From high-energy to low-energy cosmic rays: mind the gap !

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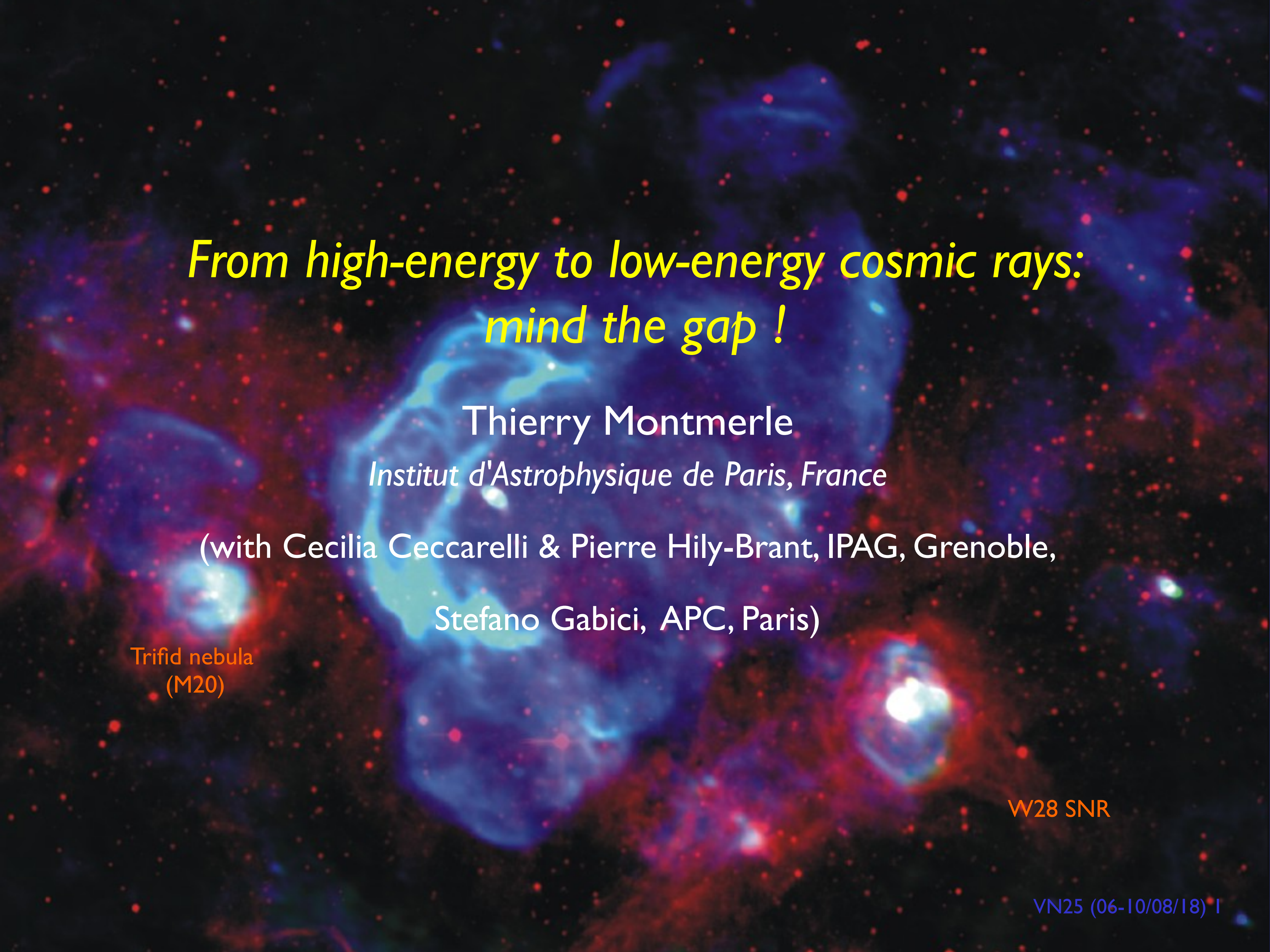
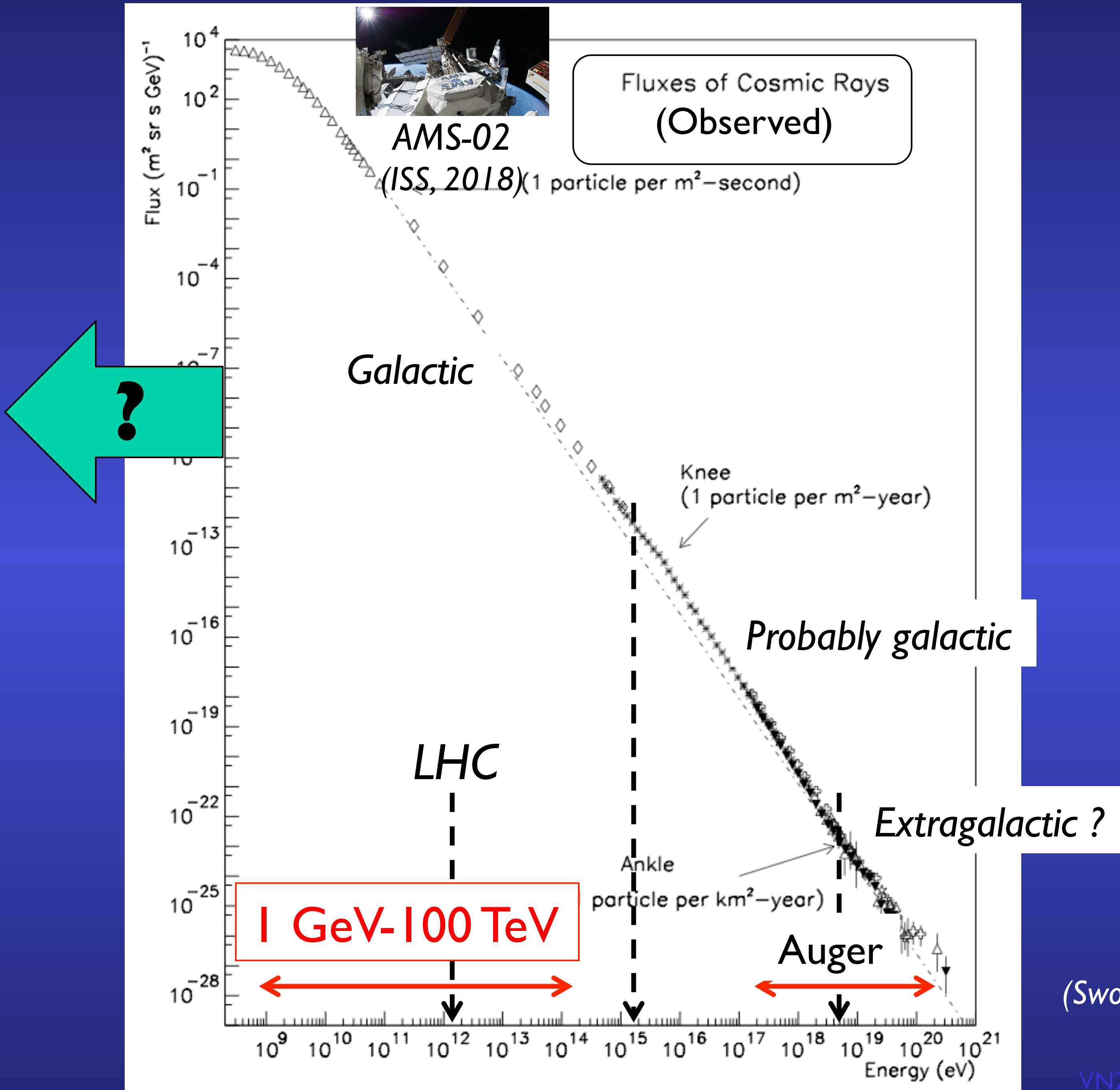


Outline

1. Cosmic Rays today (in a nutshell)
2. Importance of low-energy cosmic rays
3. Bridging the gap ? New mysteries
4. Conclusions and open issues

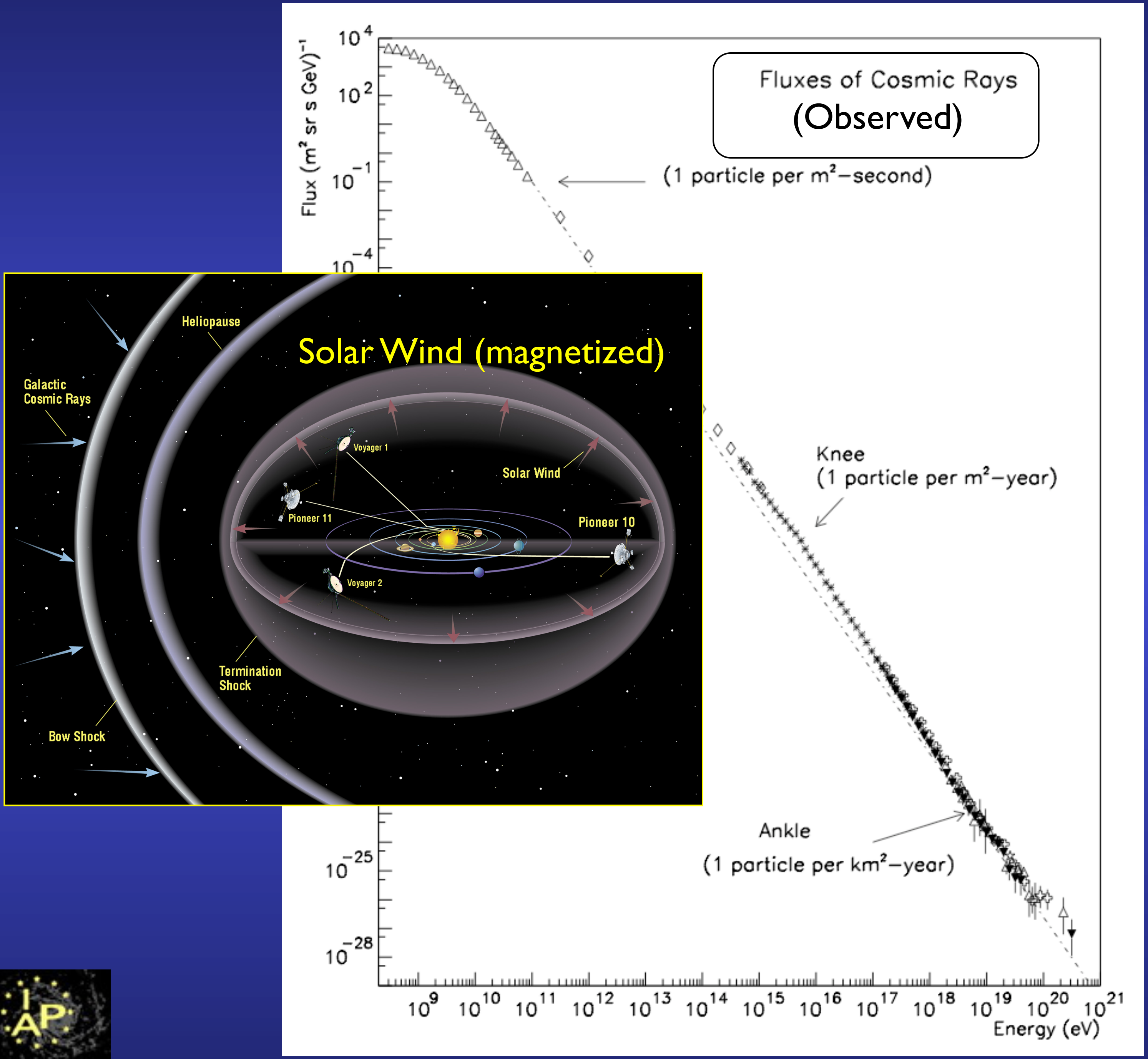
1. Cosmic Rays today

(in a nutshell)



Fluxes of Cosmic Rays
(Observed)
AMS-02
(ISS, 2018)
(1 particle per m²–second)
Galactic
?
Knee
(1 particle per m²–year)
Probably galactic
LHC
Extragalactic ?
Ankle
particle per km²–year)
1 GeV-100 TeV
Auger
Flux (m² sr s GeV)⁻¹
Energy (eV)
10^4
10^2
10^-1
10^-4
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21

