Studying the life-cycle of the interstellar medium in galaxies with far-infrared spectral lines.

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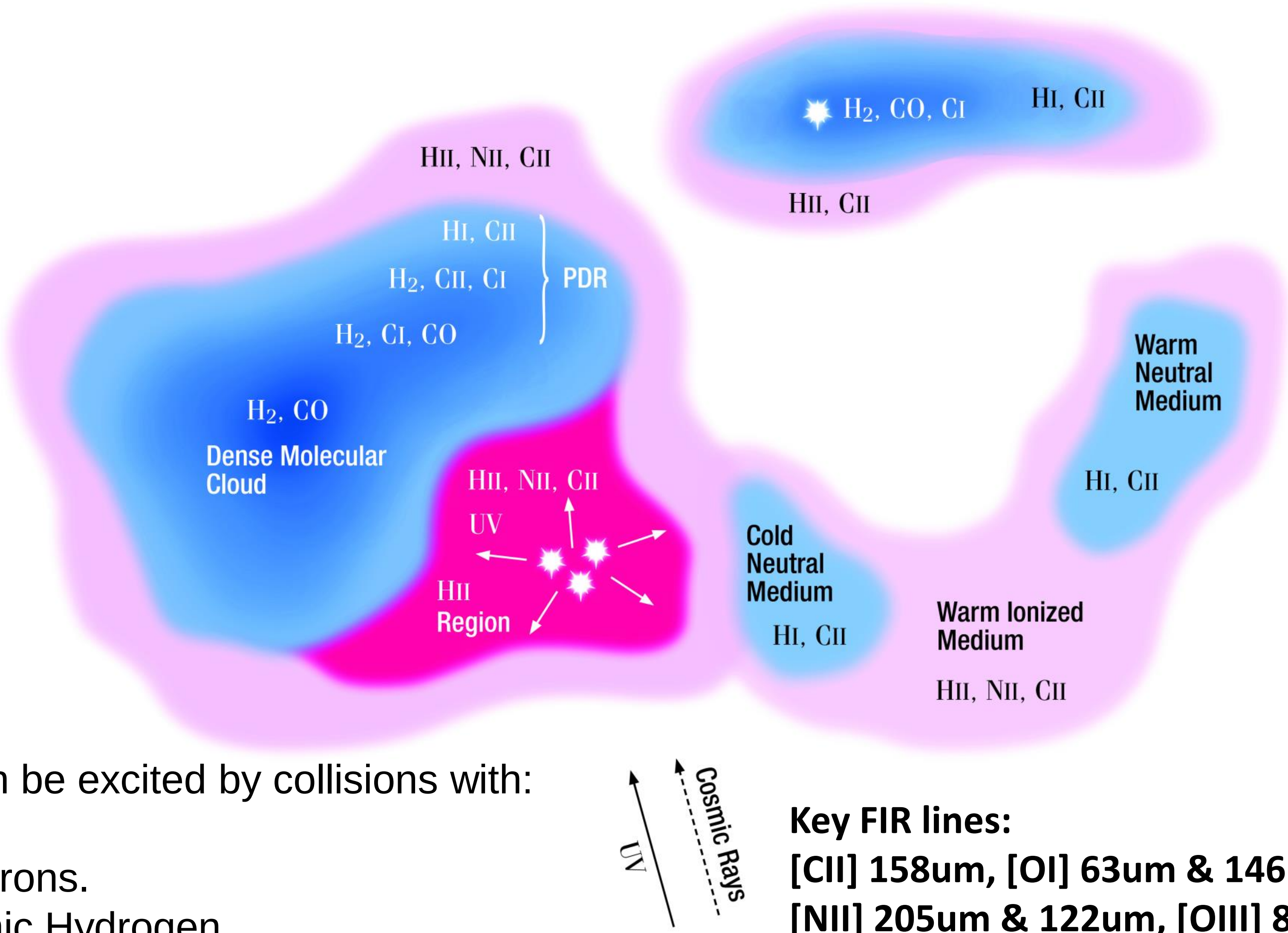
Goal: Understand the lifecycle of the interstellar medium



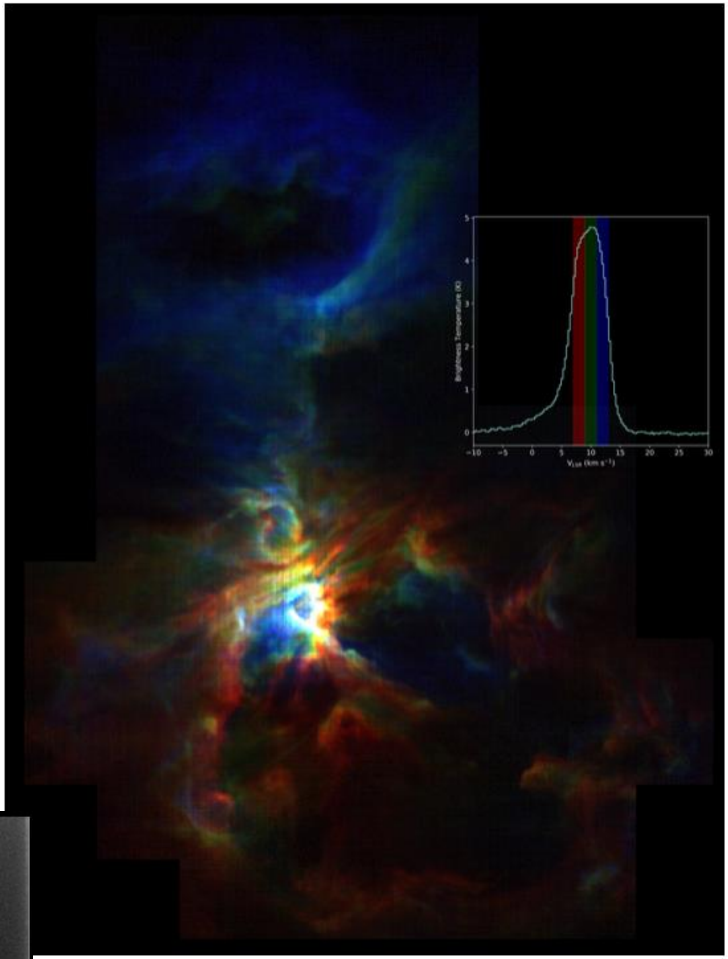
[CII] can be excited by collisions with:

- Electrons.
- Atomic Hydrogen.
- Molecular Hydrogen (dense or diffuse).

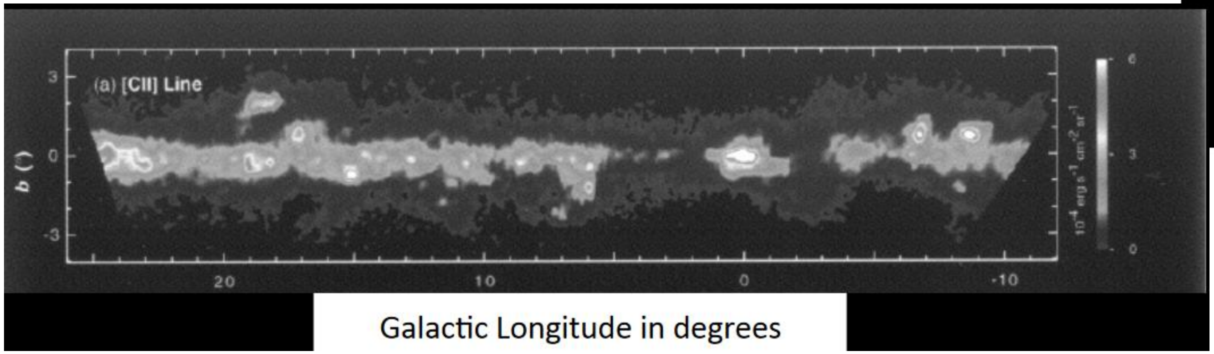
Key FIR lines:
[CII] 158um, [OI] 63um & 146um, [NII] 205um & 122um, [OIII] 88um.
Other useful lines: CO, Hydrogen RRLs.

