Osservatorio Astrofisico di Arcetri (INAF-OAA)

Fifth Workshop on Millimetre Astronomy in Italy

Bologna, 12-14 of June 2023

First ALMA maps of cosmic-rays ionization rate in high-mass star-forming regions

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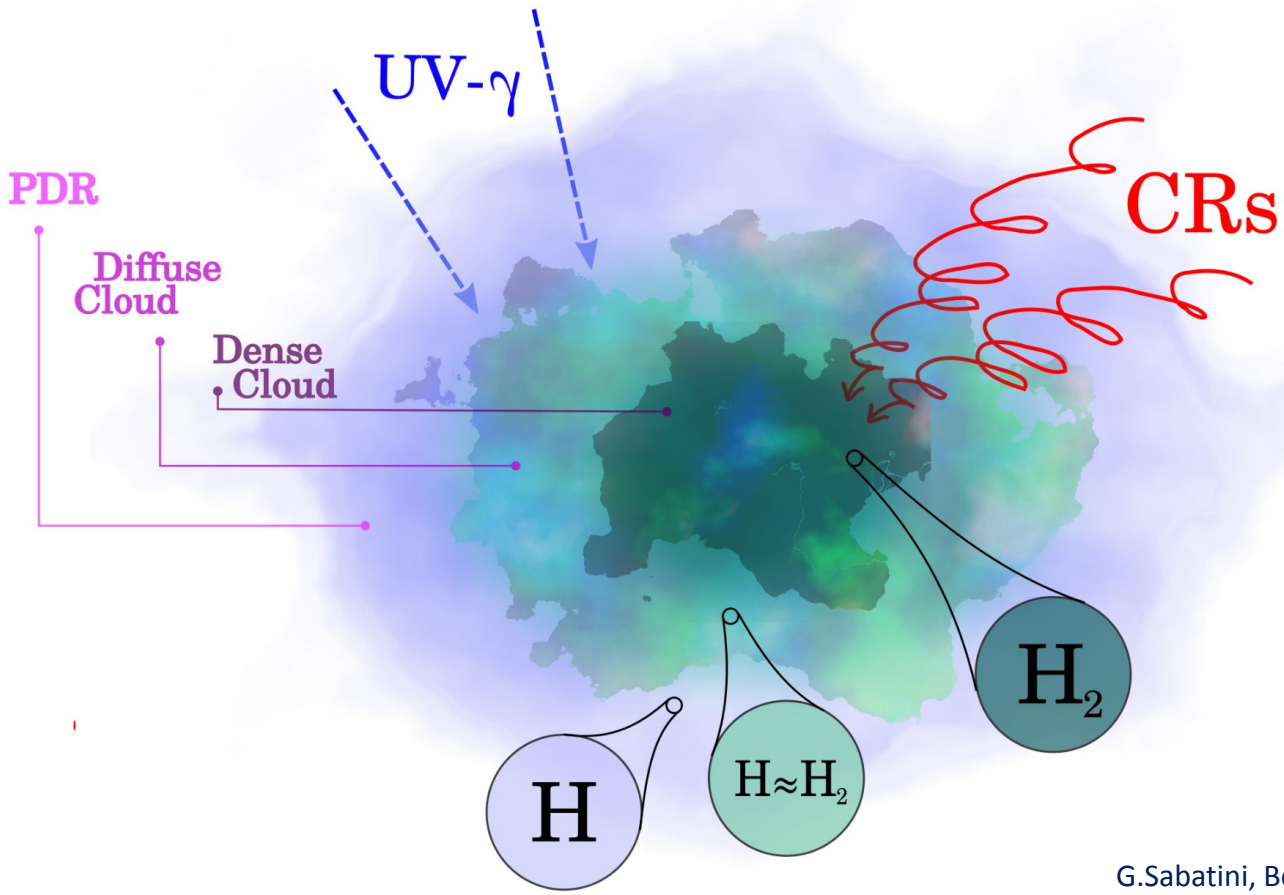
EUROPEAN ARC
ALMA Regional Centre || Italian

PRIN – 2020
BEYOND-2p
Astrochemistry beyond the Second Period Elements

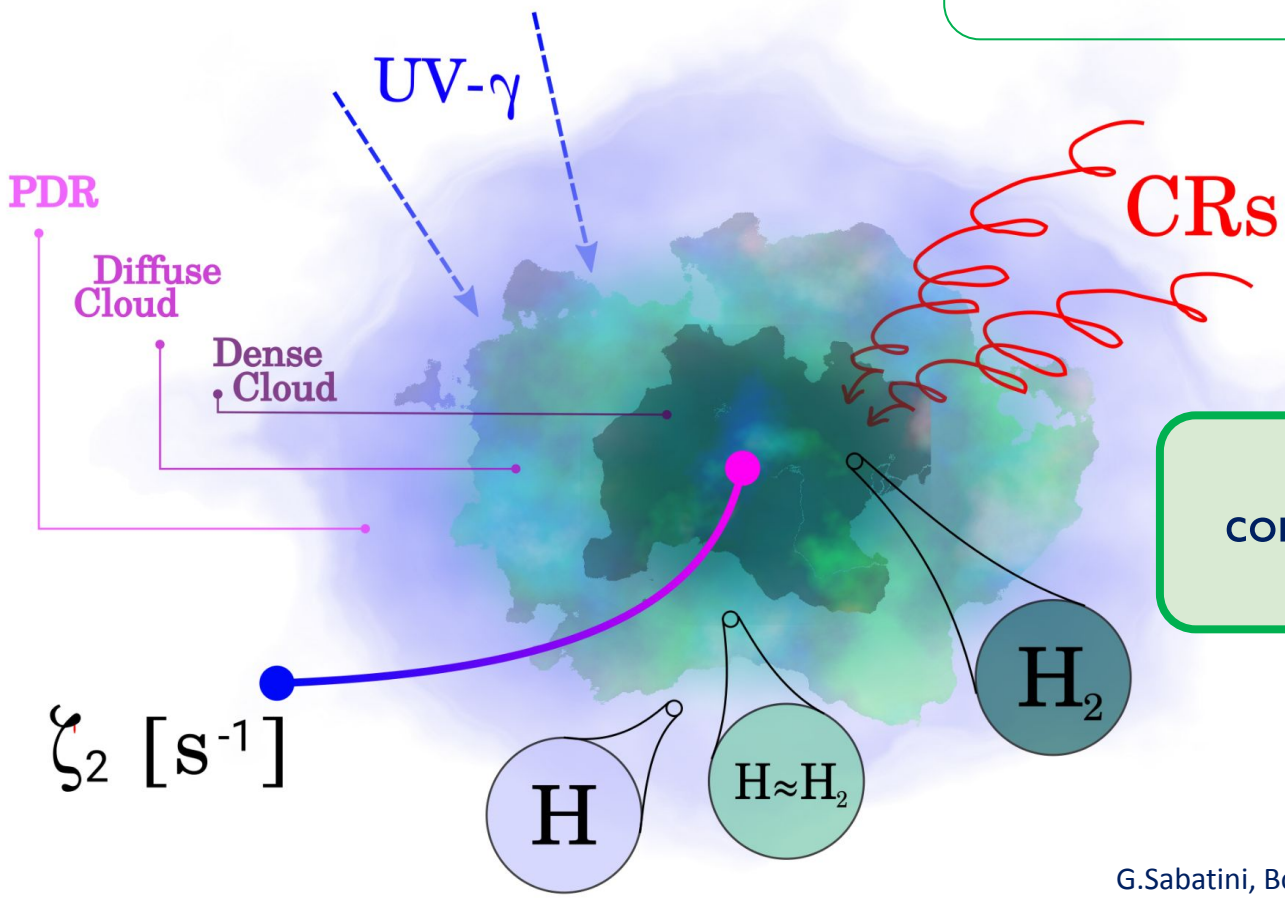
CRs and Star Formation



CRs and Star Formation

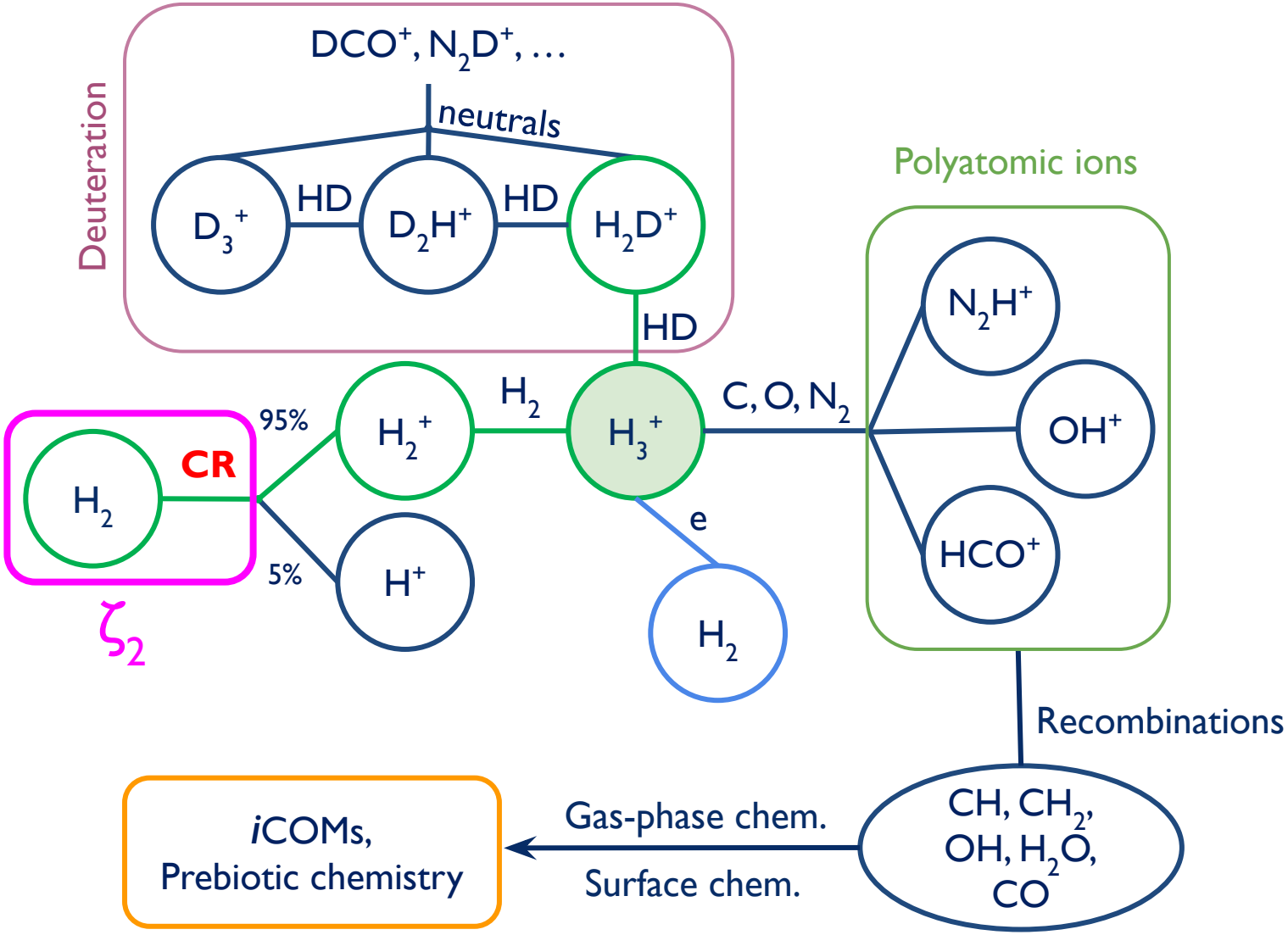
Mechanisms driving the cloud collapse

Dust physics



Chemical complexity in the ISM

CRs: the dawn of chemistry



(e.g. *Ceccarelli* et al 2014, 2022 and refs therein)

Estimates of the ζ_2

(1) $H_2 + CR \rightarrow H_2^+ + e^-$

(2) $H_2^+ + H_2 \rightarrow H_3^+ + H$

(e.g. *Geballe* et al 1999, *Indriolo* & *McCall* 2012, *Neufeld* & *Wolfire* 2017, *Oka* et al 2019)

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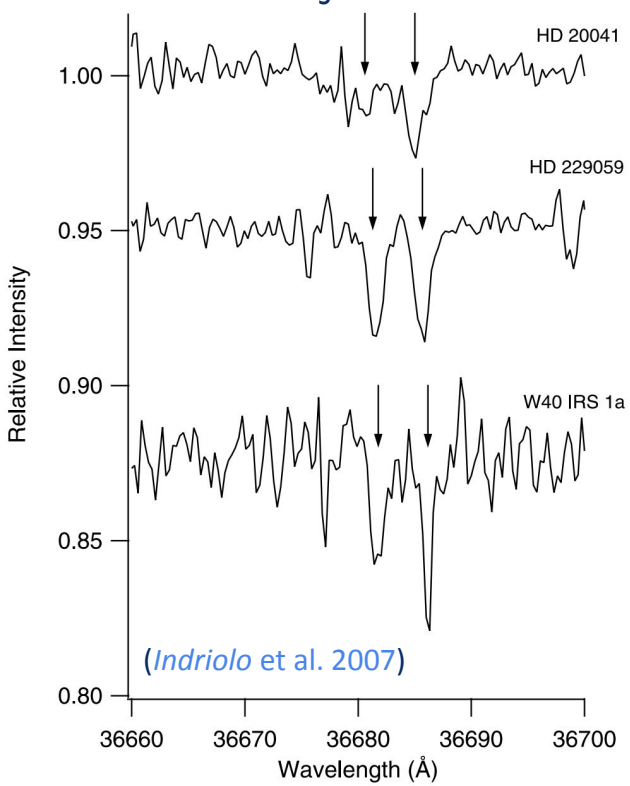
H_3^+ doublet



(*Indriolo* et al. 2007)

In diffuse clouds: direct determination of ζ_2 from H_3^+ doublet absorption lines.