(Swordy 2001)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(Observed)
(1 particle per m²–second)
Knee
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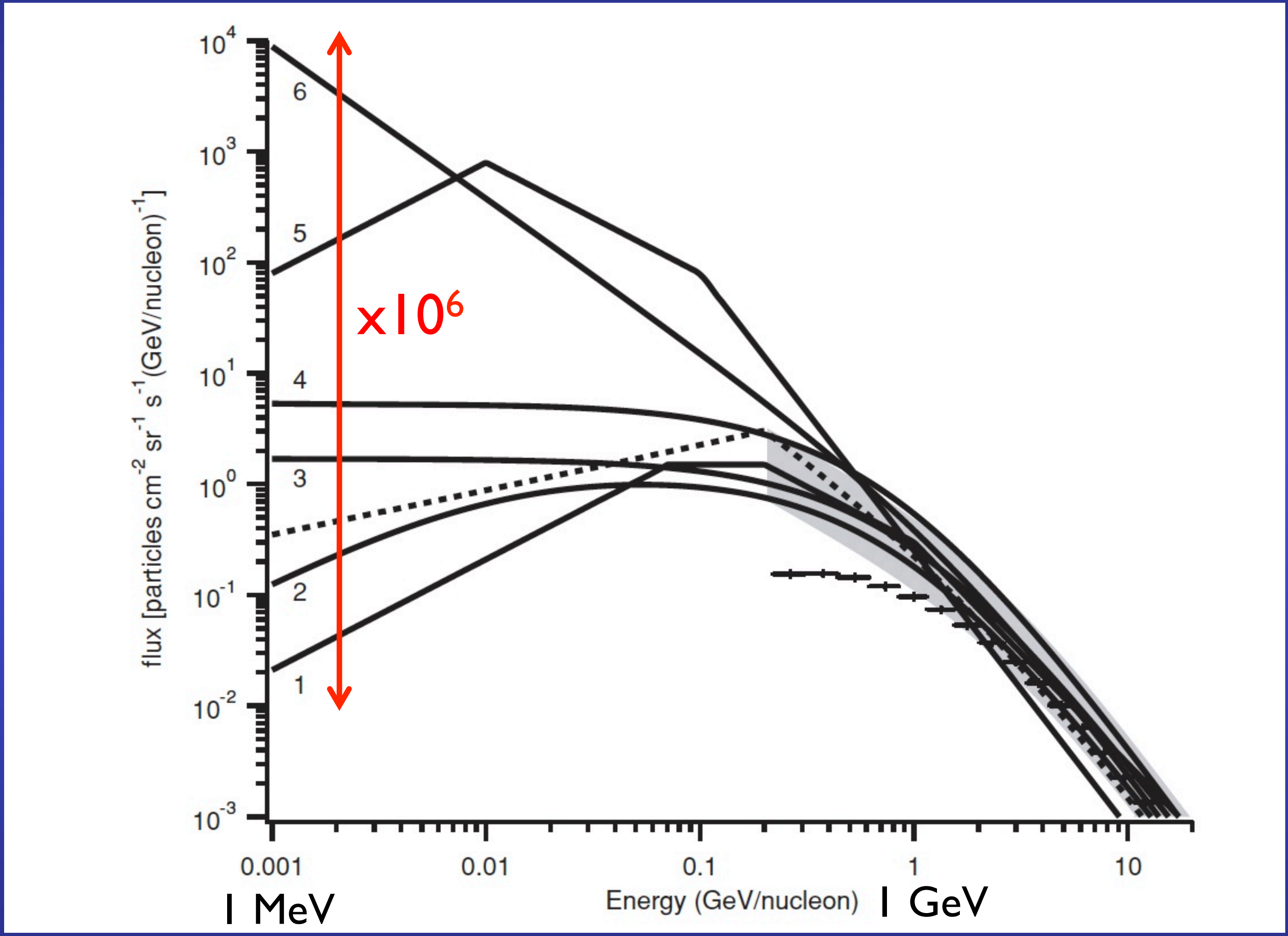
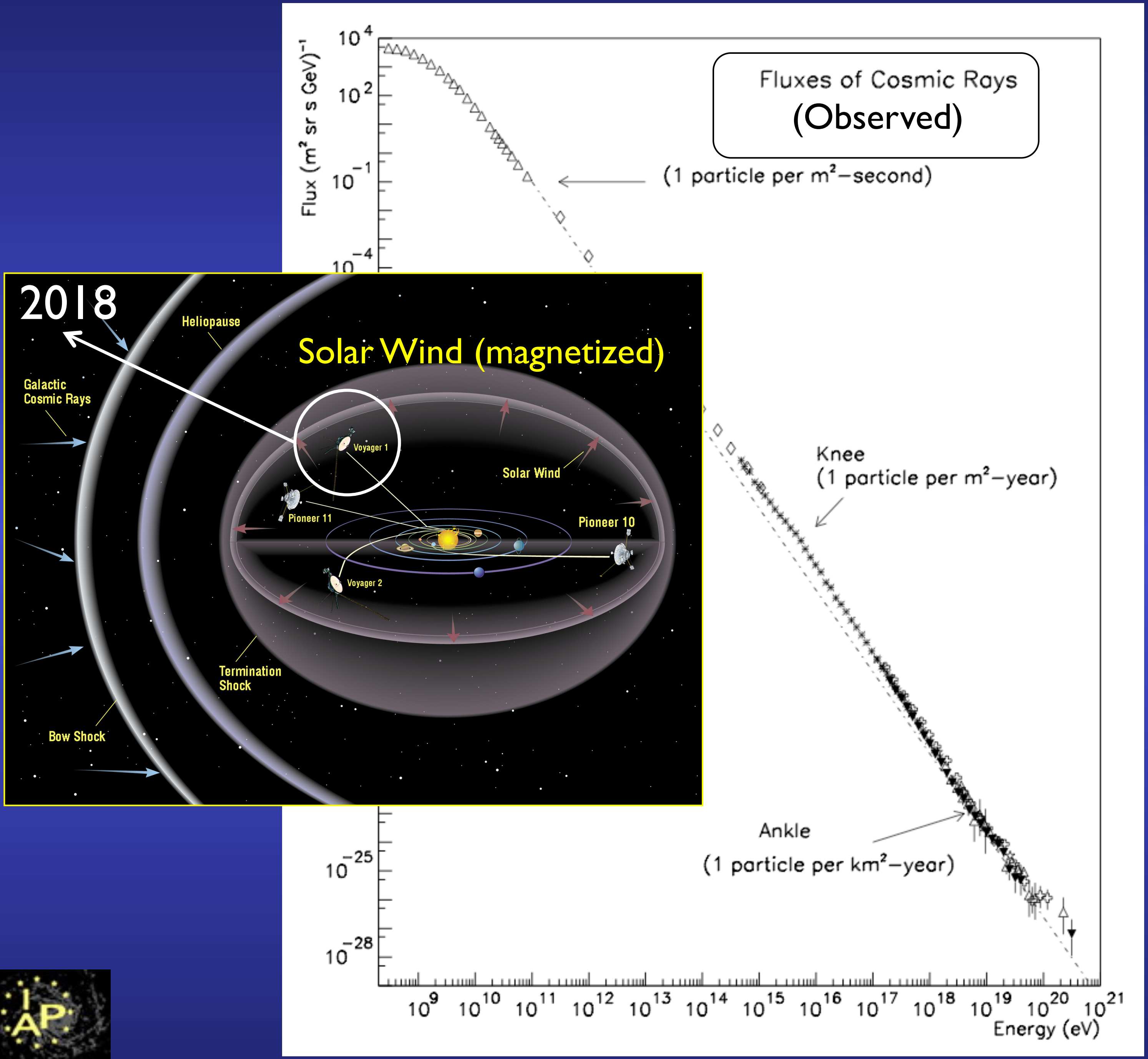
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)
Solar Wind (magnetized)
Heliopause
Galactic Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination Shock
Bow Shock

(Swordy 2001)

Various proposed low-energy CR spectra



Indriolo+ 2009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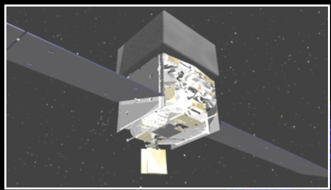
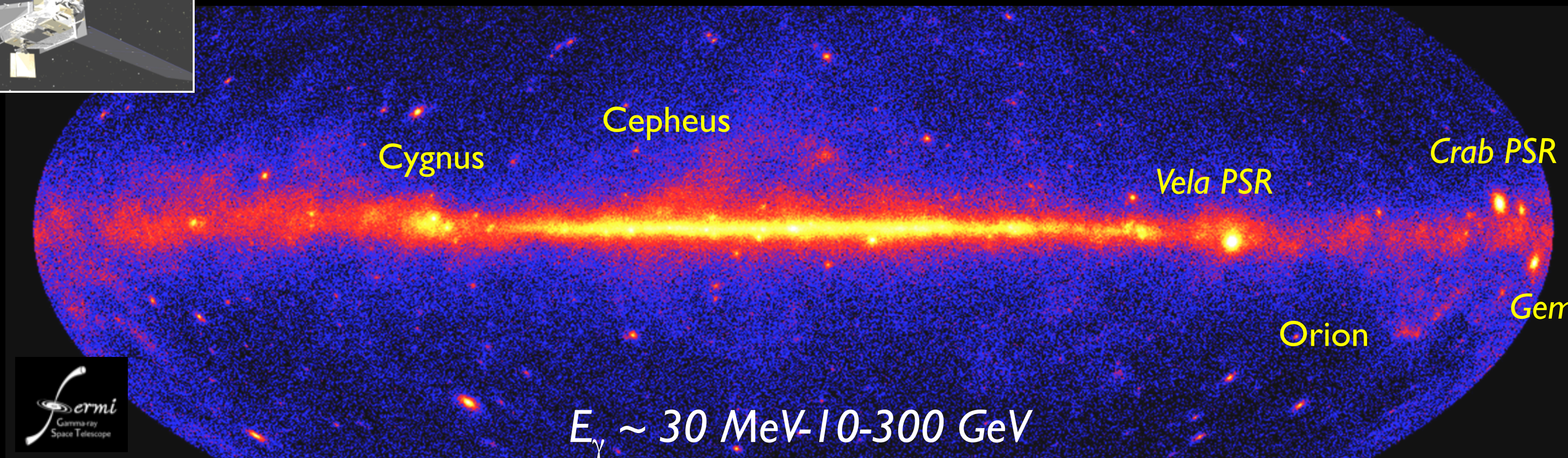
(Swordy 2001)

High-Energy CR in the Galaxy: Proof from γ-rays ?

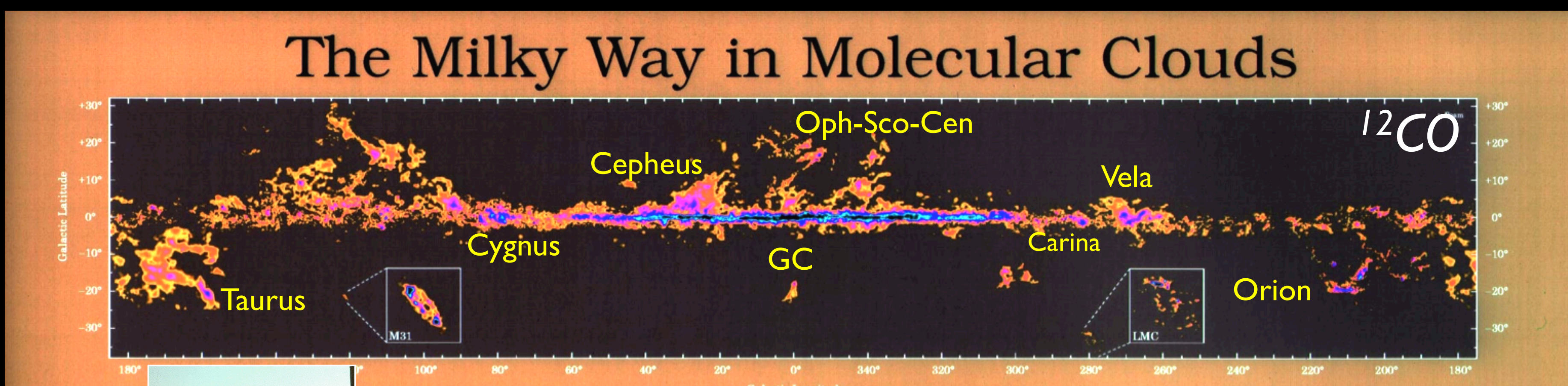
- High-energy cosmic rays (HECR= > 10 GeV CR: p, α, e^-) are traced by high-energy γ-rays (> GeV) when they interact with the interstellar medium (ISM: matter + ambient photons)
  - π° decay (p, α + H, He) *(Hayakawa 1954)*
  - Inverse Compton (e^- + hν)
  - Bremsstrahlung (e^- + Z)
- As a result, γ-ray emission is expected from throughout the Galaxy (diffuse emission)
- Also, a γ-ray "source" *may* be associated with a localized CR source (e.g., a Supernova Remnant), with other consequences (ionization of molecular clouds, contamination by radioactive products….)
- π° decay dominant mechanism (except in some localized regions)

Galactic scale: p(HECR) + p(ISM) —> π° —> 2γ

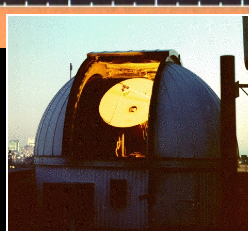




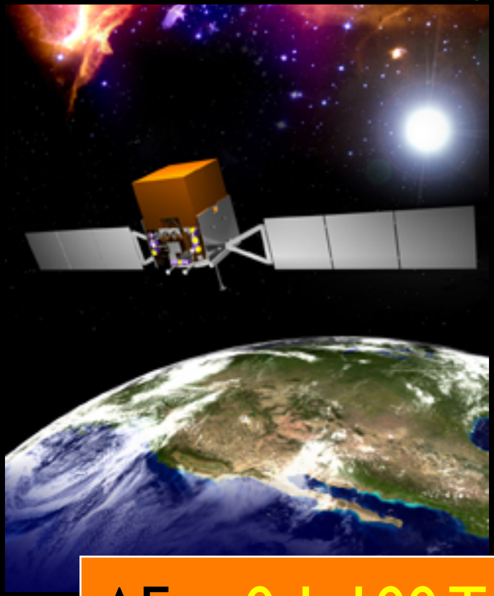
2nd Fermi catalog (2009)



