Probing cosmic rays with molecules

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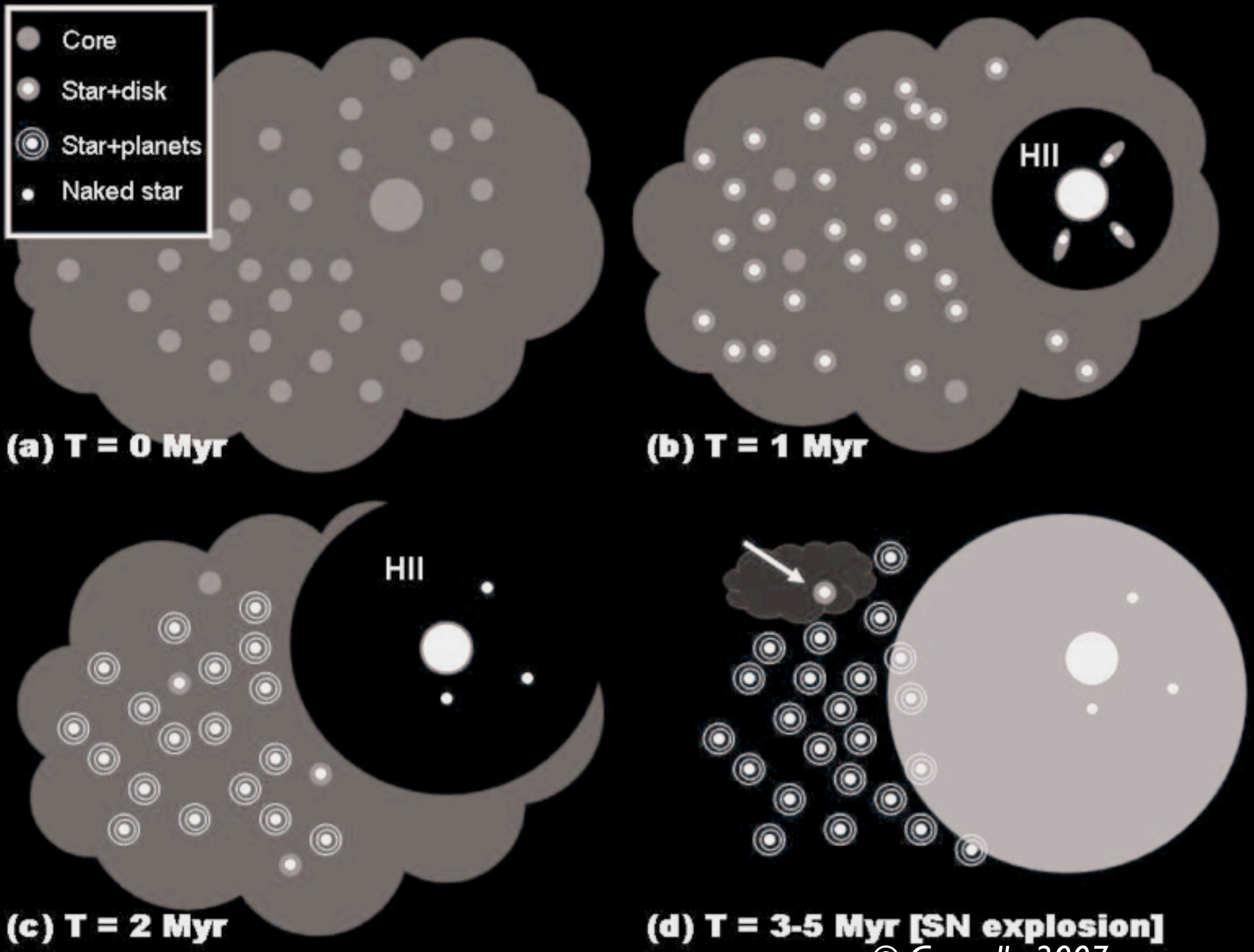
Ref.: Vaupré et al. 2014, A&A, 568, A50

IC443 SNR

Context: Early evolution of an OB association
=> supernova remnants interacting with molecular clouds !
=> sites of CR acceleration + targets (see TM 1979…)



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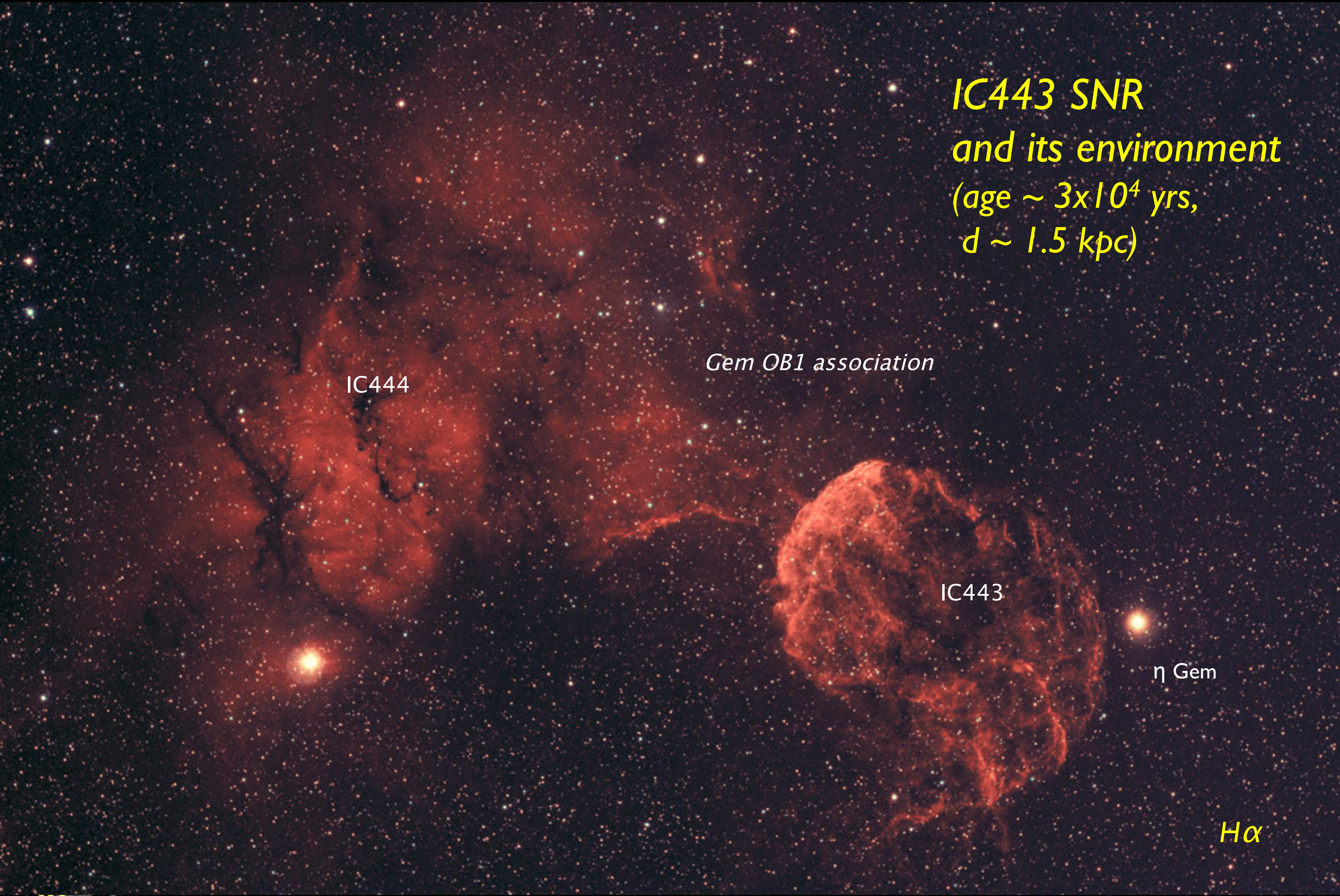
IC443 SNR and its environment

(age ~ $3\mathrm{x}10^4$ yrs, d ~ 1.5 kpc)



IC443 SNR and its environment

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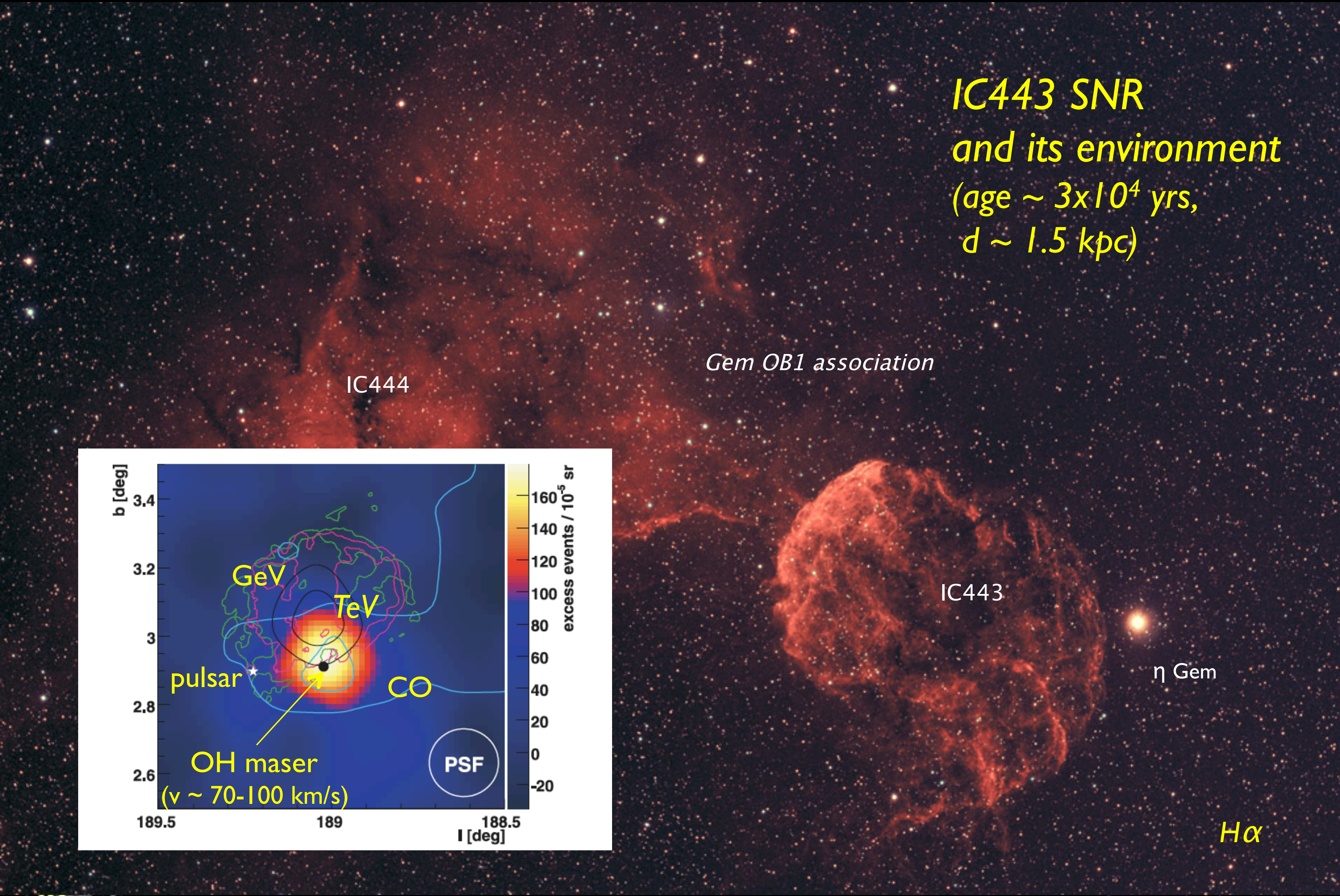
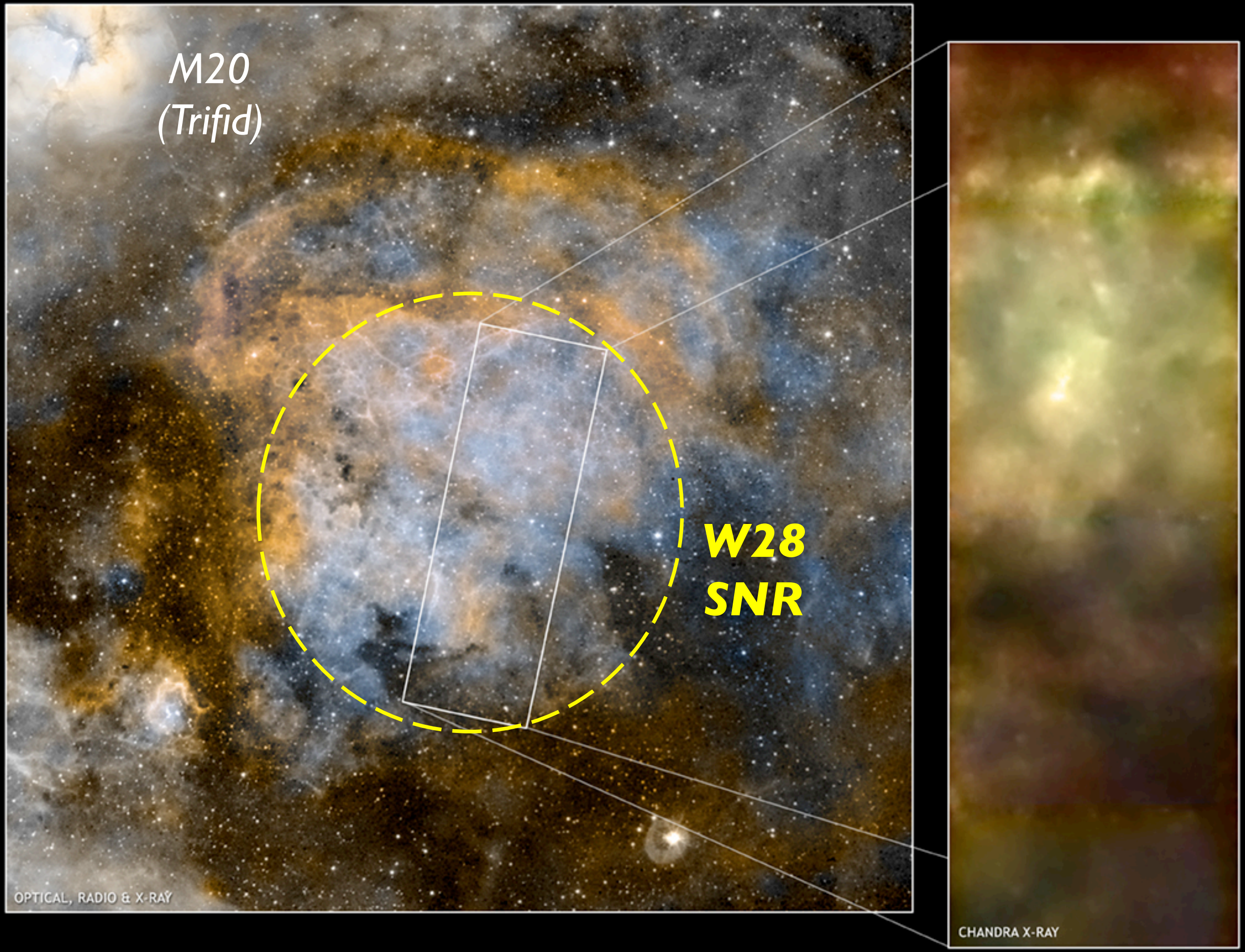
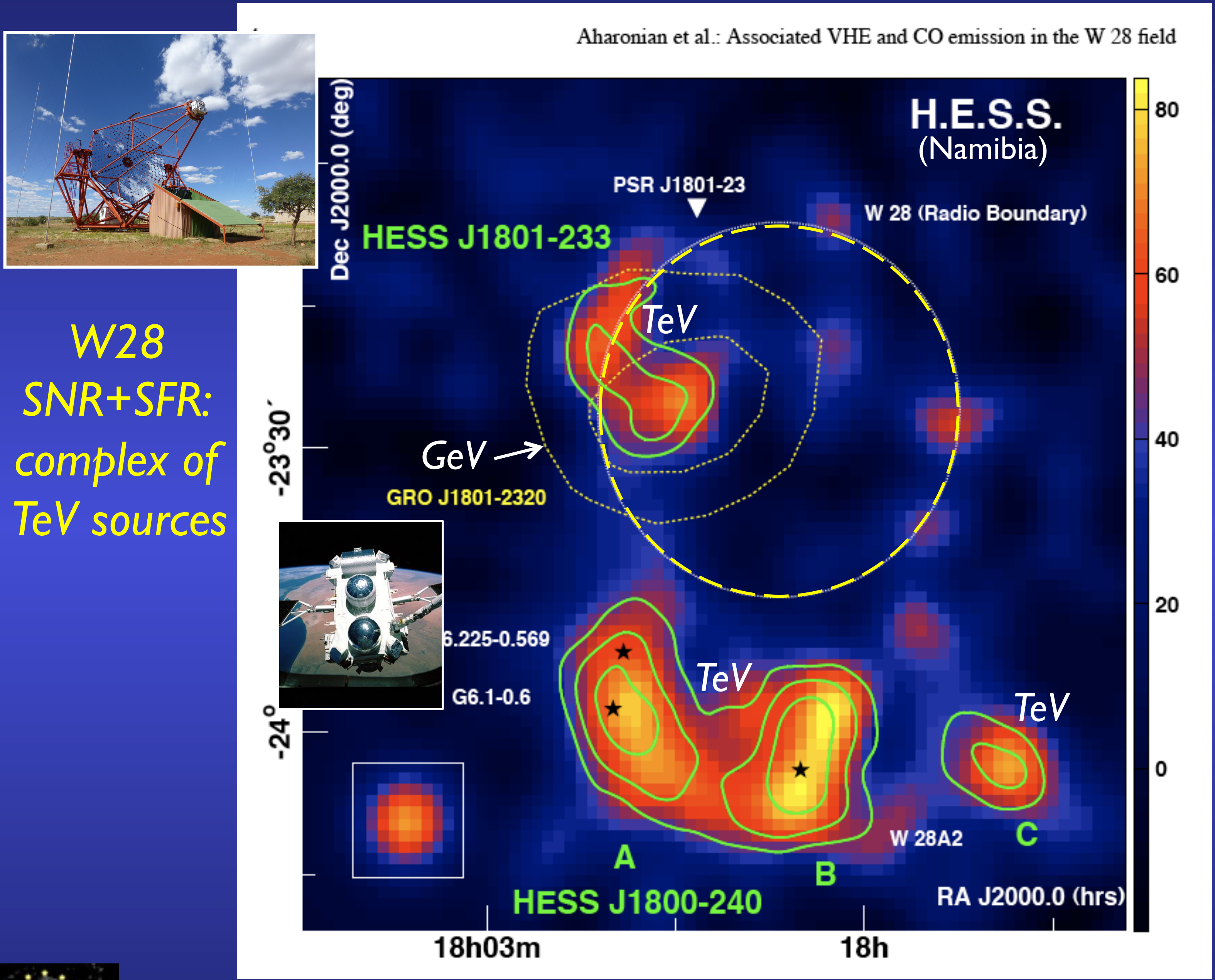




