

Cosmic-Ray Acceleration in SNR shocks

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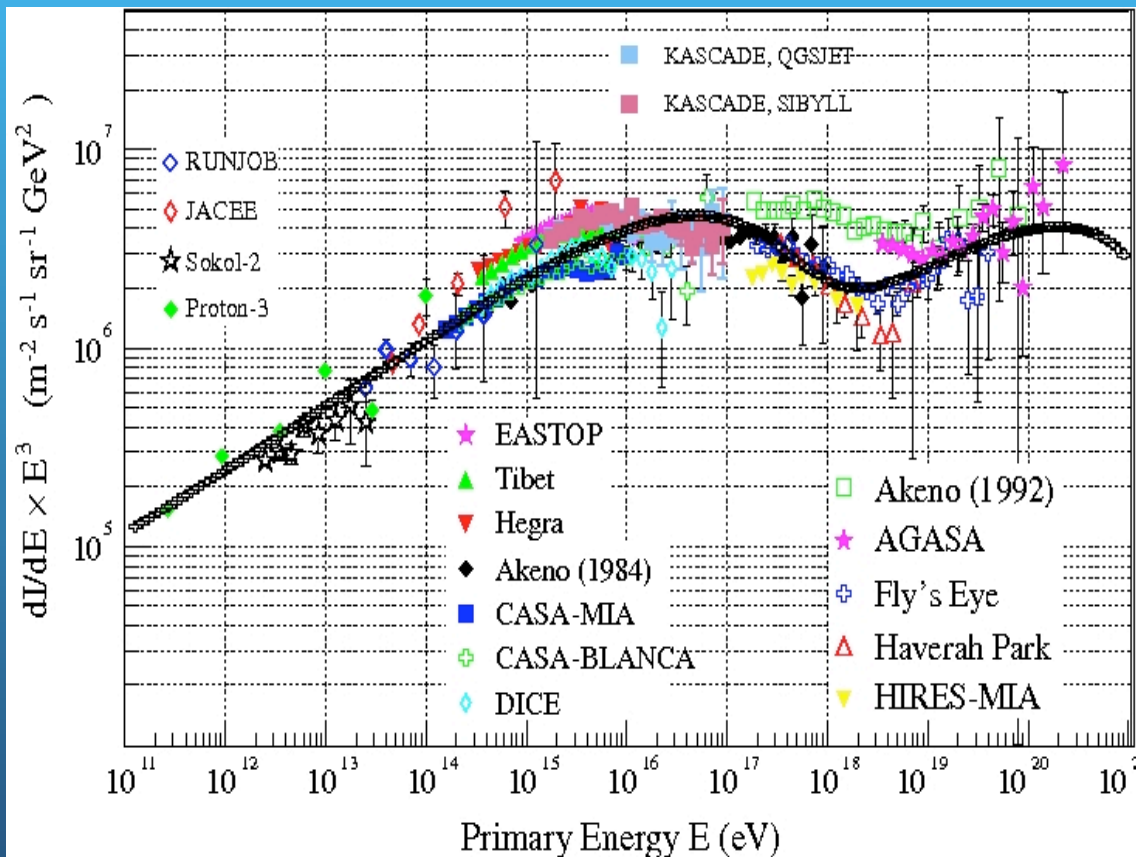
Nov. 18th 2009

Outlines

- Cosmic-Rays (CRs)
 - What is CRs?
 - Sources of CRs
 - Why SNRs?
- Shock acceleration in SNRs
 - Observational evidence
 - Fermi Mechanism
 - Linear and Non-linear theory
- How can we see CRs?
- Summary

CRs' spectrum---piecewise power-laws

(Dar 2006)



CRs are important:

- Important ionization source
- tell us the compositions of different sources
- Important for earth's atmosphere
- Teach us how to accelerate particles
-

Energy Balance Implies that SNRs are possible sources:

local galactic CR energy density 1.8 eV/cm^3 (Webber 1998)
 CR power per unit area in the Galaxy $3 \times 10^{38} \text{ erg s}^{-1} \text{ kpc}^{-2}$

SN kinetic energy per unit area in the Galaxy $2 \times 10^{39} \text{ erg s}^{-1} \text{ kpc}^{-2}$
 ($W_{\text{sn}} = 10^{51} \text{ erg}$, $50 \text{ Myr}^{-1} \text{ kpc}^{-2}$)

→ $\sim 15\%$ efficiency of CR acceleration

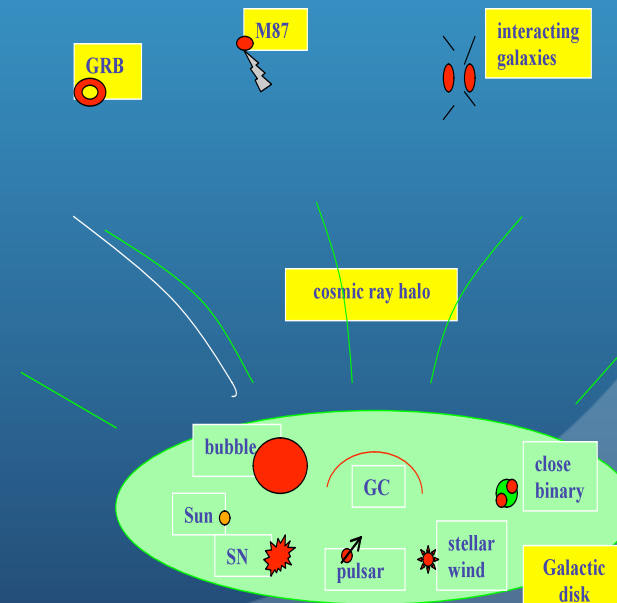
+ pulsars

+ stellar winds

have a smaller typical power compared with CR power.

