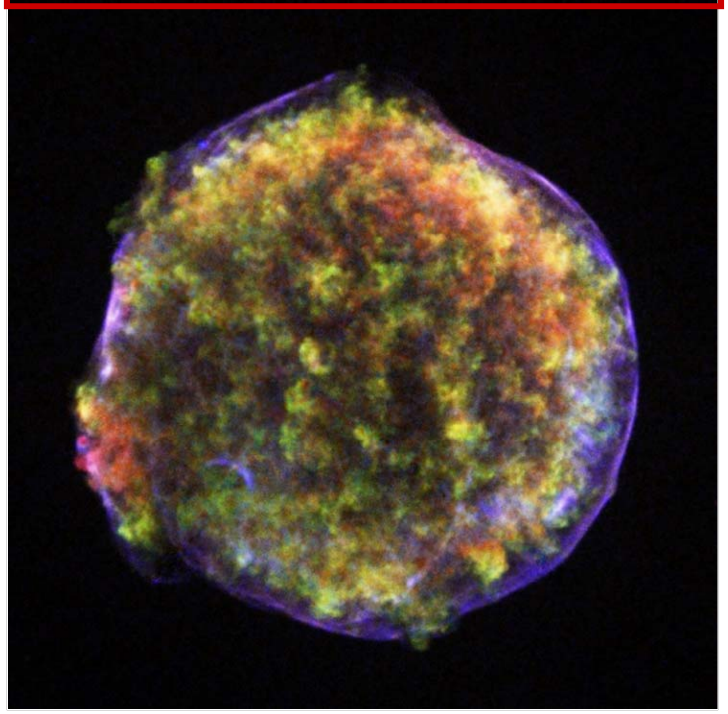
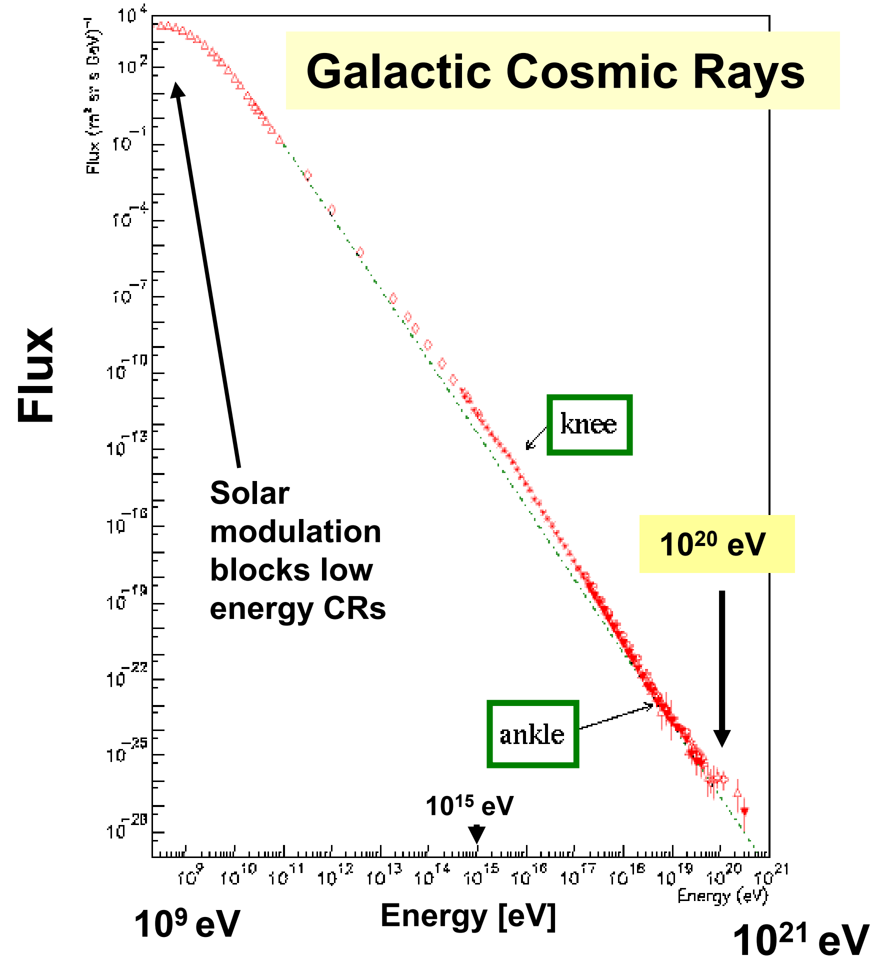
Particle Acceleration Mechanisms in Astrophysics

Don Ellison, North Carolina State Univ.

Tycho's Supernova Remnant



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



Hillas_Rev_CRs_JPhysG2005.pdf

Particle Acceleration Mechanisms in Astrophysics

Don Ellison, North Carolina State Univ.

Nonthermal particle distributions are ubiquitous in diffuse plasmas in space → result of low densities and large magnetic fields

Possible acceleration mechanisms →

1) Magnetic reconnection (Solar flares, GRBs?)

2) Charge separation (double layers)

3) Pulsar mechanisms (rotating B-fields, Poynting fluxes, jets)

4) Second-order Fermi acceleration

➡ **5) Shock acceleration (first-order Fermi mechanism, also called Diffusive Shock Acceleration - DSA)** ⬅

Particle Acceleration in Collisionless Shocks

Why collisionless shocks?

How does particle acceleration occur in collisionless shocks?

Applications of Diffusive Shock Acceleration (DSA) in astrophysics (mainly in Supernova Remnants)

In diffuse regions of space have large bulk speeds compared to typical thermal speeds → supersonic flows and, therefore, shocks:

$$\text{Mach\#} = M_S = \sqrt{\frac{3\rho V^2}{5P}}, \quad V = 200\frac{km}{s}, \quad T = 10^6 K, \quad M_S = 1.7$$

Note: solar wind speed ~400 km/s, $T_{sw} < 10^6$ K

In diffuse space plasmas, particle-particle collisions are rare.

$$\lambda_{\rm coll} \propto \frac{1}{n\sigma_C}$$ collision mean-free-path

Collision mean-free-path much too large to produce collective effects like planetary bow shocks

But thin shocks are observed → collective effects from charged particles interacting with background magnetic turbulence replaces particle-particle collisions ($\lambda_B << \lambda_{coll}$)

Important difference between particle-particle collisions and B-field-particle interactions ➔ B-field interactions are nearly elastic:

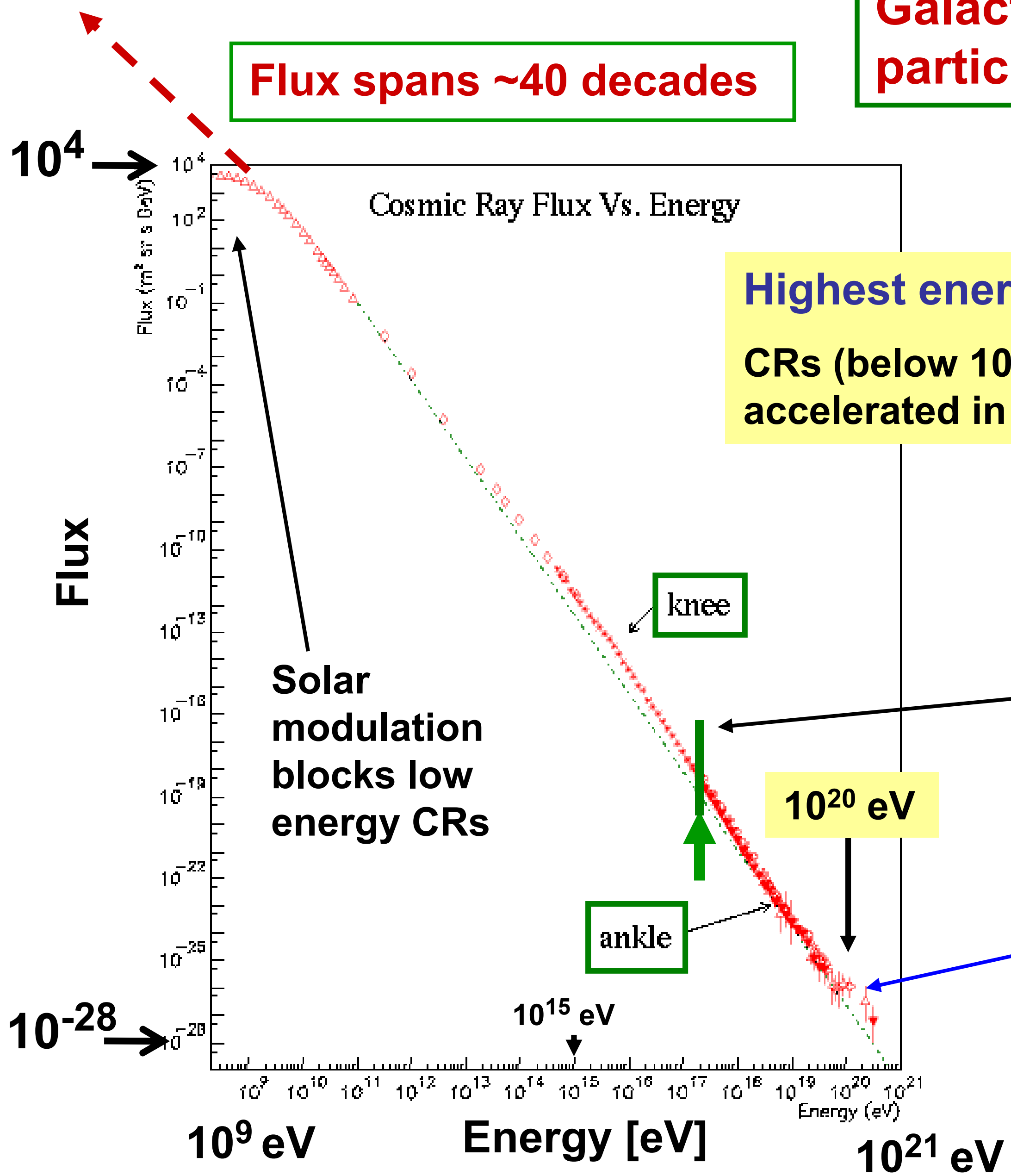
High energy particles don't share energy with low energy ones

In collisionless plasmas, strongly nonthermal particle distributions can persist for long times.

The most extreme case: Galactic Cosmic Rays

Jones_&_Ellison_review_paper_SSR91.pdf

Galactic Cosmic Ray all particle spectrum



Highest energy particles ever observed!

CRs (below 10^{15} eV, at least) most likely accelerated in collisionless shocks

LHC ~10 TeV proton ~ 2×10^{17} eV cosmic ray energy

Highest energy CRs have extra-galactic origin: Still unknown ?

Hillas_Rev_CRs_JPhysG2005.pdf

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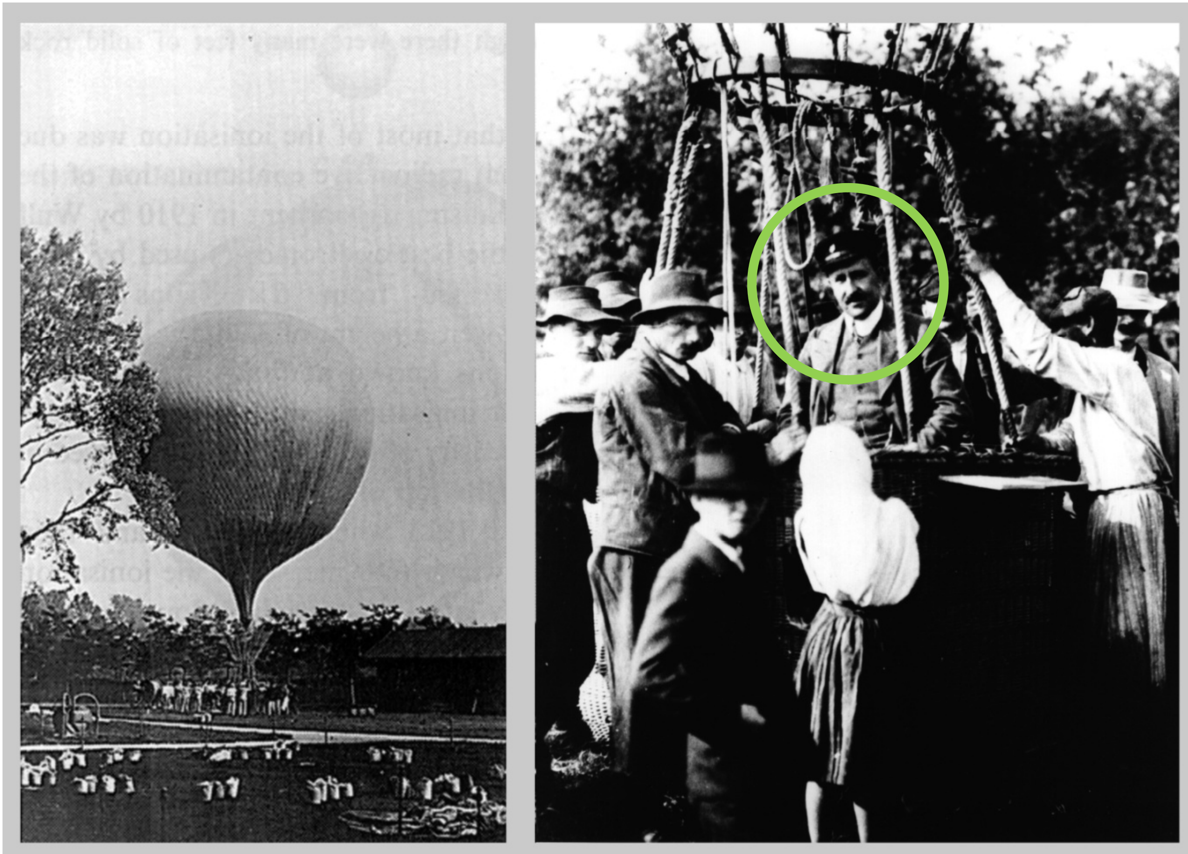

100 year anniversary of discovery of Cosmic Rays by Victor Hess !

Victor Hess (1883-1964) proved CRs come from space. His balloon experiments in 1911-12 showed background ionization to be 4 times greater at 5000m than at ground level. Received Nobel Prize in 1936.

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Two cosmic ray questions immediately come to mind:

1) After 100 years, why are CRs still interesting and important ?

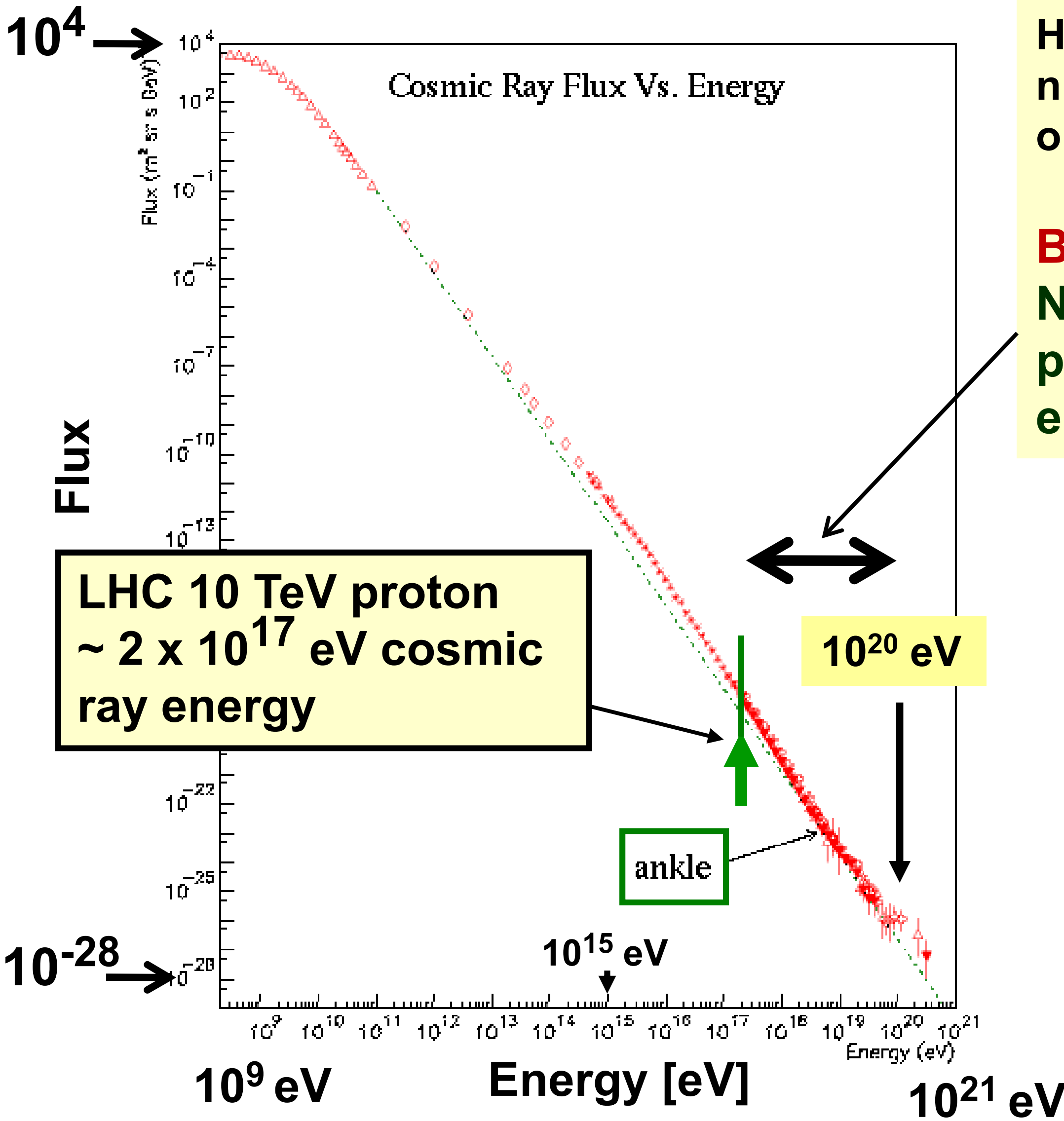
2) Why is it taking so long to understand the origin and acceleration of CRs ?

Cosmic Rays are still interesting because:

► **Highest energy particles ever measured !**
>10^{20} eV (1000 times greater than Large Hadron Collider center of mass energy

► **Great mystery of acceleration**
(3x10^{20} eV CR proton has the energy of tennis ball served by Serena Williams)

► **Highest energy CRs carry nuclear physics information obtainable nowhere else**



Highest energy CRs carry nuclear physics information obtainable nowhere else.

Blessing and curse :
Need to know nuclear physics to interpret highest energy CR observations

Hillas_Rev_CRs_JPhysG2005.pdf

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Cosmic Rays are still interesting because:

► Highest energy particles ever measured ! >10^{20} eV (1000 times greater than Large Hadron Collider center of mass energy)

► Great mystery of acceleration

► Highest energy CRs carry nuclear physics information obtainable nowhere else

► Only measured source of Matter from outside solar system (exceptions: few ISM dust grains collected by spacecraft, dust grains in meteorites, ~20 neutrinos from SN1987A)

► Learn things photons can't tell us

► Elemental composition & Isotope ratios give unique information on nucleosynthesis and Supernova explosions, etc.

