Characterizing the Multi-Phase Origin of [CII] Emission in M101 and NGC 6946 with Velocity Resolved Spectroscopy

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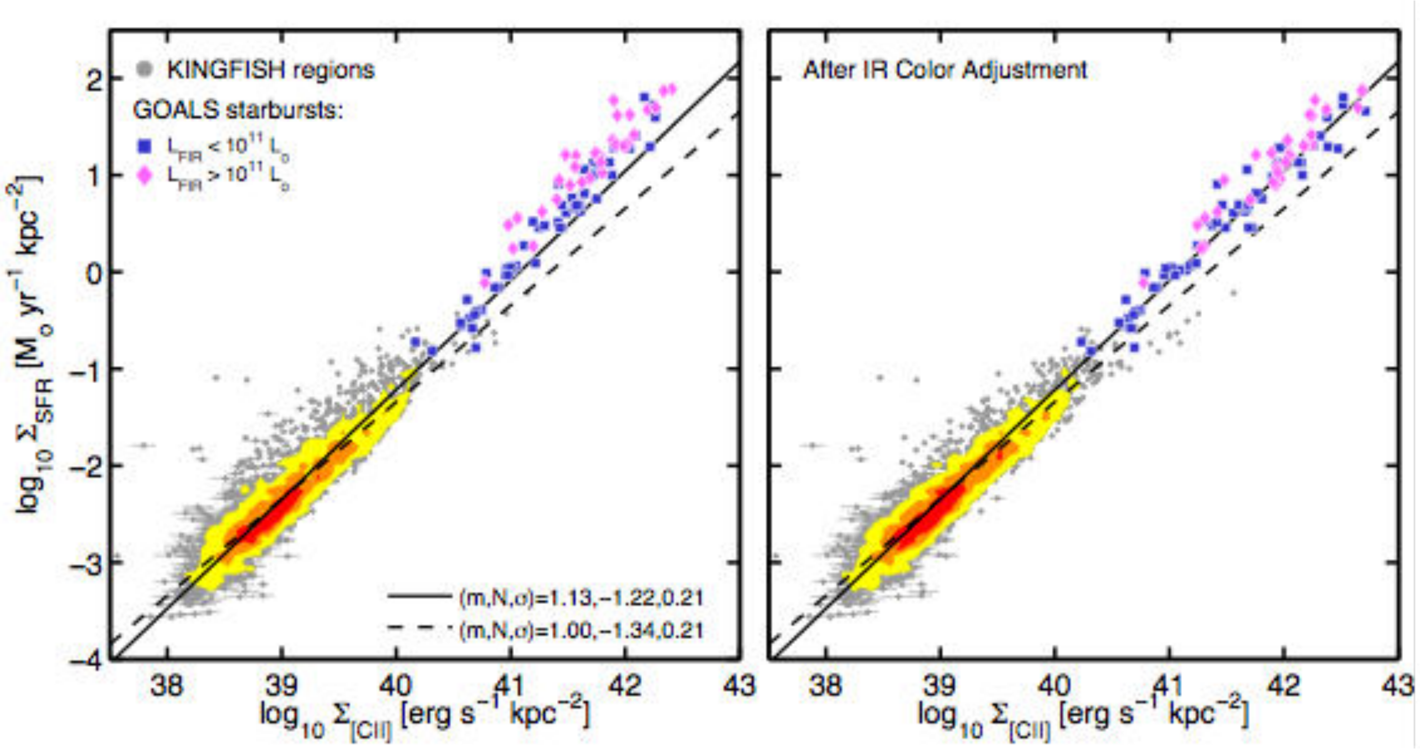
Importance of [CII] Emission

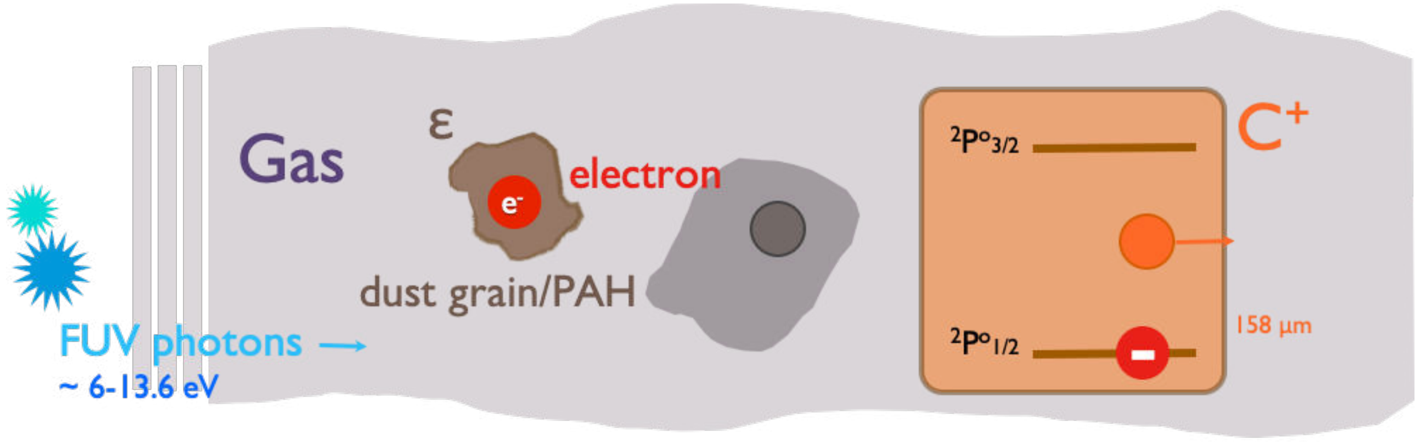
One of the brightest lines in the FIR (~1% total FIR continuum) in both local and high-z universe (e.g., Crawford+ 1985, Stacey+ 1991, Zanella+ 2018)

Tracer of star formation (e.g., Stacey+ 1991, Boselli+ 2002, De Looze et al. 2014, Herrera-Camus+ 2015)



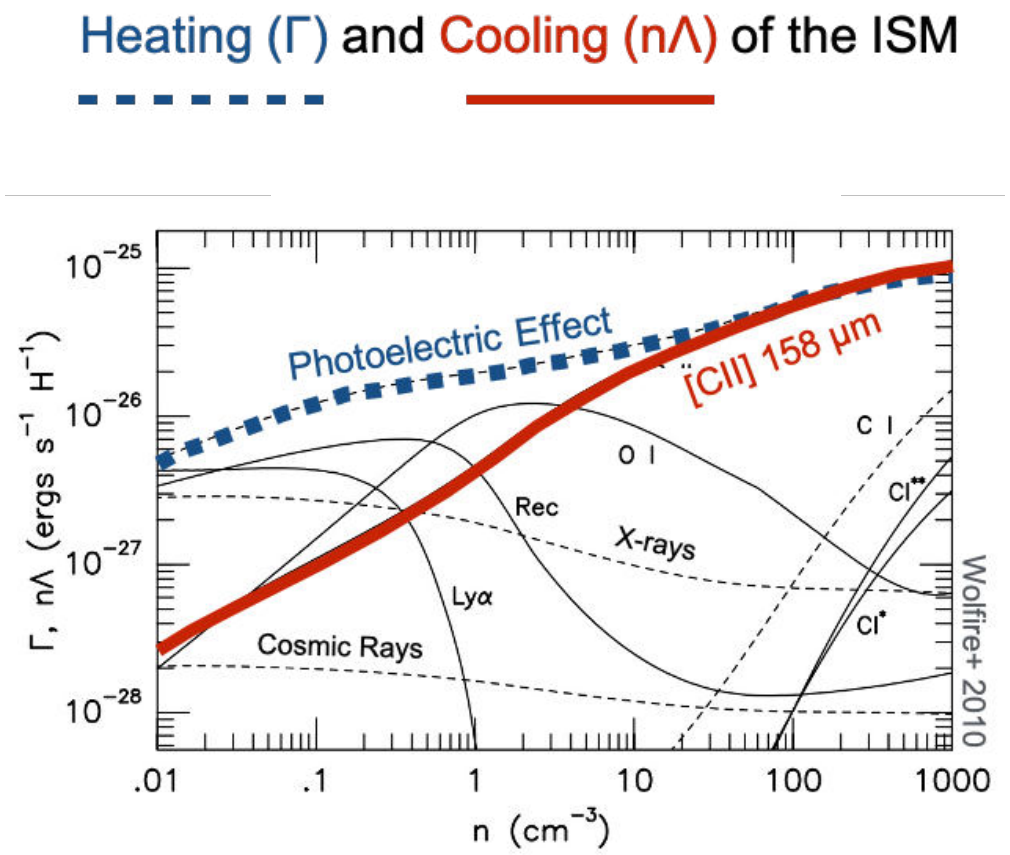
Herrera-Camus+ 2015

[CII] is a major coolant of the neutral gas



In thermal balance:

heating ≈ cooling
(star formation) ([CII])



