The evolution of the IR-radio relation for AGN hosts and starbursts at intermediate and high redshift in the COSMOS field

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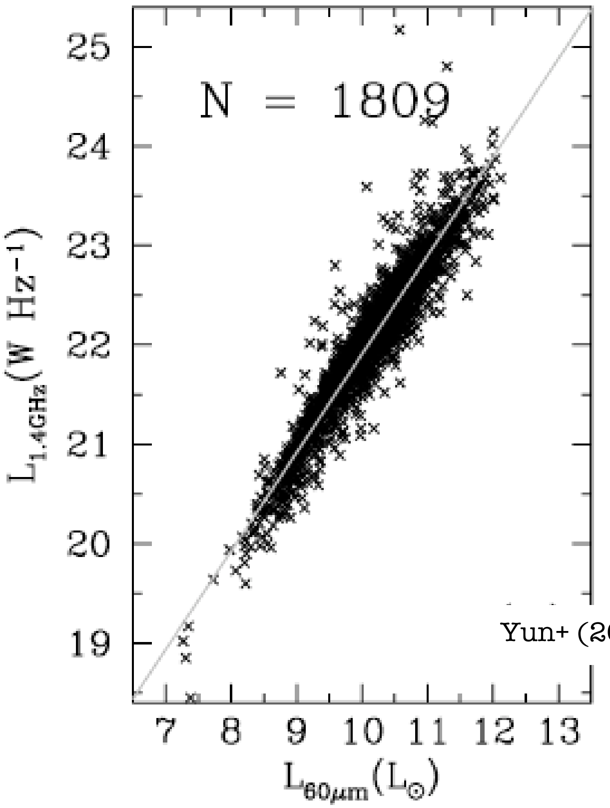
Today's talk...

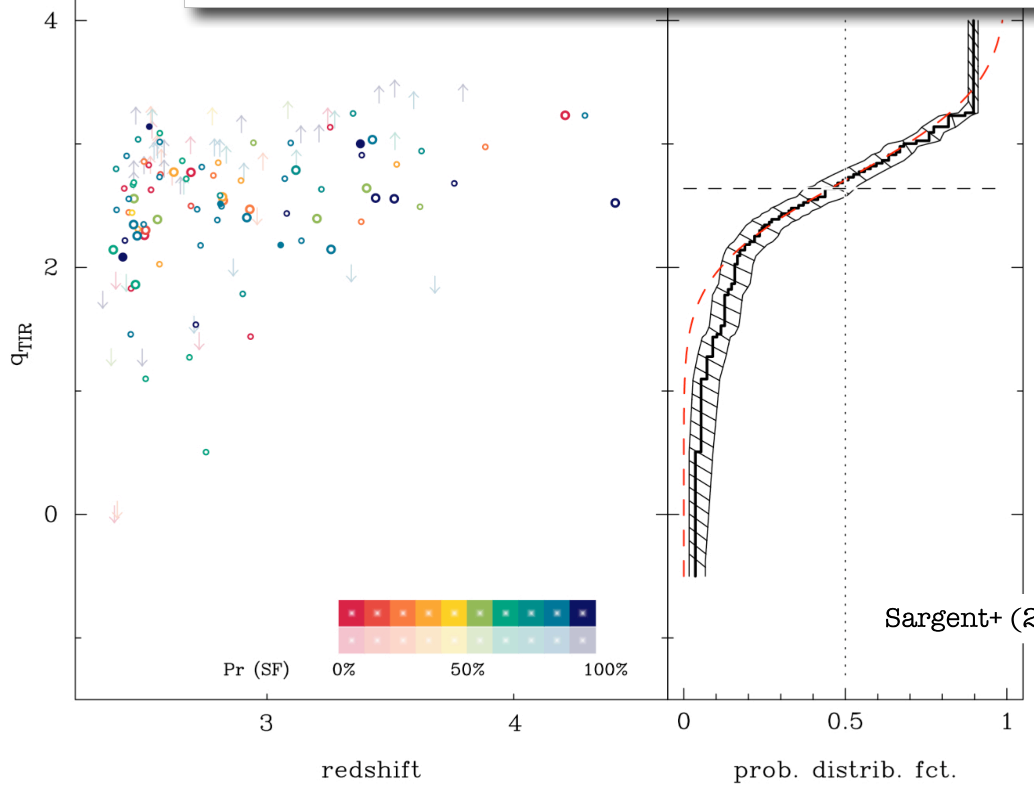
- Introduction
- The IR-radio relation with the SKA
    - sensitivity improvements
    - free-free rather than non-thermal emission
- Current status
    - direct detections @ 10^4 rms(SKA)
    - stacked detections @ 10^2 rms(SKA)
- Application: star formation history of mass-selected galaxies
- Selection biases
- Summary

Introduction - I

$$q_{\mathrm{TIR}} = \log\left(\frac{L_{\mathrm{TIR}}}{3.75 \times 10^{12}\,\mathrm{W}}\right) - \log\left(\frac{L_{1.4\,\mathrm{GHz}}}{\mathrm{W\,Hz^{-1}}}\right)$$



Yun+ (2001)



Sargent+ (2010a)

- Does the correlation evolve (cf. also Garrett '02, Appleton+ '04, Frayer+ '06, Ibar+ '08, Garn+ '09, Seymour+ '09 , Ivison+ '10) and what is the - unbiased - average (monochromatic or FIR) IR/radio ratio?
- What systematic effects arise due to: *canonical* synchrotron spectral index/*limited no.* of IR broad band measurements/*confusion* in the far-IR?

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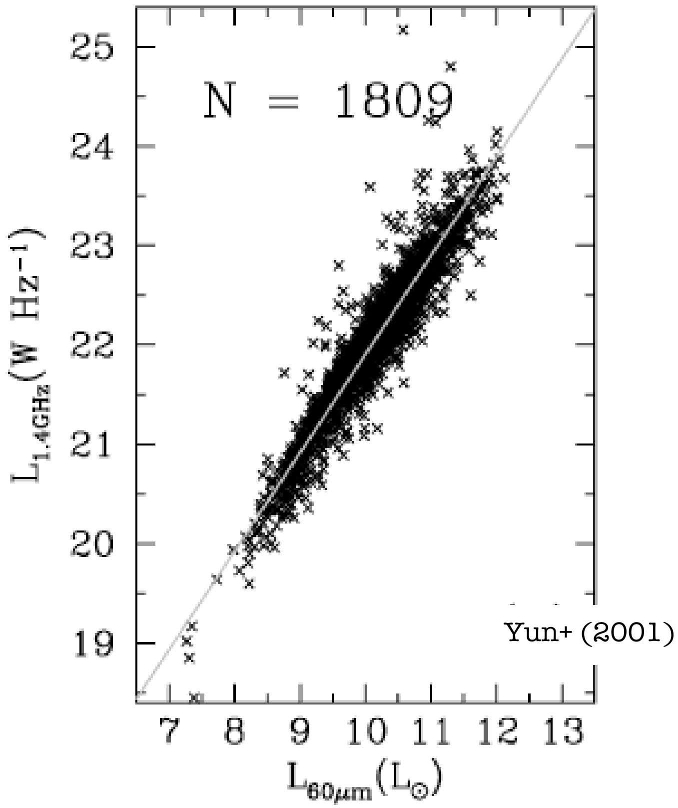

