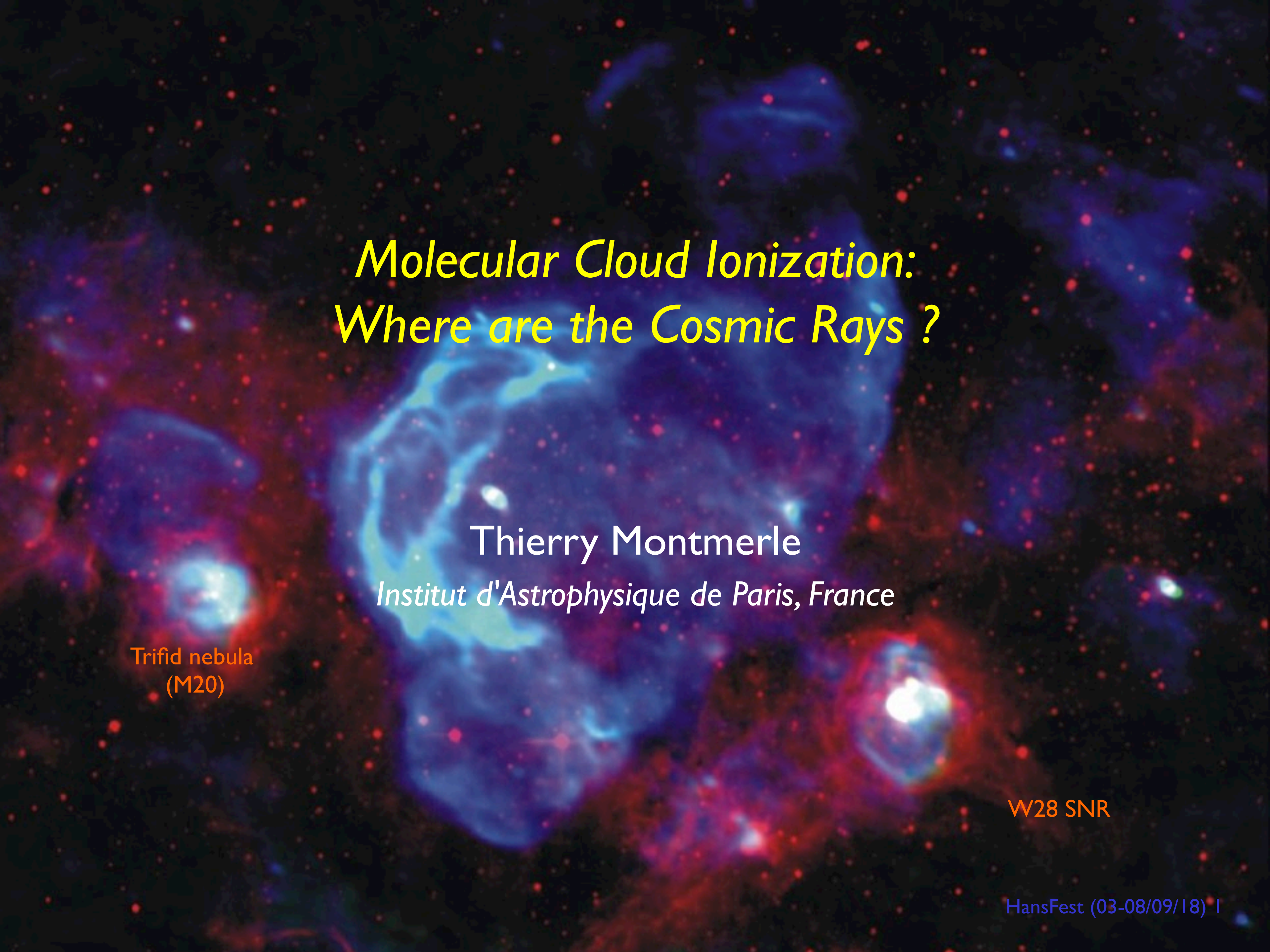
Molecular Cloud Ionization: Where are the Cosmic Rays ?

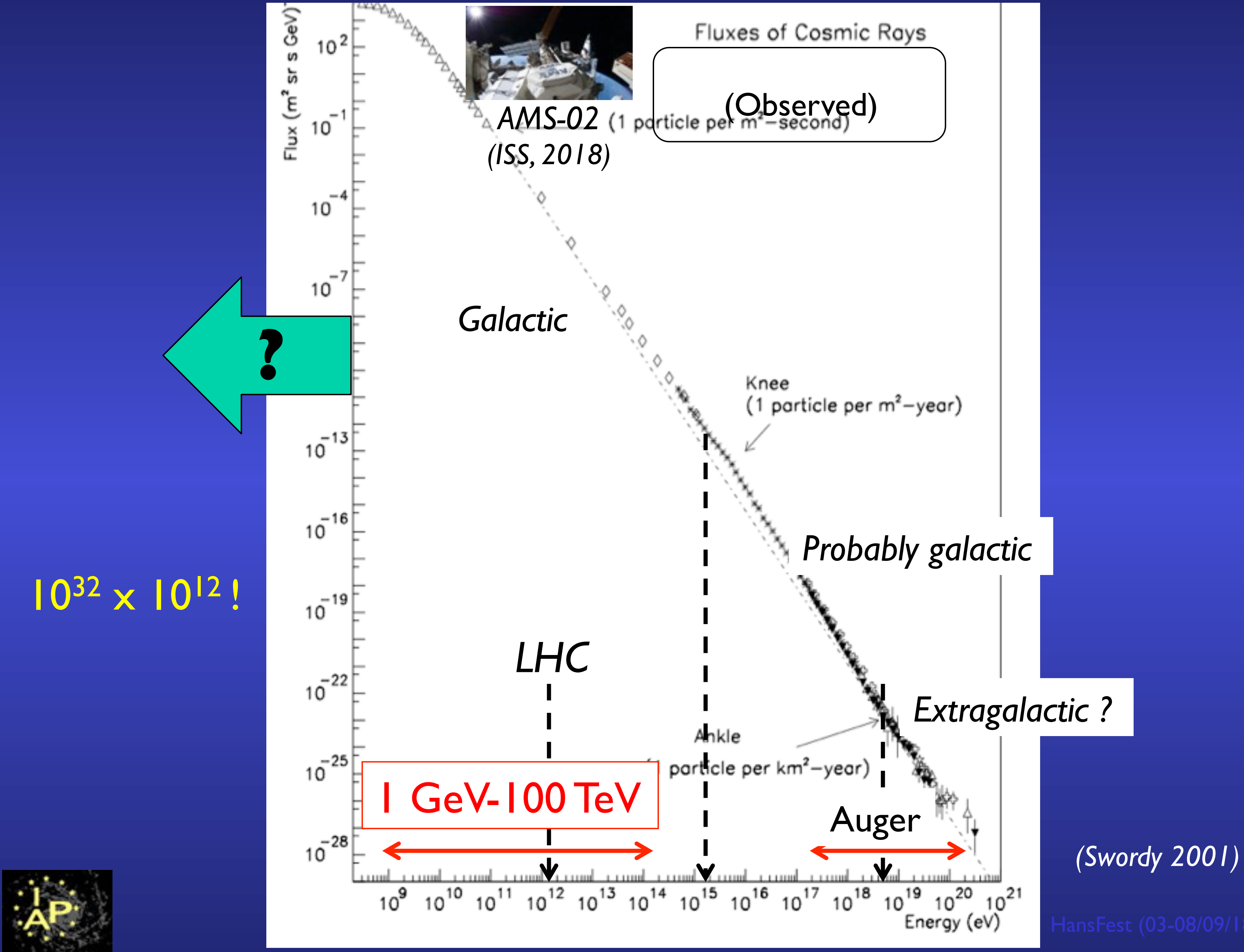
Thierry Montmerle
Institut d'Astrophysique de Paris, France



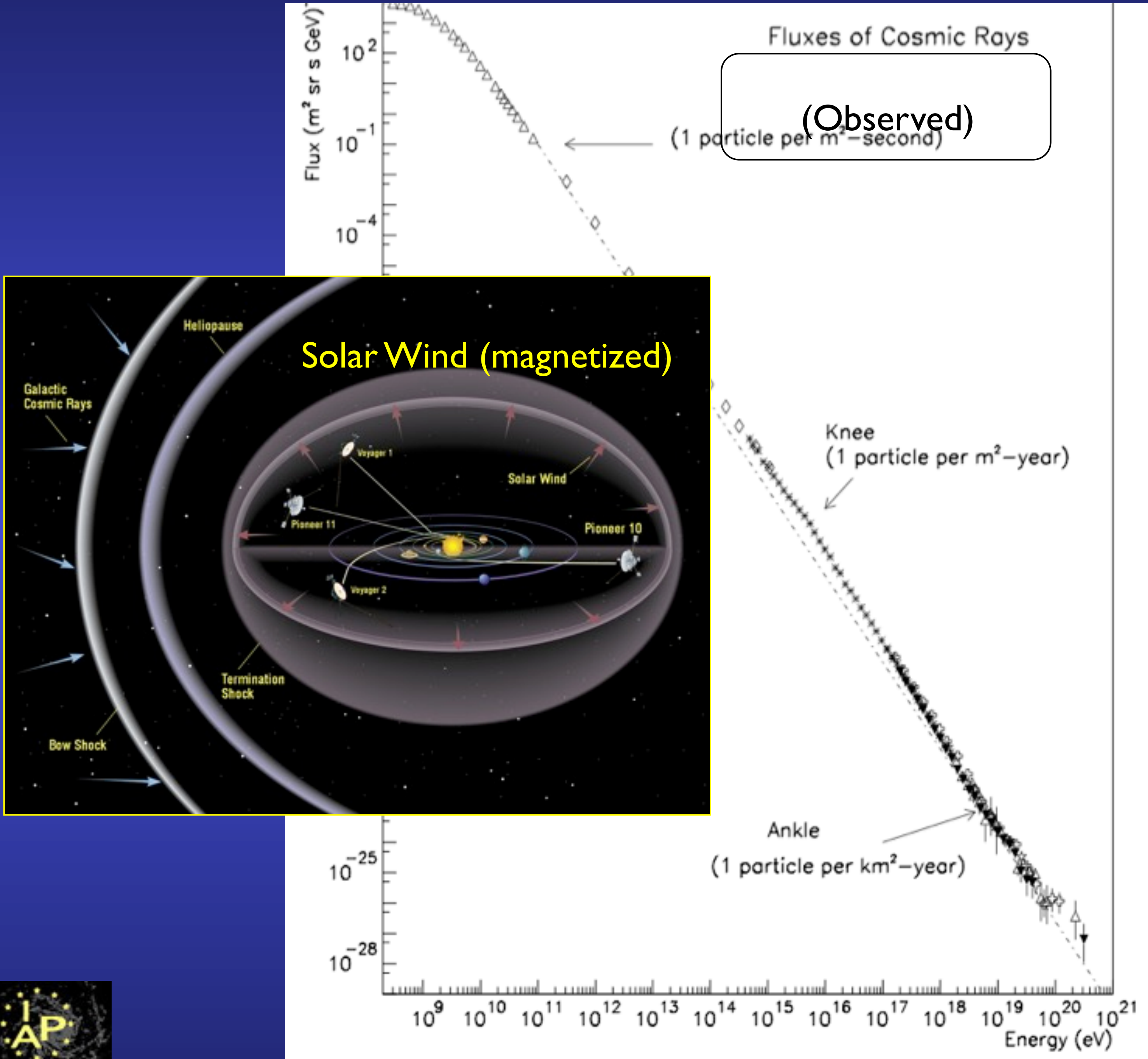
Outline

1. Cosmic Rays in a nutshell
2. Importance of low-energy cosmic rays
3. Bridging low and high energies
4. Concluding remarks

