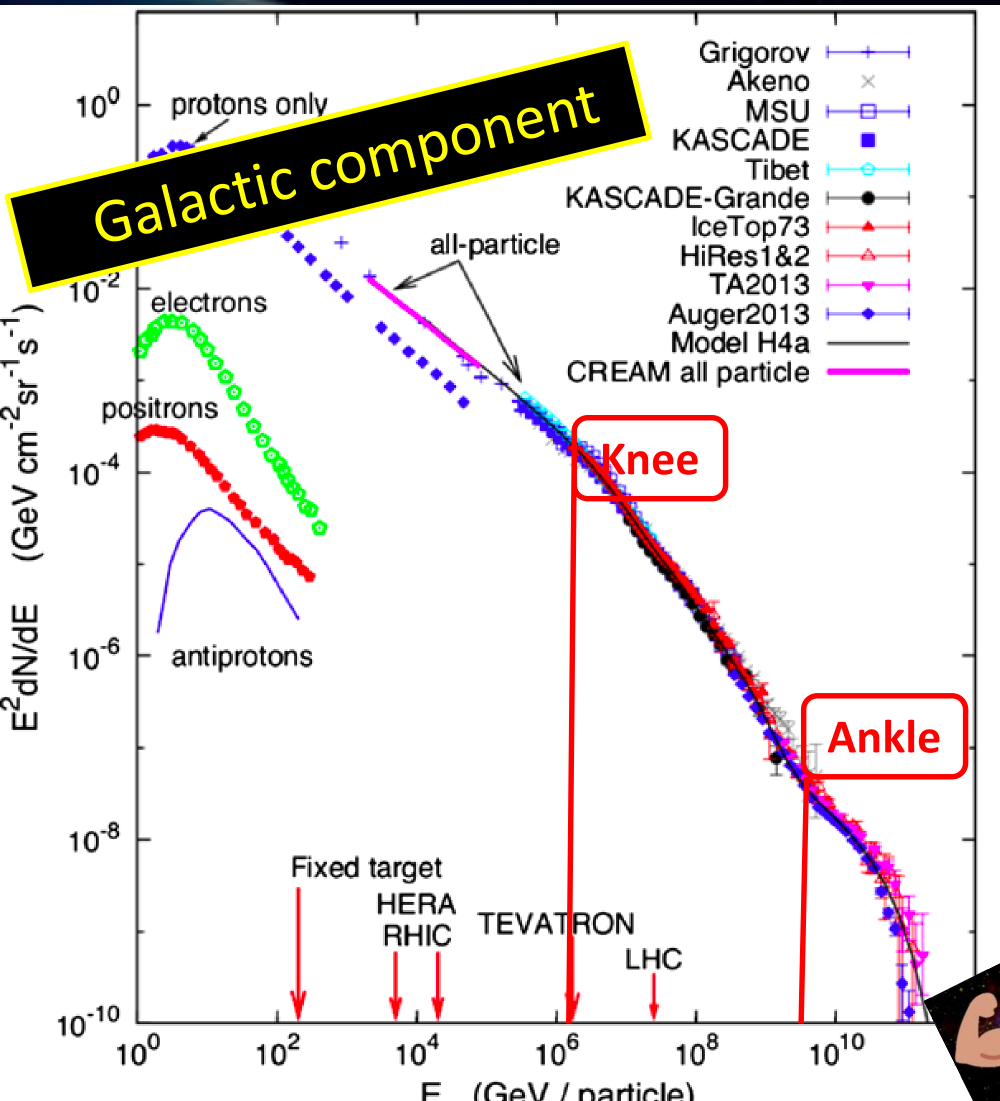
A TPC for MeV Astrophysics
13 April,2017-Ecòle Polytechnique

Cosmic Rays & Supernova Remnants love story: The Importance Of MeV energies

Martina Cardillo [*INAF- IAPS]*
martina.cardillo@iaps.inaf.it

Cosmic-Ray overview

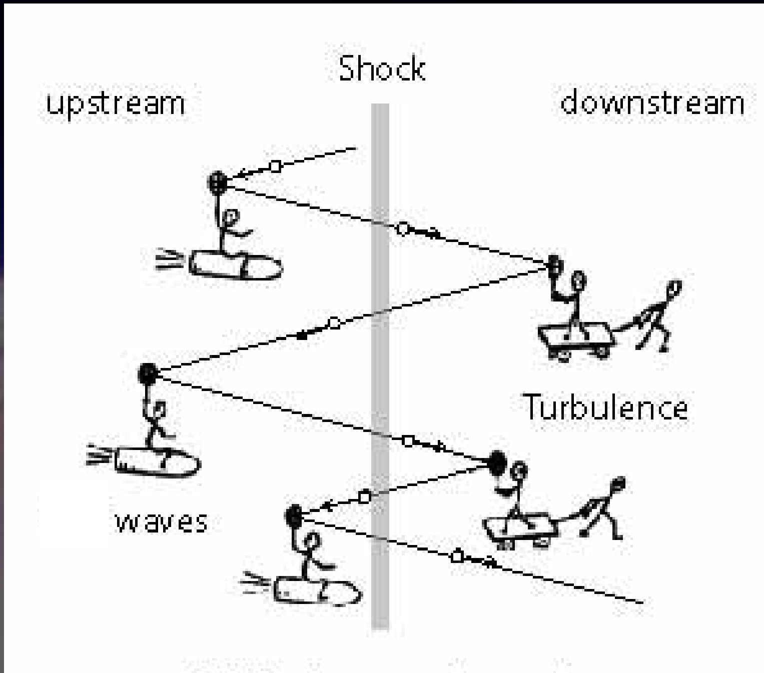


- High-energy particles (mostly protons and nuclei) up to 10^{20} eV
- Bending below 30 GeV due to solar modulation
- Power-law distribution with an index $\alpha \simeq 2.7$ up to PeV energies
- Two main features:
  - Steepening at PeV energies, $\alpha \simeq 3.1$ (*Knee*, 1 part/m^2/yr)
  - Hardening at about E=10^{18} eV (*Ankle*, 1 part/km^2/yr)
- Galactic component likely originates in the SNR shocks

Energetics → with only 10% of SN energy we can explain CR energy density
$\varepsilon_{CR} \cong 10^{40} erg/s$

SNR and Diffusive Shock Acceleration

SNRs have to be able to accelerate particles up to 10^{15} eV



First order Fermi acceleration:

- Fast and high gain $\frac{\Delta E}{E} \sim \frac{V_S}{c}$
- Power-law injection index $\gamma_E = 2$

$$N(E)dE \propto E^{-\gamma_E} dE = 4\pi p^2 p^{-\gamma_p} dp$$

$$\gamma_p = \frac{3\mathcal{R}}{\mathcal{R}-1} \qquad \mathcal{R} = \frac{u_u}{u_D} = \frac{4M_s^2}{3+M_s^2}$$

