SNRs : an Odyssey in space after stellar death

June, 6-11, 2016

Middle-aged SNRs W44 (& IC443) and Cosmic-Rays: most likely reacceleration

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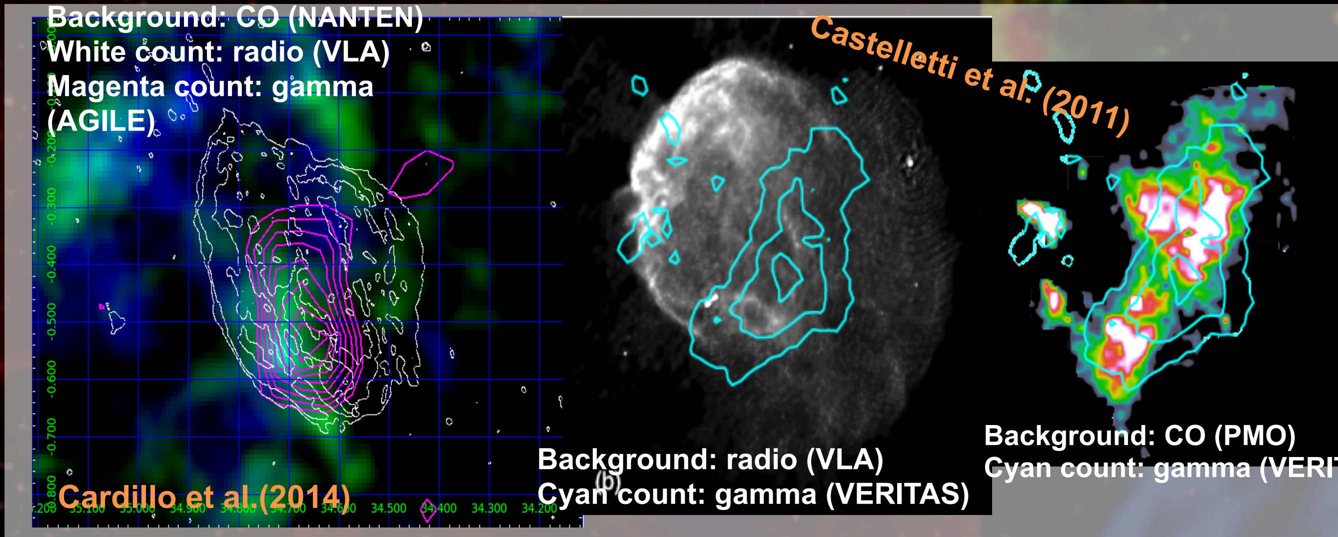
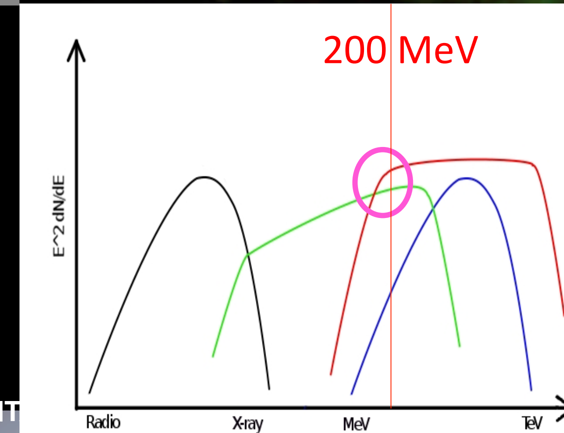
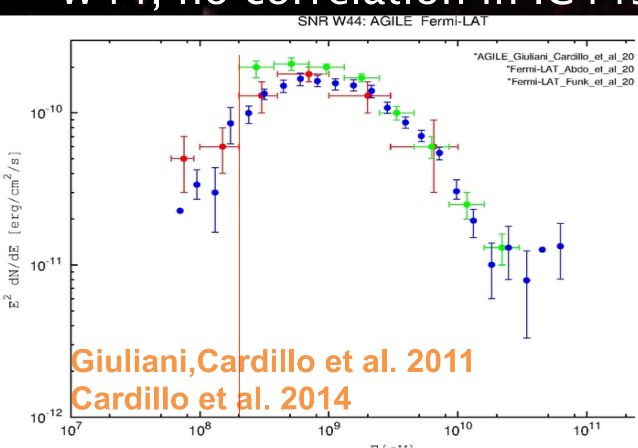
OVERVIEW

