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# The physical properties of LIRGs: unveiling the dust


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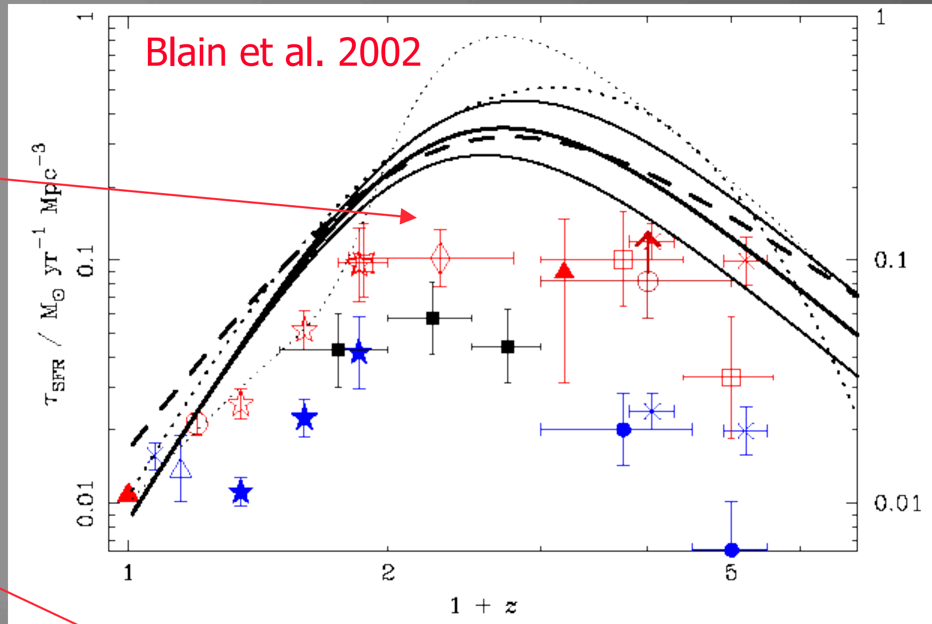
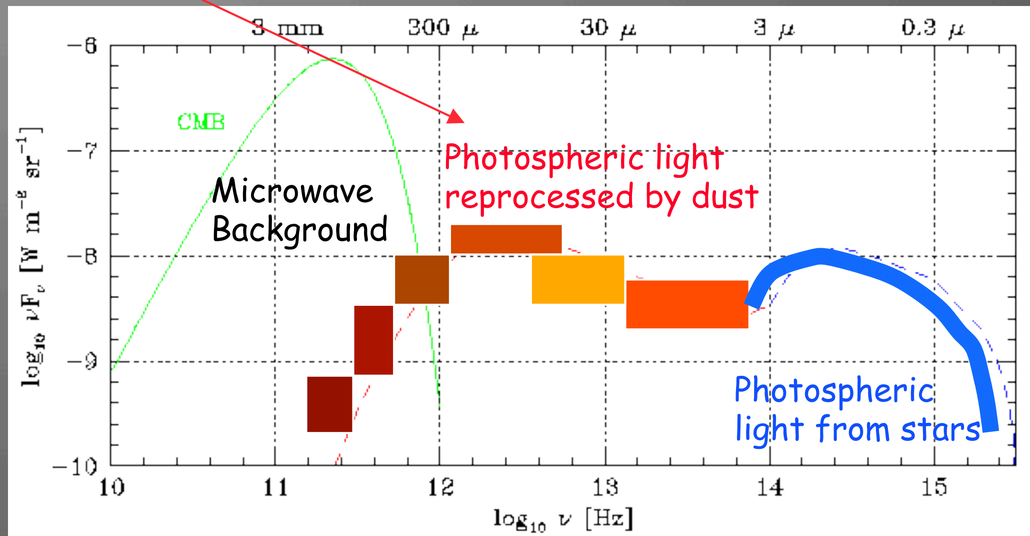
Papers:

*Diaz-Santos, VC, Armus, et al. 2010, ApJ, 723, 993*
*Diaz-Santos, VC, Armus, et al. 2011, ApJ, 741, 32*
*Diaz-Santos, Armus, VC, et al. 2013, ApJ, 774, 68*

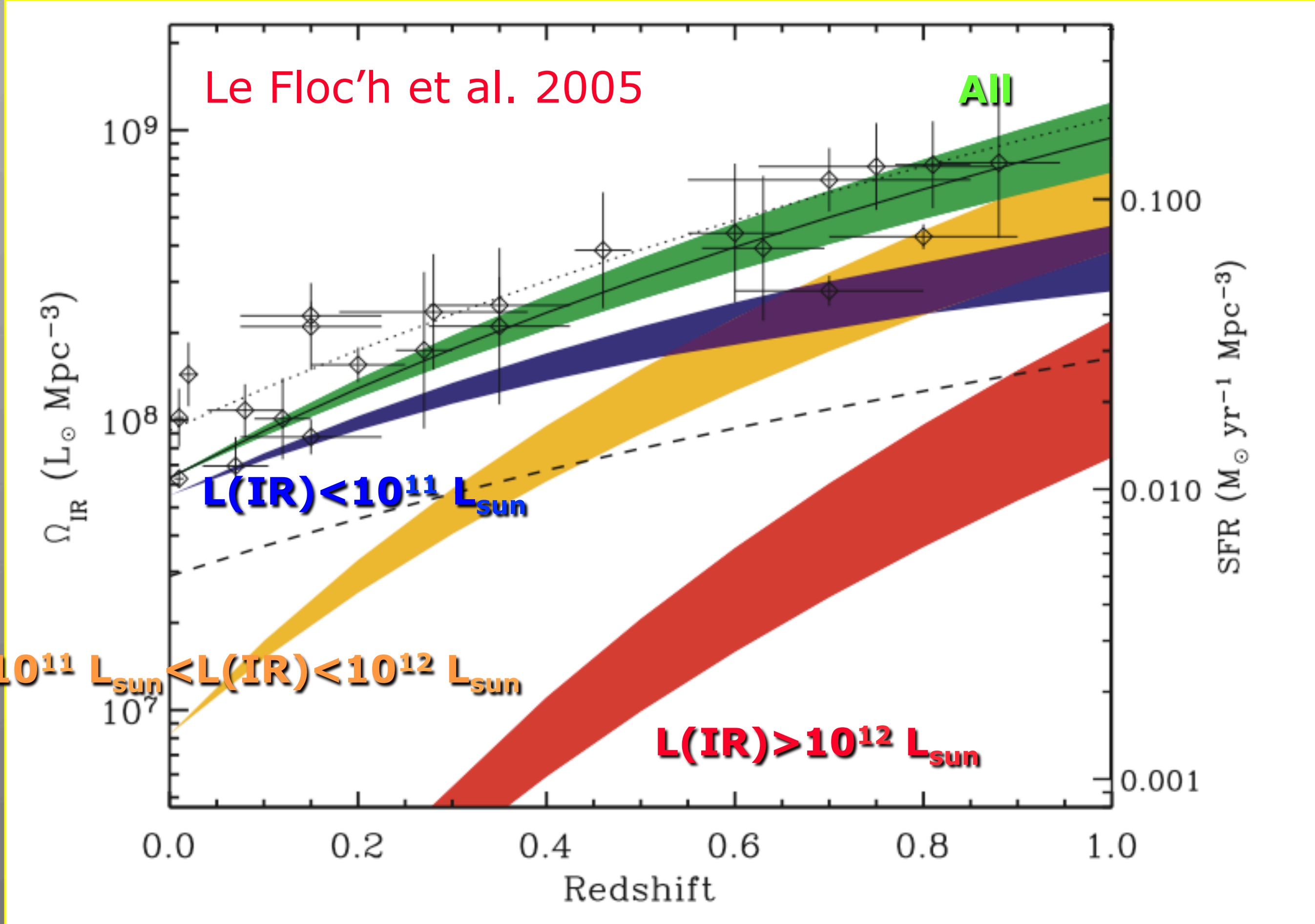
# History of Star-Formation in the Universe

- Optical surveys indicate that the mean SFR in the Universe was much greater at z > 1 (e.g. Madau et al. 1996)
- COBE revealed a cosmic far-IR background with energy > the integrated UV/optical light ⇒ dust extinction is important in the early Universe!
- IR/sub-mm surveys indicate even greater rates of star formation than seen in optical.
- To accurately determine the "SFR" requires both optical and far-IR/sub-mm surveys.