Multi-phase nature of [CII]

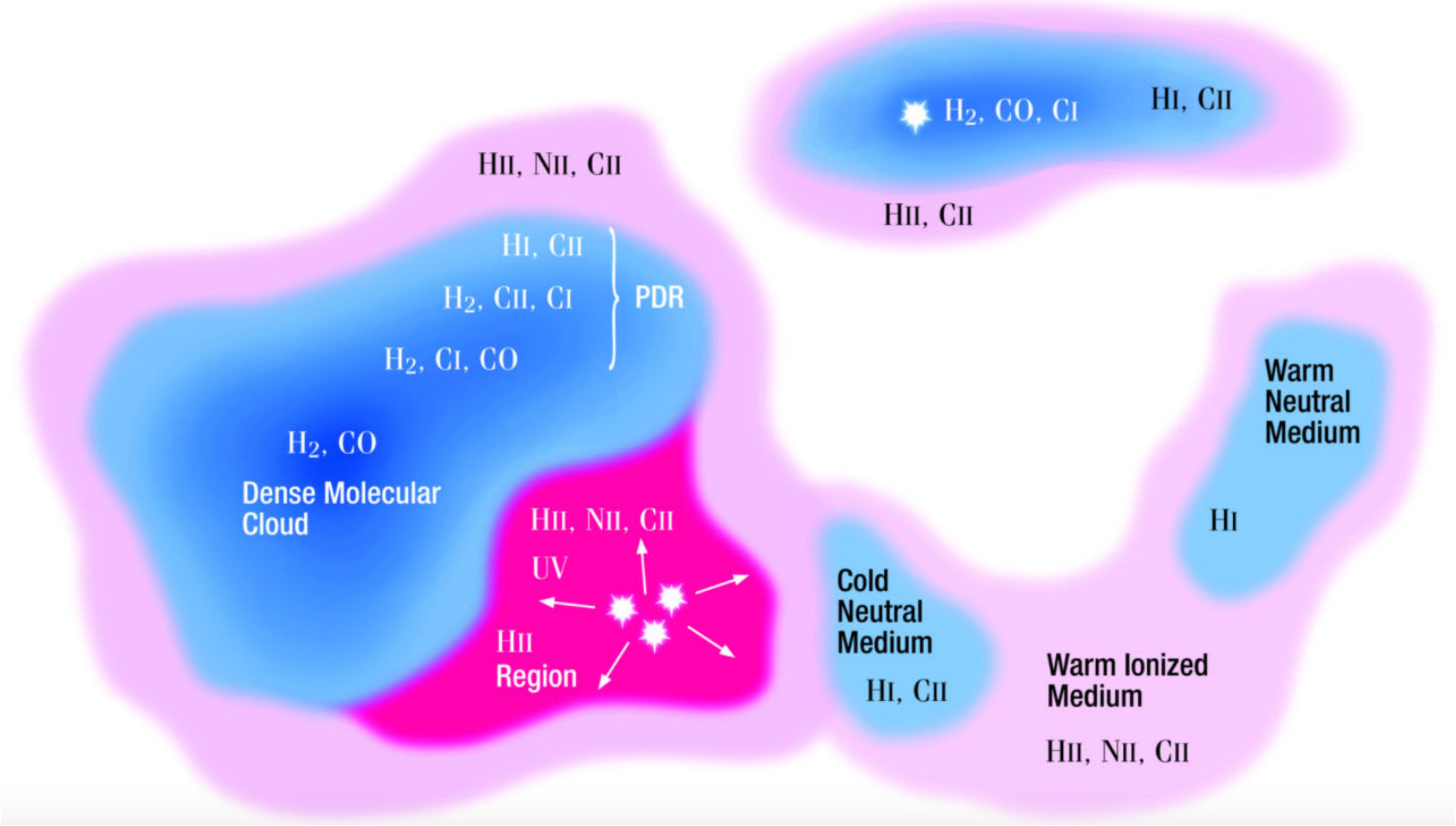


Image credit: Jorge Pineda

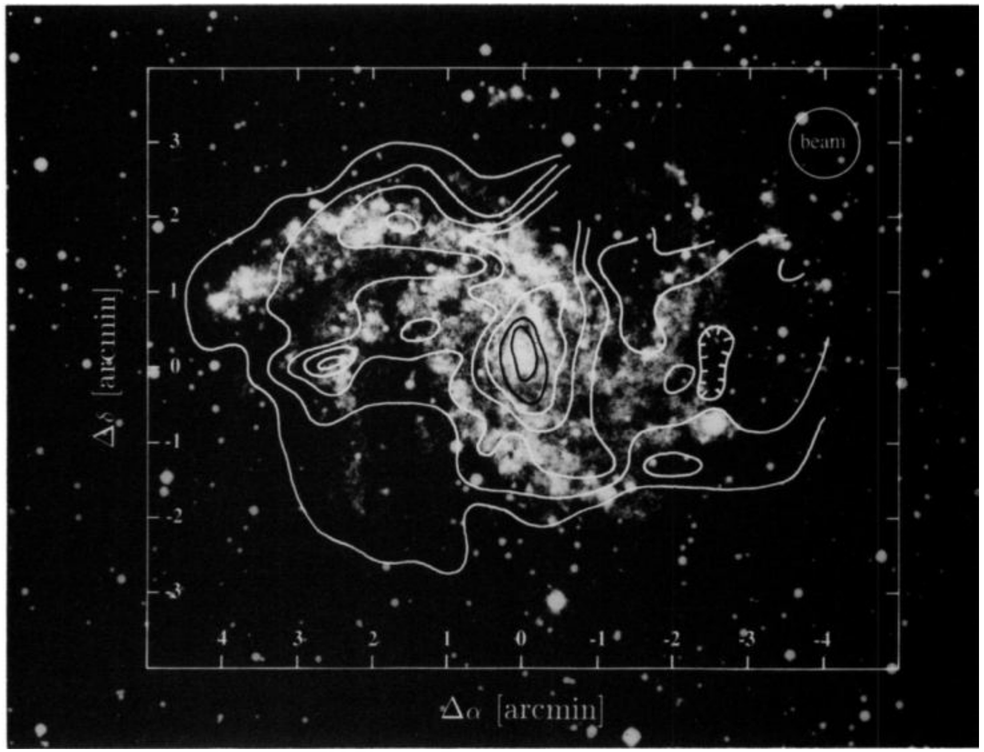
$E_{ion} < 13.6$ eV and is easily produced in $n \sim 50 - 300$ cm^{-3} gas with $T \gtrsim 50$ K

[CII] therefore exists in:

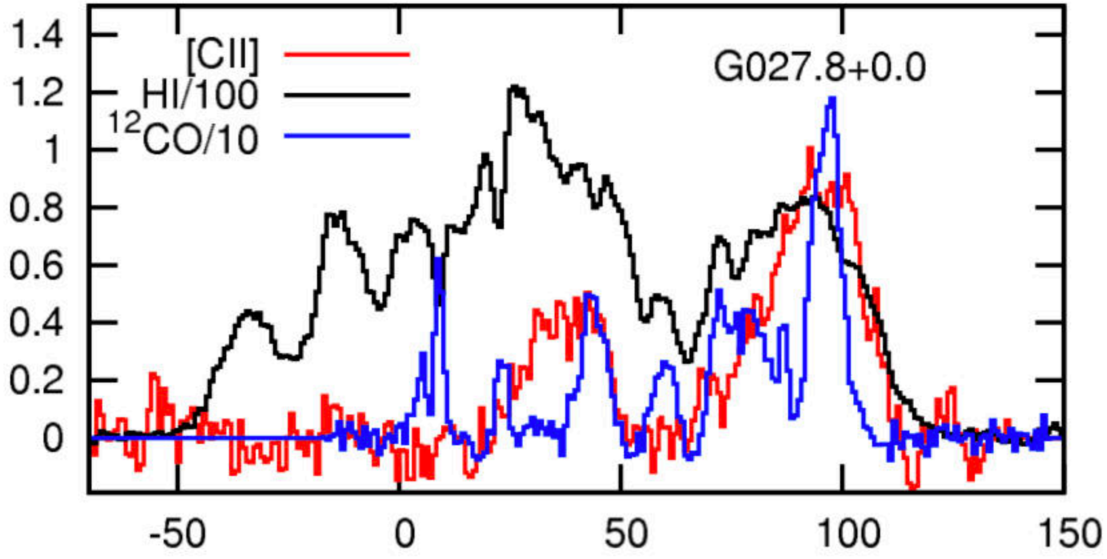
- photodissociation regions (PDRs)
- cold neutral medium (CNM)
- warm ionized medium (WIM)
- HII regions