d ~ 2-3 kpc
D ≈ 20 pc
Age ~ 35-150,000 yrs

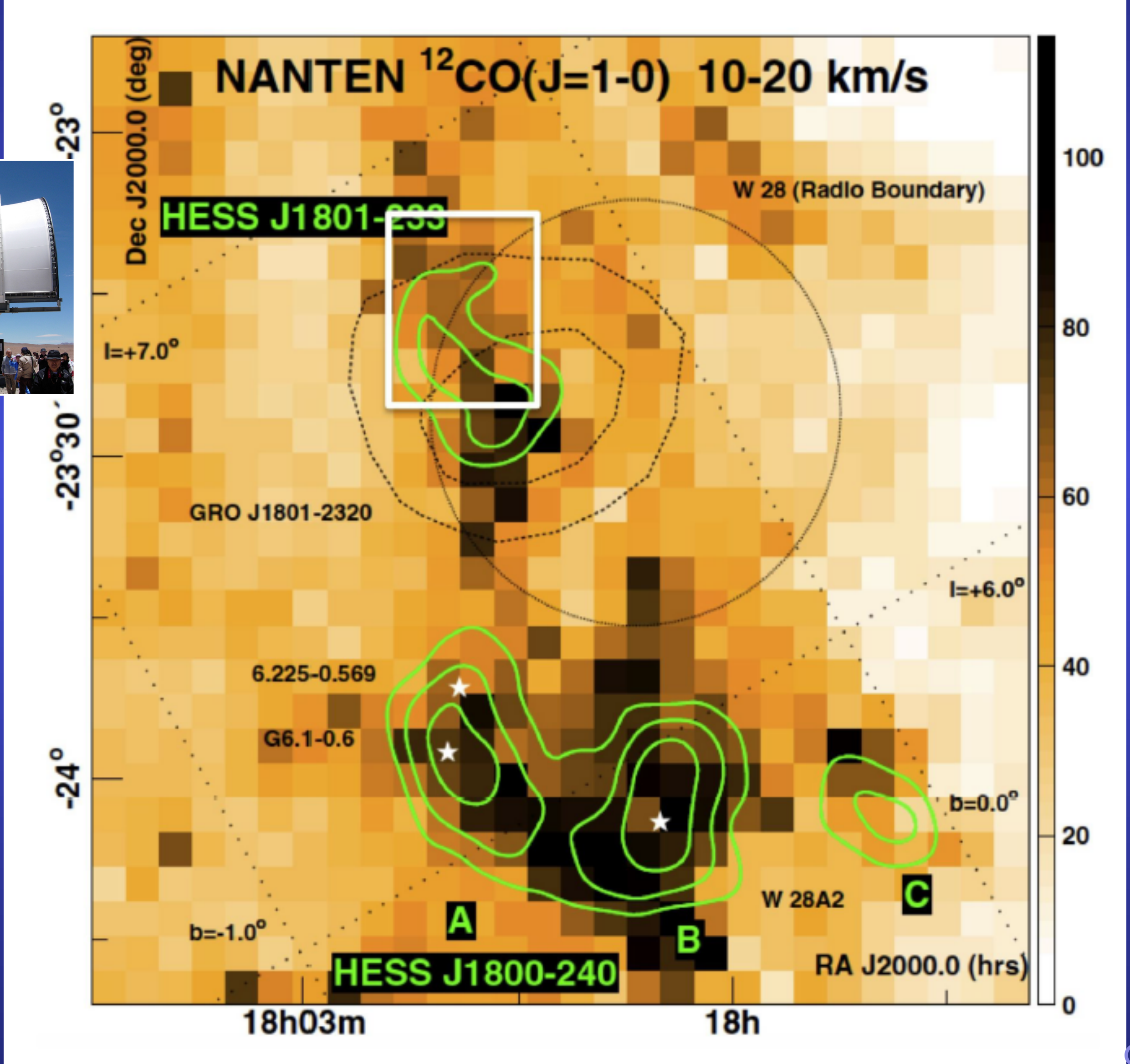
W28
SNR+SFR:
complex of
TeV sources



Aharonian et al. 2009

=> High-energy CR interactions with molecular material (GeV-TeV g-rays)

+ Evidence for slow shocks (OH masers, ~ 100 km s^{-1})



W28 GeV emission: first strong evidence for p° decay
from cut-off in sub-GeV g-ray range (confirmed by Fermi*)*

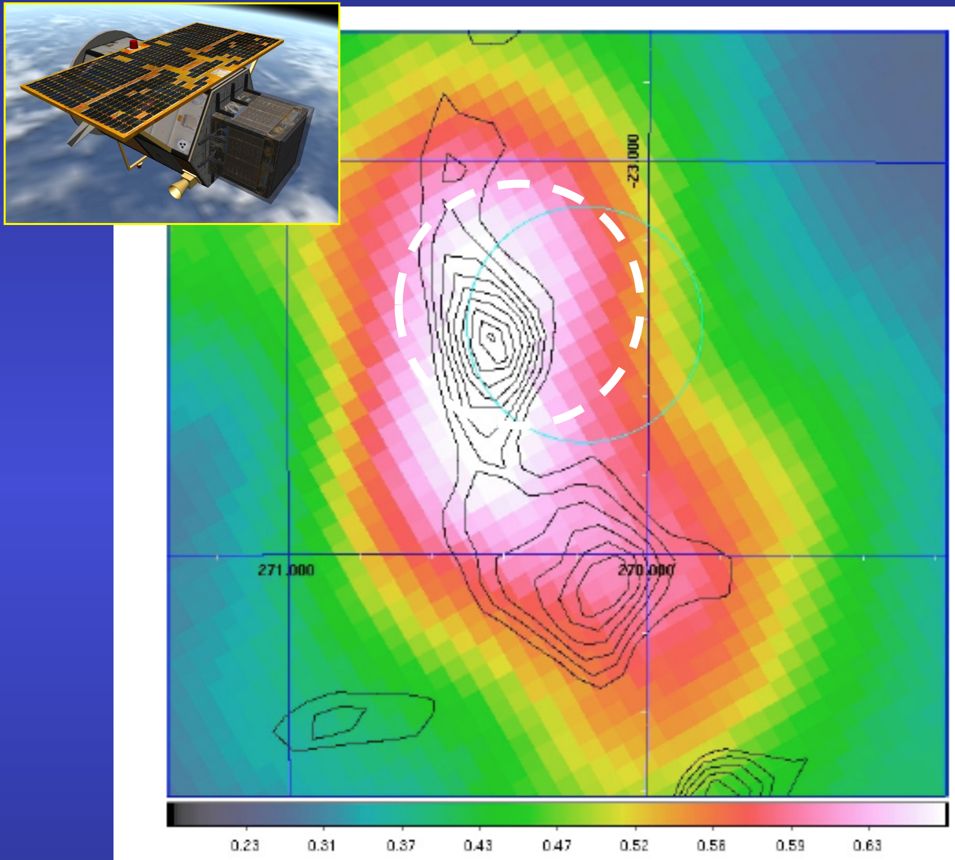
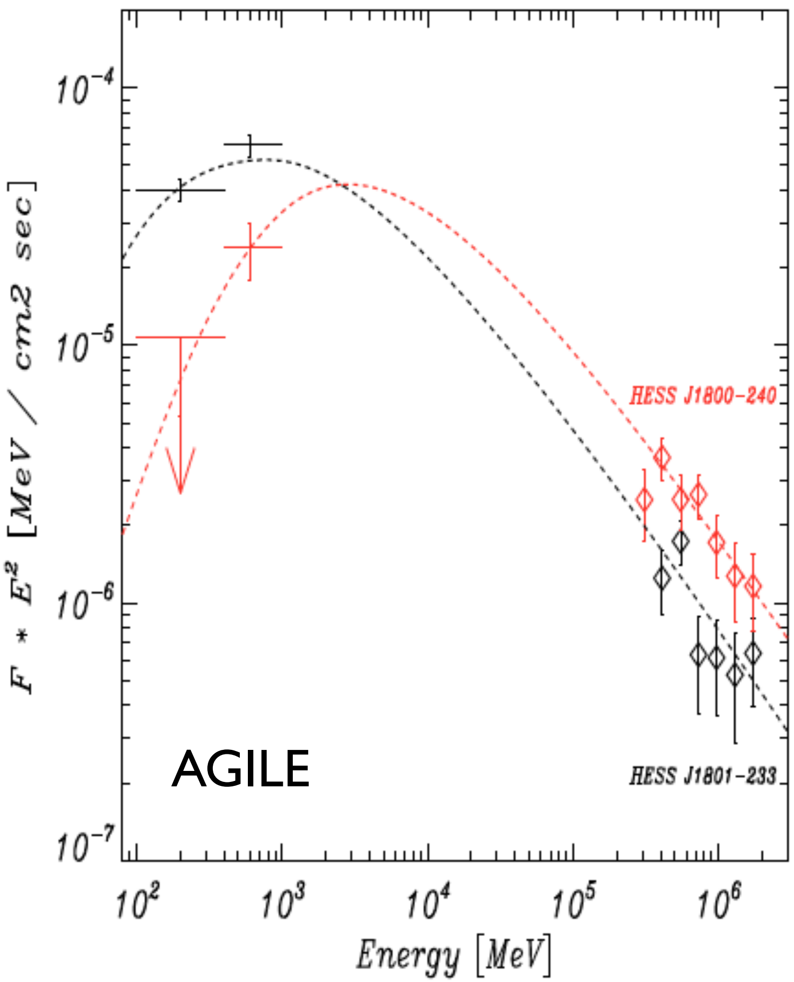
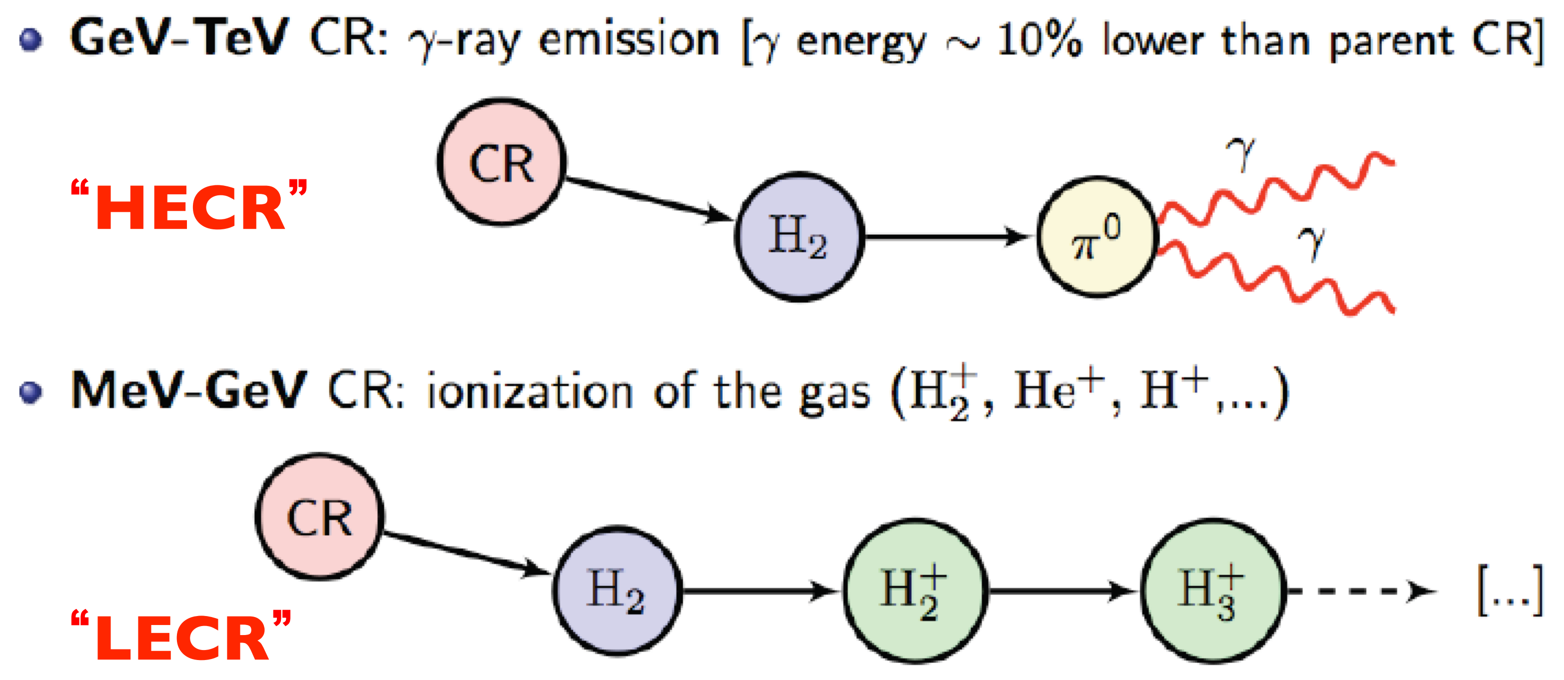


Fig. 3. Gaussian-smoothed AGILE counts map in Galactic coordinates for the W28 region (counts bin^{-1}). Only photons of energy greater than 400 MeV have been used. The blue circle indicates the radio location of the supernova remnant W28. As in Fig. 1, the black contours indicate the CO intensity emission.



