

(Very) High Energy Radio: breaking news on cosmic-ray diffusion

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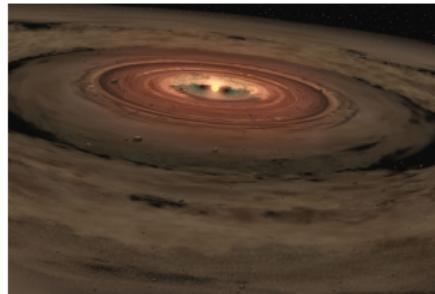


Today

15 orders of magnitude in energy...

... from radio observations to cosmic rays properties

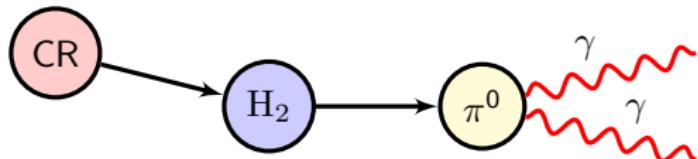
Interest in cosmic-rays



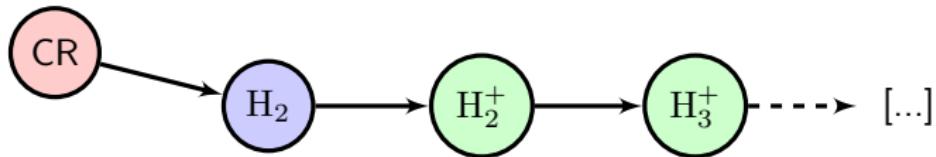
- Star formation
- Disk turbulence
- ISM chemistry
- Space weather
- High energy physics
- ...

Effects of cosmic-rays on dense gas

- **GeV-TeV** CR: γ -ray emission [γ energy $\sim 10\%$ lower than parent CR]



- **MeV-GeV** CR: ionization of the gas (H_2^+ , He^+ , H^+ , ...)



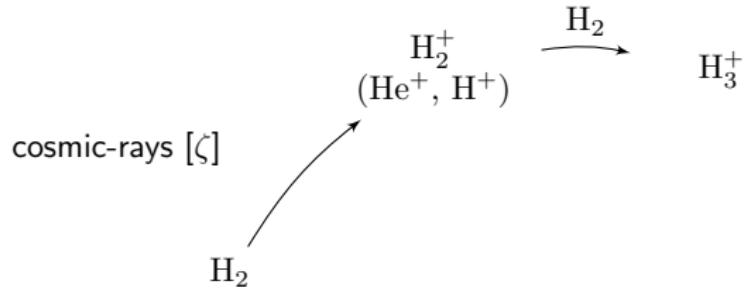
To observe CR properties

⇒ look at the effects on the surrounding gas !

