OBSERVATIONAL EVIDENCES OF CR ACCELERATION IN SNR SHOCKS

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OUTLINE

- **Non-thermal radiative processes from accelerated particles in SNRs**
- **Kinetic approach to DSA for stationary (and *semi-stationary*) solutions**
- **Application of nonlinear DSA to young SNRs**
  - ***RX J1713.7-3946***
  - ***SN 1006***
  - ***Tycho***
- **A novel suggestion to solve the problem of electron injection**

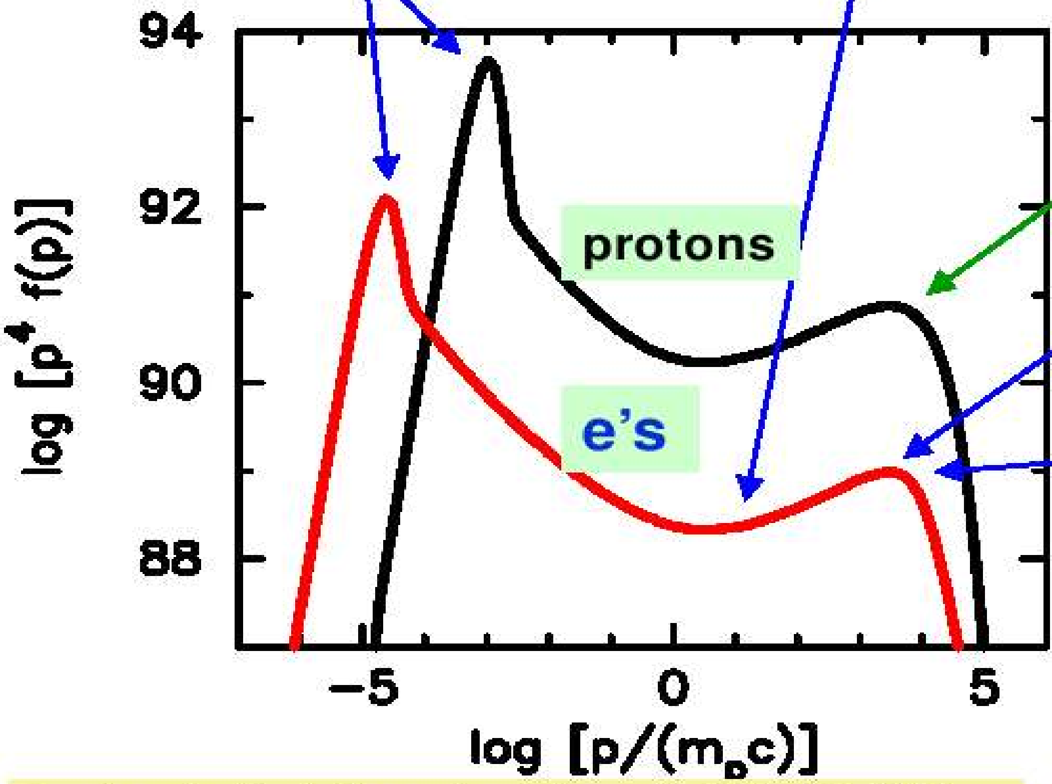
Can DSA explain the radiation from SNRs?

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

Thermal X-rays (keV)

Radio Synch

Pion-decay (GeV-TeV) only emission from protons



compete at GeV-TeV energies

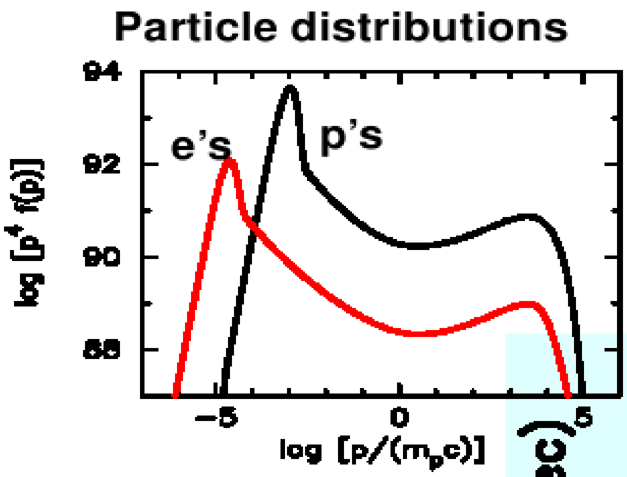
X-ray Synch (keV X-rays)

Inverse Compton (GeV-TeV γ-rays) from electrons

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

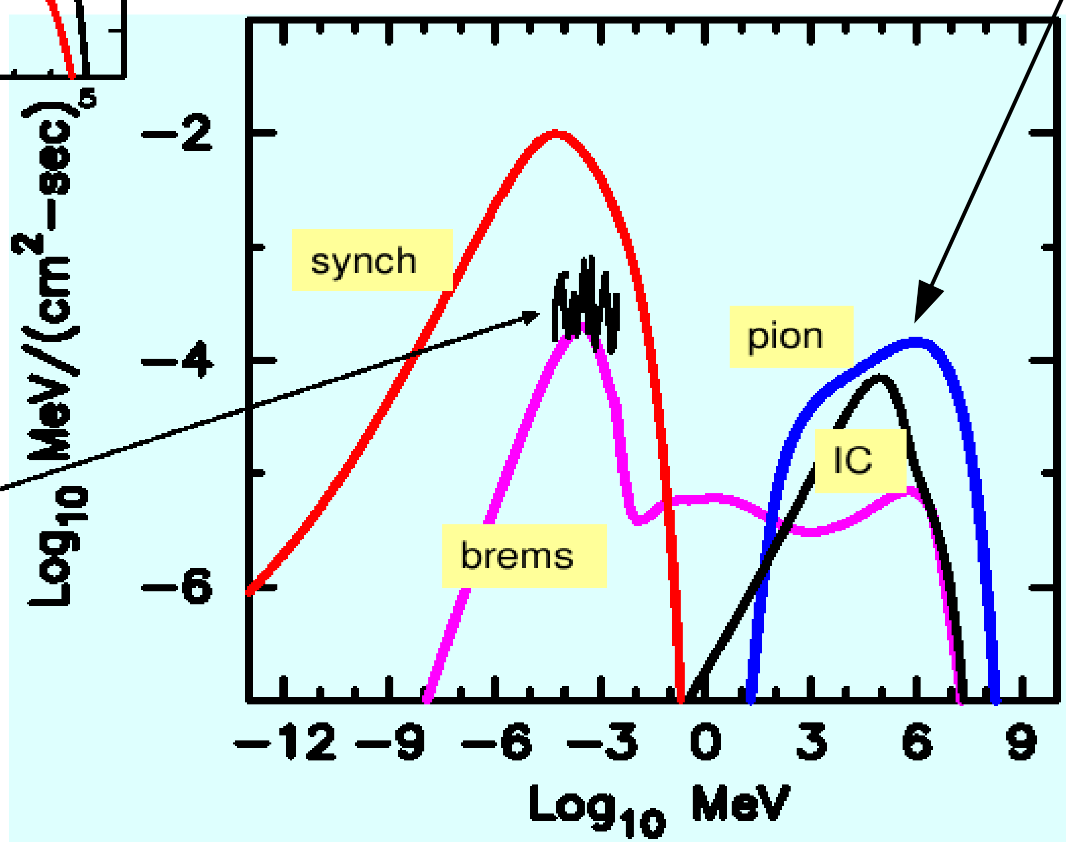
Several free parameters required to characterize particle spectra, including B-field, e/p ratio, diffusion coefficient

EM radiation from accelerated particles



continuum emission

Pion decay and IC are competitive mechanisms



In addition, emission lines in thermal X-rays

The Kinetic Model: Basic Ingredients

- Solution of stationary transport equation in a plane shock geometry

$$\frac{d f_{CR}(x,p)}{dt} = \frac{\partial f_{CR}}{\partial t} - u(x)\frac{\partial f_{CR}}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f_{CR}}{\partial x}\right] + \frac{1}{3}\frac{du(x)}{dx}p\frac{\partial f_{CR}}{\partial p} + Q(x,p) \equiv 0$$

- Bohm-like diffusion coefficient in the amplified magnetic field

$$D(x,p) = \frac{1}{3} c r_L(\delta B) = \frac{1}{3}\, c\, \frac{p c}{e\, \delta B(x)}$$

- Magnetic field amplification:
  - resonant streaming inst.
  - non-resonant (Bell, 2004)
  - NO DAMPING

$$\left(\frac{\delta B(x)}{B_0}\right)^2 \simeq 2 M_A \frac{P_{CR}(x)}{\rho_0 u_0^2} \quad + \quad \left(\frac{\delta B(x)^2}{8\pi}\right) \simeq \frac{u(x)}{2c}\, \epsilon_{CR}(x)$$

- Particle injection according to the *thermal leakage* model

$$\eta_{inj} \equiv \frac{n_{inj}}{n_{gas}} = \frac{4}{3\sqrt{\pi}}\left(R_{sub}-1\right)\, \xi^3\, e^{-\xi^2}$$

[P. Blasi (2002)]
[P. Blasi et al.(2005)]
[Amato & Blasi (2006)]

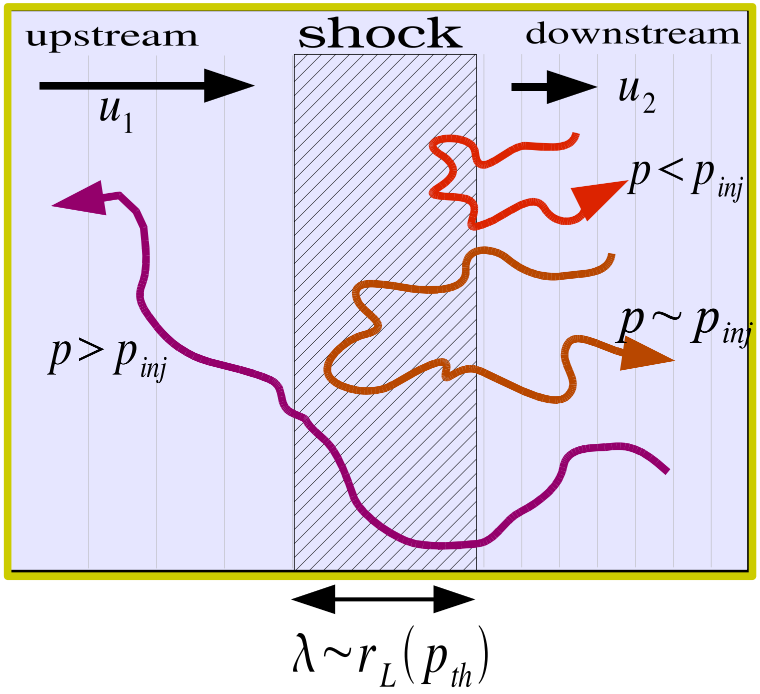
- Jump conditions including CRs and magnetic field pressure and energy

$$\left[\rho u^2 + p_{gas} + p_{CR} + p_w\right]_1^2 = 0$$

$$P_{w,1}(x) \equiv \frac{\delta B_\perp^2(x)}{8\pi \rho_0 u_0^2}$$

The recipe for the proton *injection:*
Thermal Leakage Model

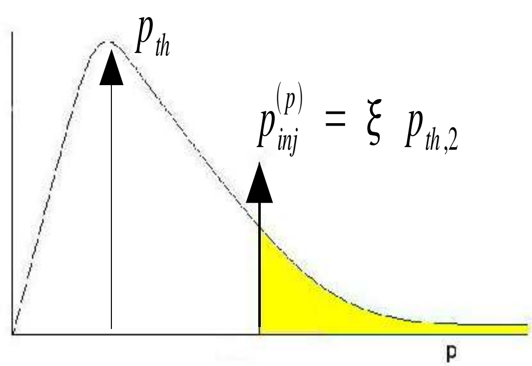
We assume that particles from upstream thermalize into the *sub-shock* layer



- ➔ **Astrophysical shocks are collisionless**
- ➔ **Ions dominate the energetic ➔ Sub-shock thickness is of the order of the Larmor radius of thermal ions**
- ➔ **Injection occurs only for particles with**

$p > p_{inj}$ **with** $p_{inj} = \xi \, p_{p,th}$

free parameter



$$Q_{inj}(x,p) \propto \delta(x)\,\delta(p - p_{inj})$$

Electrons are assumed to be injected at the same p_{inj} of protons.
The number of injected electrons is a free parameter: $f_e = K_{ep} f_p$.

