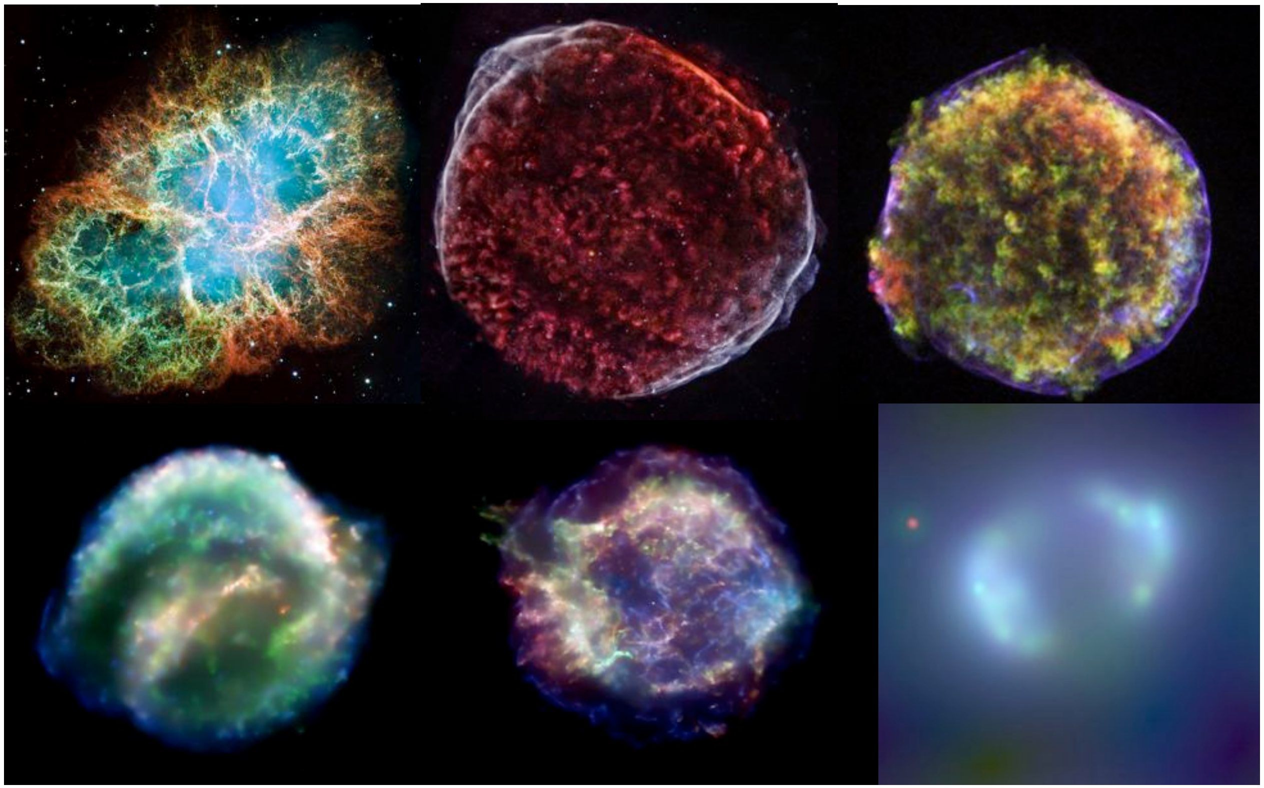
VULCANO Workhop 2014

Frontier Objects in Astrophysics and Particle Physics

Vulcano, 18-24 May 2014

SNRs as Cosmic Accelerator



Marco Miceli

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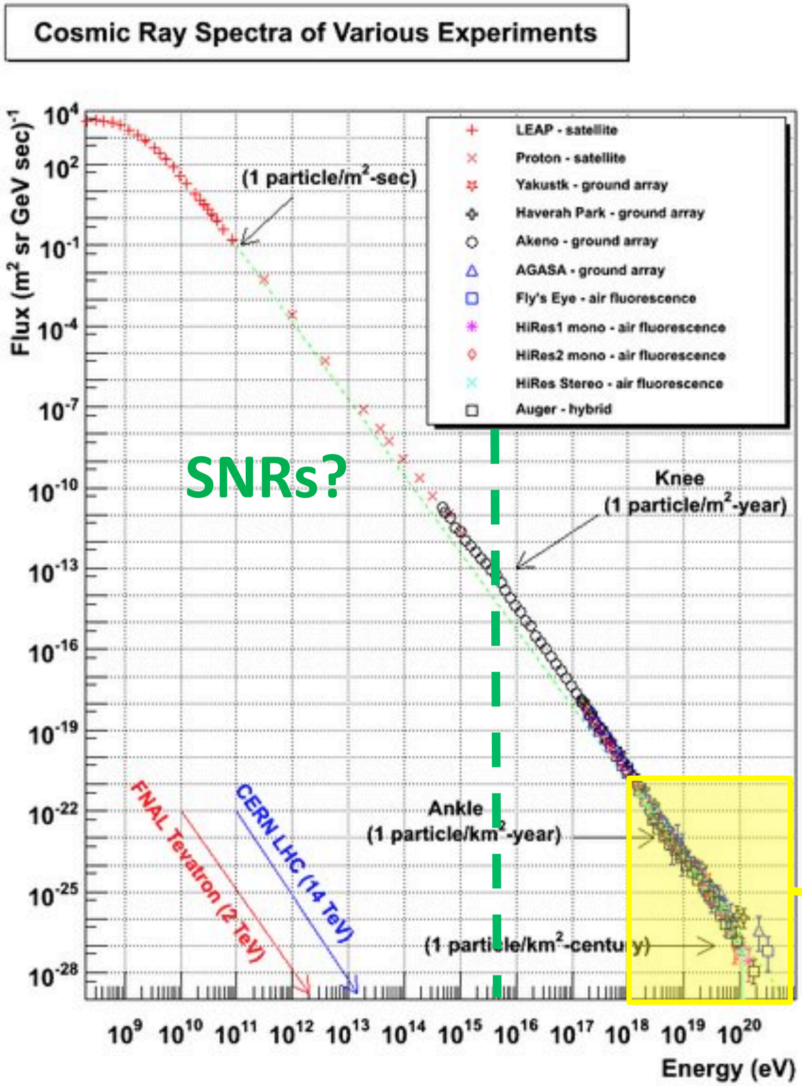
Outline of the talk

- Introduction
- The energy argument
- The acceleration mechanism and its effects on the SNR
    - Fermi acceleration
    - Back-reaction and shock modification
    - Magnetic field amplification
- Theory vs. observations
    - Radio emission
    - X-ray synchrotron emission
    - X-rays emission as probe of shock modification
    - Gamma ray emission (leptons vs. hadrons)
- Future perspectives

SNRs and CRs: an old story



COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. *Introduction.*—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

(1) The intensity of cosmic rays is practically independent of time. This fact indicates that the origin of these rays can be sought neither in the sun nor in any of the objects of our own Milky Way.

The constant power slope of 2.7 over many decades (up to the knee) suggests a unique acceleration mechanism

Gyro-radius larger than the thickness of the Galactic disk indicates extragalactic sources

The Energy argument

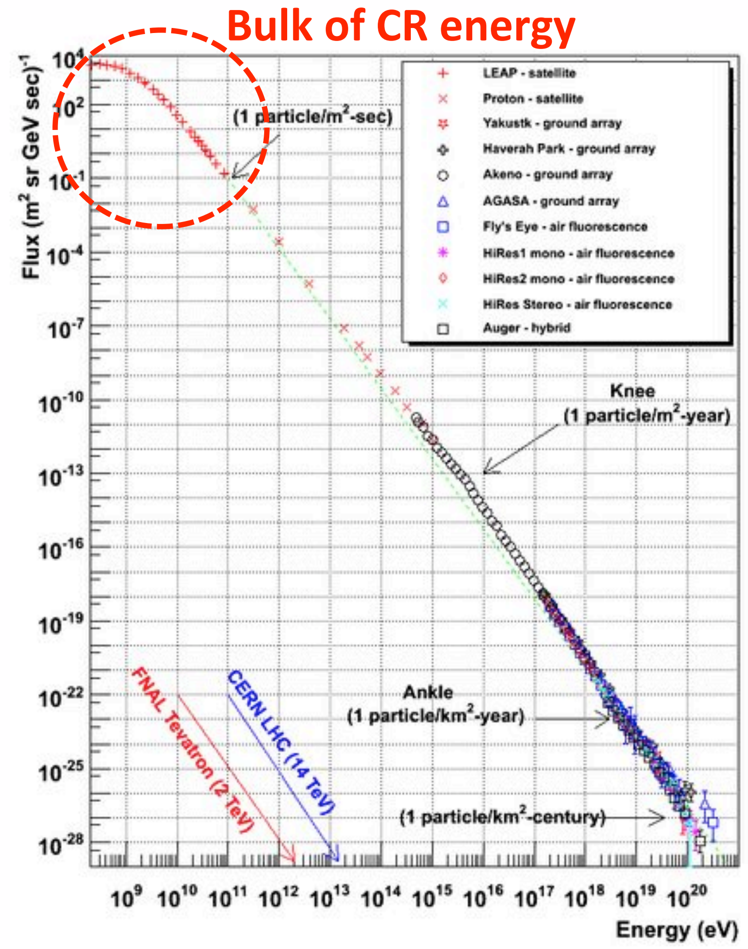
Most of the CR energy is at low (GeV) energies (where the CR spectrum is heavily modified by solar modulation.

A careful estimate of the **galactic energy density** of CRs, ε_{CR}, has been obtained by Webber 1998 (using data from the Voyager and Pioneer spacecrafts at ~ 60 AU from the Sun)

$$\varepsilon_{CR} \sim 1.8 \text{ eV/cc}$$

cf.
- $\varepsilon_{starlight} \sim 0.3$ eV/cc
- $\varepsilon_{B} \sim 0.25$ eV/cc
- $\varepsilon_{turbulence} \sim 0.3$ eV/cc
- $\varepsilon_{thermal} \sim 0.01$ eV/cc

Fundamental component for the galactic energy budget

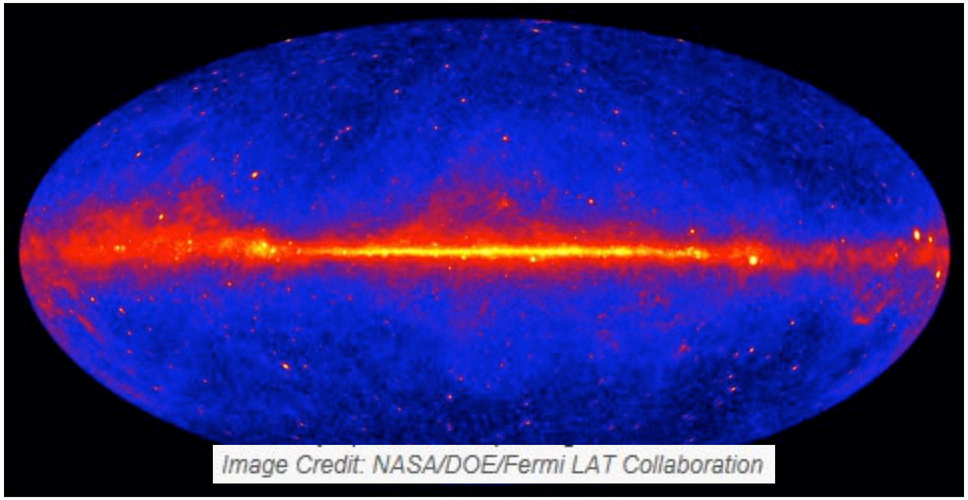


Isotope studies (see, e.g., Yanasak et al. 2001) show that CRs (with GeV energies) diffuse out of the Milky Way with a characteristic **galactic confinement time**

$$\tau_{esc} = 15 \pm 1.6 \text{ Myr}$$

The Energy argument

CRs are ubiquitous in the Milky Way (radius of the disk ~ 15 kpc, thickness ~0.5 kpc)



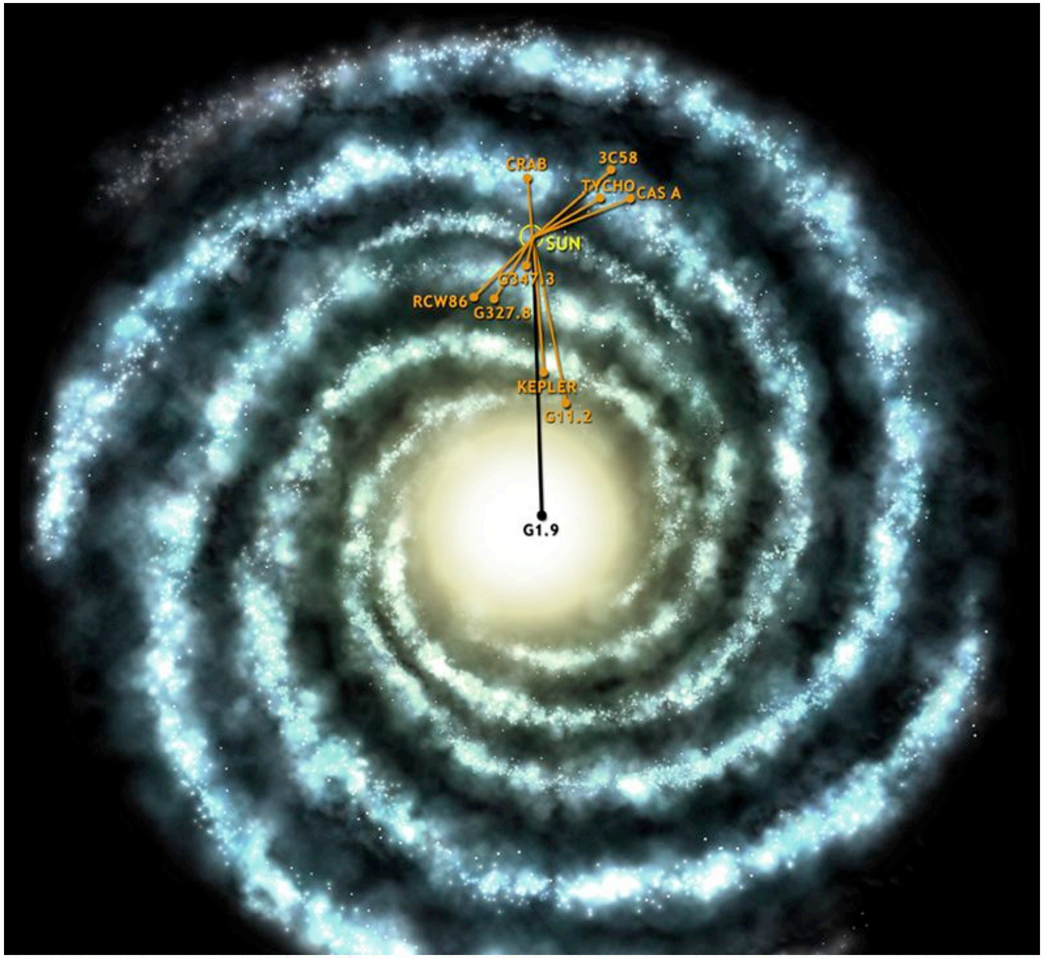
$$\frac{\varepsilon_{CR} V}{\tau_{esc}} \sim \mathbf{2 \times 10^{50}\ erg/century}$$

