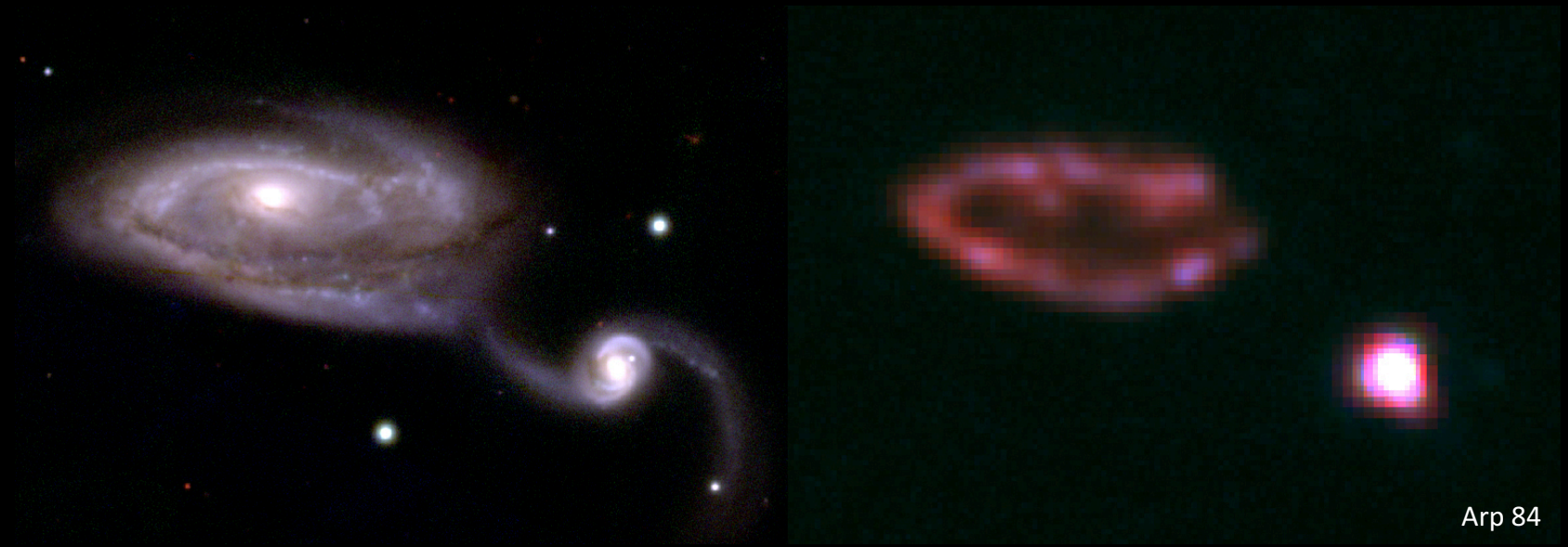
Understanding Luminous Infrared Galaxies in the *Herschel* Era



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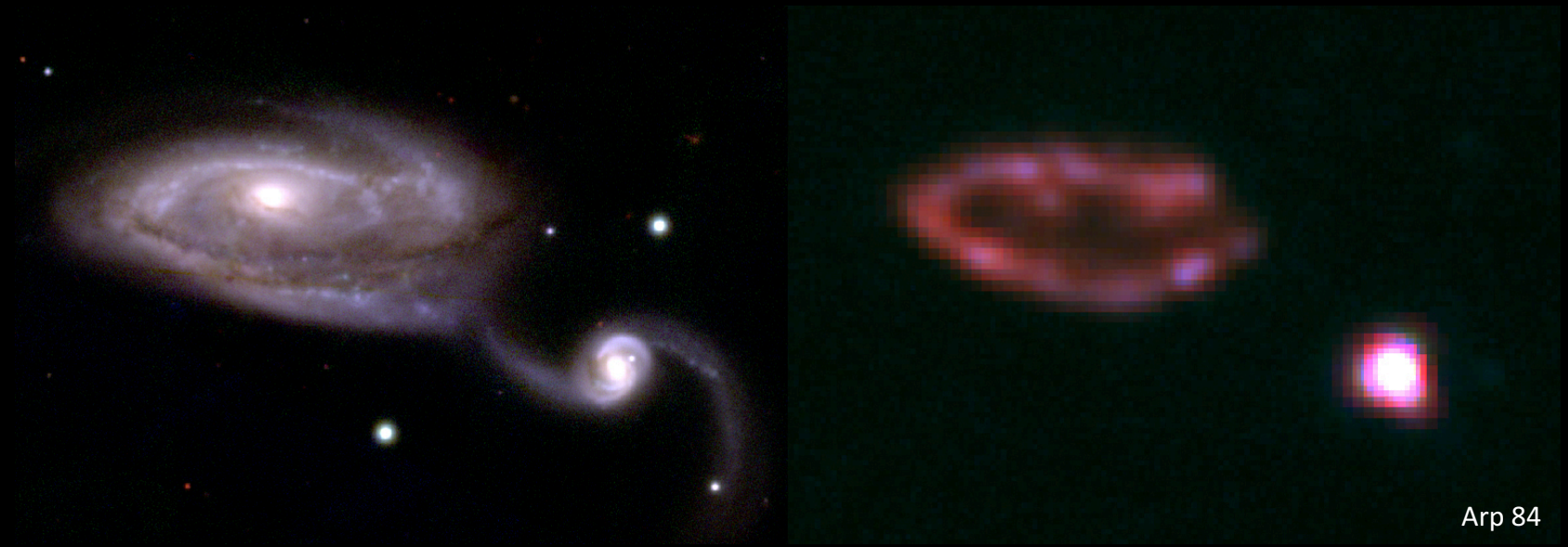
Collaborators: Jason Chu (IfA), Kirsten Larson (Caltech/IPAC), Joseph Mazzarella (Caltech/IPAC), Lisa Kewley (ANU)

Understanding submm-selected LIRGs in the *Herschel* Era

SMG20 – Durham – 8/01/17



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Understanding Luminous Infrared Galaxies in the *Herschel* Era

I. $Z \sim 0$ (PACS+SPIRE) The Herschel-GOALS atlas

II. $Z \sim 2.3$ (BPT diagram) Herschel vs. MOSDEF selection

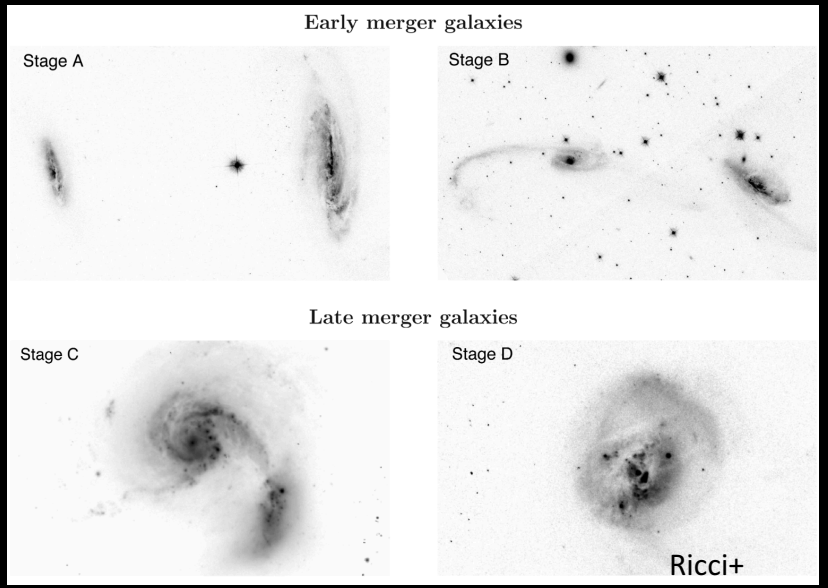
Why Study Luminous IR Galaxies?

- Hundreds of luminous infrared galaxies (LIRGs) first discovered in the 1980s.