Strong shock: $M_s \to \infty$, $\mathcal{R} \to 4, \gamma_E \to 2$

Acceleration time must to be lower than the source age and the loss time

$$t_{acc} \approx \frac{D(p)}{V_s^2} = \min(t_{age}, t_{loss})$$

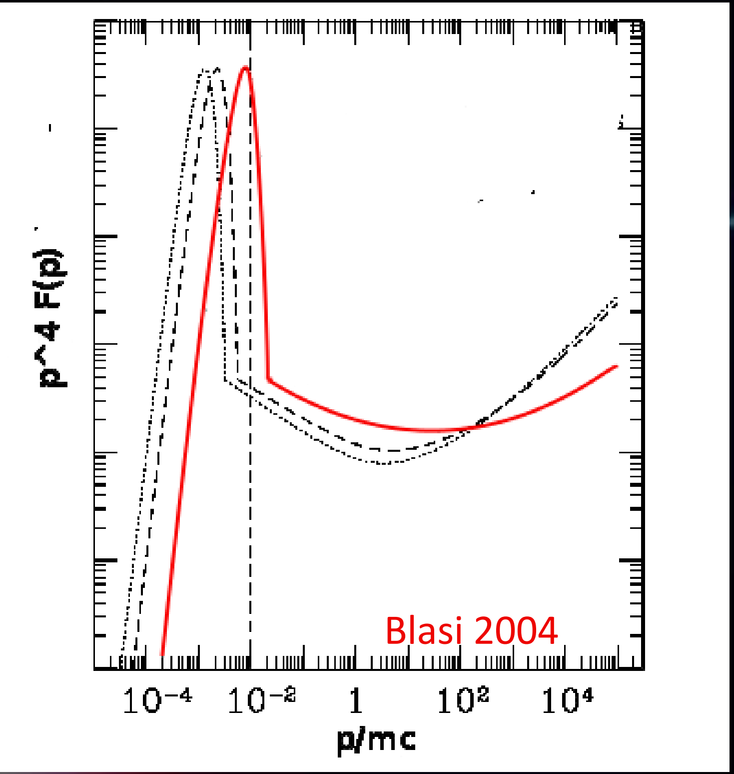
$$\begin{cases} D(p) = \frac{1}{3} c r_L \left(\frac{L_c}{r_L}\right)^{\delta\prime} \\ r_L = \frac{\gamma m v}{eB} \end{cases} \Longrightarrow$$

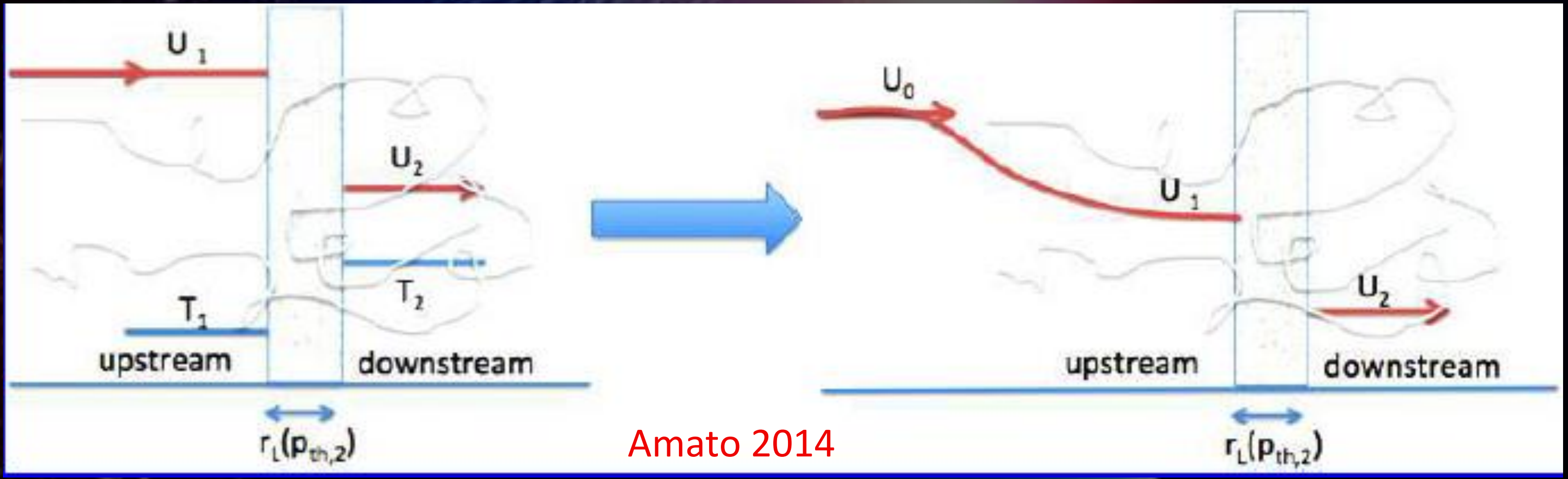
Magnetic Field Amplification

Non-Linear Diffusive Shock Acceleration

Magnetic field Amplification leads to CR back reaction
→ no more test particle

- Precursor Formation
  - concavity ($\gamma_E < 2$)
- Lower Downstream Temperature
  - thermal peak at lower energies



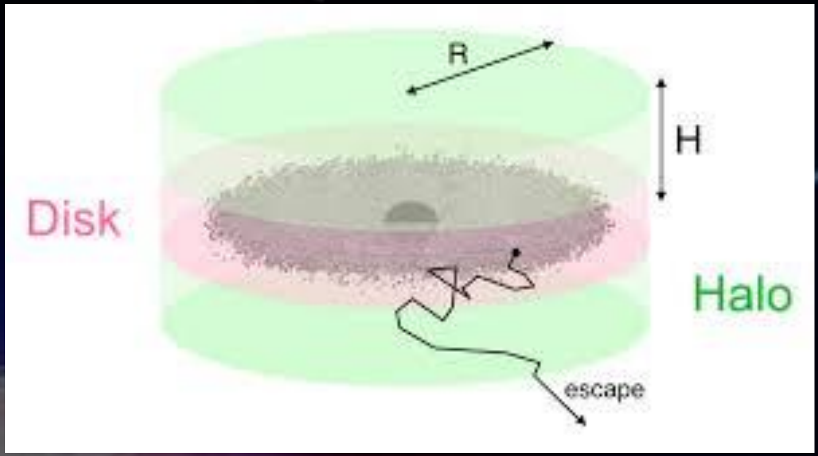


Observed Spectrum: CR propagation

Leaky Box Model

$$\tau_{esc} \approx \frac{H^2}{D(E)} \qquad D(E) = D_0 E^{\delta}$$

$$N(E) \approx \frac{N_s(E)\mathcal{R}_{SN}\tau_{esc}}{2\pi R_D^2 H} \approx E^{-(\gamma_E+\delta)}$$



We can have an estimation of the diffusion index measuring secondary to primary ratio (B/C).

$$N_{SEC}(E) \approx N(E)\mathcal{R}_{spal}\tau_{esc} \approx E^{-(\gamma_E+2\delta)} \longrightarrow \frac{N_{SEC}(E)}{N(E)} \propto E^{-\delta}$$

$$\begin{cases} 0.7 > \delta > 0.3 \\ 2 < \gamma_E < 2.4 \end{cases} \Rightarrow$$

Degeneration broken considering CR anisotropy due to discreteness of the sources (no leaky box)

$$\delta \sim 0.3 \qquad \gamma_E \sim 2.3 - 2.4$$

Messengers and Instruments

Direct Detection (E<100 GeV)

Particles

- Proportional tubes and scintillators (e.g. CREAM, TRACER)
- Magnetic Spectrometers and silicon tracker (e.g. PAMELA, AMS-02)

Gamma-rays

- Silicon Tracker and calorimeter (AGILE, Fermi-LAT)

Indirect Detection (E>100 GeV)

Particles

- Scintillators and Multiple Resistive plate chambers (e.g. KASCADE-Grande, Argo)
- Water Cherenkov (e.g. Milagro)
- Hybrid: water Cherenkov and fluorescence (e.g. Auger)

Gamma-rays

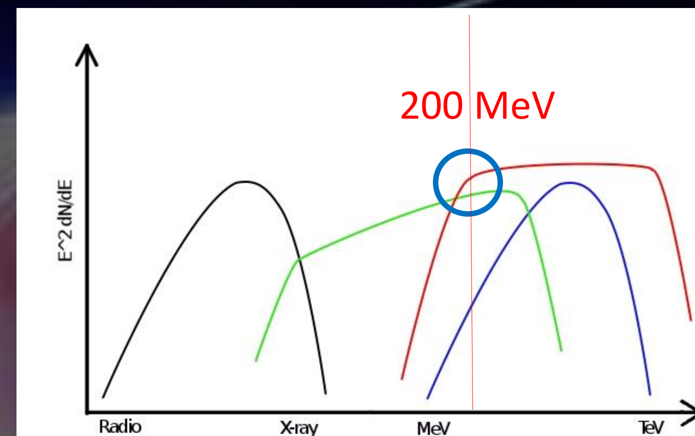
- Imaging Atmospheric Air Cherenkov (e.g. HESS, VERITAS, MAGIC)

