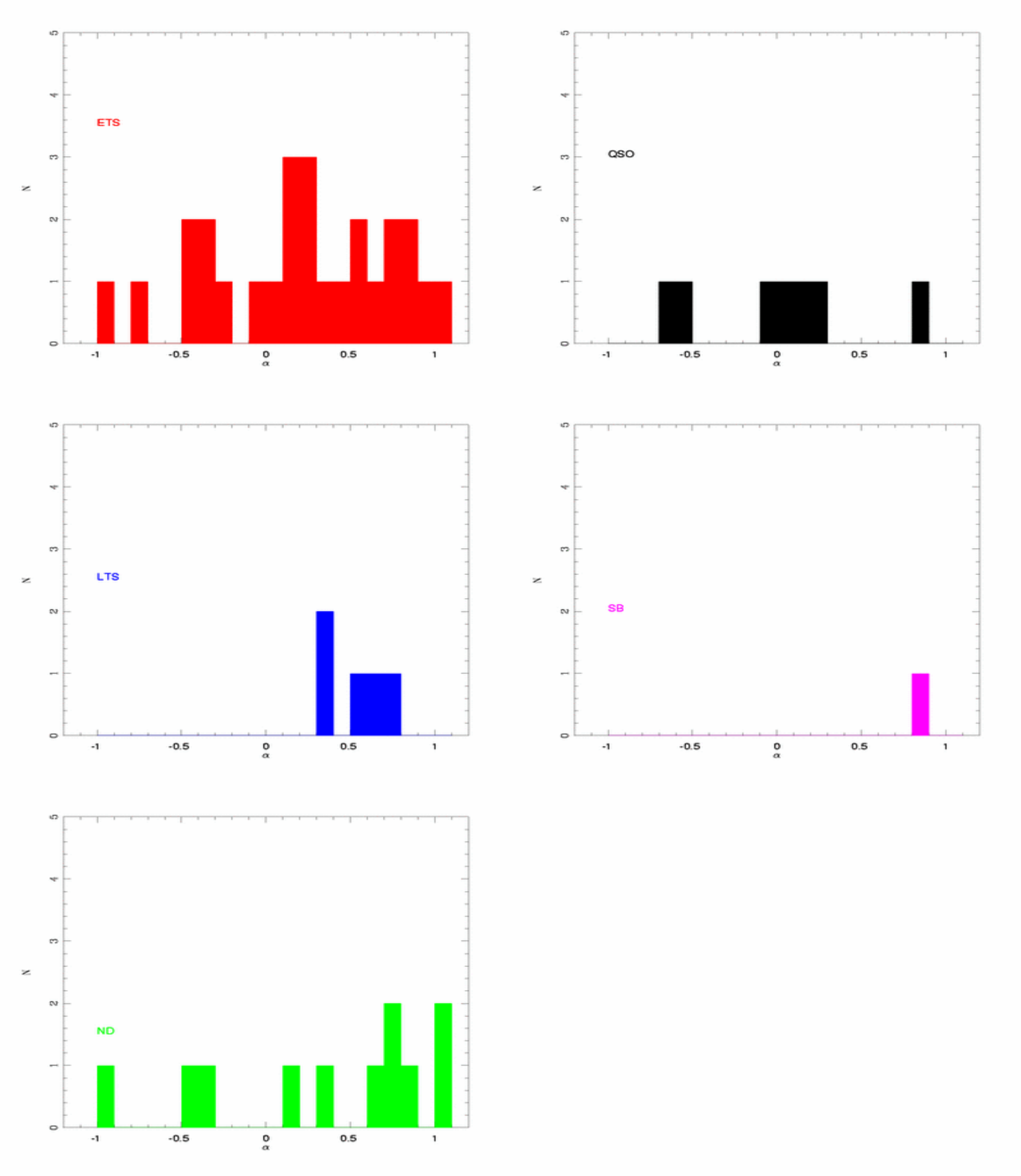


- ETS → 21<Log(P)<27
- QSO → Log(P) < 26
- LTS → Log(P) < 24
- SB → Log(P) > 25.5

Analysis Plots (3)

