Parsec-scale cosmic-ray ionisation in Orion

Socci A., Sabatini G., Padovani M., Bovino S.
& EMERGE-ERC Team

universität wien

CR3: The salt of the star-formation recipe, 24.10.24

European Research Council
Established by the European Commission

Outline

- Introduction
- Observations in Orion
- Analysis & Results
- Outlooks
- Summary

Introduction

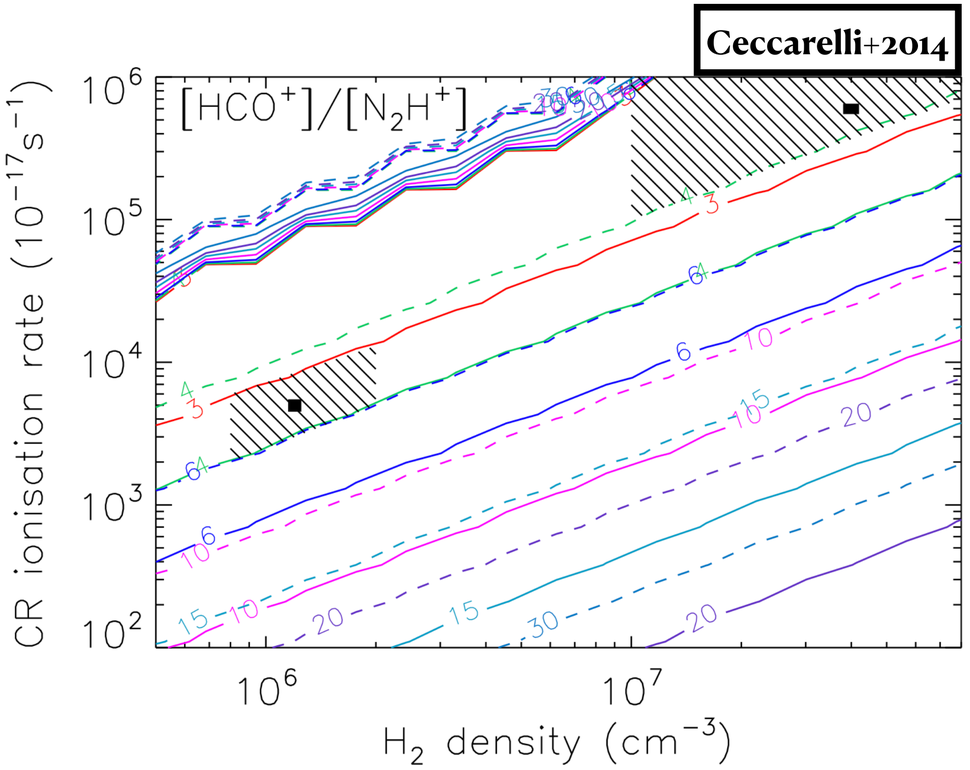
Context

- CRs influence the chemistry and dynamics of dense molecular clouds;
- Challenge to observe key species (e.g. H_3^+);

Introduction

Context

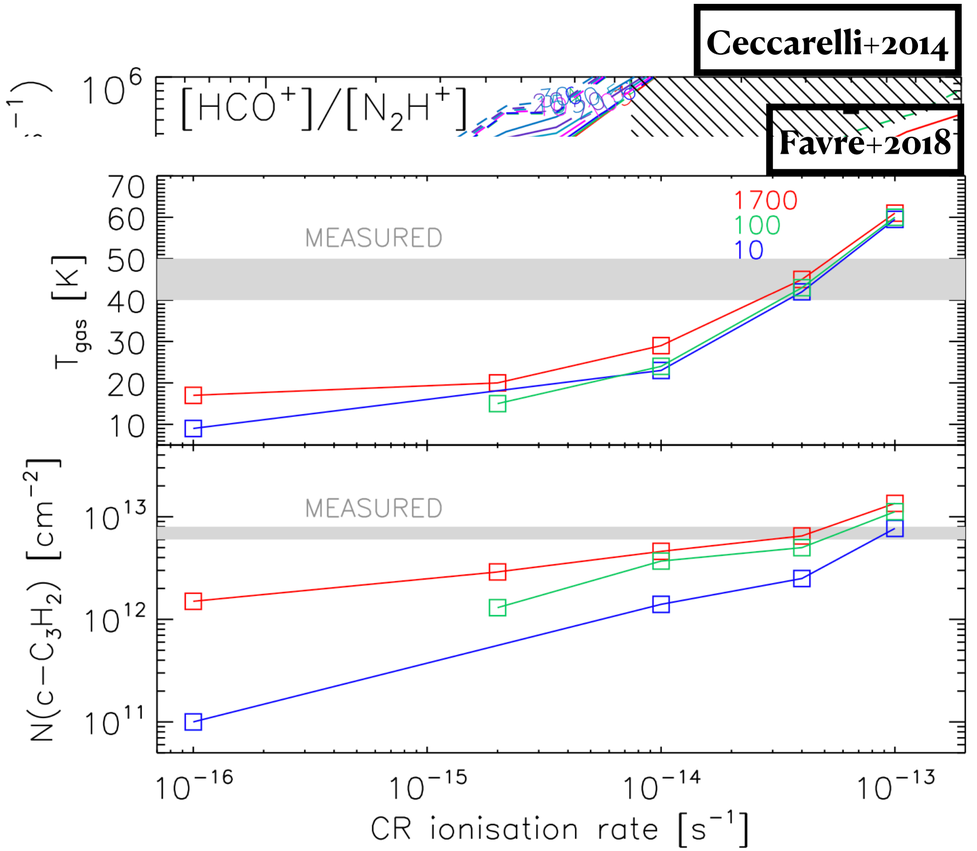
- CRs influence the chemistry and dynamics of dense molecular clouds;
- Challenge to observe key species (e.g. H_3^+, H_3^+O);
- Wide use of proxies:
  - <u>Ions</u>;



Introduction

Context

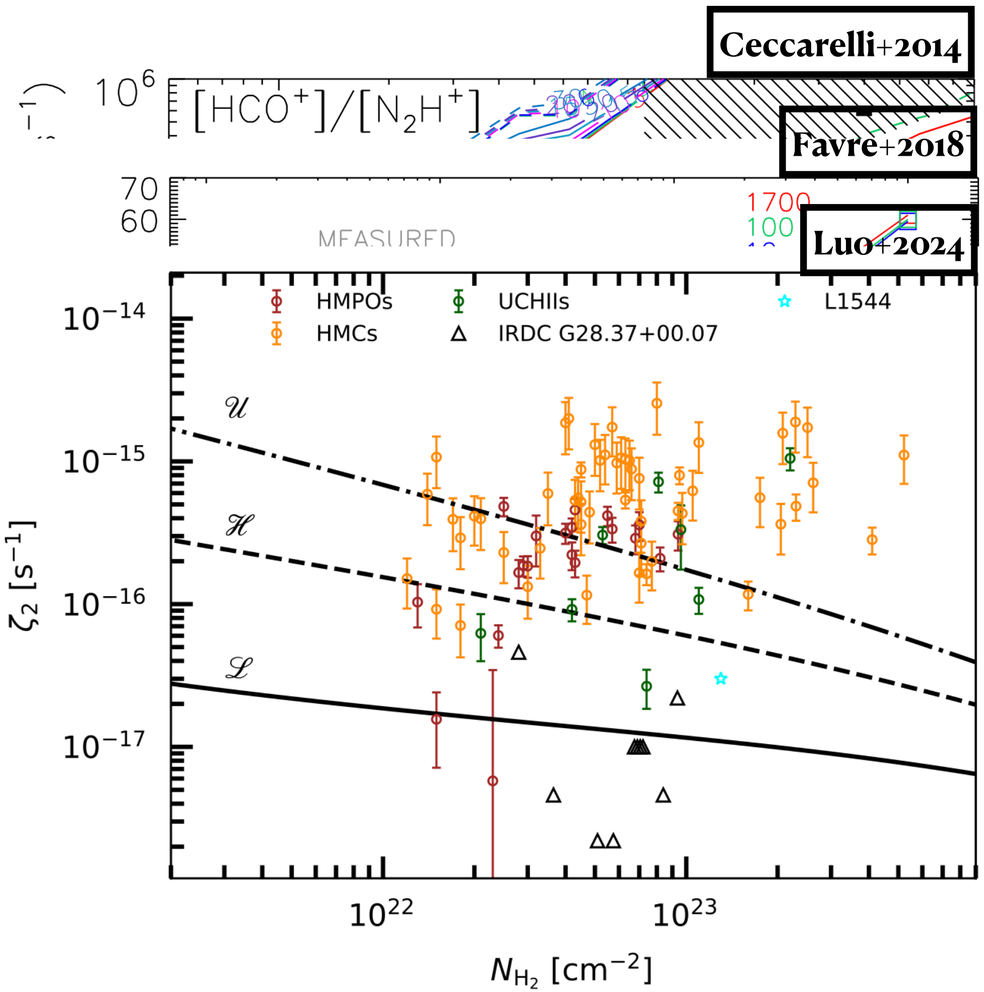
- CRs influence the chemistry and dynamics of dense molecular clouds;
- Challenge to observe key species (e.g. H_3^+, H_3^+O);
- Wide use of proxies:
  - Ions;
  - Neutrals;



Introduction

Context

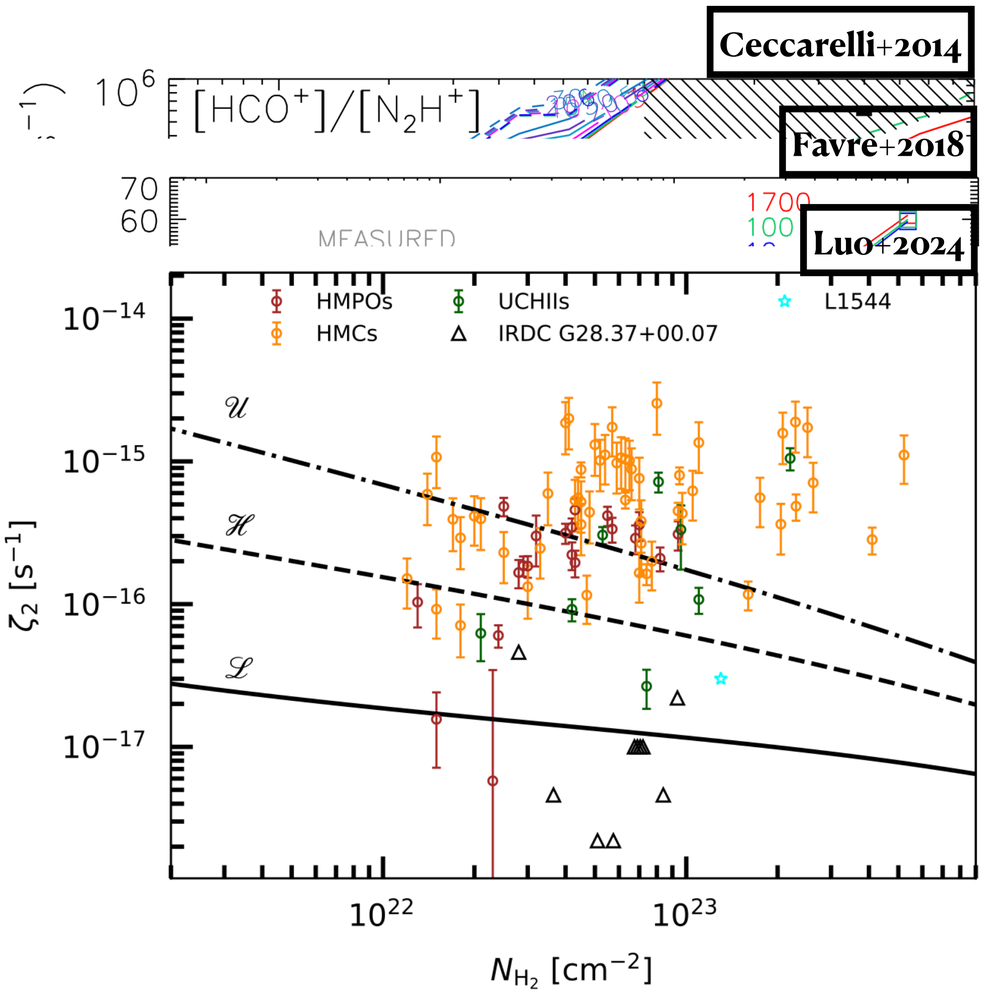
- CRs influence the chemistry and dynamics of dense molecular clouds;
- Challenge to observe key species (e.g. H_3^+, H_3^+O);
- Wide use of proxies:
  - Ions;
  - Neutrals;
  - A combination of the latter;



Introduction

Context

- CRs influence the chemistry and dynamics of dense molecular clouds;
- Challenge to observe key species (e.g. H_3^+, H_3^+O);
- Wide use of proxies:
  - Ions;
  - Neutrals;
  - A combination of the latter;
- Analytical method with o-H_2D^+ (Bovino+2020);