Disentangling the [CII] Emission

Madden+ 1993



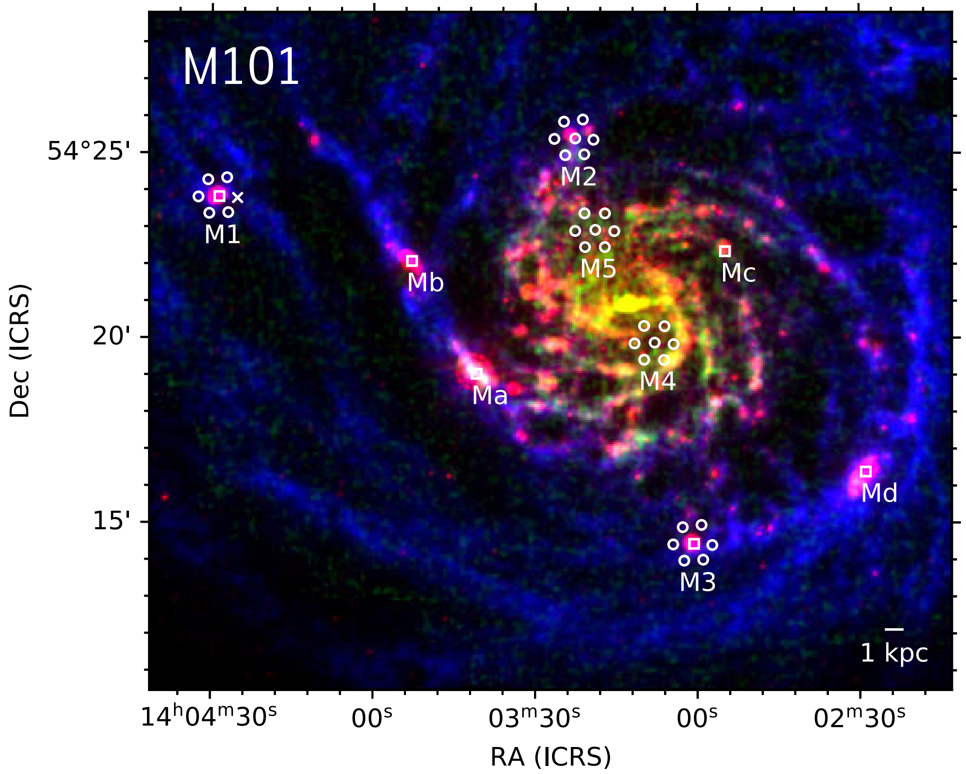
Pineda+ 2013

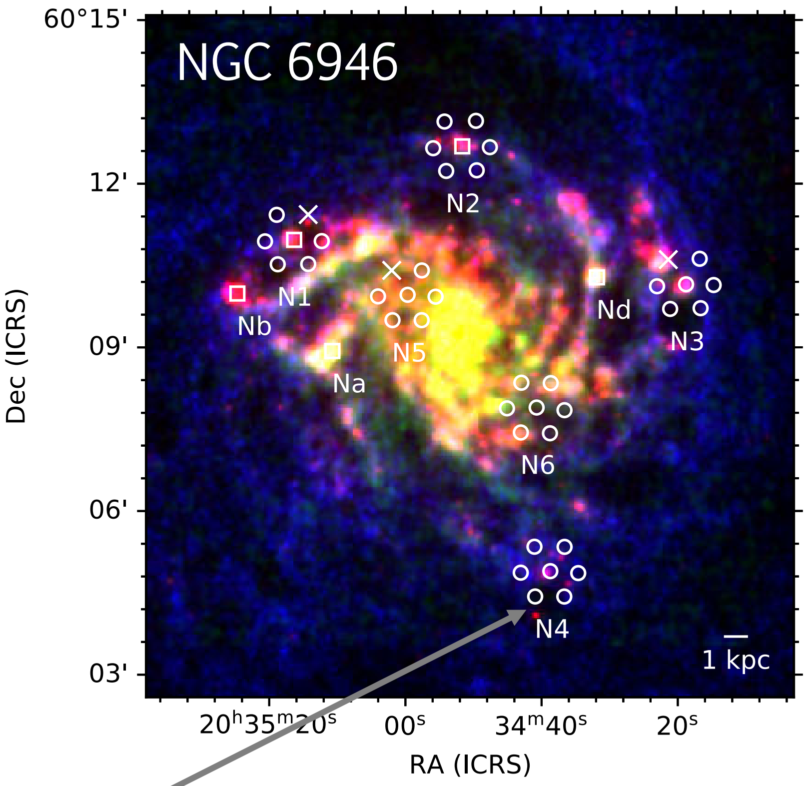


[CII] emission from atomic gas first found in NGC 6946 (Madden+ 1993, Heiles 1994)

Velocity resolved data can directly disentangle the [CII] emission (e.g., Pineda+ 2013, Mookerjea+ 2016, Fahrion+ 2017, Okada+ 2019, Lebouteiller+ 2019)

SOFIA/GREAT observations of M101 and NGC 6946



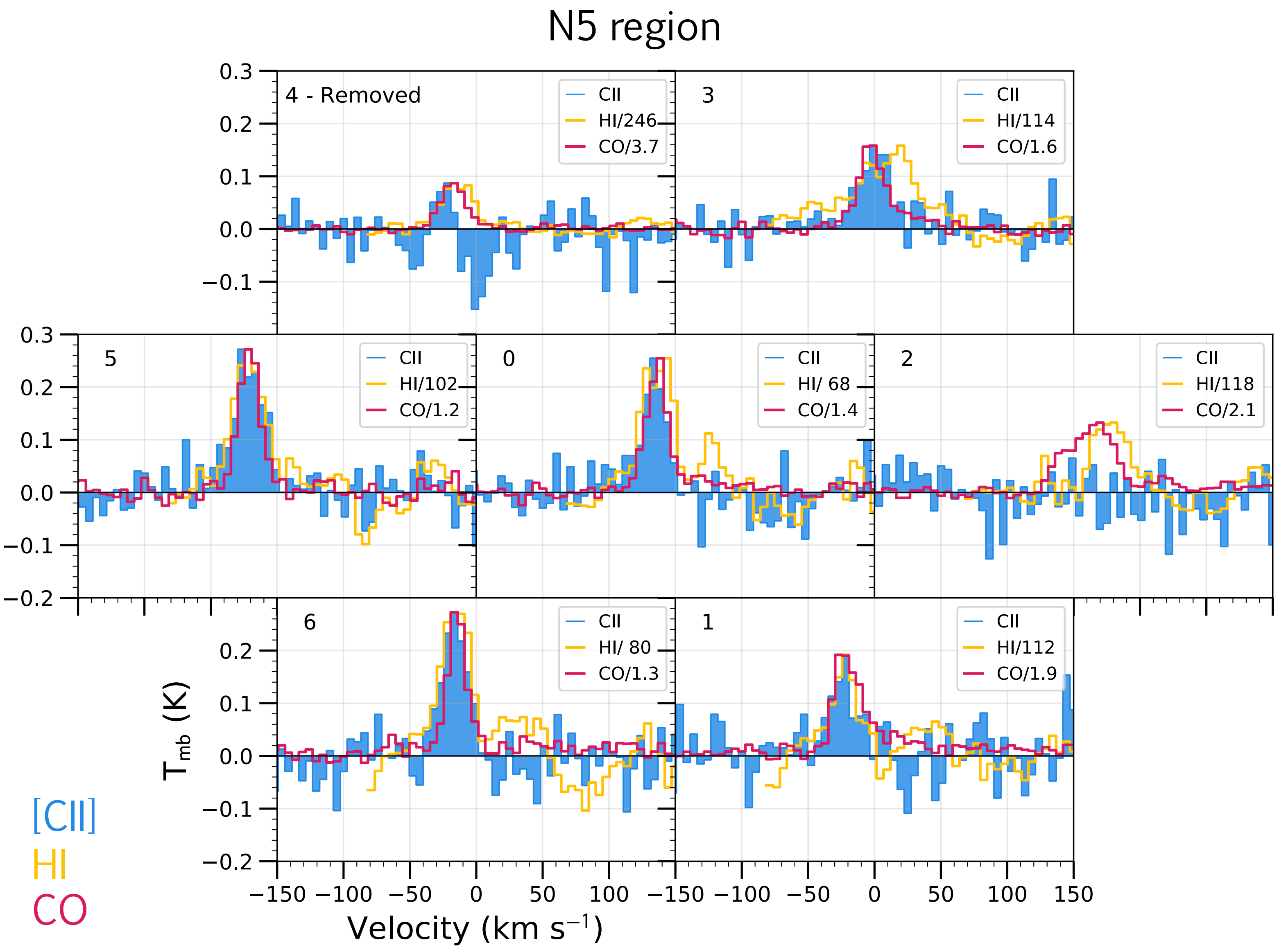


24 μm data
CO data
HI data

Pointing of the upGREAT instrument (15”)

- Cycles 2 & 4 SOFIA/GREAT
  - 78 [CII] spectra
  - 14 [NII] spectra (all non-detections)
- Resolution
  - Beam size: 15”~500 pc
  - Velocity resolution: 5.2 km/s

Trace a wide range of environments: star-forming, quiescent, metallicity, gas fraction, etc.



