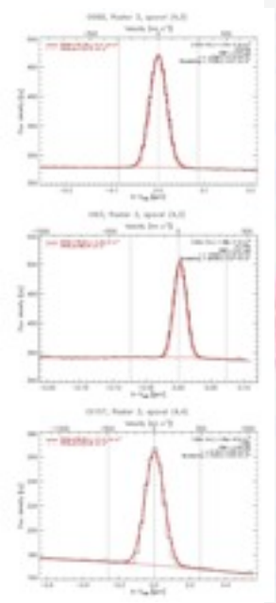
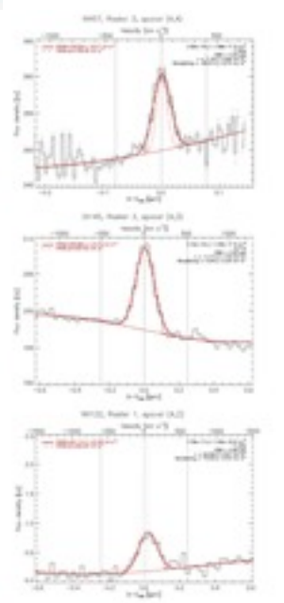


The ISM structure in low-metallicity environments probed by far-infrared cooling lines



Vianney Lebouteiller - CEA Saclay, France

S. Madden, F. Galliano, D. Cormier, S. Hony, A. Rémy, M. Sauvage, R. Wu (CEA)
R. Indebetouw (UVa), N. Abel (Cincinnati), A. Poglitsch, A. Contursi, E. Sturm (MPE), M. Meixner (STScI)

On the importance of low-metallicity

Star-formation (SF) is a process intimately dependent on metal abundance

- SF reservoir (atomic, molecular)
- SF mechanism (gas cooling, efficiency, interaction with strong radiation fields)

(At z = 0) low-metallicity implies small mass galaxy

Most remarkable differences observed at low-metallicity

- Weak/no PAH emission (e.g., Wu+ 2006; Engelbracht+ 2006; Madden+ 2006)
- Elusive molecular gas, CO(1-0, 2-1), H_2 (Tacconi+ 1987; Taylor+ 1998; Leroy+ 2006, HERACLES)
- Low dust-to-gas ratio (Hirashita 1999; Hirashita+ 2002), dust SED peaks at shorter wavelengths, sub-mm excess (see Rémy's talk)

Questions

- Mass of the H_2 reservoir? How can we trace H_2?
- How does the molecular fraction of the SF gas reservoir vary with metallicity? (e.g., Glover+ 2011)
- Is the SFE larger in dwarfs?
- What are the physical conditions in PDRs at low-metallicity?

Means

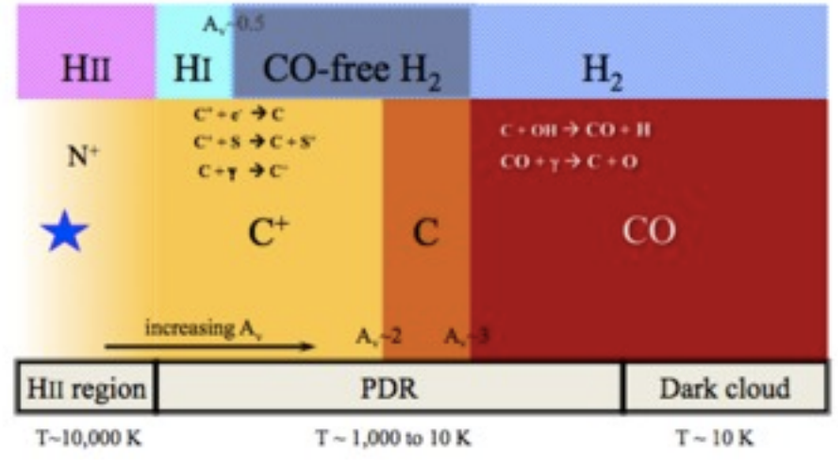
- [CII] 158μm potentially reveals PDRs and also traces a (significant) fraction of H_2
  => Need to improve our knowledge on the emission conditions of [CII]
- Learn more on how UV photons permeate into the ISM at low-metallicity
  => Need to investigate spatial distribution of IR ionized gas tracers, e.g., [OIII] 88μm

[CII] 158μm as the "dark gas" tracer

C^0 11.3eV IP, [CII] 158μm: T_{exc}~92K

Collisions with photo-e^-, H^0, and H_2. Collisions with e^- dominate the heating if ionization fraction > 1%

- dominant coolant of **atomic ISM**
- important coolant for **diffuse ionized clouds** (Heiles+ 1994; Wolfire+ 1995)
- important coolant in the **photodissociation regions** (Tielens+ 1985)



PDR paradigm

- C^+-CO transition is deeper than HI-H_2
- C^+ and C^0 trace a fraction of H_2 not seen in CO
- dark gas, too low T (<100K) for H_2 in the MIR

Low-metallicity

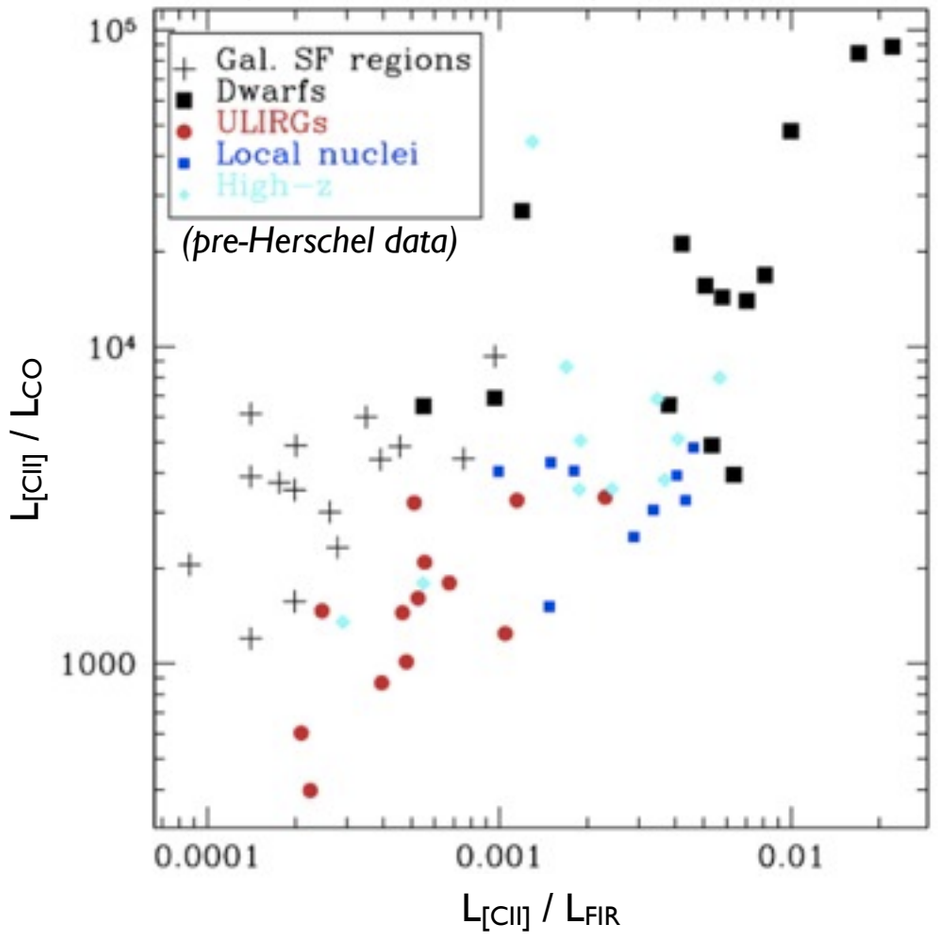
- low dust abundance, UV photons penetrate deeper, CO photodissociated, H_2 self-shielded
- small CO cores with thick layer of C^+-C^0
- [CII] / CO(1-0) larger at low-metallicity (e.g., Roellig+ 2006; Wolfire+ 2010)
- spherical geometry is essential for models (e.g., kosma-τ)

Observational evidence of dark gas invisible of CO, especially in low-metallicity galaxies (e.g., Israel+ 1997; Madden 2000; Leroy+ 2007)

