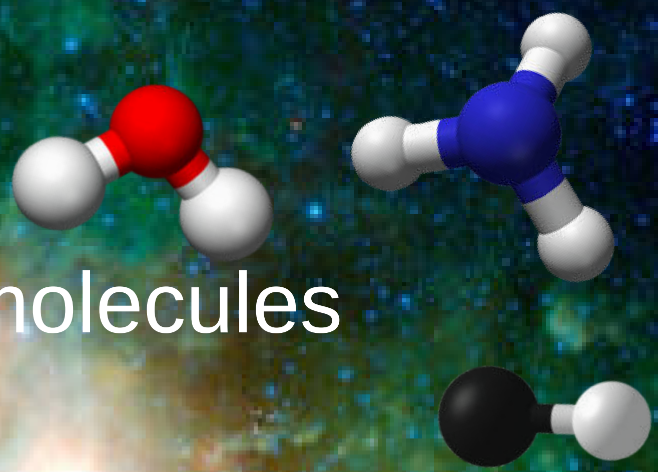
HyGAL

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



arXiv:2202.05046

Arshia M. Jacob
Johns Hopkins University

SOFIA TeleTalk May 11, 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: mid-IR NASA/WISE image consisting of the W3, W4 and W5 regions

What is HyGAL?

Targets:

- **six hydrides** (ArH^+, H_2O^+, OH^+, SH, OH, and CH)
- **two atomic gas constituents** (C^+ and O)

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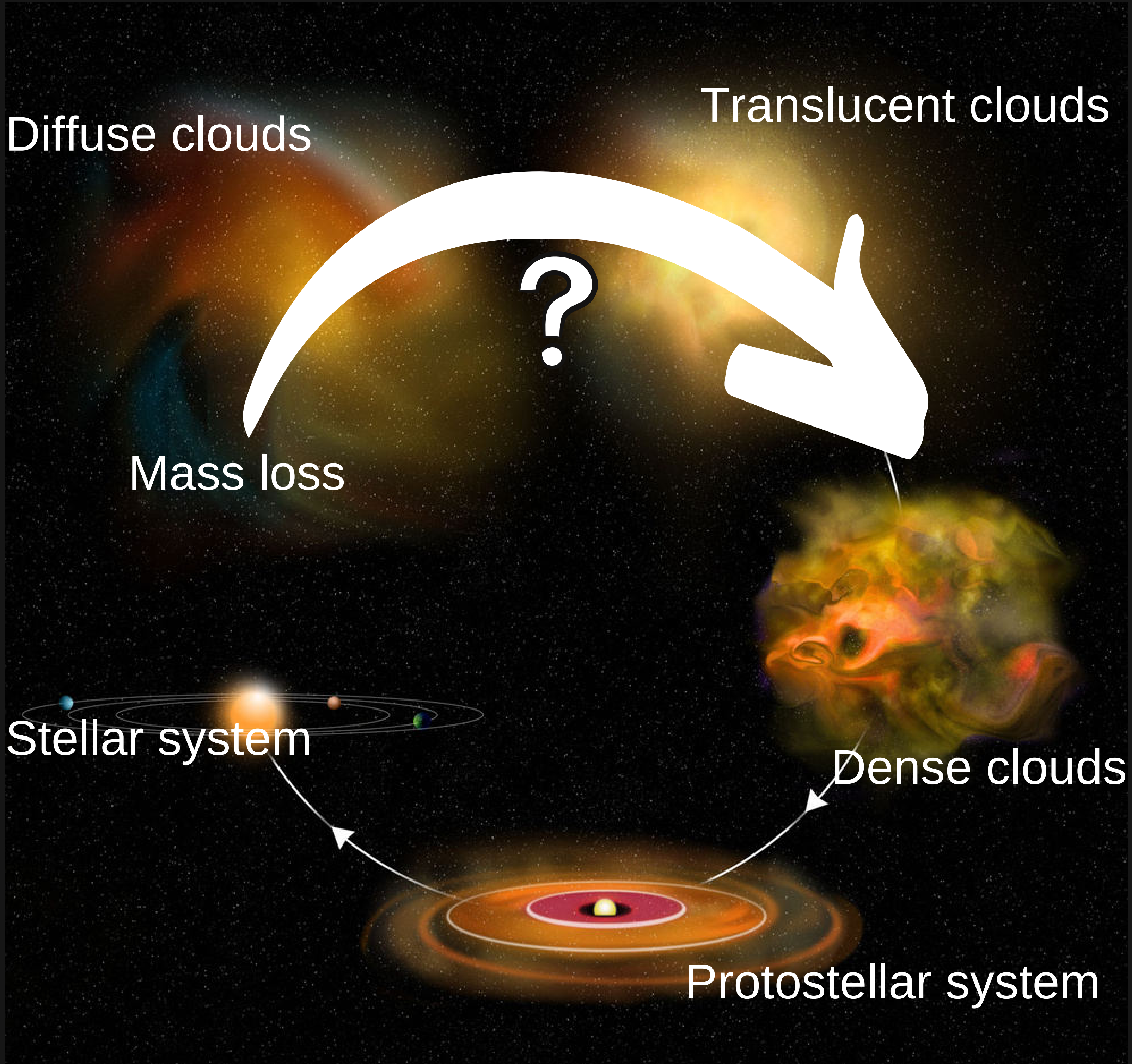

Credits: NRAO/Bill Saxton (ISM Gas life cycle schematic)

GOAL:

To understand how molecular clouds are formed and the processes that lead to the transition from **atomic to molecular gas**

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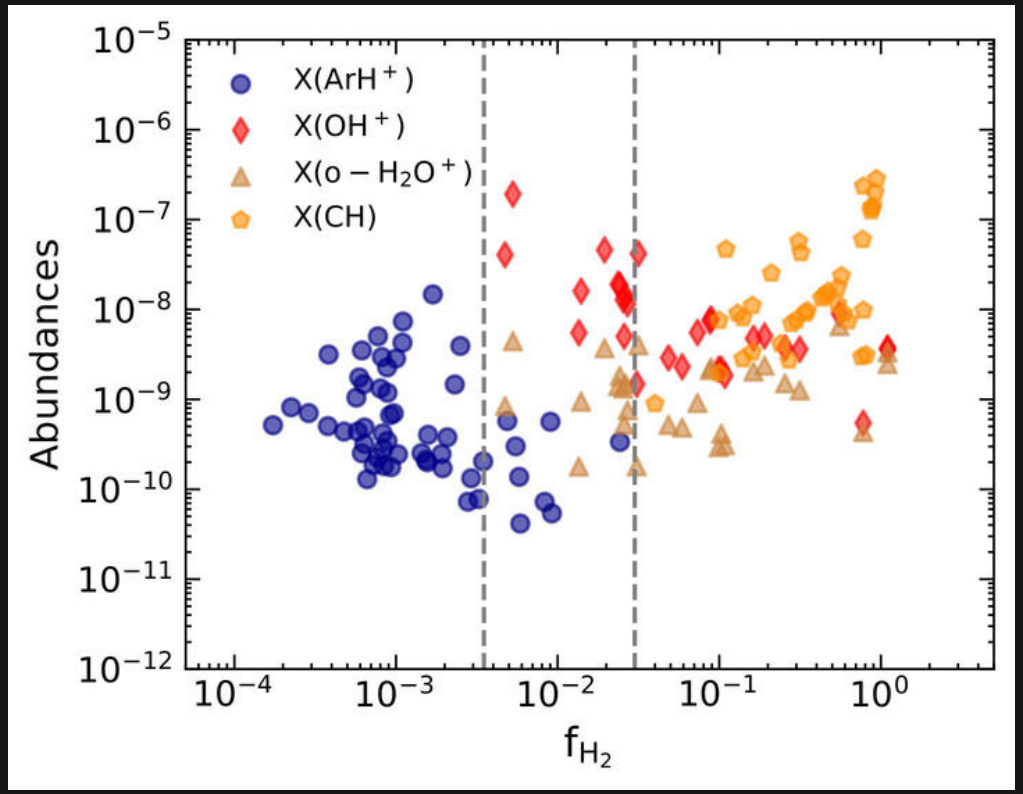
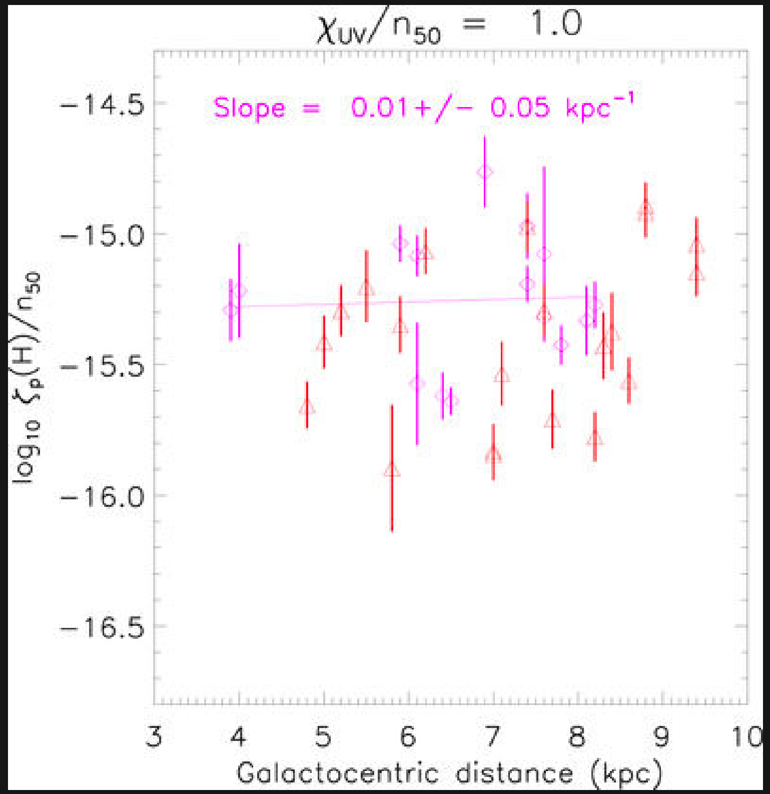
Distribution of molecular fraction in different ISM phases



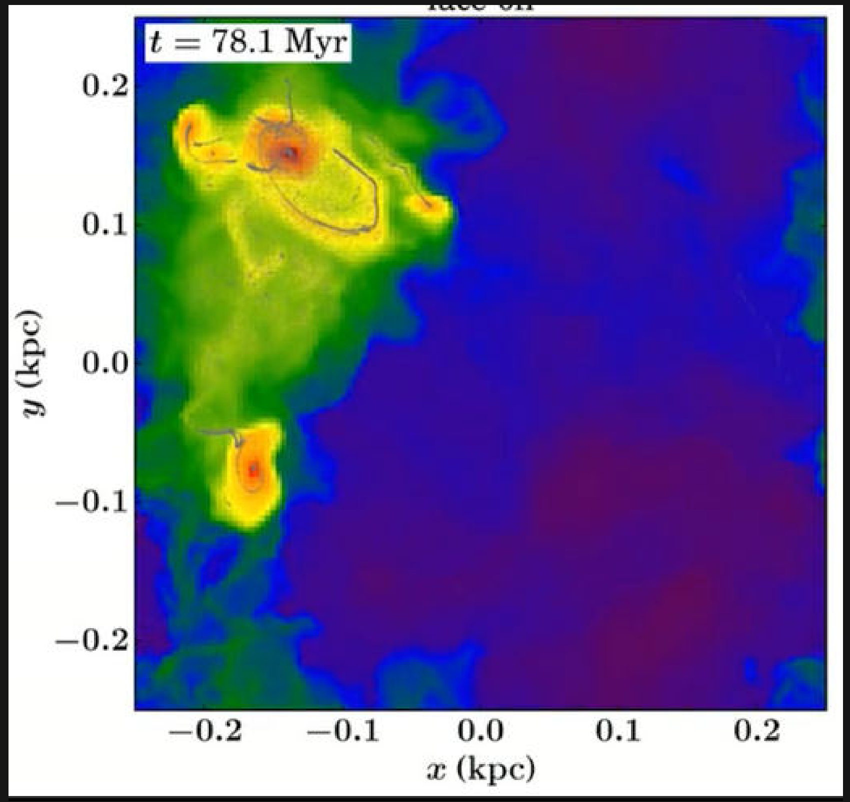
Taken from Jacob et al. (2020b)

Variation of comic-ray ionization across Galactocentric distances



Taken from Neufeld & Wolfire (2017)

Nature of turbulence in the ISM and its dissipation

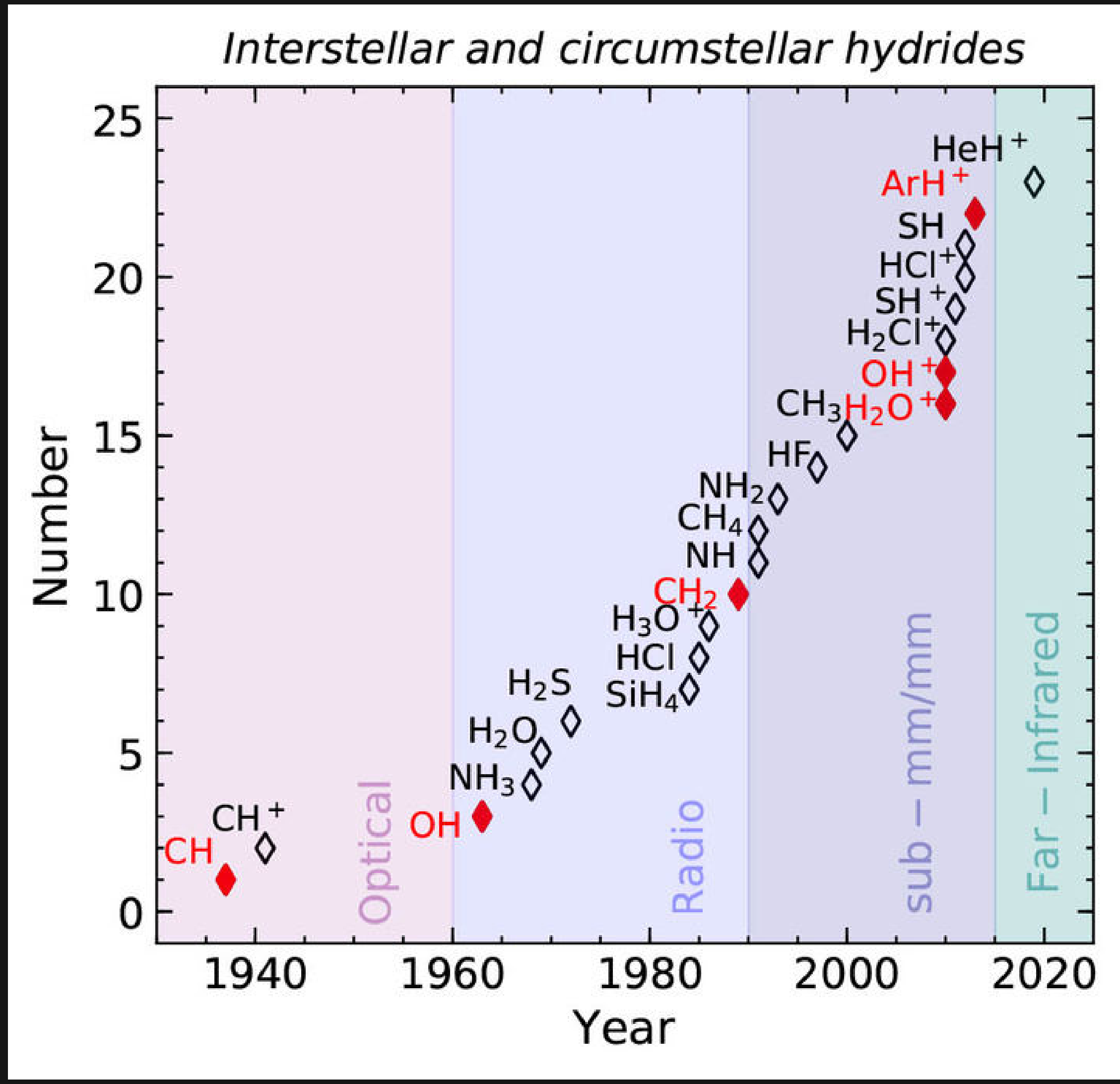


SILCC simulation

Why hydrides?

