

The ISM properties of low-metallicity star-forming galaxies



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Motivations

Is star formation proceeding differently?

What are the roles of the different gas reservoirs?

Can the PDR lines such as C+ trace the star-forming gas?

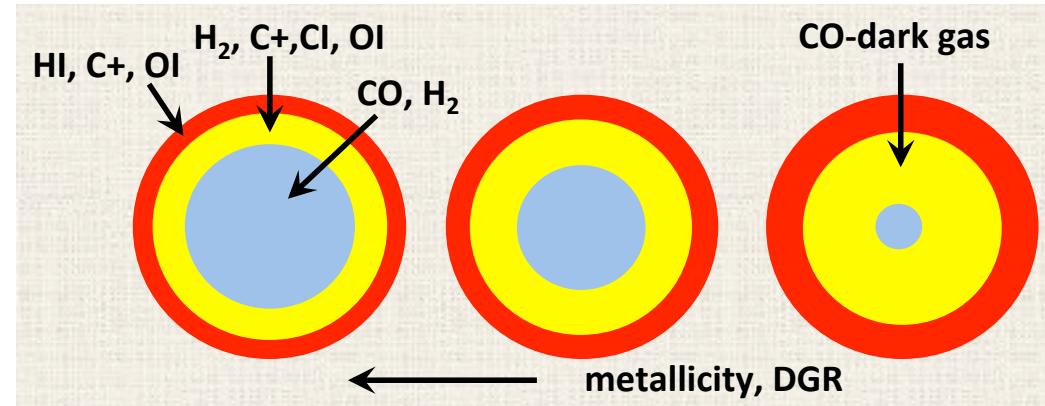
***Goal: characterize the physical conditions
and structure of the low-metallicity ISM***

FIR lines observed at high-redshift (ALMA, IRAM, CCAT)

Maiolino et al. 2009, Stacey et al. 2010, Ota et al. 2014

-> need to understand local templates

Tracing star formation with the FIR fine-structure lines

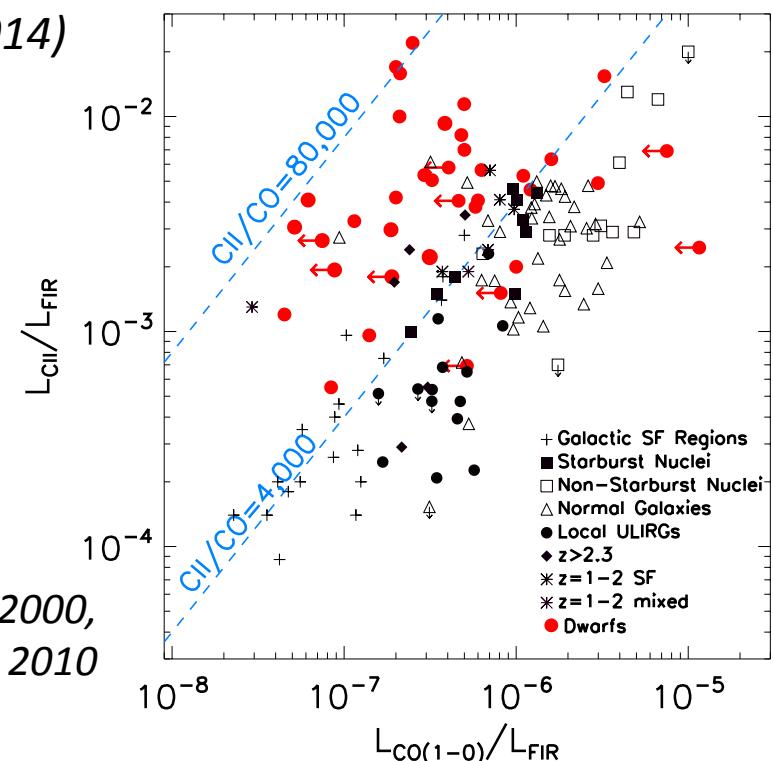


e.g. Bolatto et al. 2013

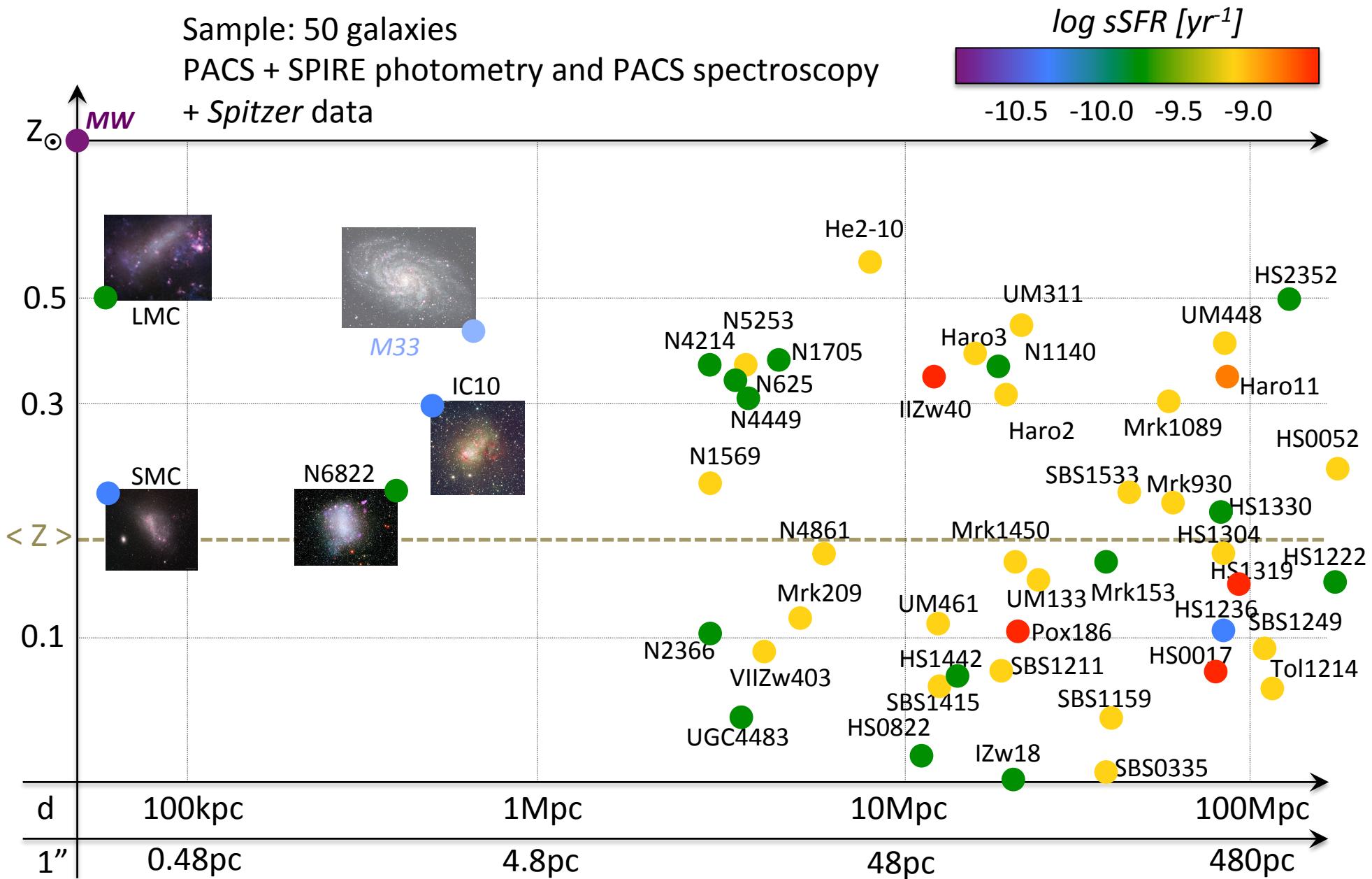
Little CO detected and evidence of CO-dark gas → No handle on total molecular gas mass
 (e.g. Poglitsch et al. 1995, Israel et al. 1997, Taylor et al. 1998, Madden 2000,
 Leroy et al. 2007, Schruba et al. 2012, Cormier et al. 2014)

