# From Low Metallicity Unresolved Dwarf Galaxies to Resolved Scales in the LMC

*Suzanne Madden, CEA Saclay, France*

# Some questions: Star formation and low metallicity ISM

Why do we care about low mass local universe dwarf galaxies?

- Small, faint, low Z, numerous…
- analogs to high z (Ouchi et al 2020)
- dominant sources of reionization of the universe. (Katz et al 2023; Atek et al. 2024)

What are the effects of low Z on the ISM ?

- Less metals in the gas – effects on gas cooling
- Less dust overall => less dust to shield each parcel of gas from UV
    - Molecule formation – depends on dust formation

*How ISM properties & structure evolve as a function of metallicity*

Consequences of low Z ISM on Star Formation

- How do stars form out of gas and dust in metal-deficient environments?
- Feedback from star formation and its effect in low Z ISM ?

What galactic properties and processes control the dust and gas evolution?

- **Modeling** unresolved dwarfs….disentangling ISM structure, radiation field, SF, etc
- **Our immediate goal here -> quantify the CO-dark gas**
- *We are rich in data at all wavelengths – better multiphase models & simulations necessary*

Zoom into our nearest neighbor low metallicity galaxies:

- The Magellanic Clouds - -> SOFIA LMC+ Legacy Program – ***Work in progress***

# Gas and Star Formation in Dwarfs: MIR & FIR spectro *observations*

How do dwarfs stand out observationally? => 3 unique observational signatures

(1) Cold ISM difficult to observe: Tacconi+1985, 1987, *Sage+1992, Taylor+1998, Gondhalekar+1998, Barrone+2000, Leroy+2005,2007, Buyle+2006,Schruba+ 2012, Elmegreen+2013, Cormier+2014, Hunt+2015, Rubio+2015Shi +2015, Grossi+2016, Cormier+2017, Amorin+2016, Hunt+2017, Cicone+2017, Zhou+2021…*

=> CO many upper limits; not detected at the lowest metallicities, inspite of their vigorous SF

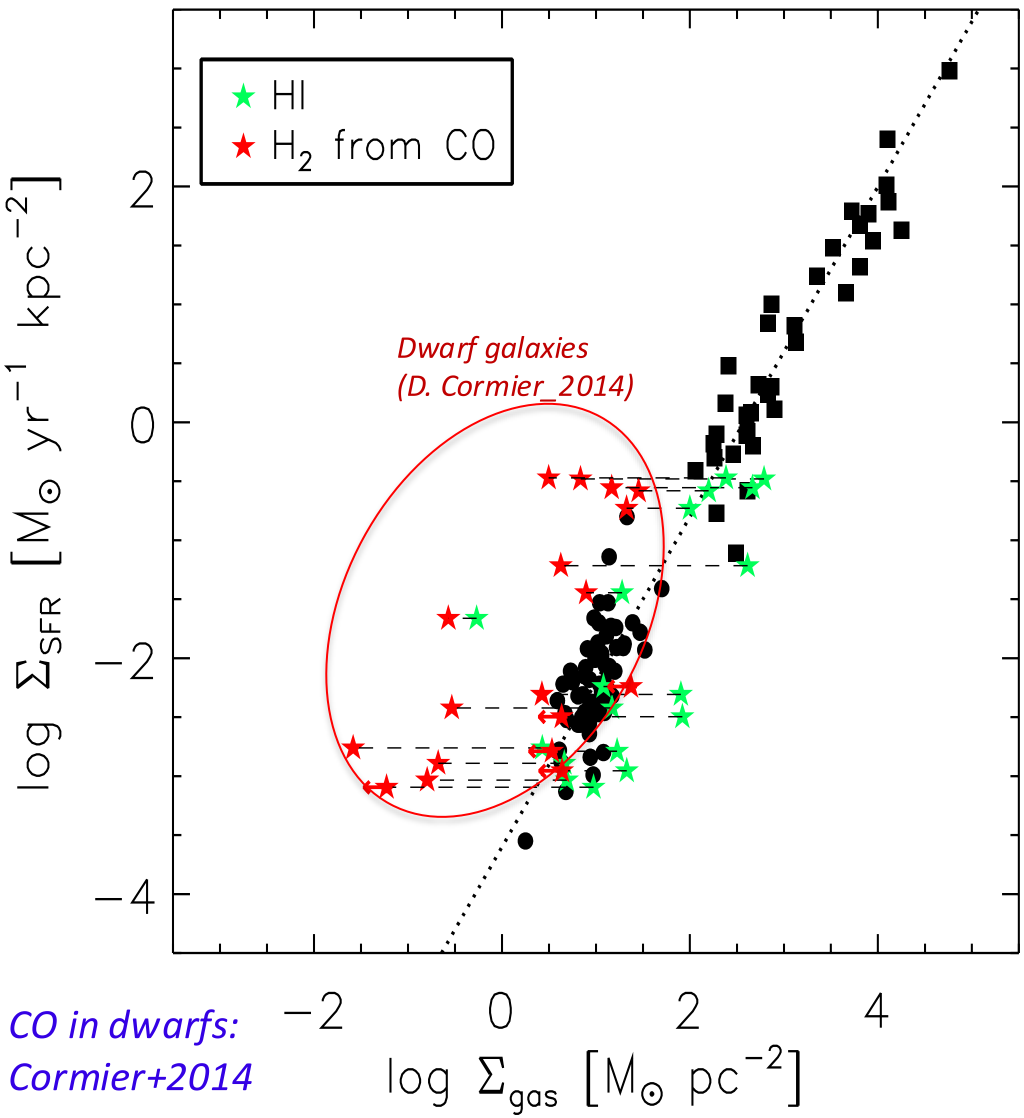
(2) Bright [CII] 158 mu, relative to CO

(3) Prominent MIR high ionization lines (>~ 35 eV)

# LMC+ Motivation: Observations: #1. Gas and Star Formation in Dwarfs

## Global scales

*Kennicutt Schmidt; Kennicutt + 1998*
*See also Kennicutt et de Los Reyes 2021*




*CO in dwarfs: Cormier+2014*

*Molecular gas is weak or undetectable in dwarf galaxies*

*(e.g.Leroy+2012, Schruba +2012, Cormier + 2014, Hunt + 2015, Grossi + 2016, Amorin + 2016)*

⇒ Efficient SF from $H_2$?

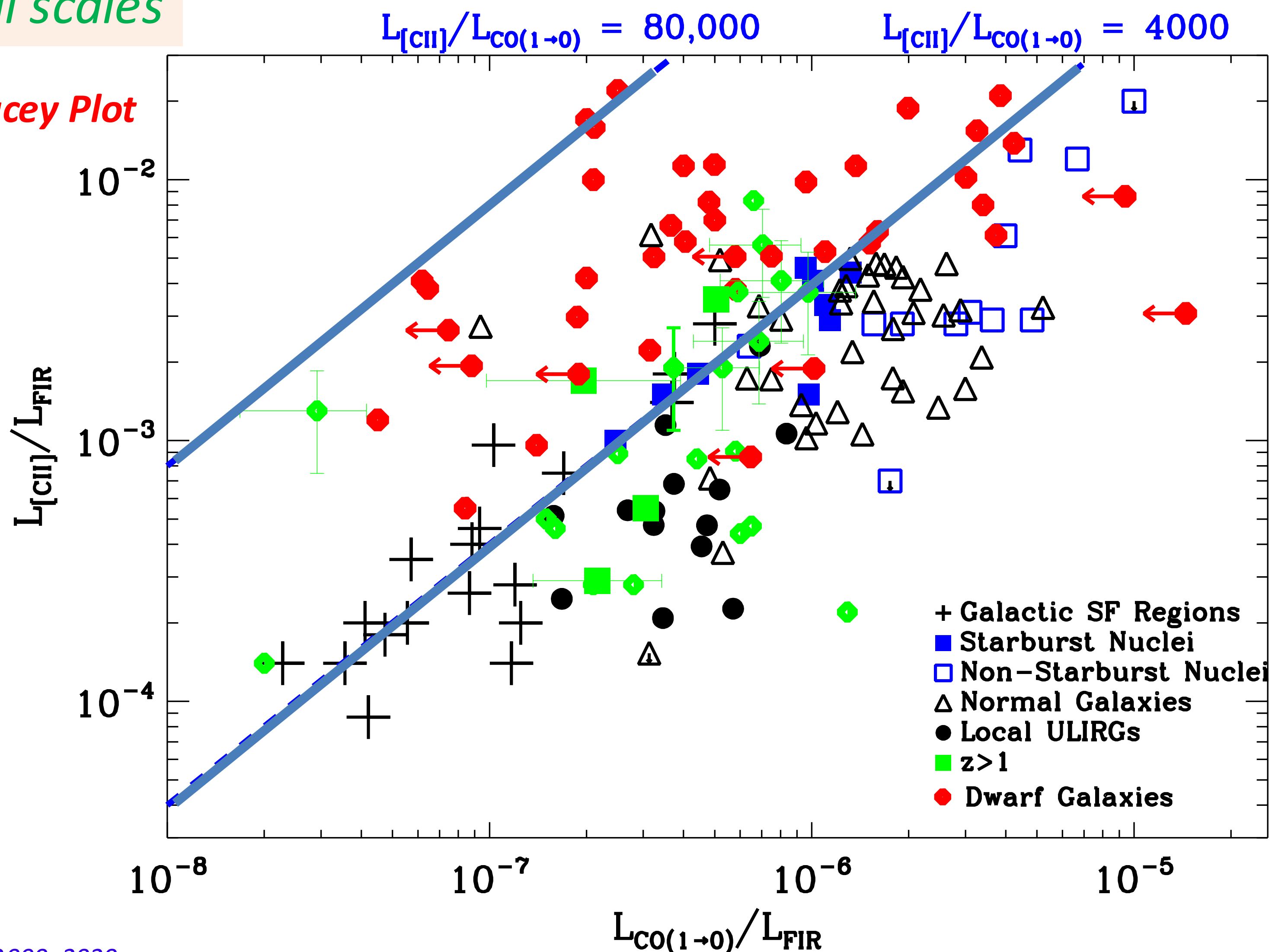
*or* CO not tracing the full $H_2$ mass?

⇒ What is the role & distribution of the different gas reservoirs in the SF process?

# LMC+ Motivation: Observations **#2**. [CII] and CO in dwarfs vs. metal-rich galaxies

*Global scales*

***The Stacey Plot***

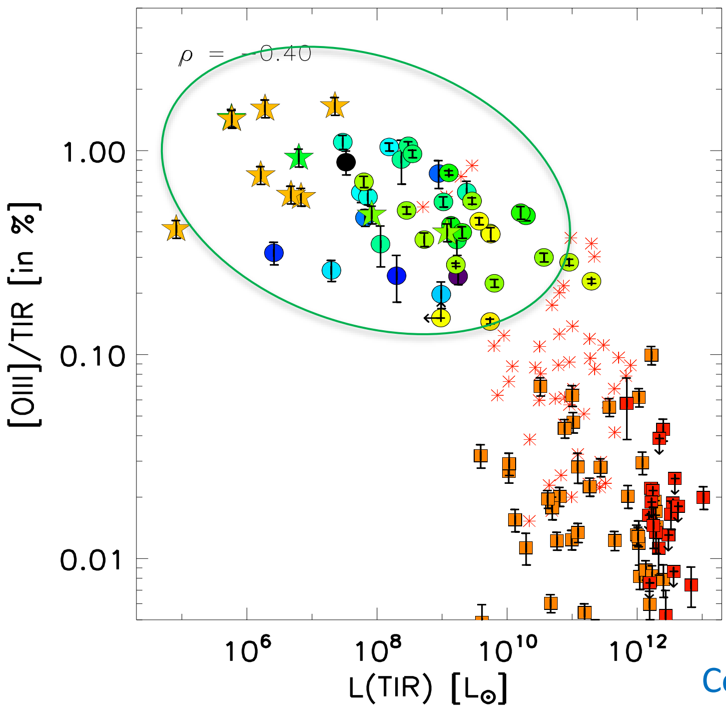


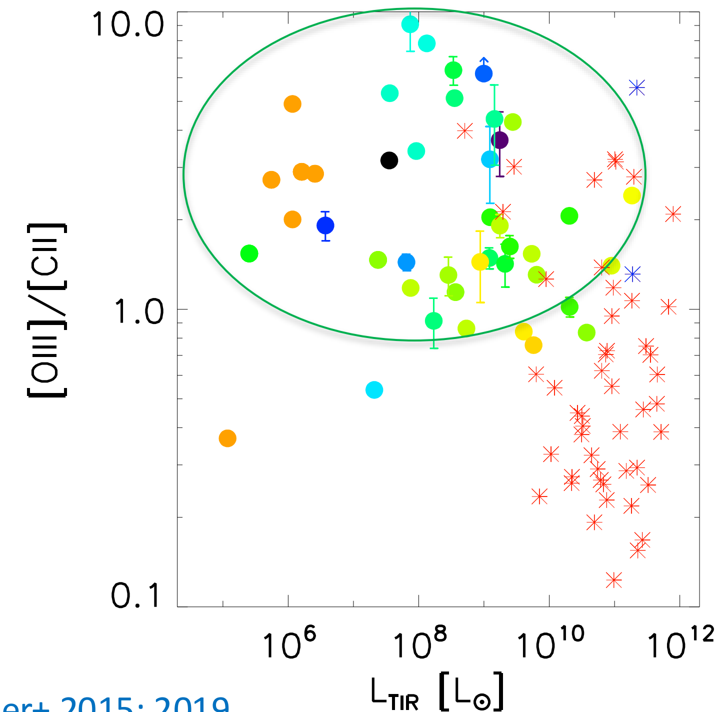

High [CII]/CO ratios observed in star-forming dwarf galaxies

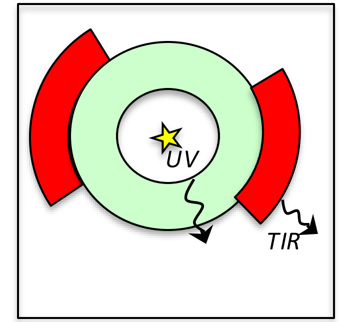
What is this telling us about the molecular cloud/PDR structure at low metallicities?

