Preamble: some statistics on Cosmic rays

ADS Abstract search: 2008-2018 (2013-2018)

"Cosmic Rays": 24992 (12076)

"Cosmic Rays, ISM": 1510 (804)

"Cosmic Rays, low-energy": 444 (222)

"Cosmic Rays, high-energy": 2153 (1118)

"Dark Matter": 40168 (21485)

Low-energy cosmic rays and star-forming regions

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Trifid nebula (M20)

W28 SNR

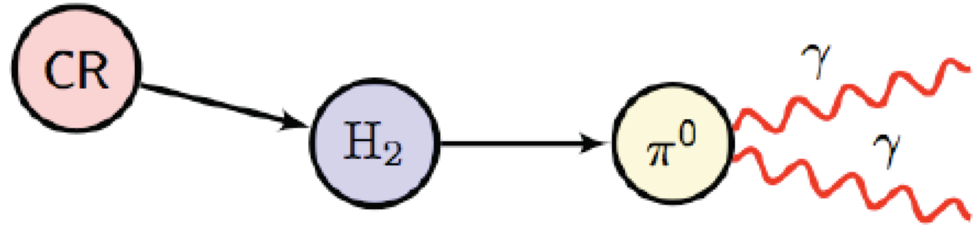
1. Low-energy cosmic rays (nuclei): background

- Major unsolved problem: spectrum and flux
  - solar modulation: < 1 GeV
  - "Local Interstellar Spectra": Voyager 1, γ-rays, etc. + propagation, etc. (Orlando 2017, Tatischeff+ 2018...)
- connection with high energy via π°-decay
  - => definition: E_p < 280 MeV, down to ~ 1 MeV/n
- tracing the first steps of (shock) acceleration
  - e.g., vicinity of SNRs
- *important feedback effects* on (local) environment (e.g., molecular cloud chemistry)
  - => ionization rate ζ, units 10^{-17} s^{-1}
- => galactic distribution (from MC): seems a priori ~ uniform, but significant deviations

=> *Idea: Search for low-energy CR*

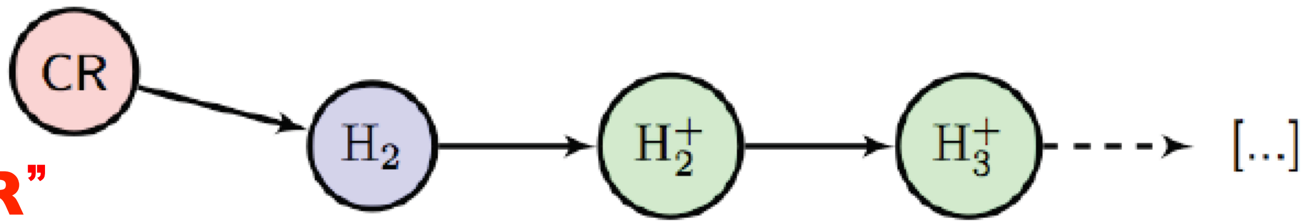
- **GeV-TeV** CR: γ-ray emission [γ energy $\sim$ 10% lower than parent CR]

"HECR"



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

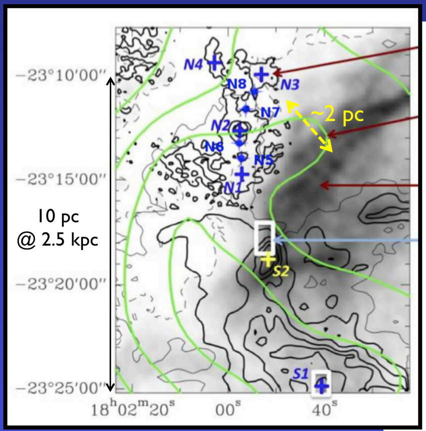
"LECR"

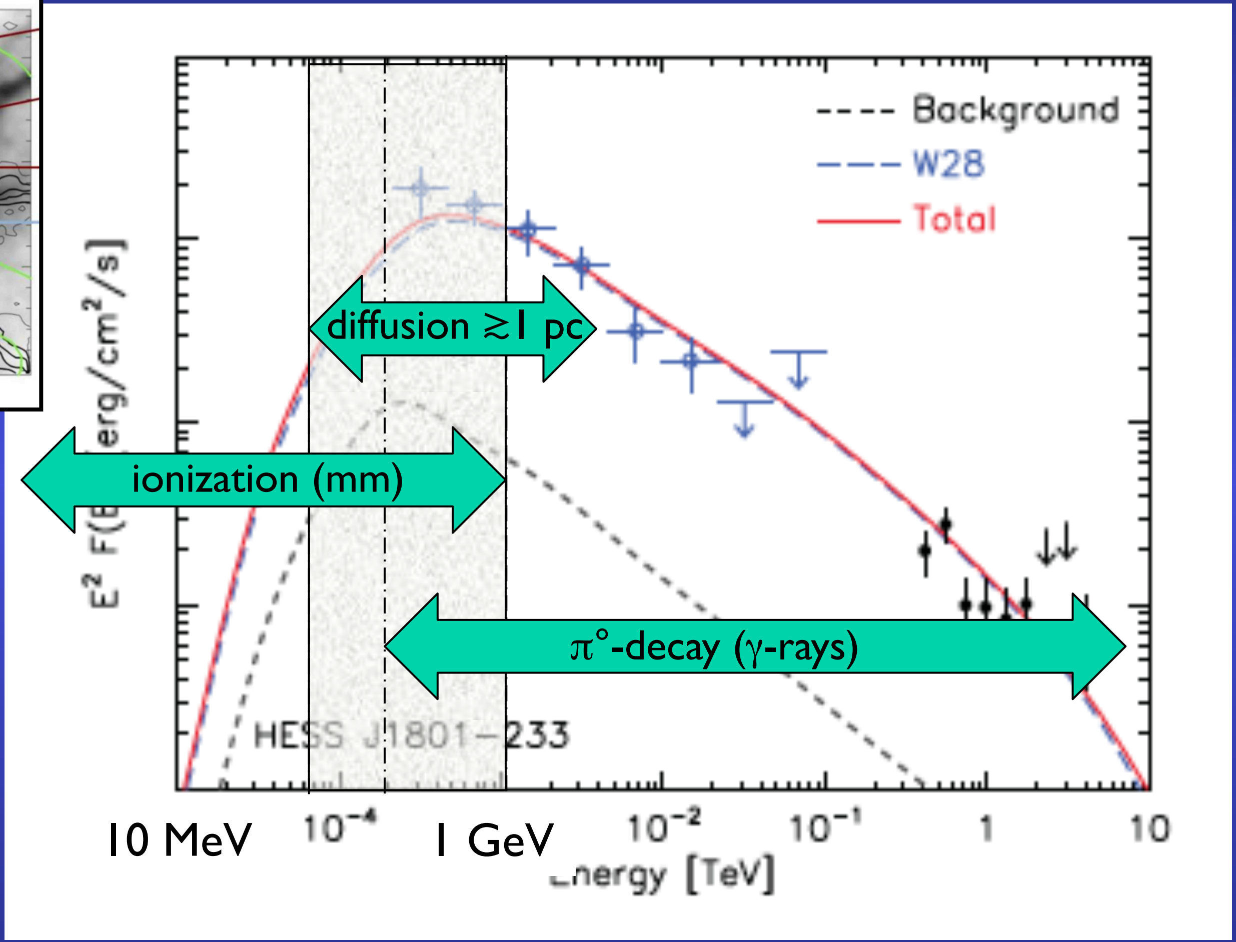


… by measuring and mapping the *ionization rate* ζ

(fiducial value $\zeta_0 \sim 10^{-17}$ s^{-1} for the Galaxy)

