CO-dark H_2 gas and the origin of [C II] emission in metal-poor galaxies: Velocity-resolved [C II] in LMC-N 11

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General motivations

What is the total gas content available for SF in galaxies and what SF efficiency?

- Intense SF in some metal-poor galaxies with little/no CO(1-0) *(Leroy+; Bolatto+)*
- Does H^0 participate in the SF process? *(e.g., Glover+ 2012, Krumholz+)*
- Non-coeval H_2 and SF?
  - Destruction, formation at onset & consumption
- High SFE *(Turner+ 2015)*?
- Hidden molecular gas *(e.g., Poglitsch+ 1995, Madden+ 1997, Grenier+ 2005, Wolfire+ 2010)*?

What diagnostic power for [C II] (and C II*)?

- Important cooling line in the neutral gas, detected at high-z *(e.g., Lagache+ 2017, Aravena+ 2016)*
- PDR physical conditions
- CO-dark H_2 gas tracer *(e.g., Madden+ 1997; Wolfire+ 1990)*
  - Dependency with environment (radiation field, metallicity)?

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Current understanding of metallicity effects on the ISM

Nearby low-metallicity SF dwarf galaxies and Magellanic Clouds

- Low D/G *(e.g., Rémy-Ruyer+ 2014)*, low abundance of AF-carriers *(e.g., Galliano+ in prep.)*
- Hard stellar radiation field, extended [O III], bright [O III] (> [C II]) *(Kawada+ 2011; Cormier+2015)*
- PDR models suggest larger PE heating efficiency due to UV field dilution *(Cormier+ 2015, 2018)*
- Low metal abundance responsible for significant ISM topology changes, e.g., PDR covering factor *(Cormier+ 2019)*

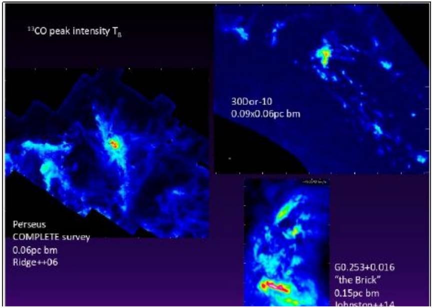

Fig.: *Direct evidence for CO photodissociation between peaks in 30 Dor vs. MW clouds (Indebetouw+ in prep.).*

Emerging picture

- Relatively porous and transparent medium
- ⇒ pervaded by UV and X-ray field diluted over large (kpc) scales
- ⇒ Low volume filling factor of dense clouds, high contrast with surrounding interclump medium

Questions

How much CO-dark gas, what tracers?

Specific influence of radiation field and metallicity?

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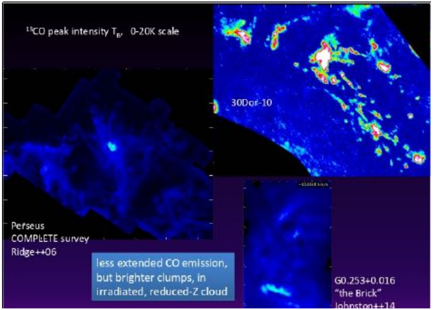

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Accessing and quantifying the CO-dark gas

Integrated measurements

- Total gas through dust mass (assuming constant – or well-behaved – D/G) (e.g., *Sandstrom+ 2013*)
- Total gas through interactions with γ-rays *(Grenier+, Rémy+, Joubaud+)*
- Neutral gas (PDR) modeling: recipe for CO-dark gas mass based on [C II] 157 μm and [O I] 63 μm *(Madden+ 2020)*

A clearer (?) picture with velocity-resolved tracers

- Tracers from every phase available in principle: [C II], [O I], [N II], H I, CO, Hα...
- Case well adapted for Milky Way *(Piñeda+, Langer+)*, Magellanic Clouds *(Okada+)*, nearby spirals *(Piñeda+)*