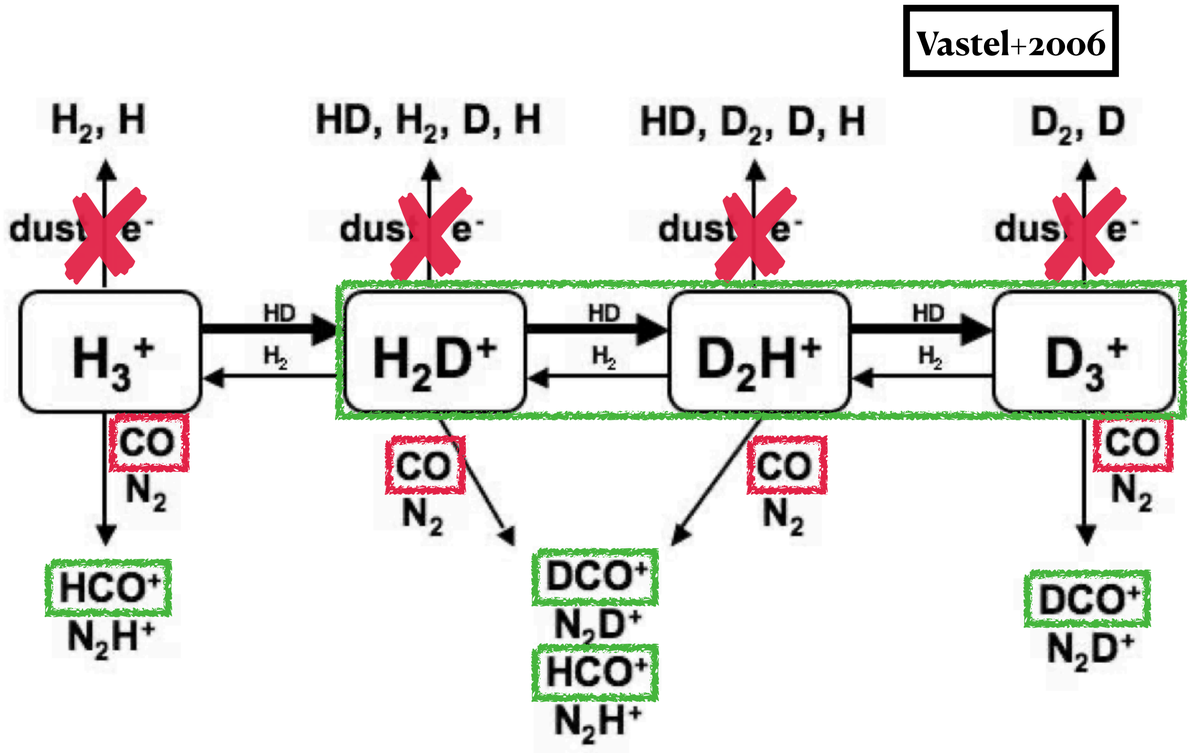
Introduction

Context

- Assumptions:
  - Main destruction pathway: CO;
  - o-H_2D^+ proxies H_3^+;

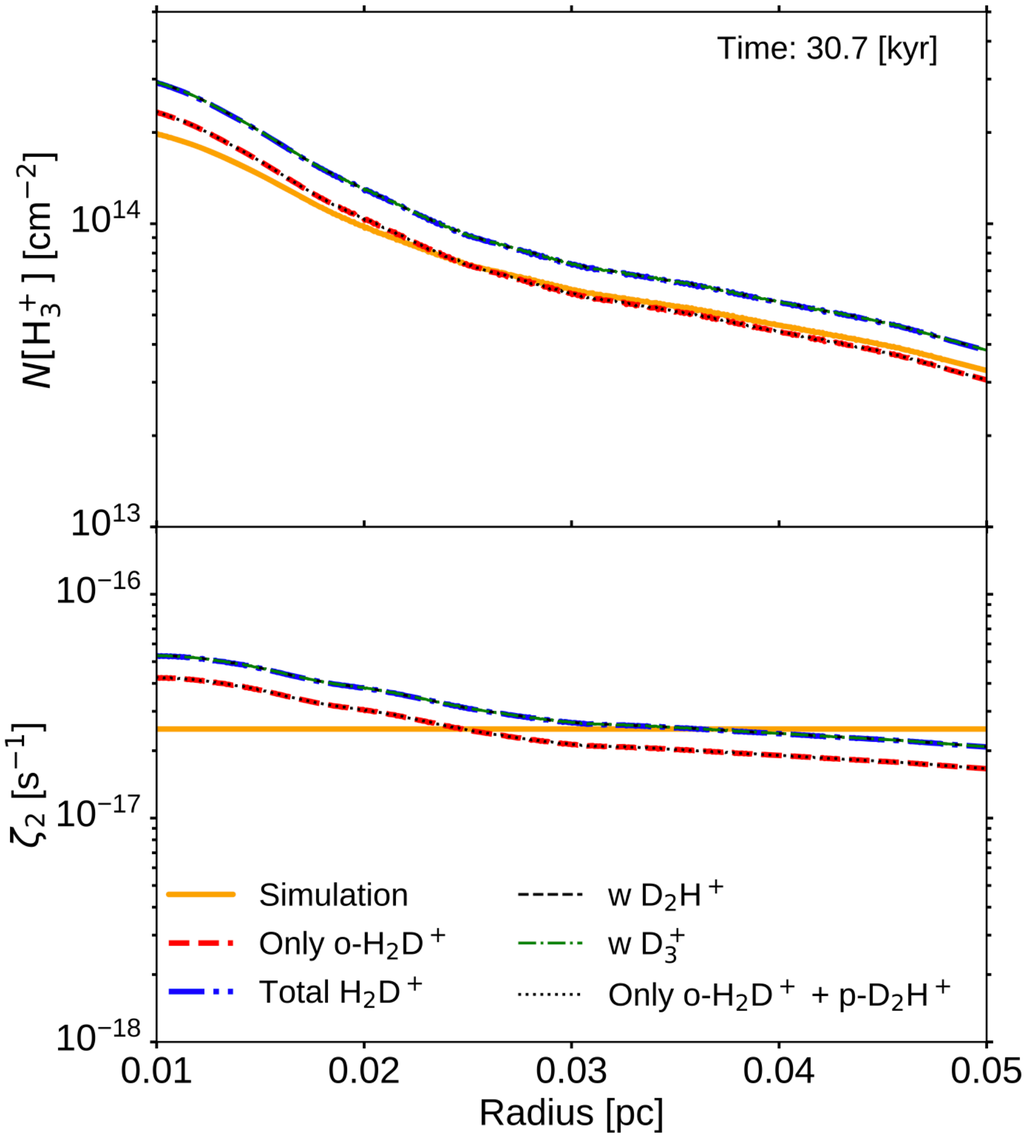
$$\zeta_2 = \bar{\alpha} k_{CO}^{H_3^+} \frac{N[CO]\,N[H_3^+]}{N[H_2]} \frac{1}{L}$$

