Toward an Extinction-Free Picture of Galaxy Evolution

Wiphu Rujopakarn
University of Arizona

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Outline

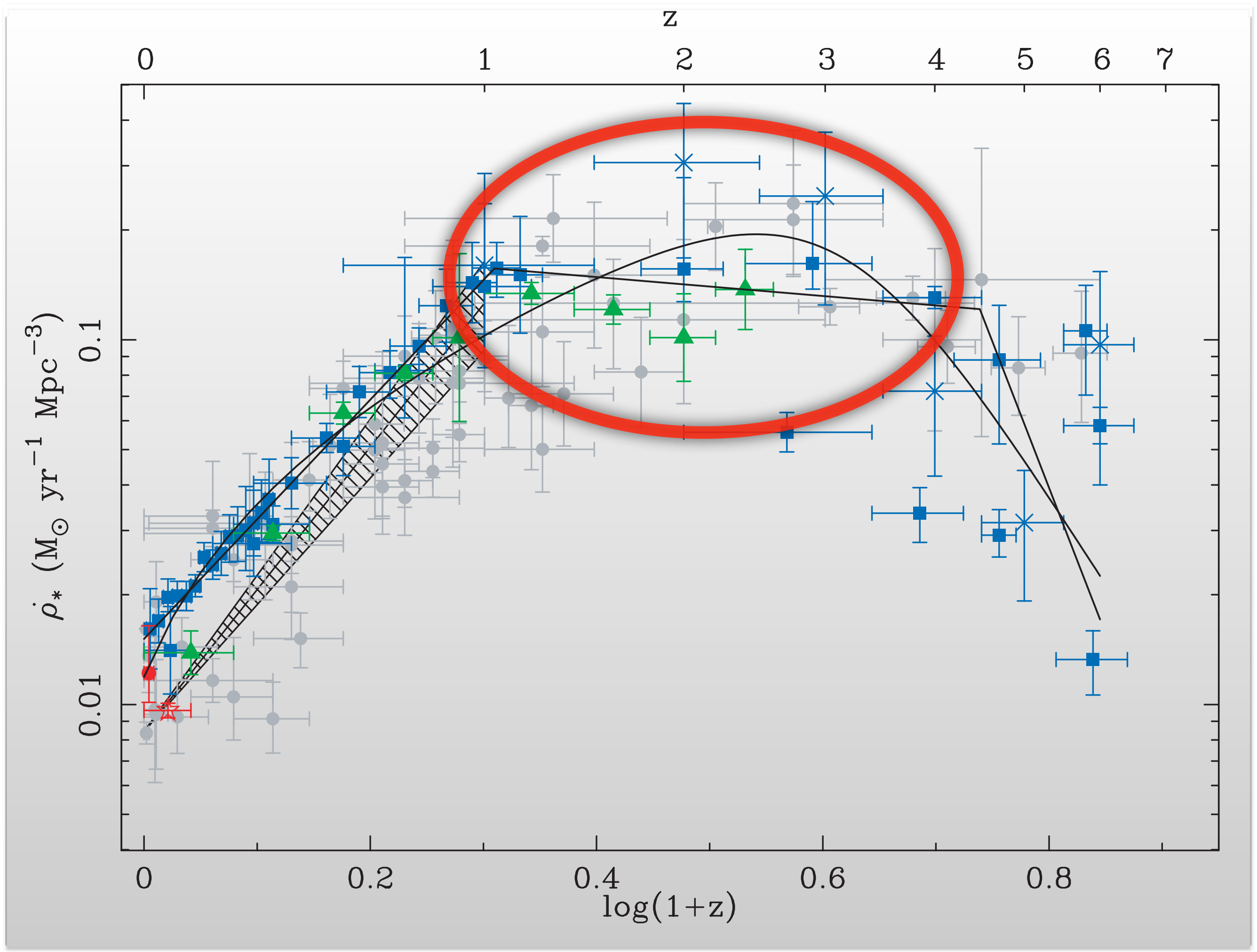
- Key questions
- The need for extinction-free tracers of star formation (SF)
- Applications: Structures of local and high-z actively star-forming galaxies
  Rujopakarn et al., 2011, ApJ, 726, 93
- Applications: Mid-IR SFR indicator and evolution of SF galaxies at $0 < z < 3$
  Rujopakarn et al., 2010, ApJ, 718, 1171
  Rujopakarn et al., 2012 ApJ, 755, 168
  Rujopakarn et al., 2013, ApJ accepted, arXiv:1107.2921
- Ongoing Jansky VLA observations

Key questions

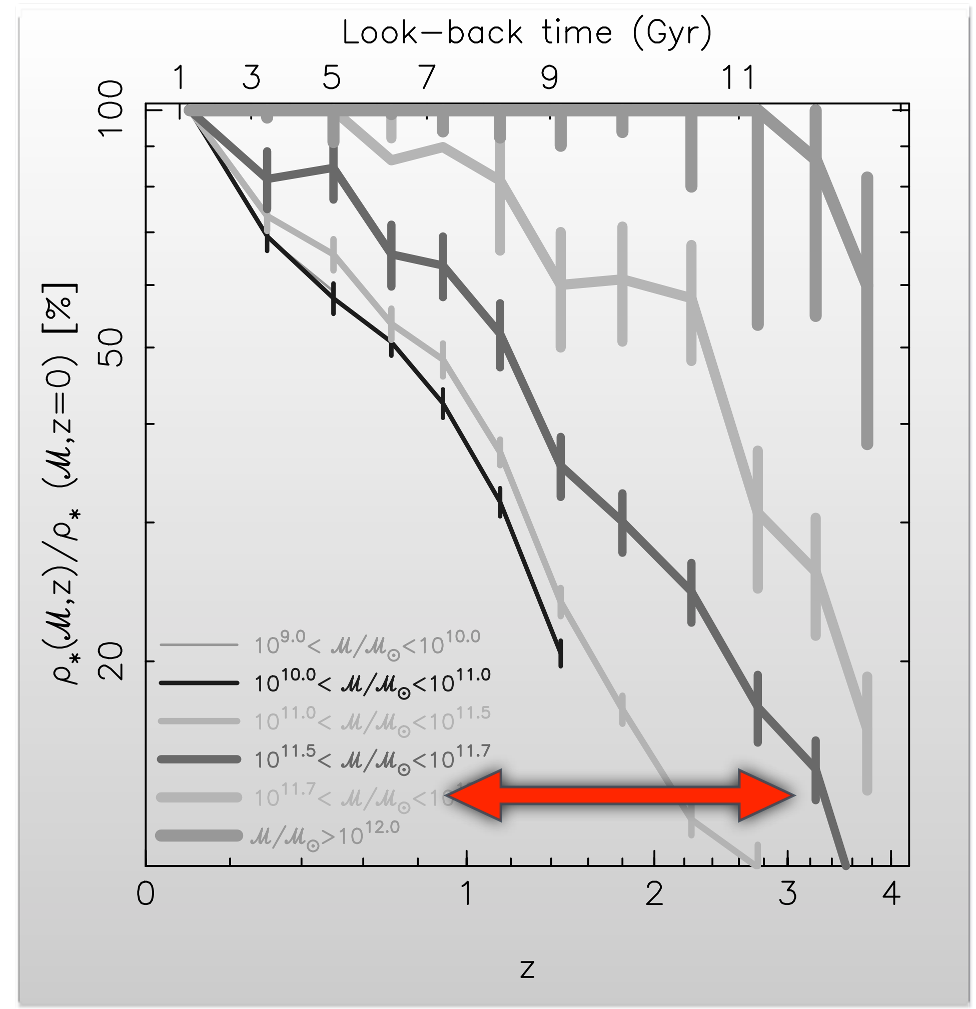
to understand the environment where most stellar masses in the universe were formed

- Were actively star-forming galaxies at high-z similar to their local counterparts?
- What triggered star-formation at high-z?
- What was the role of mergers?
- What shut off the cosmic star formation since z ~ 1?

The Peak Epoch of Cosmic Star Formation and Galaxy Assembly Activities



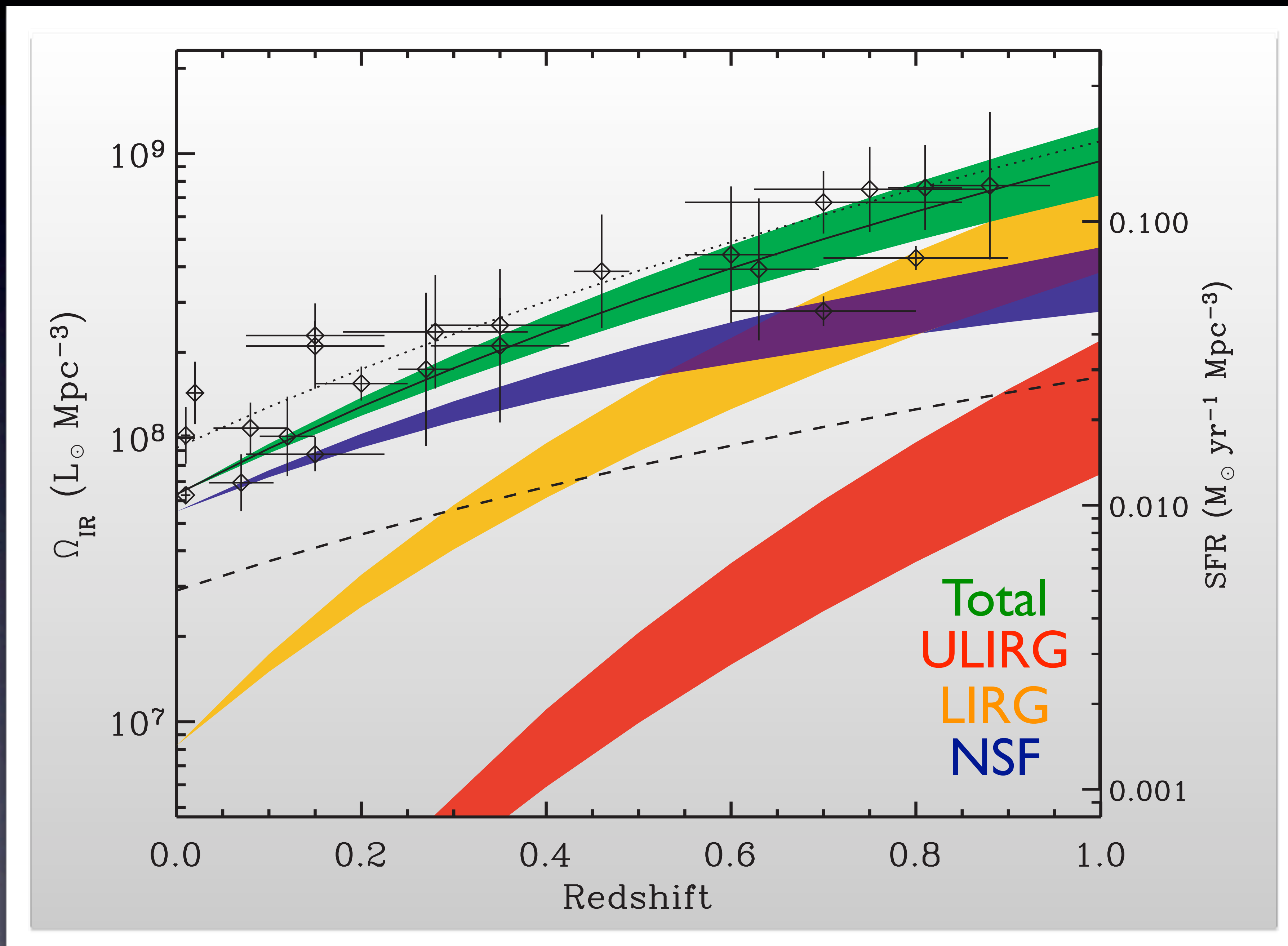
SFR Evolution



Stellar Mass Evolution

Hopkins & Beacom 05; Perez-Gonzales et al. 2008

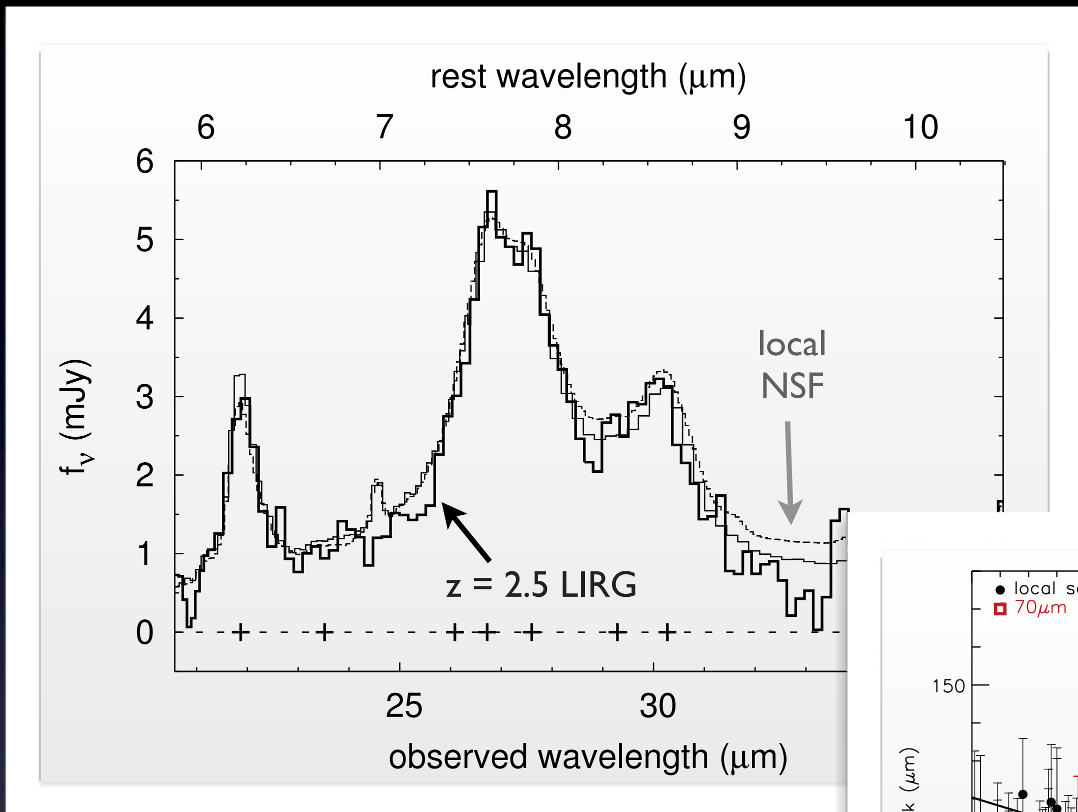
Actively Star-forming Galaxies Across the Cosmic Time



Le Floc'h et al. (2005)

