# Particle acceleration and radiation processes in supernova remnants

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# Diffusive Shock Acceleration

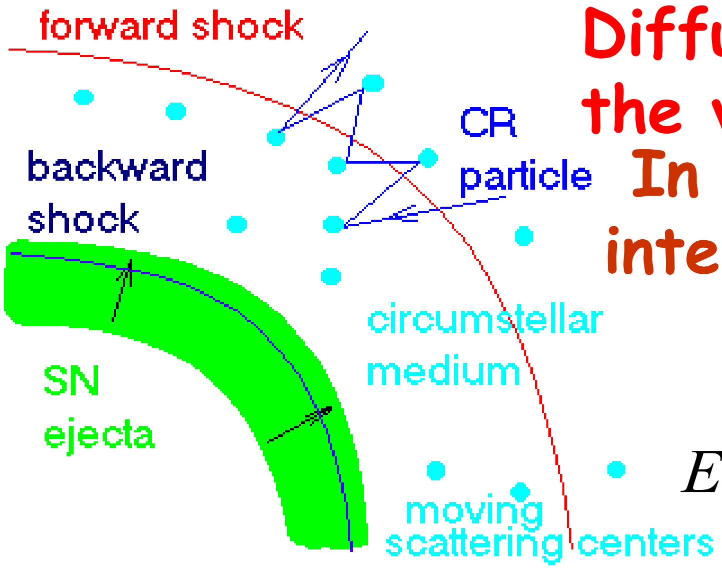
Krymsky 1977; Bell 1978; Axford et al. 1977; Blandford & Ostriker 1978

Very attractive feature: power-law spectrum of particles accelerated, $\gamma=(\sigma+2)/(\sigma-1)$, where $\sigma$ is the shock compression ratio, for strong shocks $\sigma=4$ and $\gamma=2$

Maximum energy for SN: $D \sim 0.1 u_{sh} R_{sh} \sim 3 \cdot 10^{27}\ \mathrm{cm^2/s} < D_{gal}$

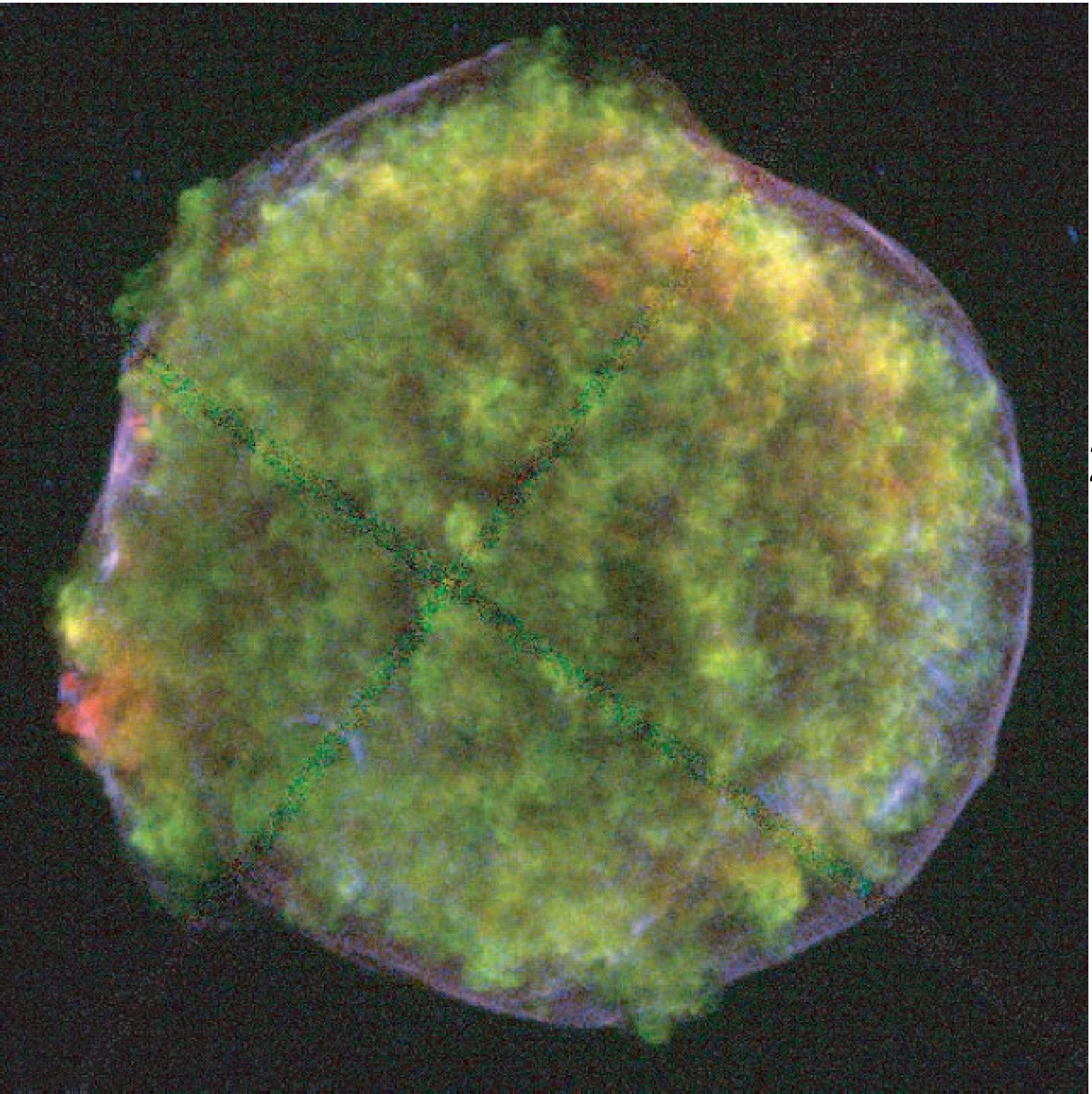
Diffusion coefficient should be small in the vicinity of SN shock

In the Bohm limit $D=D_B=cr_g/3$ and for interstellar magnetic field




$$E_{\max} = Z \cdot 10^{14}\,\mathrm{eV}\left(\frac{B}{10\,\mu\mathrm{G}}\right)\left(\frac{R_{\mathrm{sh}}}{3\,\mathrm{pc}}\right)\left(\frac{u_{\mathrm{sh}}}{3000\,\mathrm{km\,s^{-1}}}\right)$$

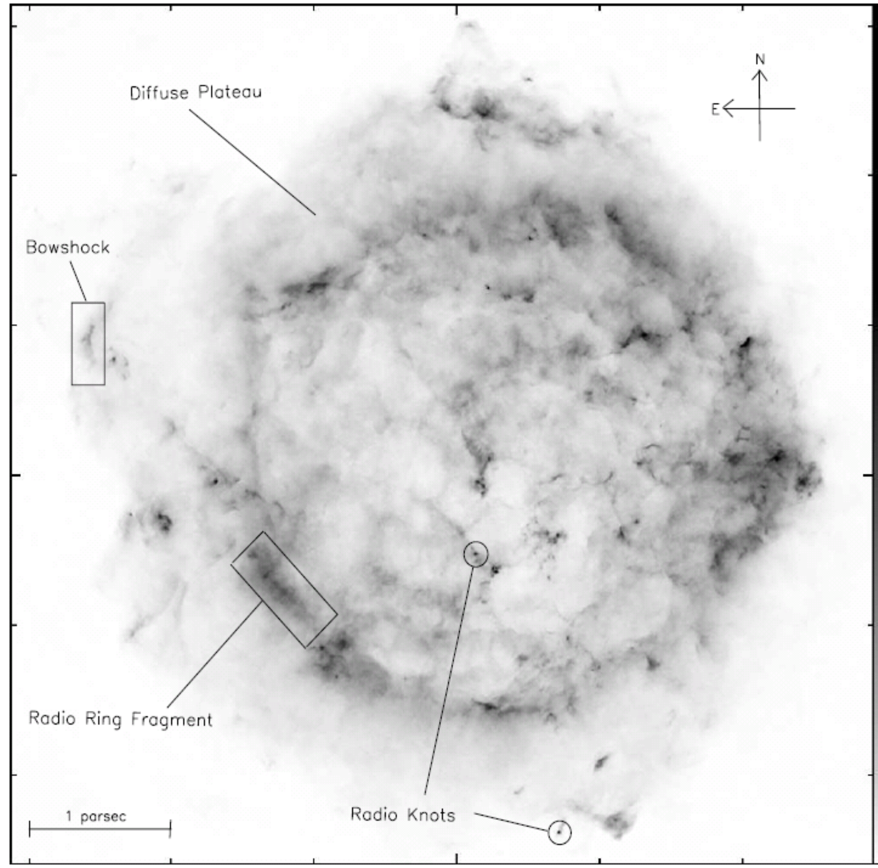
# X-ray image of Tycho SNR (from Warren et al. 2005)



