Galaxy Evolution probed by Radio Continuum emission

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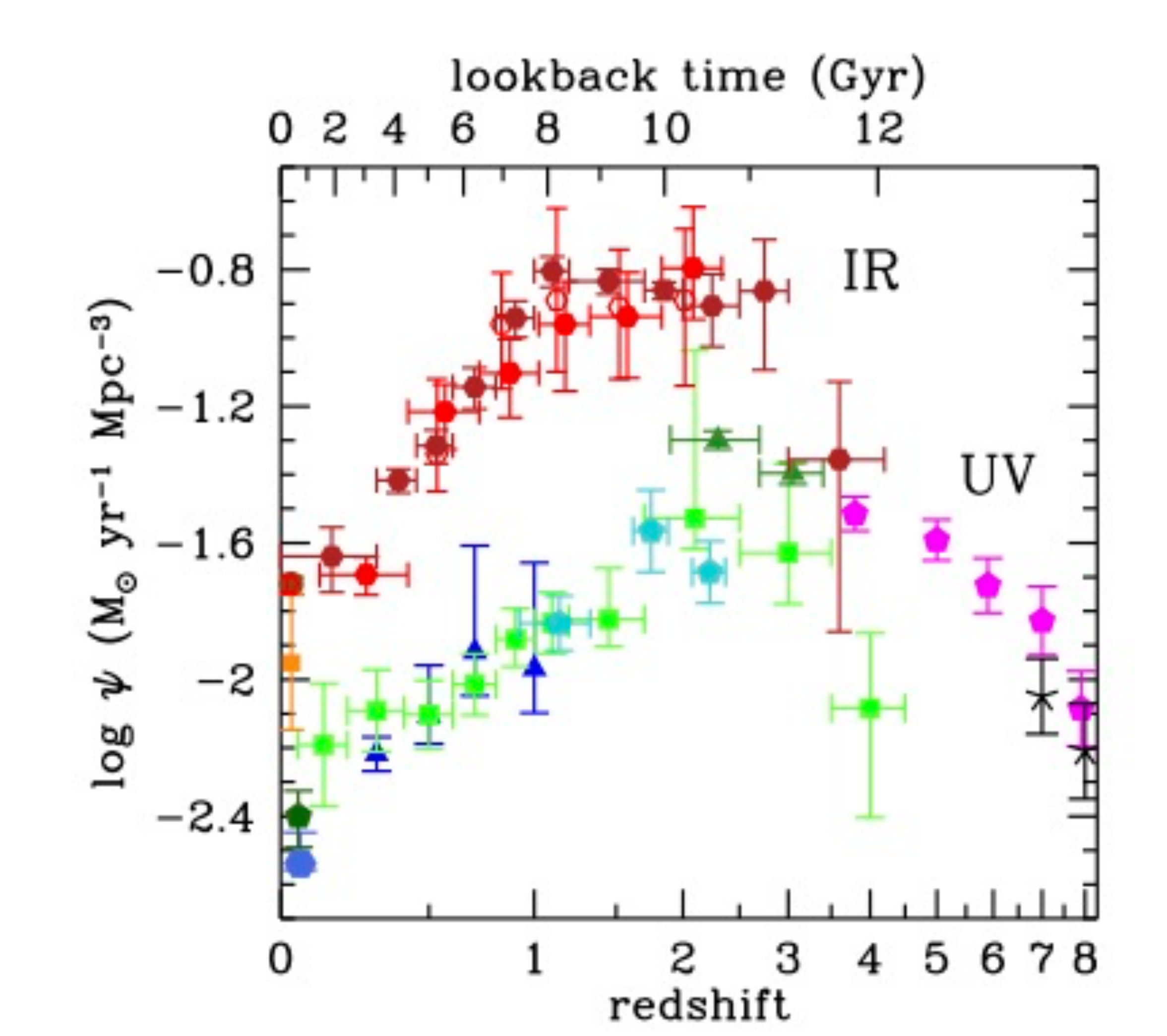
SKA AFRICA
SQUARE KILOMETRE ARRAY

Cosmic SFD History



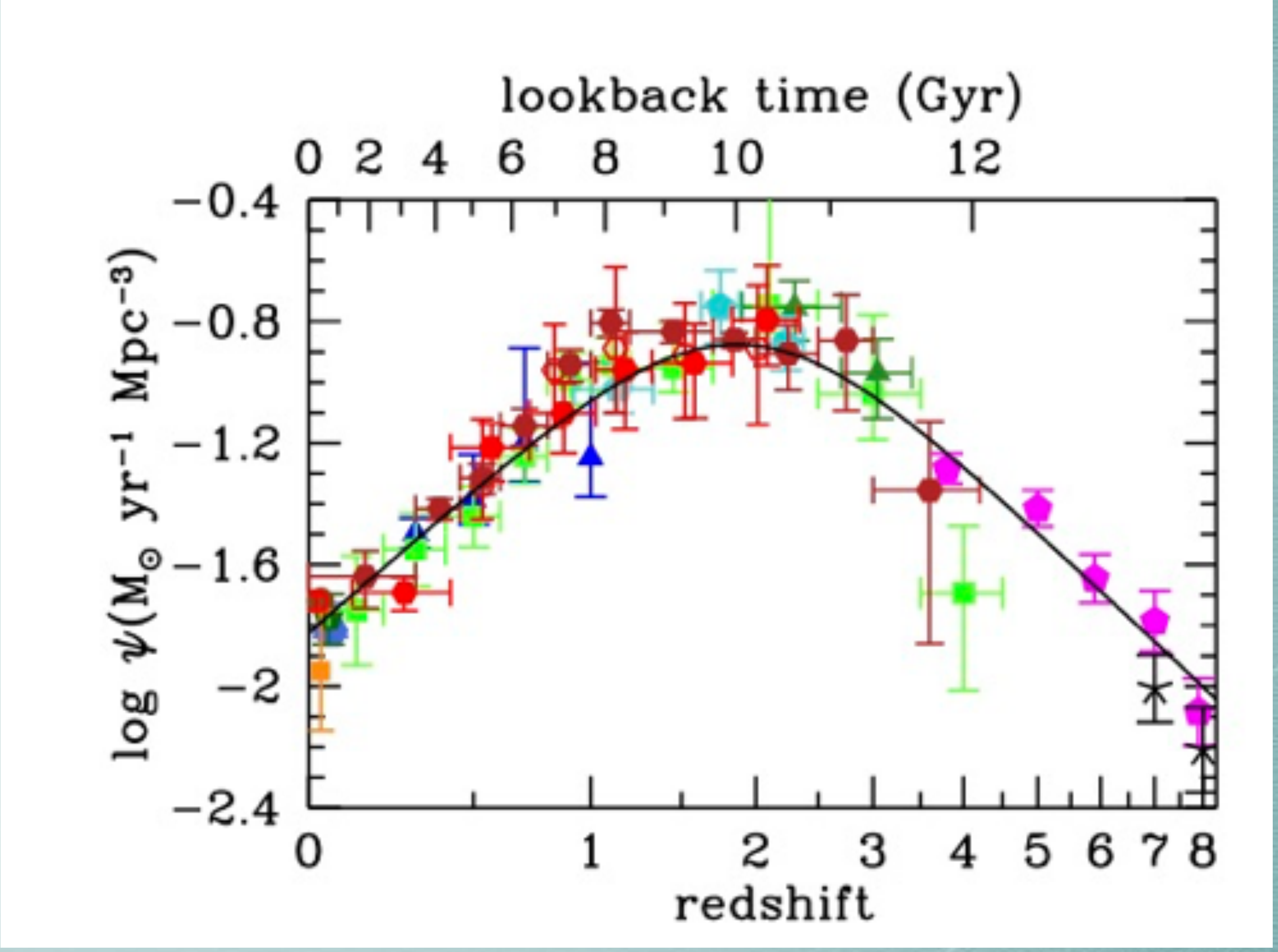


Fig. from Madua & Dickenson 2014

SFRD uncertain due to dust corrections at z>2

Peak epoch of SFR not well constrained

SFR via the FIRC

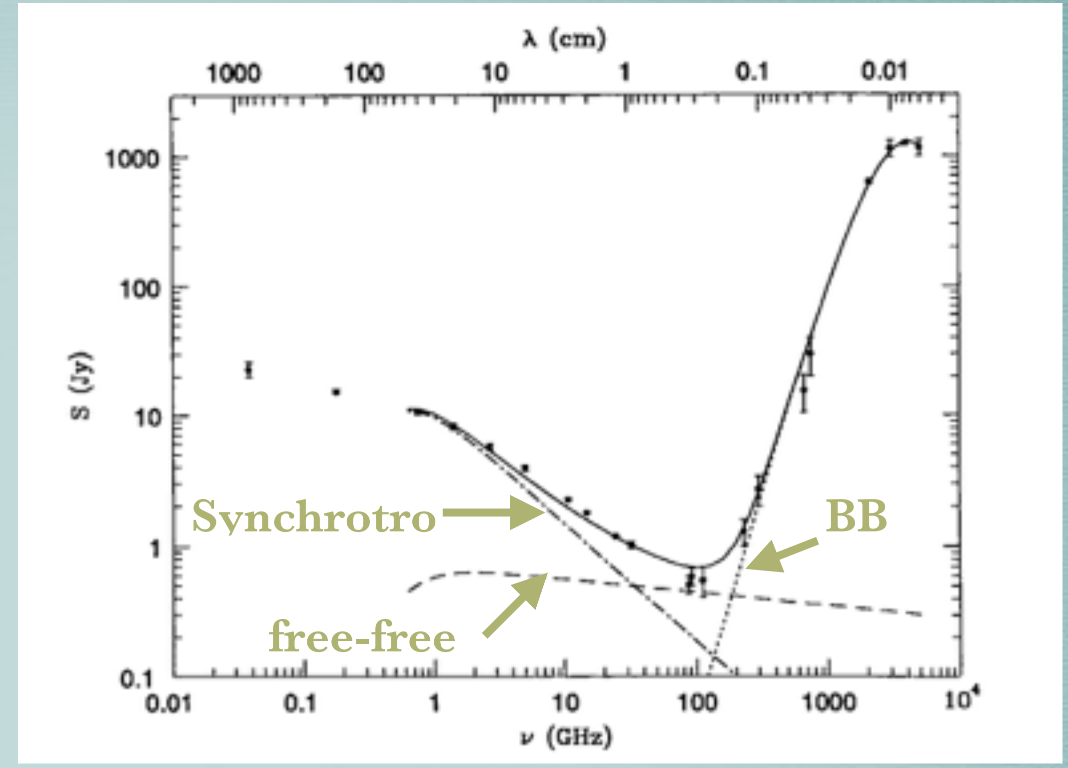
FIR is generated by dust reprocessing of UV light from young stars

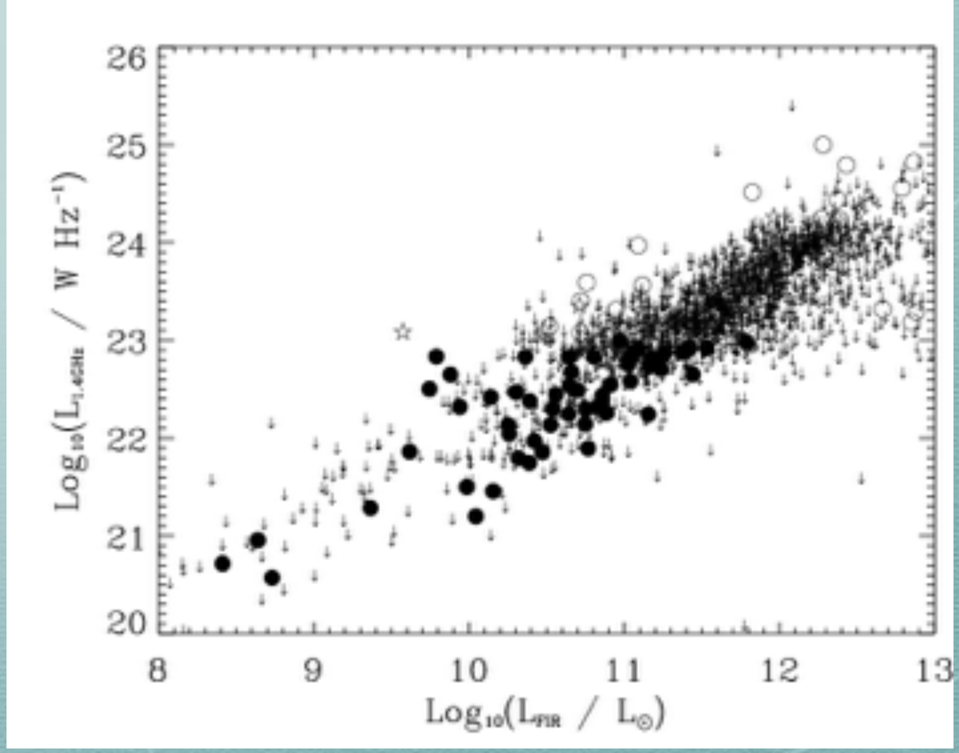
Radio is synchrotron emission from SNe remnants