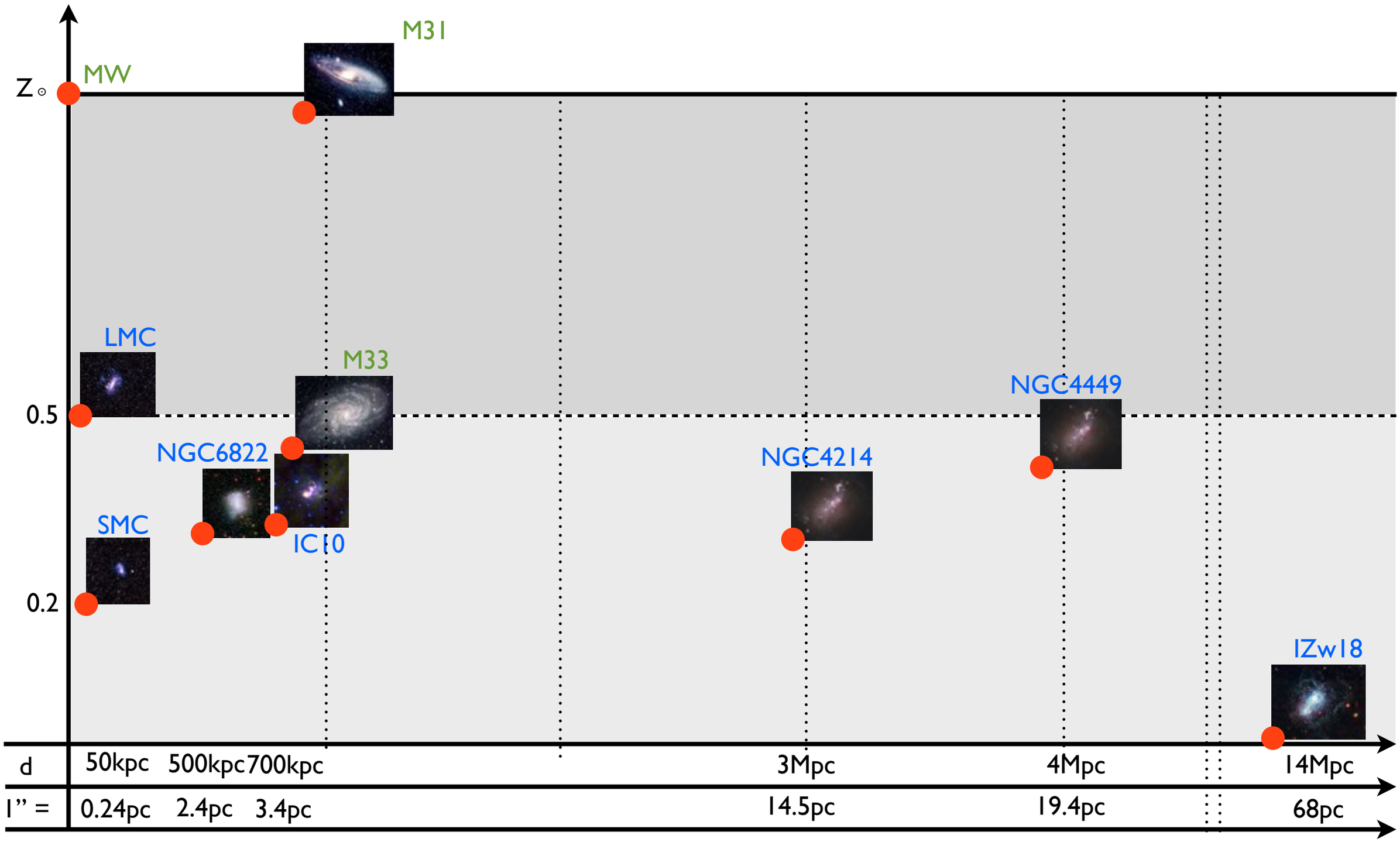
But many uncertainties on the origin of [CII] emission (diffuse ionized gas, PDRs, atomic ISM) & on the CO spectral line energy distribution

+ What are the physical conditions in PDRs? G_0, n

Hailey-Dunsheath+2010, Stacey+2010, Madden 2000



Our metal-poor neighbors



Herschel: 10" -> 34" from 50µm to 670µm
Spitzer: 3" -> 12" from 5µm to 40µm

Observation strategy

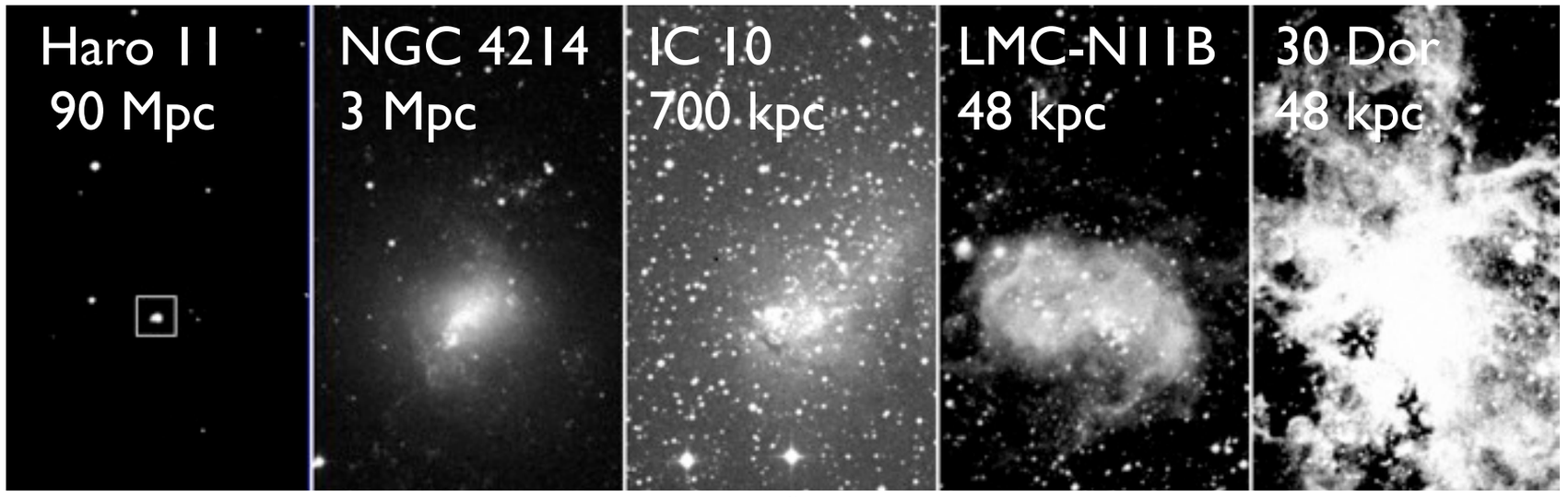
Focus on spatial resolution in the FIR lines

- Herschel/PACS 55-210μm, R~1000-5500, ~10" beam. Integrated field spectroscopy
  [CII] 158μm, [OI] 63μm, 145μm, [NII] 122μm, 205μm, [NIII] 57μm, [OIII] 88μm
- Herschel/FTS 194-672μm, R~40-1000, 16-34" beam: *[CI], CO*

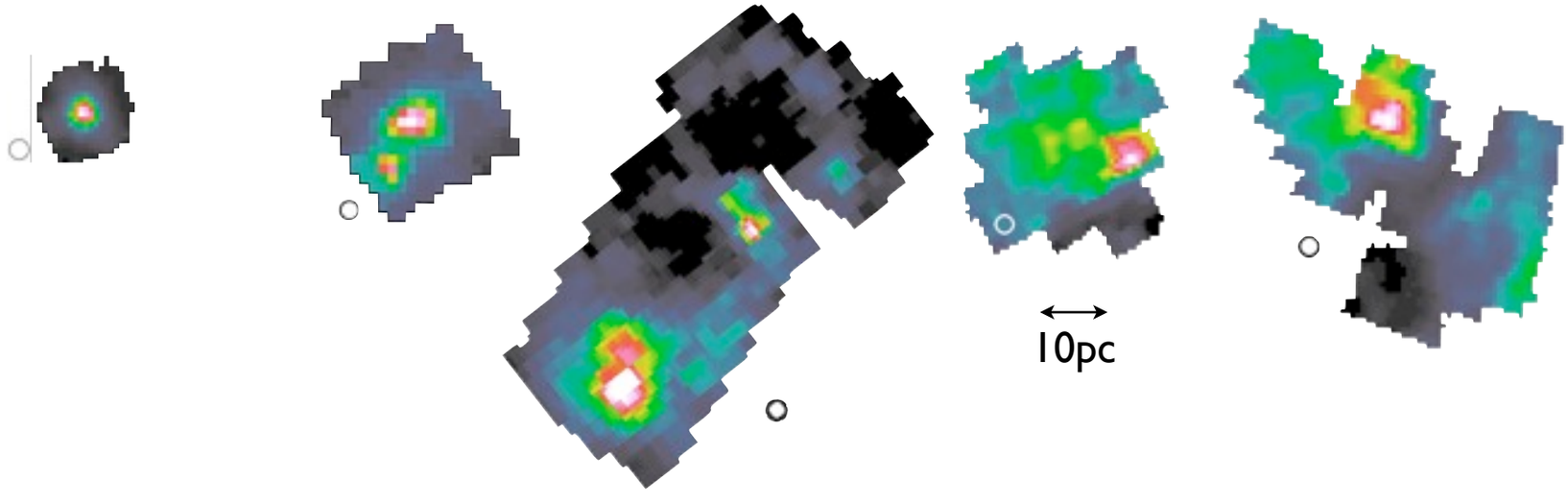
Herschel programs

- SHINING (PI Sturm), HERITAGE (PI Meixner), DGS (PI Madden, talk on Thursday)
- Ancillary data: ground-based CO observations (single-dish, interferometry), Spitzer, HI 21cm, APEX/LABOCA

LMC: LMC-N11, N157, N158, N159, N160
SMC: SMC-N66
Extended sources: NGC4449, IC10, NGC6822, NGC4214, ...
Compact sources: NGC5253, Haro 11, ...

