The ISM structure of low-metallicity star-forming dwarf galaxies

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Maud Galametz (*IoA, Cambridge*)
Ilse de Looze (*U. Gent*)
Albrecht Poglitsch (*MPE, Garching*)

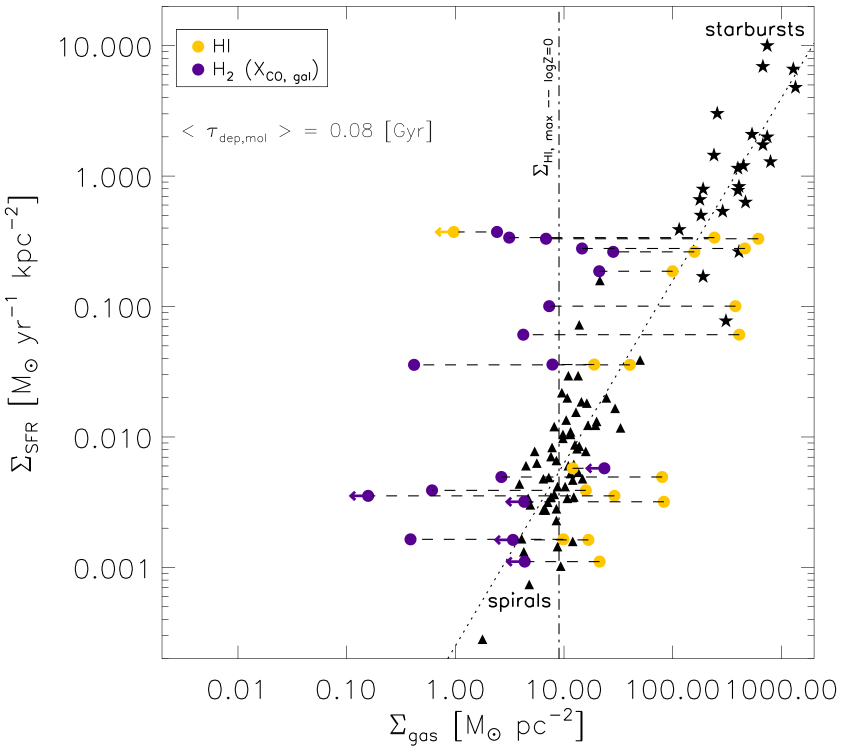
Puzzles around star formation in low-metallicity dwarf galaxies

★ **Star formation is well-correlated with molecular gas in normal galaxies (*e.g. Bigiel et al. 2008*)**
Most dwarf galaxies are **HI dominated with little CO** detected, despite evident SF episodes
(*e.g. Taylor et al. 1998, Leroy et al. 2005, Schruba et al. 2012*)

★ Strong UV fields + low-metallicity
=> CO photodissociation (*S. Madden review talk*)
H_2 can self-shield in CO-free envelopes of clouds
= **CO-dark gas** (*Grenier et al. 2005, Wolfire et al. 2010*)
Observational evidence of CO-dark gas in low-metallicity galaxies *(e.g., Poglitsch et al. 1995; Israel et al. 1997; Madden 2000; Leroy et al. 2007)*

★ The **atomic gas** starts to play a role in SF at (very) low metallicities (*e.g. Krumholz 2011, Glover & Clark 2012*)

Kennicutt et al. 1998



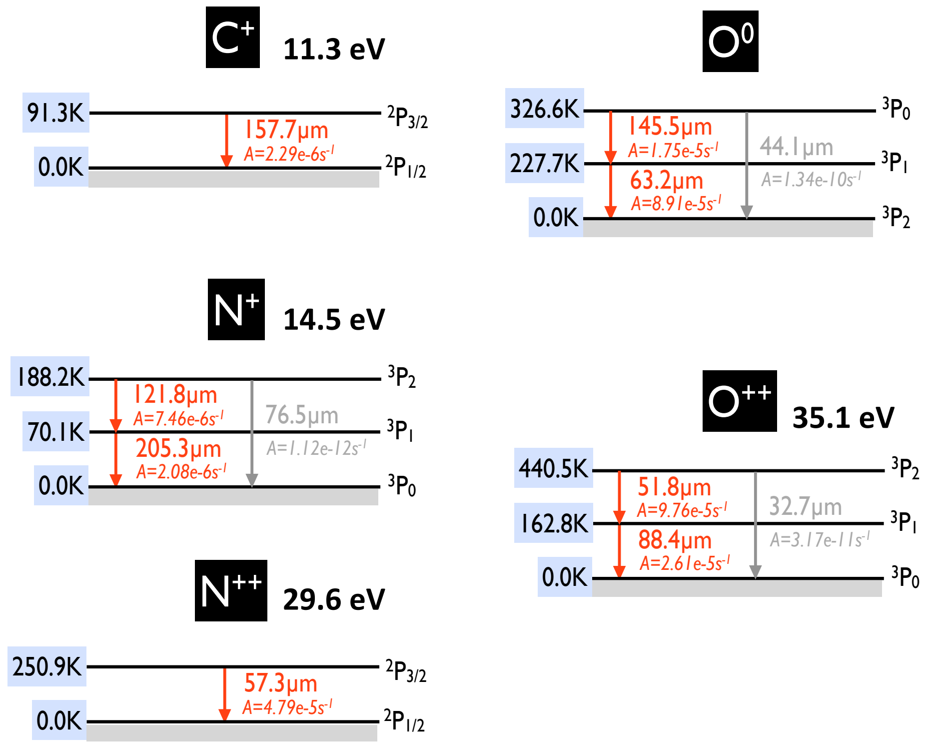
⇒ What are the true cloud/phases distributions?
⇒ What is the total molecular gas reservoir?
⇒ What is the role of the different gas reservoirs in the SF process?

How can the FIR lines, combined with CO, help understand the ISM structure of dwarf galaxies?

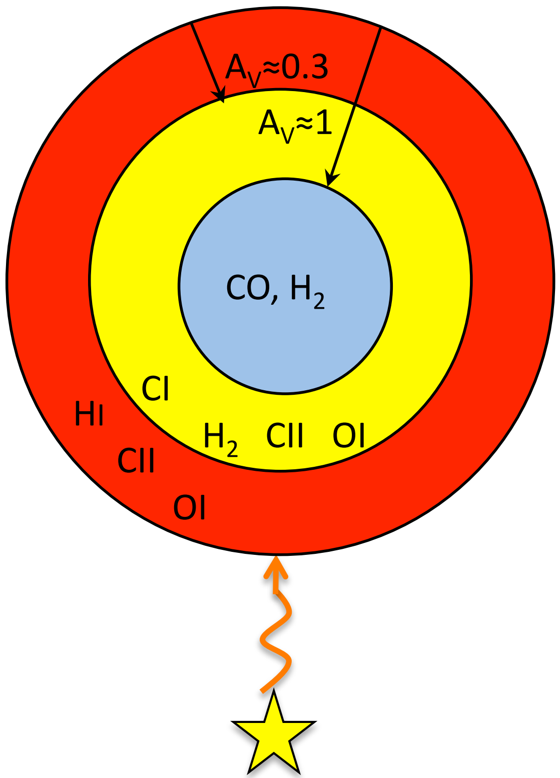
The FIR cooling lines

- ***Why are the FIR lines important?***

⇒ Major coolants of the ISM
⇒ PDR lines trace closely the star formation
[CII] 157μm is the brightest line in most SF galaxies (alone carries 1% of the FIR luminosity, e.g., *Brauher et al. 2008*)
Prime target in high-z galaxies with ALMA



C^+ / C^0 / CO layers (*Wolfire et al. 2010*)

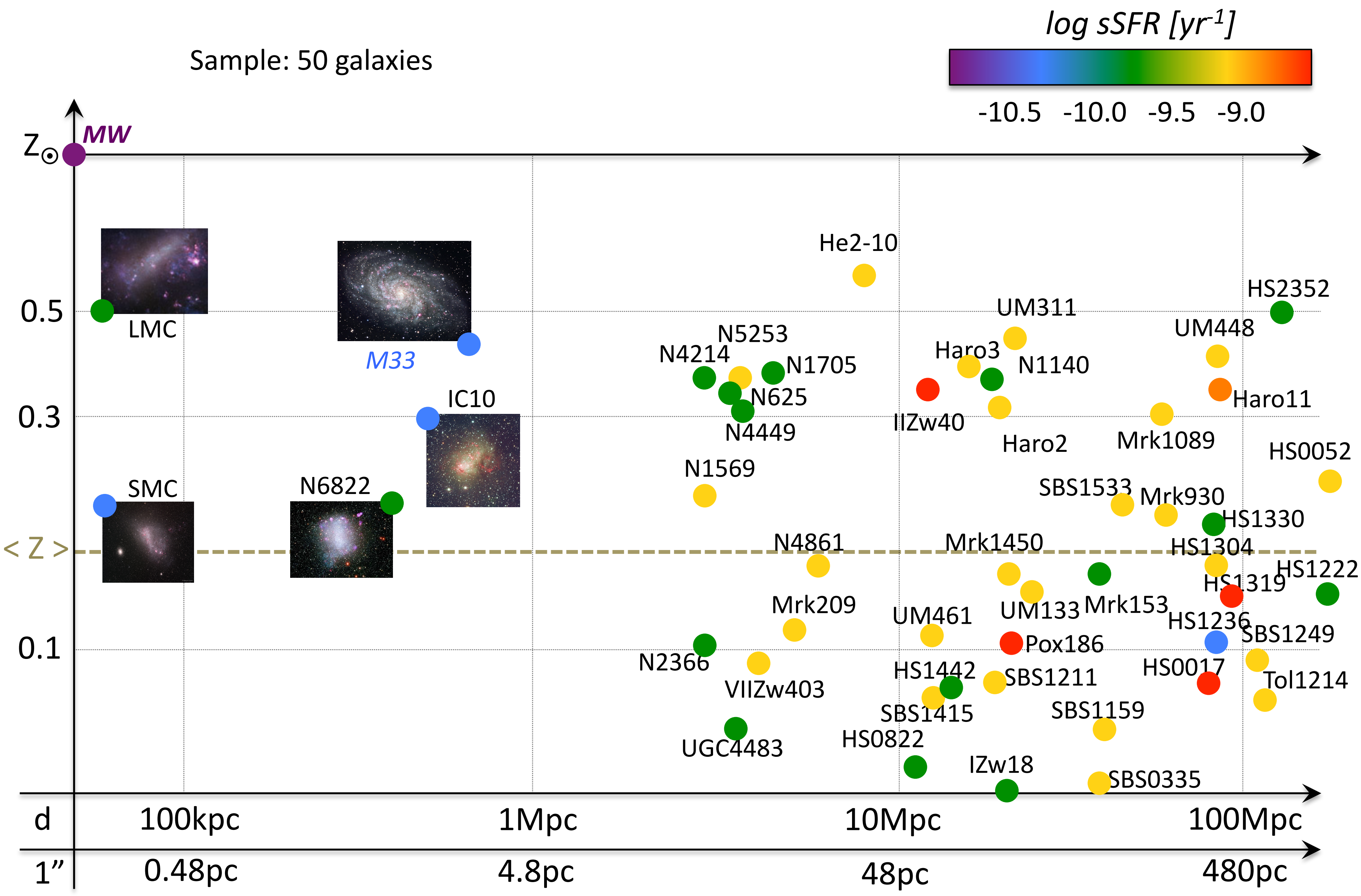


- ***Where do the FIR lines come from?***

Depends on the medium conditions
(essentially ionisation, temperature, density)

⇒ C^+ is an important coolant of the: WIM, WNM, CNM, PDR
⇒ O^0 is a main coolant of the: PDR
⇒ N^+, N^{++}, O^{++} are coolants of the: HII region, WIM

