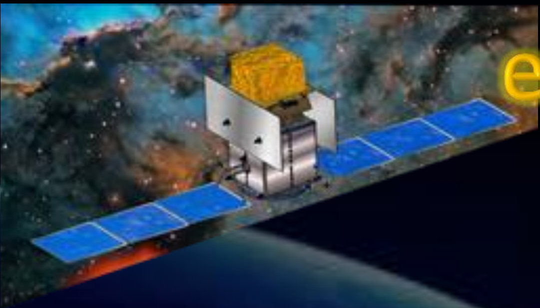

e-ASTROGAM workshop:
the extreme universe

1 March,2017-Padova

Cosmic Rays & Supernova Remnants: The Importance of E<200 MeV

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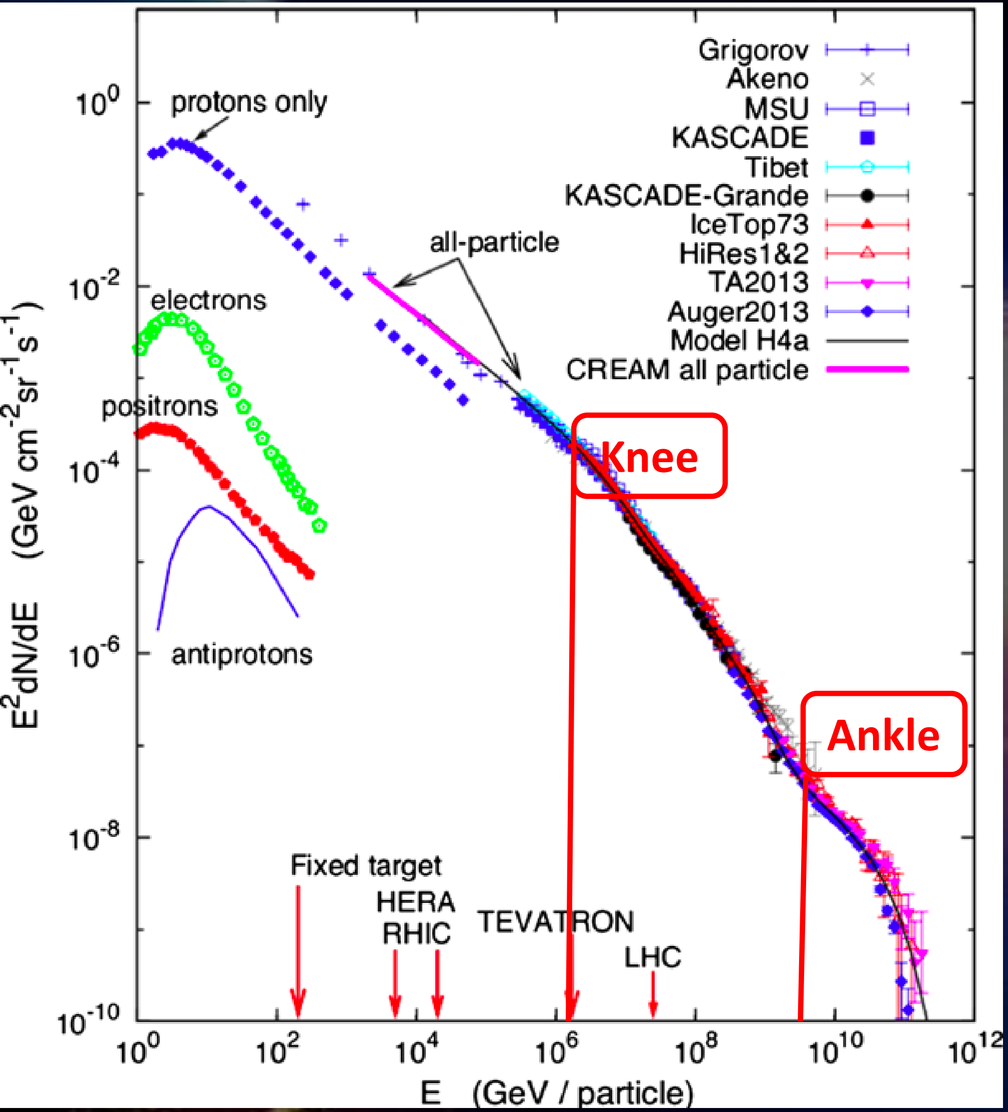
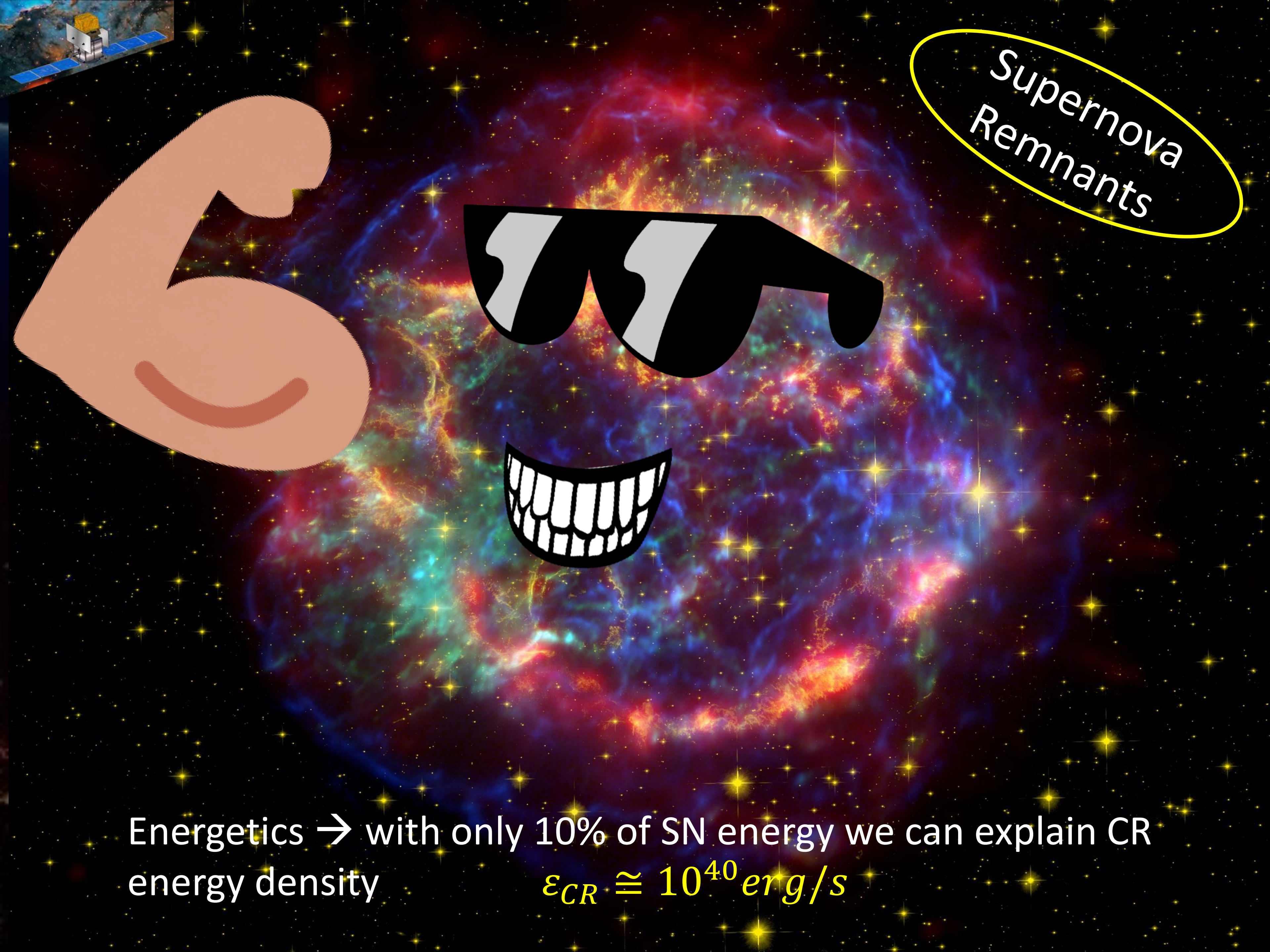
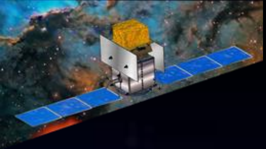
Cosmic-Ray overview



- 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)
- Knee should mark the transition from Galactic to Extragalactic component.