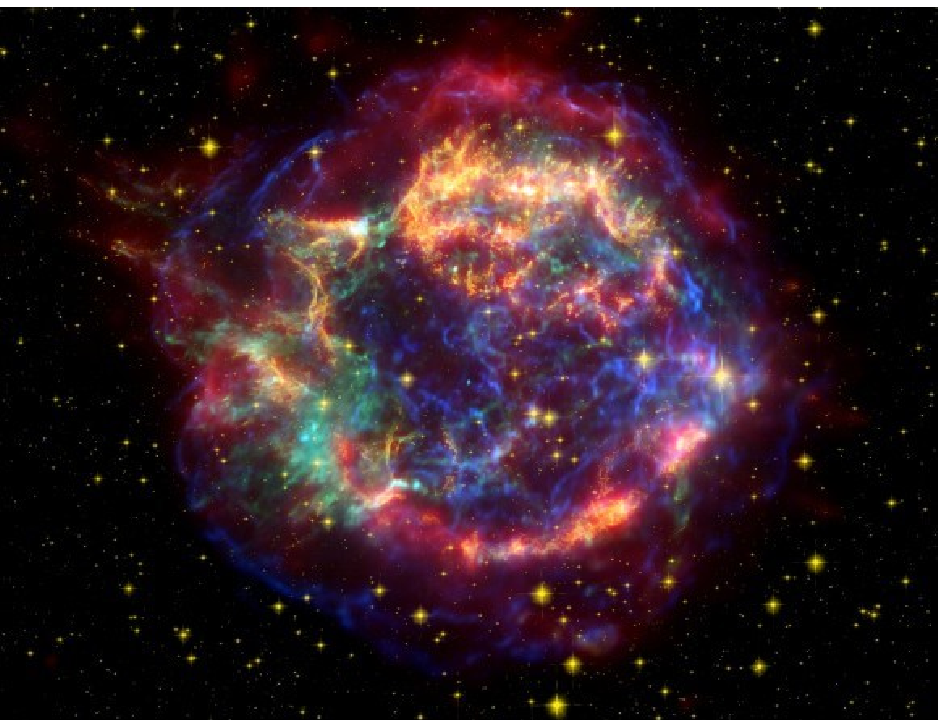
1. CD is close to the forward shock – evidence of the shock modification by CR pressure.
2. Thin non-thermal X-ray filaments at the periphery of the remnant – evidence of electron acceleration and of magnetic amplification.

Radio-image of Cas A

Atoyan et al. 2000




X-ray image of Cas A (Chandra)



Inner bright radio- and X-ray-ring is related with the reverse shock of Cas A while the diffuse radio-plateau and thin outer X-ray filaments are produced by electrons accelerated at the forward shock.

# Radio-image of RX J1713.7-3946 (Lazendic et al. 2004)

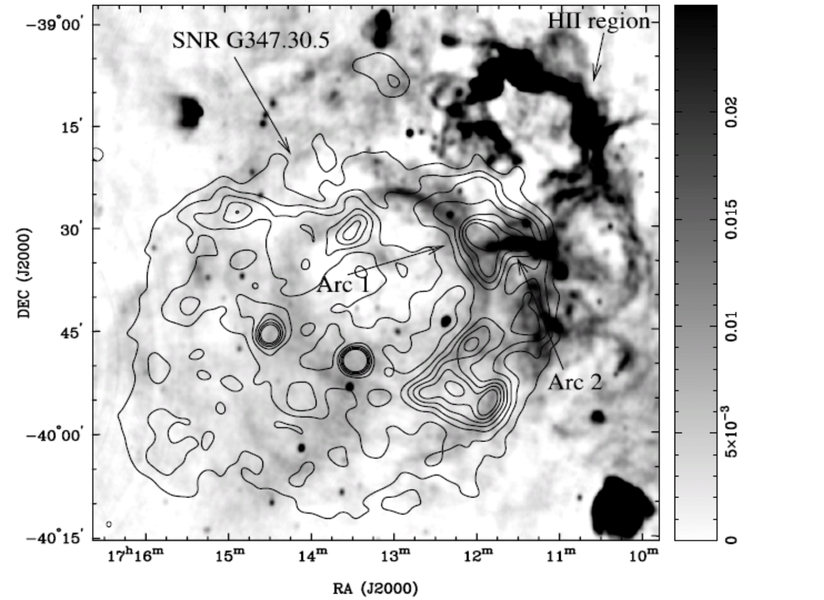



Fig. 5.—ATCA images of G347.3−0.5 and surrounding region at 1.4 GHz. The image was convolved with a Gaussian restoring beam of 46″ × 36″ (P.A. = −3°.8), shown by the tiny ellipse in the bottom left-hand corner. The image is overlaid with the *ROSAT* contours with the same levels as in Fig. 1. The linear gray scale is in units of Jy beam$^{-1}$.

# X-rays: XMM-Newton, Acero et al. 2009

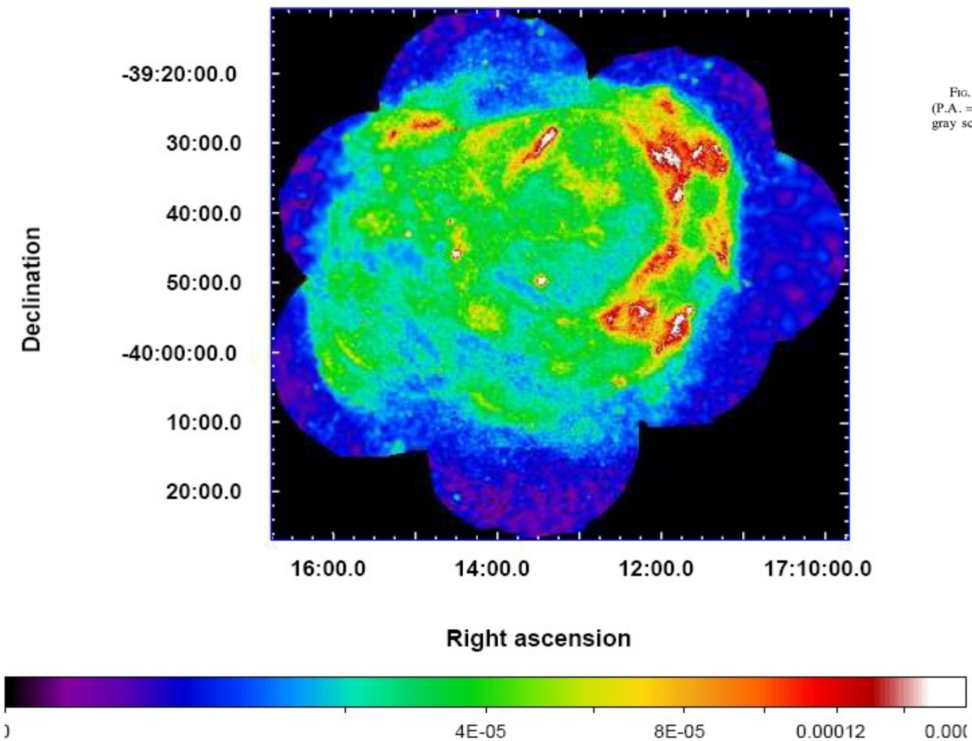



**Fig. 1.** EPIC MOS plus PN image in the 0.5-4.5 keV band. The units are ph/cm$^2$/s/arcmin$^2$ and the scale is square root. The image was adaptively smoothed to a signal-to-noise ratio of 10.

Inner ring of X-ray and radio-emission is probably related with electrons accelerated at the reverse shock.