Main coolants of the ISM are the FIR (and MIR) lines:
 [CII] 157μm, [OI] 63μm, [OIII] 88μm
 - Bright in star-forming galaxies (0.1-1% of L_{FIR})
 - Coexist in the PDR with the CO-dark gas

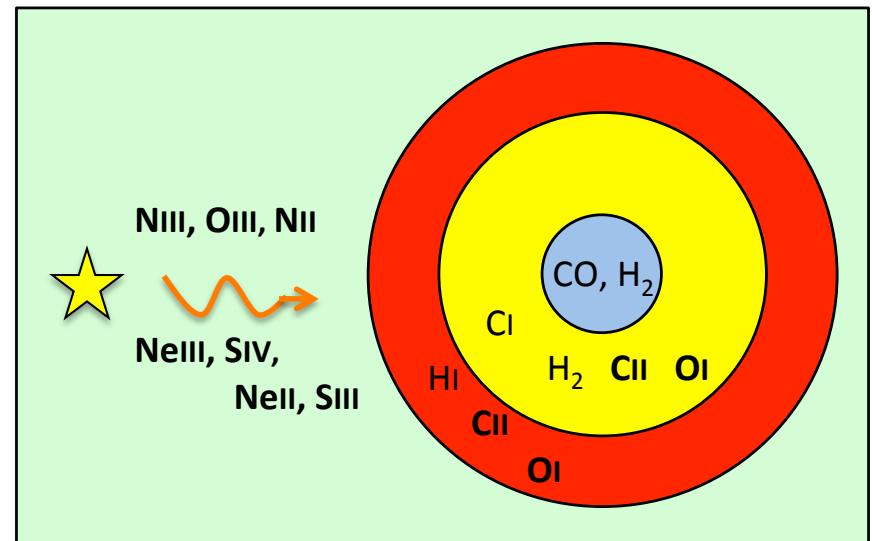
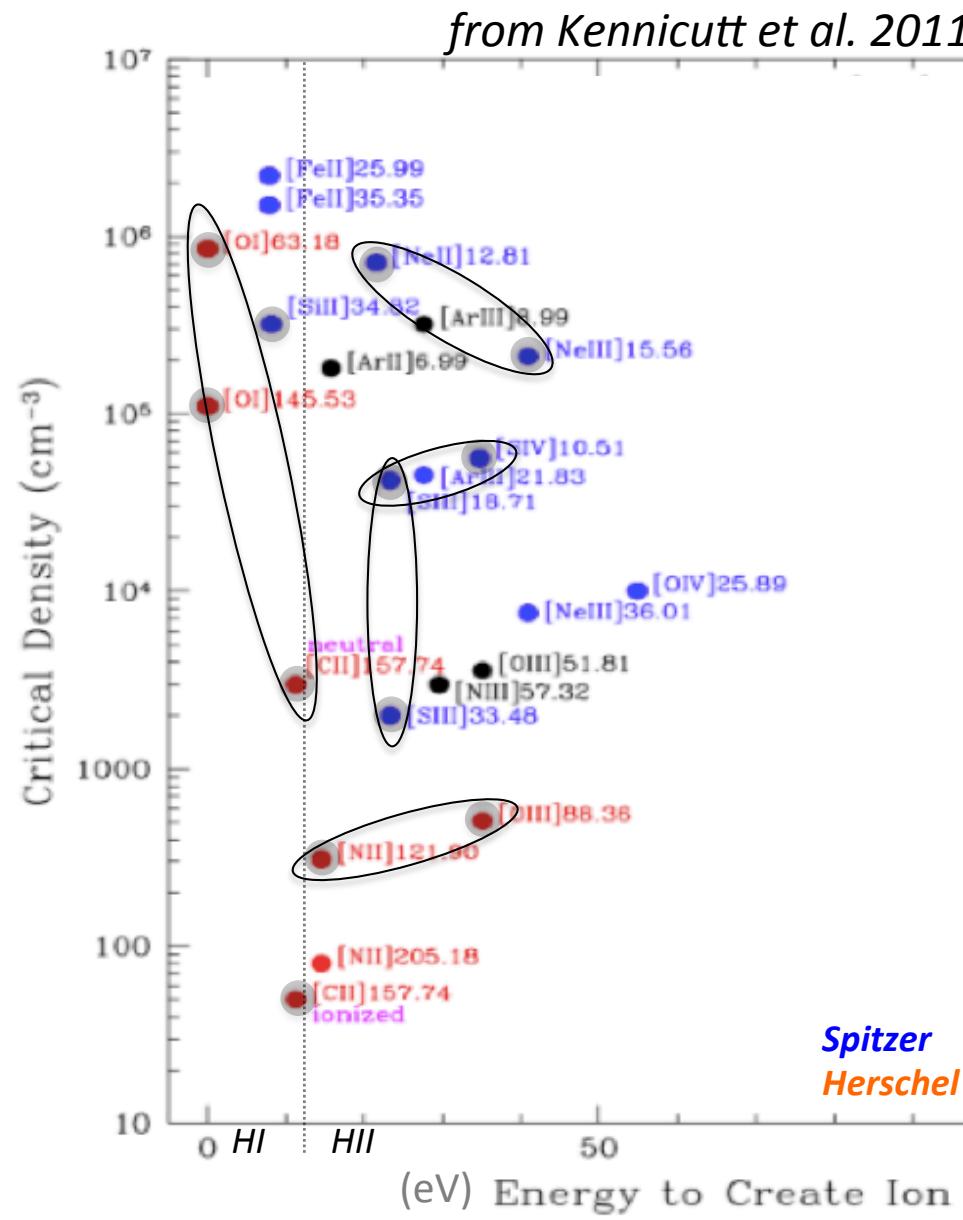
Figure adapted from: Madden 2000,
 Stacey et al. 2010, Hailey-Dunsheath et al. 2010



