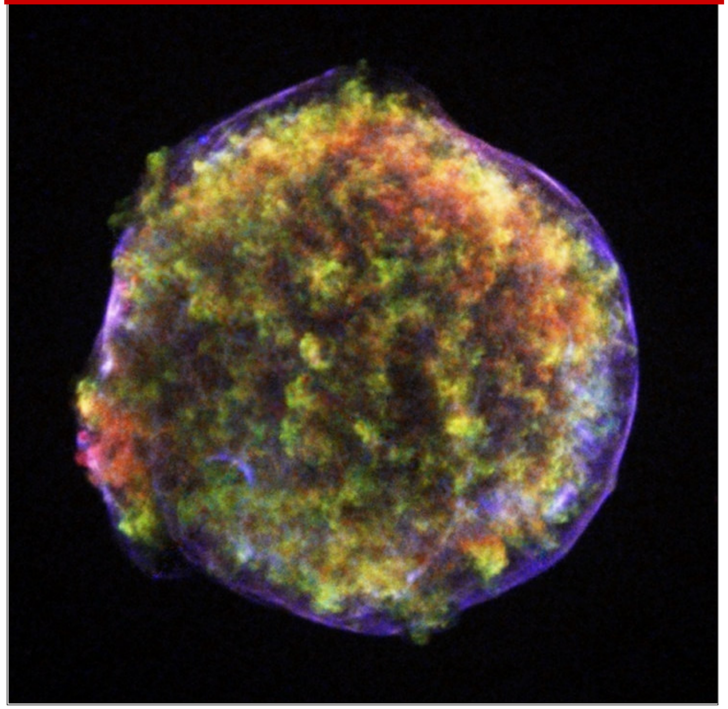
Collisionless Shocks and Particle Acceleration in Astrophysics: A Surprising Story

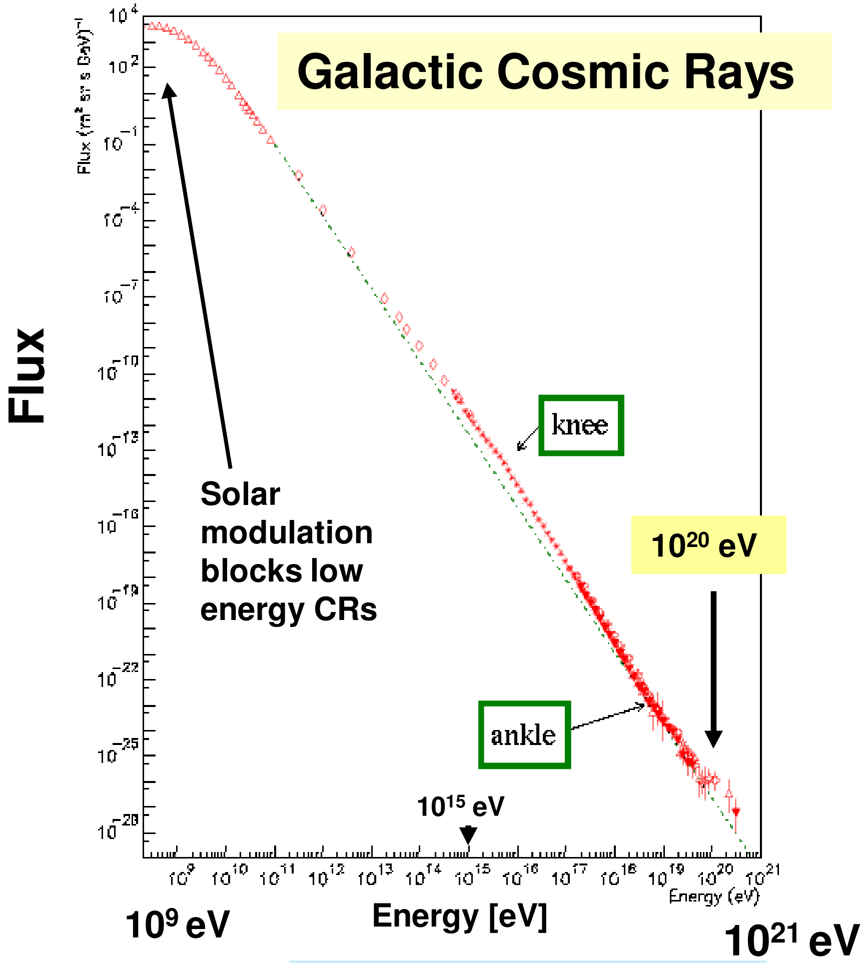
Don Ellison, NCSU

Tycho's Supernova Remnant



http://chandra.harvard.edu/photo/2005/tycho/

Galactic Cosmic Rays



Solar modulation blocks low energy CRs

Hillas_Rev_CRs_JPhysG2005.pdf

First, apologies for the many 100’s of papers I won’t mention.

Some reviews and basic papers:

Axford 1981, Drury 1983, Blandford & Eichler 1987, Jones & Ellison 1991, Jones et al 1998, Berezhko & Ellison 1999, Malkov & Drury 2001, Bell 2004,2005, Hillas 2005, Bykov et al 2009, ….

Fermi 1949, 1954

Collisionless Shocks and Accelerated particles

- In a collisionless shock, particle-particle collisions are rare and replaced with magnetic field-charged particle interactions

In a collisionless shock, the magnetic field interactions are elastic. The shock heated plasma can remain out of equilibrium ➔ If an individual particle gains extra energy it can keep it and gain more.

- Cosmic Ray (CR) acceleration can occur in collisionless shocks but not in collision-dominated shocks

Surprise #1 : Collisionless shocks do exist !
Not certain until directly observed by spacecraft

e.g., Kennel, Edmiston & Hada 1985

Earth’s Bow Shock in solar wind (artist’s conception)

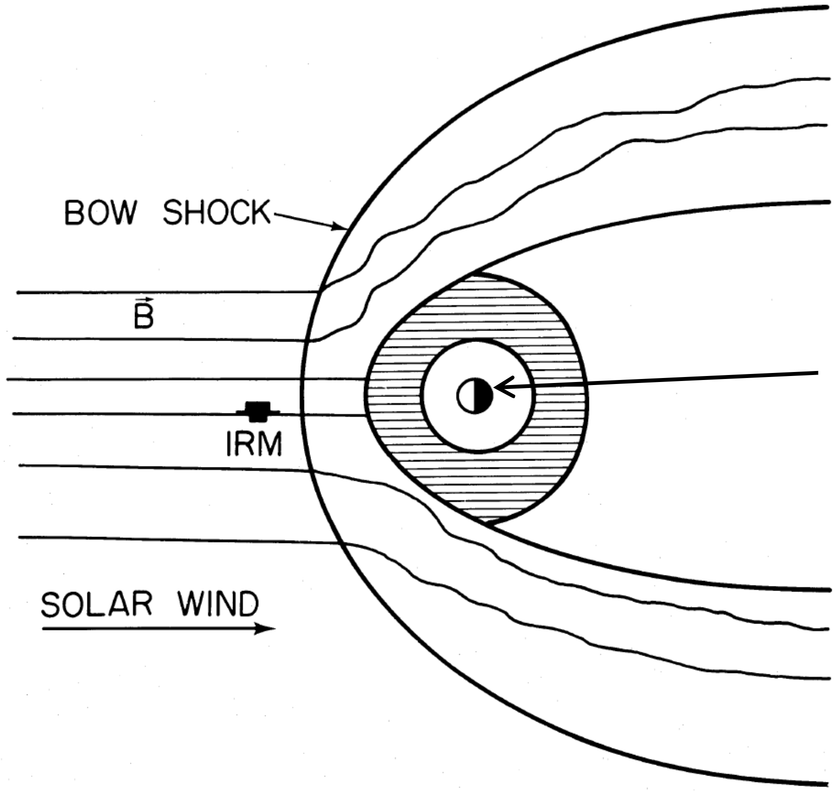


FIG. 1.—Schematic representation of the bow shock during the diffuse ion event of 1984 September 5

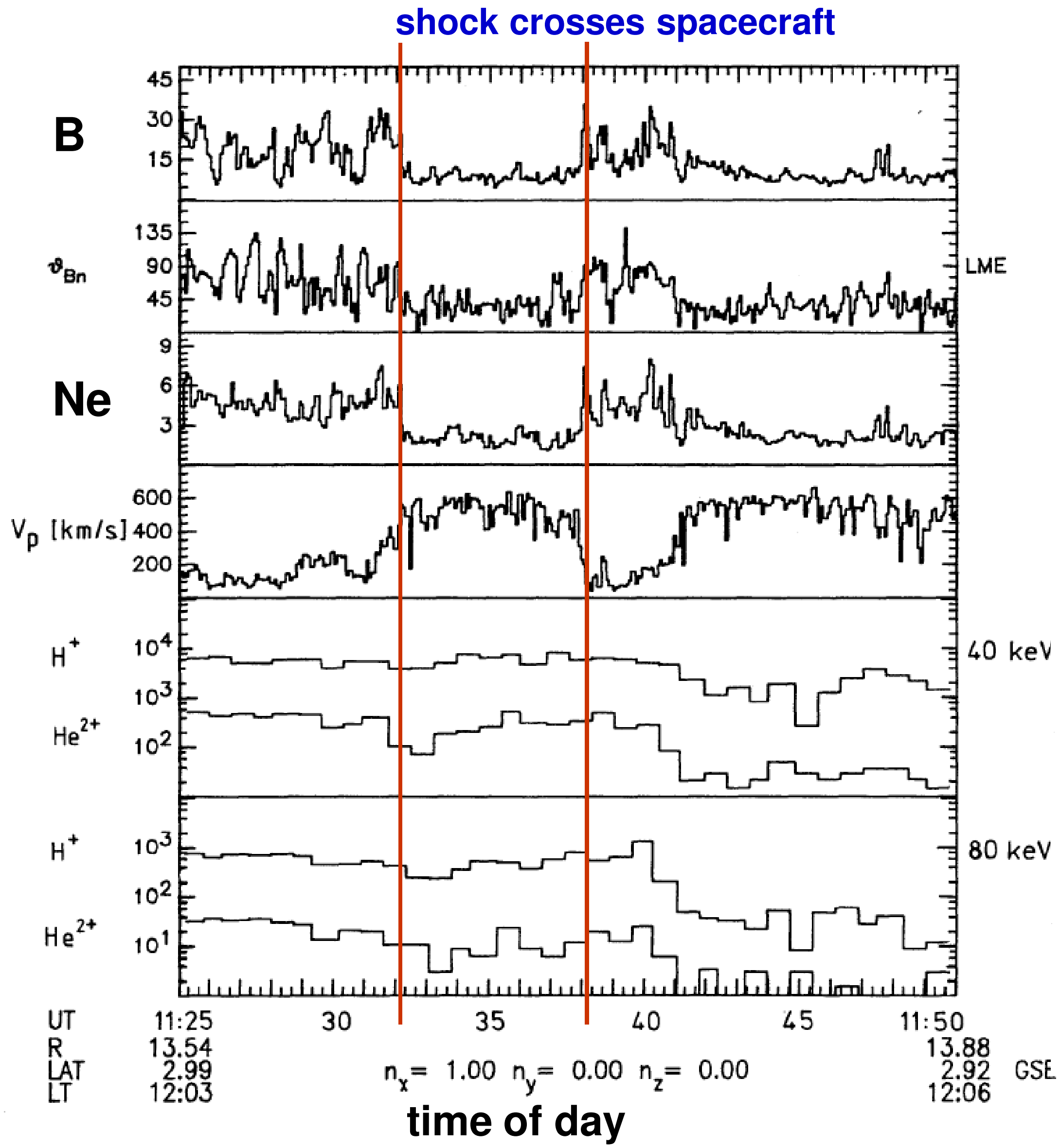
Bow shock directly observed by spacecraft

Earth

Particle-particle collision mean-free-path ~ sun-earth distance

Magnetic scattering mfp many orders of magnitude smaller !!

What does the bow shock really look like?



Earth bow shock observed by AMPTE spacecraft

(Ellison, Moebius & Paschmann 1990)

Spacecraft give a great deal of information at one point. Global information harder to determine.

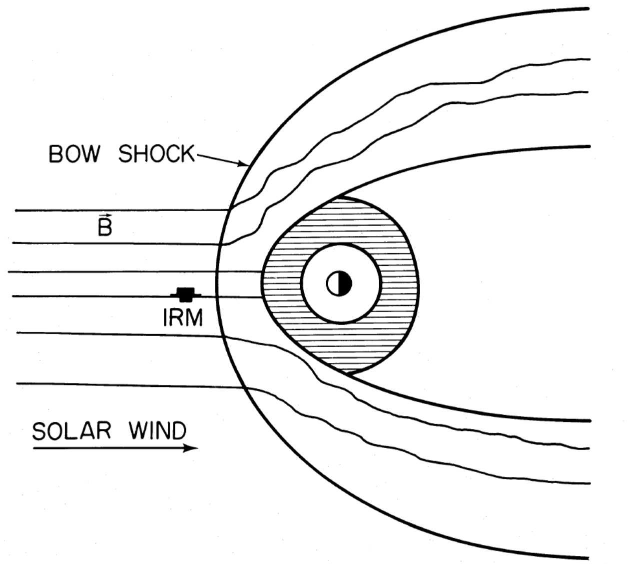


Fig. 1.—Schematic representation of the bow shock during the diffuse ion event of 1984 September 5

- Only in diffuse, low density regions of space will a collisionless shock exist.

- Hard (i.e., impossible) to see in laboratory plasmas

- In many astrophysical settings, it is easy to obtain supersonic speeds:
  - Solar wind
  - pulsar winds
  - supernova remnant (SNR) blast wave
  - radio jets
  - motion of galaxies in clusters, etc

- Magnetic fields are always present !?

Surprise #2 : Strong, high Mach # collisionless shocks are common in astrophysics

Heliosphere

Many collisionless shocks, ALL accelerate particles !