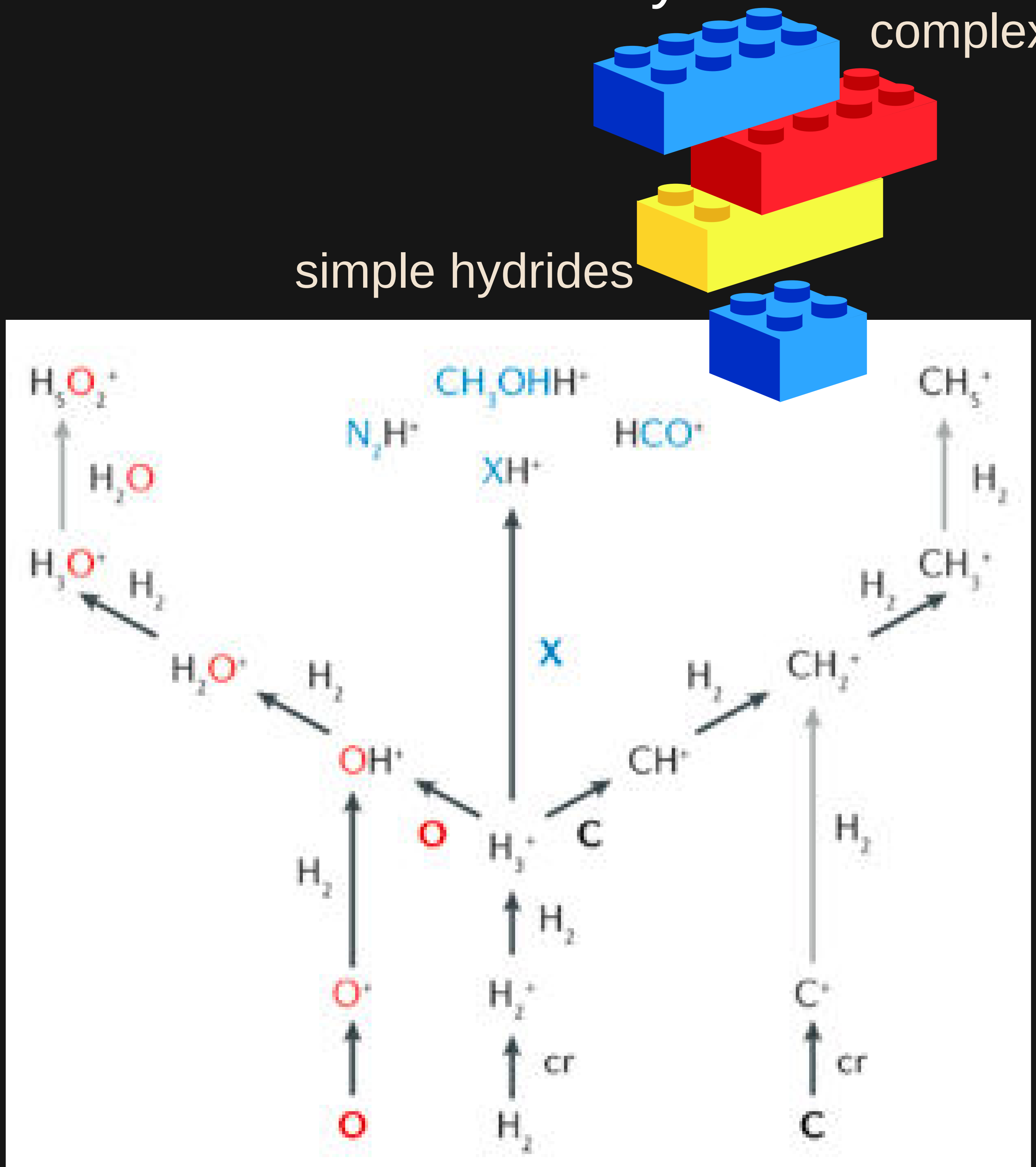
- **(X)H$_n$** and **(X)H$_n^+$**
  Reservoir for heavy elements
  (see review on Interstellar hydrides)

- First molecules detected in space
  (Swings & Rosenfeld 1937, Douglas & Herzberg 1941)



Adapted from http://www.astrochymist.org/

- Fundamental building blocks of interstellar chemistry



Taken from McGuire et al. (2020)

Renewed interest in hydrides

Small molecules + widely spaced energy levels

⟶ fundamental rotational transitions lie at **sub-mm and FIR wavelengths**

Herschel Space Telescope

APEX 12m Telescope

These observations have resulted in:

- a number of hydride discoveries
  (e.g. OH+ Wyrowski et al. 2010, HF Neufeld et al. 2010, SH+ Menten et al. 2011, etc)

- investigation of their diagnostic properties using absorption line spectroscopy
  (e.g. PRISMAS, WISH, HEXOS)

Absorption line spectroscopy

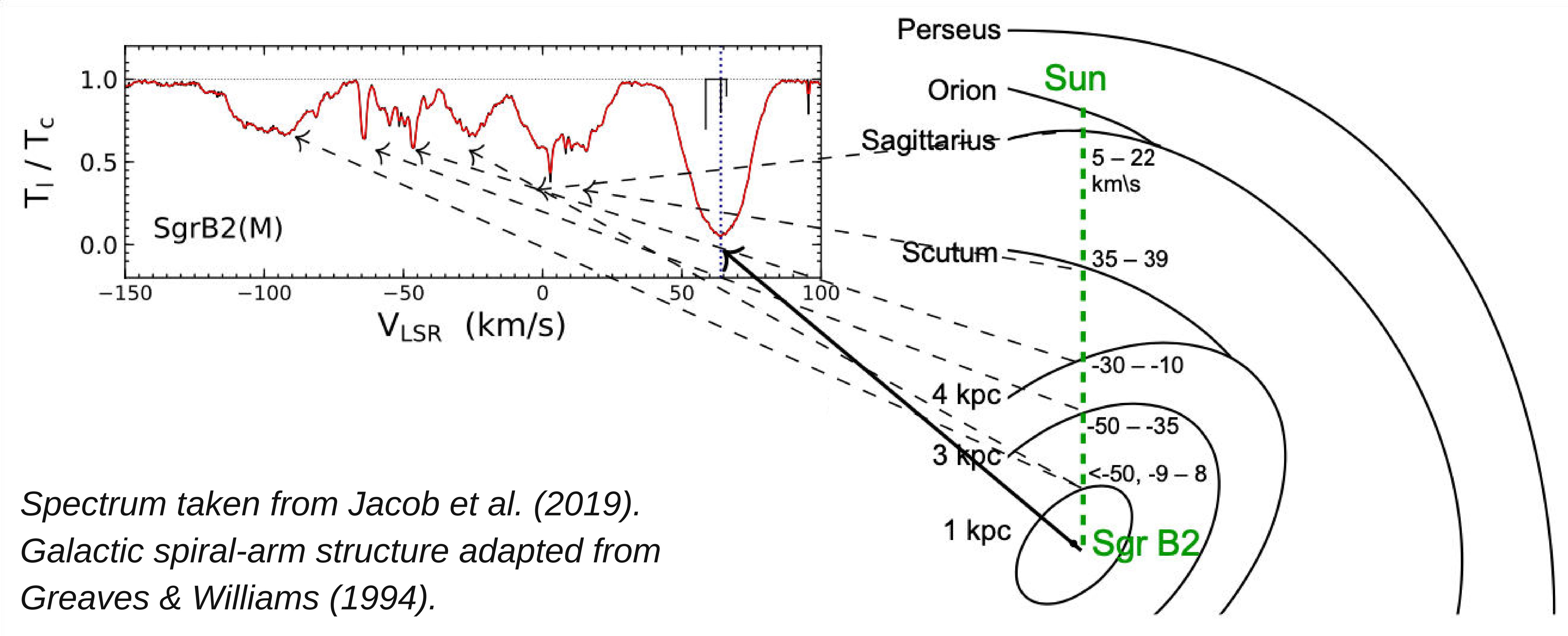
Robust tool for measuring **column densities**

optical depth

→ $T_l/T_c \propto \tau \propto N$

line-to-continuum ratio *column density*

e.g. SOFIA CH 2THz spectrum



Spectrum taken from Jacob et al. (2019).
Galactic spiral-arm structure adapted from Greaves & Williams (1994).

Foreground absorption

↑

Absorption against sub-mm and FIR bright sources

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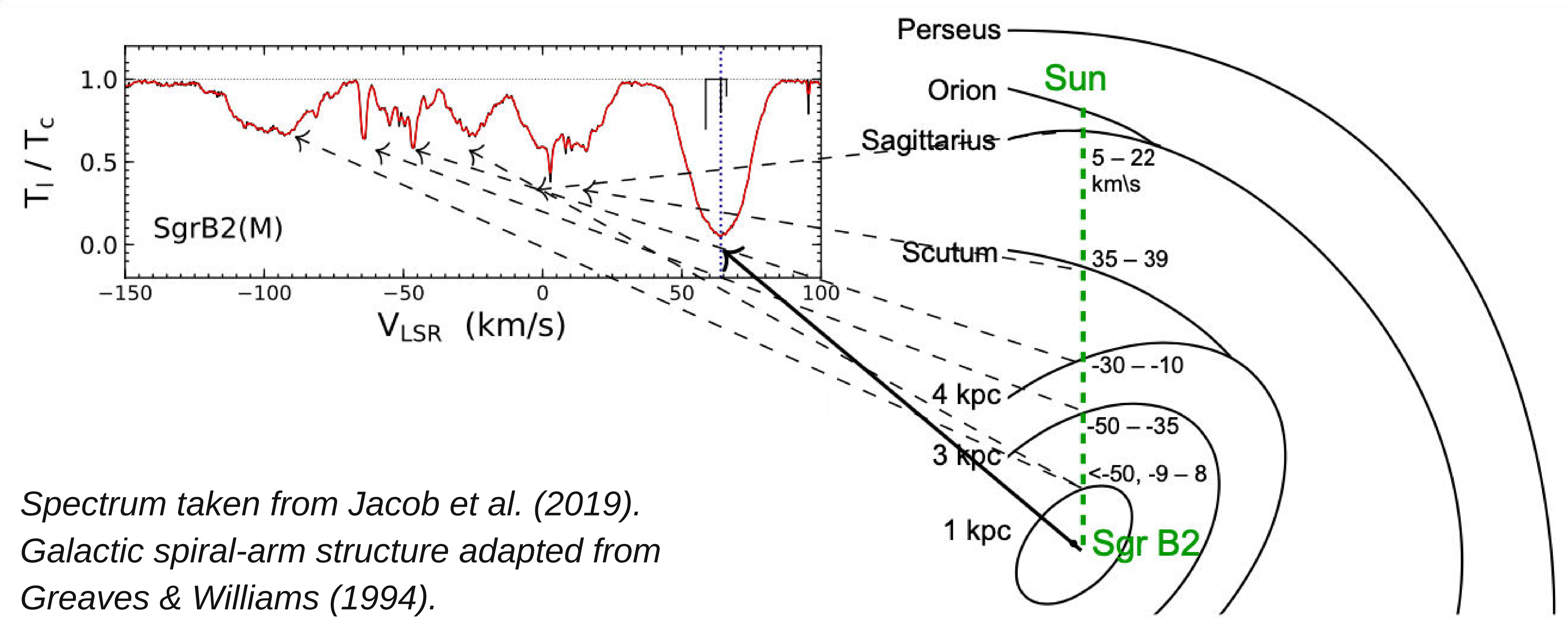


T_l / T_c

V_{LSR} (km/s)

Spectrum taken from Jacob et al. (2019).
Galactic spiral-arm structure adapted from Greaves & Williams (1994).

Foreground absorption

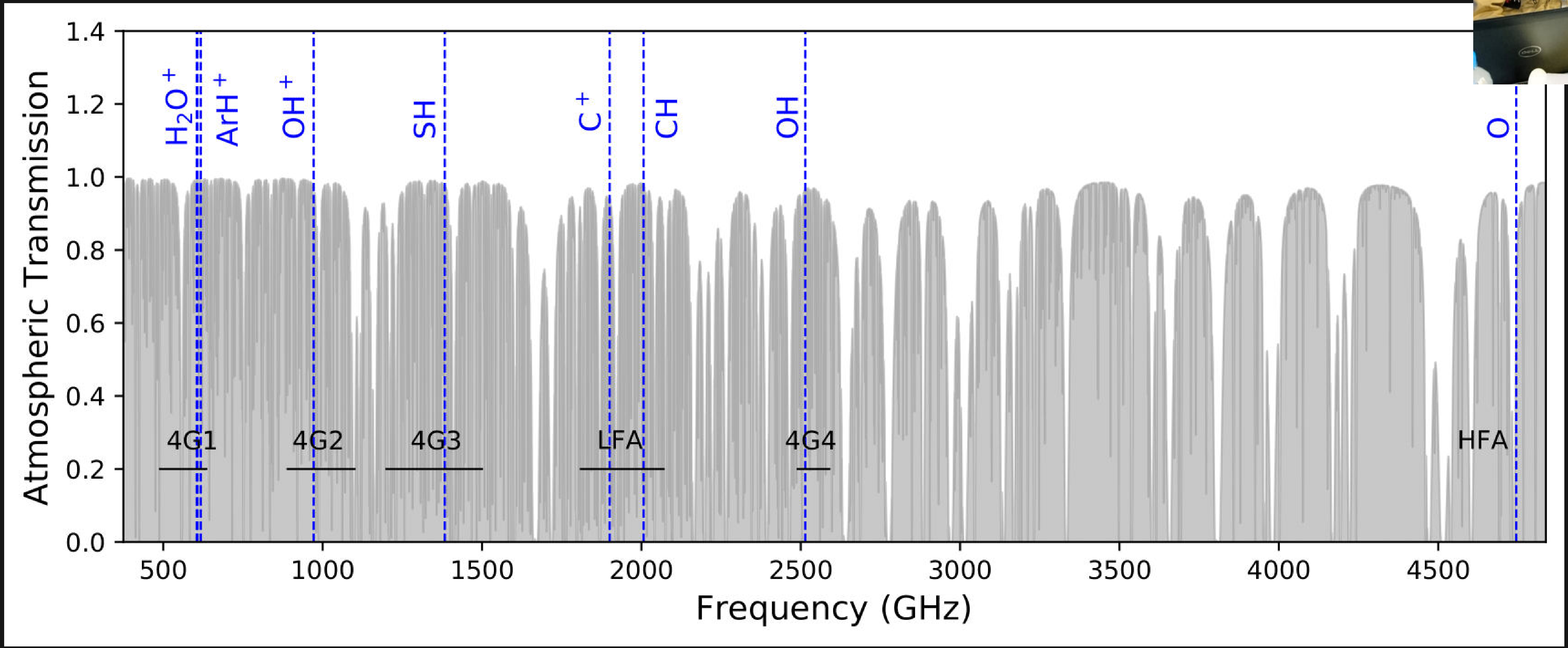
↑

Absorption against sub-mm and FIR bright sources

With the end of the Herschel mission HyGAL aims to extend its Legacy using SOFIA

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.

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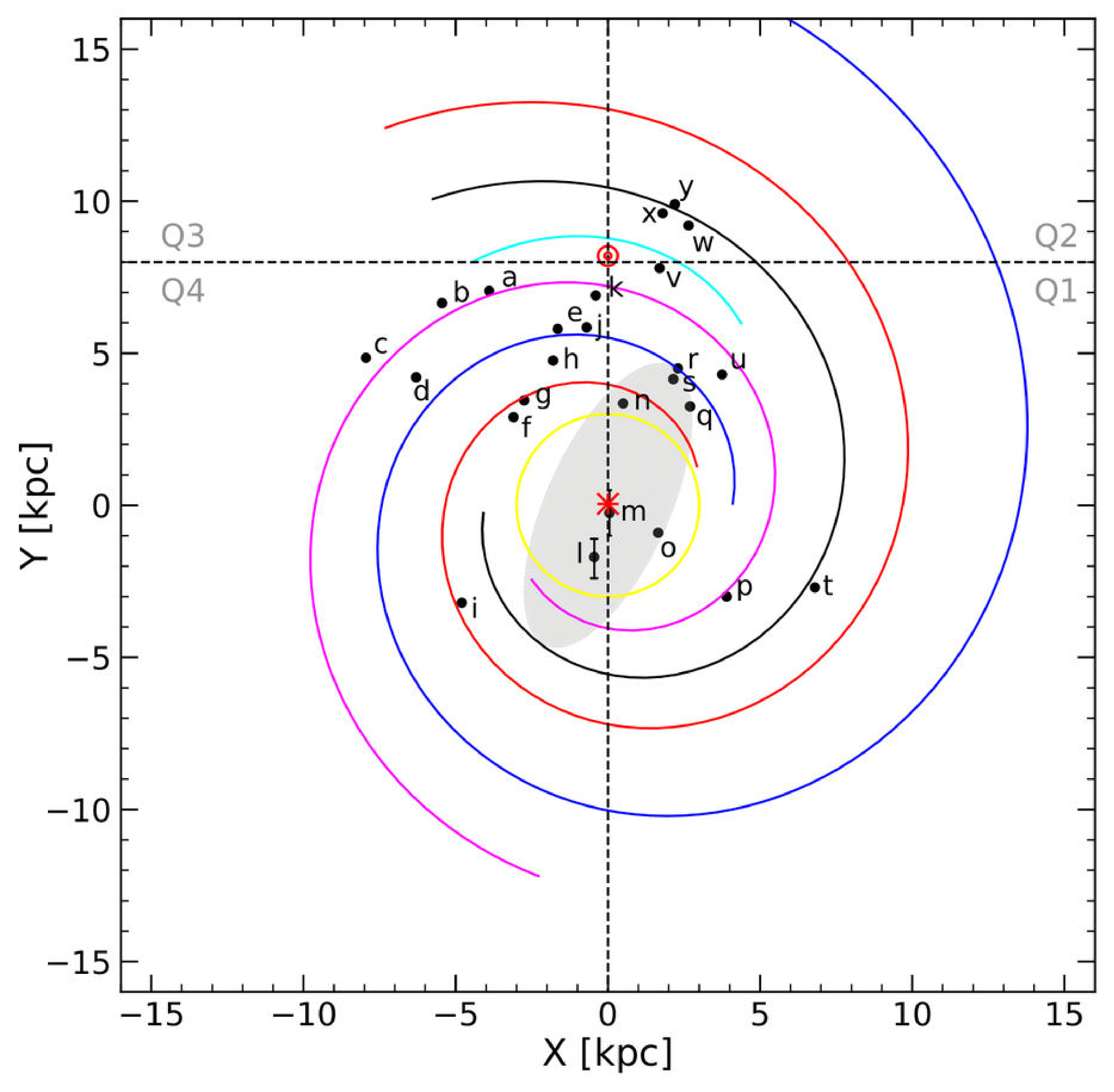


