The Interstellar Medium Properties of Nearby Luminous Infrared Galaxies

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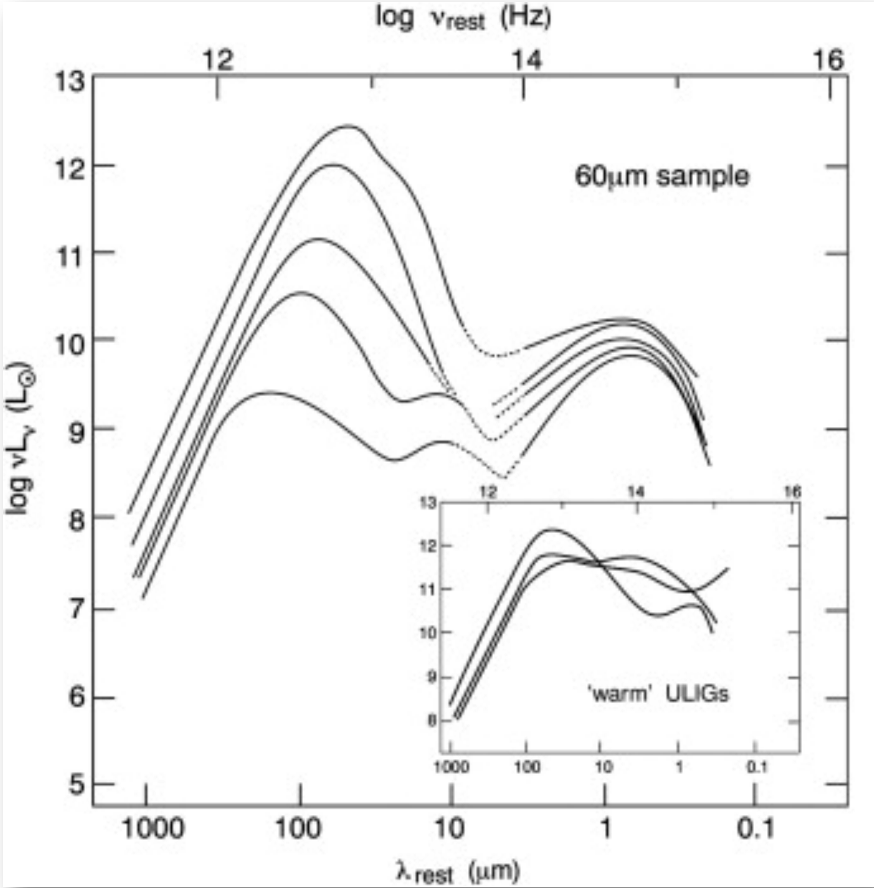
…on behalf of the GOALS Collaboration

Atacama Large Millimeter/submillimeter Array

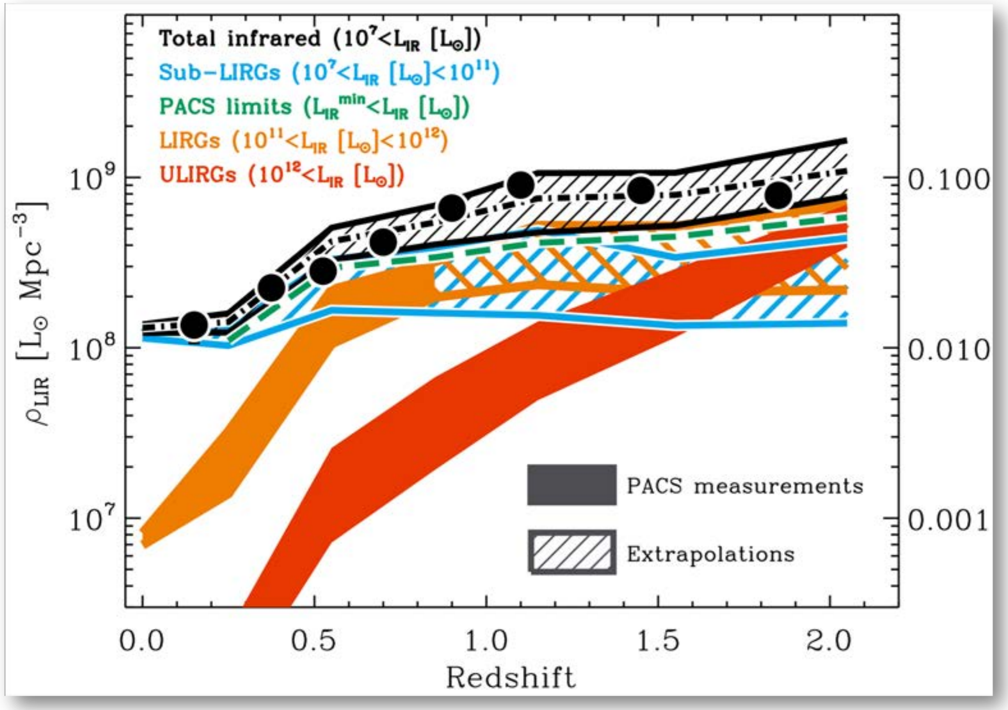
Herschel, 10 years after, May 14th 2019

Luminous Infrared Galaxies

- Luminous and Ultra-luminous Infrared Galaxies, (U)LIRGs ($L_{IR} > 10^{11\text{-}13}\ L_\odot$), are the perfect laboratories to study the triggering of obscured starbursts via galaxy mergers, and to understand the co-evolution of star formation and super-massive black hole accretion.
- High-redshift LIRGs and ULIRGs account for > 50% of the obscured star-formation in the Universe at z > 1.

