Interstellar molecules uncover cosmic rays properties

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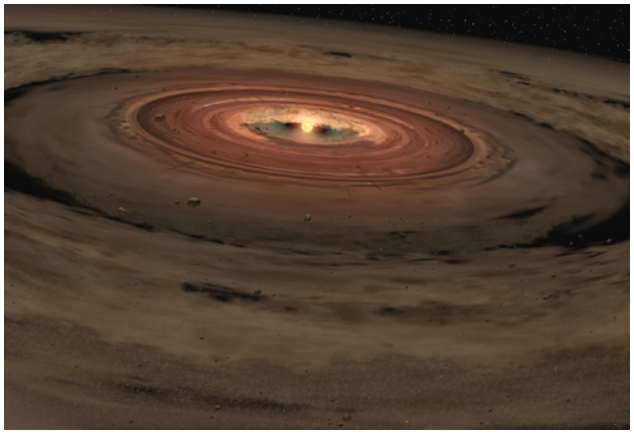
Today

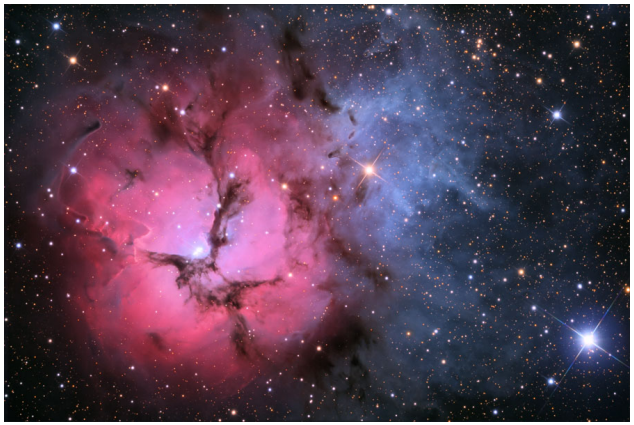
15 orders of magnitude in energy...

... from radio observations to cosmic rays properties

Interest in cosmic-rays

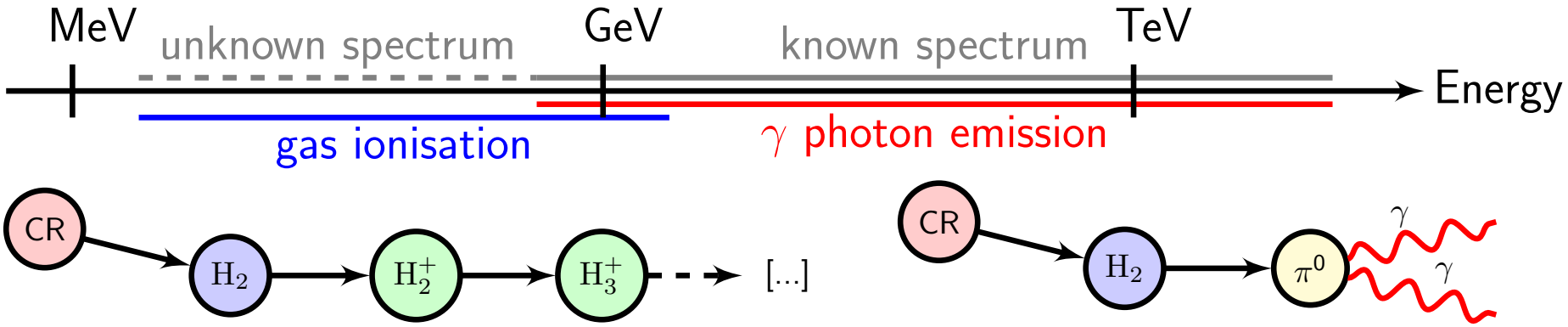


- Star formation
- Disk turbulence
- ISM chemistry
- Space weather
- High energy physics
- ...



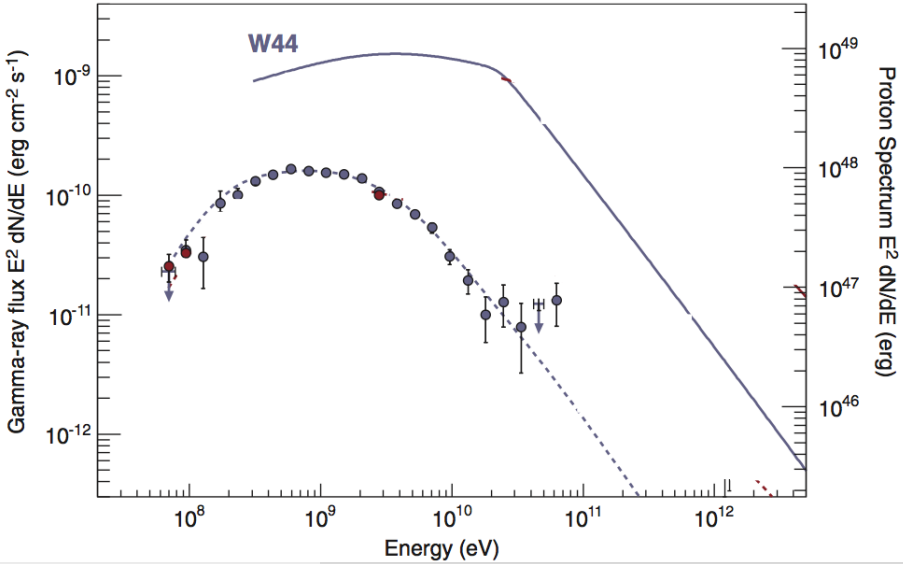
ζ

Effects of cosmic-rays on dense gas

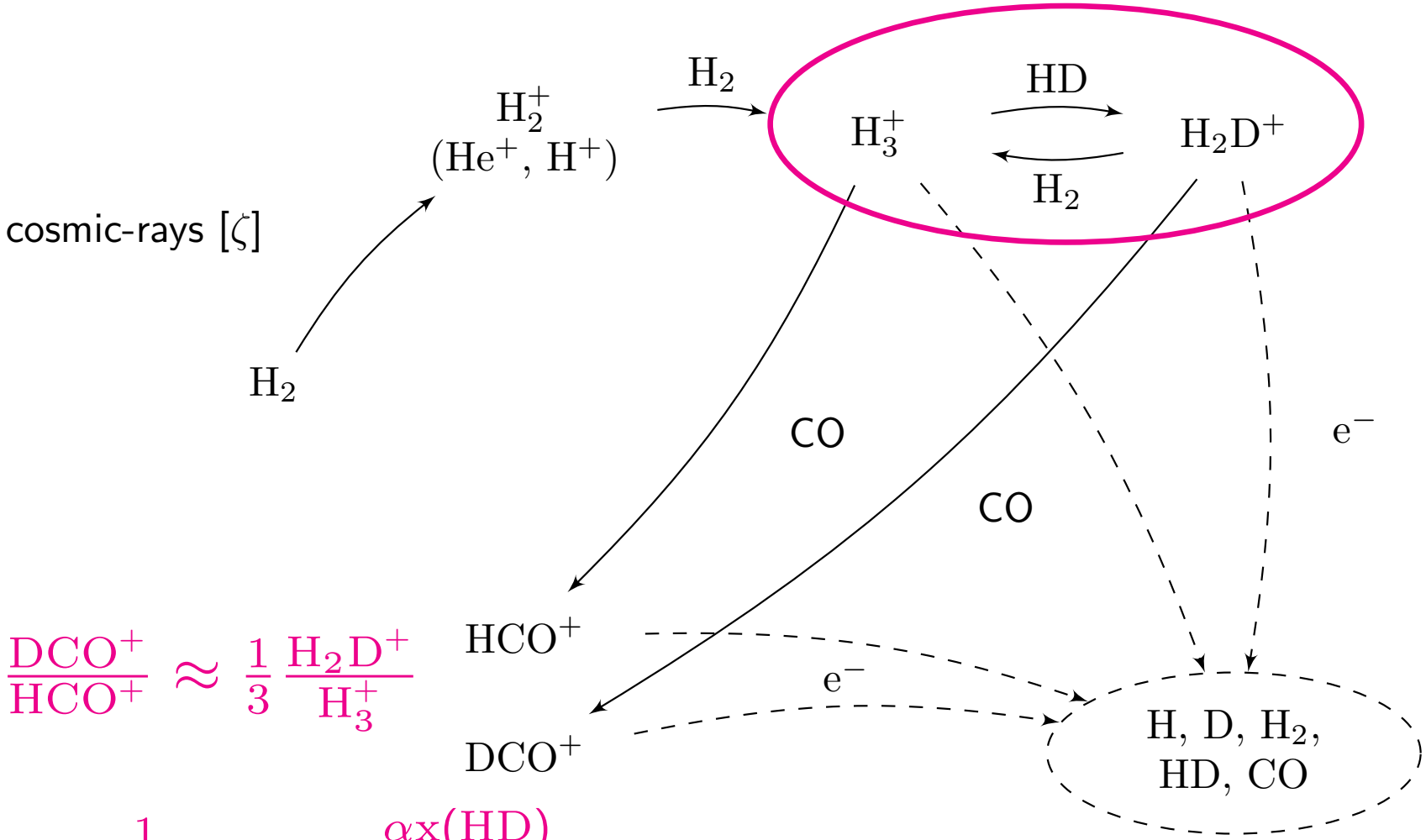


IRAM
molecular spectrosopy

FERMI-LAT, AGILE (satellites)
HESS, MAGIC, VERITAS (Cherenkov)