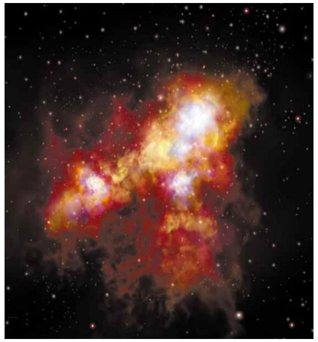
The *Herschel* Dwarf Galaxy Survey (*Madden et al. 2013*)



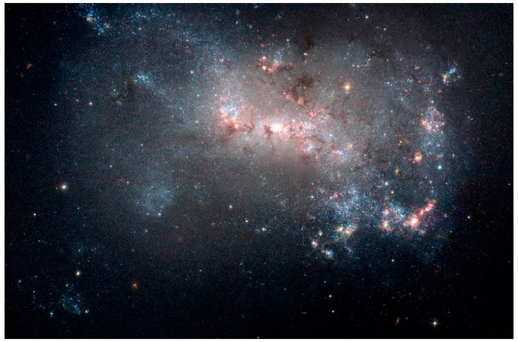
Herschel/PACS [CII] 157μm maps

<u>*Herschel*/PACS info:</u> [CII], [OI]63 and [OIII] in all galaxies, [NII], [NIII], and [OI]145 in few
FOV ≈ 47” -- Spatial resolution ≈ 9 - 12” -- Spectral resolution ≈ 90 - 240 km s^{-1}

IIZw40
12 Mpc, 1/5 $Z_{\odot}$, SFR ≈ 0.4 $M_{\odot}.yr^{-1}$

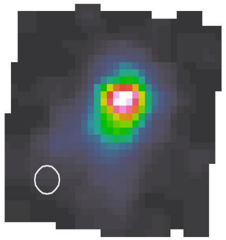


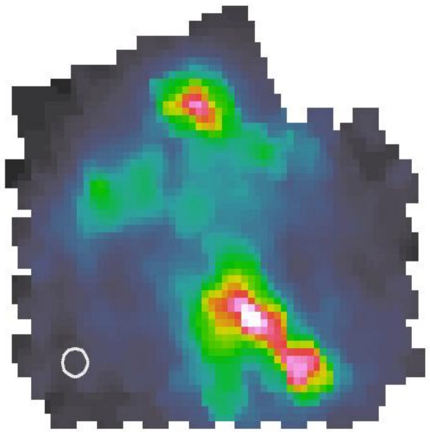
NGC4449
4.2 Mpc, 1/3 $Z_{\odot}$, SFR ≈ 0.3 $M_{\odot}.yr^{-1}$



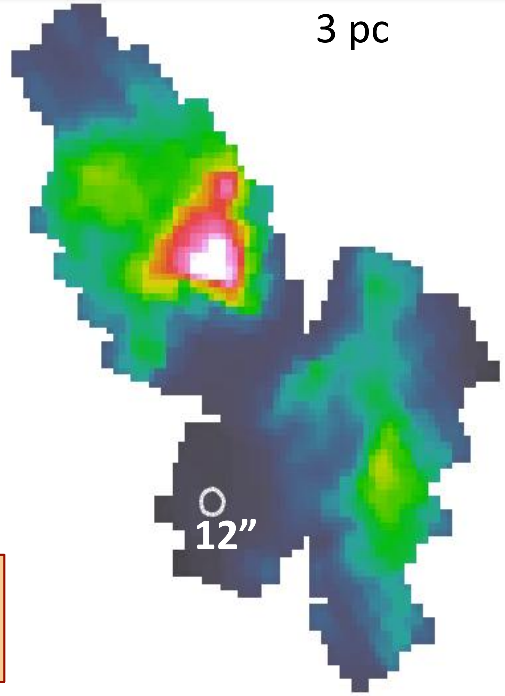
30 Doradus
48 kpc, 1/2 $Z_{\odot}$, SFR ≈ 0.01 $M_{\odot}.yr^{-1}$

12” = 700 pc 250 pc 3 pc



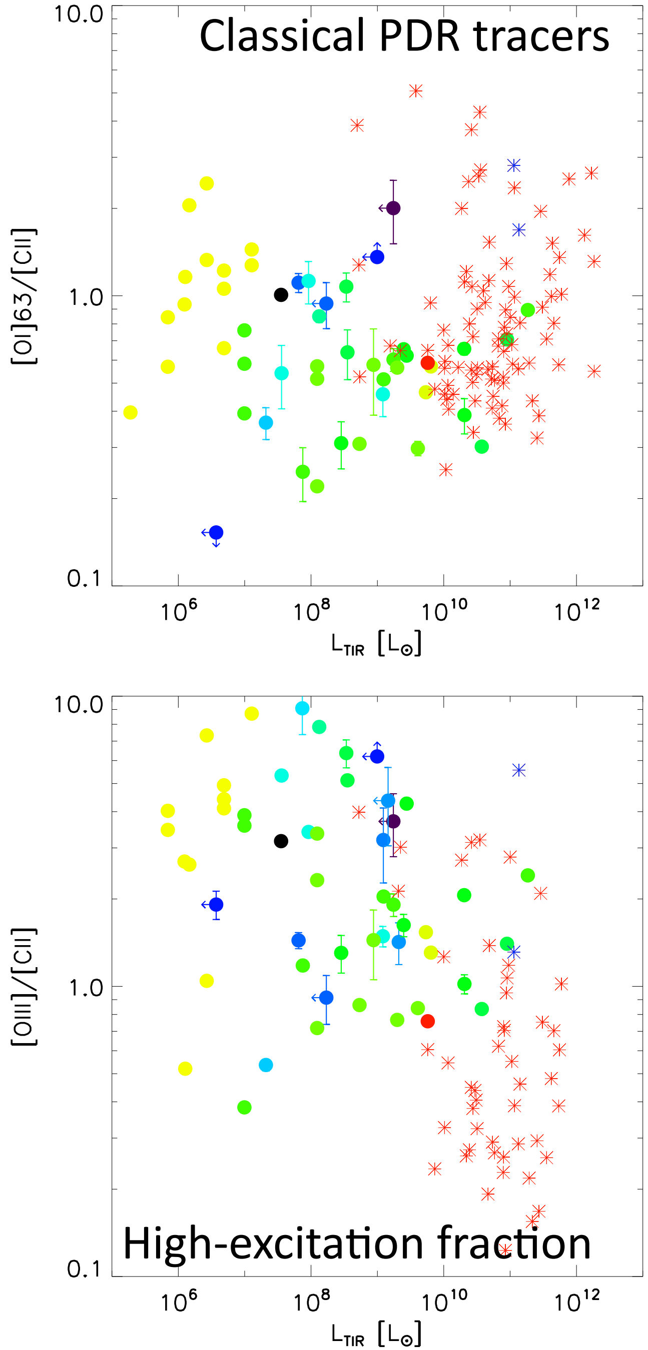


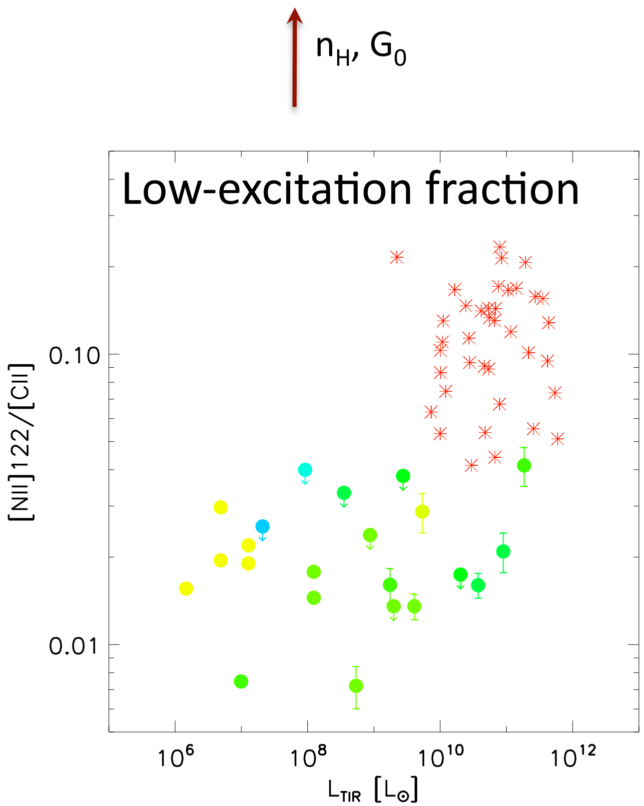
(Karczewski et al. 2013)

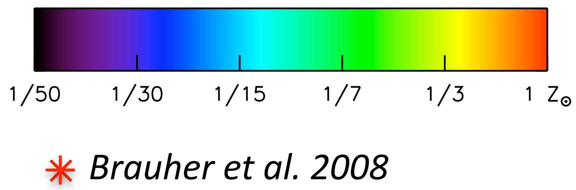


C+ detected down to Z≈1/50 $Z_{\odot}$ (IZw18 , SBS0335-052)
C+ emission bright and extended *(e.g. in N11: Lebouteiller et al. 2012)*

Line ratios and L_{TIR} correlations





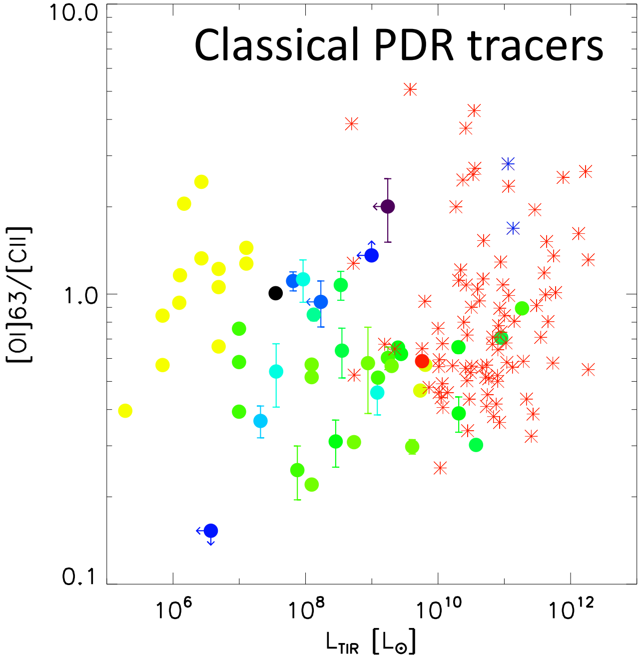


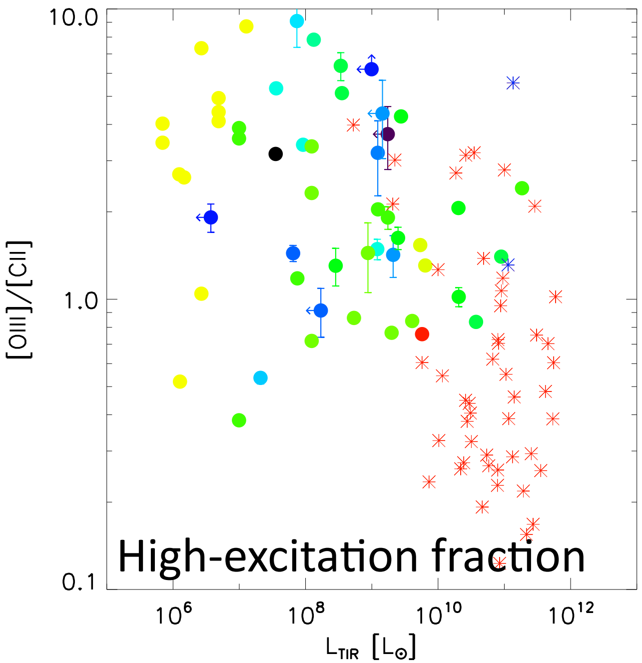
- **[OI]/[CII] ratios are average**
  ⇒ non-uniform properties