Holds over ~4 orders of magnitude

Irrespective of galaxy type
(eg Garrett et al 2002, Beswick et al 2008)

Holds out to z~1, and possibly z~2. (eg Mao et al 2011, Thomson et al 2014)





Radio : Dust-free SFR

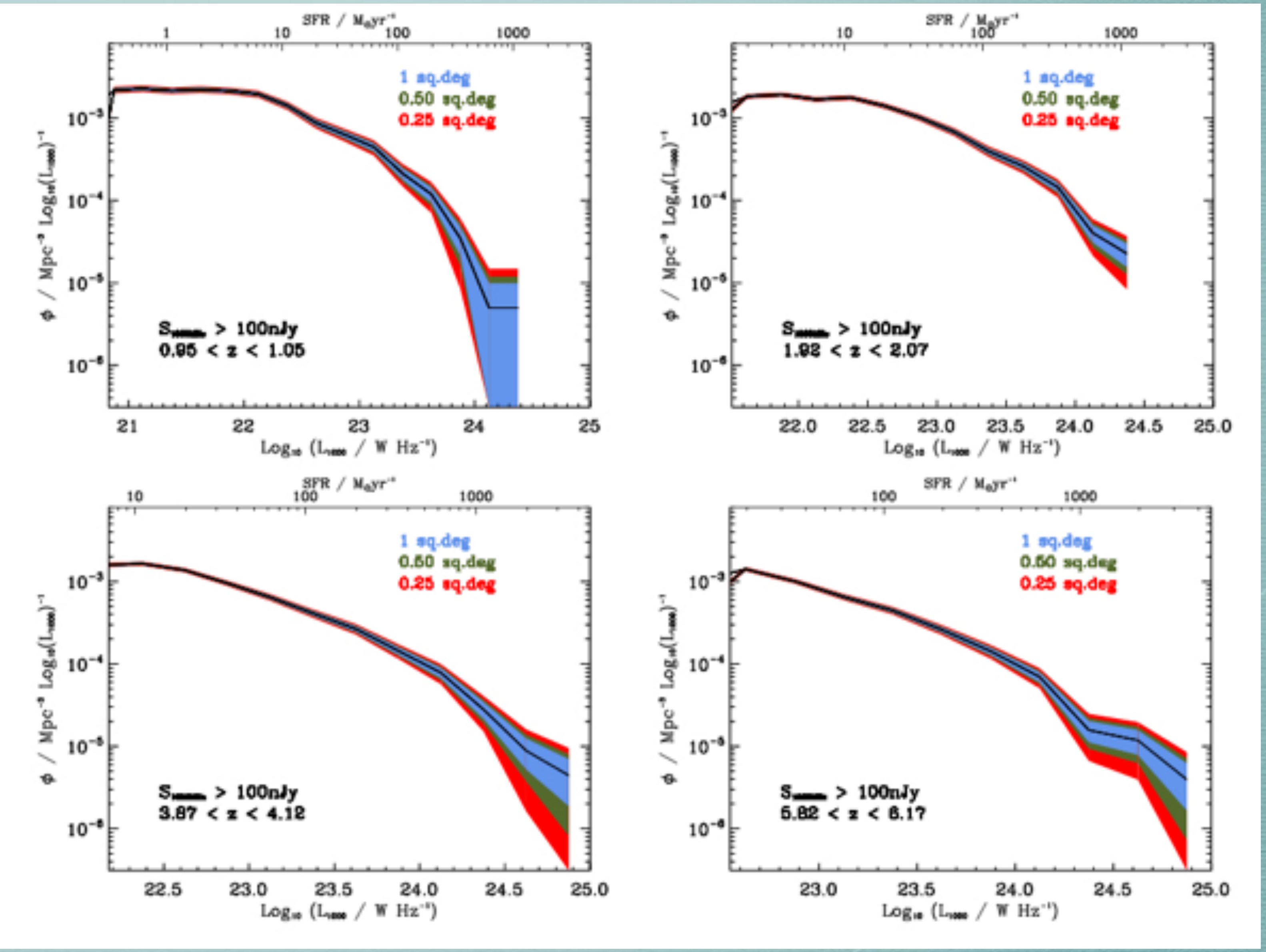
Mapping SFH of universe is a major goal of SKA and pathfinders

Radio is sensitive to <u>total</u> star formation

- obscured + unobscured

Radio has improved resolution, compared to FIR

Avoids being confusion noise limited.



The RLF of Star forming galaxies as probed by the SKA1 ultra deep tier.
Figure from Jarvis et al. 2014

The Evolution of the MS

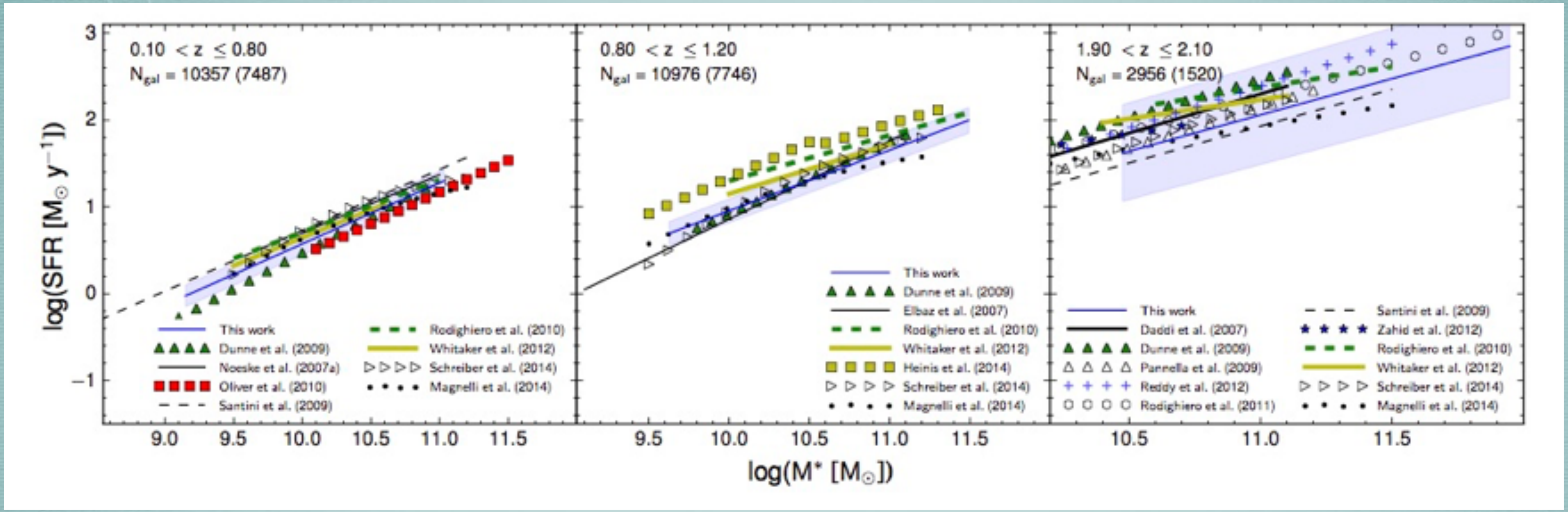


Fig. from Johnston et al. 2015

How does the MS evolve beyond z>2

Is there a turnover ?

Combine SKA+ALMA for gas depletion timescales

Downsizing, why do the most massive systems stop forming stars at earlier epochs ?

