INTERNATIONAL COSMIC RAY CONFERENCE
July 24, August 2 - 2019

The role of re-acceleration in the understanding of Cosmic-Ray direct and indirect data.

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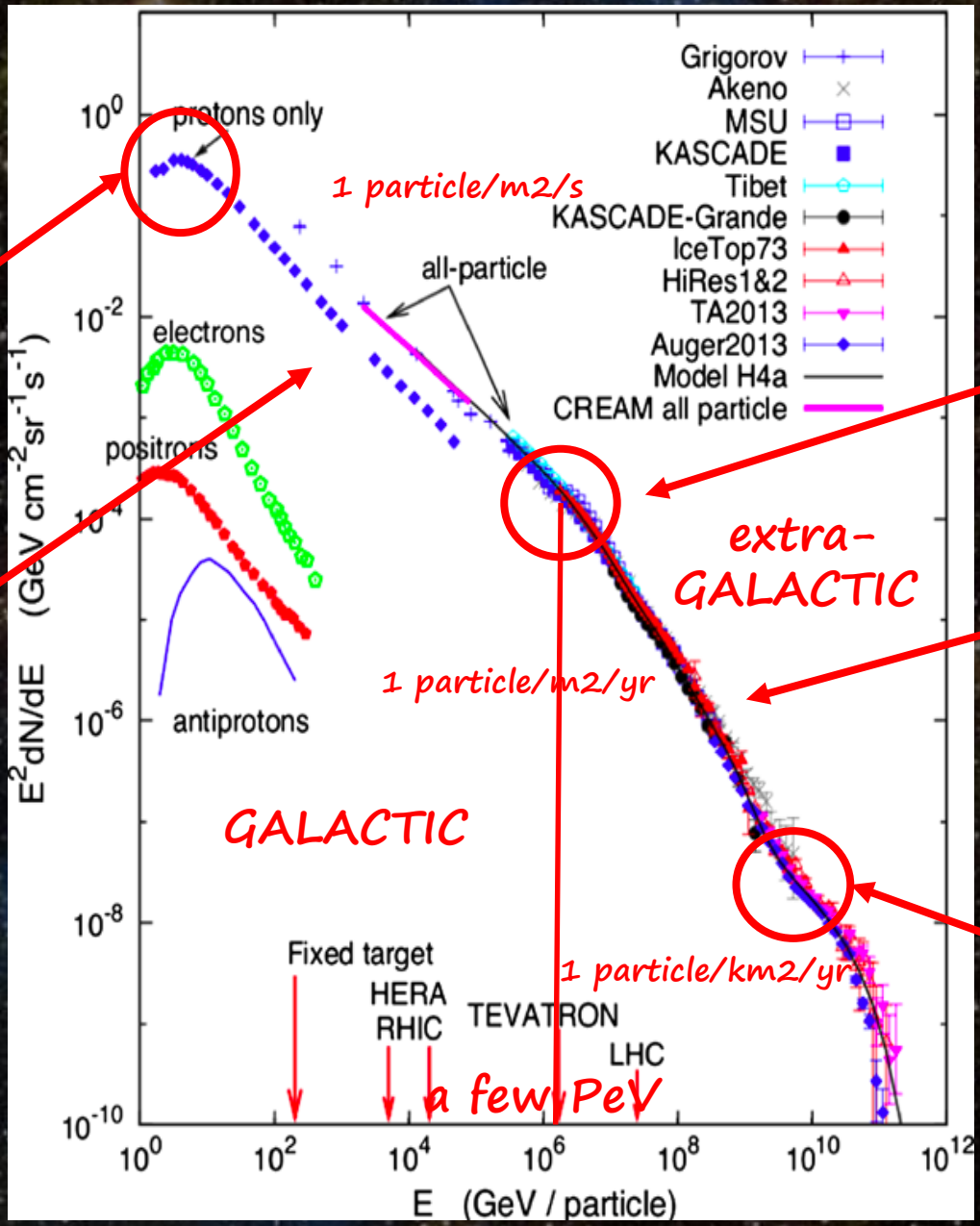
Cosmic Ray Overview

Protons (85 %)
Nuclei (13%)
Electrons/Positrons (2%)

Solar modulation

power law $E^{-2,7}$

$W_{CR} \sim 1$ eV/cm^3



CR "Knee"

power law $E^{-3,1}$

CR "Ankle"

Where do they come from?

The main hypothesis

WHERE DO THEY COME FROM ?

SUPERNOVA REMNANTS

- Energetics
- Possibility of energy gains by repeated shock crossing (I order Fermi acceleration)
- Indirect Evidences (X-ray, Balmer Lines)

HOW CAN WE OBTAIN DIRECT EVIDENCES?

GAMMA-RAY PHOTONS

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

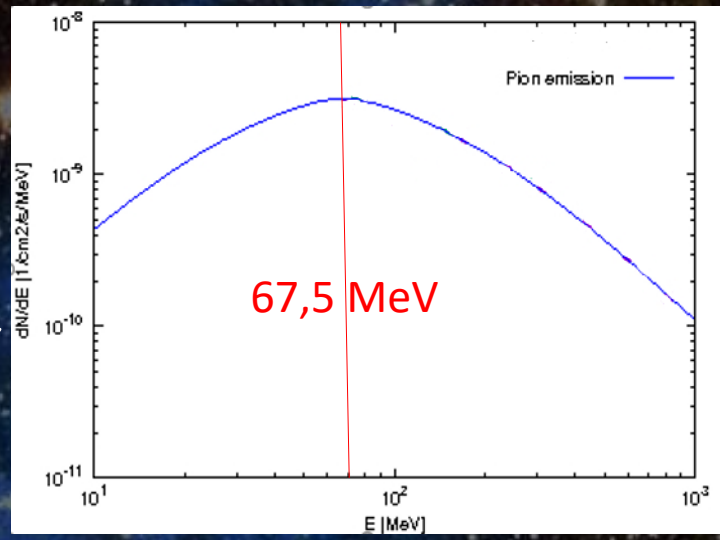
- No deviations → source direction
- Same spectrum of primary protons
- $E_{\gamma,M} \simeq 10\%\ E_{p,M}$

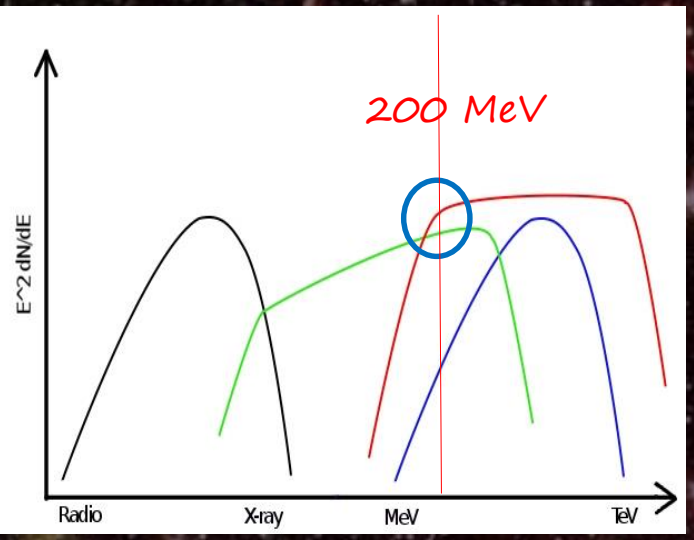
Acceleration: direct evidences

Low-Energies → ????

Hadronic or Leptonic?