- Binding energy release in a core-collapse SN: 10^{53} erg, but 99% of this energy is carried by neutrinos → **characteristic energy** of a SN, $\mathbf{E_{SN} = 10^{51}\ erg}$

- Characteristic **rate of SNe** in the Milky Way, $\mathbf{r_{SN}} \sim$ **2.5/century** (one event every 40±10 yr. see Tammann et al. 1994)

Galactic SNRs (are the only source that) can provide the required power to CRs, provided that they transfer them ~ 10% of their kinetic energy

Historical SNRs – a brief note



stellar explosions that are thought to have occurred in the last 2,000 years

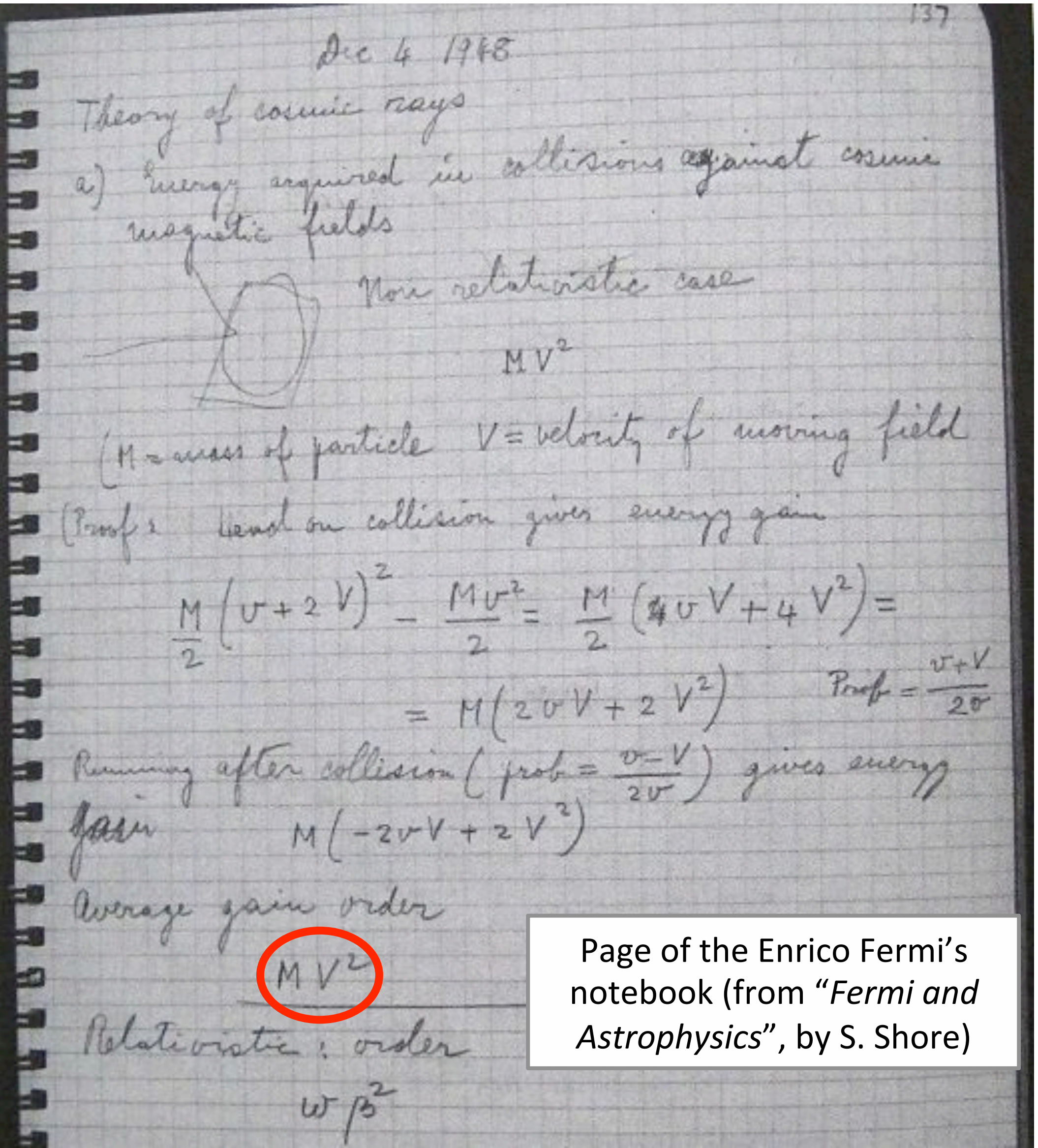
(Credit: NASA/CXC/M.Weiss)

Characteristic **rate of SNe** in the Milky Way, $\mathbf{r_{SN}} \sim$ **2.5/century** (one event every 40±10 yr. see Tammann et al. 1994)

We expect 40-60 SNRs with an age lower than 2000 yr, but **we have access only to a small portion of the Milky Way**

The acceleration mechanism – Fermi acceleration

Basic idea (Fermi 1949): collisions with moving magnetic mirrors (interstellar clouds) determine a net increase in the energy of charged particles



Page of the Enrico Fermi's notebook (from "*Fermi and Astrophysics*", by S. Shore)

Second order acceleration mechanism that results in a power-law energy spectrum

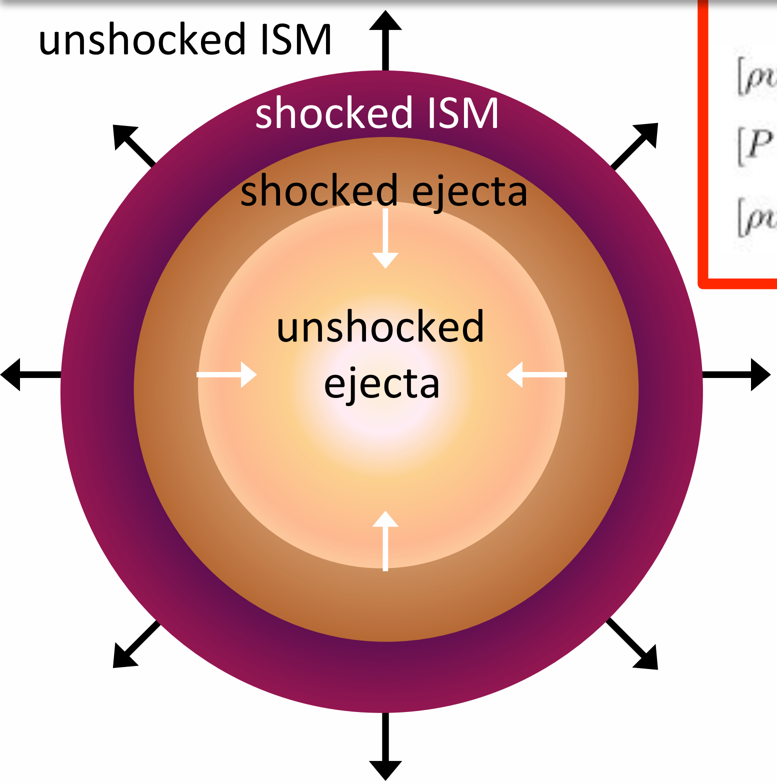
$$N(E) \propto E^{-x}$$

where $x = 1+(\alpha t_{acc})^{-1}$ and $\alpha E = dE/dt$ (but see also Blandford & Eichler 1987)

Problems:

- Characteristic velocity of interstellar clouds is $v_{cl}/c \sim 10^{-4}$-10^{-5}
- Slow process (acc from low energies can be hampered by ionization losses)
- No reason why x should be ~ 2.7

The first order Fermi acceleration in SNR shocks

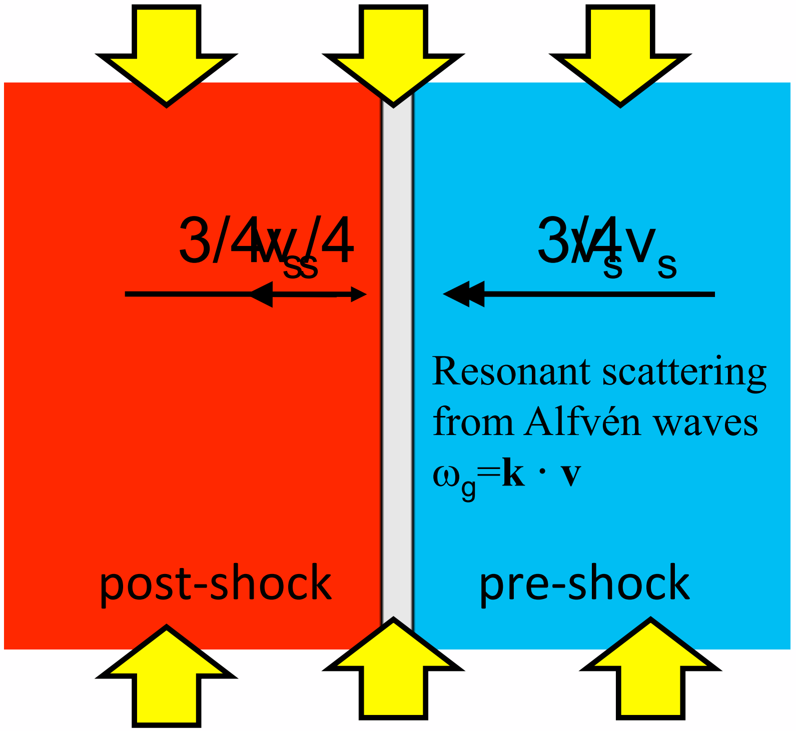


R-H conditions (adiabatic shock)

$$[\rho v_x] = 0$$
$$[P + \rho v_x^2] = [\rho v_x v_y] = [\rho v_x v_z] = 0$$
$$[\rho v_x (1/2 v^2 + h)] = 0$$

→

$$\frac{u_2}{u_1} \equiv \frac{1}{r_{\rm comp}} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{\gamma + 1}\frac{1}{\mathcal{M}^2}$$
$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma + 1}\mathcal{M}^2 - \frac{\gamma - 1}{\gamma + 1},$$



At each cross $E' = [1 + 2/3(v_{sh}/c)]E_0 = \xi E_0$

If P is the crossing probability, after m steps, one has: $E = \xi^m E_0$ and $N(\geq E) = N_0 P^m$

$$\frac{\log(N/N0)}{\log(E/E0)} = \frac{\log P}{\log \xi} = -1$$

$N(E) \propto E^{-k} dE;\ k = \log P/\log \xi - 1 = 2$

Axford, Leer & Skadron 1977; Krymsky 1977; Bell 1978a,b, Blandford & Ostriker 1978

The first order Fermi acceleration in SNR shocks

In general $N(E) \propto E^{-k}$ where $k=3R/(R-1)$

Shock speed in a young SNR, $\mathbf{v_{sh}=10^3\text{-}10^4}$ **km/s,** Mach number>>1, R=4

Since $E^m \sim (1+\beta)^m E_0$, we need 1100 shock crossings to boost a proton from 300 keV to 3 PeV if v_{sh}=6000 km/s

Characteristic **acceleration time**

$$t_{acc}=p/(dp/dt) = 3/(V_1 - V_2)\,(D_1/V_1 + D_2/V_2),$$

where 1,2 indicate the upstream/downstream bulk velocities and diffusion coefficients (Drury 1983). In the case of Bohm diffusion $D^B_{1,2} = p(1/3)c^2/(qB_{1,2})$

$$t_{acc} = \frac{125\,\eta}{B_{100\mu G}} \left(\frac{v_{sh}}{5000\text{ km/s}}\right)^{-2} \frac{E}{100\text{ TeV}} \frac{R_4^2}{R_4 - 1/4}\ \text{yr}$$

