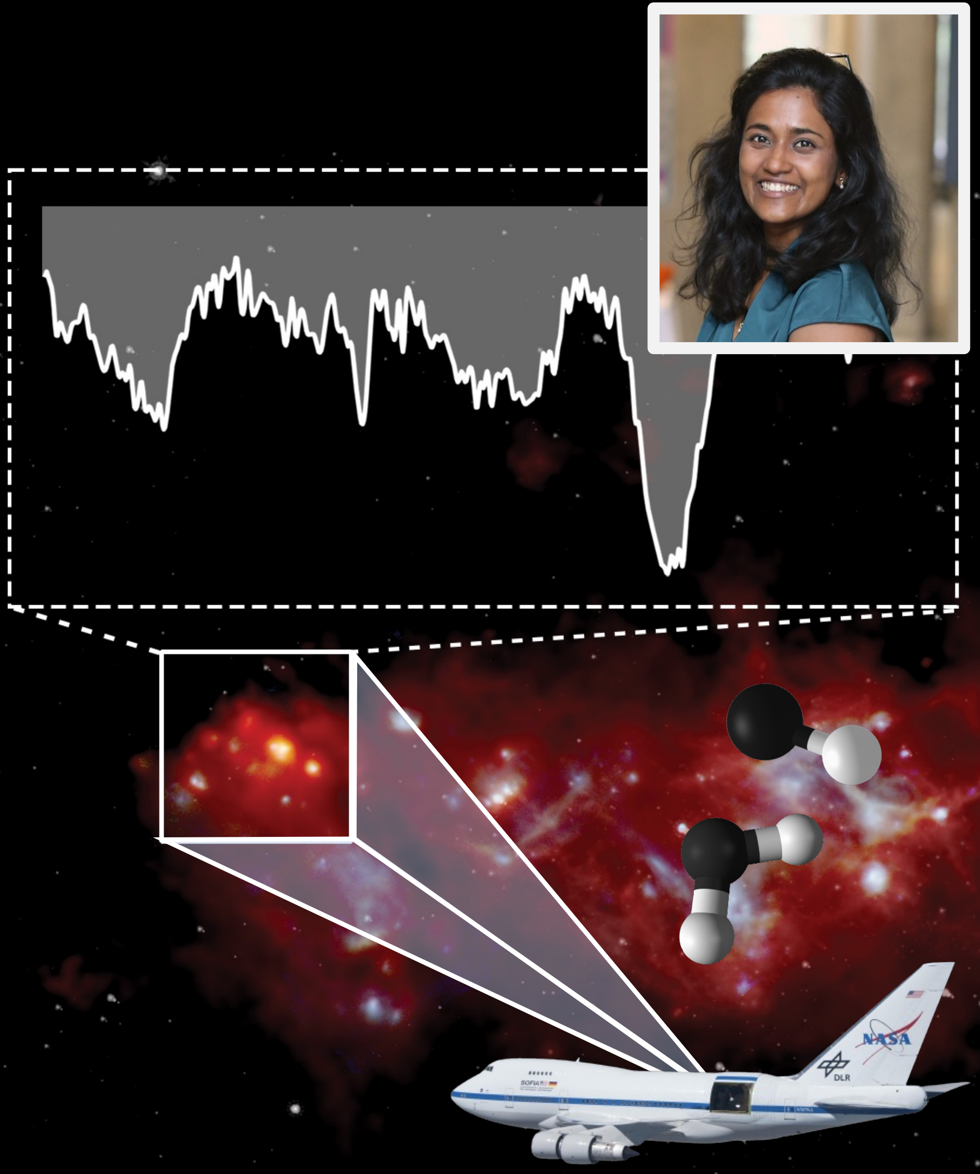
HyGAL and a series of other *GREAT* hydride observations

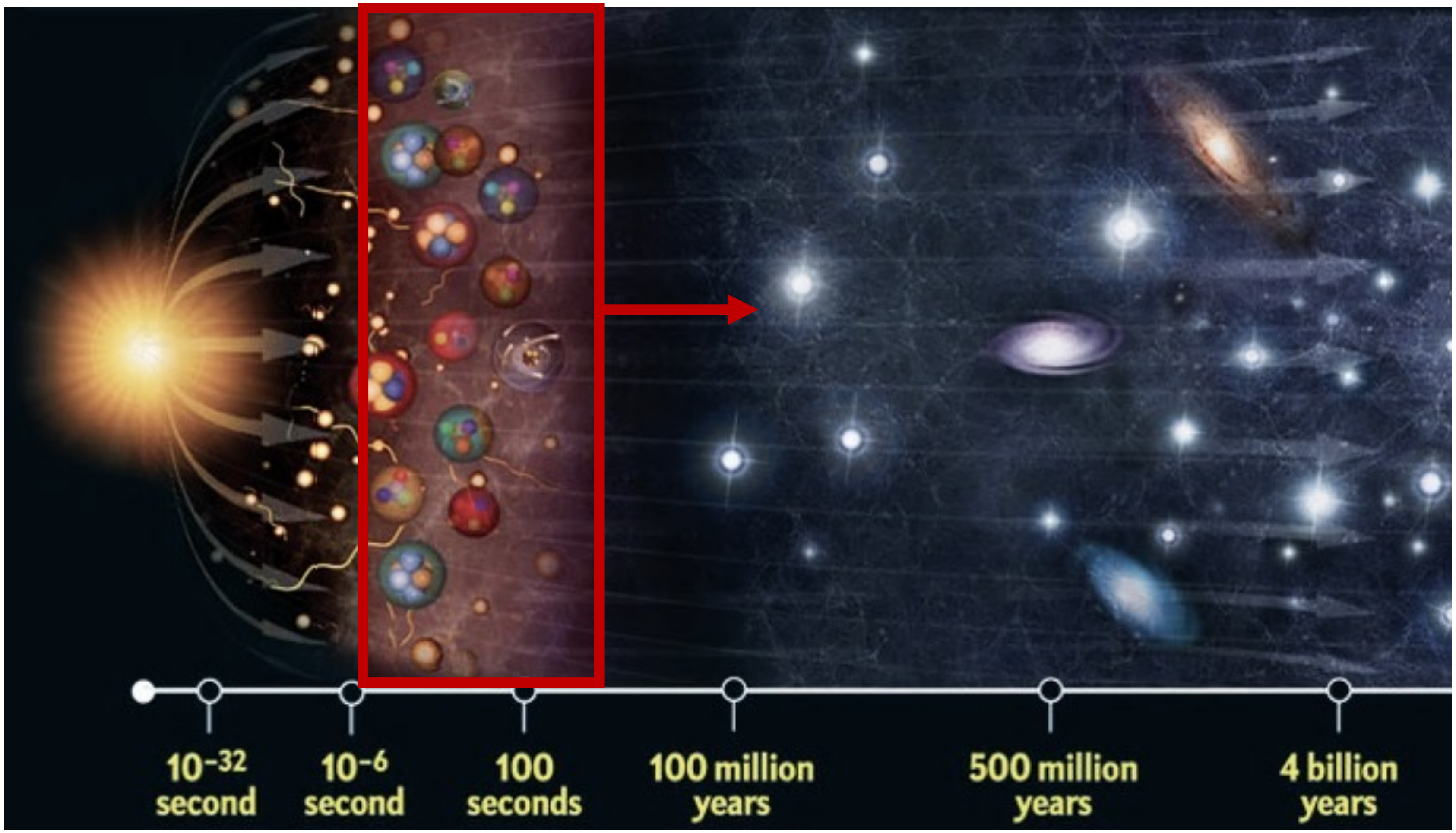
Arshia Maria Jacob
Johns Hopkins University, Max Plank Institute for Radio Astronomy
ajacob51@jhu.edu, ajacob@mpifr-bonn.mpg.de



SOFIA – Scientific Highlights and Future Perspectives
April 22nd – 26th, 2024

Background Image: ^{13}CH spectrum (Jacob+20) overlaid atop a composite infrared image of the Sgr B complex.
Credits: NASA/SOFIA/JPL-Caltech/ESA/Herschel

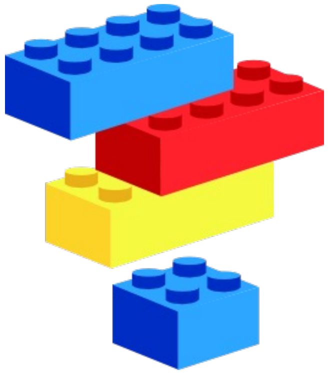
The molecular Universe



Schematic diagram of the history of the Universe.

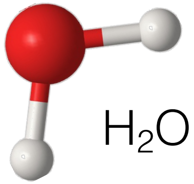
The formation of interstellar atoms and molecules in the Universe →

is a dramatic example of the emergence of *complexity*

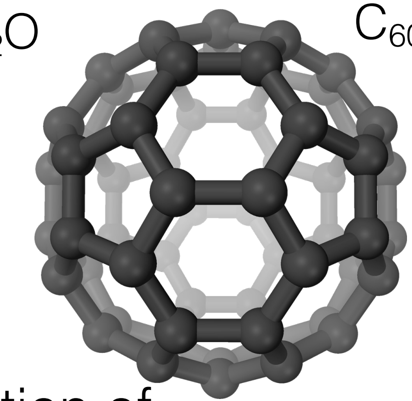


→ A rich chemistry operates particularly in the cooler regions of the interstellar medium (ISM).

Astro*chemistry*



H_2O



Fullerene C_{60}

Today -- over 290* molecules and molecular ions have been detected in the ISM

Careful interpretation of these interstellar molecules provides unique information of general astrophysical interest achieved using the combination of

Observations of astrophysical molecules

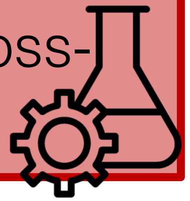
Emission line luminosities

Absorption line optical depths

Laboratory astrophysics and related theory

Spectroscopy, Collisional excitation rate coefficients, Reaction rate coefficients,

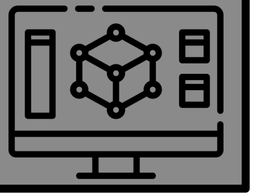
Photoionization and photodissociation cross-sections, …



Astrophysical Modelling

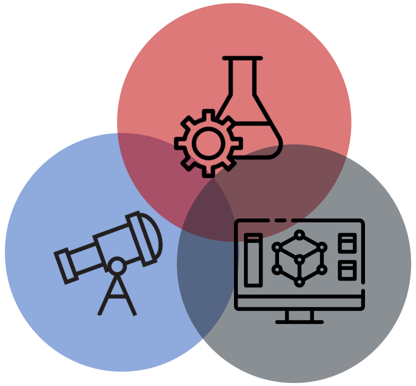
Physical and chemical conditions

Excitation and radiative transfer



*(*See McGuire 2021 -- present for a complete census)*

Astro*chemistry*



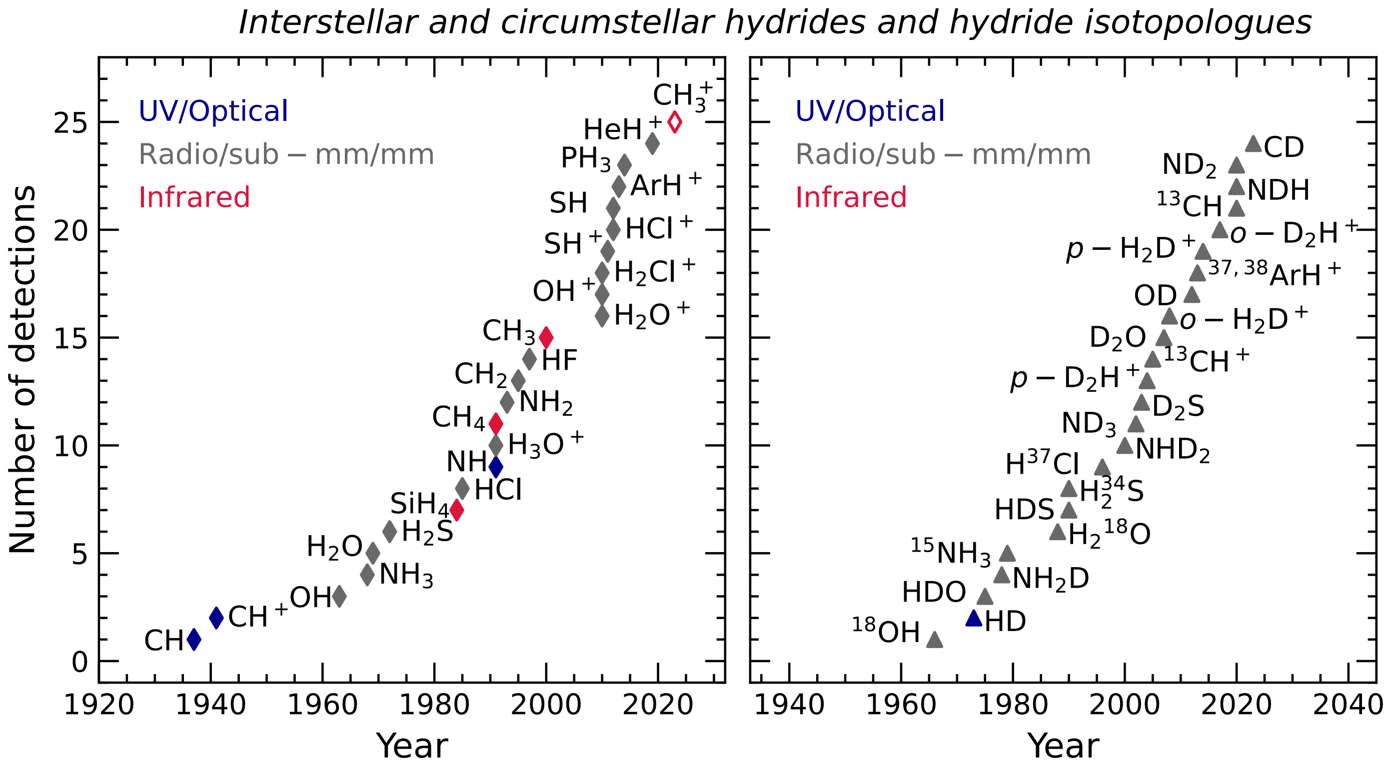
Small molecules have the greatest promise of extending our understanding of the ISM →

- Relatively well understood chemical pathways and
- Well-measured spectroscopic parameters
- Large abundances and are the building blocks for more complex species

Particularly **light hydrides**!!

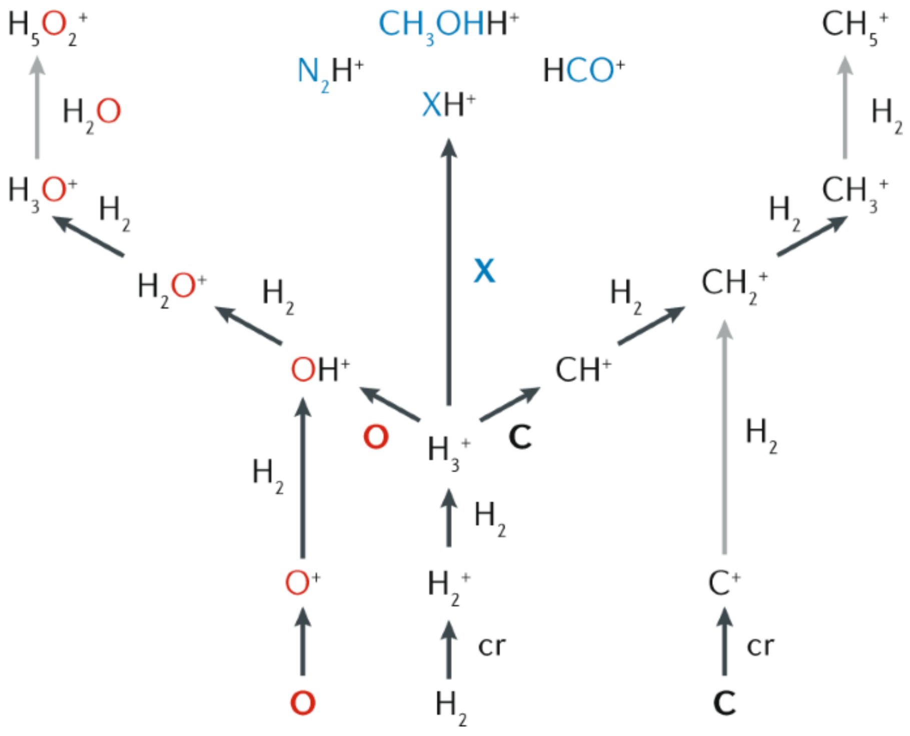
Hydrides

XH_n , XH_n^+: Reservoir for heavy elements



Taken from Jacob 2023b.

