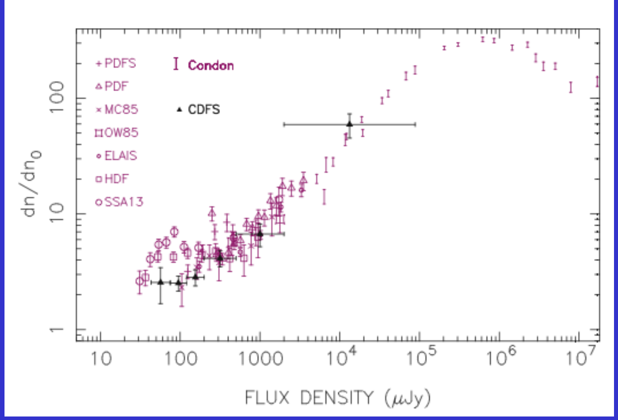
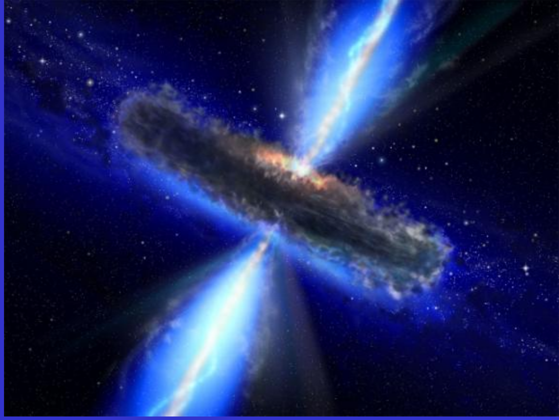


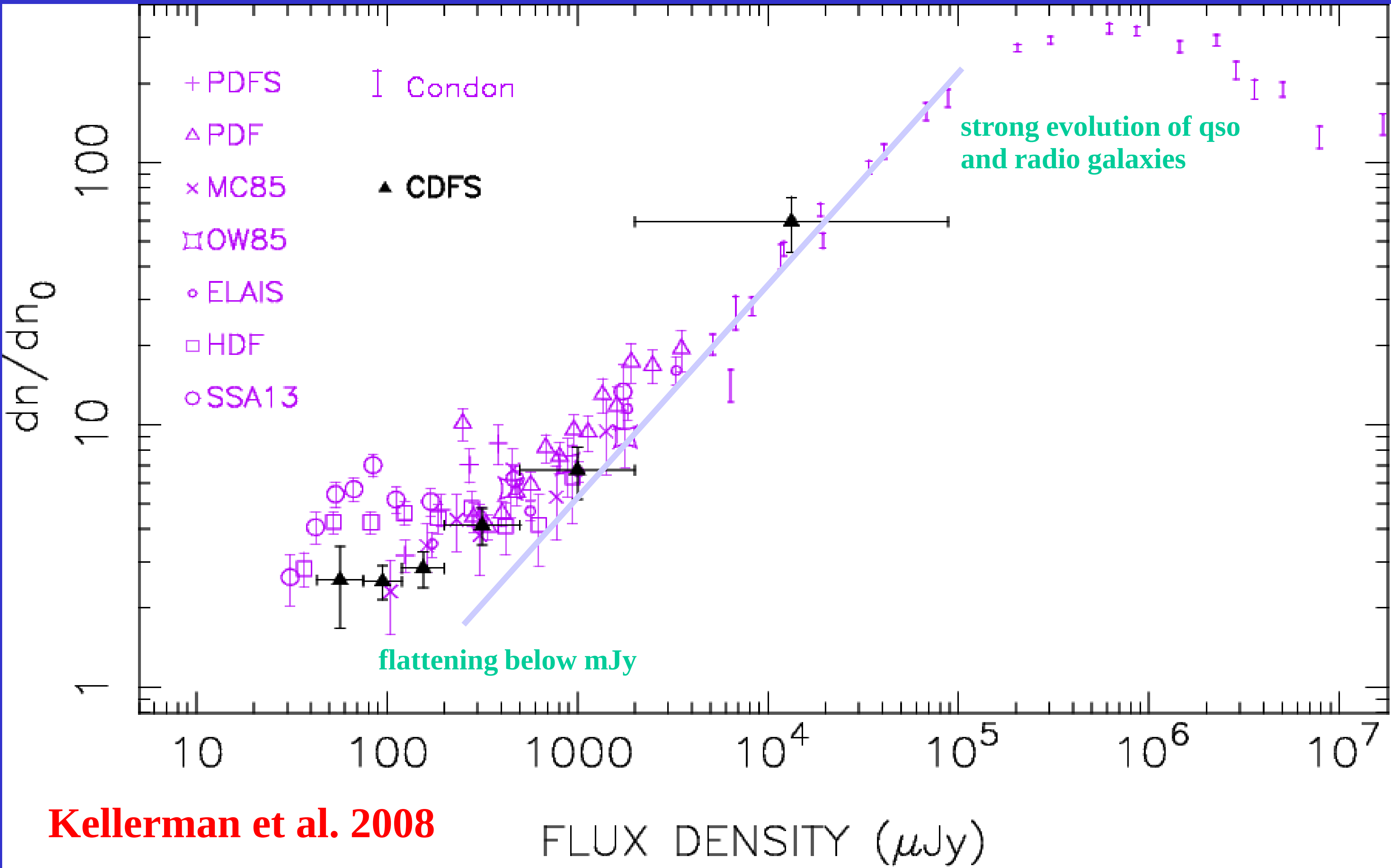


The micro- and nano-Jy sky

Paolo Padovani, ESO, Germany

- The sub-mJy source population
- Which type of sources will SKA see at micro-Jy and nano-Jy flux densities? How many of them and how faint?
- Which multi-wavelength properties will they have? How will we identify them?

Radio (1.4 GHz) number counts

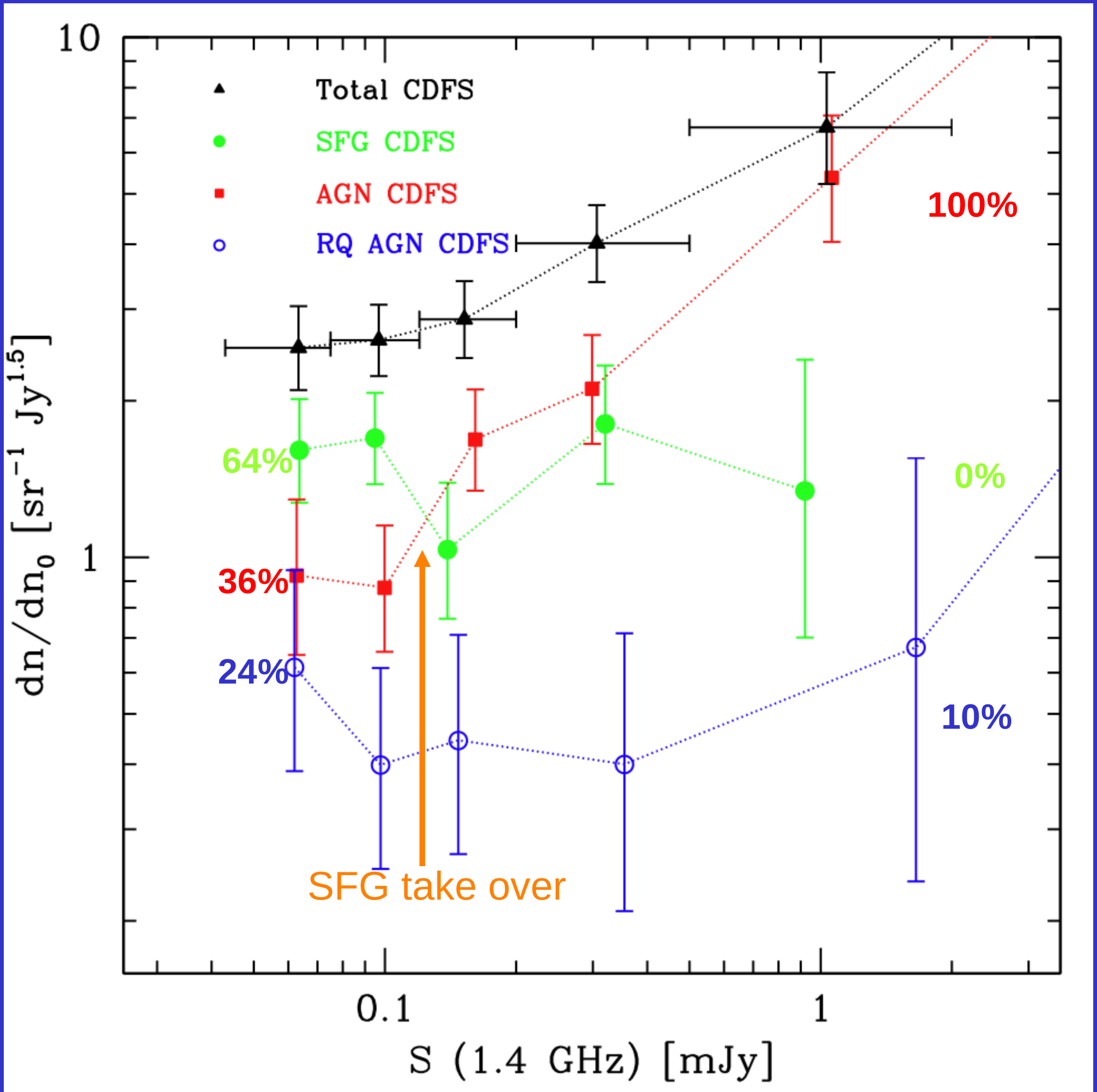


Kellerman et al. 2008

The sub-mJy population: a "hot" topic

- The composition of the sub-mJy population has been debated over the past ~ 25 years
- More than 200 refereed papers in the ADS including: Mitchell & Condon 1985; Windhorst et al. 1985; Danese et al. 1987; Benn et al. 1993; Hopkins et al. 1998; Gruppioni et al. 1999; Richards 2000; Bondi et al. 2003; Ciliegi et al. 2003; Hopkins et al. 2003; Jackson 2004; Seymour et al. 2004, 2008; Huynh et al. 2005, 2008; Prandoni et al. 2006; Fomalont et al. 2006; Simpson et al. 2006; Bondi et al. 2007; Ivison et al. 2007; Bondi et al. 2008; Owen & Morrison 2008; Smolčić et al. 2008; Wilman et al. 2008; Padovani et al. 2009; Massardi et al. 2010
- Most accepted paradigm until recently: star-forming galaxies