→ pion bump detection: distinction leptonic from hadronic component only at E<200 MeV

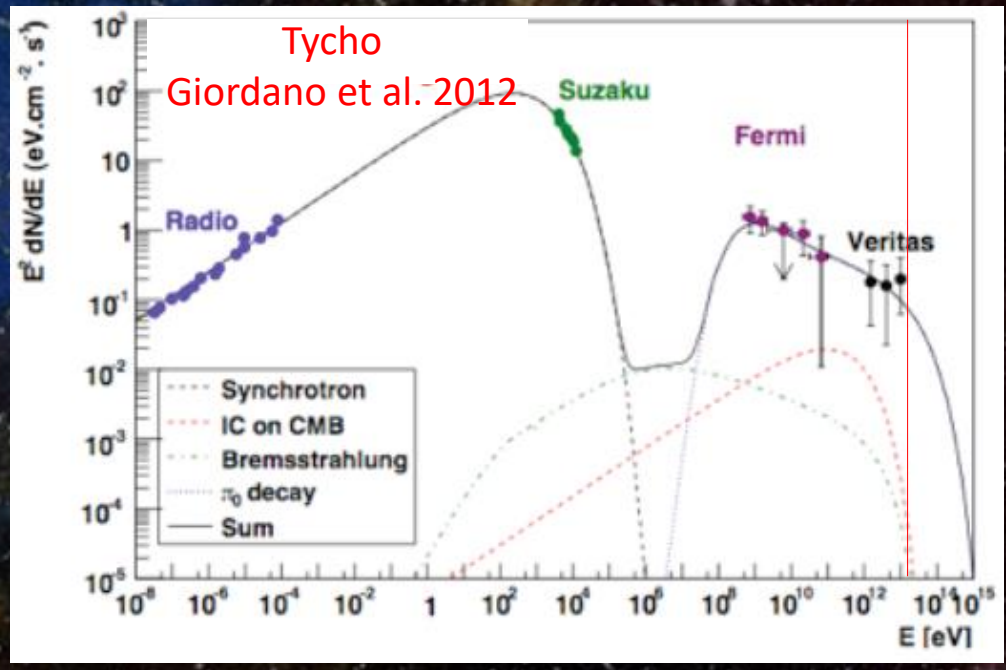




High-Energies → CTA/ASTRI

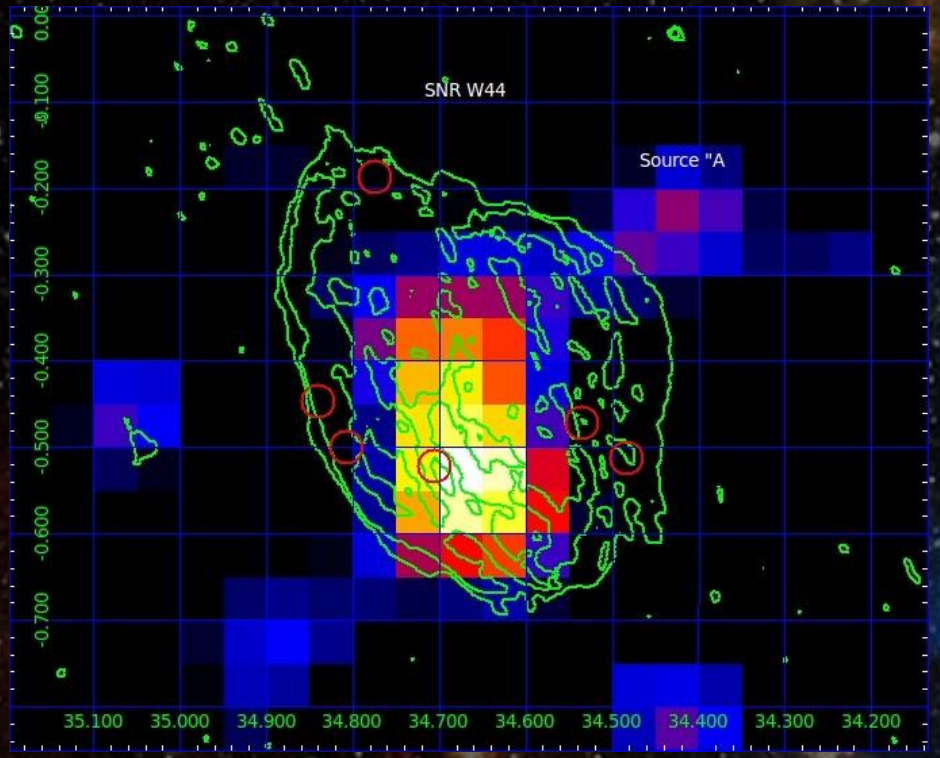
Pevatrons?

→ No young SNRs detected in the gamma-ray band with a spectrum up to E= 100 TeV



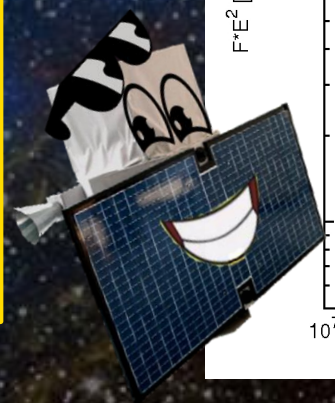
The breakthrough: W44

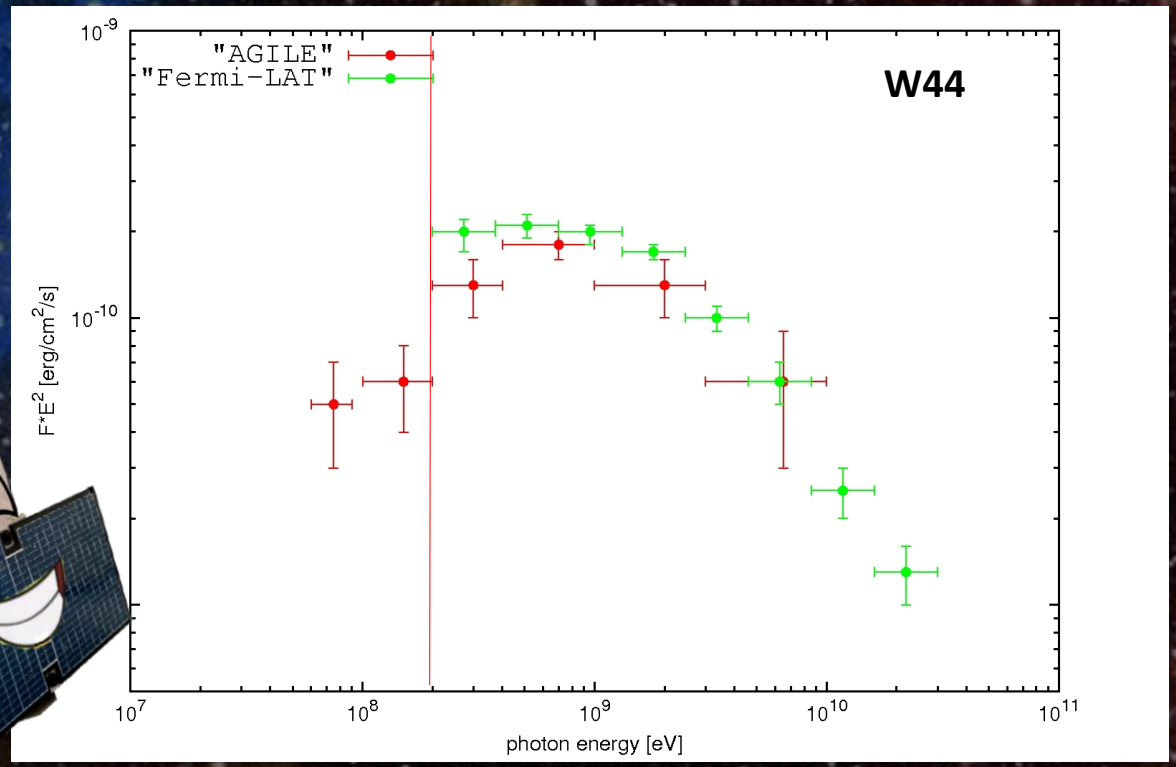
Giuliani,Cardillo et al. 2011
Cardillo et al. 2014



