PARTICLE ACCELERATION AROUND ASTROPHYSICAL SHOCKS

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OUTLINE

- **The importance of shock physics**
  - ***Cosmic Rays and their connection with shock physics***

- **Acceleration at collisionless non-relatvistic shocks**
  - ***Basic concepts***
  - ***Problems for the test-particle approach***
  - ***Acceleration in non-linear regime***

- **Application to SNR shocks**
  - ***Non-thermal emission from SNRs***
  - ***Magnetic field amplification***
  - ***The role of turbulence***

- **Collisionless shocks propagating in partially neutral plasma**

- **Conclusions & open problems**

Why astrophysical shocks are important?

- ***Collisionless Shocks*** **occurs everywhere in the Universe**
  - Solar System
  - Galaxy (Pulsar, SNR, Stellar wind)
  - Extra-galactic (AGN, Hot Spot, GRB)
  - Galaxies mergers
  - Clusters of Galaxies

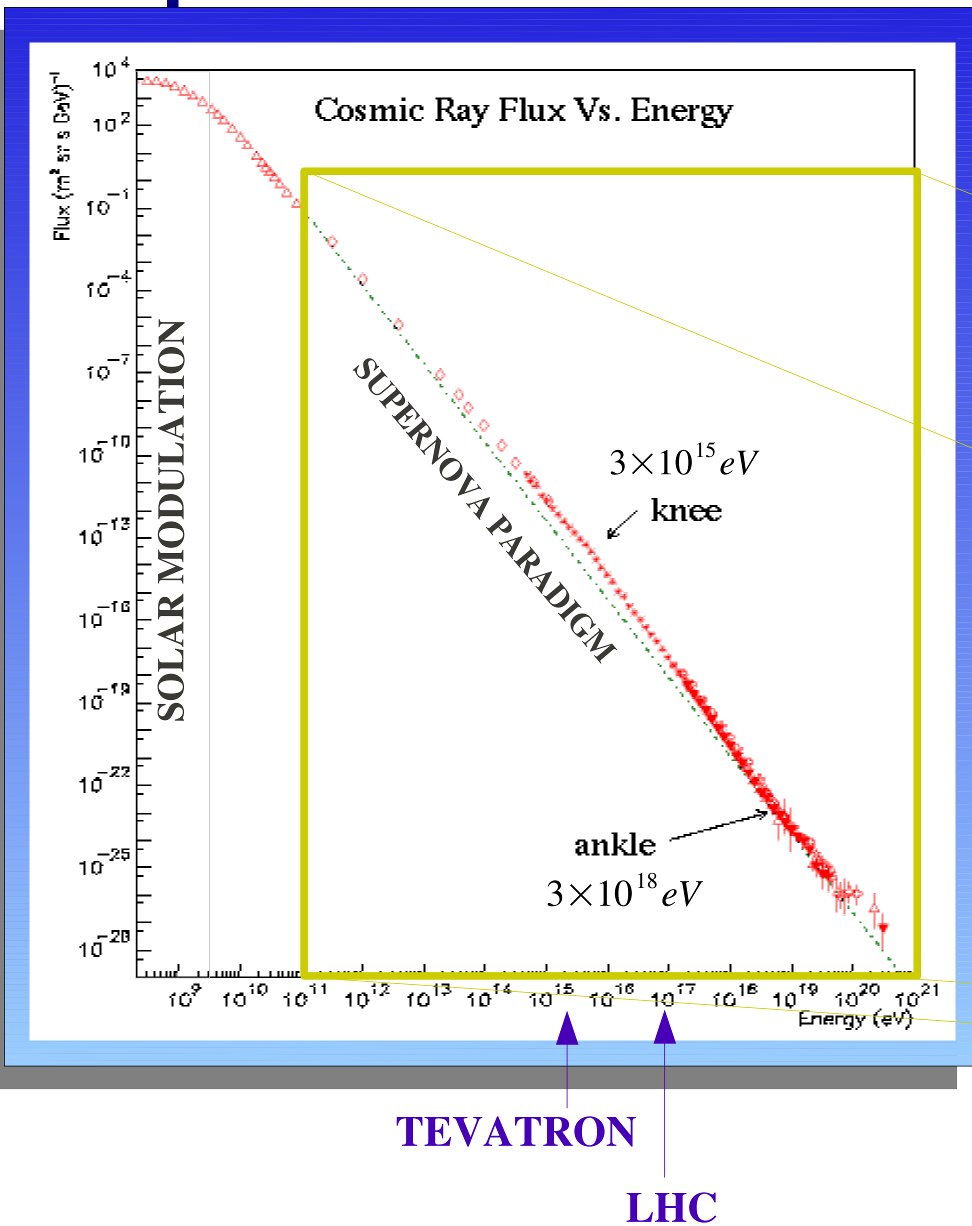
- **Shocks convert macroscopic kinetic energy into thermal energy**

- **They can also convert kinetic energy into non-thermal energy**

- **<u>Diffusive Shock Acceleration (DSA)</u> is one of the principal mechanism able to produce non-thermal particle populations in the Universe**

- **Study of shock physics is especially important for its connection with the Cosmic Rays**

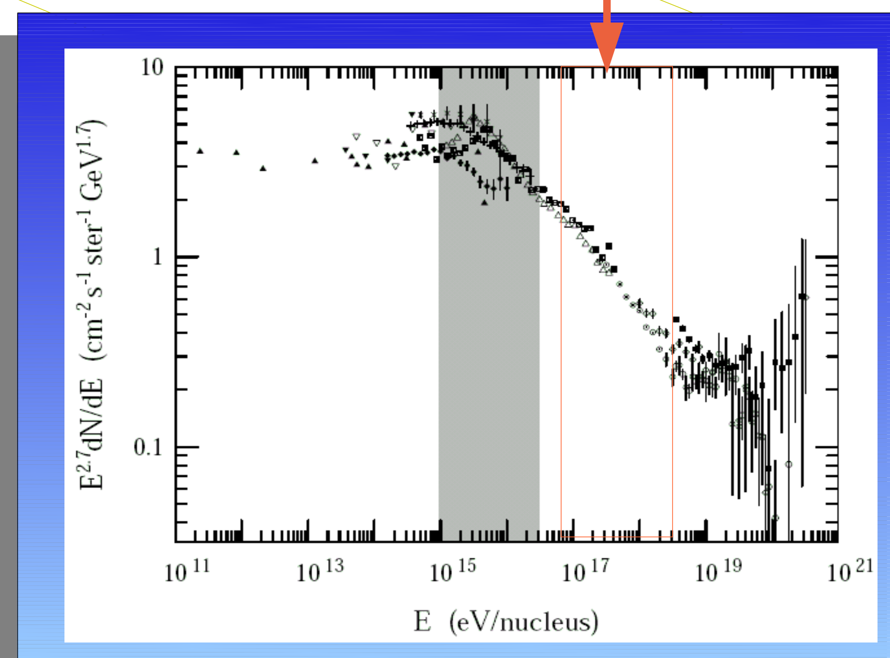
From Galactic to ExtraGalactic CRs



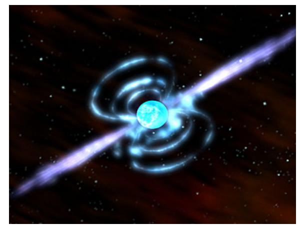
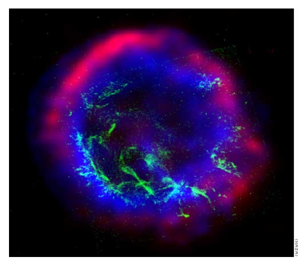
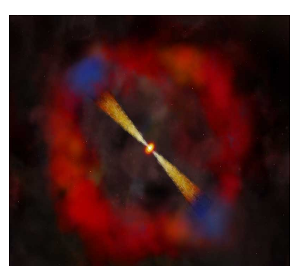
Incredible energy extension: up to $3\text{x}10^{20}$ eV !!!

Particles with a Larmor radius greater that the typical dimension of the Galaxy cannot be confined. Their origin has to be extragalactic.

Somewhere between 10^8 GeV and 10^{10} GeV the transition from Galactic to Extragalactic occurs



Possible candidates for CRs

Astrophysical sources		E_{max}	Type of shock
Galactic: NSs		$10^{15}\,eV$ $(Crab\ Pulsar)$	**Relativistic**
Galactic: SNRs		$Z\times10^{15}\,eV$	**Non-relativistic**
Extra Galactic: AGNs		$10^{16}\div10^{19}\,eV$	**Relativistic and non-relativistic**
Extra Galactic: GRBs		$10^{19}\div10^{23}\,eV$	**Relativistic**

Supernova remnant paradigm for the origin of Galactic CRs

Galactic CRs ($E < 10^{17}$-10^{18} eV) are believed to be produced by SNRs:

1 – Power needed to supply observed CRs

$$W_{CR} = U_{CR} Vol_{CR} / \tau_{res} \approx 10^{40}\, erg/s$$
$$W_{SN} = R_{SN} \; E_{SN} \approx 3 \cdot 10^{41}\, erg/s \quad \Rightarrow \quad \frac{W_{CR}}{W_{SN}} \approx 0.03 \div 0.3$$

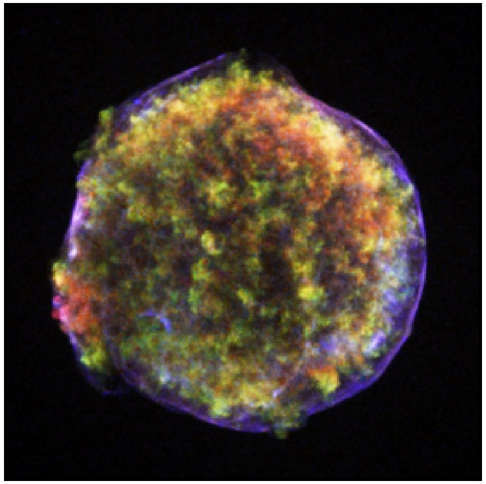
2) Spectrum shape from *linear theory*
(i.e. *test-particle approach*)

$$N(E) \propto E^{-2.7} \quad \textit{observed spectrum for } E < E_{knee}$$

$$N(E) \propto Q_{inj}(E)\, \tau_{esc}(E)$$
$$\tau_{esc}(E) \propto E^{-0.3} \quad \Rightarrow \quad Q_{inj}(E) \propto E^{-2.1}$$

3) SNRs are sources of non-thermal radiation
→ presence of non-thermal particle population

SNR shock (Tycho)



HOW DO SHOCKS ACCELERATE PARTICLES?

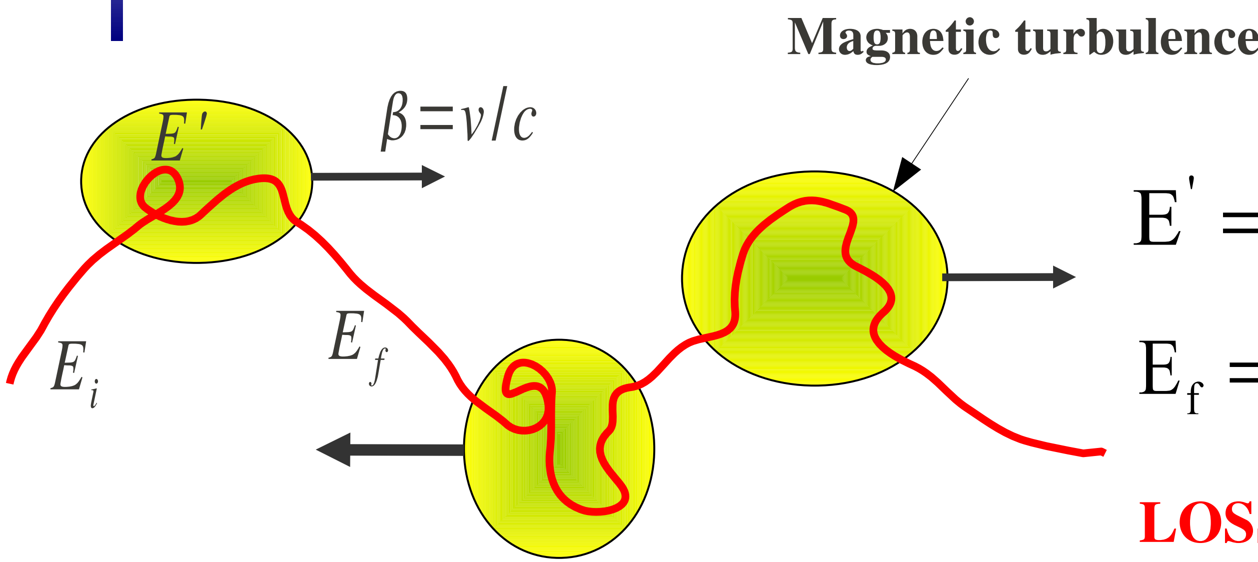
Basic concepts

- ➔ ALL ACCELERATION MECHANISMS ARE ELECTROMAGNETIC IN NATURE
- ➔ MAGNETIC FIELDS DO NOT MAKE WORK ON CHARGED PARTICLES!
- ➔ WE NEED ELECTRIC FIELDS
- ➔ BUT FOR THE MAJORITY OF ASTROPHYSICAL ENVIRONMENT THE CONDUCTIVITY $\rightarrow\infty$, HENCE $\langle E \rangle = 0$
- ➔ THE MAJORITY OF ACCELERATION PROCESS ARE STOCHASTIC