CR data from Ahn et al 2010

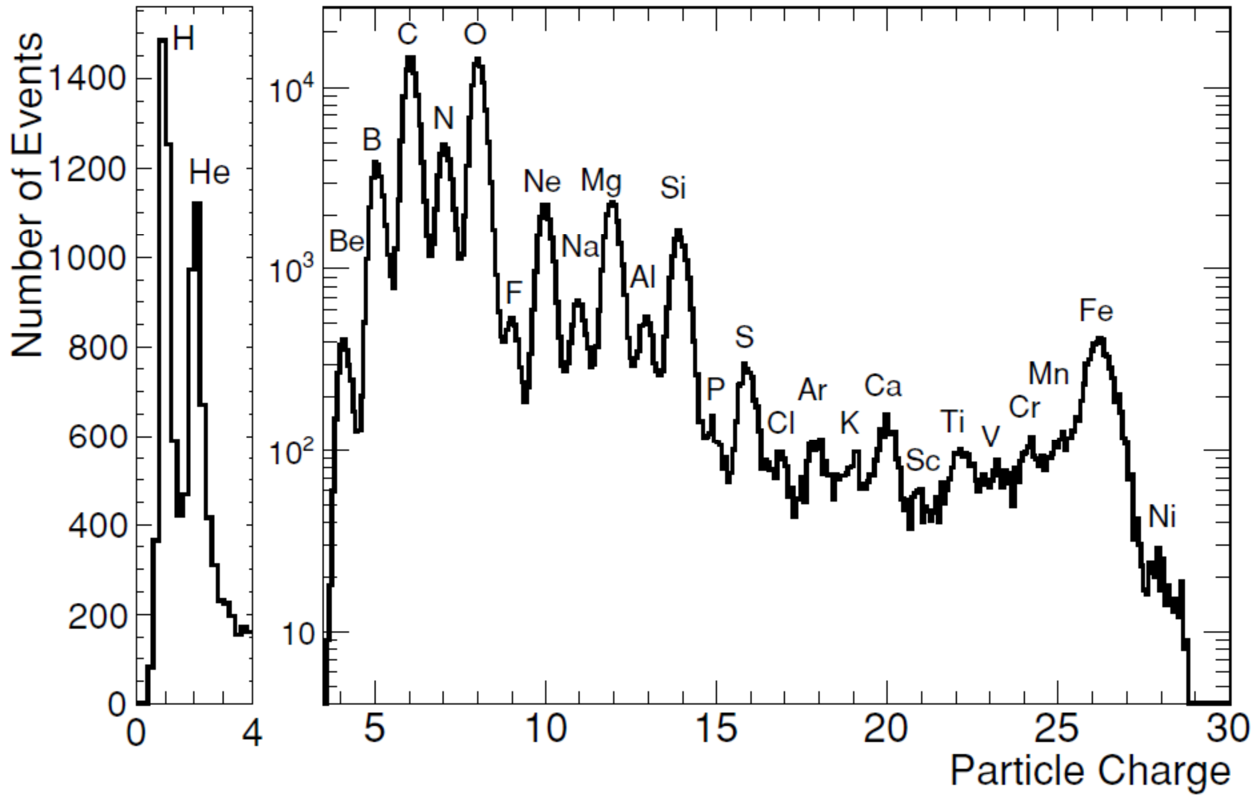

Figure 2. Distribution of cosmic-ray charge measured with the SCD. The charge reconstructed for a fraction of the flight data is shown in units of the elementary charge e. The individual elements are clearly identified. The charge resolution is better than $0.2e$ for proton and helium, $0.2e$ for oxygen, and slightly worse than $0.2e$ for higher charges. The relative abundance in this plot has no physical significance, because needed corrections for interactions and propagations have not been applied to these data.

Cosmic ray abundances are well-mixed ISM with enhancements of elements locked in dust and heavy volatile elements, i.e., Argon, Xenon

(e.g., Meyer et al 1997)

► **Strongly non-thermal particles common throughout astrophysics.**

► **Radio emission from relativistic electrons ➔ signature of violent activity**

► **In some sources, non-thermal particles contain large fraction of energy budget !**

► **CRs are prototype for most non-thermal particles in universe ➔**

Understanding acceleration of CRs will help our understanding of objects as diverse as solar flares, the Earth bow shock, extra-galactic radio galaxies & gamma-ray bursts.

► Strongly non-thermal particles common throughout astrophysics. CRs are the most extreme example

► In some sources, non-thermal particles contain majority of energy budget !

► Understanding CRs will help our understanding of objects as diverse as solar flares, the Earth bow shock, extra-galactic radio galaxies & gamma-ray bursts.

► CRs have enough energy density to influence Interstellar Medium, molecular clouds, & star formation

► Propagation of CRs through ISM gives information on local space environment   Interaction of Charged particles (vs. neutral photons) with interstellar & inter-galactic magnetic fields

►Diffuse gamma-ray emission produced by CRs during propagation is critical background for *Fermi Spacecraft* and dark-matter studies (e.g., Galprop modeling of CR propagation & diffuse emission)

Why, after 100 years, don't we have all the answers for CRs ?

- ► We don't see CR sources directly
  - ► CRs are charged particles, not neutral photons. CRs diffuse in interstellar magnetic field.
  - ► Except for highest energy extra-galactic CRs, all source direction lost in propagation.
- ► Most important clue to origin is Elemental Composition
  - ► Once it was realized that Supernovae were most likely sources of CRs, expected that measuring CRs at Earth would allow us to "See nucleosynthesis in action"
  - ► But, turns out CR composition is mainly well-mixed ISM with some important exceptions ► NOT mainly fresh supernova ejecta material

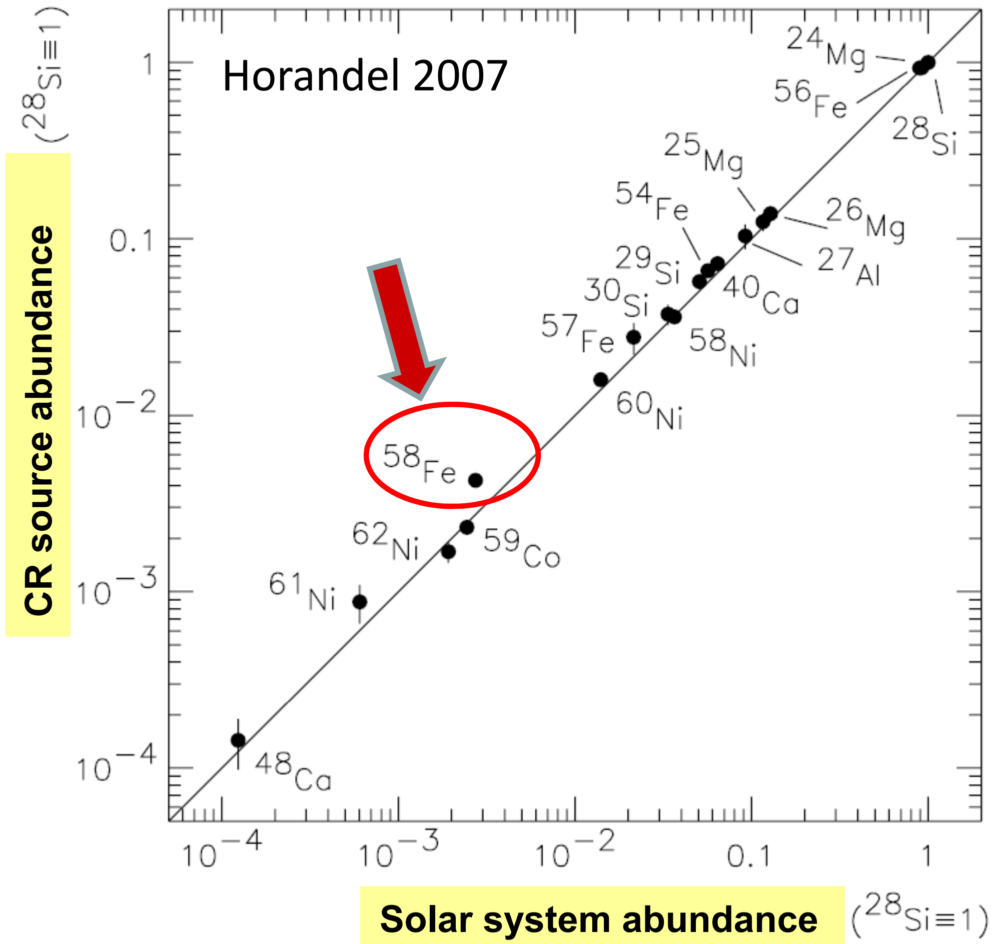

Fig. 5. Comparison of derived galactic cosmic-ray (GCR) source abundances of refractory nuclides with solar-system abundances according to measurements with ACE/CRIS normalized to ^{28}Si (Wiedenbeck et al., 2003).

CR source abundances of Refractory Nuclides

^{58}Fe plus ^{22}Ne/^{20}Ne enhancement (not shown) only isotopic anomalies

Other than inferred Wolf-Rayet component from ^{22}Ne,
No smoking gun for Core-collapse SNe or exotic objects like pulsars, etc.

CRs come mainly from well-mixed ISM, but . . .

With improved sensitivity, expect to see signatures of Type Ia, Type II SNe, etc in composition

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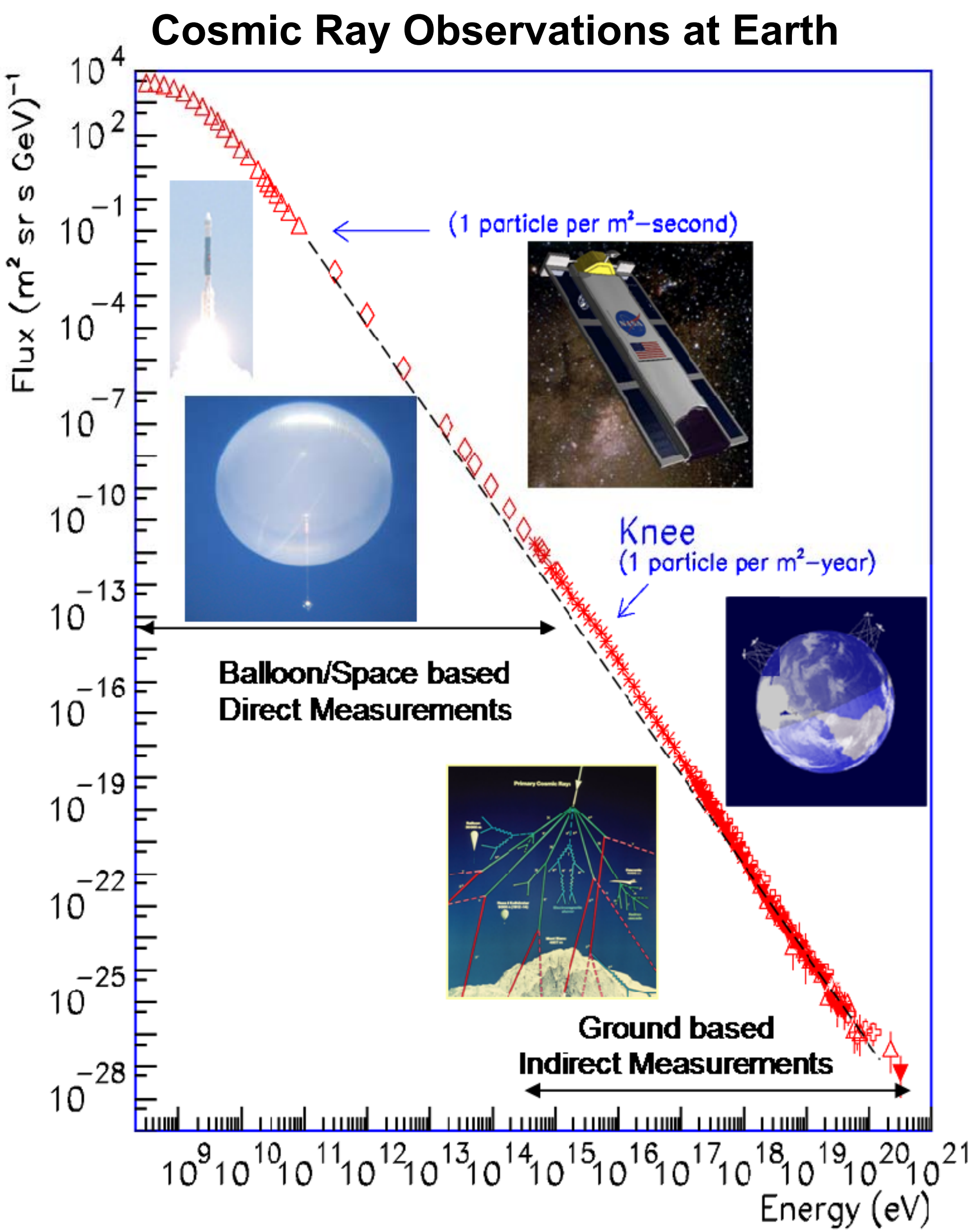
► Biggest problem: Cosmic Rays are hard to measure & hard to model



Steep spectrum! Flux drops drastically with energy

➔ Need large & heavy detectors

Only can make direct detection with balloons or spacecraft at low energies below "Knee."

➔Near knee and above, indirect detection: air showers measured in atmosphere (Cherenkov or fluorescence) or on ground

➔Must match very different methods at critical regions like "Knee."

Direct detection of CRs by balloons

Victor Hess 1911

CREAM: Cosmic Ray Energetics and Mass, 2011 in Antarctica

http://orbiterchspacenews.blogspot.com/2010/12/nasa-nsf-scientific-balloon-launches.html

Just because a technology has been around for a while doesn’t mean it’s outdated

Windmills in Greece

Just because a technology has been around for a while doesn't mean it's outdated

Wind mills in Spain

From Wikipedia

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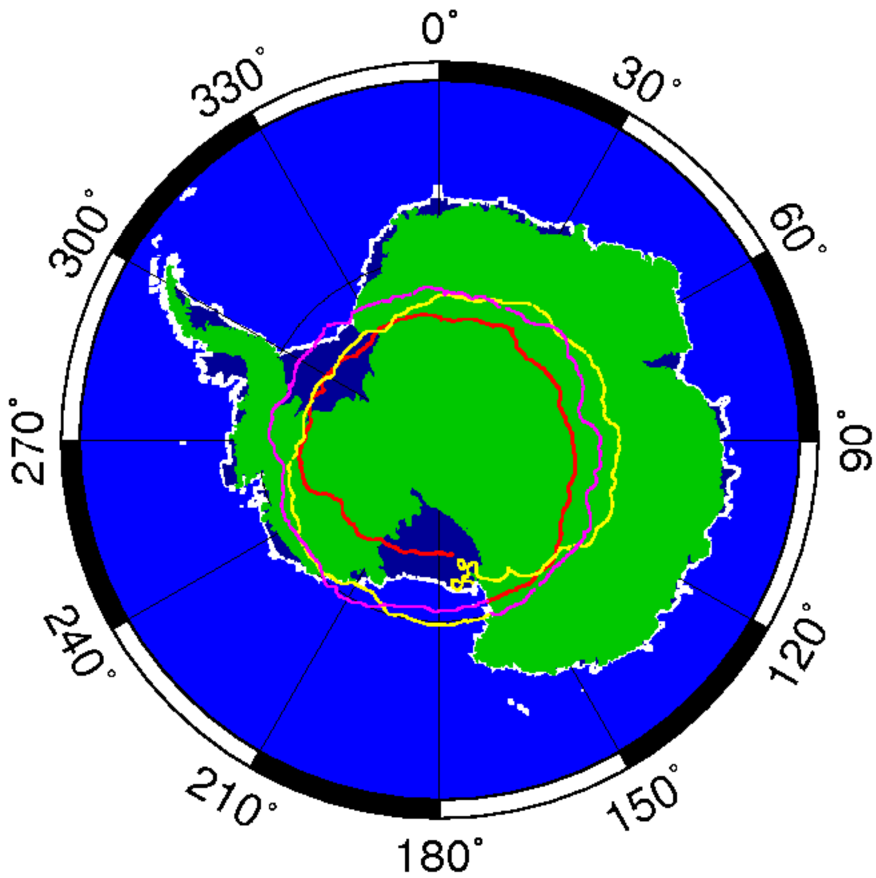
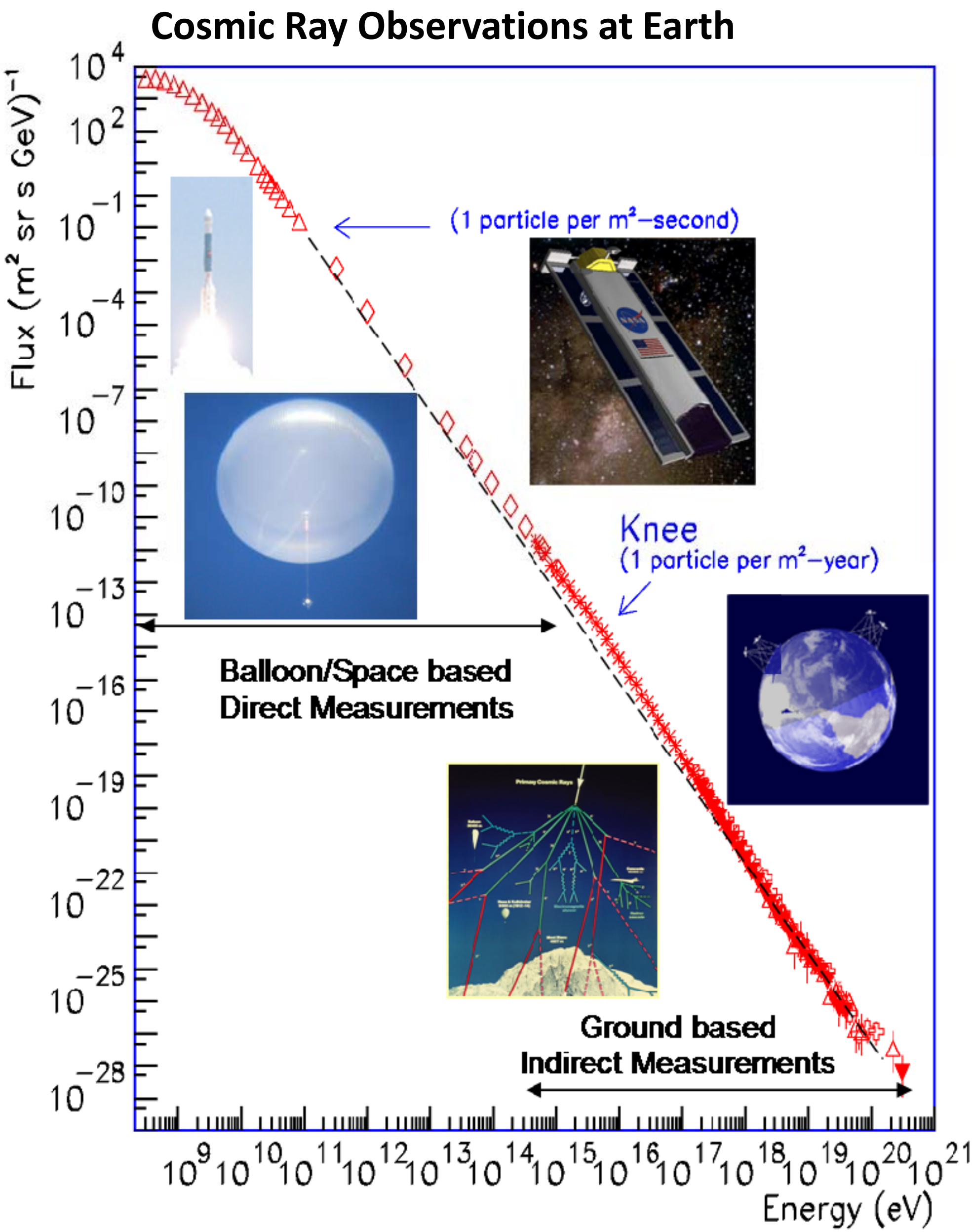
CREAM Balloon flights in Antarctica



Suspend >1000kg above >98% of atmosphere at fraction of cost of going into space.

