# Efficient Particle Acceleration in Collisionless Shocks:

# Cosmic Ray Production in Young Supernova Remnants

KITP, Santa Barbara, May 2005

Don Ellison, North Carolina State Univ.

**OUTLINE:**

1) Brief summary of non-linear Diffuse Shock Acceleration, (NL DSA)
2) Observations of young SNRs ➔ X-rays, radio, Gamma-rays
3) Morphology of SNRs ➔ Evidence of efficient, NL DSA ??
4) Recent detection of G347 by HESS at TeV energies !
5) Asymmetry of SN1006 ➔ Parallel vs. Perpendicular shock acceleration
6) Brief mention of Magnetic field amplification ➔ Evidence for large B-fields in SNRs and the Bell & Lucek effect

## Efficient Particle Acceleration in Collisionless Shocks:

## Cosmic Ray Production in Young Supernova Remnants

➔ From energy considerations, we know that supernovae are the only known source capable of producing bulk of the galactic cosmic rays (CRs) below the knee

➔ The CR acceleration mechanism must be efficient: >15% of total SN explosion energy must be put into CRs (Hillas 05)

➔ There is strong evidence that the outer blast wave shock accelerates electrons to relativistic energies

➔ Detailed observations of SNRs at many different wavelengths offer hope of actually understanding the shock acceleration mechanism, but need broad-band photon emission models

➔ I will discuss the First-order Fermi (Diffusive Shock) Acceleration mechanism (DSA) (other mechanisms may be important, e.g., second-order Fermi)

**PROBLEMS:**

► Unambiguous **evidence for Cosmic Ray ION production** in SNRs still **lacking** → Requires detection of pion-decay feature in GeV-TeV photons → HESS ?, GLAST ??

► **What is maximum energy SNRs can produce?** **$10^{15}$ eV? $10^{18}$eV?**

► Energetic particle **spectra from individual SNRs** (assuming nonlinear shock acceleration) **may be too flat** – even with liberal interpretation of galactic propagation models → complex models

ALSO, basic questions concerning shock acceleration remain:

► **Is acceleration efficient enough in SNRs for nonlinear effects** to be important? – Still **not clear how injection occurs**, or how it varies with **shock obliquity**, **B-field amplification?** Bell & Lucek

► Not known how shocks inject **electrons relative to protons**

**Modeling of thermal X-ray and broad-band continuum emission from young SNRs may help answer these and other questions**

## Young SNRs may be the best place where we can study high Mach number shocks, accelerating relativistic particles

(1) **Global view** of blast wave shock

(2) **High Mach numbers**, much higher than heliospheric shocks

(3) **Array of observatories**, space and ground-based, with good spatial and energy resolution → see emission from accelerated electrons AND (hopefully) ions

(5) **Broad-band continuum** from radio to TeV gamma rays

(4) see **X-ray emission lines.** Contain a great deal of information: density, equilibration times, etc.

(6) **Different classes of SNRs** (Type Ia, II)

(7) See similar types in **different environments, at different ages**, etc

# DIFFUSIVE SHOCK ACCELERATION in SNRs

► In **collisionless** plasmas, charged particles are coupled by **magnetic fields** → strongly **non-equilibrium particle spectra** possible.

► **Shocks** set up converging plasmas making **acceleration rapid and efficient**

► We know collisionless **shocks exist and accelerate particles.** →
Evidence of **efficient** shock acceleration of ions in the **Heliosphere** →
Particle-in-cell plasma simulations show injection of ions

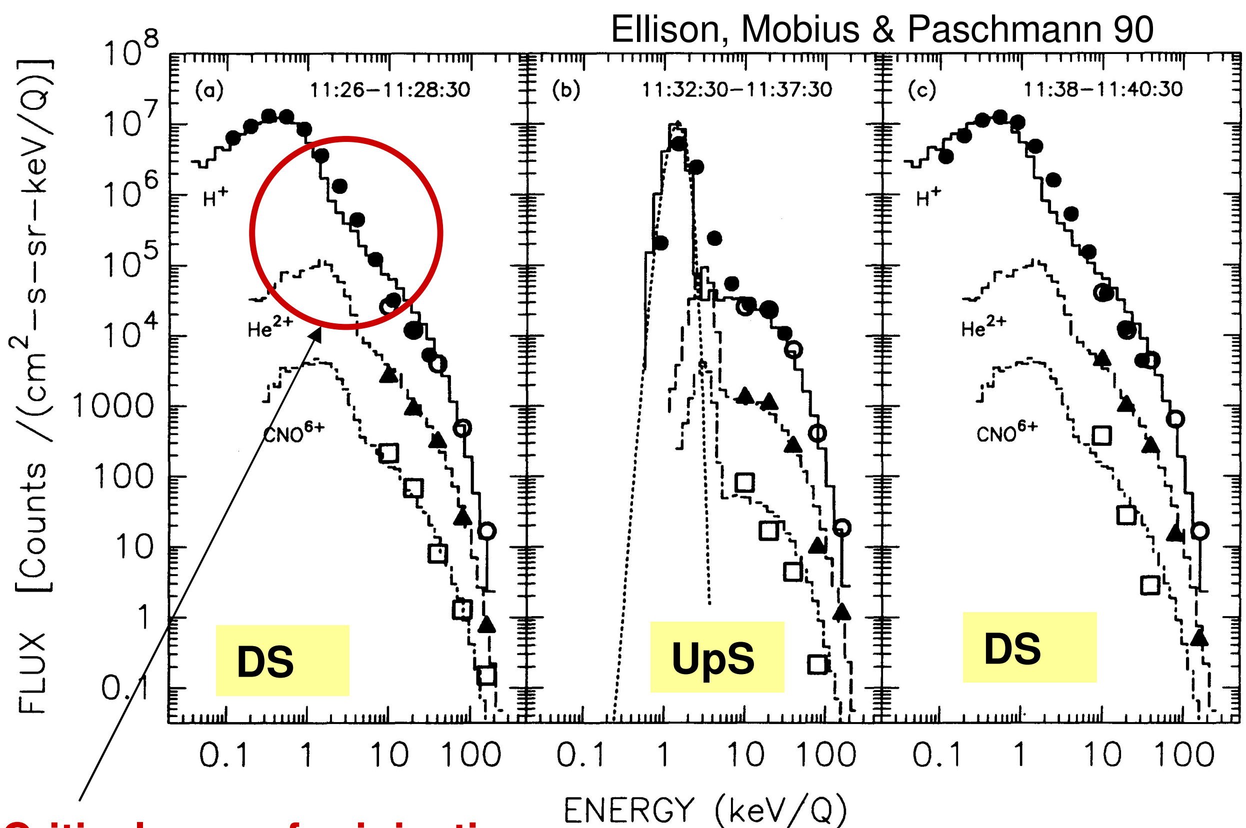
► Much stronger **SNRs shocks should be efficient ION accelerators**

**The efficient acceleration of Cosmic Ray ions impacts:**

1) **Thermal properties of the shock heated, X-ray emitting gas,**
2) **SNR evolution, and**
3) **broad-band emission**

## Real shocks inject thermal ions:

### Earth Bow Shock




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.**

**Data → ~25% accel. efficiency**

**Confirmed predictions of A/Q enhancement**

**Indication of NL effects and $r_{tot} > 4$.**

**Smooth injection of thermal solar wind ions**

**Scholer, Trattner, Kucharek 1992 found similar results with hybrid PIC simulations**

# Earth Bow Shock

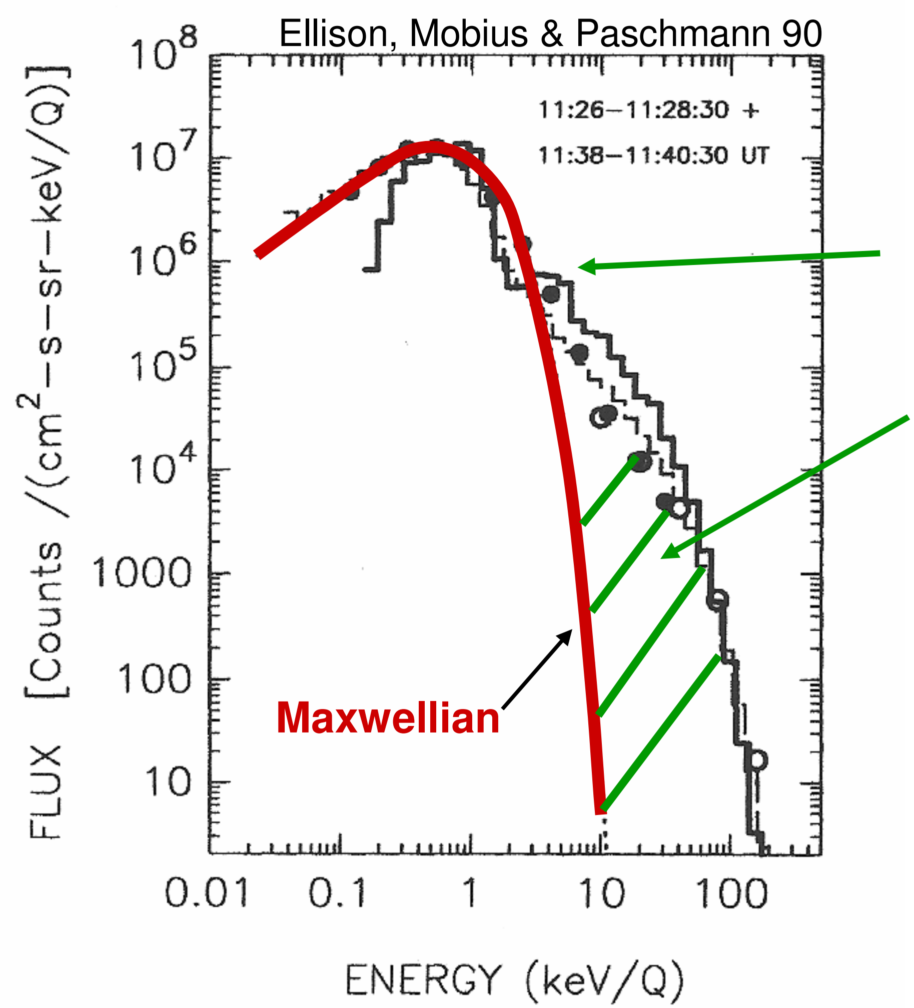



FIG. 13.—Downstream spectra (*points plus dashed line*) compared to a thermal distribution (*dotted line*). The thermal distribution has a temperature of $6 \times 10^6$ K, a density of 5.7 $cm^{-3}$, and a velocity of 115 km $s^{-1}$. Also shown is the Monte Carlo simulation result for a discontinuous shock transition (dotted line in Fig. 9). The heavy solid line shows the best fit obtainable for the given solar wind conditions when no upstream slowing of the solar wind is assumed.

**Observed acceleration efficiency is quite high:**

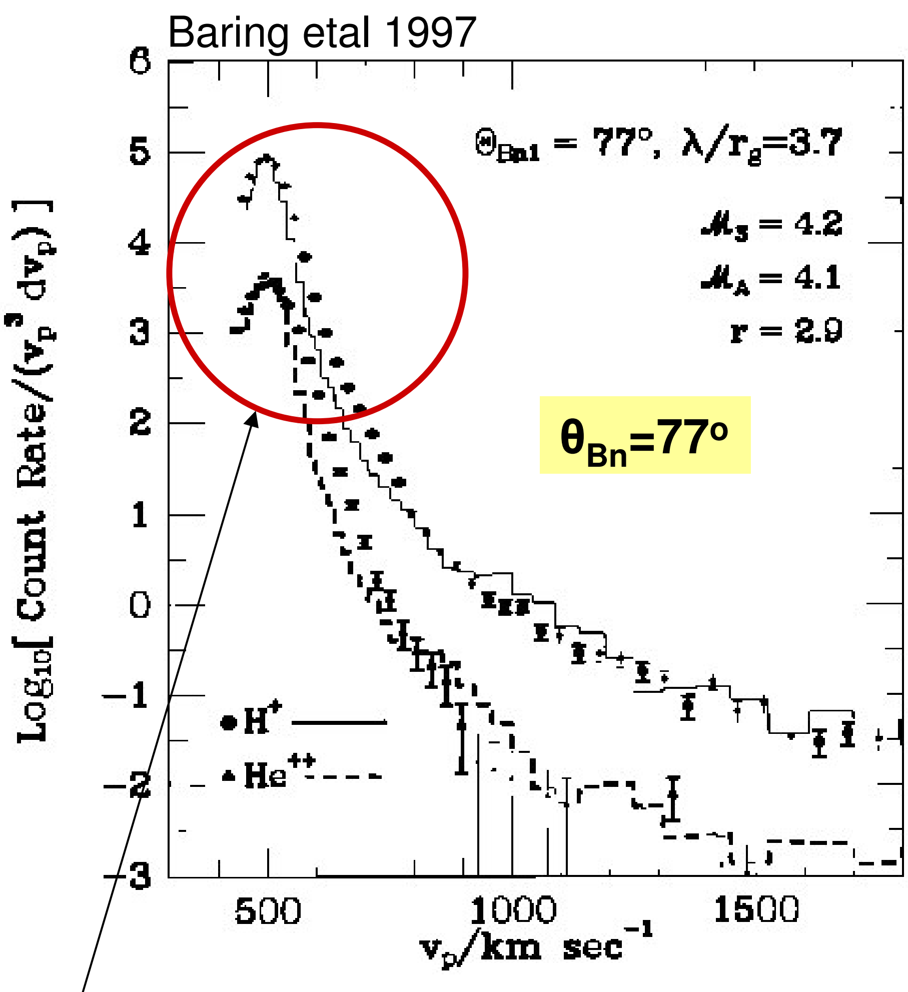
**Dividing energy ~4 keV**

**gives ~2.5% of proton density in superthermal particles, and**

**>25% of energy flux crossing the shock in superthermal protons**

Real shocks, even oblique ones, inject thermal ions:

# Interplanetary shock




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 but must less efficient that Bow shock

## Interplanetary Shock Obs. With GEOTAIL, 21 Feb 1994

Shimada, Terasawa, etal 1999

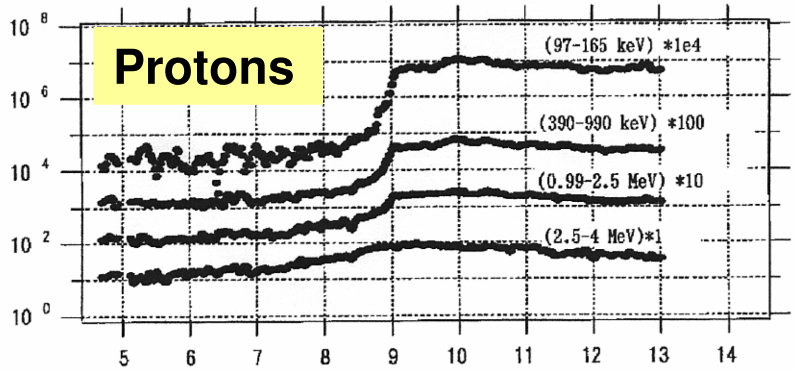



*Figure 1.* Omnidirectional counts for ions (protons/sample) of four different energy channels observed during the interval of 0445-1300 UT on 21 February 1994.

