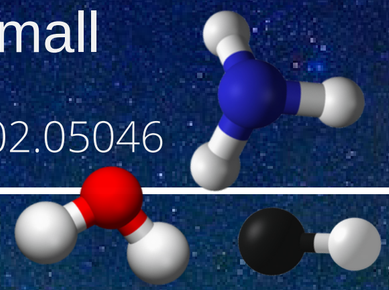
HyGAL

Characterizing the Galactic ISM with observations of hydrides and other small molecules



arXiv:2202.05046

Arshia M. Jacob (Johns Hopkins University)

March 1, 2022

PIs: D. Neufeld (JHU), P. Schilke (UzK)

W.-J. Kim, A. Sterberg, B. Godard, D. Lis, D. Elia, M. Gerin, M. Wolfire, N. Indriolo, H. Wiesemeyer, V. Ossenkopf-Okada, S. Bialy, D. Seifried, P. Sonnetrucker, V. Valdivia, S. Walch, F. Wyrowski, K. M. Menten, M. Busch, M. R. Rugel, A. Sánchez-Monge, R. Higgins, E. Falgarone, P. Hennebelle, S. Molinari

Background Image:GLIMPSE/Spitzer IR image of the Milky Way Credits: NASA/JPL-Caltech/Univ. of Wisconsin

HyGAL

Targets **six hydrides** (ArH+, H2O+, OH+, SH, OH, and CH) and **two atomic constituents** (C+ and O)

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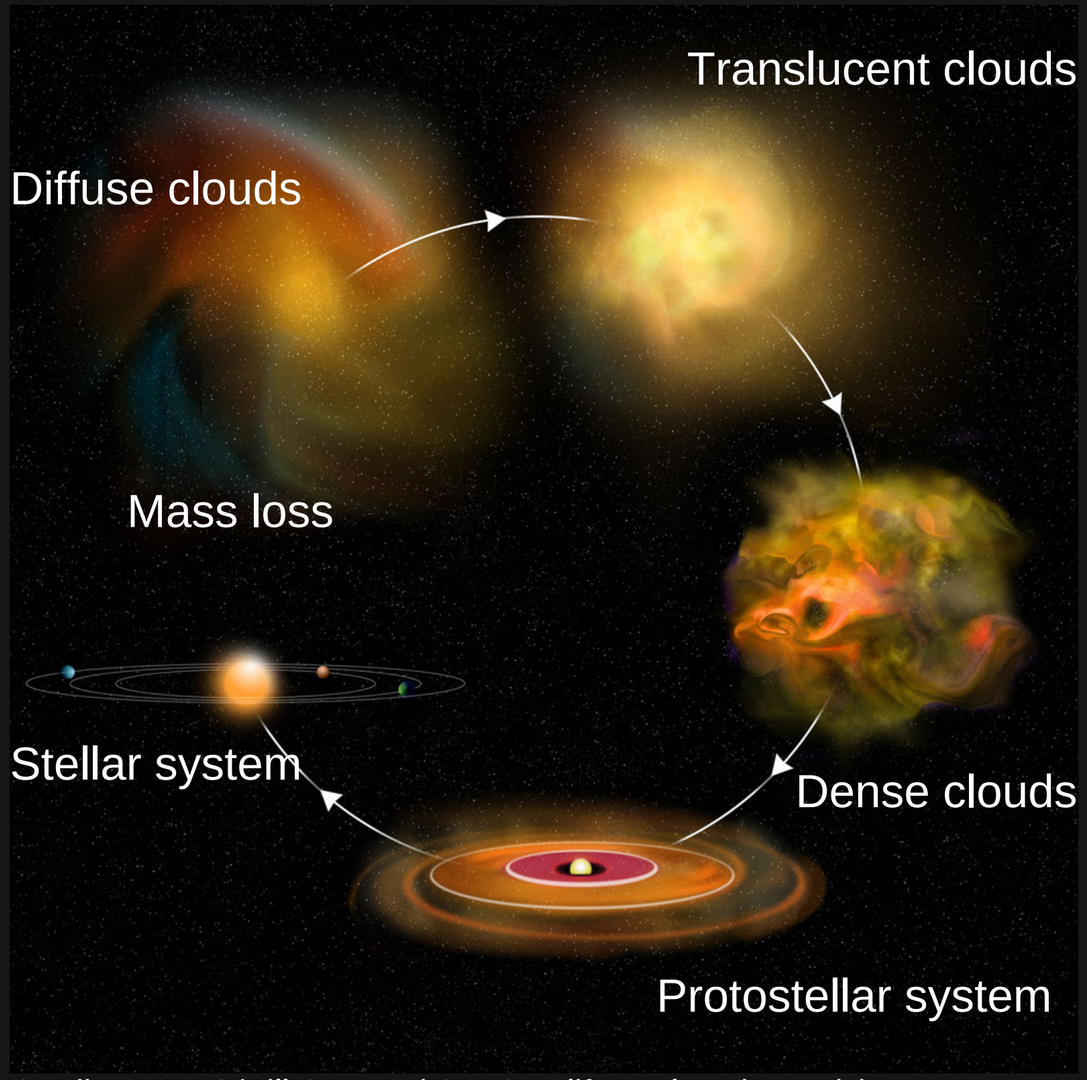

Credits: NRAO/Bill Saxton (ISM Gas life cycle schematic)

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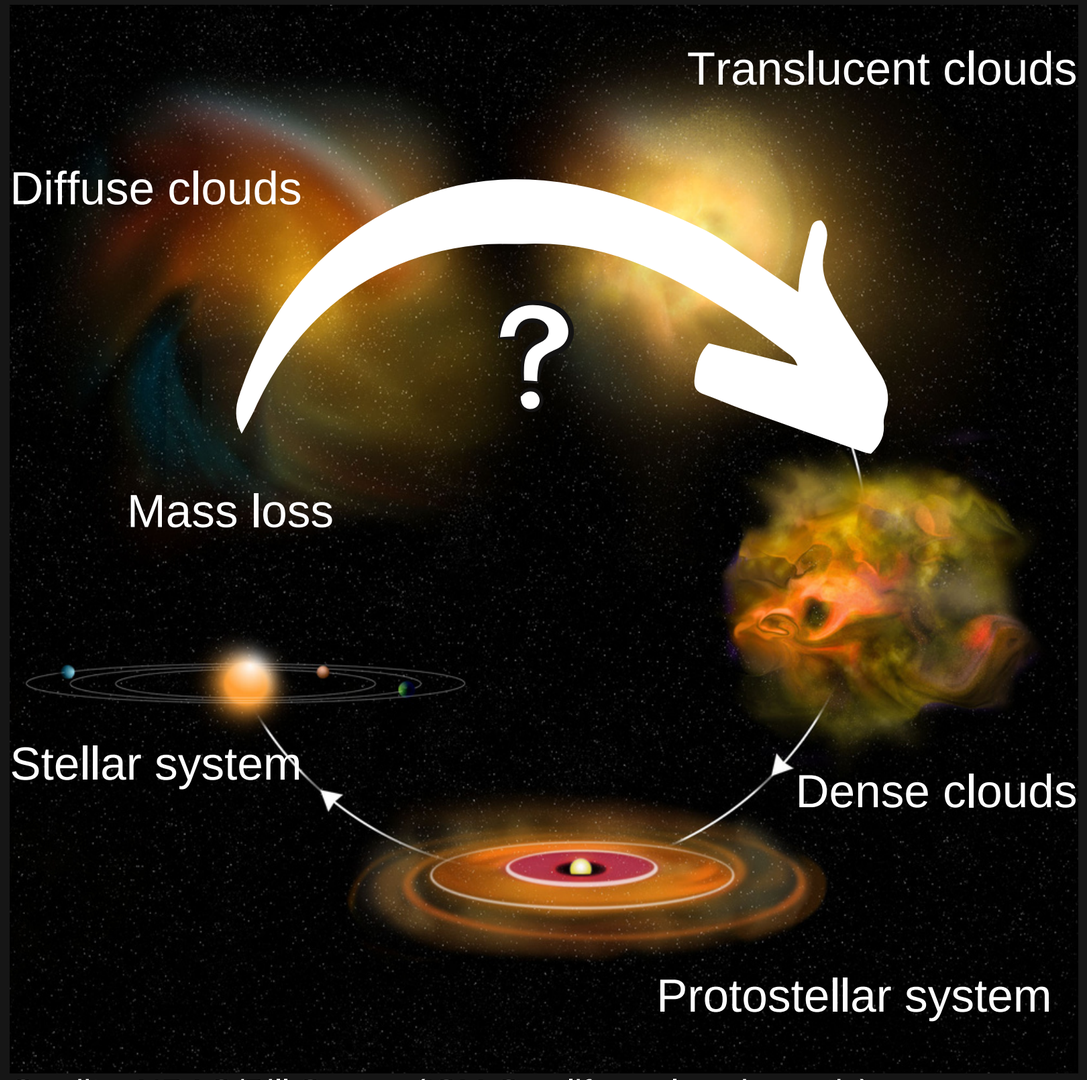

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GOAL:

To understand how molecular clouds are formed and the processes that lead to the (HI-to-H2) phase transition.