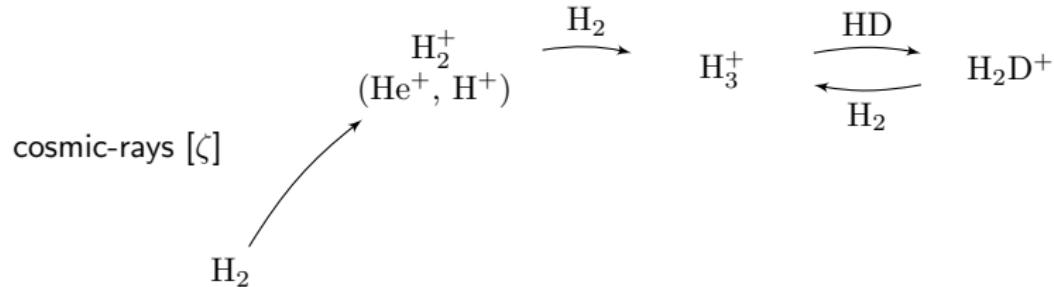
CR-induced chemistry of DCO⁺ and HCO⁺

H₂

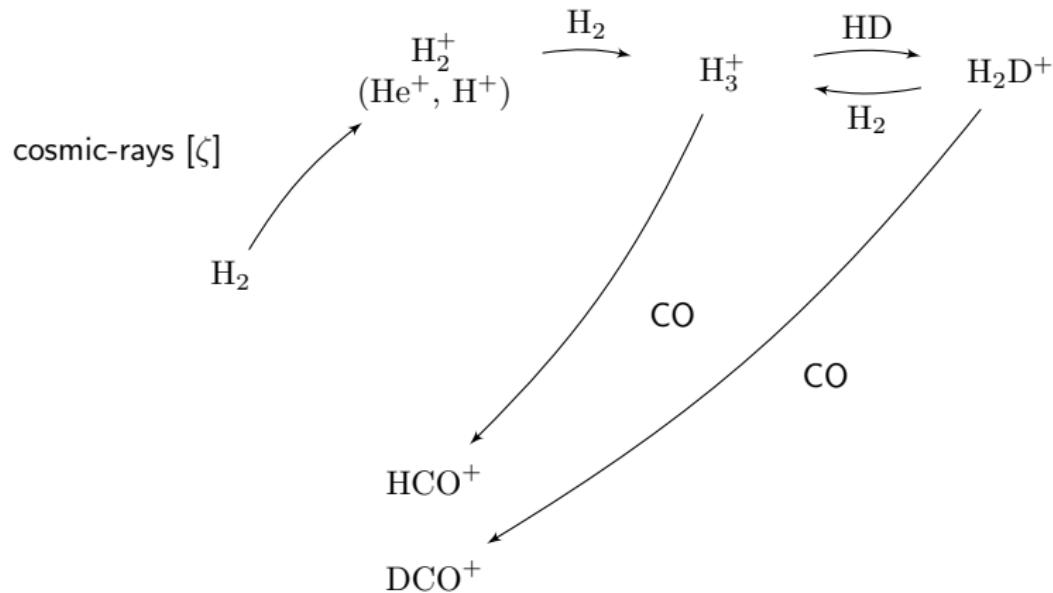
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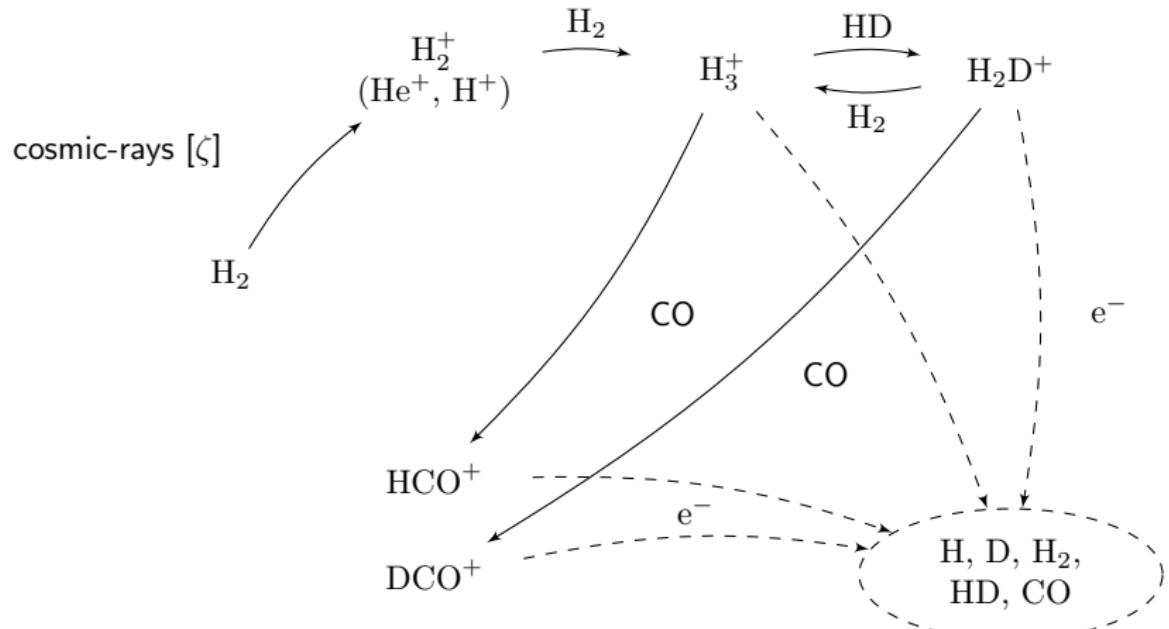
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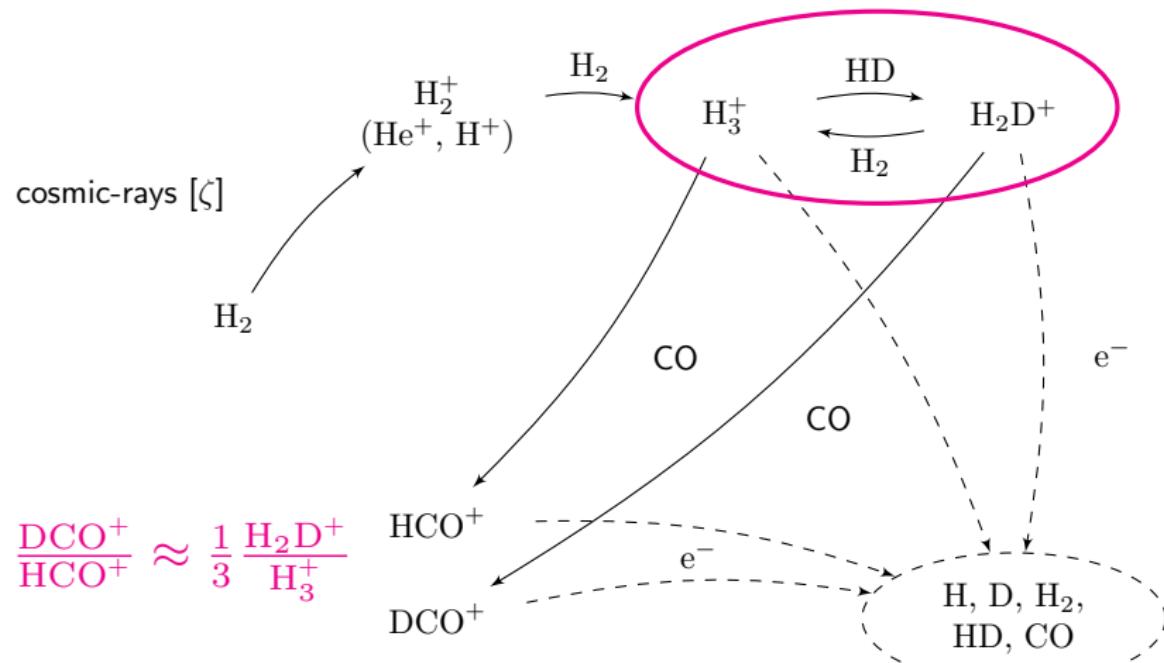
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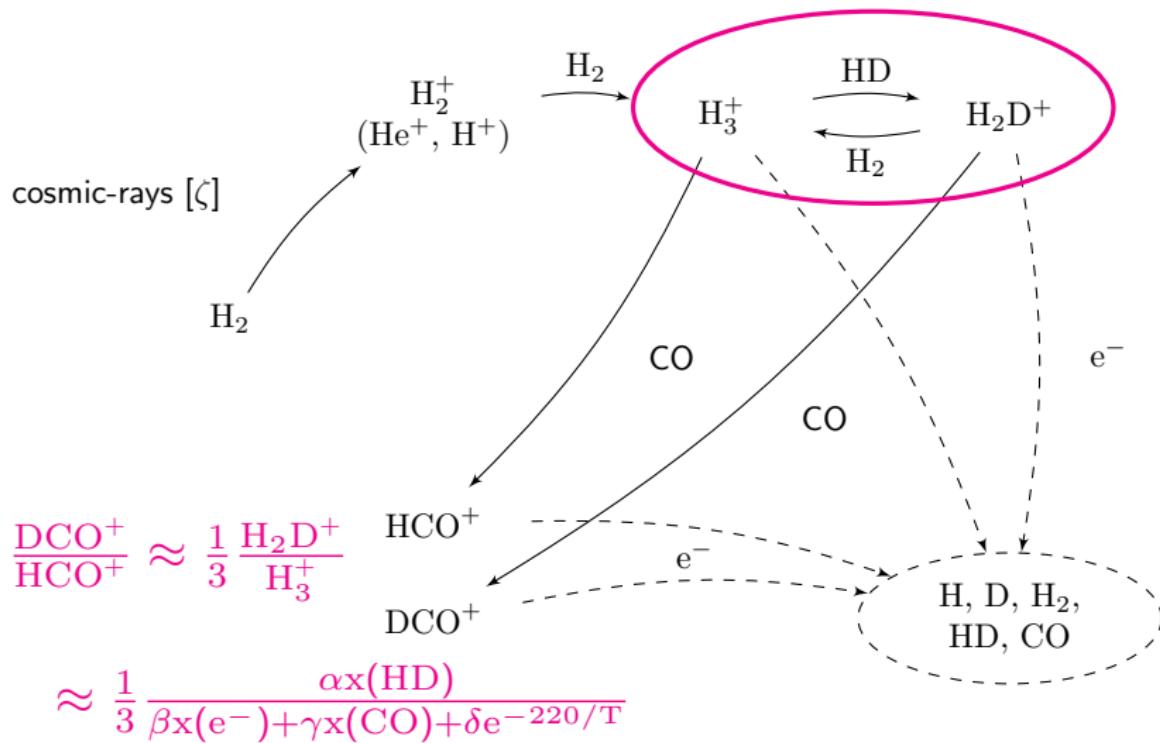
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$$\frac{\text{DCO}^+}{\text{HCO}^+} \approx \frac{1}{3} \frac{\text{H}_2\text{D}^+}{\text{H}_3^+} \approx \frac{1}{3} \frac{\alpha x(\text{HD})}{\beta x_e + \gamma x(\text{CO}) + \delta e^{-220/T}}$$

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observations

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e⁻ abundance

T dependent

CR-induced chemistry of DCO⁺ and HCO⁺

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e^- abundance

T dependent

{ abundance ratio DCO⁺/HCO⁺ + temperature } \Rightarrow electron abundance x_e

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T dependent

{ abundance ratio DCO⁺/HCO⁺ + temperature } \Rightarrow electron abundance x_e

$$x_e \propto \sqrt{\zeta/n_H}$$

\rightarrow need physical conditions to make sure **no ionization by UV/X**
(i.e. high CO column density)