Sub-mJy populations



Sub-mJy sources:
57±8% SFG
41±6% AGN
19±5% RQ AGN
(46% of all AGN)

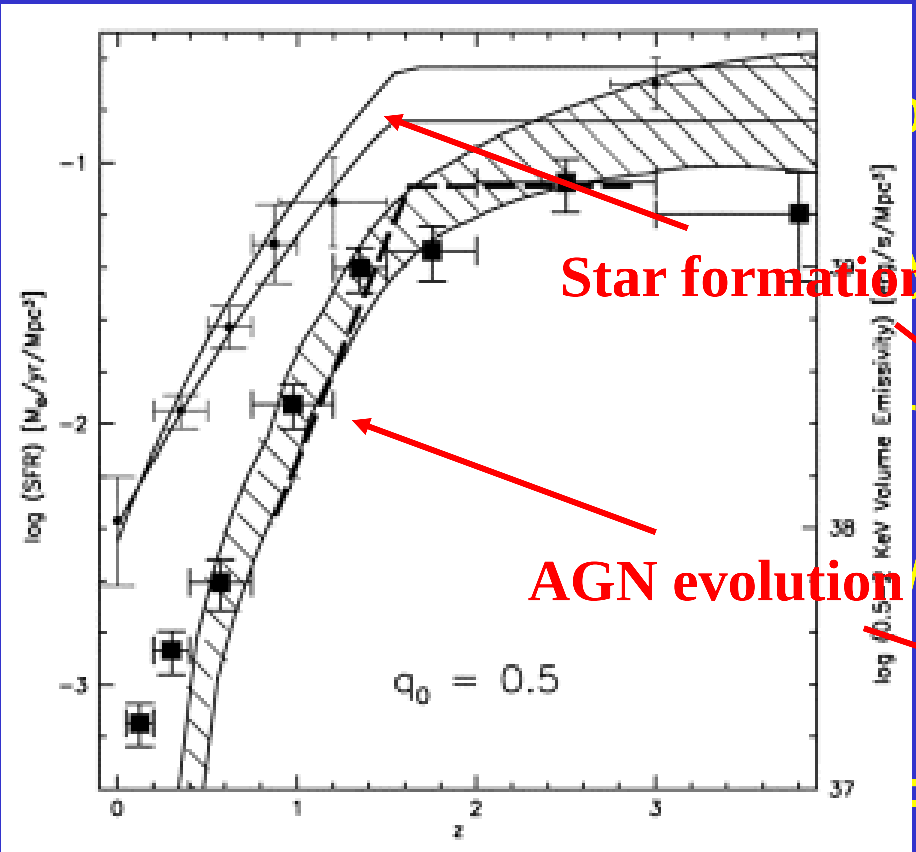
≈1/2 SFG **≈1/2 AGN**

≈1/2 RL (low-power!) **≈1/2 RQ**

Broadly consistent with, e.g., Smolčić et al. 2008 and Seymour et al. 2008

Padovani et al. 2009

AGN and star formation in the Universe



Franceschini et al. 1999

black ho… er

…y back…

…rate sta…

…way all … on

…though … in

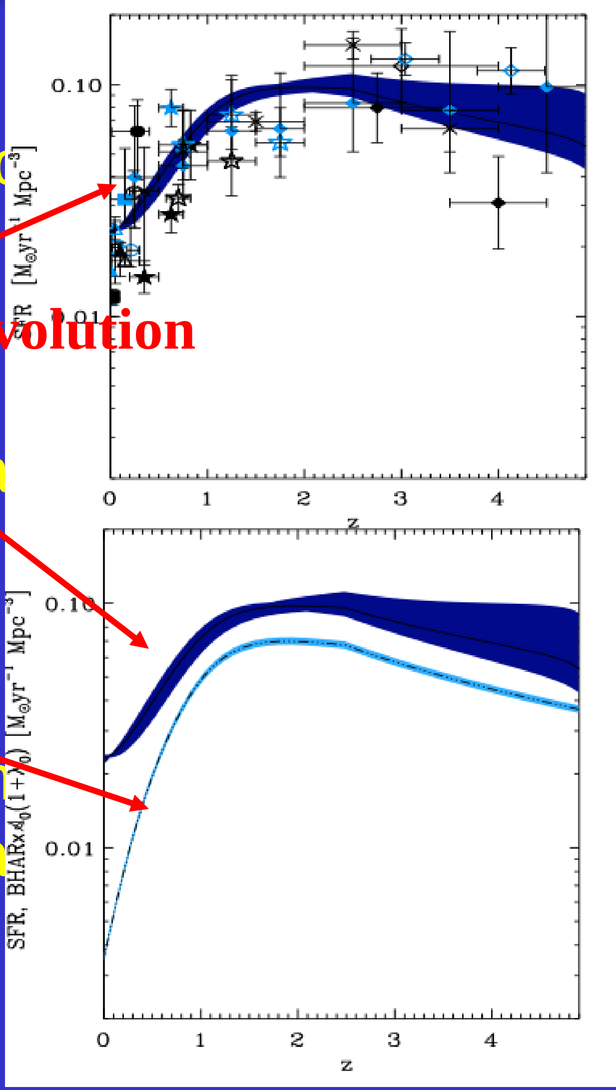
Feedba…

(e.g., Cattaneo et al. 2009)