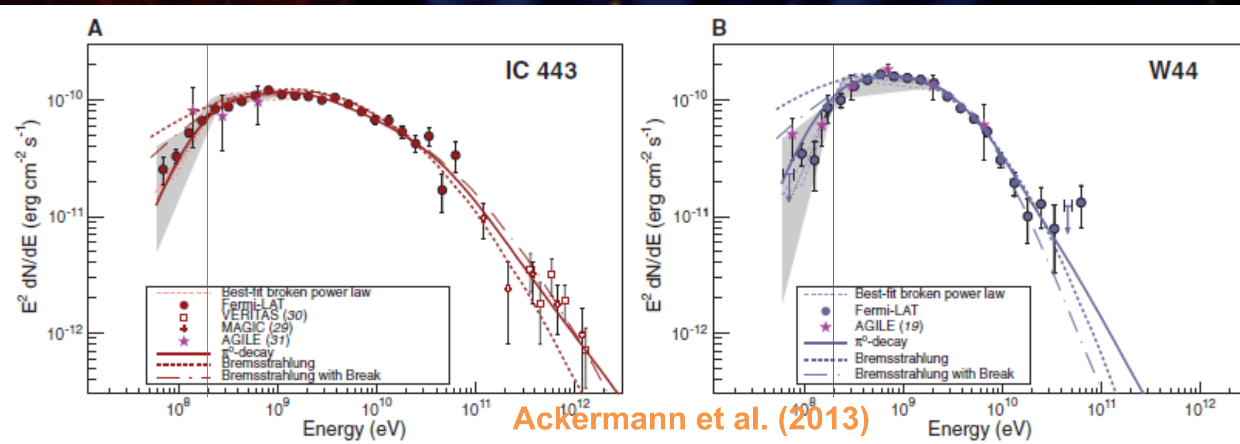




- Middle aged SNRs ($t \geq 10^4$ yrs) with a slow shock velocity ($v_s \sim 100$ km/s)
- Interaction with a molecular cloud (high average density, $n \sim 200$ cm^{-3})→ correlated with GeV (and TeV for IC443) gamma-ray emission
- Correletion with part of the radio emission in W44, no correlation in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

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

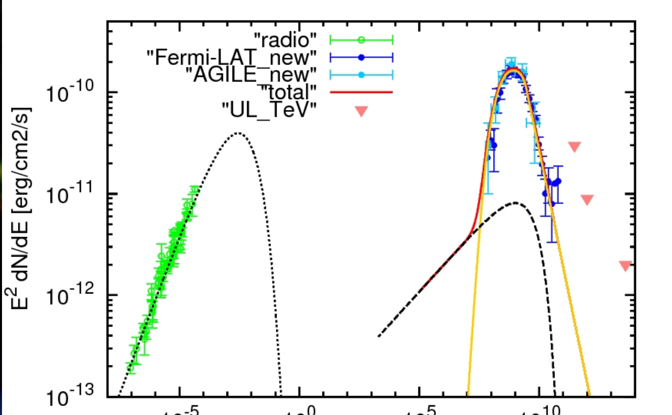




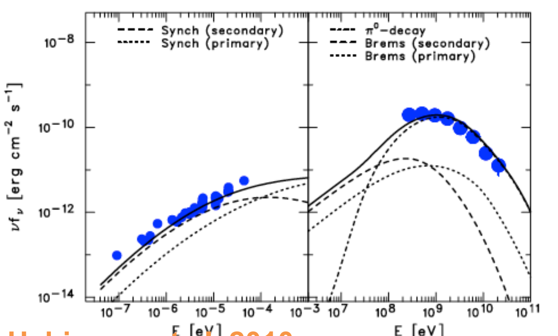
REACCELERATION OR ACCELERATION?

ACCELERATION

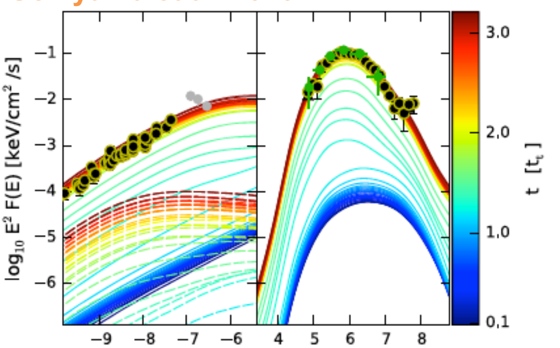
- ✧ Freshly accelerated CRs with a spectral index $\alpha=(3r_{sh})/(r_{sh}-1)$ at low-energies
- ✧ Broken power-law $\alpha=2.2$ below E~10 GeV and $\alpha=3.2$ above E~10 GeV
- ✧ Malkow steepening due to Alfvèn damping



Cardillo et al. 2014



Uchiyama et al. 2010



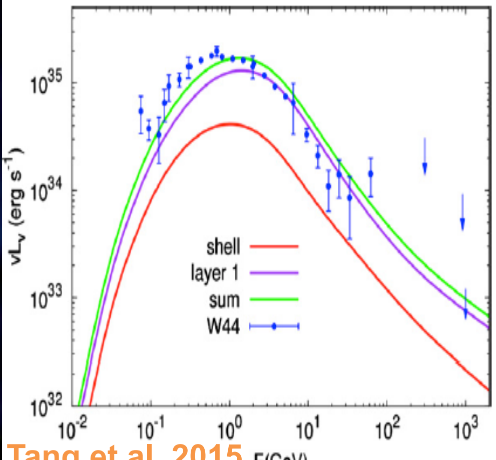
Lee et al. 2015

REACCELERATION

Crushed Cloud model (Blandford & Cowie 1982)