Application to the remnant *RX J1713.7-3946*

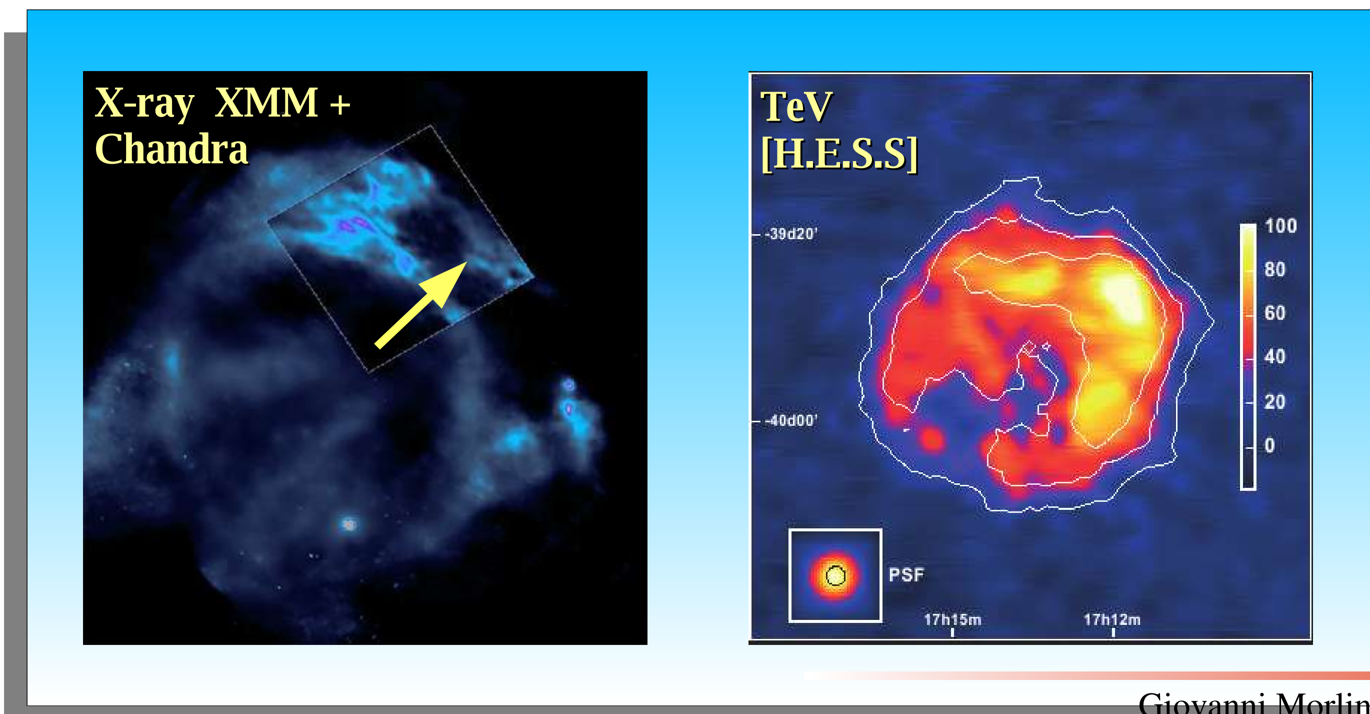
GM, E. Amato, P. Blasi, 2008

MODEL PARAMETERS

$t_{SNR} = 1600 \ yr$	SNR age	(FIXED)
$T_0 = 10^6 \ K$	External temperature	(FIXED)
u_0	Shock velocity	(FREE)
n_0	Upstream density	(FREE)
B_0	Upstream magnetic field	(FREE)
ξ	Injection threshold	(FREE)
K_{ep}	e/p number ratio	(FREE)

Two possible mechanisms to explain TeV radiation:

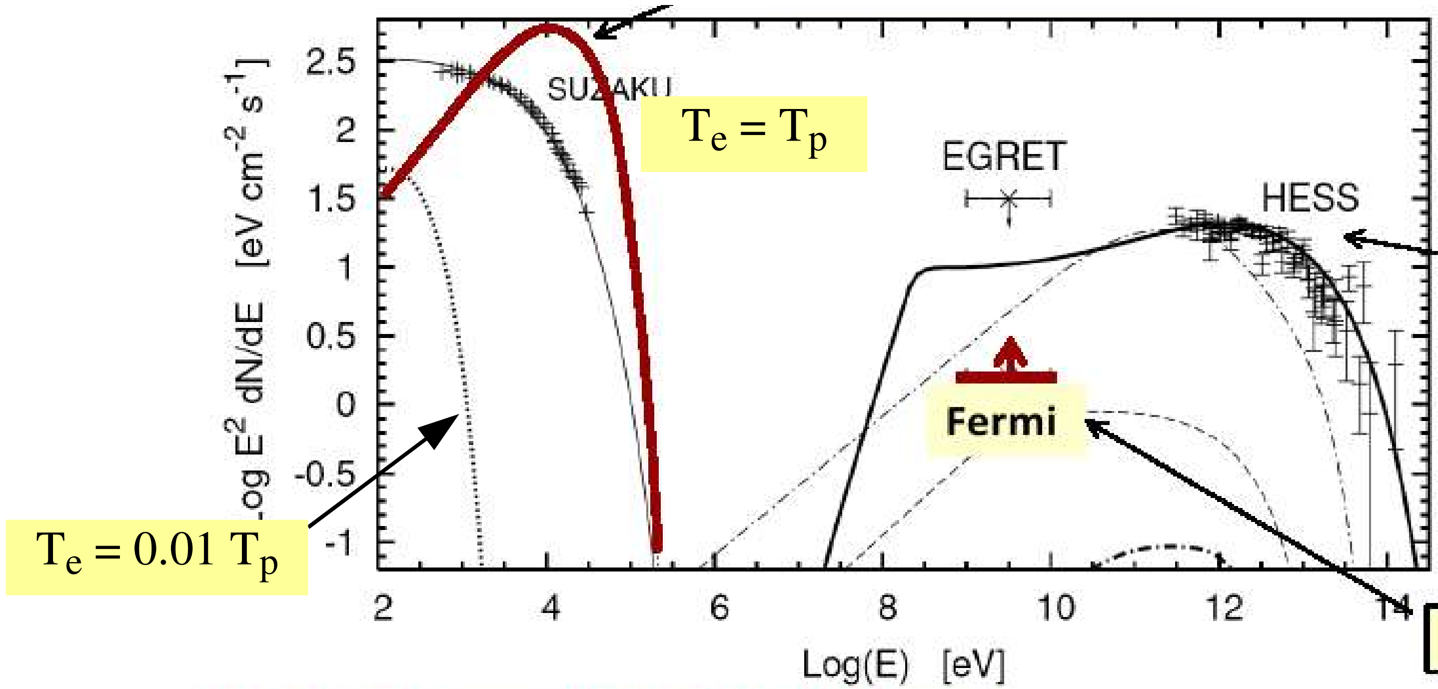
- **Neutral pion decay due to hadronic interactions**
- **Inverse Compton Scattering of energetic electrons**



Application to *RX J1713*: efficient scenario

n_0[cm^{-3}]	T_0 [K]	B_0[μG]	u_0[km/s]	ξ	K_{ep}
0.12	10^6	2.6	4300	3.8	8×10^{-5}

ε	η_{ing}	R_{sub}	R_{tot}	B_1/B_0	B_2[μG]	T_2 [keV]	$p_{p,max}$ [GeV]	t_{acc} [yr]
26%	6.5×10^{-5}	3.95	5.35	25.5	100	19.5	1.25×10^5	780



Pion-decay dominates at TeV energies

Excellent fit, but requires high ISM density

Also implies MFA consistent with other estimates

Hopefully, Fermi will help

High density overproduces thermal emission

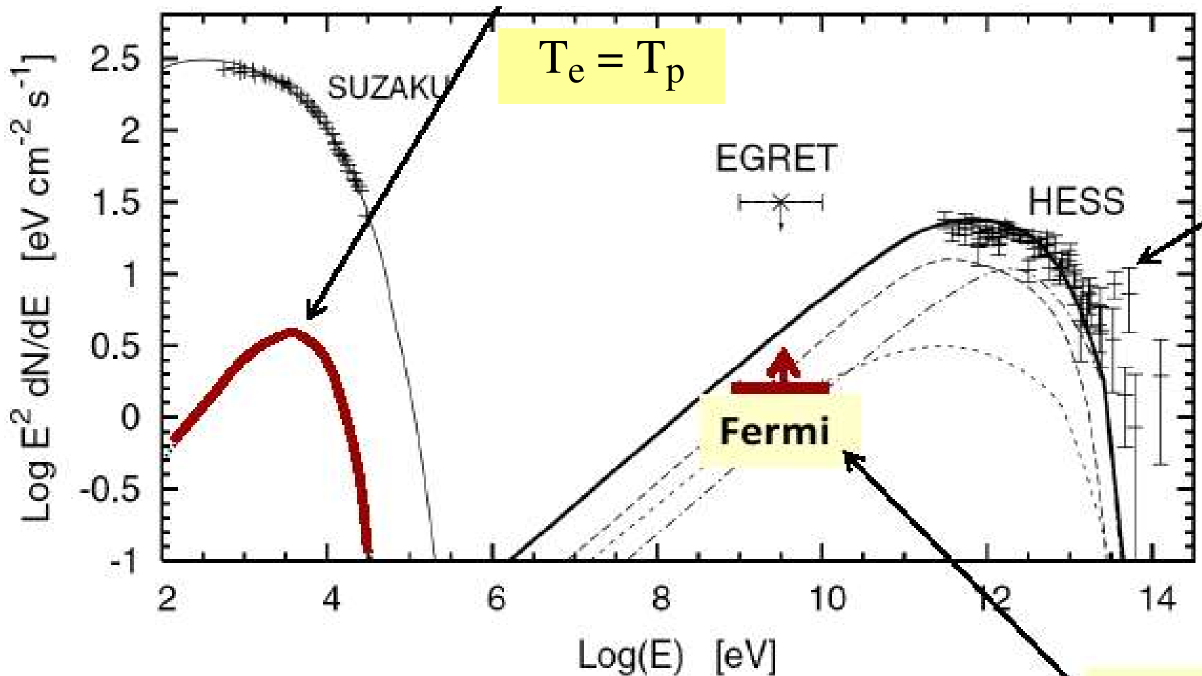
Thermal X-ray emission depends on electron temperature which is uncertain – efficient DSA results in lower shocked temperatures. Can the thermal emission be argued away??

With pion-decay fits, must assume e/p ratio $< 10^{-4}$, which is much lower than suggested by CR observations

Application to *RX J1713*: inefficient scenario

n_0[cm^{-3}]	T_0 [K]	B_0[μG]	u_0[km/s]	ξ	K_{ep}
0.01	10^6	1.5	4300	4.1	1.3E-2

ε	η_{ing}	R_{sub}	R_{tot}	B_1/B_0	B_2[μG]	T_2 [keV]	$p_{p,max}$ [GeV]	t_{acc} [yr]
1.6%	7.7×10^{-7}	3.96	4.03	4.0	23	23	9.3×10^4	1600

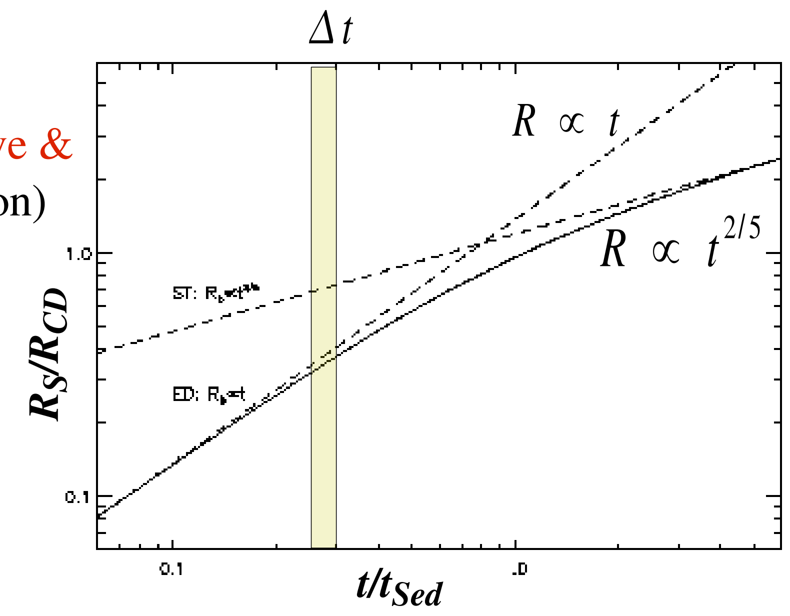


IC dominates at TeV energies
But fit at highest energies not as good as with pion-decay