(Giuliani et al. 2010)

=> *Idea: Search for* low-energy *CR in W28…*



- **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”

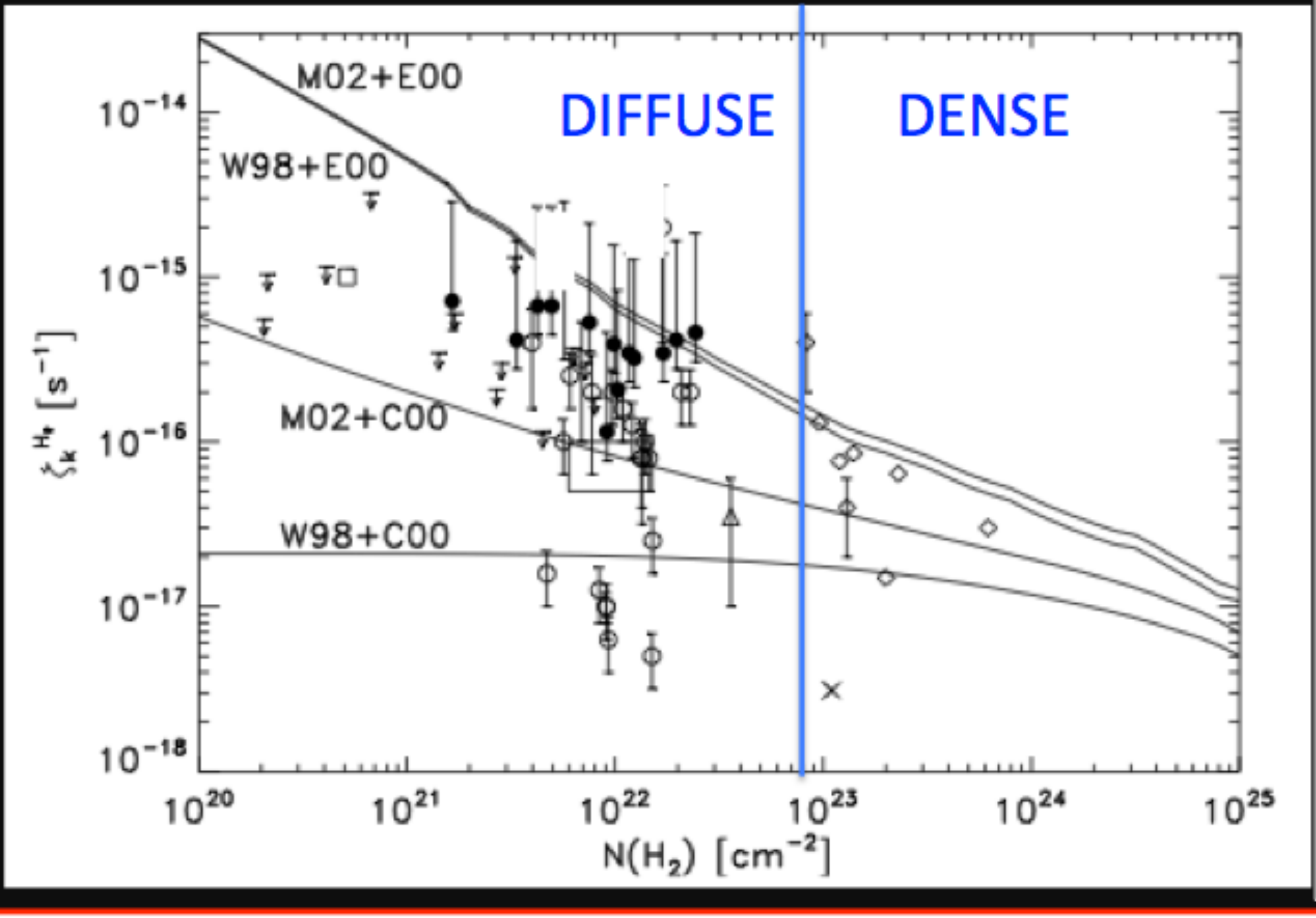
… by measuring and mapping the *ionization rate* Z

(fiducial value $Z_0 \sim 10^{-17}$ s^{-1} for the Galaxy)

- ⇔ ***Low-energy interactions***
- General idea: assume TeV g-rays come from > TeV protons (p° decay) accelerated by the SNR shock
- => Enhanced molecular cloud ionization comes from associated low-energy GCR (≳ 0.1-500 MeV) (e.g., Galli & Padovani 2013)
- => Link with MeV/GeV/TeV flux

- => Measure *ionization degree x_e*: local CR flux enhancement
  - Usual value [illegible]$_0$ ~ 10^{-17}-10^{-16} s^{-1} => for n_{H2} ~ 10^4-10^5 cm^{-3},
    - x_e ~10^{-8}-10^{-7} (e.g., Caselli et al. 1998)
  - => important chemical effects (=> H_3^+ ; H_2D^+ ; radicals…)
  - => *role in star formation ?* (+ magnetic fields: ambipolar diffusion)
- *Methods to measure the ionization and* [illegible]:
  - NIR absorption lines (background stars): H_3^+ (NIR: IC443, Indriolo et al. 2010); N-MIR emission lines (Schuppan et al. 2012): *diffuse outer layers* (A_V < a few)
  - mm emission lines: DCO^+/HCO^+ (mm, or *meV emission !*): *deep, dense molecular material* (A_V > 40-50)

Diffuse vs. Dense Clouds



Padovani, Galli & Glassgold 2009

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

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

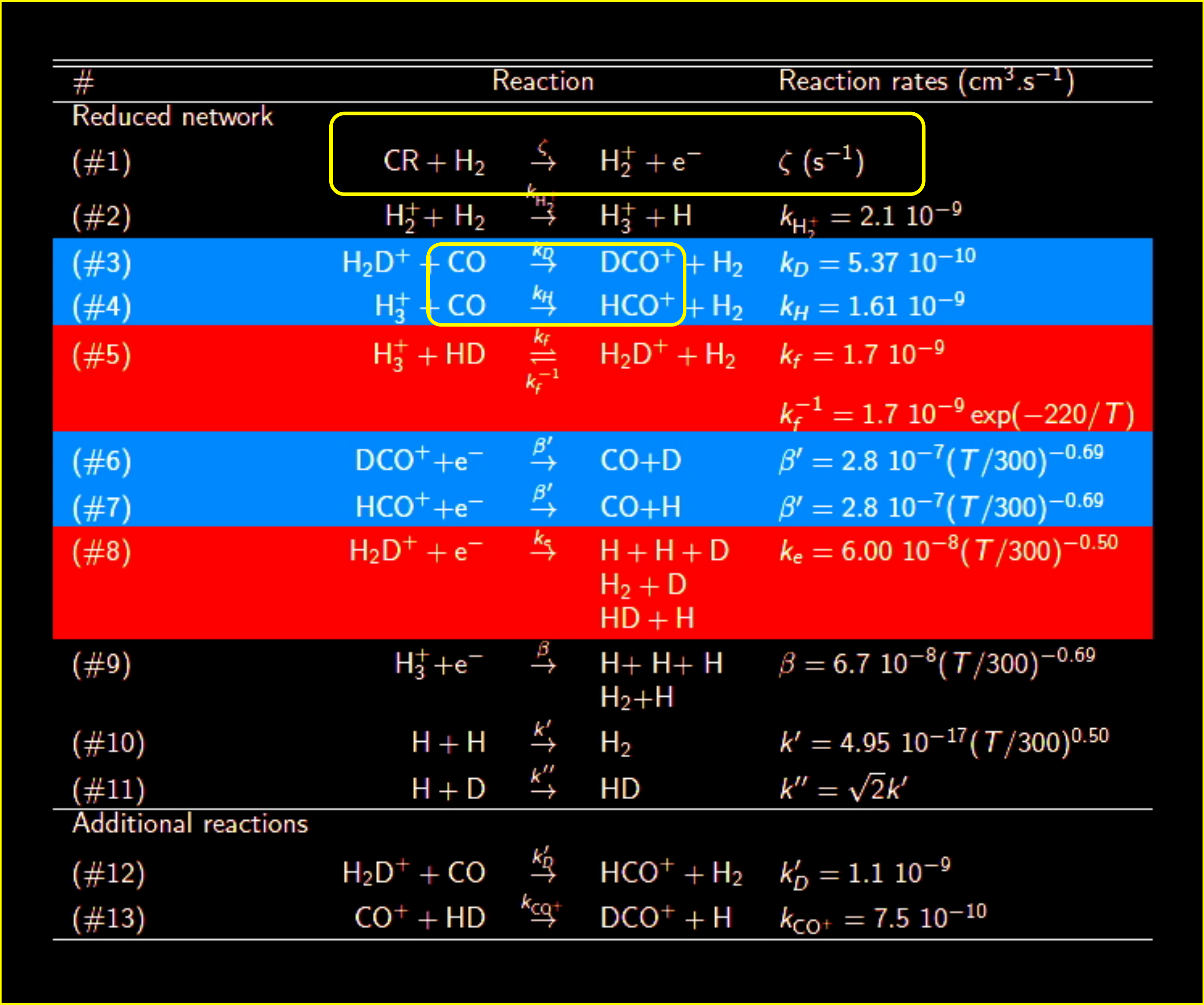
- Dense clouds: “DCO^+/HCO^+ ionization test”:
  IRAM-30m program (Ceccarelli, Hily-Blant, Dubus, TM, Vaupré, Lefloch)
  - Sample of TeV sources:
    - SNOB-like sources (IC443, W28, W51C, Cyg OB1)
  - mm observations: HCO^+, DCO^+, ^{12}CO, ^{13}CO
    - $CO + H_3^+ \rightarrow HCO^+ + H_2$
    - $CO + H_2D^+ \rightarrow DCO^+ + H_2$
    - First-order analytical approximation:

$$\frac{\mathrm{H_2D^+}}{\mathrm{H_3^+}} = \frac{2 \cdot [\mathrm{D}]k_1}{k_\mathrm{e}x_\mathrm{e} + k_\mathrm{CO}x_\mathrm{CO} + 2k_{HD}[\mathrm{D}]} = 3\ DCO^+/HCO^+$$

(e.g., Guélin et al. 1977)

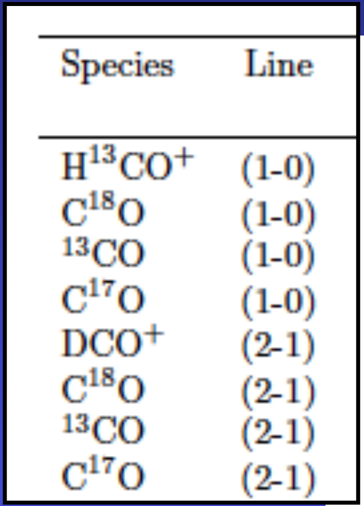
- x_e (but requires chemical model if x_e too high; see later)
- + cloud T, density and $N(H_2)$ from ^{12}CO and ^{13}CO measurements

Chemical reactions network: Molecules… and radicals



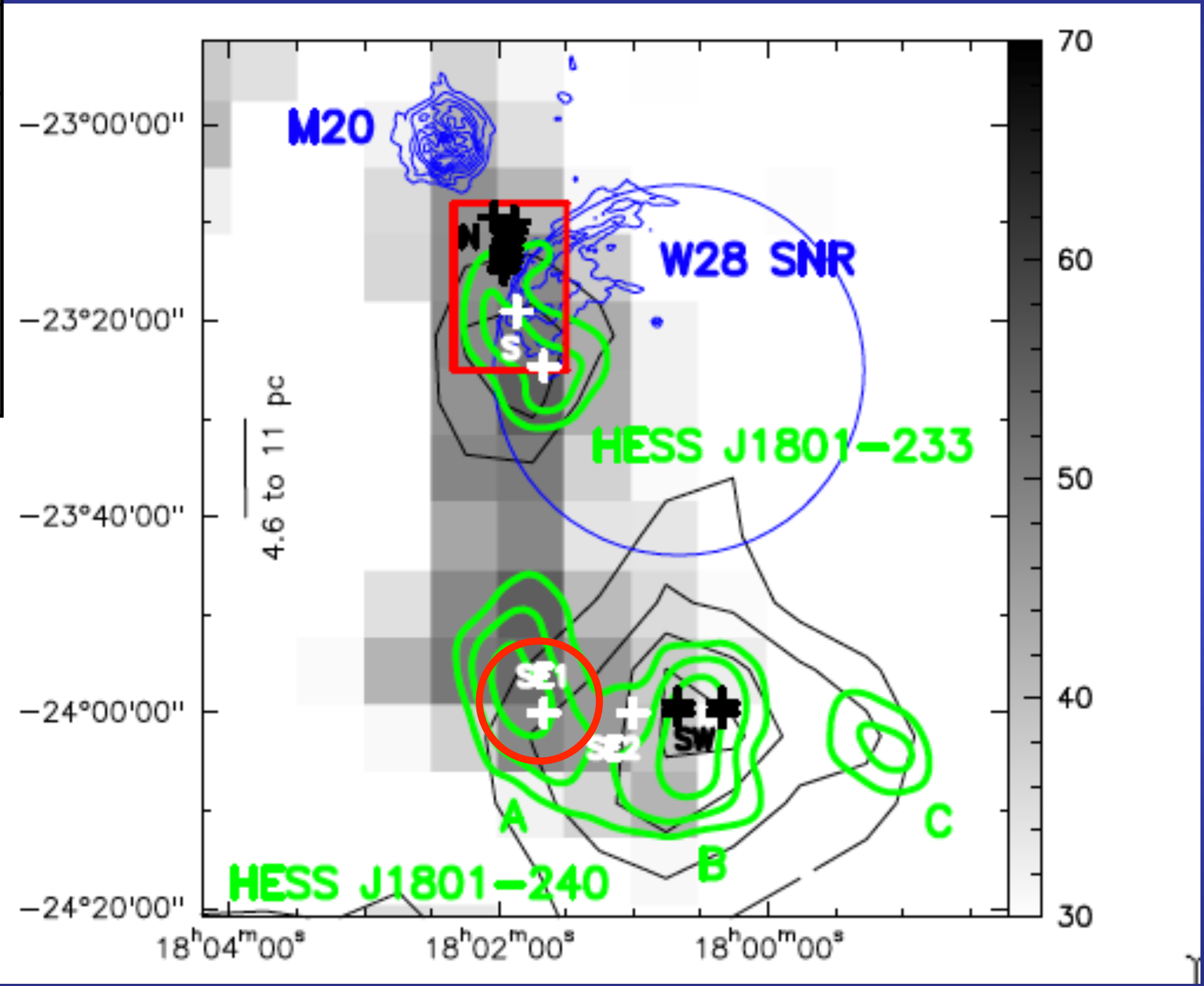
#	Reaction	Reaction rates ($cm^3.s^{-1}$)
Reduced network		
(#1)	$CR + H_2 \overset{\zeta}{\rightarrow} H_2^+ + e^-$	ζ (s^{-1})
(#2)	$H_2^+ + H_2 \overset{k_{H_2^+}}{\rightarrow} H_3^+ + H$	$k_{H_2^+} = 2.1\ 10^{-9}$
(#3)	$H_2D^+ + CO \overset{k_D}{\rightarrow} DCO^+ + H_2$	$k_D = 5.37\ 10^{-10}$
(#4)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