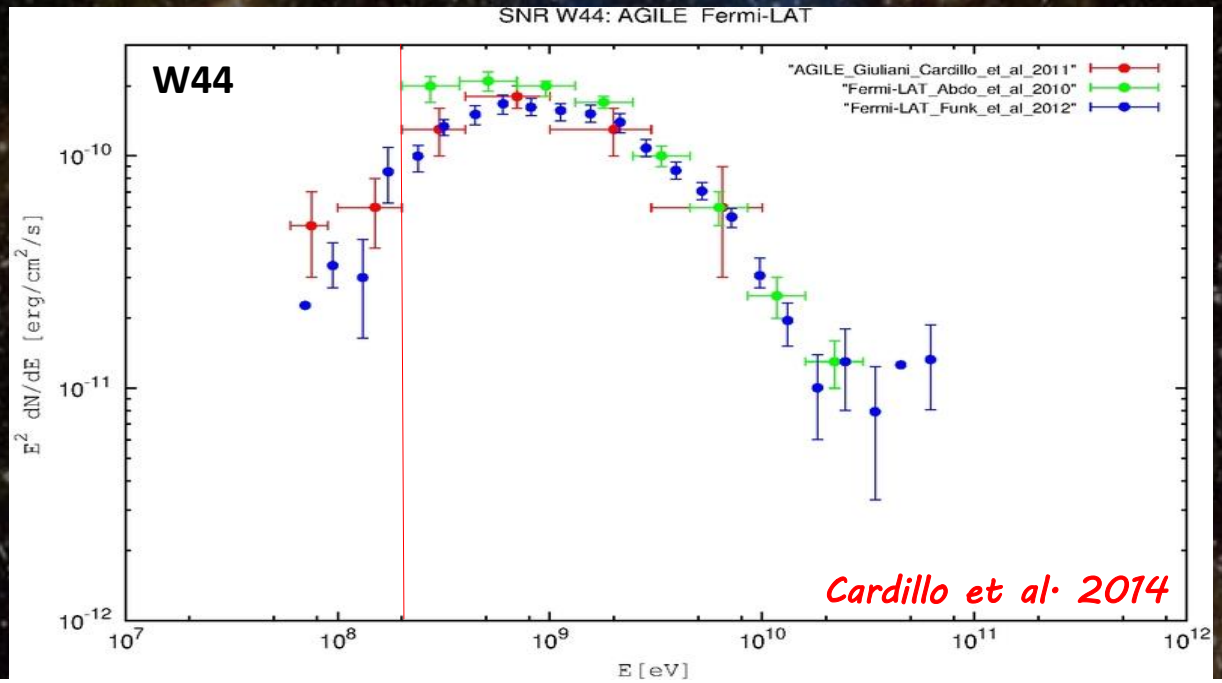
- Very bright radio middle aged Supernova Remnants
- Interaction with a molecular cloud (high average density, $n \sim 200\ cm^{-3}$)
- Fermi-LAT detected (low sensitivity at the lowest energies (Abdo et al. 2010))

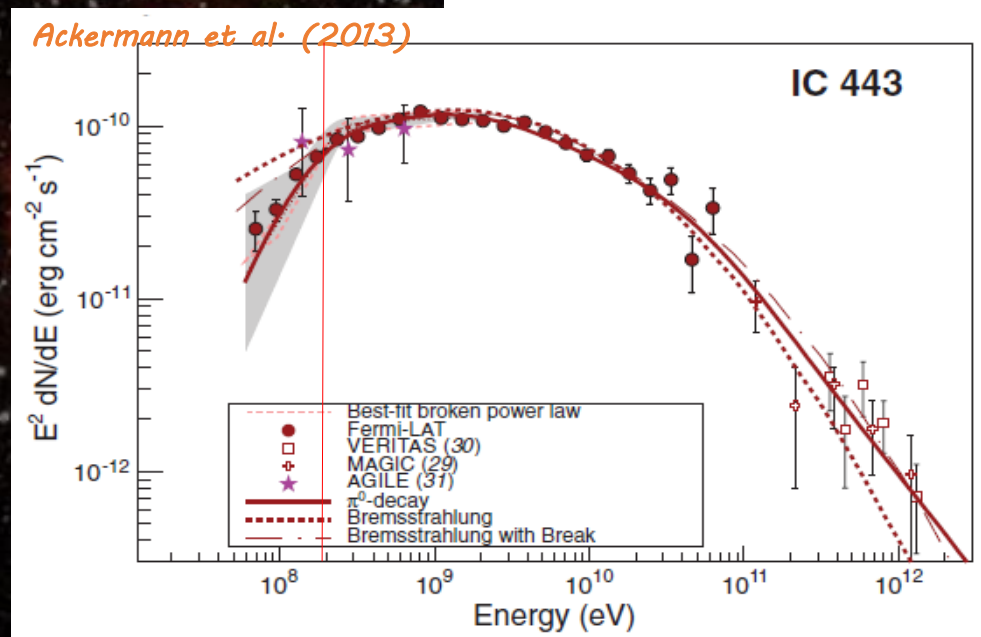
Gamma-ray emission below 200 MeV detected, for the first time, by AGILE (Astro Rivelatore Gamma ad Immagini LEggero) from the SNR W44