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

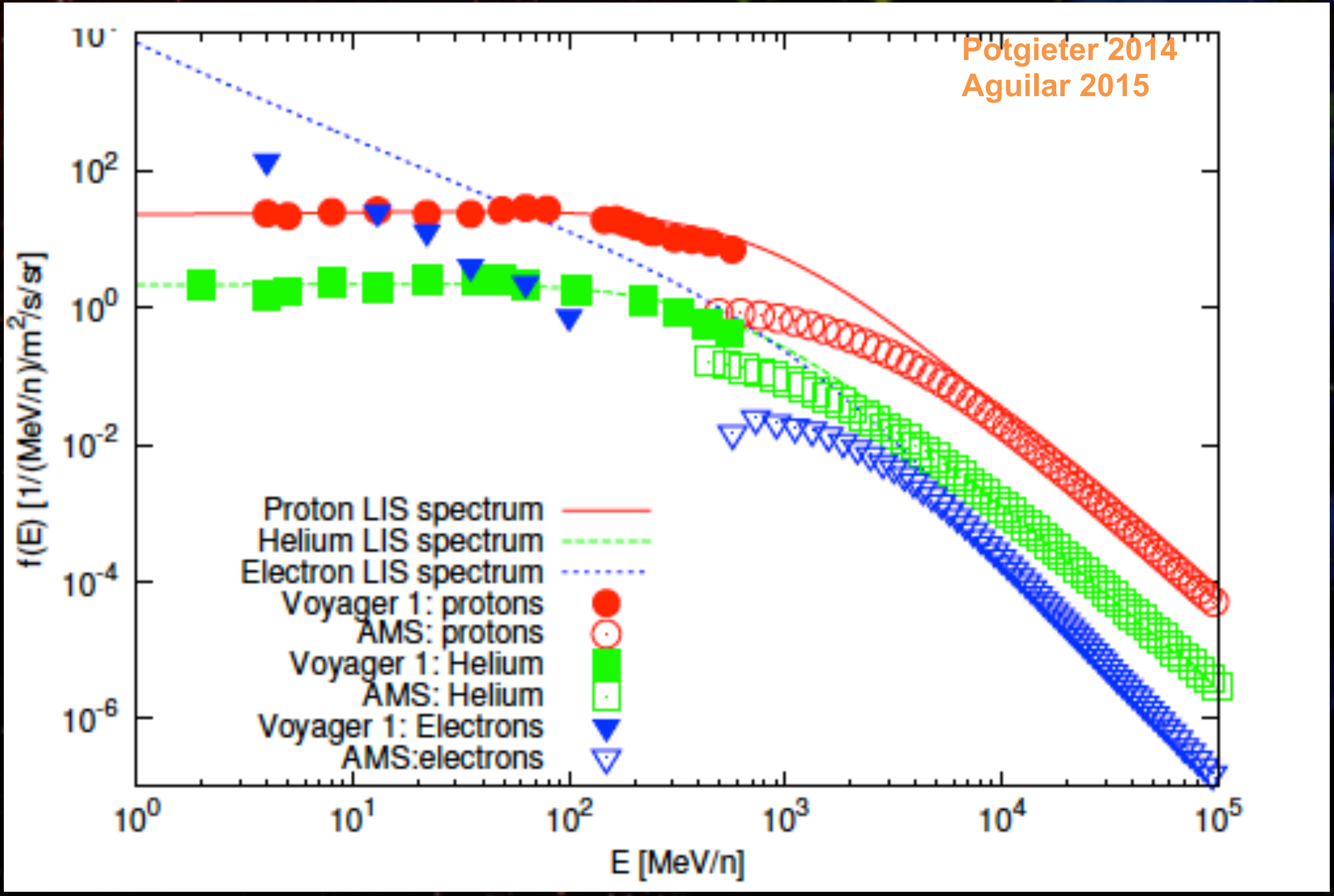


Tang et al. 2015

See Tang's talk of Monday

GALACTIC SPECTRUM: VOYAGER 1 + AMS

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



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)

Maximum momentum

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

Kolmogorov Turbulence

$D(E)=1/3\ r_L c\ (k/k_0)^{2/3}$

$L_c \sim 0.09$ pc

$n_0=200\ \mathrm{cm}^{-3}$

$v_{sh}=130$ km/s

$t_{int} \sim 8400\ \mathrm{yrs} < t_{age}$

$b= (V_A/1.84)\ \mathrm{km/s} \sim 2.4$

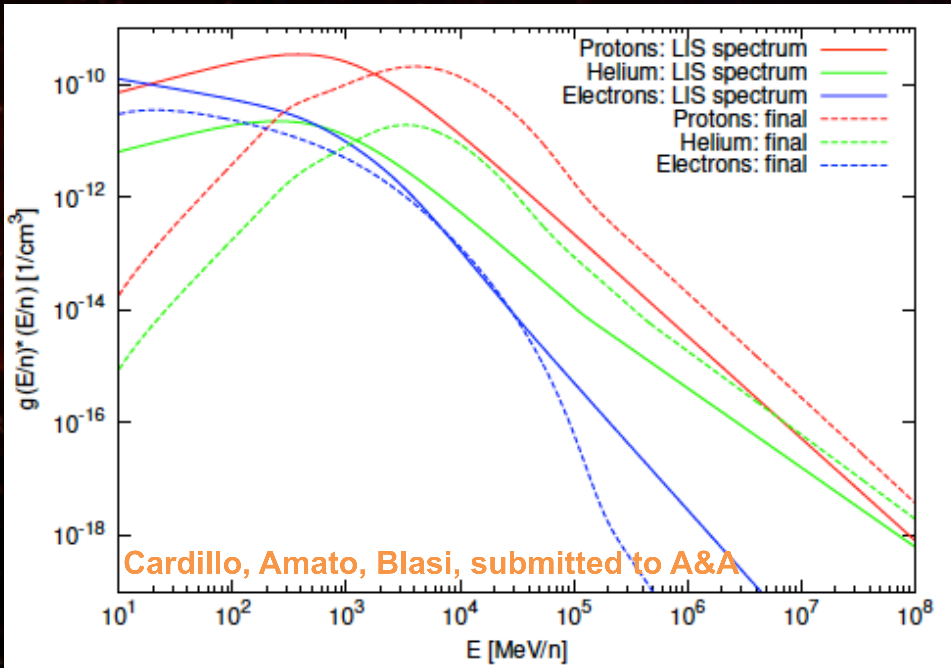
$B_0=b\ (n_0/1\mathrm{cm}^{-3})^{1/2} \sim 34\ \mu G$

