The FIR/radio correlation and radio spectral index of galaxies in the SFR-$M_\star$ plane up to z~2

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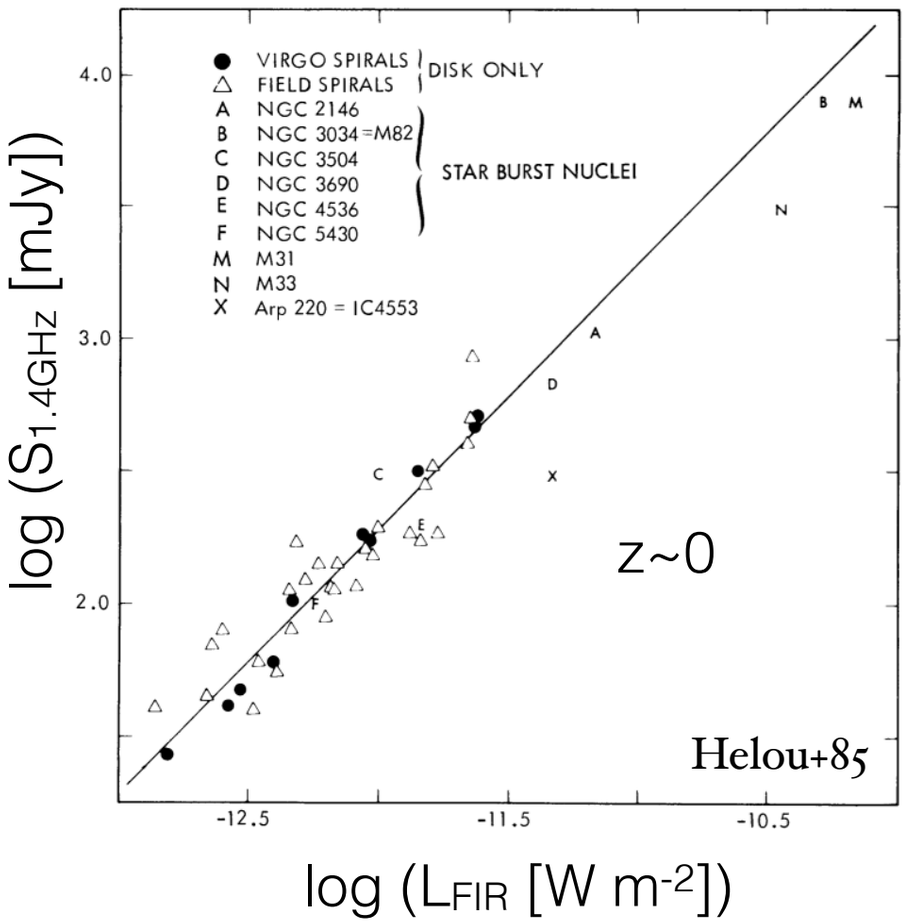
the PEP & HerMES team

EWASS 2015, Tenerife, Spain

The local Universe



$$q \equiv \log\left(\frac{\mathrm{FIR}}{3.75 \times 10^{12}\ \mathrm{W\ m^{-2}}}\right) - \log\left(\frac{S_{1.4\ \mathrm{GHz}}}{\mathrm{W\ m^{-2}\ Hz^{-1}}}\right)$$

- The global IR and radio luminosities of a variety of SF galaxies ($\sim 10^9 < L_{IR}[L_\odot] < \sim 10^{12}$) are linearity correlated
- This FIR/radio correlation is not well understood but is one of the tightest extragalactic correlation yet known
- On smaller galactic scales, this correlation still holds but with some significant variations

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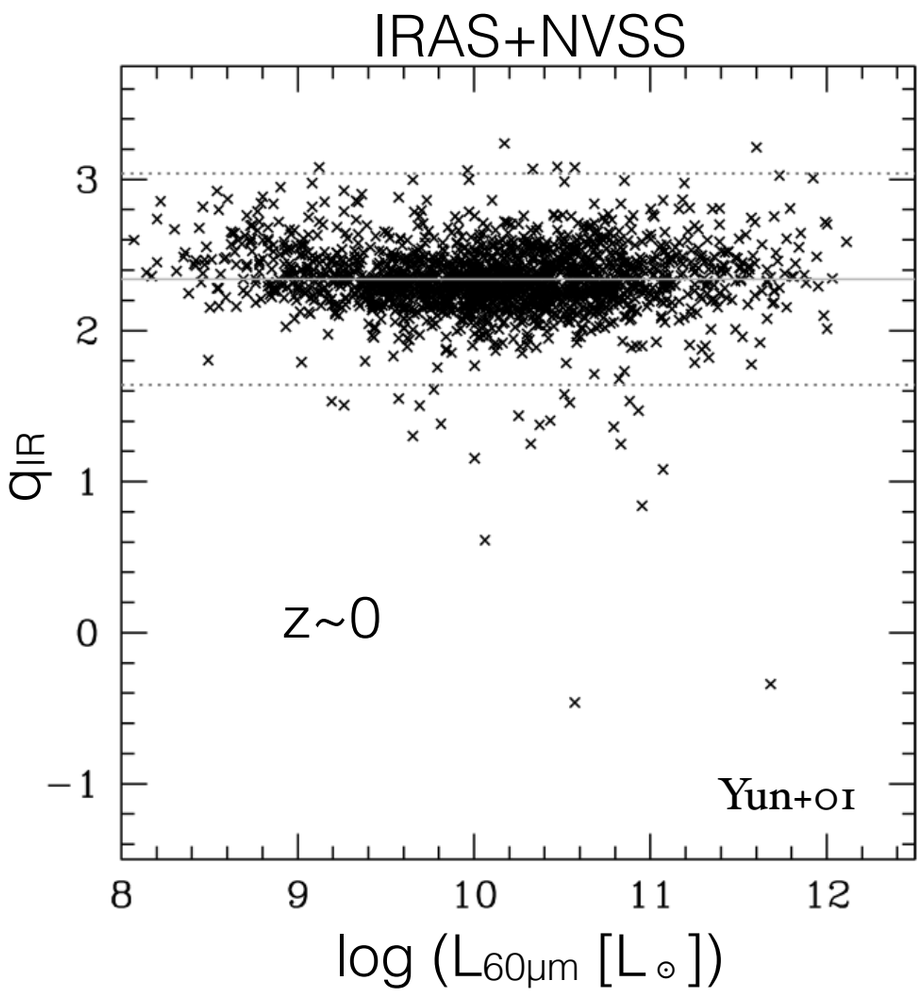

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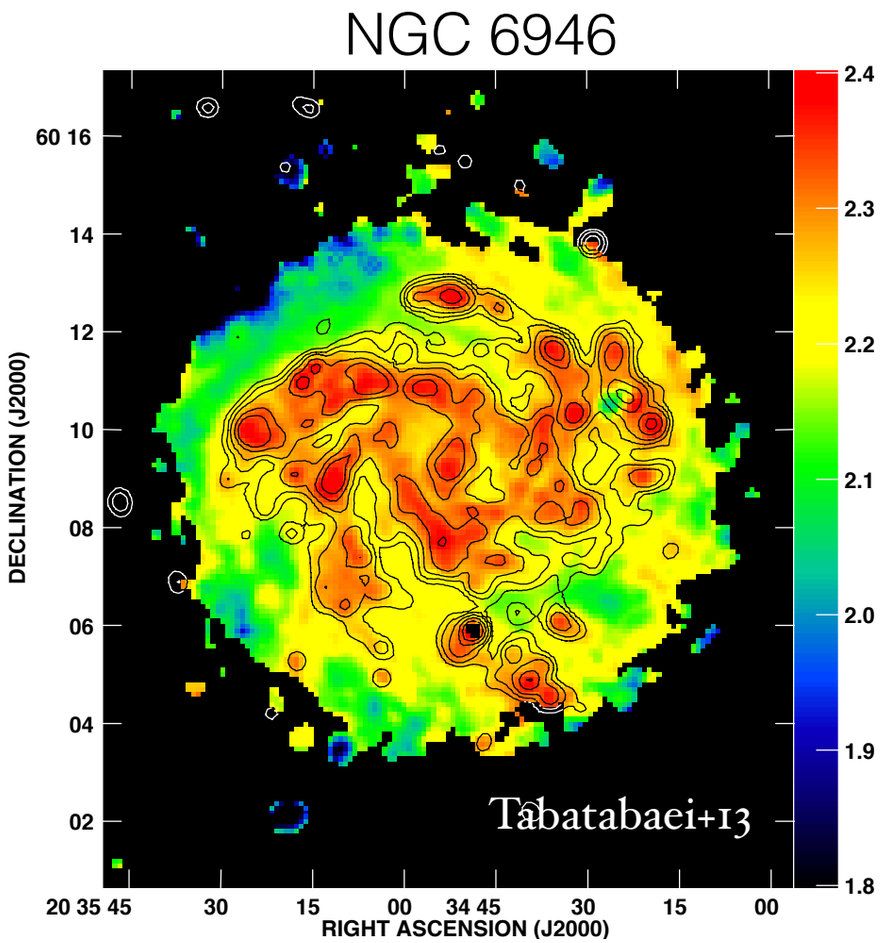

q_{FIR} + contours(Free-Free)

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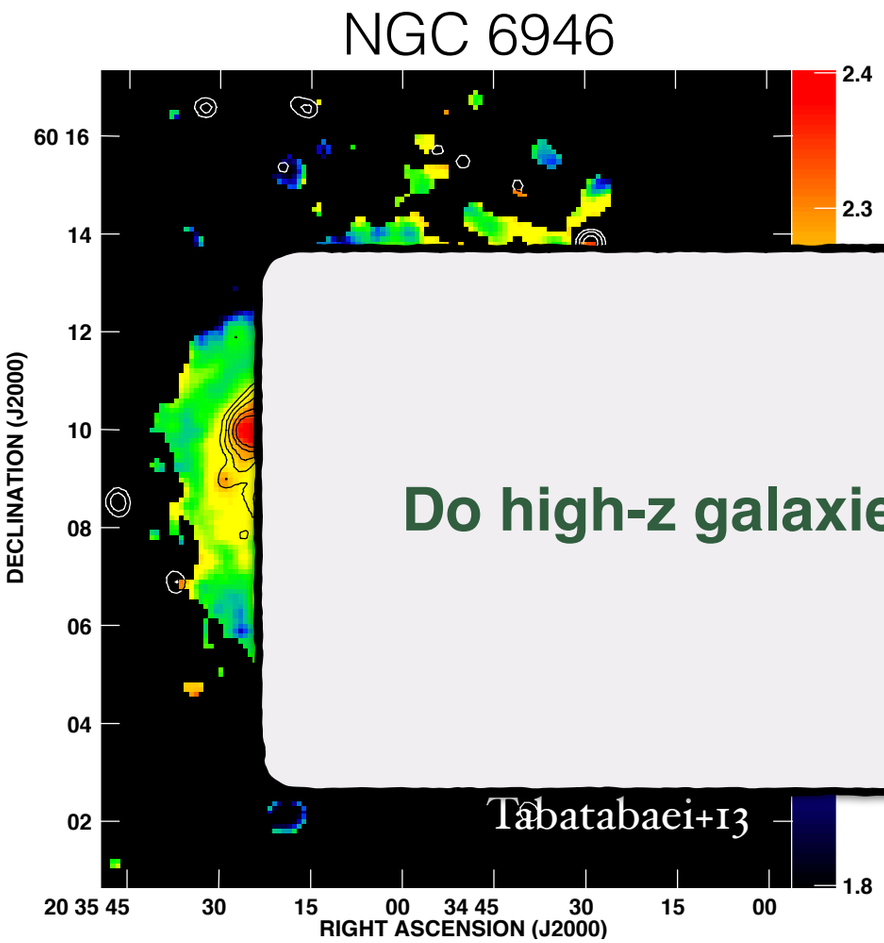

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Do high-z galaxies follow the same FIR/radio correlation ?

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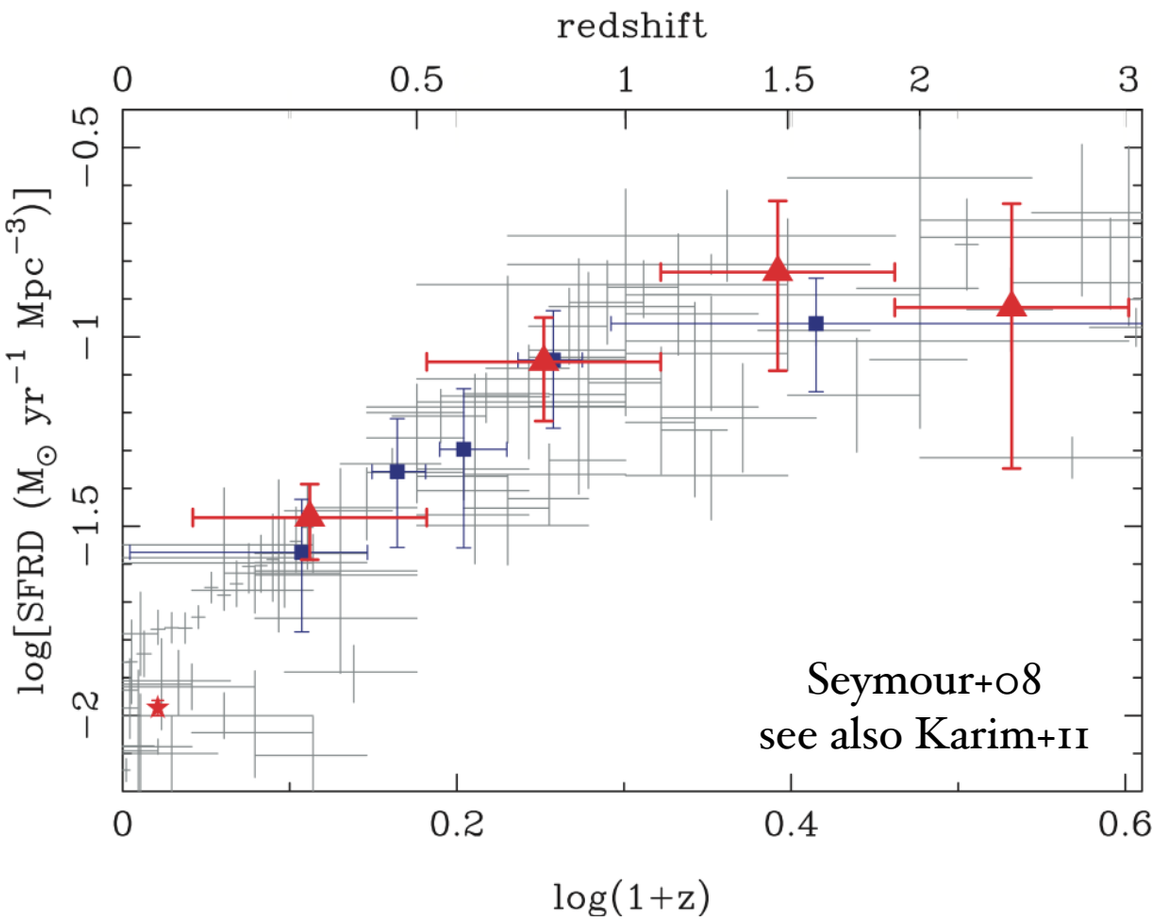
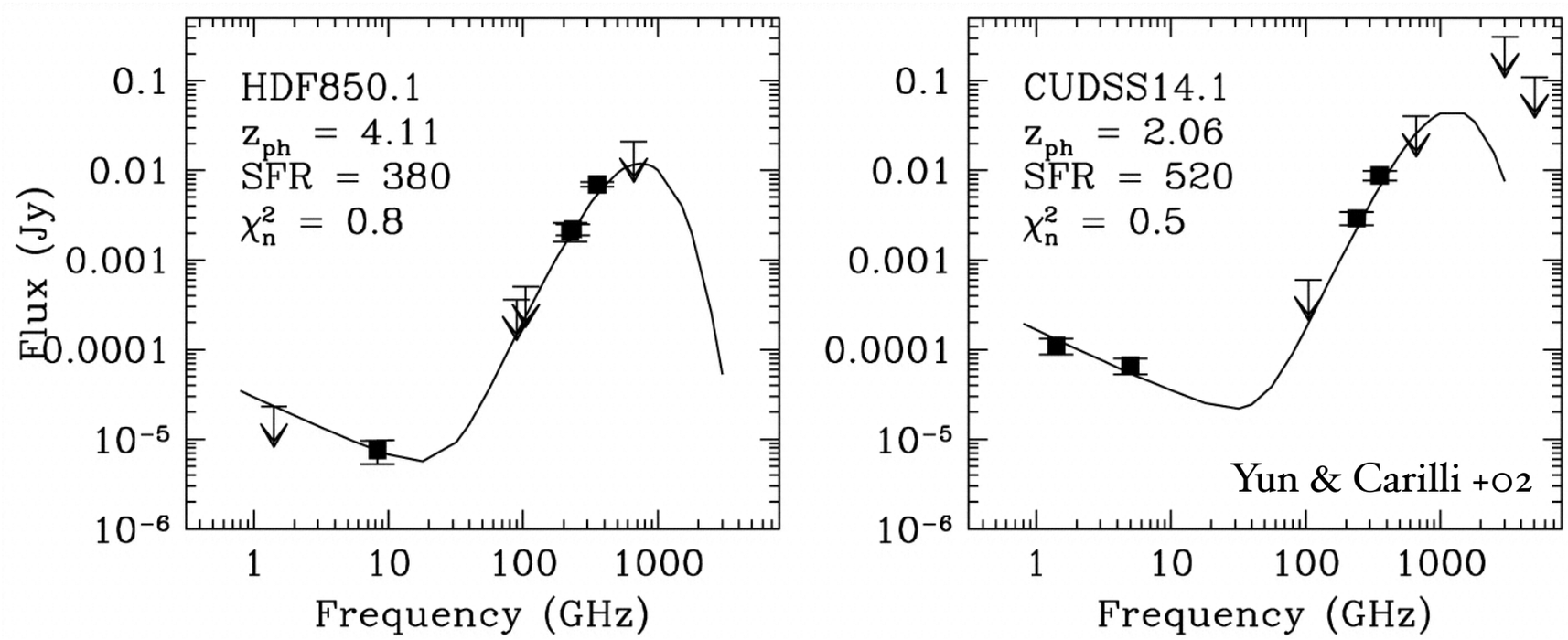
The FIR/radio correlation as a tool for high-z studies