- They emit the bulk of their bolometric luminosities in the infrared: $L_{IR} = L(8\text{-}1000\ \mu m)$.
  - LIRG: $11 \leq \log(L_{IR}/L_{\odot}) < 12$
  - ULIRG: $12 \leq \log(L_{IR}/L_{\odot}) < 13$

- Many are interacting/merging

- (U)LIRGs much more common in the high-z universe (detected as SMGs).



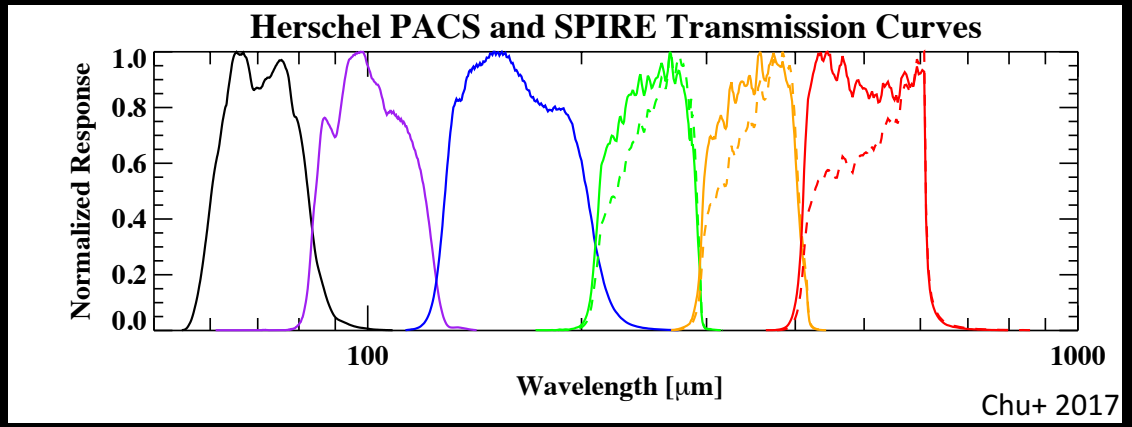
GOALS Great Observatory All-sky LIRG Survey

- Consists of the 201 brightest galaxies in the Revised Bright Galaxy Sample (RBGS) with $L_{IR} \geq 10^{11}\ L_{\odot}$.
- GOALS is a statistically complete, flux-limited local sample of infrared luminous galaxies.
- They represent a complete picture of galaxy evolution in the local universe.

➔ Critical to study these galaxies in the FIR/submm, where they emit the bulk of their bolometric luminosity.

I. *Herschel*-GOALS Observations

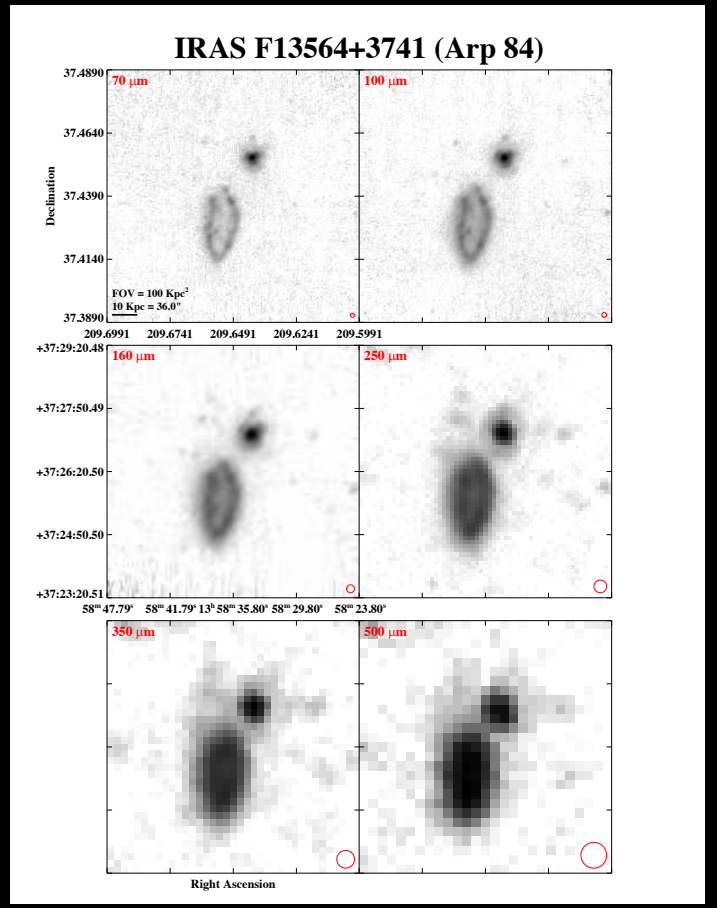
- Entire GOALS sample imaged by PACS and SPIRE (PI: Sanders).
- Photodetector Array Camera and Spectrometer (PACS)
  - 70 μm ➔ 5.6” beam FWHM
  - 100 μm ➔ 6.8”
  - 160 μm ➔ 11.4”
- Spectral and Photometric Imaging Receiver (SPIRE)
  - 250 μm ➔ 18.1”
  - 350 μm ➔ 25.2”
  - 500 μm ➔ 36.6”



The *Herschel*-GOALS Atlas

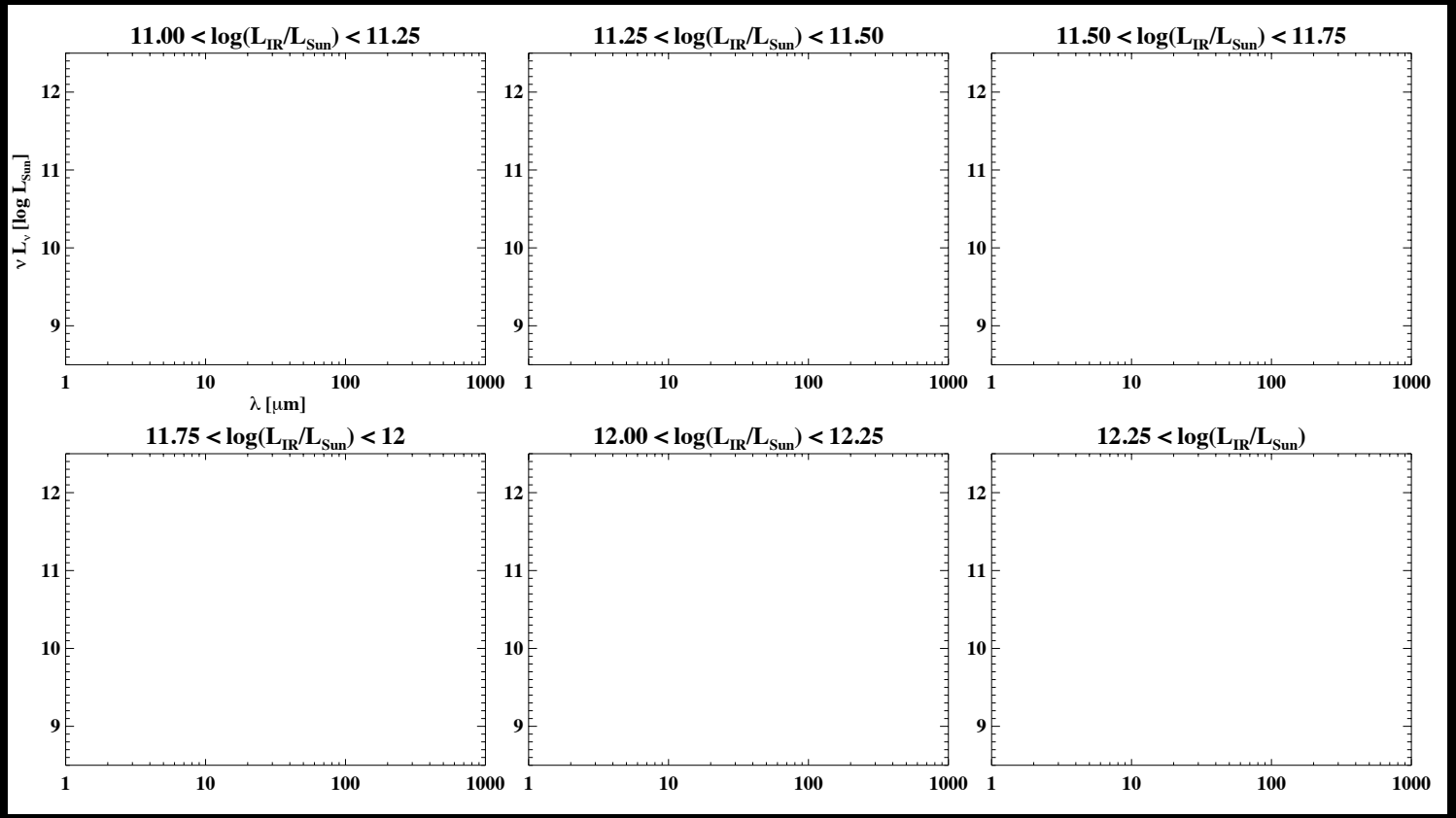
- Maps of all 201 GOALS systems have been published for all six *Herschel* bands in Chu et al. (2017).
- Aperture photometry measured for every GOALS object:
  - Total system fluxes.
  - Component fluxes where possible.
- Very good signal to noise ratios:
  - PACS: Typical *S/N*~10-20
  - SPIRE: Typical *S/N*~5-15