Galactic component


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



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:Indirect proofs

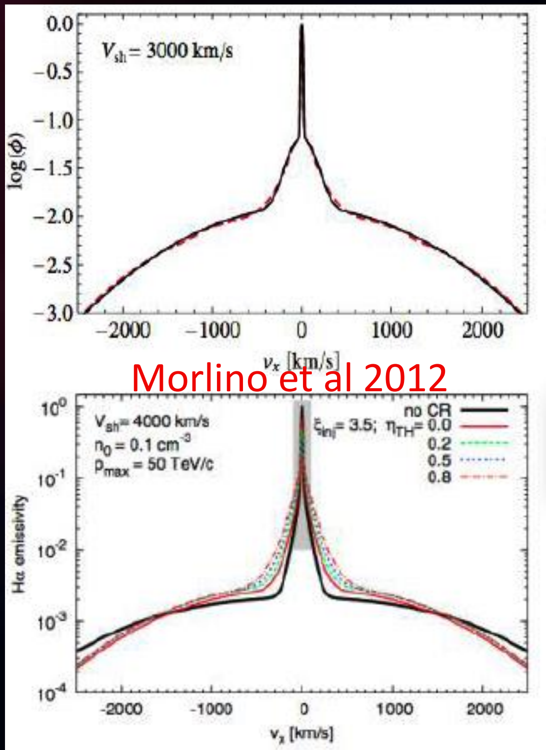
X-RAY BAND ⇨ **Magnetic Field Amplification**

In the X-ray band, young SNRs show very thin rims of about 0.01 pc due to Synchrotron emission. In Bohm diffusion limit:

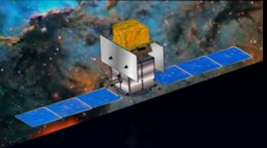
$$\sqrt{D(E)\tau_{sync}} \approx 0.04 B_{100\mu G}^{-\frac{3}{2}}\ pc \Longrightarrow B \approx 100\mu G$$

OPTICAL BAND ⇨ **CR acceleration**

- Neutrals leads to a third component in the Balmer lines spectrum due to Neutral return flux
- In presence of accelerated CR
  - Narrower broad line → T_{down} → CR pressure
  - Broader narrow line
- Steepening of CR spectrum



Morlino et al 2012



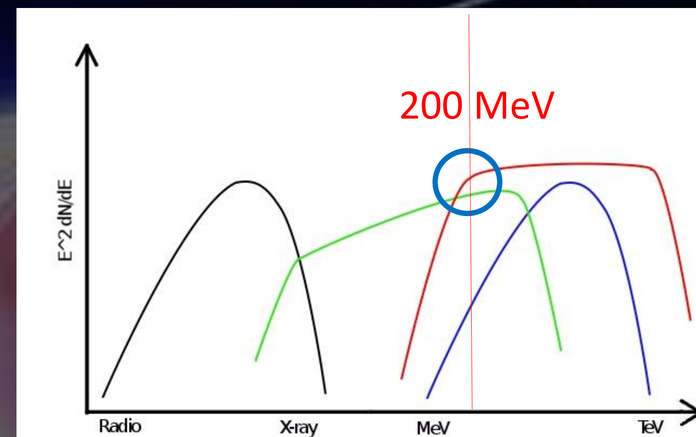
SNRs and CRs: direct proofs

See also Bykov talk

GAMMA-RAY PHOTONS

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

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

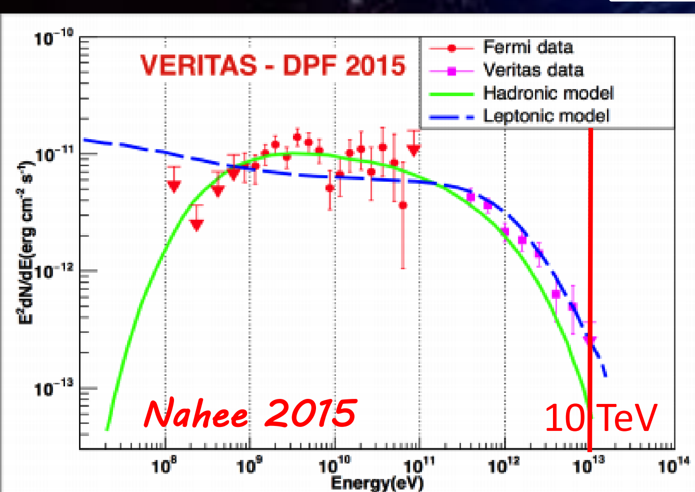


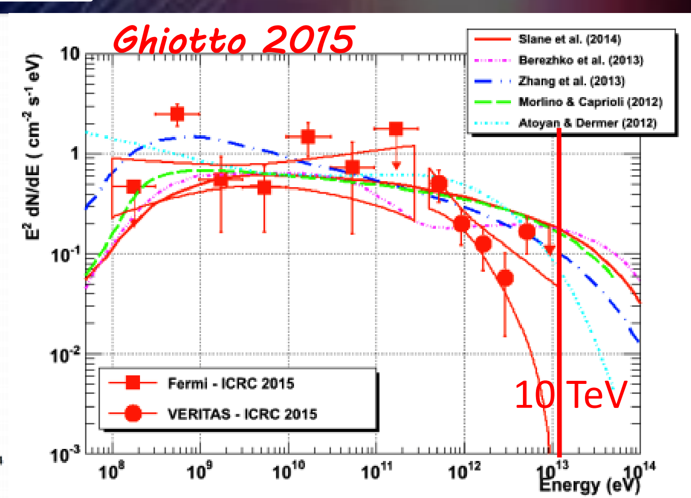
Low-Energies

Confirming hadronic origin

→ We can distinguish leptonic from hadronic component only at E<200 MeV [see Strong talk]