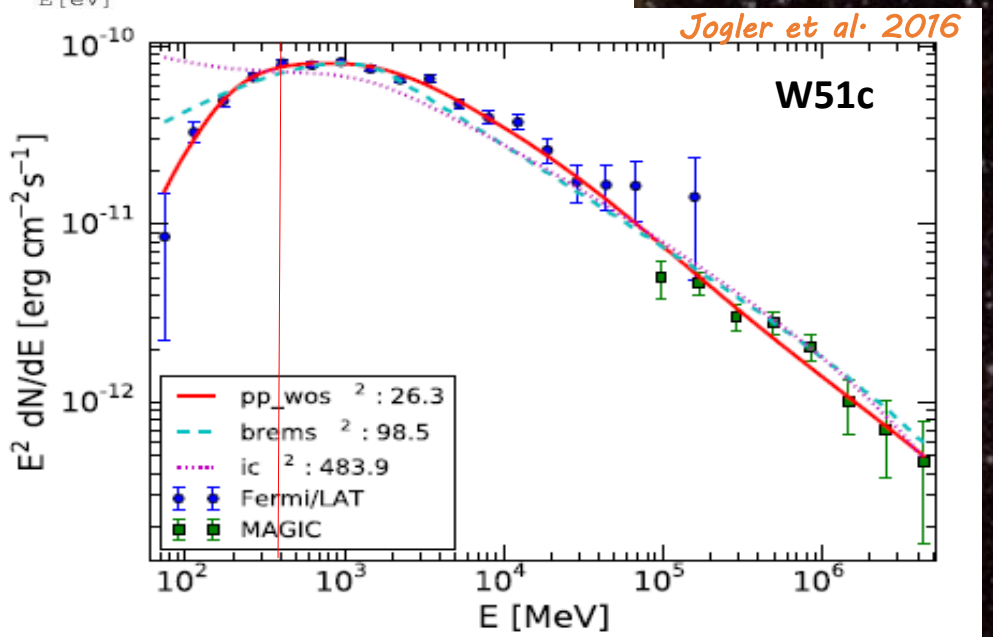




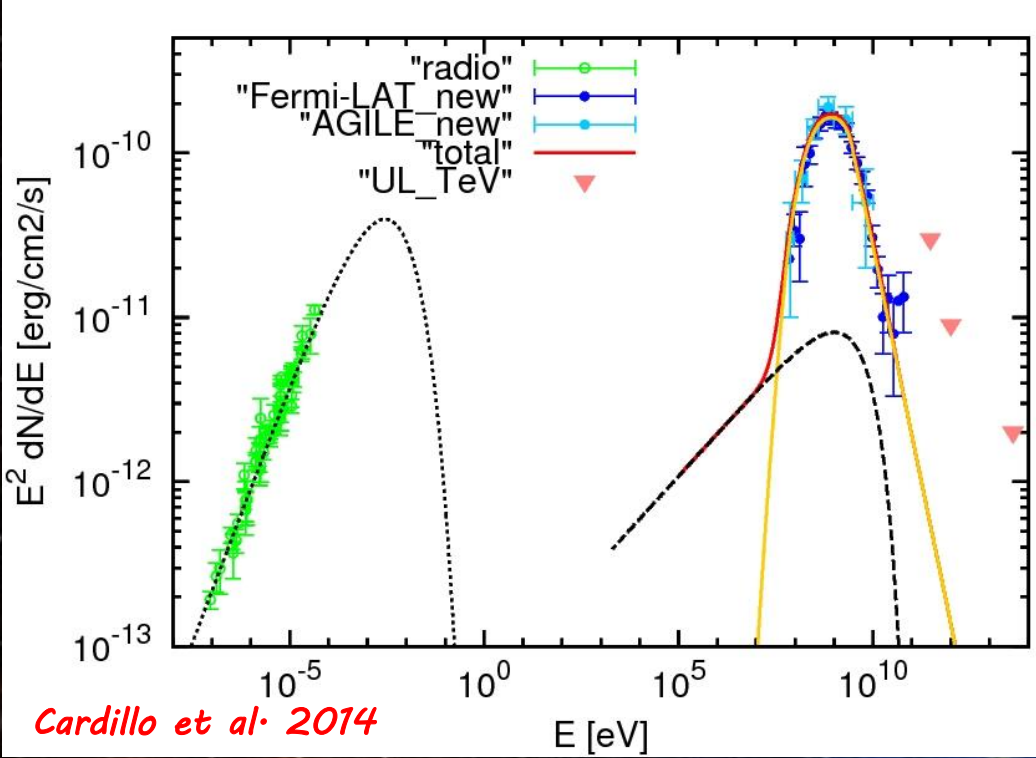
The breakthrough: confirmation





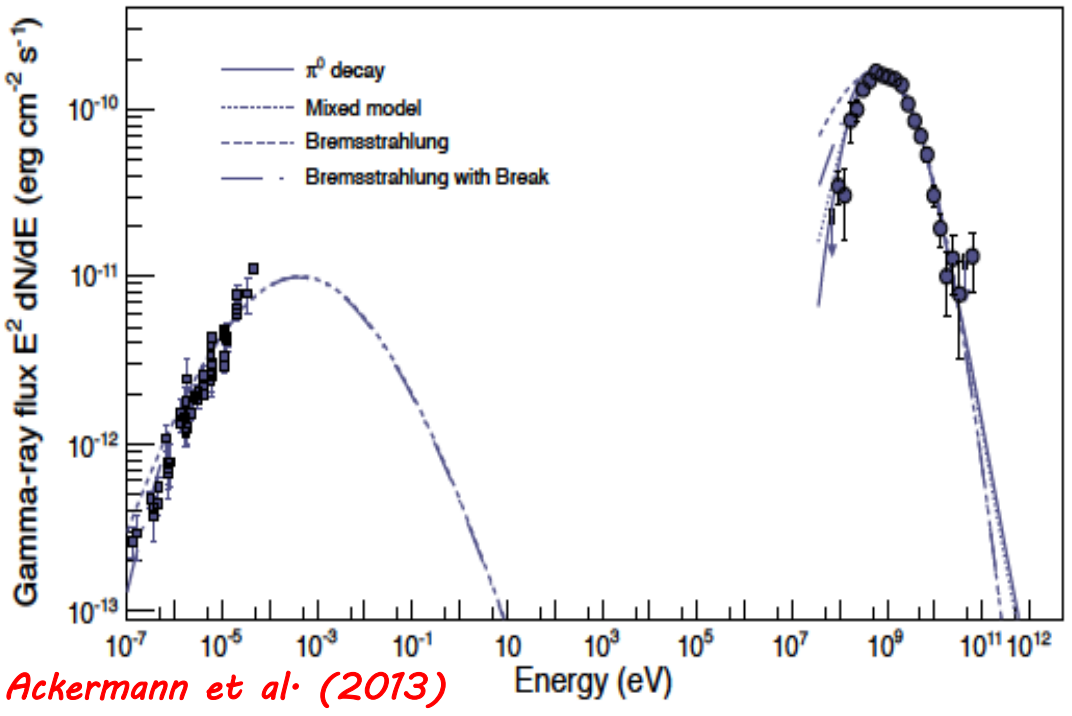


The breakthrough: acceleration?



Cardillo et al. 2014

W44



Ackermann et al. (2013)

- Presence of a broken PL and of a very steep HE spectral index

  → not expected from diffusive shock acceleration theory;

- The shock of middle-aged remnants are slow (vs < 100 km/s)

  → acceleration efficiency ξ_{CR} has to be too high in order to explain the emission:

$$P_{CR} = \xi_{CR} \rho v_{sh}^2$$

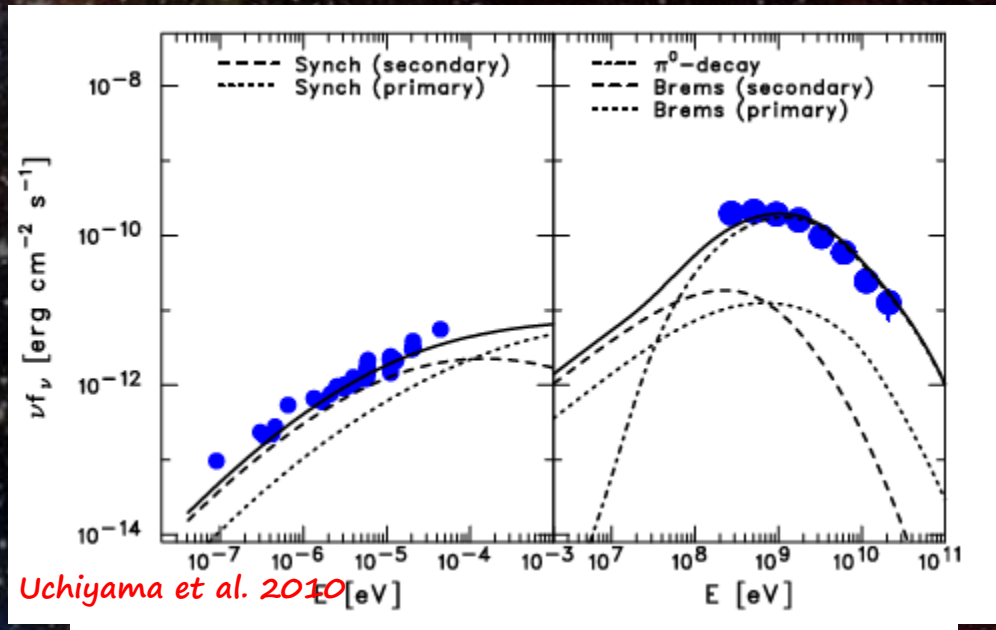
Acceleration vs Reacceleration

- Thermal Particle injection
  - micro-physics
- First order Fermi acceleration
- Injection Spectrum:
  - Power-law with index γ_p due to shock compression ratio
- HE cut-off due to time and loss limitation
- Normalization proportional to $\xi_{CR}\rho v_{sh}^2$