Data: http://irsa.ipac.caltech.edu/data/GOALS/galaxies/



Results: Infrared SEDs of (U)LIRGs

(Chu+ 2017bc, in prep.)



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IRAS

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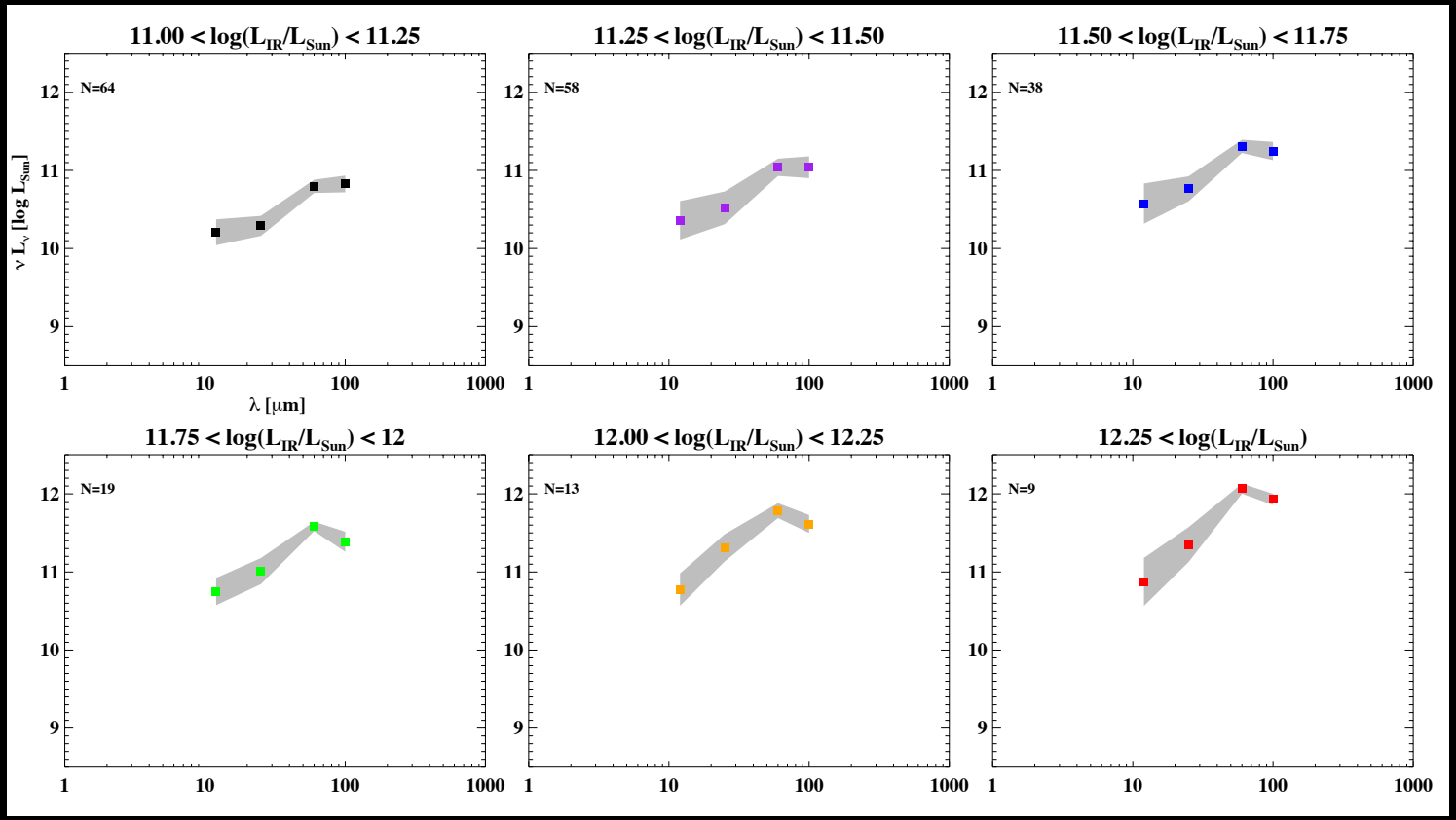

Results: Infrared SEDs of (U)LIRGs

IRAS + Spitzer + WISE

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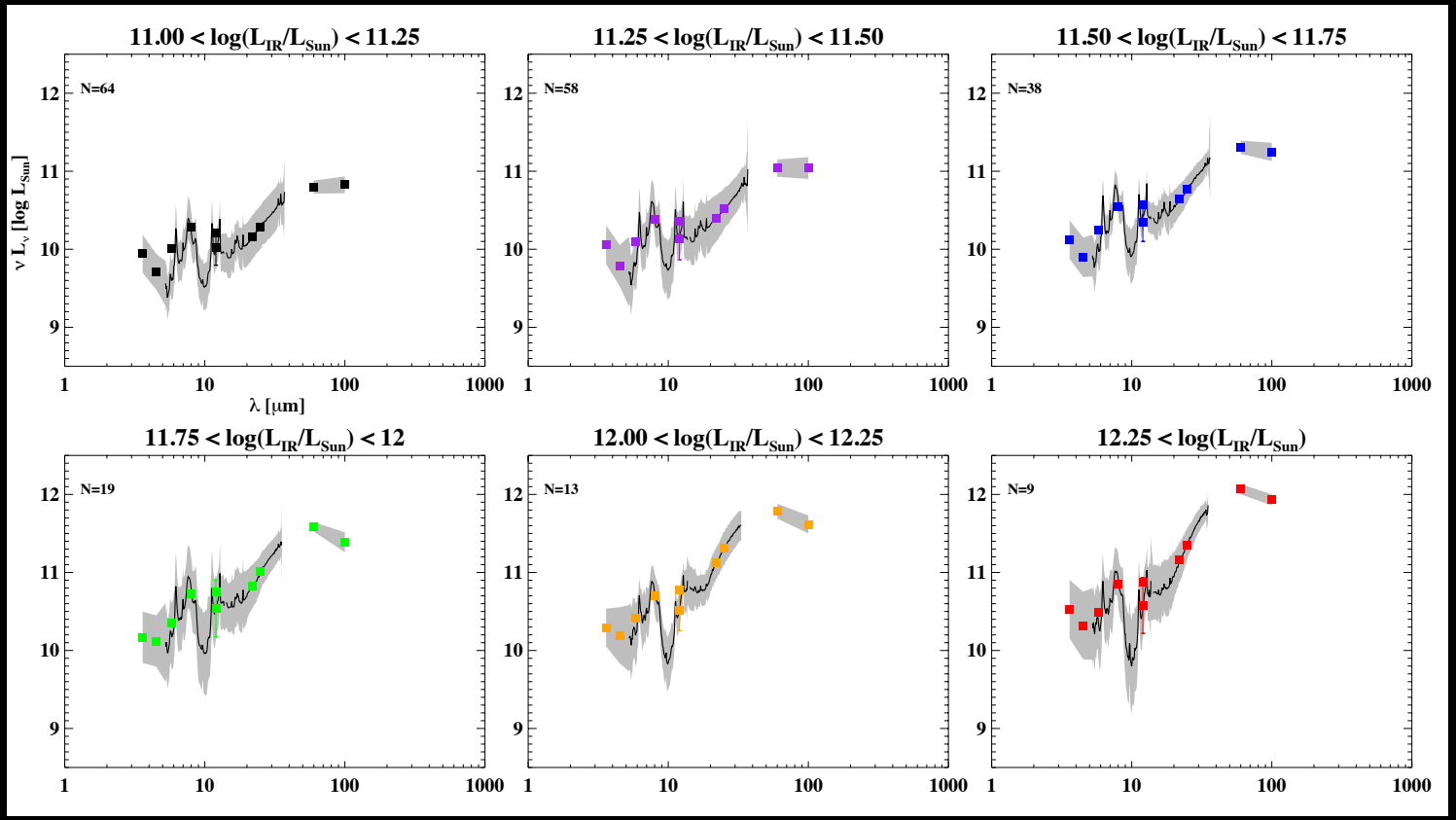