- high-resolution spectroscopy + bright background sources

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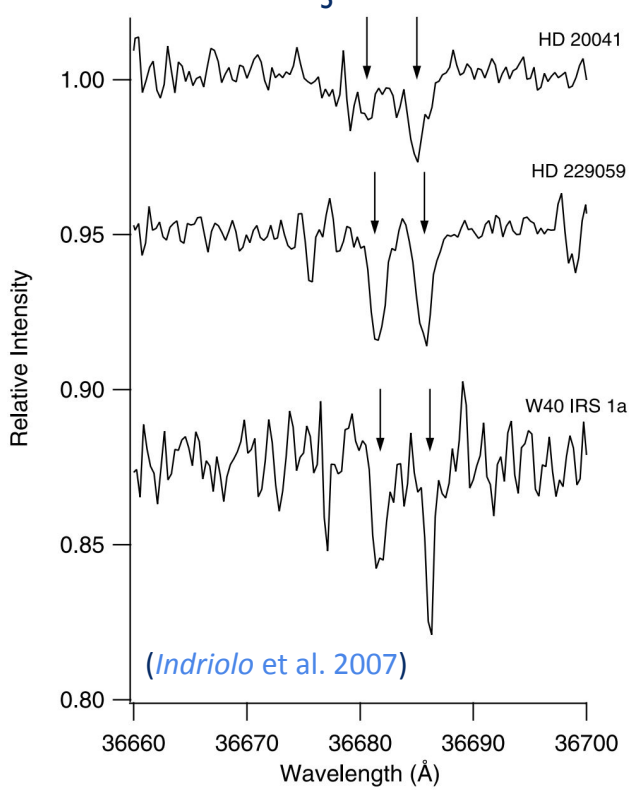

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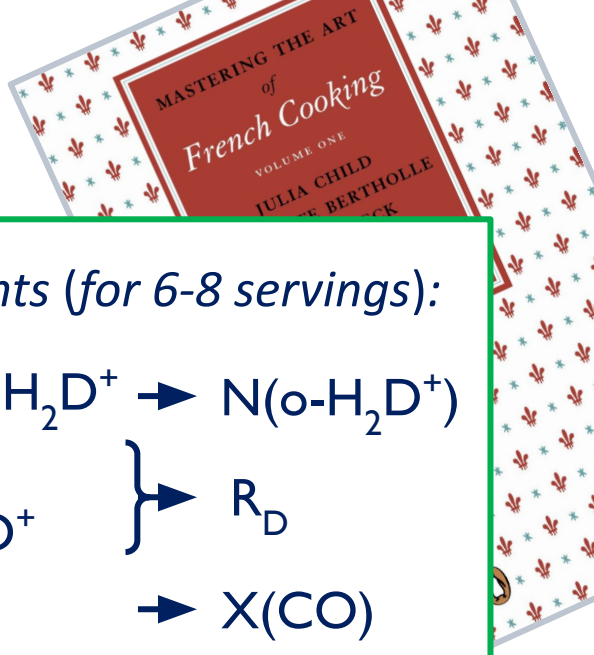
Not applicable in dense molecular clouds (shielded from the interstellar UV radiation field)

Estimates of the ζ_2



CR ionization rate of H_2 molecule (also ζ_2)

$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{X(CO)\, N(o-H_2D^+)}{3\, R_D\, \ell}$$

path-length used to estimate *N*

Ingredients (for 6-8 servings):

- ortho-H_2D^+ → $N(o\text{-}H_2D^+)$
- DCO^+
- $H^{13}CO^+$

} → R_D

- $C^{18}O$ → $X(CO)$

(Bovino et al. 2020)

➢ **More methods by**: *Guélin+77, Caselli+98* (DCO^+, HCO^+, CO), *Ceccarelli+14, Redaelli+21b* (HCO^+, N_2H^+, N_2D^+), *Fontani+17* (HC_3N, HC_5N), *Favre+18* (c-C_3H;), *Bialy 2020, Padovani+22* (H_2 NIR-lines)

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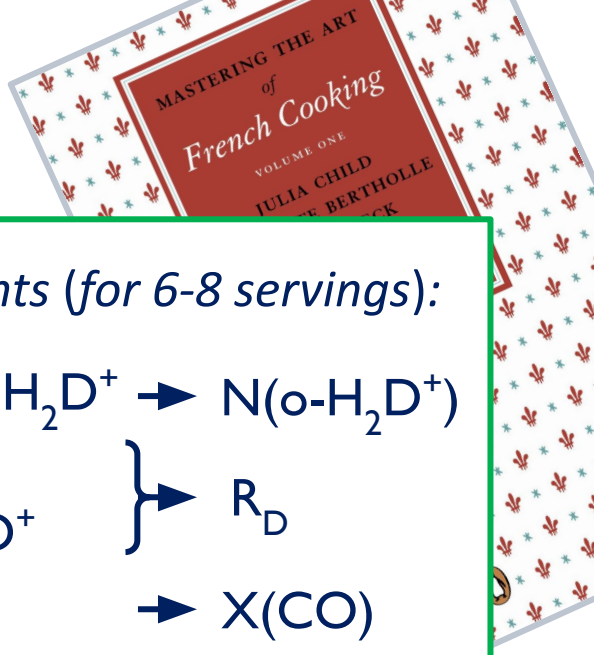

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} → R_D

→ $X(CO)$

(Bovino et al. 2020)

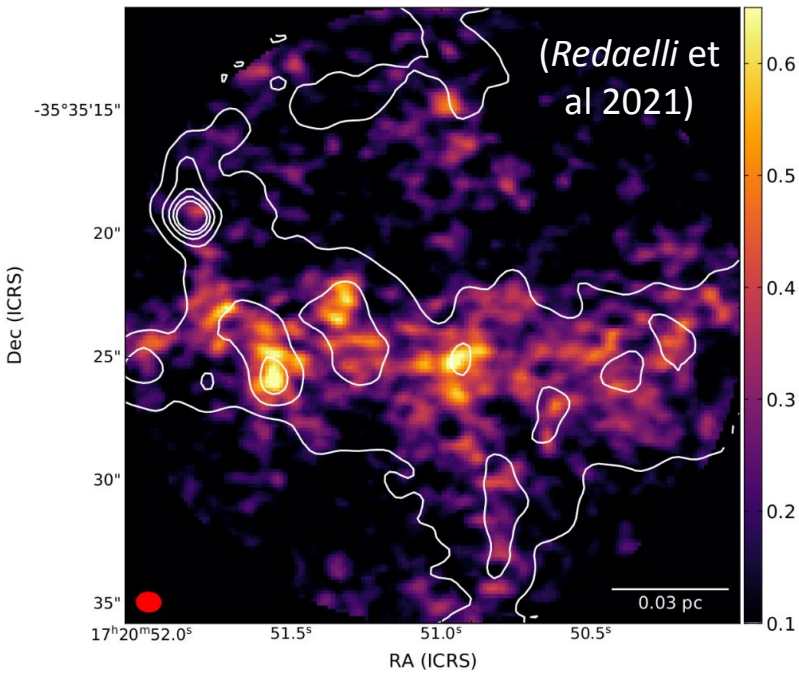
Method assumptions:

1. CO ⟶ main source of destruction for H_3^+;
   a. The deuterium fraction R_D from DCO^+/HCO^+ traces most of the deuteration;
2. Need for o-H_2D^+ (i.e. valid in prestellar/cold environments);
3. Dependent on the assumed path-length;

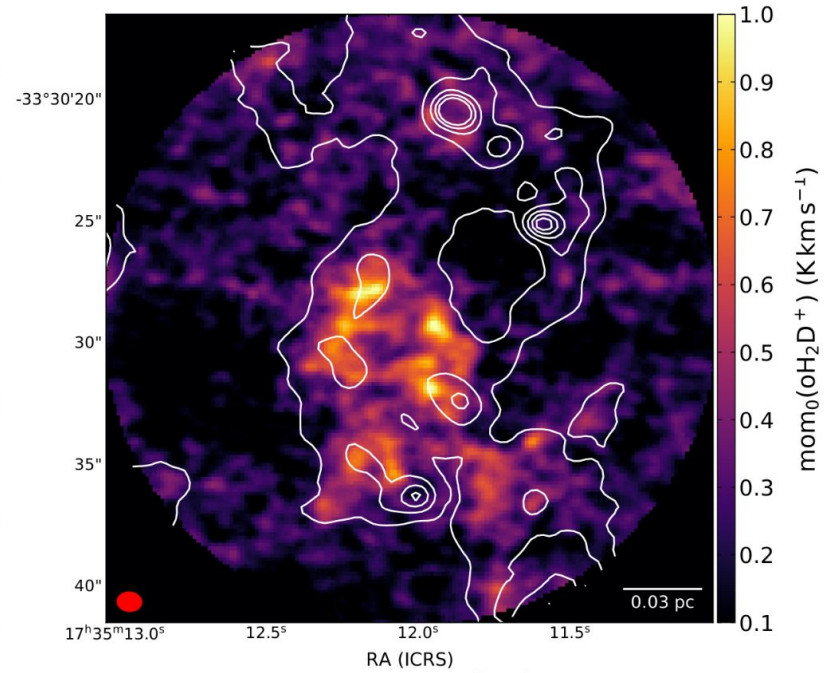
➢ **More methods by**: *Guélin+77, Caselli+98* (DCO^+, HCO^+, CO), *Ceccarelli+14, Redaelli+21b* (HCO^+, N_2H^+, N_2D^+), *Fontani+17* (HC_3N, HC_5N), *Favre+18* (c-C_3H;), *Bialy 2020, Padovani+22* (H_2 NIR-lines)