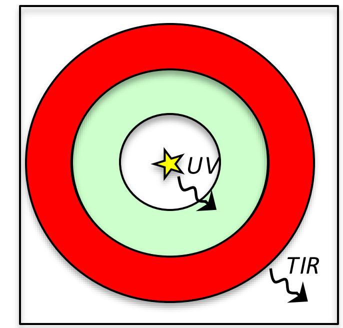
*Madden + 2000, 2020*
*Gullberg + 2015, Aravena + 2016; Maiolino + 2005, Wang + 2013,*
*Figure adapted from:*
*Stacey + 1991, 2010, Hailey-Dunsheath et al. 2010,*

# Gas and Star Formation in Dwarfs #3. [OIII]/LTIR, [OIII]/[CII]




Cormier+ 2015; 2019

- ✳ *Brauher et al. 2008*
- ■ *Farrah et al. 2013*
- ■ *Gracia-Carpio et al. 2011*
- ● *Cormier et al. 2015*

*See also Fernandez-Ontiveros 2016*

SMC: K. Jameson + 2018

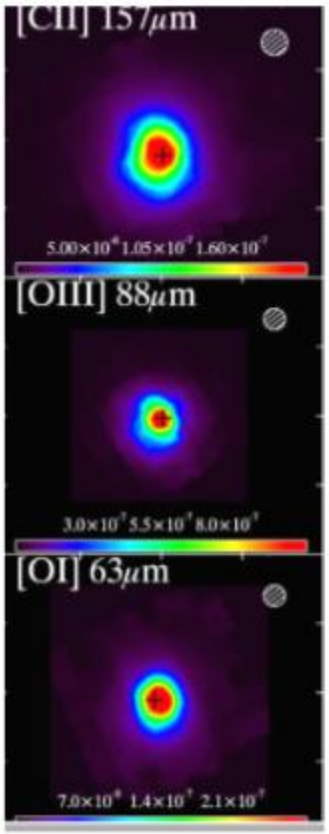
LMC: A. Lambert-Huyghe

- High [OIII] (35 eV)/$L_{TIR}$ &
- High [OIII](35eV)/[CII] (11.3 eV)
- High [NeIII] (41.0eV) / [NeII] (21.6eV)
- [SIV] (34.8eV) / [SIII] (23.3eV)

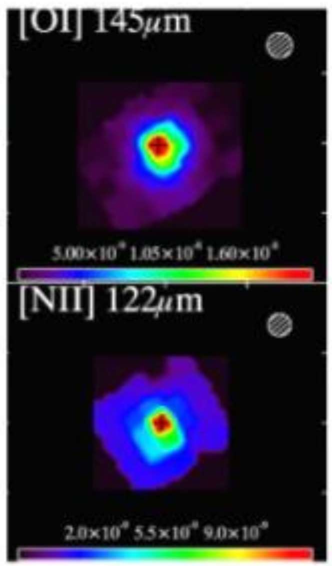
***ISM structure at low Z: VERY porous, clumpy. Small covering factor of PDRs. High filling factor of diffuse gas where hard UV photons escape from HII regions.***

# *The Multiphase ISM in Dwarf Galaxies*
# Modeling: Linking ionized & neutral gas phases

**Spatially unresolved emission of spectral lines**




+ ...




Cormier et al. 2015

⇒ **19 emission lines** + 7 detection upper limits with *Spitzer & Herschel*

*How to use the obsrevations to describe the multiphase ISM of unresolved galaxies*

**Multiphase distribution of the ISM**

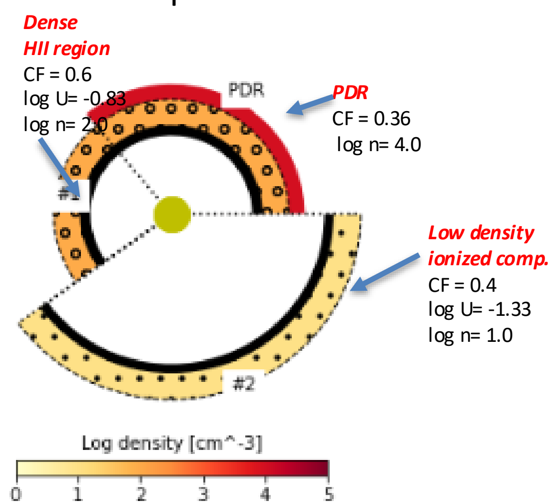

*López-Sánchez et. al (2007)*

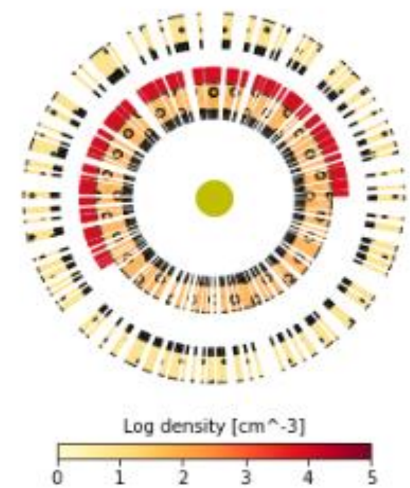
# I. Modeling the Multiphase ISM of dwarfs SBS0335-052

(2 component Cloudy modeling. Cormier+2019)

SBS0335-052

Two component model



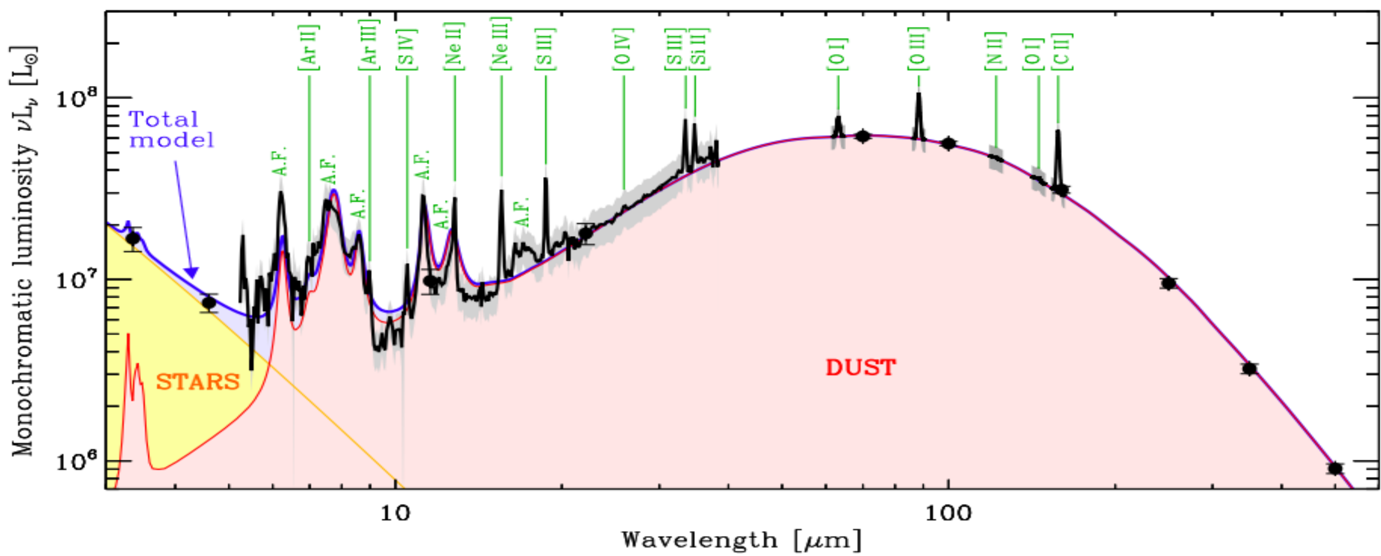




*SBS0335-052*

***Dense HII region**: n=100 cm$^{-3}$, log U = -0.83, covering factor 60%*

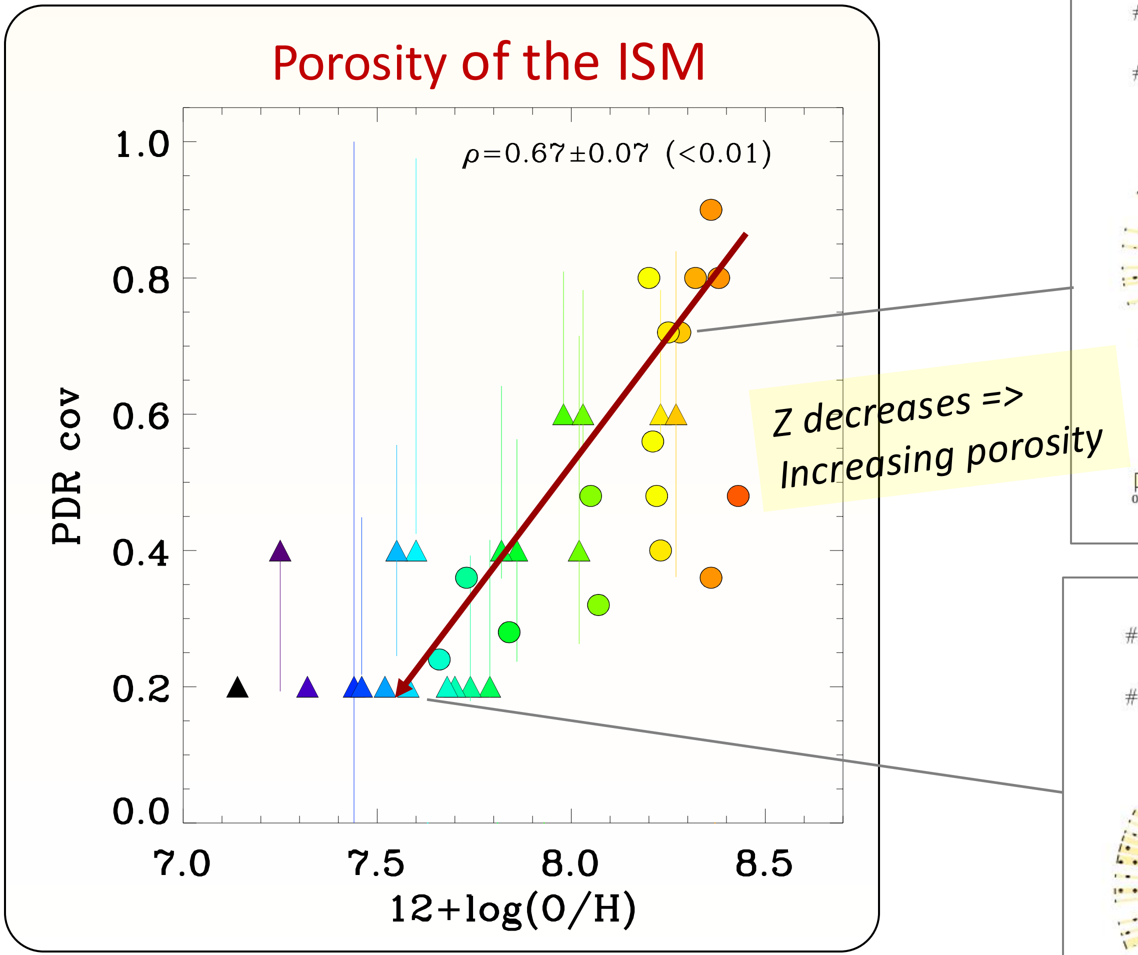
***Diffuse ionized component**: n=10 cm$^{-3}$, log U = -1.33, covering factor = 40%*

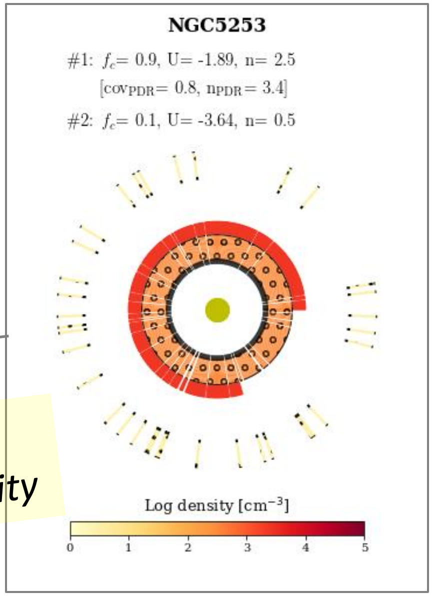
***PDR**: n=10000 cm$^{-3}$, covering factor = 30%*

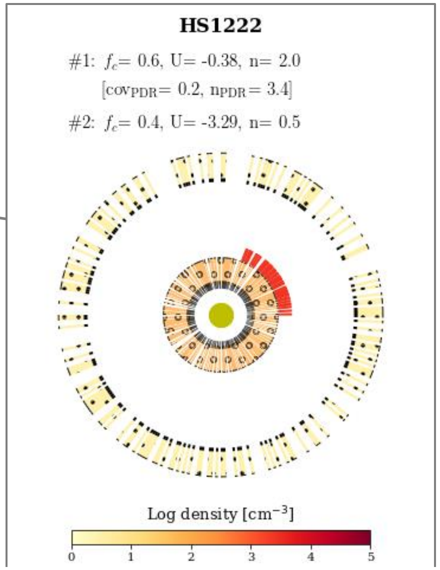


# Modeling of the ISM –MIR-FIR lines to physical conditions & ISM structure

*Cormier et al. 2019*



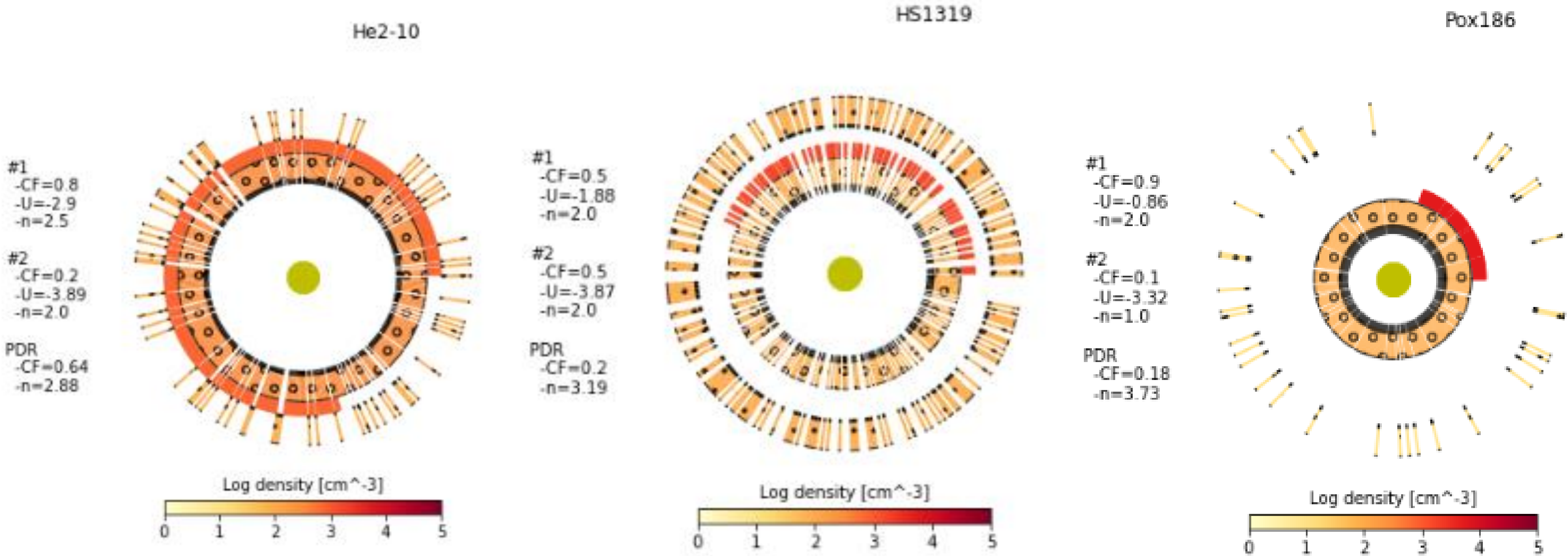




PDR covering factor: fraction of solid angle of PDR gas covering the ionization source. *(Ramambason et al 2022)*