$n_m=94\ n_0\ b\ (v_{sh}/10^7\ \mathrm{cm/s}) \sim 10^4\ \mathrm{cm}^{-3}$

$B_m=(3/2)^{1/2}(n_m/n_0)\ B_0 \sim 1$ mG

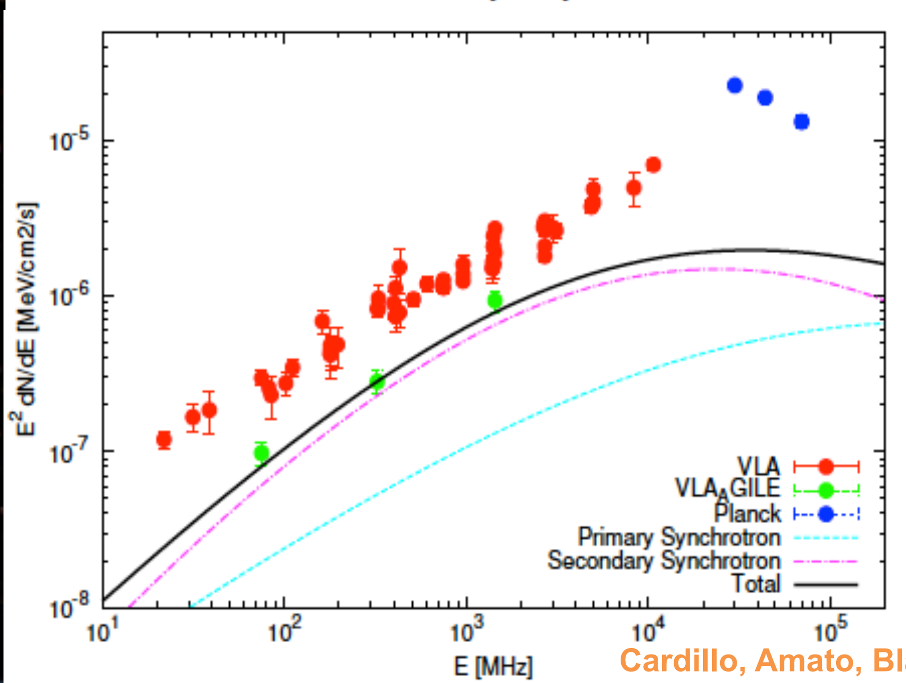
$p_M \sim 11$ GeV/c

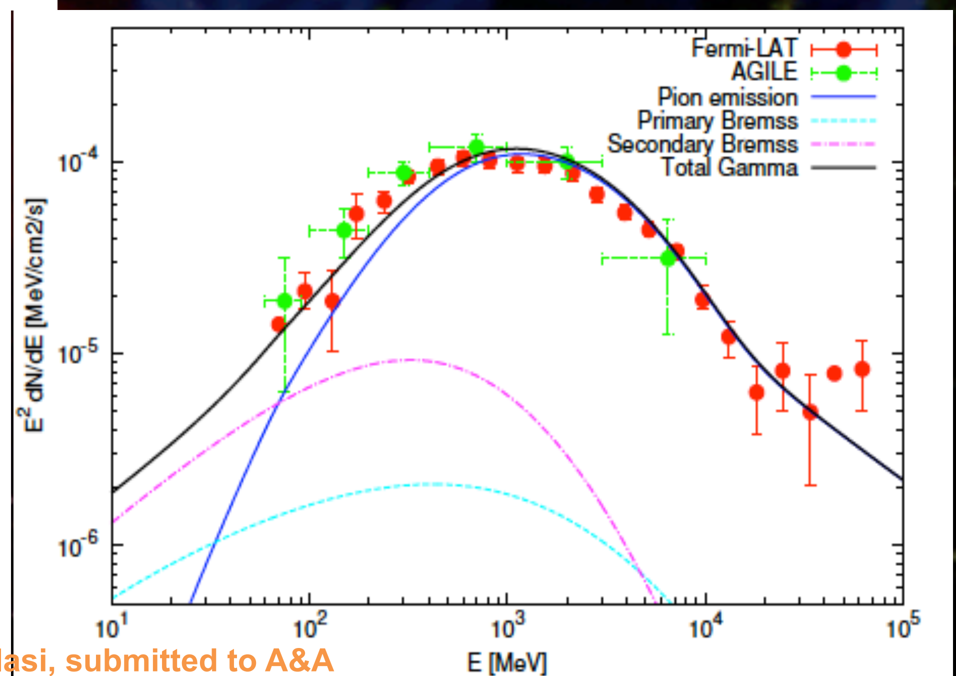
REACCELERATION: our model



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

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





Cardillo, Amato, Blasi, submitted to A&A