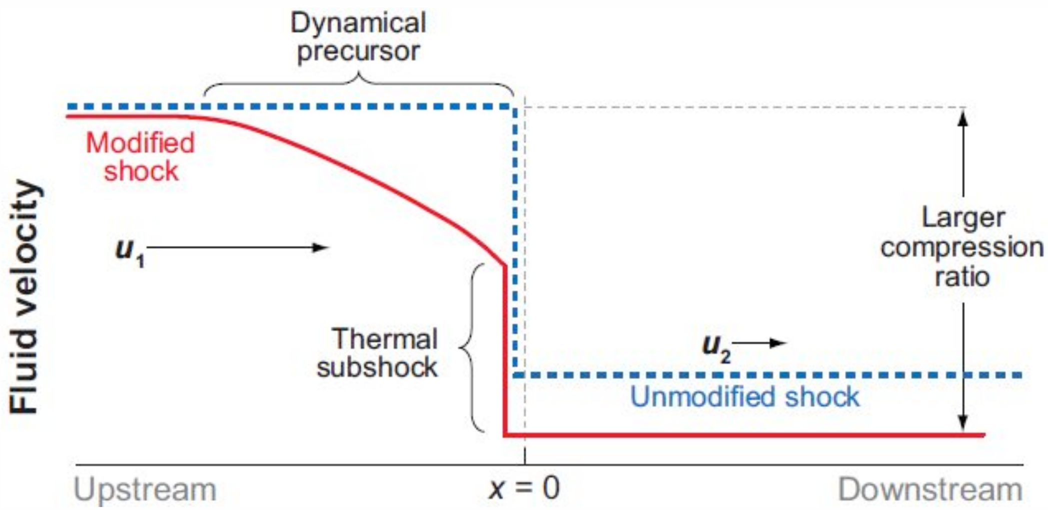
where

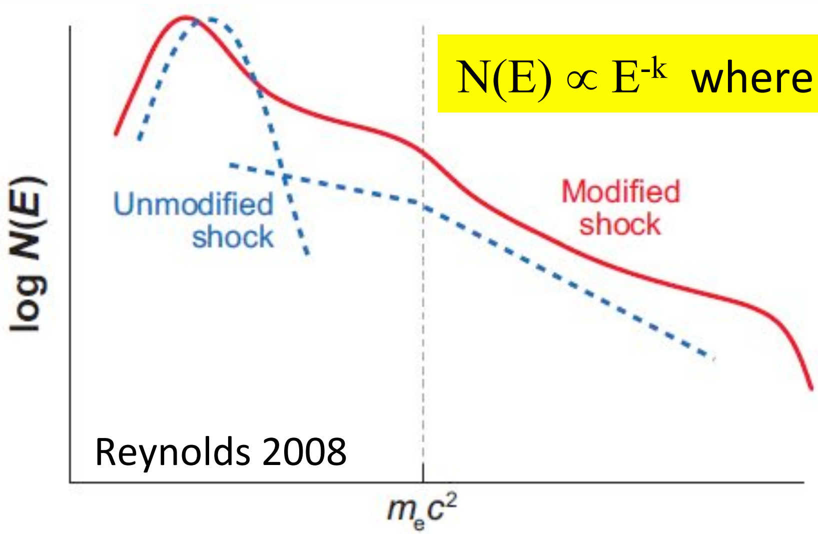
$\eta = D/D^B$ is the gyrofactor and R_4 is the shock compression ratio in units of 4 (Parizot et al.2006)

Shock modification – particle backreaction

Hadrons do not suffer radiative losses so we expect them to reache higher E than e⁻

Effects of the accelerated particles on the shock dynamics (e.g., Blandford & Eichler 1987, Malkov & Drury 2001,Blasi 2002,2004)



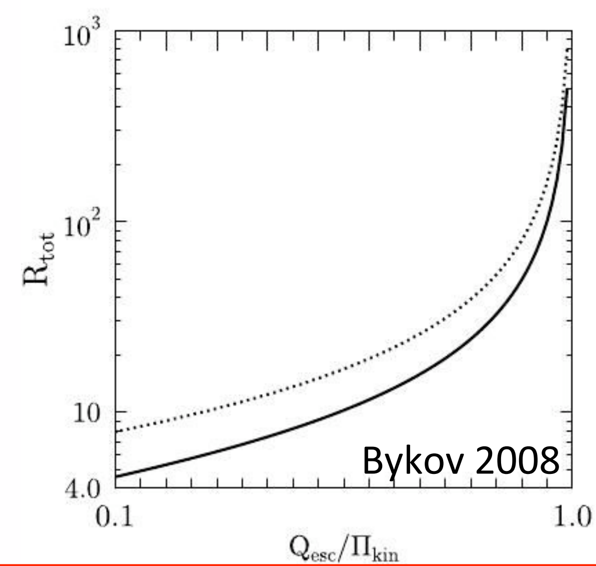


$N(E) \propto E^{-k}$ where $k=3R/(R-1)$

- Non-negligible ram pressure of ultra-relativistic hadrons (adiabatic index $\gamma=4/3$), $R_{tot}=(\gamma+1)/(\gamma-1)=7$ not 4

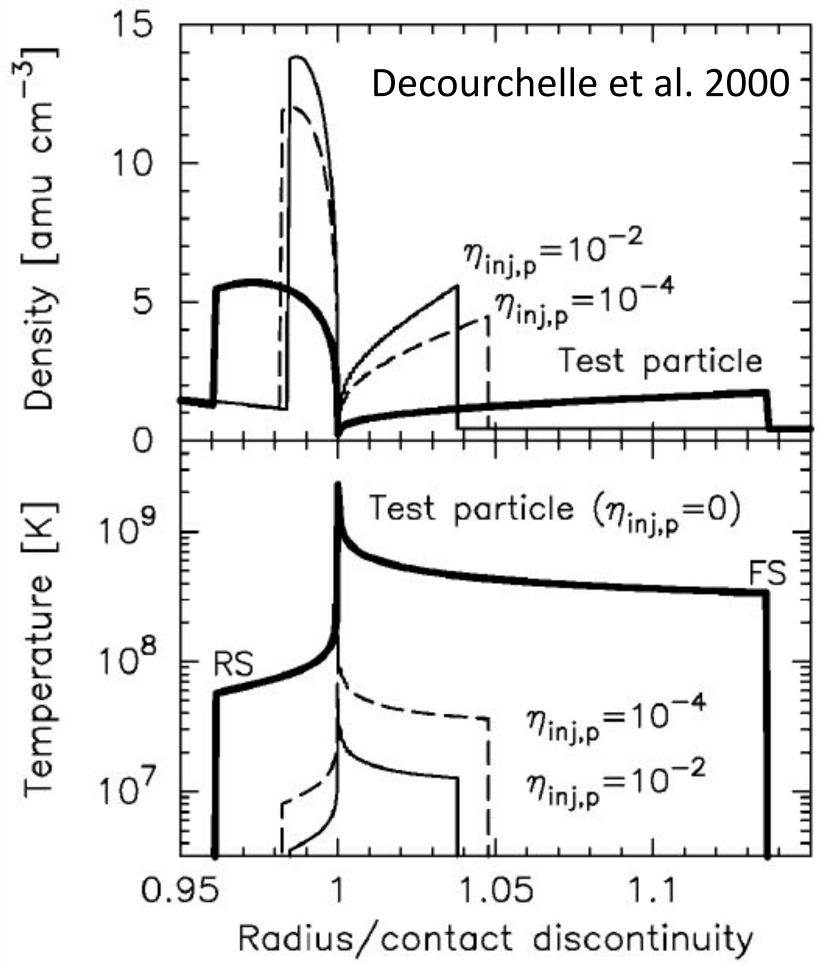
- The shock is not adiabatic (energy drain by escaping particles) and:

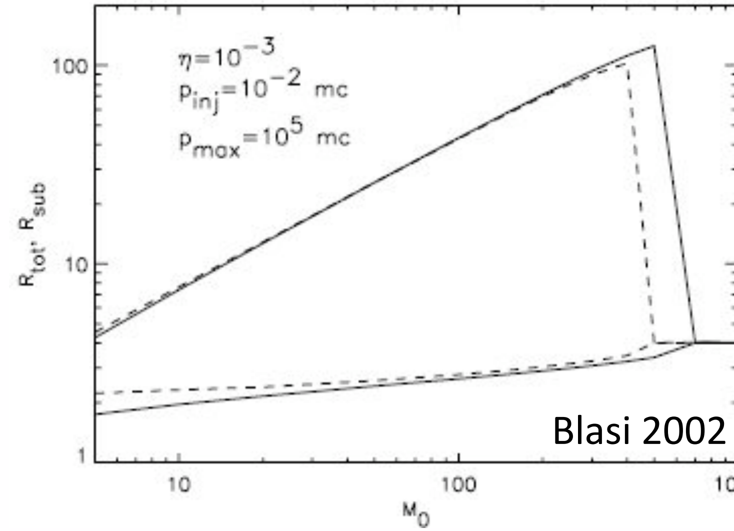
$$r_{\rm tot} = \frac{\gamma+1}{\gamma - \sqrt{1+2(\gamma^2-1)Q_{\rm esc}/\rho_a v_{\rm sh}^3}}$$

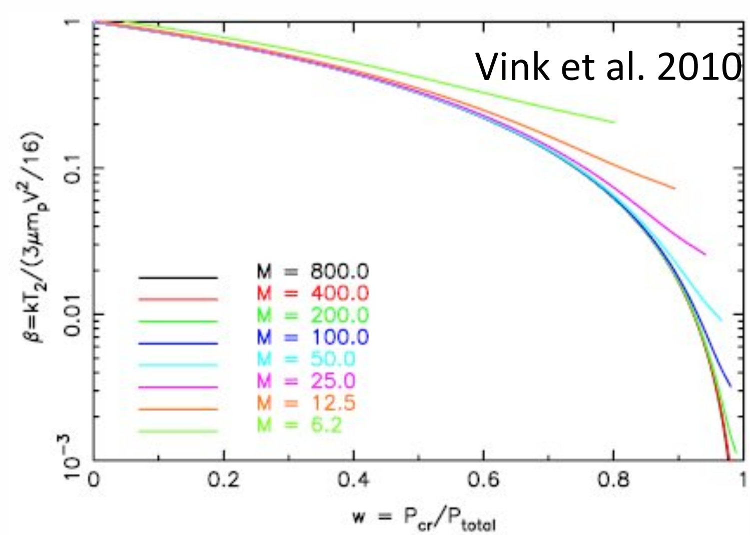


Shock modification – particle backreaction

Effects of the injecion efficiency and of the Mch number on the shock modification (e.g., Blasi 2002, 2004, Blasi et al. 2005, Decourchelle et al. 2000, Vink et al. 2010)







The shock modification is expected to decrese the post-shock temperature with respect to the test-particle case

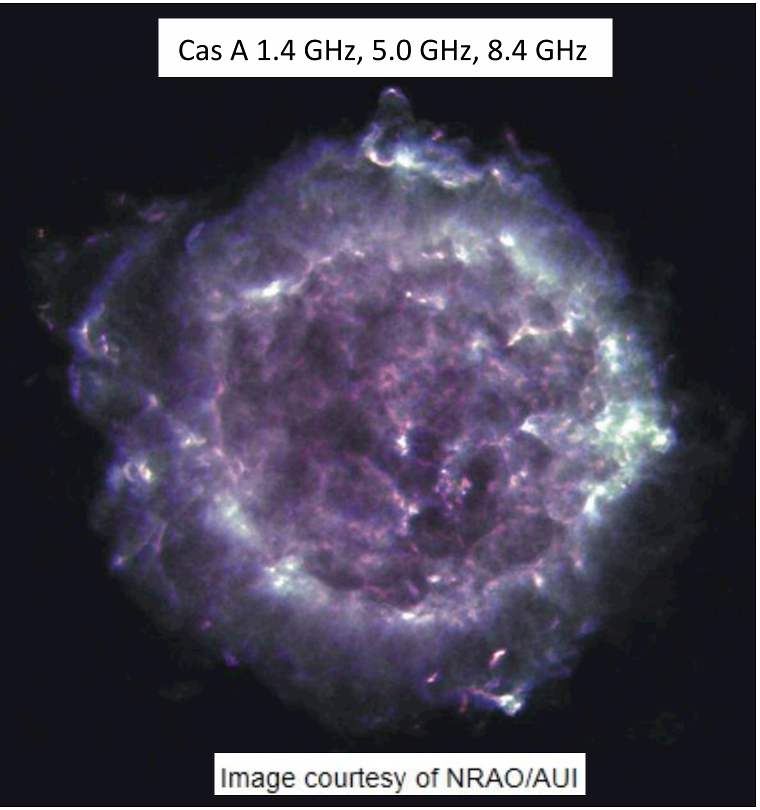
Radio emission:
SNRs accelerate electrons

Electronic acceleration – radio emission

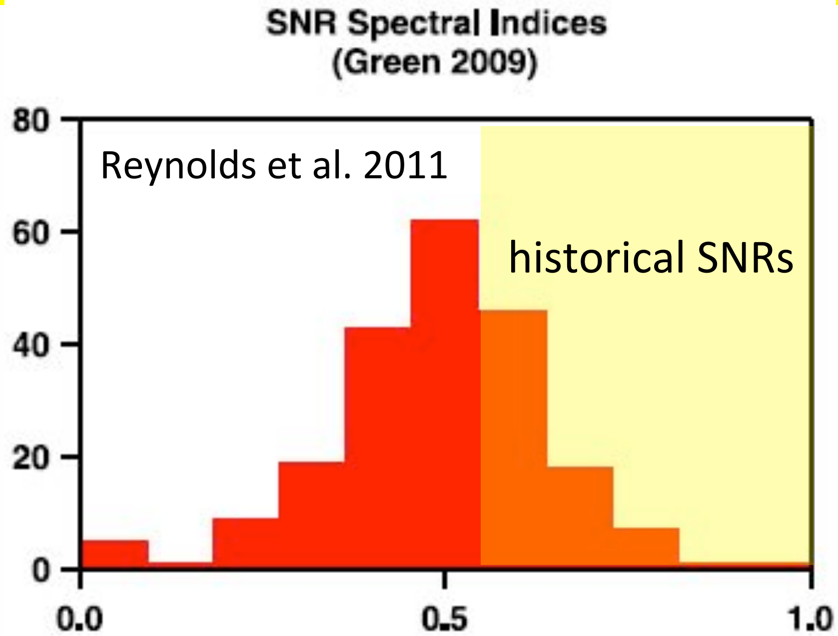
Synchrotron emission from SNRs has been detected since the early days of radio astronomy (e.g., the detection of the previously unknown SNR Cas A, Shklovskii 1953, Minkowski 1957)

The synchrotron emission of ultrarel. e^- at energy E_{GeV} peaks at $\nu_{peak} = 3\ E^2_{GeV} B_{100\mu G}$ GHz

Radio emission from the shell traces the presence of GeV electrons at the shock front



All the 274 galactic SNRs listed in the Green's catalogue (https://www.mrao.cam.ac.uk/projects/surveys/snrs/) have known radio properrties



α=0.5 in the photon spectrum corresponds to an index k=2α+1=2 in the electron spectrum

...but large spread and time dependent variations of α

Radio emission – Energy content

Synchrotron luminosity of a SNRs: $L_\nu = A(\alpha) V \kappa B^{1+\alpha} \nu^{-\alpha}$

