The Herschel/PACS View on the Heating and Cooling of the ISM in local LIRGs

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Motivation

- Luminous and Ultra-luminous Infrared Galaxies, (U)LIRGs ($L_{IR} > 10^{11\text{-}13}\ L_{\odot}$), account for > 50% of the obscured star-formation in the Universe at z > 1

- However, the most likely local counterparts are not the most luminous systems, but galaxies with $L_{IR} < 10^{12}\ L_{\odot}$, i.e., LIRGs.

- Mid-IR provides information about highly ionized gas in HII regions, warm dust, and PAH emission; but misses the cold dust and the cooling carried out in the PDRs through far-IR emission lines such as [CII]158μm or [OI]63μm.

- Combining mid- and far-IR observations from Spitzer and Herschel we can provide a global picture on the heating and cooling of the ISM in the most representative galaxy class of the dominant high-redshift population.

The Sample

- The Great Observatories All-sky LIRG Survey (GOALS; Armus+2009) is a complete, local ($z < 0.12$) galaxy sample containing the 202 systems (~290 individual galaxies) with $L_{IR} > 10^{11} L_{\odot}$ (180 LIRGs, 22 ULIRGs) included in the 60μm flux-limited Revised Bright Galaxy Sample (RBGS) observed with IRAS.

- It covers the entire merger sequence: from isolated galaxies or widely separated pairs to late-stage mergers in which the galactic nuclei have already coalesced. (Haan+2011)

Observations

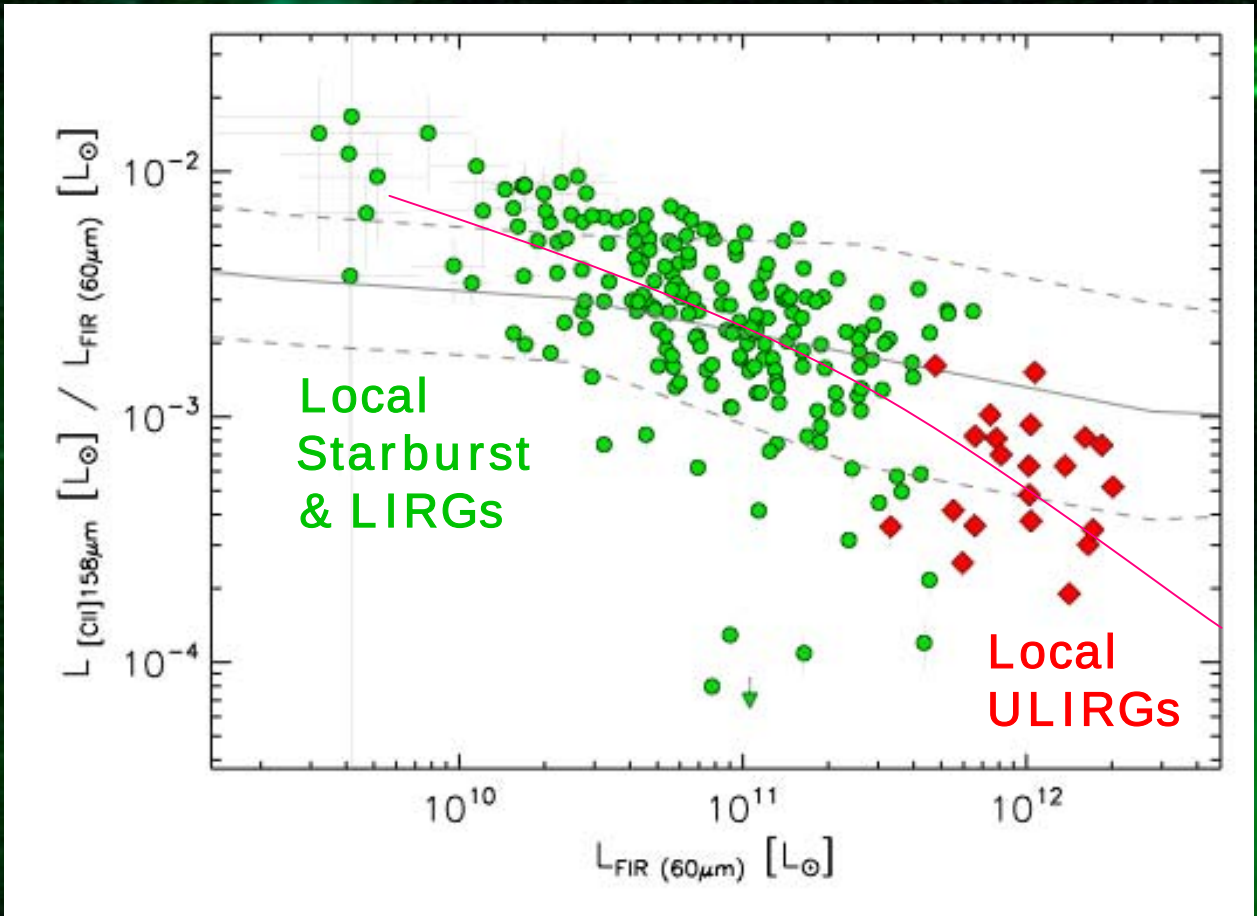
- Wealth of data: Spitzer IRAC/MIPS imaging & IRS spectroscopy, HST optical and near-IR imaging, GALEX, Chandra, CARMA, Palomar, Nobeyama, ALMA, GBT, Keck…