$$\frac{1}{3} \frac{N[o-H_2D^+]}{R_D}$$

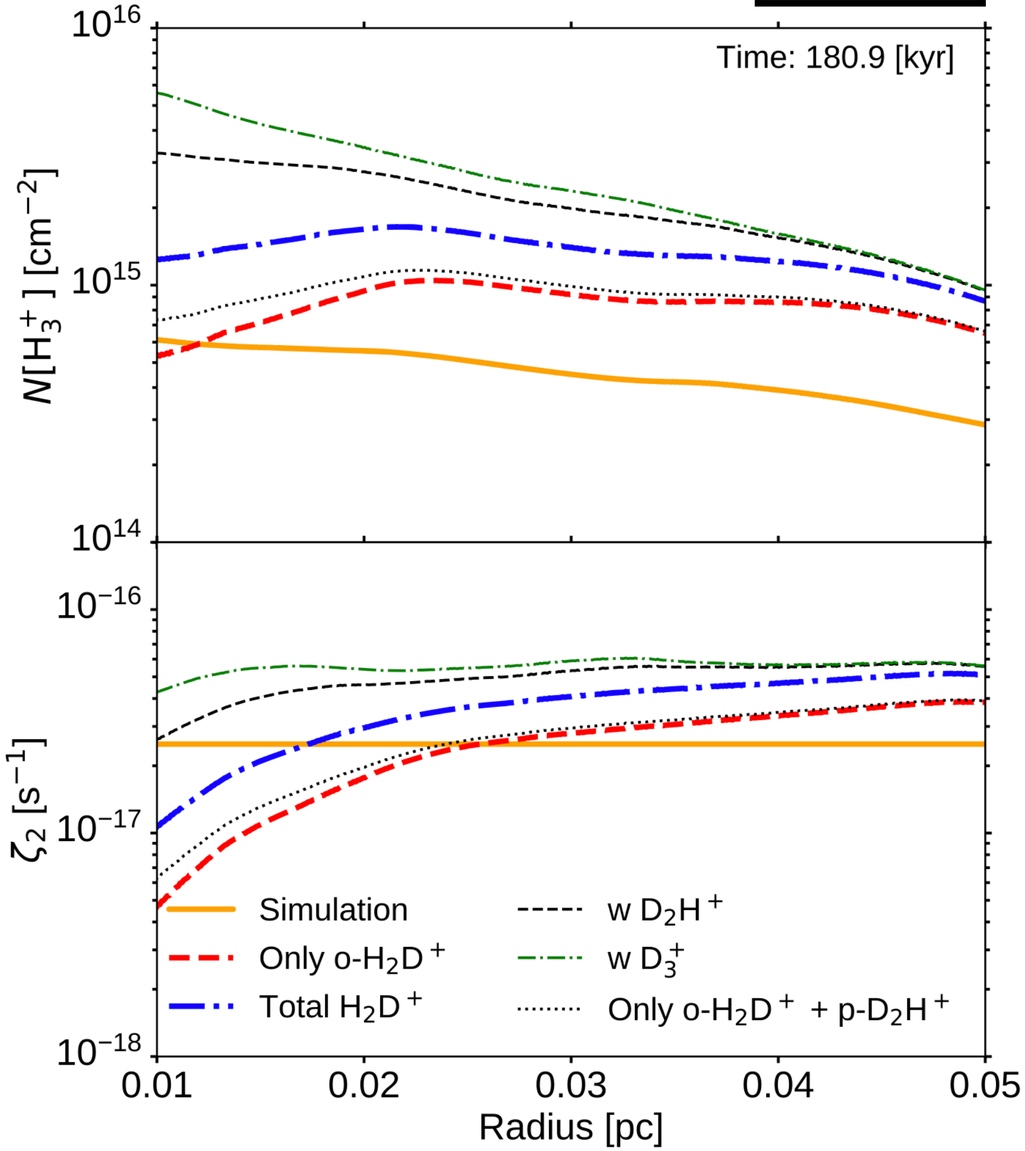


Introduction

Context

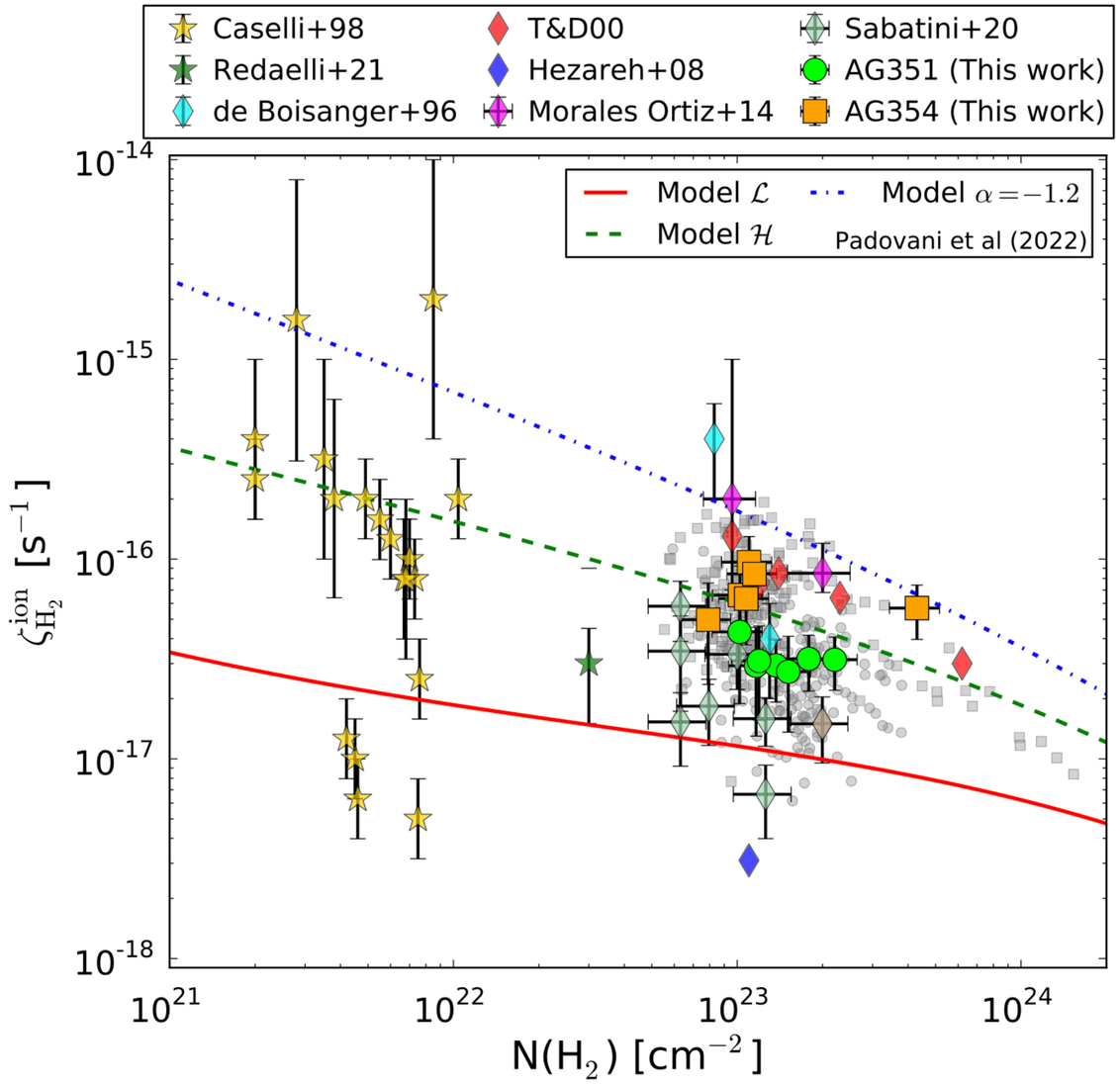


Bovino+2020

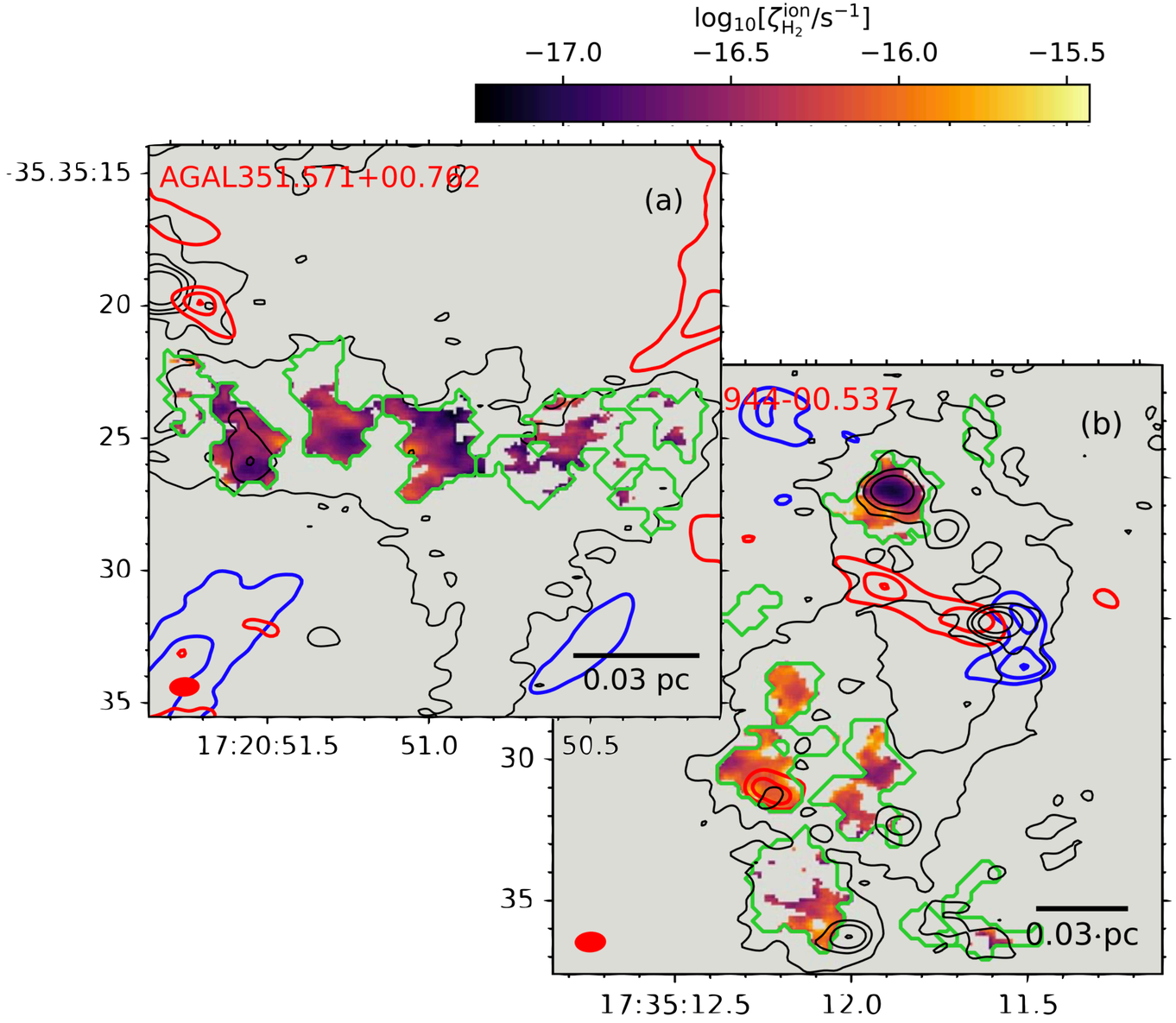


Introduction

Context



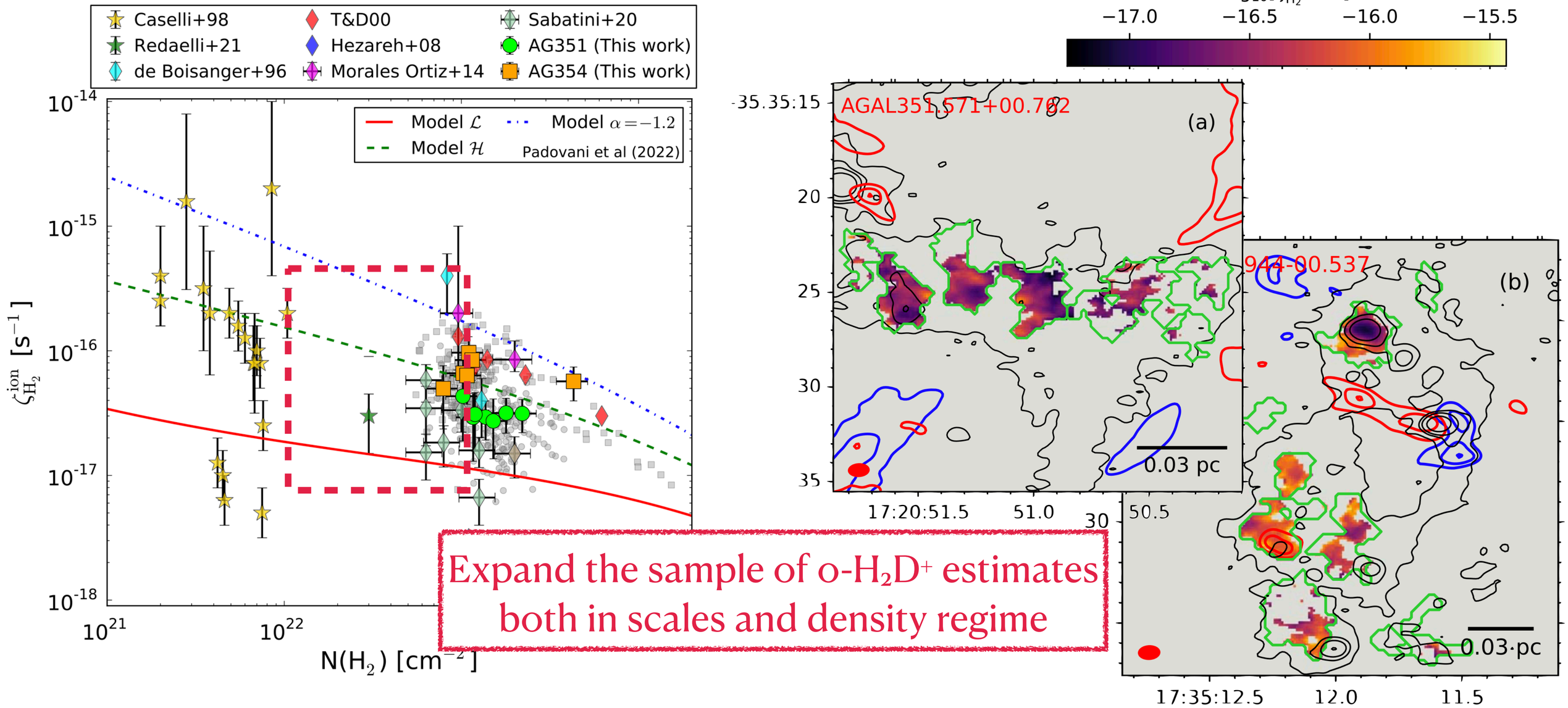
Sabatini+2023



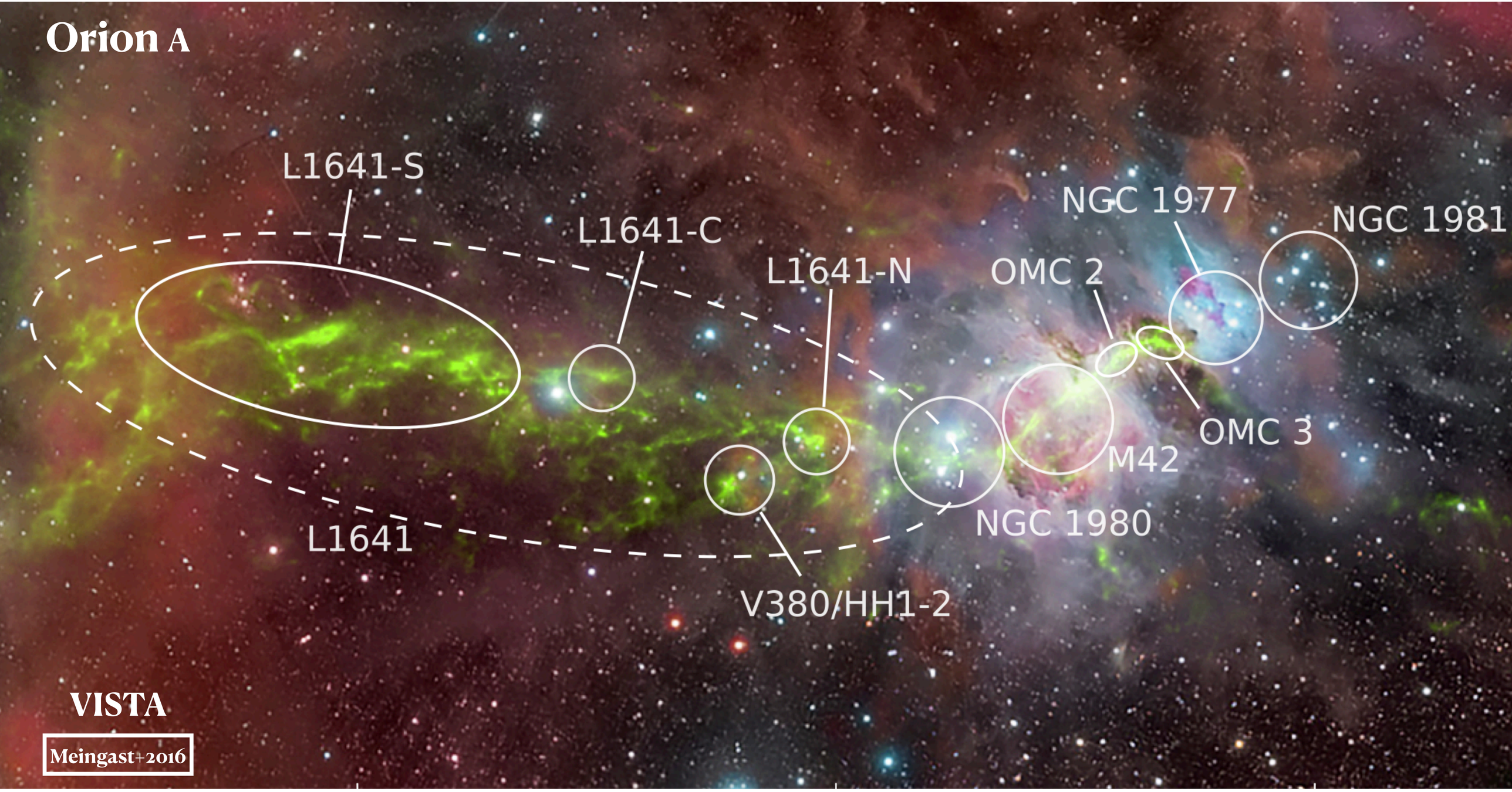
Introduction

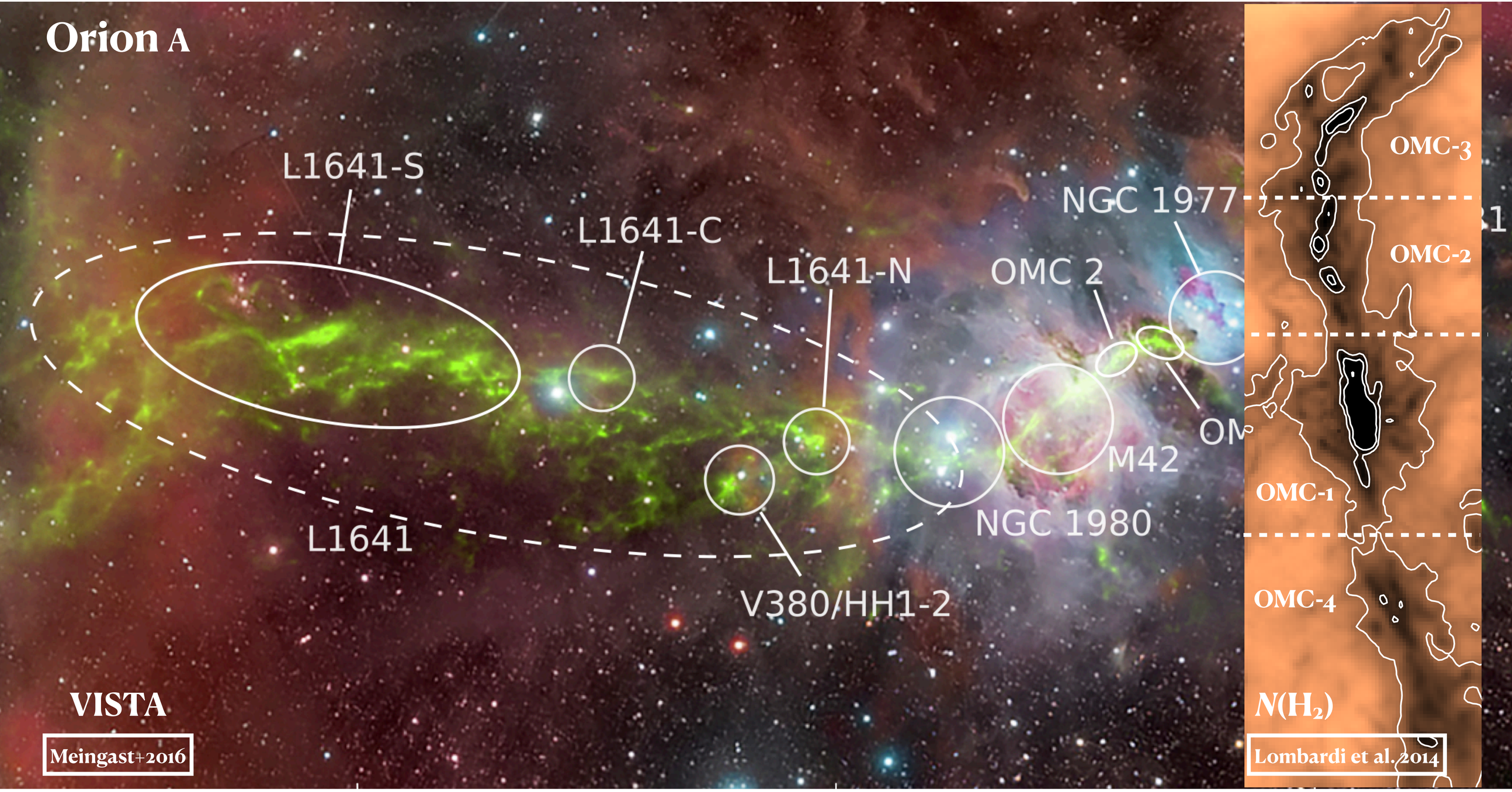
Scientific question

Sabatini+2023