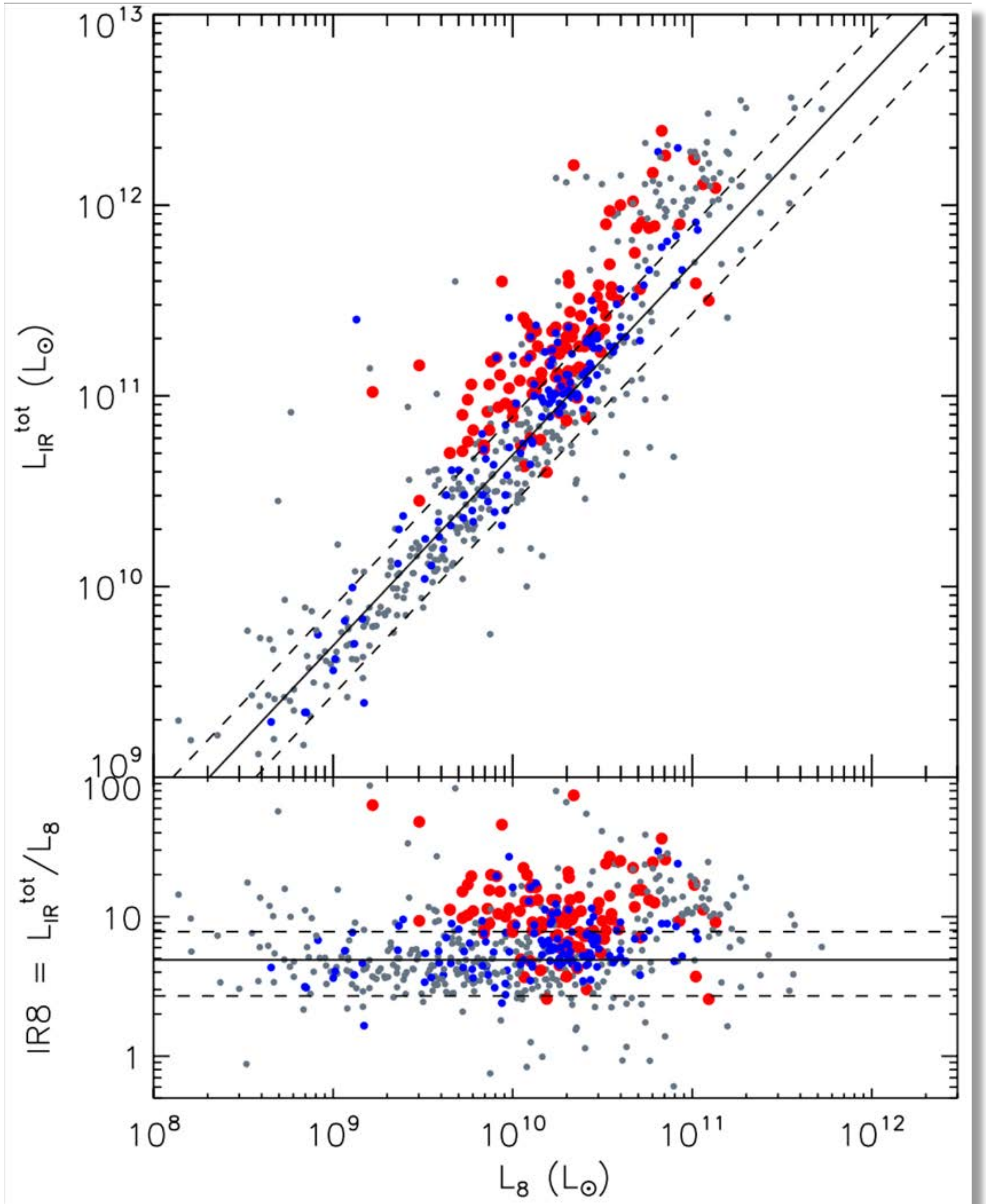


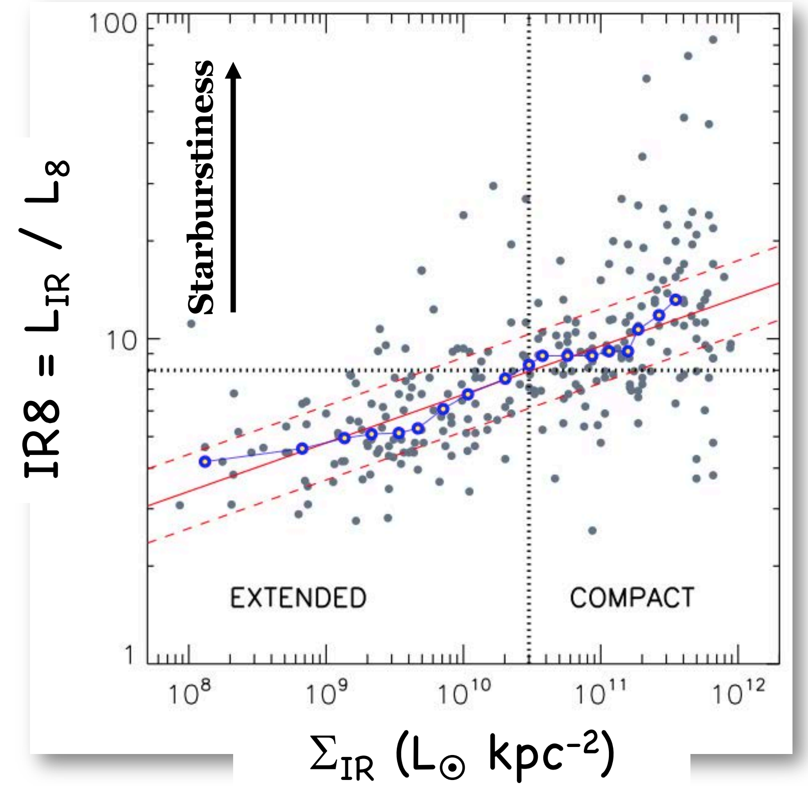
Sanders+1996



Magnelli+2013

A Main Sequence For Star Forming Galaxies



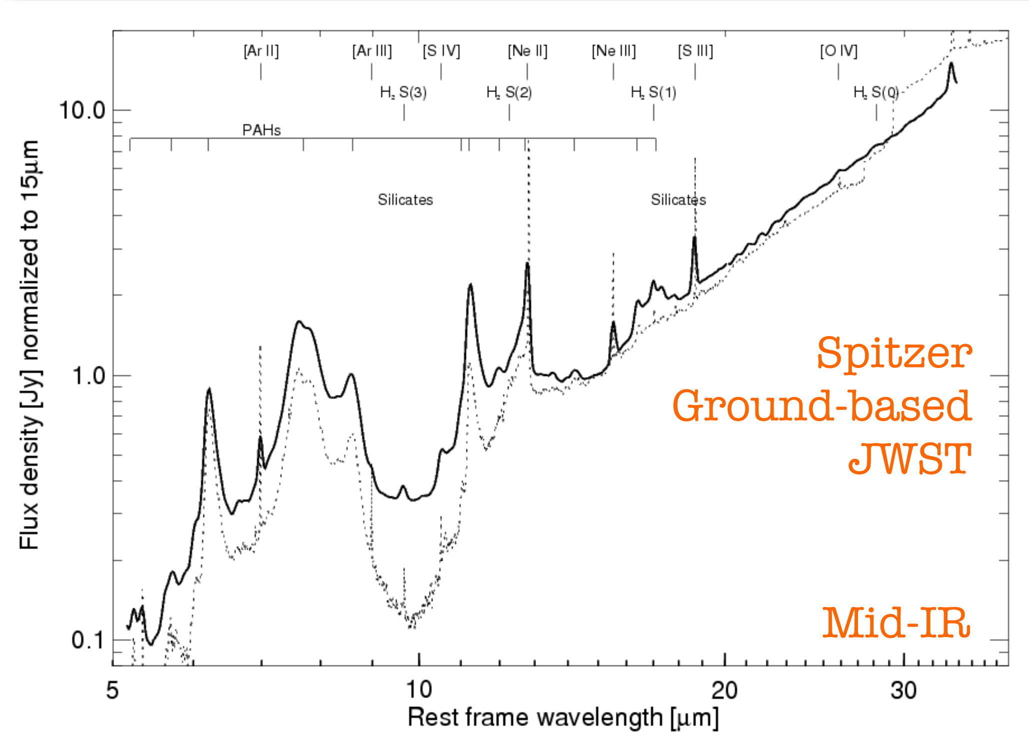


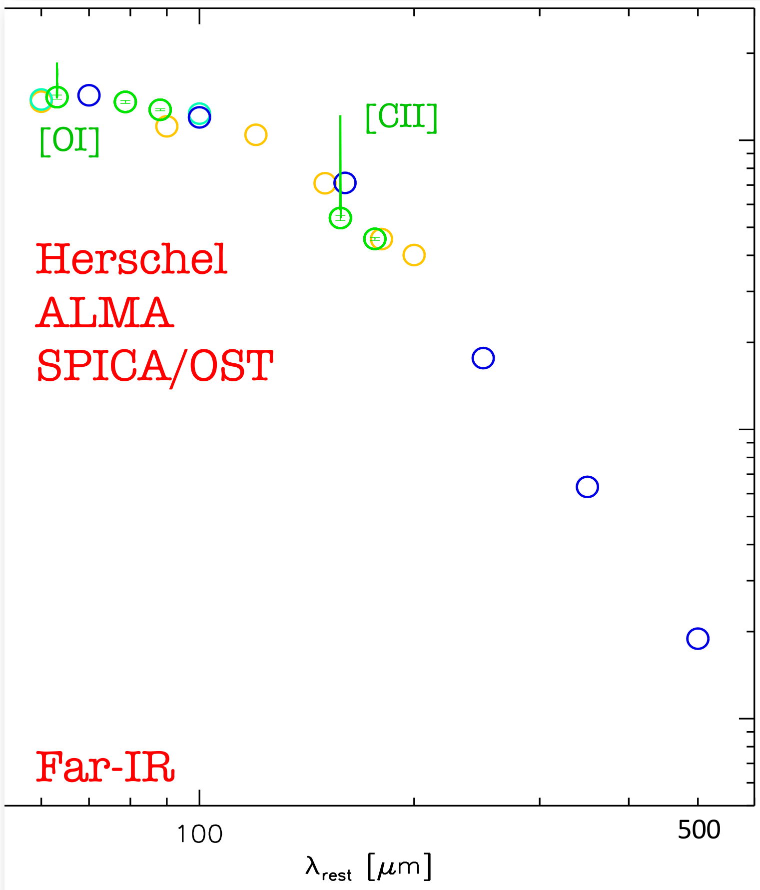
- Most galaxies at any redshift live in a main sequence (MS) (Elbaz+2011; GOODS-N,S). Star formation is a steady process and is extended, taking place over several kpc-scale areas.
- As the IR luminosity increases, galaxies rise above the MS and tend to be more starbursting and compact.

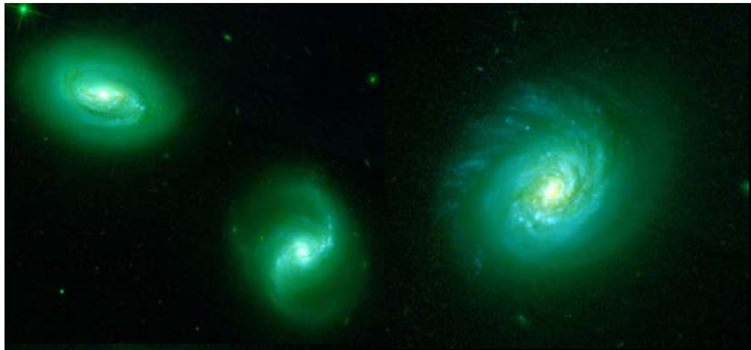
Elbaz+2011

The Interstellar Medium

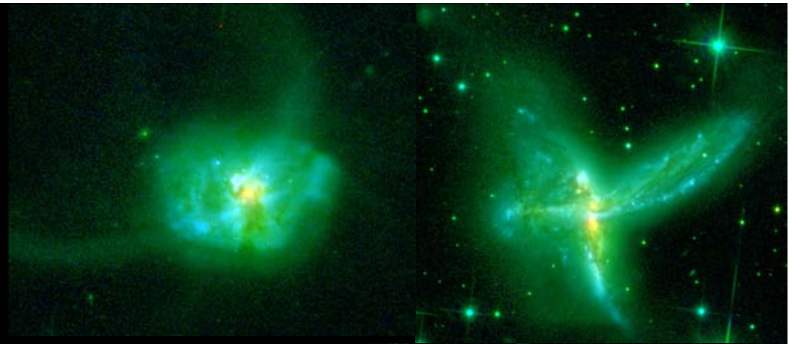
- Studying the ISM of the most luminous galaxies can give us an insight on the physical state of the gas and dust in the most extreme environments. Only by combining mid- and far-IR observations we can study the regulation of the heating and cooling of the ISM in (U)LIRGs at any redshift.
- Mid-IR provides information about highly ionized, hot gas in HII regions, warm dust, and PAH emission → gas and dust heating
- Far-IR probes the cold dust emission and gas cooling carried out in the PDRs through fine-structure emission lines, mainly [CII]158μm and [OI]63μm.