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

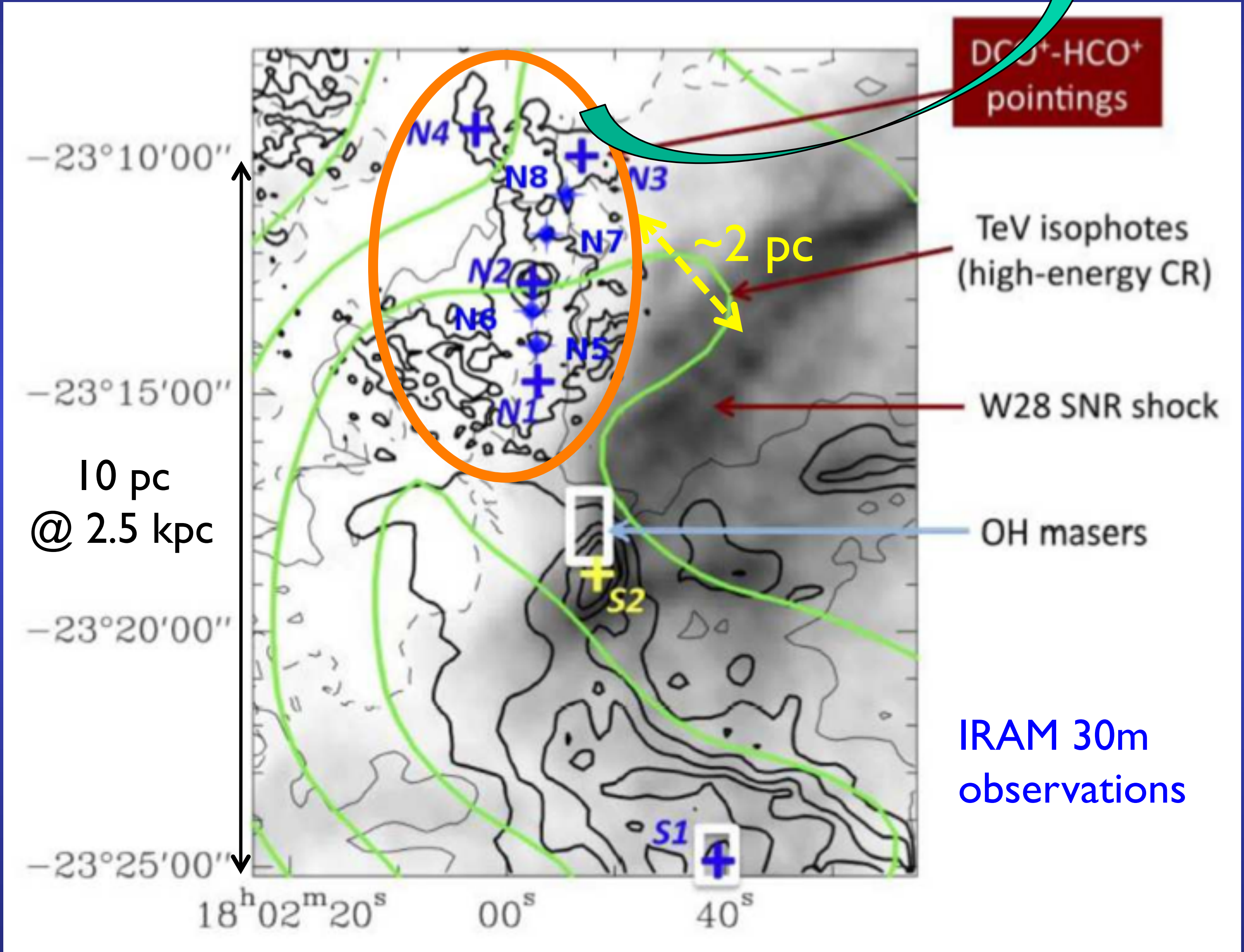


Species	Line
$H^{13}CO^+$	(1-0)
$C^{18}O$	(1-0)
^{13}CO	(1-0)
$C^{17}O$	(1-0)
DCO^+	(2-1)
$C^{18}O$	(2-1)
^{13}CO	(2-1)
$C^{17}O$	(2-1)

16 pointings



low-energy CR ⇔ *ionization “map”* (molecules/radicals) ⇔ CR *diffusion*



DCO⁺-HCO⁺ pointings

TeV isophotes (high-energy CR)