Fundamental building blocks of interstellar chemistry

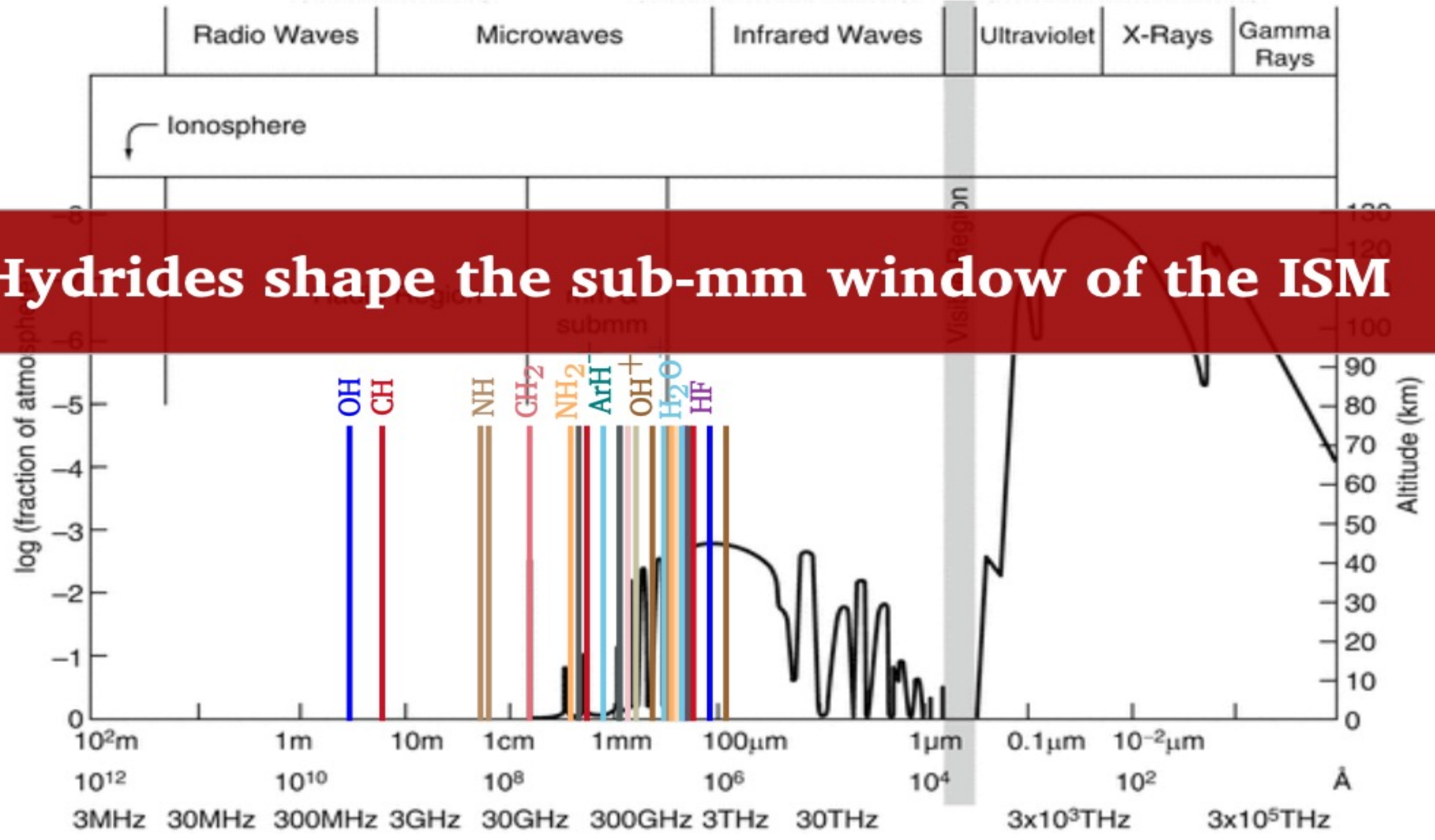


Taken from McGuire et. al 2020.

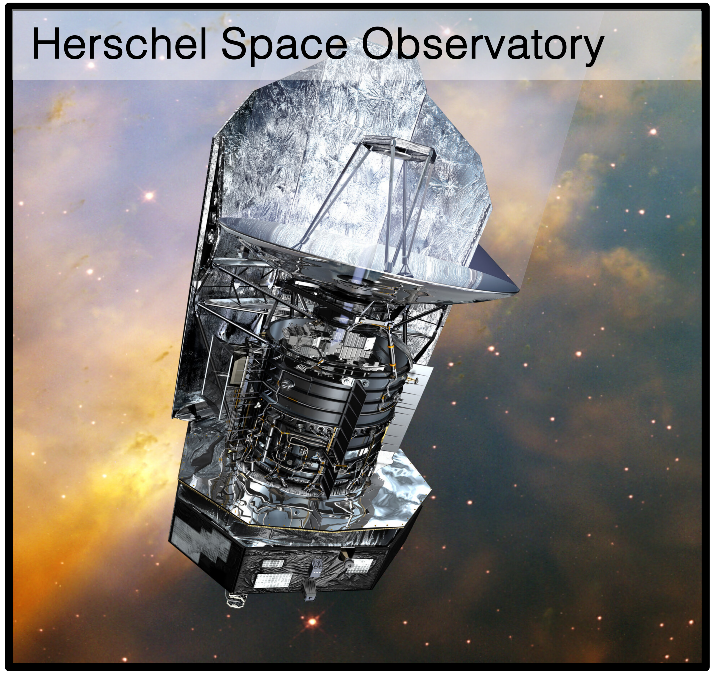
Renewed interests in Hydrides

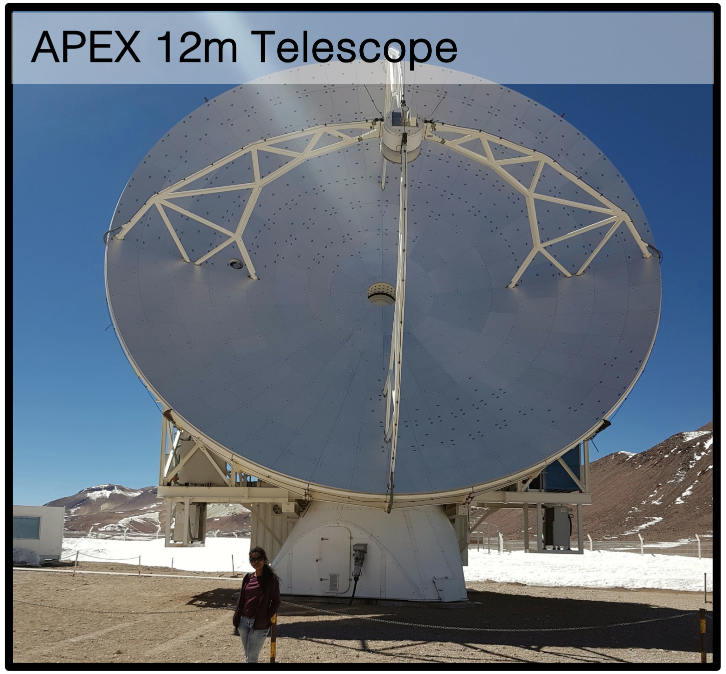
- Since they are small molecules → widely spaced energy levels
  → Fundamental rotational transitions lie at sub-mm and FIR wavelengths
- Advancements in (heterodyne) receiver technology

Hydrides shape the sub-mm window of the ISM



Renewed interests in Hydrides





<u>Several hydride discoveries</u>

For example:

H_2Cl^+ Lis et al. 2010

H_2O^+ Ossenkopf et al. 2010

OH^+ Wyrowski et al. 2010

SH^+ Menten et al. 2011

HCl^+ De Luca et al. 2012

ArH^+ Barlow et al. 2013, Schilke et al. 2014

Detailed modeling of absorption line spectra (e.g., PRISMAS, WISH, HEXOS) have led to the establishment of specific hydrides as diagnostic probes of different phases and processes in the ISM.

Absorption line spectroscopy

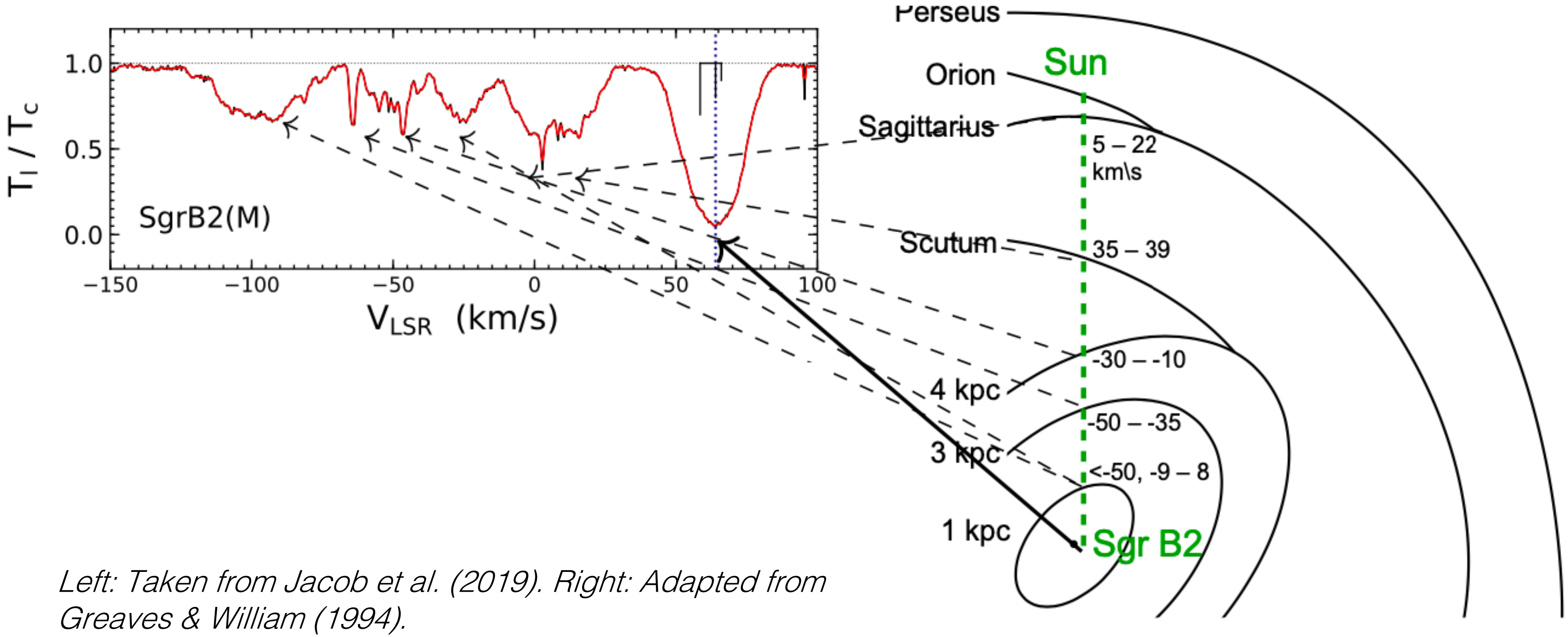
<u>Robust tool for measuring column densities</u>

optical depth

→ $T_l/T_C \propto \tau \propto N$

line-to-continuum ratio   column density

e.g., SOFIA CH 2THz spectrum toward Sgr B2 (M)



Left: Taken from Jacob et al. (2019). Right: Adapted from Greaves & William (1994).

Galactic Tomography!

Absorption line spectroscopy

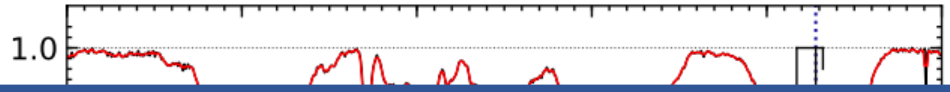
<u>Robust tool for measuring column densities</u>

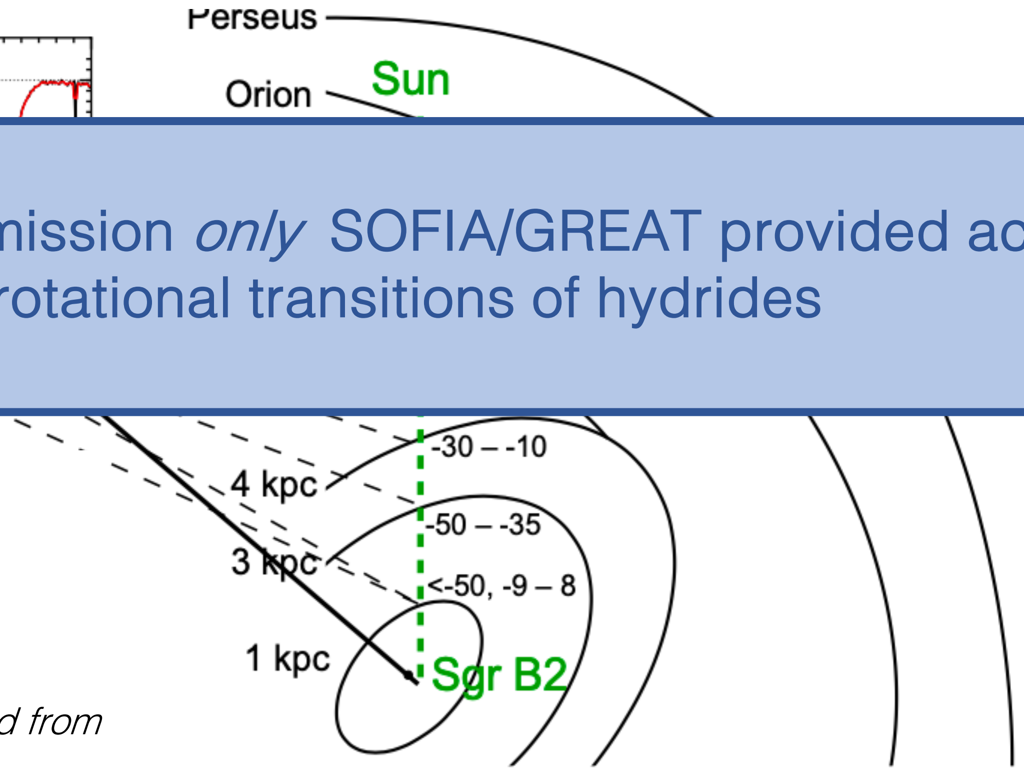
optical depth

$\rightarrow \mathrm{Tl/Tc} \;\propto\; \tau \;\propto\; N$

line-to-continuum ratio — column density

e.g., SOFIA CH 2THz spectrum toward Sgr B2 (M)



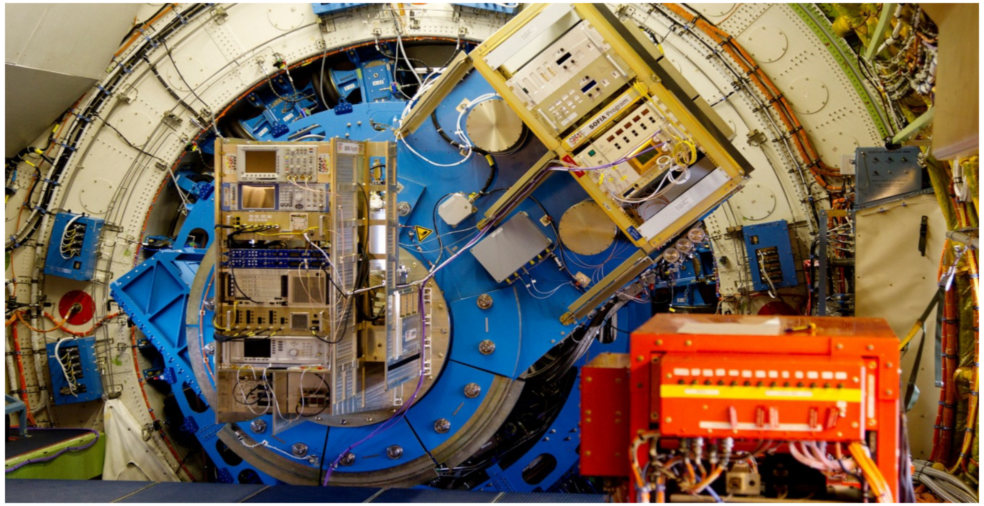


With the end of the Herschel mission *only* SOFIA/GREAT provided access to the high-lying rotational transitions of hydrides

Left: Taken from Jacob et al. (2019). Right: Adapted from Greaves & William (1994).