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



Tracers of the ISM conditions



ISM diagnostics:

$[\text{SIII}]18/33 \Rightarrow$ electron density

$[\text{NIII}]/[\text{NII}]$

$[\text{SIV}]/[\text{SIII}]18 \Rightarrow$ radiation field hardness

$[\text{OIII}]/[\text{NII}]$

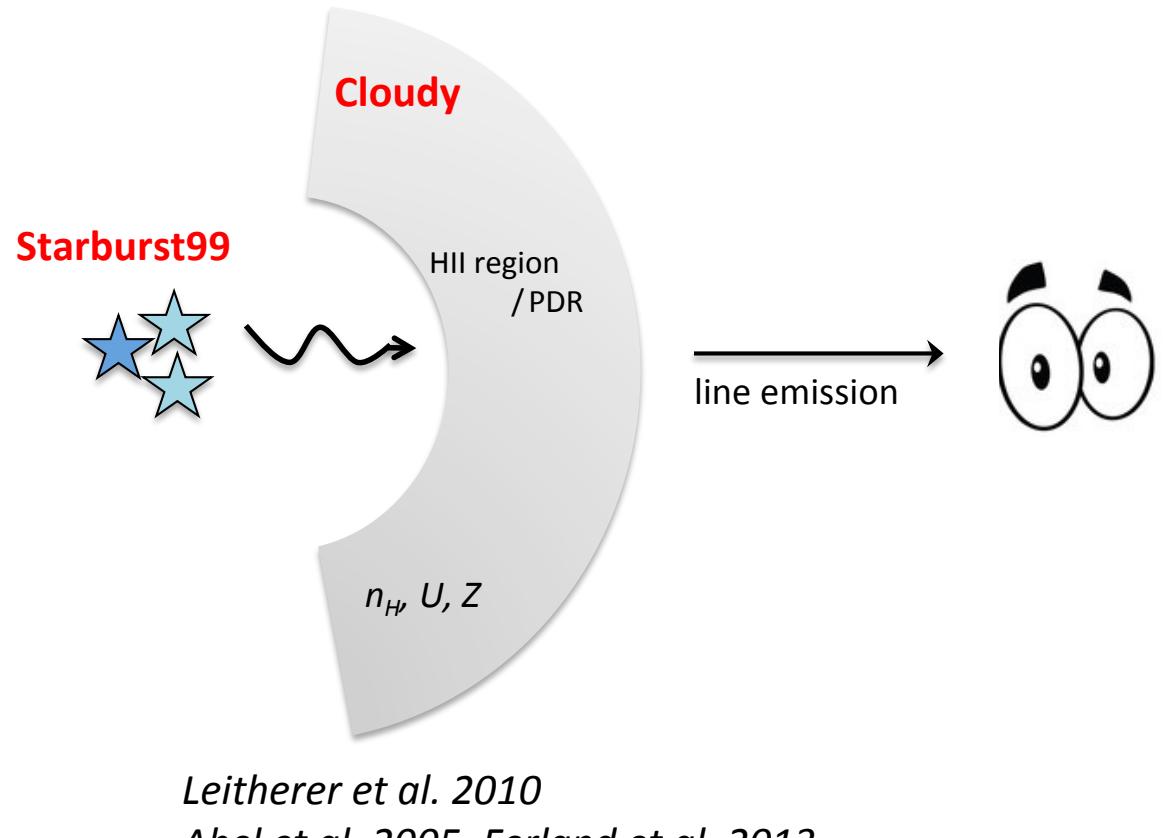
$[\text{OI}]/[\text{CII}] \Rightarrow$ temperature, density

Comparison to metal-rich galaxies: radiative transfer models

Model setting:

Continuous SF of 10 Myr
ISM abundances
Grids varying: n_H and U
Stopped at $A_V = 10$ mag

$Z = 0.15 Z_\odot$ (dwarfs)
 $Z = 2 Z_\odot$ (metal-rich)



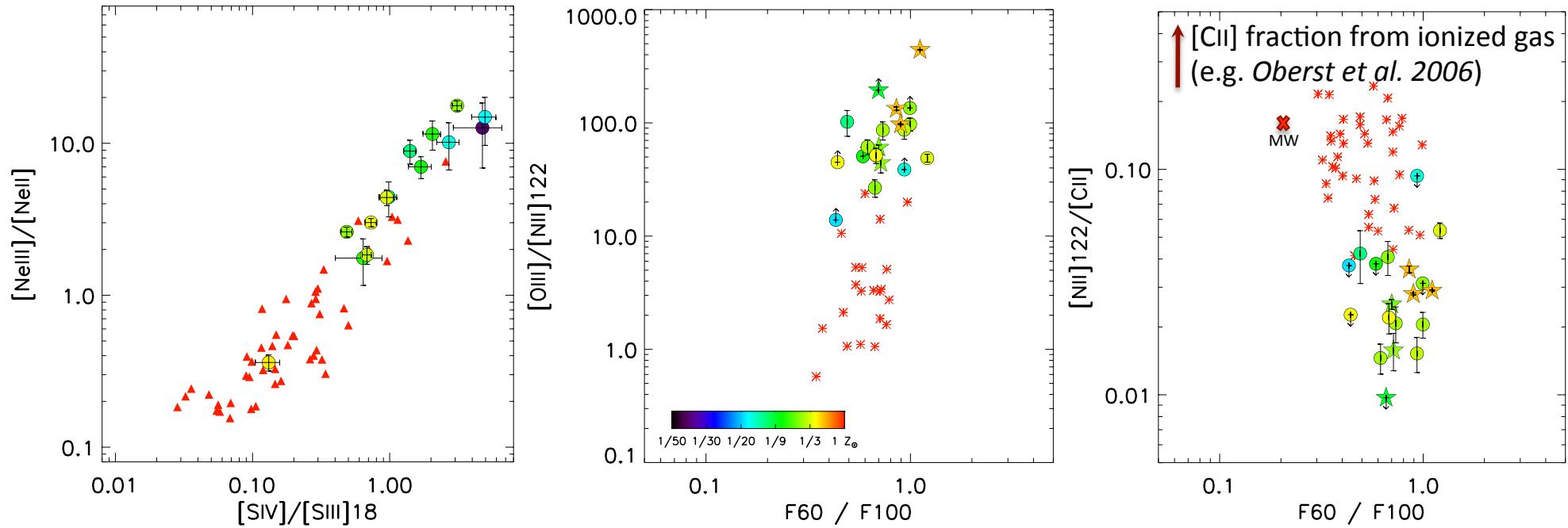
Observations at high metallicity:

Spitzer MIR lines
GOALS (*Inami et al. 2013*)
SINGS (*Dale et al. 2009*)