Some important caveats

- Velocity decomposition method: how to extract statistically significant results?
- Difference in spatial resolution between observed tracers (e.g., H I)

Motivations for the study *(Lebouteiller+ 2019)*

1. Get some meaningful results about the origin of [C II] and the fraction of CO-dark H_2 gas
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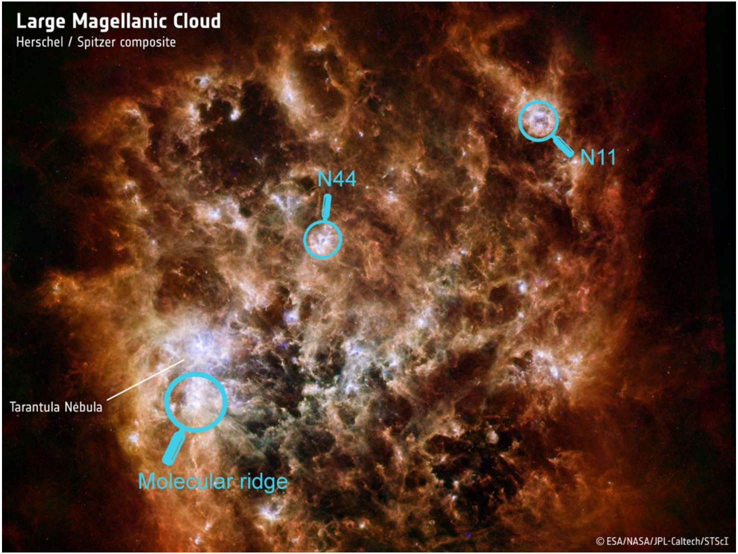
LMC-N 11


Large Magellanic Cloud
Herschel / Spitzer composite
N11
N44
Tarantula Nebula
Molecular ridge
© ESA/NASA/JPL-Caltech/STScI

LMC-N 11

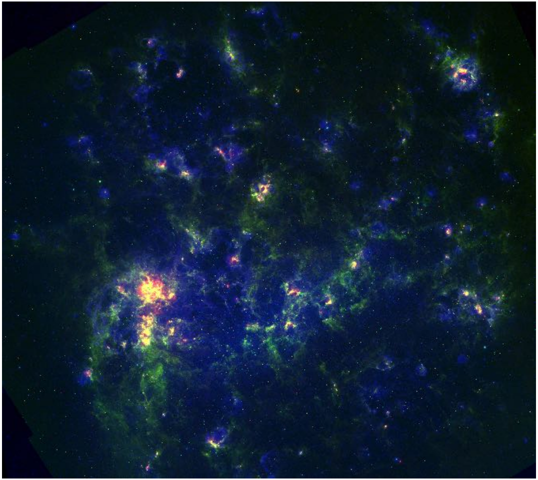


Fig.: *MCELS*, 8 μm, 24 μm *(Carlson+ 2012).*

LMC-N 11

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New observations with SOFIA/GREAT and ALMA

Dataset

- Follow-up of *Herschel*/PACS observations *(Lebouteiller+ 2012)*
- SOFIA/GREAT: [C II] 157 μm and [N II] 205 μm
- PDRs, quiescent CO clouds, ultracompact H II region, stellar cluster in a 0.5 $Z_{\odot}$ environment
- + CO(1-0) MOPRA & ALMA, opacity-corrected H I ATCA+Parkes, *Herschel*/PACS