Ancillary spectrally resolved HI (THINGS, Walter+ 2008) and CO (HERACLES, Leroy+ 2009) data

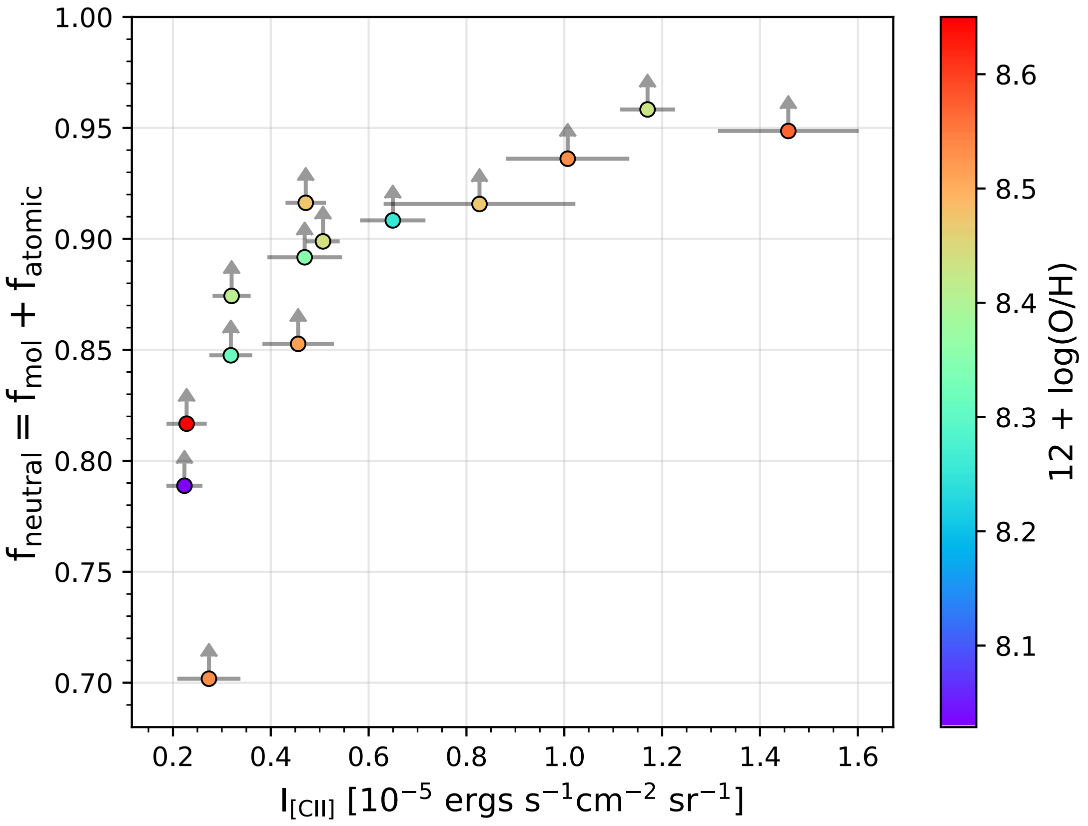
Spectral profiles trace the bulk motions of the gas → **we use the shape of the profile to trace the origin of [CII]**

[CII] associated with the ionized gas

- [NII]/[CII] → density independent measure of the amount [CII] is associated with the ionized gas (Oberst+ 2006)
- No [NII] detections, use lower limits

Average upper limit of $f_{ionized} \sim$ 12%

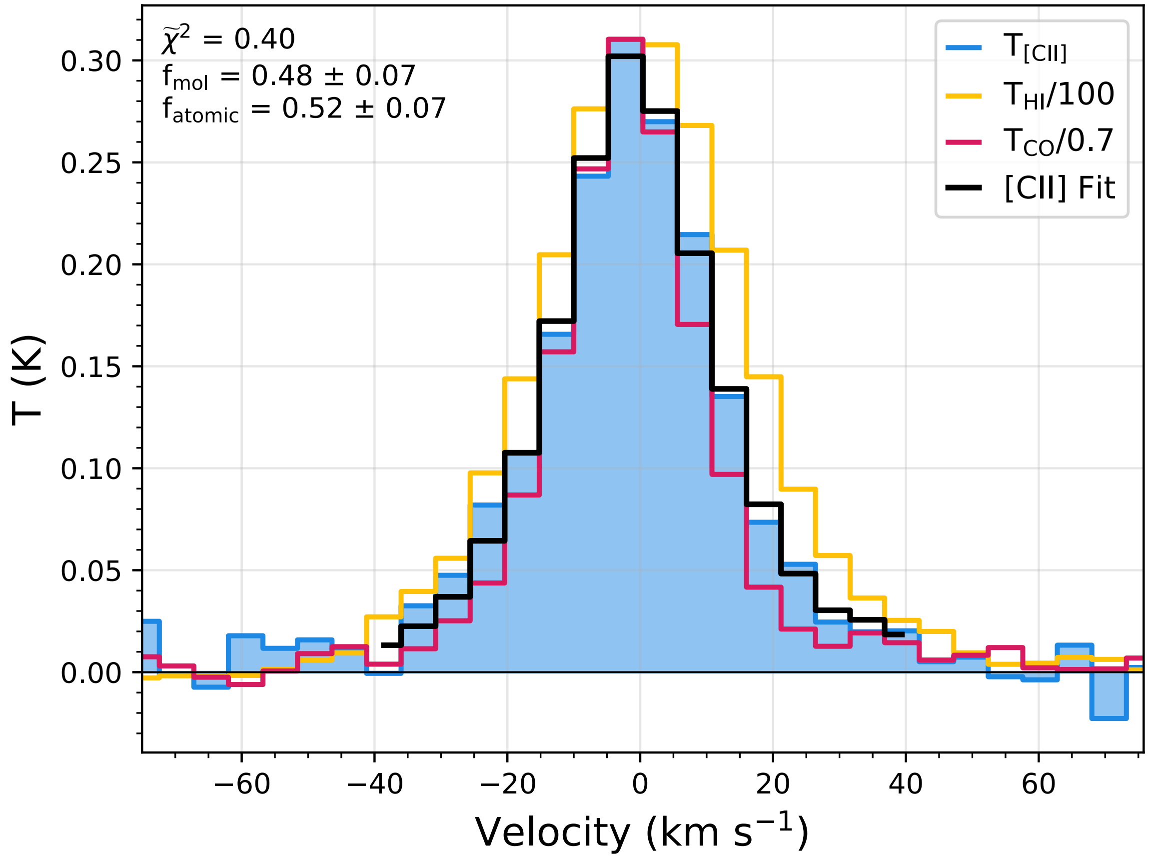
- Similar to other estimates (Croxall+ 2017, Cormier+ 2019, Lebouteiller+ 2019)
- Assume ionized gas is negligible in the [CII] decomposition