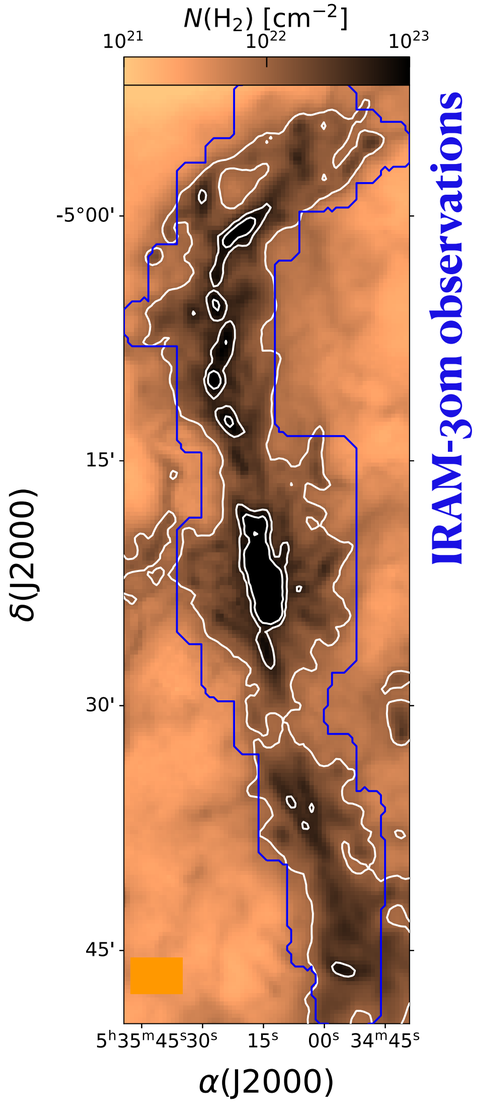
Expand the sample of o-H_2D^+ estimates both in scales and density regime


Orion A
L1641-S
L1641-C
L1641-N
OMC 2
NGC 1977
NGC 1981
OMC 3
M42
NGC 1980
L1641
V380/HH1-2
VISTA
Meingast+2016

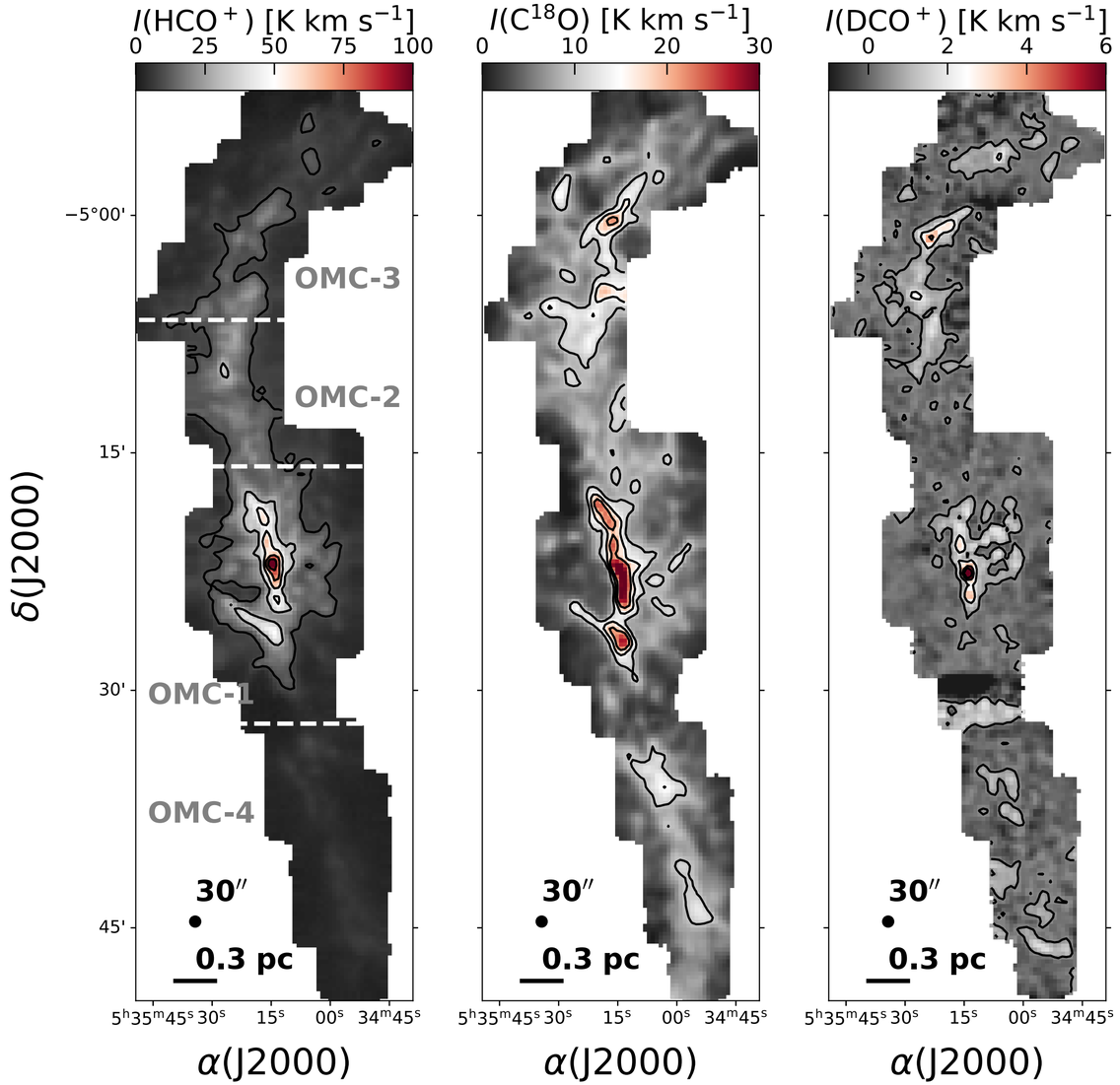

Orion A
L1641-S
L1641-C
L1641-N
OMC 2
NGC 1977
L1641
V380/HH1-2
NGC 1980
M42
OM
OMC-3
OMC-2
OMC-1
OMC-4
VISTA
Meingast+2016
N(H2)
Lombardi et al. 2014