- Key Spitzer results:

  - Wide range of PAH and high ionization line emission. (Stierwalt+2012; Inami+2012)
  - AGN activity contribute < 15% to their bolometric luminosity, on average. (Petric+2011)
  - The mid-IR sizes of galaxies are between < 1.5 kpc and few tens of kpc. (Diaz-Santos+2010,11)

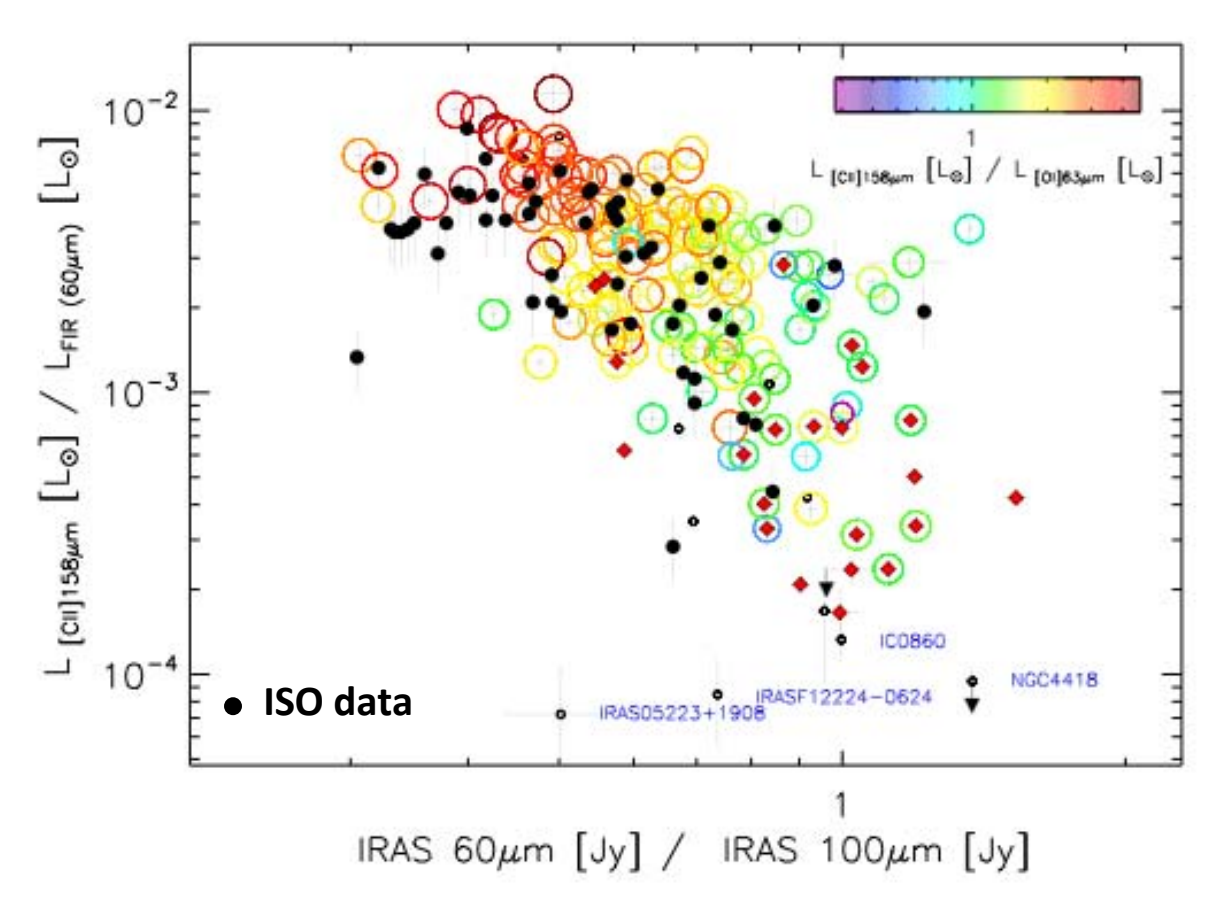
- As part of a Herschel OT1 program (PI: Lee Armus), and in combination with other key projects (HerCULES, SHINING), we have obtained [CII]158μm, [OI]63μm, and [OIII]88μm spectroscopic observations with PACS for the entire GOALS sample. We also have PACS and SPIRE photometry (PI: D. Sanders) and SPIRE FTS spectra for 1/2 of the sample (PI: N. Lu)