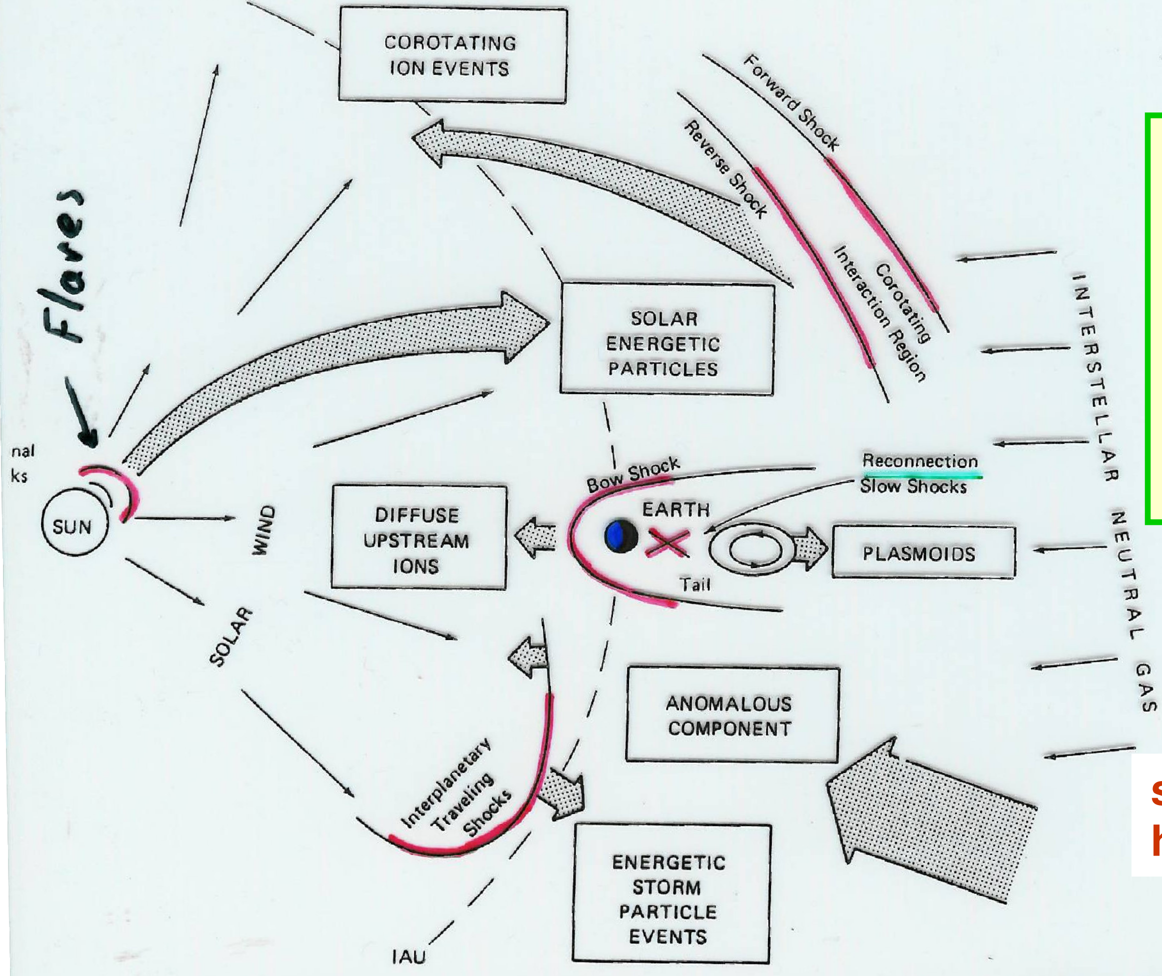


Fig. 2. Various particle acceleration sites within the heliosphere (adapted from [262]).

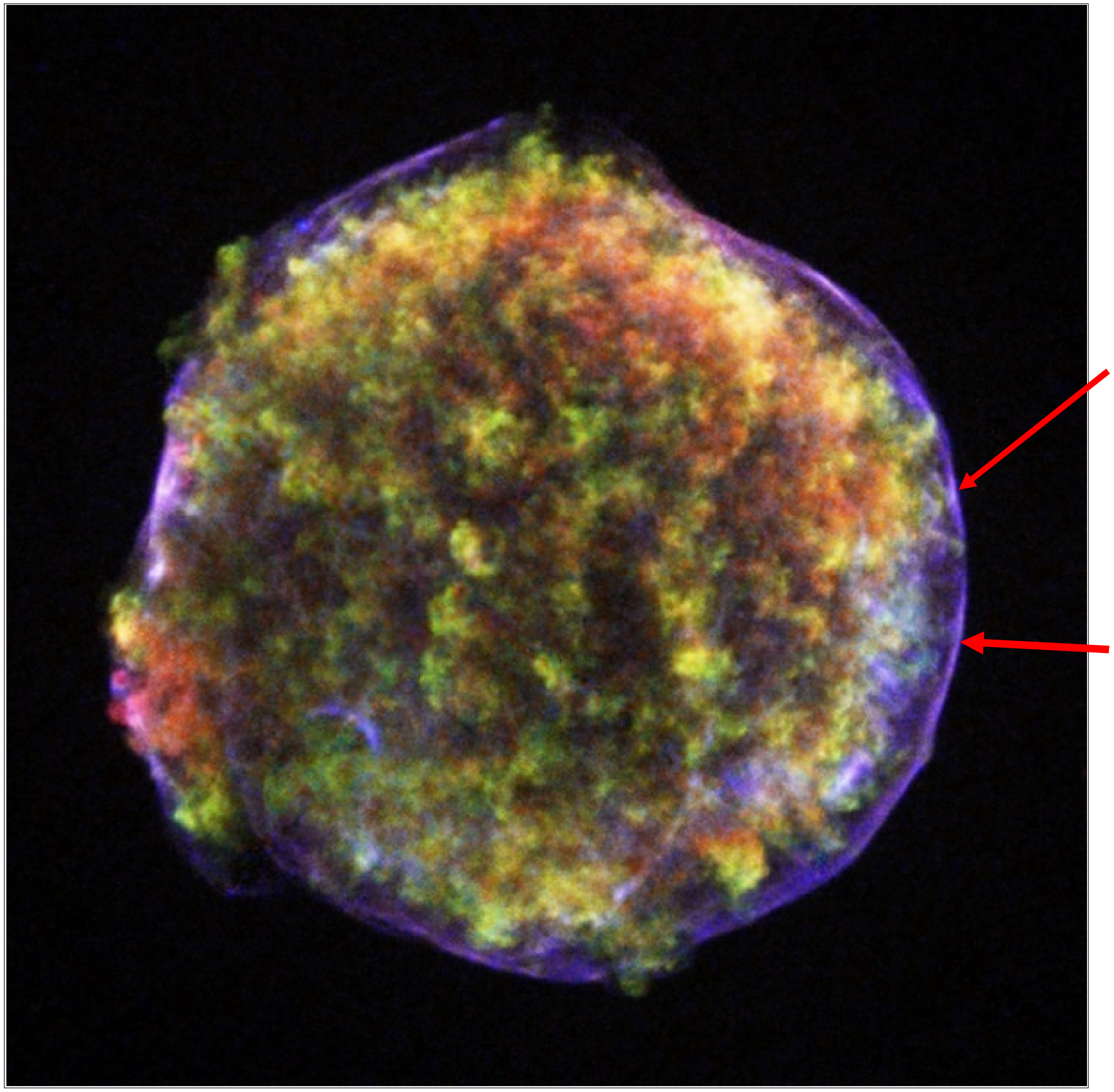
e.g. Scholer 84

Can study shock acceleration In detail with in-situ spacecraft observations

However, Shocks in Heliosphere are all low Mach number (M_S<10)

solar wind termination shock has been observed !!

Tycho's Supernova Remnant



http://chandra.harvard.edu/photo/2005/tycho/

Exploded in 1572

Chandra X-ray image

Shock heated gas (green and red) expanding inside a more rapidly moving shell (filamentary blue)

Blue is nonthermal X-ray emission (synchrotron) from shock accelerated relativistic, TeV electrons

Blast wave shock

Acceleration of ions to ~100 TeV highly likely but not as certain

Jet from quasar 3C 273

Bow shock where jet interacts with IGM?

Radio contours and optical image of jet from quasar 3C 273.
(Bahcall et al., 1995)

Radio emission means relativistic electrons. Short lifetimes show these electrons must be accelerated locally, presumably at jet-IGM shock-interface

Collisionless hocks occur on wide scales from Earth bow shock to galaxy clusters

➡ Everywhere see a high Mach # (M>3) collisionless shock see superthermal particles!

► Why is particle acceleration so general?

➡ Collisionless shocks MUST accelerate particles to exist:
For supercritical shock (Mach # $\geq$ 3) to produce enough entropy to conserve energy and momentum, must reflect some downstream particles back upstream

► Reflected particles return back across the shock as superthermal particles

➡ Surprise #3 : Strong collisionless shocks always inject and accelerate superthermal particles (i.e., CRs)

- **Details of thermal particle injection* complex and still obscure because it's hard to model mathematically or simulate**
  - **Highly anisotropic particle distributions**
  - **Hard for PIC simulations ➔ MUST be done in 3-D to properly describe injection. Also, must be run long enough for mature wave-field**

➡ **But, real shocks have no problem with thermal particle injection* and acceleration**

My mechanism of choice for particle acceleration:

First-order Fermi mechanism, also called

Diffusive Shock Acceleration (DSA)

*** By thermal injection, I mean cold, thermal, upstream particles turned into CRs**

Why must PIC simulations be done in 3-D?

It has been proven that reduced dimensionality in PIC and Hybrid plasma simulations restricts particles to motion along a given field line.

Cross-field diffusion does not occur!

Jokipii, Kota & Giacalone, 1993, GRL

Jones, Jokipii & Baring, ApJ 1998

For particle injection at shocks, particularly oblique shocks, cross-field diffusion is a critical effect

CHARGED-PARTICLE MOTION IN ELECTROMAGNETIC FIELDS HAVING AT LEAST ONE IGNORABLE SPATIAL COORDINATE.

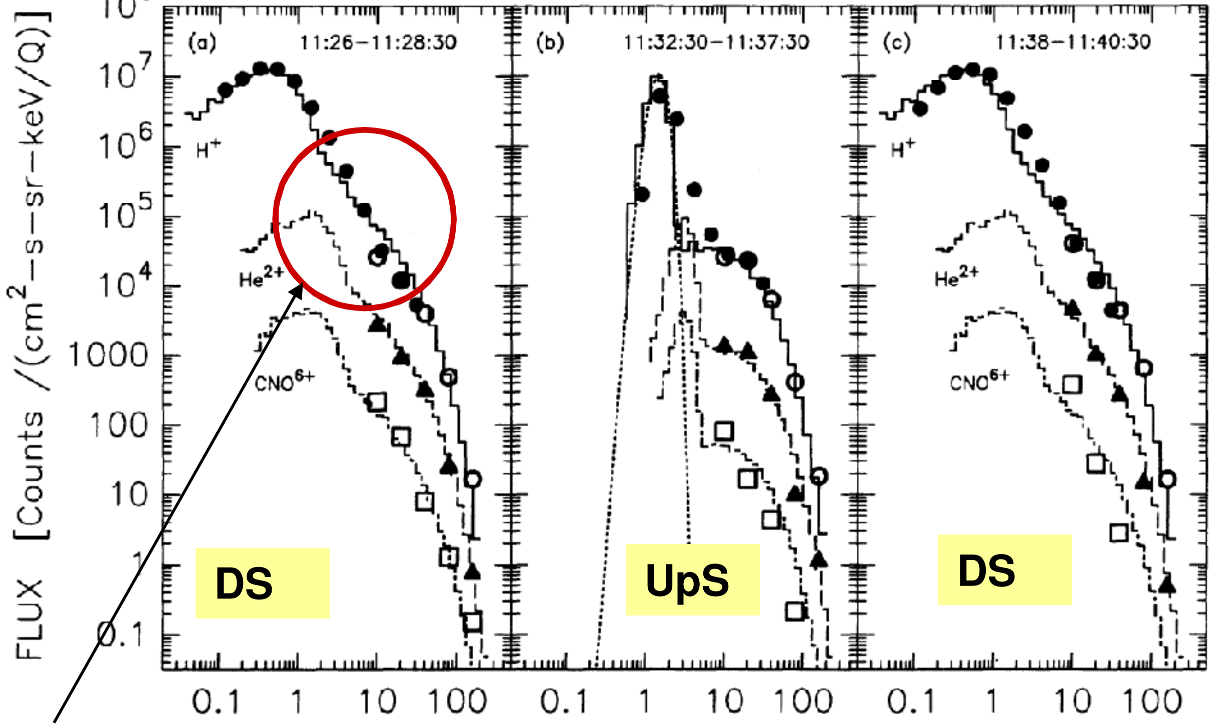
FRANK C. JONES,[1] J. RANDY JOKIPII,[2] AND MATTHEW G. BARING[1,3]

4. CONCLUSIONS

In this paper we have provided a rigorous proof of the JKG theorem and have emphasized that the most important application of the theorem is that the assumption of reduced dimensionality often used in modeling charged-particle motion has severe effects on the validity of the conclusions that may be drawn. In particular, any processes that may depend on particle motion across the magnetic field cannot, in principle, occur. This therefore casts doubt on those models or simulations that are complex enough that the contribution of cross-field motion cannot be independently assessed. In such cases the only recourse is to construct a fully three-dimensional model.

Monte Carlo Model of Earth Bow Shock: Ion injection & acceleration

Ellison, Moebius & Paschmann 90



Critical range for injection

AMPTE observations of diffuse ions at Q-parallel Earth bow shock

H+, He2+, & CNO6+

Observed during time when solar wind magnetic field was nearly radial.

Precise modeling with few free parameters. Except for S/C turbulence generation, all NL effects from efficient DSA in Monte Carlo model

Data & model confirm: self-generated turbulence, R > 4, CR modified shock, Enhancement of high A/Z ions, Spatial distribution of precursor ions, Upstream CR escape

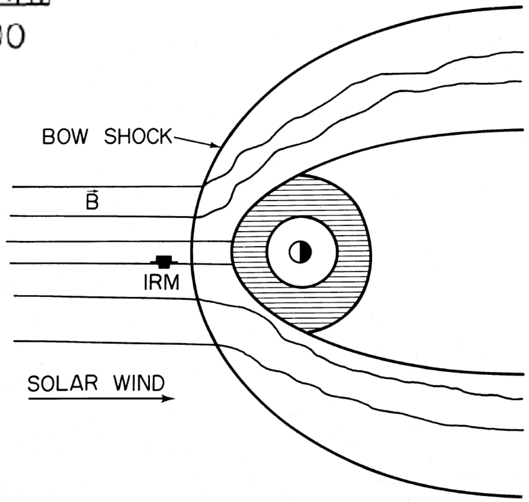
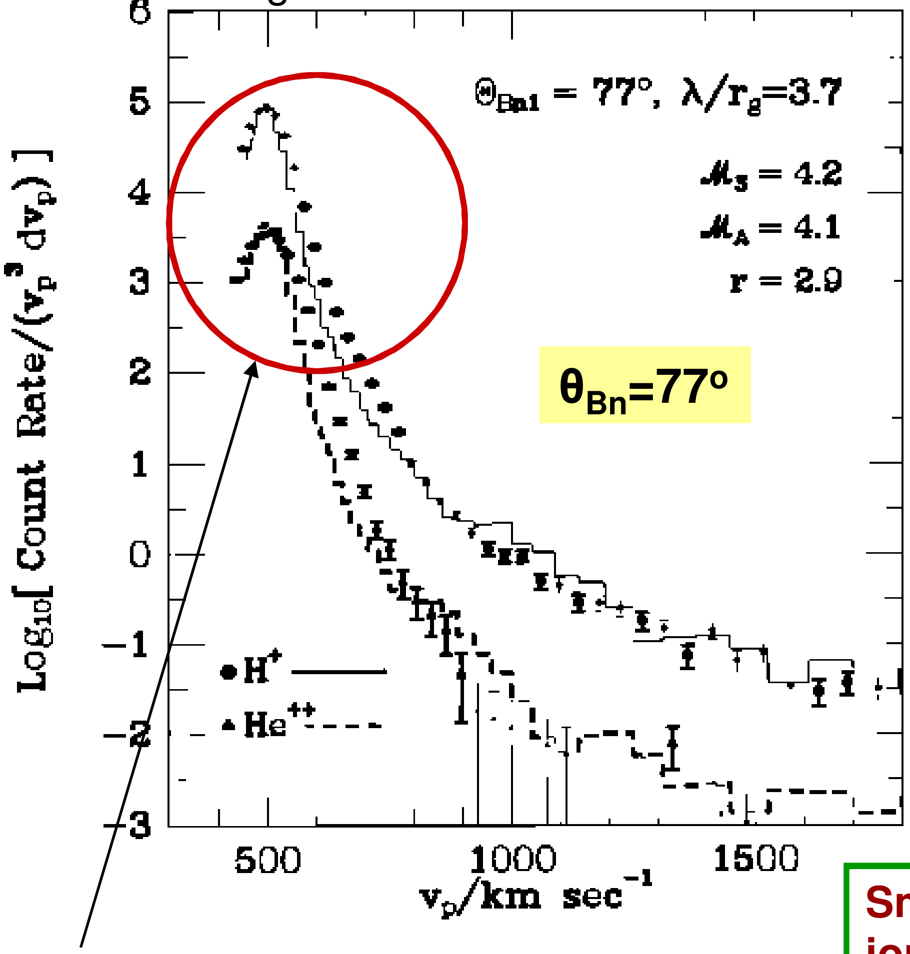


Fig. 1.—Schematic representation of the bow shock during the diffuse ion event of 1984 September 5

Oblique Interplanetary shock



Baring etal 1997

Critical range for injection

ULYSSES (SWICS) observations of solar wind THERMAL ions injected and accelerated at a highly oblique Interplanetary shock

Monte Carlo modeling implies strong scattering $\lambda \sim 3.7\ r_g$

Simultaneous H^+ and He^{2+} data and modeling supports assumption that particle interactions with background magnetic field are nearly elastic

Essential assumption in DSA

Smooth injection of thermal solar wind ions but much less efficient than Quasi-parallel Bow shock

Another heliospheric shock:

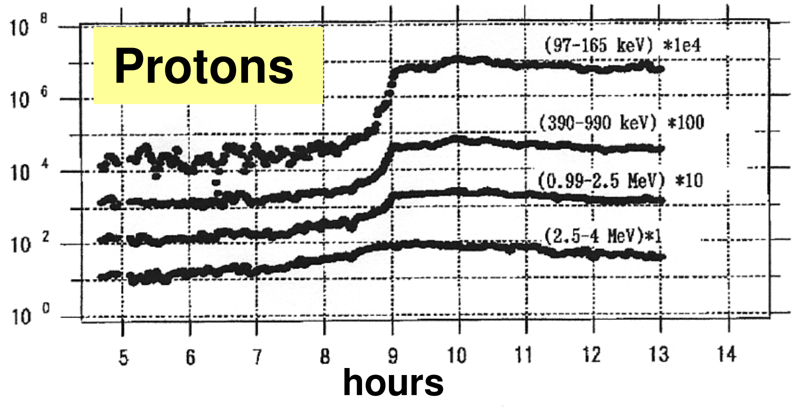


Figure 1. Omnidirectional counts for ions (protons/sample) of four different energy channels observed during the interval of 0445-1300 UT on 21 February 1994.