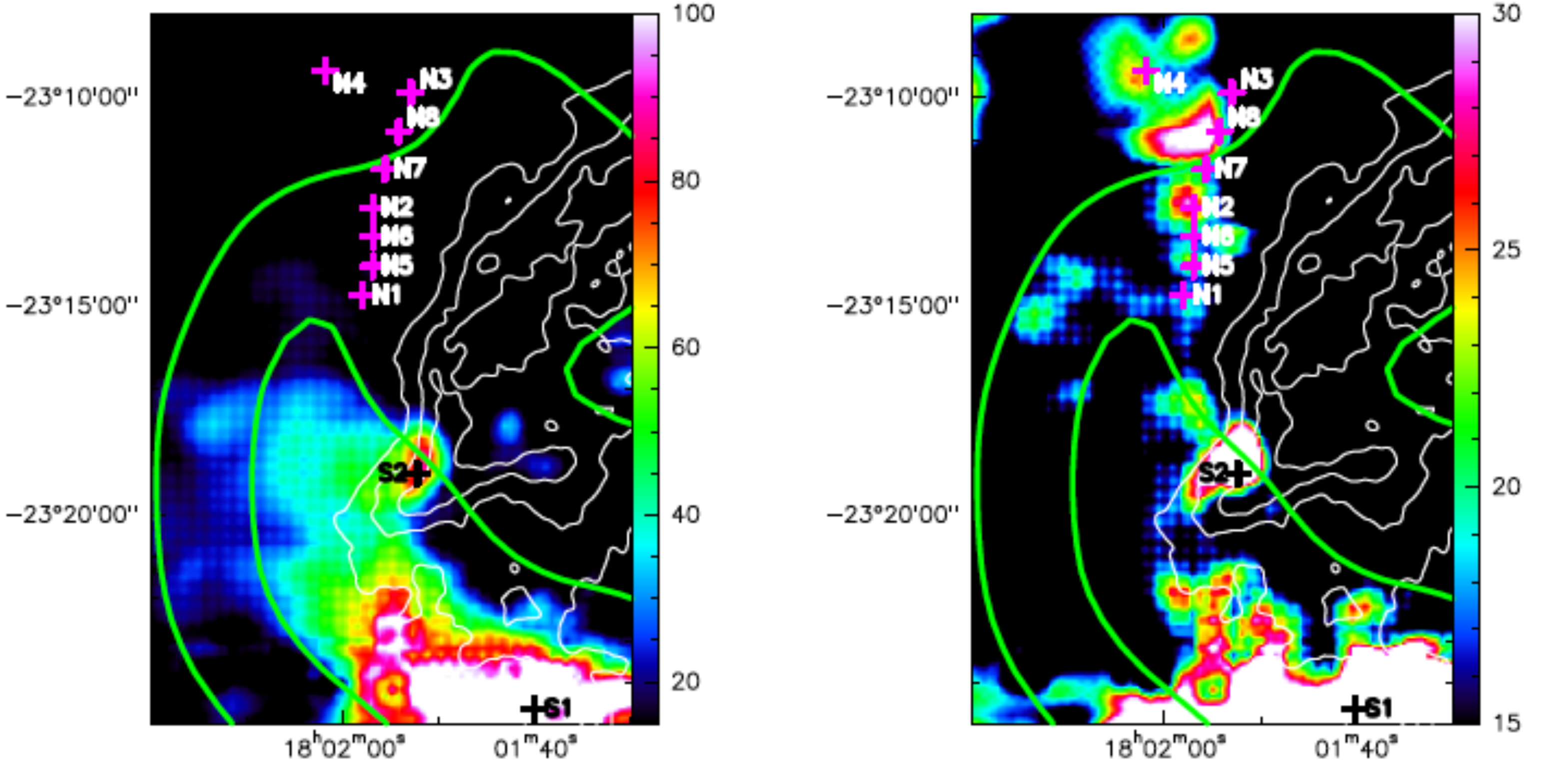
W28 SNR shock

OH masers

~2 pc

10 pc
@ 2.5 kpc

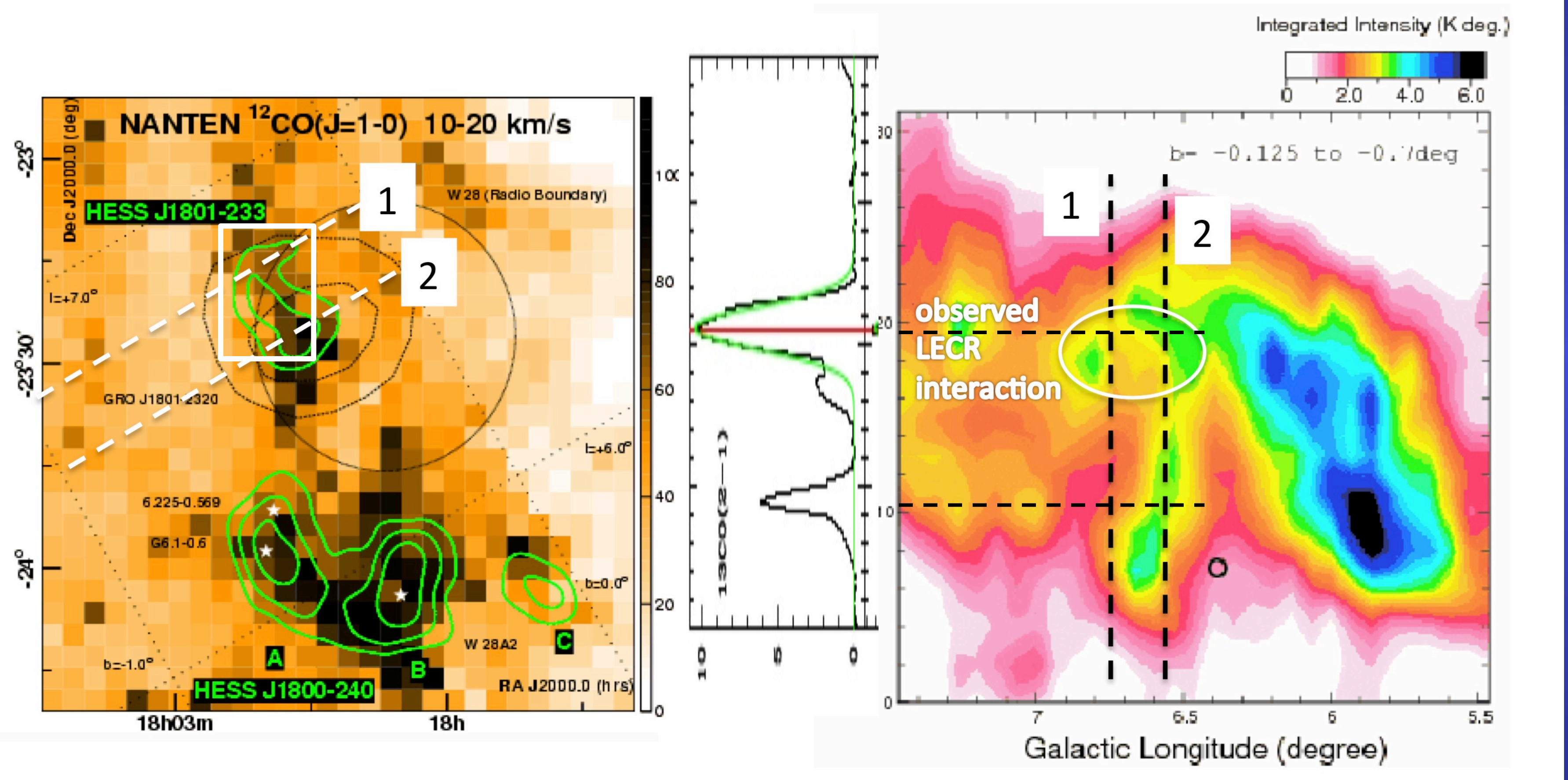
IRAM 30m observations

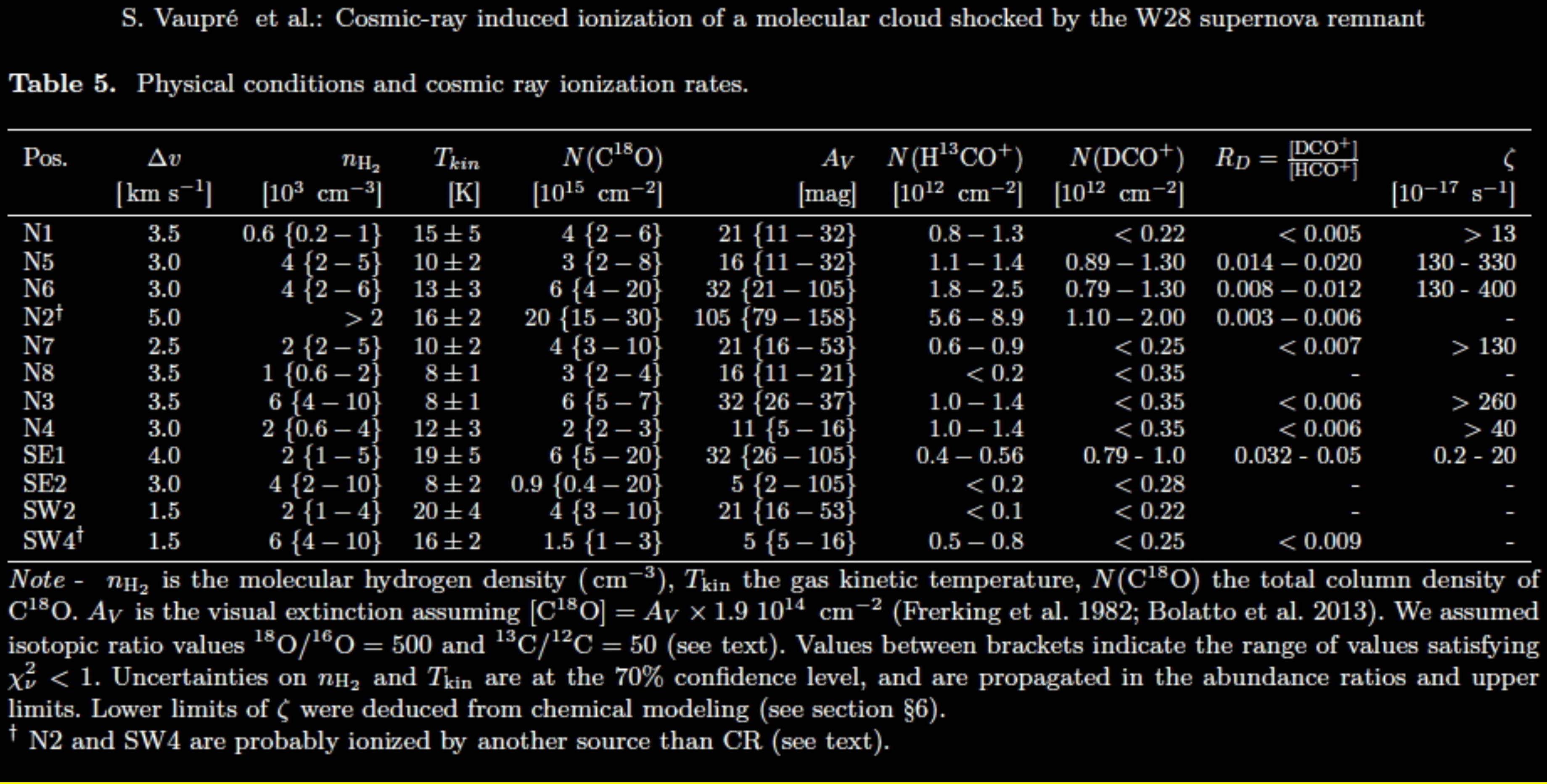


(Left): CO(3 – 2), 5-15 km.s^{-1} (Right): CO(3 – 2), 15-25 km.s^{-1}
Free-free 20 cm emission (white), HESS TeV emission (green)

Vaupré et al. 2014, A&A, in press

W28 NE: molecular cloud environment with large velocity dispersion (20 km/s !)





S. Vaupré et al.: Cosmic-ray induced ionization of a molecular cloud shocked by the W28 supernova remnant

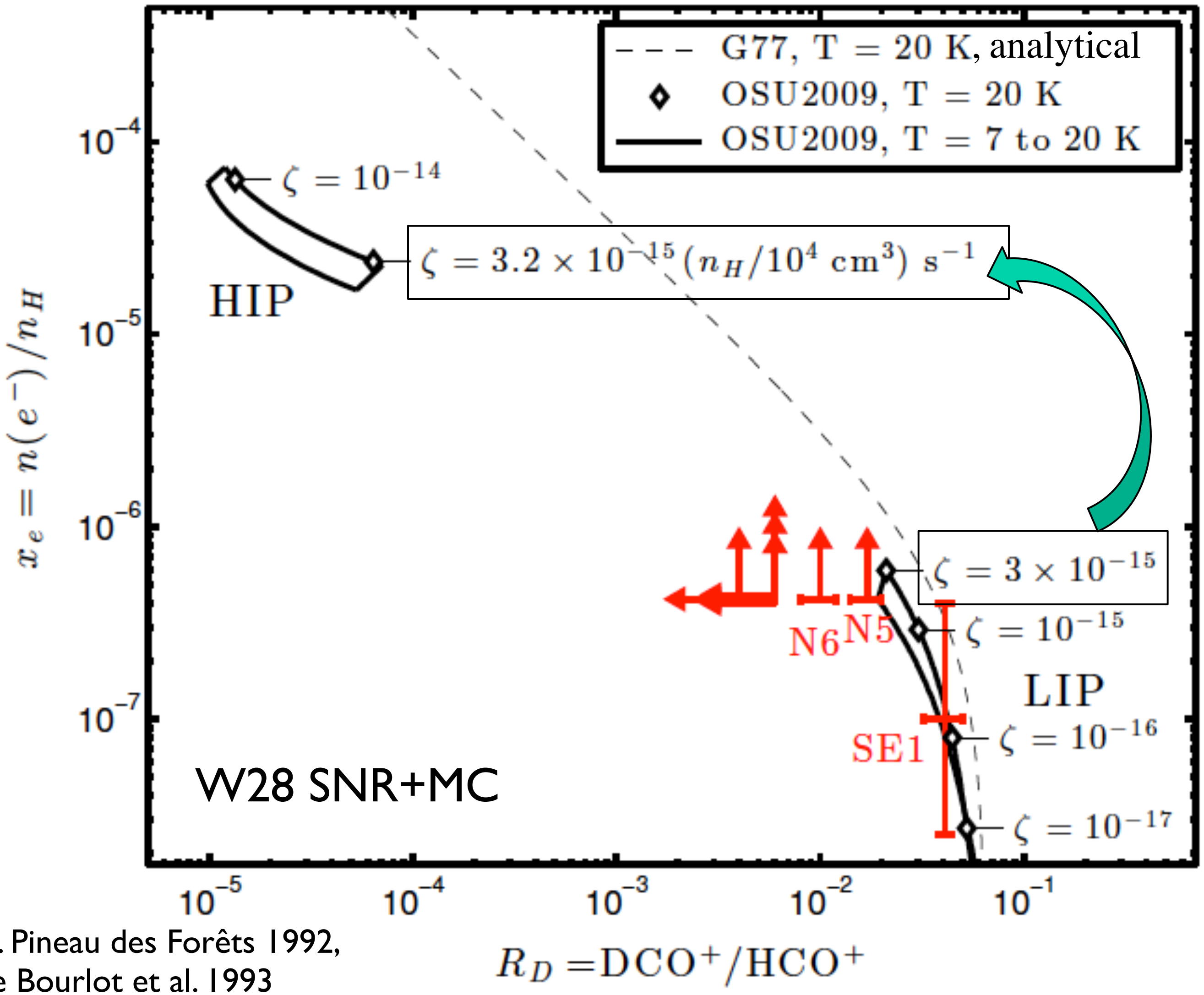
Table 5. Physical conditions and cosmic ray ionization rates.

Pos.	Δv [km s^{-1}]	n_{H_2} [10^3 cm^{-3}]	T_{kin} [K]	$N(\mathrm{C}^{18}\mathrm{O})$ [10^{15} cm^{-2}]	A_V [mag]	$N(\mathrm{H}^{13}\mathrm{CO}^+)$ [10^{12} cm^{-2}]	$N(\mathrm{DCO}^+)$ [10^{12} cm^{-2}]	$R_D = \frac{[\mathrm{DCO}^+]}{[\mathrm{HCO}^+]}$	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	>13
N5	3.0	4 $\{2-5\}$	10 ± 2	3 $\{2-8\}$	16 $\{11-32\}$	$1.1-1.4$	$0.89-1.30$	$0.014-0.020$	130 - 330
N6	3.0	4 $\{2-6\}$	13 ± 3	6 $\{4-20\}$	32 $\{21-105\}$	$1.8-2.5$	$0.79-1.30$	$0.008-0.012$	130 - 400
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	-	-
SW4†	1.5	6 $\{4-10\}$	16 ± 2	1.5 $\{1-3\}$	5 $\{5-16\}$	$0.5-0.8$	<0.25	<0.009	-

Note - n_{H_2} is the molecular hydrogen density (cm^{-3}), T_{kin} the gas kinetic temperature, $N(\mathrm{C}^{18}\mathrm{O})$ the total column density of $\mathrm{C}^{18}\mathrm{O}$. A_V is the visual extinction assuming $[\mathrm{C}^{18}\mathrm{O}] = A_V \times 1.9\ 10^{14}$ cm^{-2} (Frerking et al. 1982; Bolatto et al. 2013). We assumed isotopic ratio values $^{18}\mathrm{O}/^{16}\mathrm{O} = 500$ and $^{13}\mathrm{C}/^{12}\mathrm{C} = 50$ (see text). Values between brackets indicate the range of values satisfying $\chi^2_\nu < 1$. Uncertainties on n_{H_2} and T_{kin} are at the 70% confidence level, and are propagated in the abundance ratios and upper limits. Lower limits of ζ were deduced from chemical modeling (see section §6).

† N2 and SW4 are probably ionized by another source than CR (see text).

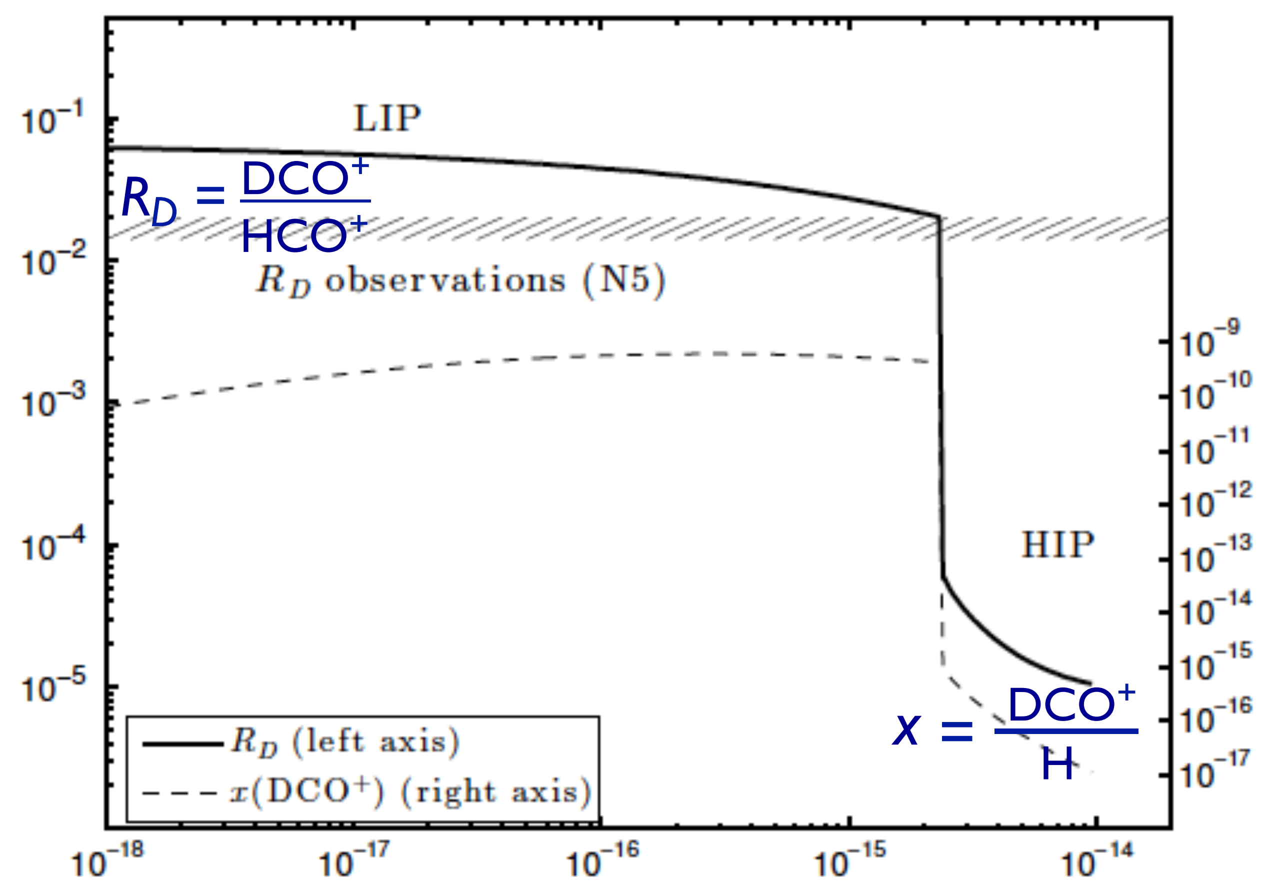
Results for W28: first evidence for « High Ionization Phase » regions



cf. Pineau des Forêts 1992,
Le Bourlot et al. 1993

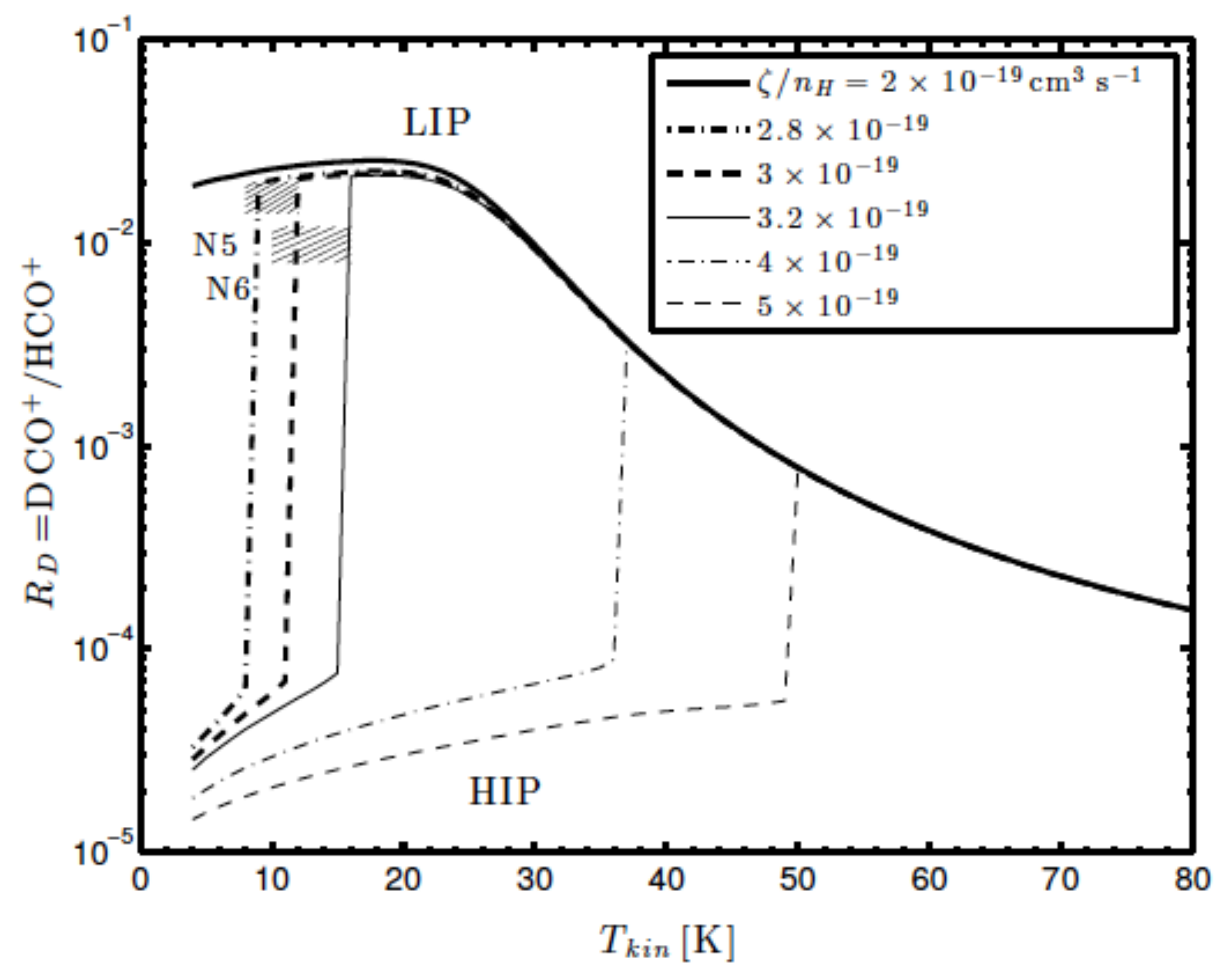
The collapse of DCO^+ *at high ionization* ($\zeta > 100\,\zeta_0$):

predicted instability in the chemical reactions network (non-linear change in charge carriers);

