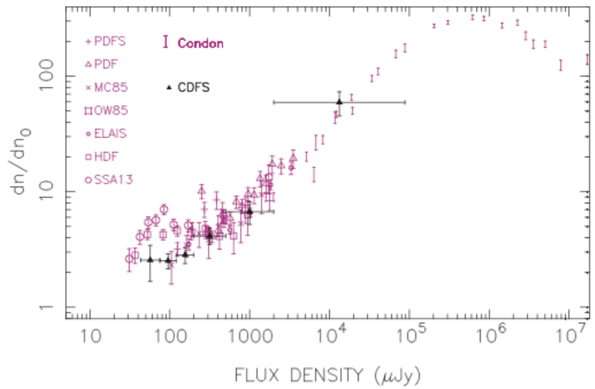
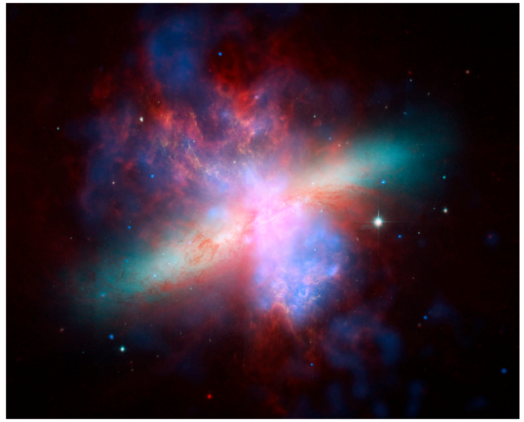




The SKA and its pathfinders and their synergy with the ELTs*

Paolo Padovani, ESO, Germany

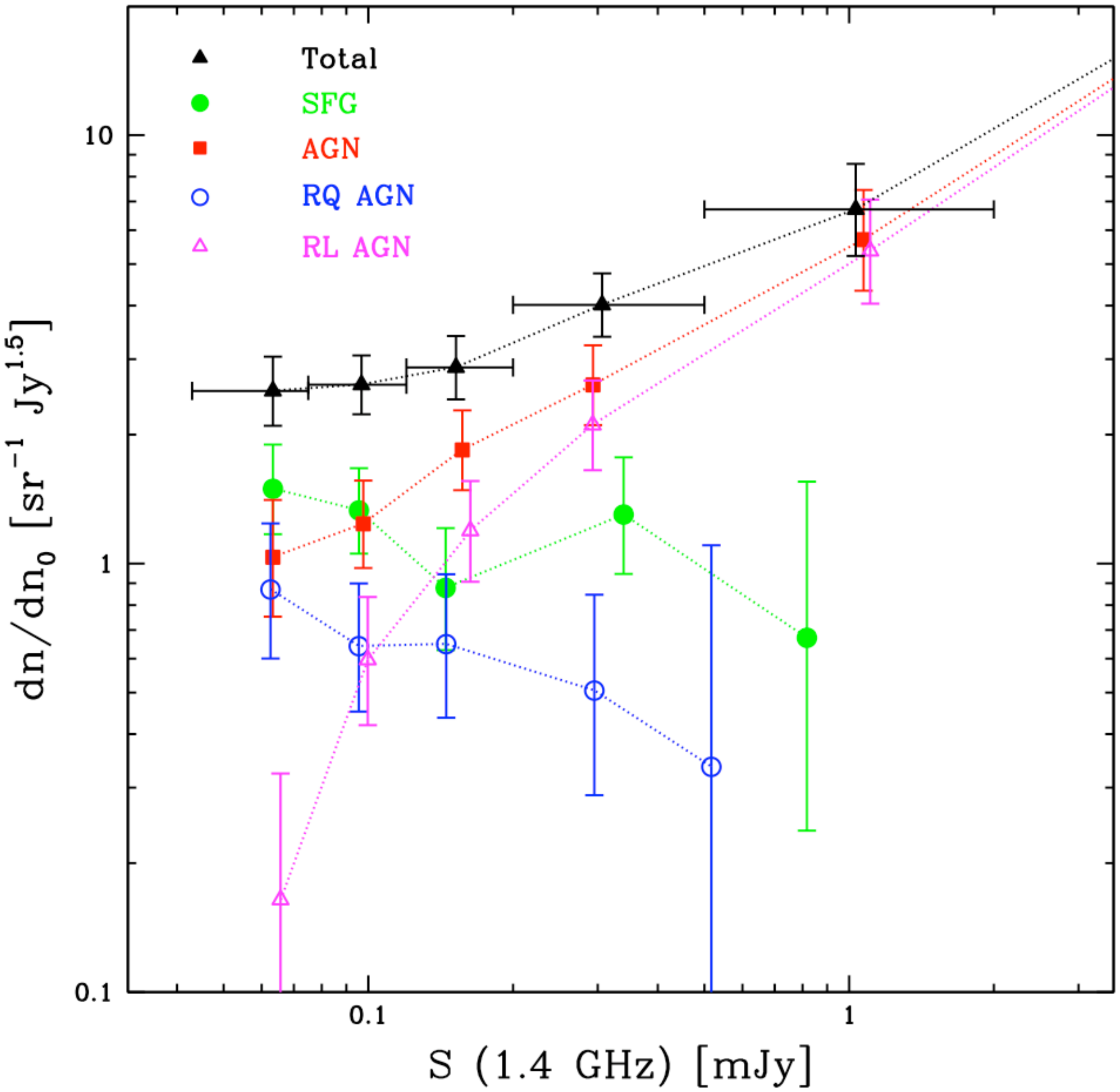
- Radio astronomy in the XXI century
- Which type of sources will the SKA see?
- Which optical properties will they have? Will we be able to take spectra of them? The role of the ELTs

