ISM properties of local LIRGs: From MS to Starbursts Galaxies

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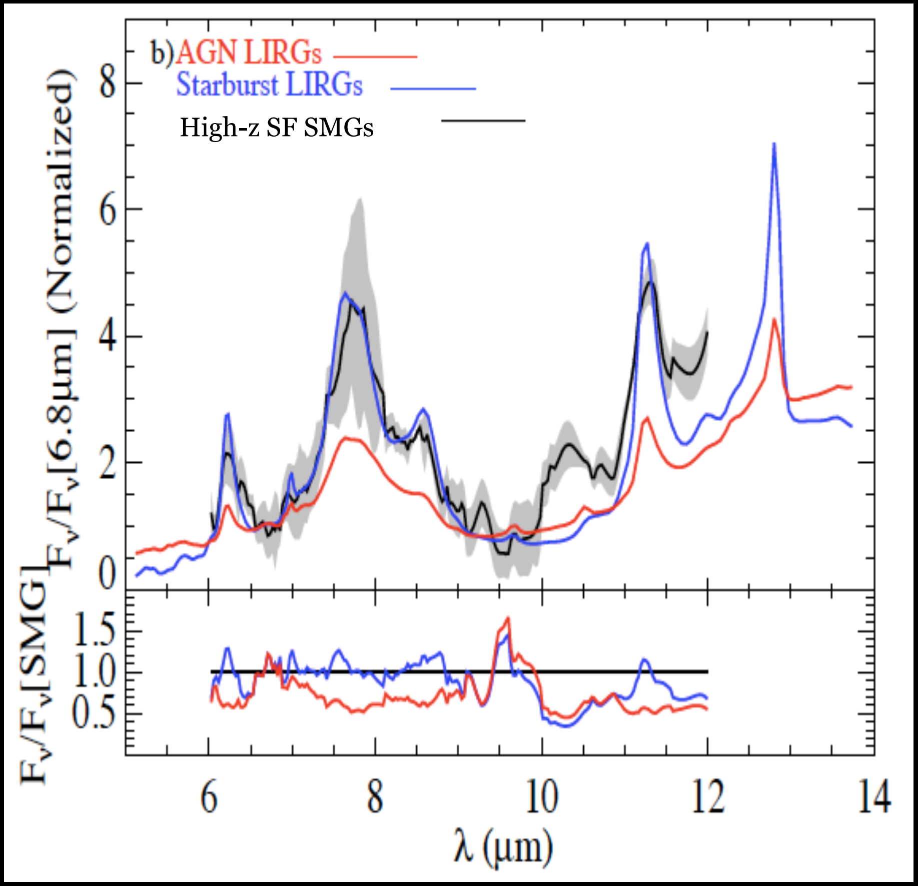
LIRGs and ULIRGs: Near and Far

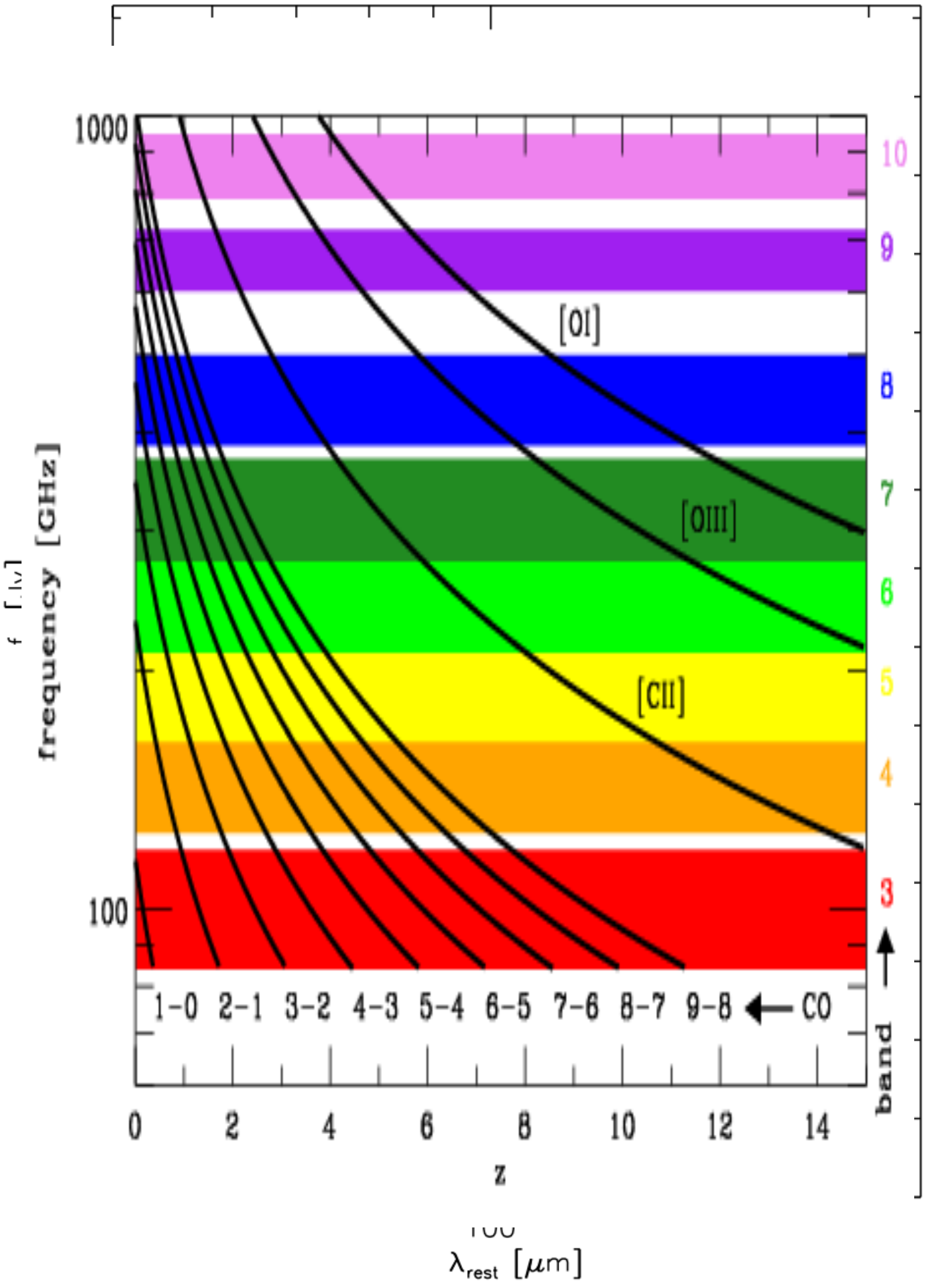
- LIRGs and ULIRGs are not common at low-z but dominated the SFR of the Universe at z > 1
- Most high-z star-forming galaxies follow a main-sequence of SF and resemble more to local LIRGs and normal starburst rather than ULIRGs
- Out of MS galaxies (starbursts) still account for up to ~20% of the SFR (*Schreiber+2015*)

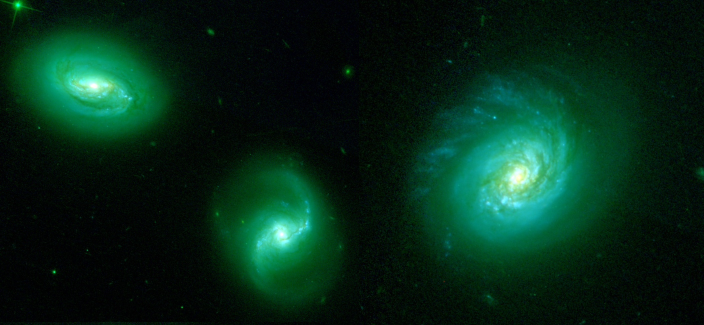


Stierwalt+2013

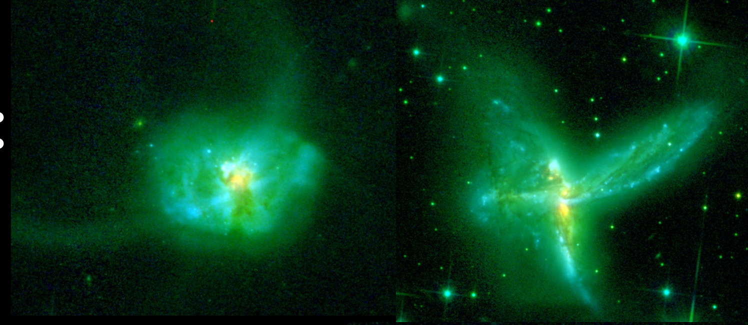
WHY FIR FINE STRUCTURE LINES?

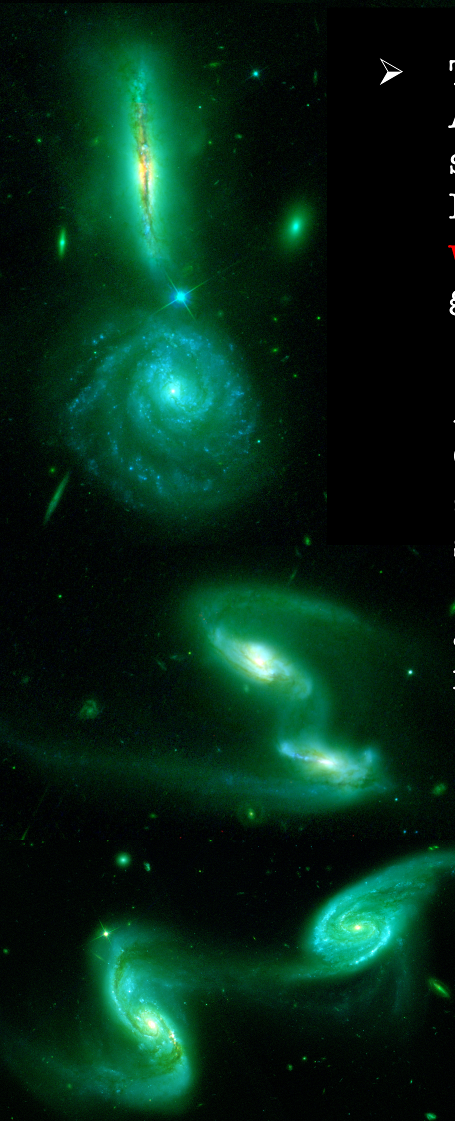
- ALMA provides a view into the ISM physics of high-redshift galaxies via FIR emission lines.
- The [CII] line can account for 0.1-1% of the bolometric luminosity of a galaxy. Can be observed at z > 2 with ALMA, allowing us to study the ISM in galaxies at the time at which the SF in the Universe was at its peak.
- [CII] is often used as a dust-unbiased star formation rate tracer but... is it really accurate?
- Many ALMA studies are already starting to exploit diagnostics based in this and other FIR lines to infer properties of high-z galaxies. However, many caveats should be born in mind when doing so.