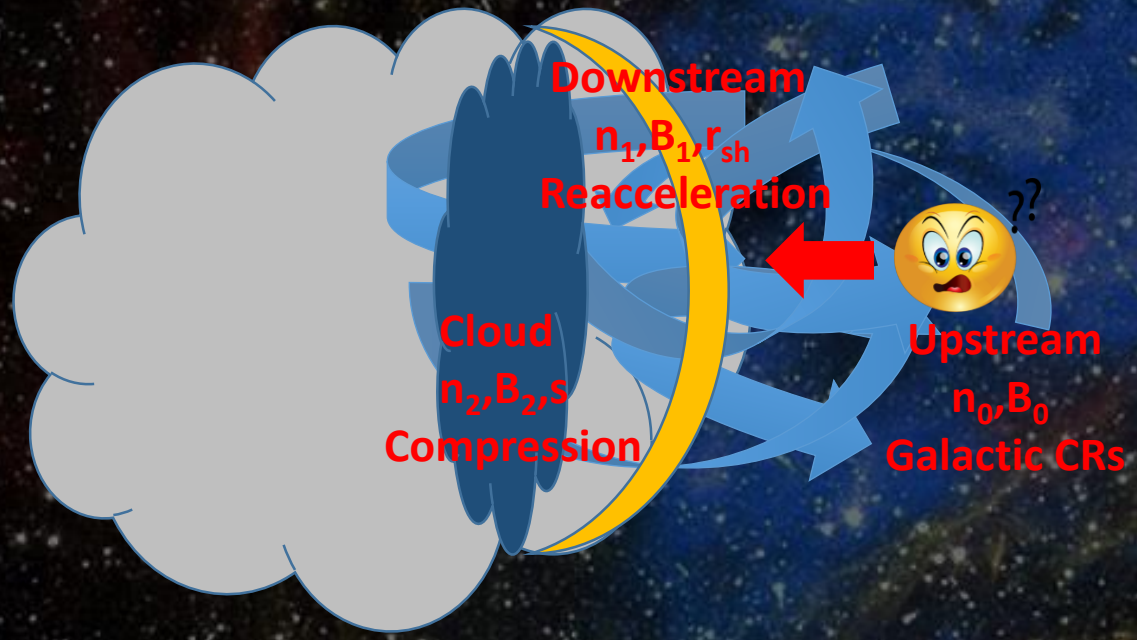
- Pre-existing CR particles
  - from Voyager data
- First order Fermi acceleration
- Injection Spectrum:
  - if it is harder than γ_p → same of parent population
  - if steeper than γ_p, it hardens to γ_p
- HE cut-off due to time and loss limitation
- Normalization depending on shock compression ratio and on pre-existing CR normalization

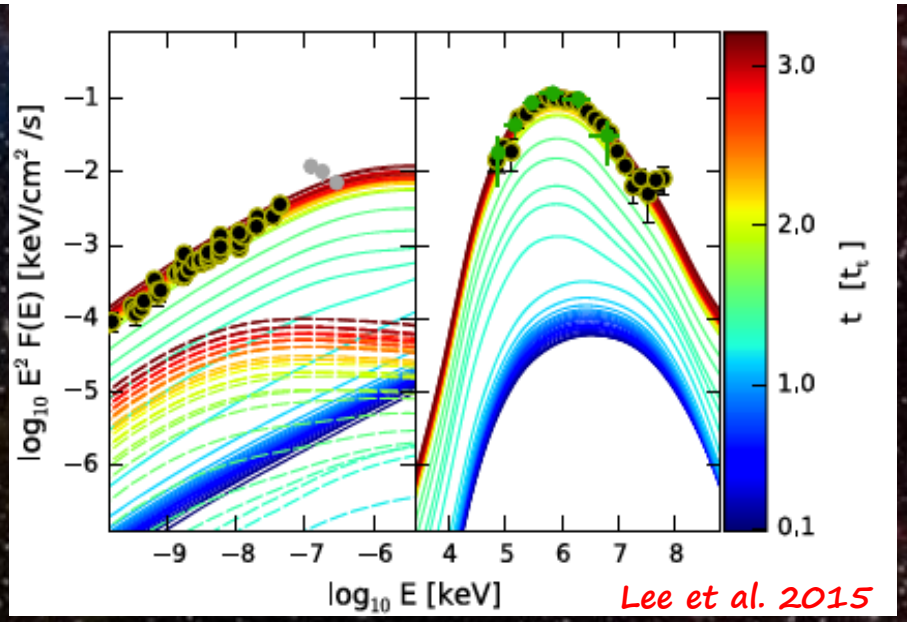
W44: Reacceleration – First models

- ✧ Reacceleration of pre-existing CRs
  - ➢ spectrum measured inside the heliosphere
- ✧ Adiabatic Compression (crushed cloud, Blandford 1982)
  - → higher energies, higher normalization
- ✧ Energy losses → (pp/ionization & ioniz/synch/Brems/IC)