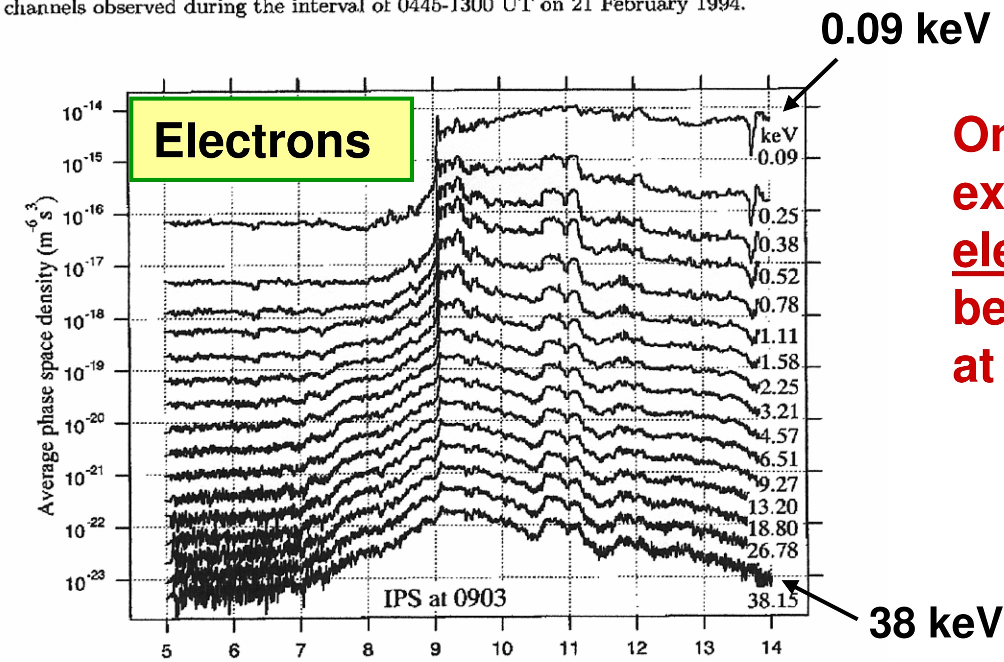



*Figure 2.* Average phase space densities for electrons during the interval of 0500-1400 UT on 21 February 1994. The representative energy for each energy channel is shown in the figure.

**One of the very few examples where <u>thermal electrons</u> were observed to be injected and accelerated at heliospheric shocks**

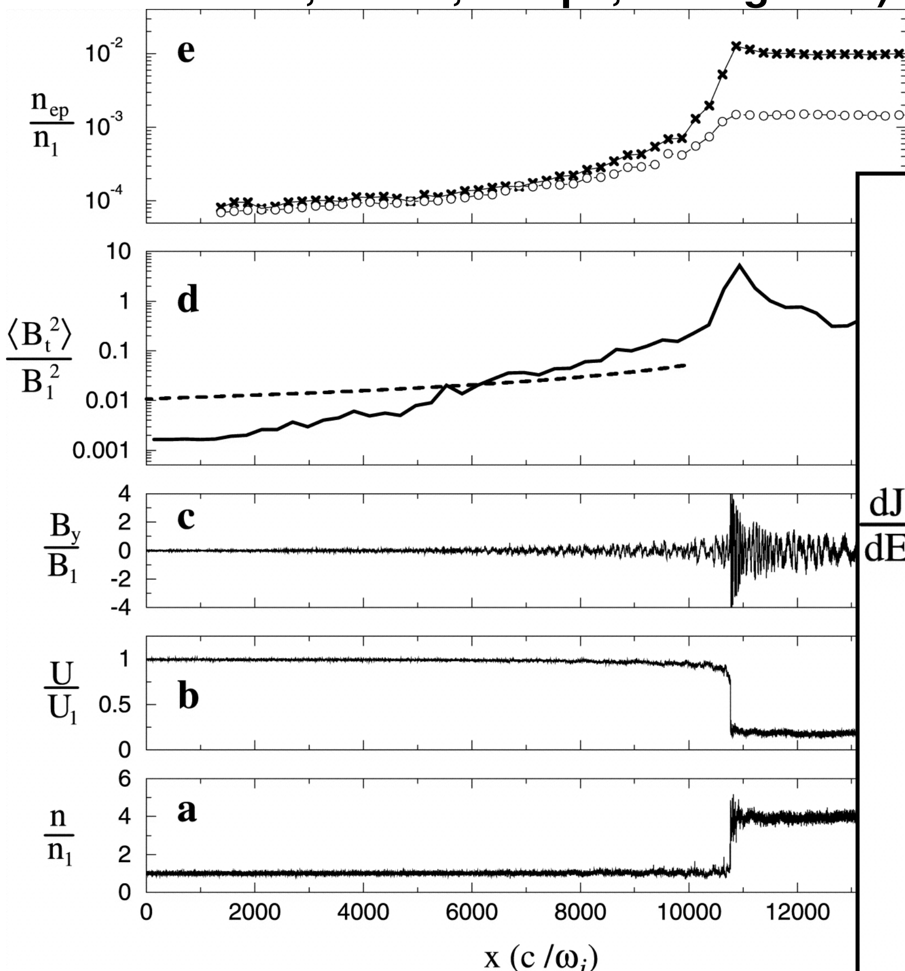
**Most observations of heliospheric shocks do not show the acceleration of thermal electrons**

# Hybrid PIC simulations:

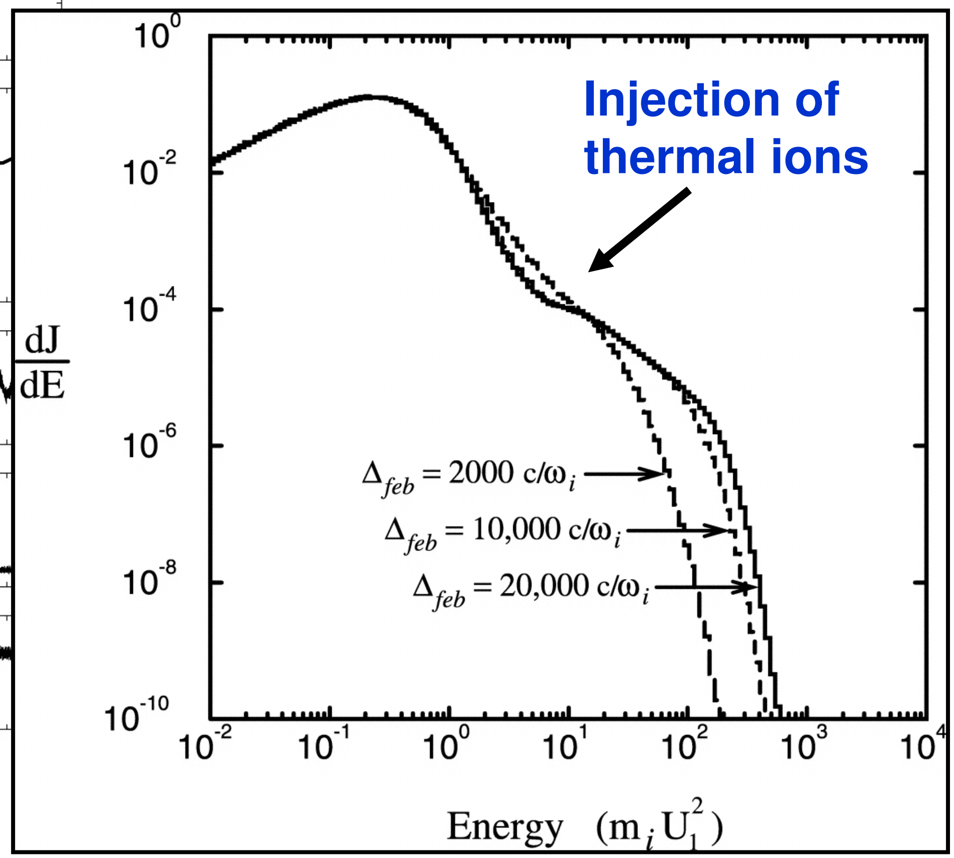
**Simulations still highly restricted by computational limits.**

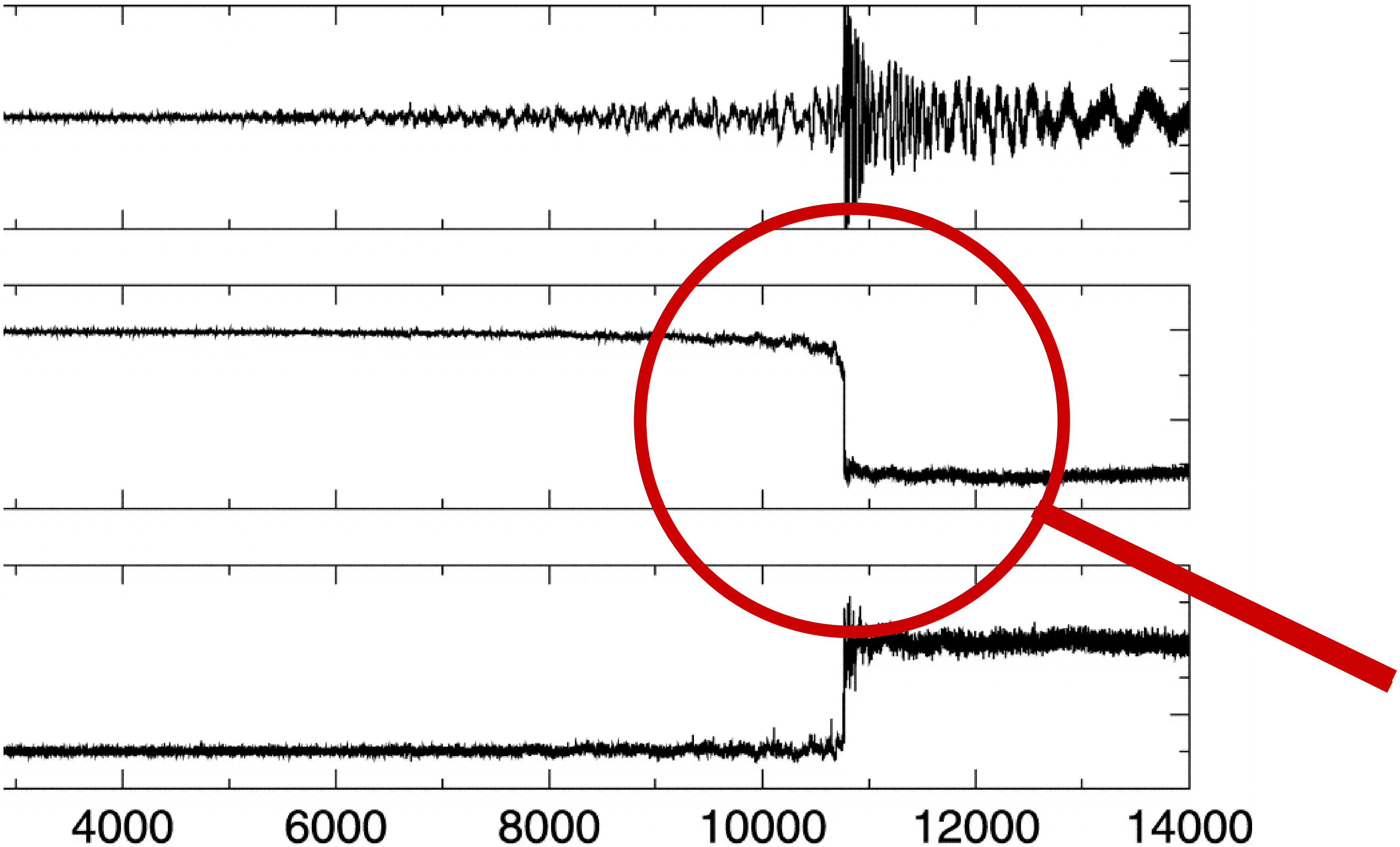
**Must be cautious about dimensionality of PIC simulations (Jokipii, Kota, Giacalone 1993, Jones, Jokipii, Baring 1998)**

**Must do oblique shocks in 3-D to model cross-field diffusion correctly**




**1-D Parallel Shock simulation,** Giacalone 2004



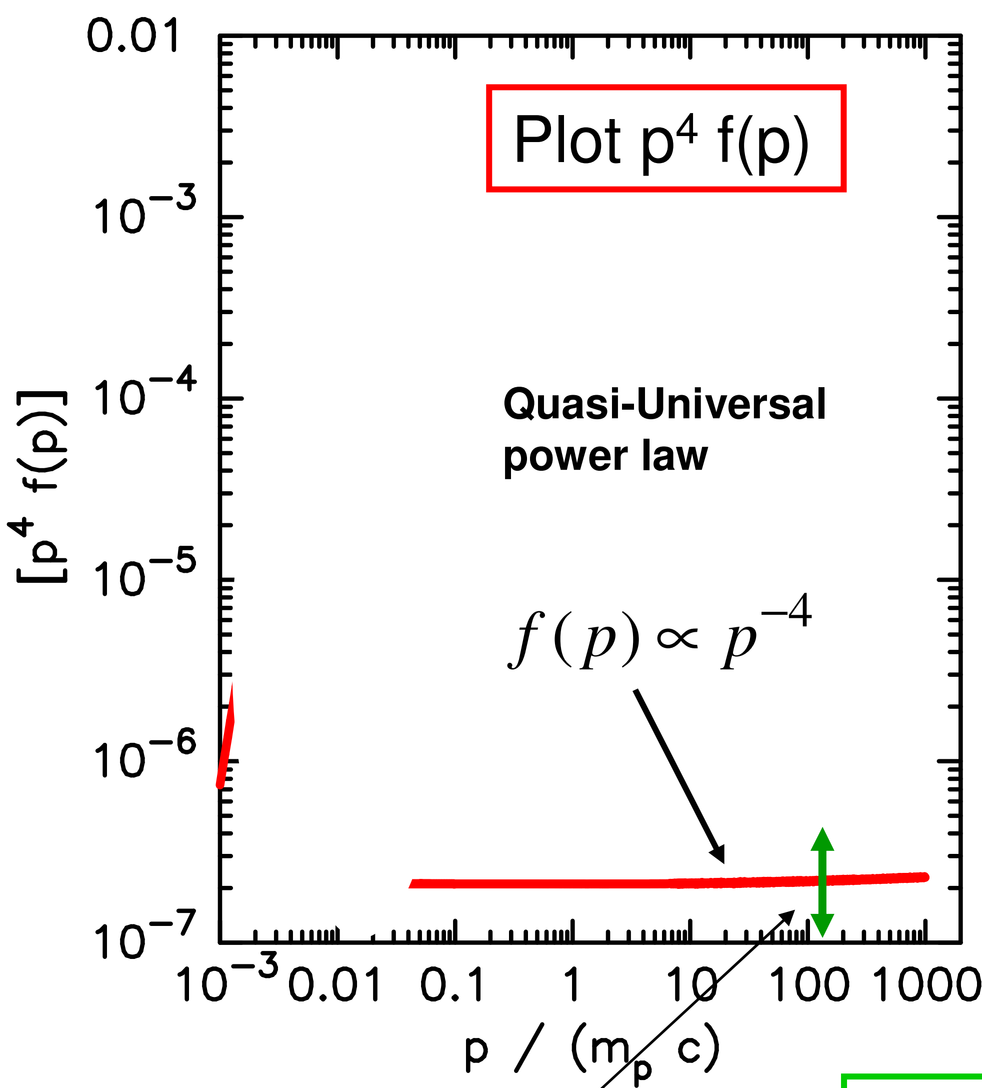



**Shock smoothing** from backpressure of accel. particles?

**Parallel Shock simulation,** Giacalone 04

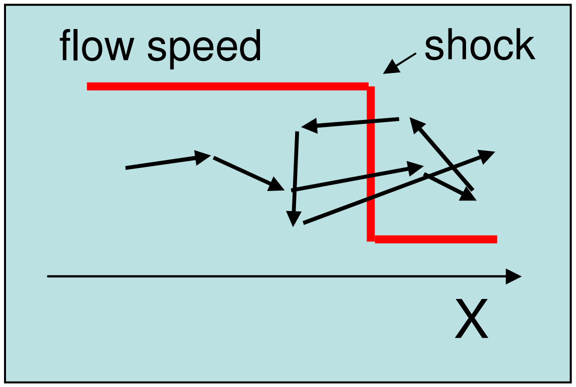
# Test Particle Power Law

Krymsky 77, Axford at al 77, Bell 78, Blandford & Ostriker 78




$f(p) \sim p^{-3r/(r-1)}$ where **r** is compression ratio, f(p) $d^3p$ is phase space density