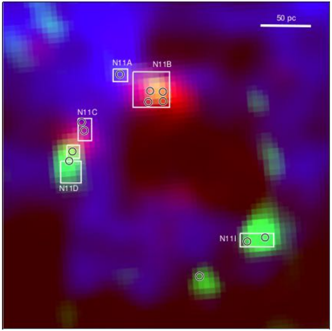

Fig.: *N 11 (Hα, CO, H I). GREAT beam size is ≈ 3 pc.*

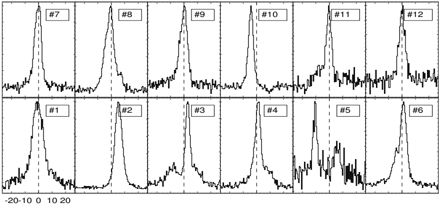

Fig.: *Overview of the SOFIA/GREAT [C II] profiles.*

Photoelectric effect heating efficiency: importance of PAHs

Method and objectives

- Sum of coolants: [C II] + [O I], power absorbed by dust and/or AF that goes into gas heating: PAH emission, FIR, TIR...
- Revisiting results that PAHs trace/dominate the neutral atomic gas heating *(Helou+ 2001, Croxall+ 2012, Lebouteiller+ 2012, Okada+ 2013)*

Result

- Confirmation of well-behaved relationships: PAH trace well gas heating, probably dominate as well
- More measurements on the way in other LMC and SMC regions *(Lambert-Huyghes+ in prep.)*

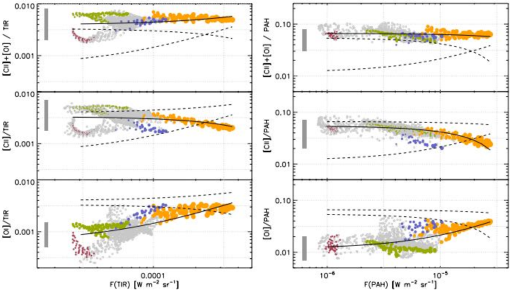

Fig.: *PE heating efficiency proxy in N 11B (Lebouteiller+ 2012).*

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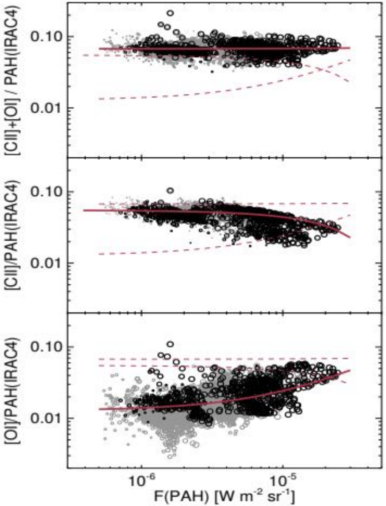
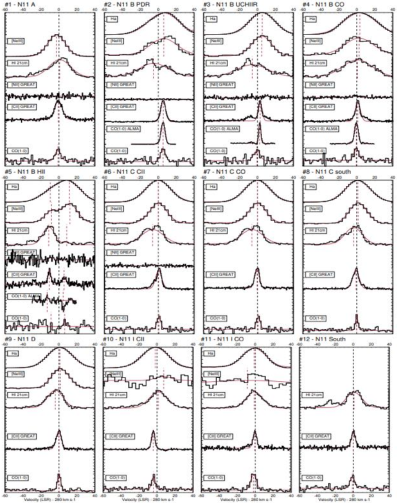
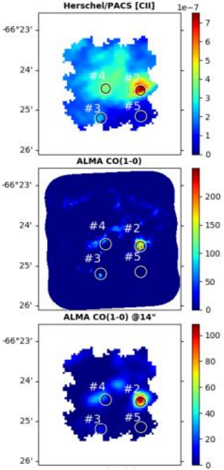


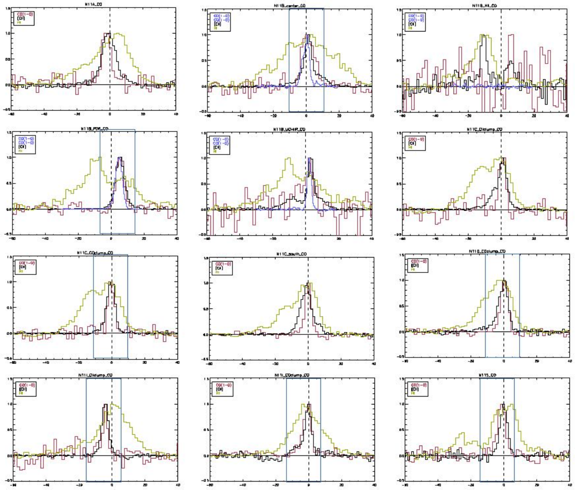
Fig.: *PE heating efficiency proxy in N 11* *(Lebouteiller+ 2019)*.