The GOALS Sample



The Great Observatories All-sky LIRG Survey (GOALS; Armus+2009) is a complete galaxy sample ($z < 0.09$) containing all the 202 systems with $L_{IR} > 10^{11}$ $L_{\odot}$ (180 LIRGs, 22 ULIRGs) included in the 60μm flux-limited IRAS Revised Bright Galaxy Sample (RBGS). It includes ~290 individual galaxies with $10^{10-12.3}$ $L_{\odot}$

1) It spans the entire merger sequence of galaxies: from isolated/disks and separated pairs to late-stage mergers. *(Stierwalt+2013,14; Kim+2013; Haan+2011)*

2) It covers the range from main-sequence (MS) galaxies to starbursts in the local Universe. Around 1/4 – 1/3 of GOALS are MS galaxies! *(Diaz-Santos+2013)*

Herschel Observations for ~240 Galaxies

- Three GOALS Herschel OT1/2 programs:

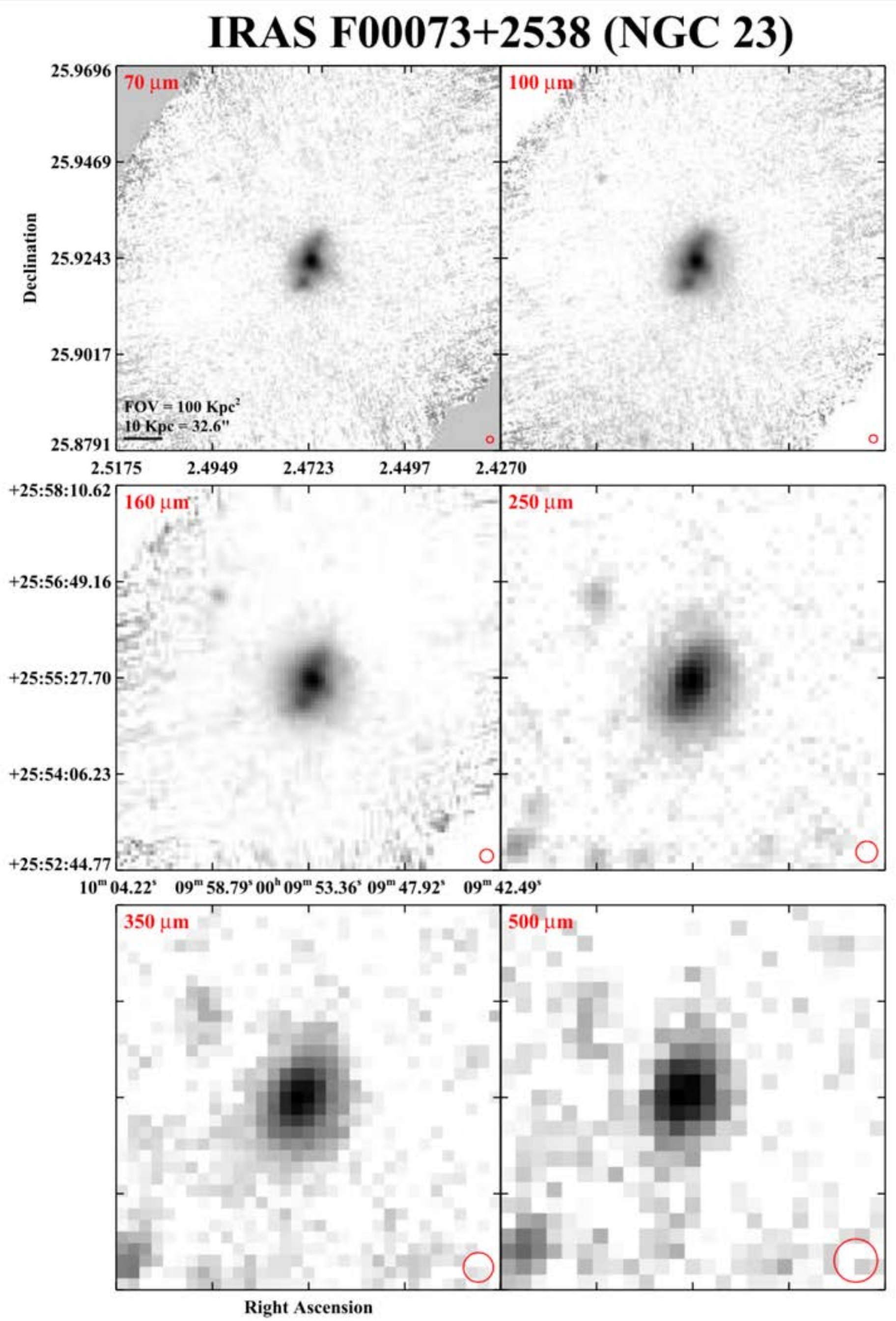
  OT1: ~85h of PACS/SPIRE photometry (PI: Sanders)
  OT1 + OT2: ~167h + 70h = 247h of PACS spectroscopy (PI: Armus)
  OT1: ~83h of SPIRE spectroscopy (PI: Lu)

- PACS and SPIRE photometry also for all LIRG systems *(Chu et al. 2017)*

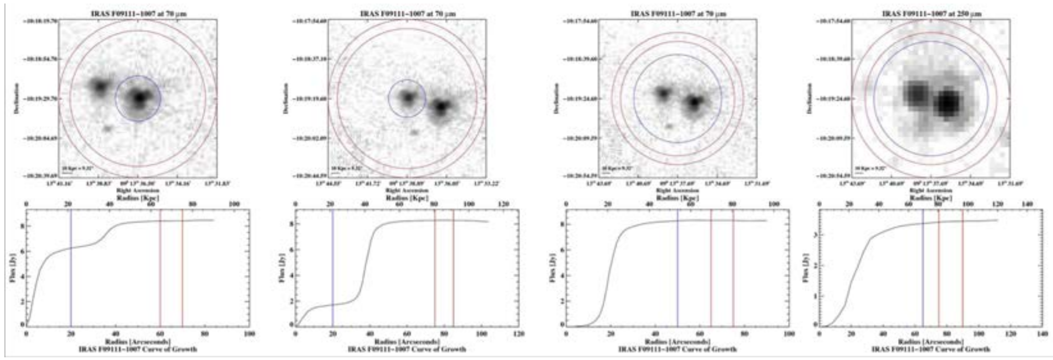
- In combination with other key projects (mainly SHINING and HerCULES), to observe [CII]158μm, [OI]63μm, [OIII]88μm, and [NII]122μm spectroscopic observations with PACS for the entire GOALS sample.

- SPIRE FTS spectra include the [NII]205μm and neutral carbon lines, as well as the mid-J CO ladder for ~1/2 of the sample *(Lu et al. 2017)*