**If r = 4, & $\gamma$ = 5/3, f(p) ~ $p^{-4}$**




Normalization of power law not defined in TP approximation

Test particle results: ONLY for superthermal particles, no information on thermal particles

## BUT Not so simple

Consider **energy in accelerated particles** assuming NO maximum momentum cutoff and **r ~ 4** (i.e., high Mach #, non-rel. shocks)

$$\int_{p_{inj}}^{\infty} E p^2 p^{-4} dp \propto \int_{p_{inj}}^{\infty} dp / p$$

$$N(p) \propto p^2 f(\vec{p})$$

$$= \ln p \,|_{p_{inj}}^{\infty}$$

**Diverges if r ≥ 4**

But $r \approx \frac{\gamma + 1}{\gamma - 1}$

If produce relativistic particles → $\gamma < 5/3$ → compression ratio increases (r ↑)

Spectrum flatter → Worse energy divergence → **Must have high energy cutoff in spectrum** to obtain steady-state → particles escape at cutoff, **"escape" should occur in evolving SNRs (Berezhko et al 1996)**

But, if particles escape, compression ratio increases even more **. . .**
Acceleration becomes strongly nonlinear

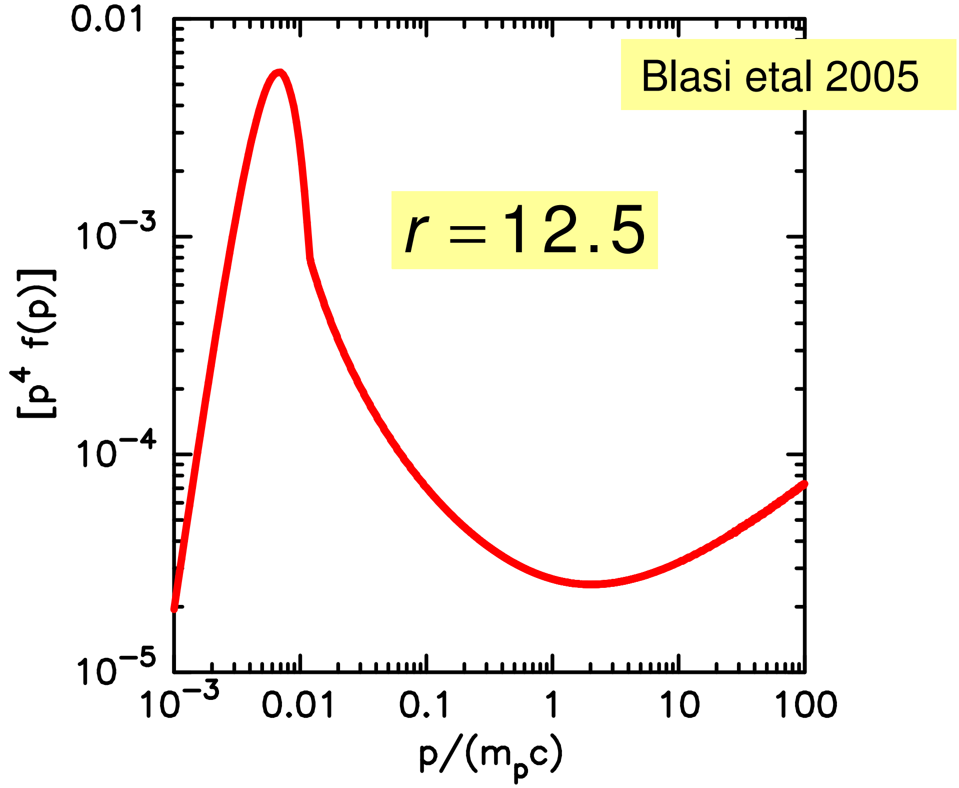
►**Strong shocks will be efficient accelerators with large comp. ratios even if injection occurs at modest levels (1 ion in $10^4$)**

**Large compression ratio ➔ flat spectrum**

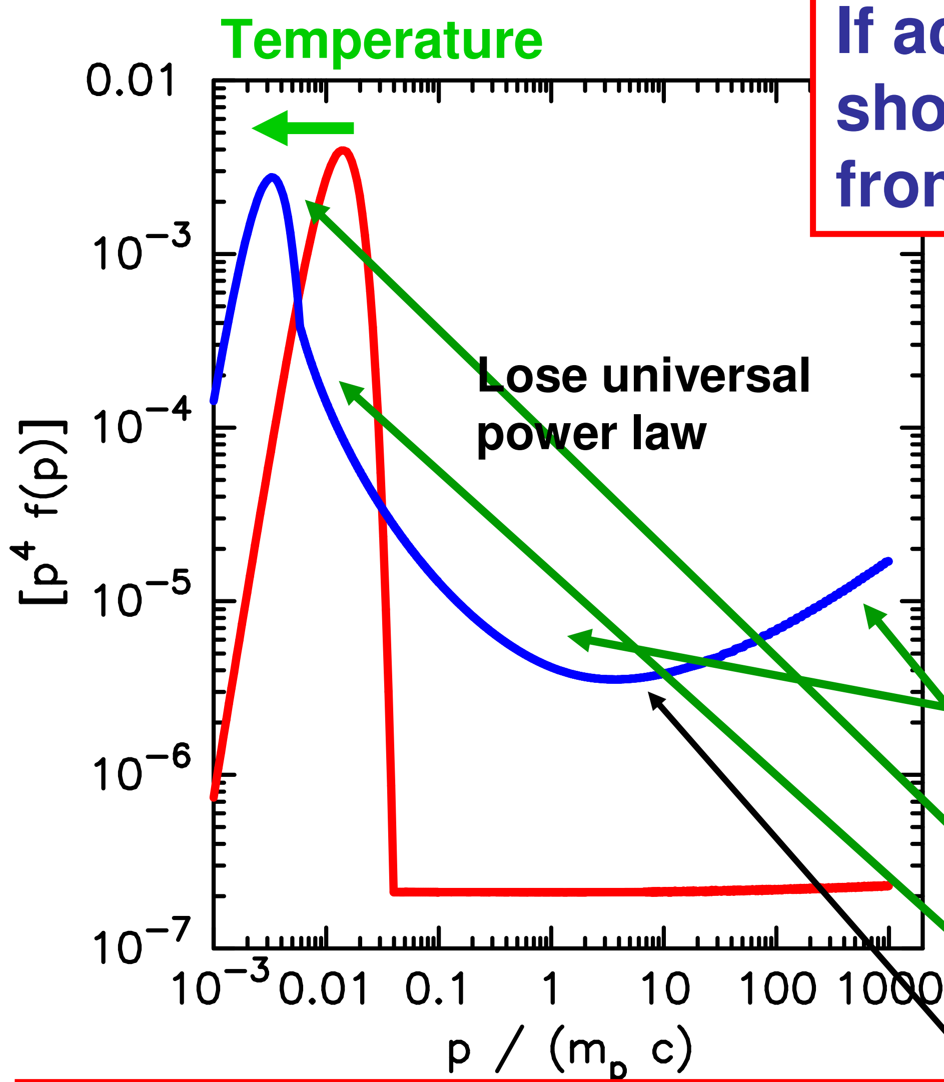
For $r = \infty, \quad f(p) \propto p^{-3}$

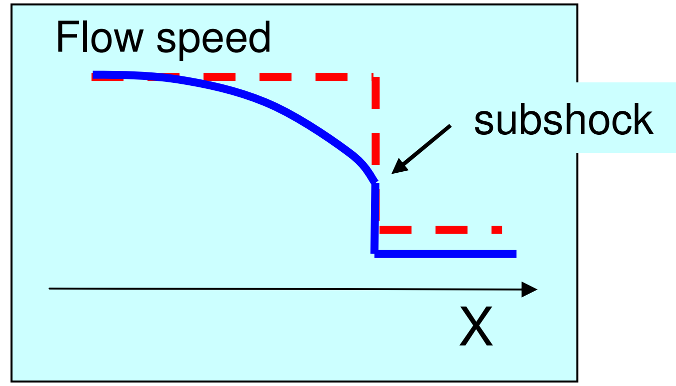
**If diffusion coefficient is an increasing function of momentum, the superthermal spectrum will be curved:**

**Note: If diffusion coefficient independent of momentum, superthermal spectrum will be a power law even if r > 4.**



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

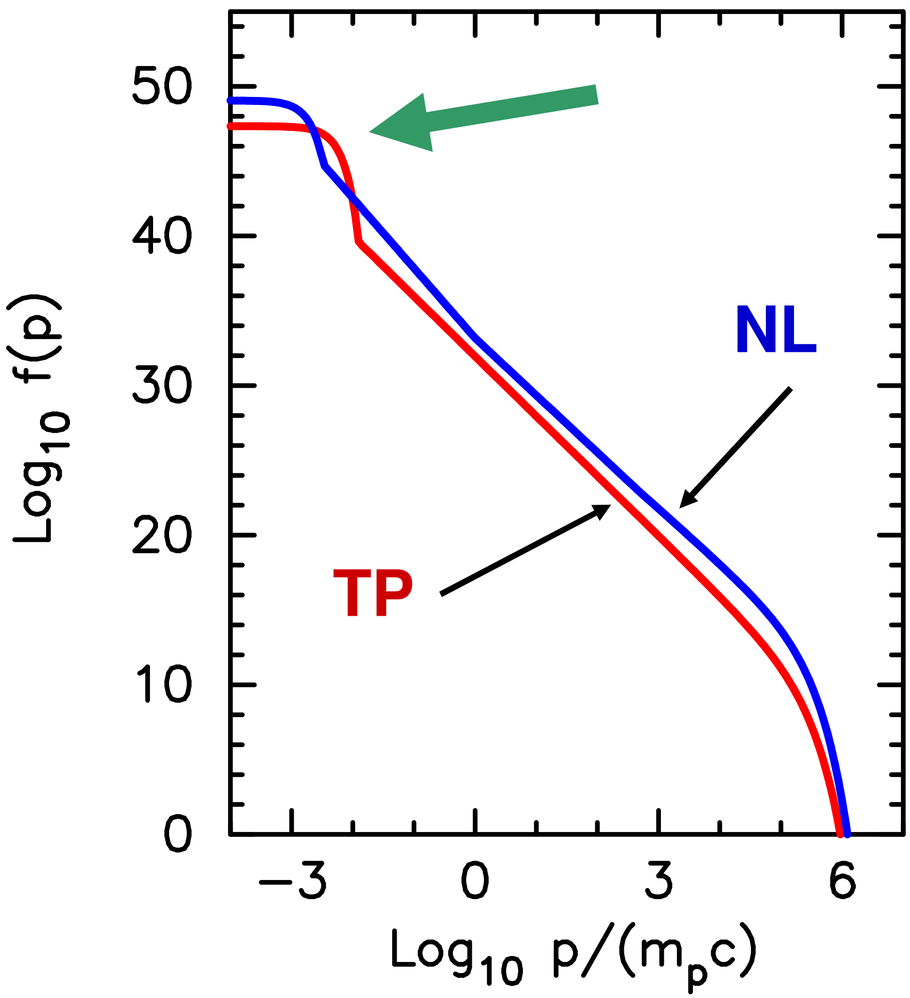



- ► **Concave spectrum**
- ► **Compression ratio, $r_{tot} > 4$**
- ► **Low shocked temp. $r_{sub} < 4$**
- ► **Nonthermal tail on electron & ion distributions**

Here show analytic model of Blasi (2002)

**In efficient accel., entire spectrum must be described consistently connects photon emission across spectrum from radio to γ-rays**

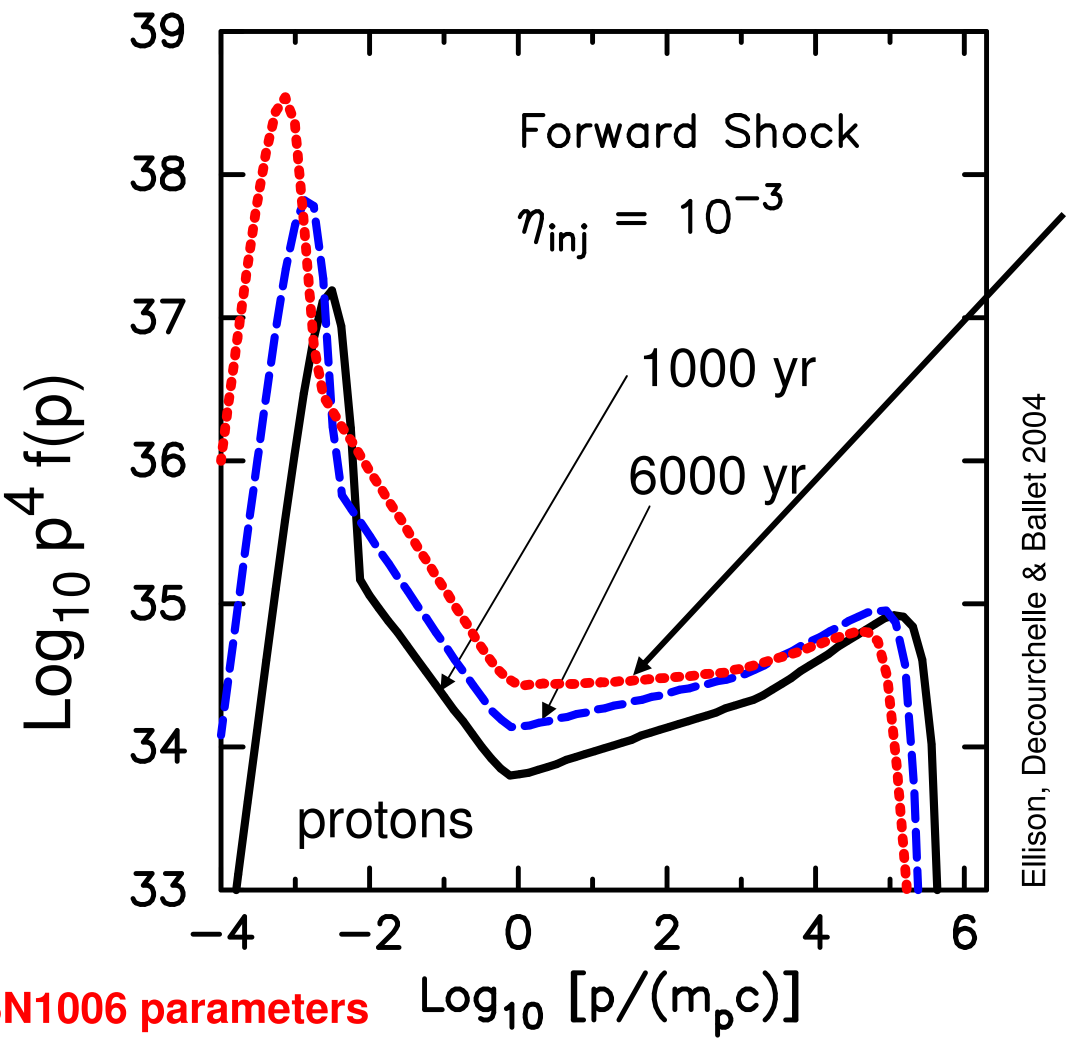



Without $p^4$ factor in plot, nonlinear effects much less noticeable → hard to see in cosmic ray obs.