High-Energies → CTA

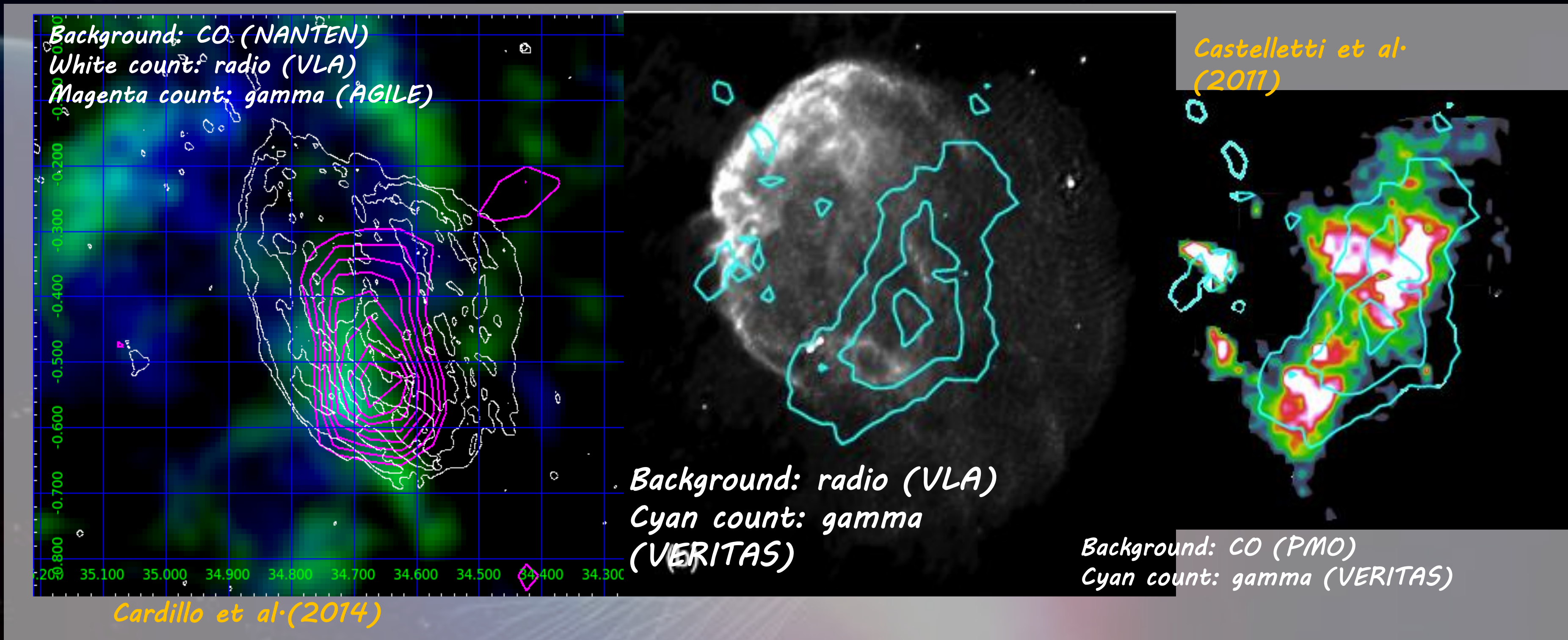




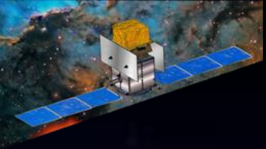
Revealing PeV emission from young SNRs

→ 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

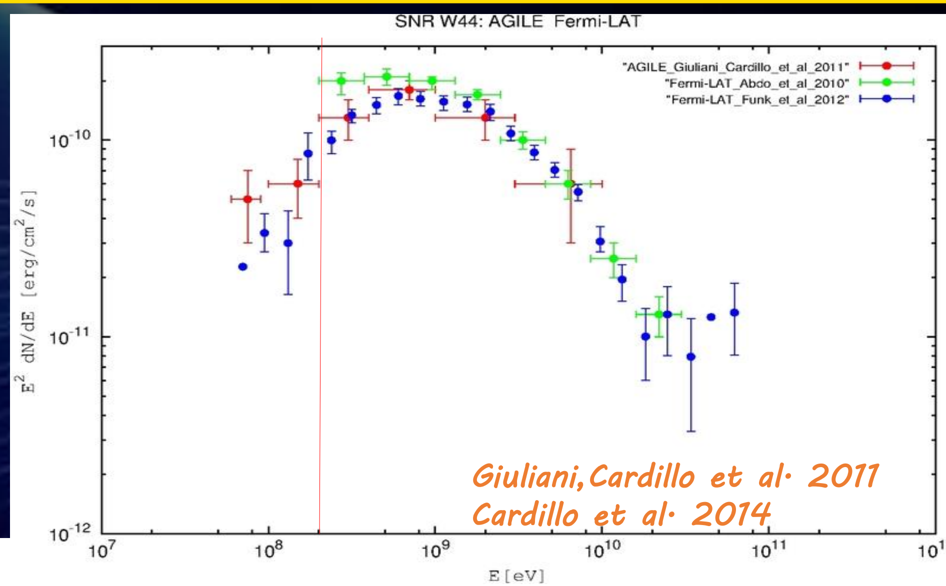


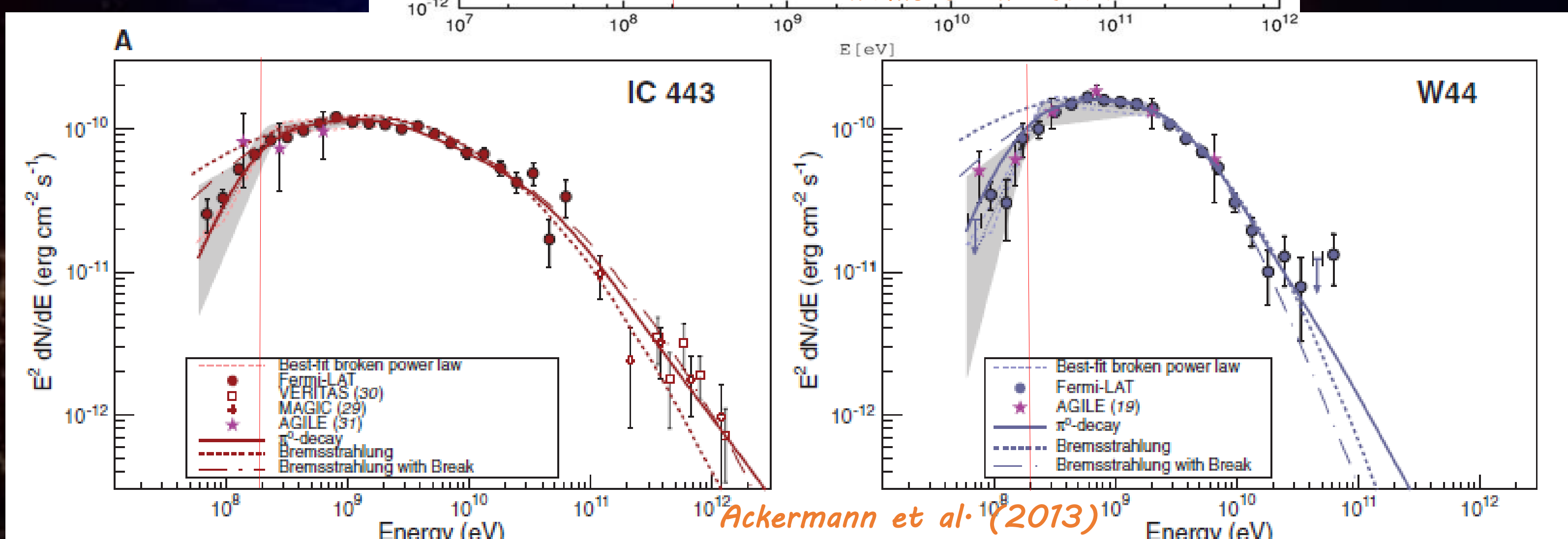
- Middle aged SNRs ($t \geq 10^4$ yrs) with a slow shock velocity ($v_s \sim 100$ km/s)
- Interaction with a molecular cloud (high average density, $n \sim 200\ cm^{-3}$)→ correlated with GeV (and TeV for IC443) gamma-ray emission
- Correletion with part of the radio emission in W44, no correlation in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