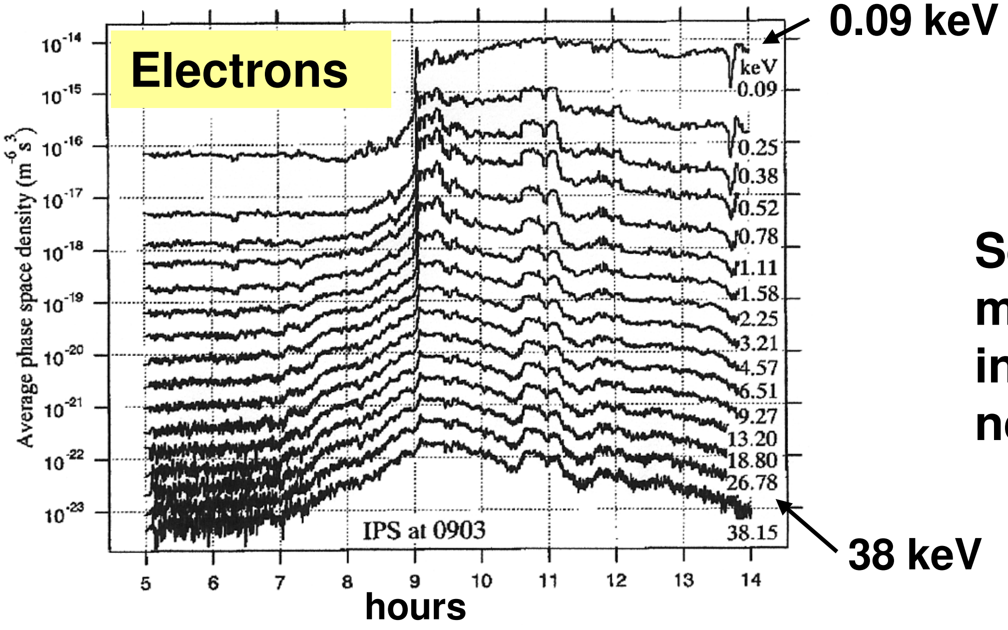


Figure 2. Average phase space densities for electrons during the interval of 0500-1400 UT on 21 February 1994. The representative energy for each energy channel is shown in the figure.

Interplanetary Shock Obs.
With GEOTAIL, 21 Feb 1994

Shimada, Terasawa, etal 1999

Simultaneous injection and acceleration of electrons and protons !!

$\theta_{Bn} \sim 68^o$

$M_A \sim 6$

See local enhancement of magnetic turbulence, including whistler waves needed by electrons

- ► Collisionless shocks inject and accelerate particles by magnetic “scattering”
- ► Need magnetic turbulence for this to work
- ► Some background turbulence always exists in space plasmas but this is not enough: typically far too weak
- ► For acceleration over wide CR energy range, need strong turbulence with wide wavelength range
- ► CRs need B-field turbulence, but turbulence must be generated by CRs ➔ resonant & non-resonant interactions

➡ Surprise #4 : Turbulence, $\Delta B/B$, self-generated in shocks

Self-generated turbulence at weak Interplanetary shock

Baring et al ApJ 1997

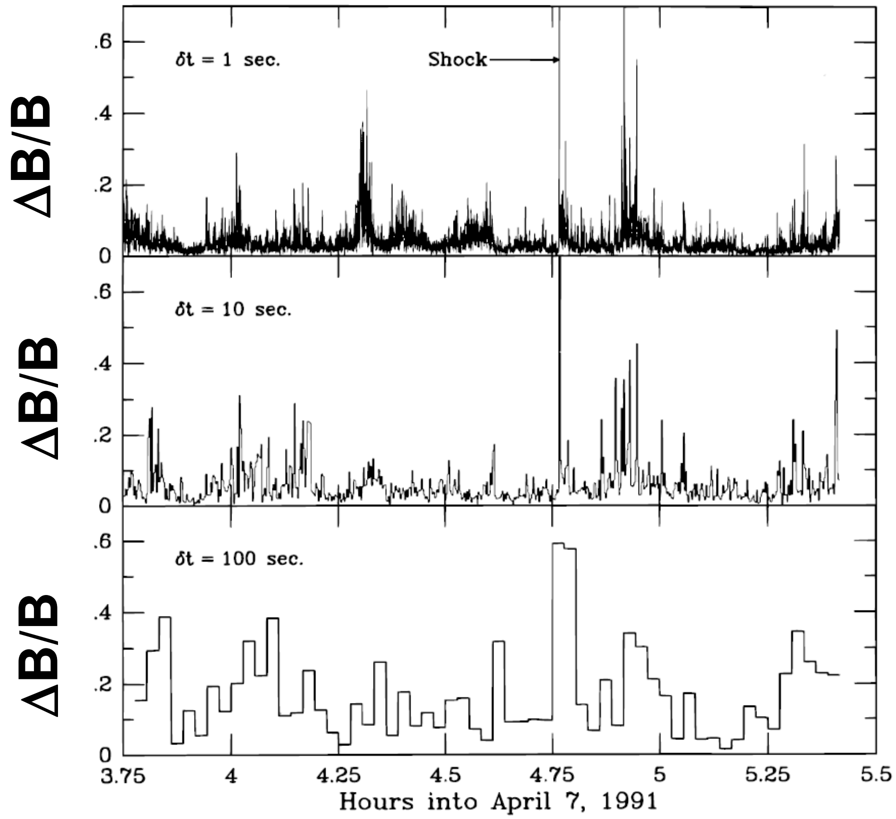
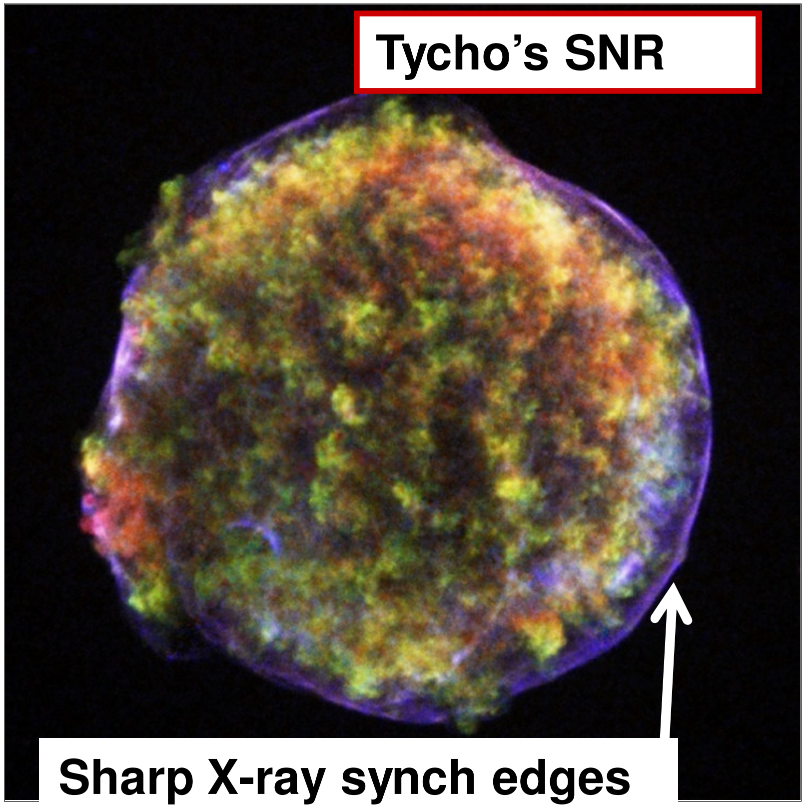


FIG. 6.—Turbulence measure $|\delta \boldsymbol{B}|/|\boldsymbol{B}|$, defined in eq. (5), for tim surrounding the 91097 shock, obtained using the field data displayed i Fig. 5*a*. Binning is exhibited on three timescales δt, as labeled, indicating slow increase in turbulence measure with timescale. Clearly the degree turbulence is similar on the two sides of the shock, therefore indicating th in Fig. 5, $|\delta \boldsymbol{B}|$ scales with $|\boldsymbol{B}|$. The data at the shock for timescales of 1 an 10 s yield $|\delta \boldsymbol{B}|/|\boldsymbol{B}|$ in excess of unity.

Indirect evidence for strong turbulence produced by CRs at strong SNR shocks



Tycho's SNR

Sharp X-ray synch edges

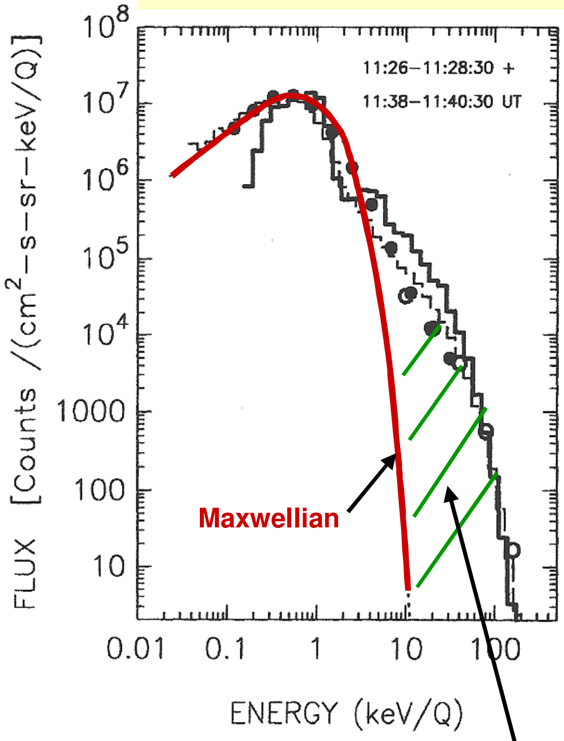
- Observations show DSA can be efficient
- CR pressure must modify shock structure

- Injection must be self-consistently connected to production of highest energy CRs

In strong shocks, doubly nonlinear system:
CR acceleration ←→ ΔB/B ←→ shock structure
←→ CR acceleration ←→ ΔB/B …..

➡ **Surprise #5 : Strong collisionless shocks are efficient accelerators and CRs must modify shock structure**

Bow shock observations



direct evidence for efficient acceleration

~25% of solar wind energy flux into superthermal ions

- For strong shocks, energy put into CRs will diverge unless acceleration stopped by finite size or finite age. This, combined with self-generation of turbulence ➔ some of the highest energy CRs must escape upstream from the shock

- If DSA is efficient, a significant fraction of energy goes into escaping CRs

- Escaping CRs reduce shocked pressure ➔ increase compression ratio ➔ increase acceleration efficiency

- The more energy loss to upstream escaping CRs, the more efficient the acceleration process becomes !

- **Surprise #6 :** Upstream escape of CRs important in strong collisionless shocks

- Was long believed that shocks could self-generate turbulence, i.e., produce $\Delta B/B \sim 1$

- If $\Delta B/B > 1$, believed wave energy transferred quickly to heat

- For ISM, $B < 10$ μG

➡ Recent X-ray observations of some young SNRs suggest that B-field at blast wave $>> 10$ μG. This suggests $\Delta B/B >> 1$

- B-field is most important parameter determining maximum CR energy a shock can produce, etc. Also, B determines synchrotron luminosity

➡ Surprise #7 : Magnetic field amplification $\Delta B/B >> 1$ may be intrinsic part of DSA in strong shocks (e.g., Bell 2001, 2005)

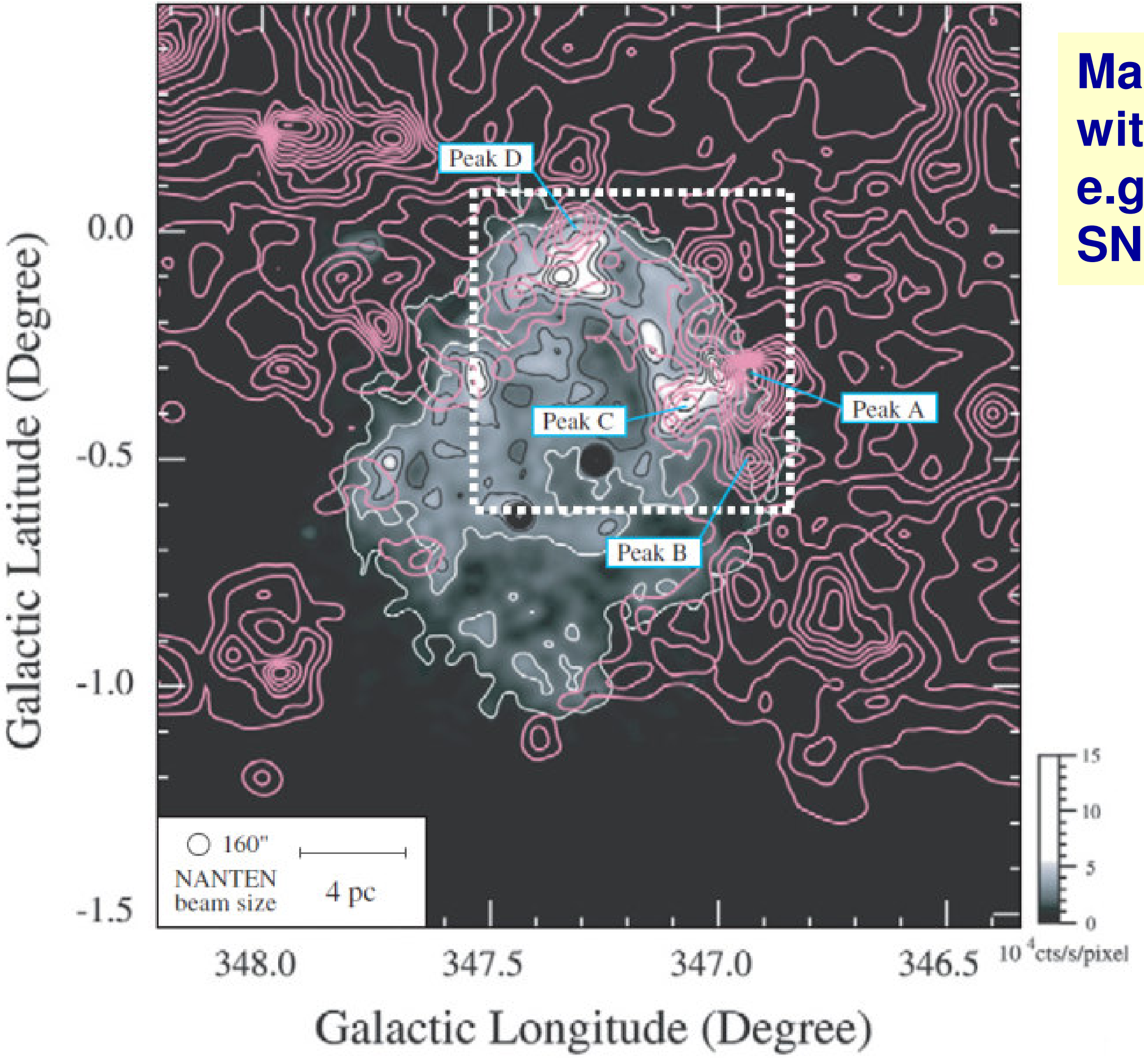
Put everything together in Composite SNR Model (CR-hydro-NEI code)
SNR hydrodynamics, Nonlinear Shock Acceleration, Continuum and Line Radiation ➔ reasonably self-consistent