Galactic Tomography!

SOFIA/GREAT observations



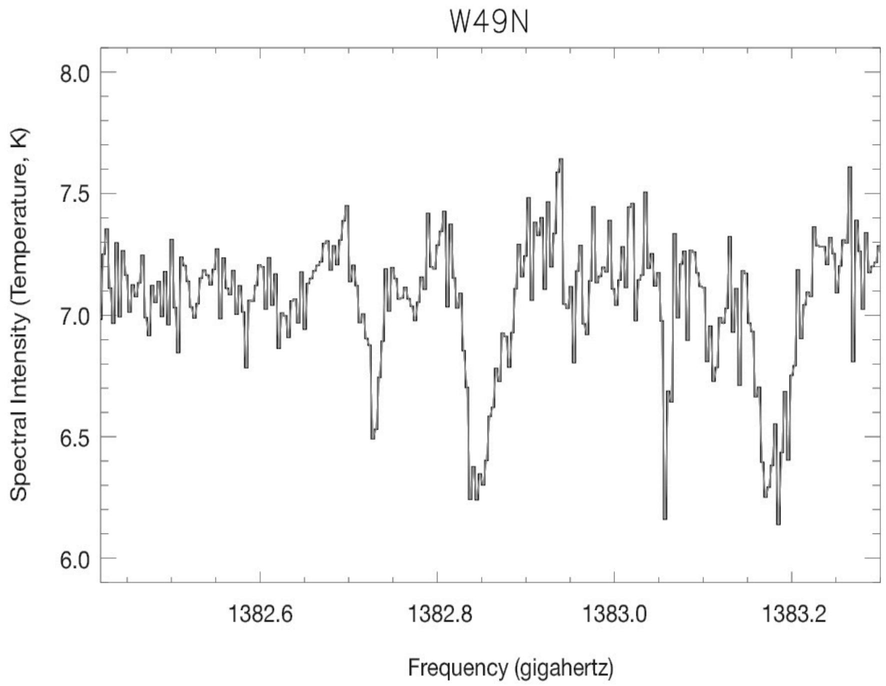
German Receiver for Astronomy at Terahertz frequencies

High resolution, heterodyne instrument
→ Can observe hydride transitions in every channel!

Channels	Frequency Range [THz]	T_{rec} Double Sideband	FWHM	Astronomical Lines of Interest
upGREAT HFA	4.7447 +/– 100 km/s	1250 K	6"	[OI]
upGREAT LFA-H	1.835–2.007	1000 K	15"	[CII], CO, $OH\,^2\pi_{1/2}$
upGREAT LFA-V	1.835–2.007 2.060–2.065	1000 K	15"	[OI], [CII], CO, $OH\,^2\pi_{1/2}$
4GREAT	2.490–2.590	3300 K	12"	$OH\,^2\pi_{3/2}$, $^{18}OH\,^2\pi_{3/2}$
	1.240–1.395 1.427–1.525	1100 K	19"	[NII], CO, OD, HCN, SH, H_2D^+
	0.890–0.984 0.990–1.092	>600 K 300 K	25"	CO, CS
	0.491–0.555 0.560–0.635	<150 K	50"	NH_3, [CI], CO, CH

SOFIA/GREAT hydride discoveries

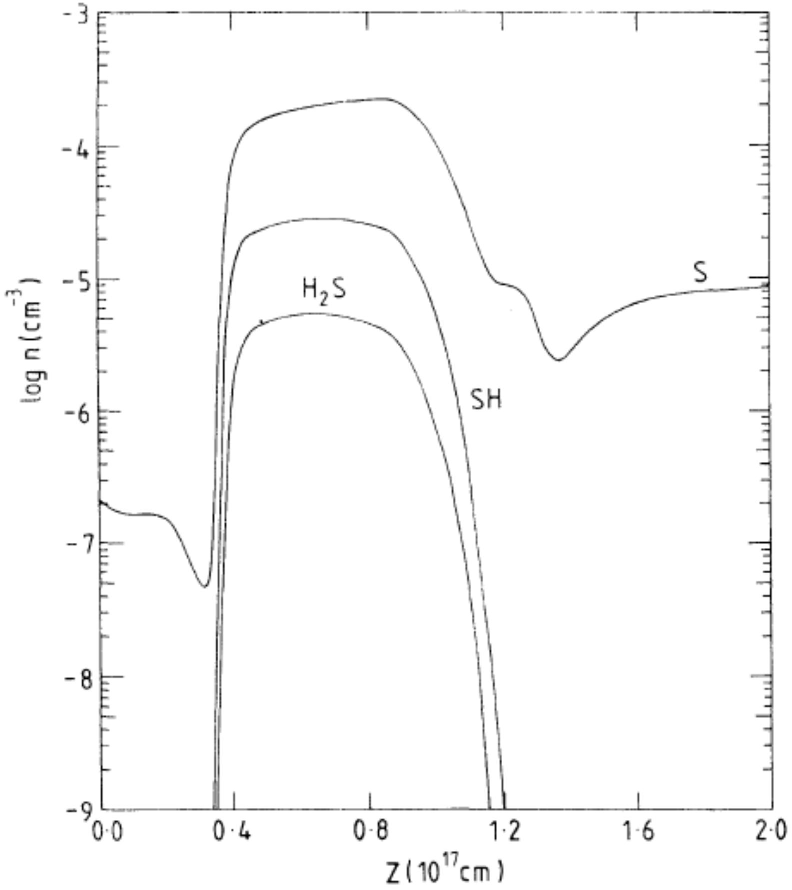
SH at 1383 GHz
(Neufeld et al. 2012)



S^+ nor S can react exothermically with H_2, with endothermicities of 10^4K

But SH^+ and SH are observed in large abundances!

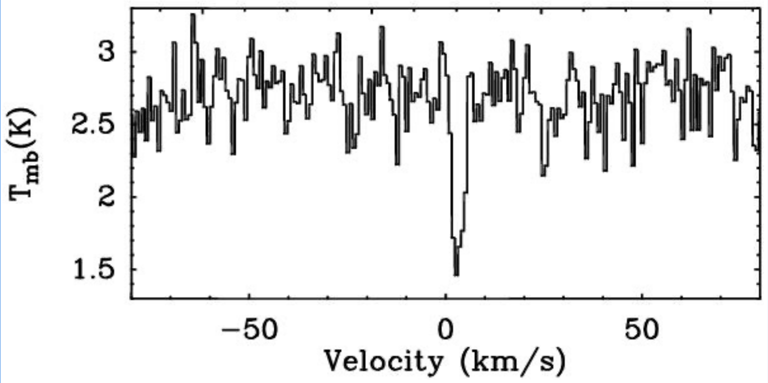
→ evidence for elevated temperatures or ion-neutral drift in material affected by shocks or the dissipation of turbulence



Pineau des Forets et al. (1986)

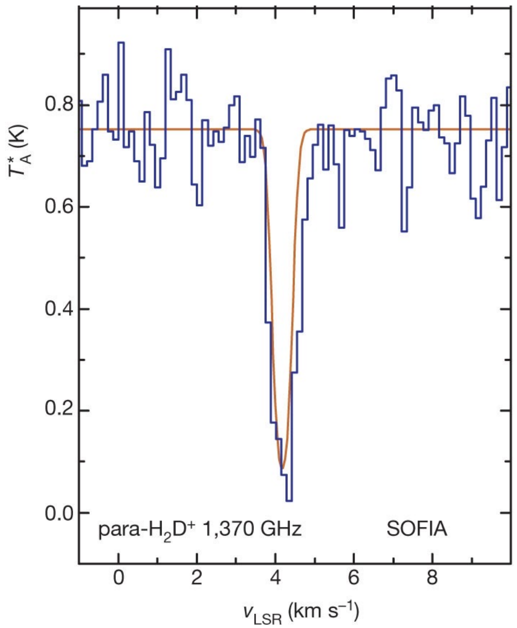
SOFIA/GREAT hydride discoveries

OD at 1319.5 GHz (Parise et al. 2012)



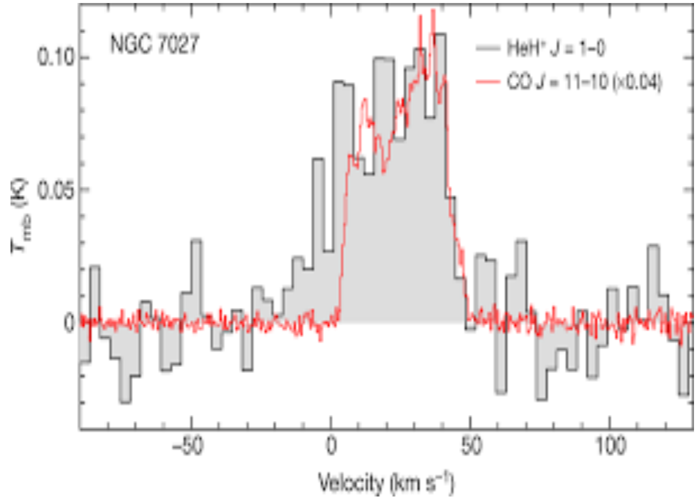
OD formed via (OH + D) can help **constrain the formation of H_2O**

H_2D^+ at 1370 GHz (Brünken et al. 2014)



Probes the **age** of a system → ortho-/para- ratio

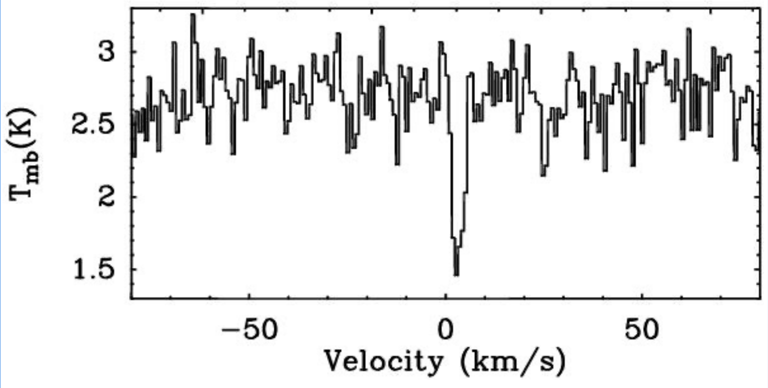
HeH^+ at 2.01 THz (Güsten et al. 2019)



Discovery of the **first molecule formed** in space! Constraints on chemistry in the Early Universe

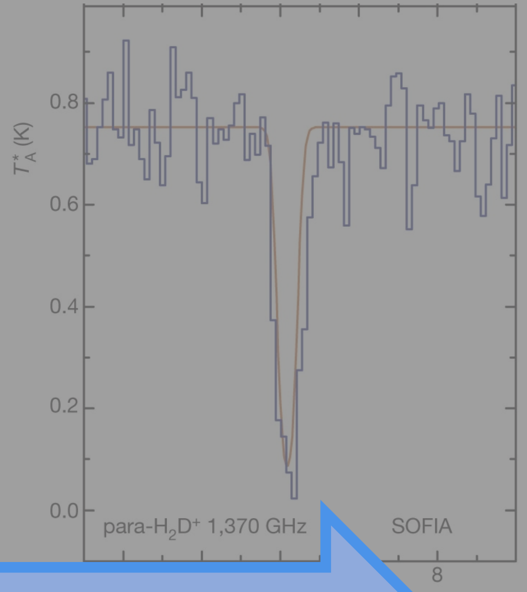
SOFIA/GREAT hydride discoveries

OD at 1319.5 GHz (Parise et al. 2012)



OD formed via (OH + D) can help **constrain the formation** of H_2O

H_2D^+ at 1370 GHz (Brünken et al. 2014)



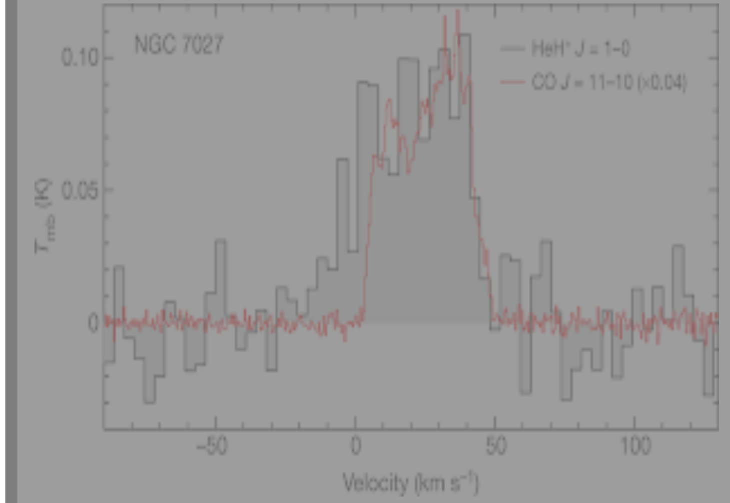
a system

→ ortho-/pa a- ratio

See Karl Menten's talk

See Helmut Wiesemeyer's talk

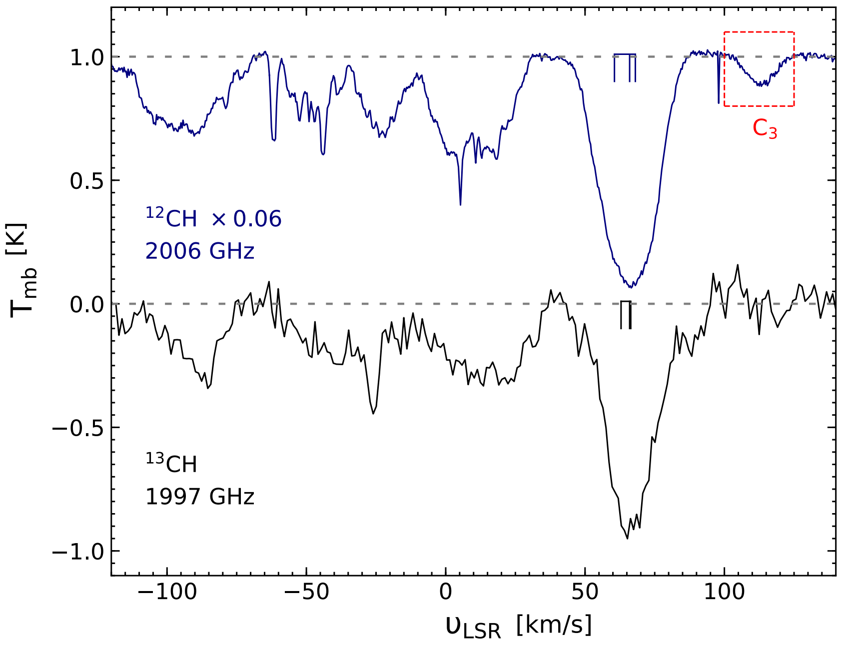
HeH^+ at 2.01 THz (Güsten et al. 2019)