HyGAL

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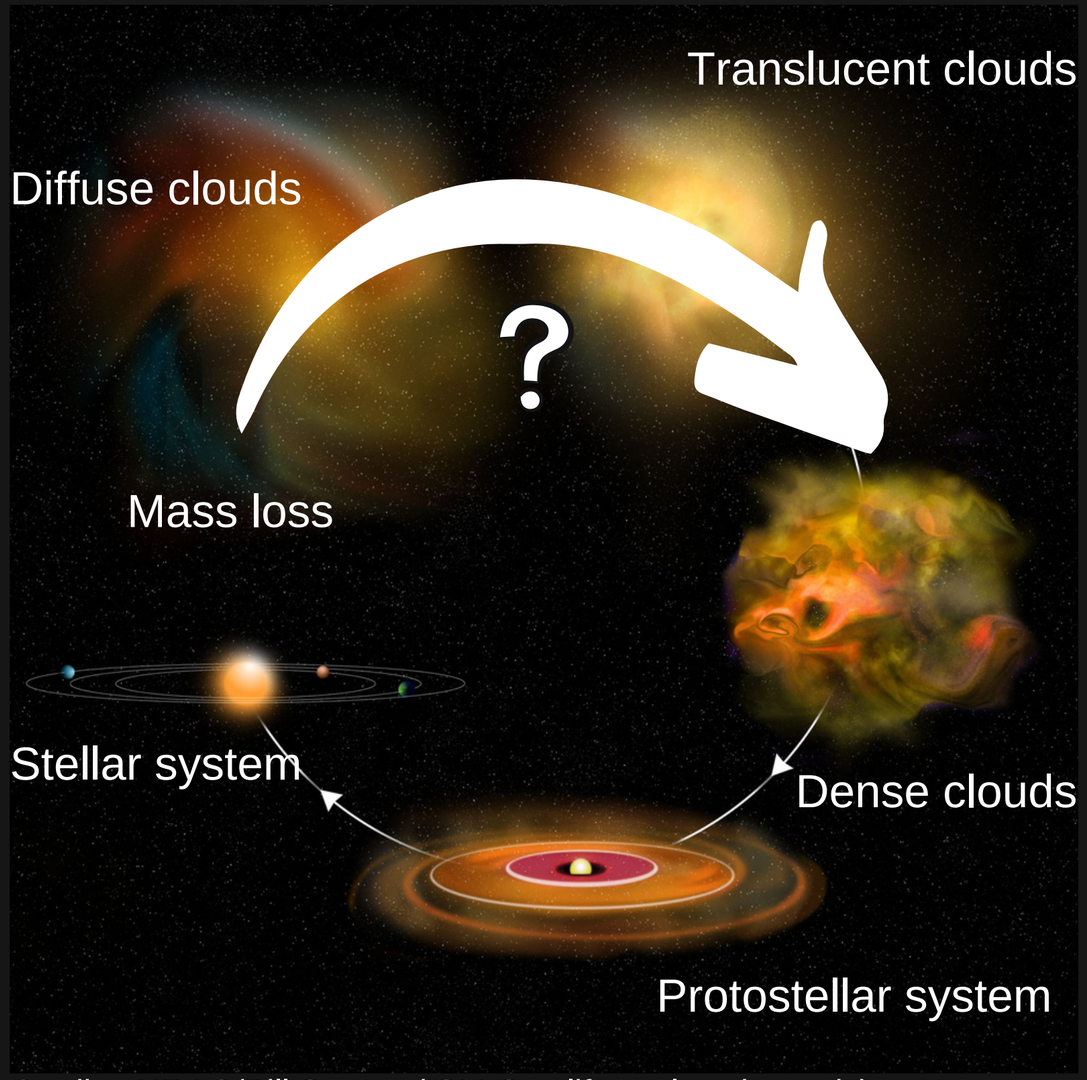

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GOAL:

To understand how molecular clouds are formed and the processes that lead to the (HI-to-H2) phase transition.

- Distribution of **molecular fraction** in the interstellar medium (ISM)
- Variation of **comic-ray ionization** across Galactocentric distances
- Nature of **turbulence** in the ISM and its dissipation

Diagnostic properties of hydrides

Tracing the total neutral gas column

Atomic hydrogen: *direct observations*

- HI 21cm transition
- **ArH+, OH+, H2O+** have been shown to be excellent tracers of (almost purely) **atomic gas**

(*see talk by David Neufeld*)

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Molecular hydrogen: *direct observations*

- weak quadrupole transitions (E > 500 K)
- electronic transitions near 1100 A

No observable infrared/radio emission from the cold ISM

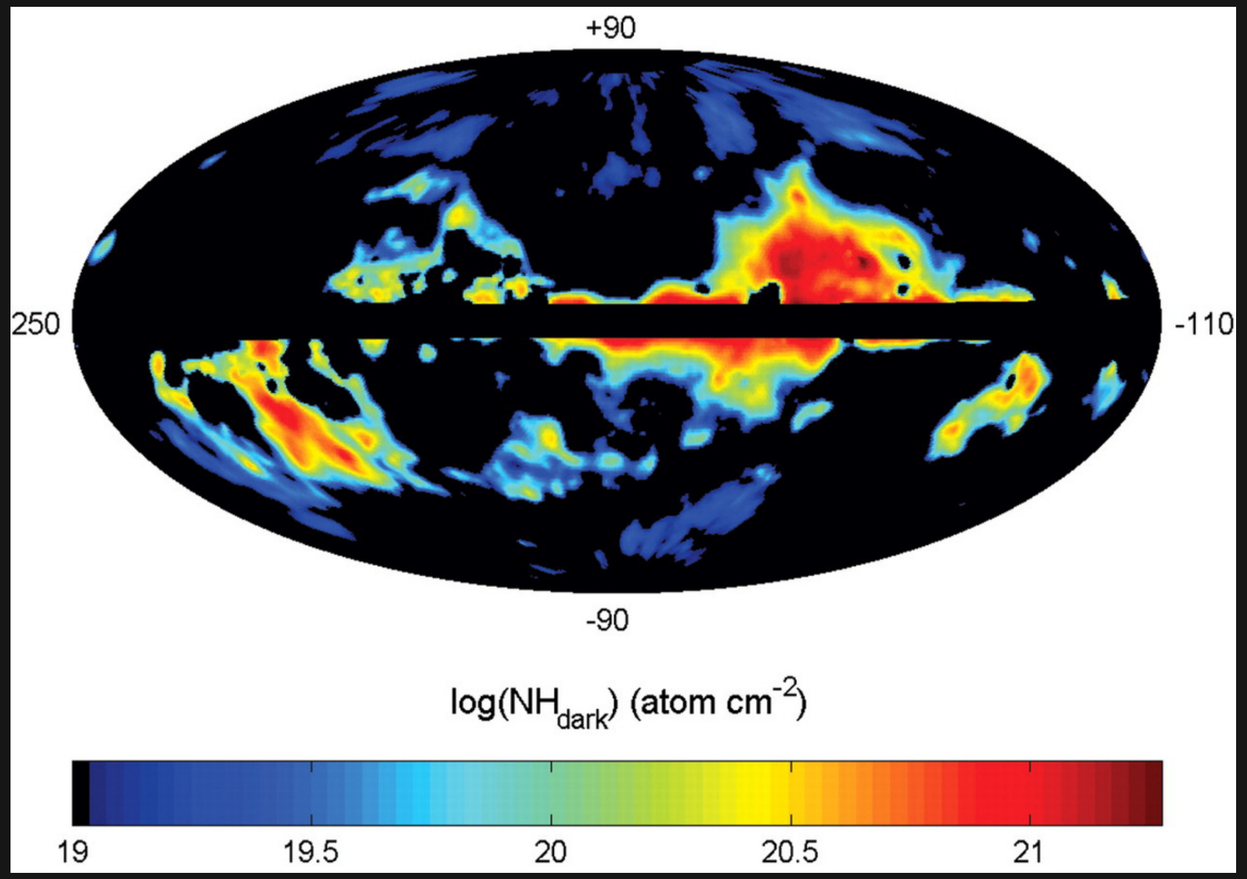
Need for indirect observations or proxies like CO 2.6 mm

Diagnostic properties of hydrides

Tracing the total neutral gas column

EXCESS GAS!