But the energy of CRs from SNR is limited by the size:

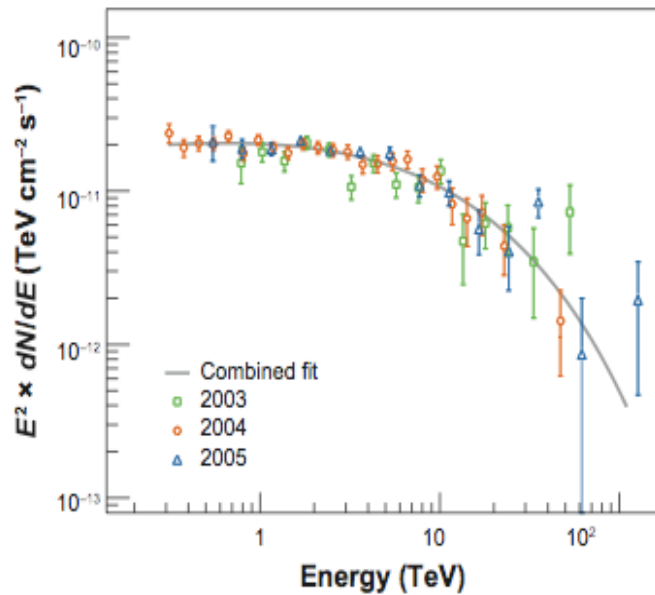
$$r_g = 1.08 E_{17} / (Z B_{10\mu\text{G}}) \text{ kpc}$$



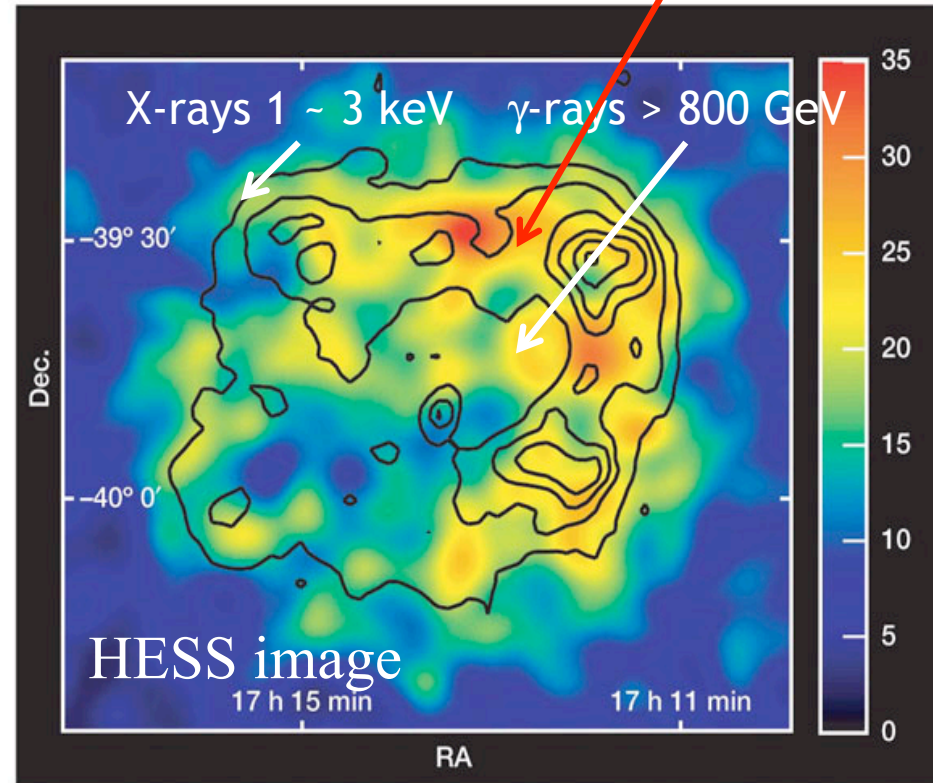
Observational Evidence

High density
Molecular Cloud

SNR RX J1713. 723946 (G347.3-0.5)



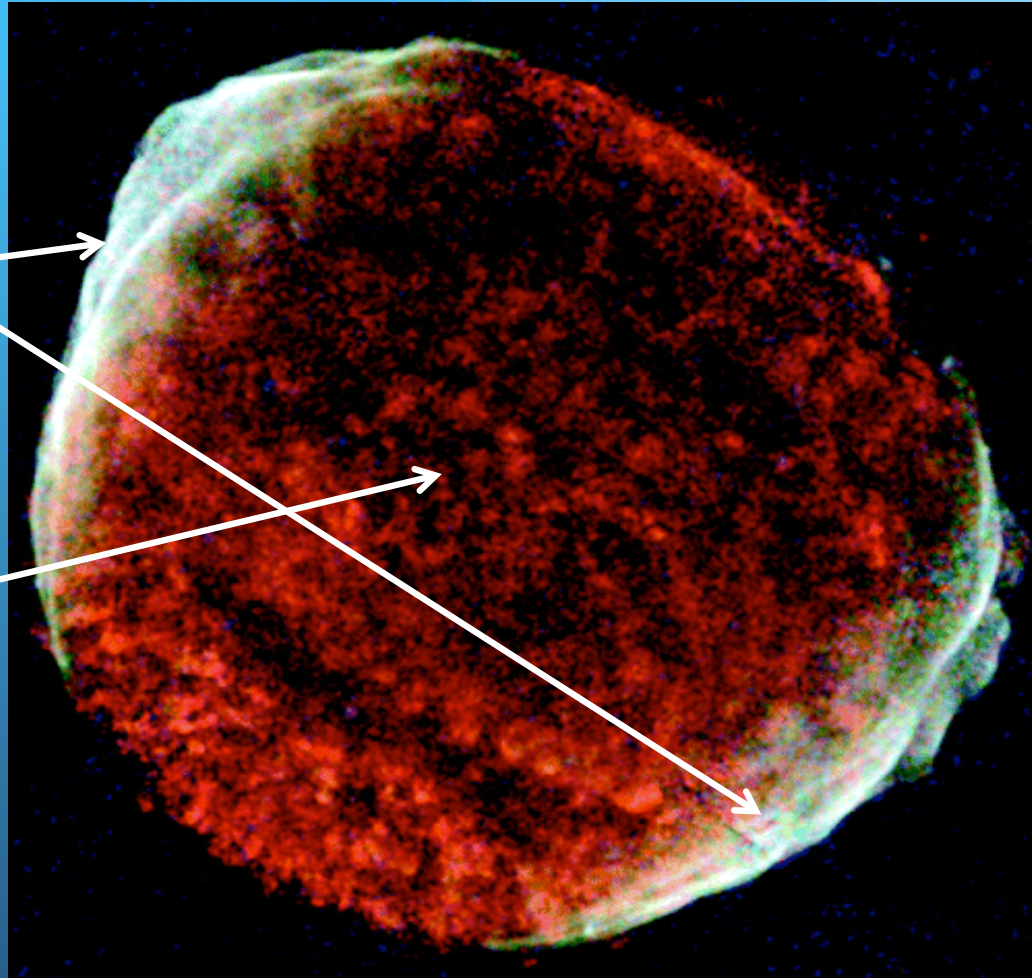
(Aharonian et al. 2004; 2007)



SNR 1006

Non-thermal X-rays
from the shock!