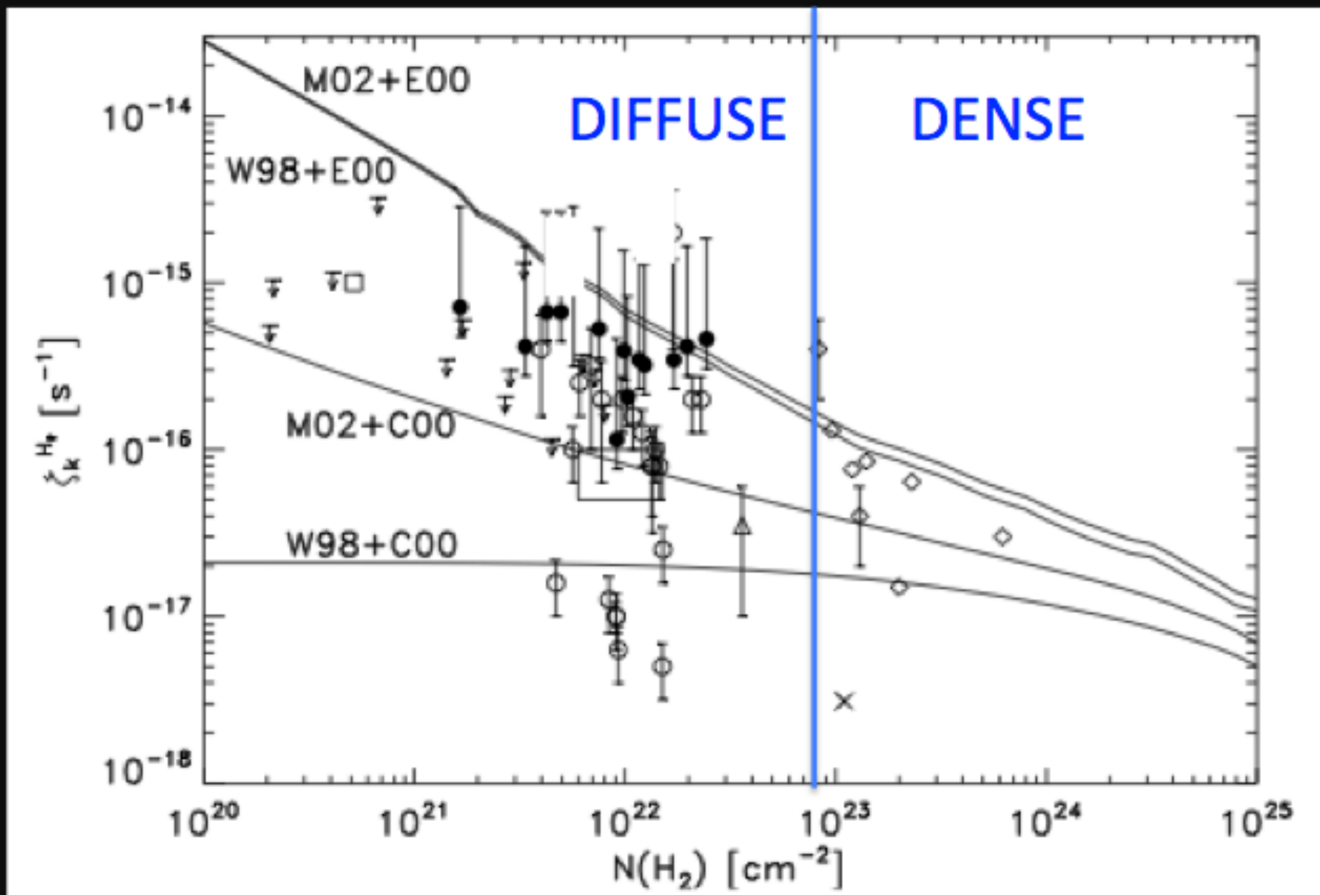
Upstream of the W28 SNR shock: probing cosmic rays





Connecting low- and high-energy CR in W44 (IRAM)
+ new constraints on high-ionization interstellar chemistry

Ionization rate measurements: Diffuse vs. Dense Clouds



Padovani, Galli & Glassgold 2009

Diffuse clouds: $\zeta \approx 0.5\text{-}3 \times 10^{-16} s^{-1}$

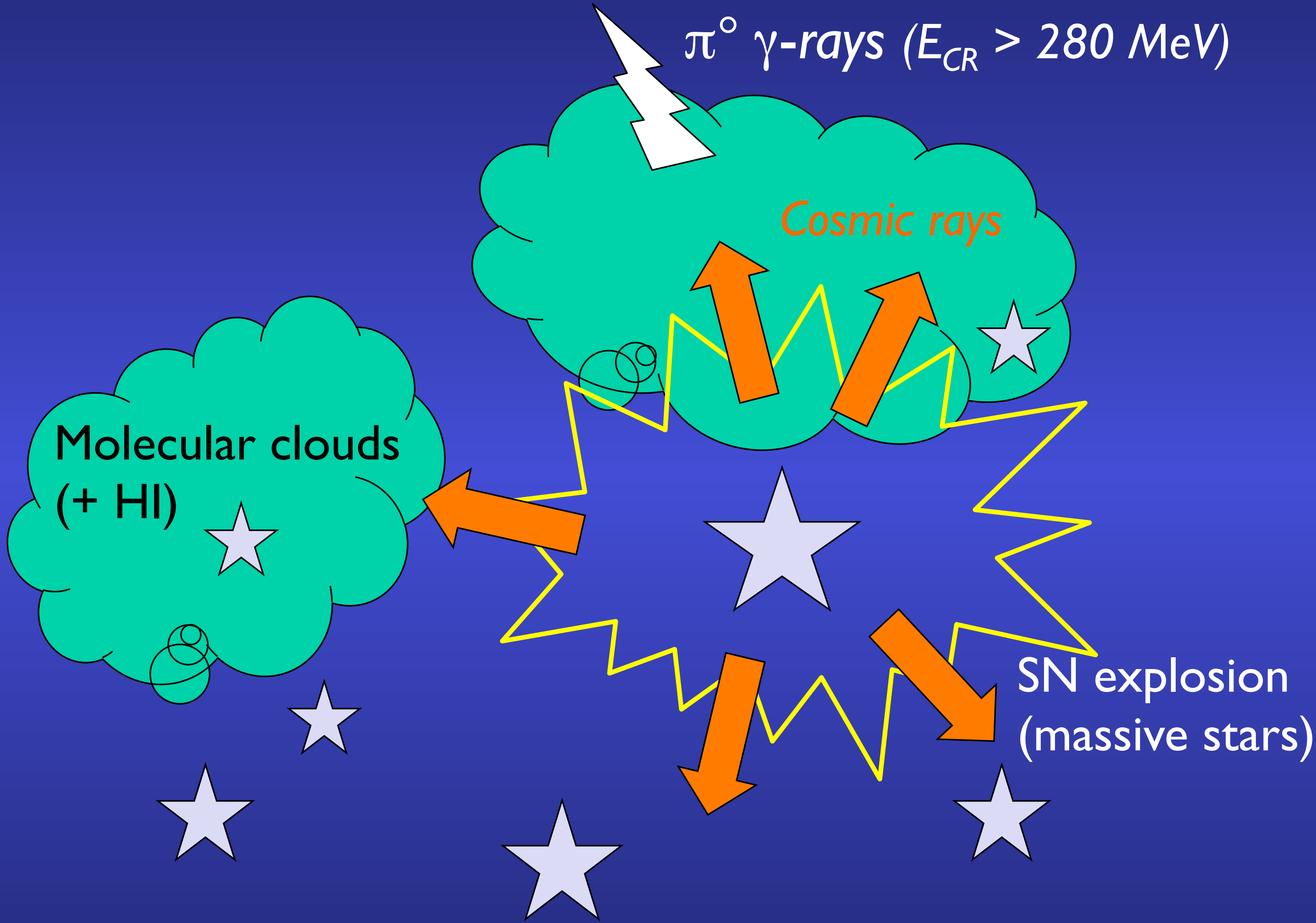
Dense clouds: $\zeta \approx 0.1\text{-}5 \times 10^{-17} s^{-1}$

2. Main processes: interactions inside dense ISM

- Collisions (p): direct ionisation (e^- cascade)
  - molecular clouds: SFR* *[* = contributions FR]*
  - enhanced: interacting SNR (and/or SW)*
- UV radiation from e^- secondaries
  - "diffuse UV" inside molecular clouds (Prasad+ 1983, Haeys+ 2017)
- chemistry (=> physical conditions: n_H, T)
  - tracers (molecules, radicals)*
  - => most used: DCO^+/HCO^+ (IRAM 30m)*,
    N_2H^+/HCO^+ (*Herschel*)*
- Other tracers
  - diffuse X-ray emission: Fe I Kα line @ 6.40 keV (*Suzaku*): ~MeV protons
- Feedback effects
  - CO line ratios (Peñalosa+ 2017)
  - CR-induced desorption in small grains (Iqbal+ 2018)*
  - link w/ young Sun ? Protostars (Padovani+2017, Favre+ 2014)*
- Pb of penetration of CR in molecular clouds
  - MHD effects (Afvén waves) in diffuse envelopes* (Ivlev+ 2018)

Chemical reactions network: Molecules… and radicals

#	Reaction	Reaction rates ($cm^3.s^{-1}$)
Reduced network		
(#1)	$CR + H_2 \xrightarrow{\zeta} H_2^+ + e^-$	ζ (s^{-1})
(#2)	$H_2^+ + H_2 \xrightarrow{k_{H_2^+}} H_3^+ + H$	$k_{H_2^+} = 2.1\ 10^{-9}$
(#3)	$H_2D^+ + CO \xrightarrow{k_D} DCO^+ + H_2$	$k_D = 5.37\ 10^{-10}$
(#4)	$H_3^+ + CO \xrightarrow{k_H} HCO^+ + H_2$	$k_H = 1.61\ 10^{-9}$
(#5)	$H_3^+ + HD \underset{k_f^{-1}}{\overset{k_f}{\rightleftharpoons}} H_2D^+ + H_2$	$k_f = 1.7\ 10^{-9}$
		$k_f^{-1} = 1.7\ 10^{-9} \exp(-220/T)$
(#6)	$DCO^+ + e^- \xrightarrow{\beta'} CO + D$	$\beta' = 2.8\ 10^{-7}(T/300)^{-0.69}$
(#7)	$HCO^+ + e^- \xrightarrow{\beta'} CO + H$	$\beta' = 2.8\ 10^{-7}(T/300)^{-0.69}$
(#8)	$H_2D^+ + e^- \xrightarrow{k_e} H + H + D$	$k_e = 6.00\ 10^{-8}(T/300)^{-0.50}$
	$H_2 + D$	
	$HD + H$	
(#9)	$H_3^+ + e^- \xrightarrow{\beta} H + H + H$	$\beta = 6.7\ 10^{-8}(T/300)^{-0.69}$
	$H_2 + H$	
(#10)	$H + H \xrightarrow{k'} H_2$	$k' = 4.95\ 10^{-17}(T/300)^{0.50}$
(#11)	$H + D \xrightarrow{k''} HD$	$k'' = \sqrt{2}k'$
Additional reactions		
(#12)	$H_2D^+ + CO \xrightarrow{k'_D} HCO^+ + H_2$	$k'_D = 1.1\ 10^{-9}$
(#13)	$CO^+ + HD \xrightarrow{k_{CO^+}} DCO^+ + H$	$k_{CO^+} = 7.5\ 10^{-10}$