Profiles


#1 - N11 A
#2 - N11 B PDR
#3 - N11 B UCHIIR
#4 - N11 B CO
#5 - N11 B HII
#6 - N11 C CII
#7 - N11 C CO
#8 - N11 C south
#9 - N11 D
#10 - N11 I CII
#11 - N11 I CO
#12 - N11 South


Herschel/PACS [CII]
ALMA CO(1-0)
ALMA CO(1-0) @14"

Profiles (details)



Components

- Globally [C II] resembles CO ⇒ most [C II] can be dynamically associated with CO
- Some [C II] components may be associated with H I ⇒ [C II] in neutral atomic gas?
- No [C II] component without CO or H I ⇒ no [C II] required in ionized gas?
- Many H I components with neither [C II] nor CO ⇒ beam effects

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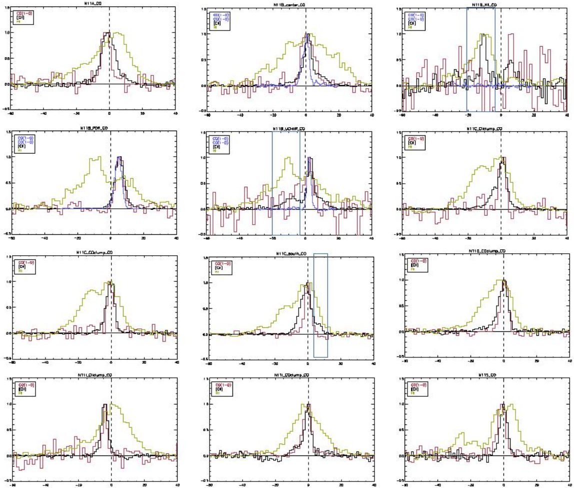

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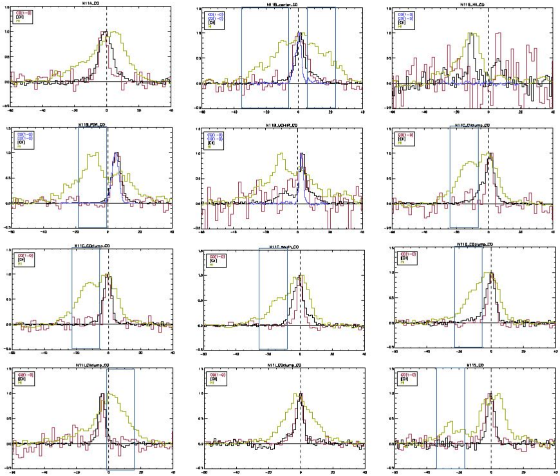

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[C II] in the ionized gas

[C II]$_{\rm ionized}$ from integrated [N II] 122, 205 μm + C^+/N^+

- Integrated measurements with PACS yield < 30% contamination

[C II]$_{\rm ionized}$ from velocity-resolved [N II] 205 μm + C^+/N^+

- Only available for 6/12 pointings
- All except one pointing indicate no significant contamination from [C II] in the ionized gas

[C II] line width

- Smaller than thermal broadening in ionized gas, especially if profile made of several components