SNRs and CRs: direct proofs

GAMMA-RAY PHOTONS

- No deviations → source direction
- Same spectrum of primary protons
- $E_{\gamma,M} \simeq 10\% \ E_{p,M}$

$$p + p_{target} \rightarrow \cdots + \pi^0 \rightarrow 2\gamma$$

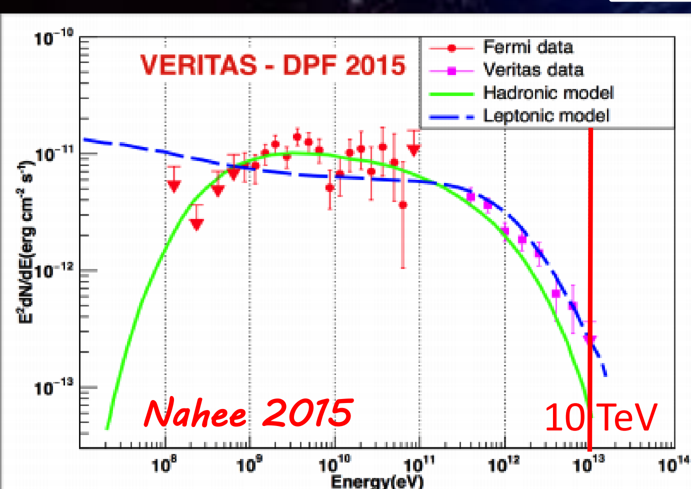


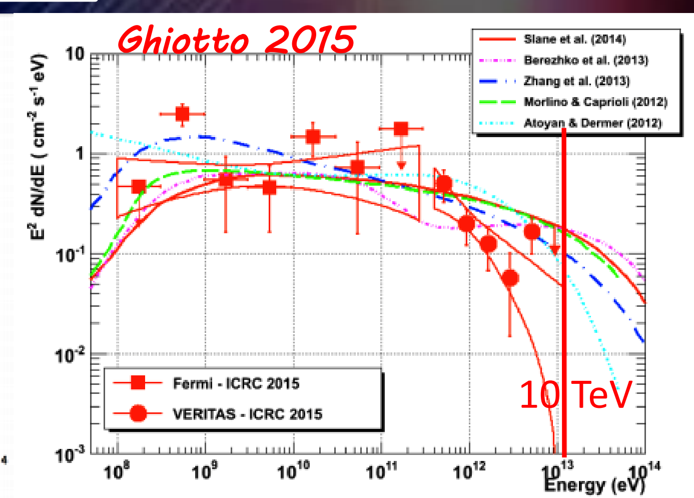
Low-Energies

Confirming hadronic origin

→ We can distinguish leptonic from hadronic component only at E<200 MeV

High-Energies ➡ CTA

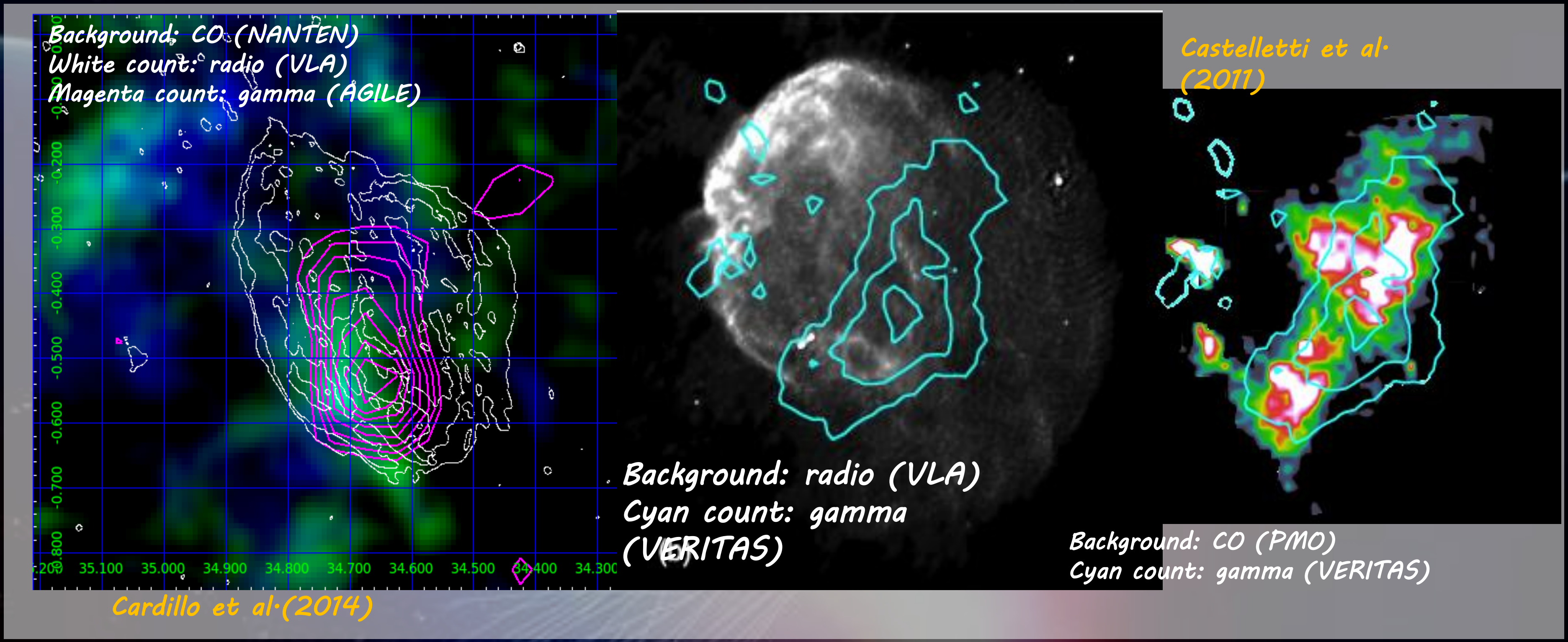




Revealing PeV emission from young SNRs

→ In spite of the large number of young SNRs detected in the gamma-ray band, none of these seems to reach E= 100 TeV

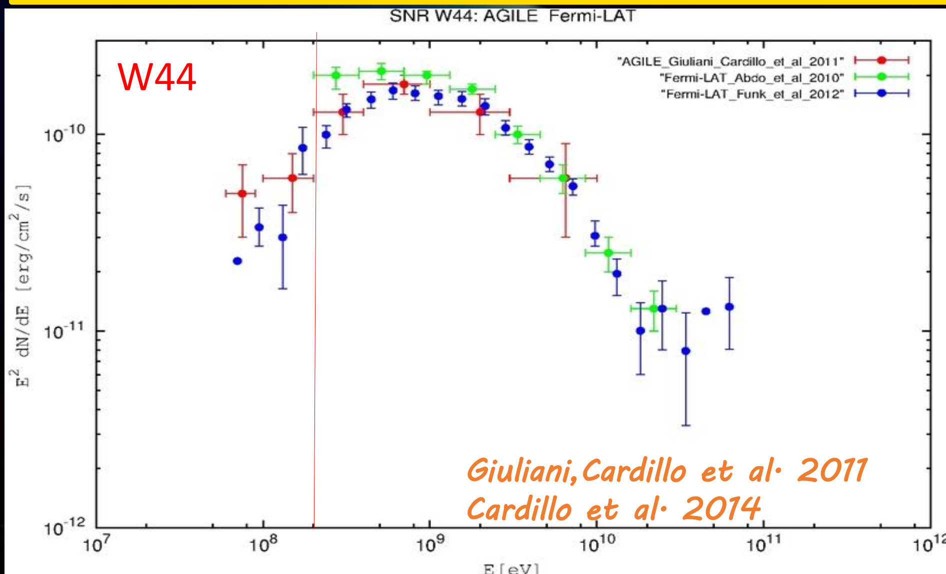
Low-energy gamma-rays



- ✧ Middle aged SNRs ($t \geq 10^4$ yrs) with a slow shock velocity ($v_s \sim 100$ km/s)
- ✧ Interaction with a molecular cloud (high average density, $n \sim 200\ cm^{-3}$) → correlated with GeV (and TeV for IC443) gamma-ray emission
- ✧ Correletion with part of the radio emission in W44, no correlation in IC443