ISO FIR lines
Brauher et al. 2008

Leitherer et al. 2010
Abel et al. 2005, Ferland et al. 2013

The Herschel Dwarf Galaxy Survey: HII region diagnostics

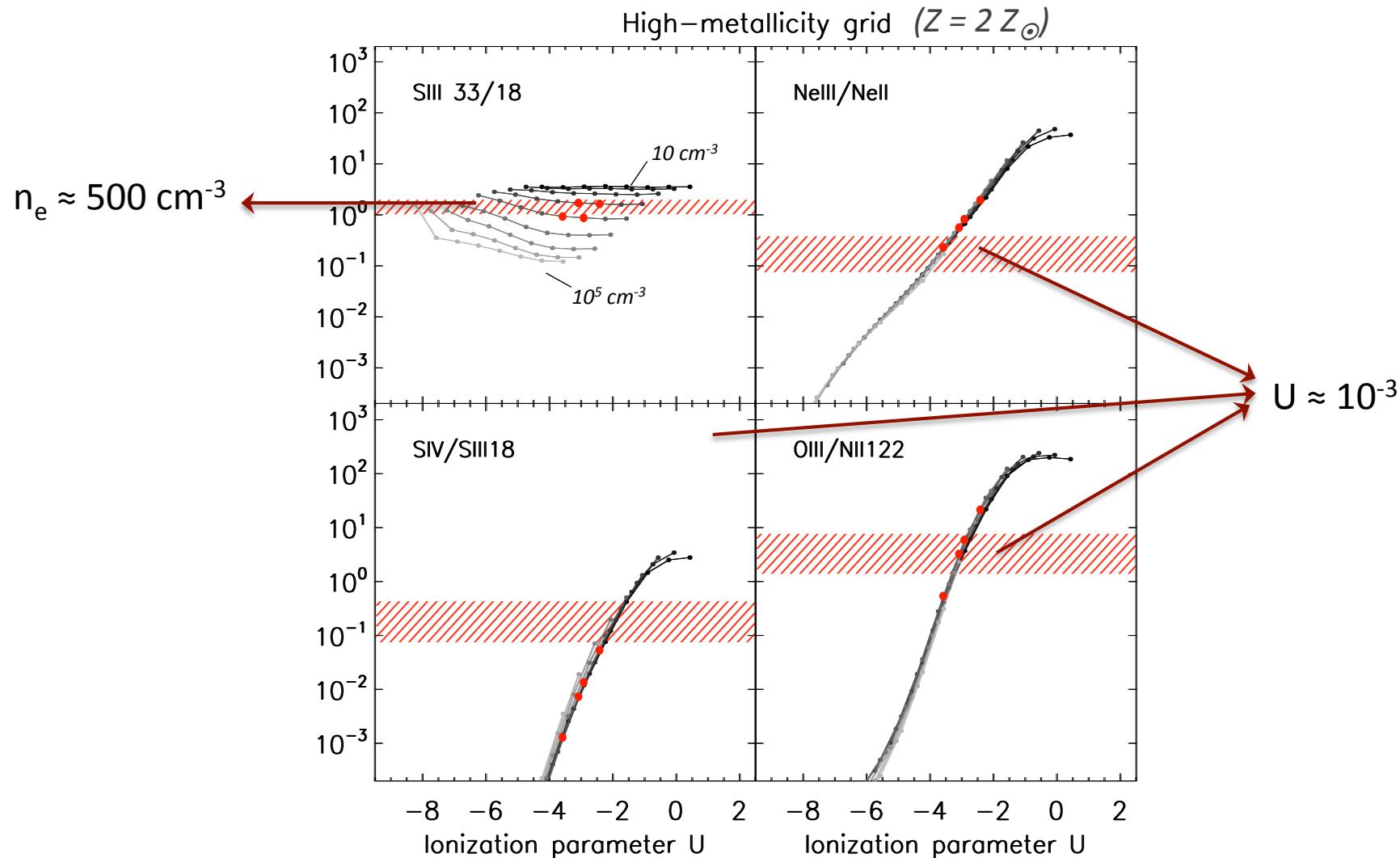


- ▲ Spitzer MIR lines
GOALS (*Inami et al. 2013*)
SINGS (*Dale et al. 2009*)
- * Brauher et al. 2008
ISO data of normal galaxies
- Cormier et al. subm.
Herschel/PACS data of dwarfs

- High $[N_{III}]/[N_{II}]$ (41.0eV) / $[N_{III}]/[N_{II}]$ (21.6eV),
 $[S_{IV}]/[S_{III}]$ (34.8eV) / $[S_{IV}]/[S_{III}]$ (23.3eV),
 $[O_{III}]/[N_{II}]_{122}$ (35.1eV) / $[O_{III}]/[N_{II}]_{122}$ (14.5eV) ratios
 \Rightarrow harder radiation fields
- Little $[C_{II}]$ (11.3eV) from the ionized gas
($\approx 50\%$ in normal galaxies; e.g. *Malhotra et al. 2001*)

See also Hunter et al. 2001

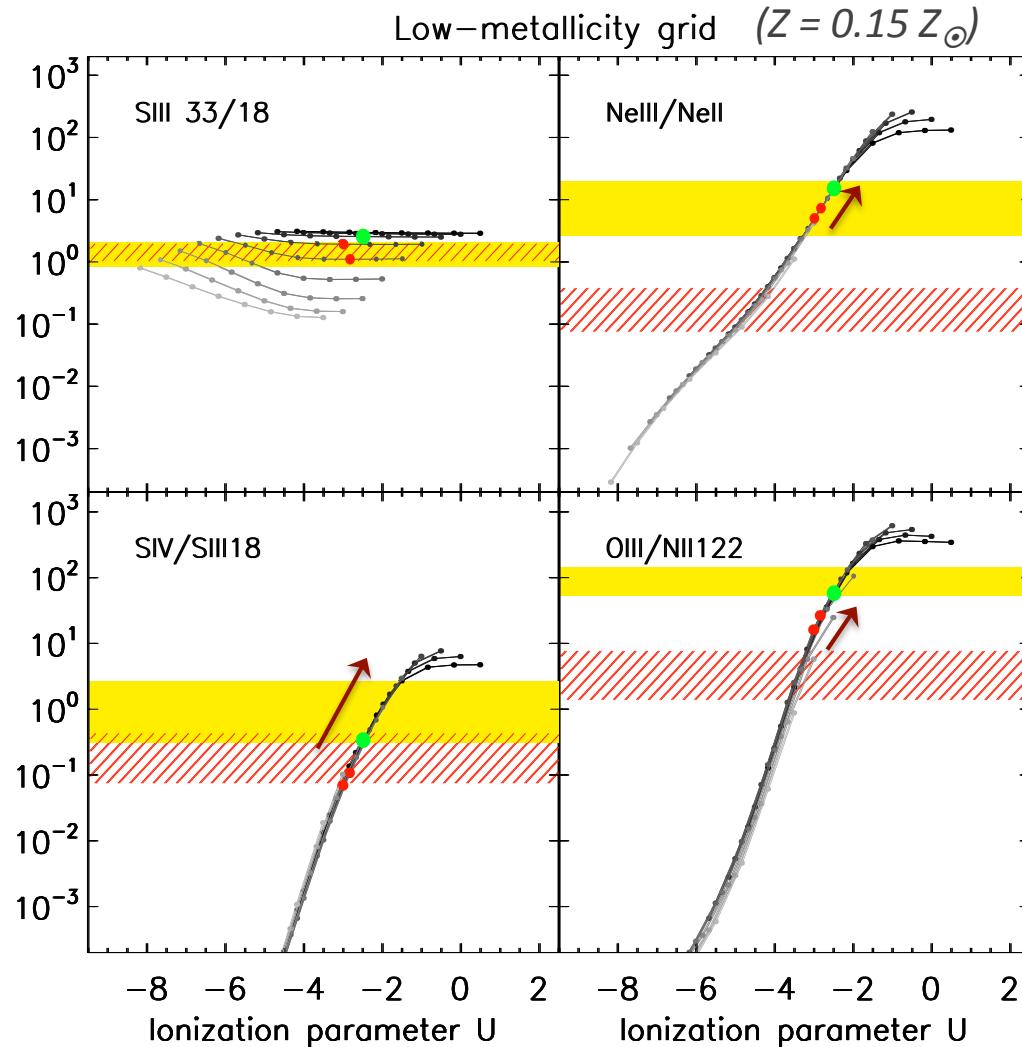
Comparison to metal-rich galaxies: HII region at high metallicity