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

Compression ratios, $r_{tot} > 4$ result from: (1) contribution to pressure from rel. particles ($\gamma=4/3$, $r_{tot} \rightarrow 7$) and (2) particle escape ($r_{tot} \rightarrow$ infinity)

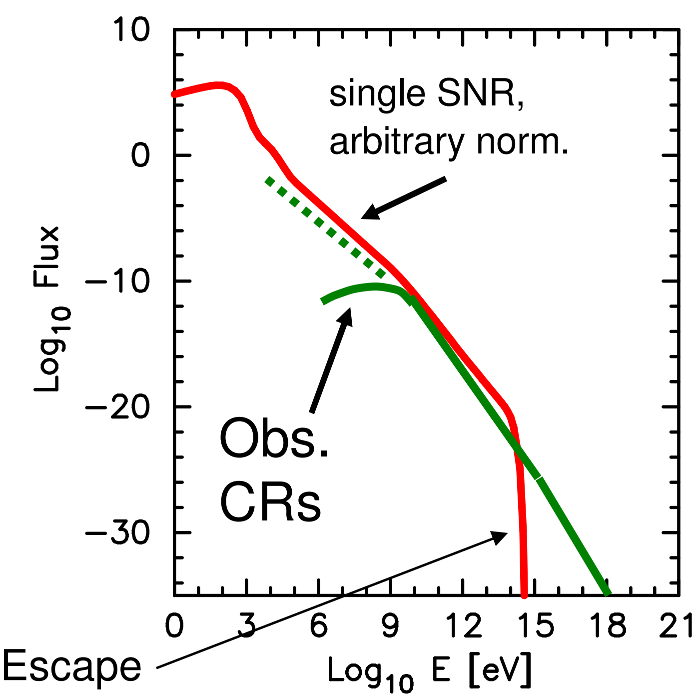
## Total contribution to Cosmic Ray flux after 40,000 yr from 1 SNR




After 4 x$10^4$ years, total CR spectrum is steepened, BUT still **not steep enough to match observed CR all particle spectrum** !

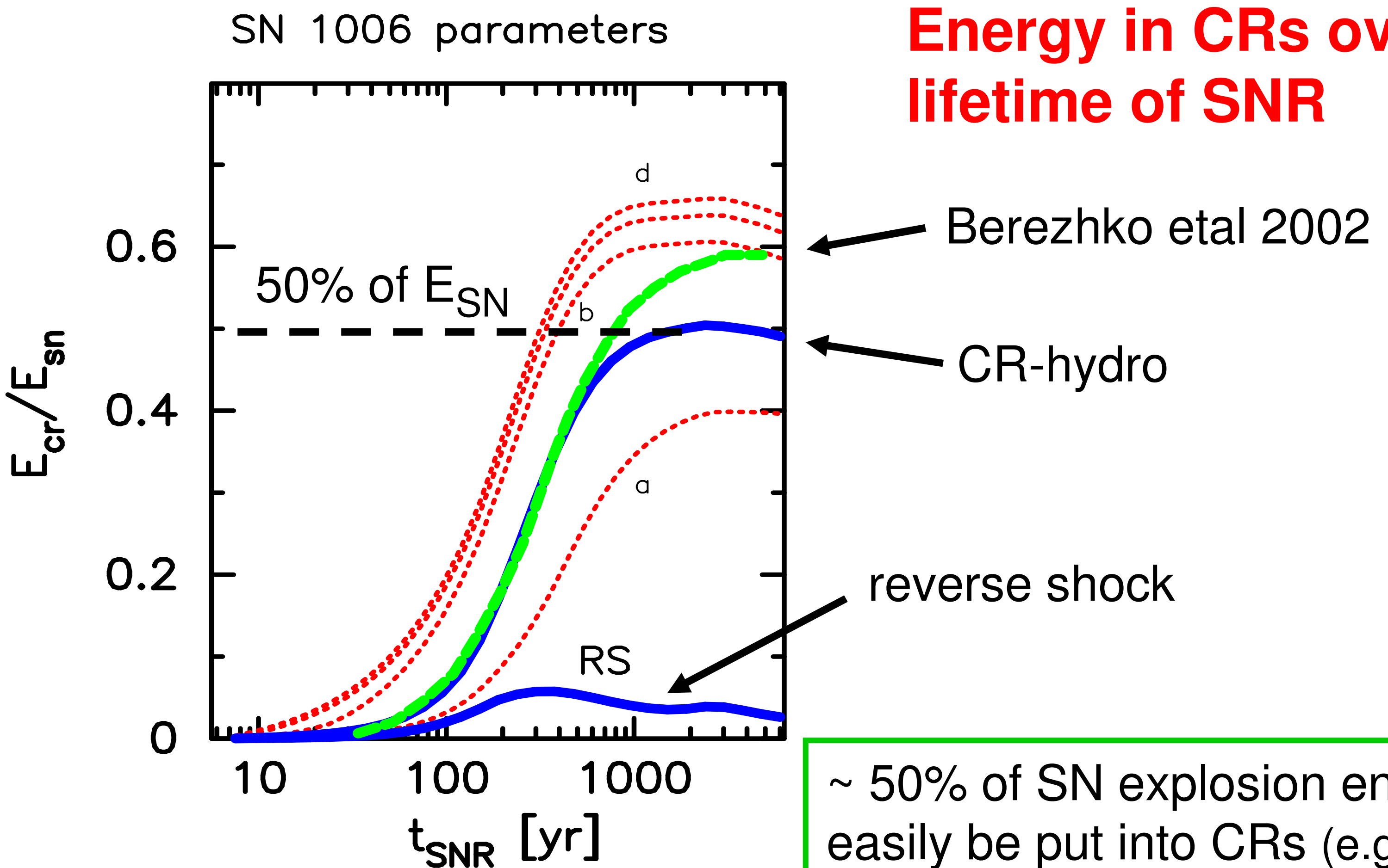
**SN1006 parameters**

Ellison, Decourchelle, & Ballet 2004




Includes energy dep. Escape

# Energy in CRs over lifetime of SNR




Ellison, Decourchelle, & Ballet 2004

~ 50% of SN explosion energy can easily be put into CRs (e.g. Dorfi etal)

Only need to have efficient accel. over fraction of SNR blast wave to power CRs (e.g. Berezhko etal 2002)

**Theory suggests shocks in SNRs can be extremely efficient. What do observations say?**

# Active X-ray Spacecraft


**INTEGRAL**

**Gamma Rays 20 keV and 8 MeV**

**In SNRs, Thermal X-rays come from shock heated gas,**

**Radio, non-thermal X-rays, and gamma-rays, come from shock accelerated particles**

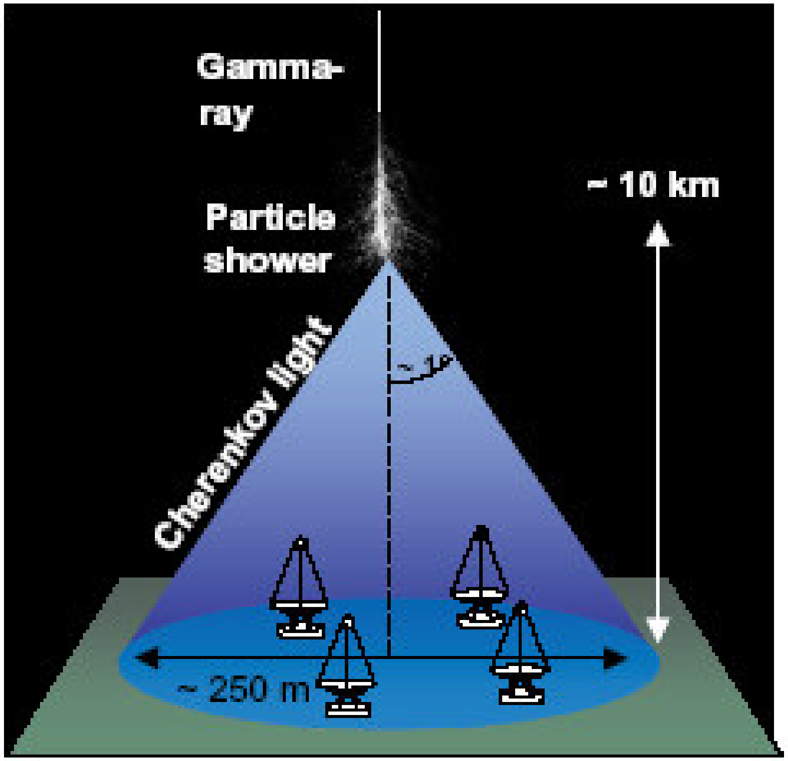
Ground based radio telescopes

**Very Large Array** (VLA) Plains of San Agustin, NM

(a)

(b)

## Ground based Gamma-ray telescopes




High energy gamma-ray produces blue <u>Cherenkov light</u> as it passes through atmosphere (similar in water)

If human eyes were $10^6$ times more sensitive, particle shower would look about like a meteor

# HESS:
# Namibia 2004

**Cosmic gamma-rays in the 100 GeV energy range.**

**Two main features:**

**Simultaneous observation of air showers with several telescopes – stereo mode**

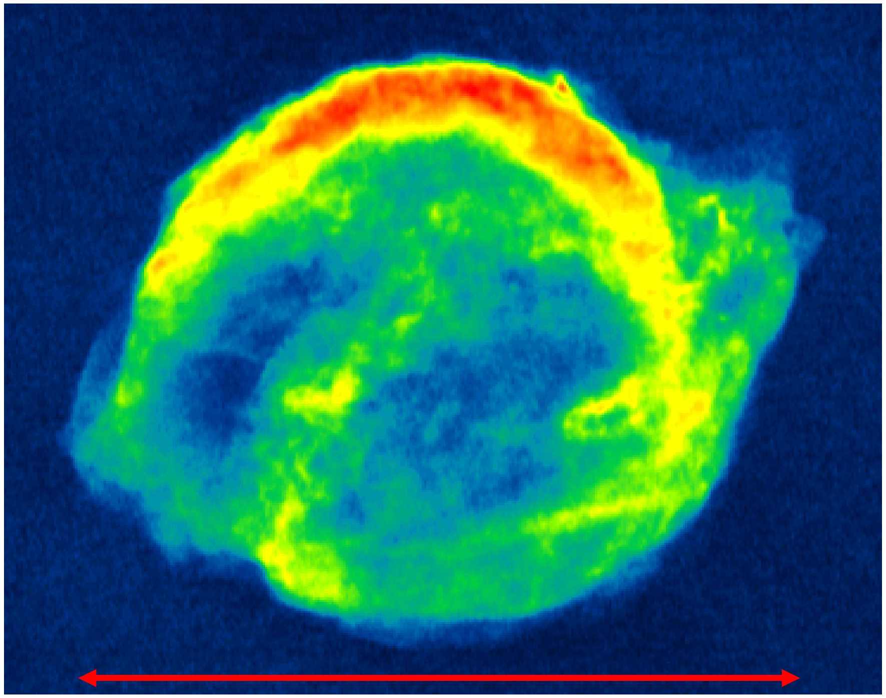
**Different viewing angles, and the combination of telescopes increases the effective detection area for gamma rays.**

**H.E.S.S. detects gamma-ray sources at few milli-Crab level**

**High Energy Stereoscopic System (H.E.S.S.), a European/African collaboration**

## Kepler's SNR

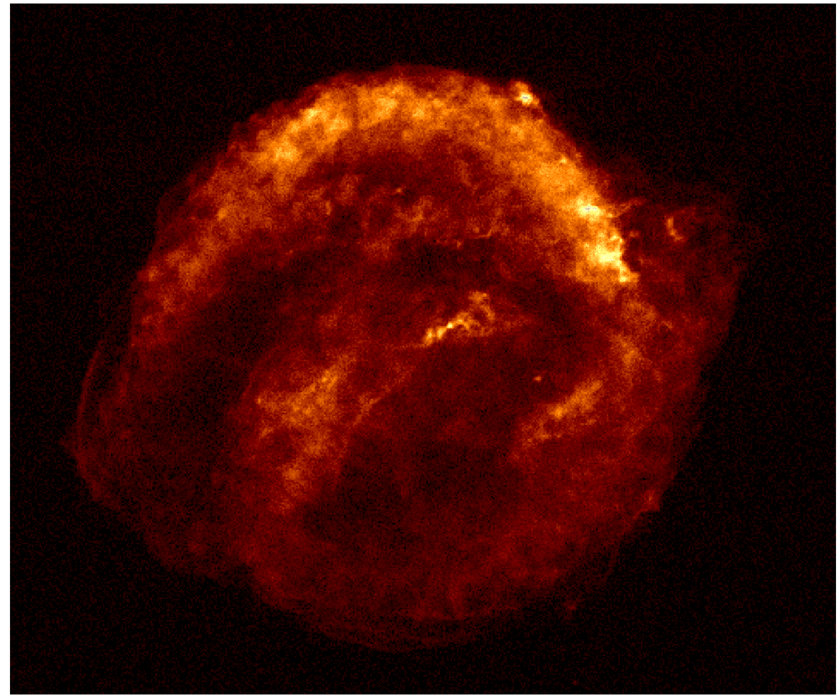
Radio VLA 6 cm



3 arcmin

Radio is Synchrotron emission from GeV electrons

X-ray Chandra 0.5-10 keV

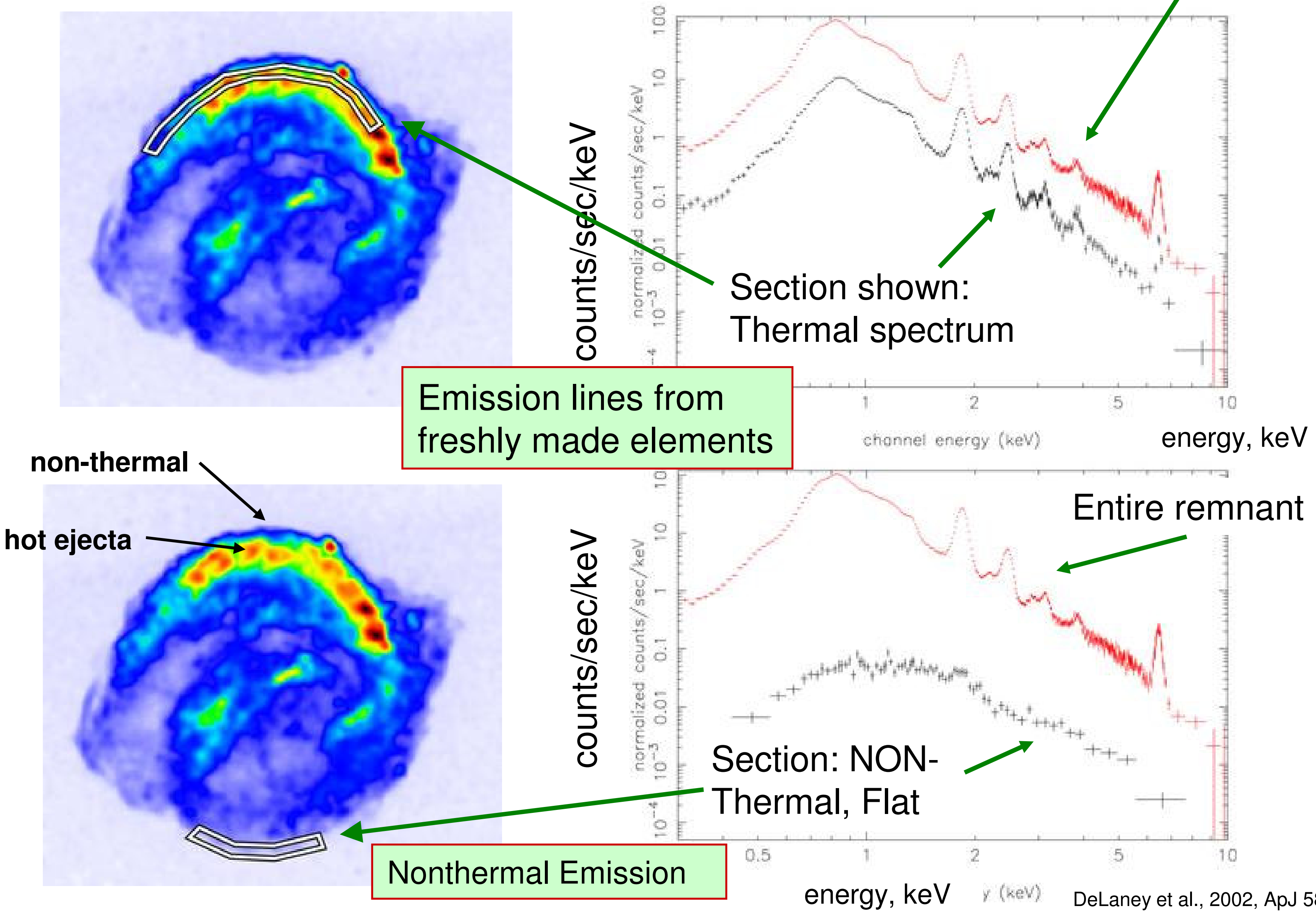


**Xrays: Mixture of thermal from shocked heated ejecta gas (T~$10^6$K) and non-thermal**

**Non-thermal is Synchrotron emission from TeV !!! electrons**

**DeLaney et al., 2002, ApJ 580, 914**

# Chandra obs. of Kepler's SNR




DeLaney et al., 2002, ApJ 580, 914

**Non-Thermal X-ray emission (up to ~10 keV) is very clear evidence that shocks accelerate electrons to energies up to ~10-100 TeV, i.e, $10^{14}$ eV**