Star formation rate evolution

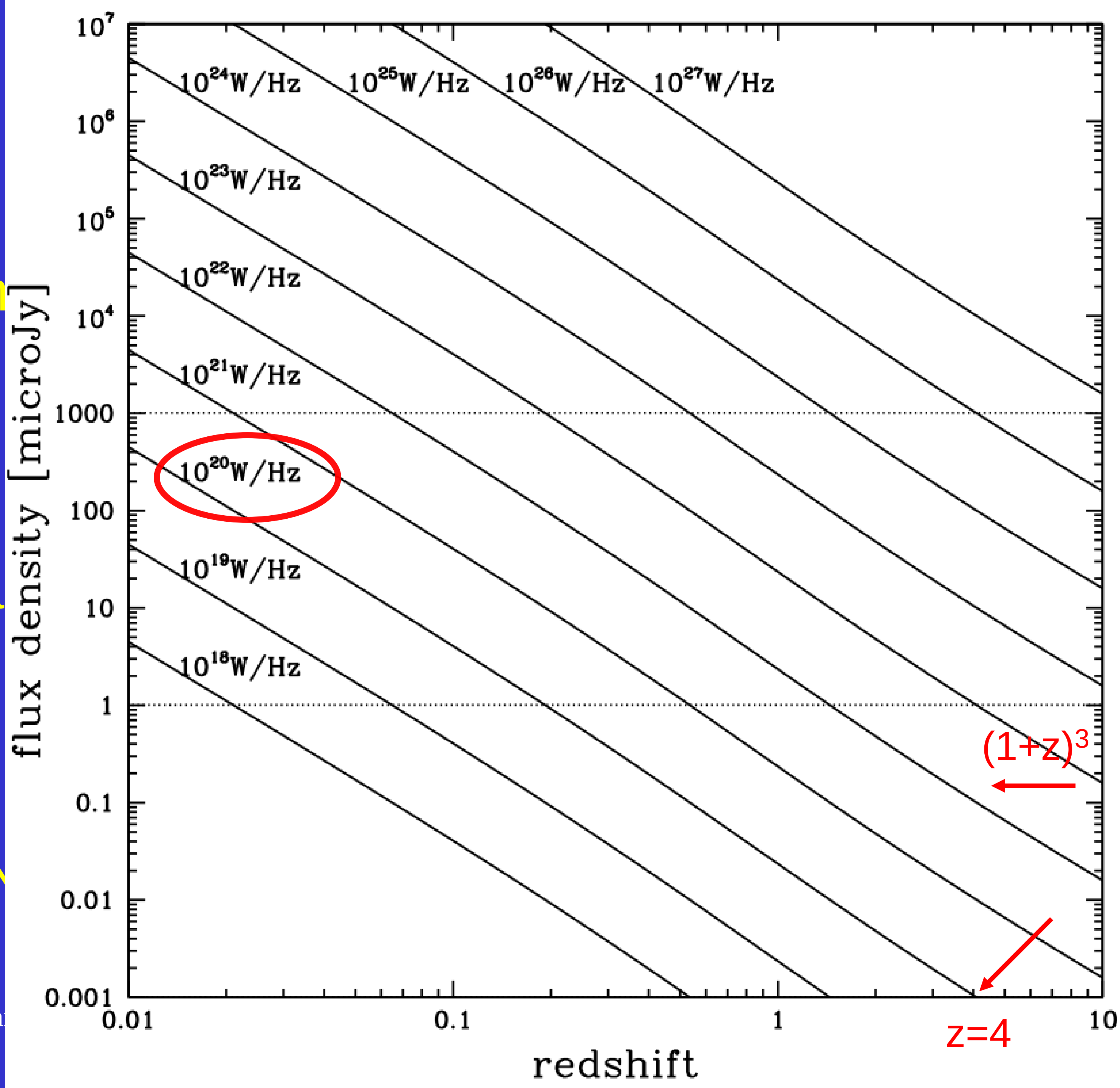
AGN evolution

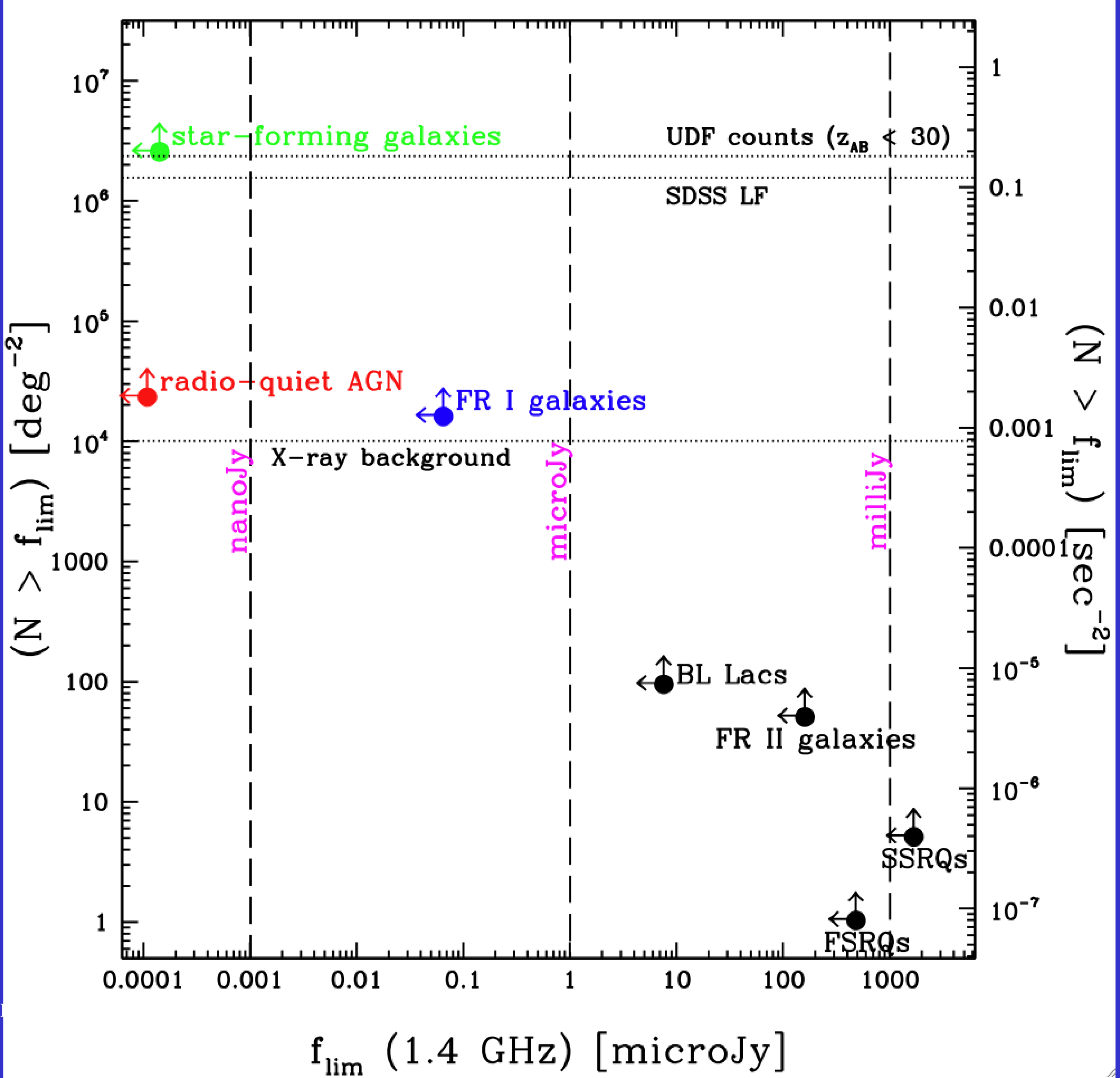
Merloni et al. 2006



- Sm … s on:
  - ✓
  - ✓
  - ✓
- La … s on:
  - ✓
  - ✓
  - ✓

N





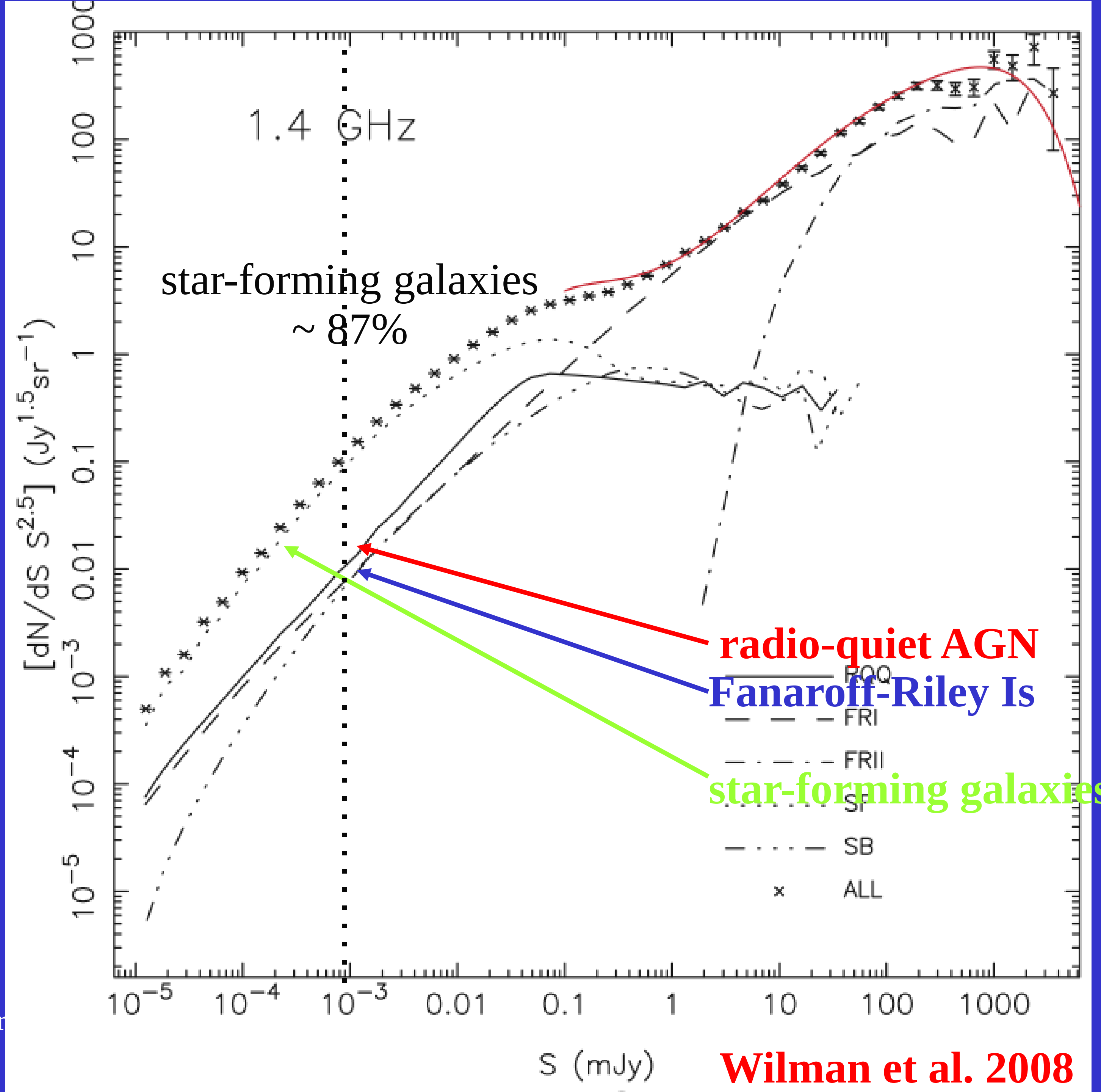
star−forming galaxies
UDF counts (z_{AB} < 30)
SDSS LF
radio−quiet AGN
FR I galaxies
X−ray background
nanoJy
microJy
milliJy
BL Lacs
FR II galaxies
SSRQs
FSRQs
10^7
10^6
10^5
10^4
1000
100
10
1
1
0.1
0.01
0.001
0.0001
10^{-5}
10^{-6}
10^{-7}
0.0001
0.001
0.01
0.1
1
10
100
1000
$(N > f_{lim})$ [deg^{-2}]
$(N > f_{lim})$ [sec^{-2}]
f_{lim} (1.4 GHz) [microJy]

Going fainter: a more complex approach

- Assume/derive luminosity function for the *relevant populations*
- Assume/derive evolution
- Assume cosmology
- Calculate number counts:

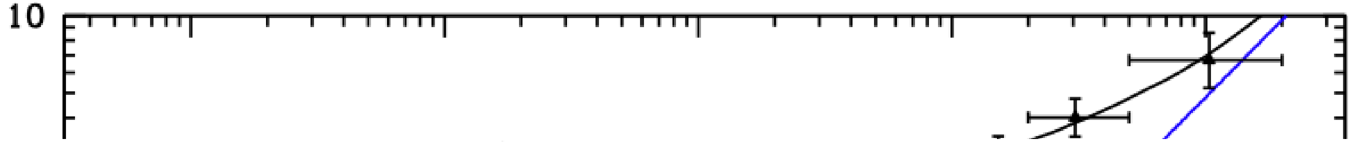
$$\frac{N(S)}{4\pi} = 4\pi \frac{c}{H_0} \int_{z_{\min}(S)}^{z_{\max}(S)} \frac{\phi[L(S,z),z] D_L^4(z) dz}{(1+z)^{(3-\alpha)}\sqrt{(1+z)^2(1+\Omega_m z) - z(z+2)\Omega_\Lambda}}$$

- Previous modelling work reaching flux densities < 1 μJy include Hopkins et al. (2000), Windhorst (2003), Jackson (2004), Jarvis & Rawlings (2004), and Wilman et al. (2008) [SKA Design Study]


1.4 GHz
star-forming galaxies
~ 87%
radio-quiet AGN
Fanaroff-Riley Is
star-forming galaxies
RQQ
FRI
FRII
SF
SB
ALL
[dN/dS S^2.5] (Jy^1.5 sr^-1)
S (mJy)
Wilman et al. 2008