* Based on Padovani, 2011, MNRAS, 411, 1547

Radio astronomy at the verge of a revolution

- Square Kilometre Array (SKA: 2020?) >≈ 100 times more sensitive than current facilities (≈ 15 microJy at 1.4 GHz) → SKA will enter the nanoJy regime
- Many projects in the lead-up to the SKA (so-called "Pathfinders"): LOFAR (The Netherlands + European partners: now), EVLA (USA: now), e-Merlin (UK: now), ASKAP (Australia: 2012), Apertif (The Netherlands: 2013), Meerkat (South Africa: 2016), ATA (USA), etc.
- Pathfinders will reach ≈ 1 microJy (small areas) or ≈ 10 - 40 microJy (large areas) at a few GHz. And will generate many surveys!

Sub-mJy populations



Sub-mJy sources:

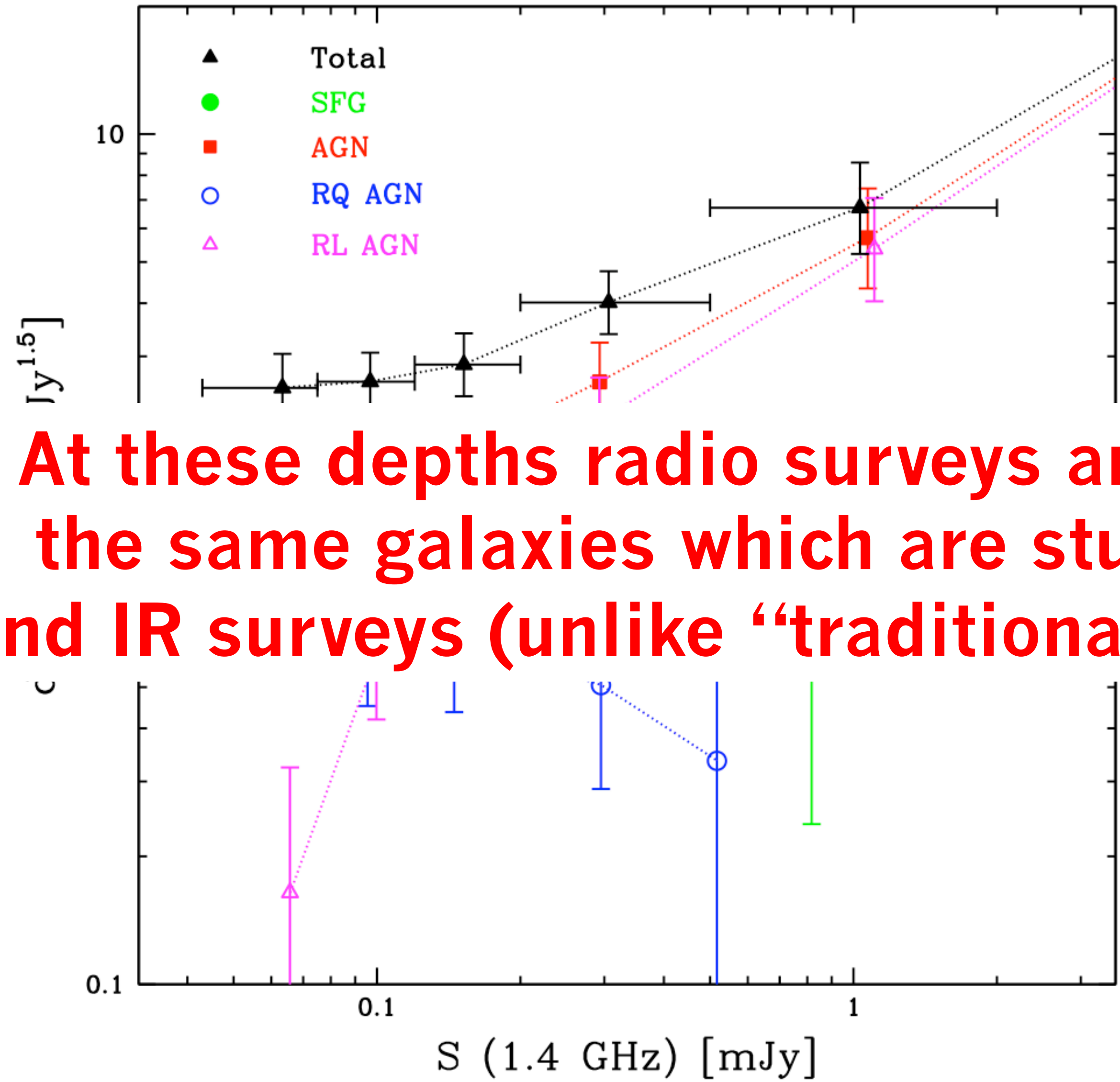
≈1/2 SFG

≈1/2 AGN

- ≈1/2 radio-loud (mostly radio-galaxies: Fanaroff-Riley I [FR Is])
- ≈1/2 radio-quiet

Padovani et al. 2011, ApJ, in press (arXiv:1107.2759)

Sub-mJy populations



Sub-mJy sources:

≈1/2 SFG

≈1/2 AGN

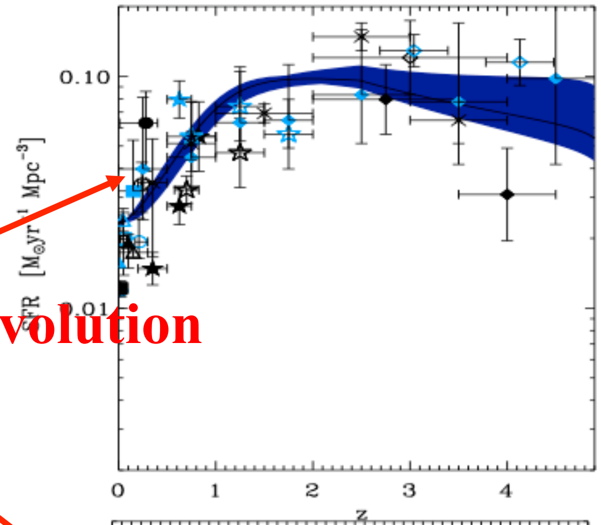
At these depths radio surveys are dominated by the same galaxies which are studied by optical and IR surveys (unlike "traditional" radio surveys)!

