Investigating the cosmic-ray ionization rate in diffuse atomic clouds

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COSMIC RAYS 2: The salt of star formation recipe
★ November 9, 2022 ★

Background Image: The Spitzer IRAC-MIPS mosaic of the W49 star-formation region. The colour composite shows the 3.6μm, 8μm and 24μm emissions in blue, green and red, respectively.

Low-energy cosmic-rays

Recap

What is their importance?

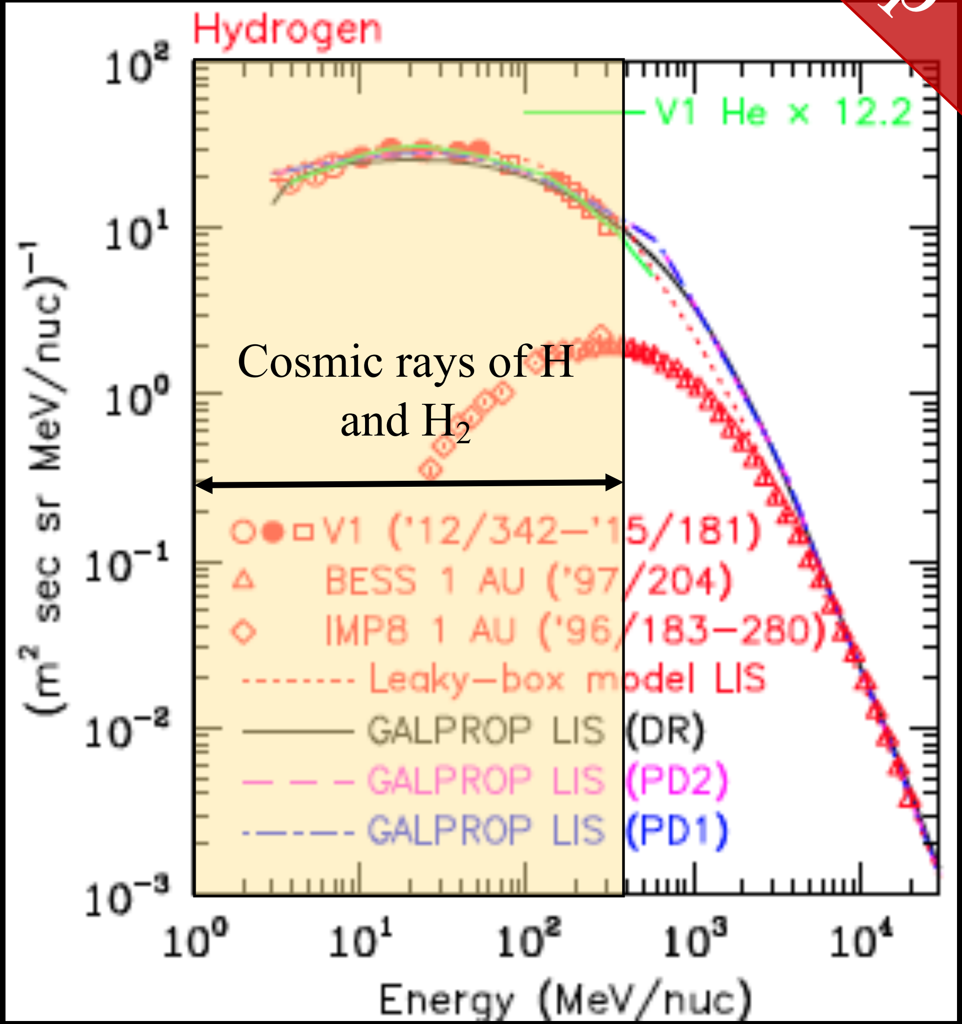
- Important source of heating and ionization in the ISM
- Drives interstellar chemistry in diffuse and dense regions
- Produces diffuse γ-ray flux via π^0 decay and light elements via spallation

Why study them?

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

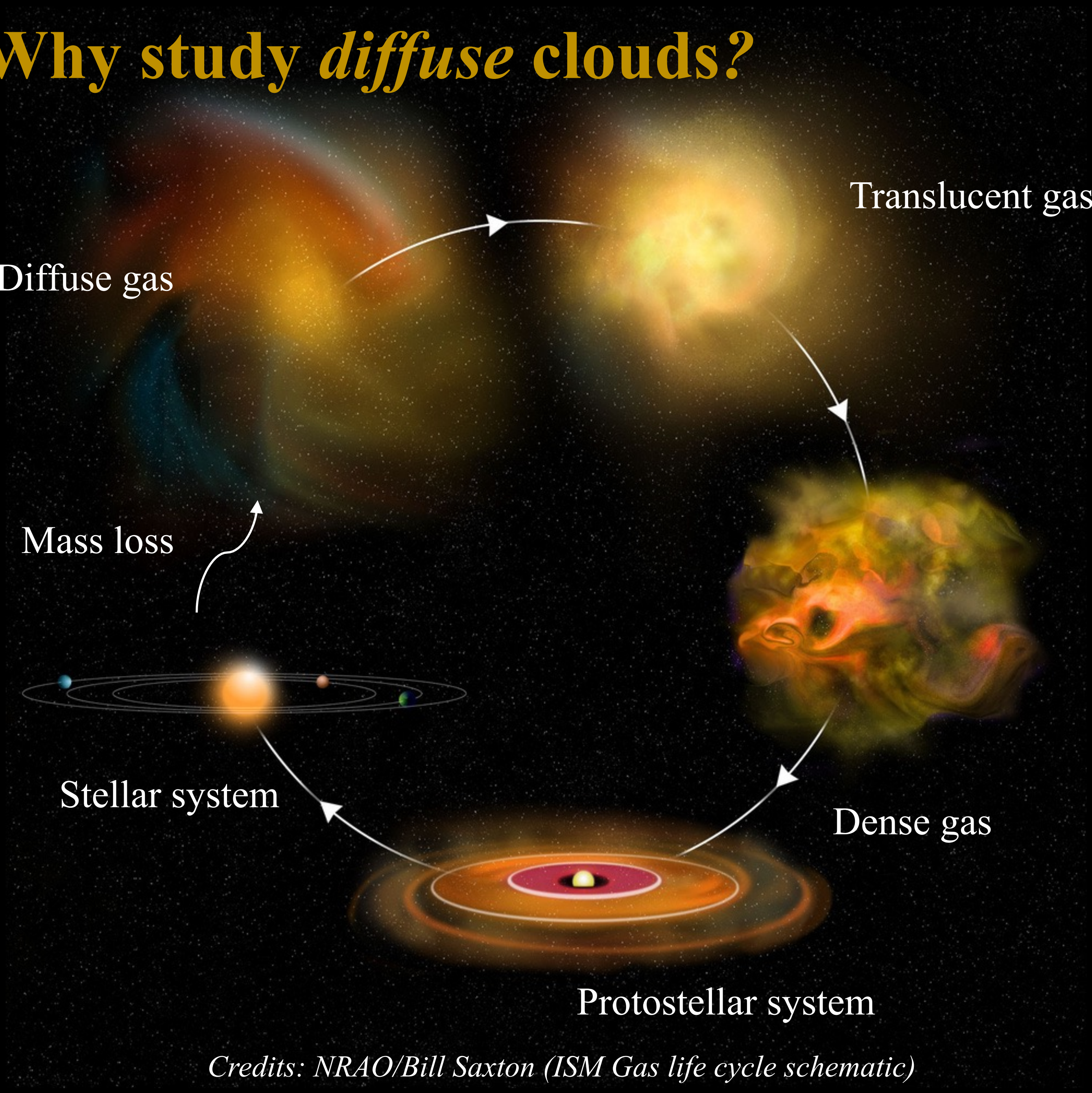
How do we study them?