STOCHASTIC ACCELERATION

$\langle E \rangle = 0 \qquad \langle E^2 \rangle \neq 0$

A quick look to 2nd order Fermi acceleration (Fermi, 1949)



$$E' = \gamma E_i (1 - \beta\mu)$$

$$E_f = \gamma^2 E_i (1 - \beta\mu)(1 + \beta\mu')$$

LOSSES AND GAINS ARE PRESENT BUT DO NOT COMPENSATE EXACTLY

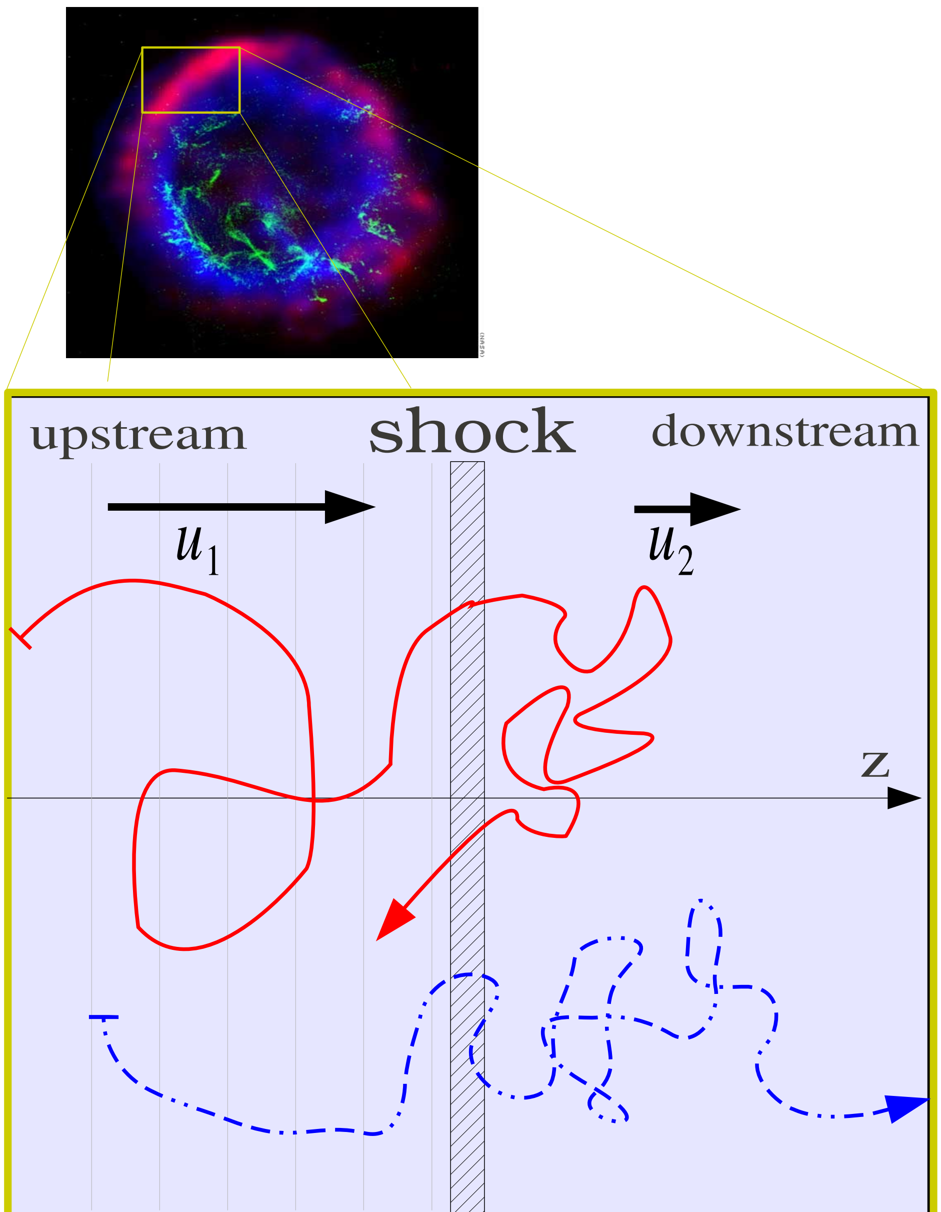
$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu'} = 2[\gamma^2 (1 - \beta\mu) - 1]$$

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\mu} = \int_{-1}^{1} d\mu \, \frac{1}{2}(1 - \beta\mu) \, 2\left(\gamma^2 (1 - \beta\mu) - 1\right) \propto \beta^2$$

PROBABILITY OF ENCOUNTER

Very low energy gain to account for observed non thermal particle energy

Fermi mechanism applied to shock: test particle approach



MICROSCOPIC APPROACH

Assuming isotropic distribution in all reference frames:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\,\frac{u_1 - u_2}{c}; \quad P_{esc} = 4\,\frac{u_1}{c};$$

Stochastic acceleration:

$$n(E) = \frac{dN}{dE} \propto E^{-\alpha};$$

$$\alpha = 1 - \frac{\ln P_{ret}}{\ln \Delta E / E} \approx 1 + \frac{P_{esc}}{\Delta E / E} = \frac{r+1}{r-1}$$

For strong shocks and mono-atomic gas:

$$r \equiv \frac{u_1}{u_2} \rightarrow 4$$

$$n(E) = E^{-2} \sim n(p) = p^{-4}$$

Problems with linear theory

1 - Observation: CRs power is non negligible fraction of SNR explosion energy

$$W_{CR} \sim U_{CR} Vol_{CR} / \tau_{res} \approx 10^{40}\, erg/sec$$
$$W_{SN} \sim R_{SN}\ E_{SN} \approx 3\,10^{41}\, erg/sec \ \ with \ \ R_{SN} = 0.03$$
$$\Rightarrow \quad \frac{W_{CR}}{W_{SN}} \approx 0.03 \div 0.3$$

Lower Limit!! (Average value)
Instantaneous power can be greater

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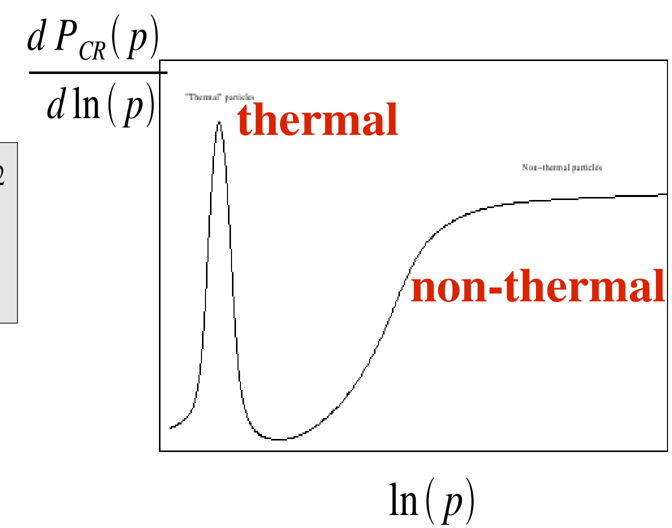
Lower Limit!! (Average value) Instantaneous power can be greater

2 – Theory: CRs pressure can be > thermal pressure

$$P_{CR} \propto \int d\ln(p)\ v(p)\, p^4 f_{CR}(p) \quad \Rightarrow \quad \frac{P_{CR}}{P_{gas}} \approx 2.3\ \xi \left(\frac{\eta}{10^{-5}}\right) \ln\left(\frac{p_{max}}{10^5\, GeV/c}\right) \left(\frac{T}{10^5\, K}\right)^{-1/2}$$



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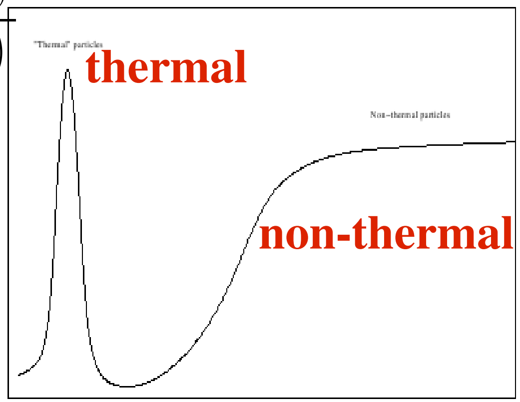
$\frac{d P_{CR}(p)}{d\ln(p)}$



$\ln(p)$

3 – Theory: Maximum CR energy

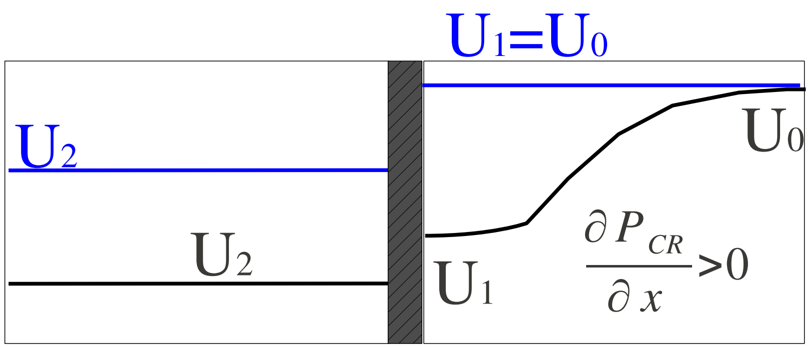
Linear theory (with self generated magnetic turbulence) predict for protons

$$\delta B < B_{Gal} \quad \Rightarrow \quad E_{max} \le 10^4\, GeV$$

BUT

$$E_{knee} \simeq 3 \cdot 10^5\, GeV$$

Including the CR Back-Reaction



velocity profile u(x)

What happen when non-thermal particles exert non negligible pressure?

1 – CRs pressure compresses the gas upstream

➔ **The subshock compression factor decreases**

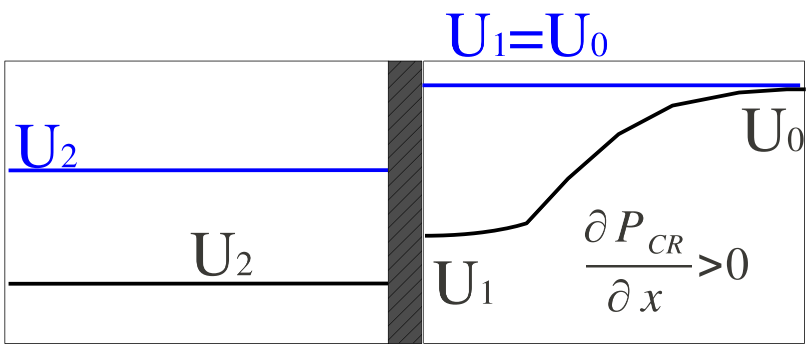
$$r_{sub} = \frac{U_1}{U_2} < 4$$

2 – CRs subtract energy from the downstream plasma which becomes more compressible

➔ **The total compression factor increases**

$$r_{tot} = \frac{U_0}{U_2} > 4$$

Including the CR Back-Reaction



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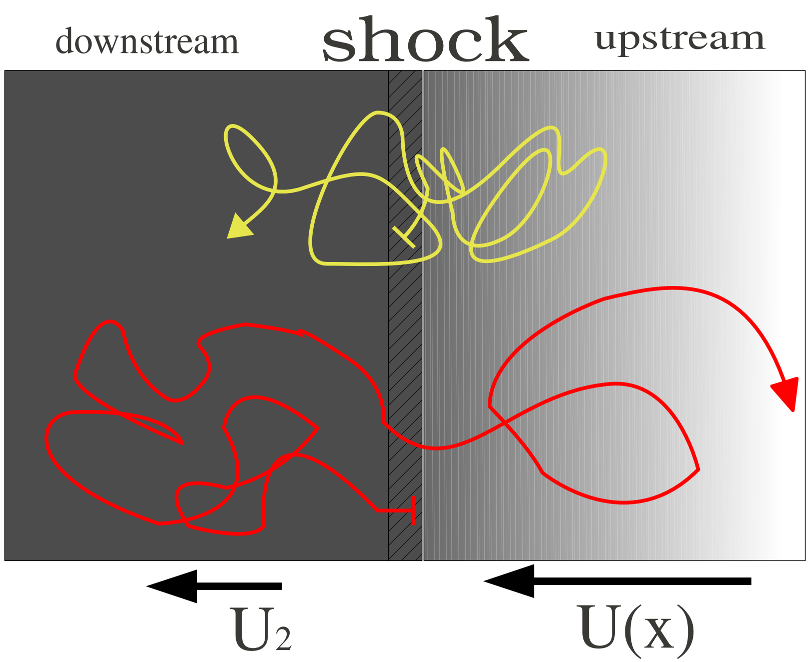