Cormier et al. subm.

See also: Dale et al. 2009, Inami et al. 2013

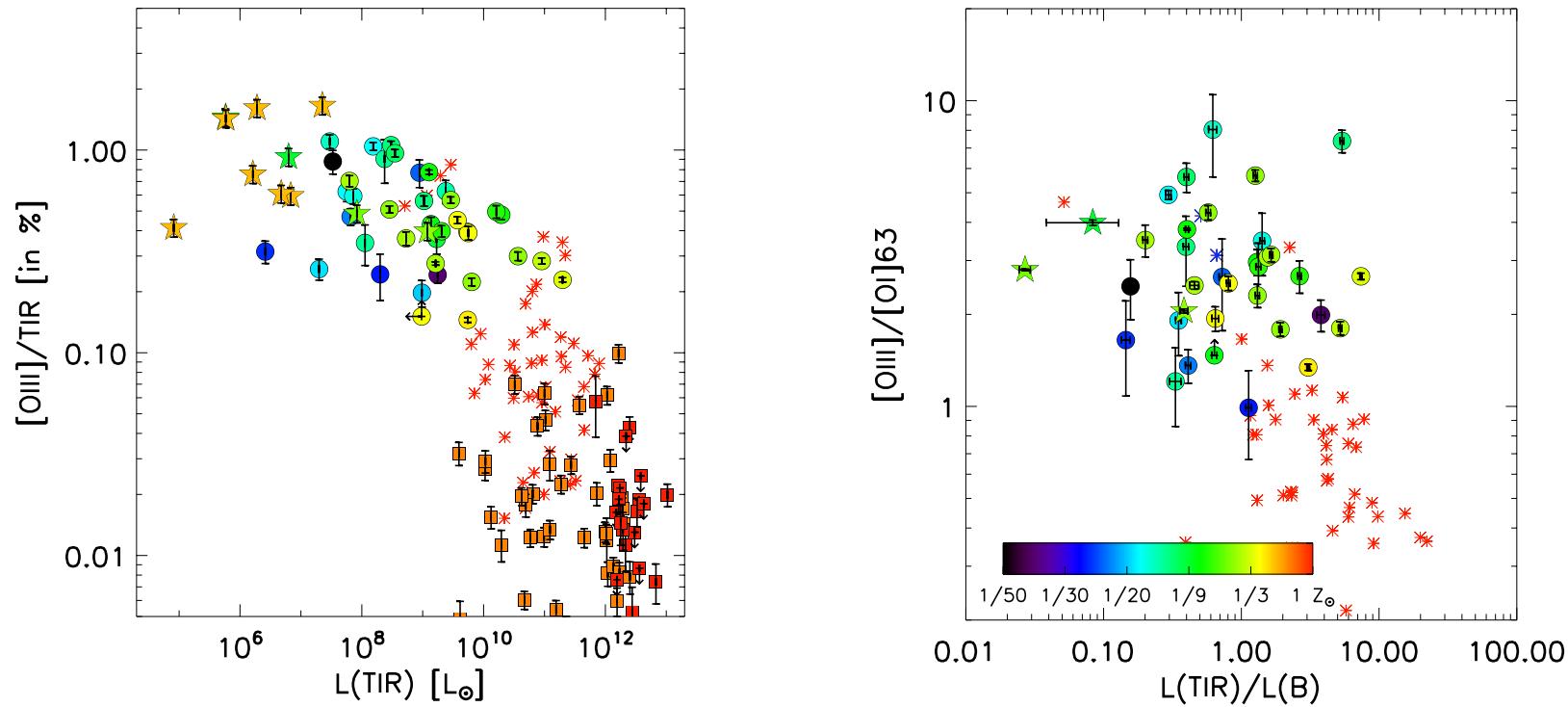
Comparison to metal-rich galaxies: HII region at low metallicity



$n_e \approx 200 \text{ cm}^{-3}$
 $U \approx 10^{-2.5}$

⇒ larger filling factor of ionized gas ($R_{\text{low-}Z} \approx 3 R_{\text{high-}Z}$)