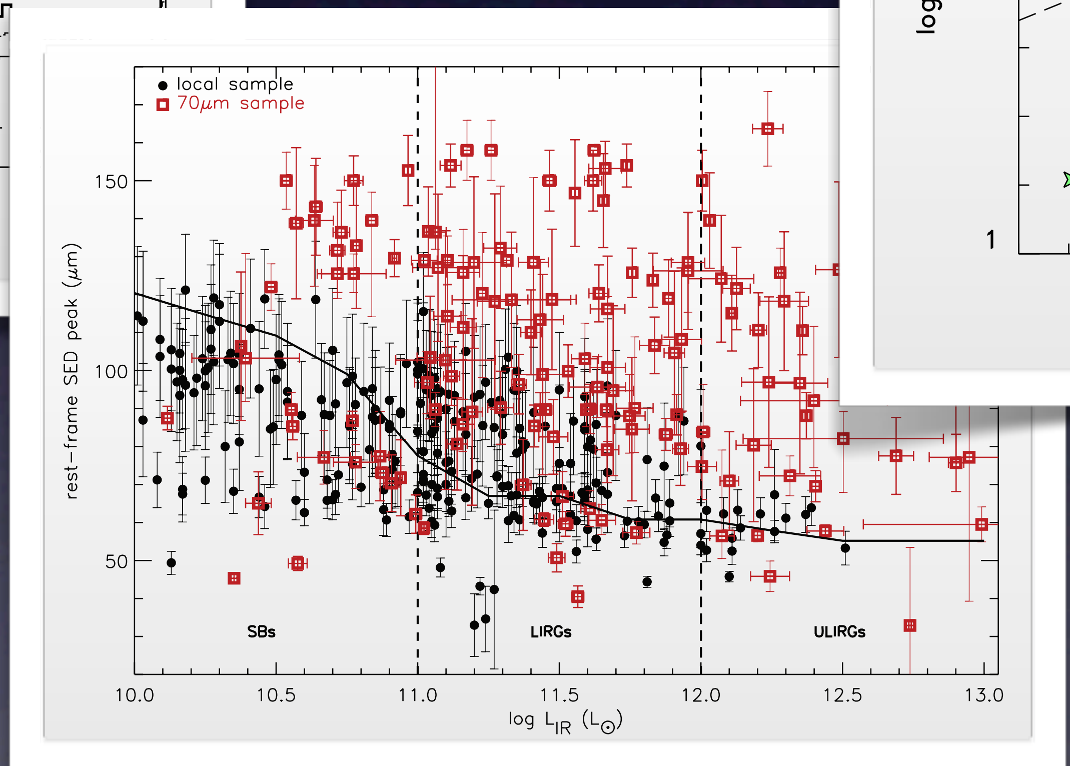
How are high-z starbursts different from locals?

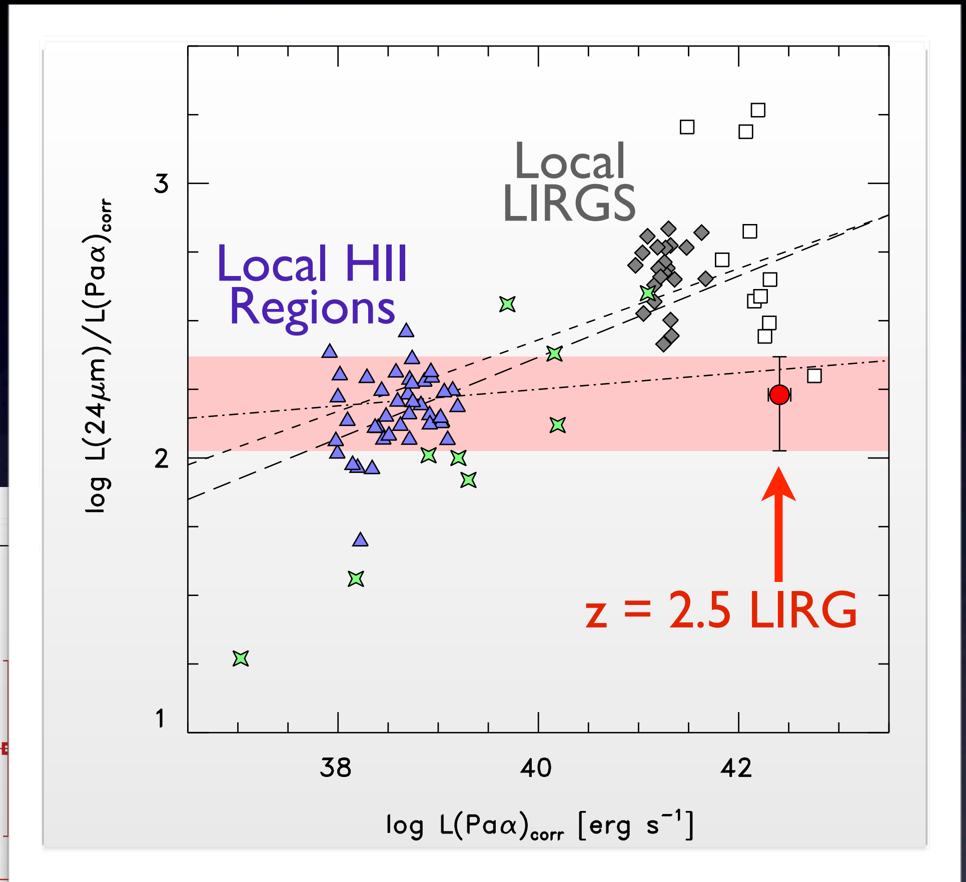
Hints from early *Spitzer* data



Rigby+08

Symeonidis+09

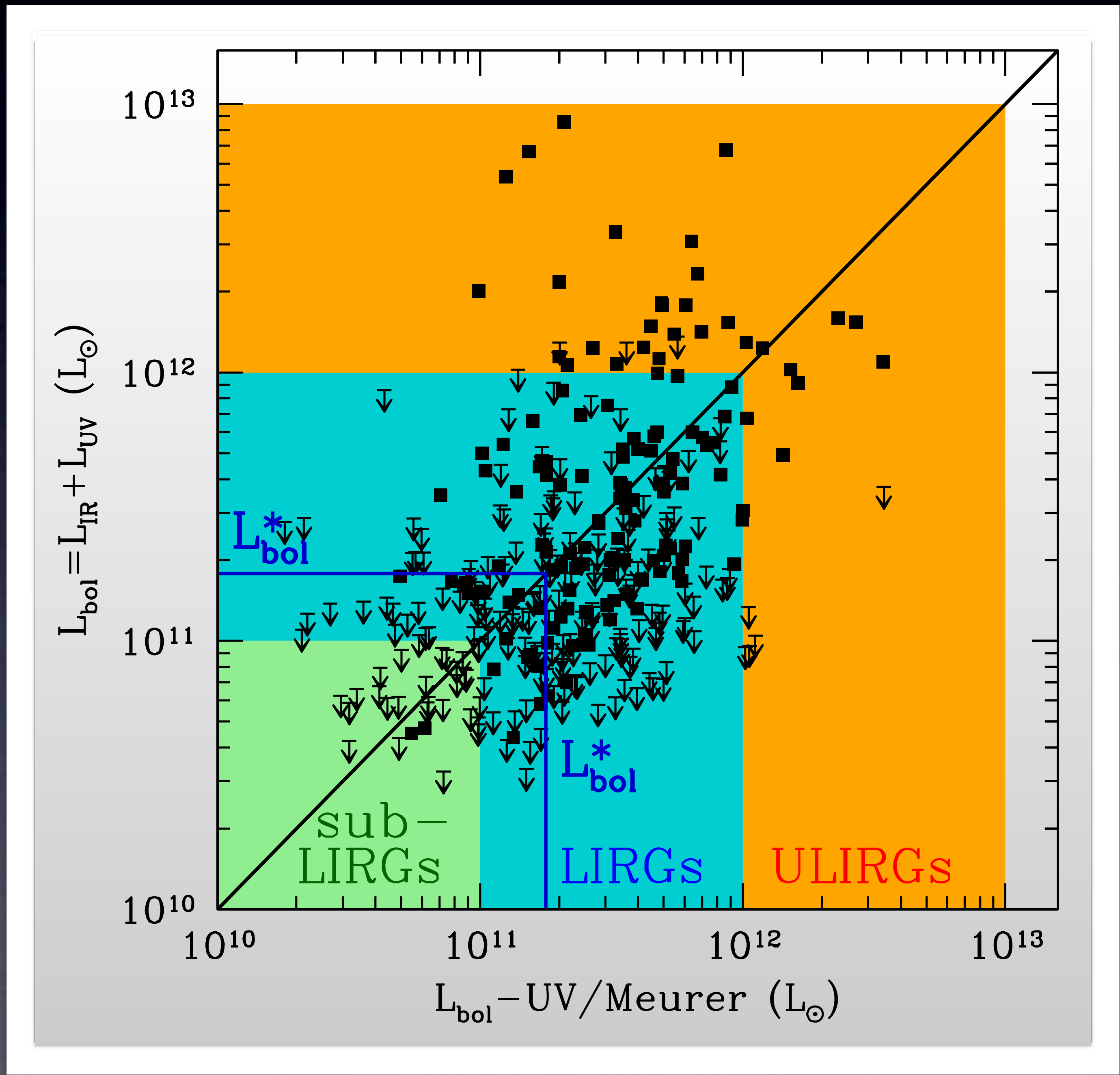




Papovich+09

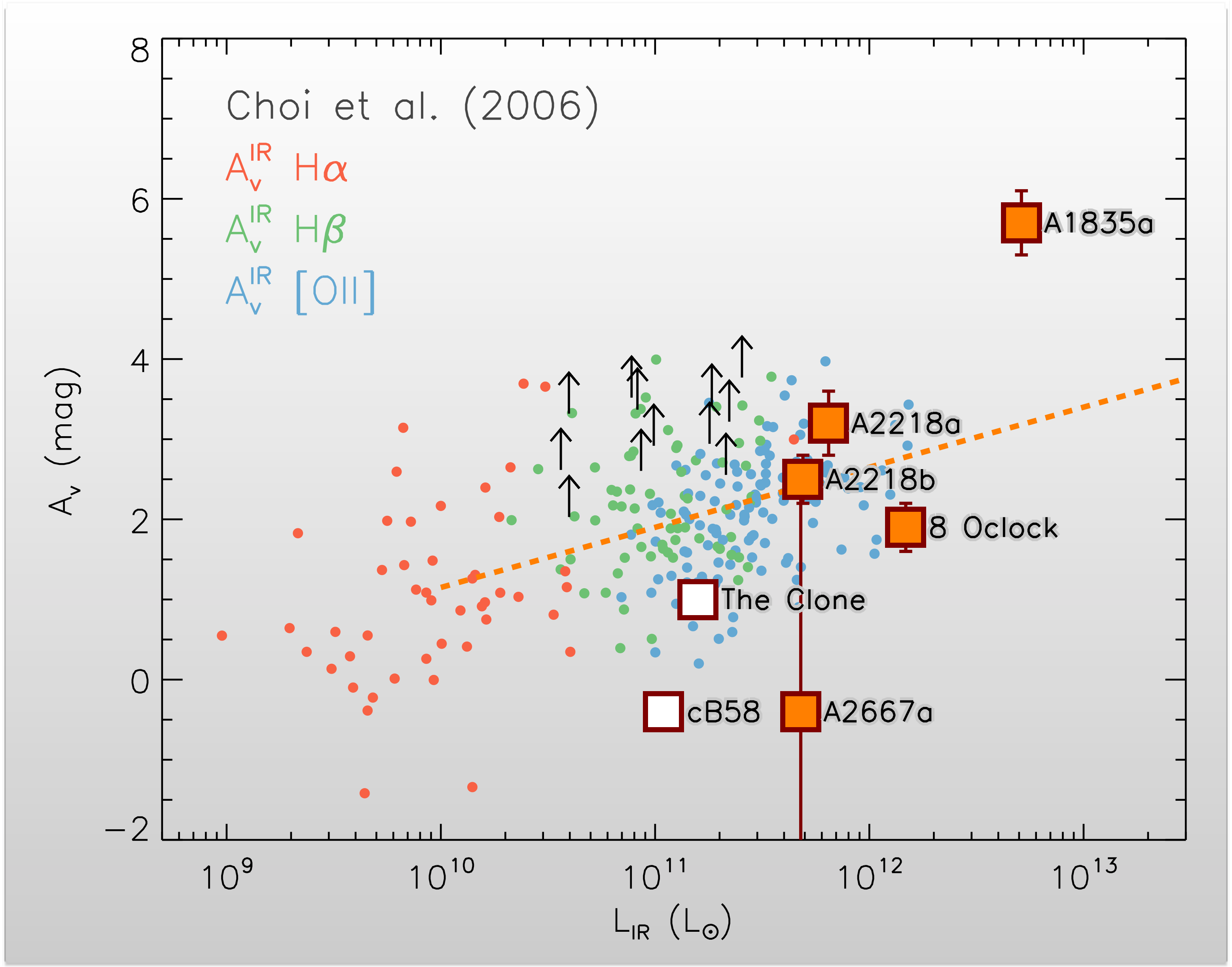
Need to understand the structures of SF regions in high-z galaxies!