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Particles feel a different compression factor depending on their momentum

$$r(p) = \frac{\bar{U}(p)}{U_2}$$

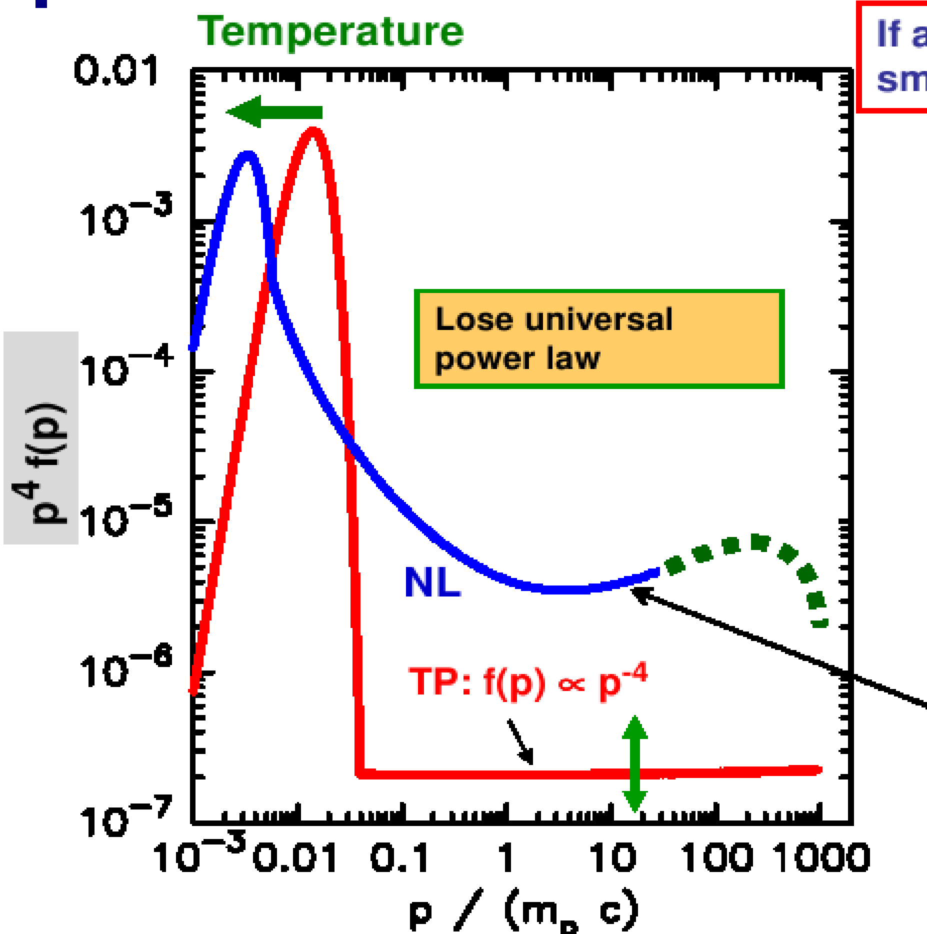
↓

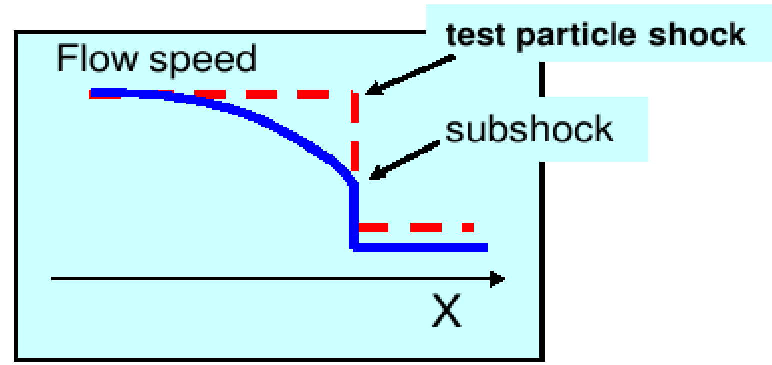
We expect a momentum dependent slope

$$n(E) = E^{-s(p)}$$

Including the CR Back-Reaction

If acceleration is efficient, shock becomes smooth from backpressure of CRs





- Concave spectrum
- Compression ratio, $r_{tot} > 4$
- Low shocked temp. $r_{sub} < 4$

In efficient acceleration, <u>entire spectrum</u> must be described consistently, including escaping particles

➔ much harder mathematically

BUT, connects photon emission across spectrum from radio to γ-rays

Magnetic field amplification

In order to be isotropized upstream of the shock, CRs need to transfer momentum to the plasma via magnetic field.

Assume particles are drifting with velocity $V_D > V_A$

Initial momentum → **final momentum**

$$n_{CR}\, m\, \Gamma_{CR}\, v_D \rightarrow n_{CR}\, m\, \Gamma_{CR}\, v_A$$

$$\frac{dP_{CR}}{dt} = \frac{n_{CR}\, m\, \Gamma_{CR}\, (v_D - v_A)}{\tau}$$

$$\frac{dP_W}{dt} = \gamma_W \frac{\delta B^2}{8\pi} \frac{1}{v_A}$$

Growth rate

$$\rightarrow \gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A} \right) = 10^{-3} \text{ yr}^{-1}$$

$$\left(\frac{\delta B}{B_0} \right)^2 \simeq 2 M_A \frac{P_{CR}}{\rho_0 u_0^2}$$

Saturation level of magnetic turbulence (*in linear theory*)

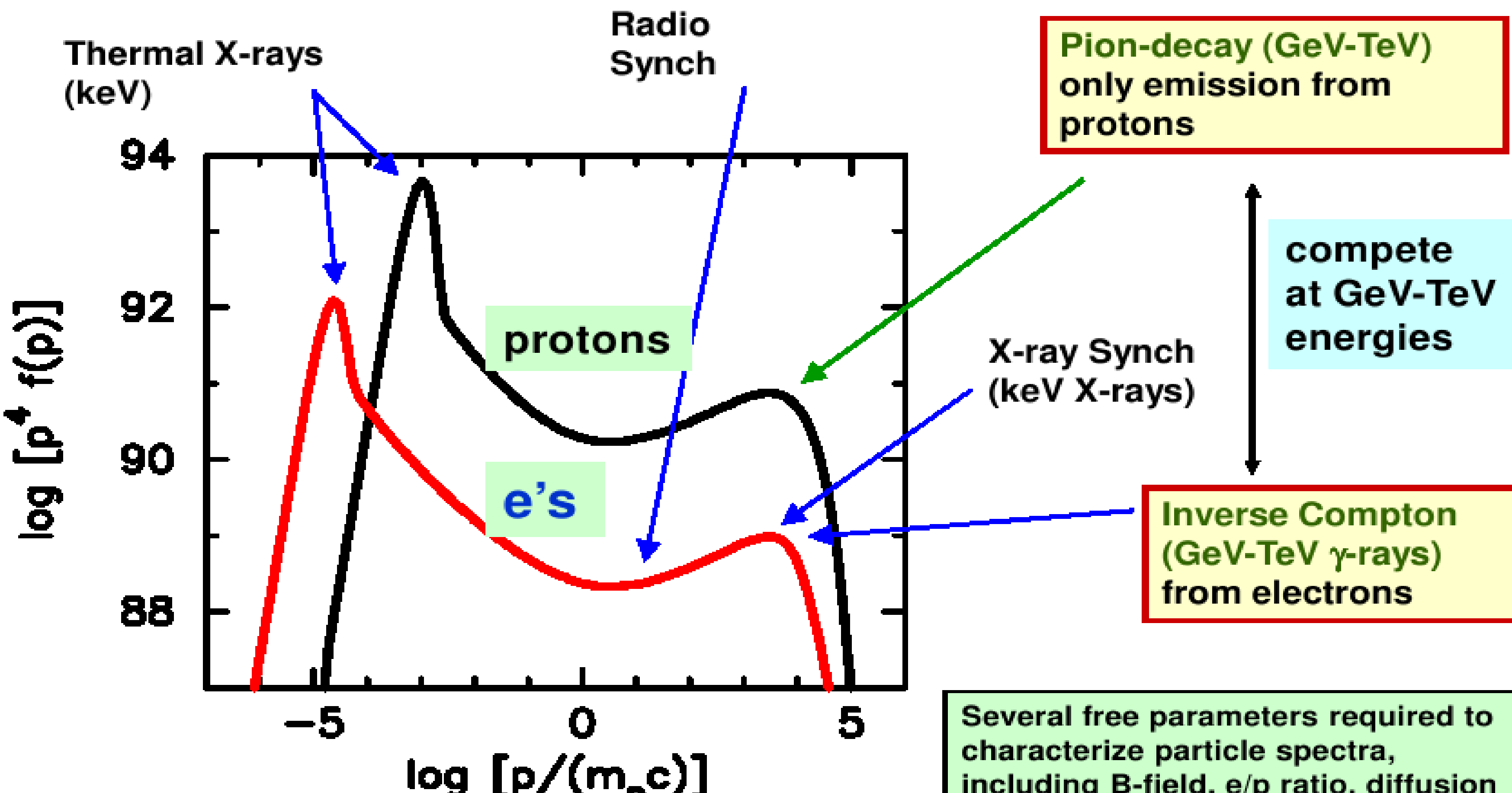
IF $P_{CR} \approx \rho_0 u_0^2$ **THE MAGNETIC FIELD CAN GROWTH UP TO** $\delta B \gg B_0$

Starting with B_{ISM} ~ 1-10 μG we end up with B ~ 100-500 μG at the shock

PARTICLE ACCELERATION AT SNRs

EM radiation from accelerated particles

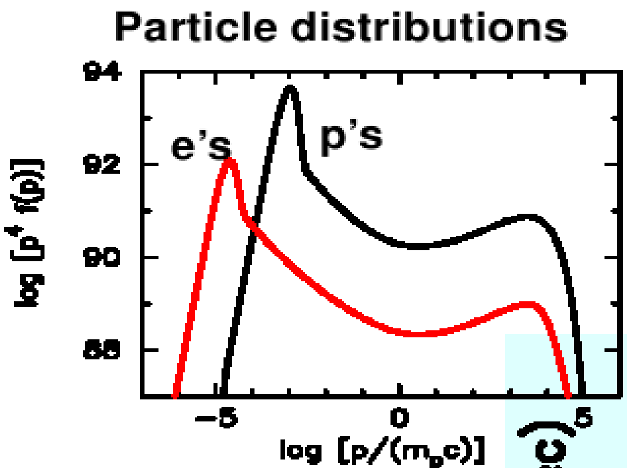
Electron and Proton distributions from efficient (nonlinear) diffusive shock acceleration



Spectra calculated with semi-analytic model of Blasi, Gabici & Vannoni 2005

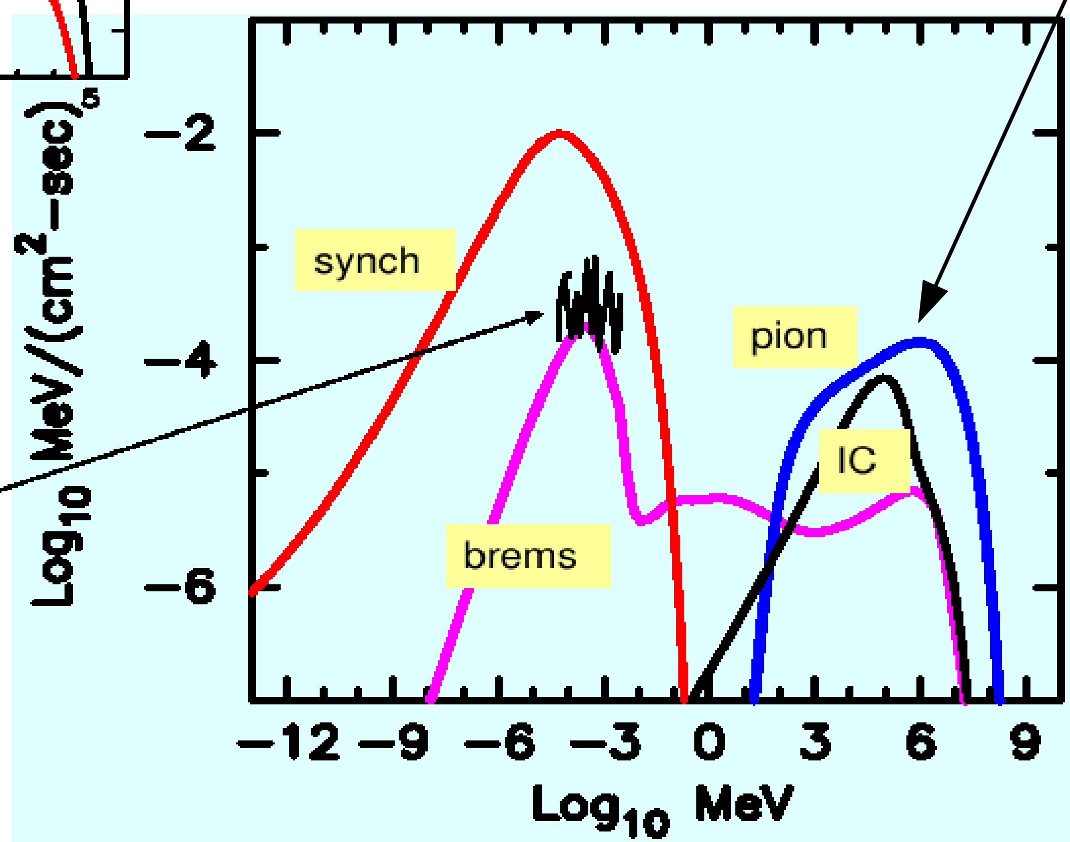
Several free parameters required to characterize particle spectra, including B-field, e/p ratio, diffusion coefficient

EM radiation from accelerated particles



continuum emission

Pion decay and IC are competitive mechanisms



In addition, emission lines in thermal X-rays

SNRs in TeV from Cherenkov telescope

- A possible way to test the presence of CR is to look for pion decay in TeV band

$$p\,p \rightarrow \pi^0 \rightarrow \gamma\gamma$$

- Many SNRs has been detected in TeV band by Cherenkov telescope

- All show correlation with non-thermal X-ray

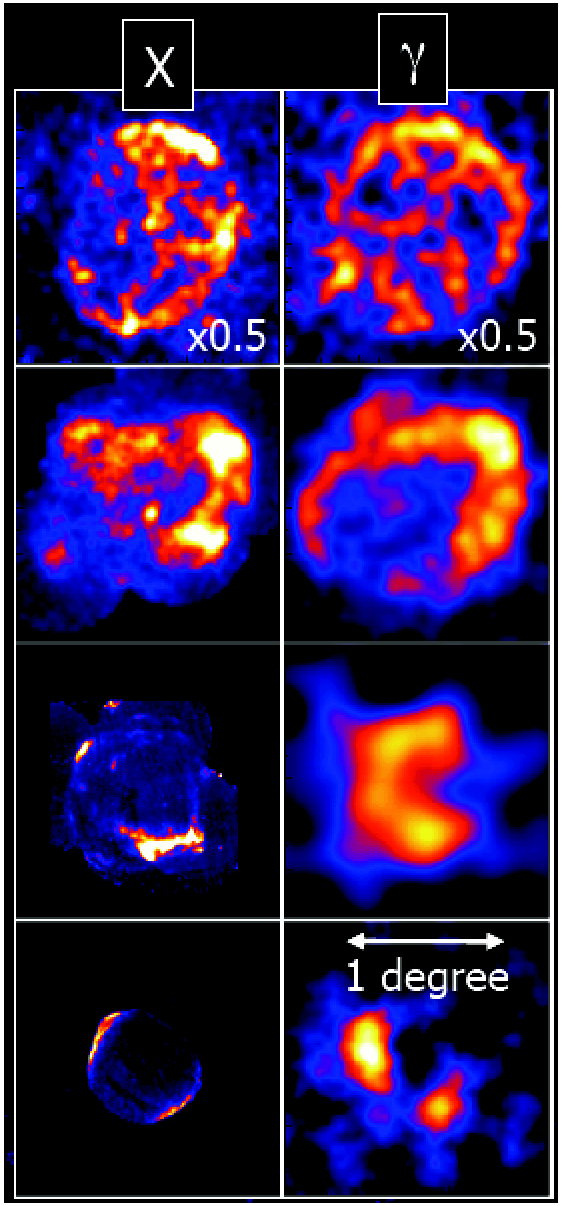
- It is difficult to discriminate between "hadronic" and "leptonic" origin of TeV emission (i.e. inverse Compton scattering or electron bremsstrahlung)