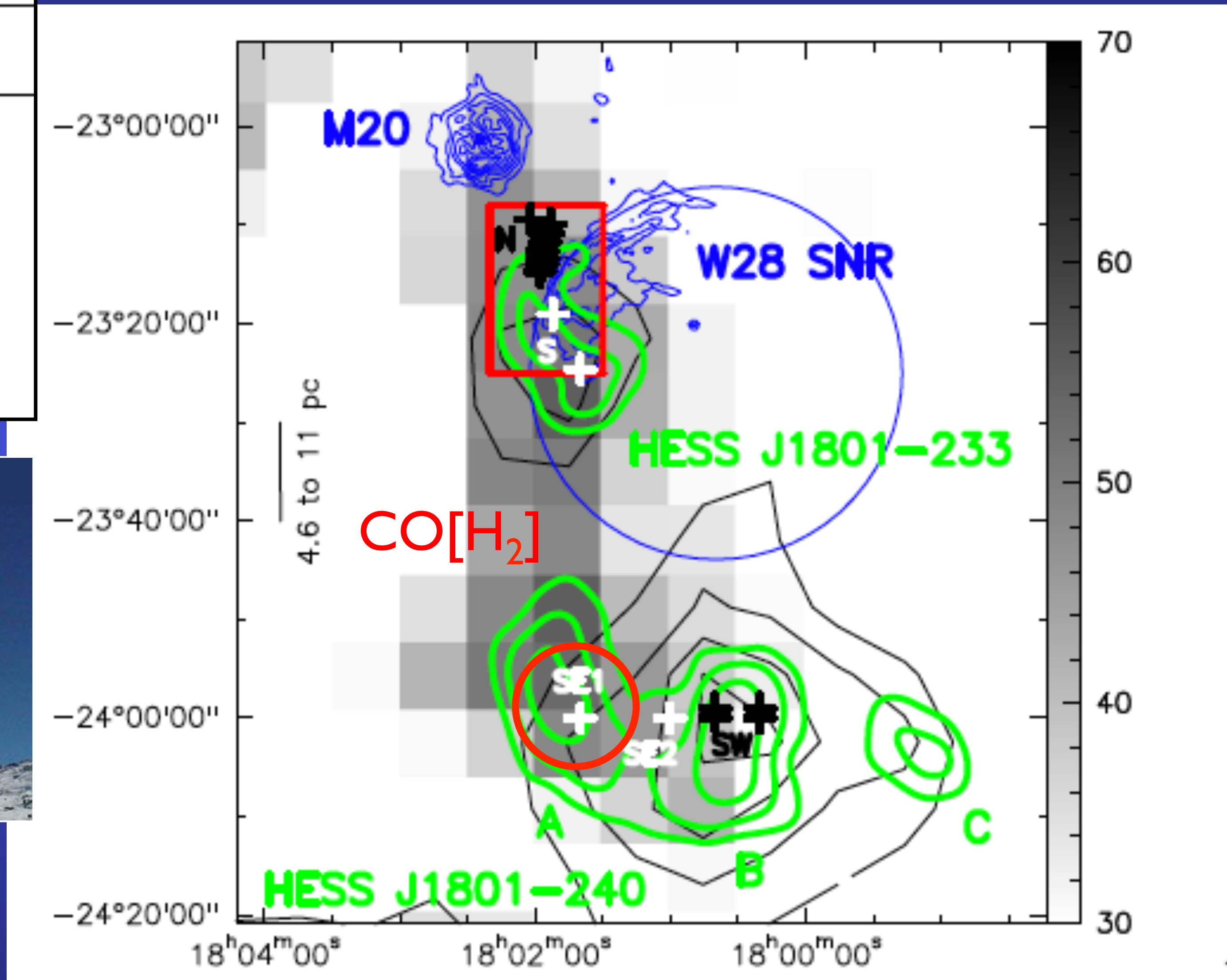
π° γ-rays (E_{CR} > 280 MeV)
Cosmic rays
Molecular clouds (+ HI)
SN explosion (massive stars)

IRAM 30-m observations of W28: near and far from the shock

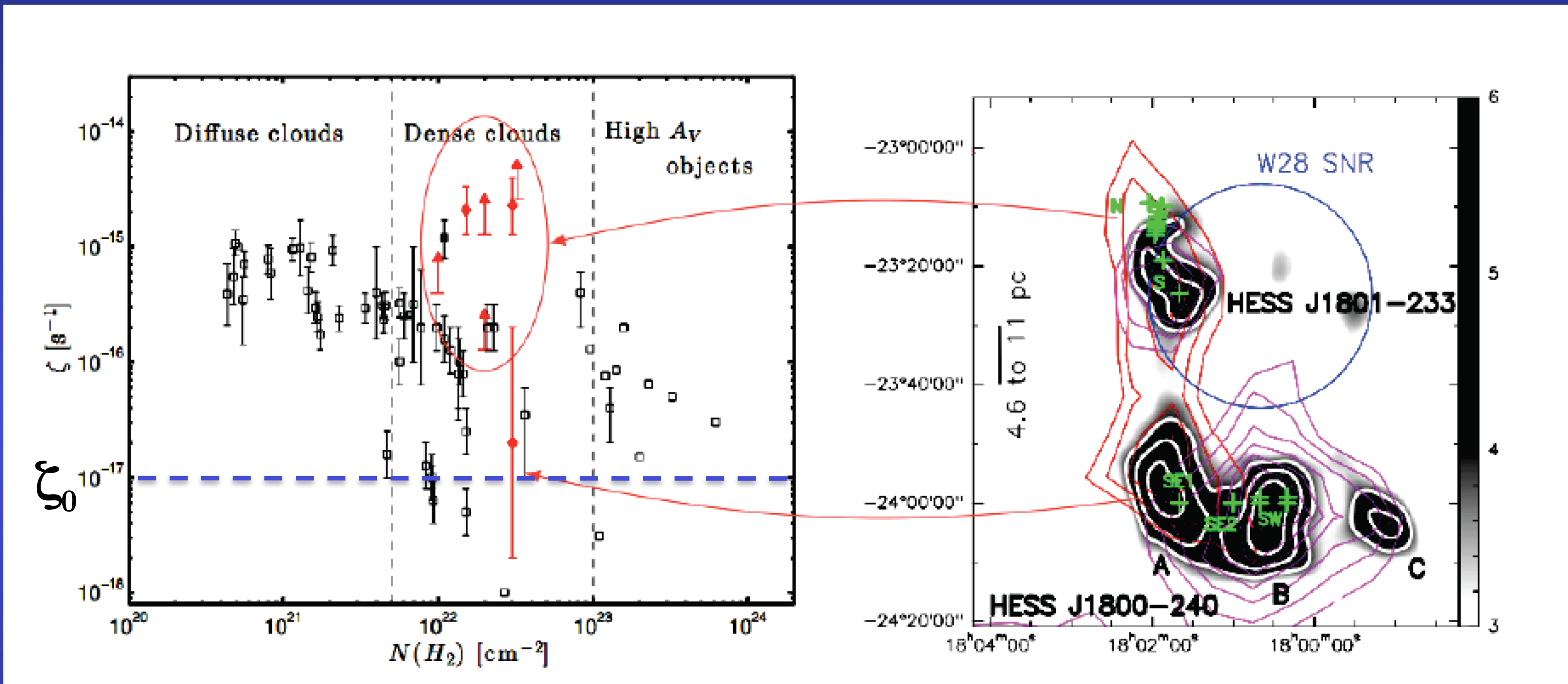
Species	Line
$H^{13}CO^+$	(1-0)
$C^{18}O$	(1-0)
^{13}CO	(1-0)
$C^{17}O$	(1-0)
DCO^+	(2-1)
$C^{18}O$	(2-1)
^{13}CO	(2-1)
$C^{17}O$	(2-1)

16 pointings

Vaupré et al. 2014



W28: Enhanced ionization (x ~100) downstream of the shock => enhanced LECR ! *But standard value far from the shock*