Discovery of the **first molecule formed** in space! Constraints on chemistry in the Early Universe

SOFIA/GREAT hydride discoveries

^{13}CH at 1997 GHz
(Jacob et al. 2020)



CH has a tight correlations with H_2 →
important molecular gas tracer

See Wonju Kim's talk

Sheffer et al. 2008 ($[CH]/[H_2] = 3.5 \times 10^{-8}$)

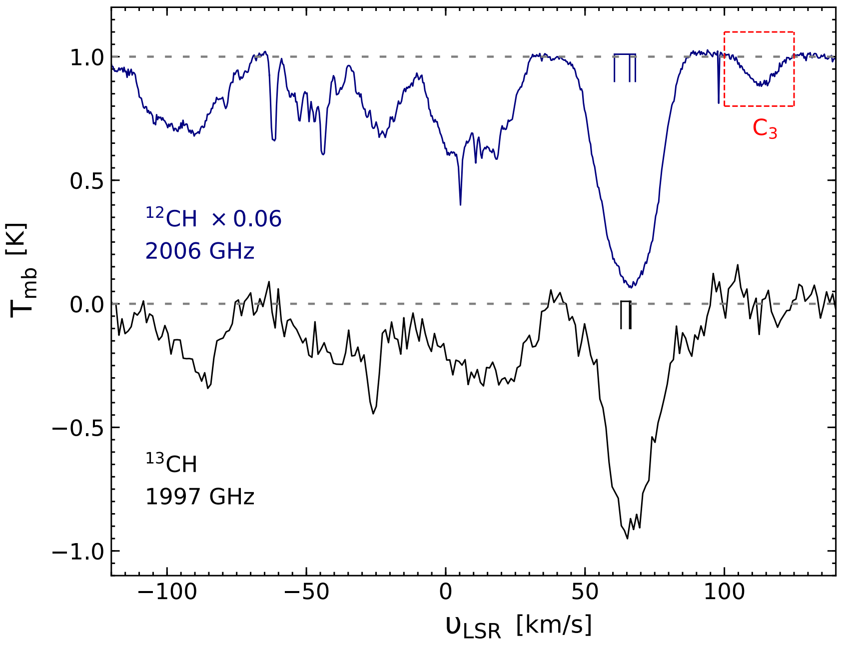
Primary product of nucleosynthesis
Formed from the first stars

$$\frac{^{12}C}{^{13}C}$$

Secondary product of nucleosynthesis
Formed from enriched stars as a by-product of the CNO cycle

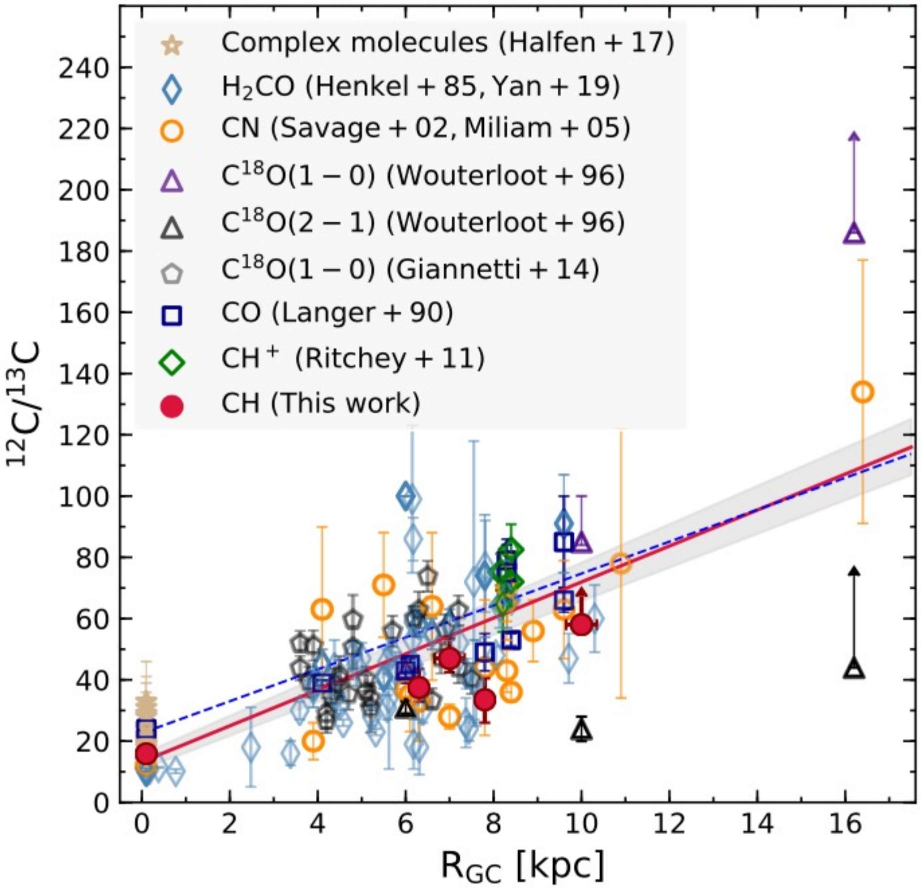
SOFIA/GREAT hydride discoveries

^{13}CH at 1997 GHz (Jacob et al. 2020)



No fractionation effects → $^{12}CH/^{13}CH$ unbiassed probe of $^{12}C/^{13}C$ ratio

$$^{12}C/^{13}C = 5.87(0.45)R_{GC} + 13.25(2.94)$$



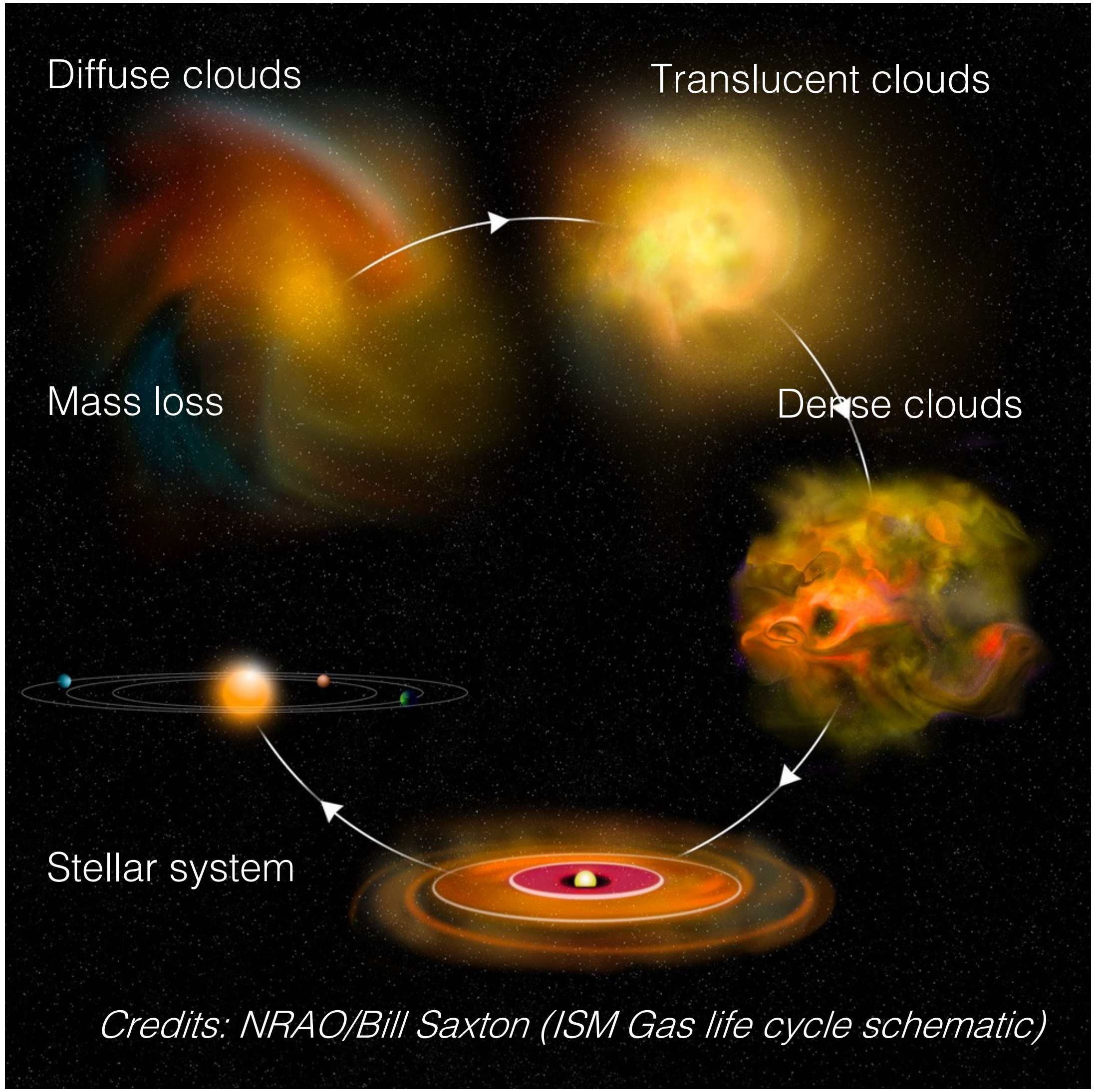
- Places constraints on **galactic evolution models**
- Chemical link to study **isotopic enhancements in large and complex interstellar** molecules

HyGAL – "Hydrides in the GALaxy"

Characterize the diffuse Galactic ISM with observations of hydrides and other small molecules

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

W.-J. Kim, A. Sternberg, 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. Sańchez-Monge, R. Higgins, E. Falgarone, P. Hennebelle, S. Molinari, A. M. Jacob



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

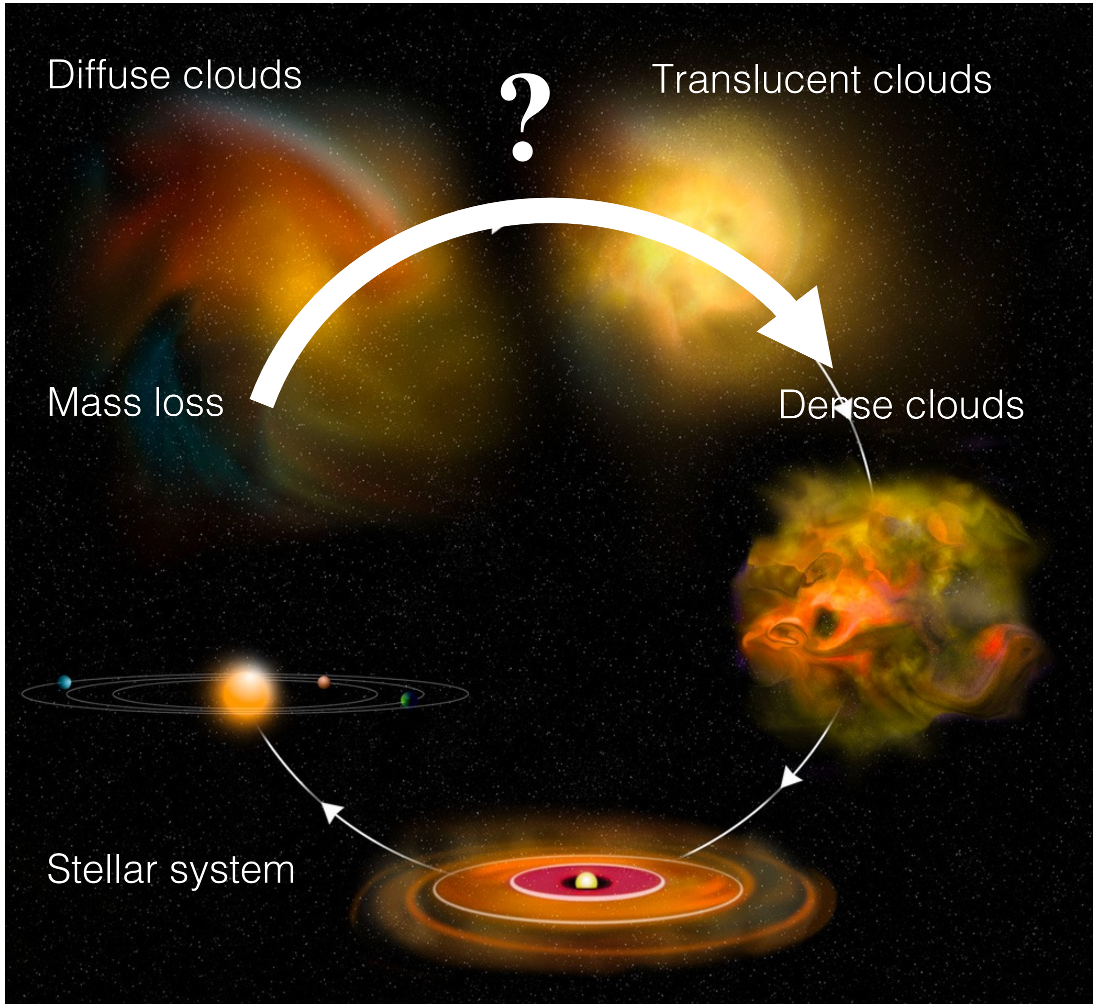
HyGAL – “Hydrides in the GALaxy”

Characterize the diffuse Galactic ISM with observations of hydrides and other small molecules

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

W.-J. Kim, A. Sternberg, 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. Sańchez-Monge, R. Higgins, E. Falgarone, P. Hennebelle, S. Molinari, A. M. Jacob

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

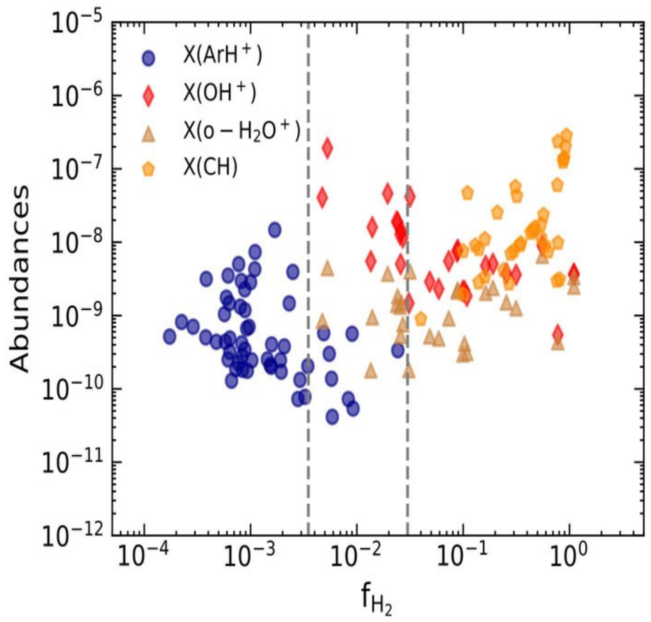


Credits: NRAO/Bill Saxton (ISM Gas life cycle schematic)