Vela Junior

RX J1713

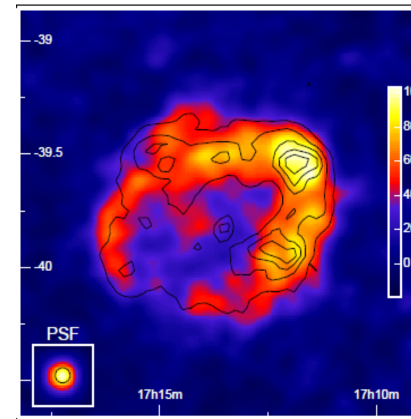
RCW 86

SN 1006



Observations in GeV band

Detection in GeV band by satellite experiments (FermiLAT, AGILE) are extremely useful to discriminate between leptonic and hadronic

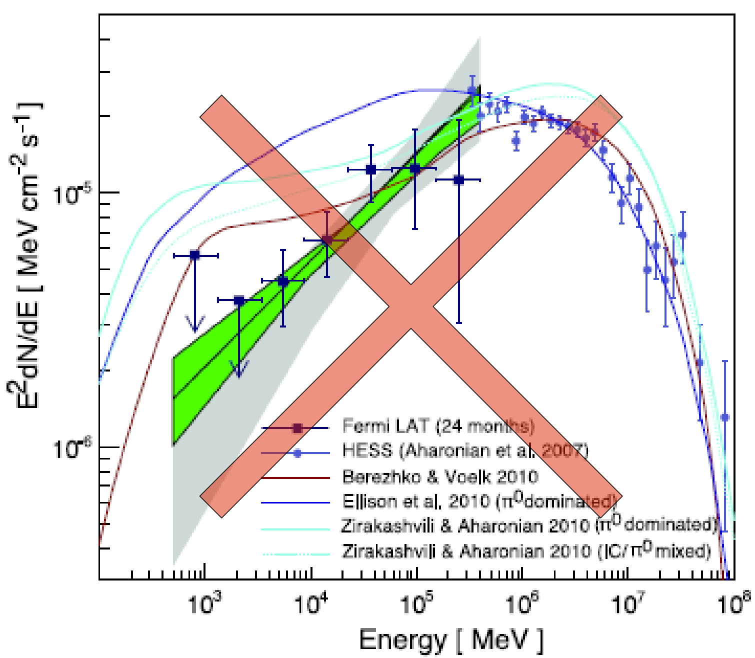


RX J1713.7-3946 detected by HESS

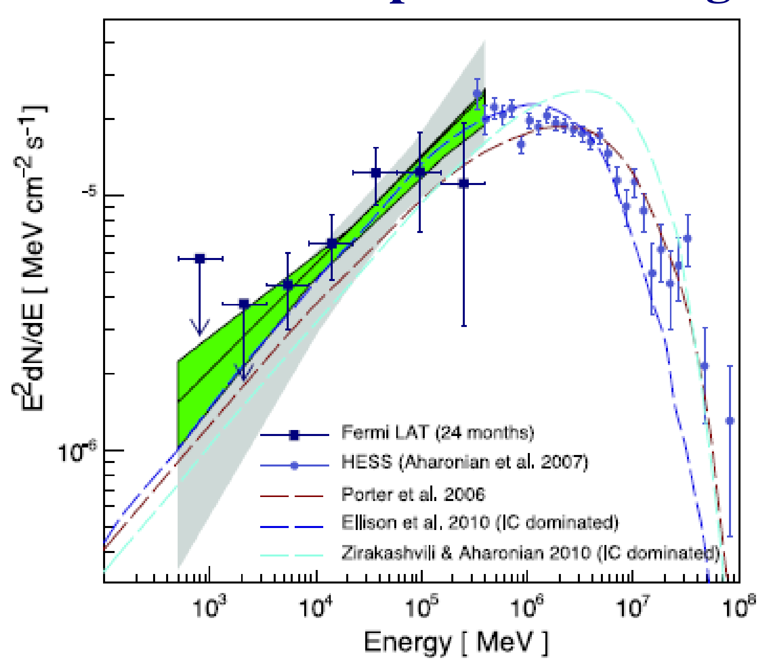
The remnant **RX J1713.7-3946** has been considered the most promising candidate to prove the existence of accelerated hadrons

FermiLAT revealed a probable leptonic origin

Hadronic model: $\pi^0 \rightarrow \gamma\gamma$



Leptonic model: inverse Compton scattering

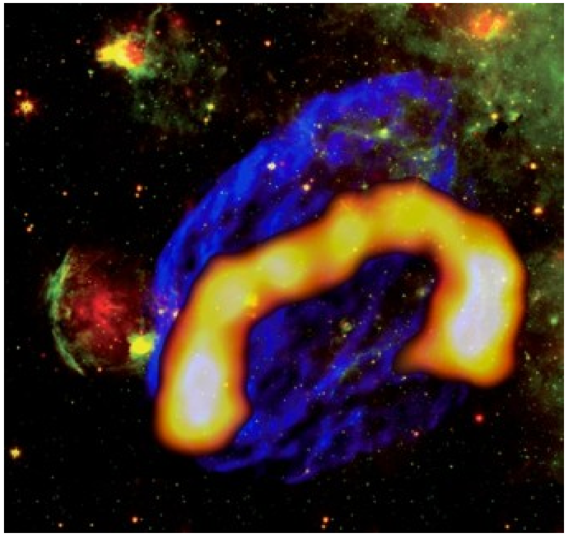


Observations in GeV band

Recently the AGILE collaboration detected the unequivocal signature of hadron acceleration in SNR W44:

low energy cut-off in gamma-ray emission at ~ 1 GeV

→ typical signature of π^0 decay



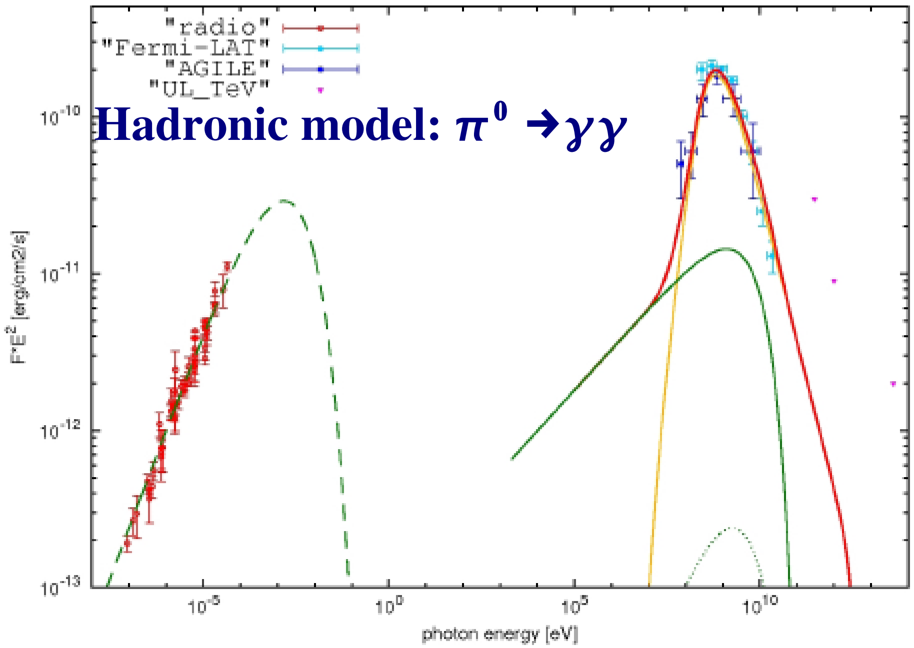
W44 seen by AGILE [Giuliani et al. 2011]

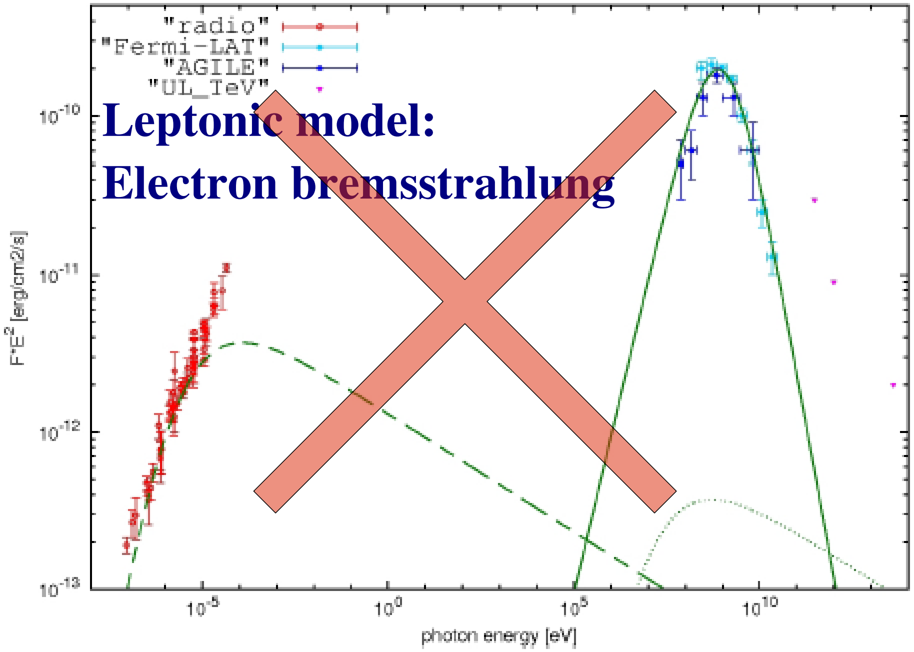
BUT

1) Spectrum $N(E) \sim E^{-3}$

2) Maximum energy of proton ~ 6 GeV(SNR age ~20,000 yr)

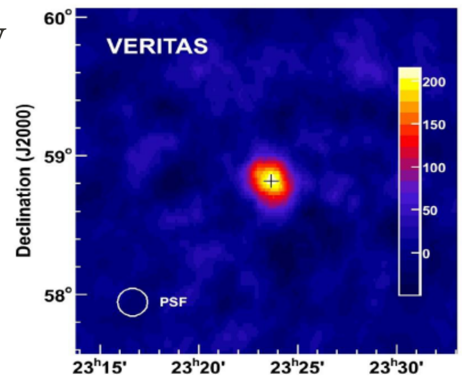
→ Cannot explain observed CRs at Earth



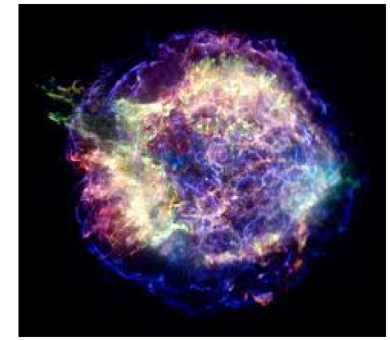


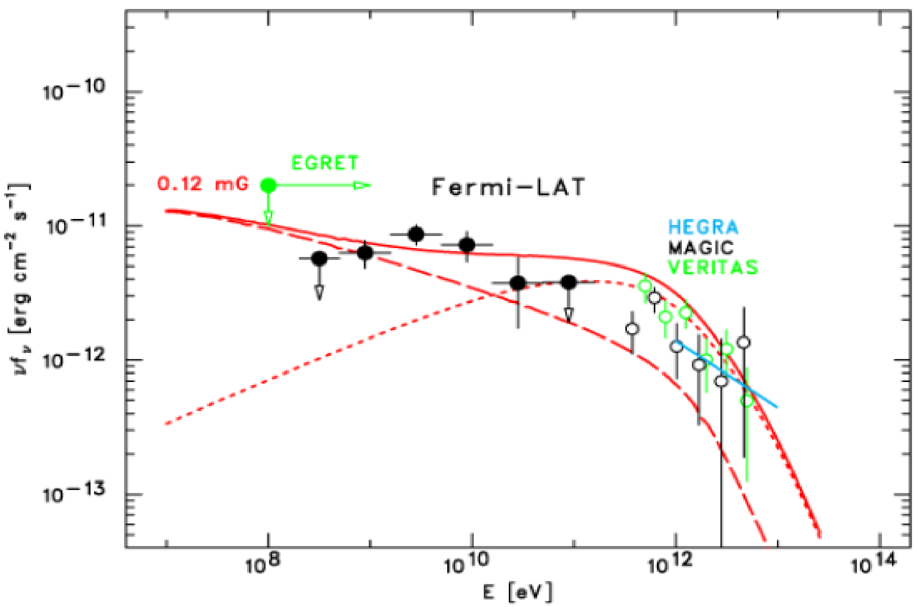
Gamma-ray detection: the case of Cas A

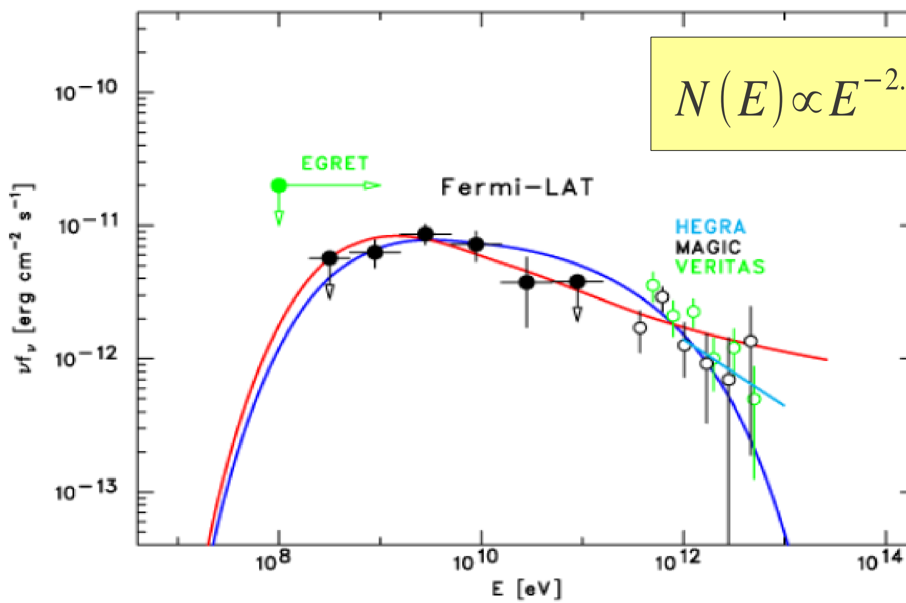
Cas A in TeV
(*VERITAS*)