Chemistry summary

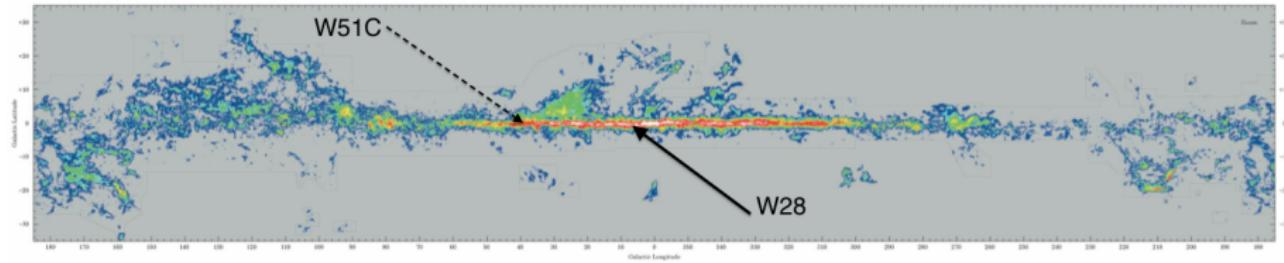
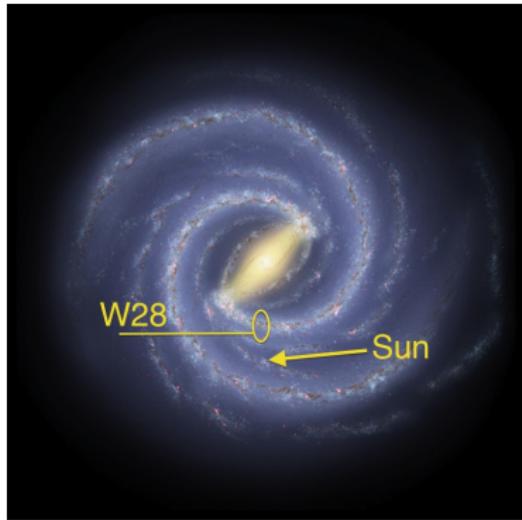
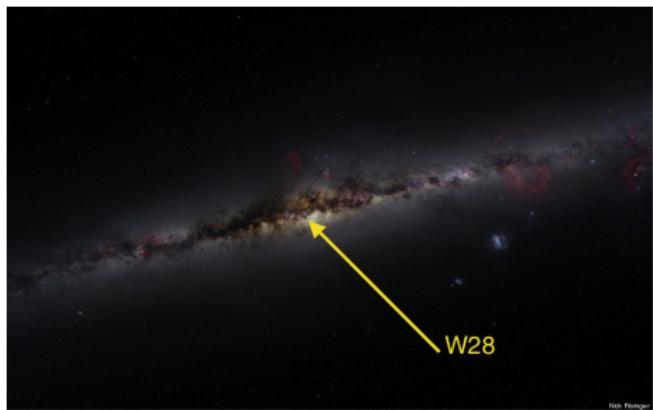
- $\text{DCO}^+/\text{HCO}^+$ is determined by electrons and gas temperature
- e^- abundance is linked to ζ through gas density
- make sure high column density so ionization is dominated by CR

⇒ We need physical conditions and $\text{DCO}^+/\text{HCO}^+$ ratio to derive ζ

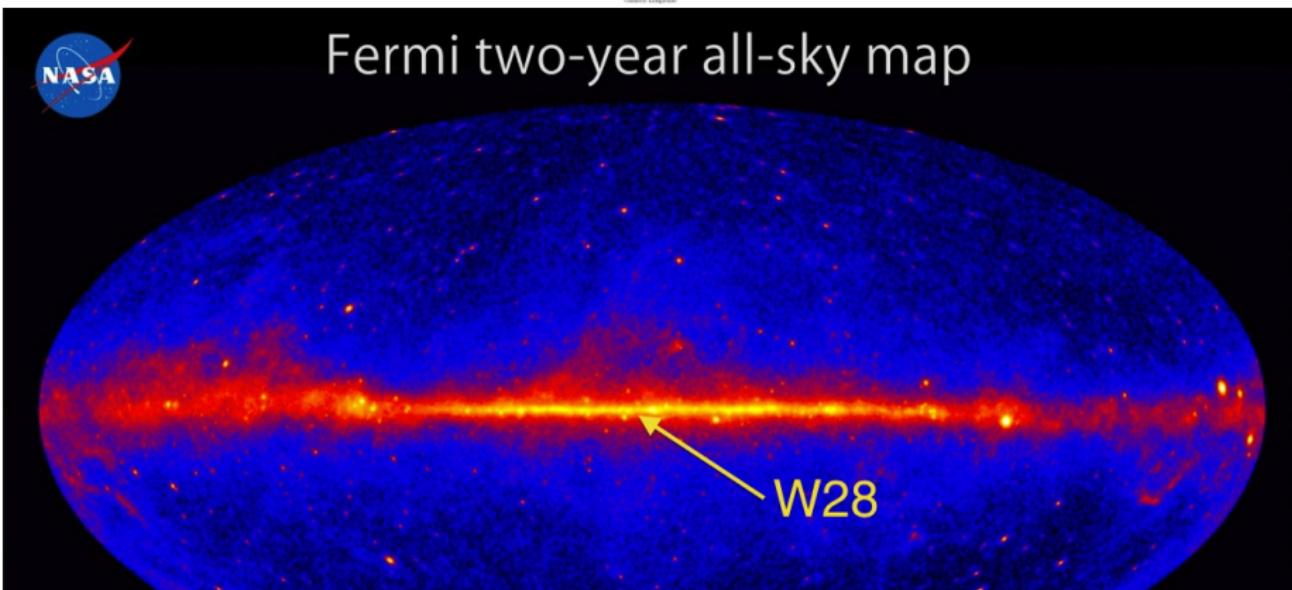
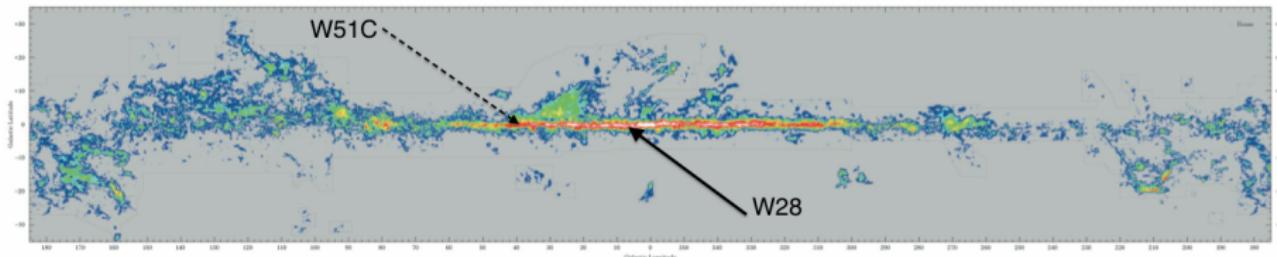
Program

- 1 Source: W28 SNR/MC association
- 2 CR ionization rate ζ from radio observations
- 3 CR properties