25 bright background continuum sources
(5 of which are located in the Outer Galaxy)

Source selection:

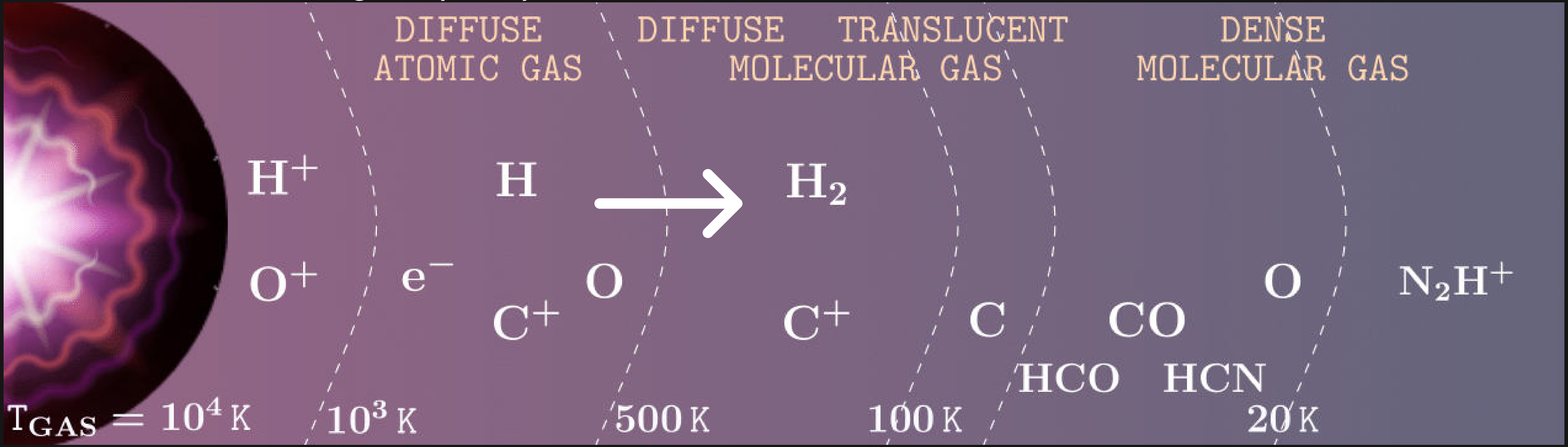
160 μ continuum flux > 2000 Jy in the Inner Galaxy
> 1000 Jy in the Outer Galaxy

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

HyGAL source distribution taken from Jacob et al. 2022.

Diagnostic properties of hydrides

Photodissociation region (PDR)



Adapted from Hollenbach & Tielens (1999)

Phase transition from atomic to molecular gas

- essential for **cloud formation**
- initiating **chemical growth**

Diagnostic properties of hydrides

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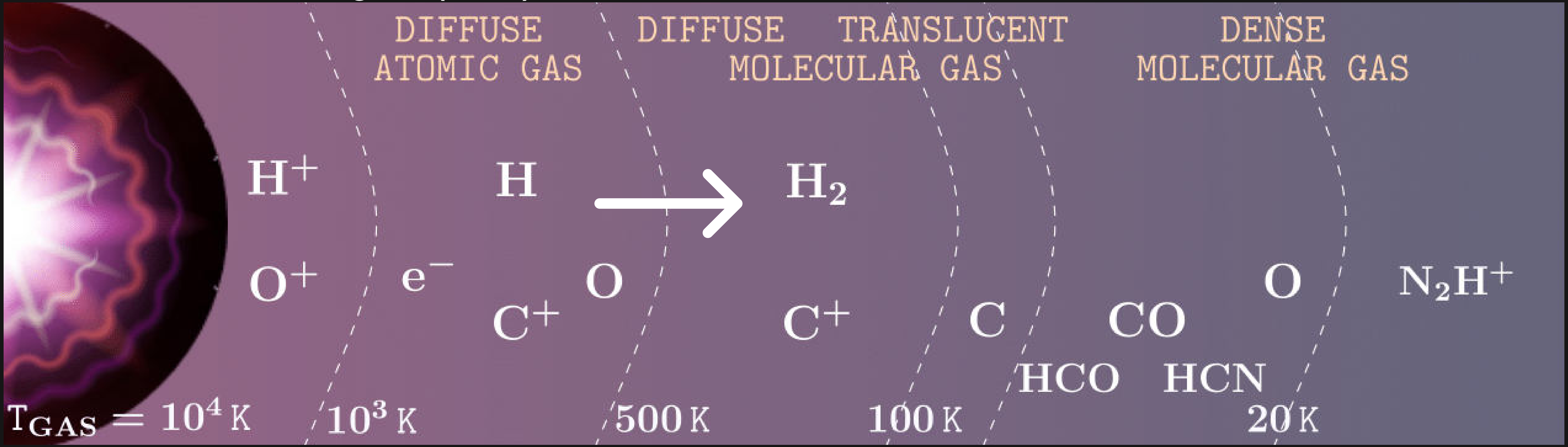


Adapted from Hollenbach & Tielens (1999)

Phase transition from atomic to molecular gas

- essential for **cloud formation**
- initiating **chemical growth**

→ molecular fraction

$$f(H_2) = \frac{2N(H_2)}{(N(H) + 2N(H_2))}$$

Diagnostic properties of hydrides

Tracing the total neutral gas column

Atomic hydrogen: *direct observations*

- HI 21cm transition

Molecular hydrogen: *direct observations*

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

No observable infrared/radio emission from the cold ISM

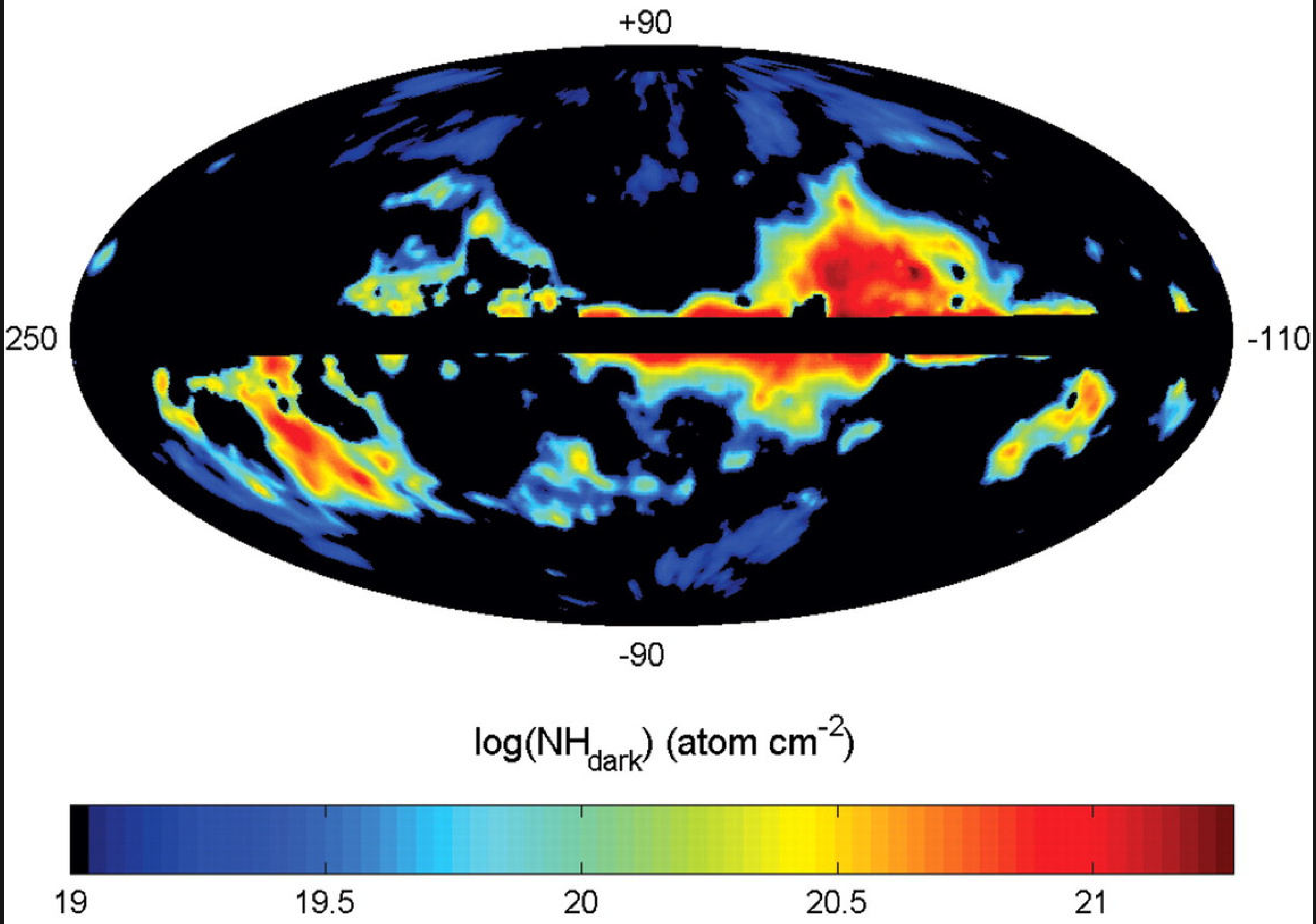
Need for *indirect observations* or proxies like CO 2.6 mm

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

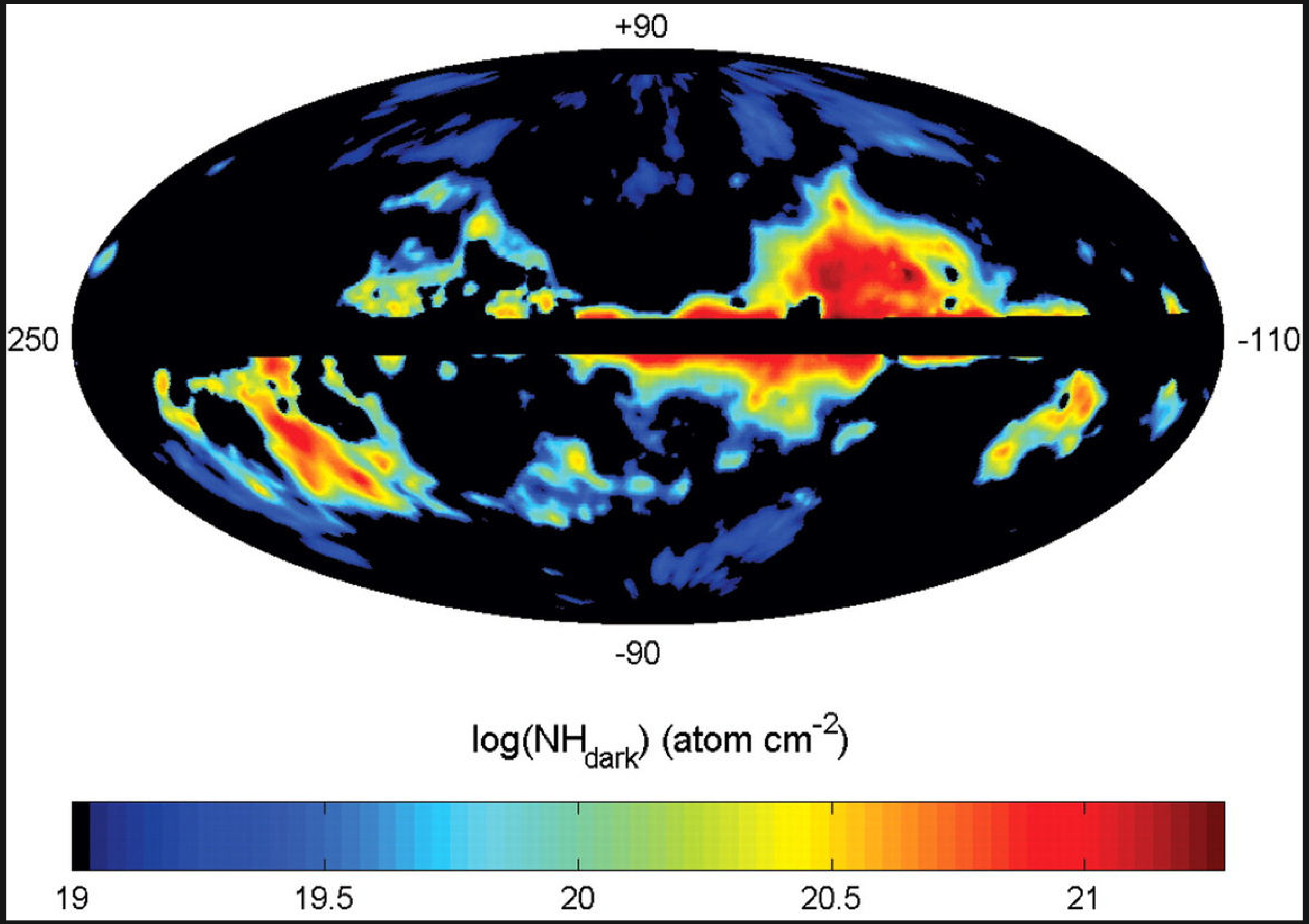
Tracing the total neutral gas column

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)

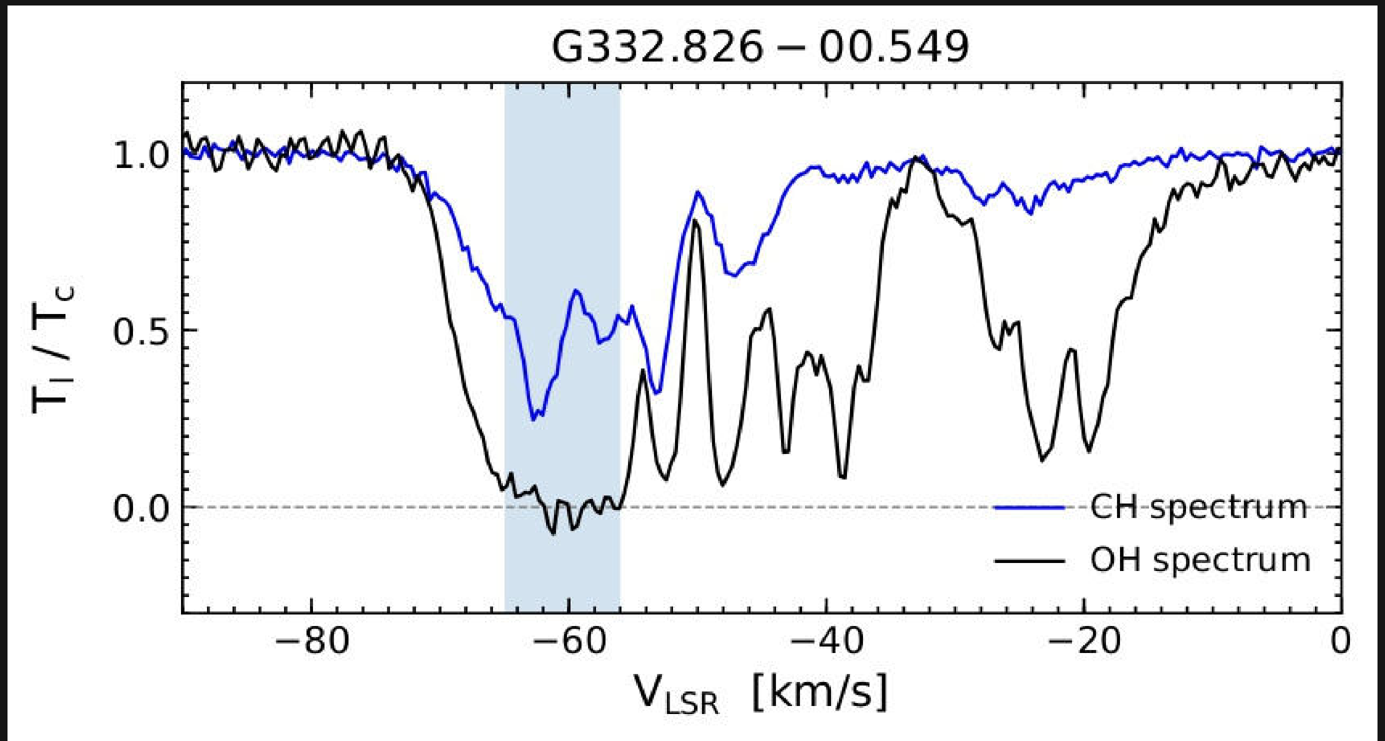
Hydrides as tracers for CO-dark gas

Several hydrides have been shown to be excellent CO-dark gas probes like HF, OH, CH etc

See also Helmut Wiesemeyer's 2018 SOFIA teletalk

Why use CH?