- Using molecular line observations



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

Why study *diffuse* clouds?



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

- Essential for cloud formation
- Initiating chemical growth

Cosmic-ray ionization rate inferred from *observations* of the local ISM

(Discussed in David Neufeld's talk yesterday)

Taken from Snow & McCall 2008

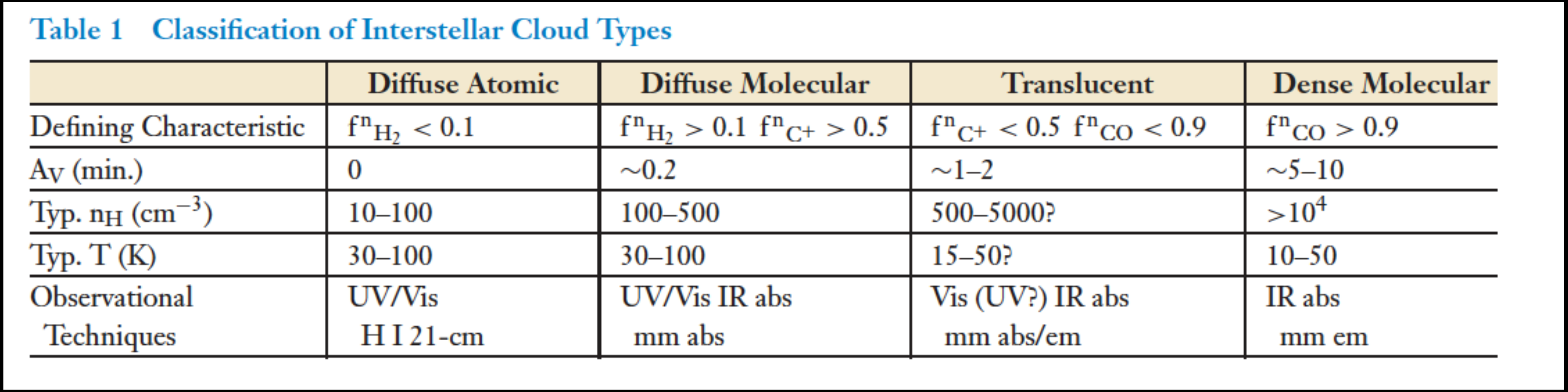


Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n{}_{H_2} < 0.1$	$f^n{}_{H_2} > 0.1$ $f^n{}_{C+} > 0.5$	$f^n{}_{C+} < 0.5$ $f^n{}_{CO} < 0.9$	$f^n{}_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

?

From H_3^+

$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}\ s^{-1}$

From HCO^+

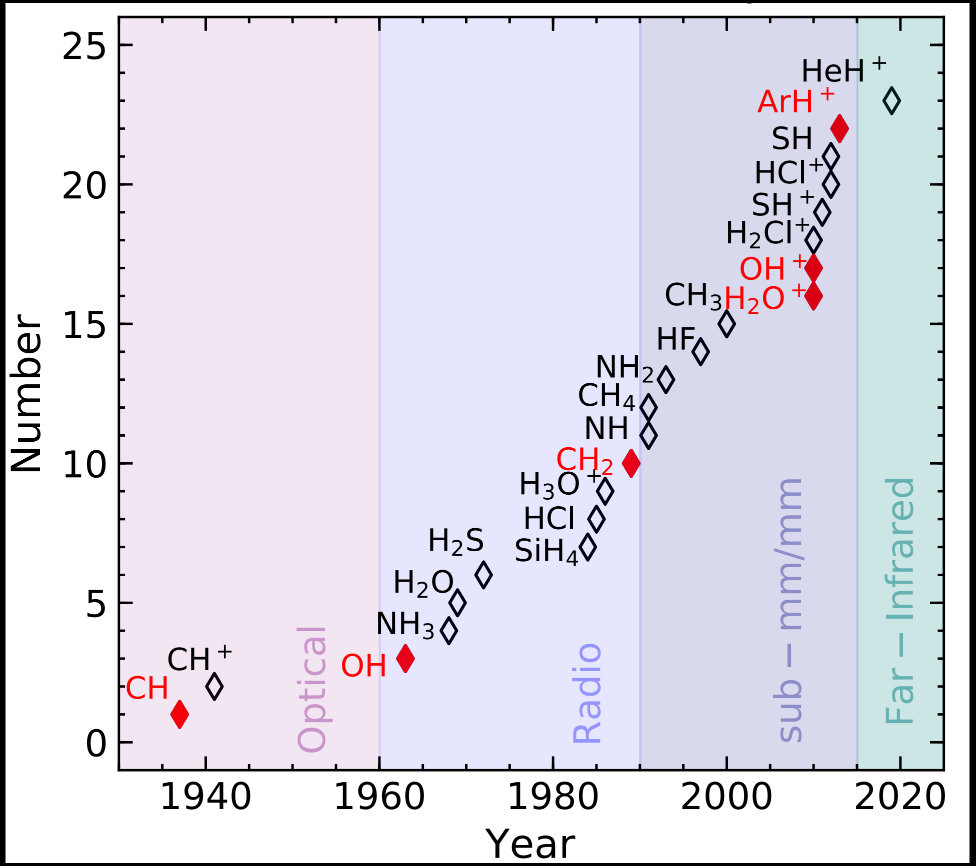
$\zeta_p(H) = 1.1 \times 10^{-17}\ s^{-1}$

Measuring the cosmic-ray ionization rate in *diffuse atomic gas* with *hydride ions*

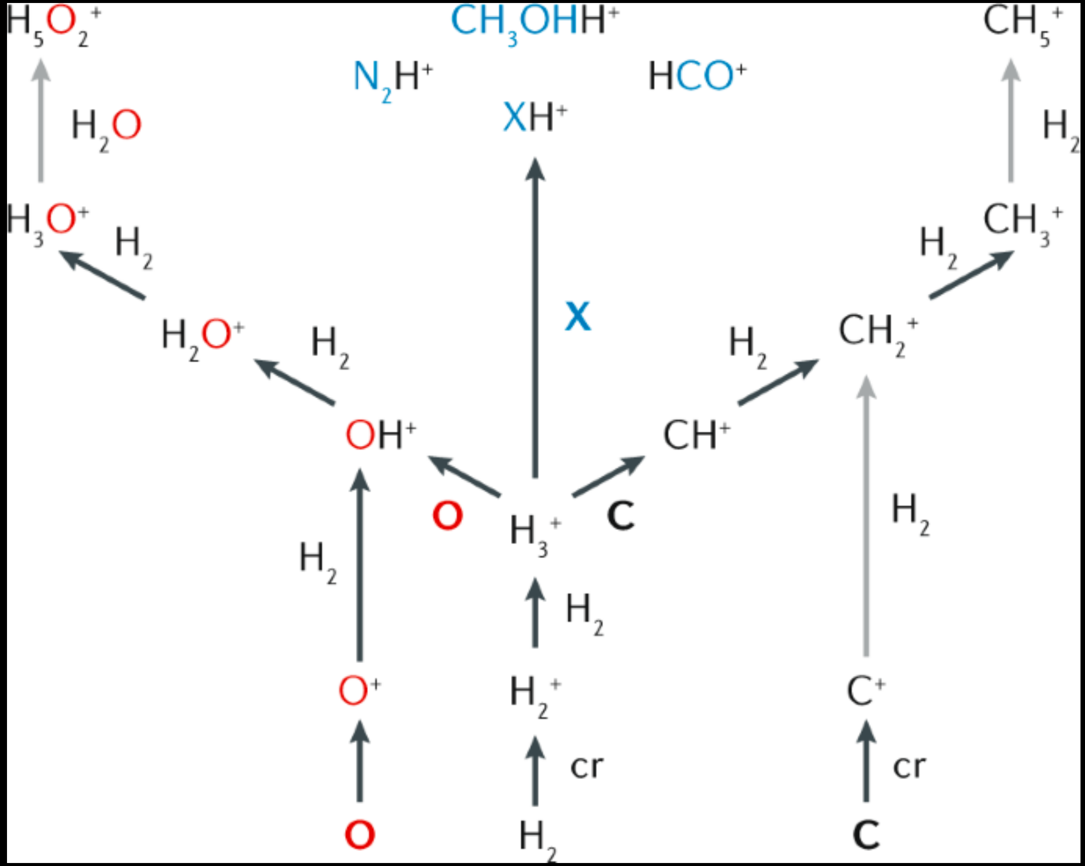
- *$(X)H_n$* and *$(X)H_n^+$* : Reservoir for heavy elements
- First molecules detected in space