- Optically thick HI emission
- CO 'dark' molecular gas



Taken from *Grenier et al. 2005*

Diagnostic properties of hydrides

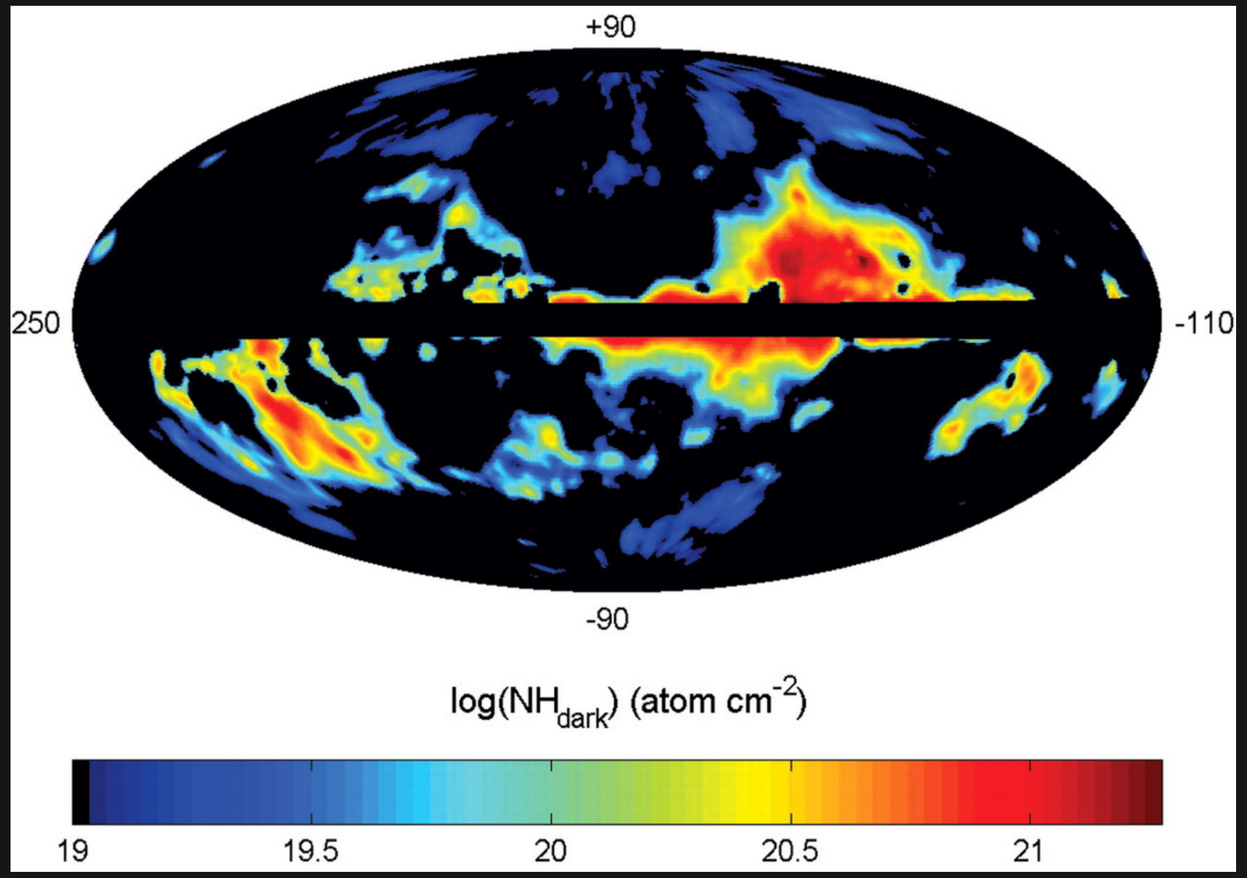
Tracing the total neutral gas column

EXCESS GAS!

- Optically thick HI emission - HI absorption
- CO 'dark' molecular gas - New tracers

Dominant component

(Pinneda et al. 2013; Liszt et al. 2018; Murray et al. 2018)



Taken from *Grenier et al. 2005*

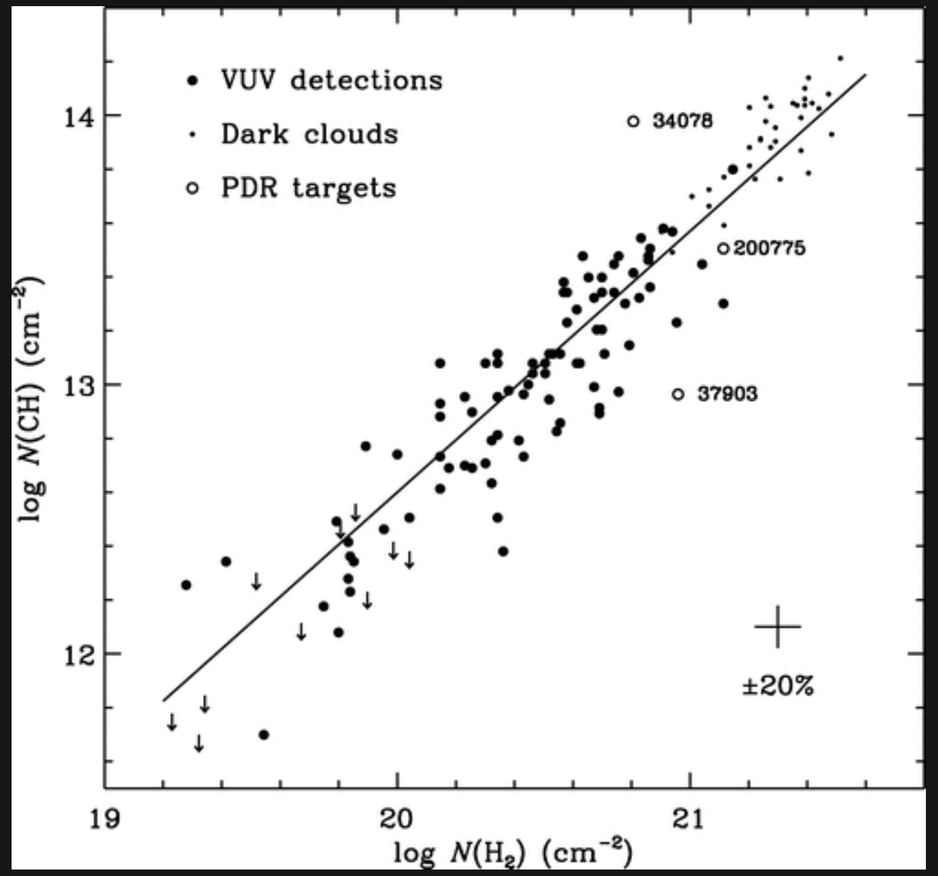
Diagnostic properties of hydrides

Hydrides as tracers of CO dark molecular gas

Why use CH?

- Ubiquitous
- Unsaturated absorption profiles
- Tight correlation with H2

(*See poster by Michael Busch on the use of OH as a tracer for CO dark gas)*



Taken from *Sheffer et al. 2008*

Diagnostic properties of hydrides

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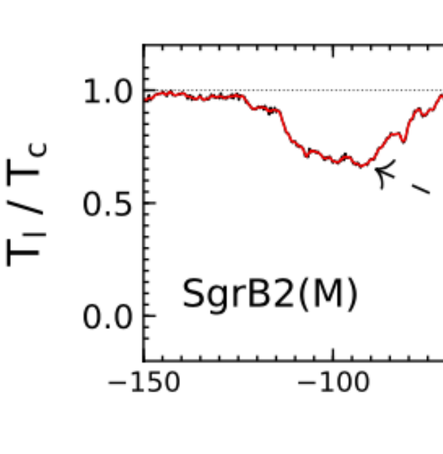
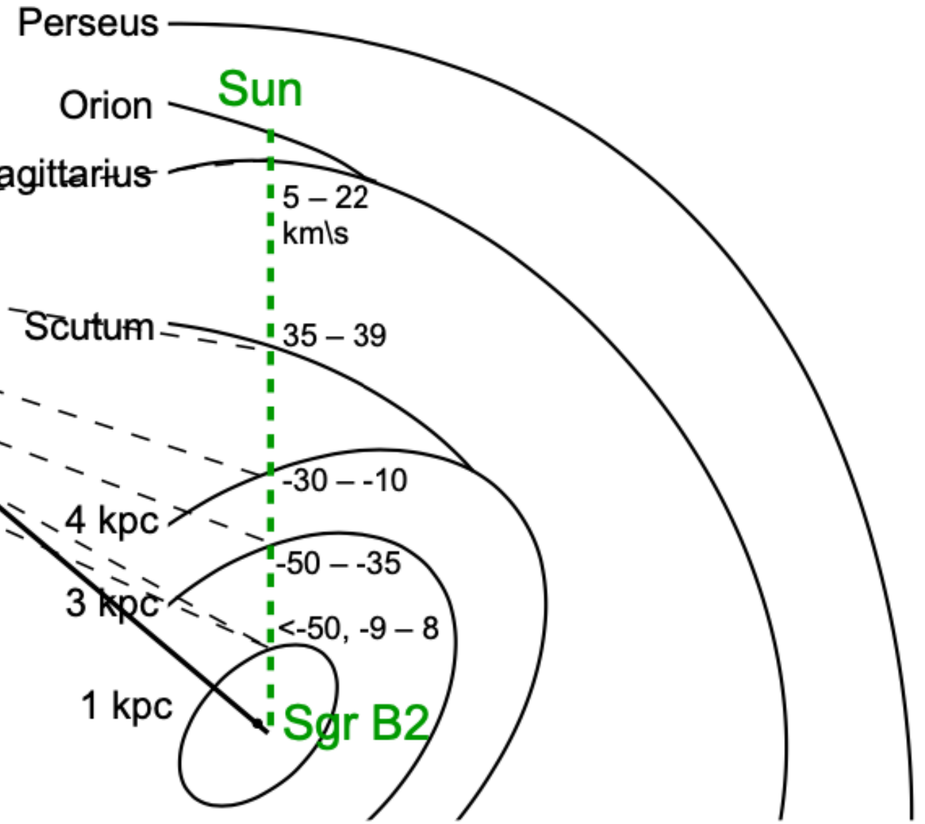


CH 2 THz spectrum toward Sgr B2(M)