- Ubiquitous
- Unsaturated absorption profiles
- Tight correlation with H_2



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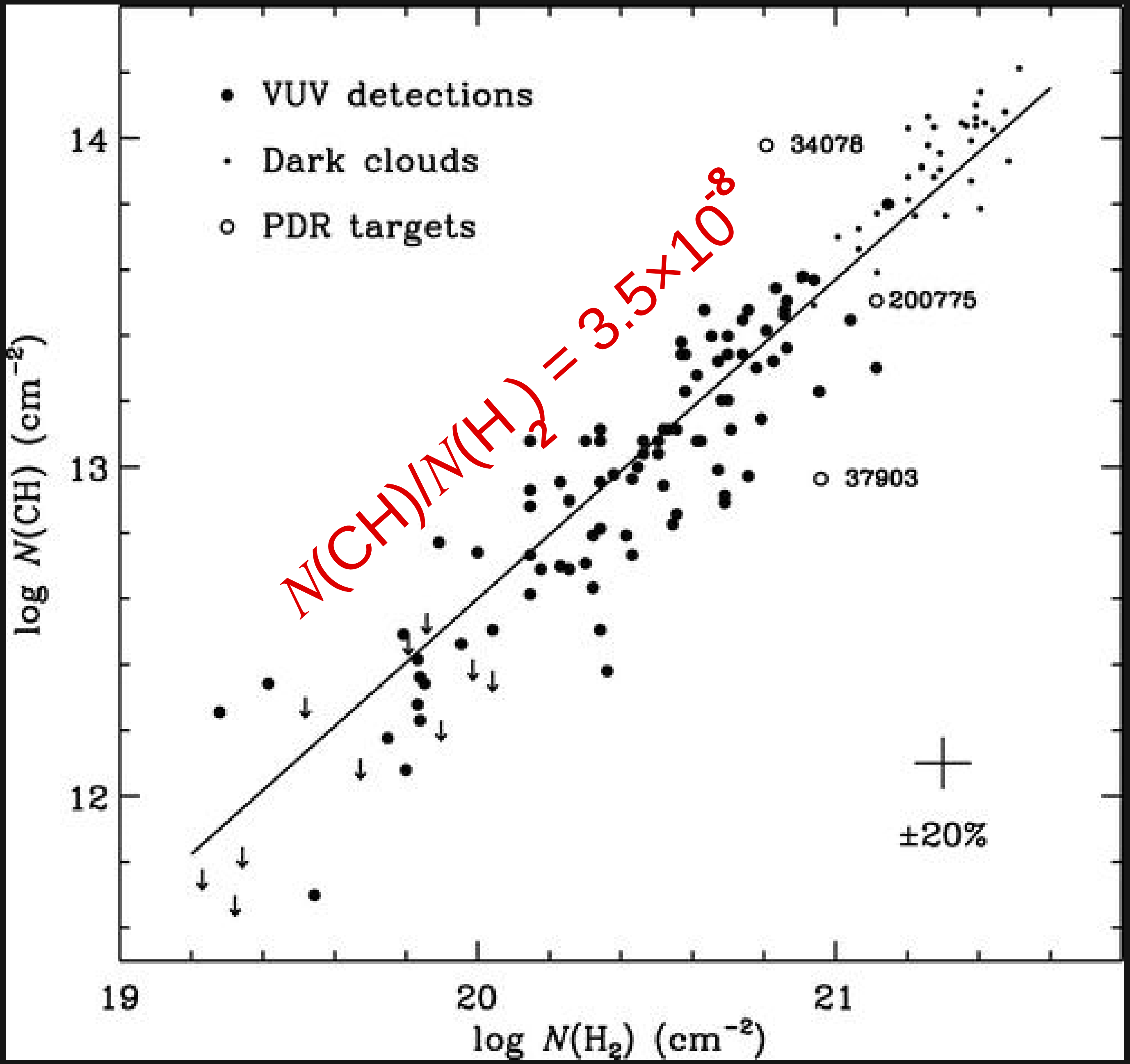

Taken from Sheffer et al. (2008)

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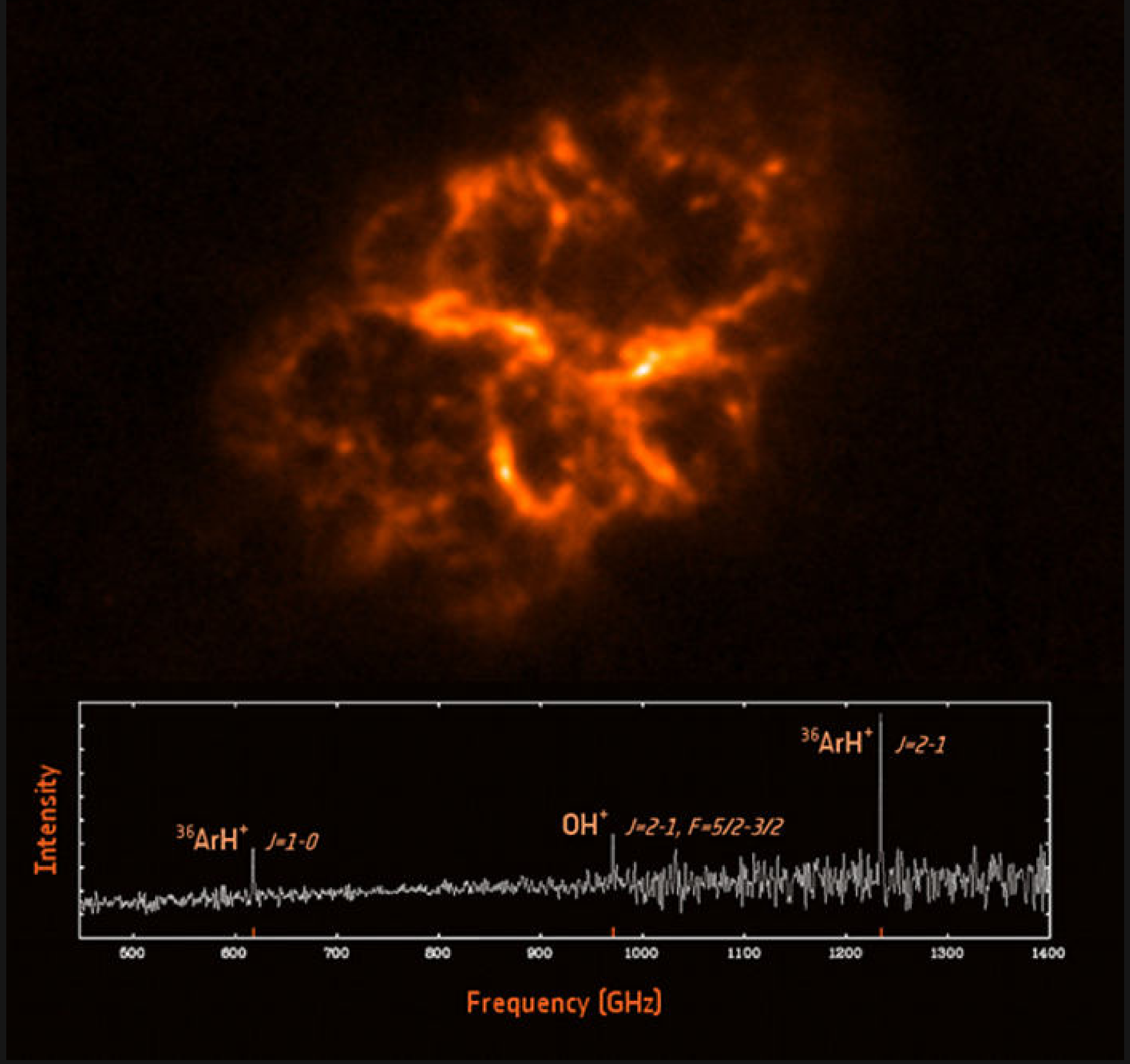
Need for *indirect observations* or proxies like ~~CO 2.6 mm~~ **CH, OH, HF**

Molecules as tracers of atomic gas?

Discovery of the **first Nobel gas bearing molecule** in space - **ArH^+**

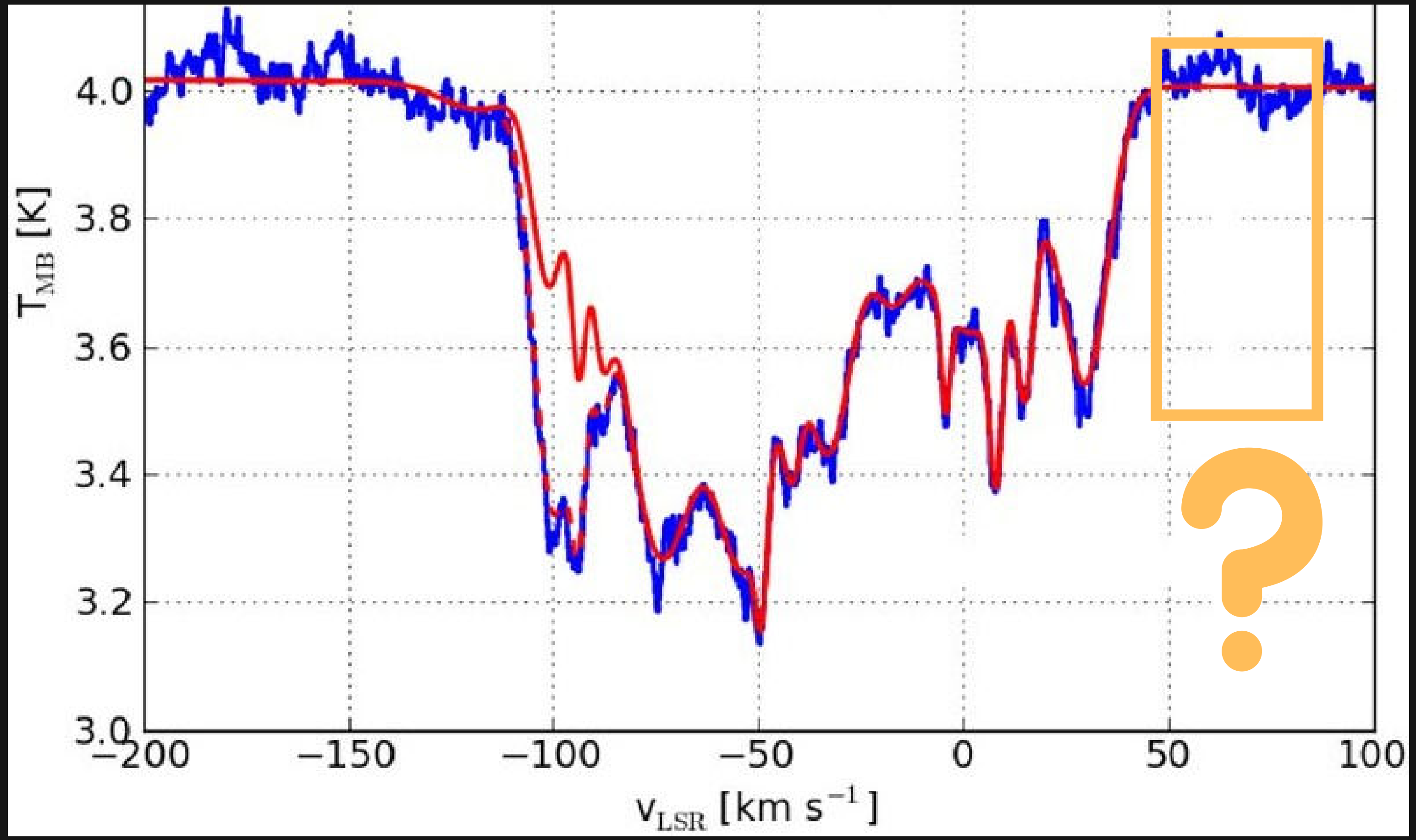
(See also David Neufeld's 2015 SOFIA tele-talk)

Crab Nebula Supernova Remnant



Taken from Barlow et al. (2013)

Unidentified absorption features



Taken from Schilke et al (2014)

- Ar-36 is the dominant isotope in space
- No absorption at the systemic velocity of the source

Molecules as tracers of atomic gas?

Lack of systemic absorption can be explained with chemistry!

▶ **Formation**

$$\mathrm{Ar} \xrightarrow{\mathrm{CR}} \mathrm{Ar}^+ \xrightarrow{\mathrm{H_2}} \begin{cases} \mathrm{ArH}^+ + \mathrm{H} \\ \mathrm{ArH}_2^+ \rightarrow \mathrm{ArH}^+ + \mathrm{H} \end{cases}$$

Chemistry initiated by cosmic rays (CRs)

▶ **Destruction**

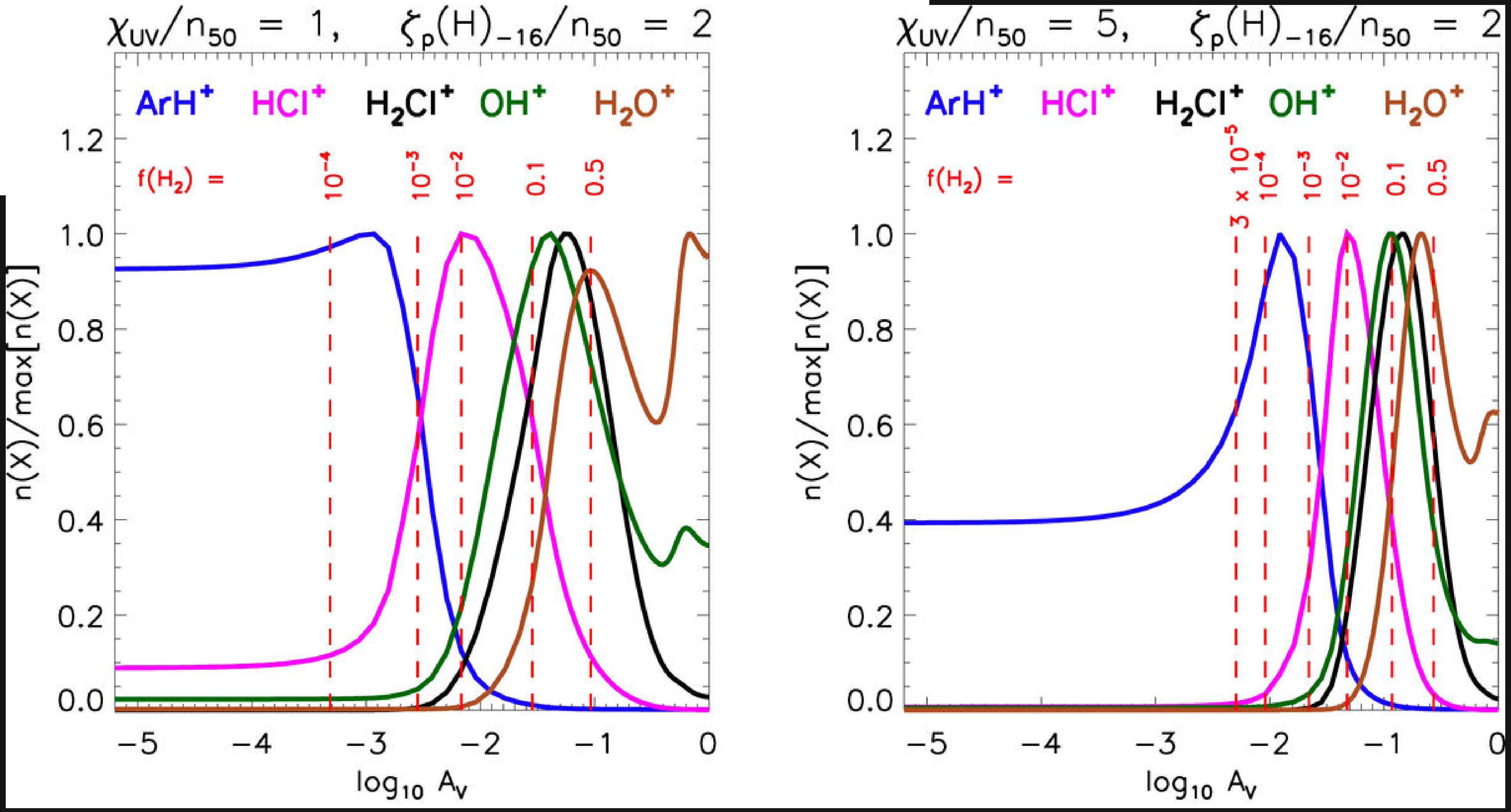
$$\mathrm{ArH}^+ + \mathrm{H_2} \rightarrow \mathrm{Ar} + \mathrm{H_3^+}$$

$$\mathrm{ArH}^+ + \mathrm{O} \rightarrow \mathrm{Ar} + \mathrm{OH}^+$$

$$\mathrm{ArH}^+ + e^- \rightarrow \text{extremely slow}$$

Survival ⇒ low molecular fraction ($f_{\mathrm{H_2}}$)

ArH^+ traces almost purely atomic gas similar to OH^+ and H_2O^+



Taken from Neufeld & Wolfire (2016)