Source selection

AGAL351.571+00.762



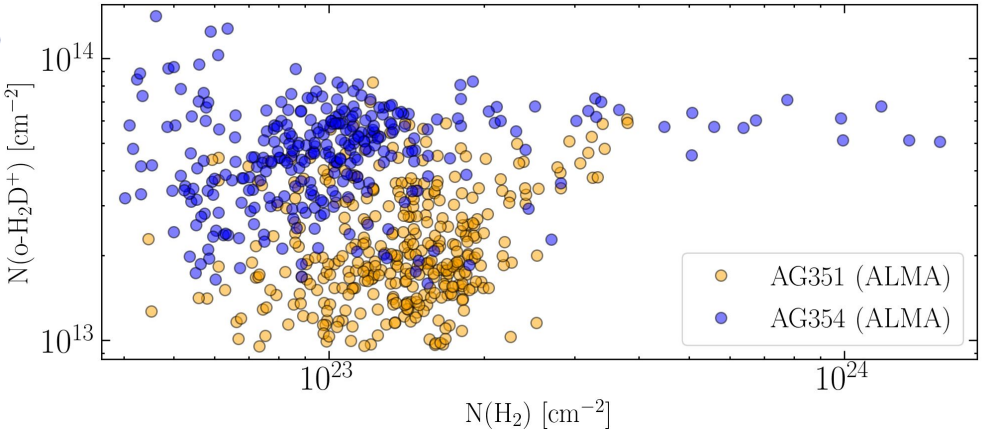
AGAL354.944-00.537

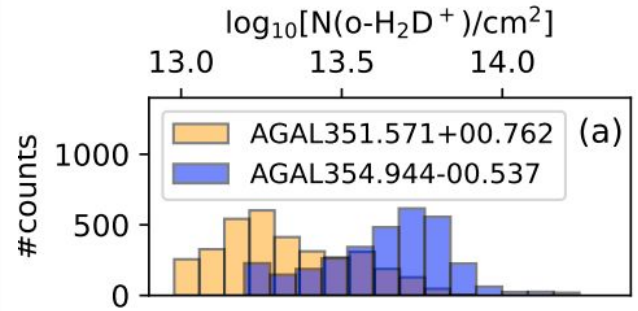


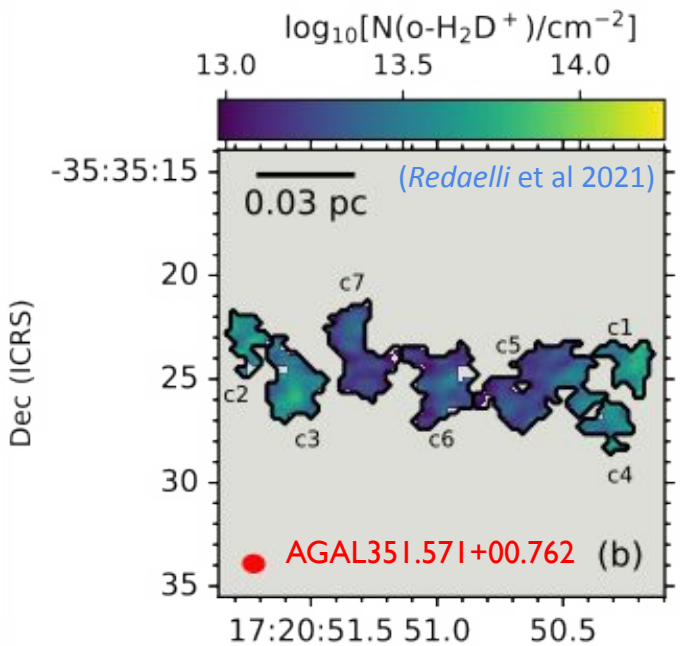
- Nearby (D ~ 1.3-1.9 kpc; 1"~1600 AU @ 1.6 kpc) (Koenig et al 2017, Giannetti et al 2017)
- Intermediate-mass clumps (M_{clump}~170-150 $M_\odot$)
- Quiescent/70μm-dark clumps: o-H_2D^+ detected with APEX (Sabatini et al 2020)
- **SCIMES**: core-finding algorithm (*Colombo* et al 2015)

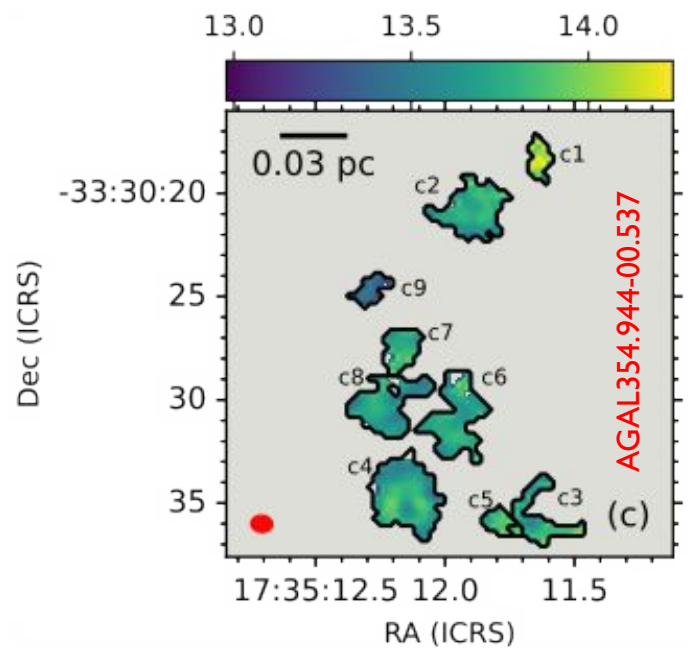
(see ***Redaelli's Poster***, for more details)

ζ_2 with ALMA - o-H_2D^+







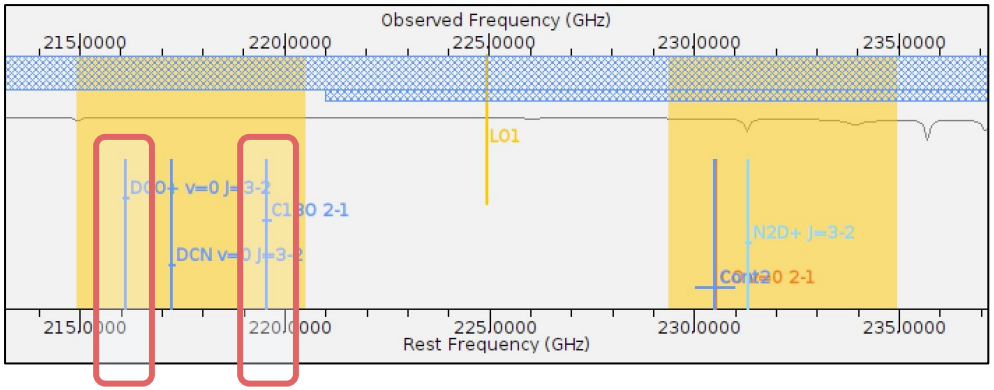


ζ_2 with ALMA - the setup

Observed from Apr to Aug 2022

Config. 1 - Band 6 (~ 216-231 GHz)

(Sabatini et al 2023)

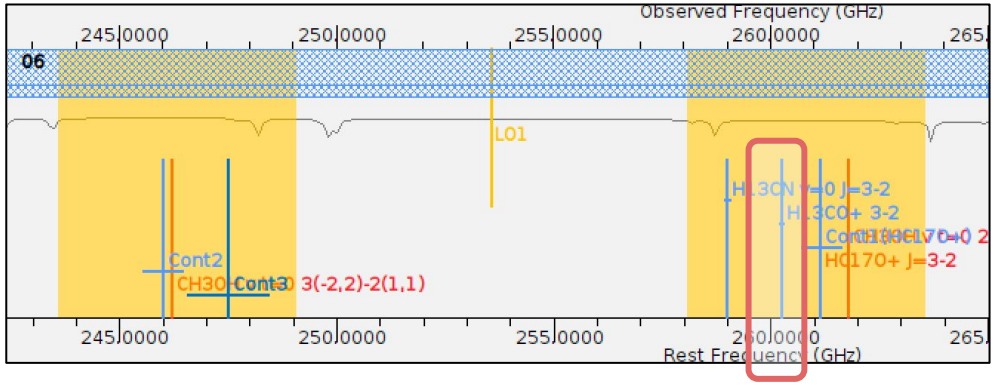


$C^{18}O$ (2-1)

DCO^+ (3-2)

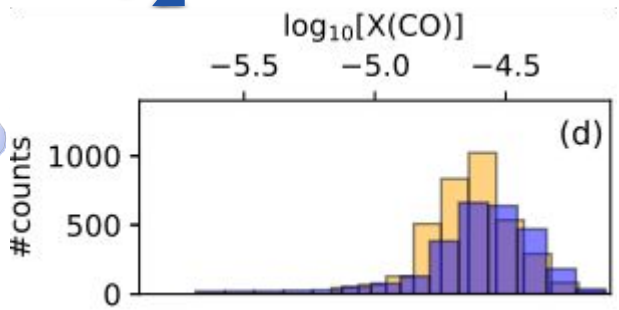
Config. 2 - Band 6 (~ 248-260 GHz)

$H^{13}CO^+$ (3-2)



- *Calibration*: ALMA pipeline (v2021.2.0.128)
- *Imaging*: 12m + 7m + TP manually combination (e.g. *Plunkett* et al 2023)

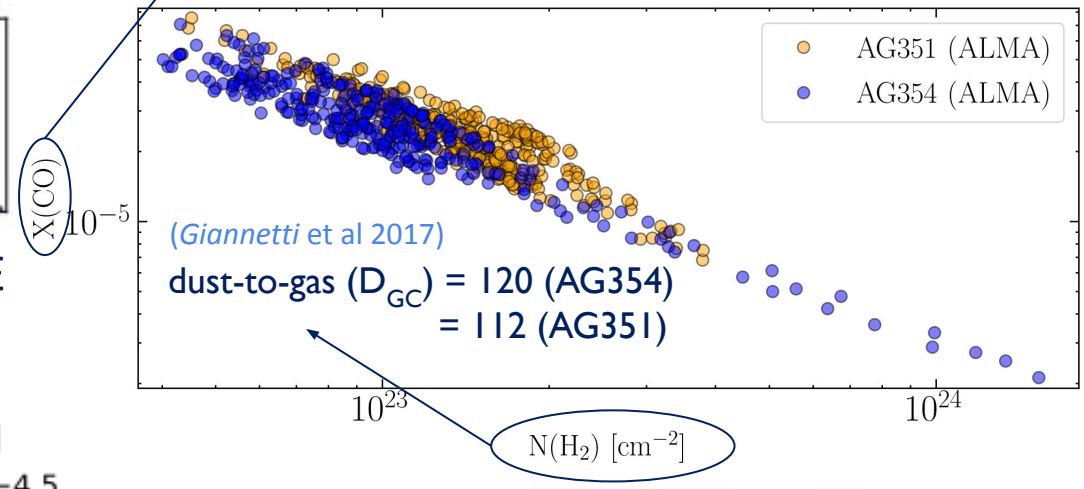
ζ_2 with ALMA - $C^{18}O$



- $N(C^{18}O)$ assuming LTE

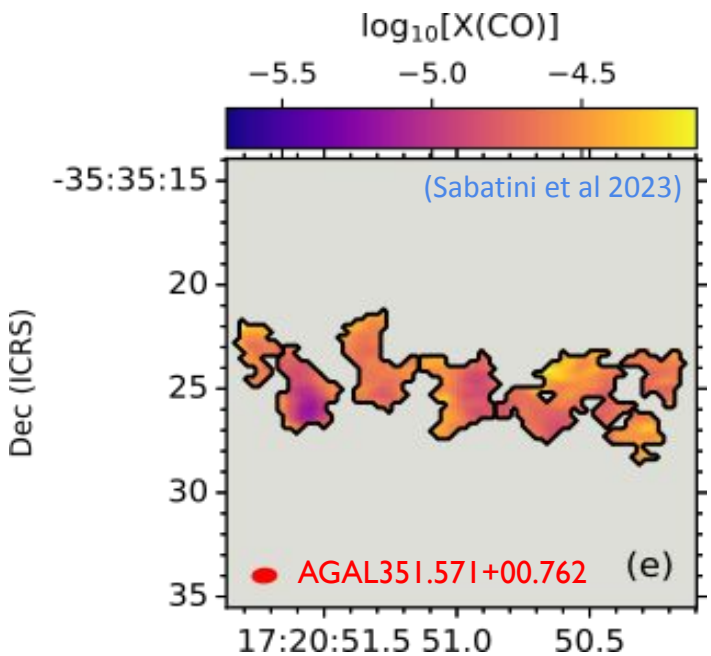
  $T_{ex} = T_{dust} = 18$ K

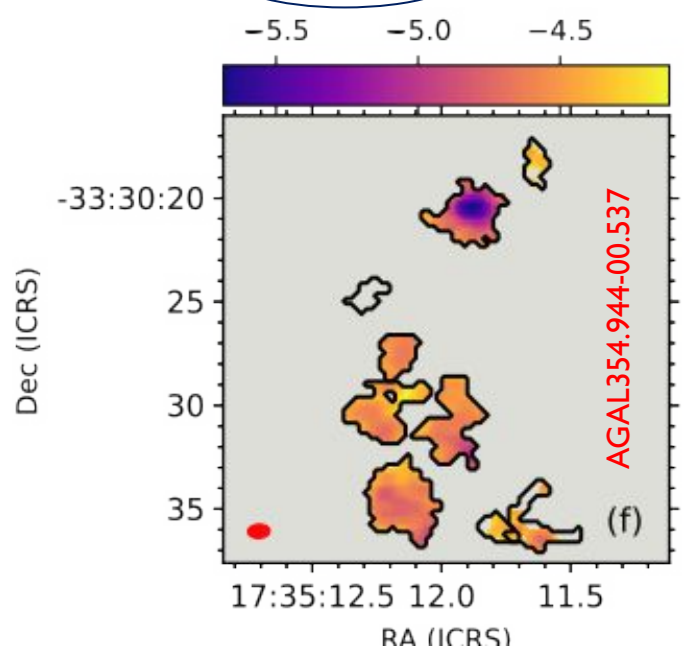
$[^{16}O]/[^{18}O] = 58.8\,D_{GC} + 37.1$ (*Wilson & Rood* 1994)