Observations in Orion

The maps

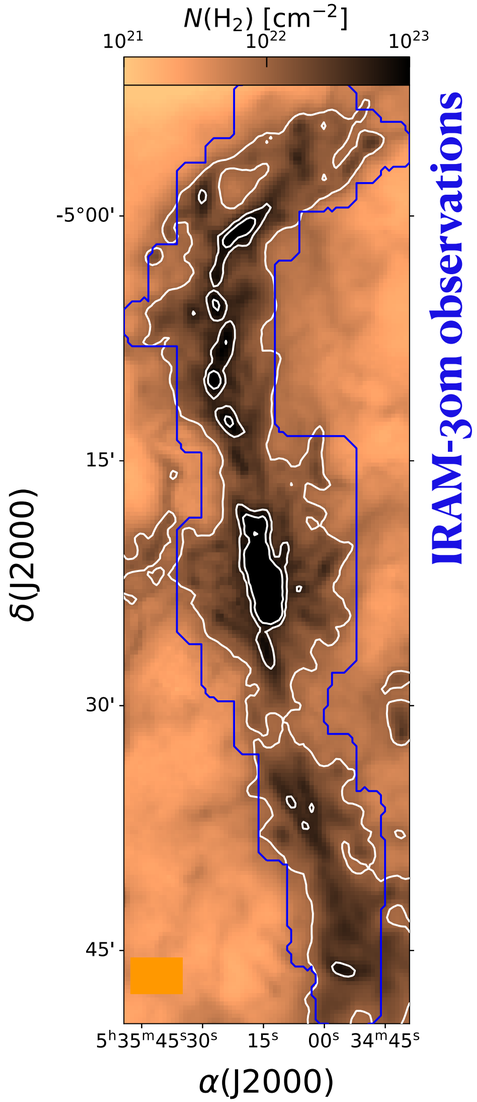


IRAM-30m observations

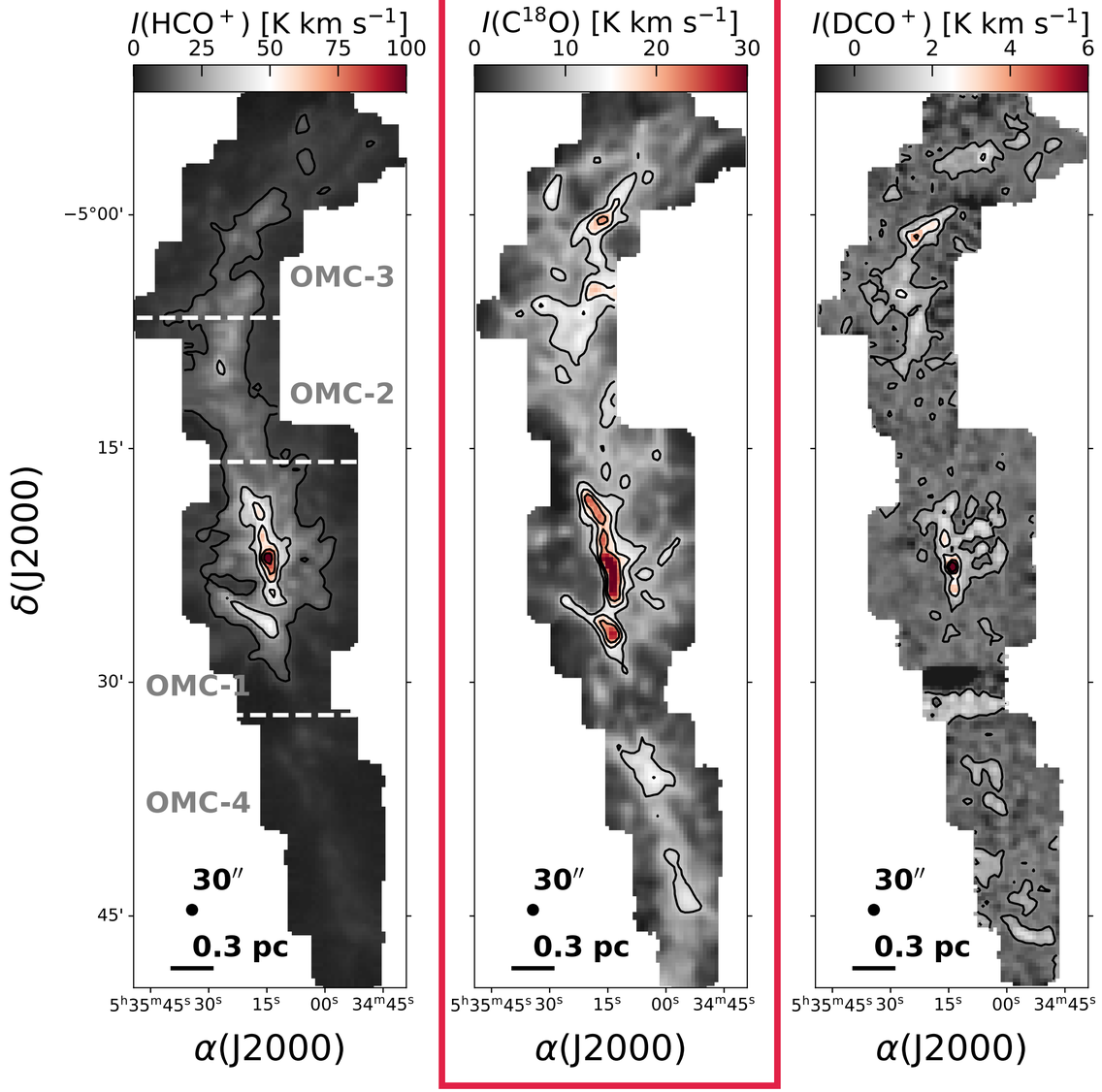


Observations in Orion

Proxy for o-H_2D^+



IRAM-30m observations

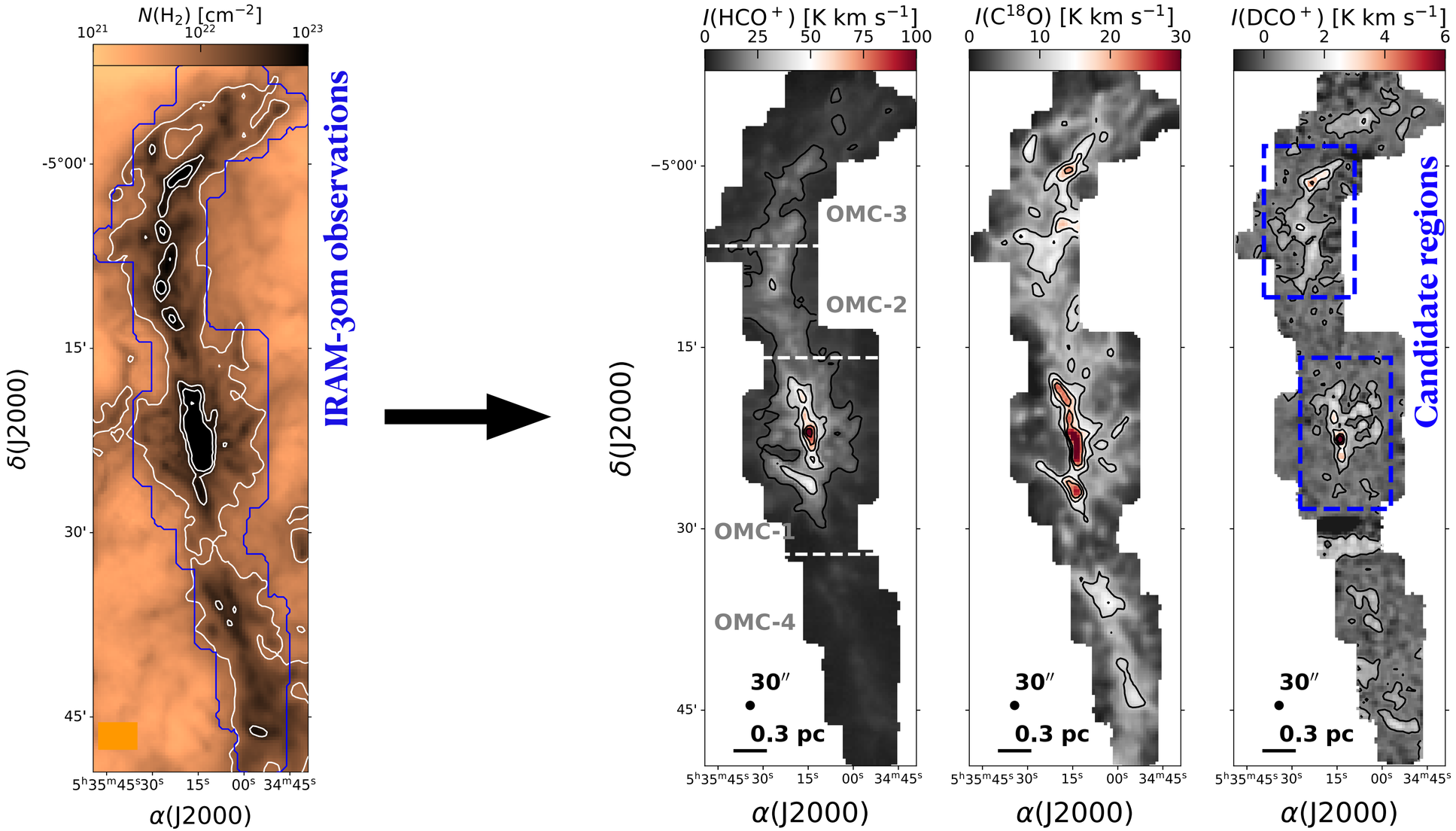


$$\frac{N(\mathrm{o-H_2D^+})}{N(\mathrm{H_2})} = \frac{10^{0.05}\, f_\mathrm{D}}{10^{10.46}}$$

Sabatini+2020

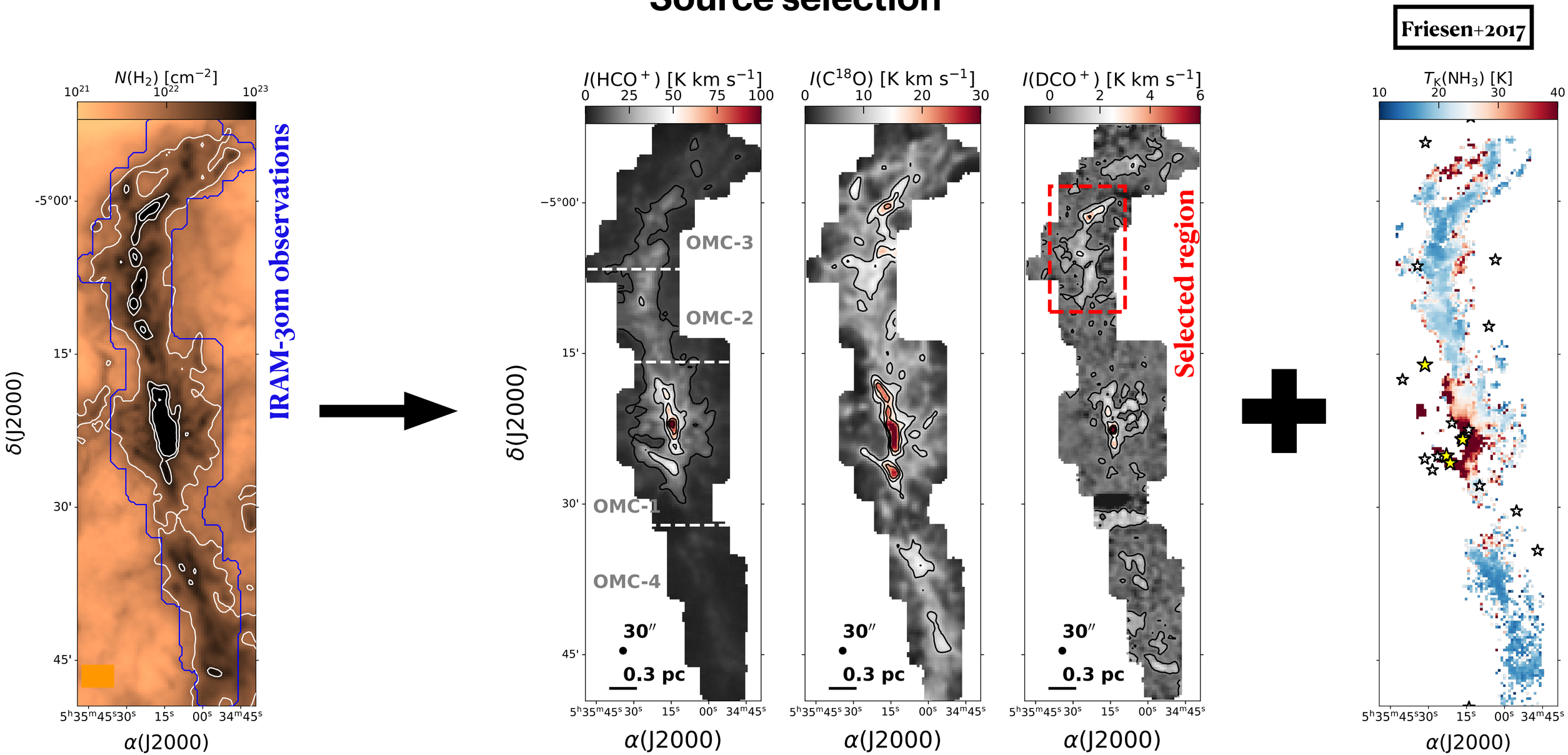
Observations in Orion

Source selection



Observations in Orion

Source selection



Analysis & Results

Method

$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{10^{0.05 f_D - 10.46} \times N(CO)}{3 R_D \times l}$$

- Measured:

$$f_D = \frac{X_0(C^{18}O)\ N(H_2)}{N(C^{18}O)}$$

- optically thin, LTE at T_K (Tafalla+2023);
- $X_0(C^{18}O)$ (Giannetti+2017);

Analysis & Results

Method

$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{10^{0.05 f_D - 10.46} \times N(CO)}{3 R_D \times l}$$

- Measured:
  - $f_D = \dfrac{X_0(C^{18}O)\ N(H_2)}{N(C^{18}O)}$
  - $N(CO) = N(C^{18}O)\ X_{18}^{16}$ [⊙ X_{18}^{16} (Wilson & Rood 1994);

Analysis & Results

Method

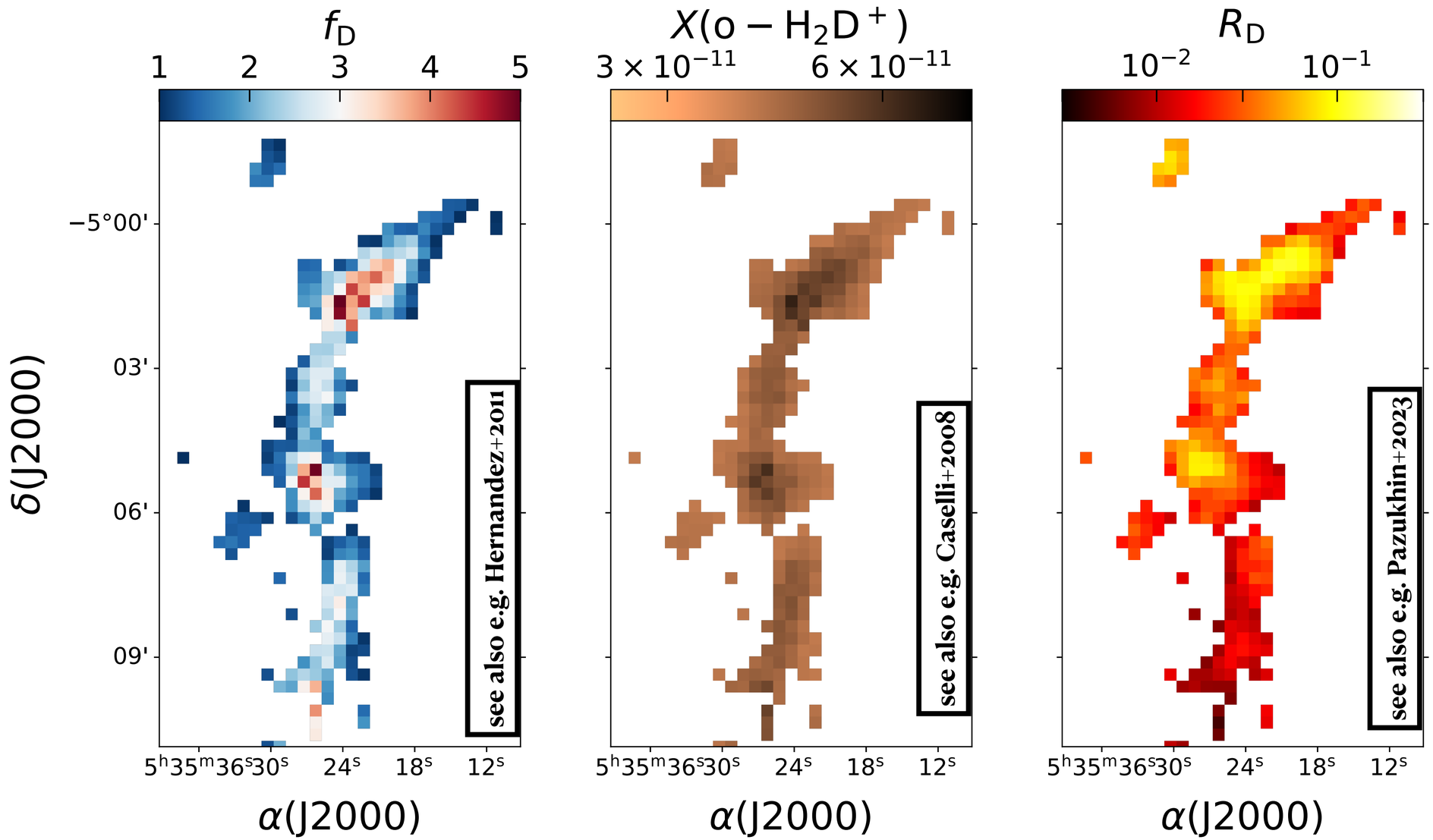
$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{10^{0.05 f_D - 10.46} \times N(CO)}{3 R_D \times l}$$