[CII] As Star Formation Rate?



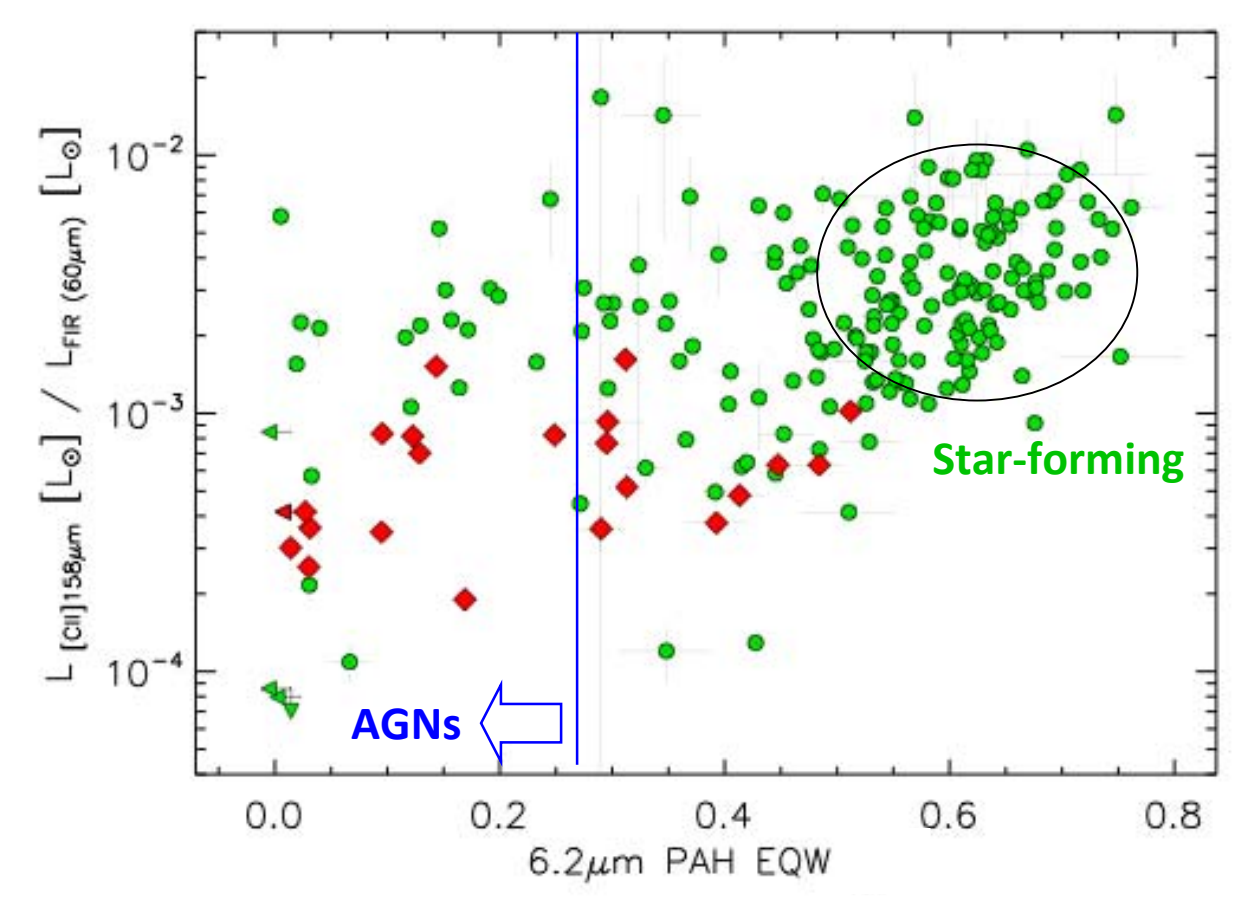
- [CII] and FIR luminosity are correlated but relation is not linear.
- The [CII]/L_{FIR} ratio decrease as IR luminosity of galaxies increases. (see also Malhotra+1997,2001; Gracia-Carpio+2010; Sargsyian+2012)
- The [CII]/L_{FIR} ratio is reduced by a factor of ~ 20-40
- ULIRGs show the largest deficits with a median [CII]/L_{FIR} ratio ~ 6.3 x 10^{-3}