Goals

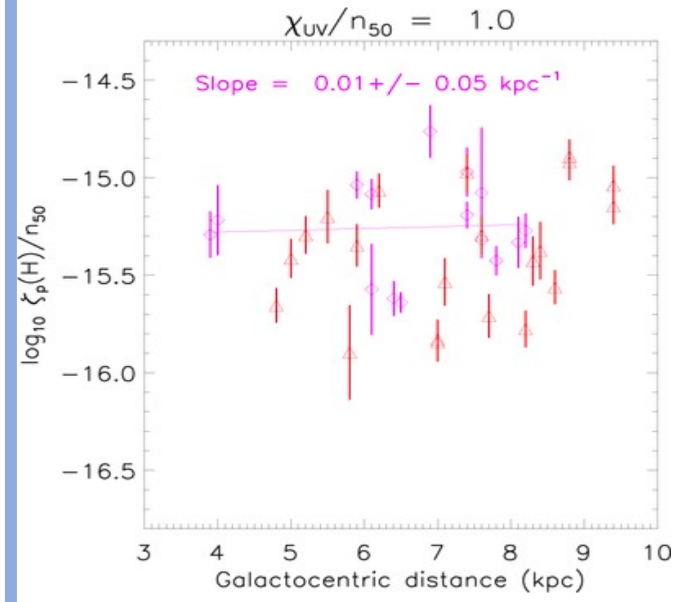
To understand how molecular clouds are formed and the processes that lead to the transition from atomic to molecular gas

Distribution of molecular fraction in different ISM phases



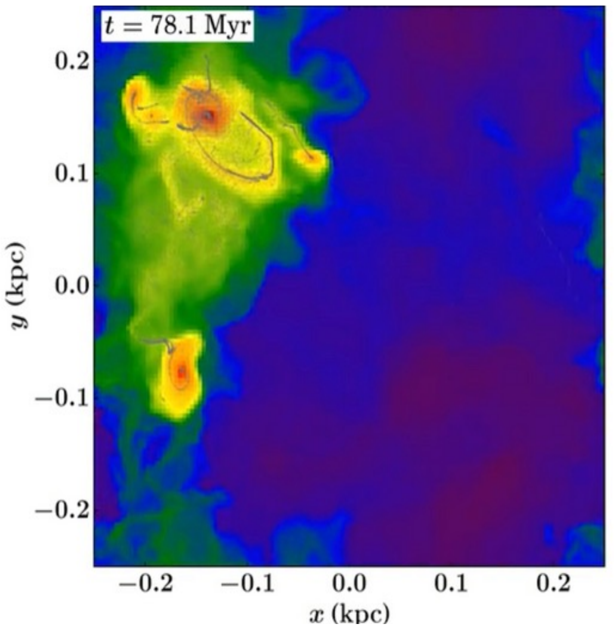
Taken from Jacob et al. (2020b)

Variation of comic-ray ionization across Galactocentric distances



Taken from Neufeld & Wolfire 2017

Nature of turbulence in the ISM and its dissipation



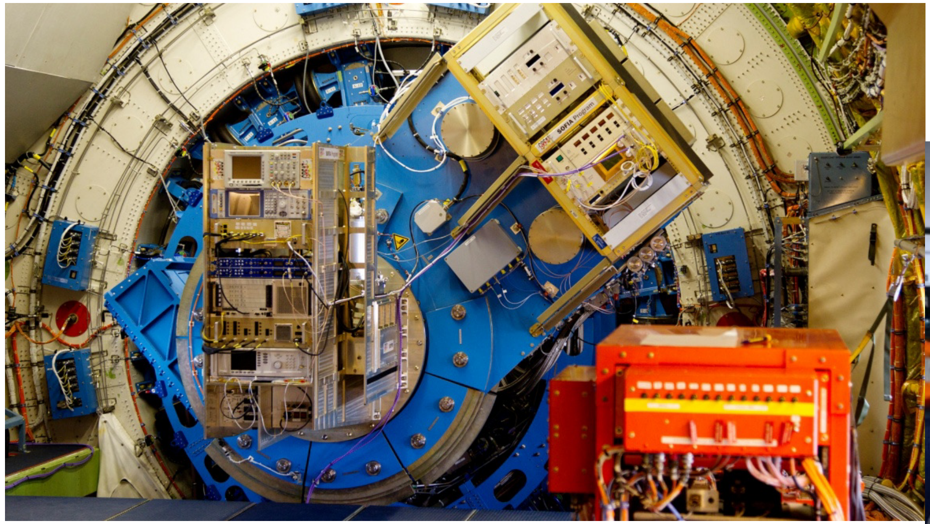
SILCC Simulation

SOFIA HyGAL observations

- Six key hydrides: ArH^+, H_2O^+ OH^+, SH, CH and OH
- Two atomic gas constituents: C^+, O

High resolution spectroscopic observations using upGREAT and 4GREAT

With three tunings to disentangle any sideband contamination



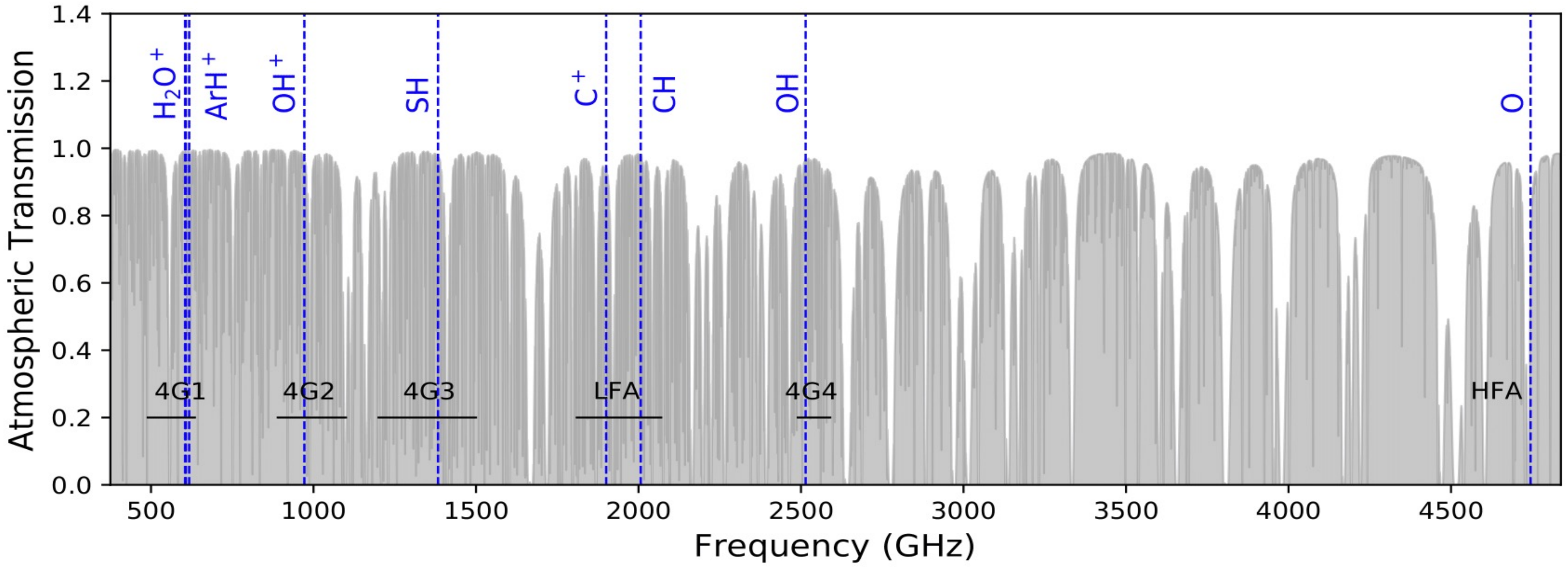
German Receiver for Astronomy at Terahertz frequencies (GREAT)

SOFIA HyGAL observations

- Six key hydrides: ArH^+, H_2O^+ OH^+, SH, CH and OH
- Two atomic gas constituents: C^+, O

High resolution spectroscopic observations using upGREAT and 4GREAT

With three tunings to disentangle any



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.

SOFIA HyGAL observations

- Six key hydrides: ArH^+, H_2O^+ OH^+, SH, CH and OH
- Two atomic gas constituents: C^+, O

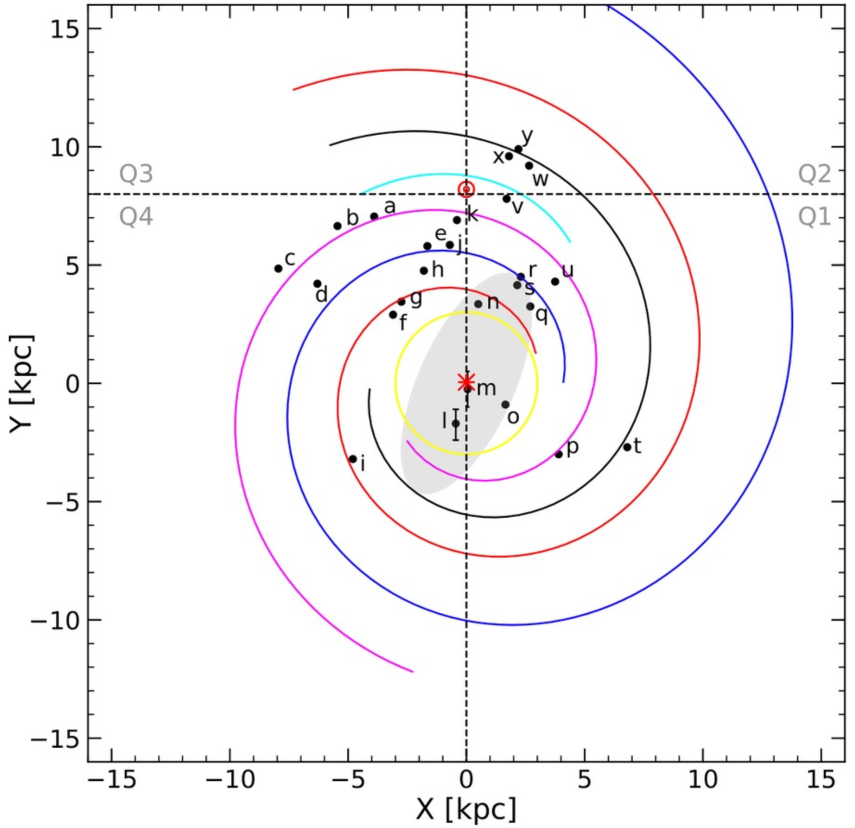
High resolution spectroscopic observations using upGREAT and 4GREAT

With three tunings to disentangle any sideband contamination

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

<u>Source selection:</u>
160 µm continuum flux > 2000 Jy (Inner Galaxy)
> 1000 Jy (Outer Galaxy)
From the Hi-GAL source catalogue (Elia et al. 2021)

82% of the proposed data observed!