**Seen in ~10 young SNRs – could possibly be present is all young SNRs – in G347, only non-thermal X-rays are seen, no thermal**

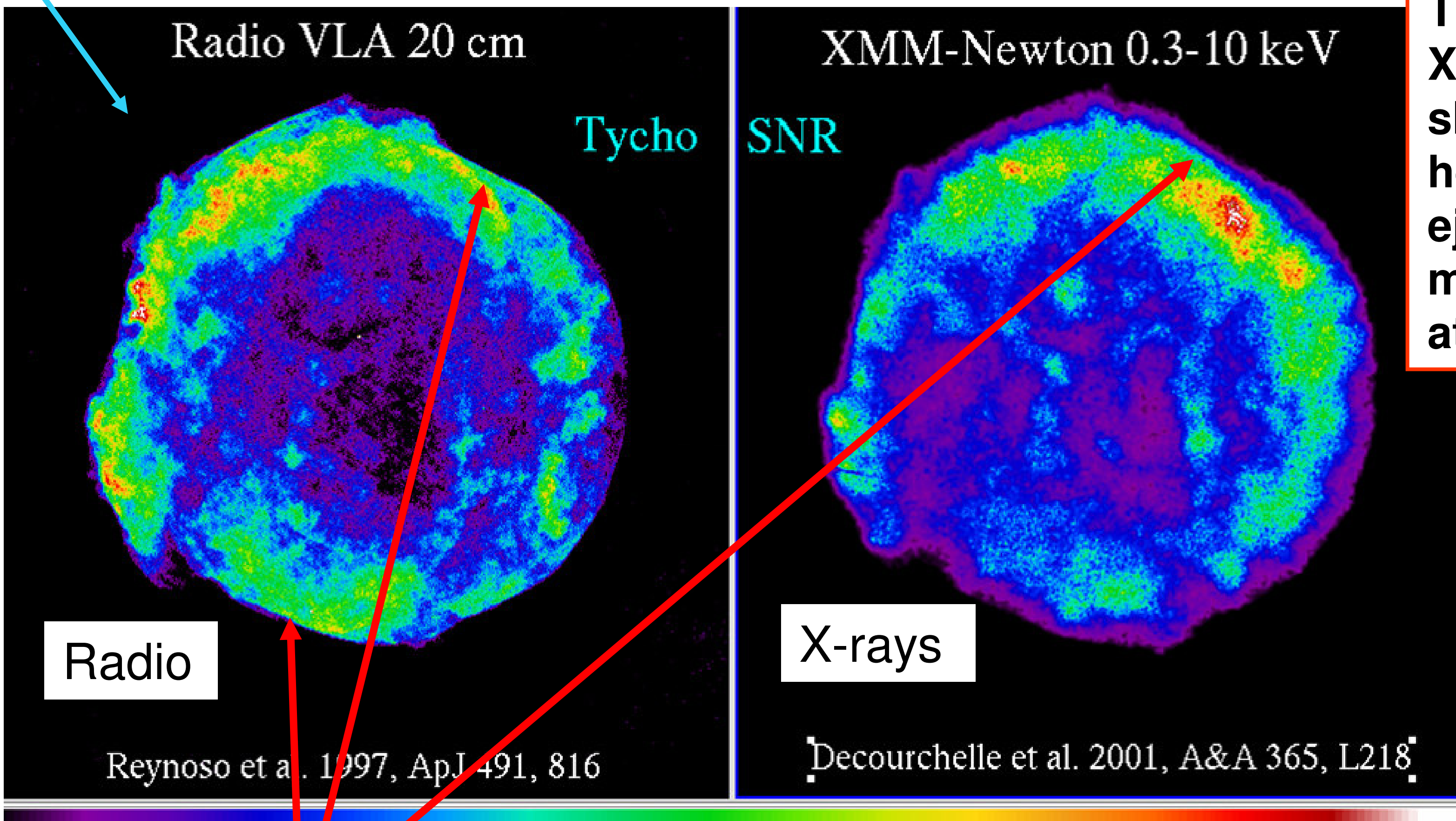
**What about efficiency of shock acceleration? This is determined by the acceleration of IONS not electrons.**

**So far, no unambiguous evidence for ion acceleration in SNRs.  Direct evidence requires observation of pion-decay photons produced from proton-proton collisions.**

**Indirect evidence may come from Morphology of SNRs**

# Impact of Efficient Cosmic Ray production on morphology of Supernova Remnants

Radio: $e^-$s accelerated by outer blast wave shock



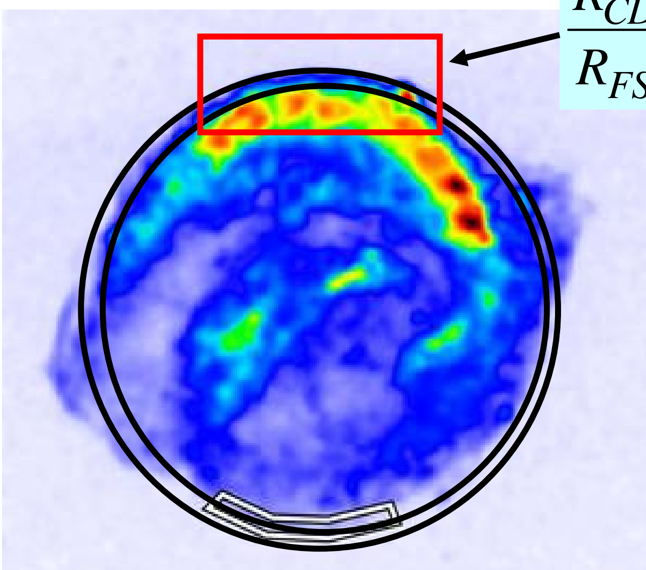

Thermal X-rays: shock heated ejecta material at CD

Tycho's SNR

Radial distance between outer shock and contact discontiuunity seems extremely small in some cases

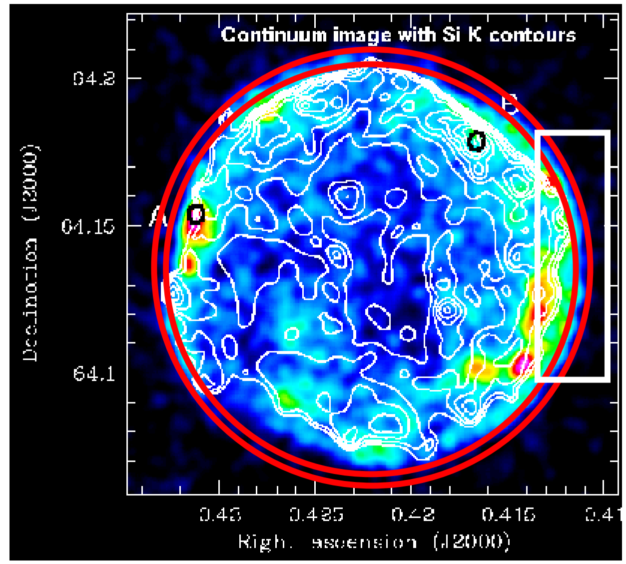
# Morphology of Young Supernova Remnants (SNRs)

**Kepler's SNR**



$$\frac{R_{CD}}{R_{FS}} \geq 0.9$$

**Tycho's SNR**




$$\frac{R_{CD}}{R_{FS}} \geq 0.9$$

Decourchelle etal 2001

In some young SNRs, outer blast wave shock (inferred from radio or nonthermal X-ray emission) is extremely close to inner shocked ejecta material from explosion (inferred from X-ray line emission). $(R_{CD} / R_{FS})_{obs} > 0.9$

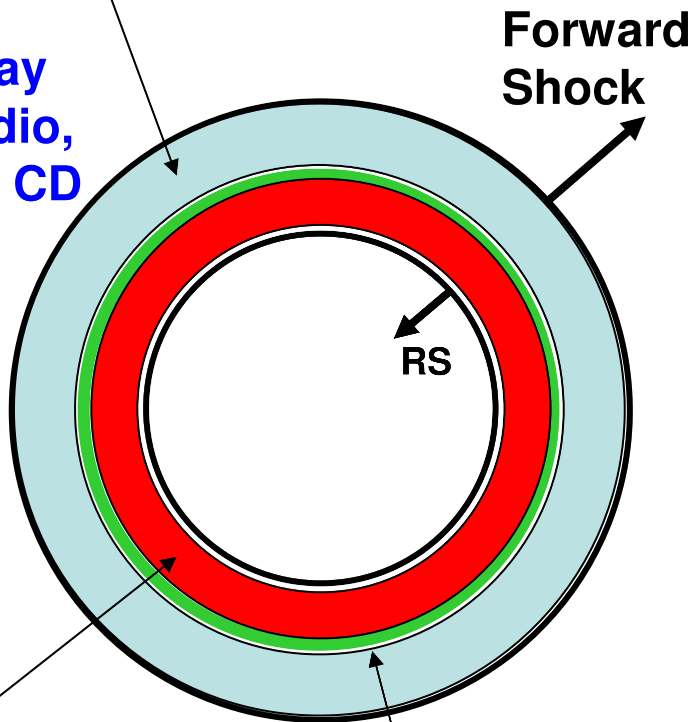
In **normal hydro models**, the outer forward shock (FS) is well separated from the ejecta or contact discontinuity (CD). $(R_{CD} / R_{FS})_{hydro} < 0.8$

**Possible explanation: SNR shocks are efficiently accelerating cosmic rays, i.e., ~50% of shock ram K.E. goes into relativistic IONS**

## 1-D SNR model

**Shocked ISM material :**

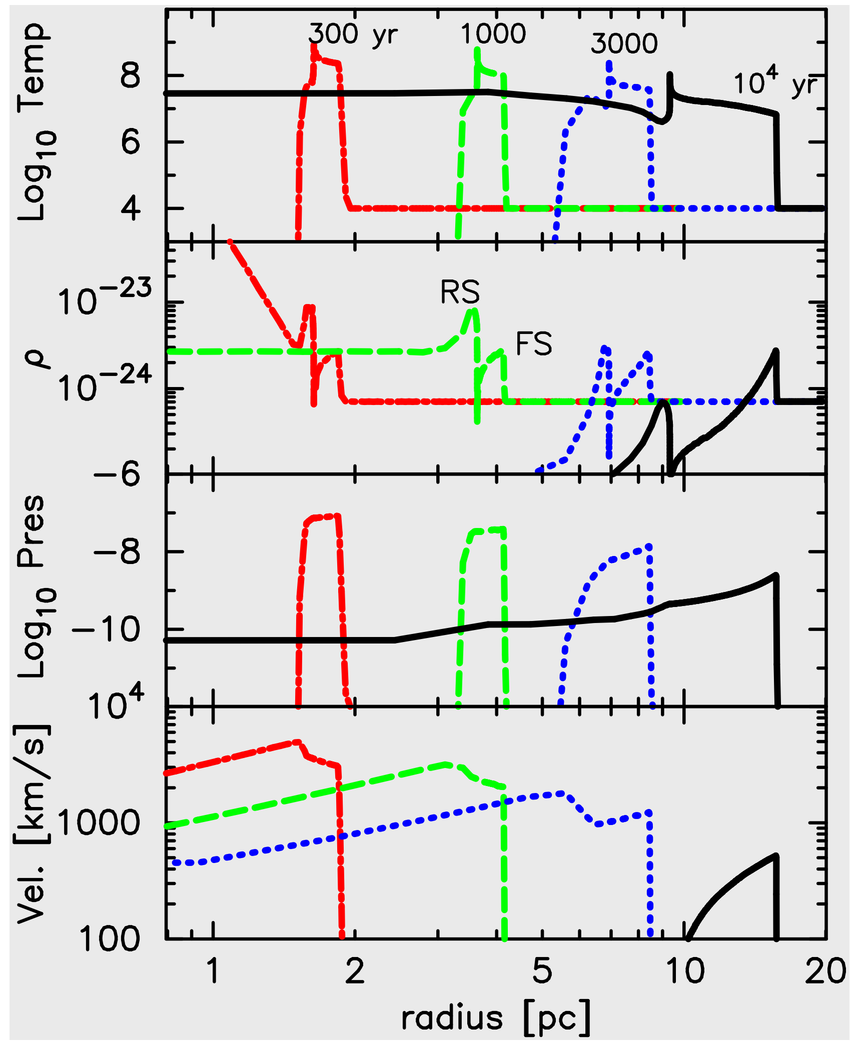
Weak X-ray lines; Radio, Strong at CD



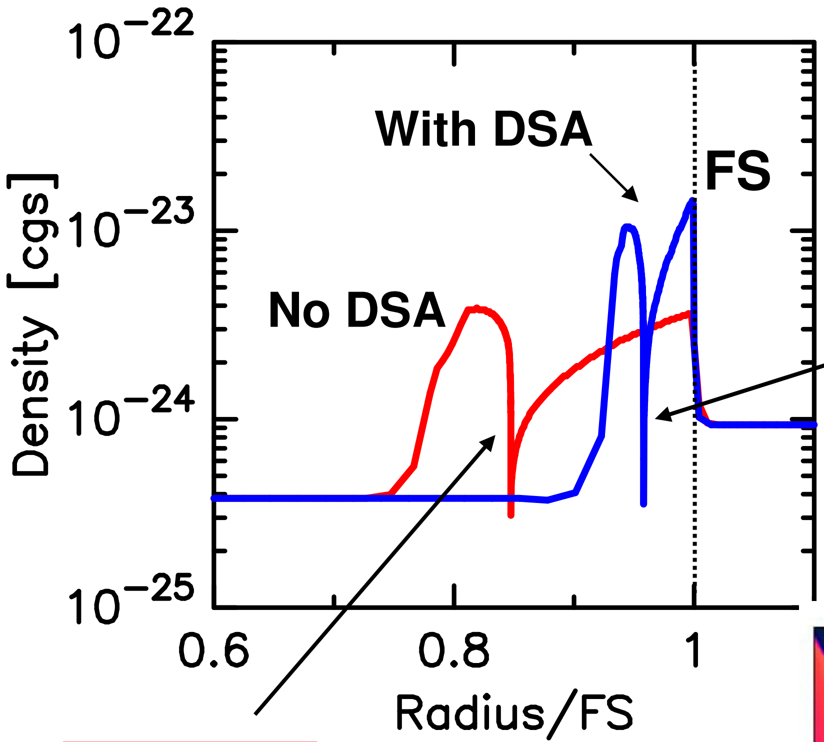

**Shocked Ejecta material : Strong X-ray emission lines, but expect no radio if B is diluted progenitor field**

Contact Discontinuity

hydro simulation – NO Shock Accel.