Large difference in IC and pion-decay predictions at Fermi energies

Lower density ISM lowers thermal emission
Assumption for e/p ratio ~ 10^{-2}, consistent with CR observations
Requires low B-field ➔ little MFA, Also requires large ad hoc IR photon field

The *semi-stationary* evolution model



- For the *forward shock* position and shock speed we use the Truelove & McKee (1999) solution (analytical fit to a full hydrodynamic solution)
  - *at this step we neglect the CRs pressure*

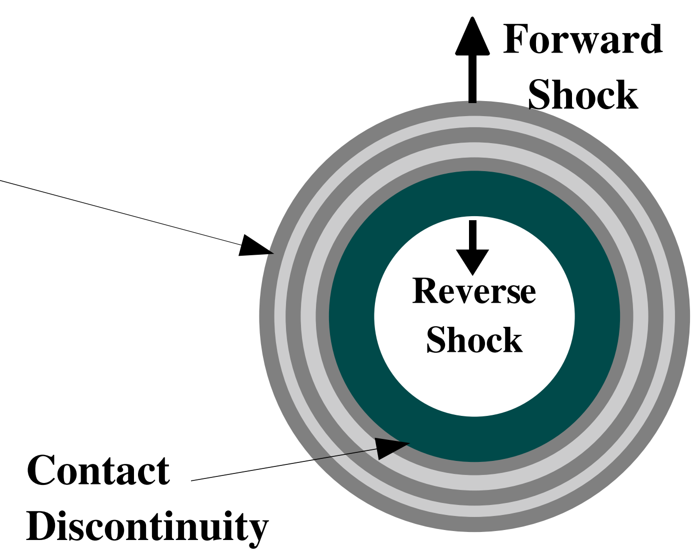
$$E_{SN},\ M_{eje},\ n_0 \rightarrow R_{sh}(t),\ u_{sh}(t)$$

- For each step Δt we apply the stationary solution for the DSA with fixed:

$$T_{0,}\quad B_{0,}\quad \xi_{inj}$$

- In order to compute the evolution of the *downtream* plasma (thermal fluid+ CRs component) we assume:
  - entropy conservation within each single shell
  - pressure equilibration between close shells

this gives the downstream density profile and the adiabatic losses



Application to the *Tycho* remnant

GM, D. Caprioli, P. Blasi, G. Cassam-Chenai

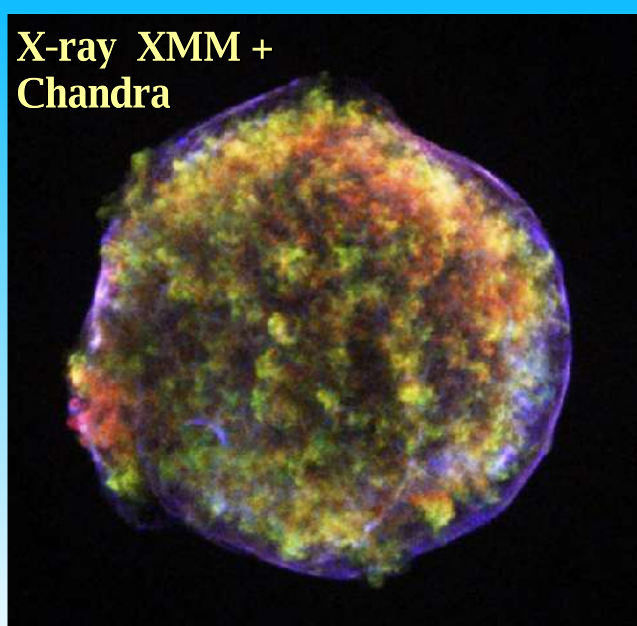
work in progress.

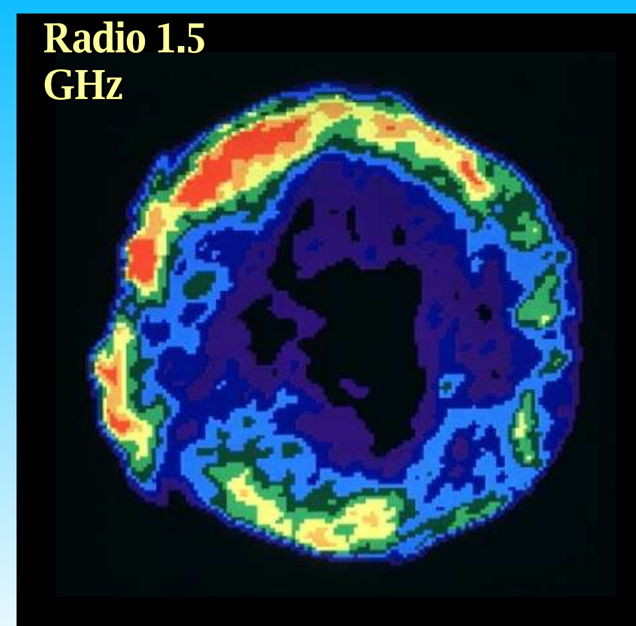
- Type Ia SN age 437 yr
- Uniform ambient medium $n_0 = 0.2$

$n_0 < 0.3$ from the absence of thermal emission at the FS [Cassam-Chenai (2007)]

Imput parameters $T_0 = 10^4\,K; \quad B_0 = 3\,\mu G; \quad E_{SN} = 10^{51}\,erg; \quad M_{eje} = 1.4\,M_{Sol}$

Output $R_{sh} = 3.95\,pc; \quad u_{sh} = 5070\,Km/s; \quad d = 3.4\,kpc$

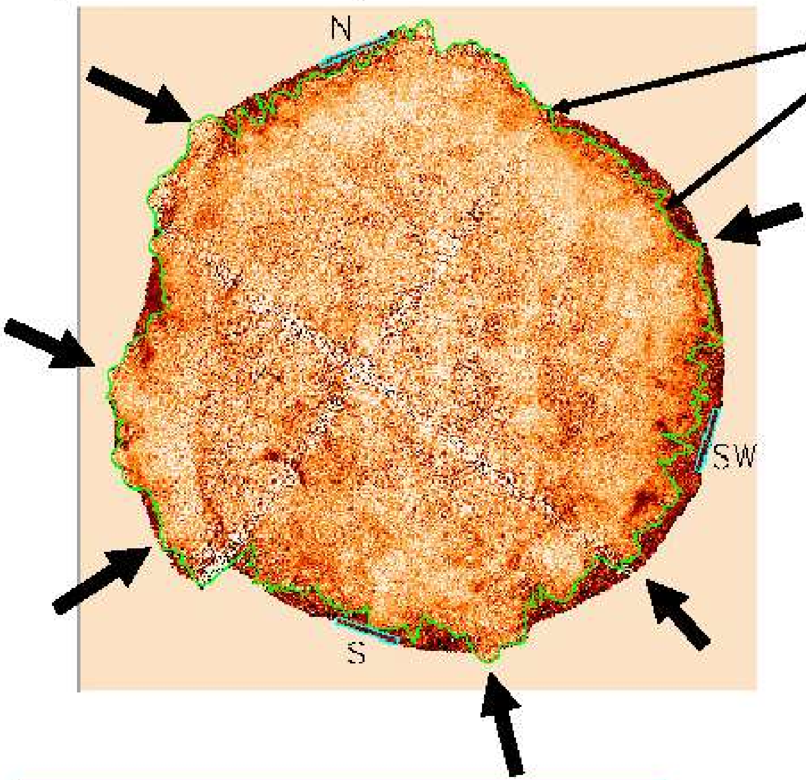




Evidence for efficient shock acceleration in SNRs

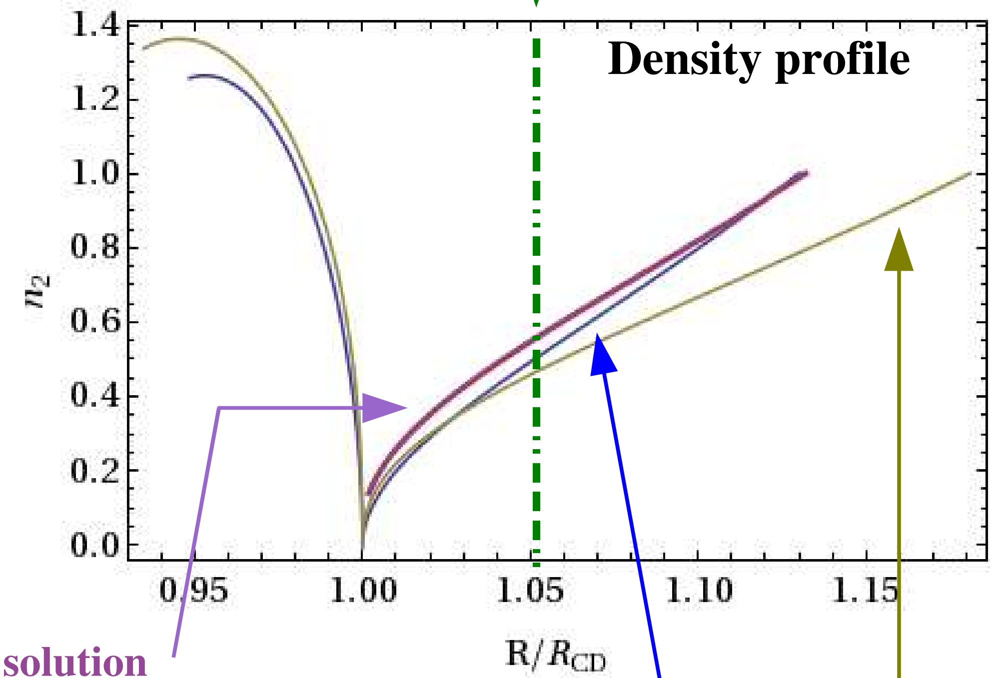
$\xi = 3.5$

Chandra observations of Tycho's SNR
(Warren et al. 2005)



Green line is contact discontinuity (CD)

CD lies close to outer blast wave determined from 4-6 keV (non-thermal) X-rays

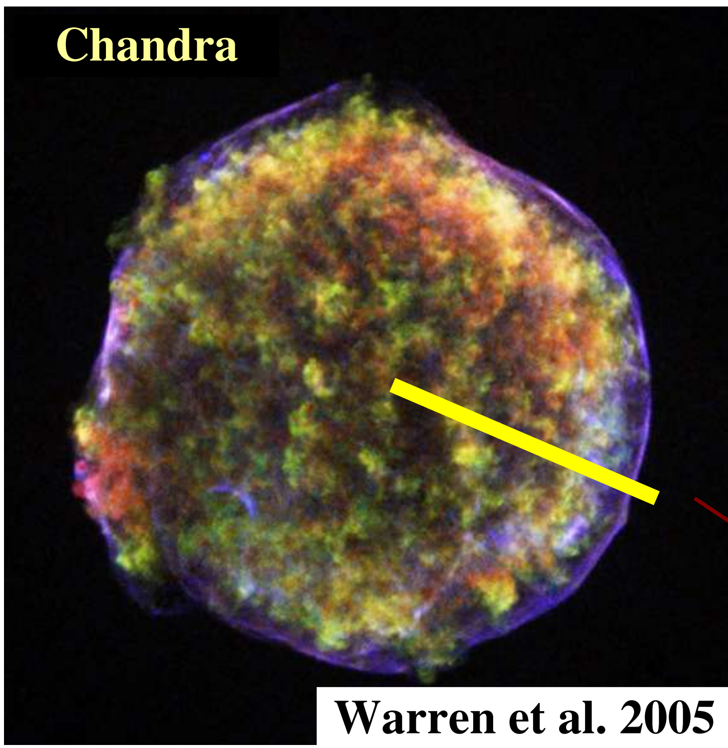


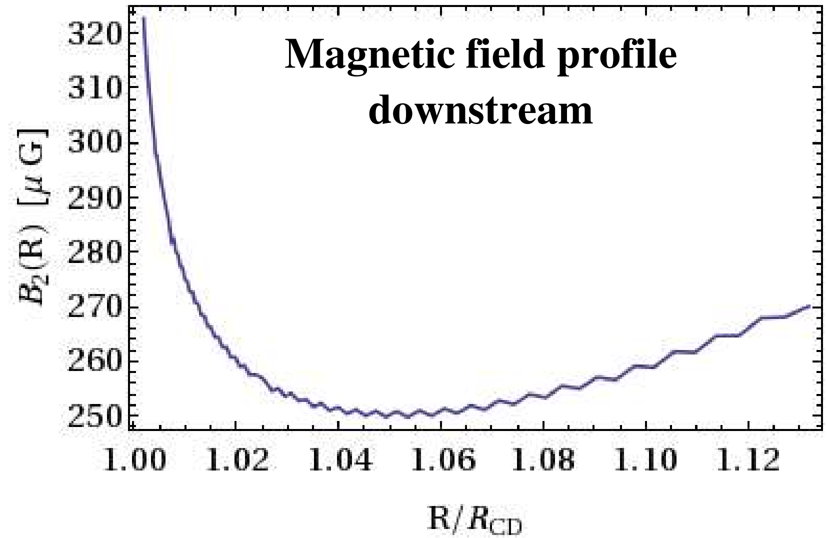
data shows $<R_{FS}/R_{CD}> < 1.05$
implies shock compression ~ 6-10
implies efficient DSA