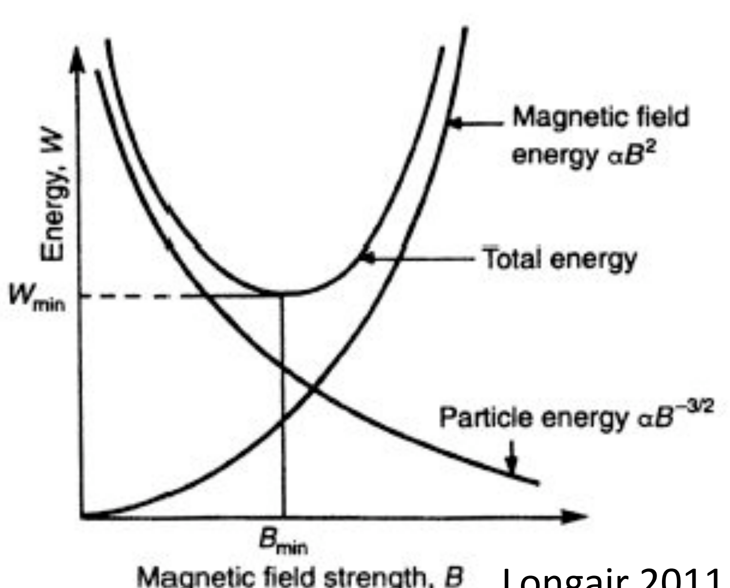
produced by an electron spectrum: $N(E)dE = \kappa E^{-p}$ where $p=2\alpha+1$

If we assume that the protons have energy β times that of the electrons, that is,

$\varepsilon_p = \beta\varepsilon_e$, $\varepsilon_{tot} = (1+\beta)\varepsilon_e = \eta\varepsilon_e$

where $\varepsilon_e = \int EN(E)dE$

The total energy present in the SNR responsible for the radio emission is $W_{\rm total} = V\varepsilon_e + V\frac{B^2}{2\mu_0}$



Longair 2011

$$W_{\rm total} = G(\alpha)\eta L_\nu B^{-3/2} + V\frac{B^2}{2\mu_0}$$

$$B_{\rm min} = \left[\frac{3\mu_0}{2}\frac{G(\alpha)\eta L_\nu}{V}\right]^{2/7}$$

$$W_{\rm mag} = V\frac{B^2_{\rm min}}{2\mu_0} = \frac{3}{4}W_{\rm particles}$$

Cassiopeia A:

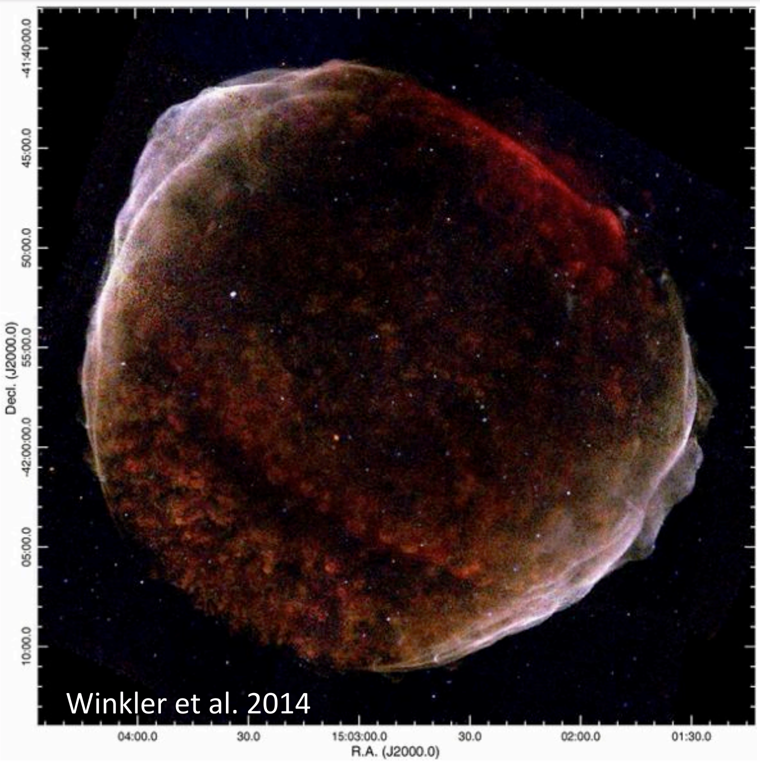
- $L_{1GHz} = 2.6 \times 10^{25}$ erg/s/Hz
- $V \sim 10^{56}$ cm^3
- $\alpha \sim 0.77$
- $B_{min} = 100\eta^{2/7}$ μG

→ **$W_{min} = 2 \times 10^{48}\eta^{4/7}$ erg**

...but GeV electron do not prove that SNRs are Pevatrons

X-ray emission:
- The maximum electron energy
-Probing shock modification
- Probing B amplification

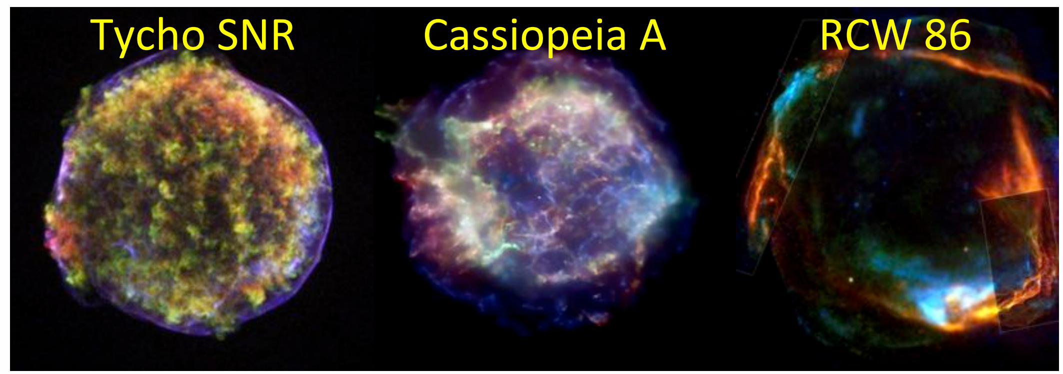
X-ray synchrotron emission



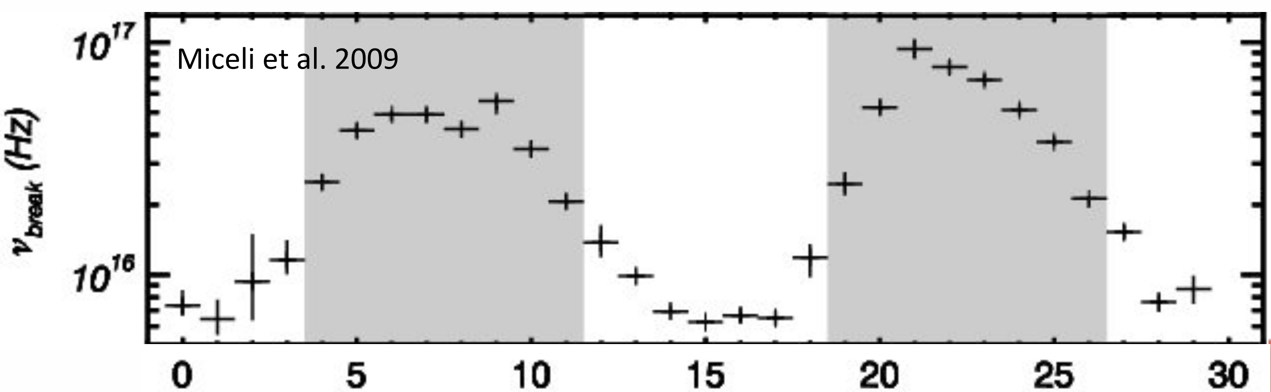
Detection of synchrotron X-ray emission from the remnant of SN 1006 AD (Koyama et al. 1995, see also Reynolds and Chevalier, 1981) and then in other young SNRs proves that the electron energy ≥10 TeV!

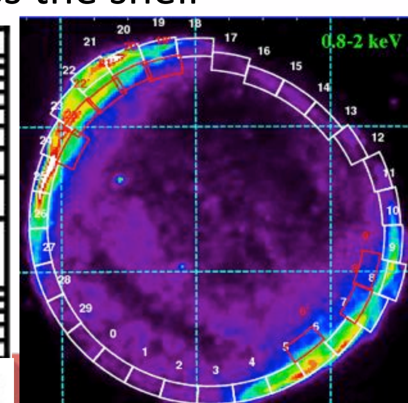
$$h\nu_{\rm ch} = 13.9\left(\frac{B_\perp}{100\ \mu{\rm G}}\right)\left(\frac{E}{100\ {\rm TeV}}\right)^2\ {\rm keV}$$

Other examples



The nonthermal X-ray spectrum shows a **cutoff** associated with the maximum energy achieved by the electrons in the acceleration process that may vary across the shell





X-ray synchrotron emission – maximum energy

Three possible mechanisms can limit the electron energy in the acceleration (see Reynolds 08)

- **Loss limited:** energy limited by the radiative losses ($E_{max} \propto B^{-0.5}$)
- **Time limited:** limited acceleration time ($E_{max} \propto B$)
- **Escape limited:** change in the availability of MHD waves above some wavelength ($E_{max} \propto B$)

The **loss-limited** scenario shows a characteristic spectral shape (Zirakashvili & Aharonian 2007, see) also Blasi (2010)

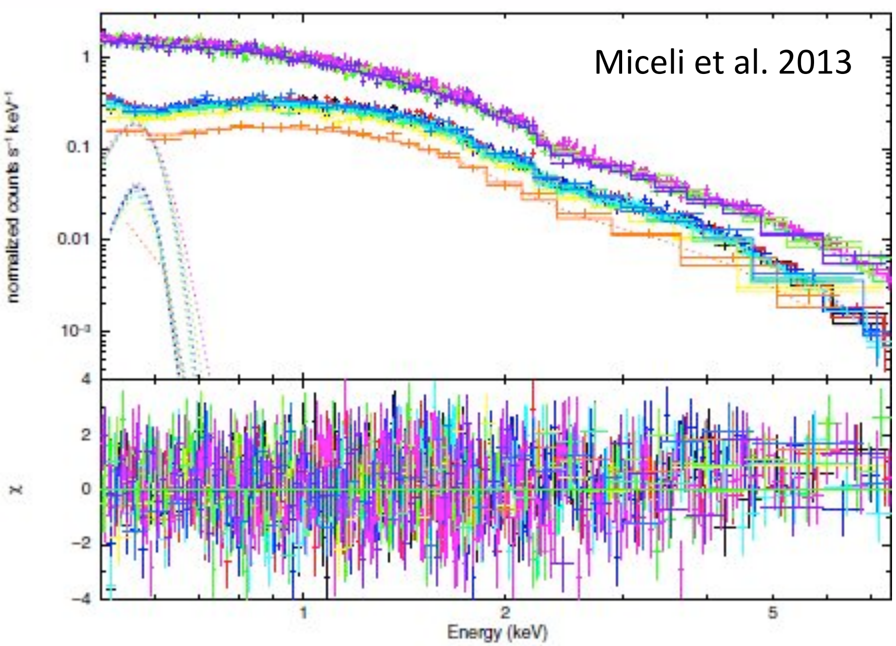
$$N(E) \propto E^{-2}[1 + a(E/E_0)^b]^c \exp\left[-(E/E_0)^2\right]$$

electron spectrum

$$S_X^{ll} \propto h\nu^{-2}[1 + l(h\nu/h\nu_0)^m]^n \exp\left(-\sqrt{h\nu/h\nu_0}\right)$$

photon spectrum

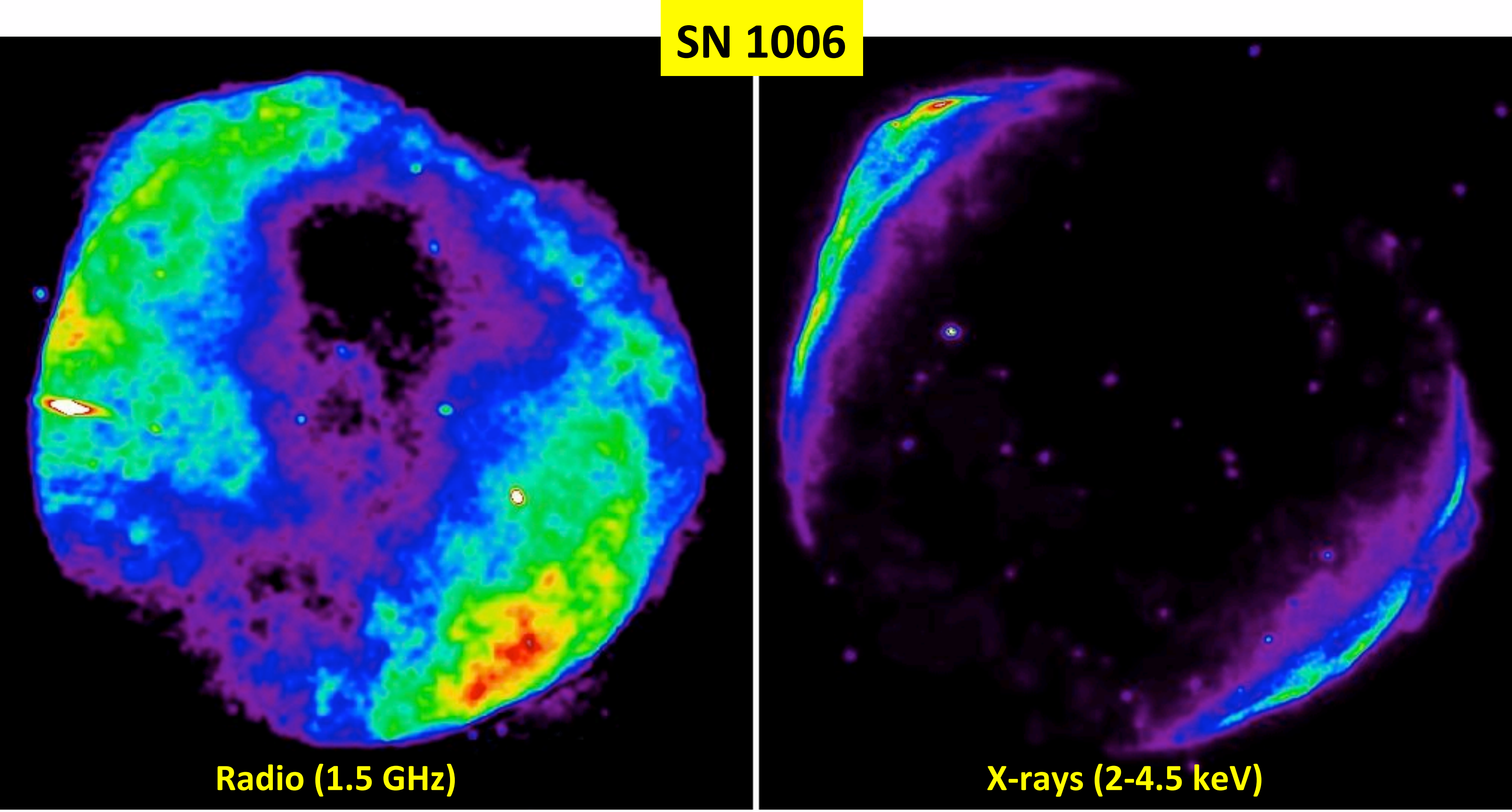
where $a = 0.66\ (0.523)$, $b = 5/2\ (9/4)$, $c = 9/5\ (2)$, $l = 0.46\ (0.38)$, $m = 0.6\ (0.5)$, $n = 11/4.8\ (11/4)$, for $B_2 = B_1$ ($B_2 = \sqrt{11} B_1$)