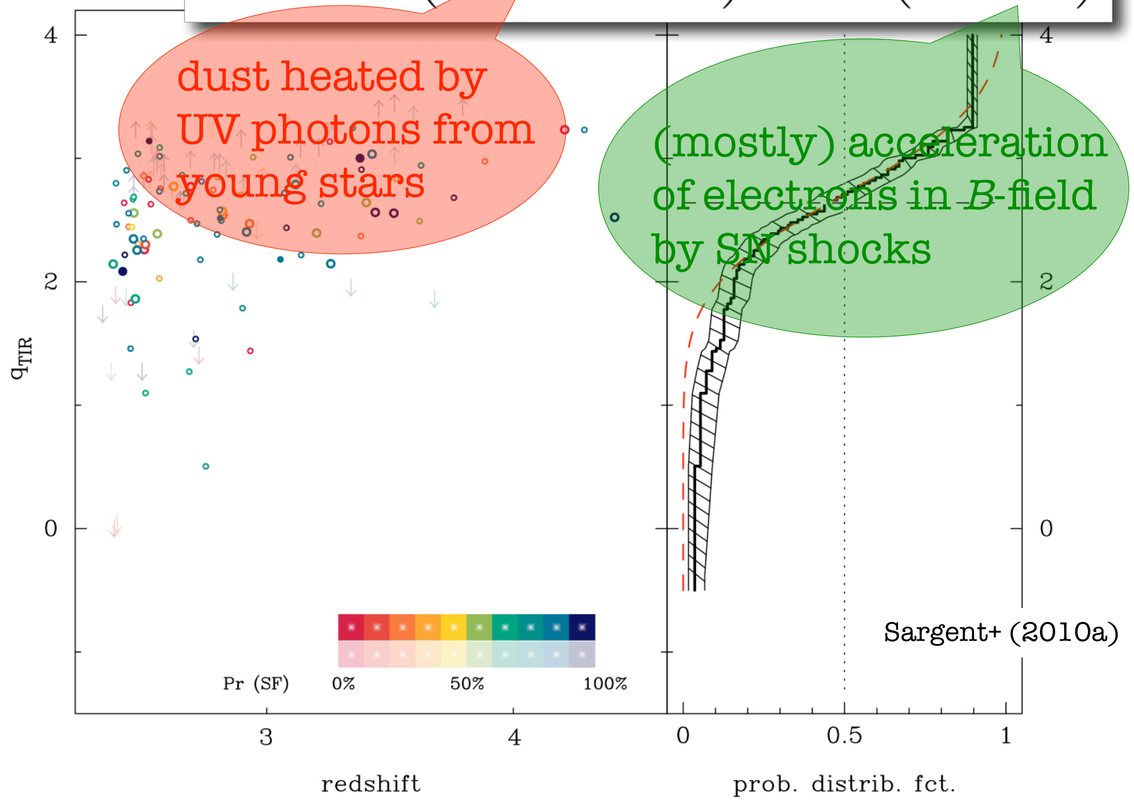

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Introduction - II

What are the benefits of studying the (evolution of the) IR-radio relation (with the SKA)?

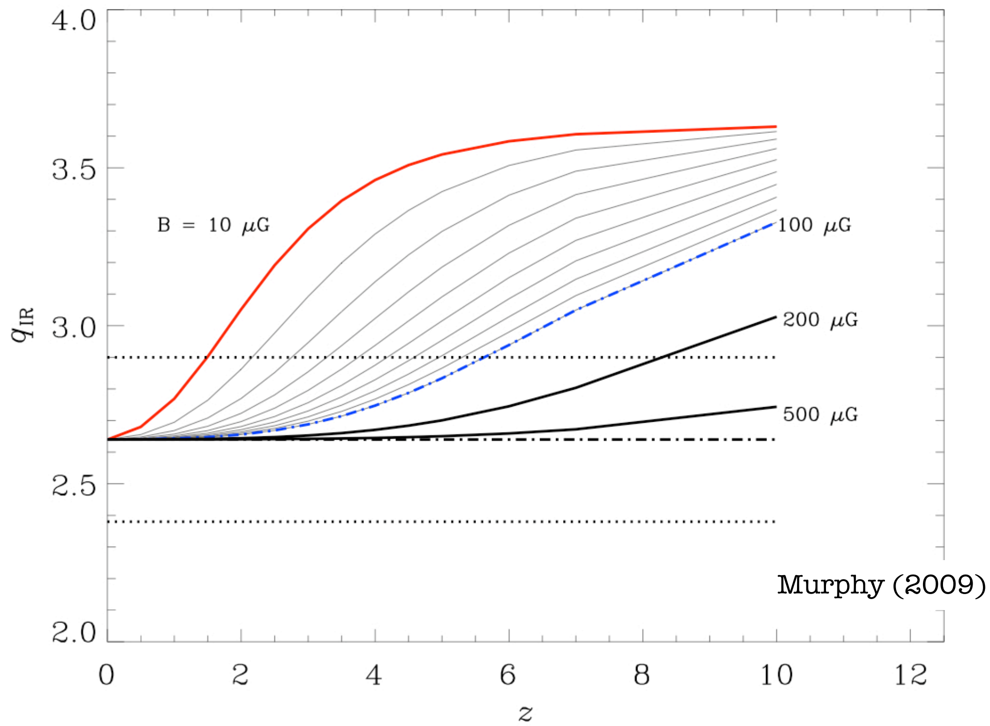
• Improved measurements of the star formation (SF) history of the universe (e.g. Haarsma+ '00, Seymour+ '08, Dunne+ '09, Smolčić+ '09):

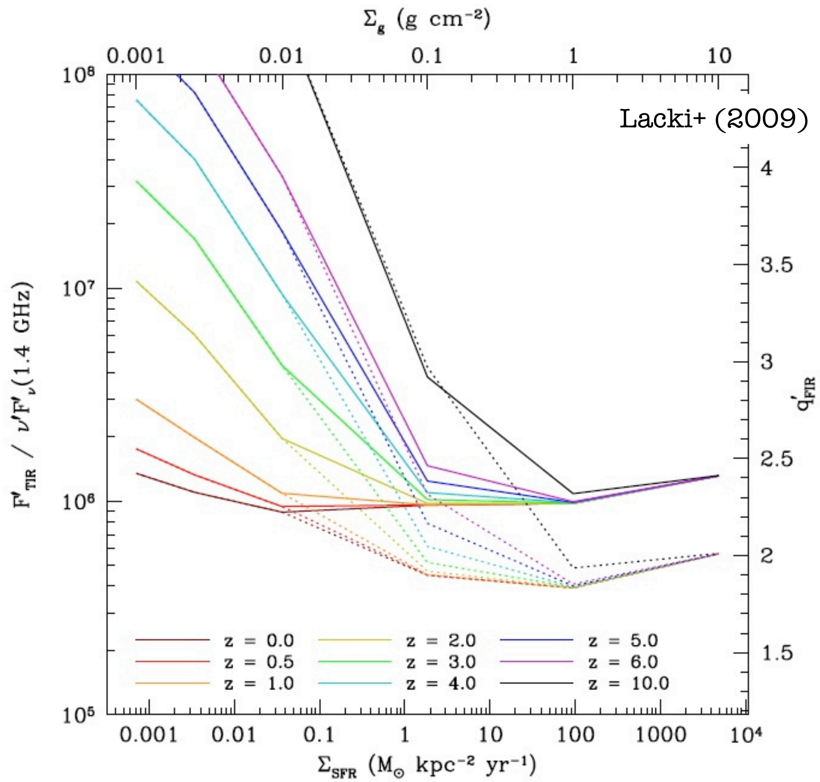
- map the hierarchical build-up of stellar mass by tracing (obscured) SF in as small/faint systems as possible and in a *dust-unbiased* manner
- determine the spatial and temporal progression of SF within star forming systems (e.g. inside-out in spiral galaxies?)