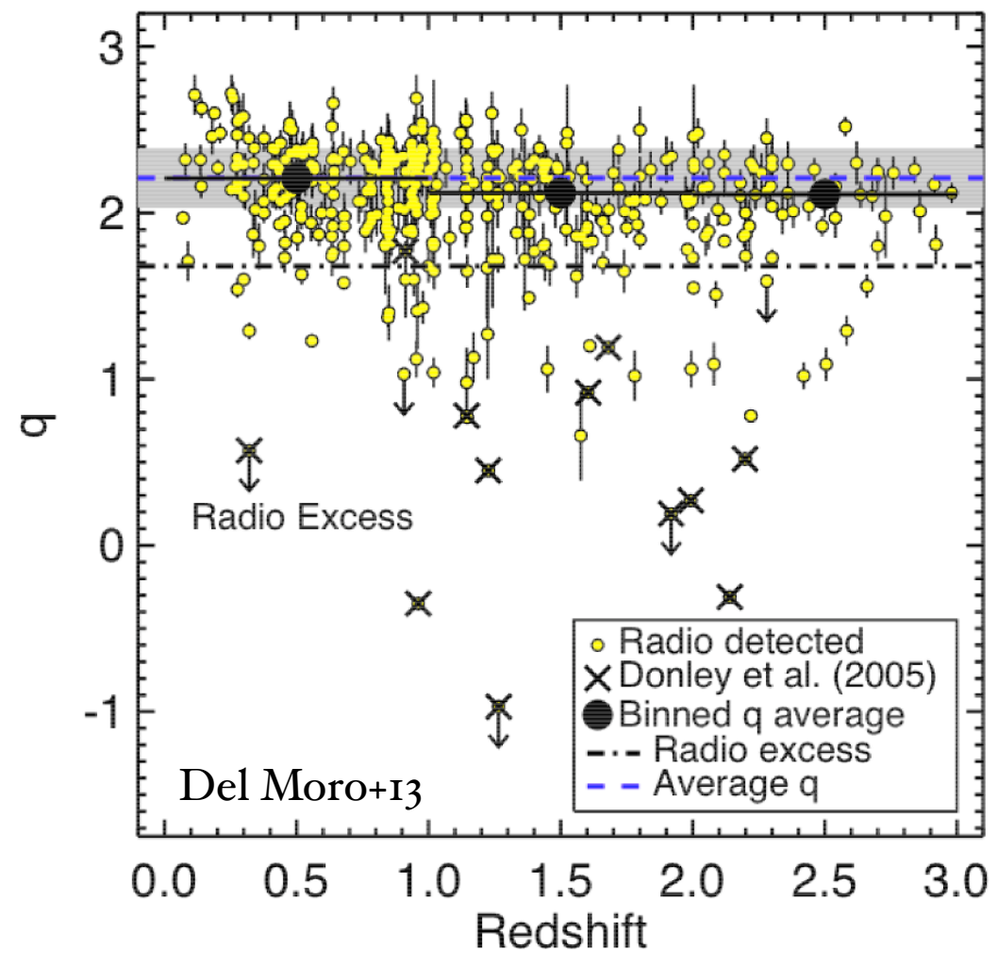
The FIR/radio correlation can be used to calibrate the radio luminosity as an extinction-free SFR indicator for high-z galaxies, allowing us to take advantage of radio observations that are often deeper than FIR surveys with better spatial resolution

The FIR/radio correlation as a tool for high-z studies



The FIR/radio correlation can be used to estimate the redshift of SMGs for which optical spectra are extremely hard to obtain

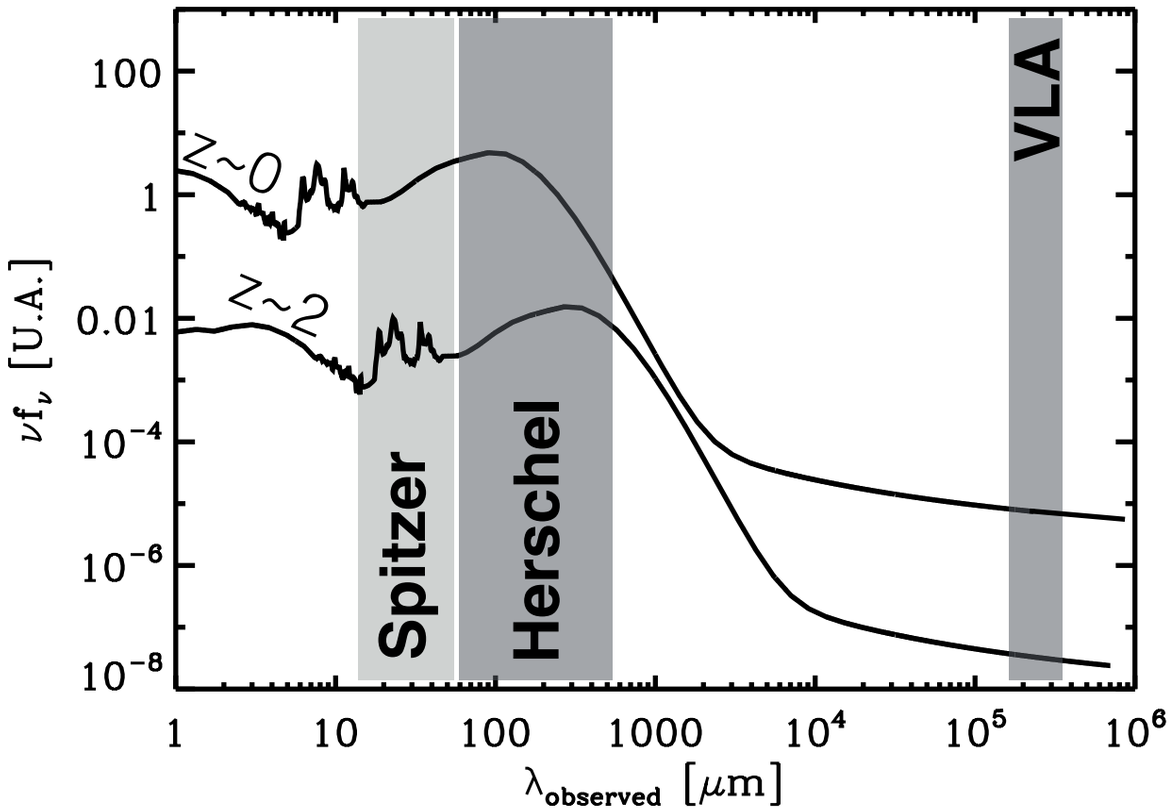
The FIR/radio correlation as a tool for high-z studies



Outliers of the FIR/radio correlation (“radio excess sources”) can be used to detect AGN activities in distant star-forming galaxies hidden to other AGN selection criteria

Redshift evolution of the FIR/radio correlation

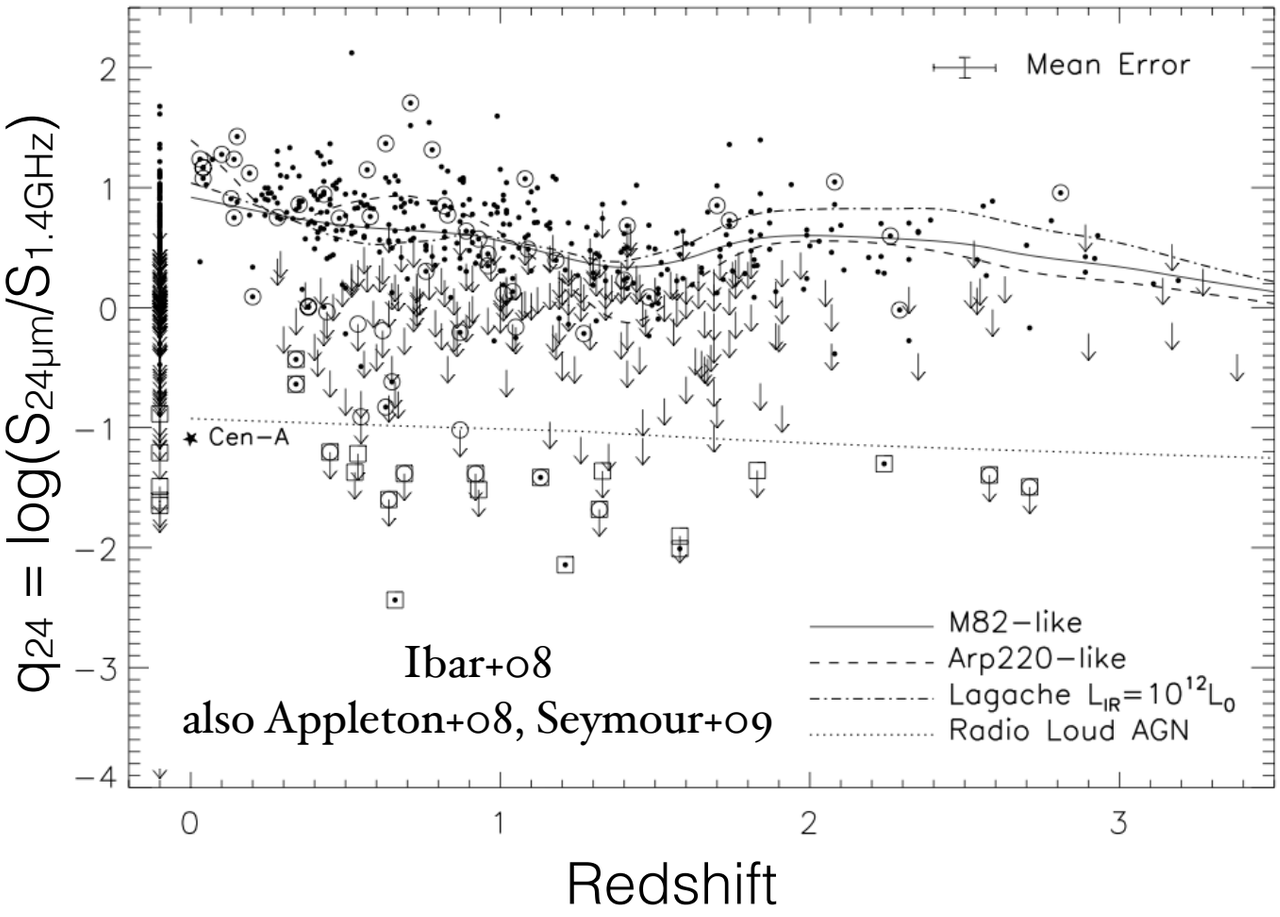
Although the FIR/radio correlation is characterised well at low-z, its form and thus its applicability at high-z still have to be firmly demonstrated.



Constraining the FIR/radio at high-z is a challenging task !

Redshift evolution of the FIR/radio correlation

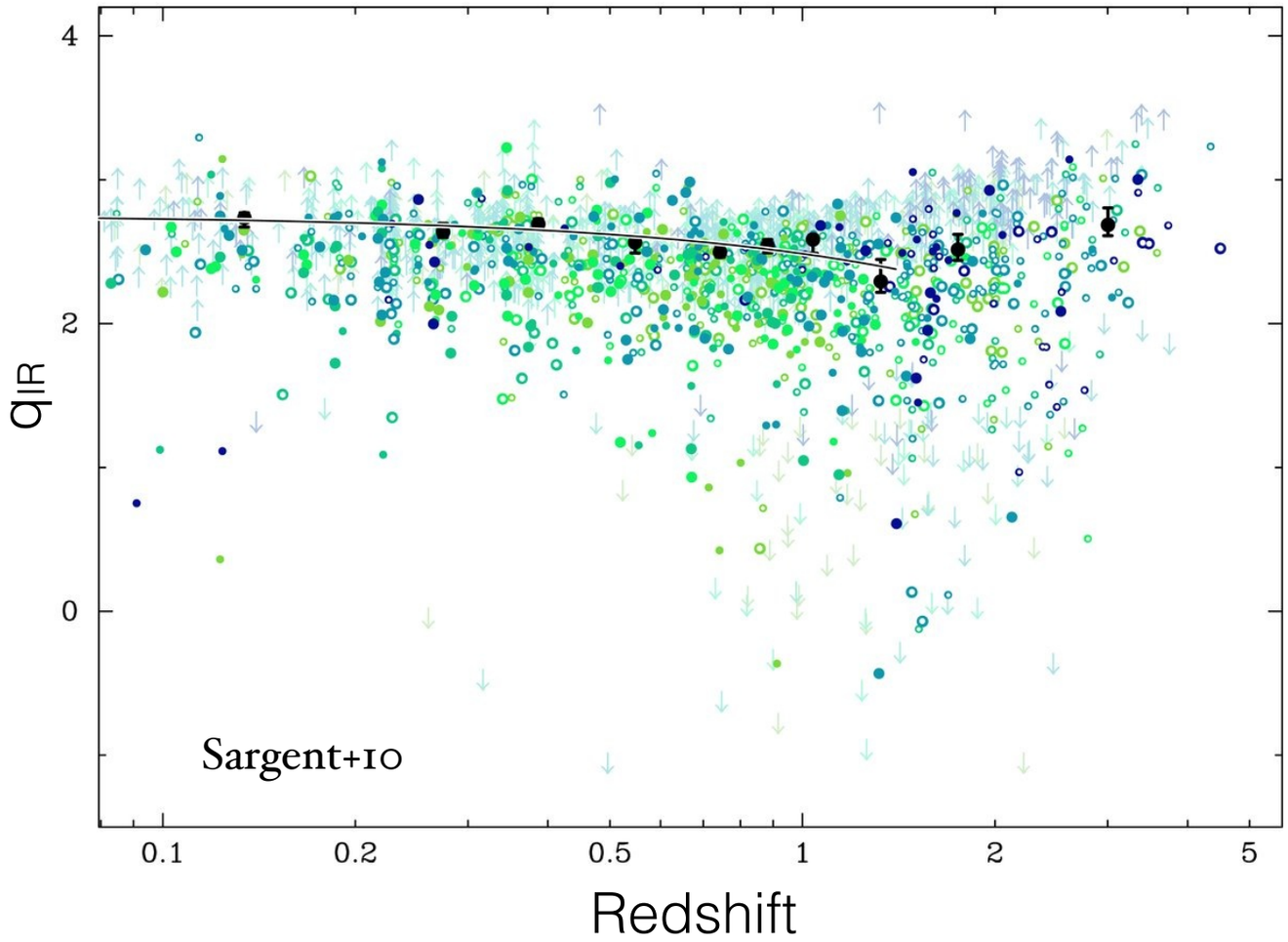
VLA selected + Spitzer detections —> No Evolution



Because of the relatively sparse IR coverage, use of monochromatic flux density ratio, i.e., q_{24}

Redshift evolution of the FIR/radio correlation

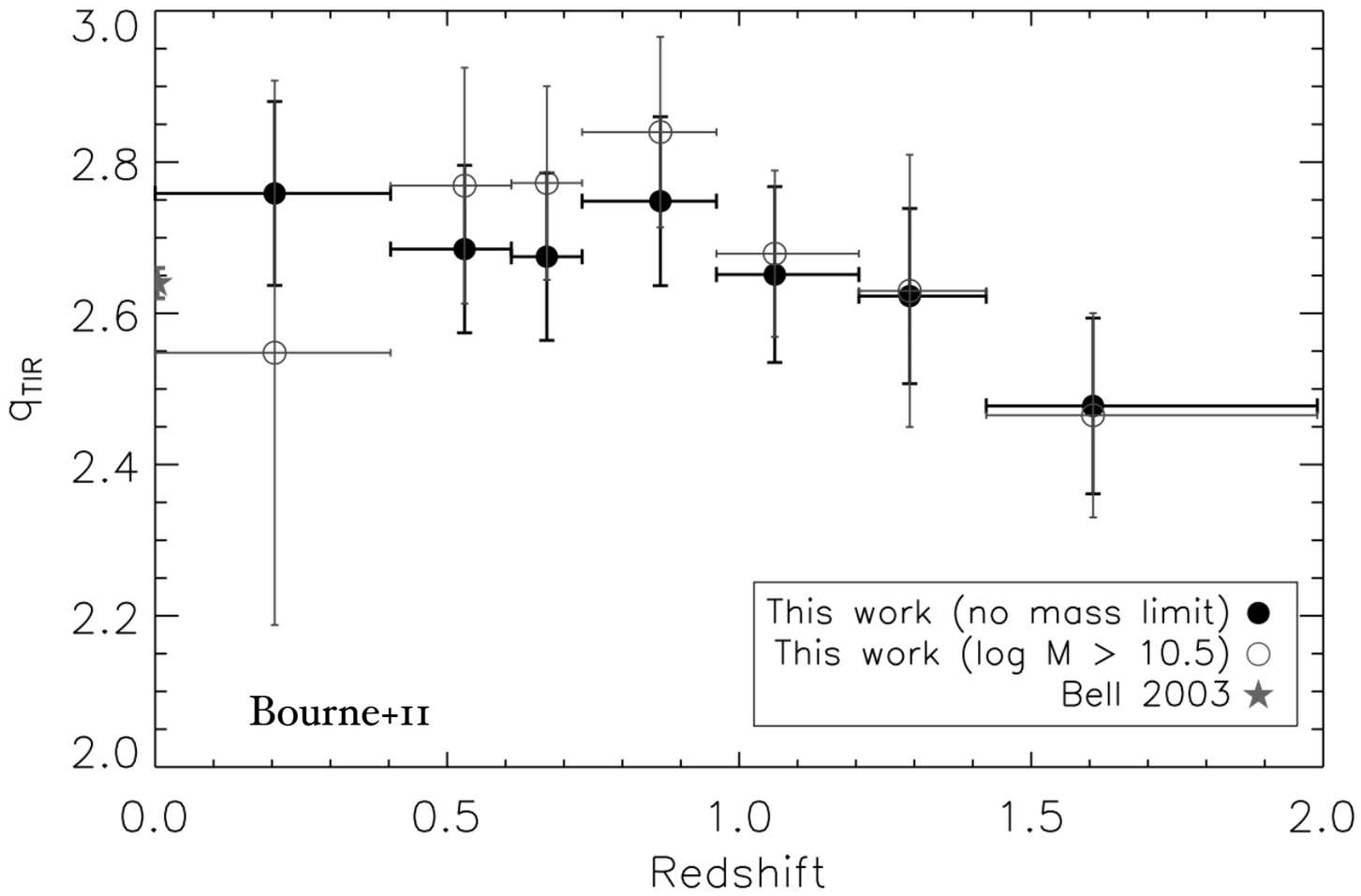
VLA/Spitzer selected + detections/limits —> No (significant) evolution