(Dunham 1937; Swings & Rosenfeld 1937)

- Fundamental building blocks of interstellar chemistry
- Hydrides shape the FIR-radio window

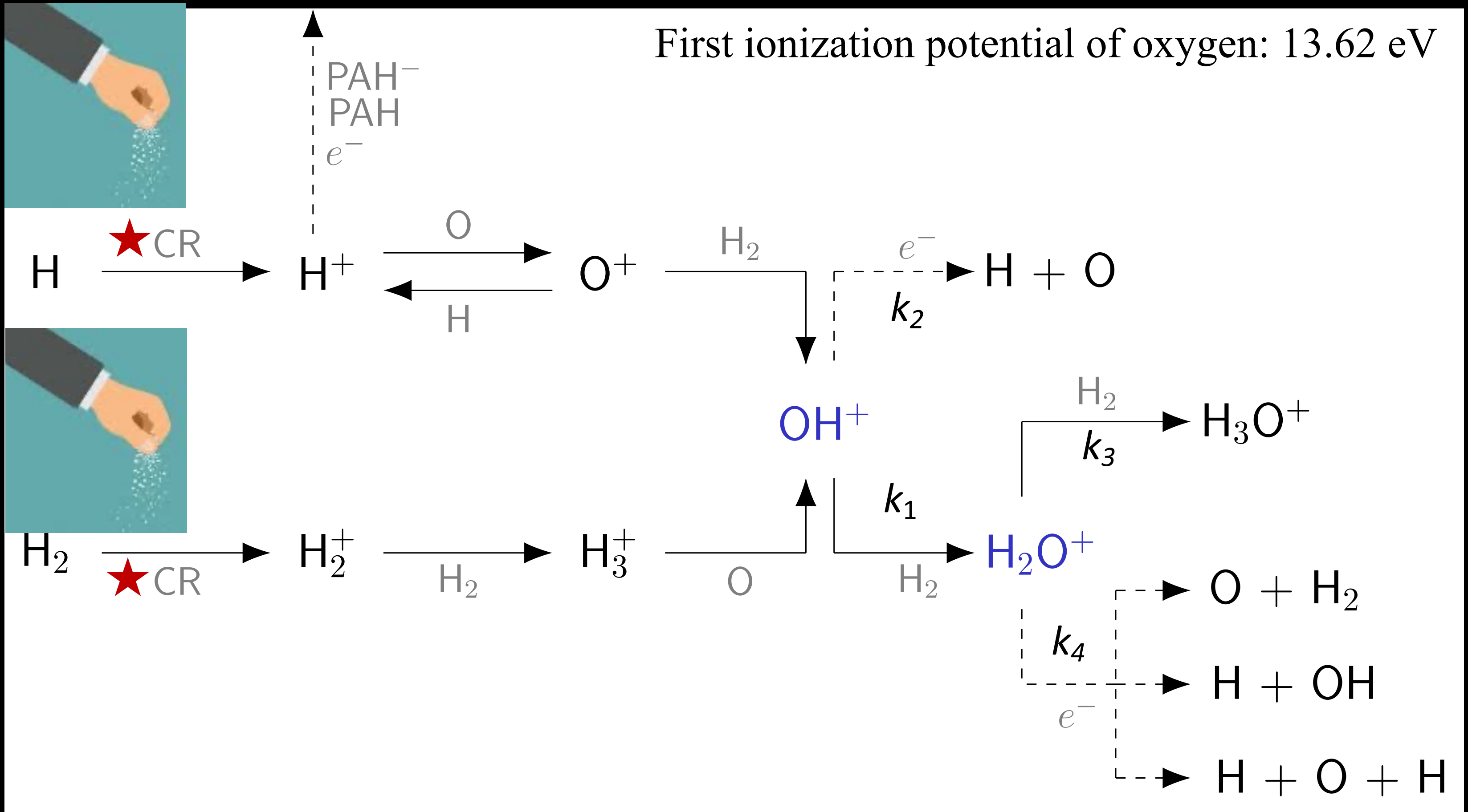


Adapted from http://www.astrochmyst.org/.



Taken from McGuire et al. (2020).

Closer look at *Oxygen* chemistry



First ionization potential of oxygen: 13.62 eV

Taken from Jacob et al. 2022b.

- First detected in the ISM via its rotational transitions at 909 GHz in absorption by *Wyrowski et al. 2010*.

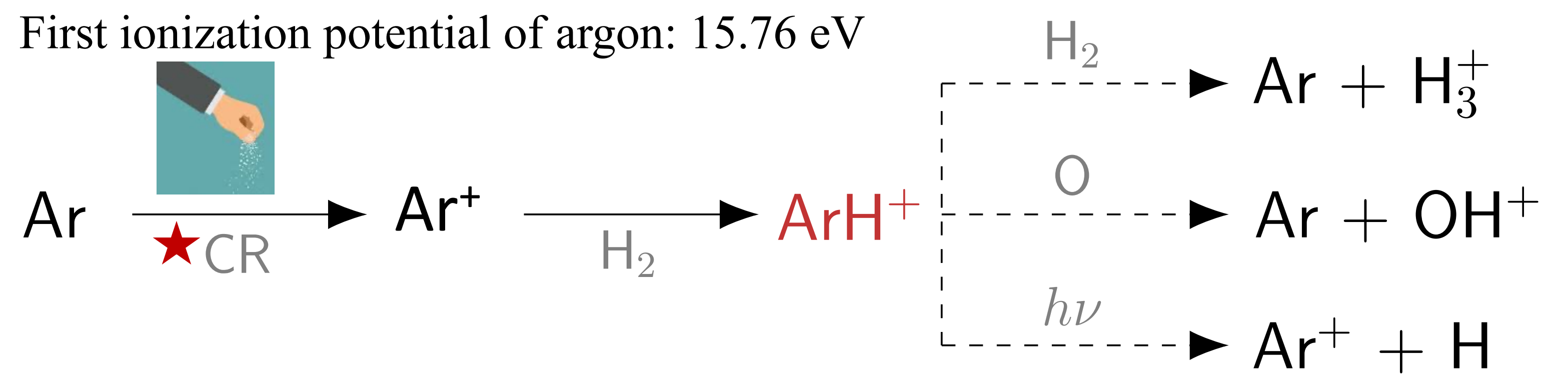
- Constraints the cosmic-ray ionization rate and molecular fraction.