CR-induced chemistry of DCO^+ and HCO^+



$$\frac{DCO^+}{HCO^+} \approx \frac{1}{3}\frac{H_2D^+}{H_3^+}$$

$$\approx \frac{1}{3}\frac{\alpha x(HD)}{\beta x(e^-)+\gamma x(CO)+\delta e^{-220/T}}$$

CR-induced chemistry of DCO^+ and HCO^+

T dependent

observations

$$\frac{DCO^+}{HCO^+} \approx \frac{1}{3}\frac{H_2D^+}{H_3^+} \approx \frac{1}{3}\frac{\alpha x(HD)}{\beta x_e + \gamma x(CO) + \delta e^{-220/T}}$$

e^- abundance

{ 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

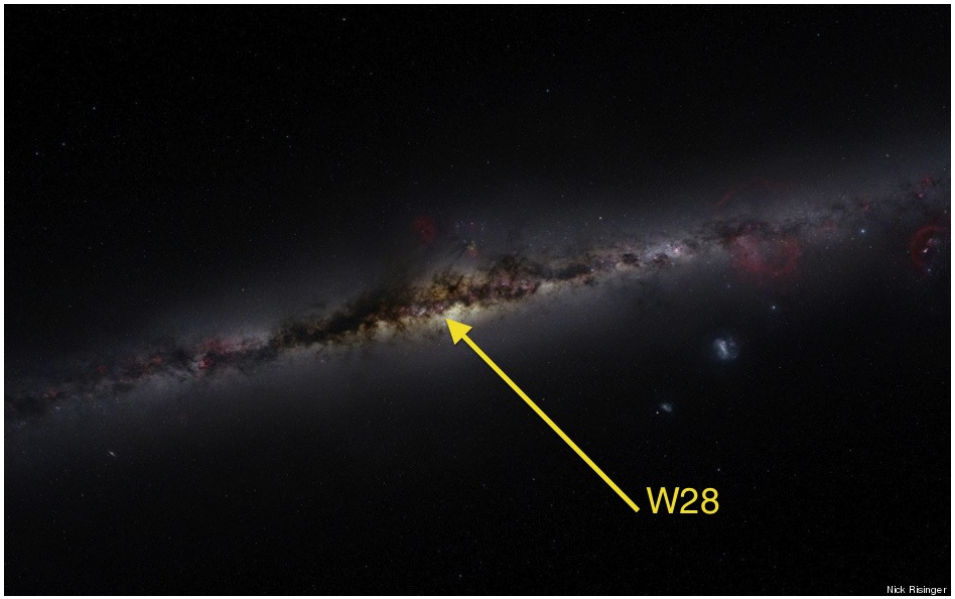
- $\mathrm{DCO^+/HCO^+}$ is determined by electrons and gas temperature
- $\mathrm{e^-}$ abundance is linked to ζ through gas density
- make sure high column density so ionization is dominated by CR

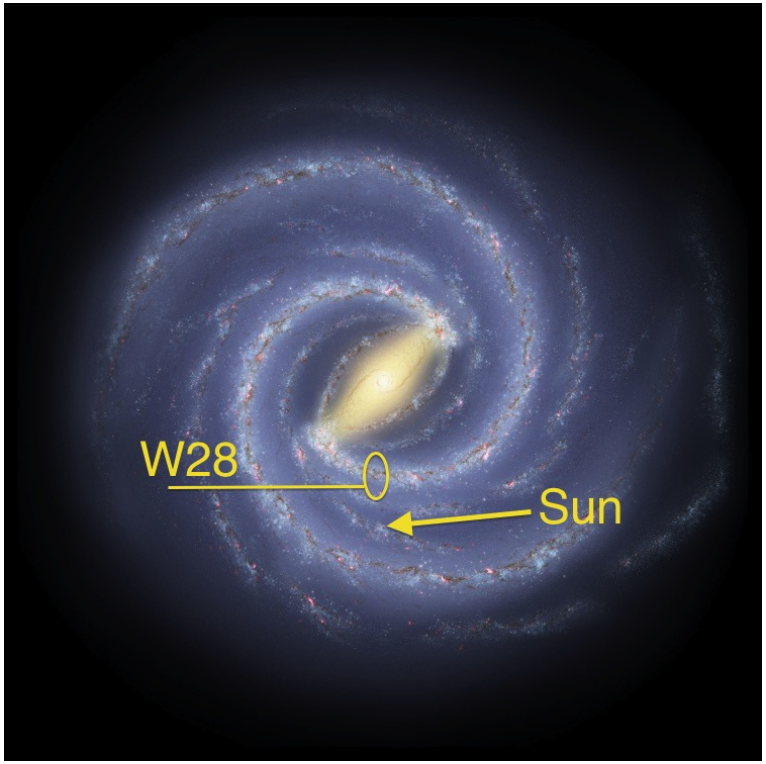
$\Rightarrow$ We need physical conditions and $\mathrm{DCO^+/HCO^+}$ ratio to derive ζ