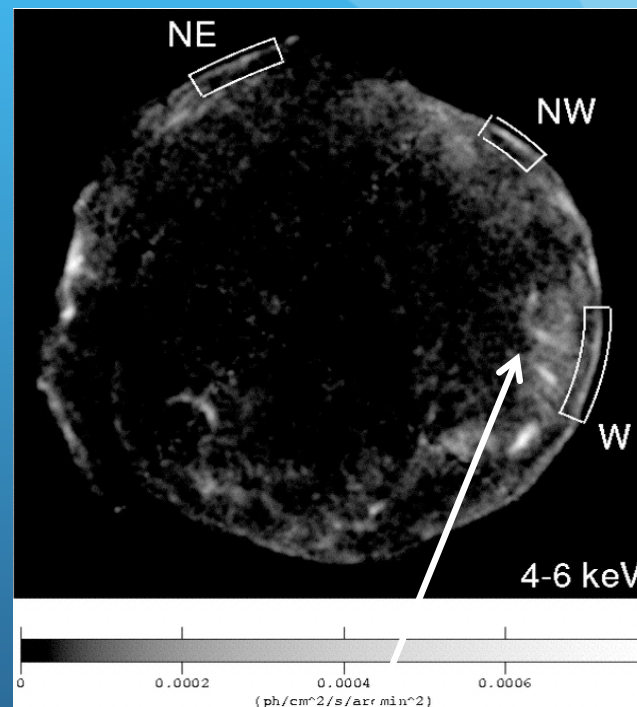
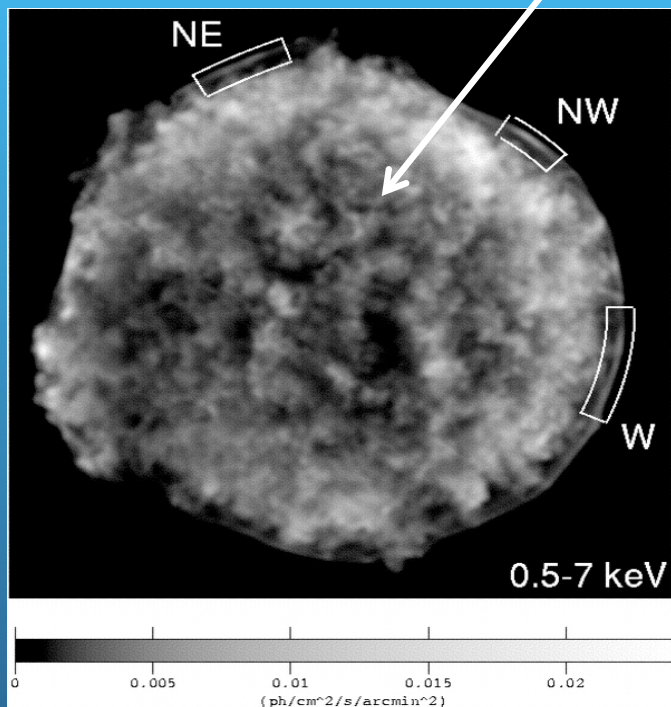
Thermal X-rays



Cassam-Chenaï et al. 2008

Tycho

Thermal X-rays

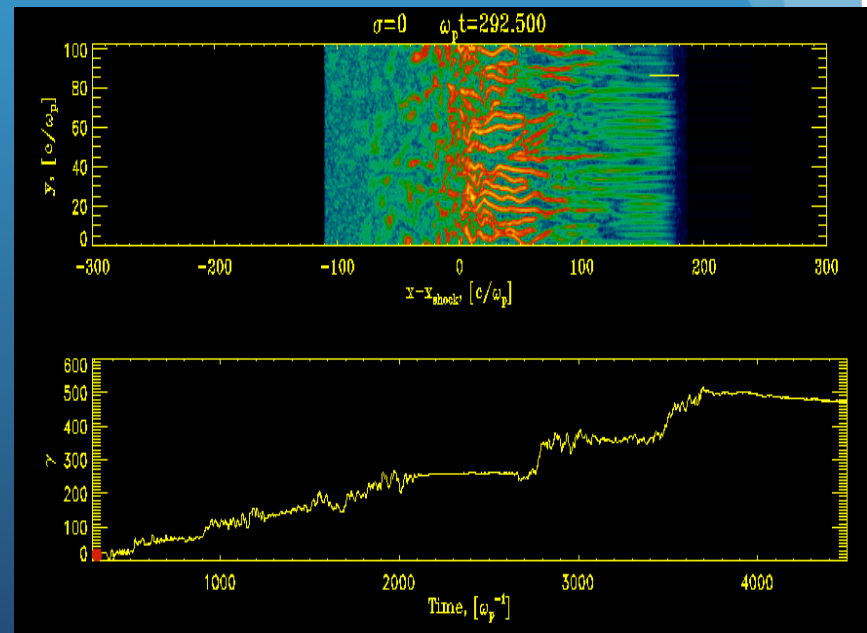
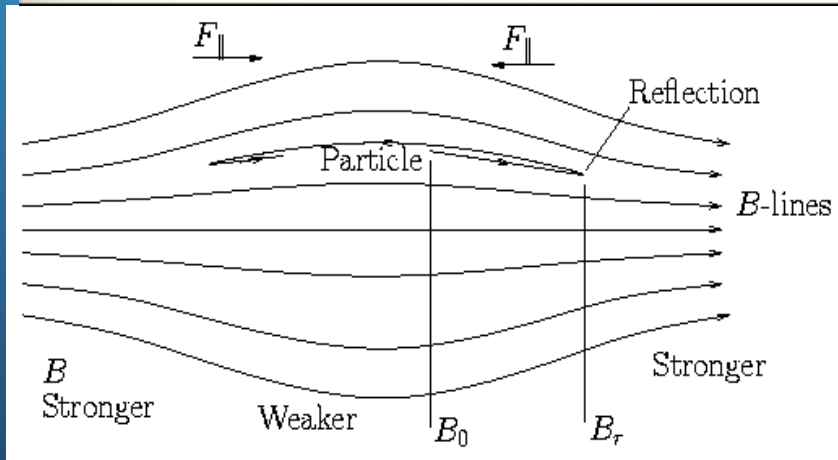
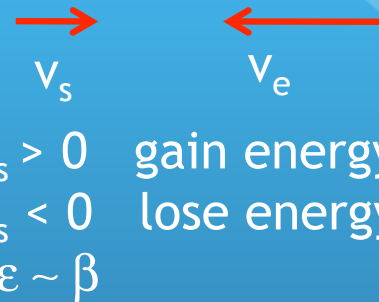
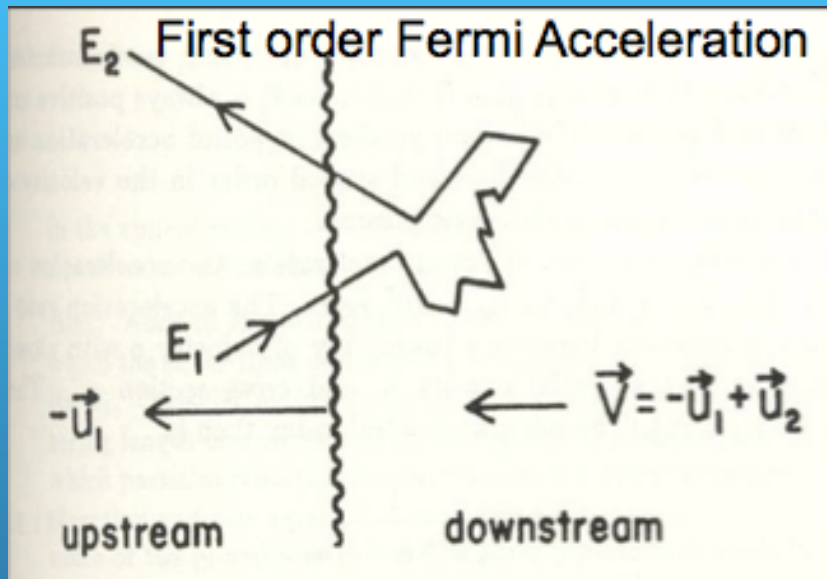