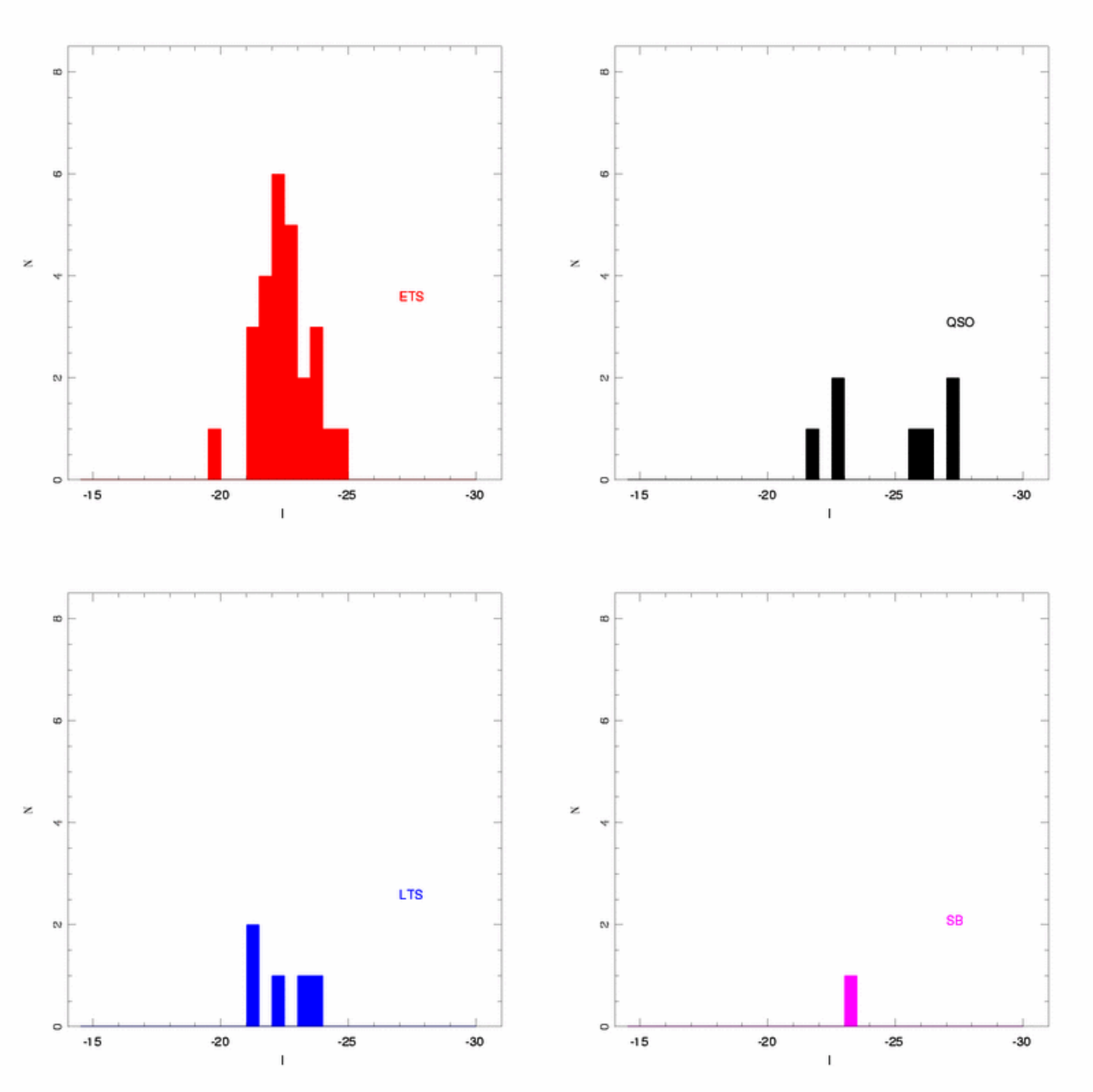
- **N vs Spectral Index**

- ETS (also inverted spectra!)
- QSO → mainly flat spectra
- LTS → steep spectra (SF)
- SB → steep spectra (SF)



Analysis Plots (4)

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



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

mJy & Sub-mJy Surveys

- Study of the evolution of RLF (high z cut-off)

  LBDS (Leiden Berkley Deep Survey), *Waddington et al. 2001*

  - $Flux_{1.4GHz}$ > 1 mJy
  - Area = 1.2deg^2
  - N_{rad} = 72
  - 2/3 z_{spec} 1/3 z_{phot}
  - More luminous radio sources preferentially form at earlier epochs.
  - Less massive galaxies will typically take longer to become active and will have a lower radio luminosity .