(*Giannetti* et al 2017)

dust-to-gas (D_{GC}) = 120 (AG354)
= 112 (AG351)





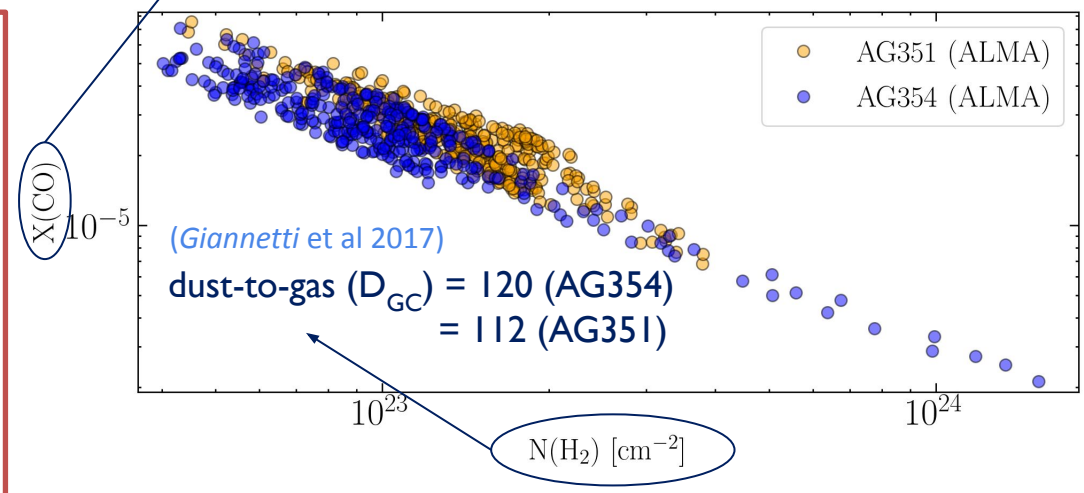
ζ_2 with ALMA - $C^{18}O$

Depletion factor (f_D)

Ratio between the '*expected*' abundance of CO relative to H_2 ($\chi^E_{C^{18}O}$) and the '*observed*' value ($\chi^O_{C^{18}O}$) :

$$f_D = \frac{\chi^E_{C^{18}O}}{\chi^O_{C^{18}O}}$$

$[^{16}O]/[^{18}O] = 58.8\, D_{GC} + 37.1$ (*Wilson & Rood* 1994)

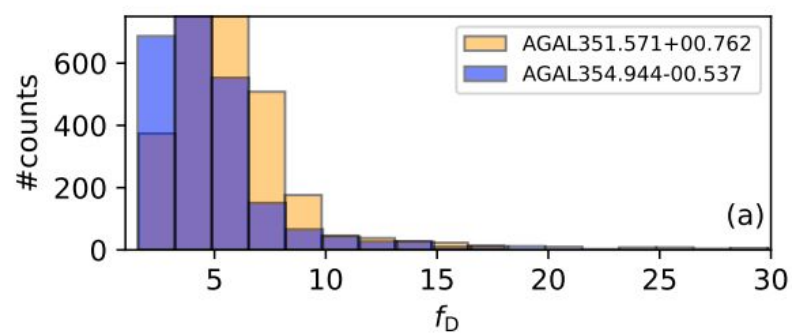


(*Giannetti* et al 2017)

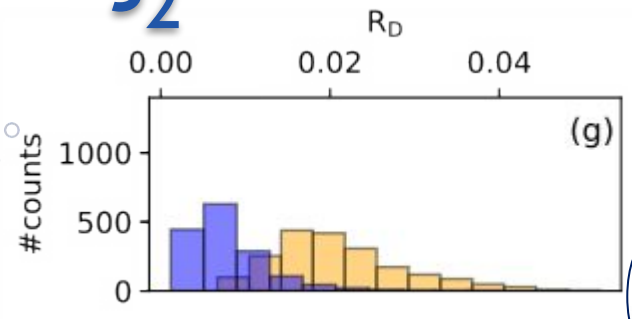
dust-to-gas (D_{GC}) = 120 (AG354)
= 112 (AG351)

- f_D agree with the typical values recently found in prestellar cores in the **ASHES**-survey

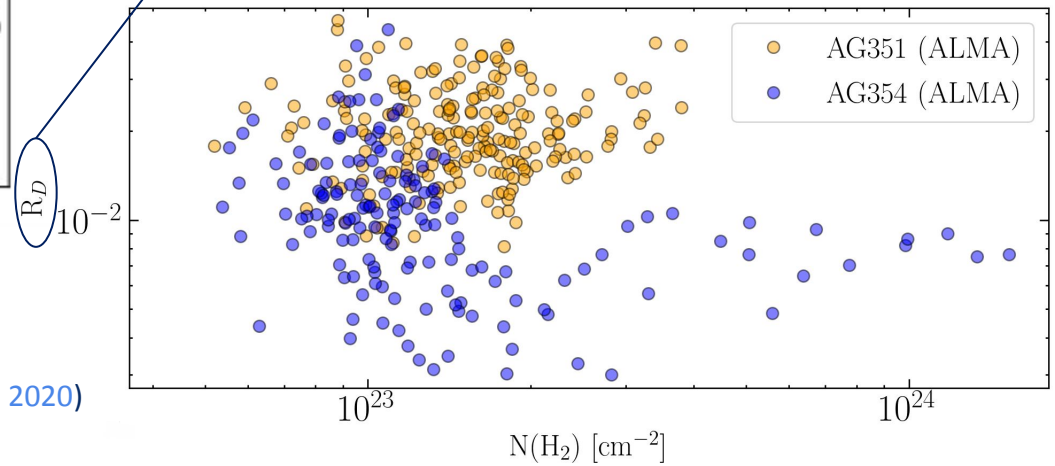
(Sabatini et al 2022)



ζ_2 with ALMA - R_D

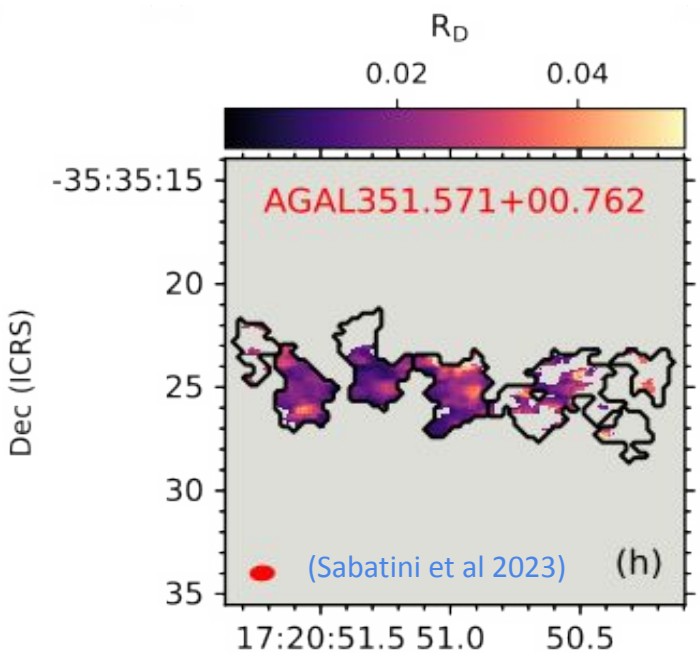


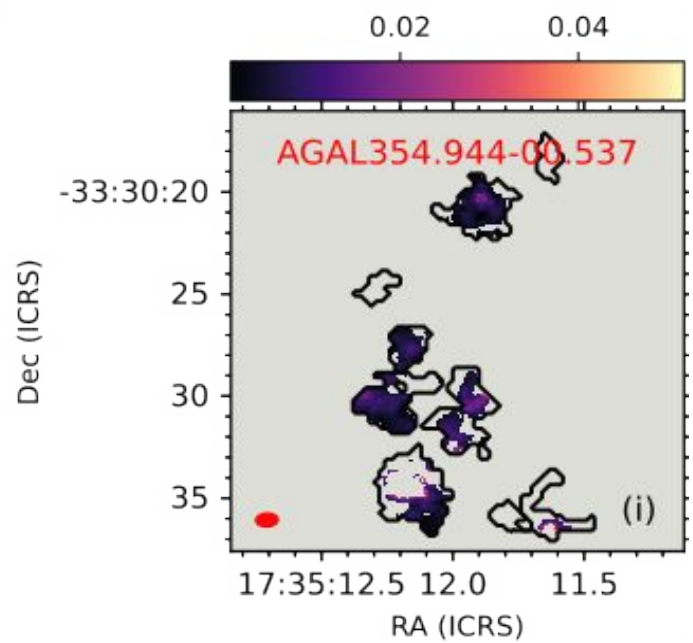
$[^{12}C]/[^{13}C] = 6.1\ D_{GC} + 14.3$ *(Feng et al 2016)*



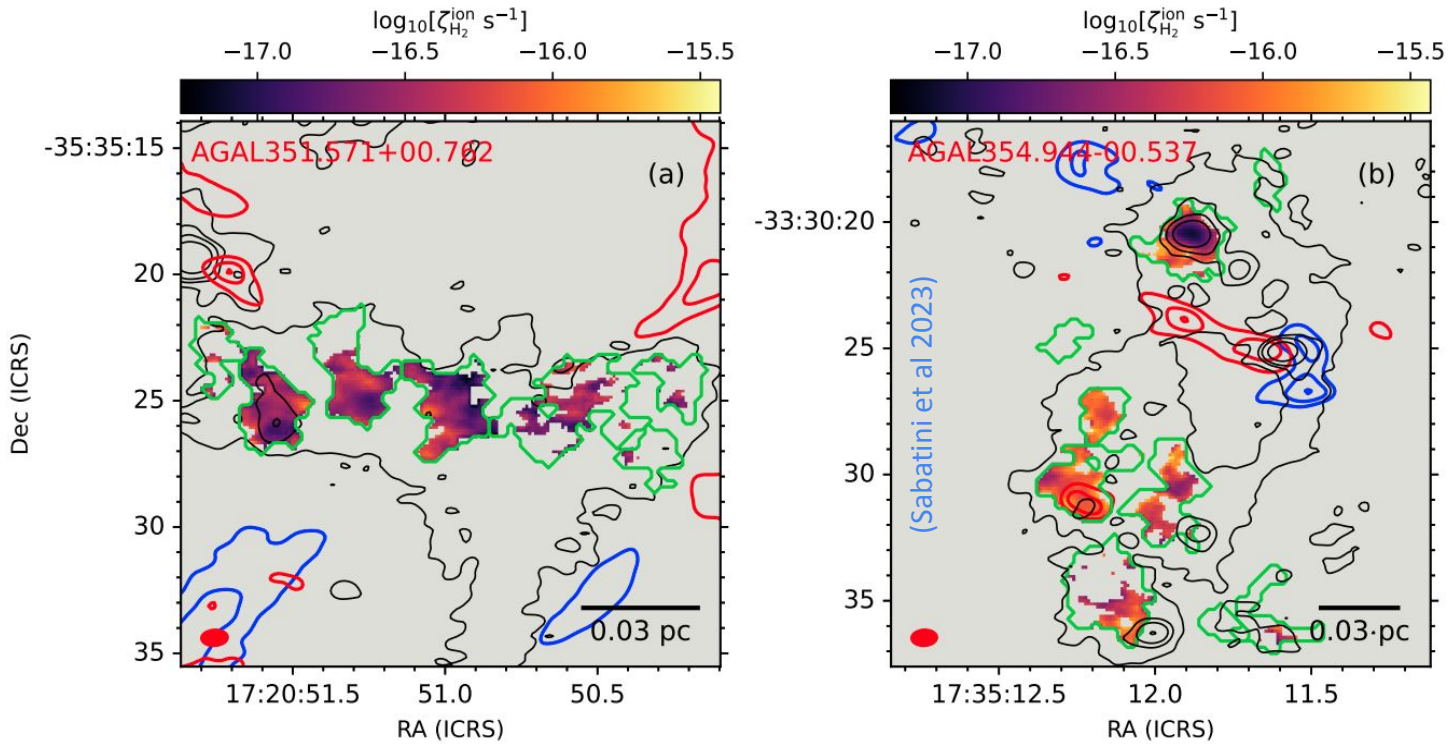
- T_{ex} = 10 K (= $T_{o\text{-}H2D+}$)
- R_D between 1-5%