Life-cycle of the ISM studies

- Detailed ISM studies in the Galactic star forming regions on the have been done with Herschel and now SOFIA.
- But to understand the ISM lifecycle in the Milky Way as a whole large scale, high spectral resolution observations are needed.



Pabst et al. 2019



Nakagawa et al. 1998

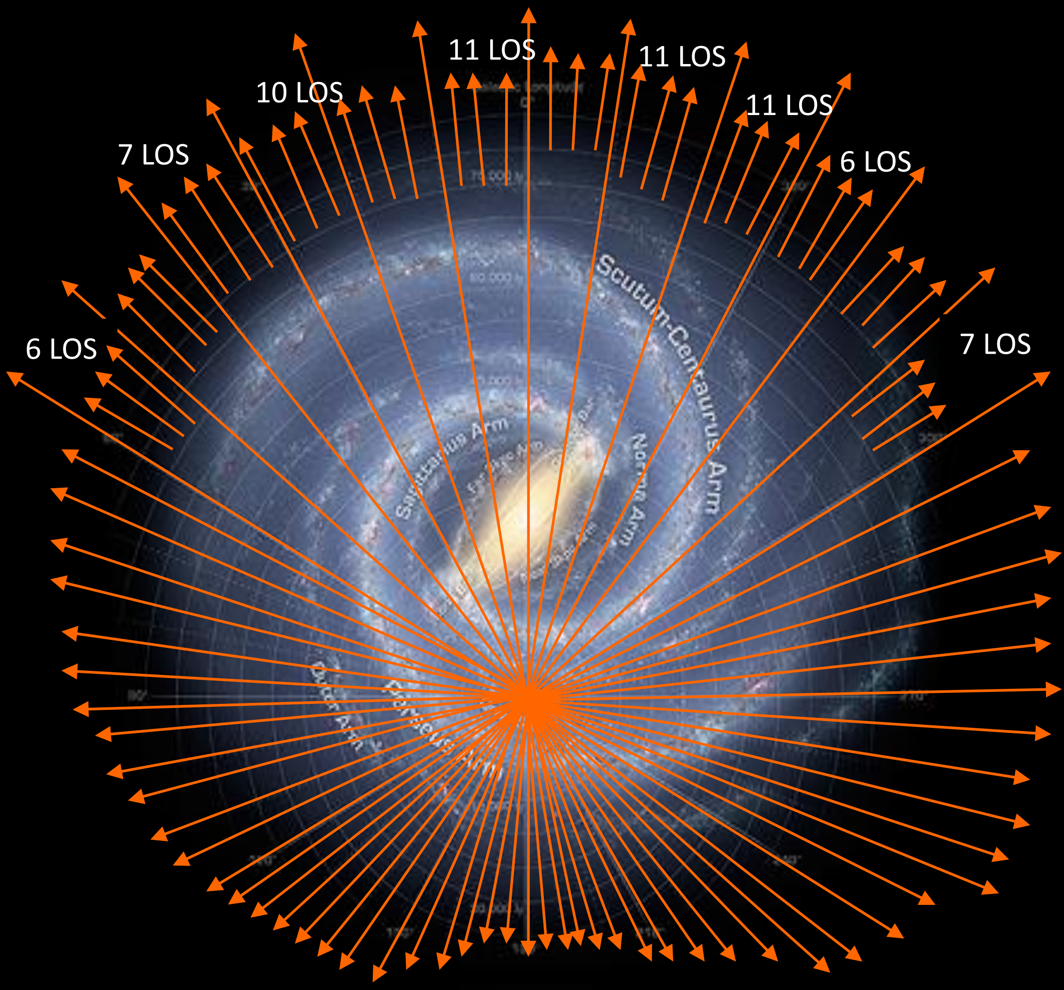
Herschel: GOT C+ [CII] 1.9 THz Survey

GOT C+ is a volume weighted sample of ≈500 LOSs in the disk of the Milky Way.

We sample the Galactic plane every one degree in the inner galaxy and every two in the outer galaxy.

GOAL: Sample as many different clouds as possible over a wide range of physical conditions.

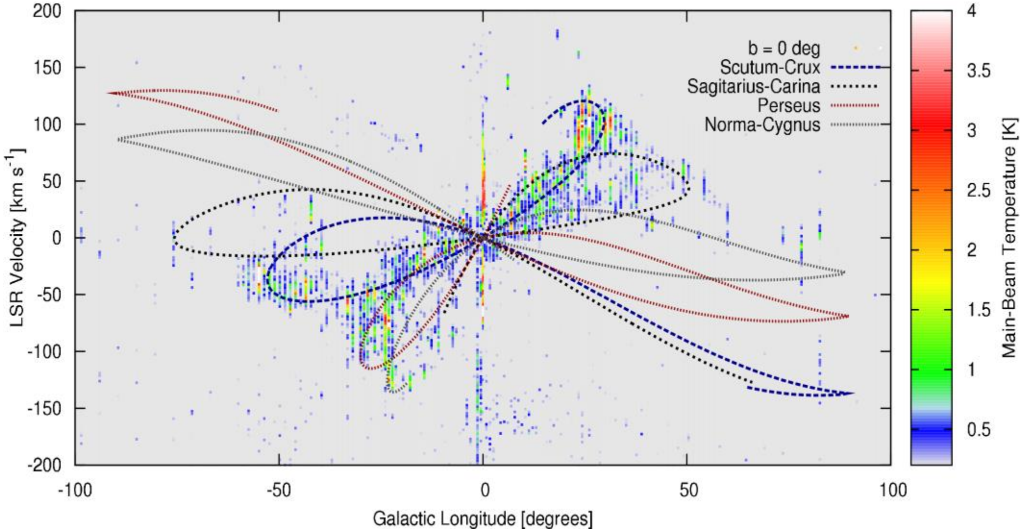
This allow us to obtain statistical information about the clouds in the Milky Way.

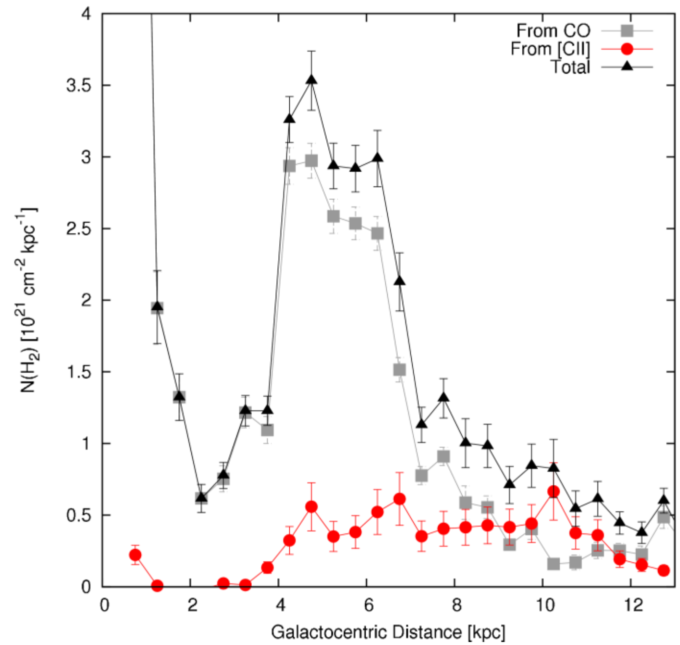


PI: Bill Langer

The [CII] distribution of the Milky Way:

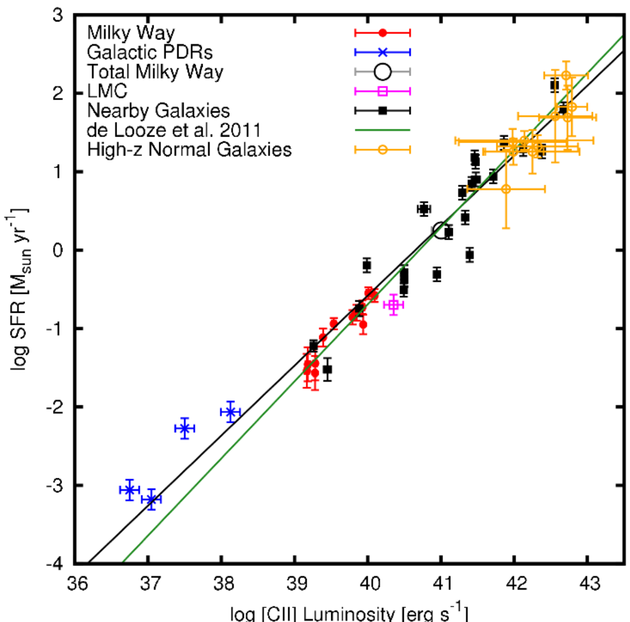
The lines are projection of the Milky Way's spiral arms into the Longitude-Velocity map.





~30% of the molecular mass is CO-dark.

Pineda et al. (2013) A&A 554, A103



[CII] is will correlated with star formation in the Galactic plane (and normal galaxies).

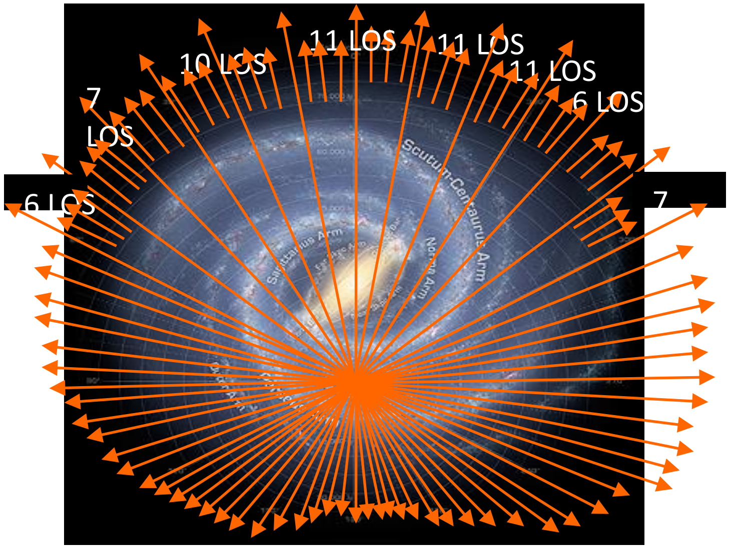
Pineda et al. 2014 A&A 570, A121

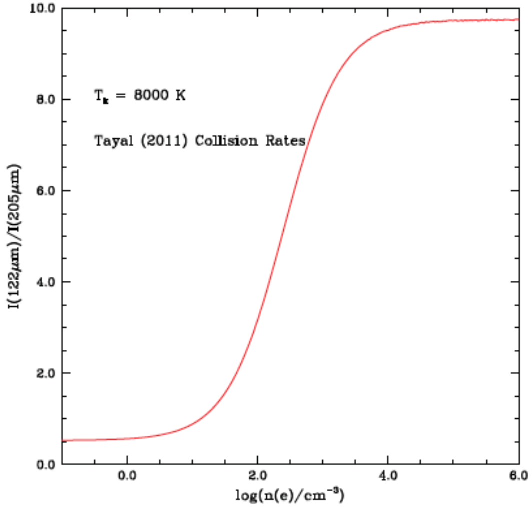
GOTC+ provided the first glimpse on the structure of the ISM in the Milky Way in [CII].

The Herschel [NII] Galactic Plane Survey

- 140 GOT C^+ lines of sight at $b=0^o$ observed in [NII] 205 um and 122um with PACS (velocity unresolved).
- 10 selected lines of sight in [NII] 205um with HIFI (velocity resolved).
- Nitrogen IP is 14.5 eV so found **only** in regions where H completely ionized.
- The [NII] 122um/205um, provides an accurate determination of the electron density.

PI: Goldsmith

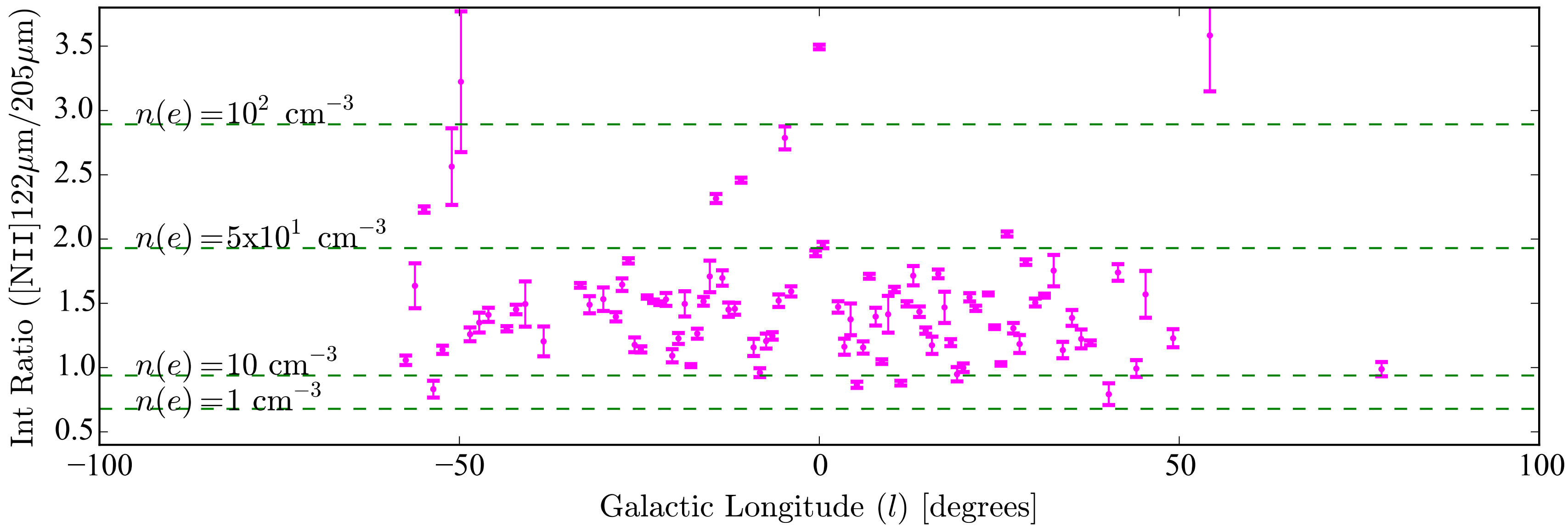




For a single density along LOS n(e) determines **I(122)/I(205)** and vice-versa

Distribution of Electron Densities as Function of Galactic longitude

Goldsmith et al. 2015



A few positions near Galactic Center have n(e) > 50 cm^{-3} and up to 200 cm^{-3}