Results: Infrared SEDs of (U)LIRGs

IRAS + Spitzer + WISE + Herschel

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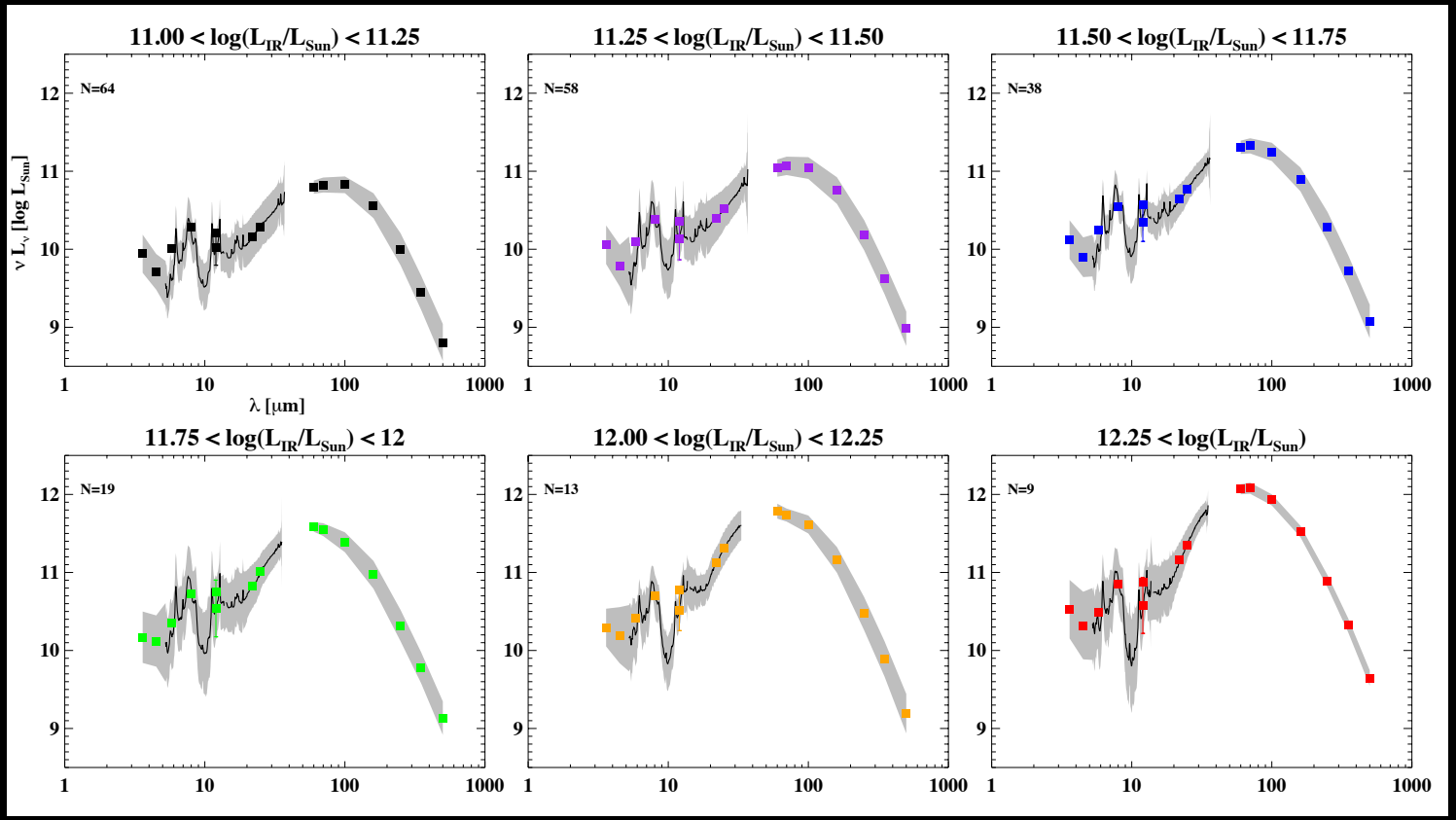
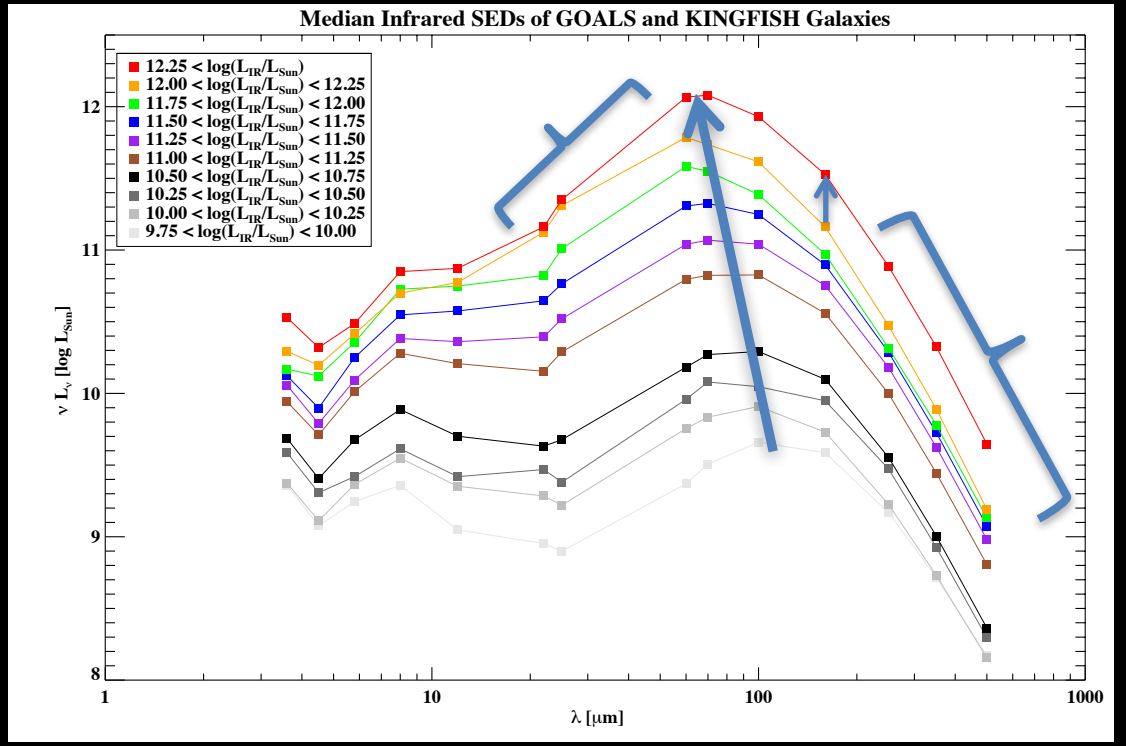