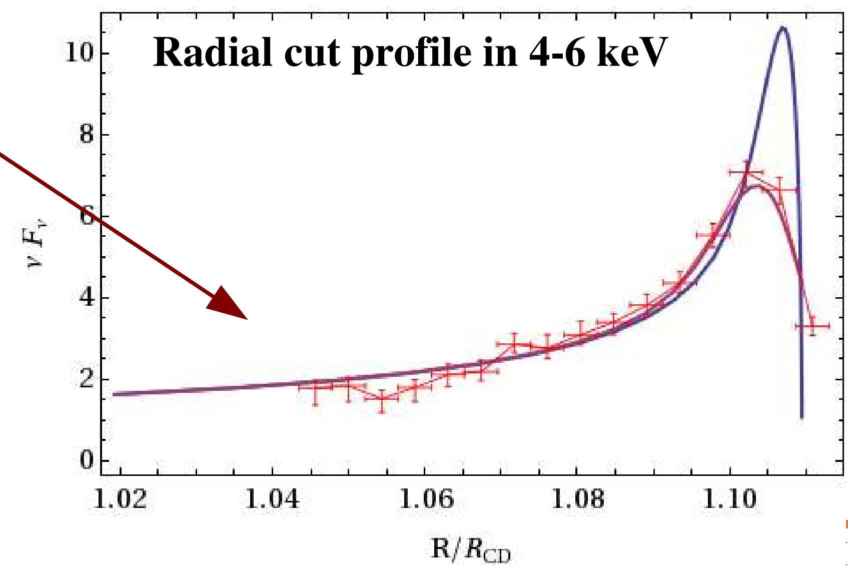
Our solution
Self similar solution with no CR
Self similar solution with no 50% of energy into CRs
[A.R. Chevalier, 1982]

Thin filaments in X-rays

Strong magnetic field ➔ large synchrotron losses ➔ thin rim



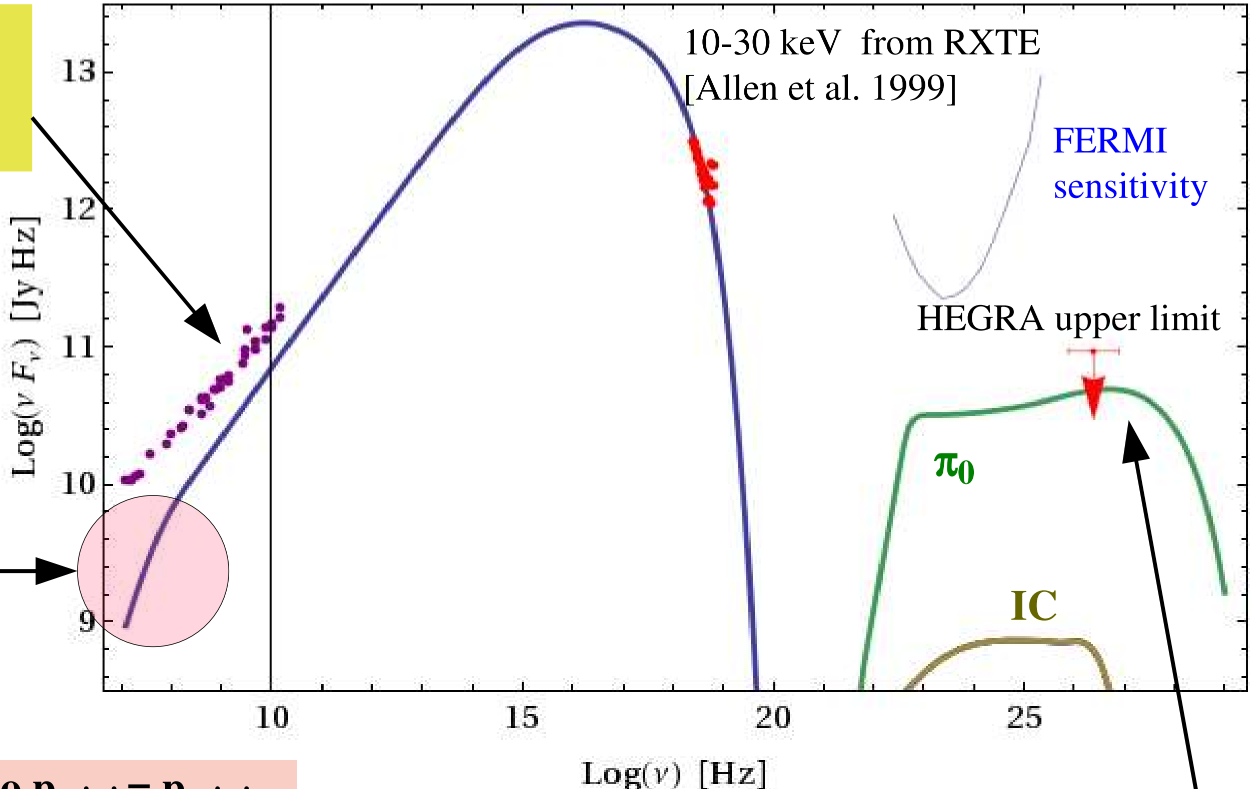




Multiwavelength nonthermal emission

$\xi = 3.5; \quad u_{sh} = 5070\, Km/s; \quad B_0 = 3\,\mu G; \quad B_2 = 270\,\mu G;$

Different slope:
theory ~0.5
esperimental ~0.65



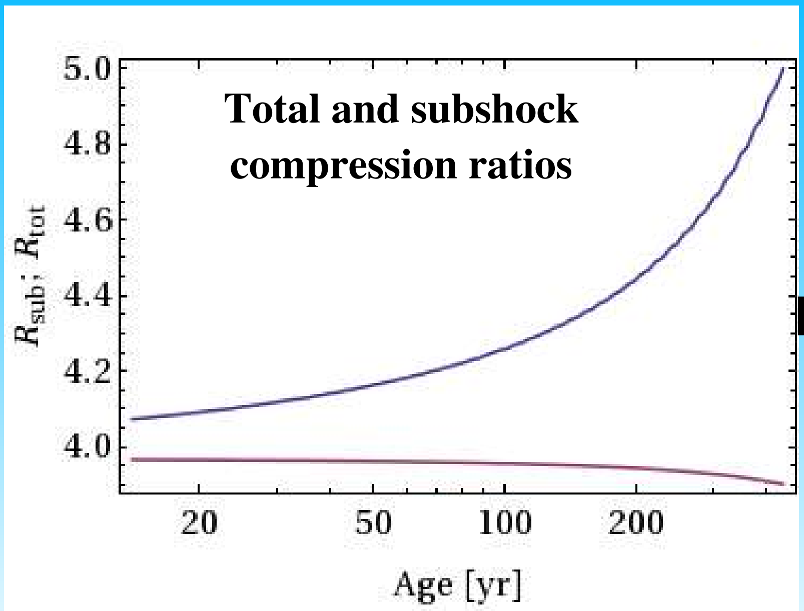
Artificial cutoff due to $p_{e,inj} = p_{p,inj}$

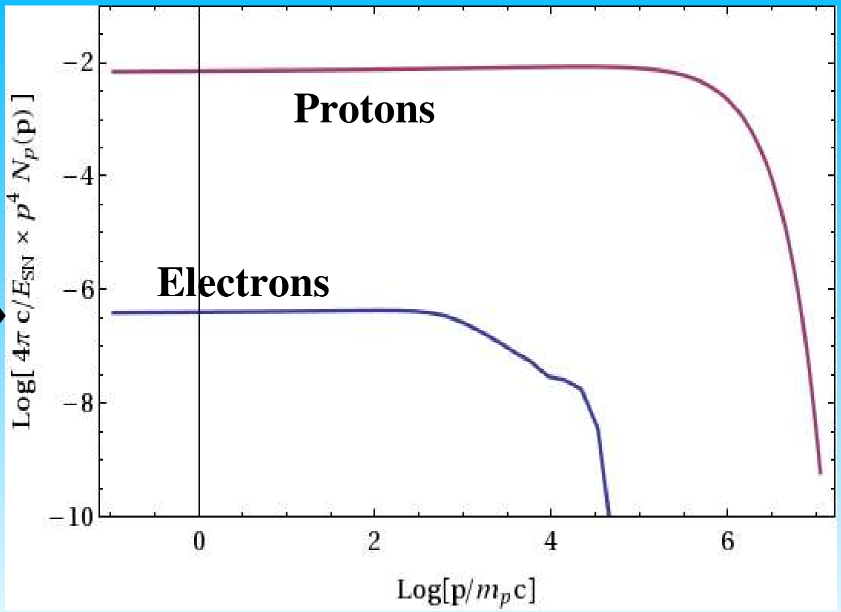
Is it possible to explore electron injection region?

Upper limit emission assuming
$n_0 = 0.2\ cm^{-3}$
$n_0 < 0.3\ cm^{-3}$ from lack of thermal emission

The effect of magnetic field pressure

Even if the CR production efficiency is high, R_{sub} is very close to 4 because the magnetic field pressure is strong compared with the upstream thermal pressure





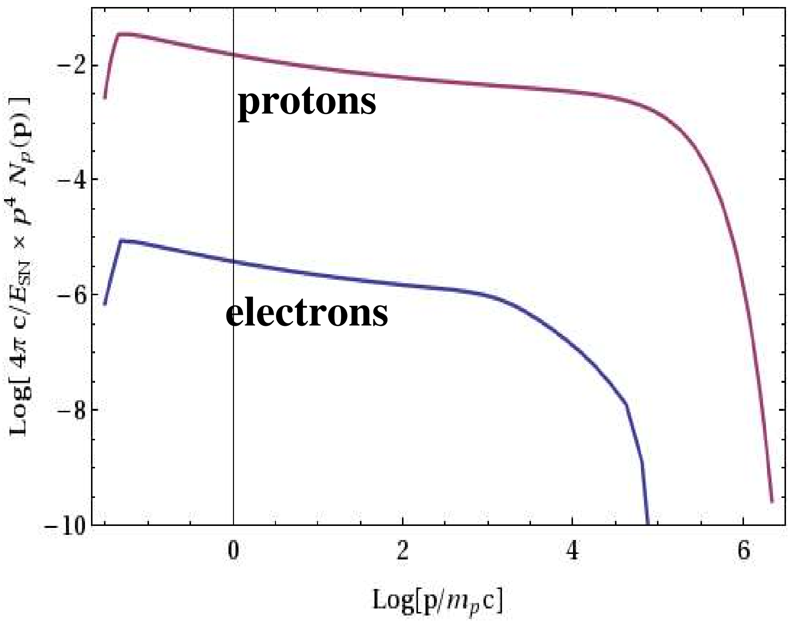
HOW TO GET A PRONOUNCED CURVED SPECTRUM?