LIRG Sample: GOALS

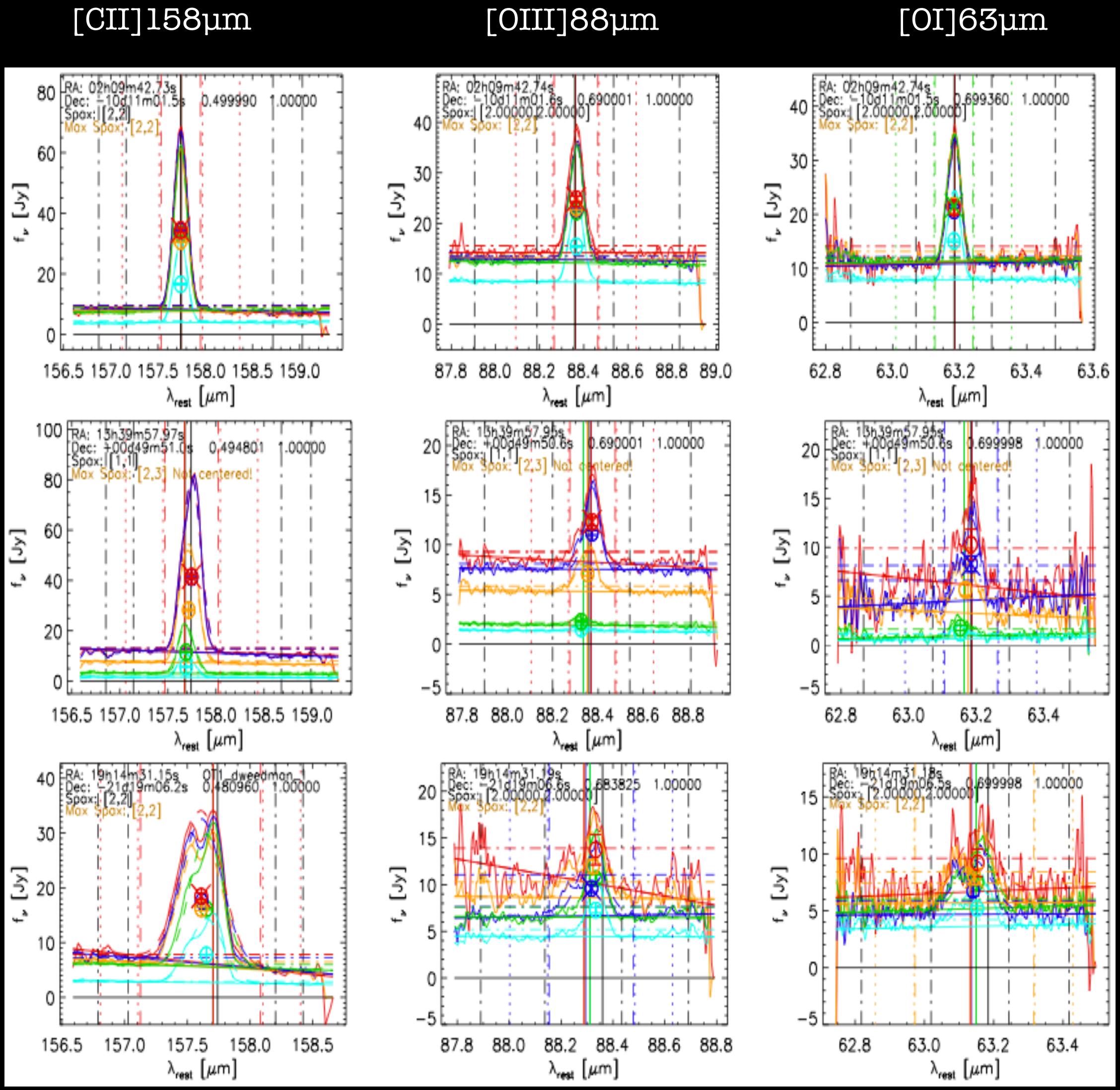




- The Great Observatories All-sky LIRG Survey (GOALS; Armus+2009) is a complete, local ($z < 0.09$), 60μm-selected galaxy sample of 202 LIRG systems, $L_{IR} > 10^{11}$ $L_{\odot}$ (180 LIRGs, 22 ULIRGs): ~244 individual galaxies with $10^{10-12.3}$ $L_{\odot}$. It covers the entire merger sequence of galaxies. *(Haan+2011; Stierwalt+2013, 2014; Kim+2013)*

Herschel OT1 and OT2 programs (PI: L. Armus) in combination with other key projects (HerCULES, SHINING) provide [CII]158μm, [OI]63μm, and [OIII]88μm spectroscopy with PACS for the entire GOALS sample; [NII]122μm for half. Also PACS and SPIRE photometry, and SPIRE FTS spectra for 1/2 of the sample, which includes CO ladder and [NII]205μm *(N. Lu presentation)*

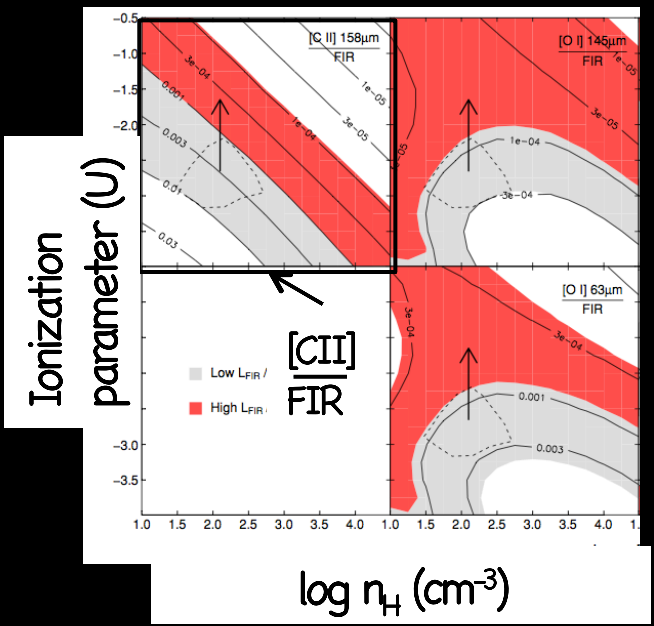
PACS Spectroscopy of (U)LIRGs

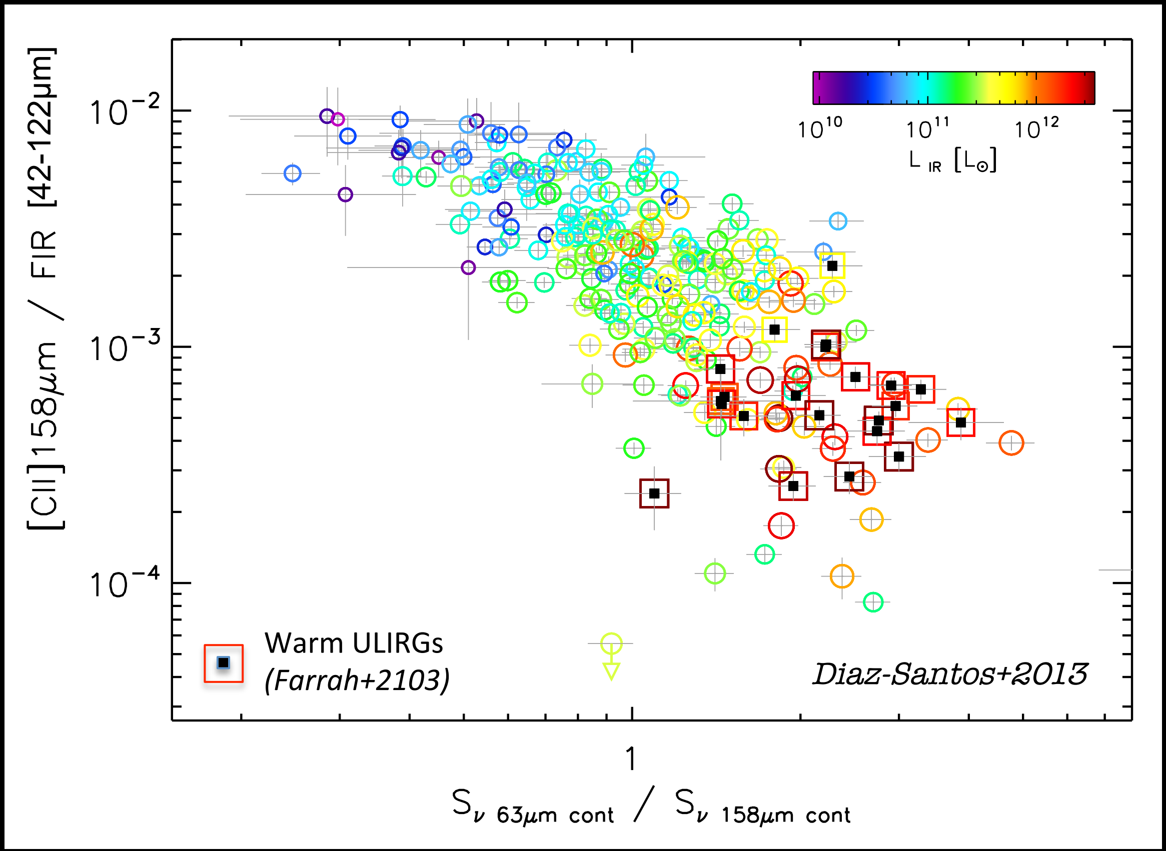


- There is a variety of line profiles: Unresolved line emission, broad/ asymmetric lines, double peaks.
- Very complex kinematics reflecting the dynamical state of the system: from isolated grand-design spirals to interacting galaxies at all merger stages.

[CII] Deficit or far-IR Excess?

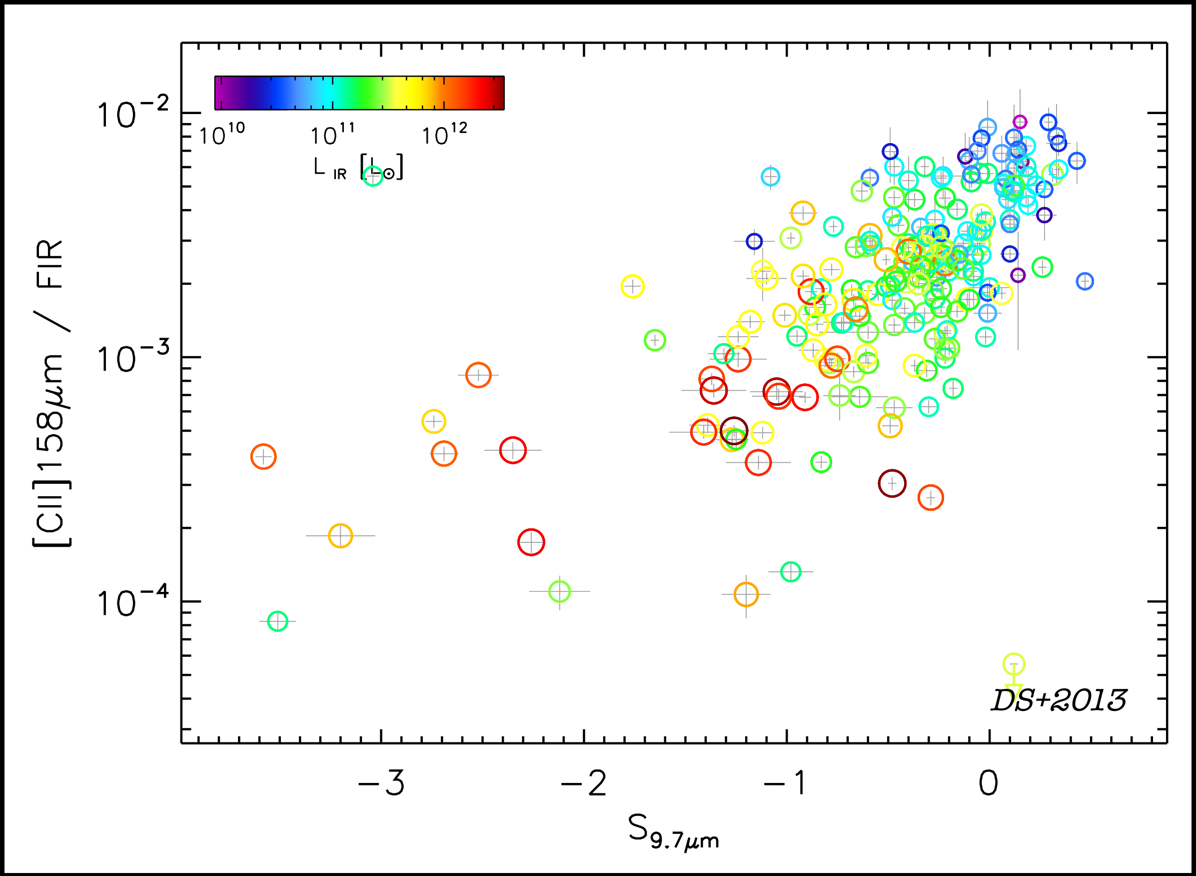
Gracia-Carpio+2011

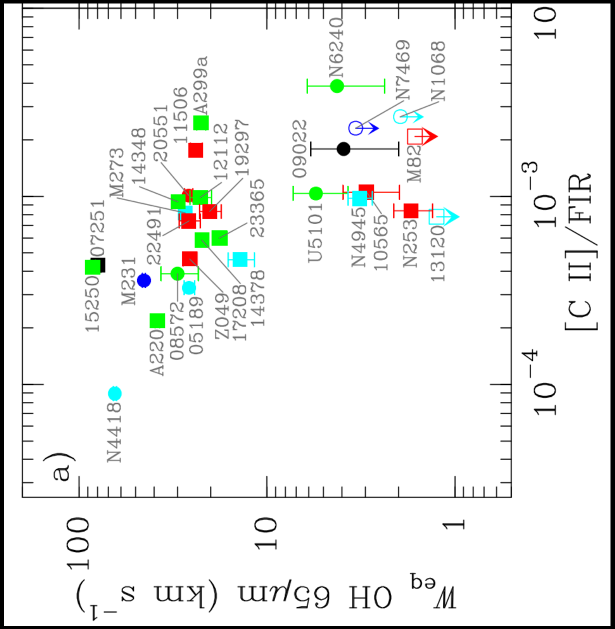




- [CII]/FIR decreases in sources with warmer T_{dust} due to an increase of the ionization field (*see also Malhotra+1997,2001; Helou+2001; Gracia-Carpio+2010, Stacey+2010*). Increased dust-to-gas opacity in progressively more dust-bounded HII regions (*Abel+2009; Draine2011*). UV photons heat the dust before reaching the PDRs -> lower gas heating efficiencies and higher T_{dust}