$$\epsilon\zeta_p = \frac{N(OH^+)}{N(H_2O^+)} n_H \left[\frac{f_{H2}}{2} k_1 + x_e k_2\right]$$

$$f_{H_2} = (2x_e k_4/k_1)/(\frac{N(OH^+)}{N(H_2O^+)} - \frac{k_3}{k_1})$$

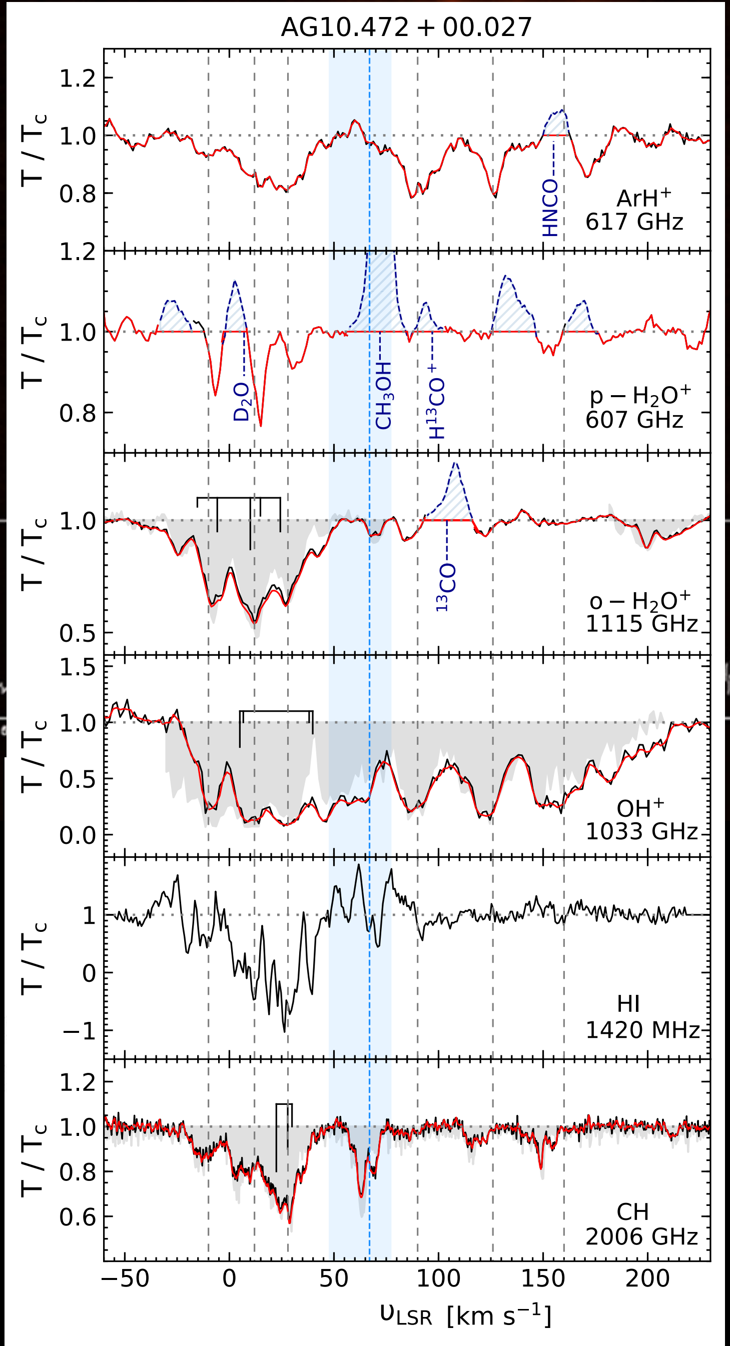
(Neufeld et al 2010)

Closer look at *Argon* chemistry



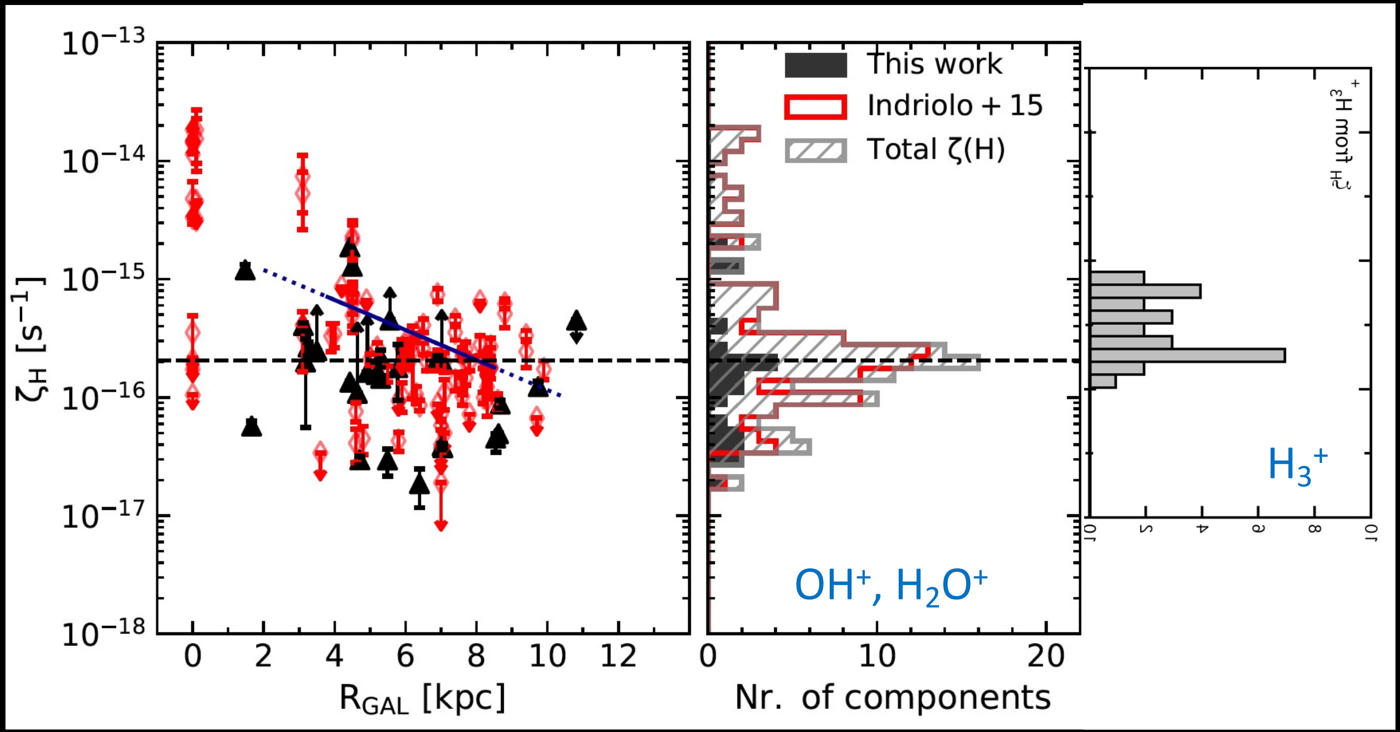
Taken from Jacob et al. 2022b.

- Serendipitous discovery in the Crab Nebula *(Barlow et al. 2013)*
- Identified in ubiquitous absorption at 617.525 GHz *(Schilke et al. 2014)*
- Survival → low molecular fractions (f_{H2} ~ 10^{-3})
- Absorption spectroscopy → robust measurements of column density



Taken from Jacob et al. 2020a.

Herschel survey of Galactic OH^+ and H_2O^+



- Cosmic-ray ionization rate of atomic H toward specific velocity components is derived by balancing the steady state chemistry.