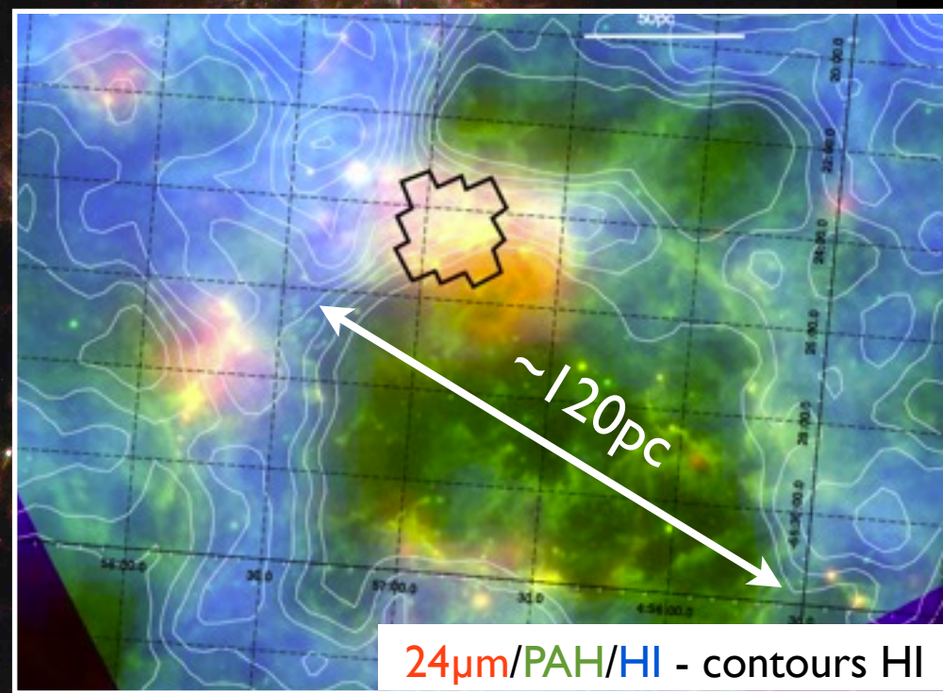


[CII] maps:



N11

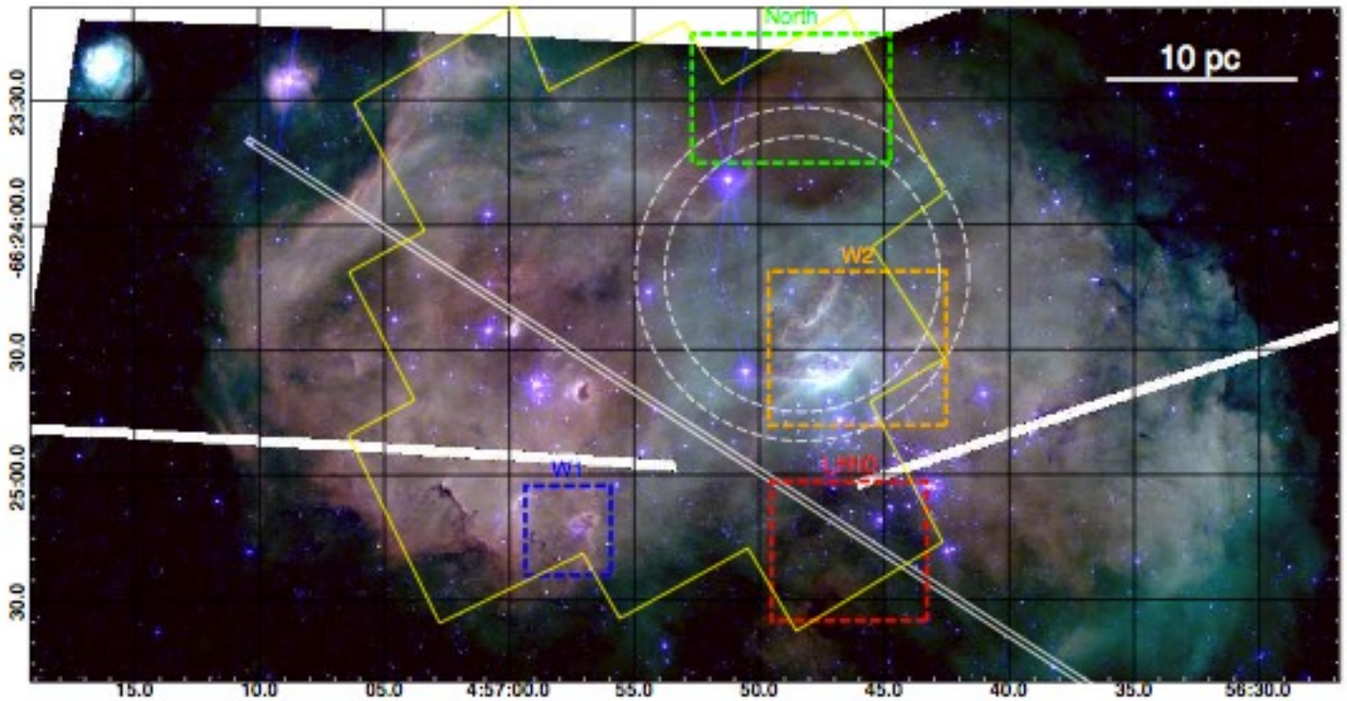
30Dor

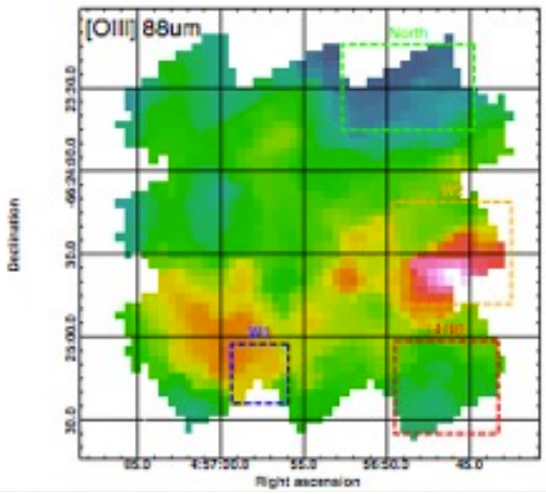


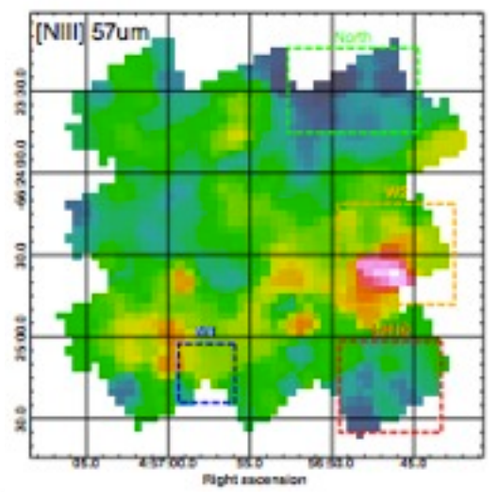
LMC-N11B: ionized gas

Lebouteiller+ (submitted to A&A)

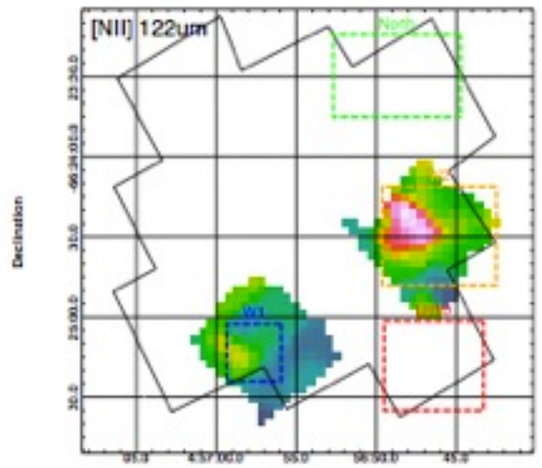
several OB clusters, photoionization fronts, 2 ultra-compact HII regions



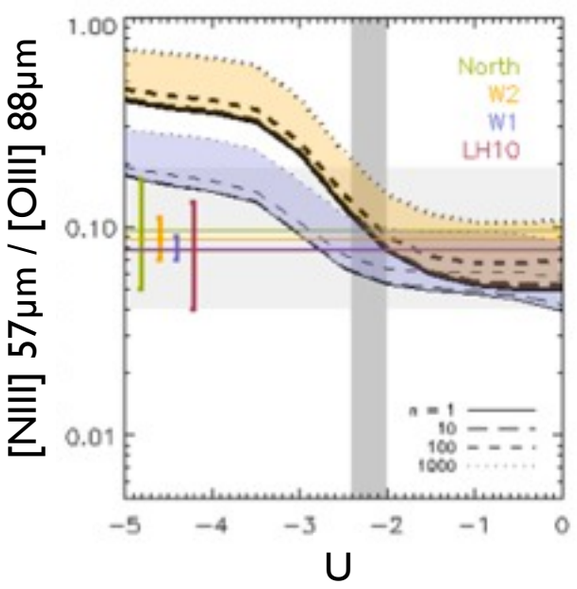


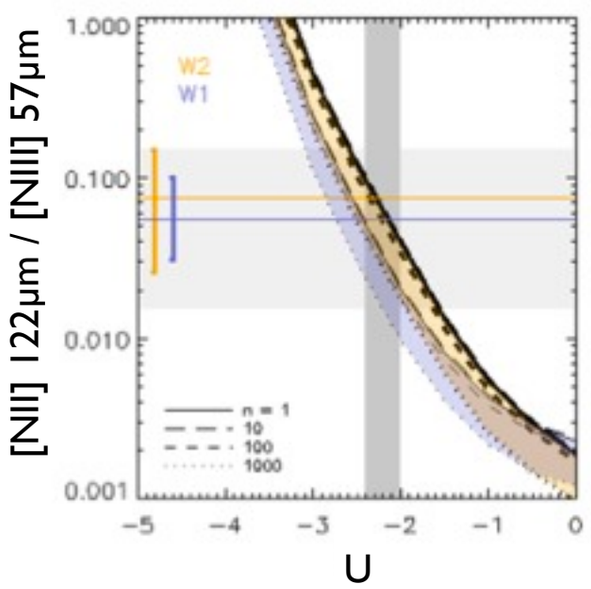


10pc



n_e, T_e, U derived from [NIII], [OIII], [NII] diagnostics with photoionization code Cloudy