Warm and Cold Dust

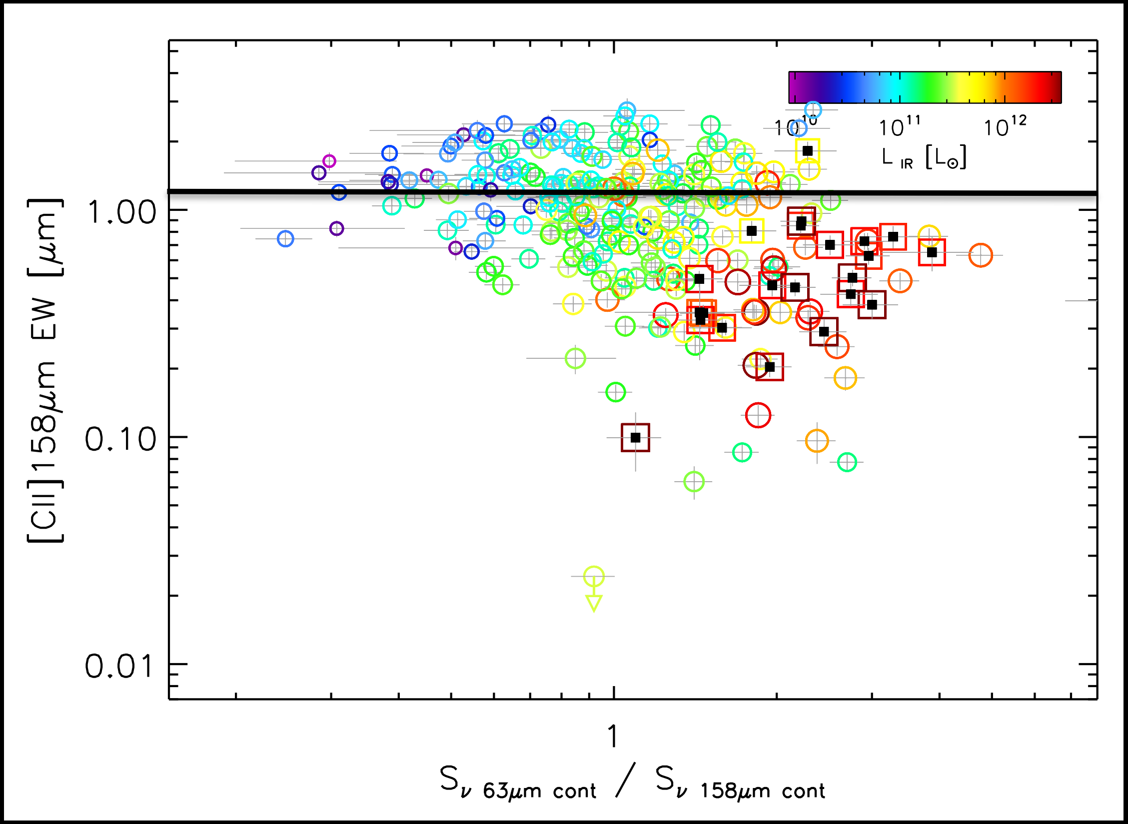




Gonzalez-Alfonso+2015

- There is a correlation between the [CII]/FIR ratio and the strength of the silicate absorption feature at 9.7μm.
- This suggests that the cooler dust responsible for the dust opacity in the MIR is spatially related to the dust producing the warm FIR "excess" emission, creating the line deficit.

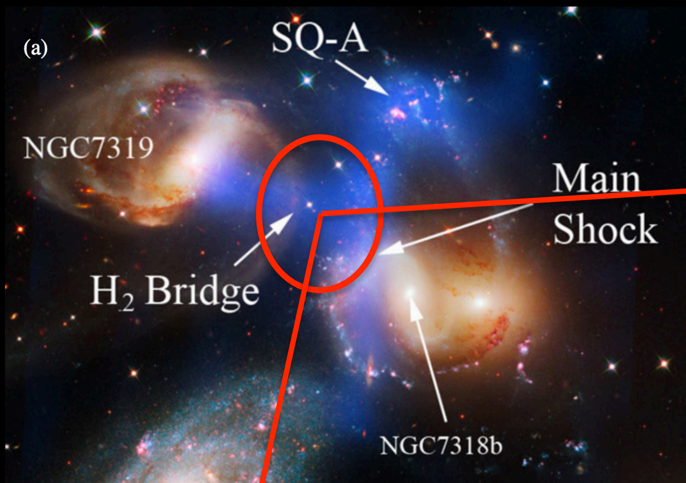
A Caveat to the [CII]/"FIR" Ratio



DS+2013

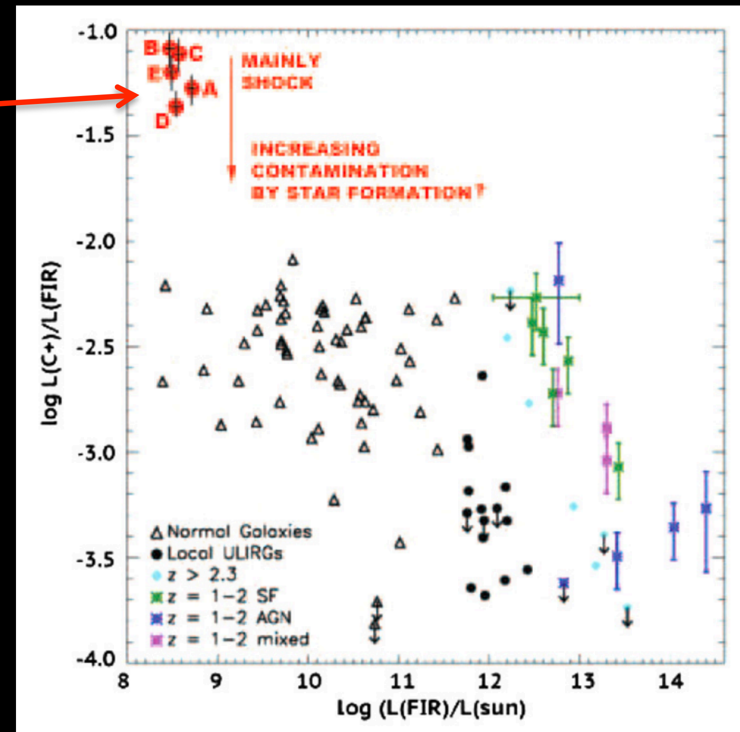
- The [CII] deficit almost disappear when [CII] is compared to colder dust at ~160μm
- If one has ALMA [CII] data and only the continuum under the line to estimate the FIR luminosity, what one has is NOT the [CII] deficit. It's the [CII] EW.

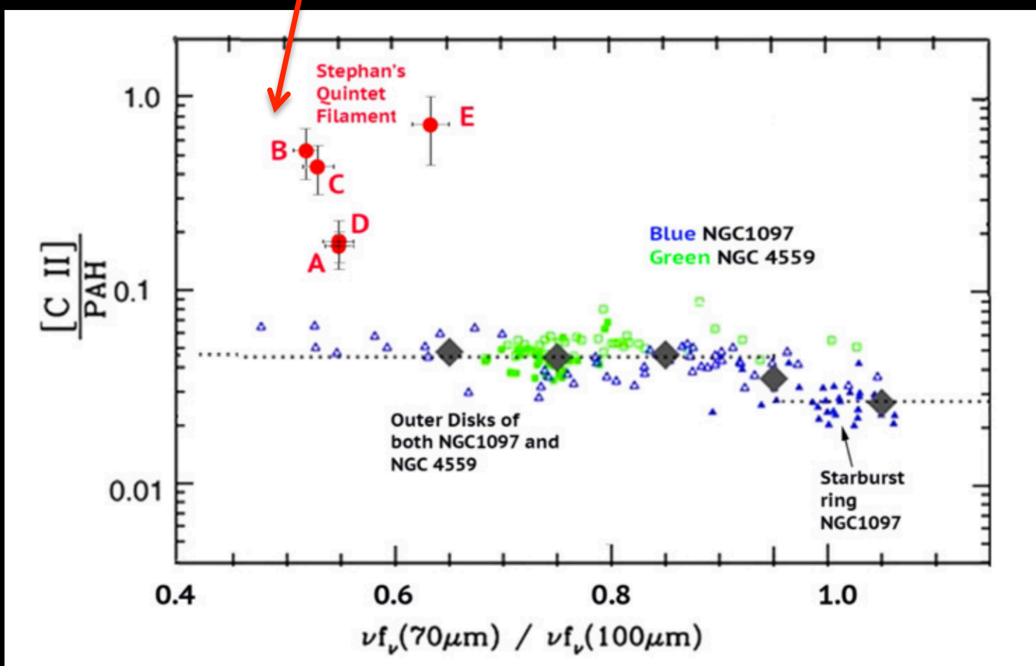
Other Contributions to [CII] - In Mergers



STEPHAN'S QUINTET

Appleton+2013





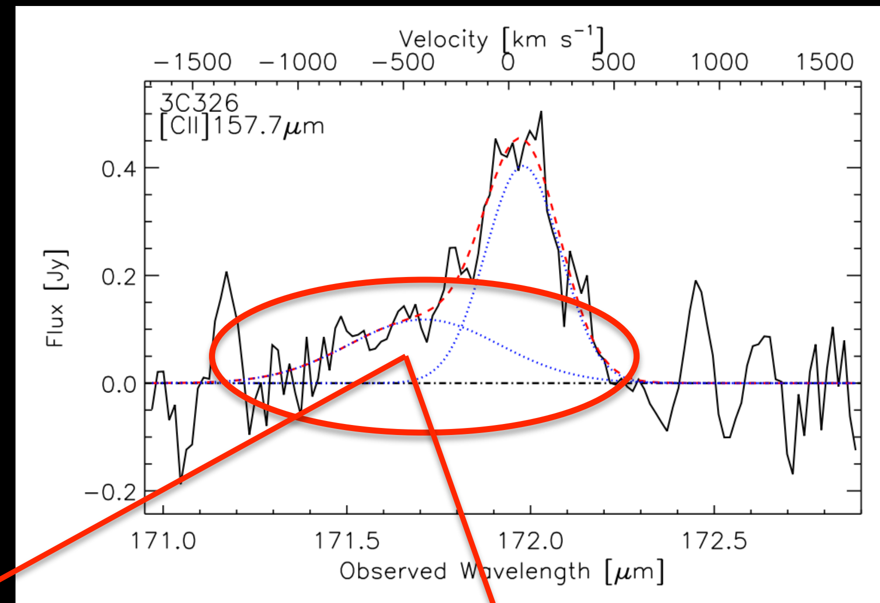
- Merger-driven shocks in Stephan's Quintet:

PAHs destroyed, but [CII] enhanced in low velocity shocks that leave behind them a turbulent medium in which [CII] is an excellent cooling line to dissipate the kinetic energy.