Galaxies with SFR > 20 M_{sun}/yr can be completely obscured



Reddy+10

Extinction spread in high-z starbursts is large



requires extinction-free SF tracers

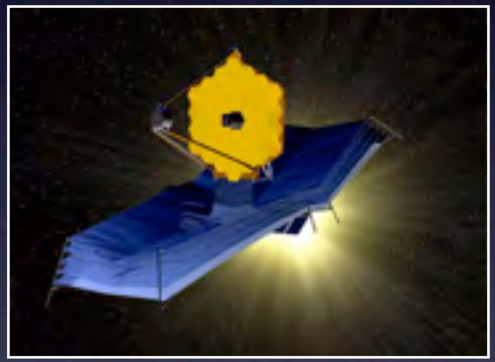
Rujopakarn et al. 2012a

Extinction-free Tracers of Star Formation

- Paα *(nearly extinction free)*
- Mid-IR
- Radio non-thermal continuum

1.87 μm; 0.2”
2.4 m; local only*

24 μm; 5.8”
0.85 m

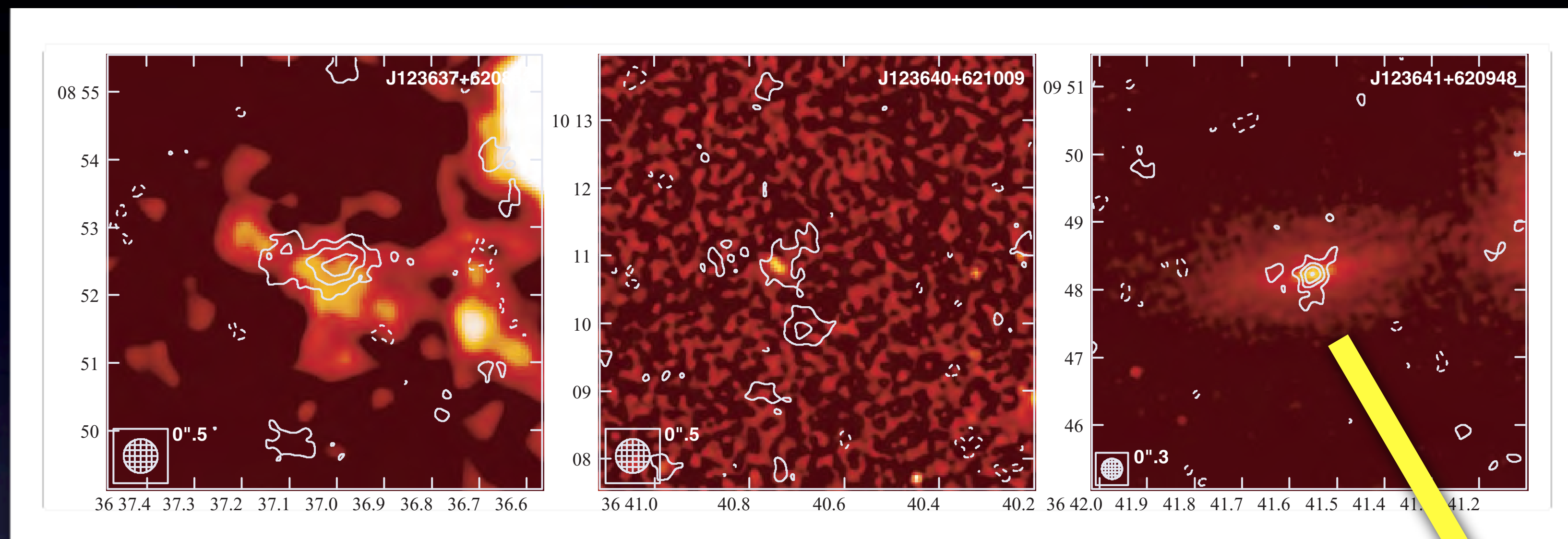


20 μm; 0.6”
6.5 m; 2018

4-8 GHz; 0.3”
36 km using A-array

* Paα at z ~ 2 (redshifted to 5 μm) needs JWST to achieve 0.2” resolution

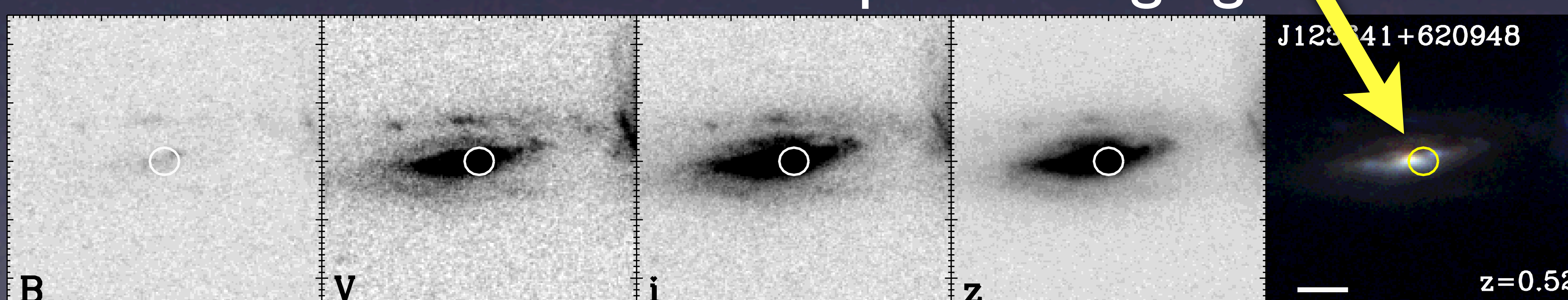
The most basic structural parameter: physical size (i.e., diameter)



VLA+MERLIN 1.4 GHz continuum observation in HDF (Muxlow+05)
0.2" - 0.5" resolution; all but one of 92 galaxies resolved

Can't be measured from optical imaging

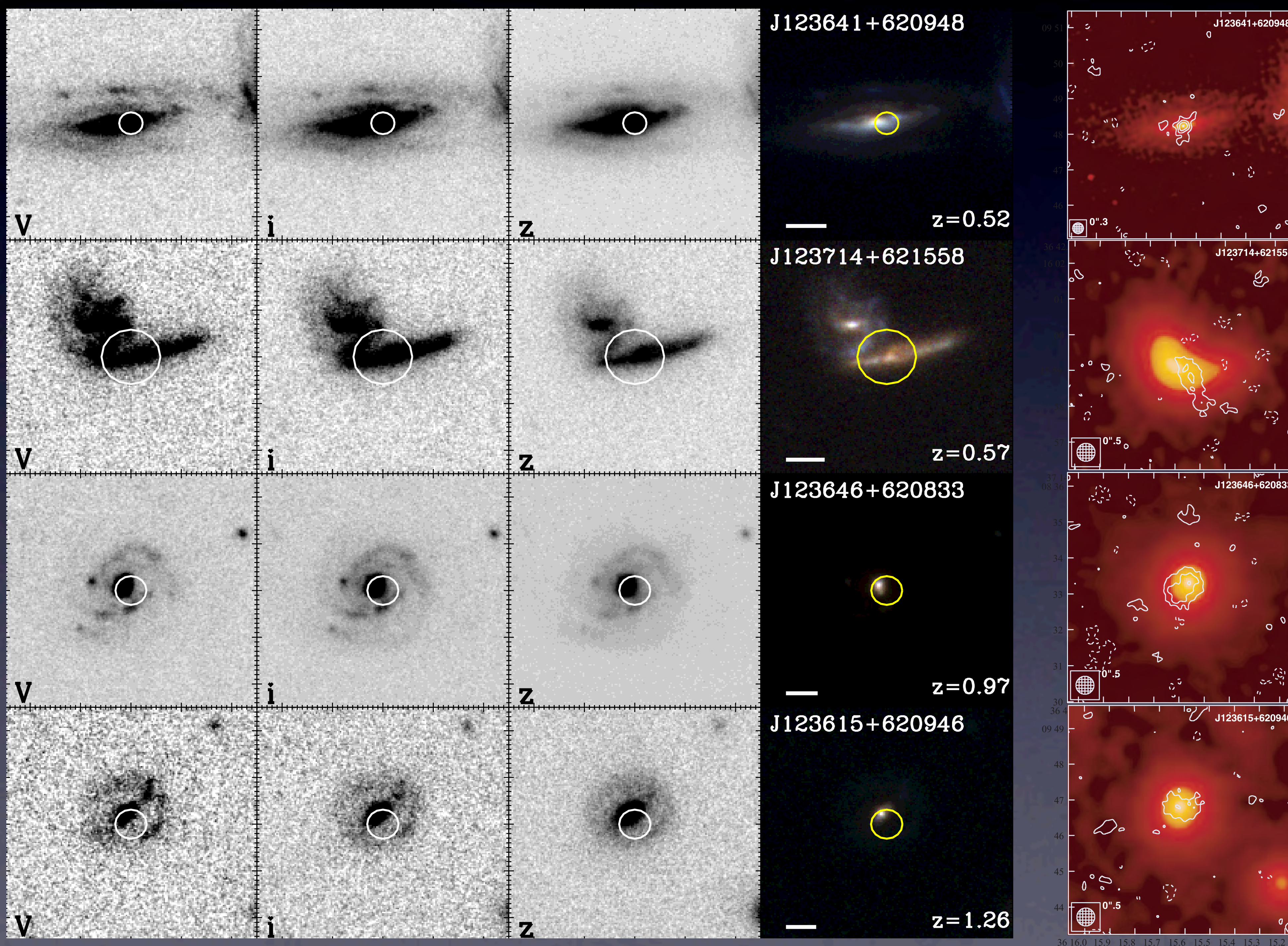
Rujopakarn et al. (2011)



Synchrotron radio continuum
(1) High-res; (2) Extinction-free view of SF; (3) no old stars

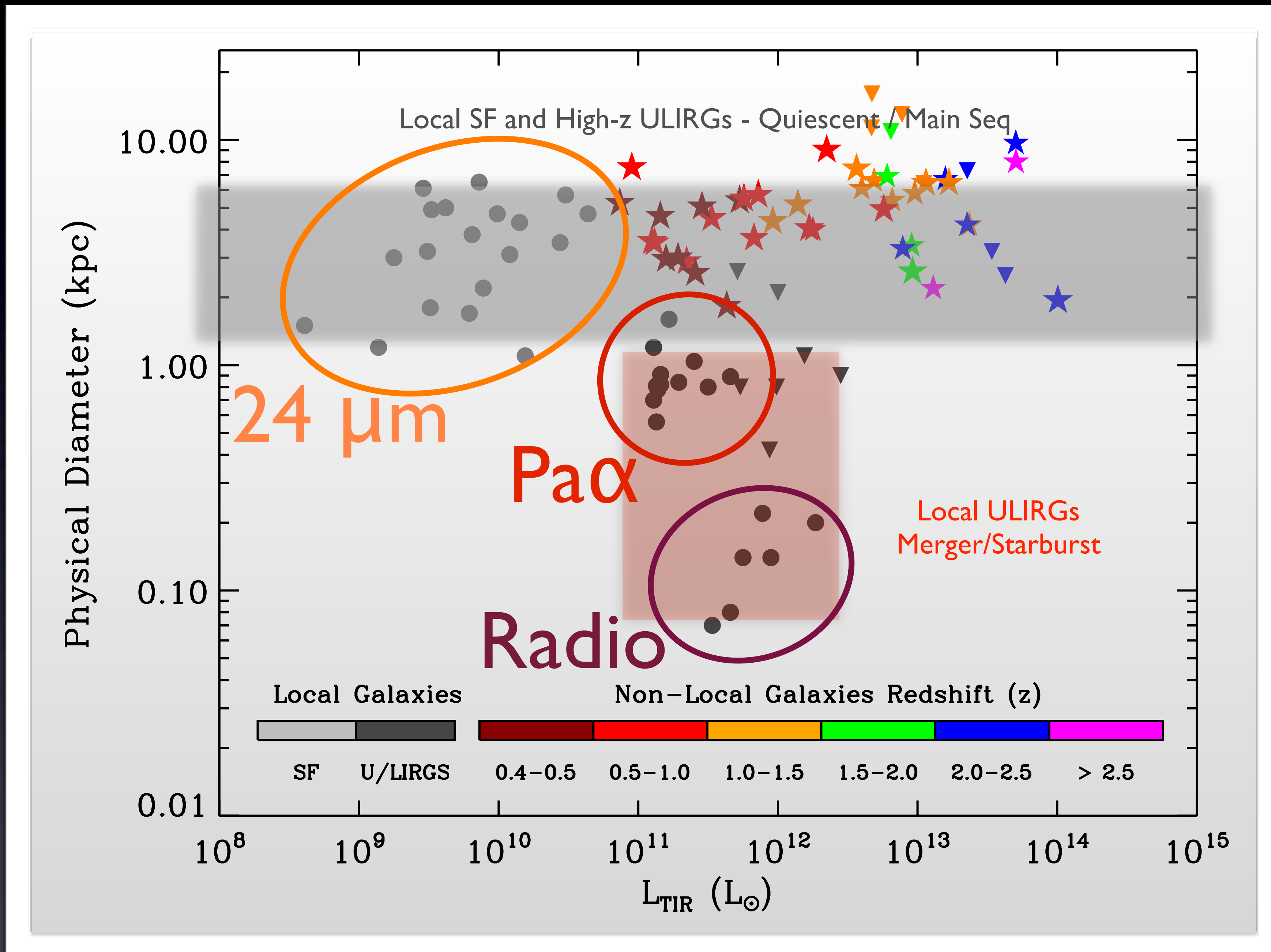
Morphology of Star-Forming Regions at high-z

Optical Radio



Muxlow et al. 2005; Rujopakarn et al. 2011

Physical Size Differences of Local and High-z ULIRGs



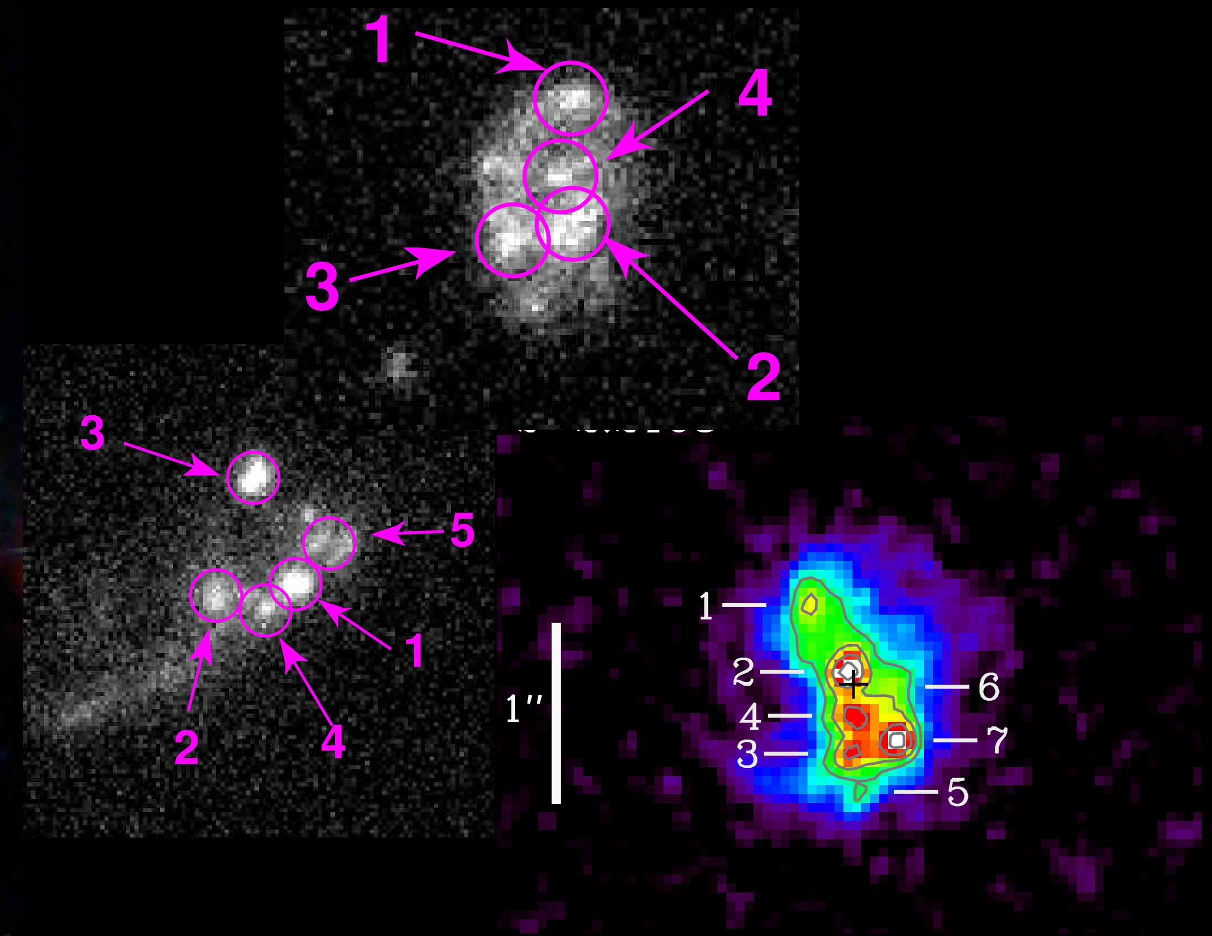
U/LIRGs beyond the local volume are much larger (3-10 kpc) than local U/LIRGs (sub-kpc) at similar L_{IR}