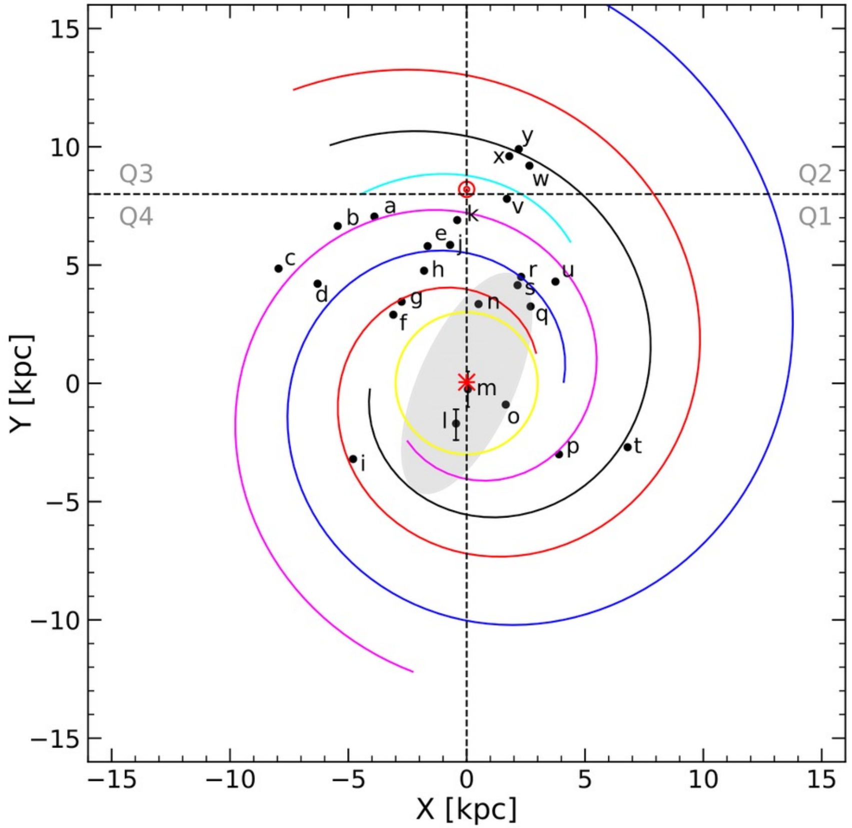


SOFIA HyGAL observations

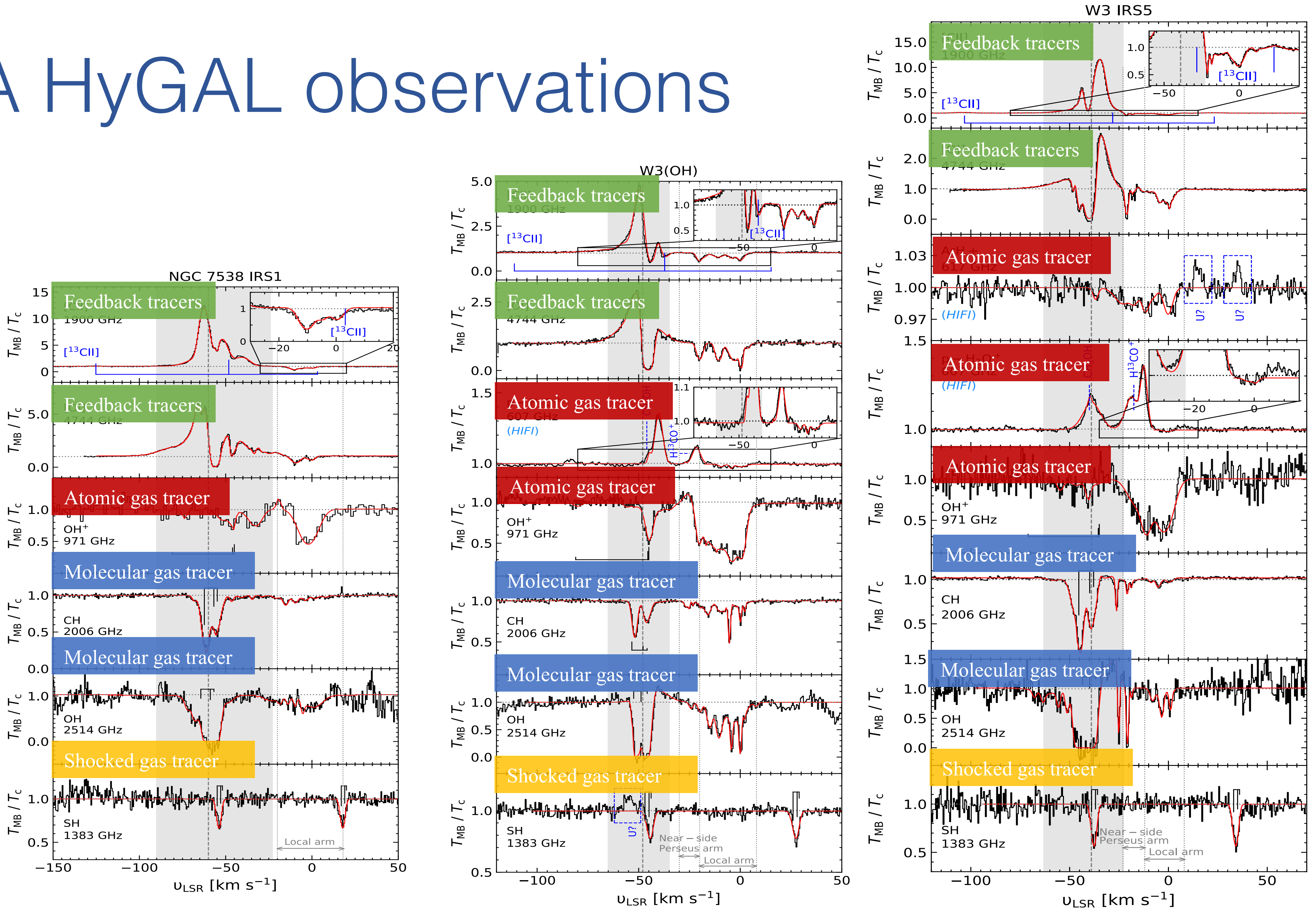
#	Source Designation	Right Ascension [hh:mm:ss]	Declination [dd:mm:ss]	Gal. Long. [deg]	Gal. Lat. [deg]	$v_{\rm LSR}$ [km s^{-1}]	d [Ref] [kpc]
a	HGAL284.015−00.86	10:20:16.1	−58:03:55.0	284.016	−0.857	9.0	5.7 [1]
b	HGAL285.26−00.05	10:31:29.5	−58:02:19.5	285.263	−0.051	3.4	4.3 [2]
c	G291.579−00.431	11:15:05.7	−61:09:40.8	291.579	−0.431	13.6	8.0 [3]
d	IRAS 12326-6245	12:35:35.9	−63:02:29.0	301.138	−0.225	−39.3	4.6 [4]
e	G327.3−00.60	15:53:05.0	−54:35:24.0	327.304	−0.551	−46.9	3.1 [5]
f	G328.307+0.423	15:54:07.2	−53:11:40.0	328.309	+0.429	−93.6	5.8 [6]
g	IRAS 16060−5146	16:09:52.4	−51:54:58.5	330.953	−0.182	−91.2	5.3 [7]
h	IRAS 16164−5046	16:20:11.9	−50:53:17.0	332.827	−0.551	−57.3	3.6 [8]
i	IRAS 16352−4721	16:38:50.6	−47:28:04.0	337.404	−0.403	−41.4	12.3 [4]
j	IRAS 16547−4247	16:58:17.2	−42:52:08.9	343.126	−0.063	−30.6	2.7 [8]
k	NGC 6334 I	17:20:53.4	−35:47:01.5	351.417	+0.645	−7.4	1.3 [9]
l	G357.558−00.321	17:40:57.2	−31:10:59.3	357.557	−0.321	5.3	9.0–11.8 [10]
m	HGAL0.55−0.85	17:50:14.5	−28:54:30.7	0.546	−0.851	16.7	7.7–9.2 [11]
n	G09.62+0.19	18:06:14.9	−20:31:37.0	9.620	+0.194	4.3	5.2 [12]
o	G10.47+0.03	18:08:38.4	−19:51:52.0	10.472	+0.026	67.6	8.6 [13]
p	G19.61−0.23	18:27:38.0	−11:56:39.5	19.608	−0.234	40.8	12.6 [14]
q	G29.96−0.02	18:46:03.7	−02:39:21.2	29.954	−0.016	97.2	4.8 [15]
r	G31.41+0.31	18:47:34.1	−01:12:49.0	31.411	+0.307	98.2	3.7 [15]
s	W43 MM1	18:47:47.0	−01:54:28.0	30.817	−0.057	97.8	3.1 [15]
t	G32.80+0.19	18:50:30.6	−00:02:00.0	32.796	+0.191	14.6	9.7 [15]
u	G45.07+0.13	19:13:22.0	+10:50:54.0	45.071	+0.133	59.2	7.8 [15]
v	DR21	20:39:01.6	+42:19:37.9	81.681	0.537	−4.0	1.5 [16]
w	NGC 7538 IRS1	23:13:45.3	+61:28:11.7	111.542	0.777	−59.0	2.6 [17]
x	W3 IRS5	02:25:40.5	+62:05:51.	133.715	1.215	−39.0	2.3 [18]
y	W3(OH)	02:27:04.1	+61:52:22.1	133.948	1.064	−48.0	2.0 [18, 19]

High resolution spectroscopic observations using upGREAT and 4GREAT

With three tunings to disentangle any sideband contamination



SOFIA HyGAL observations



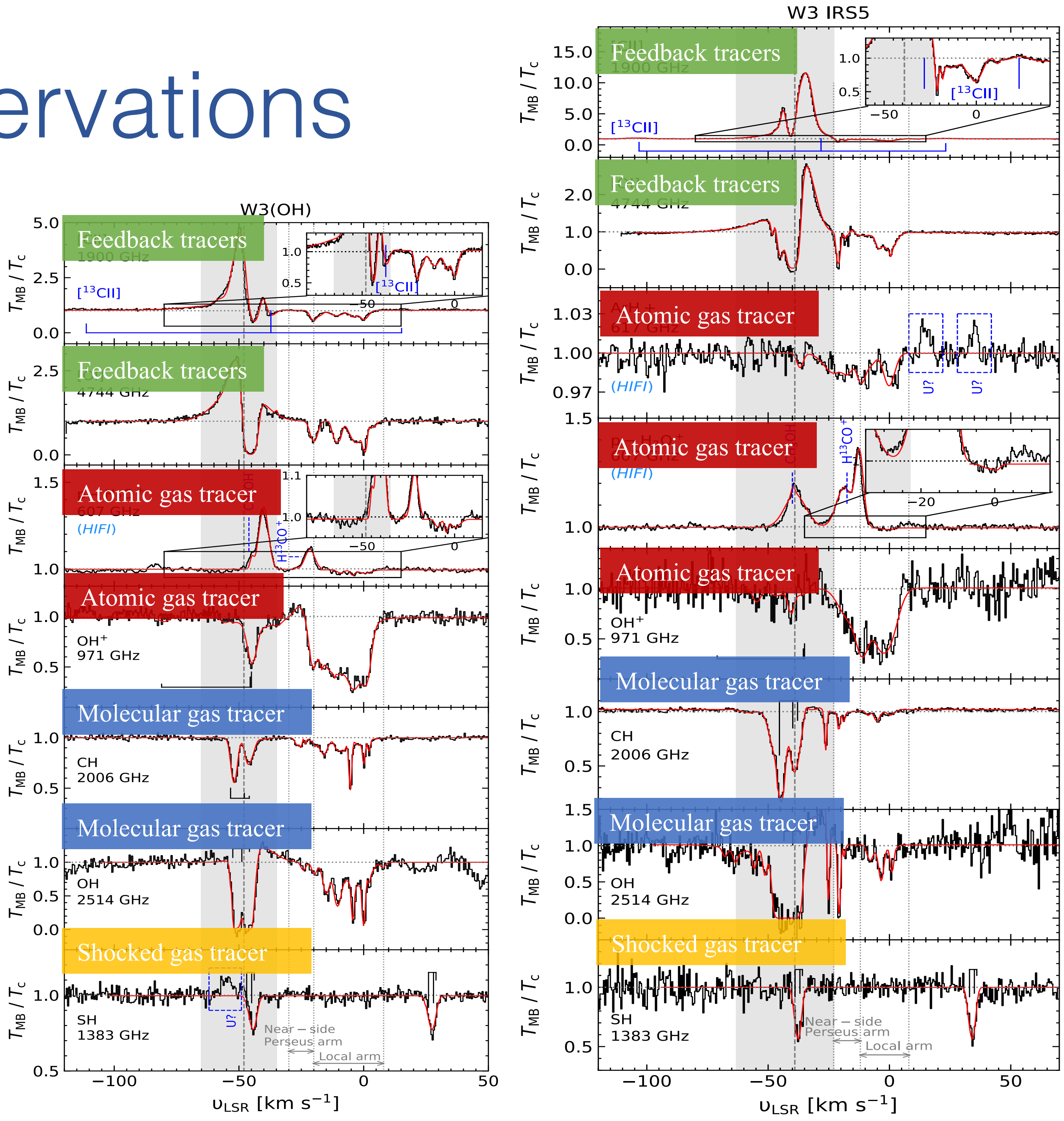
SOFIA HyGAL observations

What makes these specific hydrides good diagnostic probes?

FEEDBACK talk's!

See Wonju Kim's talk

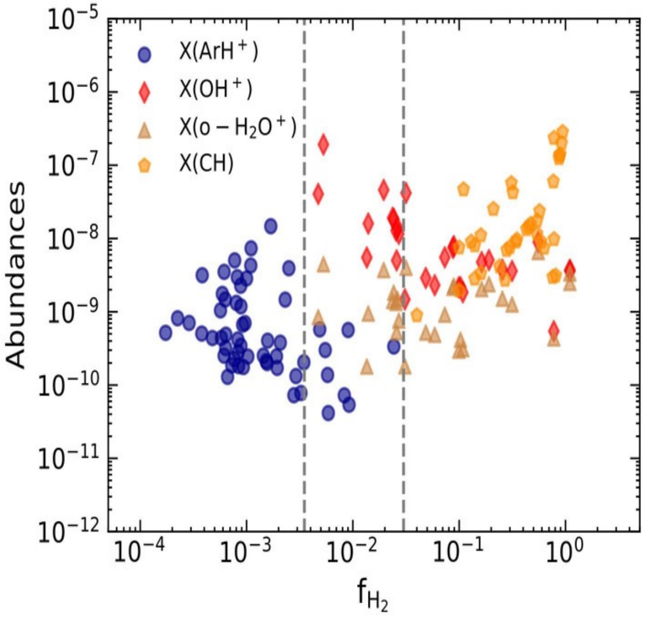
See Michael Busch's poster



Goals

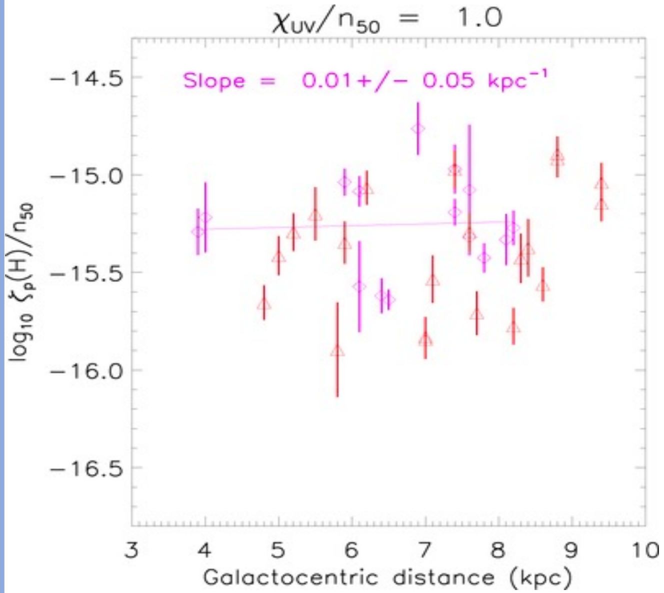
To understand how molecular clouds are formed and the processes that lead to the transition from atomic to molecular gas

Distribution of molecular fraction in different ISM phases



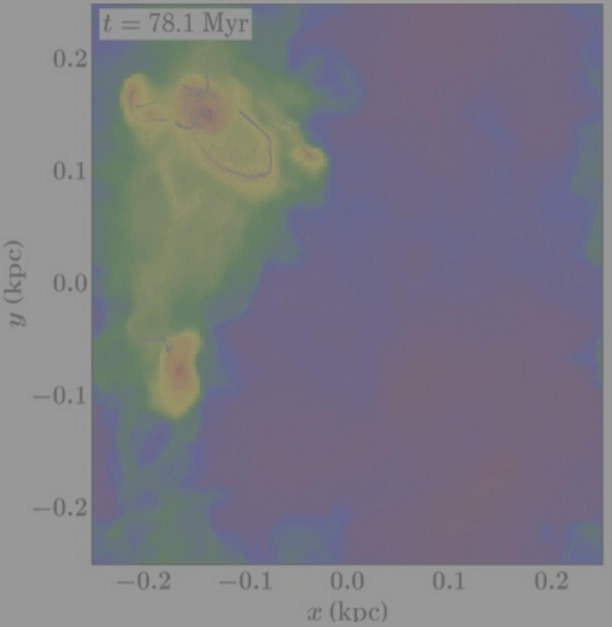
Taken from Jacob et al. (2020b)

Variation of comic-ray ionization across Galactocentric distances



Taken from Neufeld & Wolfire 2017

Nature of turbulence in the ISM and its dissipation

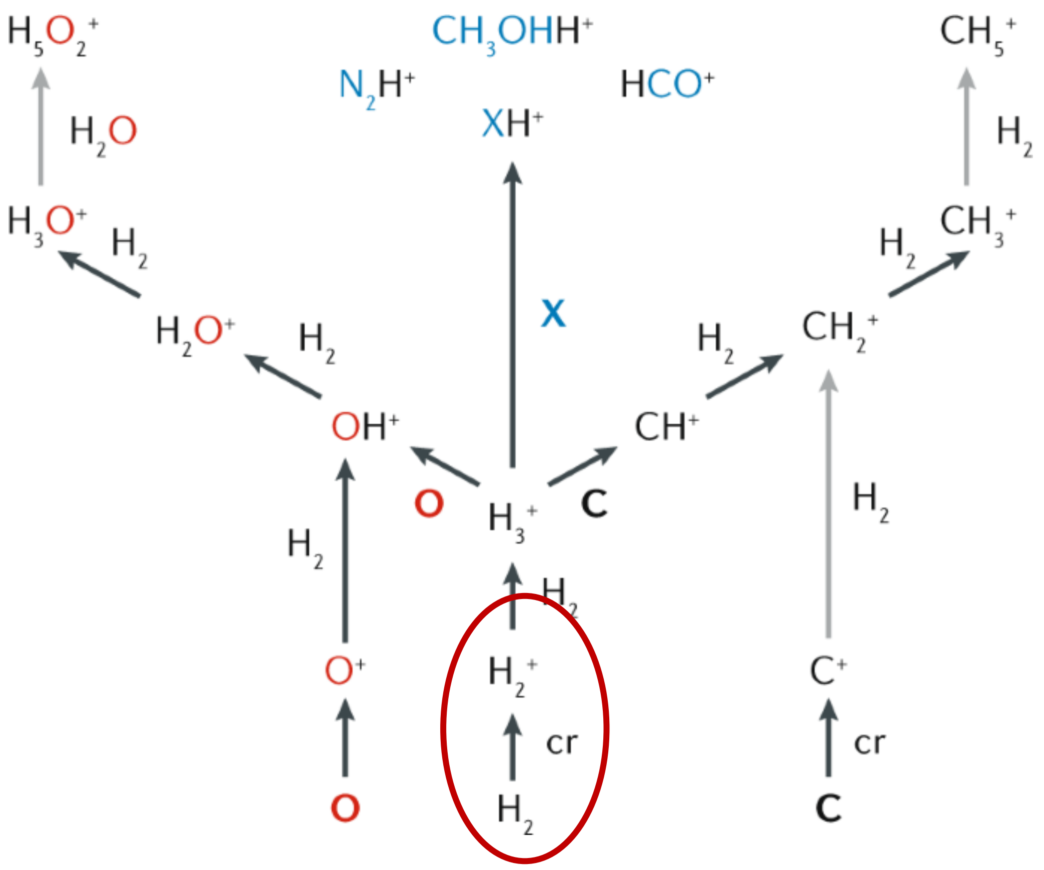


SILCC Simulation

Low-energy cosmic-rays

Importance of CRs in the ISM

- Source of **heating and ionization** in the ISM
- Produces diffuse **γ-ray flux** and **light elements** via spallation
- Drives **interstellar chemistry**
- Couples with **magnetic fields**



Taken from McGuire et al. 2021.