Cassam-Chenai et al. 2007

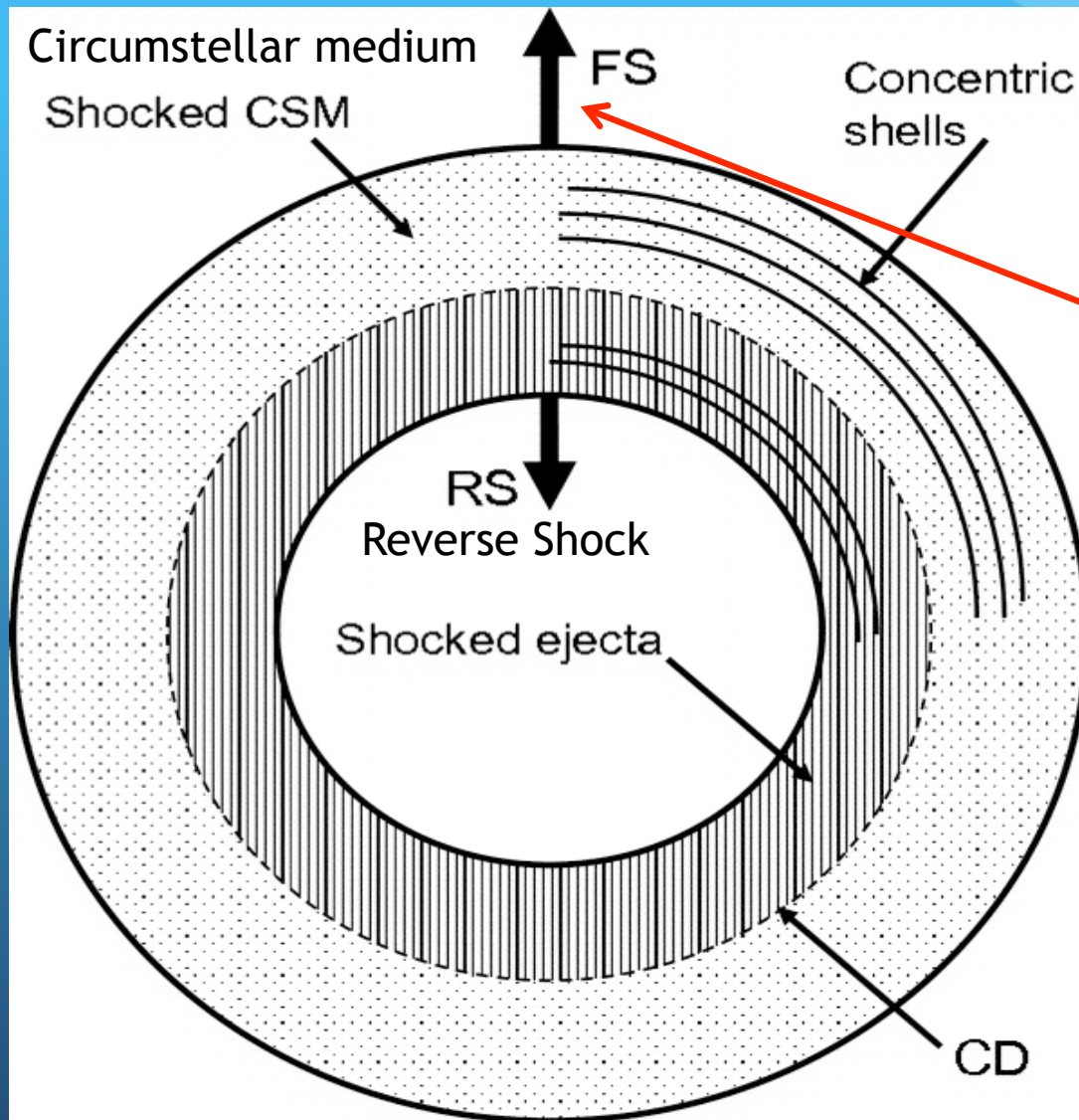
Non-thermal X-rays

Diffusive Shock Acceleration (Fermi Mechanism)

Fermi 1949;
Spitkovsky 2008;



Collisionless shock in SNR



Ellison et al. 2004

We see CRs here!
(Forward Shock)

Contact discontinuity

Test Particle Theory

Blandford & Ostriker 1978;
Bell 1978;
Blandford & Eichler 1987;

Assumptions:

- Shocks are plane and steady
- Accelerated particles are injected at a constant rate with a monoenergetic spectrum
- CRs do not change the structure of the shock
- CRs propagate in the simple leaky box model (Cesarsky 1980)

$$f(p) = 4\pi p^2 \times C_0 p^{-q} = 4\pi C_0 p^{2-q},$$

For strong shock, $q \sim 4$, close to observations

$$q = \frac{3\tau}{\tau - 1},$$

$$\frac{1}{\tau} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{\gamma + 1} \frac{1}{\mathcal{M}^2}.$$

The normalization is very uncertain.