# LIRGs dominate the IR/SFR at z~1



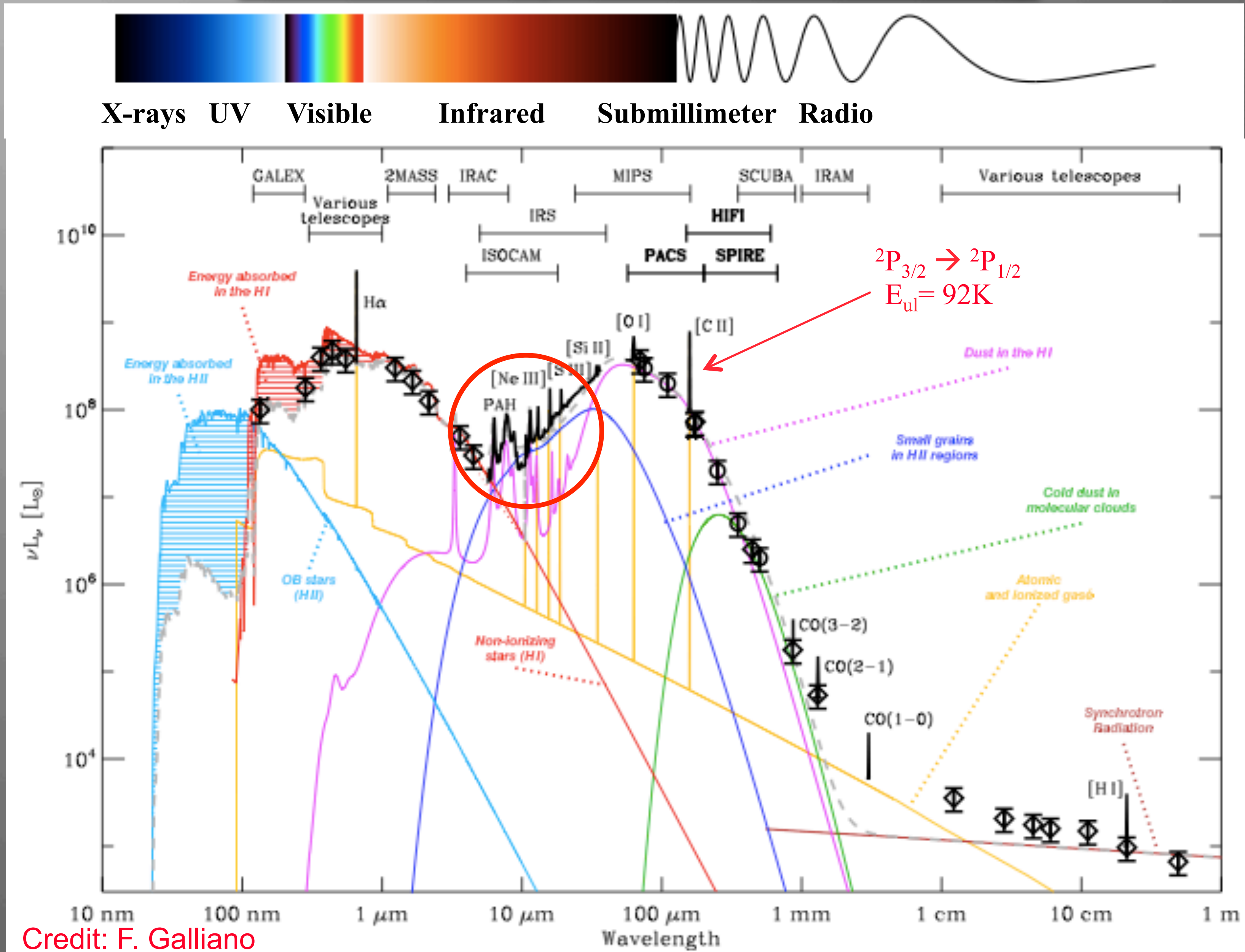

Luminous Infrared Galaxies dominate the star formation rate and energy density per co-moving volume at z >~1

# Motivation

- A number of the observational properties of galaxies detected at sub-mm at z~2 with $L_{IR}>10^{12} L_{\odot}$ (SMG) such as:
  - *cold infrared colors*
  - *energy production dominated by star formation* ( > 100 $M_{\odot}$/yr)
  - *mid-IR spectral features (ie PAH strength*

  … resemble those of local LIRGs rather than ULIRGs.
- Kinematical evidence from ionized (Hα) and molecular (CO) gas are often consistent the presence of extended (~5kpc) star forming disks
- There is a "broad" connection between mid- & far-IR emission and star formation rate (with some caveats…)
- We wish to
  - quantify the extended extranuclear emission in local LIRGs in the 5-15μm range to contribute additional evidence in the analogy between the physics of the ISM excitation in LIRGs and the conditions seen in SMGs and ULIRGs at z>1.
  - combine mid- and far-IR line measurements, in particular the [CII] 158μm line to probe the excitation and cooling of the gas in photo dissociation regions