• Co-eval star formation and AGN activity... (e.g. Haarsma & Partridge '98, Silverman+ '09)

• ISM physics at different redshifts: growth of magnetic fields, intensity of interstellar radiation field, influence of CMB photons on the ISM (inverse Compton scattering)

The IR-radio relation with the SKA - I





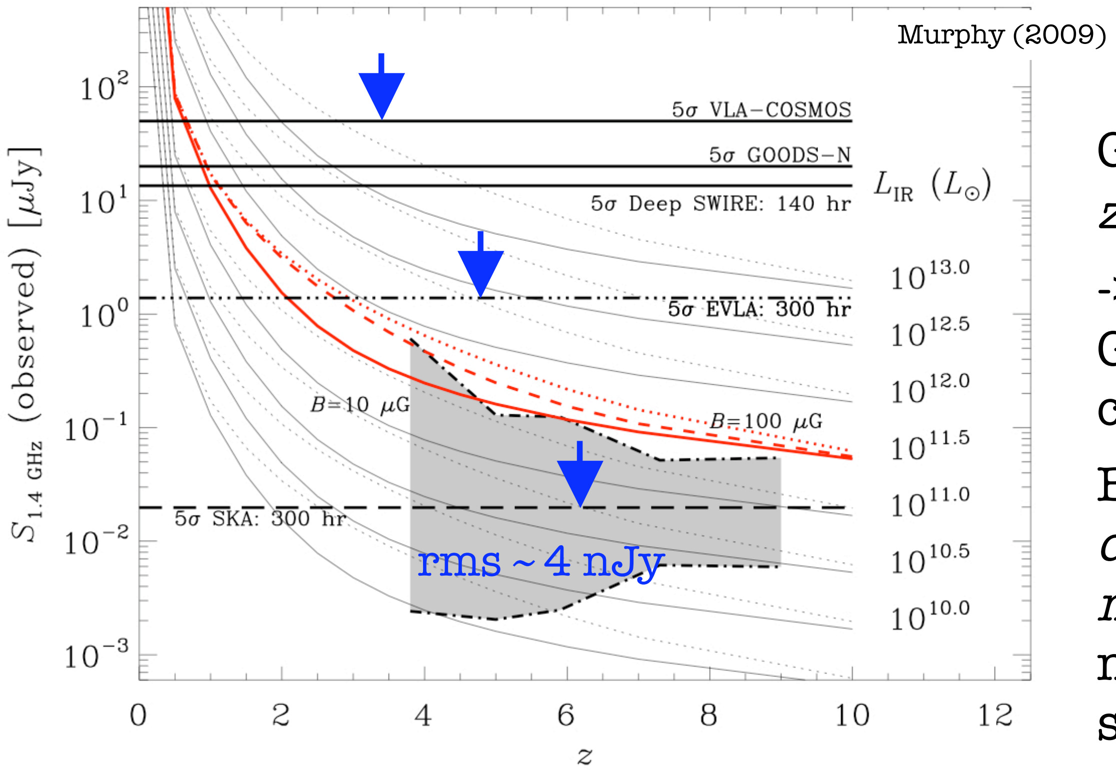
- interplay of multiple ISM-processes (IC, Bremstrahlung, ionization losses...) & magnetic field strength determines redshift evolution of average IR/radio ratios

  -> hard to infer SFR from ~ 1.4 GHz continuum observations

- q_{TIR} will approach ratio between IR and *thermal* (rather than non-thermal) radio flux

  -> cosmological *and* 'ISM-physical' flux dimming to be compensated by SKA sensitivity

The IR-radio relation with the SKA - II

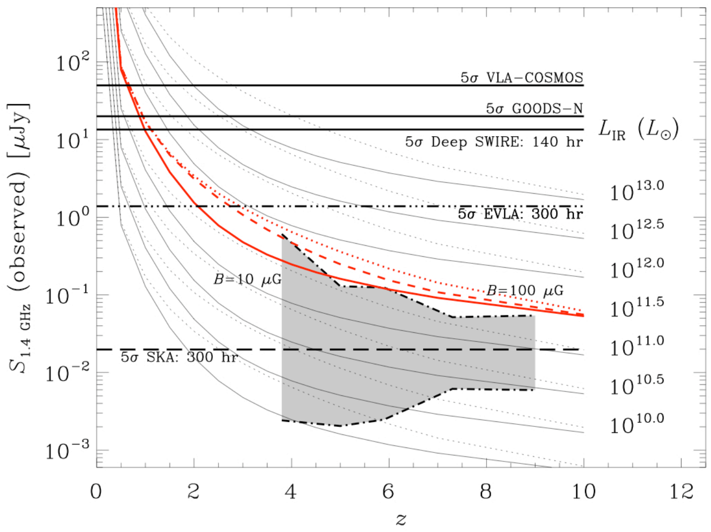


Goal: detect *all LIRGs out to z ~ 10*

-> need 10^3-fold increase of 1.4 GHz sensitivity compared to currently deepest surveys

But: at fixed *z* & luminosity, *detectability depends on magnetic field* if prefentially non-thermal emission is sampled

The IR-radio relation with the SKA - II



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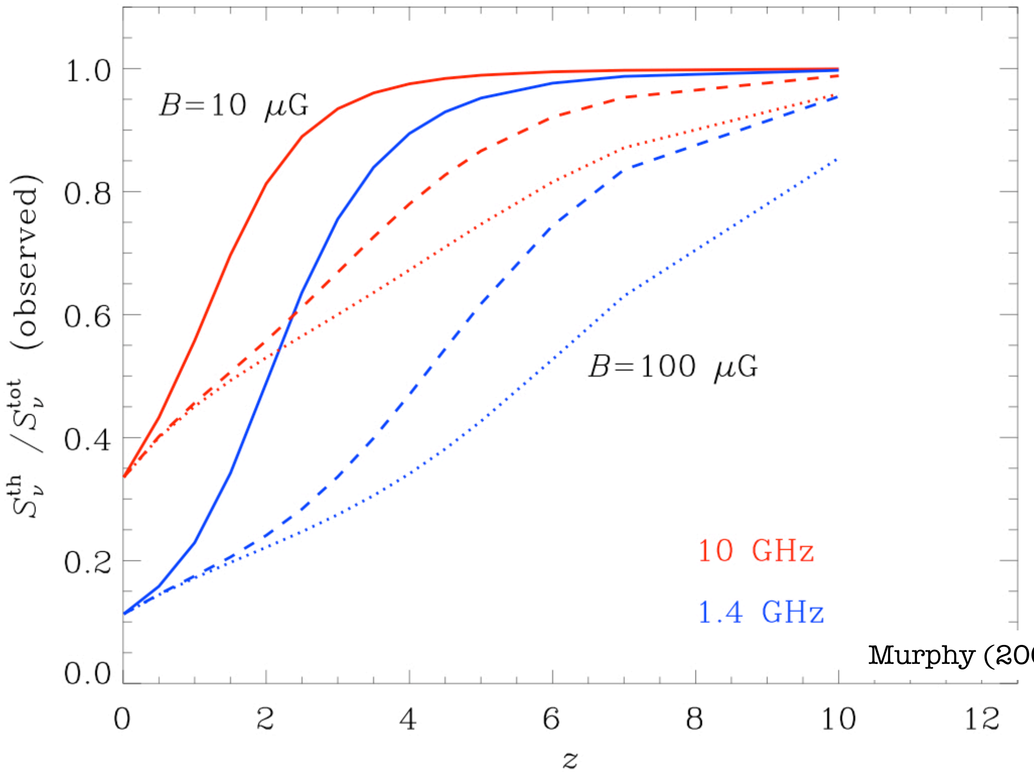
Thermal (free-free) radio emission (associated with Ly-continuum photons) is a direct tracer of SF & not biased by dust

