Gamma-ray (and broad-band) emission from SNRs

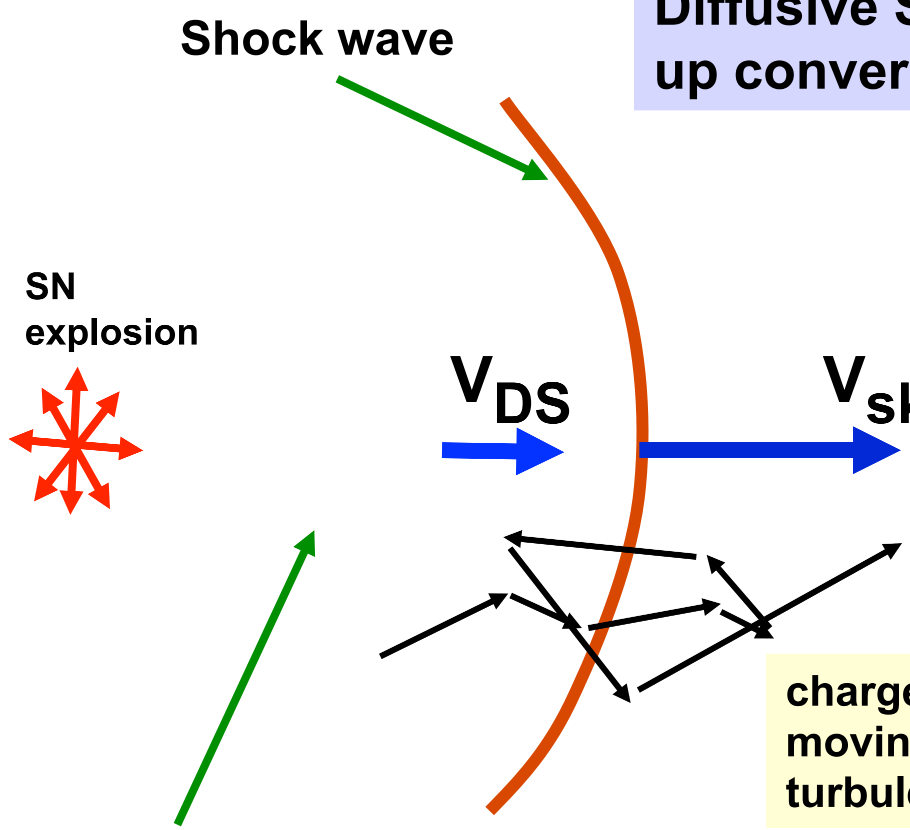
Don Ellison, NCSU

Diffusive Shock Acceleration (DSA) in Supernova Remnants
(also called first-order Fermi mechanism)

Discuss spectra and radiation expected when shock acceleration of cosmic rays (CRs) is efficient ➔ Nonlinear DSA

Diffusive Shock Acceleration: Shocks set up converging flows of ionized plasma

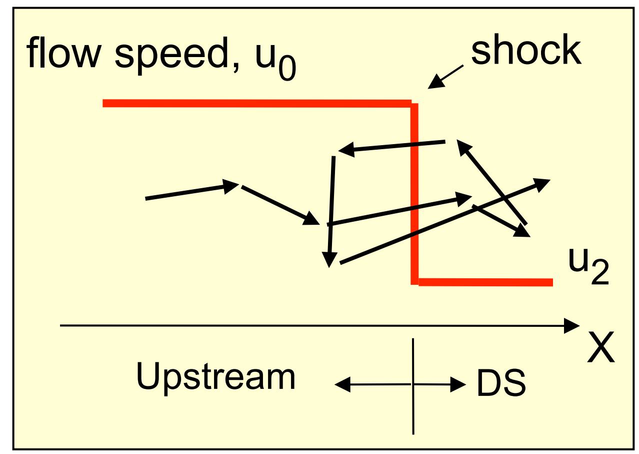
Interstellar medium (ISM), cool with speed $V_{ISM} \sim 0$



charged particle moving through turbulent B-field

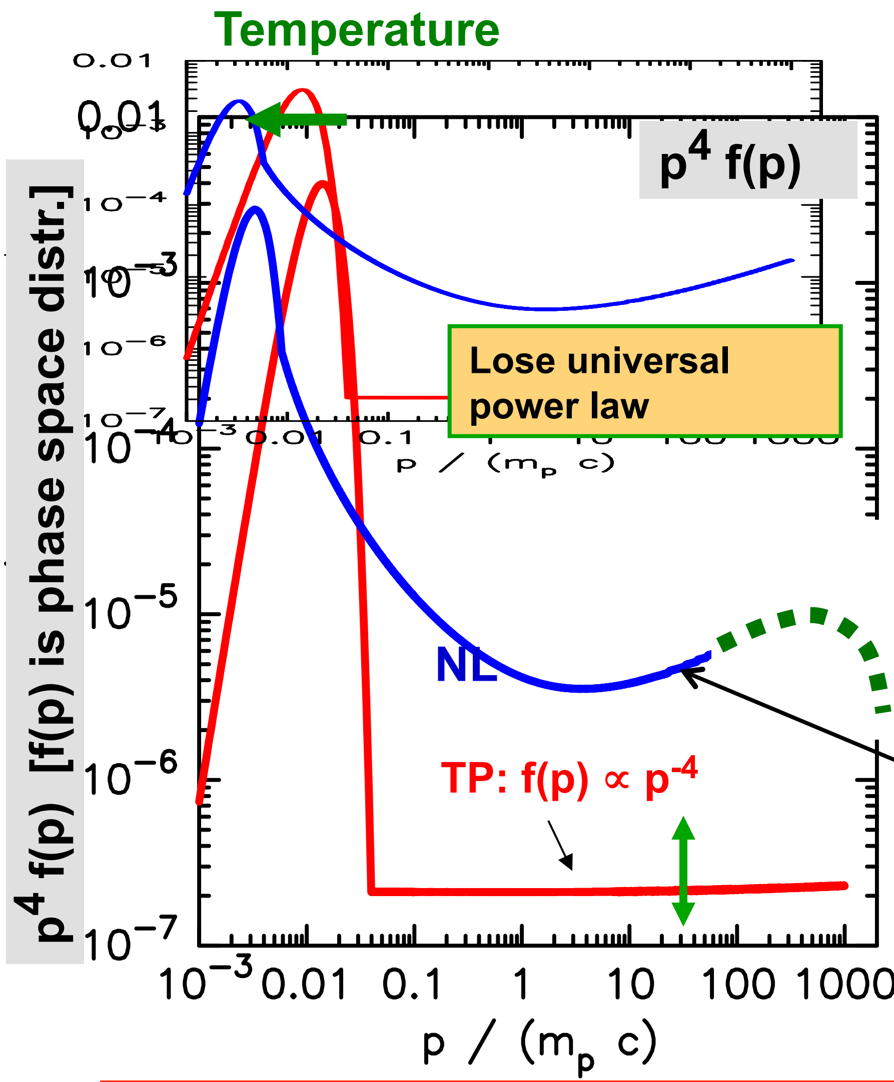
Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$

shock frame

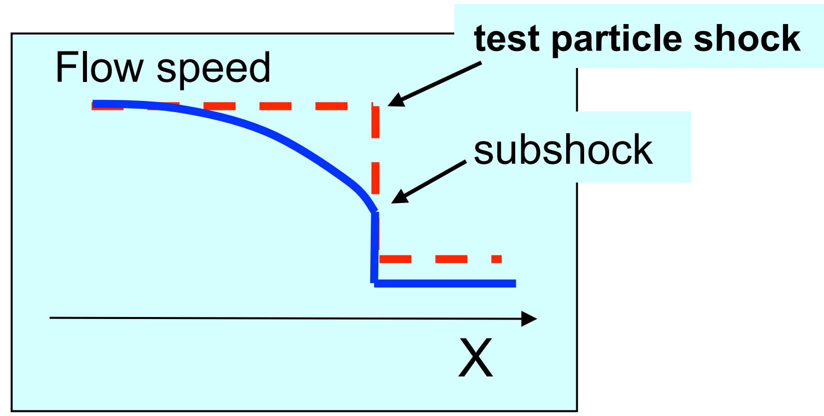


$u_2 = V_{sk} - V_{DS}$

Particles make nearly elastic collisions with background plasma
➔ gain energy when cross shock ➔ bulk kinetic energy of converging flows put into individual particle energy



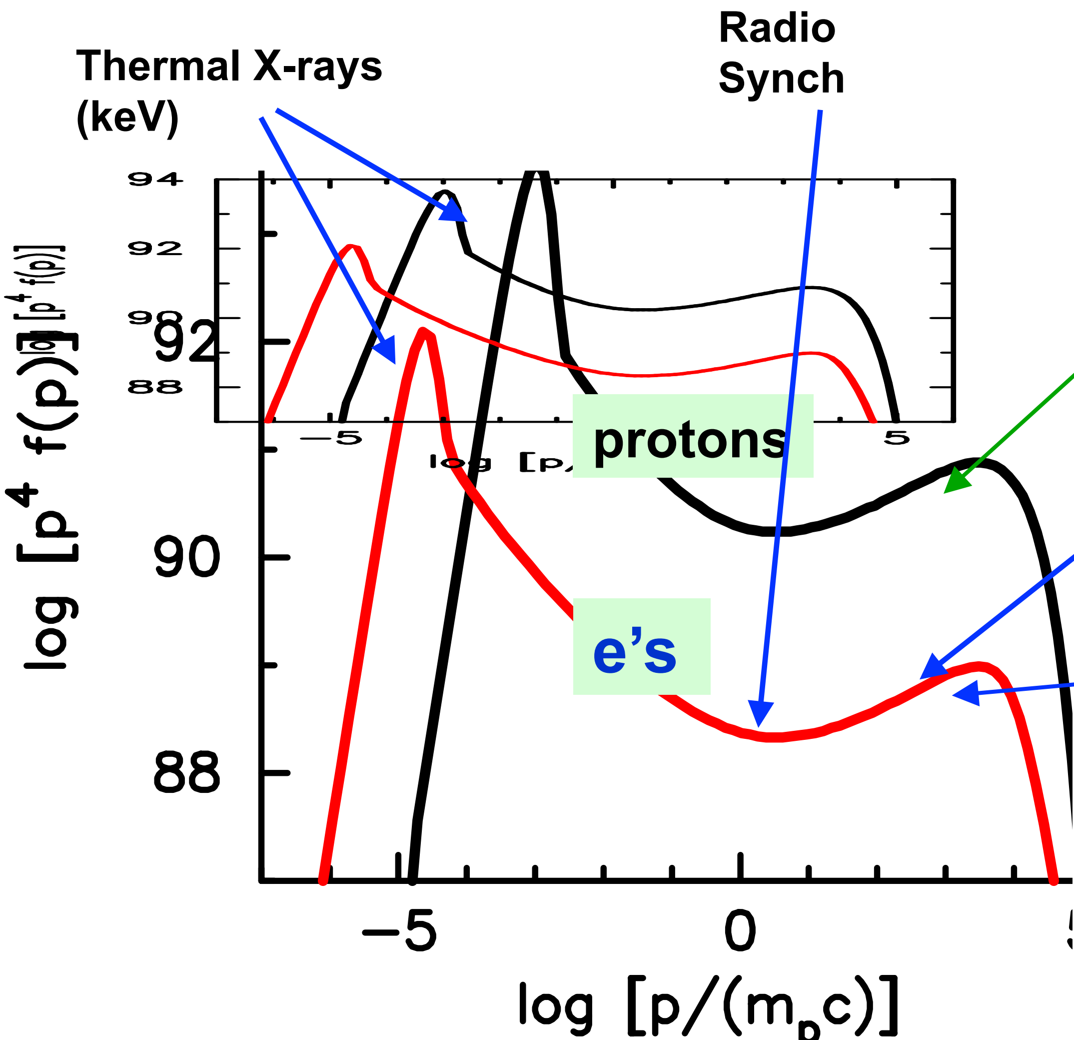
If acceleration is **efficient**, shock becomes smooth from backpressure of CRs



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

In efficient acceleration, entire particle spectrum must be described consistently, including escaping particles ➔ much harder mathematically
BUT, connects photon emission across spectrum from radio to γ-rays