Results: Infrared SEDs of (U)LIRGs

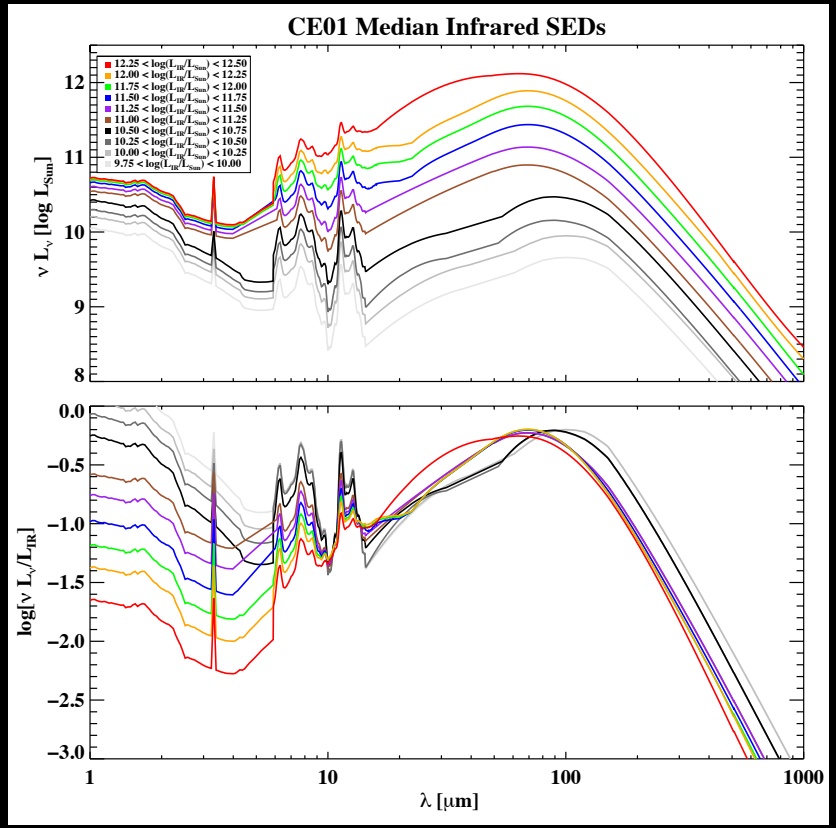
- SED peak:
  - Becomes brighter, with significant jump at highest L_{IR}.
  - Peak is at shorter wavelengths with increasing L_{IR}.
- FIR/sub-mm spectral index:
  - GOALS: Nearly constant at all L_{IR} at $\lambda \geq 250$ μm, $F \propto \nu^{4.05 \pm 0.12}$.
  - Sub-LIRGs less steep.
  - x2 extra jump in luminosity at L_{IR} at $\lambda \geq 60$ μm in highest bin.
- MIR (30-70 μm) spectral index:
  - Relatively constant for all GOALS bins, except two highest bins.



(Chu+ 2017b, in prep.)

Results: Comparison to Model SEDs

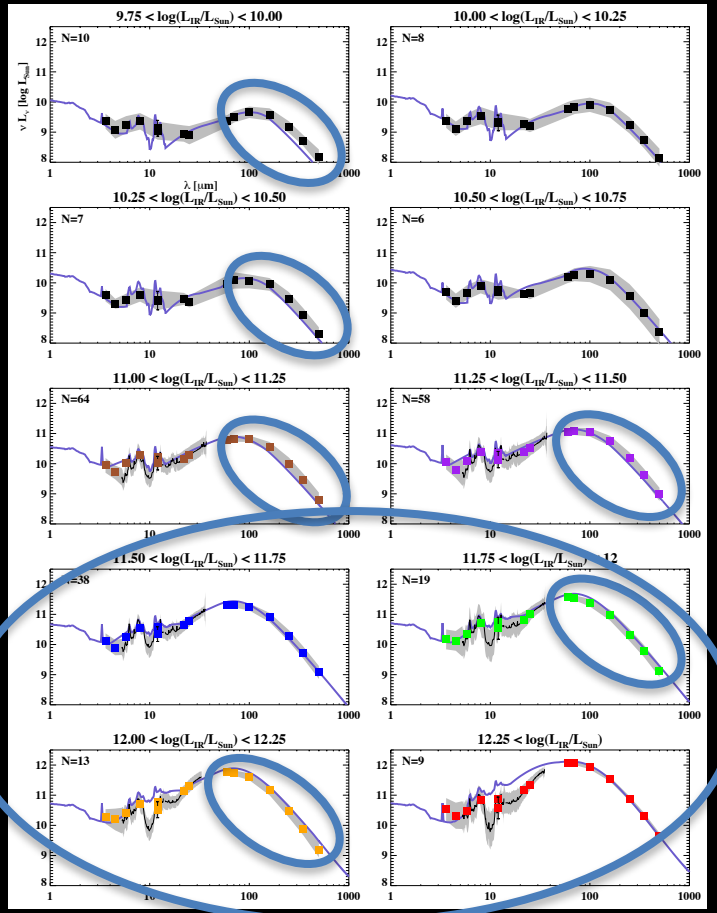
- We compared our median SEDs to the model predictions of Chary & Elbaz (2001).
- CE01 produced SED templates of galaxies as a function of IR luminosity using *IRAS*, *ISO*, and SCUBA data.



Chu et al., (2017b, in prep.)

Results: Comparison C+17 to CE01 Model SEDs

- In the FIR/sub-mm, CE01 slightly underestimates flux in some bins, while in others it overestimates.
- In the MIR, CE01 matches the data well except in highest L_{IR} bins where it overestimates.

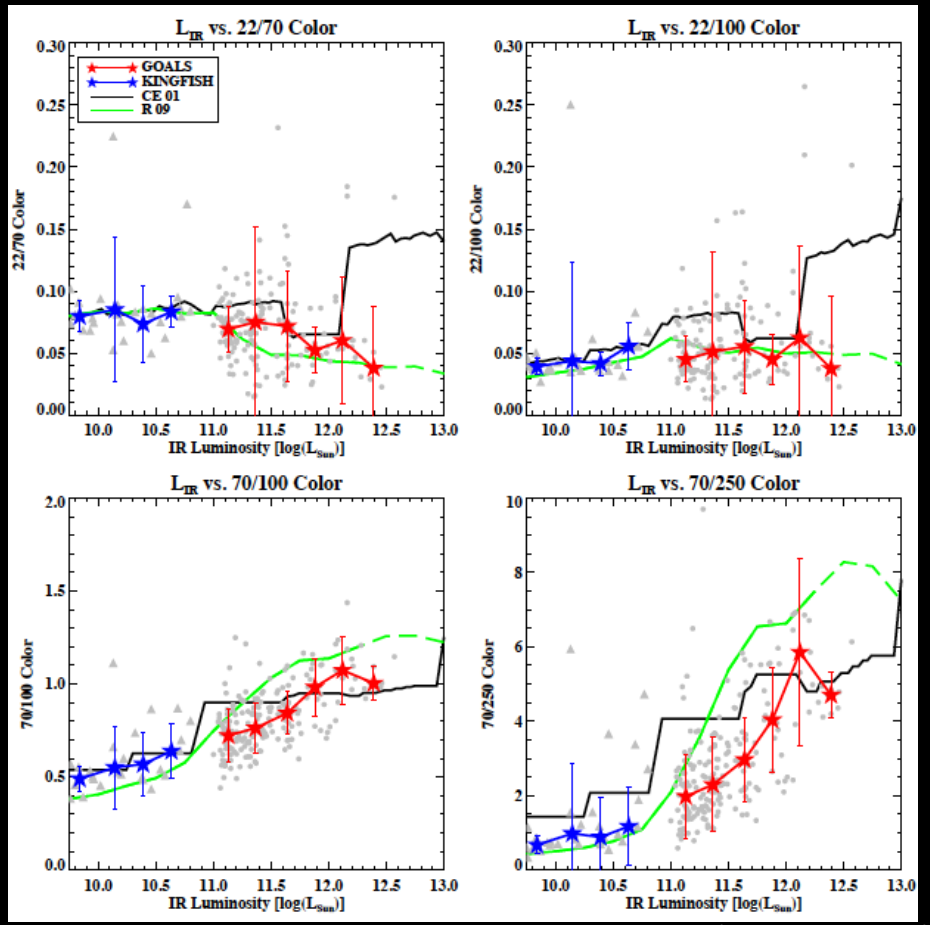


Chu et al., (2017b, in prep.)