1. Cosmic Rays in a nutshell



Fluxes of Cosmic Rays
(Observed)
AMS-02 (1 particle per m²–second)
(ISS, 2018)
Galactic
?
Knee
(1 particle per m²–year)
Probably galactic
LHC
Extragalactic ?
Ankle
(1 particle per km²–year)
1 GeV-100 TeV
Auger
Flux (m² sr s GeV)⁻¹
Energy (eV)
10^{32} x 10^{12} !
(Swordy 2001)



(Observed)

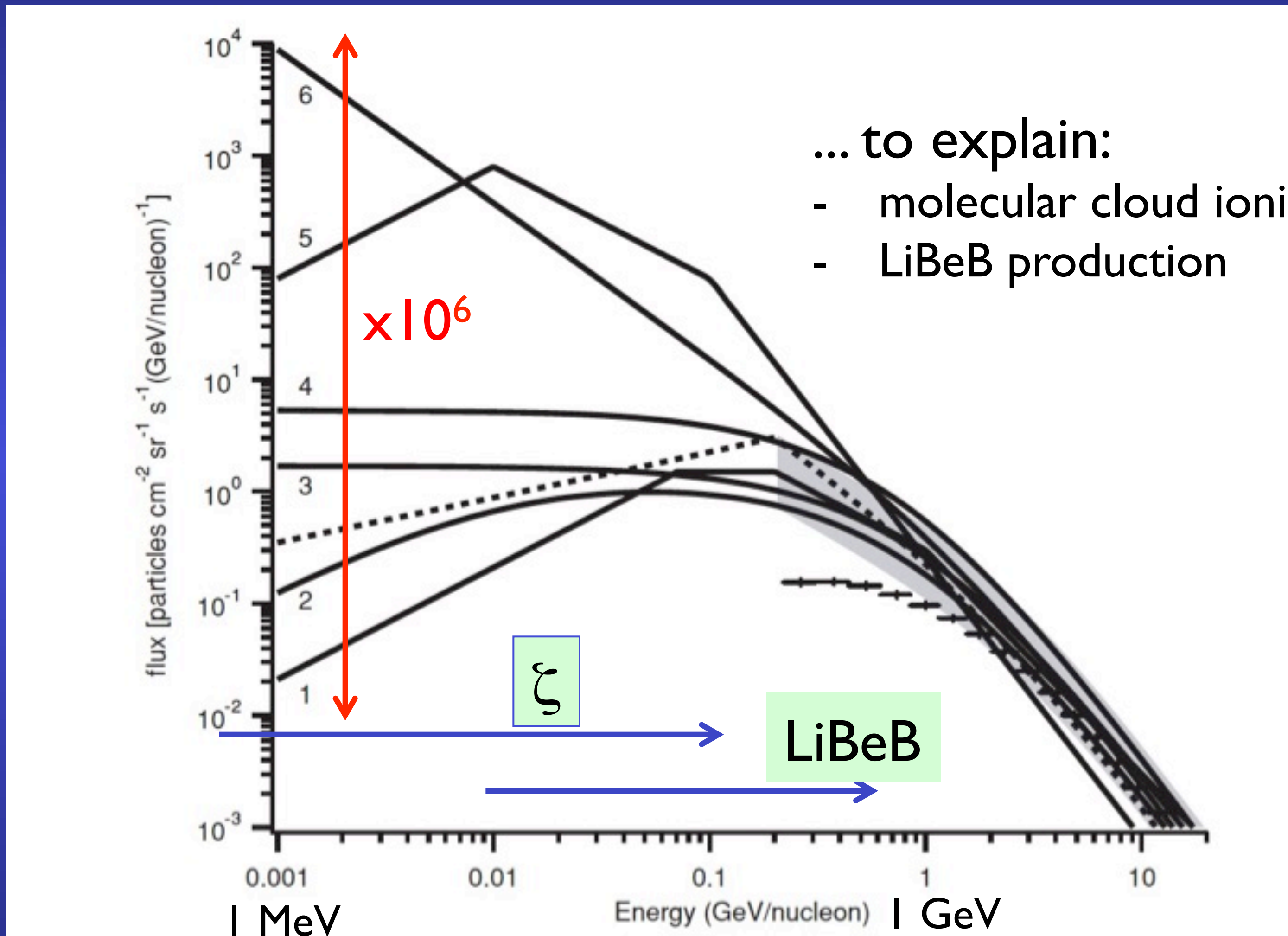
Solar Wind (magnetized)

(Swordy 2001)

Various proposed "demodulated" low-energy CR spectra

... to explain:

- molecular cloud ionization (ζ)
- LiBeB production



Indriolo+ 2009

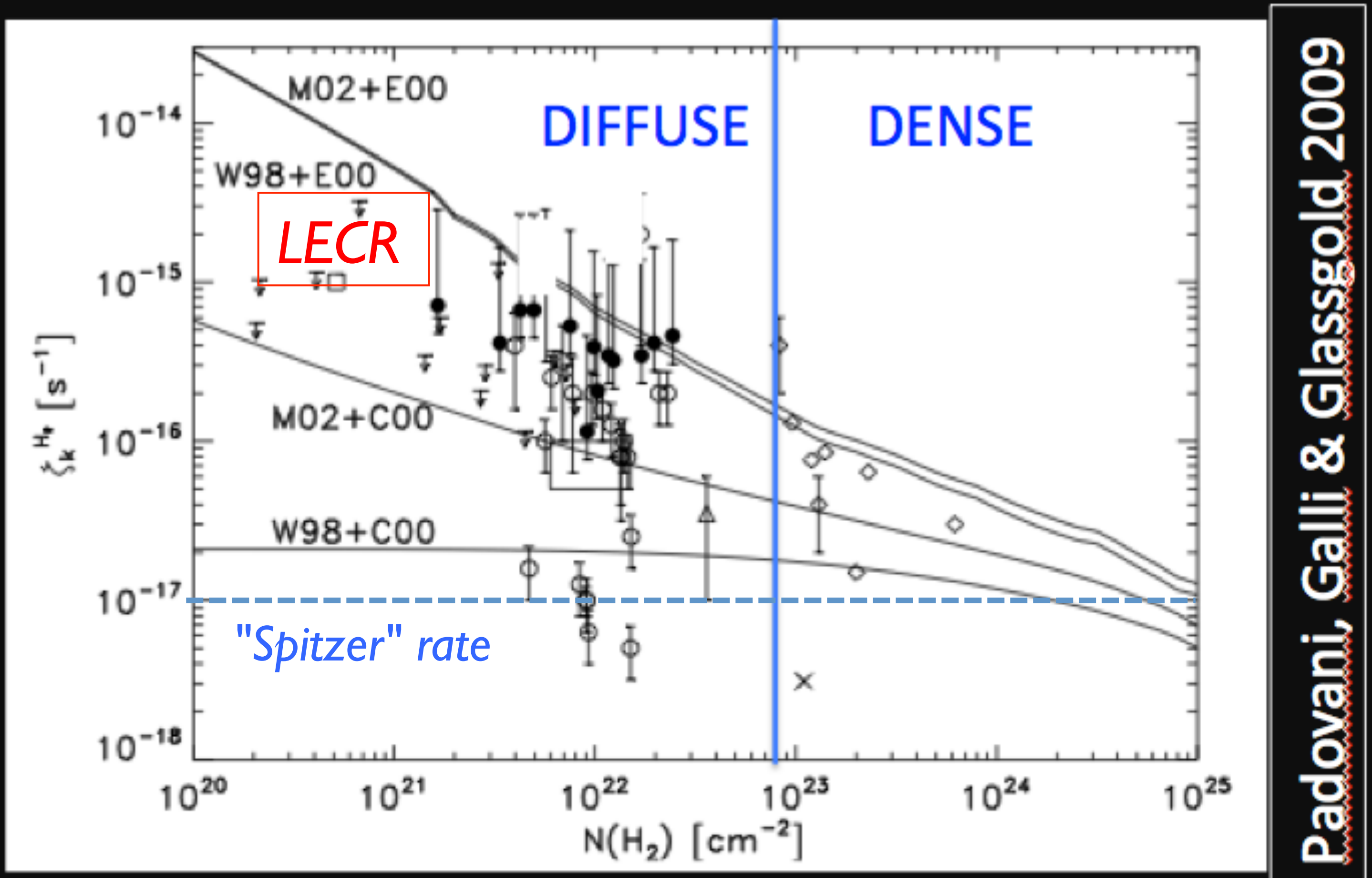
2. Importance of low-energy cosmic rays in the Galaxy

Low-energy cosmic rays (LECR)