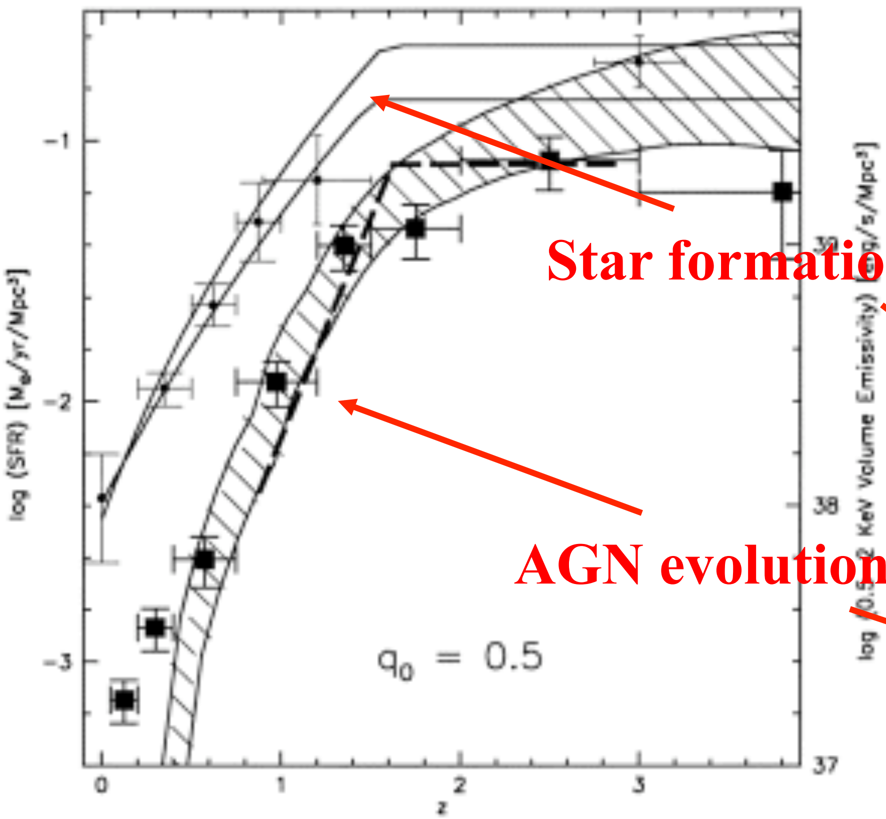
-Riley I [FR Is])

Padovani et al. 2011, ApJ, in press (arXiv:1107.2759)

AGN and star formation in the Universe

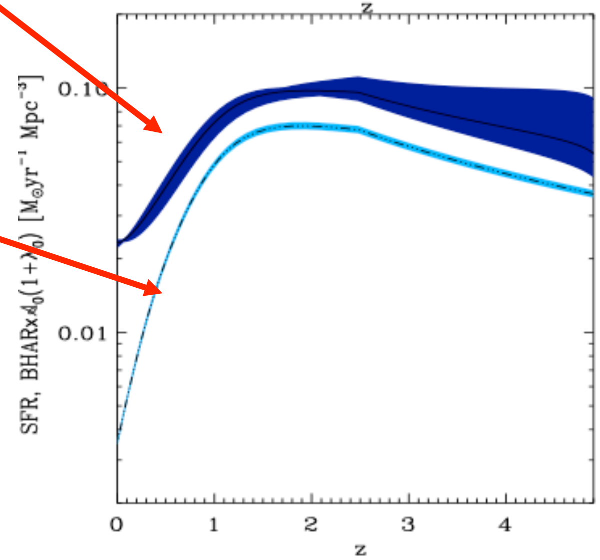
Merloni et al. 2006





Star formation rate evolution

AGN evolution



Franceschini et al. 1999

AGN and star formation in the Universe

- A complex relationship
  - ✓ accreting gas feeding black hole *might* trigger starbursts
  - ✓ black hole feeds energy back through winds and jets:
    - winds *might* accelerate star formation (gas compression)
    - winds *might* blow away all gas (stopping accretion and star formation)
- AGN thought to play major role in galaxy evolution

→ **AGN Feedback** (e.g., Cattaneo et al. 2009)