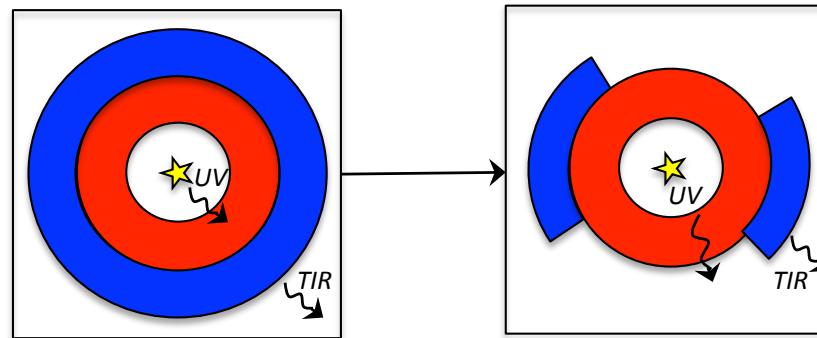
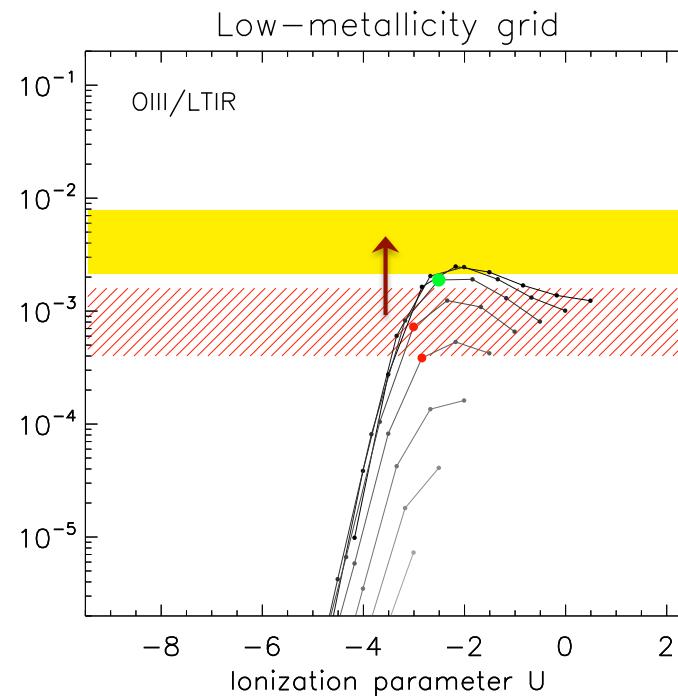
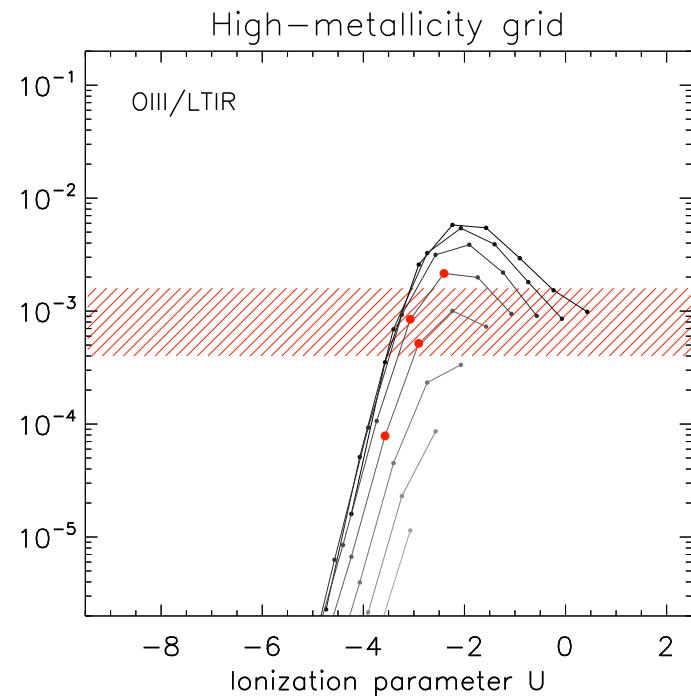
The Herschel Dwarf Galaxy Survey: phase distribution



- * *Brauher et al. 2008*
- *Farrah et al. 2013*
- *Gracia-Carpio et al. 2011*
- *Cormier et al. subm.*

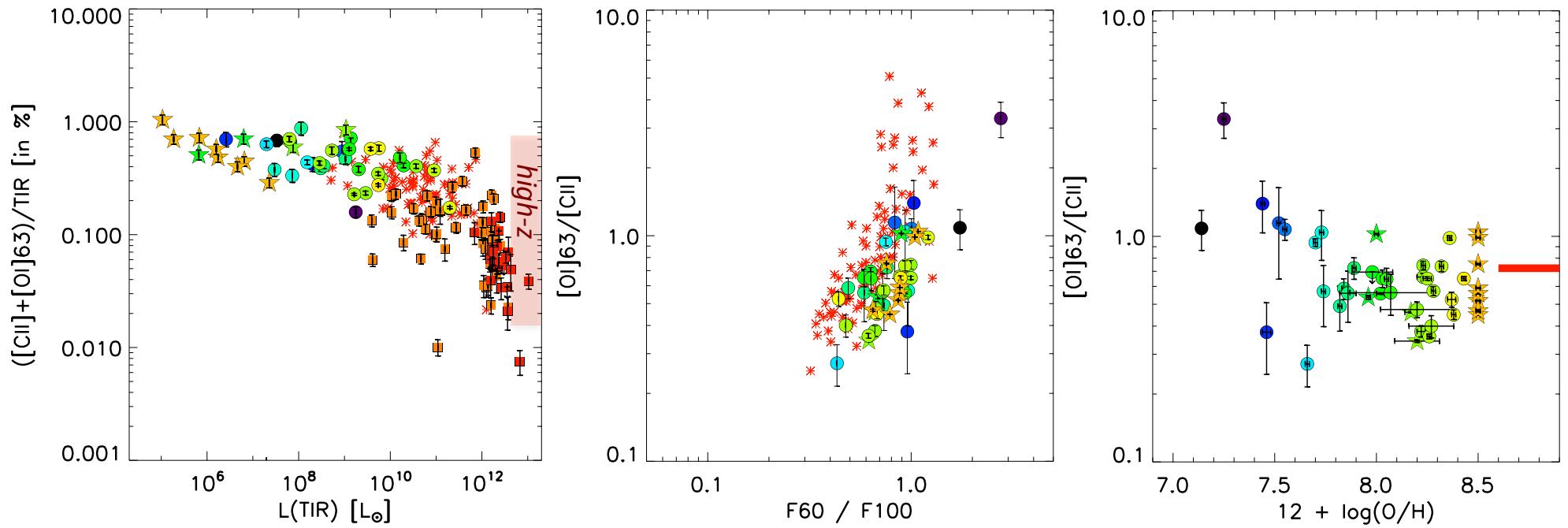
• High $[OIII]/[OI]$ and $[OIII]/TIR$ ratios
 ⇒ different filling factor of ionized/neutral gas

Comparison to metal-rich/metal-poor galaxies: phase distribution



⇒ UV escape fraction: higher HII/PDR filling factor (≈ 3)