The Evolution of the MS

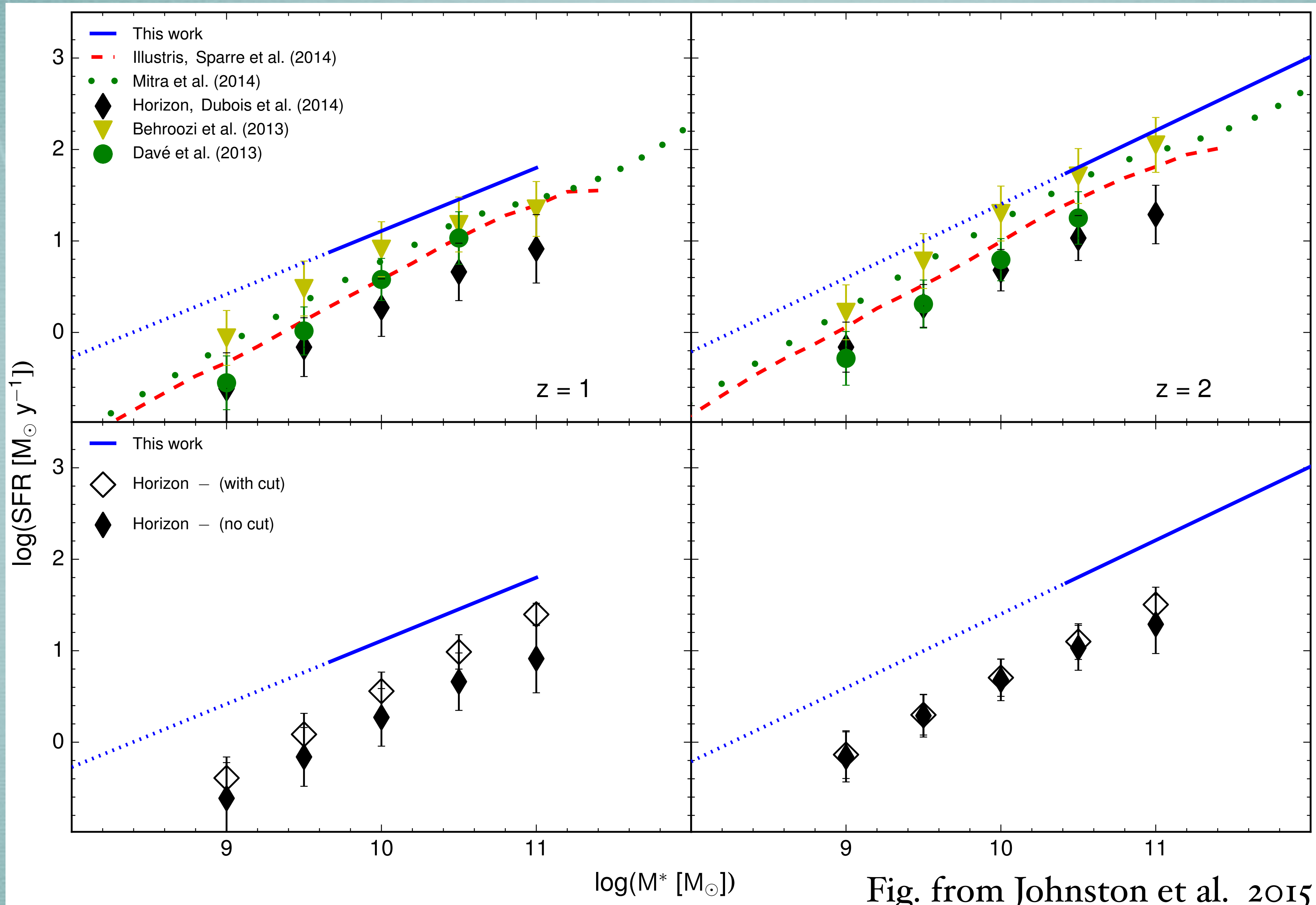


Fig. from Johnston et al. 2015

Simulations fail to reproduce MS evolution

The Evolution of the MS

Difference between Radio flux for galaxies which lie on the galaxy main sequence

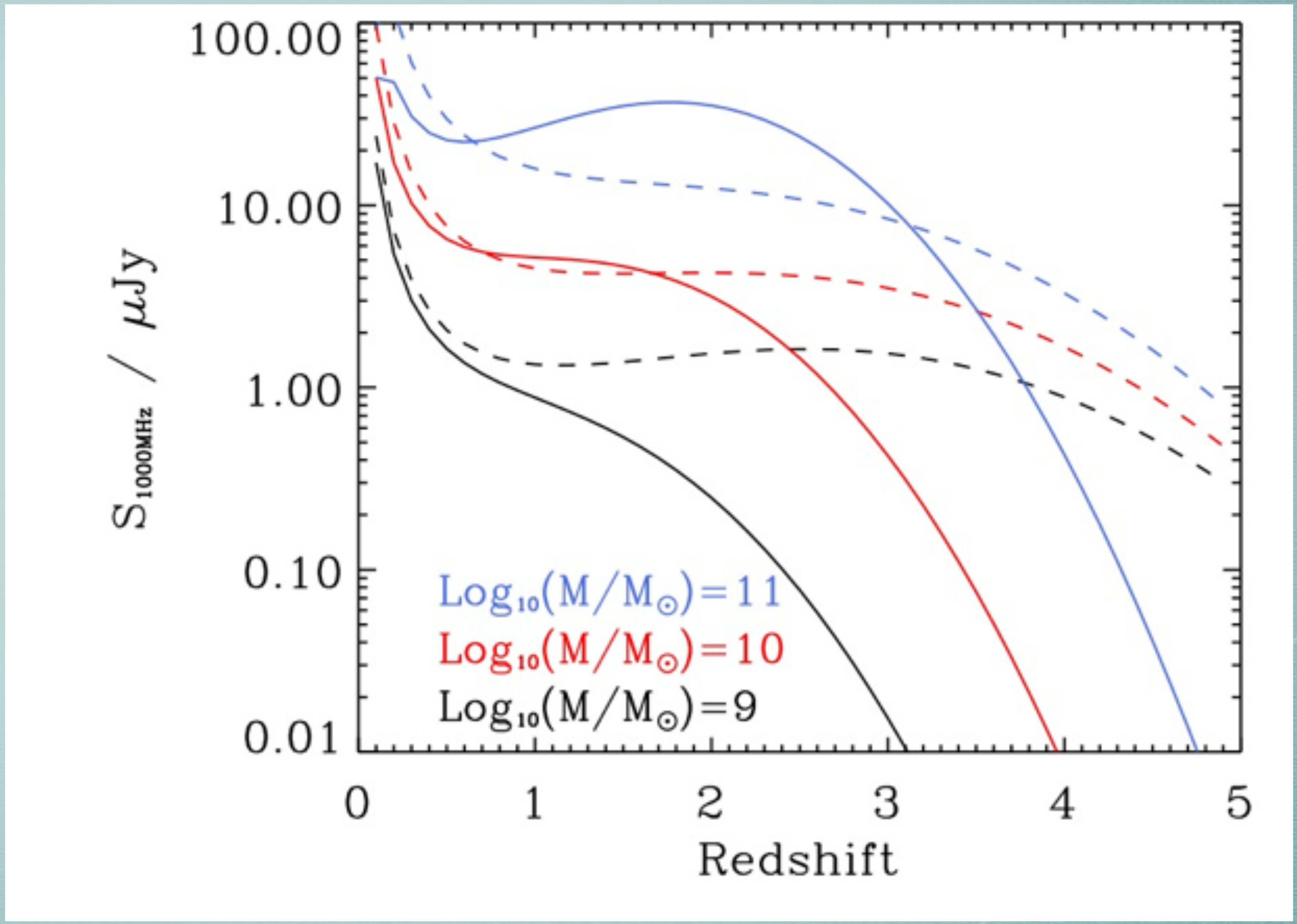


Fig. from Jarvis et al. 2014

Dashed: Whittaker et al 2012
Solid : Johnston et al 2014

The SF/AGN link

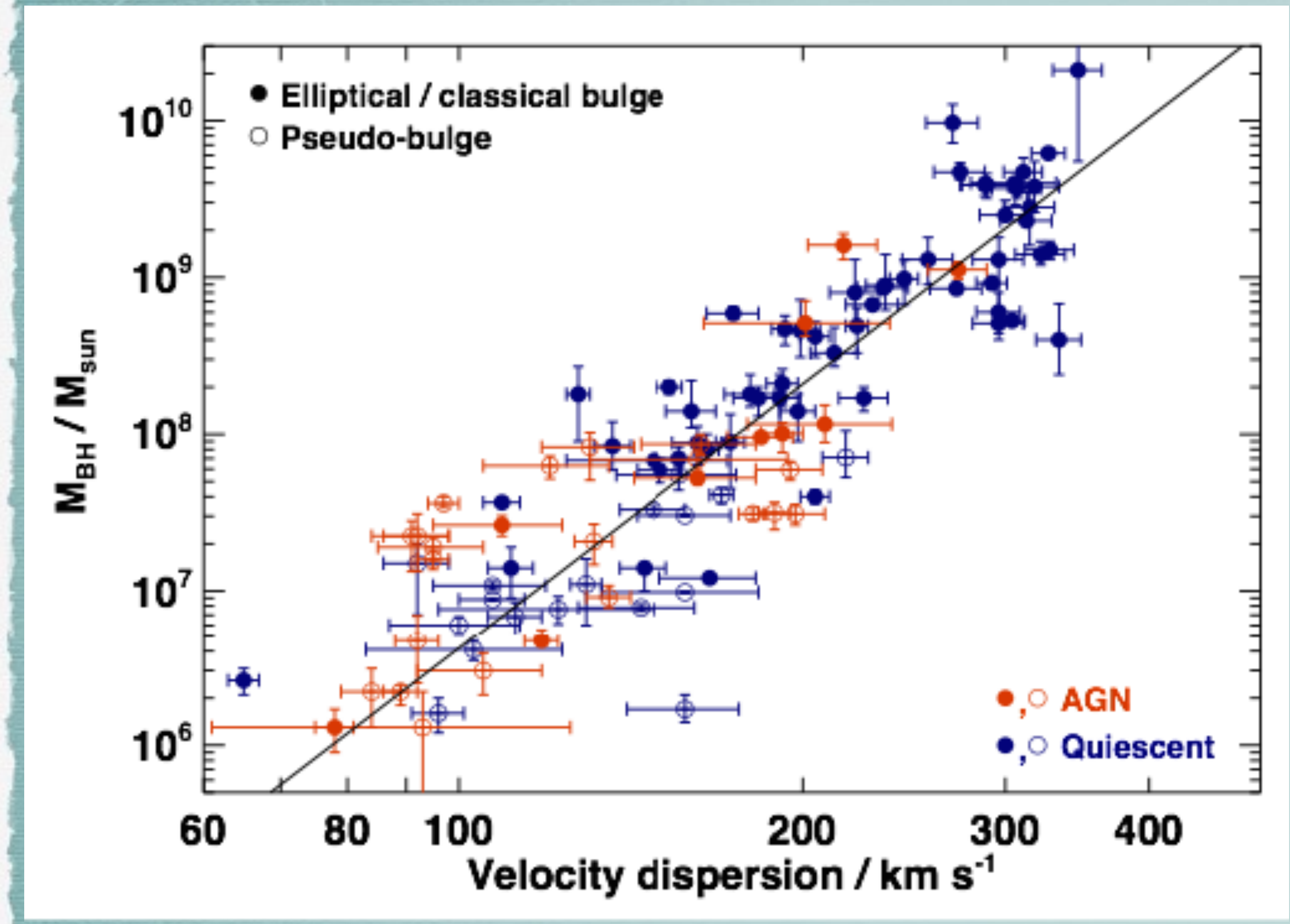


Fig. from Woo et al. 2013

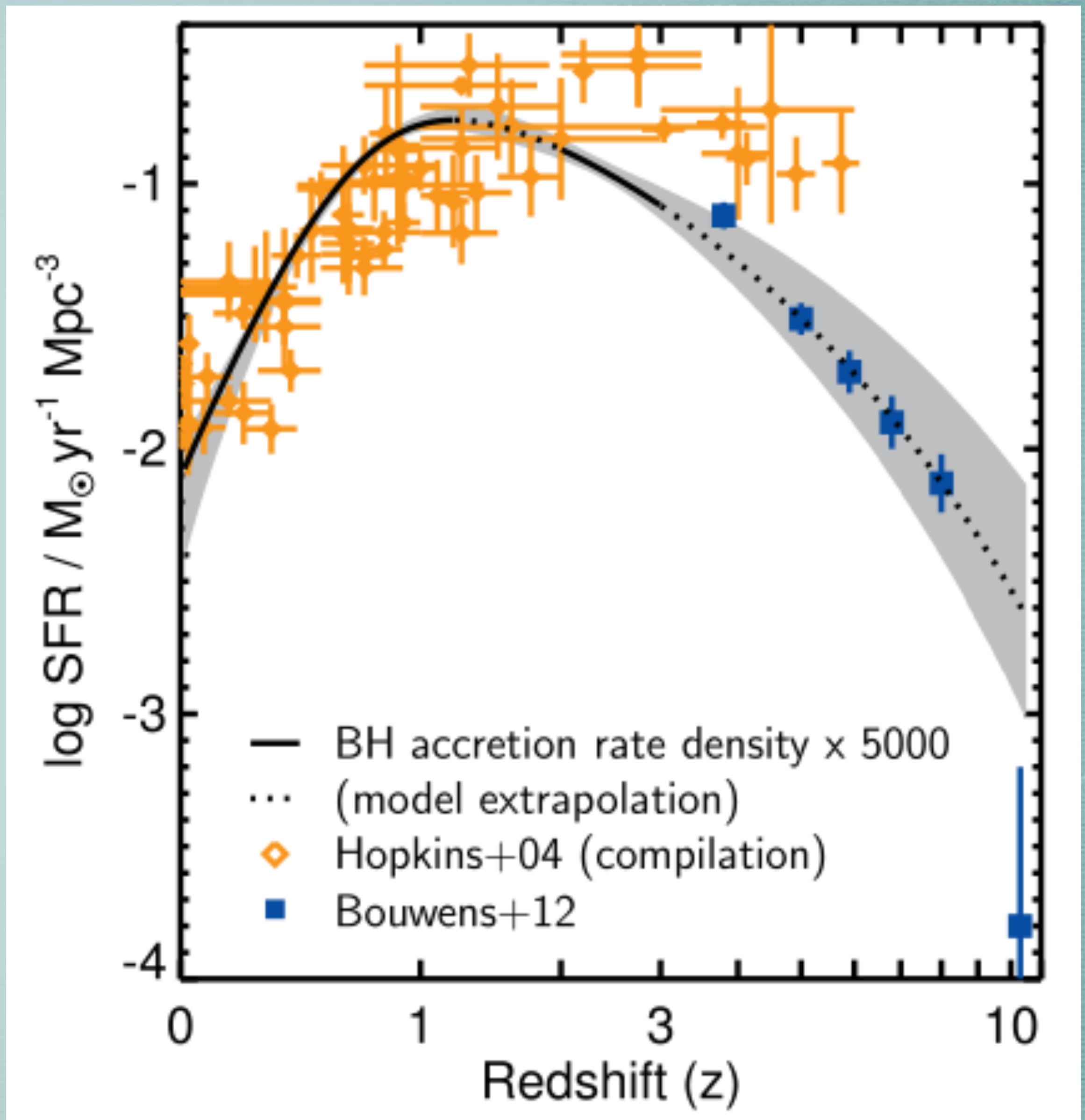


Fig. from Kormendy & Ho 2013

$$M_{\mathrm{bh}} \propto (\sigma_*, M_*)$$

in bulges in local universe

BH $\propto$ SFR across z

Theory suggests AGN ‘feedback’