Warm Galaxies



- The [CII] deficit is larger as the far-IR 60/100μm ratio increases. (see Helou+2001)
- U/LIRGs with higher dust temperatures (warmer colors) show weaker [CII].
- The trend is independent of IR luminosity. T_{dust} is the key parameter.

AGN Activity?

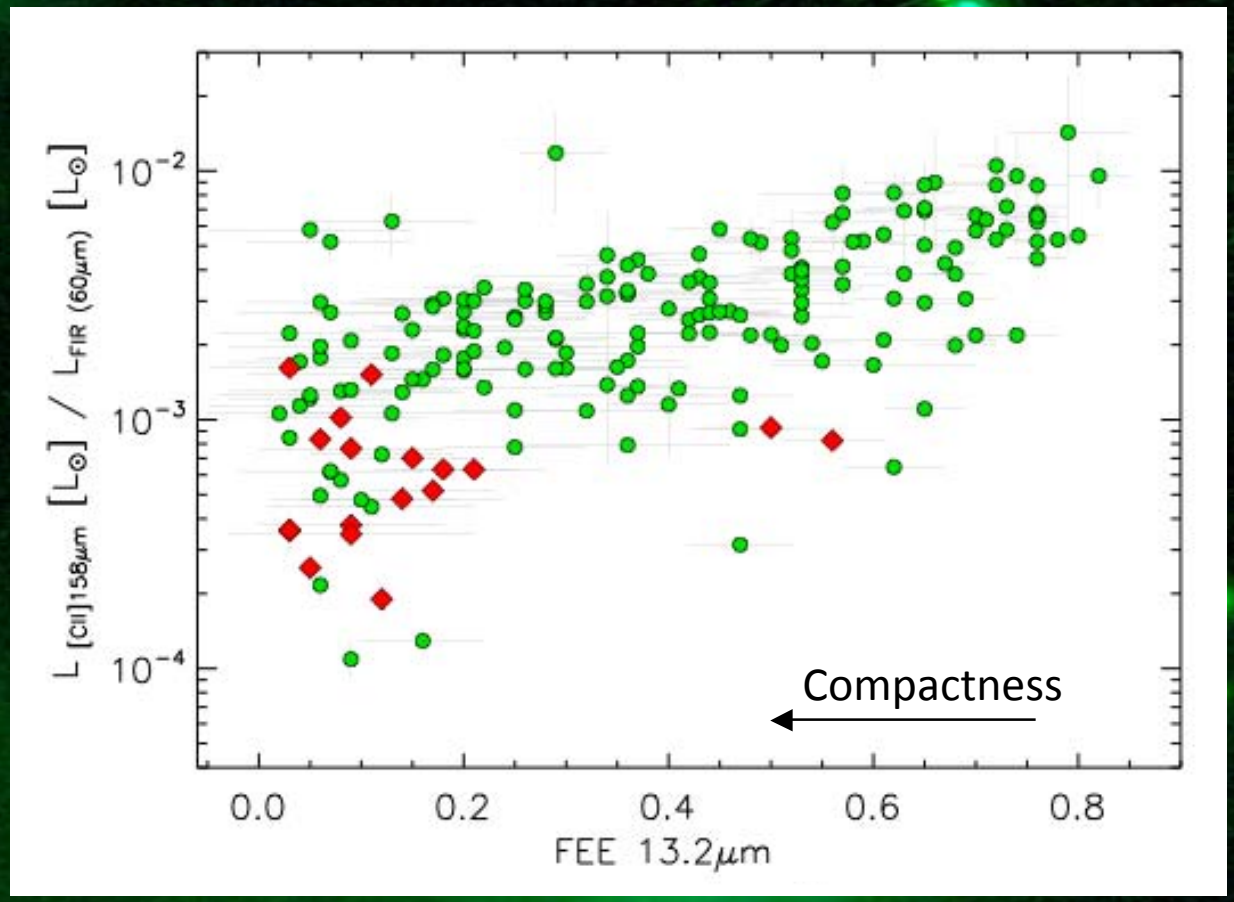


- Dust temperature and AGN-contribution are related.
- 6.2μm PAH equivalent width is commonly used to identify AGNs in mid-IR.