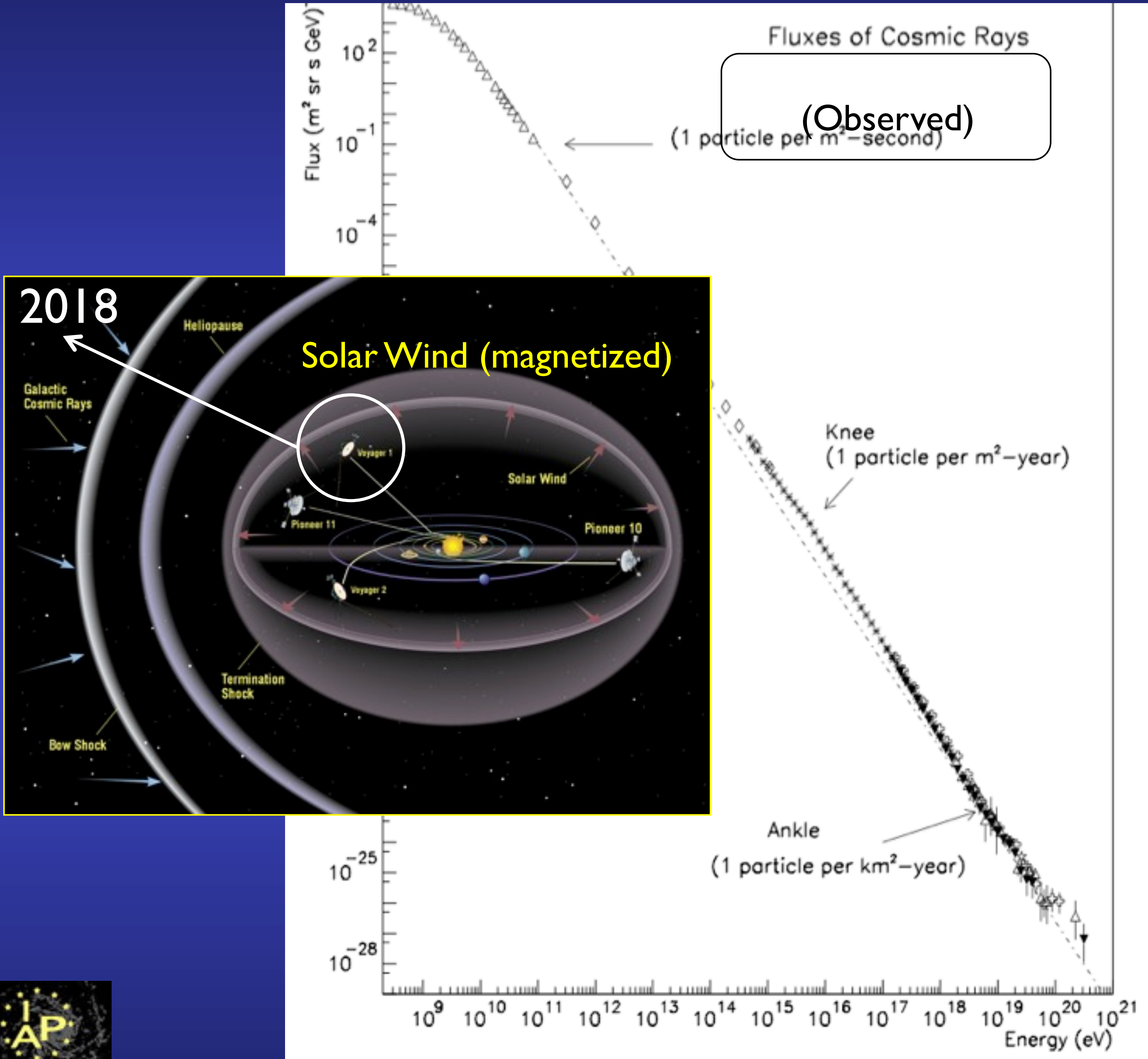
- Traditionally unknown spectrum and flux
  - solar modulation: $E_{CR} < 1$ GeV/n
  - *But new:* "Local Interstellar Spectra": Voyager 1 (Cummings et al. 2016),

    \+ propagation, etc. (Orlando 2017, Tatischeff+ 2018...)
- Tracing the first steps of (shock) acceleration ?
  - e.g., vicinity of SNRs
- *Important feedback effects* on (local) environment (e.g., molecular cloud chemistry; + electrons)
- Role in star formation (coupling "neutral" matter with ISM magnetic field)
  - => ionization rate ζ, units 10^{-17} s^{-1} ("Spitzer rate")
- => galactic distribution (from MC): ***new Voyager I data do not explain the observed rates !***

Ionization rate measurements (see later): Diffuse vs. Dense Clouds



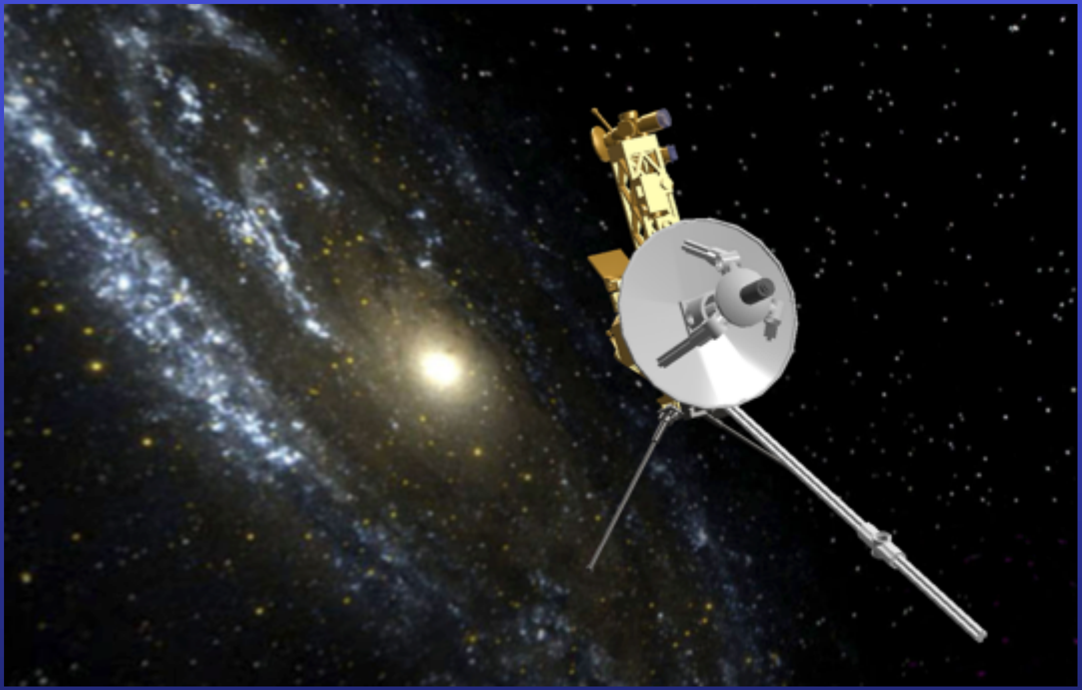
Diffuse clouds: $\zeta \approx 0.5\text{-}3 \times 10^{-16} s^{-1}$
Dense clouds: $\zeta \approx 0.1\text{-}5 \times 10^{-17} s^{-1}$

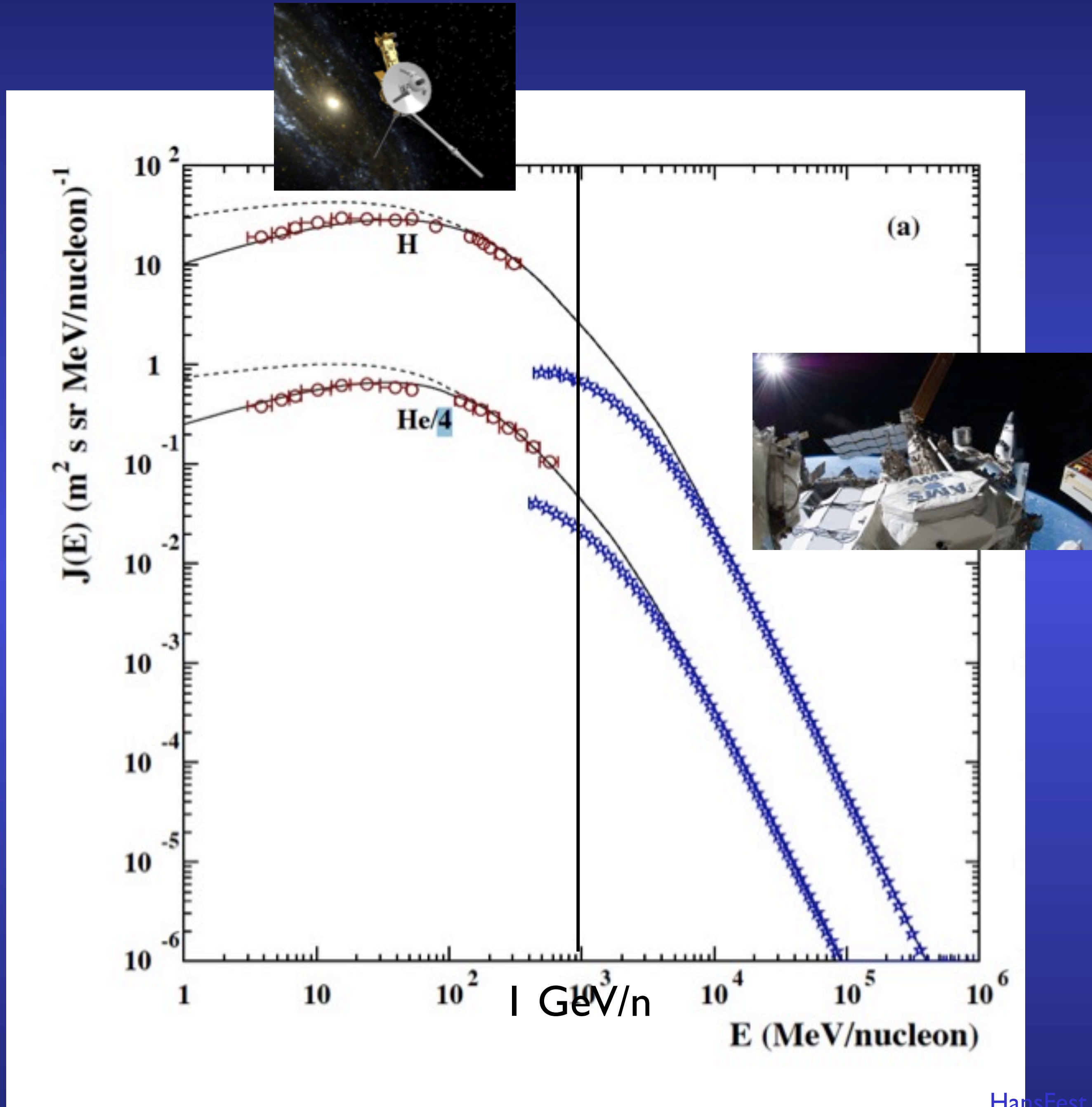

Fluxes of Cosmic Rays
(Observed)
(1 particle per m²−second)
Knee
(1 particle per m²−year)
Ankle
(1 particle per km²−year)
Flux (m² sr s GeV)⁻¹
Energy (eV)
10²
10⁻¹
10⁻⁴
10⁻²⁵
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
2018
Solar Wind (magnetized)
Heliopause
Galactic Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination Shock
Bow Shock