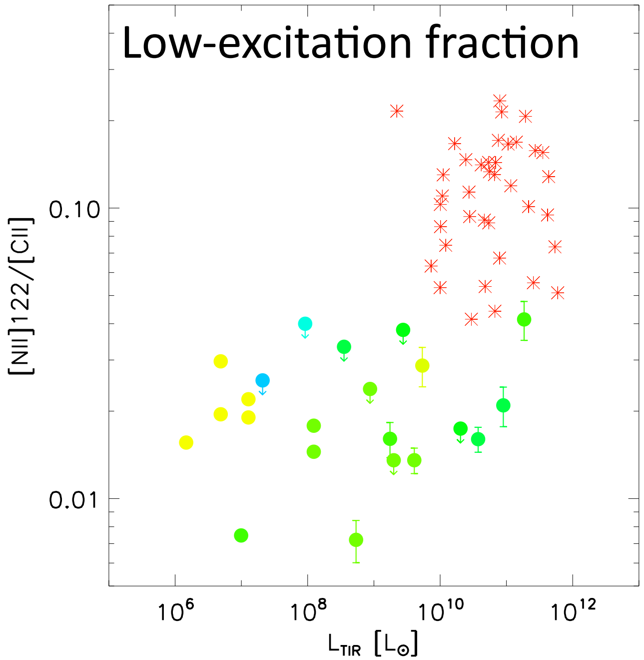
- High [OIII]/[CII] ratios
  ⇒ effect of hard UV photons
  on large spatial scales

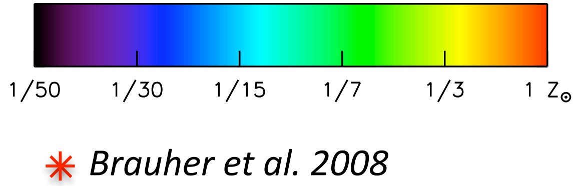
- Low [NII] 122μm fluxes
  ⇒ high-excitation gas dominant

Line ratios and L_{TIR} correlations









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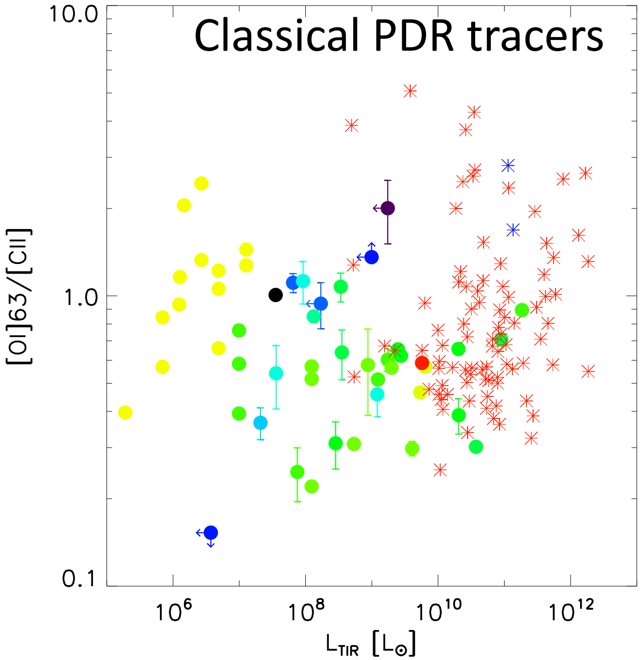
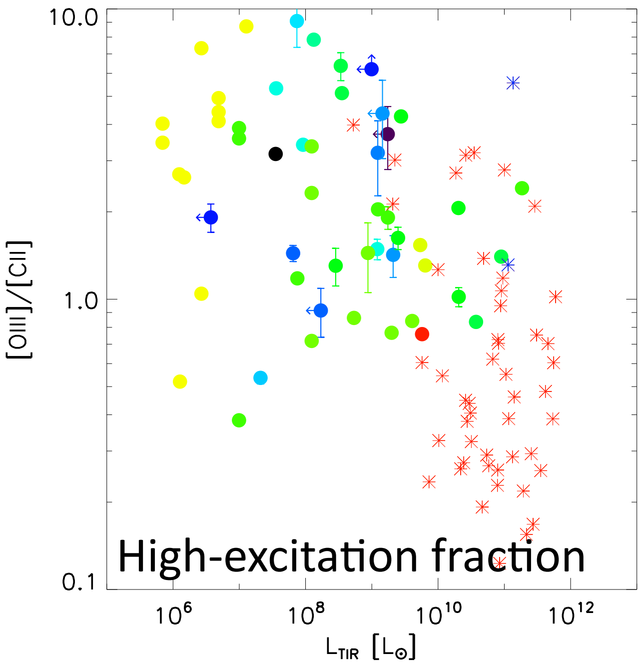
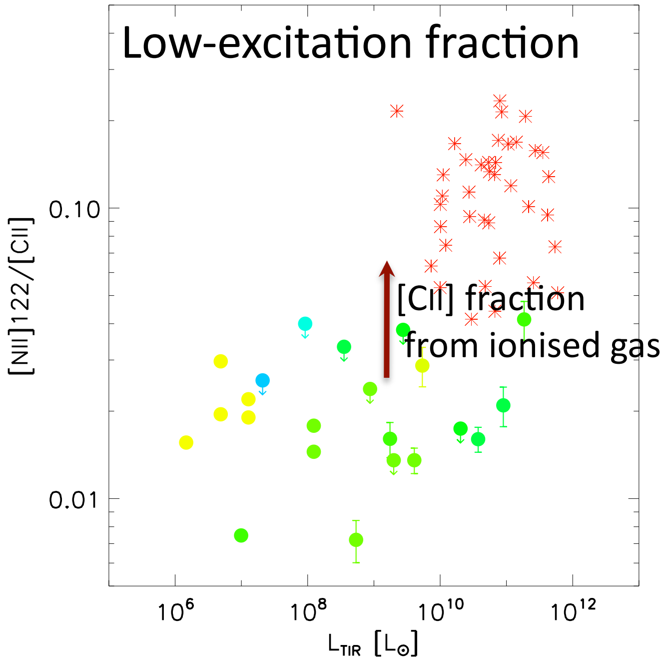
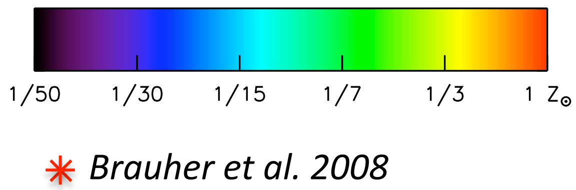
See also Hunter et al. 2001

Line ratios and L_{TIR} correlations









- [OI]/[CII] ratios are average
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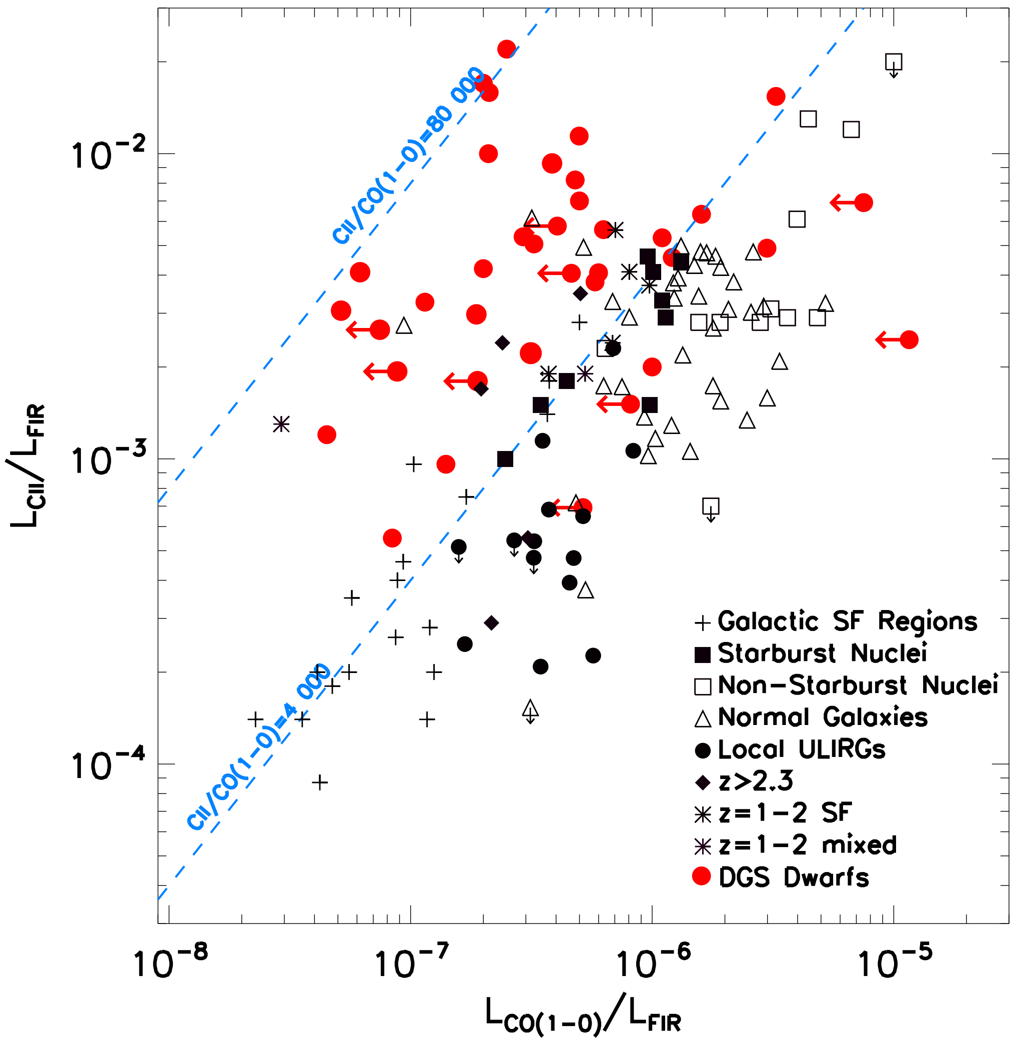
Metallicity and the [CII]/CO ratio

- CO is detected in few dwarf galaxies and faint compared to their SF activity
- CO not detected to metallicities lower than ≈ 1/5 $Z_\odot$ (with the exception of WLM, *Elmegreen et al. 2013*)



Madden 2000
Hailey-Dunsheath et al. 2010
Stacey et al. 2010
Madden et al. 2013, in prep.