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



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

compete at TeV energies

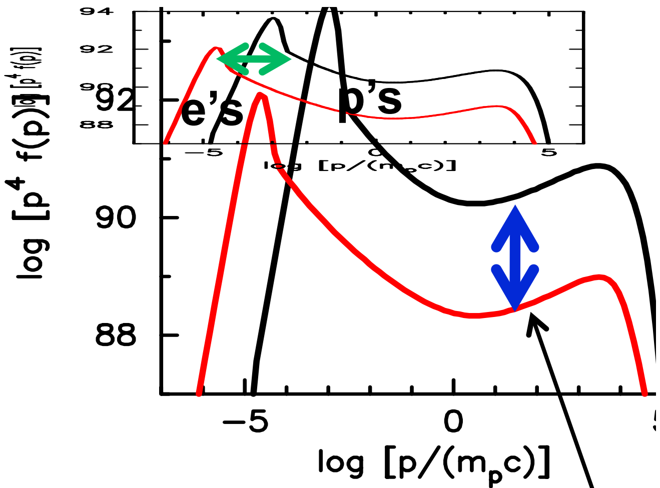
X-ray Synch
(keV X-rays)

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

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

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

Particle distributions

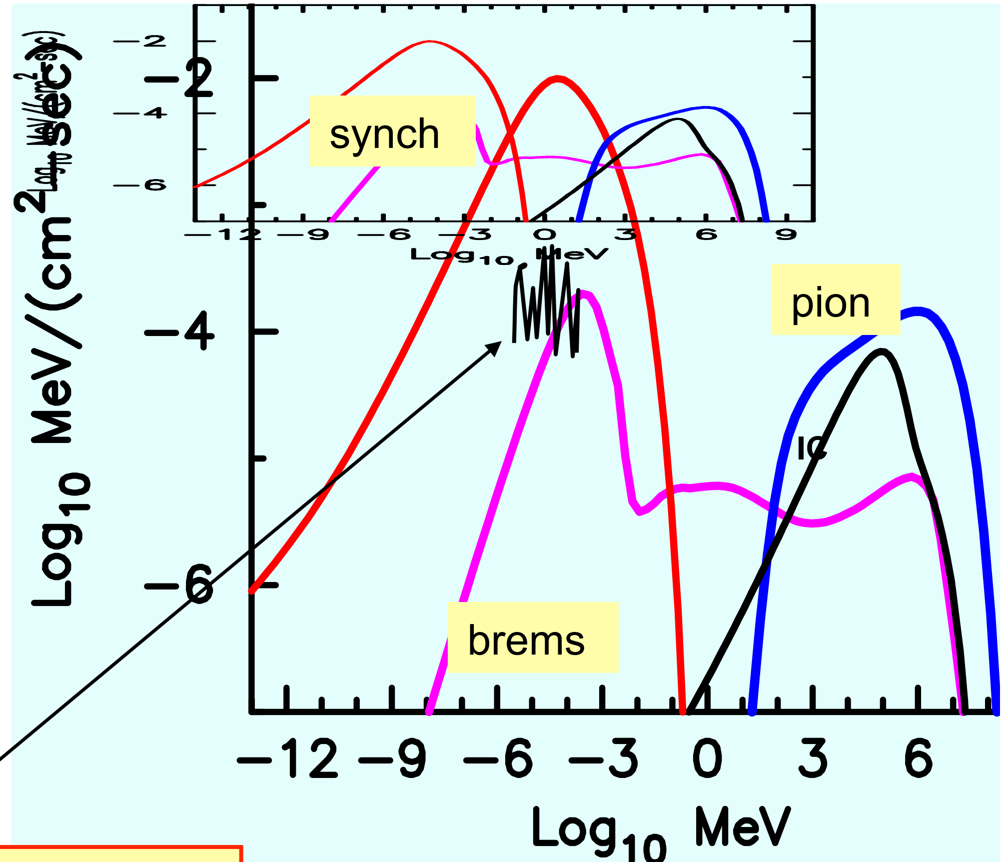


For electrons, need two extra parameters

Electron/proton ratio, K_{ep}

K_{ep} important for p-p/IC ratio at GeV-TeV

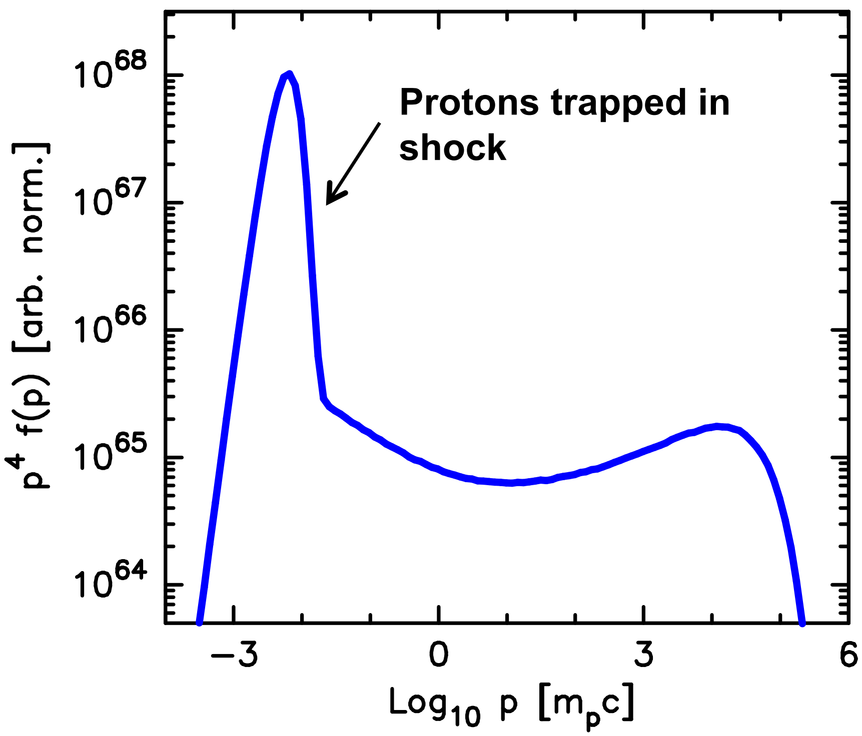
continuum emission



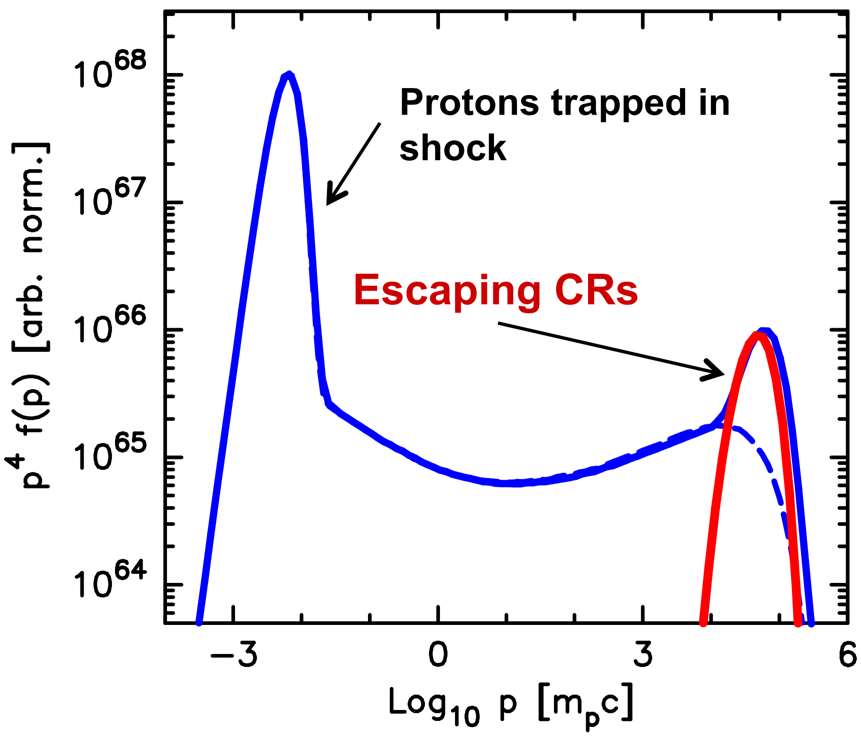
In addition, emission lines in thermal X-rays. Depend on T_e/T_p

K_{ep} and T_e/T_p not yet determined by theory or plasma simulations!

Work in progress: **Must also consider escaping CRs. For efficient DSA, a large fraction of CR energy can be in Qesc**



For efficient DSA, a large fraction of CR energy can be in Qesc



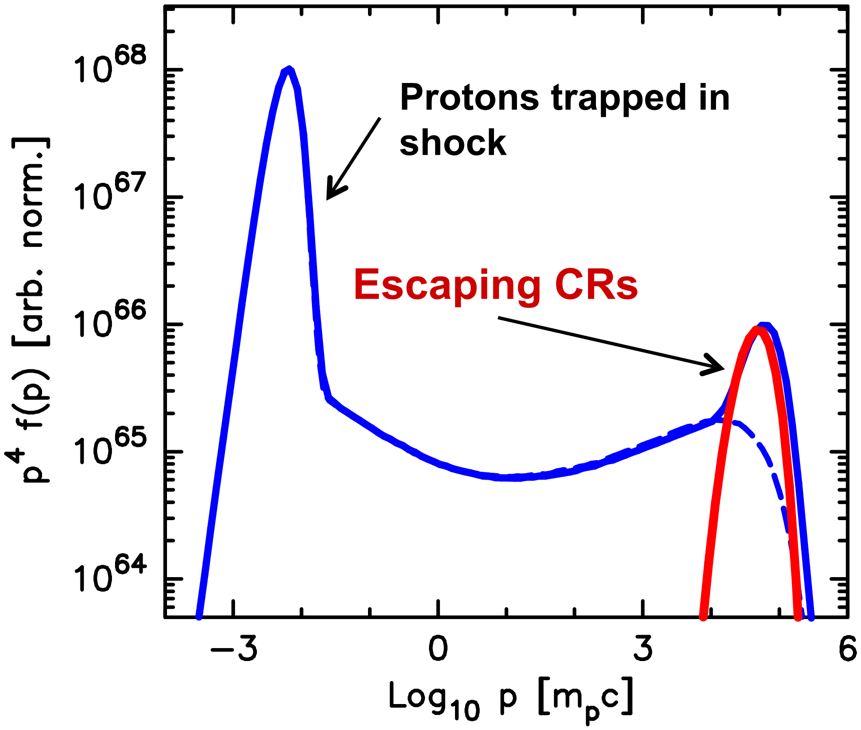
For this example, for ε_{DSA} = 80%, 20% of SN explosion energy goes into CRs after 1000 yr