(Swordy 2001)

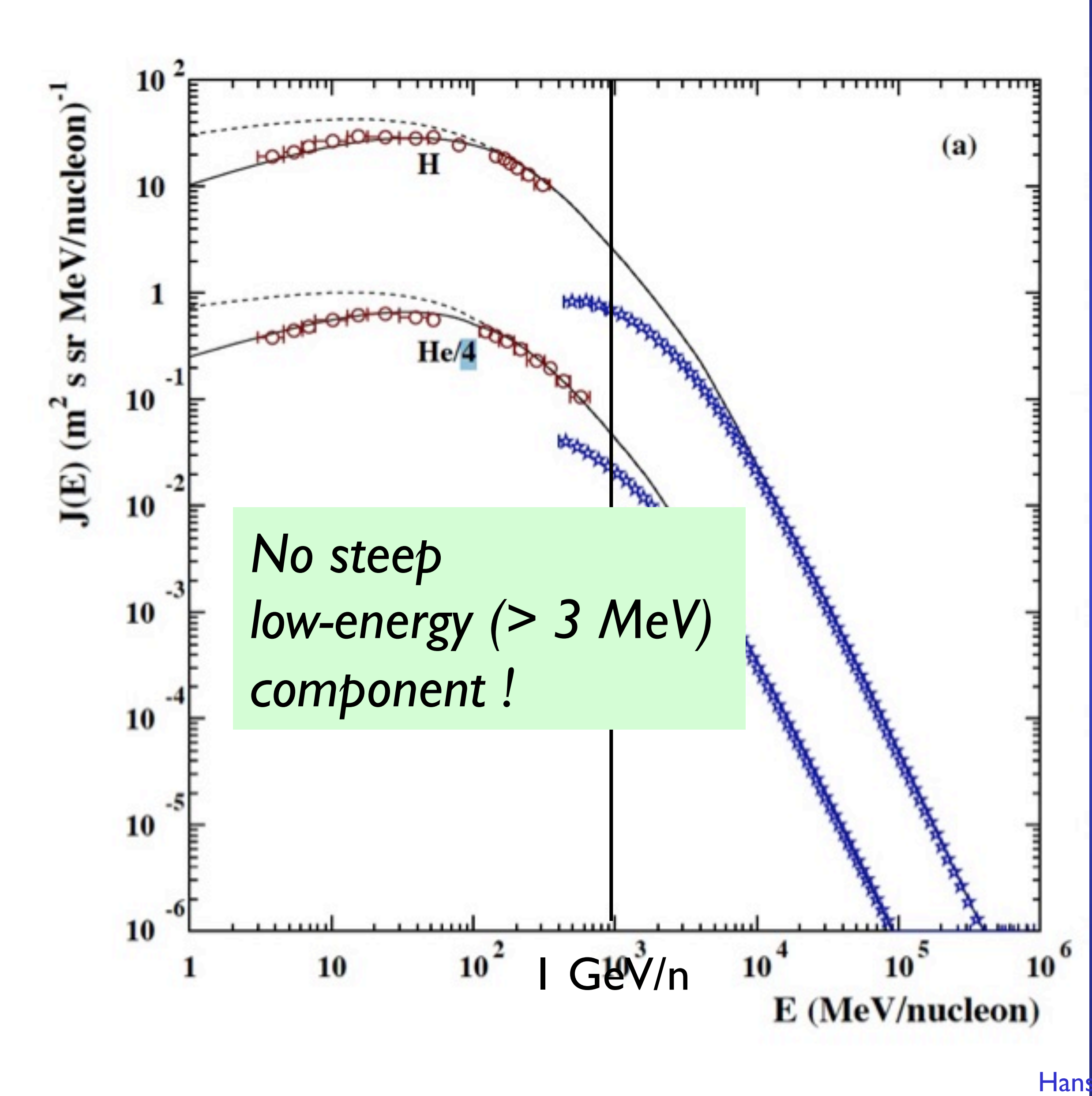
Voyager 1 @ 40 !

- Launched Sep.5, 1977
- Reached interstellar space (= beyond heliosphere) in Aug. 2012
- Engines re-started Dec.1, 2017 to re-orient the antennas
- *Now at >140 au from the Sun !*





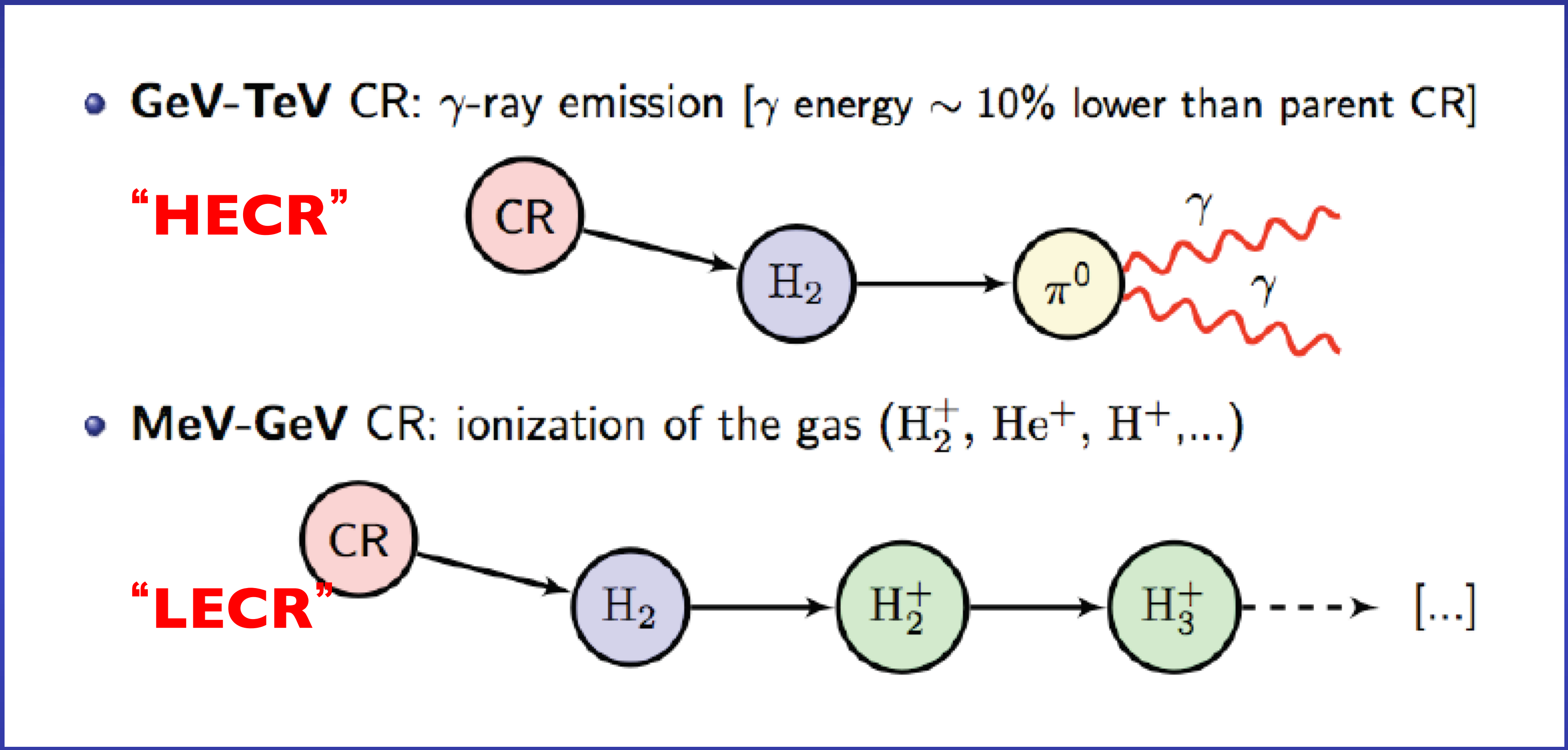
J(E) (m^2 s sr MeV/nucleon)$^{-1}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
(a)
H
He/4
1
10
10^2
10^3
10^4
10^5
10^6
1 GeV/n
E (MeV/nucleon)



J(E) (m² s sr MeV/nucleon)⁻¹
(a)
H
He/4
No steep
low-energy (> 3 MeV)
component !
1 GeV/n
E (MeV/nucleon)

3. Bridging low and high energies ?

In the Galaxy: Search for low-energy CR (LECR)
where evidence for elevated high-energy CR (HECR) flux