To ensure a statistically sound treatment of flux limits arising from non-detections employ the method of survival analysis

Redshift evolution of the FIR/radio correlation

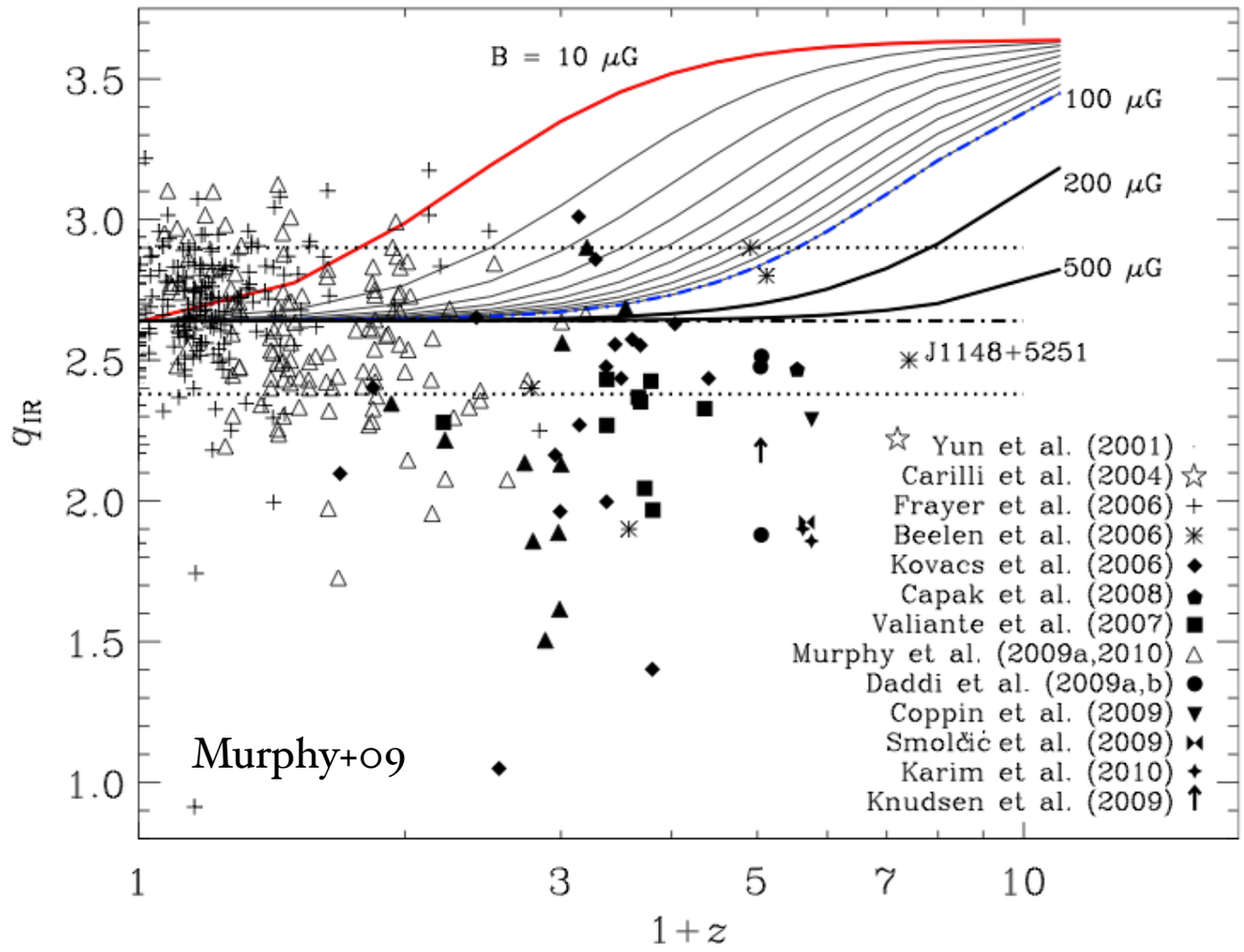
SF mass-selected + VLA/Spitzer stacking —> Evolution



In order to remove any obvious selection biases, use of a SF mass-selected sample combined with a radio and IR stacking analysis

Redshift evolution of the FIR/radio correlation

SMGs —> Evolution



SMGs galaxies situated at very high-z, i.e., z~2-3, exhibit significantly low value of q_{IR}

Redshift evolution of the FIR/radio correlation

LIR-selected + VLA/Herschel stacking —> Evolution

Is there a significant evolution of the FIR/radio correlation with redshift ?

✓ We need a complete sample of SF galaxies up to z~2
—> Use of a mass-selected galaxy sample

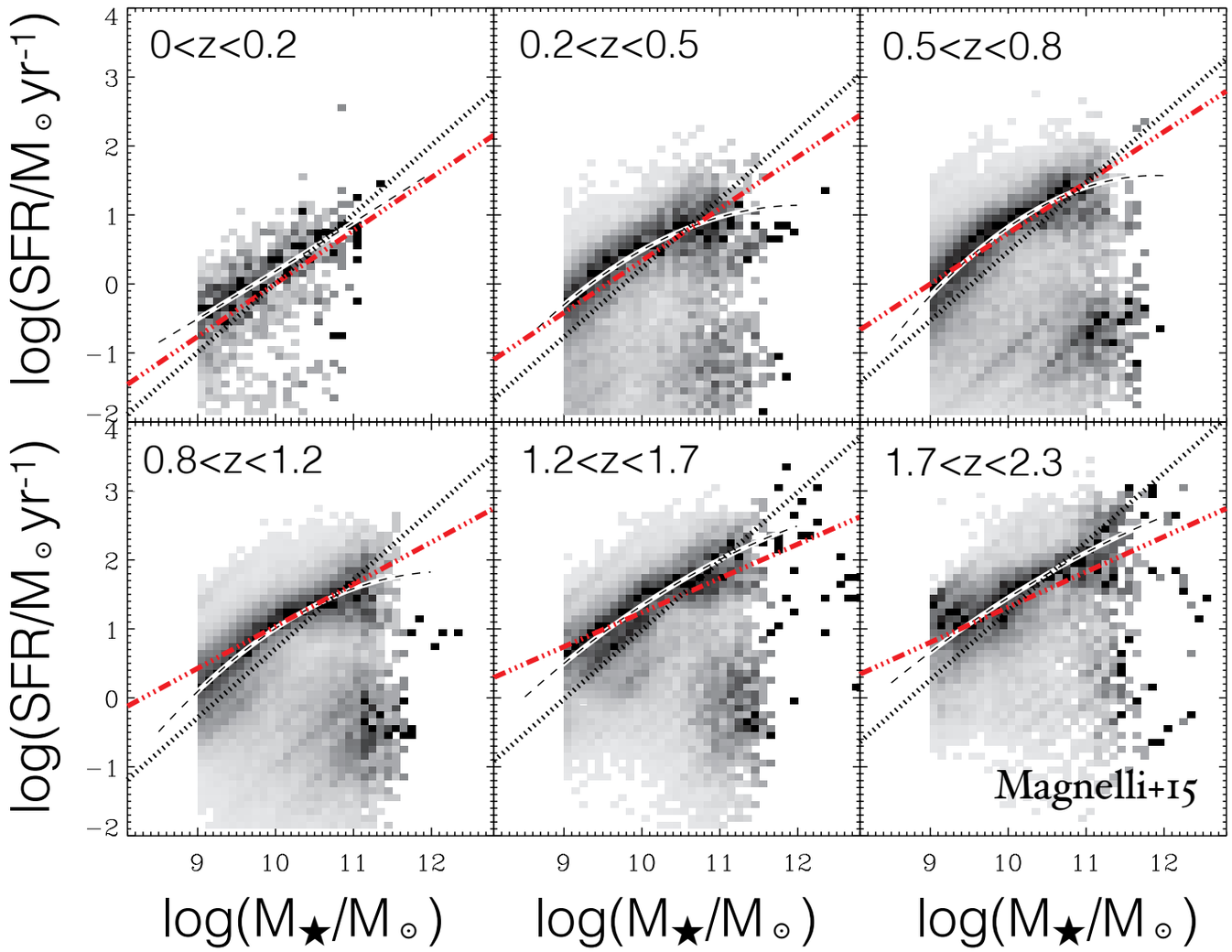
✓ We need accurate L_{IR} estimates
—> Use of deep Herschel observations

✓ We need accurate k-corrected $L_{1.4GHz}$ estimates
—> Use of deep VLA 1.4GHz and GMRT 610MHz (Thomson+14) observations

The FIR observations provided by Herschel improve significantly our estimate of L_{IR} for high-z galaxies

The SFR - M$_\star$ plane

Mass-selected sample in the ECDFS, COSMOS and GOODS-N/S fields



Over the last 10 Gyr, we observe a correlation between the SFR and M$_\star$ of star-forming galaxies: the “main sequence” (MS) of star formation.

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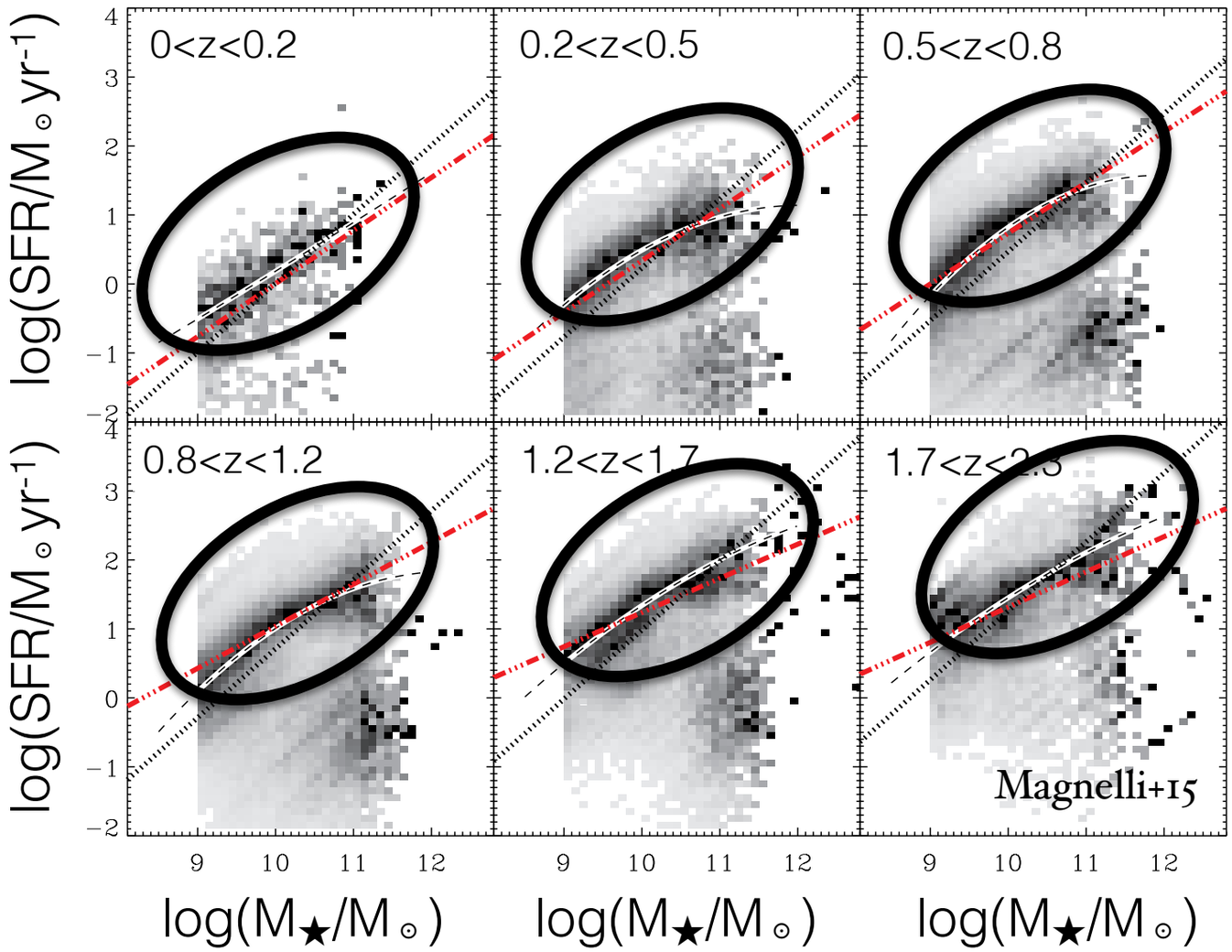

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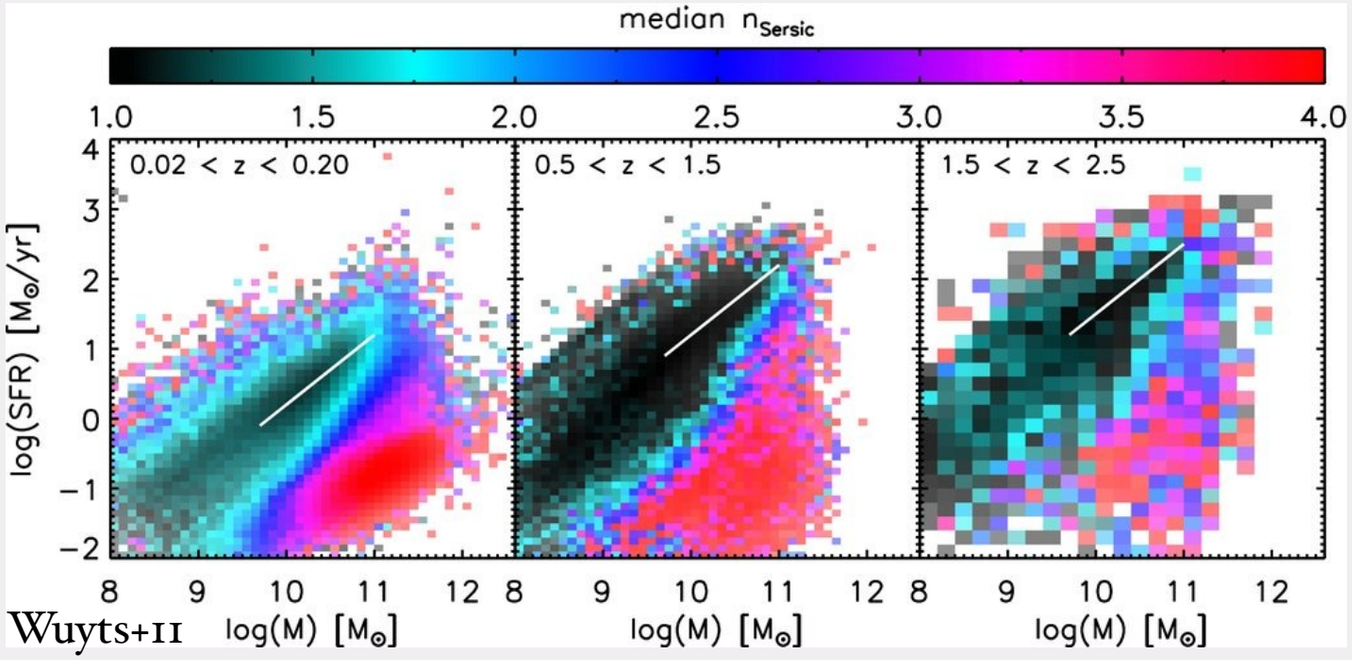
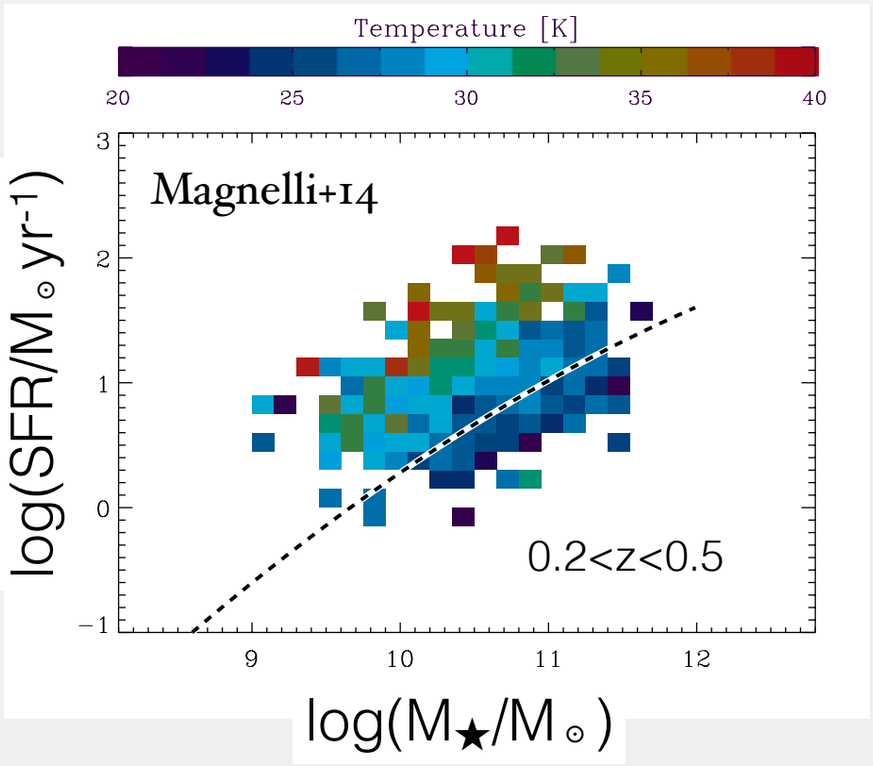