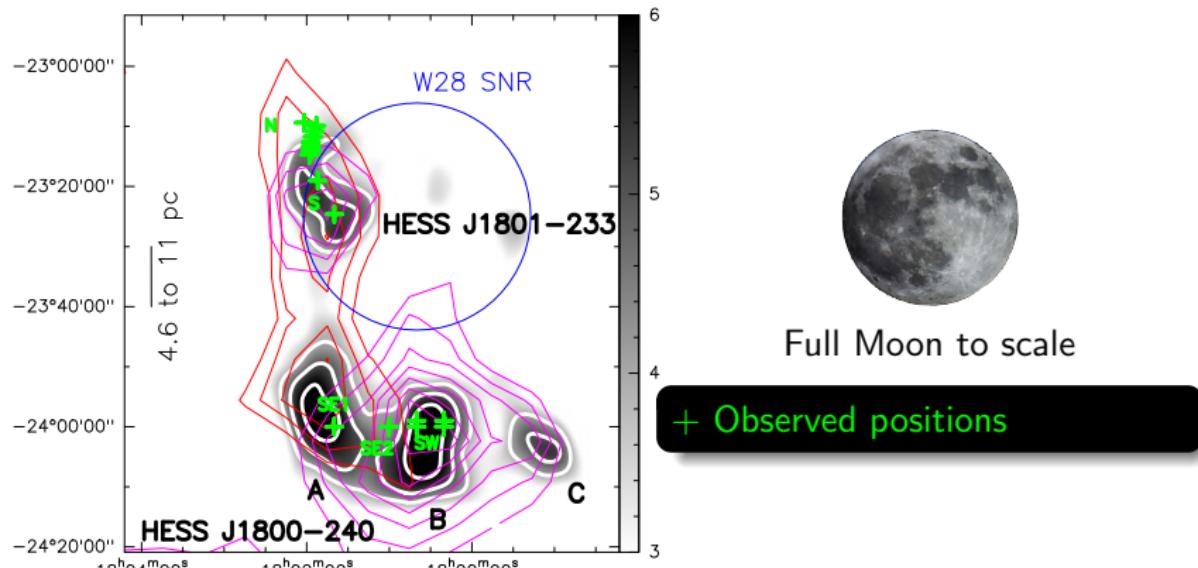
Galactic view



Galactic view



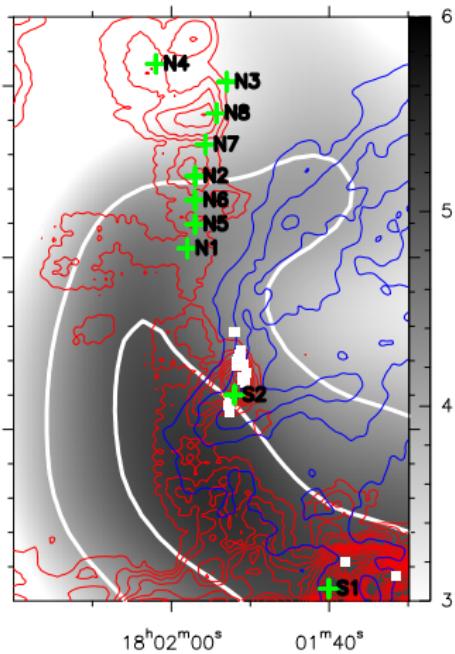
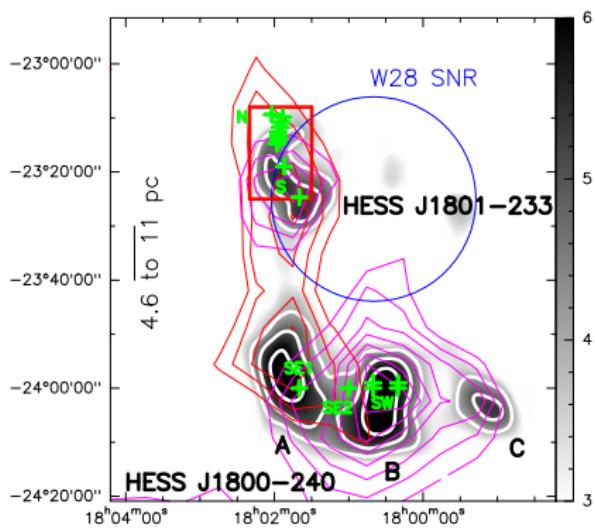
The W28 complex



[GeV- TeV CR $\rightarrow \gamma$ -ray] HESS contours (TeV emission)

[MeV-GeV CR \rightarrow ionization] molecular cloud (CO) [5-15, 15-25 km s⁻¹]

The W28 complex



Program

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Method

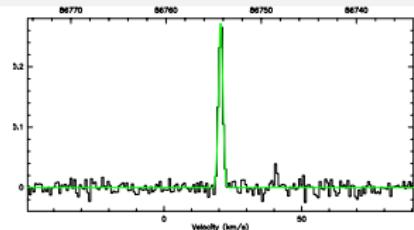
CO

DCO^+ , HCO^+

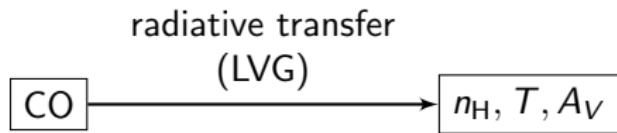
mm observations
[1mm \sim 1meV]



IRAM 30m radio-telescope



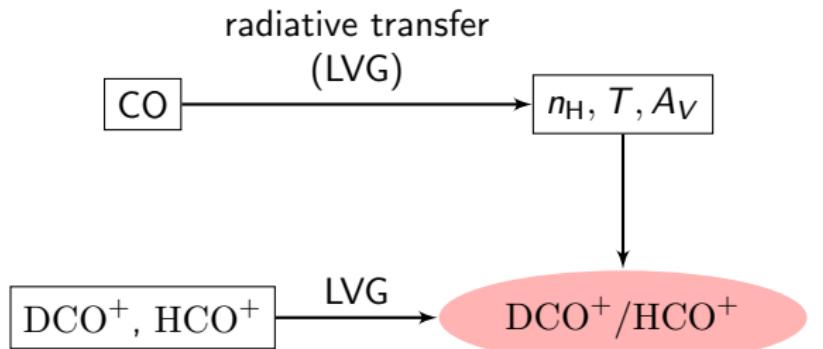
Method



$\text{DCO}^+, \text{HCO}^+$

mm observations
[$1\text{mm} \sim 1\text{meV}$]

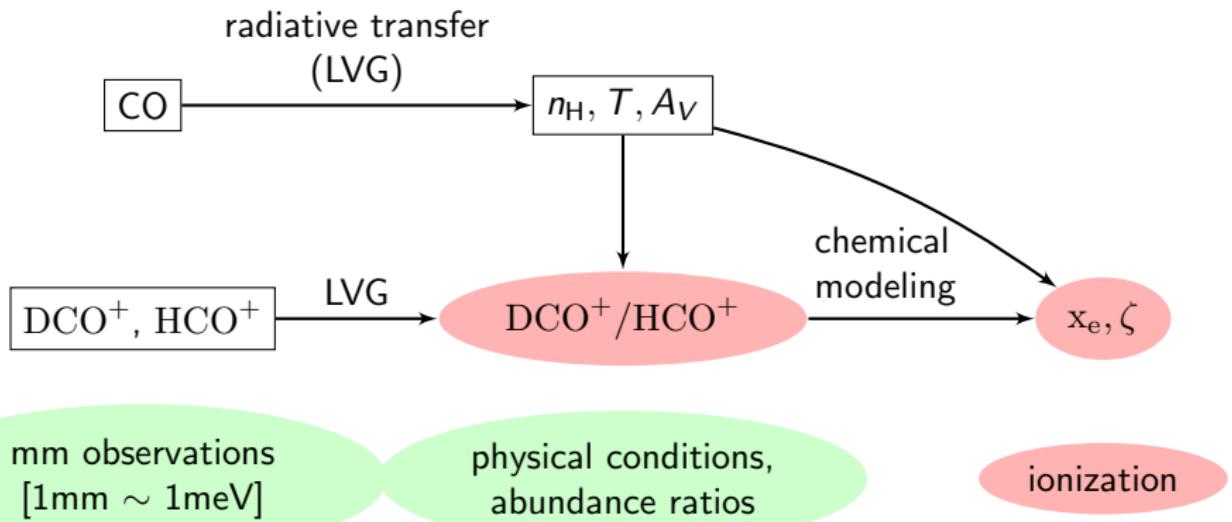
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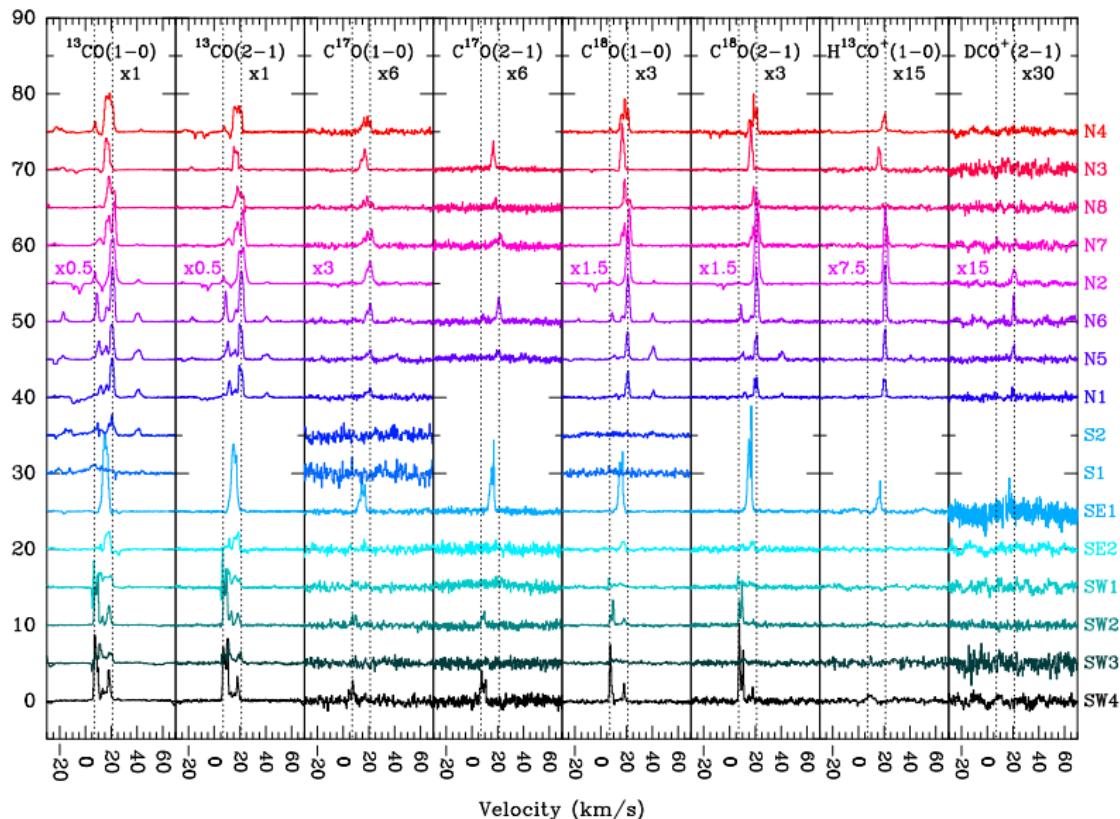
mm observations
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physical conditions,
abundance ratios