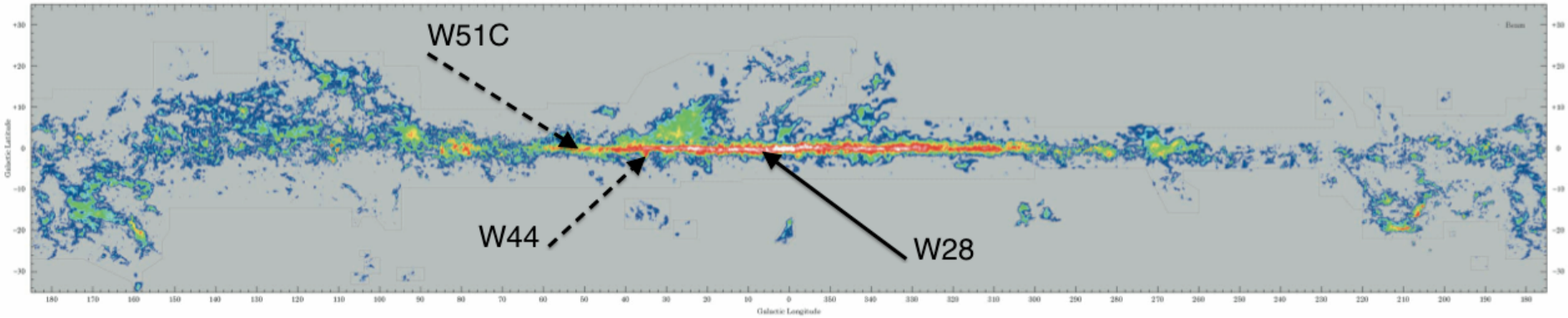
Program

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

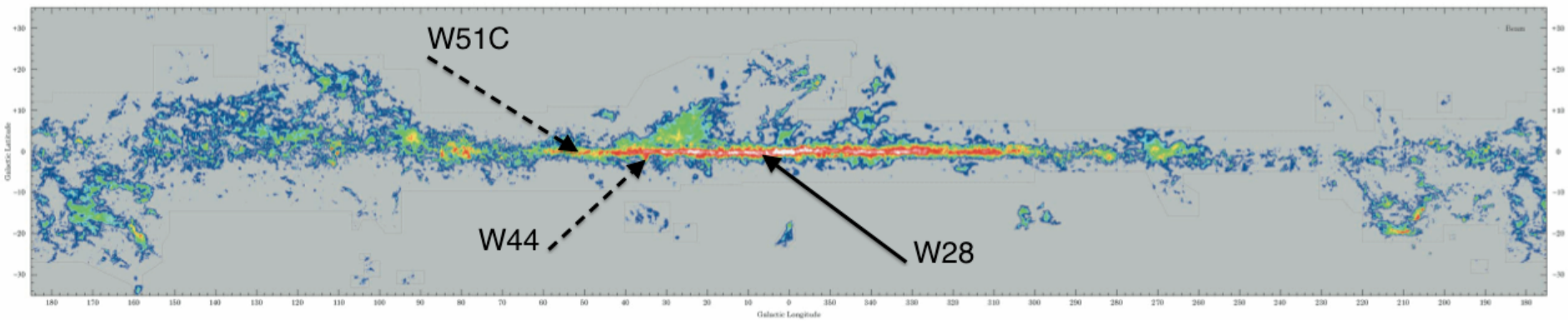
Galactic view

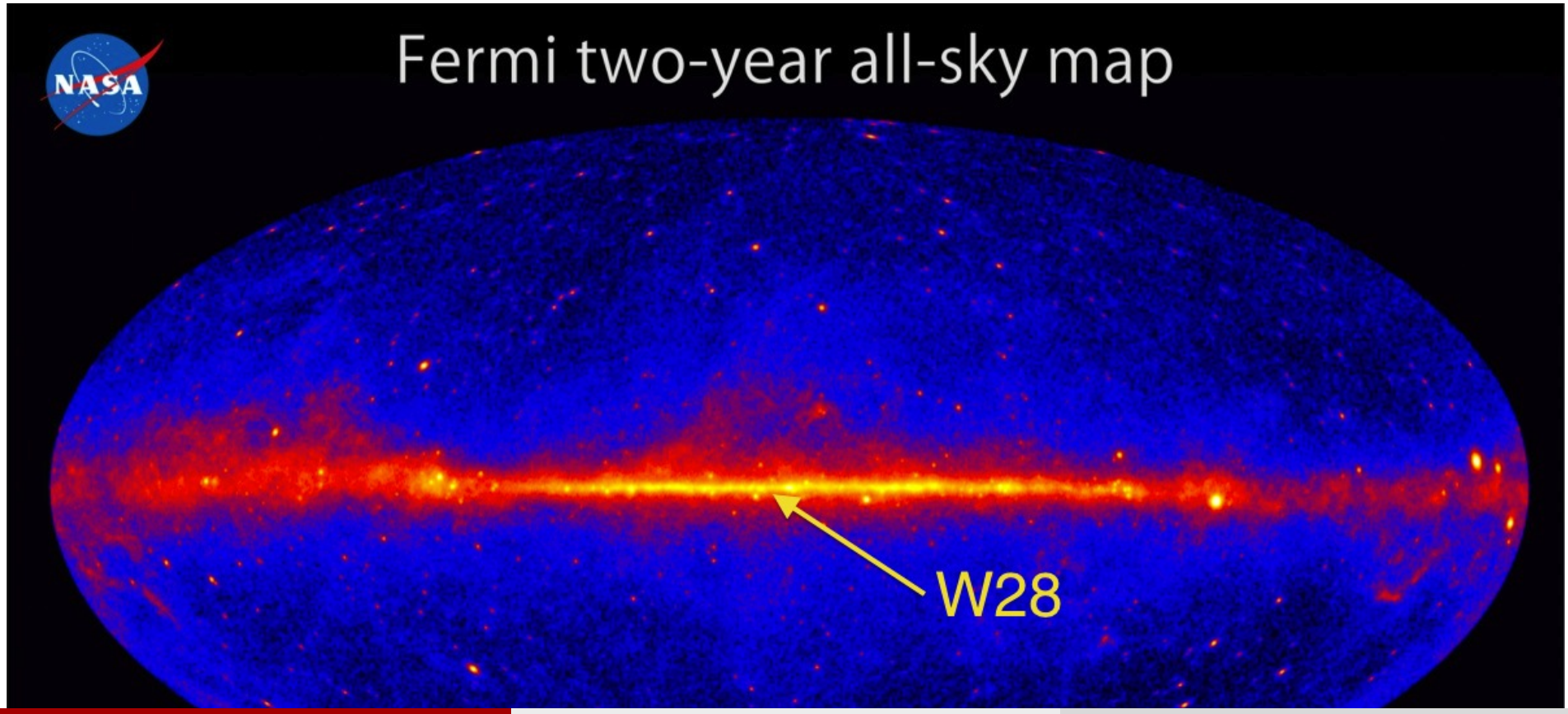




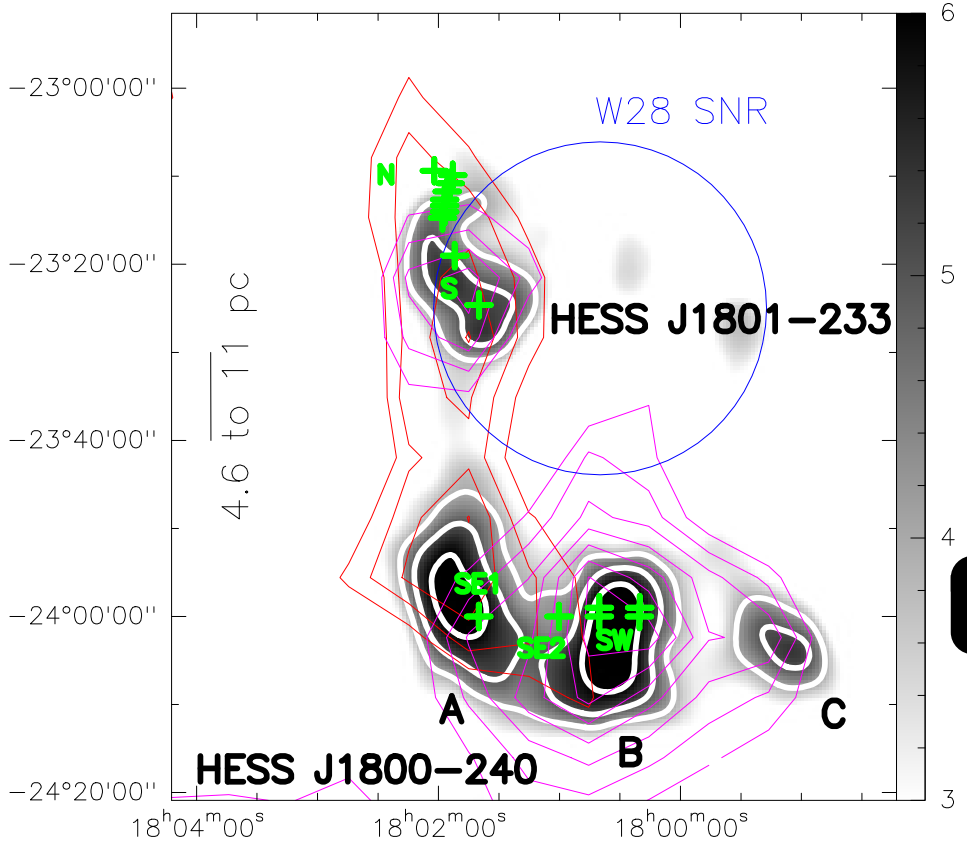


Galactic view





The W28 complex



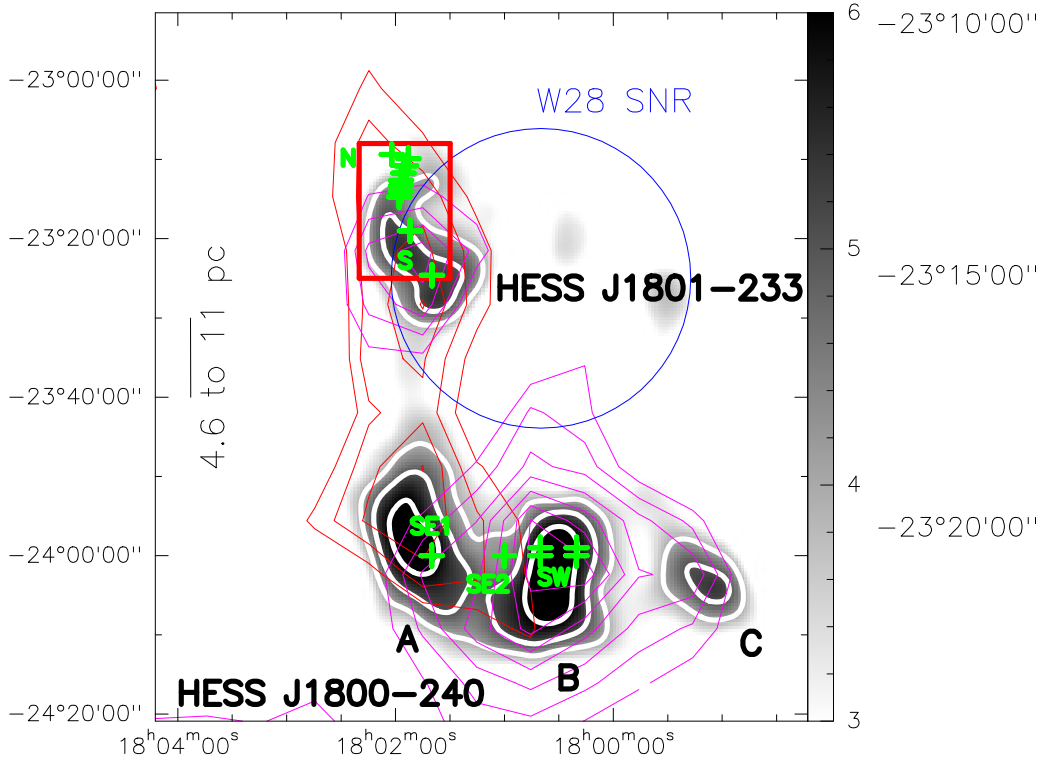
Full Moon to scale

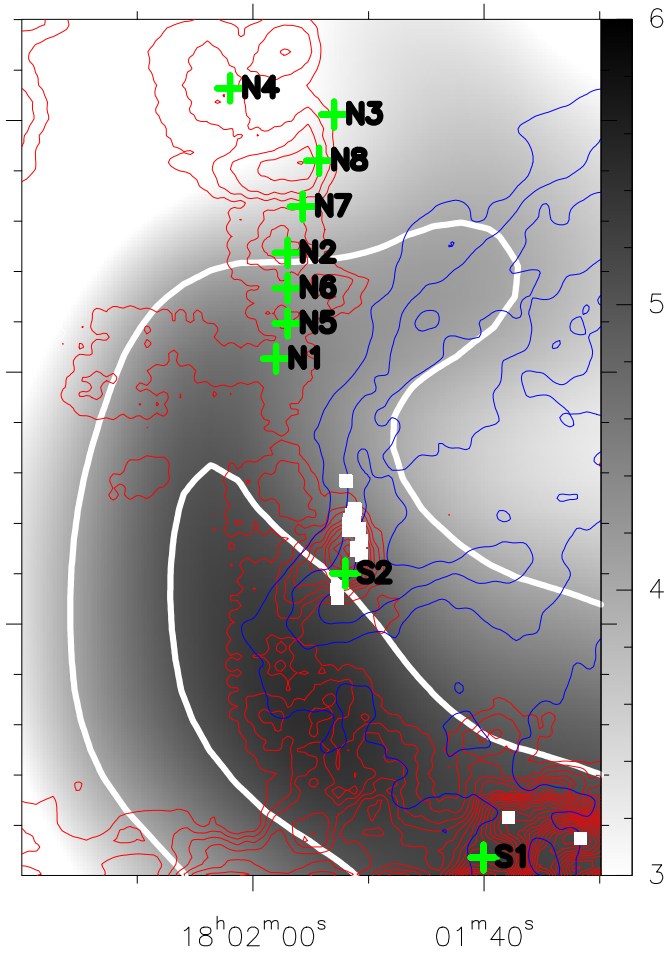