Distribution of molecular fraction

Tracing the total neutral gas column *(indirect observations)*

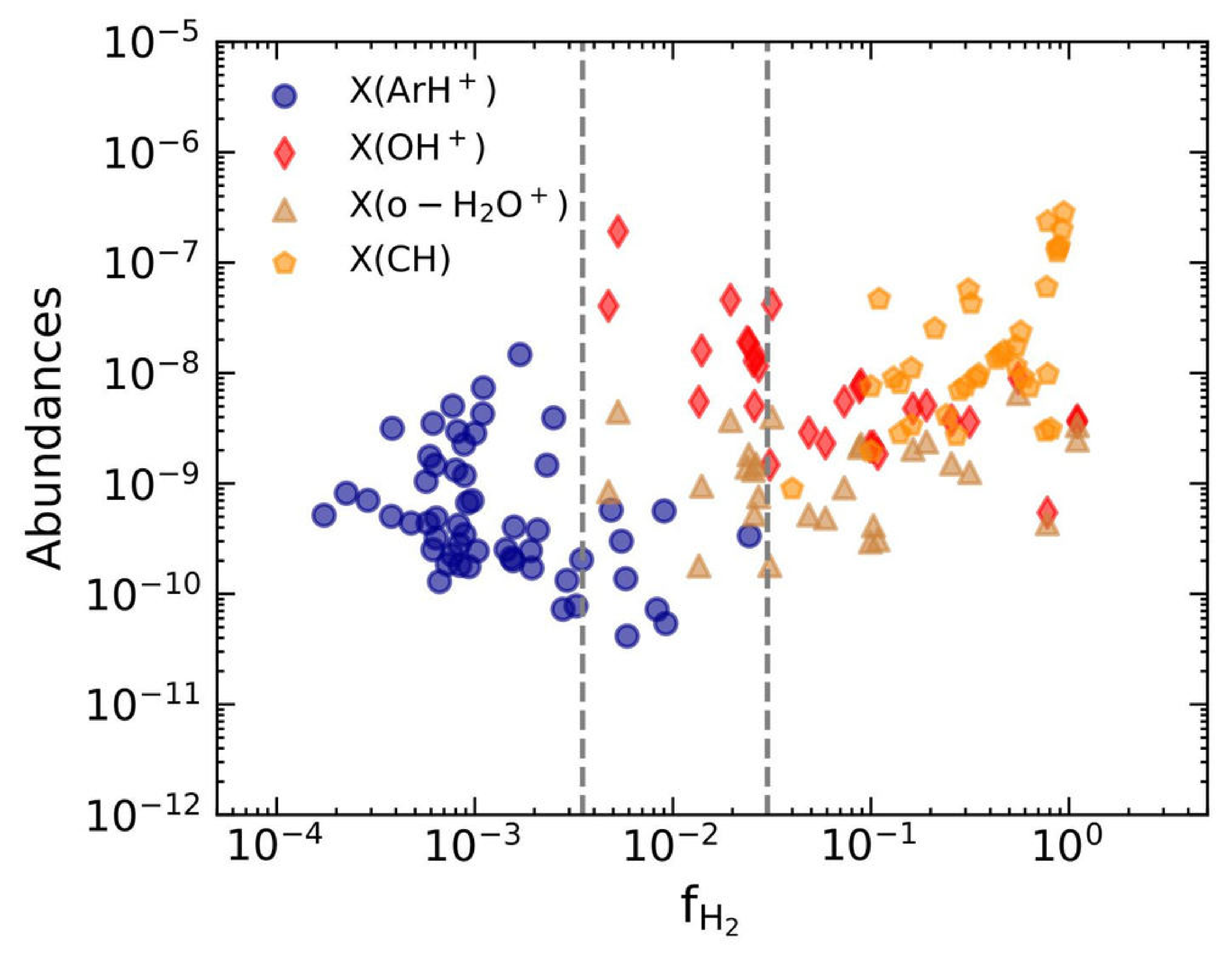
Atomic hydrogen: **ArH^+, OH^+, H_2O^+**

Molecular hydrogen: **CH, OH, HF**

Analyzing the steady state chemistry from the observed abundances

⟶ **trace the transition from diffuse atomic to diffuse and translucent molecular gas**

HyGAL will help extend this analysis across different cloud types

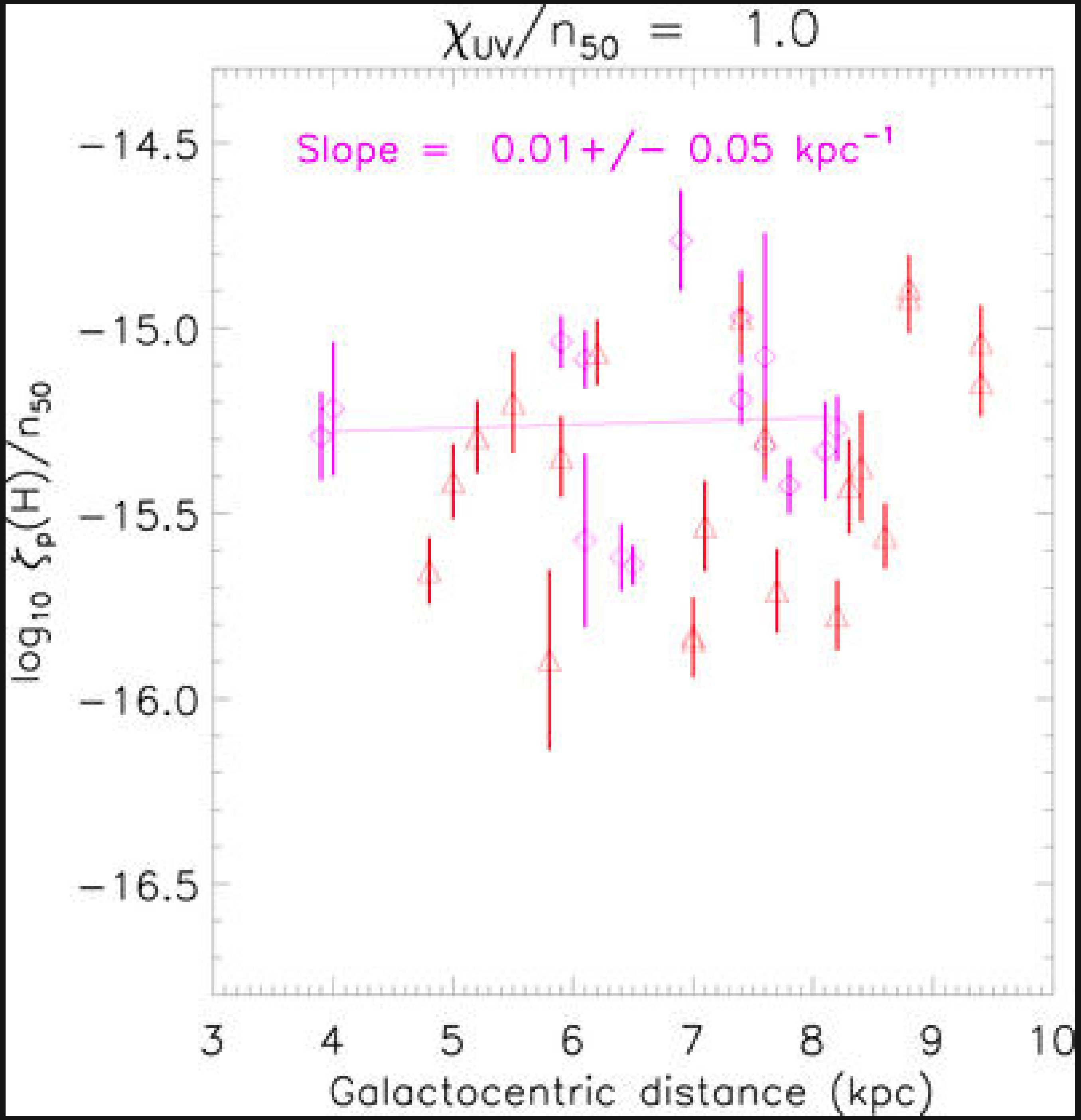


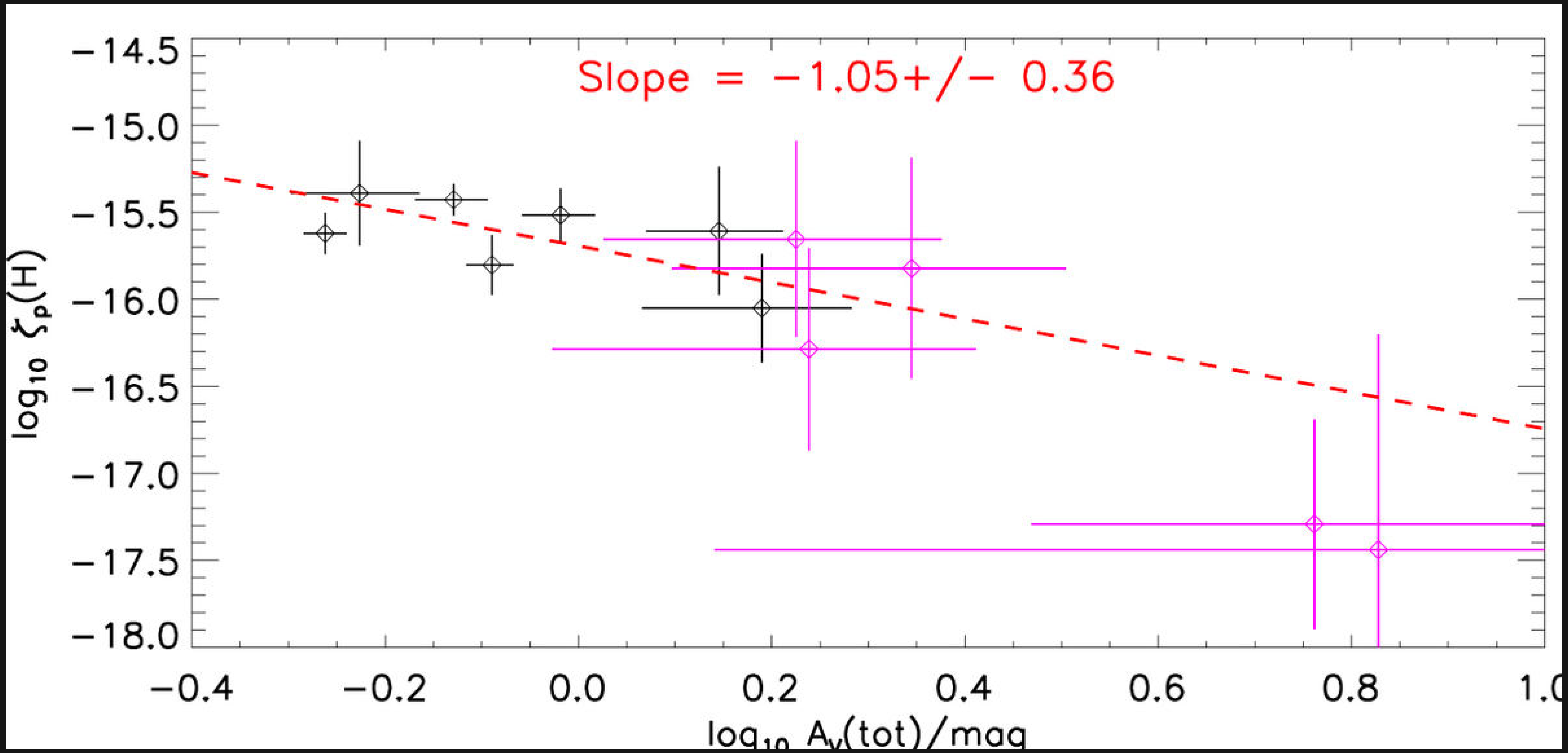
Taken from Jacob et al. (2020b)

Probing the cosmic-ray ionization rate

Ionization potentials of O (13.62 eV) and Ar (15.76 eV) > H (13.59 eV)

⟶ **ArH^+, OH^+, H_2O^+** formation can only be initiated by **cosmic-ray ionization**





Taken from Neufeld & Wolfire (2017)

HyGAL will provide better statistics to understand the nature of cosmic-ray ionization rates in different cloud environments

Synergetic data

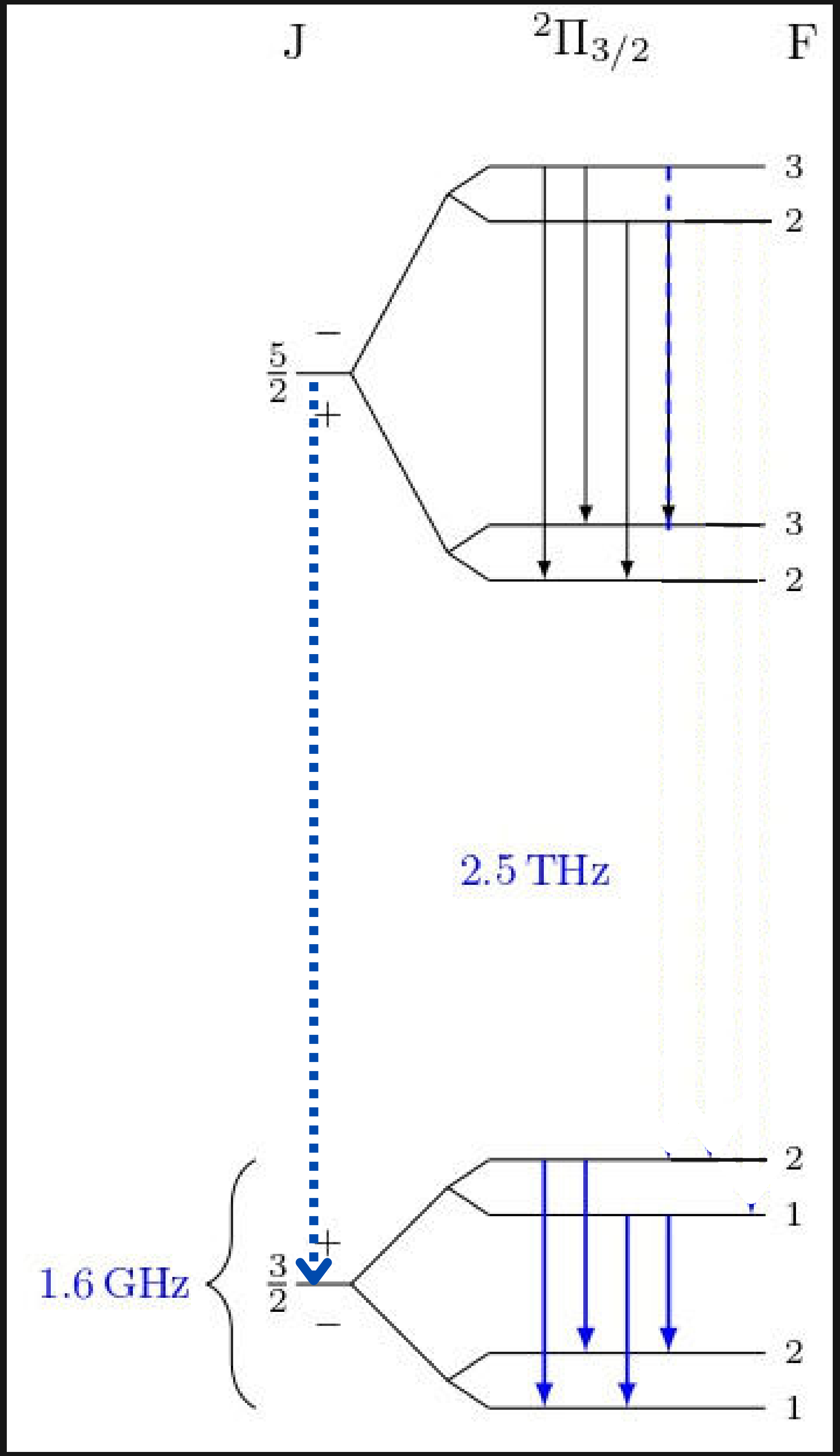
JVLA observations

- **HI absorption line** measurements ⟶ essential for **abundance estimates**
  (Michael Rugel et al. in prep)

- Hyperfine-structure transitions of the **OH ground state**

  Challenge: Anomalous excitation effects not well understood
  Solution : Radiative transfer modeling efforts constrained with
  * latest collisional rates
  * reliable OH column density measurements from SOFIA

  (Michael Busch et al. in prep)