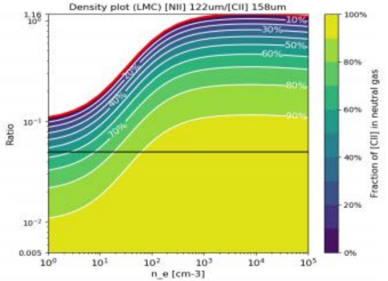

Fig.: *Ratio [N II]/[C II] in the ionized gas as a function of electron density.*

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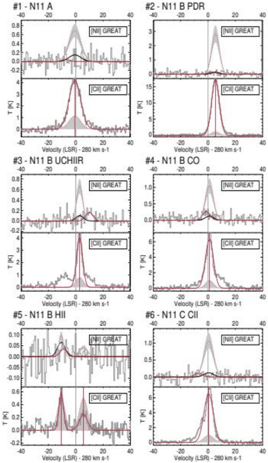
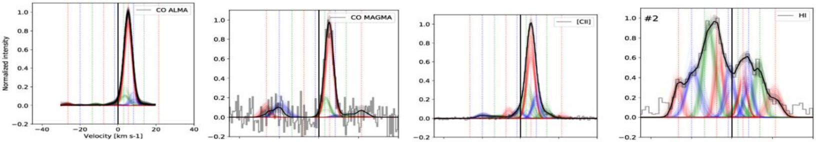


Fig.: *Solid red curve: fit to main component. Dotted red curve for [N II]: expected [N II] if [C II] fully arises in ionized gas. Dotted red curve for [C II]: brightest possible [C II] arising from ionized gas based on [N II] rms spectrum.*

Profile decomposition method

For [C II], CO, and H I

- Many different approaches tested (e.g., identifying components from simplest to most complex profiles adding components as necessary)
- Important to explore potential solutions in a statistical way
- Settled for Bayesian inference: propagating random draws to explore PDFs of ratios and quantities
- Some other parameters explored as initial conditions: number of components, minimum line width, and minimum separation between components



Direct output quantities

- H^0 column density, H_2 column density derived from CO (using fiducial LMC X_{CO} factor)
- $f(H_2|CO)$

Illustration of results

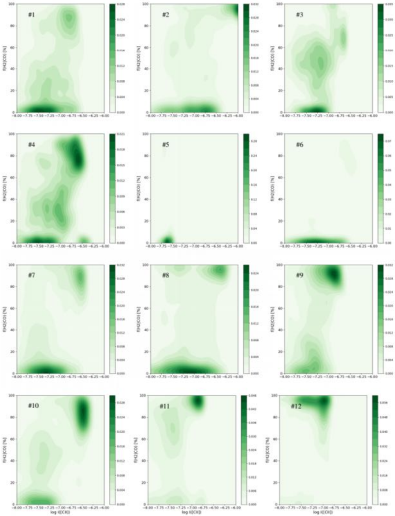
Description

- Bi-variate kernel density estimate (non-parametric probability density function) using all potential solutions (i.e., combination of N profiles and accounting for random draws around converged solution)
- Convenient way to identify regions of high-probability accounting for various decomposition hypotheses

Results

- Either $f(\mathrm{H_2}|\mathrm{CO}) < 10\%$ or $> 60\%$ ⇒ sharp transition between CO-bright H_2 gas and either CO-dark H_2 or atomic gas
- Components with a low $f(\mathrm{H_2}|\mathrm{CO})$ are our best candidates for evidence of significant CO-dark H_2 gas amount (or [C II] in atomic gas)

$f(\mathrm{H_2}|\mathrm{CO})$ vs. [C II] intensity



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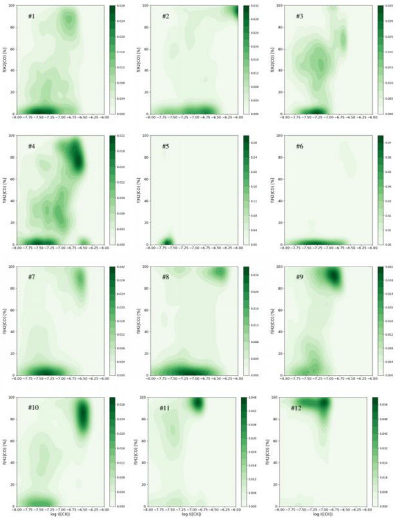