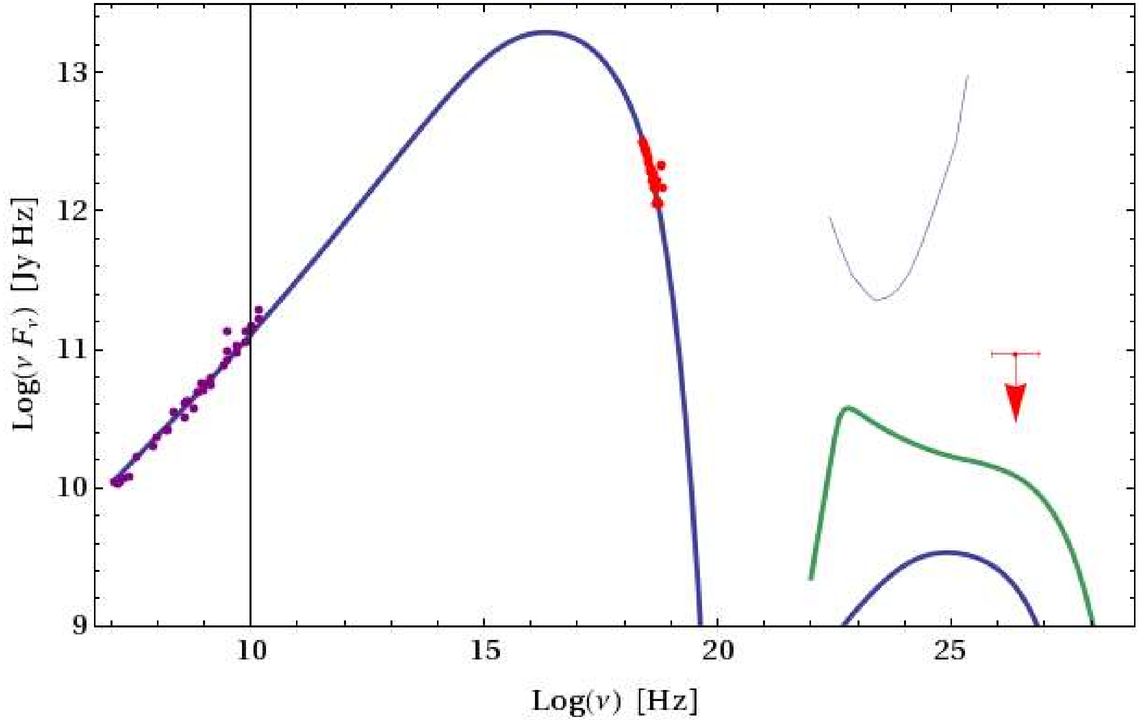
If the scattering waves move with Alfvén speen in the perturbed magnetic field, the particle spectra are steeper:

$$u(x)\frac{\partial f_{CR}}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f_{CR}}{\partial x}\right] + \frac{1}{3}\frac{du(x)}{dx}p\frac{\partial f_{CR}}{\partial p} + Q(x,p) \equiv 0$$

$$u \rightarrow u + v_A; \quad v_A = \frac{\delta B}{\sqrt{4\pi\rho}}$$

s~ 2.4



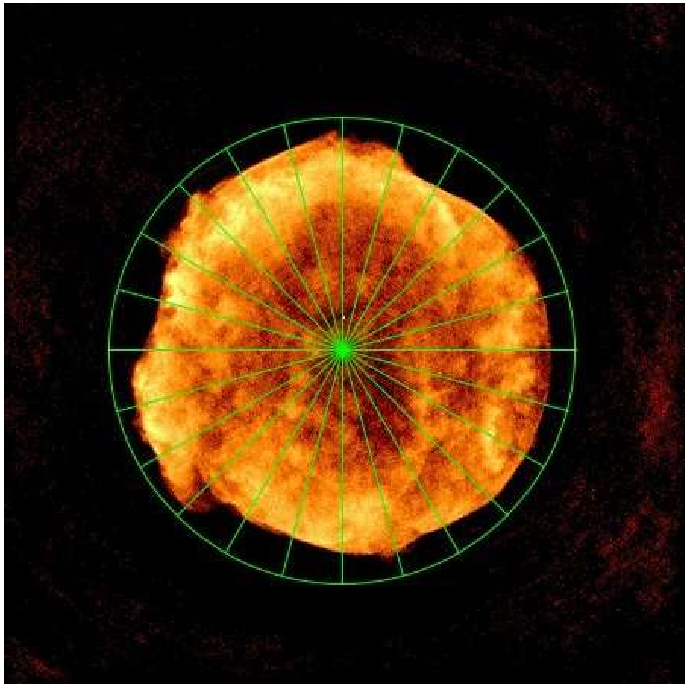


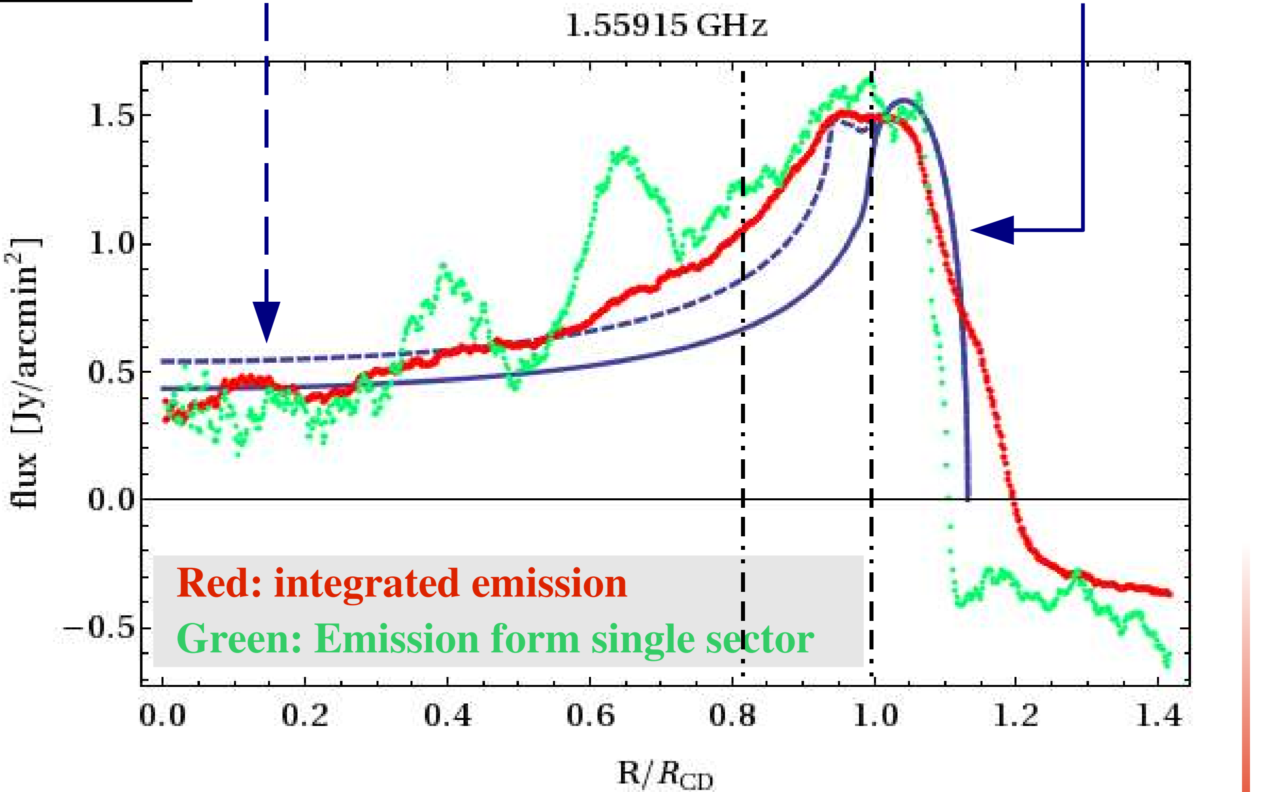
Radio emission

The model does not fit the radial profile of Radio emission.

Possible solution:

1) **Acceleration at the reverse shock ?**
2) **Instabilities at the contact discontinuity spread the shocked ISM ?**





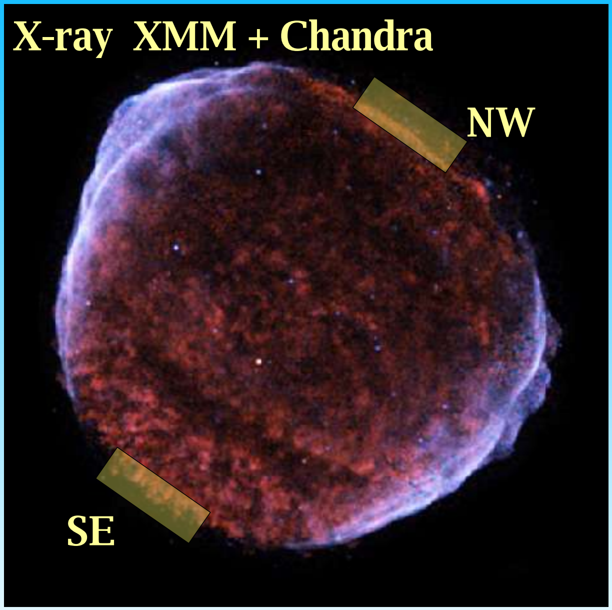
Application to the remnant *SN 1006*

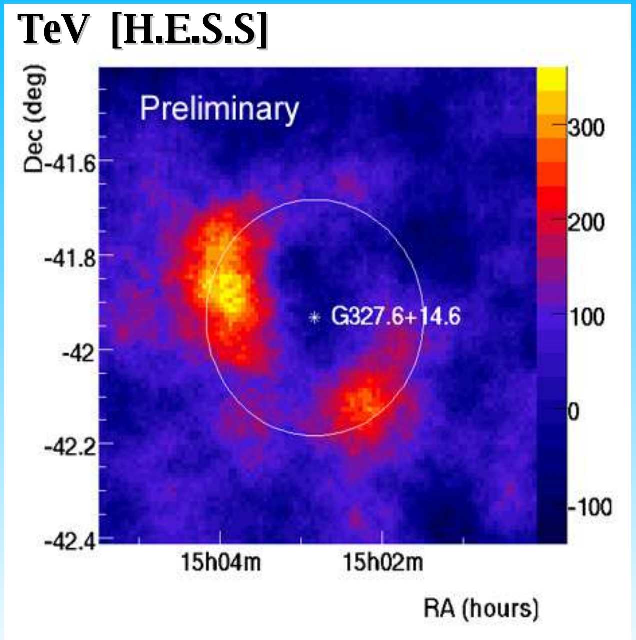
GM, D. Caprioli, P. Blasi
work in progress.

- Type Ia SN age 1000 yr expanding in a uniform ambient medium
  n_0 =0.05 from the thermal emission in SE region [Acero et al.(2007)]

Imput parameters $T_0 = 10^4 K;\quad B_0 = 3.5\mu G;\quad E_{SN} = 10^{51} erg;\quad M_{eje} = 1.4 M_{Sol}$