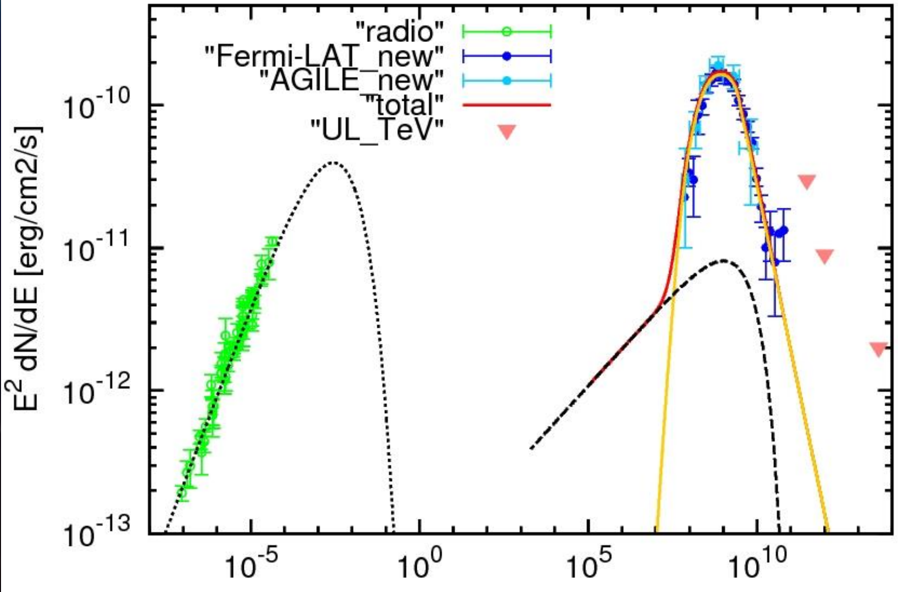
Low-energy gamma-rays

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

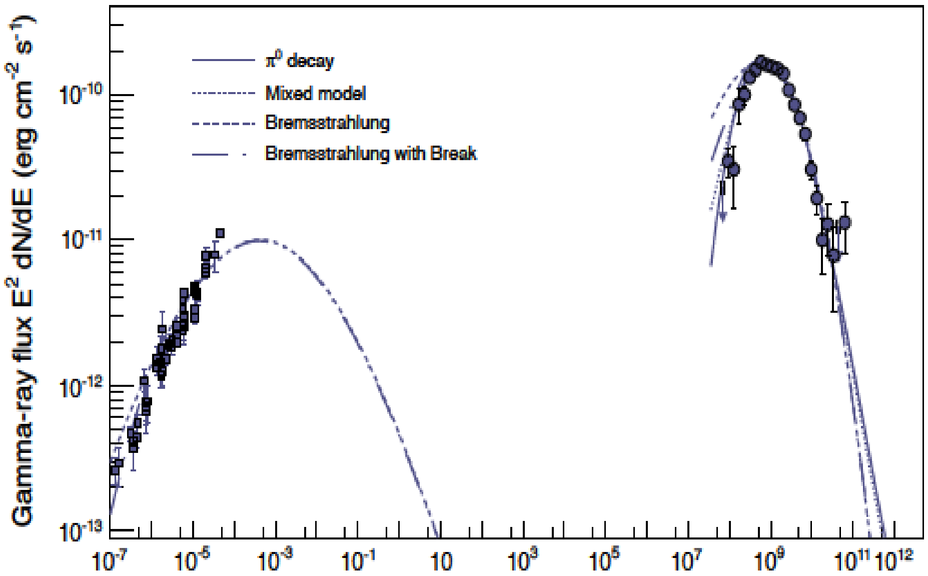




Acceleration…



Cardillo et al. 2014



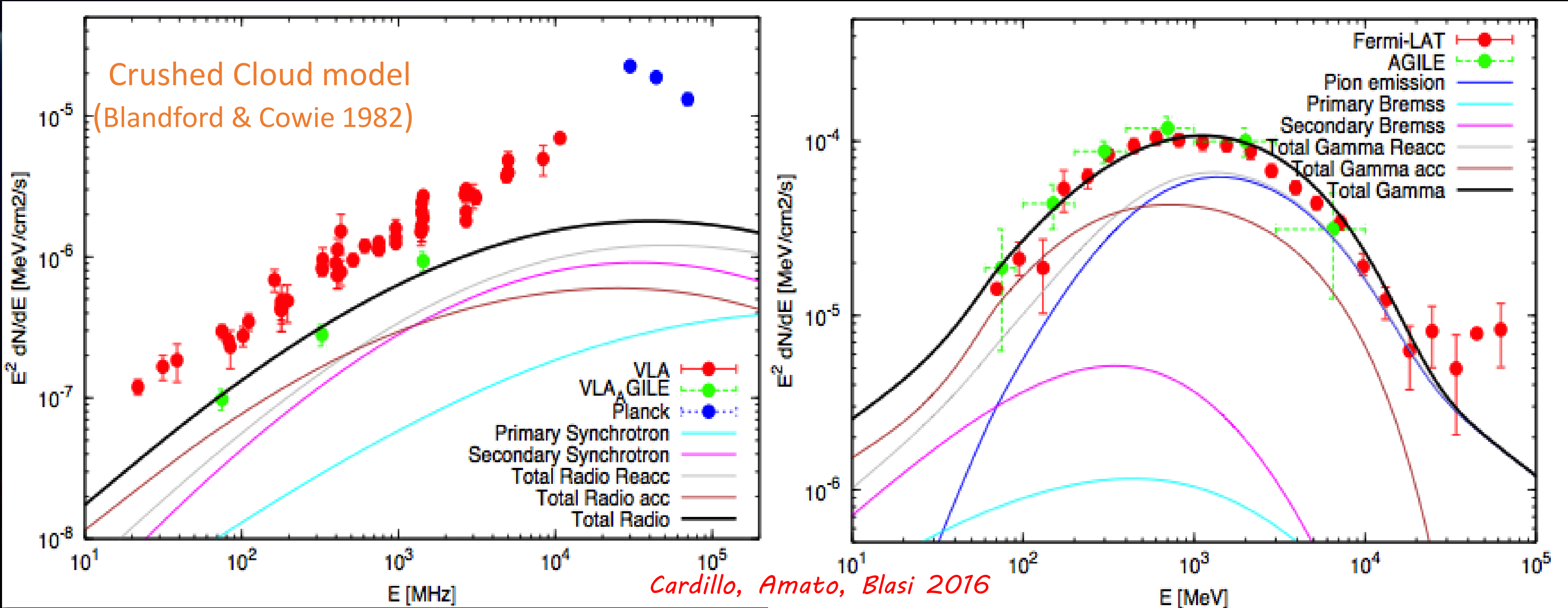
Ackermann et al. (2013)

- ✧ 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 cannot be sufficiently high.

…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 ($r_{sh} = 3.5 \div 4 \rightarrow \gamma_p=4.2\text{-}4$) 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…

The role of e-ASTROGAM

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 shocks SNRs at E<200 MeV

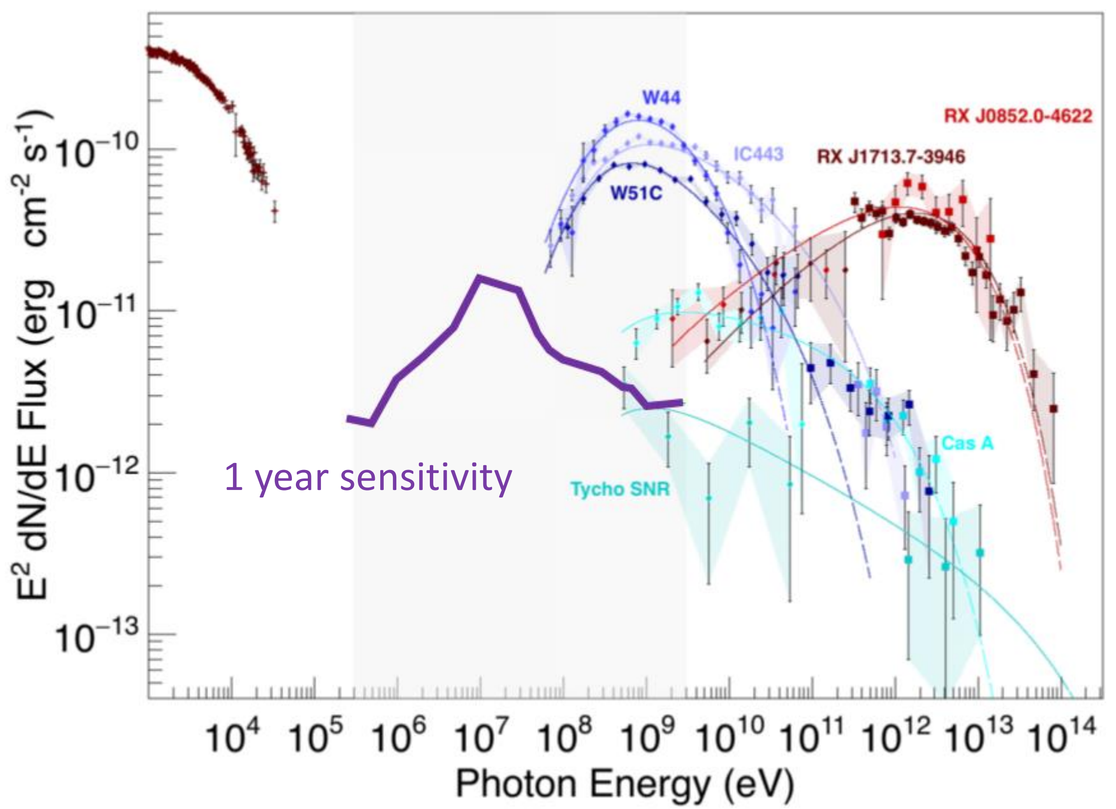
As like as CTA is fundamental in order to enhance the chance to detect young fast shock SNRs that could accelerate Pevatrons, e-ASTROGAM is fundamental in order to detect the same kind of sources at low gamma-ray energies in order to confirm freshly accelerated CRs.