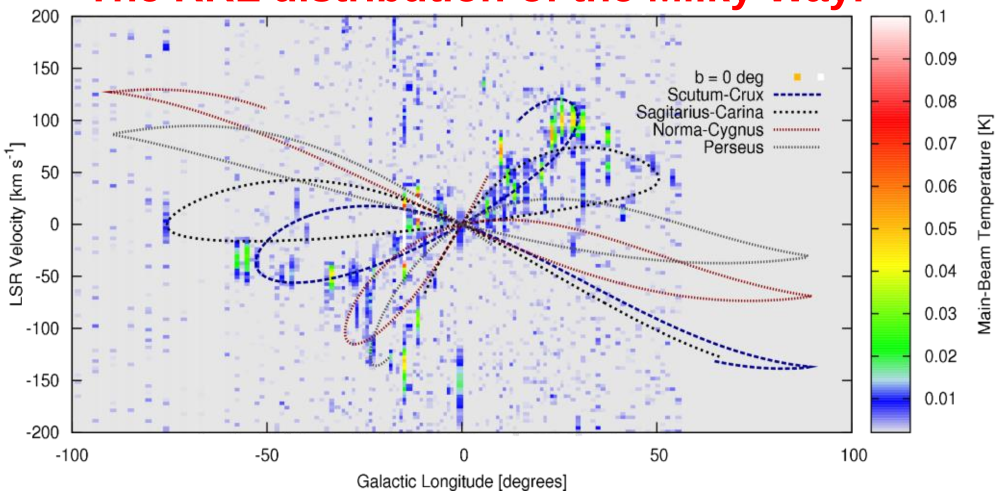
Vast majority of LOSs have 10 cm^{-3} ≤ n(e) ≤ 50 cm^{-3}; no clear trend with Galactic longitude.

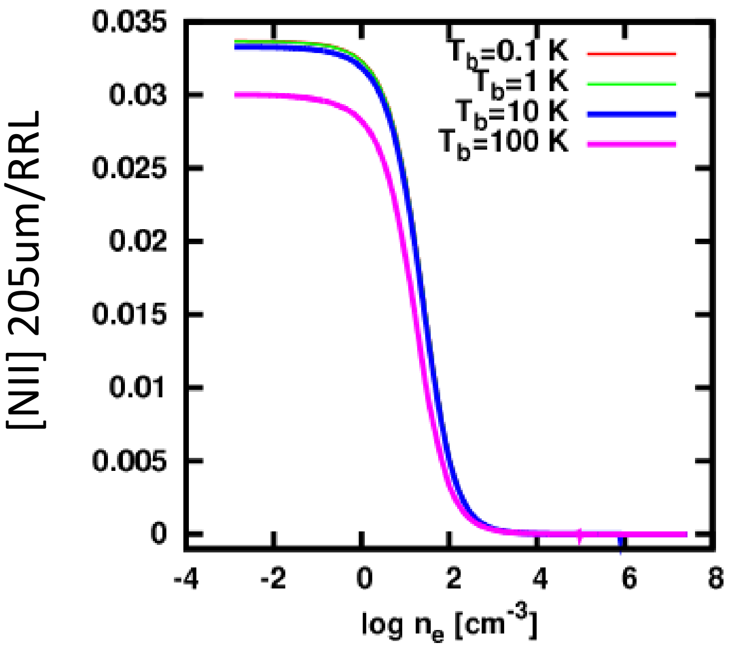
This result suggest that there is a widespread "dense" ionized gas component in plane of the Milky Way. See also Geyer et al. 2018.

[NII]/RRL ratio as a tracer of electron density.

- SOFIA's 4GREAT can be used for observation of the [NII] 205um, but 122um observations are hard at SOFIA altitudes due to atmospheric absorption.
- We can also use of the [NII] 205um to a hydrogen recombination line (RRL) ratio to solve for the electron density of the gas.
- Hydrogen recombination lines can be efficiently observed with e.g. the GBT and the NASA DSS43 station.
- This provides the possibility to study the dense ionized gas component at high spectral resolution.

The RRL distribution of the Milky Way:



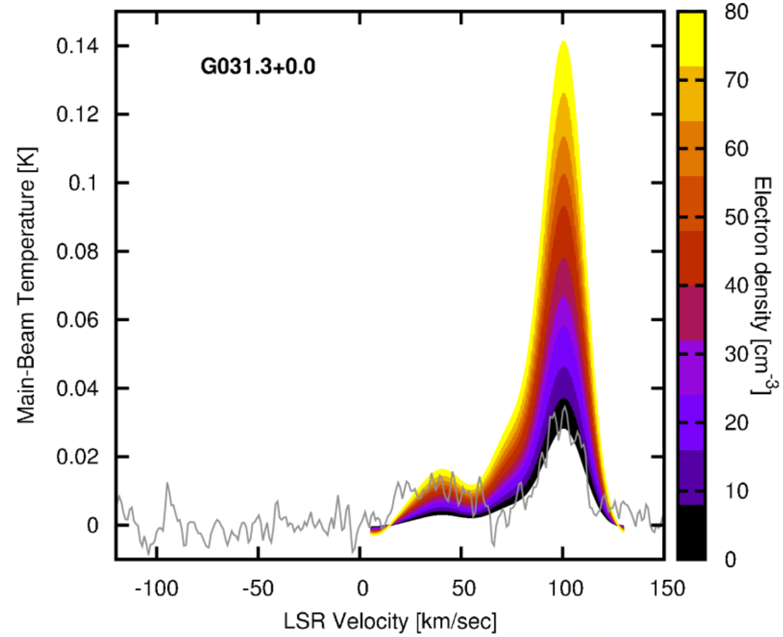


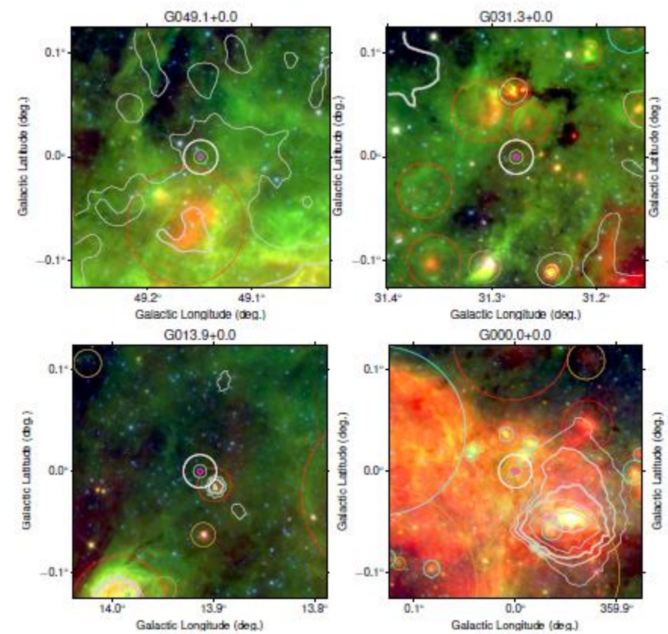
Pineda et al. 2019

[NII]/RRL ratio as a tracer of electron density.

Pineda et al. 2019

- We used this method to derive electron density in 10 LOSs where velocity resolved [NII] 205um from Herschel HIFI and SOFIA/GREAT are available and combined with GBT and DSS43 RRL observations.
- The derived densities are consistent with those derived at low spectral resolution using the [N II] 205m/122m ratio with Herschel/PACS by Goldsmith et al. 2015.
- Most of our LOSs are located in the vicinity of H II regions but do not overlap with their brightest parts, and thus are unlikely to be associated with compact H II regions.
- This dense plasma appears to be widely distributed in the Galactic plane, and thus can represent a significant fraction of the ionized gas in our Galaxy.





[CII] from ionized gas is predicted to be brighter than expected.

- The ratio of [CII]/[NII] 205um in **ionized regions** depends mostly on the C/N abundance ratio.