Open Issues

- Extrapolations; samples used typically have:
  - ✓ flux densities much larger than those of interest (e.g., equiv. $f_{1.4GHz} \approx 0.1$ Jy for radio-loud AGN)
  - ✓ lower redshifts and higher powers
  - ✓ different frequencies (requires spectral assumptions)
- Evolution is often not included self-consistently
- Radio-quiet AGN predictions (excluded by older calculations!) rely on X-ray – radio power correlation



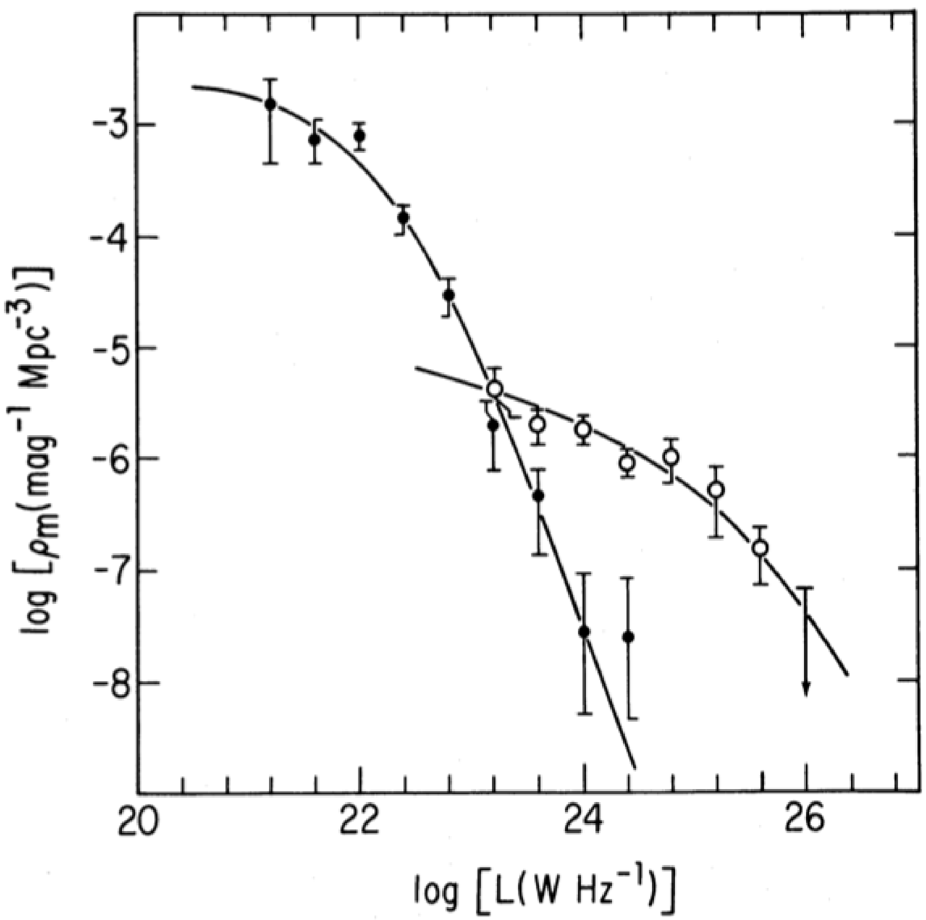


FIG. 9

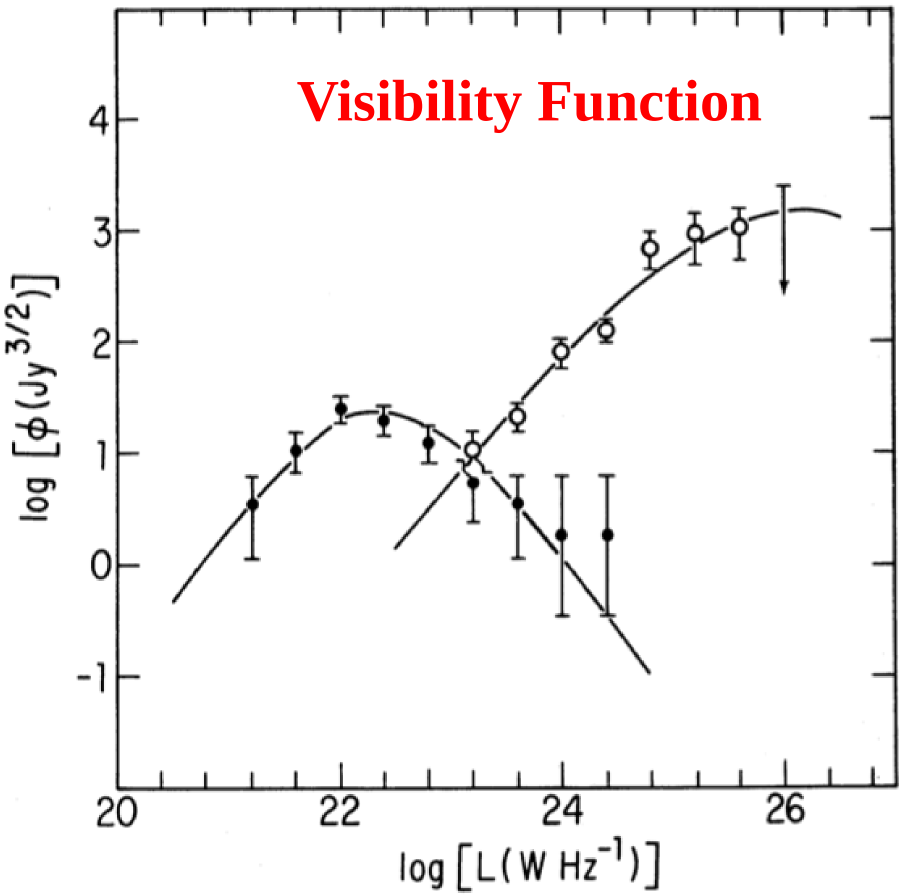
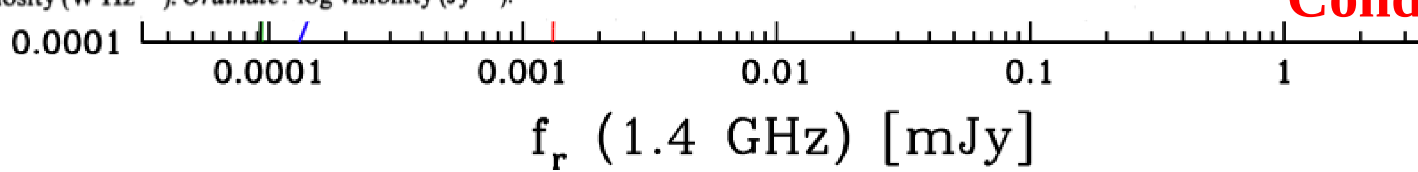


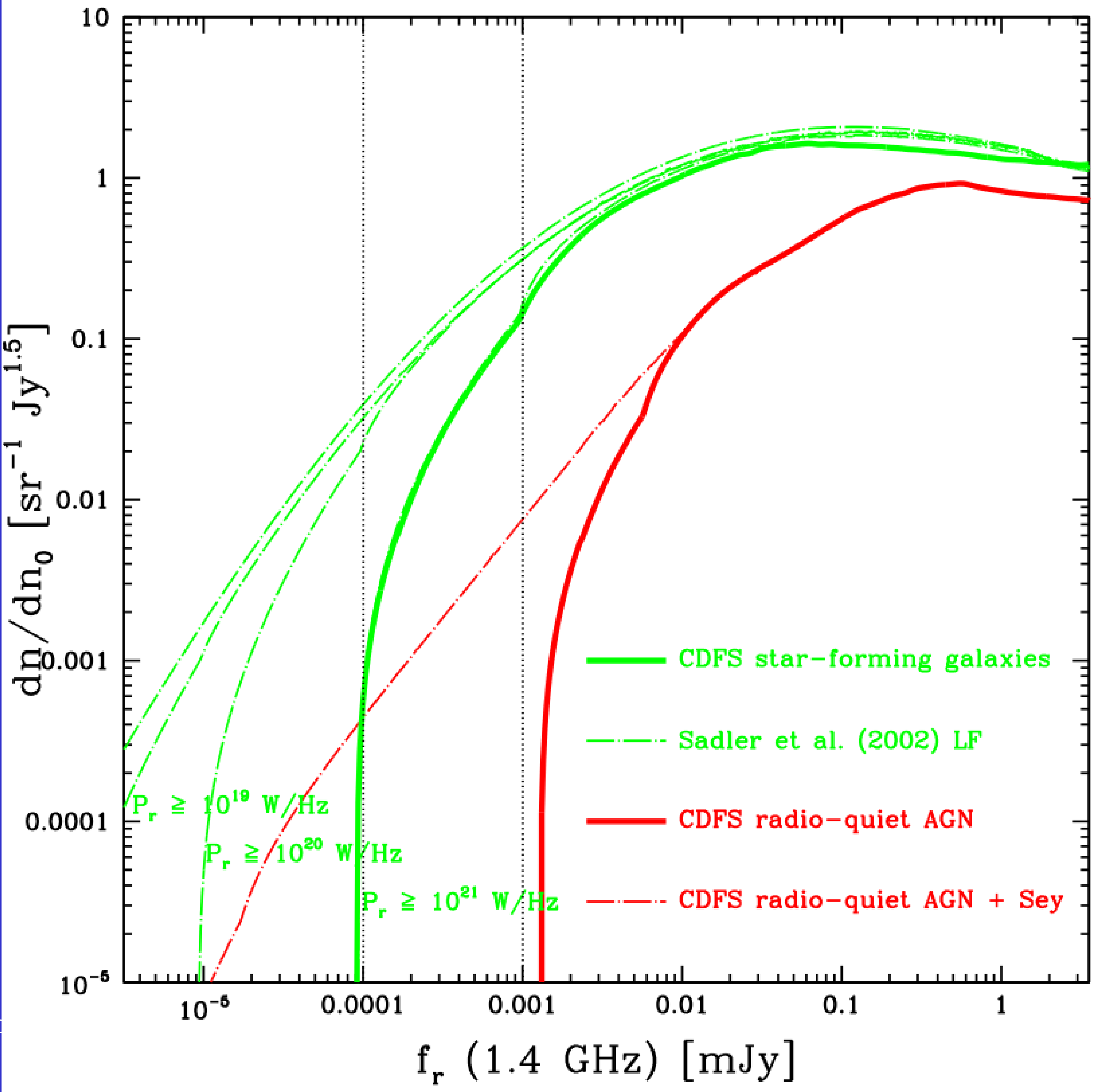
FIG. 10

FIG. 9.—The local radio luminosity functions at $\nu = 1.40$ GHz of galaxies with "starburst" (*filled symbols*) and "monster" (*open symbols*) energy sources. *Abscissa:* log luminosity (W Hz^{-1}). *Ordinate:* log density (mag^{-1} Mpc^{-3}).