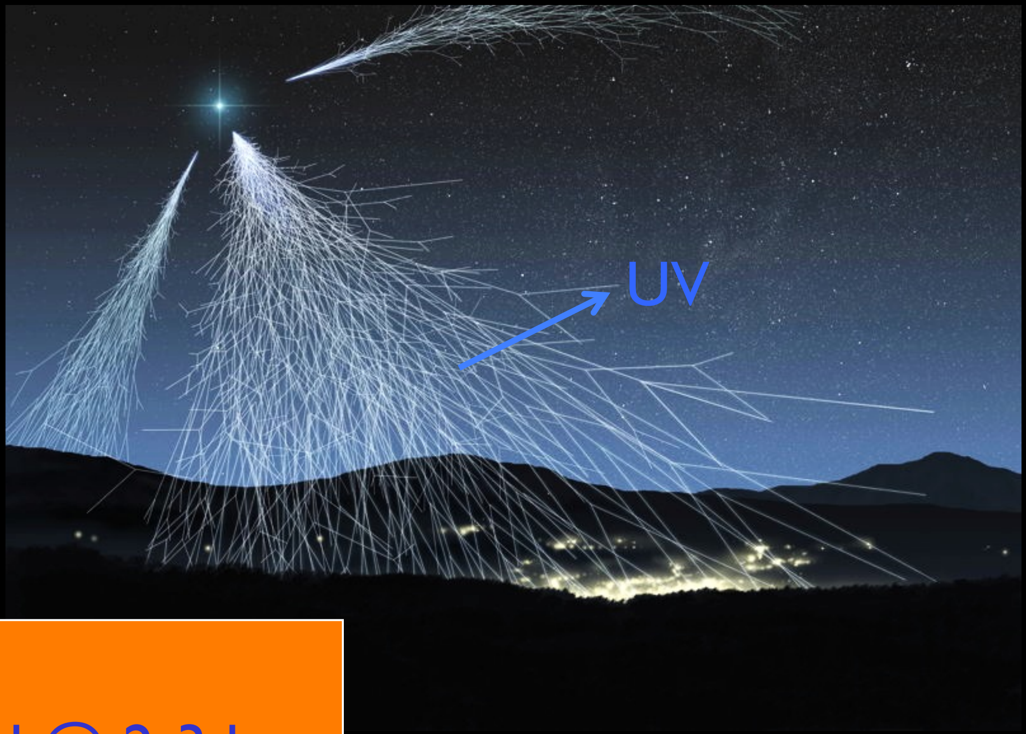
Dame et al. 2002



=> Large-scale HECR density ~ cst throughout the Galaxy *present-day γ-ray astronomy from space:* Fermi *(≳ 100 MeV – 20 GeV)*



Higher γ-ray energies: *Čerenkov telescopes on the ground (>TeV)*

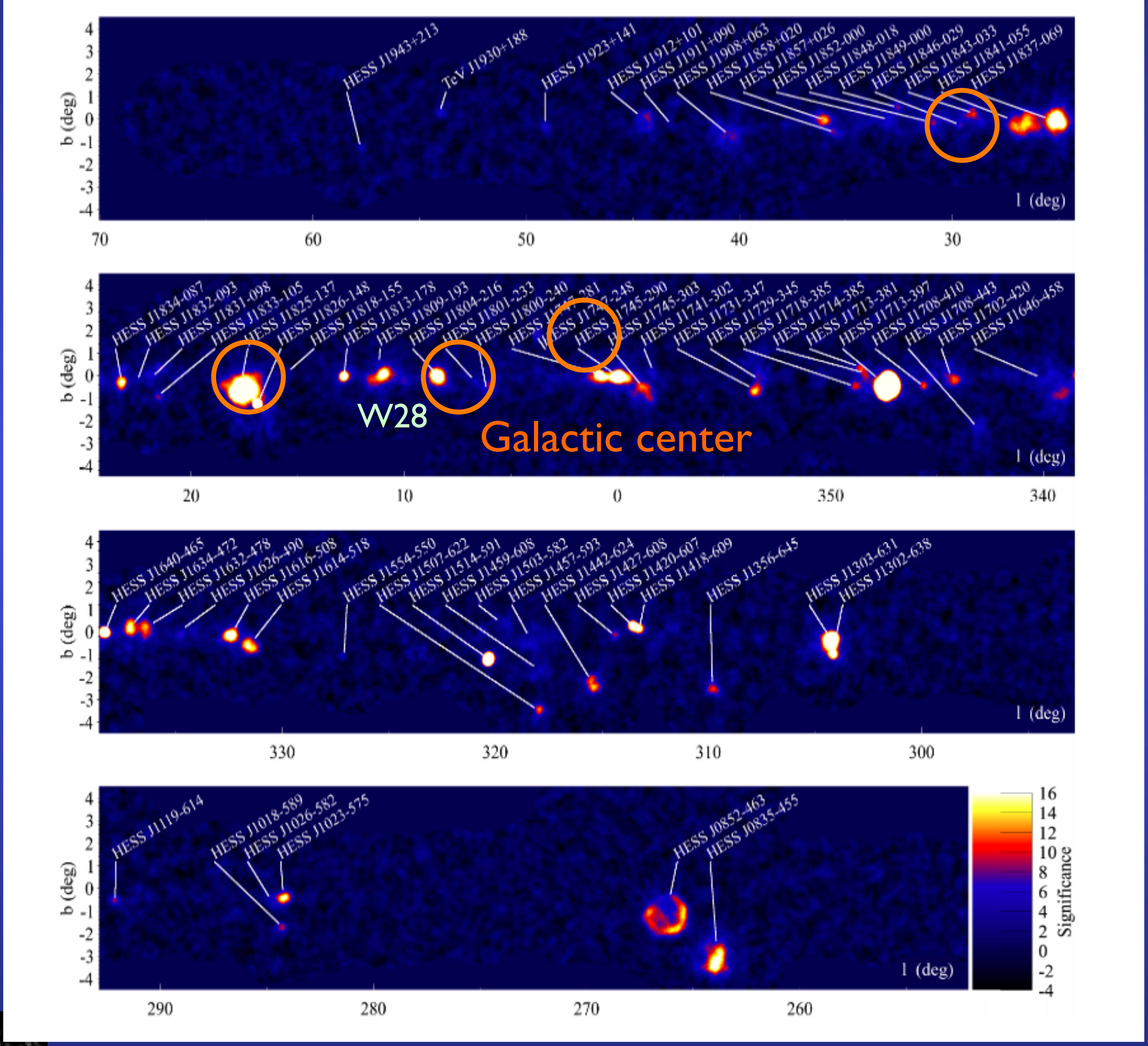


ΔE ~ 0.1-100 TeV

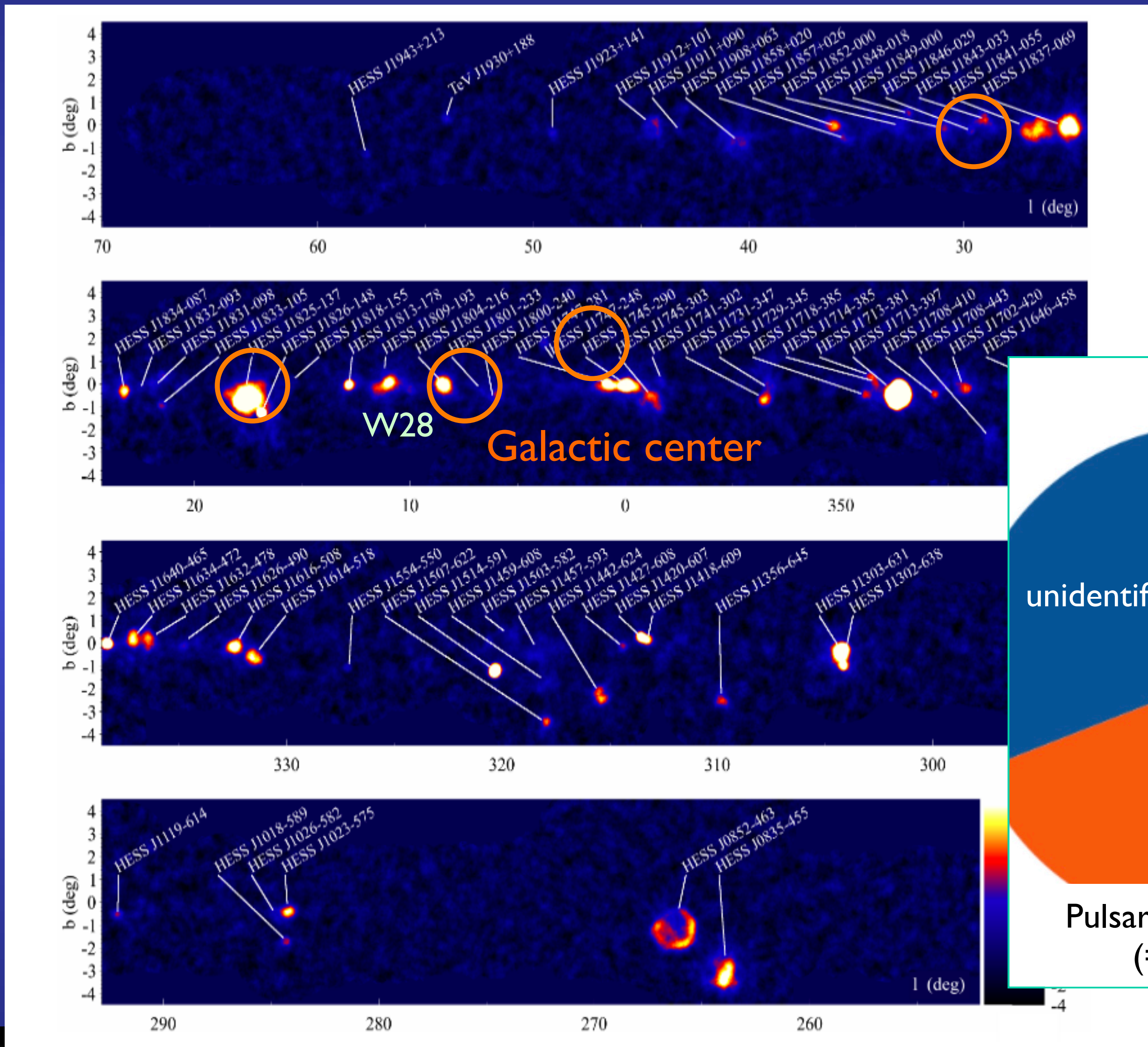
Δθ ~ 0.1° ~ mol. cloud @ 2-3 kpc

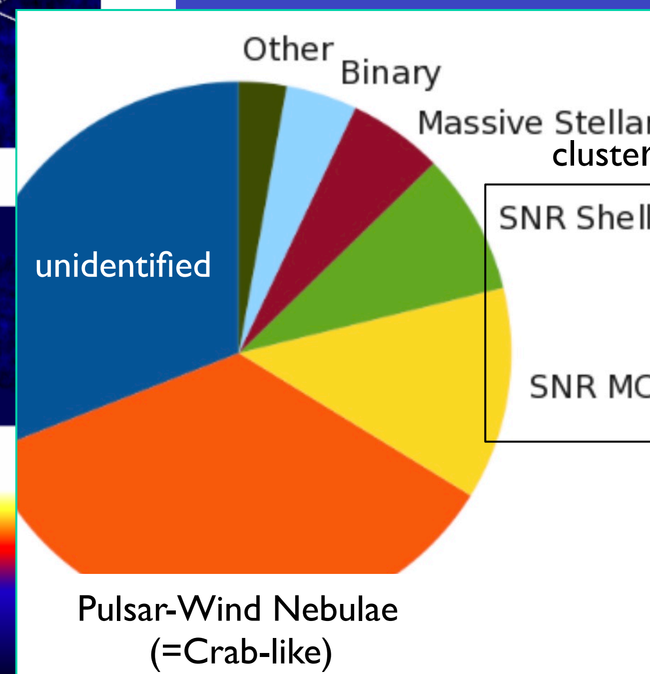
HESS II (Namibia): *High-Energy Stereoscopic System* (future: CTA)

HESS galactic plane survey 2013 (TeV γ-rays)



HESS galactic plane survey 2013 (TeV γ-rays)