Probing warm chemistry

Endothermic formation pathways of **SH, SH^+, H_2S and CH^+**

⟶ cannot be formed at low temperatures

Their large observed abundances suggest that they occupy warm ISM phases

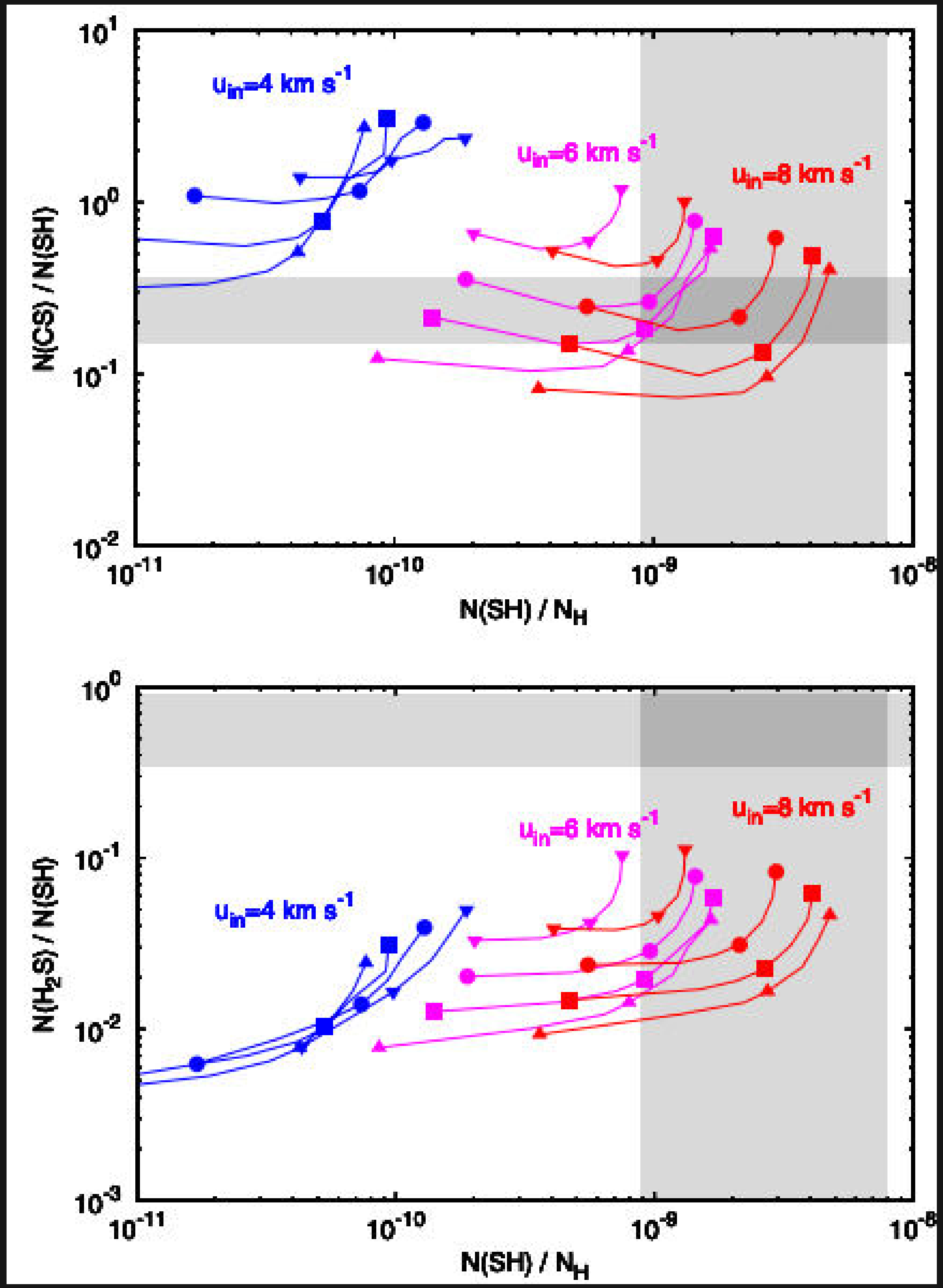
Synergetic observations with IRAM 30m telescope

3mm wavelength band

- CS, H_2S, SO_2, SO
- HCO^+, HCN, HNC, C_2H^+

(Wonju Kim et al. in prep)

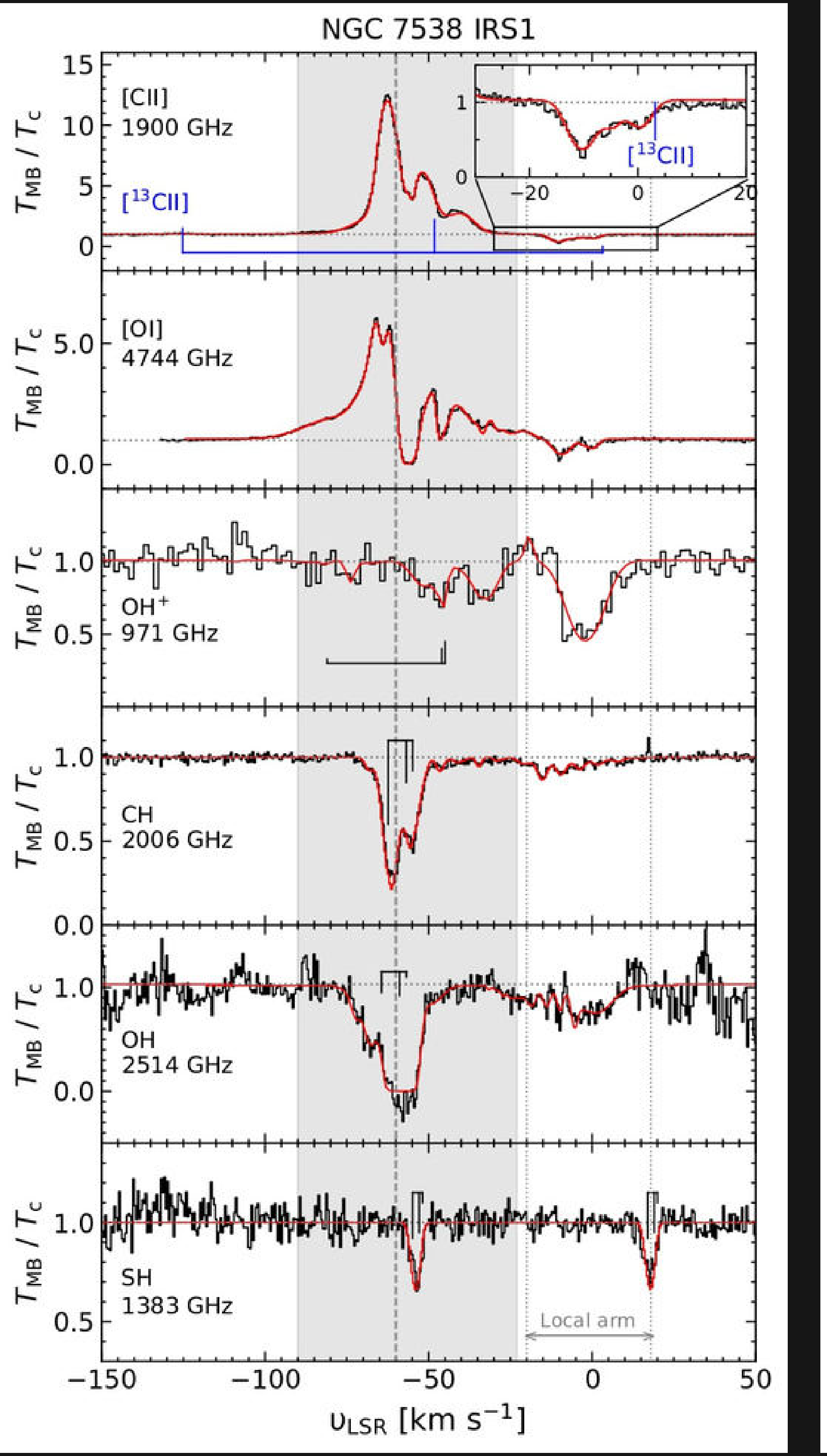
HyGAL will improve the interpretation of sulfur-bearing hydrides and sulfur chemistry in the diffuse and translucent ISM

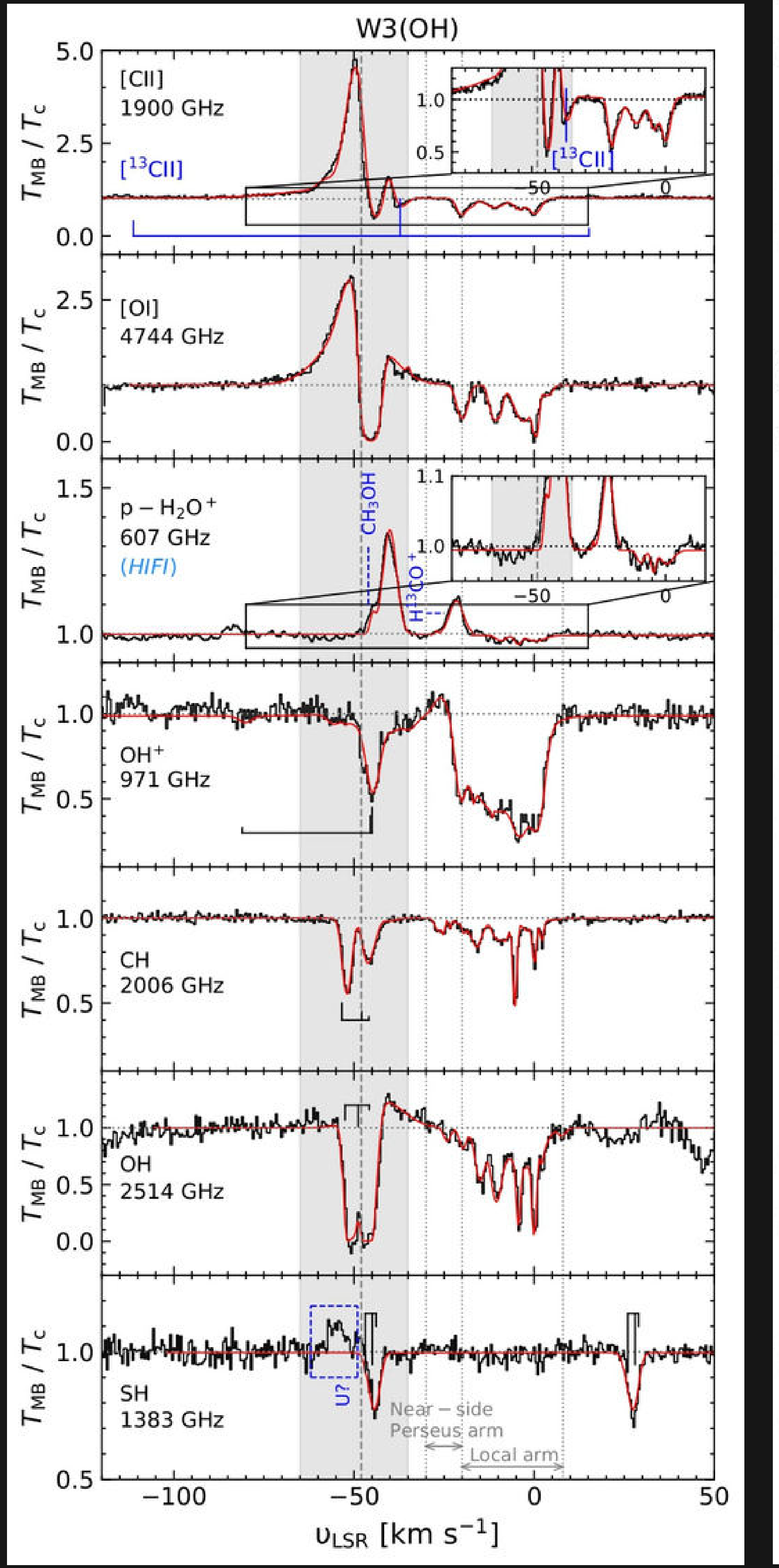


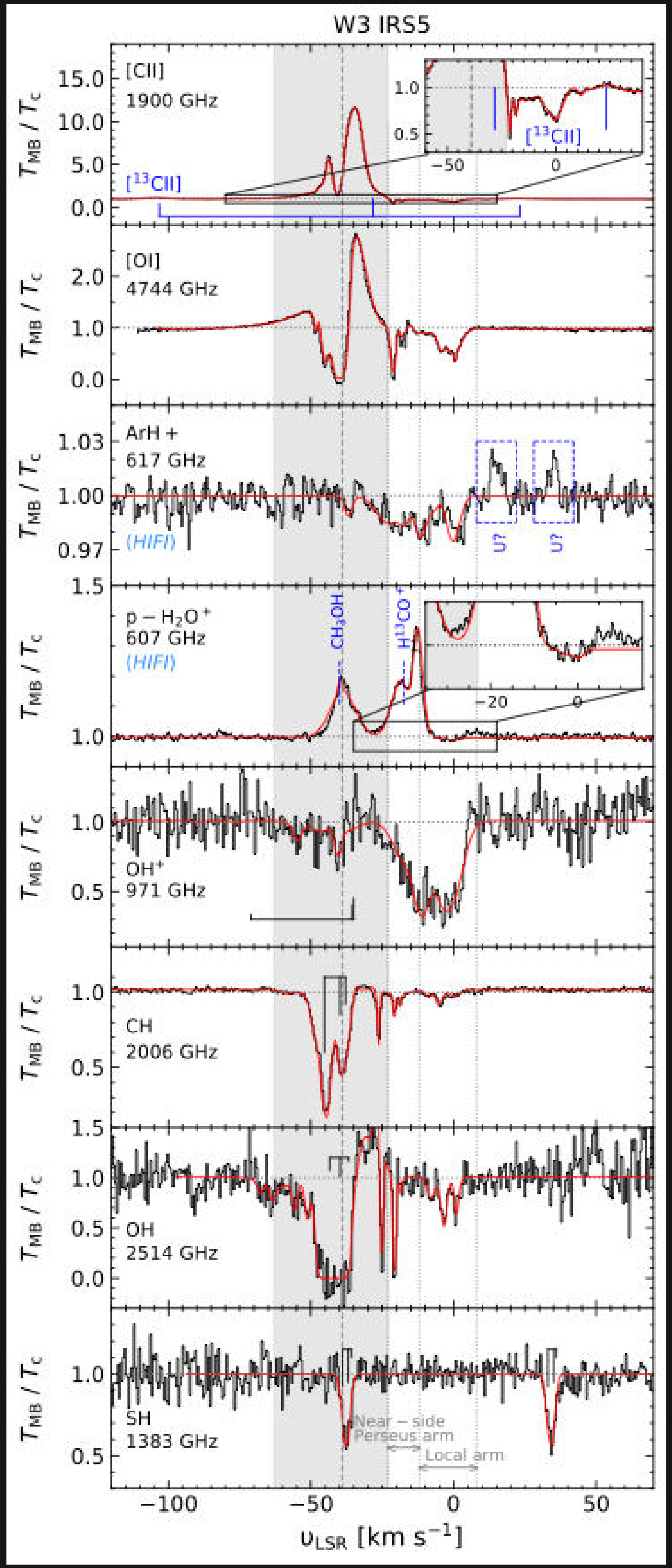
Taken from Neufeld et al. (2015)