Model

Steps

1. $[\text{C II}]_{\text{atomic}}$ using $N(\text{H}^0)$ + range of n_{H0}
2. $[\text{C II}]_{\text{CO-dark}}$ = $[\text{C II}]_{\text{observed}}$ - $[\text{C II}]_{\text{atomic}}$
3. $f_{\text{coll,H2}}([\text{C II}])$: fraction of [C II] associated with gas where collisions with H_2 dominate (i.e., the CO-dark H_2 gas)
4. $N(\text{H}_2|\text{C}^+)$: H_2 column density traced by C^+.

More inferred quantities

1. $N(\text{H}_2) = N(\text{H}_2|\text{C}^+) + N(\text{H}_2|\text{CO})$
2. $f_{\text{dark}} = \frac{N(\text{H}_2|\text{C}^+)}{N(\text{H}_2)}$
3. $f_{\text{H2}} = \frac{2 \times N(\text{H}_2)}{2 \times N(\text{H}_2) + N(\text{H}^0)}$

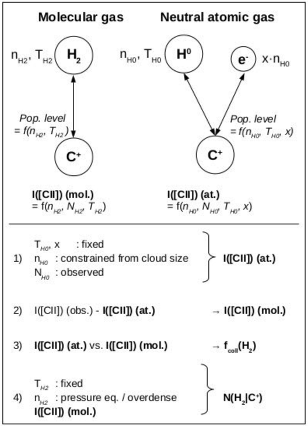


Fig.: *Model: neutral atomic & molecular phase only, collisions with H^0, H_2, e^-.*

Model results: origin of [C II]

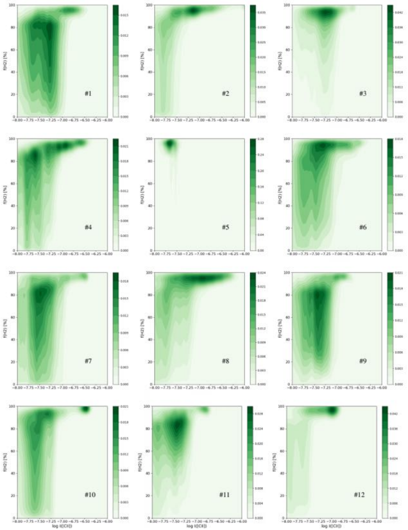
Results (now including CO-dark gas)

- Many upper limits for f_{H2} at low [C II]
- Globally $> 95\%$ of [C II] can be attributed to CO-dark H_2 gas
- Thermal pressure in the CO-dark H_2 gas: $\approx 10^{3-5}$ K cm^{-3} *(see also Piñeda+ 2017 for CO-faint LMC regions)*

[C II] in neutral atomic gas?

- Dependency of f_{H2} and $f_{coll,H2}$([C II]) with [C II] intensity: contribution from neutral atomic clouds occurs preferentially toward faint [C II] components (not toward components with low [C II]/CO)
- Even toward these faint components, contribution of $[C\ II]_{atomic} < 30\%$
- Low [C II] surface brightness: place to look for [C II] in atomic gas

$f(H_2)$ vs. [C II] intensity



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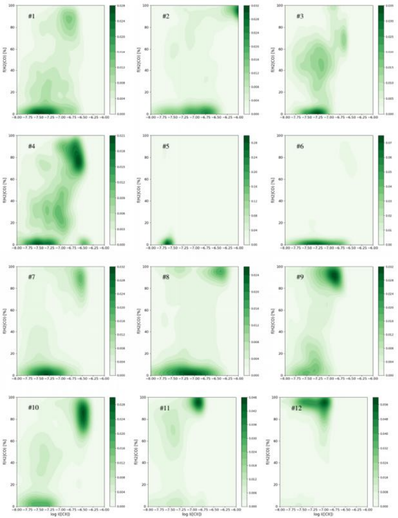