+ Observed positions

[**GeV- TeV CR** → γ-ray] HESS contours (TeV emission)

[**MeV-GeV** CR → ionization] molecular cloud (CO) [5-15, 15-25 km s^{-1}]

The W28 complex

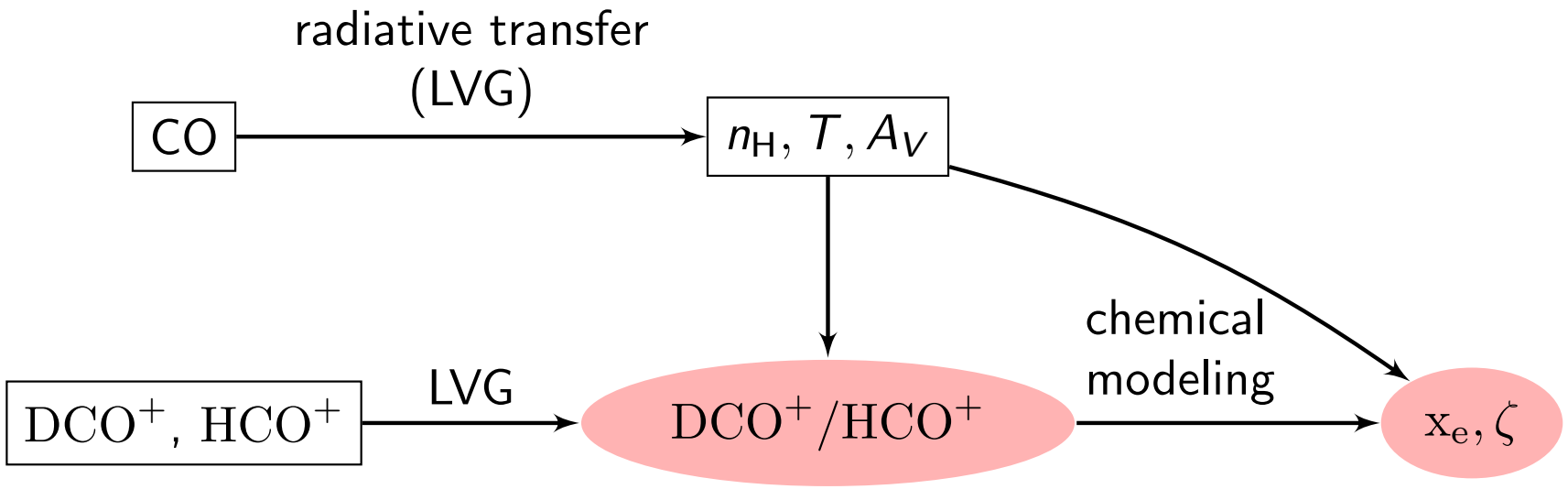




Program

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

Method

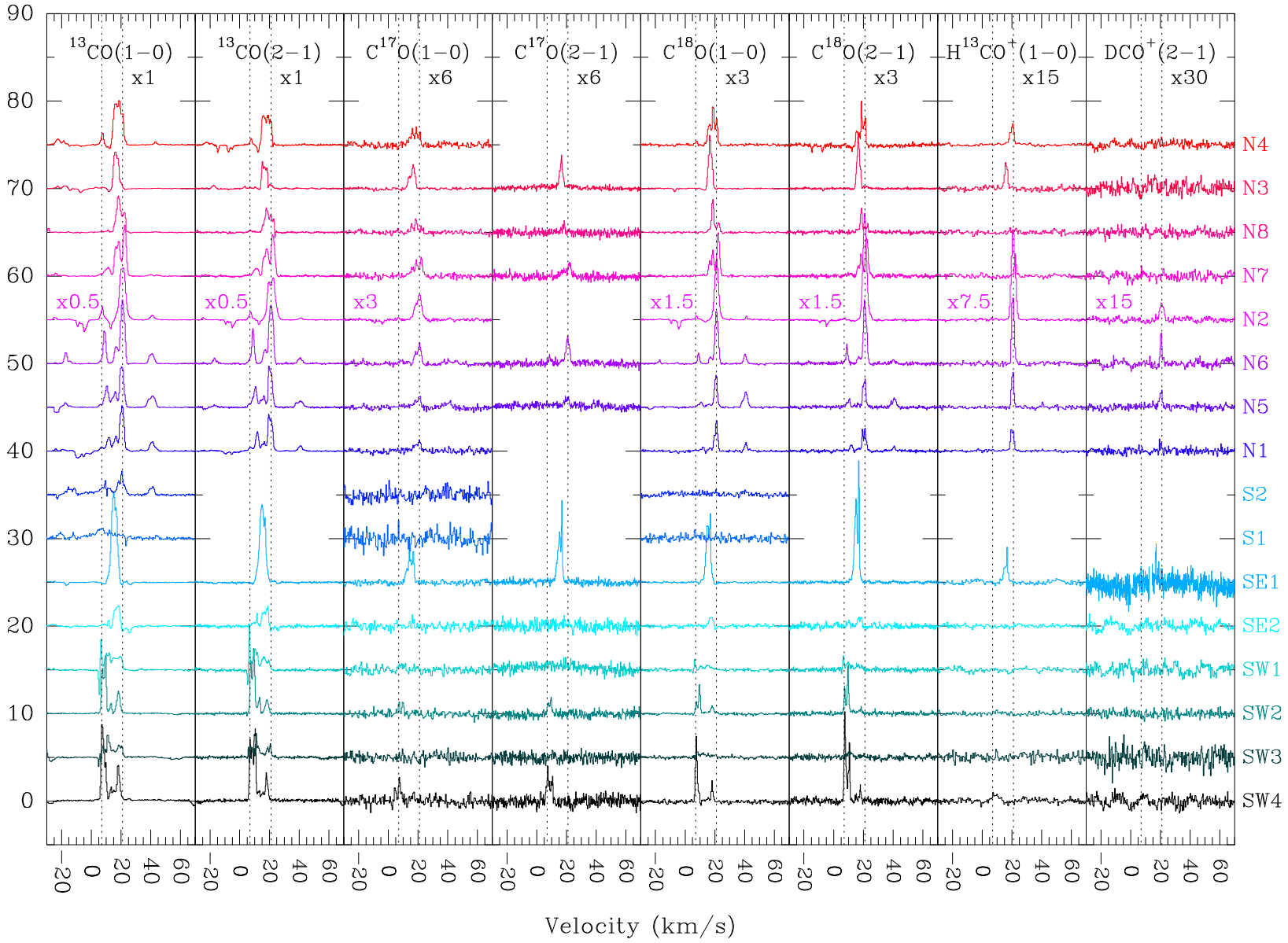


mm observations
[1mm $\sim$ 1meV]