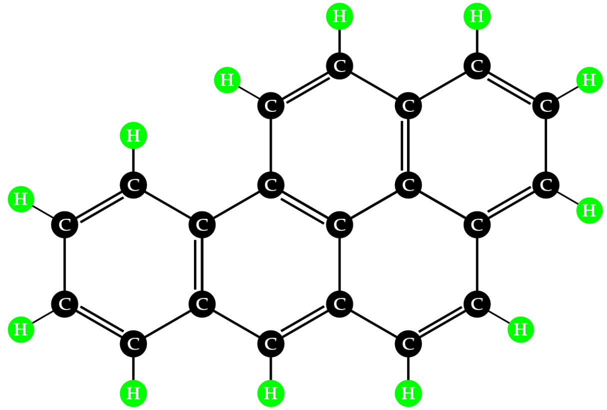
# SED Decomposition of a Galaxy



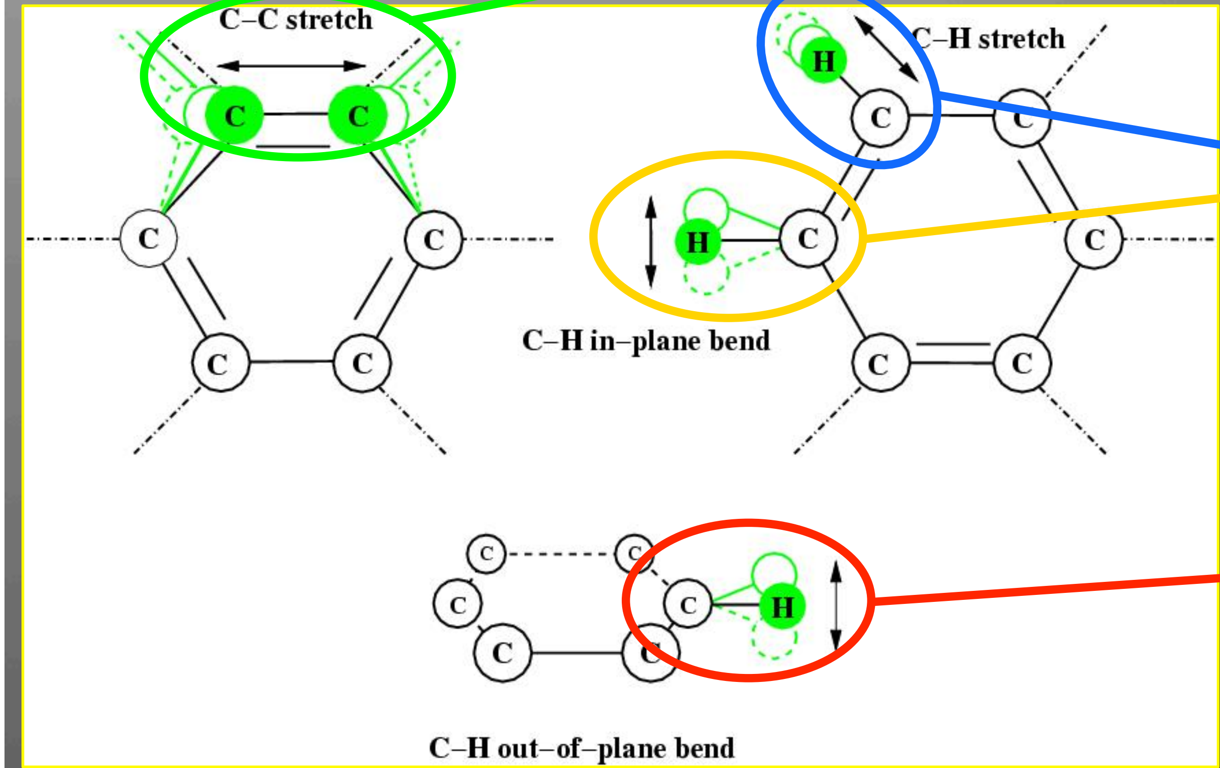

Credit: F. Galliano

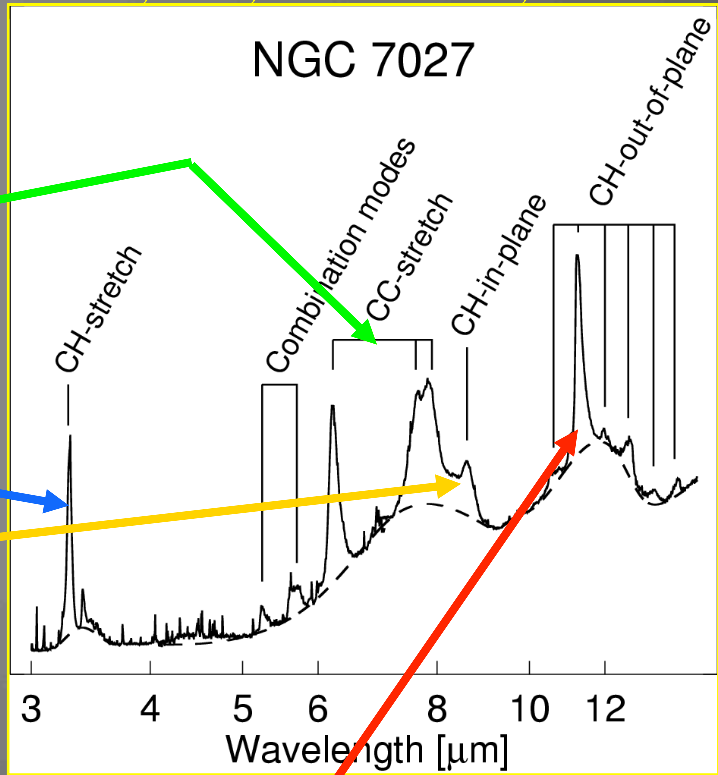
# PAH Normal Modes

- **10-20% of the total IR luminosity of a galaxy**
- Tens - hundreds of C atoms
- Bending, stretching modes ⇒ 3.3,6.2,7.7,8.6,11.2,12.7 μm
- PAH ratios ⇒ ionized or neutral, sizes, radiation field, etc.



PAH molecule



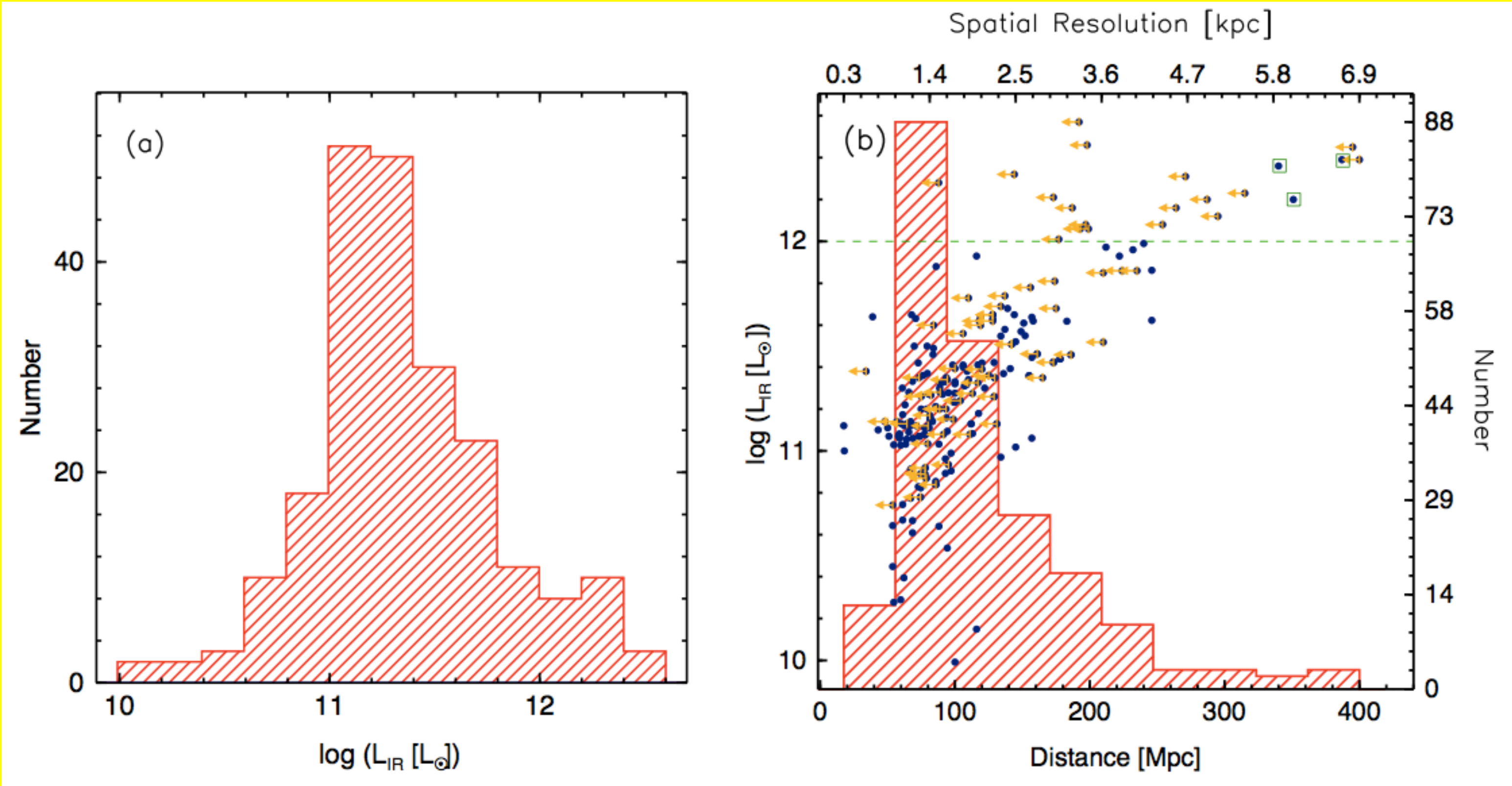





Leger & Puget (1984)
Sellgren (1984)
Desert, et al. (1990)
Draine & Li, (2001)
Peeters, et al. (2004)

# The Sample

- The sample is based on the Great Observatory Allsky LIRG Survey (GOALS; Armus et al. 2009) of 202 systems (181 of which are LIRGs)
- It covers the entire merger sequence: From isolated galaxies to merger remnants (Haan et al. 2011)
- All systems are observed with all four Spitzer/IRS modules (~5-37μm)
- Additional Spitzer & Herschel, as well as HST, GALEX, VLA, CO