- Starburst-dominated galaxies show a rather constant, large [CII]/L_{FIR} ratio.
- At low PAH EQW, sources span the full range of [CII]/L_{FIR} ratios. (Sargsyan+12)

Compact Sources

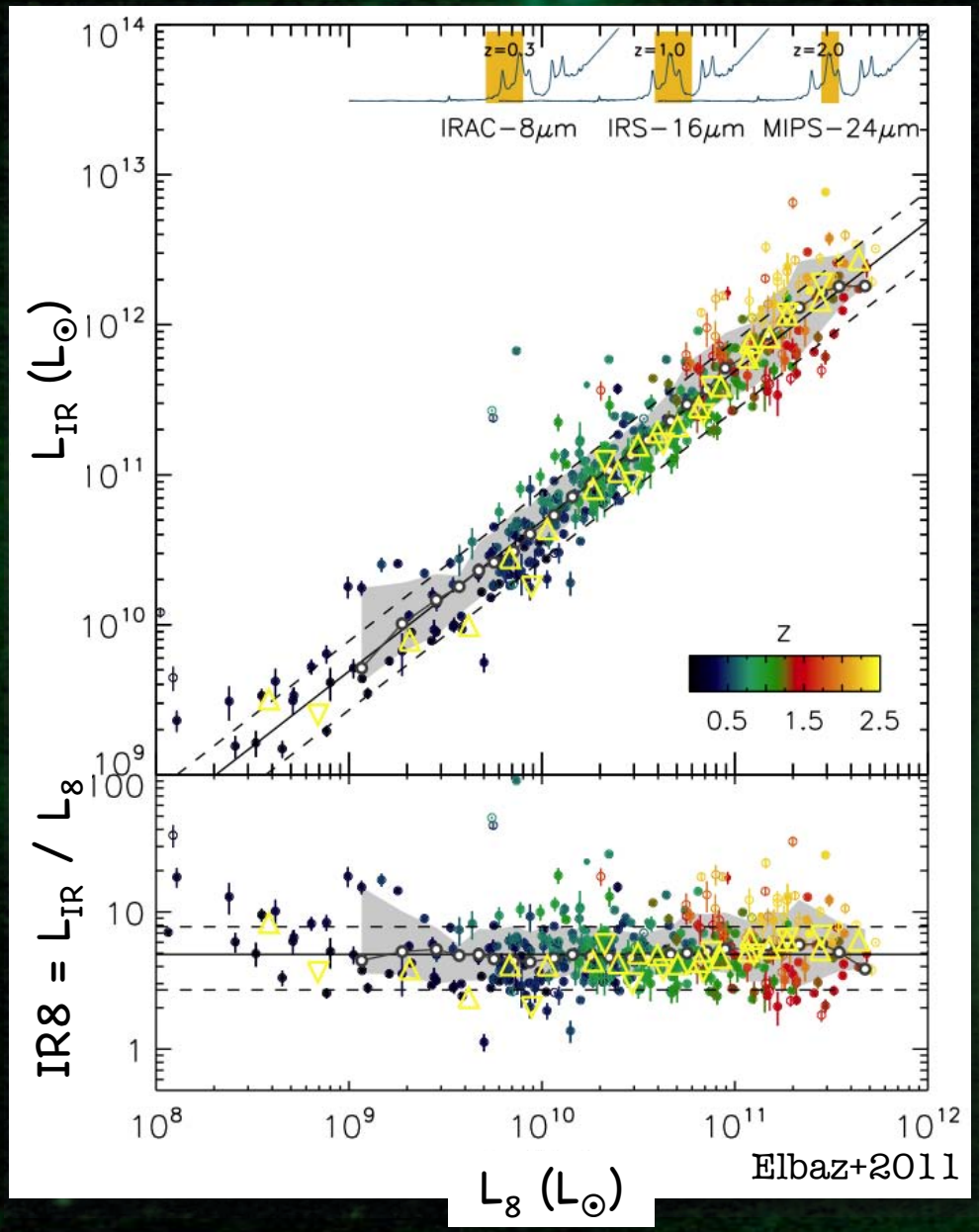
- Fraction of Extended Emission (FEE; Diaz-Santos+2010,11) at 13.2μm (or compactness = 1 - FEE), is correlated with the [CII]/L_{FIR} ratio.