Cas A in X-rays
(*Chandra*)







$$N(E) \propto E^{-2.3}$$

Leptonic Model
B=120μG, PL (-2.34) + cutoff @ 40 TeV
Dashed Line – Bremsstrahlung
Dotted Line – IC (dominated by FIR)

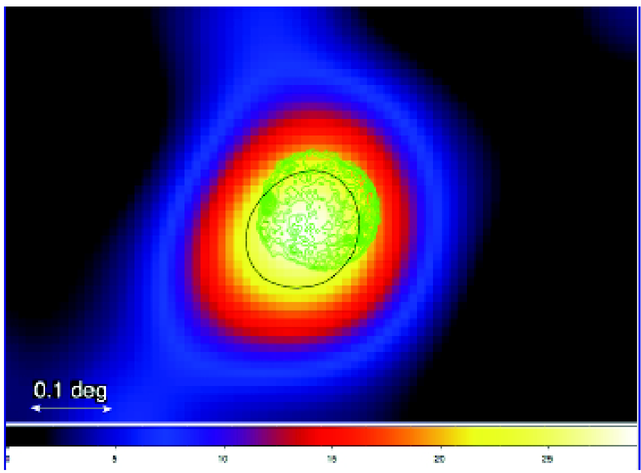
Hadronic Models
Blue: PL (-2.1) + cutoff @ 10 TeV
Red: PL (-2.3)

Hadronic model is favored, but leptons not ruled out

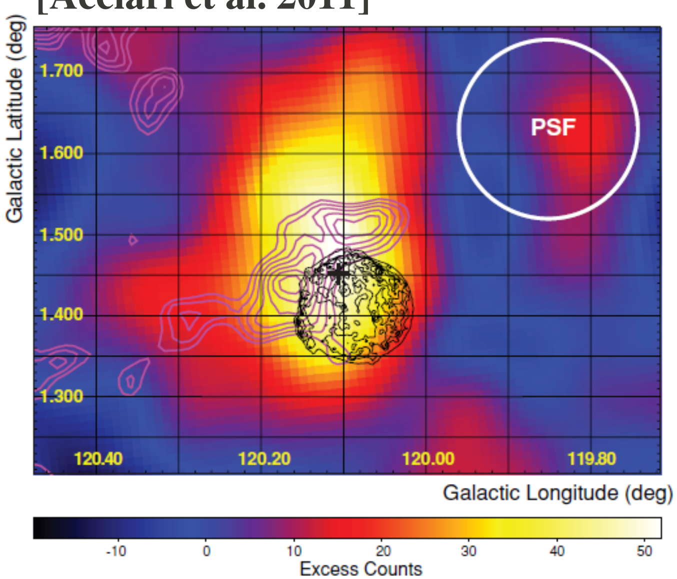
Abdo et al. ApJL 710 (2010)

Gamma-ray detection: the Tycho's remnant

Fermi TS map 1-100 GeV
[Giordano's talk]

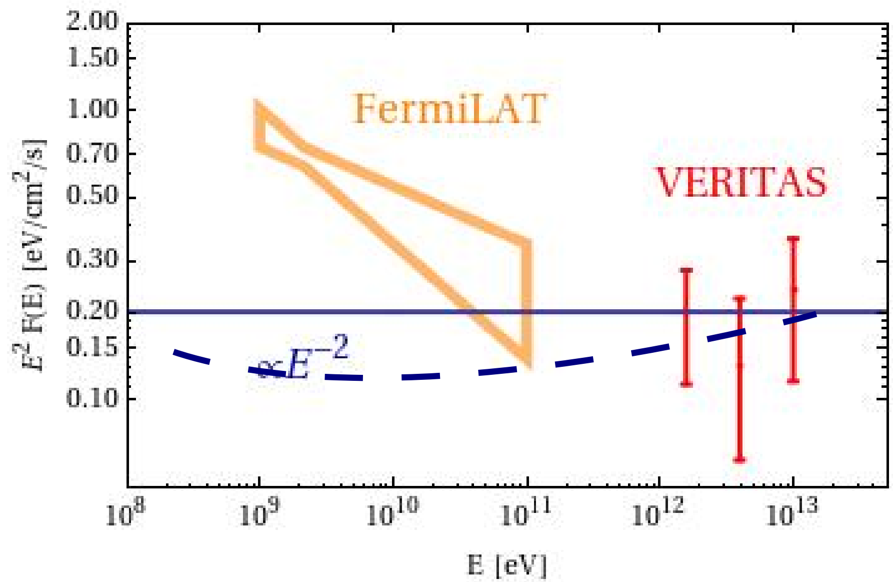


VERITAS map $E > 1$ TeV
[Acciari et al. 2011]



Measured spectral slope in gamma-rays:

FermiLAT $\Gamma = 2.3 \pm 0.1$ [Giodano et al. 2011]
VERITAS $\Gamma = 1.95 \pm 0.51_{stat} \pm 0.30_{sys}$ [Acciari et al. 2011]



Linear theory → $f_p(E) \propto E^{-2} \Rightarrow F(\pi_0 \rightarrow \gamma\gamma) \propto E^{-2}$

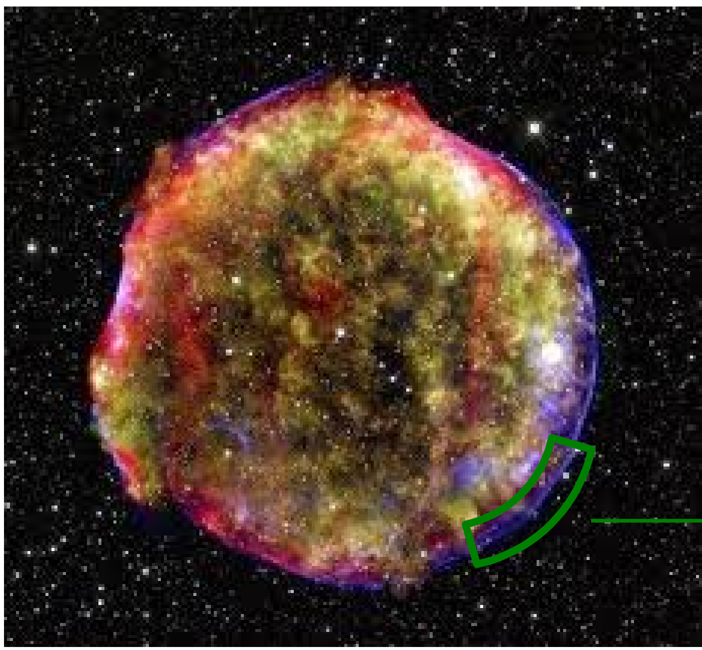
Non-linear theory → $f_p(E) \propto E^{-\Gamma}, \quad \Gamma > 2$

Is it possible to build a model able to explain the γ-ray spectrum and contemporary all the other spectral and morphological properties?

X-ray observations: evidences for magnetic field amplification

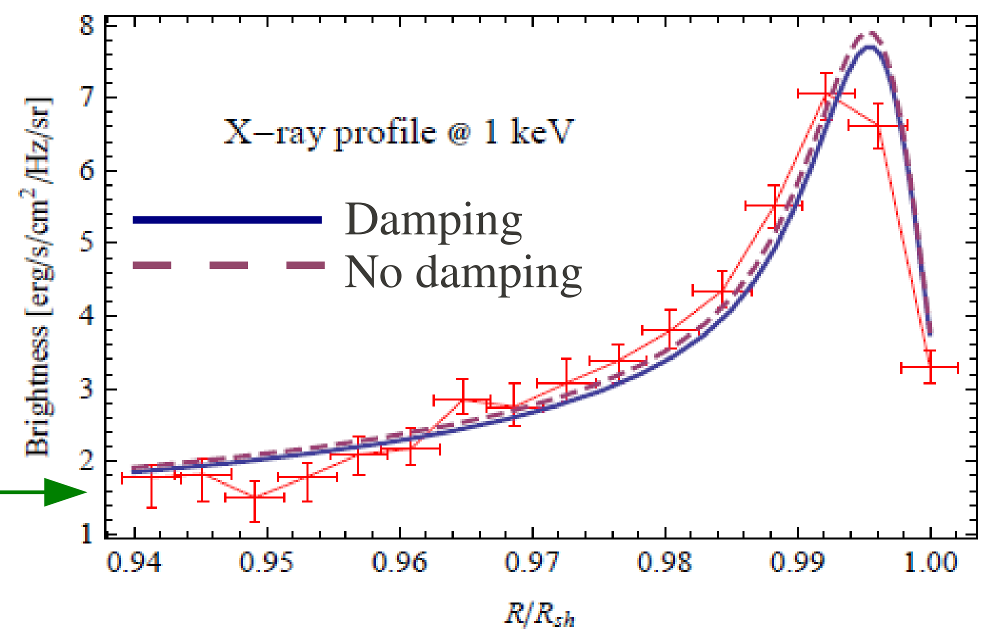
Thin non-thermal X-ray filaments

If due to electron synchrotron losses → evidence for magnetic field amplification (B~200-300 μG)



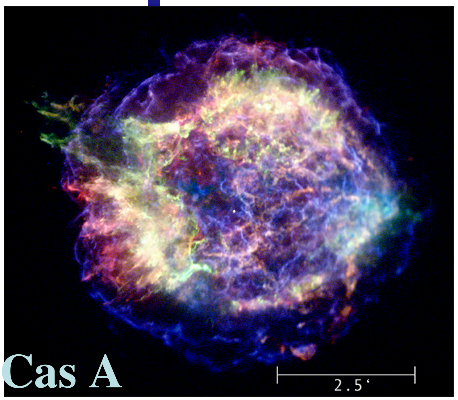
Chandra X-ray map.
Data for the green sector are from Cassam-Chenaï et al (2007)

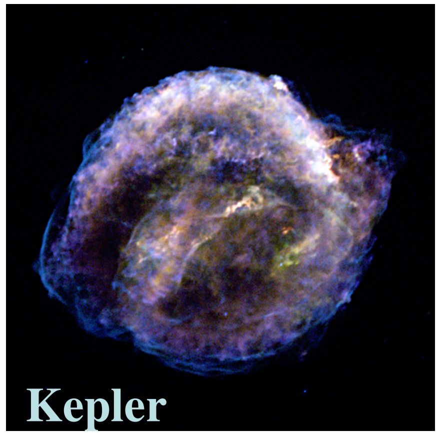
[Hwang el al(2002); Bamba et al (2005)]

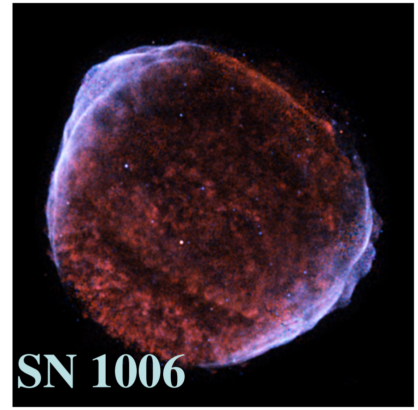


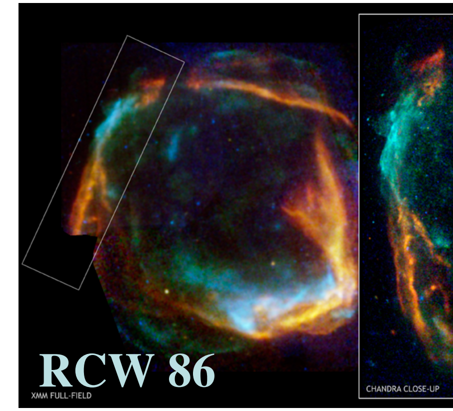
$$B \gg B_{ISM} \approx 3\,\mu G$$

Evidence for magnetic field amplification









SNR	B_{ds} (μG)	$P_{w,ds}$(%)
Cas A	250-390	3.2-3.6
Kepler	210-340	2.3-2.5
Tycho	240-530	1.8-3.1
SN1006	90-110	4.0-4.2
RCW 86	75-145	1.5-3.8

Inferred B fields assuming that the thickness of X-ray rims are determined by electron synchrotron losses and using the information from the X-ray frequencies.