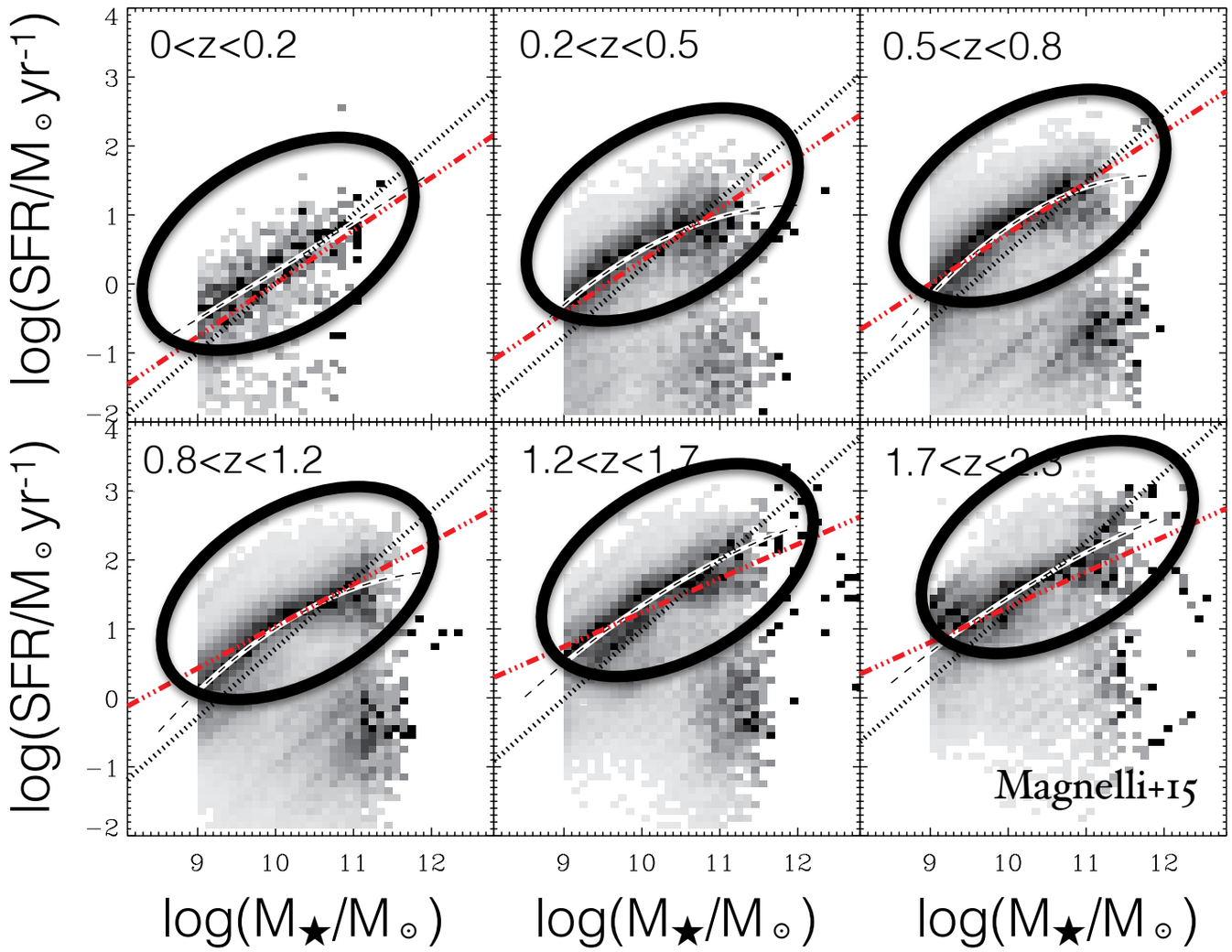


—> The localization of galaxies with respect to the MS correlates some of their physical properties, suggesting that on- and off-MS galaxies experience different mode of star-formation

of star-forming galaxies: the "main sequence" (MS) of star formation.

The SFR - $M_\star$ plane

Mass-selected sample in the ECDFS, COSMOS and GOODS-N/S fields



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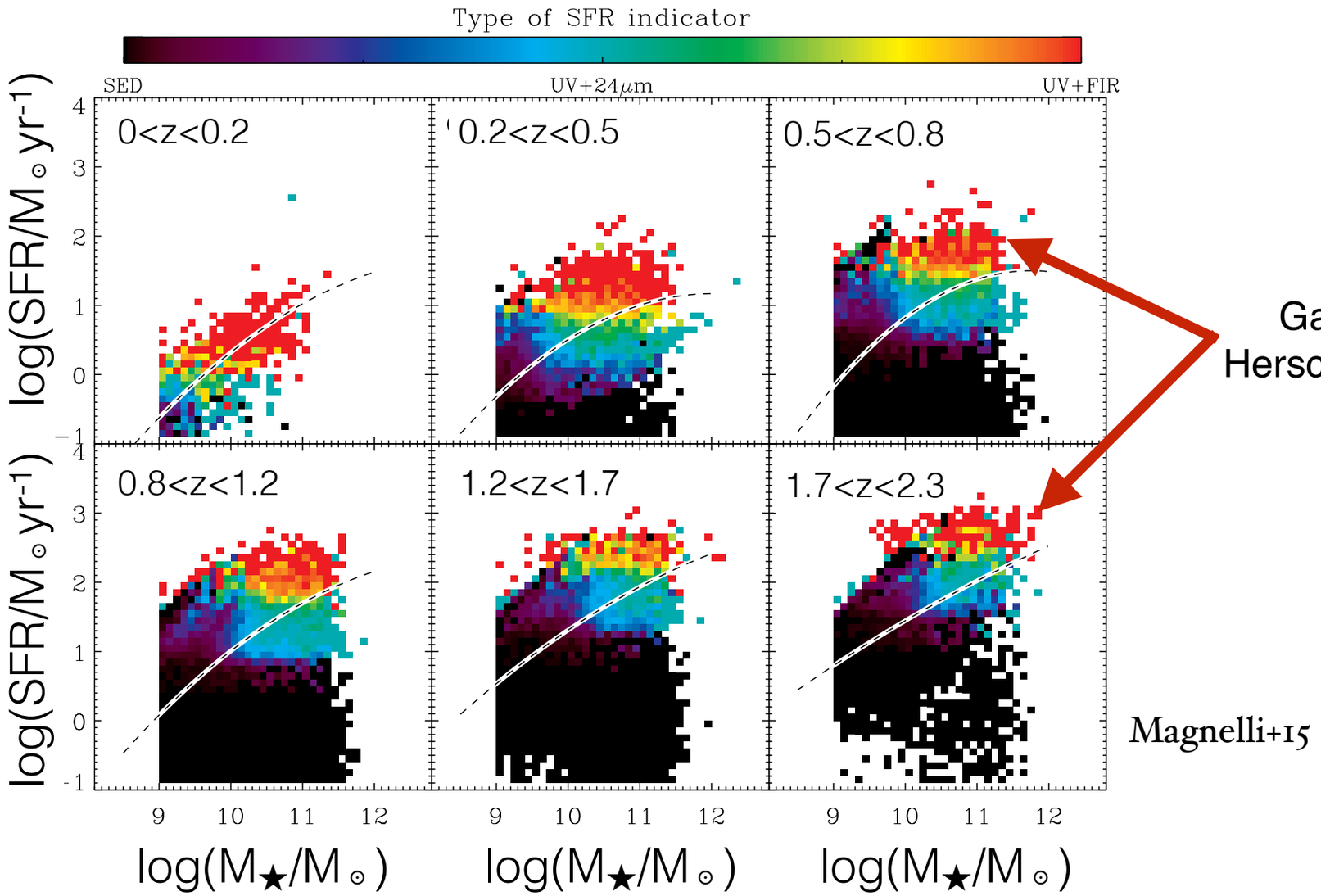
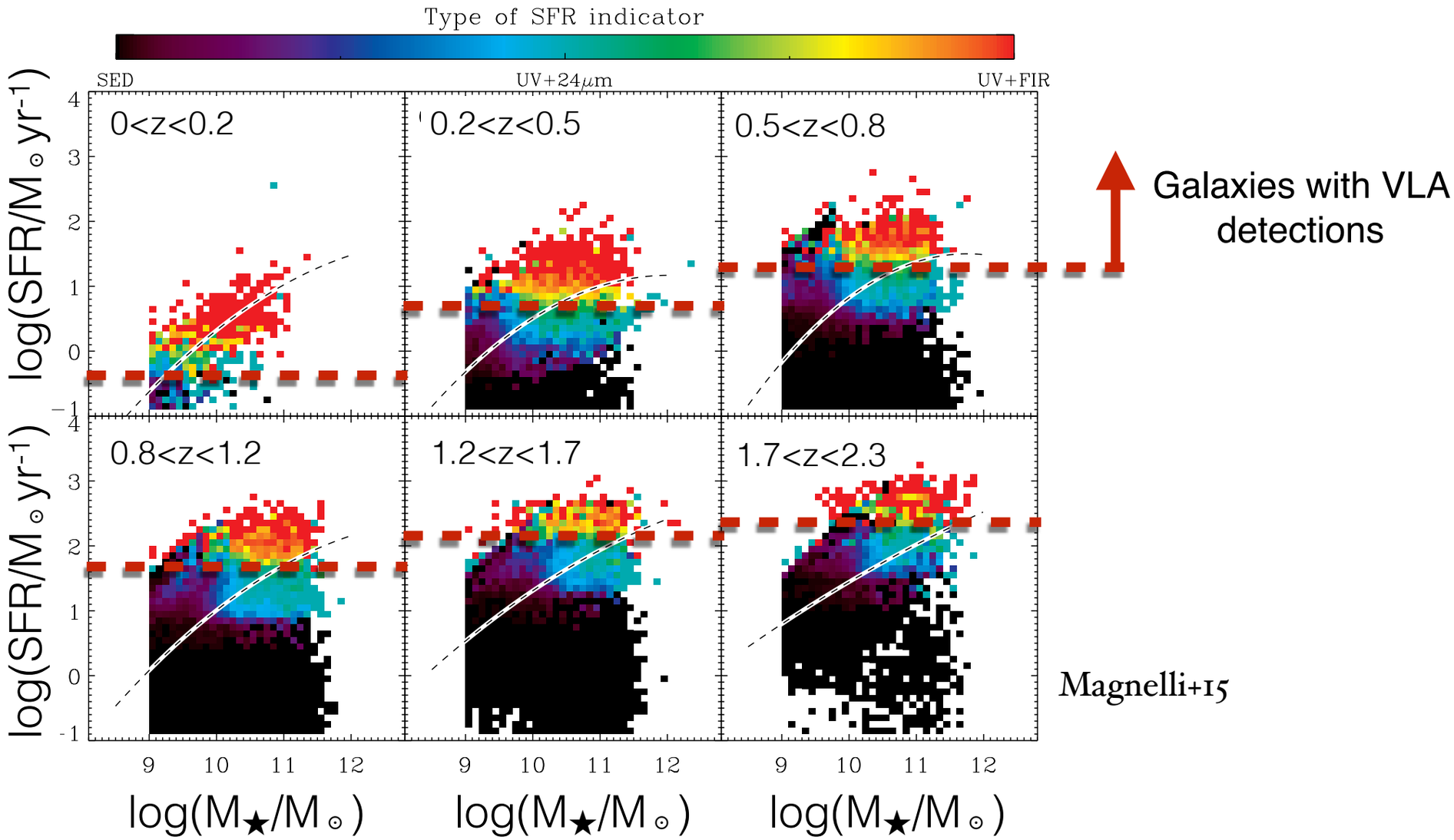


The Herschel observations needed for accurate L_{IR} estimates probe the MS only at the highest stellar masses

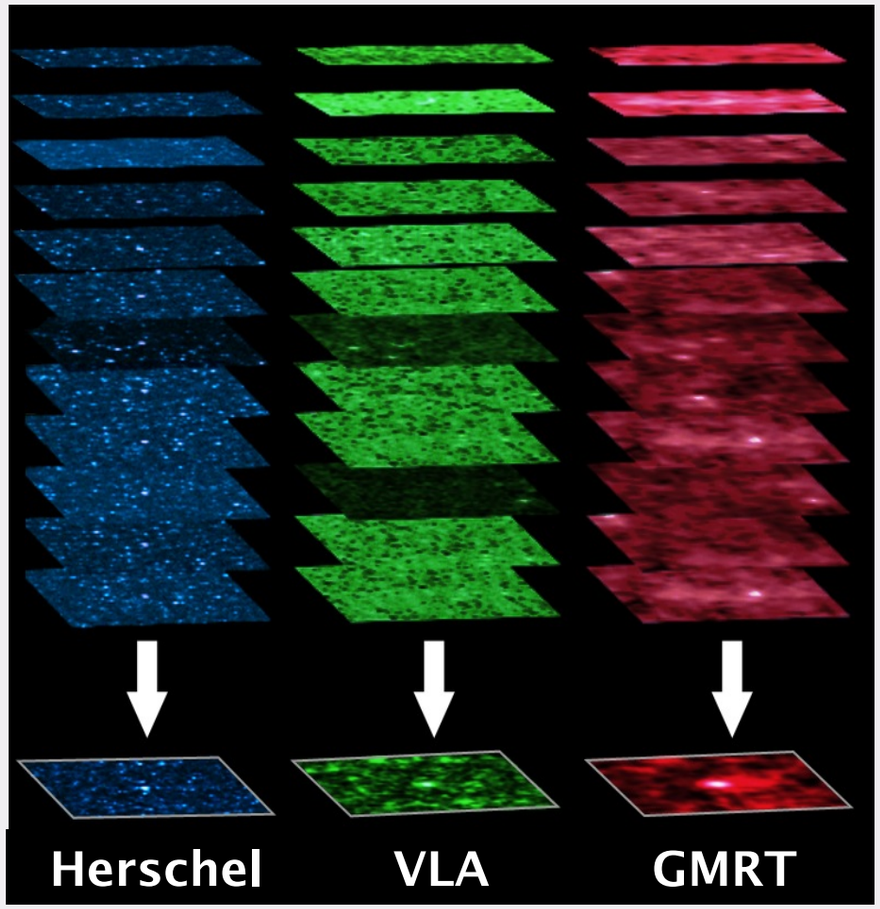
The SFR - M$_\star$ plane



VLA observations (as well as GMRT) probe only the high-mass end of the MS of star-formation