Output $R_{sh} = 7.7\, pc;\quad u_{sh} = 4400\, Km/s;\quad d = 1.8\, kpc$



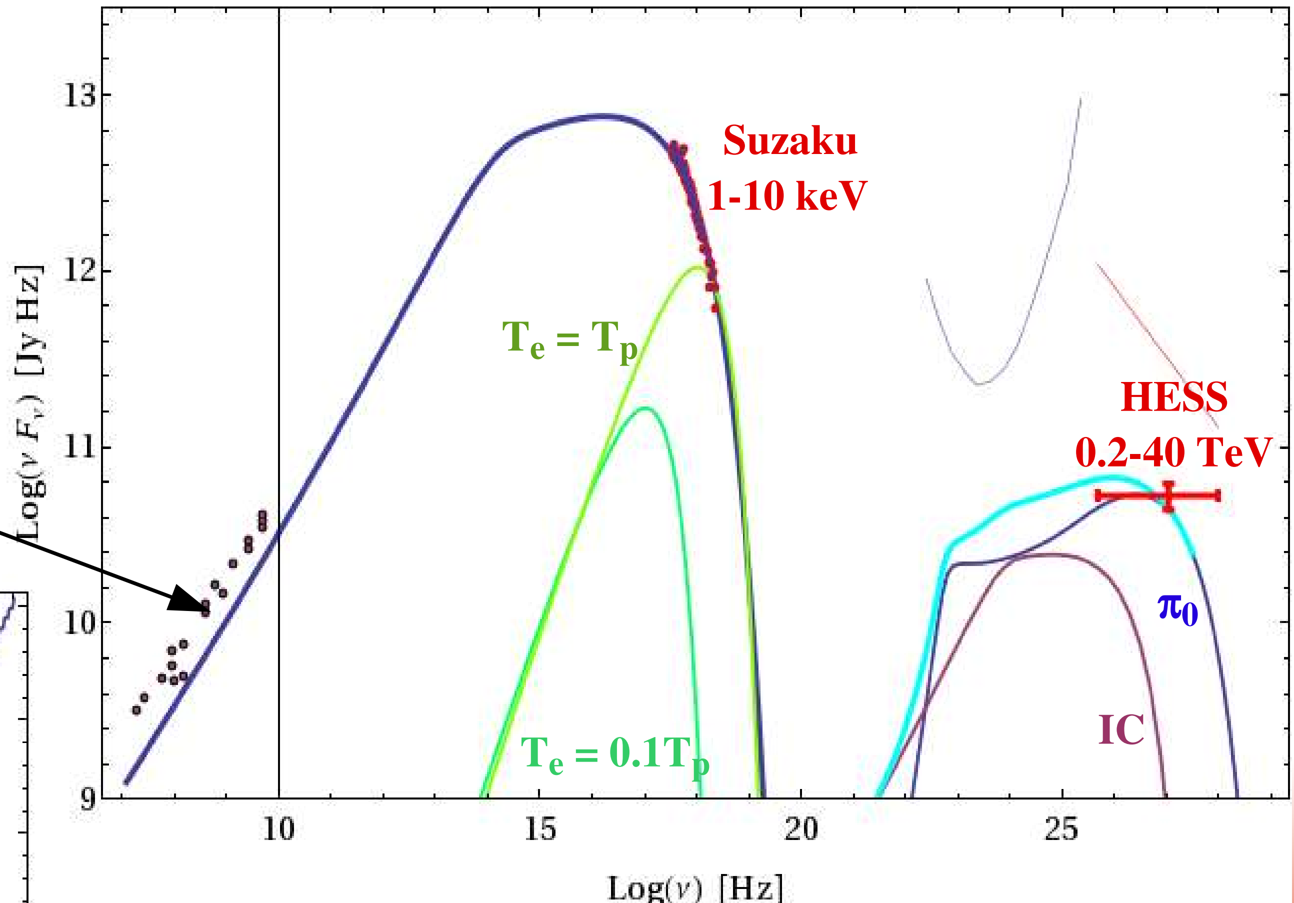


Scenario with efficient acceleration

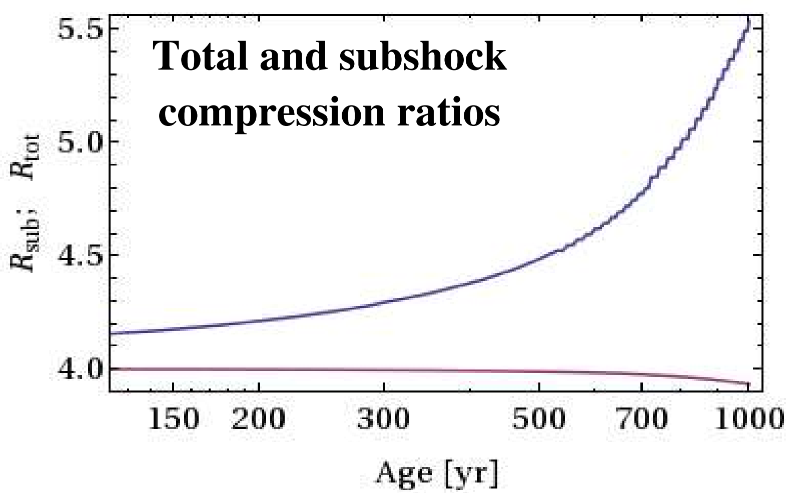
$\xi_{inj} = 3.9; \quad u_{sh} = 4400\,Km/s \rightarrow B_2 = 97\,\mu G$

Energy converted into CRs

$\epsilon_{CR}/(\rho_0 u_0^2) = 0.24$

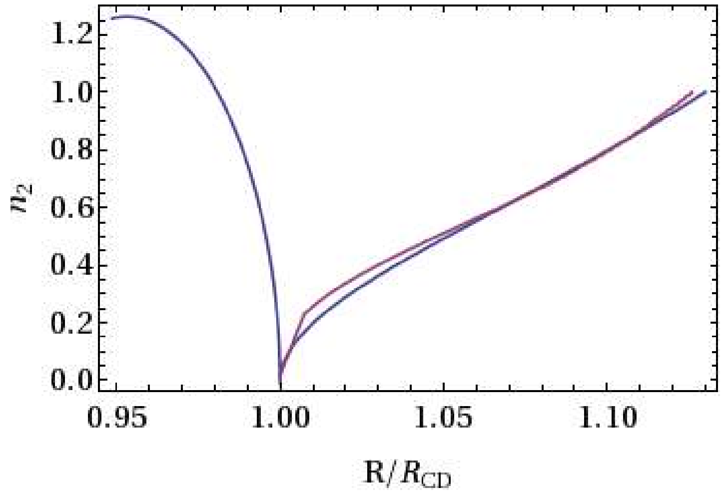


The slope is in good agreement



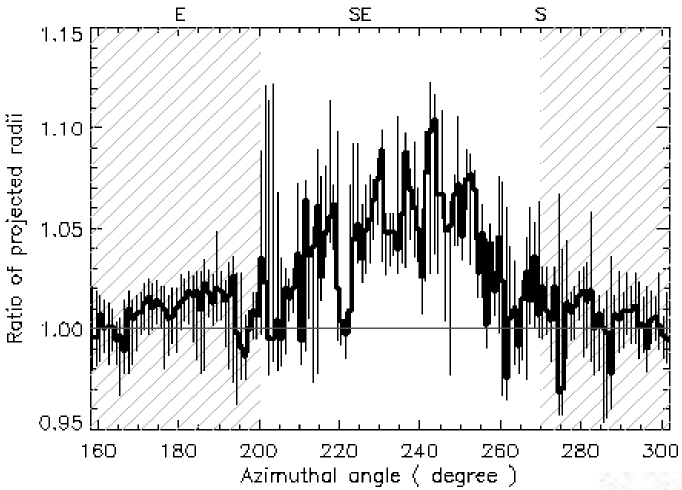
Scenario with efficient acceleration

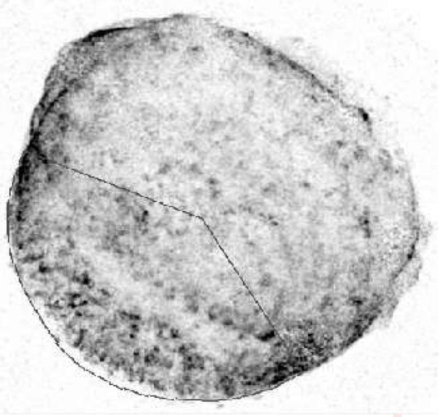
Distance between CD an FS



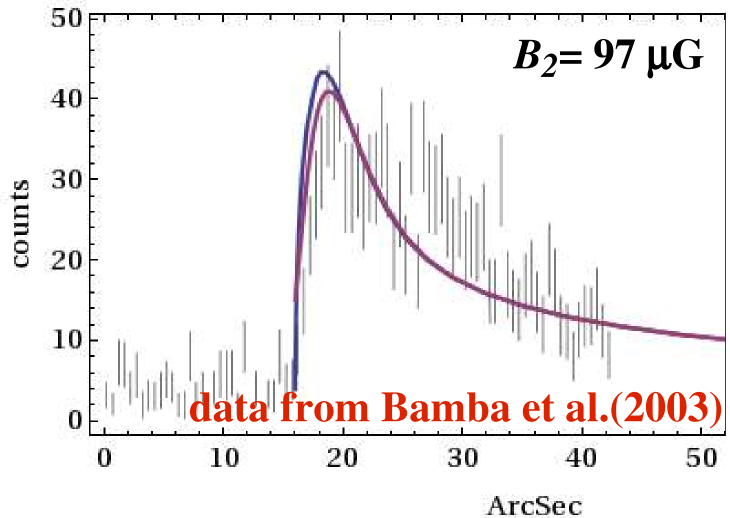
Cassam-Chenai et al.(2008)

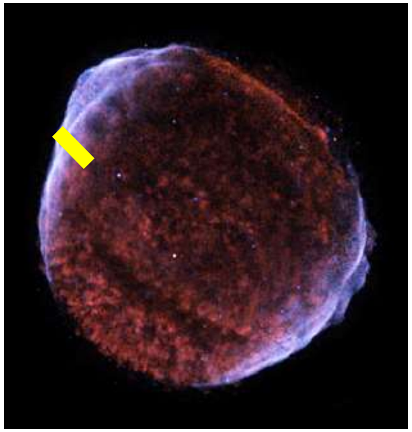
$\frac{R}{R_{CD}}$





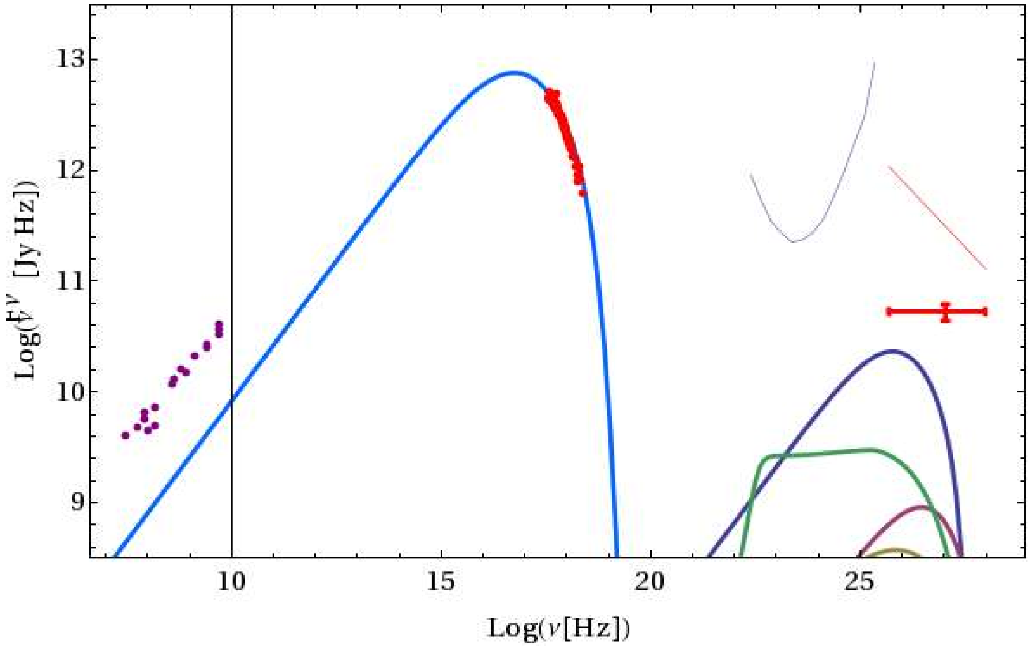
X-ray profile



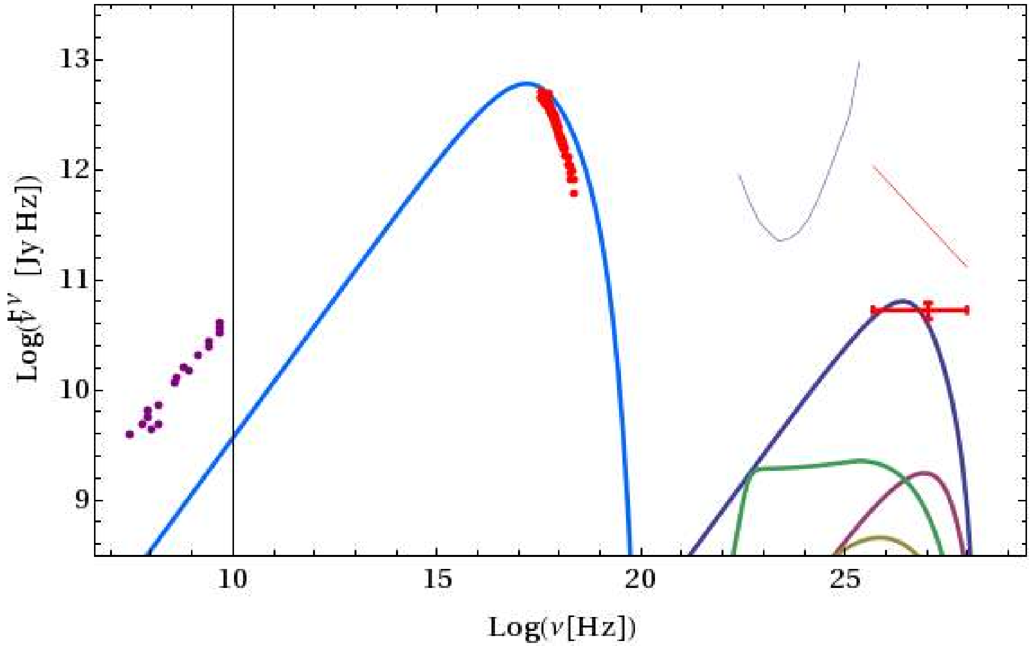


Inefficient acceleration

$\xi_{inj}=4.1 \rightarrow B_2=36\,\mu G$



$\xi_{inj}=4.15 \rightarrow B_2=20\,\mu G$

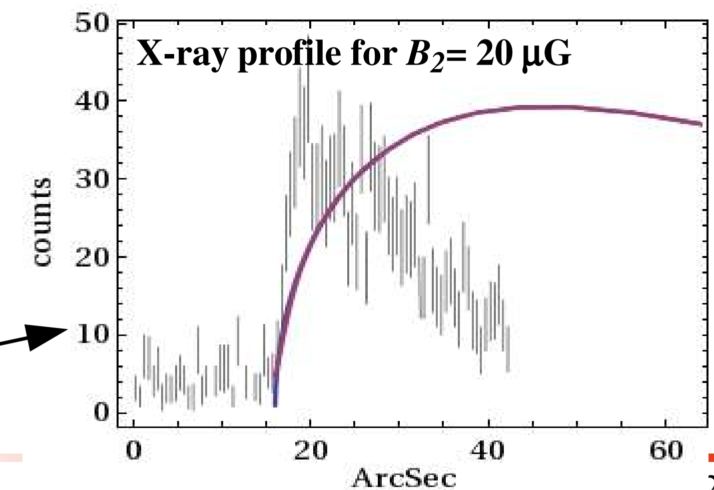


1) Radio and X-ray are difficult to fit together

2) For $B_2 < 20\ \mu G$ the E_{max} of electrons is determined by t_{SNR} ➔ the shape of the cutoff change!!