CII/CO(1-0) traces the star formation activity in galaxies

High CII/CO(1-0) ratios observed on average in star-forming dwarf galaxies

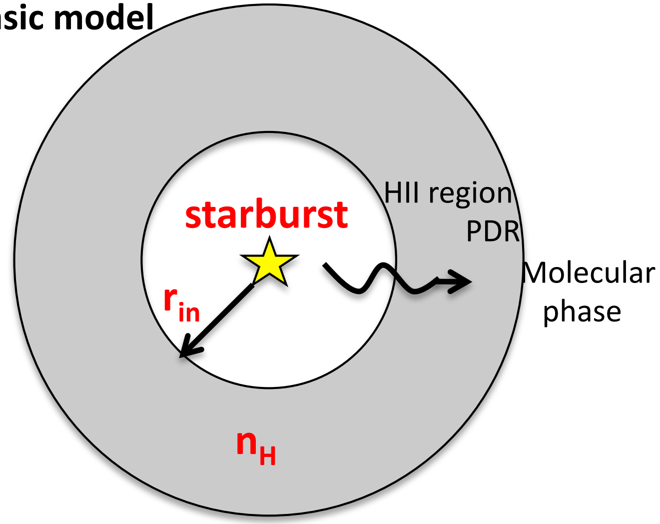
CII/CO is a strong function of Av

Cloudy modeling (work with Nick Abel)

HII regions and PDR model

Cloudy (Ferland et al. 2013, Abel et al. 2005)

Basic model



$Z \approx 1/10\ Z_{\odot}$

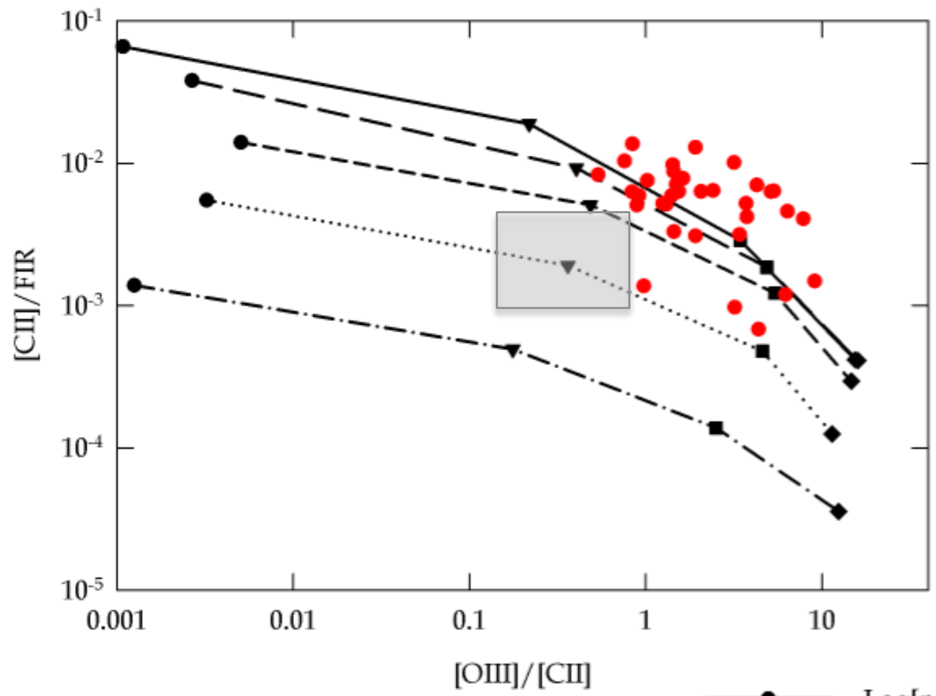
SMC-type grains

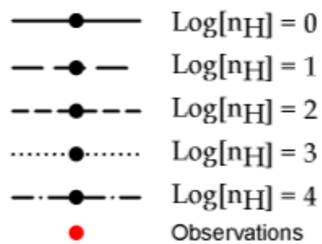
Grid varying: n_H, U, A_V

Focus on: CII/FIR, CII/CO, and OIII/CII

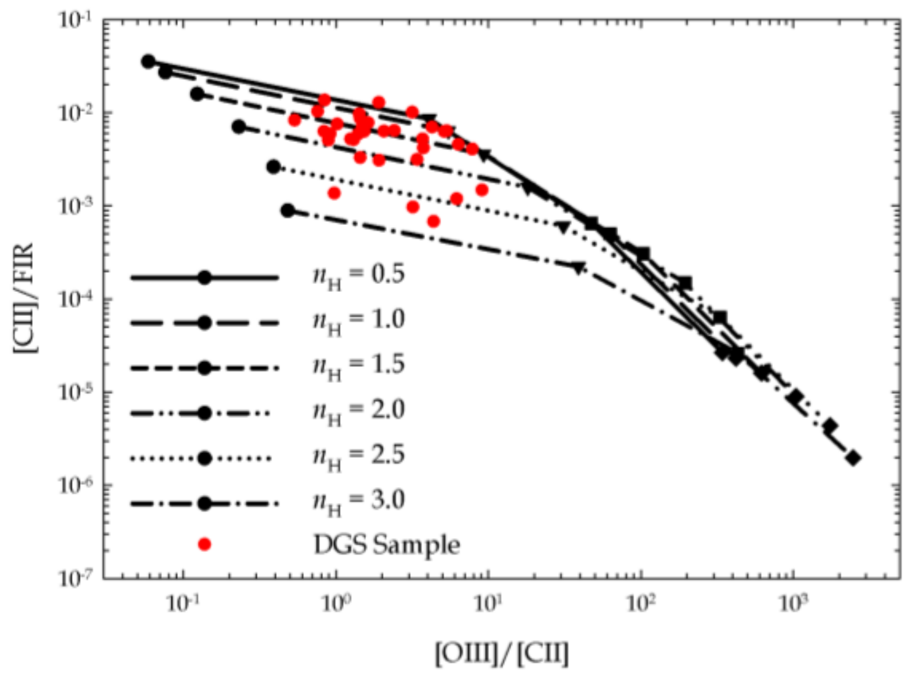
Cloudy modeling (work with Nick Abel): CII/FIR vs. OIII/CII

H+ Region Plus PDR Models of CII/FIR vs OIII/CII





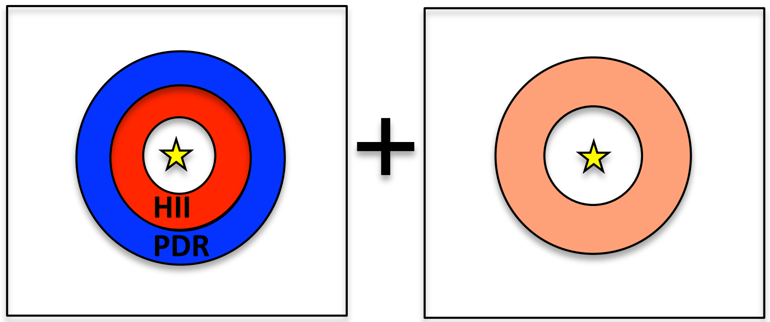
H+ Region Models of CII/FIR and OIII/CII



Ionisation parameter:

- ● log U = -4
- ▲ log U = -3
- ■ log U = -2
- ◆ log U = -1

⇒ Need for an escaping
low density ionised phase
Combined with a low covering factor PDR



Cloudy modeling (work with Nick Abel) : CII/CO(1-0) vs. OIII/CII

Ionisation parameter:
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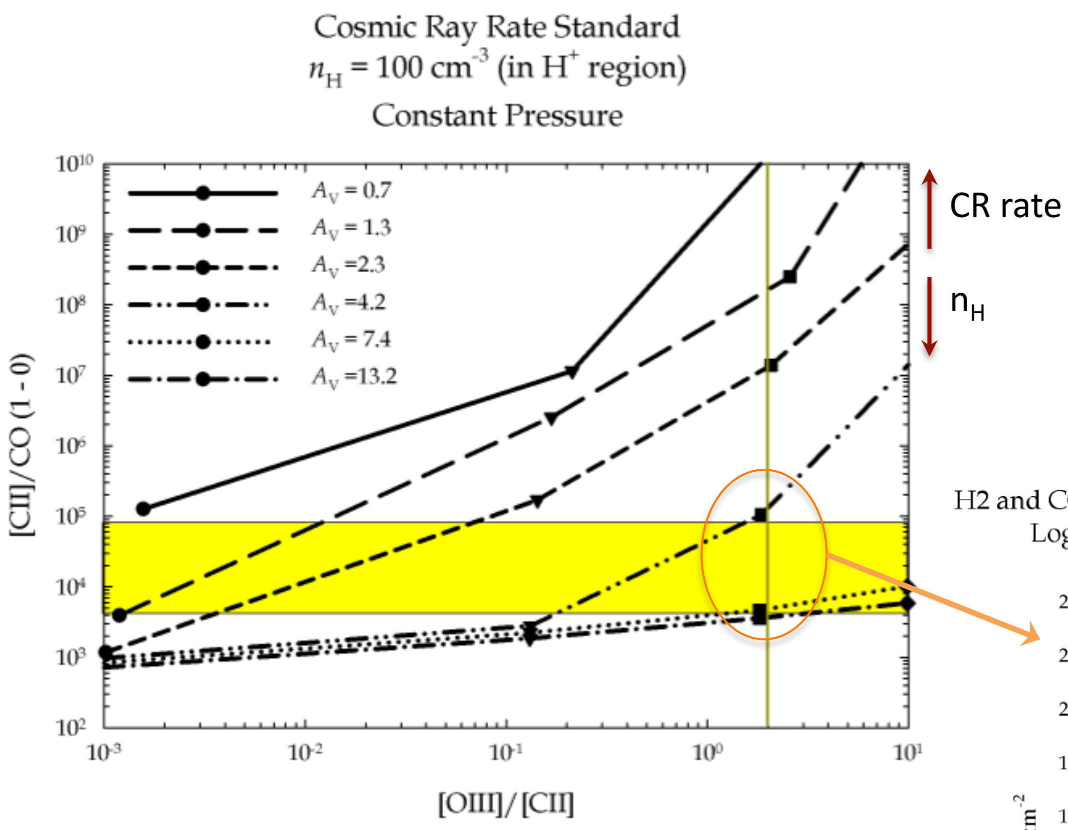
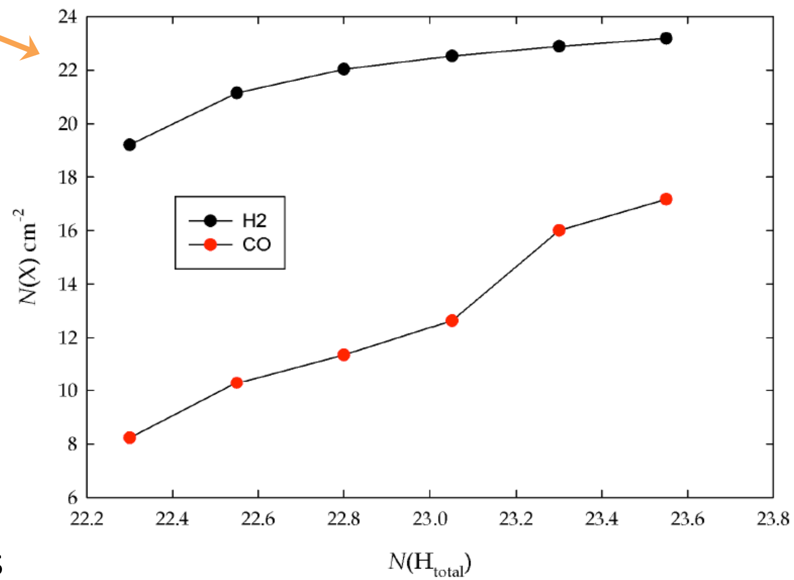


H2 and CO column densities as a function of total hydrogen column density for Log[nH] = 2, Log[U] = -2, and a cosmic ray ionization rate 10 times the average ISM value



Effect of cosmic rays: CO suppressed in favor of more ions
Tracers: H3+, but OH+ and H_2O => difficult to observe

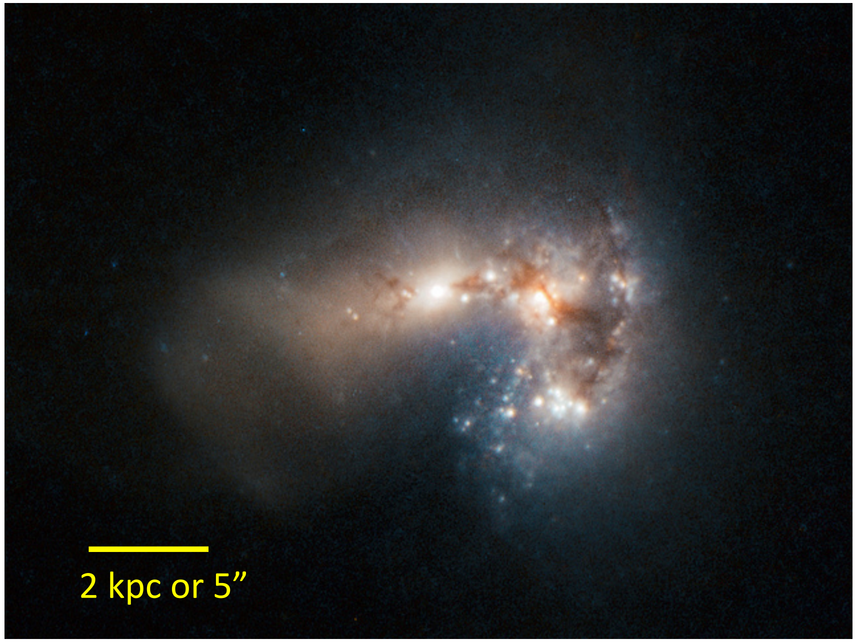
Madden et al. 2013, in prep.