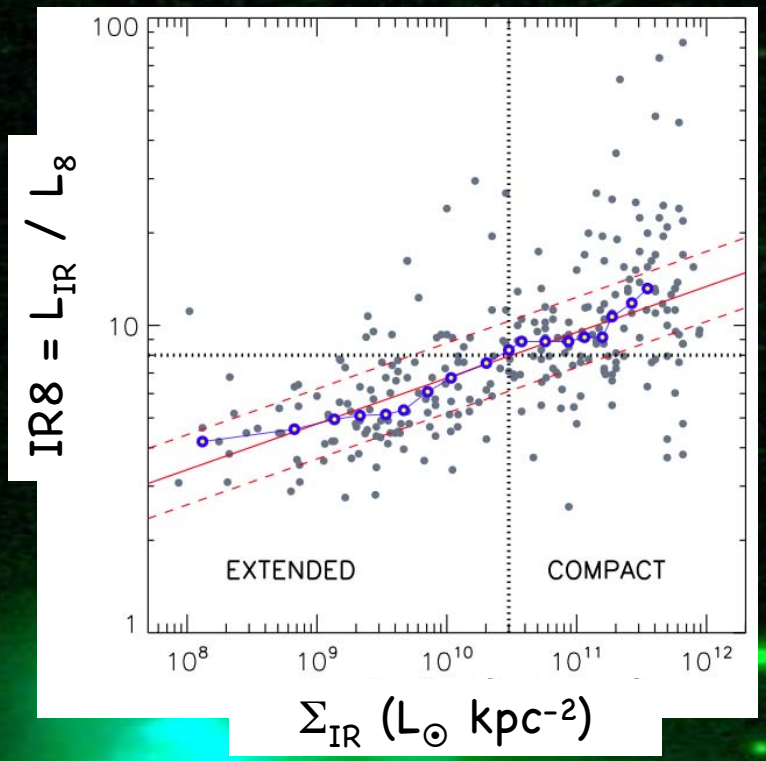
- Irrespectively of what creates the deficit (AGN or compact starburst), the compactness of the emitting source is what matters.



- In compact galaxies the number of available photons per hydrogen atom (the ionization parameter, *U*) as well as per dust particle is larger -> UV radiation is preferentially absorbed and re-radiated by dust at higher T, producing the observed line deficit. (Gracia-Carpio+2011)