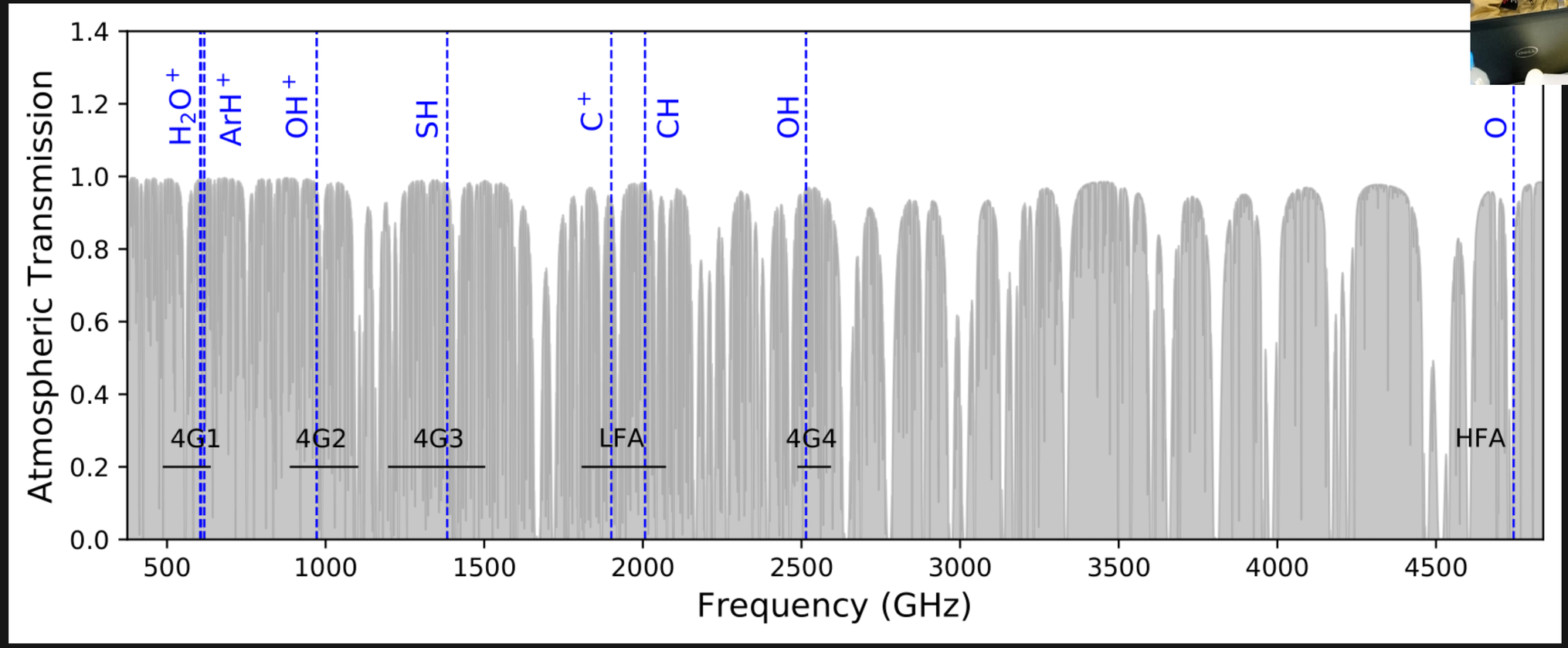
Left: Taken from Jacob et al. (2019).

Right: Taken from Greaves & Williams (1994).

Galactic spiral-arm structure

How?

- High resolution spectroscopic observations using **upGREAT and 4GREAT**
- **Three tunings** used to disentangle any sideband contamination



Atmospheric transmission at 38,000 feet with the HyGAL observing setups marked and labelled.
Plot created using ATRAN *(Lord et al. 1992)* online tool https://atran.arc.nasa.gov/cgi-bin/atran/atran.cgi.

How?

- High resolution spectroscopic observations using **upGREAT and 4GREAT**
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Extends the ***Herschel*** Legacy → doubling the number of sight lines studies

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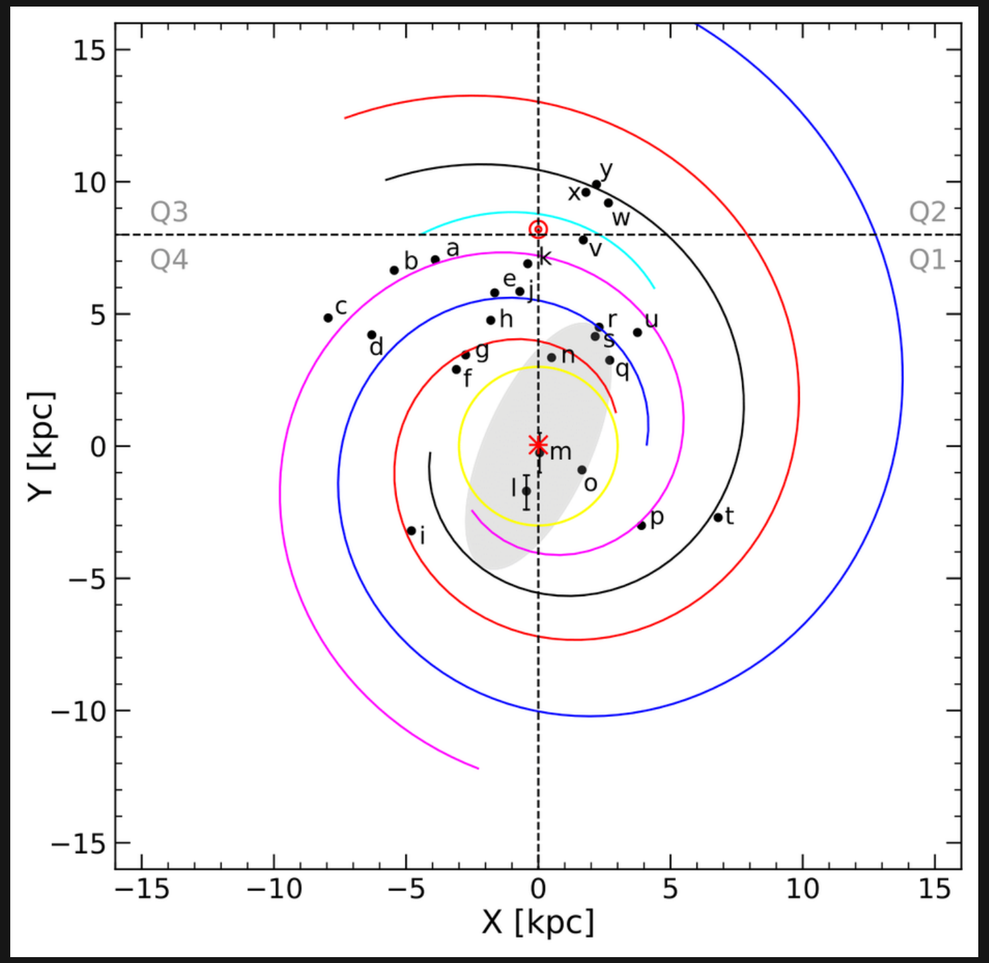
Extends the ***Herschel*** Legacy ⟶ doubling the number of sight lines studies



25 bright background continuum sources
(5 of which are located in the Outer Galaxy)

Source selection:

160 mu continuum flux > 2000Jy in the Inner Galaxy
> 1000Jy in the Outer Galaxy

From the Hi-GAL source catalogue (*Elia et al. 2021*)

Figure taken from *Jacob et al. 2022*.
Sources are designated using alphabets for clarity.

How?

Status of observations:

- 40% of the planned observations are completed (as of September 2021)
- LFA+HFA observations scheduled in the April 2022 Palmdale deployment

Sources	ArH+	p-H2O+	OH+	SH	OH	CH	CII	OI
IRAS 16060-5146	x	x	x	x	x	x	x	x
IRAS 16164-5046	x	x	x	x	x			x
NGC 6334 I	x	x	x	x	x	x	x	x
G10.47+0.03							x	x
G29.96-0.02	x	x	x	x	x	x	x	x
G32.80+0.19	x	x	x	x	x	x	x	x
G45.07+0.13	x	x	x	x	x	x	x	x
DR21						x	x	x
NGC 7538 IRS1	x	x	x	x	x	x	x	x
W3 IRS5	x	x	x	x	x	x	x	x
W3(OH)	x	x	x	x	x	x	x	x

x - observed ; x - unobserved due to tuning issues

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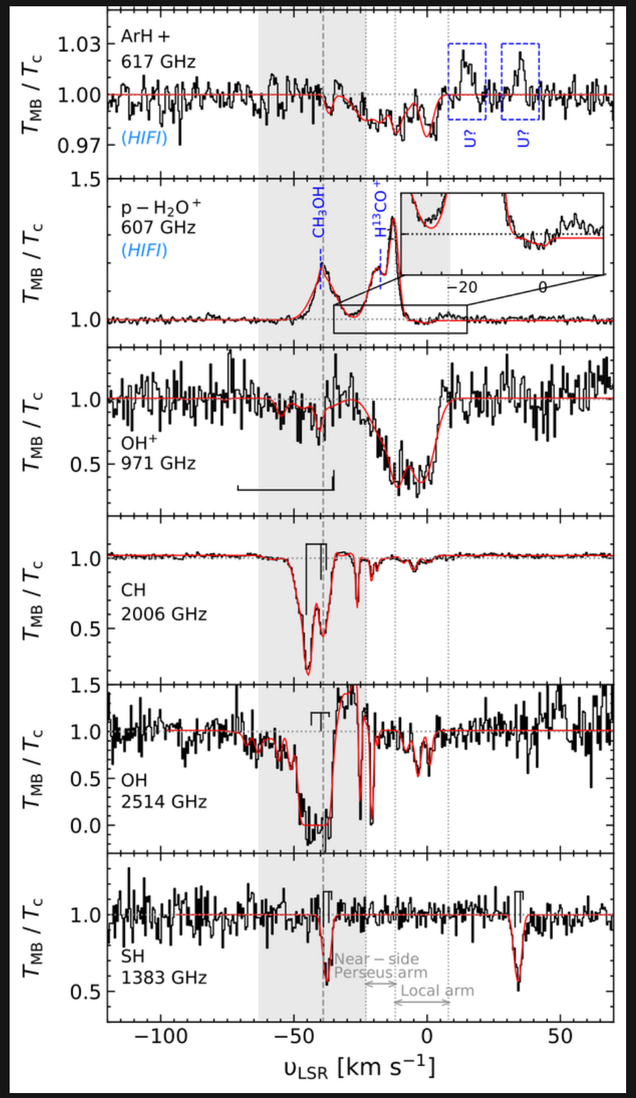
First look at the data