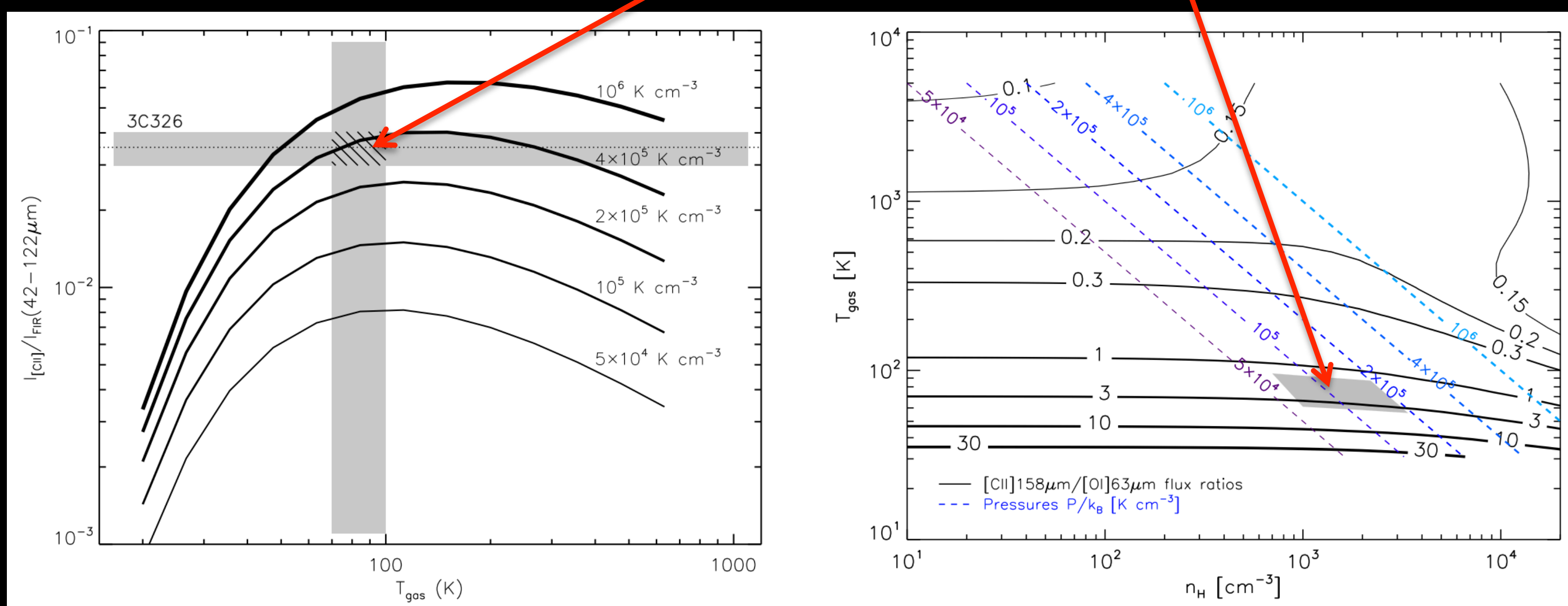
Other Contributions to [CII] – In AGNs

- 3C 326N. An AGN-driven outflow:

The AGN injects turbulent energy regularly into the ISM via short-lived jets. The cooling time is similar to the jet lifetime so the gas remains turbulent.



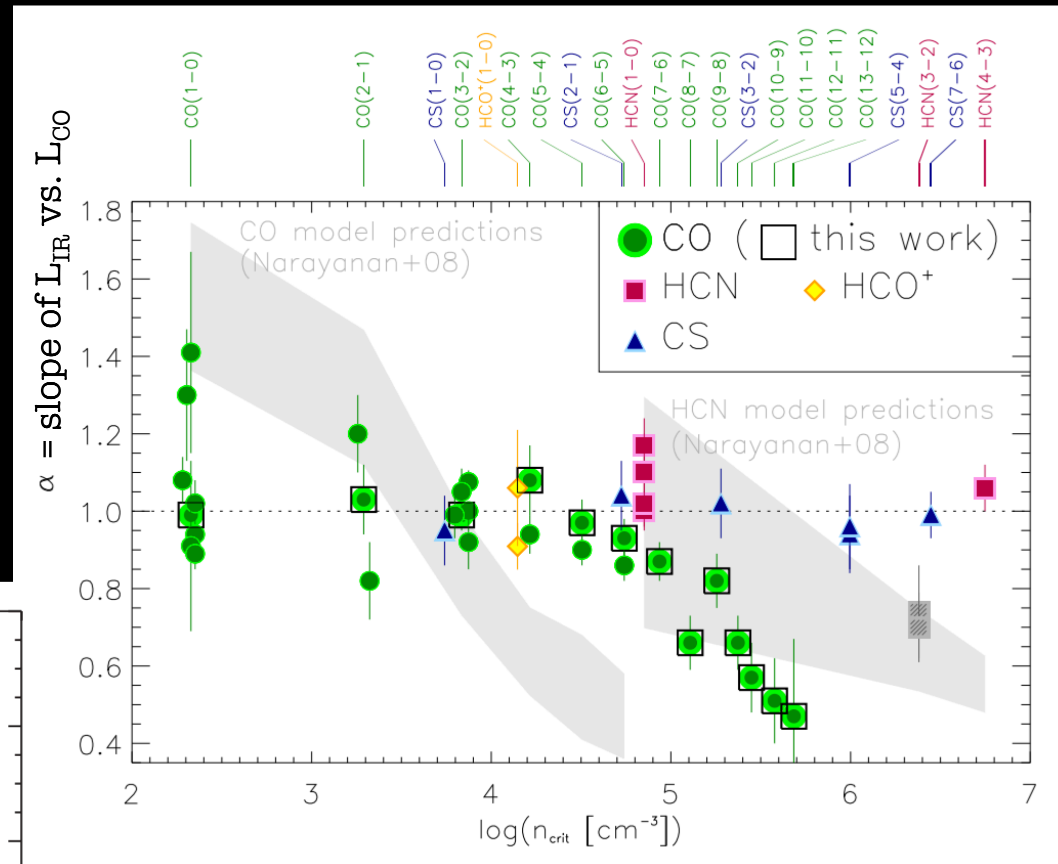
Gillard+2015

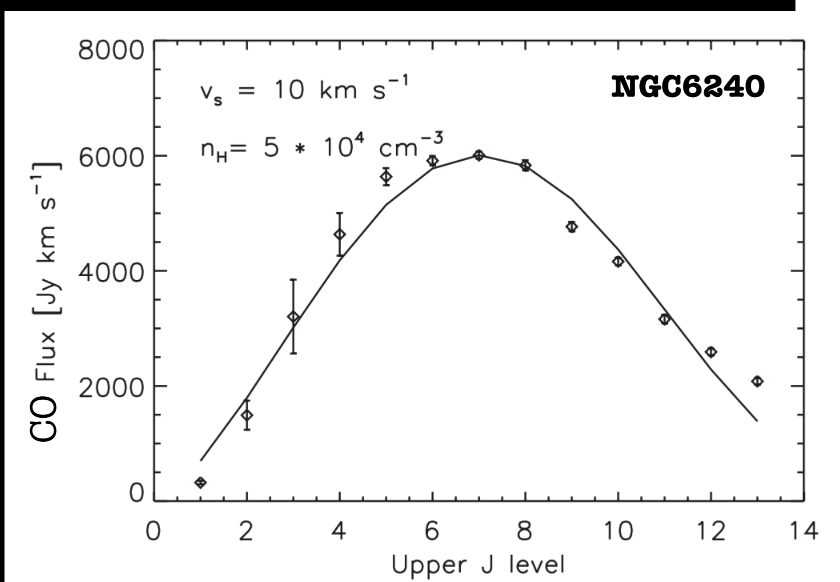


CO Ladder – Mechanical Heating

HerCULES: Greve+2014

- The slope in the correlation of L_{FIR} vs. L_{CO} for different J transitions has a turnover around J=7-6, becoming sub-linear.
- Above that threshold, mechanical heating could provide extra energy. Example: NGC6240