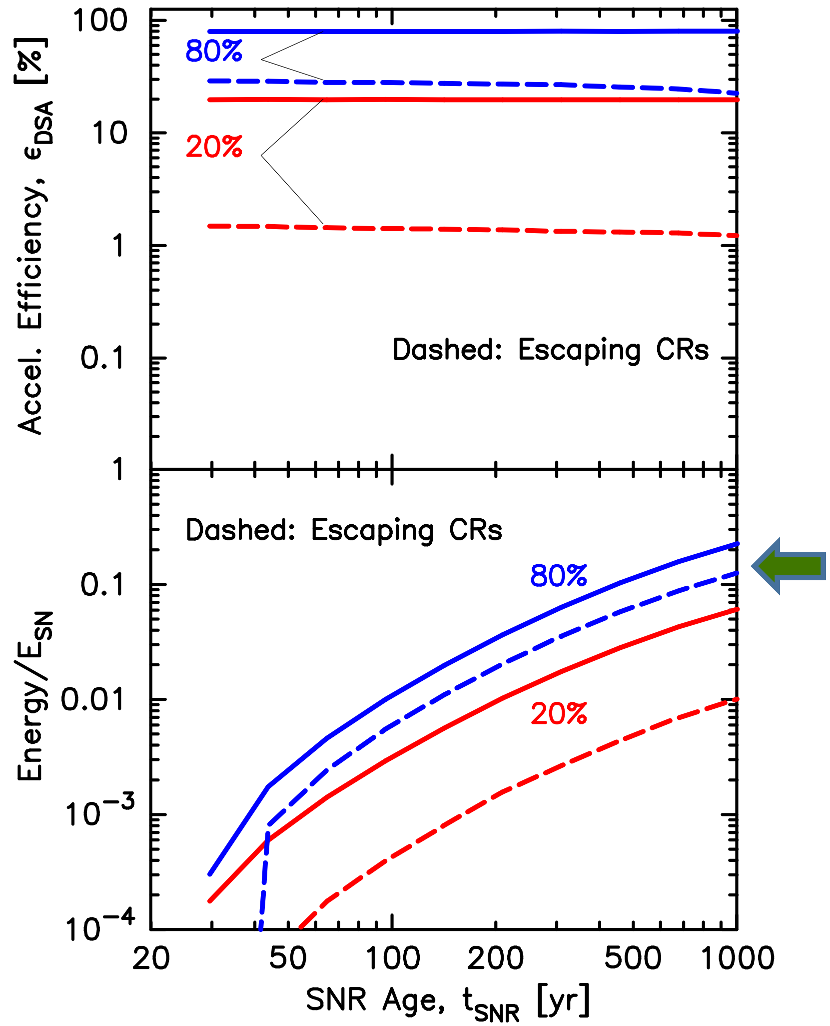
1/2 of this is in escaping particles

Very different spectral shape from trapped CRs

Escaping CRs produce gamma-rays if impact dense material

For efficient DSA, a large fraction of CR energy can be in Qesc





For this example, for ϵ_{DSA} = 80%, 20% of SN explosion energy goes into CRs after 1000 yr
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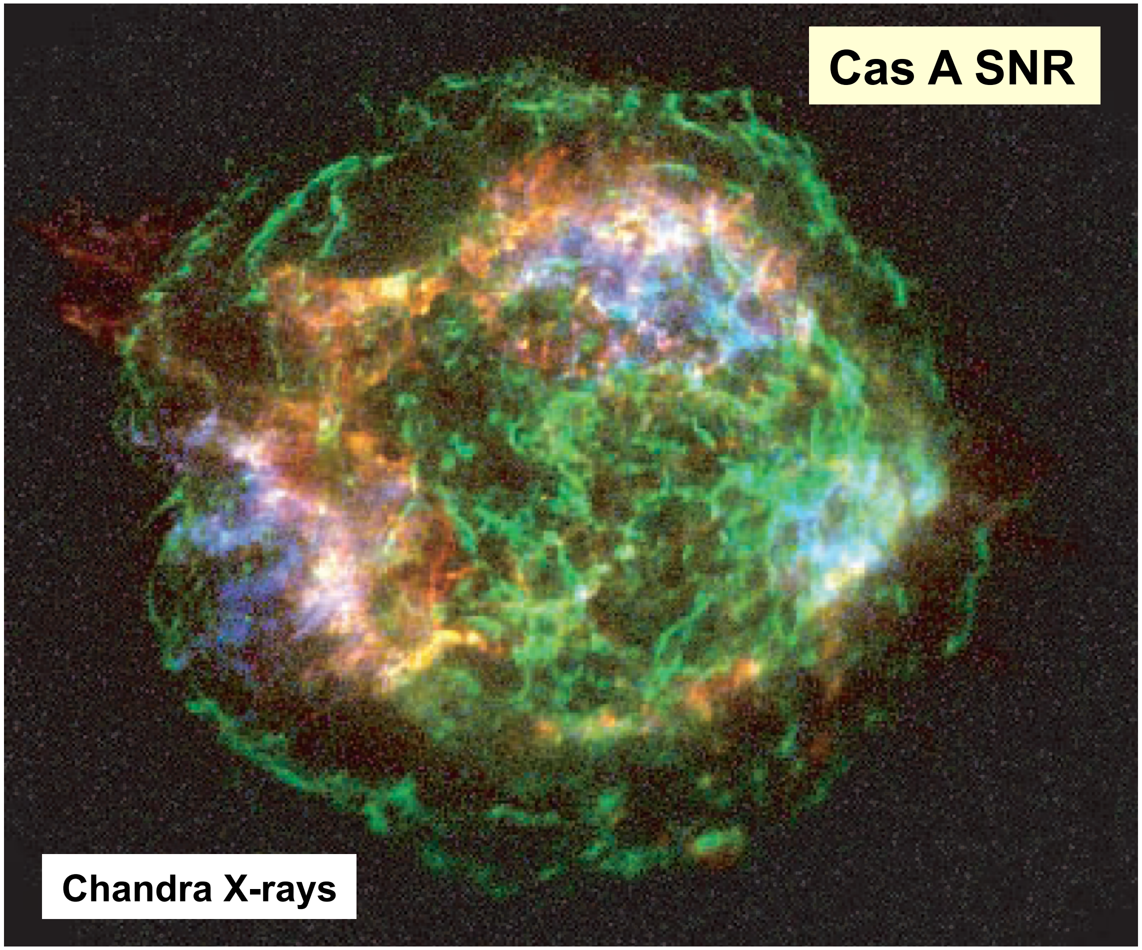
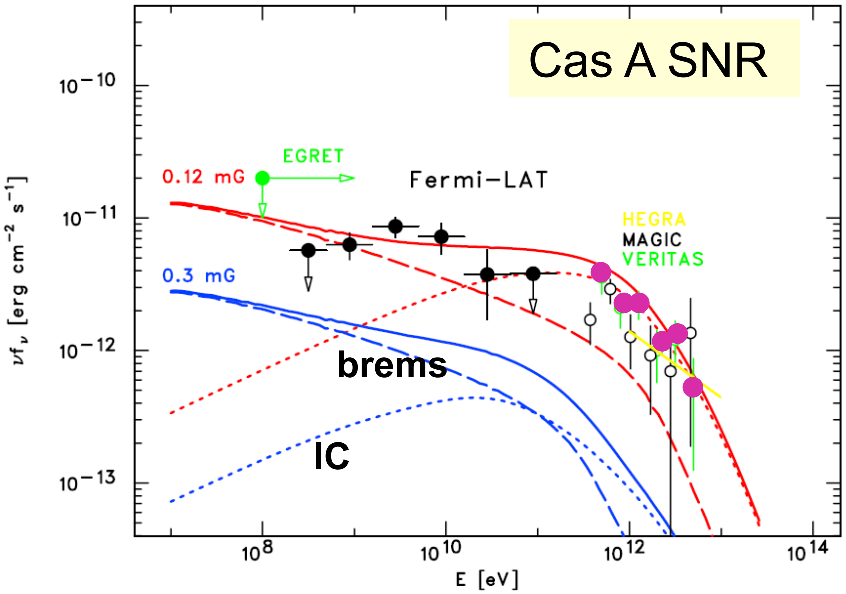
Escaping CRs produce gamma-rays if impact dense material

How do important parameters influence GeV-TeV emission in SNR models?

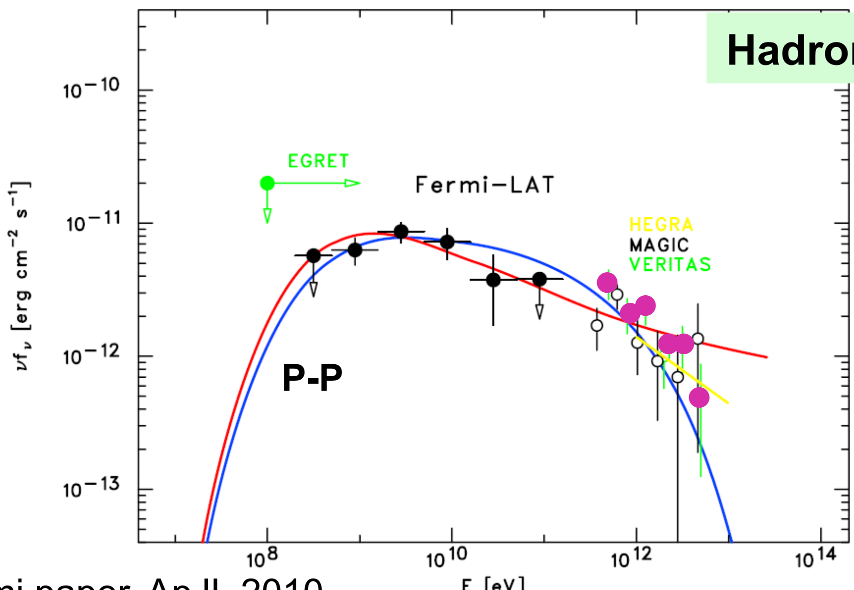


Hwang et al 2004

How do important parameters influence GeV-TeV emission in SNR models?



Lepton model, Inverse-Compton & brems. from electrons



Hadron model: pion-decay from protons

What parameters determine these fits?

What observations are needed to constrain them?

Fermi paper, ApJL 2010

(No escaping CRs in these models)

Some (but not all) of the important parameters in SNRs & nonlinear DSA:

1) electron/proton ratio, K_{ep} (uncertain by 2 orders of magnitude!)
   a) Most important factor for pion-decay vs. Inverse-Compton
   b) ➔ Synchrotron intensity (Radio & X-rays)

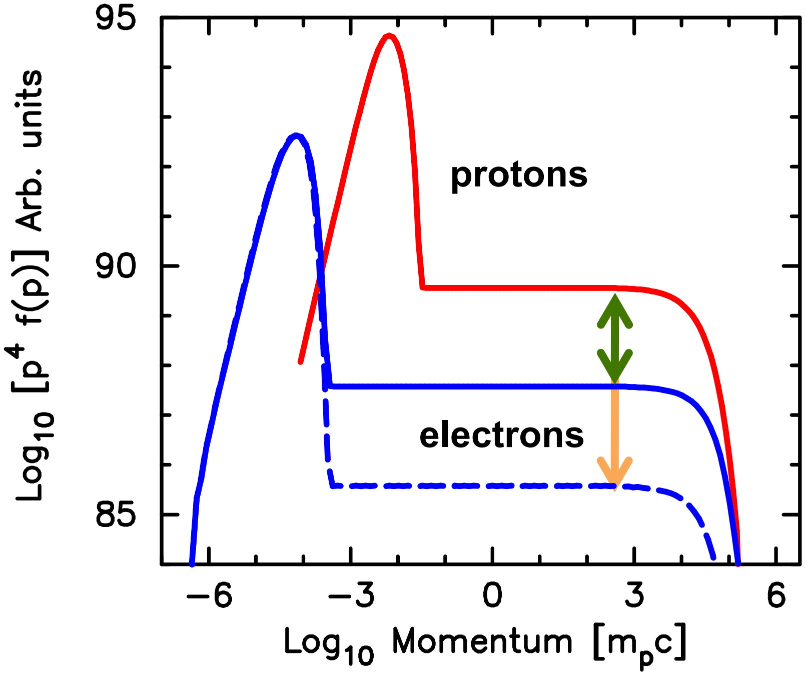
2) DSA efficiency, ε_{DSA} (Expect to be high ~50-75%)
   a) Modifies shape of spectrum ➔ concave curvature
   b) Increases overall intensity of nonthermal emission

3) Amplification factor for magnetic field, B_{amp} (≥10 in some cases)
   a) Extends proton Emax
   b) Reduces electron Emax
   c) Larger B ➔ less important IC (need fewer electrons to produce radio)
   d) Changes shape and intensity of synch.

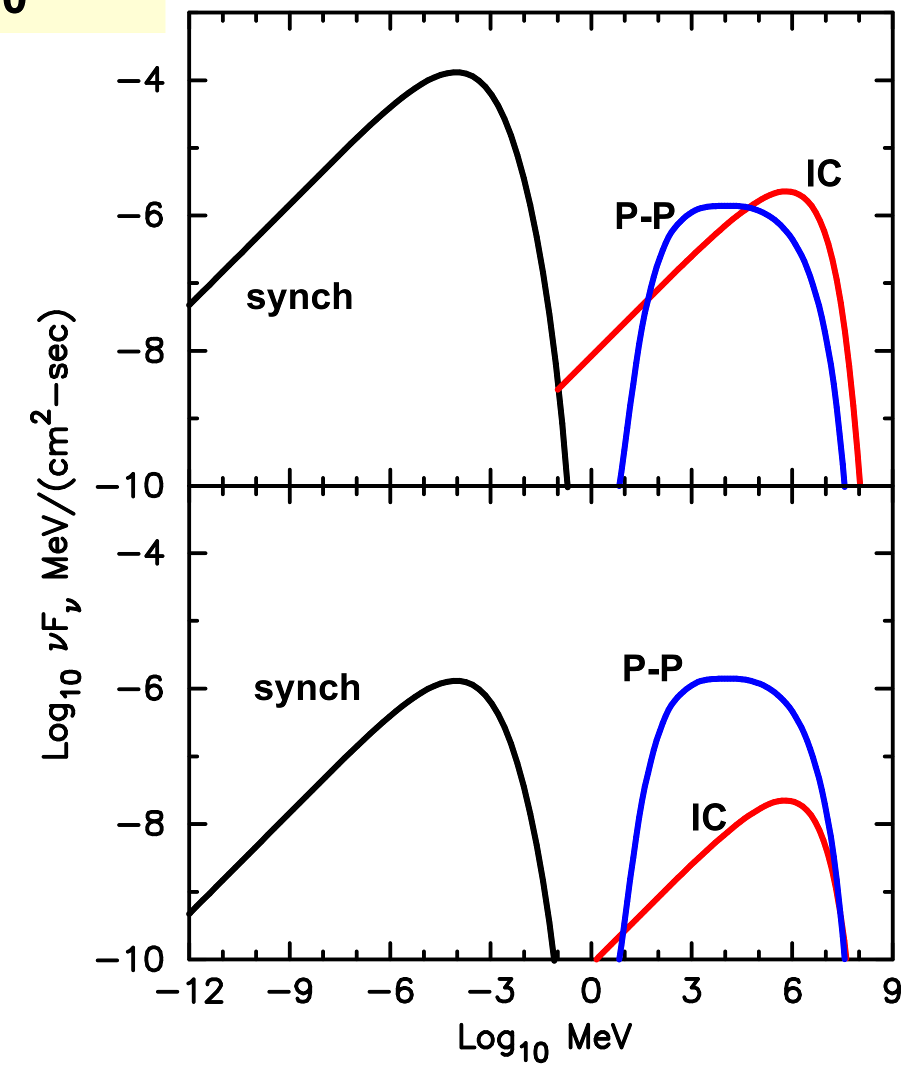
4) Shape of particle spectra near maximum
   a) Not yet determined by theory ➔ depends on turbulence generation
   b) ➔ shape of protons and pion-decay emission
   c) ➔ shape of e's and X-ray synch near 1 KeV if B small

Other parameters: ambient density, Size of acceleration region, pre-SN shells, etc….