*Also: Polles et al. 2018 : resolved SF regions in IC10* => matter bounded leaking ionizing photons

# Structure and Metallicity Effects: covering factor of PDR




Metallicity (Z) decreasing

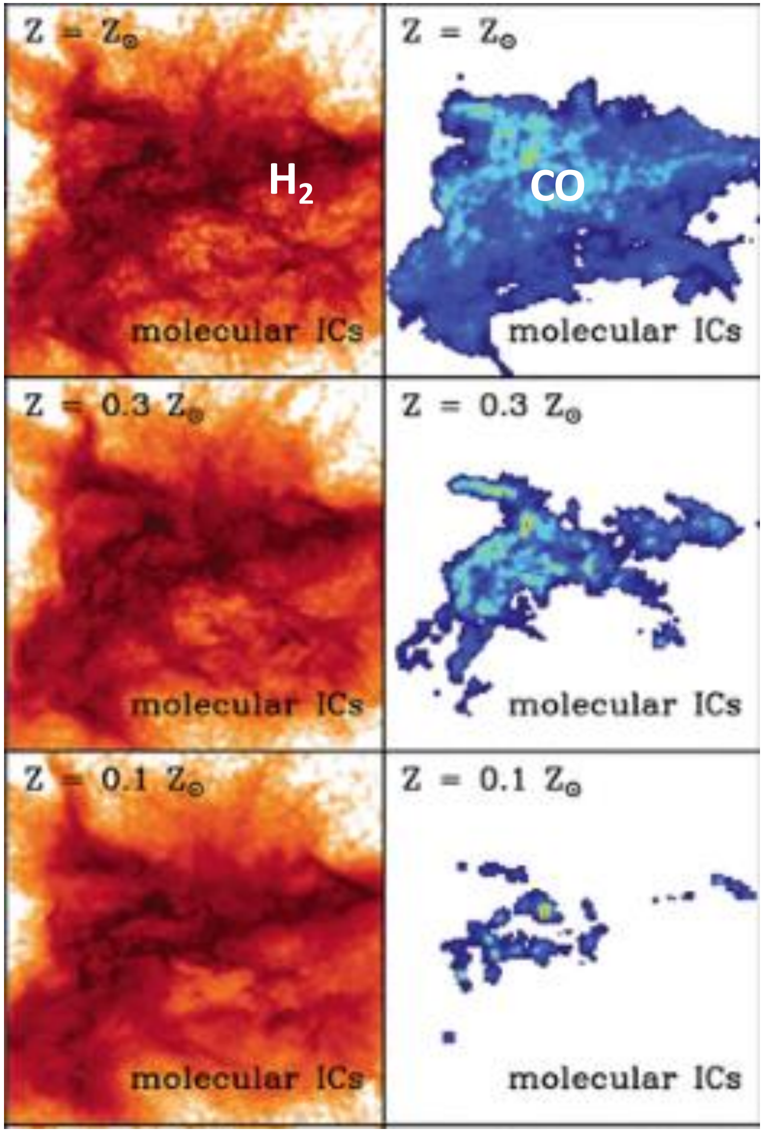
PDR Covering factor decreases

*How much $H_2$ is there really in SF dwarfs while CO is barely detectable?*

*Quantify the CO-dark gas in dwarf galaxies*

# Hydrodynamical simulations of dwarf galaxies

*(e.g. Krumholz 2012, Glover & Clark 2012, Hu+2016, 2017, Forbes+2016., Gong+2018, Seifried+2022, Hu+2023),, Ebagezio+2023*

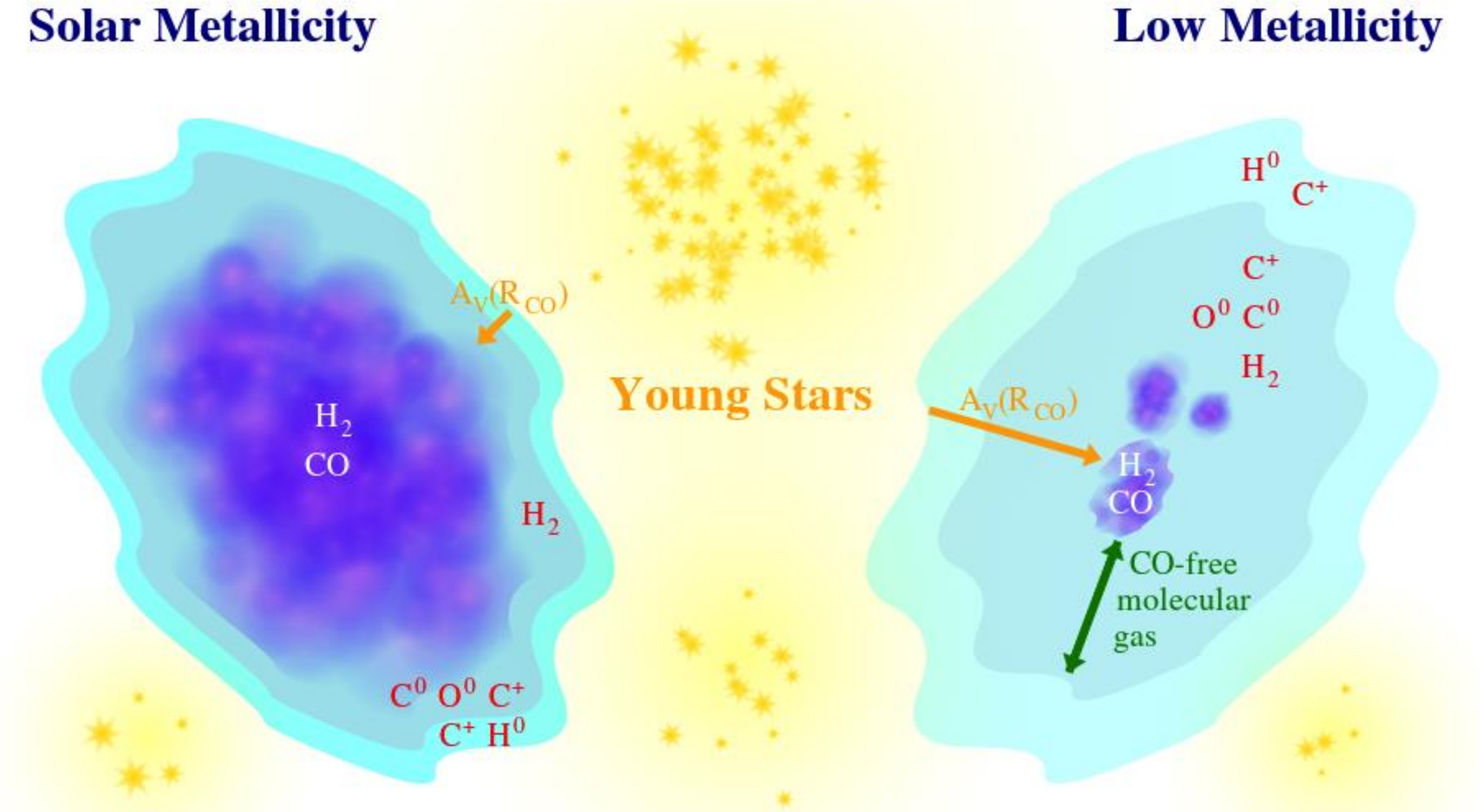



How much H2 is there in SF dwarf galaxies while CO is barely detectable?
How much $H_2$ are we missing by using CO ?

Is this $H_2$ reservoir playing an important role in SF in dwarfs?

Local dwarfs (IC10, LMC, SMC, NGC6822)
10-100 times more CO-dark than CO-bright gas mass:
*e.g. Poglitsch +1995, Israel +1997, Madden+1997, Leroy+2011; Togi&Smith 2016; Jameson+2018*

# Low metallicity effects – where is the CO-dark gas?




Madden+2020

# Modeling of the ISM –MIR-FIR lines to physical conditions & ISM structure

## What is the total $H_2$ in galaxies? From [CII] to The CO-dark gas

$M(H_2)_{total}$ from our models

$M(H_2)_{CO}$ from observations

$M(\text{CO-dark gas}) = M(H_2)_{total} - M(H_2)_{CO}$

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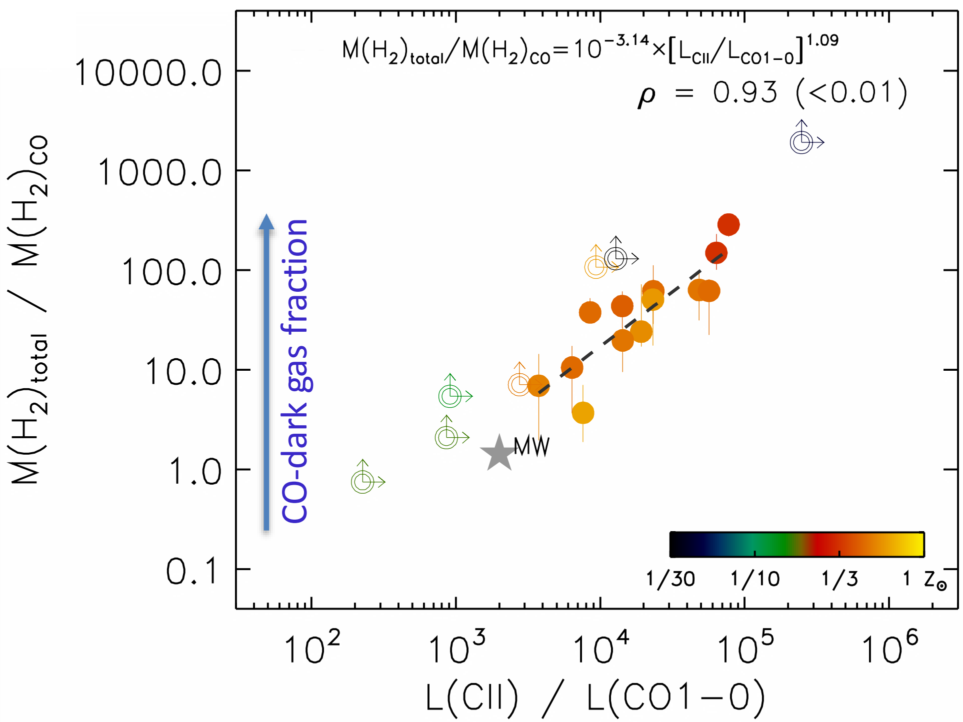
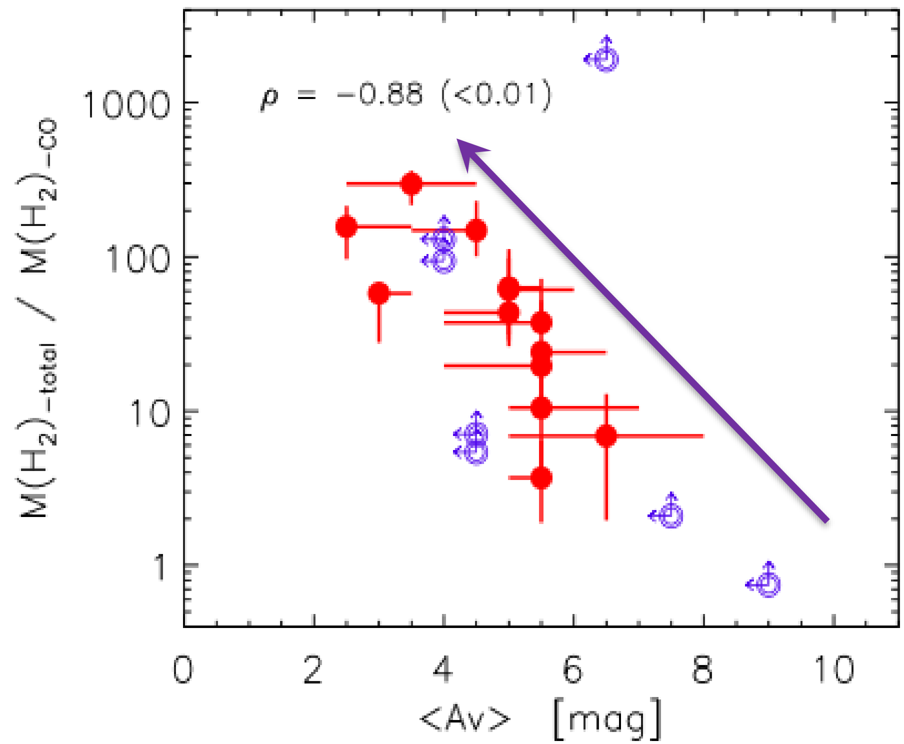
*Madden + 2020*




$L_{[CII]}/L_{CO}$ (observed) => CO-dark gas fraction




CO-dark gas mass fraction & Av

** Av ↓ -> CO-dark gas fraction ↑

*See also e.g. Accurso +2017; Gong + 2018; Li + 2018, Zanella + 2018; Bisbas + 2015, 2017, 2021; Lebouteiller + 2019; Chevance + 2020, Hu + 2016,2021*