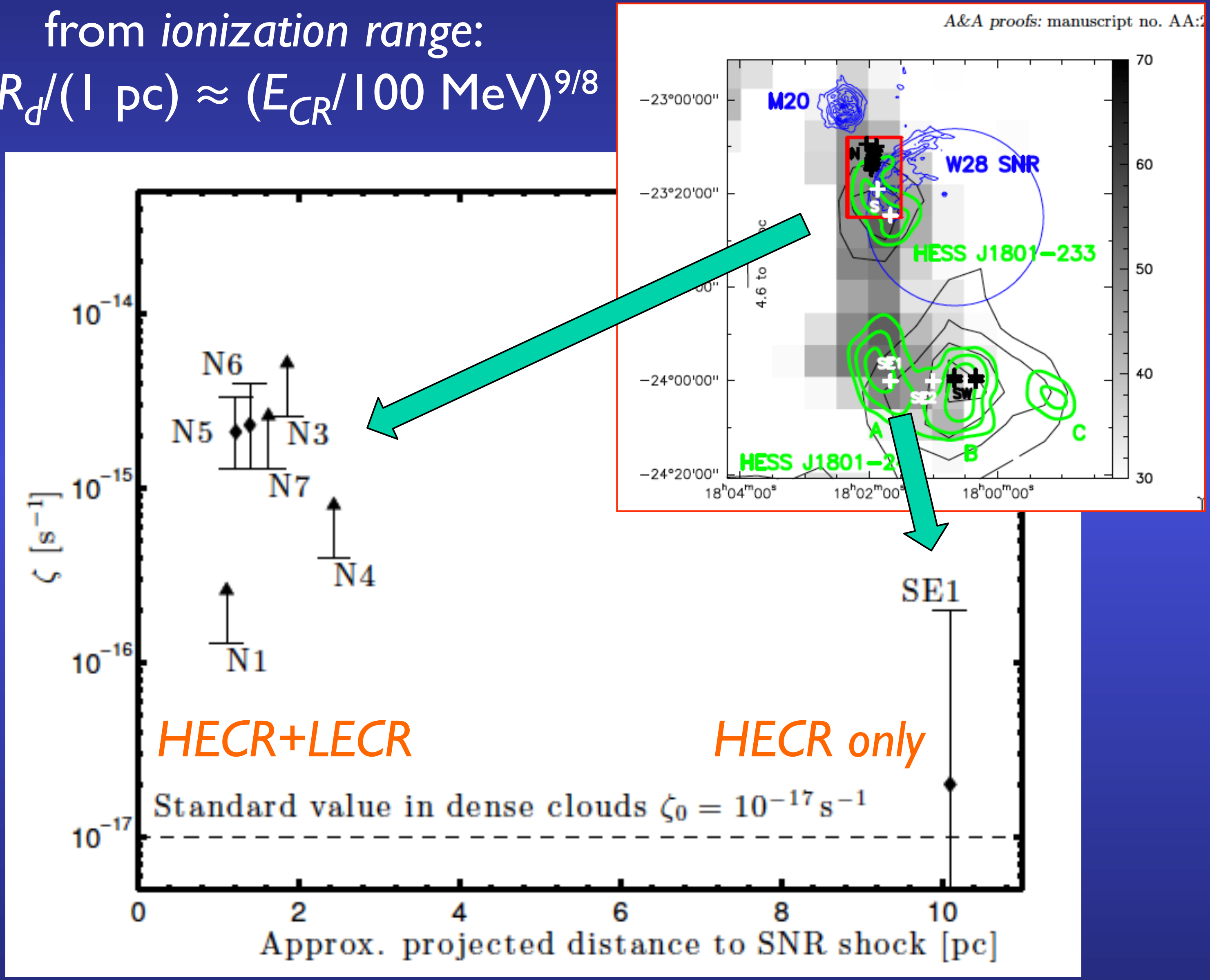


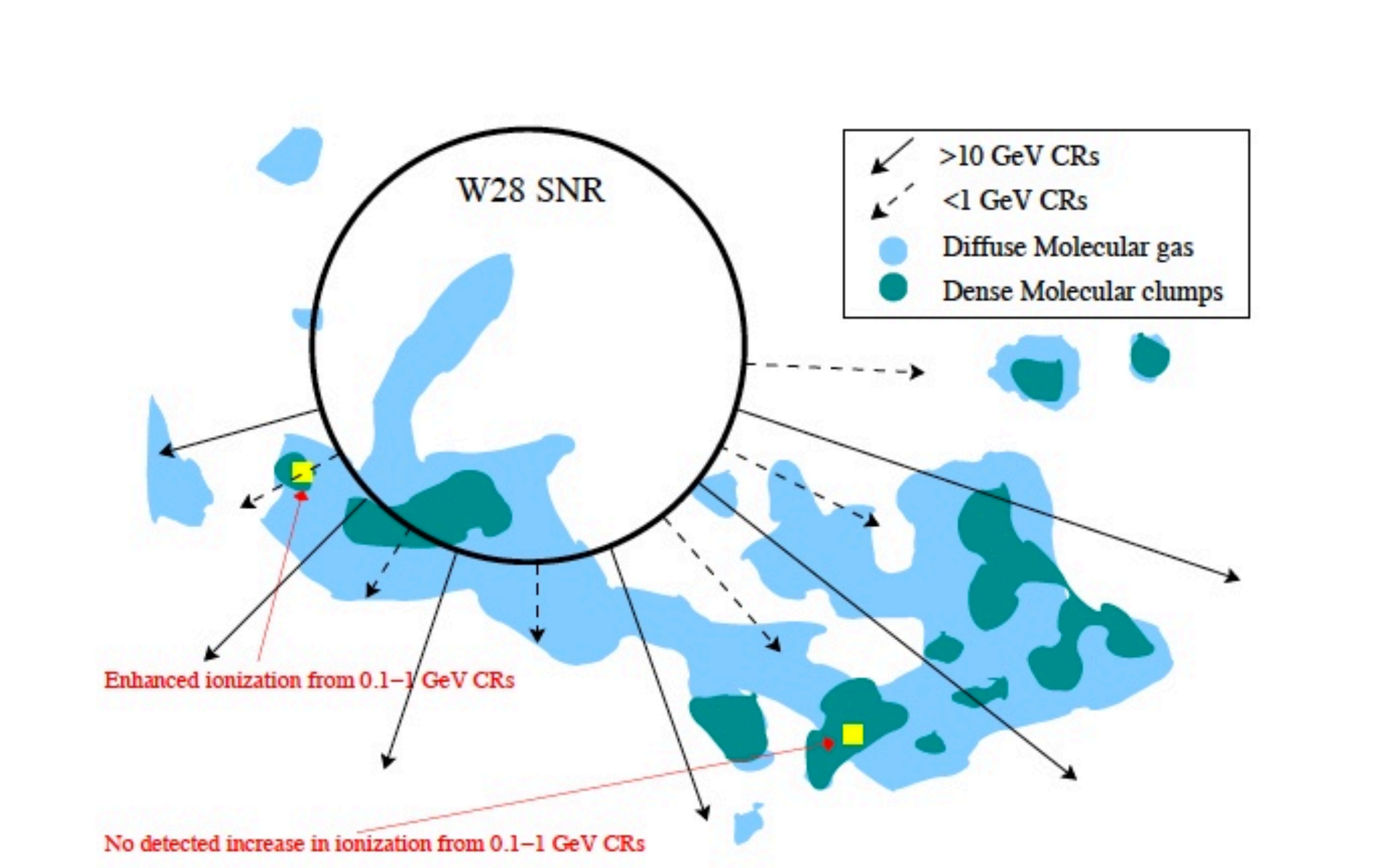
⇔ comparable to HECR enhancement from π°-decay γ-rays

⇒ *constraints on CR acceleration/diffusion theories ("Diffusive Shock Acceleration"…)*