40 million cubic foot balloon
Float between ~38 and ~40 km
Average atmospheric overburden of ~3.9 g/cm^2

Cumulative exposure for 5 flights of ~156 days



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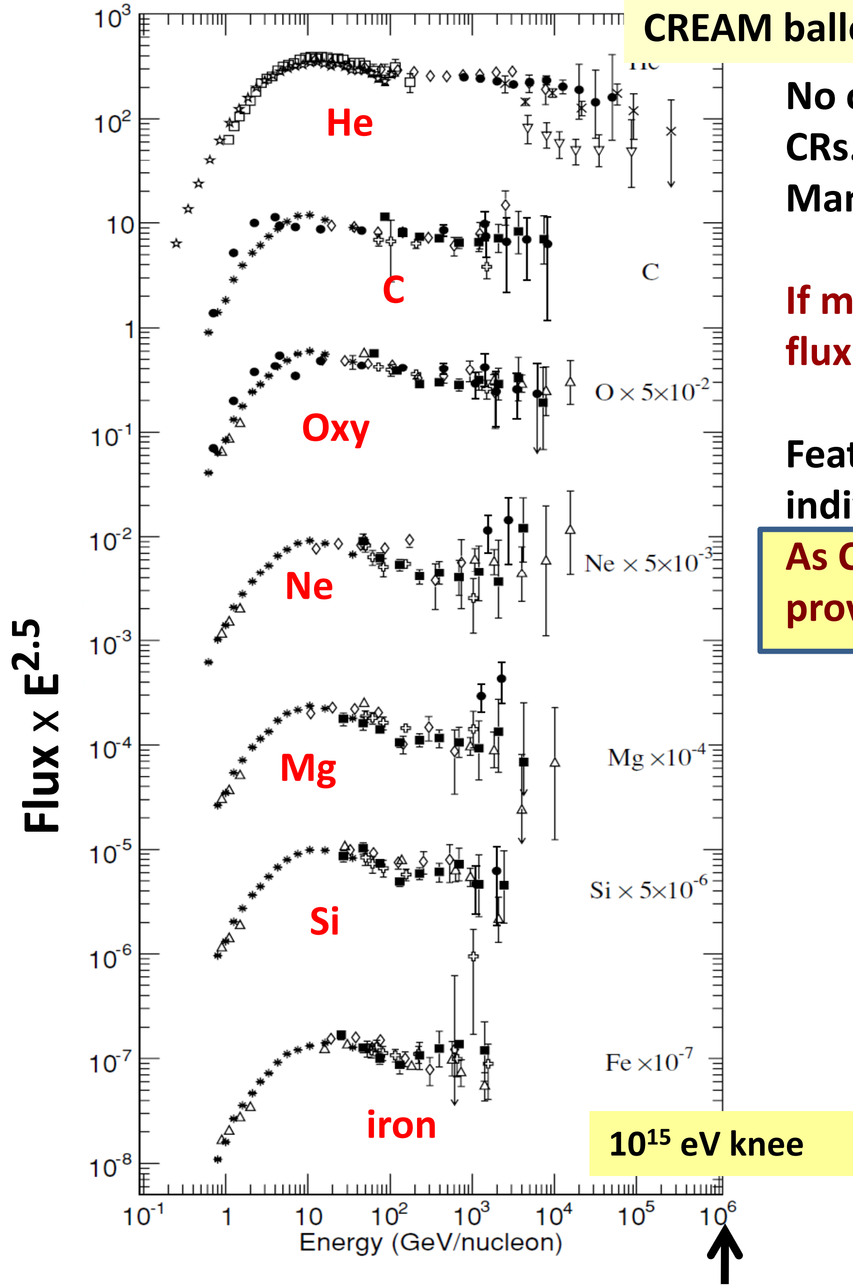
Nevertheless, get such a nice power law !?

Not such a nice power law with a closer look

CREAM balloon obs

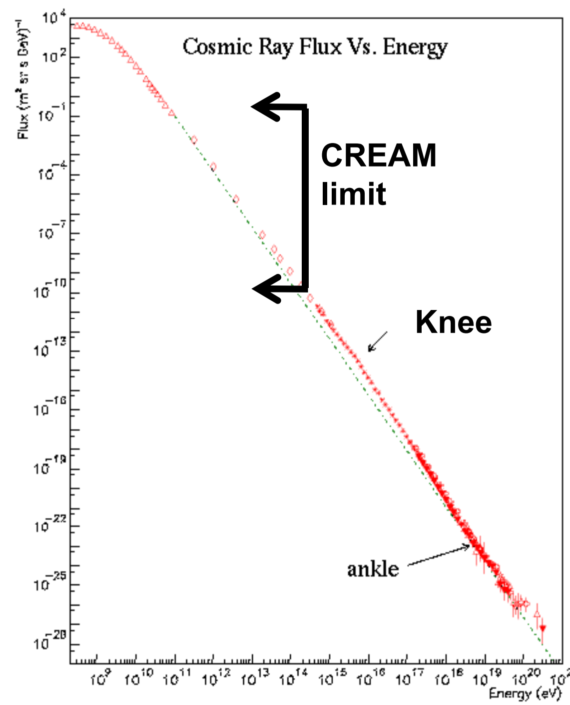


No one should expect a single source to produce all CRs.
Many individual sources with different properties

If many different sources, why should the total CR flux be a perfect power law?

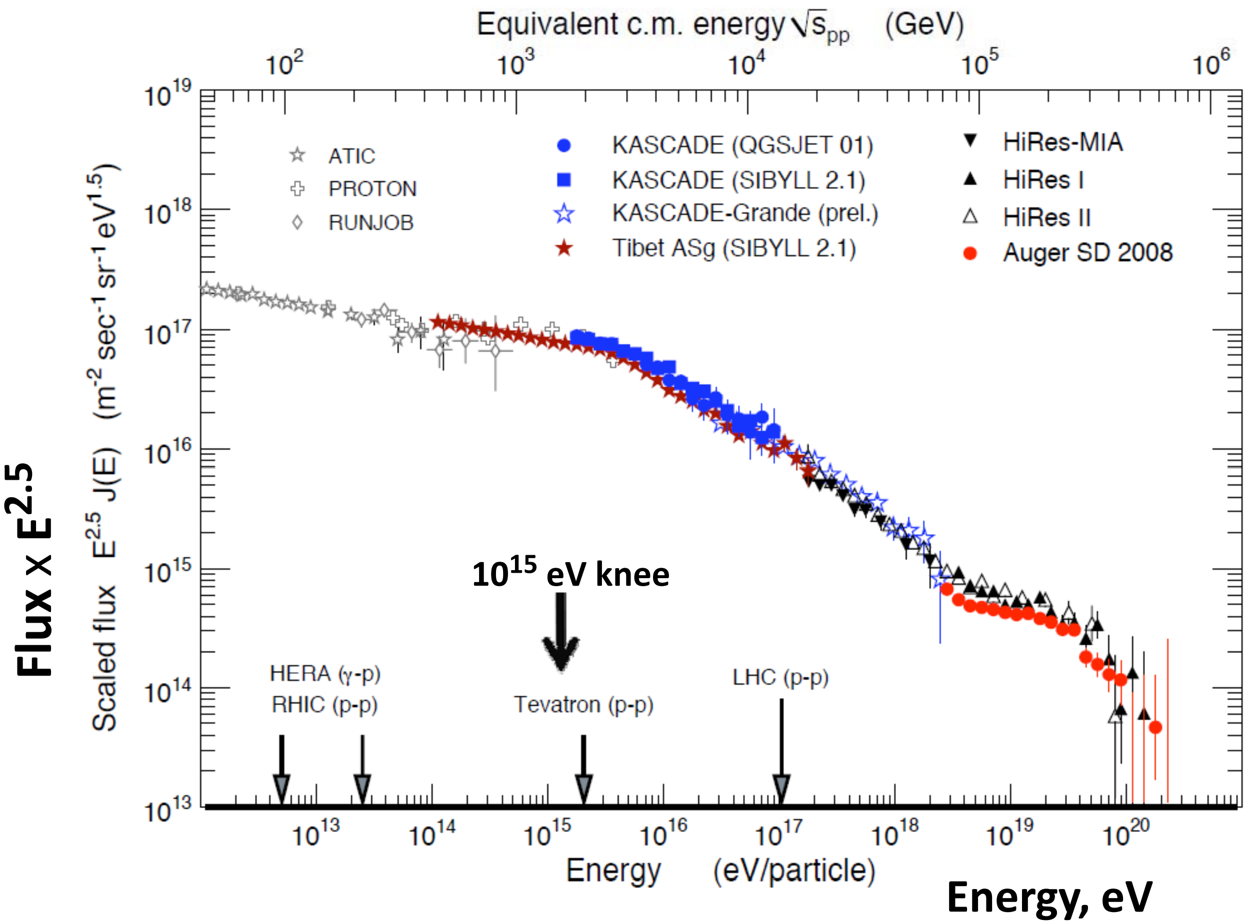
Features in spectrum may stem from some nearby individual sources: e.g., nearby SNRs, pulsars ??

As CR observations improve, spectral features may provide important clues to origin.



CR data from Ahn et al 2010

Blumer, Engel & Horandel 2009



CRs at knee and above:

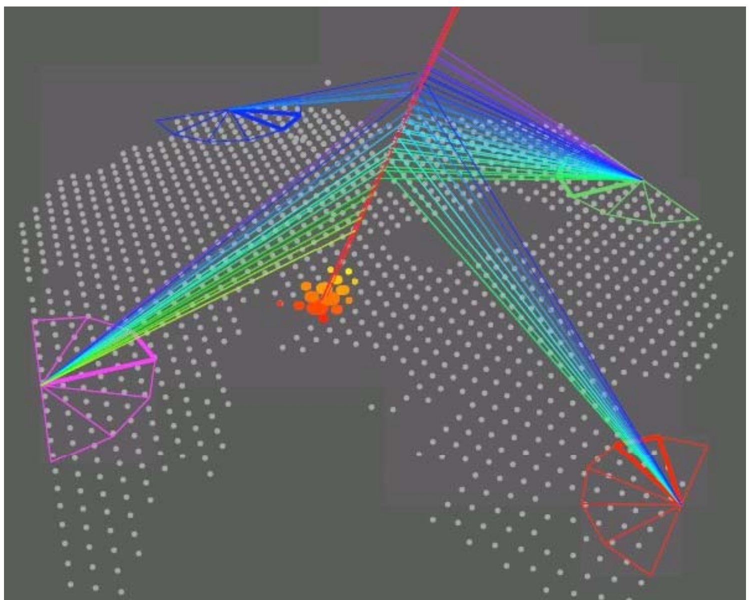
Understanding of CR origin will improve as sensitivity improves and features become confirmed or not

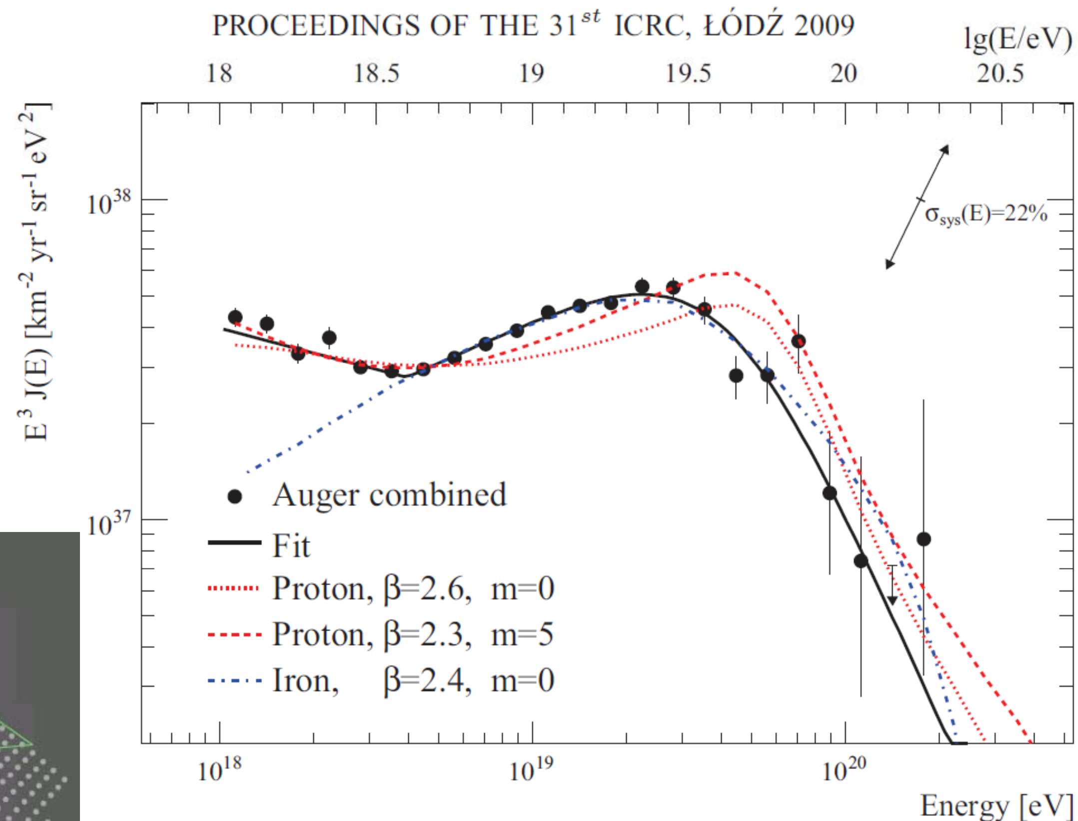
Figure 7: All-particle cosmic-ray energy spectrum as obtained by direct measurements above the atmosphere by the ATIC [280, 281], PROTON [282], and RUNJOB [284] as well as results from air shower experiments. Shown are Tibet ASγ results obtained with SIBYLL 2.1 [285], KASCADE data (interpreted with two hadronic interaction models) [286], preliminary KASCADE-Grande results [287], and Akeno data [288, 42]. The measurements at high energy are represented by HiRes-MIA [289, 290], HiRes I and II [291], and Auger [221].

Pierre Auger Observatory

Unprecedented accuracy at 10^{19} eV and above.

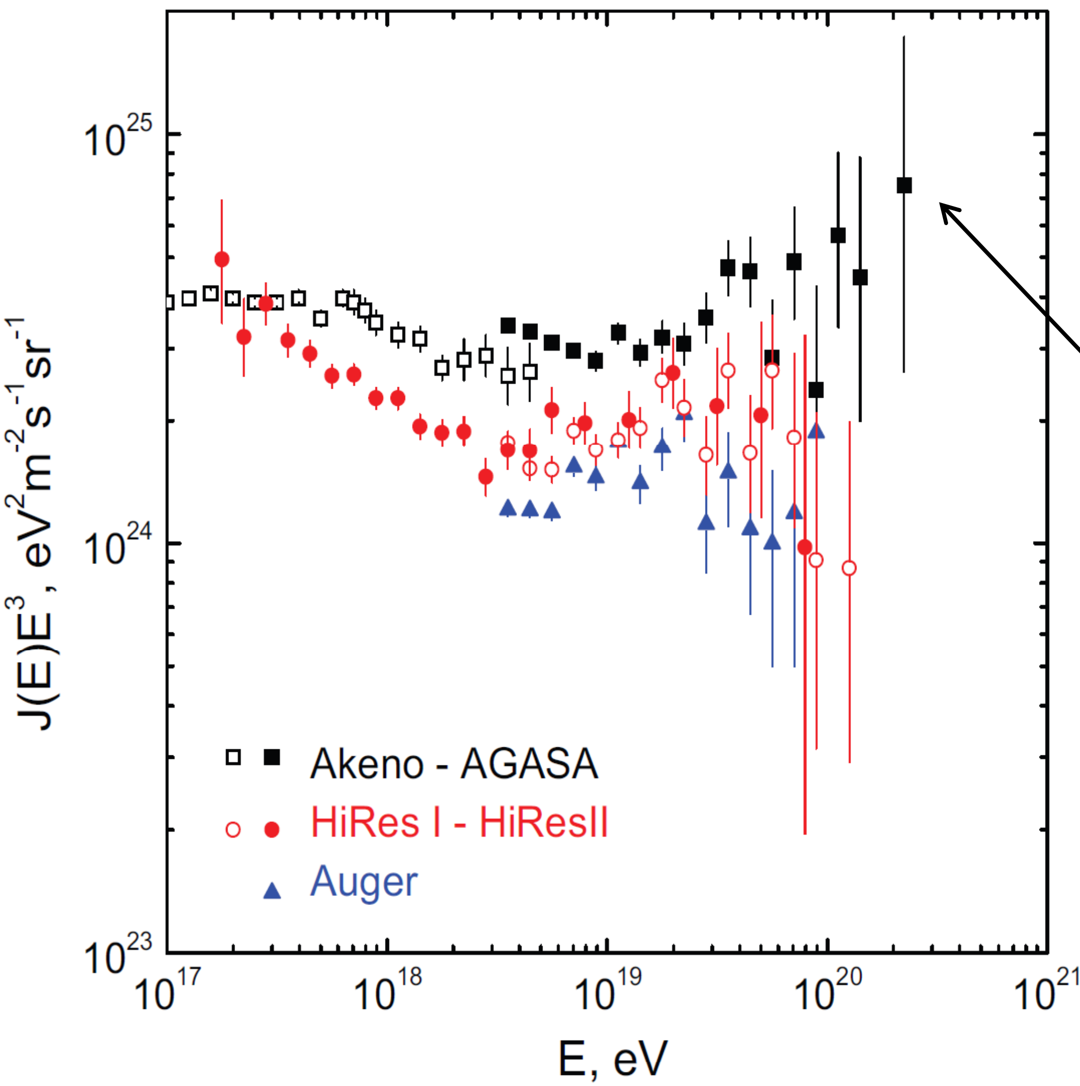
GZK cutoff confirmed!
Information on composition etc.





GZK : Greisen–Zatsepin–Kuzmin

Beware !!



Data from a few years ago suggested conflict with GZK cutoff

➔ "New physics"

100's of papers published explaining how GZK cutoff could be violated.

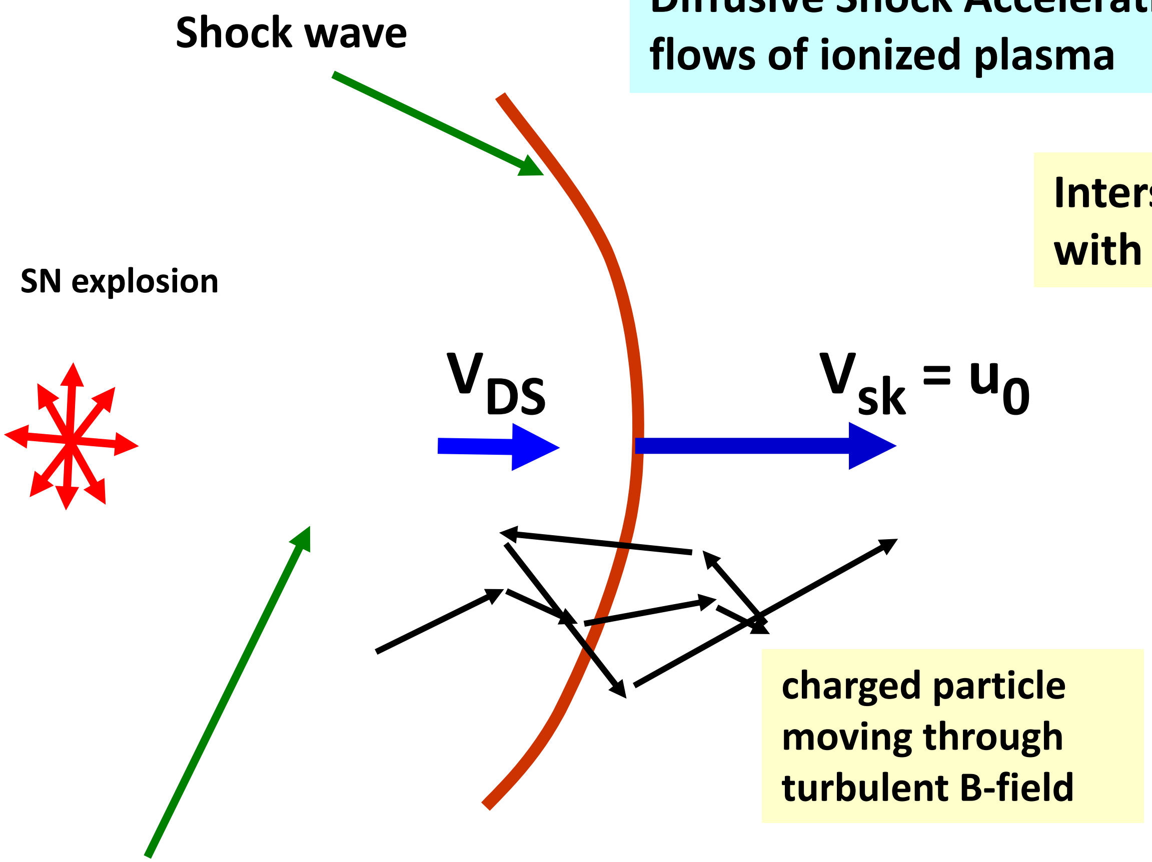
How do collisionless shocks accelerate particles?