Perfect complementarity in the context of CR/SNR issue

[see Buehler talk]

The role of e-ASTROGAM

Very good sensitivity at low-energies

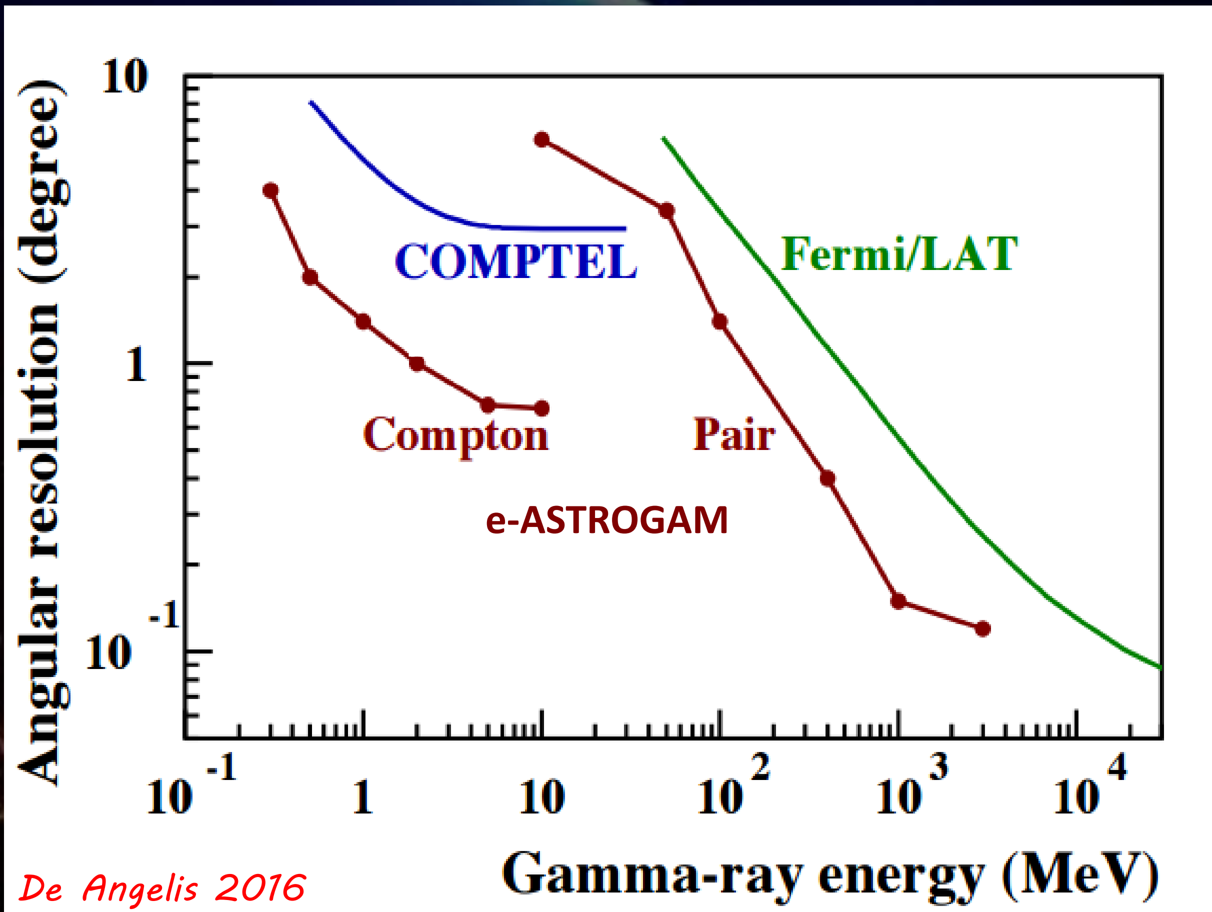


De Angelis 2016

- ✧ Will allow us to enhance the number of SNRs detected in this important gamma-ray energy range
- ✧ Consequently we will have more chances to detect young remnants at E<200 MeV where efficient CR acceleration can take place and contribute more than reacceleration

The role of e-ASTROGAM

Very good angular resolution
(<1.5° at E<100 MeV)



- Its good angular resolution at lower energies, will allow us to correlate in a better way gamma-ray emission with the other wavelengths → more information for more parameters

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

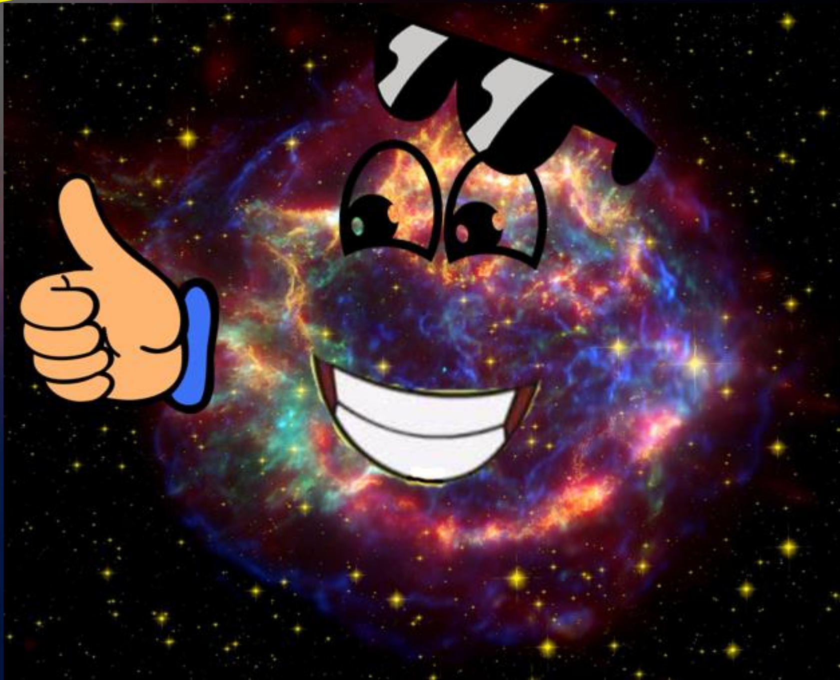
→ e-ASTROGAM low-energy sensitivity will enhance the chances of detection

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

→ e-ASTROGAM low-energy improved angular resolution will allow a better multiwavelength correlation

e-ASTROGAM is a fundamental instrument that could bring at a real breakthrough in searching an answer to the question:

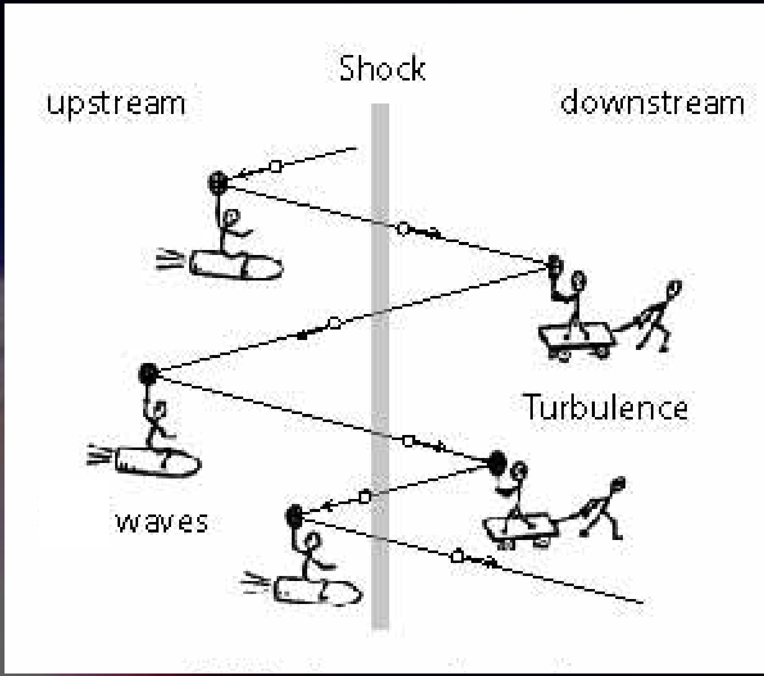
CAN SNRs ACCELERATE GALACTIC CRs?




Thank you
very much!

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: $M_s \rightarrow \infty$, $\mathcal{R} \rightarrow 4$, $\gamma_E \rightarrow 2$

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

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

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

Magnetic Field Amplification

Magnetic Field Amplification

CR acceleration requires perturbations of the same scale of particle Larmor radius ($kr_L=1$)

RESONANT INSTABILITY (Skilling 1975)

Excitation of Alfvén waves with $\lambda \cong r_L$

- saturation at $\delta B/B \cong 1$
- $E_M < 1$ PeV

NON RESONANT INSTABILITY (Bell 2004)

Purely growing waves at wavelengths $\lambda \ll r_L$, driven by the CR current j_{CR}