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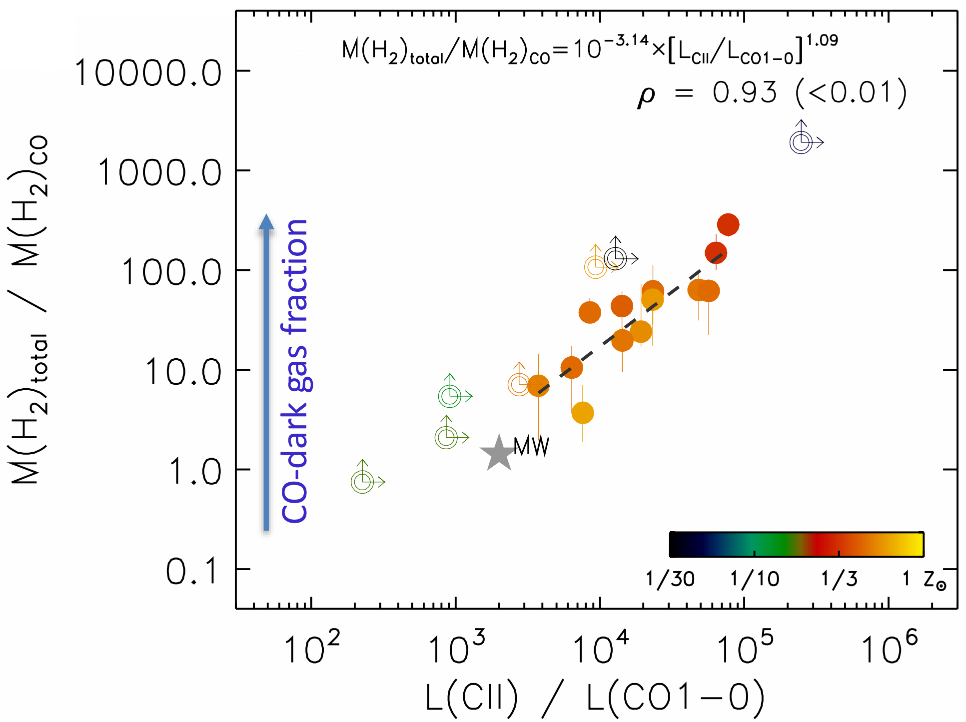
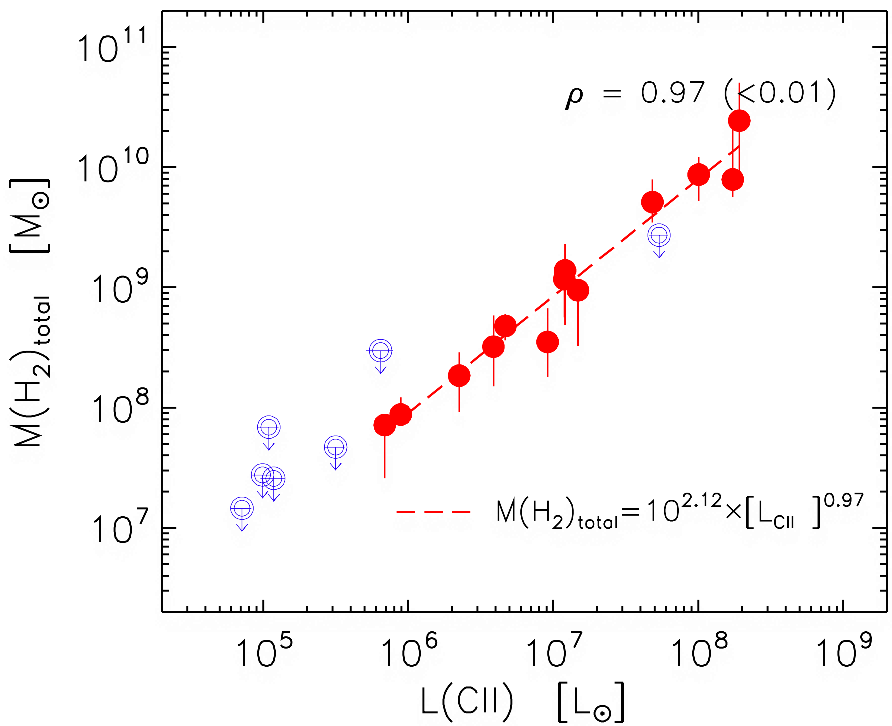
*Madden + 2020*



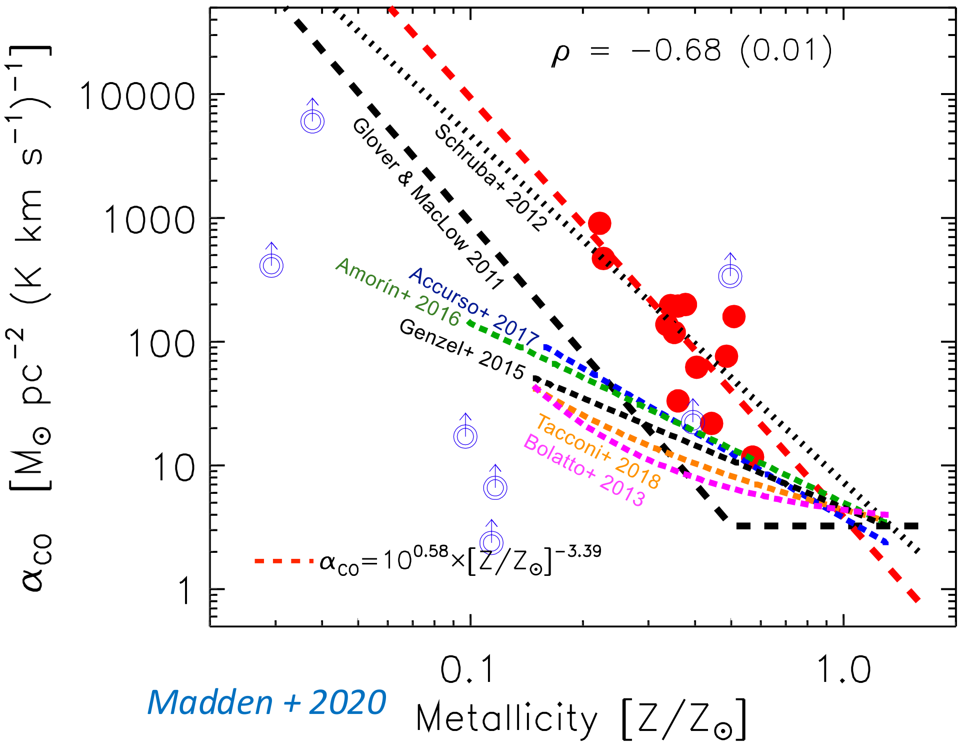




$L_{[CII]}/L_{CO}$ (observed) => CO-dark gas fraction

$L_{[CII]}$ (observed) => Total $MH_2$ (model)

*See also e.g. Accurso +2017; Gong + 2018; Li + 2018, Zanella + 2018; Bisbas + 2015, 2017, 2021; Lebouteiller + 2019; Chevance + 2020, Hu + 2016,2021*

# CO-dark $H_2$ reservoir - > CO-$H_2$ Conversion Factor & KS




*Madden + 2020*

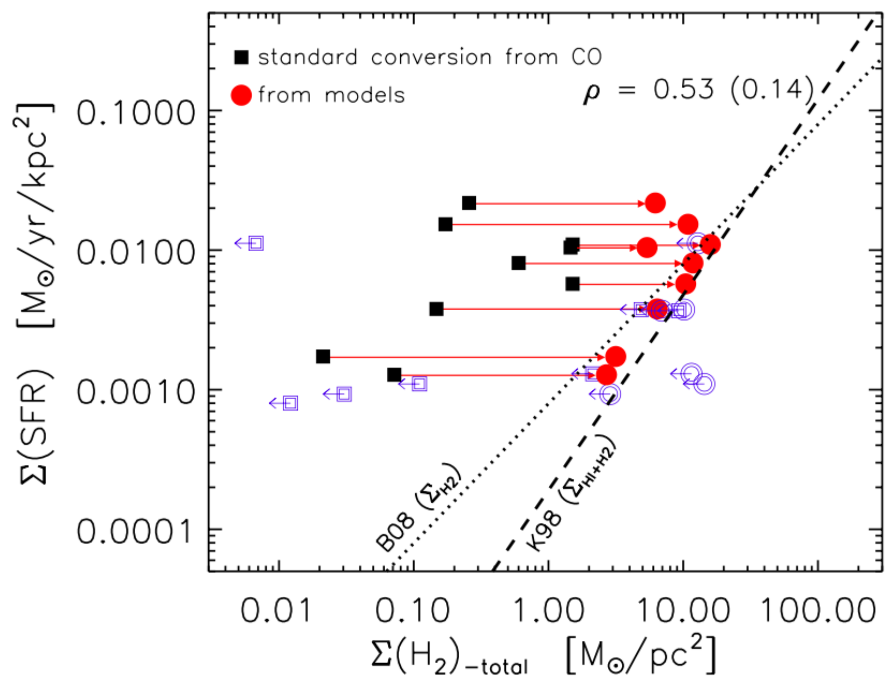
***New CO-H2 conversion factor:***

Steeply rising as metallicity is decreasing.

$\alpha_{CO} = 10^{0.58} \times [Z/Zo]^{-3.39}$

Black squares are before, with H2 from CO; only

Red dots are total H2 determined from modeling



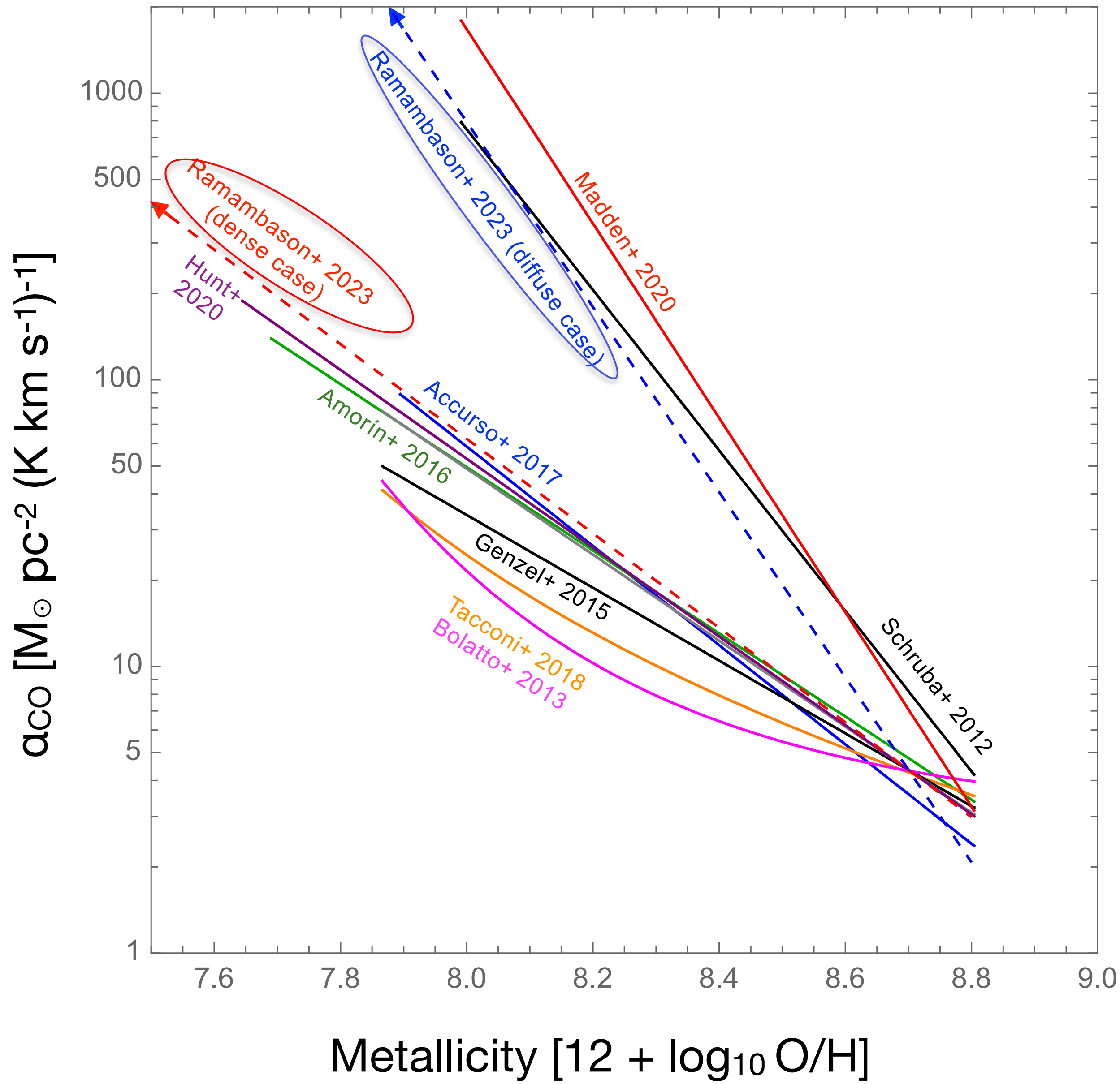

***Revisit Kennicutt-Schmidt relation :***

*Taking into account the TOTAL (including CO-dark) $H_2$ brings these galaxies onto the KS-relationship*

# CO-$H_2$ Conversion factors vs Metallicity

Most recent modeling of DGS:
*Ramambason +2024*
Multisector Bayesian approach with clump distribution