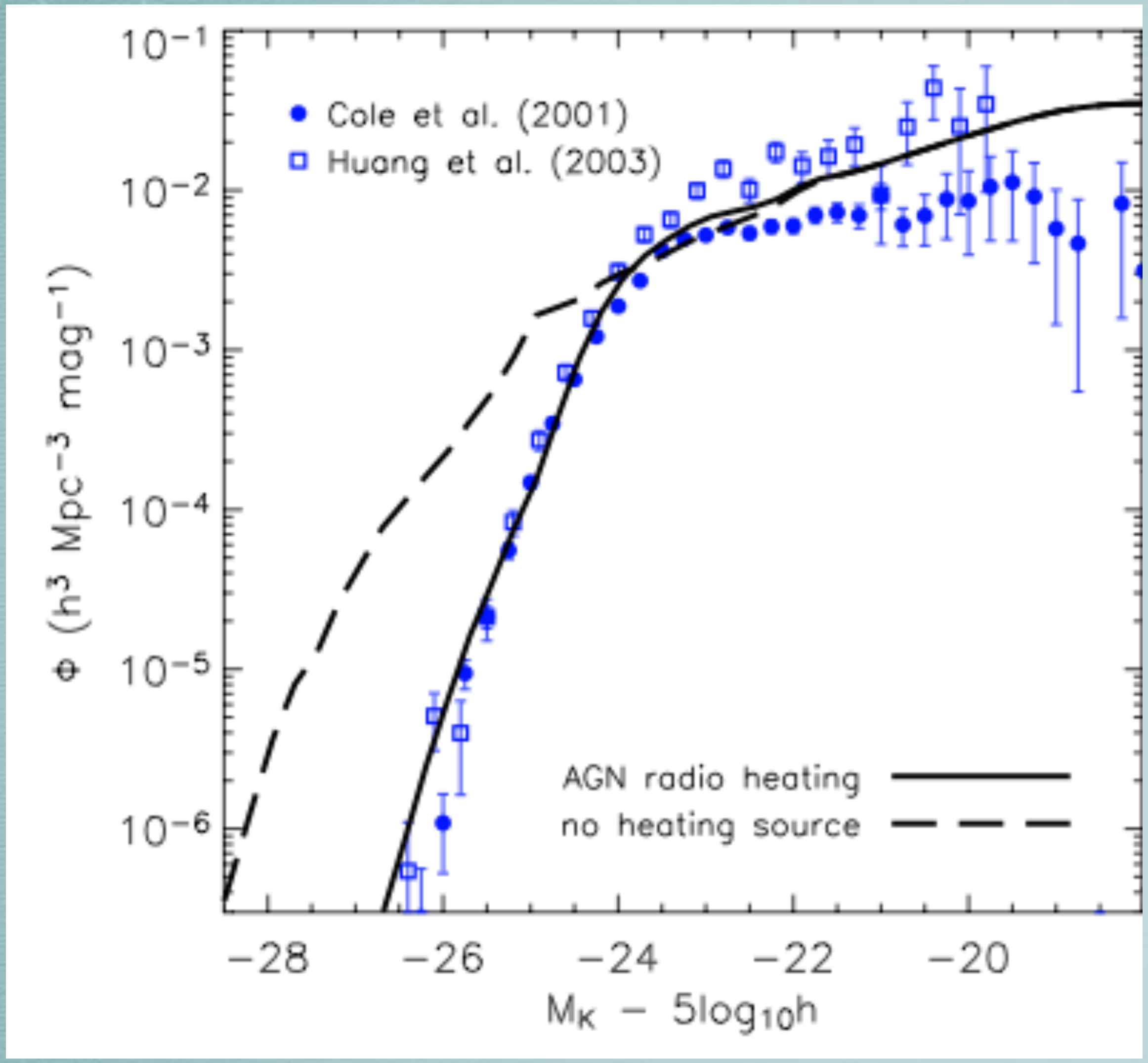


Fig. from Croton et al. 2006

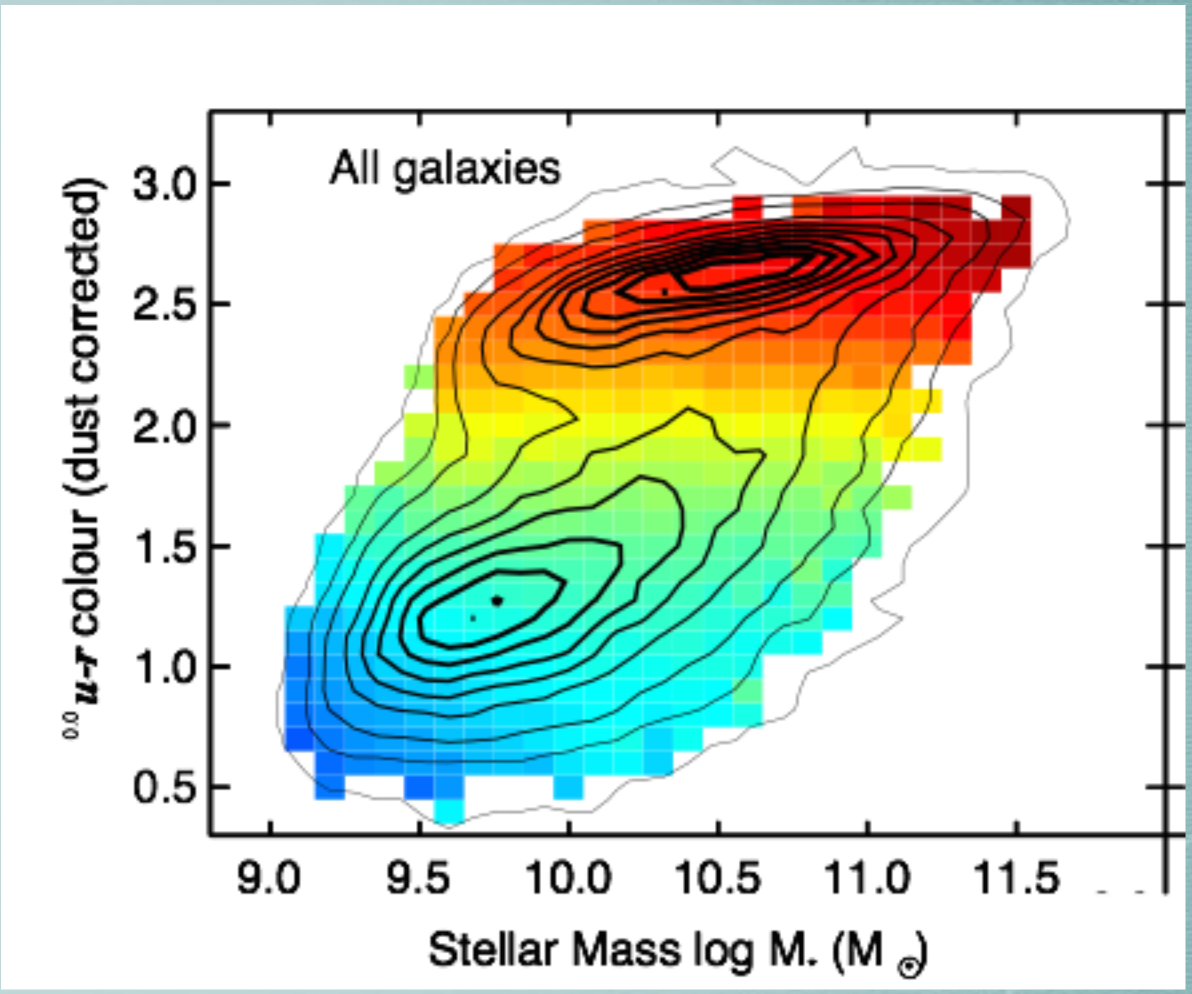


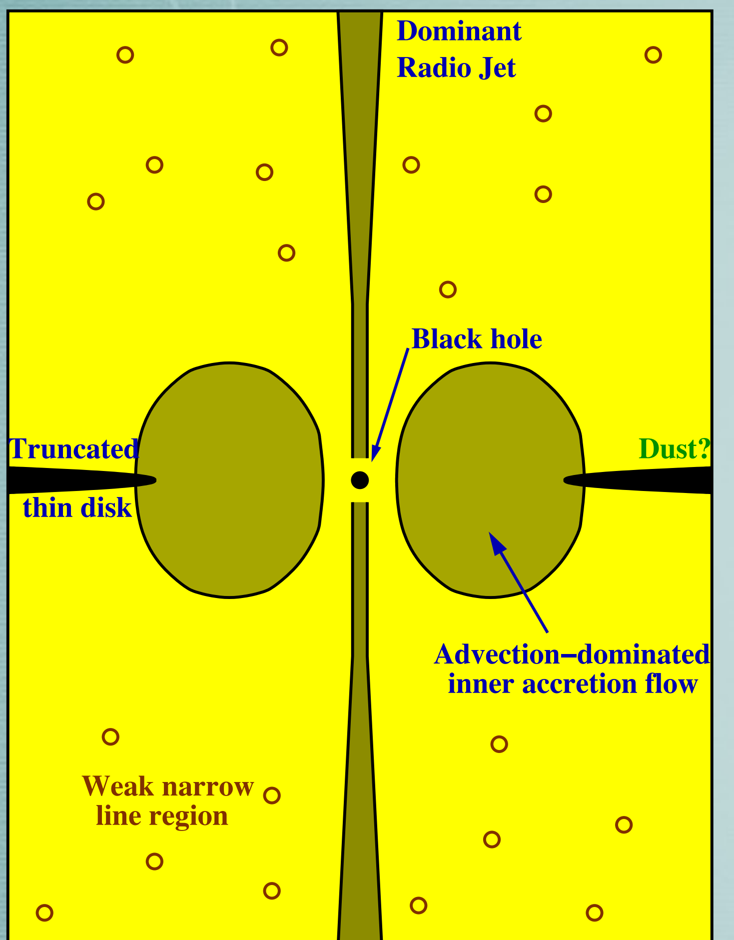
Fig. from Schawinski et al. 2014

Exponential cut-off at bright end of LF

Most Massive Galaxies are ‘red and dead’ ellipticals

Two Modes of AGN accretion

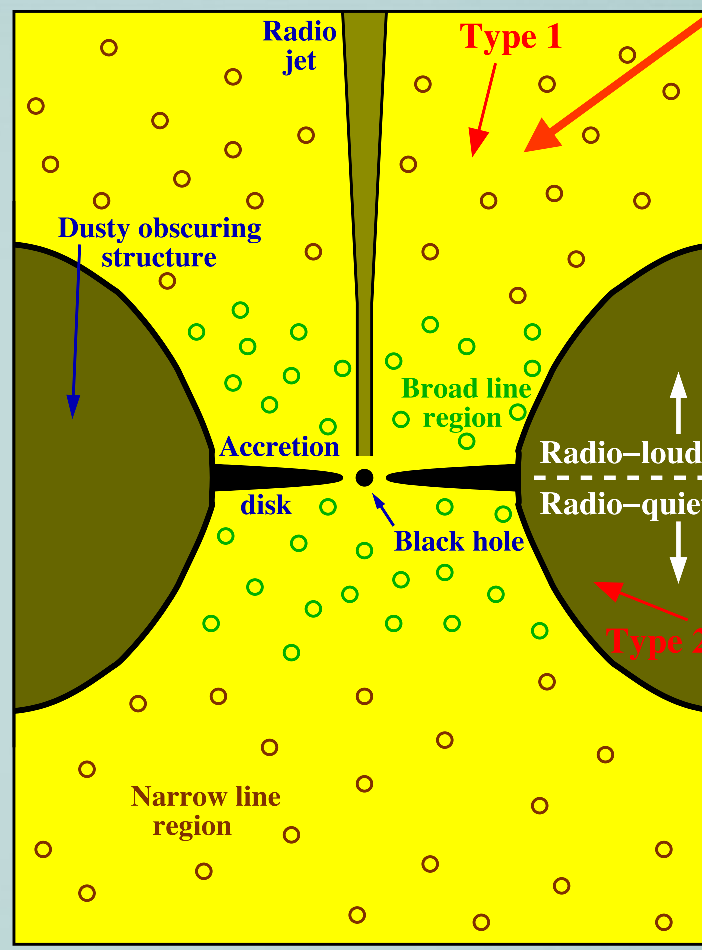
Hot mode

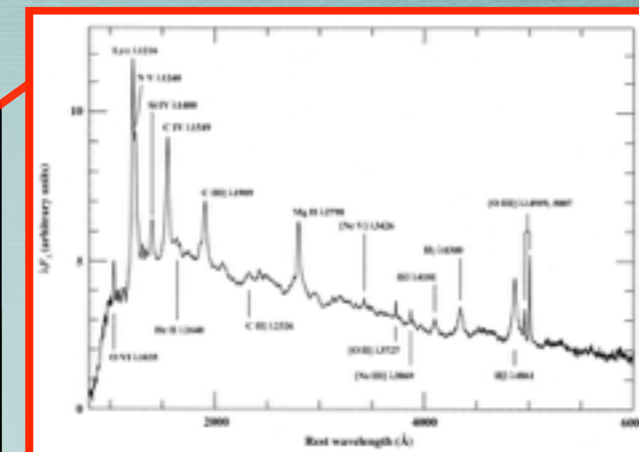


$L/L_{Edd} \leq 0.01$

Low Excitation Radio Galaxy

Cold mode





$L/L_{Edd} \geq 0.01$

High Excitation Radio Galaxy

QSO & Seyferts : Type 1 & 2

Radiative vs Jet Feedback

AGN driven winds

- thermal heating of gas
- radiation pressure on dust

Observed Outflows

- > 1000 km/s , >100 $M_{\odot}\text{year}^{-1}$
- prevalence, longevity ? $> 10^{45}$ erg/s