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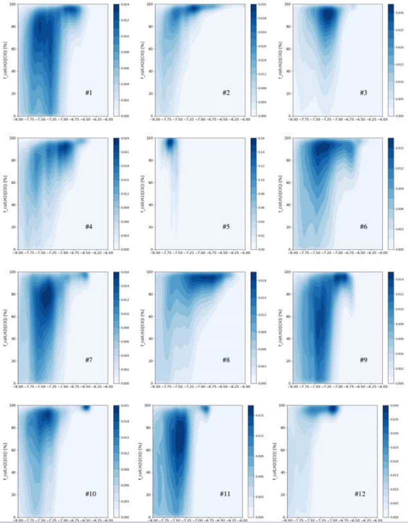

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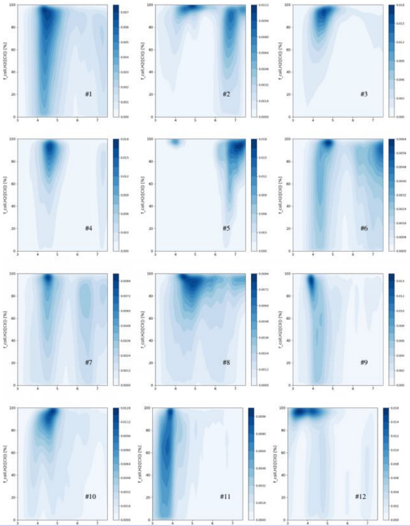


Model results: fraction of CO-dark H_2 gas

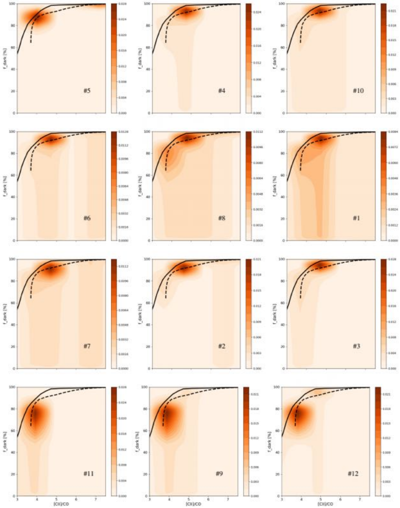
Results

- Most of the molecular gas is CO-dark overall ($f_{\rm dark} > 60\%$)
- Compatible with dust-based method across N 11 *(Galametz+ 2016)*
- Similar values obtained in other low-metallicity environments *(Fahrion+ 2017, Requena-Torres+ 2016, Chevance 2016)*

[C II]/CO and $N(H_2|CO)$

- $f_{\rm dark}$ anti-correlated with CO column density ($N(H_2|CO)$)
- There is more CO-dark gas in regions with little CO ($\sim 100\%$ for 10^{20} cm^{-2}) as compared to CO peaks ($\sim 70-90\%$ for 10^{21} cm^{-2})
- Reminiscent of findings by *Okada+ (2015)* in LMC-N159
- We derive an effective $X_{\rm CO}$ factor compatible with *Israel 1997, Galliano+ 2011, Chevance 2016*

$f_{\rm dark}$ vs. [C II]/CO



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[C II]/CO and $N(\mathrm{H_2|CO})$

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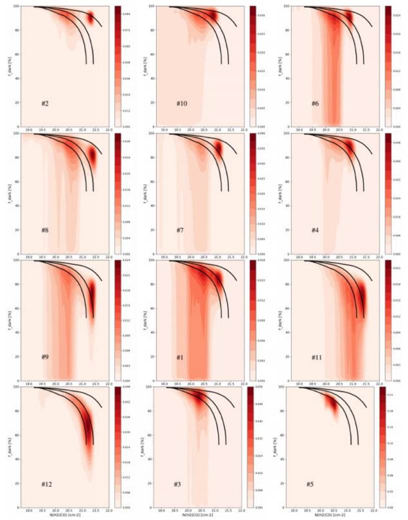
f_{dark} vs. $N(\mathrm{H_2|CO})$