Contribution from Acceleration

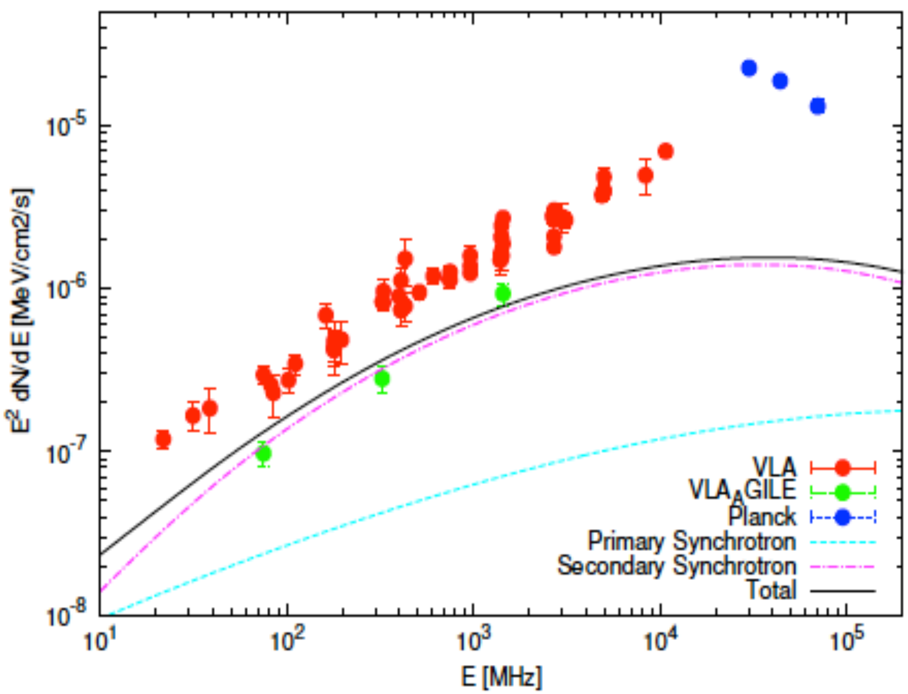
Very high fraction ξ of the SNR shell has to be covered by the cloud in order to obtain a good explanation of the data.

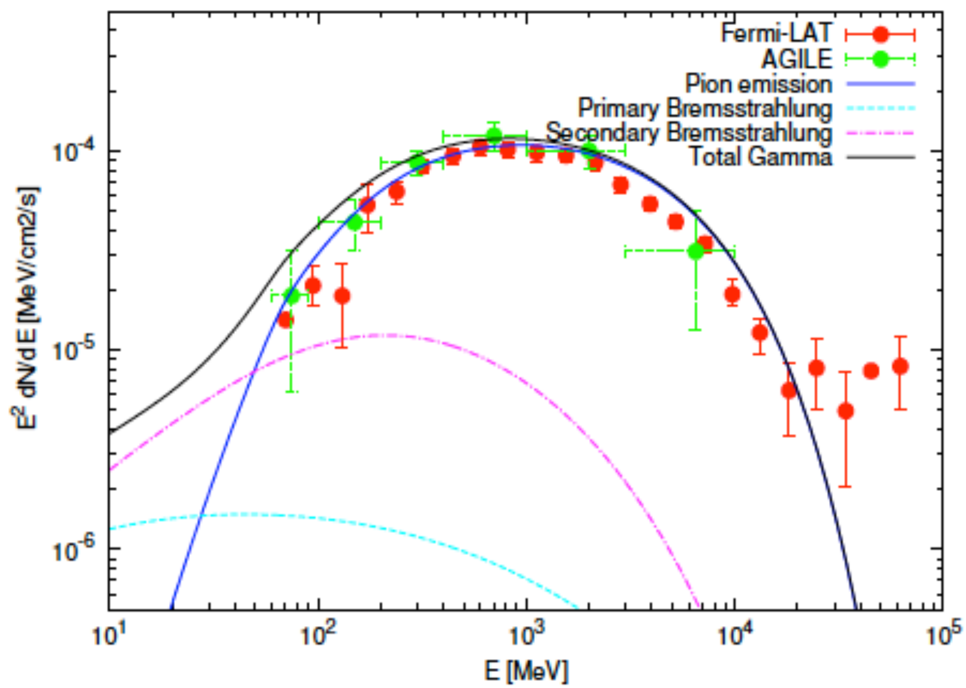
↓

We consider a possible contribution from freshly accelerated CRs in order to alleviate this problem and we found a good fit for:

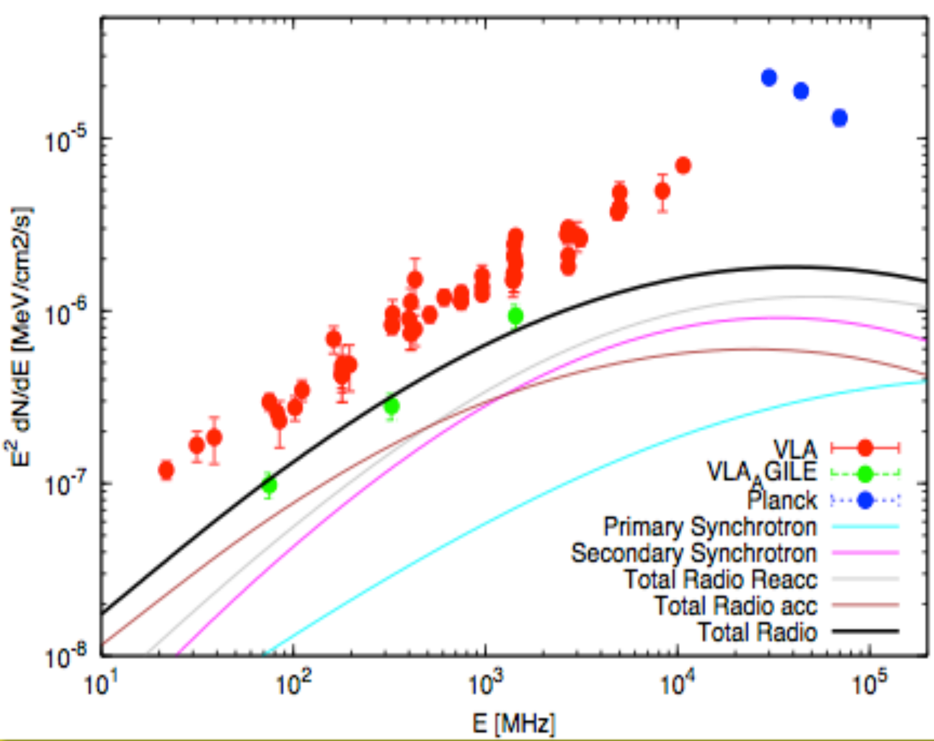
$$\boxed{\xi \times \xi_{cr} \sim 6.4 \times 10^{-5}}$$

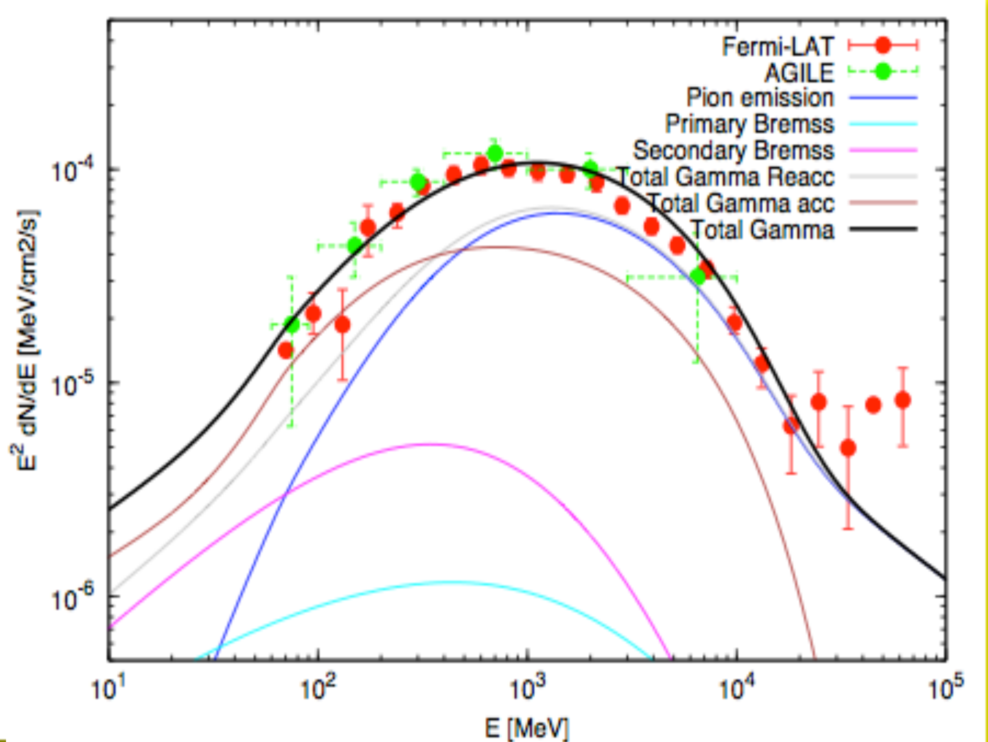
Cardillo, Amato, Blasi, submitted to A&A