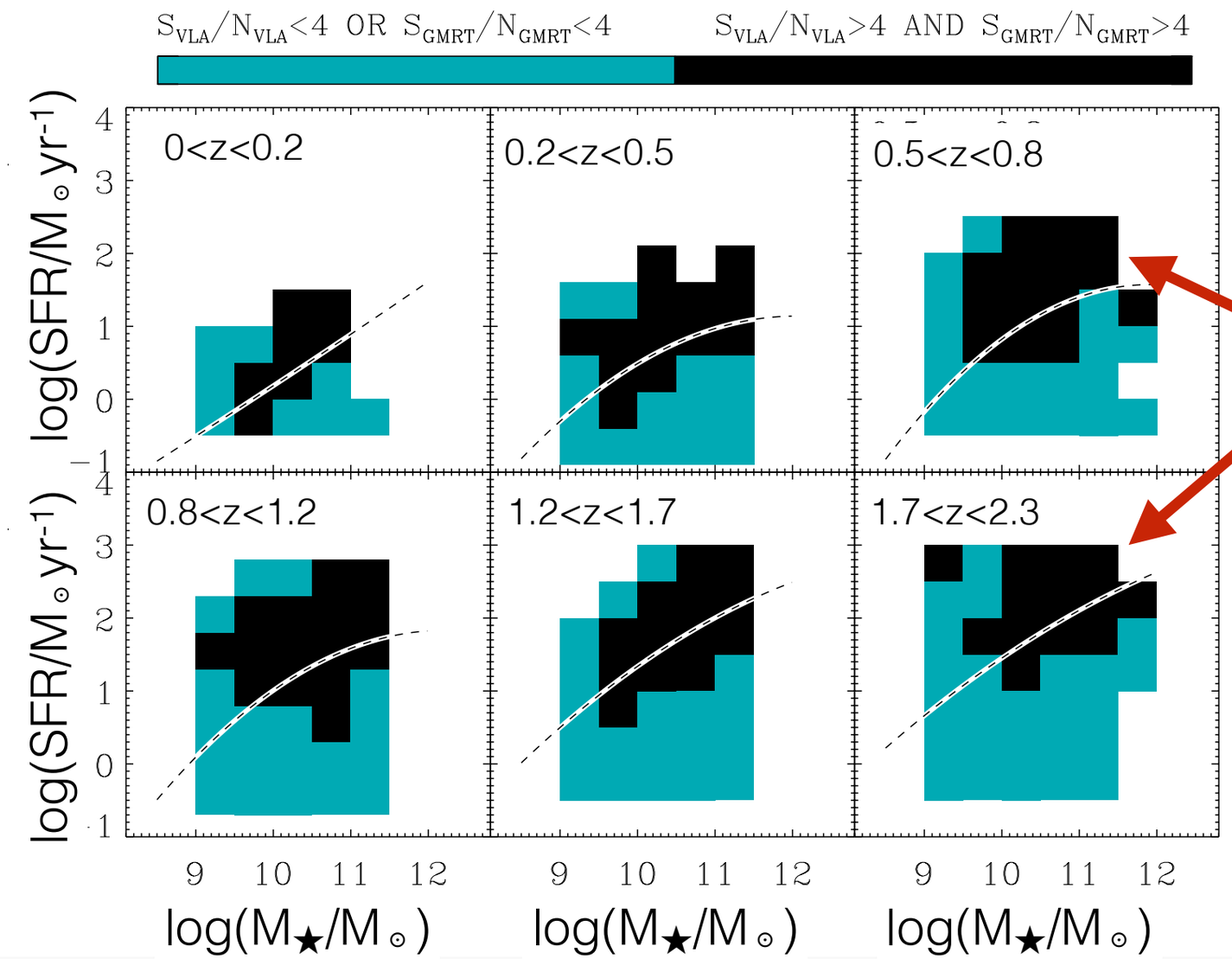
The SFR - M* plane

We need to use a stacking analysis



FIR [illegible] use the uncertainties on L_{IR}

A FIR and radio stacking analysis



Our stacking analysis allows us to obtain the radio spectral index of ALL star-forming (on- and above-MS) galaxies with $M_\star > 10^{10}\ M_\odot$

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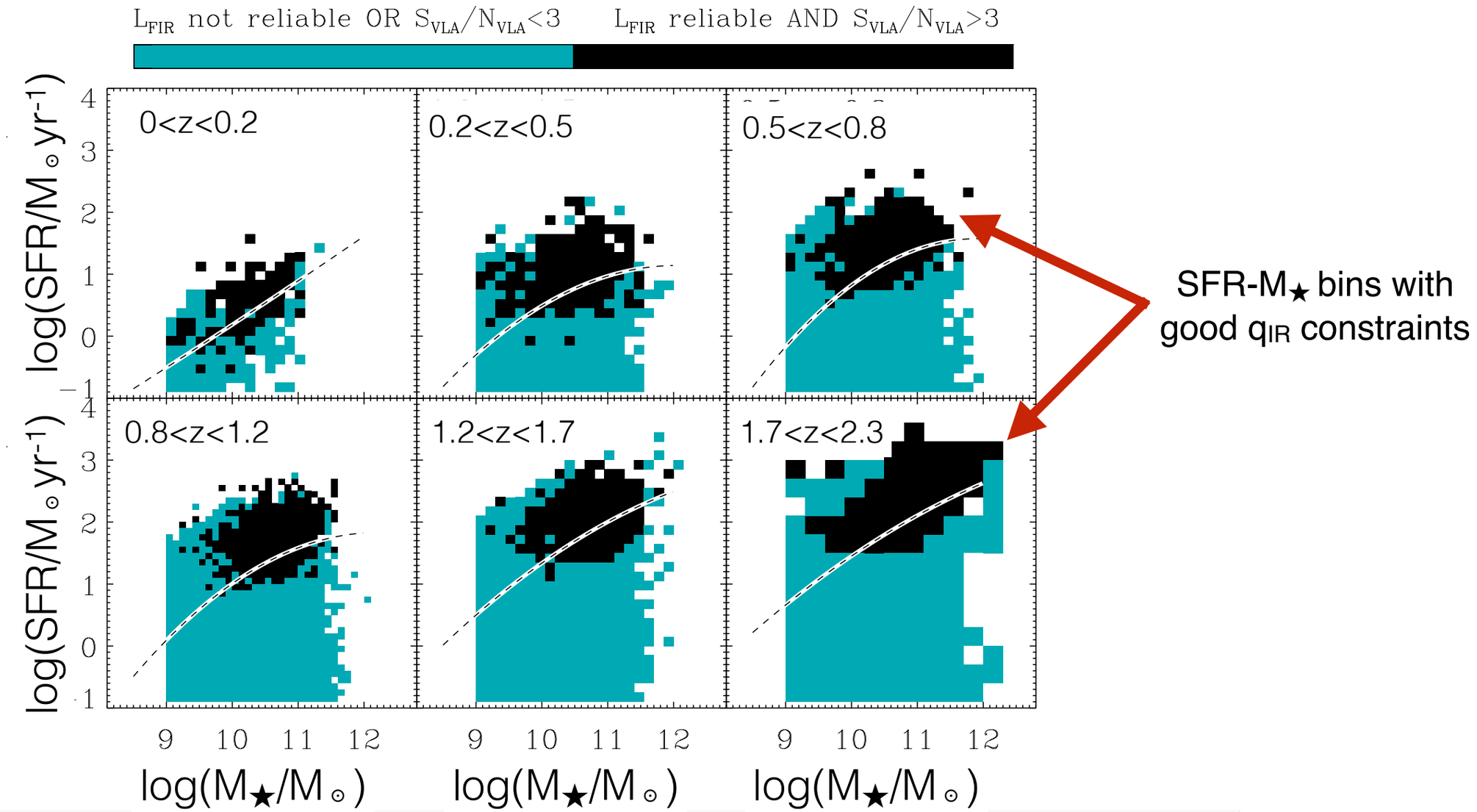
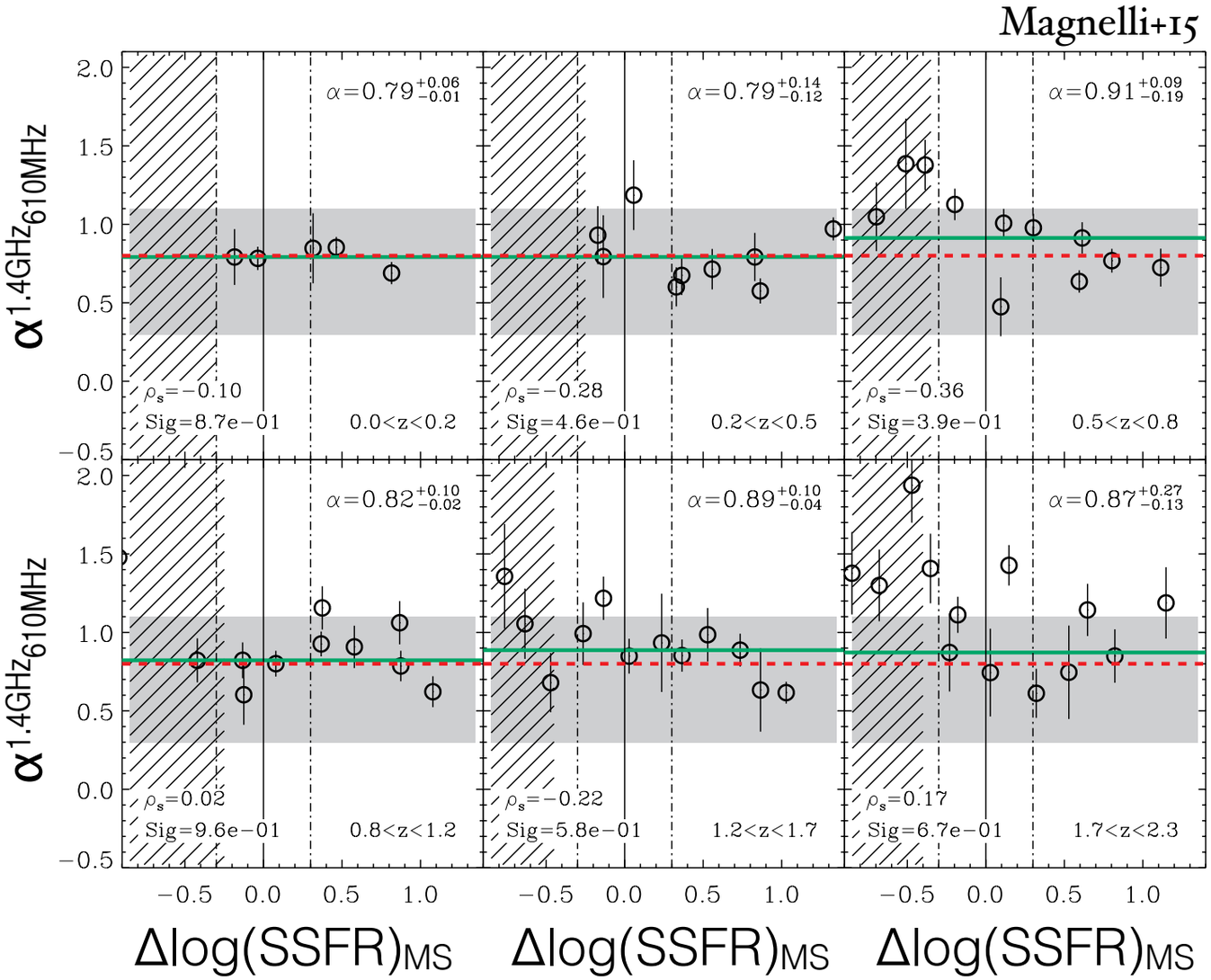
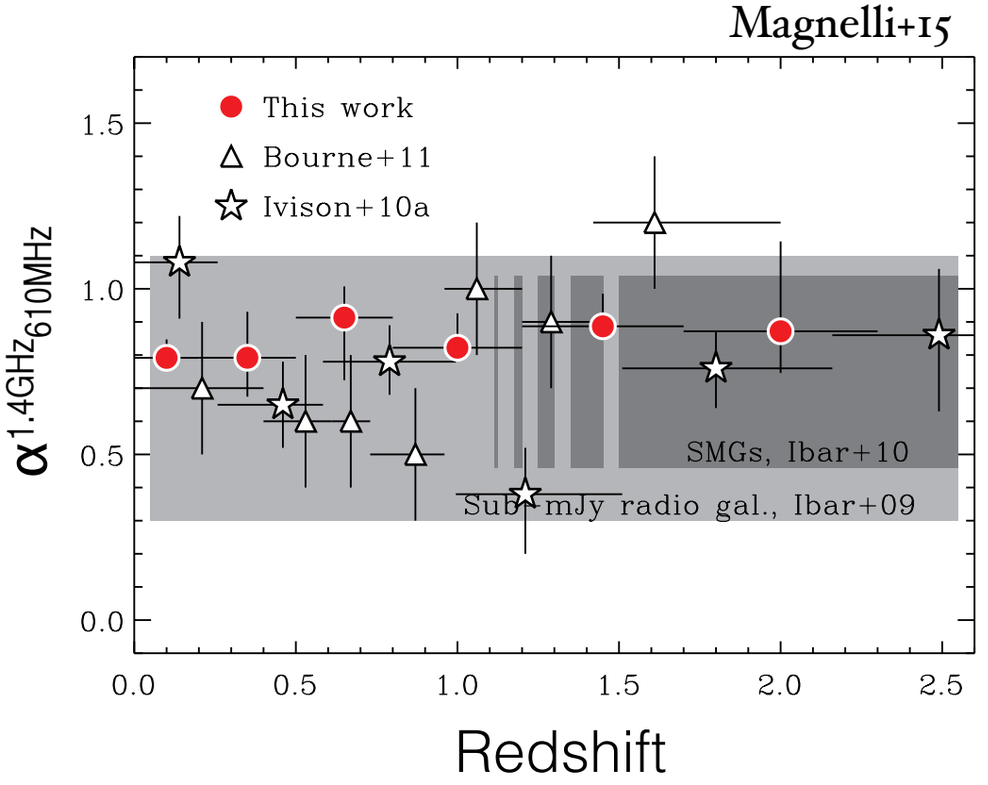


Our stacking analysis allows us to constrain the FIR/radio correlation of ALL star-forming (on- and above-MS) galaxies with $M_\star > 10^{10}\ M_\odot$

The radio spectral index





We do not observe any significant evolution of the radio spectral index, $\alpha^{1.4GHz}_{610MHz}$, within the SFR - $M_\star$ plane and with redshift

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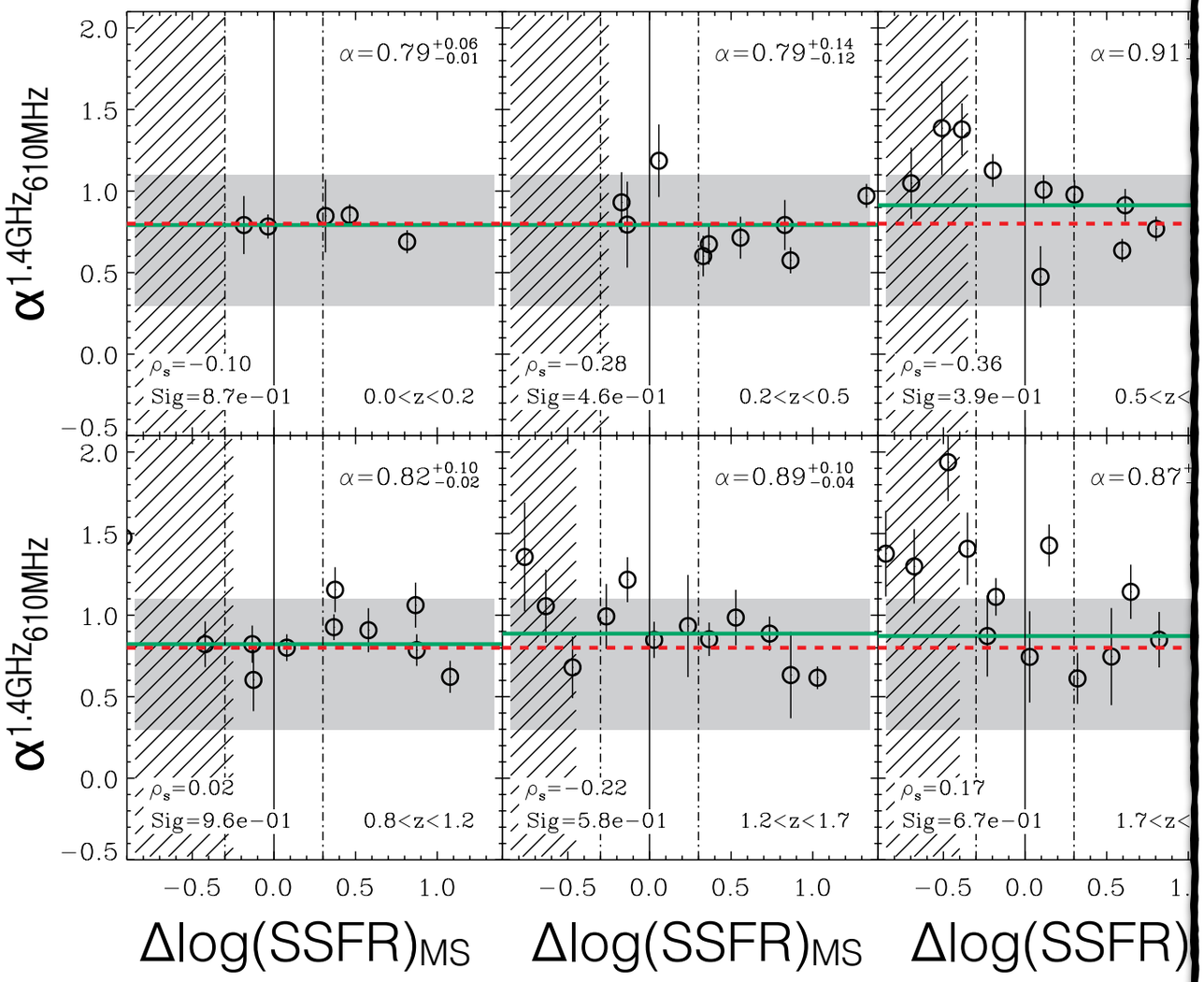