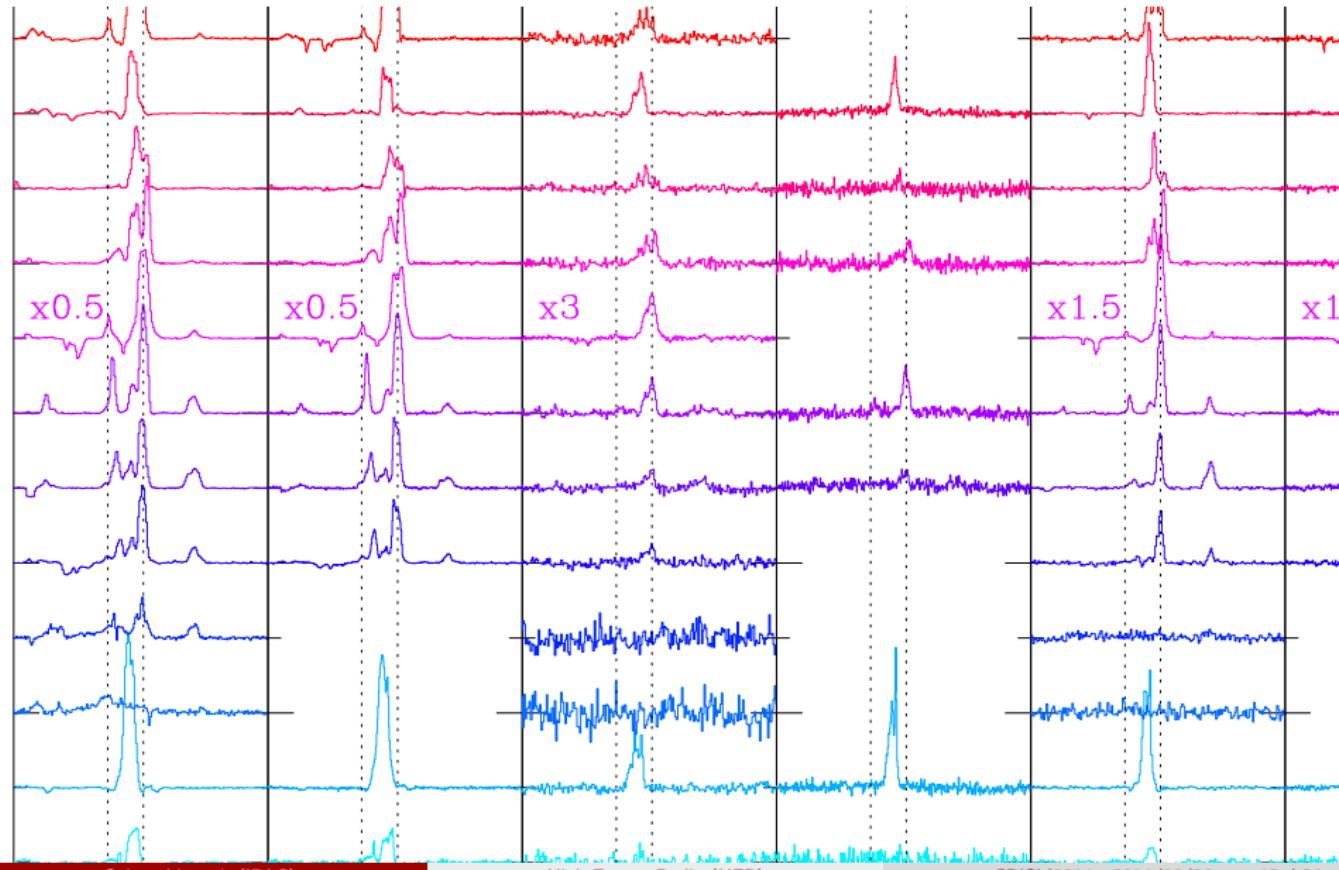
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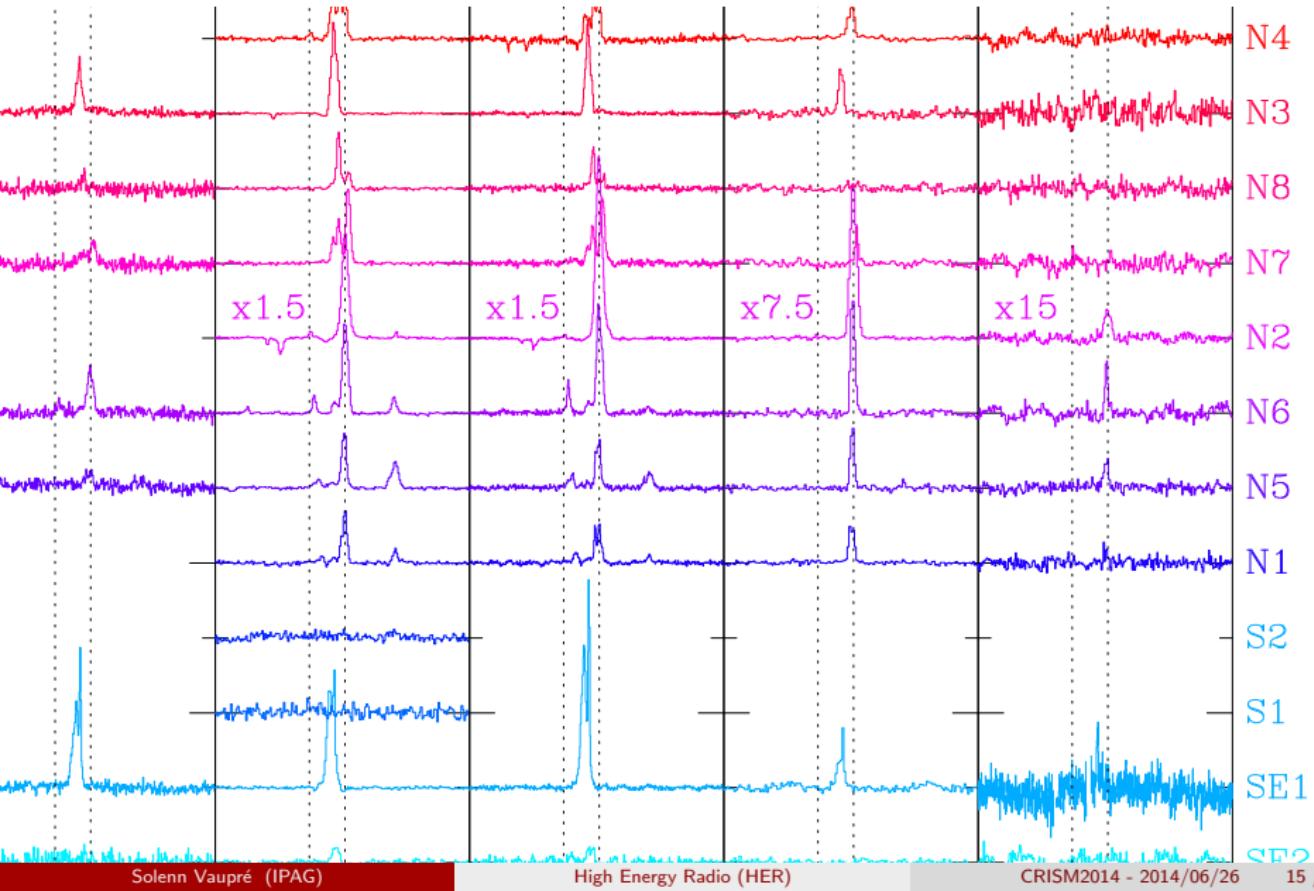
Spectra