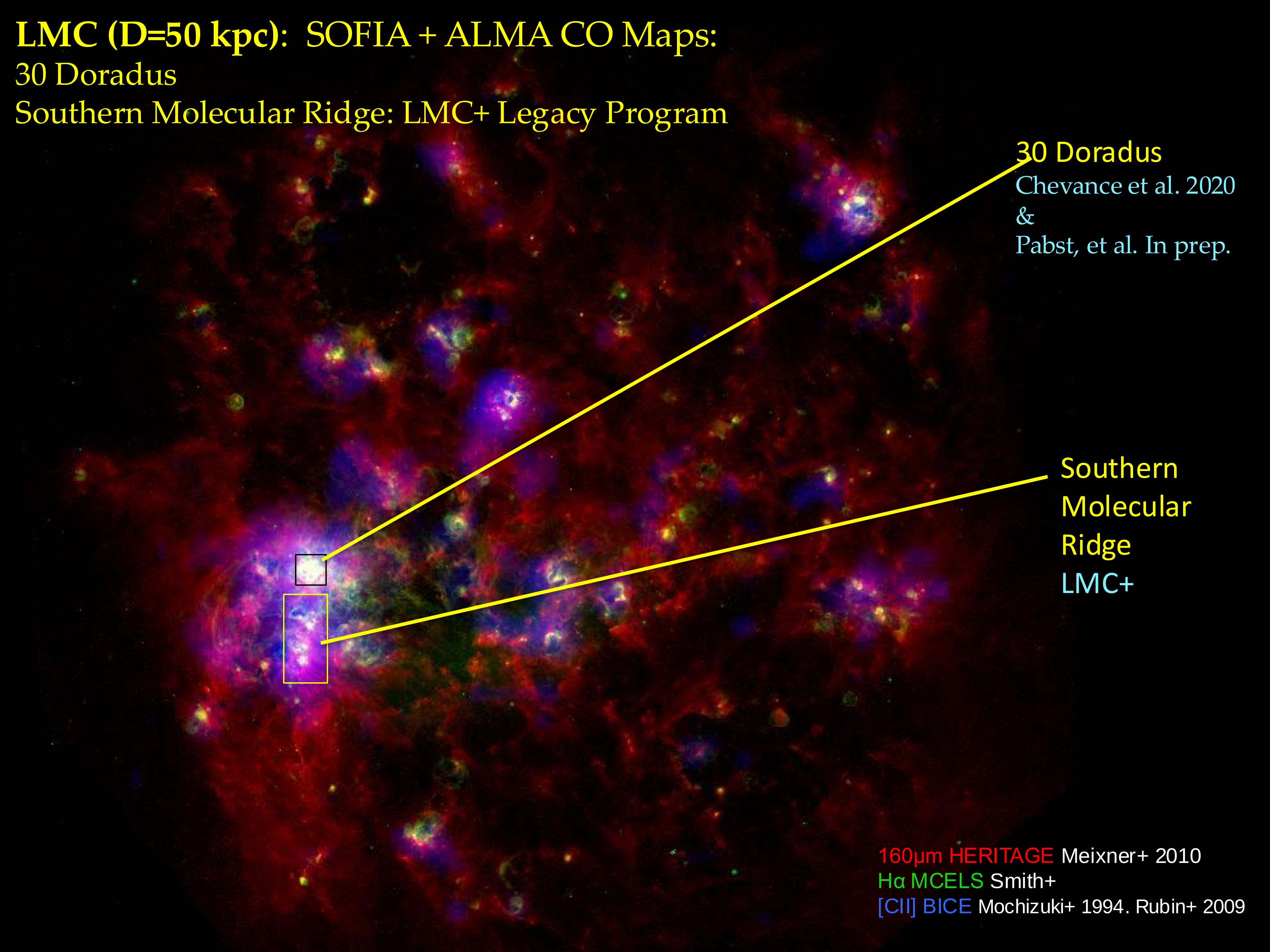
Requires:
A convrsion for dense gas case
**and**
A steeper conversion for diffuse gas case



# LMC (D=50 kpc): SOFIA + ALMA CO Maps:

30 Doradus

Southern Molecular Ridge: LMC+ Legacy Program

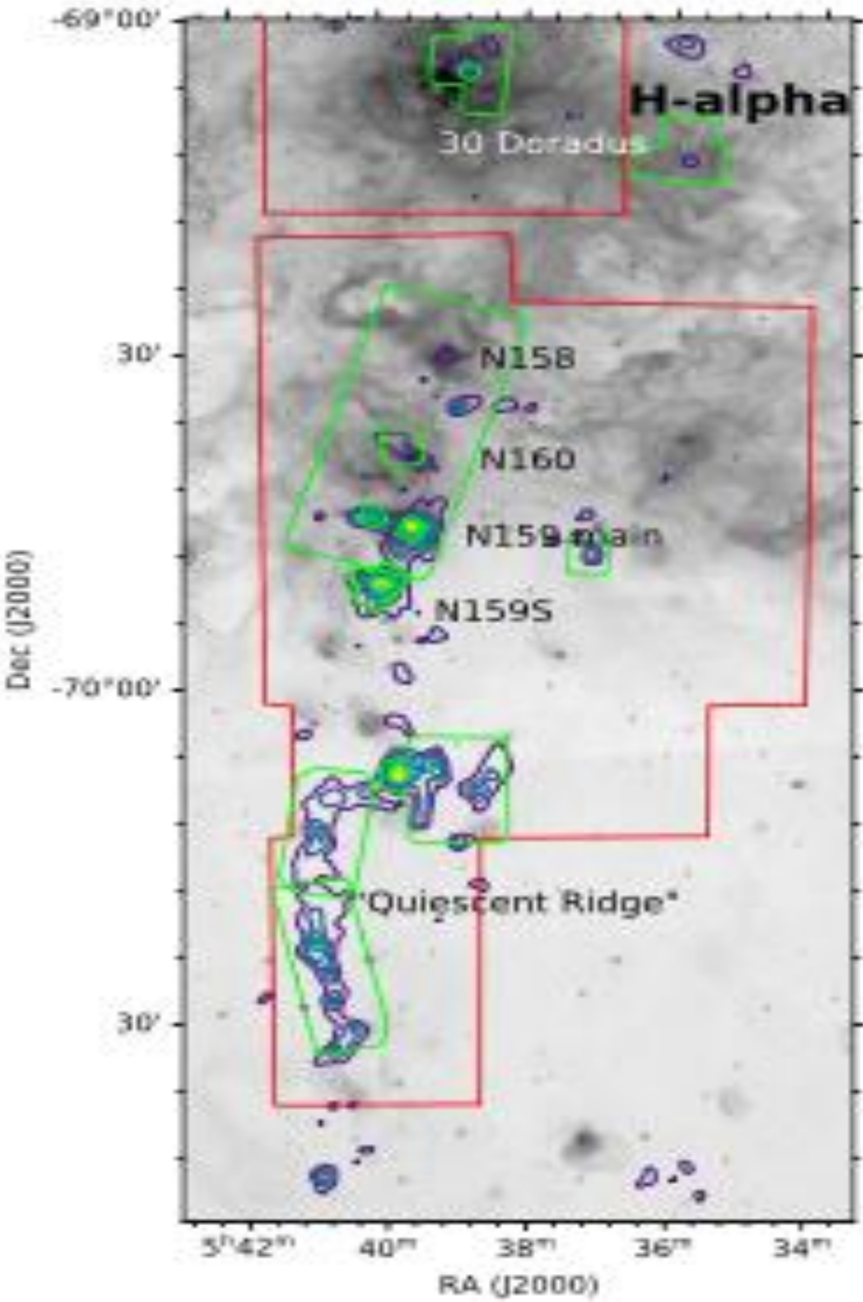


# LMC$^{+}$

## SOFIA Legacy Program


Image:
***Maja*** *Kazmierczak-Barthe*

**S. Madden, A. Krabbe, C. Fischer, W. Vacca, R. Indebetouw, N. Abel, A. Beck, F. Bigiel, A. Bolatto, M. Chevance, S. Colditz, D. Fadda, M. Finn, M. Galametz, F. Galliano, D. Hu, A. Hughes, C. Iserlohe, M. Kazmierczak-Barthel, R. Klein, A. Lambert-Huyghe, S. Latzko, V. Lebouteiller, A. Poglitsch, F. Polles, M. Rubio , E. Tarantino, H. Zinnecker**




Halpha map & ALMA CO & LMC+ SOFIA region

# SOFIA Joint Legacy Program:

(Madden, Krabbe et al.)

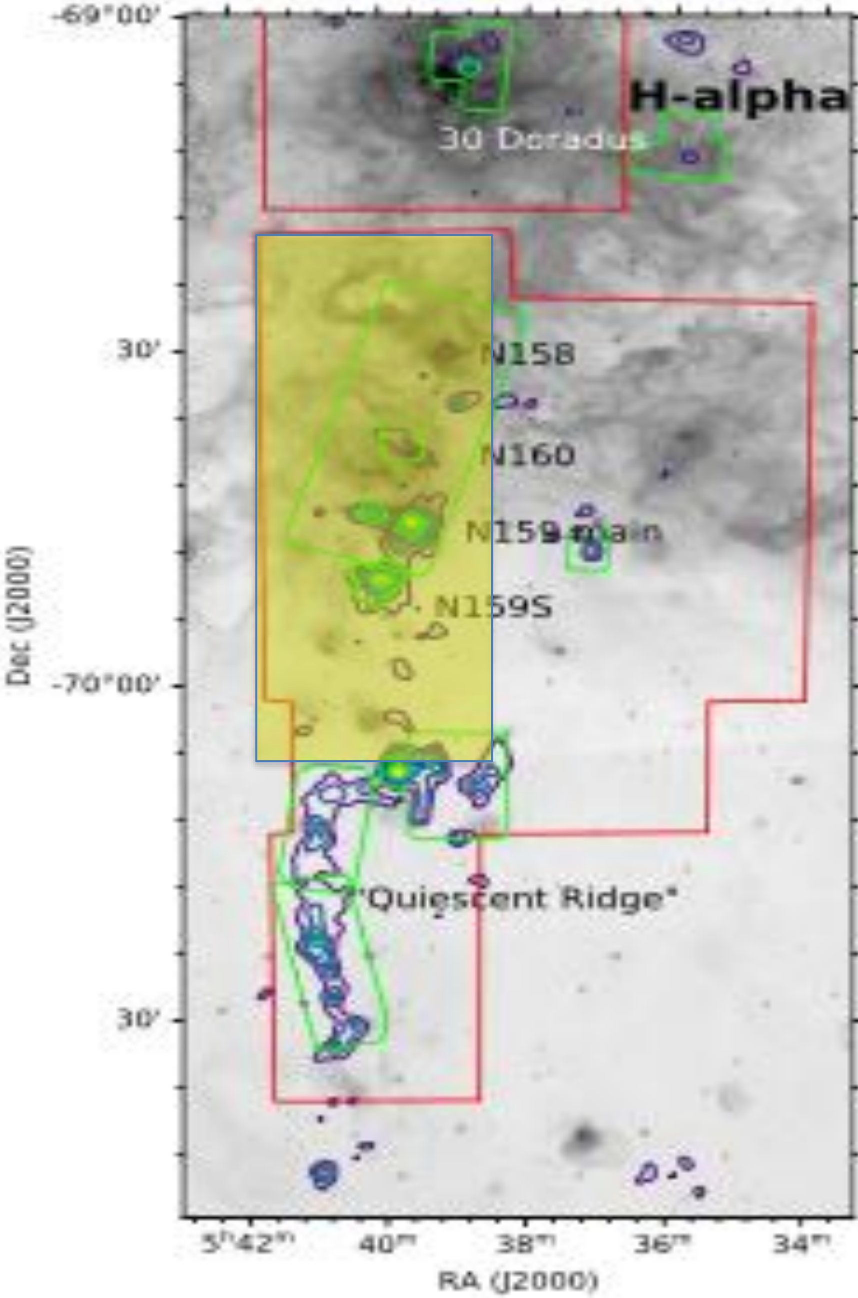
LMC+: [CII] 158mu & [OIII] 88mu OTF maps
LMC: D= 50kpc Z=0.5Zo

40' X 20' ~ 600 pc x 300 pc @ 2.5 pc

Note:
*30 Dor mapped with FIFI-LS*
*(Mélanie Chevance presentation today*

*30Dor mapped with upGREAT*
*(Cornelia Pabst presentation yesterday)*

***Many complementary observations***
*Halpha, NIR FIR, ALMA, APEX dense gas tracers*
*optical, MIR-submm continuum, radio, etc…*




Halpha map & ALMA CO & LMC+ SOFIA region

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LMC+: [CII] 158mu & [OIII] 88mu OTF maps
LMC: D= 50kpc Z=0.5Zo

40' X 20' ~ 600 pc x 300 pc @ 2.5 pc

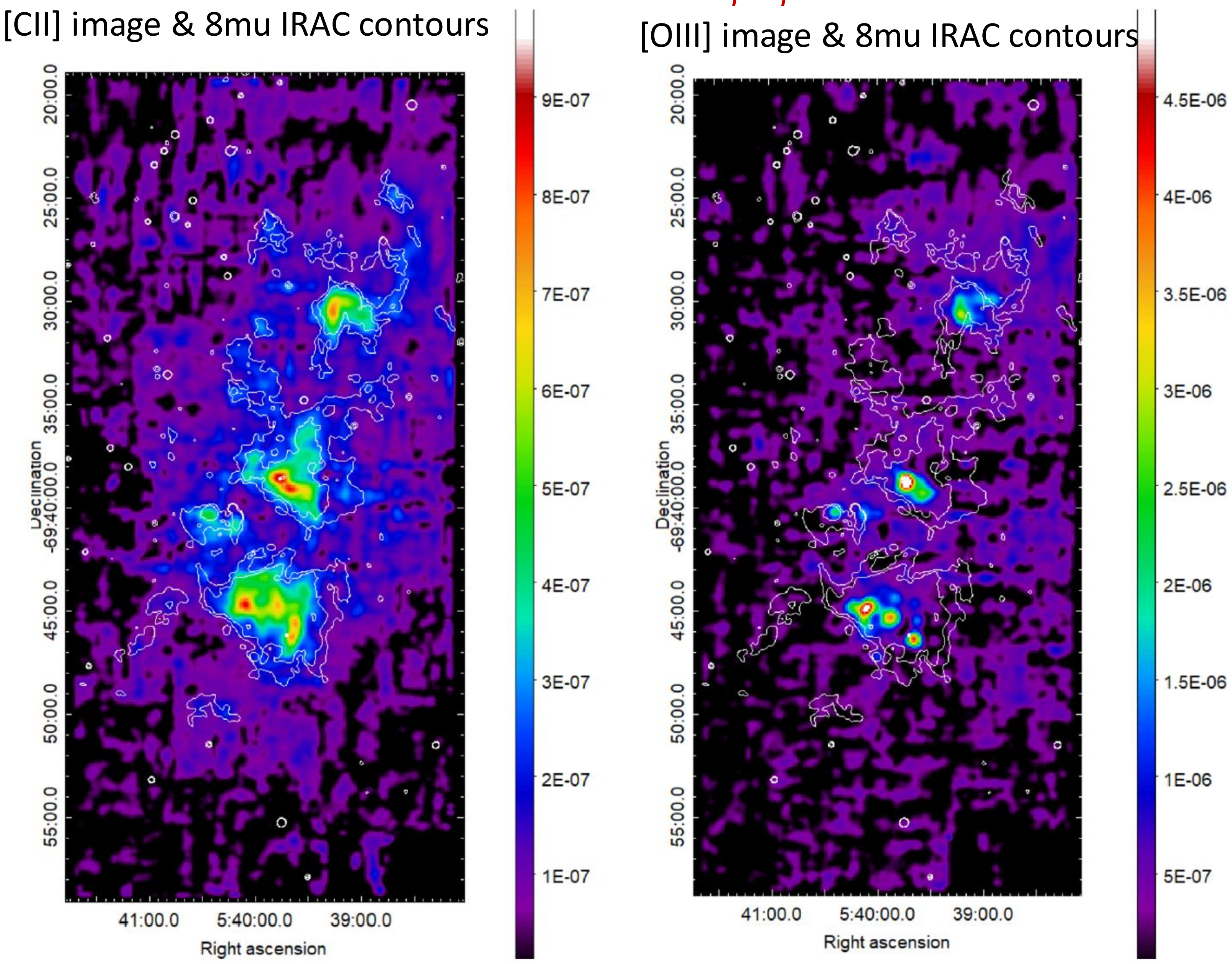
**Major Players** observation setup, OTF pipeline, data treatment, X-calibration, etc
-> Christian Fischer, Nadine Fischer, Dario Fadda....