PACS and SPIRE Photometry

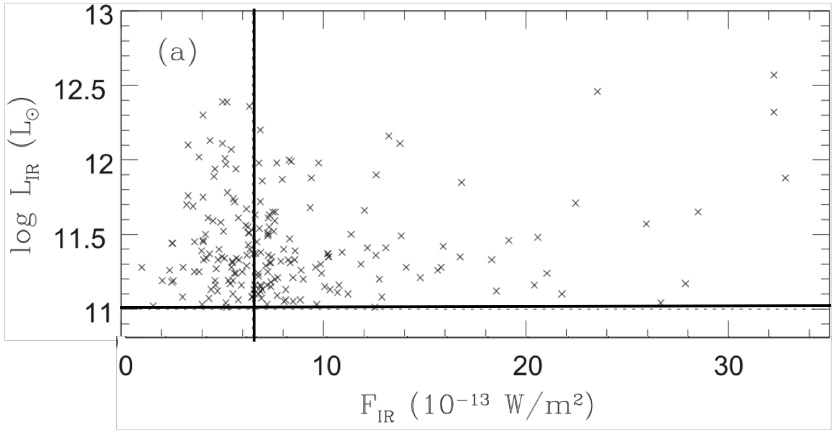


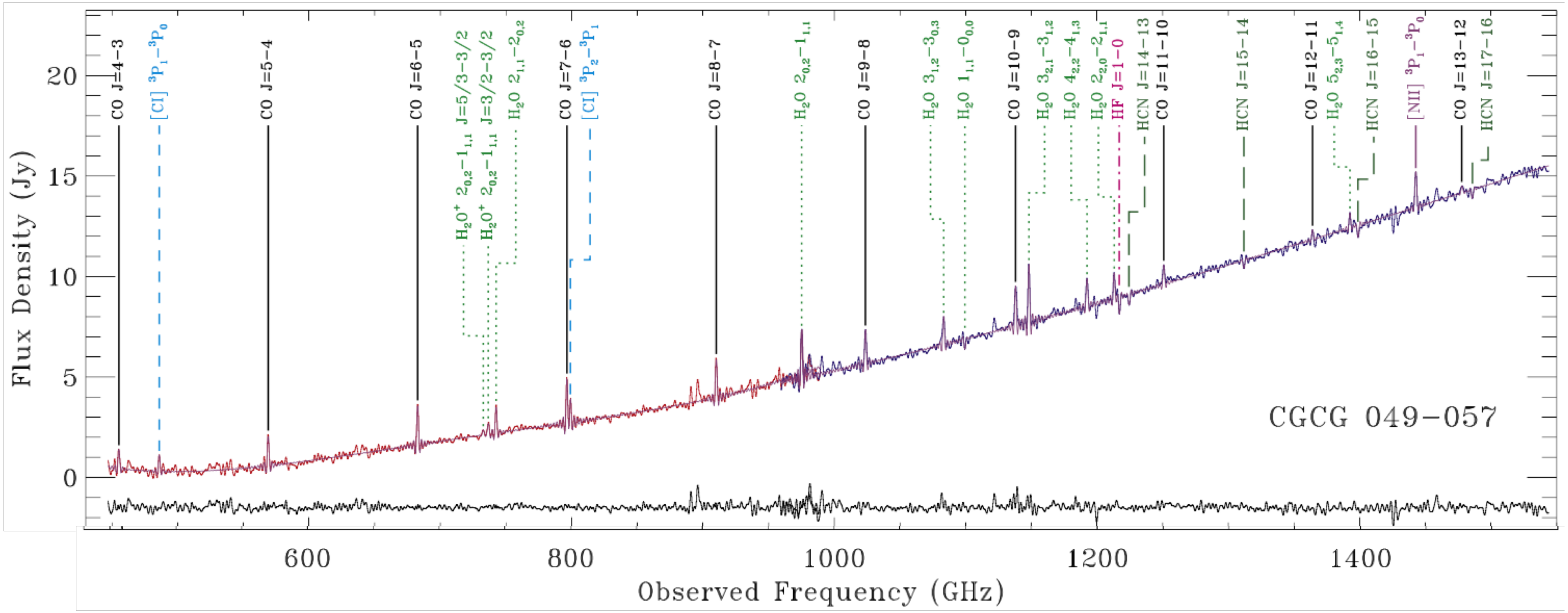
- Image atlas for all the sample at 70, 100, and 160µm (PACS) and 250, 350 and 500µm (SPIRE), optimized to reveal structures at both high and low surface brightness levels.
- This data set constitutes the imaging and photometric component of the GOALS Herschel OT1 observing program, and is complementary to atlases presented for the HST, Spitzer and Chandra.
- **All measurements available in Chu et al. 2017**
- Flux densities of companion galaxies in merging systems are provided where possible, along with integrated system fluxes.



SPIRE FTS Spectroscopy

- 121 (U)LIRGs, FIR > 6.5 x 10^{-13} Wm^{-2}, including 7 ULIRGs
- Continuous coverage from 194 to 671µm. Main lines: CO transitions from 4-3 to 13-12, as well as neutral carbon [CI] at 370 and 609µm, and [NII] 205µm. Also multiple transitions of H_2O, H_2O^+, HCN, CH^+ and HF.
- **All line measurements available in <u>Lu+2017</u>**





SPIRE FTS Spectroscopy

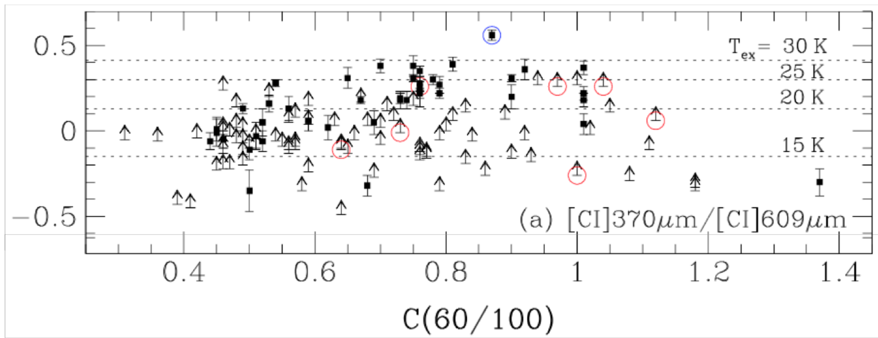
- Slope of L_{CO}/L_{IR} ratio as a function of FIR color (dust temperature) varies with transition, from negative (CO4-3), to flat (CO7-6) to positive (CO10-9).

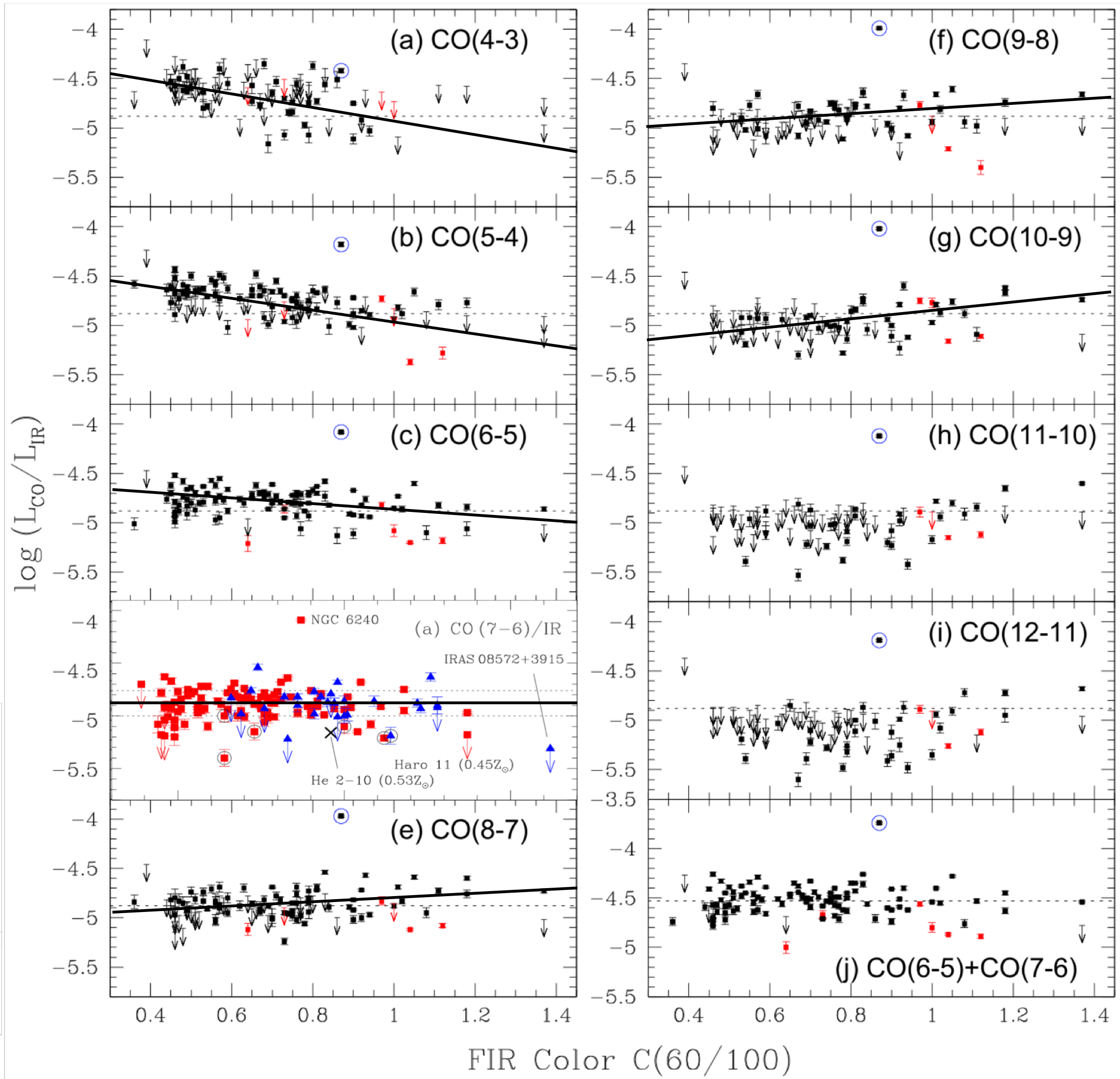
- CO7-6 can be used to predict the IR luminosity and therefore SFR of galaxies, including ULIRGs.

- Useful for ALMA studies of high redshift galaxies.

  (Lu et al. 2014, 2015, 2017)