Reacceleration + Acceleration





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

$\xi \sim 30\%$

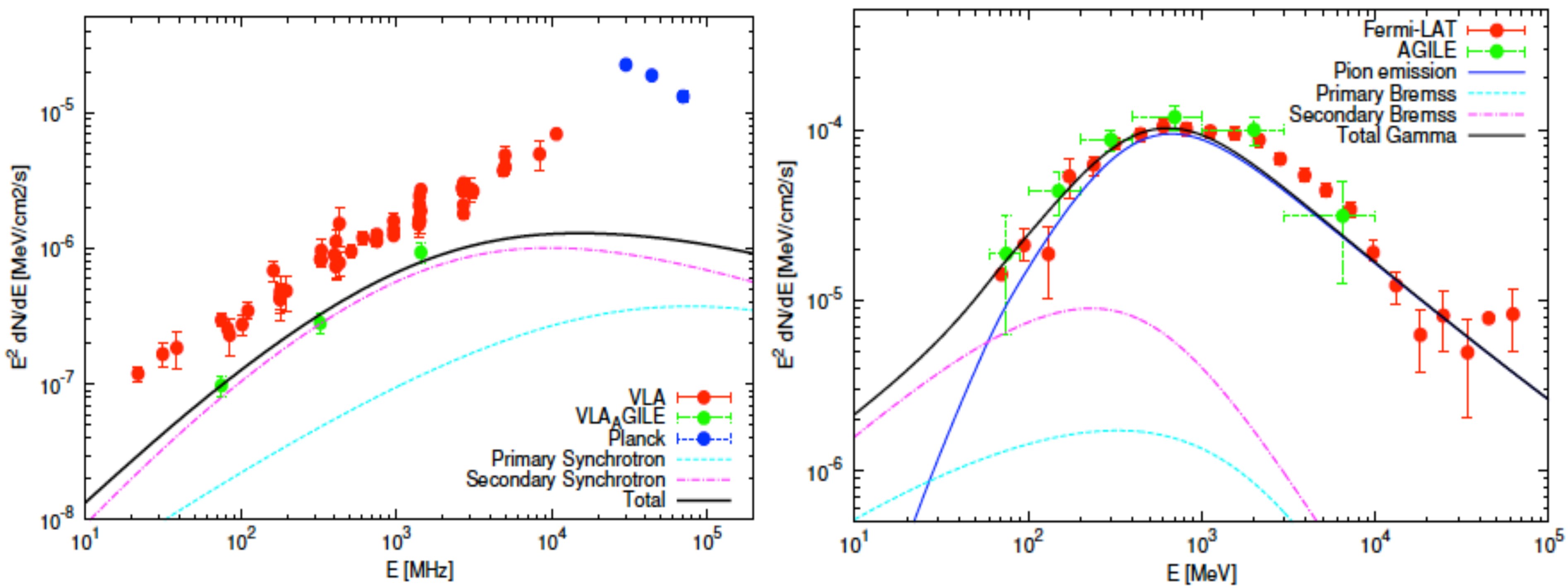
Only Compression

Cardillo, Amato, Blasi
submitted to A&A

Very weak shock of middle aged SNRs

Possible neutrals presence

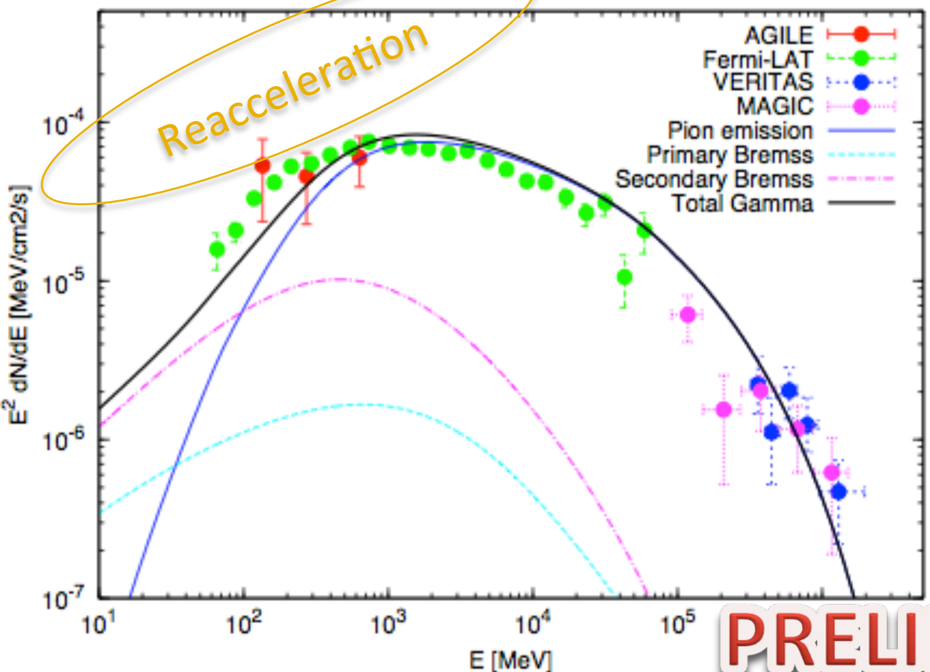
Possible Inhibition of the reacceleration and only compressed particle contribution