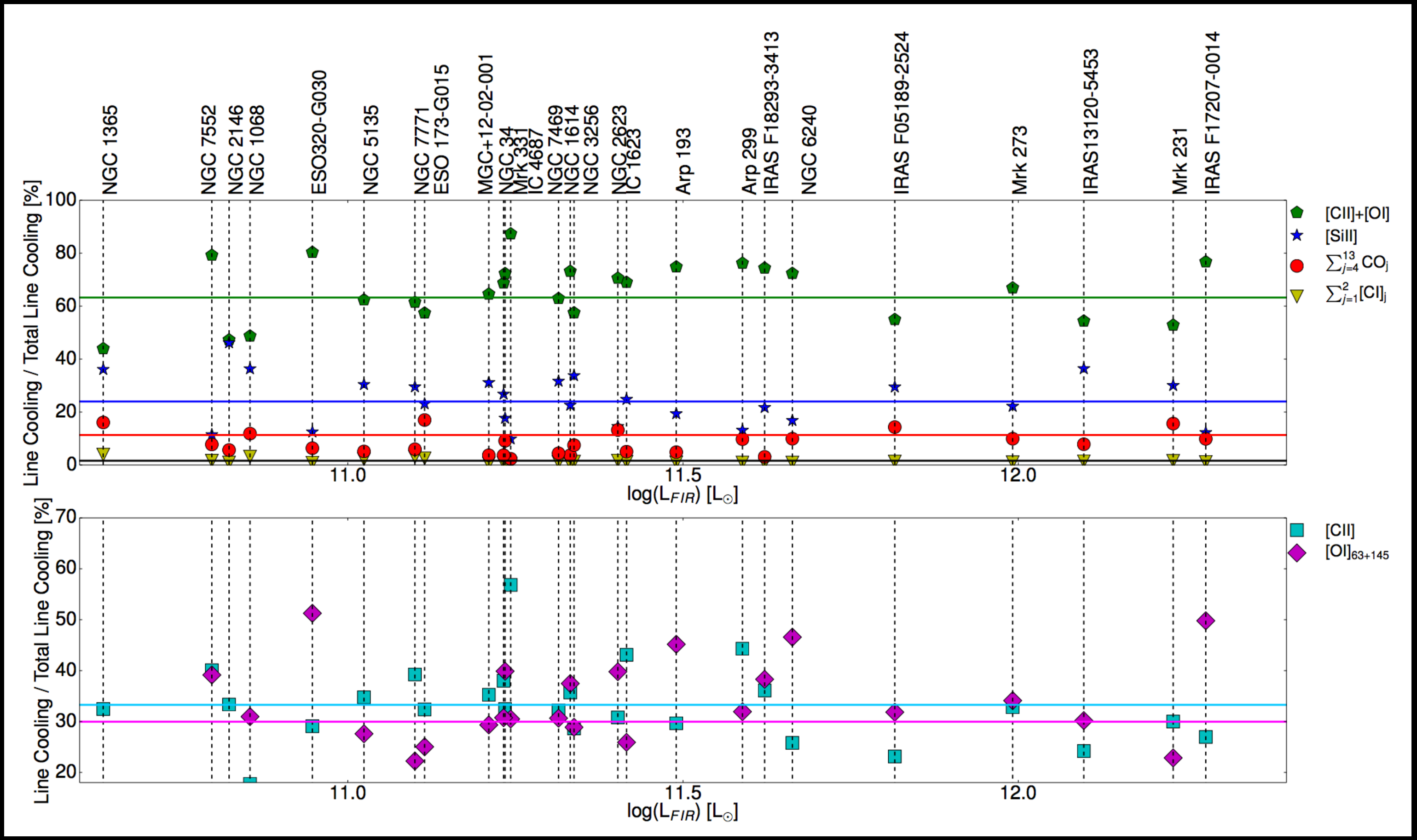




Meijerink+2013

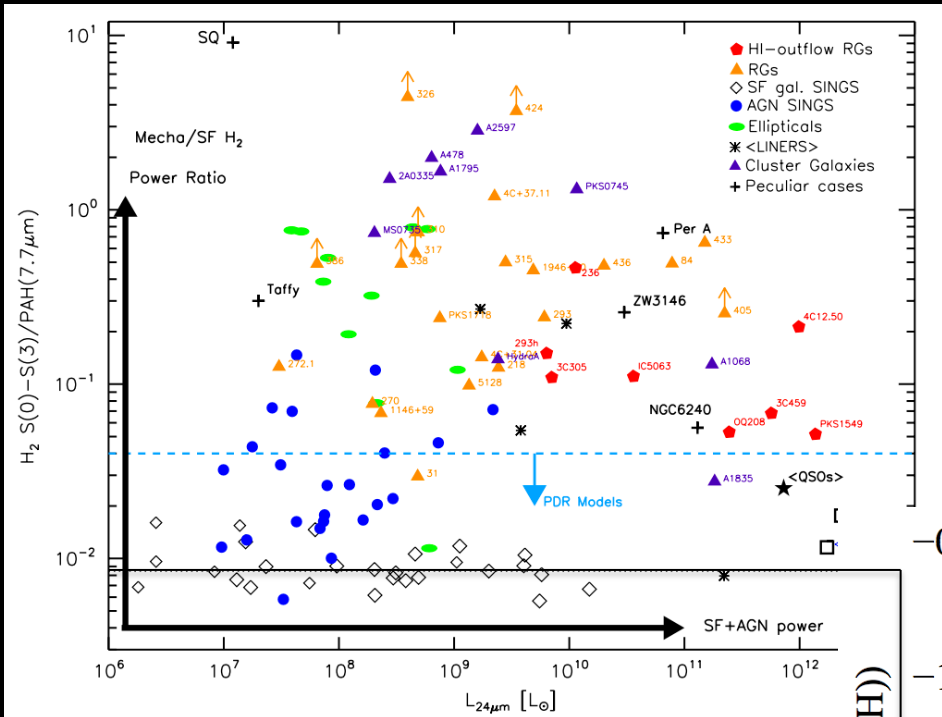
Global Line Cooling Budget

HerCULES: Rosenberg+2015



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

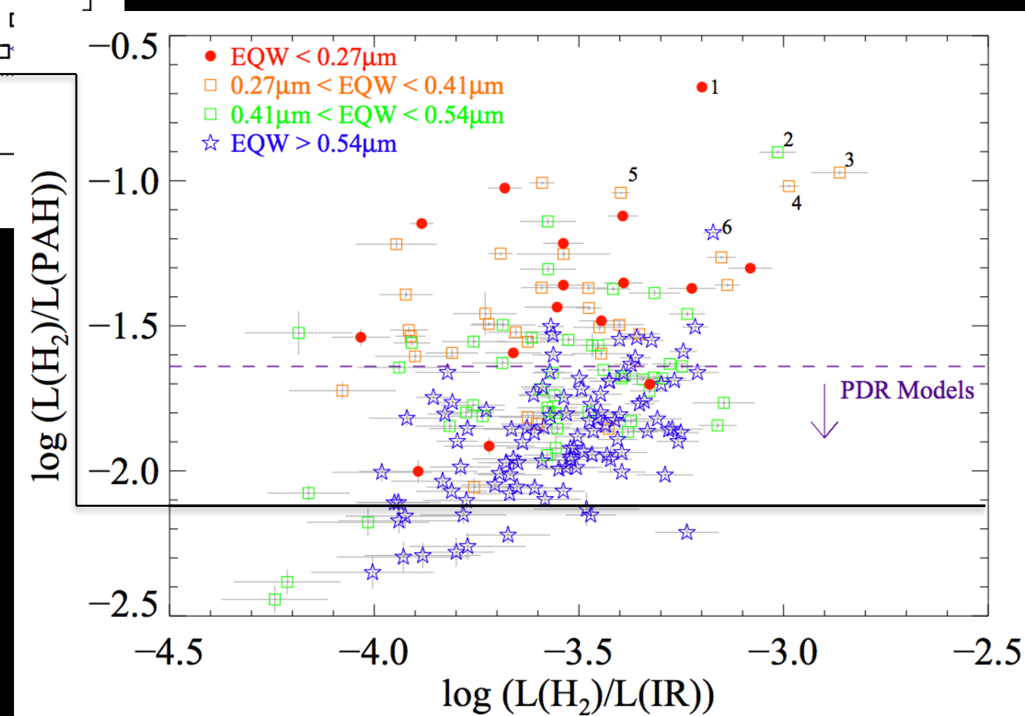
Shocked Gas on Large Scales?



Guillard+2012

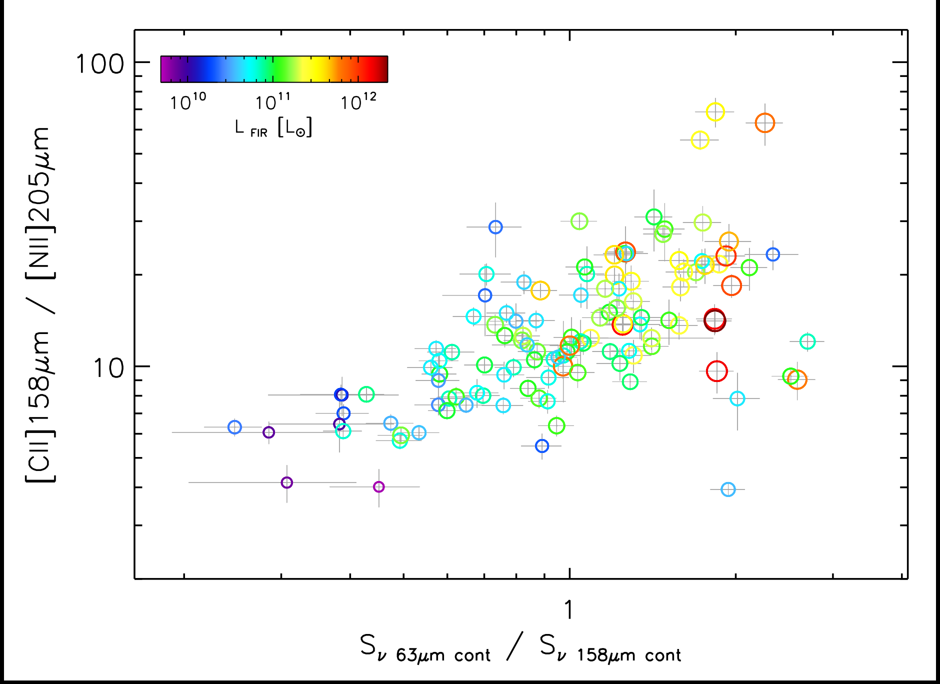
- PDR models cannot reproduce extreme H2/PAH ratios, like those found in radio galaxies and some AGN.

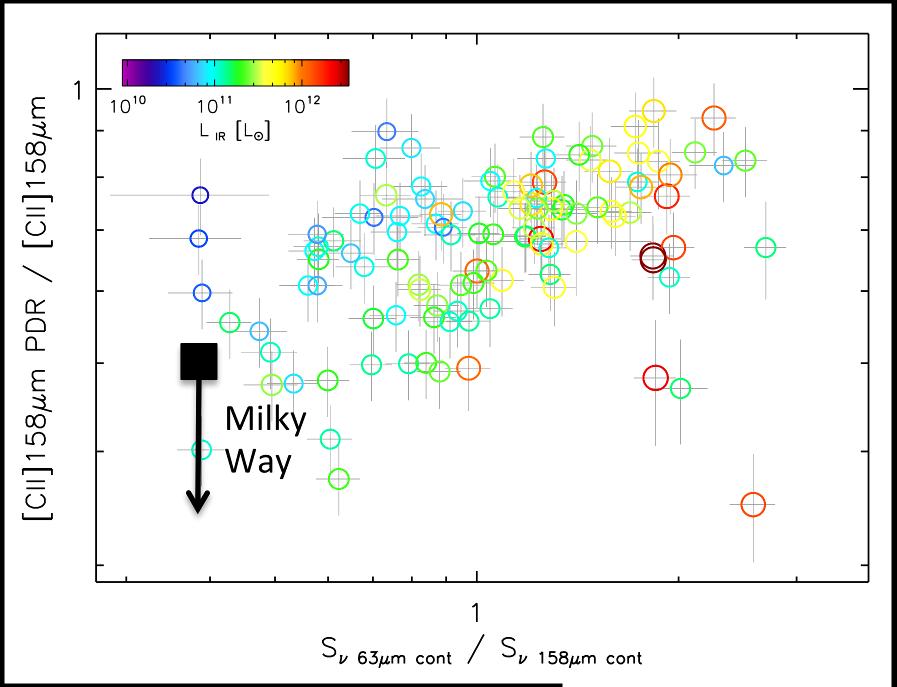
Stierwalt+2014

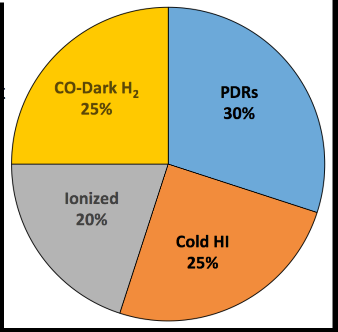


- However, only a few LIRGs cannot be explained in terms of PDR emission.

Disentangling Ionized from PDR [CII] Emission





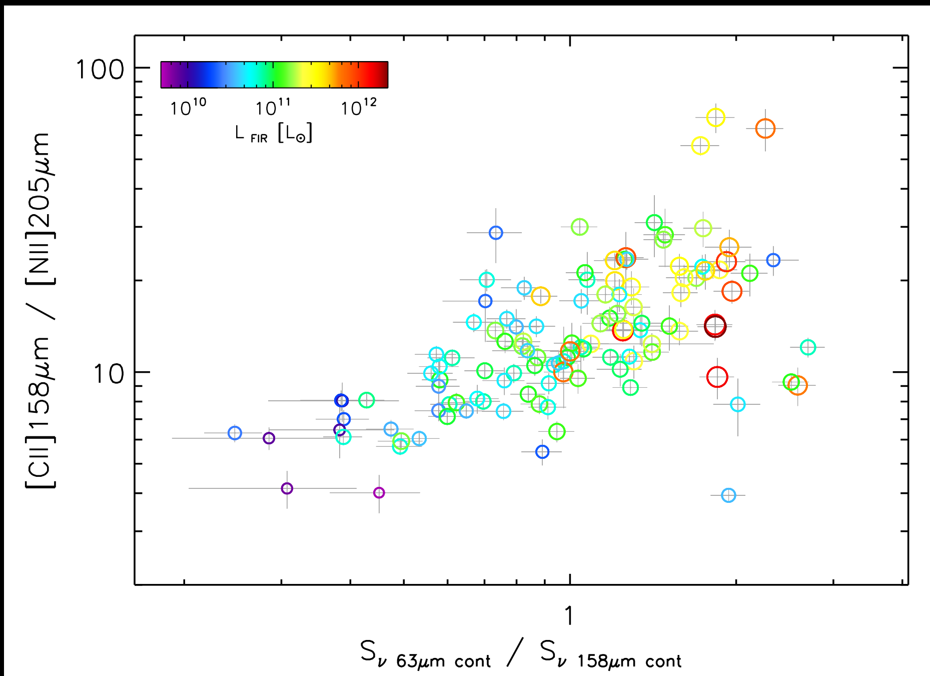


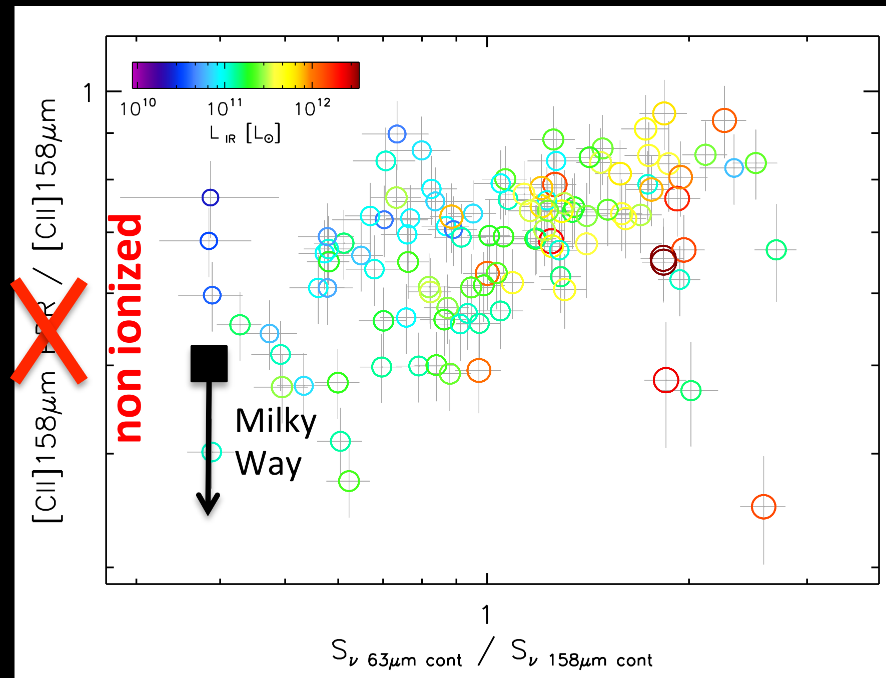
- We use the [NII]205 line to estimate the contribution of the ionized gas to the [CII] emission. The [CII]/[NII] ratio is constant for a large range of electron densities so any excess of [CII] is due to PDR emission.