(e.g. Fontani et al 2011, Feng et al 2020)



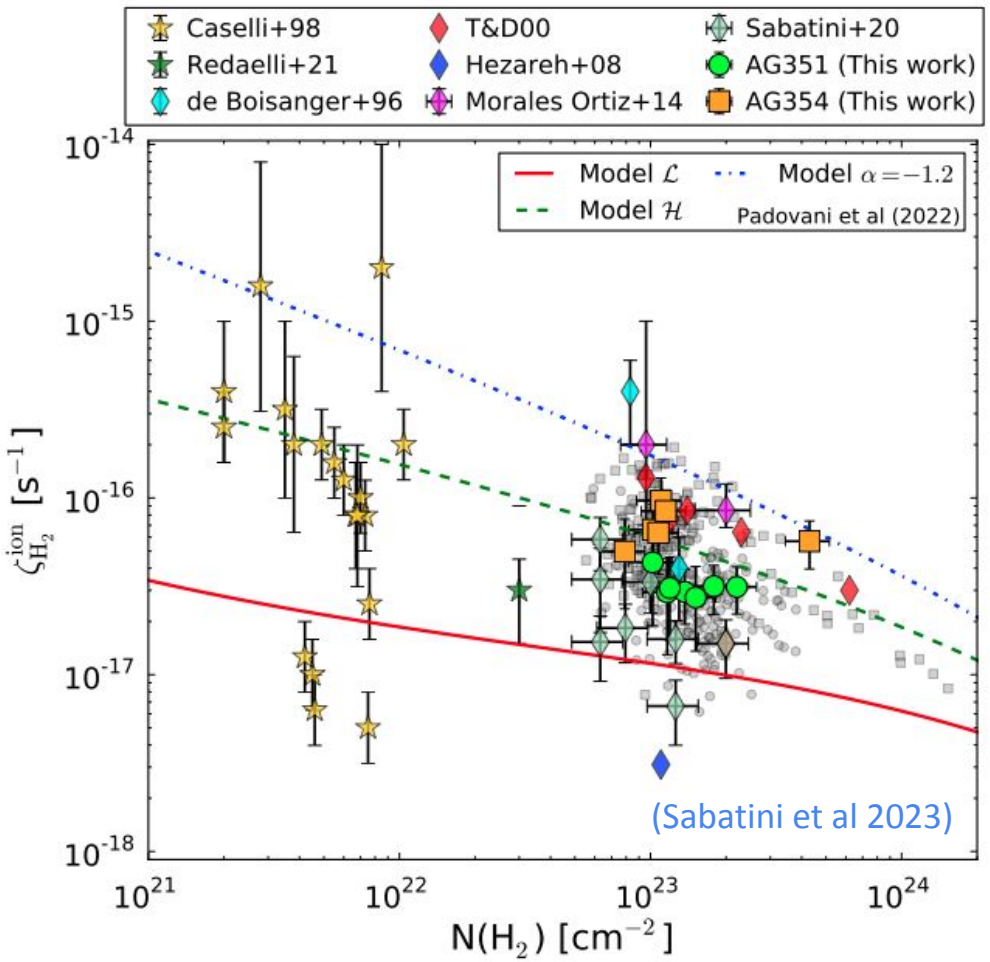


ζ_2 maps with ALMA



- Protostellar molecular outflows identified using the CO (2–1) emission (12m + 7m + TP)
- One evidence only in a continuum identified core of AG354

ζ_2 vs $N(H_2)$



Conclusions

- Cores belonging to the same parental clump have comparable $\langle\zeta_2\rangle$
- $\langle\zeta_2\rangle$ in AG354 is ≈ 3 higher than in AG351;
- Global decreasing trend of $\langle\zeta_2\rangle$ with $N(H_2)$ (see *Padovani* et al. 2022)

(see *Padovani* et al 2020 and *Gabici* 2022 reviews)

Summary

Aims of the study:

a. To take a first look at the ζ_2 distribution within two high-mass star-forming regions;

b. To investigate if/how ζ_2 varies from source-to-source and as a function of $N(H_2)$;

We find:

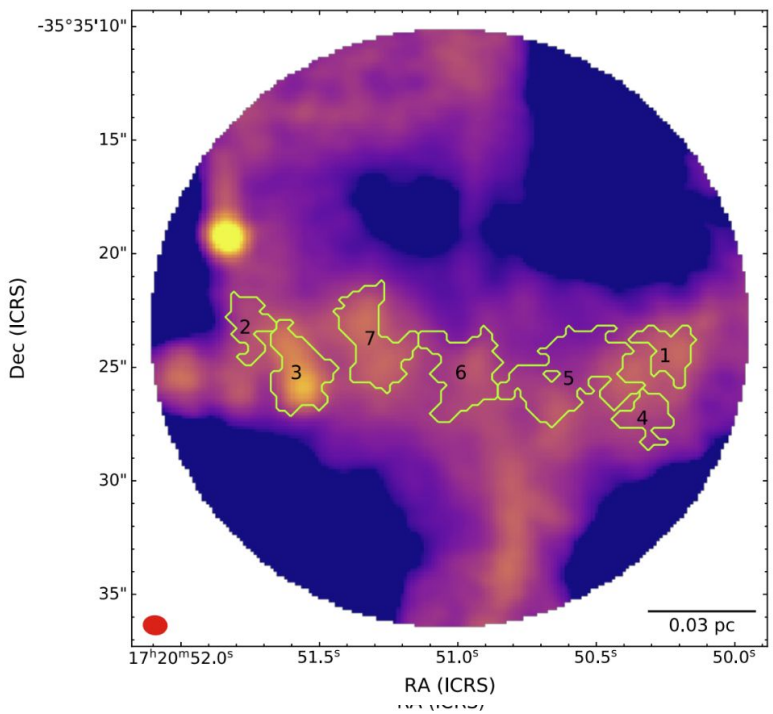
1. Similar ζ_2 between cores harboured in the same parental clumps;
2. A difference of a factor of 3 between the $\langle\zeta_2\rangle$ obtained in the two cores populations;
3. A general decreasing trend of ζ_2 as a function of $N(H_2)$;

Thank you

Backup slides

o-H_2D^+ with ALMA

AGAL351.571+00.762



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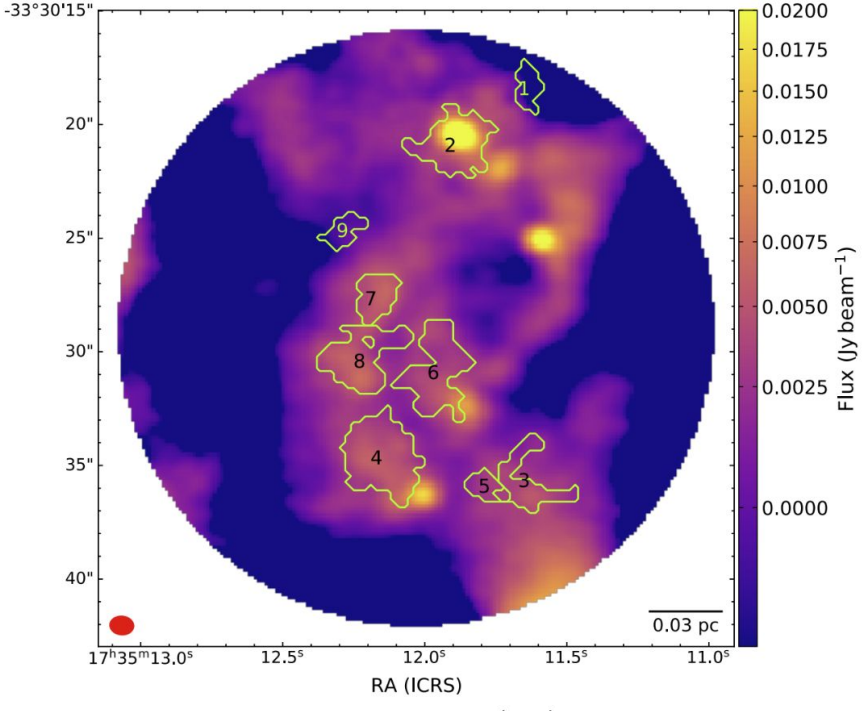
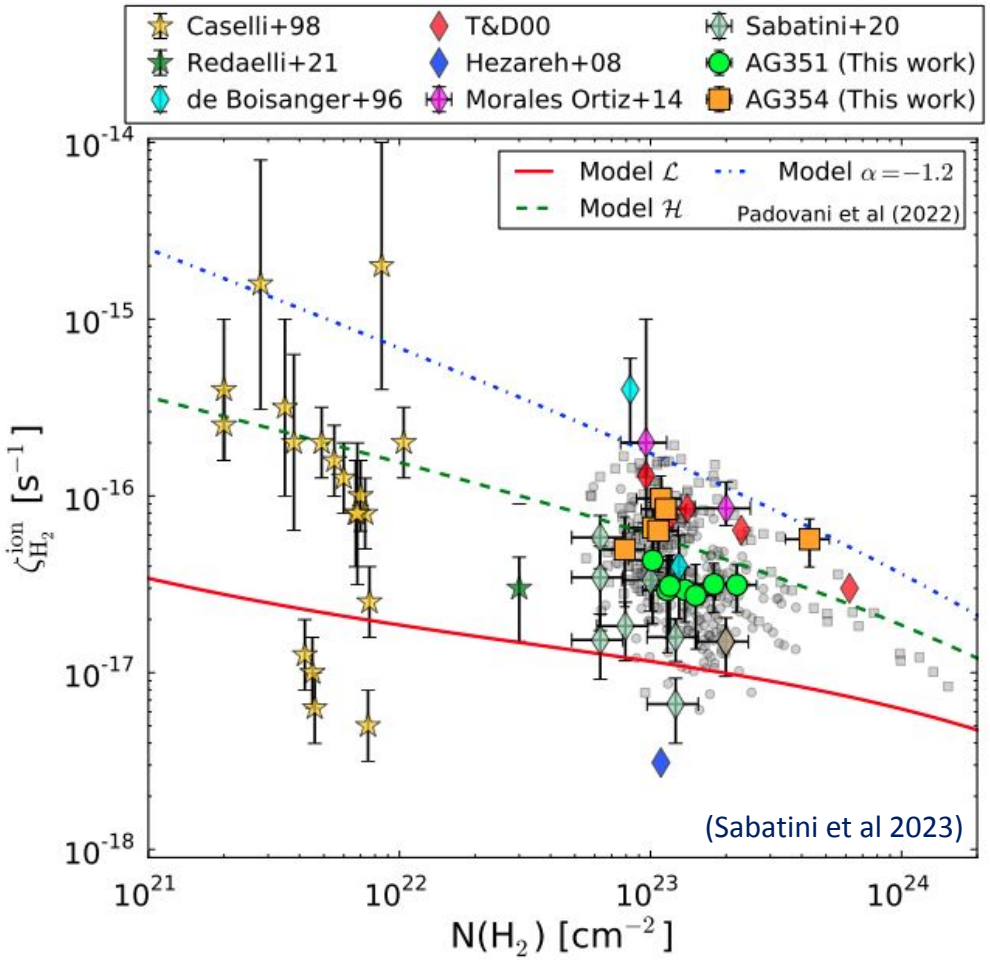