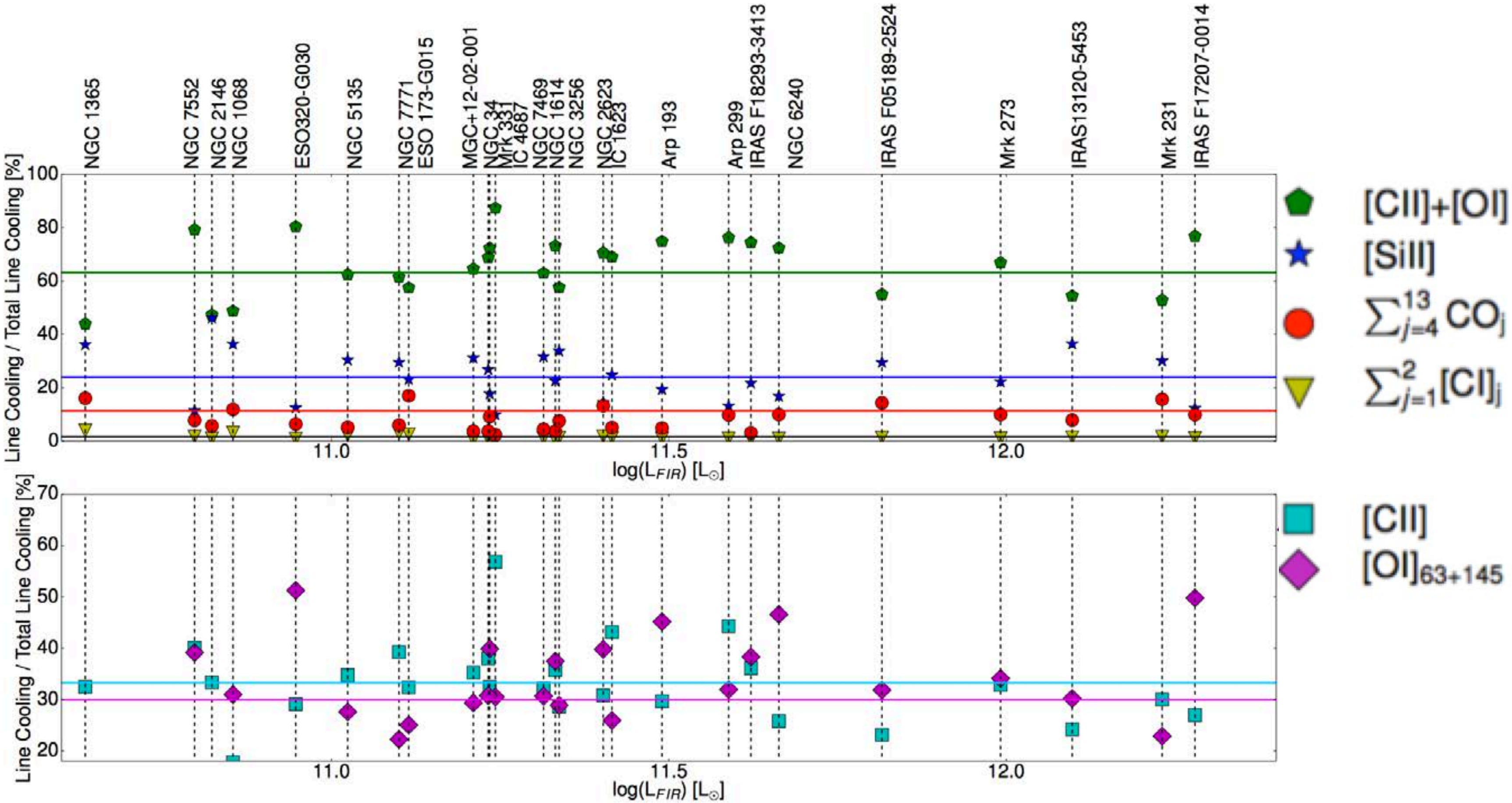
- The flux ratios of the two [C I] lines imply modest excitation temperatures of 15–30 K





Global Emission Line Cooling Budget

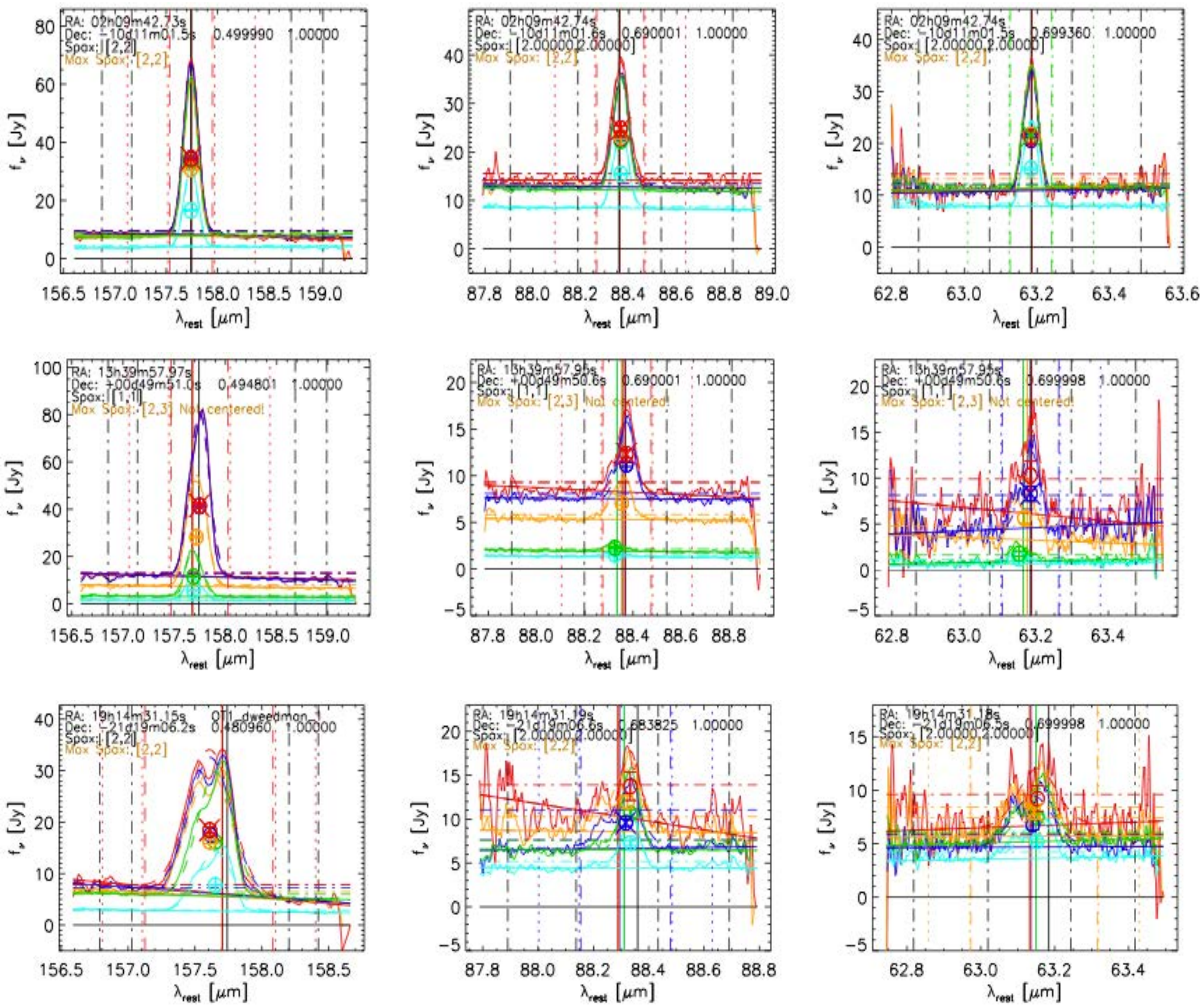
HerCULES: Rosenberg+2015



- The total line cooling accounted by the CO ladder is very limited (~10%).
- [CII] and [OI] account for 50 – 80%.

PACS Spectroscopy

[CII]158μm [OIII]88μm [OI]63μm



- Target the main far-IR cooling lines. HII regions and PDRs.
- There is a variety of line profiles: Unresolved line emission, broad/asymmetric lines, double peaks.
- Very complex kinematics reflecting the dynamical state of the systems.

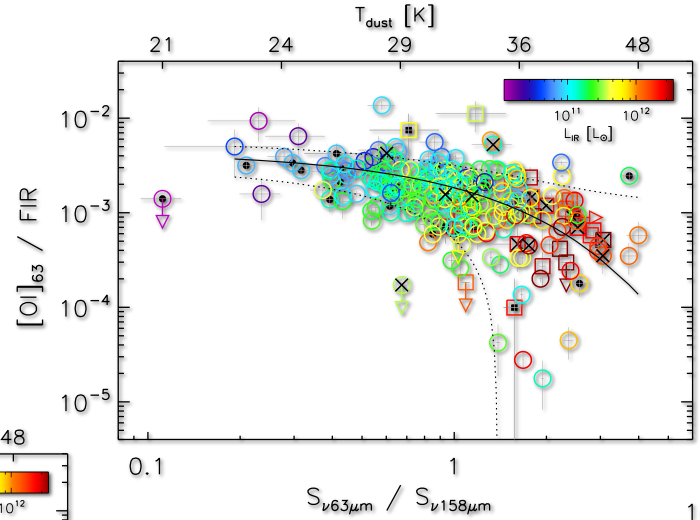
See also previous ISO works from Malhotra+2001, Brauher+2008

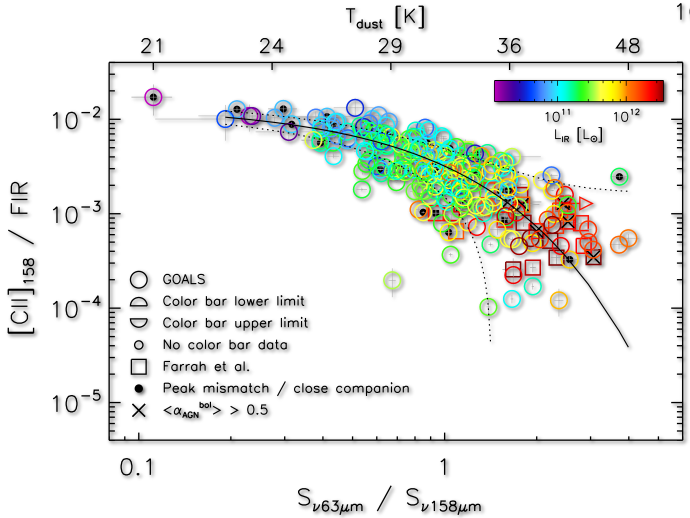
All line and continuum fluxes available in Diaz-Santos+2017 and: http://goals.ipac.caltech.edu

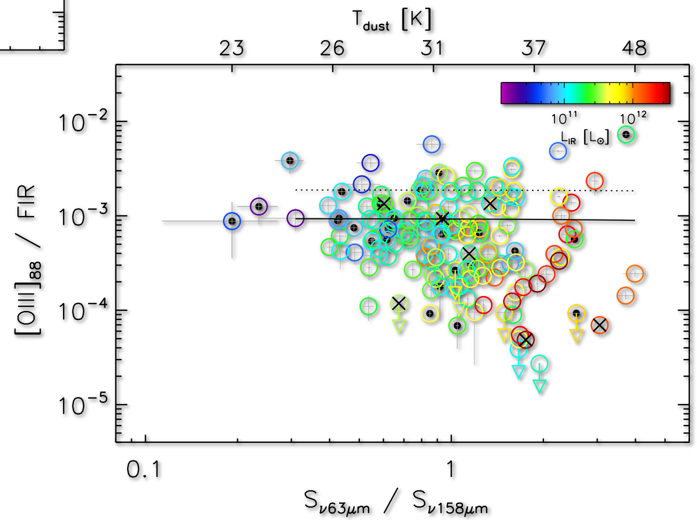
[CII] (and [OI]) deficits overall driven by a combination of a boost in *U* and an increase in dust-to-gas opacity and T_{dust}, driving up L_{FIR}.