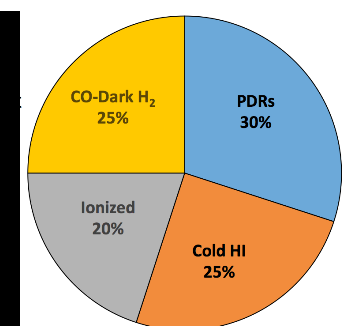
- Despite being weaker relative to the FIR, the [CII] line has a progressively larger contribution from PDRs.

Pineda+2014

Disentangling Ionized from PDR [CII] Emission







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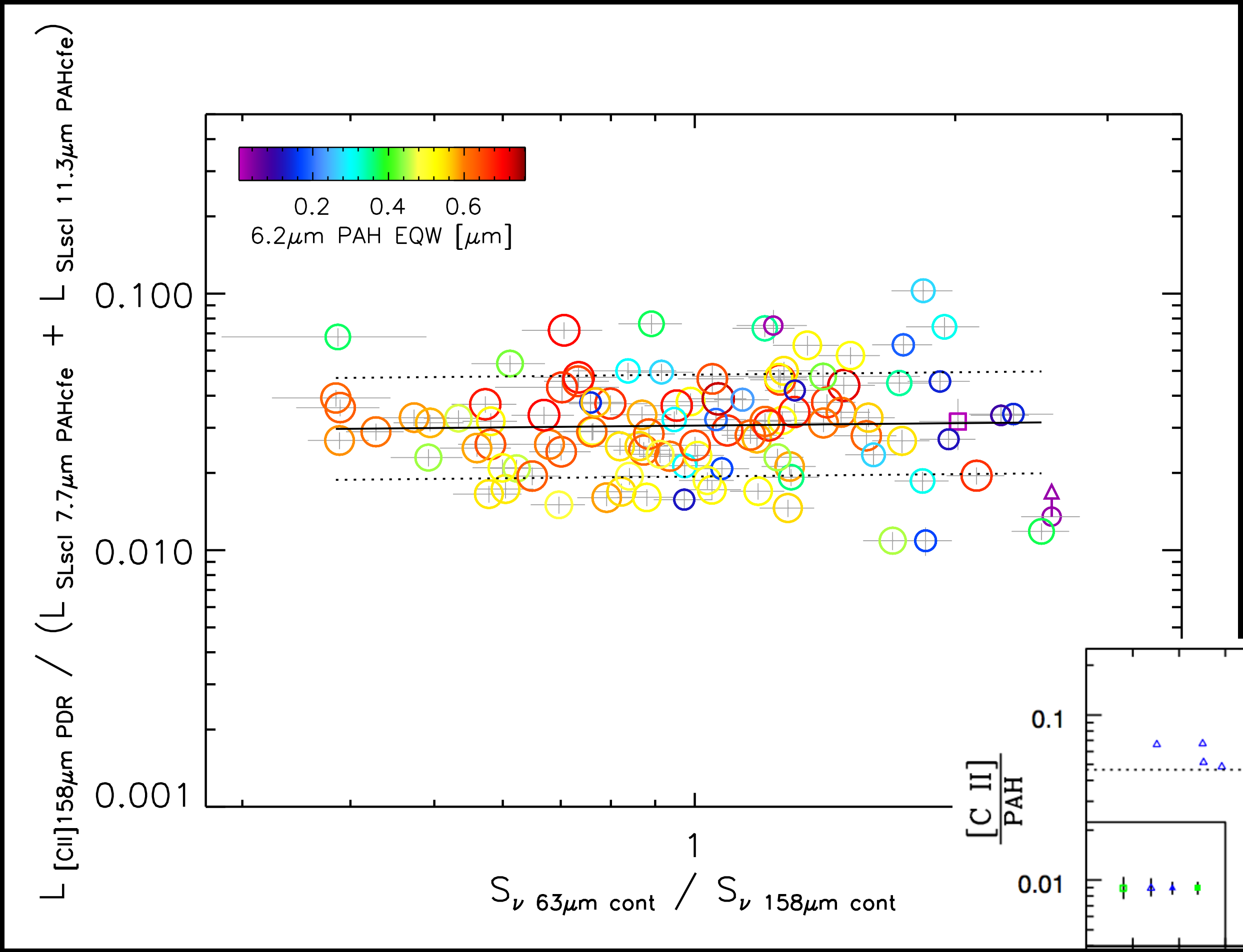
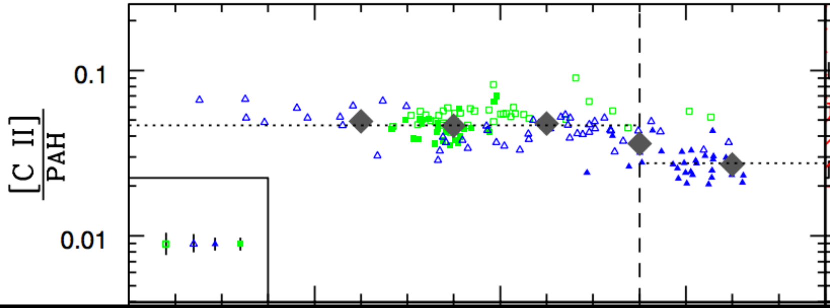
Pineda+2014

[CII]/PAH Emission



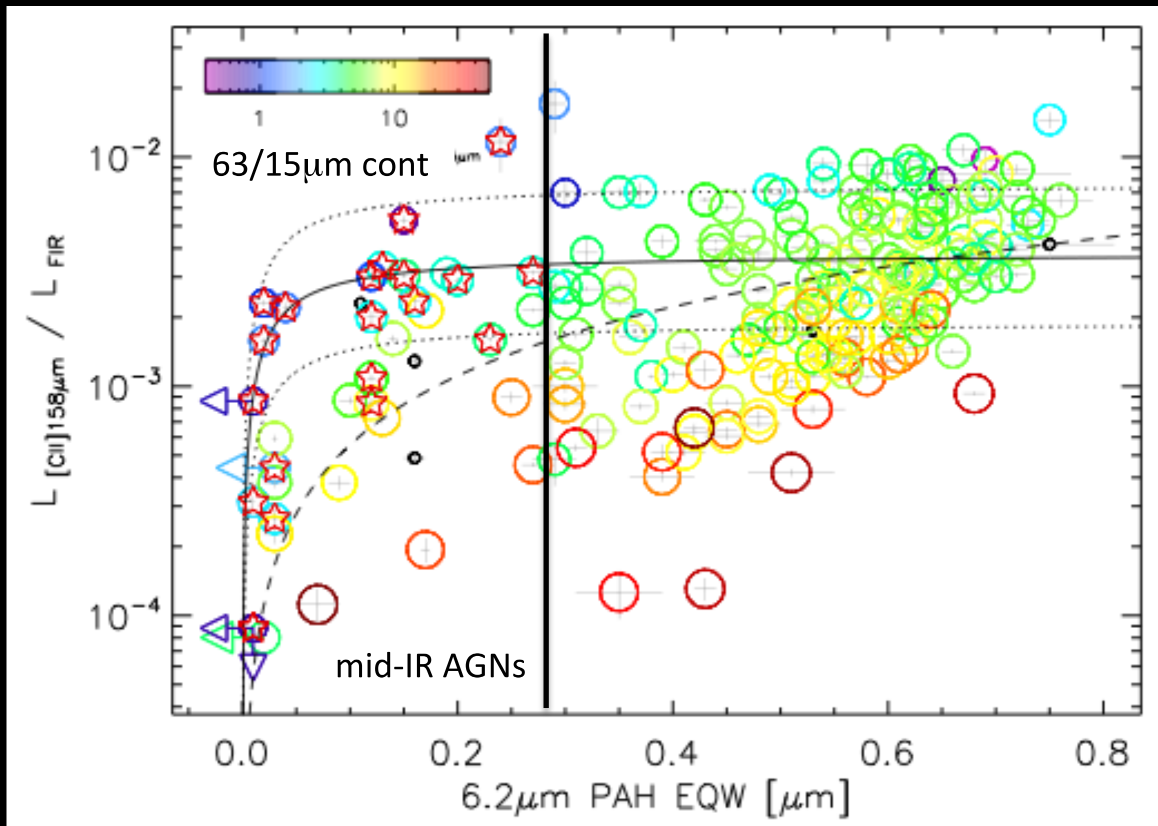
Croxall+2012



- A constant [CII]/PAH ratio suggests that PAH molecules are the main contributors of photo-electros that subsequently heat the gas in PDRs (*see also Helou+2001, Beirao+2012*).

- It looks like that, in the end, all the "non-ionized" [CII] in LIRGs is indeed coming from PDRs

The Role of AGN



DS+2013

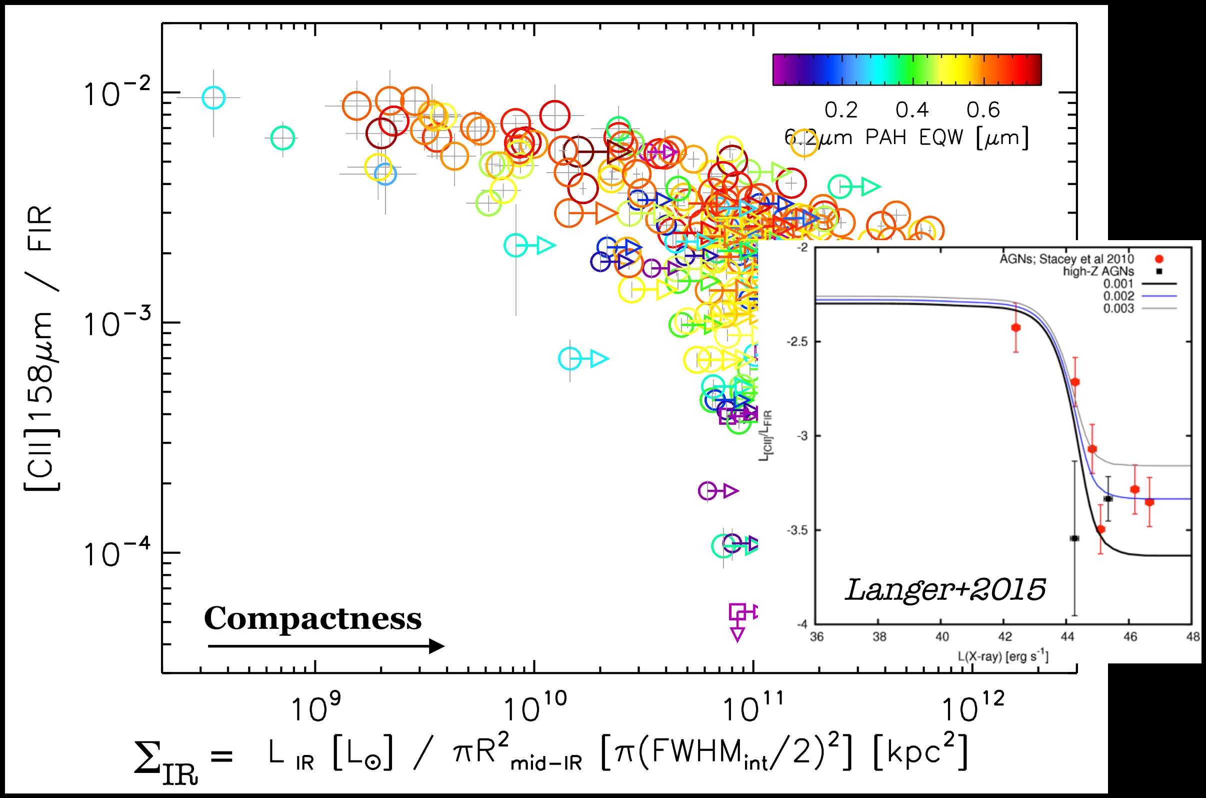
- At low PAH EQWs, sources span the full range of [CII]/FIR ratios
- 55% of mid-IR AGN have [CII]/FIR > 10^{-3}! (70% if two mid-IR diagnostics are required) -> These AGN do not contribute significantly to the far-IR emission
- Only when 6.2μm PAH EQW <~ 0.05μm the AGN can contribute ~50% to far-IR

Compactness

- [CII]/FIR is correlated with compactness (concentration of light) of the MIR emitting region, Σ_{MIR} (independently of its origin).