1) VH-1 code for hydro of evolving SNR (e.g., Blondin)
2) Semi-analytic, nonlinear DSA model from Blasi, Stefano Gabici, et al.
3) NL shock acceleration coupled to SNR hydrodynamics
4) Ad hoc model of magnetic field amplification
5) Approximate shape of trapped CR distributions at max. energy turnover
6) Continuum photon emission from radio to TeV
7) Non-equilibrium ionization (NEI) thermal X-ray line emission
8) Simple, Monte Carlo Model of escaping CR propagation

Apply to SNR RX J1713 (work with Pat Slane, Dan Patnaude, Andrei Bykov, John Raymond)

Decourchelle, Ellison & Ballet (2000); Ellison, Decourchelle & Ballet (2004); Ellison et al (2007, 2010); Patnaude et al (2009, 2010); Ellison & Bykov (2011)

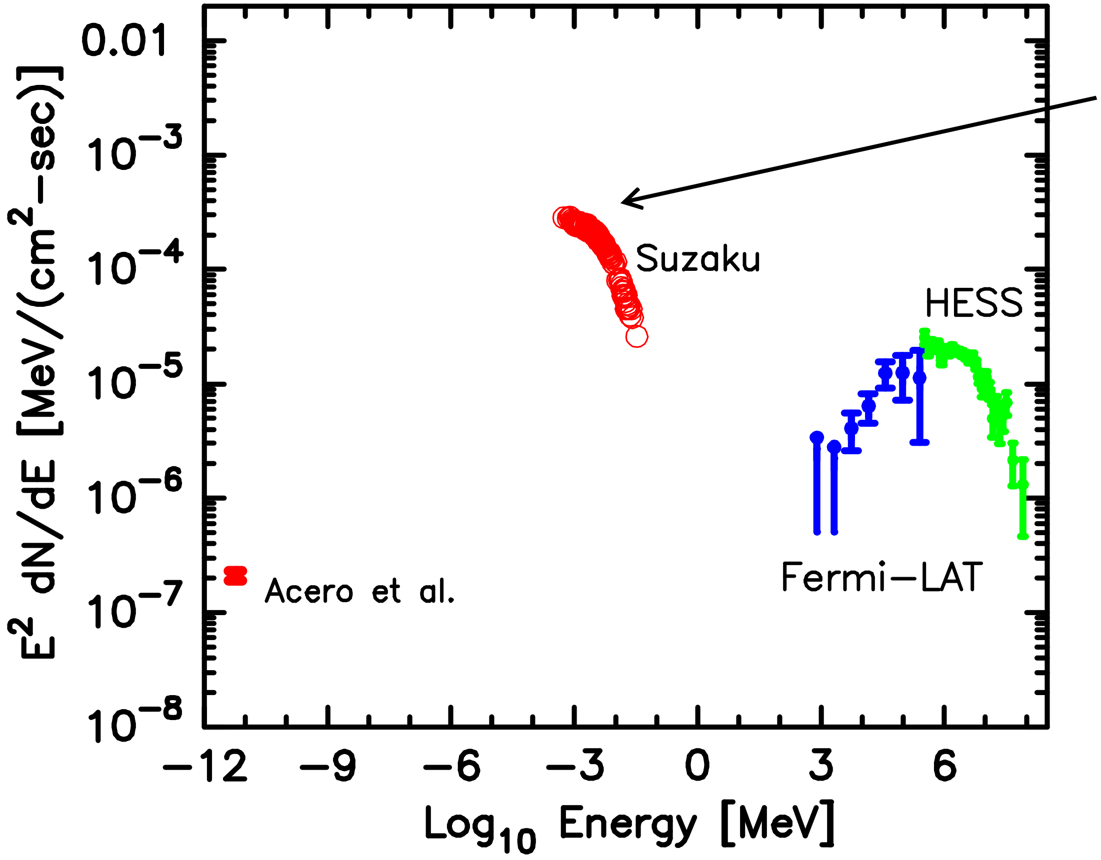
SNR RX J1713



May be interacting with dense material, e.g., core-collapse SN

Sano et al 2010

Thermal & Non-thermal Emission in SNR RX J1713



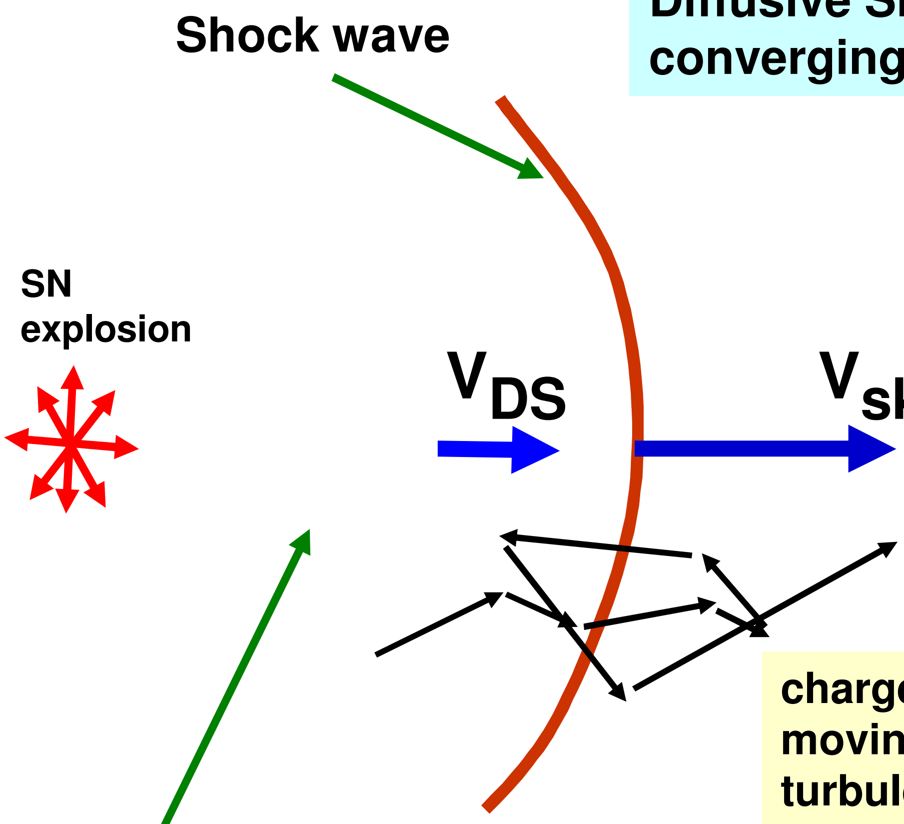
1) **Suzaku X-ray observations ➔ smooth continuum well fit by synchrotron from TeV electrons**

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

➔ Strong constraint on Non-thermal emission at GeV-TeV energies

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

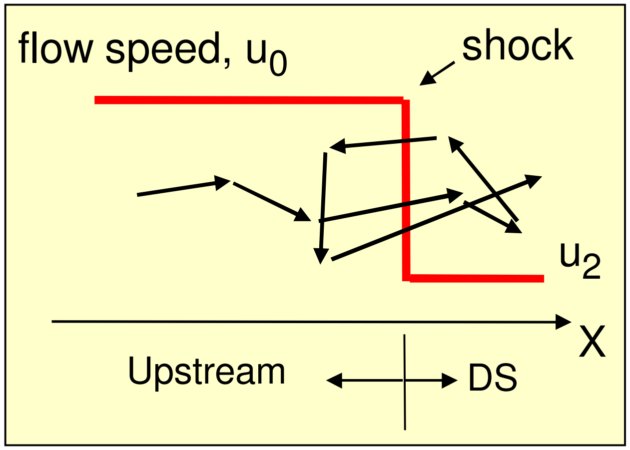
Interstellar medium (ISM), cool with speed $V_{ISM} \sim 0$



charged particle moving through turbulent B-field

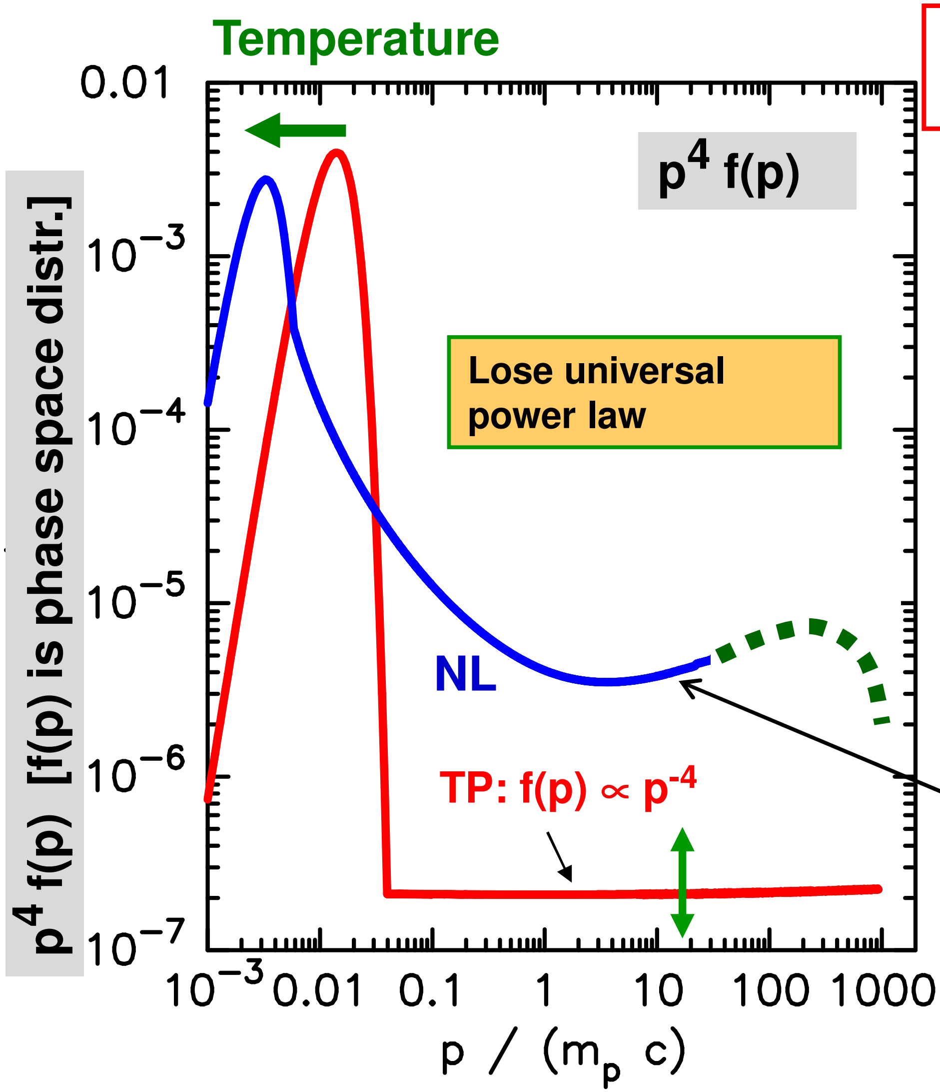
Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$

shock frame

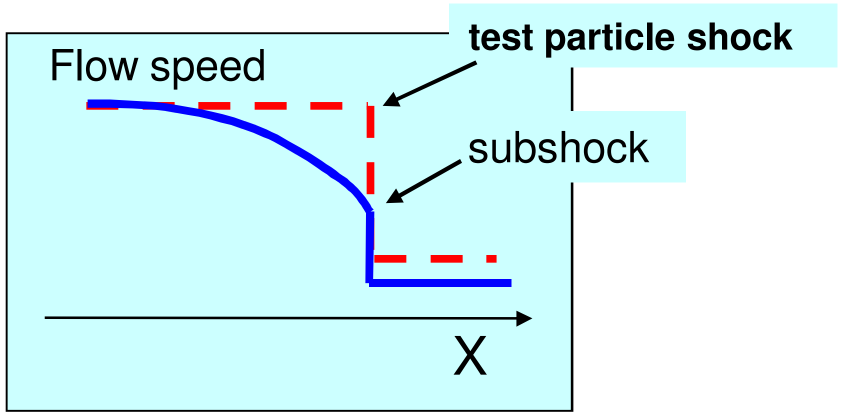


$u_2 = V_{sk} - V_{DS}$

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

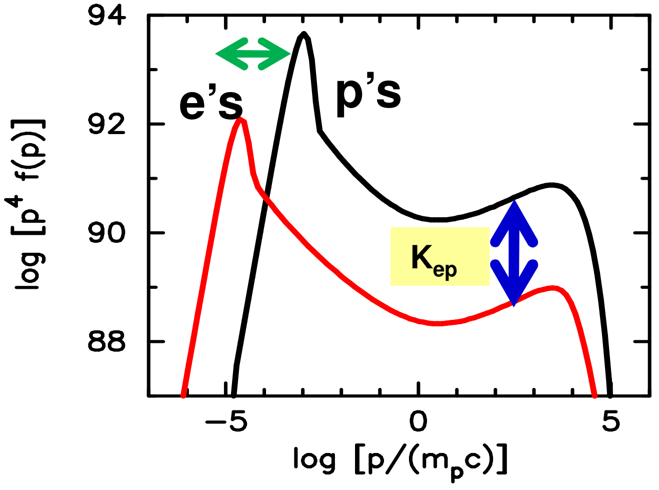


- ► Concave spectrum
- ► Compression ratio, $r_{tot} > 4$
- ► Low shocked temp. $r_{sub} < 4$

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

Particle spectra calculated with semi-analytic code of Blasi, Gabici and co-workers