Results: Far-Infrared Colors

- Plot of far-IR flux ratios as a function of L_{IR}, including the following SED templates:
  - Chary & Elbaz (2001)
  - Rieke et al. (2009)

- Comparison with models:
  - R09 predicts the KINGFISH galaxies well, except the 70/100 color.
  - CE01 predicts the KINGFISH galaxies well, except the 70/250 color.
  - Both models over-predict the 70/250 color for the GOALS galaxies.

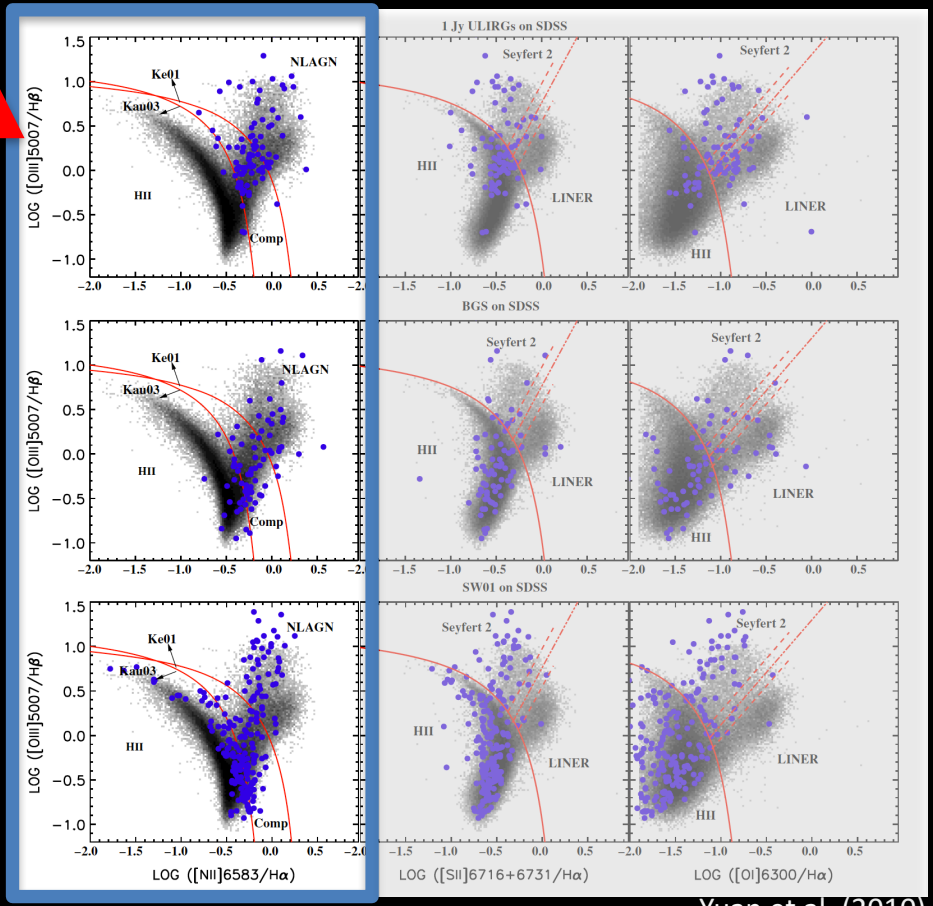


Chu et al., (2017b, in prep.)

II. Optical Line Diagnostics of (U)LIRGs

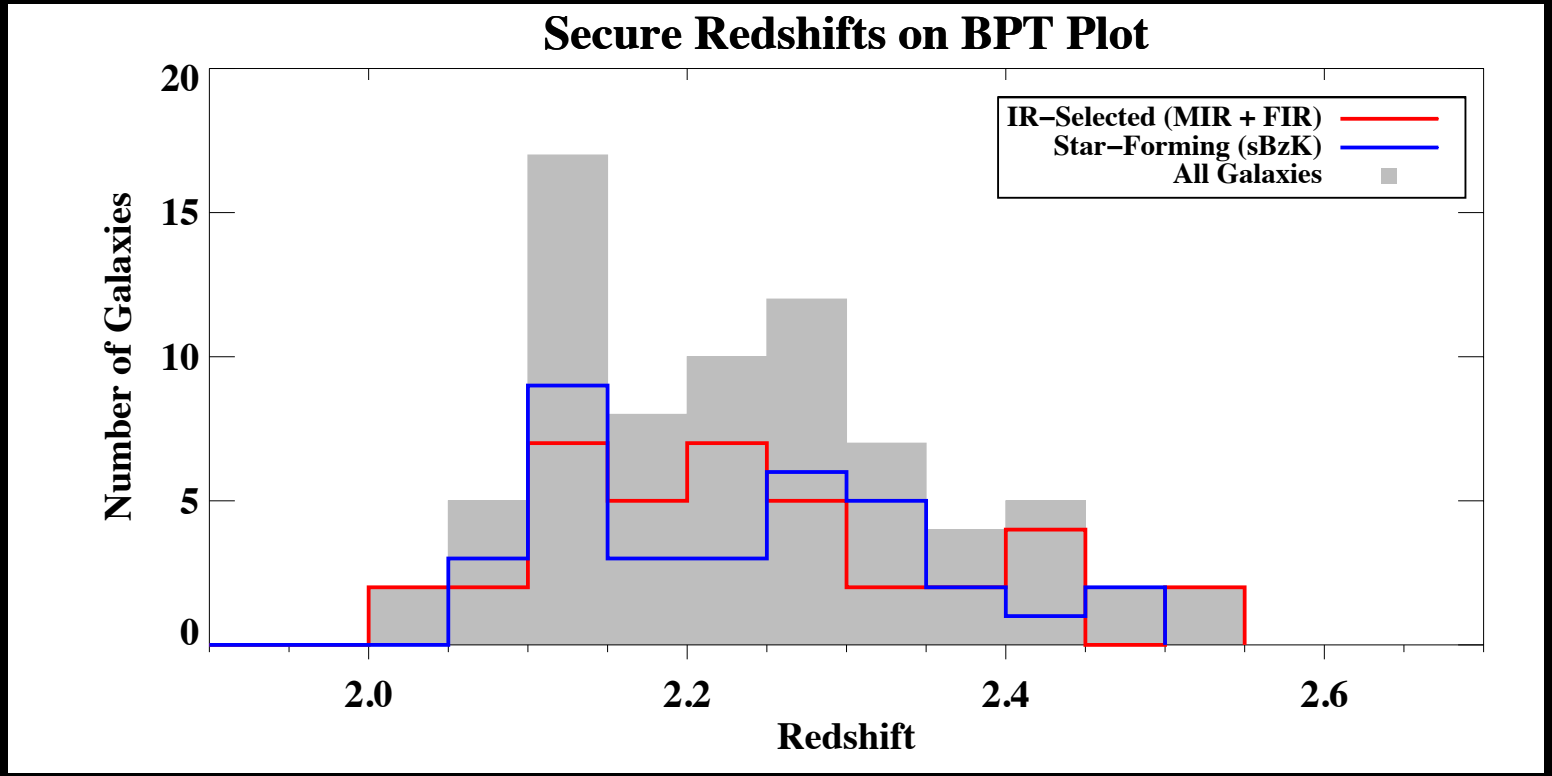
- Powerful tool to study a galaxy's ISM conditions.
  - First put forth by Baldwin, Phillips, Terlevich (1981), hence "BPT" diagrams.
- Uses optical emission line flux ratios to separate starburst and AGN galaxies:
  - [O III] λ5007 / Hβ
  - [N II] λ6583 / Hα
  - [S II] λλ6717, 6731 / Hα
  - [O I] λ6300 / Hα
- Theoretical classification lines:
  - Kewley+ 2001 proposed first set of theoretical BPT classification lines for z=0.
  - Kewley+ 2013a produced theoretical classification lines up to z=3.