Rujopakarn et al. 2011

Mental picture of U/LIRGs

Local

High-z



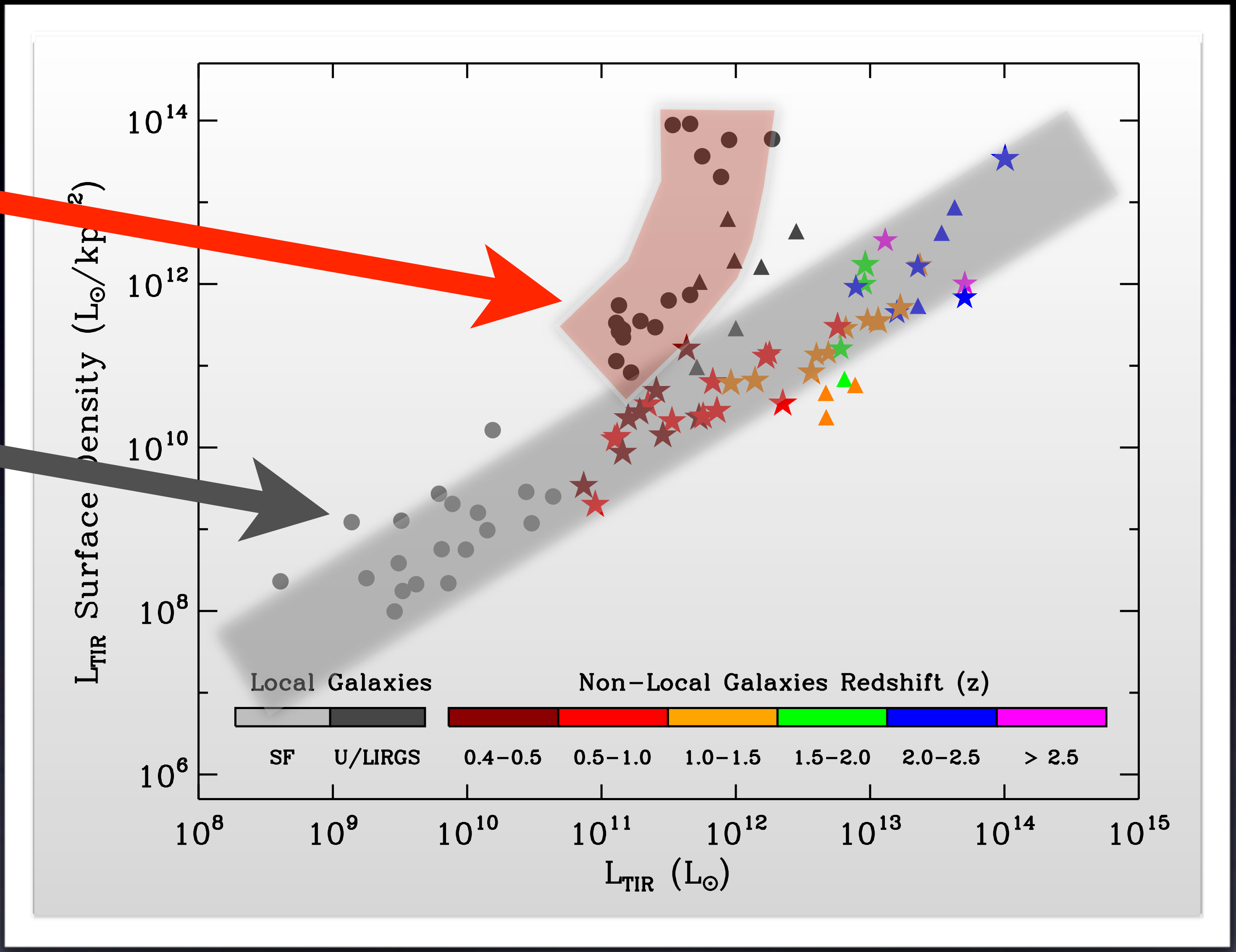
NGC 6240; Guo+12, Förster Schreiber+11

Application: $\sum_{IR}$ of Local and High-z

Local ULIRGs
Merger/nuclear starburst

Local SF and High-z ULIRGs
Quiescent / Main Sequence

Most Local NSF and high-z ULIRGs are in the IR main sequence

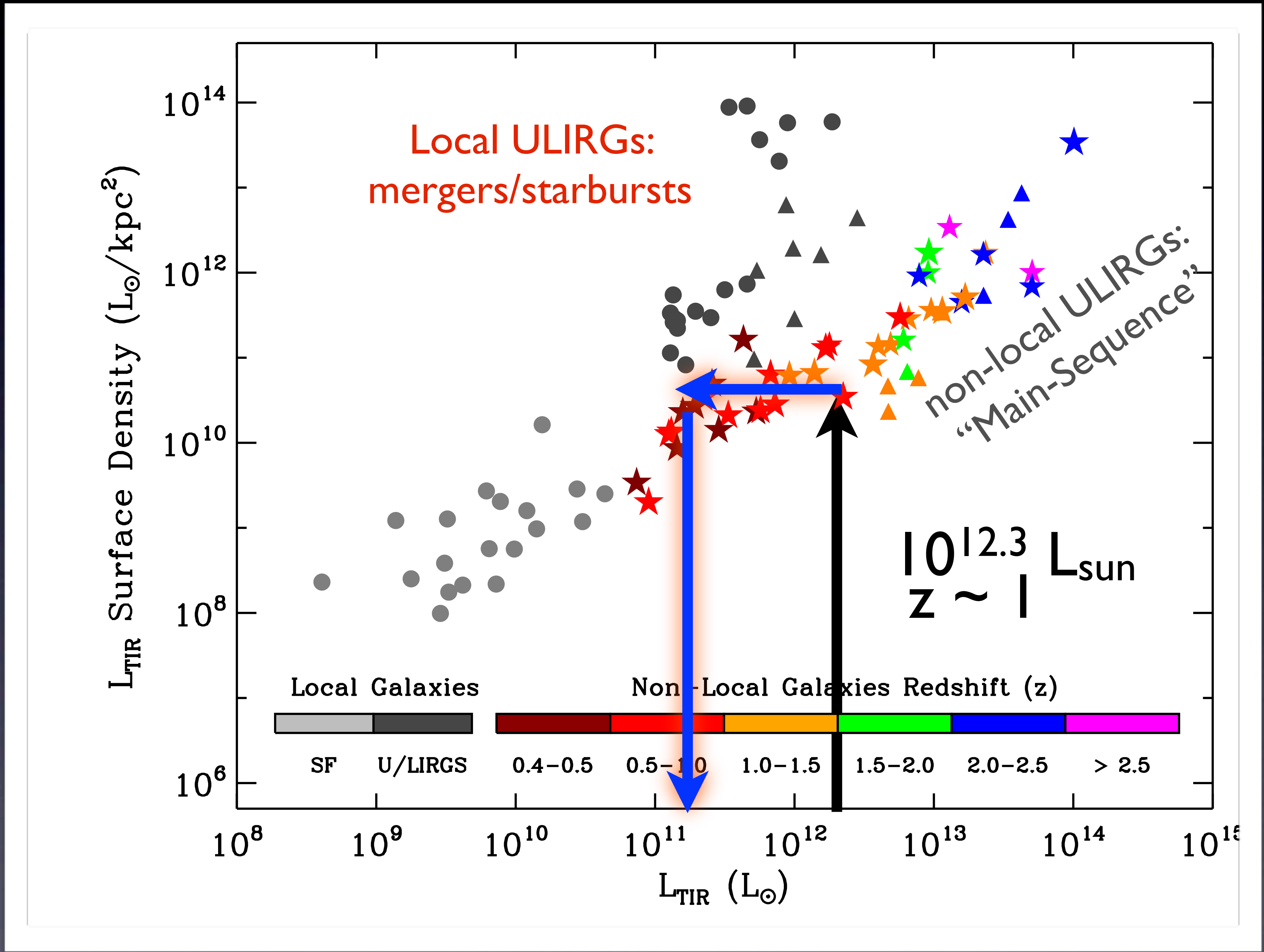


Rujopakarn et al. 2011

Local SF and high-z U/LIRG difference is mainly due to higher $\sum$IR

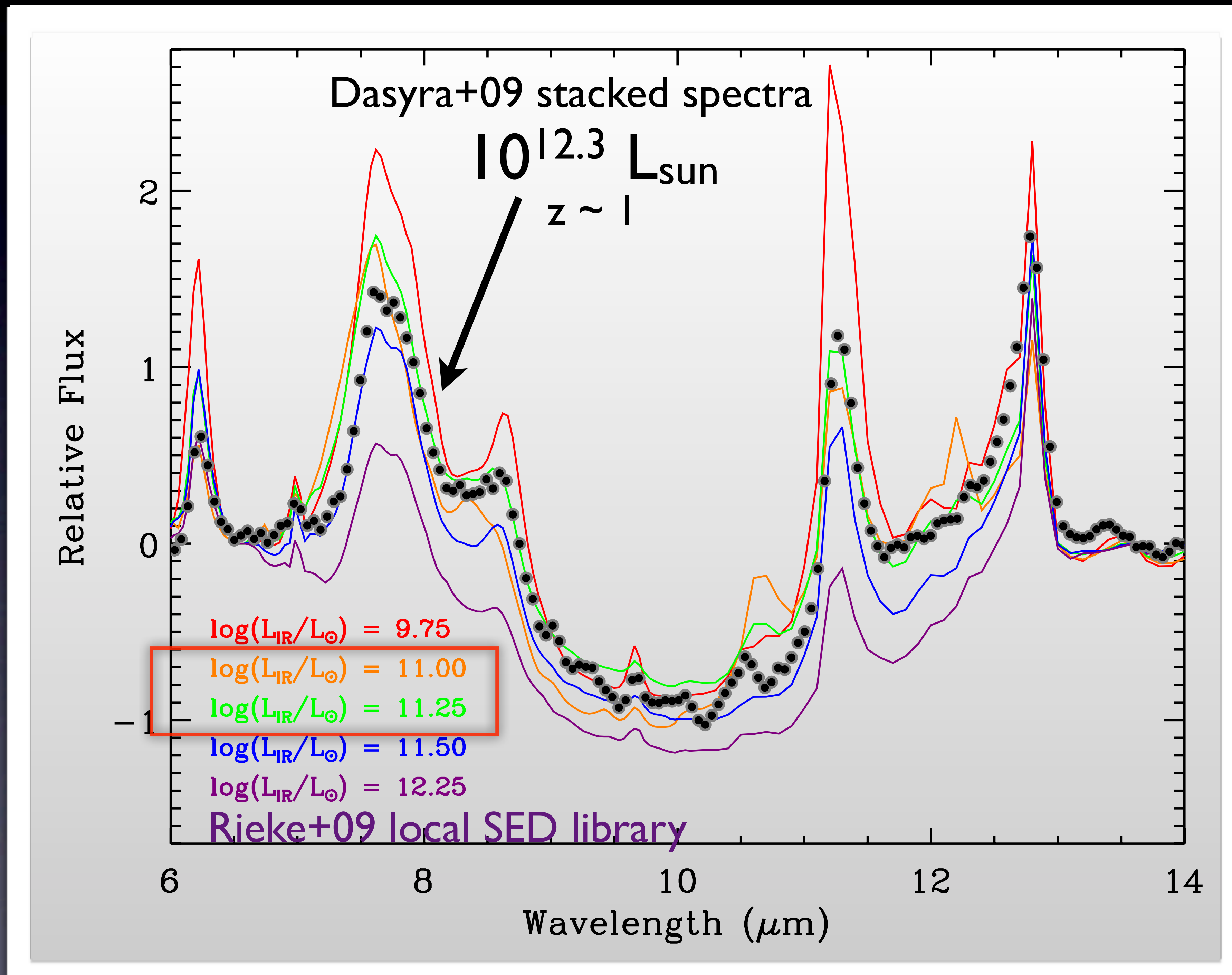
SED templates are constructed from local ULIRGs and are not applicable with high-z ULIRGs

Σ_{IR}: A Fundamental Parameter Indicating Star-Forming Galaxy SED Shape



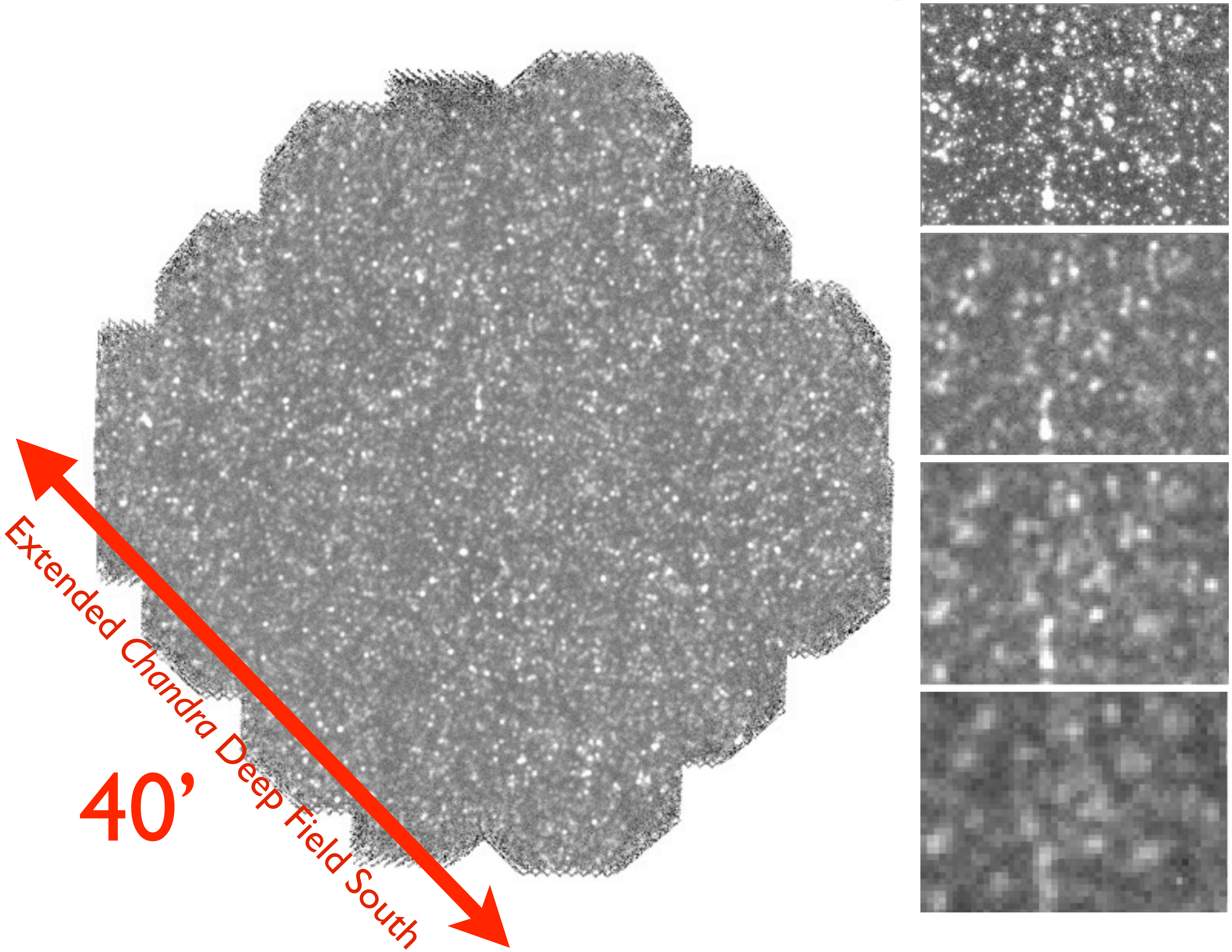
Rujopakarn et al. 2011

Application: Σ_{IR} as an indicator of SED
(instead of L_{IR})