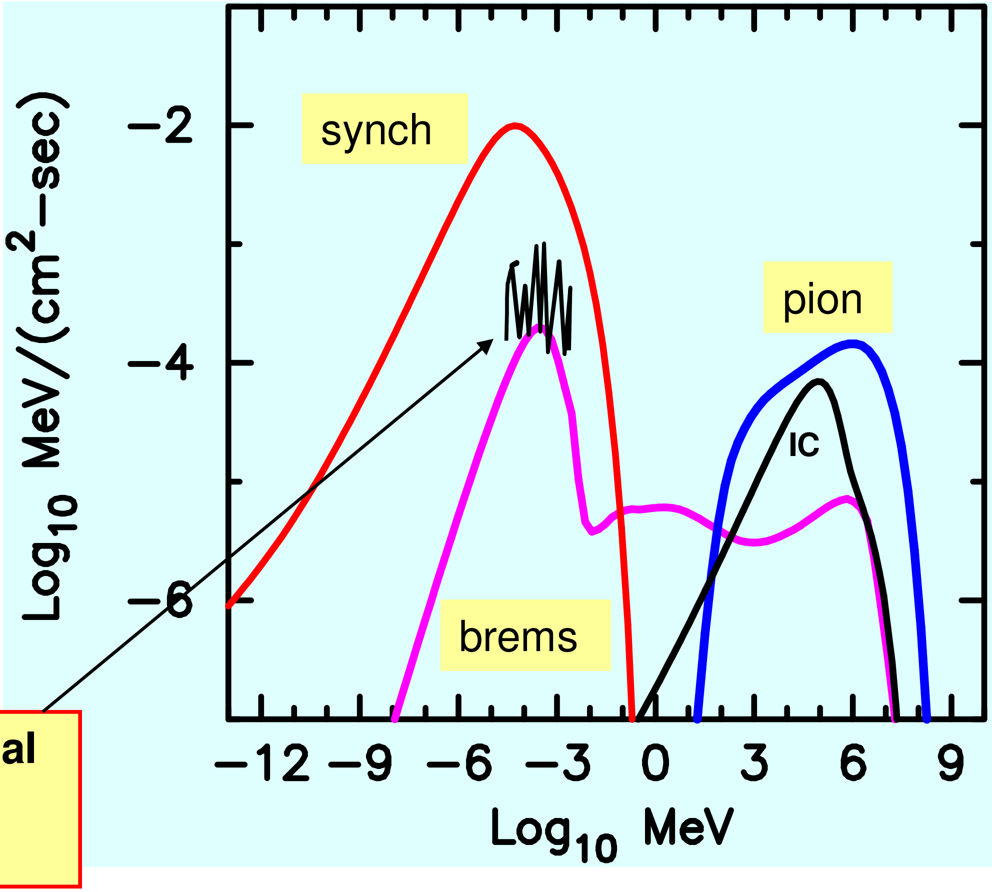
2 trapped particle distributions



Many parameters needed for modeling !!

e.g., Electron/proton ratio, K_{ep}

continuum emission



In addition, emission lines in thermal X-rays. Depends on T_e/T_p and electron equilibration model

In nonlinear DSA, Thermal & Non-thermal emission coupled

➔ big help in constraining parameters

Particle spectra calculated with semi-analytic code of Blasi, Gabici and co-workers

First, uniform ISM

SN exploding in constant ISM (e.g., Type Ia) , or

Core-collapse exploding in pre-SN wind

with no dense shell or nearby mass concentration

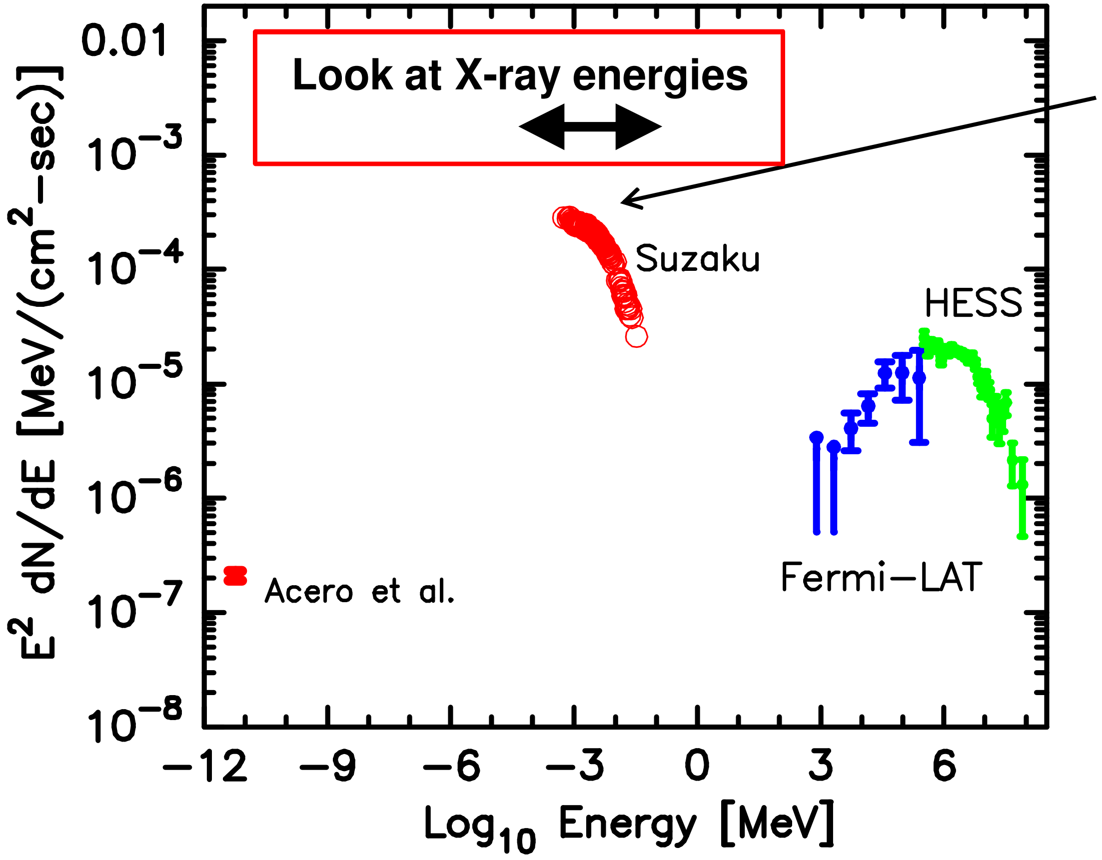
Are highest energy photons produced by

Ions (p-p collisions and pion decay) or

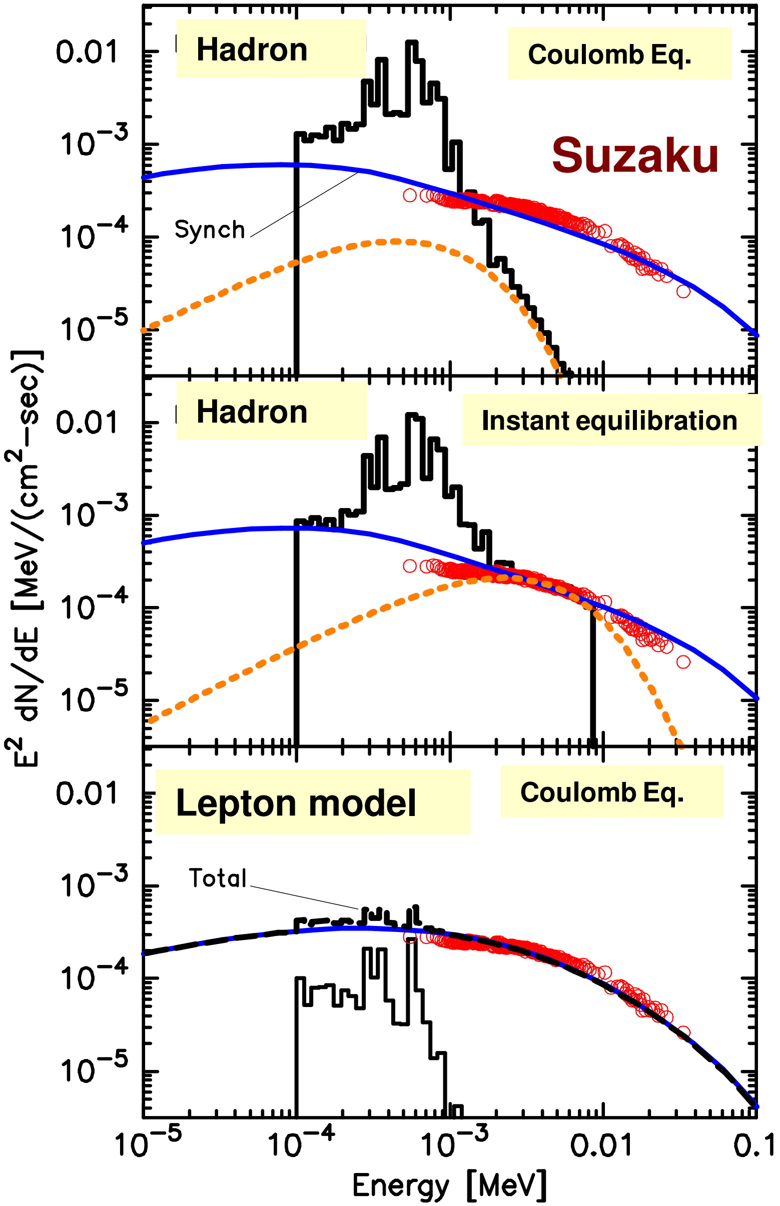
Electrons (IC off background photons) ?

(or some combination) ?

Thermal & Non-thermal Emission in SNR RX J1713



- ▶ **Suzaku X-ray observations → smooth continuum well fit by synchrotron from TeV electrons**
- ▶ **No discernable line emission from shocked heated heavy elements**
- ▶ **Strong constraint on Non-thermal emission at GeV-TeV energies**



Ellison, Patnaude, Slane & Raymond ApJ (2007, 2010)

Models including Thermal X-ray lines:

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

► **Compare Hadronic & Leptonic fits**

► **Range of electron temperature equilibration models**

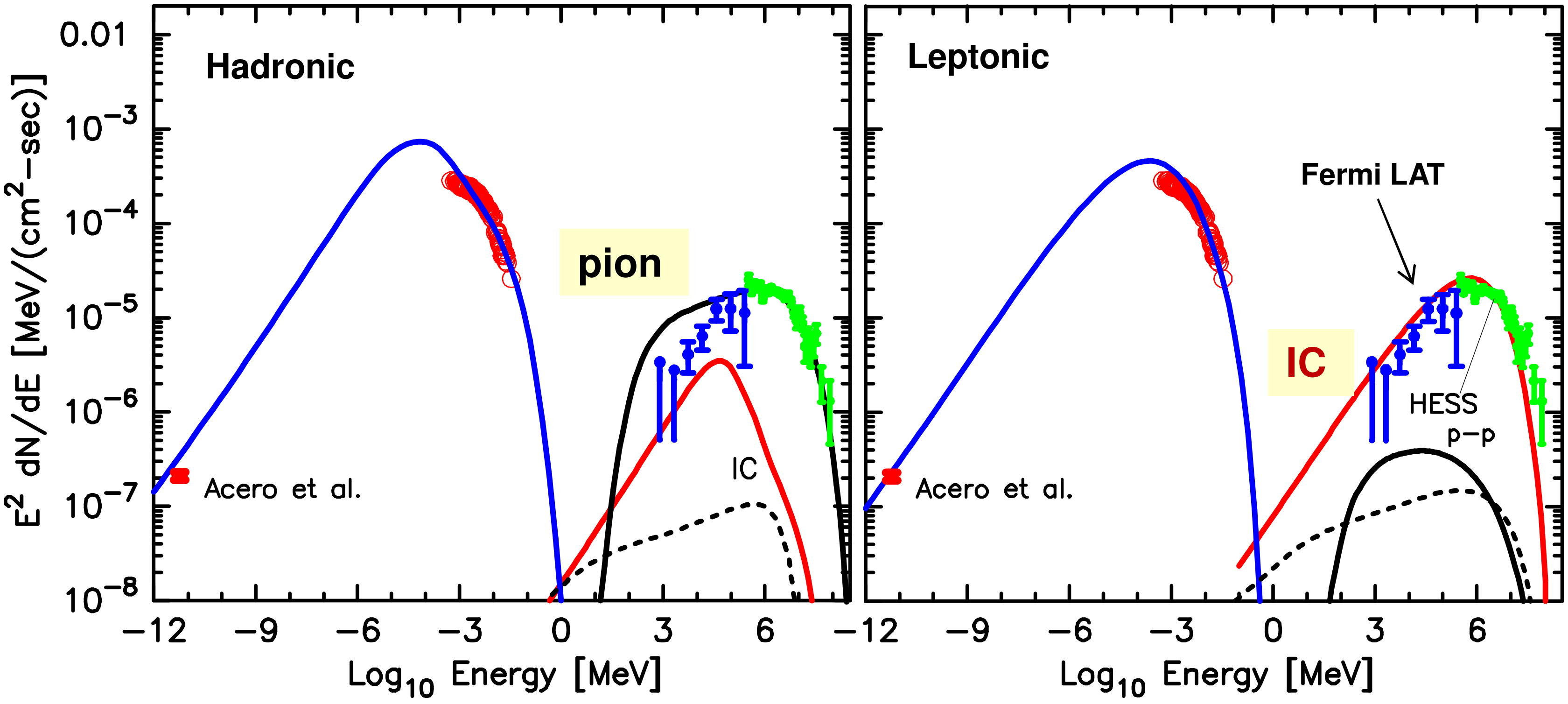
► **Find: The high ambient densities needed for pion-decay to dominate at TeV energies result in strong X-ray lines**

► **Suzaku would have seen these lines**

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

With or without pre-SN wind if no external mass concentrations

For J1713, reasonable fits possible to continuum only with either pion-decay or inverse-Compton dominating GeV-TeV emission

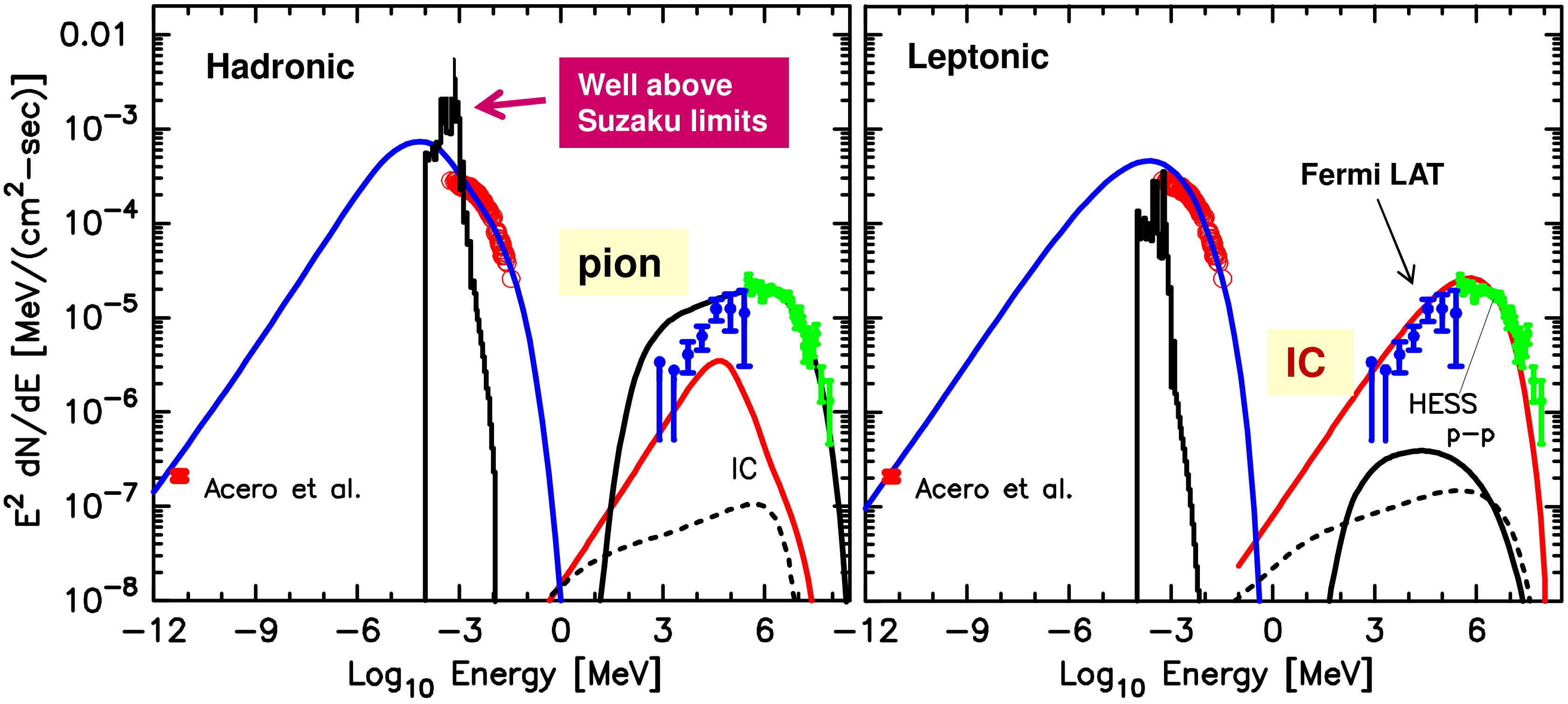


Hadron model parameters:
$n_p = 0.2\ \mathrm{cm}^{-3}$
$e/p = K_{ep} = 5\ 10^{-4}$
$B_2 = 45\ \mu G$