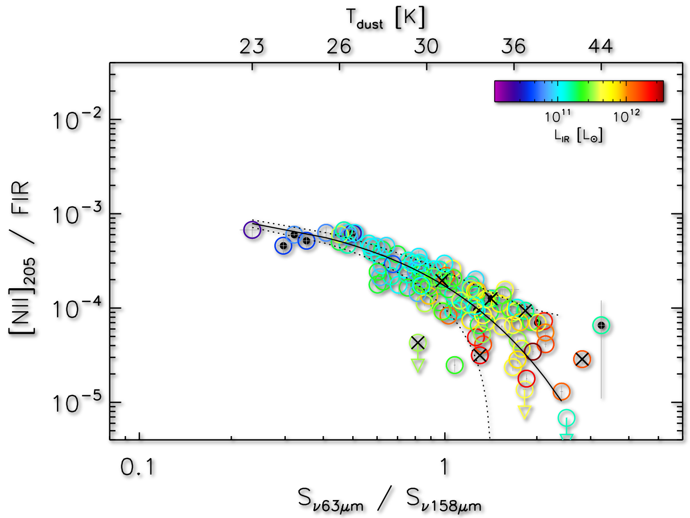
(see also Abel+2009; Gracia-Carpio+2011; Diaz-Santos+2013,14)

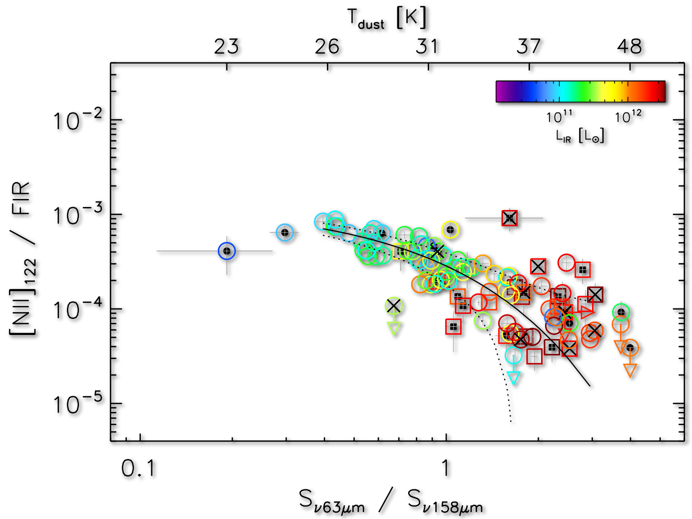
Line to FIR Ratios as a Function of T_{dust}