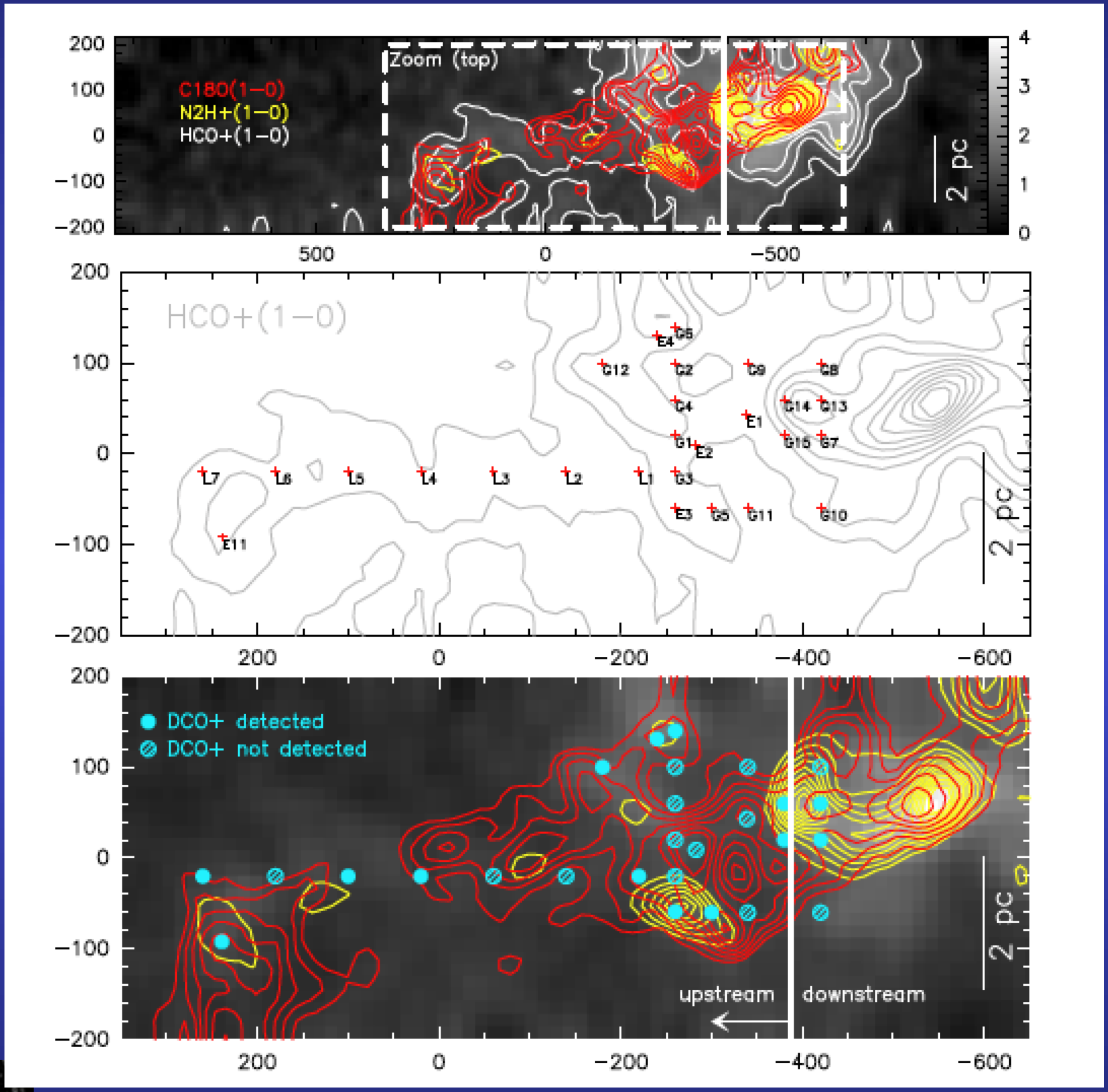
Constraints on LECR diffusion from *ionization range*:

$\leftrightarrow R_d/(1\ \mathrm{pc}) \approx (E_{CR}/100\ \mathrm{MeV})^{9/8}$





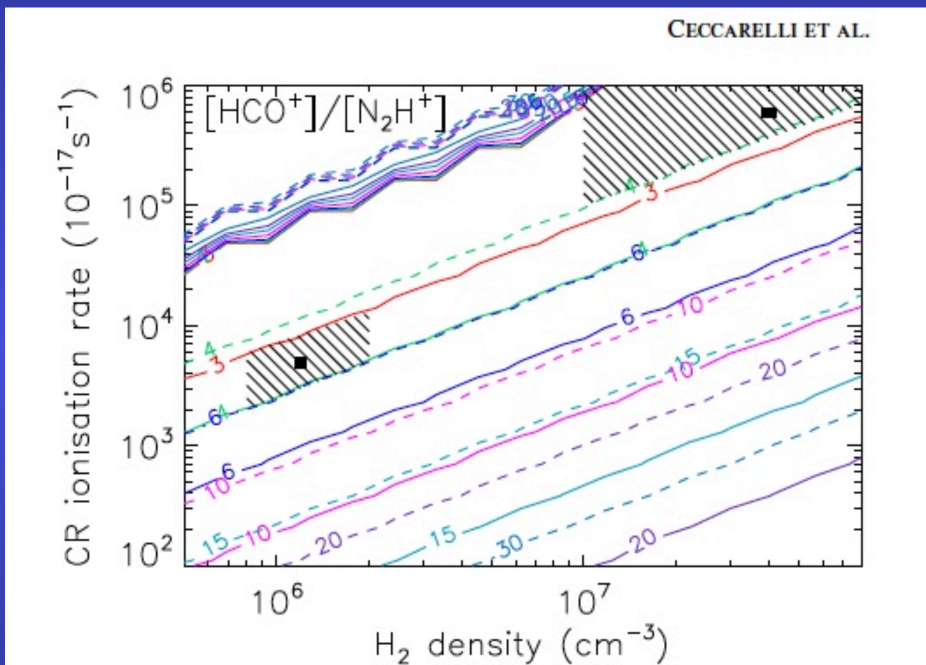
Maxted+ 2016: OH, SiO, NH3, HCO+, CS



W44 shock region

Vaupré 2015,
Vaupré et al., in progress

Energetic particles in the young protostar OMC-2 FIR4



Ceccarelli+ 2014 (*Herschel* obs.)

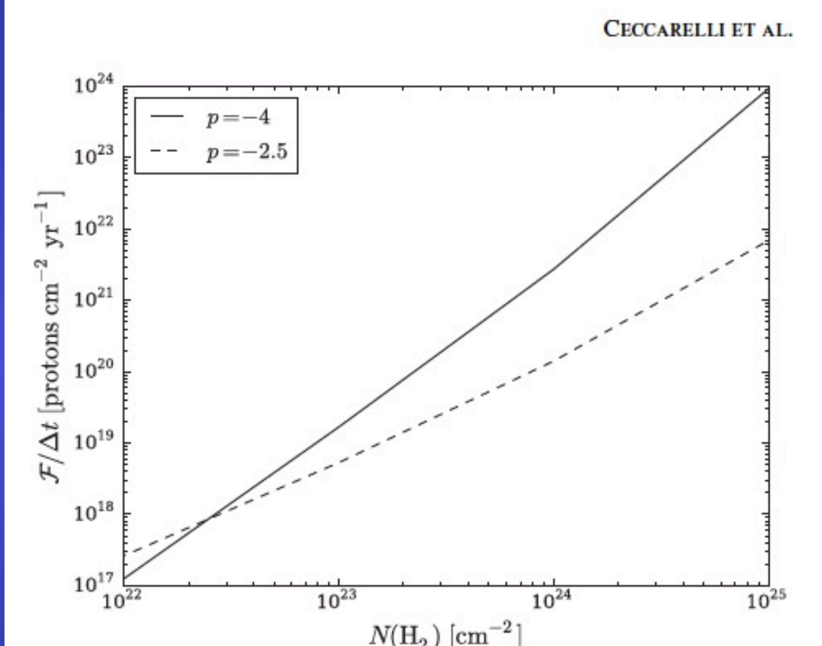


Figure 4. Flux of ⩾10 MeV particles as a function of the column density between the emitting source and 3700 AU, for an input energy spectrum $f(E) \propto E^p$ with $p = -4$ (solid line) and -2.5 (dashed line).