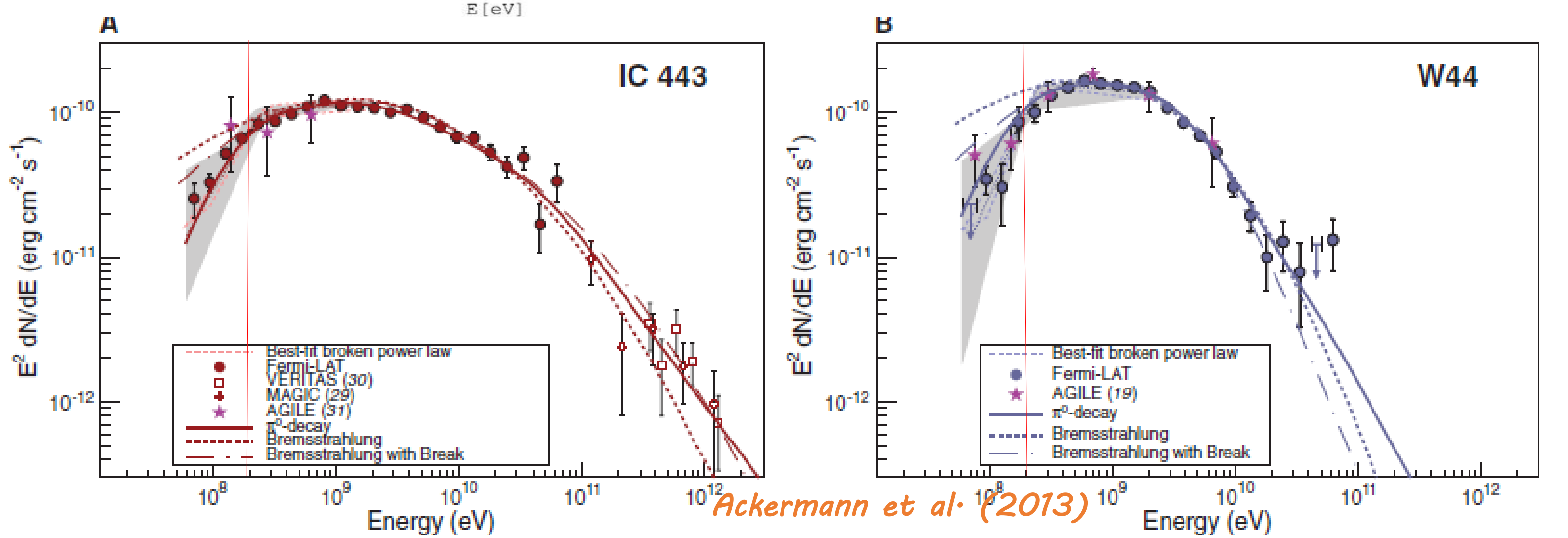
Low-energy gamma-rays

Gamma-ray emission below 200 MeV detected, for the first time, by AGILE from the SNR W44, then confirmed by Fermi-LAT, also in IC443

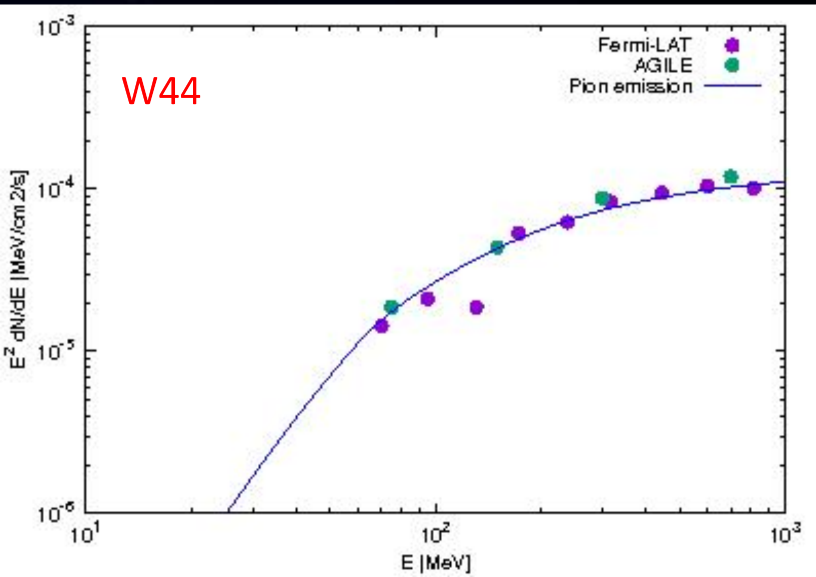


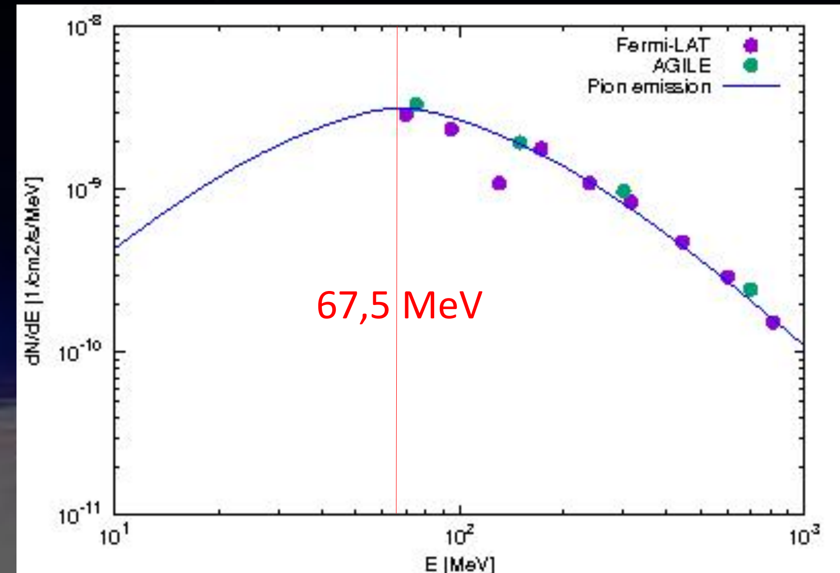
The low-energy behavior can be explained only with hadronic models → the first direct proof of CR proton presence in correspondence of a SNR shock

However....