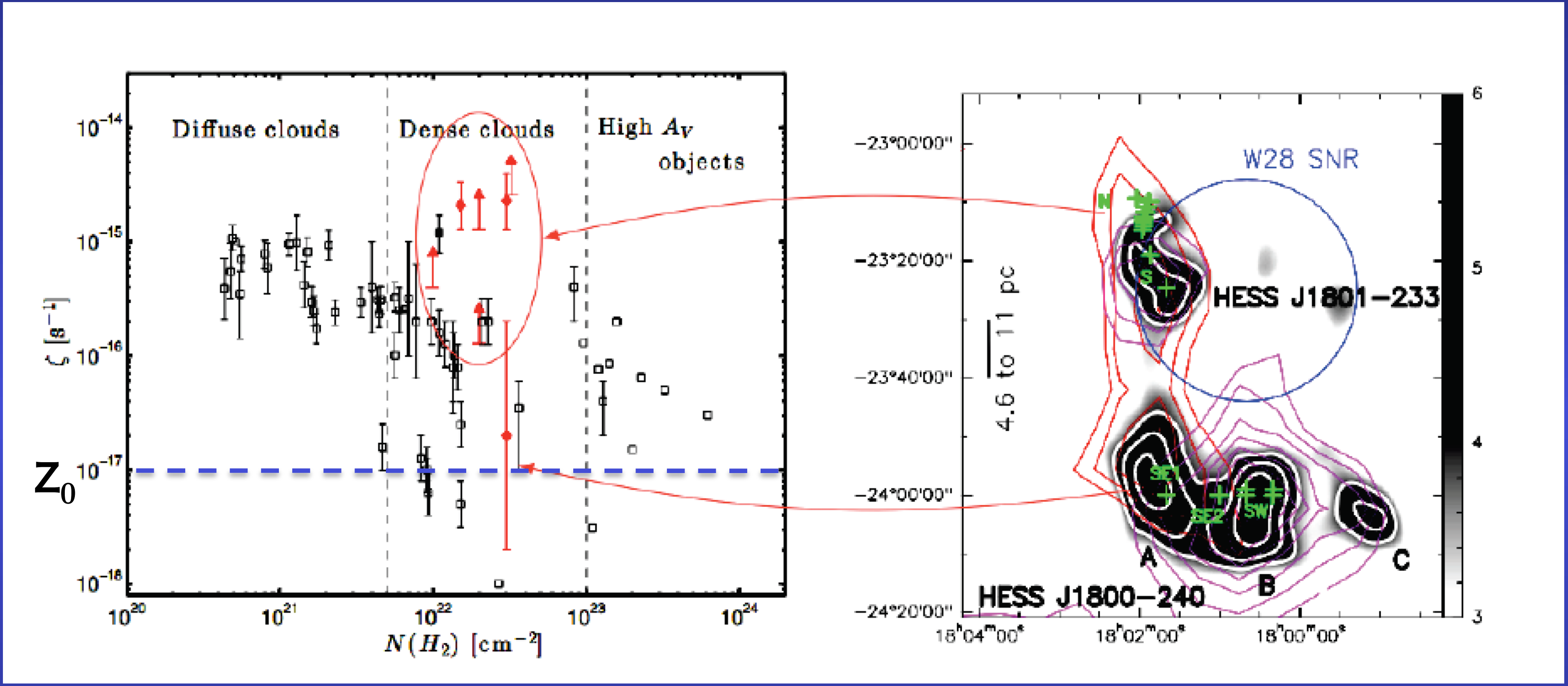


cf. Pineau des Forêts 1992,
Le Bourlot et al. 1993

HIP-LIP regimes as a function of T



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

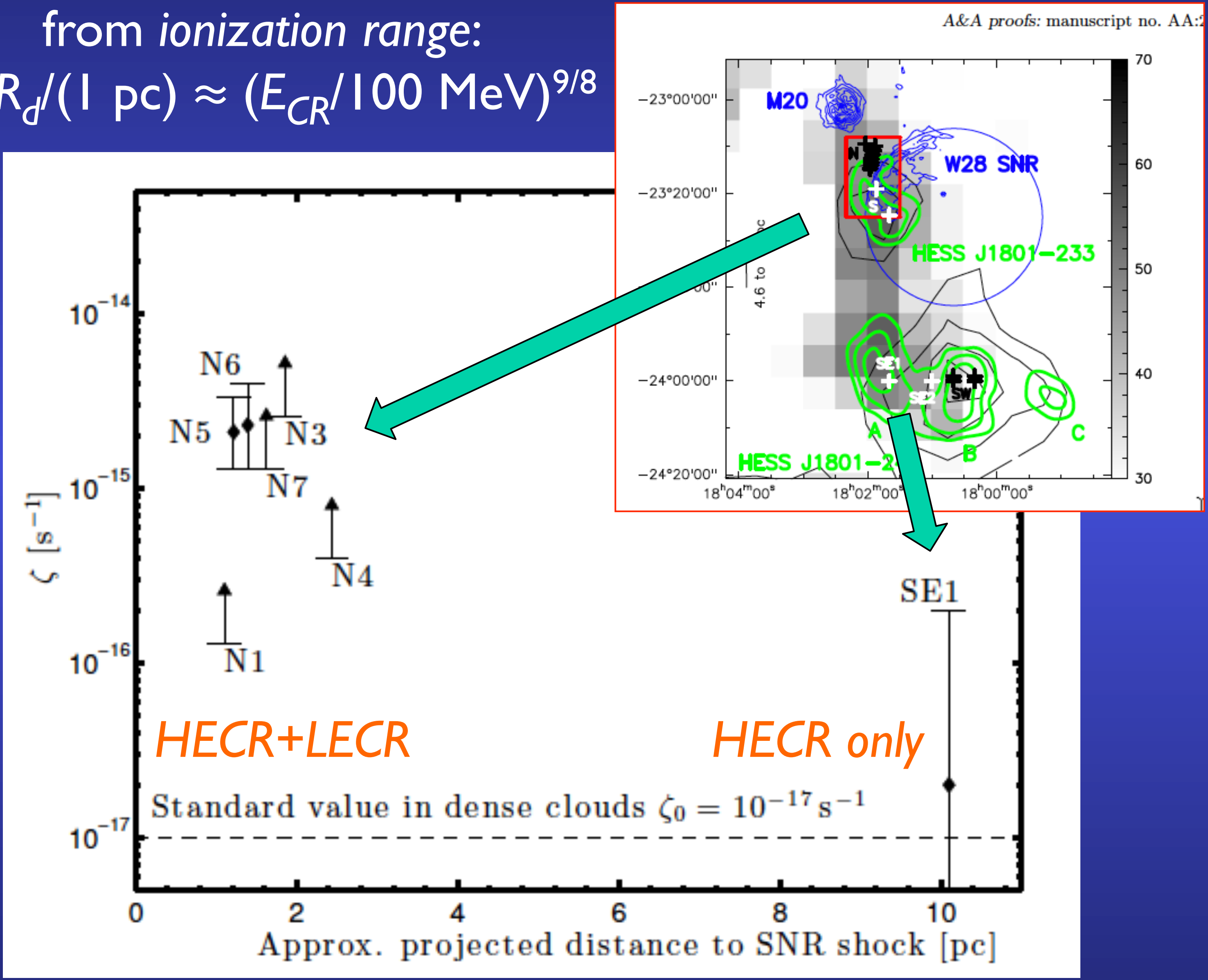


⇔ comparable to HECR enhancement from p^0-decay g-rays

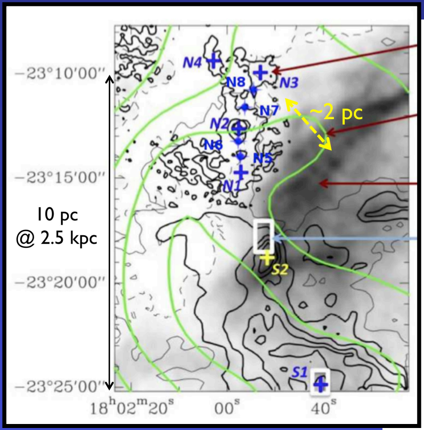
=> *constraints on CR acceleration/diffusion theories (DSA…)*

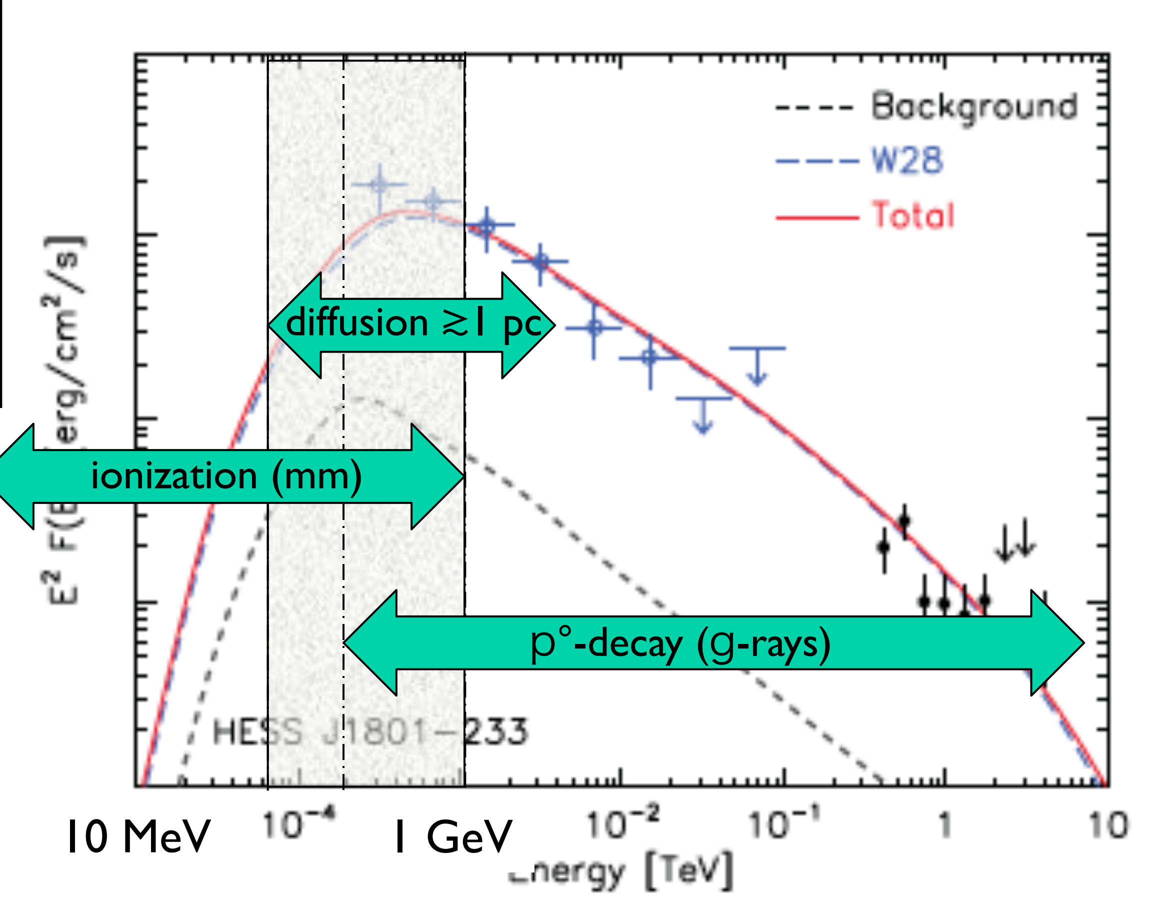
Constraints on CR diffusion from *ionization range*:

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



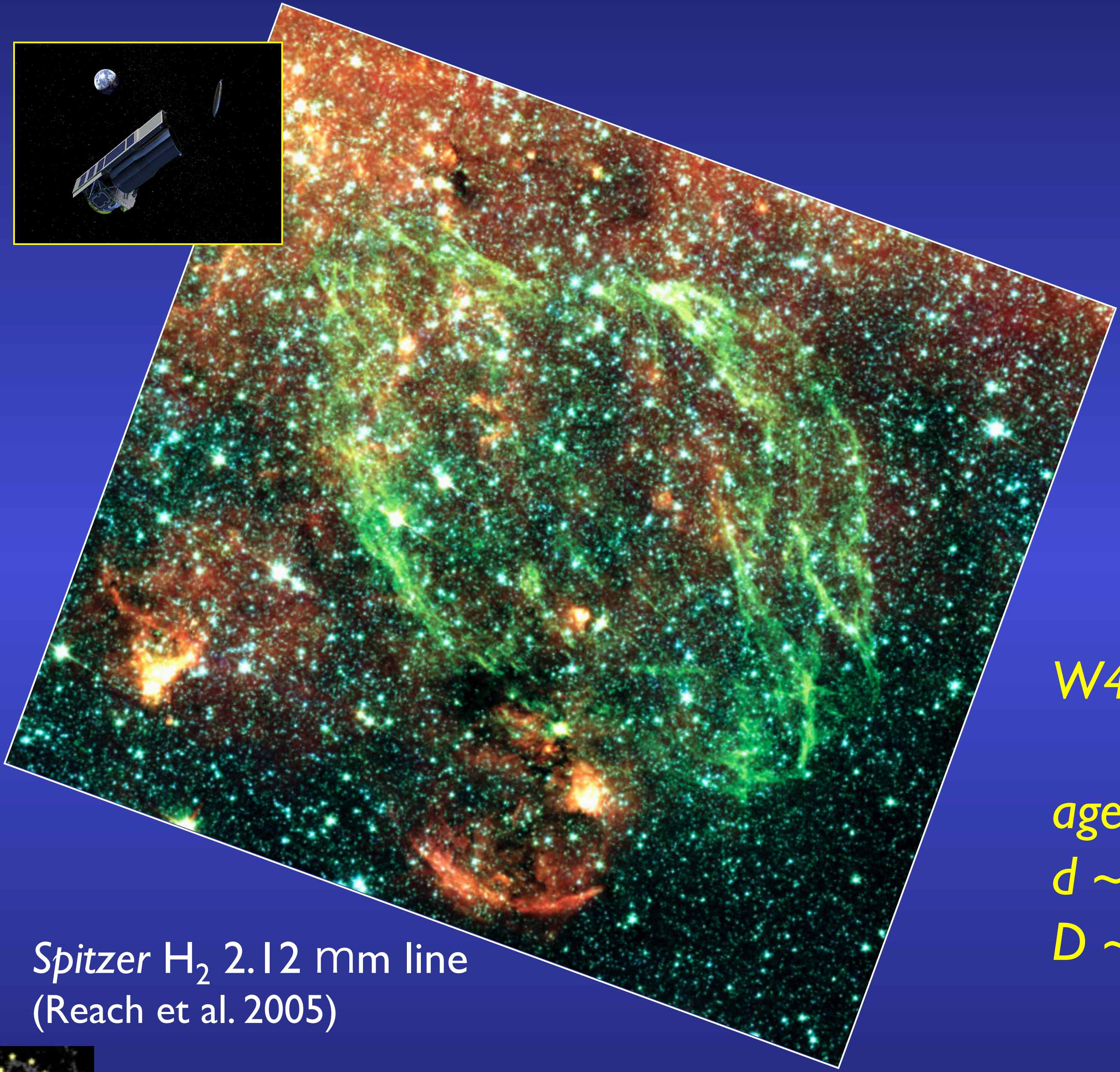
Upstream of the W28 SNR shock: probing cosmic rays





cosmic-ray energy

Next step: connecting low- and high-energy CR in W44 (obs. done)
+ new constraints on high-ionization interstellar chemistry