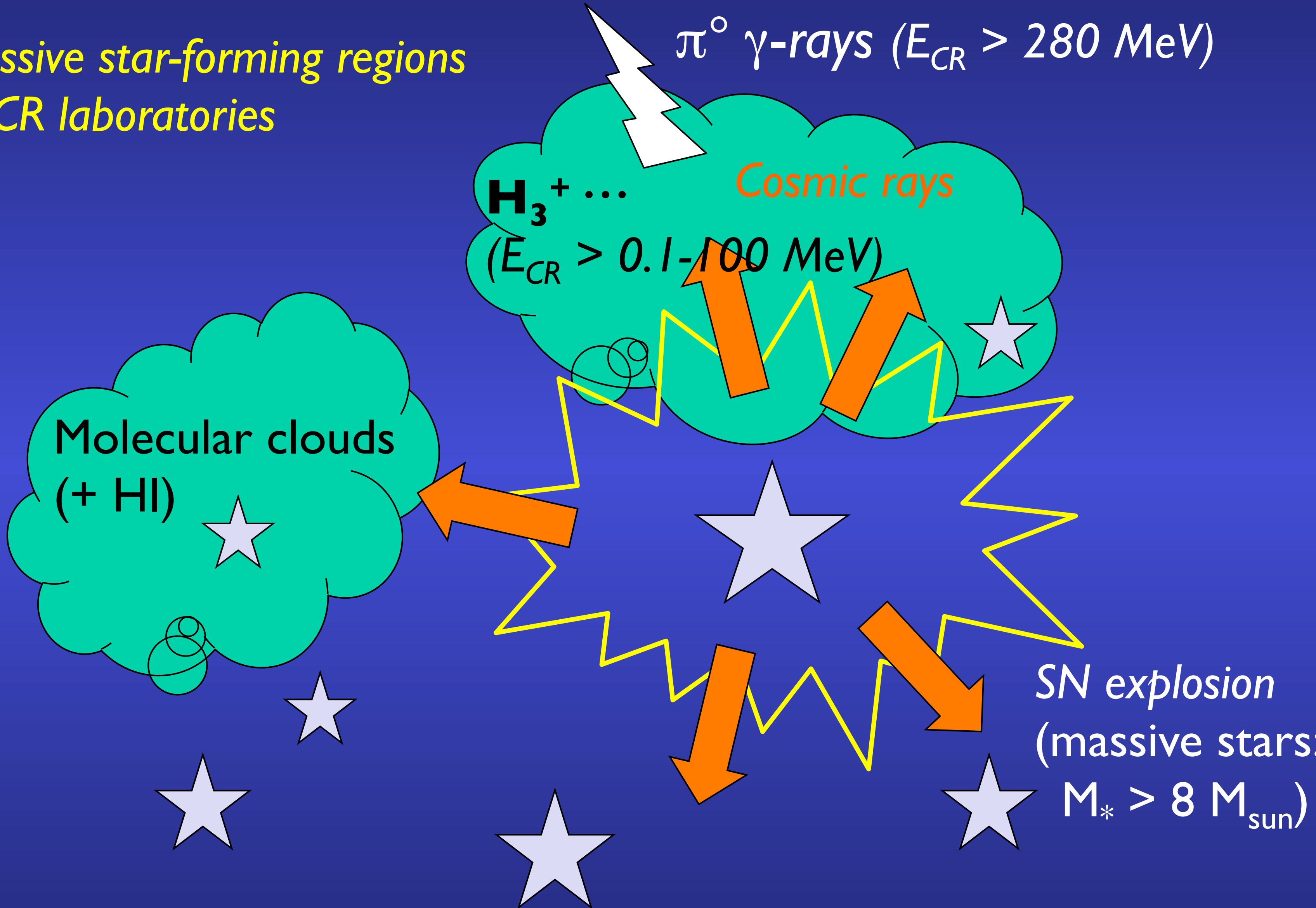
… by measuring and mapping the *ionization rate* ζ
of selected "active" molecular clouds (e.g., with SNR)
(fiducial value $\zeta_0 \sim 10^{-17}$ s^{-1} for the Galaxy: "Spitzer" rate; ionization *fraction* $\sim 10^{-7}$)

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)	$H_2D^+ + e^-$	$\xrightarrow{k_e}$	$H + H + D$ $H_2 + D$ $HD + H$	$k_e = 6.00\ 10^{-8}(T/300)^{-0.50}$
(#9)	$H_3^+ + e^-$	$\xrightarrow{\beta}$	$H + H + H$ $H_2 + H$	$\beta = 6.7\ 10^{-8}(T/300)^{-0.69}$
(#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)	$CO^+ + HD$	$\xrightarrow{k_{CO^+}}$	$DCO^+ + H$	$k_{CO^+} = 7.5\ 10^{-10}$

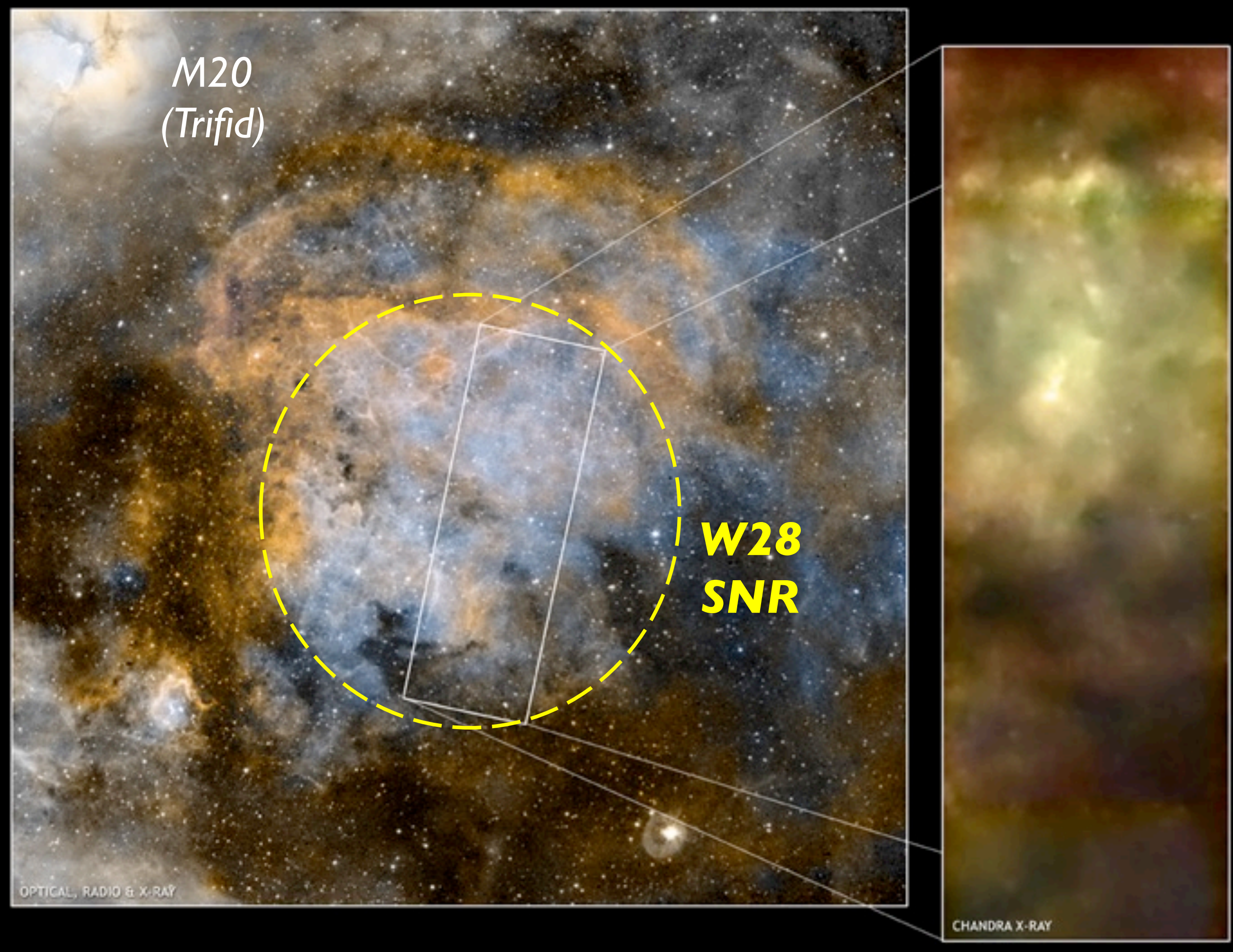
["astrochem" network]

Massive star-forming regions as CR laboratories

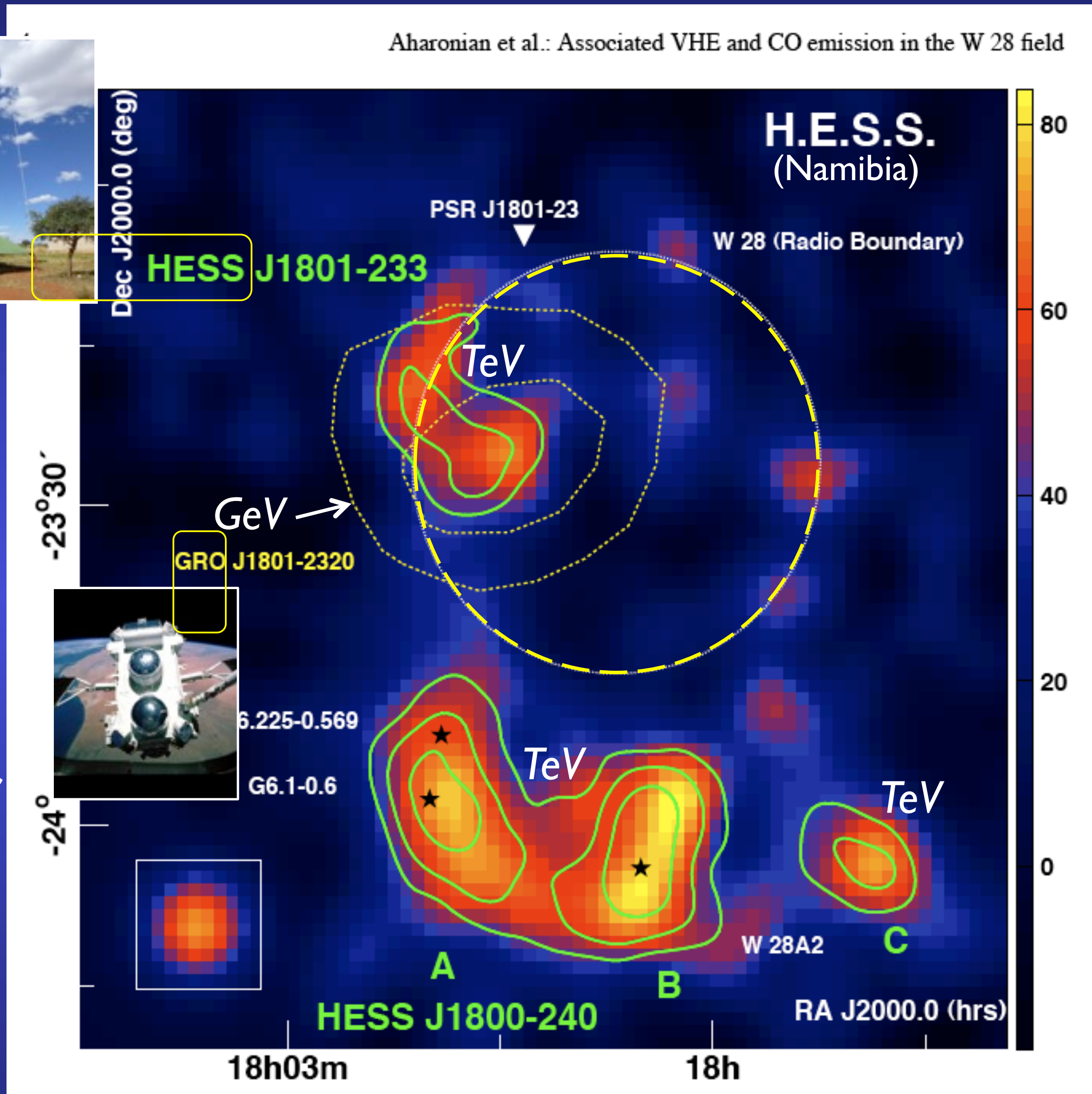


Case study:
W28
(~ galactic plane, not far from GC)