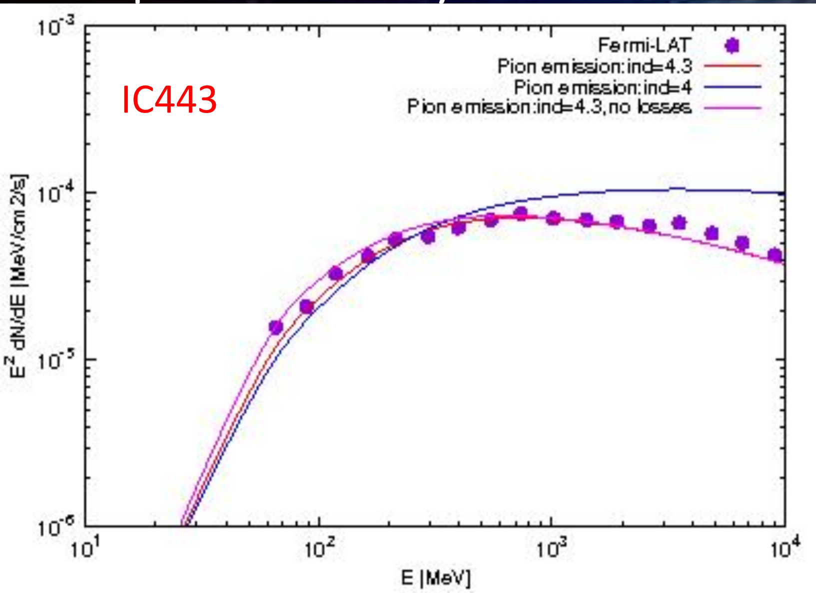


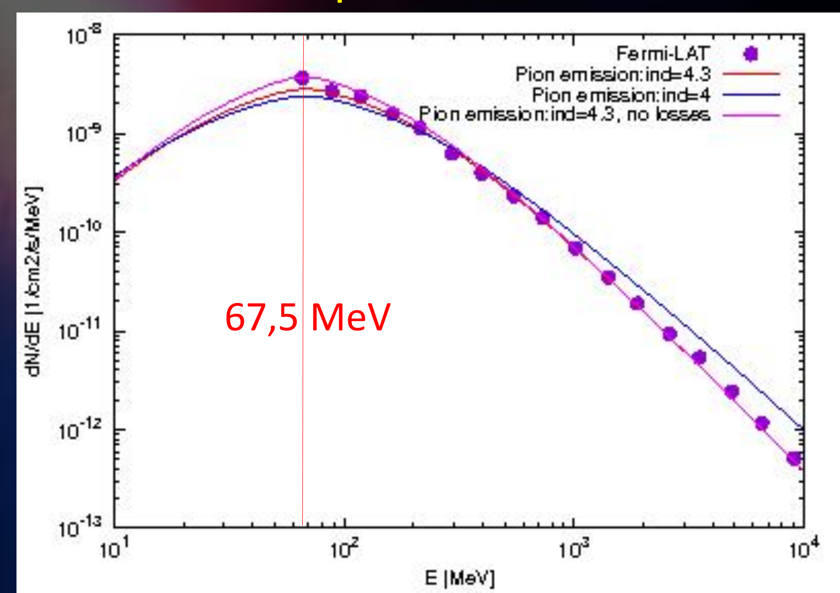
The Pion bump Issue





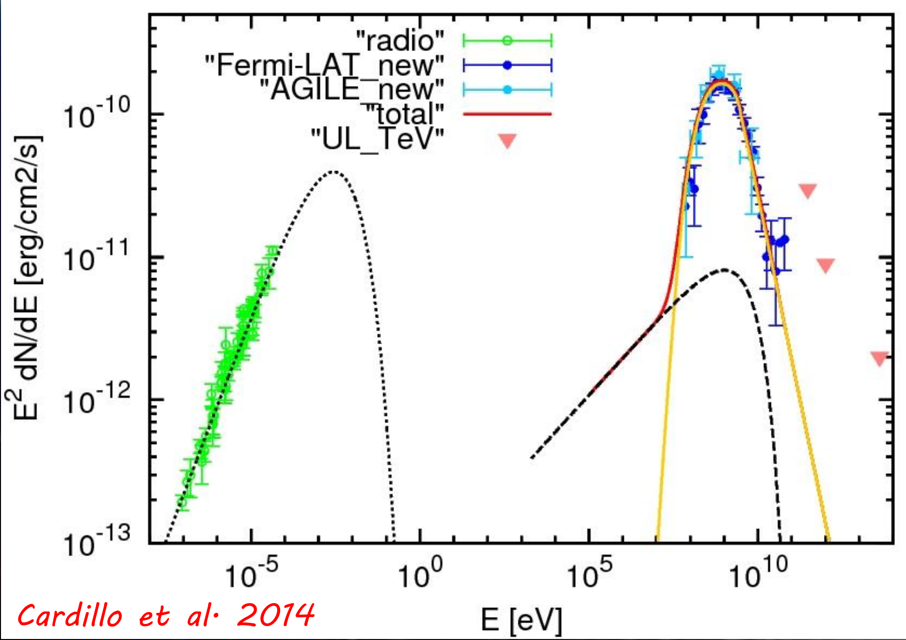
First of all, we need to reach even lower energies in order to see directly the 'pion bump' and not only its indirect effects. But there is a more important issue..

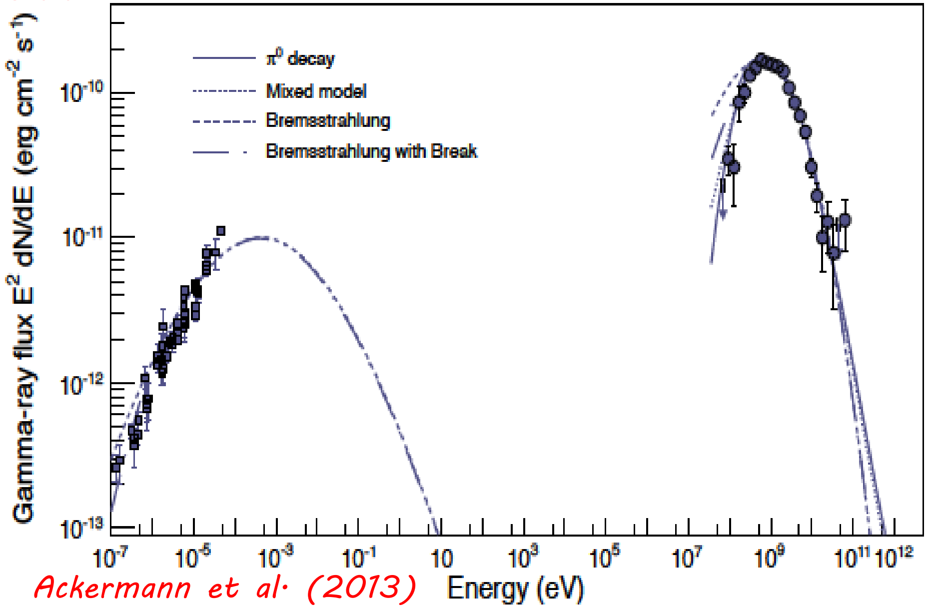




Acceleration…

W44





- ✧ Freshly accelerated CRs with a spectral index $\alpha=(3r_{sh})/(r_{sh}-1)$ at low-energies
- ✧ Broken power-law $\alpha=2.2$ below E~10 GeV and $\alpha=3.2$ above E~10 GeV
- ✧ Malkow steepening due to Alfvèn damping