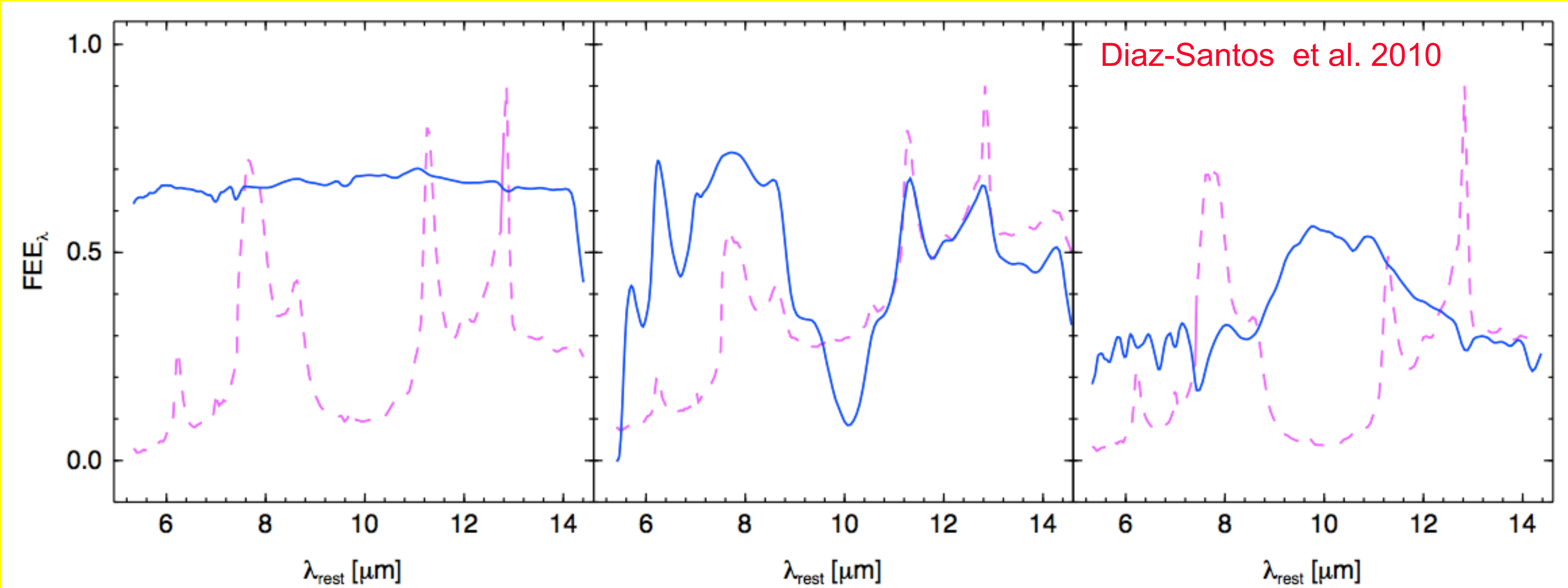


# The Method

- Use the 2D Spitzer/IRS longslit images of all sources and re-extract total 5-15μm spectrum using the same algorithms of the Spitzer pipeline
- Use a standard star (HR7341) as our unresolved point source (PSF)
- Scale the spatial profile of the standard star along the slit at every wavelength and subtract it from the corresponding profile of each source.
- Define as Fraction of Extended Emission (FEE):

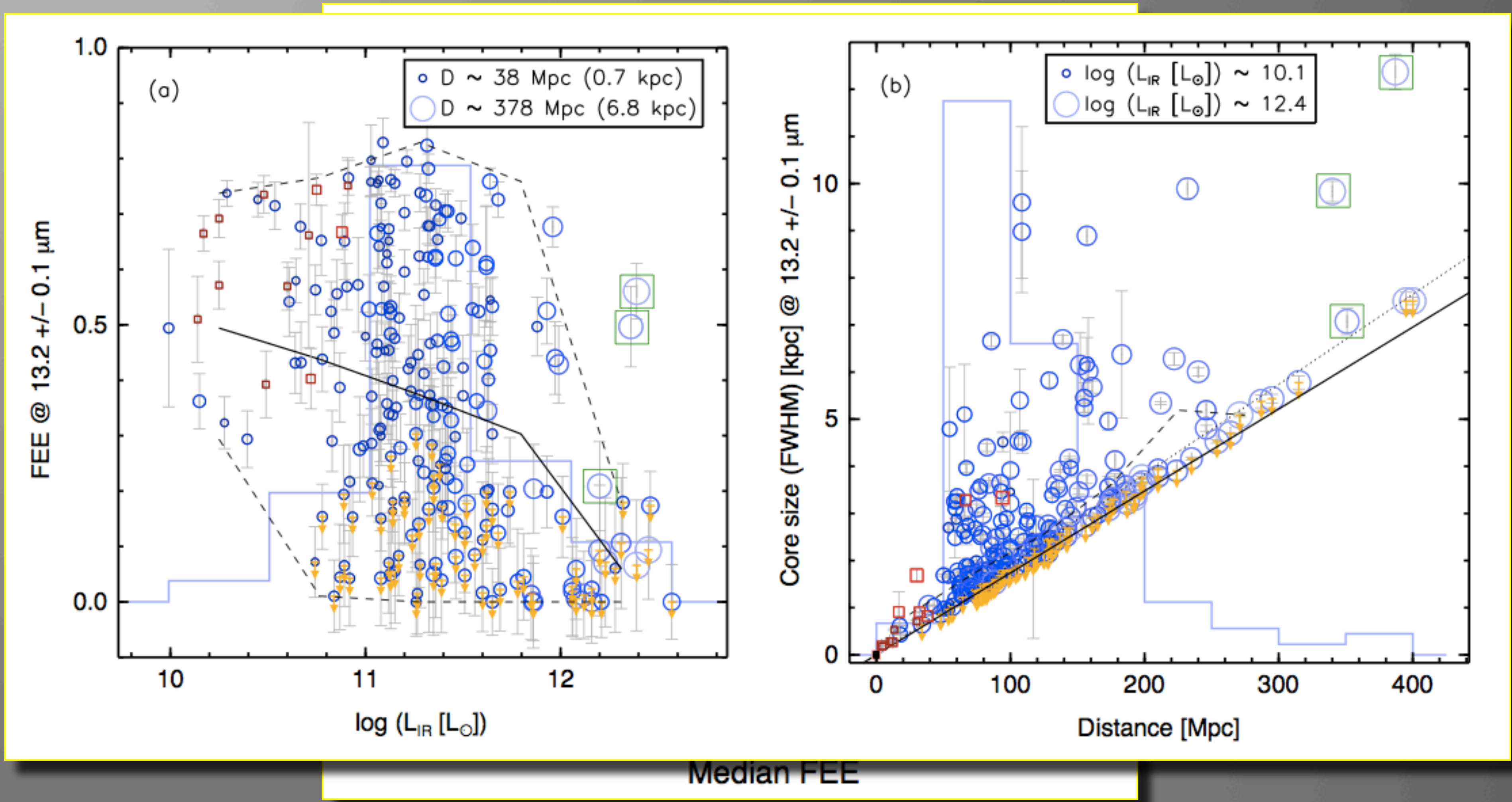
$$\text{Fraction of EE}(\lambda) = \frac{\text{Total (U)LIRG flux}(\lambda) - \text{PSF}(\lambda)}{\text{Total (U)LIRG flux}(\lambda)}$$