SCIMES (core-finding algorithm; Colombo+15)

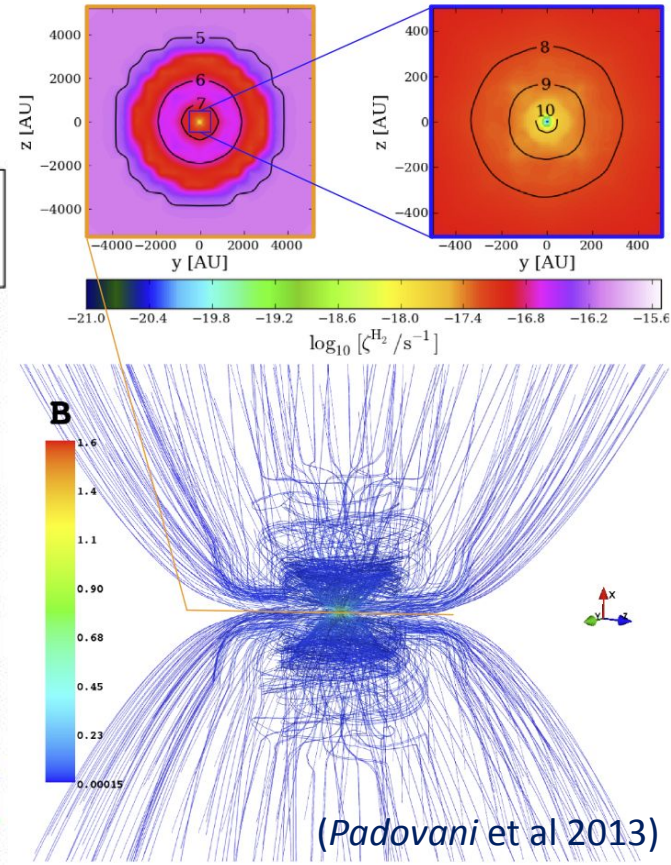
Applied to the o-H_2D^+ cube (ppv space)

$\longrightarrow$7 and 9 o-H_2D^+ cores identified in G351 and G354, respectively

ζ_2 vs $N(H_2)$



(see *Padovani* et al 2020 and *Gabici* 2022 reviews)



- The scatter $\langle\zeta_2\rangle$ at a given $N(H_2)$ may also reflect a different morphology of magnetic fields

ζ_2 with ALMA - Caselli+98

ALMA 1.34 mm + $R_{eff,\ oH2D+}$

$$x(e) = \frac{2.7 \times 10^{-8}}{R_D} - \frac{1.2 \times 10^{-6}}{f_D},$$

$$\zeta_2 = \left[7.5 \times 10^{-4} x(e) + \frac{4.6 \times 10^{-10}}{f_D}\right] x(e) n(H_2) R_H$$

(*Caselli*+98)

$H^{13}CO^+$ + ALMA 1.34 mm

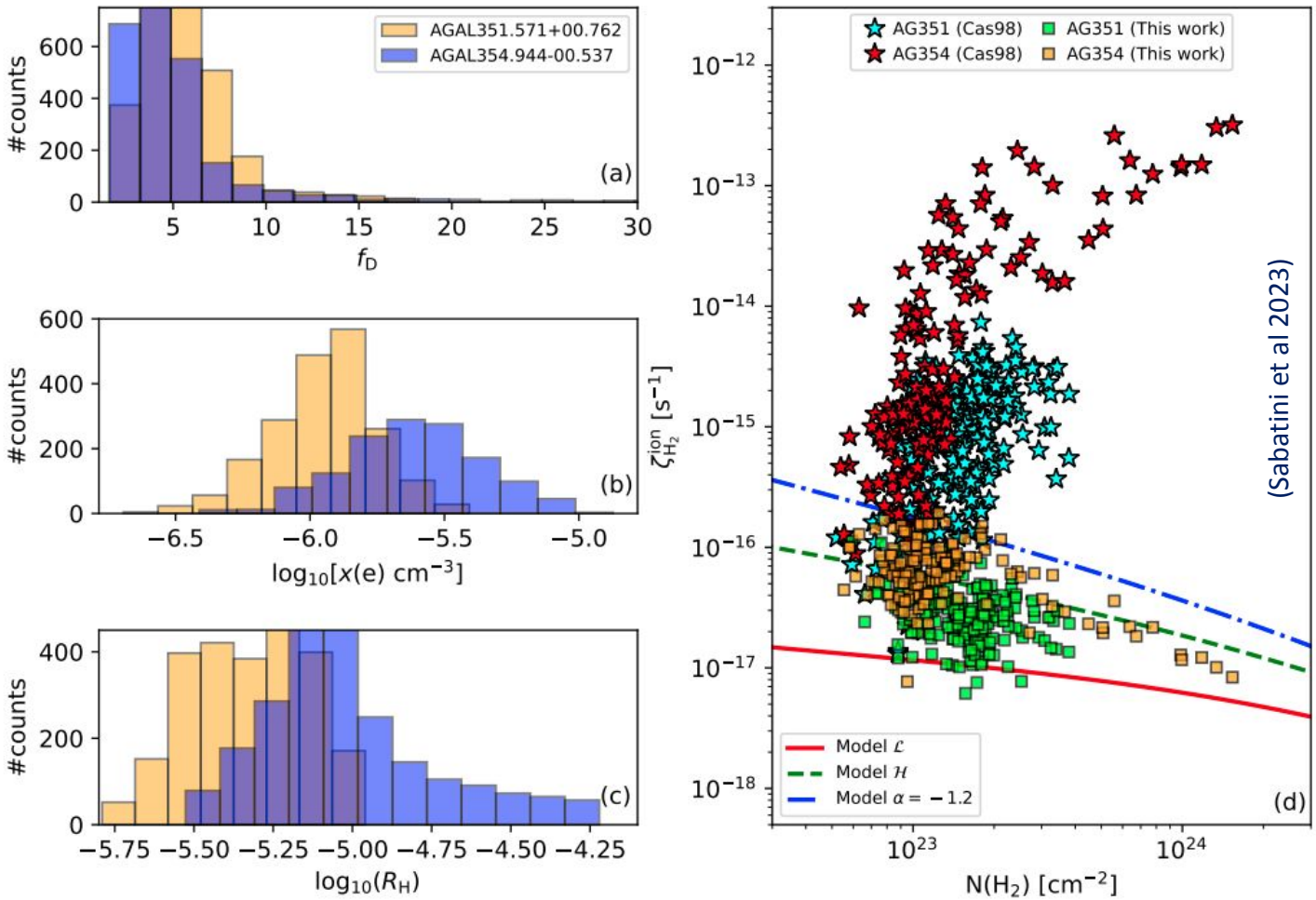
from DCO^+ and $H^{13}CO^+$

$C^{18}O$ + ALMA 1.34 mm

$$\zeta_{H_2}^{ion} = k_{CO}^{o-H_3^+} \frac{X(CO)\, N(o - H_2D^+)}{3 R_D \ell}$$

(*Bovino*+20)

ζ_2 with ALMA - Caselli+98



- ➔ x(e) 10-100 times higher than in the literature

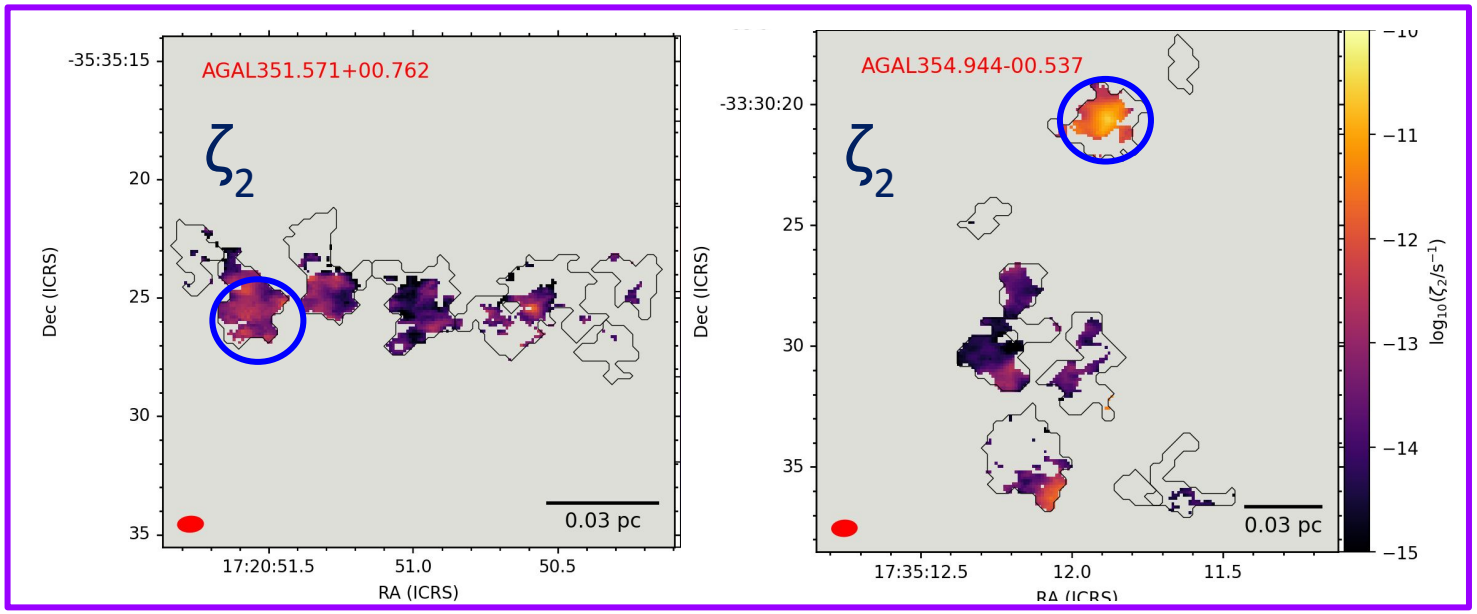
  (de Boisanger+96, Williams+98, Caselli+02, Salas+21)

- ➔ $10^{-4.5} < R_H < 10^{-3.5}$

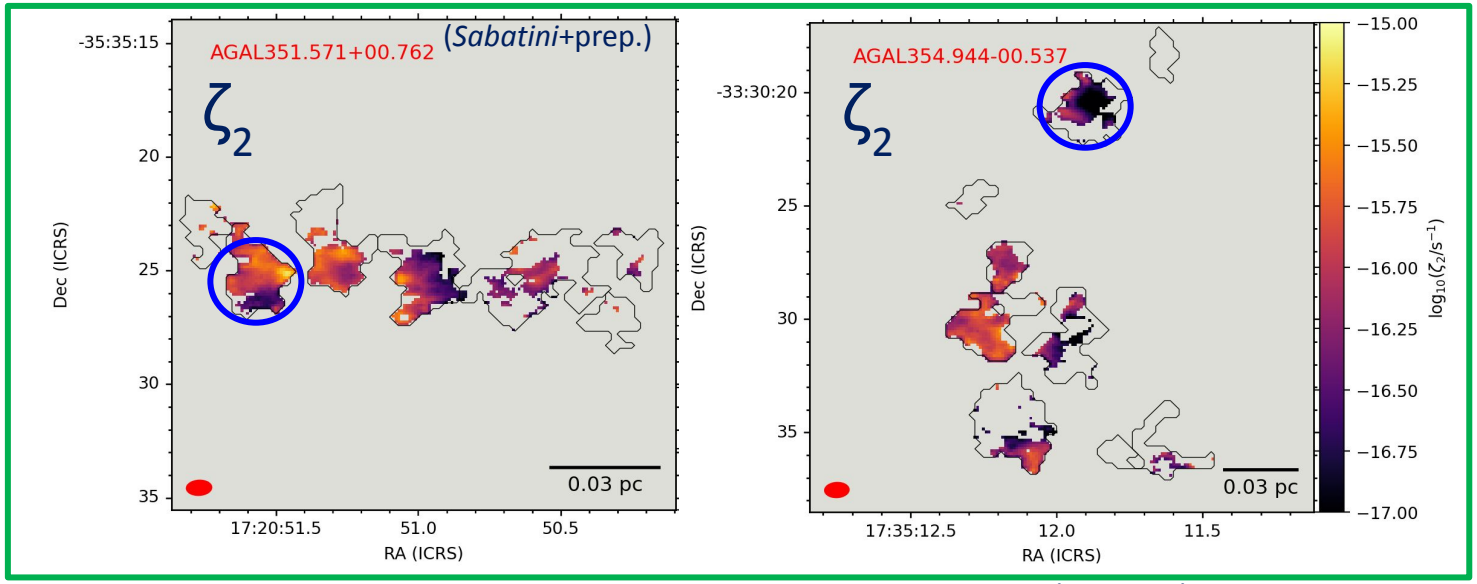
  (e.g. Caselli+98)