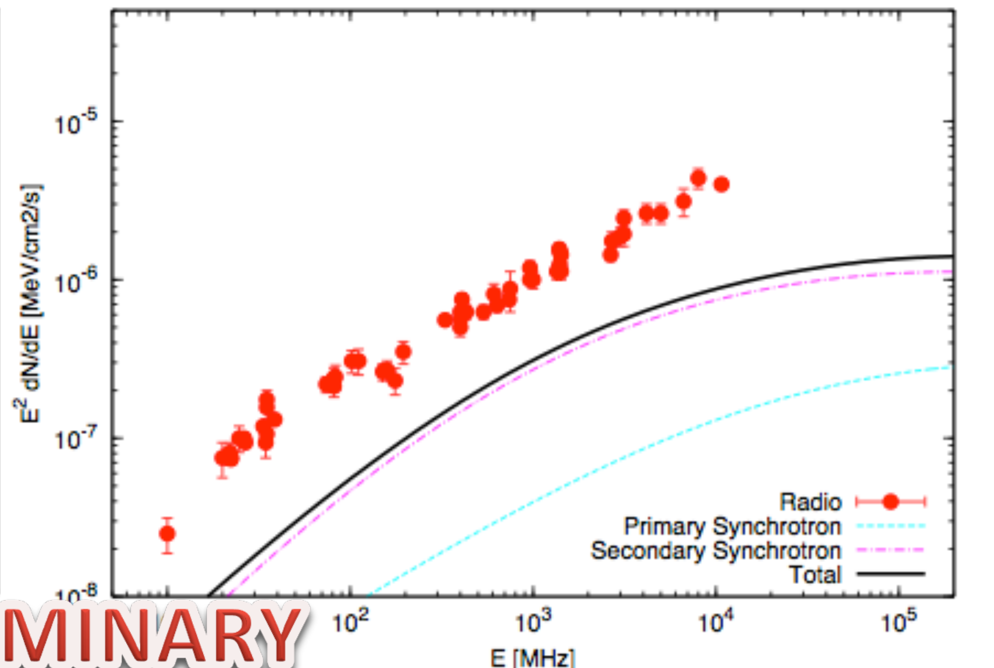


surf. filling factor ξ~ 65%

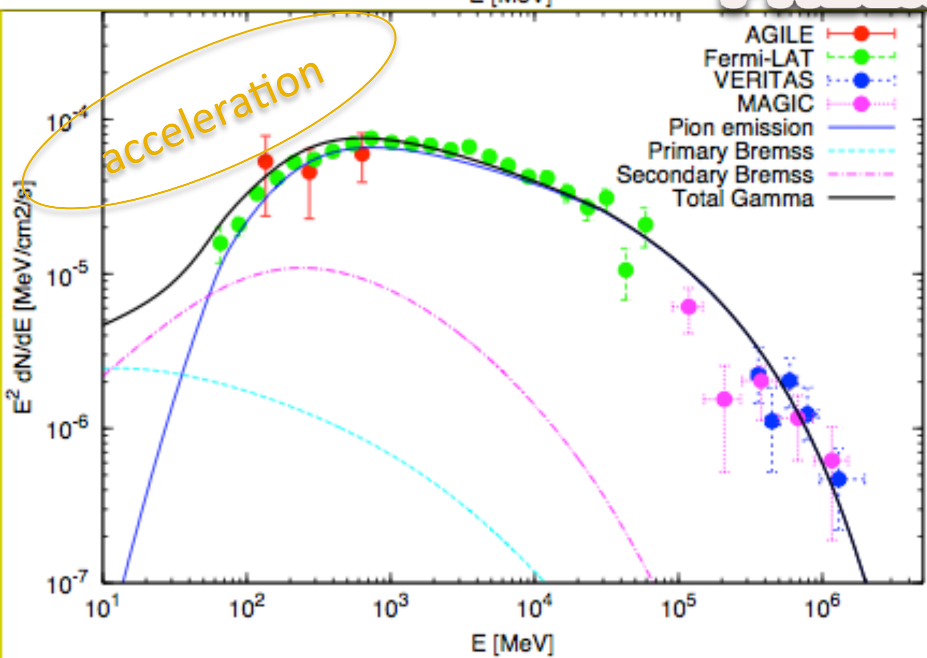
IC443

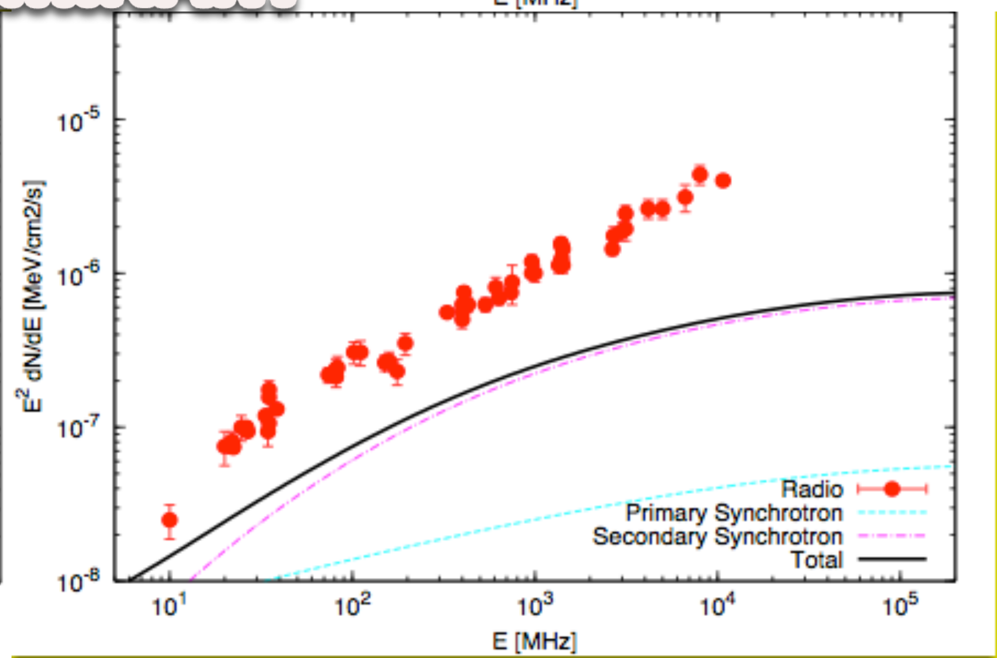
Cardillo, Amato, Blasi II
in preparation





PRELIMINARY





CONCLUSIONS

- ✧ Reacceleration and compression of pre-existing CRs can explain gamma-ray and radio emissions from W44 (and IC443)

- ✧ The basic form of the reacceleration mechanism can explain data:
  - → no broken-power law distributions
  - → no very steep high-energy index

- ✧The only compression of pre-existing Galactic CRs could explain gamma-ray emission from the two middle-aged SNRs.

- ✧ Mixed reaccelerated and weakly accelerated particles (ξ_{cr}) provide a good fit of the data, alleviating the surface filling factor problem


Thank you
very much!