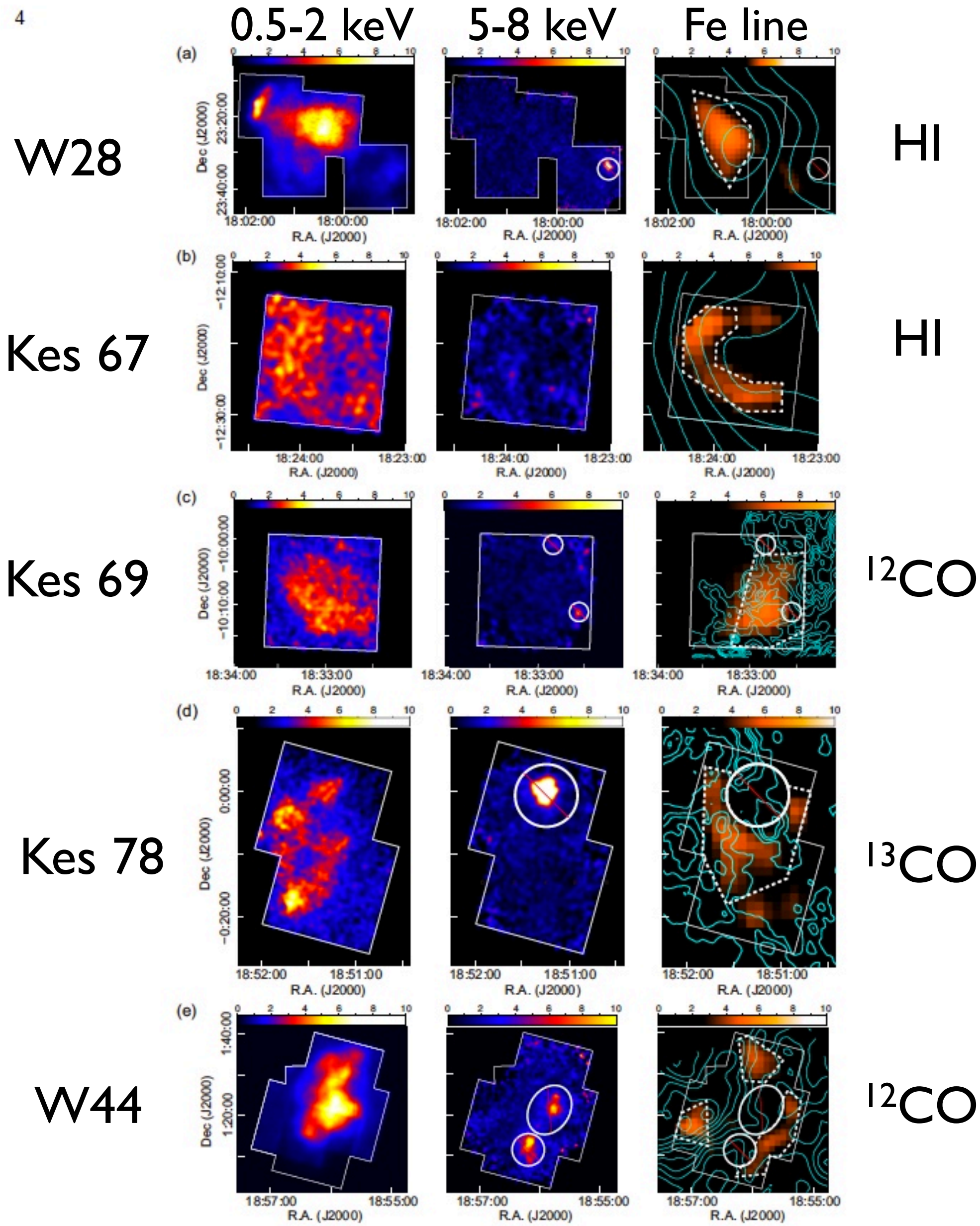
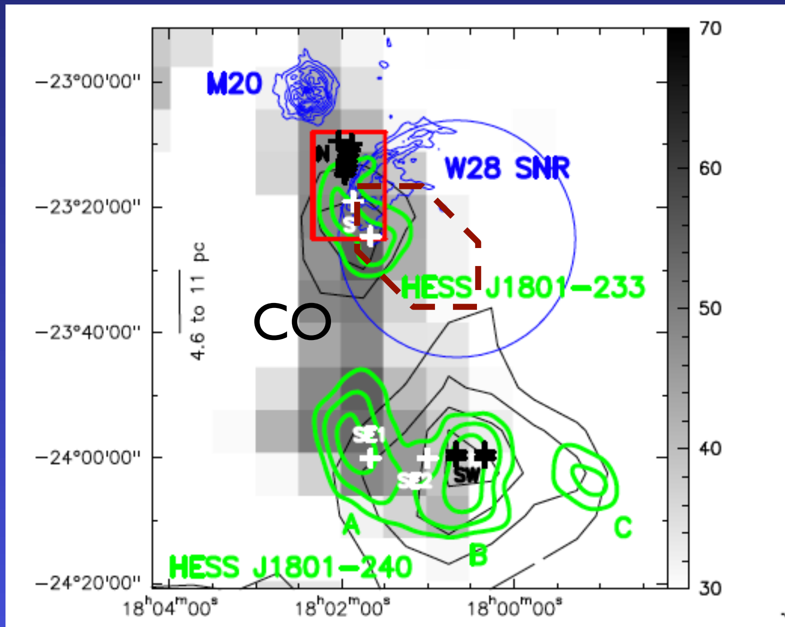


Figure 1. Band images of (a) W28, (b) Kes 67, (c) Kes 69, (d) Kes 78, and (e) W44. The left, center, and right panels show the images of the soft (0.5–2 keV), hard (5–8 keV), and the Fe I Kα line band (6.2–6.5 keV), respectively (color bars in arbitrary unit). Vignetting is corrected and the NXB is subtracted. The regions surrounded by the white lines in the individual panels show the FOVs of the XIS. Point-like or slightly extended sources are marked with solid white circle or ellipse regions, which are described in section 3.2. In the right panels, those regions are excluded from the images. The dashed lines in the right panels indicate the "enhanced regions" (see text). The contours in the right panels show the distributions of HI at 37.5 km s^{-1} (Velázquez et al. 2002), HI at 18.1 km s^{-1} (Dubner et al. 1999, the intensity of HI increases towards the east), ^{12}CO (J =1–0) at 80–81 km s^{-1} (Zhou et al. 2009), ^{13}CO (J =1–0) at 80–84 km s^{-1} (Zhou & Chen 2011), and ^{12}CO (J =2–1) at 40.0–50.3 km s^{-1} (Yoshiike et al. 2013), for (a), (b), (c), (d), and (e), respectively.

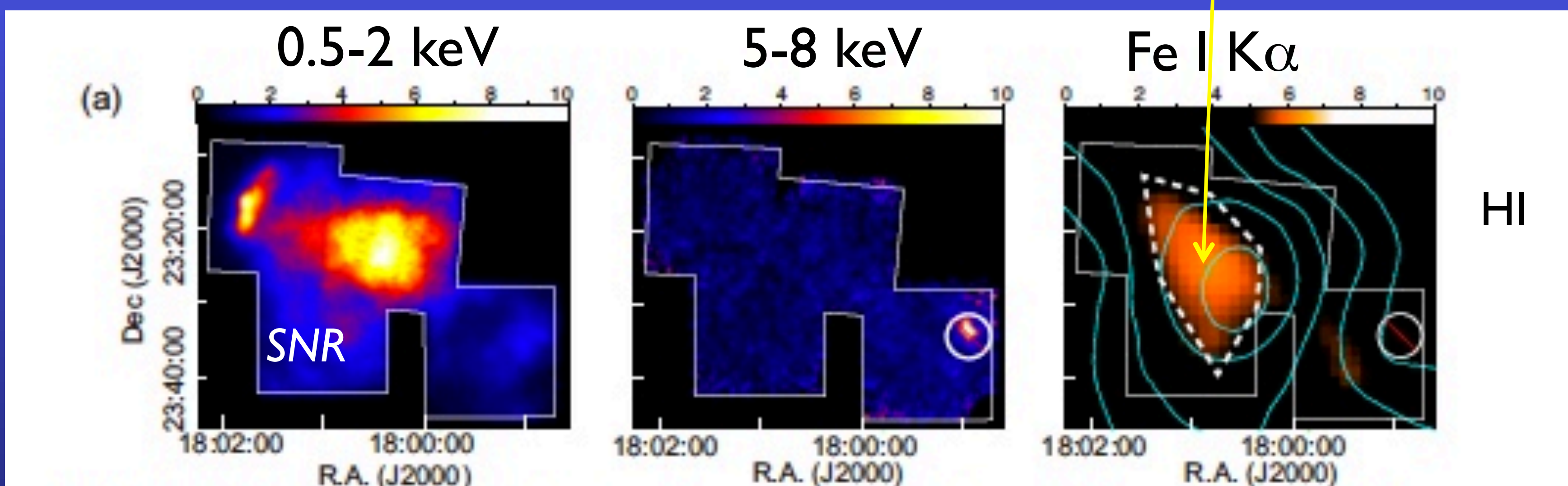
Diffuse FeI Ka line 6.40 keV (Suzaku)

(Nobukawa+ 2018)

W28 as a CR source



MeV protons



3. Main processes: interactions inside low-density ISM

- Spallation reactions in general ISM (=> Li Be B; MAR1971)
  - depends on propagation; integrated over time
  - ^{6}Li/^{7}Li ratio: = 12.2 for solar system, ~ 2 by GCR*
- The case of superbubbles: new test ?
  - Li absorption (λ6707) towards O stars
    - IC 348 SFR (Per OB2 bubble: Knauth+ 2017)
    - CMa superbubble (Fernandes+ 2018)*
- Direct detection ?
  - nuclear γ-ray lines: α (CR) + α (ISM) $\rightarrow$ ^{6}Li*, ^{7}Li*, ^{7}Be*
  - ^{7}Be* $\rightarrow$ ^{7}Li* + γ (431 keV)
  - ^{7}Li* $\rightarrow$ ^{7}Li + γ (470 keV)
  - ^{6}Li* (3.56 MeV), ^{4}He* (27.4 MeV)
  - in molecular clouds ?? (cf. V.T.)

Seeing through the Per OB2 bubble

Table 1
Stellar Data

Star	Spec. Type[a]	V^a (mag)	$B-V^a$ (mag)	$E(B-V)$ (mag)	τ_{exp} (s)	S/N at λ6708	Telescope/Instrument
HD 23478	B3 IV	6.69	0.03	0.27[b]	7680	950	Subaru/HDS
HD 24534	O9.5 Ve	6.72	0.12	0.59[c]	6900	2680	Subaru/HDS
HD 281159	B5	8.68	0.60	0.85[c]	23690	1560	HET/HRS

Notes.
[a] Simbad database, operated at CDS, Strasbourg, France. (Van Leeuwen 2007)
[b] Papaj et al. (1991).
[c] Indriolo & McCall (2012).