Uchiyama et al. 2010

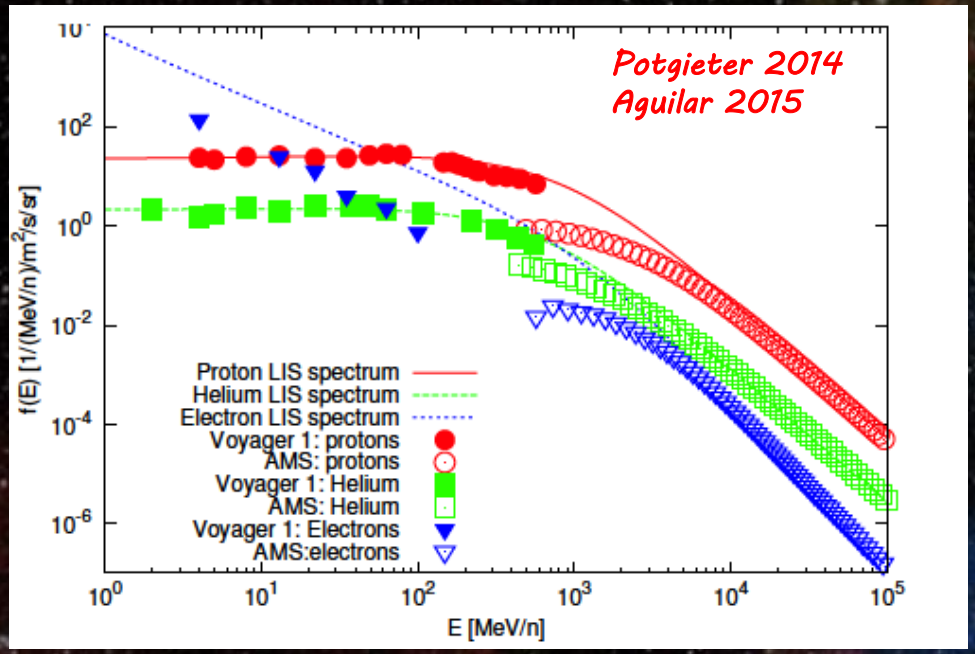




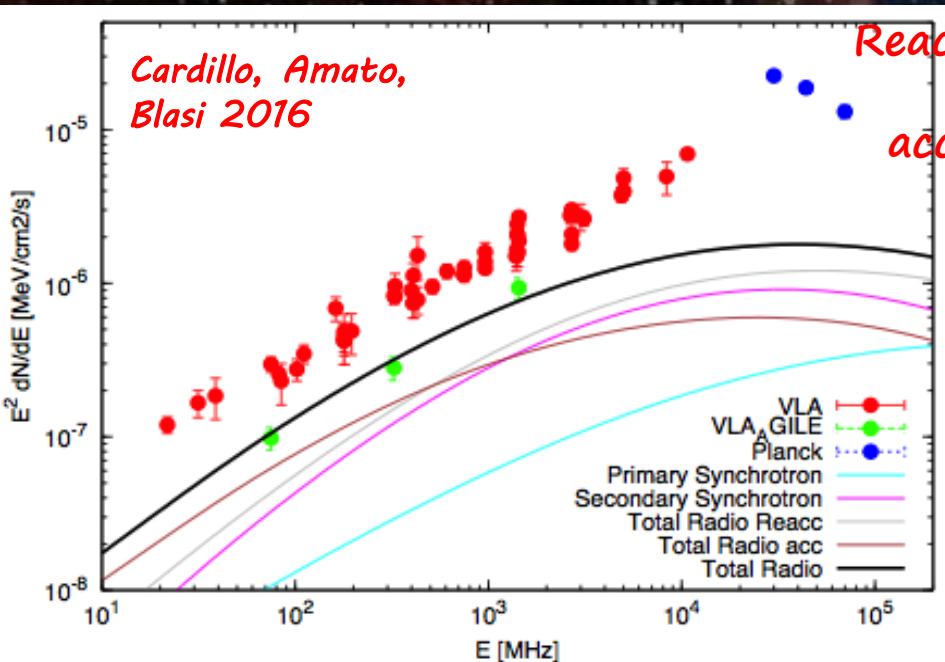
Lee et al. 2015

Low-energy cut off, no losses, no secondaries and Malkov steepening

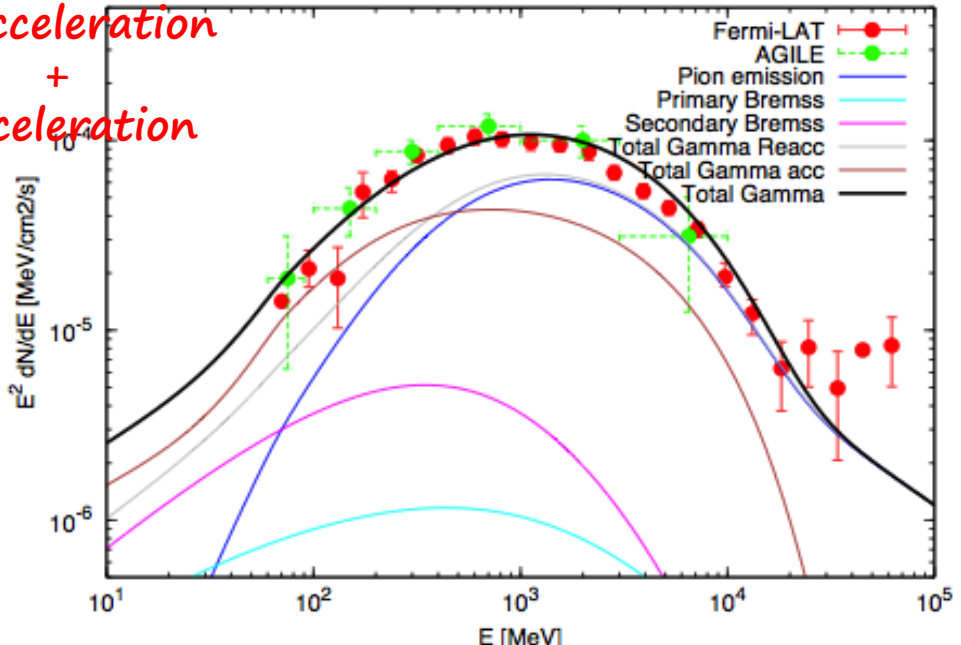
W44: Reacceleration – Last model



- Reacceleration of pre-existing Galactic CR from Voyager spectra OUTSIDE the heliosphere → VERY IS SPECTRUM
- Crushed Cloud Compression
- Secondary particles and low-efficiency accelerated CRs
- Simple PL with no steepening but HE cut-off due to the limited time (fully ionized pre-shock medium)

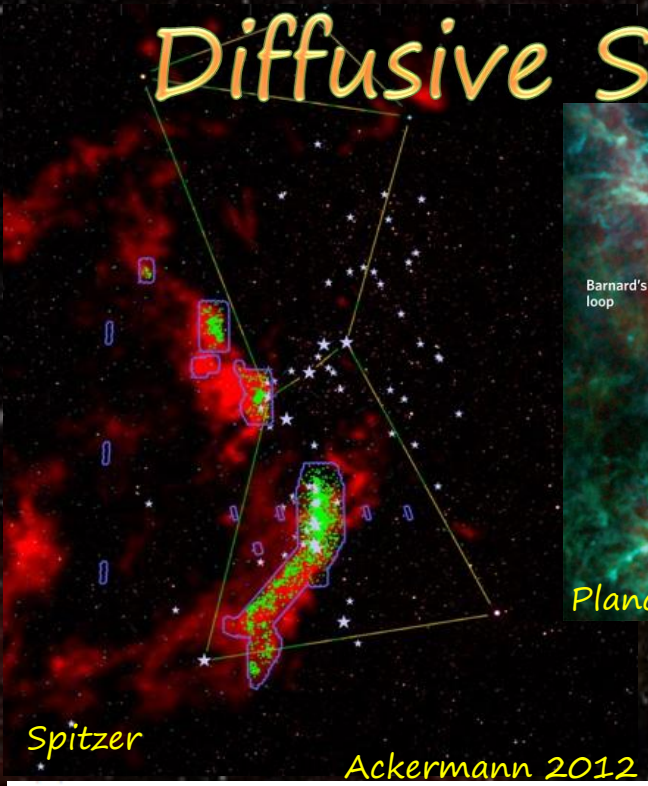


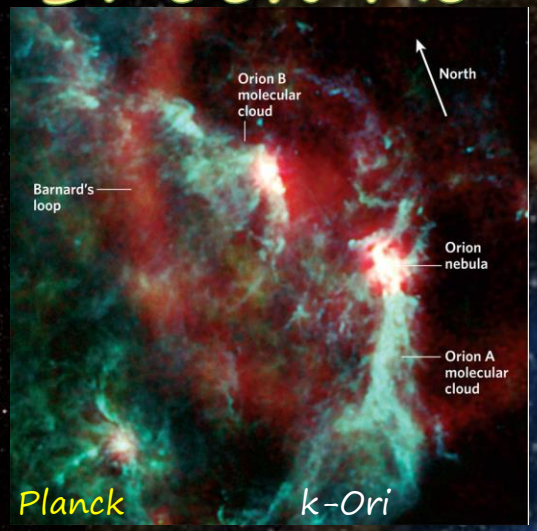
Reacceleration + acceleration



"IT CAN BE DONE!!!!"