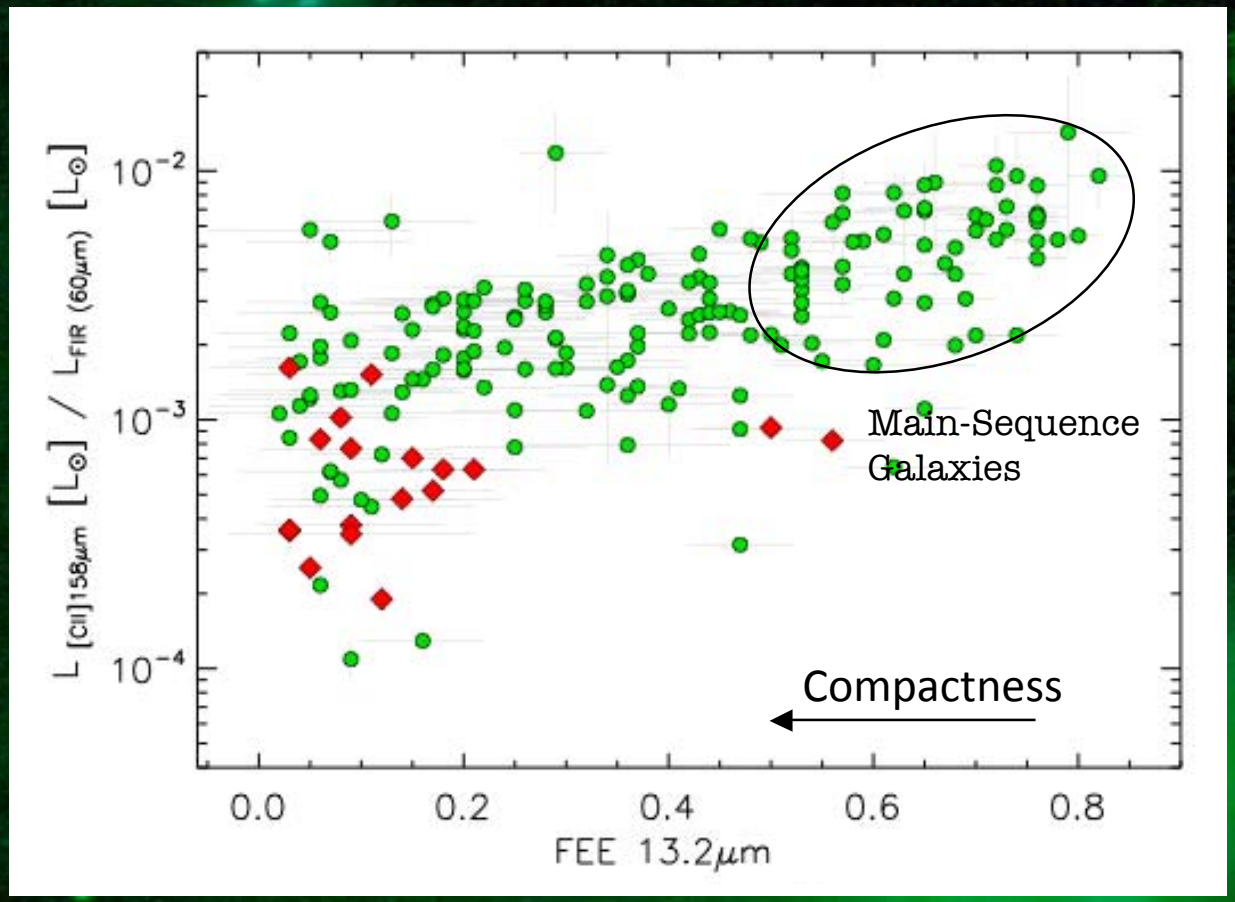
Main Sequence Galaxies at High-z





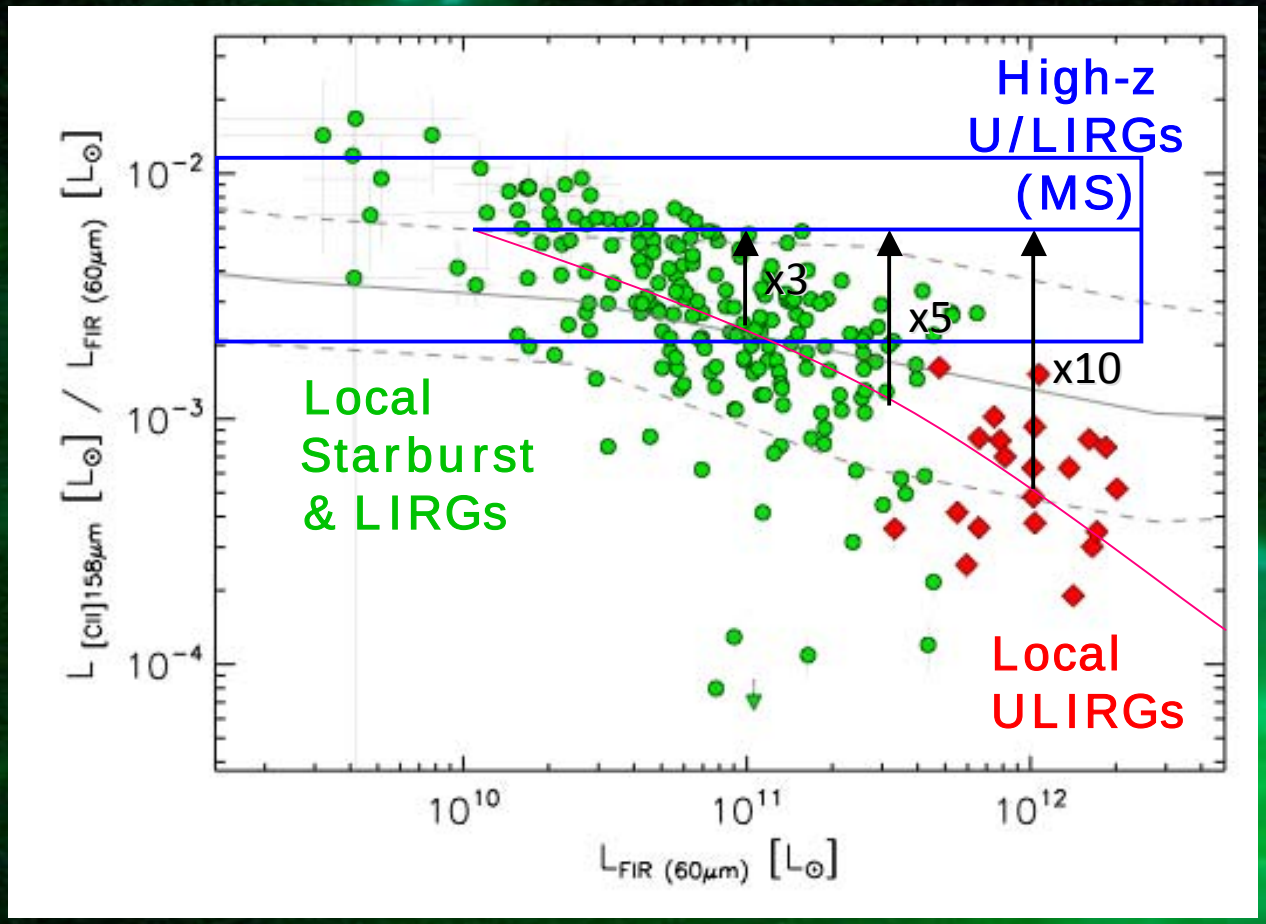
- Most IR luminous galaxies at high-z are MS (Elbaz+2011; GOODSN-S). Star formation is extended, taking place over several kpc-scale areas.
- Only a small fraction are starbursting

Compact Sources



- MS high redshift galaxies will show [CII] strengths typical of normal star-forming LIRGs
- By measuring the [CII] emission and IR luminosity of a galaxy we will be able to infer whether SF is extended (MS) or compact (starburst/merger)

[CII] Emission - CCAT Perspective



See: Stacey+10
Hailey-Dunsheath+10

- Most high redshift (MS) galaxies, at least up to $L_{IR} \sim 5 \times 10^{12}\ L_\odot$, will show large [CII]/$L_{FIR}$ ratios as compared with their local counterparts.
- Spectroscopic surveys of [CII], such as those proposed with X-Spec, will have higher than expected detection rates at all IR luminosities.

Take Away

- The [CII]/L_{FIR} ratio depends on dust temperature.
- Galaxies with large [CII] deficits are probably AGN-dominated in the mid-IR, but the opposite might not be true.
- [CII]/L_{FIR} ratio is correlated with compactness of the starburst region.
- Measurements of just [CII] and FIR luminosity alone provide information about the star-formation mode (MS/starbursting). Galaxies with extended SF have strong [CII] emission. Compact/starburst have large deficits.
- Most high redshift galaxies up to $L_{IR} \sim 5 \times 10^{12}$ are MS. Spectroscopic [CII] surveys, such as those proposed with X-spec, will detect more galaxies and probe lower IR luminosity sources than expected at higher redshifts.