-> pick frequency range dominated by *thermal emission* (at all relevant redshifts), e.g. 10 GHz



Murphy (2009)

Current data/this sample

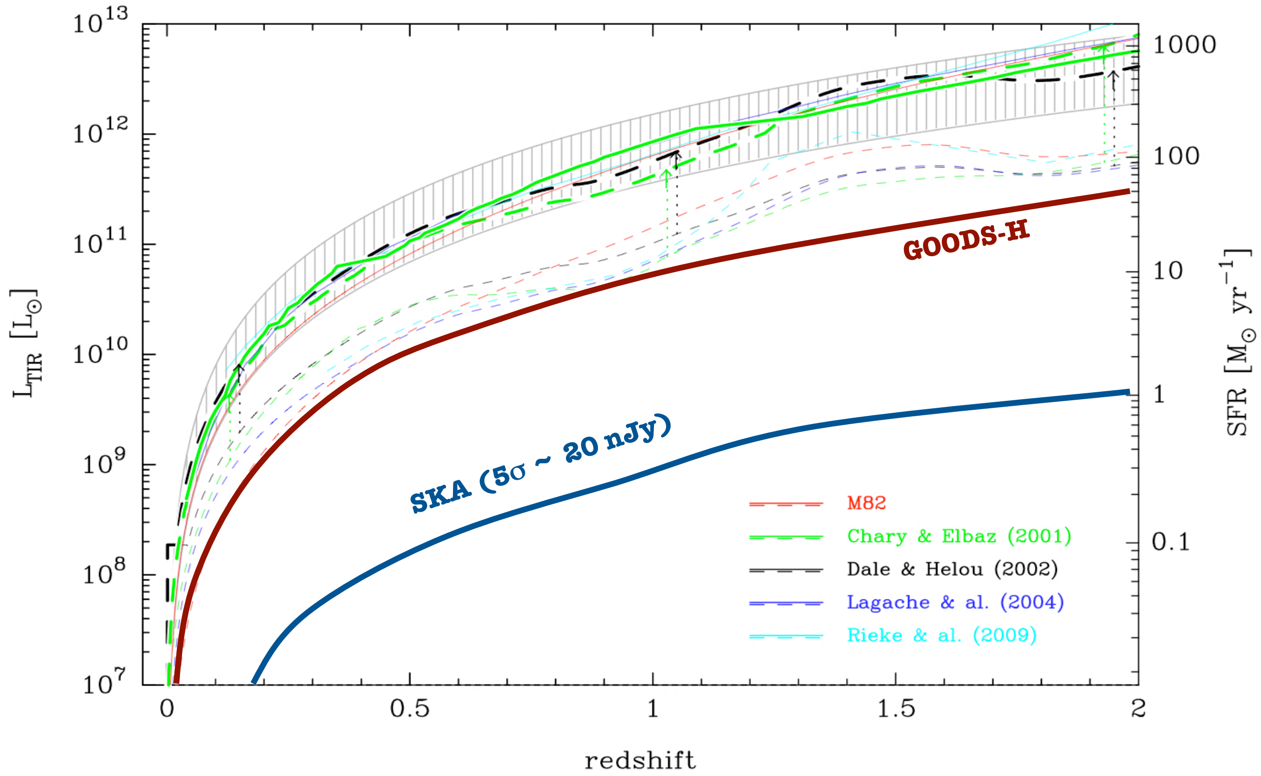
• band-merged 3σ (0.06/5/ 0.04 mJy @ 24 μm/70 μm/1.4 GHz) VLA- & S-COSMOS detections (see Le Floch'h+ '09; Frayer+ '09; Schinnerer+ '10) over 2 deg^2

• UV to near-IR photometry in 30 bands (photo-z estimates; $^2/_3$ of sample)

• spectroscopic follow-up observations ($^1/_3$ of sample)

• IR SED fits from 24 & 70 μm constraints (cf. Murphy+ '09)

-> Jointly radio- and IR- selected sample (~5,000 sources with 0.1 < z < 5).