Spatially resolved spectral analysis in **SN 1006** shows that the **maximum electron energy is limited by radiative losses** and proceed close to the Bohm limit (Miceli et al. 2013, 2014)

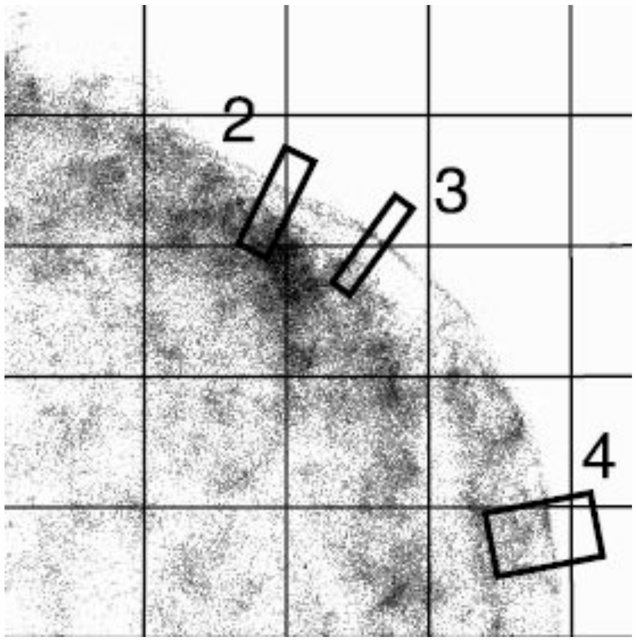
Similar indications from the global spectrum of **RX J1713.7-3946** (Zirakashvili & Aharonian 2010, Uchiyama et al. 2007) and **Tycho** (Morlino & Caprioli 2012)

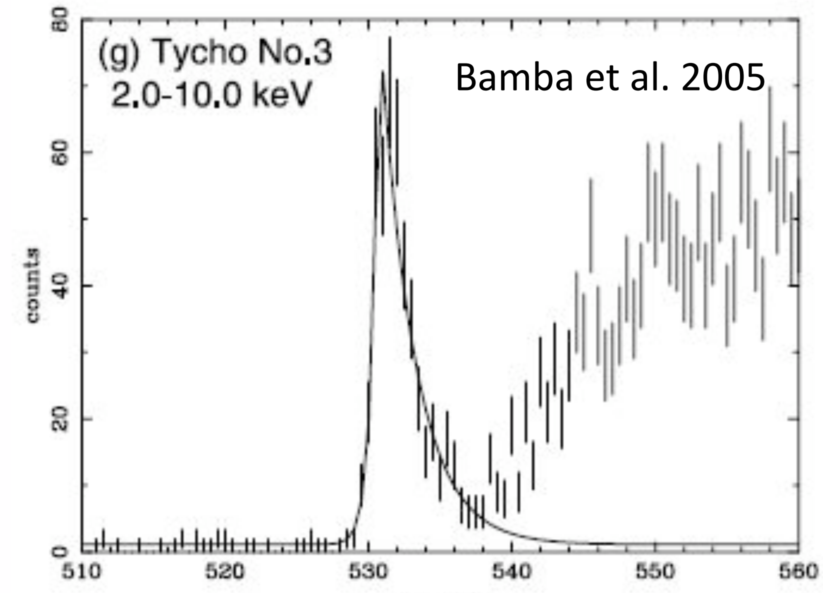
X-ray synchrotron emission – thin filaments



Magnetic field amplification

The width of the X-ray synchrotron emitting filaments can be used to infer the value of B (B~100–600 μG, Vink and Laming 2003; Berezhko et al. 2003; Bamba et al. 2004, 2005; Völk et al. 2005; Ballet 2006; Parizot et al. 2006).





$$l_{\rm adv} = t_{\rm cool} v_{\rm sh}/r$$

And given that $t_{\rm cool} = 6.37 \times 10^8 \; B_{\rm mG}^{-2} \; E_{\rm erg}^{-1}$ and $\nu_{\rm sync} = 1.82 \times 10^{15} \; B_{\rm mG} \; E_{\rm erg}^2$

$$l_{\rm adv} = t_{\rm cool} v_{\rm sh}/r = 1.8 \times 10^3 \; B_{\rm mG}^{-3/2} \; \nu_{\rm keV}^{-1/2} \; v_{1000}/r \;\; {\rm pc}$$

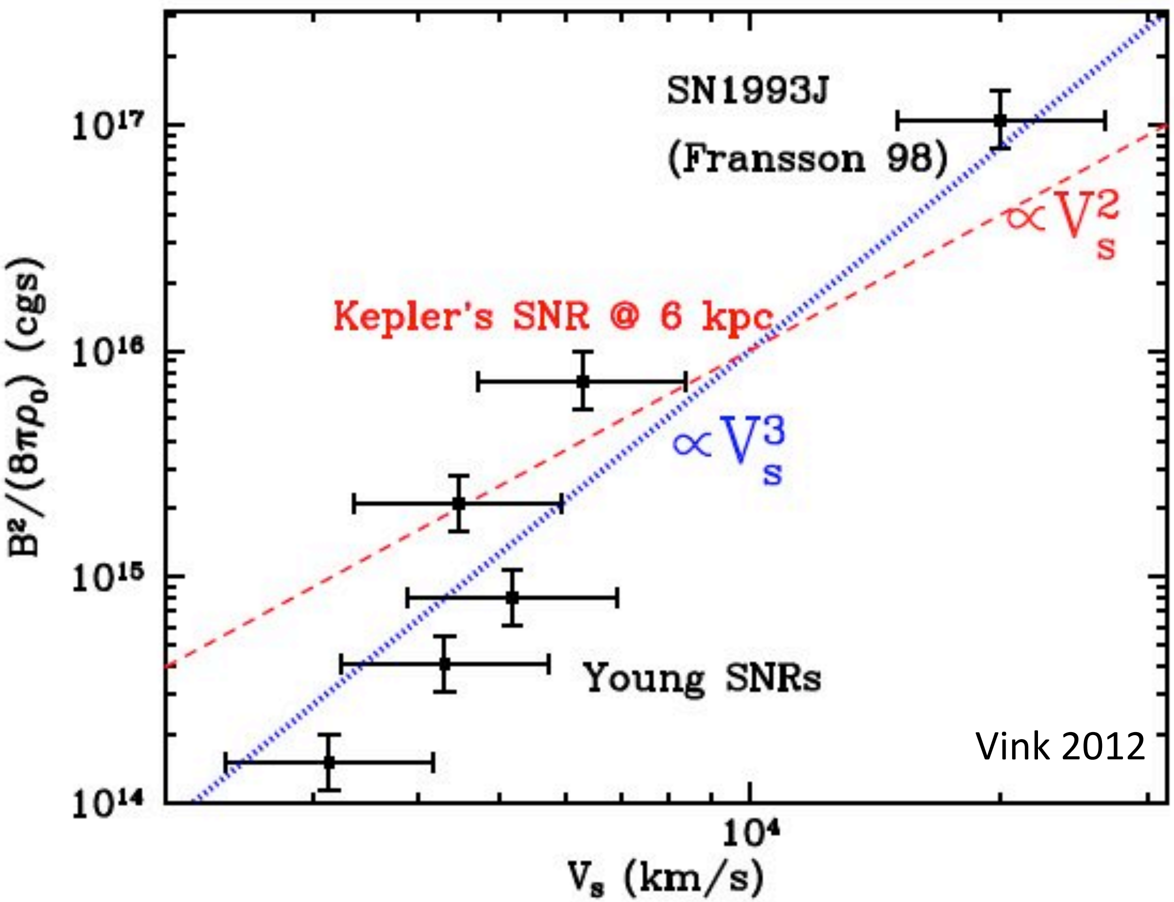
or, alterntively

$$l_{\rm dif} = \sqrt{\kappa_{\rm d} t_{\rm cool}} = 1.2 \times 10^{-3} \; B_{\rm mG}^{-3/2} \;\; {\rm pc}$$

$l_{\rm adv}/l_{\rm dif} \sim 1$ (Ballet 2006)

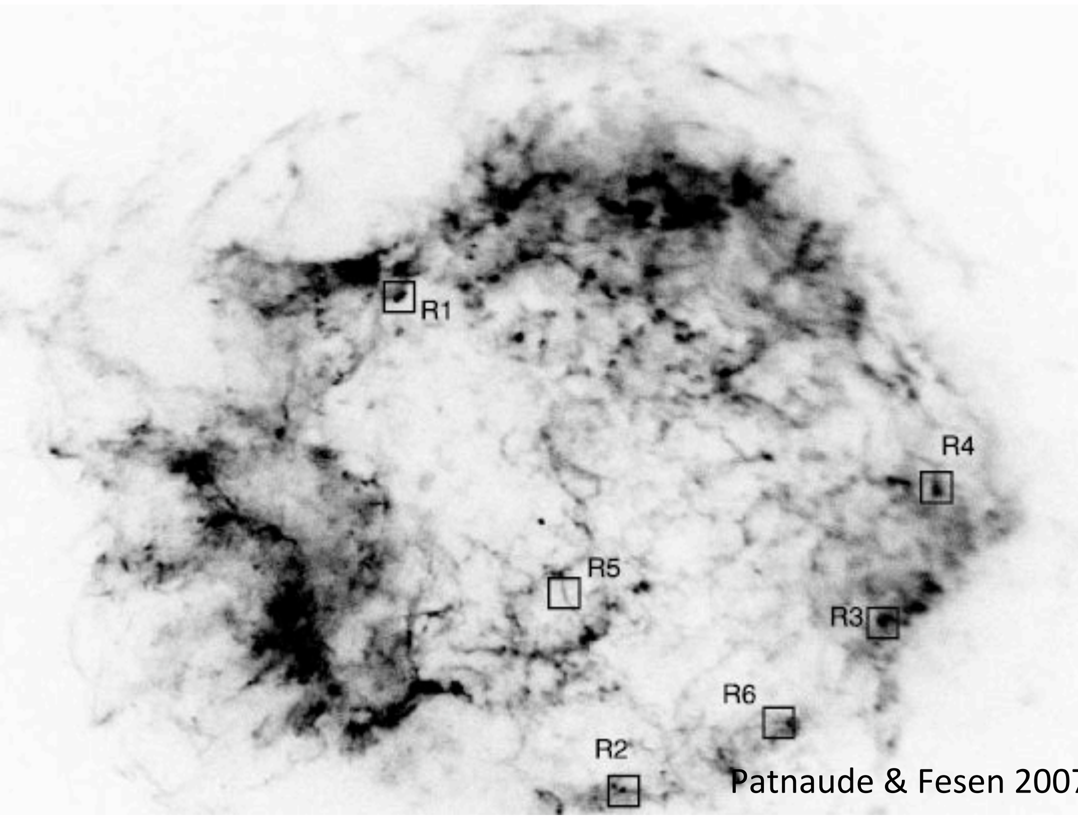
Magnetic field amplification

Predicted by Bell (2004): cosmic rays streaming outward produces an electron return current. Electrons are then deflected by the magnetic field, thus originating a turbulent, amplified magnetic field. This mechanism is expected to give $u_B \approx V_{sh} u_{cr} \propto \rho V_{sh}^3$

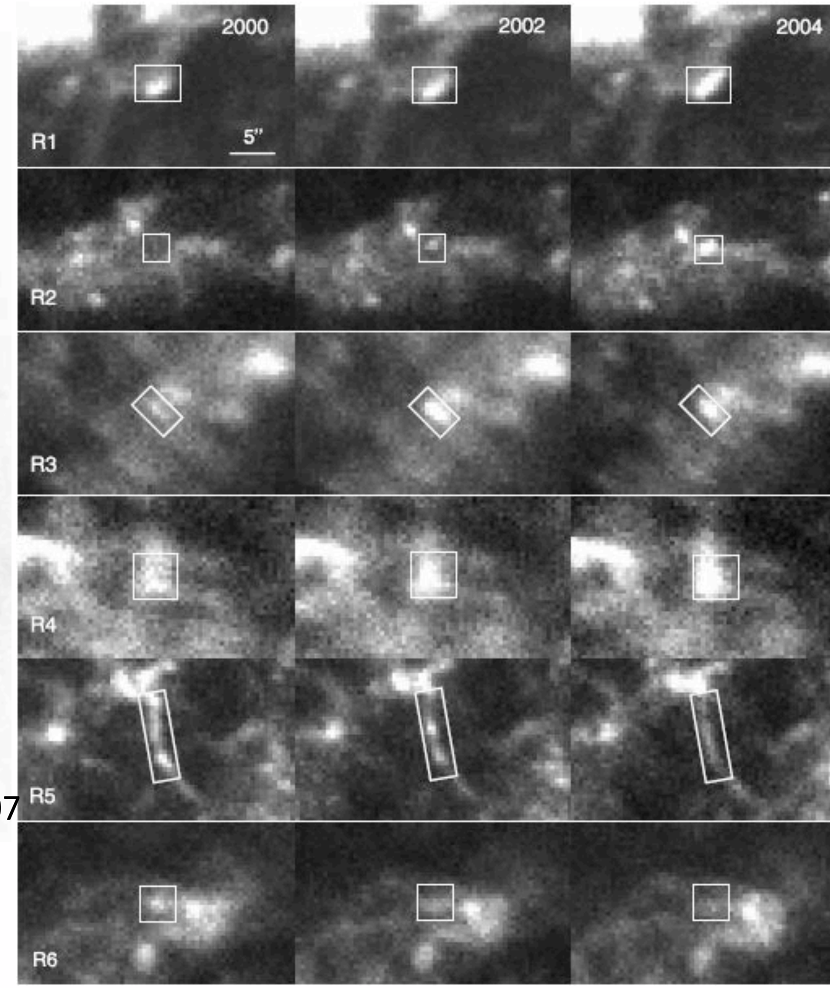


Magnetic field amplification

In a few SNRs (RX J1713.7−3946 and Cas A), **some** knotty X-ray synchrotron emitting regions seem to vary on time scales of years, which may be indicative of the synchrotron cooling time scales, and hence high B (~mG, Patnaude and Fesen 2007; Uchiyama et al. 2007; Uchiyama and Aharonian 2008)