Magnetic field strength could be over estimated if the thickness of X-ray filaments is due to magnetic damping rather than by sever electron losses

The role of scattering centers in presence of strong magnetic amplification

CRs are scattered by magnetic turbulence (Alfvén waves), whose typical speed is

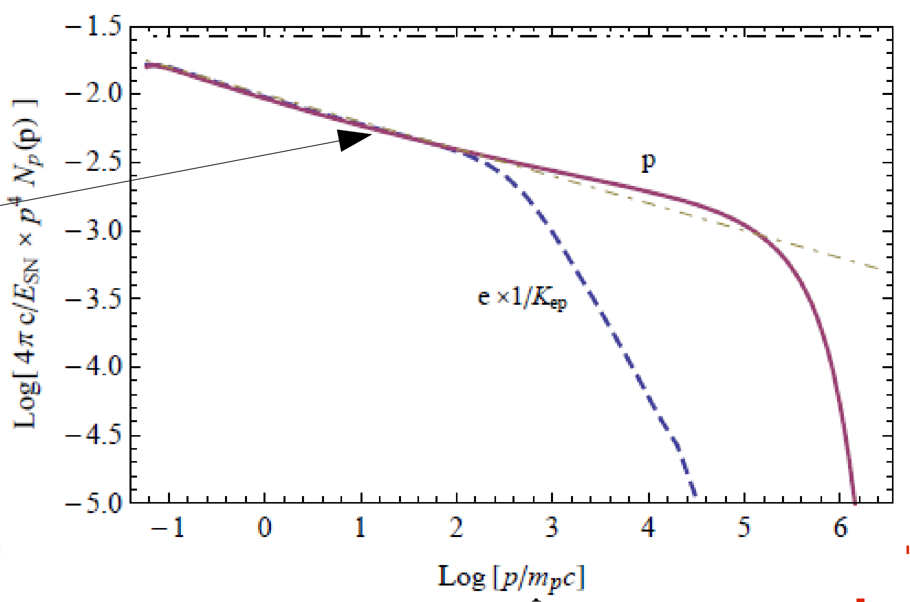
$$v_A = \frac{B_{ISM}}{\sqrt{4\pi\rho}} \approx 20\, km/s \ll V_{shock}$$

When the magnetic field is strongly amplified the Alfvén speed upstream can become a non negligible fraction of the shock speed. In this case the effective compression ratio is:

$$r = \frac{u_1 - v_{A,1}}{u_2 \pm v_{A,2}} \simeq \frac{u_1 - v_{A,1}}{u_2} < 4$$

Downstream $v_{A,2} \approx 0$ because of helicity mixing.
In the case of Tycho:

$$v_{A,1} = \frac{B_1}{\sqrt{4\pi\rho_1}} \approx 0.15 V_{sh} \rightarrow s = \frac{r+2}{r-1} \simeq 4.2 \quad \text{(2.2 in energy)}$$



1) Modelling the multi-wavelength spectrum of single SNR

[G.M. & D. Caprioli, 2011

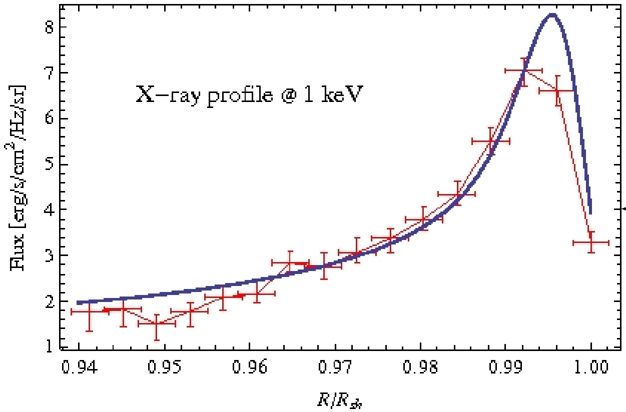
Simultaneous fit of multi-wavelength spectrum with non-linear DSA model

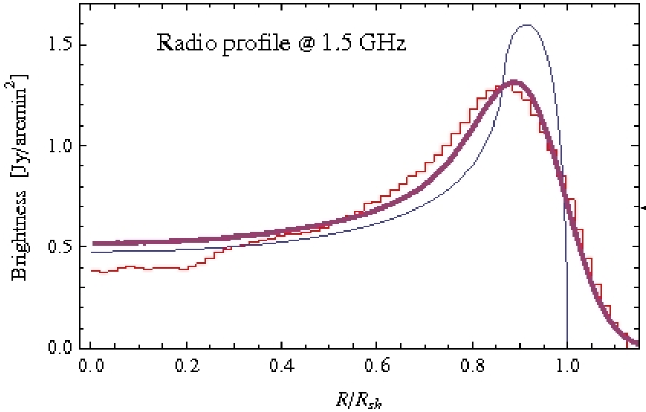
1) Maximum energy of ions $E_{max} = 470\, TeV$

2) Non-thermal spectrum $N(E) \propto E^{-2.3}$

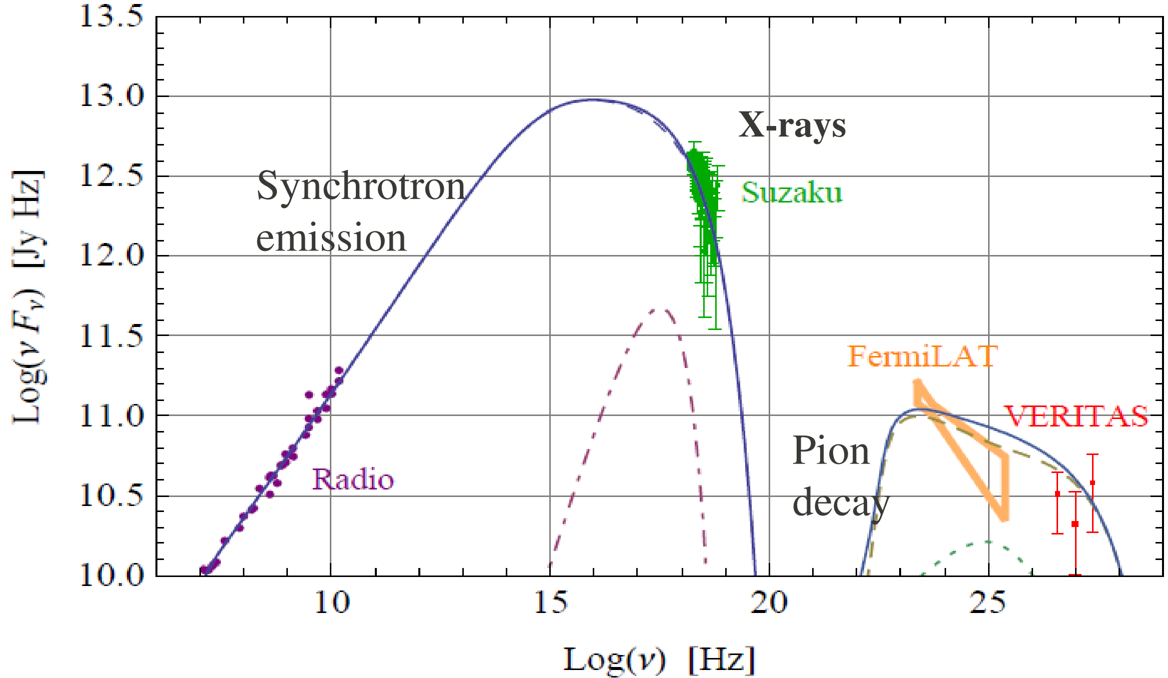
3) Amplified magnetic field $\delta B_2 \approx 300\, \mu G$

4) TOTAL CRs ENERGY $\epsilon_{CR} = 12\%\, E_{SN}$





Results for the Tycho's remnant



ARE SNR SHOCKS REALLY COLLISIONLESS?

Shocks in Partially Neutral Plasma

Theory of shock acceleration is usually developed in <u>totally ionized plasma</u>

Shock thickness

$$\lambda \approx \xi r_{L,th} \approx 10^{10} \left(\frac{B}{\mu G} \right) \left(\frac{T}{10^8 K} \right)^{1/2} cm \ll \lambda_{coll}$$

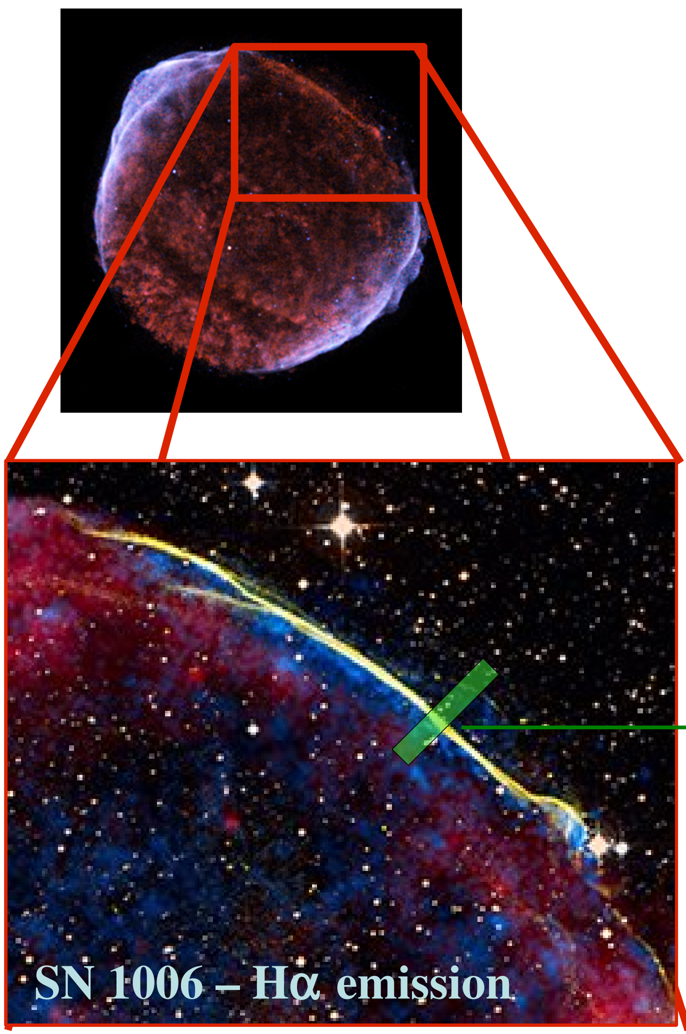
- Good approximation for Type II SNR which expand in the pre-stellar wind (T~ 10^5-10^7 K)
  → hydrogen is totally ionized

- Bad approximation for Type I/a SNR which expand in the ISM (T~ 10^4 K)
  → hydrogen is partially ionized
  → even if T < 10^4 K → minimum degree of ionization for young SNR is ~20% due to the ionizing radiation coming from the remnant itself

At zeroth order the neutral component does not feel the electromagnetic shock discontinuity, but...

Balmer-Dominated Shocks

… neutral particles do produce radiation associated with shock transition



Balmer-dominated shocks are observed around young SNR

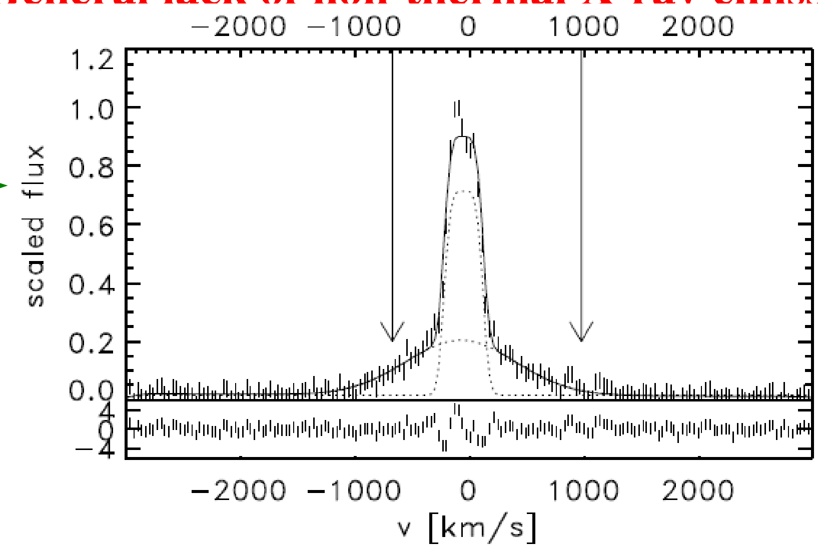
1) Shock speed ~ 200-9000 km/s

2) Typical ISM density ~ 0.1-1 cm^{-3}

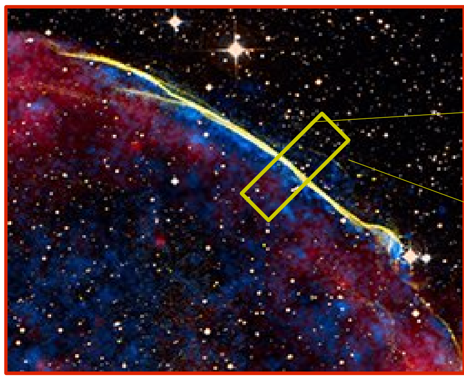
3) Associated with faint optical filaments

4) Presence of strong hydrogen lines with *narrow* (10 km/s) and *broad* (1000 km/s) components