Lepton model parameters:
$n_p = 0.05\ \mathrm{cm}^{-3}$
$e/p = K_{ep} = 0.02$
$B_2 = 10\ \mu G$

Ellison, Patnaude, Slane & Raymond ApJ 2010

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



Well above Suzaku limits

pion

IC

Fermi LAT

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

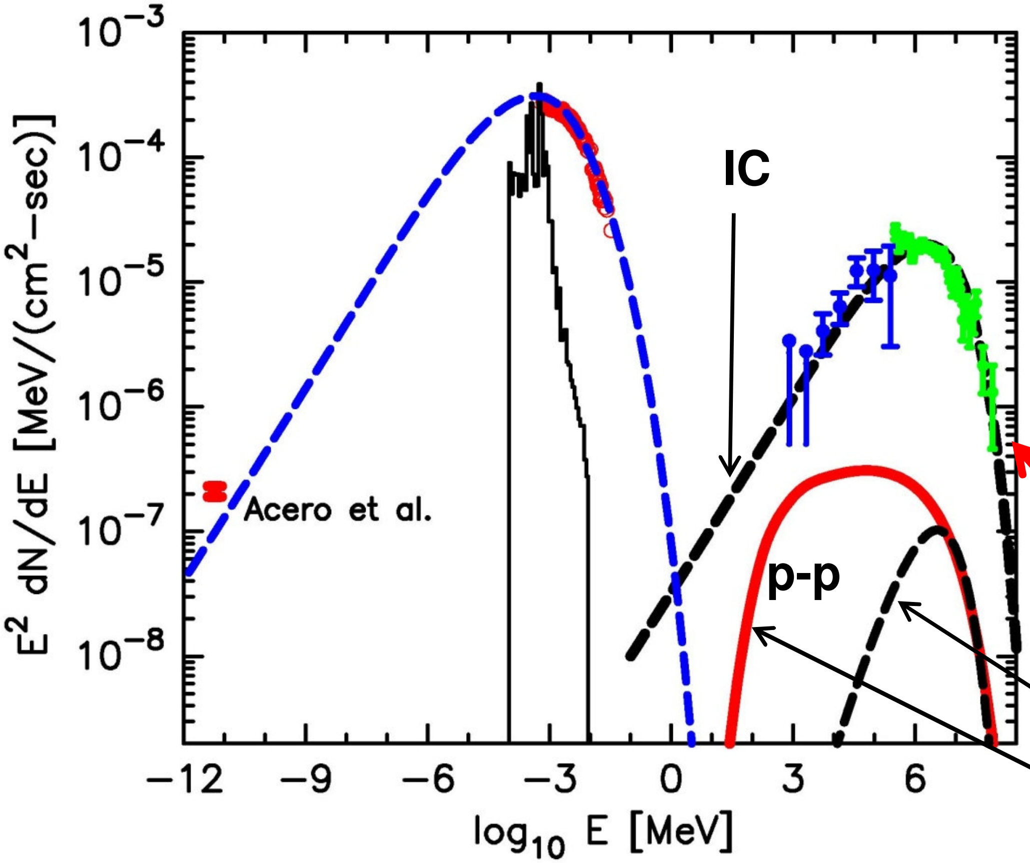
Lepton model parameters:
n_p = 0.05 cm^{-3}
e/p = K_{ep} = 0.02
B_2 = 10 µG

Here, use only CMB photons for IC emission

Ellison, Patnaude, Slane & Raymond ApJ 2010

Recent Fermi LAT data consistent with leptonic model

Work in progress with Slane, Patnaude, Bykov:
Core-collapse SN with pre-SN wind model for SNR RX J1713



SN explodes in a $1/r^2$ pre-SN wind. **Shell of swept-up wind material**

➔ Inverse-Compton dominates GeV-TeV emission

Better fit to highest energy HESS observations

p-p from escaping CRs

p-p from trapped CRs

Inverse-Compton fit to HESS obs: Pre-SN wind magnetic field lower than ISM ➔ Can have magnetic field amplification and still have B-field low enough to have high electron energy. **For J1713, shocked B ~ 10 µG !**

What happens if escaping CRs are interacting with dense external material ?

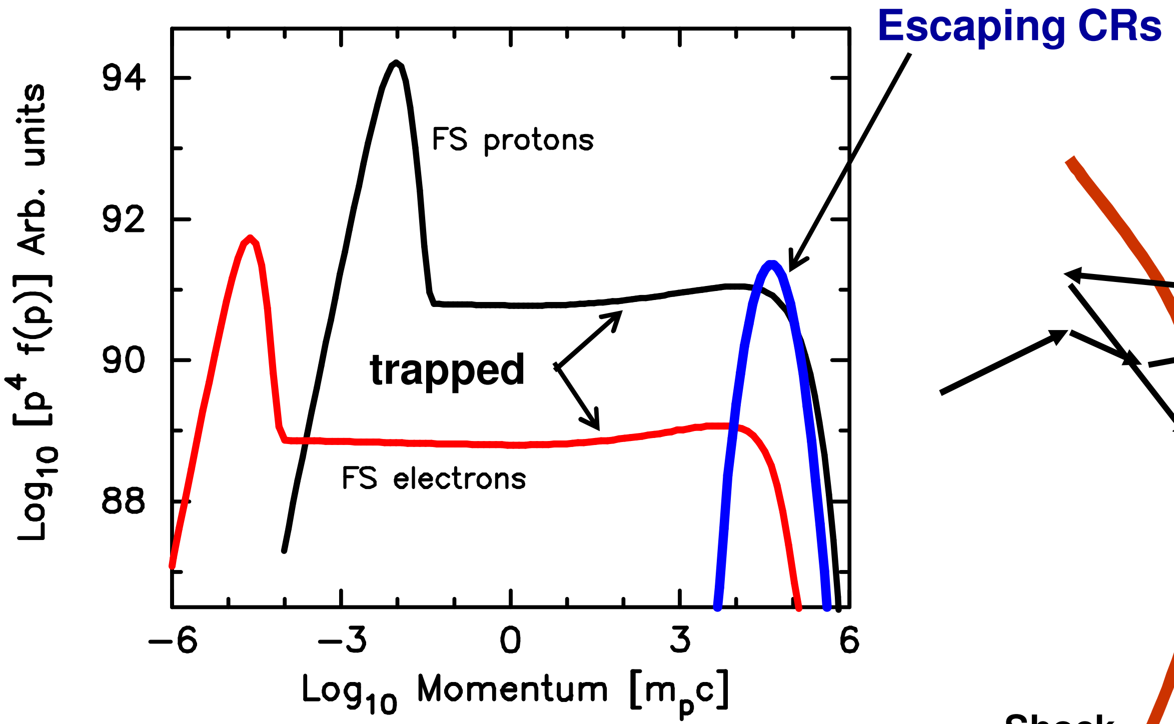
Some references for escaping CRs in DSA:

Ellison, Jones & Eichler (1981); Aharonian & Atoyan (1996);
Ptuskin & Zirakashvili (2005);
Gabici & Aharonian (2007); Gabici, Aharonian & Casanova (2009);
Caprioli et al. (2010); Drury (2010); Ohira et al. (2010,2011);
…..

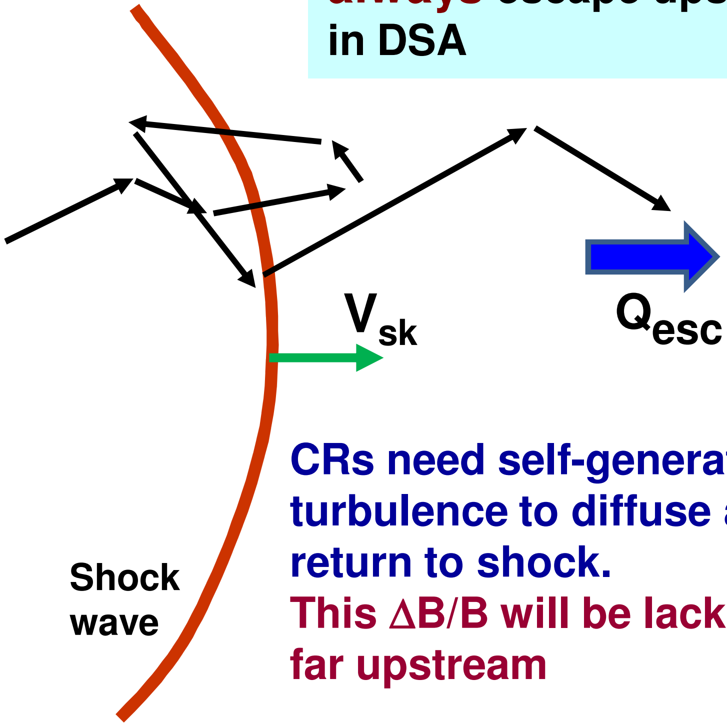
Forward shock of SNR produces 3 particle distributions that will contribute to the photon emission

1) Ions accelerated and trapped within SNR
2) Electrons accelerated and trapped within SNR
3) CRs escaping upstream (mainly ions)

If the shock is producing relativistic particles, some fraction of the highest energy CRs **will always** escape upstream in DSA



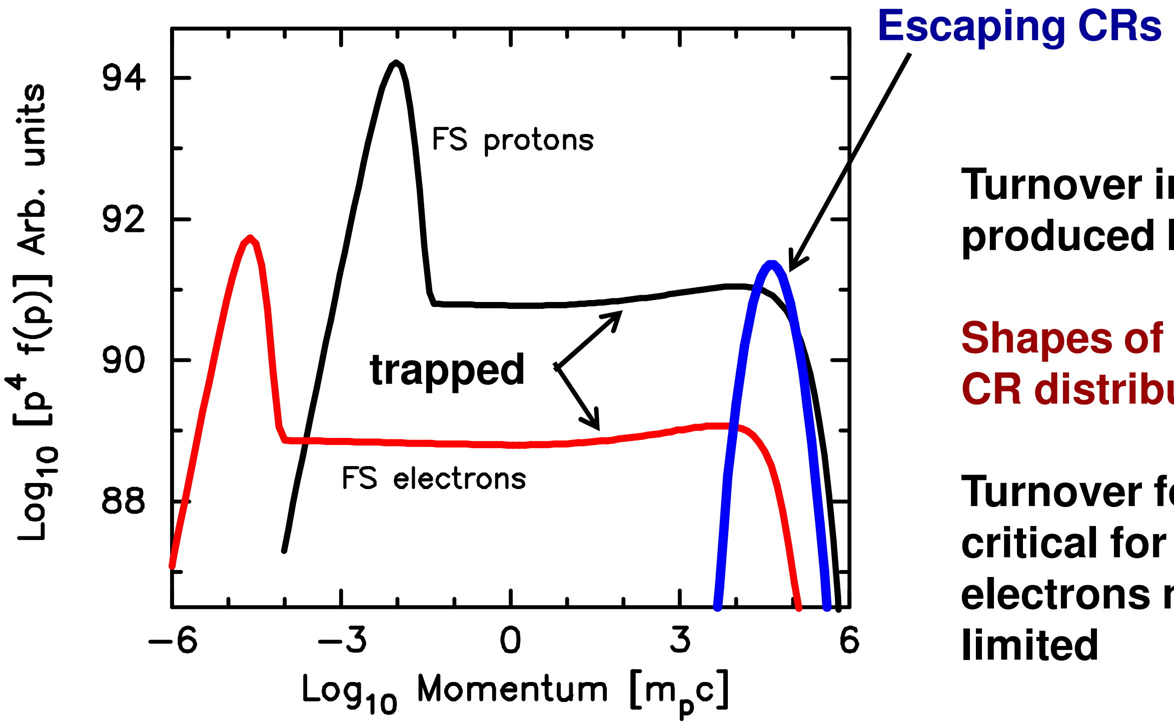
Ellison & Bykov 2011



CRs need self-generated turbulence to diffuse and return to shock.
This $\Delta B/B$ will be lacking far upstream

Forward shock of SNR produces 3 particle distributions that will contribute to the photon emission

1) Ions accelerated and trapped within SNR
2) Electrons accelerated and trapped within SNR
➡ 3) CRs escaping upstream (mainly ions)



Turnover in trapped distribution produced by escaping CRs.

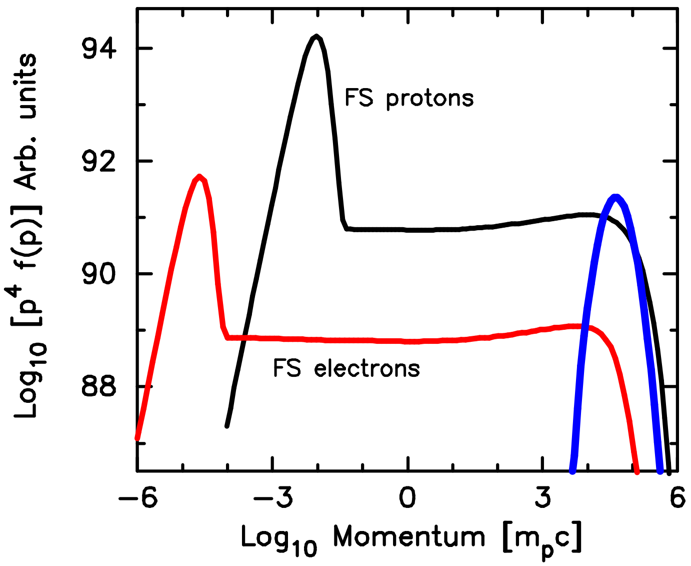
Shapes of trapped and escaping CR distributions not independent.