Haro11: observations

L_{IR}=1.6 $10^{11} L_{\odot}$
84 Mpc away
Z = 0.3 $Z_{\odot}$

3 main star-forming regions
~60 SSCs, hundreds of young (<3Myrs) clusters
SFR = 22 $M_{\odot}$ yr^{-1}

Unresolved in Spitzer and Herschel bands



HST image of Haro11

OIII/CII ≈ 2.5

CII/OI ≈ 1

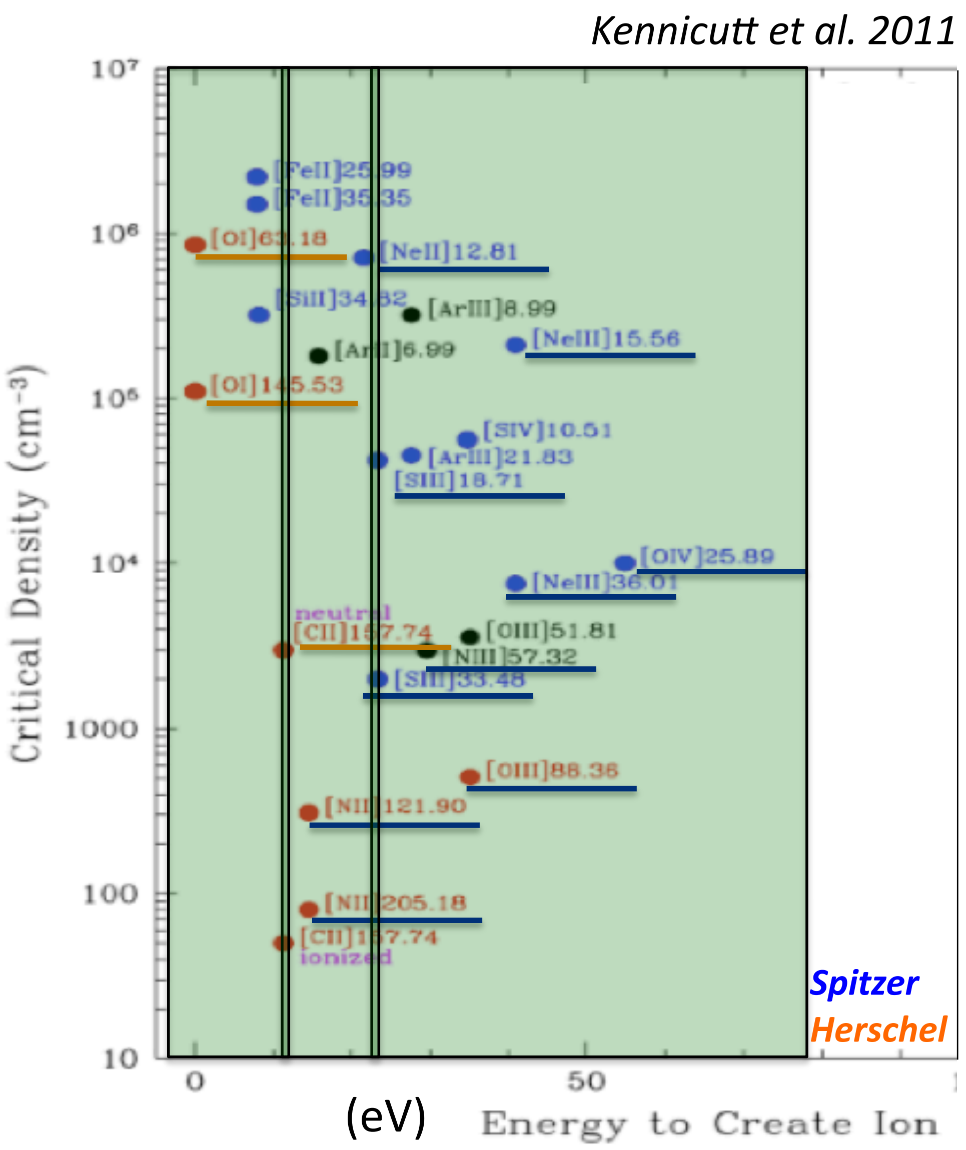
CII/CO > 20 000

CII/TIR ≈ 0.1 %

Only upper limits on
HI 21-cm and CO(1-0)
Bergvall et al. 2000

Bright MIR and FIR cooling lines
Detected in CO(2-1) and CO(3-2)
Cormier et al. 2012, Cormier et al. 2013 (submitted)

Haro11: Cloudy modeling

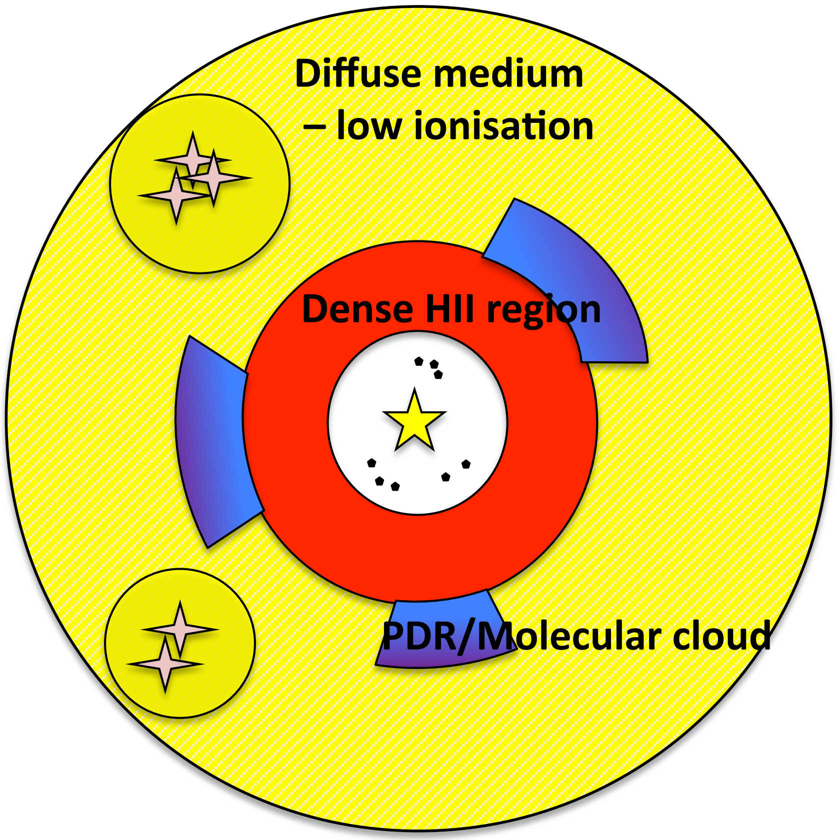


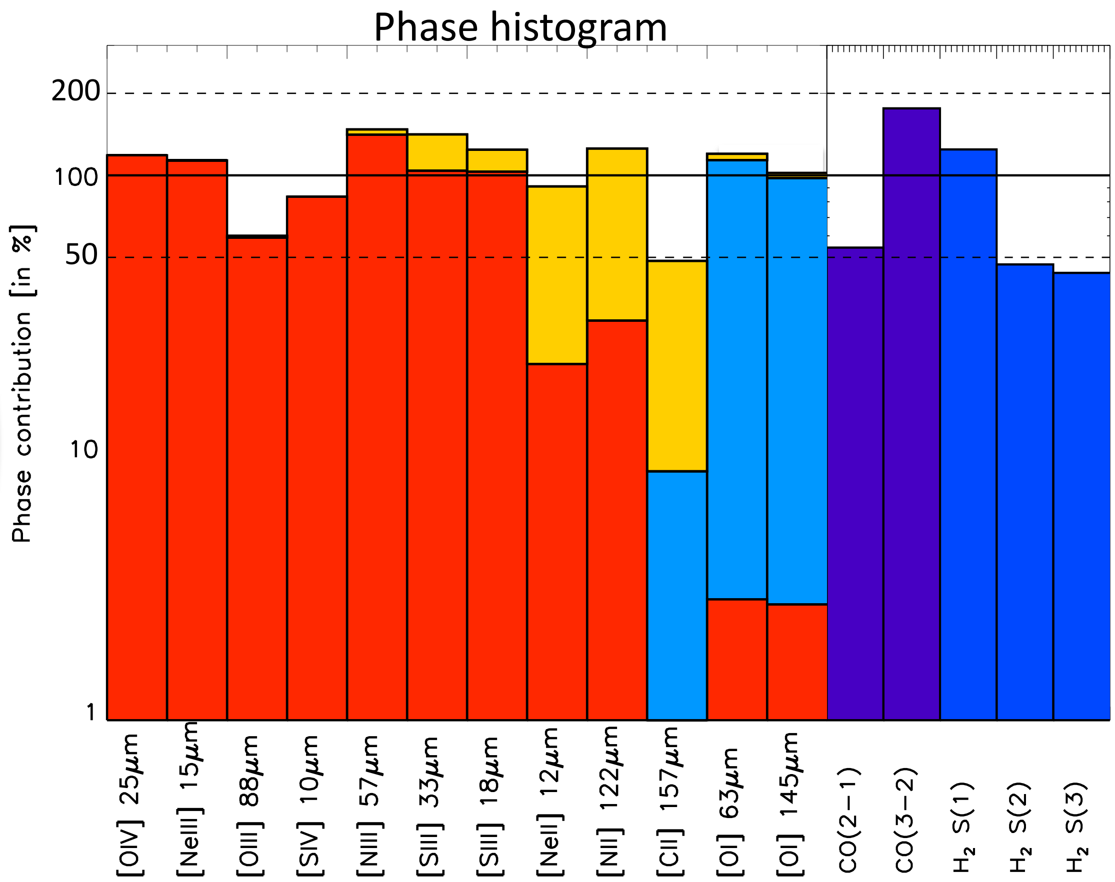
→ ***Multi-phase ISM:***
Search for 3 main phases

1. ***Compact HII region***
2. ***Diffuse gas***
3. ***Dense PDR***

Haro11: The multiphase picture

Compact HII region: $n_H = 10^3\ cm^{-3}$, $A_{burst} = 4$ Myr
Dense PDR model: $n_H = 10^5\ cm^{-3}$, $G_0 = 10^3$ Habing
Diffuse medium: $n_H = 10\ cm^{-3}$, $T_{eff} = 35\ 000$ K





Summary

Herschel brings a new view on the ISM of dwarf galaxies

- FIR lines enhanced on *galaxy-wide* scales.
- Leaky structure with high filling fraction of diffuse gas where UV photons permeate ([OIII], [NII]), and dense clumpy PDRs ([OI]).