Vary e/p ratio K_{ep} between 10^{-2} & 10^{-4}



Example: Not for a specific SNR



► Low K_{ep} ➔ low IC and low synch.
➔ Pion-decay dominates GeV-TeV

Some (but not all) of the important parameters:

1) electron/proton ratio, K_{ep} (uncertain by 2 orders of magnitude)
   a) Most important factor for P-P/IC ratio
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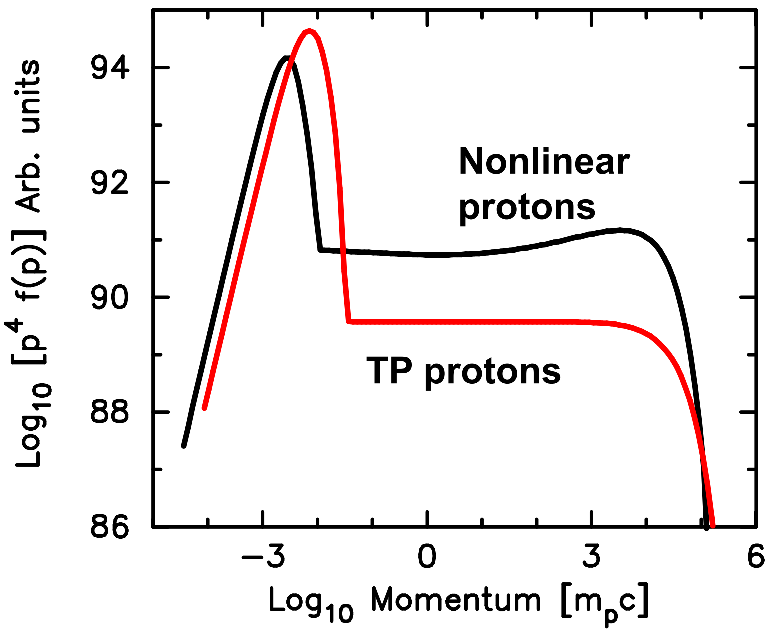
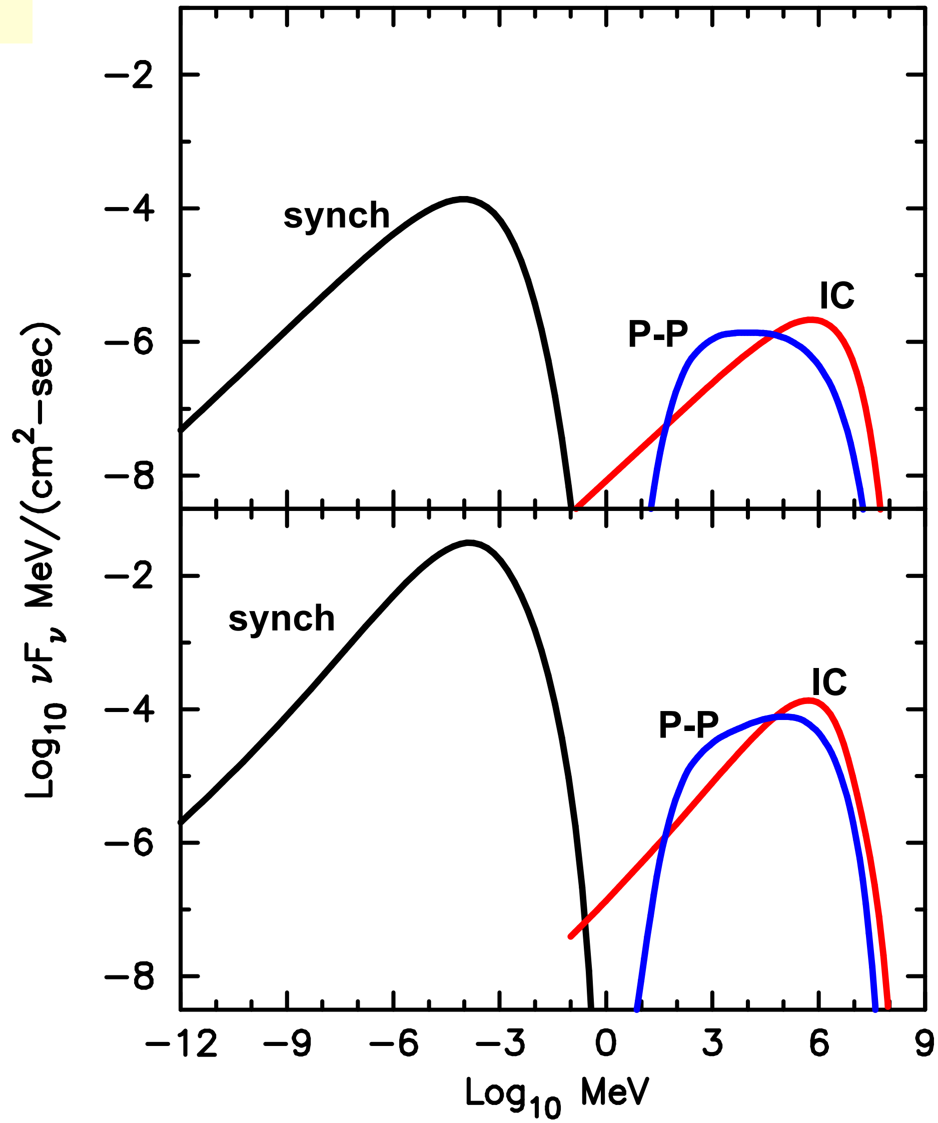
Other parameters: Density, Size of acceleration region, pre-SN shells, etc.…

Vary ε_{DSA} between 1% and 75%





► Curvature (also in electron spectrum) important for radio to X-ray match.

► Big increase in overall intensity

► Change in shape of GeV-TeV emission

Some (but not all) of the important parameters:

1) electron/proton ratio, K_{ep} (uncertain by 2 orders of magnitude)
   a) Most important factor for P-P/IC ratio
   b) ➔ Synchrotron flux (Radio & X-rays)

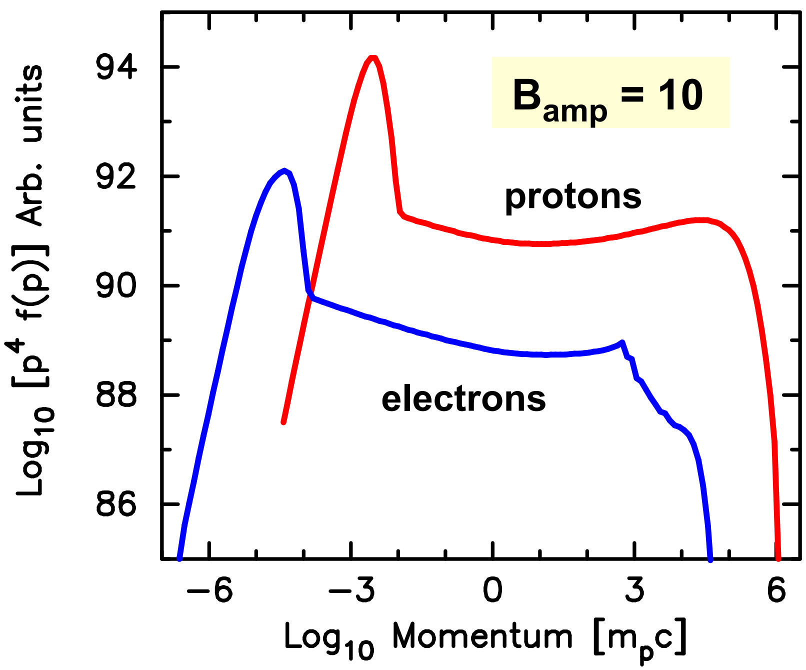
2) DSA efficiency, ε_{DSA} (Expect to be high ~50-75%)
   a) Modifies shape of spectrum ➔ concave curvature
   b) Increases overall intensity of source

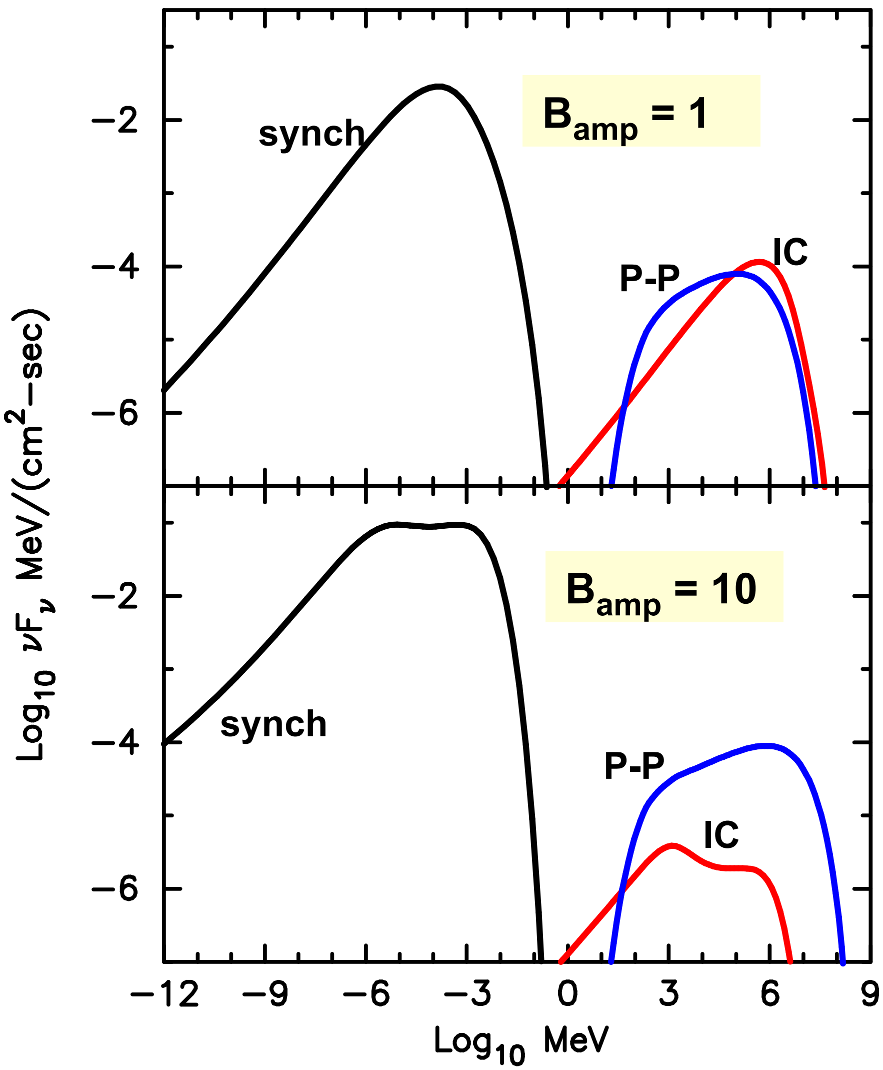
3) Amplification factor for magnetic field, B_{amp} (≥10 in some cases)
   a) Extends proton Emax
   b) Reduces electron Emax
   c) Larger B ➔ less important Inverse-Compton
   d) Changes shape and intensity of synch.

4) Shape of particle spectra near maximum
   a) Not yet determined by theory ➔ depends on turbulence generation
   b) ➔ shape of protons and pion-decay emission
   c) ➔ shape of e's and X-ray synch near 1 KeV if B small

Other parameters: Density, Size of acceleration region, pre-SN shells, etc….

Vary B_{amp} between 1 and 10





► More energetic protons, less energetic electrons
► IC less important vs. pion-decay
► Big change in shape of X-ray synch.