PROBLEMS WITH ACCELERATION

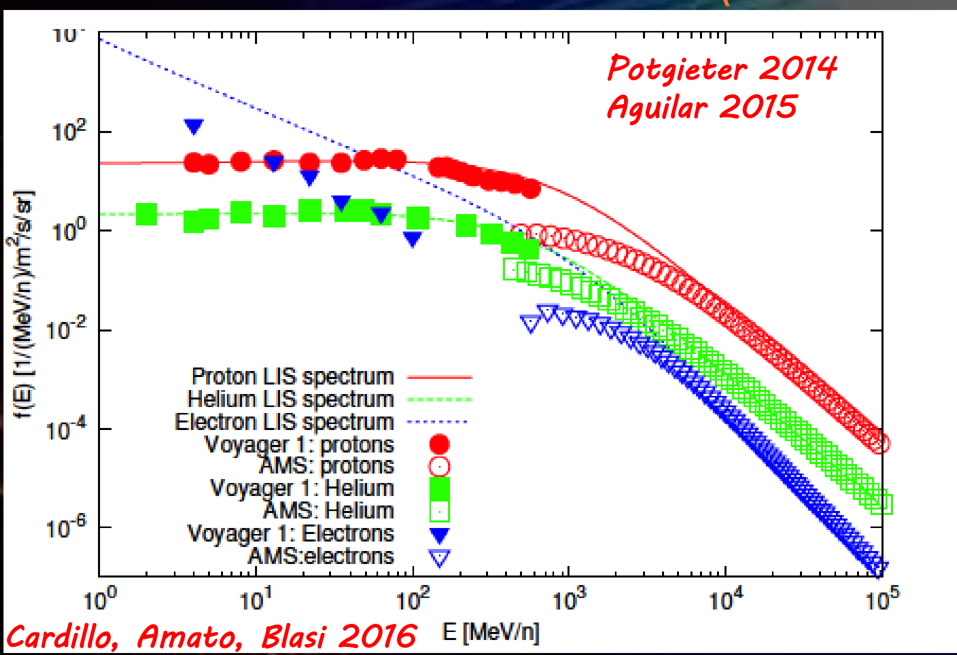
- Presence of a broken PL and of a so steep HE spectral index → not expected from diffusive shock acceleration theory;
- The shock of middle-aged remnants are slow → acceleration efficiency ξ_{CR} cannot be sufficiently high ($\rightarrow P_{CR}=\xi_{CR}\rho v_{sh}^2$)

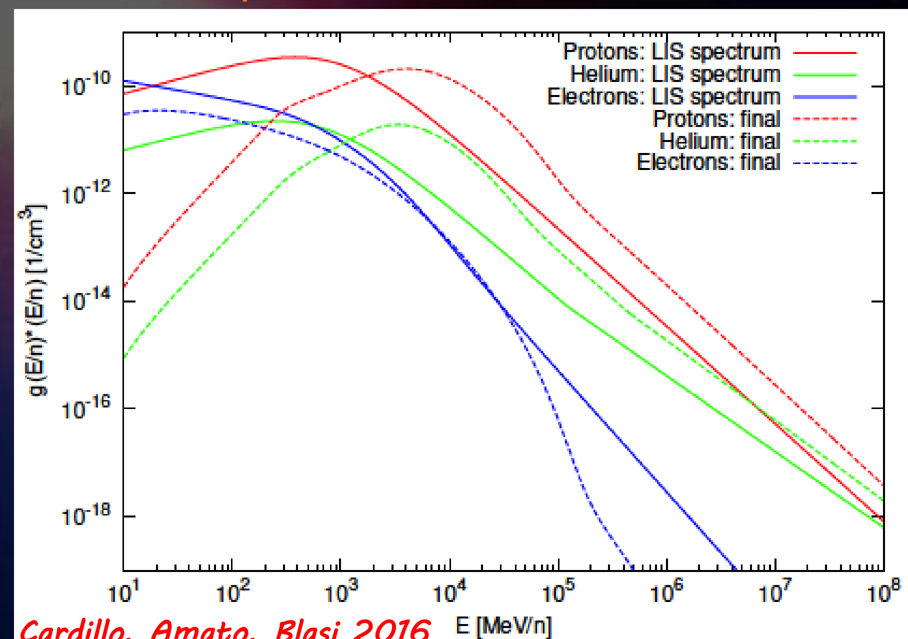
…or reacceleration?

- Pre-existing Galactic CR protons, Helium nuclei and electrons (Voyager spectra)
- Reacceleration → hardening of spectral indices steeper than $\alpha=(3r_{sh})/(r_{sh}-1)$
- Compression → higher energies, higher spectrum ($s=(n_2/n_0)/r_{sh}$)
- Contributions from secondary particles and low-efficiency accelerated CRs
- Simple PL spectrum ($r_{sh} = 3.5 \div 4$ → $\gamma_p=4.2\text{-}4$) with no steepening but HE cut-off due to the limited time (fully ionized pre-shock medium)
- A lot of parameters: magnetic field, density, interaction time, correlation length, shock velocity…

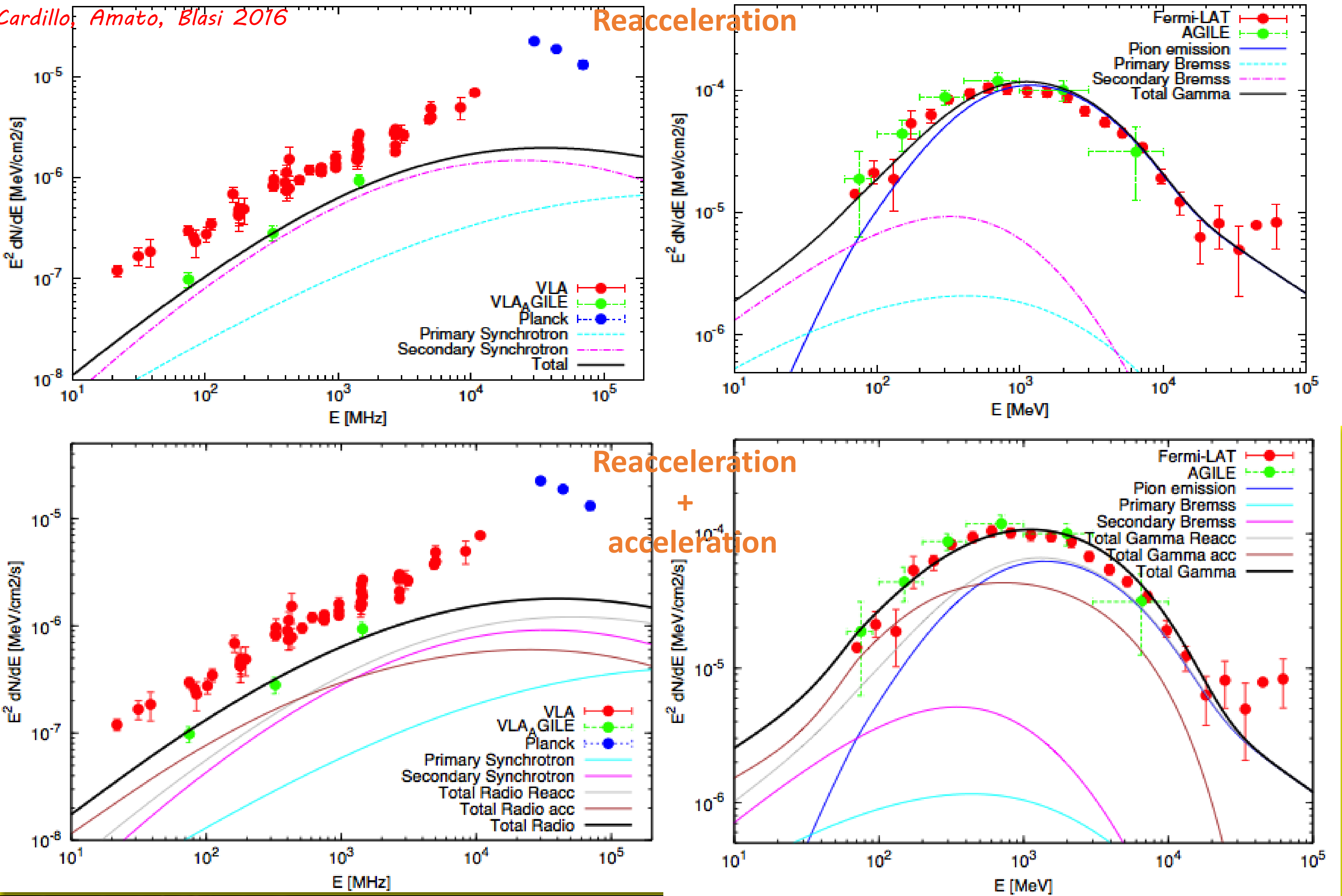
Crushed Cloud model

(Blandford & Cowie 1982)