Multi-phase modeling to retrieve structural information

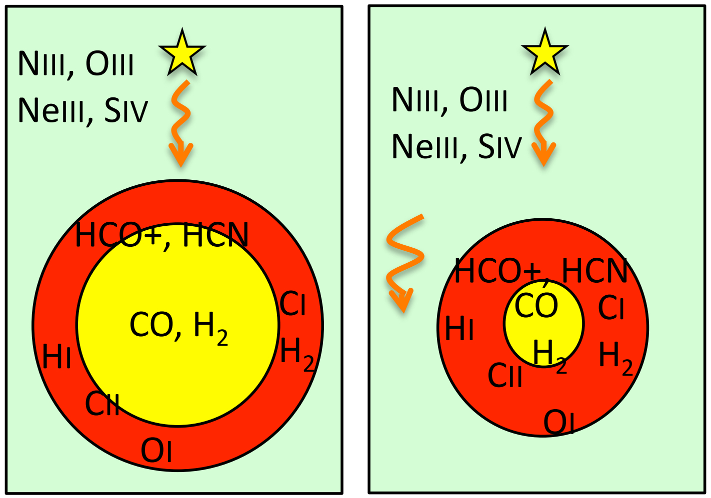
- 3 model components: HII region, fragmented PDR, diffuse gas
- Importance of the ionised gas and diffuse medium, in particular when using [CII] as a PDR tracer in unresolved objects

Elusive molecular gas in dwarf galaxies

- CO difficult to detect due to clumpiness: need ALMA
- Quantifying the molecular gas mass is uncertain

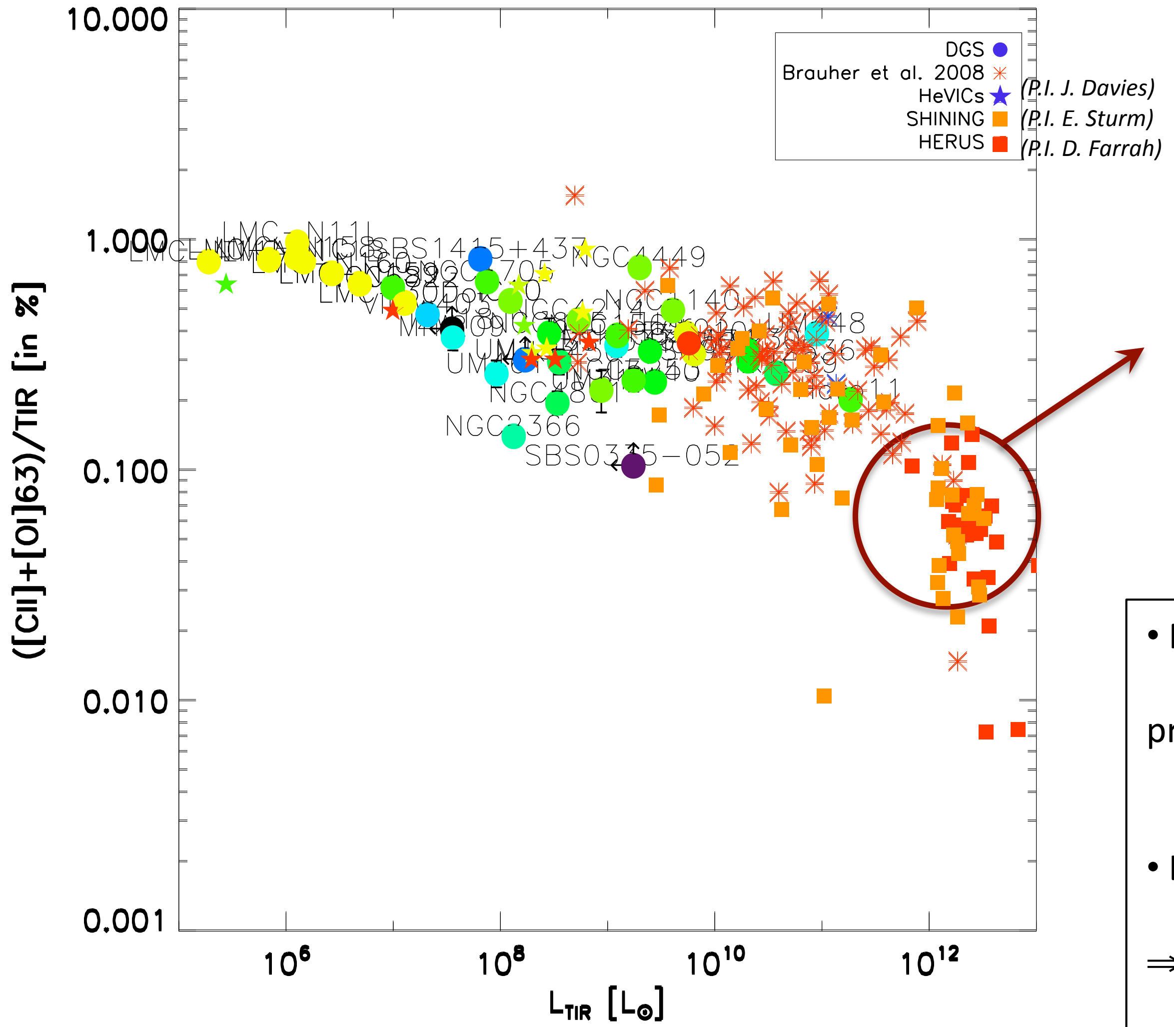
→ The dark-gas fraction can be accessed through models

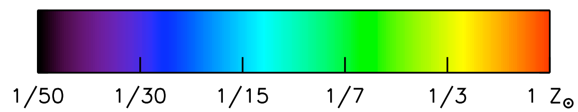
→ Other tracers to be calibrated (e.g. velocity-resolved CII with SOFIA, CI, HCO+, HCN with APEX)



THE END

II. The *Herschel* view of star-forming dwarf galaxies: *heating/cooling balance*





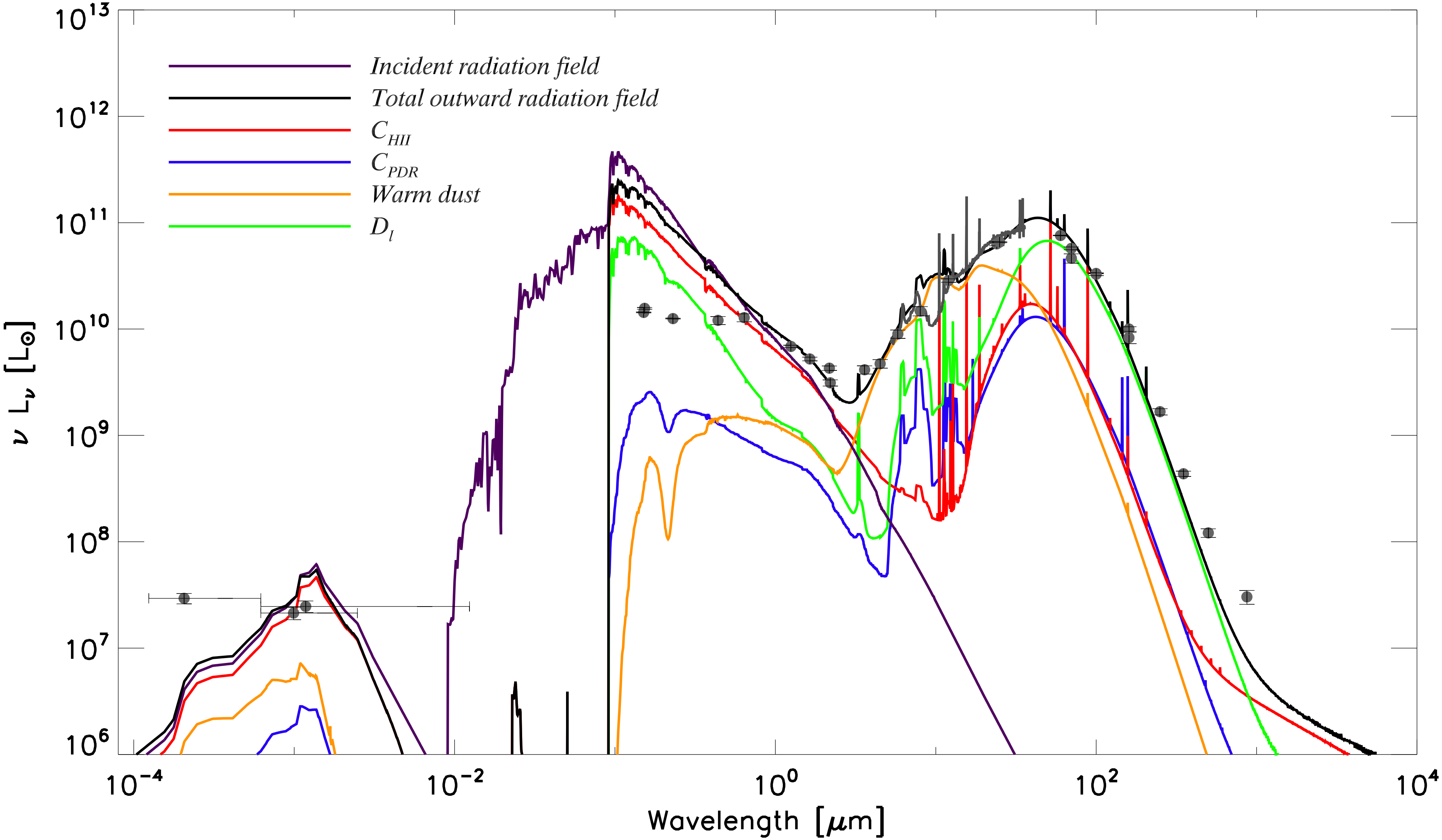
FIR line deficit:
dust screening, grain charging
(*Luhman et al. 2003,*
Gracia-Carpio et al. 2011,
Croxall et al. 2012)

• Measure of $\frac{gas-cooling}{dust-cooling}$ and
proxy for photoelectric efficiency

• Line cooling enhanced on galaxy-wide scales

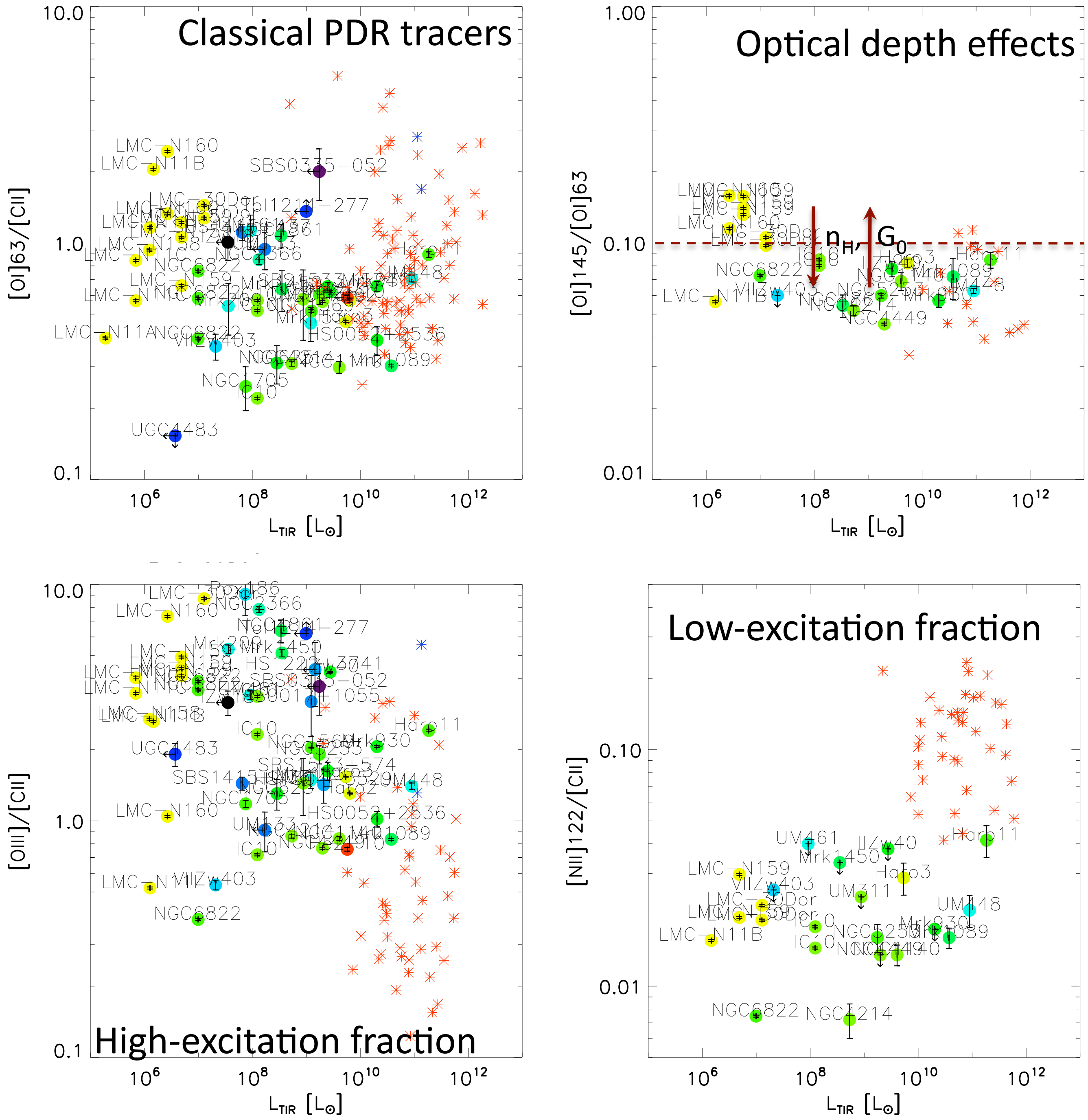
⇒ Higher PE efficiency?
from higher small grain abundance
and UV field dilution