[CII] decomposition method

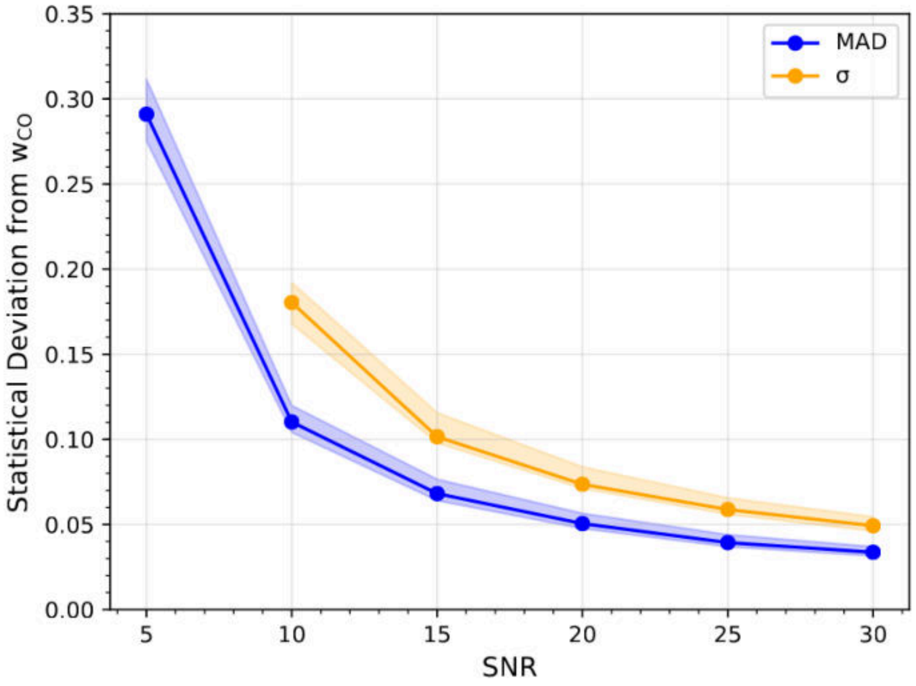
- Assume: [CII] comes from the molecular gas (as traced by CO) and atomic gas (as traced by 21 cm HI emission)
  - CNM and WNM kinematically similar/well mixed
  - Dense CO-dark molecular gas is kinematically similar to CO
- Fit a linear combination of the CO and HI spectra that best reproduced the [CII] spectra

$$T_{\text{[CII],model}} = w_{\text{CO}} T_{\text{CO}} + w_{\text{HI}} T_{\text{HI}}.$$

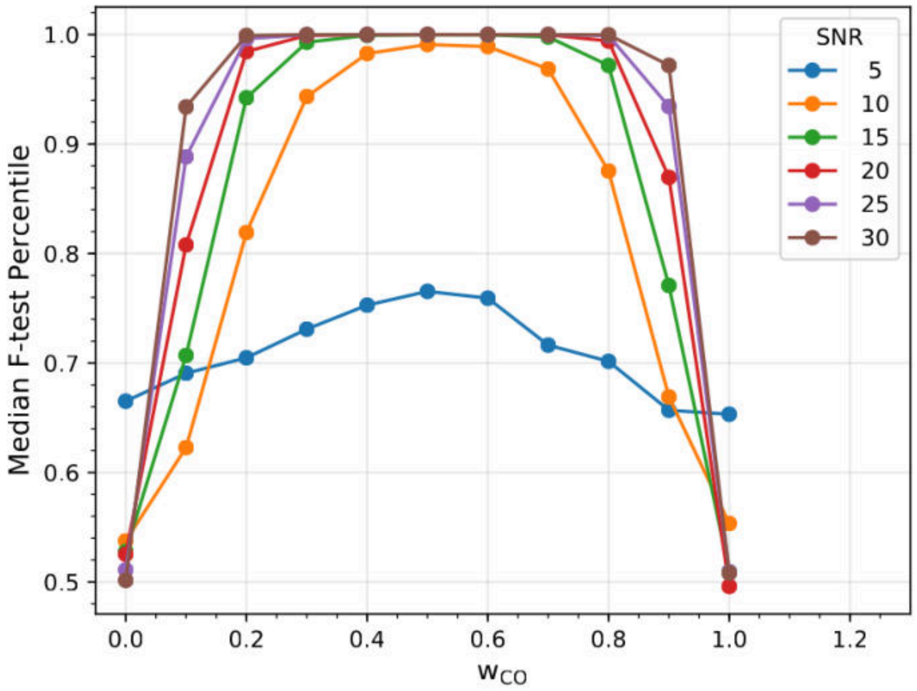


Evaluating the [CII] decomposition method

Peak SNR for decomposition to be accurate



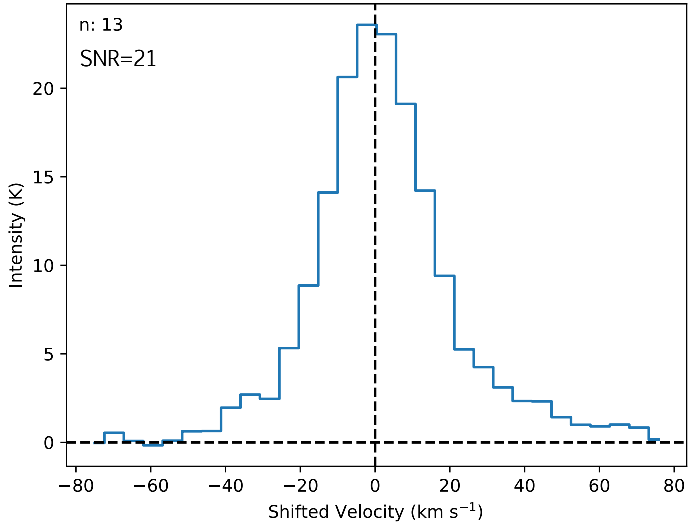
Peak SNR for decomposition to be unique



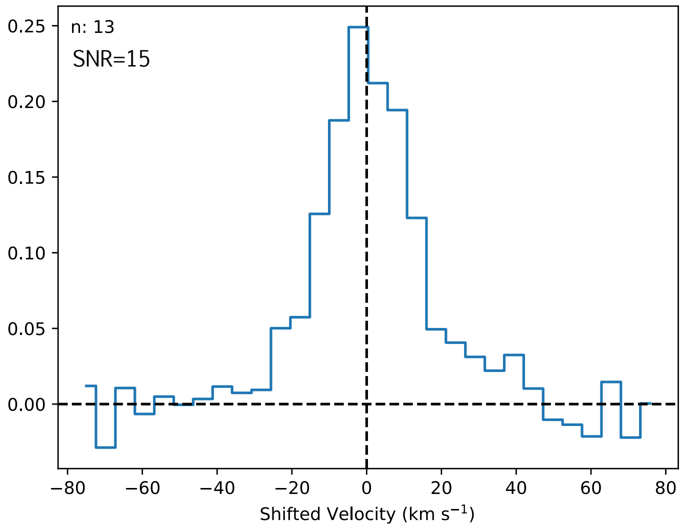
Need a peak SNR≈10-15 → we stack the data

Stacking and binning the data

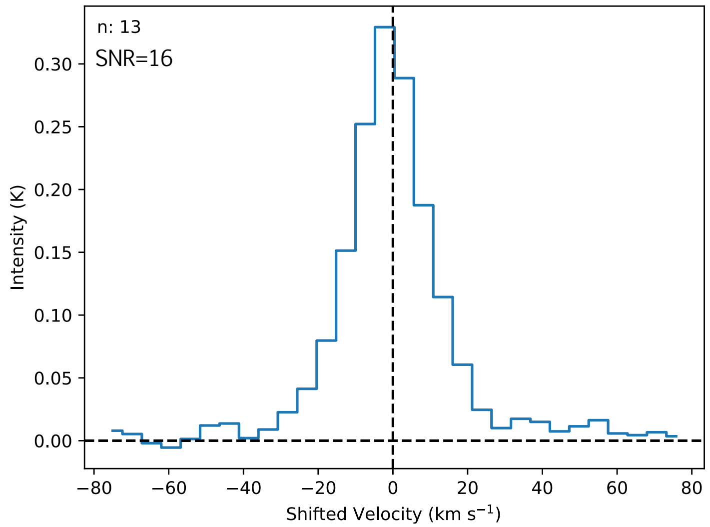
HI



[CII]



CO(2-1)



Stack spectra on the velocity of the HI

- Highest SNR
- Gaussian shaped
- Detections for all regions

Group spectra by bisecting on a property in the galaxy (metallicity, star formation rate, etc.)