3) The IC cutoff in the TeV region is very steep

4) X-ray profile does not fit the data



Magnetic field amplification vs Electron injection

SNR	B_{dw} (μG)	K_{ep}	B_{dw} (μG)	K_{ep}
RX J1713	100	8 · 10^-5	126	1 · 10^-4
SN1006	97	5 · 10^-4	150	4 · 10^-4
Tycho	270	9 · 10^-5	350 – 412	5 · 10^-4
Kepler			340	1.3 · 10^-4
Cas A			250 – 390	
RCW 86			75 – 145	

Present work

Other works

from Berezhko, Voelk and collaborators

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.

Large magnetic field values ➔ low electron/proton ratio ~ 10^{-4}: how can be explained?

NOTE:

1) The *e/p* ratio ~10^{-4} is related to young SNRs, and is different from the *e/p* ratio measured at Earth, which is of the order of K_{ep}~10^{-2}

2) We stress that the majority of electrons seen at Earth come from the latest stage of the sources, and the value of K_{ep} can change during the age of the remnant.

3) If the K_{ep} in young SNRs is assumed to be K_{ep}~10^{-2}, than SNRs can convert only ~1% of their enrgy into CRs, probably too low to explain the CR flux.

The problem of electron injection

The well-known difficulty is that thermal electrons cannot easily be scattered by Alfven waves, because of their small gyroradii.

Thermalization of bulk kinetic energy

$$\frac{1}{2} m_e u_{shock}^2 = K_B T_e \Rightarrow p_e = \frac{m_e}{m_p} p_p$$

Thermalization between electrons and protons

$$T_{e,2} = T_{p,2} \Rightarrow p_e = \sqrt{\frac{m_e}{m_p}} p_p$$

$$\Rightarrow \quad p_{e,th} \ll p_{inj}$$

Electron injection requires Lorentz factor $\gamma > 3$-10

➔ **Injection from a thermal pool to mildly relativistic energies by some other mechanism is required.**
There are indications that electrons can be pre-accelerated from thermal energies up to relativistic energies in the shock layer by electromagnetic waves that could be generated by protons themselves.
These studies require detailed simulations of the physics inside the shock (Monte Carlo; particle-in-cell)
➔ **No firm conclusions up to now.**
[see e.g. Galeev (1984), Levinson (1996), Amano & Hoshino (2007), Baring & Summerling (2007)]

Electron injection from ionization of heavy elements

GM, work in progress.

Can the problem of electron injection be solved in a different way?

1) If a SNR expands into ISM with T ~ 10^4 K, atoms havier than H are not fully ionized. (The presence of Hα emission indicate that even hydrogen is not fully ionized)

2) Partially ionized atoms which start the acceleration process are stripped during the acceleration and eject electrons

3) If the ionization time is >> than the acceleration time

- ➔ **ionization occurs when ions move relativistically**
- ➔ **ejected electrons have enough energy to start the acceleration (i.e. $p > p_{inj}$)**

Electron injection from ionization of heavy elements

Using linear acceleration theory we compare the acceleration versus the ionization times

Acceleration time for linear shock acceleration

$$t_{acc}(p) = \frac{3}{u_1 - u_2} \left(\frac{D_1(p)}{u_1} + \frac{D_2(p)}{u_2} \right) = 1.7 \left(\gamma - \gamma^{-1} \right) \left(\frac{B_1}{\mu G} \right)^{-1} \left(\frac{u_{shock}}{1000\, km/s} \right)^{-2} \left(\frac{Z}{Z_{eff}} \right) \; yr$$

Ionization time due to Coulomb collisions with thermal plasma

$$\tau_{coll} = \left[c\, \sigma_{coll}\, 2 \left(\frac{n_1}{t_1} + \frac{n_2}{t_2} \right) \right]^{-1} = 2.4 \times 10^{-3} \left(\frac{I}{Ryd} \right)^{2} \left(\frac{n_1}{1\, cm^{-3}} \right)^{-1} \; yr$$

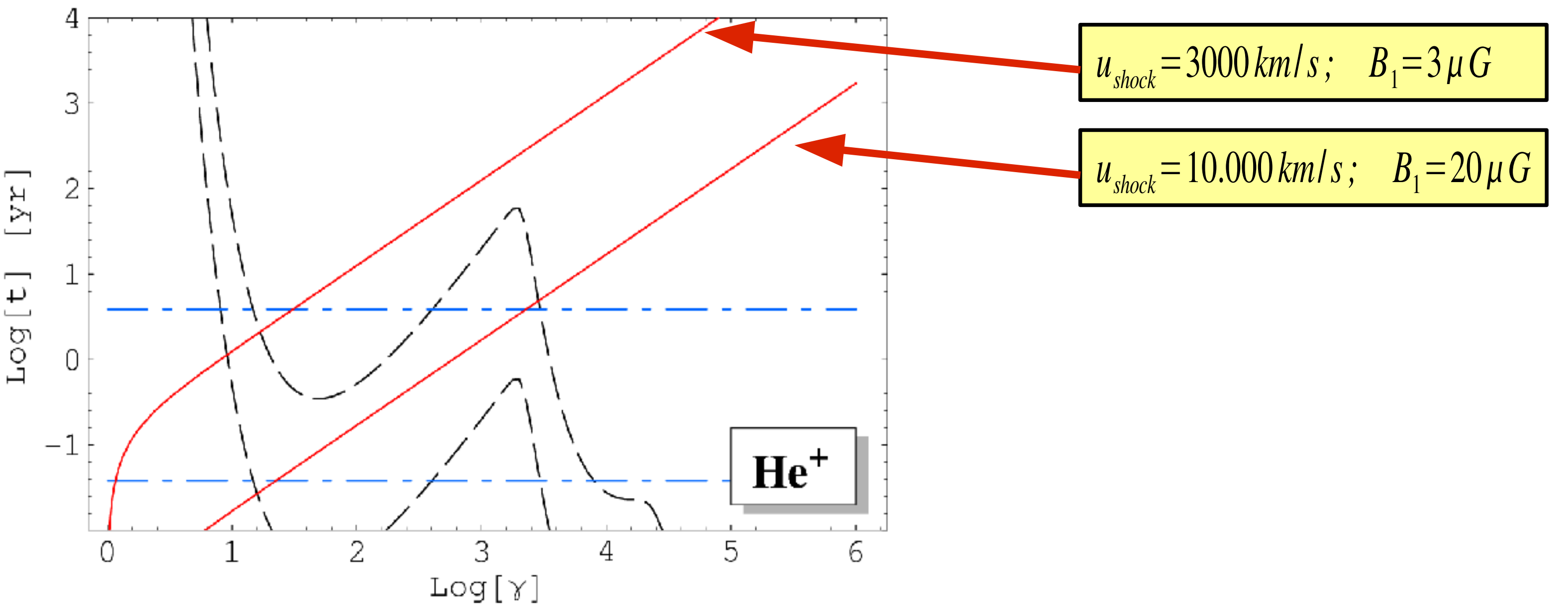
Ionization time due to photoionization

$$\tau_{ph}(\gamma) = \left(\int \frac{dn_{ph}(\epsilon)}{d\epsilon}\, c\, \sigma_{ph}(\gamma \epsilon)\, d\epsilon \right)^{-1} \simeq 0.01\, Z^2 \left(\frac{n_{ph}(I/\gamma)}{1\, cm^{-3}} \right)^{-1} \; yr$$

Electron injection from ionization of heavy elements

Comparison between acceleration and ionization times

$He^+ \rightarrow He^{++} + e^-$



Acceleration time for linear shock acceleration

Electron injection from ionization of heavy elements

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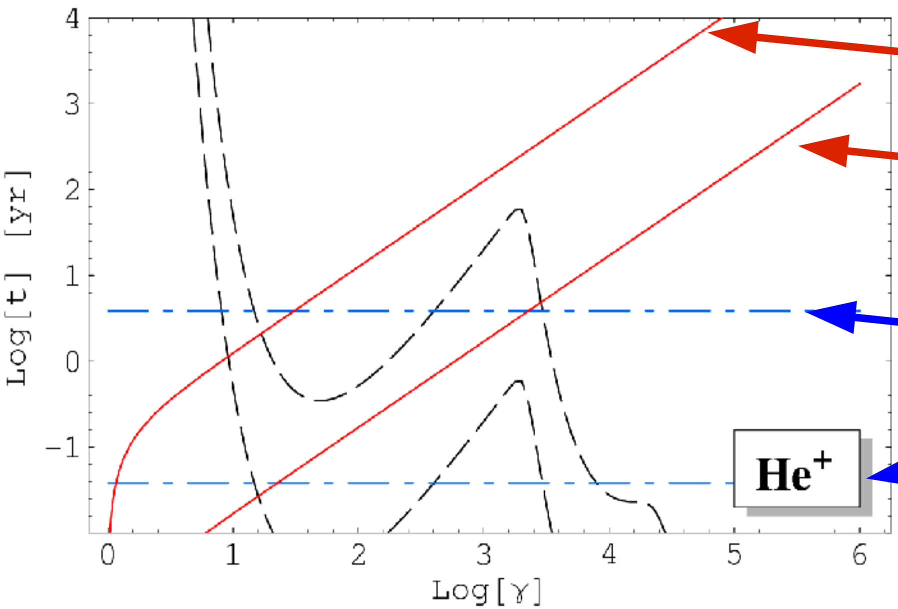

$u_{shock} = 3000\, km/s; \quad B_1 = 3\, \mu G$

$u_{shock} = 10.000\, km/s; \quad B_1 = 20\, \mu G$

Acceleration time for linear shock acceleration

$n_{gas,1} = .01\, cm^{-3}$

$n_{gas,1} = 1\, cm^{-3}$

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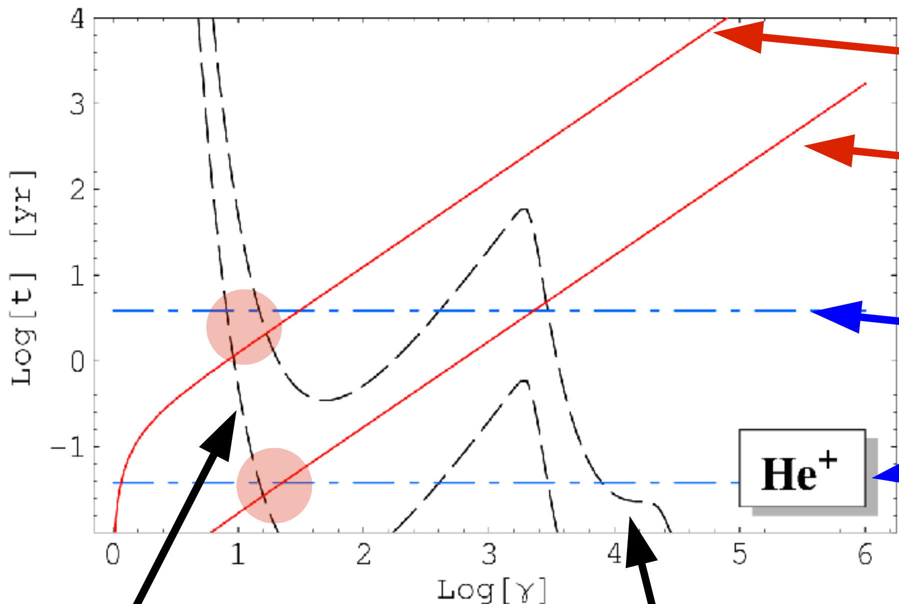