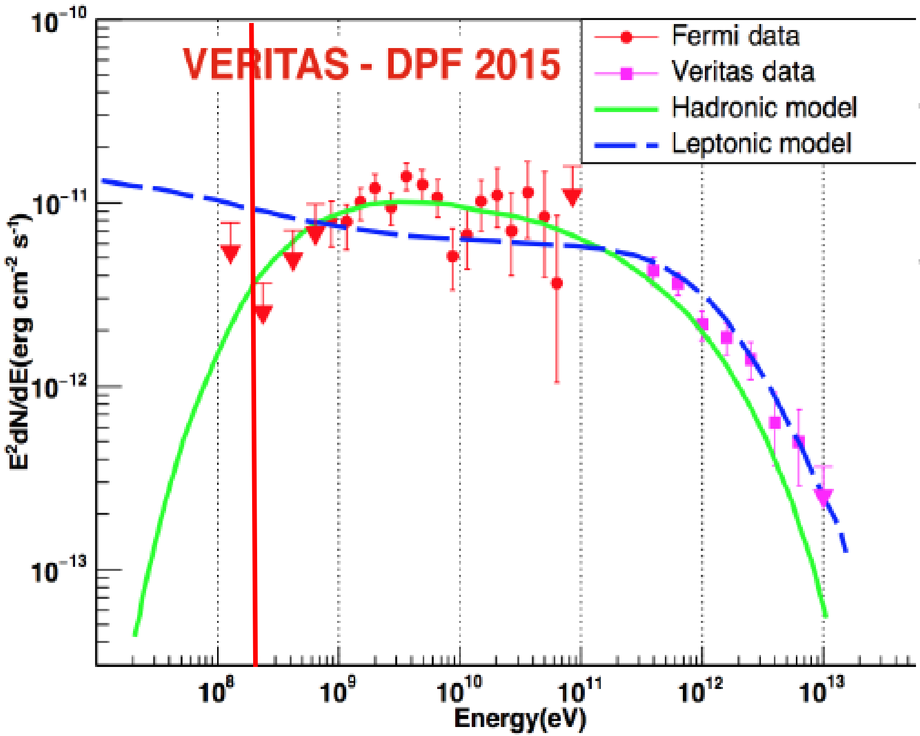


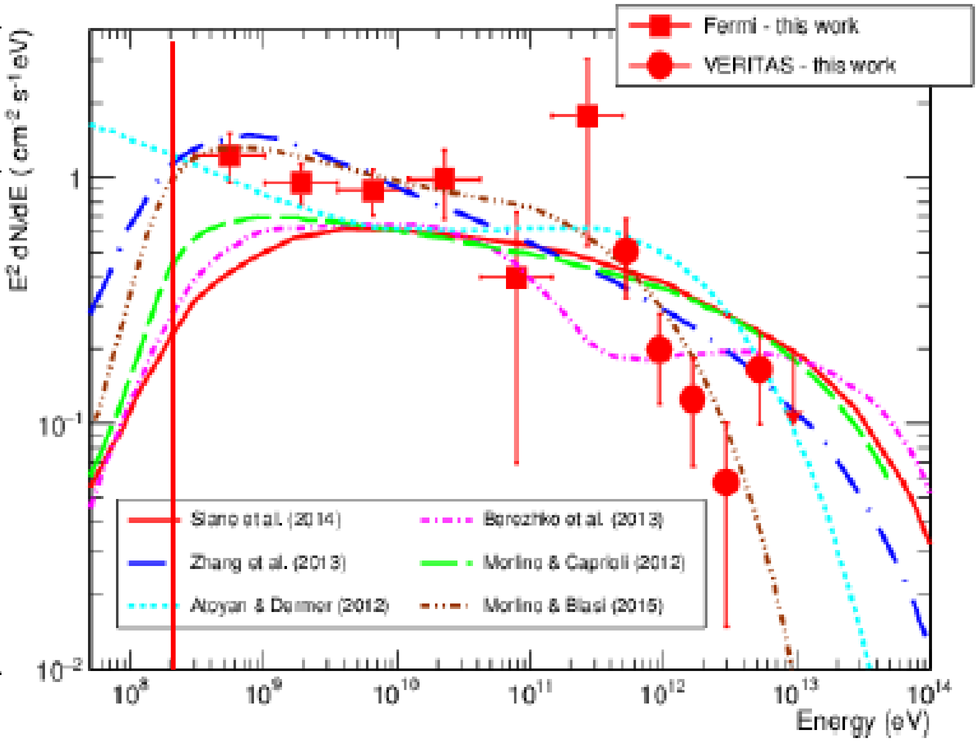
…or reacceleration?



The importance of young SNRs at MeV energies

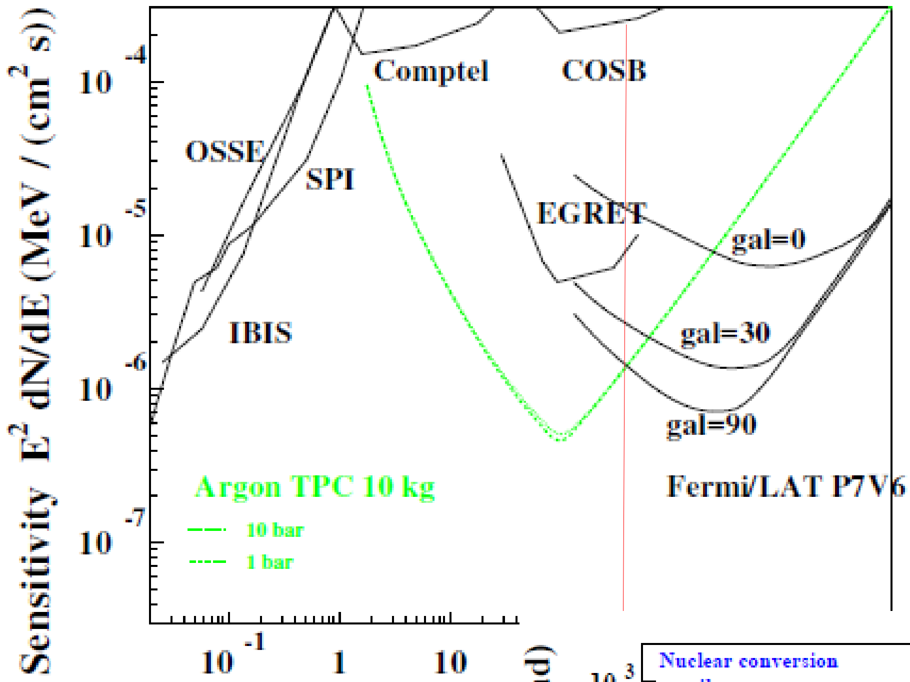
In order to have more chances to confirm the presence of freshly accelerated CRs in correspondence of the SNRs shocks, we need to detect young-fast ($\geq 10^3\ km/s$) shocks SNRs at E<200 MeV.