Ellison, Decourchelle Ballet 2004




Power law ejecta distribution with no pre-SN stellar wind

Ellison, Decourchelle & Ballet 2004

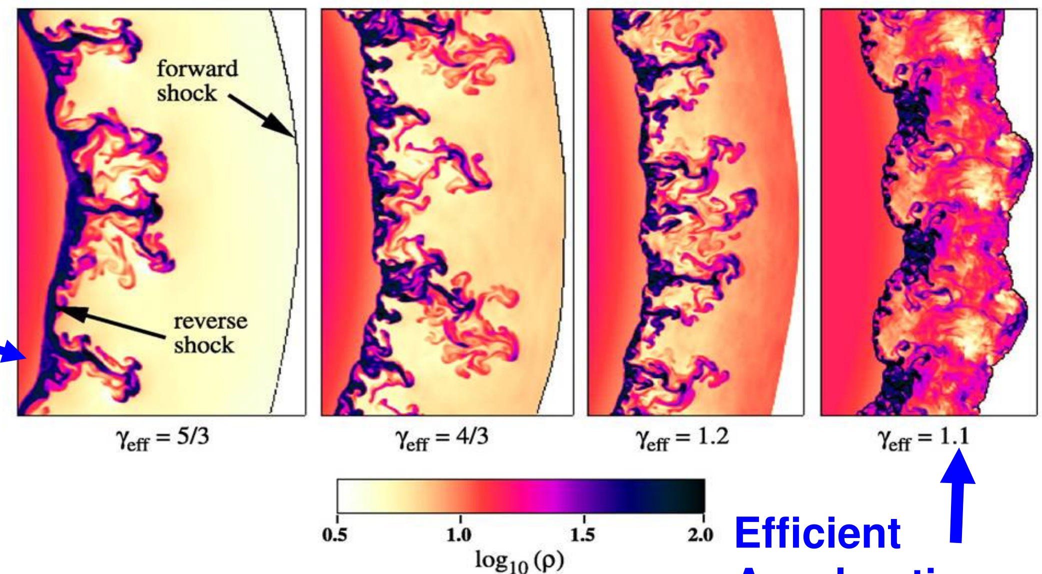
**1-D, spherically symmetric hydro simulation of SNR with nonlinear DSA coupled to hydrodynamics**

$$\frac{R_{CD}}{R_{FS}} > 0.95$$

$$\frac{R_{CD}}{R_{FS}} \sim 0.8$$

**vary $\gamma_{eff}$ effective**

**No acceleration**




**Efficient Acceleration**

2-D Hydro simulation Blondin & Ellison 01

**Signature of efficient diffusive shock acceleration:**

**Interaction region between RS and FS narrower & denser than expected**

**Shocked proton temperature less than expected**

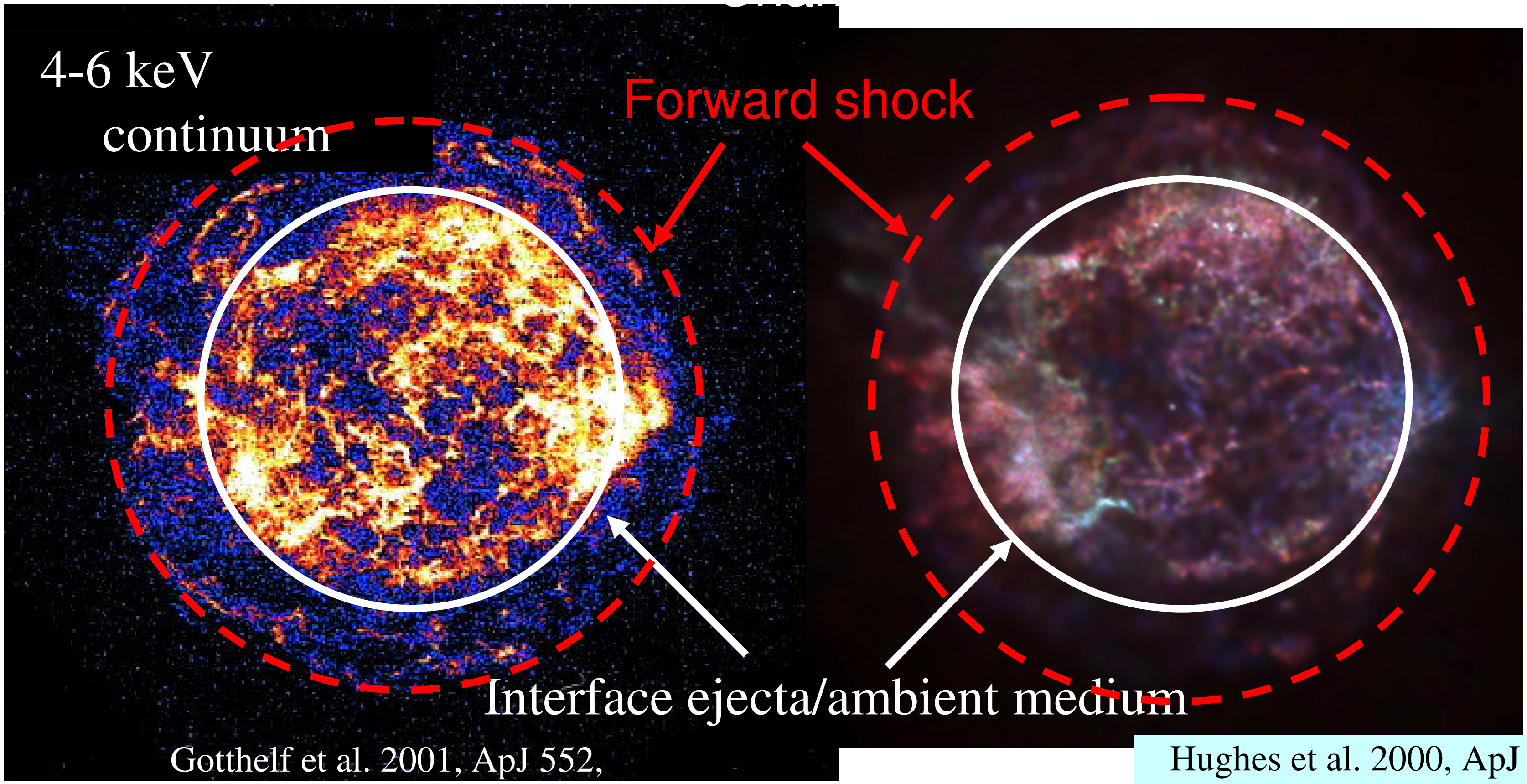
**Morphology of some SNRs consistent with efficient acceleration of IONs**

➔**Use photons emitted by electrons (radio, thermal and non-thermal X-rays) to deduce ION acceleration !**

➔ **However, not so obvious in some cases:**

# Cas A SNR

Color image: **0.6-1.6 keV**
**1.6-1.2 keV** **2.2-7.5 keV**

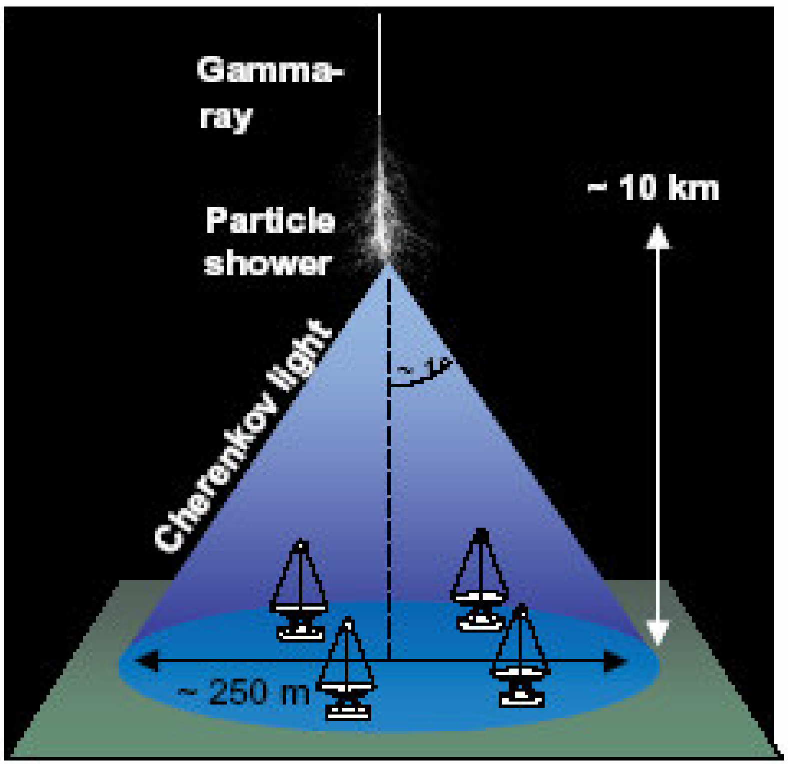



Hughes et al. 2000, ApJ 528, L109

**Forward shock seems well separated from shocked ejecta➔ (1) Inefficient shock acceleration, or (2) effects of pre-SN wind stellar** **(e.g., Chevalier & Oishi 2003, ApJ) (SNR E0102 similar)** **More detailed discussion in Ellison & Cassam-Chenai (2005)**

**What about direct evidence of Cosmic Ray Ion production in SNRs?**

**This is very hard to see because it requires identification of pion-decay photons at GeV-TeV energies ➔ Fluxes are low and observations are hard ➔ Air Cherenkov techniques ➔ CANGAROO, HESS**

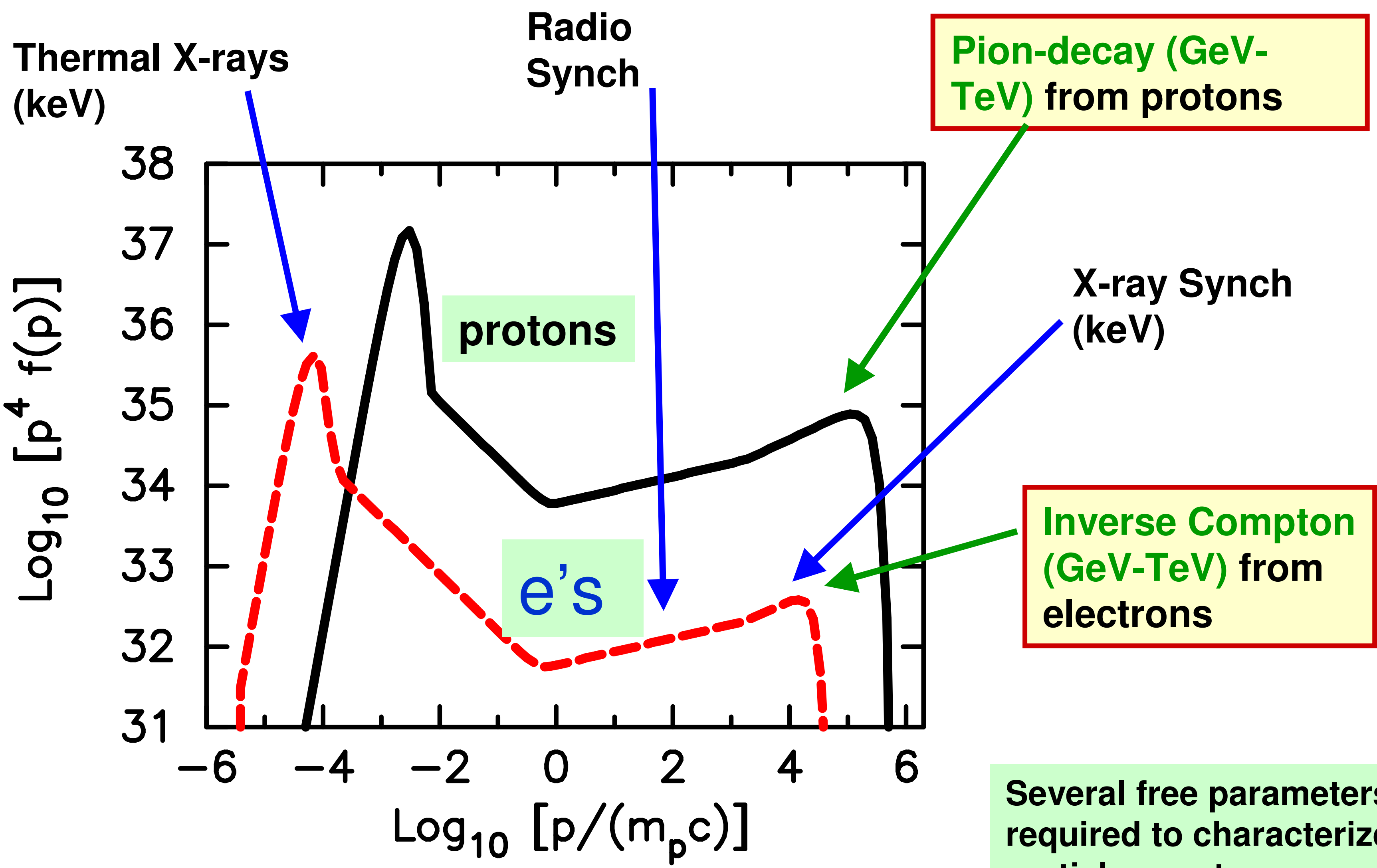



**Competition between Inverse-Compton (IC) from electrons, and pion-decay emission at GeV-TeV energies**

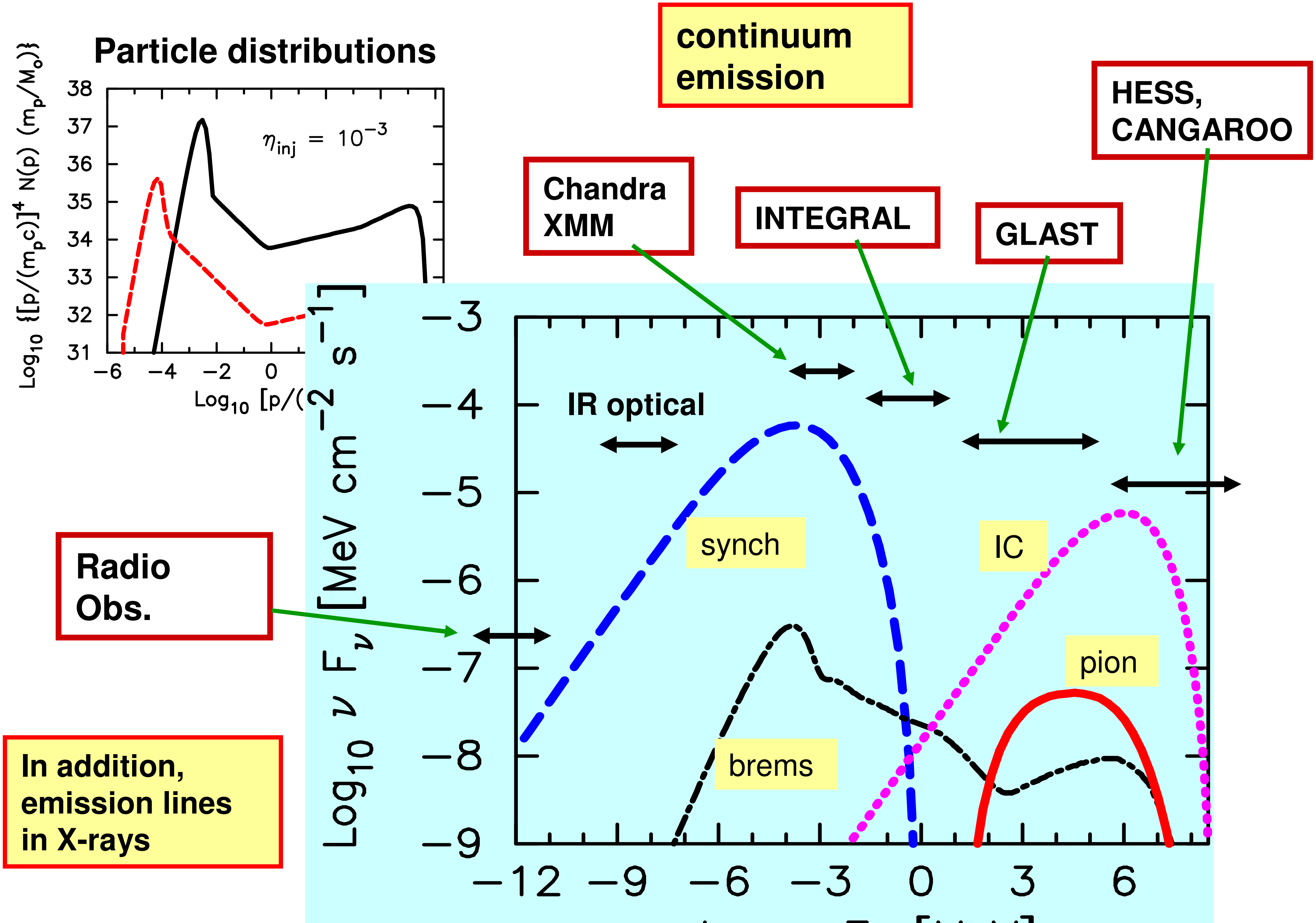
**Even if you see TeV gamma-rays, they may be from electrons**