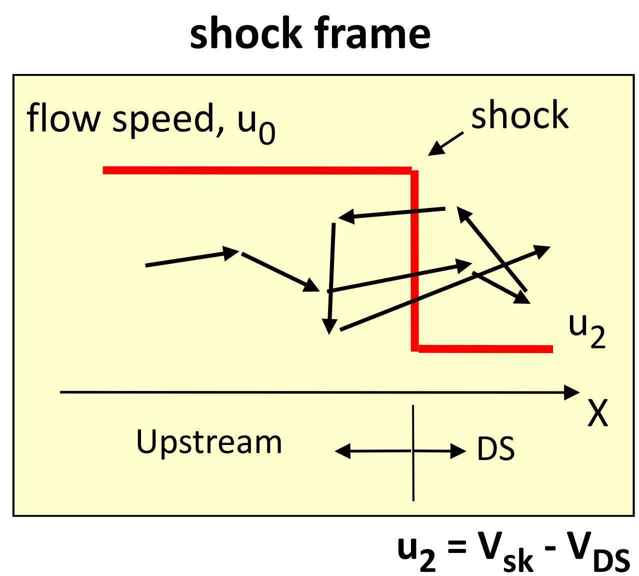
Diffusive Shock Acceleration (DSA)
First, test-particle limit

Original references: Krymskii 1976; Axford, Leer & Skadron 1977; Blandford & Ostriker 1978; Bell 1978

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

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



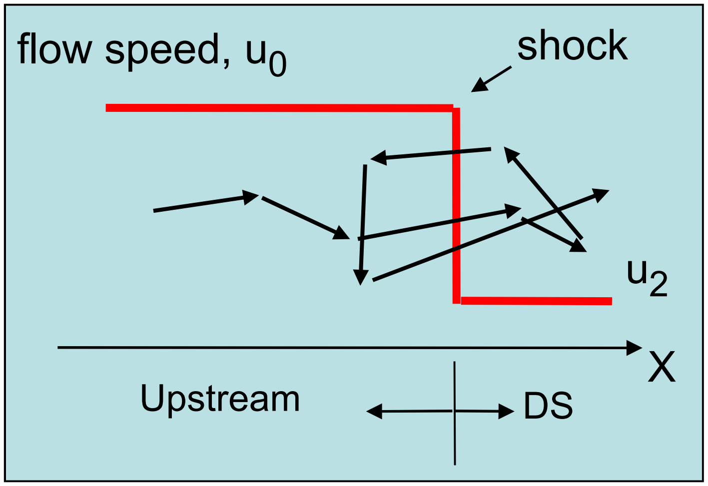


Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$

Particles make nearly elastic collisions with background plasma

➔ gain energy when cross shock

➔ bulk kinetic energy of converging flows put into individual particle energy



$$u_0 = \text{shock speed}$$

$$u_2 = \text{downstream flow speed}$$

$$r = \frac{u_0}{u_2} = \frac{\rho_2}{\rho_0} = \text{compression ratio}$$

Two frames: Upstream and Downstream

In a shock crossing, a particle gains an increment in speed: $\Delta u \sim u_0 - u_2$

(in shock frame)

Or, energy gain from Lorentz transform between frames

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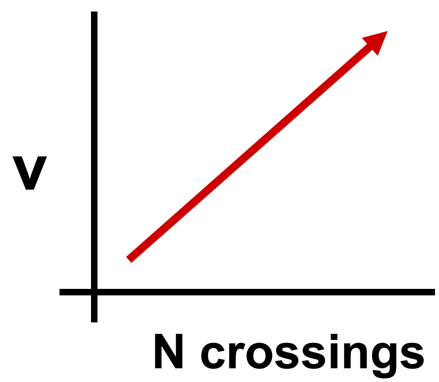
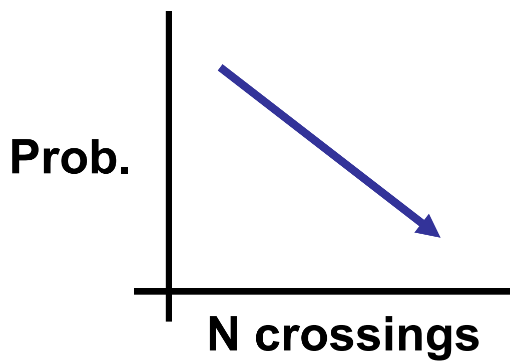
Works for relativistic particles as well

Consider non-relativistic particles with $v >> u_0$.
On each shock crossing gain $\Delta u \sim u_0 - u_2$

To obtain some speed, v, must make N crossings of shock

But, particle can be lost downstream after any crossing.
Have some probability to make N crossings





If $v >> u_0$ (near isotropic distr.), can fold these together. Result only depends on shock compression ratio, r

When folded together, find power law in momentum $f(p) \propto p^{-3r/(r-1)}$

Good for superthermal particles with $v >> u_0$ No normalization in T-P result

Note, assumption that $v >> u_0$ only needed to calculate a pitch angle average for particles crossing the shock.
The "Injection problem" is a mathematical problem!

Can describe DSA with transport equation (i.e., diffusion-convection equation)

Requires assumption that v >> u_0 to calculate the pitch angle average for particles crossing the shock

Original references: Krymskii 1976; Axford, Leer & Skadron 1977; Blandford & Ostriker 1978; Bell 1978

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

D(x,p) is diffusion coefficient

f(x,p) is phase distribution function

u is flow speed

Q(x,p) is injection term

x is position

p is particle momentum

Some modern papers:

Blasi and co-workers; Bykov and co-workers

Kang & Jones 2005

Berezhko and co-workers

Ellison and co-workers

Malkov & Drury 2001; many more

Basic idea: Charged particles gain energy by diffusing in converging flows.

Bulk K.E converted into random particle energy.

Peculiar nature of shocks gives power law with index depending only on compression ratio.

From test-particle theory, in Non-relativistic shocks (Krymskii 76; Axford, Leer & Skadron 77; Bell 78; Blandford & Ostriker 78):

$$f(p) \propto p^{-3r/(r-1)} \quad \text{if} \quad v_p \gg u_0 = V_{sk}$$

$f(p)$ is phase space density

r is compression ratio

u_0 is shock speed

Power law index is:

- **Independent of any details of diffusion**
- **Independent of shock Obliquity (geometry)**
- **But, for Superthermal particles only**

Ratio of specific heats, γ, along with shock Mach number, determines shock compression, r

For high Mach number shocks:

$$r \approx \frac{\gamma+1}{\gamma-1} = \frac{(5/3)+1}{(5/3)-1} = 4 \ !$$

$$f(p) \propto p^{-3r/(r-1)} = p^{-4}, \quad \left(\text{or, } N(E) \propto E^{-2}\right)$$

So-called "Universal" power law from shock acceleration

For shock acceleration to work, diffusion must occur and this results from charged particles moving through turbulent magnetic field.

All complicated plasma physics contained in diffusion coefficient D(x,p).

But, in test-particle limit, power law index doesn’t depend on D(x,p) !

BUT, not so easy after all. Some surprises along the way

How do collisionless shocks accelerate particles?
A surprising story !

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

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, i.e., not in Lab**

- ► **But, can collisionless processes produce a shock?**

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

Bow shock predicted ~ 1955 by T. Gold
discovered 1963-64 Sonett & Abrams (1963), Ness et al (1964)

e.g., Kennel, Edmiston & Hada 1985

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

- 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 !?

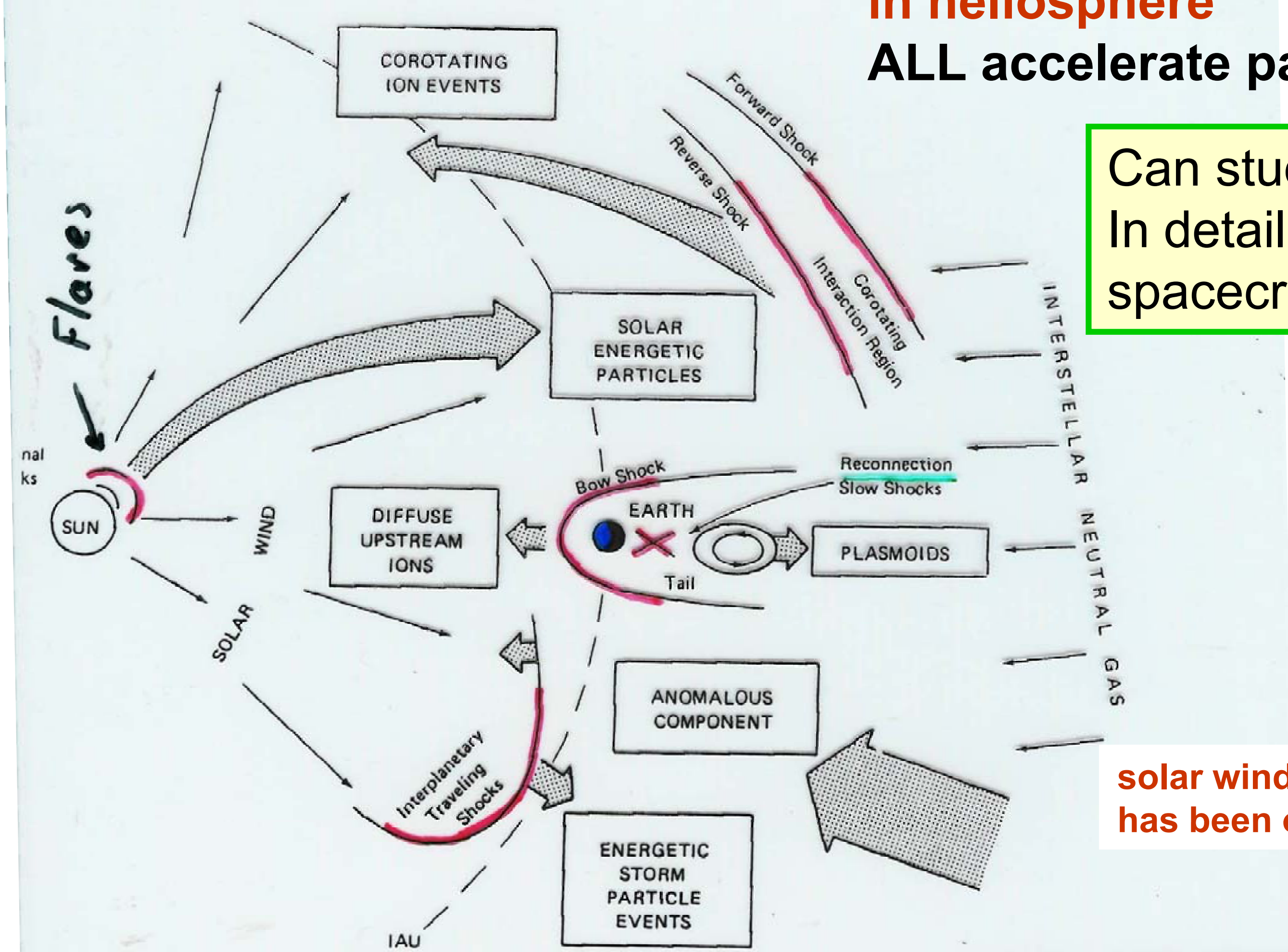
Surprise #2 : Strong, high Mach # collisionless shocks not only exist, but are common in astrophysics

Heliosphere

Many collisionless shocks in heliosphere

ALL accelerate particles !

Can study shock accel.
In detail with in-situ
spacecraft observations

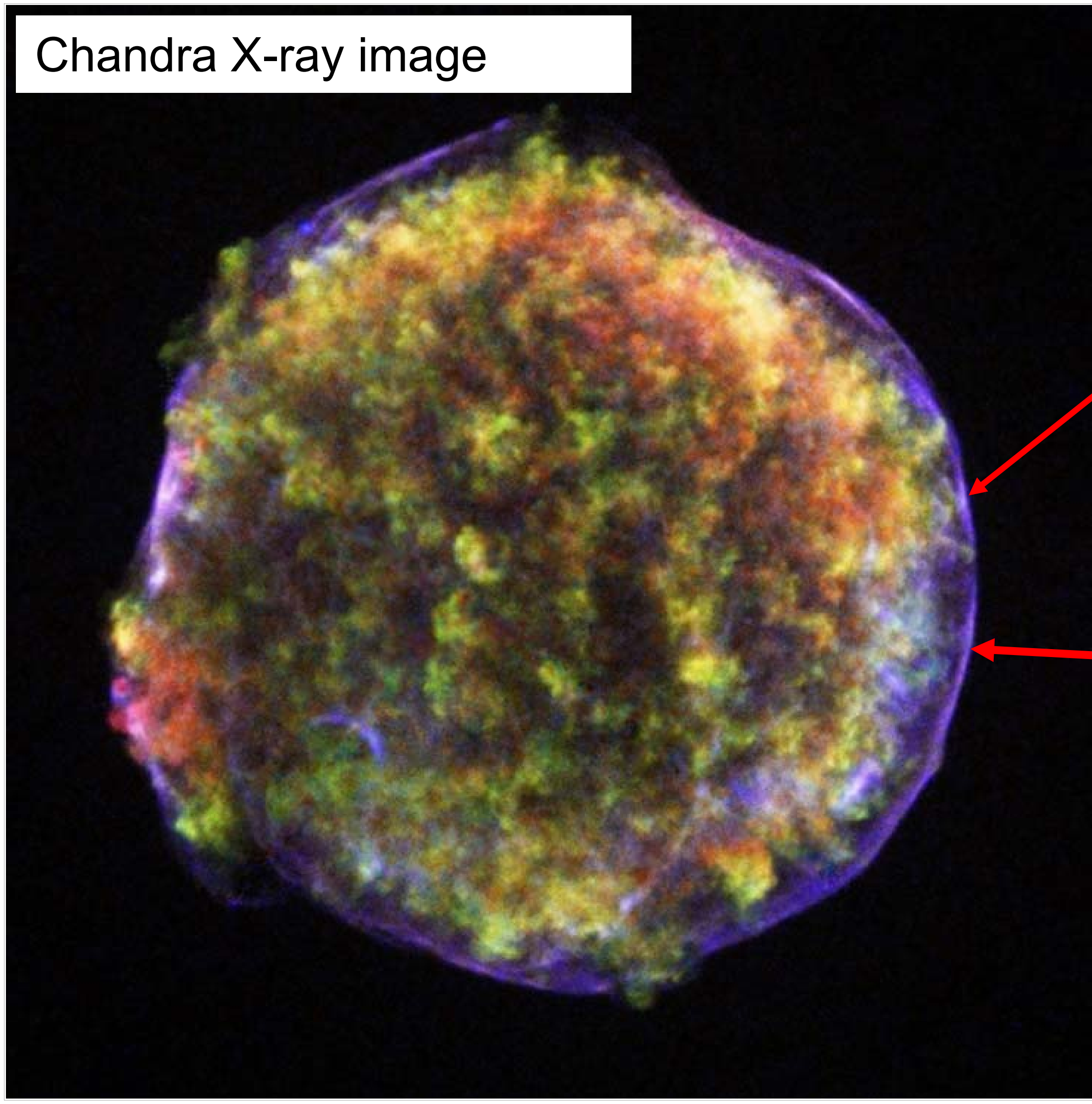


solar wind termination shock has been observed !

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

e.g. Scholer 84

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

Expect shocks to form when galaxies collide

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

Virtually everywhere see shocks, see accelerated particles

Don Ellison, NCSU

➡ 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 # ≥ 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 <u>always</u> 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 to simulate

  - ► Highly anisotropic particle distributions make analytic analysis difficult (i.e., $v >> u_0$ assumption)

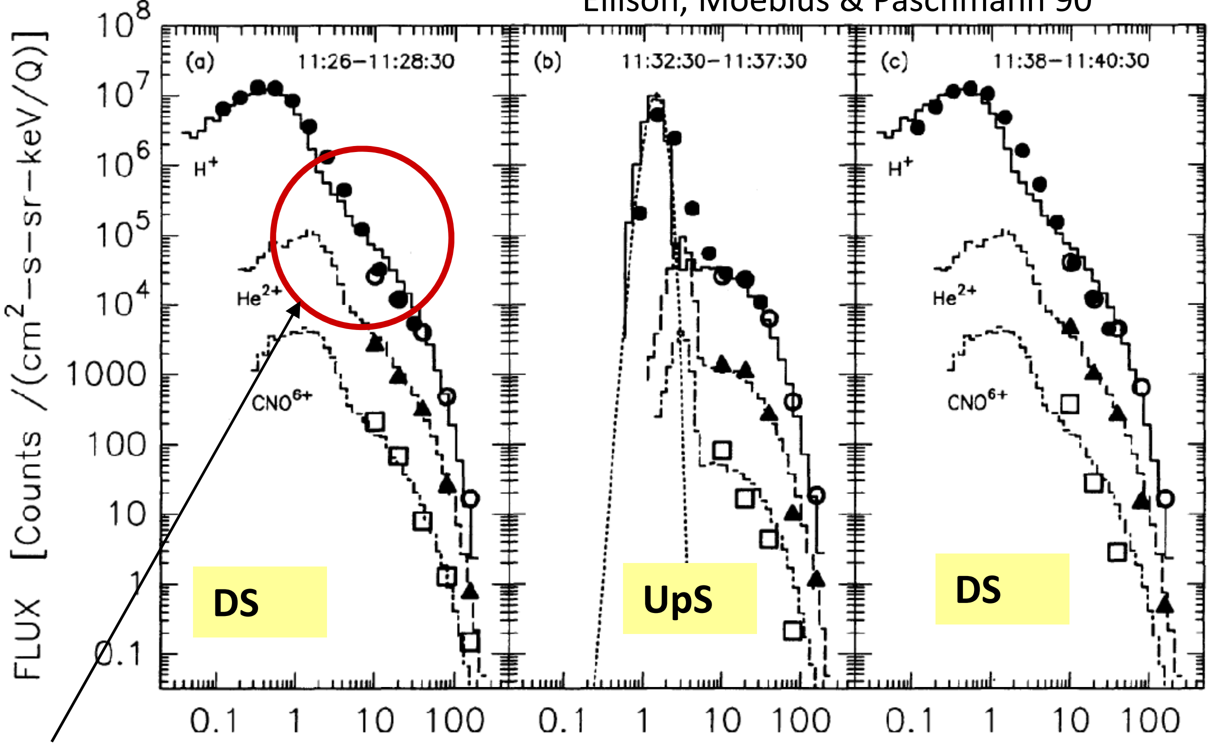
  - ► Hard for Particle-In-Cell simulations ➔ MUST be done in 3-D to properly describe injection. Must be run long enough for mature wave-field

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

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

Observations & Model of Earth Bow Shock: Ion injection & acceleration

Ellison, Moebius & Paschmann 90



Thermal 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.