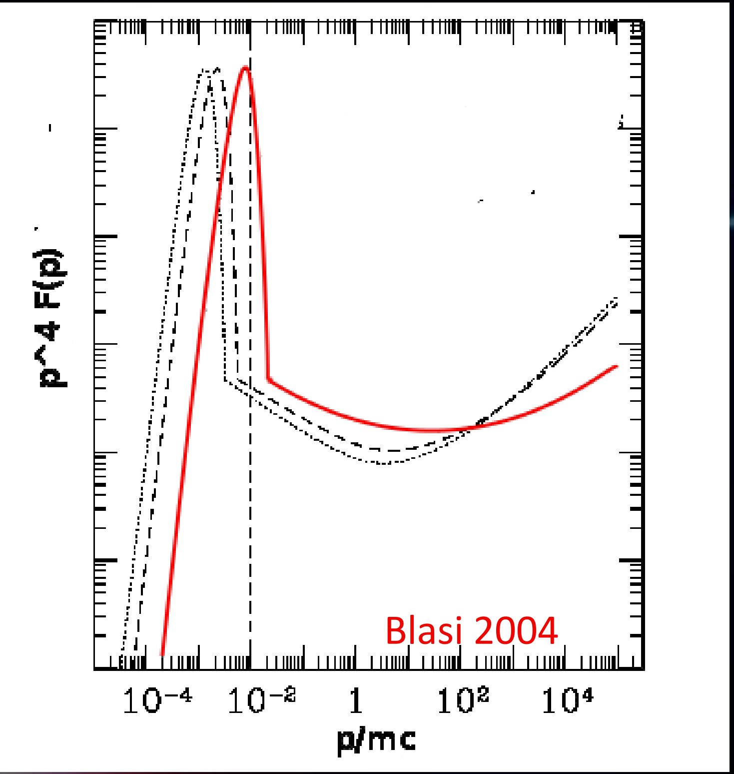
→ larger E_M

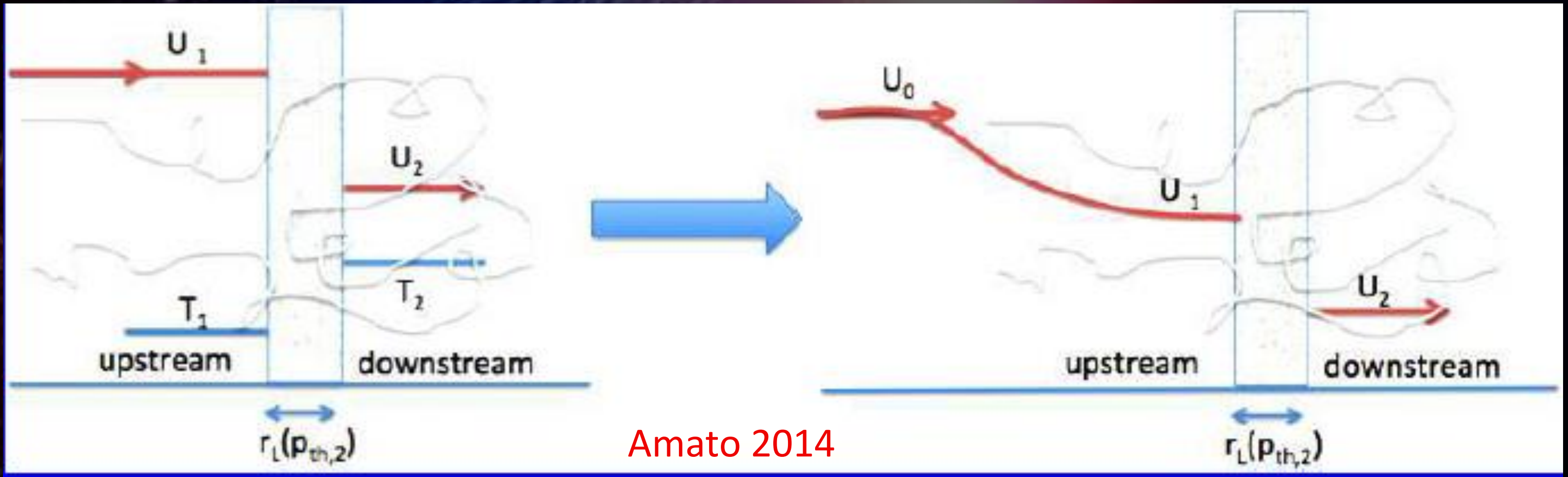
→ generation of power at larger spatial scales up to $\lambda \cong r_L$

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



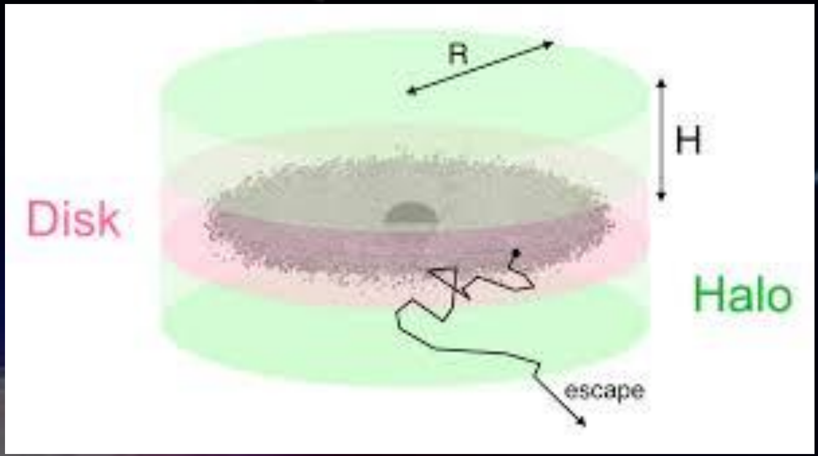


Observed Spectrum: CR propagation

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).

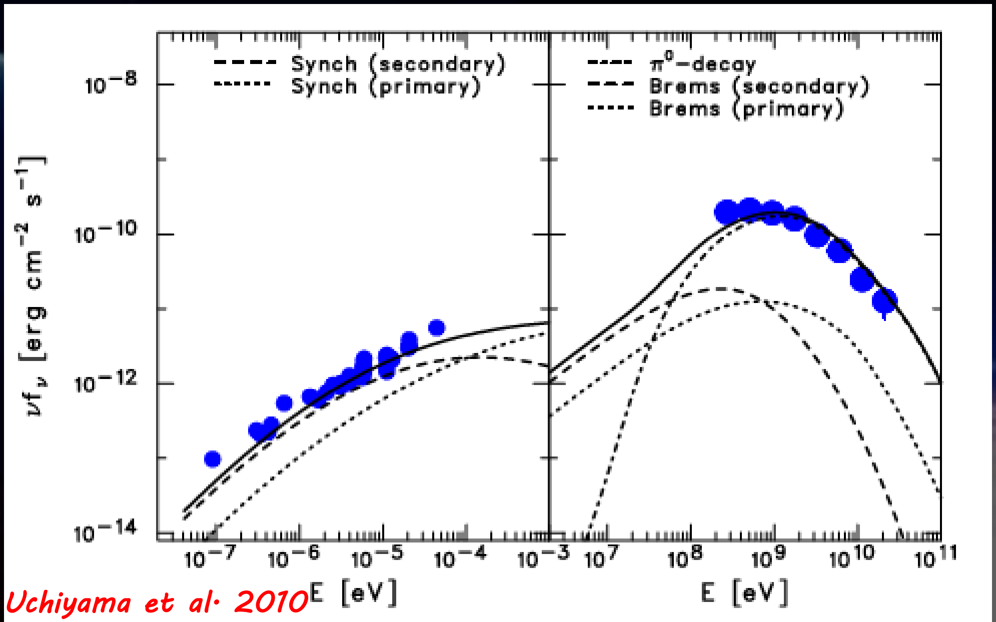
$$N_{SEC}(E) \approx N(E)\mathcal{R}_{spal}\tau_{esc} \approx E^{-(\gamma_E+2\delta)} \longrightarrow \frac{N_{SEC}(E)}{N(E)} \propto E^{-\delta}$$

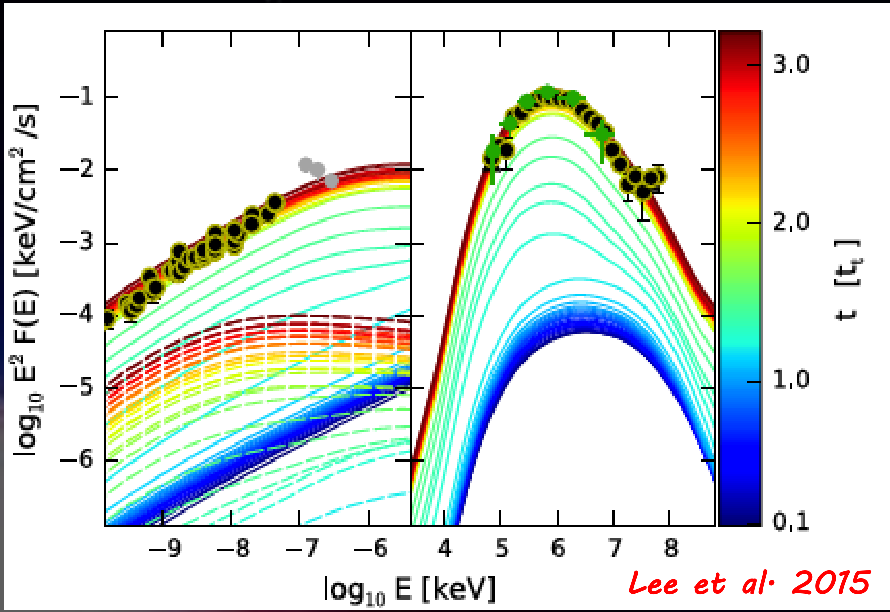
$$\begin{cases} 0.7 > \delta > 0.3 \\ 2 < \gamma_E < 2.4 \end{cases} \Rightarrow$$

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

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

…or reacceleration?