Rujopakarn et al. 2011

Far-IR observations directly trace dust emission, but are limited by source confusion



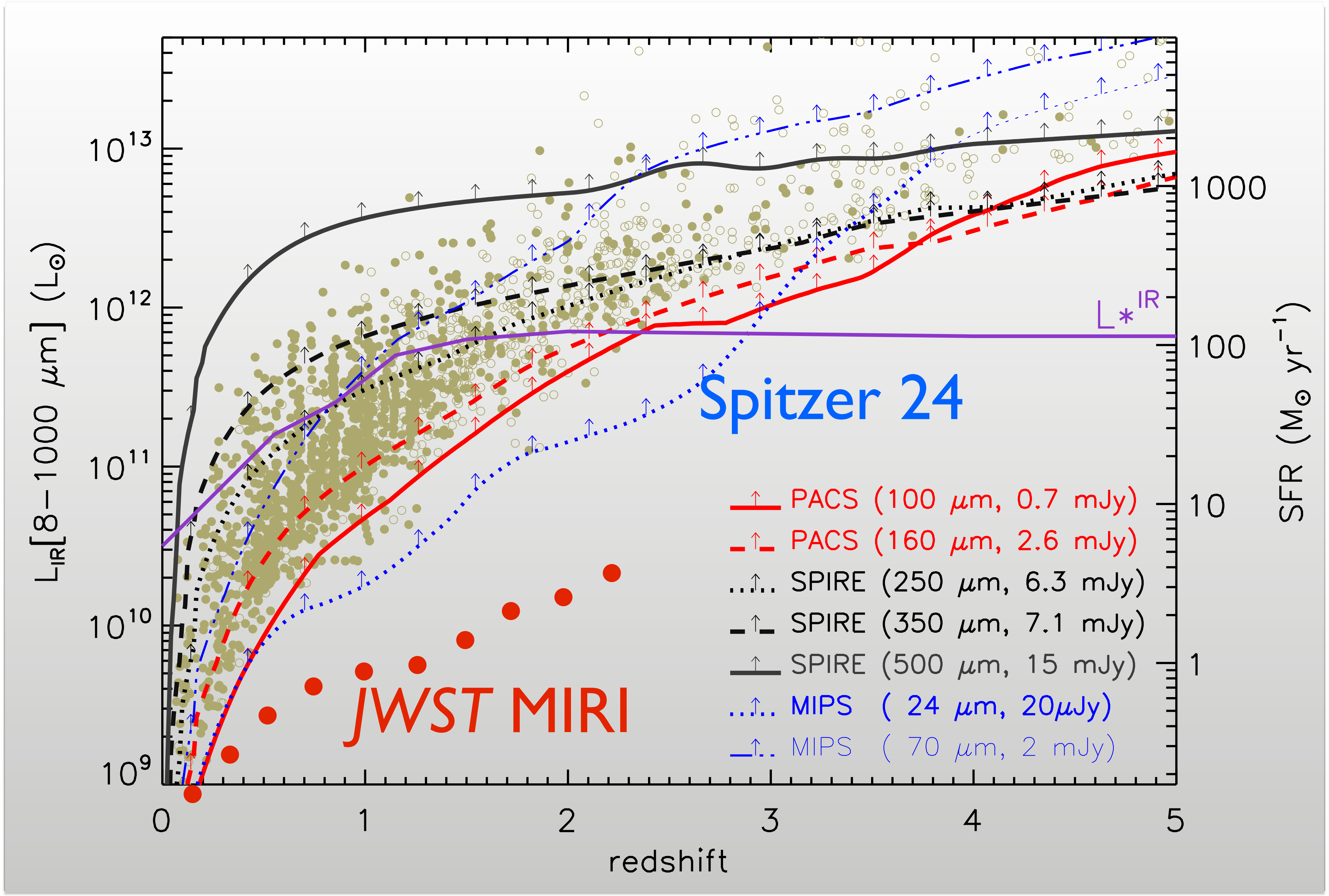
24 μm

250 μm

350 μm

500 μm

21 μm L_{IR} & SFR Indicator in the *JWST* era

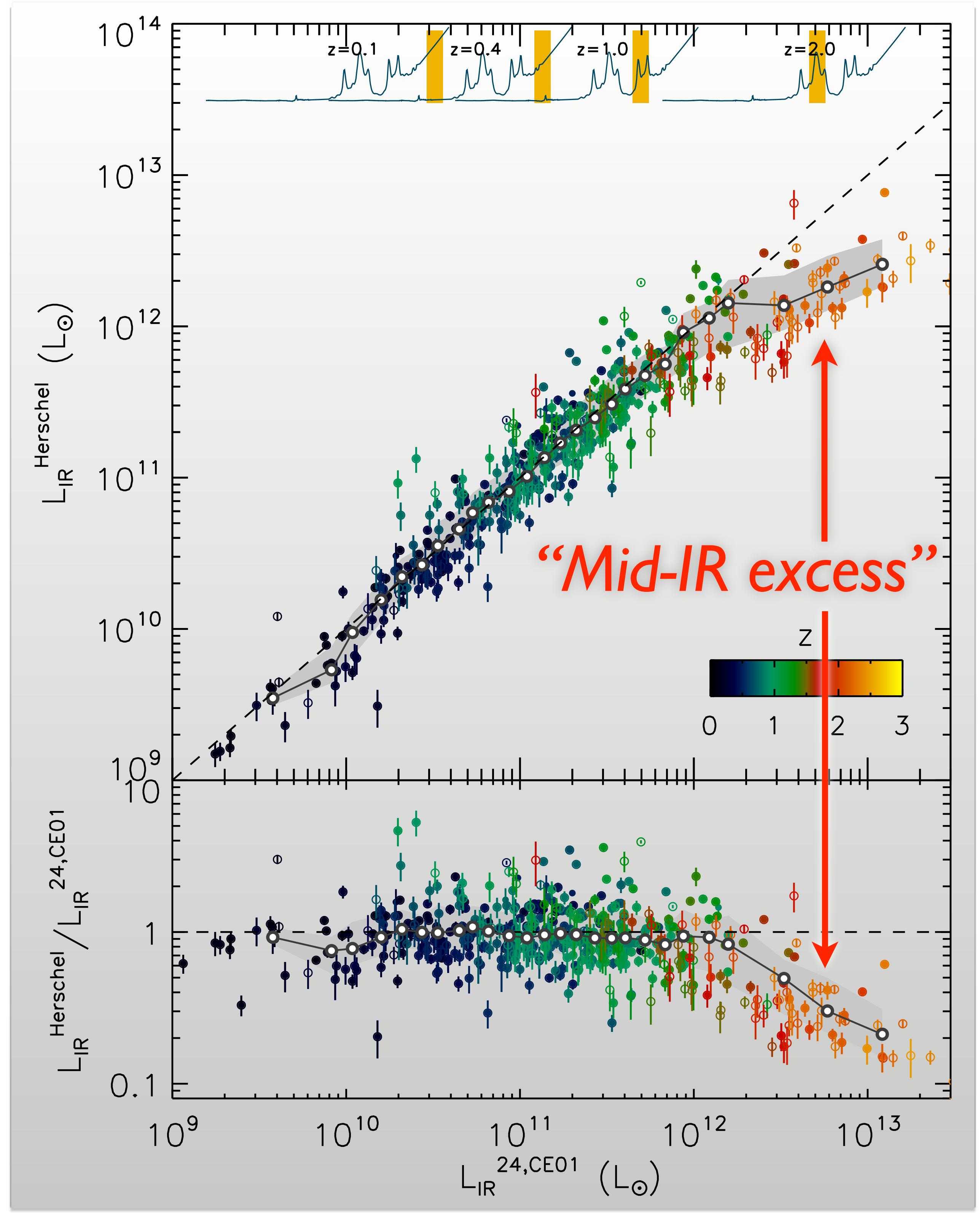


Based on Elbaz et al. (2011)

Effects of local & high-z structural difference on L_{IR} estimation at high-z

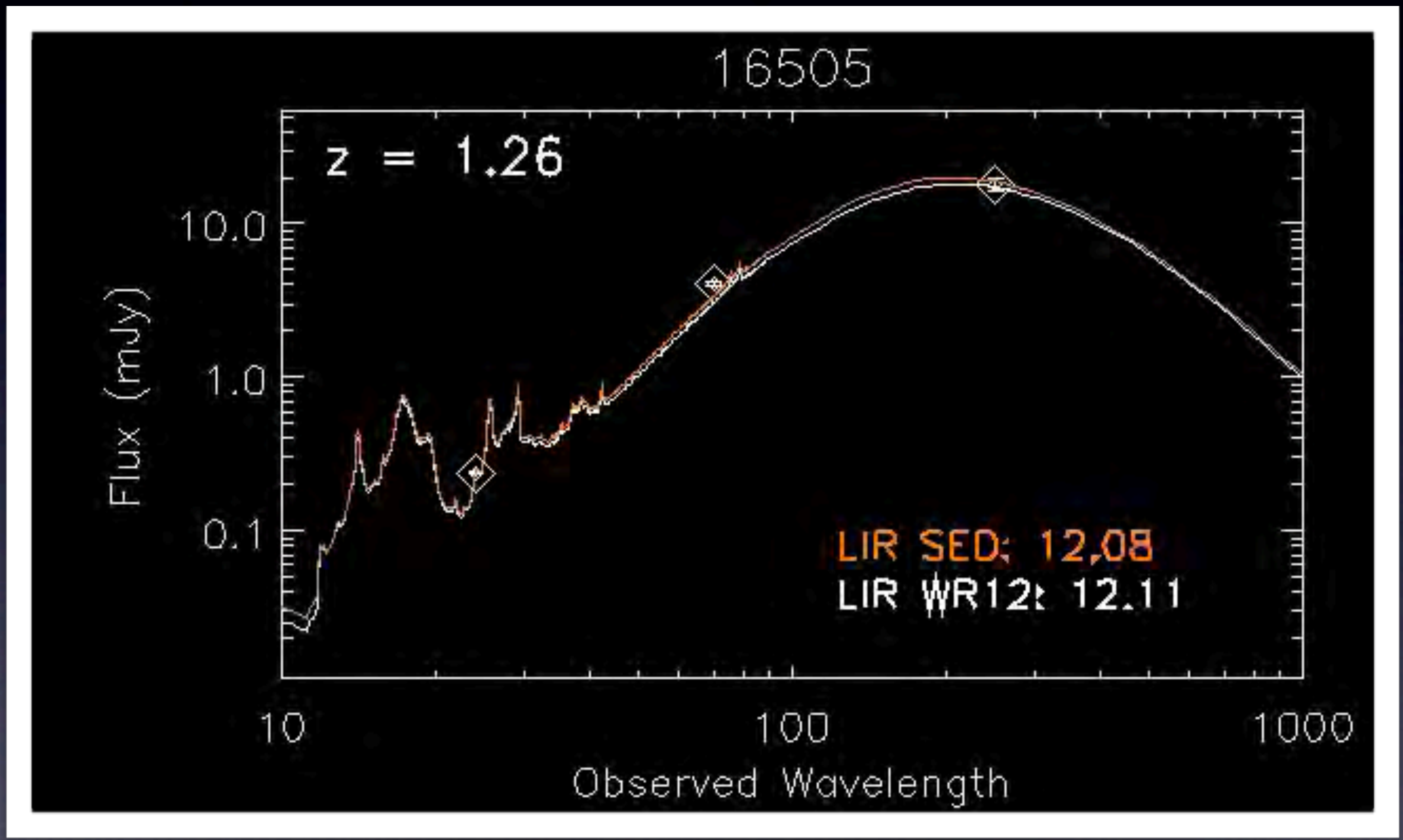
"The mid-IR excess"

Using local SEDs to extrapolate monochromatic 24 μm flux to L_{IR} results in systematic overestimation of L_{IR}



Elbaz et al. (2011)

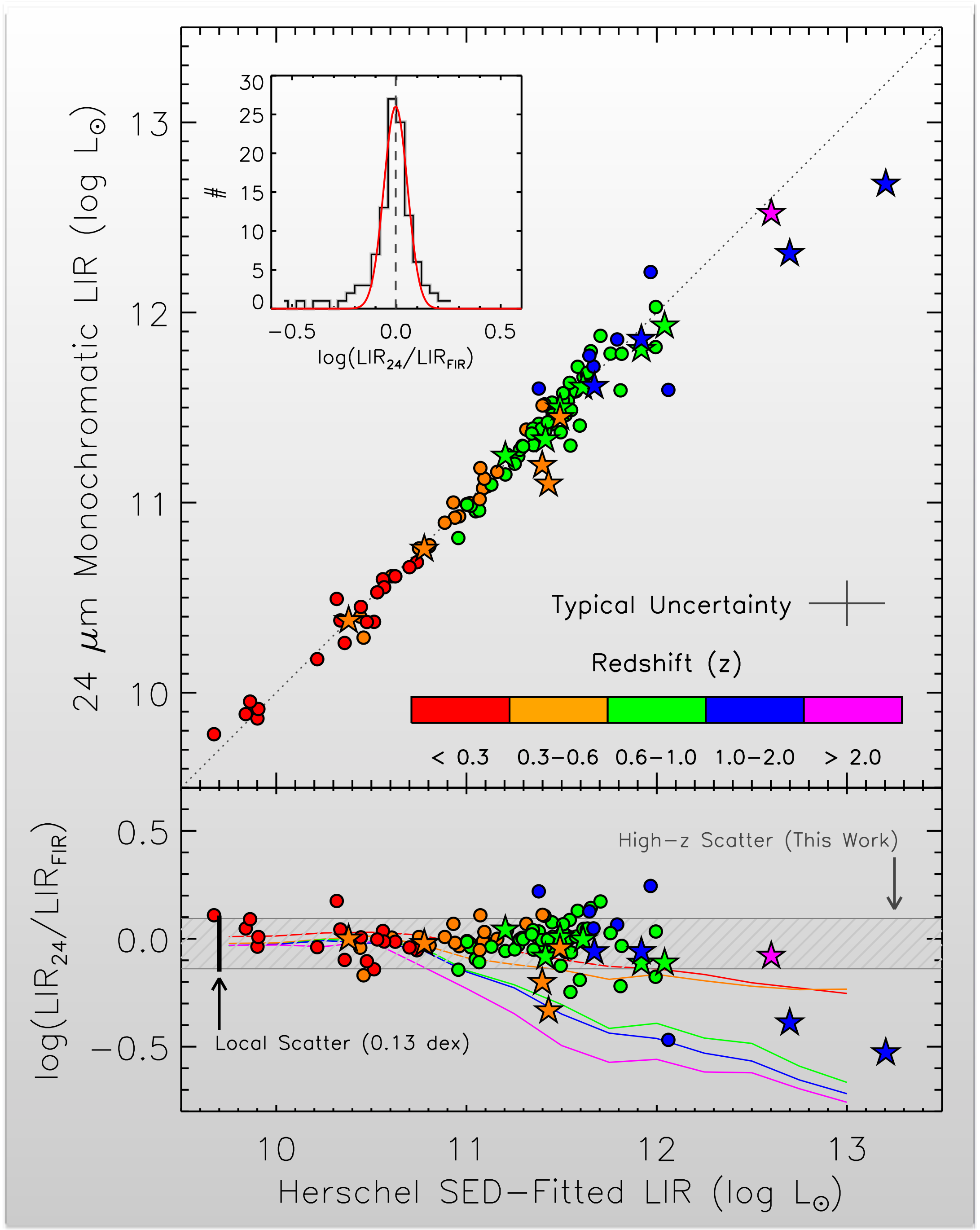
Σ_{IR} - predicted SED template vs. *Herschel* far-IR observations