physical conditions,
abundance ratios

ionization

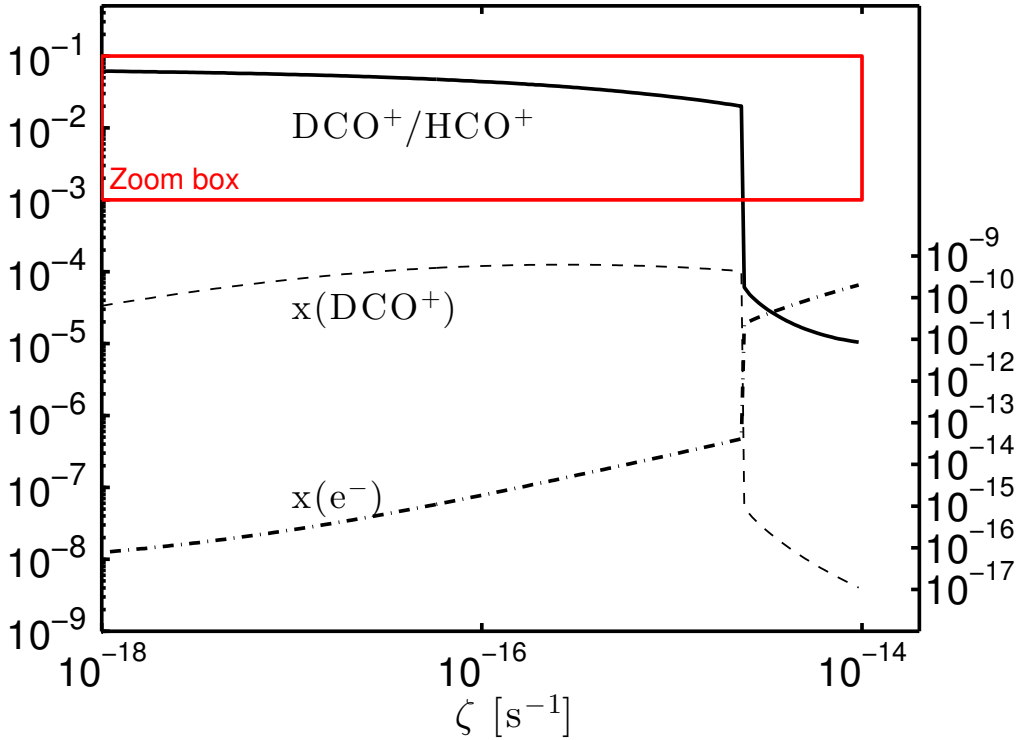
Spectra

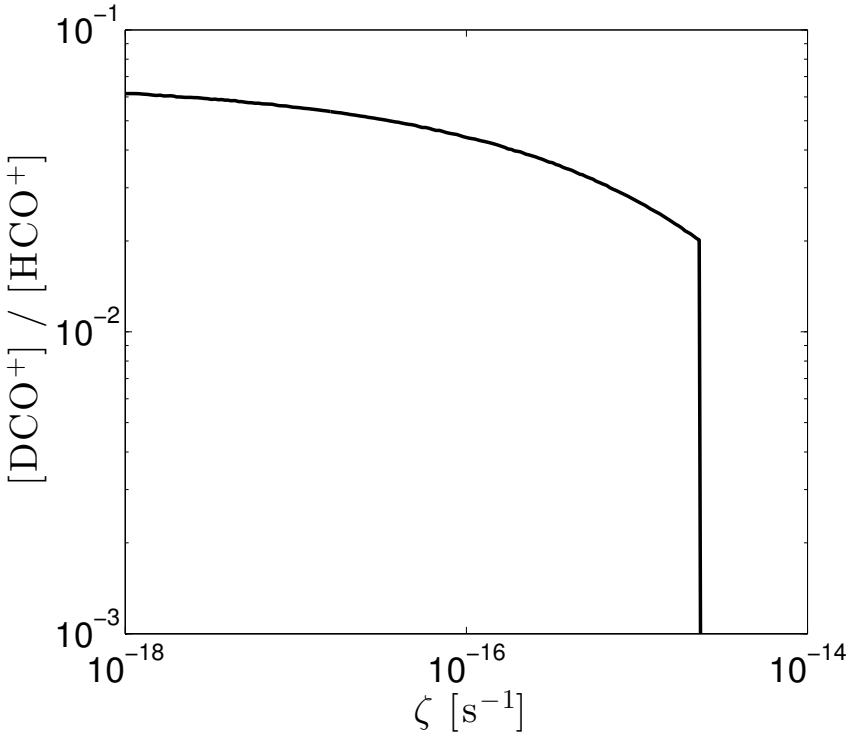

^{13}CO(1−0) x1
^{13}CO(2−1) x1
C^{17}O(1−0) x6
C^{17}O(2−1) x6
C^{18}O(1−0) x3
C^{18}O(2−1) x3
H^{13}CO$^+$(1−0) x15
DCO$^+$(2−1) x30
N4
N3
N8
N7
N2
N6
N5
N1
S2
S1
SE1
SE2
SW1
SW2
SW3
SW4
x0.5
x0.5
x3
x1.5
x1.5
x7.5
x15
Velocity (km/s)

Results

Pos.	Δv [km s^{-1}]	n_{H_2} [10^3 cm^{-3}]	T_{kin} [K]	$N(C^{18}O)$ [10^{15} cm^{-2}]	A_V [mag]	$N(H^{13}CO^+)$ [10^{12} cm^{-2}]	$N(DCO^+)$ [10^{12} cm^{-2}]	$\frac{[DCO^+]}{[HCO^+]}$	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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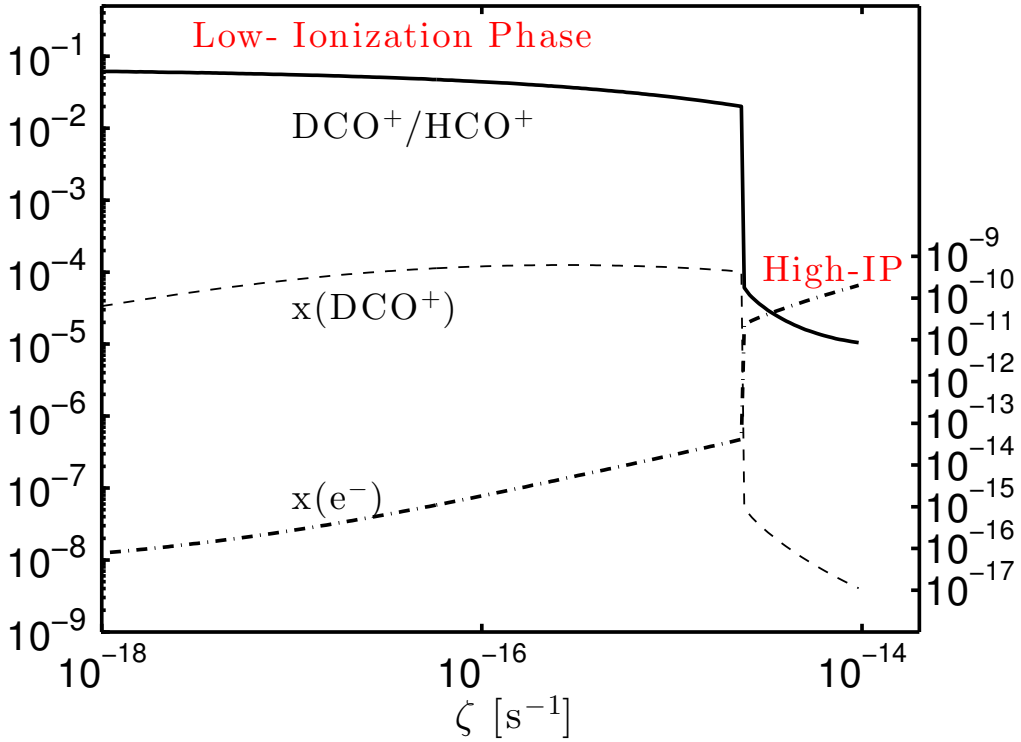