# Types of mid-IR spatial profiles



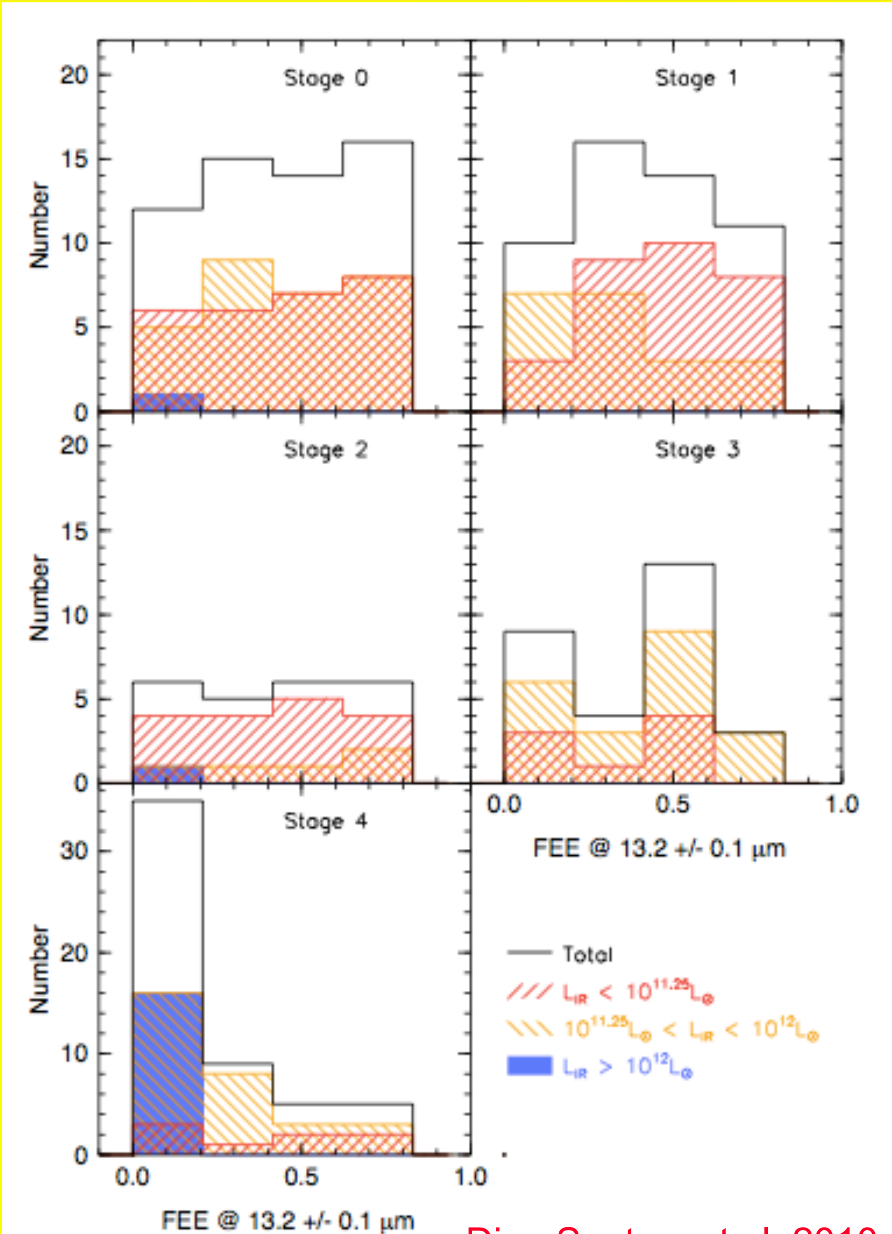

- Three spatial profiles are visually identified:
  *Constant: no variation as a function of λ (~50% of sample),*
  *PAH/line extended: 20-70% of PAH flux is extended (~17% of sample),*
  *Si "extended": Si at 9.7μm appears extended (~24% of sample) -> suggests that integrated spectrum underestimates nuclear extinction.*

# Extended Emission and L(IR)




The median fraction of extended emission decreases when $L_{IR}$ increases.
Similarly for the 13.2μm continuum emission

# Extended Emission and Interaction stage

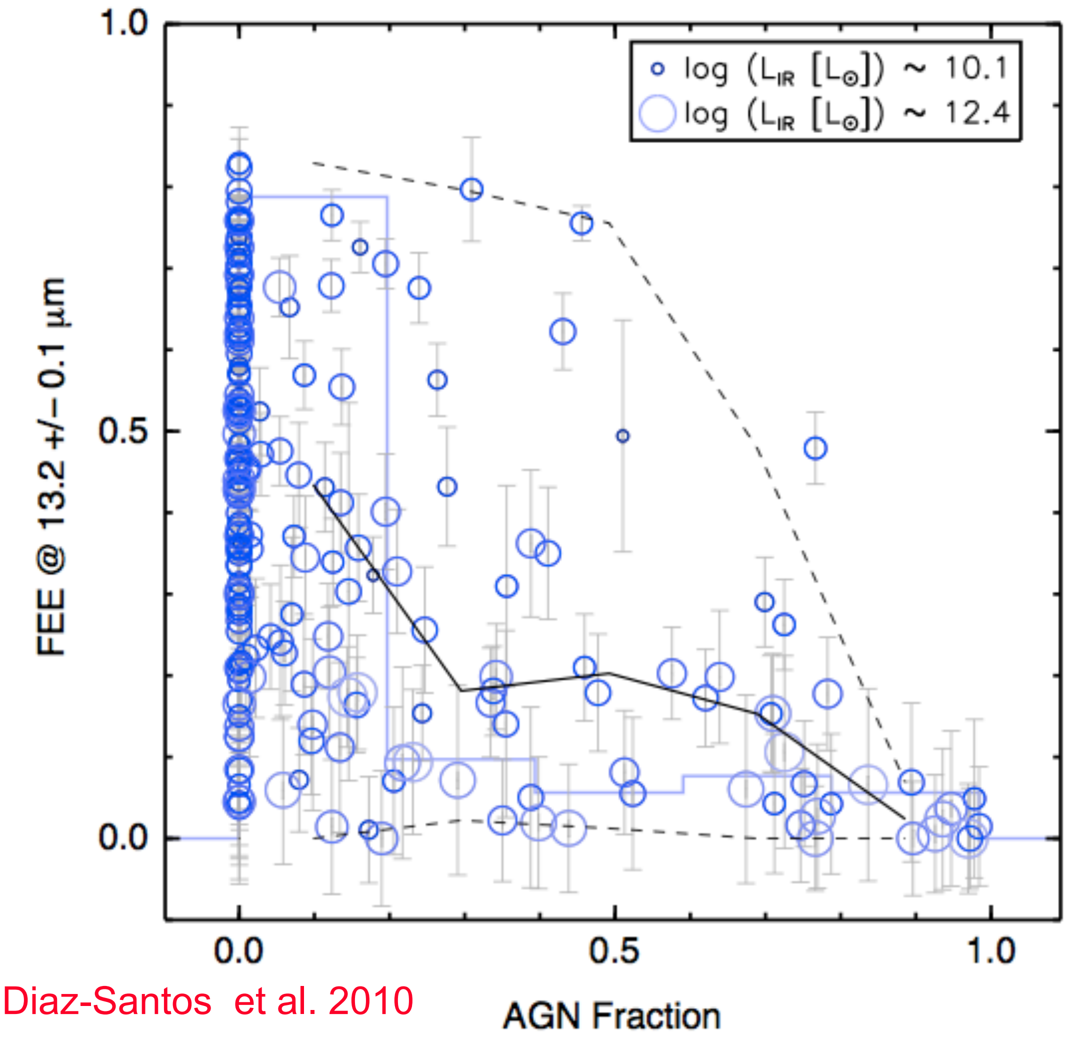



Diaz-Santos et al. 2010

- ❑ Use merger stage classification relying on optical/near-IR morphology from Petric et al. (2011)
- ❑ 0: non interacting -> 5: mergers
- ❑ More advanced mergers are more luminous and also more compact in their mid-IR continuum

(Similar to what has been shown in other wavelengths)