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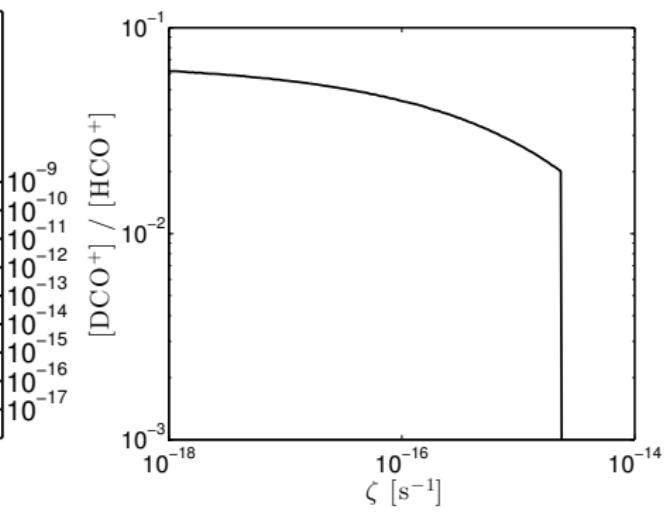
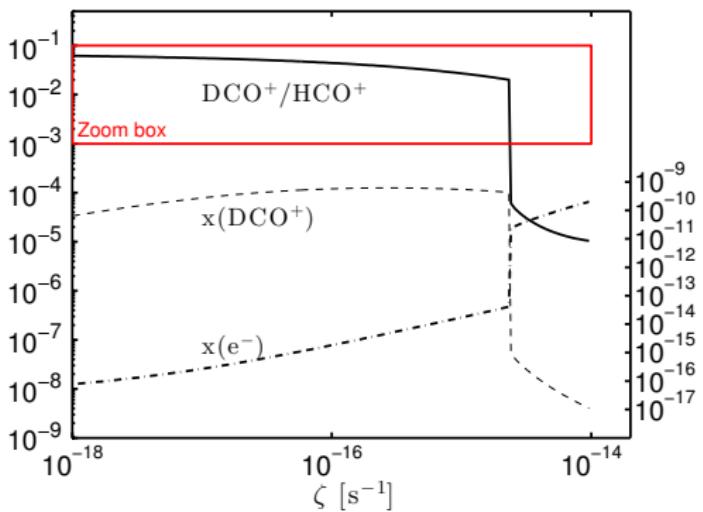
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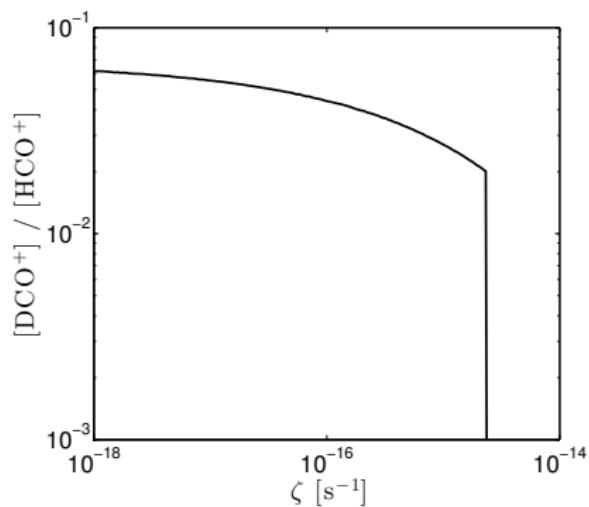
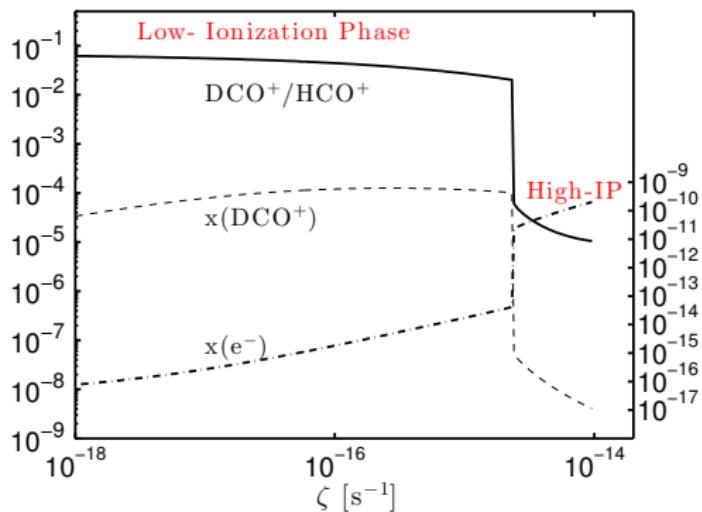
Results

Pos.	Δv [km s ⁻¹]	n_{H_2} [10 ³ cm ⁻³]	T_{kin} [K]	$N(\text{C}^{18}\text{O})$ [10 ¹⁵ cm ⁻²]	A_V [mag]	$N(\text{H}^{13}\text{CO}^+)$ [10 ¹² cm ⁻²]	$N(\text{DCO}^+)$ [10 ¹² cm ⁻²]	$\frac{[\text{DCO}^+]}{[\text{HCO}^+]}$	ζ [10 ⁻¹⁷ s ⁻¹]
N1	3.5	0.6 {0.2 – 1}	15 ± 5	4 {2 – 6}	21 {11 – 32}	0.8 – 1.3	< 0.22	< 0.005	
N5	3.0	4 {2 – 5}	10 ± 2	3 {2 – 8}	16 {11 – 32}	1.1 – 1.4	0.89 – 1.30	0.014 – 0.020	
N6	3.0	4 {2 – 6}	13 ± 3	6 {4 – 20}	32 {21 – 105}	1.8 – 2.5	0.79 – 1.30	0.008 – 0.012	
N2 [†]	5.0	> 2	16 ± 2	20 {15 – 30}	105 {79 – 158}	5.6 – 8.9	1.10 – 2.00	0.003 – 0.006	
N7	2.5	2 {2 – 5}	10 ± 2	4 {3 – 10}	21 {16 – 53}	0.6 – 0.9	< 0.25	< 0.007	
N8	3.5	1 {0.6 – 2}	8 ± 1	3 {2 – 4}	16 {11 – 21}	< 0.2	< 0.35	-	
N3	3.5	6 {4 – 10}	8 ± 1	6 {5 – 7}	32 {26 – 37}	1.0 – 1.4	< 0.35	< 0.006	
N4	3.0	2 {0.6 – 4}	12 ± 3	2 {2 – 3}	11 {5 – 16}	1.0 – 1.4	< 0.35	< 0.006	
SE1	4.0	2 {1 – 5}	19 ± 5	6 {5 – 20}	32 {26 – 105}	0.4 – 0.56	0.79 – 1.0	0.032 – 0.05	
SE2	3.0	4 {2 – 10}	8 ± 2	0.9 {0.4 – 20}	5 {2 – 105}	< 0.2	< 0.28	-	
SW2	1.5	2 {1 – 4}	20 ± 4	4 {3 – 10}	21 {16 – 53}	< 0.1	< 0.22	-	
SW4 [†]	1.5	6 {4 – 10}	16 ± 2	1.5 {1 – 3}	5 {5 – 16}	0.5 – 0.8	< 0.25	< 0.009	