Spectra and analysis:

- **XCLASS** - An automated spectral line identification and fitting tool *(Moeller et al. 2017)*

W3 IRS5



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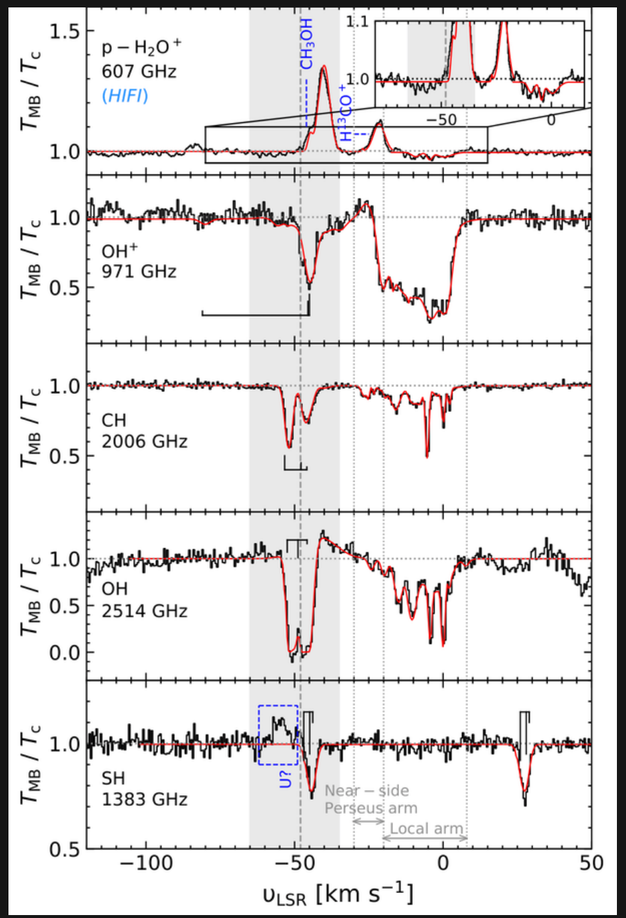
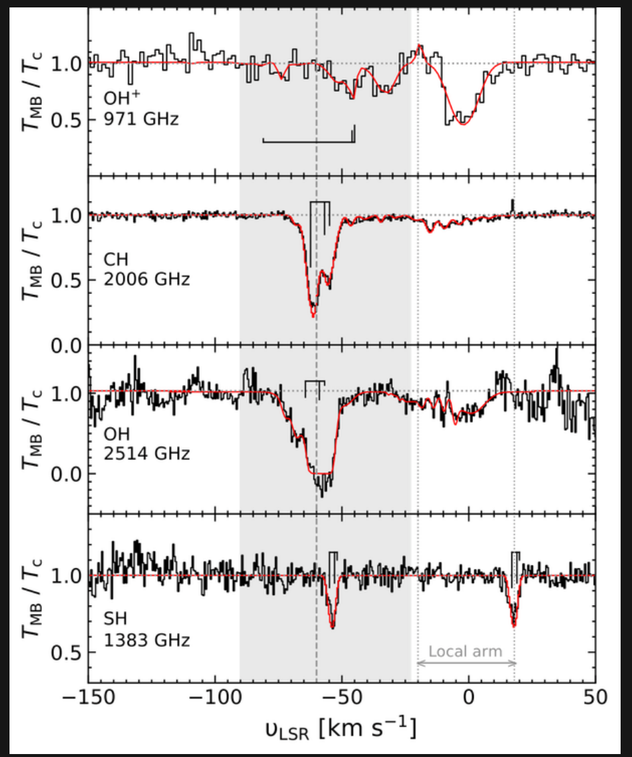


NGC 7538 IRS1



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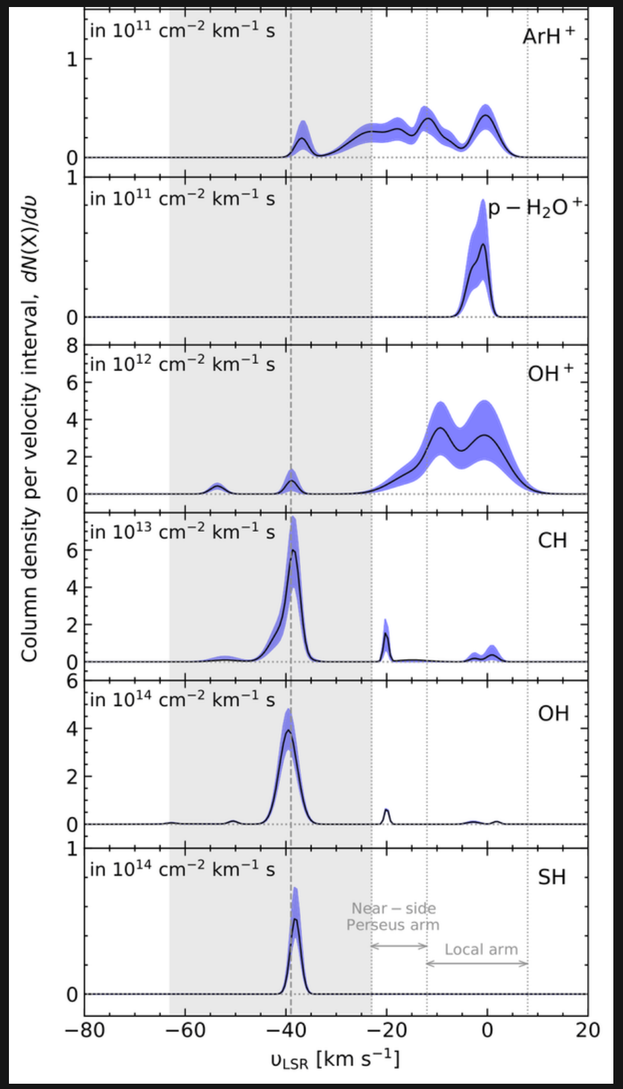

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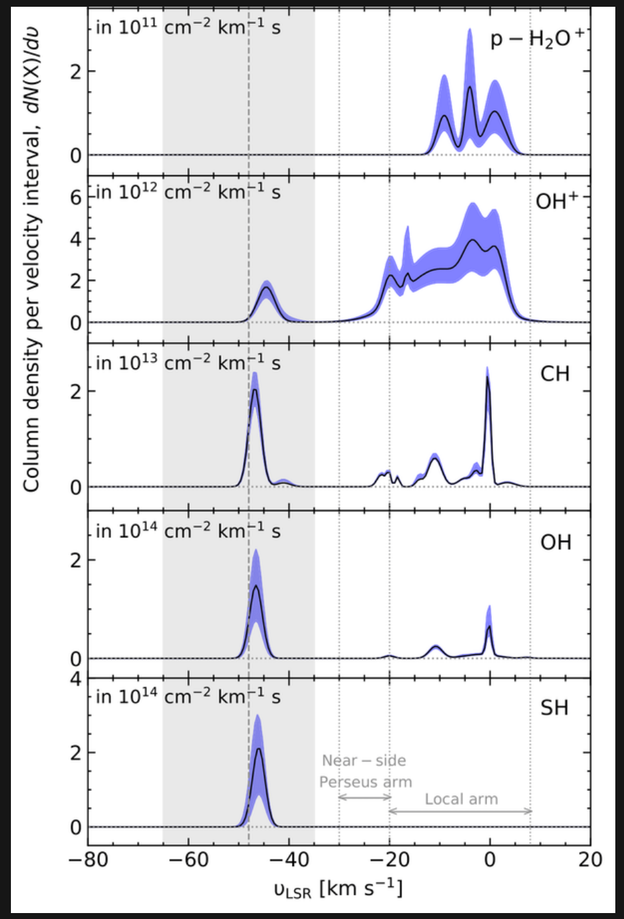