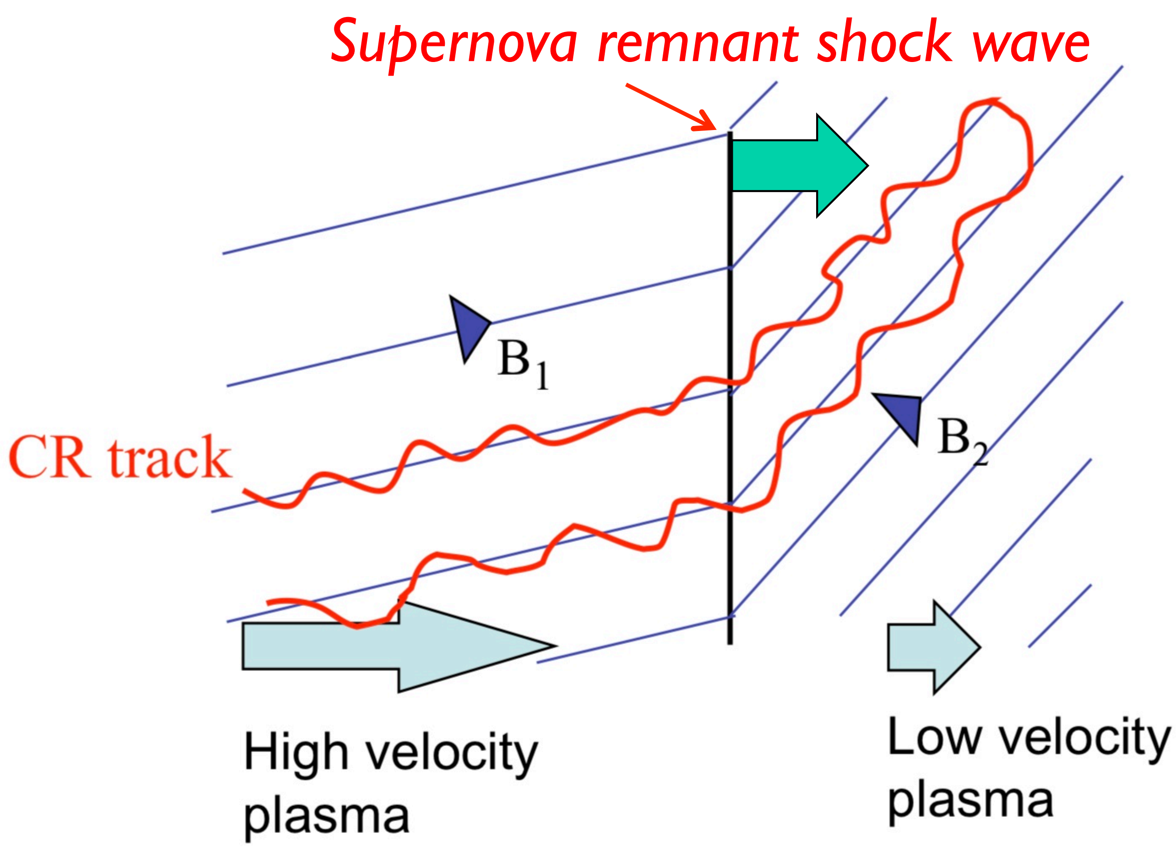




Origin of (galactic) cosmic rays

- Many possible sources
- Galactic CR: *Role of supernovae*
  - high-speed shocks (~10^4-100 km/s)
  - energetics OK (~ 10% of CR energy density ≈ 0.1 eV/cm^3)
- Pulsars (= highly magnetized neutron stars)
- Acceleration mechanisms
  - Sun & highly magnetized media: magnetic reconnection
  - Interplanetary/interstellar shocks: "diffusive shock acceleration" (DSA) in *magnetized interstellar medium* ("Fermi mechanism")

Diffusive Shock Acceleration



Due to scattering, CR recrosses shock many times
Gains energy at each crossing

(after Bell 2011)

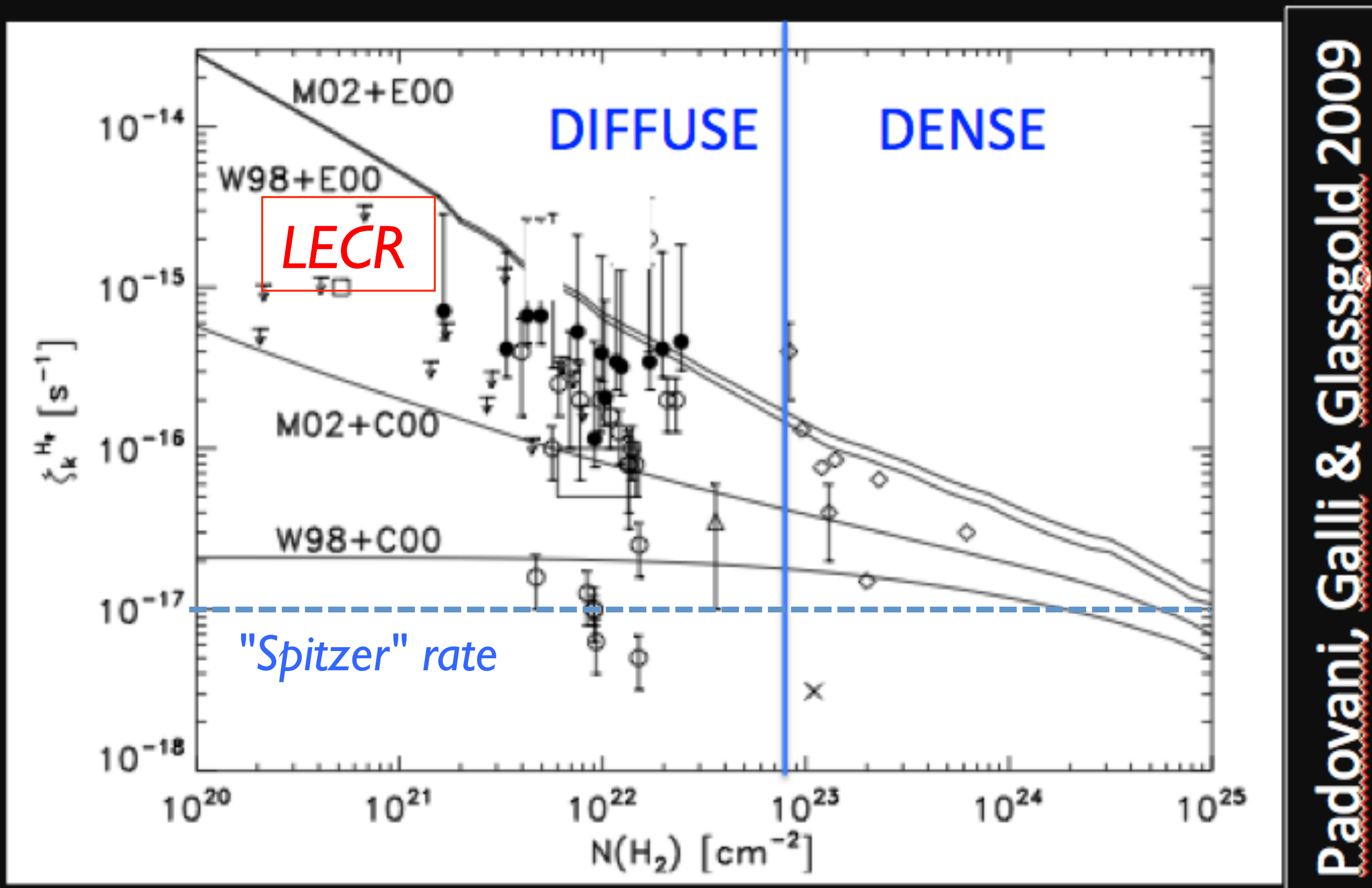
2. Importance of low-energy cosmic rays in the Galaxy

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 !***

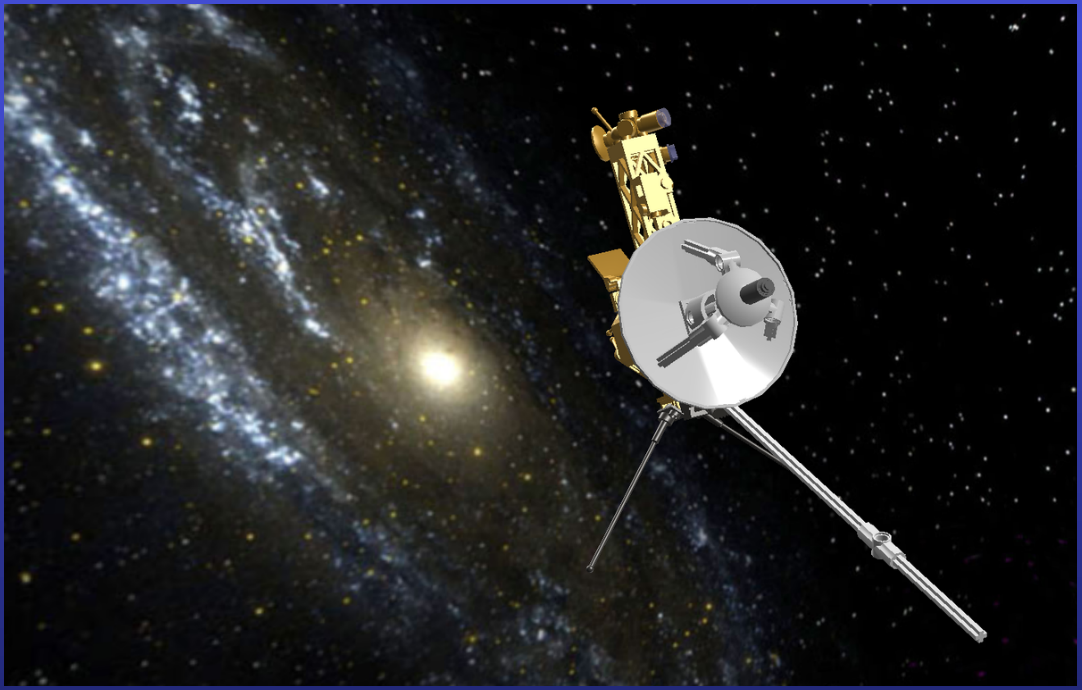
Ionization rate measurements (see later): Diffuse vs. Dense Clouds