# Youngest galactic SNR G1.9+0.3 (T~100 yr)

X-ray image

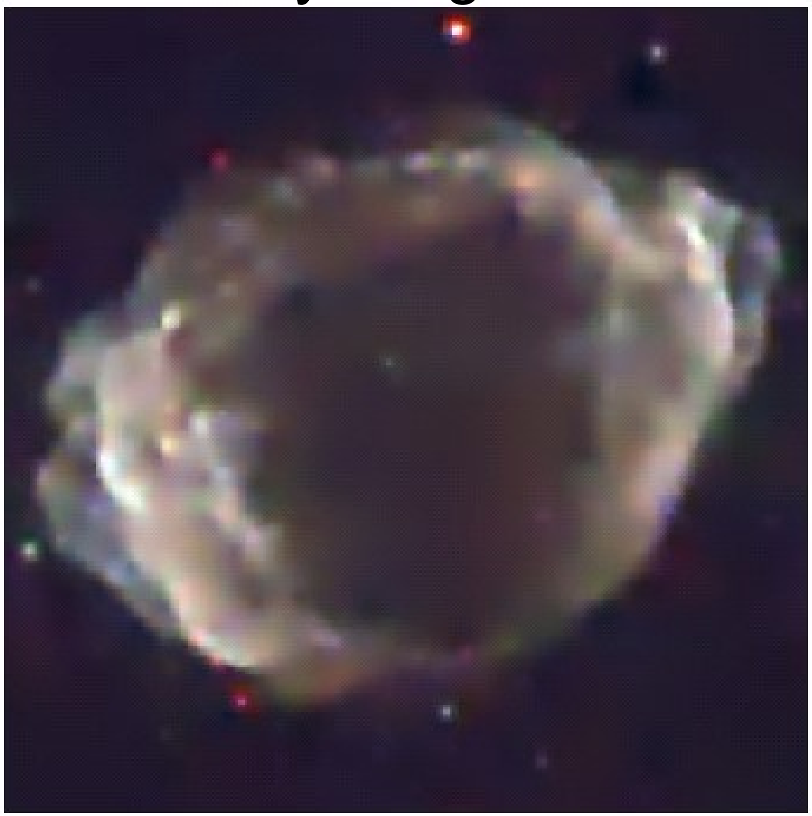
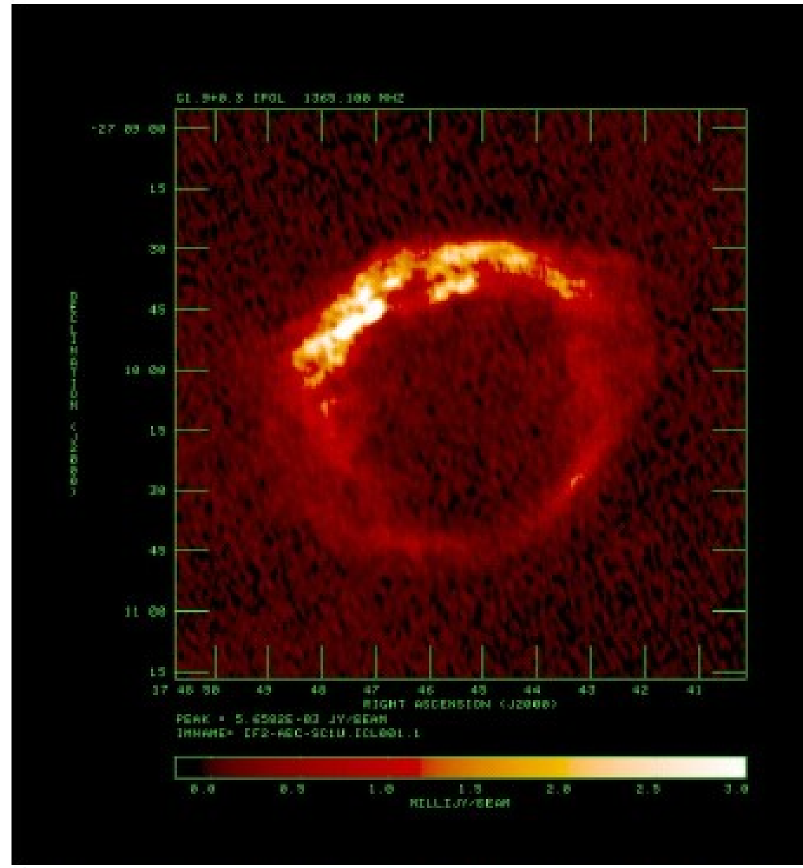


**Figure 1.** *Chandra* image of G1.9+0.3. Red, 1–3 keV; green, 3–4.5 keV; and blue, 4.5–7.5 keV. Image size is 127″ × 121″.

Thermal X-rays and 4.1 keV Sc line (product of $^{44}$Ti) are observed from bright radio-regions (ejecta)

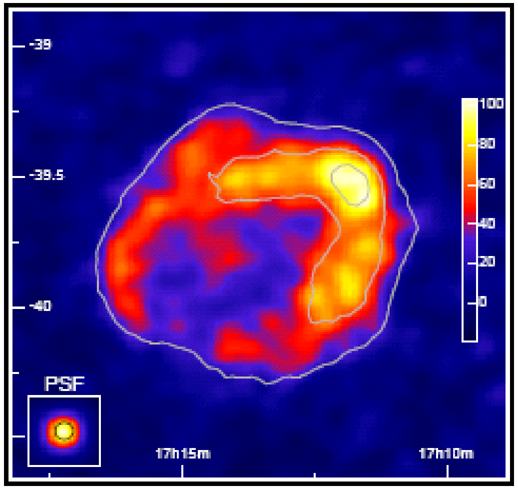
radio-image




Borkowski et al. 2010

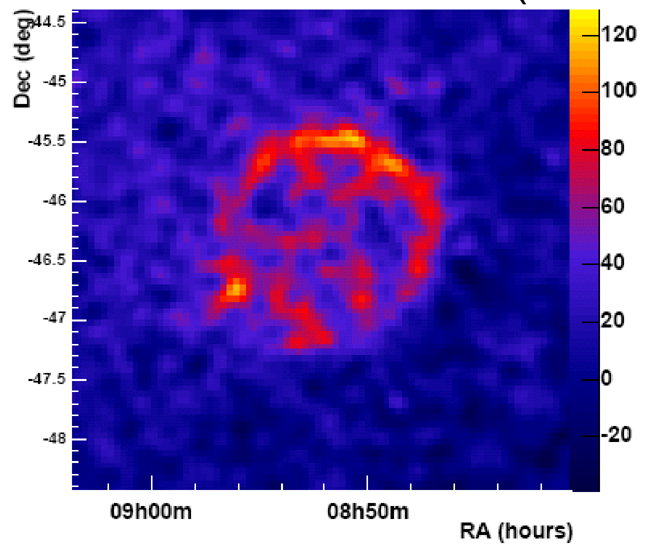
# TeV gamma-rays from young SNRs

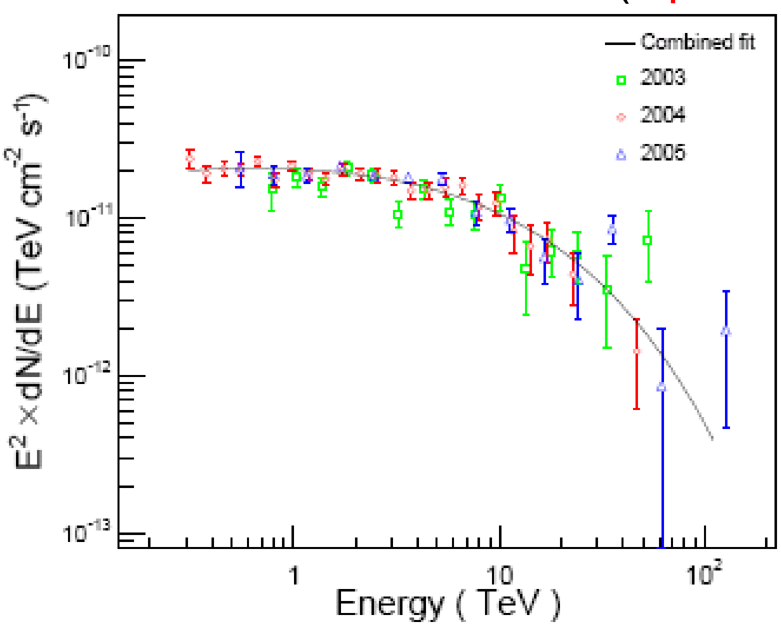
Aharonian et al 2008 (HESS)