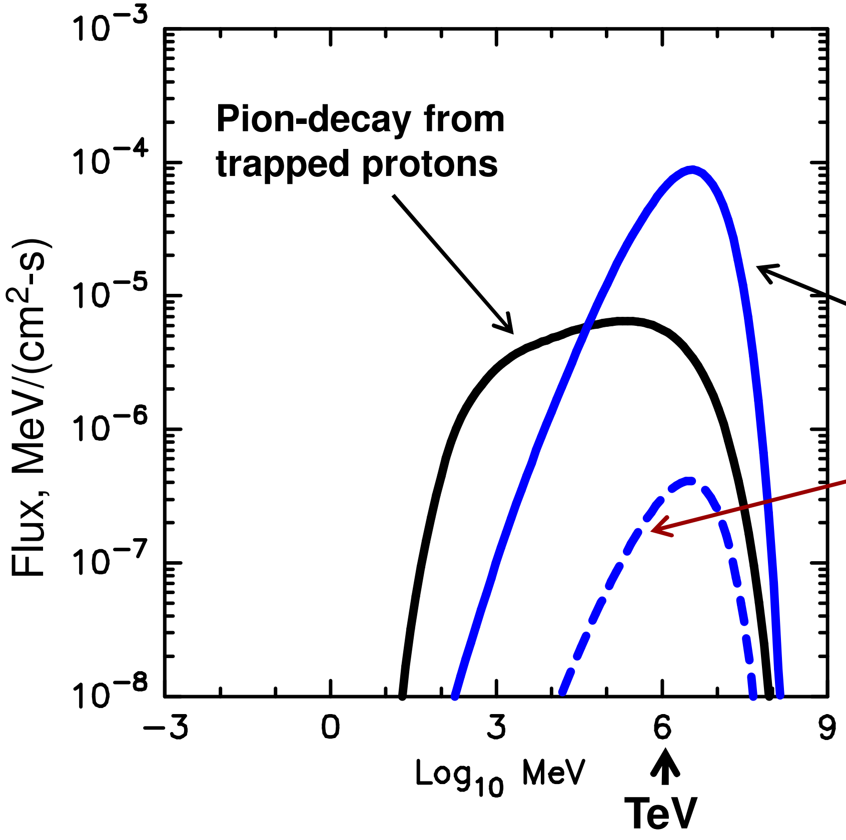
Turnover for trapped electrons critical for X-ray synch. fits if electrons not radiation loss limited

Ellison & Bykov 2011

Trapped CRs interact with compressed ISM within SNR

Escaping CRs may interact with dense <u>external</u> material: molecular cloud, shell from pre-SN wind





Pion-decay from escaping protons:

From dense external shell

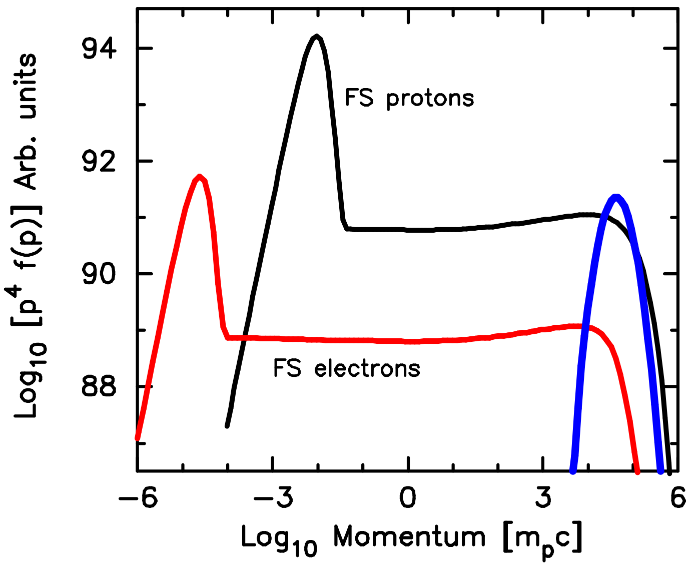
From low-density, uniform ISM

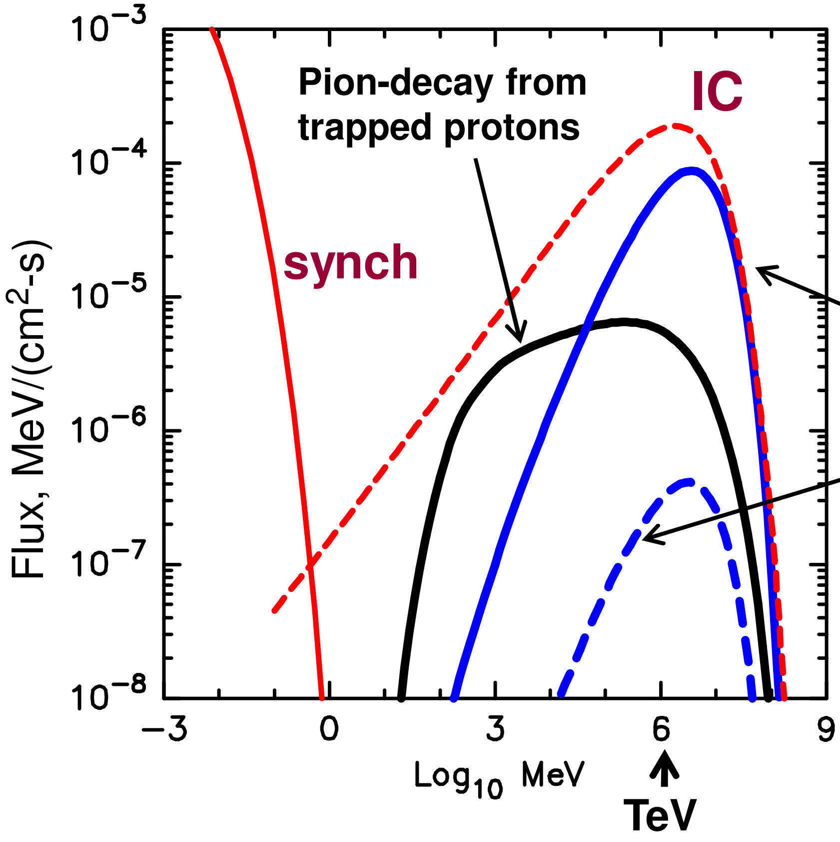
Escaping vs. trapped CRs:

1. **Different spectral shape**
2. **Strong variation with environment**

Trapped CRs interact with compressed ISM within SNR

Escaping CRs may interact with dense external material: molecular cloud, shell from pre-SN wind





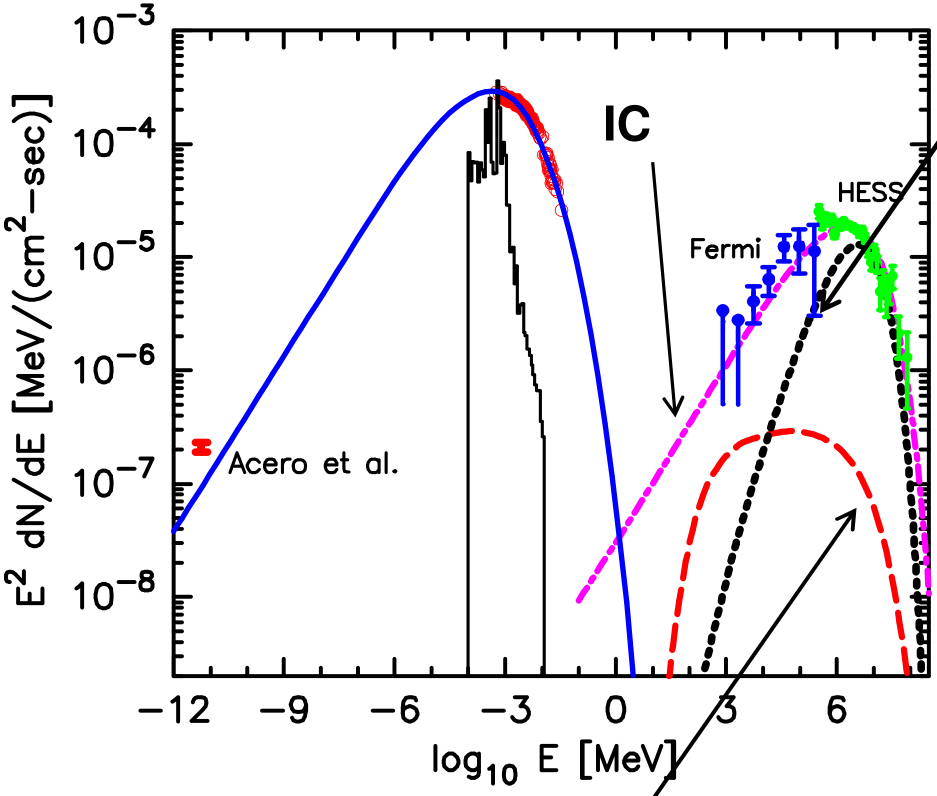
Pion-decay from escaping protons:

From dense external shell

From low-density, uniform ISM

Other parameters: B, K_{ep}, n_p determine relative importance of IC (electrons) vs. pion-decay (protons)

Preliminary work (Ellison, Slane, Patnaude Bykov): Spherically symmetric model



Pion-decay from escaping CRs with 10^4 M_0 of **external** material

Pion-decay from trapped CRs

Pion-decay from escaping CRs can be important at TeV energies without producing lines but

this requires >> 100 M_0 of external material

Also, problems with still unknown shape of escaping CR distribution

Simple models for escaping CRs suggest the distribution will be too narrow

At any instant, it is most likely that escaping CRs will have a peaked distribution. Exact shape uncertain because it depends on wave generation by highest energy CRs with anisotropic distributions. Time evolution of escaping CRs is even more uncertain.

Warning: many uncertainties in model, but

For SNR RX J1713 :

Observations NOT consistent with pion-decay origin for GeV-TeV emission

Inverse-Compton is best explanation for GeV-TeV (Note: other remnants may be Hadronic)

Hadron model for J1713 only possible if escaping CRs interact with >>100 M_0 of external material without producing X-ray lines.
Not so easy to arrange this

Note, most CR energy is still in ions even with IC dominating the radiation ➔ SNRs produce CR ions!

Inverse-Compton result not a problem for CR origin but does impact expected neutrino fluxes

Word on observations of rapid time variability in SNR synchrotron emission

Extremely fast acceleration of cosmic rays in a supernova remnant

RX J1713 **Nature 2007**

Yasunobu Uchiyama[1], Felix A. Aharonian[2,3], Takaaki Tanaka[1,4], Tadayuki Takahashi[1] & Yoshitomo Maeda[1]

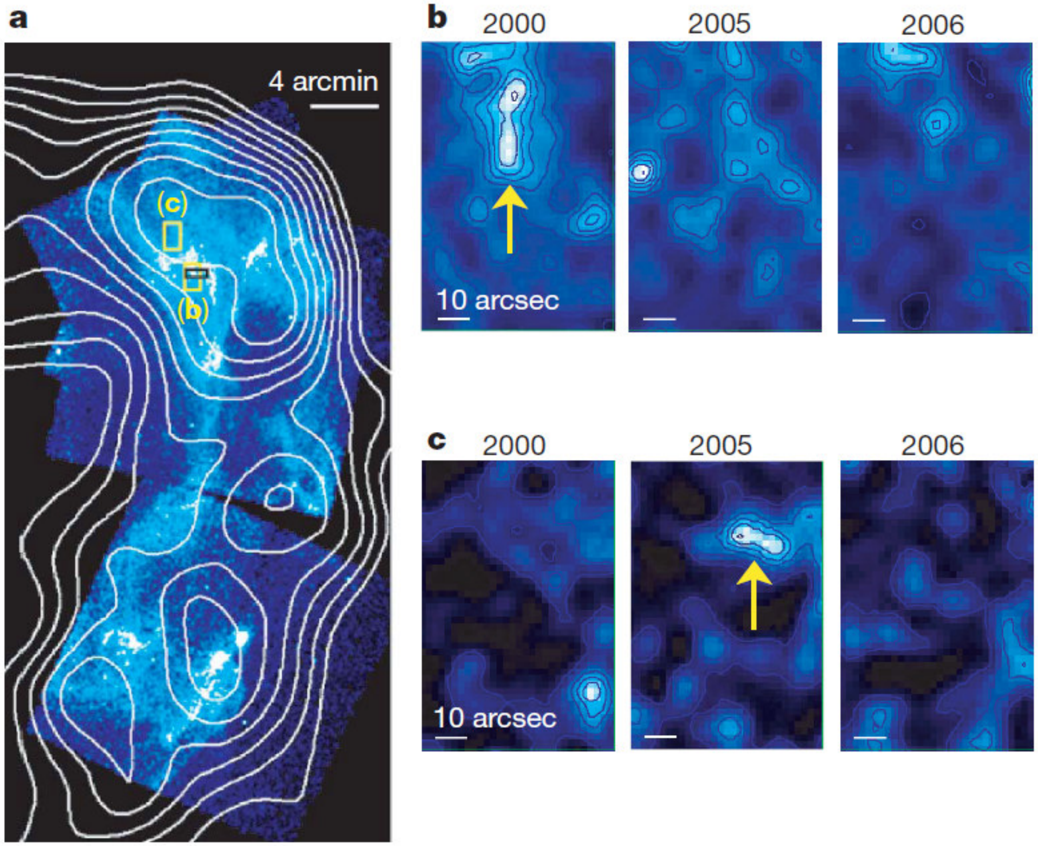


Figure 1 | Chandra X-ray images of the western shell of SNR RX J1713.7−3946. **a,** A Chandra X-ray mosaic image is overlaid with TeV

1-2.5 keV X-rays

Interpreted by Uchiyama et al. as time-scale for synchrotron losses in B > 1 mG fields !

We predict much lower B-fields

FAST VARIABILITY OF NONTHERMAL X-RAY EMISSION IN CASSIOPEIA A: PROBING ELECTRON ACCELERATION IN REVERSE-SHOCKED EJECTA

Yasunobu Uchiyama,[1] & Felix A. Aharonian[2,3]