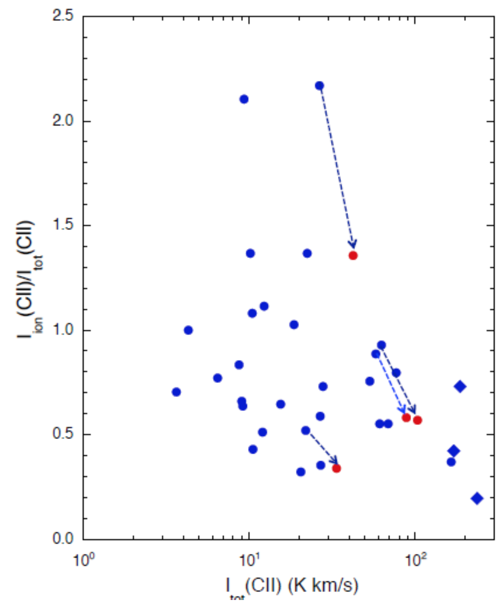
- The [CII] contribution from ionized gas can be therefore estimated from the [NII] 205um and an assumption on the C/N ratio.

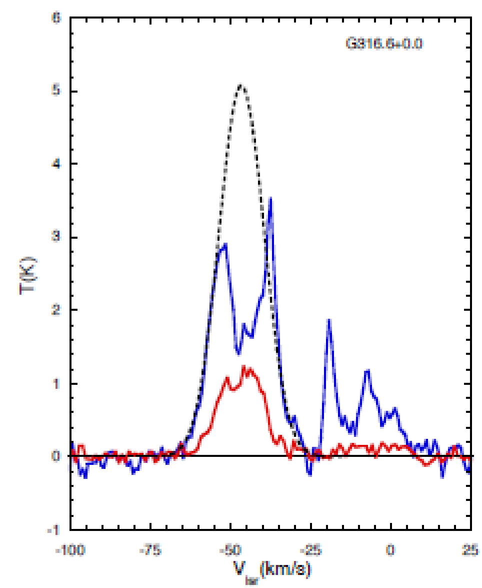
- We find that the predicted [CII] contribution from ionized gas is sometimes all or more than observed!

- This has also been observed in nearby galaxies by SOFIA (Roellig et al. 2016)

- One possibility is that C is at ionization states higher than C^{+}.

- High spectral resolution of e.g. [NIII] 57um and [OIII] 88um lines to characterize the ionization environment. **No current SOFIA instrumentation is available for high spectral resolution at those wavelengths.**



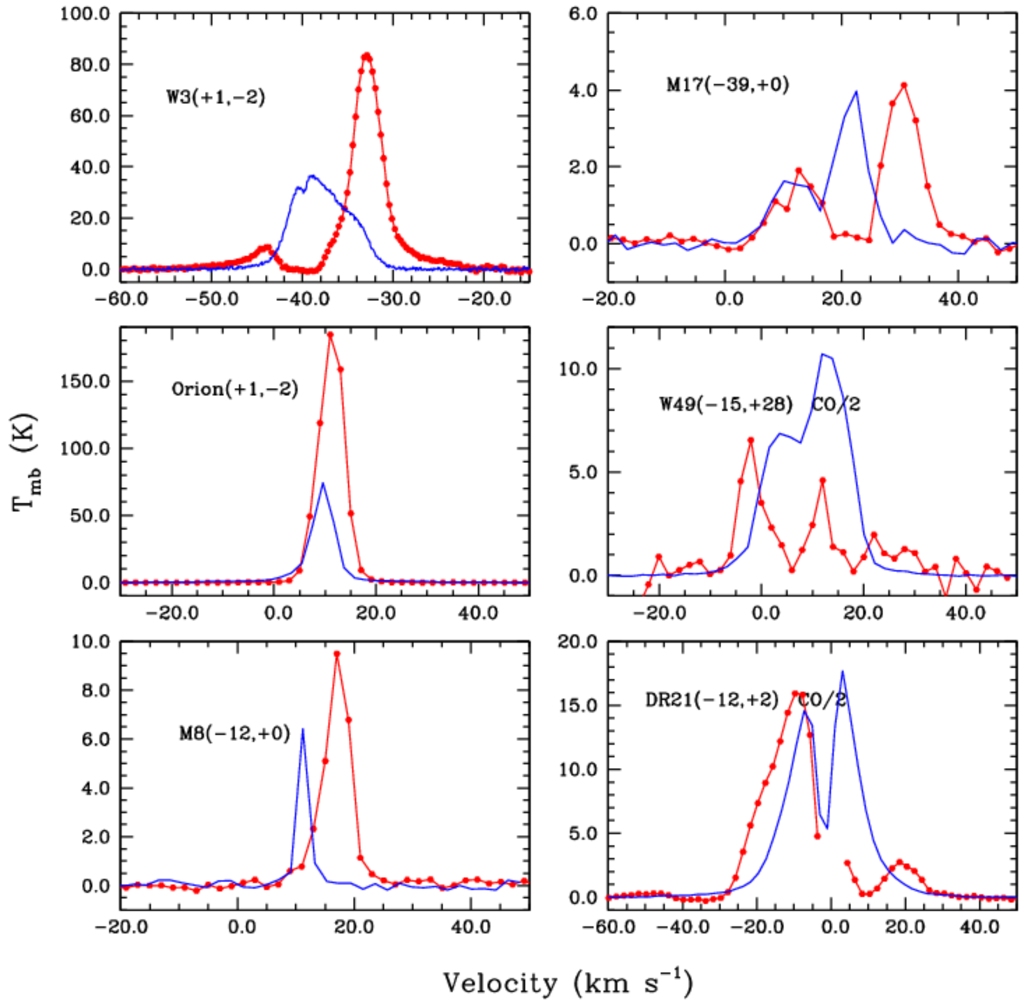


Langer et al. 2016

Atomic Oxygen emission in the Milky Way.

- Recent SOFIA observations of the [OI] 63um line shows that it is highly self-absorbed in the brightest parts of PDRs.
- Self-absorption make it difficult the interpretation of [OI] emission from velocity-unresolved observations.
- Observations of the optically thin [OI] 146um will be useful for interpreting these observations. upGREAT currently has this capability.

Goldsmith et al. 2020, in prep.