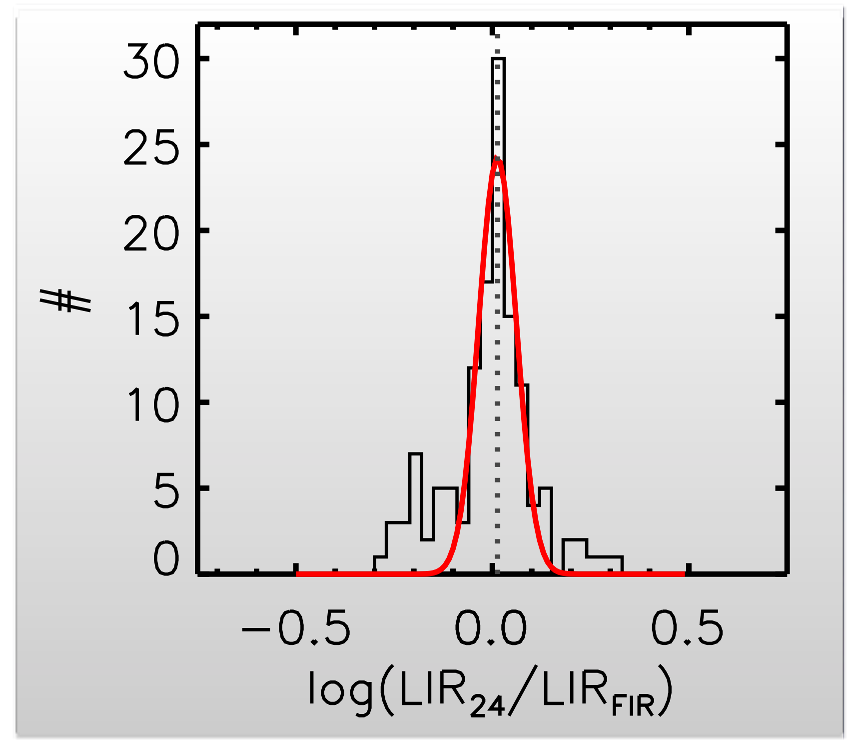
Good agreement leads to a new single-band 24 μm L_{IR} & SFR indicator

Rujopakarn et al. 2012b

Testing the single-band L_{IR} indicator: *Herschel* comparison



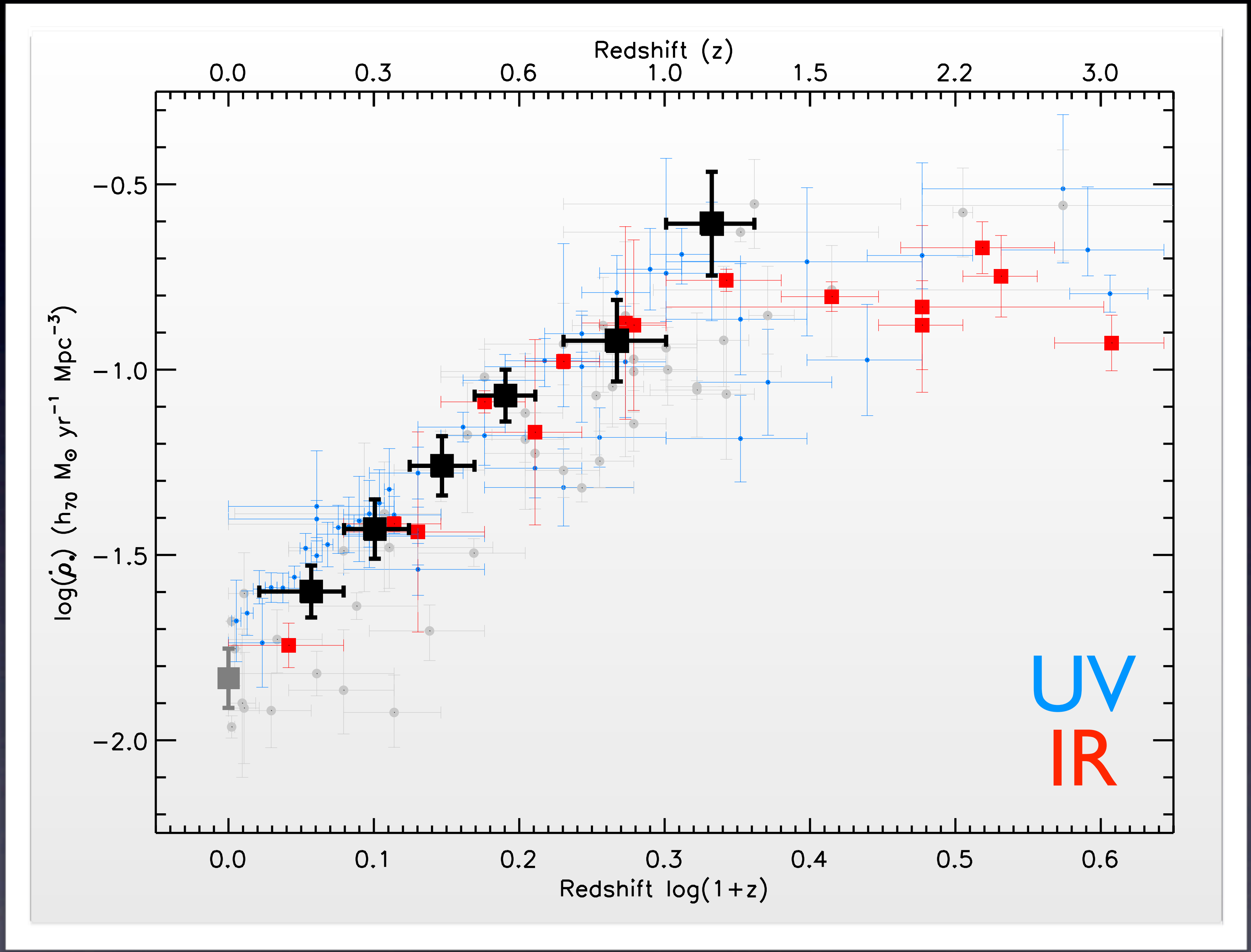
Avg. scatter ~ 0.1 dex



Rujopakarn et al. 2012b
arXiv: 1107.292

Caveats: AGNs; extended structure assumption

Cosmic Star Formation at 0 < z < 1.2

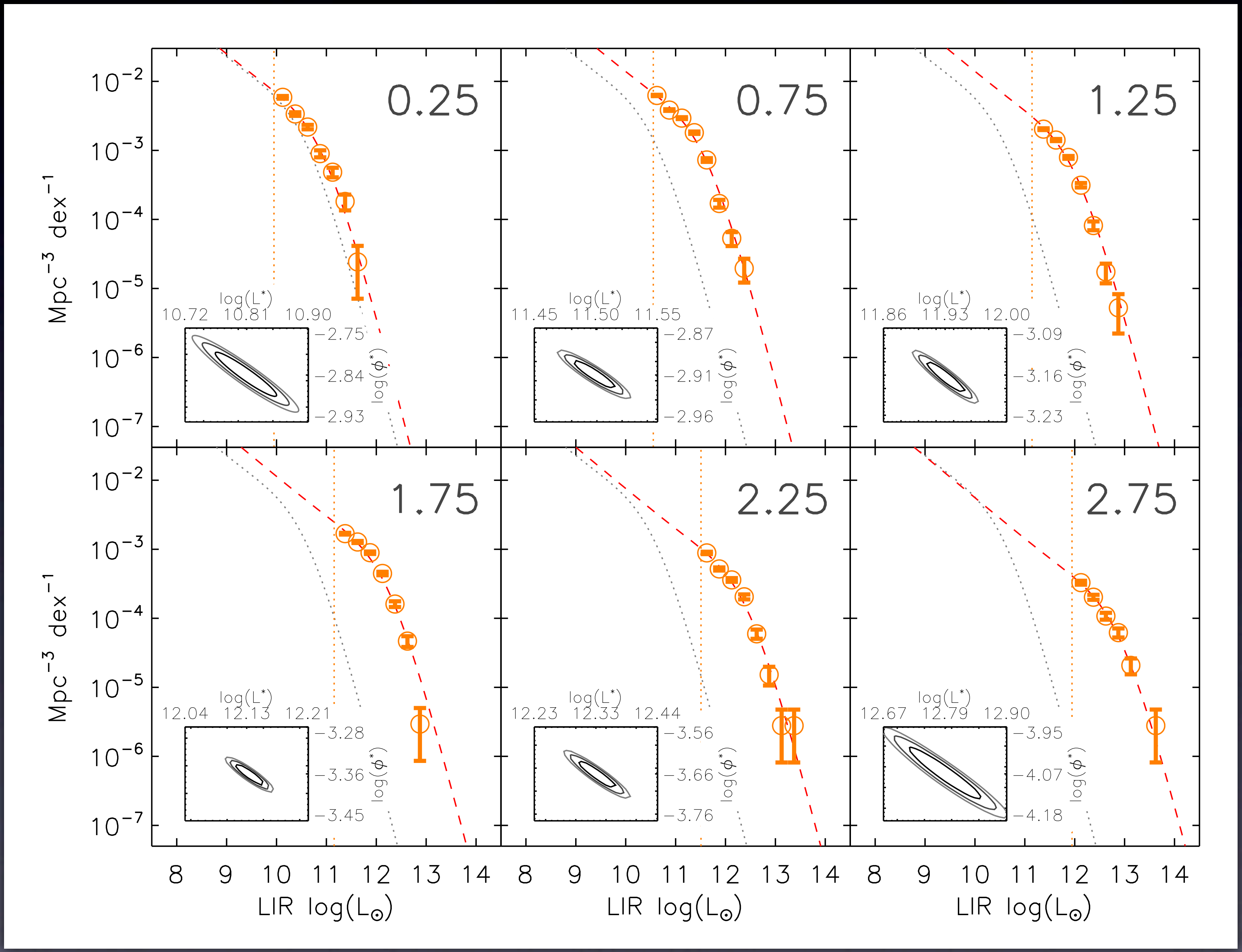


SFR evolution of star-forming galaxies from 24 micron observations out to z ~ 1

Rujopakarn et al. 2010

IR Luminosity Functions at 0 < z < 3

300,000 galaxies in GOODS-N, GOODS-S, EGS

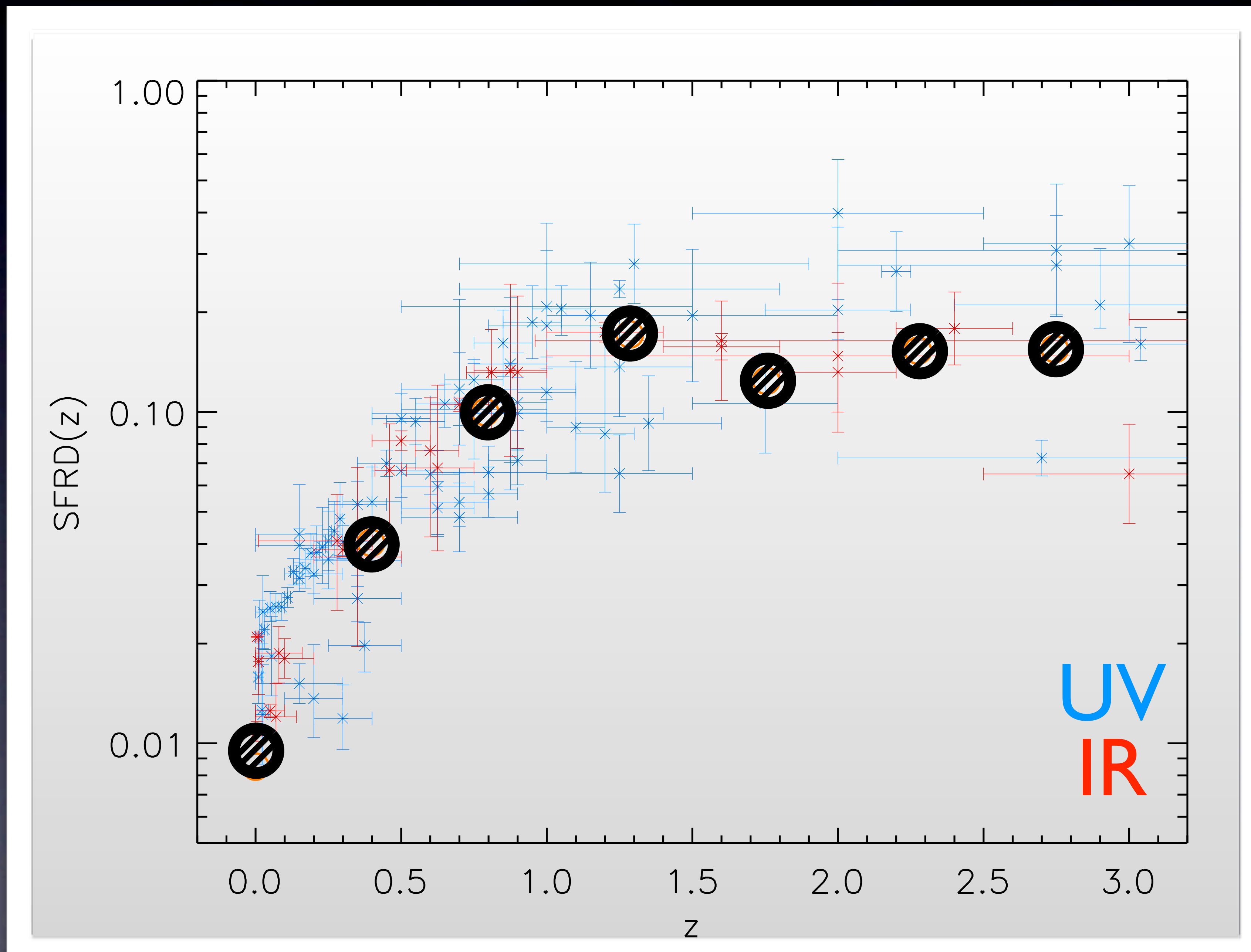


Maximum typical starburst L_{IR} of ~10^{13} L_{sun} or ~1,000 M_{sun}/yr

Rujopakarn et al. 2013, in prep.