Patnaude & Fesen 2007

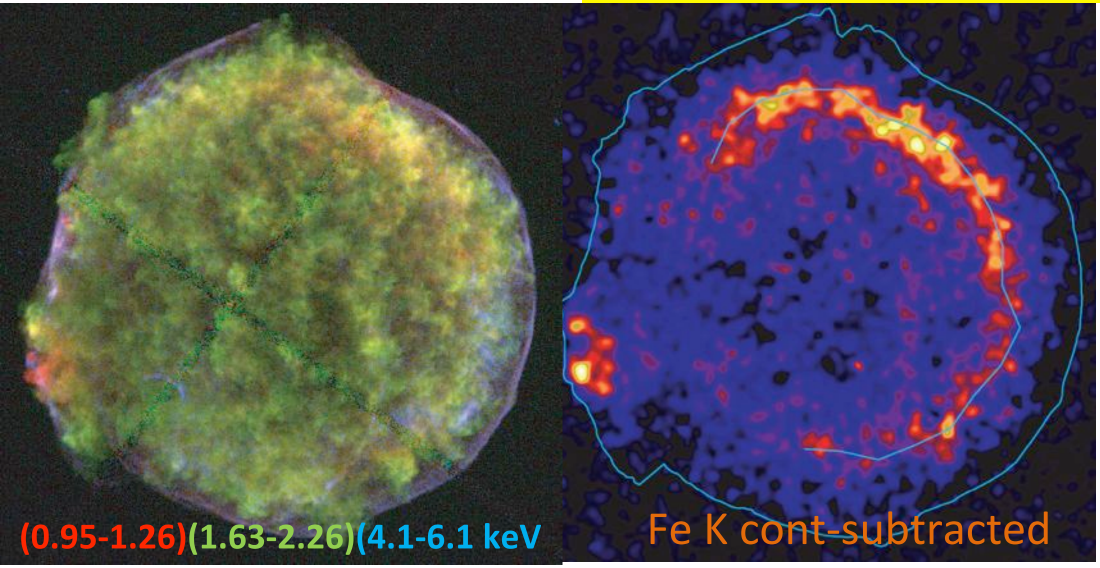


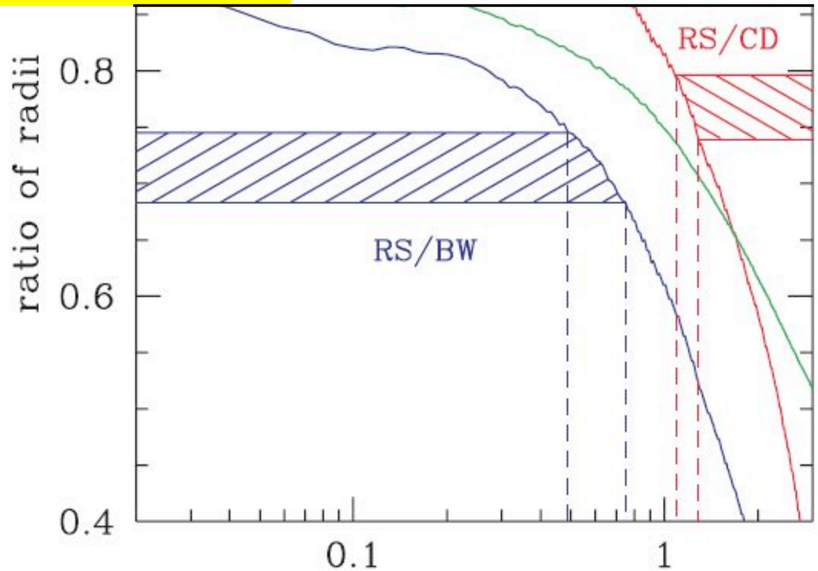
Alternative explanation: varying B due to passages of large scale plasma waves (Bykov et al. 2008)

Shock modification – observational evidences

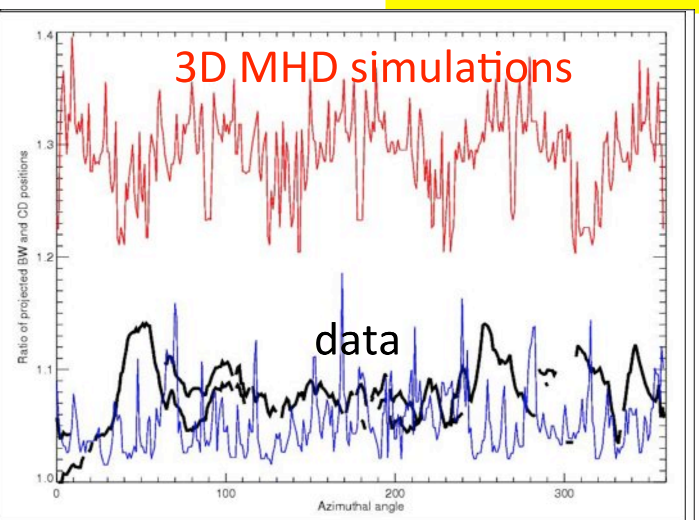
Higher compressibility ➡ lower distance between blast shock and contact discontinuity

Observed in **Tycho** (Warren et al. 2005)





and in **SN 1006** (Cassam-Chenai et al. 2008, Miceli et al. 2009)

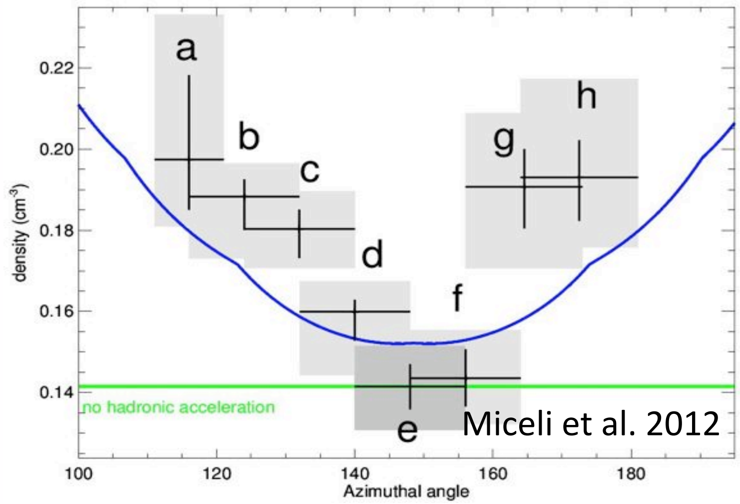


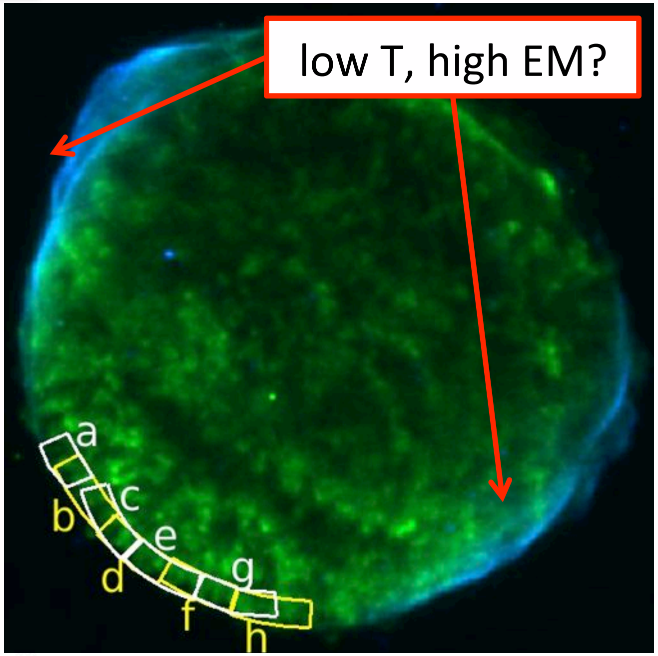
The proximity of BW and contact discontinuity may **not** be an effect of shock modification

3D MHD simulations with ejecta clumping (Orlando et al. 2012)

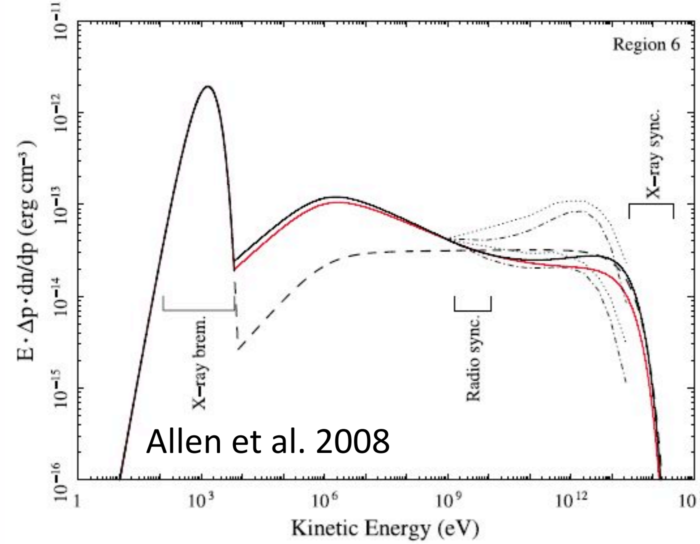
Shock modification – observational evidences

Detection of the post-shock ISM and variations in the shock compression ratio in SN 1006 (Miceli et al. 2012 see also Winkler et al. 2013)





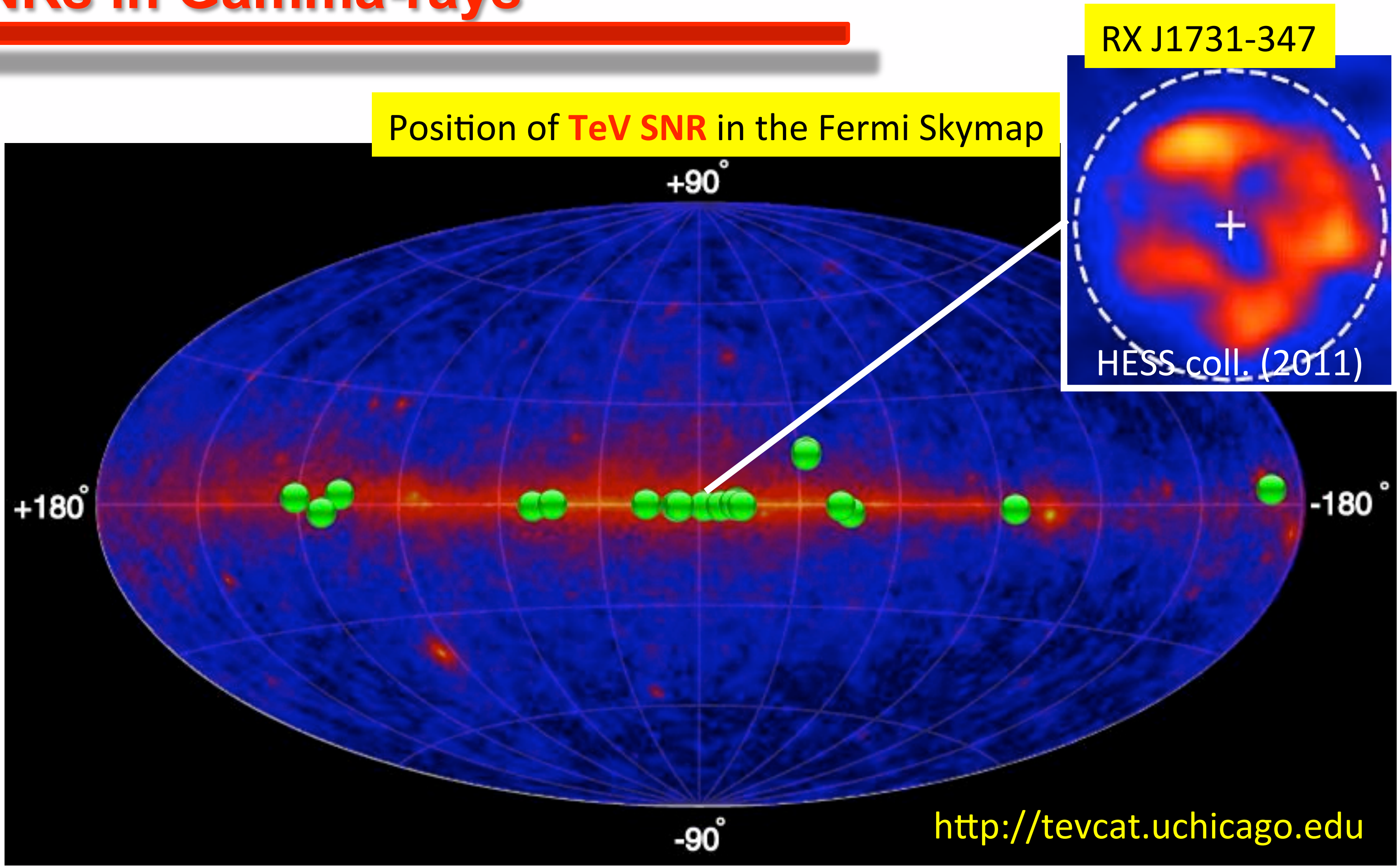
Indications of spectral curvature in the synchrotron radiation derived from the analysis of radio and X-ray observations of SN 1006 (Allen et al. 2008)