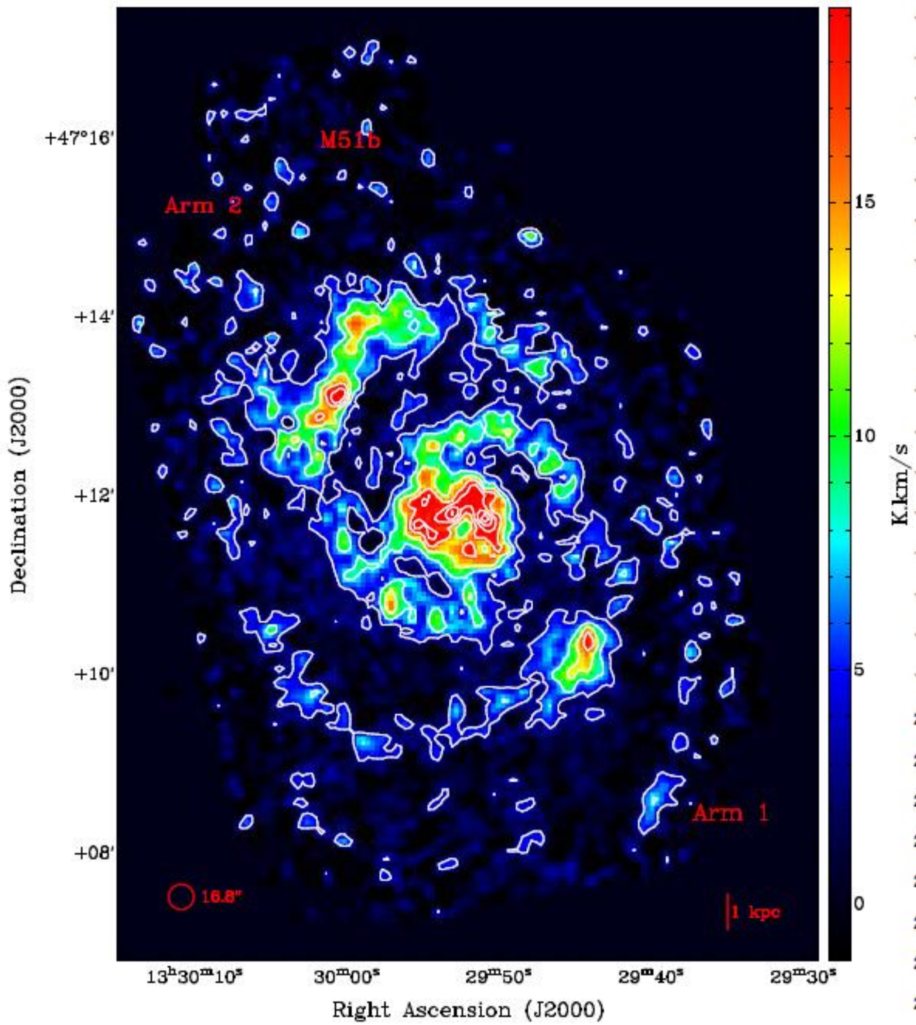


Red [OI] 63um; Blue CO 8-7

Impact of spiral density waves on the evolution of the ISM and star formation

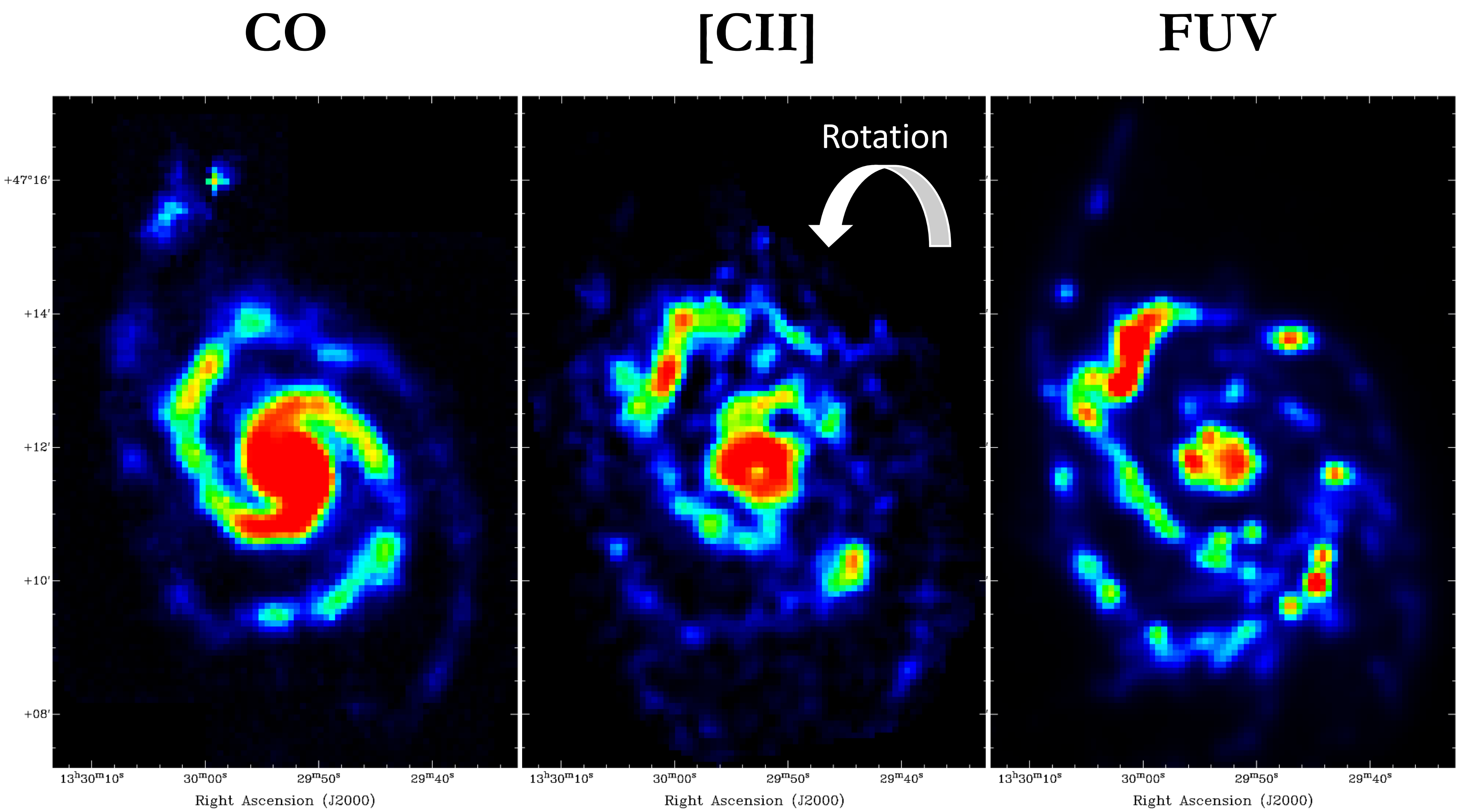
- Another approach for studying the structure of the ISM are observations of nearby galaxies.
- Spiral density waves play a fundamental role in compressing gas, making it available for star formation.
- Dense molecular gas can be traced by CO emission.
- Obscured star formation activity can be traced by [CII].
- When massive stars disrupt their progenitor material, FUV photons can escape, and they can be traced by FUV emission.

SOFIA upGREAT [CII] M51 map



Pineda et al. 2018, Pineda et al. 2020 submitted

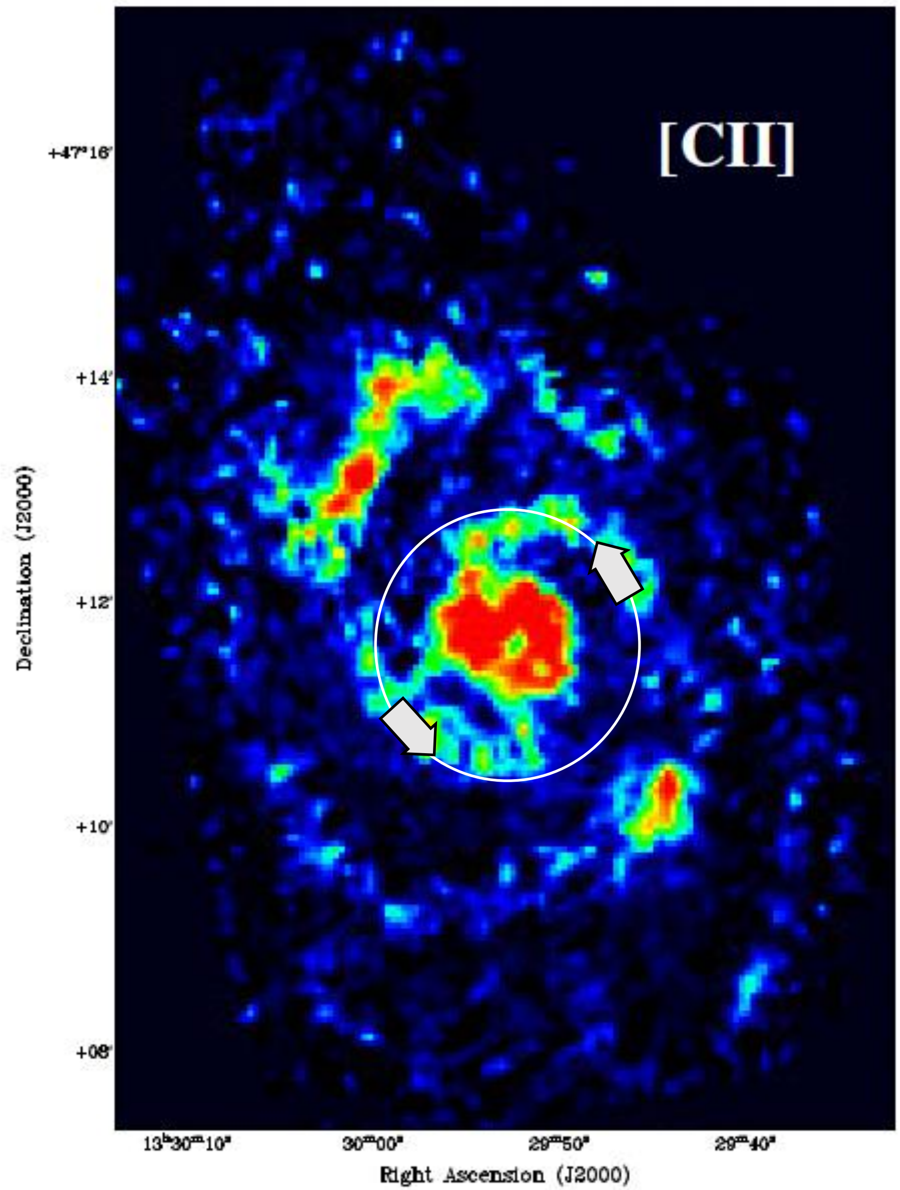
Impact of spiral density waves on the evolution of the ISM and star formation