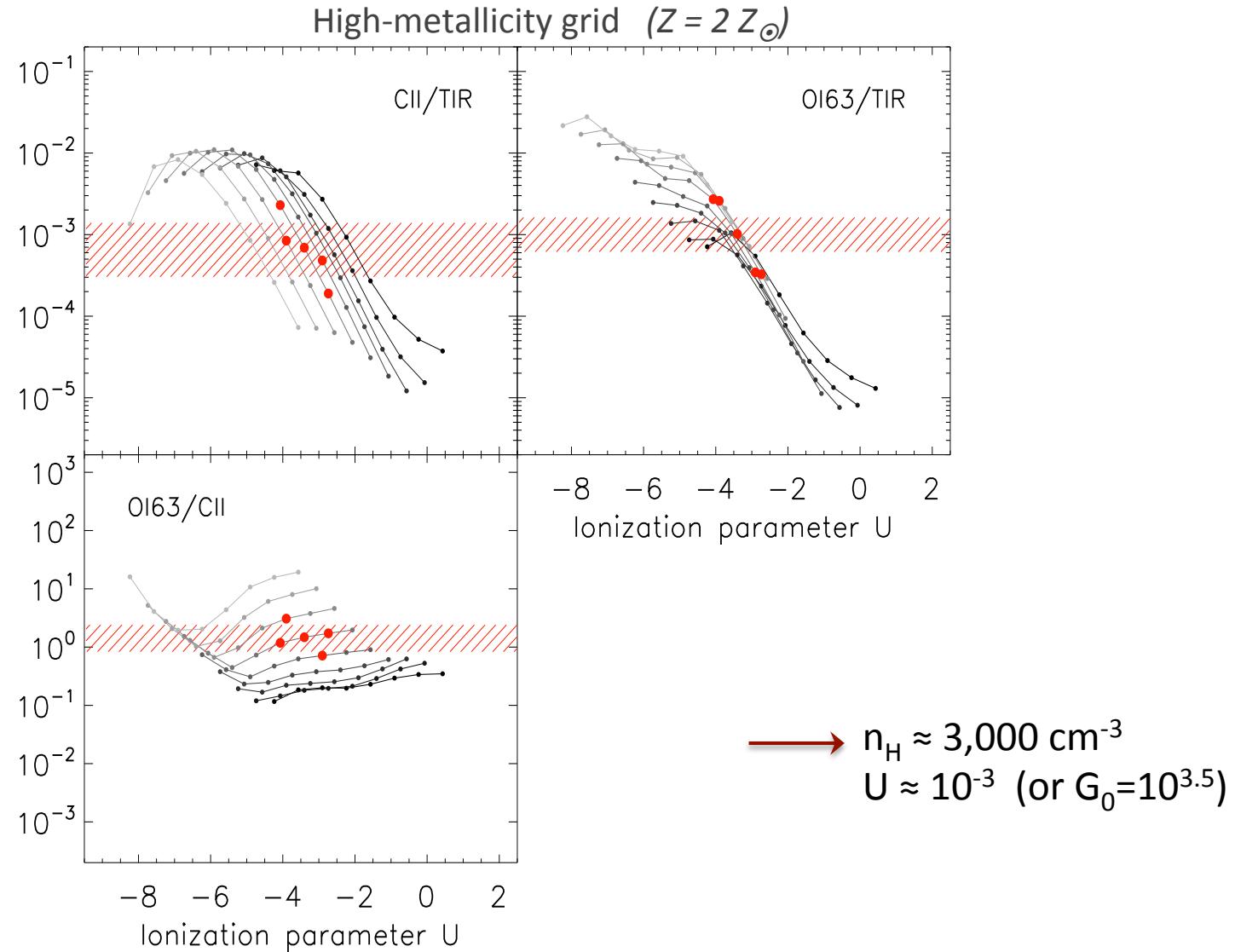
The Herschel Dwarf Galaxy Survey: PDR diagnostics



- * *Brauher et al. 2008*
- *Farrah et al. 2013*
- *Gracia-Carpio et al. 2011*
- *Cormier et al. subm.*

- No line deficit, emission enhanced on galaxy-wide scales
- [OI]/[CII] ratios vary by one order of magnitude
⇒ non-uniform properties
- No clear trends identified with metallicity

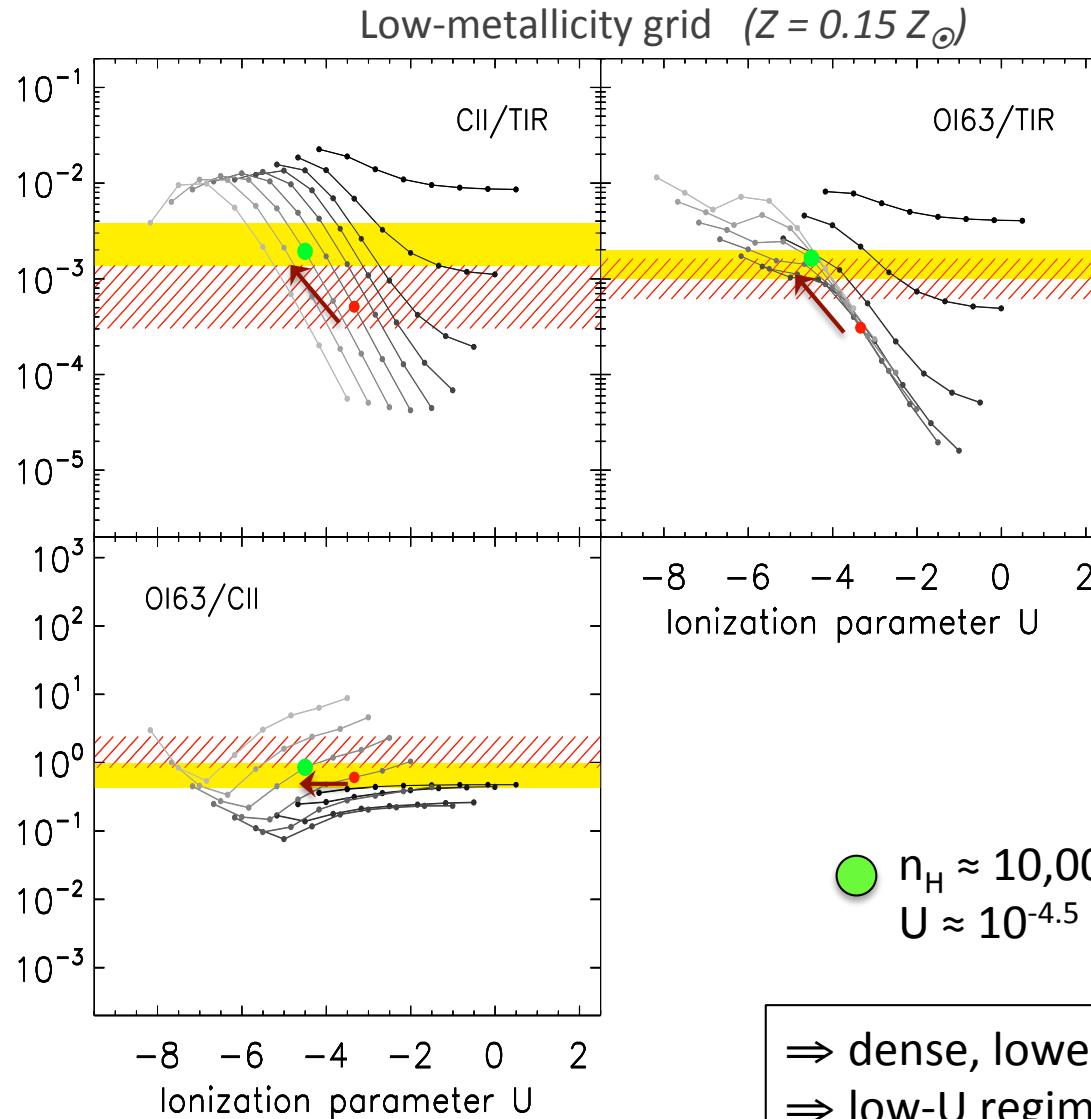
Comparison to metal-rich galaxies: PDR at high metallicity