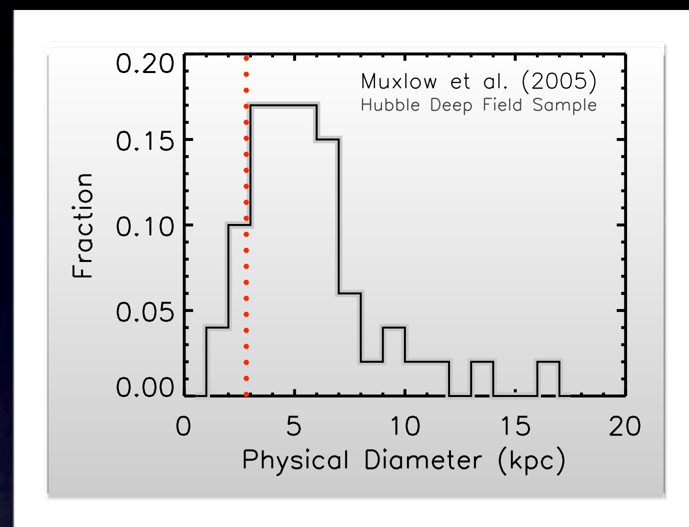
Cosmic Star Formation History at 0 < z < 3

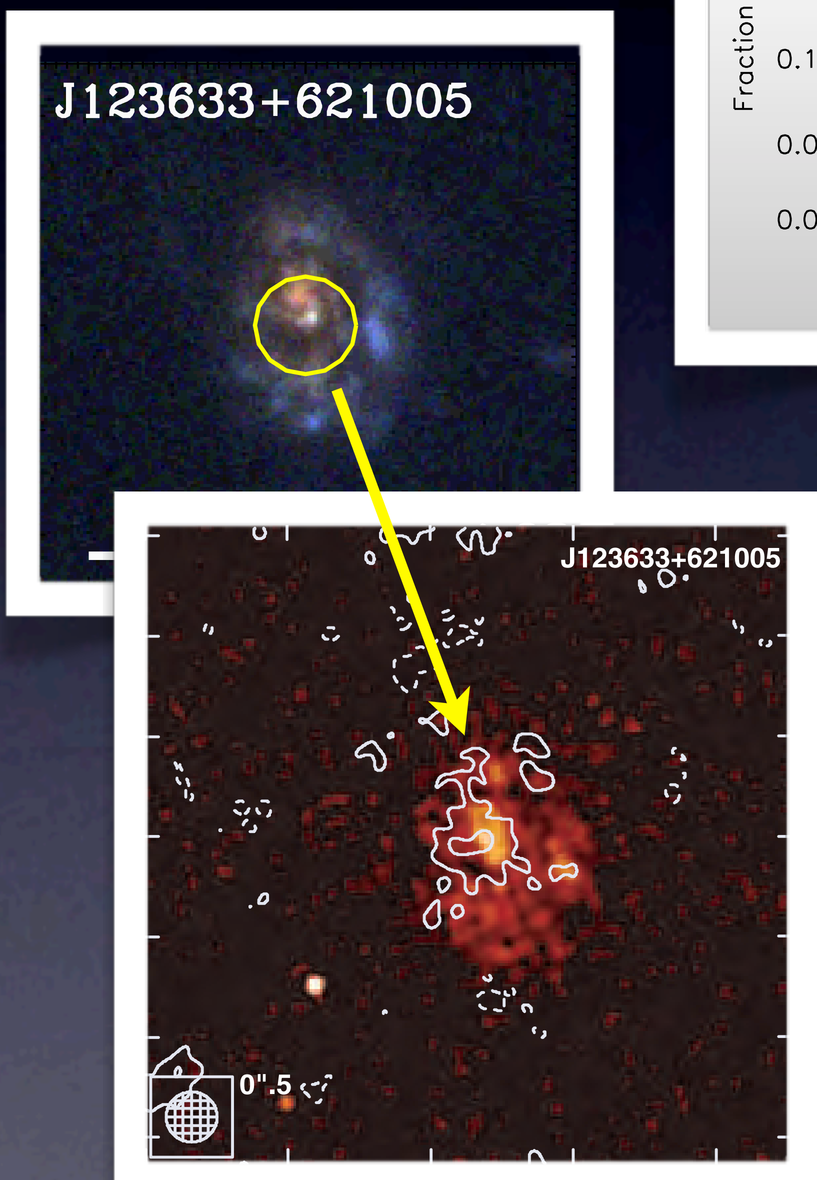
300,000 galaxies in GOODS-N, GOODS-S, EGS



Rujopakarn et al. 2013, in prep.

Ongoing: Resolving the sites of star formation at the peak of galaxy assembly





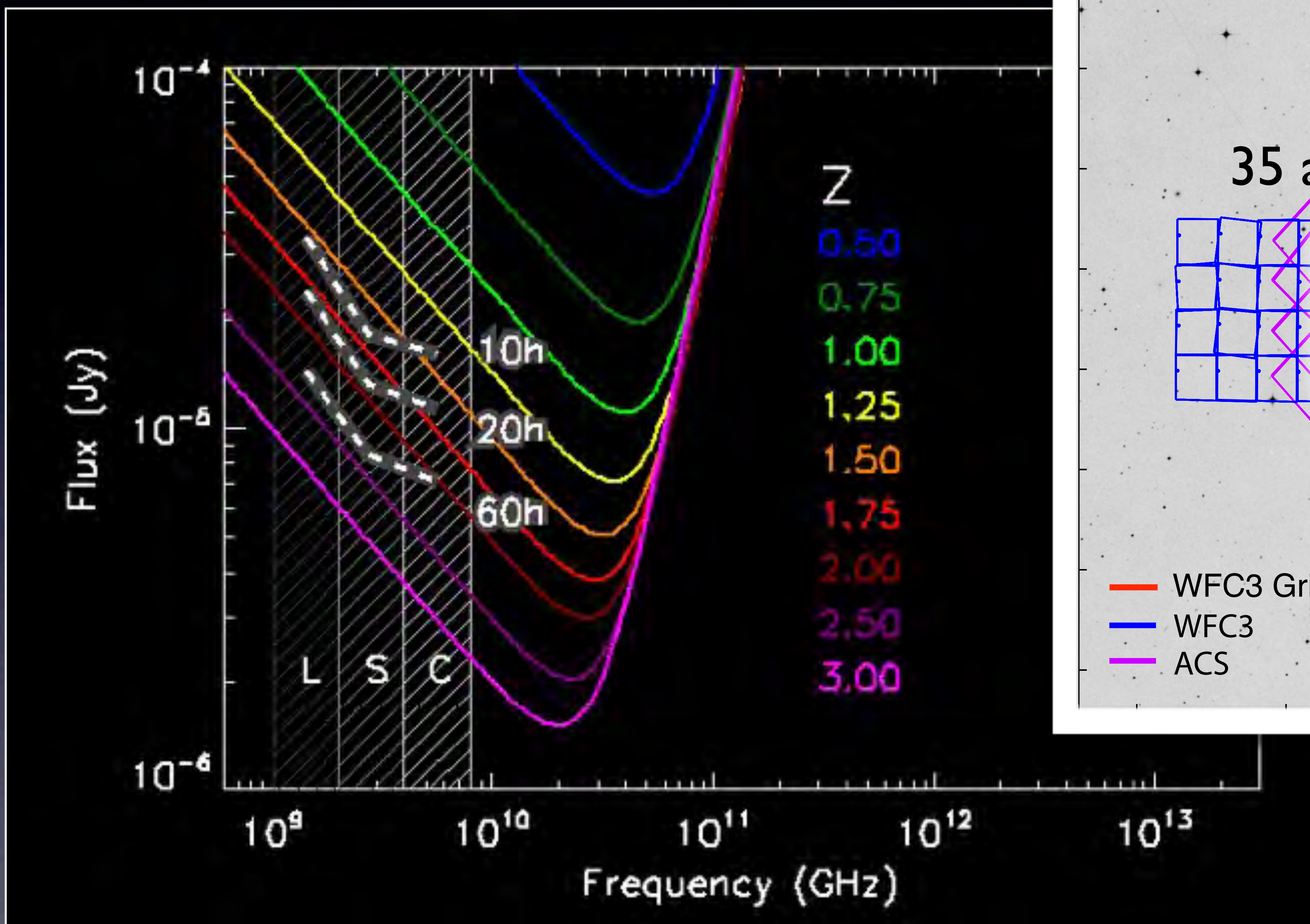
Muxlow et al. (2005); Rujopakarn et al. (2011)

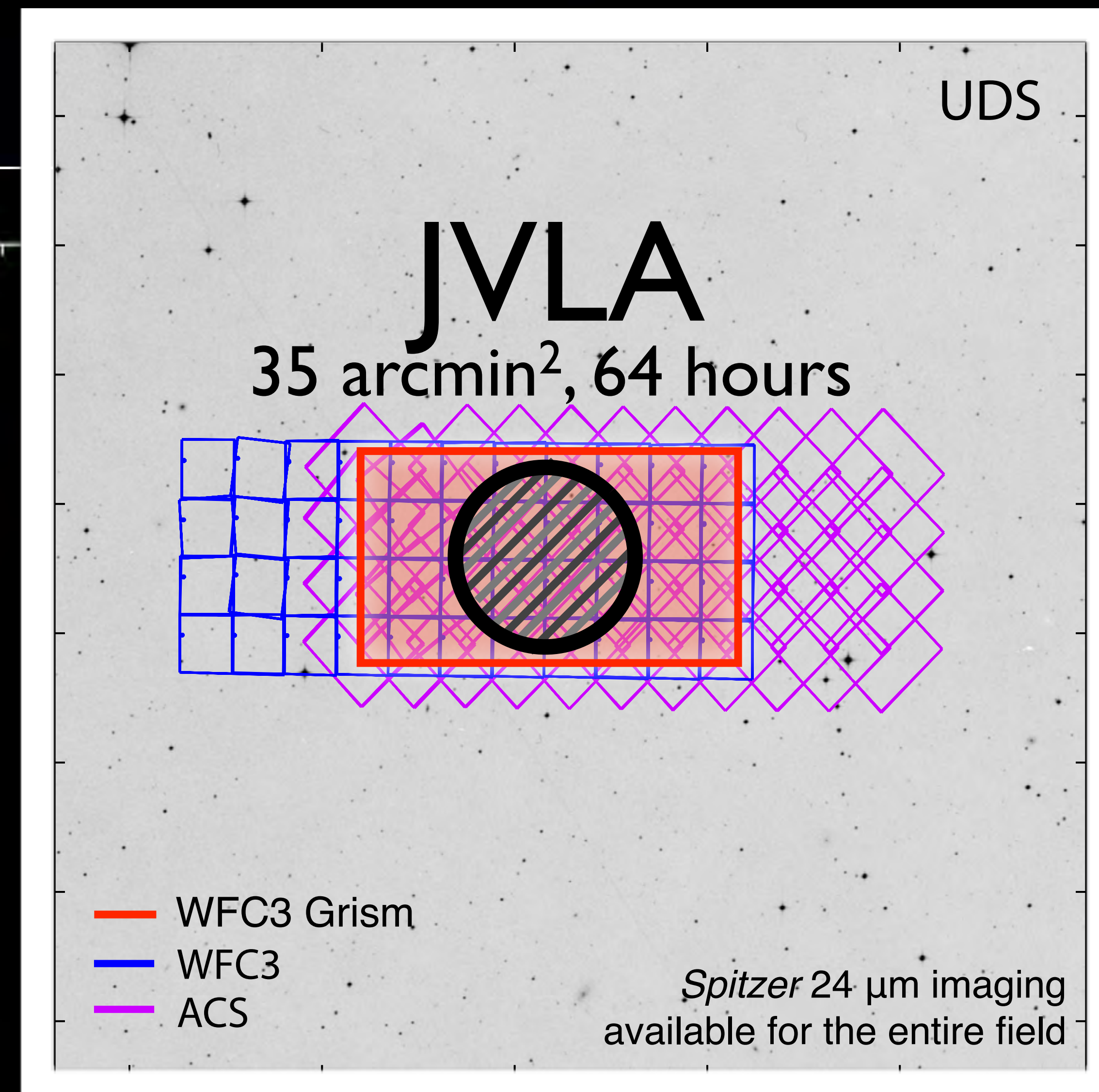
Goal: Compare with CANDELS to study morphologies of SF in relation to old stars

Target galaxies at $z = 1$-2

- 64 hrs, starting October 2012
- 4 - 8 GHz, 0.35" resolution 35 arcmin^2
- 2x deeper than the best survey to date (in HDF-N)
- Select targets across large range of Σ_{IR} for molecular observations to study the SF law

Ongoing: Jansky VLA Survey of the SXDS/UDS

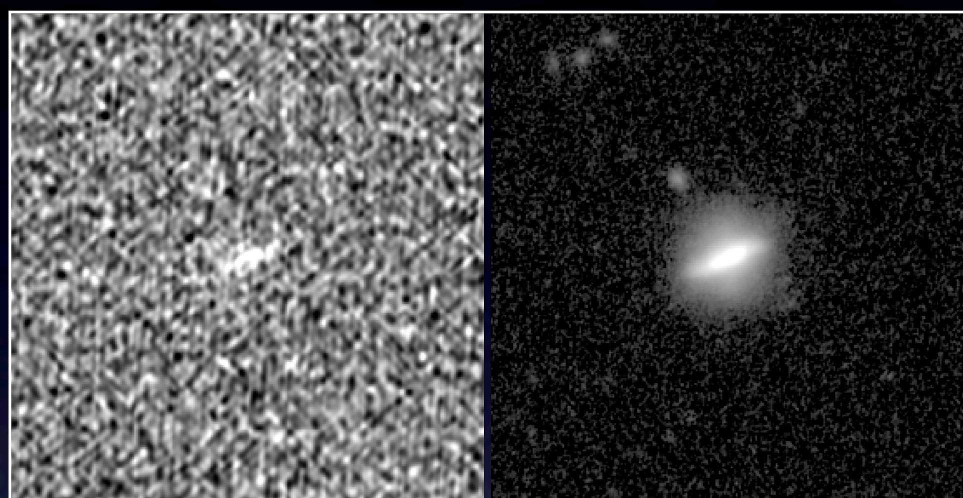




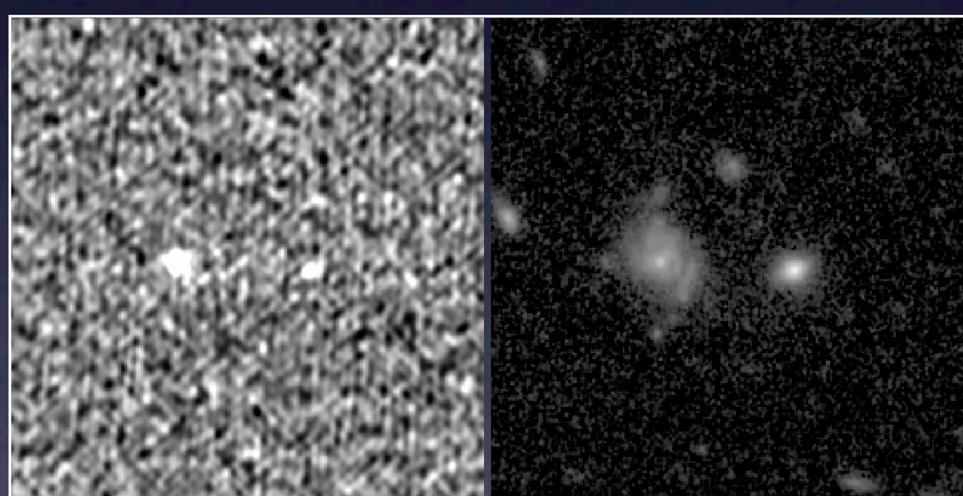
JVLA integration time to obtain integrated flux of 12σ for ULIRG with Arp 220's IR lumiunosity, 2×10^{12} L_{sun}