Cartoon of Earth bow shock and IRM spacecraft

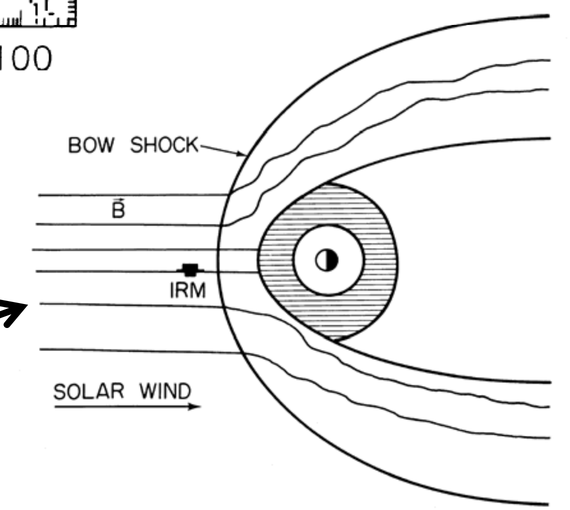
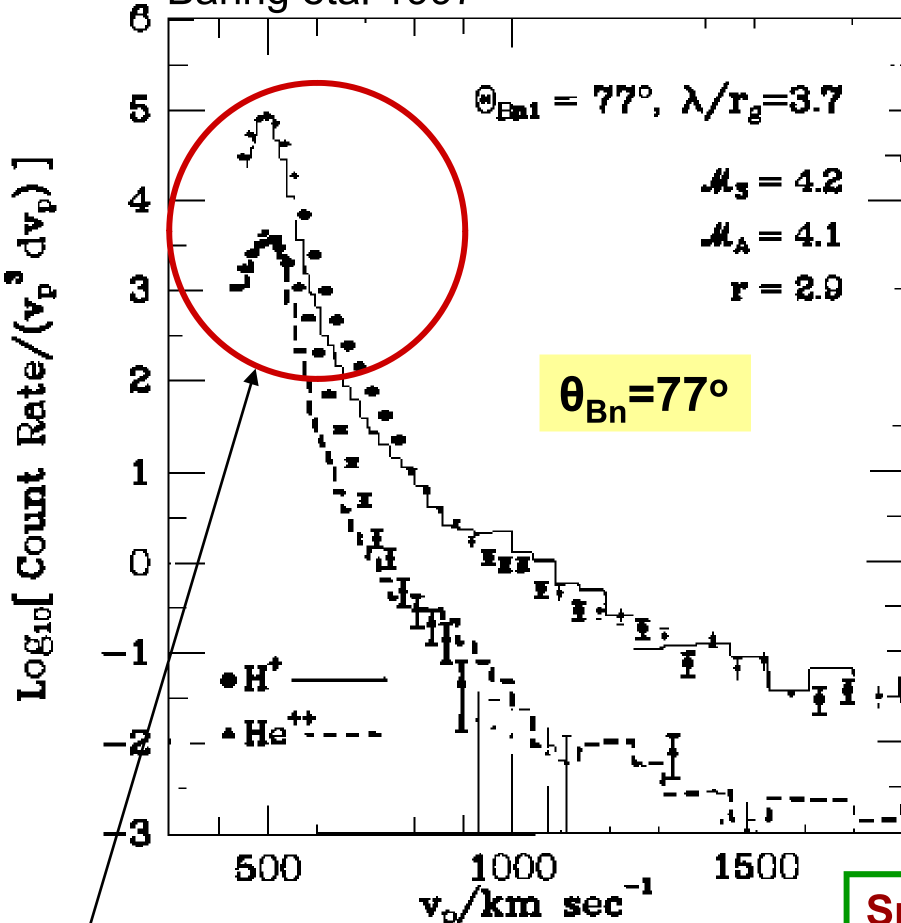


FIG. 1.—Schematic representation of the bow shock during the diffuse ion event of 1984 September 5

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 λ ~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

- ► 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**

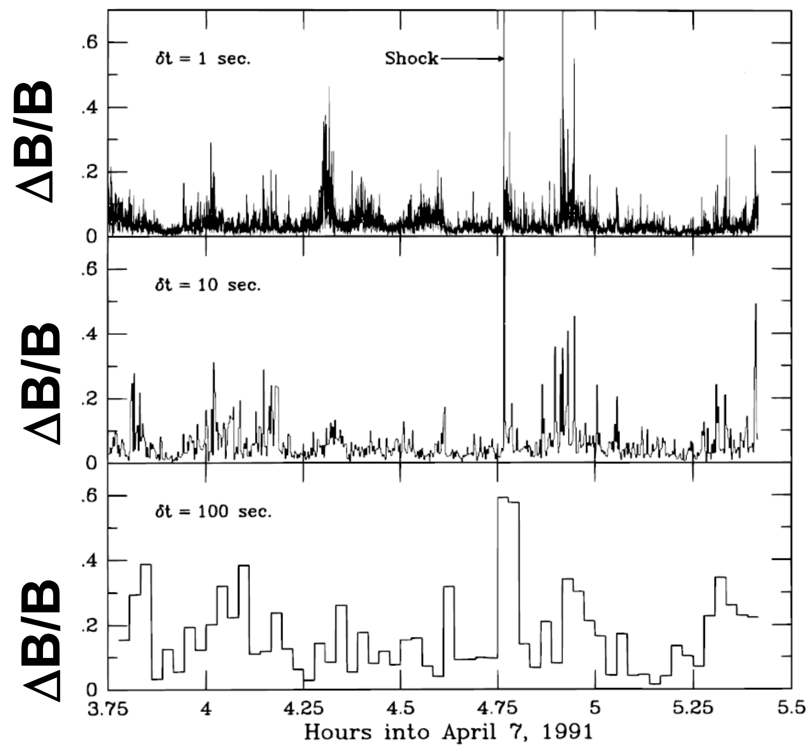
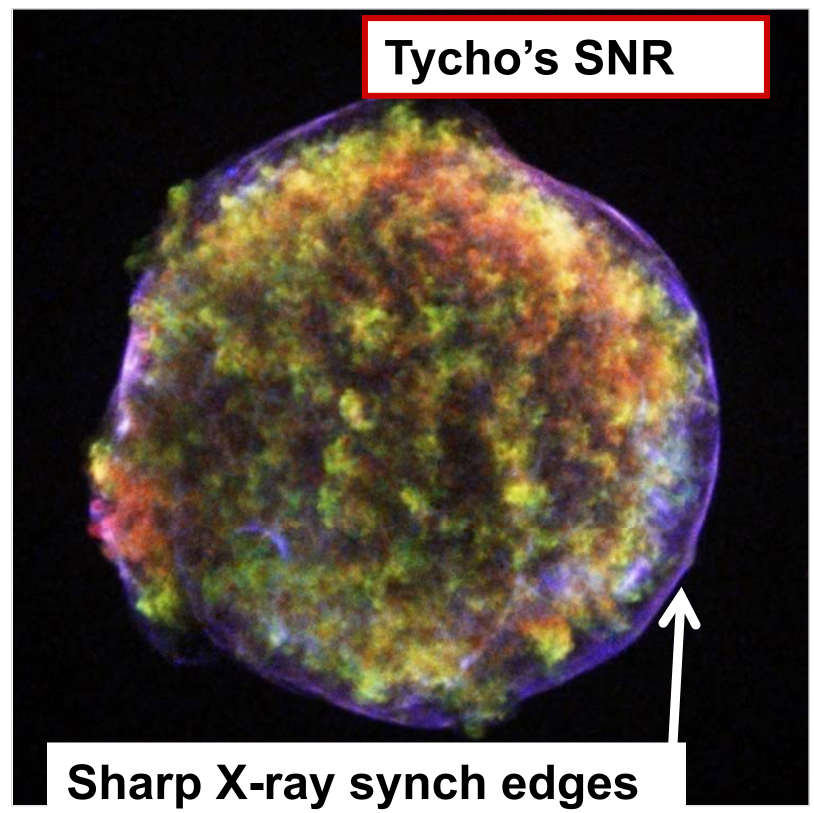


FIG. 6.—Turbulence measure $|\delta \boldsymbol{B}|/|\boldsymbol{B}|$, defined in eq. (5), for tim surrounding the 91097 shock, obtained using the field data displayed i Fig. 5*a*. Binning is exhibited on three timescales δt, as labeled, indicating slow increase in turbulence measure with timescale. 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.

Self-generated turbulence at weak Interplanetary shock

Baring et al ApJ 1997

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



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

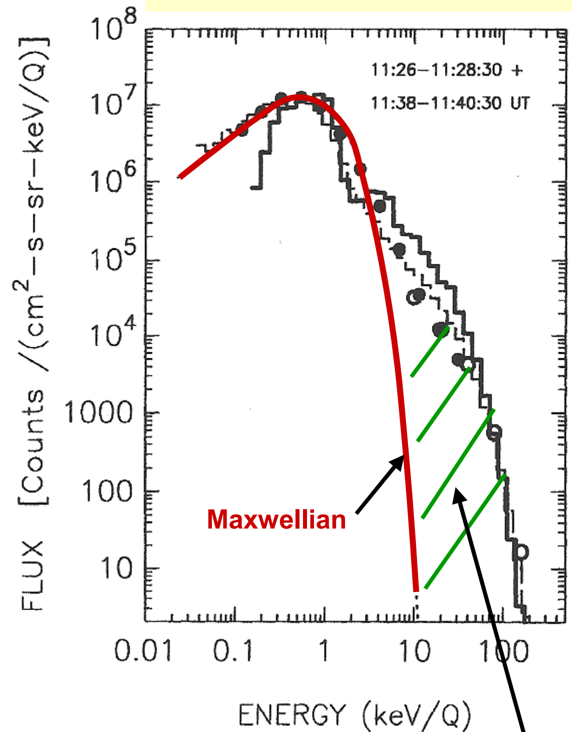
- ► Injection must be self-consistently connected to production of highest energy CRs

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

Lose nice "Universal power law" from test-particle result

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 is 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, $B < 10\ \mu G$

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

- 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 $\Delta B/B \gg 1$ may be intrinsic part of DSA in strong shocks (e.g., Bell 2001, 2005)

Key elements of Diffusive Shock Acceleration:

1) Shocks form easily in diffuse regions of astrophysics

2) Strong collisionless shocks must accelerate particles to exist

3) We have a well developed acceleration mechanism: DSA

4) DSA is predicted to be efficient with >10% of ram kinetic energy put into CRs

5) Observational support for high efficiencies

6) Efficient acceleration ➔ nonlinear effects. Accelerated CRs must modify shock structure

7) Magnetic turbulence self-generated in shocks. May have strong Magnetic Field Amplification

8) Escaping CRs important in efficient DSA

Supernova remnant (SNR) shocks:

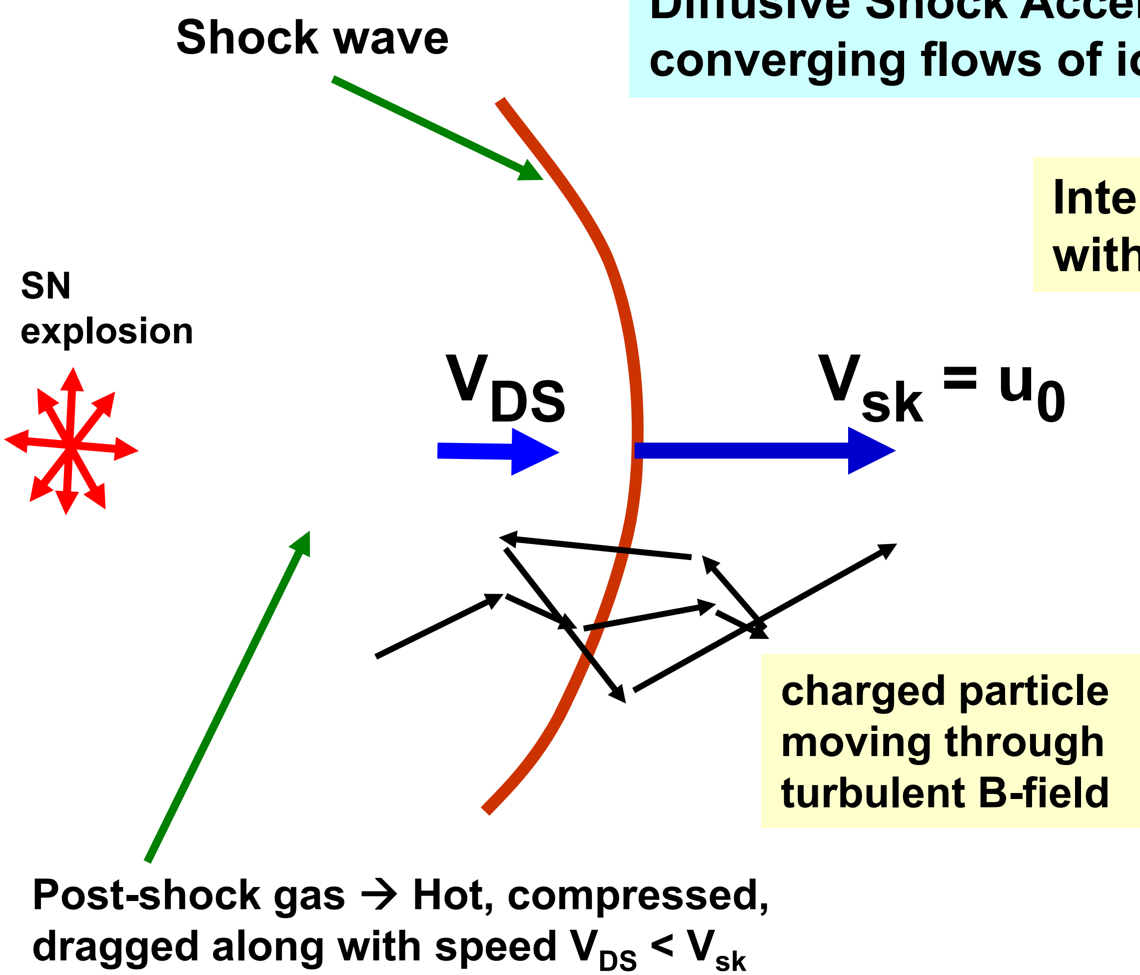
Outer blast wave is almost certain to be the main source of cosmic rays up to 10^{15} eV

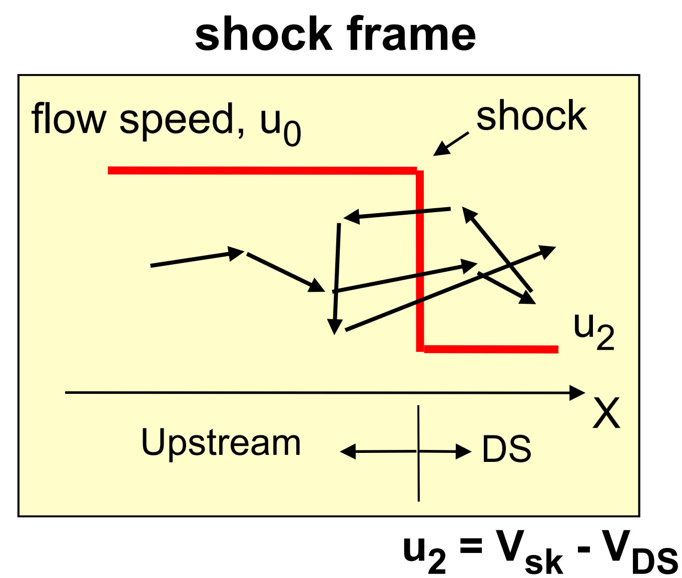
SNRs may accelerate cosmic rays to above 10^{17} eV or even higher

Put previous elements together
Model Supernova Remnants with Diffusive Shock Acceleration

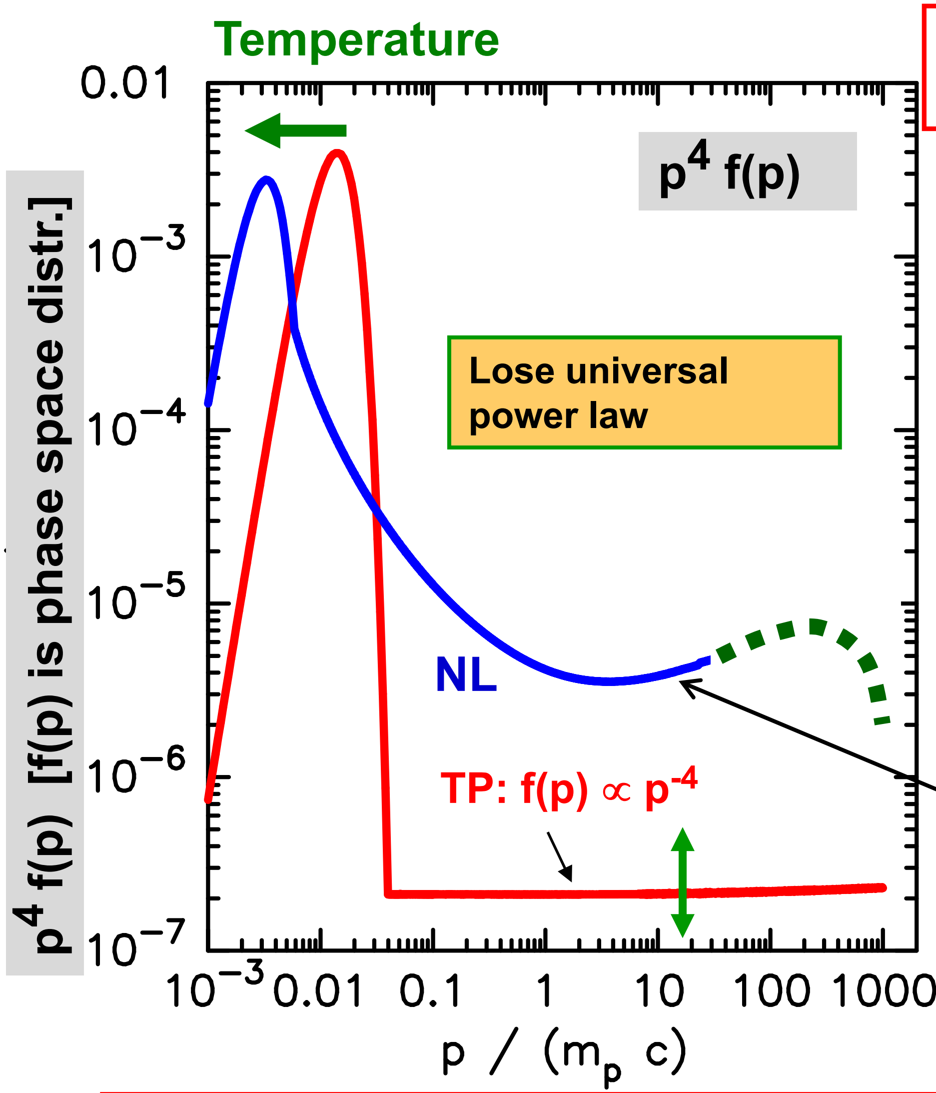
Diffusive Shock Acceleration: Shocks set up converging flows of ionized plasma

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

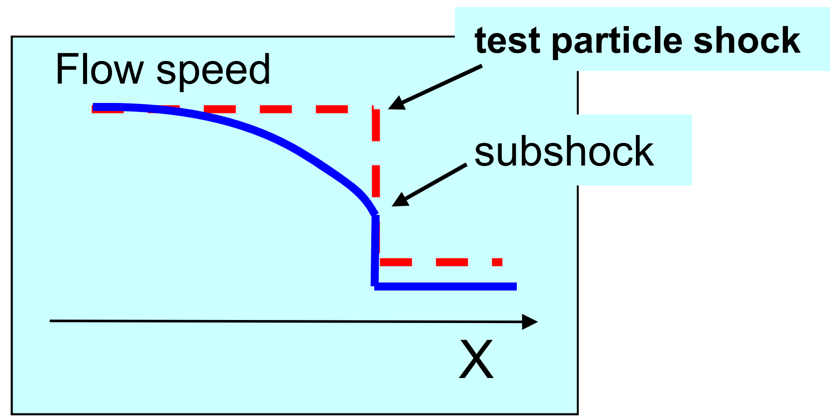




Particles make nearly elastic collisions with background plasma
➔ gain energy when cross shock ➔ bulk kinetic energy of converging flows put into individual particle energy