Direct detections - 10^4 expected rms of the SKA

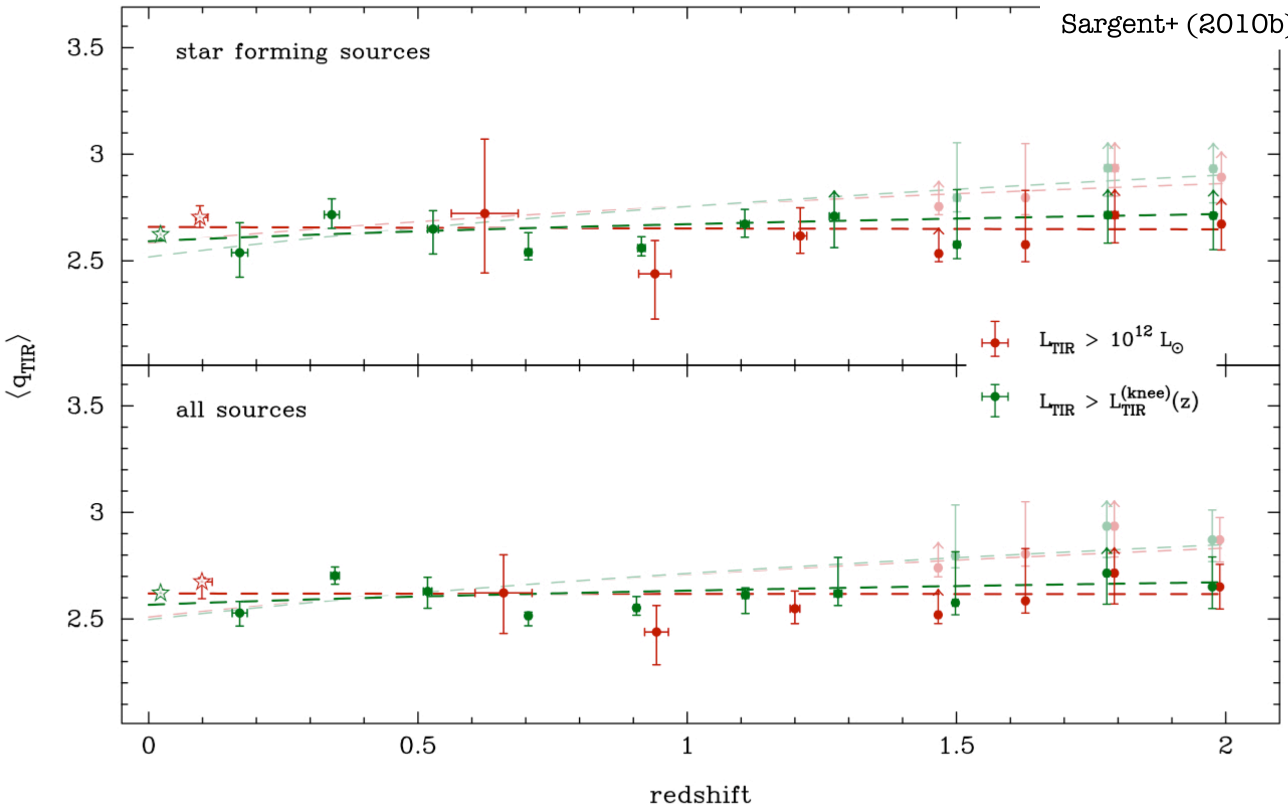
Evolution of the brightest IR-emitters

Median IR/radio ratios in volume-limited samples of ULIRGs:

(rather than comparing most strongly starbursting systems at high z with mixture of high & low luminosity systems at low z)

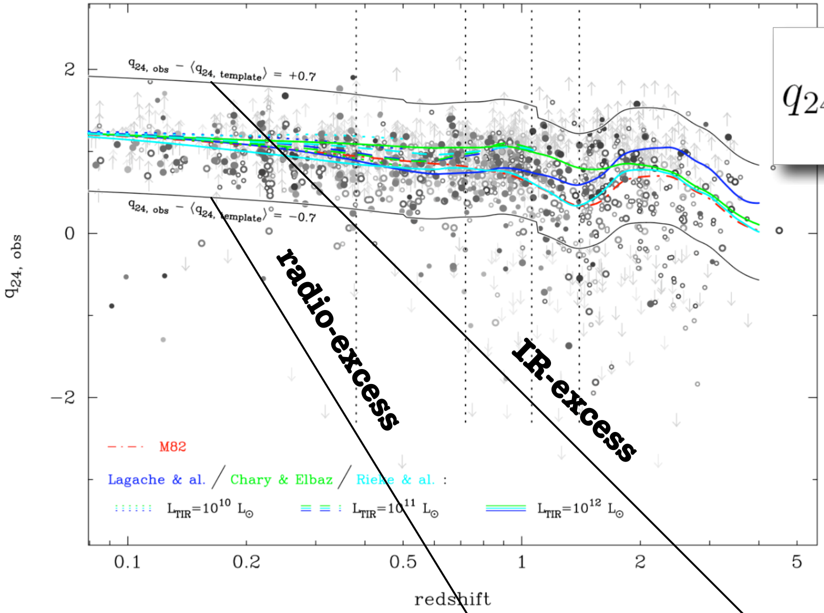
After compensating for selection biases - *NO* evolution at z < 2 (implies B ~ 50 μG).

Sargent+ (2010b)



- large (2 deg ^{2}) COSMOS field + deep 24 um data -> *sufficiently numerous* IR-bright sources at *all z* < 2
- IR/radio non-detections included with *survival analysis*
- *probabilistic* (using rest-frame optical colours) *classification* into SFGs/AGN (cf. Smolčić+ '08)

AGN with starburst IR/radio ratios



$$q_{24\,[70]} = \log\left(\frac{S_\nu(24\,[70]\ \mu\mathrm{m})}{S_\nu(1.4\,\mathrm{GHz})}\right)$$

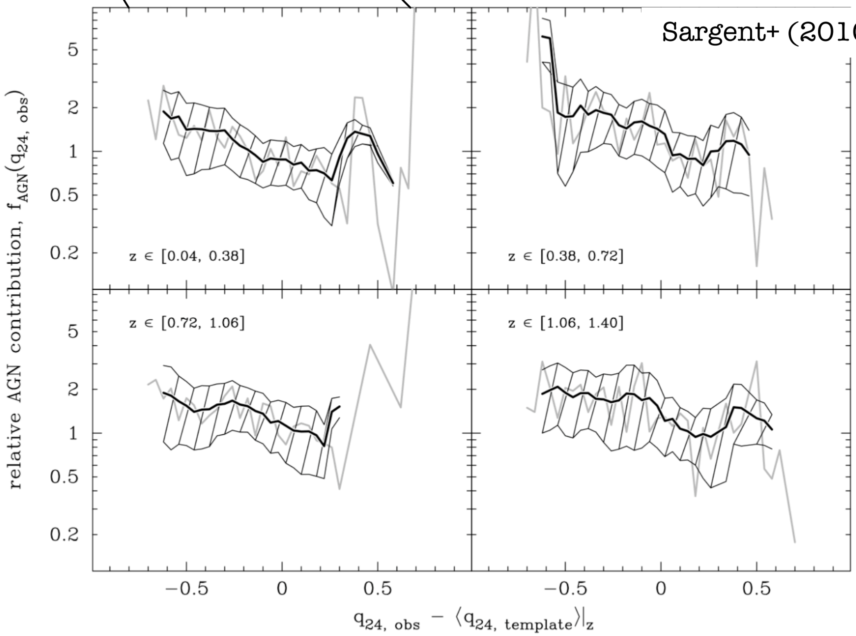
- Similar IR/radio ratios...

(cf. also Sopp & Alexander ‘91; Roy+ ‘98; Murphy+ ‘09)

... at *both* 24 & 70 μm

- Involves *no assumptions* about IR SED or radio spectral index!

Relative abundance of AGN-hosts on starburst locus:



Sargent+ (2010a)

Caused by coincidence...