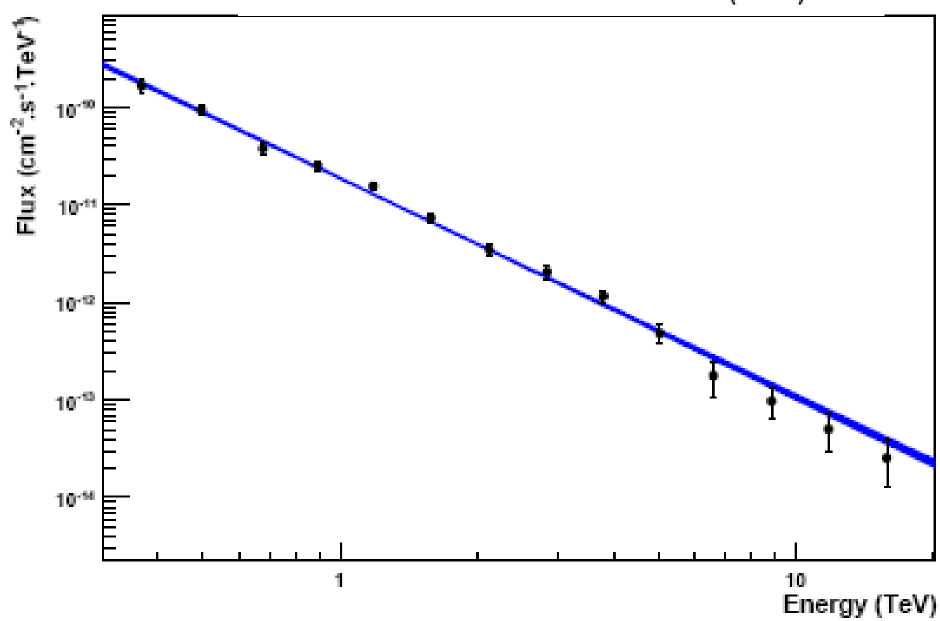

Particles accelerated up to100 TeV in these SNRs. Gamma-rays can be produced in pp collisions (hadronic models) or via the Inverse Compton scattering of IR and MWBR photons on the electrons accelerated (leptonic models)

Aharonian et al 2007 (HESS)