Prevalence of the ionized gas

- [OIII] 4x brighter than [CII] on the scale of the PACS map ([CII] already carries ~1% of the FIR luminosity)
- [OIII] often brighter than [CII] in unresolved dwarfs (Madden's talk)

UV photon mean free path

- Flat [OIII] distribution & U value consistent with UV field dilution over spatial scales on the order of the size of N11B (>~30pc)
- Important implications for PDR physical conditions

PDRs and the relation between [CII] and PAHs

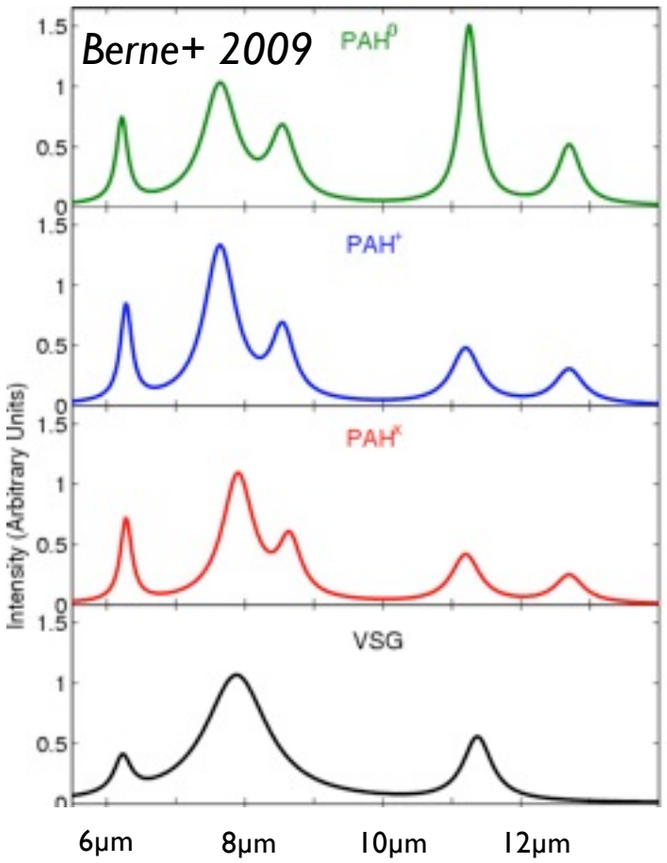
Using PAHs as PDR tracers to understand the origin of [CII] in spatially-resolved sources

- PAH emission dominated by PDRs in SF galaxies
- PAHs are important for the photoelectric effect (small size)
- Electron fraction in PDRs. PAH + e^- => PAH^-, PAH^- + C^+ => PAH + C^0

KINGFISH

2 nearby super-solar galaxies: NGC1097, NGC4559

- Tighter [CII]/PAH than [CII]/FIR => PAHs dominate the gas heating where [CII] emits (see also Helou+ 2001; Rubin+ 2009)



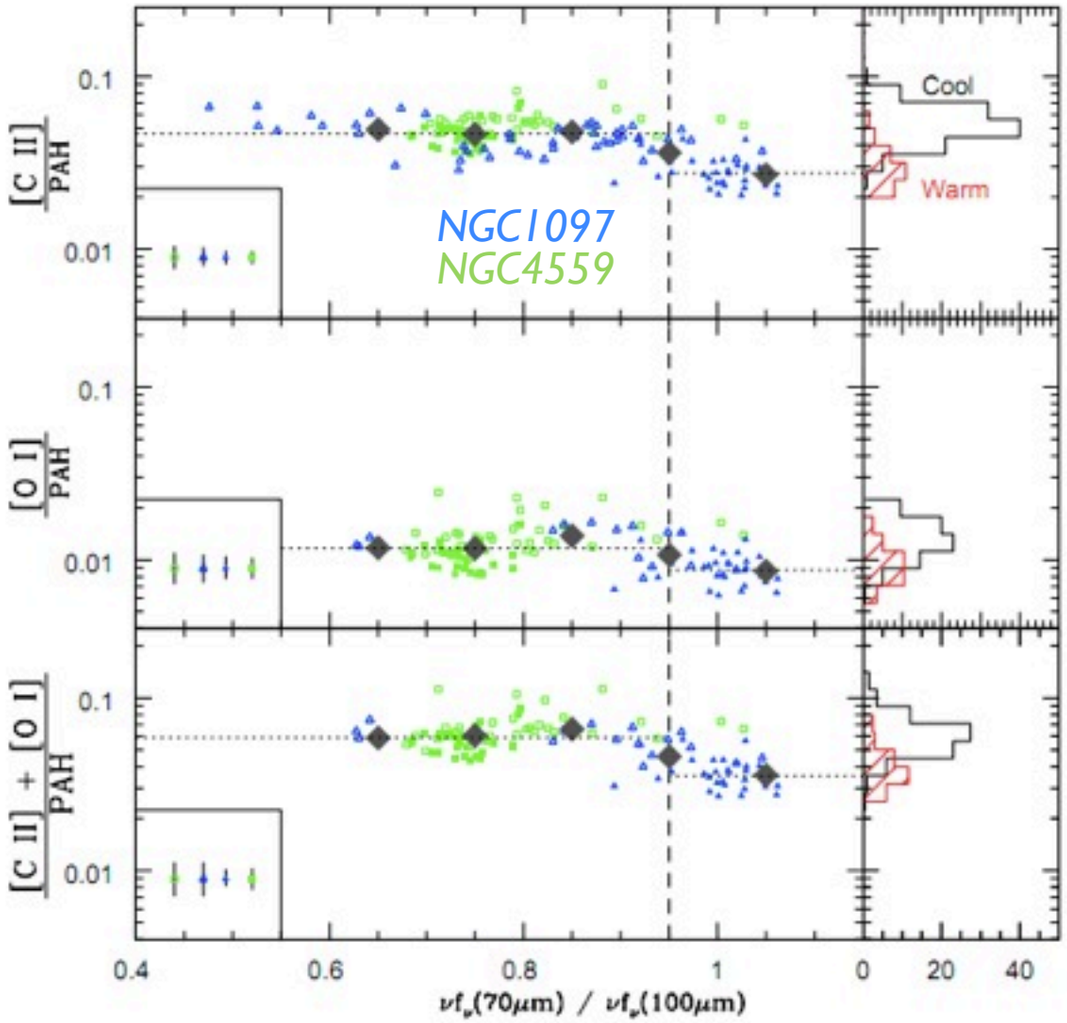
[CII] & [OI] deficit

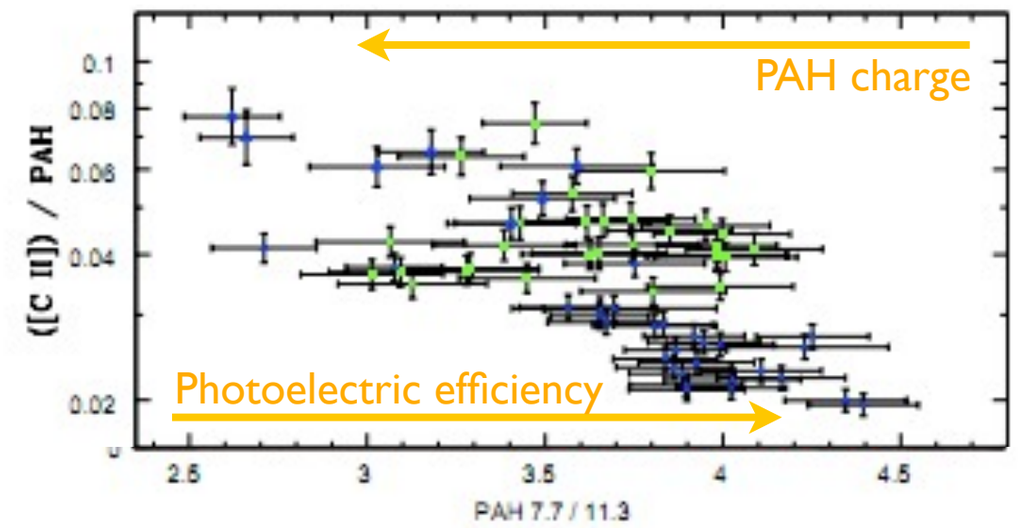
- not a result of density: [OI] doesn't compensate [CII] in denser regions