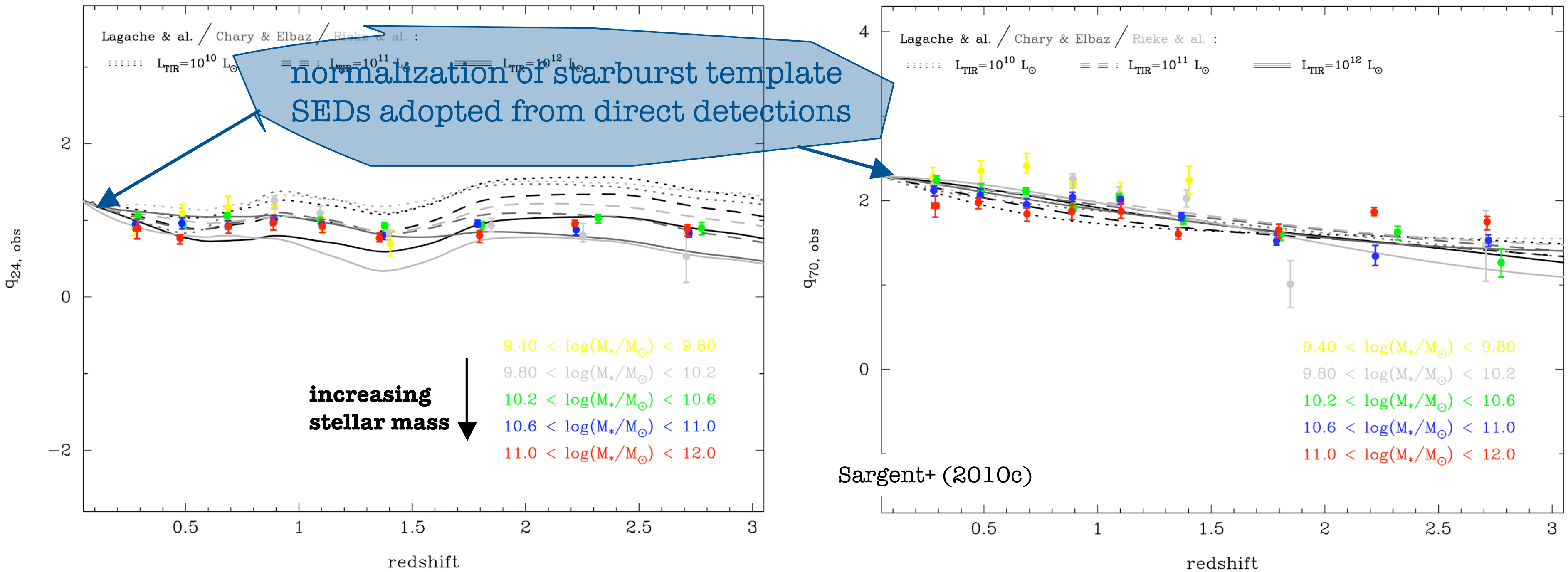
(e.g., Sanders et al. 1989; Colina & Perez-Olea 1995)

... or by star formation

(e.g., Barthel 2006)?

Stacked detections - 10^2 expected rms of the SKA

Average IR/radio ratios of mass-selected galaxies

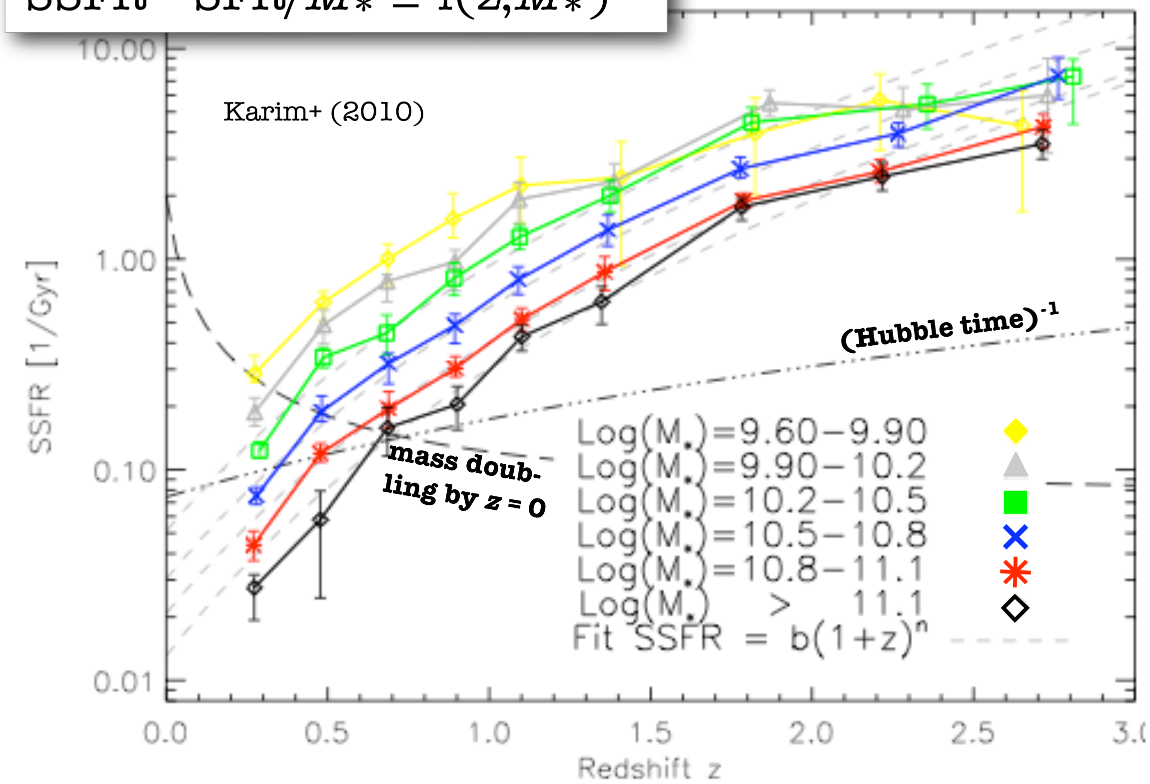


- Sample based on 3.6 μm *IRAC detections* in COSMOS field (cf. Sanders+ '07, Ilbert+ '09) -> expect unbiased estimate of average IR/radio ratios
- *Actively star forming galaxies* selected with (NUV-r) colours (cf. Ilbert+ '09)
- 1.4 GHz image stacks of reach rms noise of ~400 nJy thanks to 100s of sources in each mass/redshift bin -> *statistical detections* of LIRG luminosities out to *z* ~ 3

No differing behaviour between stacked and high(er) luminosity samples!

Applying the correlation - Evolution of specific SFR

$SSFR = SFR/M_* \equiv f(z, M_*)$



Separable effects:

- mass dependence
- redshift evolution

$SSFR = M_*^{-0.7} \times (1+z)^{4.2}$

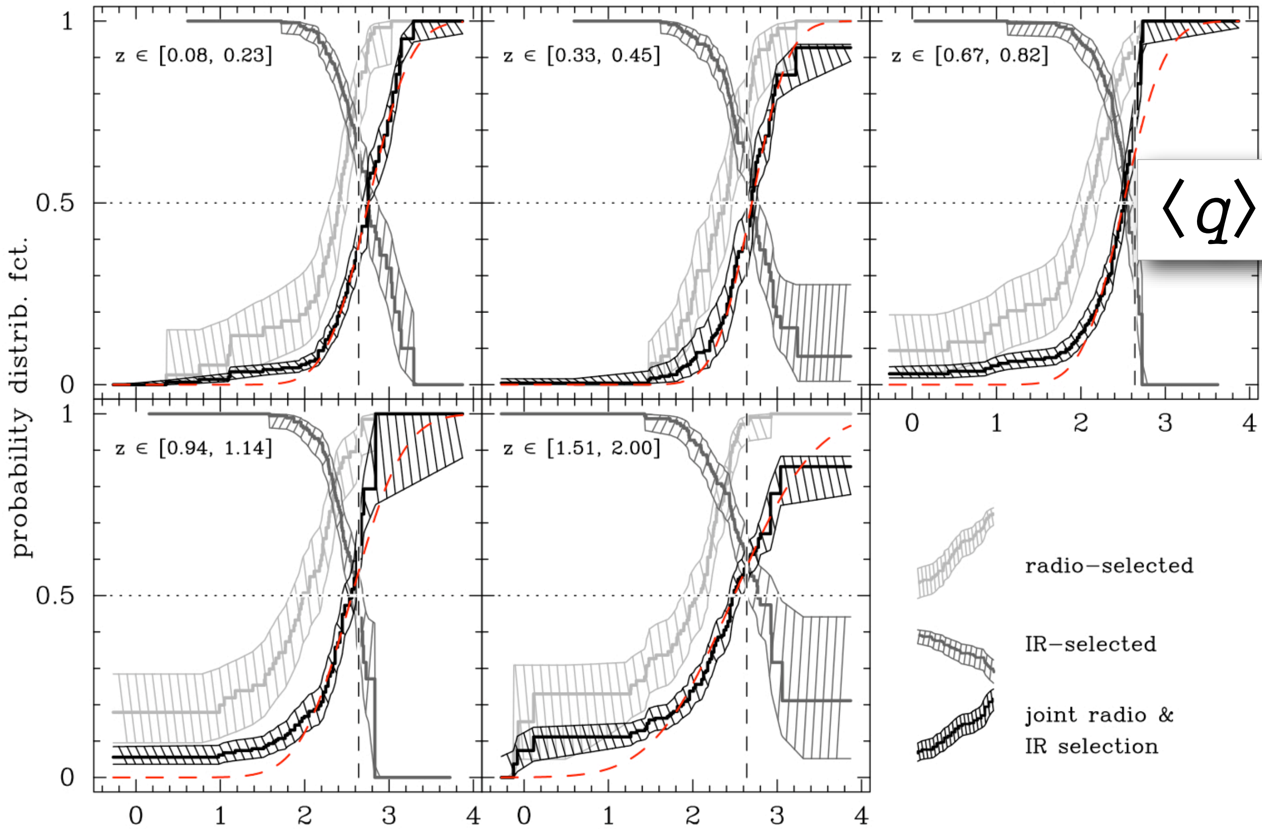
-> the SSFR is *higher in low-mass galaxies*, and...