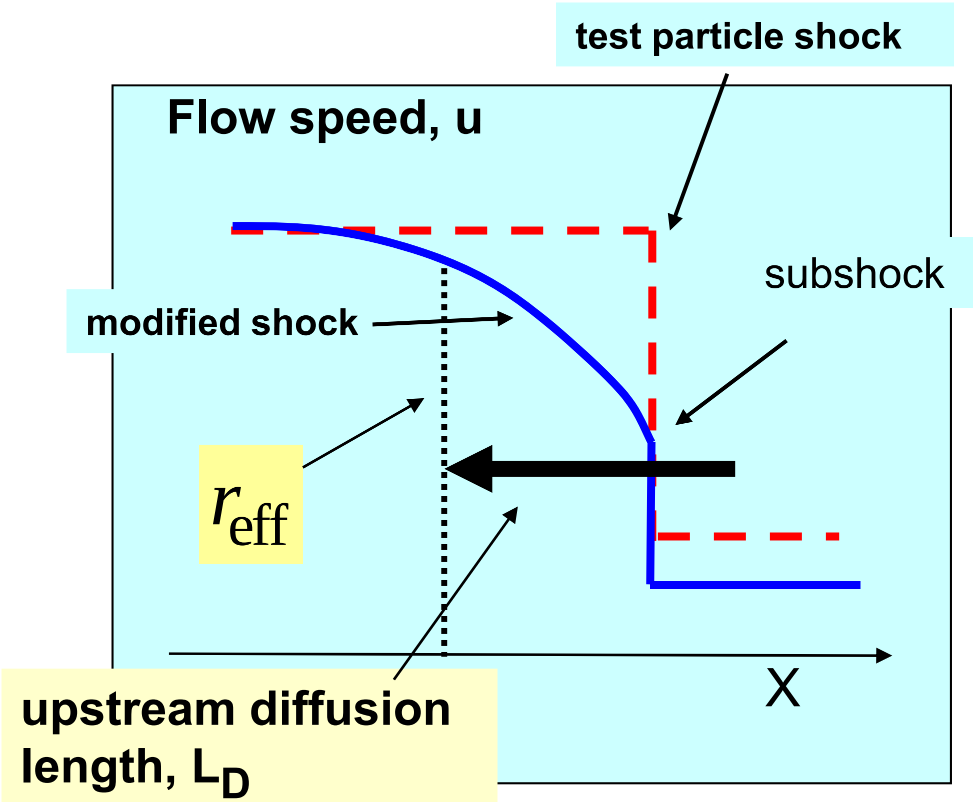
If acceleration is efficient, shock becomes smooth from backpressure of CRs



- **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



Upstream diffusion length,
$L_D \sim D/u$

$D \propto \lambda v$, λ is diffusion mean free path. Take proportional to gyroradius, rg= p/(eB)

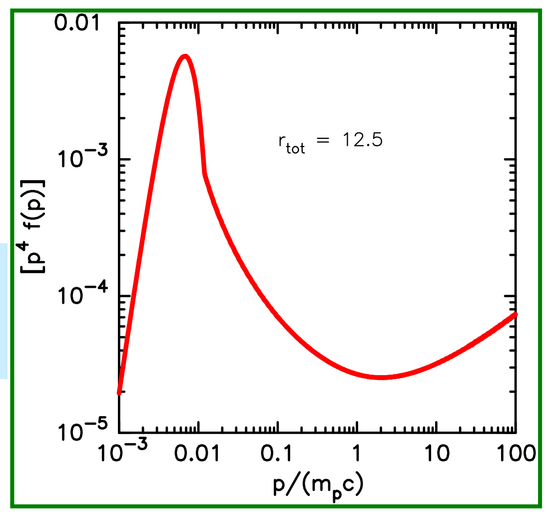
$L_D \propto vp/B$

High momentum particles diffuse farther upstream than low p particles.

High p particles "feel" a larger compression ratio in modified shocks ➔ get accelerated more.

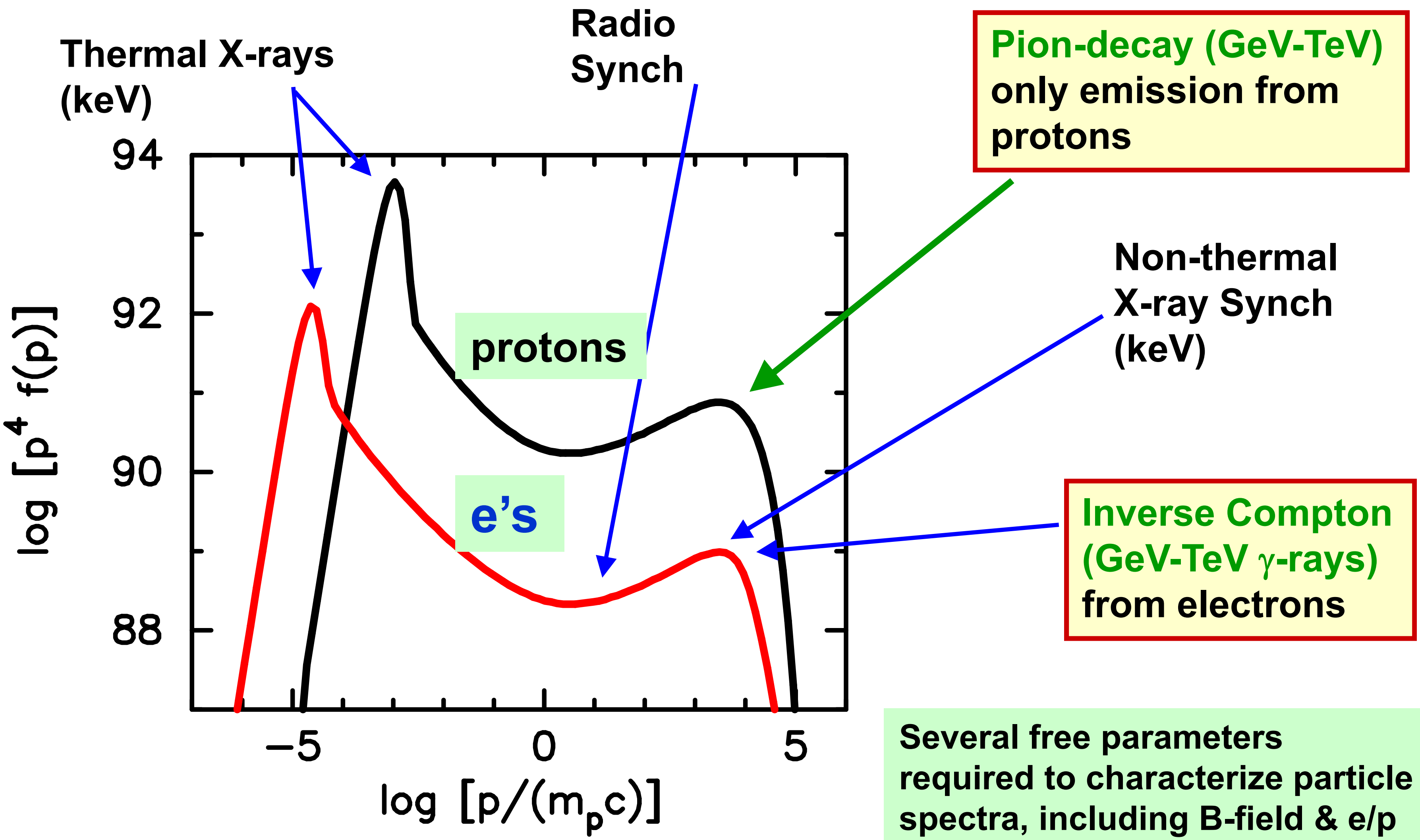
If acceleration is efficient, shock becomes smooth from backpressure of CRs

Concave spectrum is unique prediction of DSA



Don Ellison, NCSU

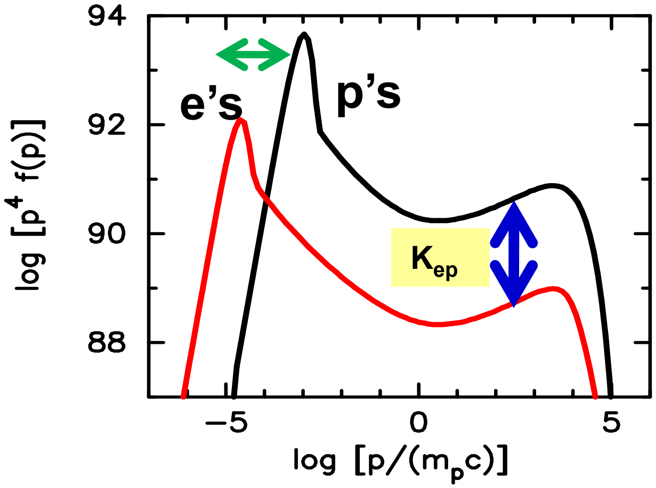
Electron and Proton distributions from efficient (nonlinear) diffusive shock acceleration (toy spectra from Blasi et al. accel. model)



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

Don Ellison, NCSU

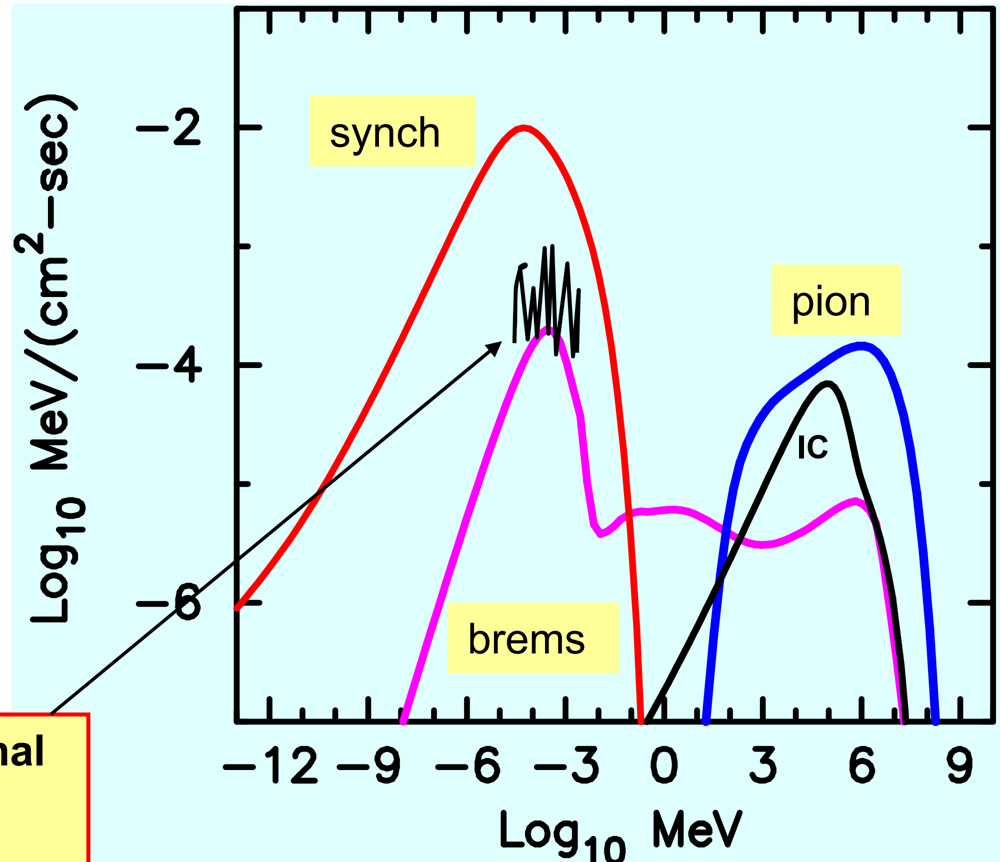
2 trapped particle distributions



Many parameters needed for modeling !!

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

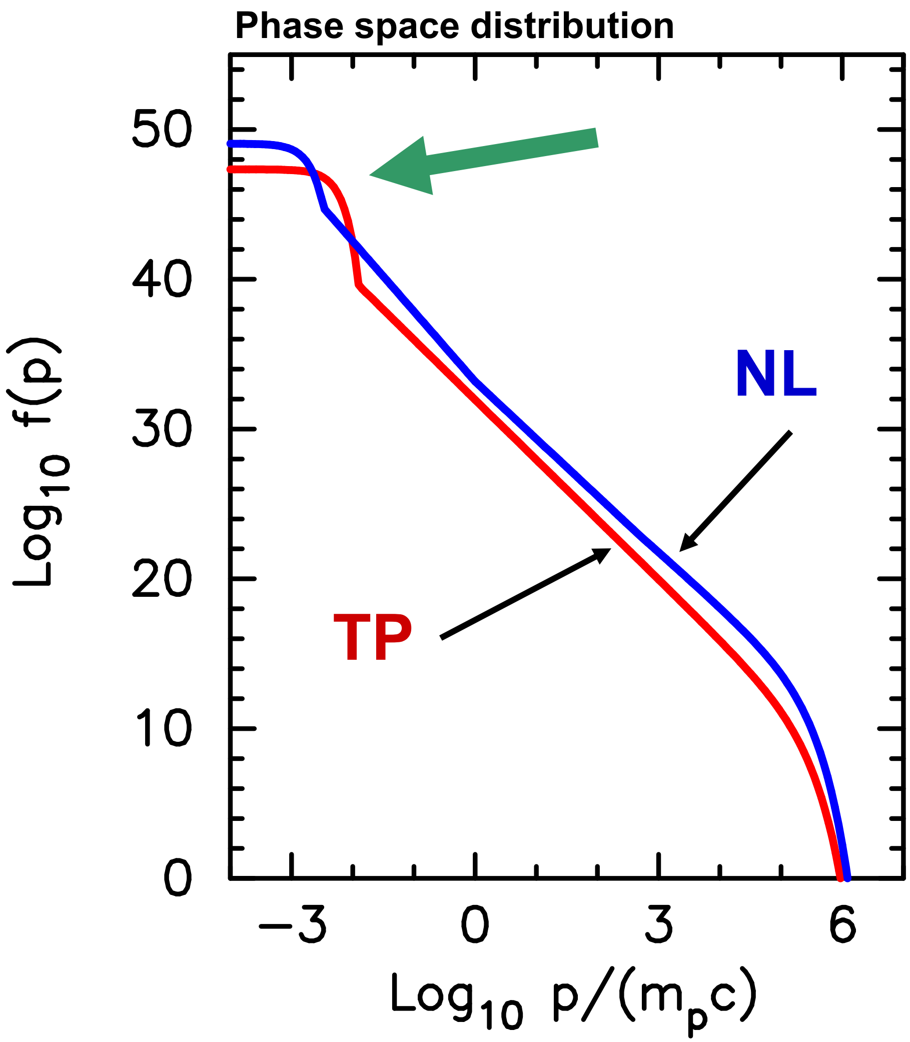
continuum emission



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

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



Without p^4 factor in plot, nonlinear effects much less noticeable → hard to see in cosmic ray obs.

Most important point for <u>X-ray</u> observations:
the more efficient the cosmic ray production, the lower the shocked temperature.

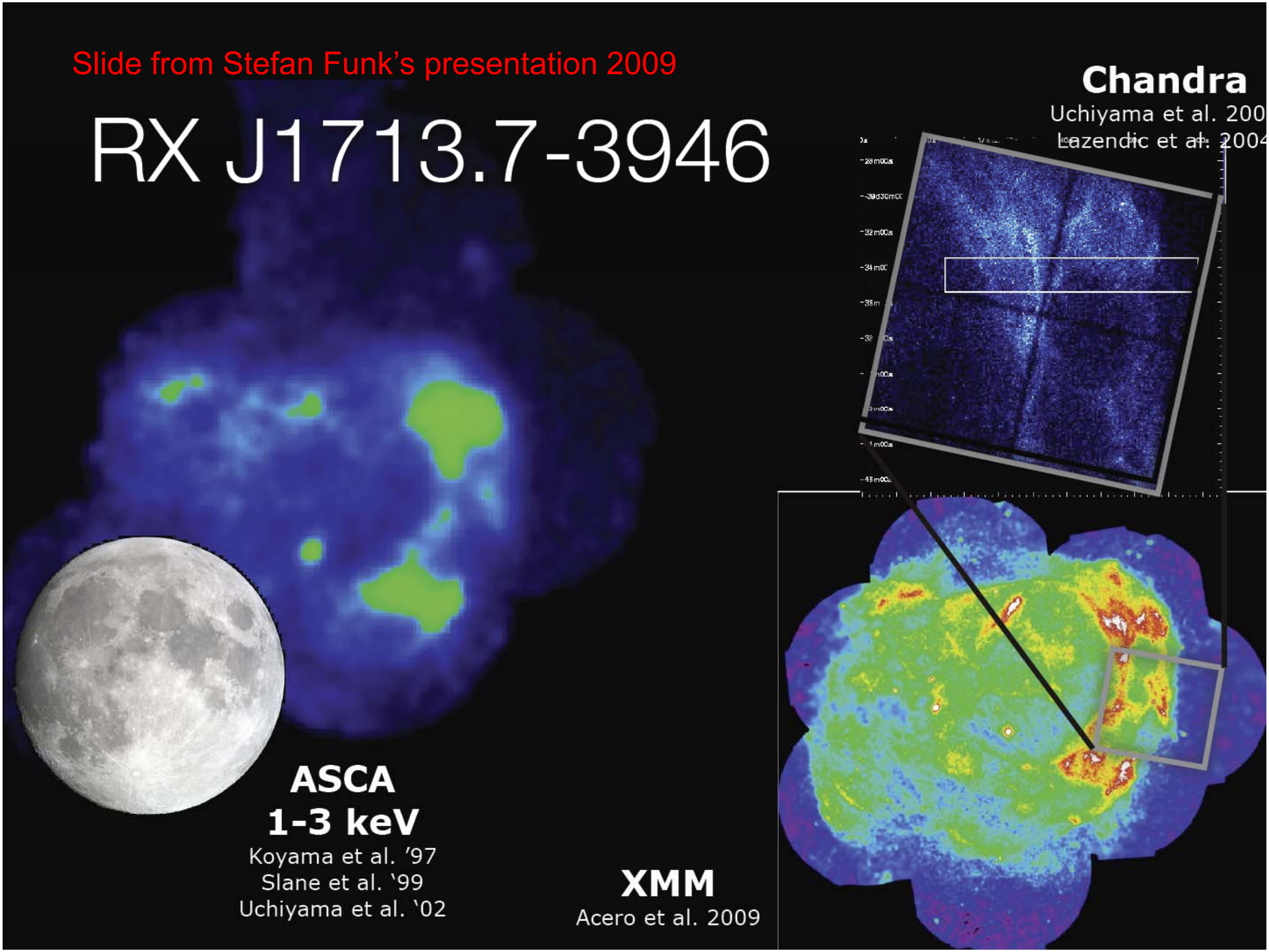
This is a large effect

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

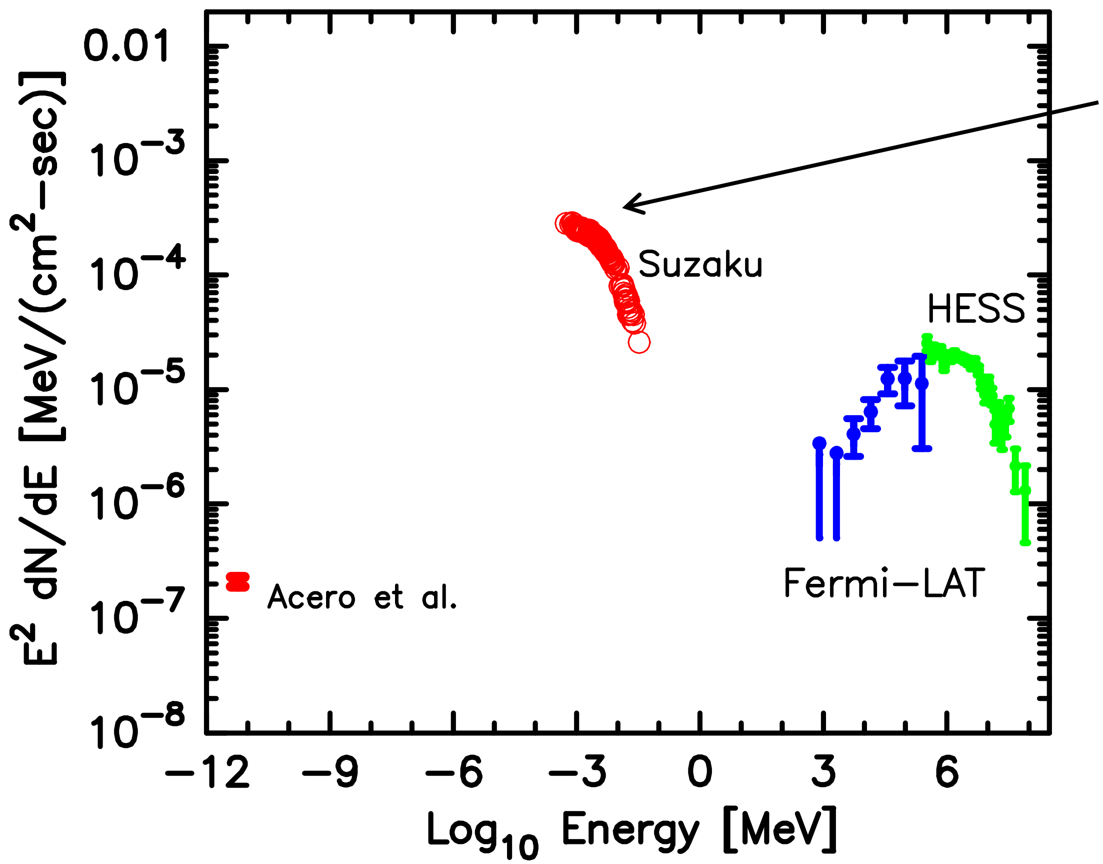
1) VH-1 code for hydro of evolving SNR (e.g., Blondin)
2) Semi-analytic, nonlinear DSA model from Blasi, Stefano Gabici, et al.
3) NL shock acceleration coupled to SNR hydrodynamics
4) Ad hoc model of magnetic field amplification
5) Approximate shape of trapped CR distributions at max. energy turnover
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)