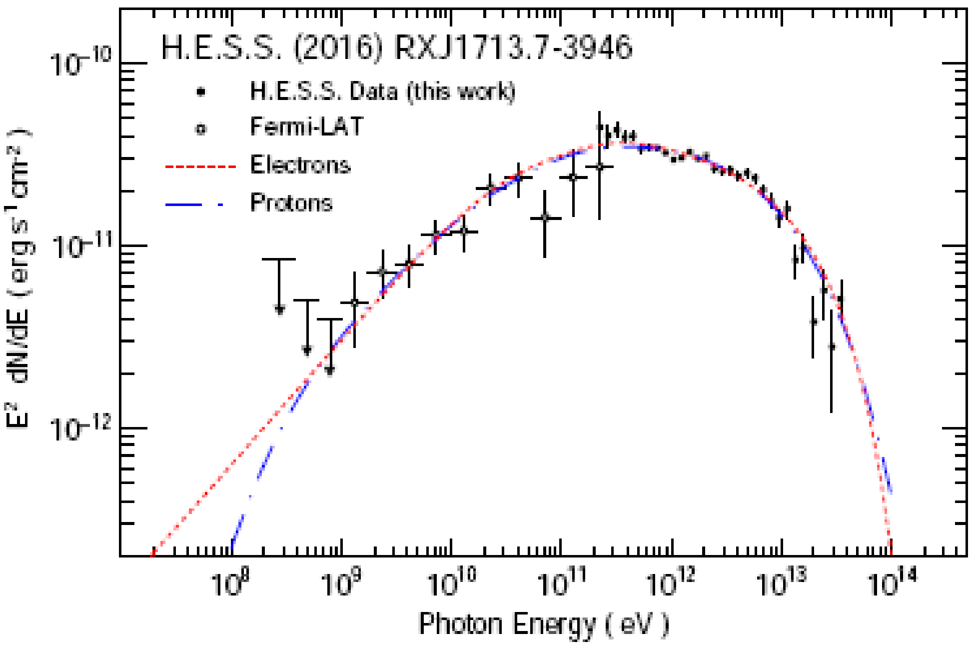

RX J1713.7-3946



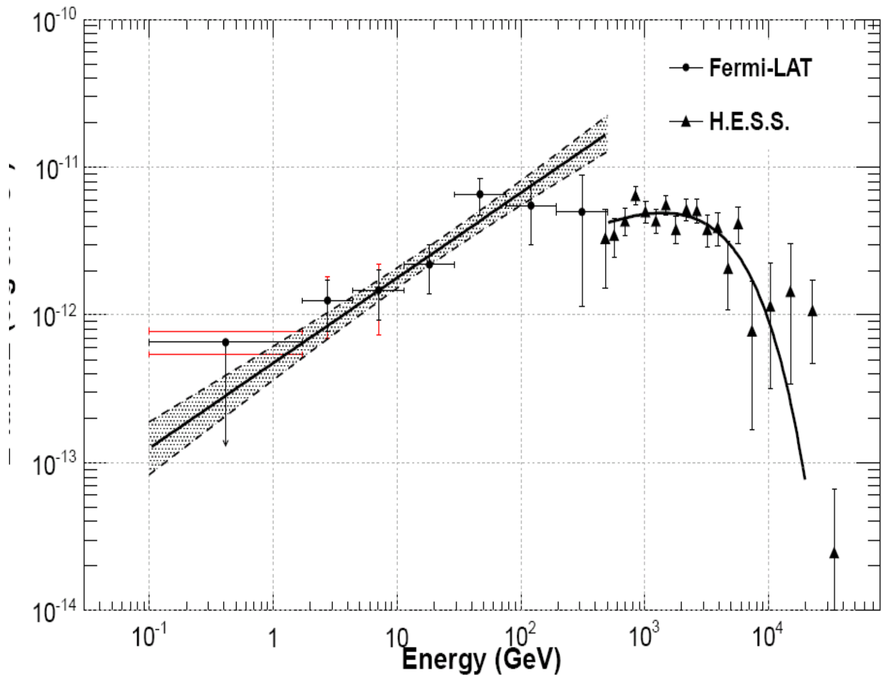

Vela Jr

# Young SNRs in low density medium (wind blown bubbles)

RX J1713.7-3946 $n_H \leq 0.1 cm^{-3}$ RCW86




Abdalla et al. 2017




Ajello et al. 2016

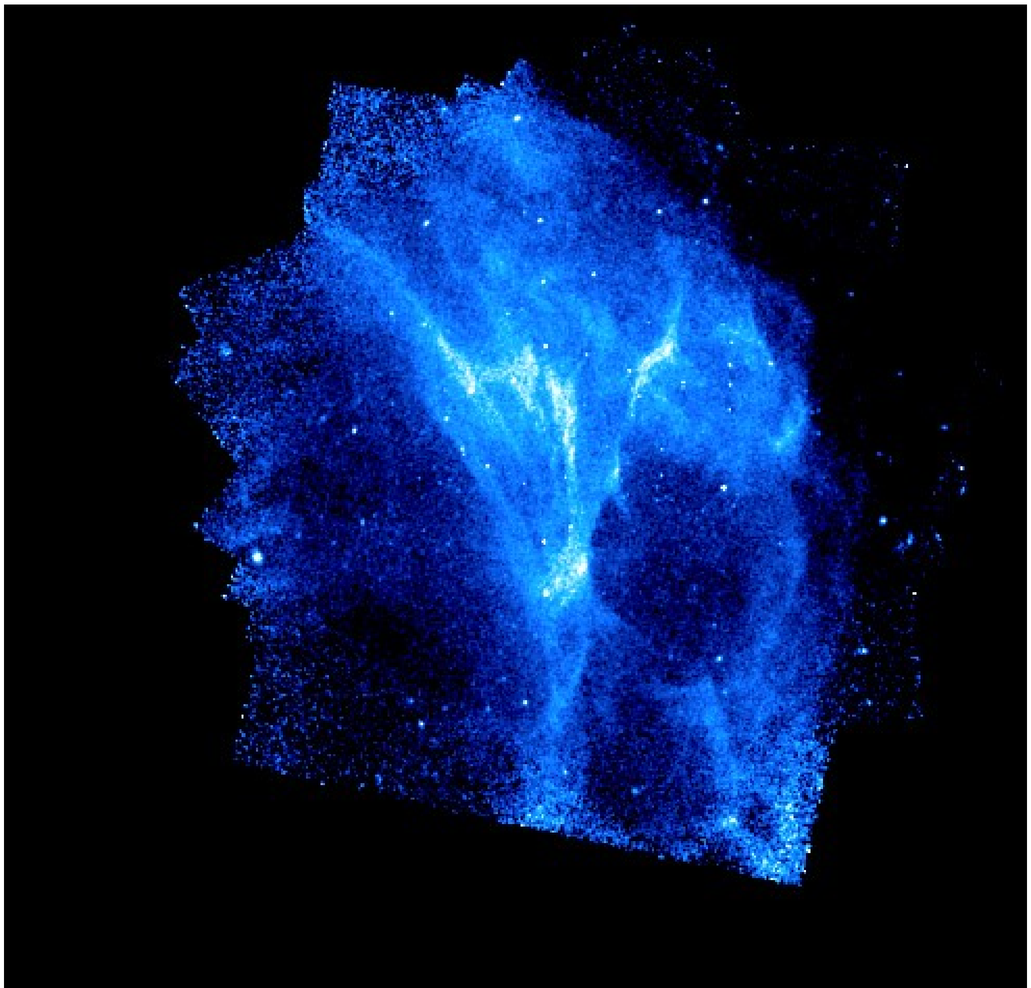
T~1600 yr

T~2000 yr

Probably the leptonic origin of gamma emission, however hadronic gamma rays from multiple small compact clouds are not excluded. In both cases protons are accelerated up to energies ~100 TeV

# Multiple compact clouds in RX J1713.7-3946

X-ray image (Higurashi et al. 2020)



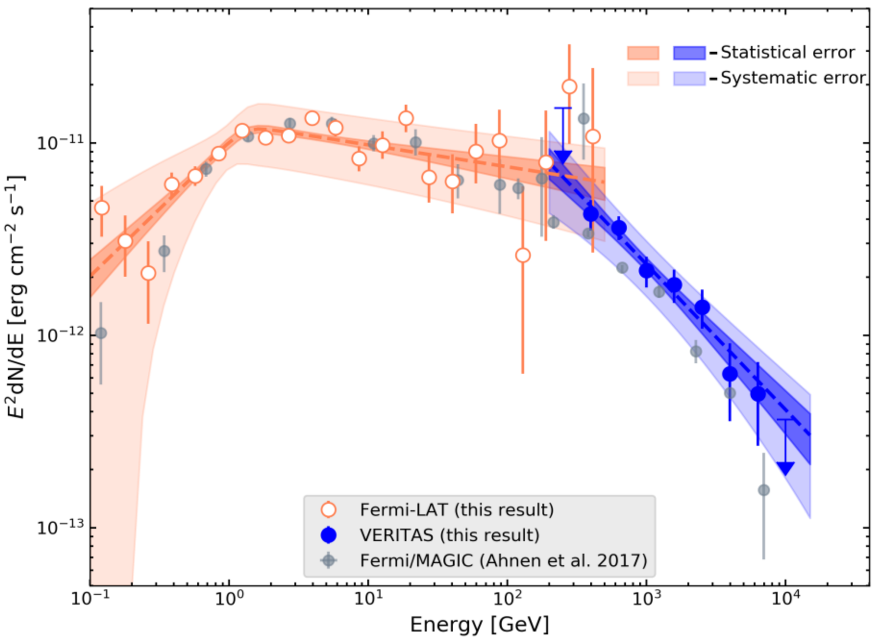
Hot X-ray spots are produced by secondary electrons from pp interactions in compact clouds

Compact molecular clouds are also detected in CO observations (Sano et al. 2020)

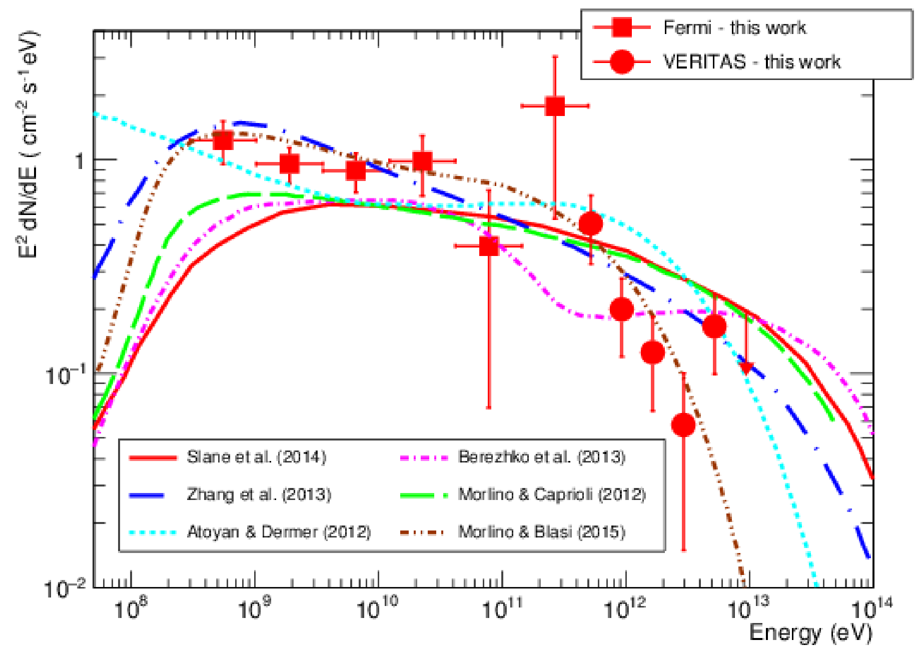
More intensive gamma emission
from pp interactions