... SSFR *decreases with time*

What causes the decline in cosmic star formation activity?

- general decrease in SSFR - *yes*
- faster evolution of high-mass end - no
- difference between actively star forming galaxies & entire galaxy population - no

Selection biases...



$\langle q \rangle_{\text{IR-sel.}} > \langle q \rangle_{\text{radio-sel.}}$

Sargent+ (2010a)

q_{TIR}

source counts

dispersion of correlation

Analytical prediction of offset $\Delta q_{bias} = \ln(10)\,[\beta-1]\,\sigma^2$ (e.g. Kellermann 1964; Condon 1984) can reconcile discrepant values in the literature, e.g. $\langle q_{24} \rangle \sim 1.2$ (Rieke et al. 2009) vs. $\langle q_{24} \rangle \sim 0.9$ (Appleton et al. 2004; Ibar et al. 2008).

Summary

- No evidence for significant evolution of the IR-radio relation for
  - ULIRGs & LIRGs out to at least $z \sim 2$
  - ultra-luminous starbursts at $2.5 < z < 5$

-> The SKA may detect evolution in systems with less extreme energetics.

- Many optically-selected AGN at $z < 1$ have similar IR/radio ratios as SFGs

-> The resolution and broad-band frequency coverage of the SKA will facilitate distinguishing between nuclear and SF activity with spectral and morphological indicators.

- (Analytically predictable) selection biases can reconcile discrepant measurements of average IR/radio properties reported in the literature. Neglecting these may lead to spurious evolutionary trends.

-> Studies based on flux-limited samples selected in deep SKA imaging must make according corrections.

- Detecting systems with moderate SFRs (~25 $M_{\odot}$/yr) out to $z \sim 10$ requires a rms sensitivity of ~4 nJy. It may be advantageous to use SKA-hi (at ~10 GHz) to measure SFRs based on thermal radio emission.

That’s all.

References: Karim et al. 2010, ApJL, in progress
Murphy 2009, ApJ, 706, 482
Sargent et al. 2010a, ApJS, 186, 341
Sargent et al. 2010b, ApJL, in press (arXiv:1003.4271)
Sargent et al. 2010c, ApJ, in progress

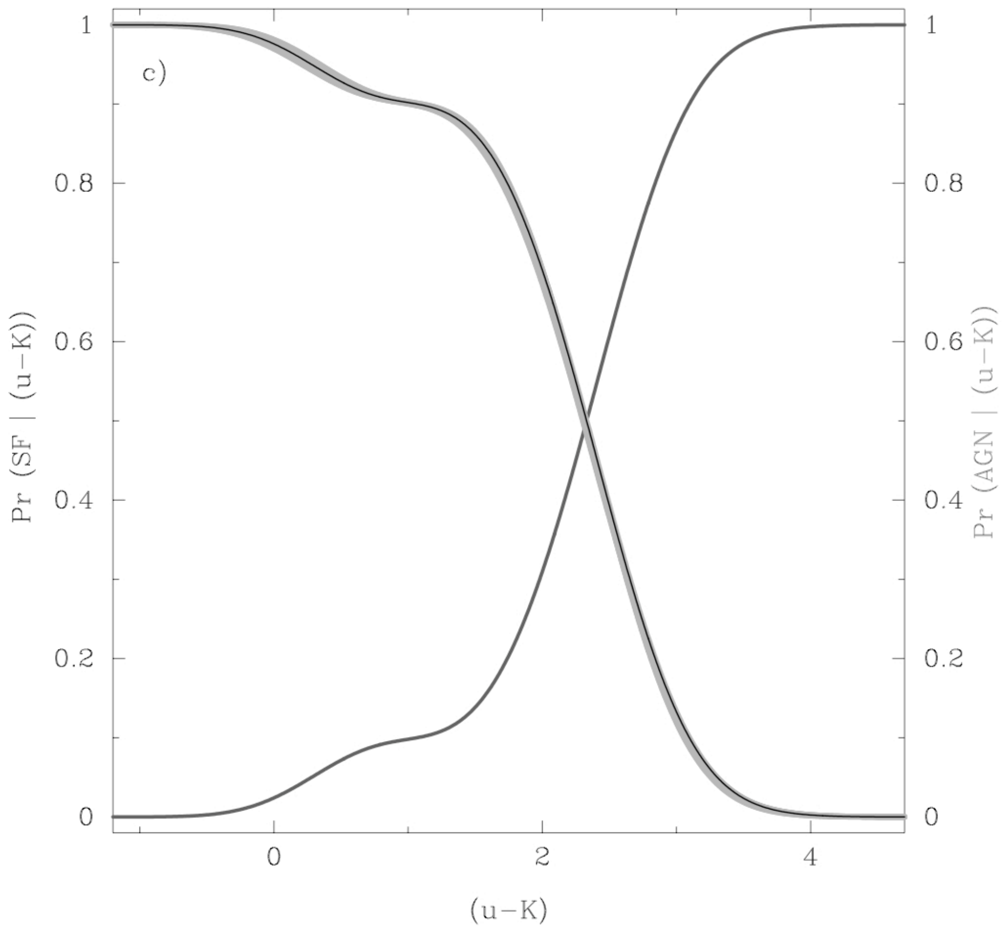
Probabilistic SF/AGN classification

Simple approach for separa-ting star forming (SF) from AGN systems:

rest frame optical colours

(cf. Smolčić et al., 2008)...