# Extended Emission and AGN

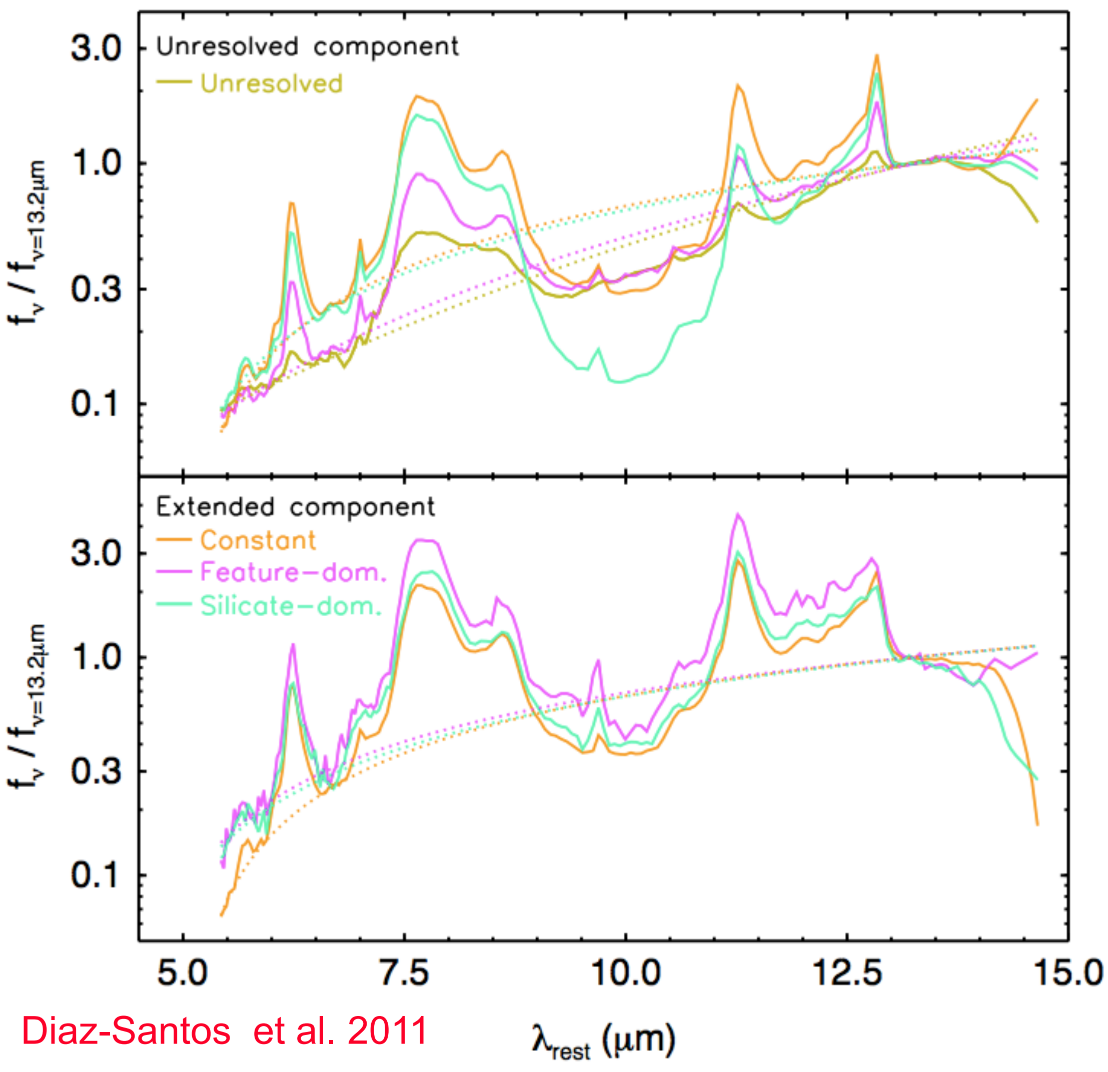



Diaz-Santos et al. 2010

- Use mid-IR AGN classification (Petric et al. 2011) based on the s "Laurent diagram" which probes the presence of at hot dust component (Laurent et al. 2000)
- AGN dominated sources also more compact in their mid-IR continuum

Note that we refer to mid-IR dominant AGN, not bolometricaly

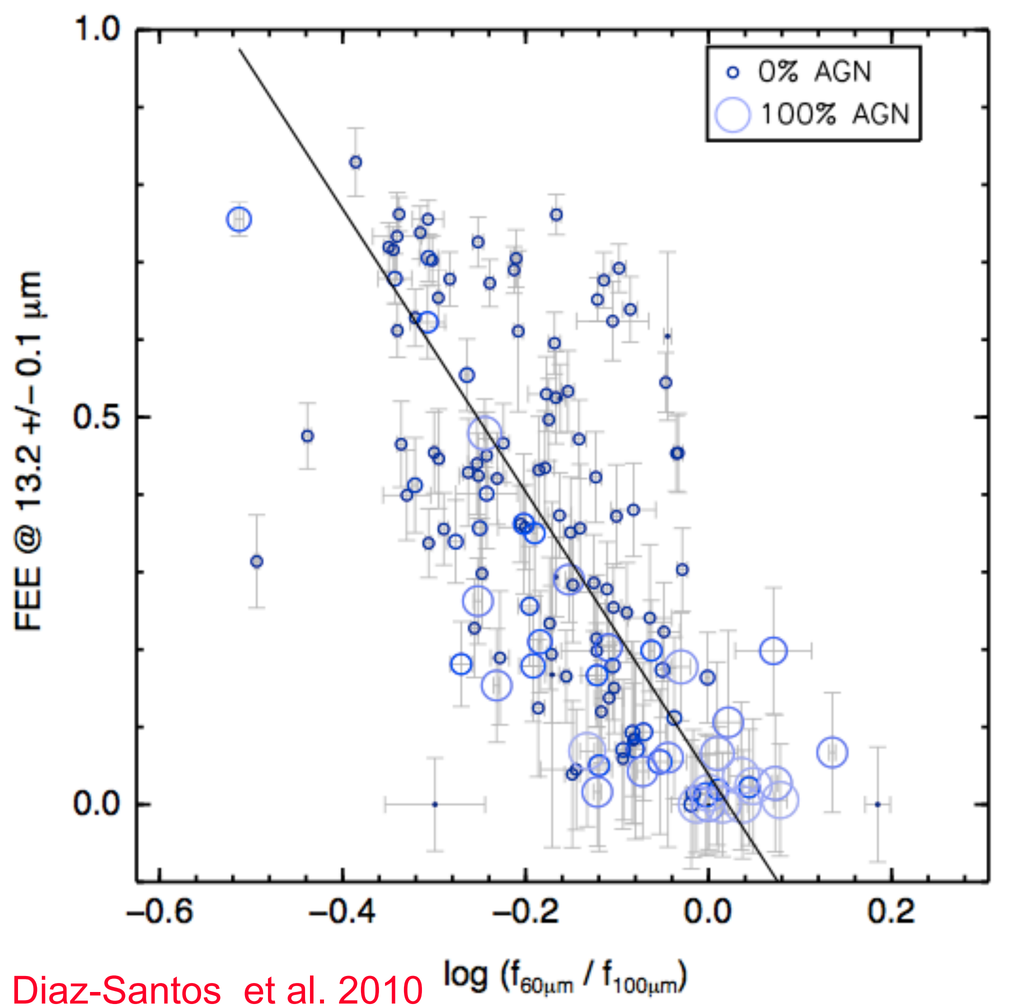
# The spectrum of extended & compact components




Diaz-Santos et al. 2011

- The 5-15μm spectrum of the nuclear component varies depending on spectral type.
- The 5-15μm spectrum of the extended component is similar for all three spectral types.
- Suggests common mechanism in the excitation (ie star formation) and dust properties