Some (but not all) of the important parameters:

1) electron/proton ratio, K_{ep} (uncertain by 2 orders of magnitude)
    a) Most important factor for P-P/IC ratio
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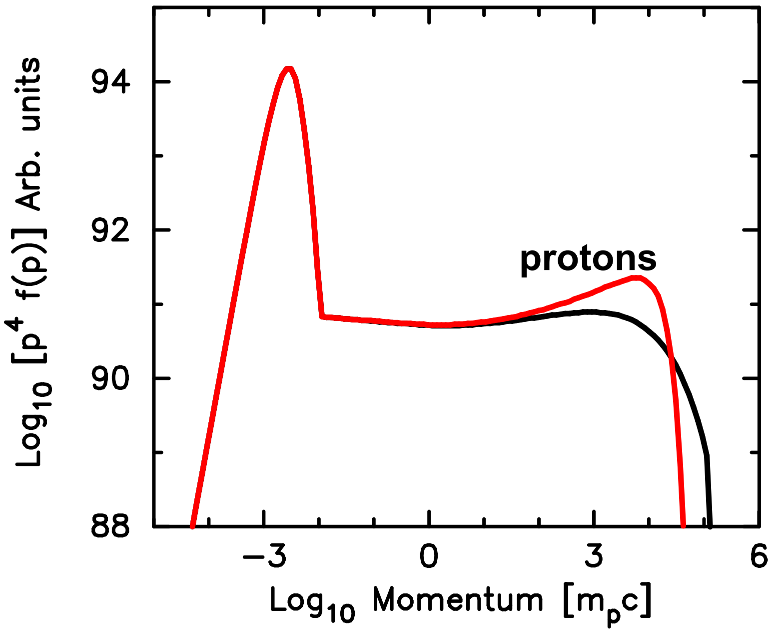
    c) Larger B ➔ less important IC
    d) Changes shape and intensity of synch.

4) Shape of particle spectra near maximum, AND Emax
    a) Neither shape nor Emax yet determined by theory !! ➔ depend on turbulence generation
    b) ➔ shape of protons and pion-decay emission
    c) ➔ shape of e's and X-ray synch near 1 KeV if B small

Other parameters: Density, Size of acceleration region, pre-SN shells, etc….

Vary shape of cutoff

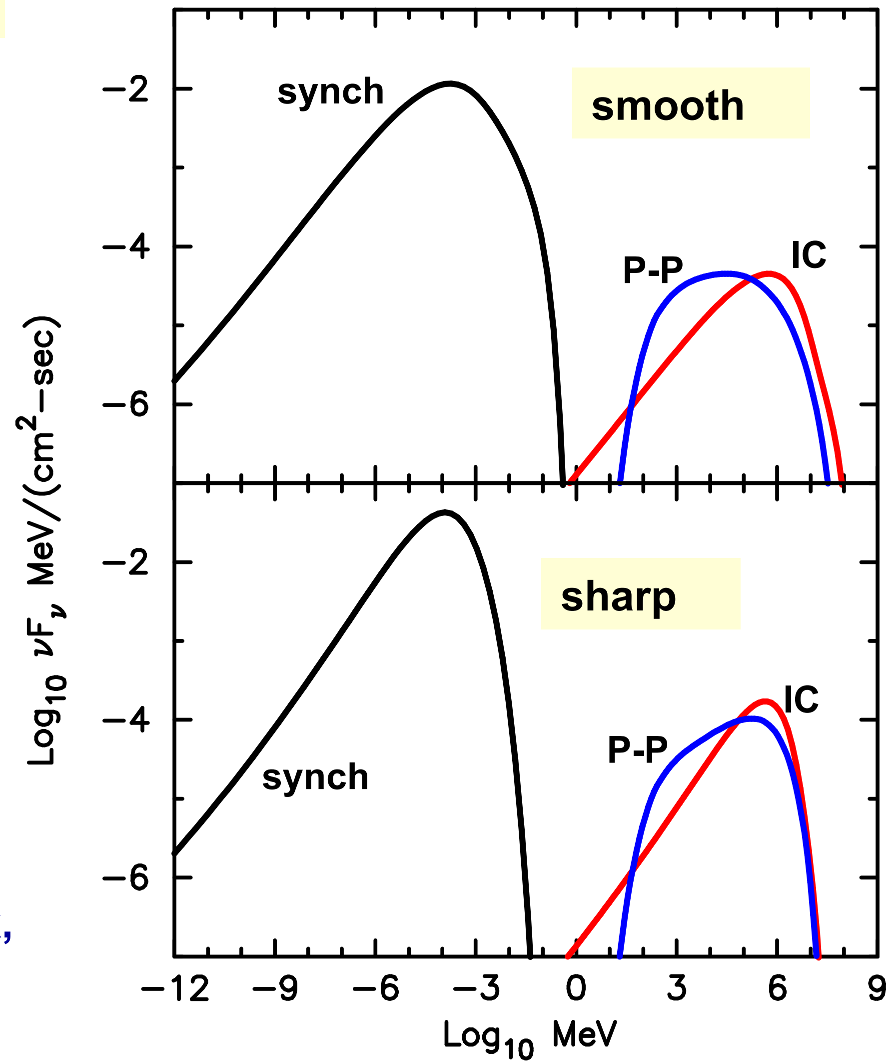


At GeV-TeV energies, **shape**, is main way to discriminate between hadronic & leptonic models

BUT, shape in cutoff region, and Emax, depend on how escaping particles produce magnetic turbulence

Neither Shape nor position (Emax) yet determined by theory

Example: Not for a specific SNR



Warning: Beware of perfect matches to broad-band observations !!

Add another piece of the puzzle:

Self-consistent calculation of thermal X-ray emission in shocks undergoing efficient DSA

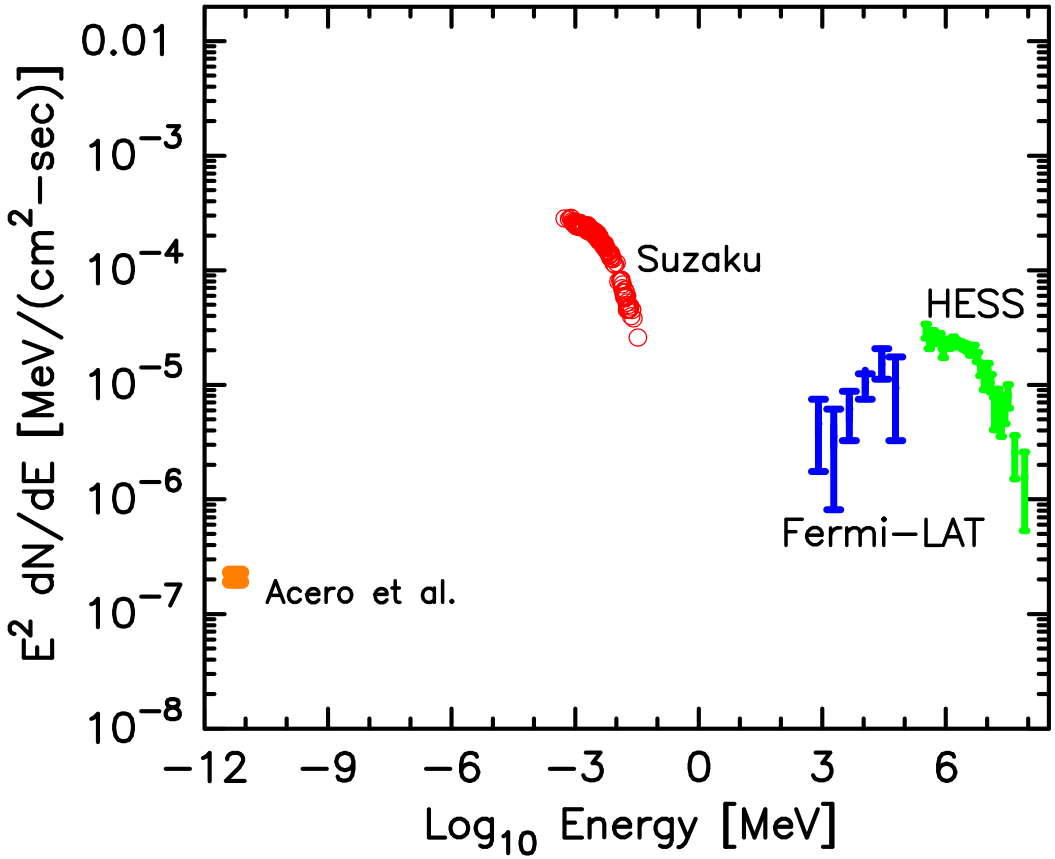
Model thermal X-ray line emission along with nonthermal continuum

If DSA is efficient:
How highest energy particles are accelerated influences the lowest energy (thermal) particles

Model SNR RX J1713

Current work with Pat Slane, Dan Patnaude, & John Raymond

Thermal & Non-thermal Emission in SNR RX J1713



1) **Suzaku X-ray observations ➔ smooth continuum well fit by synchrotron from TeV electrons**

2) **No discernable line emission from shocked heated heavy elements**

3) **Lack of thermal X-ray emission places strong constraint on Non-thermal emission at GeV-TeV energies**

Must calculate thermal & non-thermal emission consistently with Diffusive Shock Acceleration (DSA) and SNR dynamics

Example of Large B-field model for SNR J1713 ➔ TeV fit with pion-decay from protons

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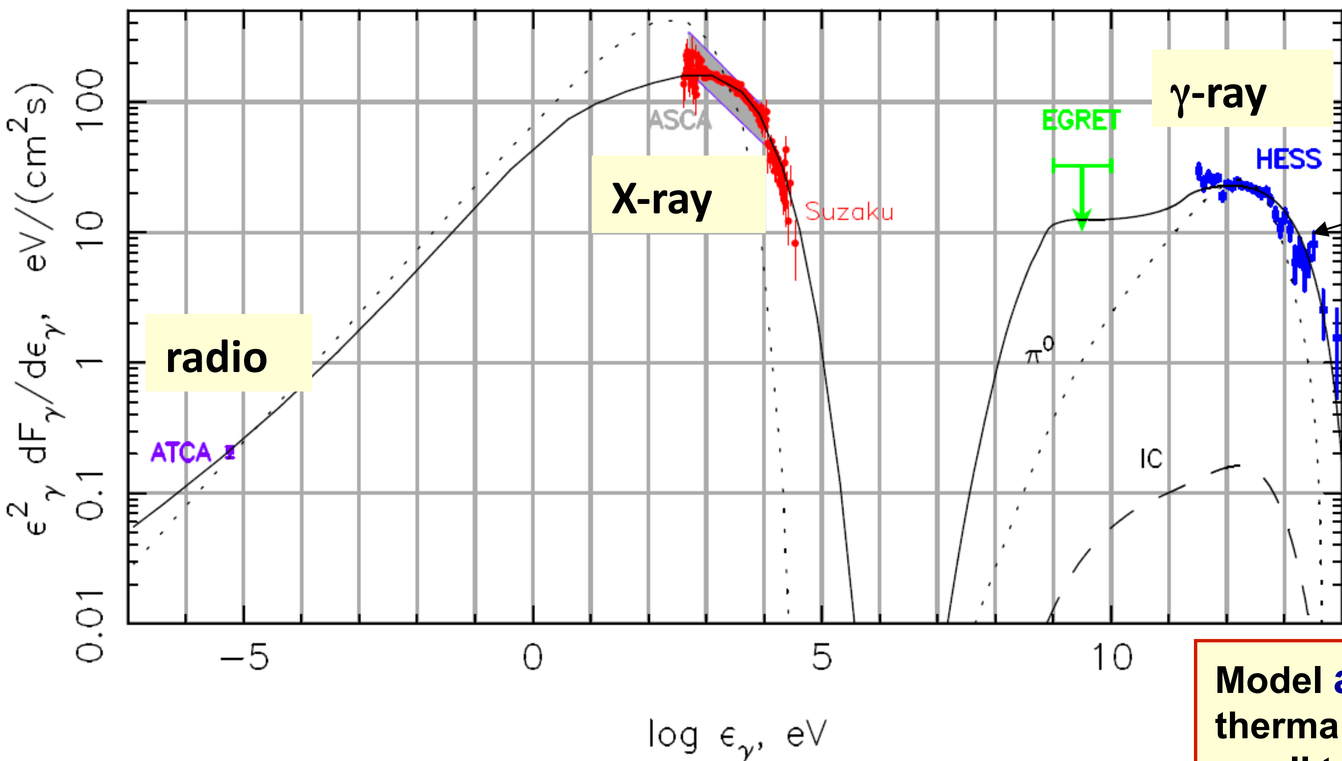
Berezhko & Voelk (2006,2008) model of SNR J1713