- not a result of dusty HII regions: no deficit observed for [NII] 122μm & [SiII] 35μm

=> **grain charging**

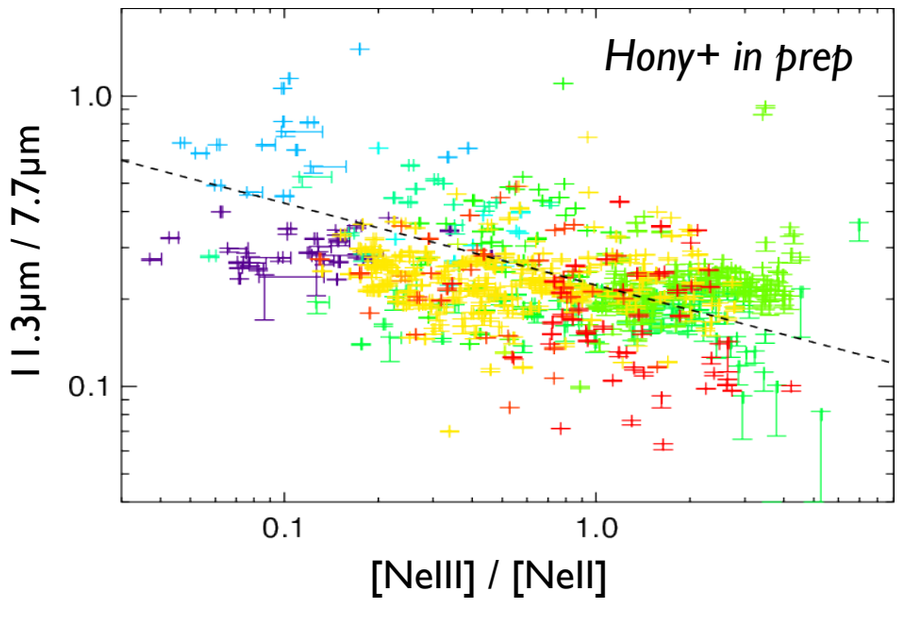
KINGFISH: Croxall+ 2012, Beirao+ 2012



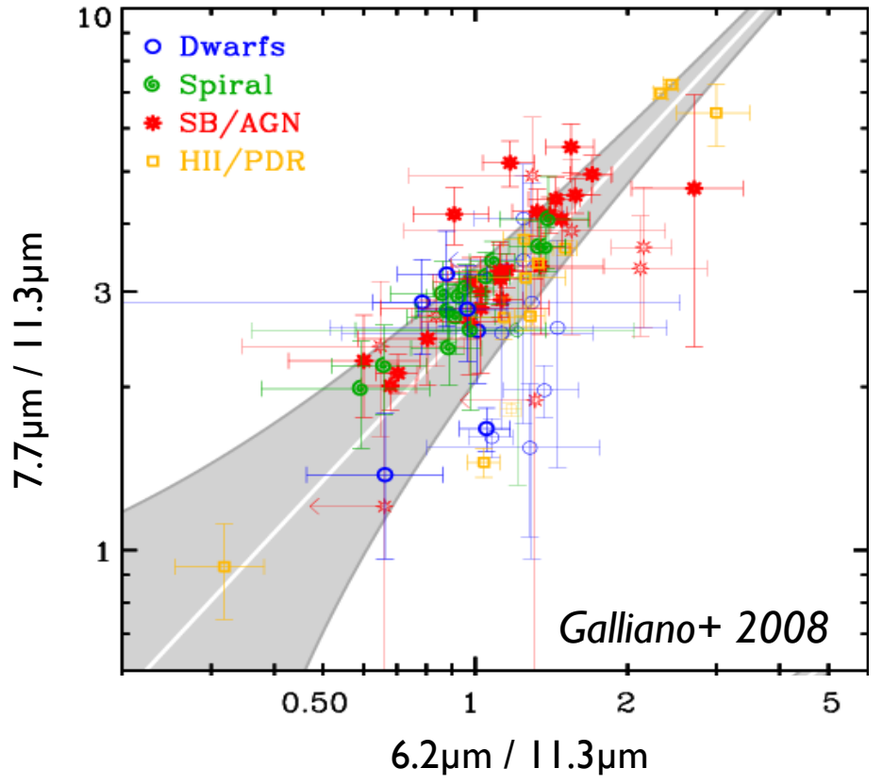


PAHs in the LMC & in dwarfs

Ionization dominates PAH band variations in LMC HII regions



Low PAH charge in dwarf galaxies



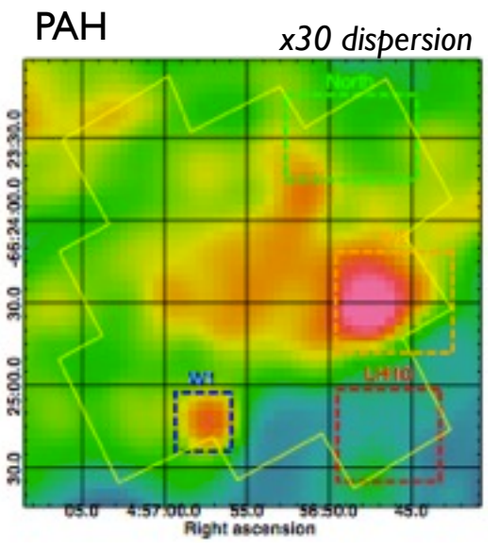
- PAHs might be mostly neutral in the LMC (see also Sandstrom+ 2012)
- UV field dilution (e.g., LMC-N11B)
  => maximum photoelectric efficiency => large [CII] / PAH?

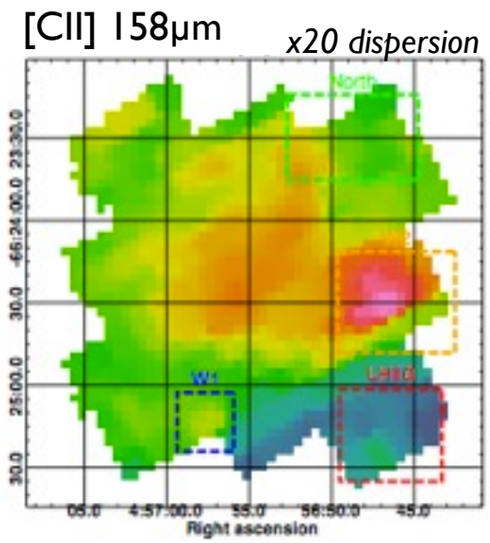
But, PAH paucity in metal-poor SF galaxies
- photodestruction, delayed injection, limited formation (Madden+ 2006; Y. Wu+ 2007; Engelbracht + 2007; Galliano+ 2008)

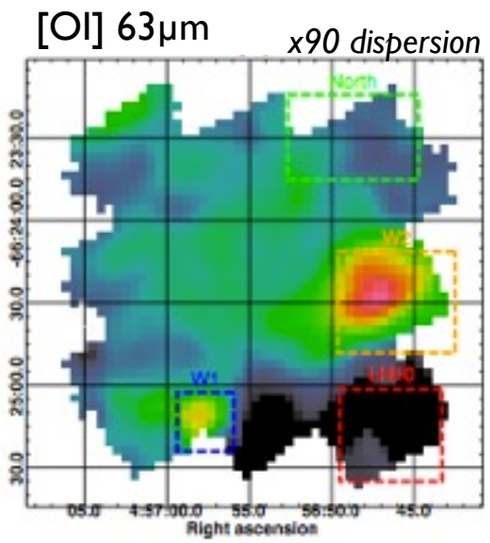
How does [CII] / PAH vary with metallicity?