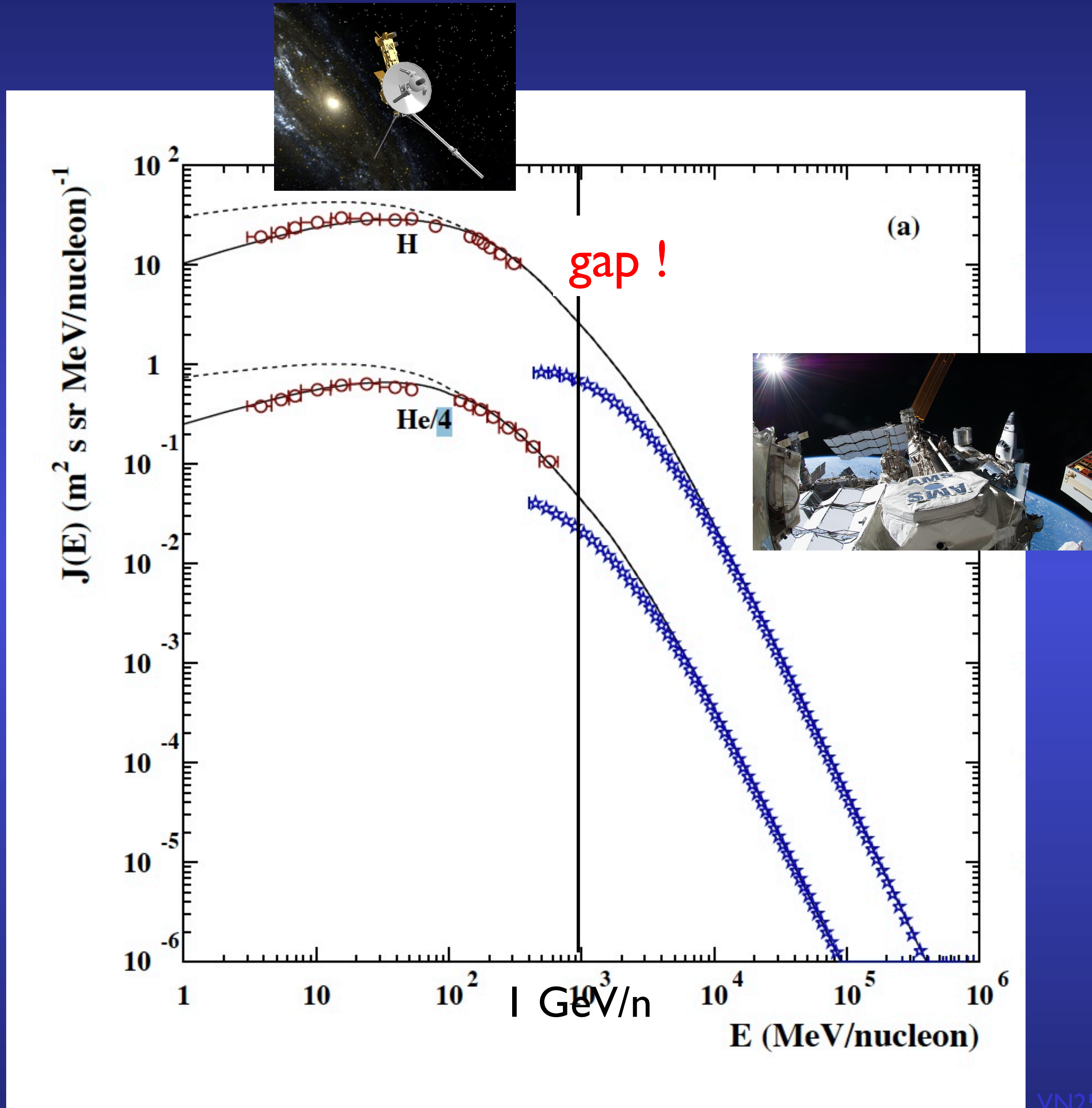


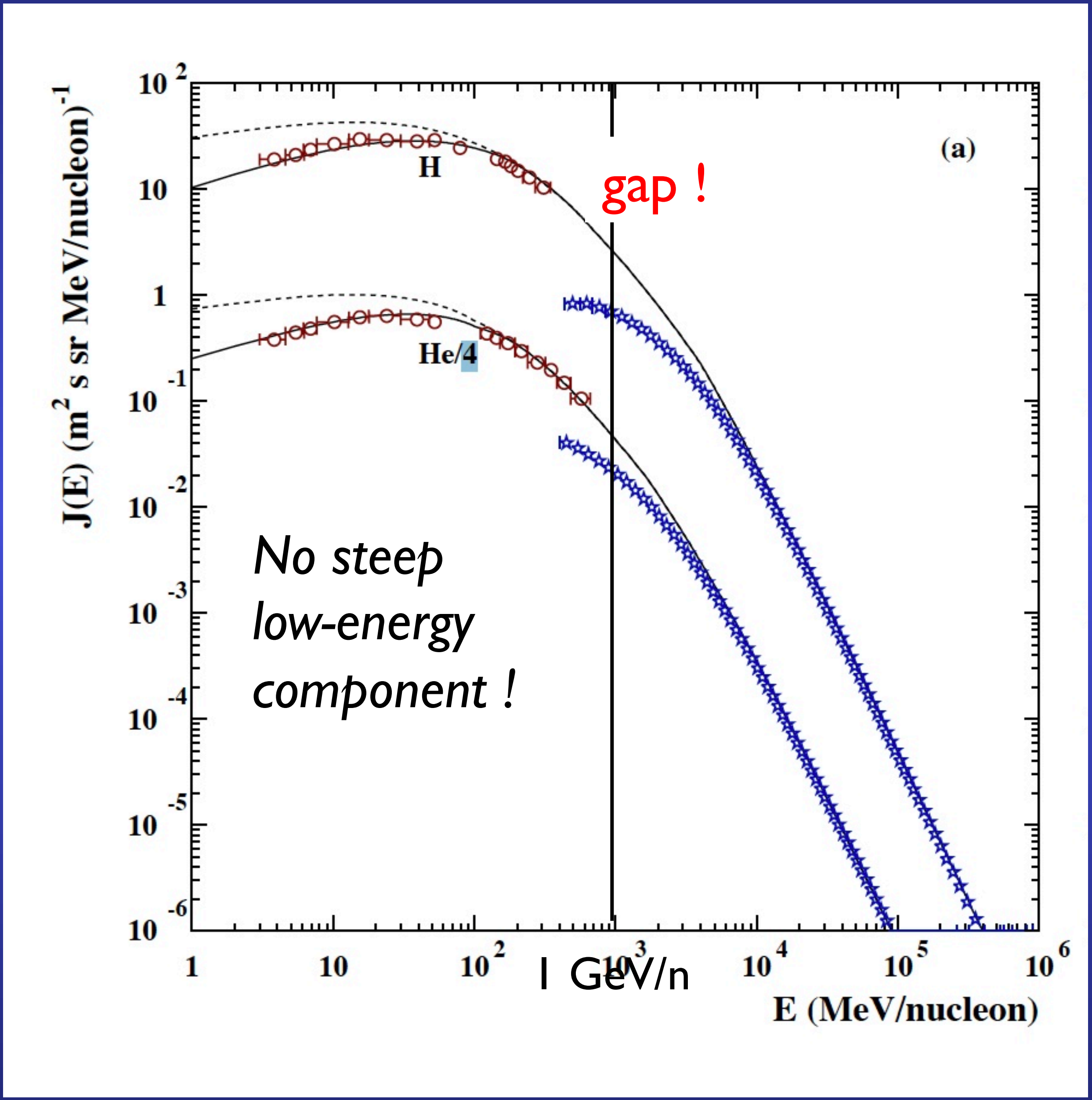
Diffuse clouds: $\zeta \approx 0.5\text{-}3 \times 10^{-16} s^{-1}$
Dense clouds: $\zeta \approx 0.1\text{-}5 \times 10^{-17} s^{-1}$

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
E (MeV/nucleon)
(a)
H
He/4
gap !
1 GeV/n
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1
10
10^2
10^3
10^4
10^5
10^6
AMS

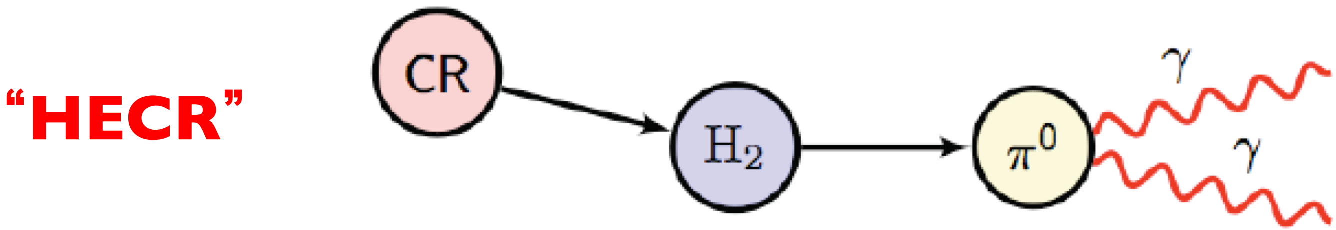


J(E) (m^2 s sr MeV/nucleon)^-1
E (MeV/nucleon)
(a)
H
He/4
gap !
No steep
low-energy
component !
1 GeV/n

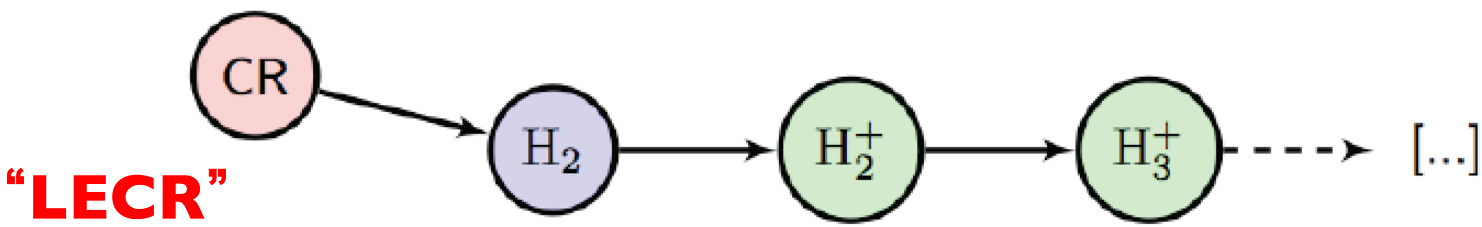
3. Bridging the gap ?

=> *In the Galaxy: Search for low-energy CR where evidence for high HECR*

- **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^+,...)



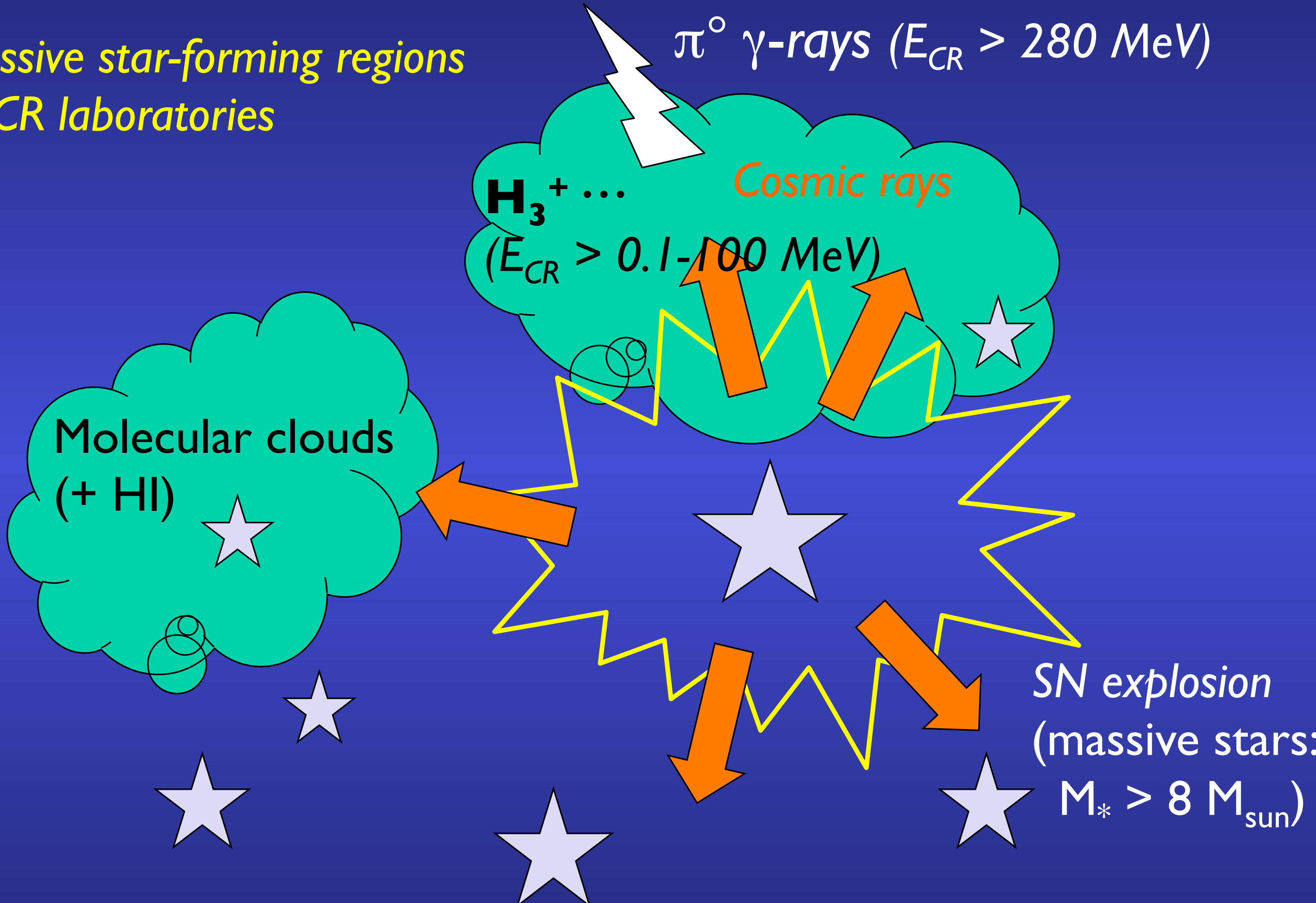
… by measuring and mapping the *ionization rate* ζ
of selected molecular clouds
(fiducial value $\zeta_0 \sim 10^{-17}$ s^{-1} for the Galaxy: "Spitzer" rate; ionization *fraction* $\sim 10^{-7}$)

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]

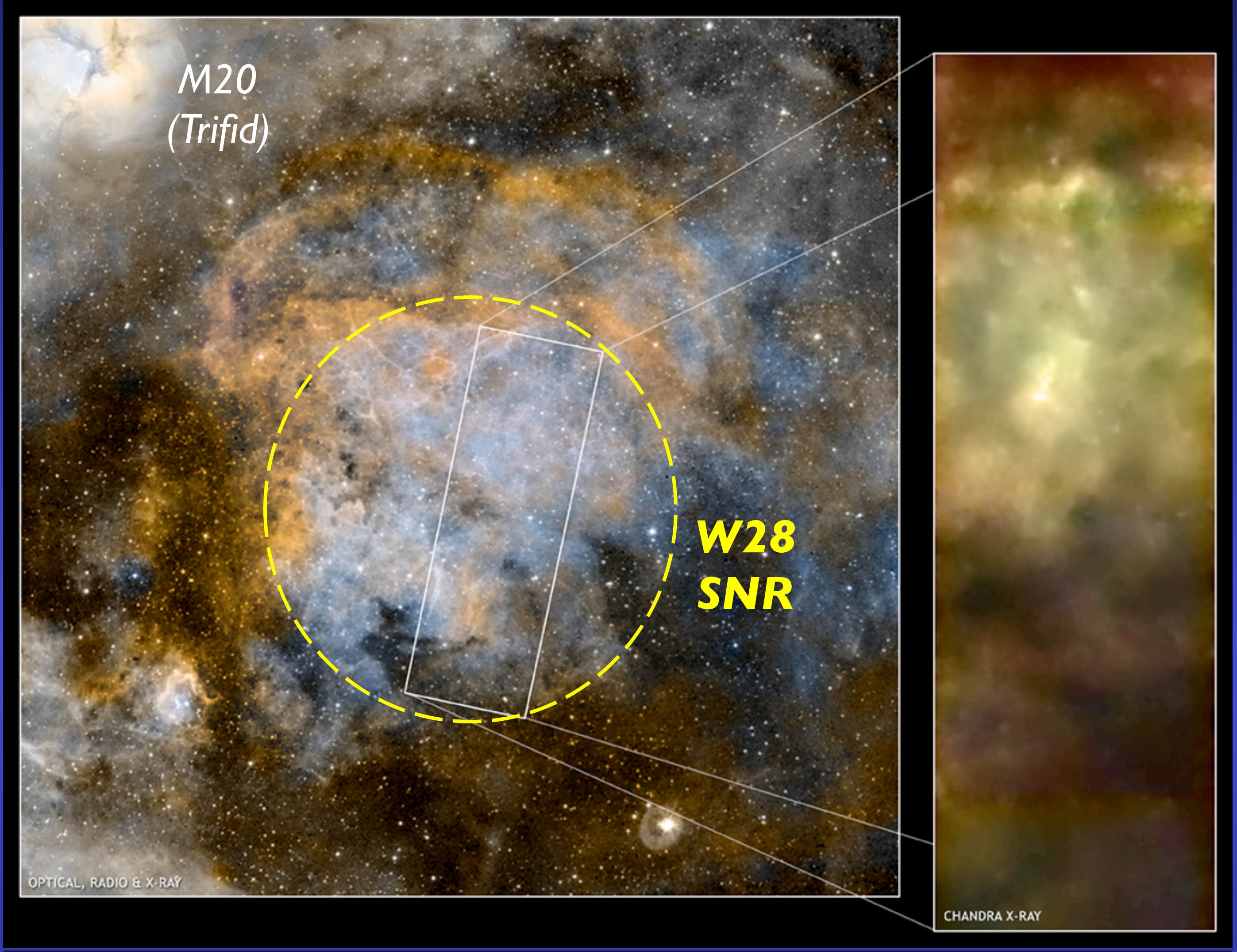
Massive star-forming regions as CR laboratories