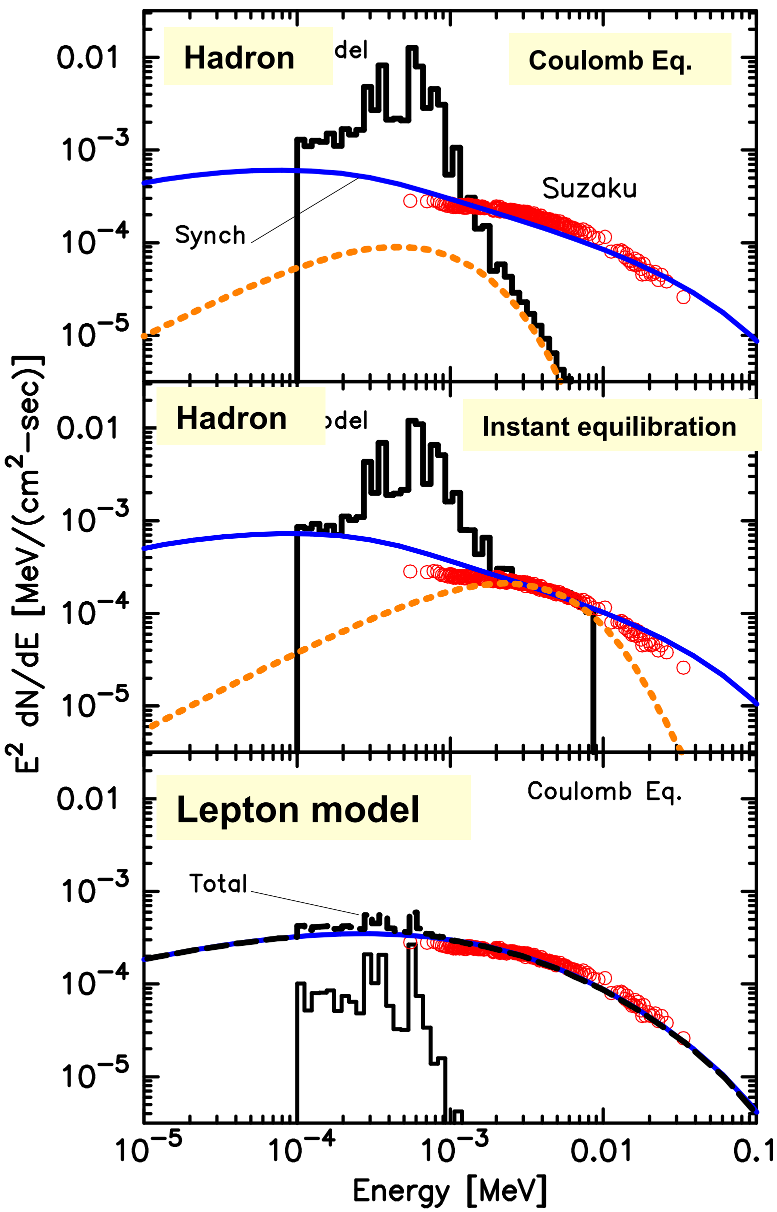


HESS data fit with pion-decay from protons.

Fit requires large B-field AND small e/p ratio (at rel. energies)

Model assumes thermal emission is small to match lack of lines in Suzaku data

Fig. 2. Spatially integrated, overall nonthermal spectral energy distribution of RX J1713.7-3946 The *solid* (10^7 eV corresponds to π^0-decay γ-ray emission, whereas the *dashed* curve indicates the Inverse Compton (IC) emission. The dotted line corresponds to the test particle limit which implies insignificant proton acceleration and magnetic field amplification (see Berezhko & Völk, 2008, for the details). The ATCA radio data, as derived by Acero et al. (2009), the ASCA X-ray data (cf. Aharonian et al., 2006), the Suzaku X-ray data (Uchiyama et al., 2007), and the 2006 HESS γ-ray data (Aharonian et al., 2007) are also shown. The EGRET upper limit for the RX J1713.7-3946 position (Aharonian et al., 2006) is included as well.



Ellison, Patnaude, Slane & Raymond ApJ 2010

Models including Thermal X-ray lines:

► **Compare Hadronic & Leptonic parameters**

► **Calculate electron temperature equilibration**

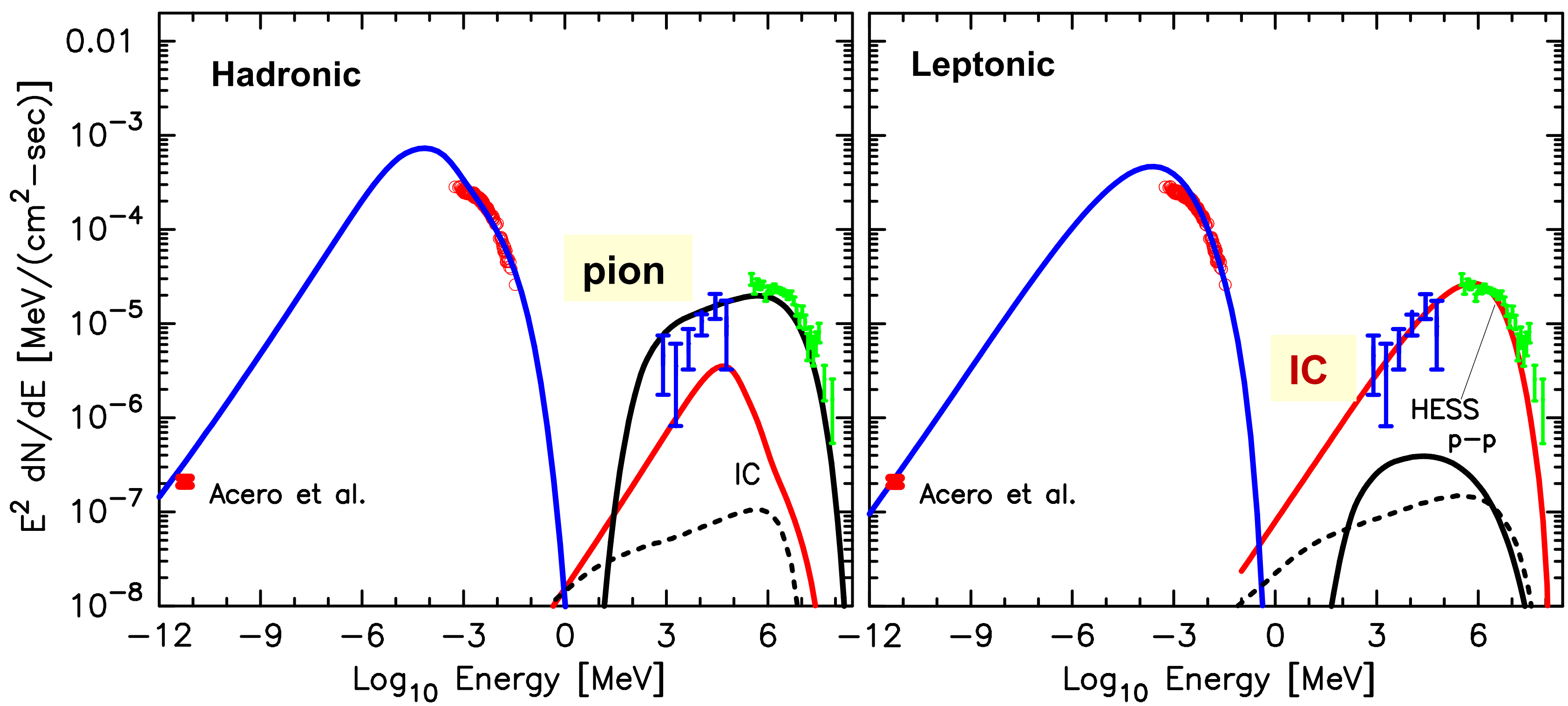
► **Non-equilibrium ionization calculation of heavy element ionization and X-ray line emission**

► **Find: High ambient densities needed for pion-decay to dominate at GeV-TeV energies produce strong X-ray lines**

► **Suzaku would have seen these lines**

➔ **Hadronic models excluded, at least for uniform ISM environments**

For J1713, good fits possible to continuum only with either pion-decay or IC dominating GeV-TeV emission



Hadronic model parameters:
n_p = 0.2 cm^{-3}

e/p = K_{ep} = 5 x 10^{-4}

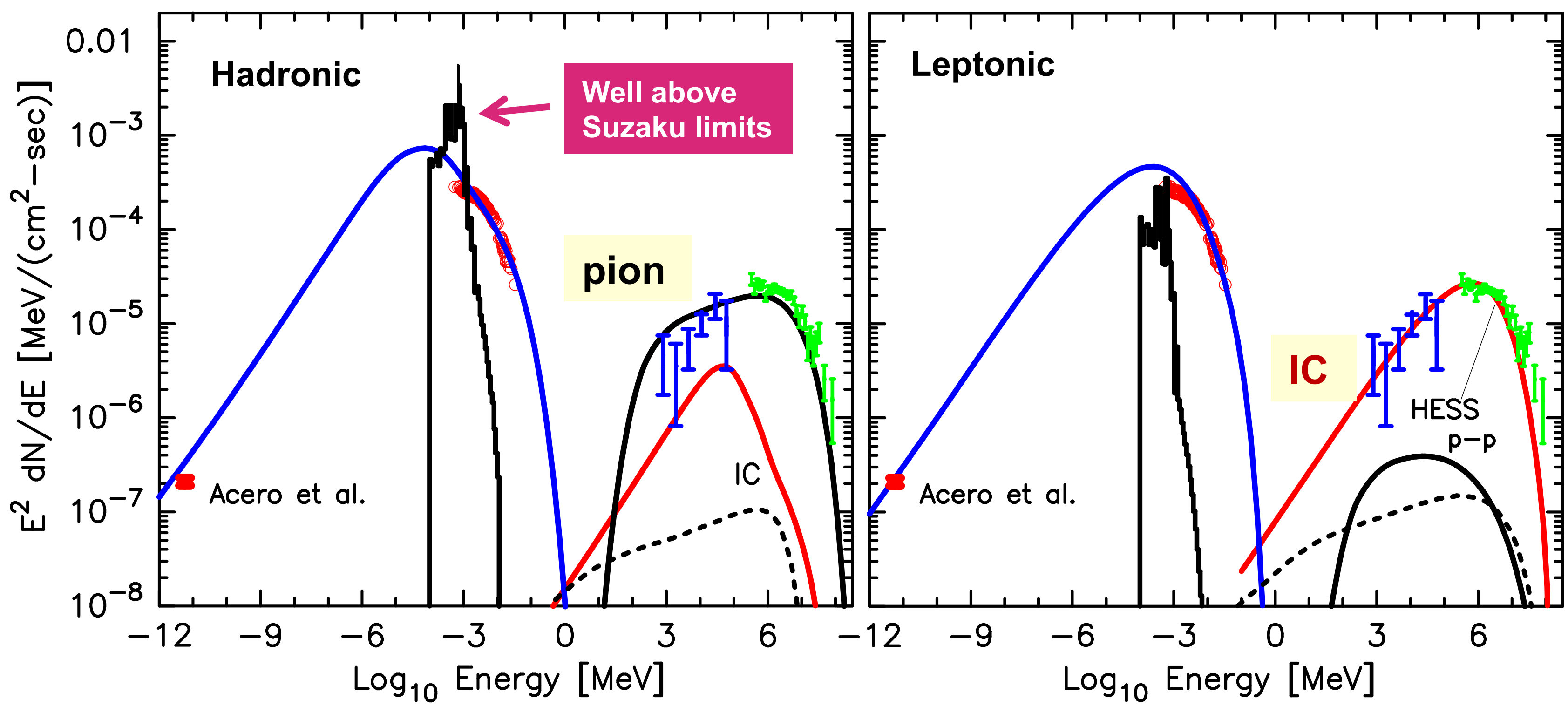
B_2 = 45 μG

Leptonic model parameters:
n_p = 0.05 cm^{-3}

e/p = K_{ep} = 0.02

B_2 = 10 μG

When X-rays are calculated self-consistently, force lower density and higher K_{ep} = 0.02, eliminates pion-decay fit



Hadron model parameters:
n_p = 0.2 cm^{-3}
e/p = K_{ep} = 5 10^{-4}
B_2 = 45 μG

Two problems with Leptonic fit:
Low B-field and poor fit to
highest energy HESS points