- Average ionization rate,

$$\zeta_p = (2.2 \pm 0.3)\times10^{-16}\ \mathrm{s}^{-1}$$

- In good agreement with values derived using H_3^+ ★

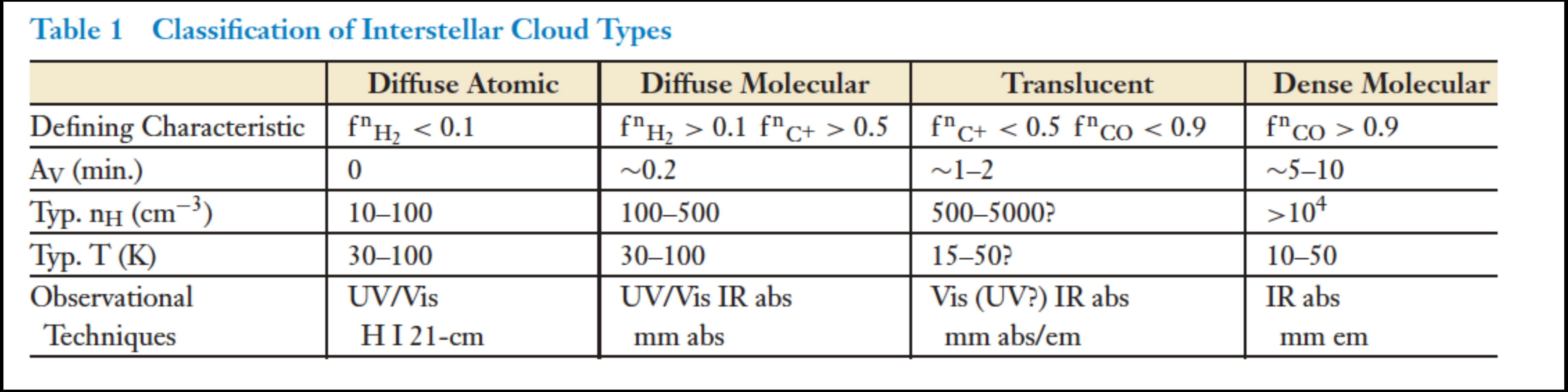
Adapted from Indriolo et al. 2015 and Jacob et al. 2020.

Chemical models by *Neufeld & Wolfire (2017)* suggest that the cosmic ray ionization rates in diffuse molecular clouds marginally decrease with cloud extinction for $A_v \geq 0.5$.

Cosmic-ray ionization rate inferred from *observations* of the local ISM

(Discussed in David Neufeld's talk yesterday)

Taken from Snow & McCall 2008



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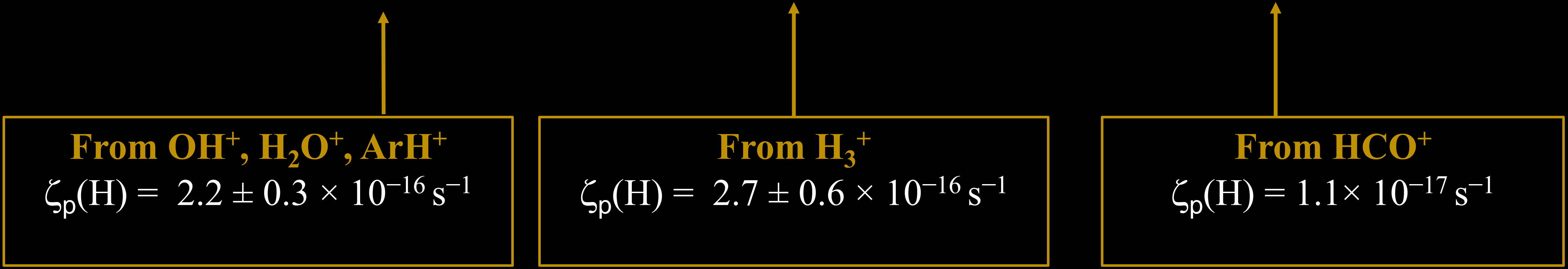

From OH^+, H_2O^+, ArH^+
$\zeta_p(H) = 2.2 \pm 0.3 \times 10^{-16}\ s^{-1}$

From H_3^+
$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}\ s^{-1}$

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Other OH^+ measurements- *EDIBLES*

(ESO Diffuse Interstellar bands large exploration survey)

- UV absorption line measurements toward 10 nearby stars *(Bacalla et al. 2019)* via the (0,0) and (1,0) $A^3\Pi - X^3\Sigma^-$ electronic bands of OH^+ near 3583 Angstrom

- Derived the cosmic ray ionization rate using N_H estimated from:

1. Direct measurements of N(H) and $N(H_2)$ (available in 5 stars)
2. E(B-V) (available in 10 stars)
3. N(KI) (available in 8 stars)

$\zeta_p = 8.5\times10^{-16}$ s^{-1}

$\zeta_p = 8.5\times10^{-16}$ s^{-1}

$\zeta_p = 7.5\times10^{-16}$ s^{-1}

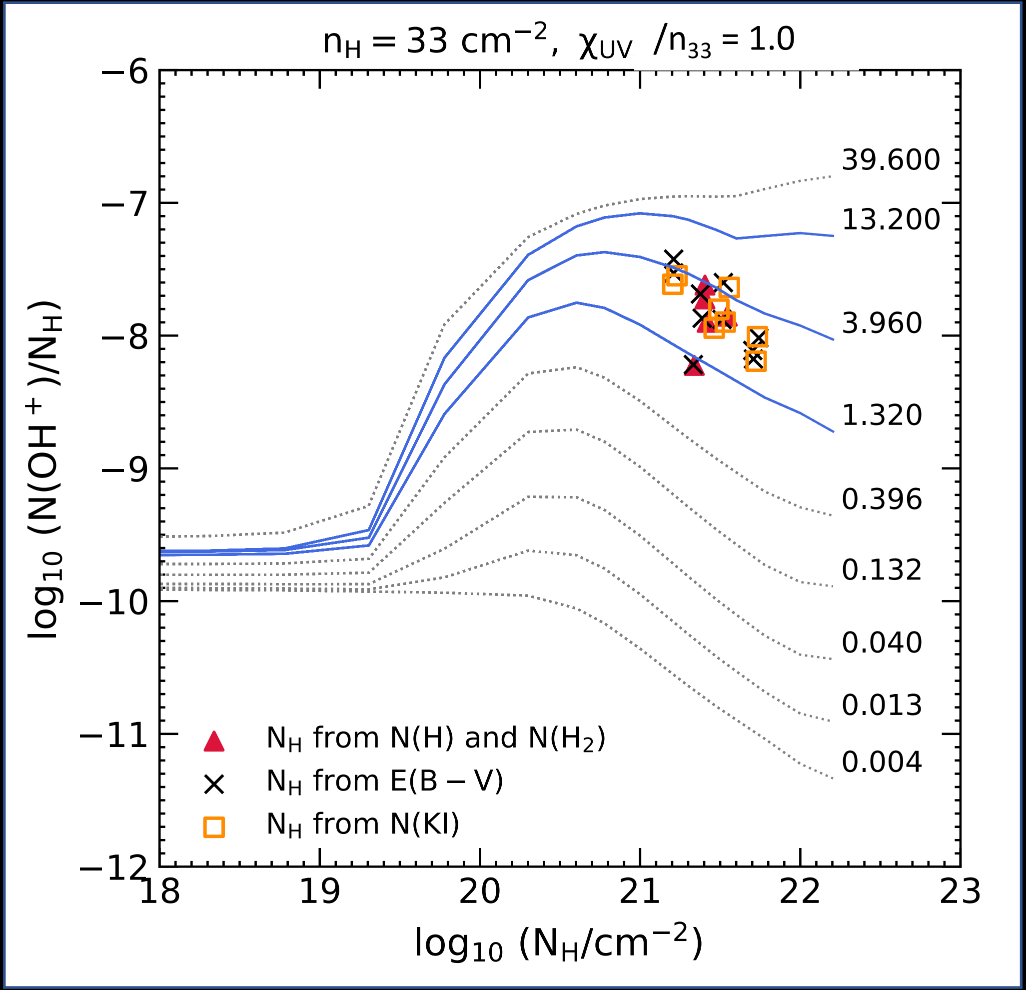
Inconsistent with the ζ_p derived using sub-mm OH^+ measurements

★ *Bacalla et al. 2019* assumed a fixed molecular fraction!