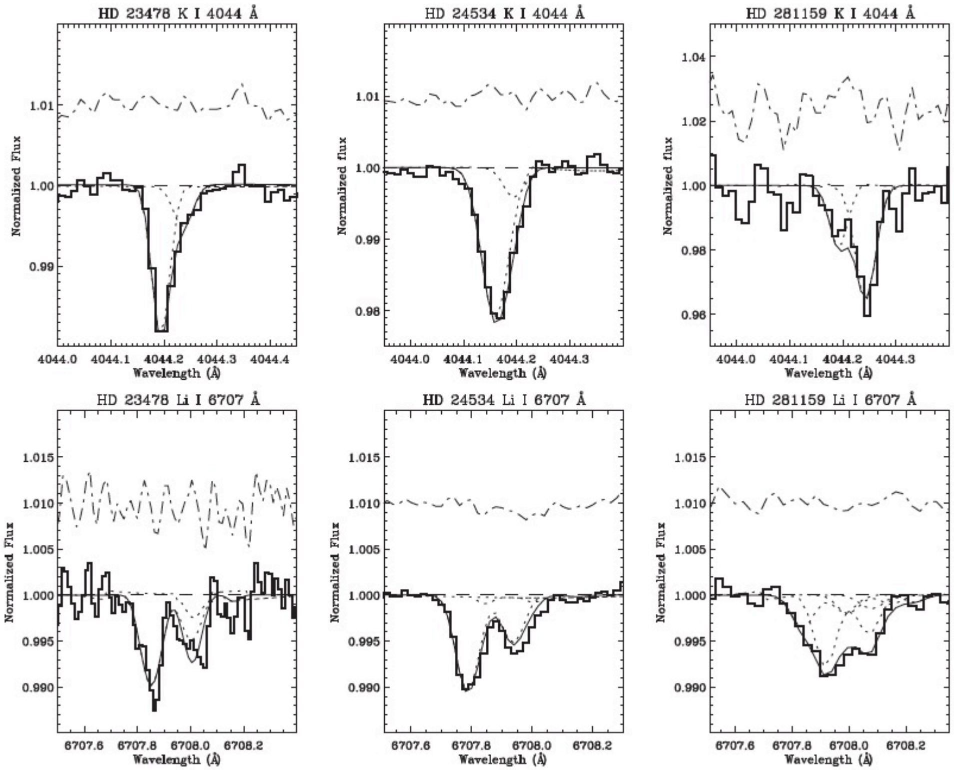
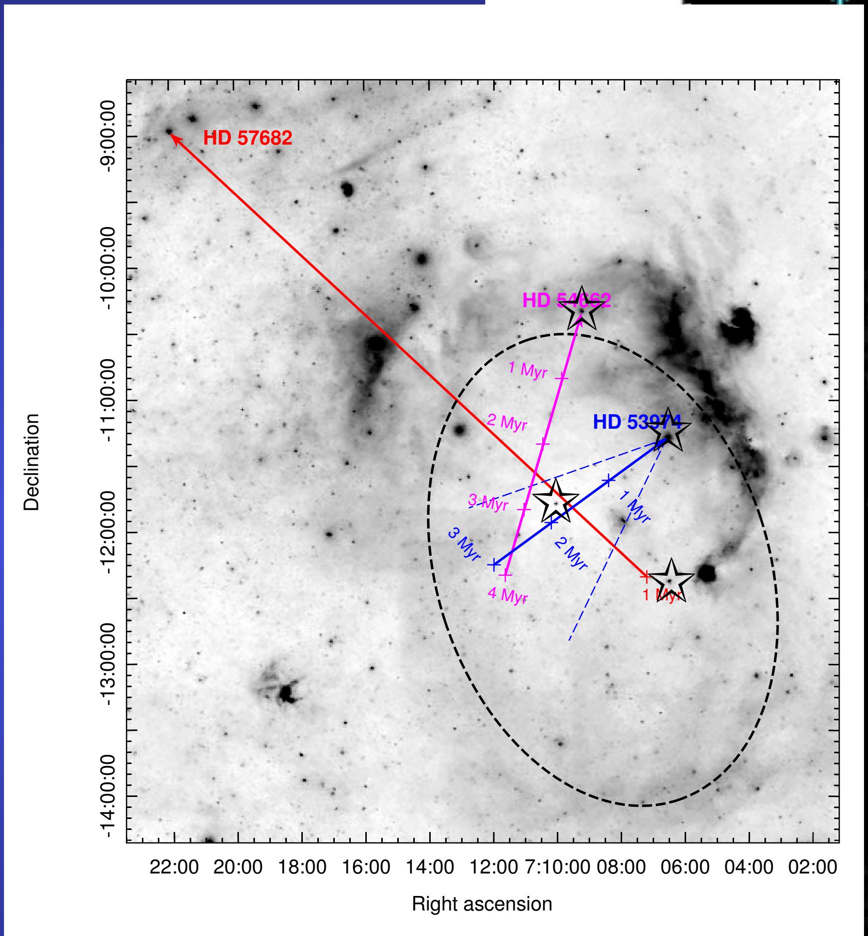


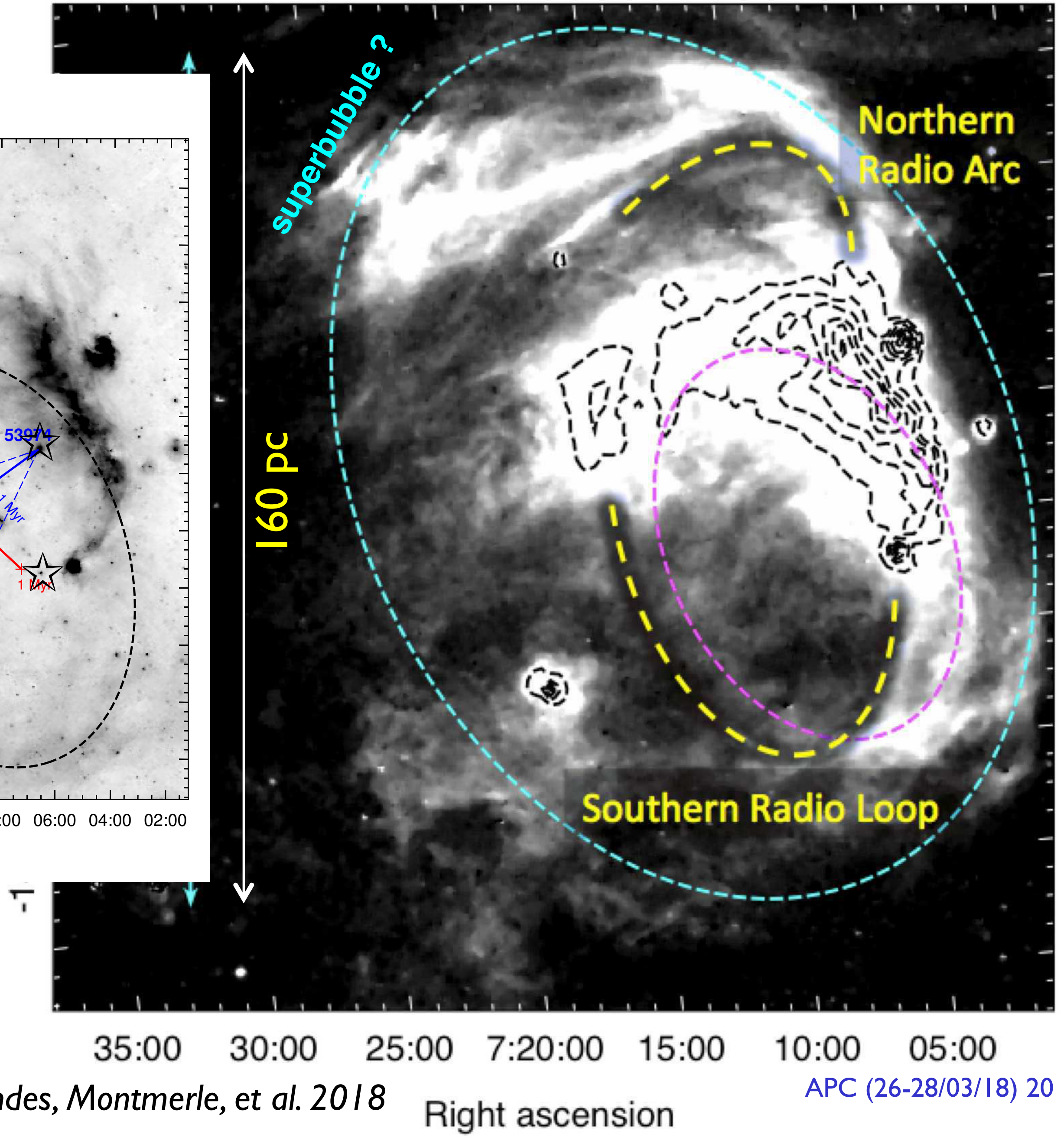
Figure 1. The top (bottom) row depicts interstellar K I (Li I) data (solid histogram) toward HD 23478, HD 24534, and HD 281159 normalized to unity. All lines of sight were best fit with two interstellar velocity components seen in K I and Li I (and in CH not presented). The two component fits are shown by the dotted lines. The dotted–dashed lines show the residuals to the fit (offset by an appropriate scaling factor), while the dashed lines denote the continuum placement. It is important to note that the ^{7}Li I profiles resemble the expected 2:1 intensity ratio toward the stars HD 23478 and HD 24534, but toward HD 281159 the profile is close to 1:1 ratio clearly indicating enhanced ^{6}Li along this line of sight.

Knauth et al. 2017

The CMa bubble/superbubble (≥ 3.5 Myr)



Federman et al., in prep.