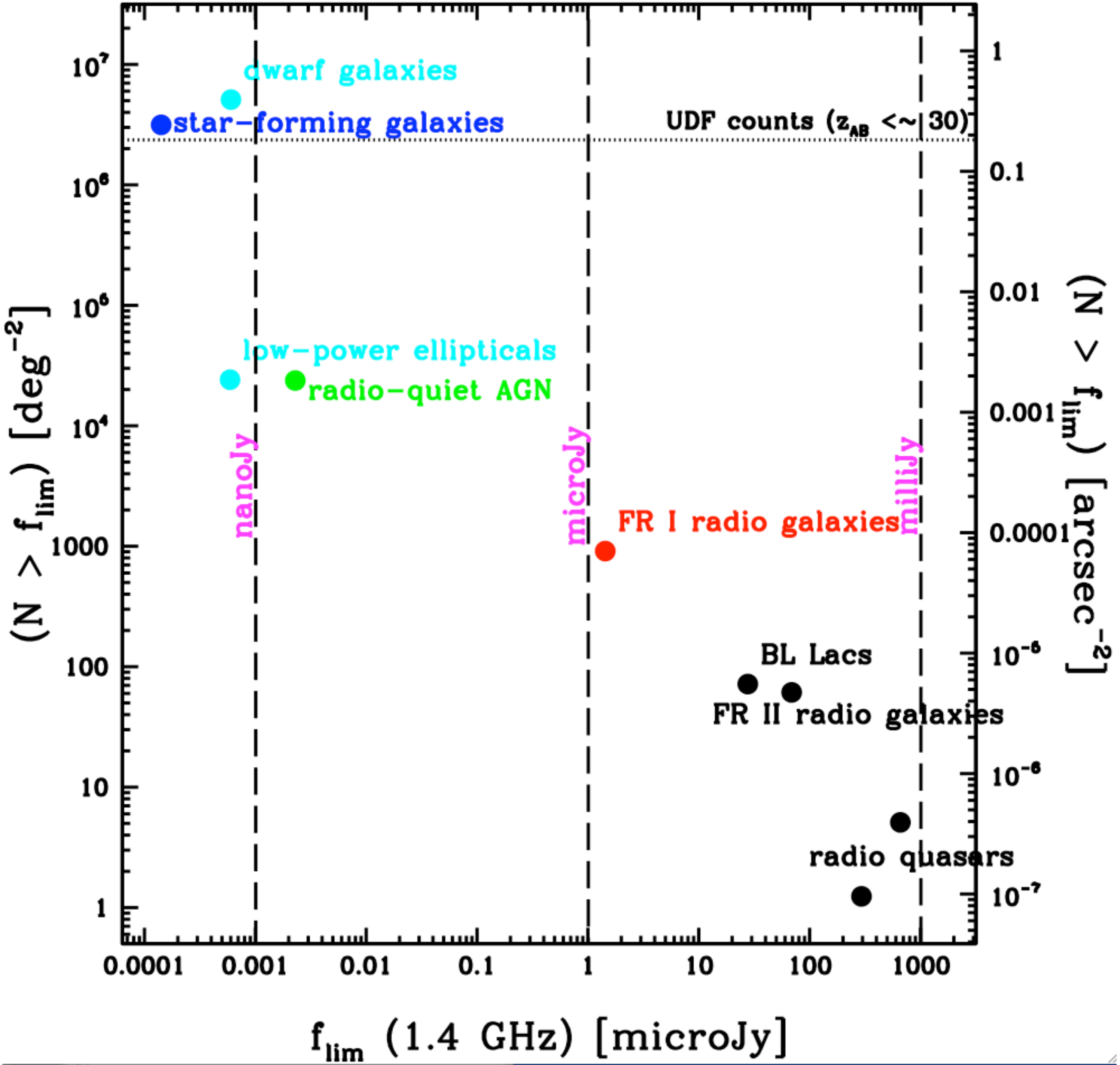
- Radio emission ("radio-mode" feedback) has important role in galaxy evolution (Croton et al. 2006)

Radio observations unaffected by absorption → vital contribution to our understanding of this co-evolution; need to go faint