Example: median metallicity is 12 + log(O/H)=8.55

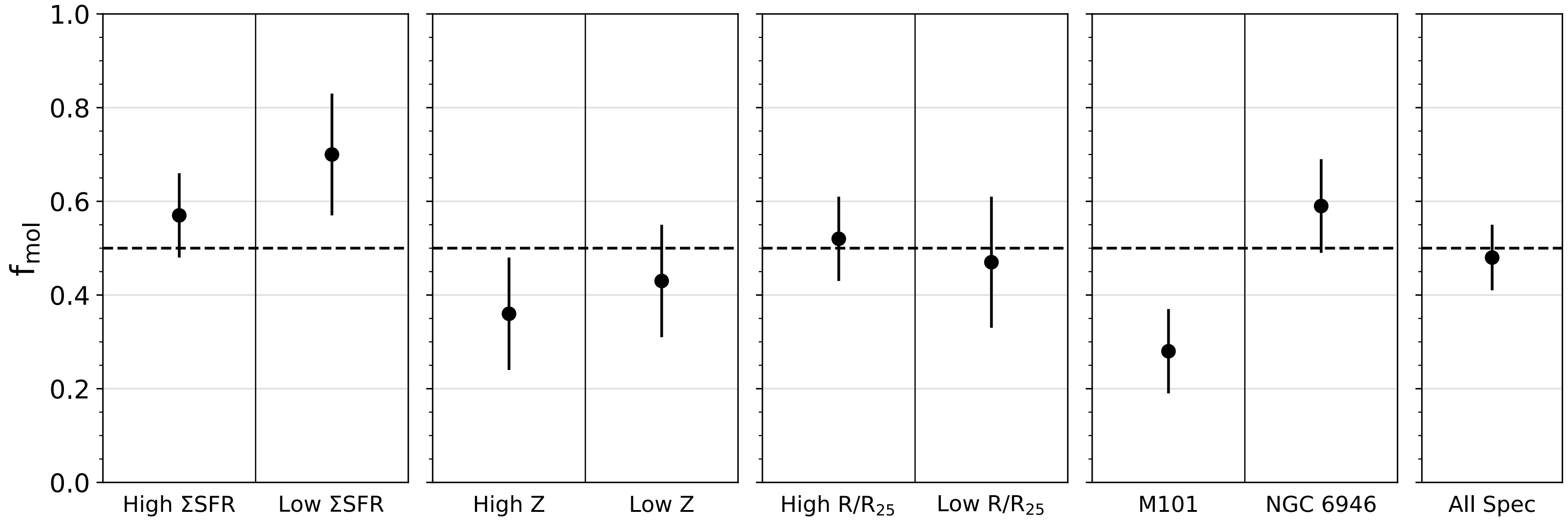
- Define a high bin where all regions > 8.55 are stacked together
- Low bin stacks spectra < 8.55

Origin of [CII] emission from stacked spectra

The [CII] emission has about an **equal contribution (~50%)** from the molecular and atomic gas, independent of SFR, metallicity, or galactocentric radius

- Significant difference between the origin of [CII] in M101 vs. NGC 6946
- Increase in f_{atomic} when fainter [CII] spectra are stacked

1σ errorbars from fit

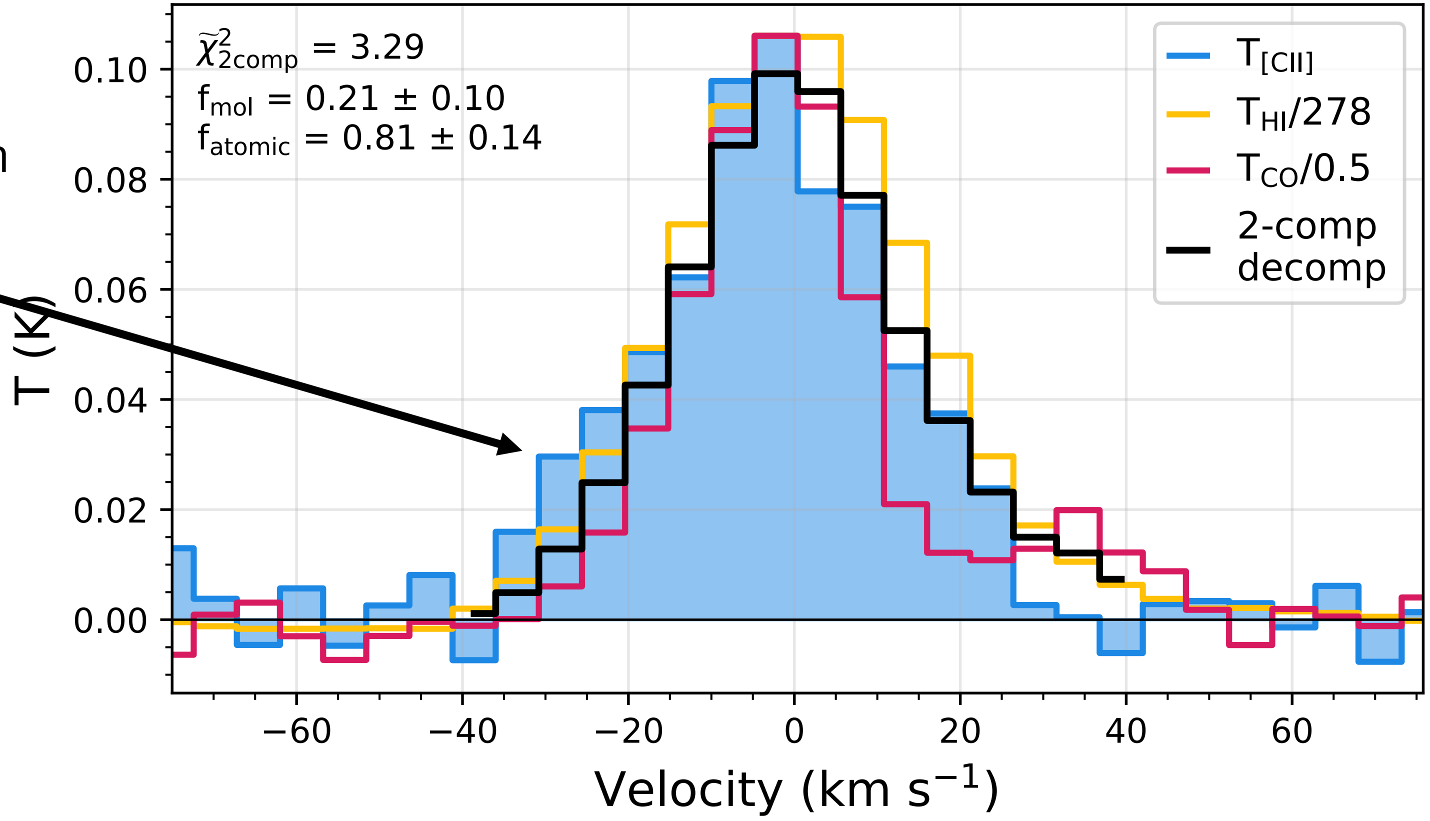


The atomic gas has a significant contribution to the [CII] emission in these regions → **[CII] may not be a good molecular gas tracer on large (500 pc) scales***

*Better data is needed to confirm this finding!

Possible CO-Dark Gas?

Excess emission on left wing



All regions with the lower metallicity stacked together

Thermal pressure in the cold neutral medium

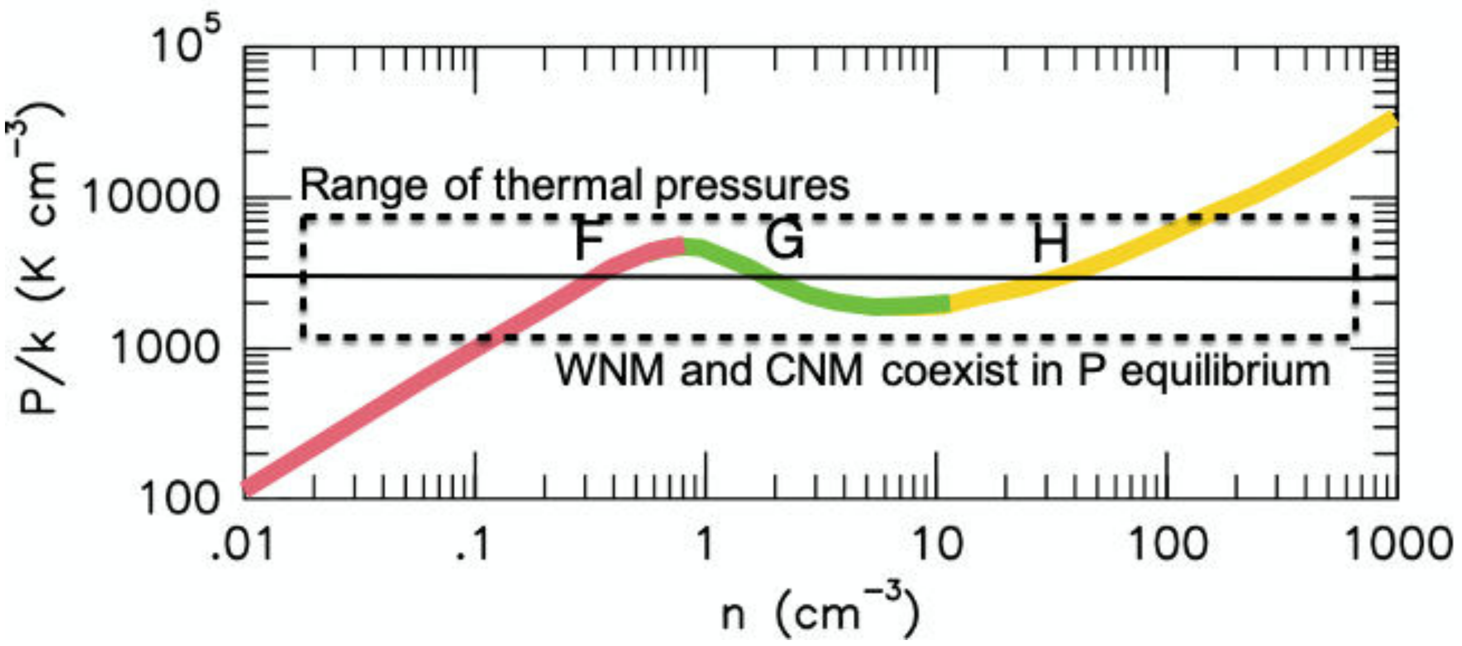
Most previous determinations of the thermal pressure focus on the Galactic Plane