Lepton model parameters:
n_p = 0.05 cm^{-3}
e/p = K_{ep} = 0.02
B_2 = 10 μG

Here, use only CMB photons
for IC emission

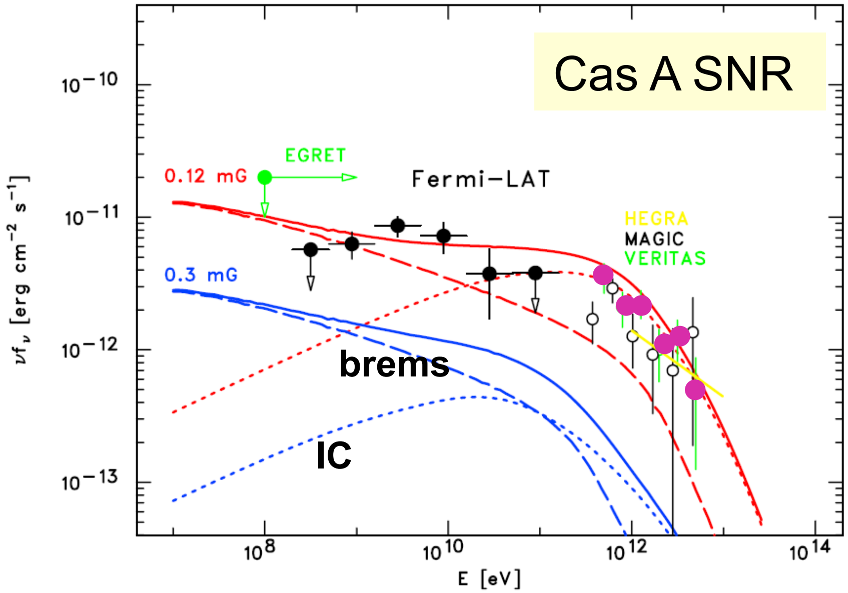
Ellison, Patnaude, Slane & Raymond ApJ 2010

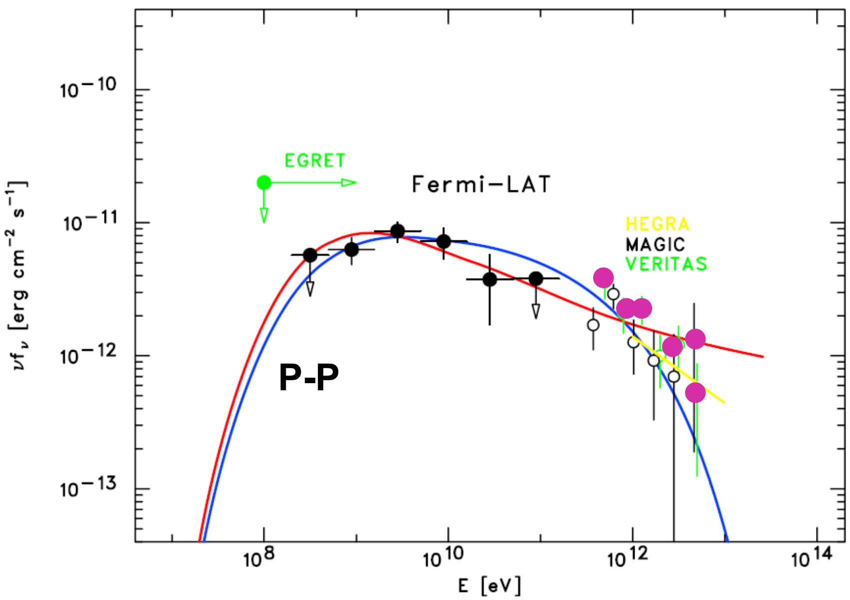
NOTE:

In both hadronic and leptonic models, have efficient production of CR protons!

Most shock energy goes into protons, not electrons.

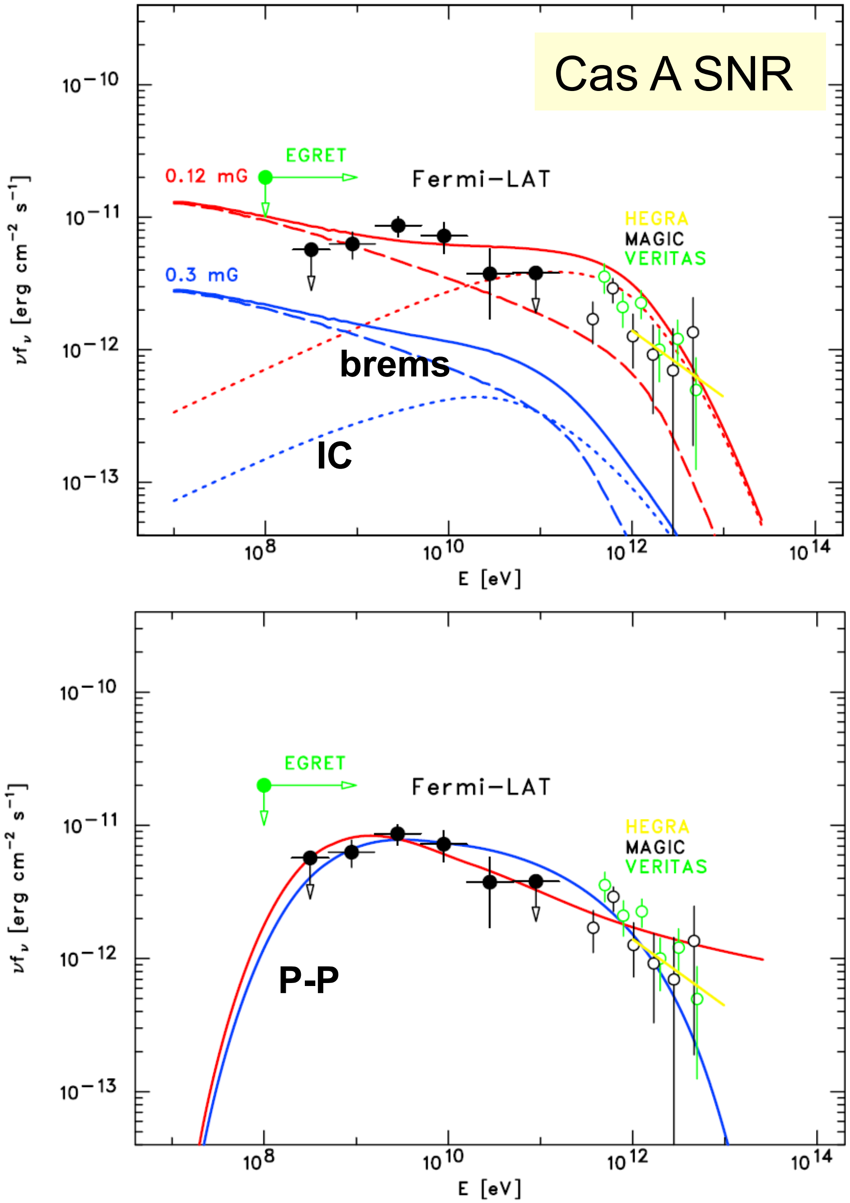
What do GeV-TeV observations tell us?





Fermi paper, ApJL 2010

What do GeV-TeV observations tell us?



Fermi paper, ApJL 2010

What do GeV-TeV observations tell us?

1)TeV Ions are produced by shocks (if can distinguish from IC)

- ► Get TeV information for electrons from X-ray synch.

2)Diffusive Shock Acceleration efficiency is high

- ► Overall intensity of GeV-TeV hard or impossible to fit with TP acceleration, Also
- ► Broadband emission, i.e., radio to X-ray match, implies efficient DSA as well, as does
- ► Morphology of remnant, CD/FS radius ratio, and
- ► Magnetic field amplification (MFA)

3)Smoking gun for TeV proton acceleration : See pion-decay bump and/or Extend observations to higher energies

a) Only way to increase proton maximum energy in DSA is by increasing B-field (MFA), BUT

b) Increasing B, decreases electron maximum energy due to radiation losses

c) As observed gamma-ray energy increases, electrons less likely and protons become only viable source

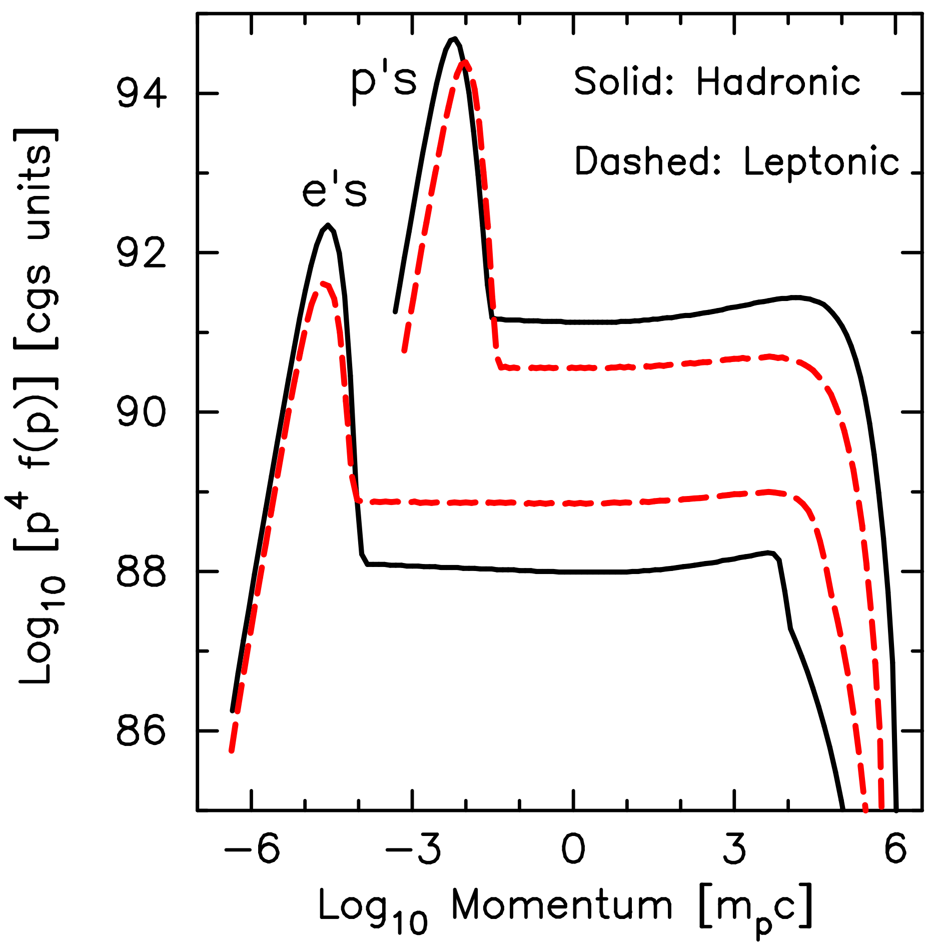
Three questions:

1)Gamma-rays: How do escaping CRs compare with trapped CRs for SNRs impacting dense media?
➔ Need self-consistent model including both

2)How does reverse shock fit in? ➔ thermal X-rays stronger from RS implying stronger limits on broad-band models
➔ DSA at reverse shock? B-field amplification?

3)What are the critical environmental and model parameters that determine if a particular SNR will be “leptonic” or “hadronic” at GeV-TeV energies?
➔ Need fully self-consistent, broad-band models