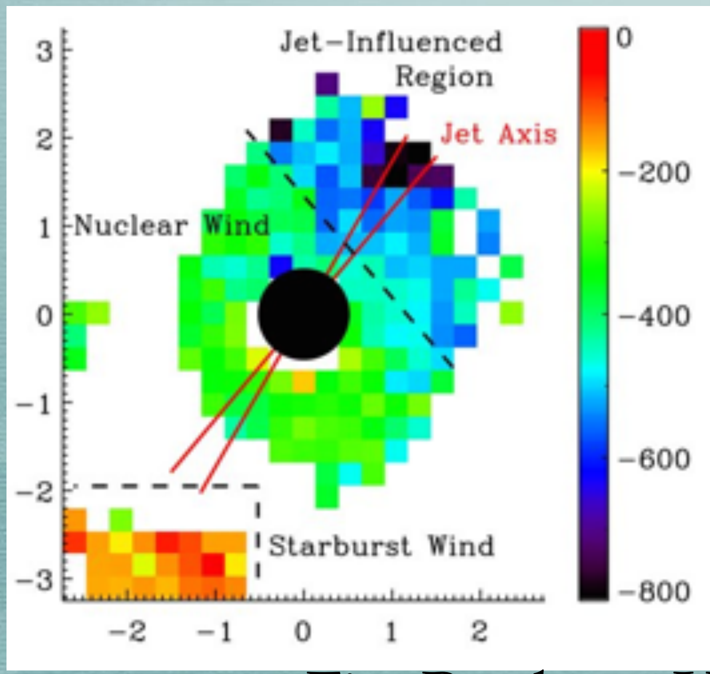
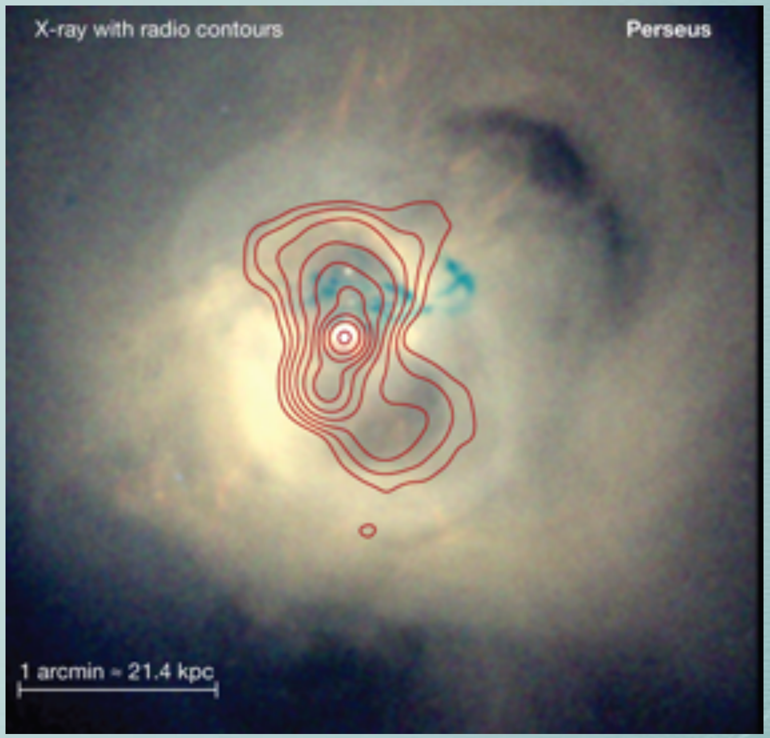


Fig. Rupke & Veilleux 2011 (MRK 231)

Jets inflate bubbles in IGM/ ICM



Fabian et al., 2006

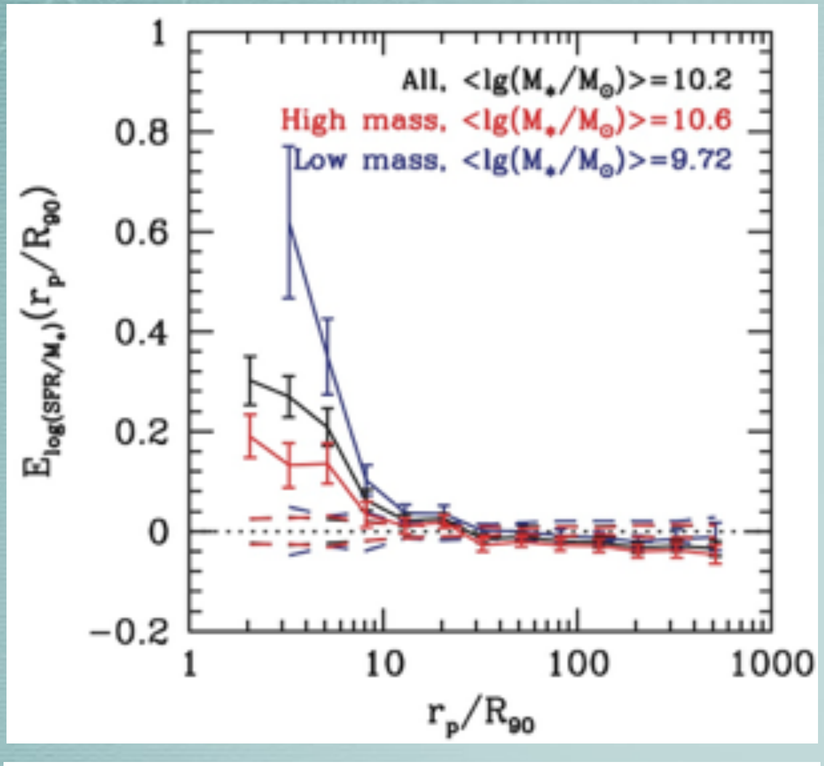
The significance of mergers ?

Mergers →

- Enhanced SF
- no-enhancement for typical AGN

AGN growth via secular processes

Mergers NB only at highest Lum



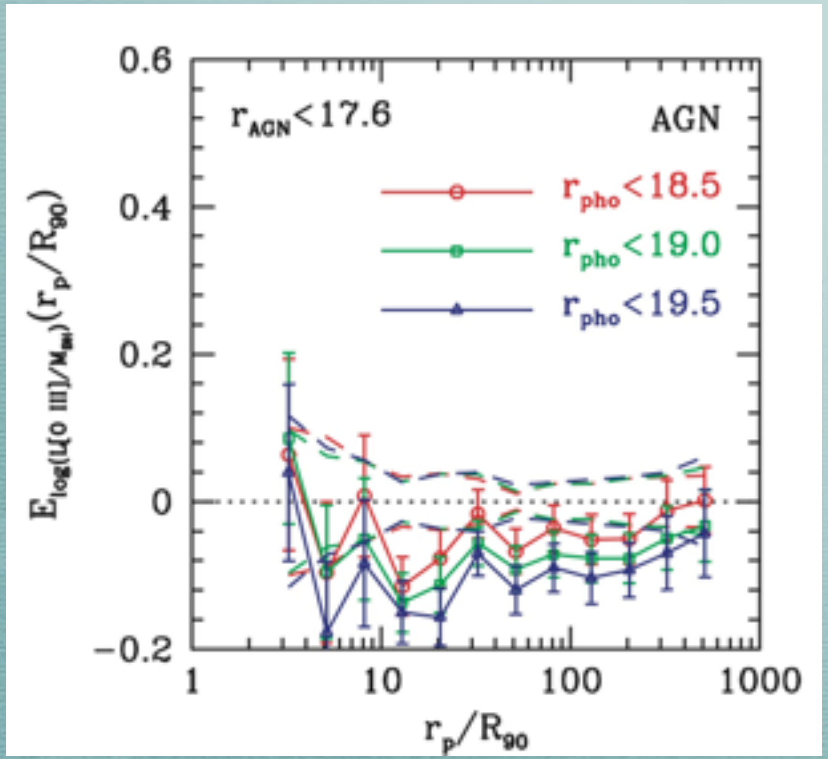


Figure from Li et al., 2008

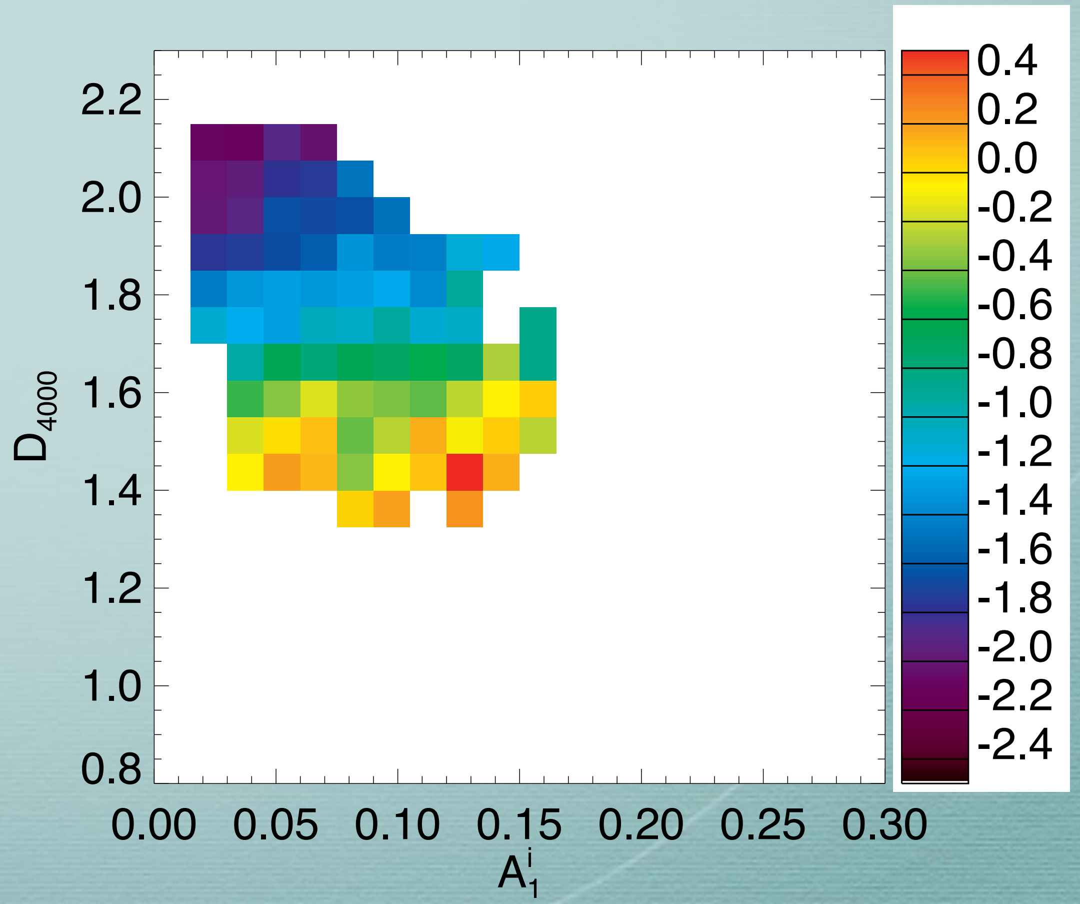


Figure from Reichard et al., 2009

AGN -SF co-evolution

Lower power AGN exists in Disks

AGN and SF fed by secular processes

Image credit:NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana), and STScI, Canada-France-Hawaii Telescope/ J.-C. Cuillandre/Coelum, G. Jacoby, B. Bohannan, M. Hanna/ NOAO/AURA/NSF

mass threshold ?

→ Elliptical Galaxies

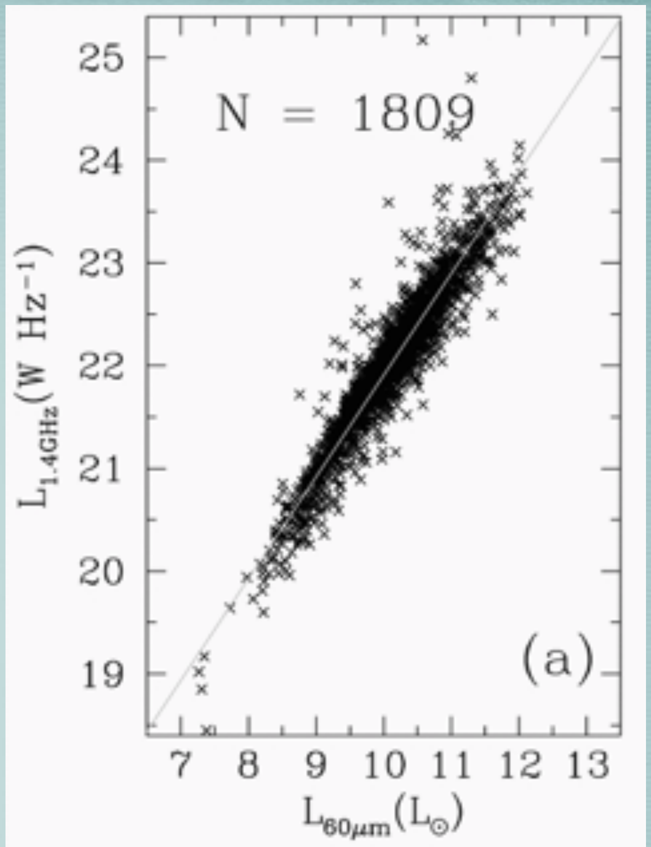
formed in major mergers

Image credit: NASA, ESA, the Hubble Heritage Team (STScI/ AURA)-ESA/Hubble Collaboration K. Noll (STScI)

- SF quenched post merger ?
- Jet mode feedback
- $M_{\rm bh} - M_*$ relation pre-built ?