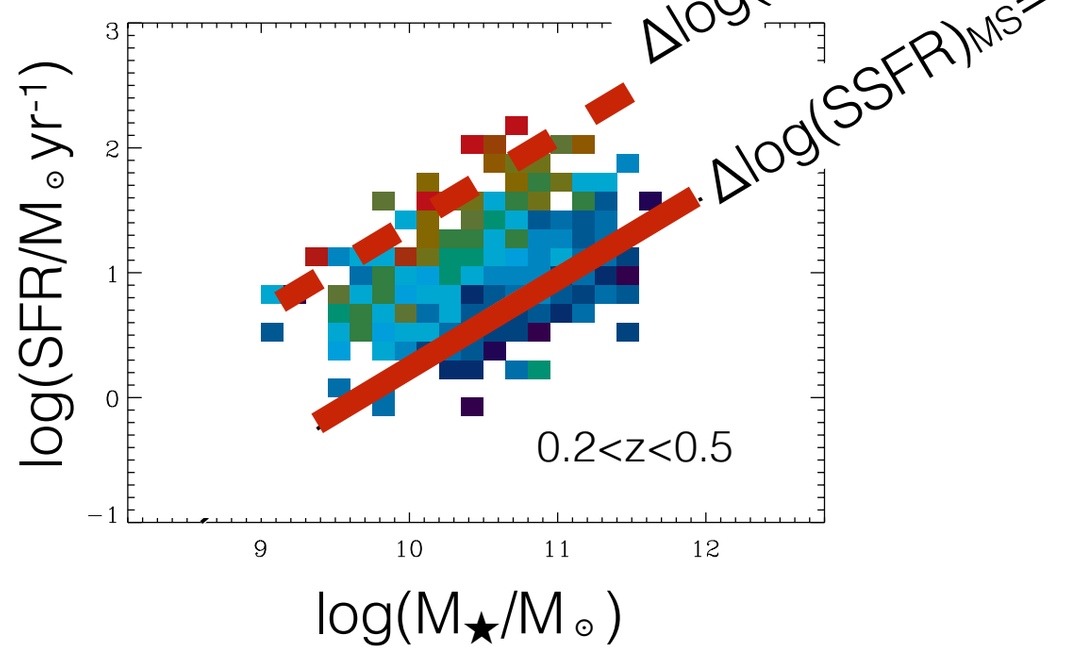

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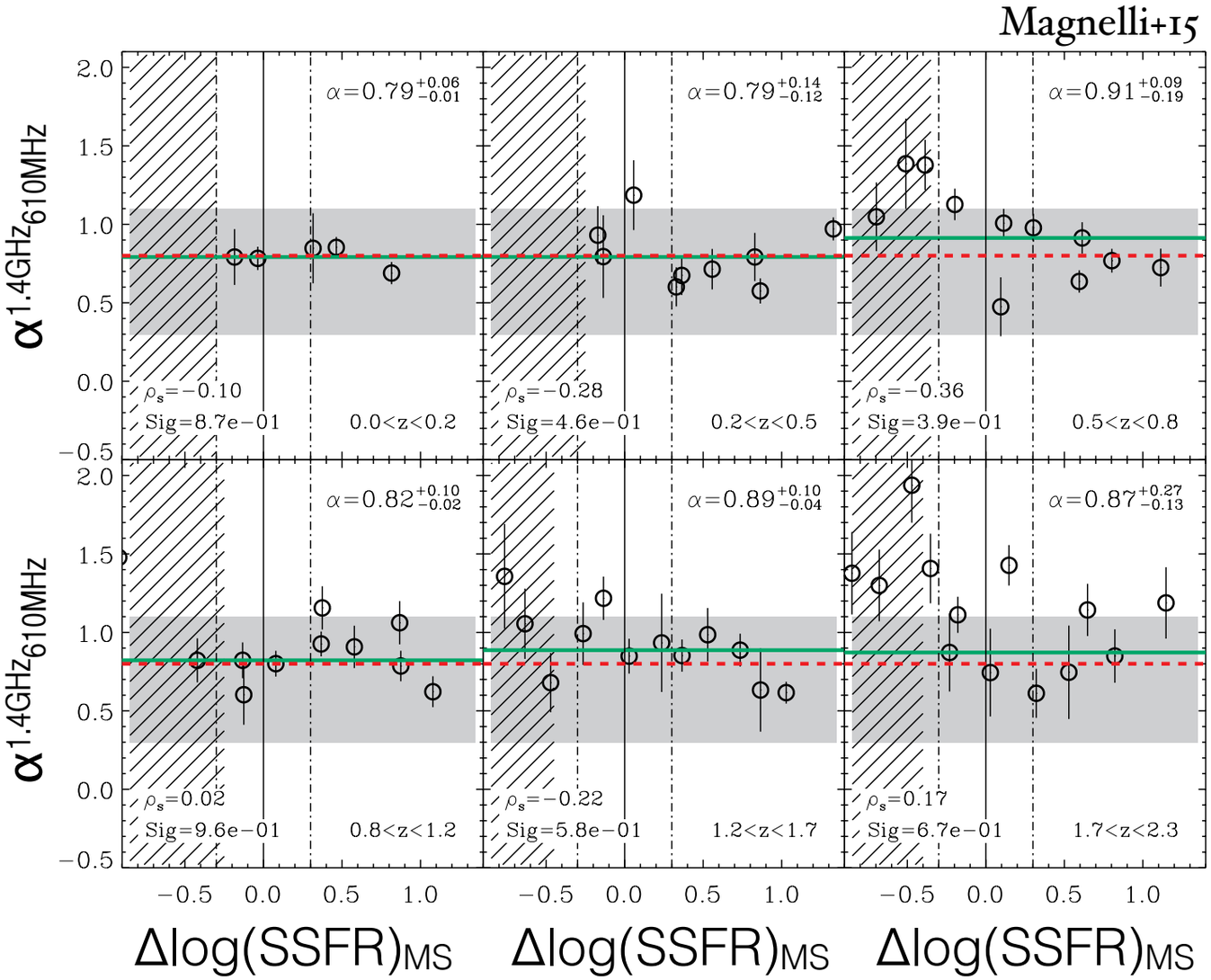

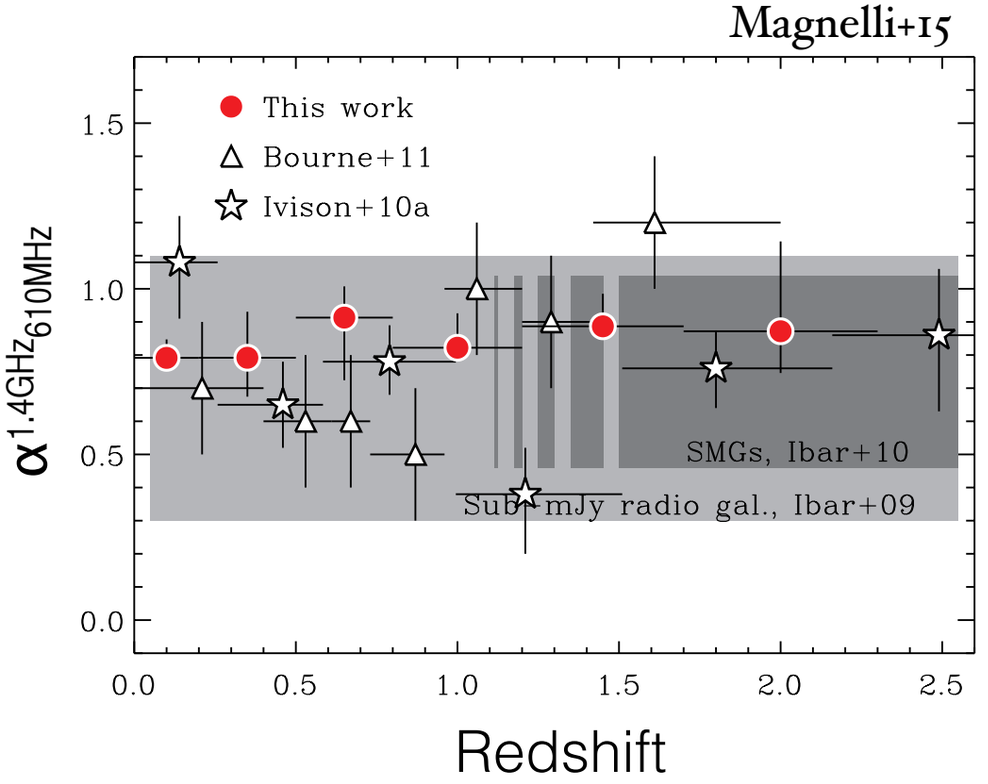

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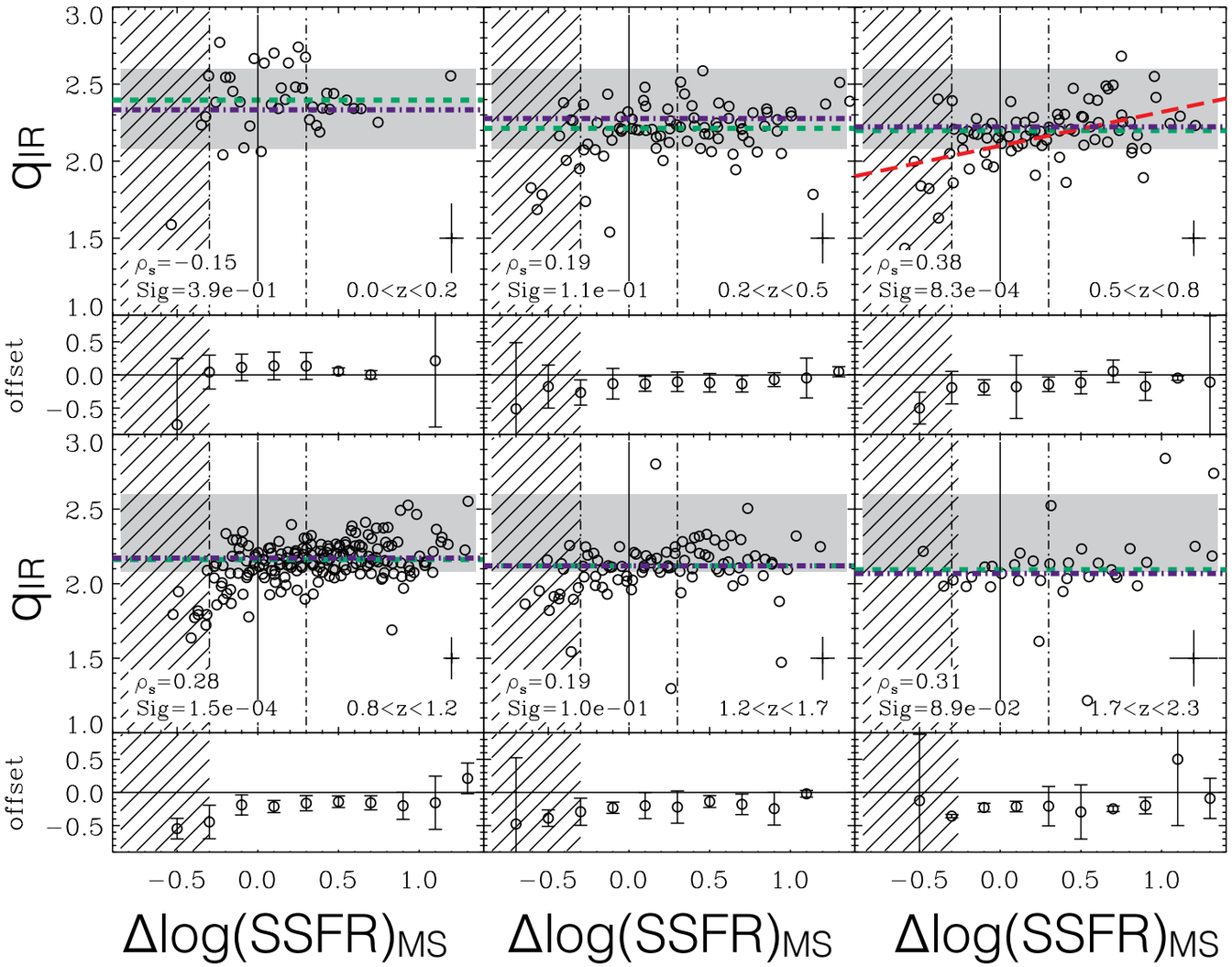
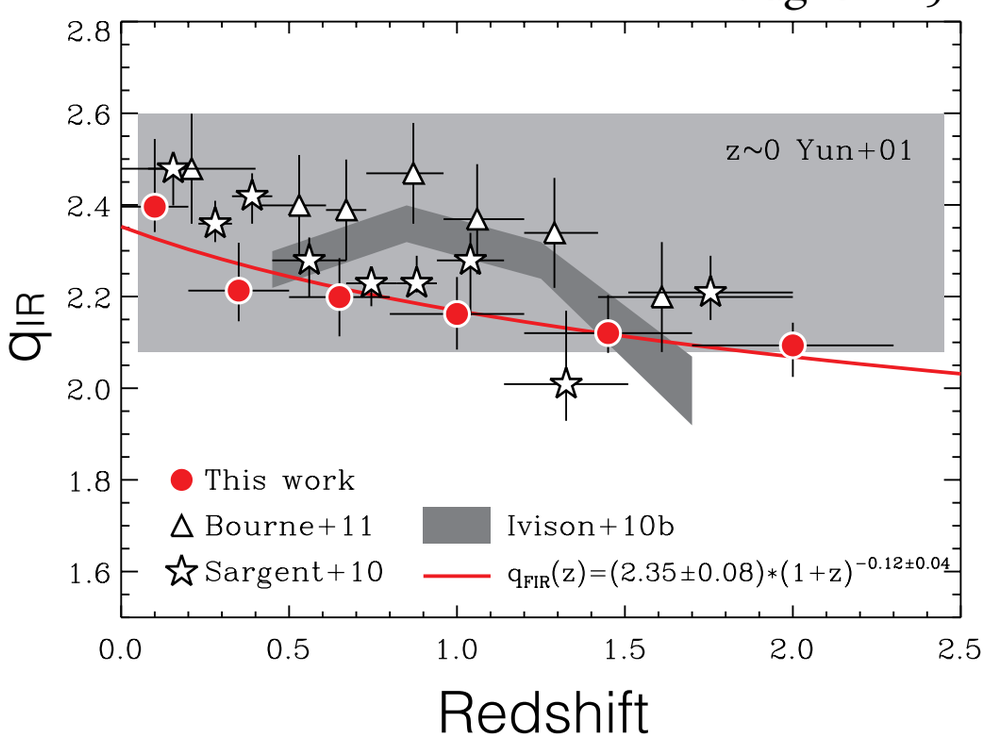
The FIR/radio correlation





- The FIR/radio correlation holds up to at least z~2
- q_{IR} displays a moderate but statistically significant redshift evolution $\propto(1+z)^{-0.12}$
- There is no significant evolution of q_{IR} within the SFR - $M_\star$ plane

Summary

- Using deep Herschel (100-500 μm), VLA 1.4GHz and GMRT 610MHz observations, we constrained the radio spectral index and FIR/radio correlation in all SF galaxies galaxies with $M_\star > 10^{10}$ $M_\odot$ and up to z~2
- The radio spectral index of normal and starbursting galaxies are consistent up to z~2 with a standard value of 0.8
- The FIR/radio correlation holds up to at least z~2, but q_{IR} displays a moderate but statistically significant redshift evolution $\propto (1+z)^{-0.12}$
- This evolution suggests that the ISM properties (e.g. magnetic field strength, gas densities, Σ_{SFR} , …) of SF galaxies evolve between z~0 and z~2

Outlook: SKA

Square Kilometre Array

"building the largest and most sensitive radio telescope in the world"

- ✓ A large total collective area of 1km^2
- ✓ Large frequency range coverage, 50MHz- 14GHz

- ❖ Emerging from the Dark Ages and the Epoch of Reionization
- ❖ Strong-field Tests of Gravity with Pulsars and Black Holes
- ❖ The Origin and Evolution of Cosmic Magnetism
- ❖ Galaxy Evolution, Cosmology & Dark Energy
- ❖ The Cradle of Life & Astrobiology

see Carilli & Rawlings 2004 and
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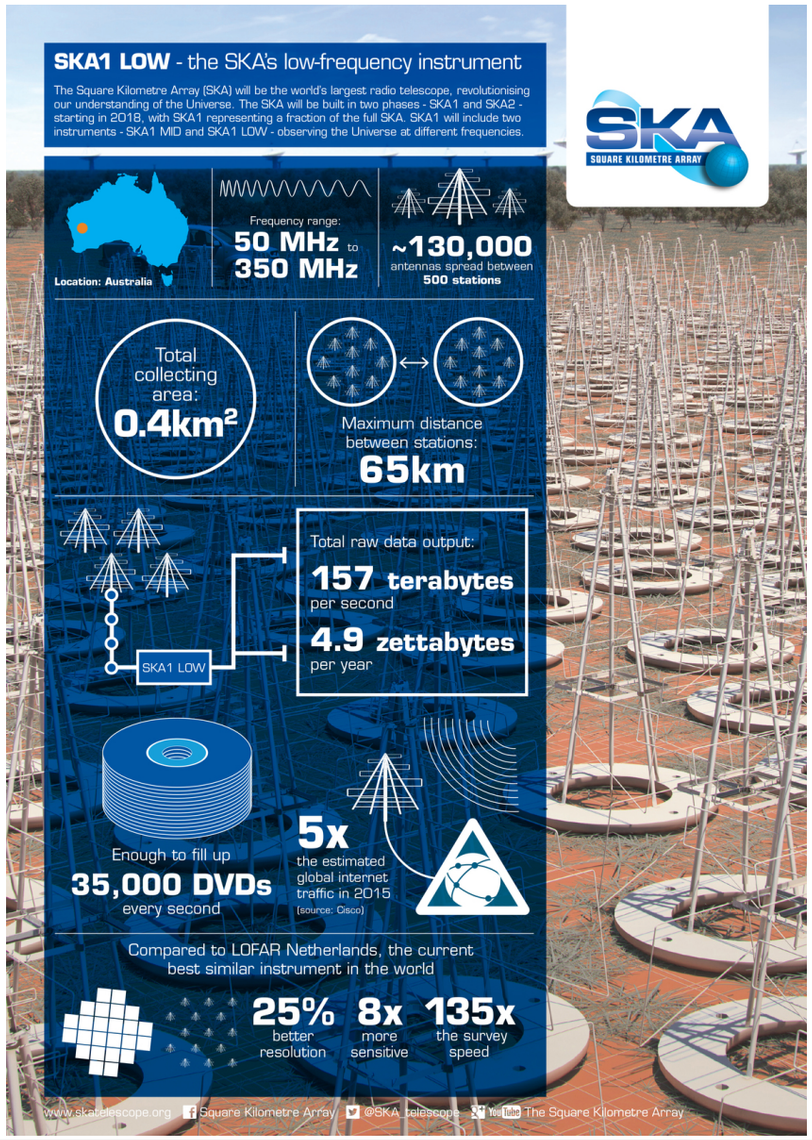
Challenging technology project (large infrastructure, big data, renewable energy …)