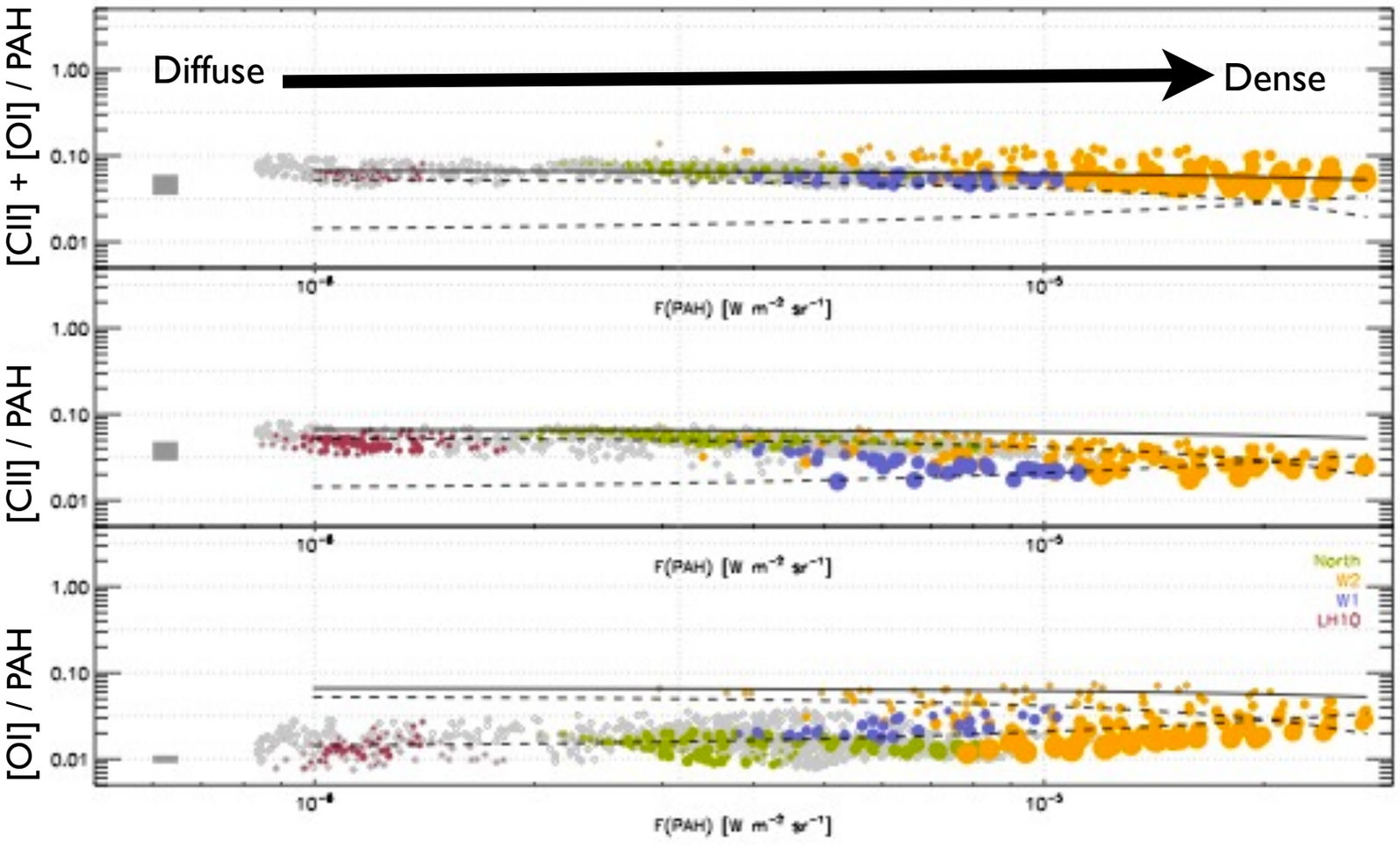
[CII] & PAH in LMC-N11B

Lebouteiller+ (submitted to A&A)









Dispersion

	[CII]	[OI]	[CII]+[OI]
PAH	4	10	3

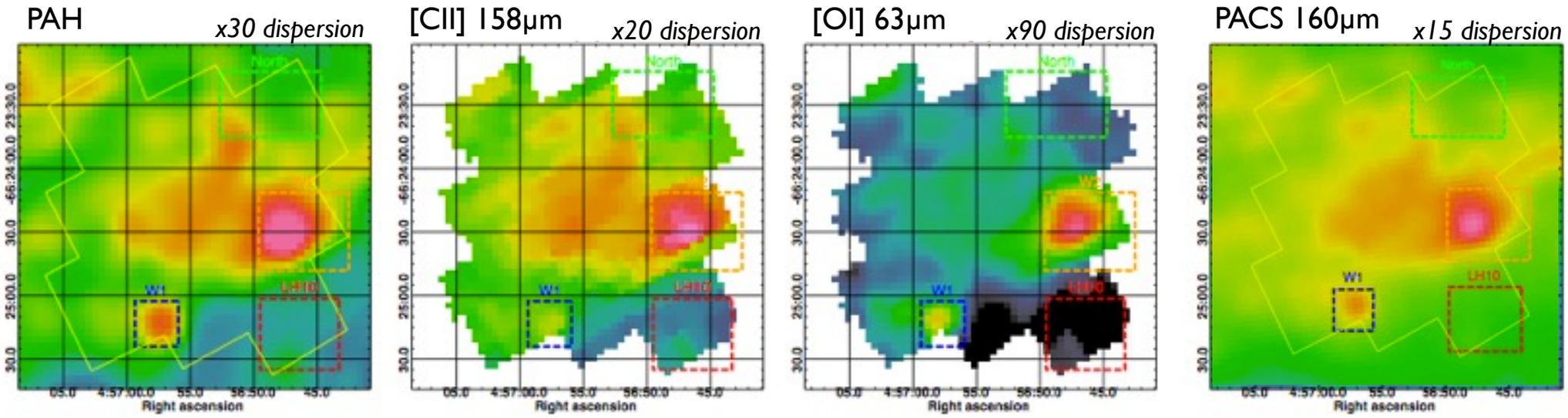
- [CII] dominant coolant in the diffuse regions
- [OI] dominant coolant in the dense regions
- [CII]+[OI] traces the total gas cooling

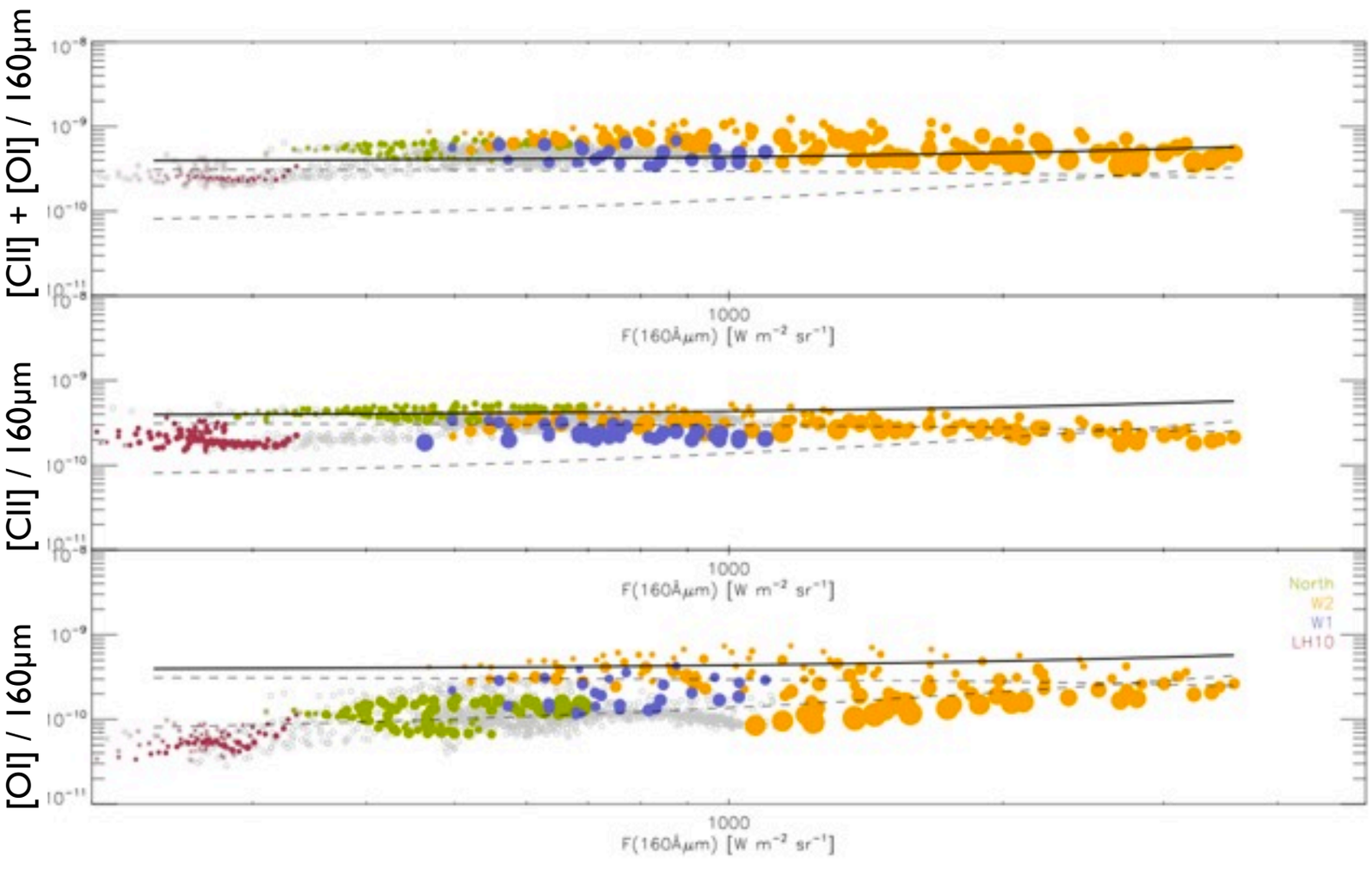
- [CII] arises mostly in PDRs where PAHs emit (confirmed with [NII])
- [CII] should therefore trace the dark molecular gas. Models underway.

- [CII]/PAH (only) slightly larger (<2) than in the more metal-rich sources => higher PE efficiency?