- **Molecular clouds (CO) -> Star formation ([CII]) -> cloud dispersion (FUV).**

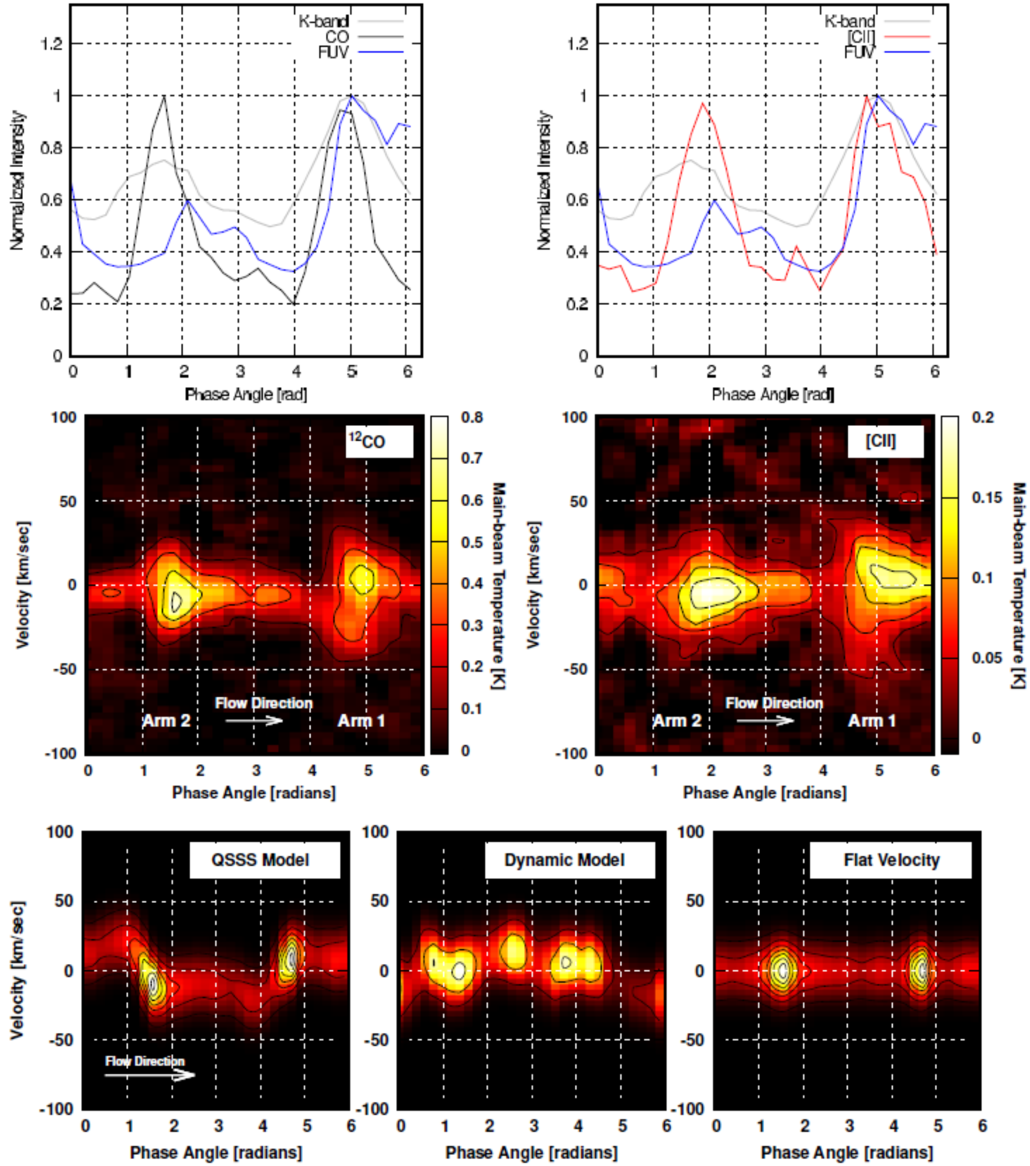
CO and [CII] position velocity maps across spiral arms

- Studying the phases of the ISM in spiral arms in galaxies can be used to test two competing theories of the nature of spiral arms in galaxies.
- In the quasi–stationary spiral structure (QSSS) hypothesis, spiral arms are thought to be rigidly rotating, long–lived patterns that persist over several galactic rotations (see Bertin & Lin 1996 for a review). The spiral density wave affects the gas flow, resulting in shocks around spiral arms, triggering phase transitions in the ISM.
- Alternatively, the transient spiral hypothesis (Goldreich & Lynden-Bell 1965) suggests that each spiral arm is a transient feature generated by the swing-amplification mechanism. Its amplitude varies on the timescale of epicyclic motions (a fraction of galactic rotation). In this theory, the gas flows toward the potential minimum of the spiral arm from both sides of the arm.