- Study the population of nearby radio galaxies at 1mJy level

  2dF Galaxy Redshift Survey, *Magliocchetti et al. 2002*

  - $Flux_{1.4GHz}$ > 1 mJy
  - Area = large
  - N_{rad} = 557 (2,3% of whole FIRST sample), identified down to b_j<19.5
  - Compostion of the sample:
    - 63% ETS, z>0.1, 10^{21}<P <10^{24}, RO>>
    - 32% (LTS+SB), z<0.1, P<$10^{21.5}$, RO<
  - majority of radiosources in merger/interaction are ETS → galaxy-galaxy interaction triggers AGN activity at low z

- Radio Spectra in sub-mJy sample

ATESP 5GHz, *Prandoni et al. 2005 (submitted)*

VLA Survey in Lockman Hole, *Ciliegi et al. 2002*

- $Flux_{5GHz} > 50$ μJy (4.5σ)
- Area = 10 $arcmin^2$
- $N_{rad} = 63$, 92% identified down to I<24.5
- Flat spectra grows at S<< (increasing number of self-absorbed AGNs among the μJy population?)
- majority of radiosources in merger/interaction are ETS → galaxy-galaxy interaction triggers AGN activity at low z
- 2% of EROS in the optical sample has radio emission → if it is a sign of AGN activity, it means that the optical IR selected EROS populations contains a small fraction of active AGN

- Study the star formation of galaxies up to z=1

Phoenix survey, *Sullivan et al. 2004*

- Goal: to study the star formation of galaxies up to z=1
- $Flux_{1.4GHz} > 0.1$ mJy (4σ)
- Area = 3 deg^2
- $N_{rad} = 839$, 79% identified down to I<25 (U,B,V,R,I,K available)
- Compostion of the sample:
  - 63% LTS, 0<z<1.3,
  - 20% ETS-AGN

VVDS-VLA Sample, *Ciliegi et al. 2005*

- $Flux_{1.4GHz} > 80$ μJy
- Area = 1.2deg^2
- $N_{rad} = 1054$, 74% identified down to I<25
- U,B,V,R,I,K (partially covered)
- Z_{phot}(RS) > z_{phot} (optical sample)
- (V-I) RS redder than median optical population
- radio detection selects high intrinsic L_{opt}

Radio Spectra analysis - II

- General agreement with what found in literature:
  - *Fomalont et al. (1991)* report a α_{med} = –0.38 and a f(α > –0.5) = 60% at fluxes 16 < $S_{5\ GHz}$ < 1000 μJy; while
  - *Donnelly et al. (1987)* report α_{mean} = –0.31 ± 0.58, α_{med} = –0.42 and f(α > –0.5) = 50% at 0.4 < $S_{5\ GHz}$ < 1.2 mJy).
  - Steeper behaviour found by *Donnelly et al. (1987)* at 1.4 GHz: α_{mean} =0.80 ± 0.49, α_{med} = –0.76 and f(α > –0.5) = 22% at 0.5 < $S_{1.4\ GHz}$ < 3 mJy → significantly different composition on the faint radio population depending of the selection frequency.