Case study: *W28*

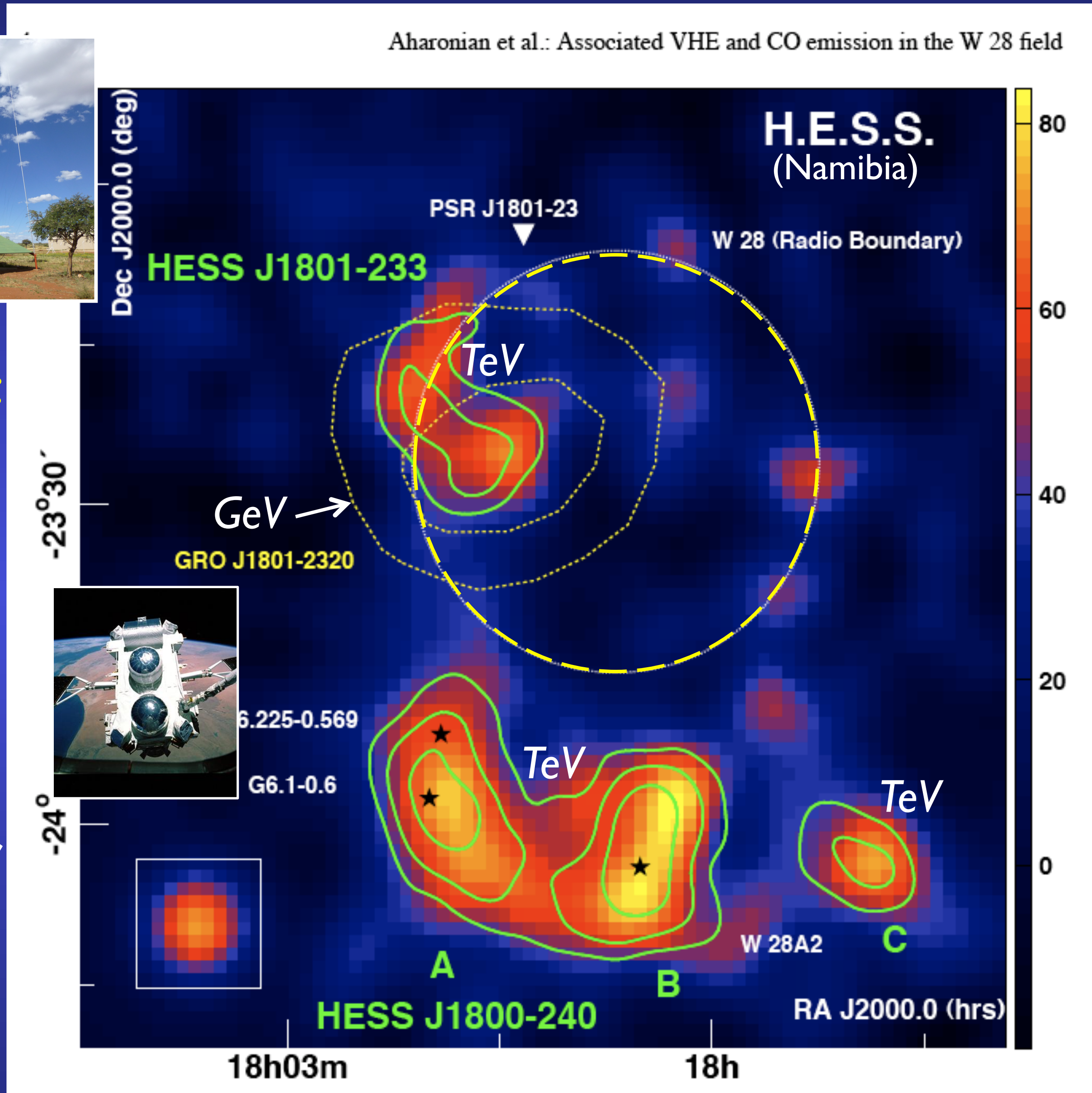
(~ galactic plane, not far from GC)

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

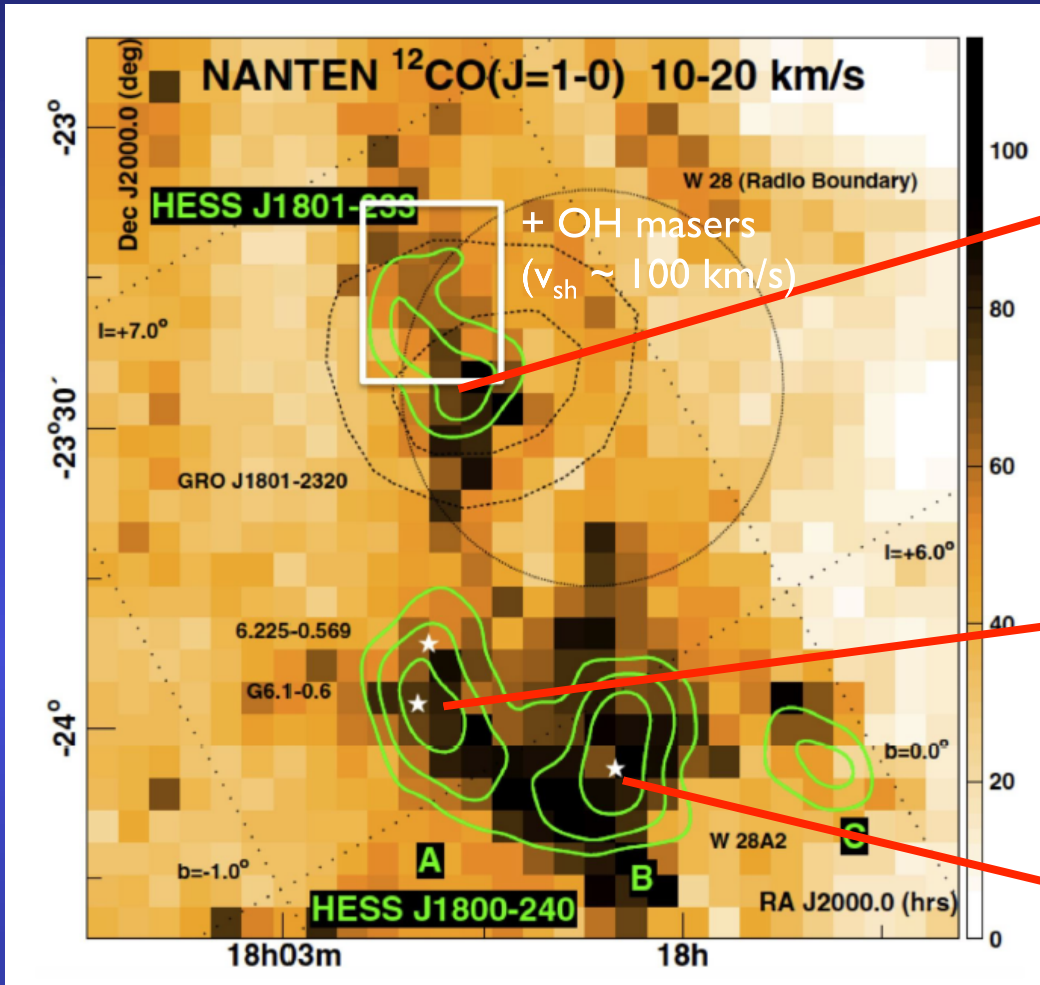


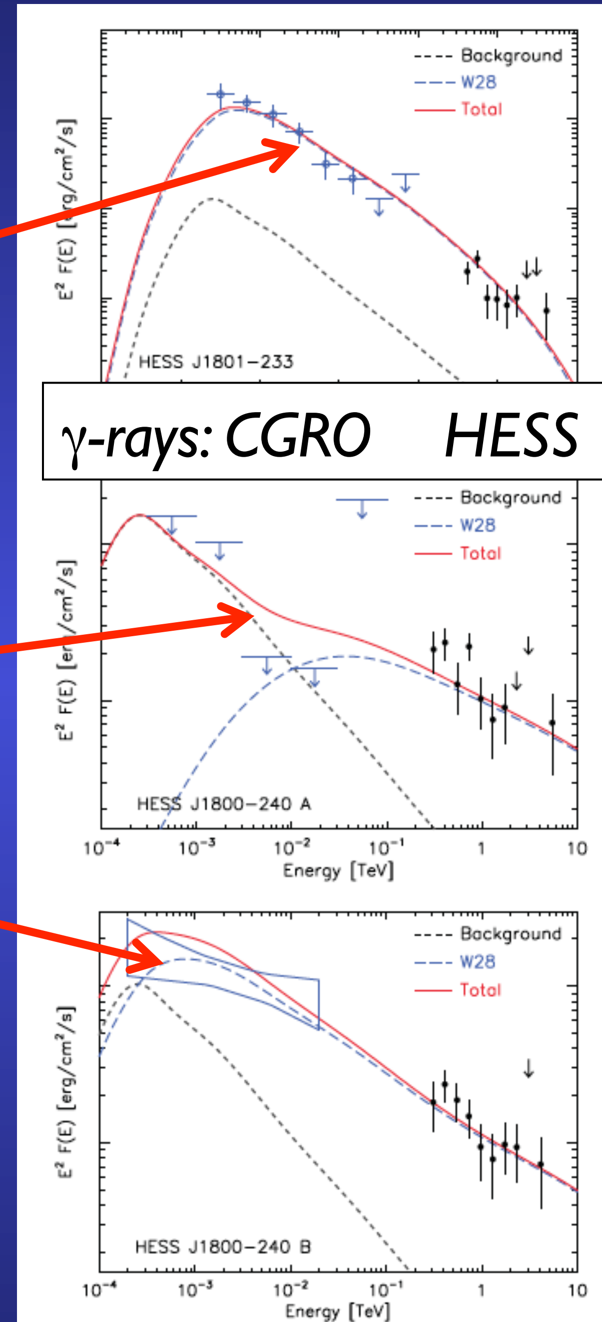
d ~ 2-3 kpc
D ≈ 20 pc
Age ~ 35-150,000 yrs

Case study:
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

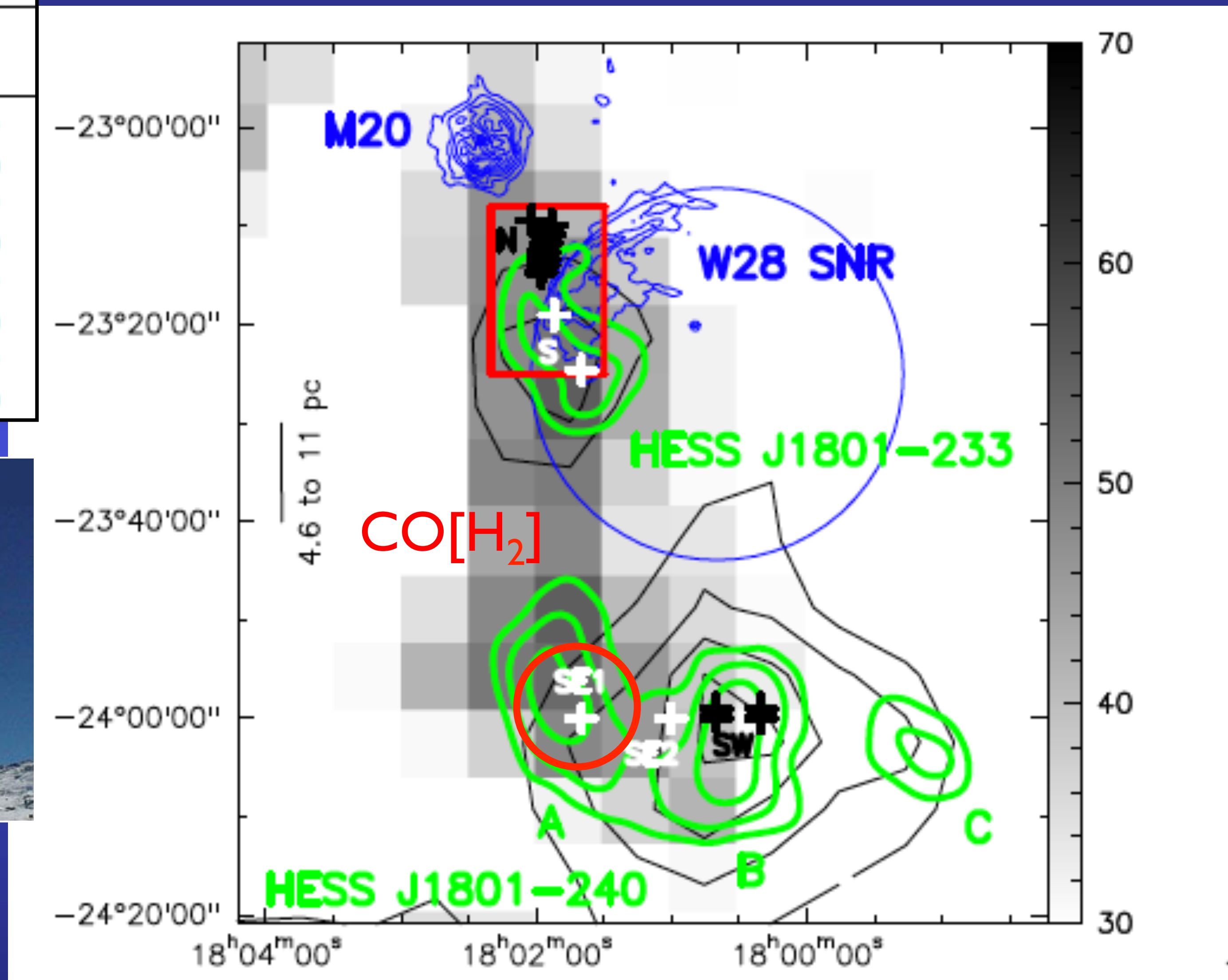
(Nava & Gabici 2013)