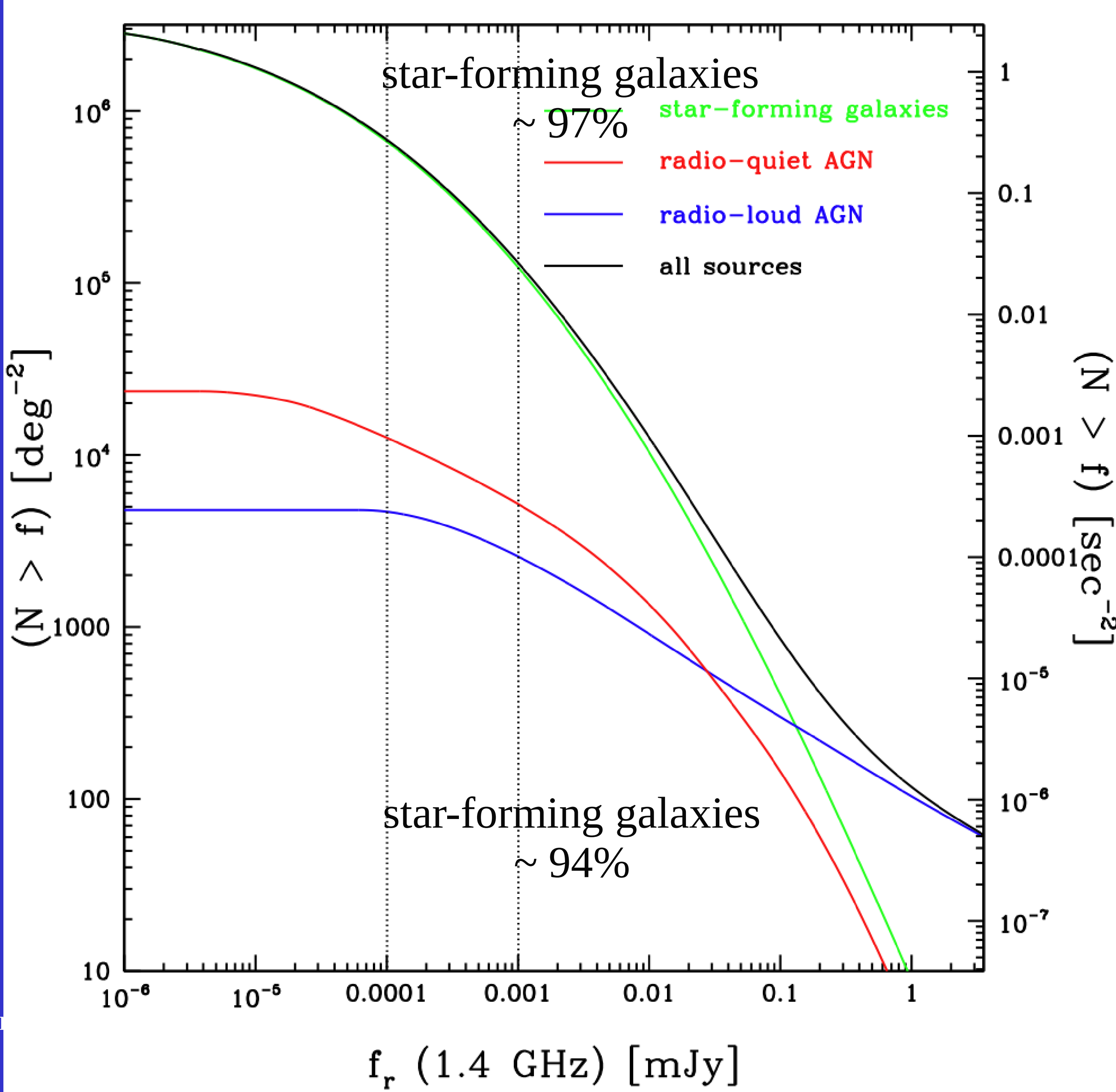
FIG. 10.—The local radio visibility functions at $\nu = 1.40$ GHz of galaxies with "starburst" (*filled symbols*) and "monster" (*open symbols*) energy sources. *Abscissa:* log luminosity (W Hz^{-1}). *Ordinate:* log visibility (Jy$^{3/2}$).

Condon 1989





10
1
0.1
0.01
0.001
0.0001
10^{-5}
dn/dn_0 [sr^{-1} $Jy^{1.5}$]
10^{-5}
0.0001
0.001
0.01
0.1
1
f_r (1.4 GHz) [mJy]
$P_r \geqq 10^{19}$ W/Hz
$P_r \geqq 10^{20}$ W/Hz
$P_r \geqq 10^{21}$ W/Hz
CDFS star-forming galaxies
Sadler et al. (2002) LF
CDFS radio-quiet AGN
CDFS radio-quiet AGN + Sey



star-forming galaxies
~ 97%
star-forming galaxies
radio-quiet AGN
radio-loud AGN
all sources
star-forming galaxies
~ 94%
(N > f) [deg^-2]
(N > f) [sec^-2]
f_r (1.4 GHz) [mJy]

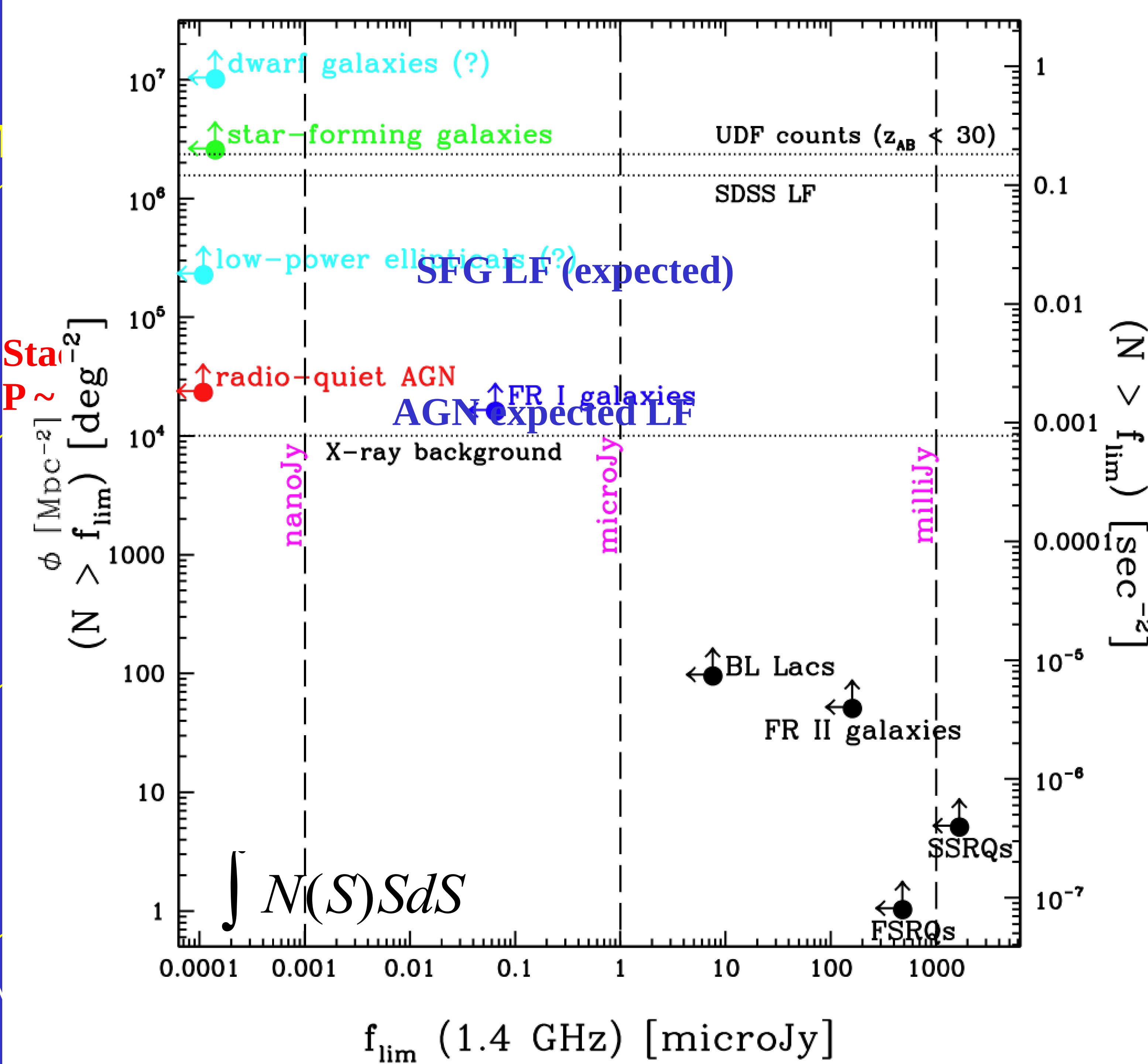
• M … :