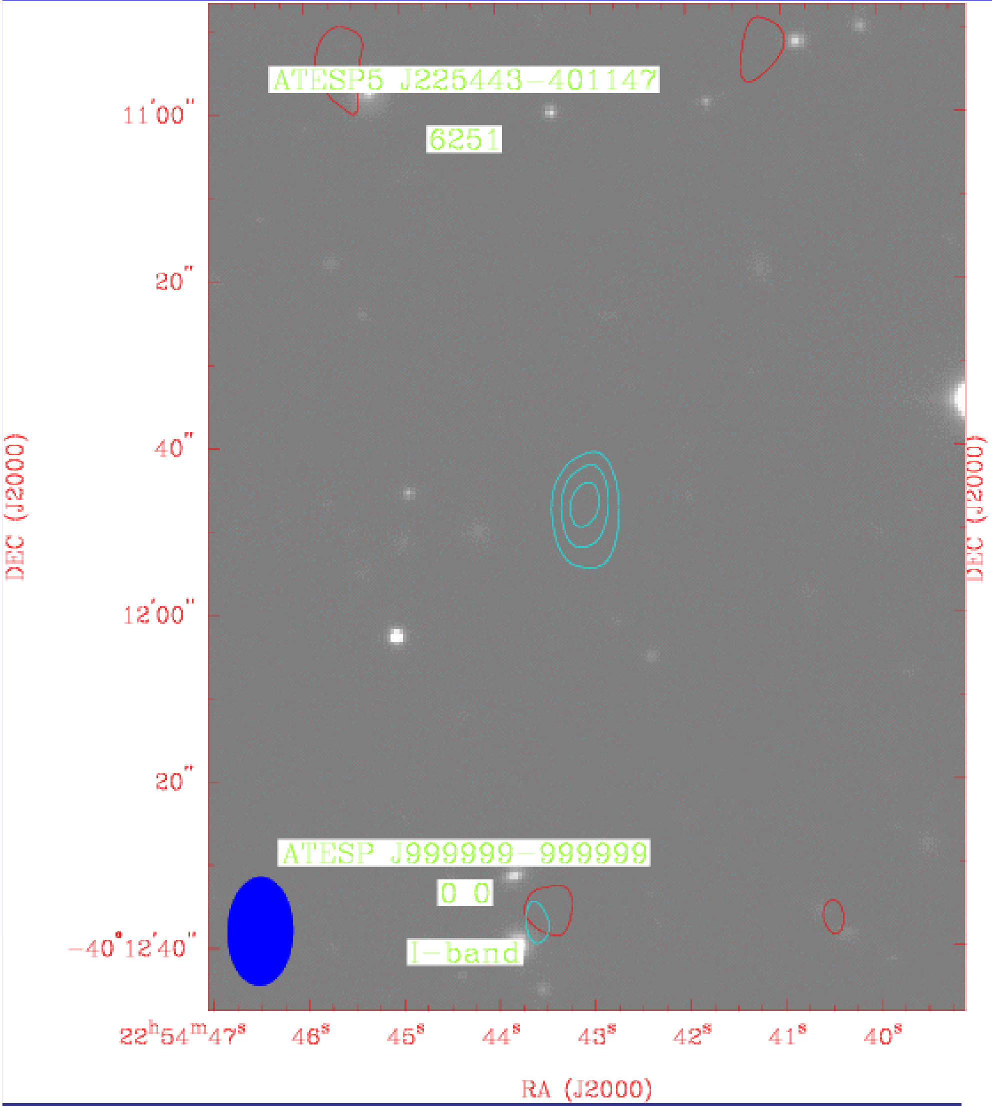
Flux range	freq.	N	weighted mean α	median α	$f(\alpha > -0.5)$	$f(\alpha > 0)$
All fluxes	1.4 GHz	109	-0.56 ± 0.33	-0.56	47 (43%)	10 (9%)
$S > 4$ mJy	1.4 GHz	22	-0.62 ± 0.28	-0.71	7 (32%)	-
$S \leq 4$ mJy	1.4 GHz	87	-0.42 ± 0.38	-0.53	40 (46%)	10 (11%)
All fluxes	5 GHz	111	-0.52 ± 0.37	-0.39	67 (60%)	28 (25%)
$S > 4$ mJy	5 GHz	13	-0.60 ± 0.29	-0.62	5 (38%)	-
$S \leq 4$ mJy	5 GHz	98	-0.43 ± 0.44	-0.29	62 (63%)	28 (29%)