First Images from the 4-8 GHz Jansky VLA Deep Field

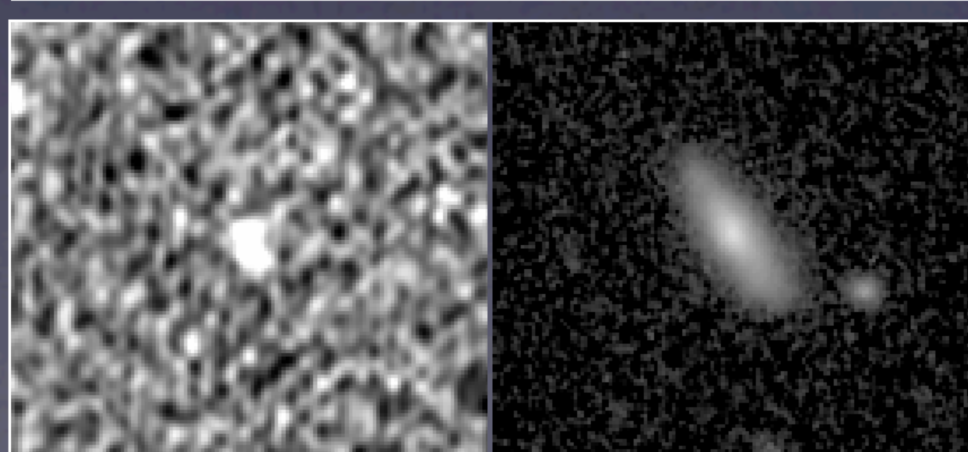
(survey completed Jan 2013)



Local, z = 0.1 star-forming galaxy

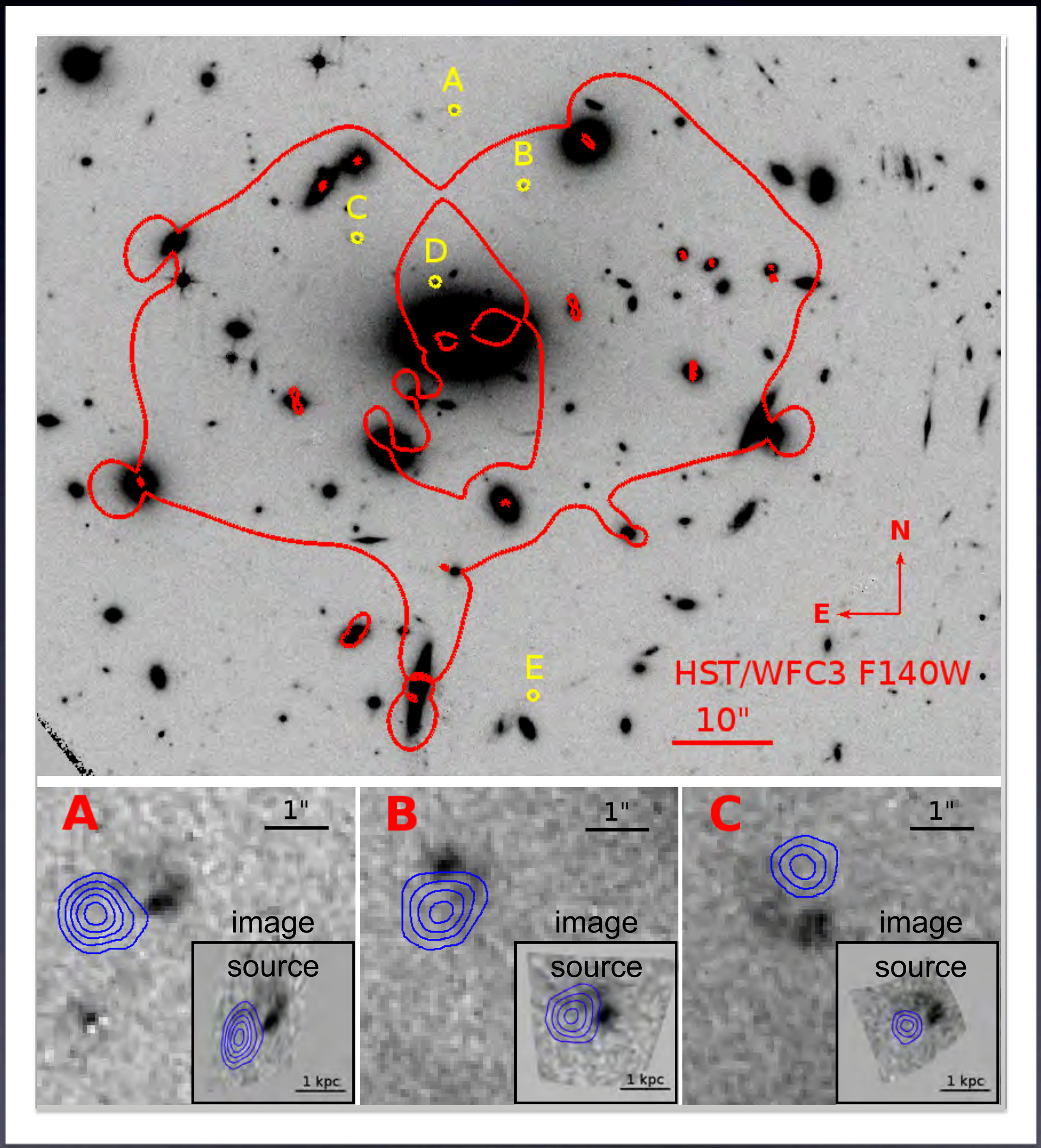


z = 2 SF/AGN in spiral core?



Extended, ~8 kpc
star forming regions at z = 1

Ongoing: Jansky VLA Observations of Herschel Lenses

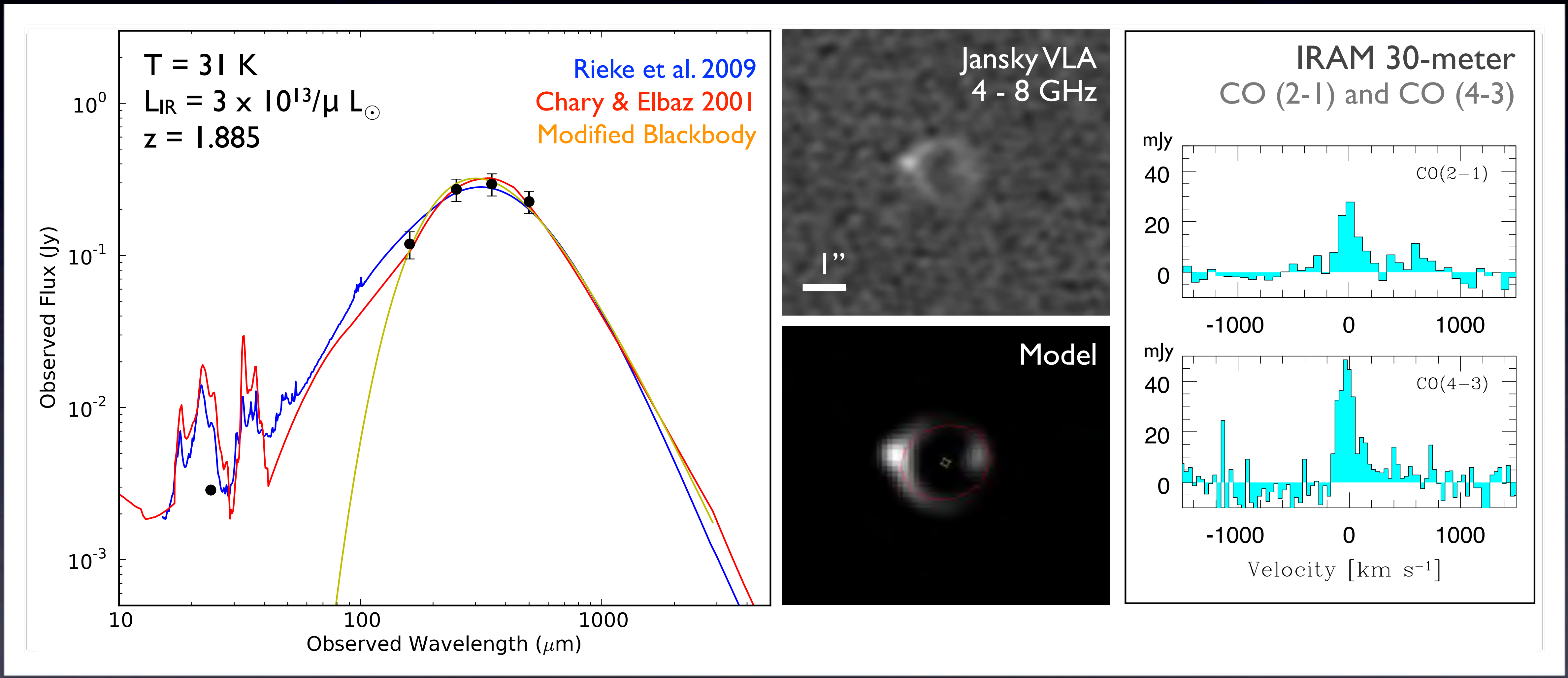


Egami et al. 2012, in prep.

- Goal: combine gravitational lensing and JVLA resolve sub-structure of SF clumps in SPIRE-selected SMGs

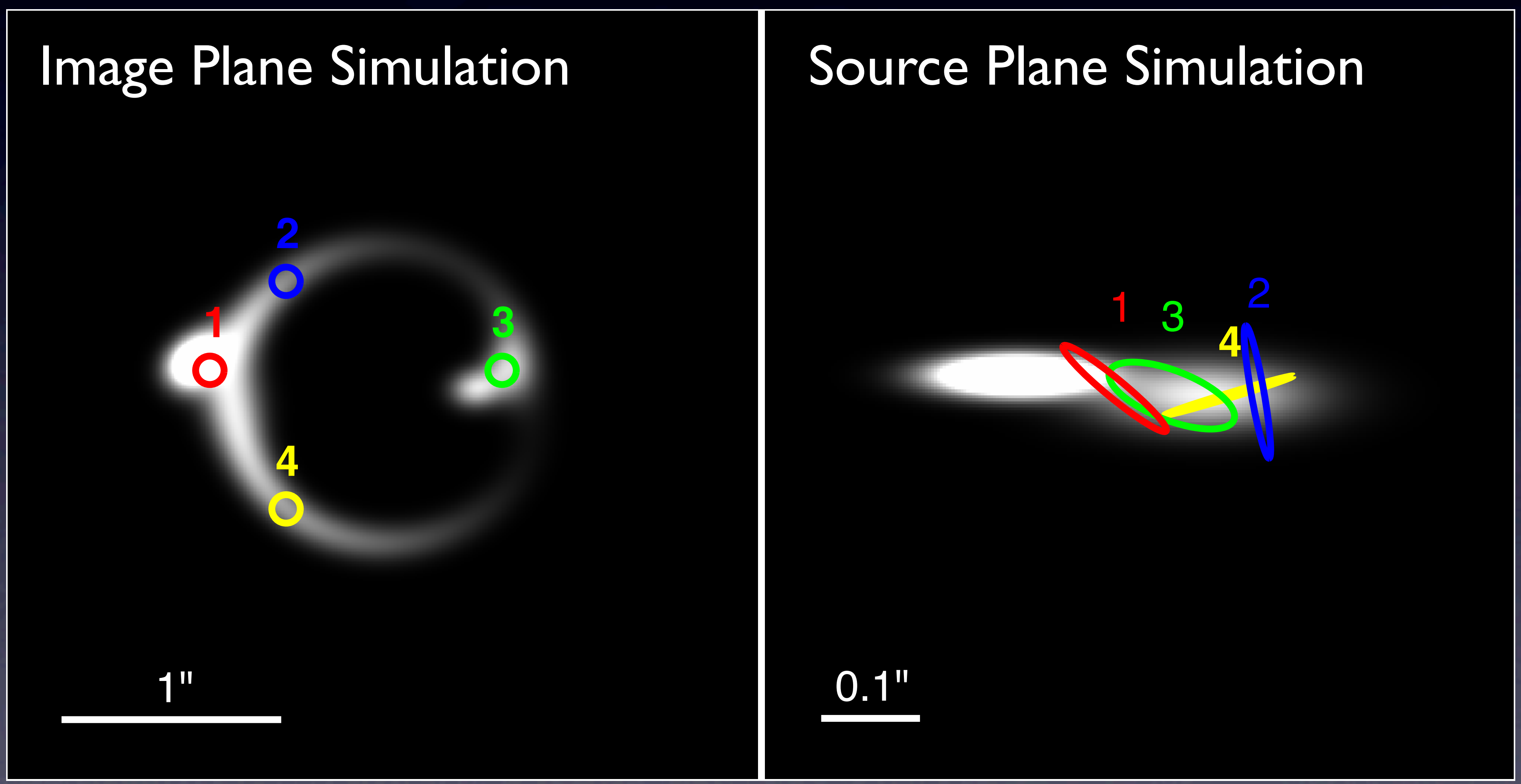
- 12 hrs, starting Sep 2012
- C-band (4-8 GHz)
- 0.35” resolution
- Three targets at z = 2-5

Strongly lensed, kinematically ordered ULIRG at z ~2



Narrow CO line widths suggest a kinematically-ordered system (e.g., disk) despite its extreme luminosity

Dissecting the intensely star-forming clumps in a z ~ 2 Einstein ring



Simulated HST WFC3 beams ... physical area probed

Scaling relations in these clumps can be studied down to ~40 pc with HST and ALMA

Summary

- High-resolution radio continuum observation is a good tracer of high-z SF morphology
- Most high-z U/LIRGs are extended, unlike merger-triggered, nuclear-concentrated local U/LIRGs
- A majority of U/LIRGs at $1 < z < 3$ do not show signs of major mergers - implications on modes of star formation and galaxy assembly