Radio surveys and the SKA

- Star-formation (FIRC) (60%)
- Hot and Cold mode Radio-Loud AGN (15%)
- Radio-Quiet AGN (25%)



FIRC (Yun et al, 2001)

Advantages of radio λ

- High resolution < $1''$
- Obscuration free,

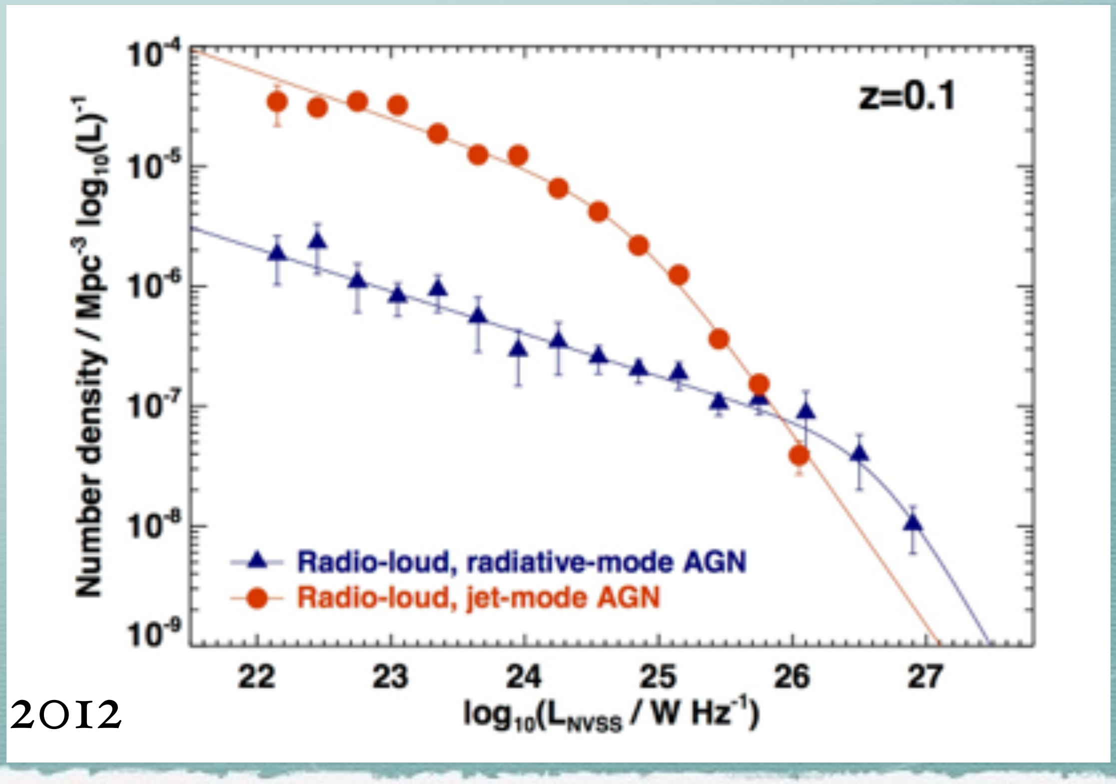
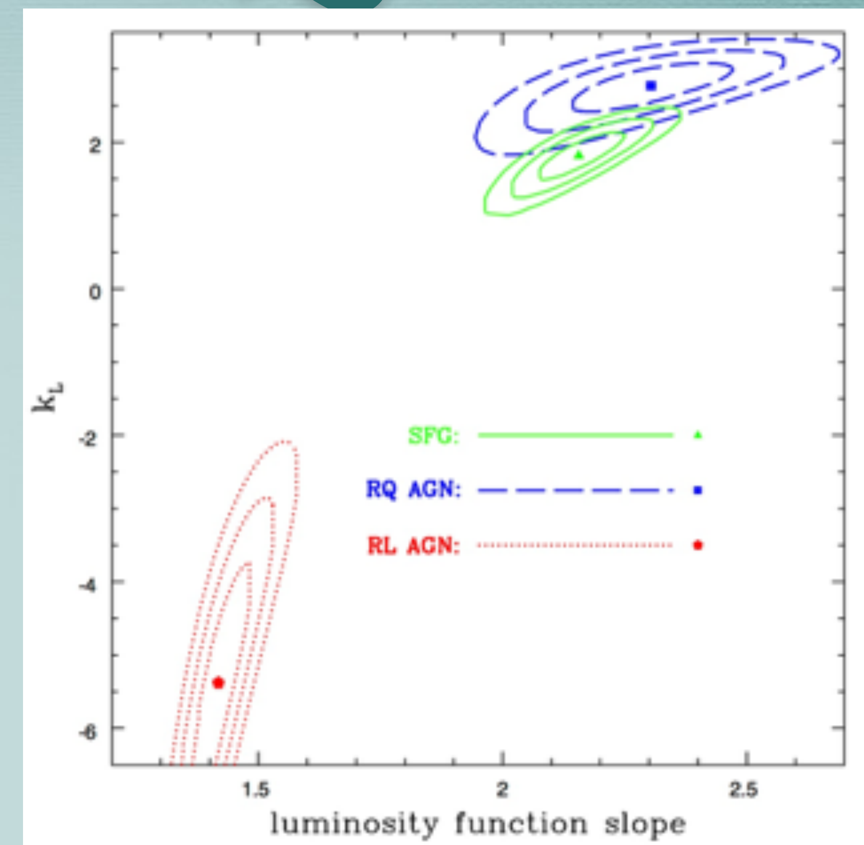


Figure Best and Heckman 2012

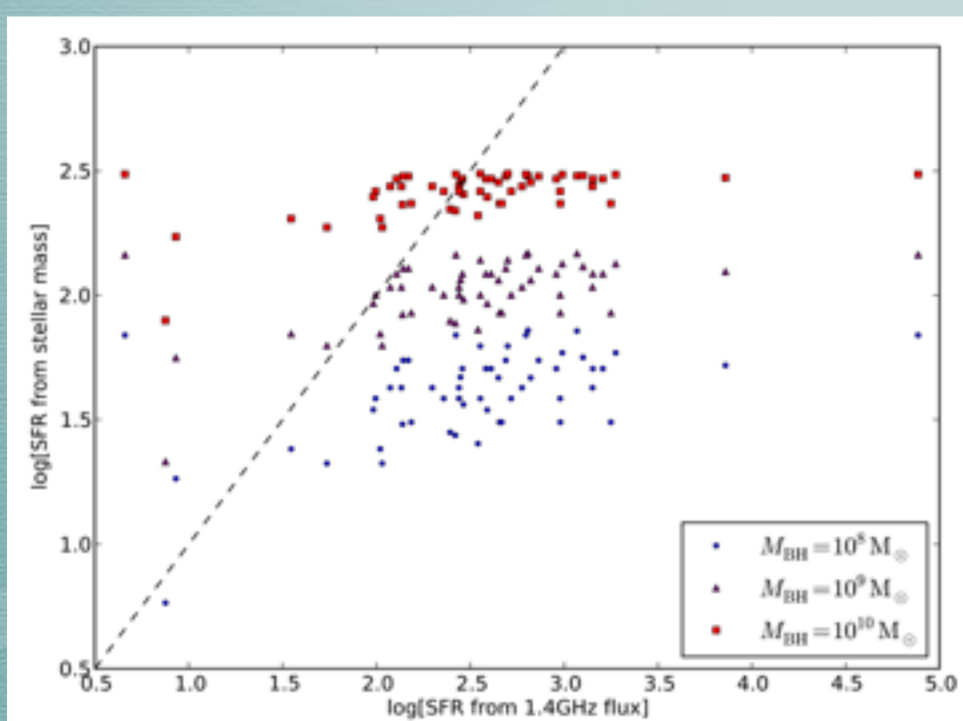
Radio emission in RQ AGN

Radio emission AGN/SF ?

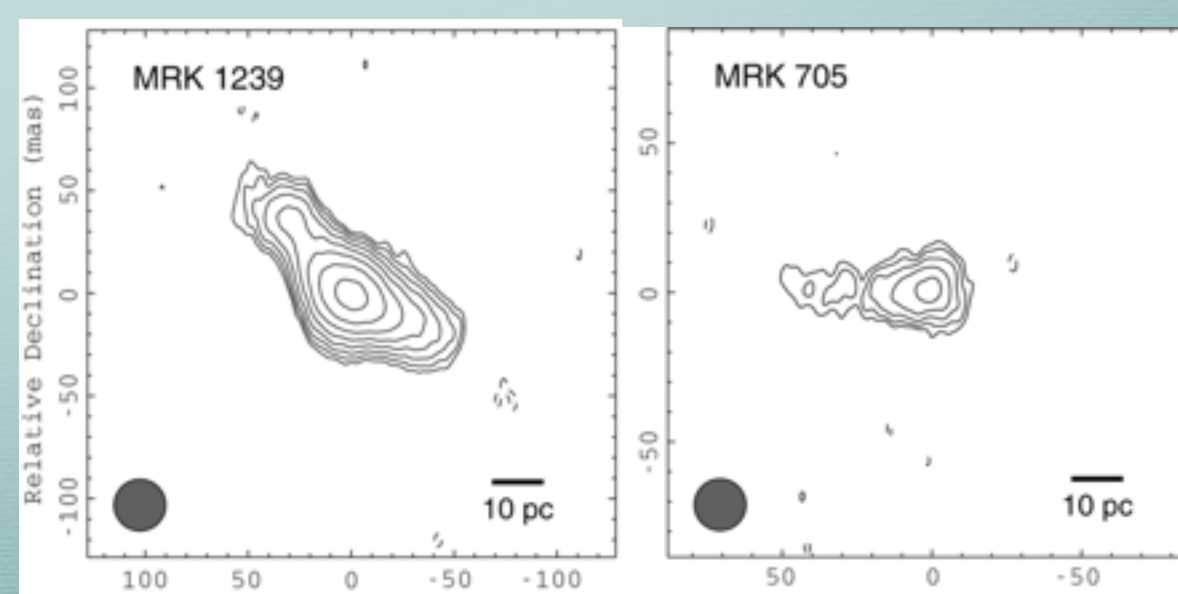
- AGN cores, mini-jets at low-z
- RQ AGN and SF similar evolution and LF
- Radio higher than expected from SF alone (White et al, in prep)



Padovani et al, 2014



White et al, in prep



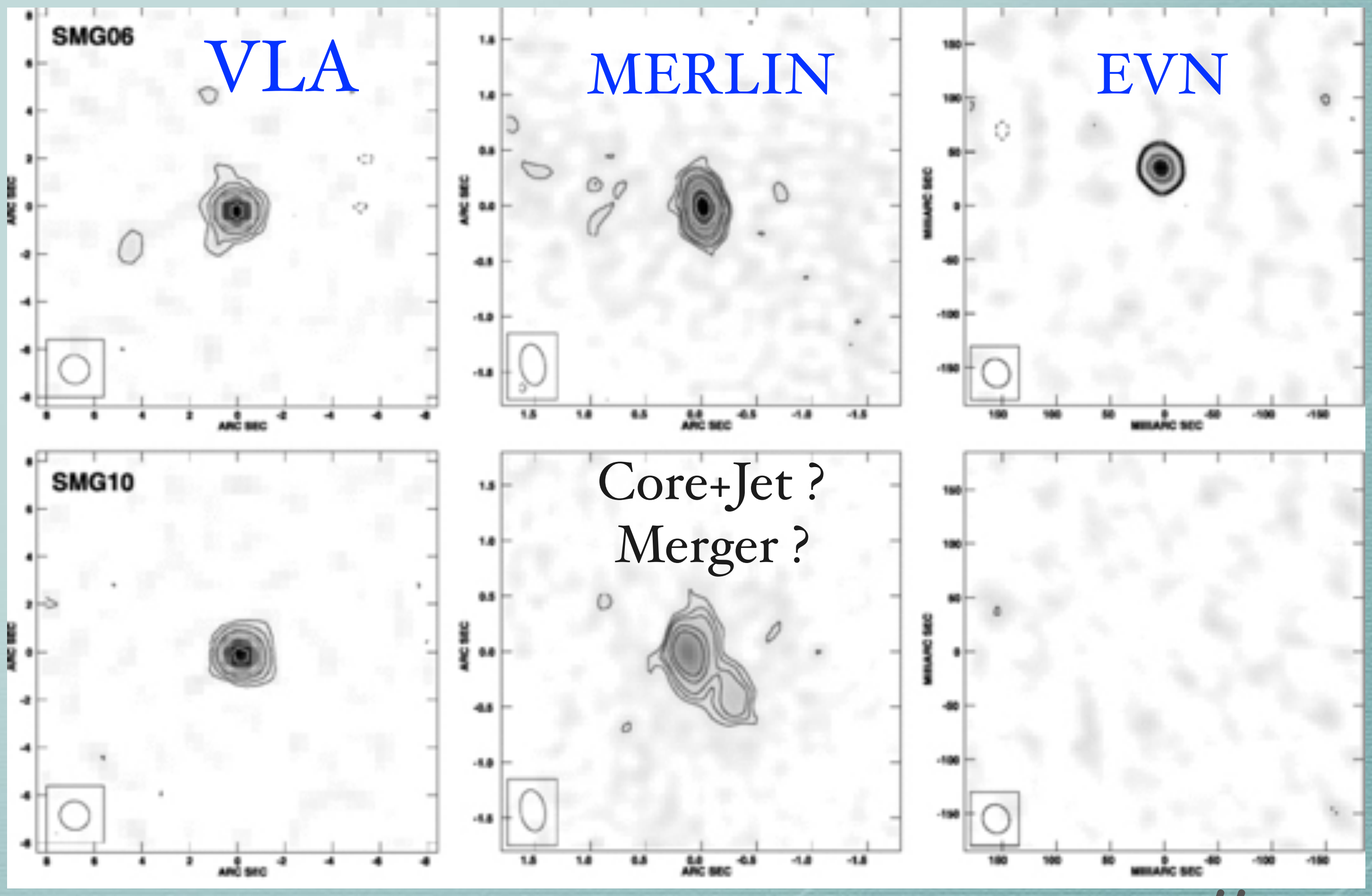
Dhoi et al, 2013

SKA Resolution

- AGN cores & inner jets $\ll 1$ kpc/$0.12''$
- Nuclear/Disk SF $\gg 1$ kpc/$0.12''$
- Large scale jets in RL AGN $\gg 10$ kpc/$1.2''$
- SF regions << 200 pc/0.03$''$