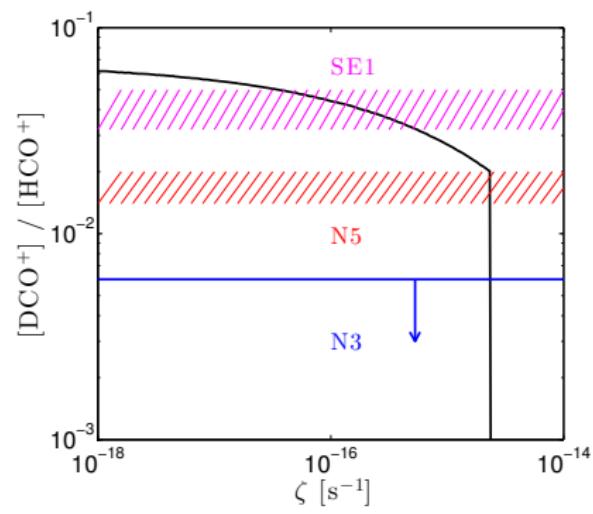
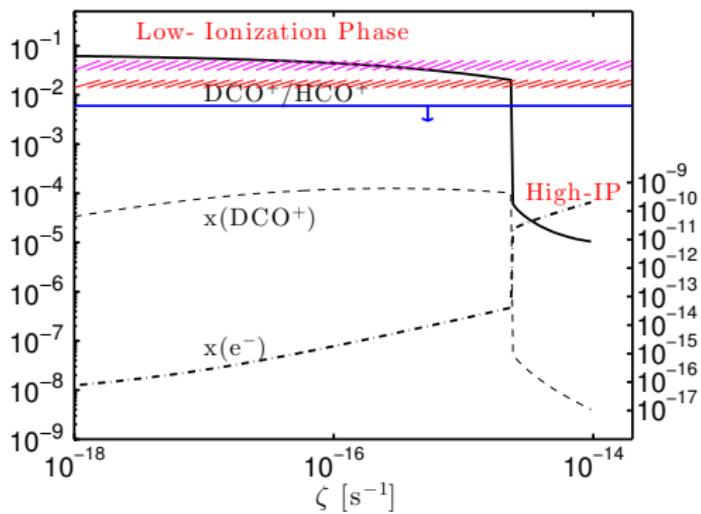
ζ from observations (astrochem code)



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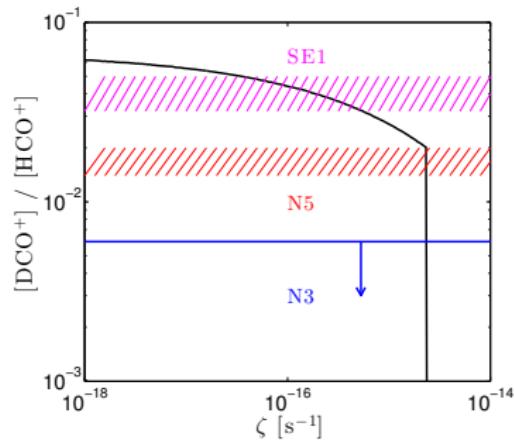


Artist view

If $\text{DCO}^+/\text{HCO}^+$ lies on the LIP...
... OK but can't exclude some HIP

If DCO^+ not detected ...
... \approx no LIP on the line of sight

If $\text{DCO}^+/\text{HCO}^+$ not on LIP ...
... HIP dominant on the line of sight
 \rightarrow structure

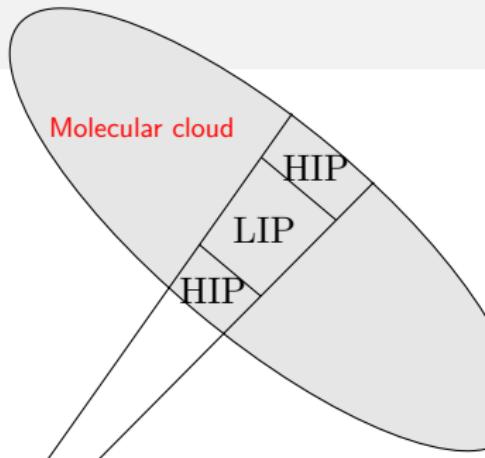


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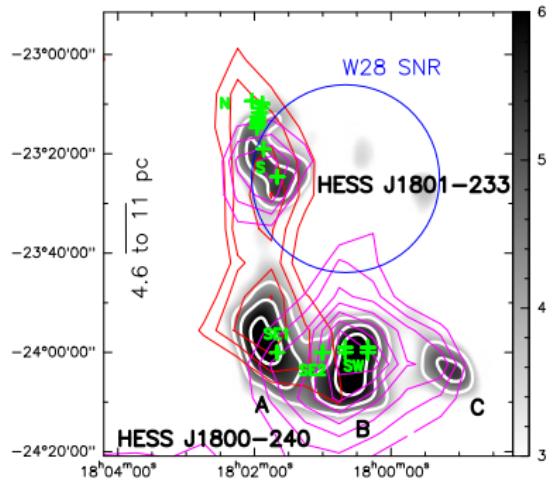
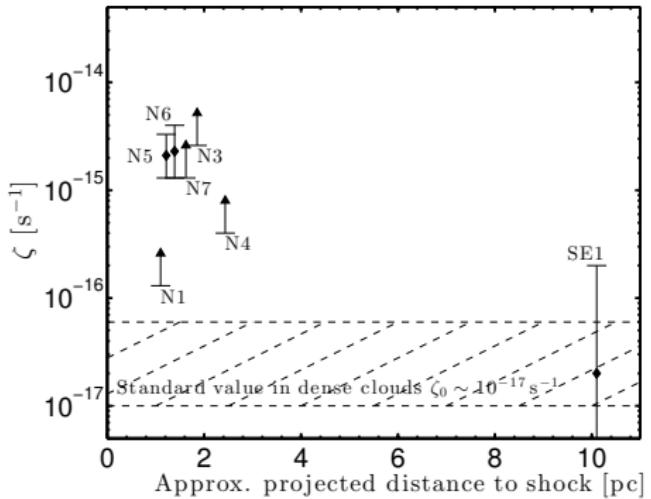
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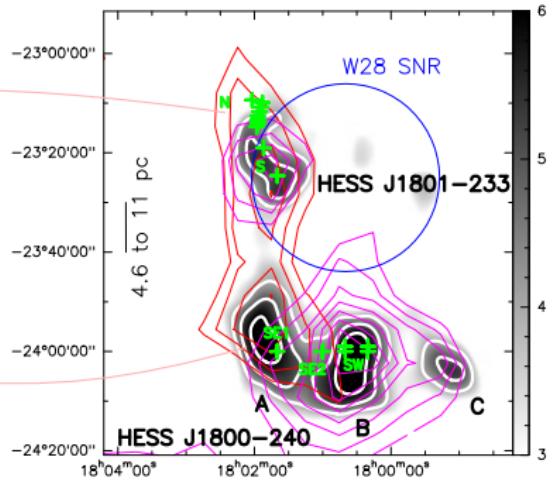
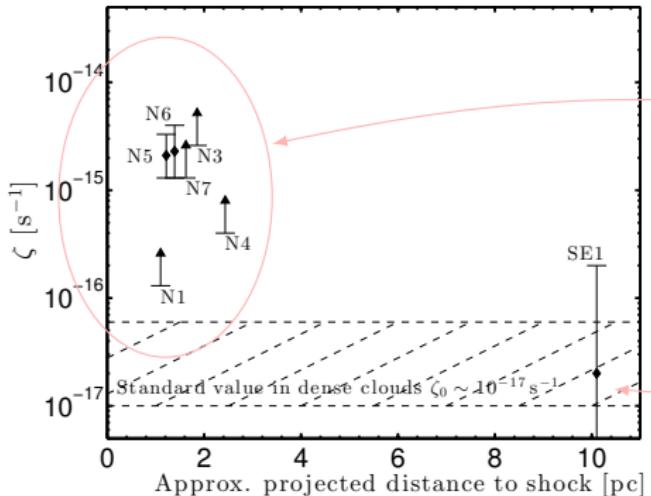
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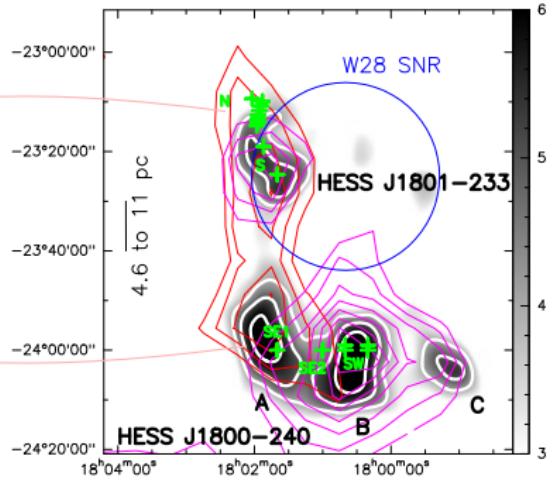
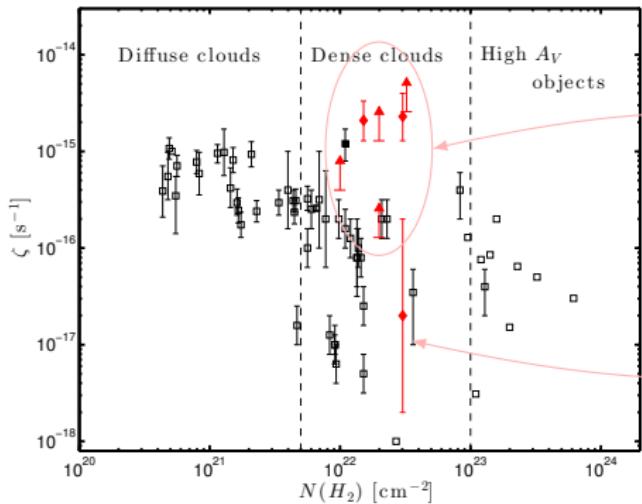
Assumed distance to W28: 2 kpc