Galactic Plane: $\langle P_{th} \rangle \approx$ 3,800 K cm^{-3}

CI absorption lines in UV spectra of local stars - Jenkins & Tripp 2011

[CII] emission in emission and absorption - Gerin et al. 2015

Two-Phase Medium Thermal Pressure versus Density Curve



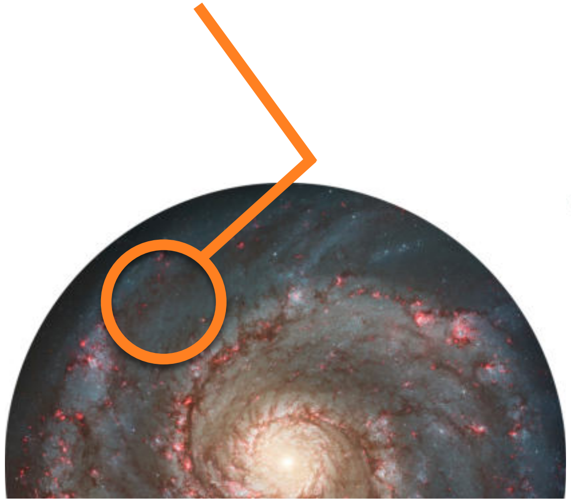
$P_{min} < P_{max} \approx 3P_{min}$

Use the cooling function of [CII]

- WNM is not dense enough to excite [CII] emission substantially (e.g. Pineda+ 2013; Fahrion+ 2017; Herrera-Camus+ 2017)
- All [CII] emission associated with the atomic gas comes from the CNM

[CII] is the dominant cooling line in the CNM → use [CII] cooling rate to determine P_{th}

Method (Kulkarni & Heiles 1987):
[CII] 158 μm arising from atomic dominated regions



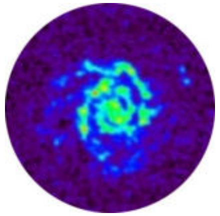
[CII] cooling rate:

$$\Lambda_{[\mathrm{CII}]} = 2.9\times10^{-20}\left[\frac{\mathrm{C}}{\mathrm{H}}\right]\left(\frac{2e^{-91.2/T}}{1+2e^{-91.2/T}+3\times10^{3}/n_{\mathrm{HI}}}\right)$$

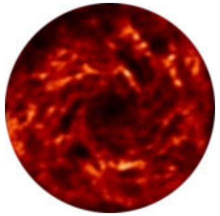
$$P_{th}/k\ [\mathrm{K\ cm^{-3}}] = 1.1 n_{\mathrm{HI}} T.$$

P_{th} in the KINGFISH Sample

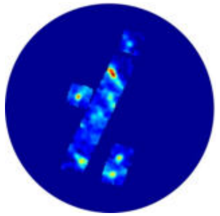
The Sample: 31 Nearby Galaxies



Molecular Gas
CO (HERACLES)



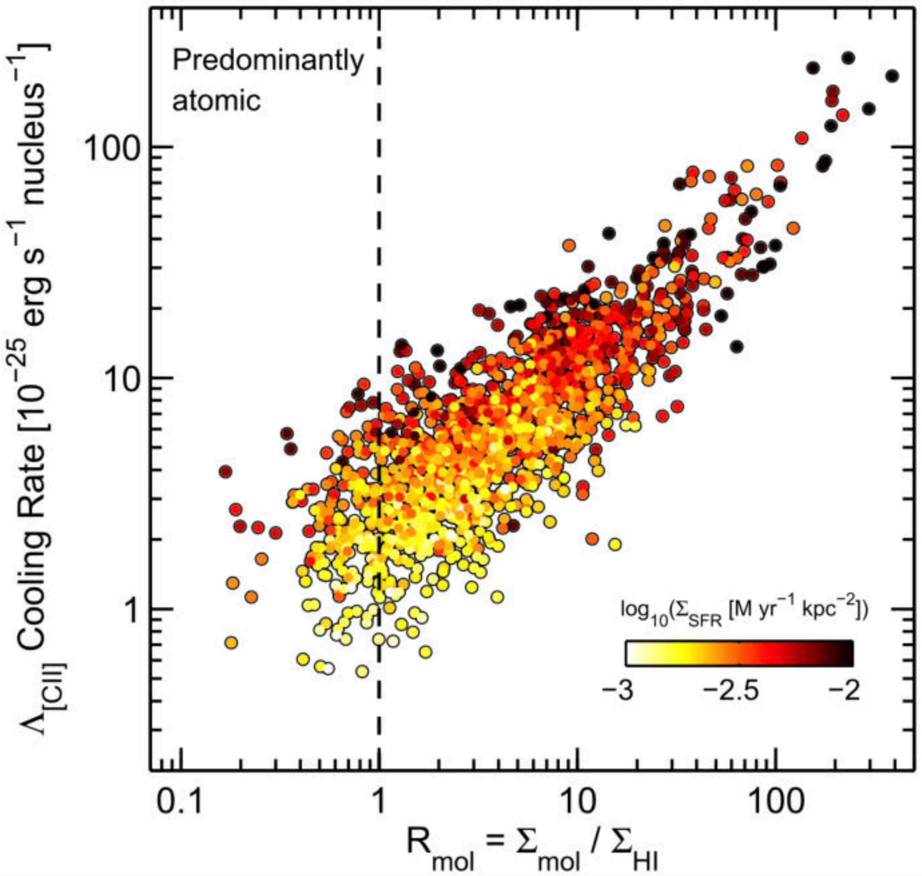
Atomic Gas
HI 21 cm (THINGS)