Where do (U)LIRGs at z~2.3 lie on the BPT diagram?

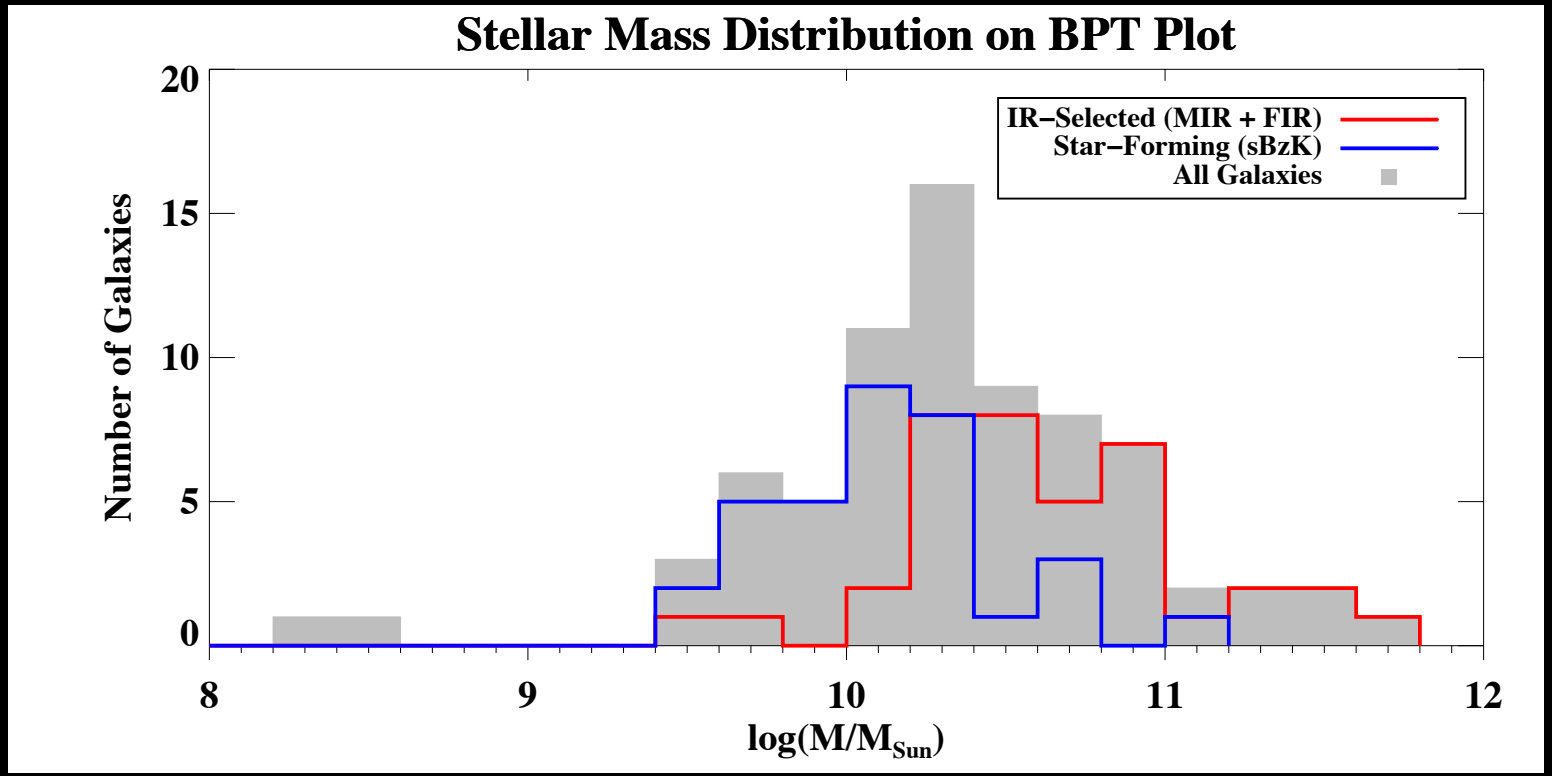


Yuan et al. (2010)

$z \sim 2.3$ Redshift Distribution

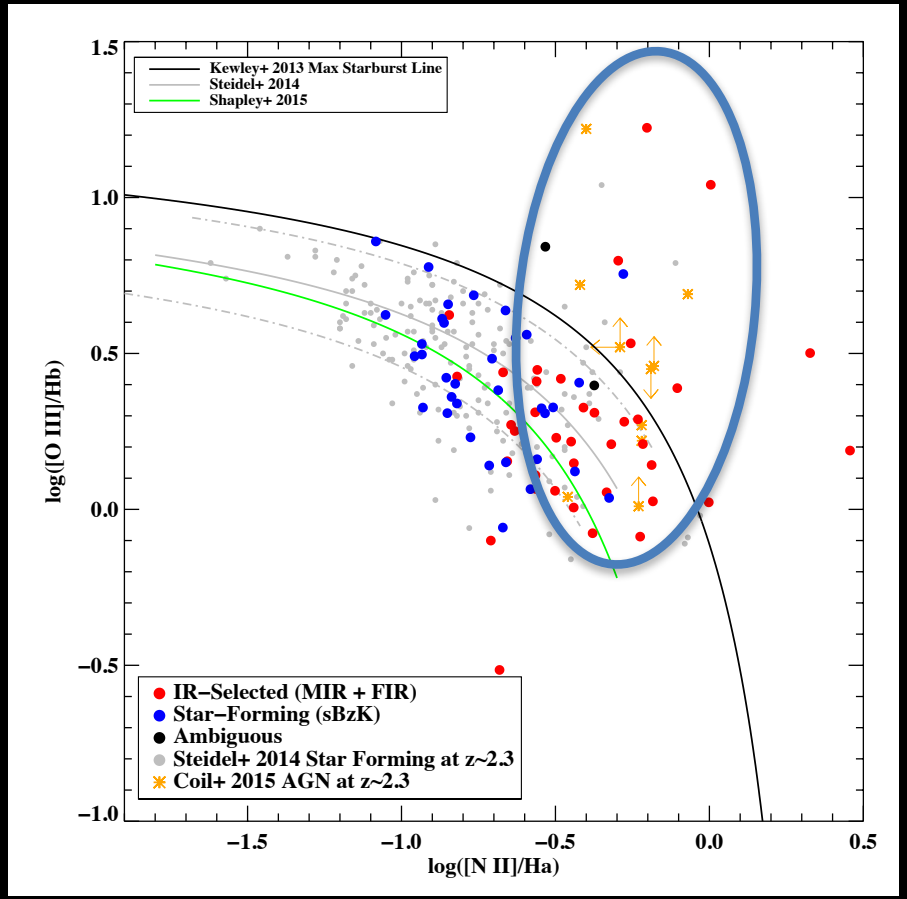


$z \sim 2.3$ Stellar Mass Distribution



Optical Line Diagnostics of (U)LIRGs @ $z \sim 2.3$

- Sample selected from COSMOS field:
  - (U)LIRGs selected by their 24 μm and/or *Herschel* detections.
  - Normal star-forming *sBzK* galaxies.
  - Photometric redshift cut between $2 < z < 2.61$
  - Complementary to rest-frame optically selected samples of MOSDEF and KBSS.
- Observations using Keck MOSFIRE (PI: Chu)
  - 7 nights (1 lost to weather) in H+K band.
  - 400 objects total observed.
  - 307 objects with secure redshifts.
- Results:
  - The *sBzK* galaxies coincide with the results from Steidel+ 2014 and Shapley+ 2015.
  - The (U)LIRGs have very similar line ratios as the AGN sample in Coil+ 2015.