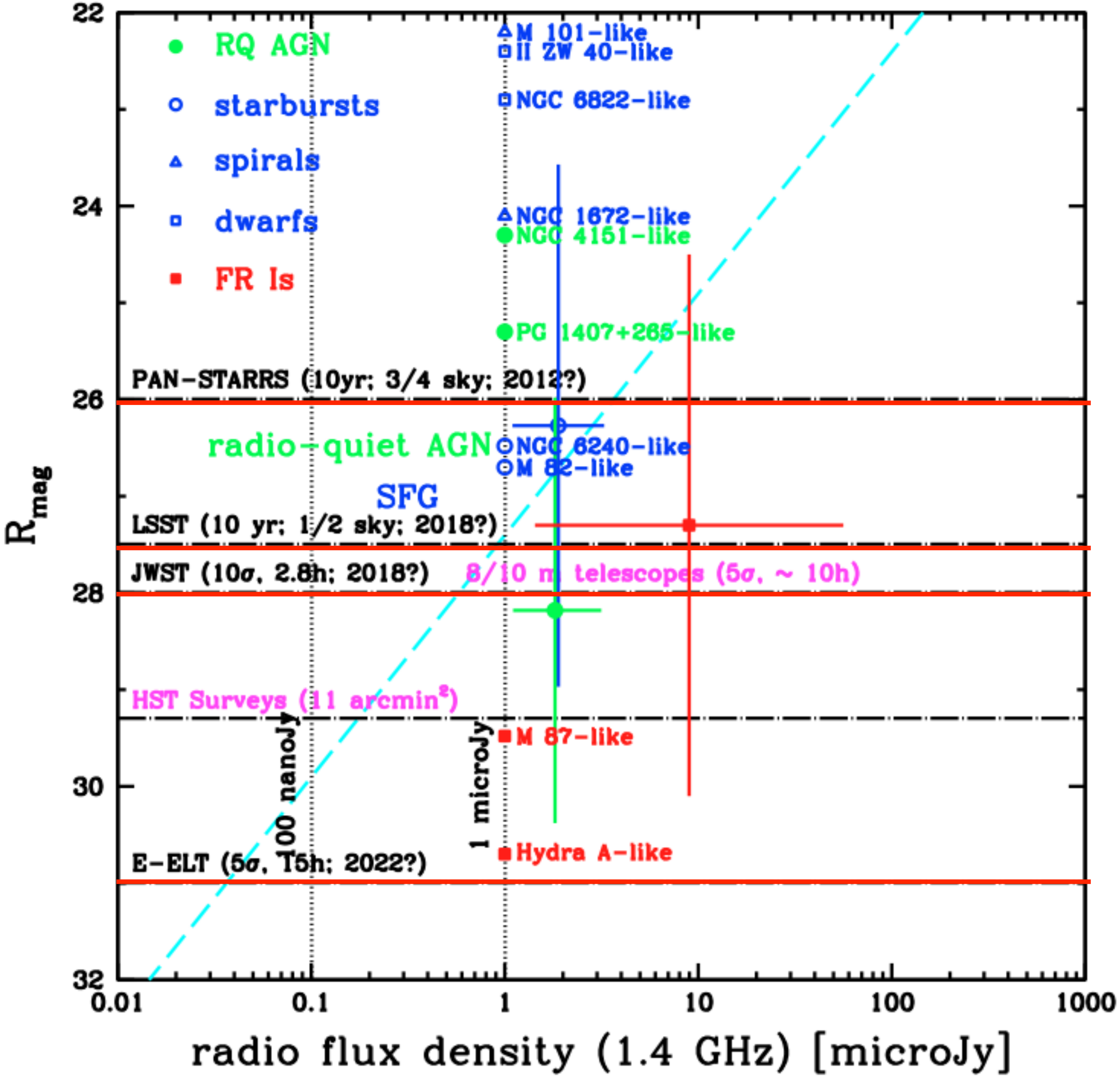
SKA and its pathfinders: further selected impact on extragalactic astronomy

- Radio-loudness and radio-quietness in AGN
- Evolution of intrinsically faint, more numerous, radio sources
- Abundance and evolution of dwarf galaxies