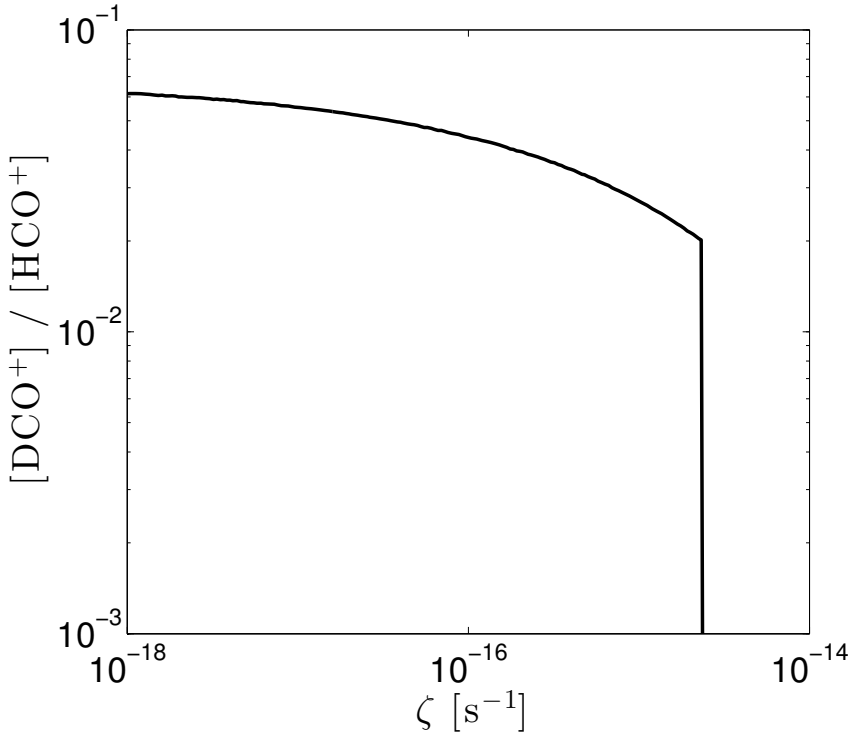

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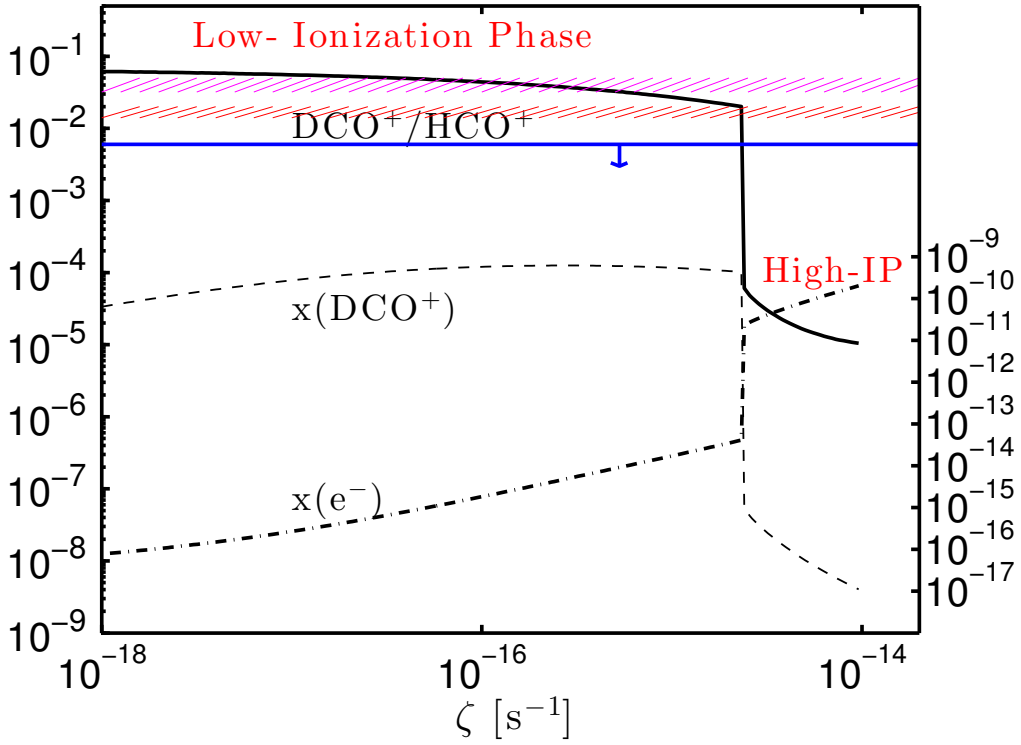
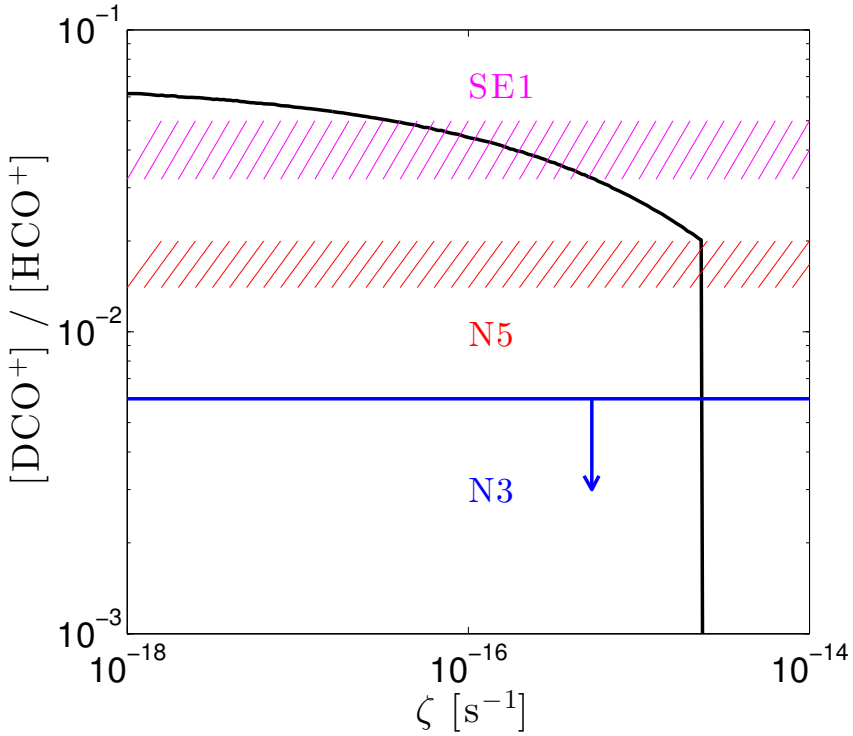