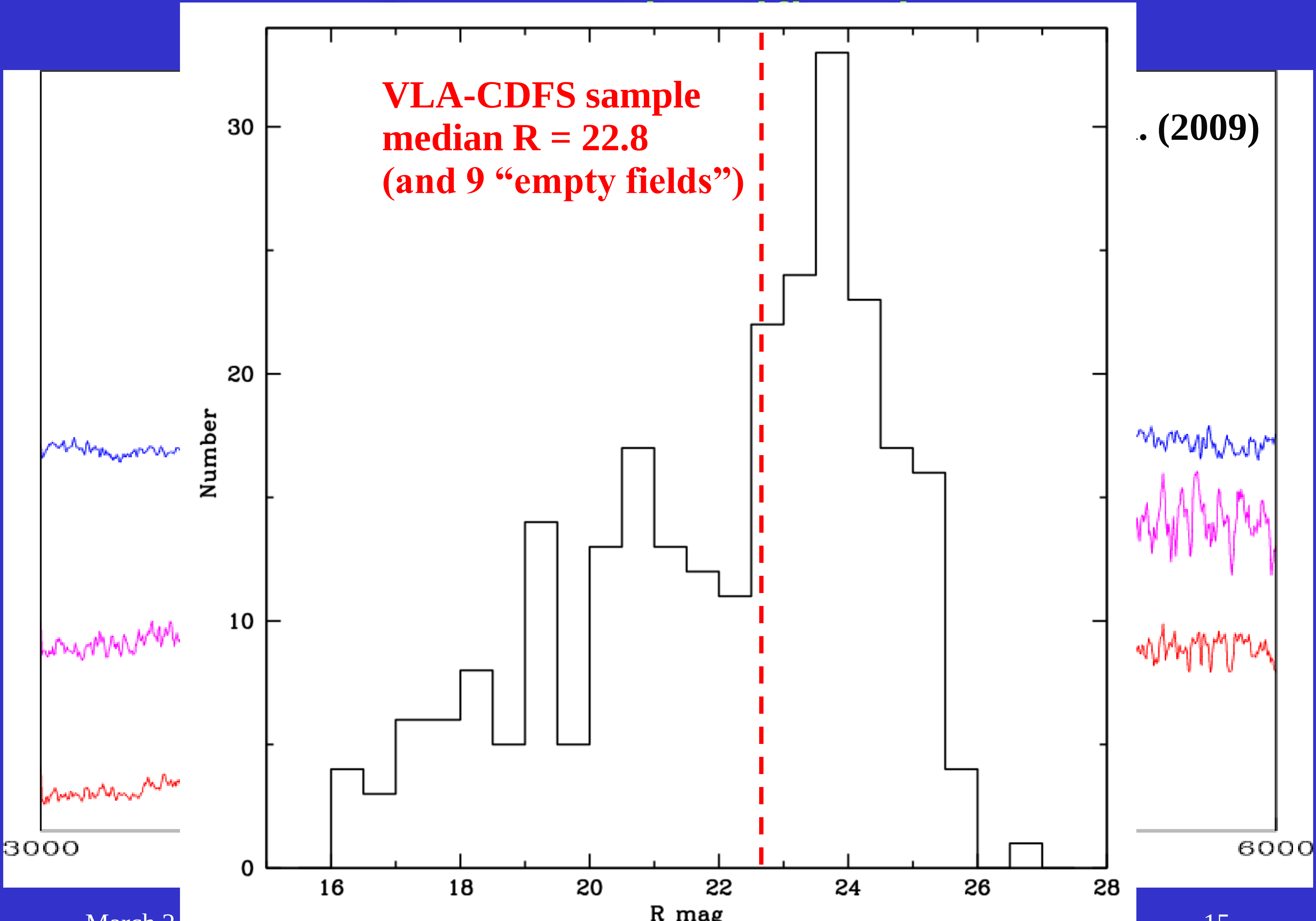
✓ … 10^{21-} … nd … et al.

✓ … each … 009; … h

✓ … y ≈ … al.

✓

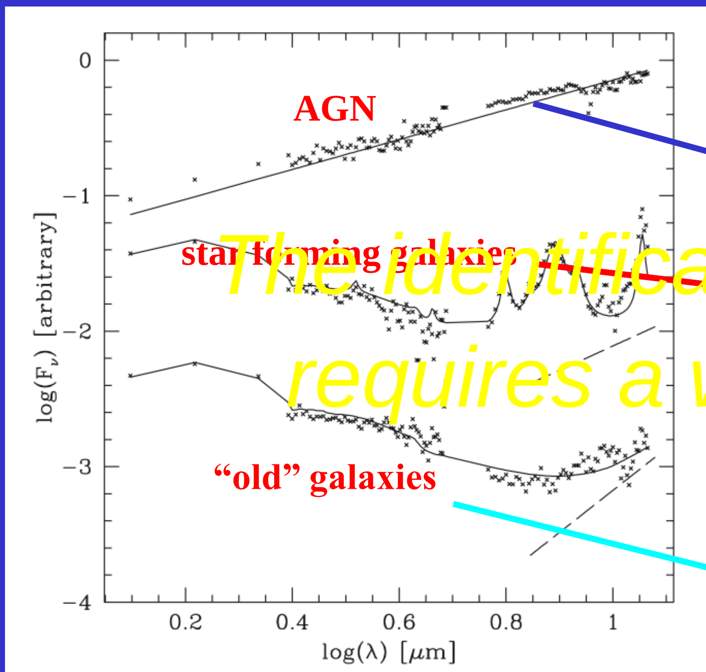


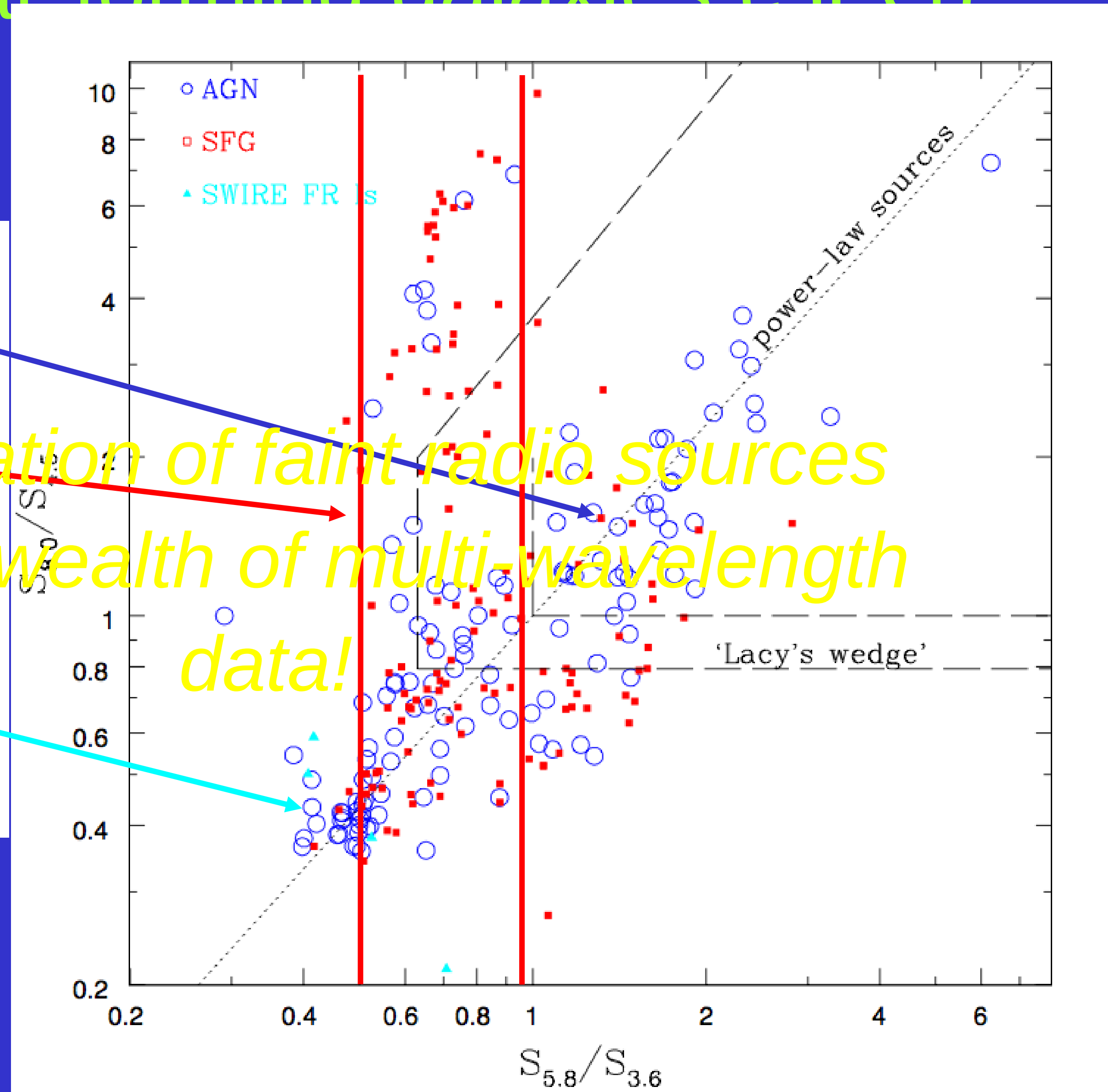

VLA-CDFS sample
median R = 22.8
(and 9 “empty fields”)
Number
R mag
30
20
10
0
16
18
20
22
24
26
28
. (2009)
3000
6000

Selecting star-forming galaxies (SFG) candidates

1. SFGs (at $z \approx 1$) are typically NOT hosted by ellipticals or lenticulars ➔ *optical morphology*
2. SFGs have relatively low radio powers [locally $P_r < 10^{24}$ W/Hz]: $P_r < 10^{24.5}$ W/Hz ➔ *spectra or photometric redshifts*
3. SFGs have relatively low radio-to-optical luminosity ratios [locally $R = \log(P_r/L_{opt}) < 1.4$]: $R < 1.7$ ➔ *optical data*
4. SFGs have relatively low X-ray powers: $L_x < 10^{42}$ erg/s ➔ *X-ray data (vital to separate SFGs from AGN)*