Slide from Stefan Funk's presentation 2009
RX J1713.7-3946
Chandra
Uchiyama et al. 200
Lazendic et al. 2004
ASCA
1-3 keV
Koyama et al. '97
Slane et al. '99
Uchiyama et al. '02
XMM
Acero et al. 2009

Thermal & Non-thermal Emission in SNR RX J1713

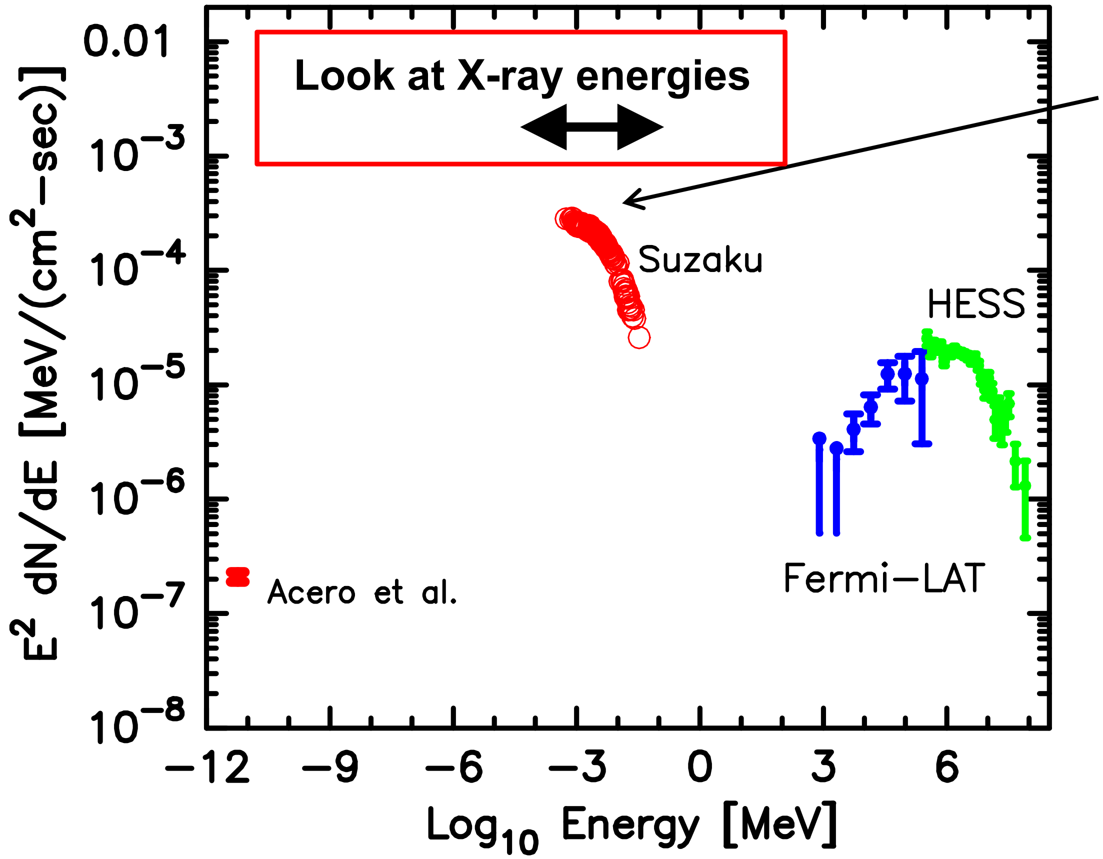


- **Suzaku X-ray observations → smooth continuum well fit by synchrotron from TeV electrons**
- **No discernable line emission from shocked heated heavy elements**
- **Strong constraint on Non-thermal emission at GeV-TeV energies**

Is GeV-TeV emission from electrons (inverse-Compton) OR protons (p-p collisions and pion-decay)

Important question for CR origin, particle acceleration mechanism, neutrino emission from SNRs

Thermal & Non-thermal Emission in SNR RX J1713



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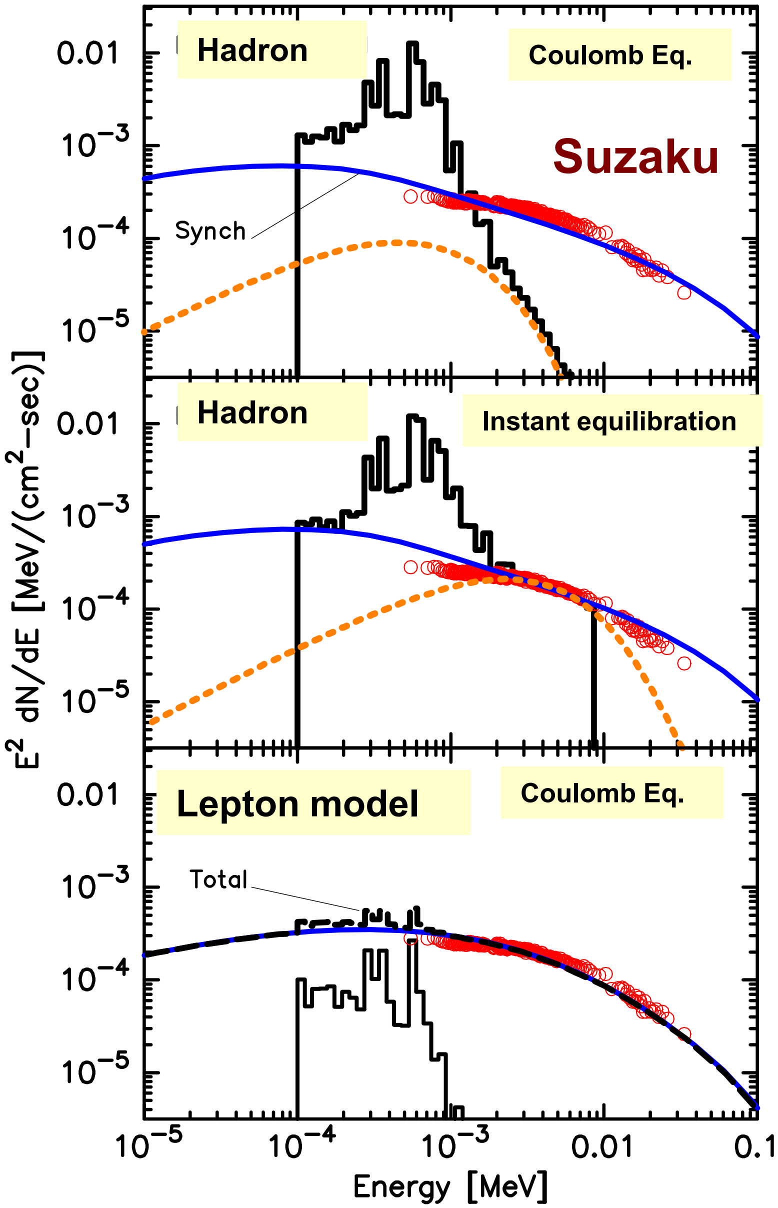


Models including Thermal X-ray lines:

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

► **Compare Hadronic & Leptonic fits to GeV-TeV emission**

► **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**

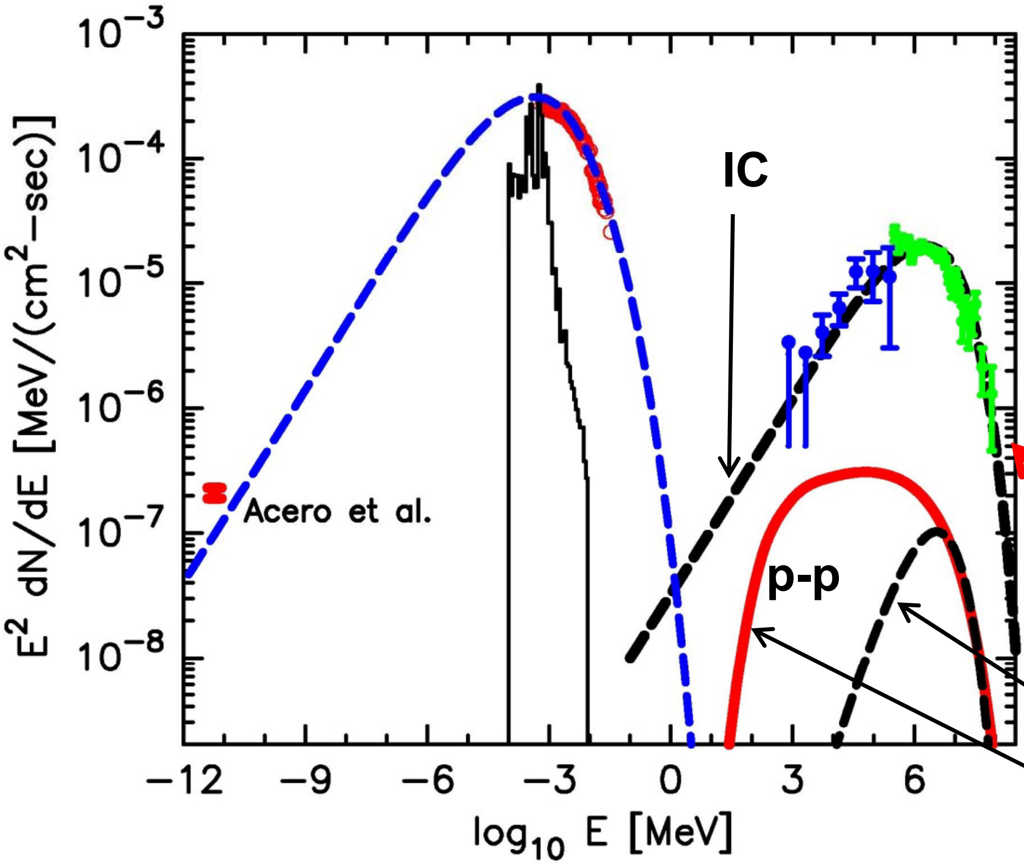
► **Suzaku would have seen these lines**

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

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

Work 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

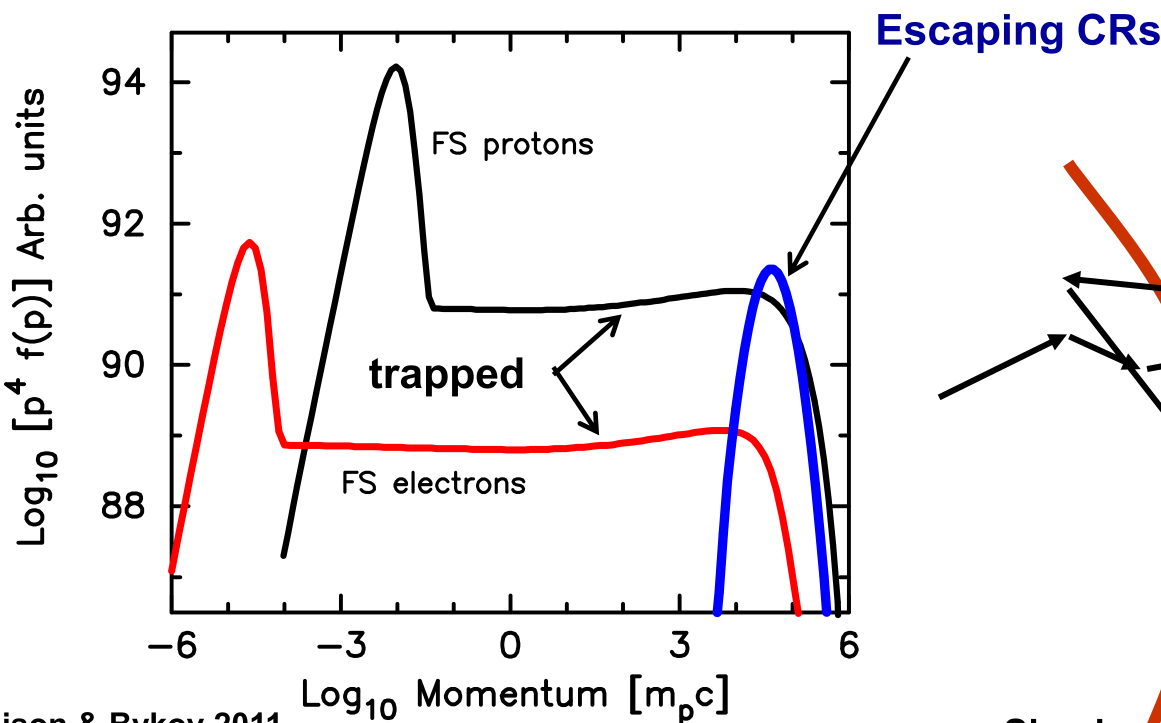
p-p from trapped CRs

Inverse-Compton fit to Fermi LAT & 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 !

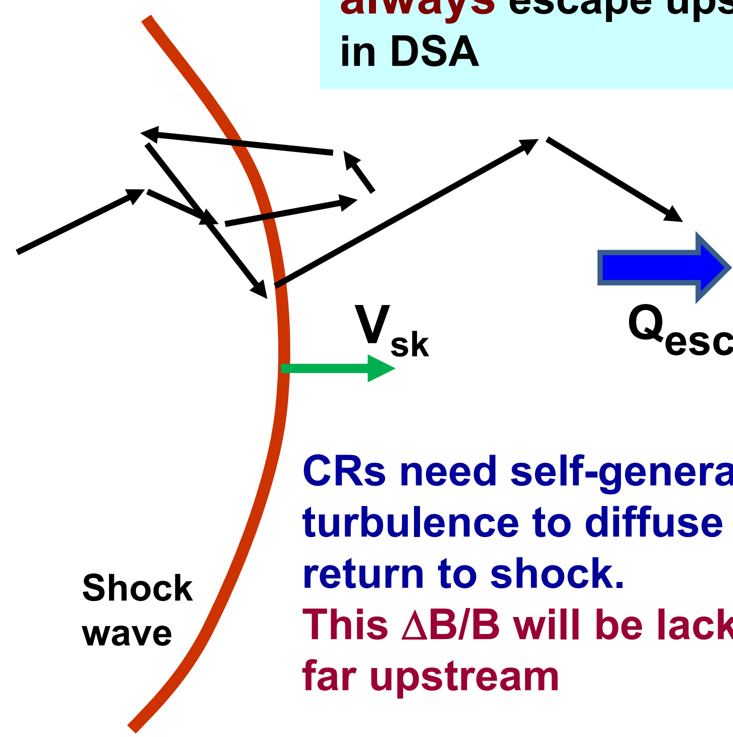
Forward shock of SNR produces 3 particle distributions that will contribute to the photon emission

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

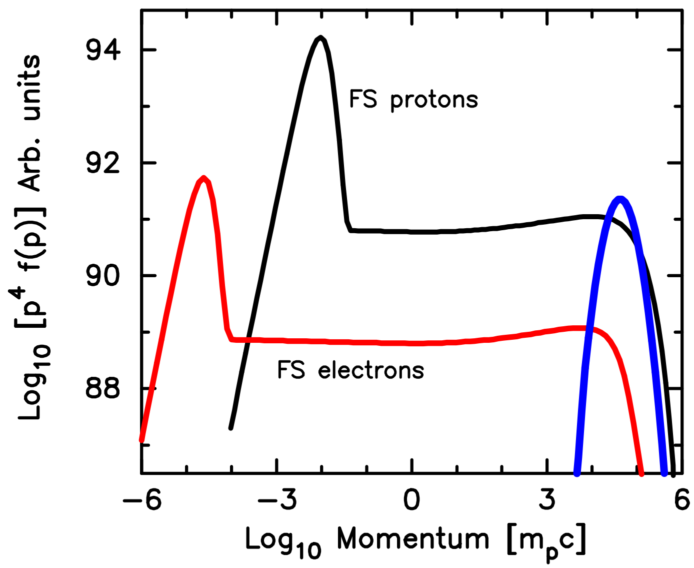


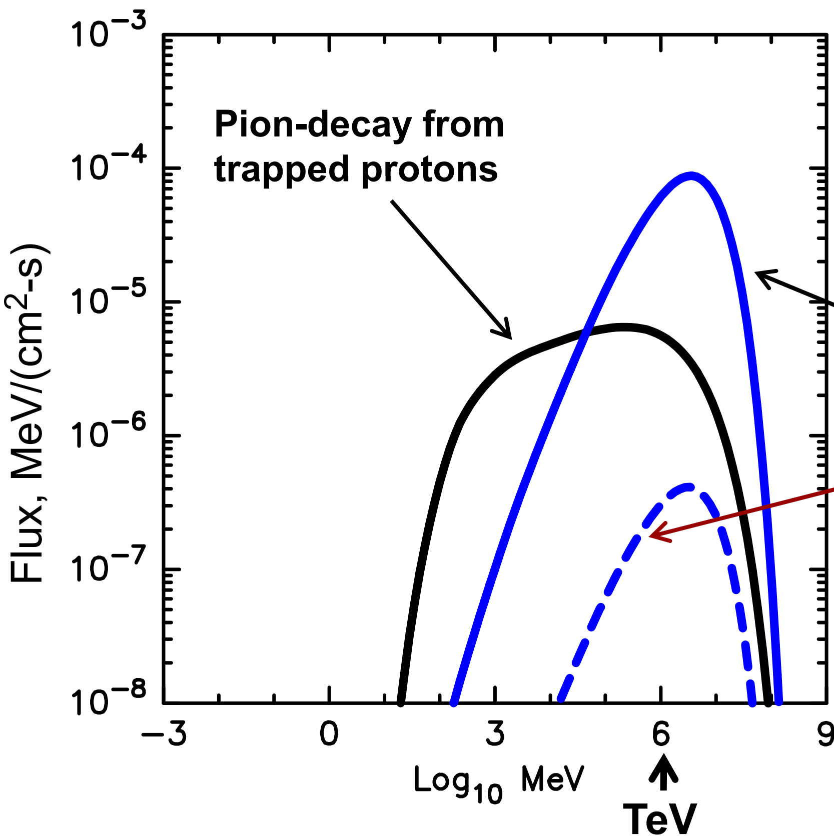
CRs need self-generated turbulence to diffuse and return to shock.
This ΔB/B will be lacking far upstream