# Electron and Proton distributions from efficient DSA

(from Berezhko & Ellison accel. model)




Several free parameters required to characterize particle spectra



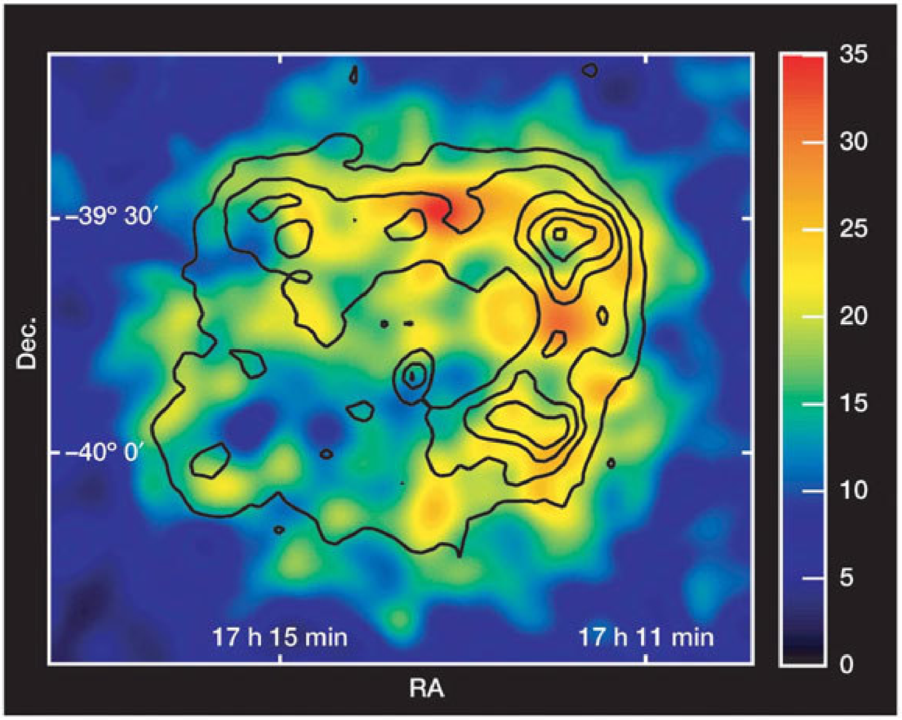
Ref: Ellison, Slane, Gaensler 01

**In previous slide, the relative intensity of IC vs. pion-decay depends strongly on ambient conditions (mainly density). Only shape of observed spectrum can distinguish between them directly at TeV energies.**

**But, broad-band models connecting Radio – X-rays – gamma-rays, in principle, can discriminate between IC and pion-decay**

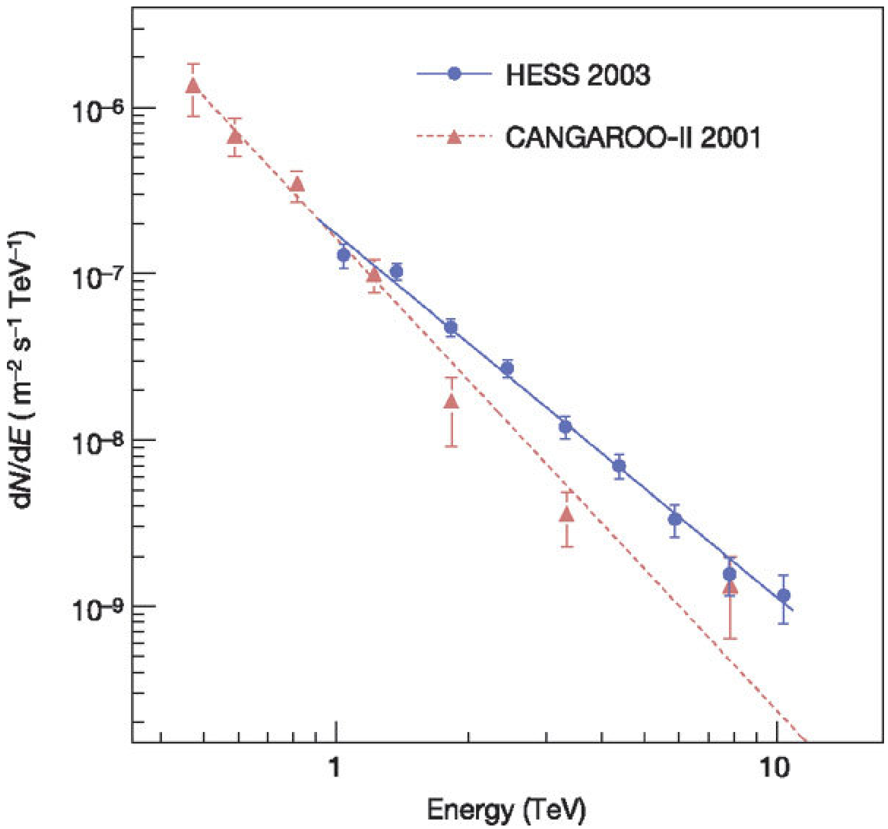
# First ever Gamma-Ray image of a SNR – HESS !!

Aharonian et al *Nature* 2004, 432, 75 - 77

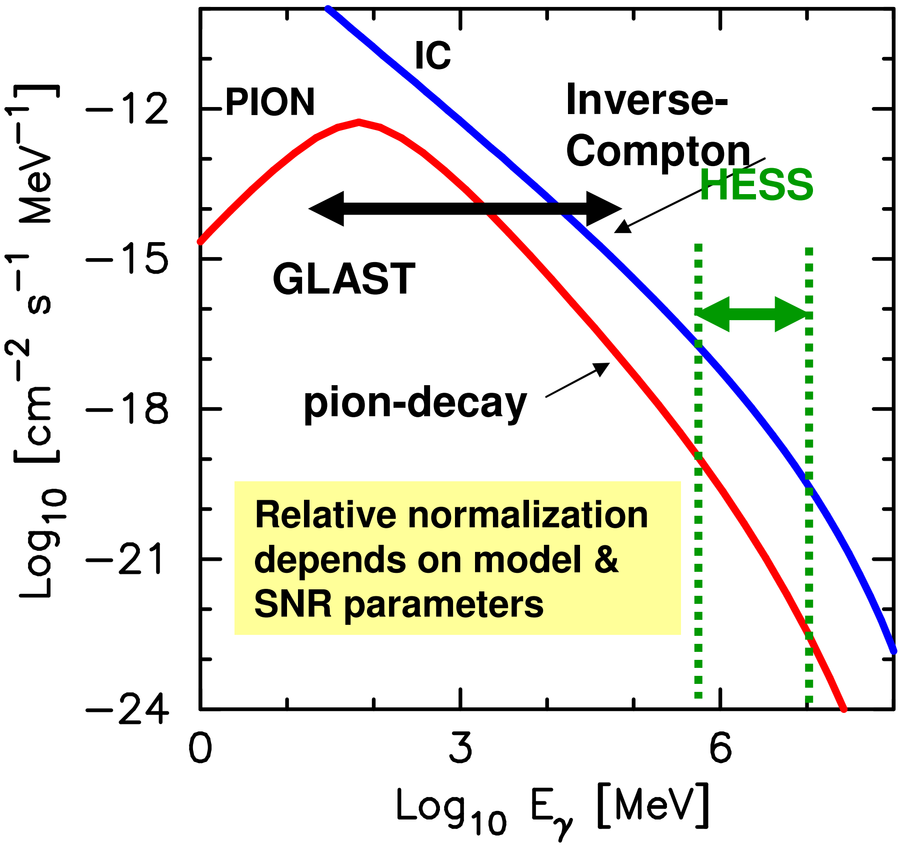



**Gamma**-ray image of the SNR RX J1713.7 (G347). Linear color scale is in units of counts.

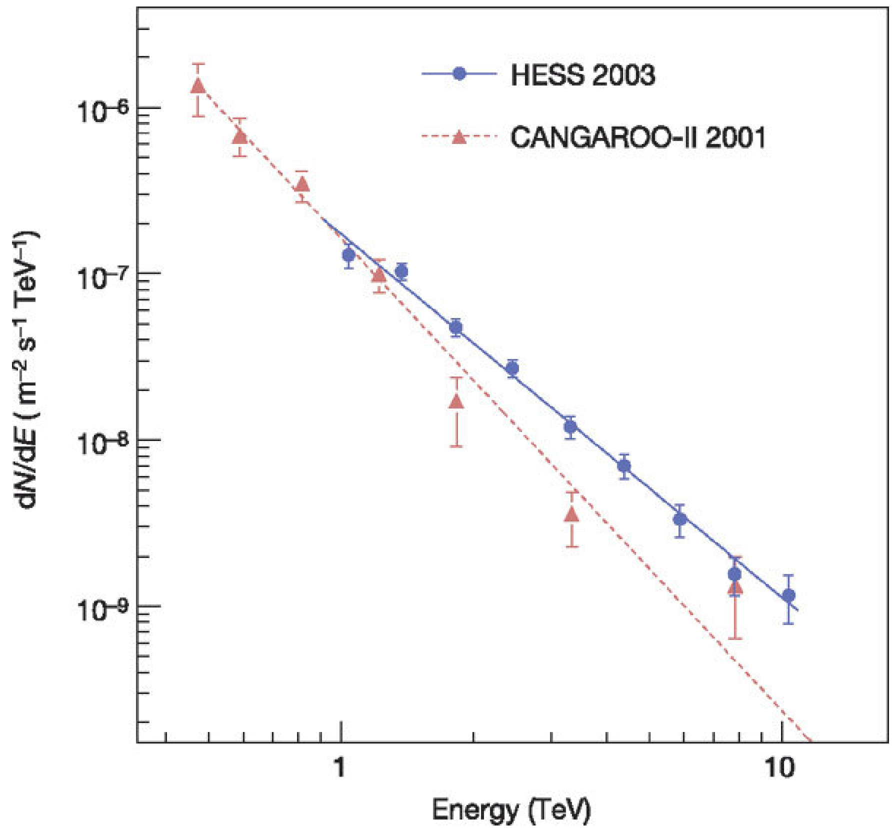
The superimposed (linearly spaced) black contour lines show the X-ray surface brightness as seen by ASCA in the 1–3 keV range.




Energy spectrum. There is no evidence for a cut-off in the data.




**Aharonian et al N*ature* 2004, 432, 75 - 77**




Energy spectrum. There is no evidence for a cut-off in the data.

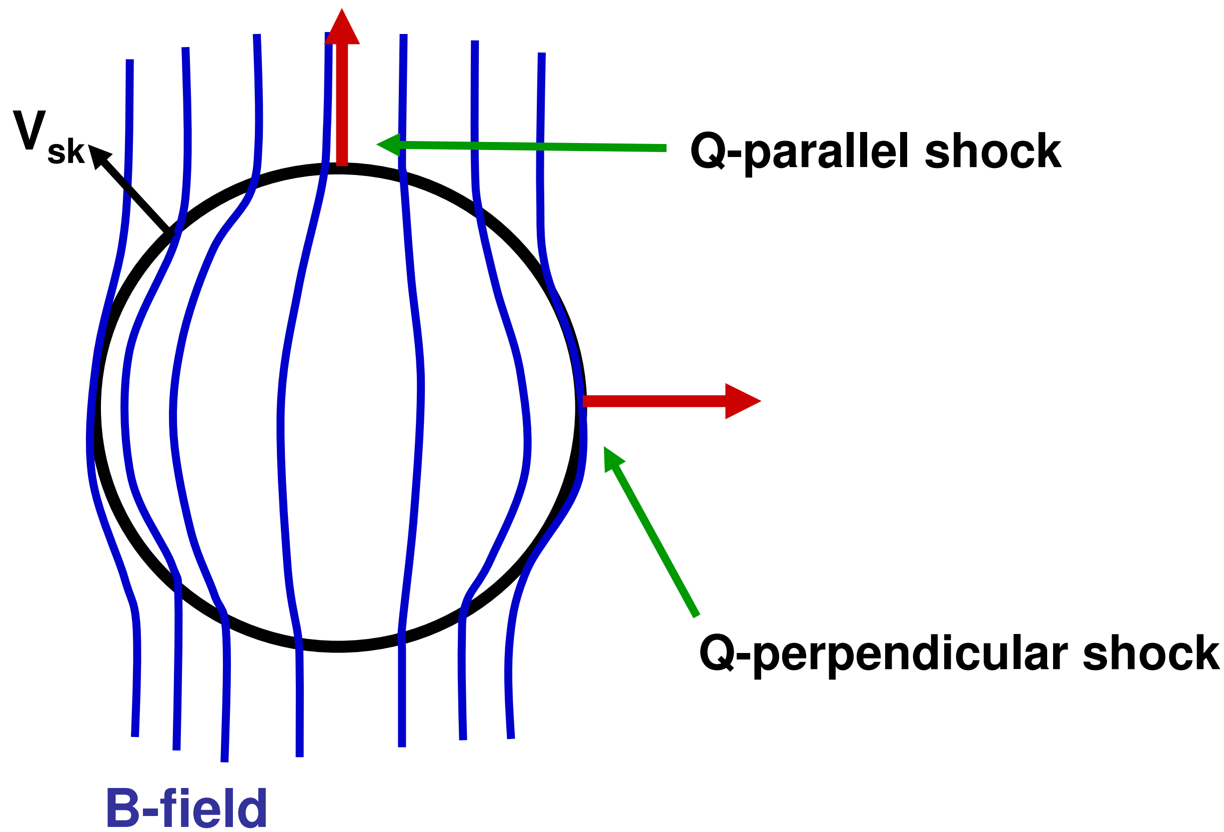
**Need extremely good statistics to differentiate by shape in limited TeV energy band. Good broad-band models are essential**

**GLAST should really help**

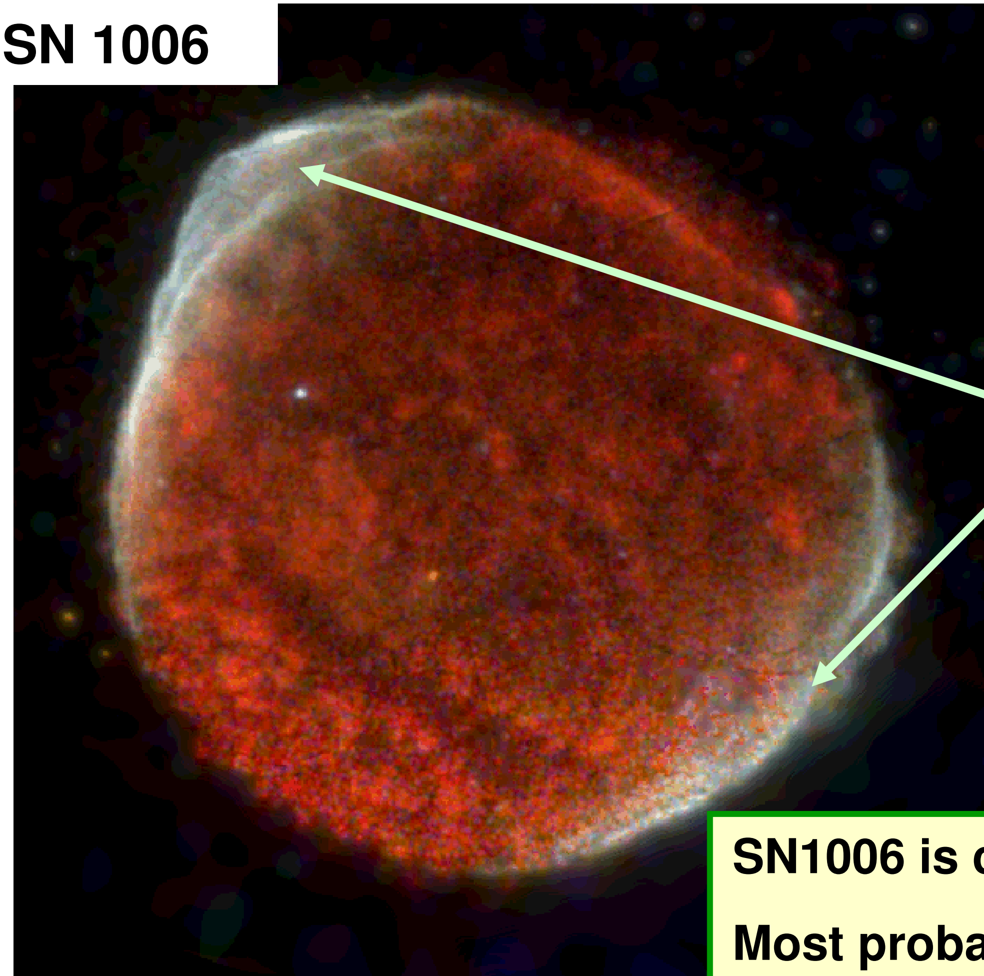
**Important question for shock acceleration concerns geometry of magnetic field.**

**Are quasi-parallel shocks more or less efficient accelerators than quasi-perpendicular ?**

**Remember the difference between high efficiency and high maximum energy**



SN 1006



Rothenflug et al. (2004)

## XMM X-ray obs. of SN 1006

Red (0.5 to 0.8 keV oxygen lines), Green (0.8 to 2 keV) Blue (2 to 4.5 keV).