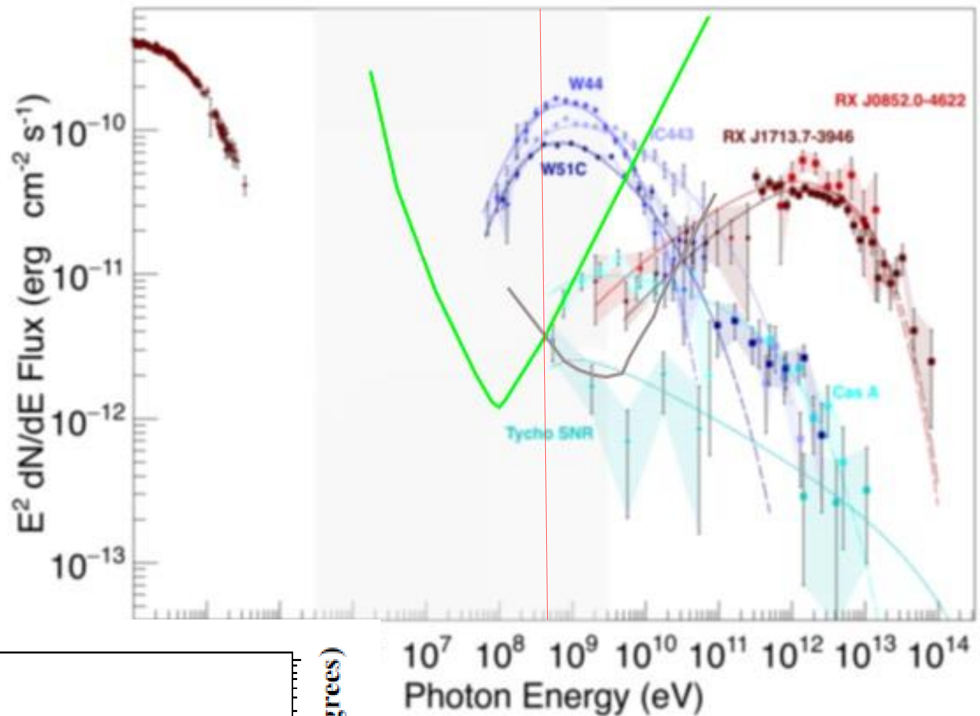


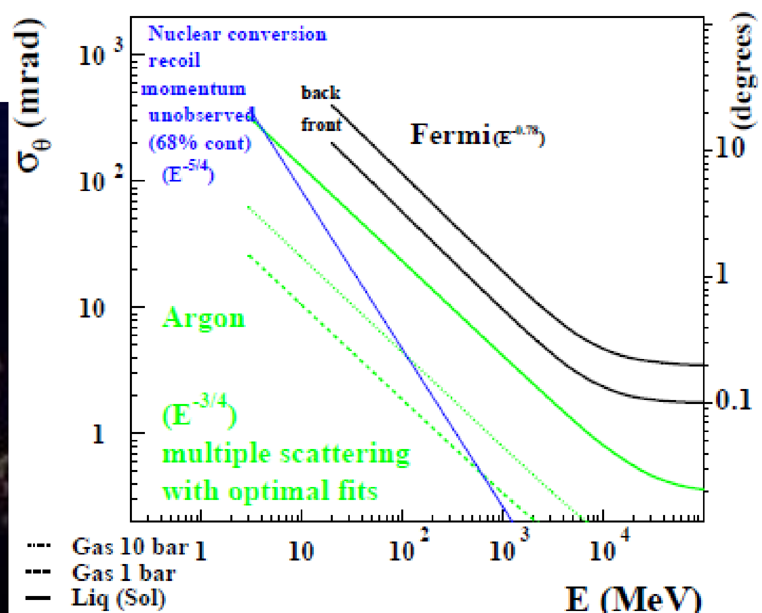


3 year sensitivity
(Bernard Document)

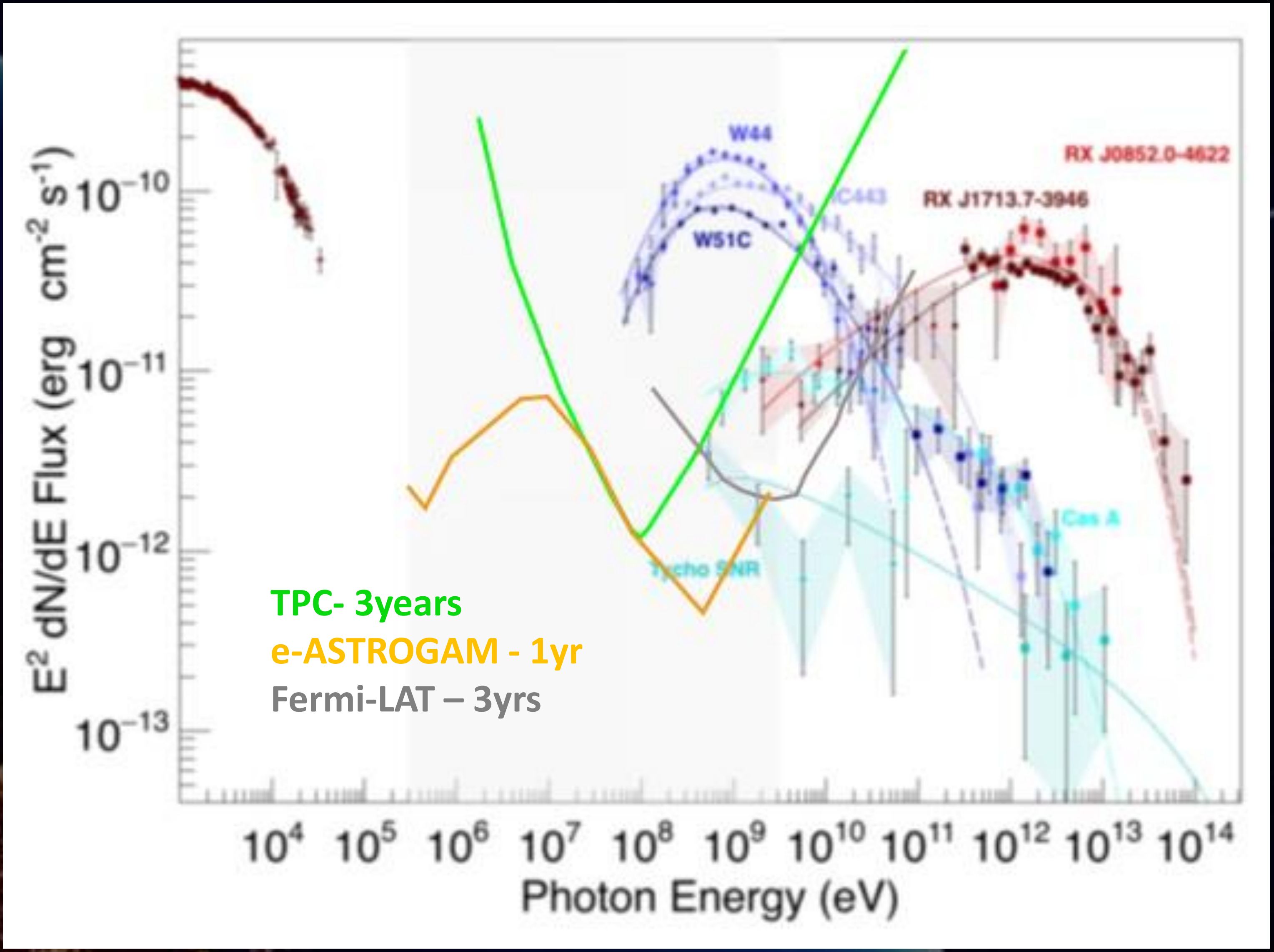
TPC performance







TPC & e-ASTROGAM



Conclusions

✧ We can have the direct proof of CR acceleration in the SNRs at very high energy (PeV → CTA) and at lowest gamma-ray energies (E<200 MeV → ?)

✧ Despite the large amount of instruments, we had detected no PeV SNRs and only two middle-aged SNRs at E< 200 MeV thanks to AGILE and Fermi-LAT → probably reaccelerated CRs

✧ We need to detect young SNRs with fast shocks at E<200 MeV in order to confirm the presence of freshly accelerated CRs

✧ Acceleration (and also reacceleration) models depend from parameters like magnetic field, correlation length, density (…) that we can know thanks to other wavelegths

We really need an instrument with improved capabilities at MeV energies in order to give the final answer to the question: how is the CR origin?


Thank you
very much!