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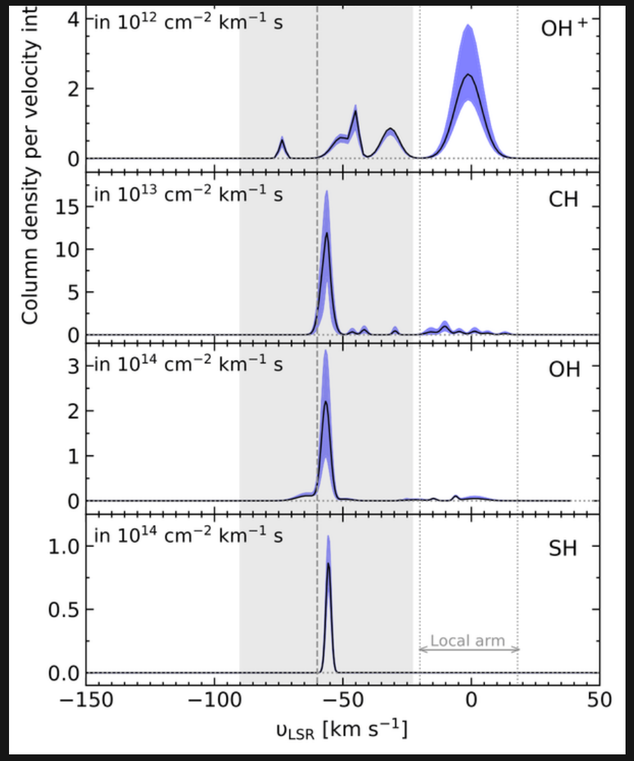

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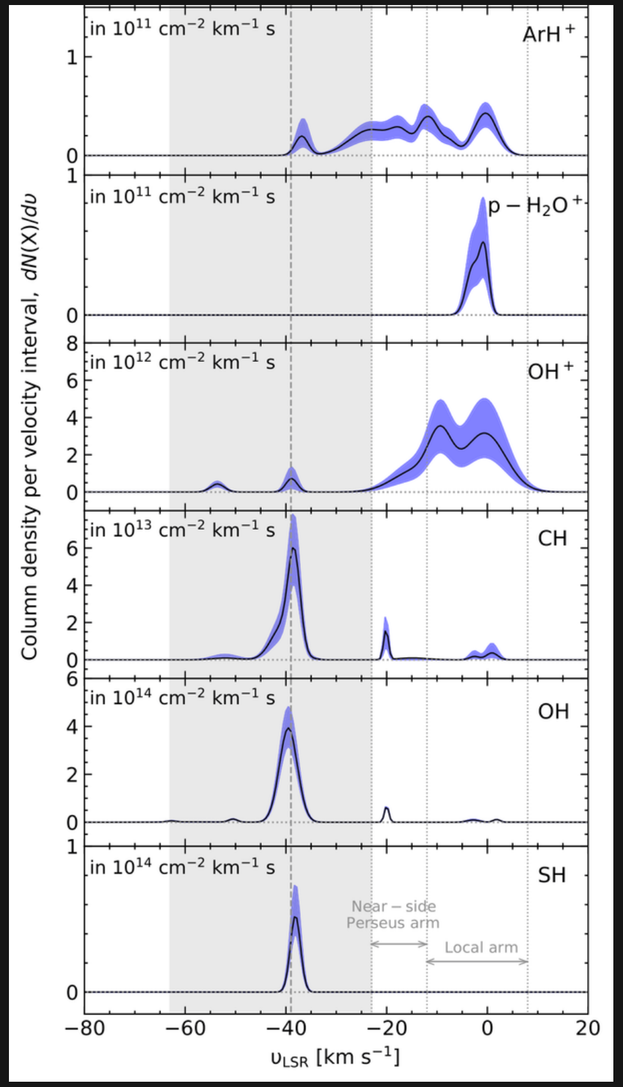
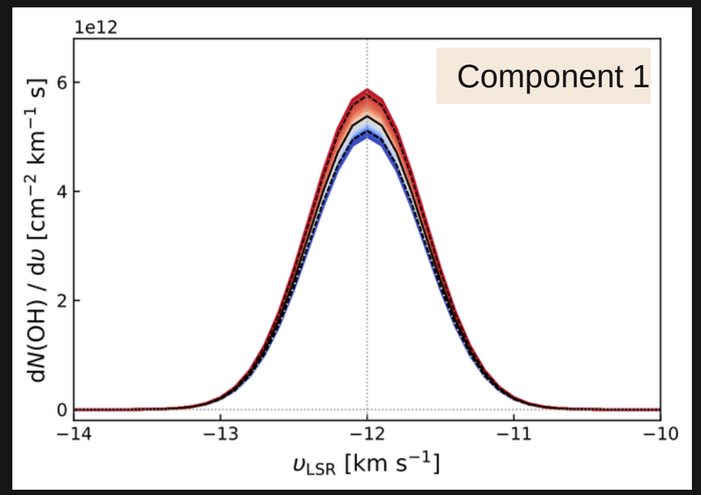
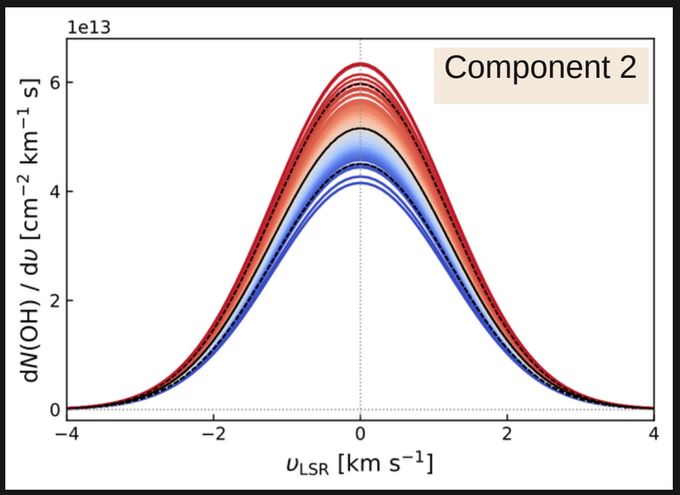


Error estimation:

Monte Carlo approach, simulating N spectra by adding a pseudo-random noise in each iteration.