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

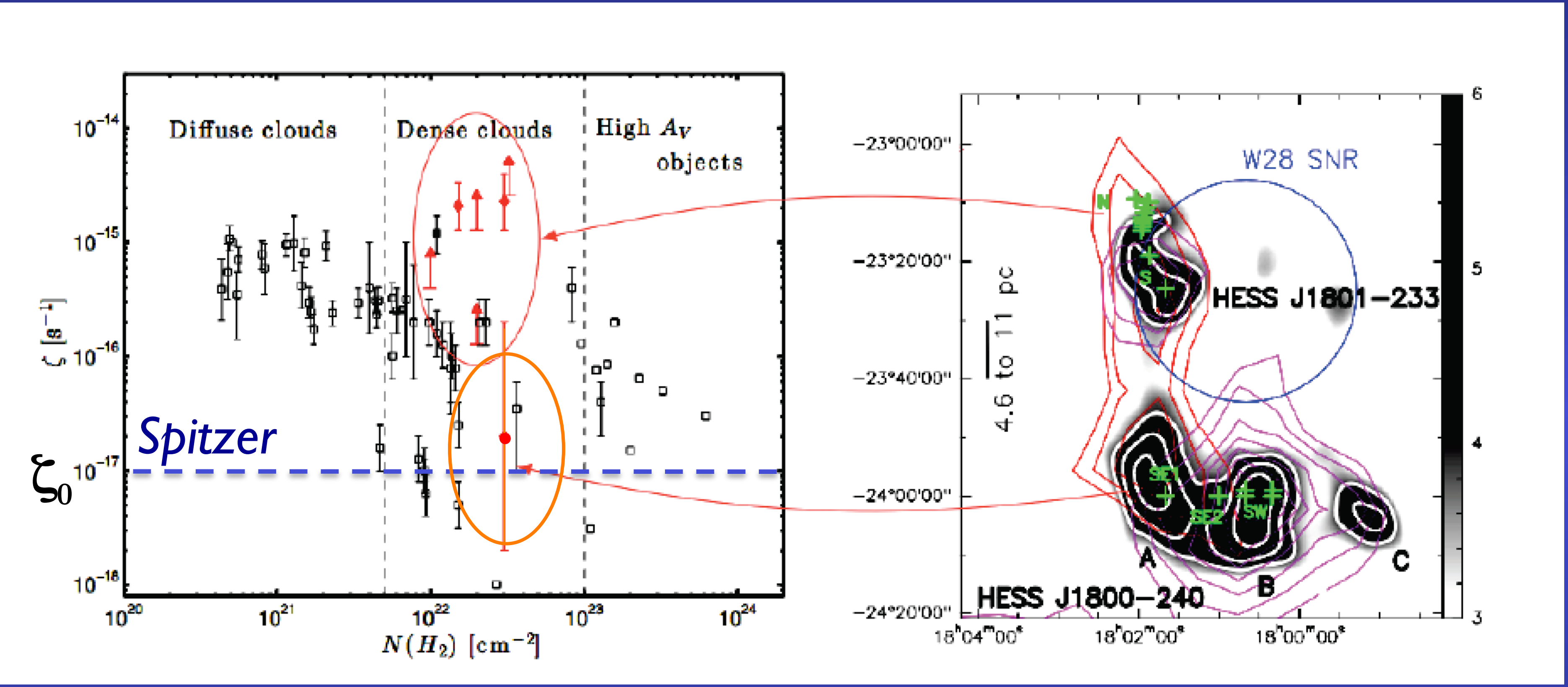
Species	Line
$H^{13}CO^+$	(1-0)
$C^{18}O$	(1-0)
^{13}CO	(1-0)
$C^{17}O$	(1-0)
DCO^+	(2-1)
$C^{18}O$	(2-1)
^{13}CO	(2-1)
$C^{17}O$	(2-1)

16 pointings

Vaupré+2014



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



⇔ enhancement of LECR

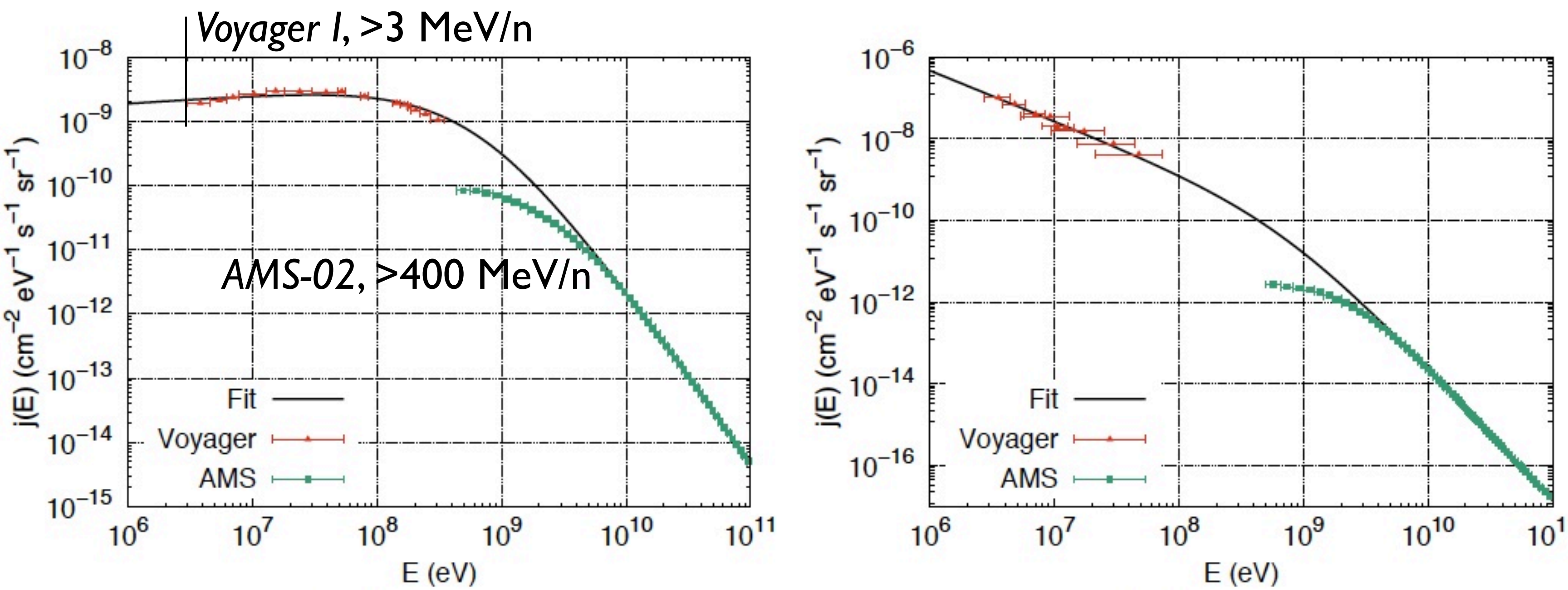
≈ enhancement of *local* HECR from π°-decay γ-rays

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

New mystery: "The ionization problem"

- Recent work by 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 (≥ 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)
- => Counterexamples ? **See W28**
- => or invoke *very-low energy* "suprathermal" CR (< 3 MeV/n) ?

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



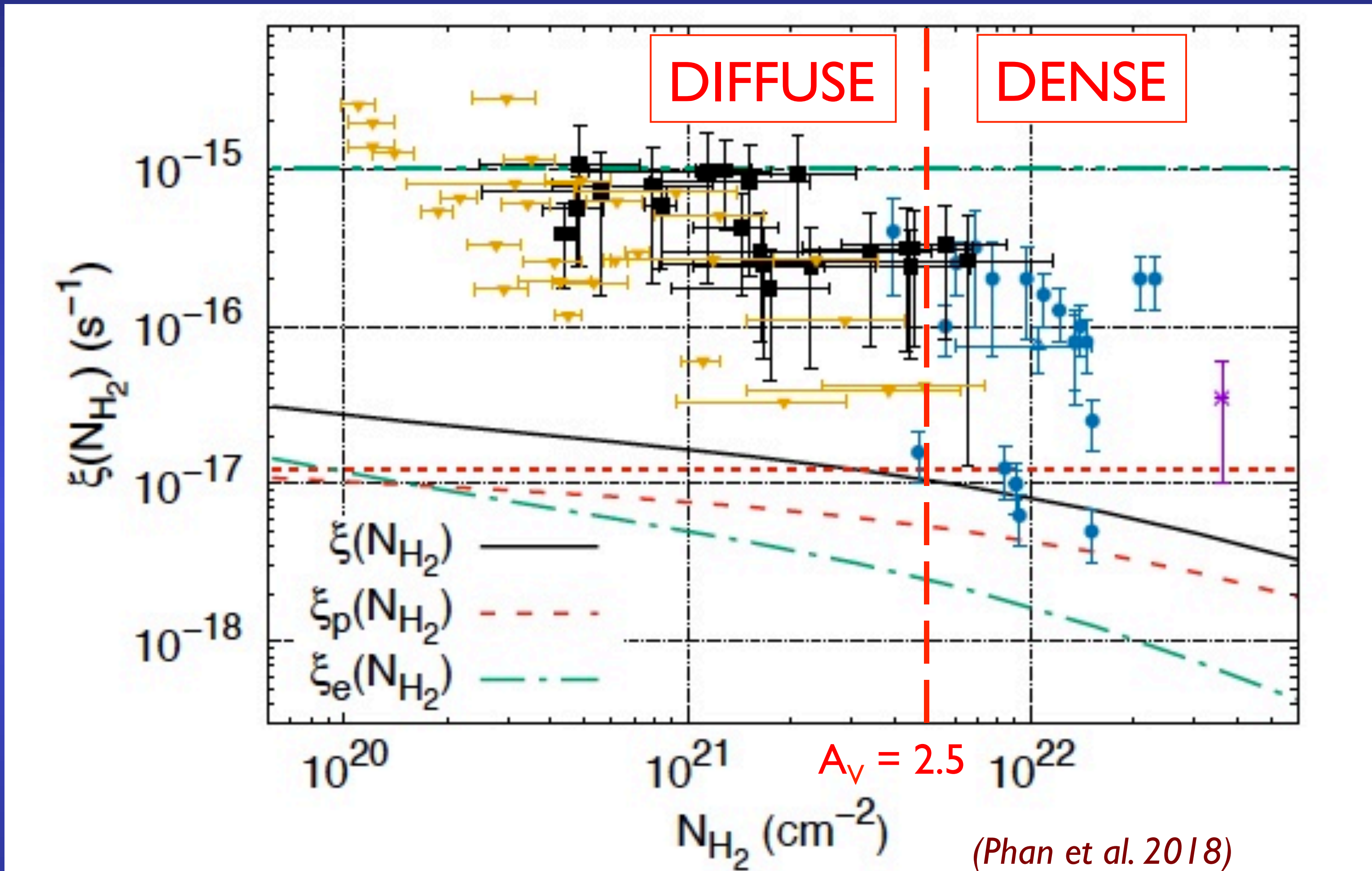
(a) CR protons

(b) CR electrons

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)

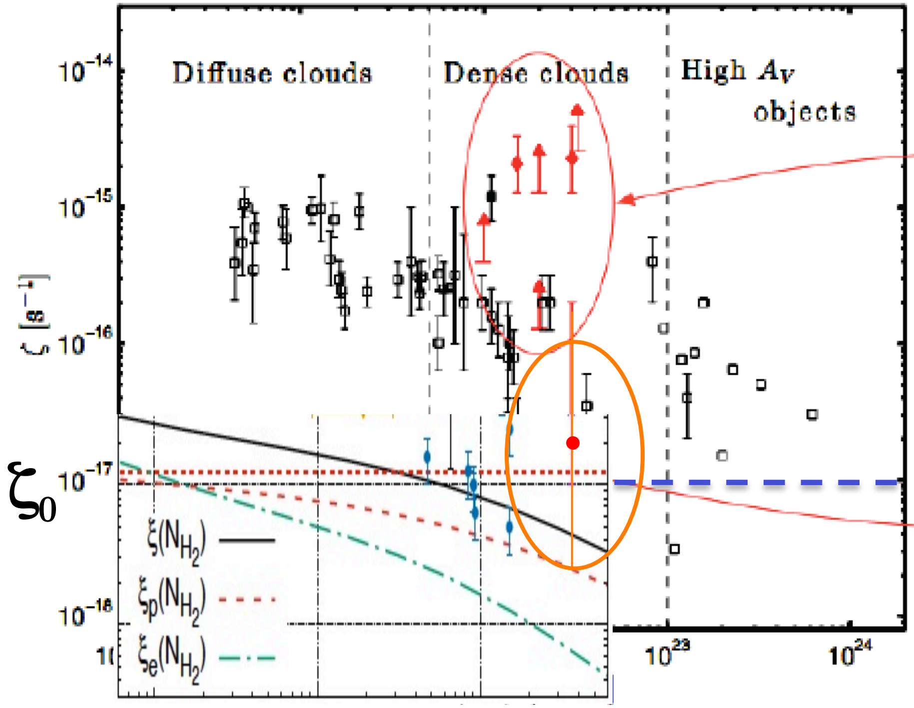
ISM ionization by GCR: fact. >10 too low !