Gamma-ray emission:

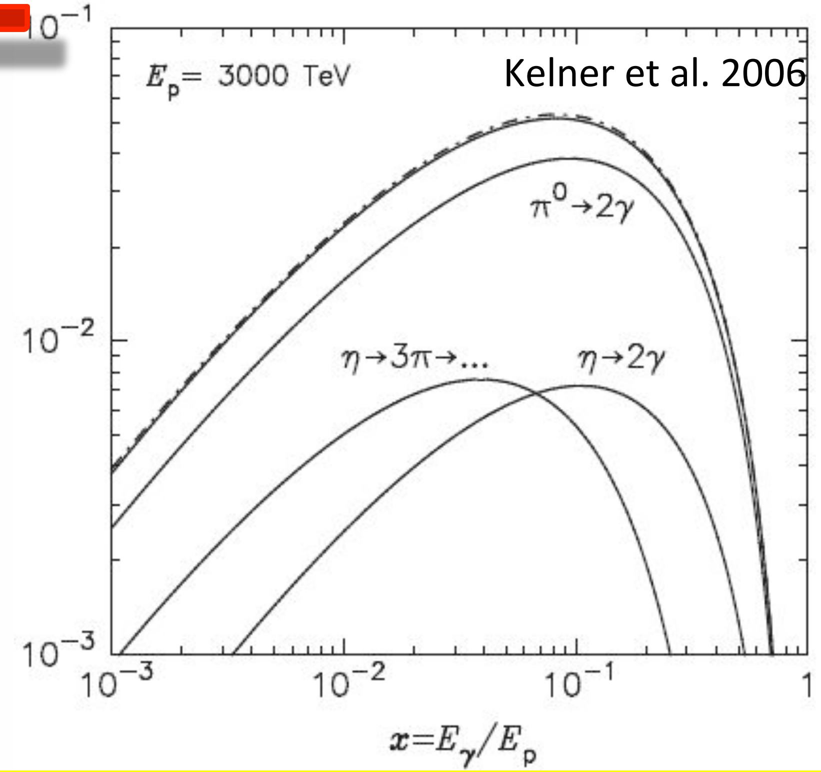
Leptonic vs. Hadronic scenarios

SNRs in Gamma-rays



1st Fermi SNR Catalog: 15 SNRs identified and >40 candidates (Brandt et al. 2014) in the Fermi band (0.1-100 GeV)

Hadronc vs. Leptonic scenarios

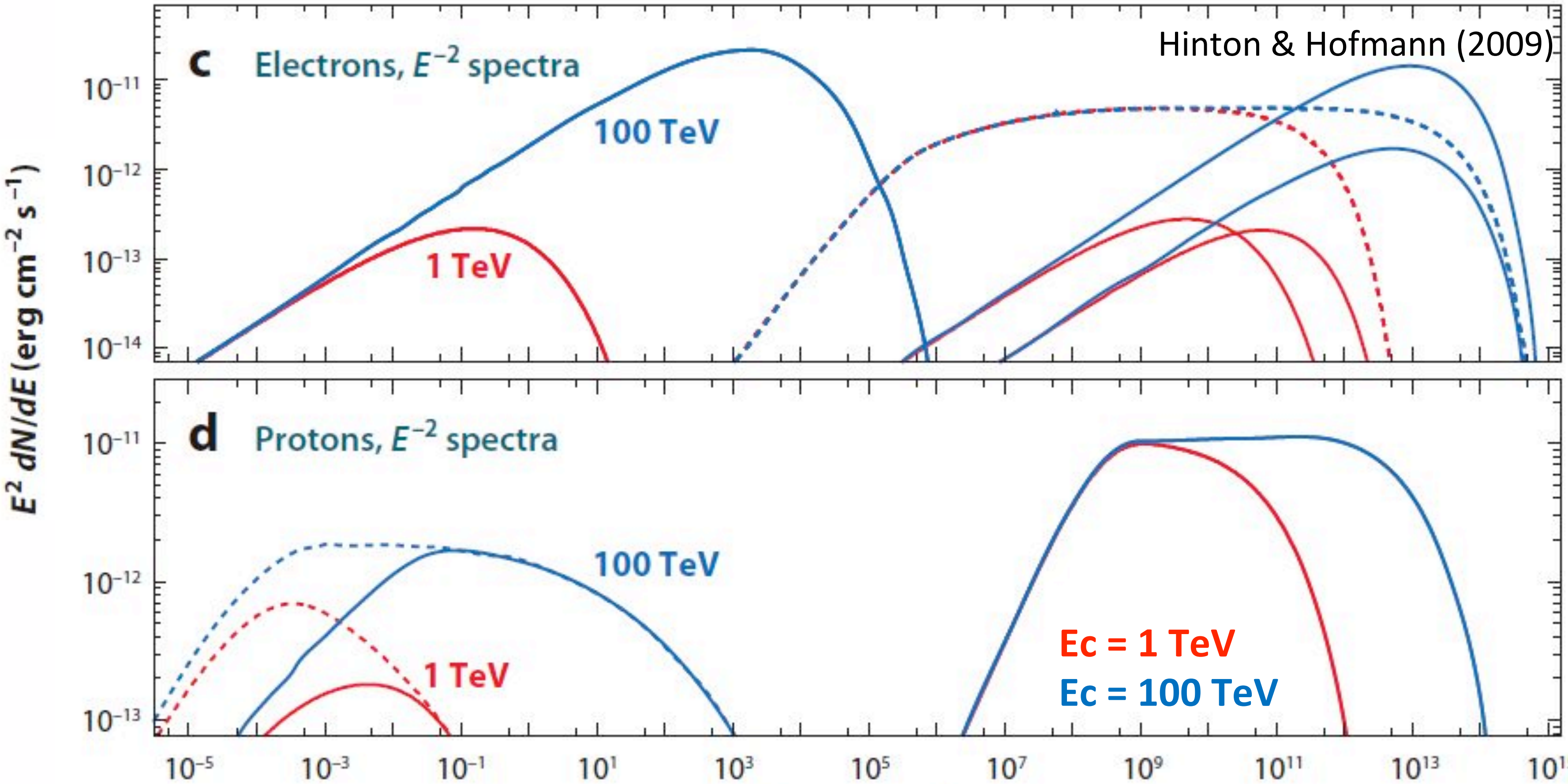


Hadronic Scenario: proton proton collision with π^0 production and subsequent 2-photons decay each with energy half of the pion rest mass (135MeV) in the rest-frame of the collision. In the observer's frame the photon energy is $\sim 0.12 E_{CR}$

The cross-section of VHE in hydrogen nuclei is weakly energy dependent (Hinton & Hofmann 2009) and is $\sigma_{pp} \sim 35$ mb, resulting in a lifetime $\tau \sim 3 \times 10^7 \, n^{-1}$ yr ➡ hadron emission requires **efficient hadron acceleration** and nearby **dense targets** (e.g., MC)

Leptonic Scenario: IC (on CMB, dust-emitted IR) and nonthermal bremsstrahlung from ultrarelativistic e^-

Hadronc vs. Leptonic scenarios



IC and synchrotron (from secondary e- in **(d)**)

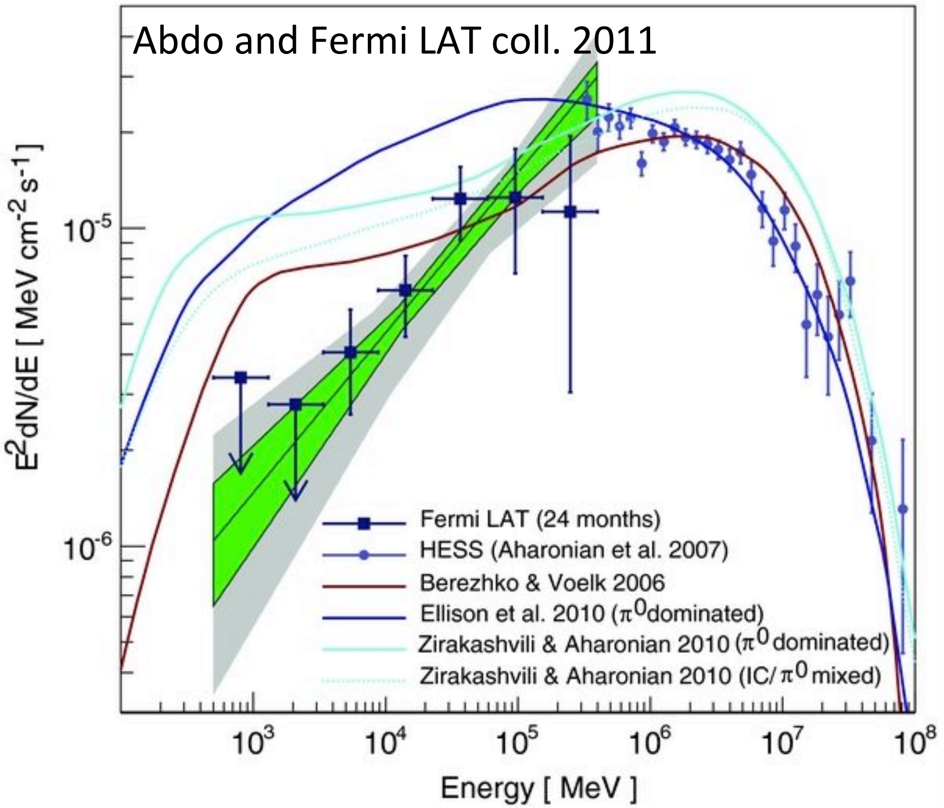
bremmstrahlung

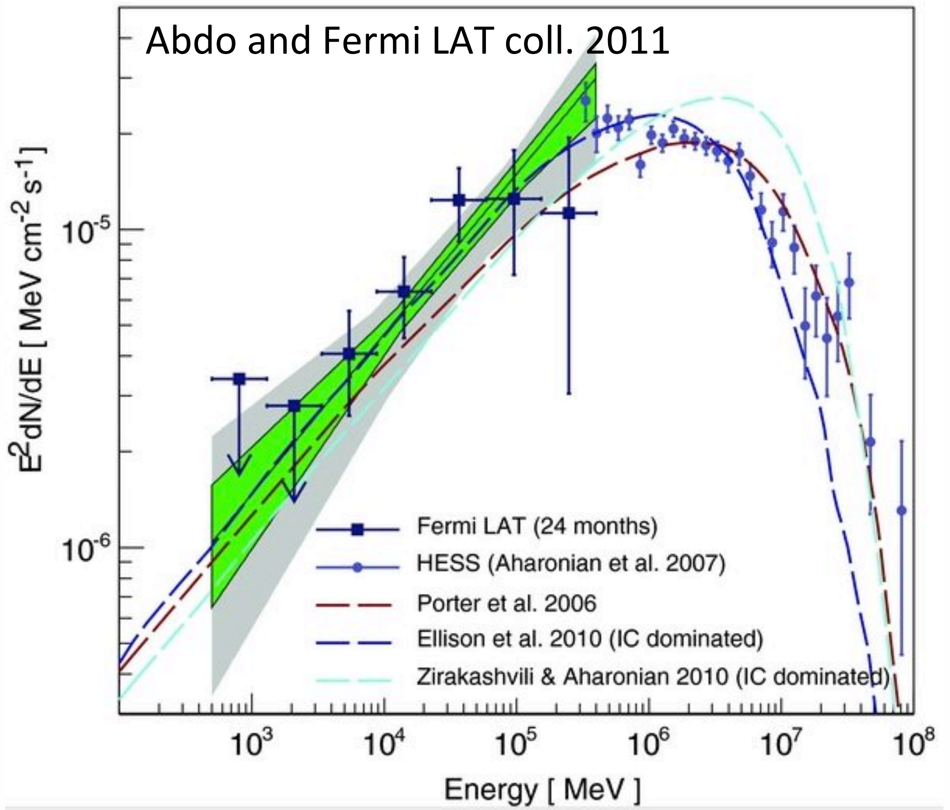
cutoff power-law distributions of particles: $dN/dE \propto E^{-2} \exp -E/E_c$

The case of RX J1713.7-3946

Very bright HESS source with **bright X-ray synchrotron emission** (Acero et al. 2009), surrounded by dense **molecuar clumps** (e.g. Fukui et al. 2012) ➡ perfect candidate for hadronic emission

Strong debate between hadronic (e.g. Ellison et al. 2010) and leptonic (Berezhko & Volk) origin