REACCELERATION

Crushed Cloud model (Blandford & Cowie 1982)

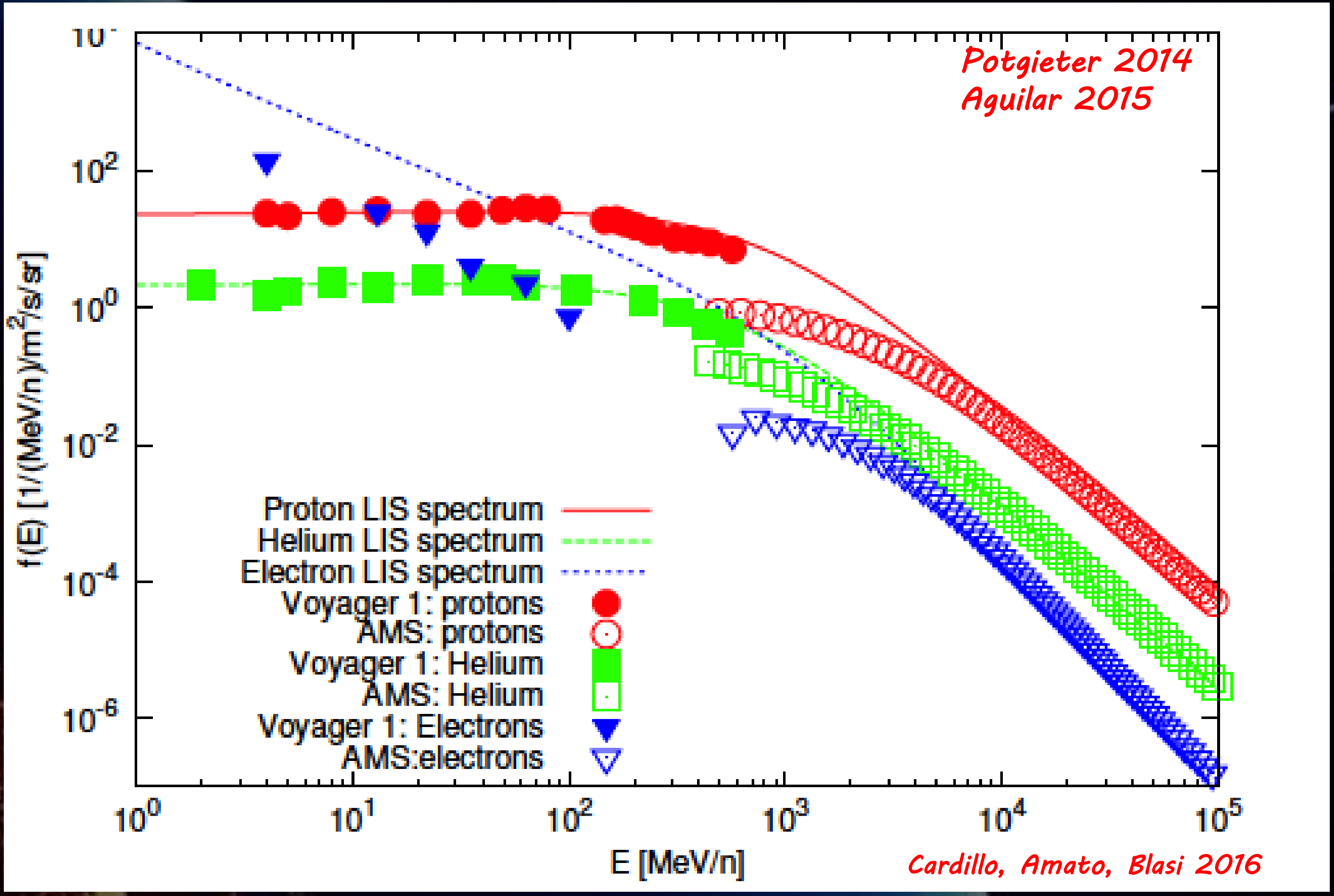
n_0, B_0 Galactic CRs (or injected CRs)	n_1, B_1, r_{sh} Reacceleration (or acceleration)	n_2, B_2, s Compression

- ✧ Pre-existing Galactic CR protons & electrons
- ✧ Reacceleration → hardening of spectral indices steeper than $\alpha=(3r_{sh})/(r_{sh}-1)$
- ✧ Compression → higher energies, higher spectrum ($s=(n_2/n_0)/r_{sh}$)
- ✧ Energy losses pp/ionization & ioniz/synch/Brems/IC
- ✧ Low-energy cut off and Malkov steepening

Pre-existing CRs

Reacceleration: our model

- Local Interstellar Spectrum from Voyager 1 (Potgieter 2013,2014)



What's new?

Reacceleration: our model

- Hydrogen and **Helium** contribution
- Consideration also of the only compressed Galactic component
- Surface filling factor: $4\pi\xi R_{sh}^2 v_{sh} t_{int}$
- Simple PL spectrum with no steepening but HE cut-off due to the limited time (fully ionized pre-shock medium)

$$p_M = 7\frac{GeV}{c}\left(\frac{B_0}{30\mu G}\right)\left(\frac{t_{int}}{15000yrs}\right)^3\left(\frac{L_c}{0.1pc}\right)^{-2}\left(\frac{V_{sh}}{130\ km/s}\right)^6$$

p_M~11 GeV/c

v_{sh}=130 km/s

n_0=200 cm^{-3}

t_{int} ~8400 yrs< t_{age}

$$b = \left(\frac{V_A}{1.84km/s}\right) \sim 2.4$$

$$B_0 = \left(\frac{n_0}{1cm^{-3}}\right)^{1/2} \sim 34\ \mu G$$

Kolmogorov Turbulence

$$D(E) = \frac{1}{3}cr_L\left(\frac{L_c}{r_L}\right)^{2/3}$$

L_c~ 0.09 pc

$$n_m = 94 n_0 b\left(\frac{V_{sh}}{10^7 cm/s}\right) \sim 10^4\ cm^{-3}$$

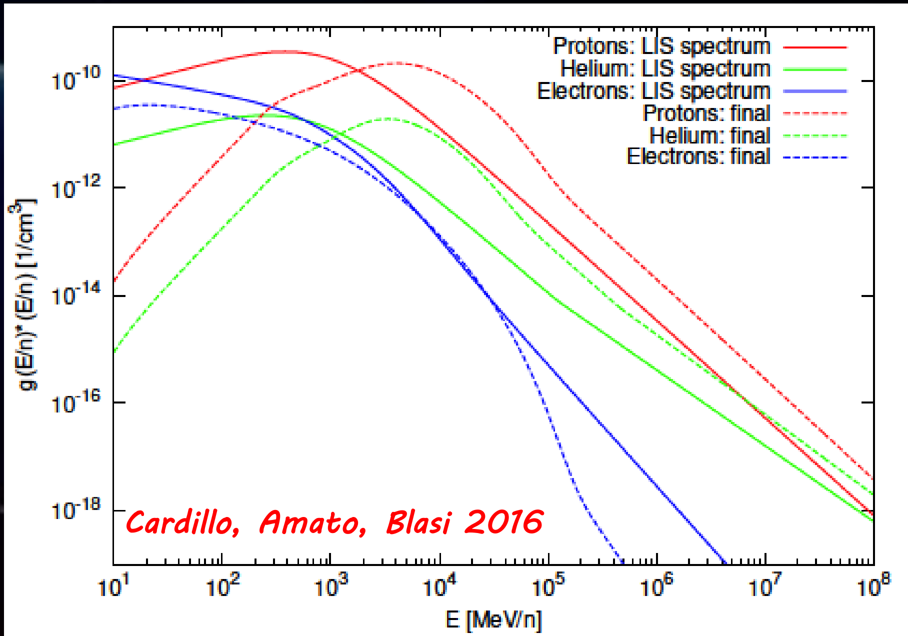
$$B_m = \sqrt{\frac{2}{3}\left(\frac{n_m}{n_0}\right)}B_0 \sim 1\ mG$$