- COSMOS multi-λ photometry fitted with ZEBRA (Feldmann et al., 2006)
- relate r.f. (u-K) to colour P1 of Smolčić et al.
- probability distribution:
  Pr (SF | (u-K))



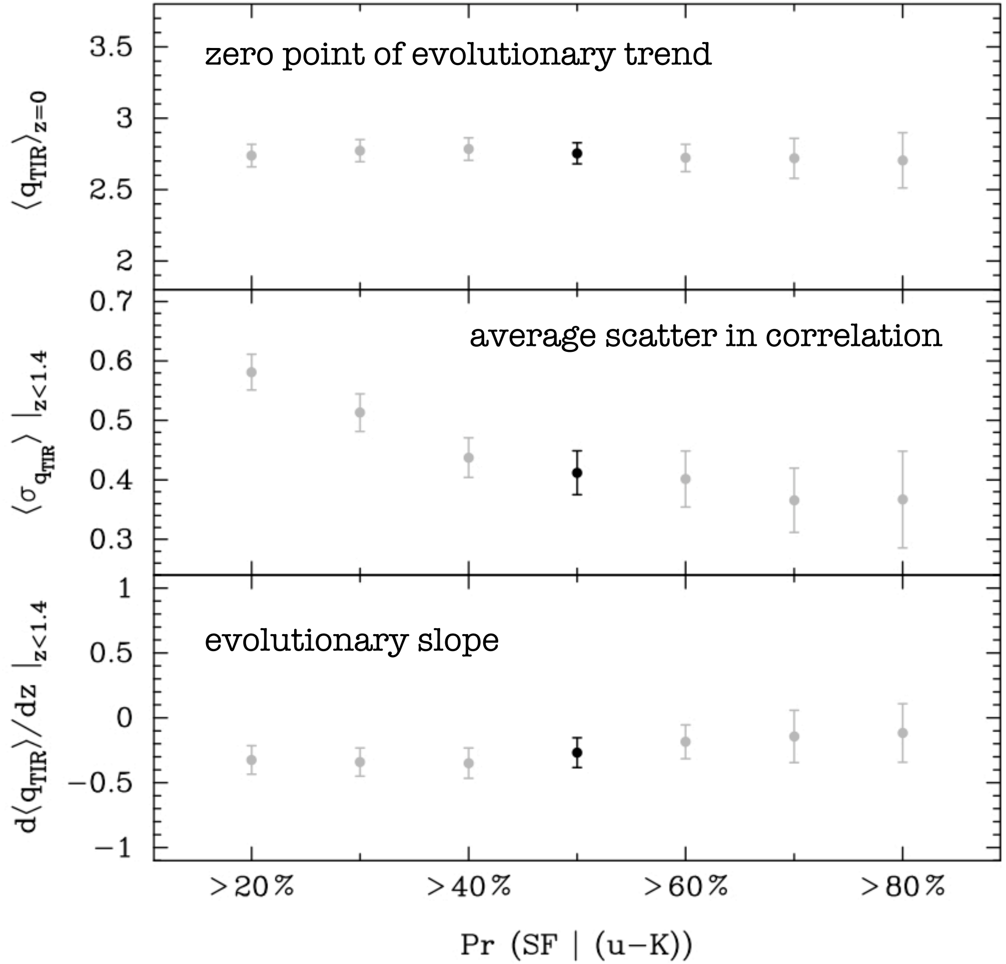
→ classify as SF if Pr (SF) > 50% (i.e. if (u-K) < 2.36)

Dependence on SF/AGN classification?

Only minor variations in the zero point & evolutionary slope of the median IR/radio ratio...

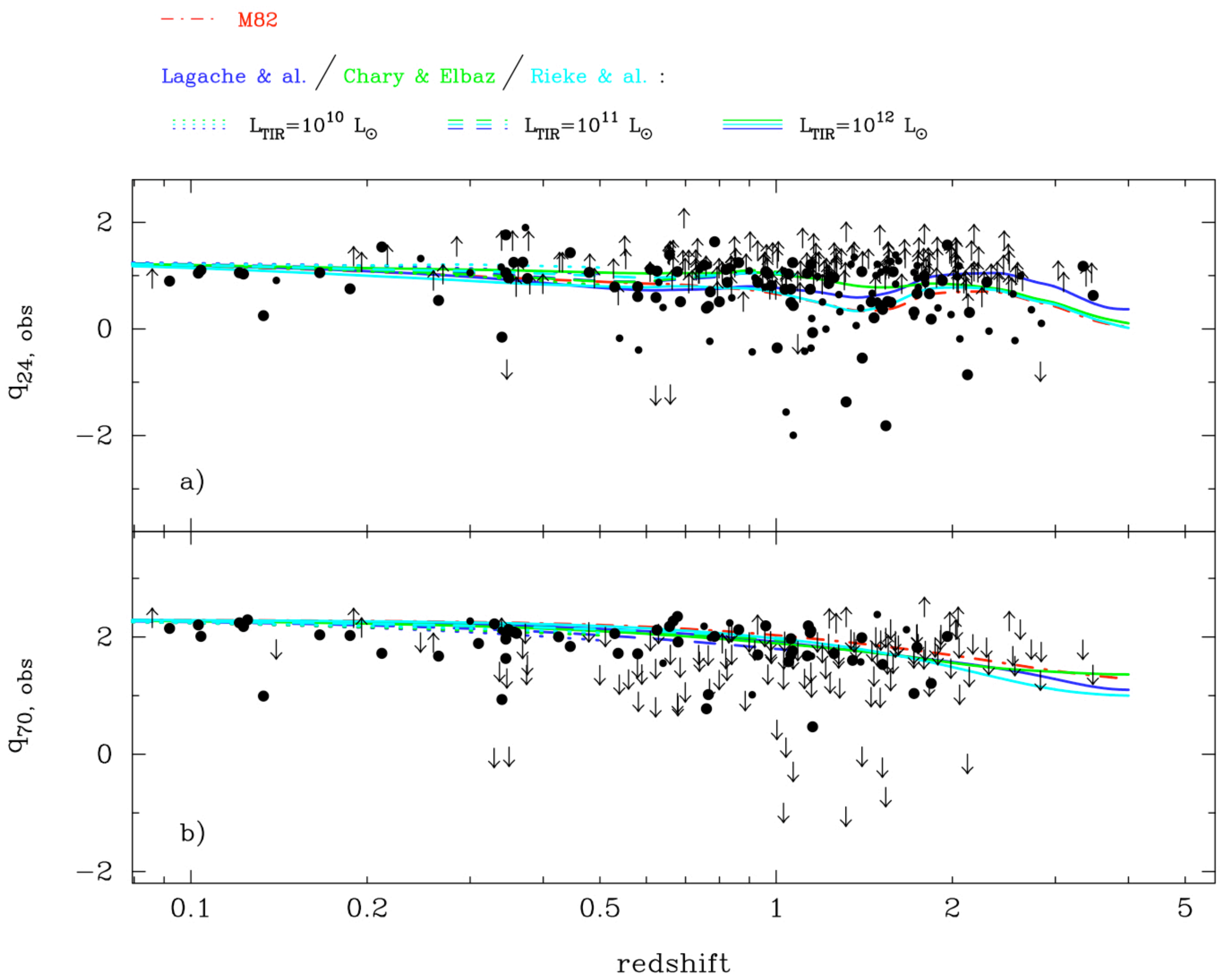
... if the selection threshold for SF systems is *chosen more conservatively*,

... or even if a *significant number of AGN is included.*



→ Many of the AGN in our sample are *radio-quiet* ...

XMM-detections



Selection biases - II