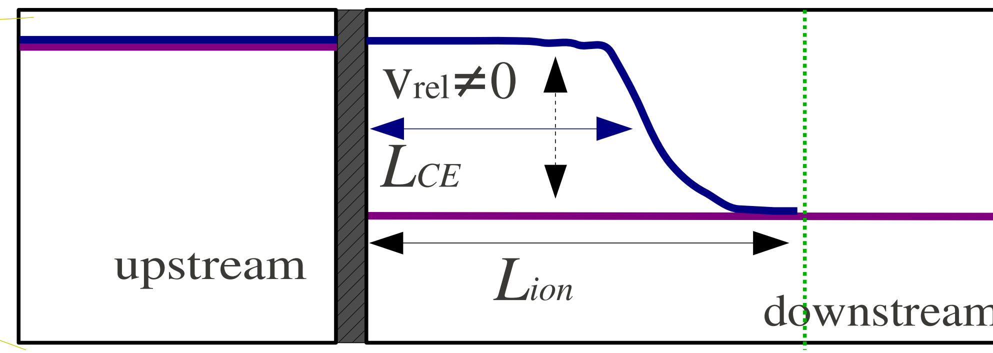
5) General lack of non-thermal X-ray emission



Effects of neutrals: study of Blamer lines

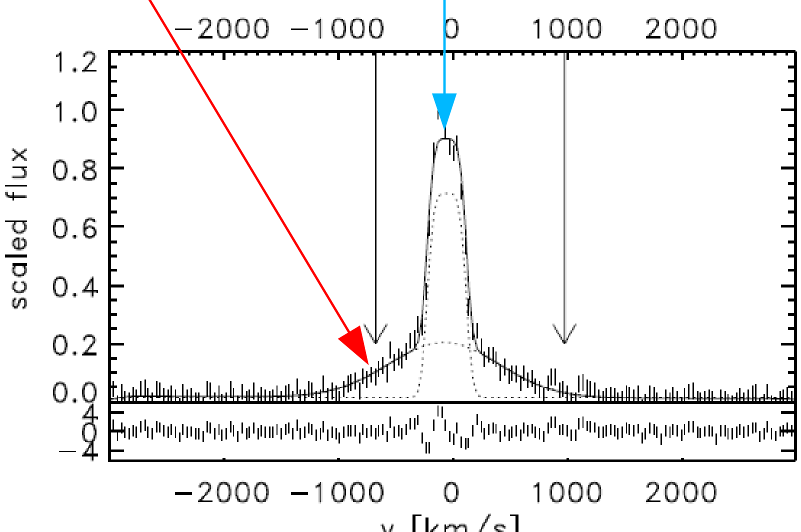


VELOCITY PROFILE

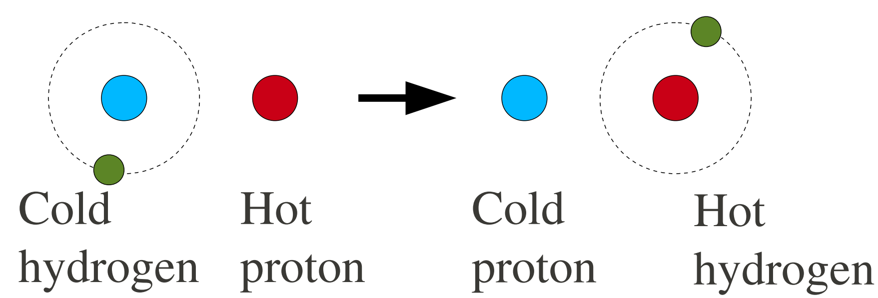


Cold hydrogen produces *narrow* Balmer lines

Hot hydrogen produces *broad* Balmer lines

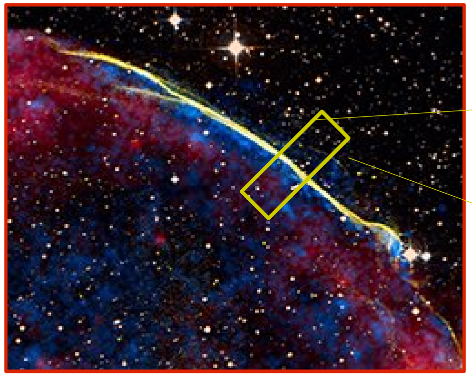


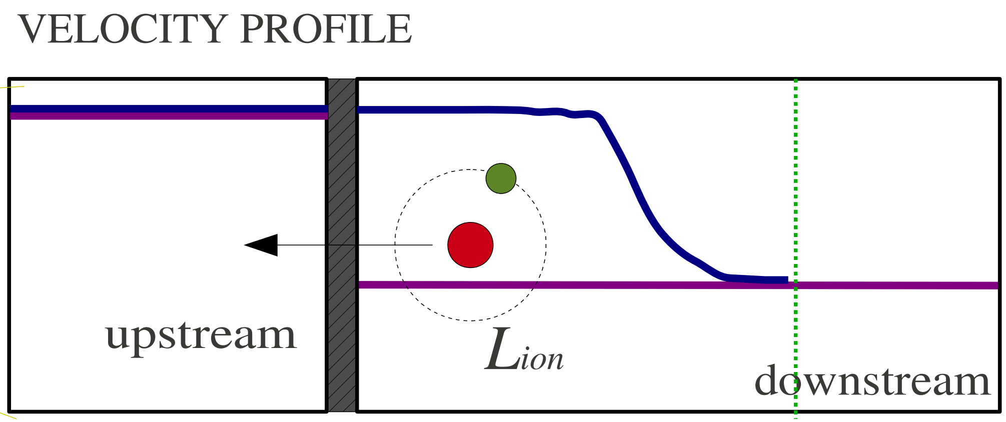
Downstream of the shock cold hydrogen atoms can charge exchange with hot shocked protons, giving rise to a population of hot hydrogen atoms



Shock structure in presence of neutrals

Neutral particles can modify the shock structure





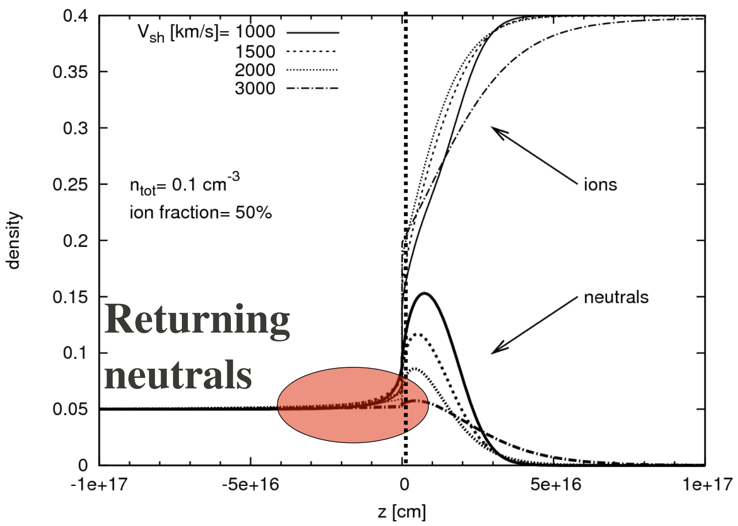
- Hot neutrals produced downstream by charge-exchange can move faster than the shock and escape towards upstream (they do not feel the electromagnetic discontinuity)
- Once upstream neutrals make ionization or charge exchange and deposit momentum and energy
- Even if the number of "escaping neutrals" is small the energy flux can be very large

➔ **The shock's structure changes dramatically**

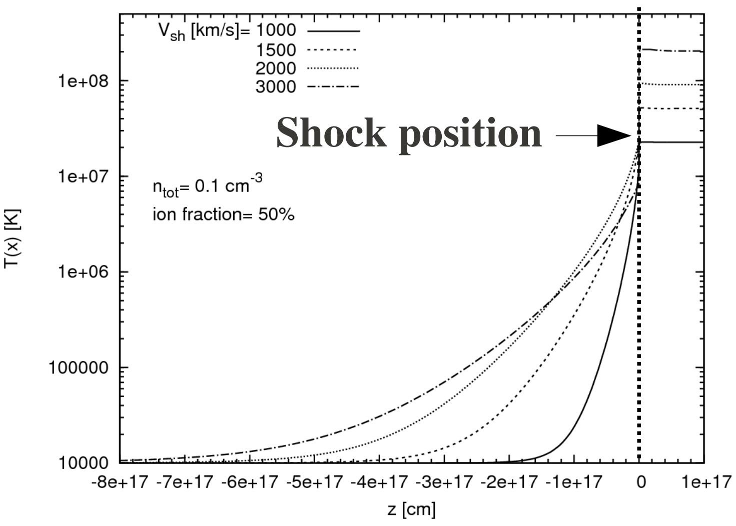
Shock structure in presence of neutrals (preliminary results)

[Blasi, G.M., Bandiera, Amato & Caprioli , submitted 2011]

Density of neutrals and ions



Ions' temperature



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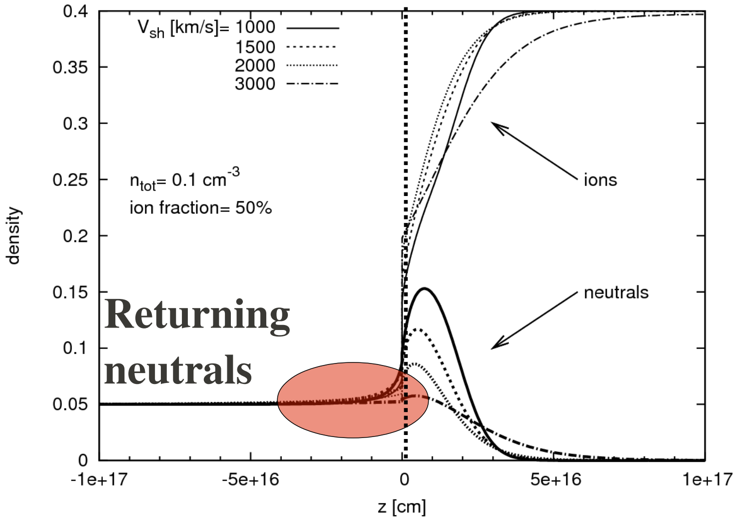

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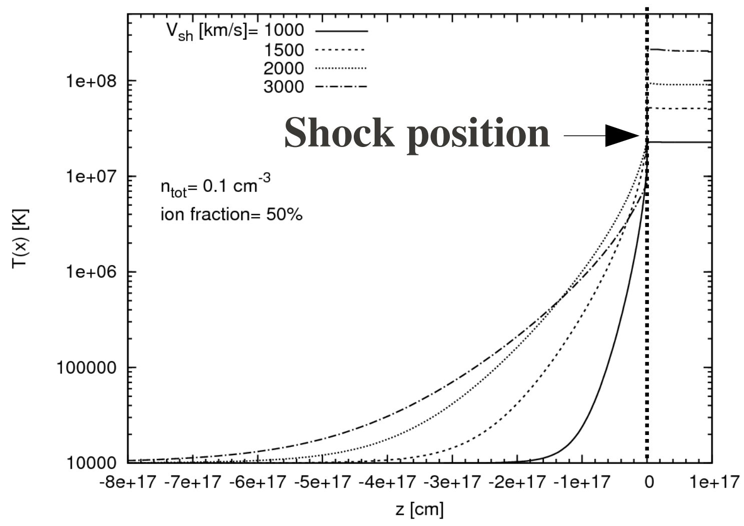
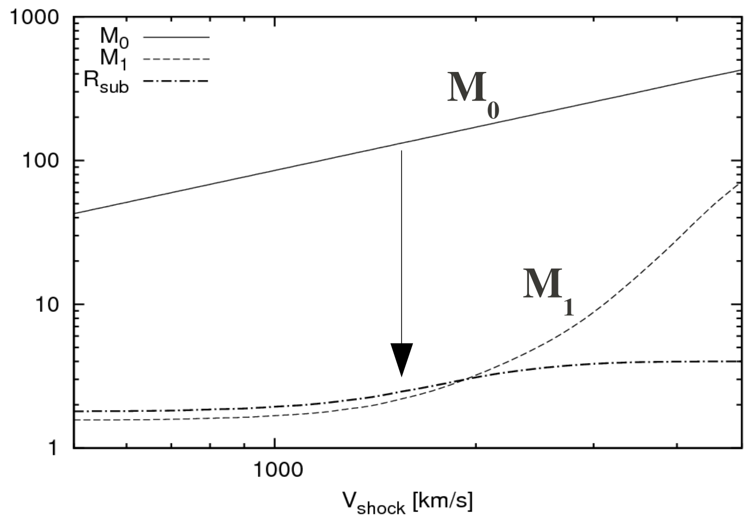
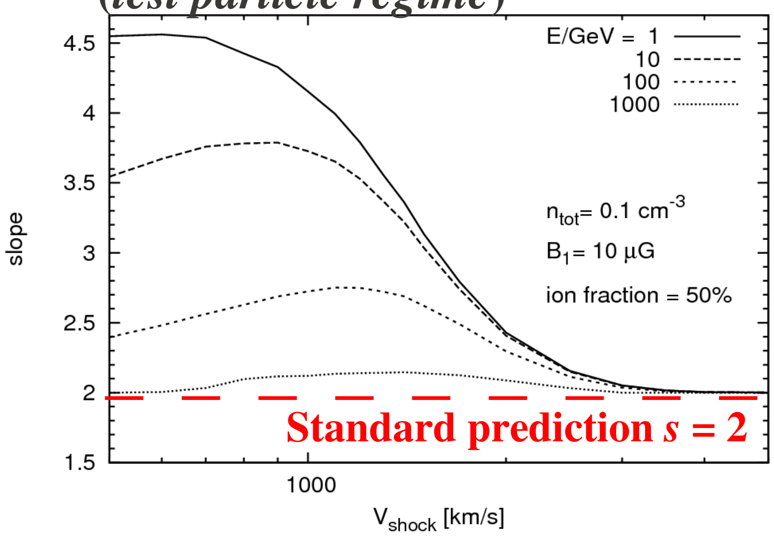