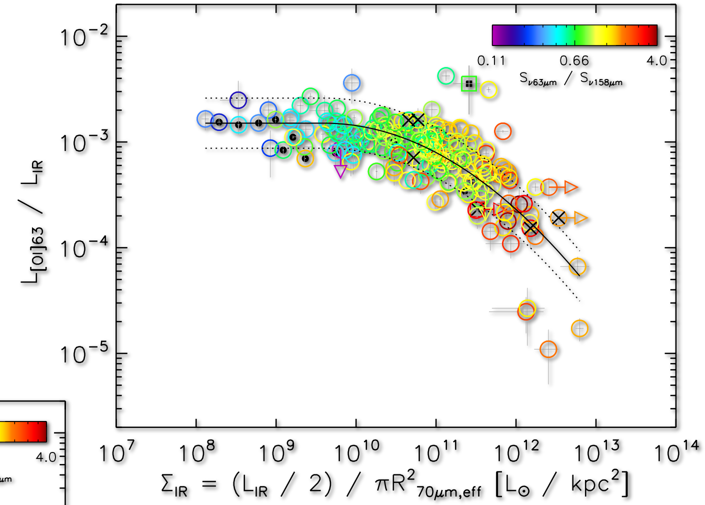


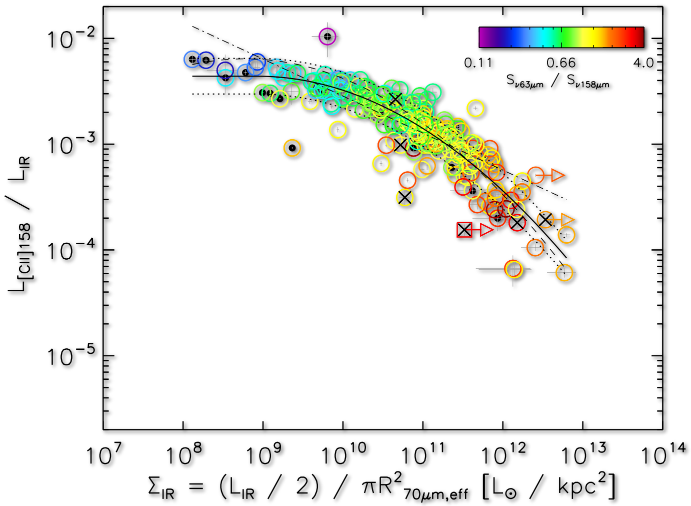




All lines show deficits as a function of the luminosity surface density, Σ_{IR}

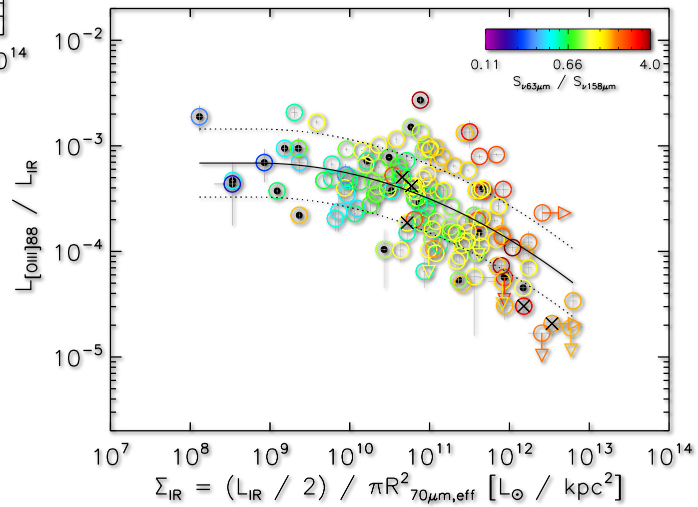
Diaz-Santos et al 2017

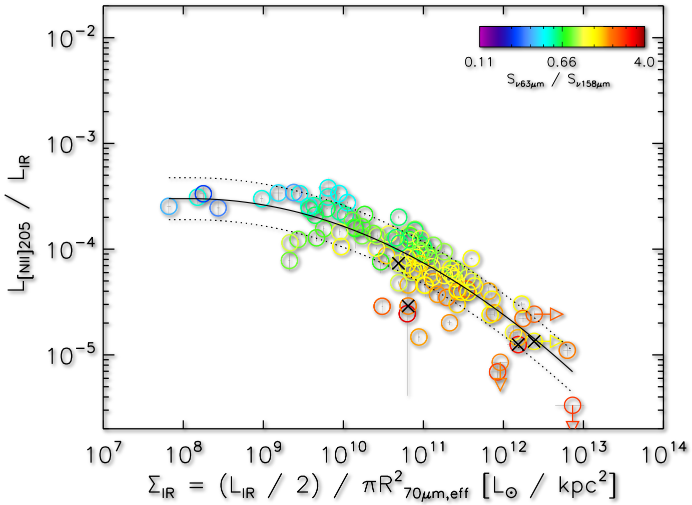


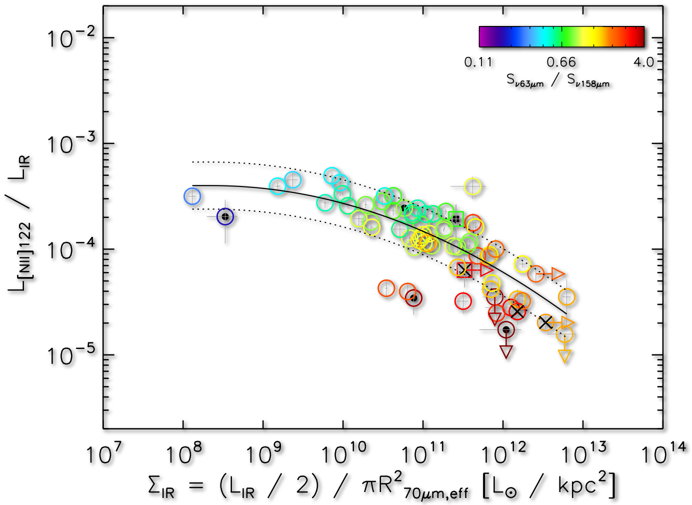


As a function of Luminosity Surface Density,

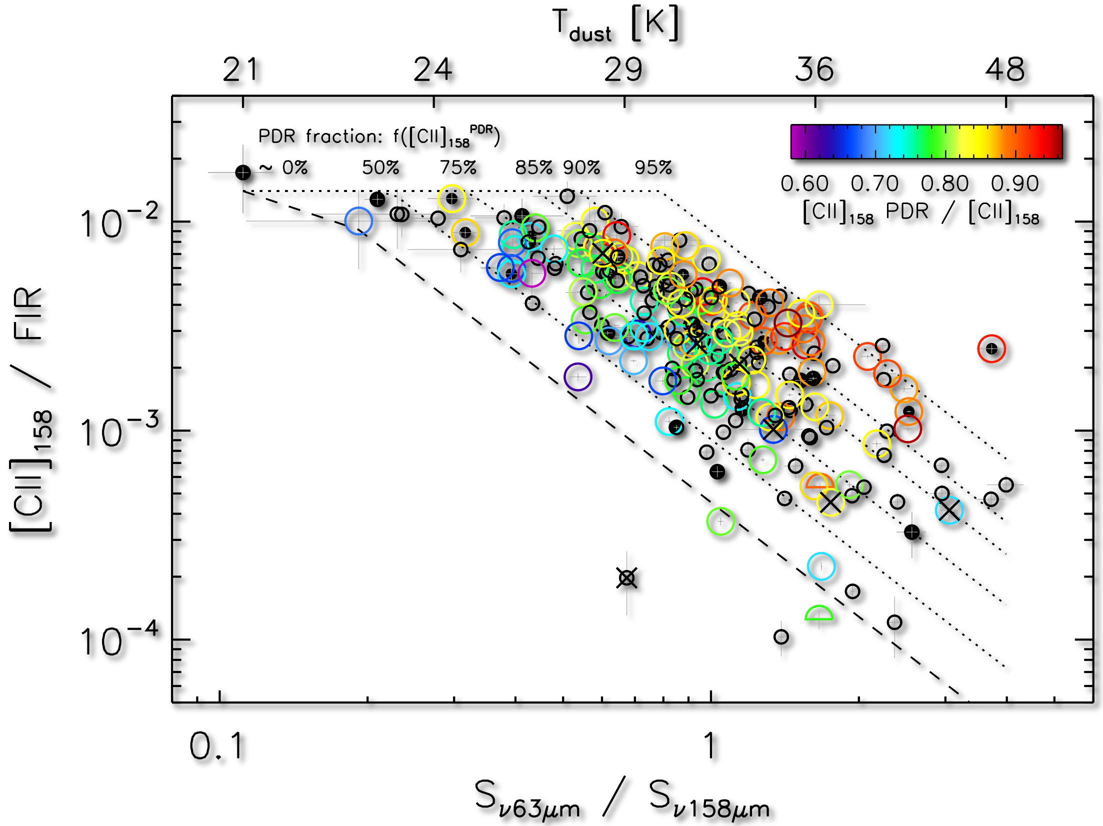
Σ_{IR}







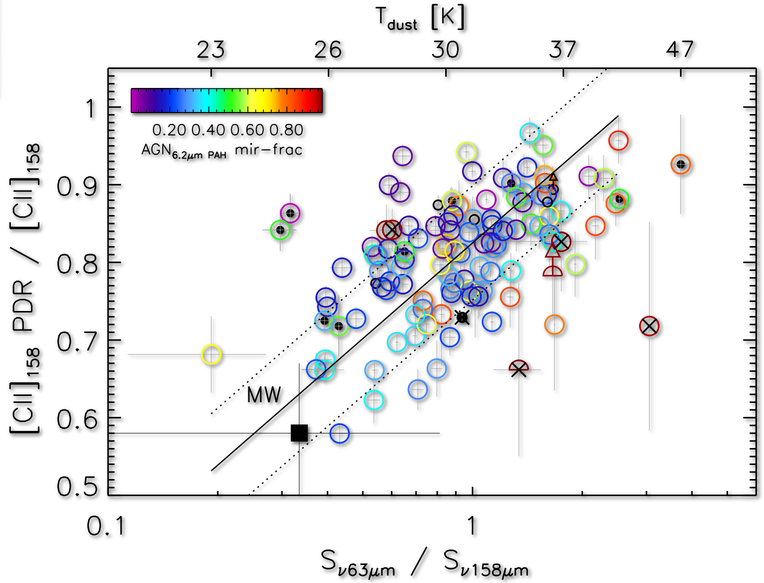
The Scatter in the [CII] Deficit is caused by Different [CII] PDR Contributions



[CII] (and [OI], [NII]) deficits overall driven by a combination of a boost in *U* and an increase in dust-to-gas opacity and T_{dust}, driving up L_{FIR}.
(see also Abel+2009; Gracia-Carpio+2011; Diaz-Santos+2013,14)

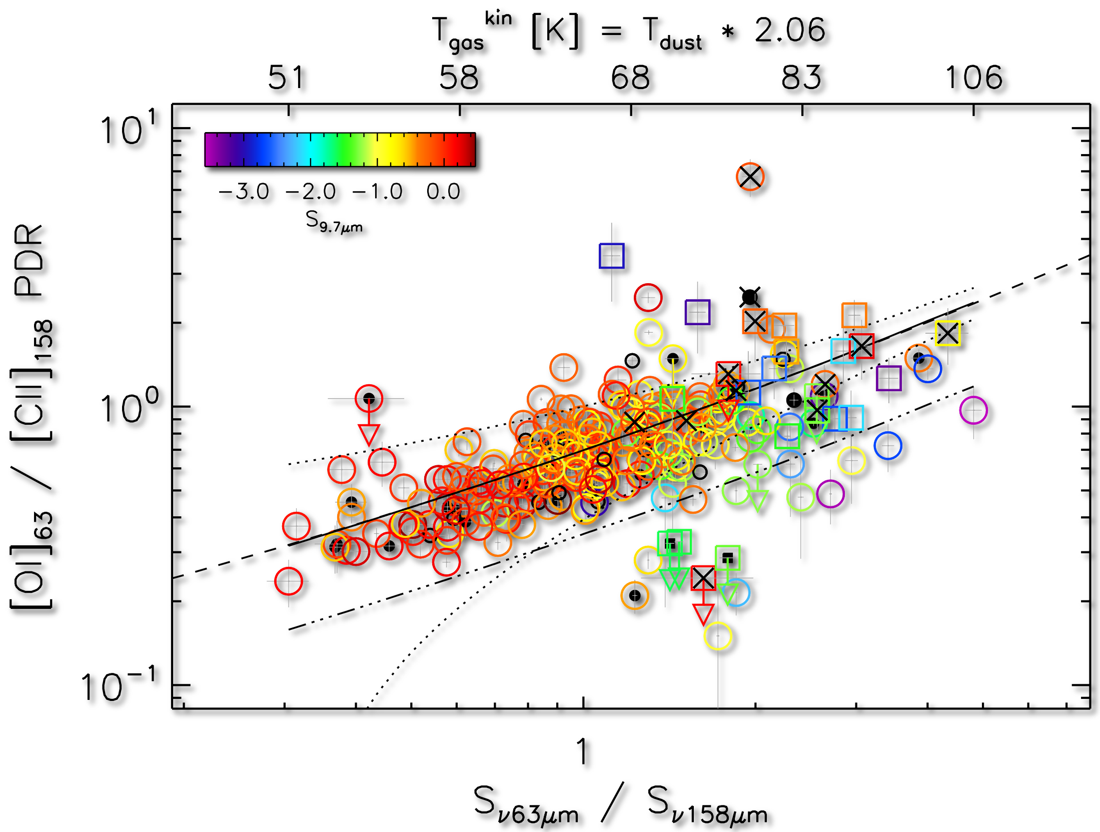
On galactic scales, the scatter is caused by varying contributions of the PDR component to the total $[CII]_{158}$ emission.

We find LIRGs span $[CII]_{PDR}$ fractions from ~60% (similar to the Milky Way) to up to 95% for the warmest galaxies.



Diaz-Santos+2017

$[OI]_{63}/[CII]_{PDR}$ as a Tracer of Gas Temperature



RADEX modeling:

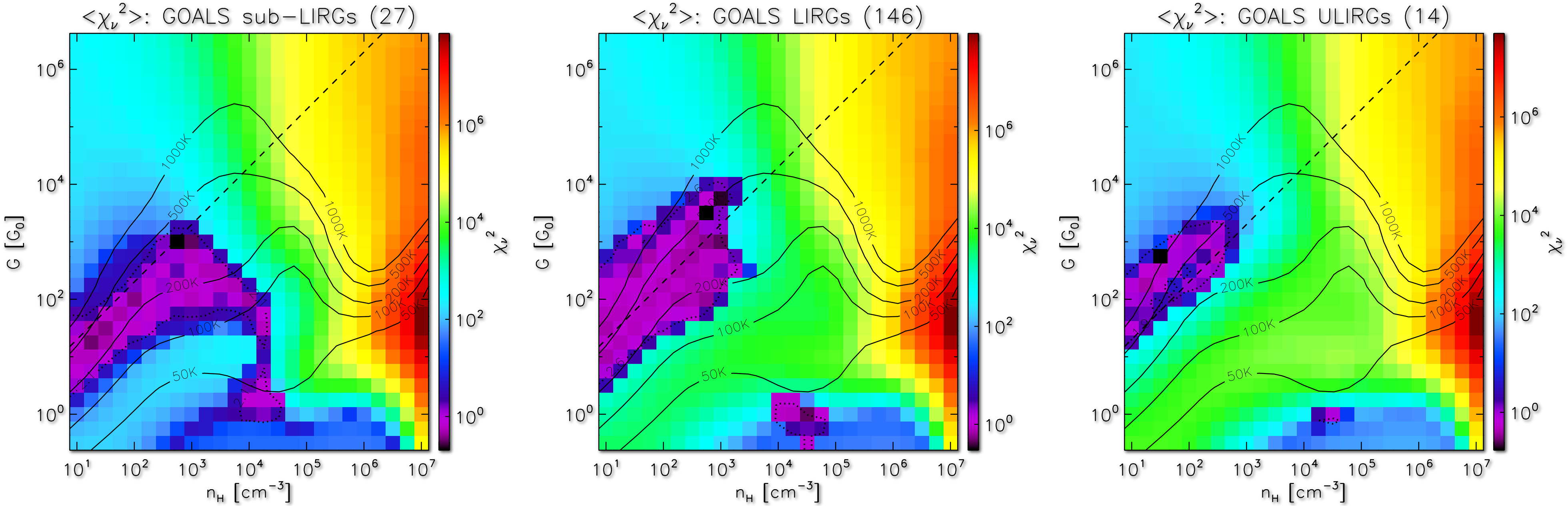
- Consider $[OI]_{63}$ and $[CII]_{158}$, optically thin and a gas density $n_H < 10^3$ cm^{-3} (below n_{crit} for both lines) --> line ratio is only dependent on gas T_{kin}.
- Assume T_{kin} proportional to T_{dust}, letting the scaling factor as a free parameter.

The model reproduces remarkably well the correlation, with galaxies falling below the trend probably being affected by optical thickness in the $[OI]_{63}$ line.

Diaz-Santos+2017

PDR modeling: PDR Tool Box

PDR Models from Kaufman+1999
PDR Tool Box:
http://dustem.astro.umd.edu/pdrt/

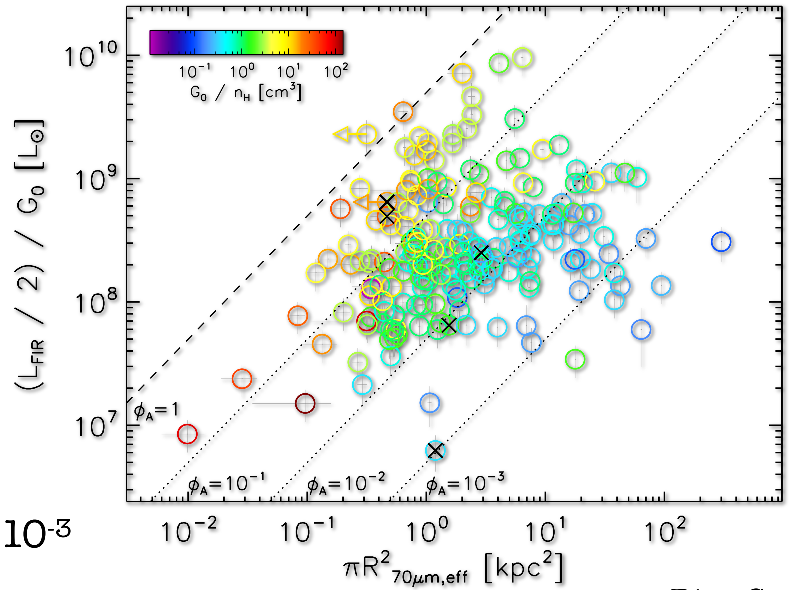


- PDR model inputs: $[CII]_{PDR}$, $[OI]_{63}$ and FIR
- Output: G (radiation field intensity) and n_H

G increase from ~10^1-10^2 G_0 in normal SF galaxies to ~10^2-10^3 G_0 in ULIRGs. The range of gas density remains constant, $n_H < 10^3$ cm^{-3}.

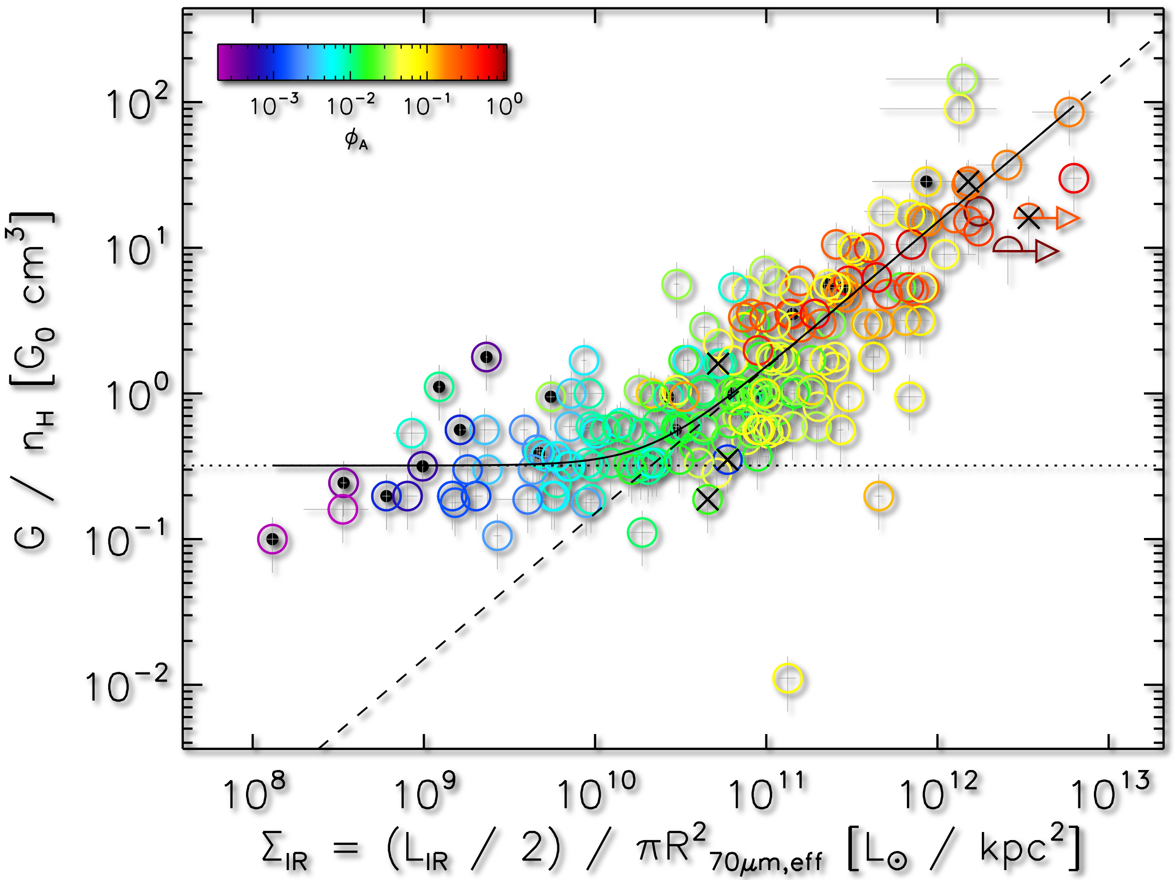
Physical conditions of PDRs are better described by G/n_H, from ~ 0.2 to > 10 G_0cm^3.

$L_{FIR} \approx 2\,G\,\pi(D/2)^2\,\Phi_A$ → PDR filling factors from ~1−10^{-3}



Diaz-Santos+2017

A Critical Transition in PDR Physical Properties



- There is a relation between G/n_H and Σ_{IR}, showing a critical break at $\Sigma_{IR}^* \simeq 5 \times 10^{10}\ L_\odot\ kpc^{-2}$.

Below Σ_{IR}^*, G/n_H remains constant, $\simeq 0.32\ G_0\ cm^3$, and variations in Σ_{IR} are driven by the number density of star-forming regions within a galaxy (Φ_A), with no change in their PDR properties.

Above Σ_{IR}^*, G/n_H increases rapidly with Σ_{IR}, signaling a departure from the typical PDR conditions found in normal star-forming galaxies towards more intense/harder radiation fields and compact geometries typical of starbursting sources.

Diaz-Santos+2017

Conclusions

- In the nearby Universe, LIRGs are the population that bridge the gap between MS galaxies and starburst and QSOs. These, while rare at all epochs (few %), account for up to 1/3 of the energy production in the Universe at virtually all redshifts (at least up to z~4).
- Far-IR fine-structure lines are fundamental to our understanding of how the ISM in galaxies cools down. Models and diagnostics provide us with tools to calculate PDR fractions, gas density and temperatures, radiation field intensities, filling factors, etc.
- Photometric and spectroscopic PACS and SPIRE catalogs available for the most complete sample of (U)LIRGs in the local Universe.
- CO(7-6) can be use to estimate the SFR in galaxies with an accuracy of ~0.2 dex regardless of the presence of an AGN. Particularly useful for ALMA studies of high-z galaxies.
- The scatter in the well-known [CII] deficit as a function of dust temperature (on galaxy-integrated scales) is caused by different contributions of the PDR component to the total [CII] flux, which varies from 60% (MW level) to up to 95%.
- G/n_H characterizes the physical conditions of PDRs, increasing more than an order of magnitude from sub-LIRGs to ULIRGs. The increase is not continuous. There's a break at $\Sigma_{IR}^* \simeq 5 \times 10^{10}\ L_\odot\ kpc^{-2}$. Above this threshold, PDR properties depart from those found in normal MW-type galaxies towards more intense/harder radiation fields and compact geometries typical of starbursting sources.