- The [CII] deficit is a fundamental property of the starburst itself.

- [CII] is not a good SFR tracer in LIRGs since it does not account for the increase in warm dust emission from the starburst* * *



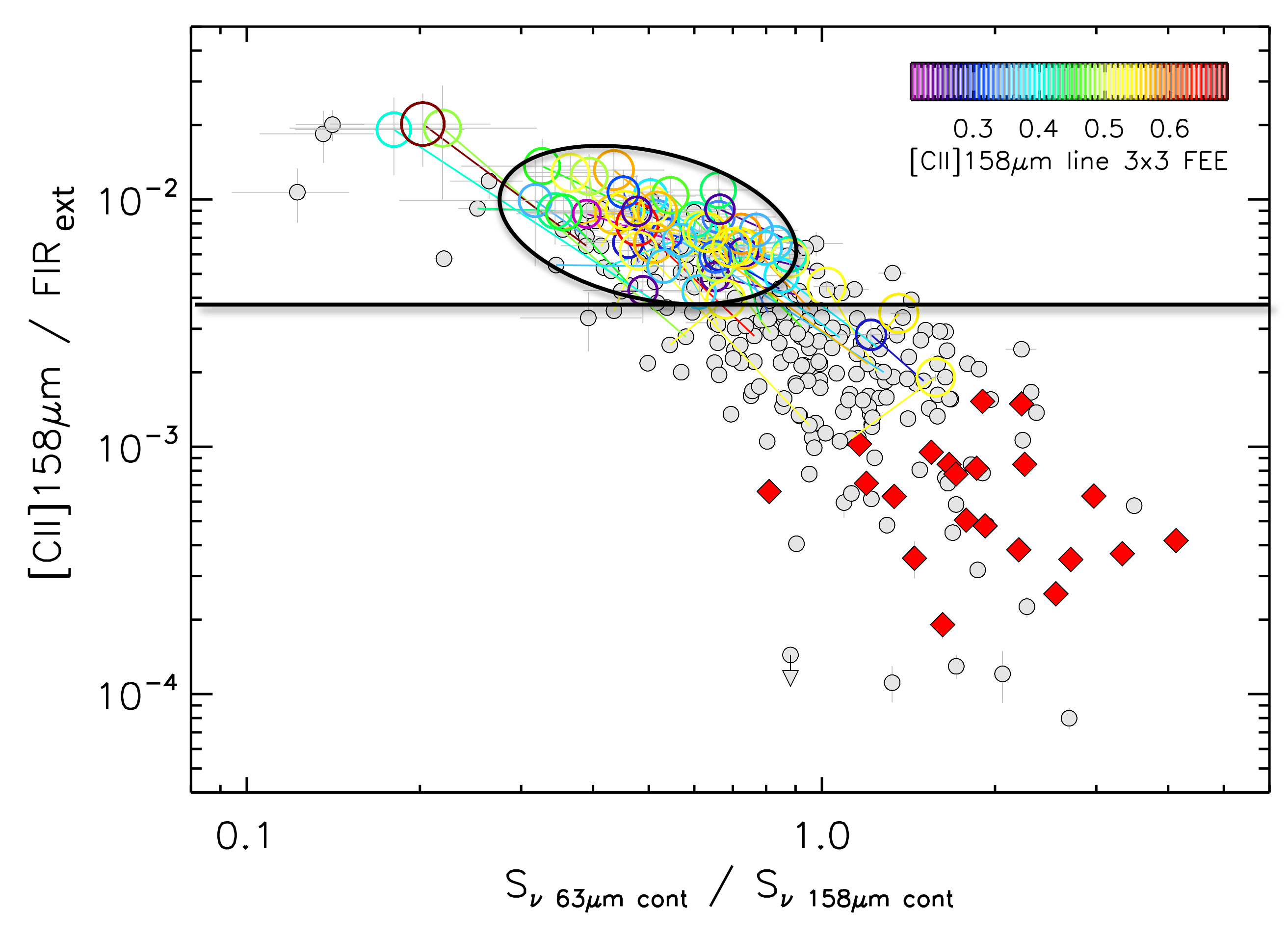
Diaz-Santos+2013

* * *Unless you are fine having an order of magnitude uncertainty in your SFR measurement.

Extended [CII]

- Extra-nuclear star-forming regions shown [CII]/FIR ratios > 4 x 10^{-3}, higher than the average nuclear value in pure star-forming LIRGs

Diaz-Santos+2014

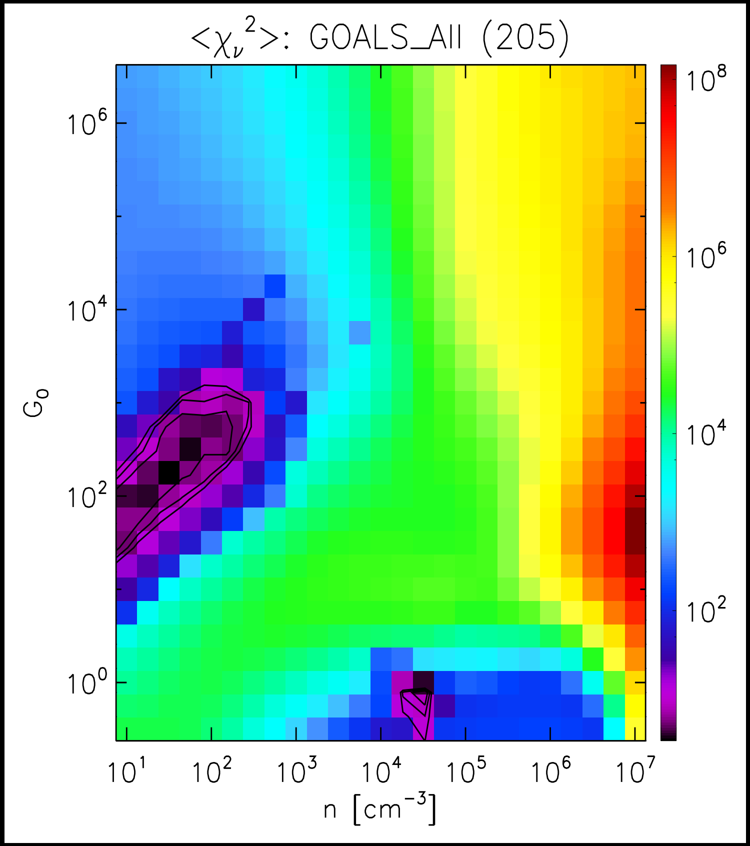


- Consistent with values measured in Galactic ISM and disks of normal star-forming galaxies.

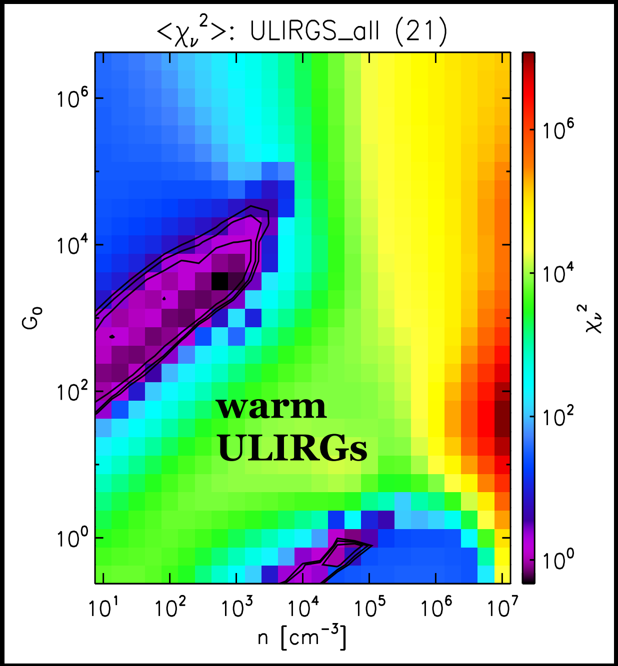
- The [CII] deficit is restricted to the LIRG nuclei

PDR Modeling

GOALS



- PDR model inputs: $[CII]_{PDR}$, [OI]63μm and FIR
- LIRGs show values of G_0 in the range of ~10^2-10^3 and gas densities of n_H ~10^1-10^3 cm^{-3}



- Warm ULIRGs have few times higher UV field intensities but similar gas densities