Chu et al., in prep.

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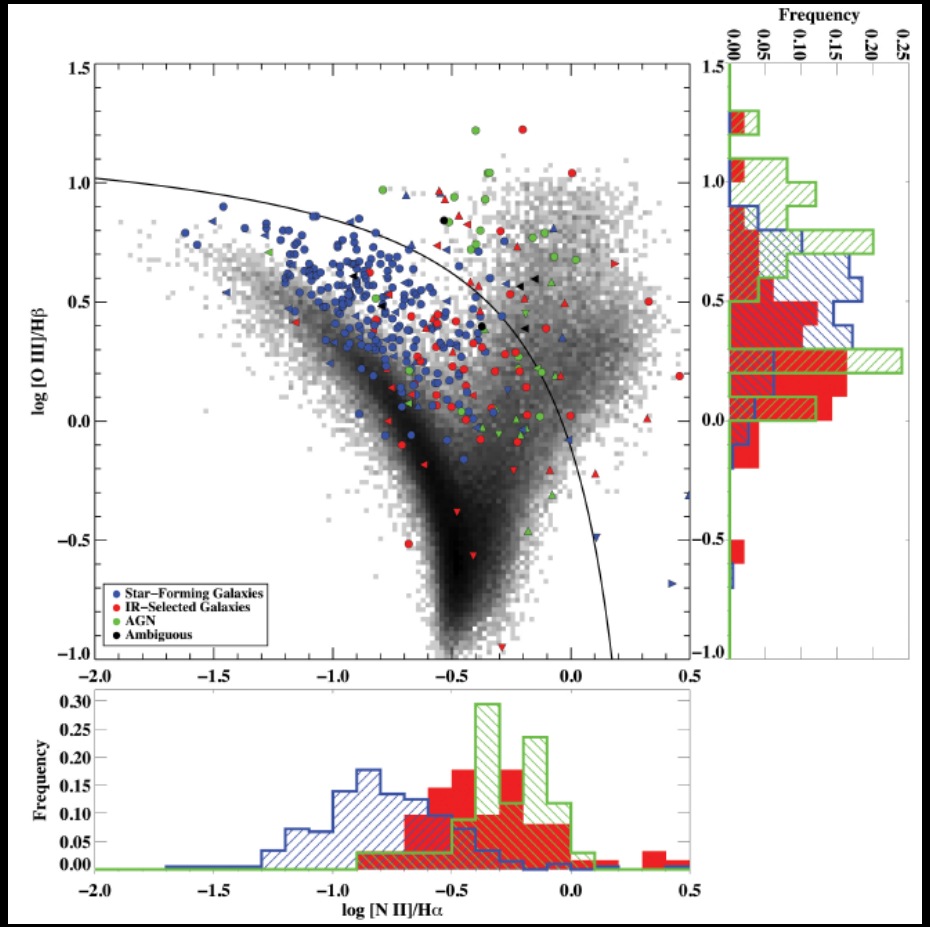


Chu et al., in prep.

Summary of Results

- Improved 3-500μm SEDs for LIRGs in the local universe .
  - The FIR peak shifts towards shorter wavelength with increasing L_{IR}.
  - The FIR/sub-mm spectral index is roughly constant ($F \propto \nu^{4.05\pm0.12}$) for (U)LIRGs, L_{IR}=10^{11} to $10^{12.5}$ $L_{\odot}$.

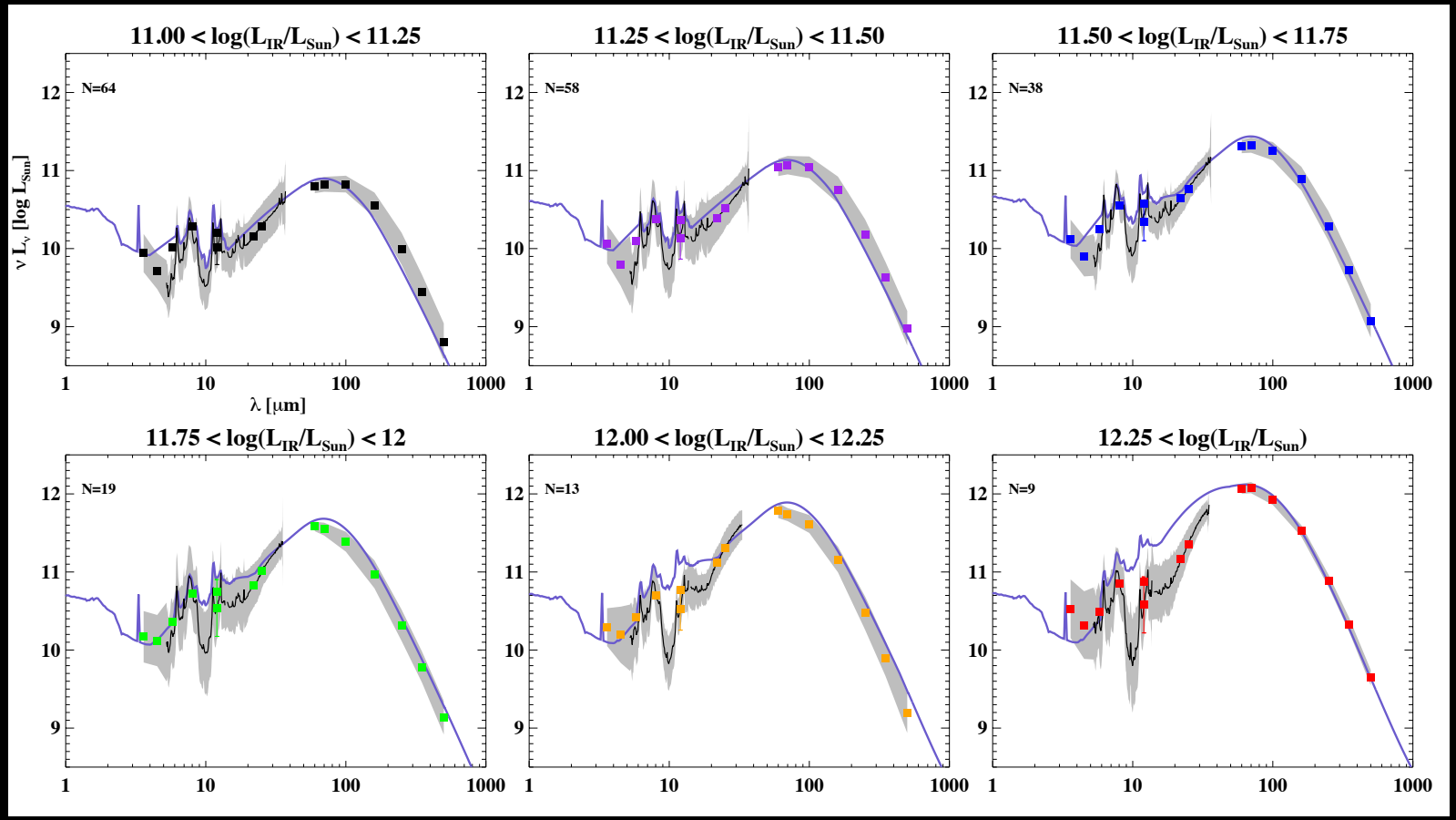
- Updates to Chary & Elbaz (2001) SED libraries will be published in Chu+17.
  - there are systematic offsets in MIR/FIR colors between CE01 and C+17.
  - CE01 significantly overestimates the MIR flux above L_{IR}~$10^{11.5}$ $L_{\odot}$.

- Optical emission line diagnostics (BPT) of (U)LIRGs at z ~ 2.3 show they are more similar to X-ray selected AGN than K-band selected (i.e. MOSDEF) objects.

- Q: How compact are the L_{IR} sources in high-z SMGs/ULIRGs ?

Contact: jasonchu@ifa.hawaii.edu GOALS webpage: http://goals.ipac.caltech.edu

Comparison CE01 and C+17



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