[CII] & 160μm in LMC-N11B

Lebouteiller+ (submitted to A&A)





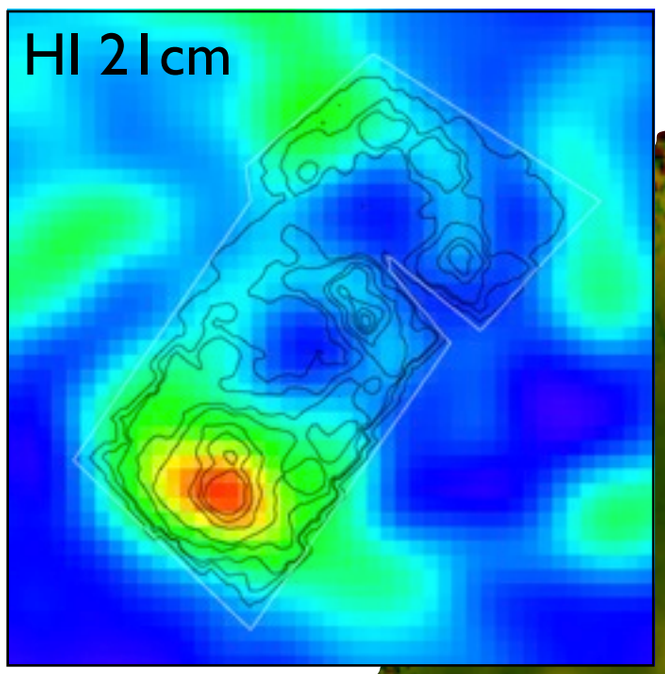
Dispersion

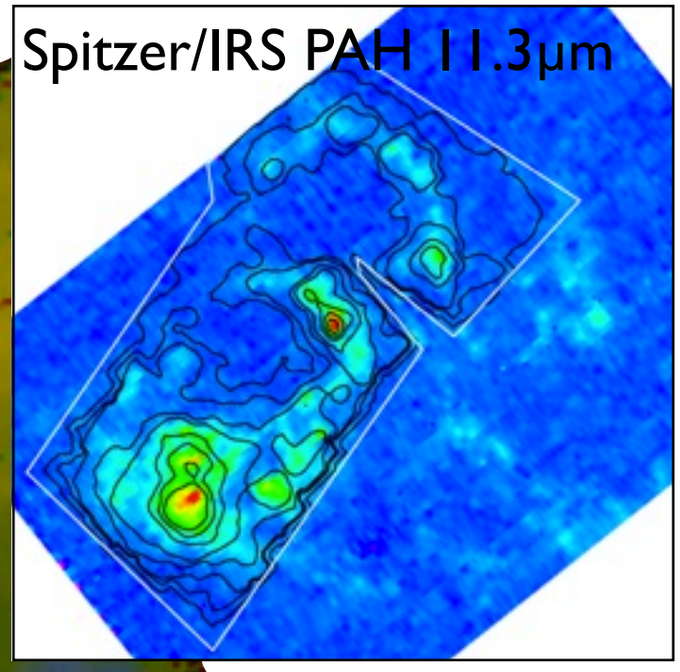
	[CII]	[OI]	[CII]+[OI]
PAH	4	10	3
160μm	4	30	7

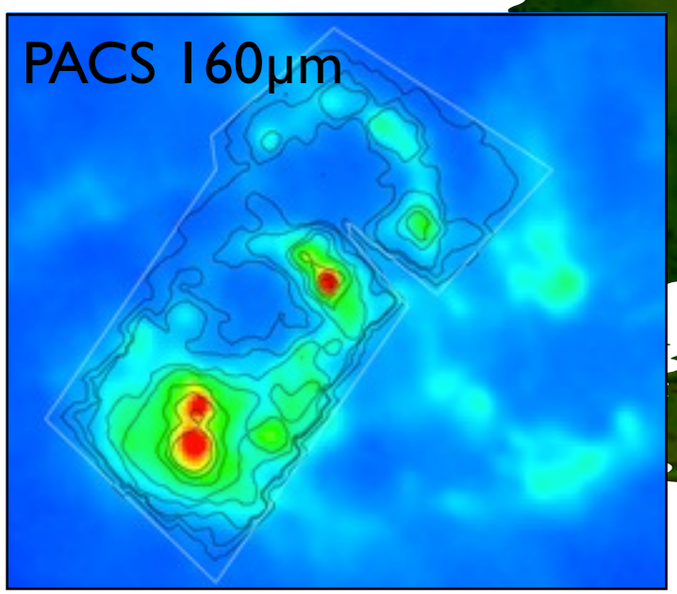
- Weaker correlation with 160μm

- 160μm can trace gas heating not corresponding to cooling by [CII] or [OI] lines (e.g., ionized gas)
- [CII]+[OI] correlates better with PAH emission

Larger spatial scales: IC10 (700kpc)