- Measured:
  - $f_D = \frac{X_0(C^{18}O)\ N(H_2)}{N(C^{18}O)}$
  - $N(CO) = N(C^{18}O)\ X_{18}^{16}$
  - $R_D = \frac{N(DCO^+)}{N(HCO^+)}$

⊙ using RADEX (van der Tak+2007);

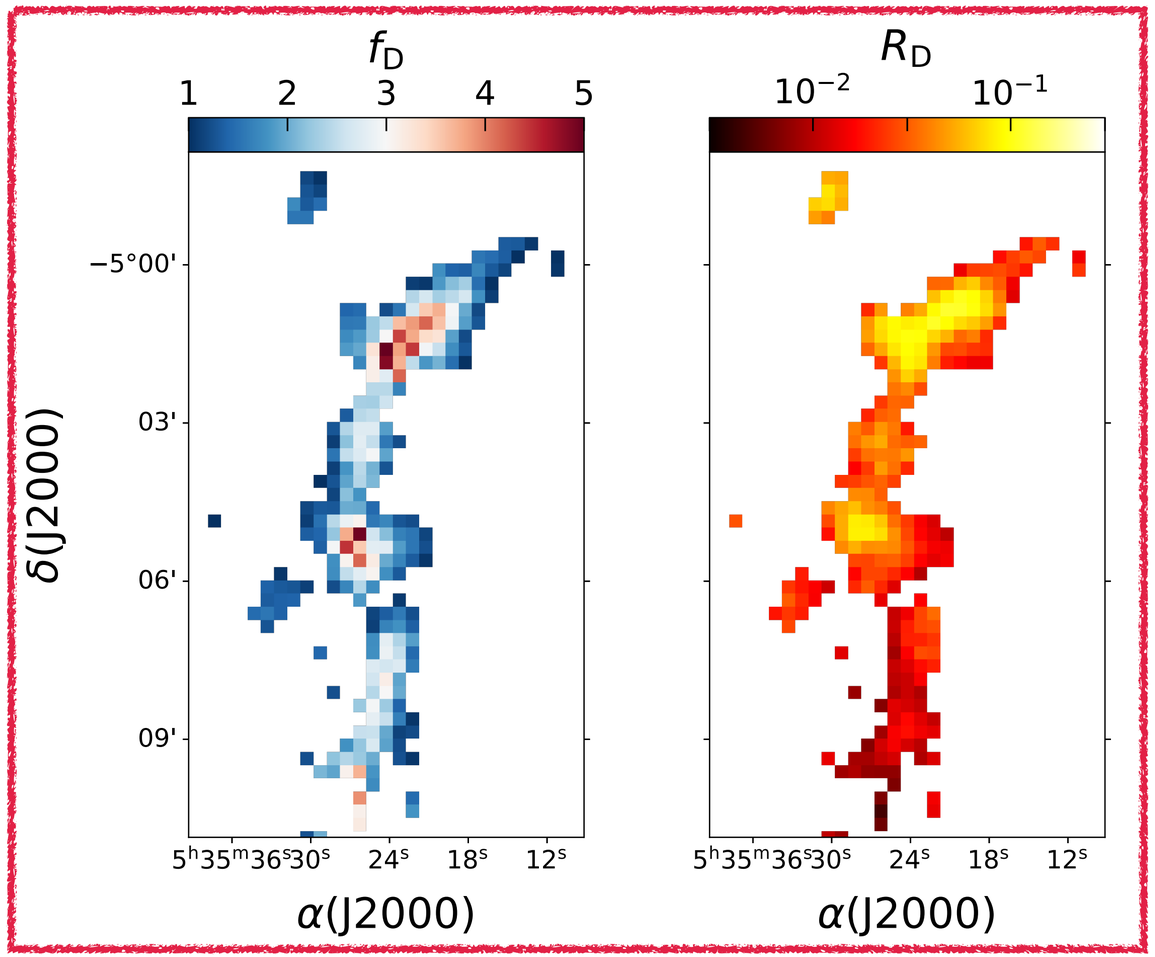
Analysis & Results

Depletion factor, o-H_2D^+ abundance, deuterium fraction

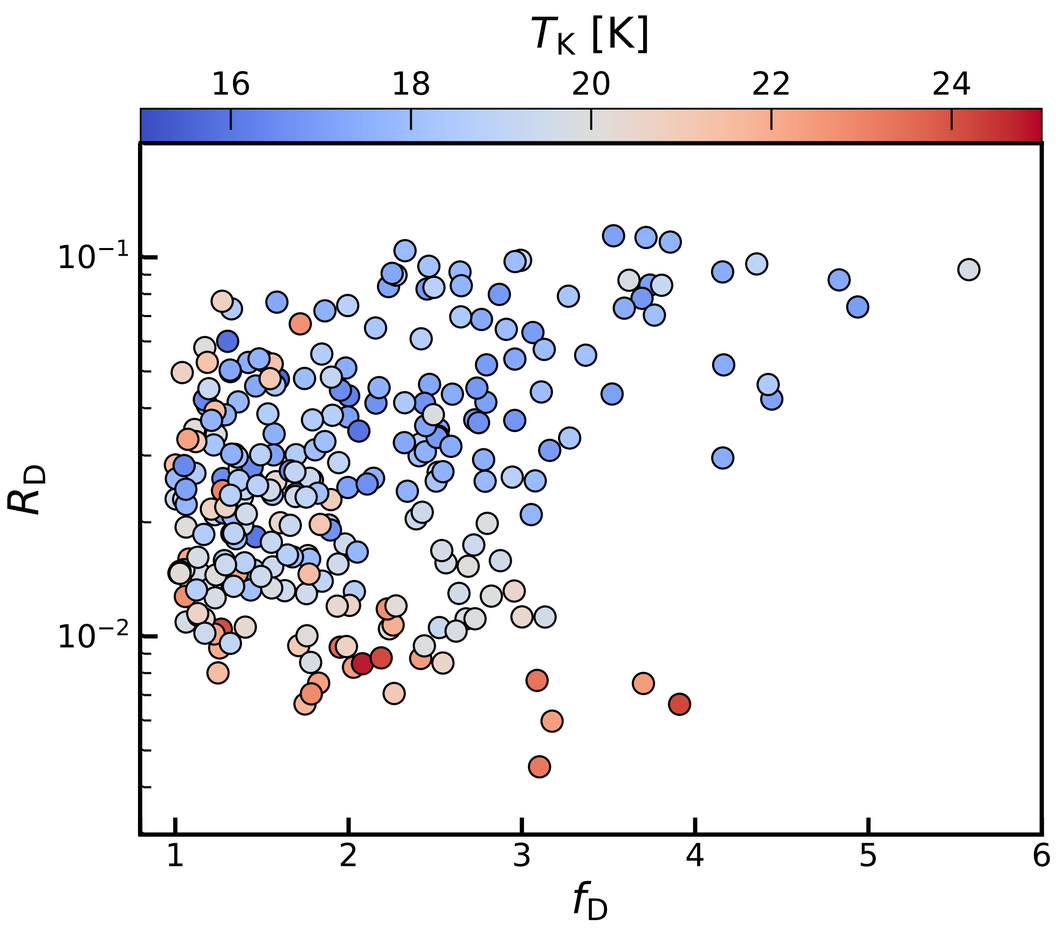


Analysis & Results

Depletion factor vs deuterium fraction



see also Crapsi+2005



Analysis & Results

Method

$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{10^{0.05\, f_D - 10.46} \times N(CO)}{3\ R_D \times l}$$

- Measured:
  - $f_D = \dfrac{X_0(C^{18}O)\ N(H_2)}{N(C^{18}O)}$
  - $N(CO) = N(C^{18}O)\ X_{18}^{16}$
  - $R_D = \dfrac{N(DCO^+)}{N(HCO^+)}$

- Other parameters:
  - $k_{CO}^{o-H_3^+}$ ◉ computed at T_K (Wakelam+12);

Analysis & Results

Method

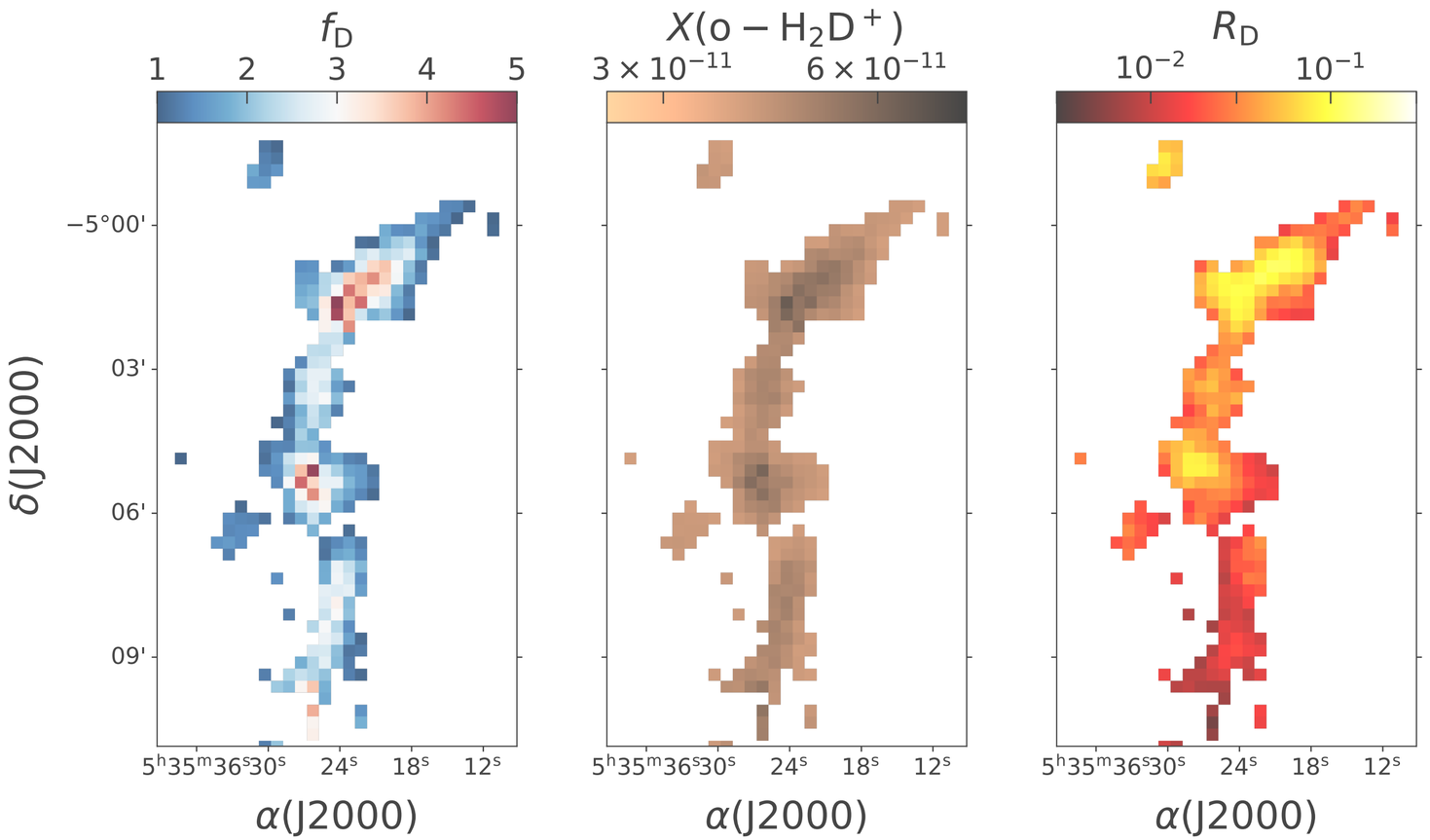
$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{10^{0.05\, f_D - 10.46} \times N(CO)}{3\ R_D \times l}$$