ζ_2 maps comparison

Caselli et al 1998



Bovino et al 2020

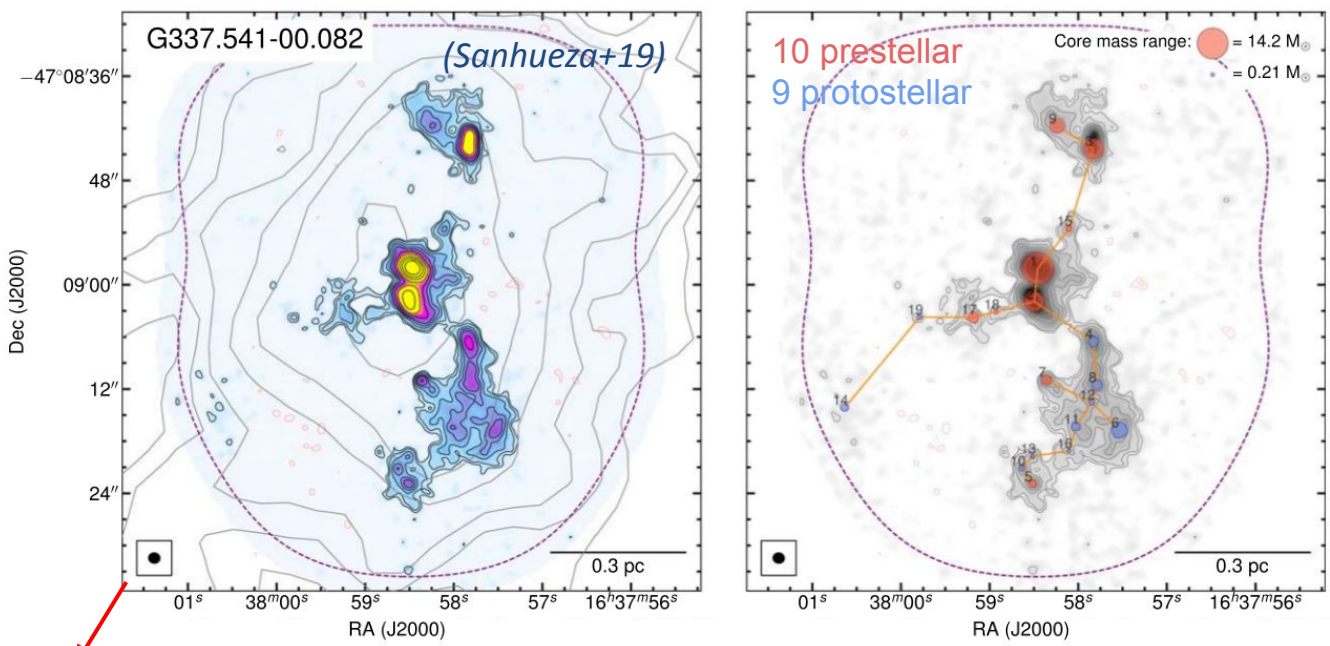


CO-depletion in ASHES

- CO-depletion study on core scale in 12 massive clumps selected from the ASHES survey;

Sabatini et al. (2022)

1.34 mm + ATLASGAL



1.29” ×1.18”
(~5000 AU)

ASHES: 294 cores with 210 prestellar cand. (e.g. no outflows or warm-gas molecular emission)

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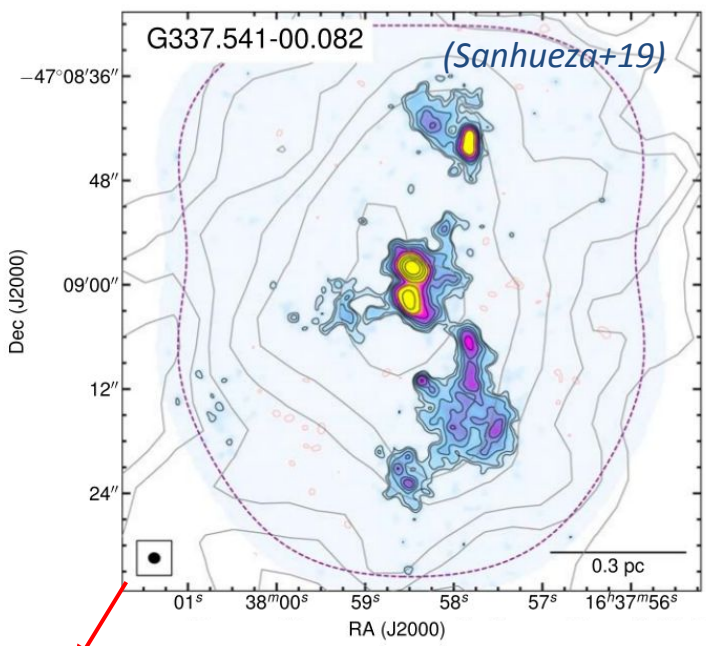

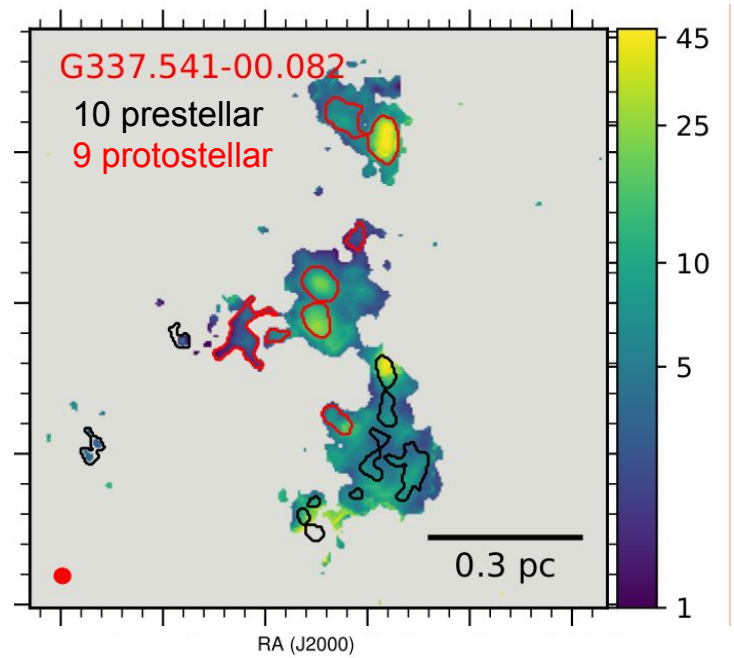

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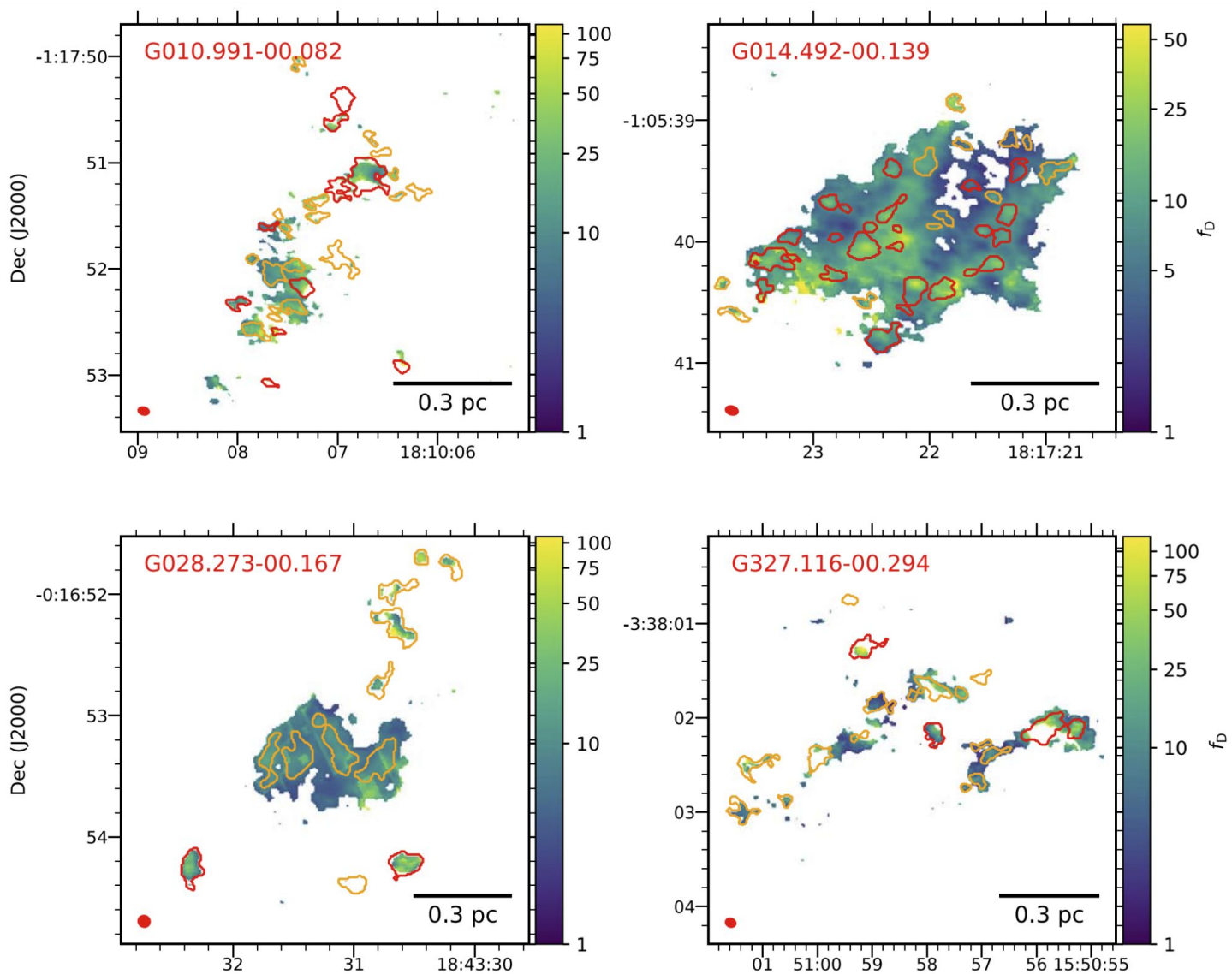
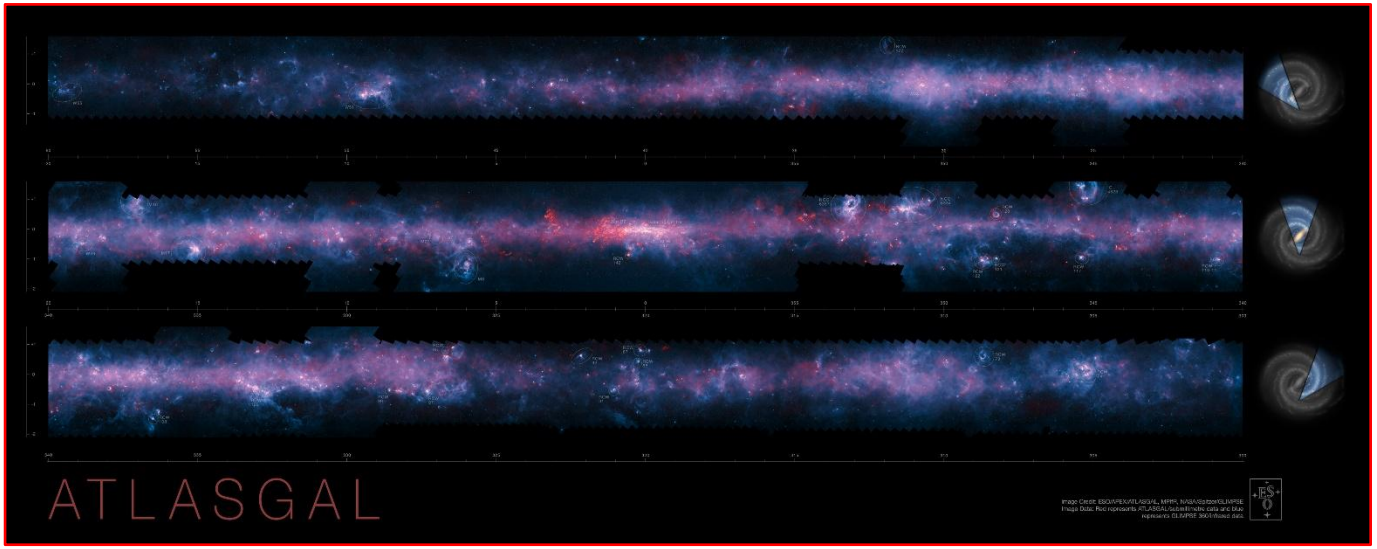