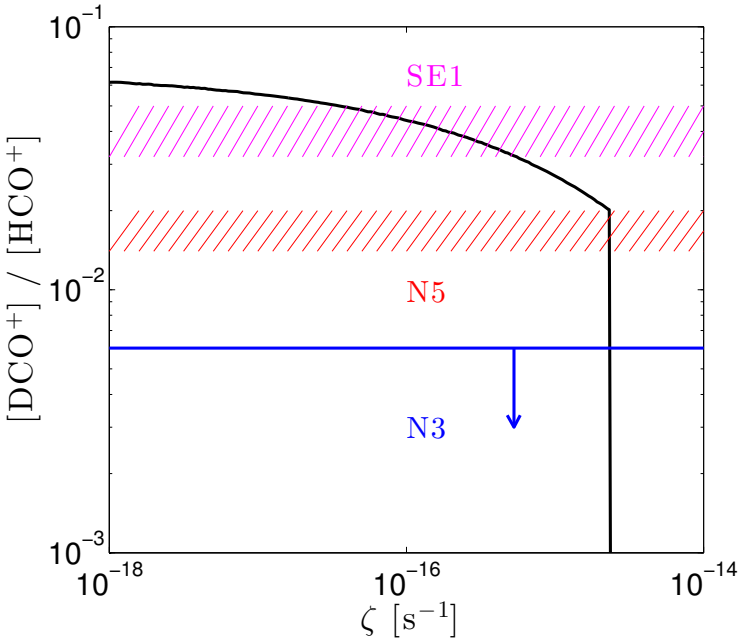


Artist view

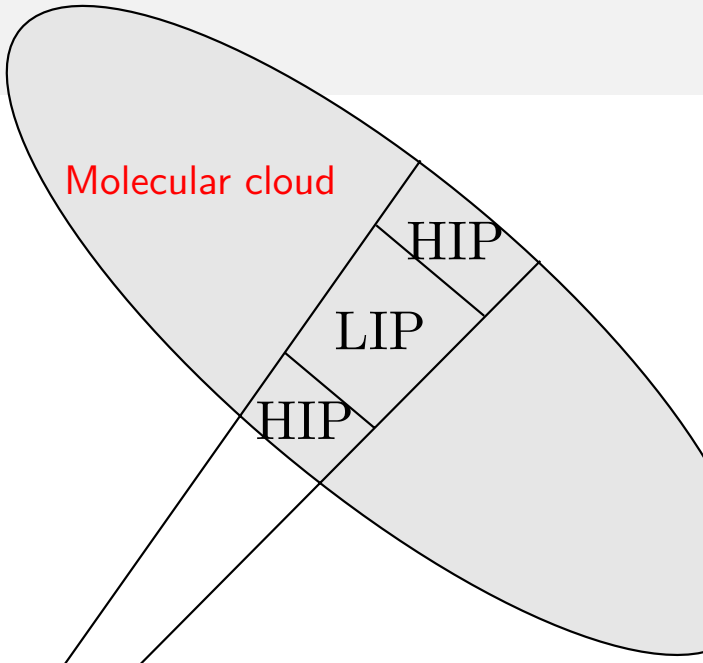
If DCO^+/HCO^+ lies on the LIP...
... OK but can't exclude some HIP

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

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



Artist view



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Results

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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	> 130
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	> 260
N4	3.0	2 $\{0.6-4\}$	12 ± 3	2 $\{2-3\}$	11 $\{5-16\}$	$1.0-1.4$	< 0.35	< 0.006	> 40
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	0.2 - 20
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	-	-
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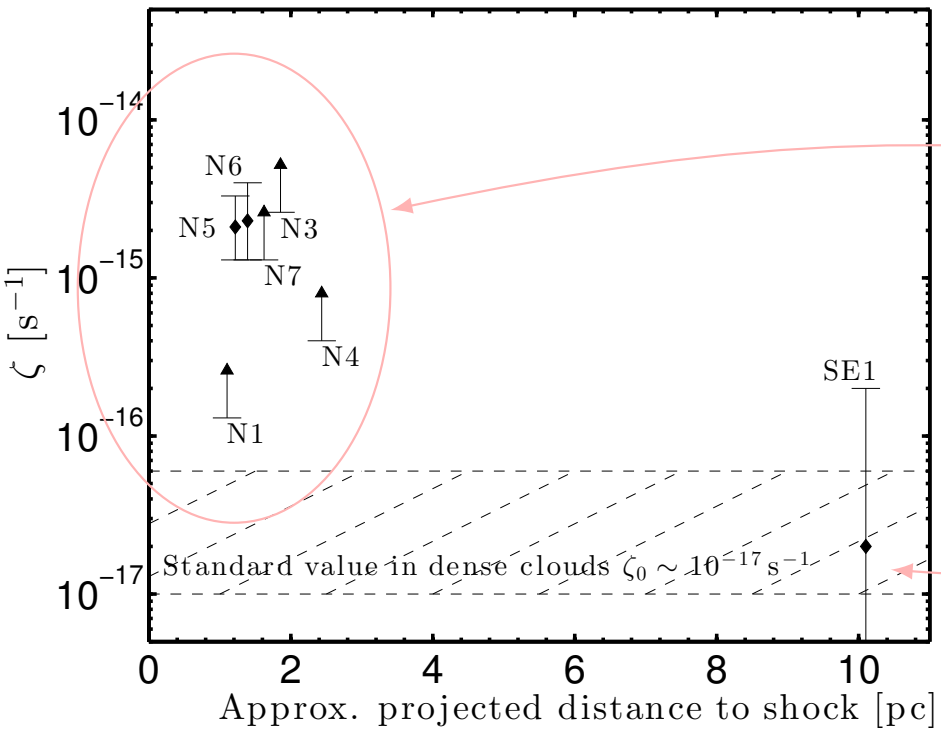
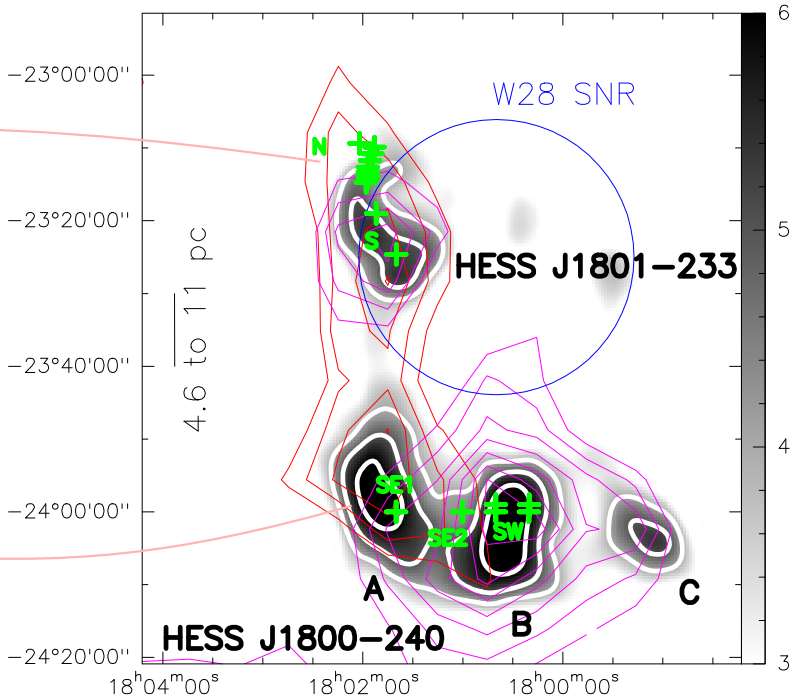
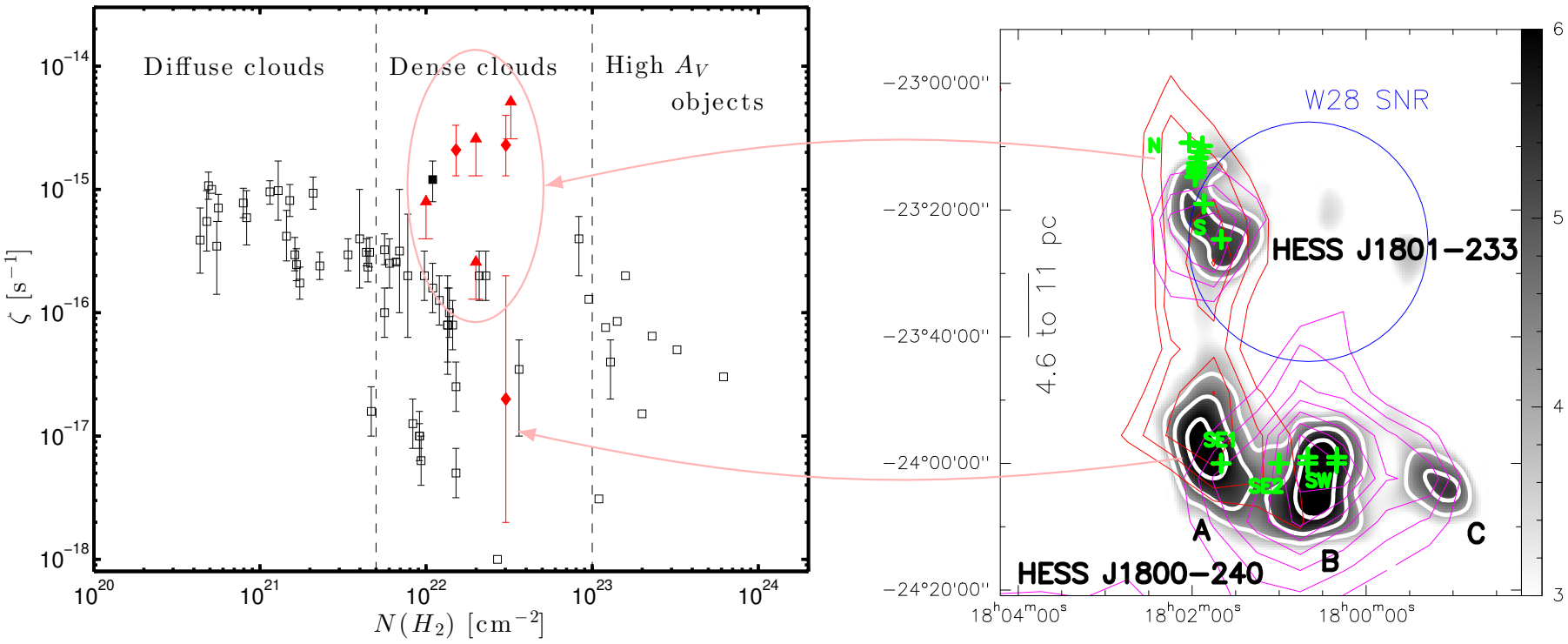
Results