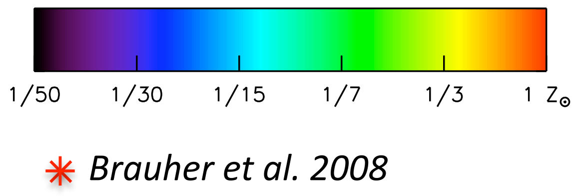
⇒ C+ emission contaminated by WIM/CNM with other excitation mechanisms at play?
large fraction from diffuse regions
on galaxy scale



Incident radiation field
Total outward radiation field
C_{HII}
C_{PDR}
Warm dust
D_I
ν L_ν [$L_\odot$]
Wavelength [μm]
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}

Line ratios and L_{TIR} correlations





- [OI]/[CII] ratios are average
  ⇒ non-uniform properties

- **Narrow [OI]145/63 ratios**
  ⇒ optical depth effects

- High [OIII]/[CII] ratios
  ⇒ effect of hard UV photons
  on large spatial scales

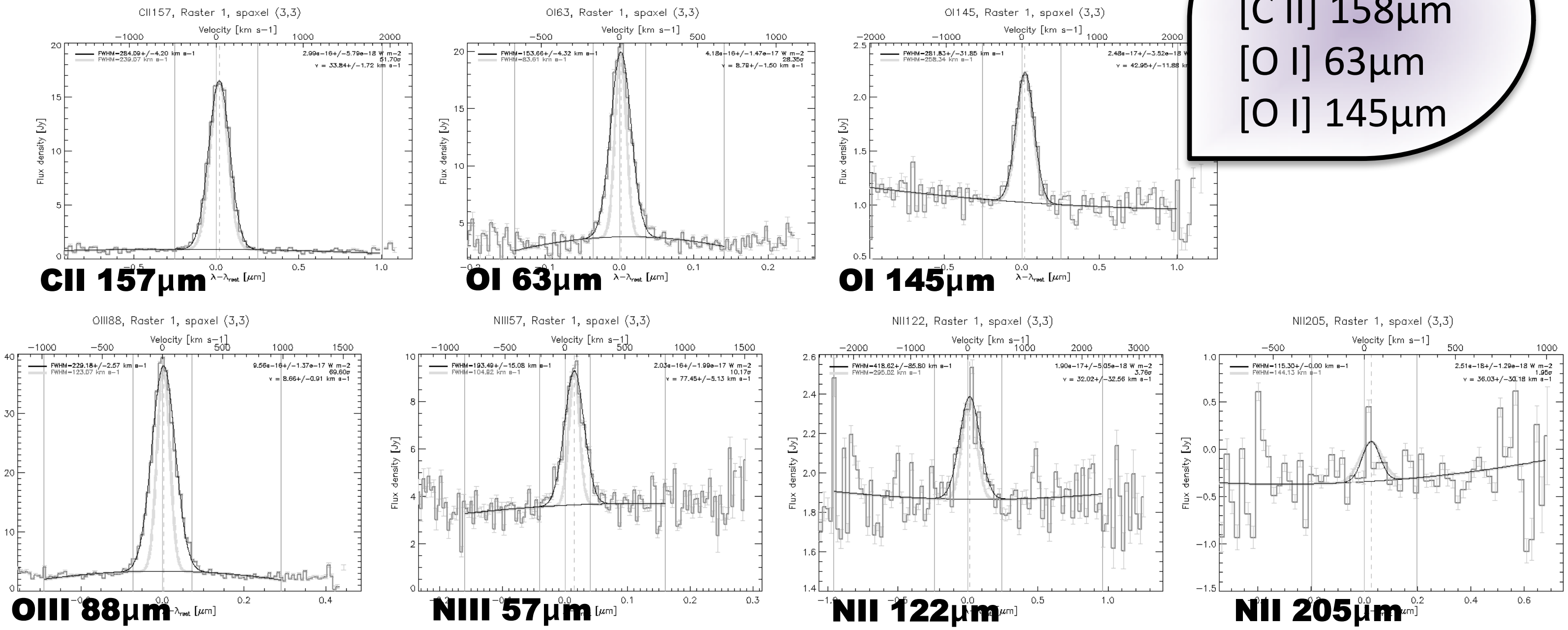
- Low [NII] 122µm fluxes
  ⇒ high-excitation gas dominant

III. Tools to interpret the observations: *observations*

Herschel/PACS

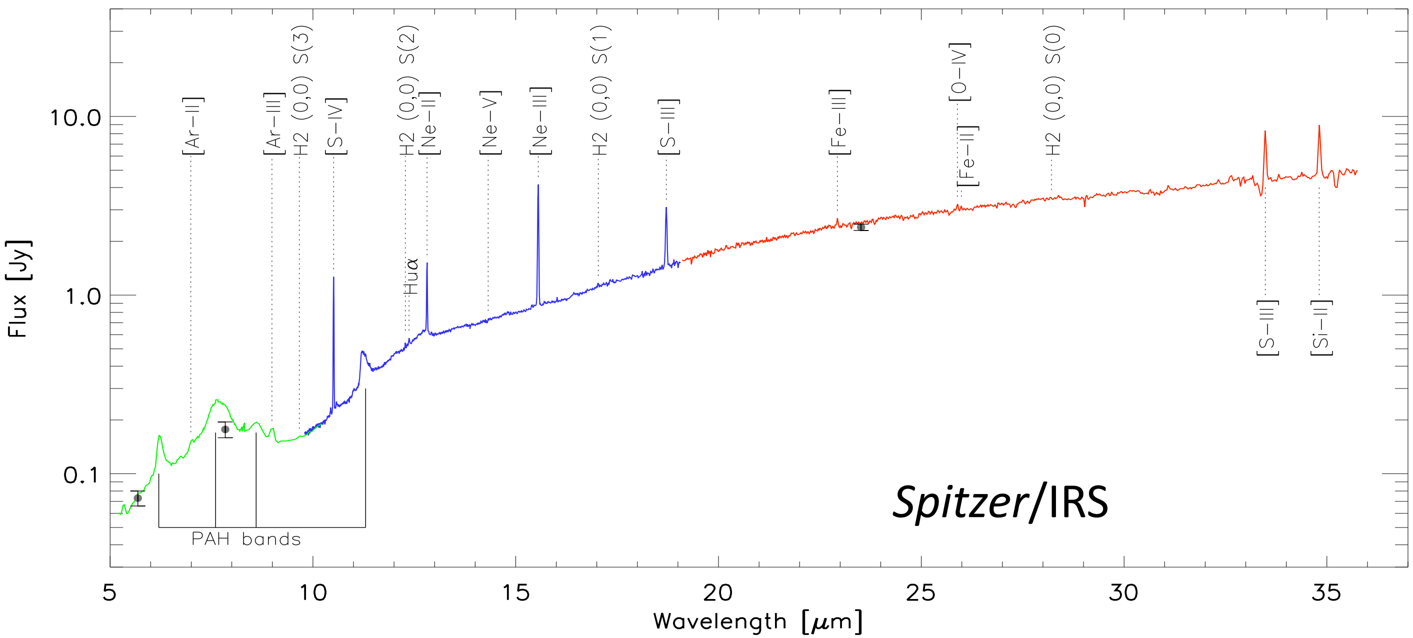
OIII/CII ≈ 2.5

Atomic gas
[C II] 158µm
[O I] 63µm
[O I] 145µm



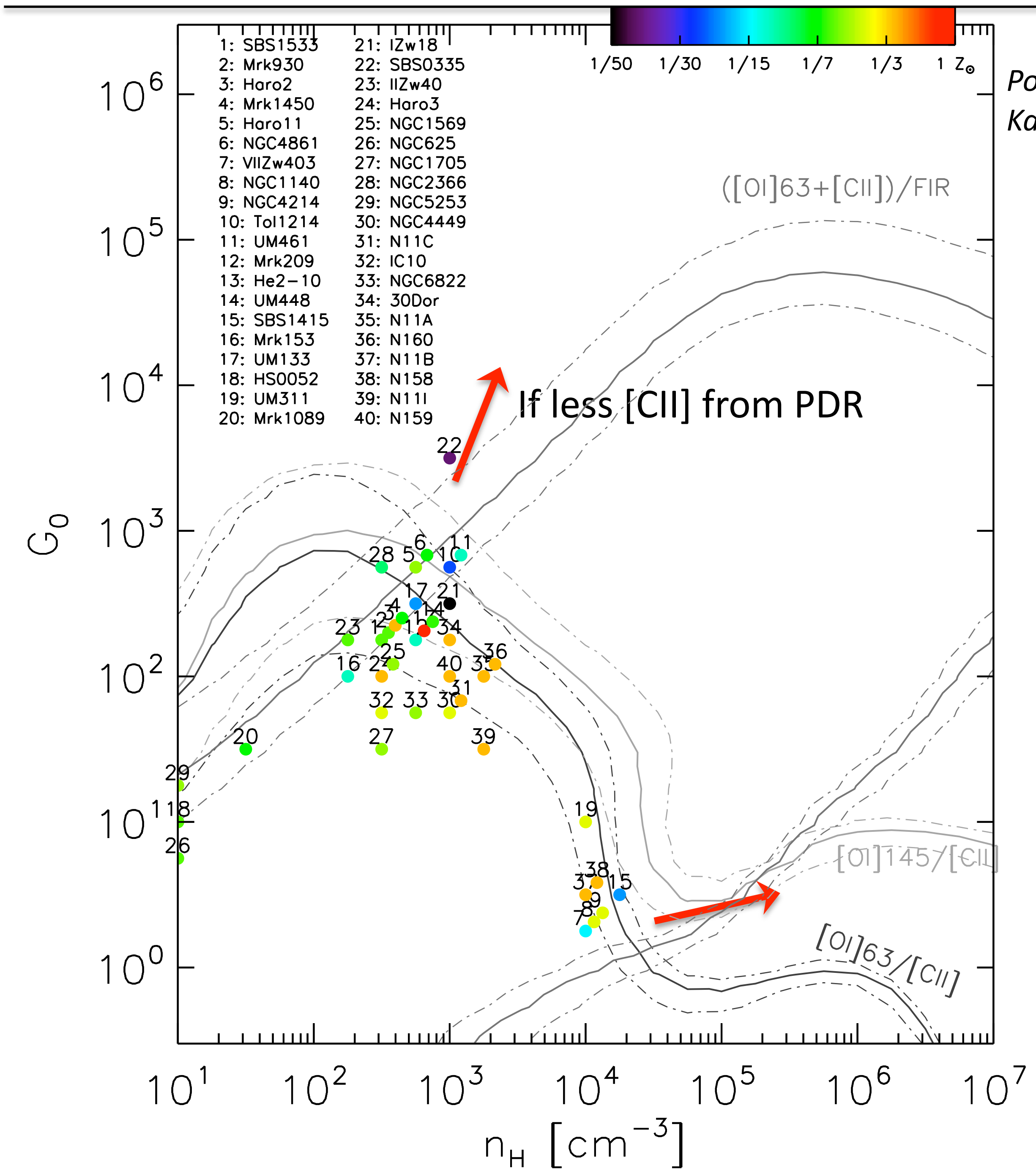
Ionized gas
[N II] 122µm
[N II] 205µm
[N III] 57µm
[O III] 88µm