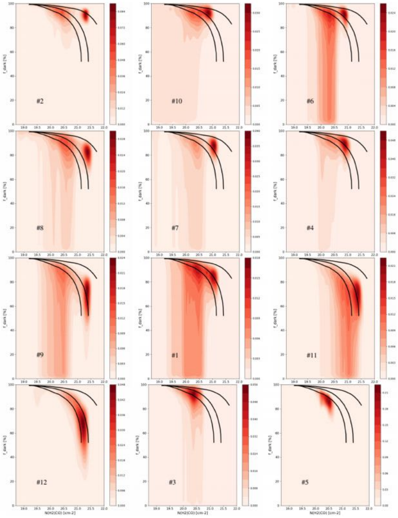


Model results: physical parameters controlling $f_{\rm dark}$

Results

- Sequence in plot correlates with presence of bright Hα and 24 μm emission
- Circumstantial evidence of larger $f_{\rm dark}$ values toward UV-bright regions
- Selective disruption and photodissociation of the most diffuse clouds $\Rightarrow$ lower extinction on average in beam?
- More tracers would be needed to constrain G_0 or $A_{\rm V}$

$f_{\rm dark}$ vs. $N({\rm H_2|CO})$



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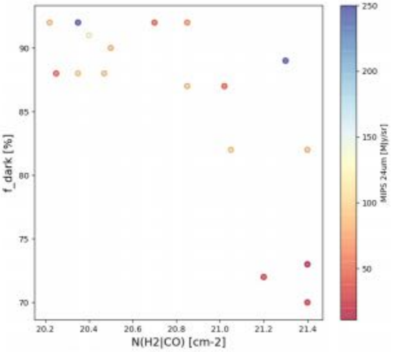

Conclusions

SOFIA results in LMC-N 11 (50% $Z_\odot$) *(Lebouteiller+ 2019)*

- Most of H_2 gas in SF regions is CO-dark, mostly distributed in the interclump medium (as opposed to layers around clouds) where CO is photodissociated
- Faintest [C II] components trace a partly atomic gas
- Possible to isolate radiation field specific effect
- Validation of the technique, potentially extremely fruitful

Accumulating evidence

- **Milky Way** *(Velusamy+ 2010; Piñeda+ 2012, 2015)*, **M 51** *(Piñeda+ 2018, 2020)*, **M 17-SW** *(Pérez-Beaupuits+ 2015)*, **NGC 4214** *(Fahrion+ 2017)*, **LMC-N 159** *(Okada+ 2015, 2019)*, **SMC H II regions** *(Requeña-Torres+ 2016)*
- [C II] traces significant CO-dark gas in star-forming regions (especially at low metallicity)
- There may be significant [C II] not directly associated with the dense star-forming material

Prospective and limitations

- PDR model per component to get to G_0, A_V... *(importance of mutual shielding: Okada+ 2019)*
- Need high spectral resolution H I data (GASKAP; *Dickey+ 2013*)
- Need high spectral resolution ionized gas data

SOFIA prospective

LMC+: Joint Legacy program with FIFI-LS

- PI: S. Madden
- 50h; $1.3^\circ \times 0.5^\circ$ in the Southern Molecular Ridge in [C II] and [O III]
- Reaching the diffuse [C II] emission where large amounts of CO-dark H_2 gas are expected due to low A_V
- Using [C II], CO, FIR as main constraints for A_V and G_0
- Using [O III] to probe propagation of energetic photons on large scales
- Complementary to the 30 Doradus field (PI Tielens; PI Chevance)