# Young SNRs in denser medium

Cas A  T=350 yr    $n_H \sim 0.3\text{-}1\ cm^{-3}$    Tycho  T=450 yr




Abeysekara et al. 2020



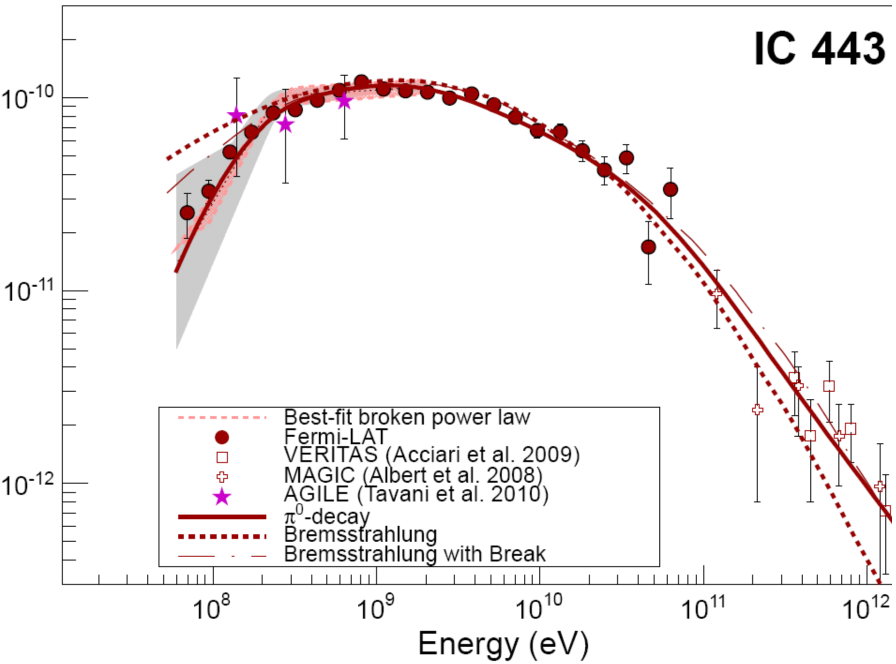

Archambault et al. 2017

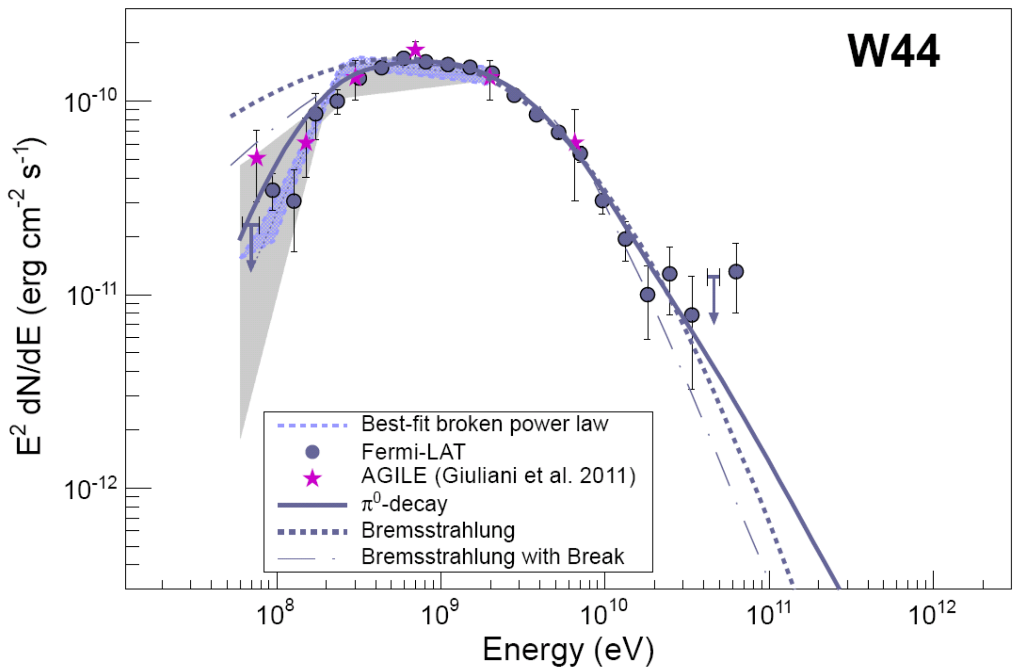
Hadronic origin of gamma-emission, spectral breaks at $E_b \sim 0.3\text{-}1$ TeV are observed. The bad accelerators at multi-TeV energies of protons.

# Old SNRs ($T>10^4$ yr) in the dense medium

$n_H > 1\ cm^{-3}$

(Ackermann et al. 2013)



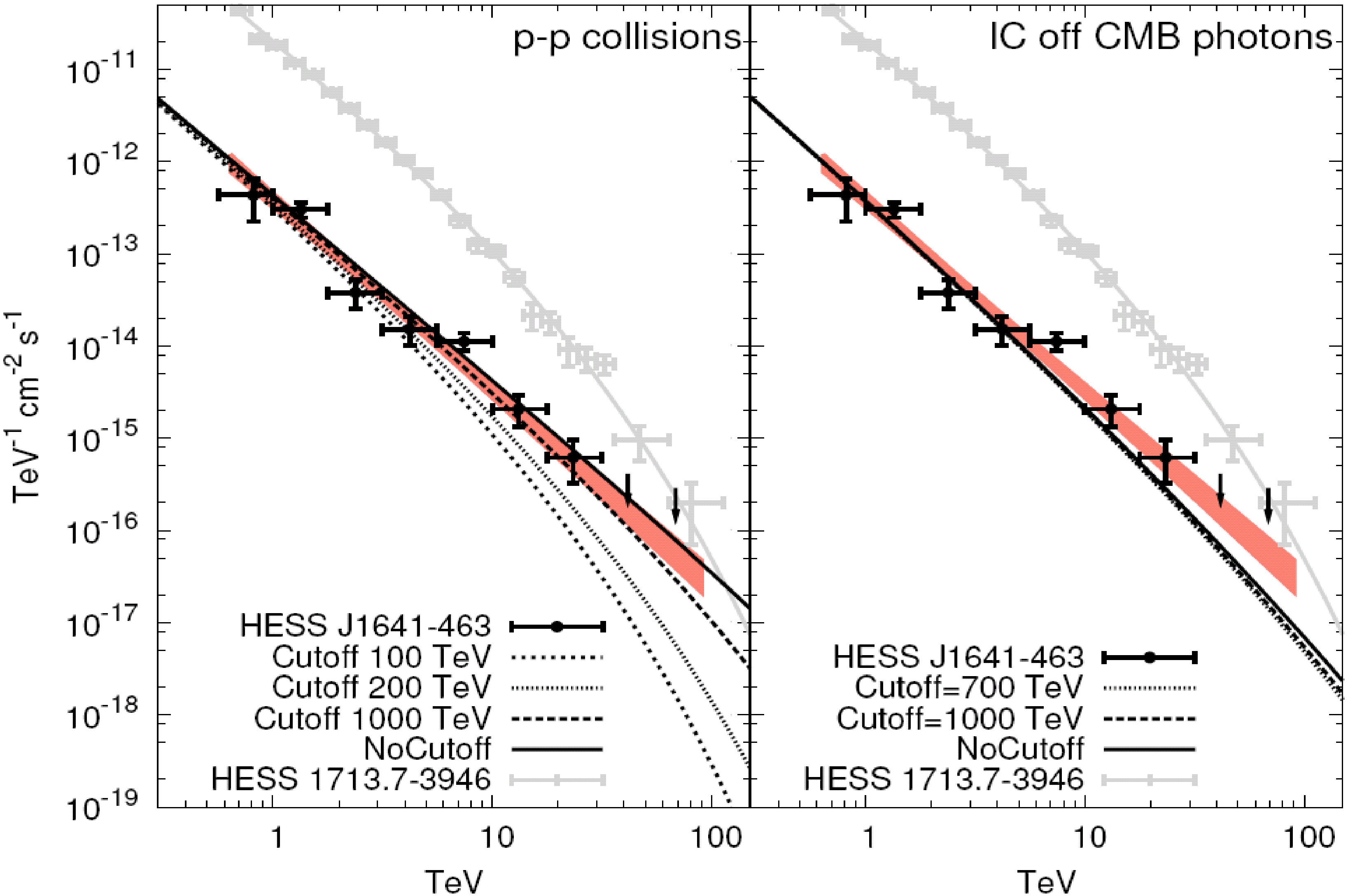

Old SNRs show gamma-ray spectra with steeper parts or cut-offs. TeV protons are not accelerated at present.

$E_{max}$ ~100 GeV in IC443 and $E_{max}$ ~10 GeV in W44. Probably because of neutral damping of MHD waves generated by accelerated particles.

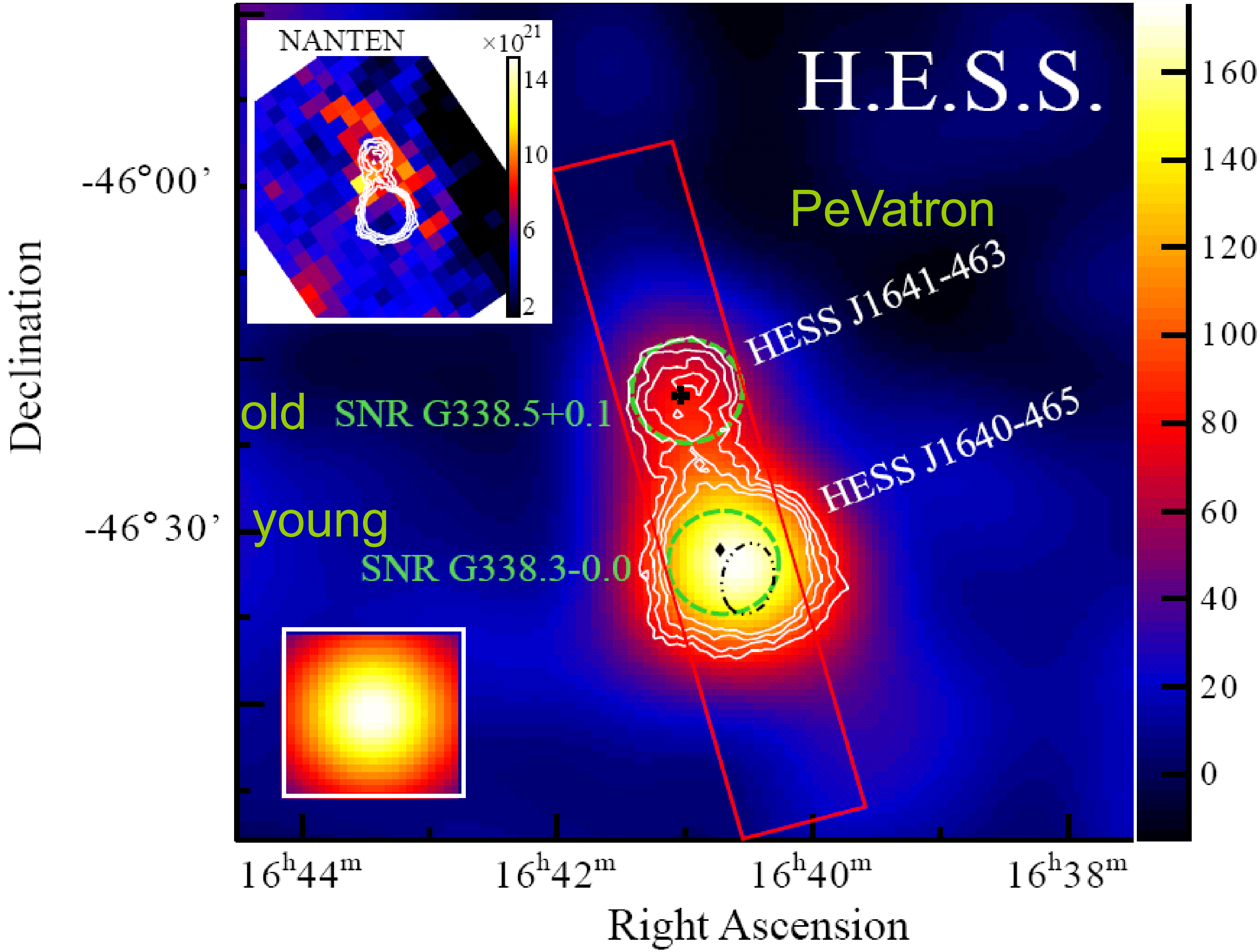
The spectral shape at E<1 GeV favors a hadronic origin of gamma-emission.