Very faint radio populations

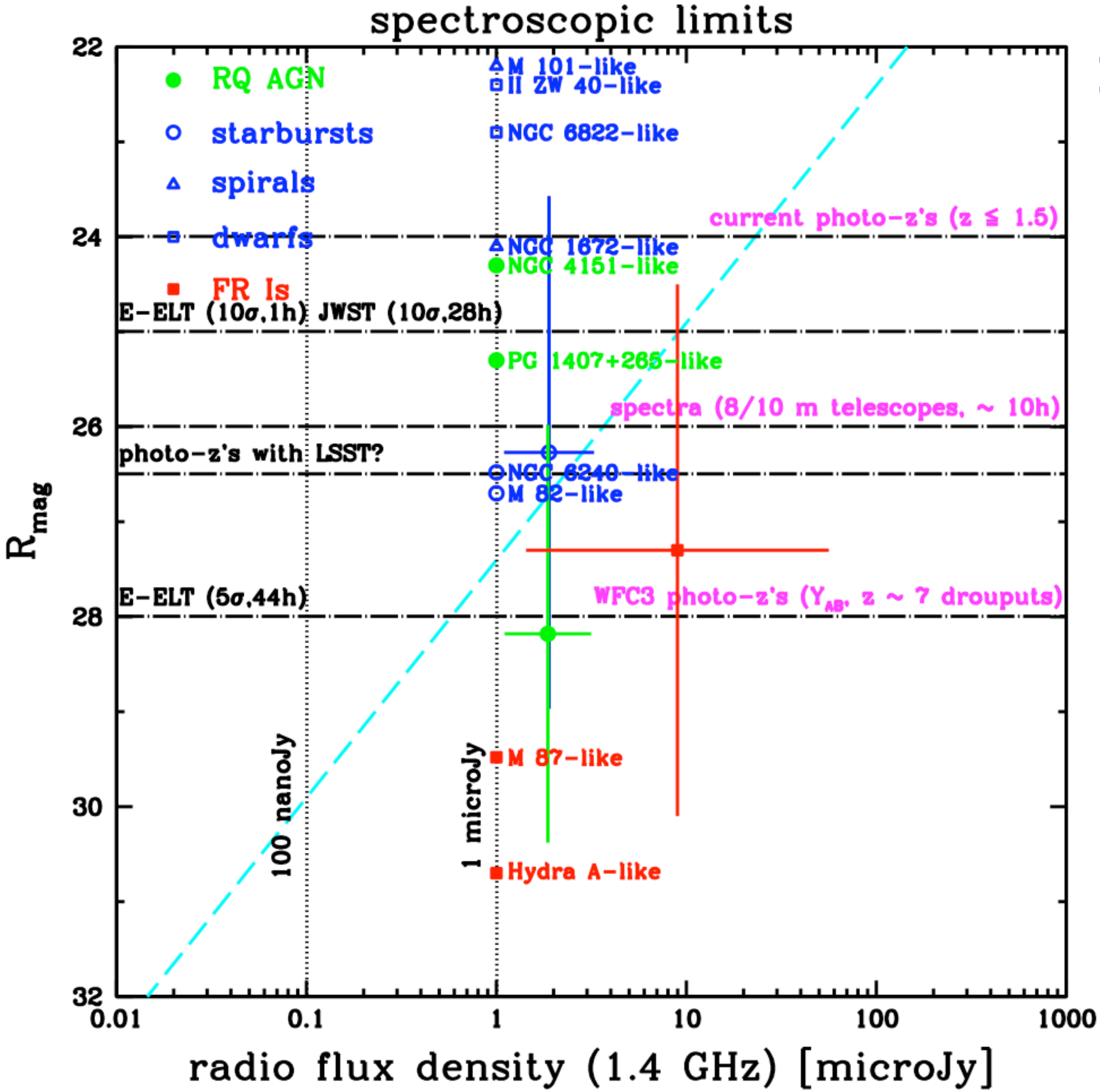

dwarf galaxies
star-forming galaxies
UDF counts (z_{AB} <~ 30)
low-power ellipticals
radio-quiet AGN
nanoJy
microJy
milliJy
FR I radio galaxies
BL Lacs
FR II radio galaxies
radio quasars
$(N > f_{lim})$ [deg^{-2}]
$(N > f_{lim})$ [$arcsec^{-2}$]
f_{lim} (1.4 GHz) [microJy]
0.0001
0.001
0.01
0.1
1
10
100
1000
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}

The multiwavelength properties of micro-Jy and nano-Jy sources: optical band


RQ AGN
starbursts
spirals
dwarfs
FR Is
M 101-like
II ZW 40-like
NGC 6822-like
NGC 1672-like
NGC 4151-like
PG 1407+265-like
PAN-STARRS (10yr; 3/4 sky; 2012?)
radio-quiet AGN
NGC 6240-like
M 82-like
SFG
LSST (10 yr; 1/2 sky; 2018?)
JWST (10σ, 2.8h; 2018?)
8/10 m telescopes (5σ, ~ 10h)
HST Surveys (11 arcmin²)
M 87-like
100 nanoJy
1 microJy
Hydra A-like
E-ELT (5σ, 15h; 2022?)
R_mag
radio flux density (1.4 GHz) [microJy]
22
24
26
28
30
32
0.01
0.1
1
10
100
1000

The multiwavelength properties of micro-Jy and nano-Jy sources: spectra

T ... of



spectroscopic limits
RQ AGN
starbursts
spirals
dwarfs
FR Is
M 101-like
II ZW 40-like
NGC 6822-like
current photo-z's (z ≤ 1.5)
NGC 1672-like
NGC 4151-like
E-ELT (10σ,1h) JWST (10σ,28h)
PG 1407+265-like
spectra (8/10 m telescopes, ~ 10h)
photo-z's with LSST?
NGC 6240-like
M 82-like
E-ELT (5σ,44h)
WFC3 photo-z's (Y_AB, z ~ 7 drouputs)
100 nanoJy
1 microJy
M 87-like
Hydra A-like
R_mag
22
24
26
28
30
32
0.01
0.1
1
10
100
1000
radio flux density (1.4 GHz) [microJy]

Summary

- The SKA and its pathfinders will detect (mostly) star-forming galaxies, (some) radio-quiet AGN, and (a small fraction of) FR I radio galaxies; *plus* (many) dwarf galaxies and also low-radio power ($P < 10^{21}$ W/Hz) ellipticals.