***Many complementary observations***

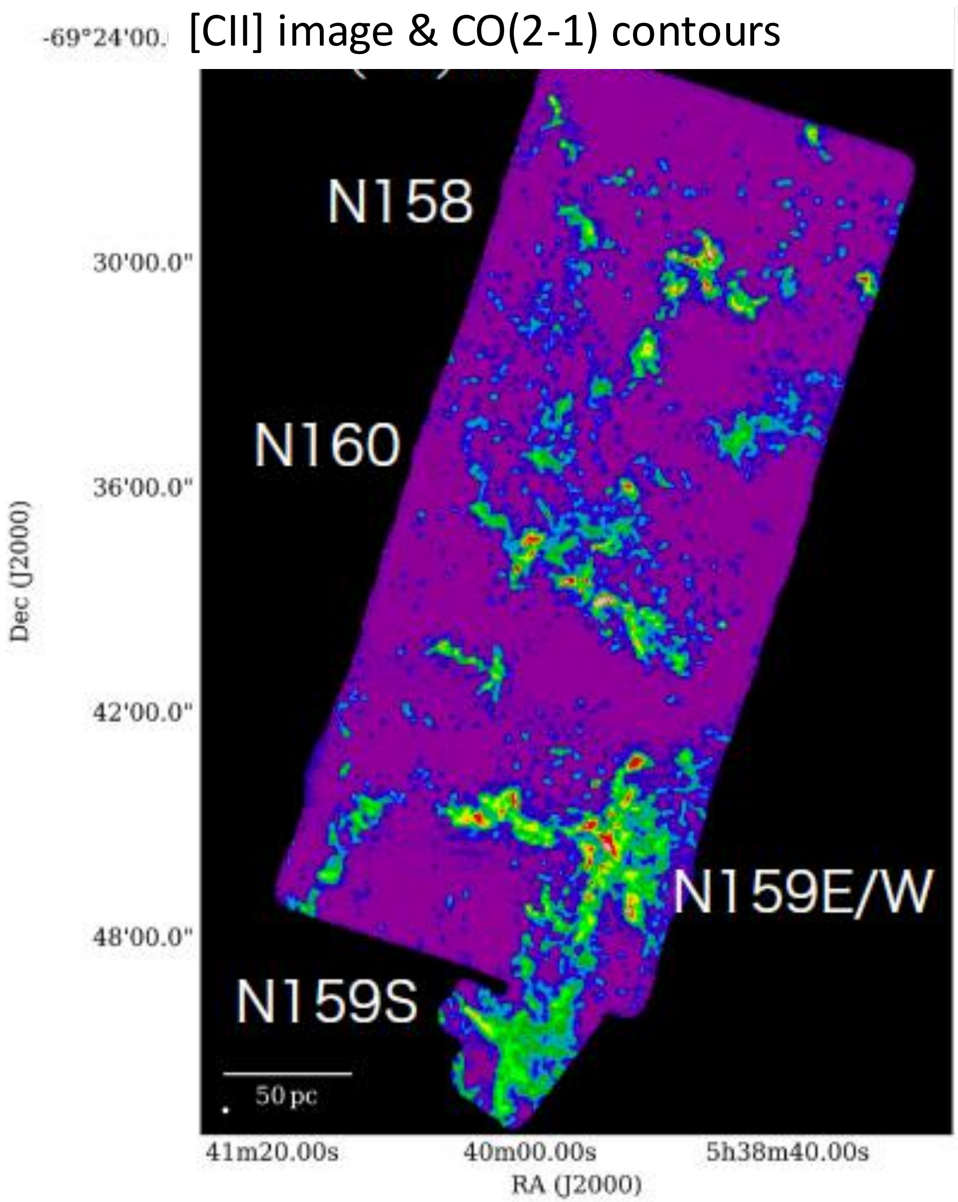
*Halpha, NIR FIR, ALMA, APEX dense gas tracers optical, MIR-submm continuum, radio, etc…*

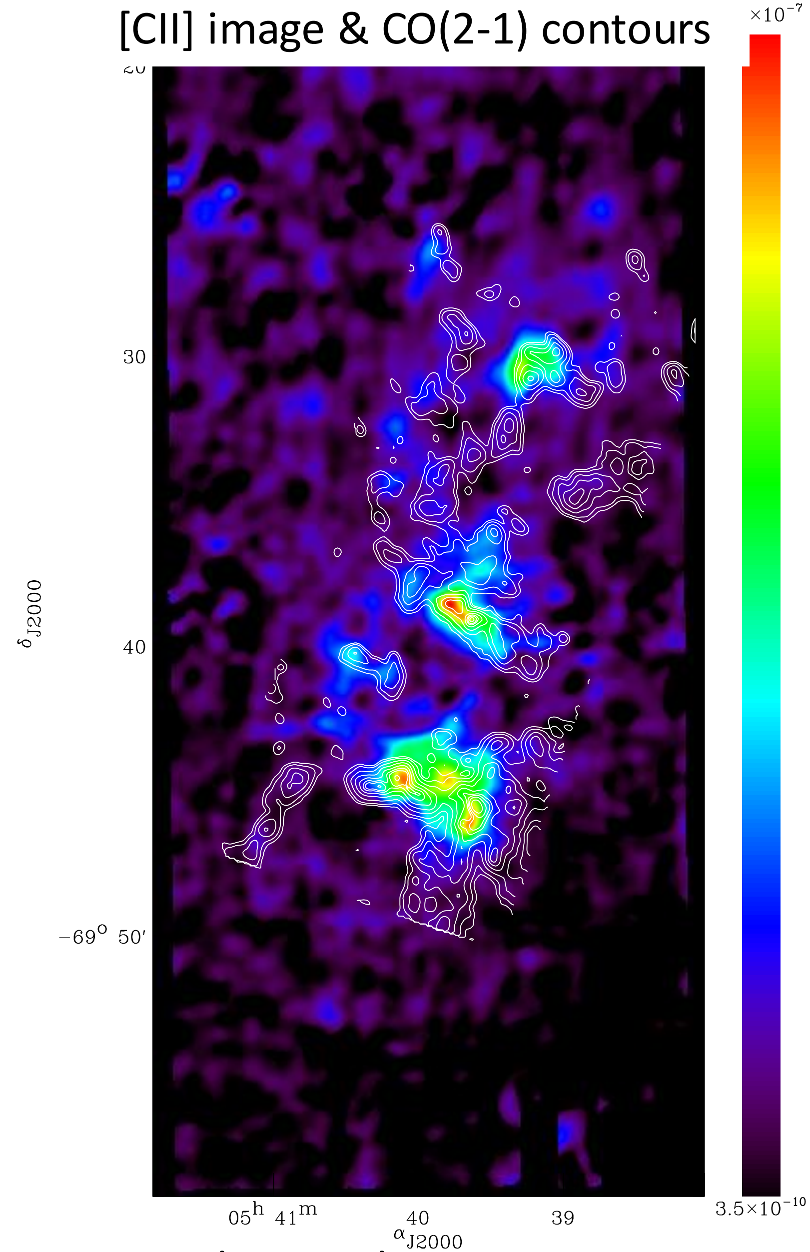
# LMC+. [CII] and 88mu [OIII] with SOFIA FIFI-LS

*Fischer et al. in prep*



# Southern Molecular Ridge : [CII] vs. CO (ALMA)




ALMA CO(2-1) ridge: Tarantino et al. in prep. &. CO in N159S: Chen et al. in prep

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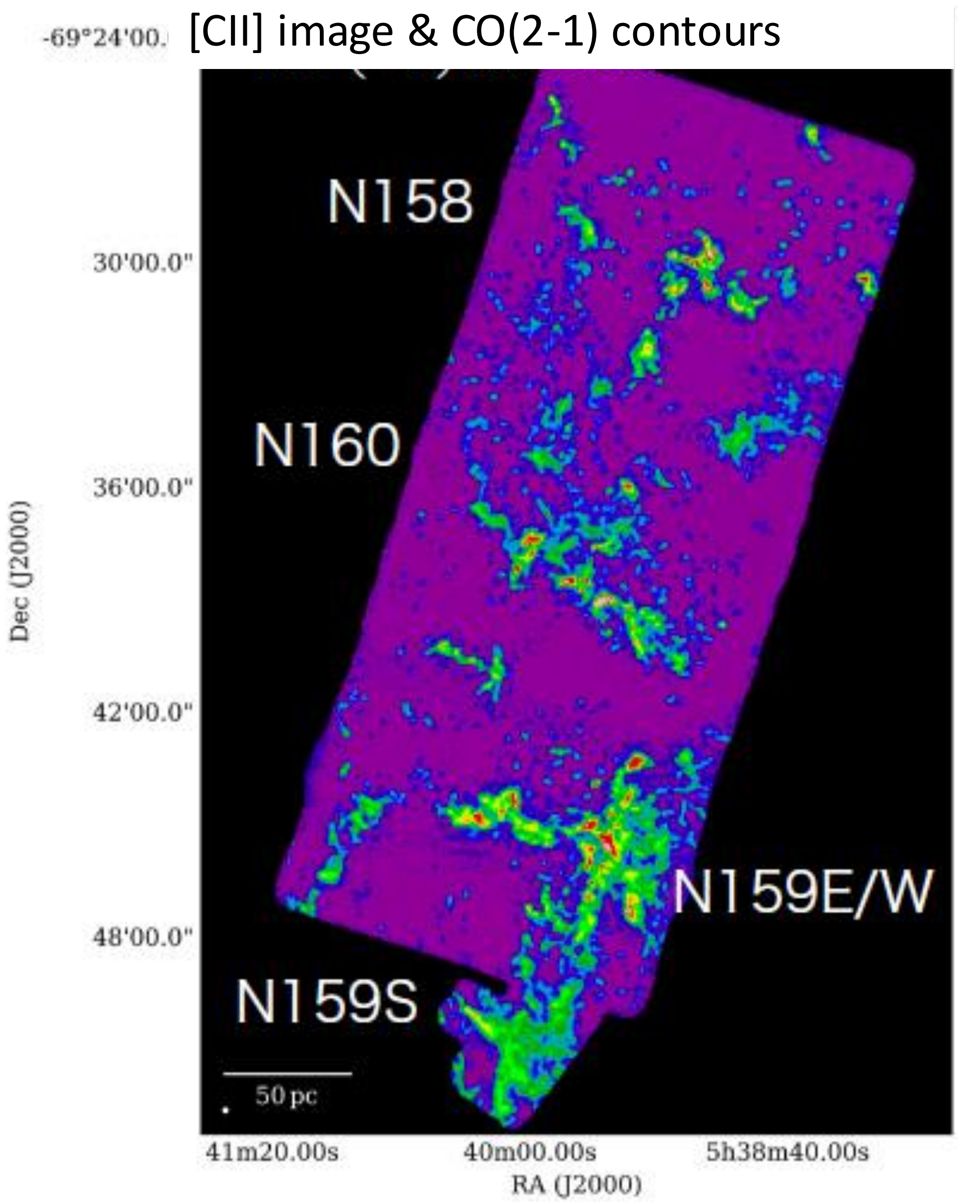
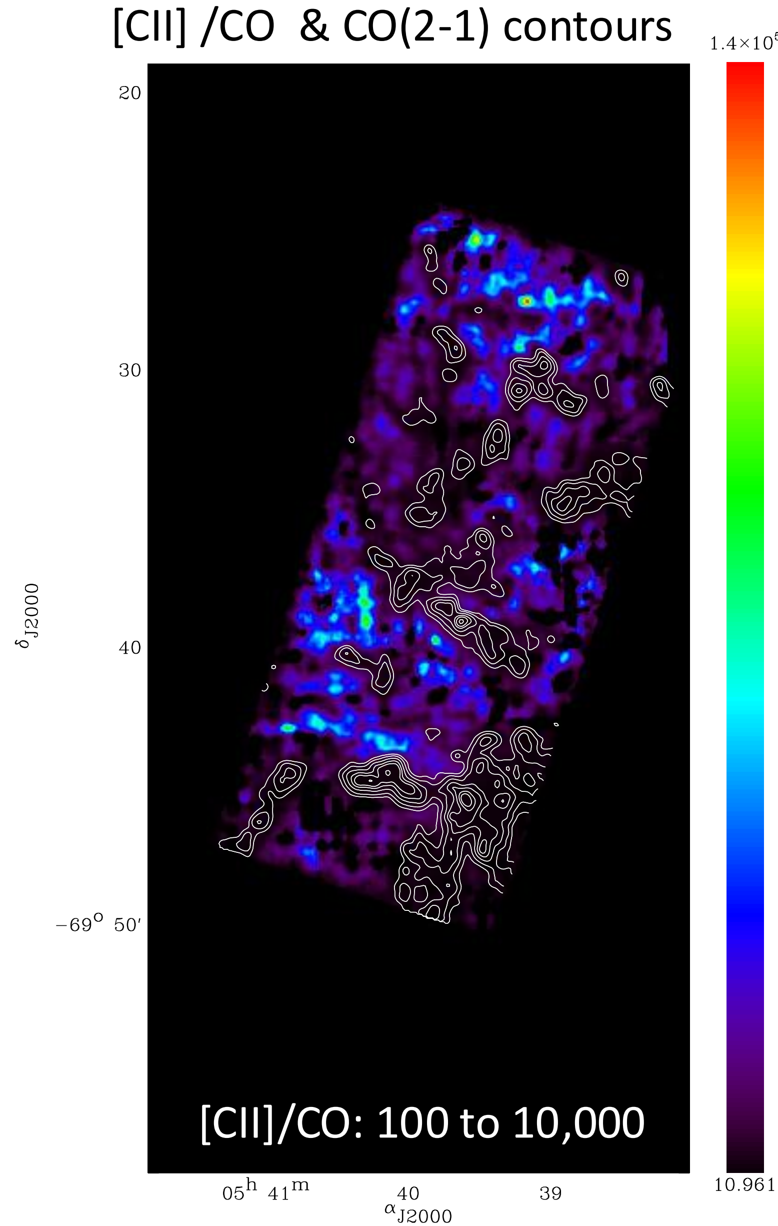
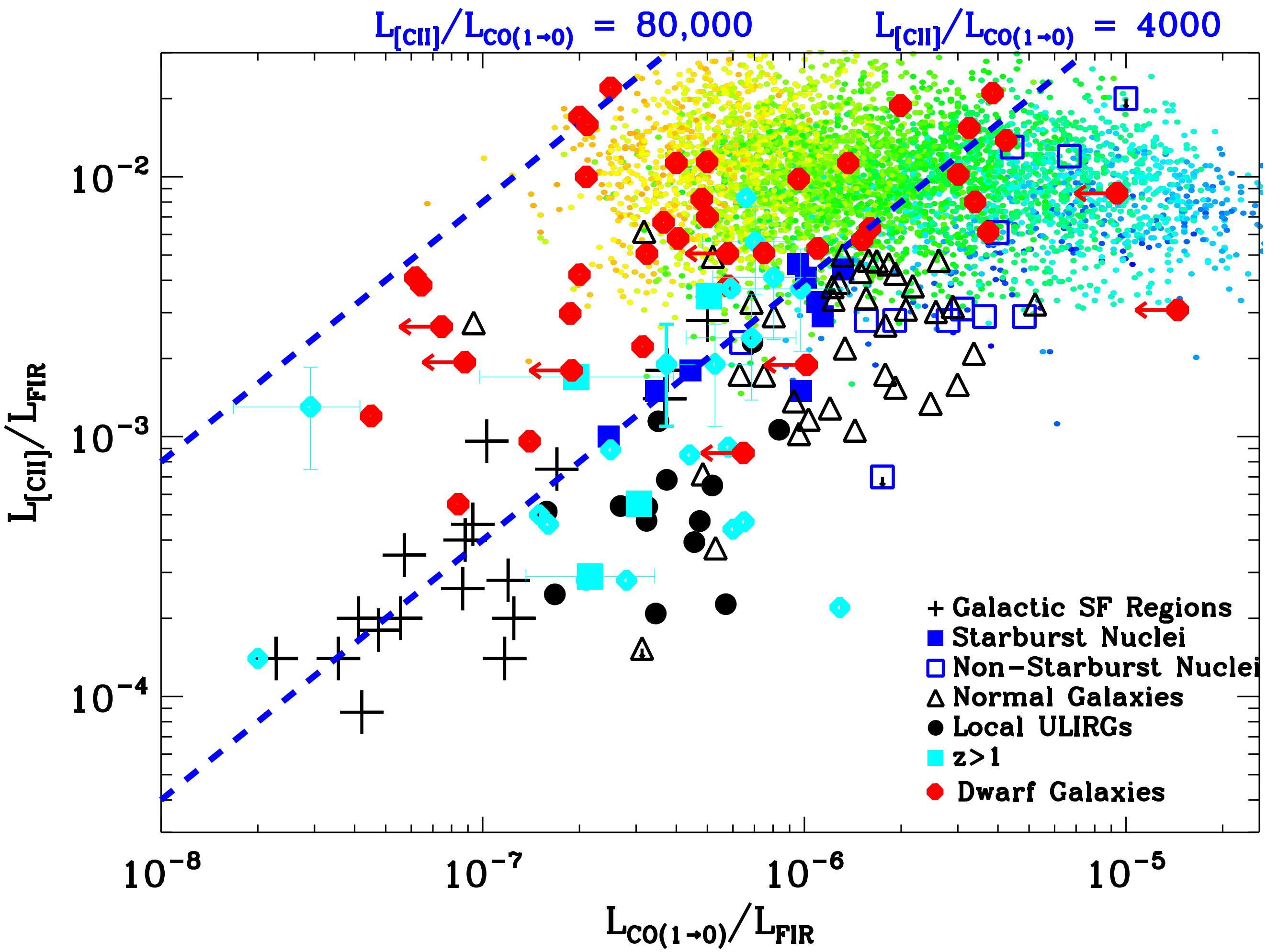