Fernandes, Montmerle, et al. 2018

$\alpha + \alpha \rightarrow$ Li spallation reactions

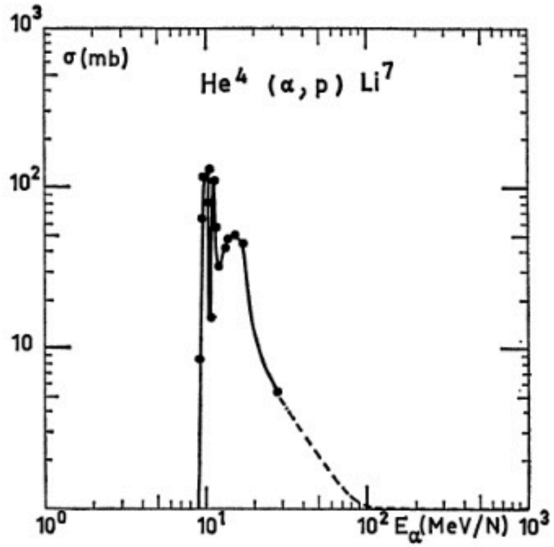


Fig. 1. Excitation curve of ^{4}He (α, p) ^{7}Li. The dots are experimental points. The dashed line is our estimate for the high energy values (see text). The same numerical values were used for the ^{4}He (α, n) ^{7}Be

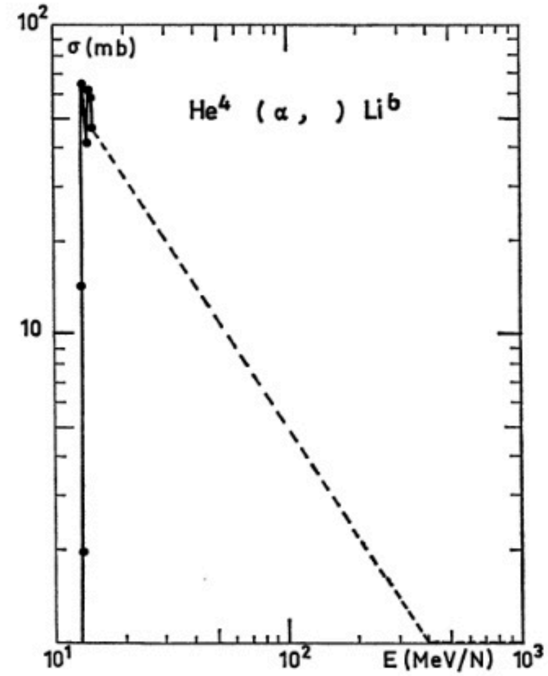


Fig. 2. Excitation curve of ^{4}He (α,) ^{6}Li. The dots are experimental points. The dashed line is our estimate for the high energy values

at high energy is generally 20% of the proton induced contribution. For product nuclei which

MAR 1971

4. Consequences and new ideas

- Main issue: feedback on star formation (MC ionization)
  - galactic scale: classical regulating mechanism for cloud collapse: ambipolar diffusion (*B*, ζ)
  - fast moving field (real role of B ? filaments ?)* (André+, Hennebelle+, etc.)
  - Evidence of LECR in protostars/young Sun ?* (Ceccarelli+ 2014, Favre+ 2017)
  - Efficiency of star formation during SNR-MC interactions (~ 1 Myr) ?

- Beyond the Galaxy
  - collisions of HVC "Magellanic stream") with the Milky Way (del Valle+ 2017)
  - star formation history in galaxies (Fontanot+ 2018)*

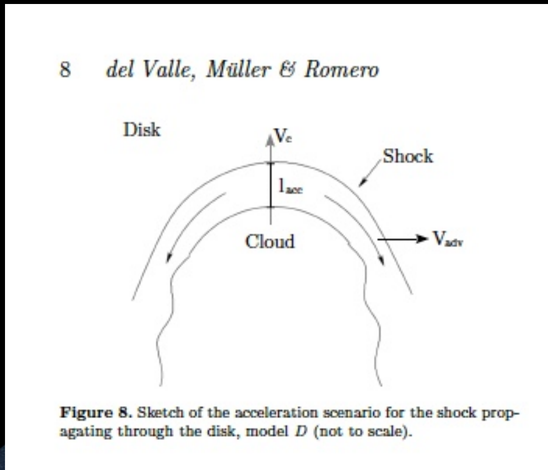
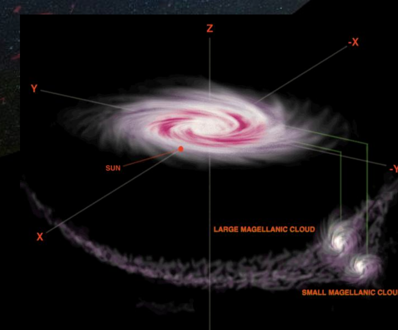


Figure 8. Sketch of the acceleration scenario for the shock propagating through the disk, model *D* (not to scale).



Impact of CR regulation on a variable IMF in galaxies

4 *Fontanot et al.*

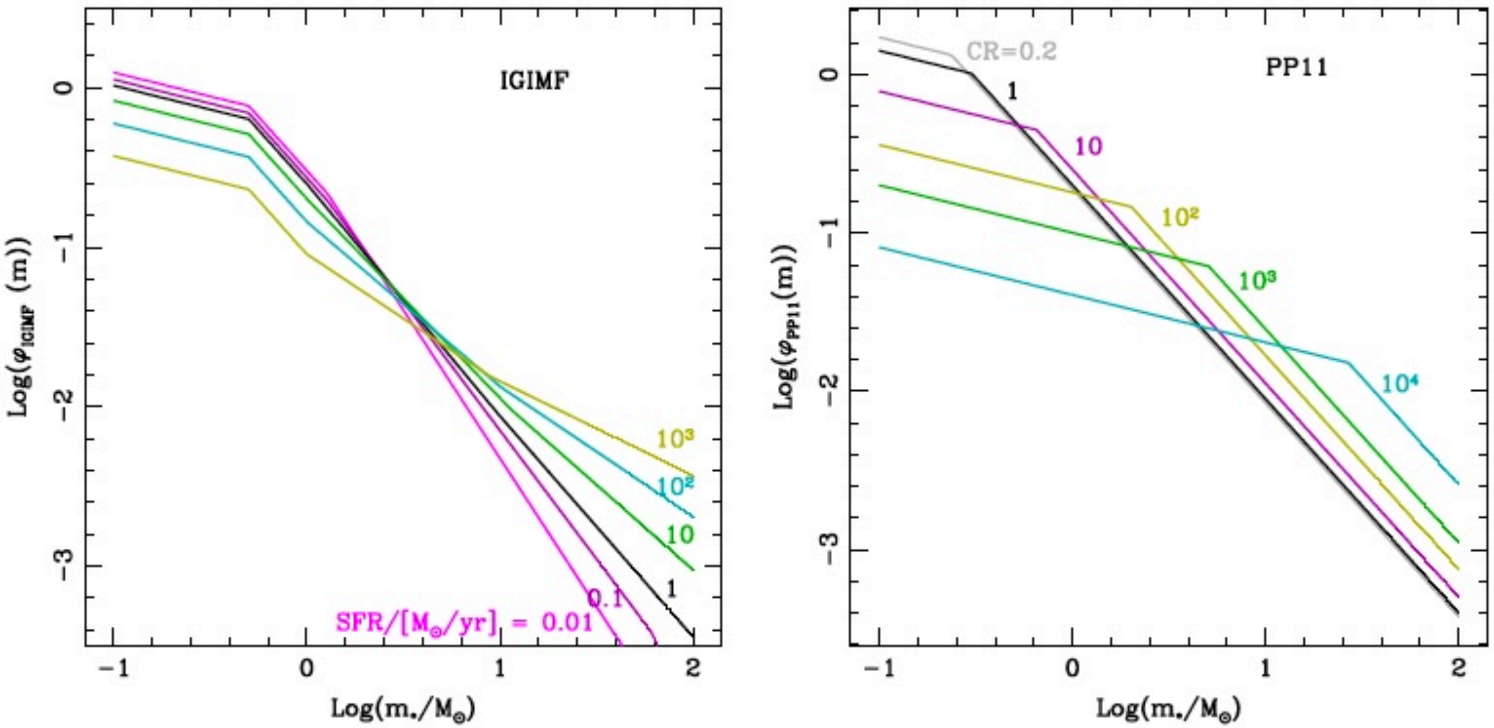


Figure 1. Variable IMF scenarios. *Left panel:* evolution of the IMF shape according to PP11. Labels close to lines report the corresponding cosmic ray densities (normalized to the Milky Way value, $CR = U_{\rm CR}/U_{\rm MW}$). *Right panel:* IMF variation as predicted by the IGIMF theory. Labels close to the lines report the reference SFRs (see also Fig. 1 in F17a). In both panels, each IMF is normalized to 1 $M_\odot$ in the stellar mass interval 0.1-100 $M_\odot$.

5. Conclusions et perspectives

- RCBE important dans de nombreux domaines, en raison de ses effets de rétroaction sur leur environnement

- Sujet très inter/multidiciplinaire
- Bien développé en France
- Intersection entre plusieurs programmes nationaux INSU
  - PNHE**
  - PCMI (nuages moléculaires, formation stellaire...)**
  - PNST (protoétoiles, disques étoiles jeunes...)*
  - PNP (formation du système solaire, météorites...)*
  - PNCG ? (formation stellaire dans les galaxies...)*