Diffusive Shock Re-acceleration: OB star wind





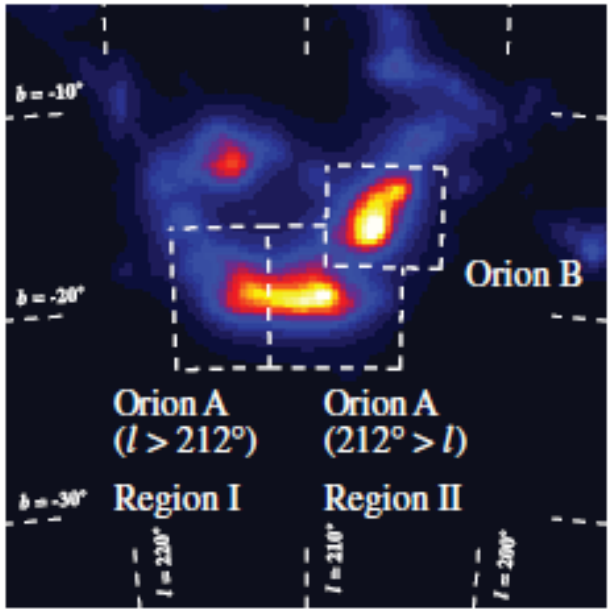
- The nearest star Forming Region
- Distant from the Galactic Plane
- Embedded in the Orion-Eridanus Superbubble.

Estimation of W_{CO}-$N(H_2)$ convertion ratio X_{CO}:

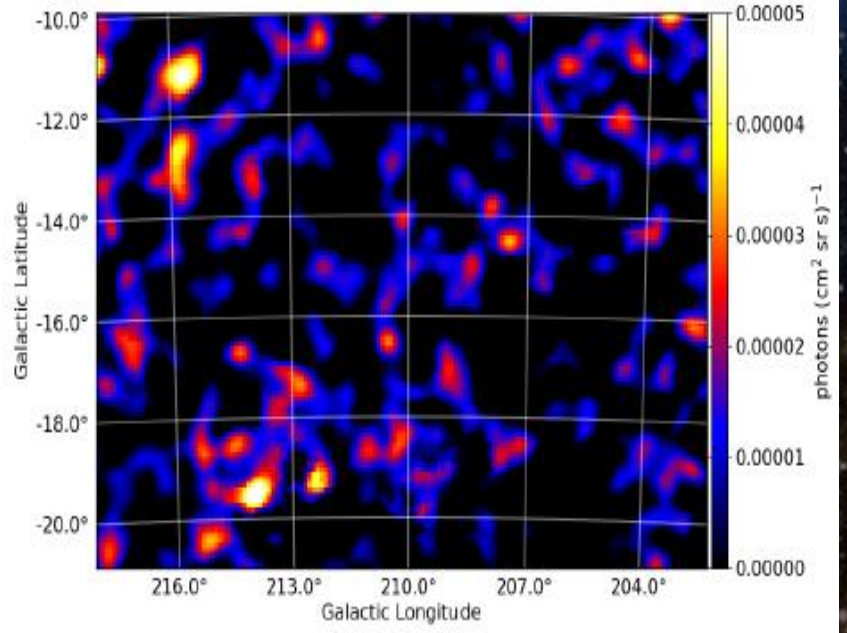
$$N(H_2) = X_{CO} W(CO\ J = 1 \rightarrow 0) cm^{-2}$$

Gamma-ray excess from Fermi-LAT and AGILE at (l,b)=[213,9,-19,5]

Ackermann 2012



Marchili, Piano, Cardillo et al. 2018

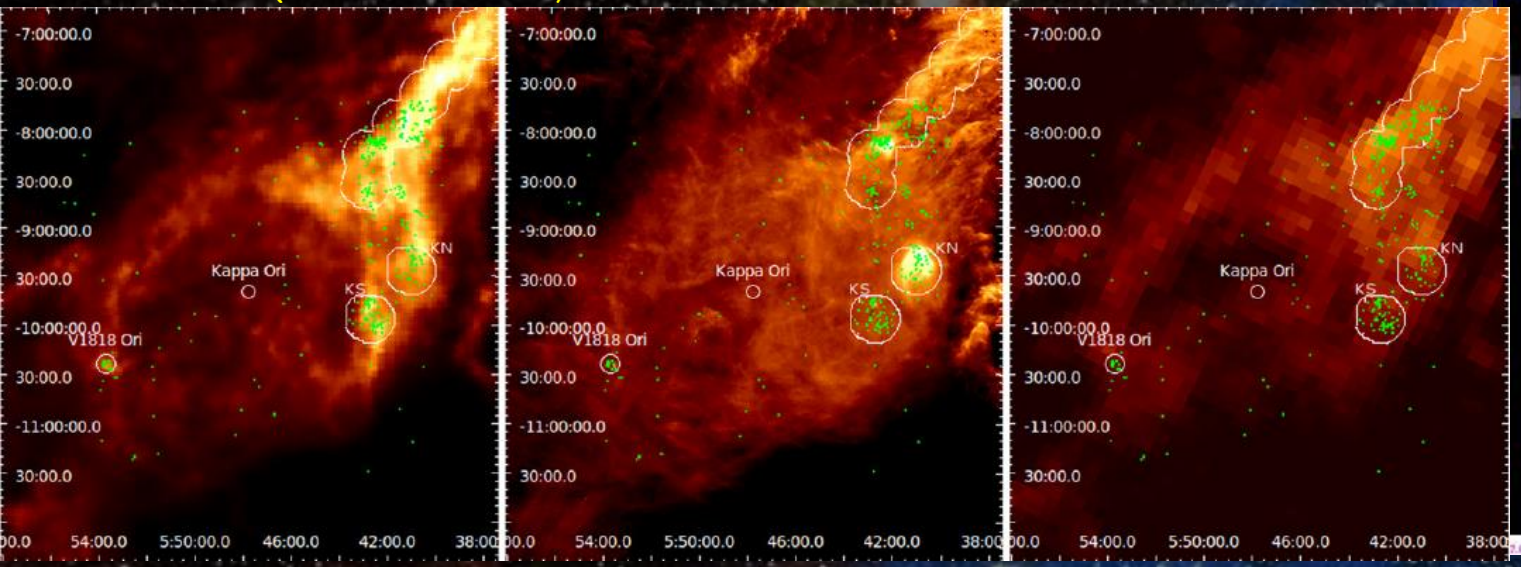


Possible explanations:

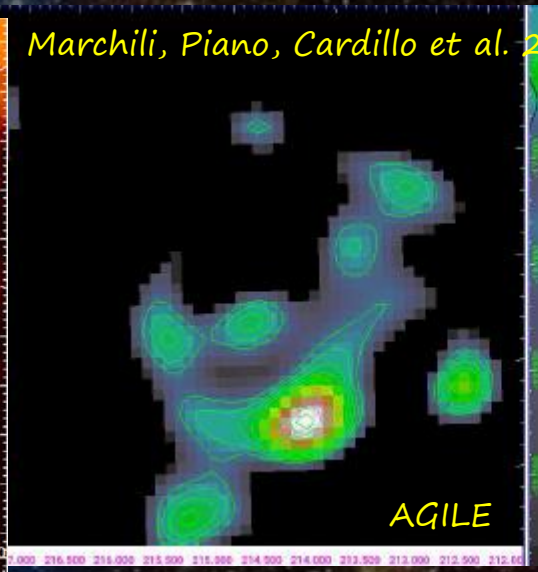
- dark gas: UV radiation at inner edge prevent CO formation
- Non linearity in the H2-CO relation (high star formation rate)