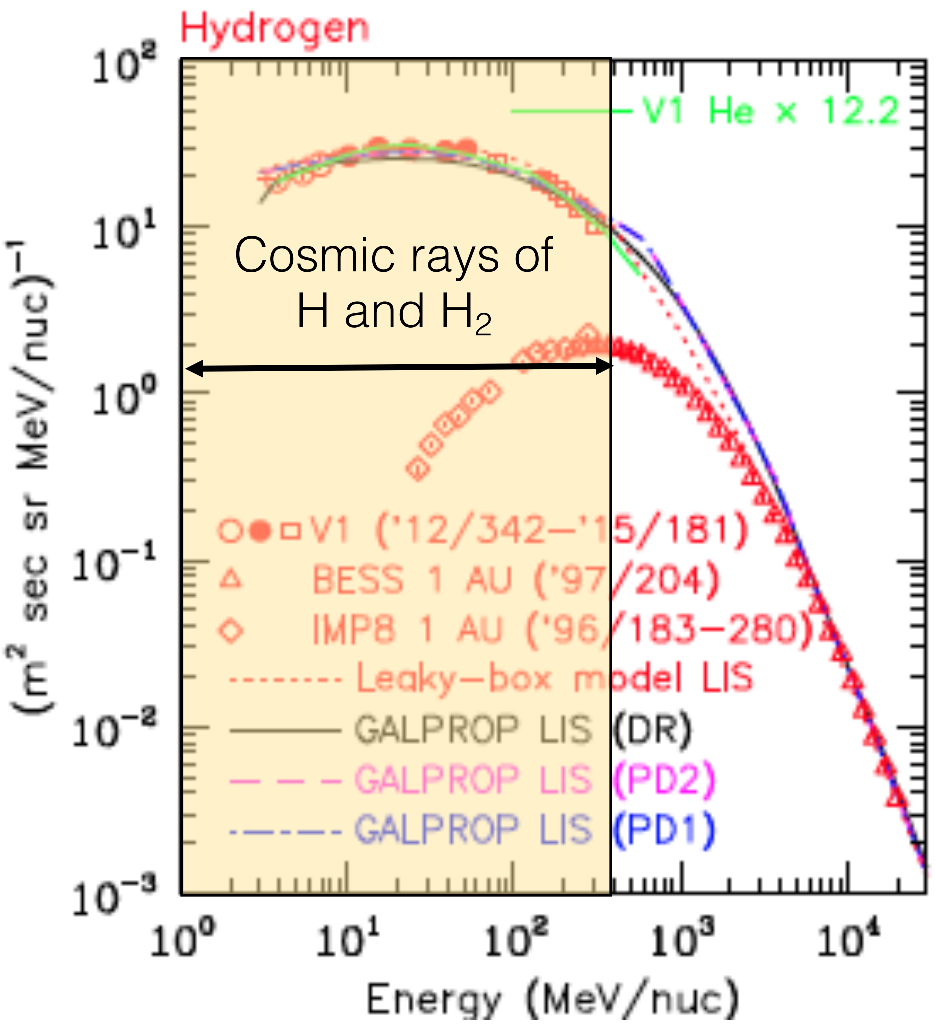
Low-energy cosmic-rays

Importance of CRs in the ISM

- Source of **heating and ionization** in the ISM
- Produces diffuse **γ-ray flux** and **light elements** via spallation
- Drives **interstellar chemistry**
- Couples with **magnetic fields**

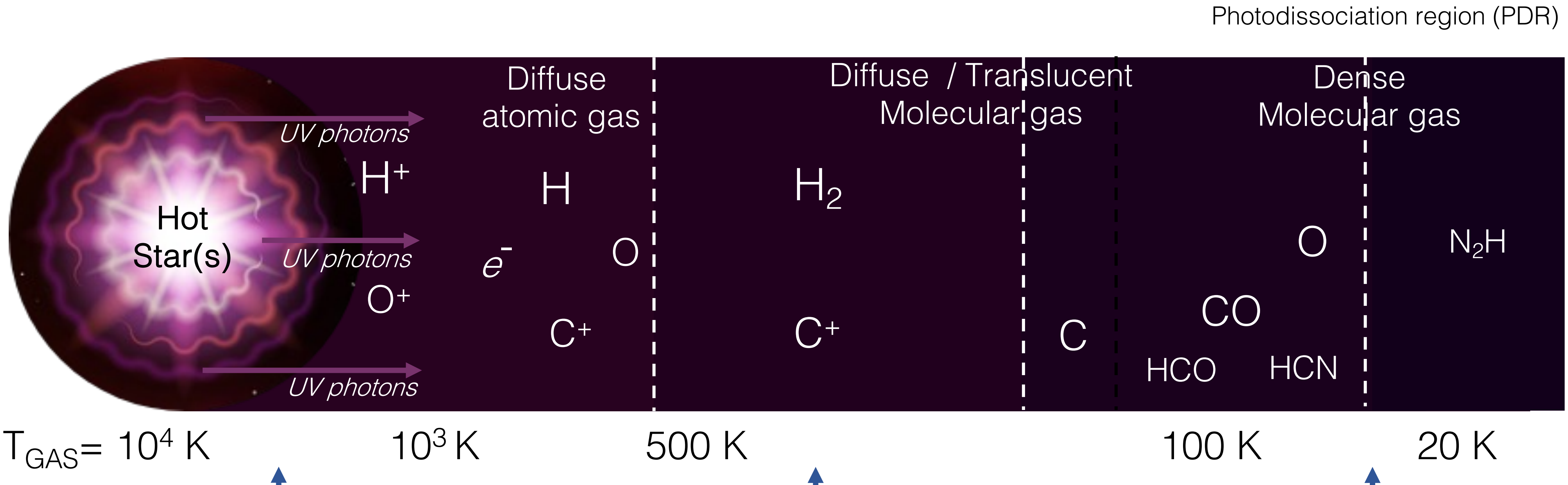
Why study CRs?

- Low energy (< 1 GeV) particle flux is poorly constrained! → Uncertainties in the results from Voyager



Cosmic ray energy distribution spectrum. Taken from Cummings et al. 2016.

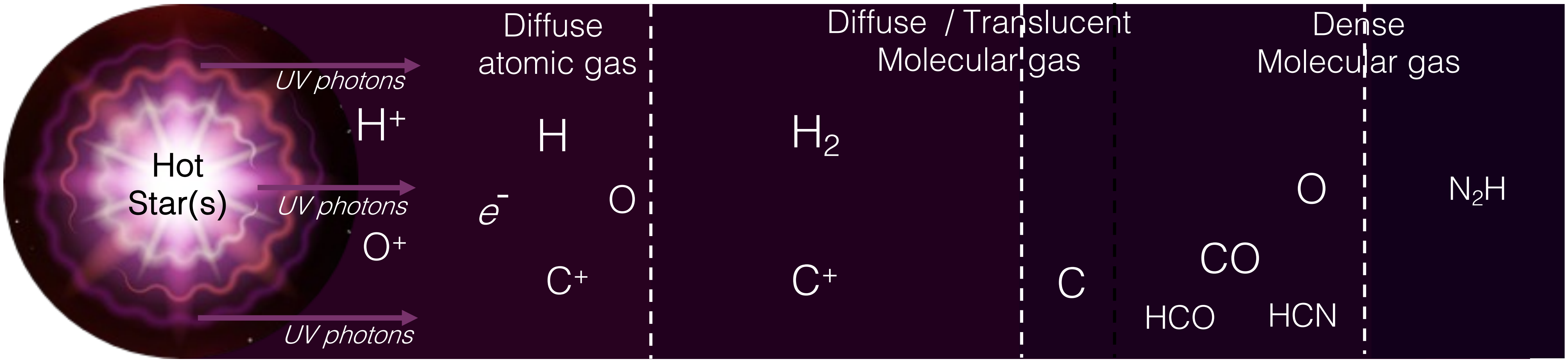
CR Ionization rates inferred from observations of the local ISM



From ArH^+, OH^+, H_2O^+	From H_3^+	From HCO^+
$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 1.1 \times 10^{-17}\,s^{-1}$
(Neufeld & Wolfire 2017)	(Indriolo & McCall 2012)	(van der Tak & van Dishoeck 2000)

CR Ionization rates inferred from observations of the local ISM

Photodissociation region (PDR)

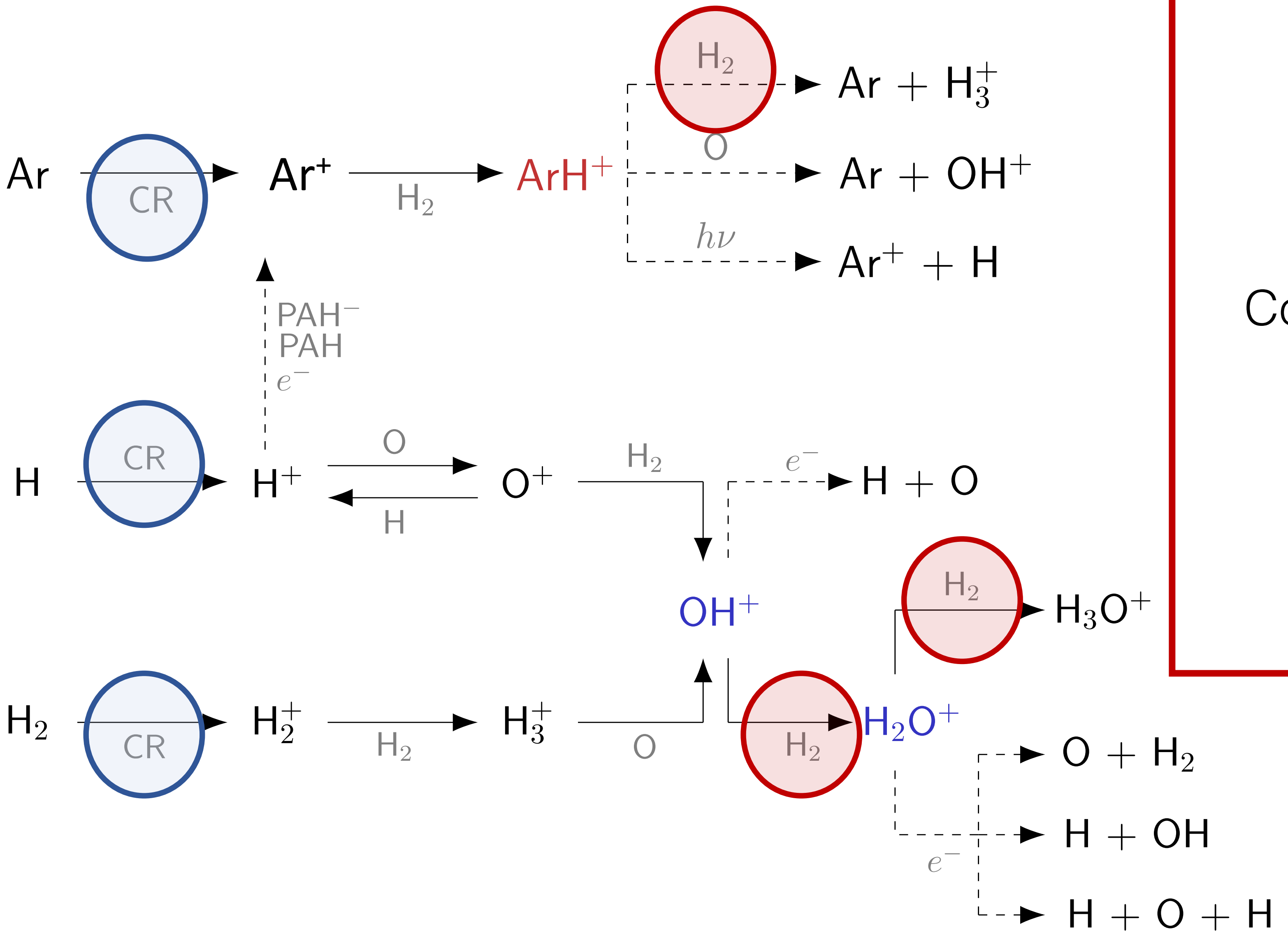


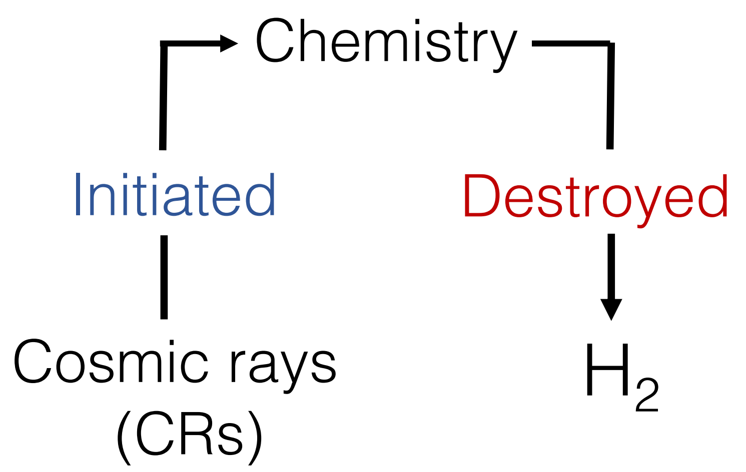
T_{GAS}= 10^4 K 10^3 K 500 K 100 K 20 K

Surprisingly characterized by the same CRIR!

From ArH^+, OH^+, H_2O^+	From H_3^+	From HCO^+
$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 1.1 \times 10^{-17}\,s^{-1}$
(Neufeld & Wolfire 2017)	(Indriolo & McCall 2012)	(van der Tak & van Dishoeck 2000)

Atomic gas tracers





→ Must trace CR ionization rates (ζ_p(H))

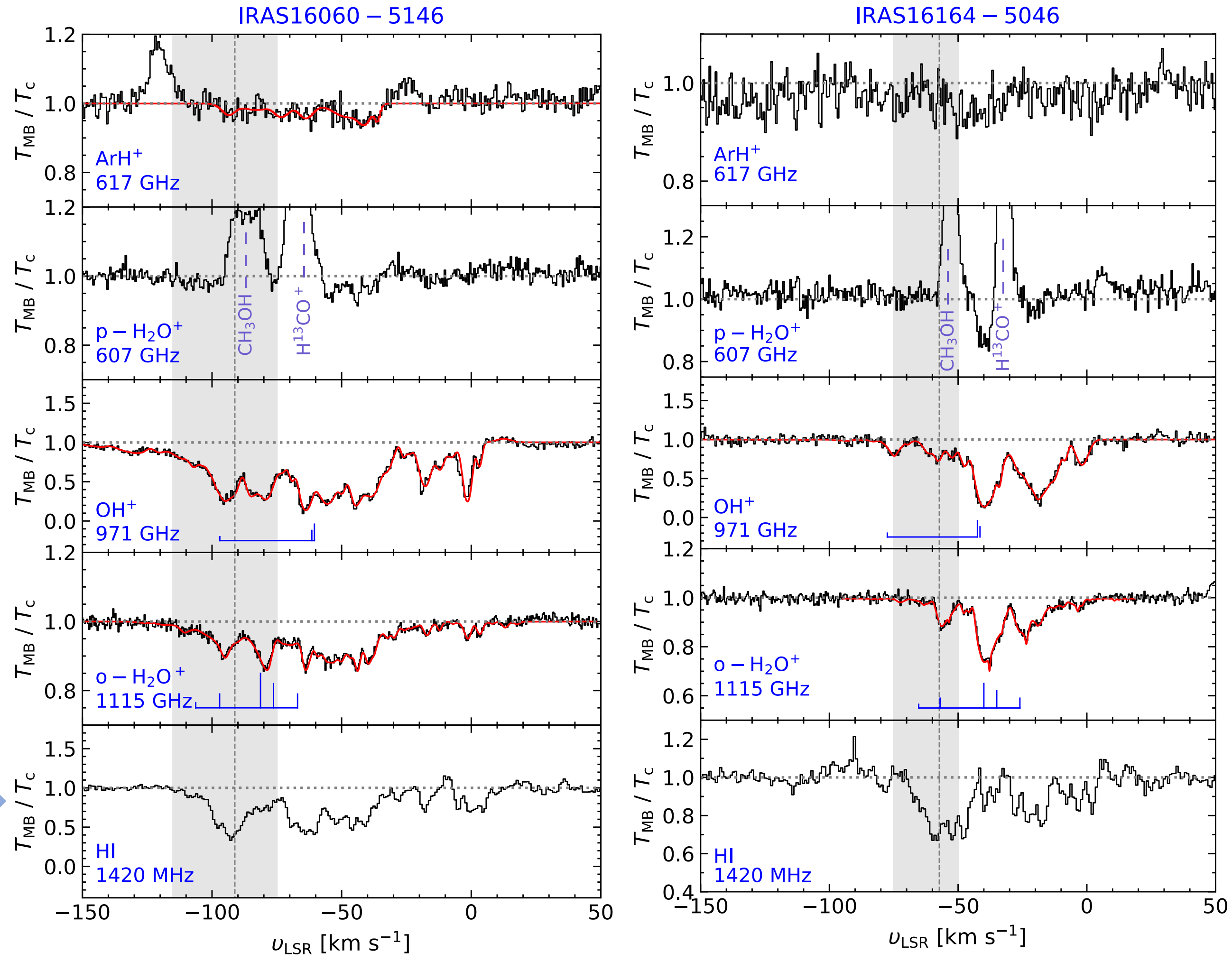
→ Atomic gas

HyGAL* data – ArH^+, OH^+, H_2O^+

(Jacob et al. in prep)