Resolving ζ_p derived from different transitions of OH^+

- Using the updated 1-D slab models presented in *Neufeld & Wolfire 2017*

(discussed yesterday in David Neufeld's talk)



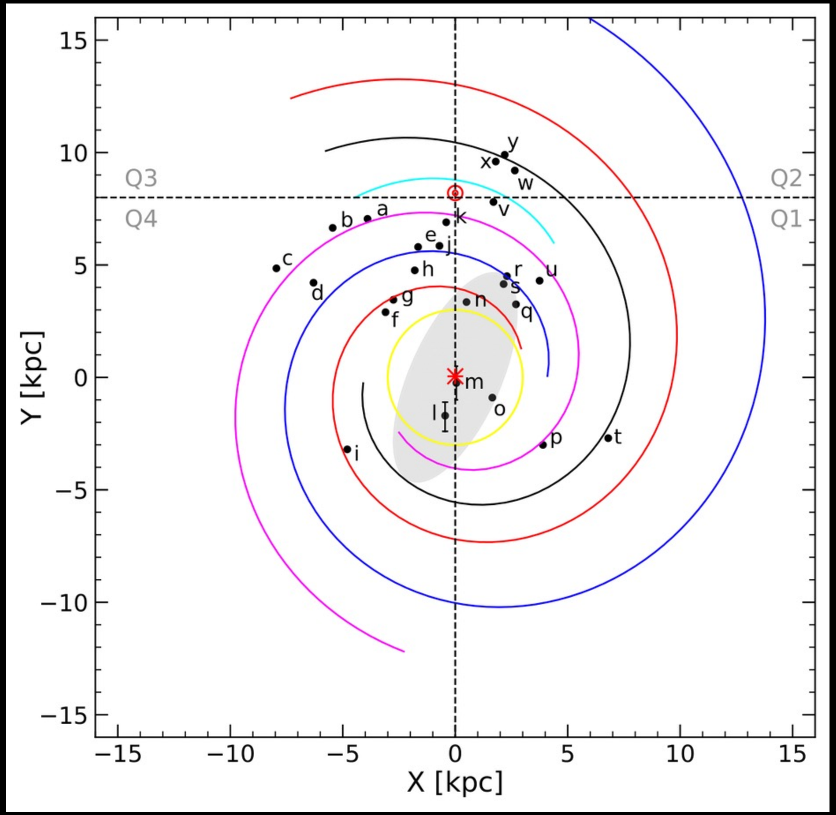
New $\zeta_p = (2.5 \pm 1.5) \times 10^{-16}\ s^{-1}$

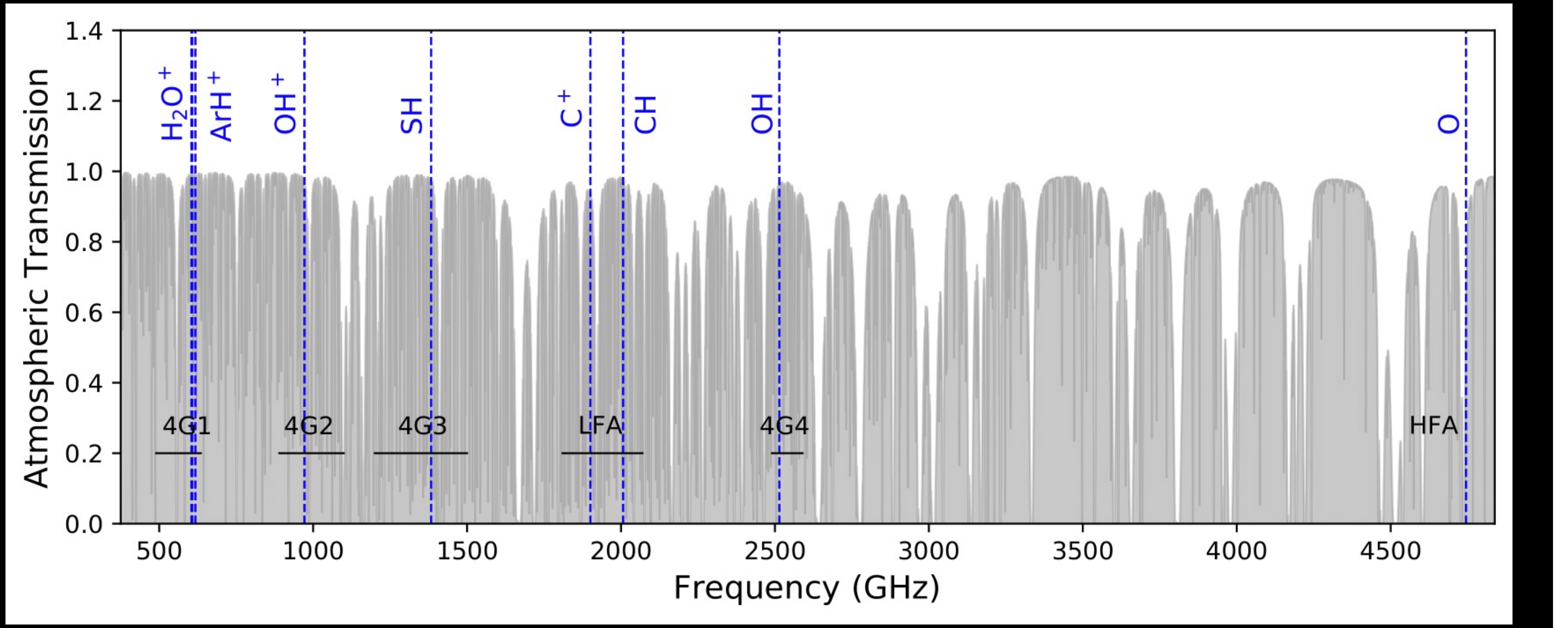
Cosmic ray ionization rates derived from UV and sub-mm OH^+ observations are perfectly consistent!