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Ionization time due to photoionization from Galactic background (CMB + IR + Opt)

It is very easy to get $\gamma > 10$ even for He

Electron injection from ionization of heavy elements

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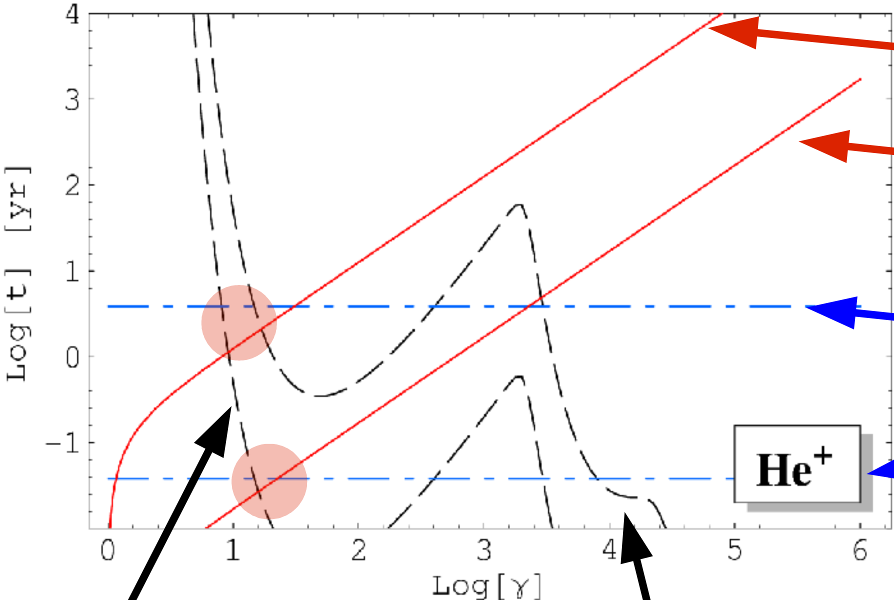

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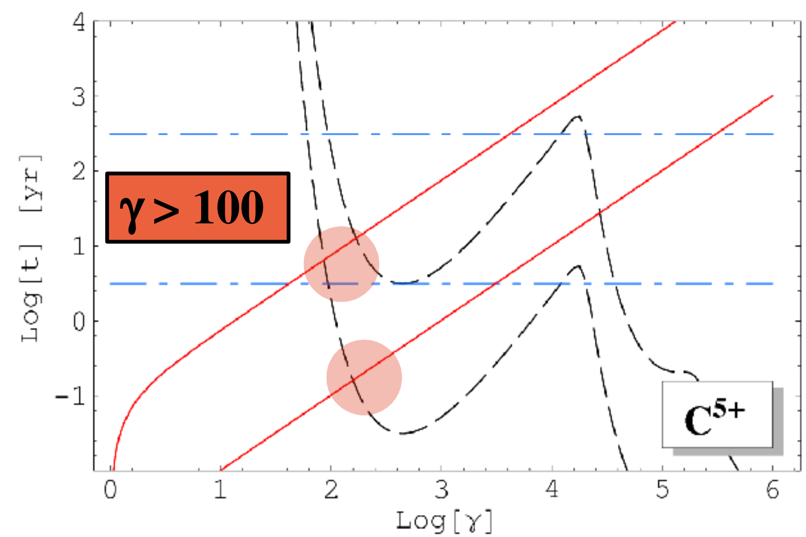
$C^{+5} \rightarrow C^{+6} + e^{-}$



Electron injection from ionization of heavy elements

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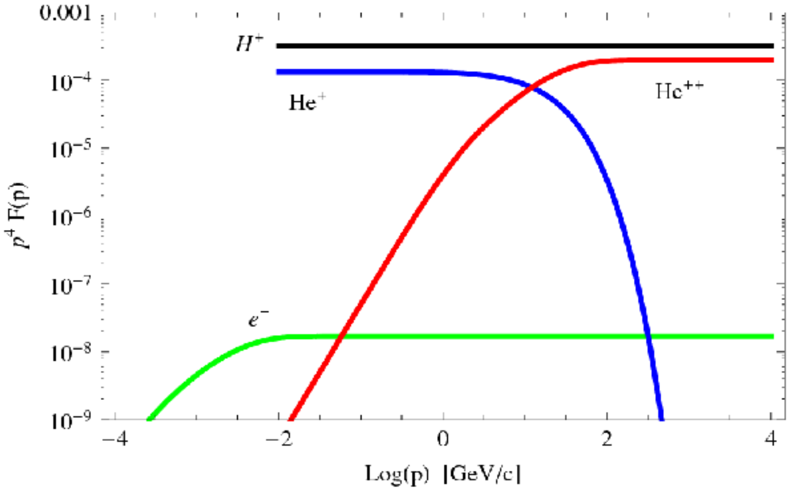
Transport equation in linear theory

$$u\frac{\partial f_i}{\partial x} = D(p)\frac{\partial^2 f_i}{\partial x^2} + \frac{du}{dx}p\frac{\partial f_i}{\partial p} + Q_i - S_i; \quad i = He^{+},\ He^{++},\ e^{-}$$



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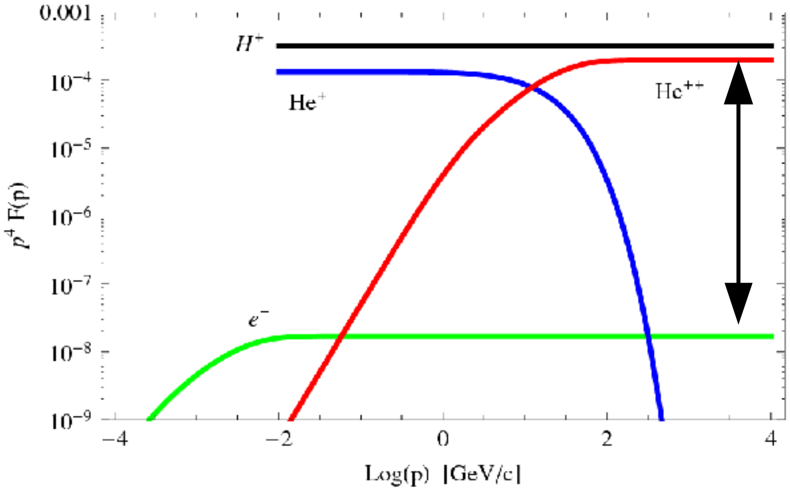
Electron/helium ratio

$$K_{e,He} \stackrel{\text{def}}{=} \frac{f_e(p)}{f_{He}(p)} = \frac{Z}{2Z-1}\left(\frac{m_e}{m_N}\right)^{s-3} \sim 8\cdot 10^{-5}$$



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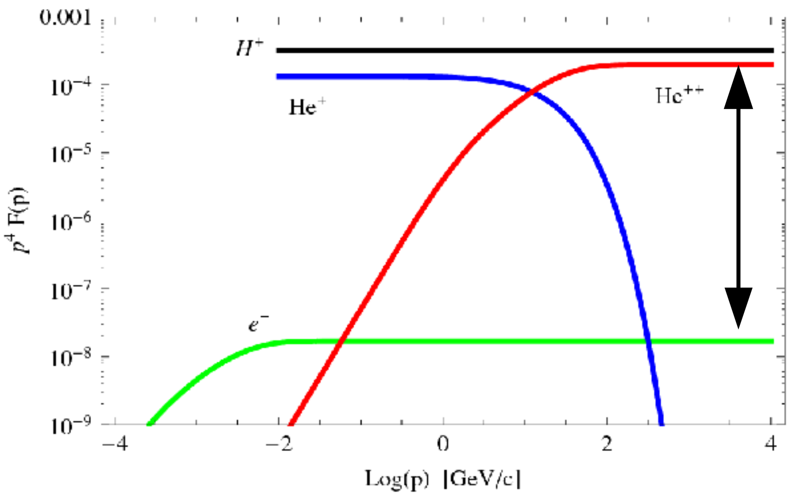

Electron/proton ratio, summing the contribution of all species:

$$K_{ep} = \sum_N \left(\frac{f_N}{f_p}\right)_{Earth} Z_N^{-\delta}\ (Z_N - Z_{N,eff})\,K_{eN} \simeq 10^{-4}$$

Abundance of CR elements measure at Earth

Correction due to propagation from the SNR to the Earth, δ ~ 0.3-0.6

Electron injection from ionization of heavy elements

$He^{+} \rightarrow He^{++} + e^{-}$

Transport equation in linear theory

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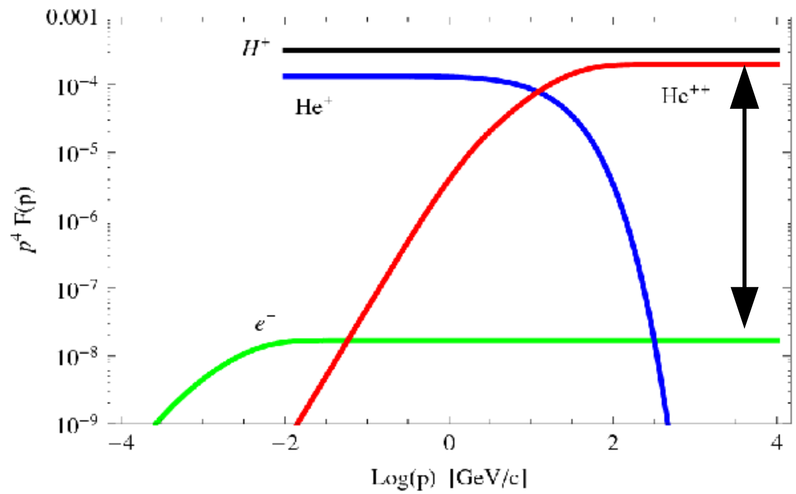
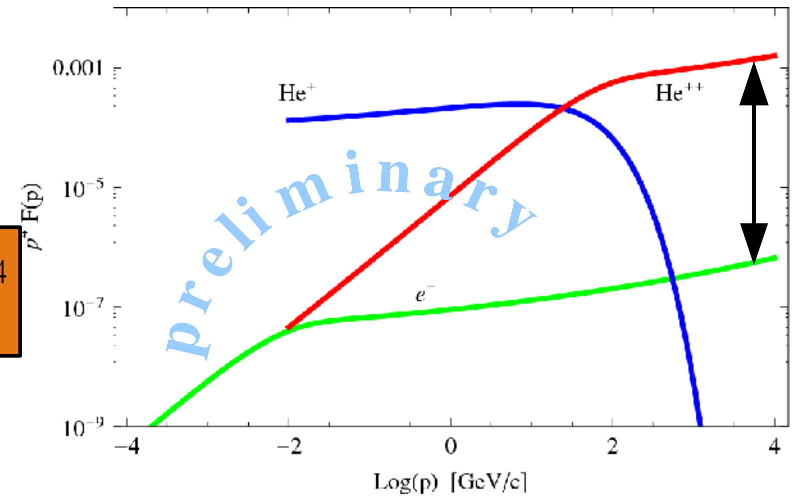
$$K_{ep} > 10^{-4}$$

Abundance of CR elements measure at Earth

Correction due to propagation from the SNR to the Earth, δ ~ 0.3-0.6



Prediction for nonlinear theory



CONCLUSIONS

1) Efficent shock acceleration model does fit pretty well the observed SNR radiation.
We have indirect, observational evidence that SNRs can put ~50% of SN explosion energy into CRs.
What ?

2) Magnetic field amplification? B-field most important parameter in collisionless shocks. Are self-generated fields MUCH larger (x100) than ISM fields? If so, how are they produced? Amplification impacts injection, maximum particle energy (TeV γ-rays), and synchrotron radiation.
Is MFA and intrinsic property of DSA?

3) What is the spectrum of particles a typical SNR contributes to galactic CRs?
The NL spectra generally too hard to match CR spectra observed at Earth!
But the spectrum predicted at the shock is NOT the same that SNRs inject into the Galaxy. Are adiabatic losses during the remnant expansion important?
Role of escaping particles?

4) What is electron/proton ratio? Efficient shock acceleration predict the *e/p* ratio~10^-4, too compared to that observed at Earth.
Is the *e/p* ratio constant during the age of the remnant?
Can the electrons be produced by other sources (e.g. pulsar)?