CO and [CII] position velocity maps across spiral arms

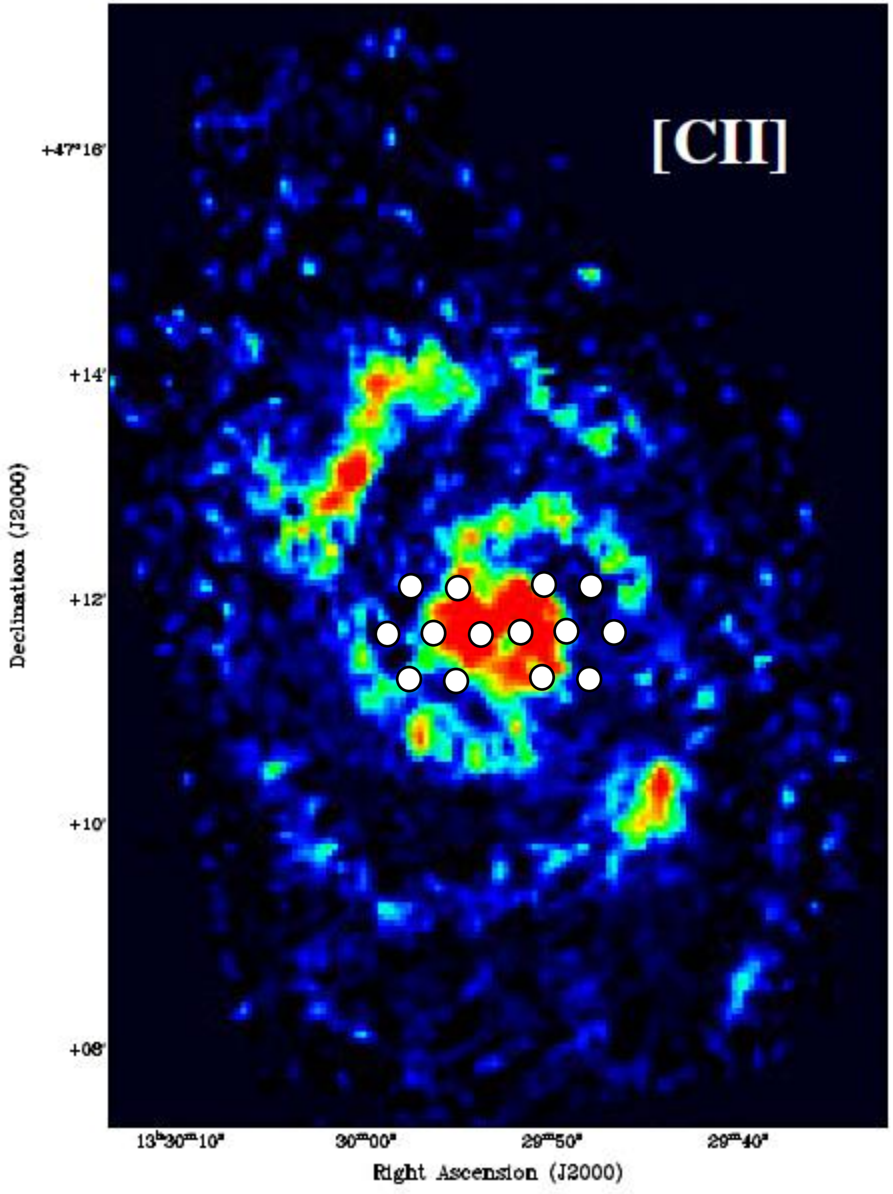
- Test of these two theories include search for offsets between different ISM tracers and the study stellar cluster age offsets. But they provide ambiguous results with different groups concluding that observations agree with opposite theories based on the same dataset.
- Position Velocity Maps across spiral arms show velocity discontinuities that are possible related to spiral shocks.
- CO is being agglomerated/compressed and peak the end of the discontinuity.
- [CII] peaks right after the CO peak, suggesting that the discontinuity triggers star formation.
- Velocity distribution is in good agreement with projected theoretical predictions for QSSS theory.



Pineda et al. 2020 submitted

Future observations with SOFIA

- upGREAT observations in Orion have shown that large maps of bright lines are currently possible with SOFIA.
- These large scales maps complement larger scale maps (but lower resolution) from Balloons like GUSTO.
- But observations of faint line over arcmin scales in nearby galaxies are currently very expensive with SOFIA.
- M51's upGREAT map required 60h. A complete survey of nearby galaxies covering a range of environments would require 1000s of hours.



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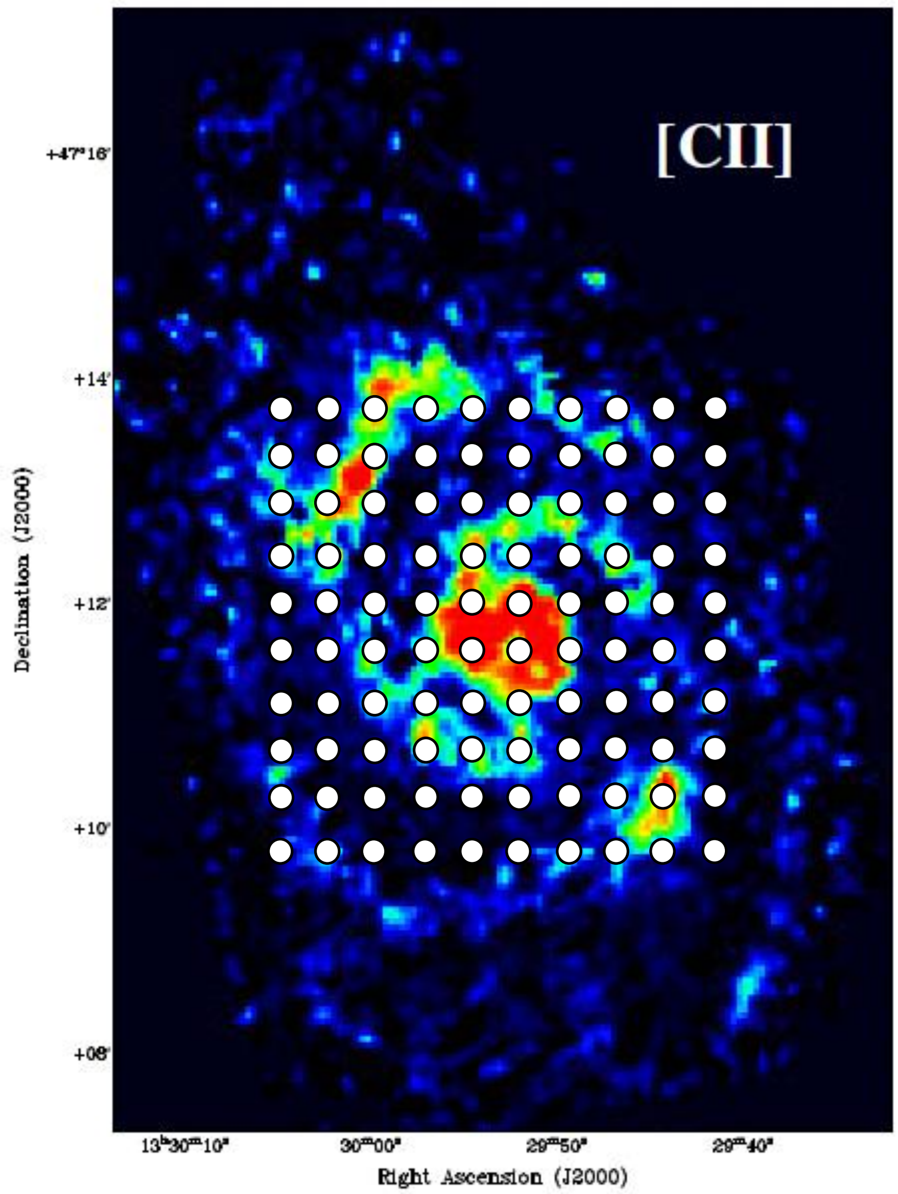
- M51's upGREAT map required 60h. A complete survey of nearby galaxies covering a range of environments would require 1000s of hours.
- Large format arrays would enable such type of surveys and open a new frontier on the science that SOFIA can do.



Summary

- Herschel and SOFIA have been used to provide critical information on the structure of the ISM in the Milky Way.

- We used [CII] to determine the distribution of CO-dark H2 and star formation in the plane of the Milky Way.

- [NII] observations have also revealed a widespread dense component of the ionized ISM.

- Velocity [CII] resolved observations in galaxy M51, have shown that we can also test theories of the nature of spiral arms in galaxies.

Future observations:

- Access to high spectral resolution in wider range of far-infrared spectral lines, such as [OIII] 88um or [NIII] 57um.

- Large format arrays, covering several far-infrared spectral lines, are needed for efficient mapping of nearby galaxies at high spectral resolution, enabling new SOFIA science.