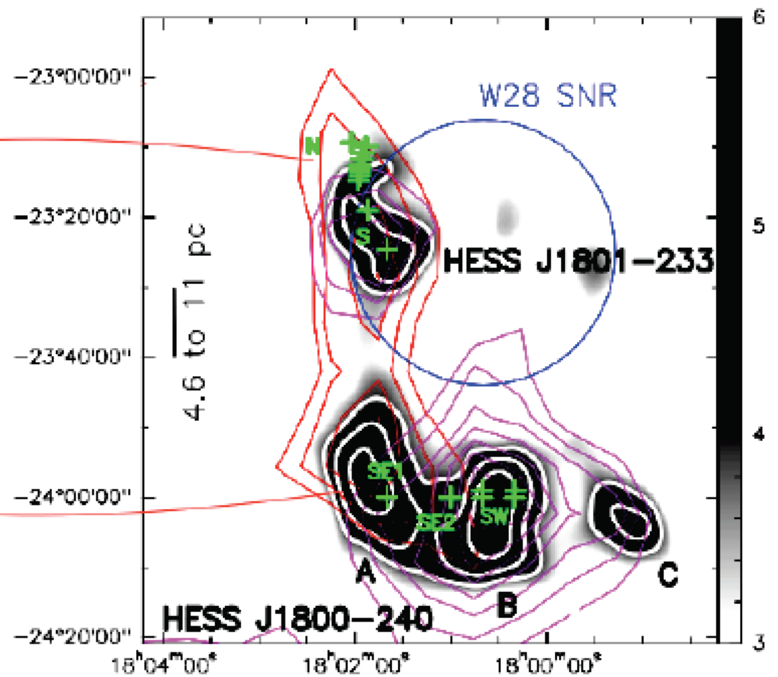


points are from Caselli et al. (1998) (blue filled circles), Williams et al. (1998) (blue empty triangle), Maret & Bergin (2007) (purple asterisk), and Indriolo & McCall (2012) (black filled squares are data points while yellow filled inverted triangles are upper limits).

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. Conclusions & open issues

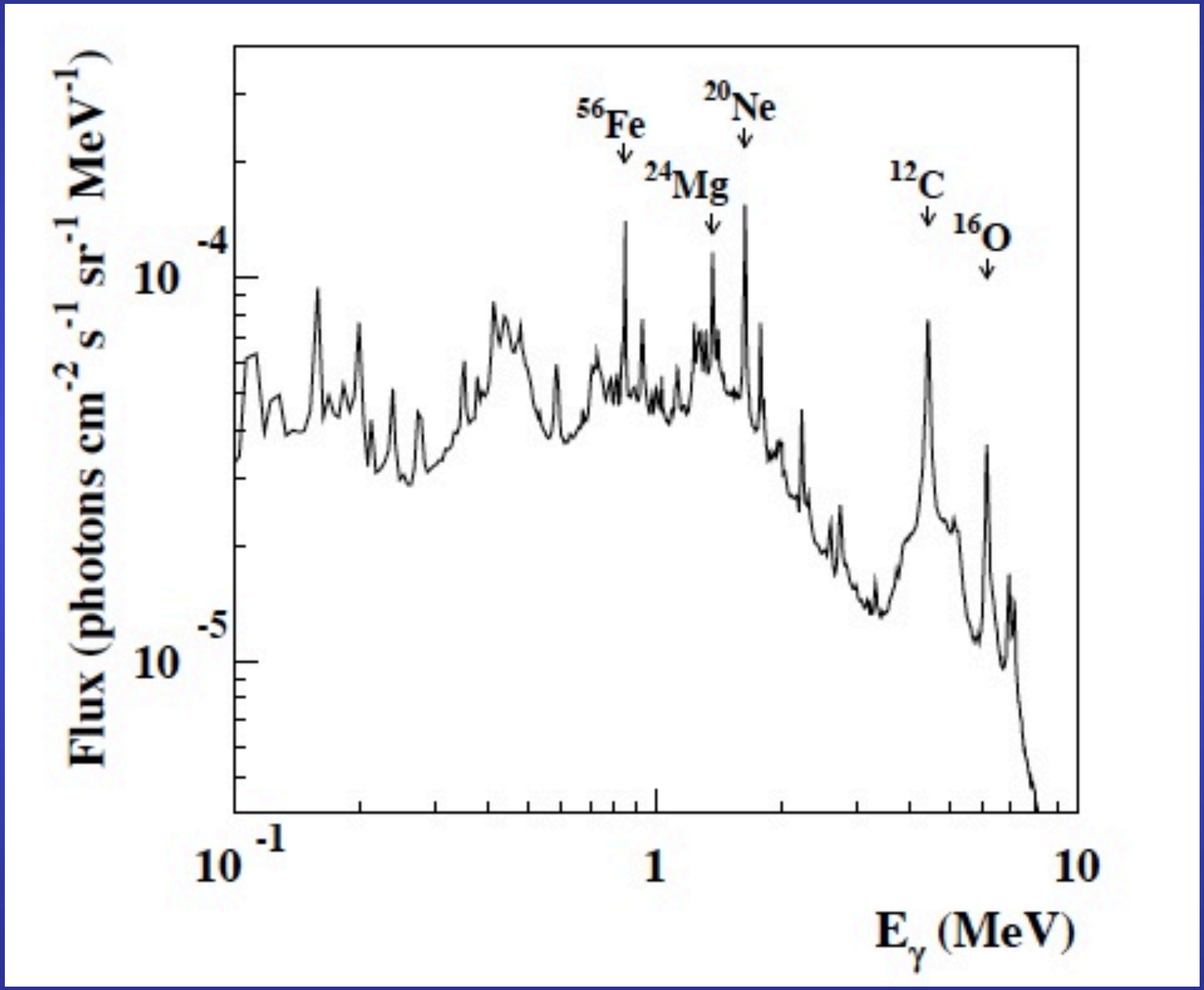
- Origin of cosmic rays still a puzzle, in spite (or because) of recent advances
- For galactic cosmic rays, supernova remnants interacting with molecular clouds are a good laboratory for studying hadron acceleration
  - via γ-rays at high energies (down to ~ 280 MeV, π°-decay threshold)
  - via mm observations+astrochemistry 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 ?*

New approach: *LECR (>10-20 MeV)* nuclear *interactions with the low-density ISM =>* γ*-ray lines(< 10 MeV)*

- 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*
- 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., e.g., Tatischeff+ 2012, 2018)

– Other: α (CR) + CNO (ISM) $\rightarrow$ ^{56}Fe, ^{24}Mg, ^{20}Ne, ^{12}C, ^{16}O...

Predicted nuclear γ-lines towards the center of the Galaxy



(Tatischeff+ 2012)

Proposed satellite experiment to detect nuclear γ-lines (among other goals): eAstrogam

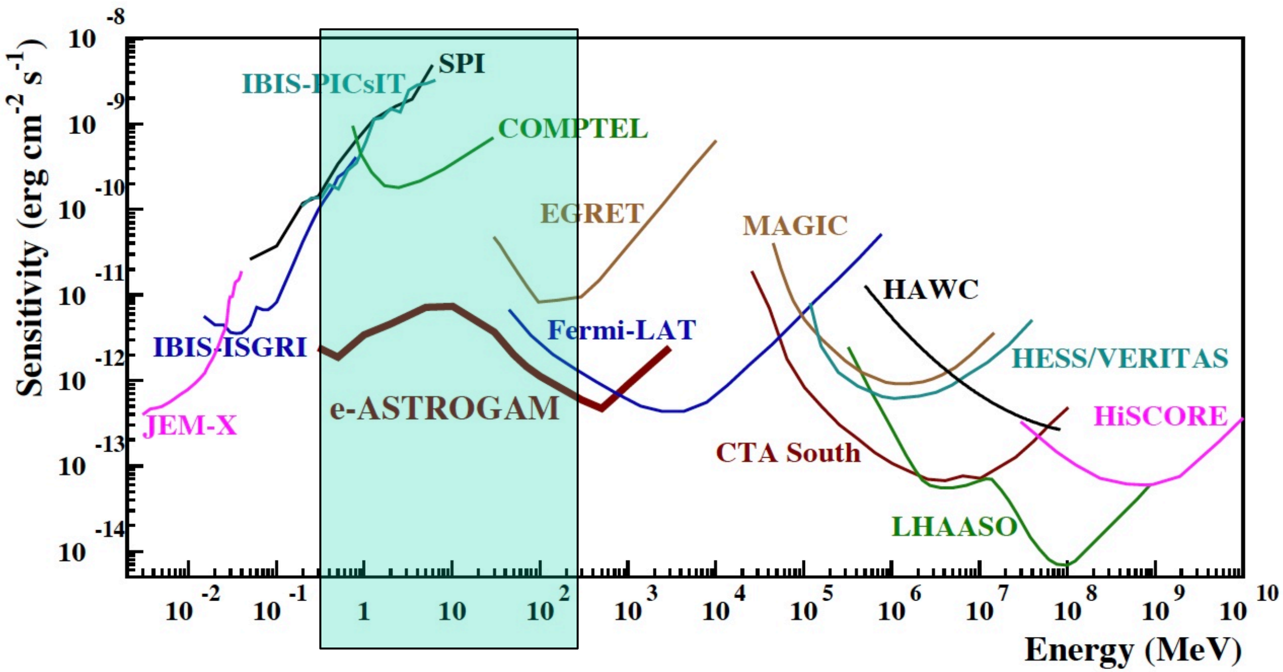
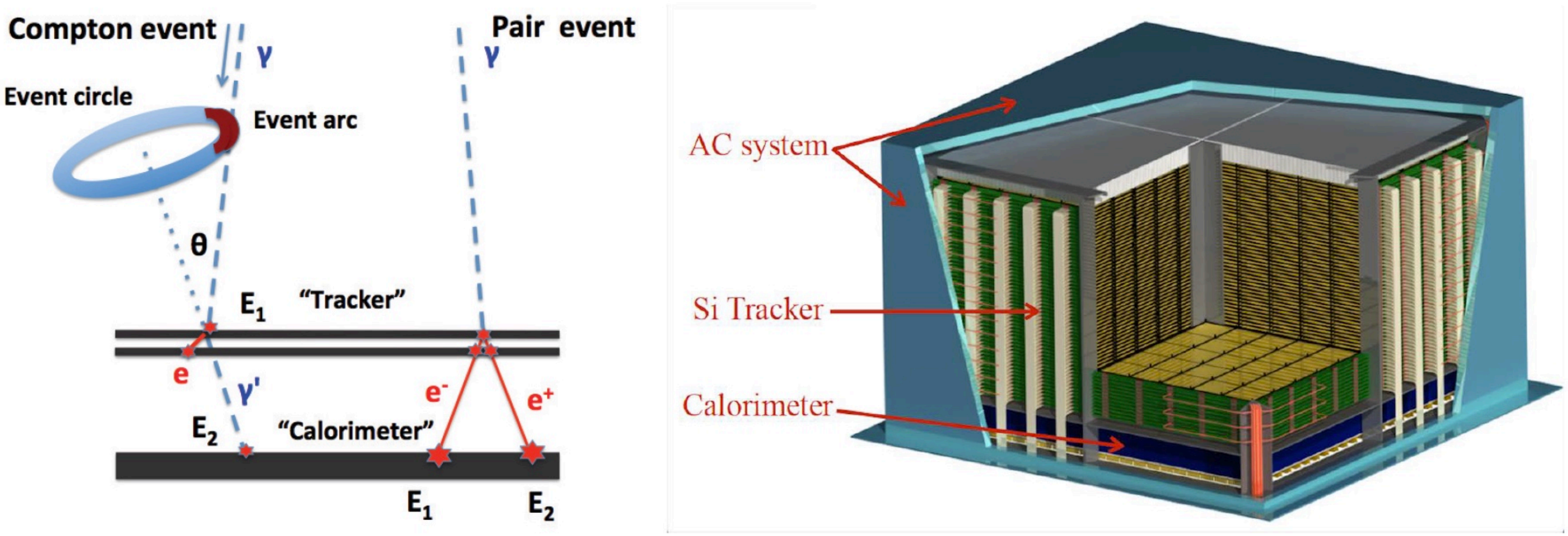


Figure 1: Point source continuum differential sensitivity of different X- and γ-ray instruments. The curves for *INTEGRAL*/JEM-X, IBIS (ISGRI and PICsIT), and SPI are for an effective observation time $T_{\rm obs} = 1$ Ms. The COMPTEL and EGRET sensitivities are given for the typical observation time accumulated during the ∼9 years of the *CGRO* mission (see Fig. 1 in Ref.[2]). The *Fermi*/LAT sensitivity is for a high Galactic latitude source in 10 years of observation in survey mode. For MAGIC, VERITAS (sensitivity of H.E.S.S. is similar), and CTA, the sensitivities are given for $T_{\rm obs} = 50$ hours. For HAWC $T_{\rm obs} = 5$ yr, for LHAASO $T_{\rm obs} = 1$ yr, and for HiSCORE $T_{\rm obs} = 1000$ h. The e-ASTROGAM sensitivity is calculated at 3σ for an effective exposure of 1 year and for a source at high Galactic latitude.

(Tatischeff+ 2018)

eAstrogam basics



(a) (b)

Figure 4: (a) Representative topologies for a Compton event and for a pair event. Photon tracks are shown in pale blue, dashed, and electron and/or positron tracks are in red, solid. (b) Overview of the e-ASTROGAM payload.

(Tatischeff+ 2018)