ApJL 2008

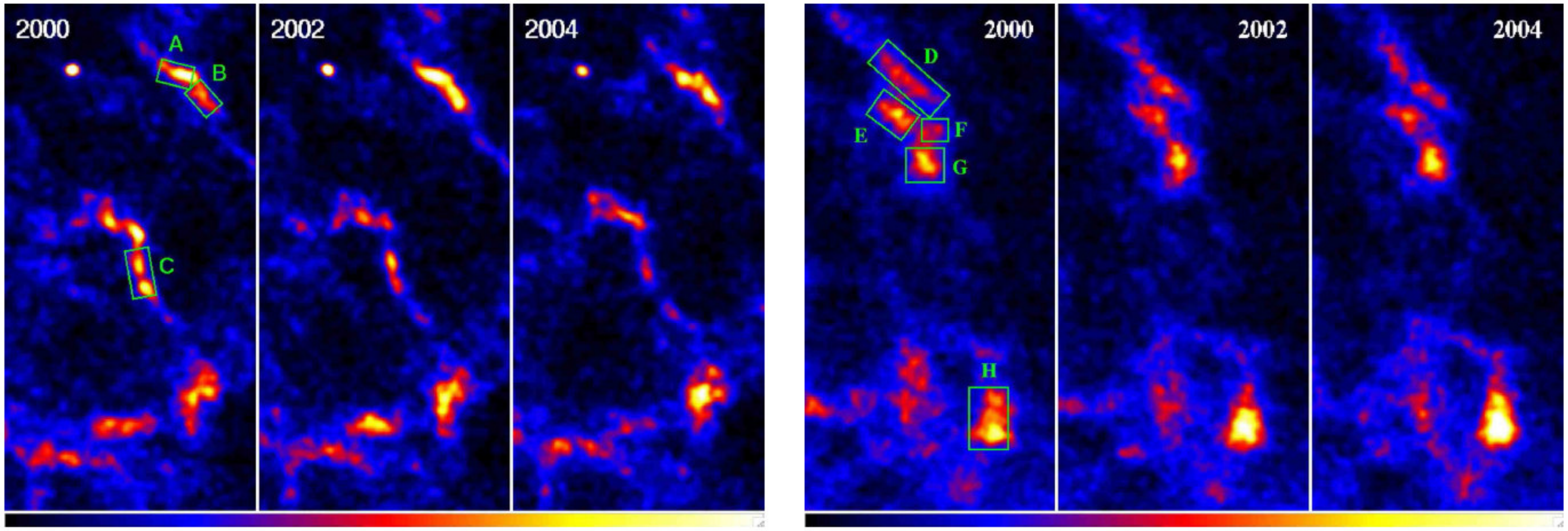


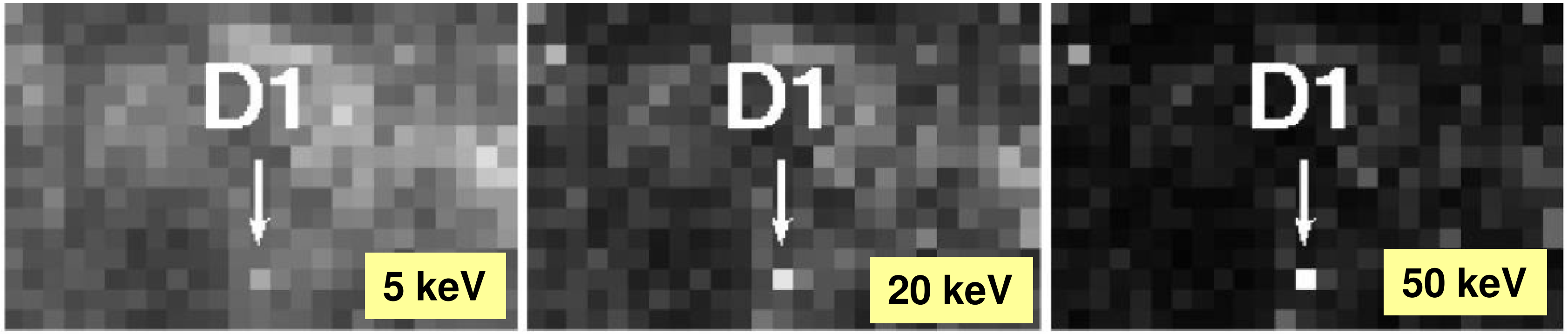
FIG. 2.— A sequence of three-epoch 4–6 keV images of the two 0.5′ × 1′ boxes in Fig. 1. The images are shown in a linear scale in a range of 0–3 counts pix^{-1} for the left panel, and 0–4 counts pix^{-1} for the right panel, respectively. Pixels have dimensions of $0.''2 \times 0.''2$. Gaussian smoothing with a kernel of $0.''8$ is applied. The central box (i.e., the left panel) is close to the aim point and therefore the PSF is sharp as is evident from the point source. The western box (the right panel) is away from the aim point, so that some of the spatial extent should be attributed to the broadening by the PSF.

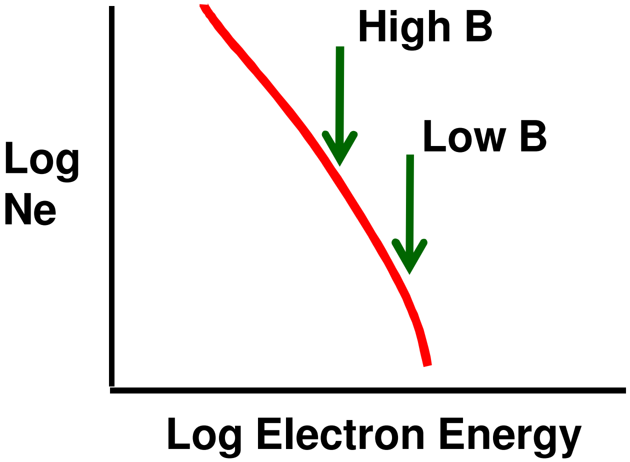
4-6 keV X-rays

Alternative explanation that doesn't set time scale of variations by radiation losses (Bykov, Uvarov & Ellison 2008)

➔ Combine turbulent magnetic field with steep electron distribution

➔ For given synchrotron emission energy, local regions with high B have many more electrons to radiate than regions of low B





➔ Local high-B regions dominate line-of-sight projection

➔ Varying magnetic turbulence produces intermittent, clumpy emission

➔ Time scales consistent with SNR observations

➔ No need for ~ 1000 μG magnetic fields

X-ray strips in Tycho's SNR (Eriksen etal 2011)

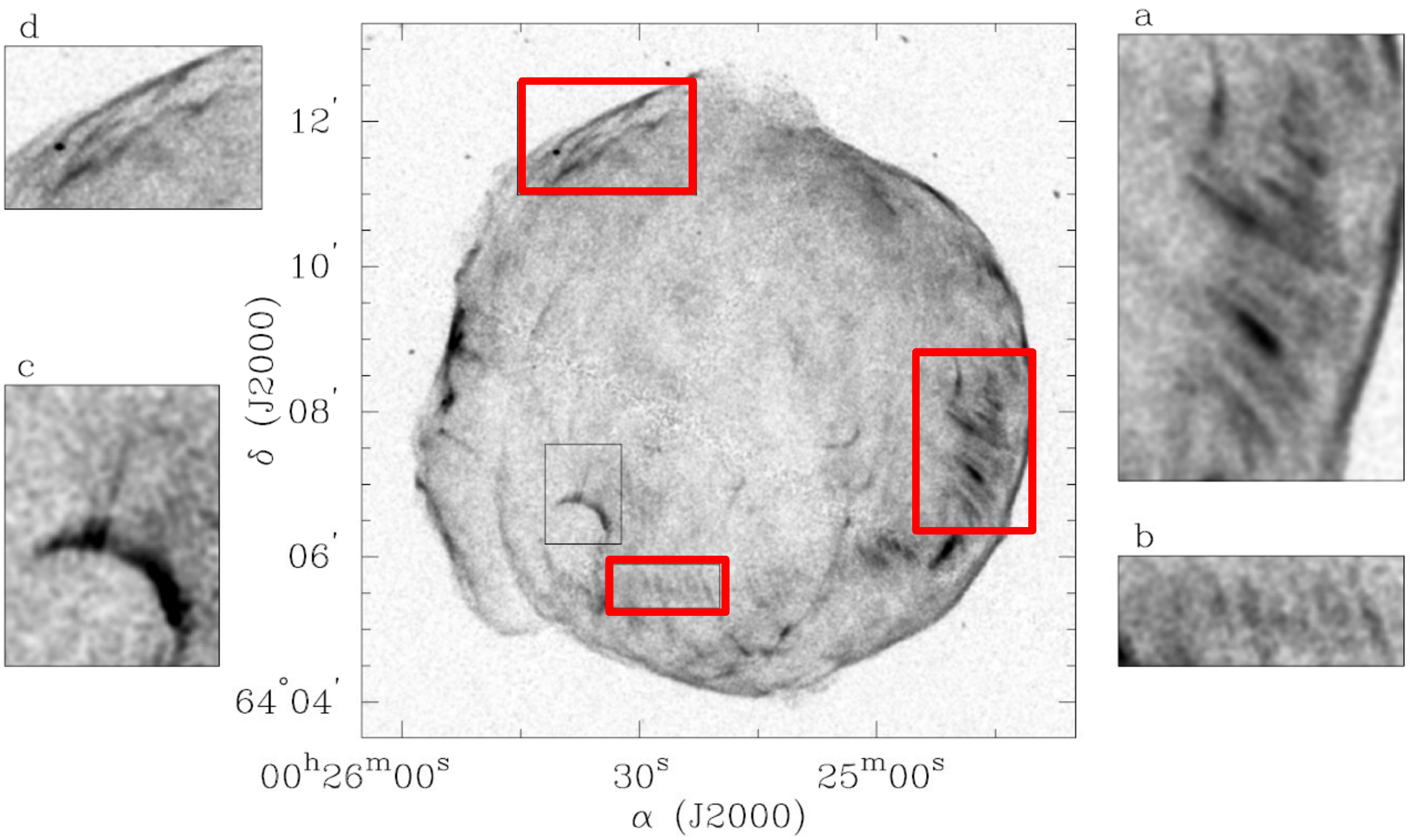
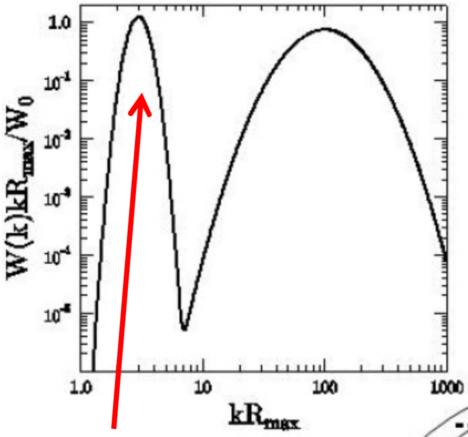


FIG. 1.— *Chandra* X-ray 4.0–6.0 keV image of the Tycho supernova remnant, smoothed with a ∼ 0.75″ Gaussian and displayed with an *arcsinh* scaling, showing various regions of striping in the nonthermal emission. Clockwise from the upper right: a) The main western stripes discussed in this Letter; b) A fainter ensemble of stripes; c) a previously-known bright arc of non-thermal emission, with our newly discovered streamers; d) filaments of "rippled sheet" morphology common in optical observations of middle-aged SNRs.

Chandra 4-6 keV X-rays

Bykov, Ellison, Osipov, Pavlov, Uvarov, ApJL submitted

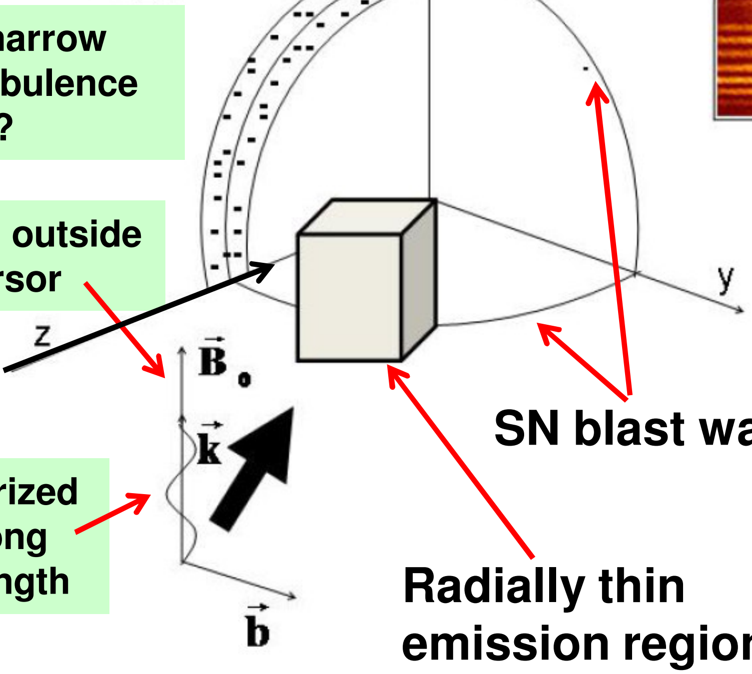


Must have narrow peaks in turbulence spectrum ??

Simulated strips

Efficient, NL shock acceleration producing ~100 TeV protons

Steep electron spectrum: enhance contrast, no strips in radio



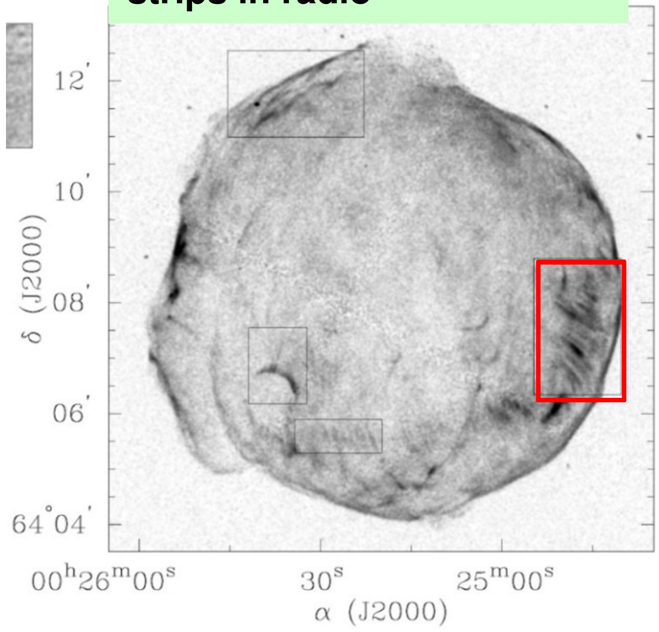
Perp. B-field outside shock precursor

Line of sight

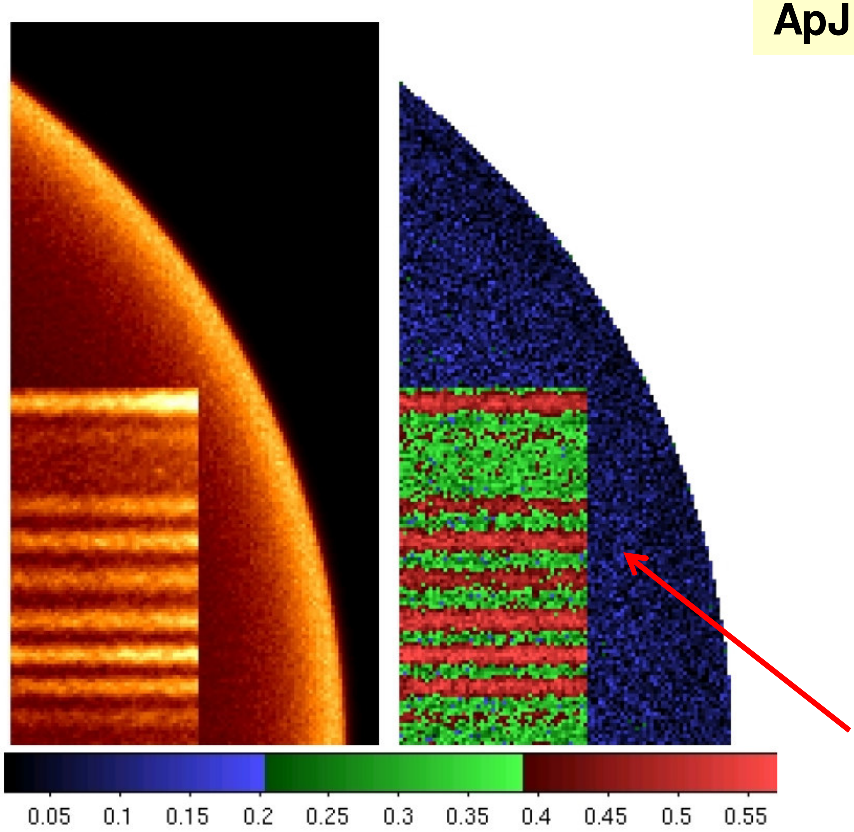
Linearly polarized waves with long coherence length

SN blast wave

Radially thin emission region



Bykov, Ellison, Osipov, Pavlov, Uvarov, ApJL submitted



Polarization fraction

No simple explanation of strips !

➔ Many shock and turbulence properties must come together to produce coherent structure on this scale.

Strong predictions NL DSA model:
Quasi-perpendicular upstream B-field

Strong linear polarization in strips

Conclusions

- ➔ Collisionless shocks are common throughout astrophysics
- ➔ Strong collisionless shocks always produce a superthermal population
- ➔ Strong magnetic turbulence (MFA) can accompany CR production
- ➔ Diffusive Shock Acceleration can be efficient, nonlinear & complicated
- ➔ Escaping CRs are important dynamically and observationally
- ➔ With complications of NL DSA come meaningful constraints

➔ Shock surprises aren't over yet !

X-ray strips in Tycho's SNR (Eriksen etal 2011)
Manifestation of NL DSA? (Bykov et al.)