— Mean
--- 5% and 95% percentiles

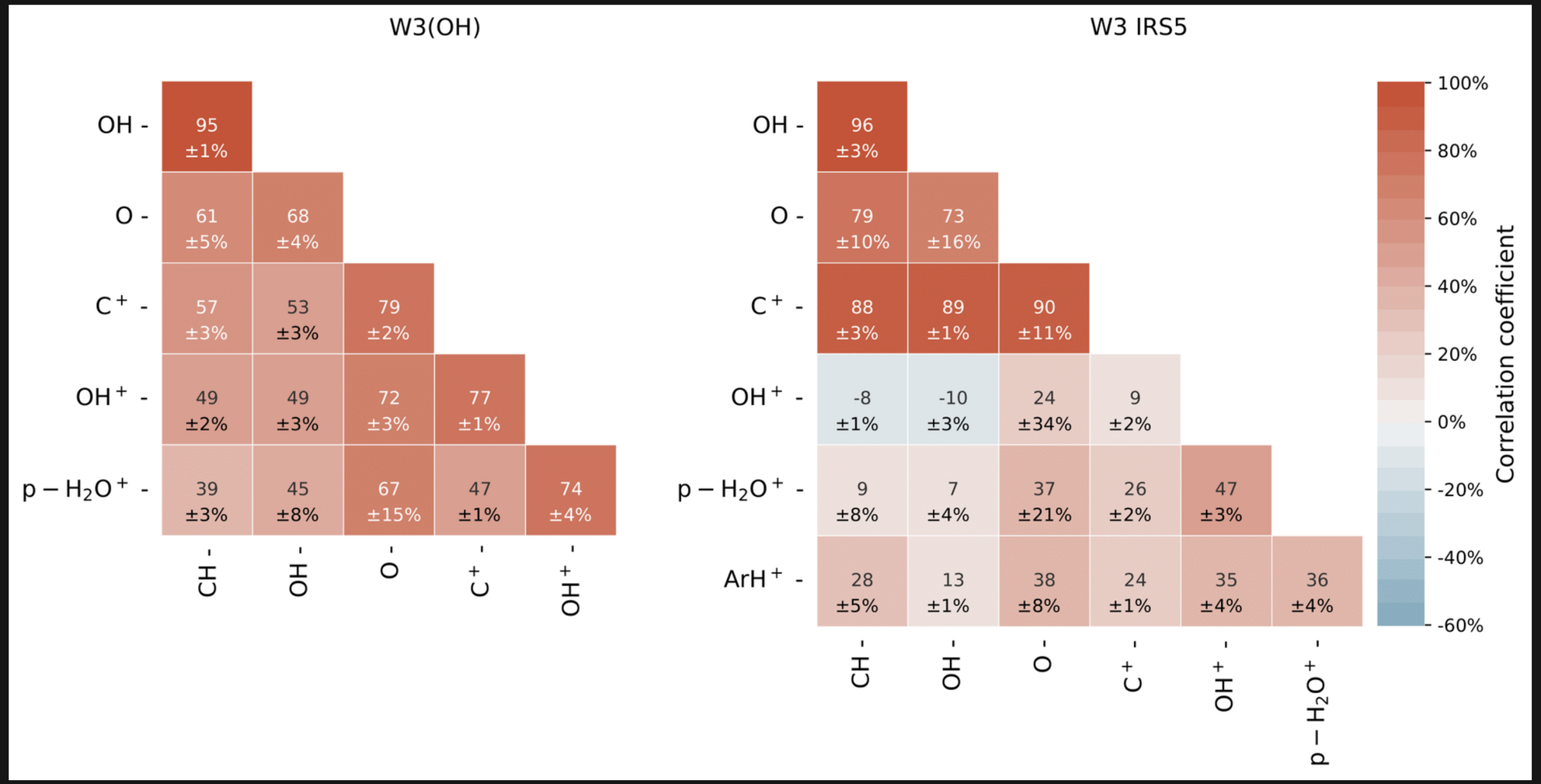




Results

Cross-correlations

Pearson product-moment correlation coefficient



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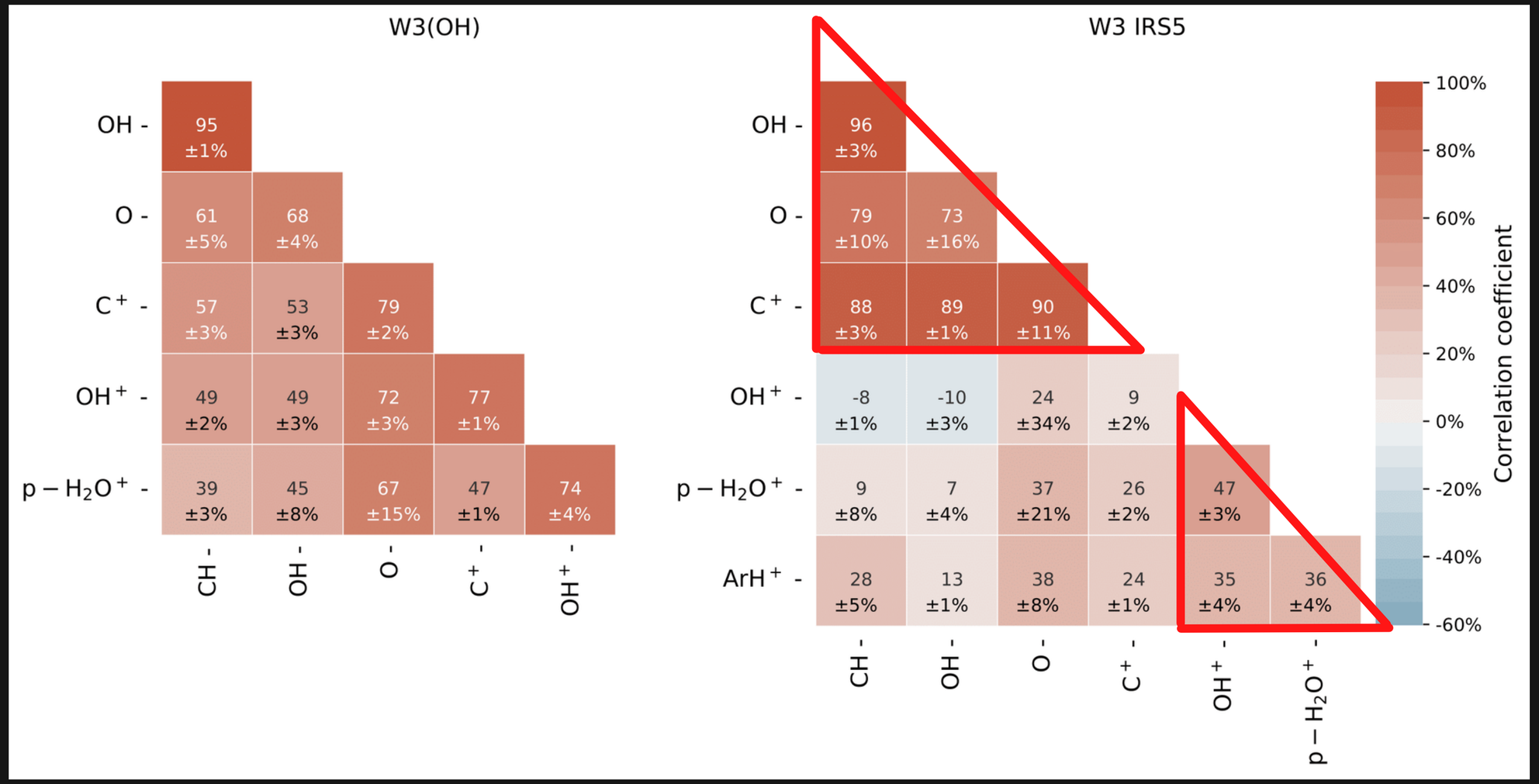
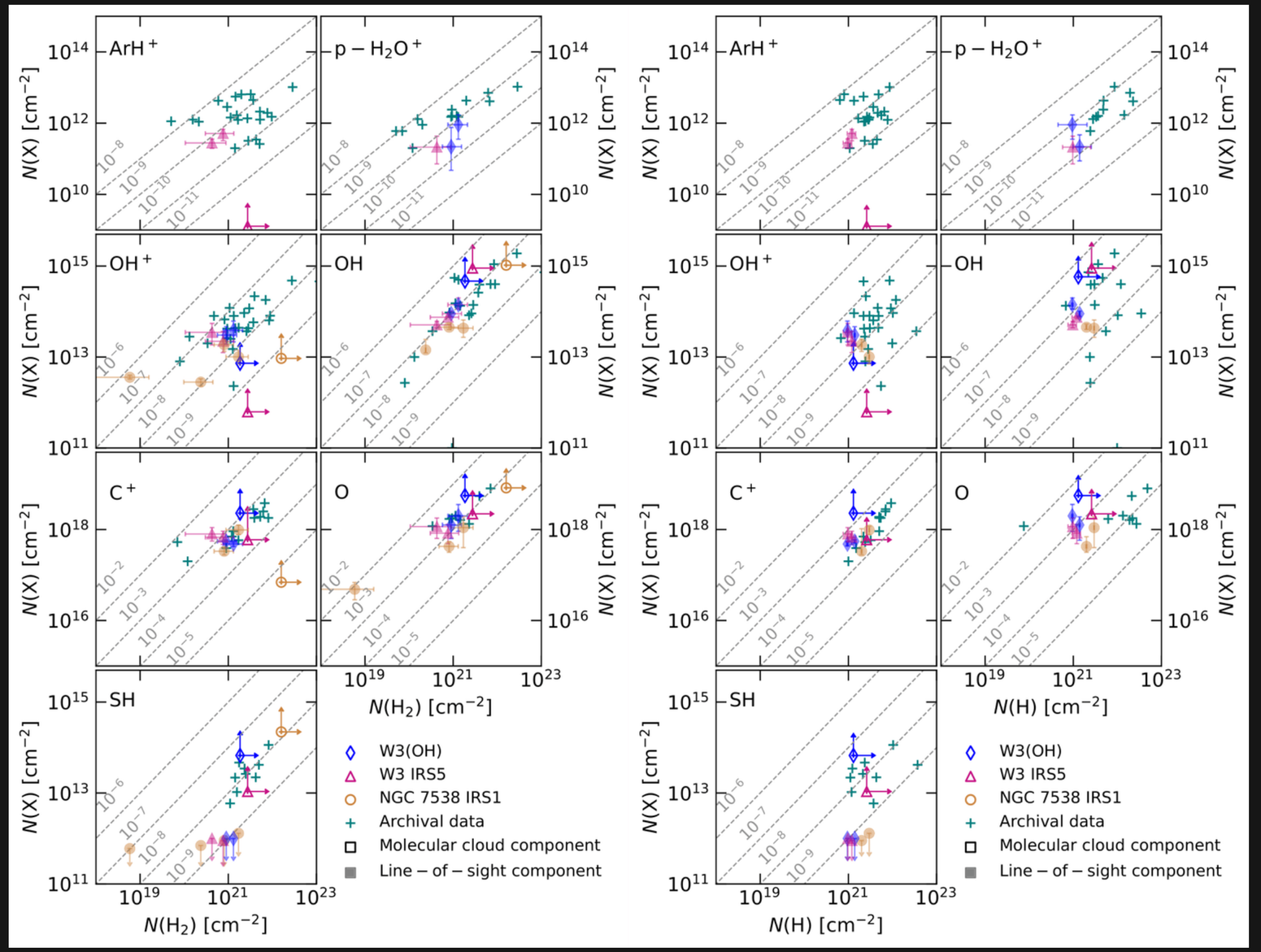


Results

Column density ratios

- H2 column densities derived from CH [CH]/[H2] = 10^-8 *(Sheffer et al. 2008)*
- HI data extracted from CGPS *(Taylor et al. 2003)*



Results

Variations along the line-of-sight

- The average properties toward all three sources are similar
- Column densities derived toward molecular cloud and line-of-sight components vary by a ~ 100
- Observed fluctuations in abundance ratios are useful in constraining properties of interstellar turbulence *(Bialy et al. 2019)*