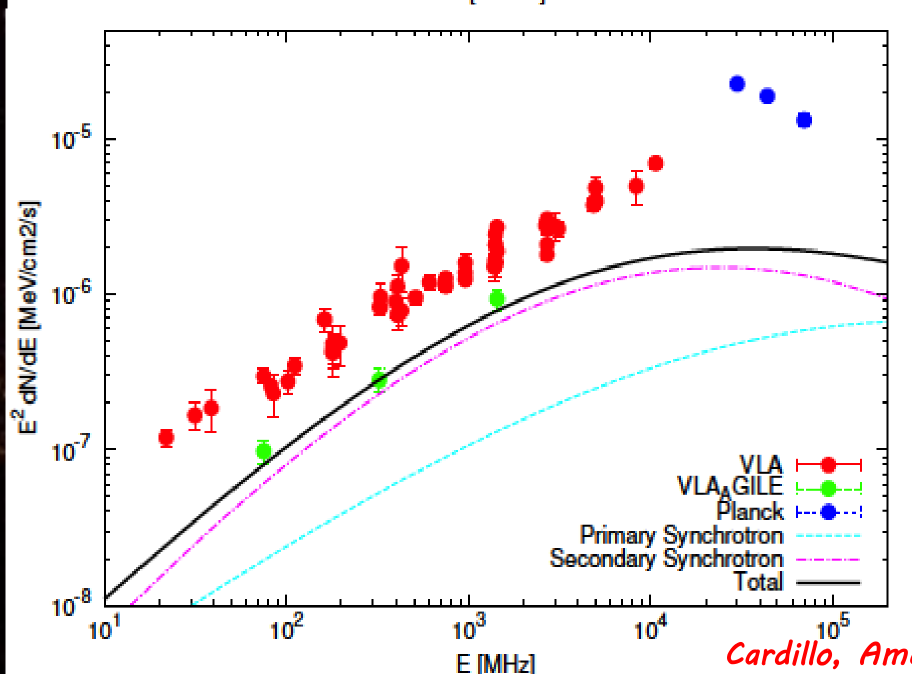
Best fit

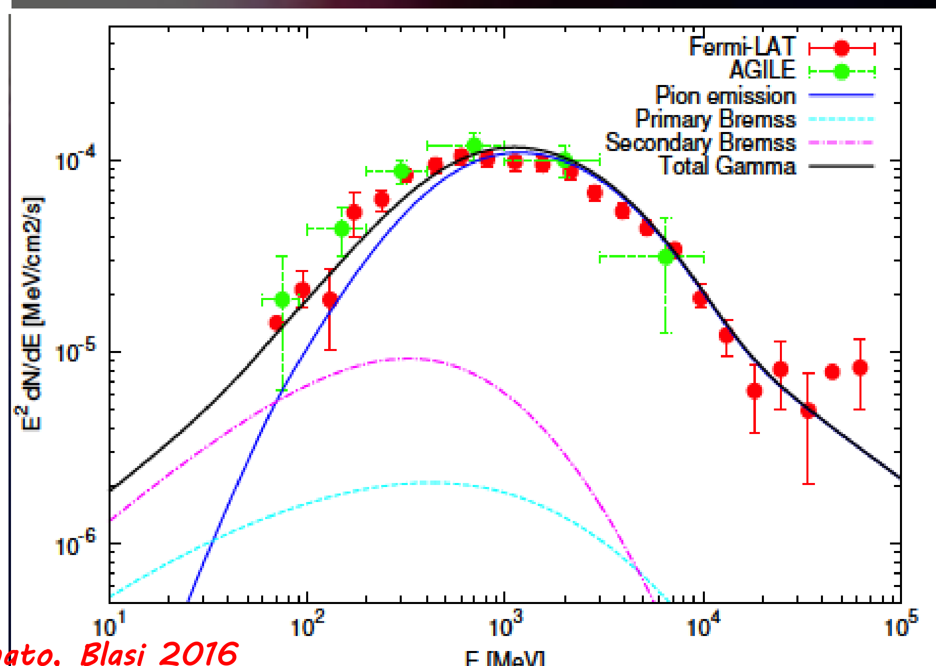
Reacceleration: our model

$r_{sh} = 3.5 \div 4 \rightarrow \gamma_p = 4.2\text{-}4$

surf. filling factor $\xi \sim 50\%$







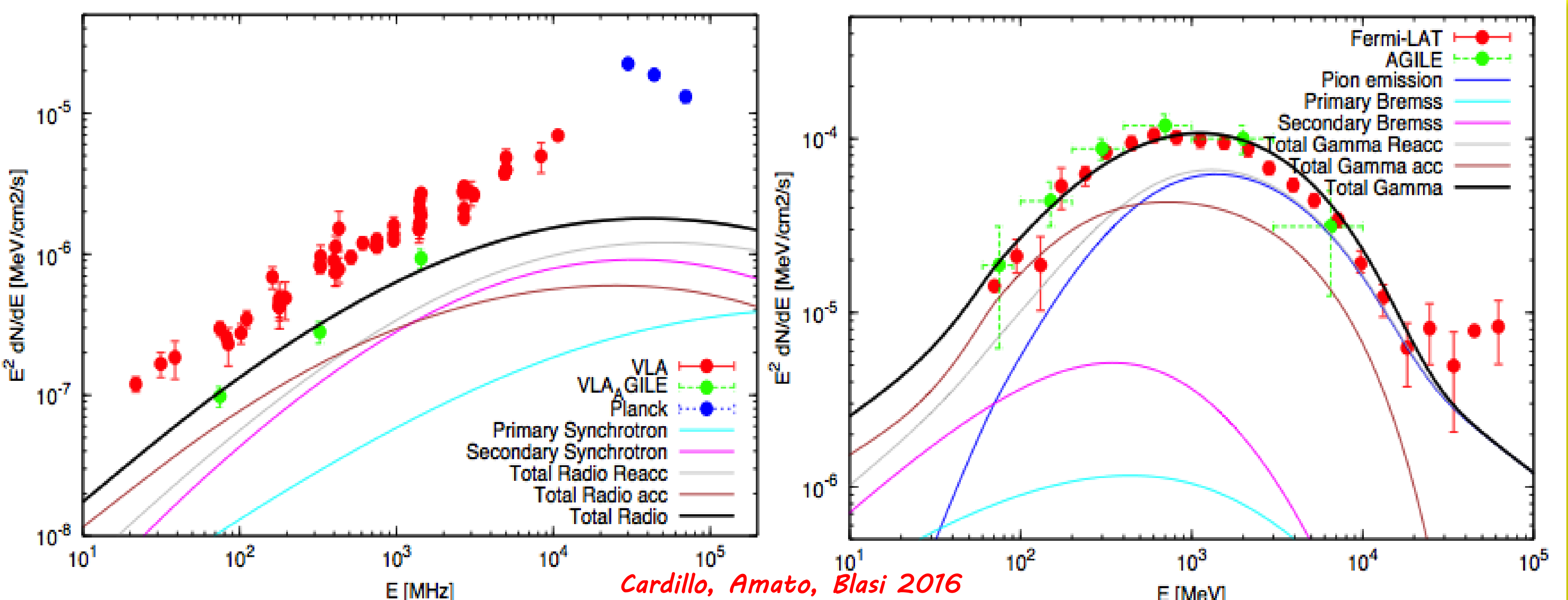
Cardillo, Amato, Blasi 2016

Acceleration contribution

Reacceleration: our model

Very high fraction ξ of the SNR shell has to be covered by the cloud in order to obtain a good explanation of the data

→ We consider a possible contribution from freshly accelerated CRs in order to alleviate this problem



Cardillo, Amato, Blasi 2016

$\xi_{cr} \sim 10^{-4}$

$\xi \sim 30\%$

Main Conclusions

Reacceleration: our model

- ✧ Reacceleration and compression of pre-existing CRs can explain gamma-ray and radio emissions from W44 (and likely IC443)
- ✧ The basic form of the reacceleration mechanism can explain data:
  - → no broken-power law distributions
  - → no very steep high-energy index
- ✧ Mixed reaccelerated and weakly accelerated particles (ξ_{cr}) provide a good fit of the data

No proof of freshly accelerated Cosmic-Rays