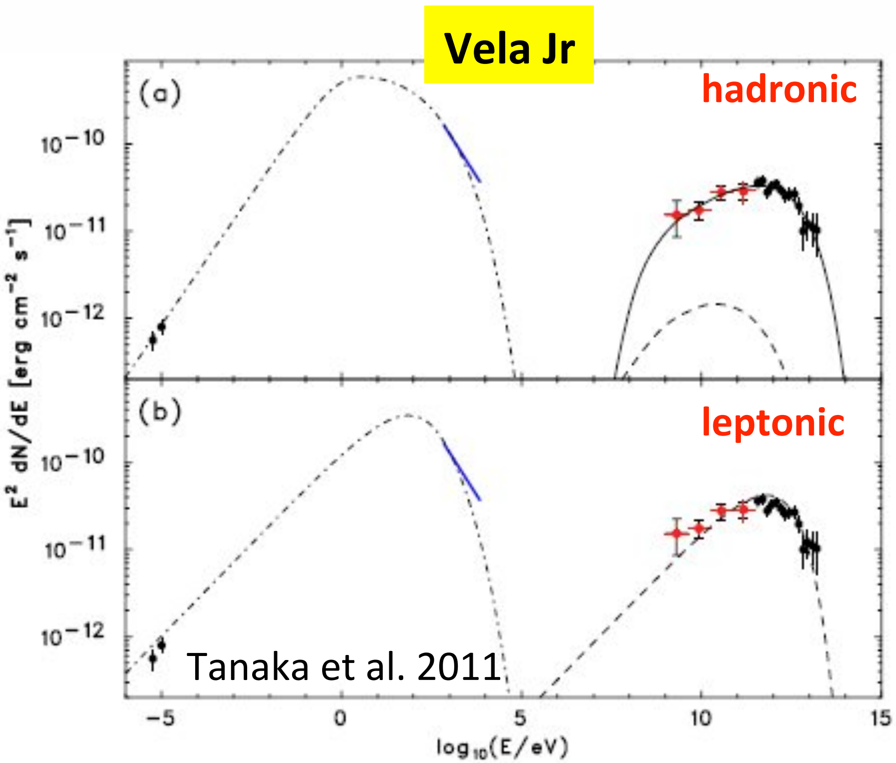


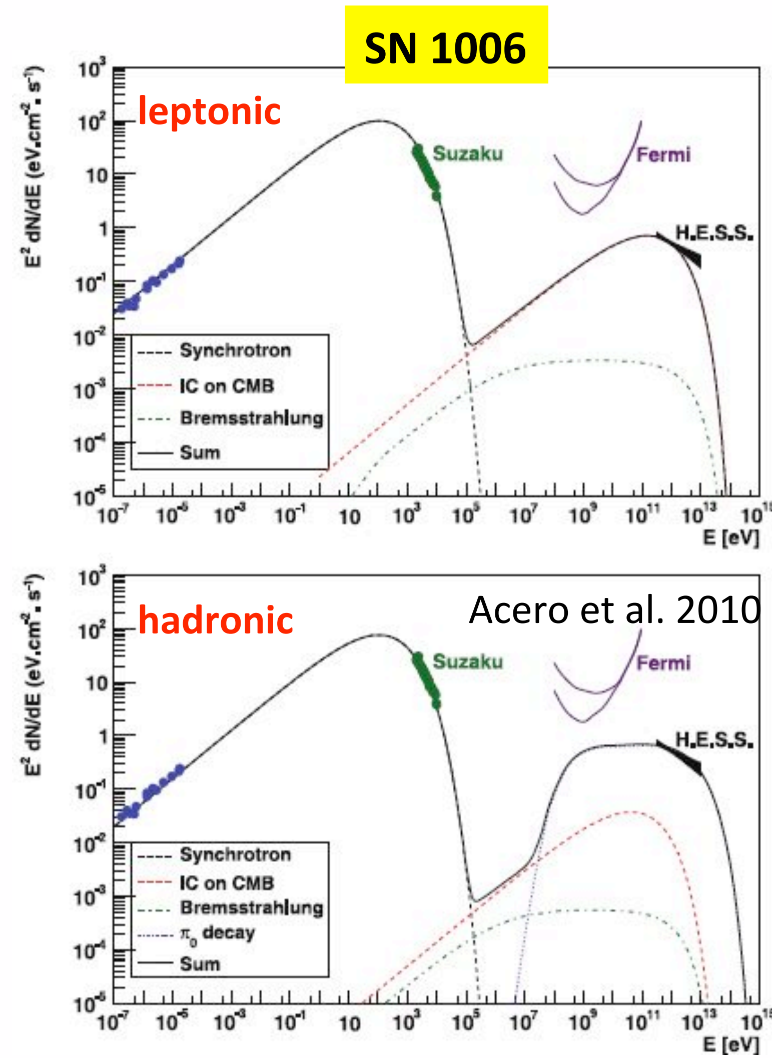
The Fermi LAT observations rule out the hadronic scenario

...though only on the base on (over-)simplified one-zone models

Young SNRs in gamma-ray

In general, the gamma-ray emisssion in young SNR presenting bright X-ray synchrotron emission is consistent with both the leptonic and the hadronic scenarios, e.g Vela Jr. (Tanaka et al. 2011) and SN 1006 (Acero et al. 2010)



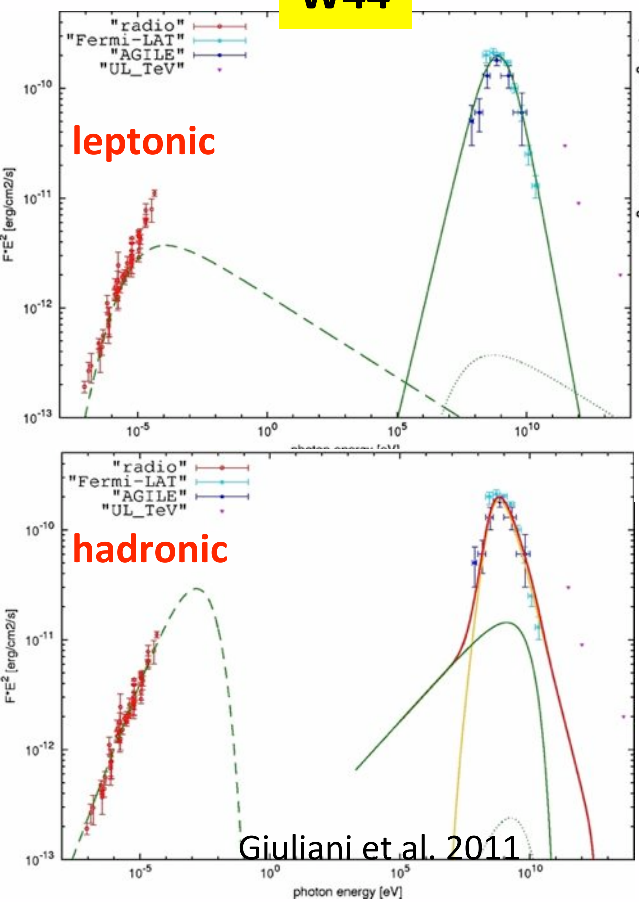


The hadronic scenario generally requires 10^{50} erg (Aharonian 2013), but the origin of the gamma-ray emission is still uncertain

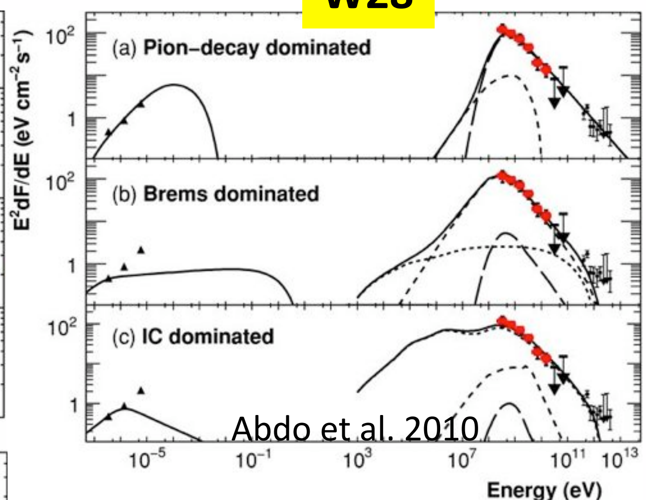
Signature of hadronic emission – old SNRs

Interestingly (and surprisingly) hadron emission appears to be the source of gamma-ray emission from **middle-aged SNRs interacting with molecular clouds**, as revealed by GeV observations (Fermi, AGILE) for W28 (Abdo et al. 2010 , Giuliani et al. 2010), W44 (Abdo et al. 2010, Giuliani et al. 2011, Uchiyama et al. 2012), and IC 443 (Tavani et al. 2010, Abdo et al. 2010)

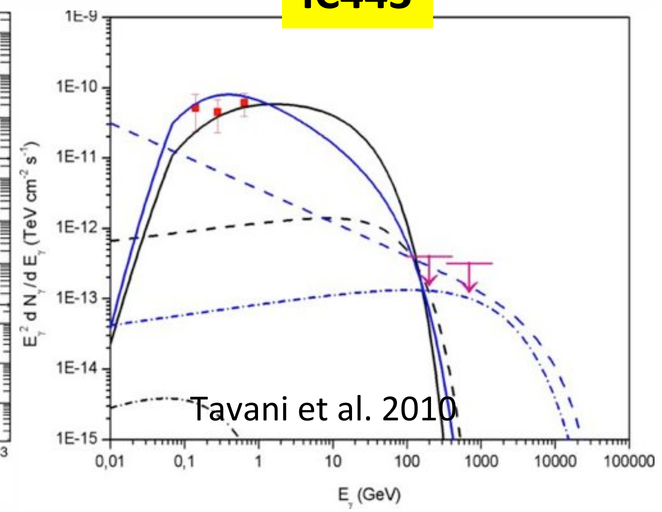
W44



W28

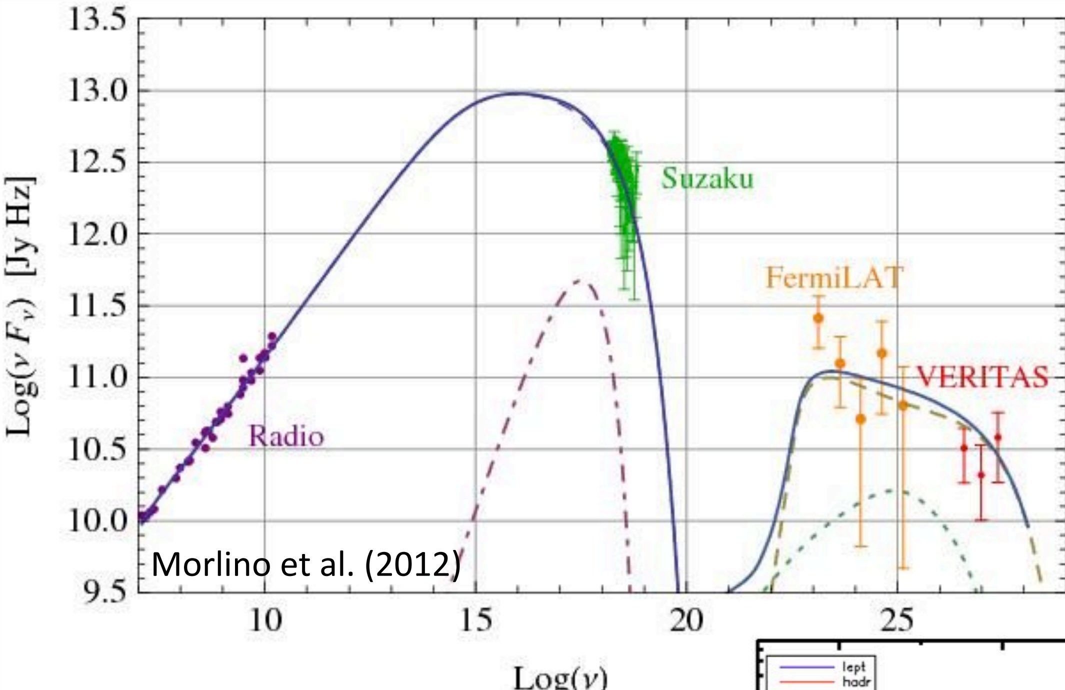


IC443



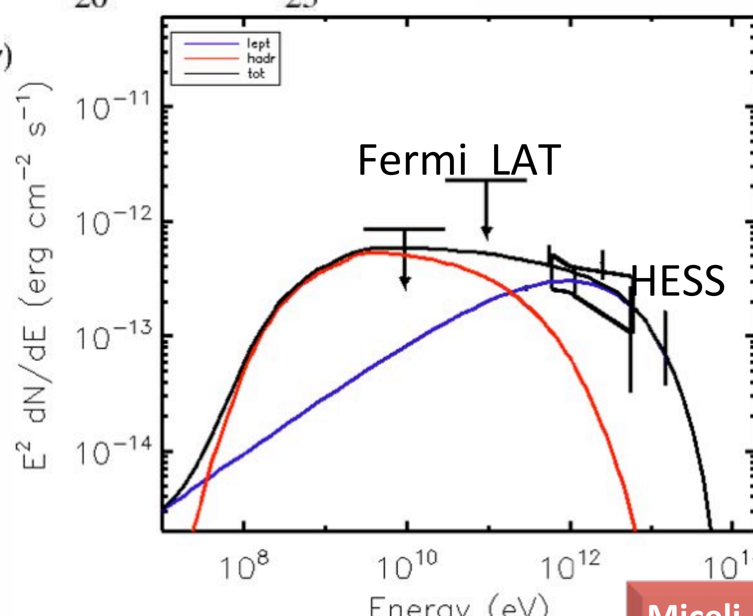
These remnants do not show X-ray synchrotron emission.
Hadrons escaped in nearby clouds?
In all these cases the hadron energy content is 1-10% E_{SN}

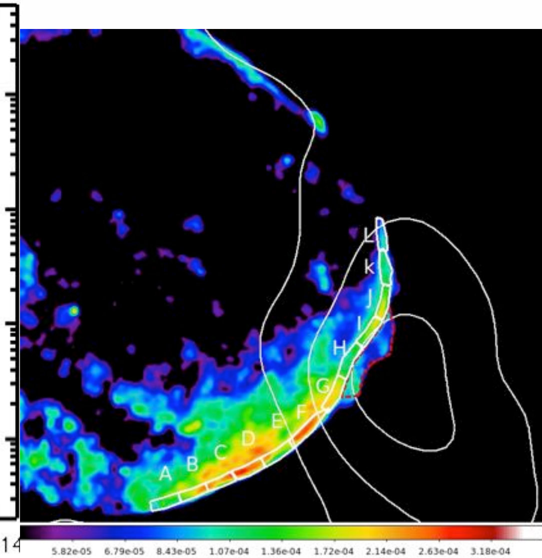
Young SNRs



The broad band SED of **Tycho** can be modelled self-consistently within the hadronic scenario (Morlino et al. 2012, see also Slane et al. 2014)

Shock-cloud interaction recently discovered in **SN 1006** (Miceli et a. 2014) may also reveal hadron emission from the southwestern limb





Future perspectives

- Spatially resolved spectral analysis of the GeV-TeV emission (CTA)
- Possible discovery of new SNRs in the gamma-ray band
- Exploration of the energy spectrum above 10 TeV (where IC is expected to fade out)
- Combined radio-X-rays-γ-ray data analysis
- Detailed diagnostics of the plasma conditions to probe the shock modification effects (X-rays, Athena)
- Importance of the Balmer Hα emission (e.g. Nikolic et al. 2013, Morlino et al. 2013)