Selecting star-forming galaxies (SFG)

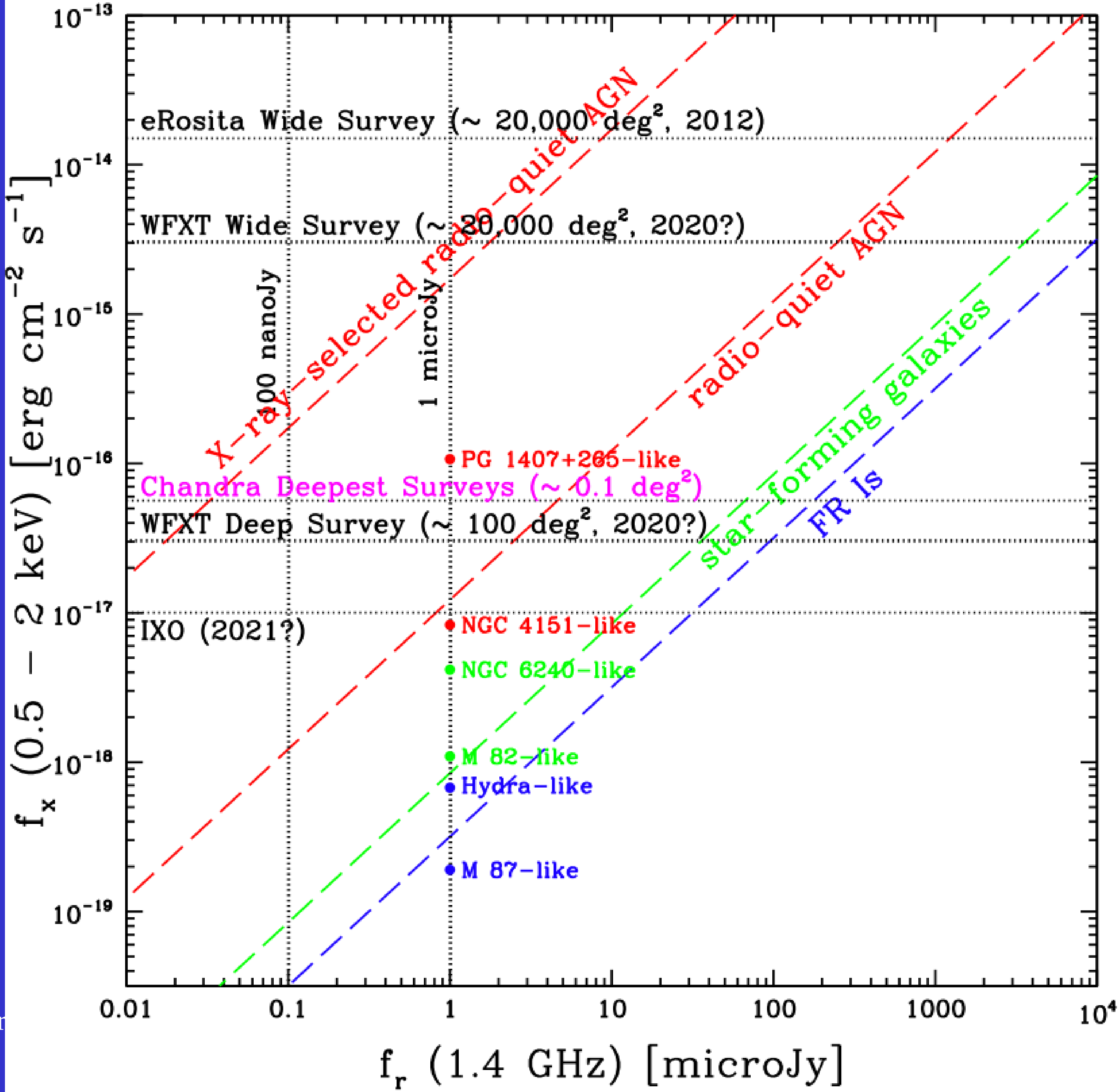




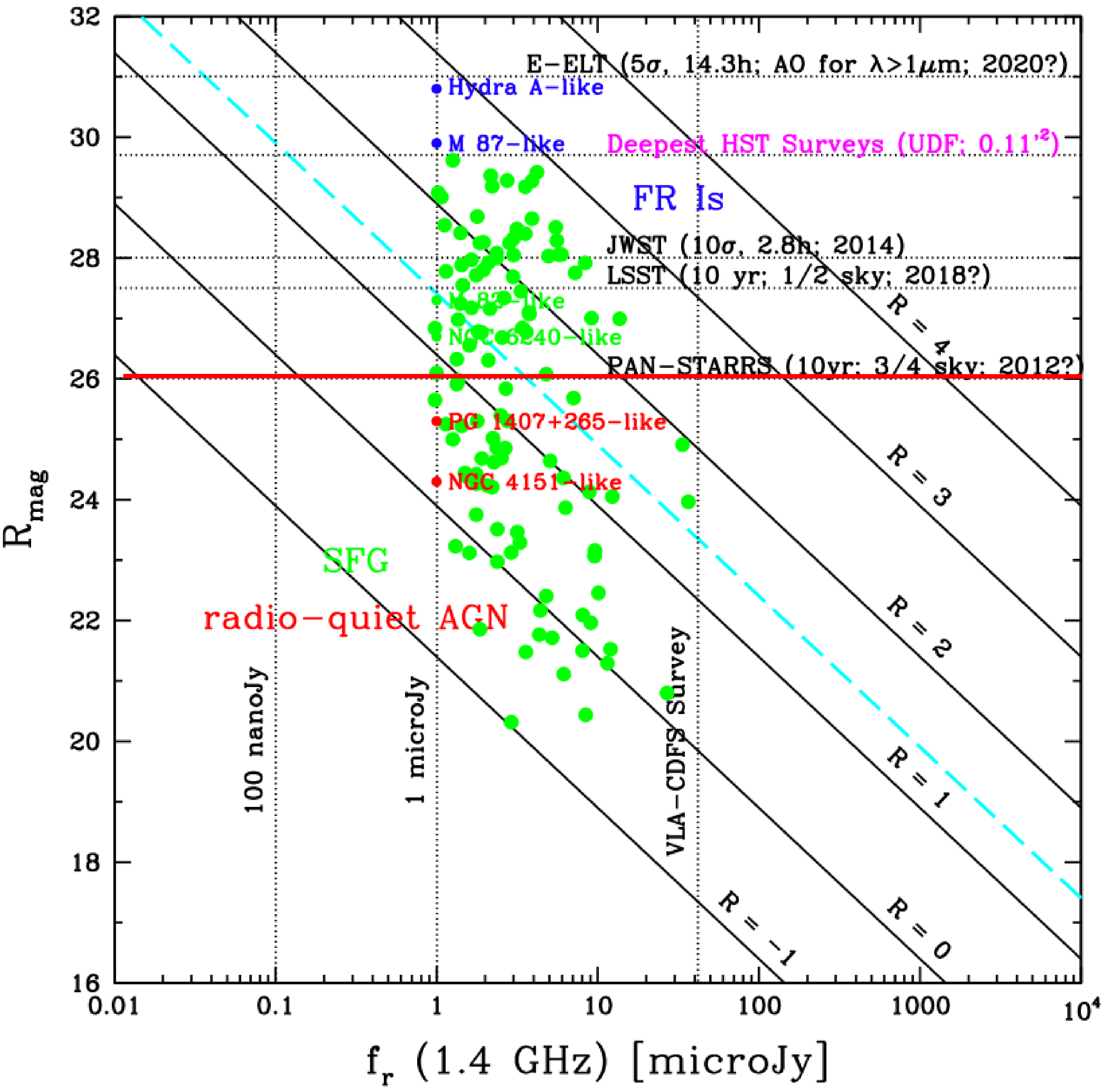
The identification of faint radio sources requires a wealth of multi-wavelength data!

Sajina et al. 2005 (also: Lacy et al. 2004, Stern et al. 2005, and others)