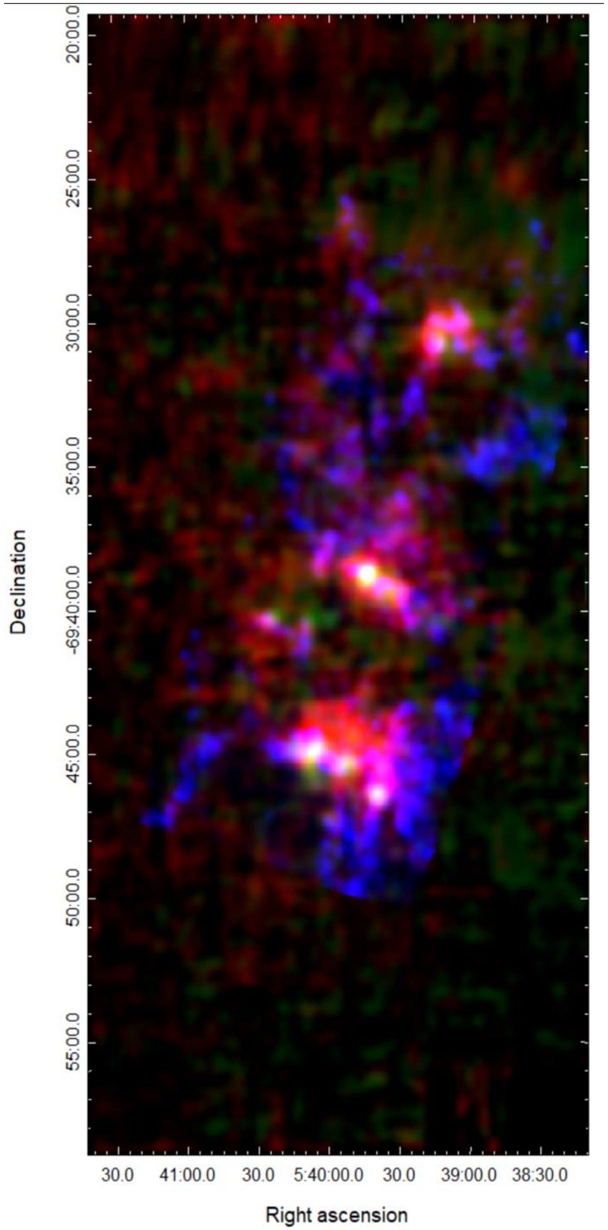

ALMA CO(2-1) ridge: Tarantino et al. in prep. &. CO in N159S: Chen et al. in prep