Spitzer H_2 2.12 mm line
(Reach et al. 2005)

W44 SNR

age ~ 20 000 yrs
d ~ 3 kpc
D ~ 20 pc

SNR W44

- Age ~20,000 yr
  <u>= Middle-aged SNR)</u>
  (e.g.,Harrus et al. 1997)

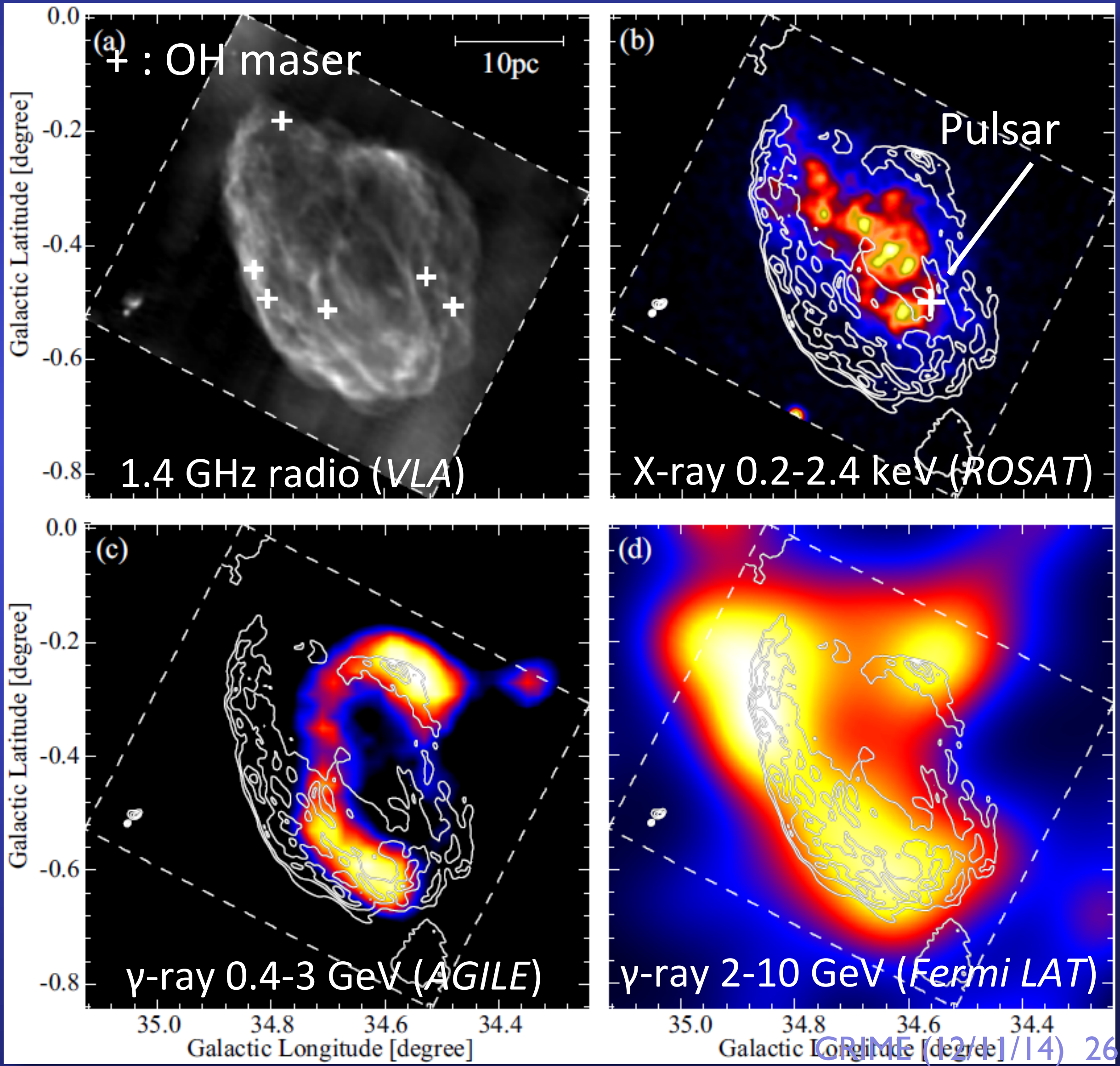
- Distance ~ 3 kpc
  (e.g.,Caswell et al. 1975)

- OH Maser (Shock tracer)
  (Claussen et al.1997)

- Interaction with Molecular and Atomic Gas
  (Seta et al.1998,2004;
  Koo & Heiles 1995)

- <u>GeV γ-rays</u>
  (Abdo et al. 2010;
  Giuliani et al.2011)

- No TeV g-rays



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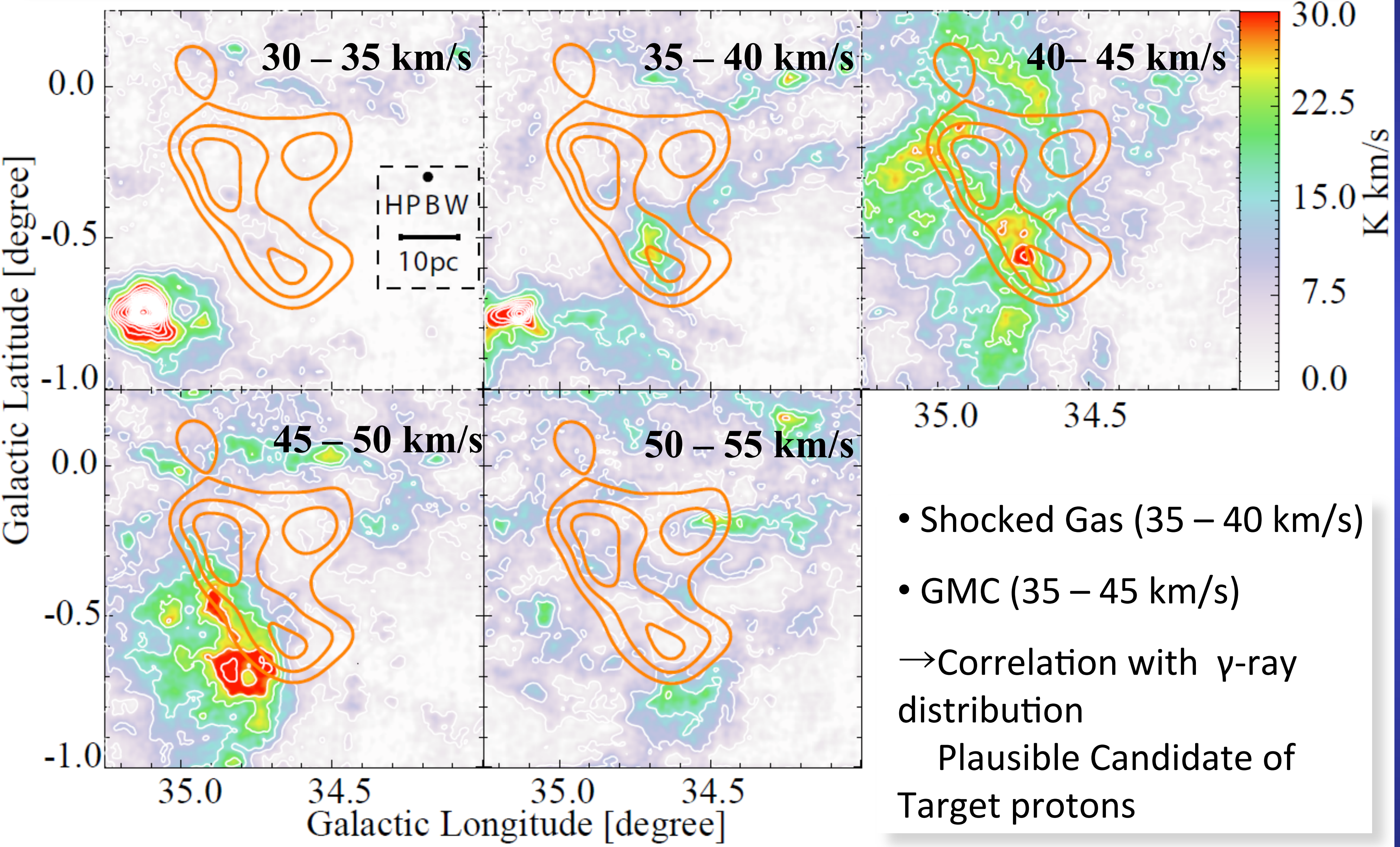
Molecular Gas vs γ-ray



- Shocked Gas (35 – 40 km/s)
- GMC (35 – 45 km/s)

→Correlation with γ-ray distribution

Plausible Candidate of Target protons

- Image … ^{12}CO(J=2-1)
- Contours … 400 MeV – 3 GeV (*Fremi LAT*)

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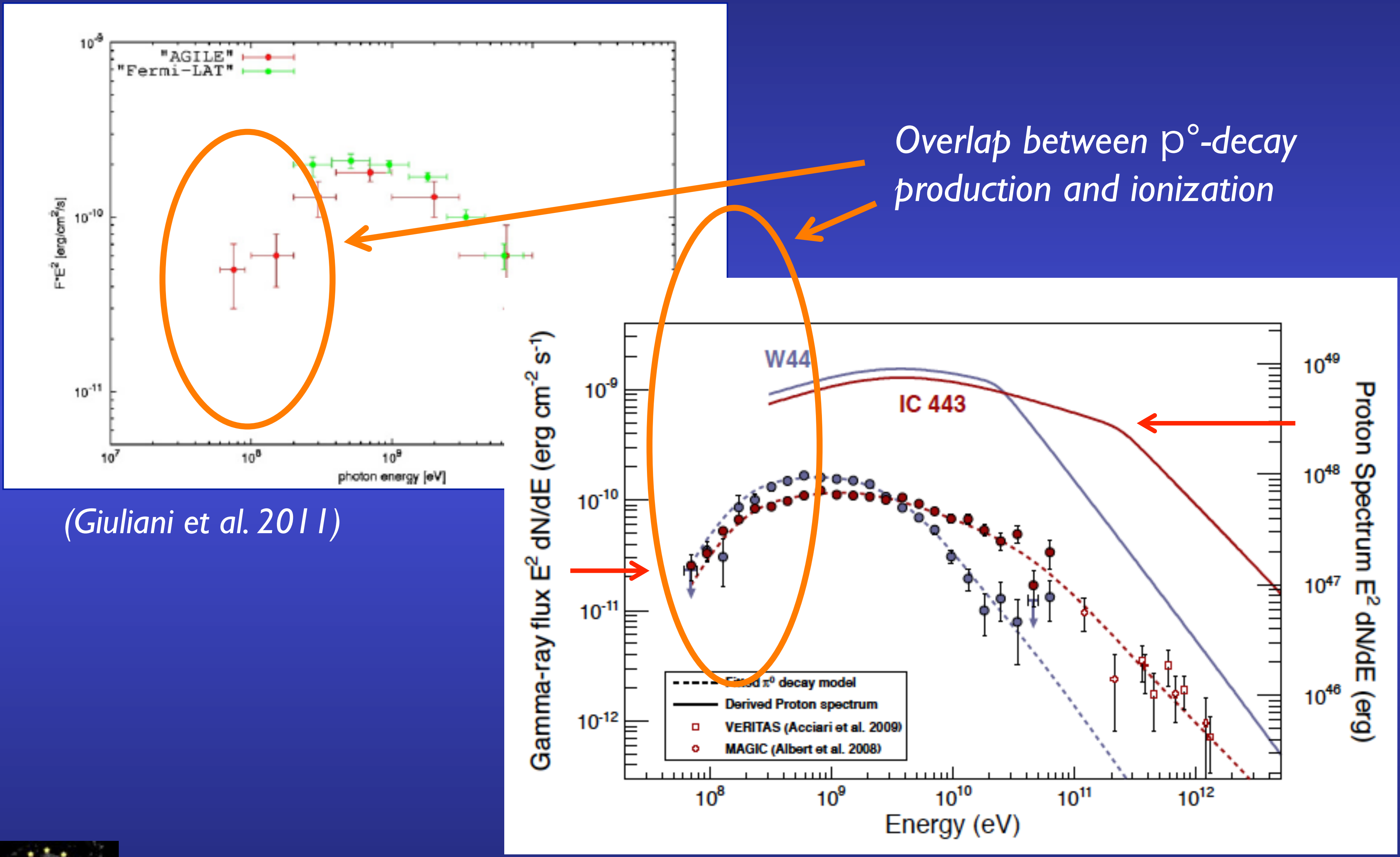
The g-ray spectrum of W44 is well fitted by a p°-decay, but…



Overlap between p°-decay production and ionization

(Giuliani et al. 2011)