- ArH^+ detected toward **17** sources (combining data from SOFIA, Herschel and APEX)
- OH^+ detected toward **23** sources
- *p*-H_2O^+ unambiguous detections of absorption in specific velocity intervals toward **15** sources (combining data from SOFIA, Herschel and APEX)

Combine with HI data → model the observed abundances → $\zeta_p(H)$



*With the end of SOFIA ~70% of the proposed HyGAL data has been collected

Diffuse cloud models

(Jacob et al. in prep)

(Neufeld & Wolfire 2017)

- Two-sided slab illuminated isotropically by UV radiation field (Draine 1978, Wolfire 2010)

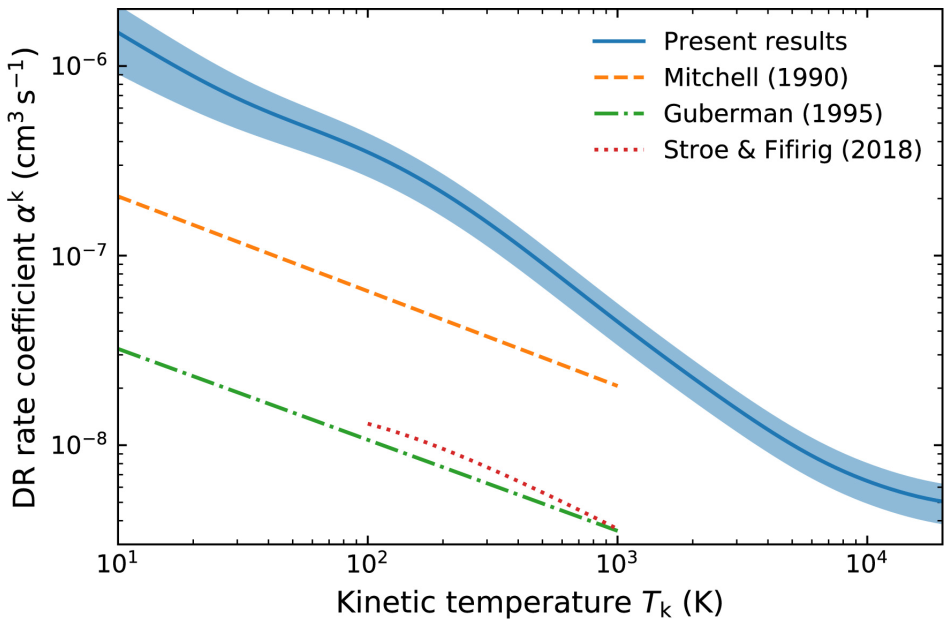
- Main grid parameters – X_{UV}, ζ_{p}(H), $Av_{(tot)}$

Diffuse cloud models

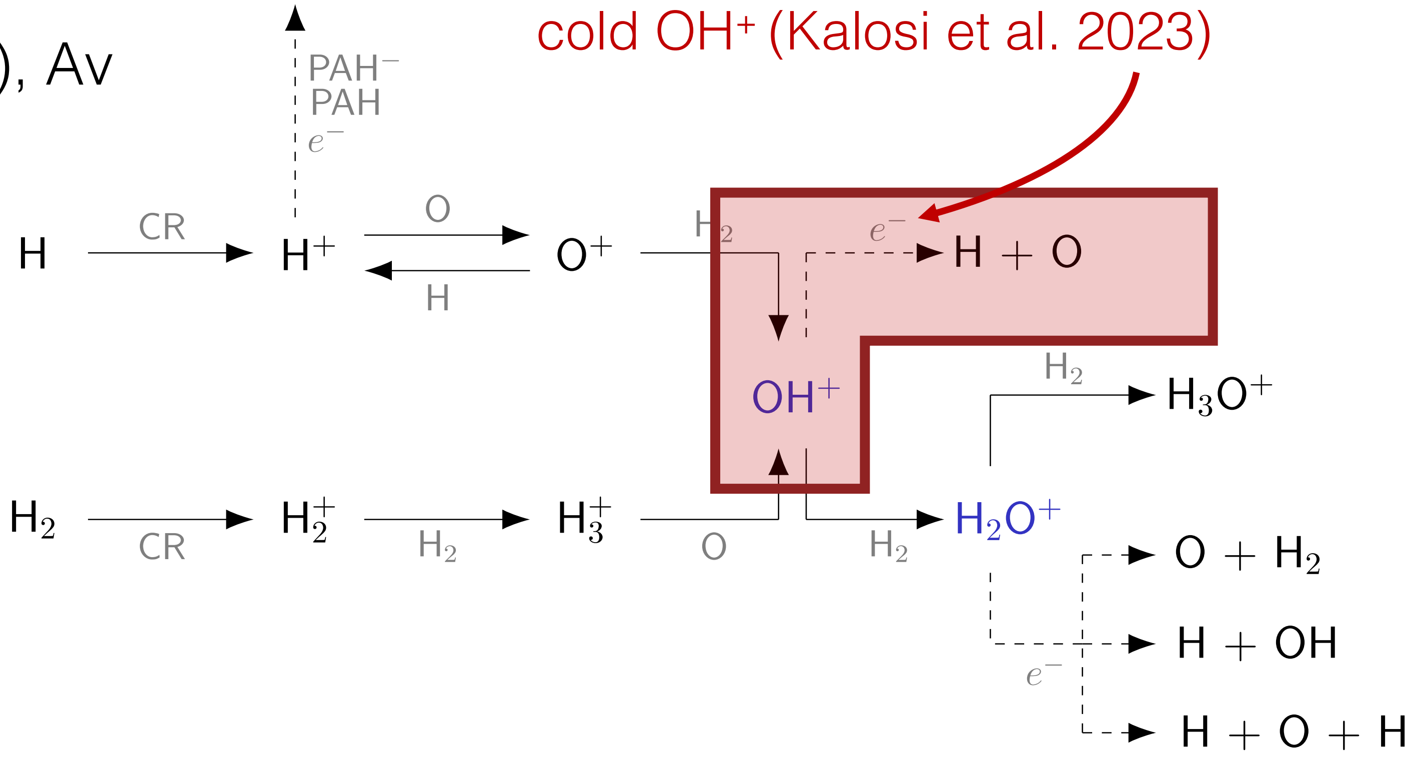
(Jacob et al. in prep)

Neufeld & Wolfire 2017)

- Two-sided slab illuminated isotropically by UV radiation field (Draine 1978, Wolfire 2010)
- Main grid parameters – X_{UV}, ζ_{p}(H), Av



Cryogenic Storage Ring measurements of dissociative recombination of rotationally cold OH⁺ (Kalosi et al. 2023)

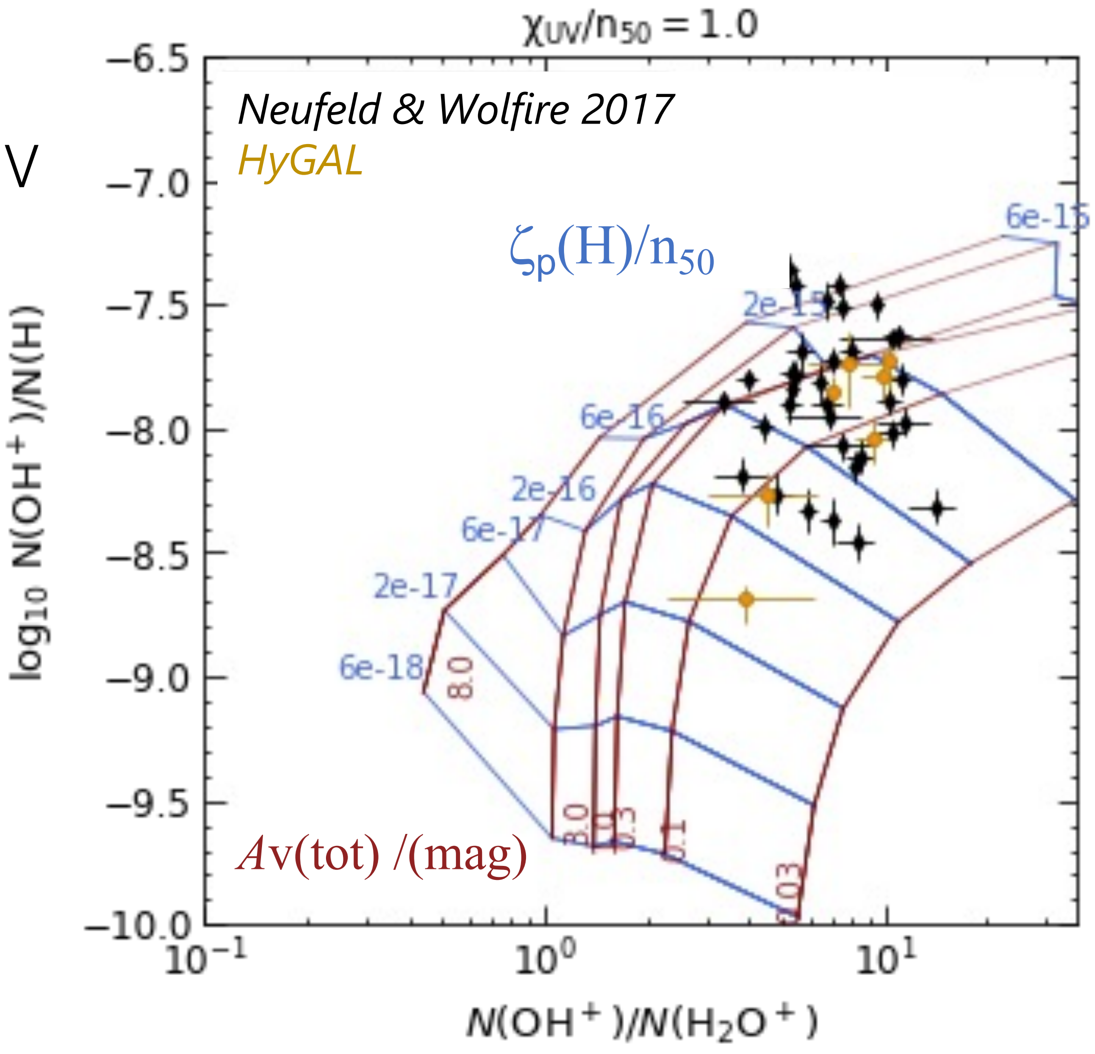


Revised $\zeta_p(H)$

(Jacob et al. in prep)

(Neufeld & Wolfire 2017)

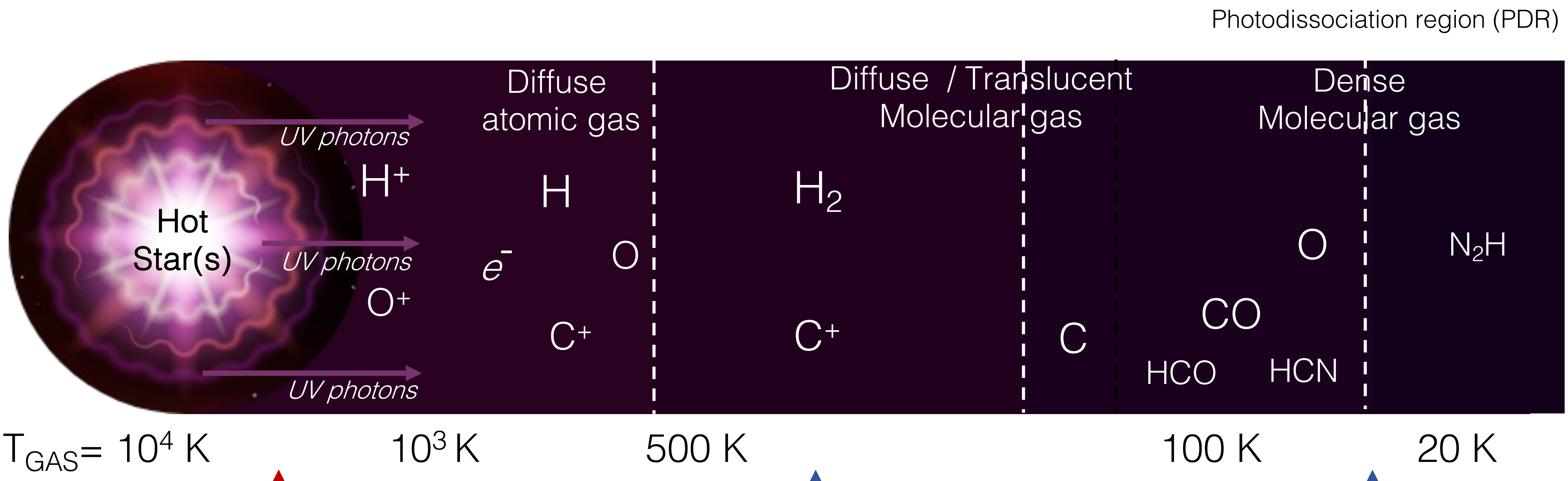
- Two-sided slab illuminated isotropically by UV radiation field (Draine 1978, Wolfire 2010)
- Main grid parameters – X_{UV}, $\zeta_p(H)$, $Av_{(tot)}$
- Revised chemical network



$<\zeta_p(H)/n_{50}> \sim 7\times 10^{-16}\ s^{-1}$

(Jacob et al. in prep – preliminary more HyGAL data points soon!)

CR Ionization rates inferred from observations of the local ISM



From ArH^+, OH^+, H_2O^+	From H_3^+	From HCO^+
$\zeta_p(H)/n_{50} \sim 7 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}\,s^{-1}$	$\zeta_p(H) = 1.1\times 10^{-17}\,s^{-1}$
(Jacob et al. in prep 2024)	(Indriolo & McCall 2012)	(van der Tak & van Dishoeck 2000)

The future of hydrides

<u>HyGAL provides:</u>

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

sources

<u>Future without SOFIA</u>

- JVLA, MeerKAT, SKA : Back to basics, explore the radio skies with diffuse tracers like CH and OH (See talk by Karl Menten, poster by Michael Busch)
  Study the properties of CO dark gas

- Balloon Missions (GUSTO)

- NASA FIR Probe (?)

… still bright