X-ray, "filled" SNR
CGRO and HESS
γ-ray source



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

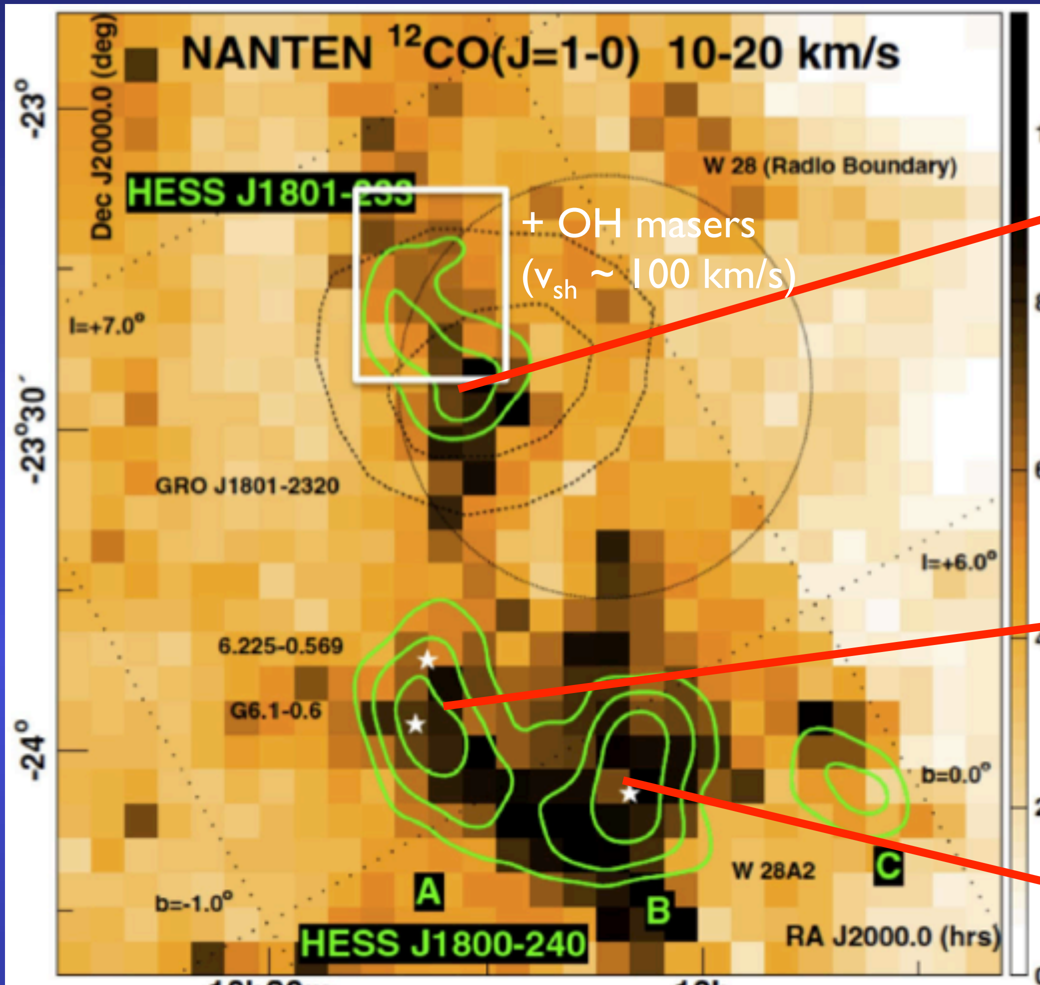


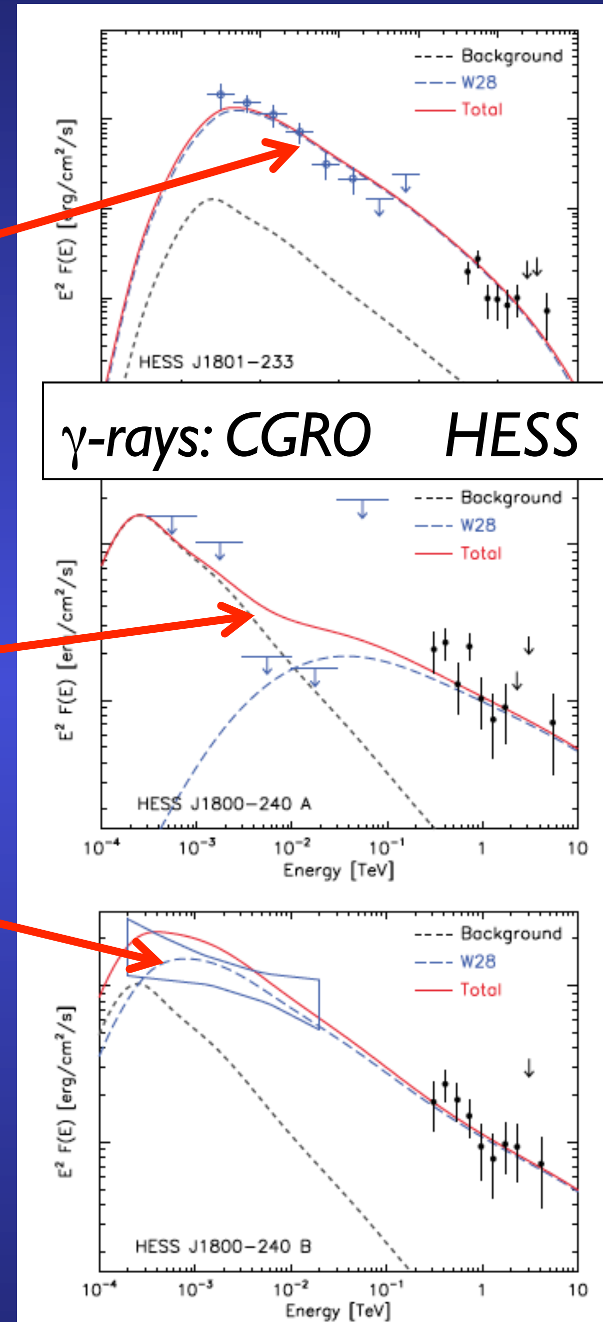
W28 = SNR+SFR, complex of GeV/TeV sources

d ~ 1.9 kpc

age ~10^4 yr

Aharonian et al. 2008



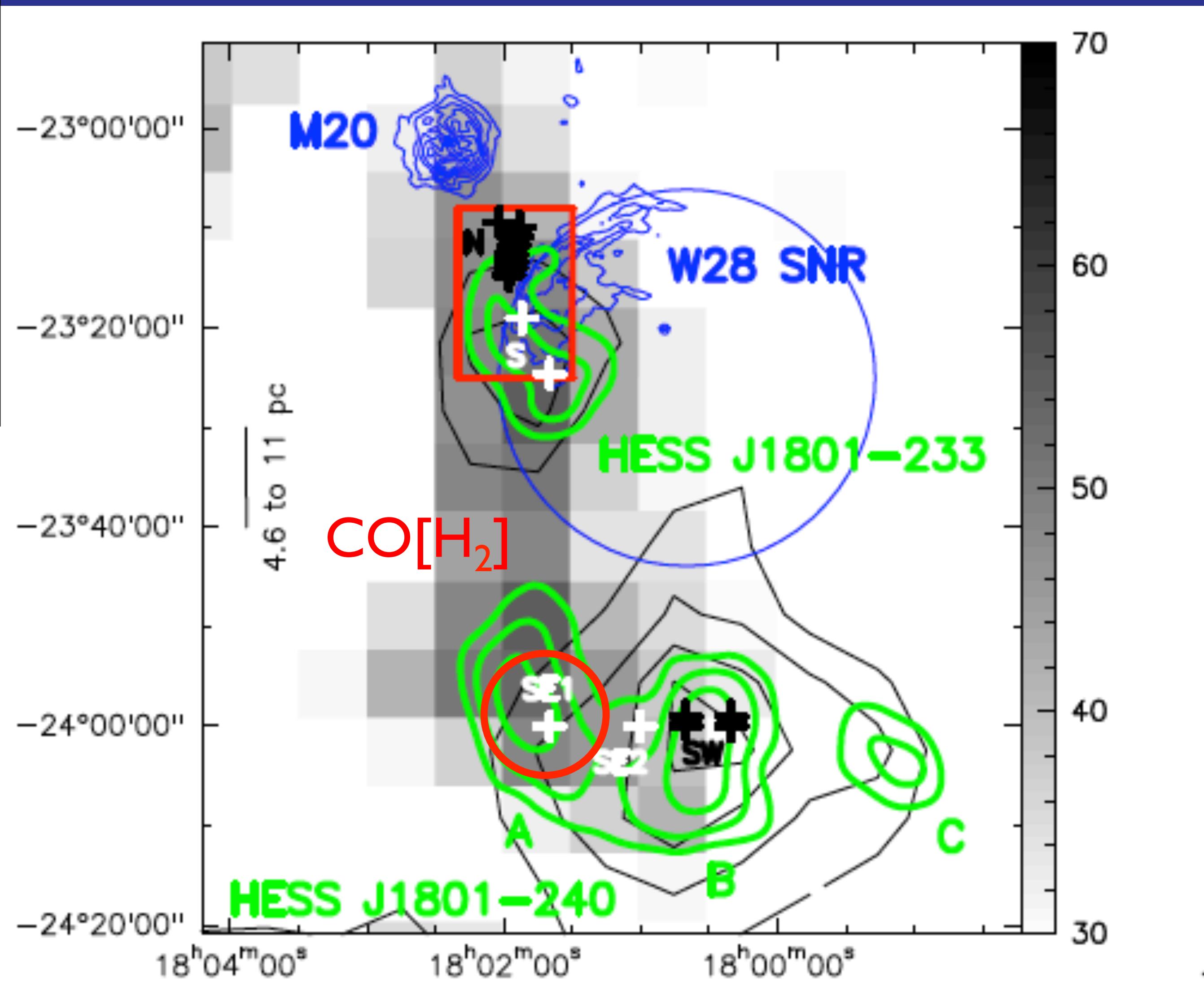


W28 spectral fitting (π°): > GeV protons

(Nava & Gabici 2013)