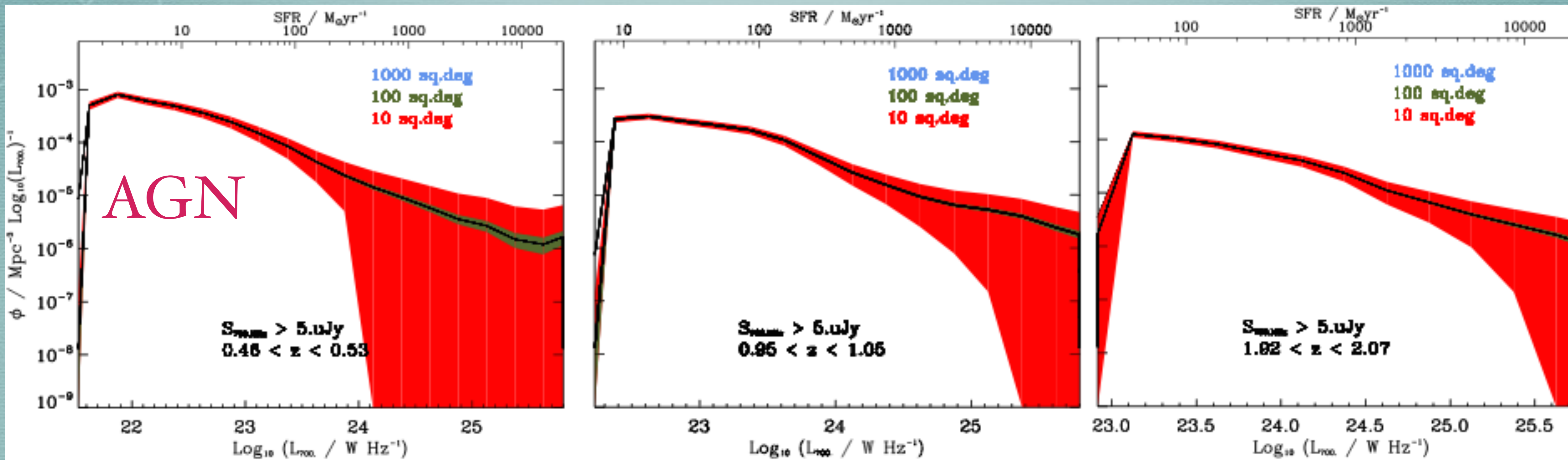
SKA decompose AGN/SF
in individual galaxies,

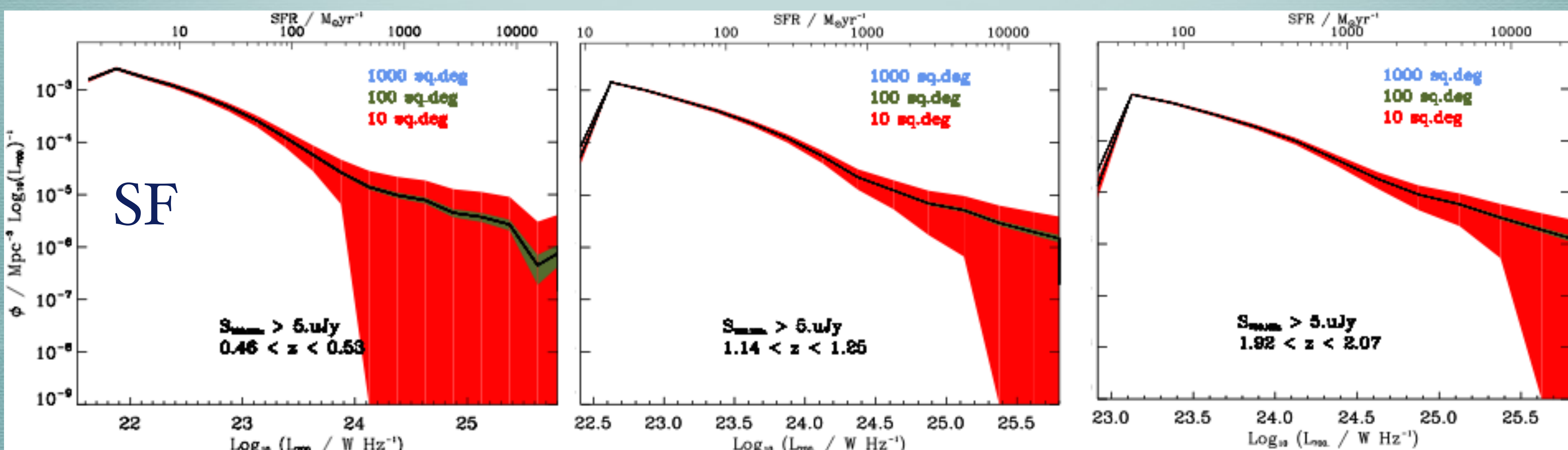
	SKA$_1$ (200 km)	SKA$_2$ (1000 km)
700 MHz	$0.6''$	$0.1''$
10 GHz	$0.04''$	$0.007''$



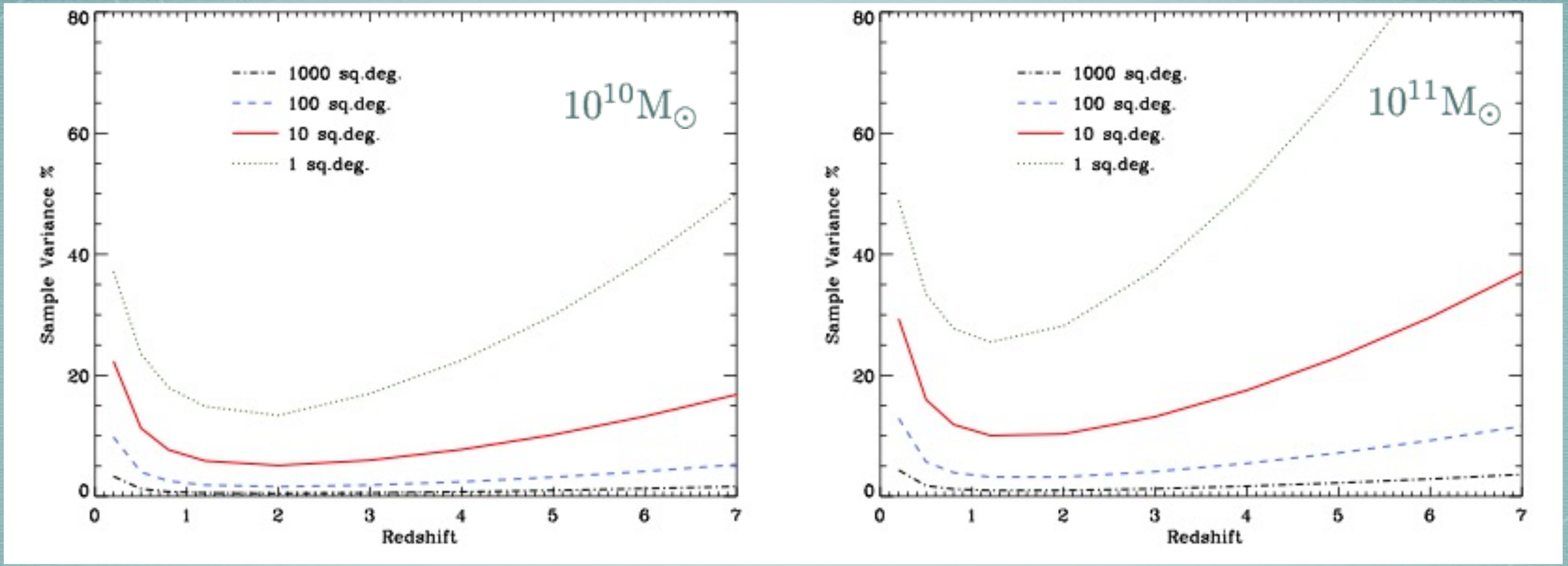
Biggs, Younger and Ivison, 2010

Wide Survey 5 microJy





Sample Variance & Wide Area Surveys



Wide areas to find rarer high mass systems, > 100 sq degrees driven by z<1

z>1 : ~ 10's of sq degrees, also limited by ancillary data
Higher resolution (<0.03 arcsec) more valuable than area
Study individual SF regions (200 pc) scales at high redshifts
JWST resolution over cosmologically significant volumes

Ancillary Data

Deep fields

- JWST
- LSST deep drilling
- XMM-Newton, Chandra

Spectroscopy

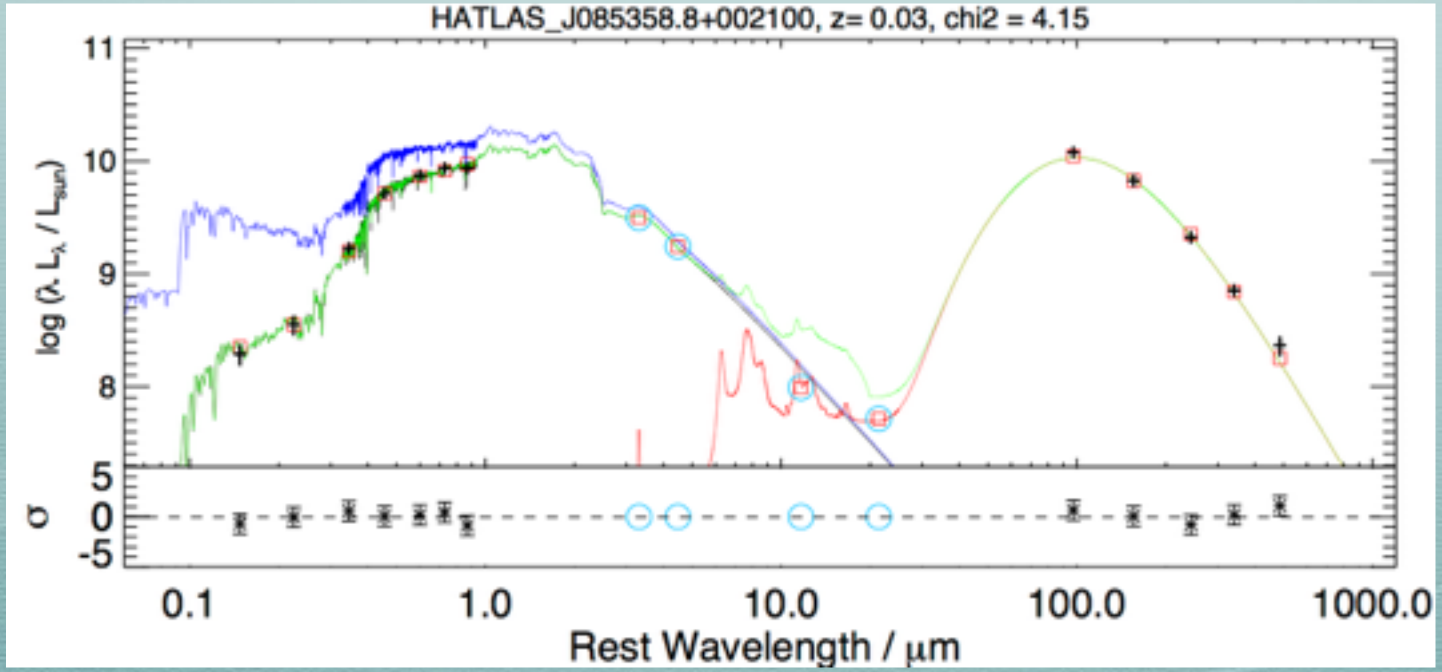
- 4MOST (VISTA)
- MOONs (VLT)
- redshifts, emission lines