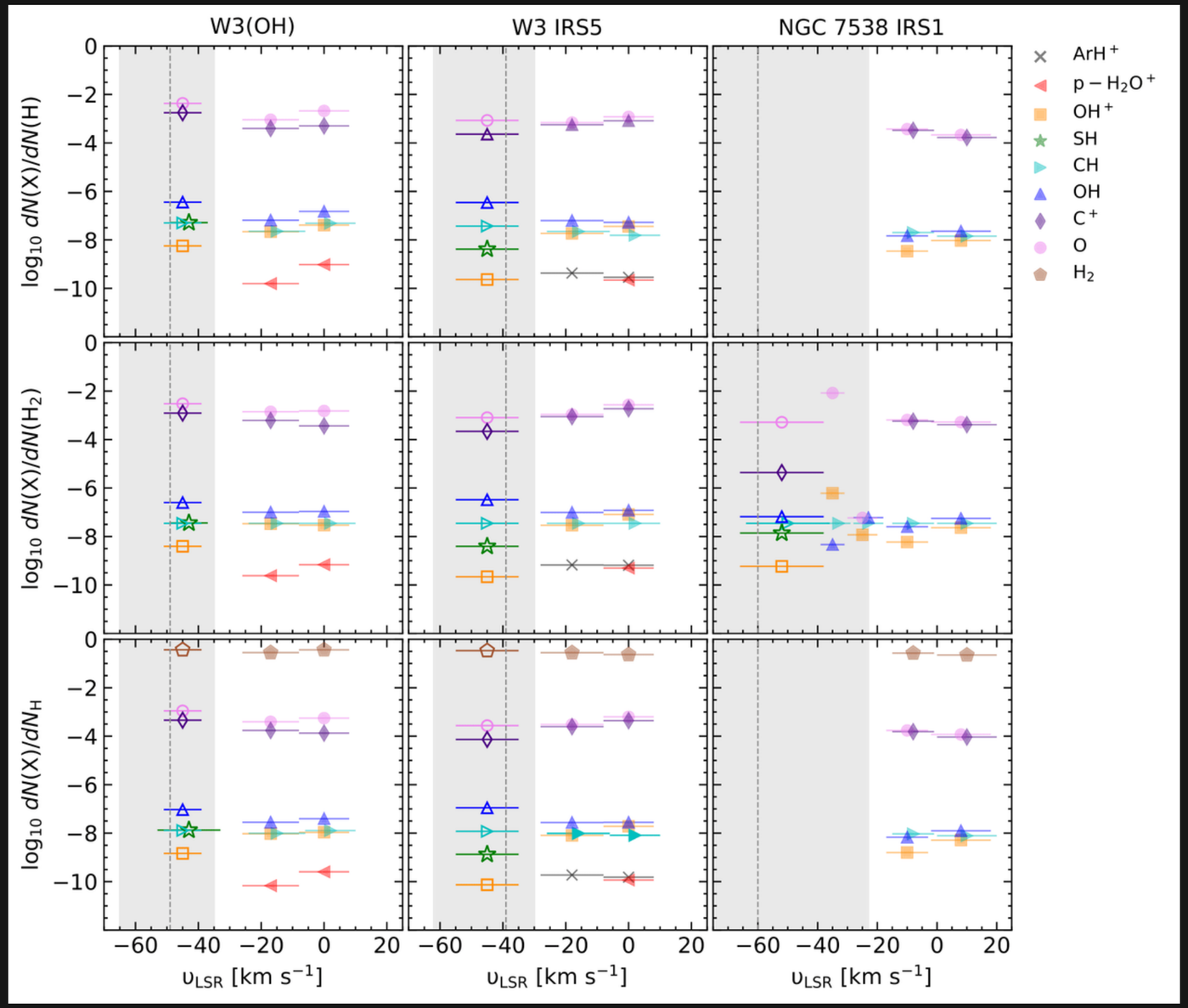
Supersonic turbulence

↓

Density fluctuations

↓

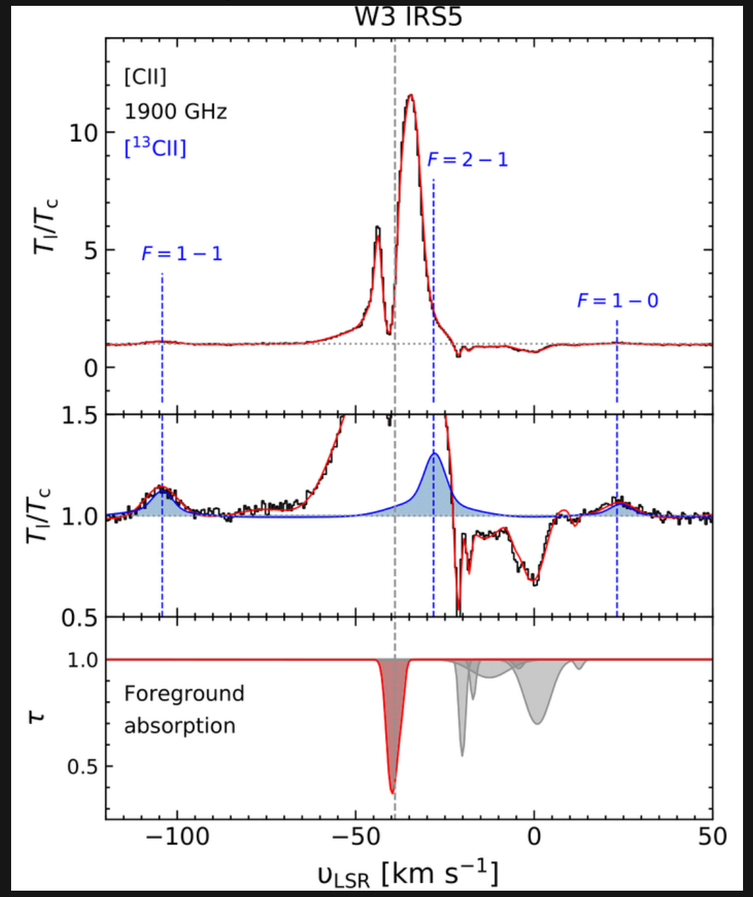
Variations in molecular abundances



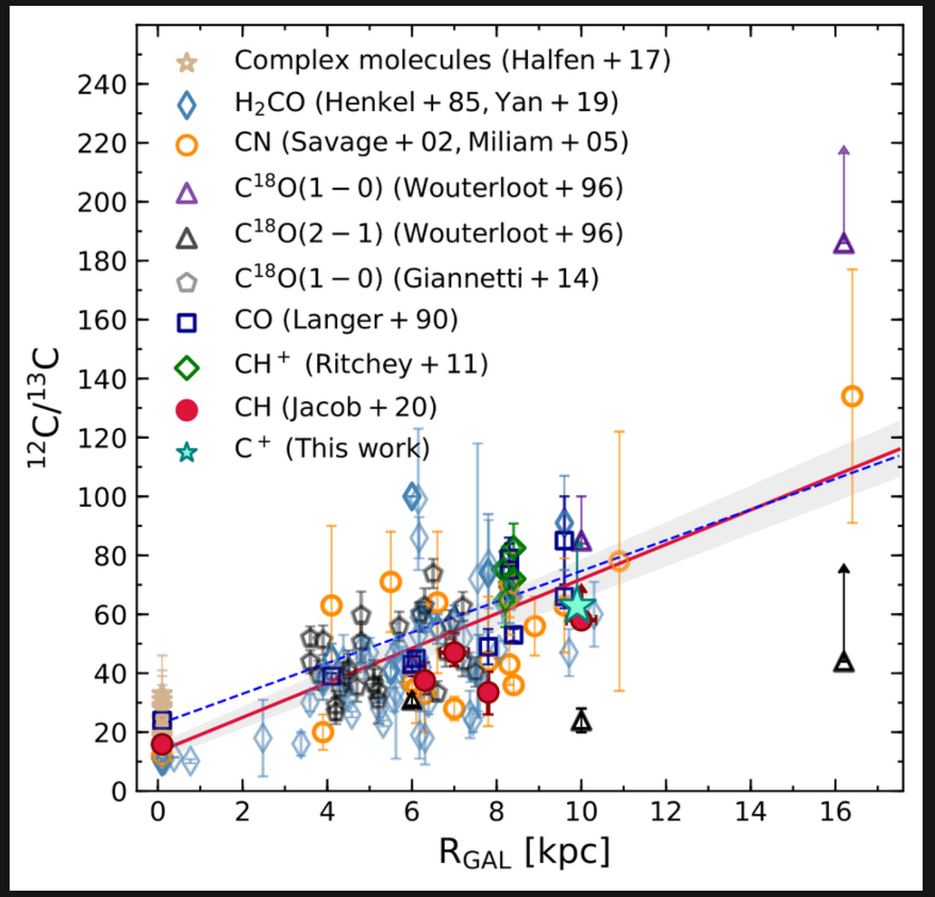
Results

HyGAL also provides a wealth of information about the **background continuum source**

For example, constraints on the 12C/13C ratio



Combined XCLASS fit to 12C+ and 13C+



12C/13C isotopic abudnance ratio as a function of Galactocentric distances

Synergies

JVLA observations *(Rugel et al. in prep, Busch et al, in prep)*

- Many of the HyGAL species originate in diffuse atomic gas -> **HI absorption line studies** essential for their interpretation *(Winkel et al. 2017)*
- Combined with the SOFIA 2.5 THz OH lines, the analysis of the ground state OH lines provide new **constraints on the excitation** of the latter.*(Jacob et al. 2021)*

(see Michael Rugel's talk)

IRAM Observations *(Kim et al. in prep)*

- Combined analysis of **S-bearing species** (SH from SOFIA + SO, H2S, CS from IRAM) *(Neufeld et al. 2015)*
- Cover **other molecular gas tracers** such as HCO+ and C2H

Summary

Extending the analysis to the entire sample will provide a systematic investigation of the properties of diffuse clouds.

Joint analysis with other data sets and chemical models will provide a wealth of knowledge also about the background sources.