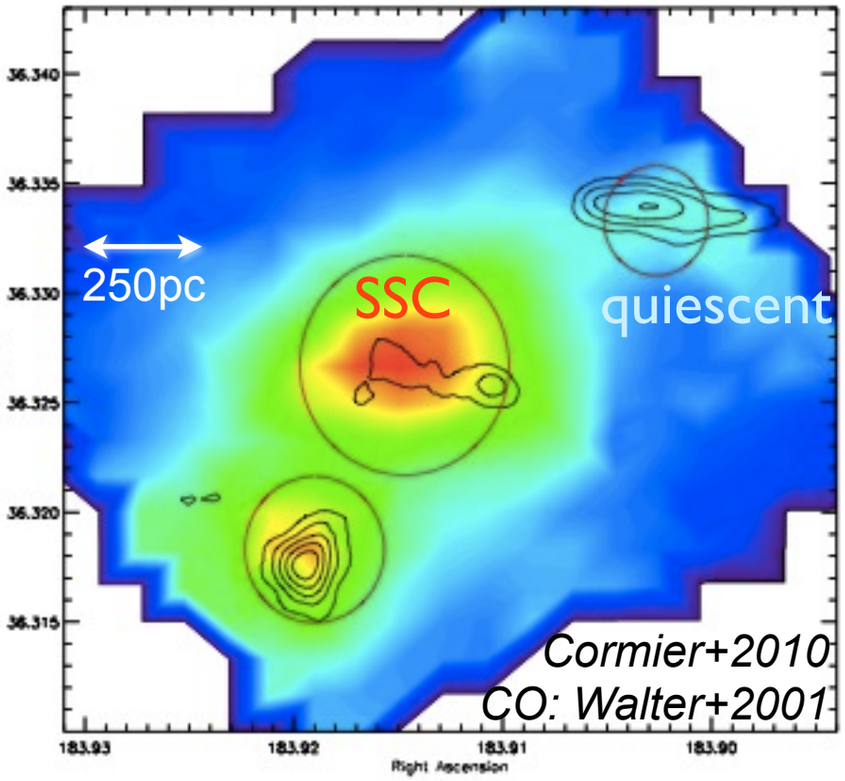


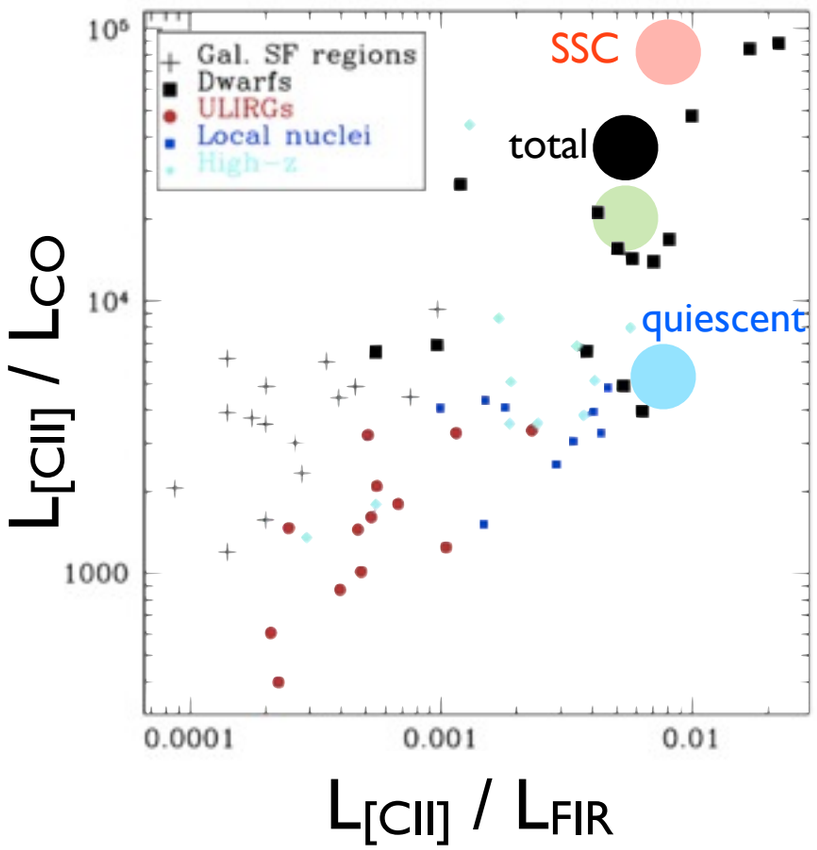


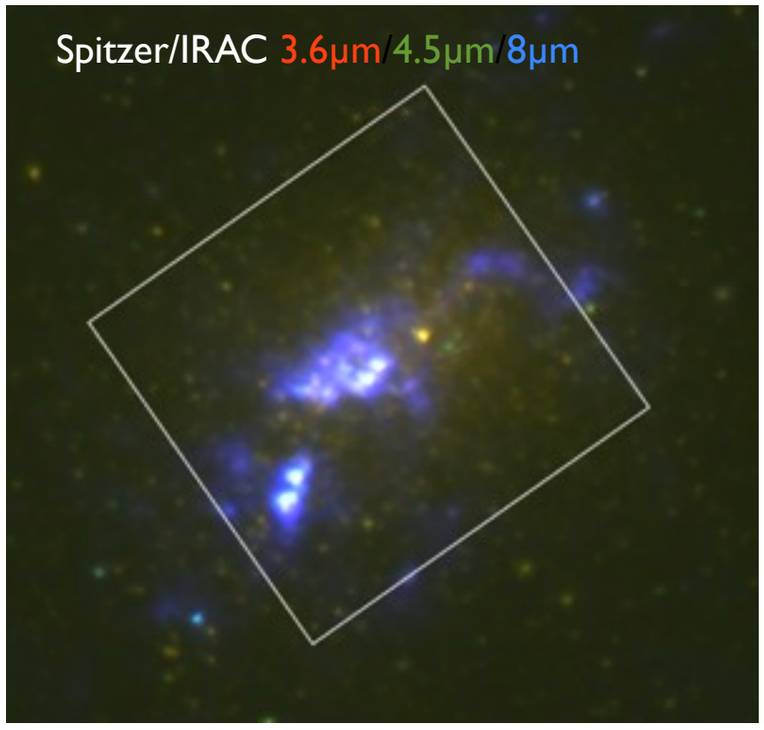


PACS 70μm
SPIRE 250μm
HI 21cm

NGC4214 *Cormier+ (2010)*



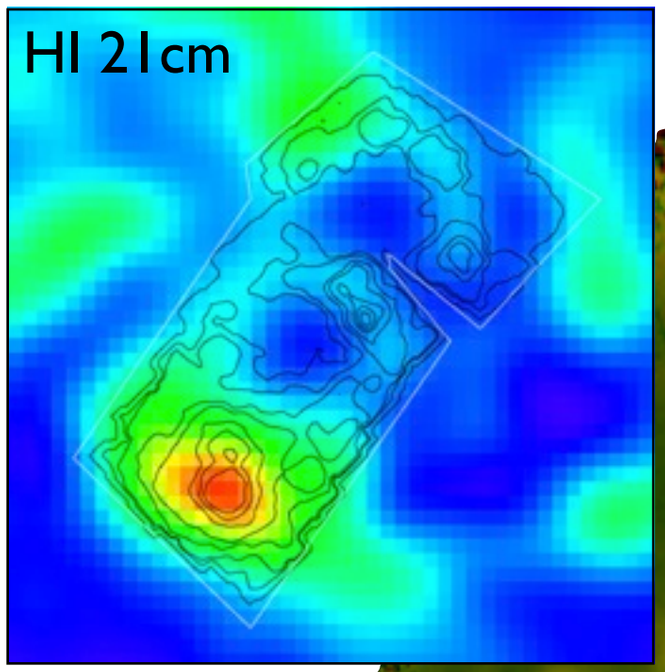


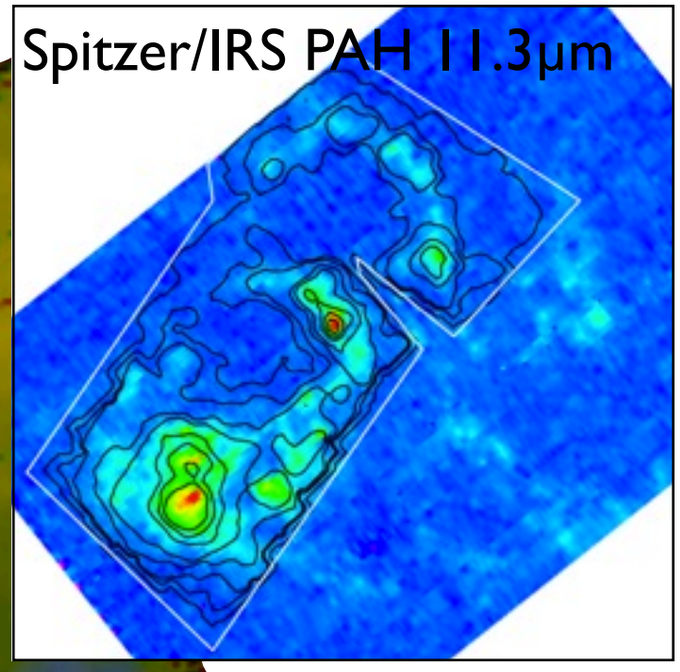


Resolved in [CII] & CO!

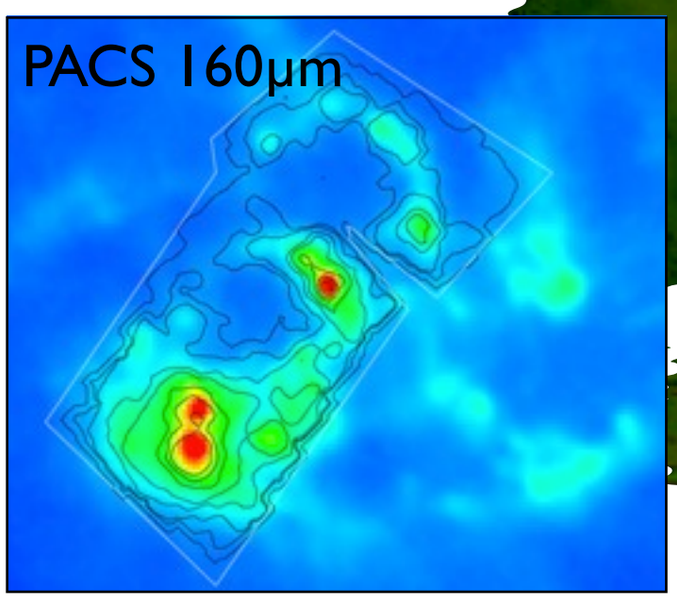
3 regions with extreme [CII]/CO ratios
- SF activity? Different CO SLEDs?
- Total emission biased toward the largest [CII] / CO
- comparison with PAHs suggests SF activity is the culprit

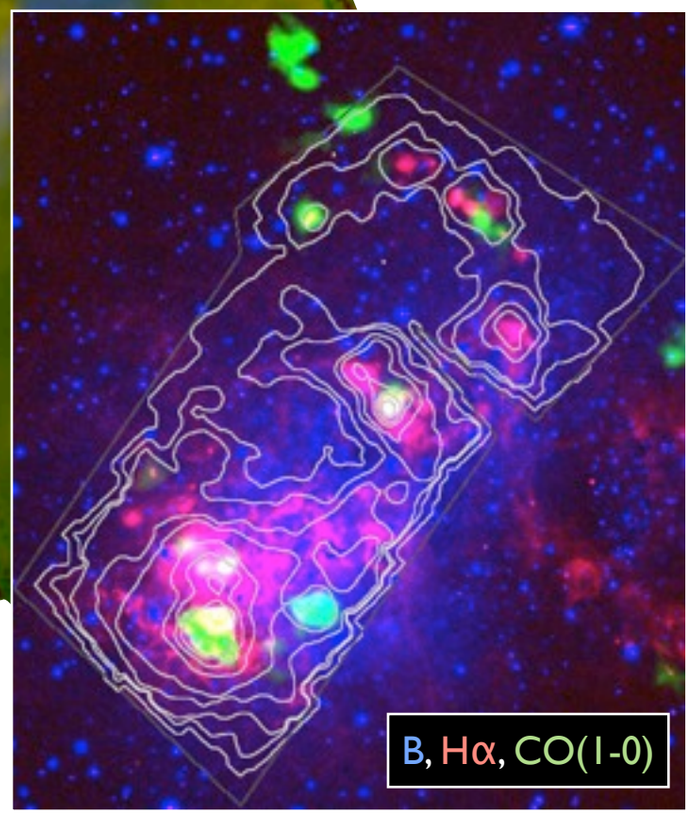
Larger spatial scales: IC10 (700kpc)





~1kpc





Summary

Objectives

How well does [CII] trace PDRs at low-metallicity?
What can we learn from the ISM morphology from the FIR fine-structure lines? Difference with a dusty galaxy?

Strategy

Most nearby & most metal-poor systems (<1/2 $Z_\odot$): LMC, SMC, IC10, NGC4214, ...
Herschel/PACS, Herschel/FTS, Spitzer, HI 21cm, CO, ...

Large filling factor of ionized gas

- prevalence of the ionized gas emission, [OIII] 88μm, in LMC-N11B & in 30 Doradus. Small PDR volume filling factor.
- Diagnostics in LMC-N11B suggest heavy geometrical dilution of UV field.
- [OIII] 88μm brightest FIR line in the most metal-poor galaxies and a workhorse diagnostic for ALMA? (Madden's talk)

Origin and emission conditions of [CII]

- [CII] dominant coolant in diffuse PDRs, [OI] compensates in denser regions
- Tight [CII]+[OI]/PAH, tighter than [CII]+[OI]/160μm => PAHs define well the gas heating where [CII] and [OI] emit
- Higher PE efficiency as compared to more metal-rich sources?

Next steps, underway

- [CII](+[OI])/PAH vs. metallicity from a sample of resolved sources (especially IC10, LMC/SMC)
- PDR modeling, dark gas mass measurements

Unresolved galaxies

- need both [CII] and [OI] for tracing the diffuse + dense PDRs
- **fraction of [CII] in PDRs? see Cormier's talk**

Molecular gas properties

- CO low-J (MOPRA, JCMT, APEX)
- high-J (FTS, ALMA)