# Extended Emission and far-IR Colors

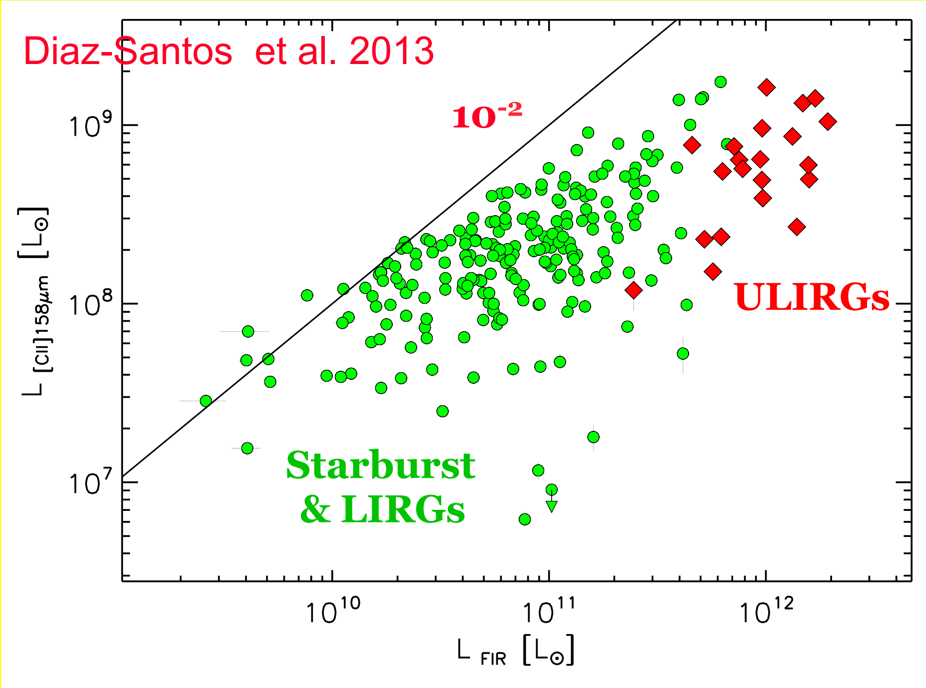


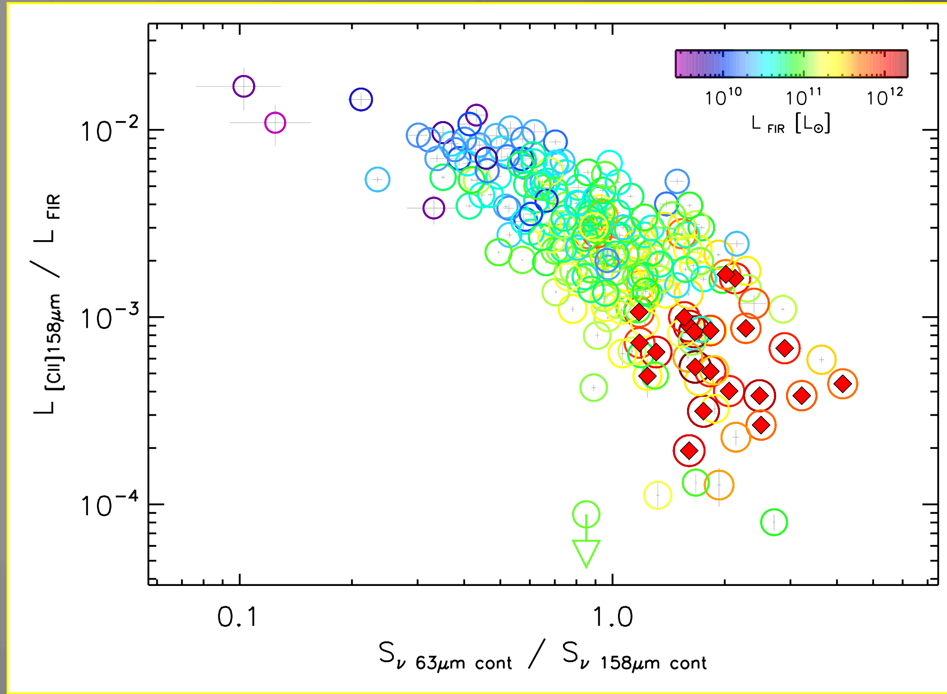

Diaz-Santos et al. 2010

- Use IRAS colors as a probe of the global ISM "temperature"
- Sources which are more compact in their mid-IR continuum have warmer far-IR colors
- This suggests that when nuclear emission is compact in the mid-IR it may dominate the energy production in the galaxy

$$FEE_{13.2\mu m} = 0.04 \pm 0.02 - (1.83 \pm 0.11) \times \log(\frac{f_{60\,\mu m}}{f_{100\,\mu m}})$$

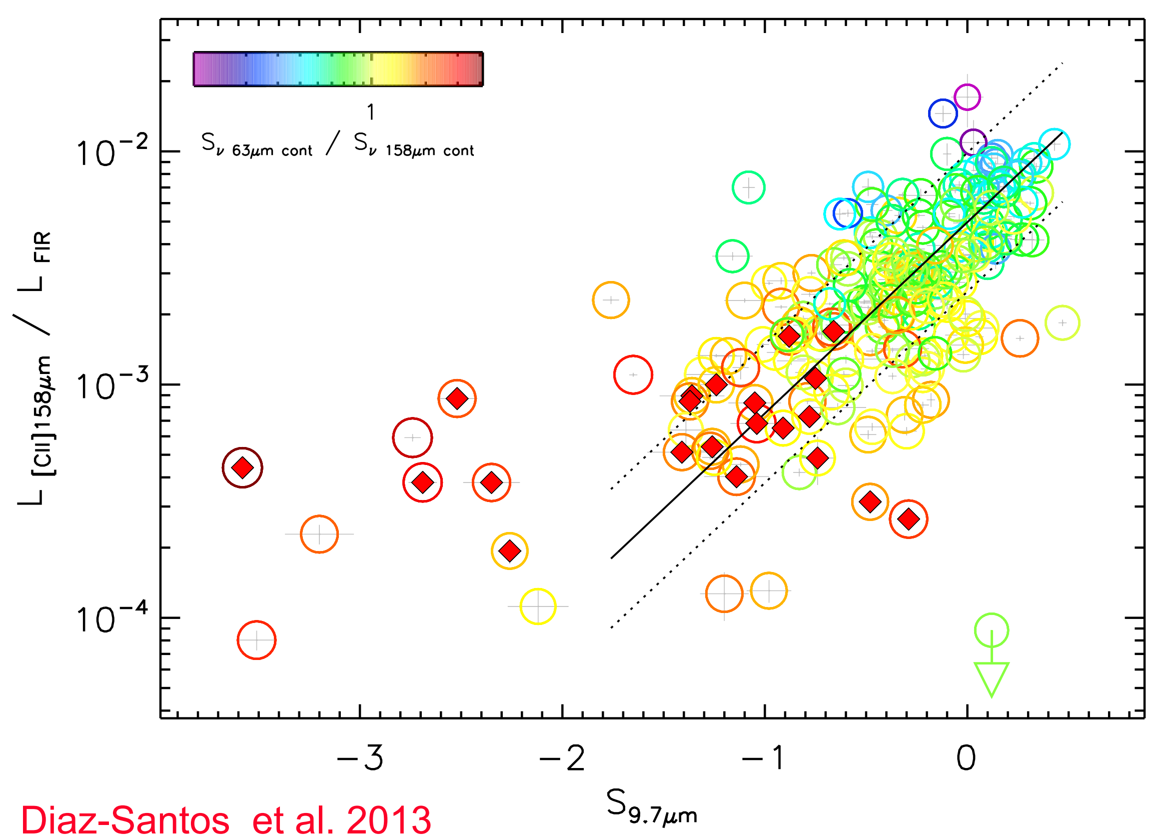
# [CII] as a star formation indicator?




- [CII] and far-IR luminosity are correlated but relation is not linear
- The [CII]/$L_{FIR}$ ratio varies with far-IR colors of galaxies, with lower values for sources with warmer dust temperatures. (see also Malhotra+1997,2001; Helou+2001; Gracia-Carpio+2010; Sargsyian+2012)
- The [CII]/$L_{FIR}$ ratio decreases by a factor of 20-50
- ULIRGs show the largest deficits with a median [CII]/$L_{FIR}$ ratio $\sim$6.5 x $10^{-4}$
- The [CII] deficit is reduced by an order of magnitude wrt. colder dust at ~160μm