The *future** of OH^+ observations

Characterizing the Galactic ISM with observations of hydrides (ArH^+, H_2O^+, OH^+, SH, CH, OH) and other small molecules

- High resolution spectroscopic observations using upGREAT and 4GREAT
- With three tunings to disentangle any sideband contamination
- 25 Galactic sightlines

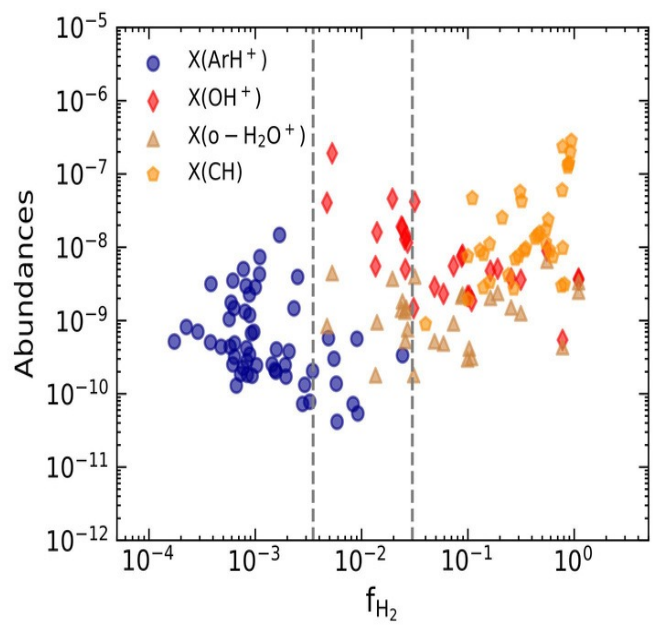




Goal

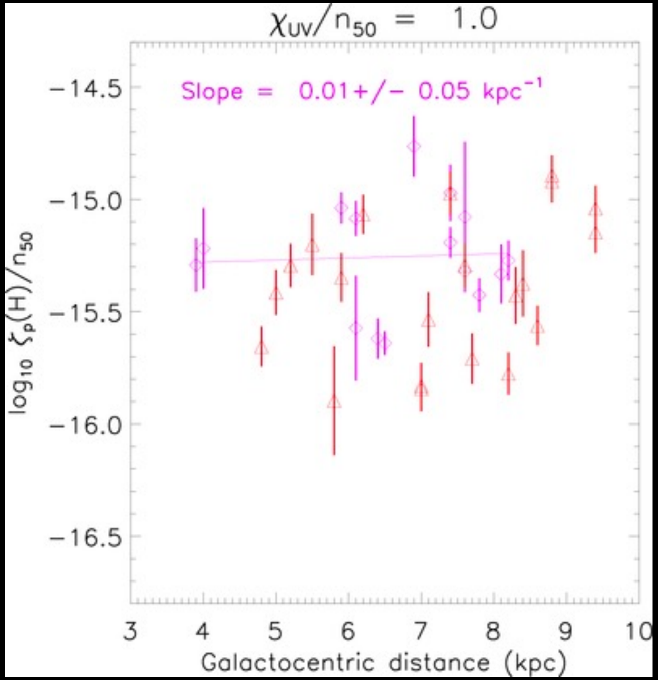
To understand how molecular clouds are formed and the processes that lead to the transition from atomic to molecular gas

- Distribution of molecular fraction in different ISM phases



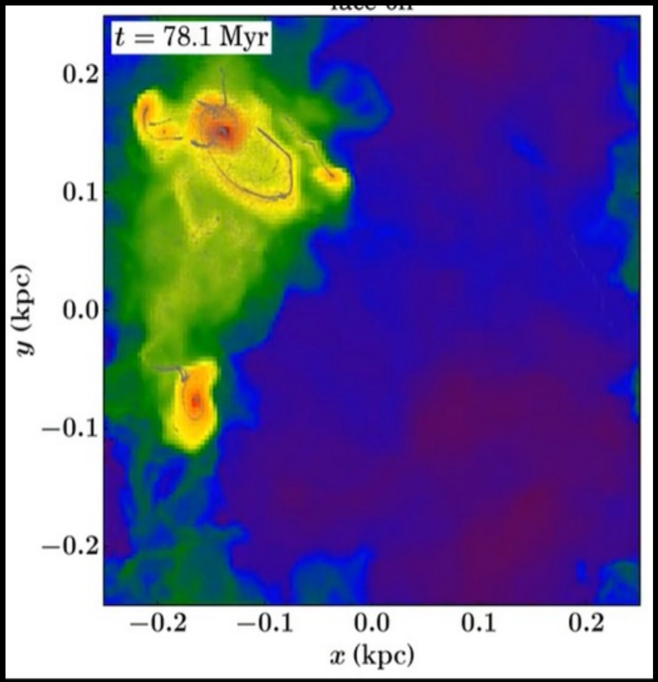
Taken from Jacob et al. (2020b)

- Variation of comic-ray ionization across Galactocentric distances



Taken from Neufeld & Wolfire 2017

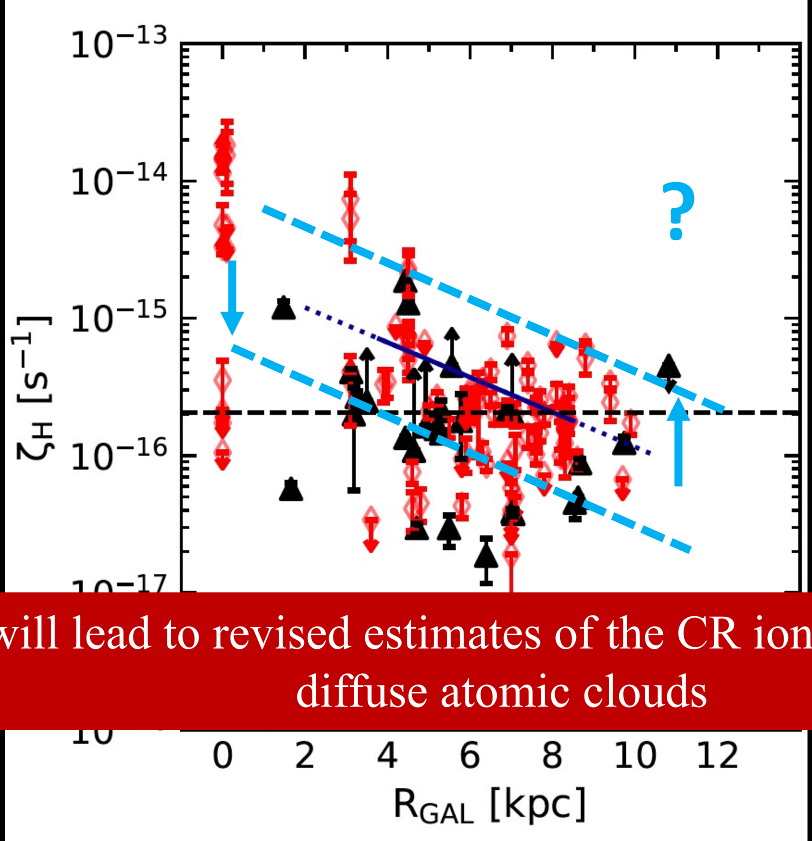
- Nature of turbulence in the ISM and its dissipation