First look at the data

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







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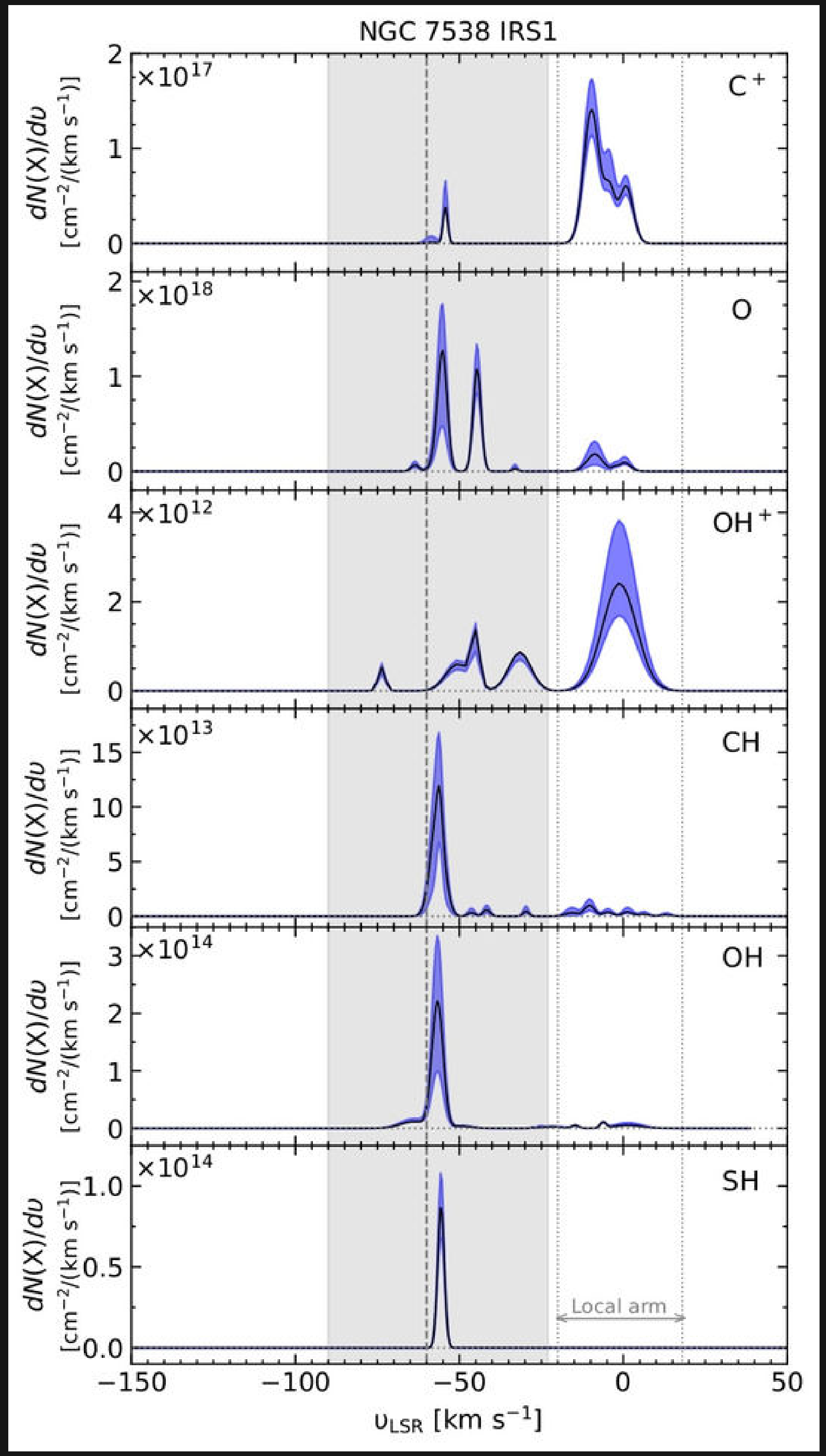
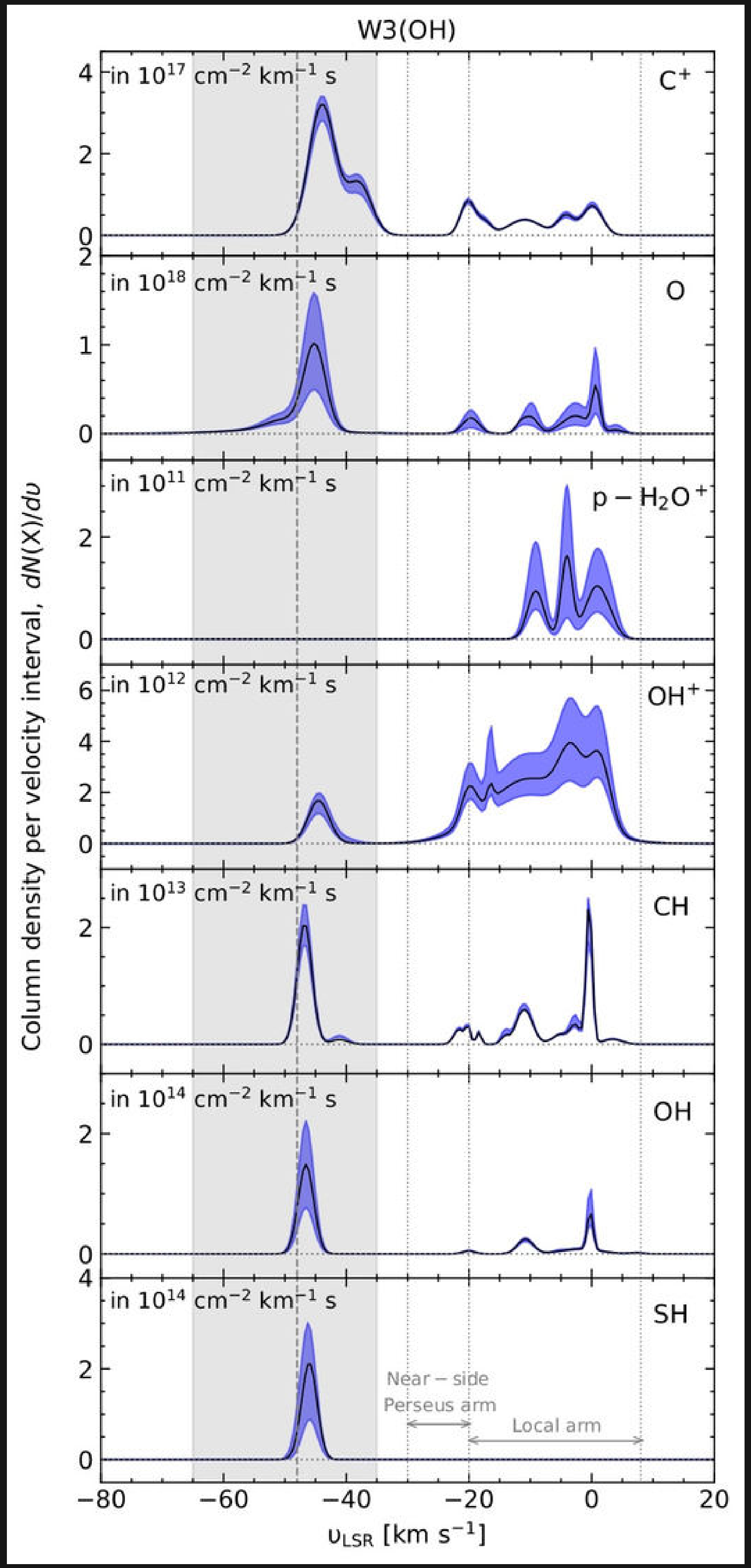
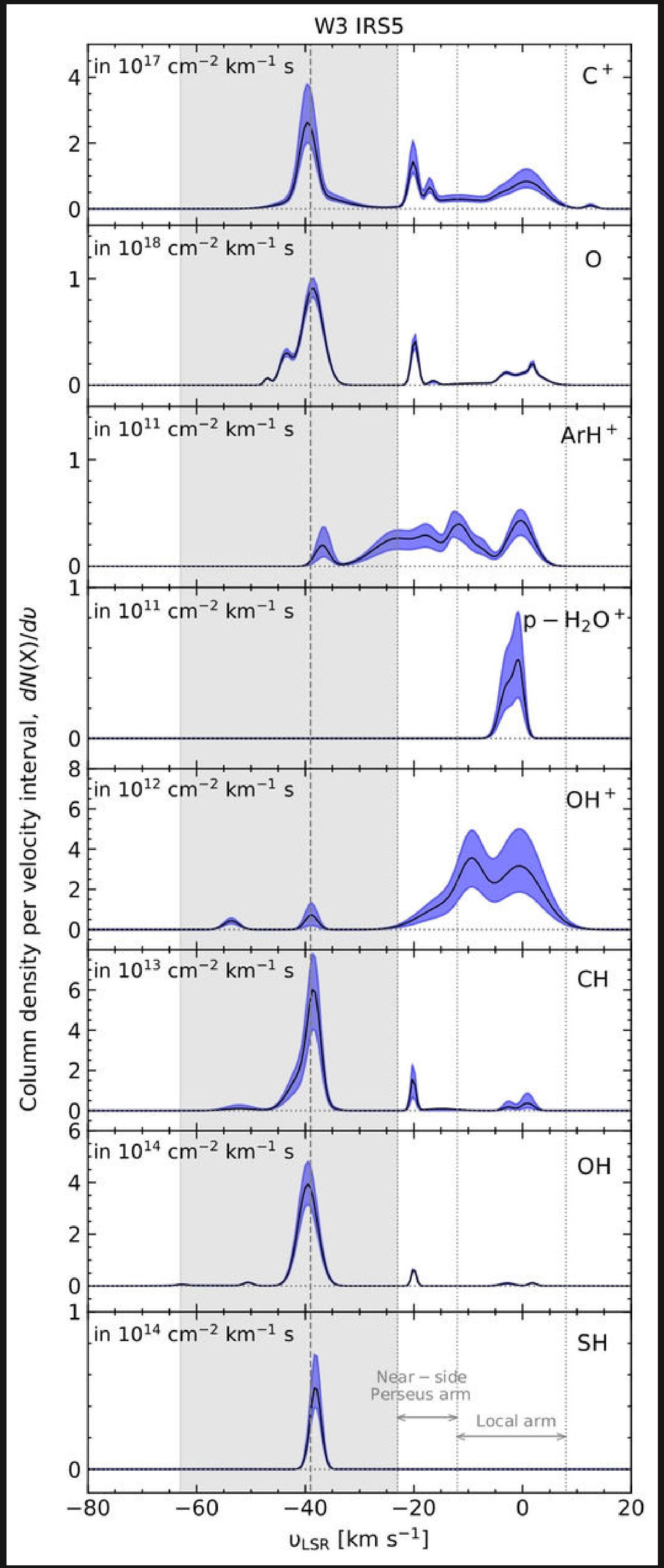


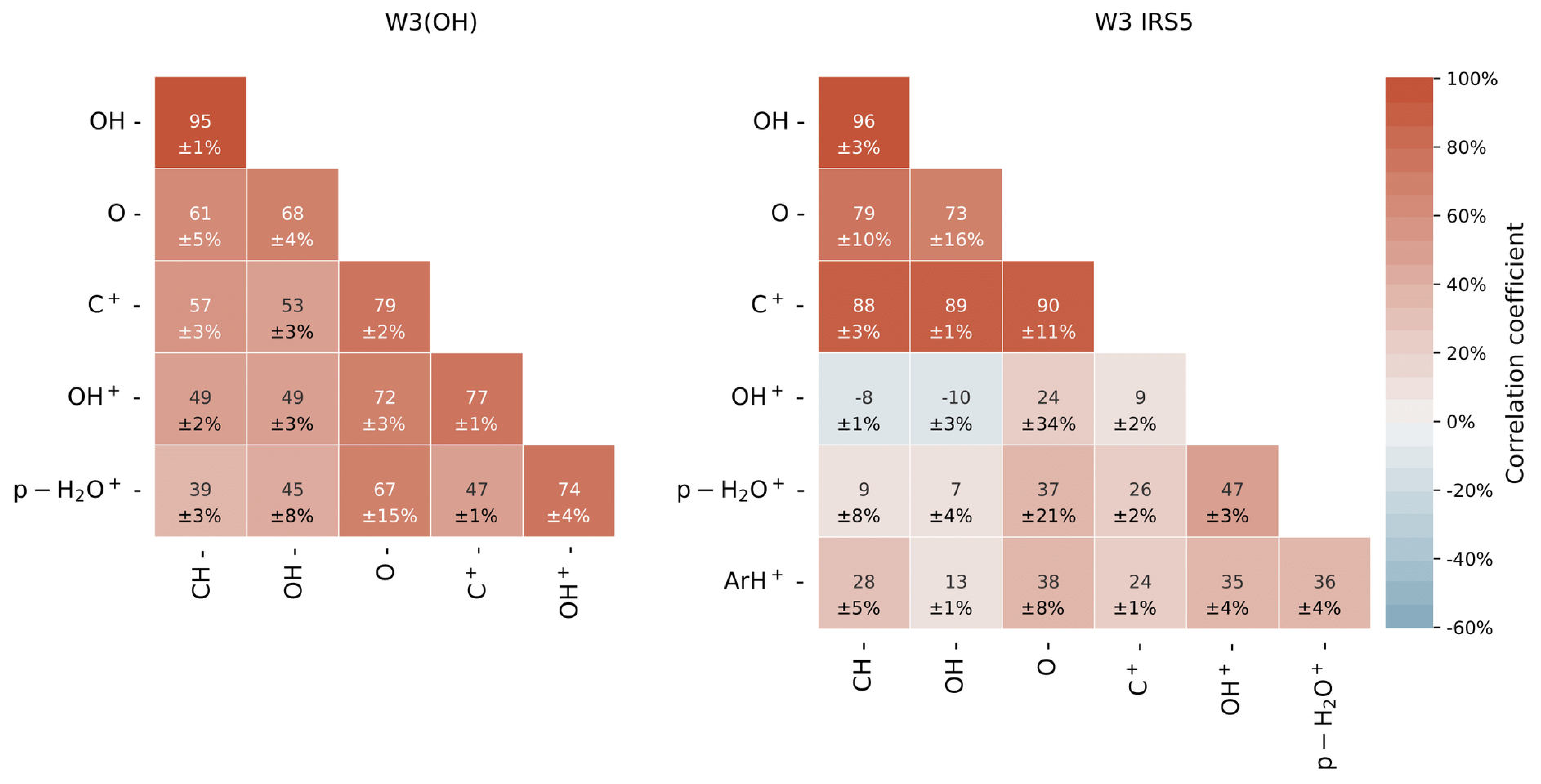




Line-of-sight properties

Cross-correlations

Pearson product-moment correlation coefficient



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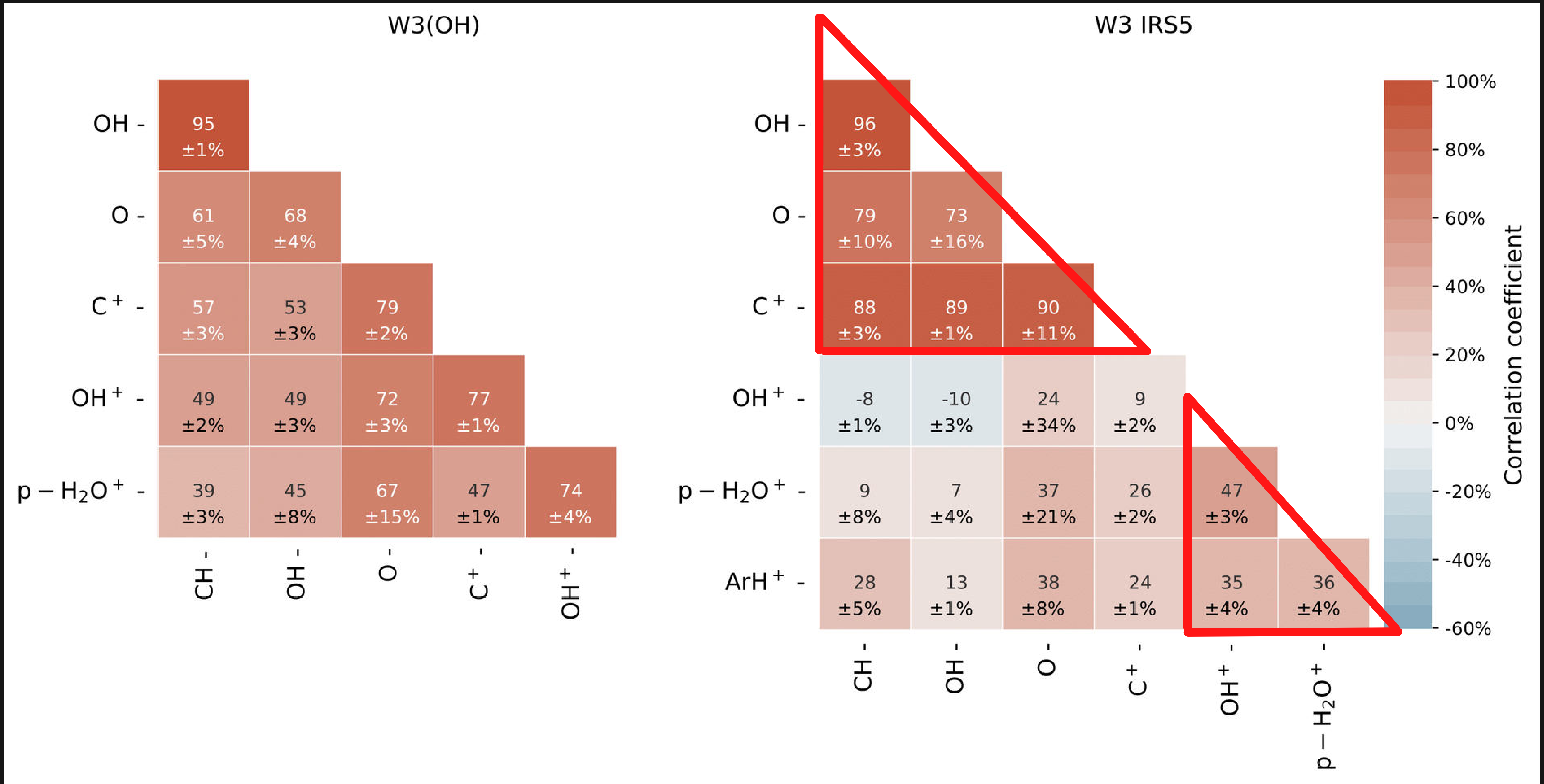
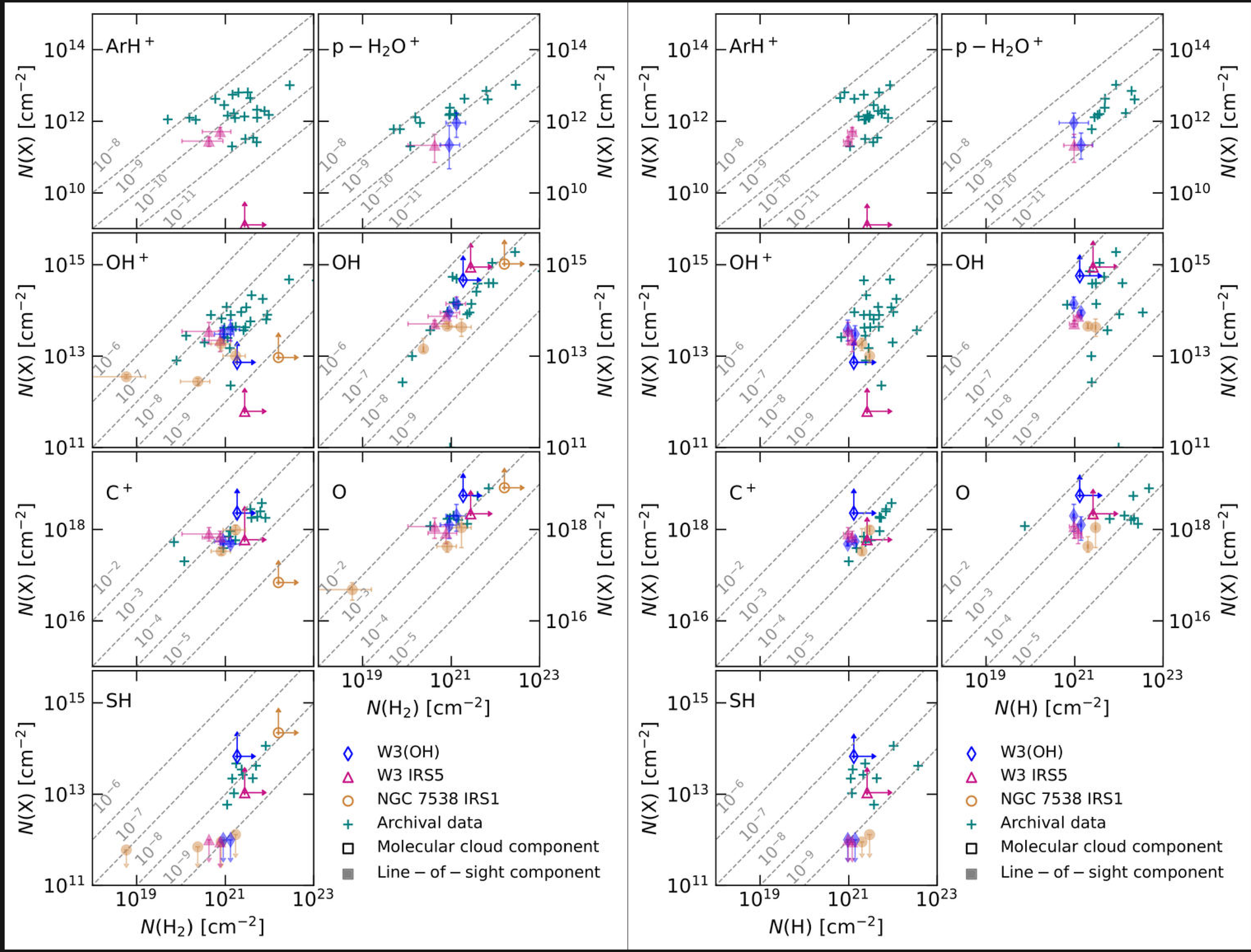