Assumed distance to W28: 2 kpc

Results

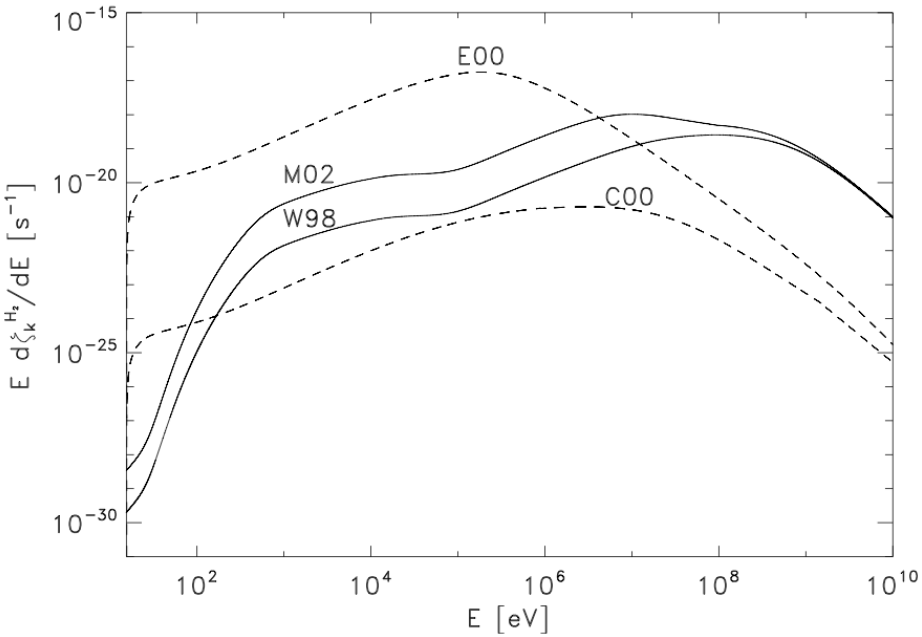


Padovani&Galli (20013)
collection of observations

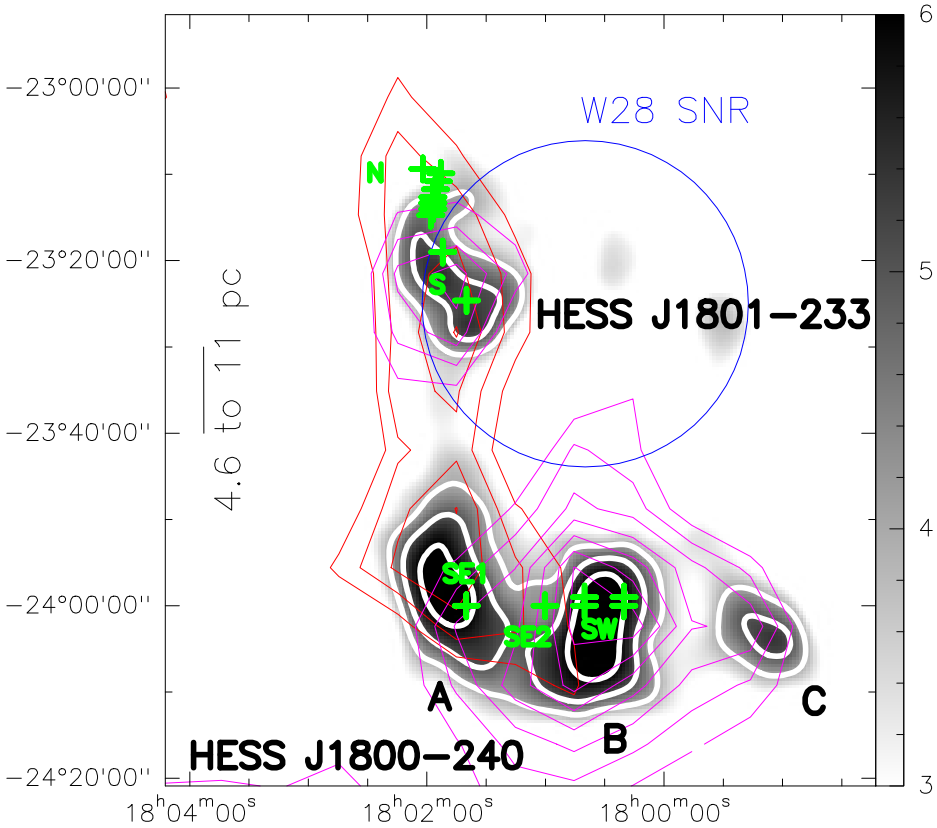
Program

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

(1) CR ionization



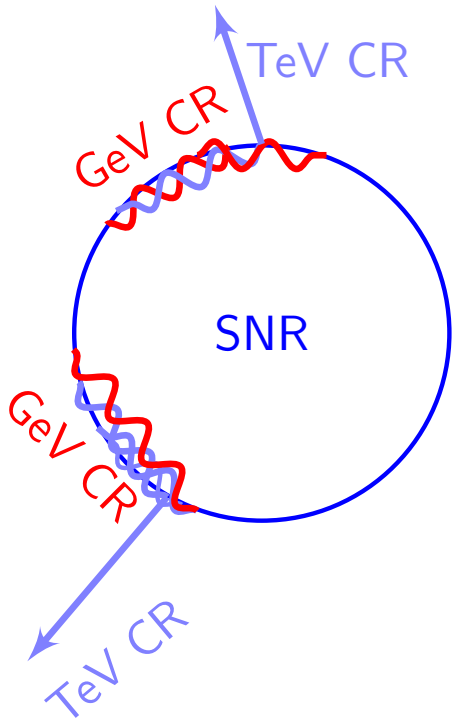
Padovani+ (2009), Fig. 14
contribution of CR to ionization

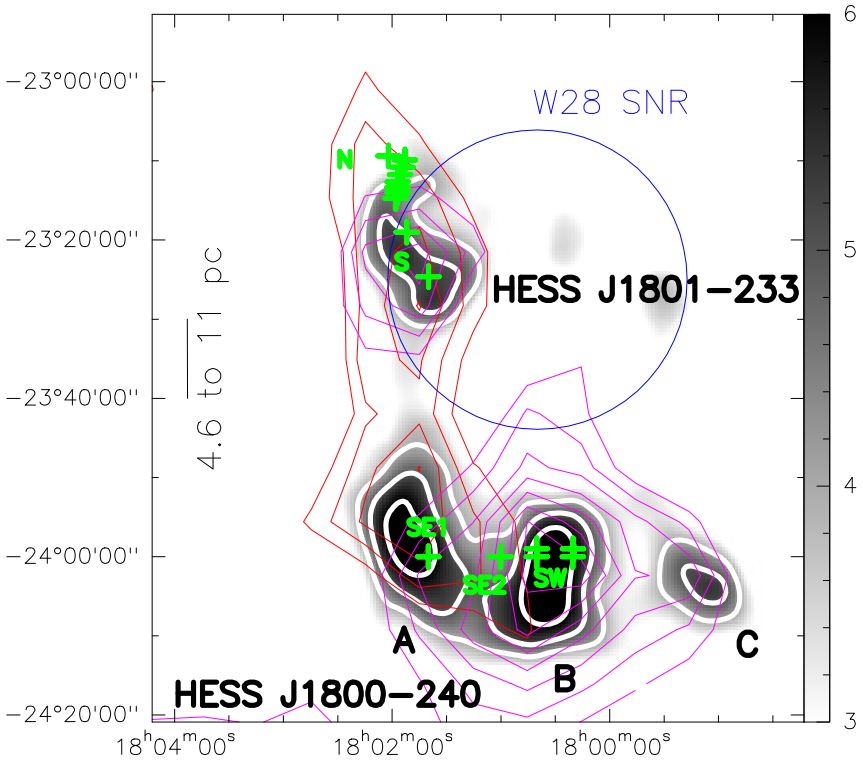


- GeV γ-rays in the North, NOT in the South (FERMI - Abdo et al. 2010)
- TeV γ-rays in the North AND in the South (HESS - Rowell et al. 2007)

$\Rightarrow$ **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 on CR

Diffusion coefficient

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

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

Ionization losses timescale

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

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

Conclusion

From radio to CR properties

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

Perspectives

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

See Vaupré+ (2014), A&A, 568
See also [W51C]: Ceccarelli+ (2011), ApJL, 740 ; Dumas+ (2014), ApJL, 786