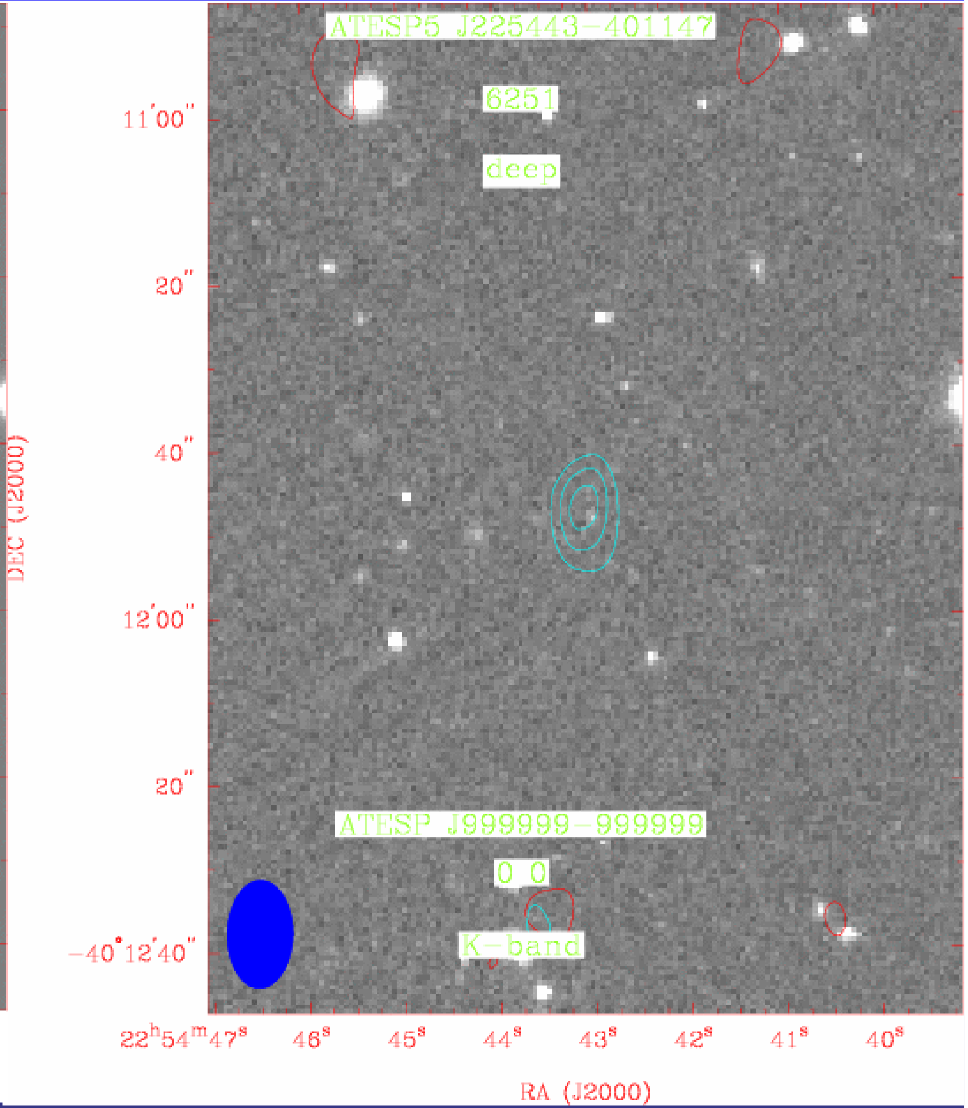
- Only U-band has a large offset beyond the normal photometric calibration error (0.1)

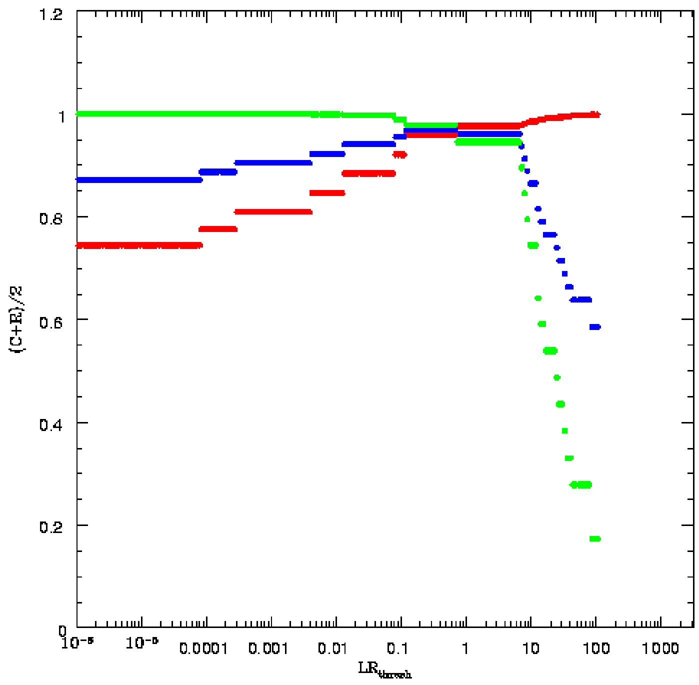
- Applied for both the fields a correction in U-band of 0.15 mags

- Few standards in U-band images
- In other filters very good agreement with Girardi model. Also comparing different instrument (WFI+Sofi) colors