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

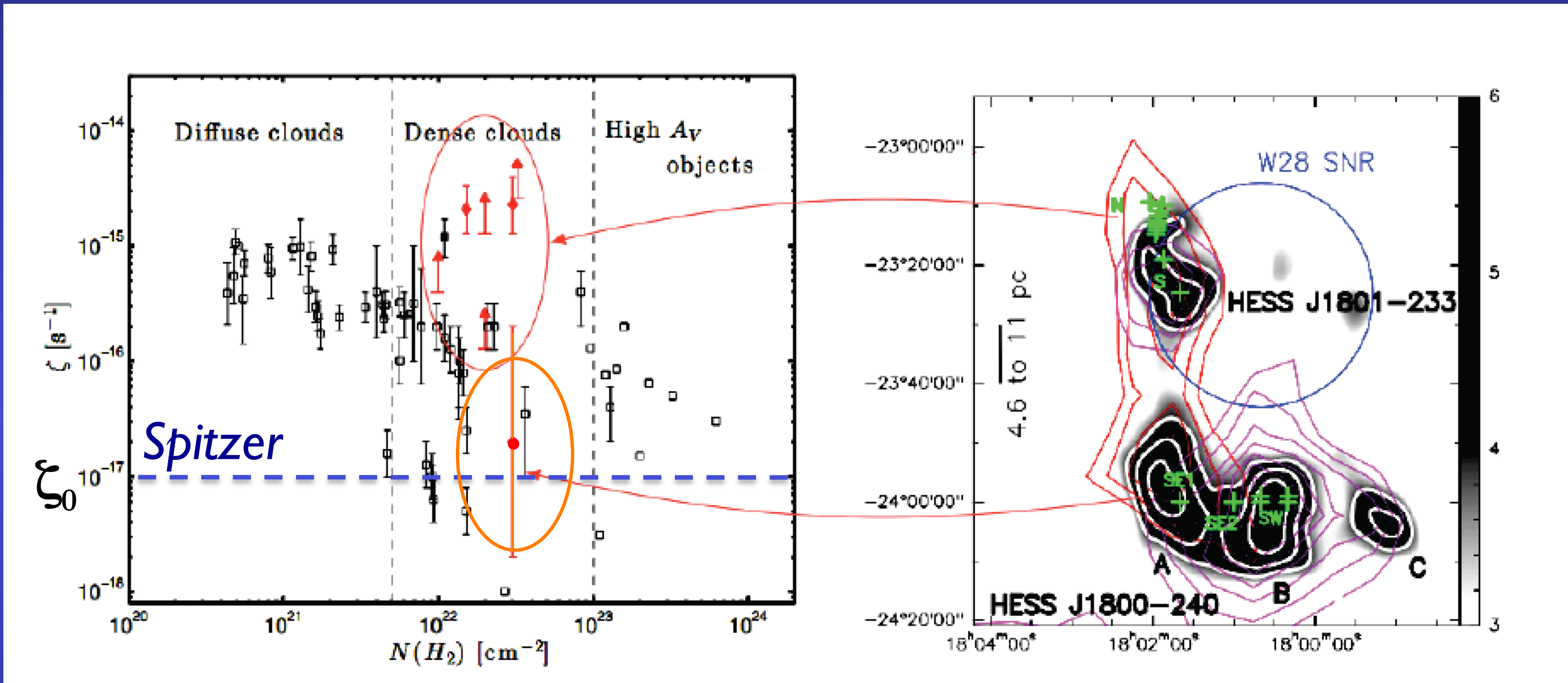
Species	Line
$H^{13}CO^+$	(1-0)
$C^{18}O$	(1-0)
^{13}CO	(1-0)
$C^{17}O$	(1-0)
DCO^+	(2-1)
$C^{18}O$	(2-1)
^{13}CO	(2-1)
$C^{17}O$	(2-1)



16 pointings

Vaupré+2014

W28: Enhanced ionization (x ~100) downstream of the shock



⇔ enhancement of LECR

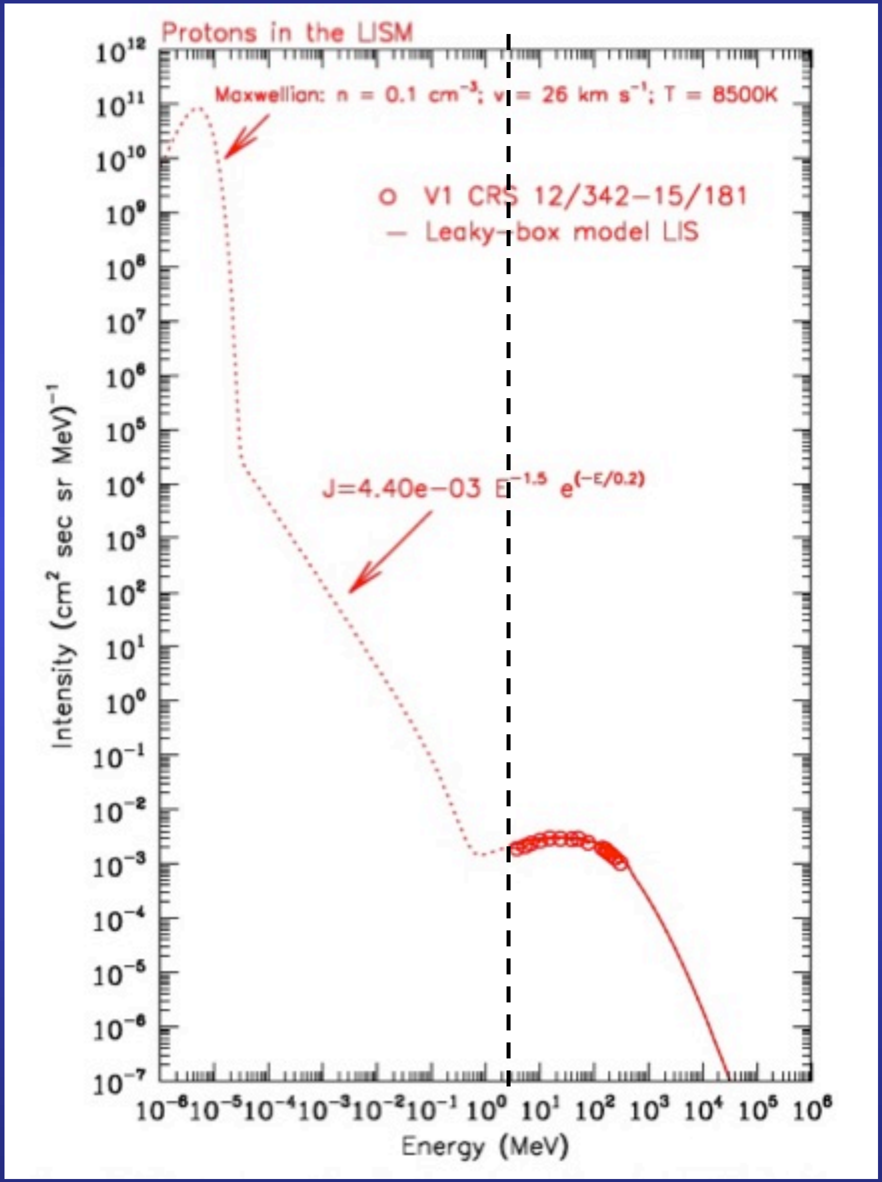
≈ enhancement of *local* HECR from π°-decay γ-rays

>> enhancement of *galactic* HECR from π°-decay γ-rays

Where are the (low-energy) cosmic rays ?

- Cummings et al. (2016) and Phan et al. (2018), taking into account the "local" interstellar LECR measurements ("Local Interstellar Spectrum", LIS: Voyager 1), have shown that if the LIS is identical throughout the Galaxy, it is *impossible to explain the observed ionization rate of molecular clouds ($\geq$ 1-2 orders of magnitude too low)*
- Phan et al. (2018) proposed a new, detailed model for the penetration of LECR into molecular clouds (with advection, diffusion, energy losses, magnetic turbulence, etc.) *and give the resulting (reduced) ionization rates* (p + e)
- => invoke *very-low energy* "suprathermal" CR (< 3 MeV/n) ?
- Counterexamples ? **See W28**