Results



Assumed distance to W28: 2 kpc

Results

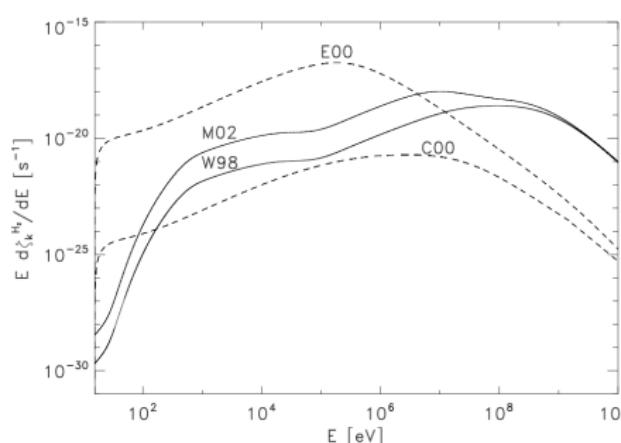


Padovani&Galli (20013)
collection of observations

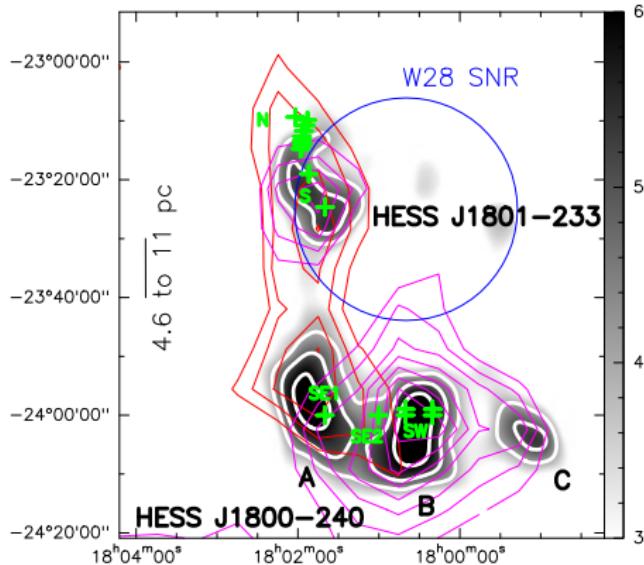
Program

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(1) CR ionization



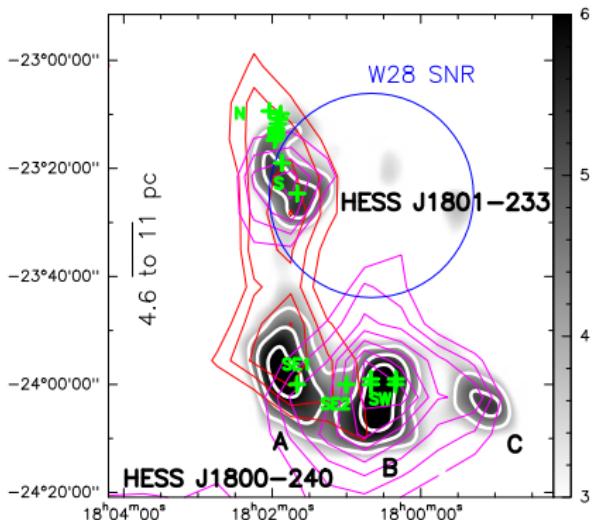
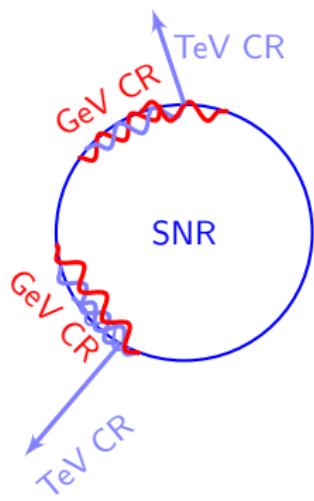
Padovani+ (2009), Fig. 14
contribution of CR to ionization



- GeV γ -rays in the North, NOT in the South (FERMI - Abdo et al. 2010)
 - TeV γ -rays in the North AND in the South (HESS - Rowell et al. 2007)
- ⇒ **ionization by 0.1-1 GeV CR**

[Some of these same CR also contribute to γ emission ($E > 0.28$ GeV)]

(2) CR escape



- GeV CR still bound to SNR shell
 - TeV CR escape sooner
- ⇒ ionizing CR have not reached the southern cloud yet
- ⇒ diffusion coeff estimate

Specific results

Diffusion coefficient

$$D_{(\approx 10 \text{ GeV})} \gtrsim 3 \times 10^{27} \left(\frac{R}{10 \text{ pc}} \right)^2 \left(\frac{t}{10^4 \text{ yr}} \right)^{-1} \text{ cm}^2/\text{s},$$

substantial agreement with e.g. Nava&Gabici (2013)

Ionization losses timescale

$$\tau_{ion} \approx 14 \left(\frac{n_H}{10^3 \text{ cm}^{-3}} \right)^{-1} \left(\frac{E}{\text{MeV}} \right)^{3/2} \text{ yr}.$$

$D \sim R_d^2 / \tau_{ion} \Rightarrow$ only CR ≥ 100 MeV can spread over $\gtrsim 3$ pc

Conclusion

From radio to CR properties

- upper limit on $\text{DCO}^+/\text{HCO}^+ \Rightarrow$ lower limit on ζ
- observation of energy-dependent CR diffusion away from the SNR
- high ionization due to 0.1-1 GeV cosmic-rays

See Vaupré+ (2014), A&A, accepted

See also about W51C: Ceccarelli+ (2011), ApJL, 740 ; Dumas+ (2014), ApJL

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- observation of energy-dependent CR diffusion away from the SNR
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Perspectives

- Increase number of sources (W28, W51C, W44, ...)
- Increase number of species to characterize ζ (tracers)

See Vaupré+ (2014), A&A, accepted

See also about W51C: Ceccarelli+ (2011), ApJL, 740 ; Dumas+ (2014), ApJL