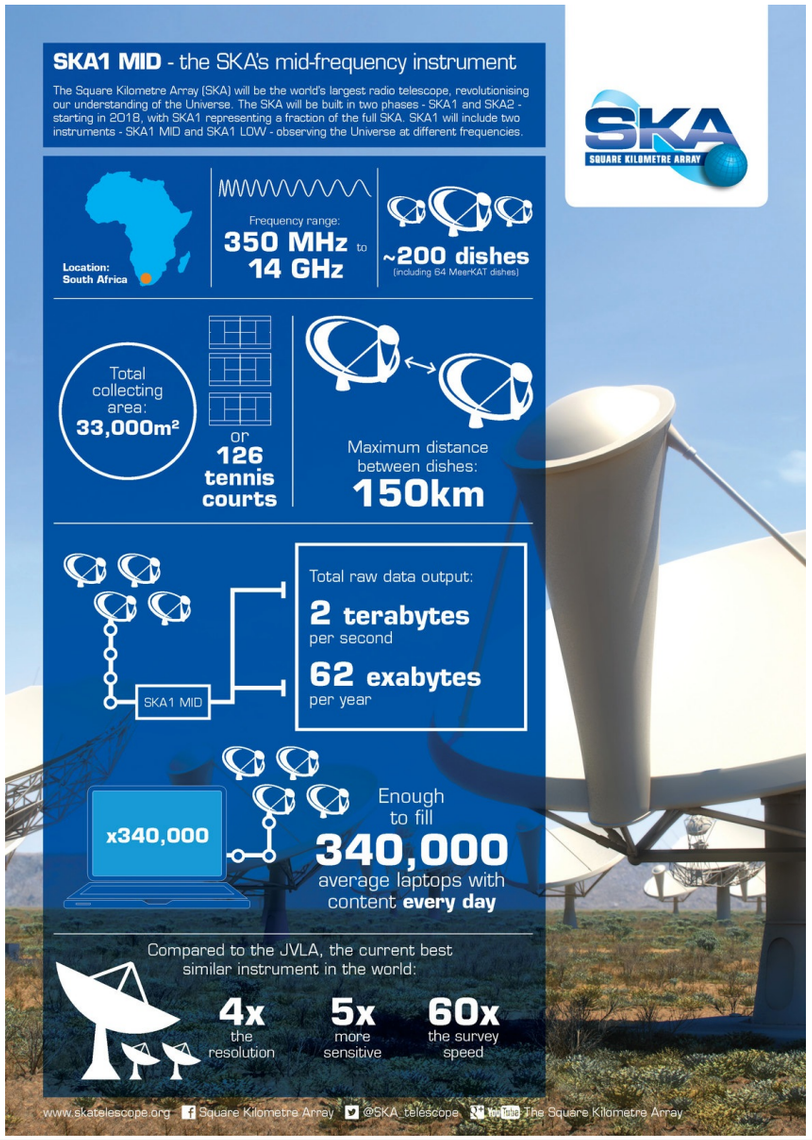
Outlook: SKA

SKA PHASE-1 (2018-2023) : ~10% SKA

SKA1-LOW



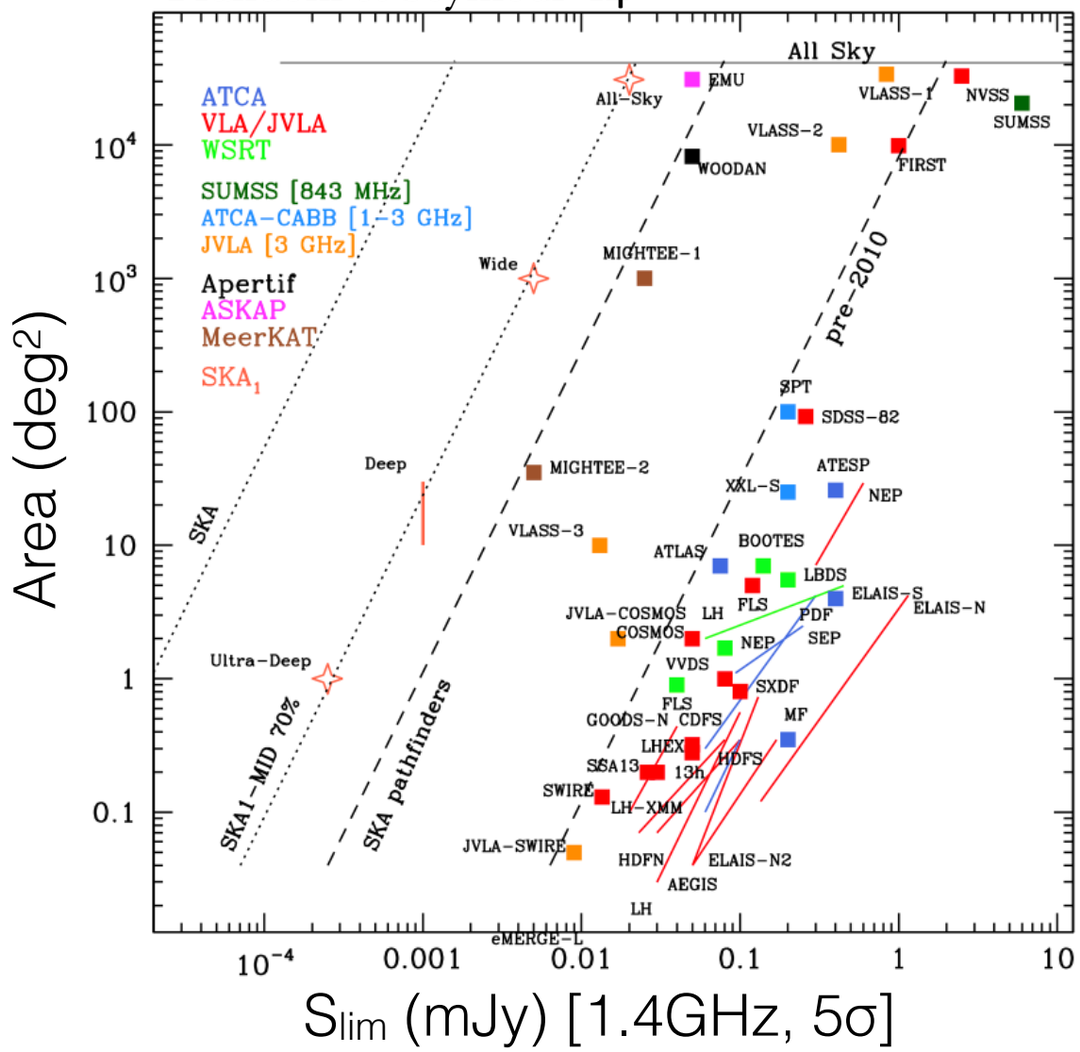
SKA1-MID



Outlook: SKA

SKA-1 continuum surveys

Prandoni & Seymour+14



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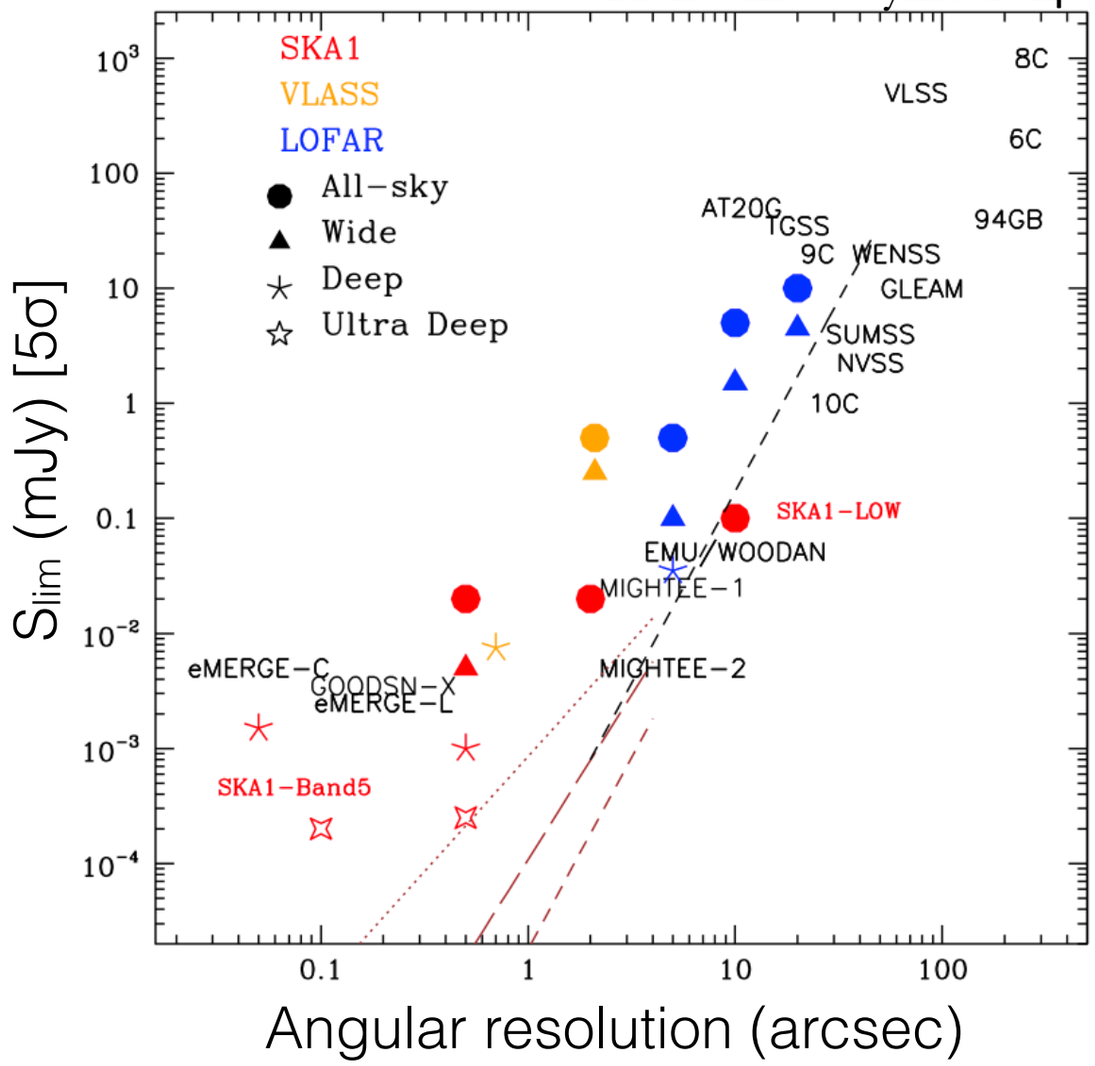

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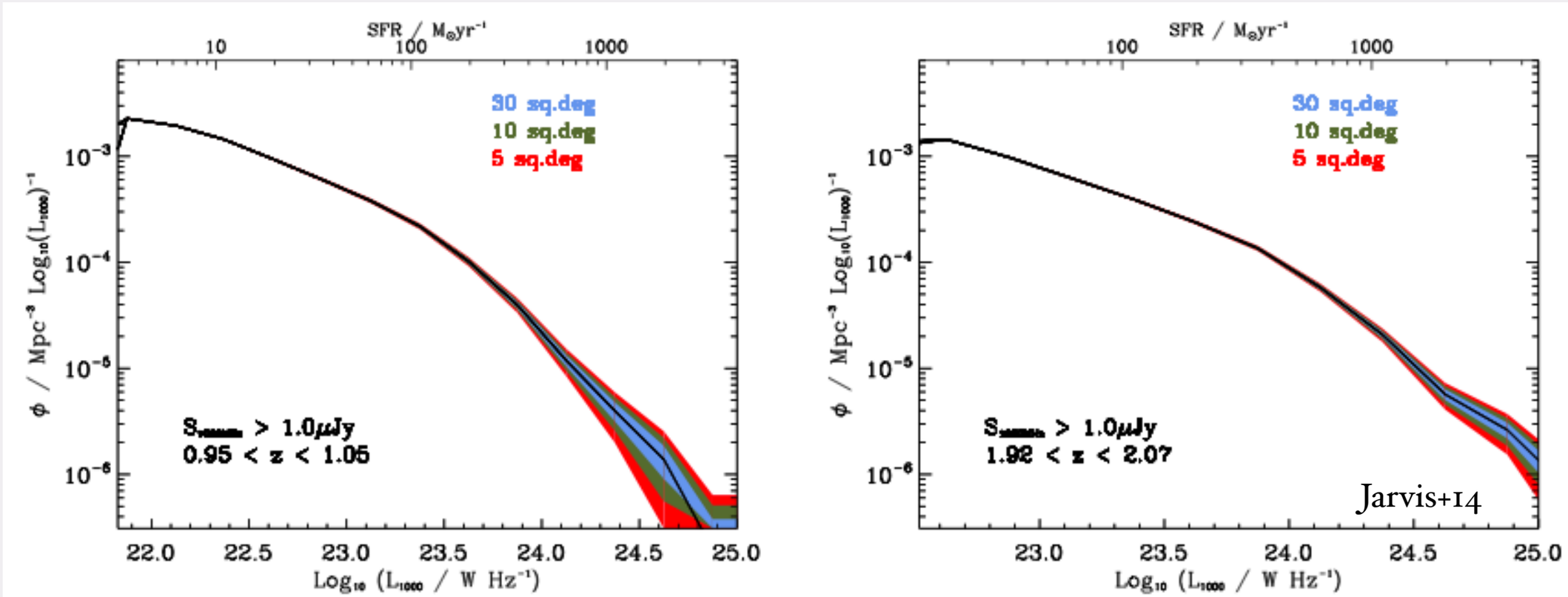

—> This classical “wedding cake” strategy allows to cover enough area of the sky at a given flux sensitivity to overcome sample variation and minimise Poisson uncertainty from z=0-6

S_{lim} (mJy) [5σ, 1.4 GHz]

Angular Resolution (arcsec)

Outlook: SKA

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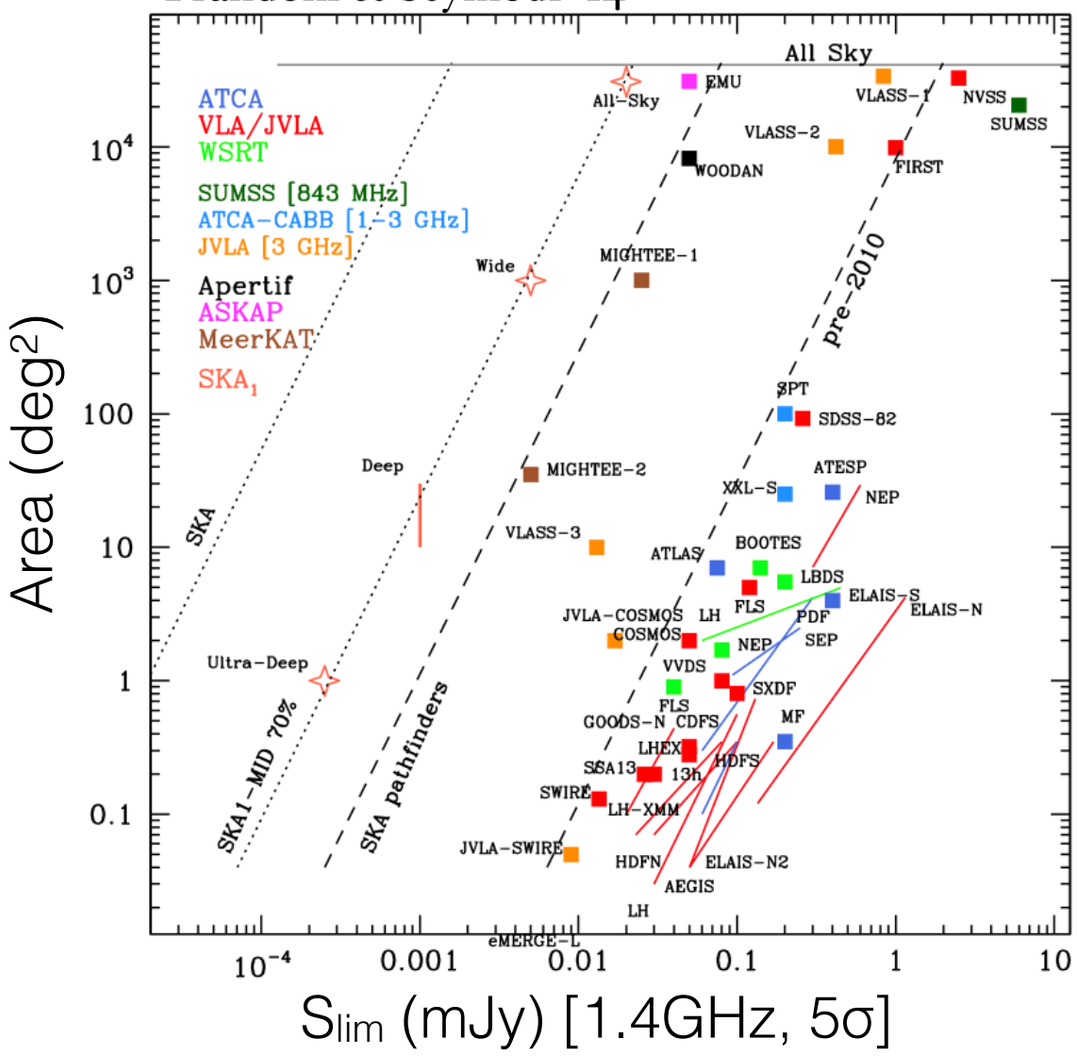
Prandoni & Seymour+14