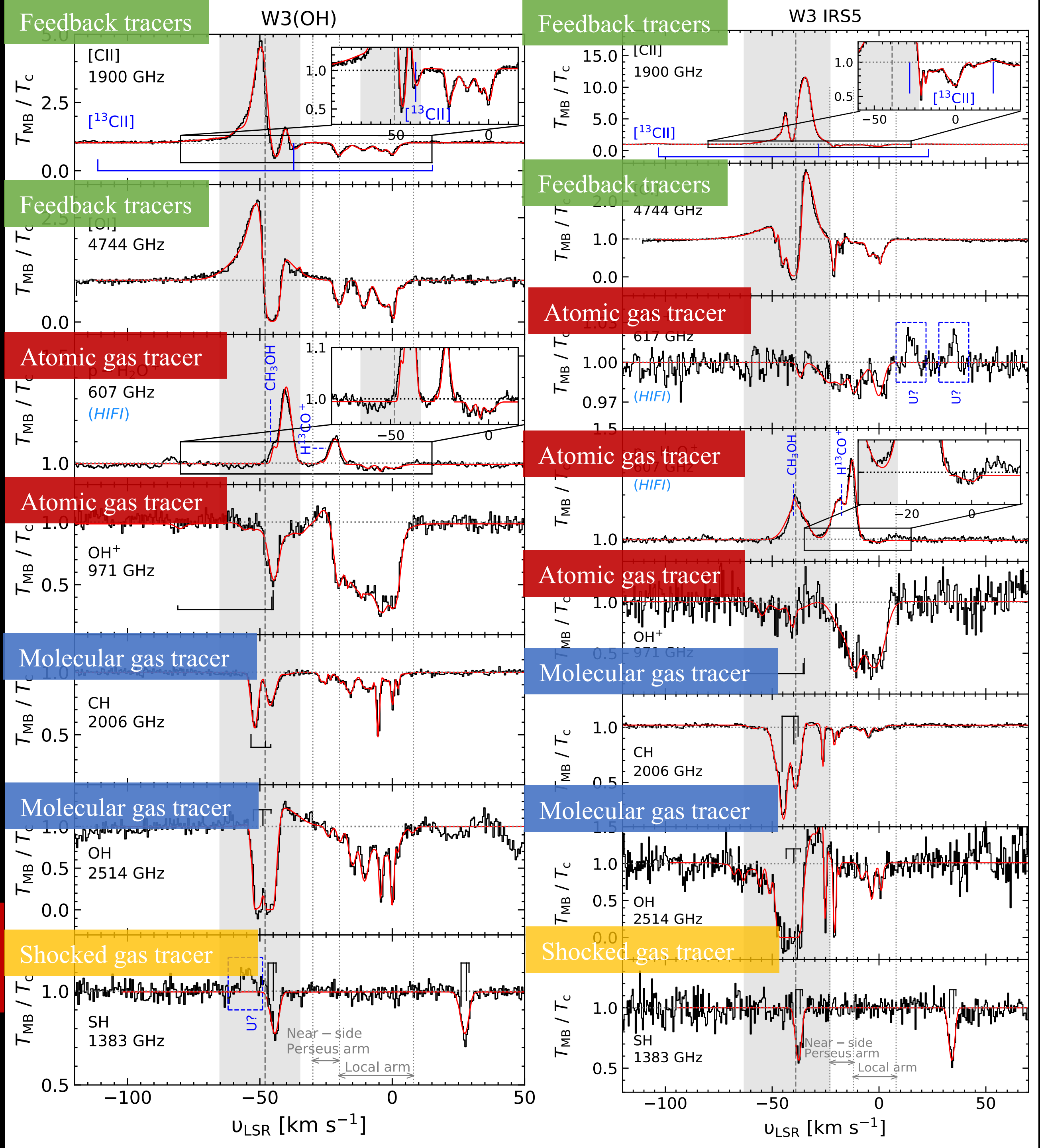
SILCC Simulation

The *future* of OH$^+$ observations

- HyGAL adds more data points
- New measurements of rotationally cold OH$^+$ dissociative recombination rate (CSR, Heidelberg; Kalosi et al. in prep)



→ will lead to revised estimates of the CR ionization rate in diffuse atomic clouds



Feedback tracers

Feedback tracers

Atomic gas tracer

Atomic gas tracer

Molecular gas tracer

Molecular gas tracer

Shocked gas tracer

Feedback tracers

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Atomic gas tracer

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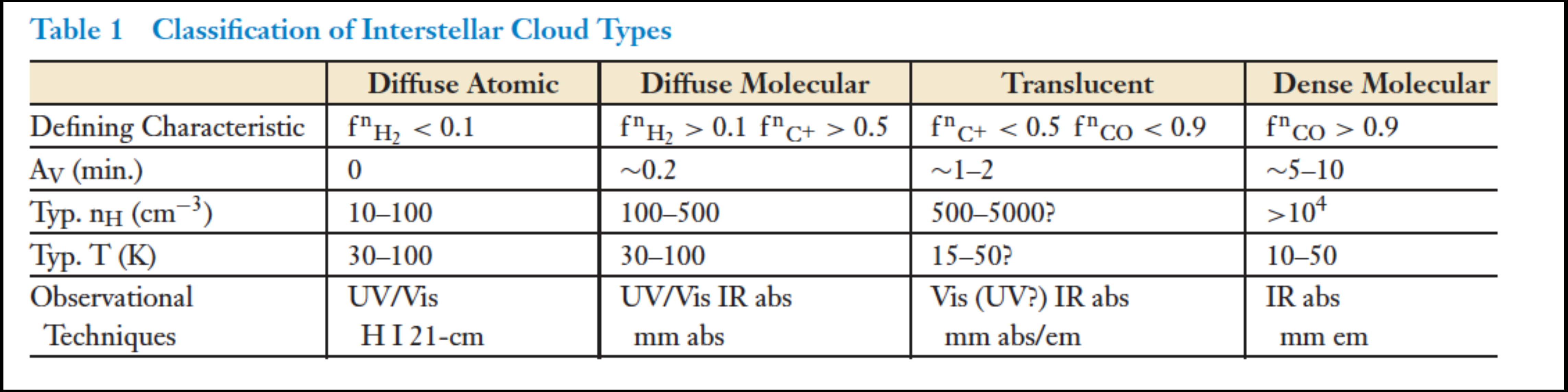

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From OH^+, H_2O^+, ArH^+

$\zeta_p(H)$ maybe greater

From H_3^+

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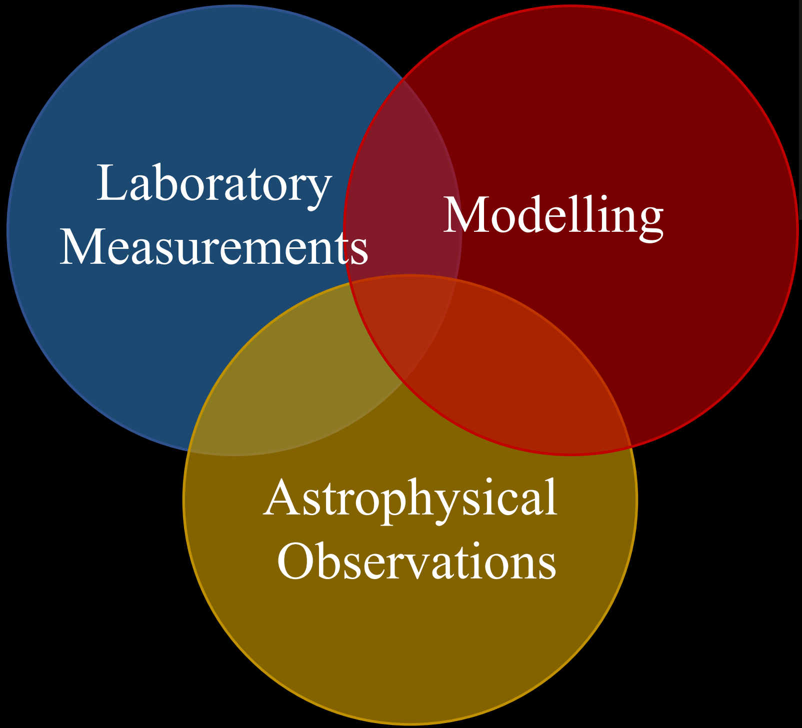
Summary

- Hydride ions like OH+, H_2O^+ and ArH^+ are excellent tracers of the cosmic-ray ionization rate in diffuse atomic gas

- Resolved inconsistencies between ζ_p(H) derived from UV and sub-mm OH^+ transitions

- New constraints from HyGAL observations
  + new measurements of the OH^+ dissociative recombination



Thank you!