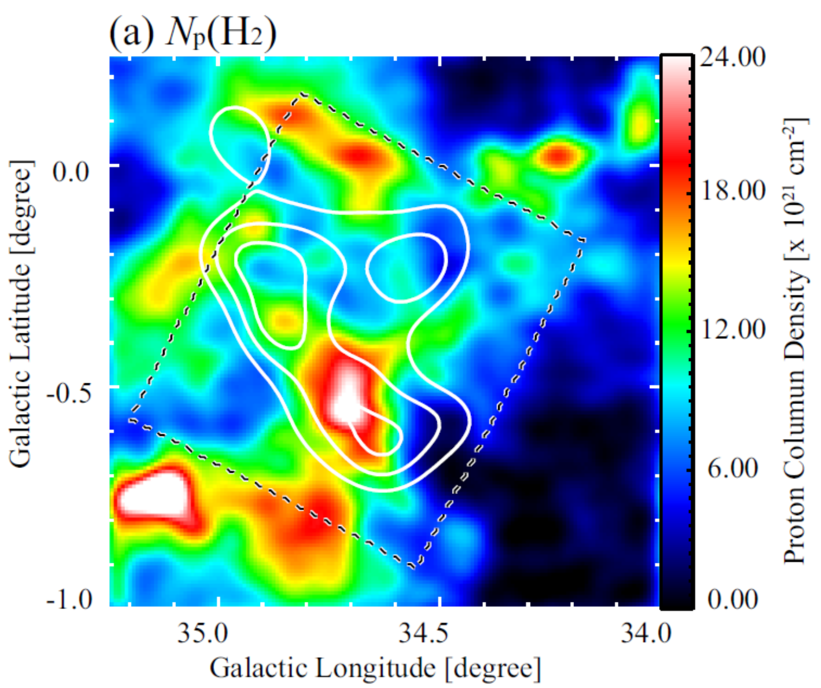
(Ackermann et al. 2013)

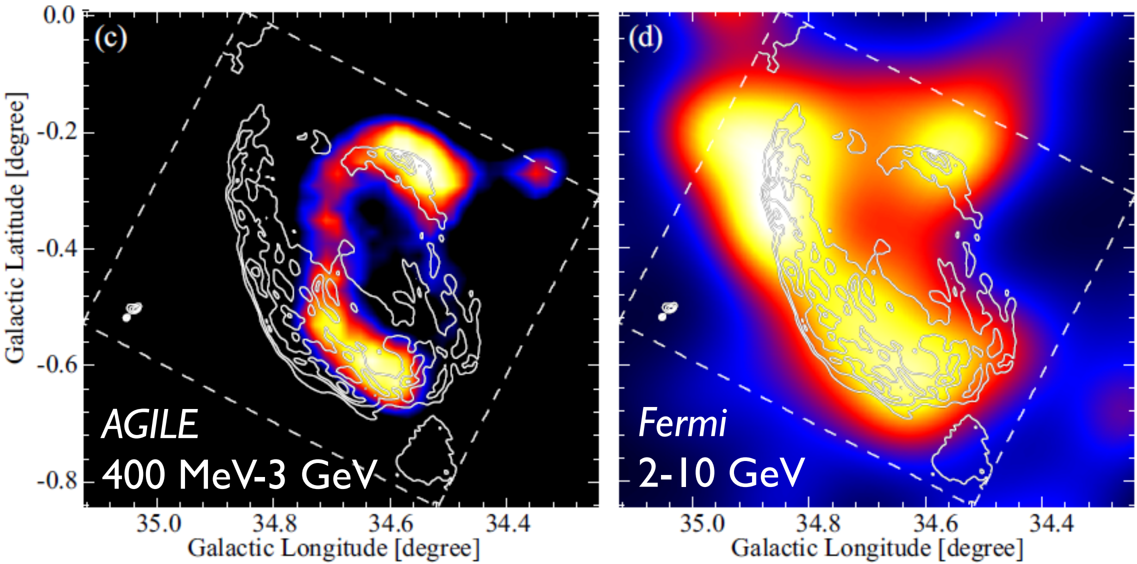
Can the distribution of matter really explain the spatial g-ray emission of W44 ?

(see later)

Evidence for "crushed clouds" inside the remnant ?

(Uchiyama et al. 2012)



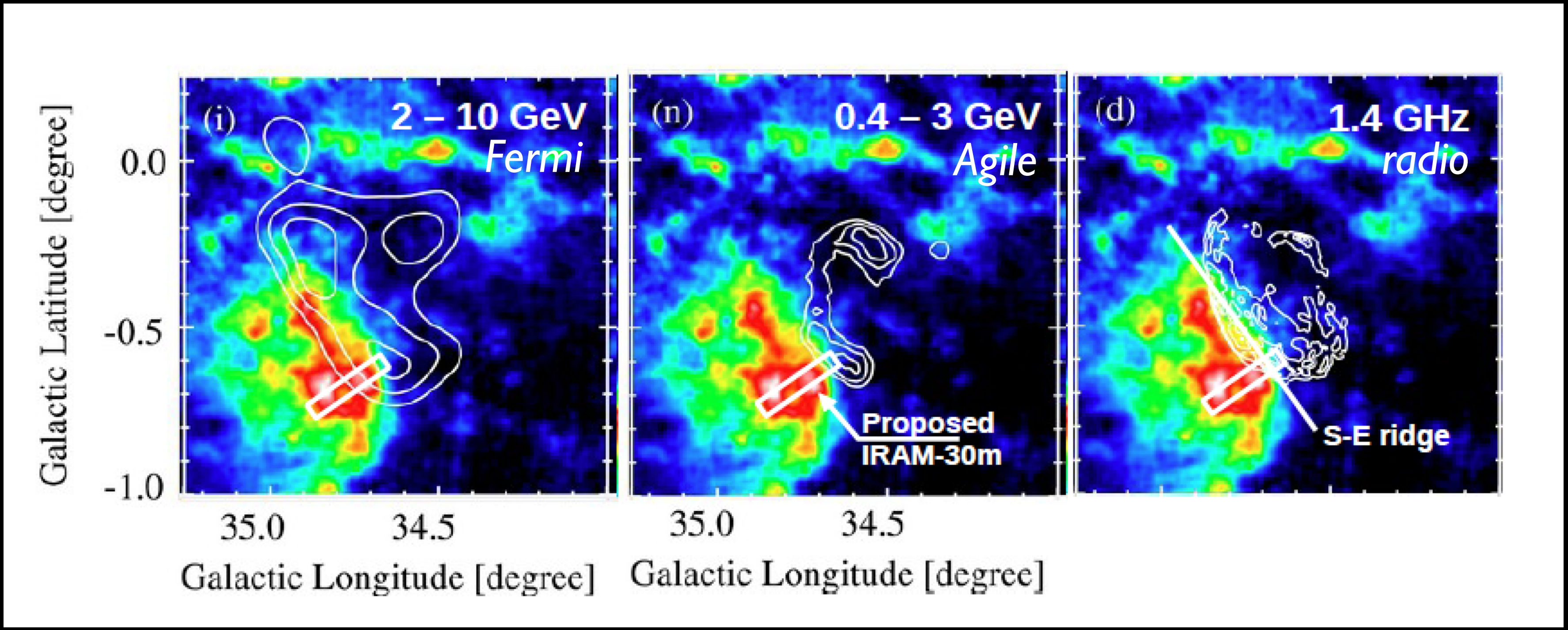


AGILE
400 MeV-3 GeV

Fermi
2-10 GeV

IRAM 30-m observations of W44:

Done in September, analysis in progress

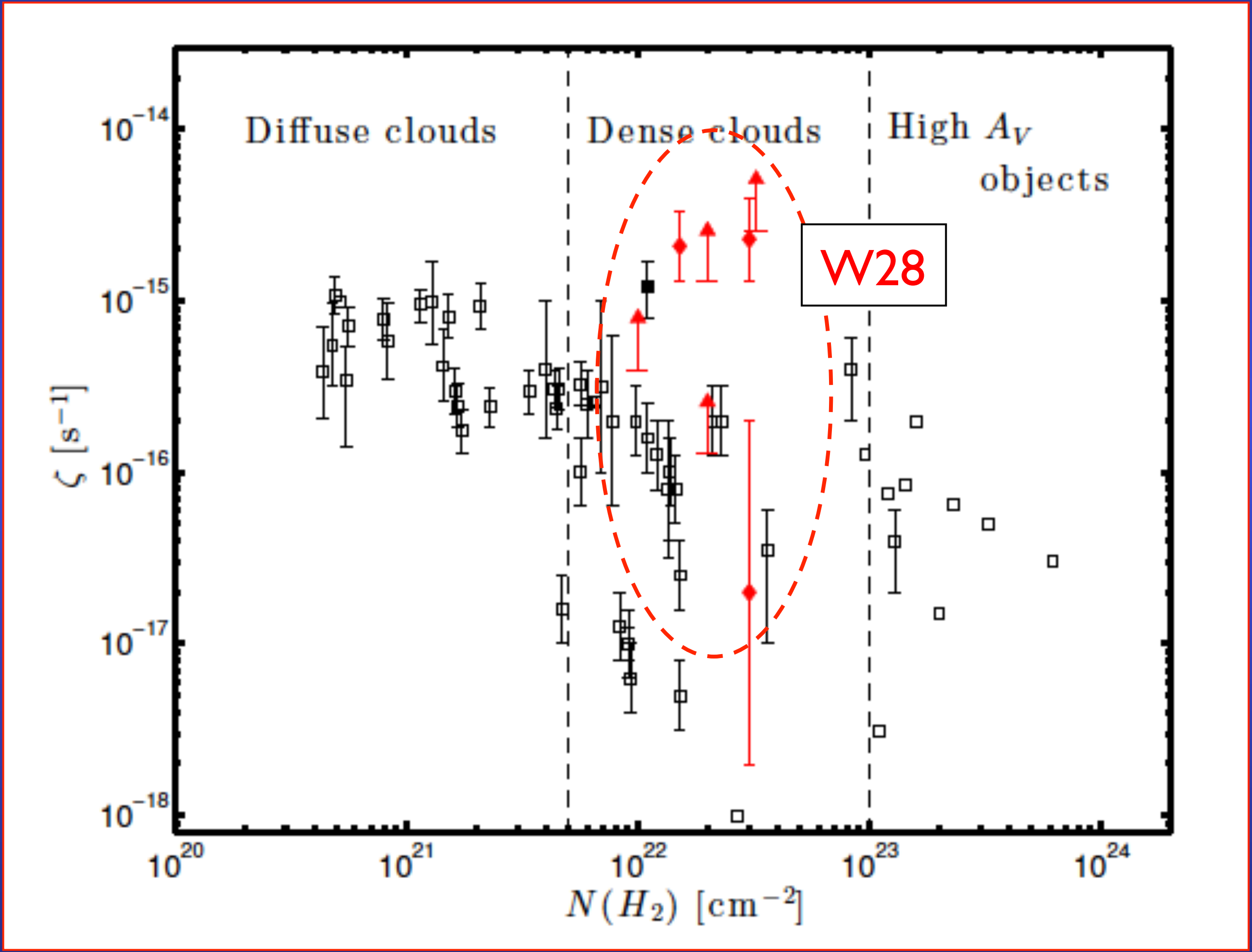


Conclusions

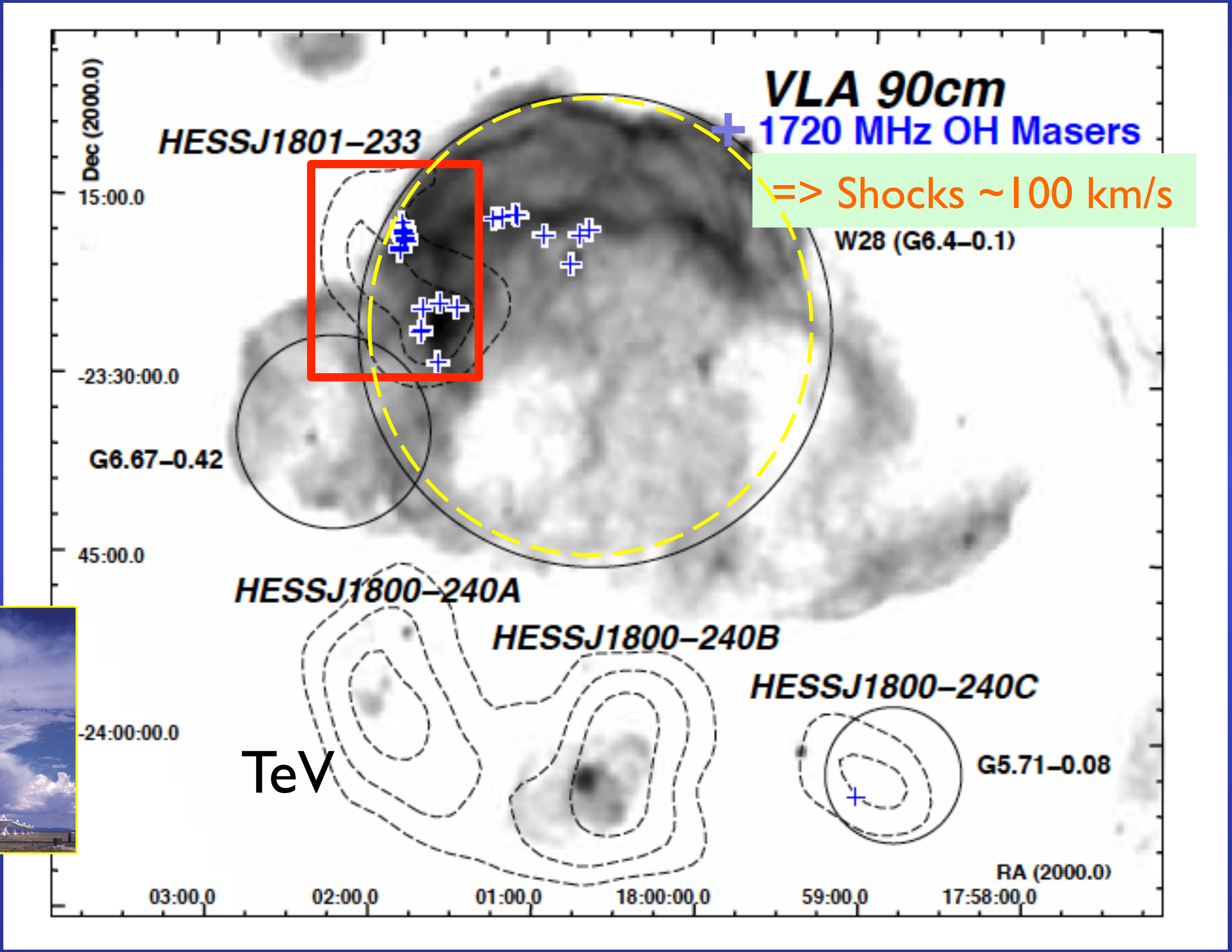
- A class of GeV-TeV g-ray sources is definitely associated with SNRs physically interacting with molecular clouds
- There is mounting evidence that the g-ray emission is dominated by HECR ($\gtrsim$ 10 GeV/n hadrons: evidence for p°-decay)
- This is confirmed by new chemical evidence for ~ *x10-100 overionization* of the same molecular clouds by LECR ($\lesssim$ 1-500 MeV)
  - Such TeV sources are unique *chemical and physical laboratories* for molecular clouds !

  - First observational evidence for HIP/LIP regime in *astrochemistry*
  - First observational evidence that LECR are the main *ionization* agent ⇔ first observational evidence of *acceleration of low-energy hadrons* by an SNR shock
  - First observational evidence that *diffusion* of LECR upstream of the shock is (at least to first order) isotropic and consistent with theoretical estimates

Comparison with "average" molecular clouds



W28 SNR: non-thermal radio emission + OH masers



=> Shocks ~100 km/s

TeV

Nicholas et al. 2011