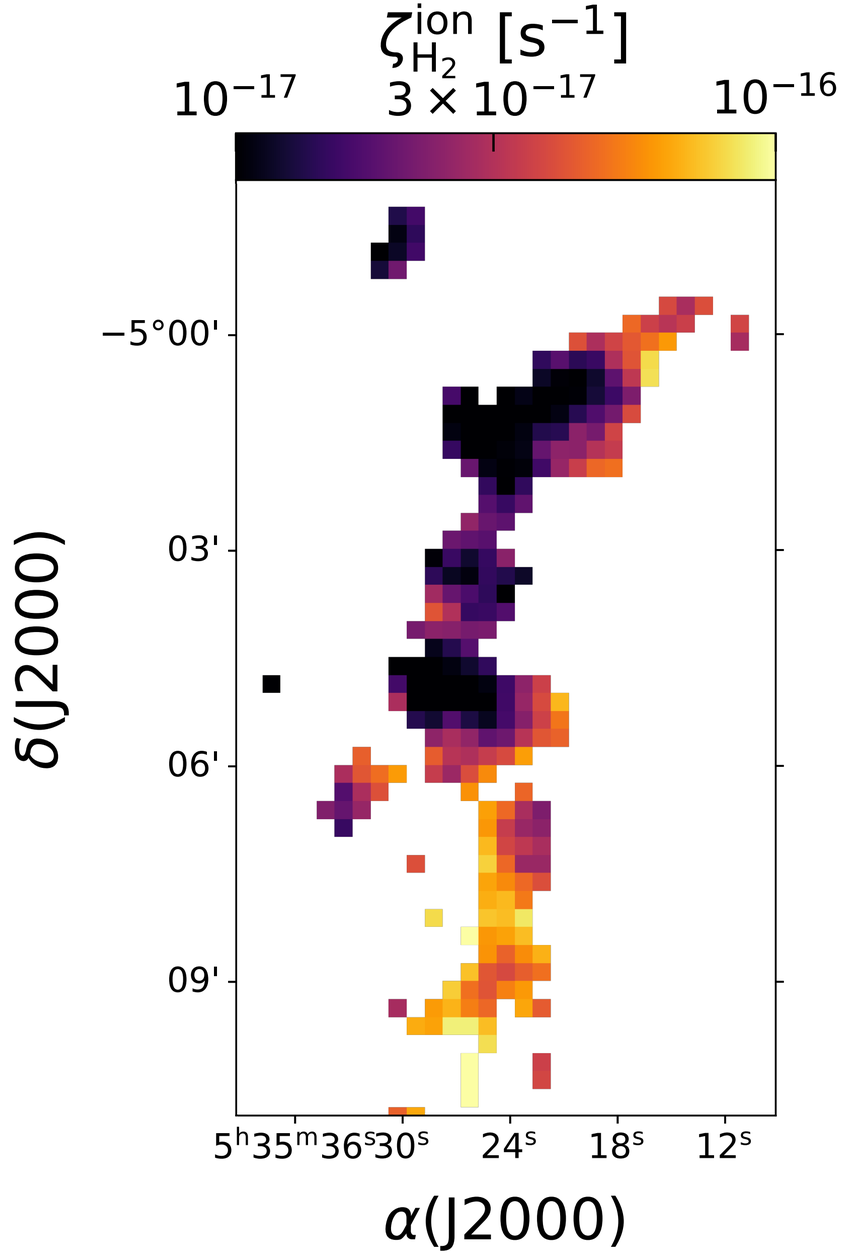
- Measured:
  - $f_D = \dfrac{X_0(C^{18}O)\ N(H_2)}{N(C^{18}O)}$
  - $N(CO) = N(C^{18}O)\ X_{18}^{16}$
  - $R_D = \dfrac{N(DCO^+)}{N(HCO^+)}$

- Other parameters:
  - $k_{CO}^{o-H_3^+}$
  - l
    - taken as 0.05 pc (Socci+24b);