Details of escaping CRs important for CR production, interaction of CRs in nearby molecular clouds, active sources

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:

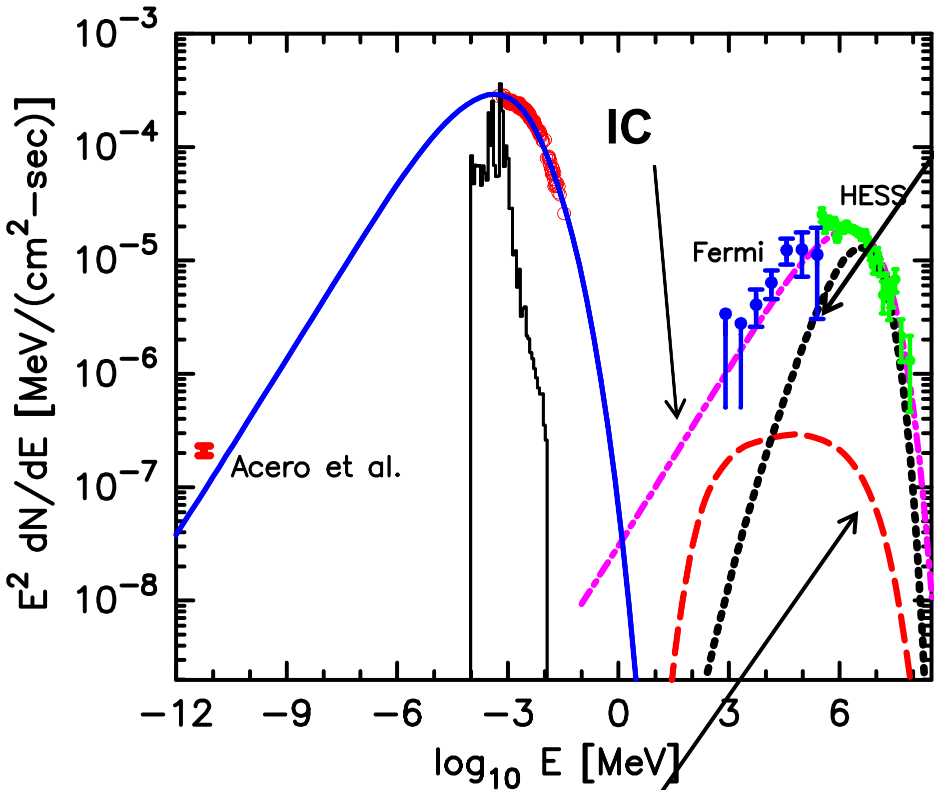
From dense external shell

From low-density, uniform ISM

Escaping vs. trapped CRs:

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

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 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

Pion-decay from trapped CRs

Exact shape uncertain because it depends on wave generation by highest energy CRs with anisotropic distributions.
Fermi Gamma-Ray telescope **observations of SNRs impacting molecular clouds critical for constraining acceleration models**

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)**

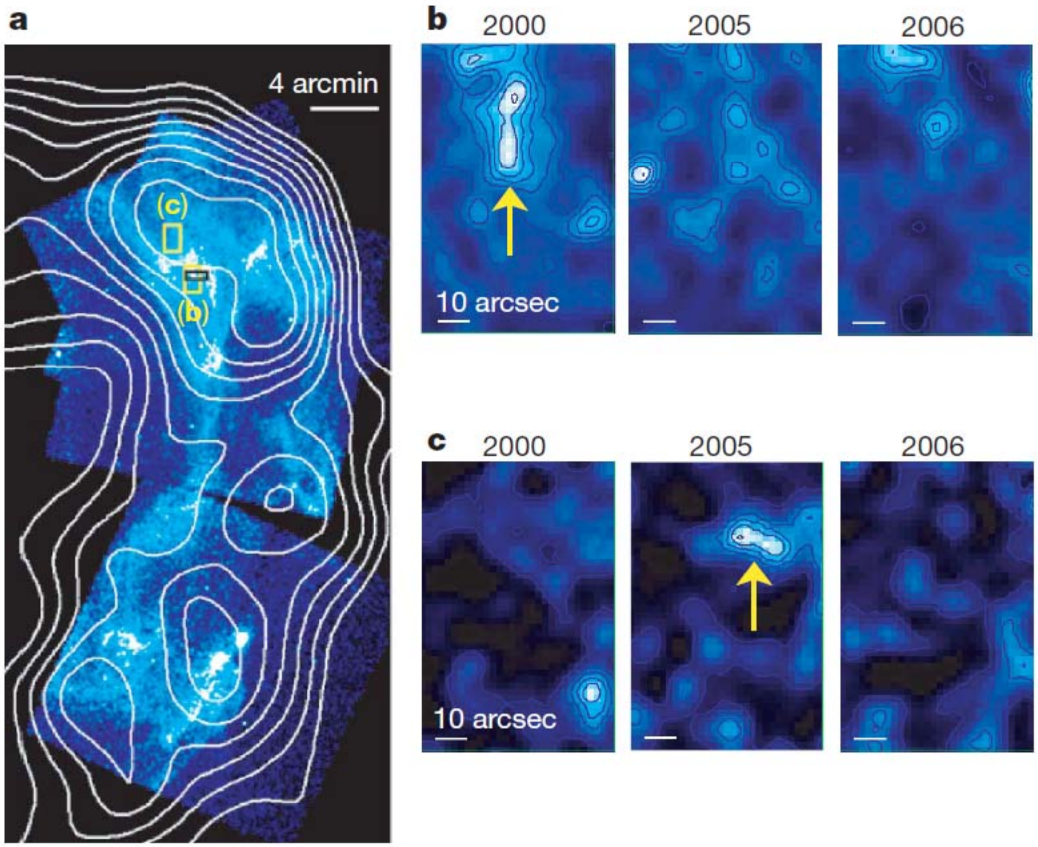
Hadron model for J1713 only possible if escaping CRs interact with >>100 M_0 of external material without producing X-ray lines.
Not so easy to arrange this

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** ⬅

Particle acceleration surprises aren't over yet

Rapid time variations in X-ray synchrotron in SNR RX J1712



1-2.5 keV X-rays

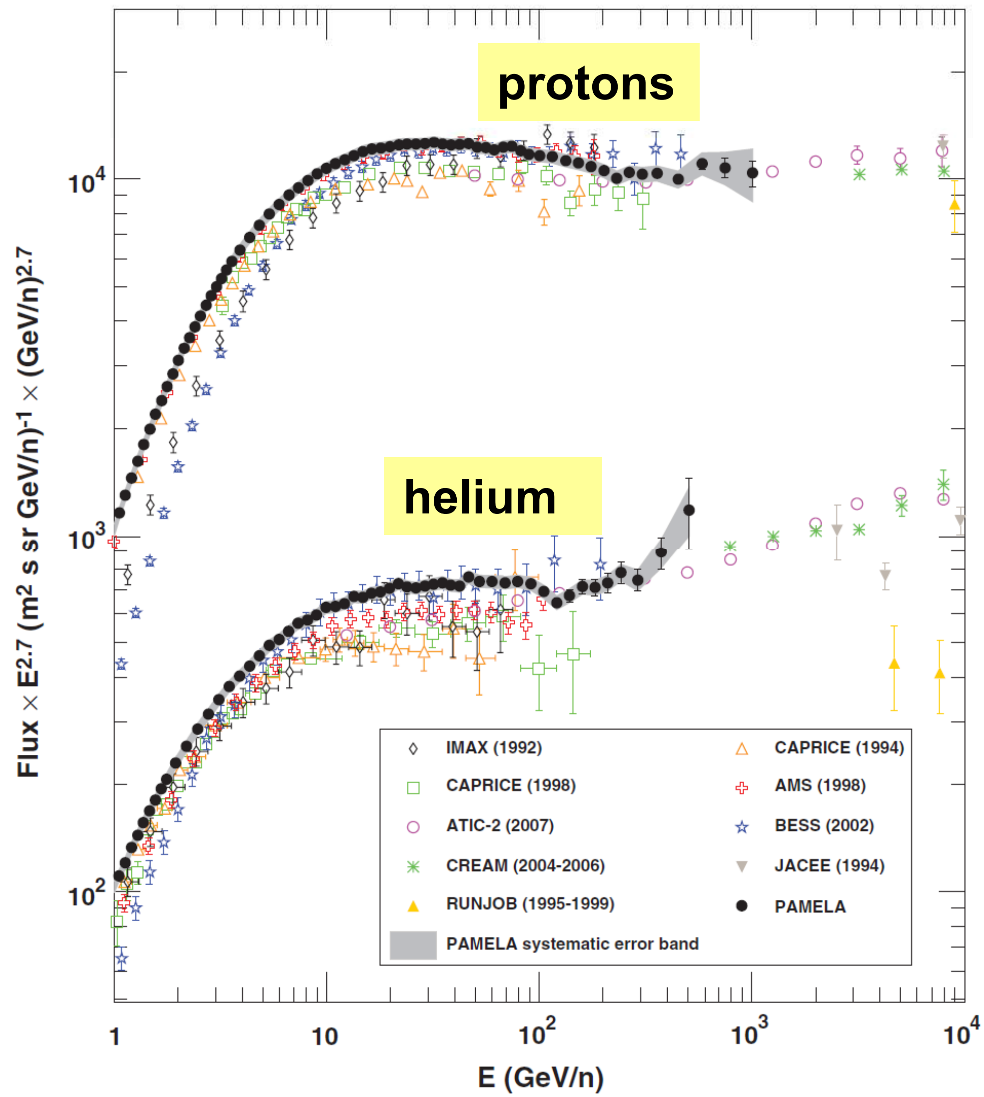
Interpreted by Uchiyama et al. as time-scale for synchrotron losses in B > 1 mG fields !

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

Uchiyama etal 2007

PAMELA observations of protons and helium spectra. Origin of different shapes ?? Accelerator ?, Propagation ?

Fig. 1. Proton and helium absolute fluxes measured by PAMELA above 1 GeV per nucleon, compared with a few of the previous measurements (*16–24*). All but one of the previous measurements (*24*) come from balloon-borne experiments. Previous data up to few hundred billion electron volts per nucleon were collected by magnetic spectrometer experiments (*20–24*), whereas higher-energy data come from calorimetric measurements. PAMELA data cover the energy range 1 GeV to 1.2 TeV (1 to 600 GeV per nucleon for He). The fluxes are expressed in terms of kinetic energy per nucleon, converted from the rigidity measured in the tracker and neglecting any contribution from less abundant deuterium ($d/p \simeq 1\%$) (where d is deuterium) and ^{3}He (^{3}He/^{4}He $\simeq 10\%$). Therefore, pure proton and ^{4}He samples are assumed. Error bars are statistical and indicate 1 SD; the gray shaded areas represent the estimated systematic uncertainty. E, kinetic energy per nucleon.



PAMELA observations (Adriani et al 2011)

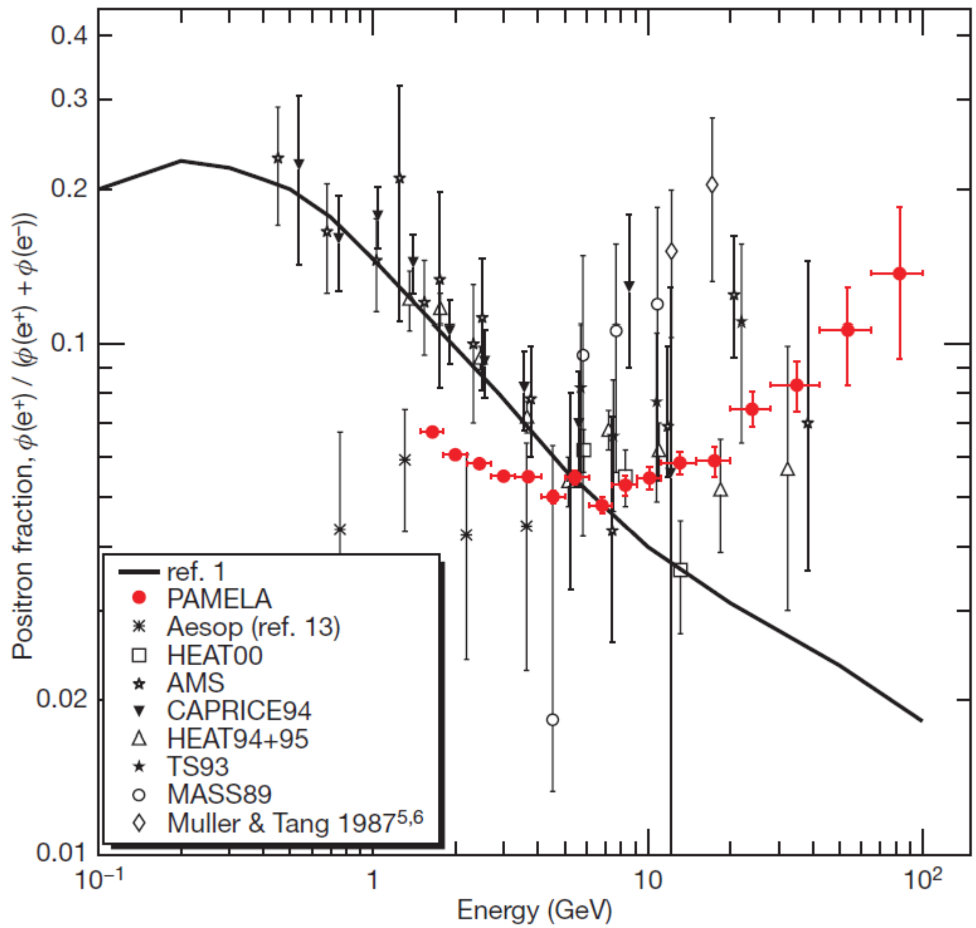


Figure 2 | PAMELA positron fraction with other experimental data and with secondary production model. The positron fraction measured by the PAMELA experiment compared with other recent experimental data (see refs 5–7, 11–13, 30, and references within). The solid line shows a calculation[1] for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes. Error bars show 1 s.d.; if not visible, they lie inside the data points.

PAMELA observations of CR positrons (Adriani et al 2009)

Evidence of Dark Matter?

Problems with CR propagation models ?

Some unknown primary source of CR positrons ?

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

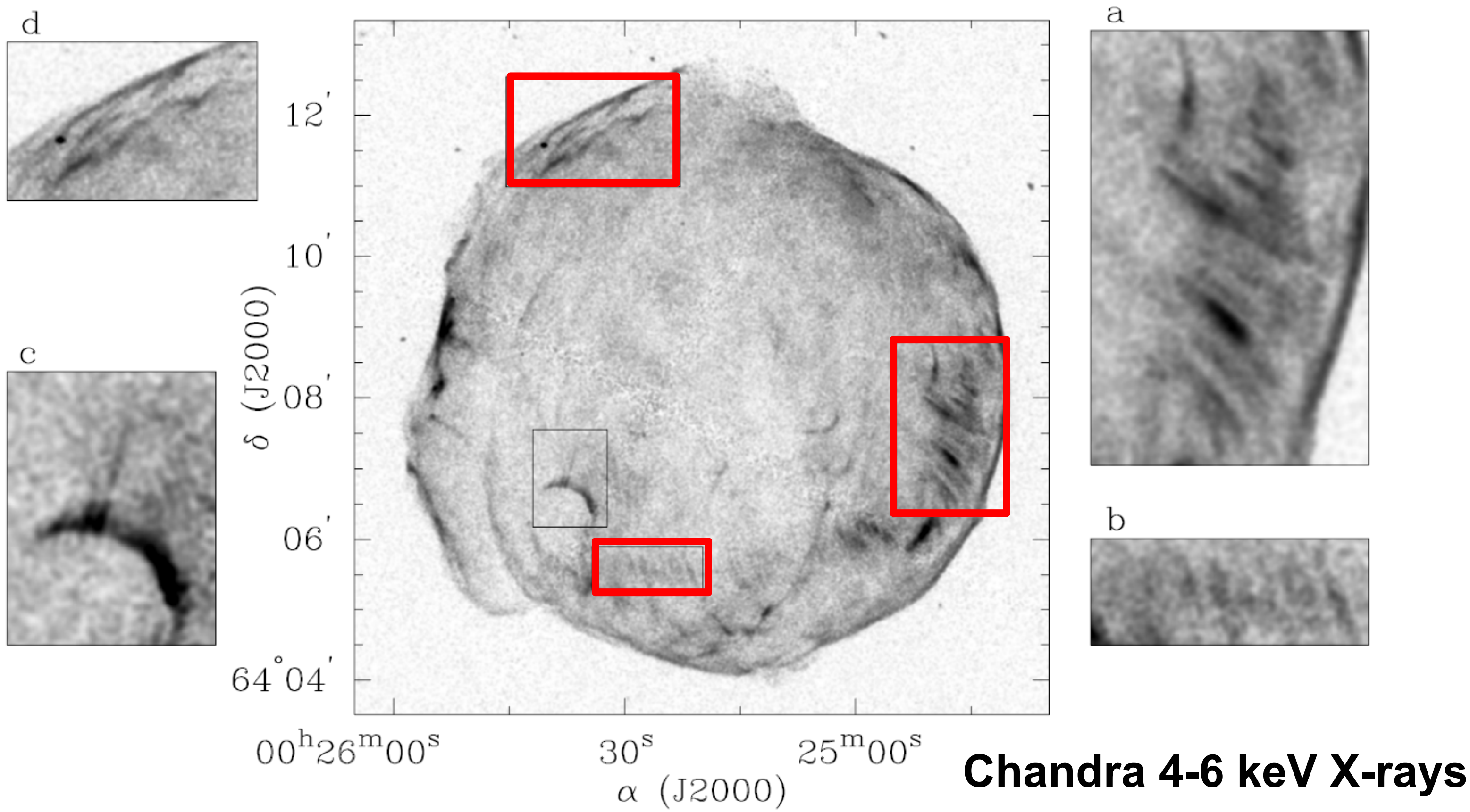


FIG. 1.— *Chandra* X-ray 4.0–6.0 keV image of the Tycho supernova remnant, smoothed with a $\sim 0.75''$ Gaussian and displayed with an *arcsinh* scaling, showing various regions of striping in the nonthermal emission. Clockwise from the upper right: a) The main western stripes discussed in this Letter; 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.

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**

Some Active Problems:

➔ **What instabilities produce magnetic turbulence? (resonant, Bell's, long-wavelength?)**

➔ **Given magnetic turbulence, how do you calculate a diffusion coefficient? (only consistent way with PIC simulations)**

➔ **Nonlinear feedback between MFA and shock structure**

➔ **Escaping particles: Calculate turbulence as highly anisotropic CRs stream away from shock. (Critical for shape and highest CR energy)**