Line-of-sight properties

Column density ratios

- H_2 column densities derived from CH
  $N(CH)/N(H_2) = 3.5\times10^{-8}$
  (Sheffer et al. 2008)
- HI data extracted from CGPS
  (Taylor et al. 2003)



Line-of-sight properties

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)*

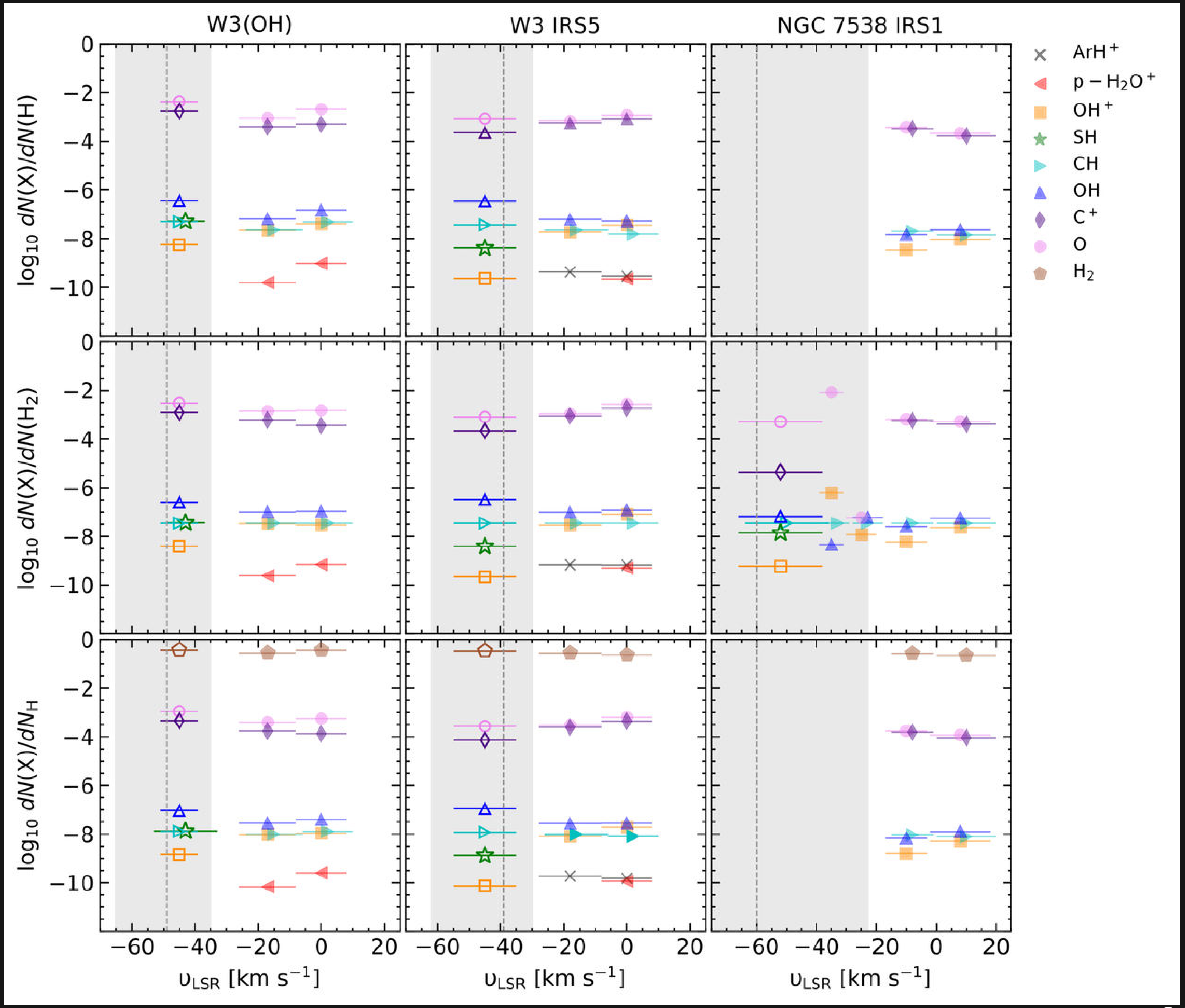
Supersonic turbulence

↓

Density fluctuations

↓

Variations in molecular abundances

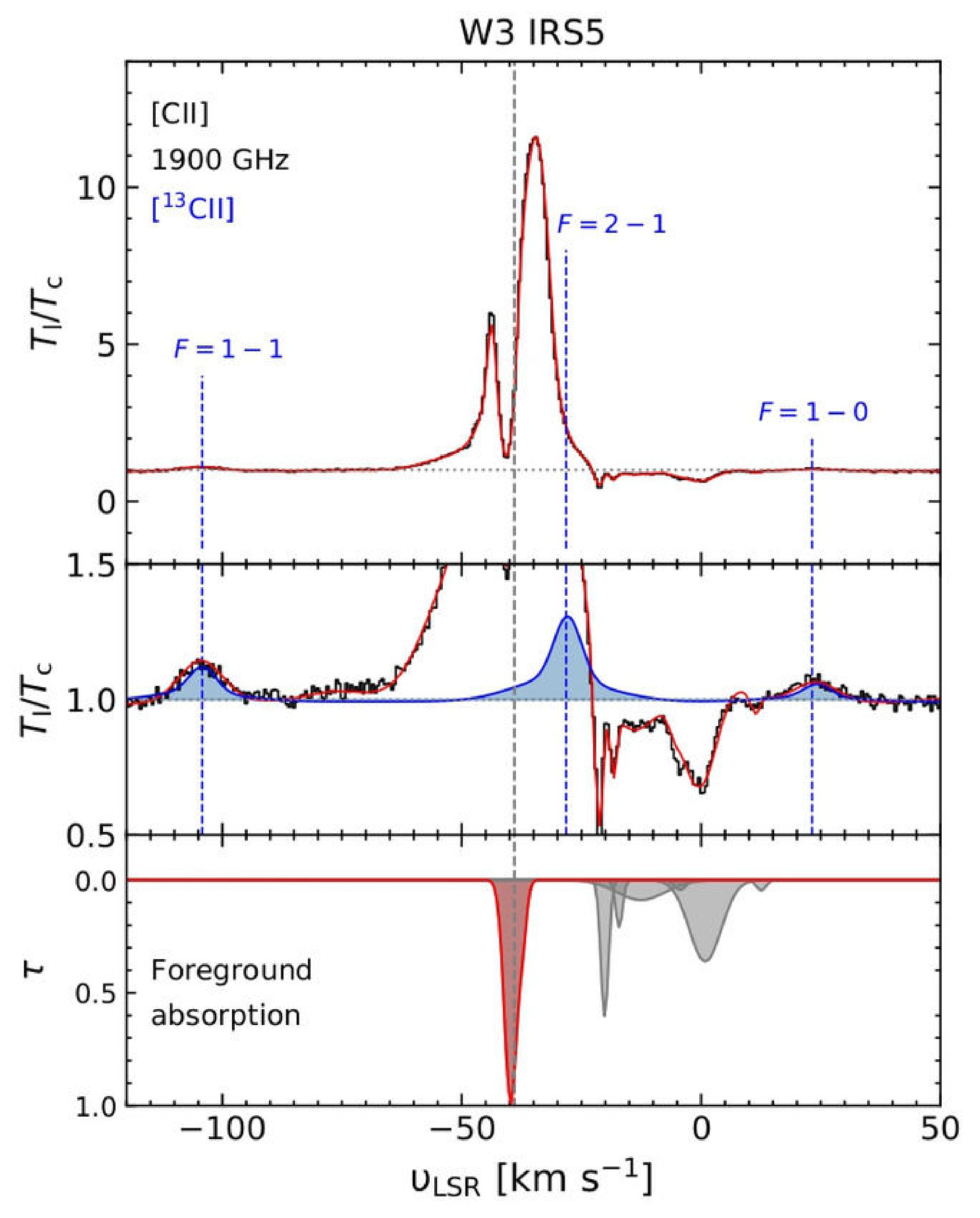


$^{12}C/^{13}C$ isotopic abundance

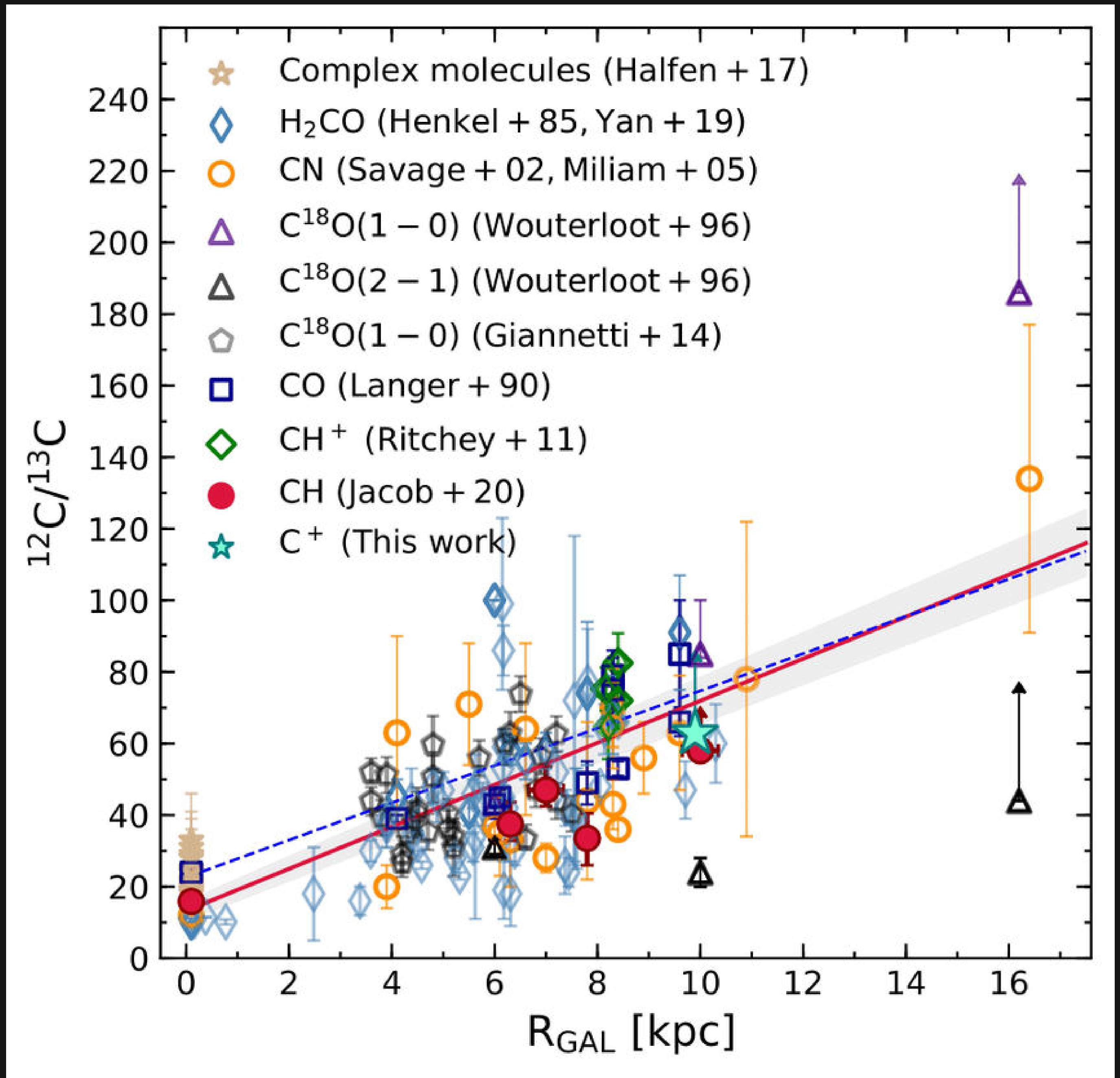
HyGAL also provides a wealth of information about the **background continuum source**

(See also my 2020 SOFIA tele-talk)

e.g., constraints on the $^{12}C/^{13}C$ ratio

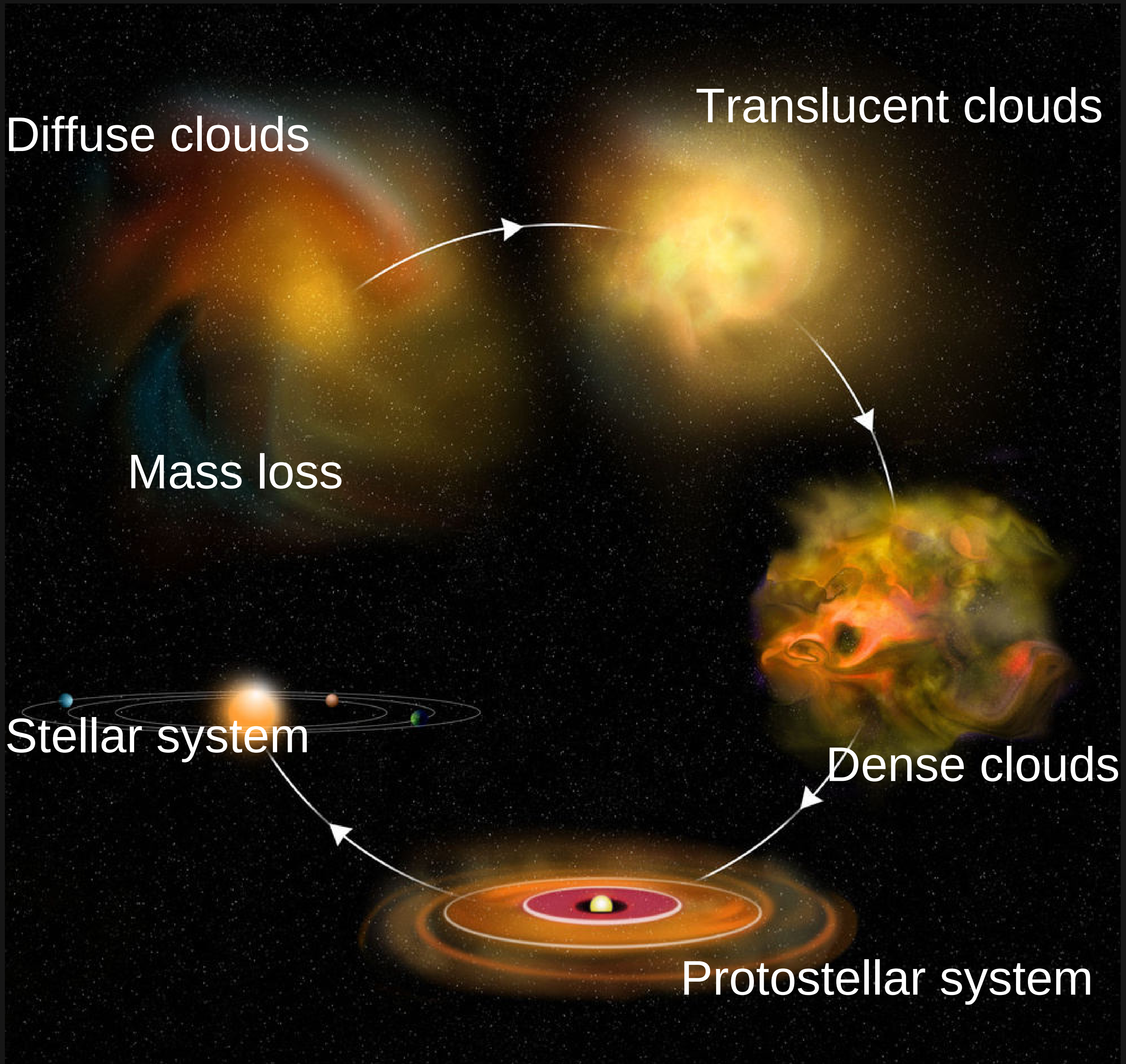


Combined XCLASS fit to both isotopes



Galactic gradient

Summary



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

HyGAL: Aims to address questions related to the formation of molecular clouds

- by observing different targeted hydrides with well established **diagnostic powers**
- using the unique capabilities and high resolution provided by **upGREAT** and **4GREAT** on SOFIA

Extending the analysis to the entire sample in combination with other data sets HyGAL will provide:

- a systematic investigation of the properties of **diffuse clouds** and
- a wealth of knowledge also about the **background sources**