The **All-sky + Wide surveys** will be key to study the cosmic SFH from z~0 to z~2 and its dependence with environment

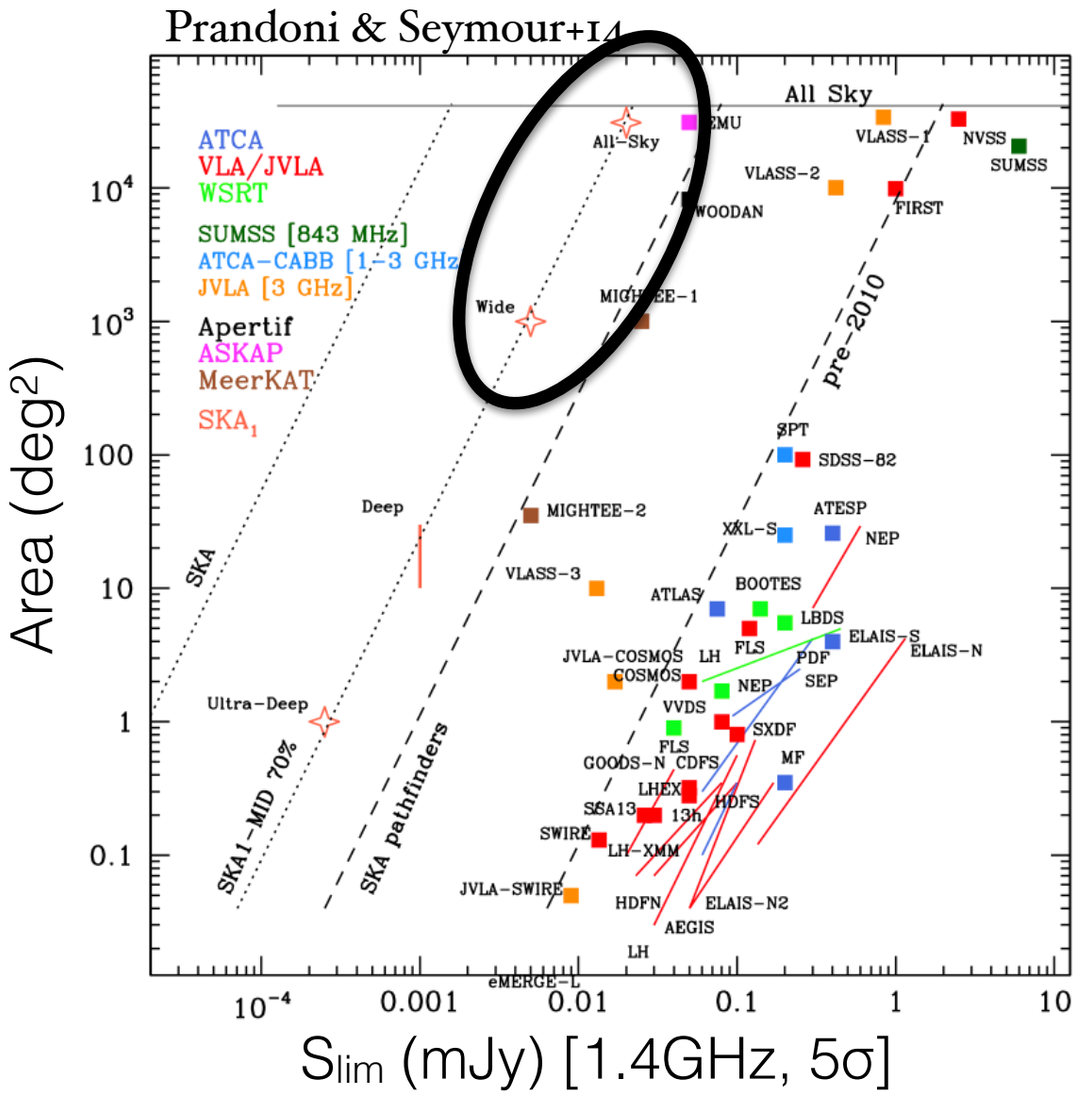
—> FIR/radio correlation will be use as an astronomical tool to estimate extinction-free SFRs

The **Ultra-deep + deep surveys** could be used to constrain the FIR/radio correlation at high-z if combined with :

- SKA1-MID 14GHz survey (free-free @ z>1-2)
- CCAT (25m antenna @350μm-2mm) survey

Outlook: SKA

SKA-1 continuum surveys



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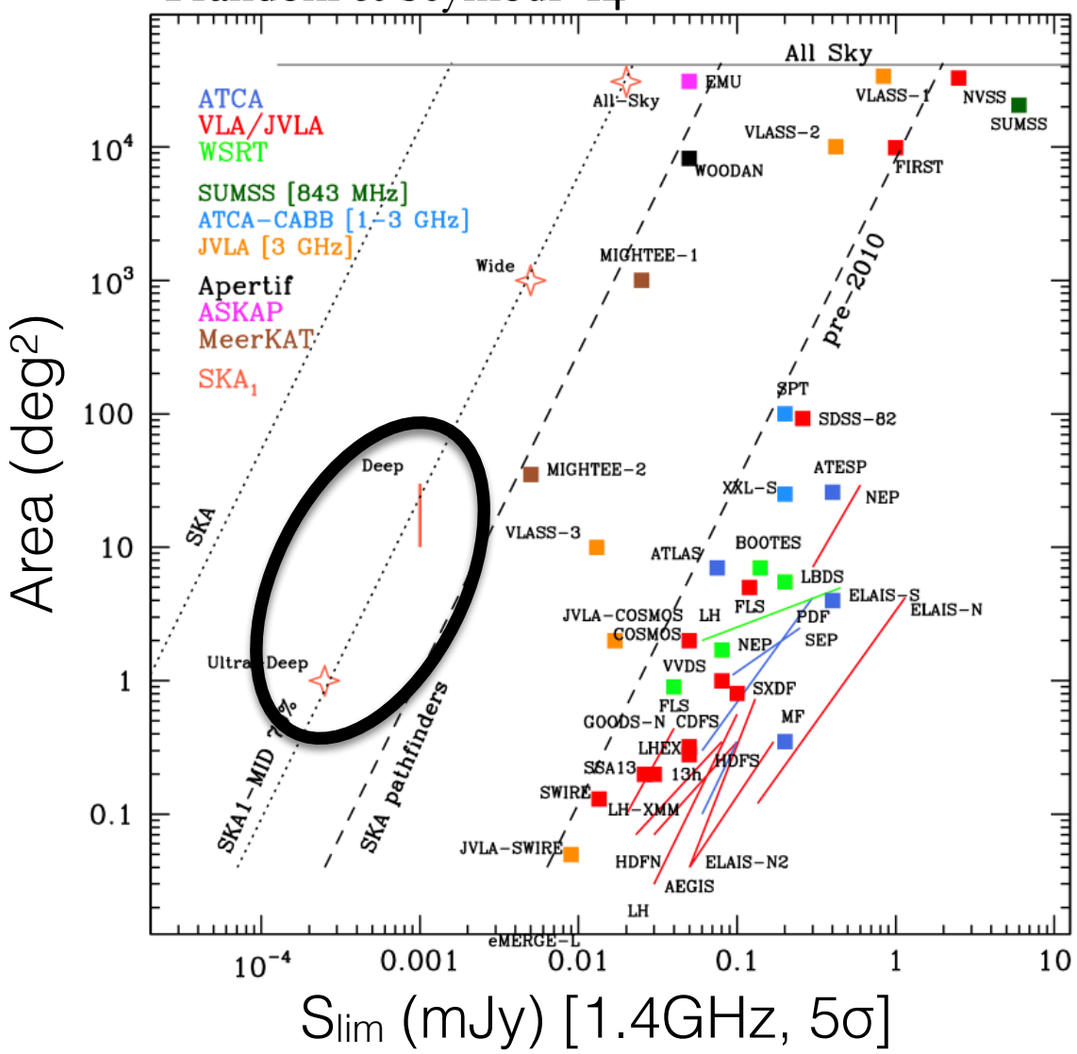

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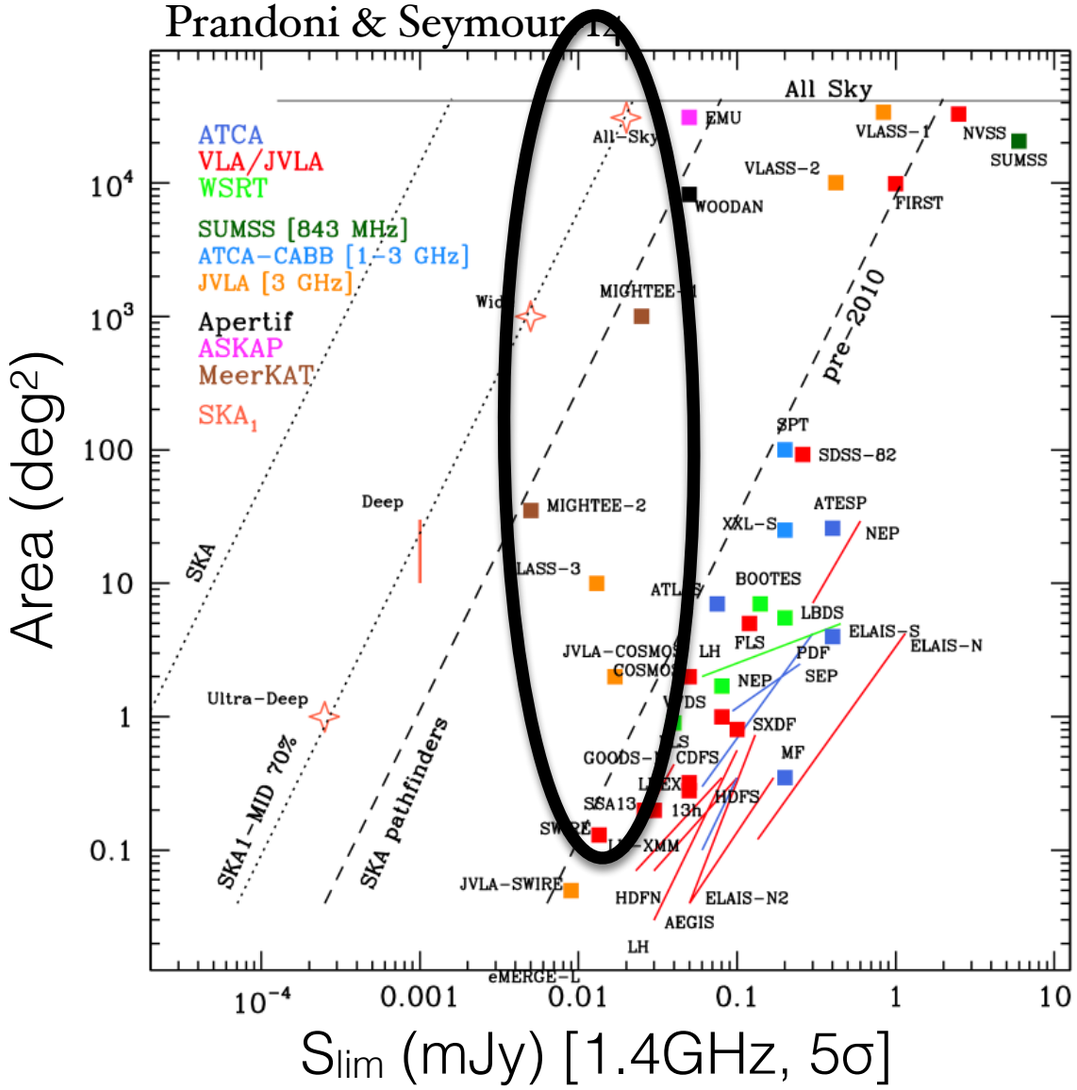
Outlook: SKA

SKA-1 continuum surveys



The **All-sky + Wide surveys** will be key to study the cosmic SFH from z~0 to z~2 and its dependence with environment

—> FIR/radio correlation will be use as an astronomical tool to estimate extinction-free SFRs

The **Ultra-deep + deep surveys** could be used to constrain the FIR/radio correlation at high-z if combined with :

- SKA1-MID 14GHz survey (free-free @ z>1-2)
- CCAT (25m antenna @350μm-2mm) survey

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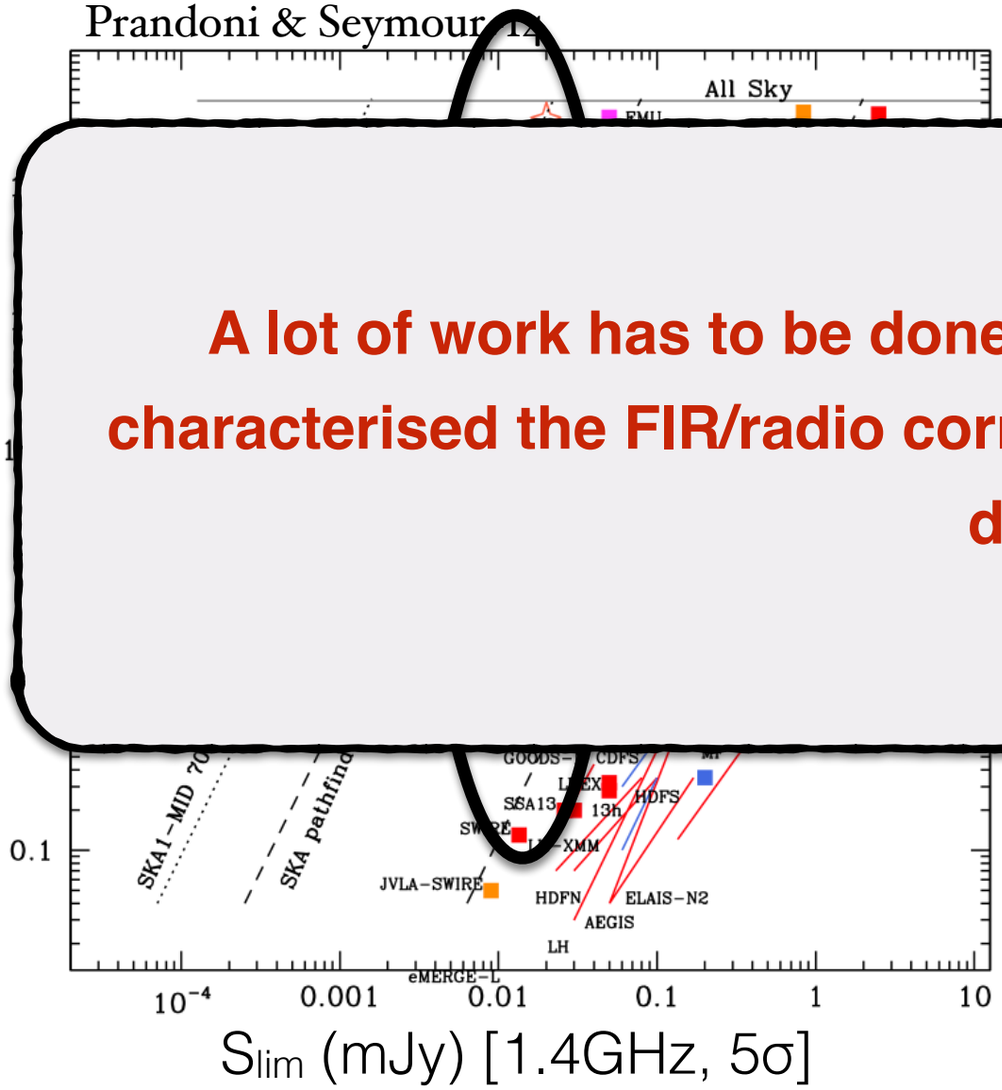
SKA-1 continuum surveys



The **All-sky + Wide surveys** will be key to study the e

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A lot of work has to be done before the first light of SKA to better characterised the FIR/radio correlation at high-z, i.e., normalisation AND dispersion !

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Summary

- Using deep Herschel (100-500 μm), VLA 1.4GHz and GMRT 610MHz observations, we constrained the radio spectral index and FIR/radio correlation in all SF galaxies galaxies with $M_\star > 10^{10}\ M_\odot$ and up to z~2
- The radio spectral index of normal and starbursting galaxies are consistent up to z~2 with a standard value of 0.8
- The FIR/radio correlation holds up to at least z~2, but q_{IR} displays a moderate but statistically significant redshift evolution $\propto (1+z)^{-0.12}$
- This evolution suggests that the ISM properties (e.g. magnetic field strength, gas densities, Σ_{SFR} , …) of SF galaxies evolve between z~0 and z~2
- The advent of SKA will revolutionised our vision of the FIR/radio correlation at high redshift