[CII] 158 μm
KINGFISH

Not velocity resolved → **need to identify atomic dominated regions**

Herrera-Camus+ 2017



Velocity resolved observations to calculate P_{th}

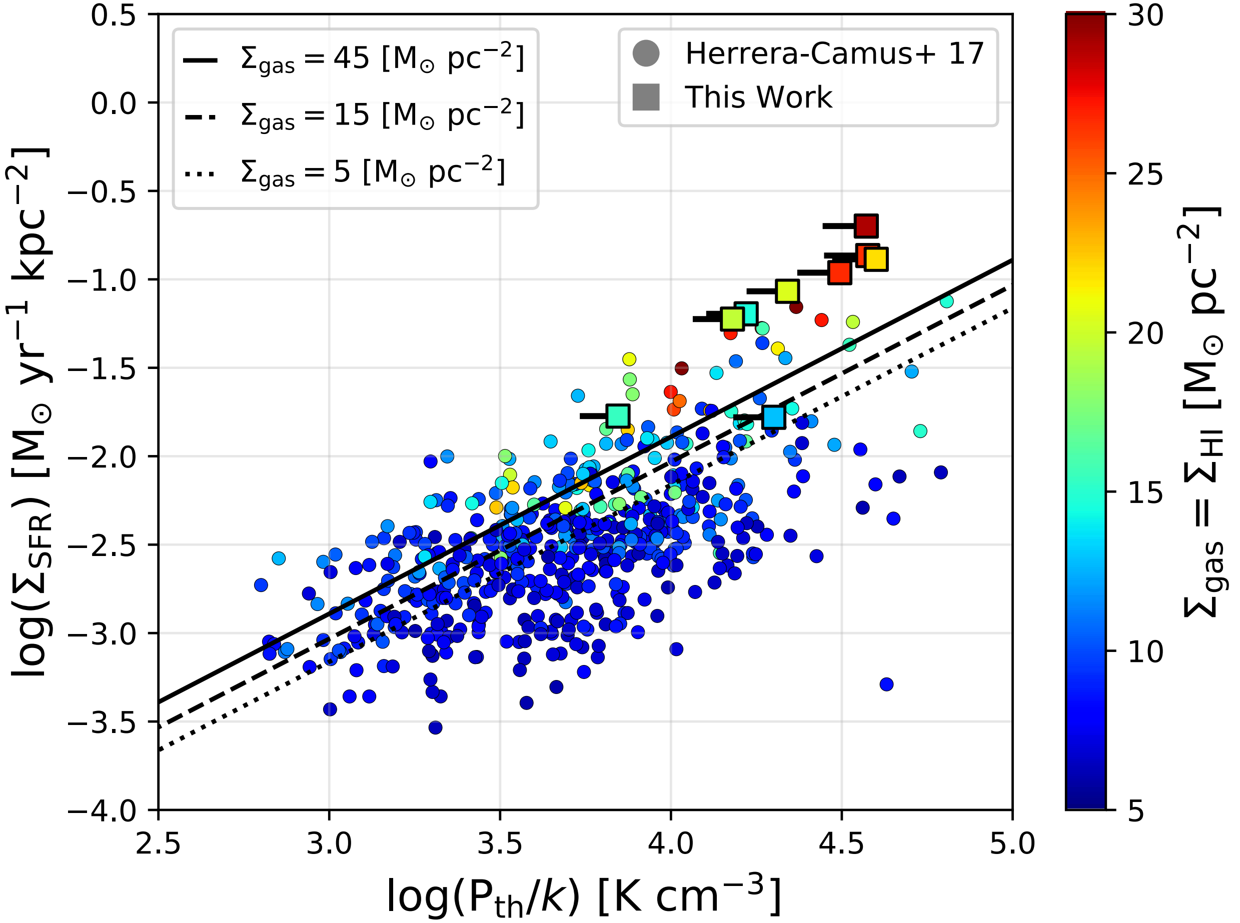
- Velocity resolved data allows us to identify the thermal pressure in any region
- Use f_{atomic} calculated from the velocity decomposition to isolate the [CII] produced only by the CNM

Models
Wolfire et al. 95, 03
Ostriker et al. 10

$$P_{\rm thermal} \propto \left(\frac{P_{\max}}{P_{\min}}\right)^{1/2} \frac{G_0'}{1+3(G_0' Z_g'/\zeta_t')^{0.4}}$$

Radiation Field Strength ($\propto \Sigma_{SFR}$)
Metallicity
CR Ionization rate ($\propto 1/\Sigma_{gas}$)

log P_{th} = 3.8 – 4.6 K cm^{-3}, slightly higher than previous determinations, but follows similar trends



Importance of scales on the origin of [CII] emission

Magellanic Clouds (3-5 pc scales)

- 5 – 15% of [CII] emission comes from the atomic gas
- Significant contribution of CO-dark gas
- Atomic phase has an increased contribution (~30%) in fainter [CII] regions (Lebouteiller+ 2019)
- Negligible ionized gas

e.g., Okada+ 2015, 2019; Requena-Torres+ 2016; Pineda+ 2017; Lebouteiller+ 2019

Galactic plane (1-3 pc scales)

- 47% from dense CO PDRs
- 28% CO-dark gas
- 21% atomic gas
- 4% ionized gas

e.g., Pineda+ 2013

External galaxies (50 – 500 pc scales)

- Origin of [CII] varies a lot!
  - ~50% from atomic gas in M101 and NGC 6946 (Tarantino+ 2021)
  - 8%–85% associated with atomic gas in M33 (Mookerjea+ 2016)
  - 46% of [CII] associated with the HI emission in NGC 4214 (Fahrion+ 2017)
  - 70% of [CII] associated with ionized gas in the center of IC 342 (Röllig+ 2016)
- Generally a high pressure atomic phase

Nuanced, depends where one observes!

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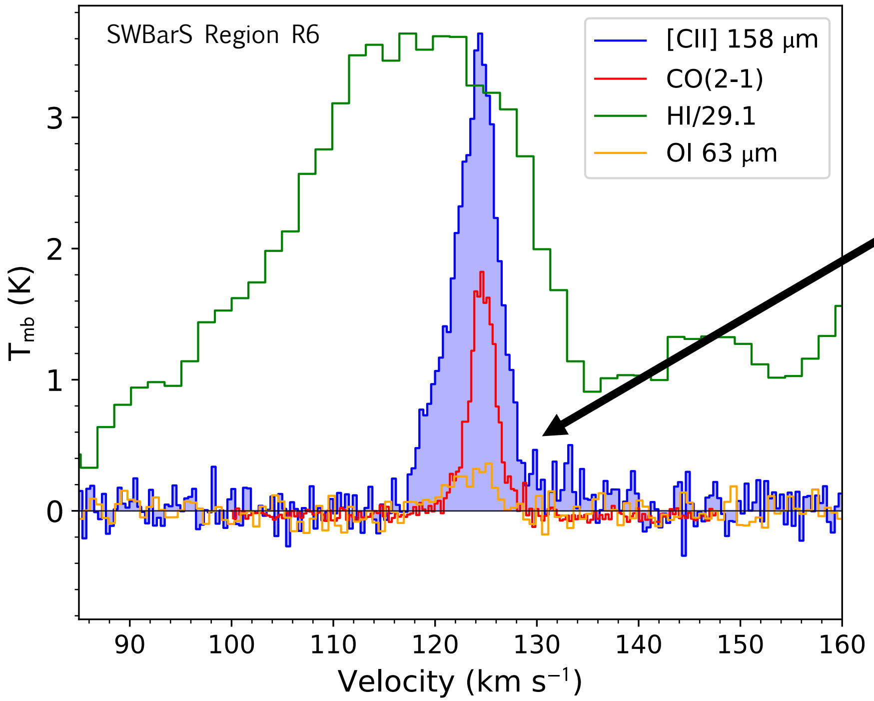
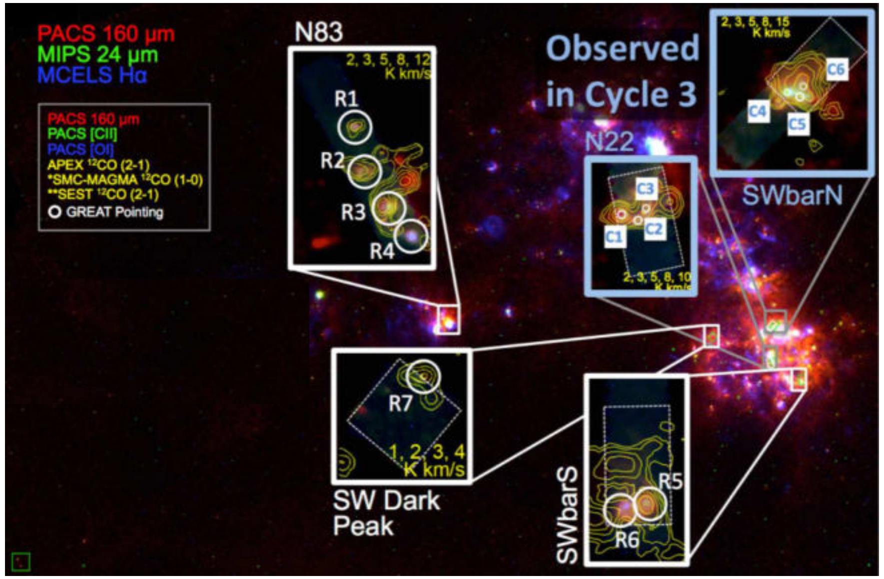
Future work: velocity resolved [CII] in the SMC



- Beam mismatch with the HI data: 98” (30 pc) compared to [CII] 15” (4.5 pc) beam
- Ongoing ASKAP observations will improve the spatial and velocity resolution for the HI



6 GREAT pointings and
7 upGREAT across the SMC

Conclusions & Summary

- Velocity resolved spectroscopy can identify the origin of [CII] emission by comparing [CII] profile shapes to other velocity resolved tracers of the ISM
- [CII] has a substantial component from the atomic gas when observing large (≈100-500 pc) scales (e.g, Contursi+ 2002, Mookerjea+ 2016, Fahrion+ 2017, Tarantino+ 2021)
  - Work on smaller (3-5 pc) scales find a larger contribution from the molecular gas (e.g., Okada+ 2019, Lebouteiller+ 2019)
- Velocity resolved [CII] can be used to find P_{th} in active regions (log P_{th} = 3.8 – 4.6 K cm^{-3} in the CNM)
- SOFIA can be used to determine the origin of [CII] emission in many more galaxies!

Thank you for your time!

Questions?

Feel free to contact me at: ejtino@astro.umd.edu