# High [CII]/CO in low metallicity environments

*[CII]/FIR vs CO/FIR* ***in LMC+***

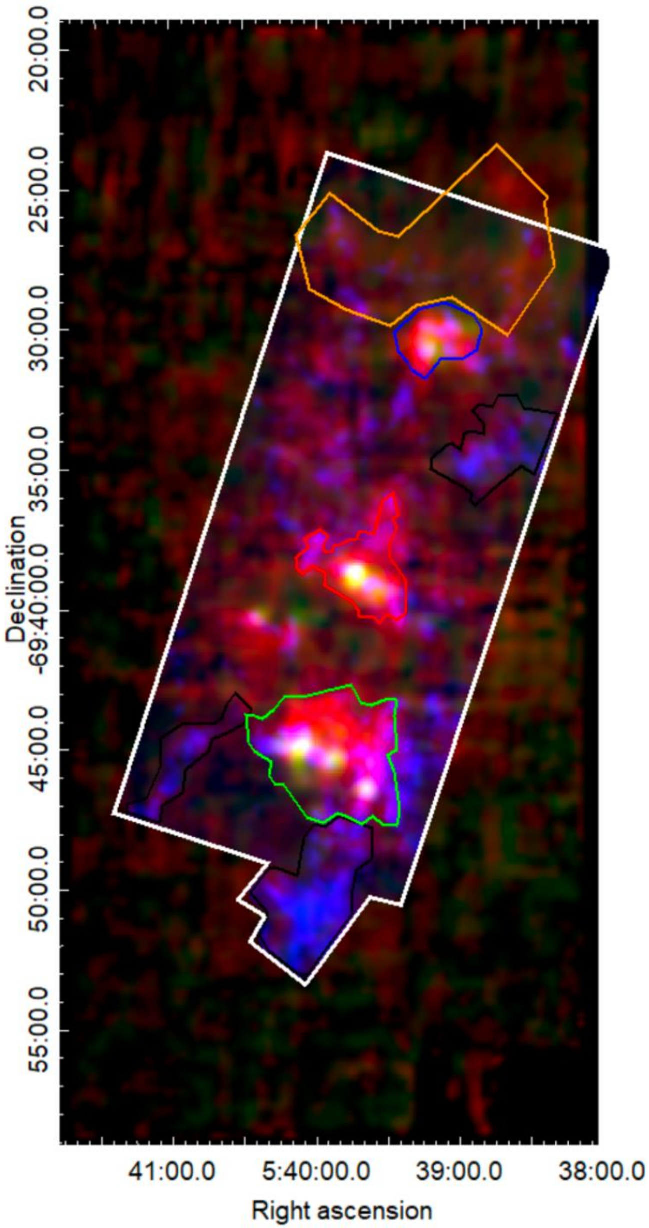


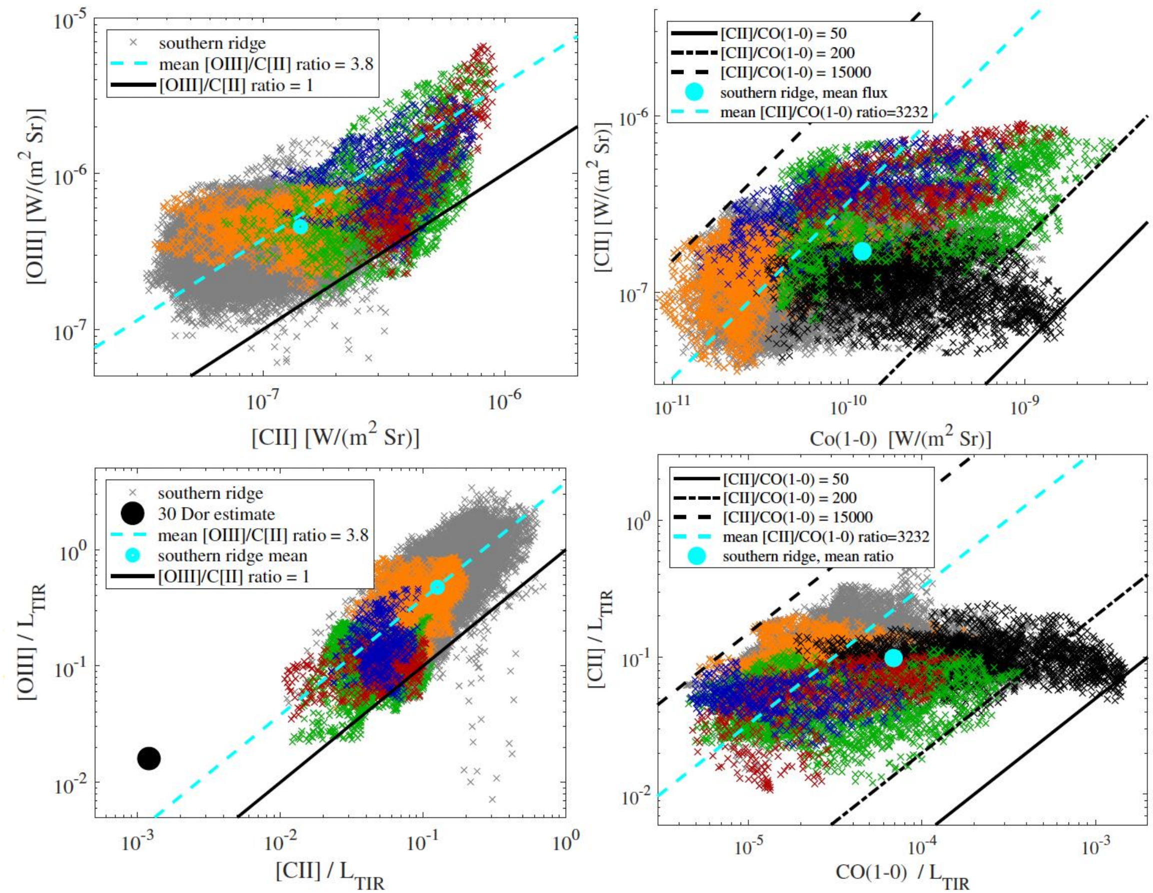
# [CII] CO [OIII] LTIR ratios




RGB:
red:CII,
green:OIII
blue: CO

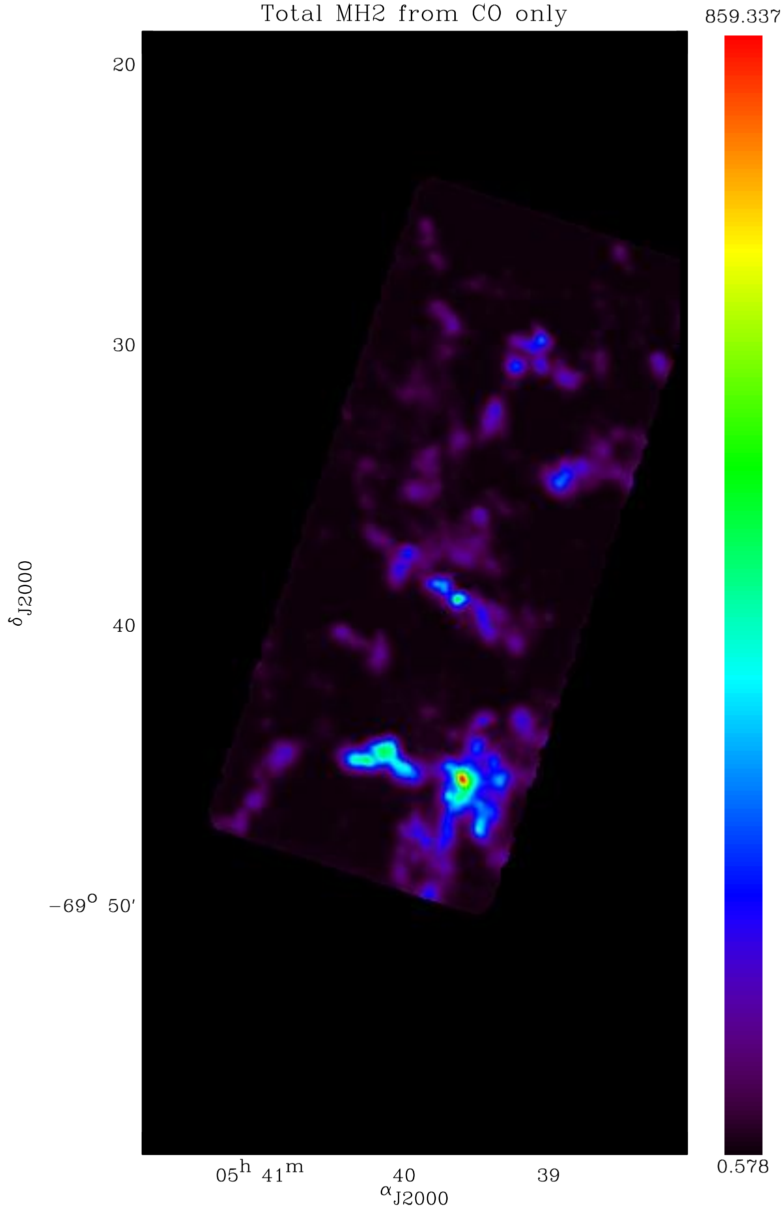
# [CII]  CO  [OIII]  LTIR ratios



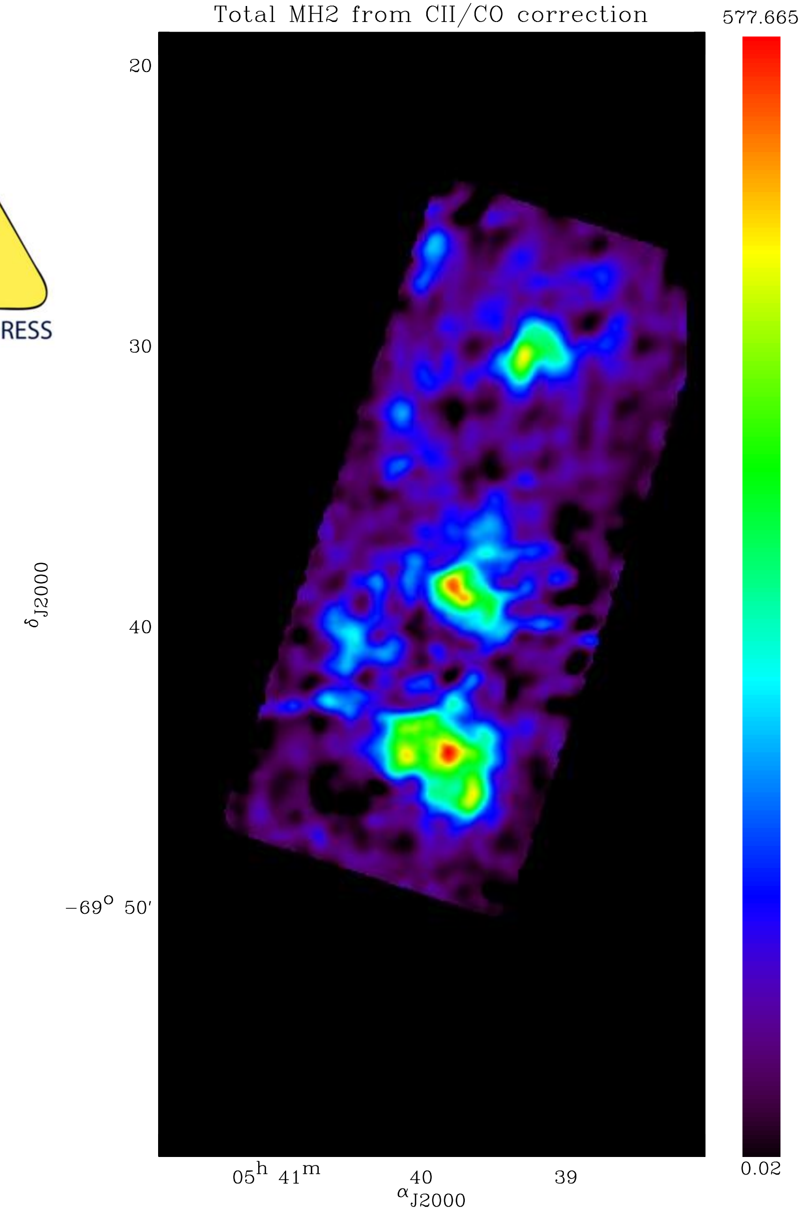




C. Fischer et in prep

# Relation between total $MH_2$ (from [CII]) and CO ($M_{sol}$ $pc^{-2}$)








$$M(\mathrm{H}_2)_{\mathrm{total}}/M(\mathrm{H}_2)_{\mathrm{CO}} = 10^{-3.14} \times [L_{[\mathrm{C\,II}]}/L_{\mathrm{CO}(1-0)}]^{1.09}. \qquad (3)$$

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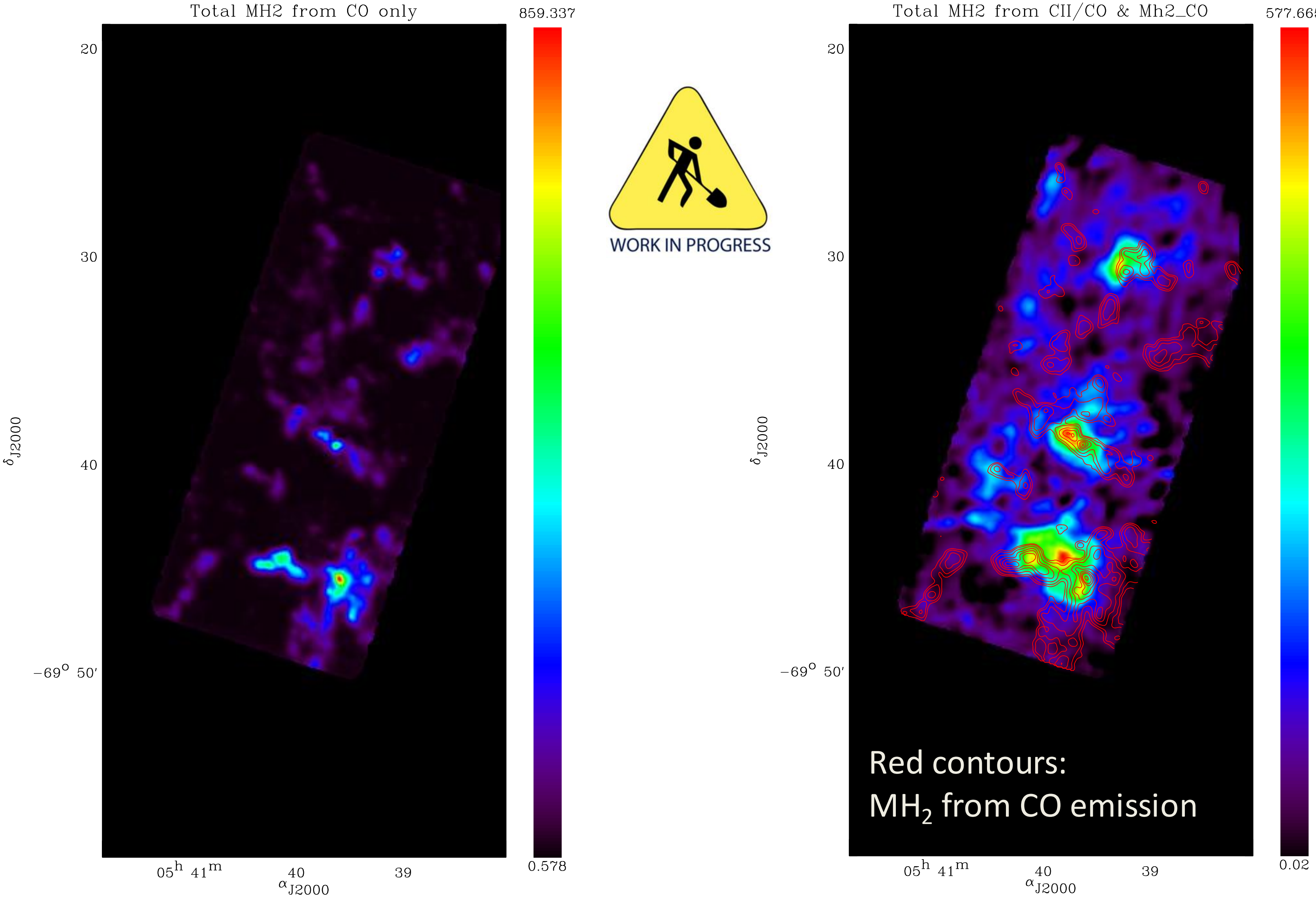


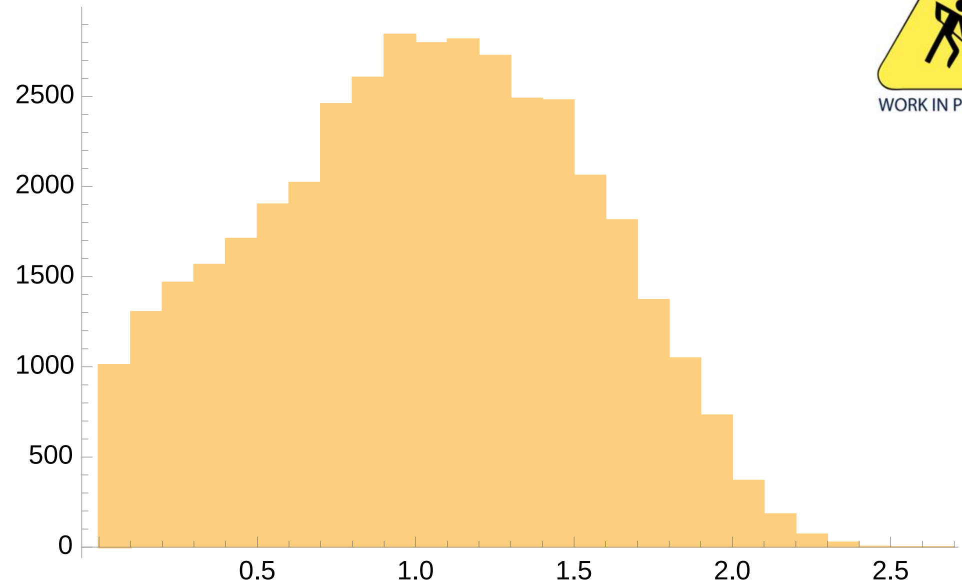

$$M(\mathrm{H_2})_{\mathrm{total}}/M(\mathrm{H_2})_{\mathrm{CO}} = 10^{-3.14} \times [L_{[\mathrm{C\,II}]}/L_{\mathrm{CO(1-0)}}]^{1.09}. \quad (3)$$

In places ~ 300 times more $MH_2$ than traced by CO. Does this dark gas have anything to do with SF?

# What is the total $H_2$ in galaxies ? From [CII] to The CO-dark gas

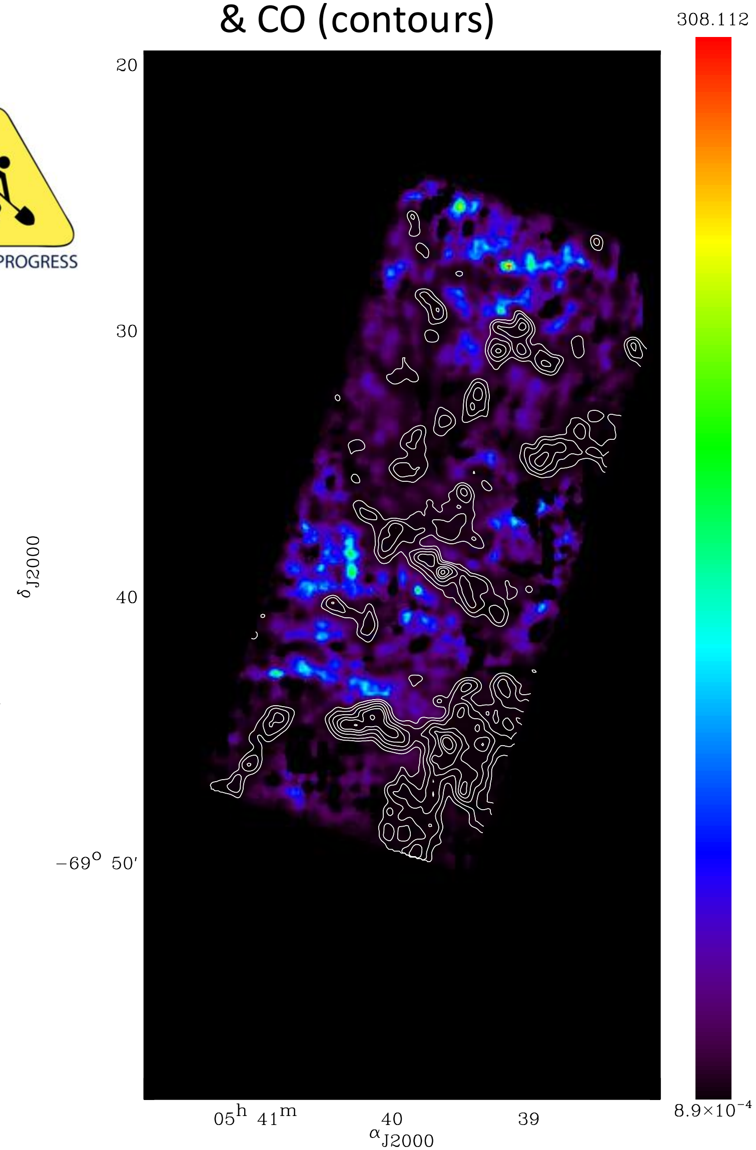
$$M(\mathrm{H_2})_{\mathrm{total}}/M(\mathrm{H_2})_{\mathrm{CO}} = 10^{-3.14} \times [L_{[\mathrm{C\,II}]}/L_{\mathrm{CO}(1-0)}]^{1.09}.$$

WORK IN PROGRESS




Log $M(H2)_{total}/M(H2)_{CO}$ based on [CII]/CO (eq. 3 in Madden et al. 2021)

$MH_2$(tot)/$MH_2$(CO) (image) & CO (contours)




The correction for total M(H2), compared to « naive » CO-to-H2 is around $\log_{10} = 1$ =>10 times more M(H2) than determined from CO, with large spread. Can be as high as a factor of 300

# Low Metallicity ISM: Some Take away Points

Gas phases at low metallicities:

- Metallicity effects on the heating & cooling of the different gas phases very pronounced

  - CO detections challenging – less dust allows for greater photodissociation
  - [CII]/CO *extreme*
  - [OIII] 88mu - brighter locally and globally in low Z - porous ISM
  - HII region: Leaky, hard radiation fields, low densities, large filling factor
  - [CII] -> CO-dark $H_2$ gas component can harbor the bulk of the $H_2$ reservoir (not CO)

  - **Key steps** ->. Magellanic Clouds at pc scales with ALMA and SOFIA – to be exploited
  - JWST followup?