Adiabatic and Radiation Loss

$$-\dot{E}_{\text{ad}} = \frac{1}{3} \frac{E}{V} \frac{dV}{dt}$$

$$B_{\text{eff}} \equiv \sqrt{B^2 + B_{\text{cbr}}^2 (1+z)^4}$$

Reynolds 1998
Jiang et al. 2009

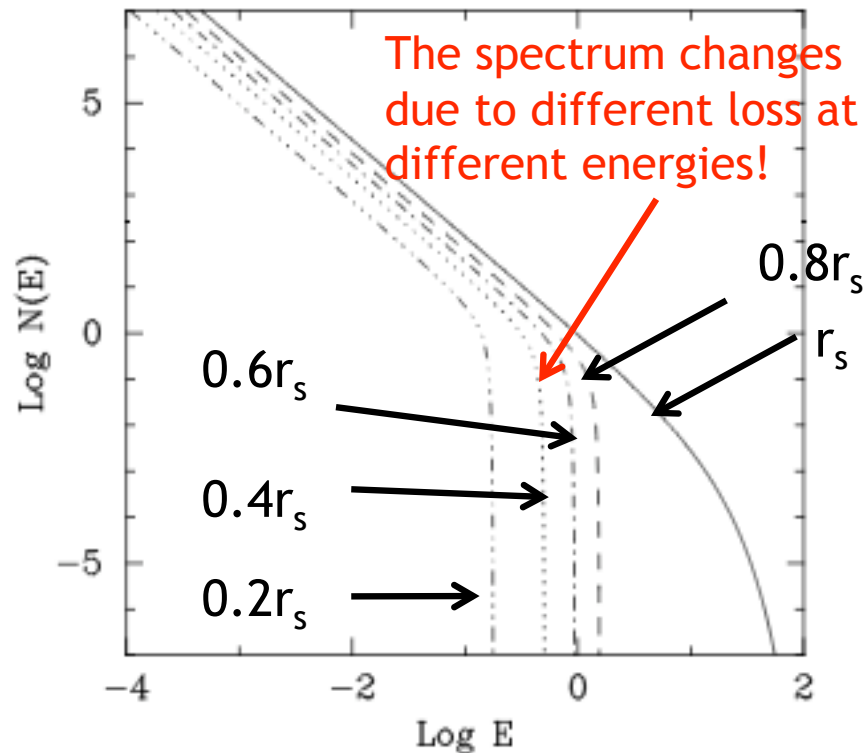
$$-\dot{E}_{\text{rad}} = \frac{4}{3} \sigma_{\text{T}} c \left(\frac{E}{m_e c^2} \right)^2 \left(\frac{B_{\text{eff}}^2}{8\pi} \right),$$

$$E(r, t) = \alpha^{1/3} \frac{E_0}{1 + \Theta E_0},$$

Compression ratio

$$\Theta(t) \equiv A \int_{t_0}^t B_{\text{eff}}^2(t) \alpha^{1/3}(t) dt.$$

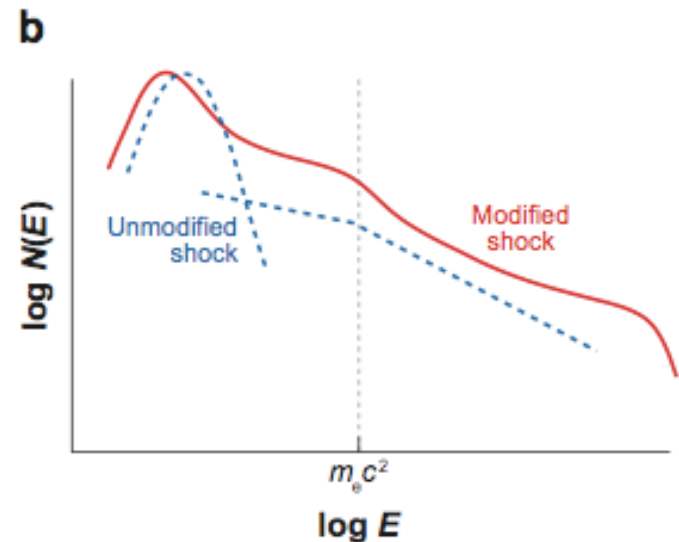
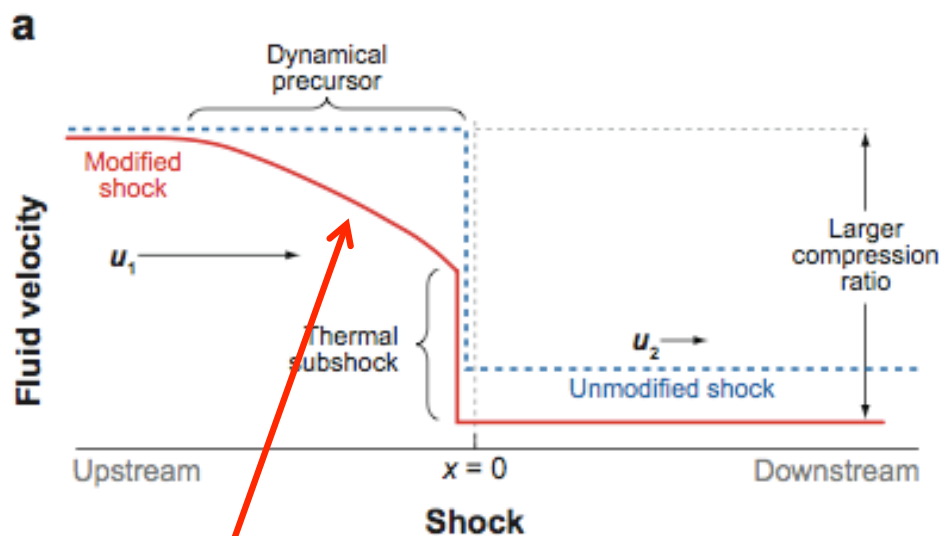
Accumulative loss



(Using Sedov Shock Wave Solution)

Non-linear theory: CRs changes the structure of the shock.

Berezhko & Ellison 1999;
Ellison et al. 2004, 2007;
Berezhko & Volk 2006;
Vladimirov et al. 2008;

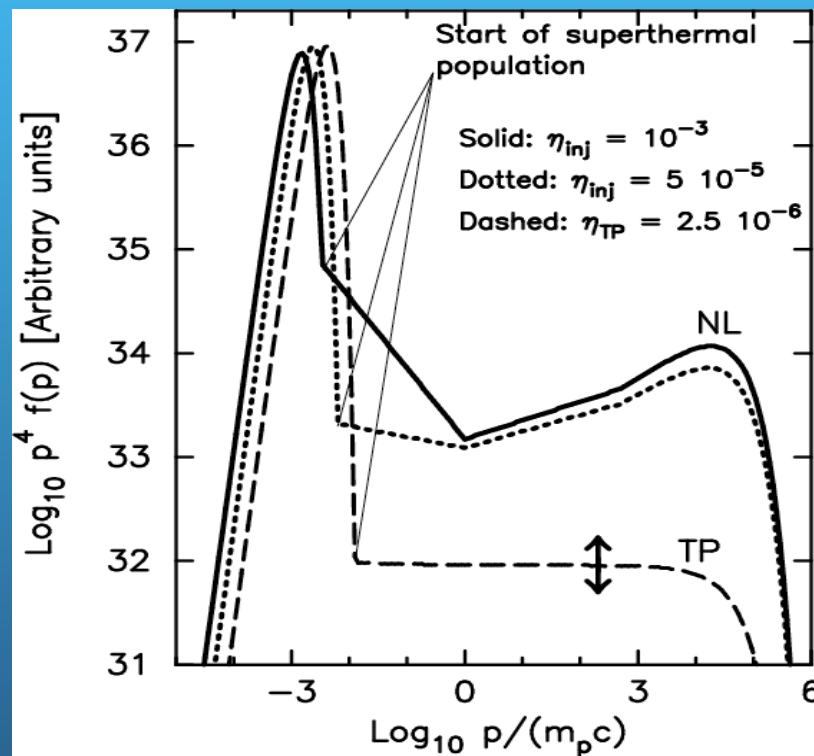


Velocity decreases
because of CRs pressure!