- *These are for the most part the same galaxies, which are studied by optical and IR surveys → radio astronomy is becoming an increasingly important component of multi-wavelength studies of galaxy evolution*

- These data will address a variety of extragalactic issues, including that of AGN and star formation in the Universe.

Summary

- These sources will be quite faint in the optical band: ≈ 50% of > 1 μJy sources might be detected by the LSST, fainter sources should be detectable only by JWST and especially the ELTs.
- As for spectra, many > 1 μJy sources might be beyond the capabilities of 8/10 m telescopes; some of them will be within reach of the ELTs. At nano-Jy levels ELTs only.
- *How will the upcoming SKA and its pathfinders profit from follow-up by the ELTs?* Substantially!

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The microjansky and nanojansky radio sky: source population and multiwavelength properties

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ABSTRACT

I present simple but robust estimates of the types of sources making up the faint, sub-microjansky radio sky. These include, not surprisingly, star-forming galaxies and radio-quiet active galactic nuclei but also two 'new' populations, i.e. low radio power ellipticals and dwarf galaxies, the latter likely constituting the most numerous component of the radio sky. I then estimate for the first time the X-ray, optical and mid-infrared fluxes these objects are likely to have, which are very important for source identification and the synergy between the upcoming Square Kilometre Array (SKA) and its various pathfinders with future missions in other bands. On large areas of the sky the SKA, and any other radio telescope producing surveys down to at least the microjansky level, will go deeper than all currently planned (and past) sky surveys, with the possible exception of the optical ones from the Panoramic Survey Telescope and Rapid Response System and the Large Synoptic Survey Telescope. The *Space Infrared Telescope for Cosmology and Astrophysics*, the *James Webb Space Telescope* (*JWST*) and in particular the Extremely Large Telescopes (ELTs) will be a match to the next generation radio telescopes but only on small areas and above $\sim$0.1 − 1 μJy (at 1.4 GHz), while even the *International X-ray Observatory* will only be able to detect a small (tiny) fraction of the microjansky (nanojansky) population. On the other hand, most sources from currently planned all-sky surveys, with the likely exception of the optical ones, will have a radio counterpart within the reach of the SKA. *JWST* and the ELTs might turn out to be the main, or perhaps even the only, facilities capable of securing optical counterparts and especially redshifts of microjansky radio sources. Because of their sensitivity, the SKA and its pathfinders will have a huge impact on a number of topics in extragalactic astronomy including star formation in galaxies and its co-evolution with supermassive black holes, radio loudness and radio quietness in active galactic nuclei, dwarf galaxies and the main contributors to the radio background.

Key words: galaxies: active – galaxies: dwarf – galaxies: star formation – infrared: galaxies – radio continuum: general – X-rays: galaxies.

1 INTRODUCTION

The radio bright ($\gtrsim$1 mJy) sky consists for the most part of active galactic nuclei (AGN) whose radio emission is generated from the gravitational potential associated with a supermassive black hole and includes the classical extended jet and double lobe radio sources as well as compact radio components more directly associated with the energy generation and collimation near the central engine. Below 1 mJy there is an increasing contribution to the radio source population from synchrotron emission resulting from relativistic plasma ejected from supernovae associated with massive star formation in galaxies. After years of intense debate, however, this contribution appears not to be overwhelming, at least down to $\sim$50 μJy. Deep ($S_{1.4\,\mathrm{GHz}} \geq 42$ μJy) radio observations of the Very Large Array (VLA)-*Chandra Deep Field* South (CDFS), complemented by a variety of data at other frequencies, imply a roughly 50/50 split between star-forming galaxies (SFG) and AGN (Padovani et al. 2009), in broad agreement with other recent results (e.g. Seymour et al. 2008; Smolčić et al. 2008). About half of the AGN are radio-quiet, i.e. of the type normally found in optically selected samples and characterized by relatively low radio-to-optical flux density ratios and radio powers (Padovani et al. 2009). These objects represent an almost negligible minority above 1 mJy.

This source population issue is strongly related to the very broad and complex relationship between star formation and AGN in the Universe. At the cosmological level, the growth of supermassive black holes in AGN appears to be correlated with the growth of

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