Th cro-

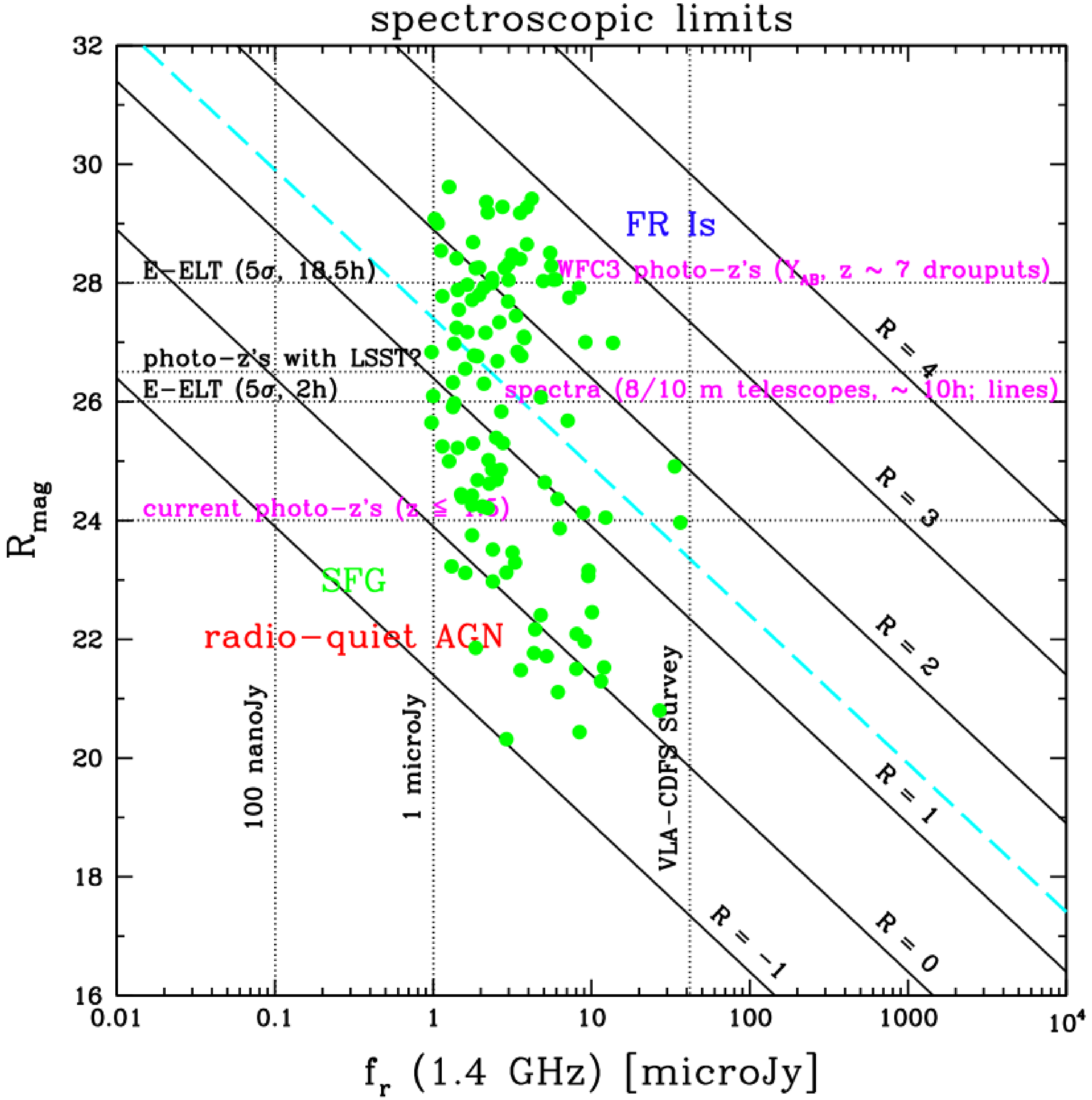

eRosita Wide Survey (~ 20,000 deg², 2012)
WFXT Wide Survey (~ 20,000 deg², 2020?)
Chandra Deepest Surveys (~ 0.1 deg²)
WFXT Deep Survey (~ 100 deg², 2020?)
IXO (2021?)
100 nanoJy
1 microJy
X-ray-selected radio-quiet AGN
radio-quiet AGN
star-forming galaxies
FR Is
PG 1407+265-like
NGC 4151-like
NGC 6240-like
M 82-like
Hydra-like
M 87-like
f_x (0.5 - 2 keV) [erg cm^-2 s^-1]
f_r (1.4 GHz) [microJy]
0.01
0.1
1
10
100
1000
10^4
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19

Th cro-



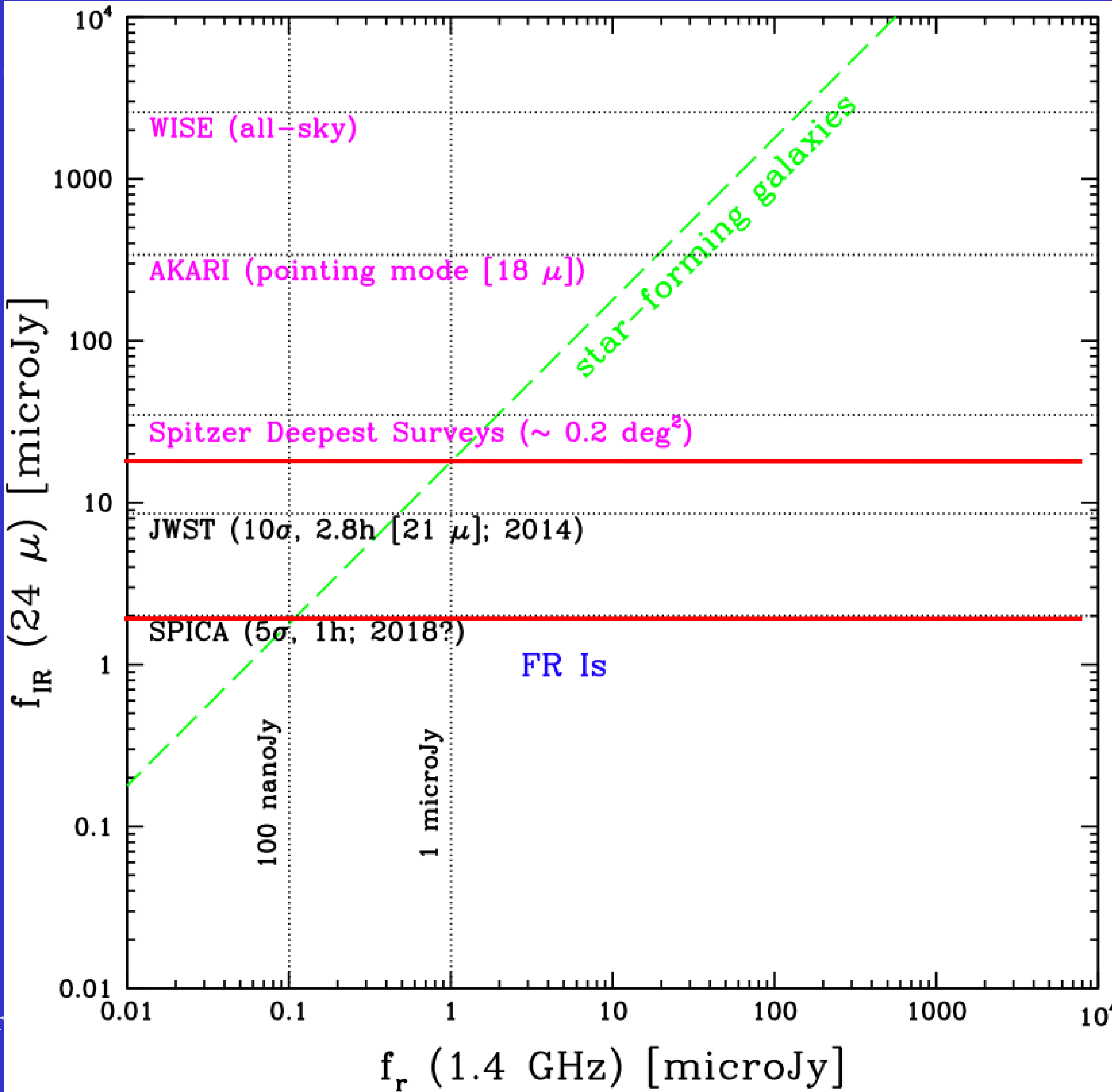
E−ELT (5σ, 14.3h; AO for λ>1μm; 2020?)
Hydra A−like
M 87−like
Deepest HST Surveys (UDF; 0.11'²)
FR Is
JWST (10σ, 2.8h; 2014)
LSST (10 yr; 1/2 sky; 2018?)
M 82−like
NGC 6240−like
PAN−STARRS (10yr; 3/4 sky; 2012?)
PG 1407+265−like
NGC 4151−like
SFG
radio−quiet AGN
100 nanoJy
1 microJy
VLA−CDFS Survey
R = 4
R = 3
R = 2
R = 1
R = 0
R = −1
R_{mag}
f_r (1.4 GHz) [microJy]
32
30
28
26
24
22
20
18
16
0.01
0.1
1
10
100
1000
10^4

The cro-



spectroscopic limits
FR Is
WFC3 photo-z's (Y_{AB}, z ~ 7 drouputs)
E-ELT (5σ, 18.5h)
photo-z's with LSST?
E-ELT (5σ, 2h)
spectra (8/10 m telescopes, ~ 10h; lines)
current photo-z's (z ≲ 1.5)
SFG
radio-quiet AGN
100 nanoJy
1 microJy
VLA-CDFS Survey
R = 4
R = 3
R = 2
R = 1
R = 0
R = -1
R_{mag}
f_r (1.4 GHz) [microJy]
32
30
28
26
24
22
20
18
16
0.01
0.1
1
10
100
1000
10^4

Th cro-



WISE (all−sky)
AKARI (pointing mode [18 μ])
Spitzer Deepest Surveys (~ 0.2 deg²)
JWST (10σ, 2.8h [21 μ]; 2014)
SPICA (5σ, 1h; 2018?)
FR Is
star−forming galaxies
100 nanoJy
1 microJy
f_IR (24 μ) [microJy]
f_r (1.4 GHz) [microJy]
10⁴
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10⁴

Summary

Q. Which type of sources will SKA see at micro-Jy and nano-Jy flux densities?

A. SFGs, FR Is, and radio-quiet AGN; *plus* dwarf galaxies and low-power (P < 10^{21} W/Hz) ellipticals, which are *not* included in current models

Q. How many of them and how faint?

A. <u>At least</u> 10^5/deg^2 above 1 μJy and 7 10^5/deg^2 above 100 nJy. Dwarfs and SFGs *should* be the most numerous classes, followed by low-power ellipticals (reaching, with radio-quiet AGN, below 0.1 nJy)

Summary (continued)

Q. Which multi-wavelength properties will they have?

A. *X-ray*: very faint!

Optical imaging: most > 1 μJy sources should be detected by LSST ("half-sky" survey); (some) fainter sources should be detectable with long exposures by JWST/E-ELT (small areas)

Optical spectra/redshifts: most > 1 μJy sources will be beyond the capabilities of 8/10 m telescopes (photo-z's with LSST?); some of them will be within reach of the E-ELT

Near Infrared: most > 1 μJy sources will be below the limits of all-sky infrared surveys; SFGs will be detectable with JWST and especially with SPICA (down to 100 nJy)

Summary (continued)

Q. How will we identify them?

A.

- ✓ On large areas of the sky SKA will be quite "alone" in the multi-wavelength arena (with the exception of the optical band and down to ≈ 1 μJy). **However, most all-sky survey sources will have an SKA counterpart!**
- ✓ JWST, the E-ELT, and SPICA will match the SKA but only above ≈ 0.1-1 μJy and on small areas. At the 10 nano-Jy level it's going to be pretty lonely …

➔ need to use as much radio information (HI redshifts, size, morphology, spectral index, etc.) as possible (but I think it won't be enough …)!