50% non-PDR emission

Malhotra et al. 2001, Negishi et al. 2001

Comparison to metal-rich galaxies: PDR at low metallicity



● $n_H \approx 10,000 \text{ cm}^{-3}$
 $U \approx 10^{-4.5}$ (or $G_0 = 10^{2.5}$)

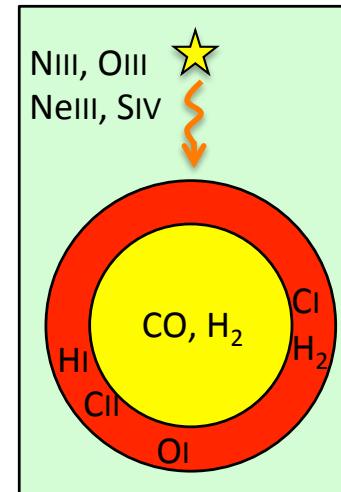
⇒ dense, lower covering factor PDRs
 ⇒ low- U regime: no line deficit
 (grain charging $\Leftrightarrow G_0/n_H$)

Conclusions and perspectives

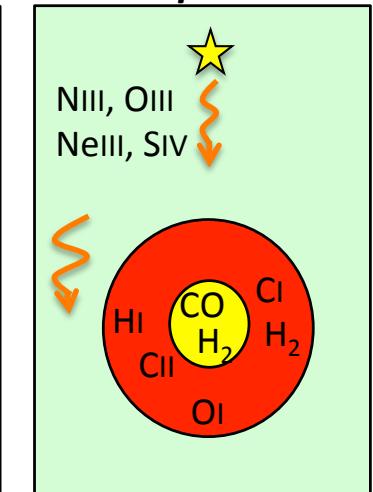
Herschel reveals the ISM of star-forming dwarf galaxies

- FIR lines detected down to $1/40 Z_{\odot}$
- Different line ratios than in metal-rich galaxies
- No direct trends with metallicity
maybe an increase of [OI]63
- Harder radiation fields (high [OIII]/[NII]) and dense clumpy PDRs ([OI])
- Leaky structure with high filling fraction of ionized gas where UV photons permeate
 - [OIII] and [OI] promising for high-redshift studies
 - More detailed PDR modeling: XDR, cosmic rays, grain properties
 - Calibrate [CII], CO and the dark gas (Madden et al. in prep.)
 - **Resolving the ISM with sensitive instruments is key**
spatial/spectral CO (ALMA, NOEMA), spectral FIR lines with SOFIA

Metal-rich ISM

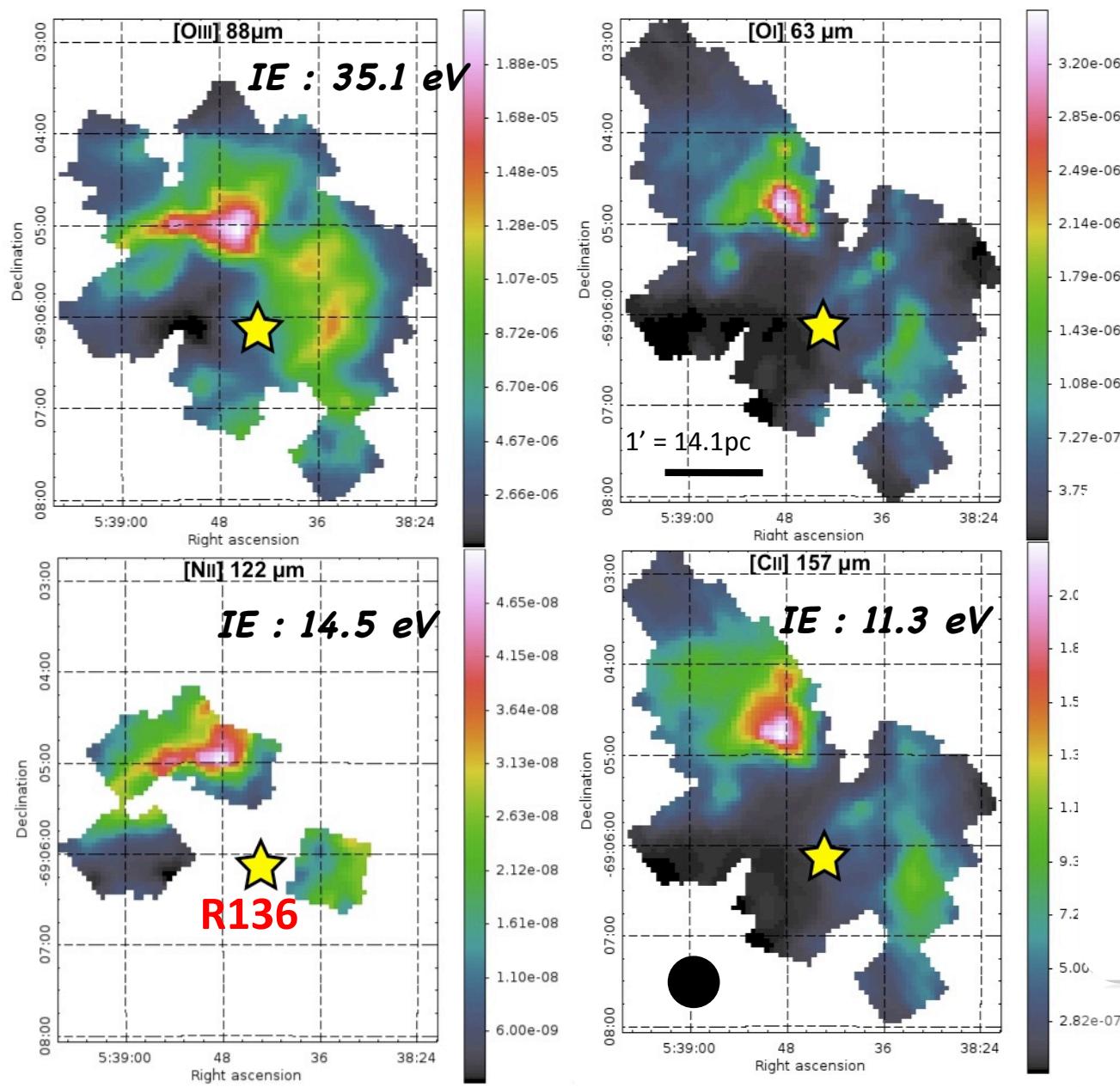


Metal-poor ISM



Magellanic Clouds: 30 Doradus ($12'' \leftrightarrow 3\text{pc}$)

Chevance et al. in prep.



Meudon PDR code (G_0, n_{H})
+
Stellar radiation field
↓
3D distribution of gas