White areas dominated by non-thermal emission

Bright limbs: Strong asymmetry in non-thermal emission

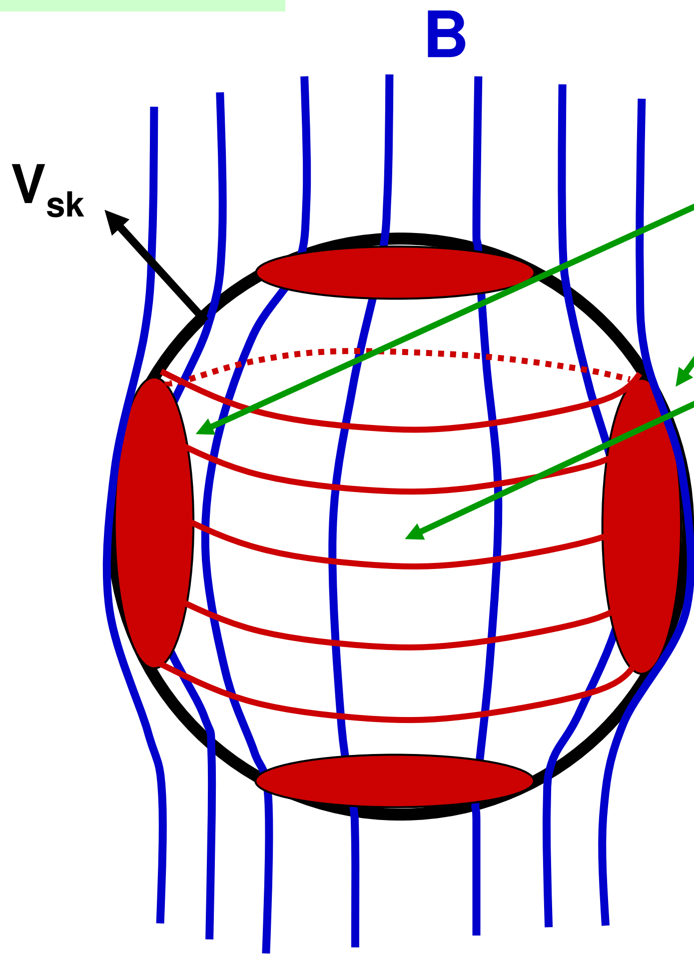
SN1006 is clear example of shell SNR.

Most probably Type Ia from white dwarf binary.

What does asymmetry in X-ray emission mean for geometry of acceleration process?

Two possibilities: Barrel geometry or polar caps

SN 1006




**Barrel Shape:** Bright limbs, Shock acceleration most efficient where magnetic field perpendicular to shock normal

BUT, predict emission in center from equatorial belt

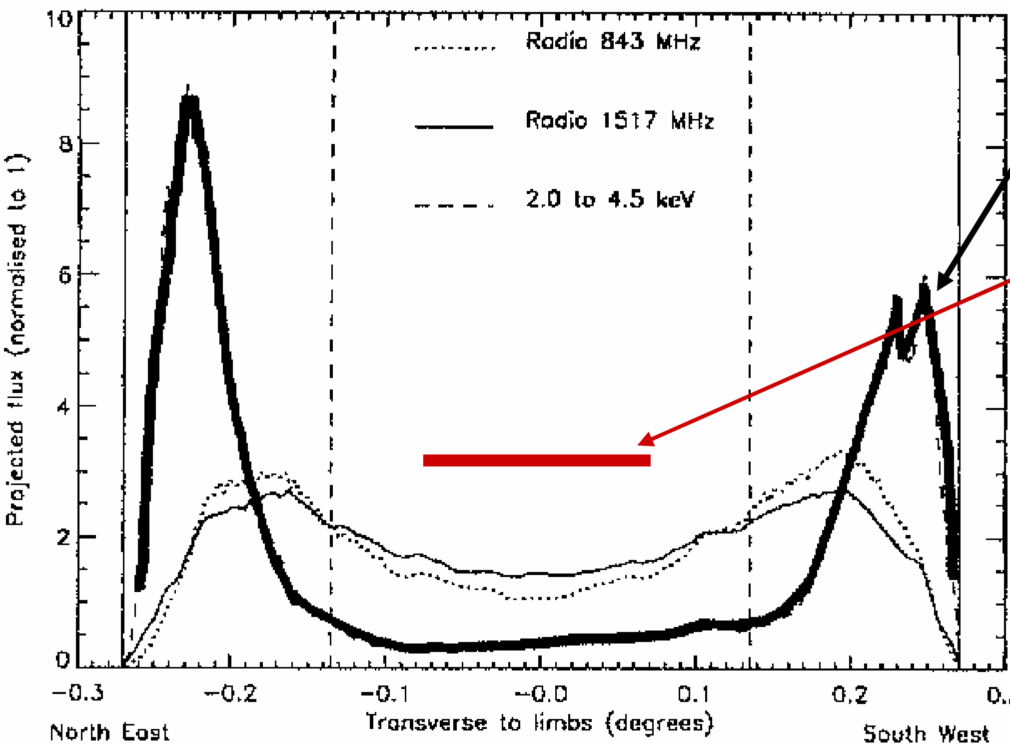
**Polar caps:** Shock acceleration most efficient where magnetic field parallel to shock normal.

Predict little or no emission in center

**Until Chandra and XMM, this was not measurable for nonthermal emission.**

Rothenflug et al. (2004)

Rothenflug et al. (2004)



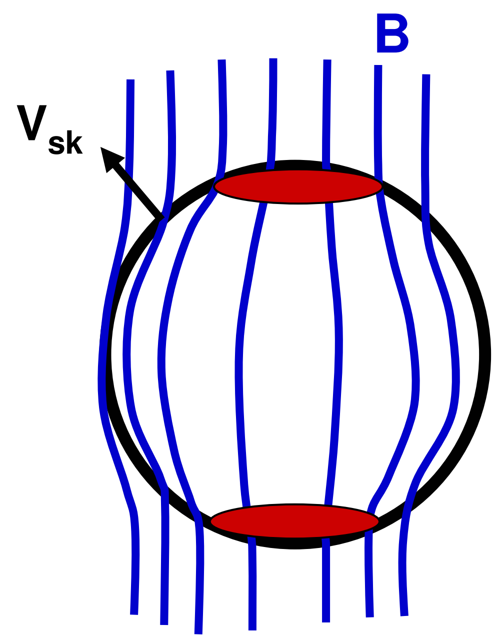

XMM observations of 2 to 4.5 keV X-rays (non-thermal)

Prediction if barrel shaped with equatorial belt

Limb

Center

Limb

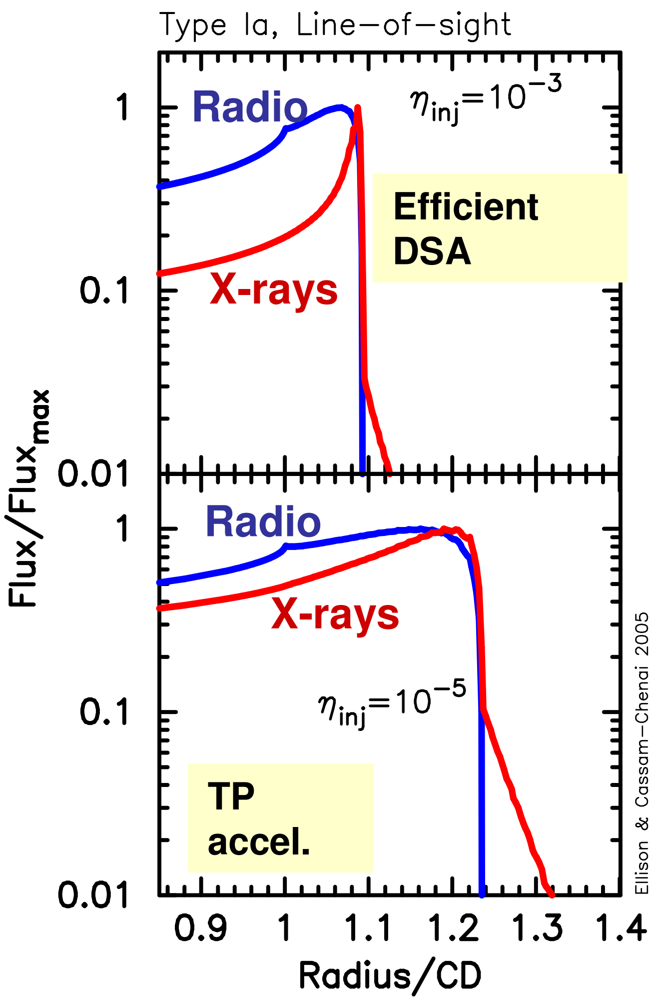



**Conclusion: Clear evidence for Polar Caps**

**For polar caps, ambient B-field lies along galactic plane !**

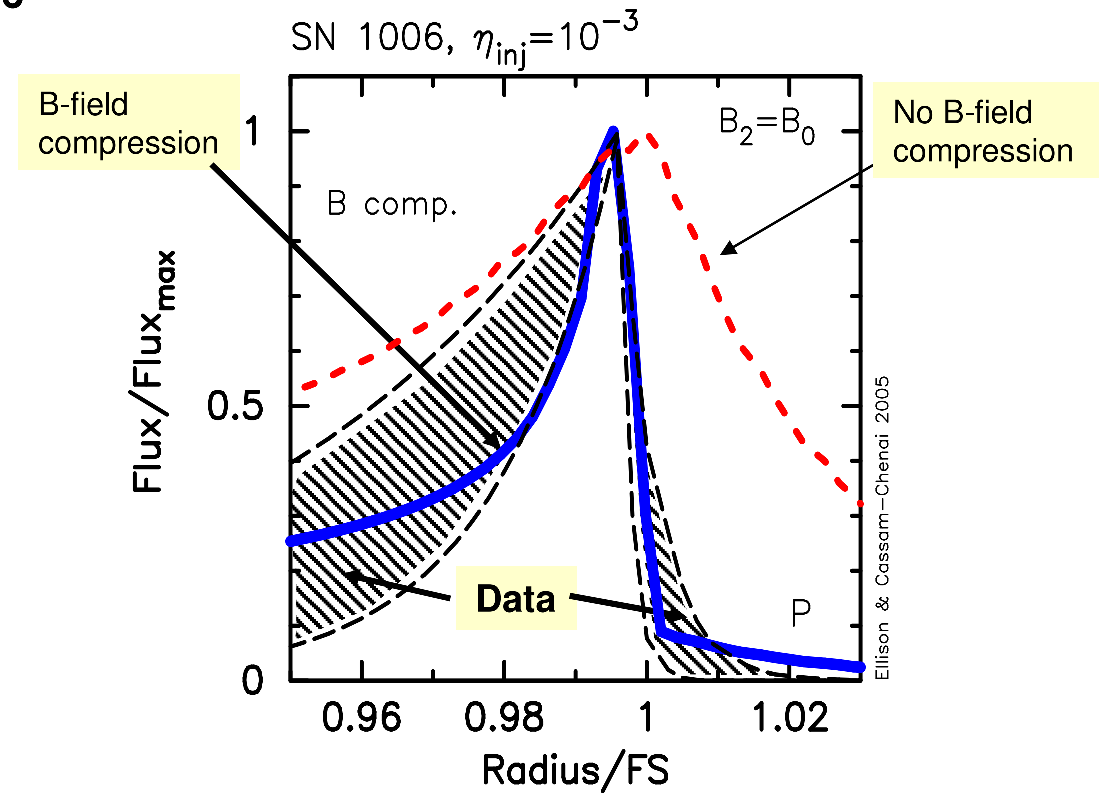
# More evidence of eff. Accel.

**Line-of-sight profiles for parameters typical of SN1006**




Ellison & Cassam-Chenai 2005

**Comparison with SN1006 data (Bamba etal 03)**




**Sharply peaked X-rays at forward shock strong evidence that shock is efficiently accelerating IONS**

**Conclusion reached earlier by Berezhko, Ksenofontov & Voelk 02**

# Magnetic Field Amplification

<u>Evidence is strong and mounting</u> that magnetic fields associated with shock acceleration in young supernova remnants are much larger than typical values assumed for ambient ISM, i.e.,

$B_{snr} >> 3 \times 10^{-6}$ G

Cas A is most extreme case so far (also youngest known SNR)

In fairly model independent estimates, find $B_{snr} > 500\ 10^{-6}$ G

This comes from fitting strong radio emission against lower limits on IC emission. Radio depends on B-field, IC does not.

See work of e.g., Berezhko, Voelk et al.; Vink & Laming; Bamba et al. for models and estimates for SN1006, Kepler, Tycho, and Cas A. Thin sheets of non-thermal emission also imply large B > 100 μG

Most likely non-linear shock acceleration is amplifying B-fields -- In fashion similar to what was suggested by Bell and Lucek (2001,2004)

CR streaming instabilities give $\Delta B/B >> 1$

Cas A can easily produce cosmic ray ions to $>10^{15}$ eV, i.e., the "knee"

# CONCLUSIONS

► Young SNRs with high Mach numbers should be efficient particle accelerators where non-linear effects are important. In fact, SNRs are our best chance to study high Mach number, high efficiency shock acceleration (e.g., Q-parallel vs Q-perp., e/p injection)

► Evidence that Non-linear effects (Low shocked temperatures, curved energetic particle spectra), are seen in (some) young SNRs

► Morphology (ejecta material close to outer blast wave shock; $r > 4$, ) suggests that ions are accelerated efficiently. (This does not say ions obtain high energies, that requires pion-decay obs.)

► No doubt that SNR shocks can accelerate electrons to TeV energies (synchrotron ➔ non-thermal X-rays)

► Detection of G347 by HESS ➔ 100 TeV particles. However, identification of these as protons rather than electrons is not so easy. Requires complicated picture with interaction of protons with nearby, dense molecular cloud. Broad-band models important here

► Large magnetic fields $B_{snr} >> B_{ism}$ now seen or inferred in several SNRs. CR knee can easily be reached by standard, parallel shocks in Cas A (300 years old; $B \sim 1$ mG) !!