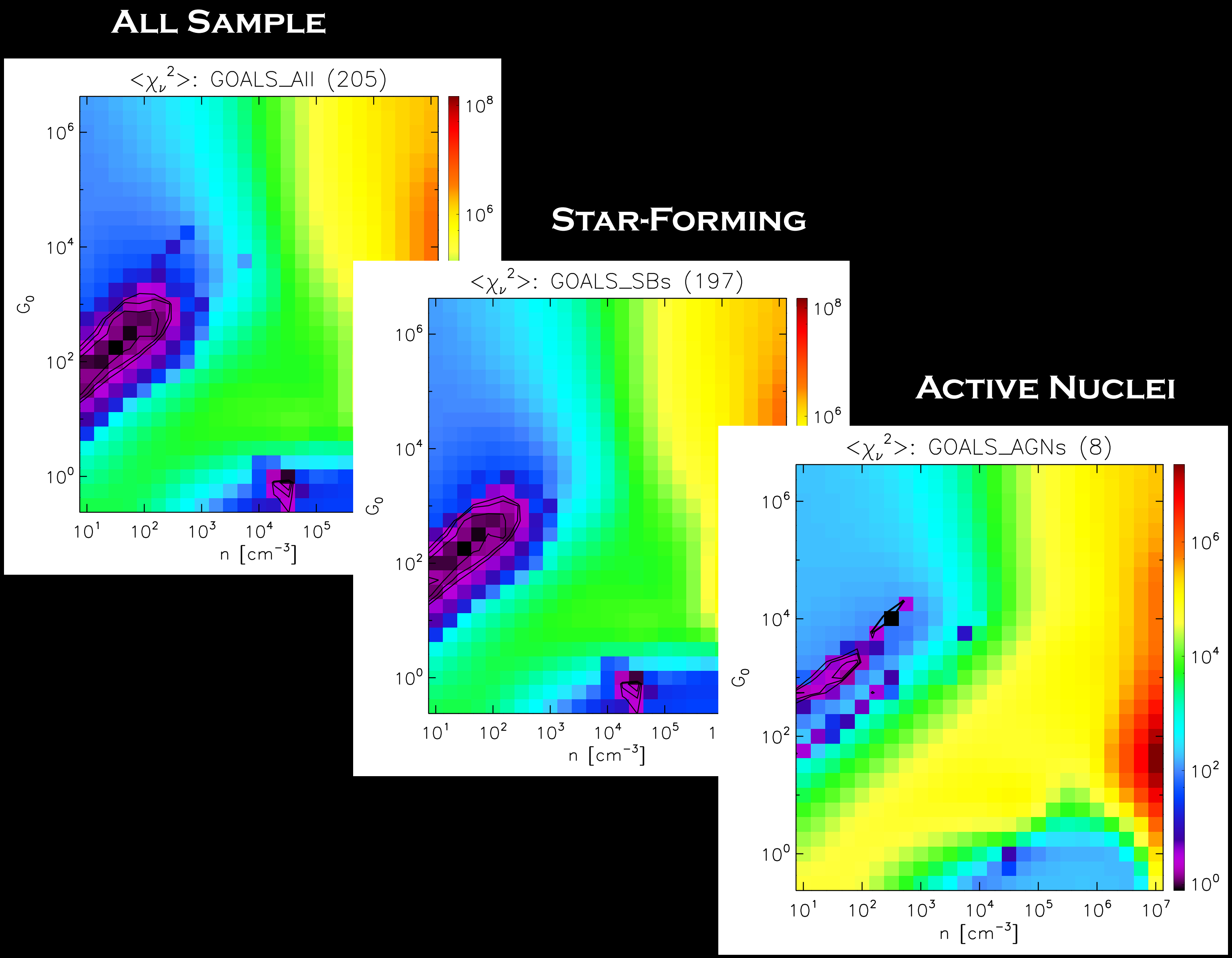
See also Farrah+2013

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

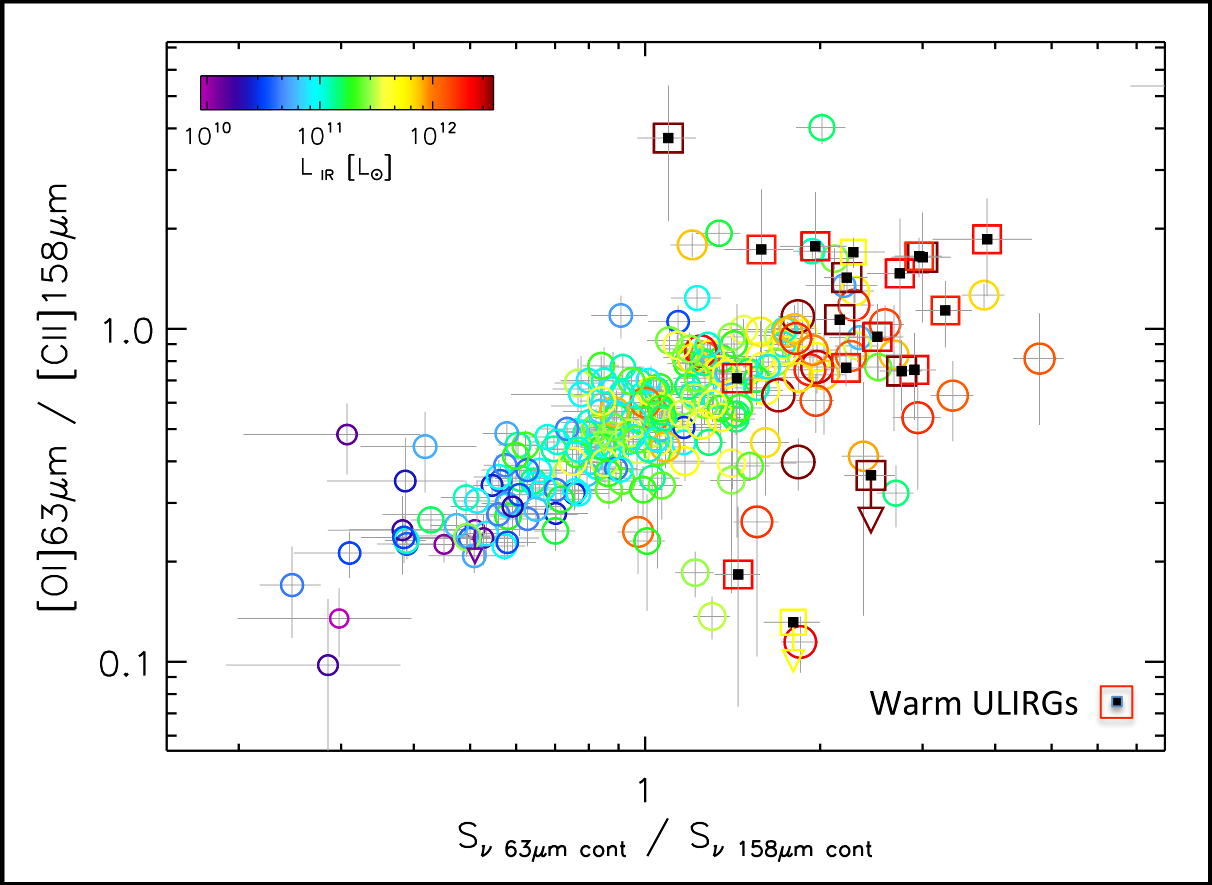
ISM Properties

PDR Models based on Kaufman +1999: PDR Tool Box (http:// dustem.astro.umd.edu/pdrt/)

GOALS



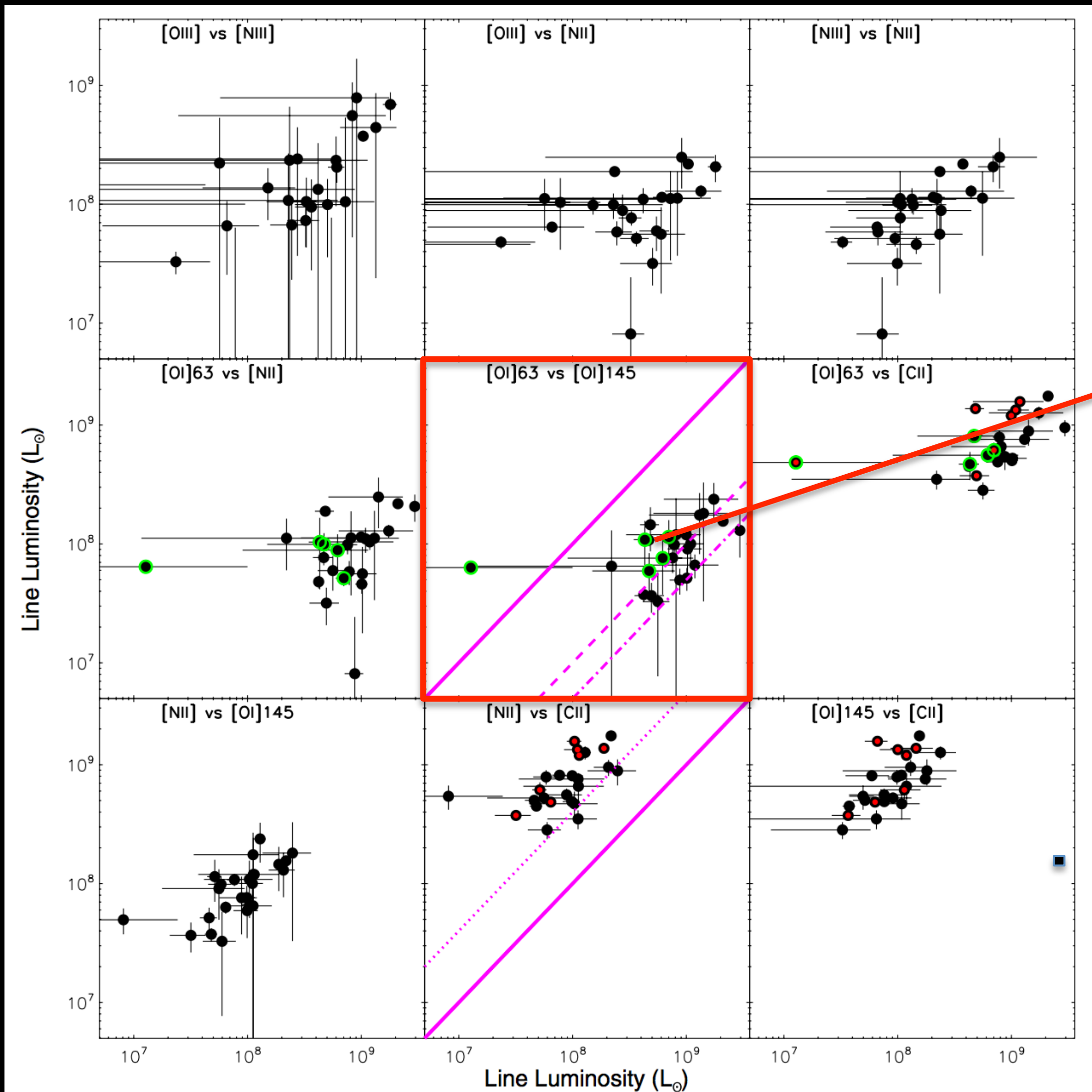
[OI]63/[CII] – A Great Thermometer



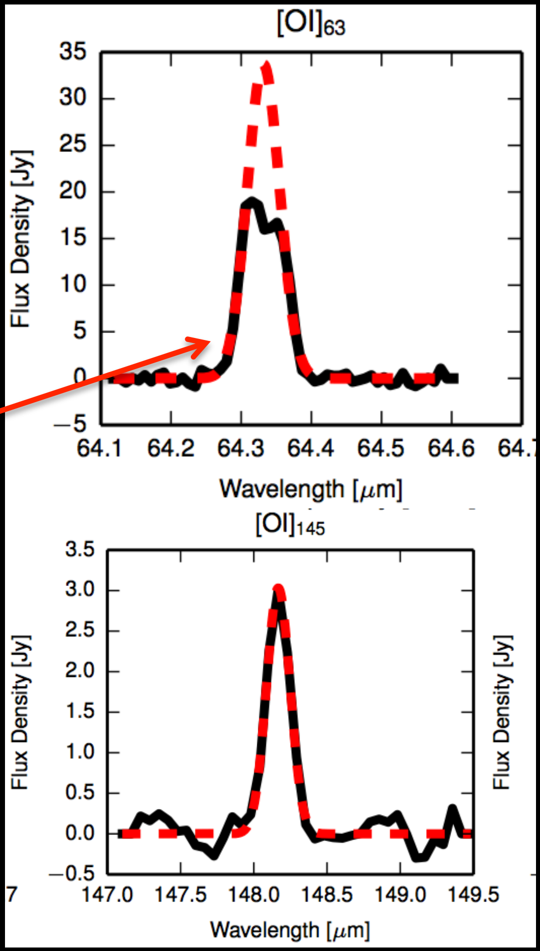
- The [OI]/[CII] ratio can be used as a thermometer for the gas, provided that the density is < 10^3 cm^{-3}. The ratio is very well correlated with the dust temperature, suggesting that both phases are well mixed.
- Only caveat comes from possible optical thickness of the [OI]63 transition.
- Unfortunately [OI]63 only available with ALMA at z > 5.5. And [OI]145 x10 fainter.

[OI]63 Self-Absorption

HerCULES: Rosenberg+2015



HERUS: Farrah+2013



- Only 30–50% of ULIRGs show clear signatures.
- LIRGs not likely to be affected by [OI] self-absorption

Conclusions

- FIR emission lines allow us to probe the conditions of the ISM in local galaxies, and provide us with very useful diagnostics for interpreting objects at high-z.
- The [CII] line is the dominant cooling line of the ISM almost at all luminosities, competing with [OI]63 in the most extreme ULIRGs. Both account for 50–80% of the line cooling. CO emission accounts only for ~10%.
- Mechanical heating (shock-driven turbulence) may be important to explain high J transitions of the CO ladder in the most luminous objects. However, PDR models still able to reproduce the [CII] and [OI] line cooling seen in most LIRGs. This is supported by the observed constant [CII]/PAH ratio.
- The [CII]/FIR ratio is related to the dust temperature and compactness of the starburst and it is not necessary to invoke the presence of an AGN to explain it, except in the most extreme cases, when < 10^{-3}
- If you don't have any other FIR indicator apart from [CII] and its underlying continuum for your high-z galaxy observed with ALMA, please use it for kinematics only because:

  1) [CII] is not a good star formation rate indicator.
  2) The continuum emission at 160μm is not telling you anything about the starburst.

- ...unless you see an excess or extreme deficit in the line equivalent width.
- LIRGs show G_0 values between 10 and 10^3 and densities between 10 and 10^3 cm^{-3}. Almost always below the [CII] critical density. ULIRGs have G_0's a few times larger.
- The [OI]63/[CII] ratio is a thermometer for the gas temperature.