$$f(p) = \begin{cases} a_{inj}(p/p_{inj})^{-q_{sub}} & \text{if } p_{inj} \leq p \leq mc, \\ a_{mc}(p/mc)^{-q_{int}} & \text{if } mc \leq p \leq p_{int}, \\ a_{max}(p/p_{int})^{-q_{min}} & \text{if } p_{int} \leq p \leq p_{max}, \end{cases}$$

Free parameters of the theory

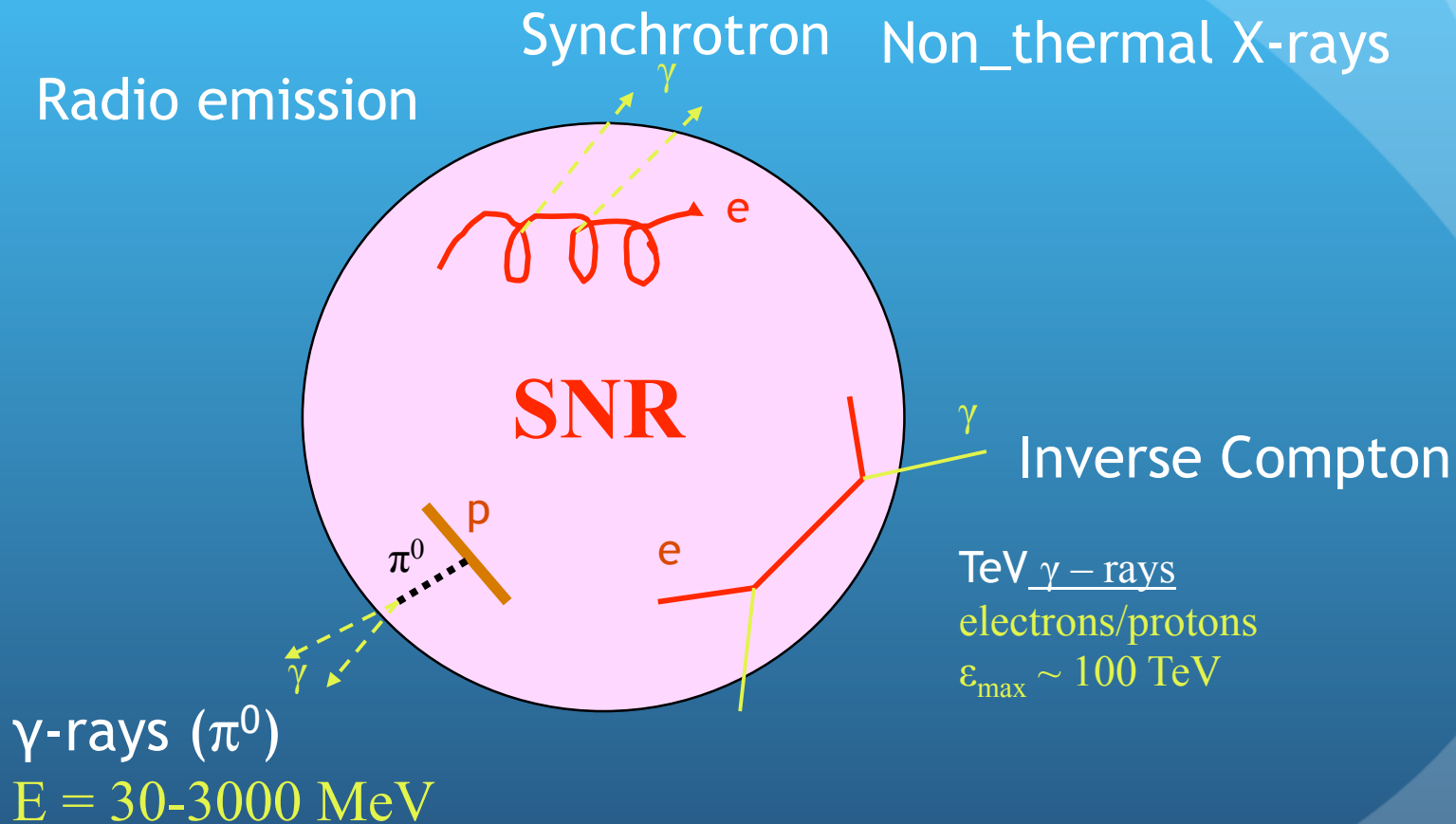
- Injection Coefficient



- Energy ratio of electrons and protons

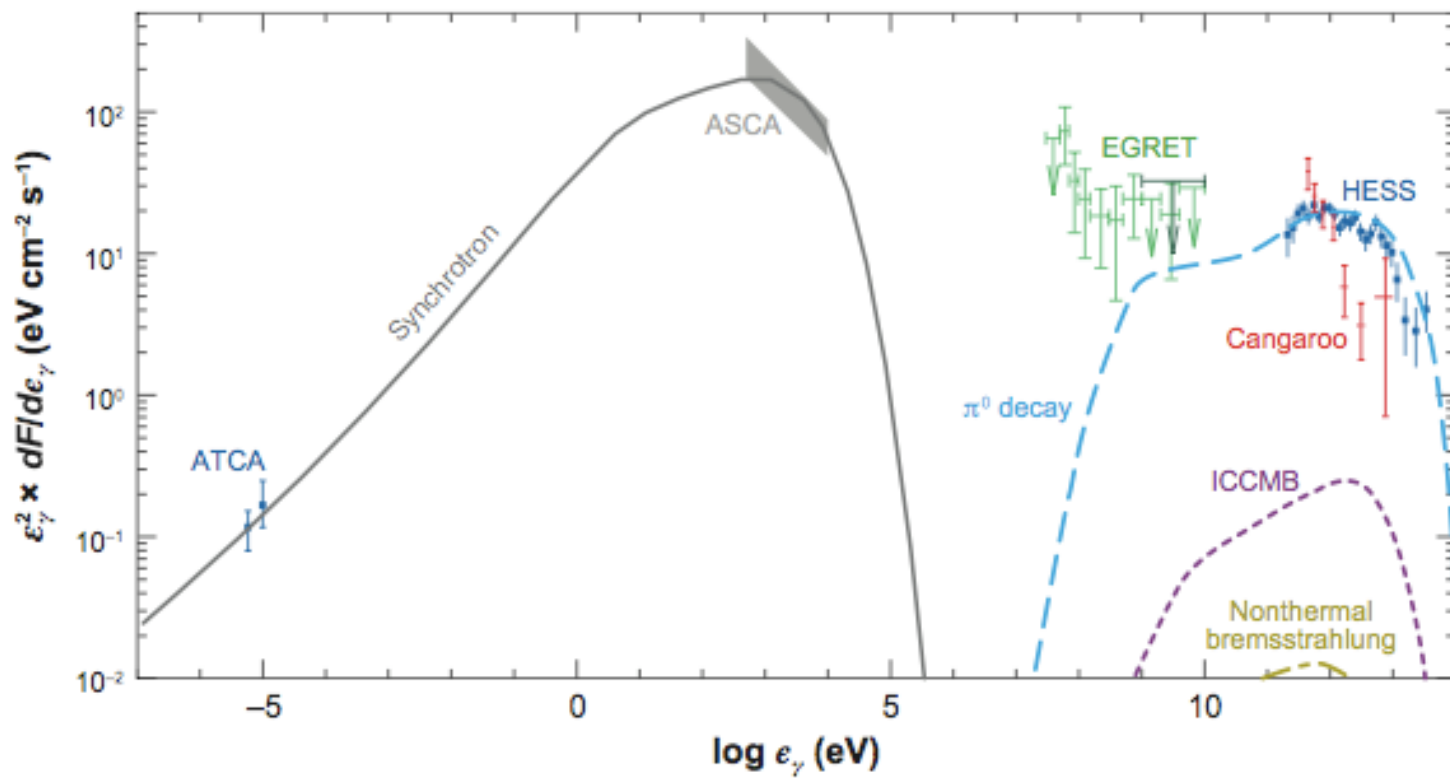
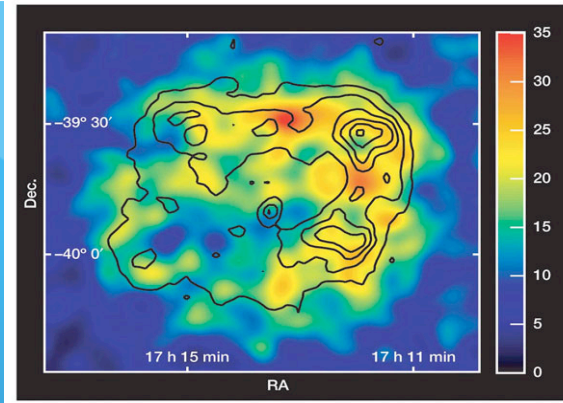
Ellison et al. 2004; 2007

Theoretical explanation for the observations:



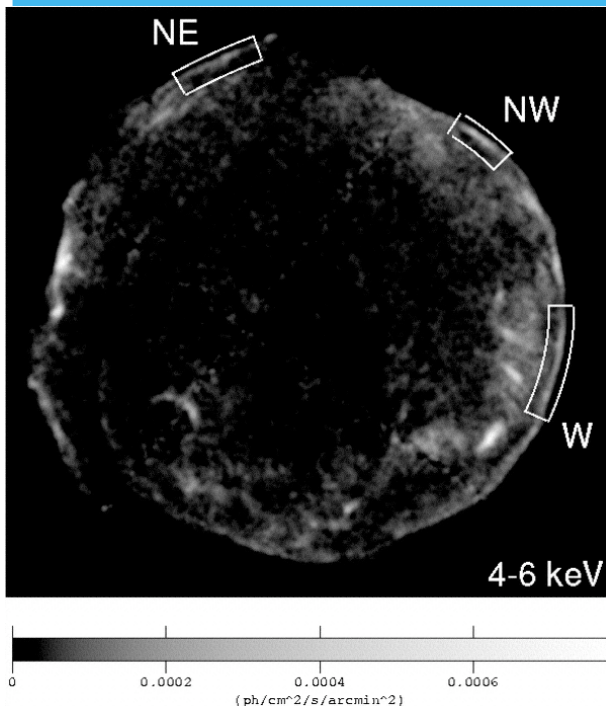
G347.3-0.5

Berezhko & Volk 2006



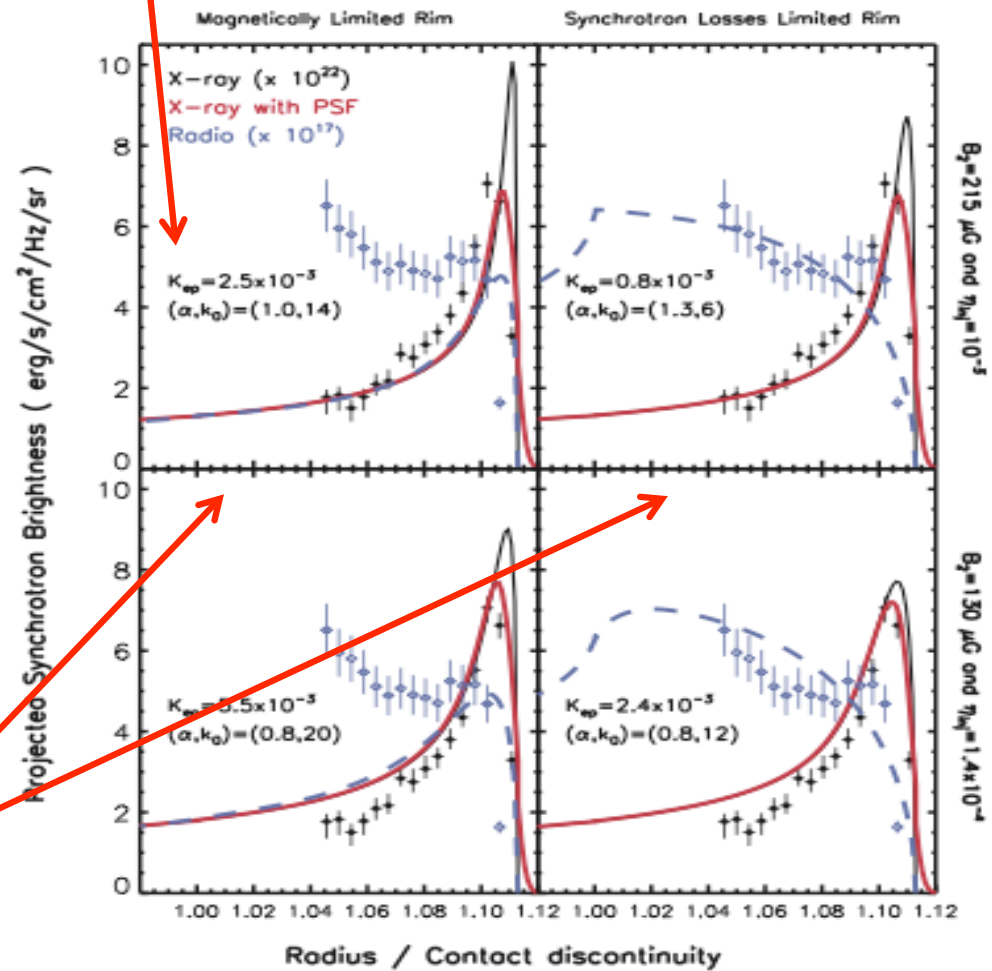
Tycho

Change the parameters for the ratio of energetic electrons and protons



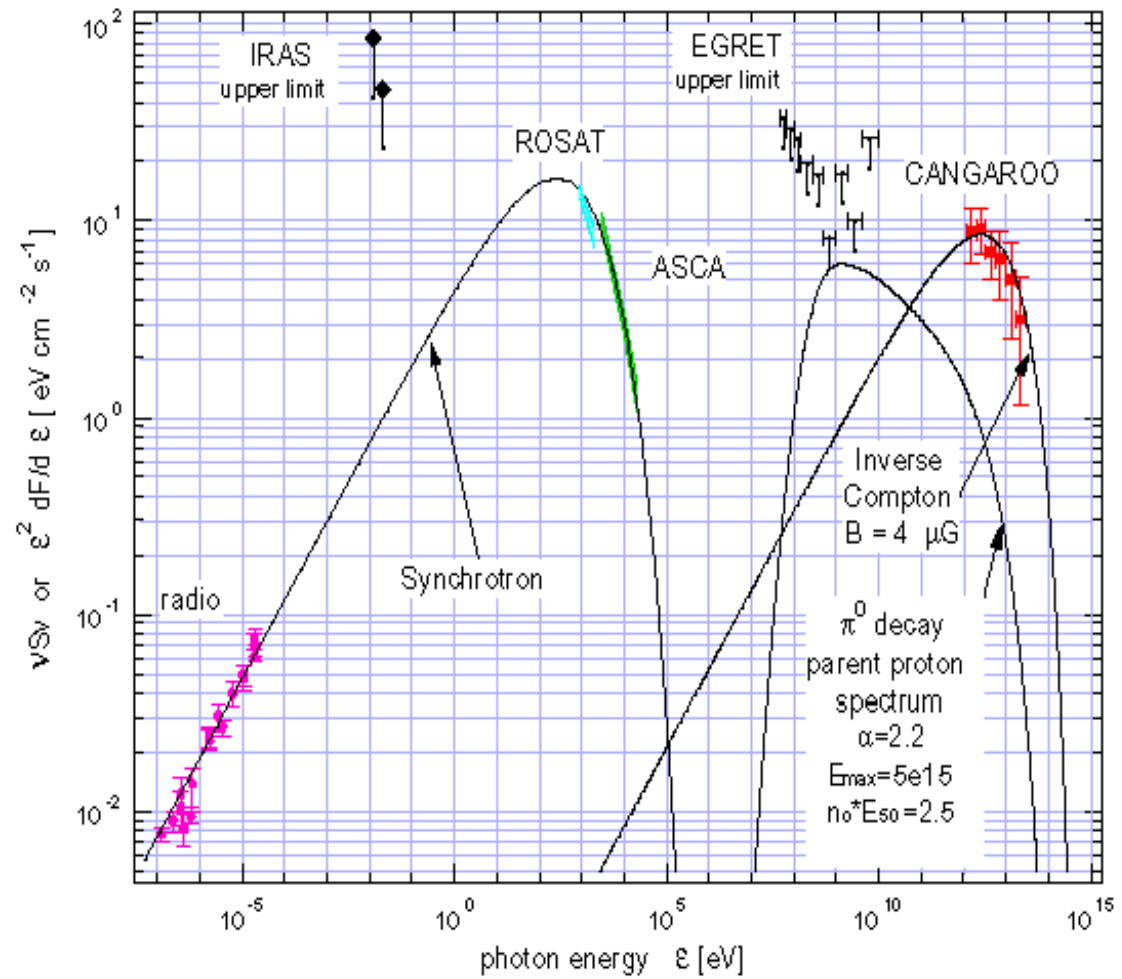
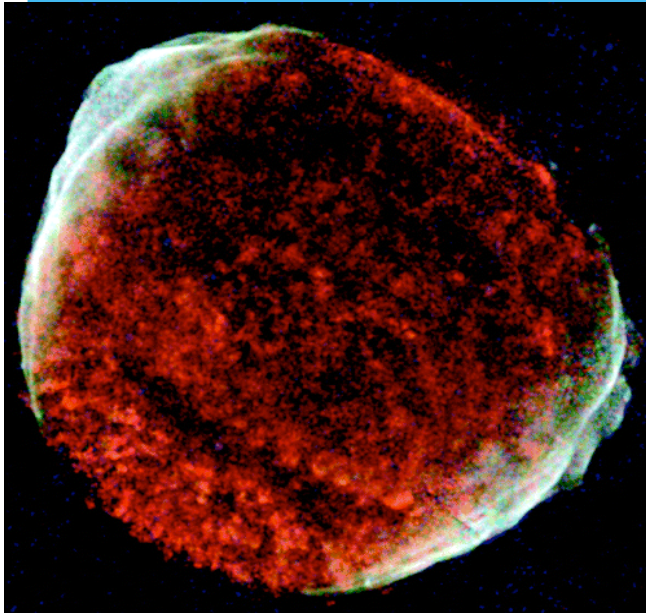
Cassam-Chenaï et al. 2007

Assume different magnetic configurations!



SN1006

Tanimori et al. 2001



Ultra-high CRs are unlikely from Milky Way because of the Larmor radius

$$r_g = 1.08 E_{17} / (Z B_{10\mu G}) \text{ kpc}$$



Summary

- SNRs are sources of CRs with energy under knee
- Fermi mechanism is the possible mechanism to accelerate the particles
- Synchrotron, Inverse Compton and π^0 decay can fit the observations from radio to hard X-ray bands very well.
- We need other sources to explain ultra high energy CRs.

References

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