# HESS PeVatrons

HESS J1641-463 (Abramowski et al. 2014), HESS J1741-302 (Tibola et al. 2008)



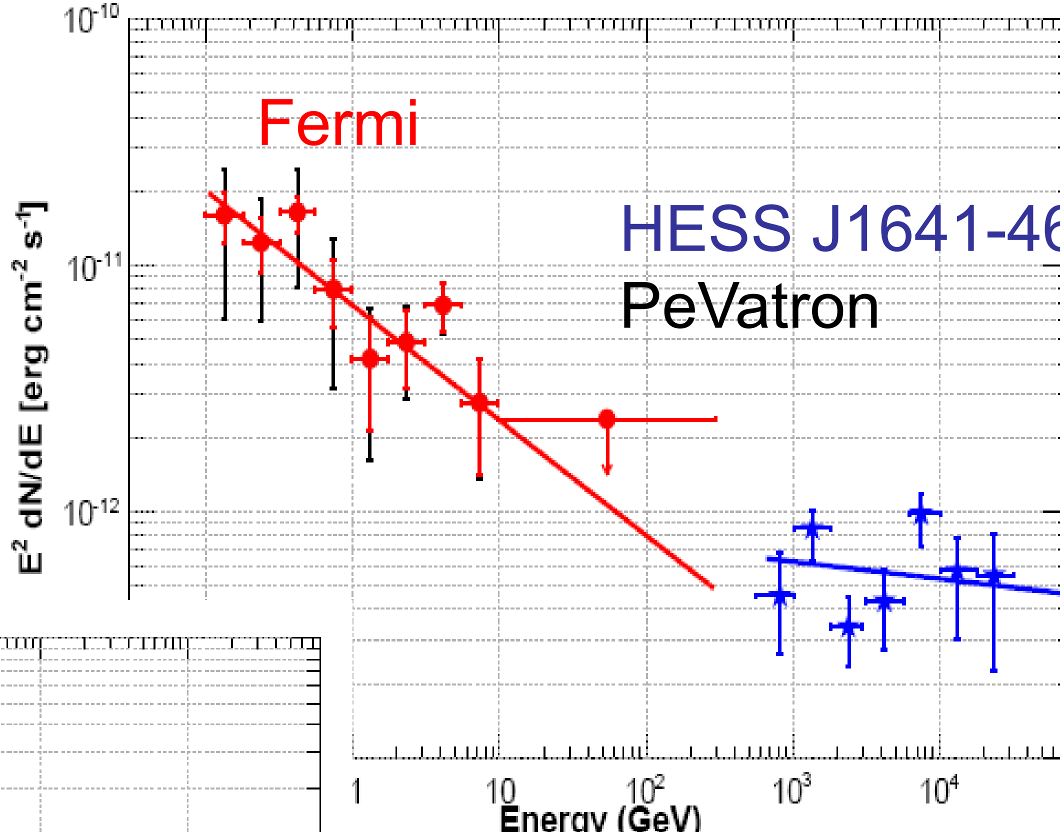
# Region around HESS 1641-463,



# Spectra of these neighboring sources

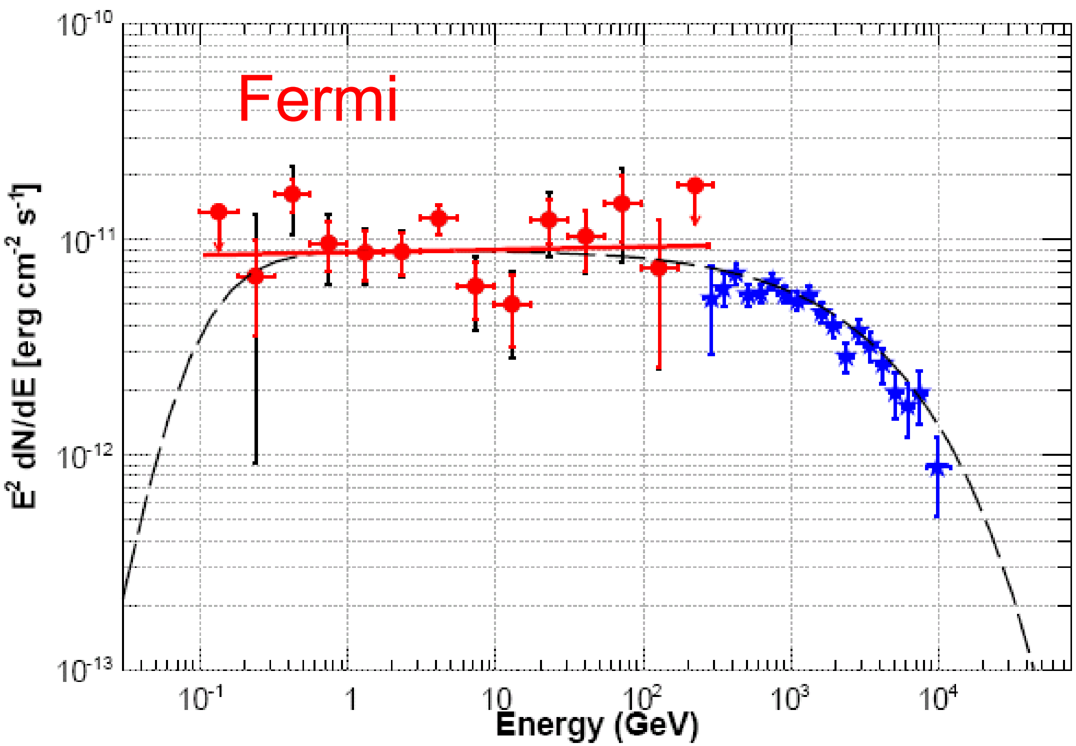
(Lemoin-Goumard et al. 2014)