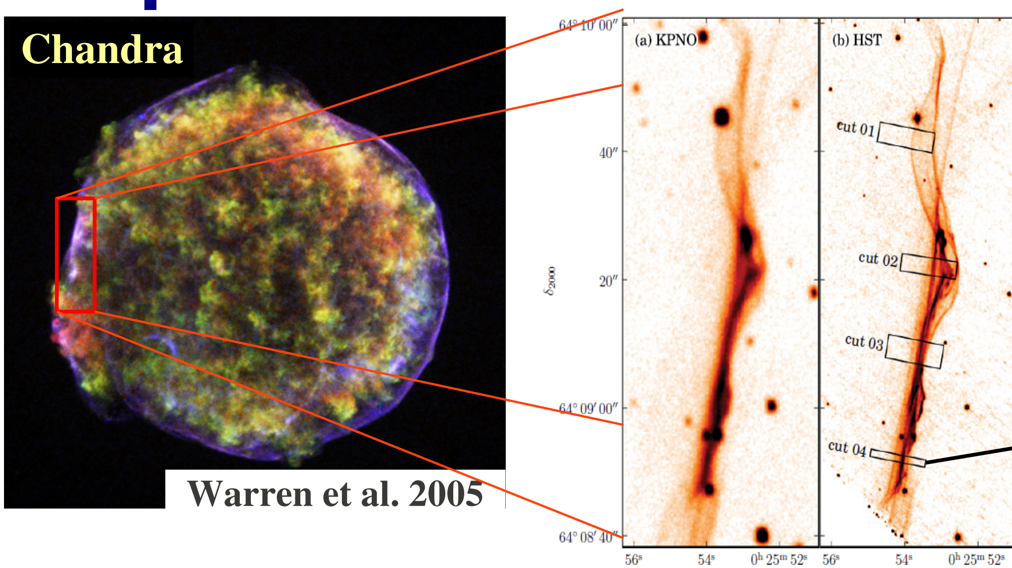
Mach number is strongly reduced



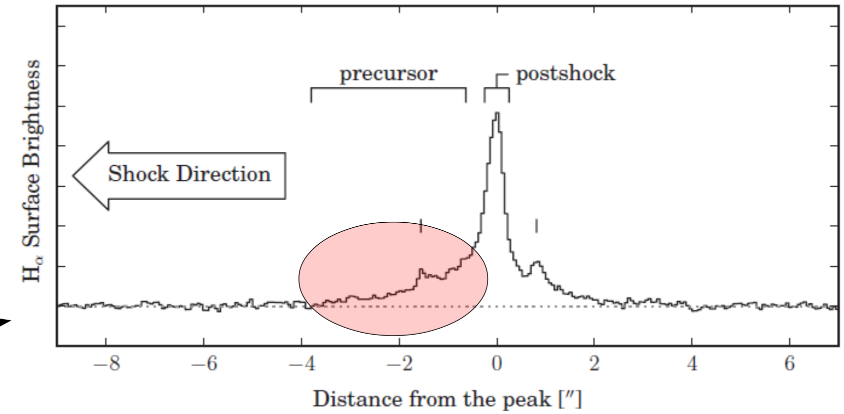
Slope of accelerated particles (*test particle regime*)



Acceleration of CRs in presence of neutrals



Lee et al., 2010
(Observation with the Hubble Space Telescope)



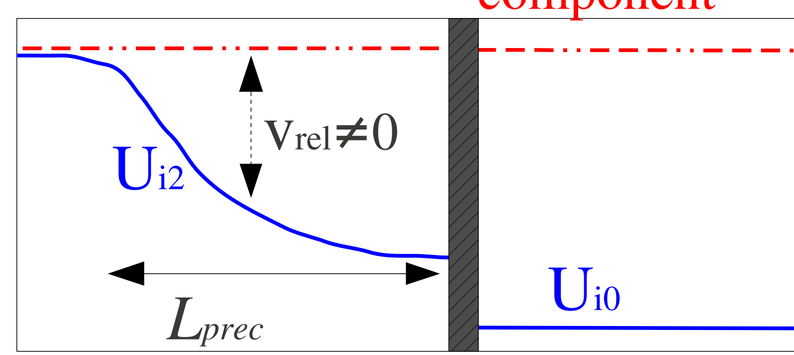
When a CR acceleration is efficient:

→ **a precursor is formed upstream of the shock**
(CRs compress and slow down the ionized plasma but not neutrals)

→ **ions and neutrals move with different bulk speed**
→ **Hα emission can be produced also in the precursor**

Shock modified by CRs

Velocity of neutral component



Velocity of ionized component

Conclusions & open problems

1) Does SNRs accelerate nuclei? GeV-TeV detector confirmed the presence of accelerated hadrons.
Even if for the most unambiguous cases maximum energy and spectrum cannot explain CRs observed at Earth.

2) Is shock acceleration as efficient as predicted?
We have indirect, observational evidence that SNRs can put ~10-30% of SN explosion energy into CRs.
What is the impact of high efficiency on other shock systems, AGNs, GRBs, etc?

3) Magnetic field amplification? B-field most important parameter in collisionless shocks.
Efficient acceleration predict magnetic field amplification which seems to be confirmed by X-ray observations
Amplification impacts injection, maximum particle energy (TeV γ-rays), and synchrotron radiation.
How does the amplification works in non-linear regime?

4) CRs acceleration is affected by the presence of neutral particles.
Balmer emission provides a new tool to test shock acceleration mechanism.
Which is the shock in presence of efficient CR acceleration and neutrals?

5) What is the spectrum of particles a typical SNR contributes to galactic CRs?
How does particles escape from the remnant?

6) What is electron/proton ratio? This is the "injection problem." Efficient shock acceleration underpredict the *e/p* ratio with respect to that observed at Earth.

Unsolved problems

1) Wrong prediction for CR anisotropy

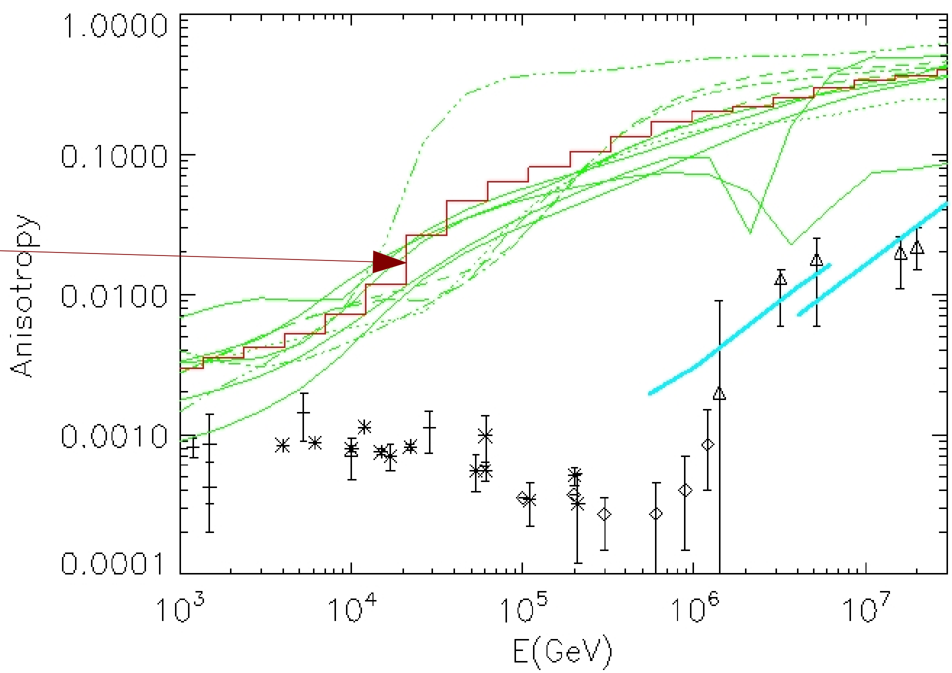
$$N_{obs}(E) \propto Q_{inj}(E)\, t_{esc}(E) \propto E^{-2.7} \quad (for\ E < E_{knee})$$

$$Q_{inj}(E) \propto E^{-2} \Rightarrow t_{esc}(E) \propto E^{-0.7}$$

The escaping time from the Galaxy must be flatter

The injection spectrum produced in SNRs must be steeper

CR ANISOTROPY AT EARTH



Unsolved problems

1) Wrong prediction for CR anisotropy

2) Unclear prediction for the transition between Galactic and extra-Galactic CRs

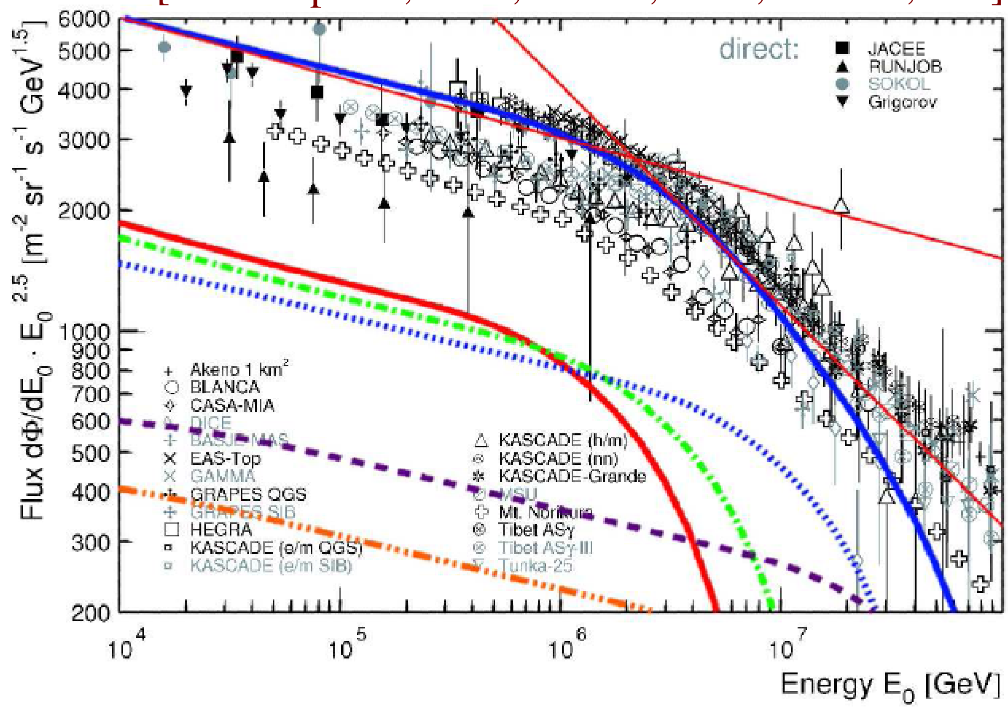
The transition region is interpreted as the sum of different chemicals (up to iron) with maximum energy $\propto$ to the nuclear charge:

$$E_{max}(N) \propto E_{max,p} Z_N$$

But there is a natural mechanism that limits the maximum energy... **IONIZATION**

TOTAL CR SPECTRUM

[from Caprioli, Blasi, Amato, 2011, APh 34, 447]



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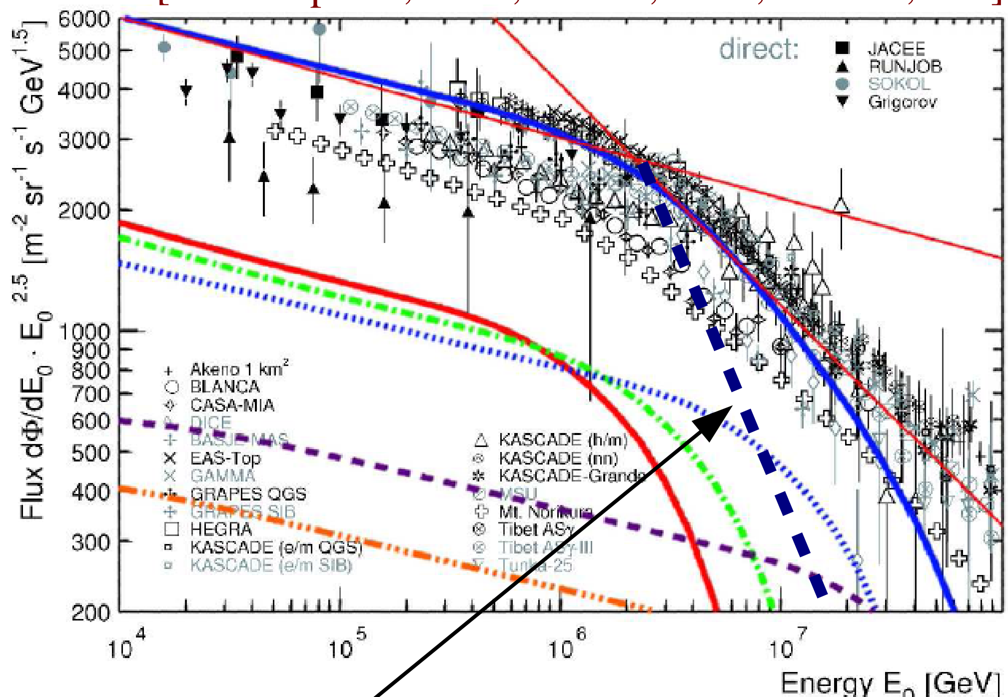
But there is a natural mechanism that limits the maximum energy... **IONIZATION**

1) Ions never start the acceleration process fully ionized
2) The photo-ionization time is comparable to the acceleration time
➔ The acceleration rate is NOT proportional to the nuclear charge, Z_N , but rather to the effective ion's charge

TOTAL CR SPECTRUM

[from Caprioli, Blasi, Amato, 2011, APh 34, 447]



$$E_{max}(N) \not\propto E_{max,p} Z_N$$ ➔ **The knee structure is no more well reproduced**
[G.M. 2010, MNRAS, 412, 2333]