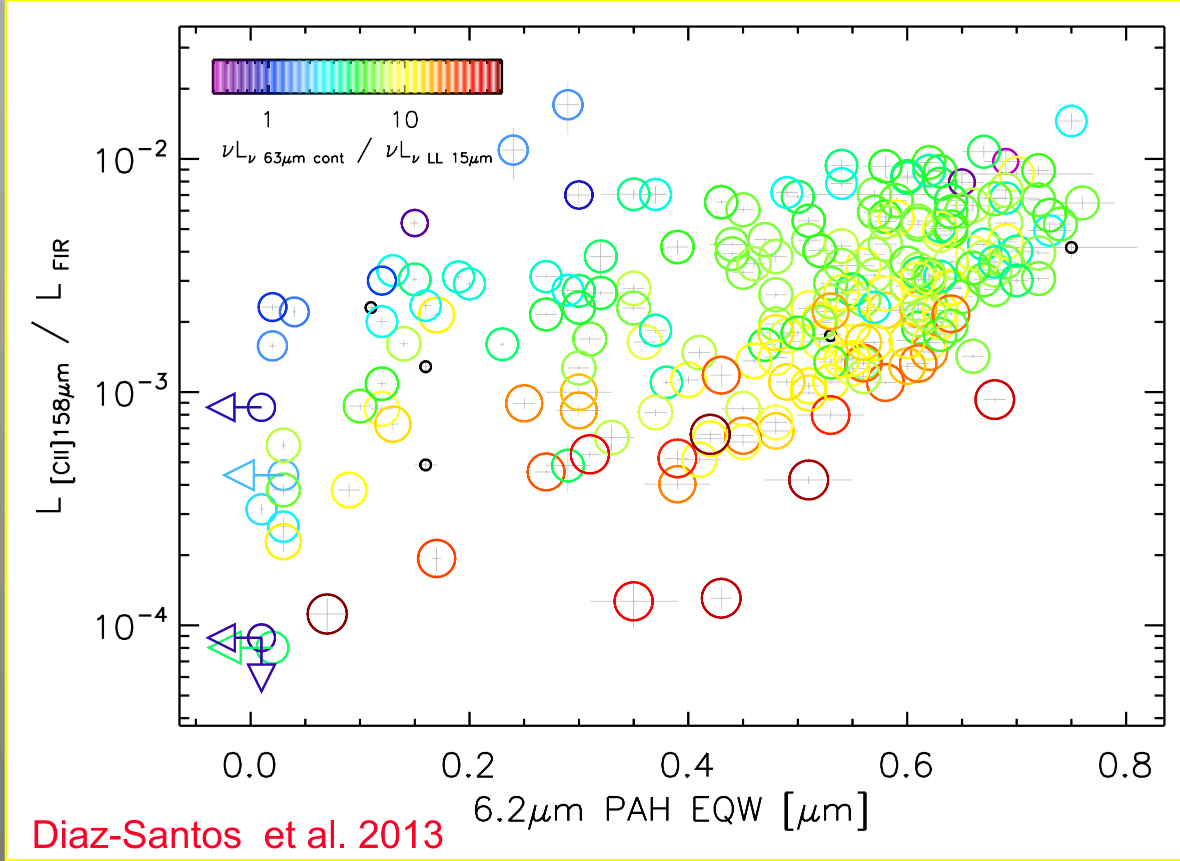
# Warm dust: emission and absorption




Diaz-Santos et al. 2013

- The [CII] deficit increases with the 9.7μm silicate strength (silicate depth)
- The dust responsible for the mid-IR absorption is also accountable for the warm far-IR emission: larger dust gradient -> larger silicate depth + larger amount of dust within HII region at higher T -> warmer 63μm/158μm colors

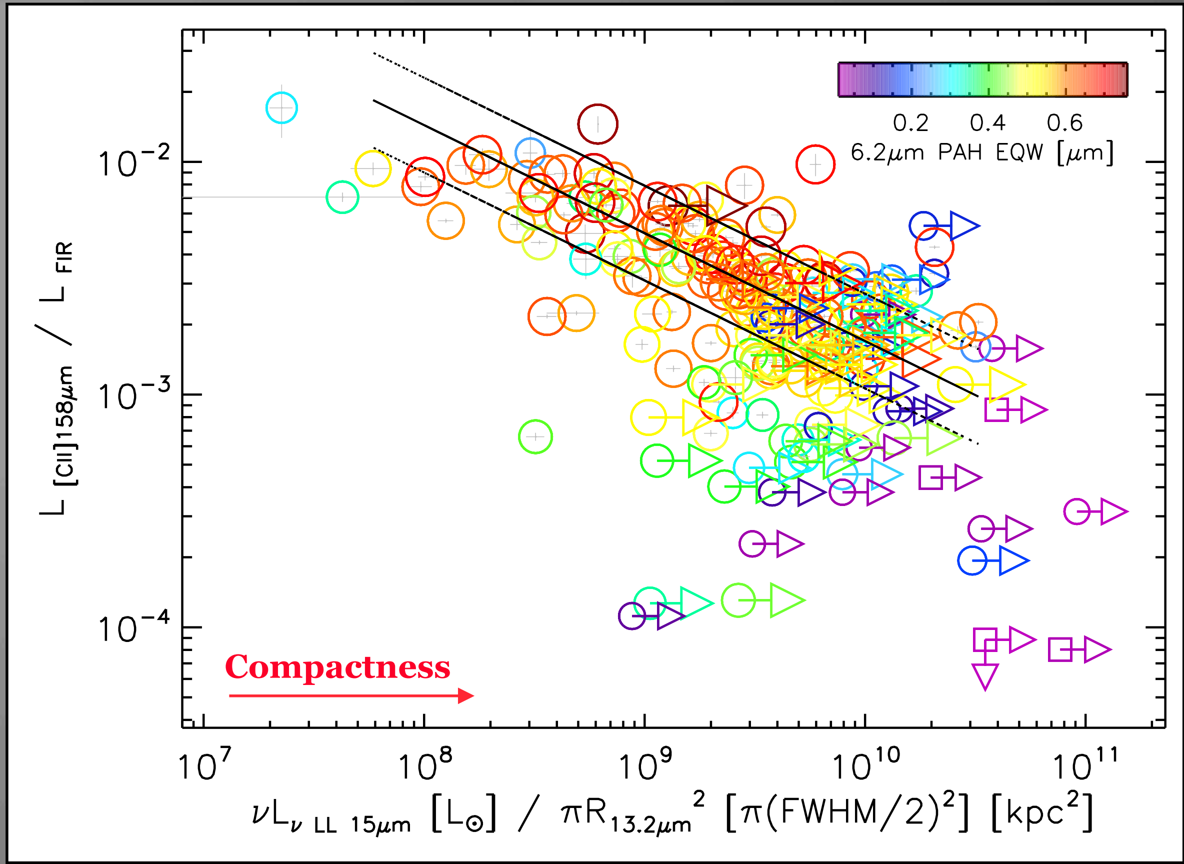
# The Role of AGN




- The 6.2μm PAH equivalent width is commonly used to identify AGNs in the mid-IR
- At low PAH EQWs, sources span the full range of [CII]/$L_{FIR}$ ratios (see also Sargsyan+12)
- 55% of mid-IR AGN have [CII]/$L_{FIR}$ > $10^{-3}$! (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

# Compact Sources

- The compactness (concentration of light) of the mid-IR emitting region (independently of its origin) is correlated with the [CII]/$L_{FIR}$ ratio
- Even when only galaxies with 6.2μm PAH > 0.5μm are considered, there is a decline of an order of magnitude, from $10^{-2}$ to $10^{-3}$




- Even in pure star-forming galaxies we see a [CII] deficit wrt to the $\Sigma_{MIR}$
- The decrease in [CII]/$L_{FIR}$ among most LIRGs is not caused by AGN activity but instead is a fundamental property of the starburst itself
- [CII] is not a good SFR tracer in most LIRGs since it does not account for the increase in warm dust emission from the compact starburst

# Conclusions

- LIRGs have substantial extended mid-IR emission in both continuum & 5-15μm features
- For at least 90% of the sample more than 20% of the mid-IR flux originates outside the nuclear unresolved region. For at least 35% of the sample more than 50% of the mid-IR flux is extranuclear
- The 13.2μm size of LIRGs is ~3.5kpc, while ULIRGs are less than 1.5kpc
- Spatial extent decrease with mid-IR AGN activity and merger stage.
- Compact sources have warmer far-IR colors
- LIRGs show [CII]/$L_{FIR}$ ratios from $10^{-2}$ to $10^{-4}$. ULIRGs have a median 6.5 x $10^{-4}$. The [CII]/$L_{FIR}$ ratio depends on the average dust temperature. The dust producing the mid-IR absorption is linked to the process driving the [CII] deficit.
- AGNs span the whole range in [CII]/$L_{FIR}$. However, more than half of mid-IR detected AGNs show ratios > $10^{-3}$ suggesting that they do not contribute significantly to the far-IR emission in these galaxies. Only when the 6.2μm PAH EQW is $\lesssim$ 0.05μm, the AGN is likely to dominate in the far-IR, with ratios < $10^{-3}$.
- Compact galaxies have lower [CII]/$L_{FIR}$ ratios, regardless of their energy source. Pure starburst alone show a drop of an order of magnitude in [CII]/$L_{FIR}$, suggesting that the [CII] line is not a good tracer of the SFR in warm and/or compact LIRGs as it is not sensitive to the warm dust heated by the youngest stars.