$n_H E_{CR} > 10^{52}$ erg cm$^{-3}$




HESS J1641-463

PeVatron




HESS J1640-465

Is not a PeVatron but an efficient accelerator

Both SNRs evolve in wind blown bubbles

# 2D MHD modeling of WR bubble

$$\dot{M} = 10^{-5} M_{\odot} \mathrm{yr}^{-1}$$

$u_w$=1000 km/s, $M_w$=20, t=300 kyr

$n_0$=10 $cm^{-3}$

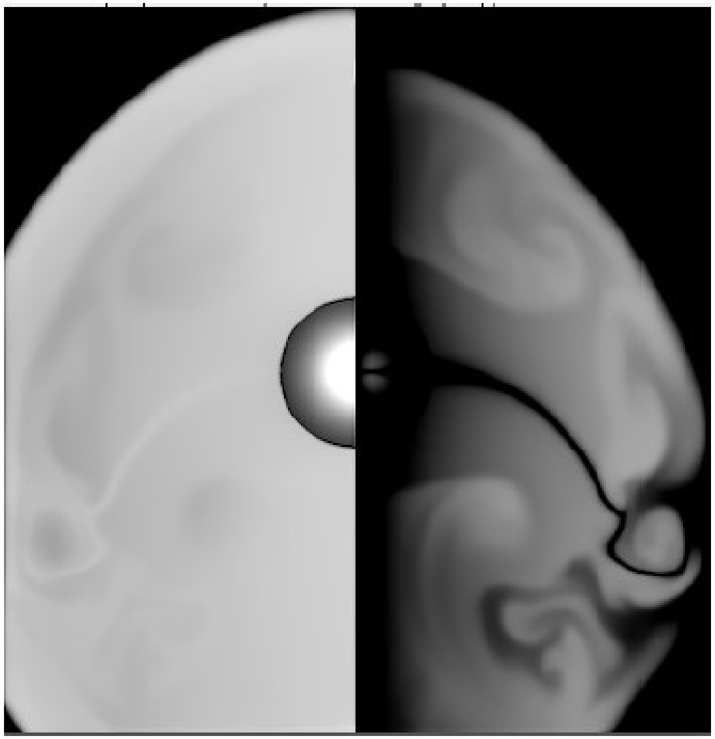
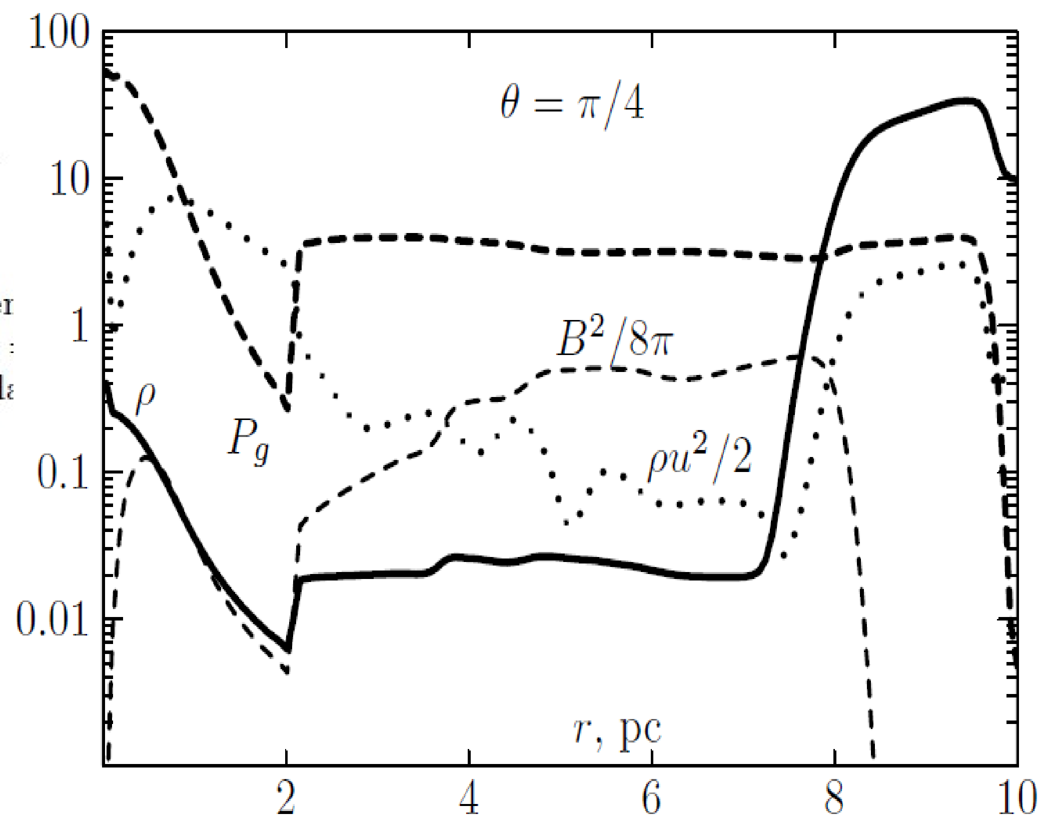


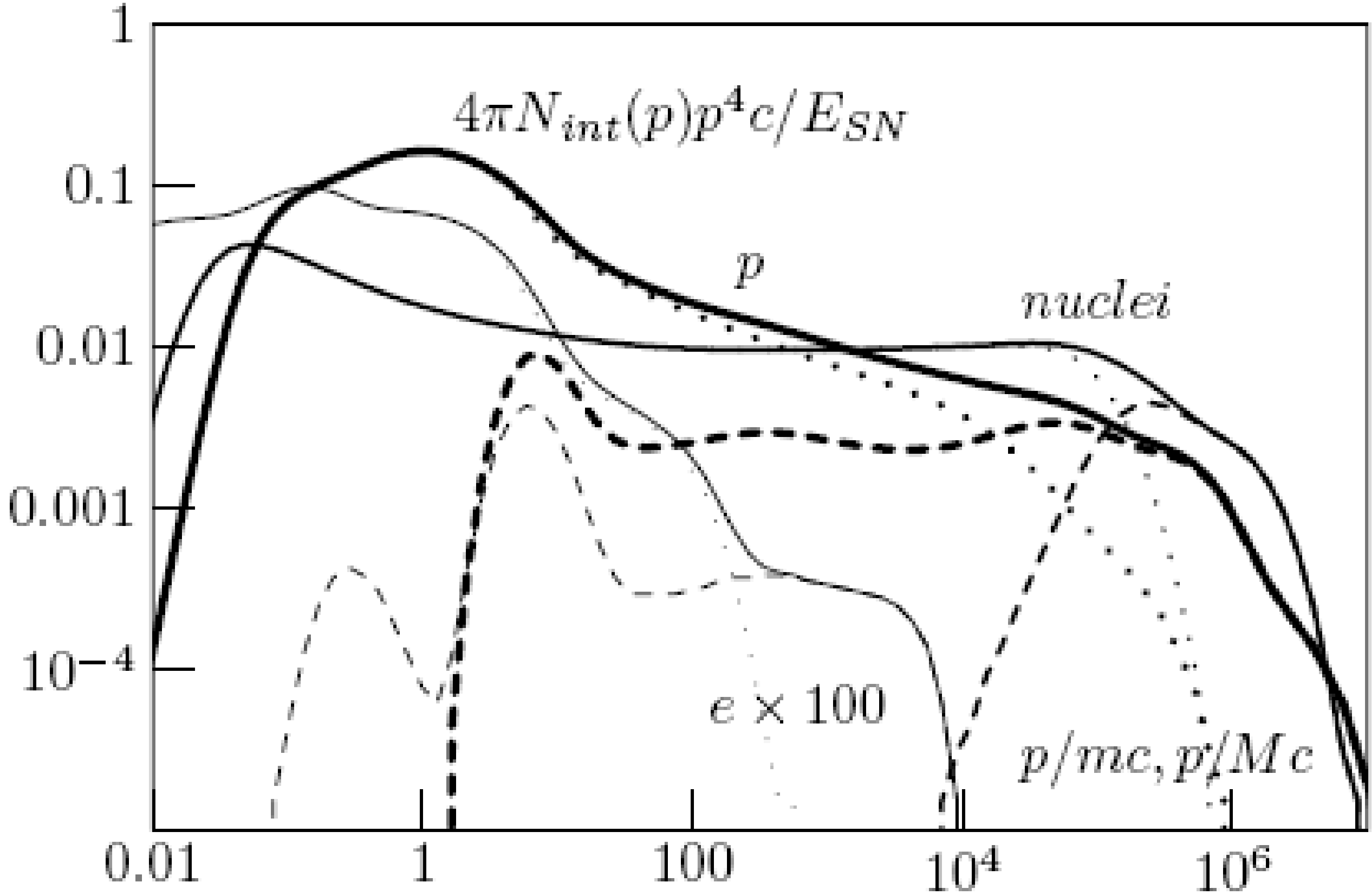
Figure 1: Gas pressure $P_g$ (left panel) and magnetic ter (right panel) distribution in the domain 10×20 pc at $t$ The logarithmic scaling is from $2.3 \cdot 10^{-12}$ erg cm$^{-3}$ (bla $2.3 \cdot 10^{-10}$ erg cm$^{-3}$ (white color).

Zirakashvili & Ptuskin 2018




B ~ 20 μG at the periphery
Medium is prepared
for efficient acceleration

# Spectra produced in remnants of Ib/c supernova (Zirakashvili & Ptuskin 2021)



# Conclusion

1. SNRs evolving in wind blown bubbles are the best cosmic ray accelerators.
2. The gamma emission produced by accelerated protons can be more intensive due to presence of multiple compact clouds in the bubble.
3. Some of such SNRs (Ib/c ) can accelerate particles up to PeV energies.