Ionized gas
[Ne III] 15µm
[Ne II] 12µm
[S IV] 10µm
[S III] 33µm
[S III] 18µm



Spitzer/IRS

III. Tools to interpret the observations: *PDR Toolbox*



Pound & Wolfire 2008
Kaufman et al. 2006

Density: 10^2-10^3 cm^{-3}
G_0: around 10^2 Habing

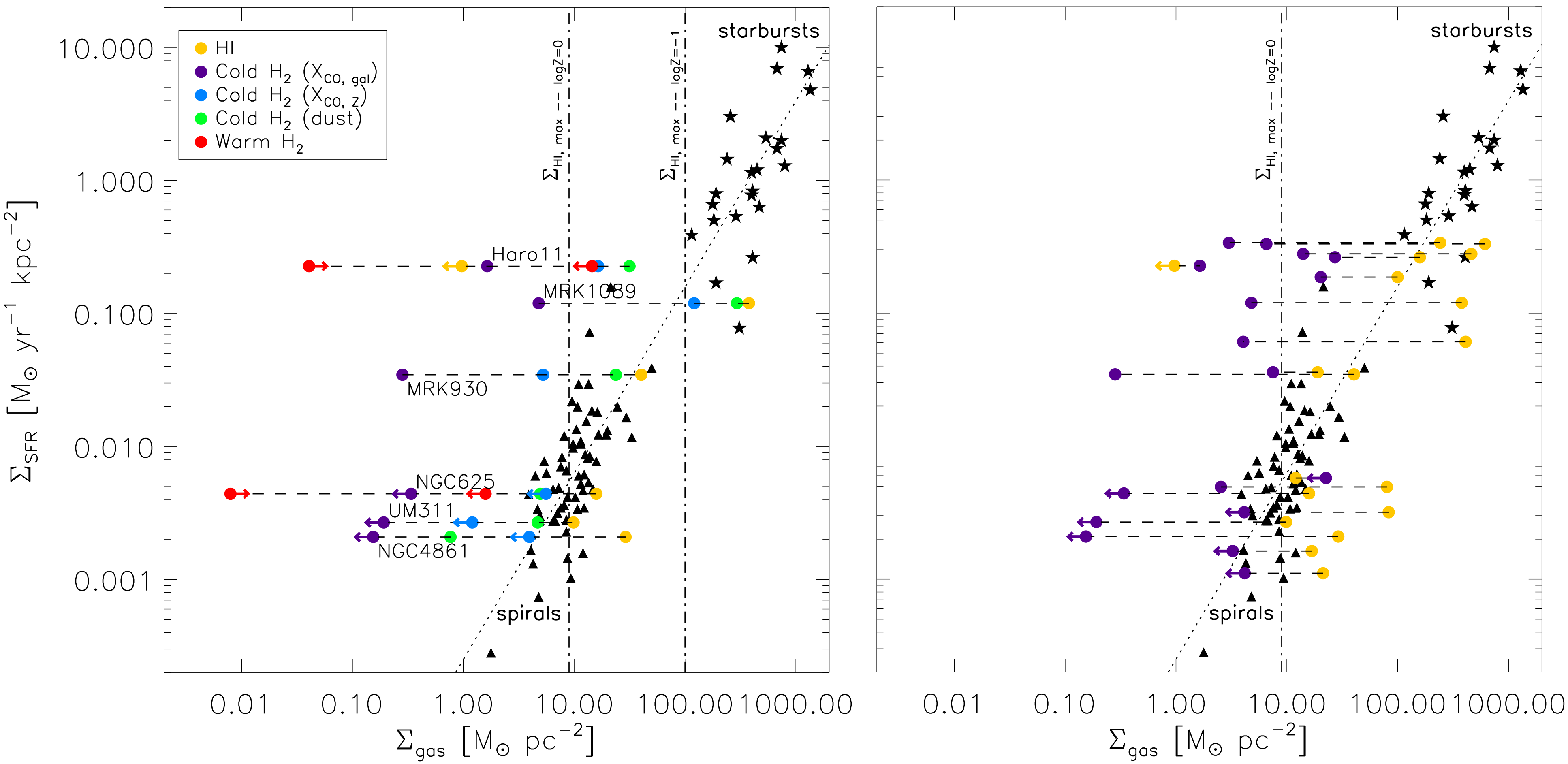
⇒ Average cloud conditions

II. The cold ISM probed by CO: *Schmidt-Kennicutt law*

Most dwarf galaxies **HI dominated**
Possible large fraction of dark gas to be calibrated

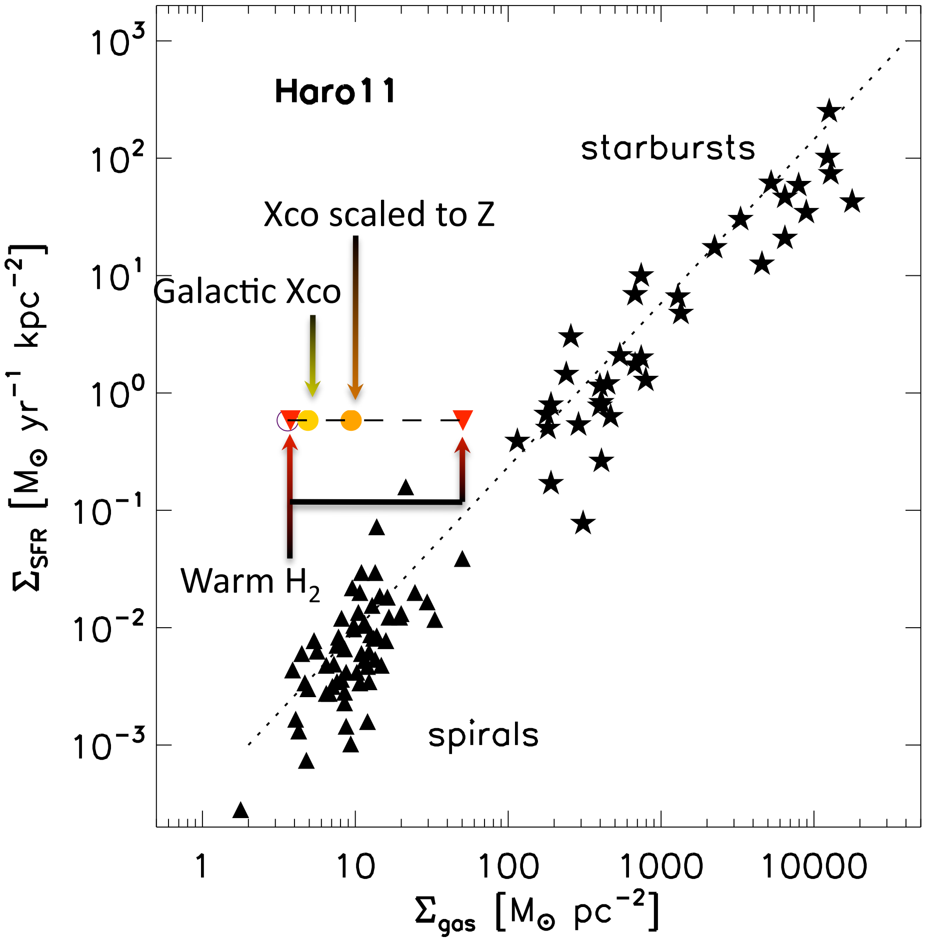
⇒ What is the role of the different gas reservoirs in the SF process?
⇒ What are the true source sizes and distribution?

Kennicutt et al. 1998

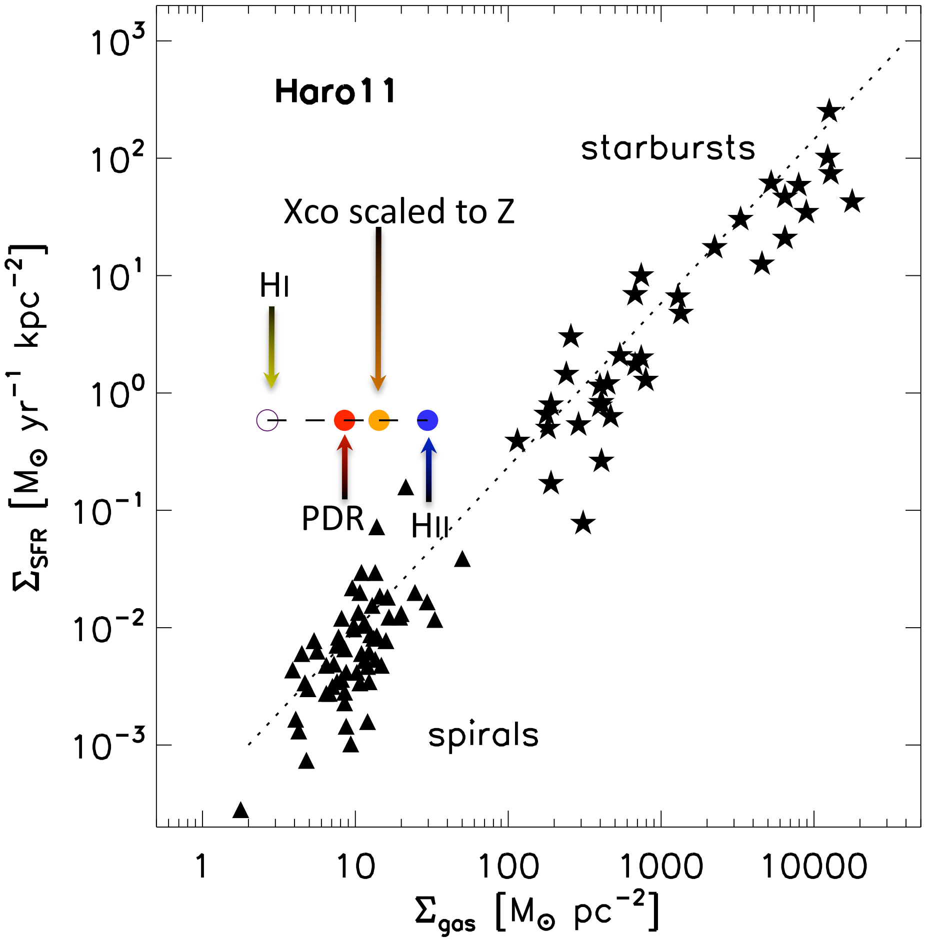


Haro11: The Schmidt-Kennicutt diagram

Observations



Models



=> $\alpha_{CO} = M(H_2)/Ico = 45$

The *Herschel* Dwarf Galaxy Survey (*Madden et al. 2013*)