Wide fields

- Euclid
- LSST
- e-Rosita

} SED fitting, Photo-z's (Euclid, LSST)

e-Rosita → Detect AGN, shallower than SKA



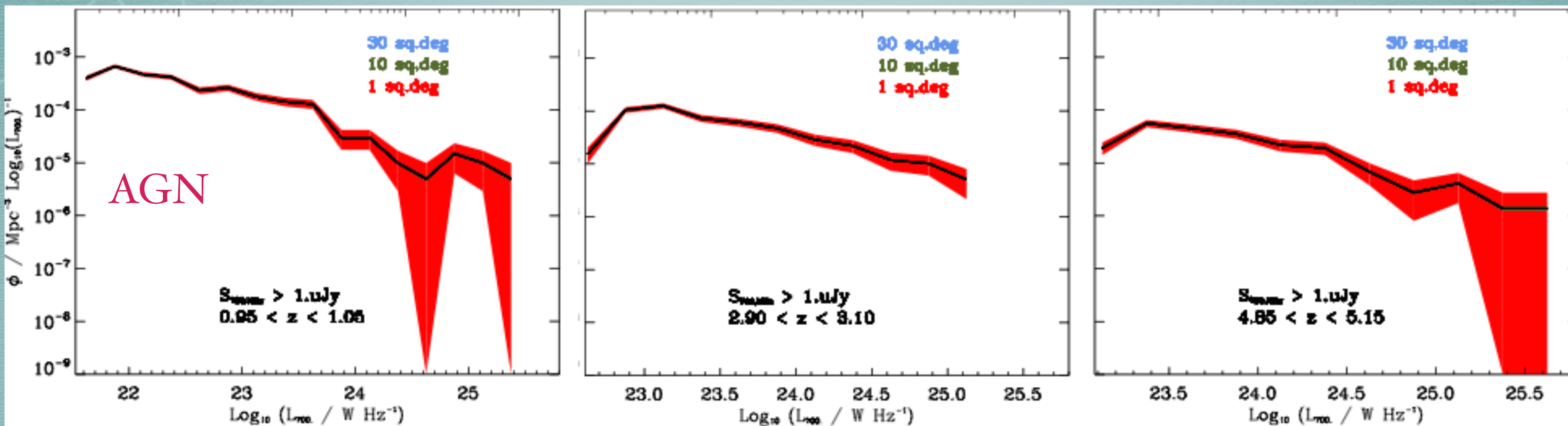
Summary

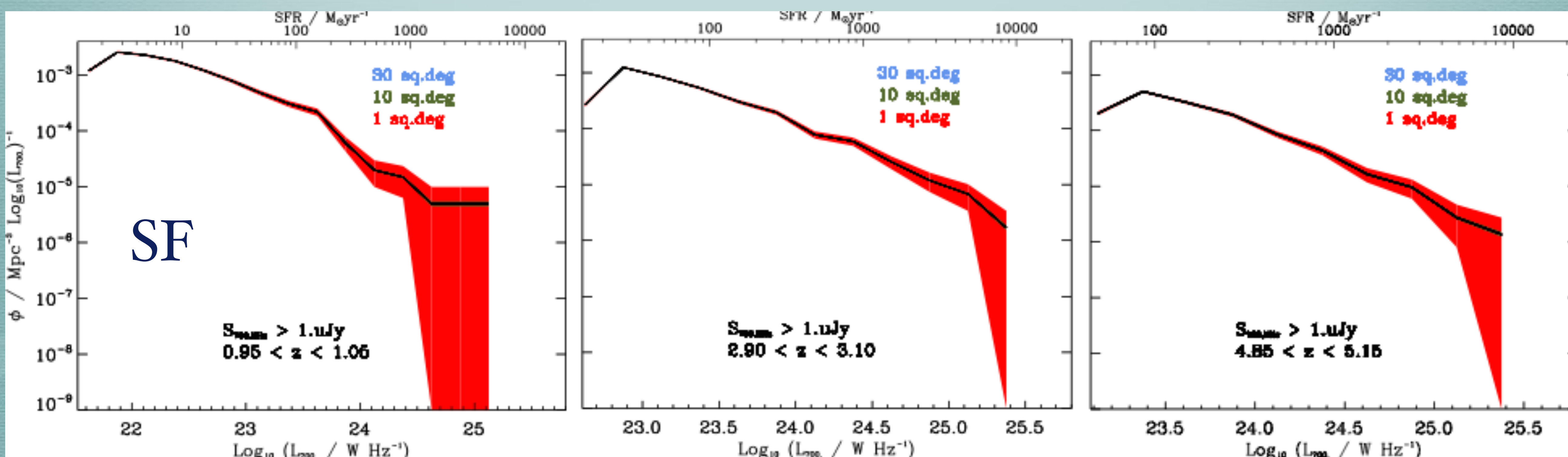
SKA has potential to solve many challenging questions in galaxy evolution

However larger areas (>100 - square degrees) not as essential as resolution and image fidelity at high redshift. Also NB ancillary datasets and multifrequency observations and gas dynamics (HI +CO)

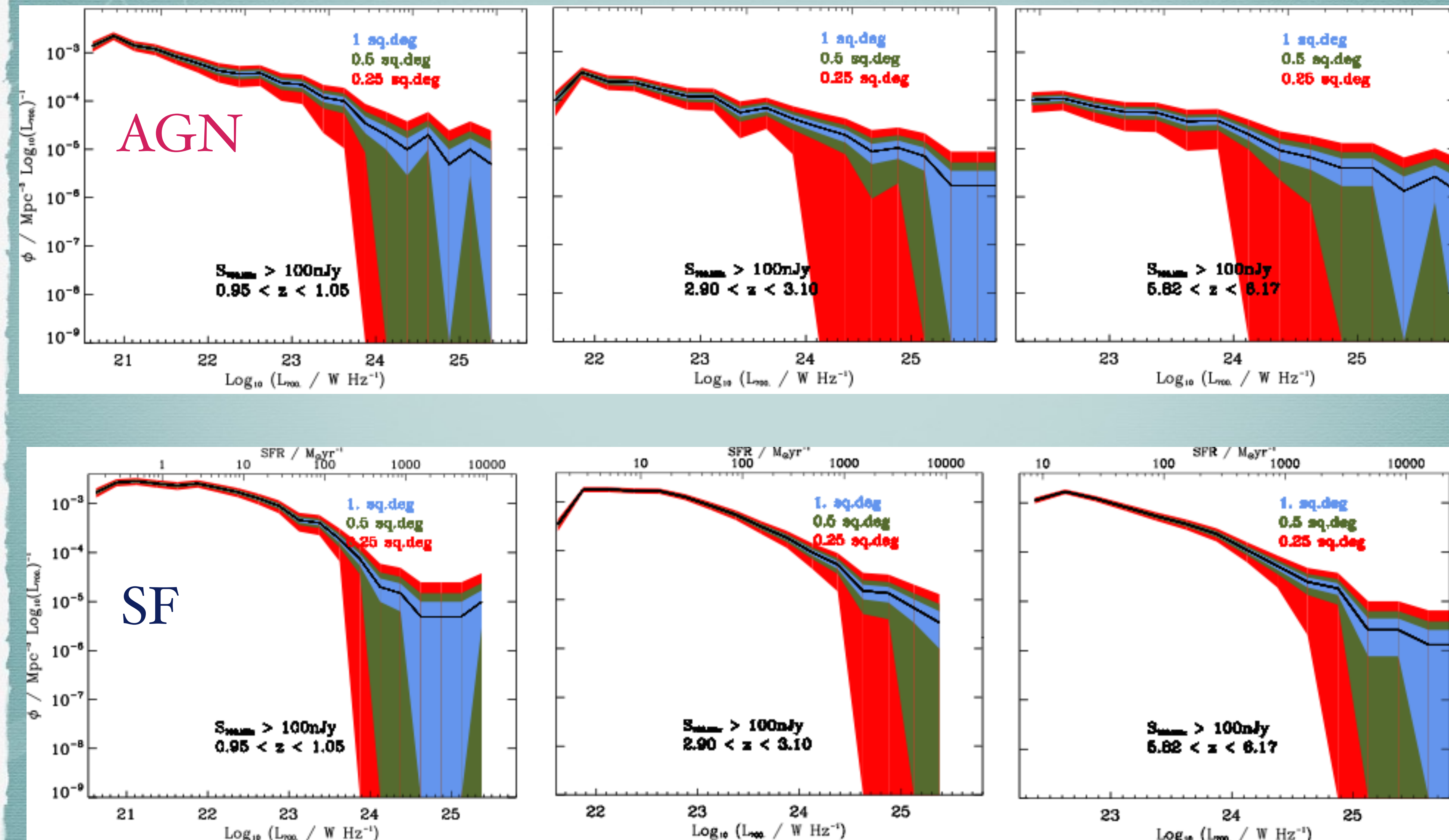
At $z<1.0$ larger areas required to sample all environments

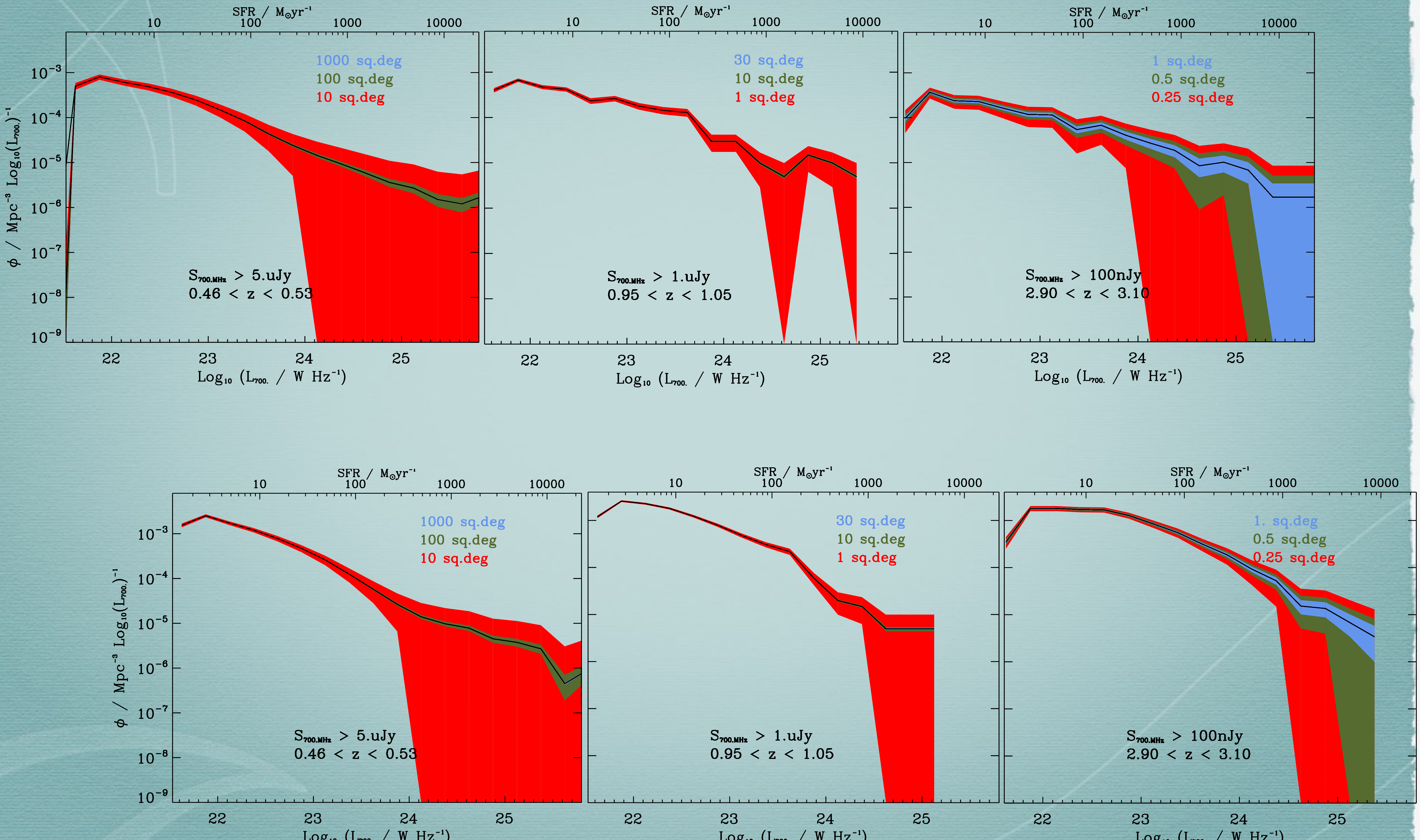
Survey 1 microJy





Survey 100 nJy





SFR / $M_\odot yr^{-1}$
10
100
1000
10000
1000 sq.deg
100 sq.deg
10 sq.deg
$S_{700.MHz}$ > 5.uJy
0.46 < z < 0.53
30 sq.deg
10 sq.deg
1 sq.deg
$S_{700.MHz}$ > 1.uJy
0.95 < z < 1.05
1 sq.deg
0.5 sq.deg
0.25 sq.deg
$S_{700.MHz}$ > 100nJy
2.90 < z < 3.10
ϕ / Mpc^{-3} $Log_{10}(L_{700.})^{-1}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
22
23
24
25
Log_{10} ($L_{700.}$ / W Hz^{-1})