o-H_2D^+ as chemical clock



106 ATLASGAL sources in two datasets:

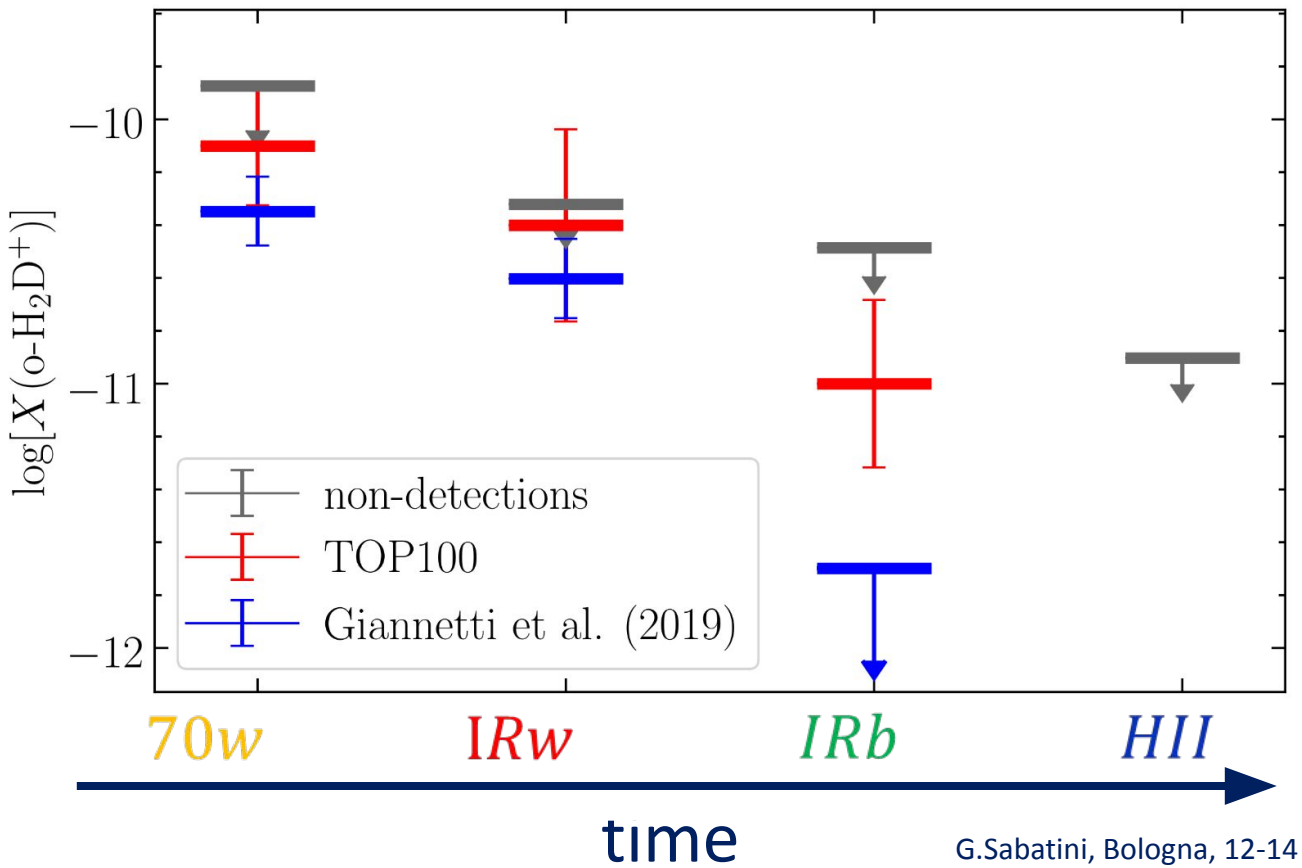
1. HMCs with high degree of deutereted NH_3; (*Wienen+21*)
2. TOP100 survey to observe N_2H^+ (372 GHz); (*Lee+21*)

- 16 sources with detection (70w:7, IRw:6 , IRb:2, HII:0);
- 46 sources for detection limits (70w:8, IRw:16, IRb:9, HII:13);

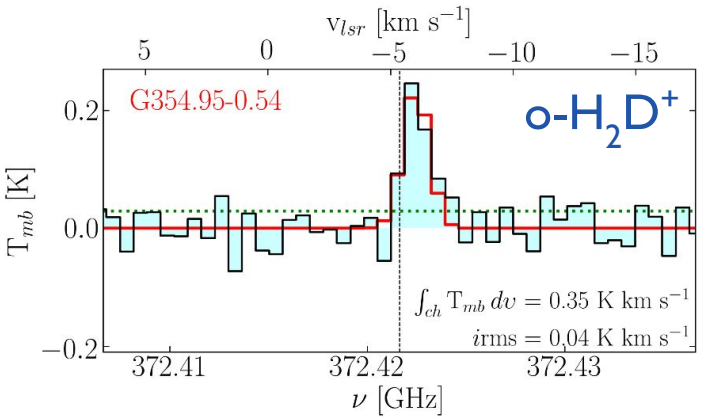
o-H_2D^+detection rate of
70w:47%, IRw:27%, IRb:18%, HII:7%

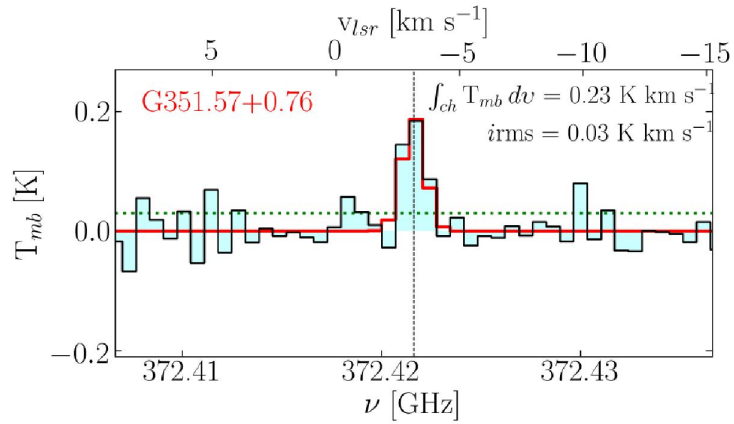
o-H_2D^+ as chemical clock

- Confirmed decreasing trend in X(o-H_2D^+) in a sample of independent HMSFRs;
- o-H_2D^+ : tracer of pre-stellar stages;



ζ_2 in ATLASGAL





- 8 sources with additional DCO^+, HCO^+, $C^{17}O$ data

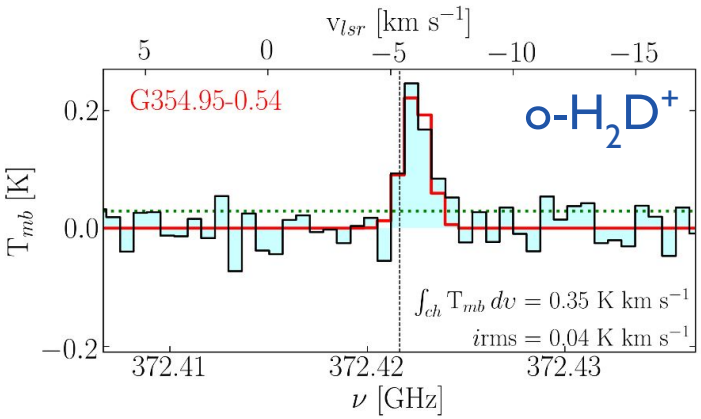
Table 2. Summary of the observations.

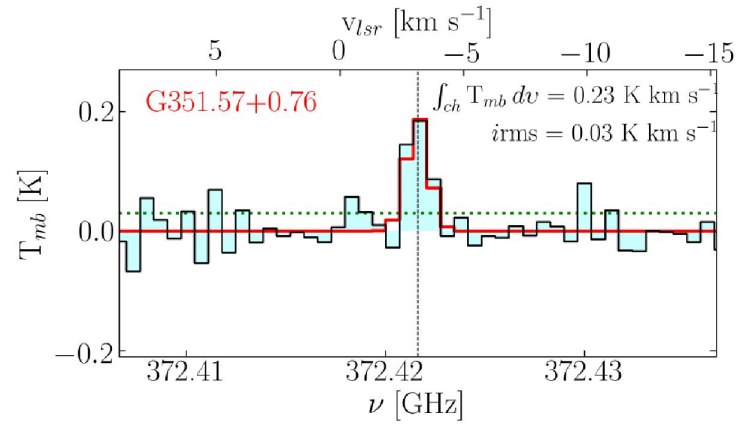
Molecules	Quantum numbers	Frequencies (GHz)	Telescopes	Beam FWHM (arcsec)	Spectral resolution (km s^{-1})	rms noise [a] (K)	References
o-H_2D^+	1_{10}–1_{11}	372.4	APEX	17	0.5–0.6	0.02–0.05	This work
$H^{13}CO^+$	1–0	86.8	IRAM-30 m	24	0.75	0.02	This work
DCO^+	1–0	72.0	IRAM-30 m	28	0.75	0.02	This work
$C^{17}O$ (TOP100)	1–0	112.4	IRAM-30 m	21	0.5	0.05	[1]
$C^{17}O$	1–0	112.4	IRAM-30 m	21	0.6	0.06	[2]

Notes. [a]The temperatures are reported on the main-beam temperature scale.

References.[1] Giannetti et al. (2014); [2] Csengeri et al. (2016).

ζ_2 in ATLASGAL





- 8 sources with additional DCO^+, HCO^+, $C^{17}O$ data

Table 5. Summary of the quantities to calculate the CRIR.

ATLASGAL-ID[(a)]	χ(CO) [(a)] (10^{-5})	R_D	ζ_2^A $\ell = 0.5R_{eff}$ (10^{-17} (s^{-1}))	ζ_2^{ref} $\ell = R_{eff}$ (10^{-17} (s^{-1}))	ζ_2^B $\ell = 2R_{eff}$ (10^{-17} (s^{-1}))
G13.18+0.06	8.0	0.002 ± 0.001	6.92	3.46	1.73
G14.11–0.57	11.5	0.011 ± 0.004	3.18	1.59	0.80
G14.23–0.51	**4.6**	0.011 ± 0.004	3.67	1.84	0.92
G14.49–0.14	4.7	0.011 ± 0.003	6.68	3.34	1.67
G14.63–0.58	5.8	0.003 ± 0.001	11.62	5.81	2.91
G15.72–0.59	**11.1**	0.018 ± 0.006	3.06	1.53	0.77
G18.61–0.07	4.6	0.005 ± 0.002	1.33	0.67	0.34
G19.88–0.54	5.8	0.005 ± 0.002	3.00	1.50	0.75