Analysis & Results

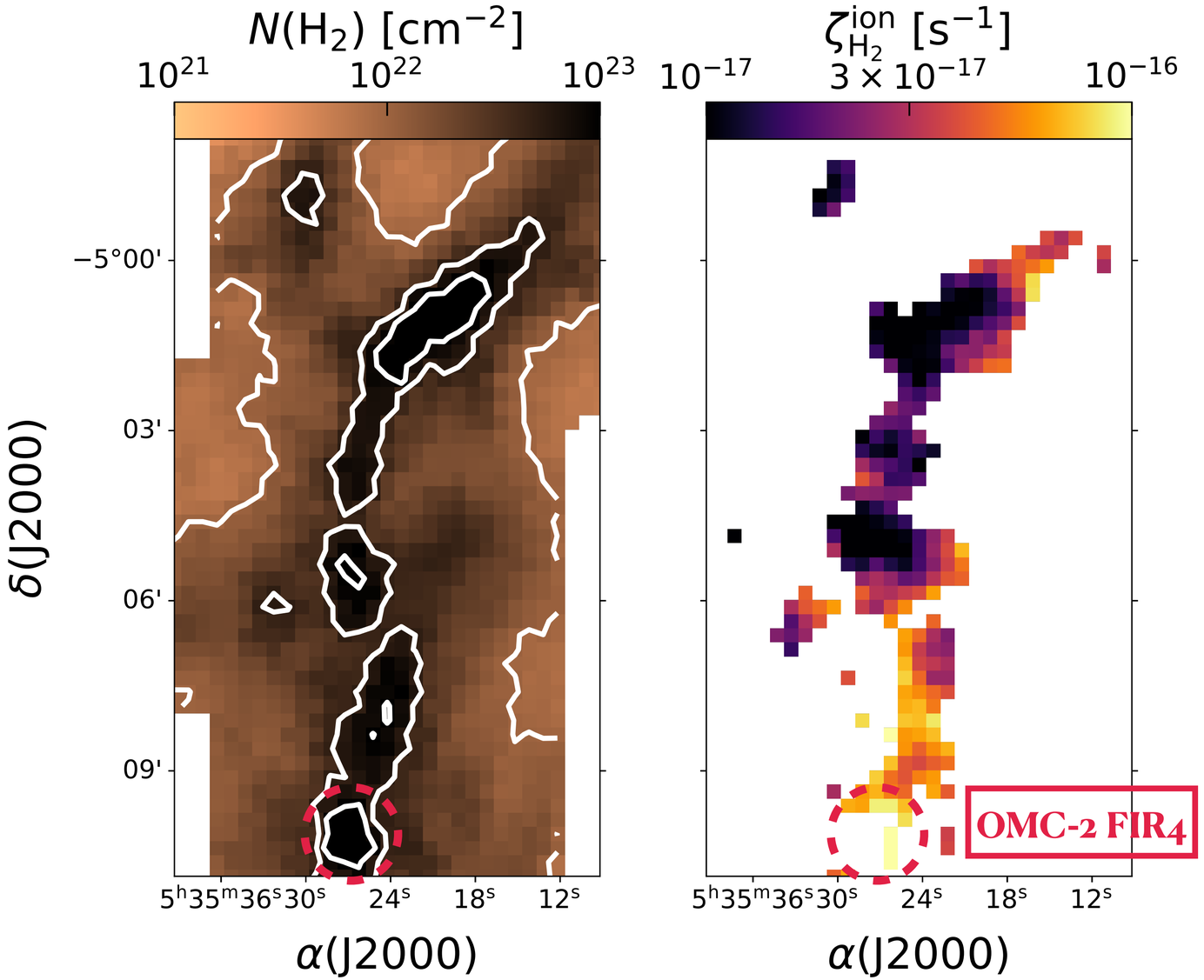
The ionisation rate map

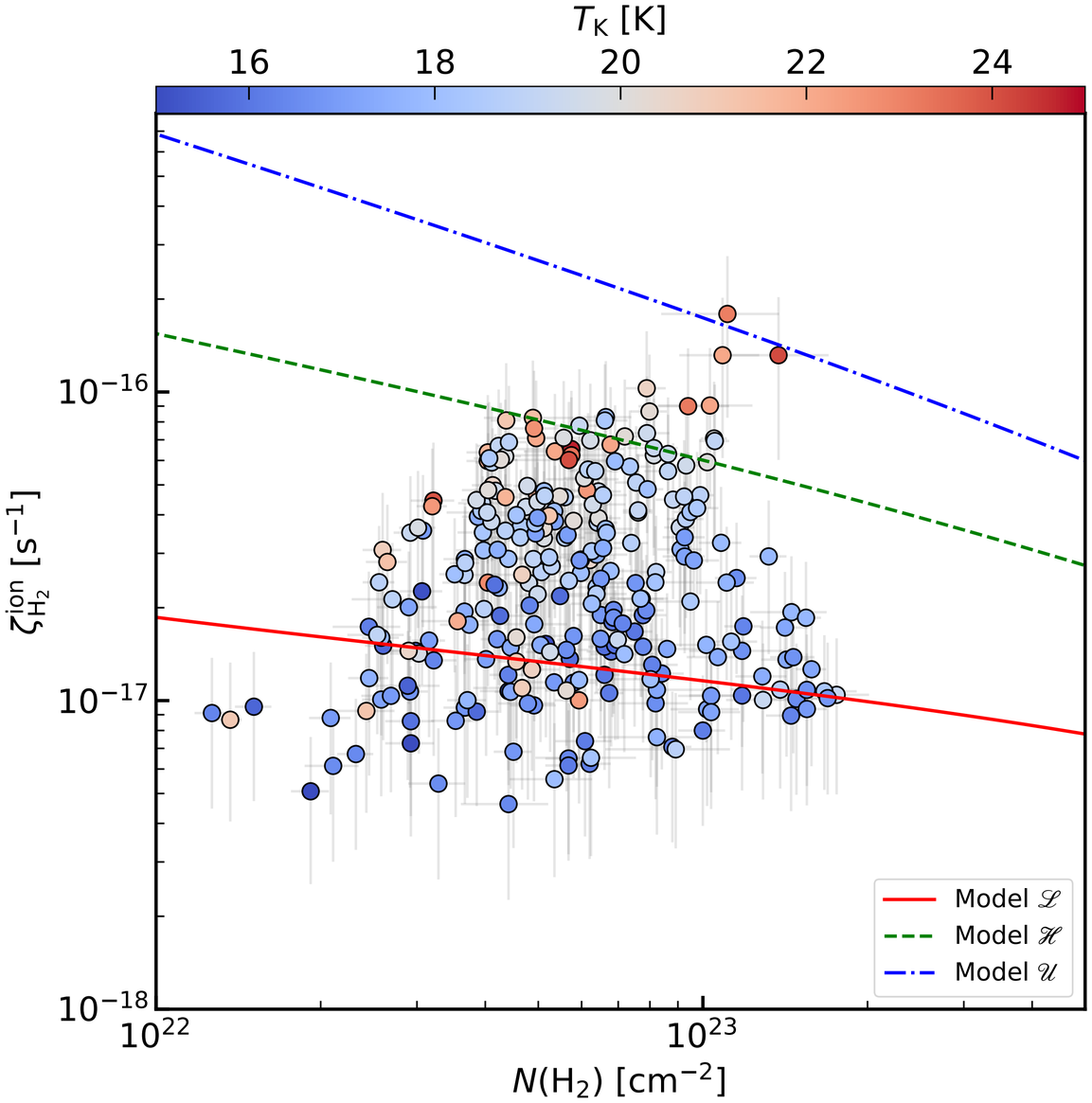




Analysis & Results

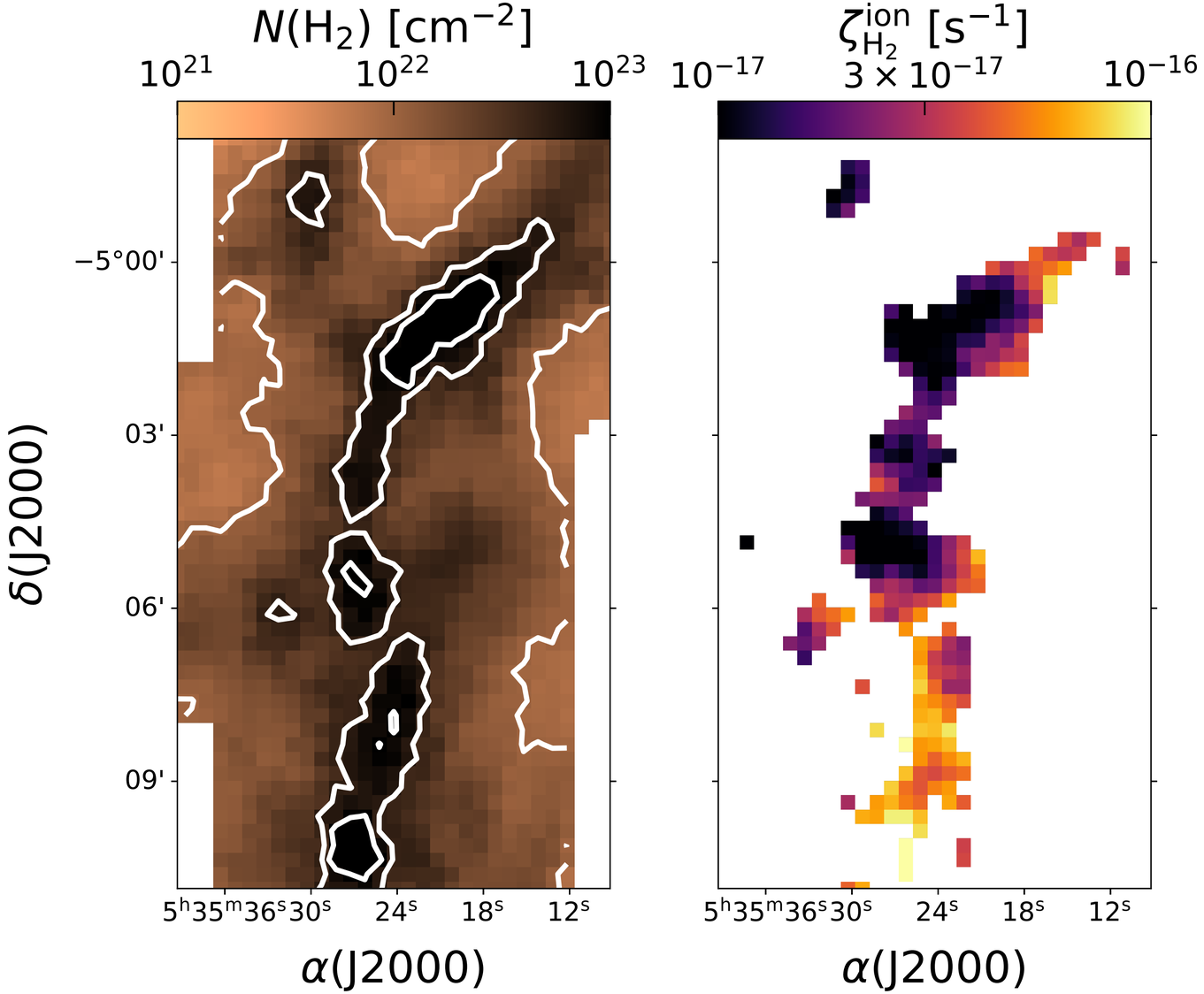
Dependence on the column density

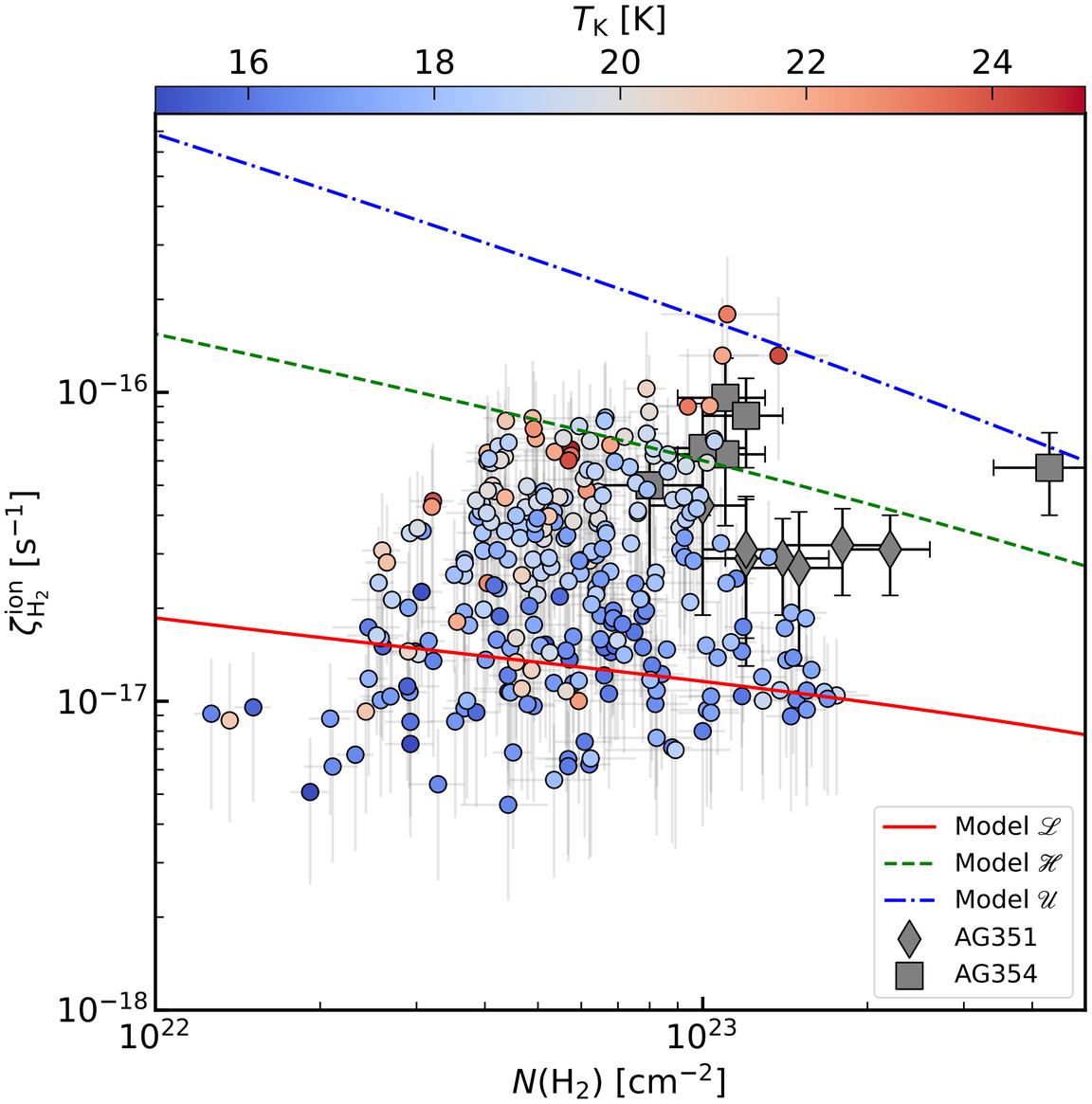




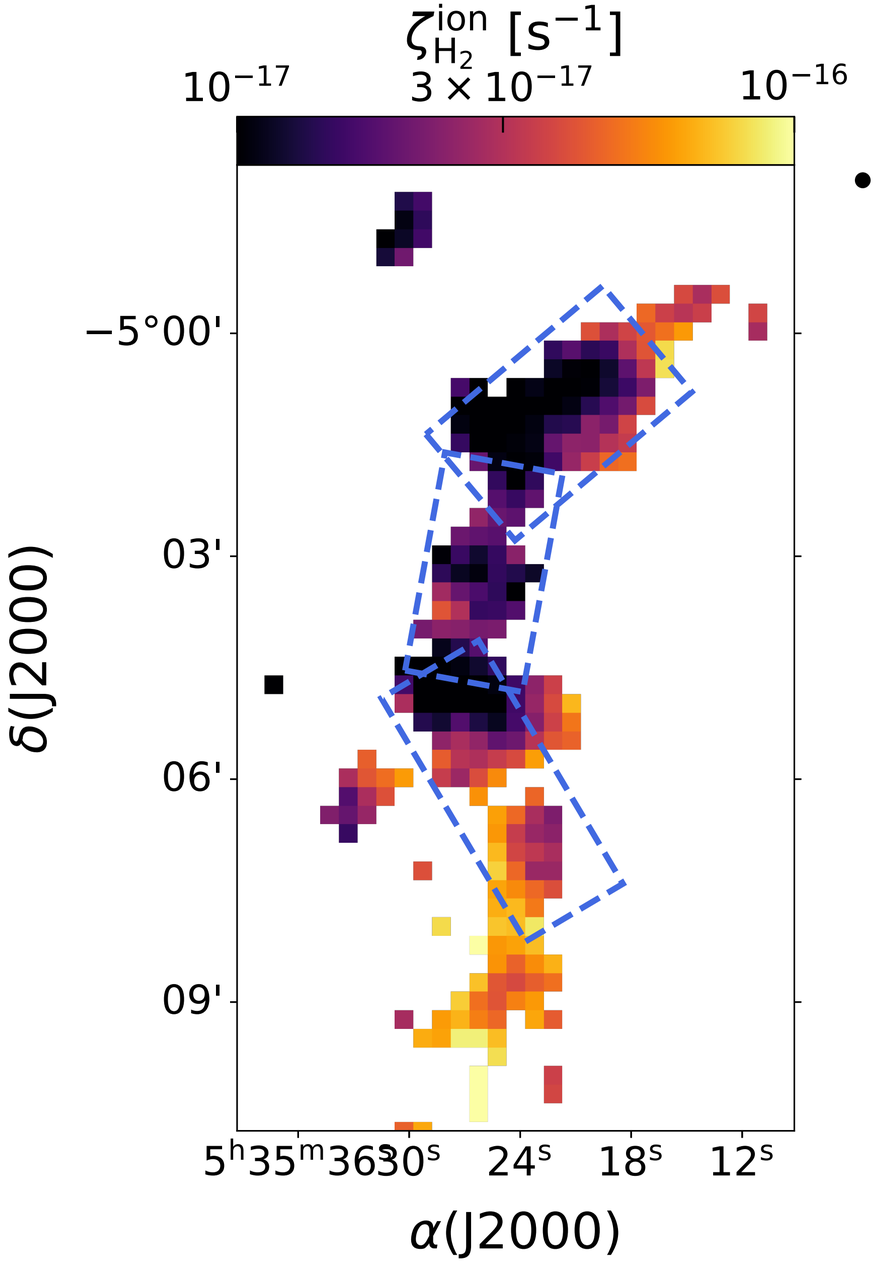
Analysis & Results

Dependence on the column density



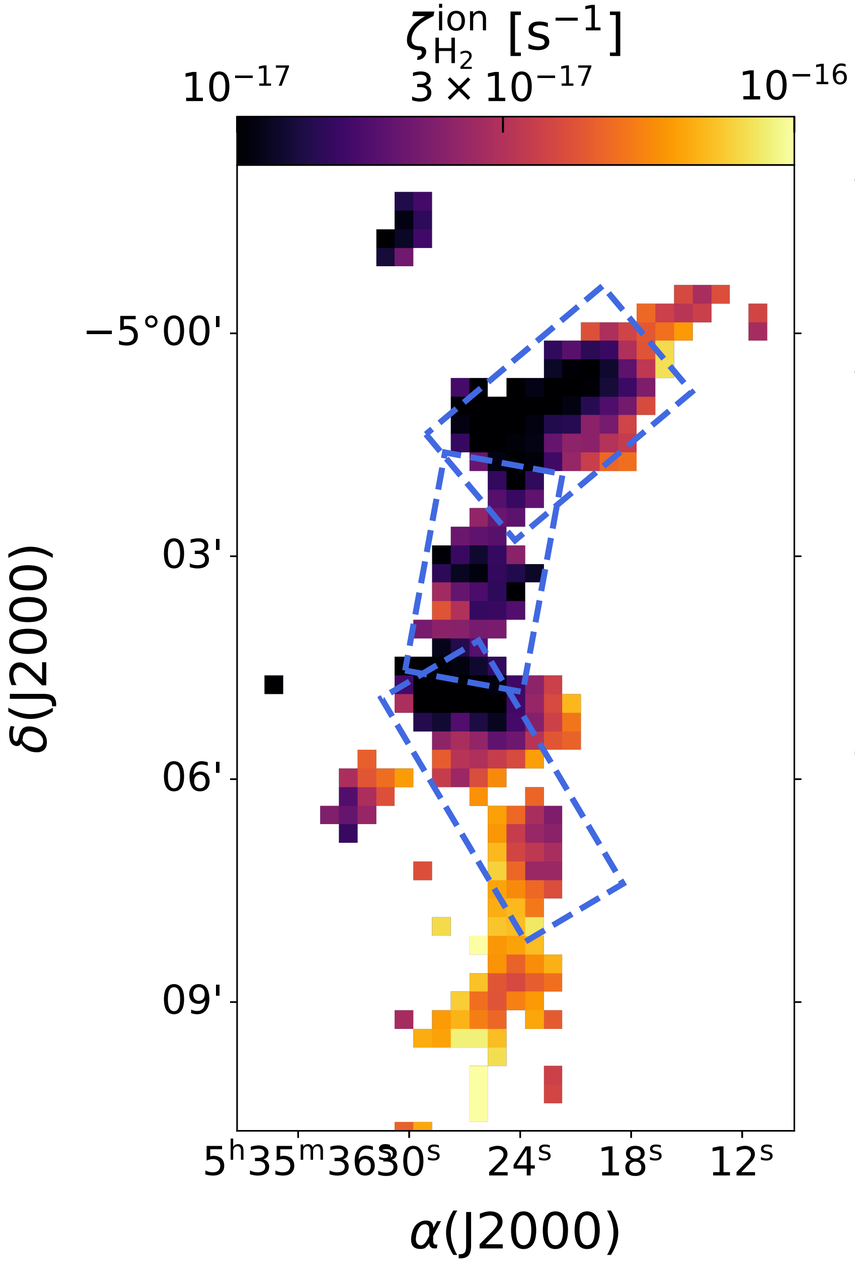


Outlooks



- **Scheduled Cycle 10 & 11 ALMA proposals** (2023.1.01643.S, 2024.1.01727.S; PI: Socci)!

Outlooks



- **Scheduled Cycle 10 & 11 ALMA proposals** (2023.1.01643.S, 2024.1.01727.S; PI: Socci)!
- Band 6 & 7 observations with ACA, including:
  - o − H_2D^+, $H^{13}CO^+$, DCO^+, N_2H^+;
  - ^{12}CO, ^{13}CO, $C^{18}O$;
- Goal: robust estimate of ζ on parsec scales via new estimates of path length, depletion factor and deuterium fraction.

Summary

- We explored ζ across OMC-2 and OMC-3 in Orion using IRAM-30m observations;
- The CO depletion was taken as a proxy for the o-H_2D^+ abundance in these regions;
- The deuterium fraction shows a dependence on the temperature;
- The depletion factor and the deuterium fraction are correlated;
- $\zeta \sim 5 \times 10^{-18} - 2 \times 10^{-16}$ s^{-1} in OMC-2/-3 with a North-South gradient;
- Local injection of cosmic rays may happen towards OMC-2 FIR4;
- ζ shows a dependence on the column density in the region.

All results part of Socci et al. (2024a)