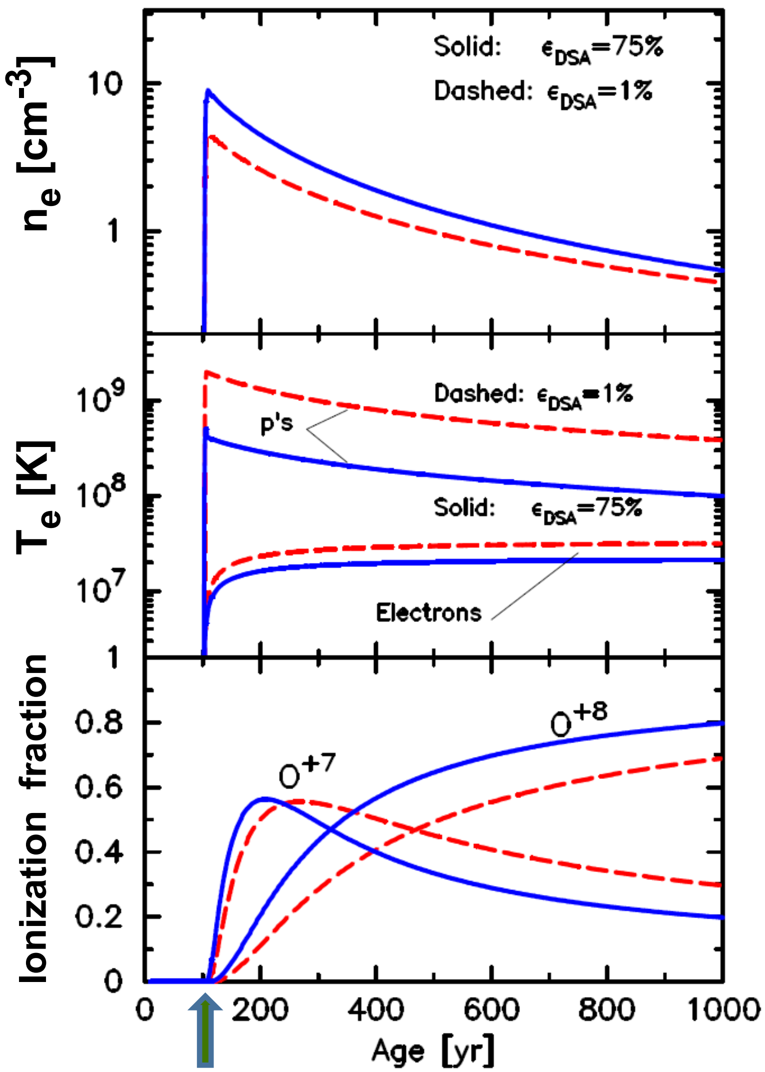
Integrated proton and electron spectra



In both leptonic and hadronic models, protons carry large majority of energy

Maximum proton energies not that much lower in leptonic model

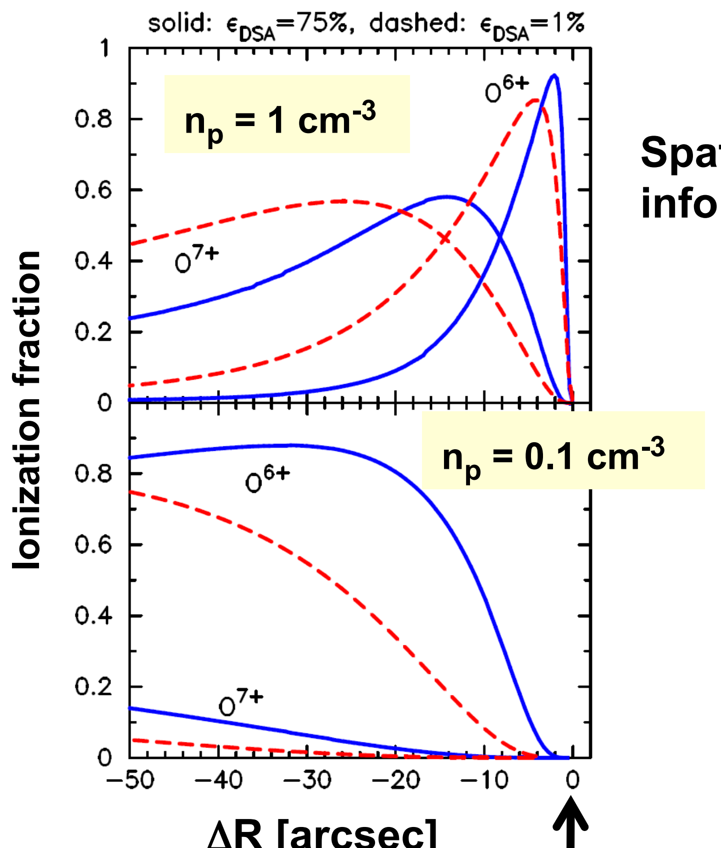
Patnaude, Ellison & Slane, ApJ 2009 : General calculations with typical SNR parameters. Find:



Time when forward shock overtakes this parcel of ISM gas

Electrons reach X-ray emitting temperatures rapidly even if DSA highly efficient

Not easy to suppress thermal X-rays



Spatial information

Forward shock

SNR J1713: Tanaka et al 2008

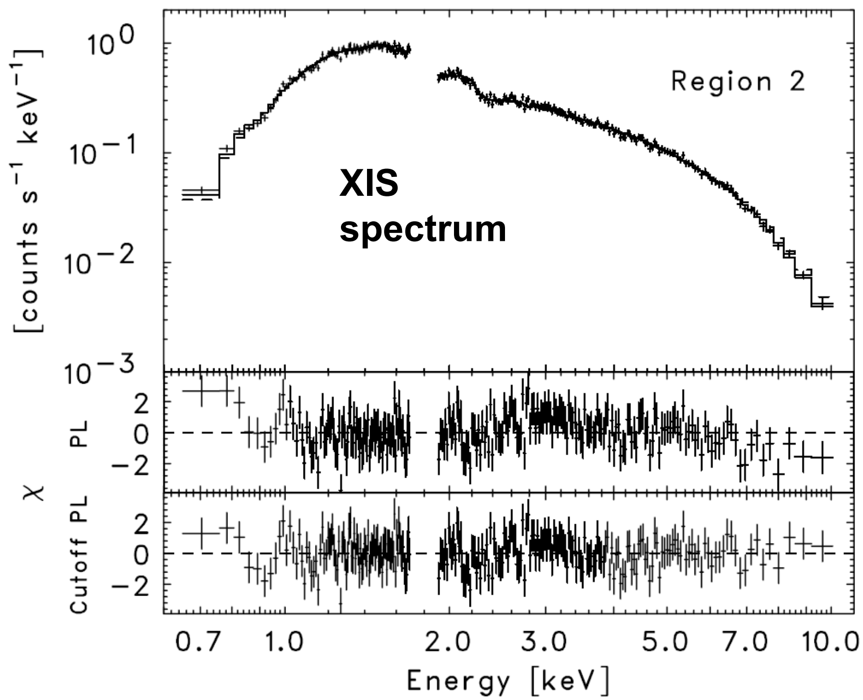
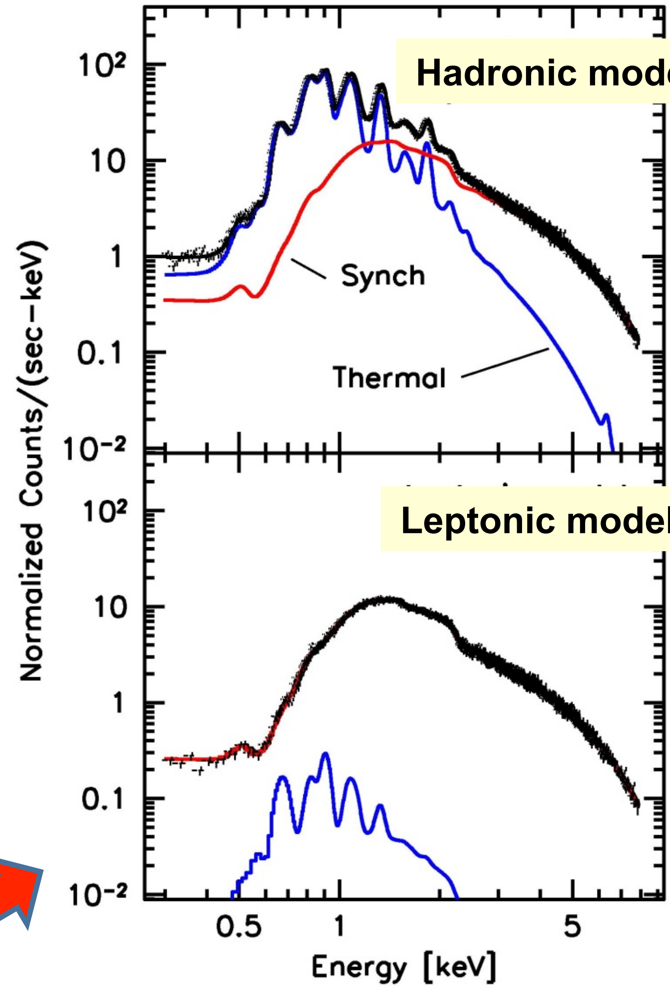


FIG. 10.—XIS (XIS 0+2+3) spectrum from region 2. The lower panels show the residuals when the spectrum is fitted with a power law and a power law with an exponential cutoff.



Simulated Suzaku XIS spectra (n_H = 7.9 10^{21} cm^{-2})

Lines produced by Hadronic model would have been seen !

To be consistent with Suzaku observations. That is, to have lines weaker than synchrotron continuum, must have low ISM density and accelerated e/p ratio, K_{ep}~ 10^{-2}

This determines GeV-TeV emission mechanism

Is there any way out of this Leptonic scenario for SNR J1713?

First, we only consider UNIFORM ISM. More complex, multiple component models may give different results. Fermi-LAT, HESS, VERITAS data may force this!

Even in uniform ISM model there are many parameters that can be varied: Ambient density, n_p; Ambient magnetic field; e/p ratio at relativistic energies; B-field amplification factor; DSA efficiency; Maximum particle cutoff energy; Shape parameter for cutoff

Warning:

Non-thermal continuum fits to X-rays and TeV observations depend strongly on details because particle spectra are turning over. Different treatments can give large differences in fitted values of all important parameters (e.g., B, n_p, K_{ep})

1) Uncertainties in Nonlinear DSA models:

a) How MFA treated: e.g. resonant vs. non-resonant instabilities
b) Role of shock precursor in MFA and shock dynamics
c) Dissipation of magnetic turbulence into heat
d) Coupling of $\Delta B/B$ to diffusion coefficient
e) Escape of highest energy particles
f) . . . . . .

Beware of perfect matches to broad-band observations !!

In contrast, since not fitting detailed line ratios, thermal X-ray emission depends only on:

(1) Heavy element composition in CSM
(2) Shocked density
(3) Shocked electron temperature
(4) Evolution of shocked plasma

Estimates for these quantities much less subject to model uncertainties

Once it's clear that lines will be produced, i.e., the electrons get hot enough, expect:

$$I_{\text{line}} \propto n_p^2 \qquad I_{\text{p-p}} \propto n_p^2$$

1) **Observations set X-ray/TeV ratio.**

2) **X-ray lines and TeV both $\propto n_p^2$ (if conditions suitable for line production)**

3) **Assuming low e/p ratio to bring down X-ray synchrotron to match Suzaku doesn't lower X-ray lines.**

4) **Changing magnetic field, acceleration efficiency, maximum particle energy will only make minor changes to this.**

Many papers claim GeV-TeV emission is from pion-decay but, somehow, thermal X-rays lines are below Suzaku limits:

1)Drury et al (2009) claim NL DSA produces too low a temp. for X-ray lines. As far as I can tell, this is based on estimates assuming DSA accel efficiency ➔ 100%. When NL DSA is done more carefully with B-field included in shock dynamics, find relatively strong proton heating for realistic J1713 parameters.

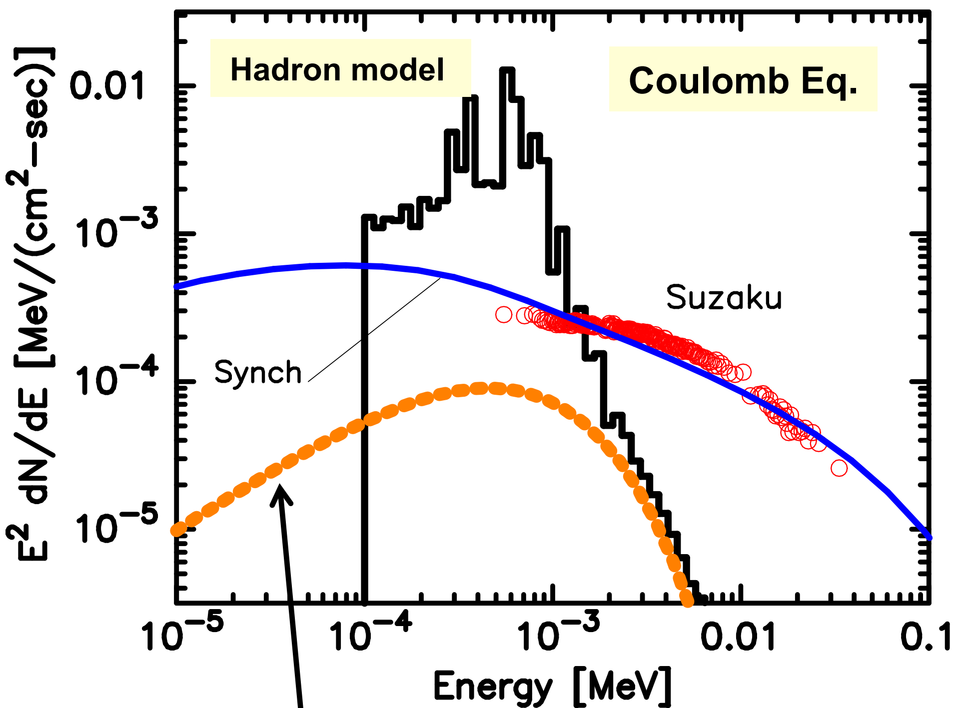
2)In Morlino, Blasi et al (2008) model for NL DSA, see protons heated in shock – but claim electrons will not be heated enough to produce X-ray lines. Equilibration time between hot protons and cold electrons might be long, but our calculation shows electrons don't have to come into equilibrium to produce X-ray emission.

3)Berezhko & Volk 2009: No X-ray lines in wind-bubble of J1713. Estimate for thermal X-ray emission from Hamilton et al (1983). Hamilton et al calculation has no nonlinear effects, or electron temperature equilibration, or SNR evolution.

Other side of the coin:

GeV-TeV from inverse-Compton:

Need to be careful here as well. Katz & Waxman (2008) claim that thermal continuum is enough to exclude pion-decay in J1713 even if X-ray lines are not considered.



If electrons heated by Coulomb collisions, bremsstrahlung continuum can be well below Suzaku limit

Thermal continuum well below Suzaku data.

X-ray lines >10 times as strong as continuum