Very *low-energy cosmic rays ??*



Cummings+ 2016

4 V. H. M. Phan et al. *(2018)*

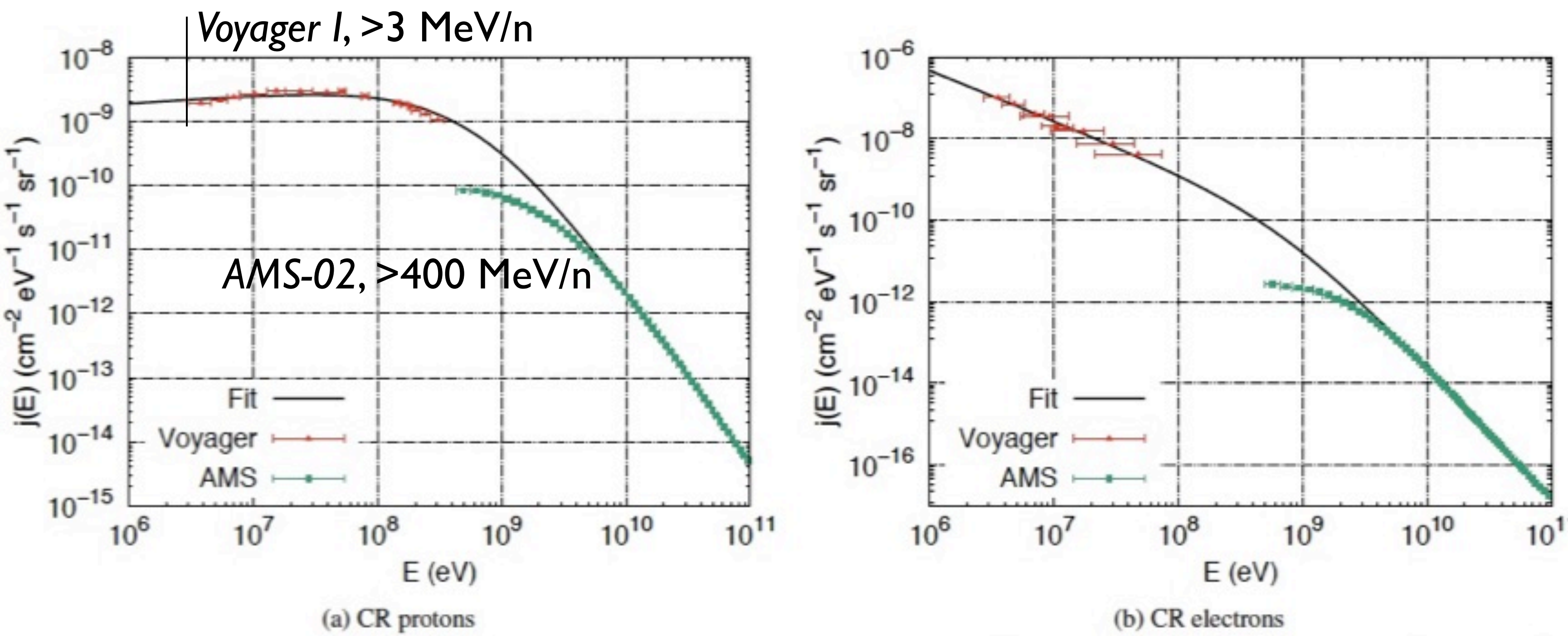
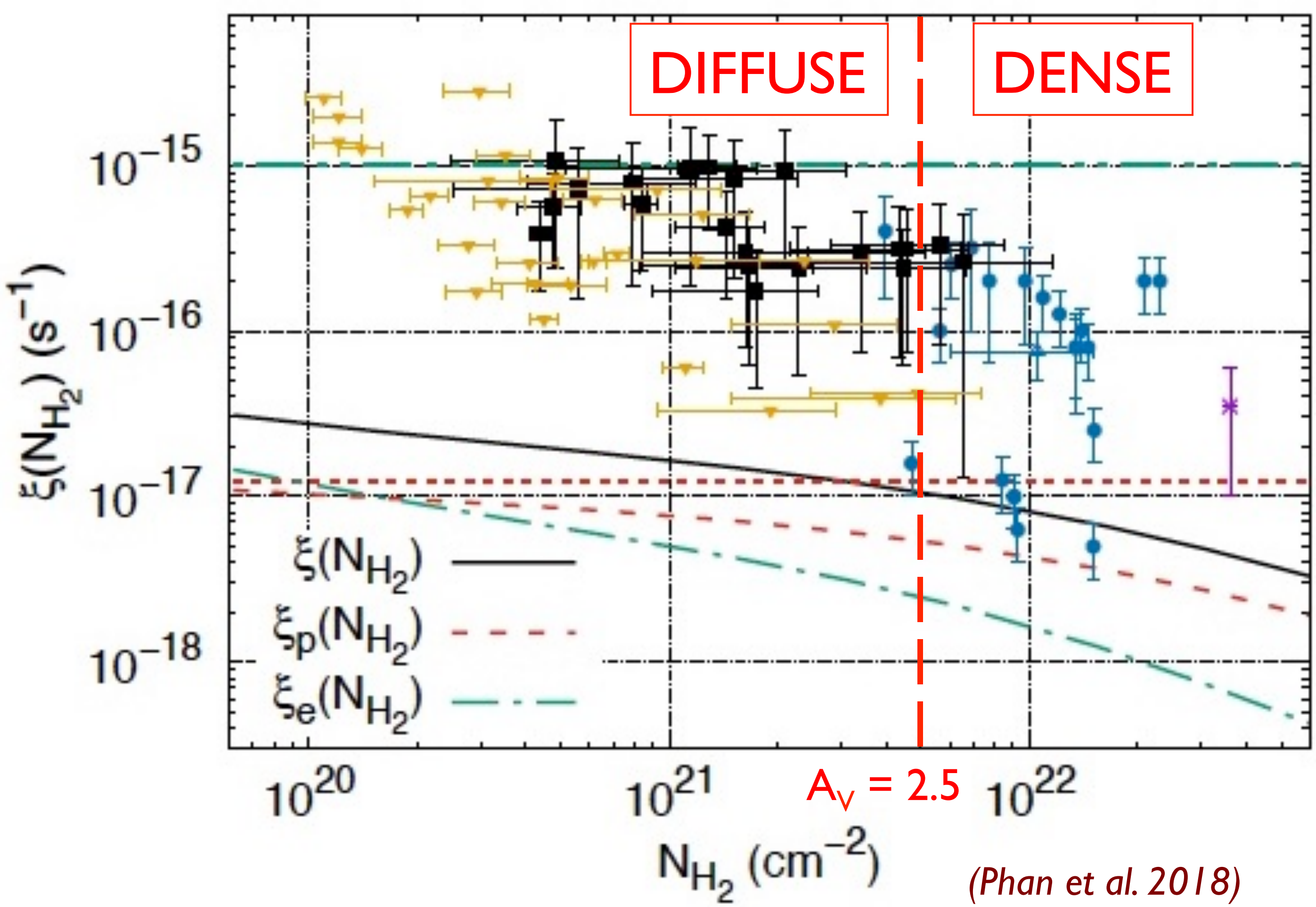


Figure 3. Data of the CR intensity for protons (left) and electrons (right) taken from Voyager 1 (Cummings et al. 2016) and AMS-02 (Aguilar et al. 2014, 2015) compared with the fitted curve used in this work.

Fit: broken power-law CR spectrum (< 3 MeV – 100 GeV)

ISM ionization by GCR: fact. >10 too low !

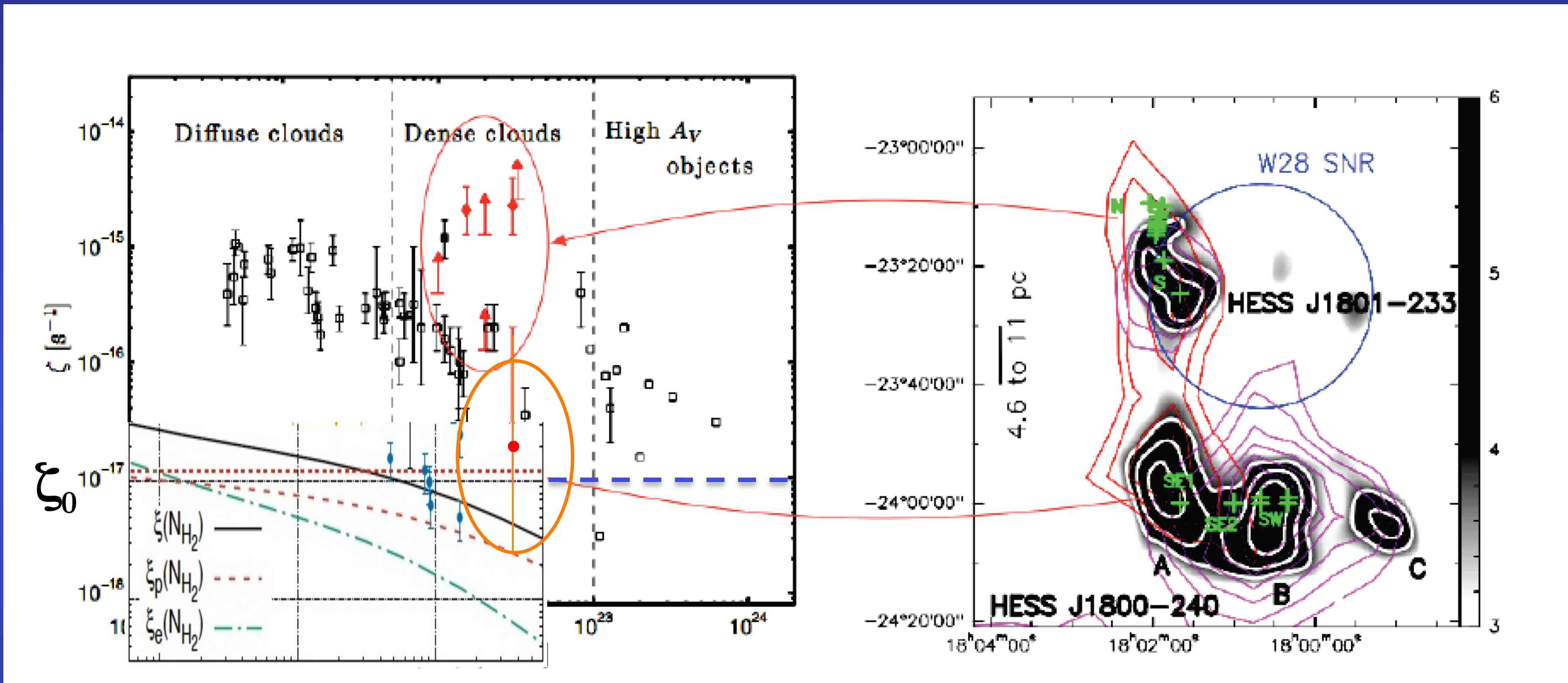


(Phan et al. 2018)

points are from Caselli et al. (1998) (blue filled circles), Williams et al. (1998) (blue empty triangle), Maret & Bergin (2007) (purple asterisk), and Indriolo & McCall (2012) (black filled squares are data points while yellow filled inverted triangles are upper limits).

LECR penetration limited by MHD effects in diffuse envelope

W28: Enhanced ionization (x ~100) downstream of the shock



⬄ enhancement of local LECR (= near SNR shock)

But ~ "Voyager value" far from the shock !?

4. Concluding remarks

- Origin of cosmic rays still a puzzle, in spite (or because) of recent advances
- For galactic cosmic rays, supernova remnants interacting with molecular clouds are a good laboratory for studying hadron acceleration
  - via γ-rays at high energies (down to ~ 280 MeV, π°-decay threshold)
  - via mm observations+astrochemistry at low energies (molecular cloud ionization)
- However, Voyager I results pose a new challenge: *where are the low-energy cosmic rays necessary for ISM ionization ?*