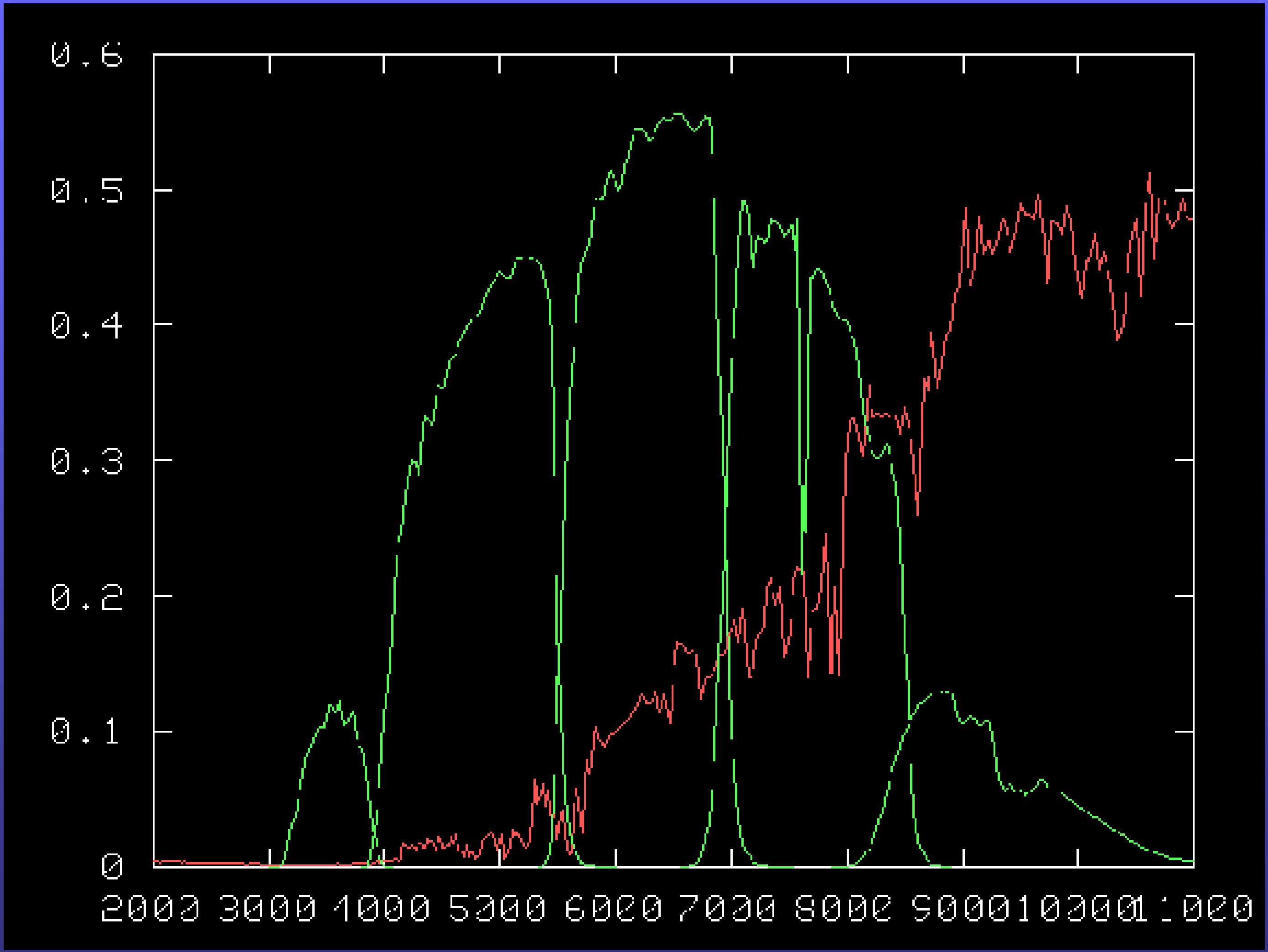
- This correction found from the color catalog (by matching) has been applied to the color catalog (reference image) → verification of the impact of the correction through the comparison with a spectroscopic sample


ATESP5 J225443-401147
6251
ATESP J999999-999999
0 0
I-band
11'00"
20"
40"
12'00"
20"
-40°12'40"
DEC (J2000)
22h54m47s
46s
45s
44s
43s
42s
41s
40s
RA (J2000)


ATESP5 J225443-401147
6251
deep
ATESP J999999-999999
0 0
K-band
11'00"
20"
40"
12'00"
20"
-40°12'40"
DEC (J2000)
22h54m47s
46s
45s
44s
43s
42s
41s
40s
RA (J2000)



(C+E)/2
LR_thresh


0.6
0.5
0.4
0.3
0.2
0.1
0
2000 3000 4000 5000 6000 7000 8000 9000 10000 11000