Diffusive Shock Re-acceleration: OB star wind

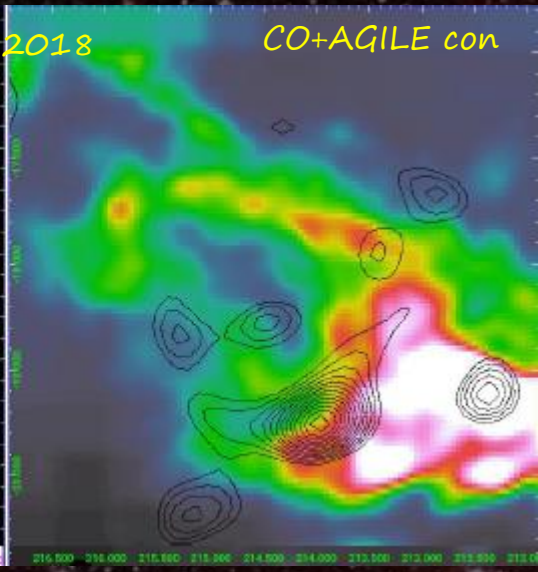
Pillittieri 2016 (R.A.-Dec J2000)



Marchili, Piano, Cardillo et al. 2018

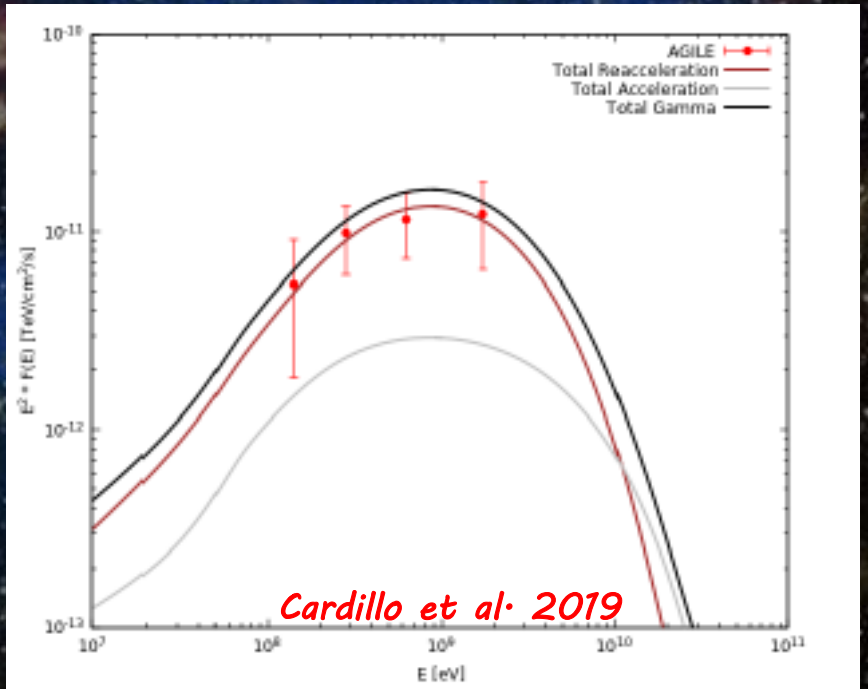


CO+AGILE con



CRs: local acceleration/re-acceleration at k-Ori wind forward shock ?

- Forward shock velocity very low (vs < 10 km/s)
- High interaction time → high losses



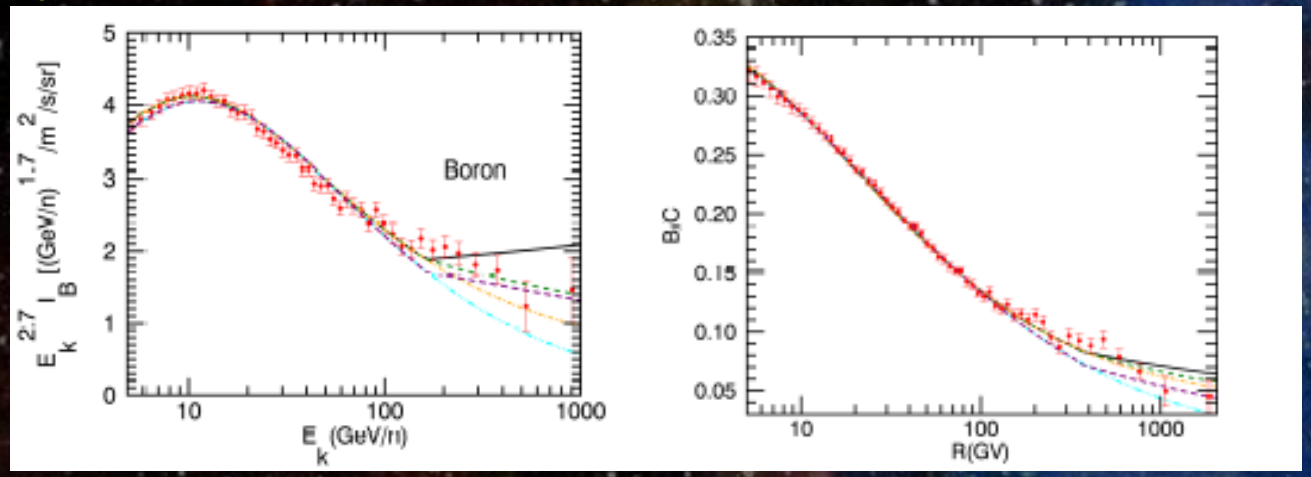
Cosmic Ray Re-Acceleration in correspondence of k-Ori wind forward shock can explain the AGILE spectrum and the lack of TeV and radio emission from that region.

Reacceleration: not only SNRs

Cardillo 2019

- Hardening of secondary CR spectra above 300 GV of rigidity

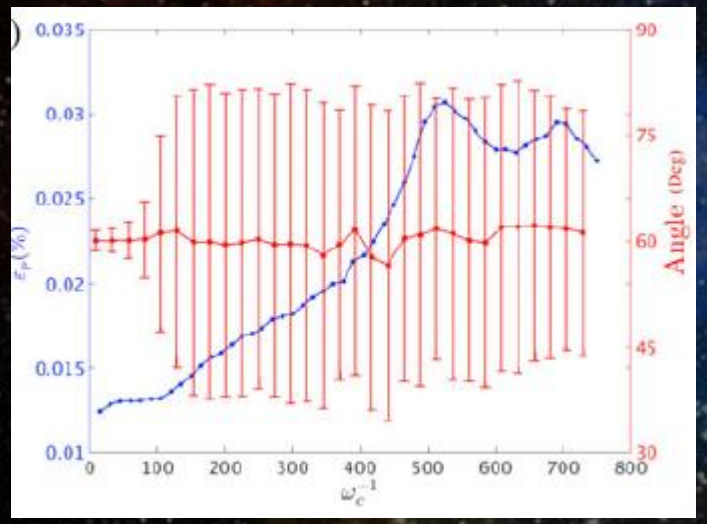
Blasi 2017



Reacceleration can explain secondary hardening:

- it hardens the secondary spectrum that follows the primary spectrum one
- it explains the B/C measurements of AMS-02

- Oblique shock cannot accelerate particles



Caprioli 2019

Reacceleration can provide a minimum level of magnetic field amplification for any SNR shock

→ changing of the inclination angle

→ injection

Conclusions

- We have the evidences that SNRs can energize Cosmic Ray particles
- All low-energy detected SNRs have gamma-ray spectra not easily explained with freshly accelerated CRs
- Diffusive shock Re-acceleration of pre-existing particles is always present if there are first order Fermi Acceleration conditions
- Particle Re-acceleration can explain middle-aged SNR (and other source) spectra and some features of secondary particle spectrum
- Whereas we keep looking for acceleration evidences, we must to take into account re-acceleration effects

We must avoid that "it is the theory which decides what can be observed"

Where do CRs come from?


Thank you very
much!