Magnetic Field Amplification in Astrophysical Shocks

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1) **Convincing evidence for Large B-fields at outer shocks in supernova remnants: $B_{shock} >> B_{ISM}$**

2) **B-fields are important for particle acceleration and for our interpretation of observation: e.g., Maximum CR energy, synchrotron emission from relativistic electrons**

3) **Source of $B_{shock} >> B_{ISM}$? Most likely, B-field amplification is an intrinsic part of efficient shock acceleration, i.e. First-order Fermi**

4) **Simple basic idea: Strong cosmic ray (CR) pressure gradient in shock precursor drives production of magnetic turbulence, $\Delta B/B >> 1$**

5) **BUT, strongly nonlinear: ΔB influences efficiency of shock acceleration and plasma physics difficult when $\Delta B/B >> 1$**

Evidence for High magnetic fields in SNRs (all indirect):

→ **Broad-band fits: Ratio of radio to TeV emission (radio/TeV).**
Same distribution of electrons produces synchrotron (radio, X-ray) and TeV (inverse-Compton, IC) (Cowsik & Sarkar 80; Berezhko, Voelk & co-workers; Vink & Laming)

Synchrotron depends directly on B-field, IC and pion-decay do not

High (radio/TeV) implies high B → Extreme case: Cas A $B_{sk} > 500\ \mu G$

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→ **Sharp X-ray edges:** Sharp outer edges seen in several young SNRs (e.g., Kepler, Cas A, Tycho, SN1006) (Berezhko etal 02; Bamba et al 03; Vink & Laming 03; Ellison & Cassam-Chenai 05; Warren et al 05)

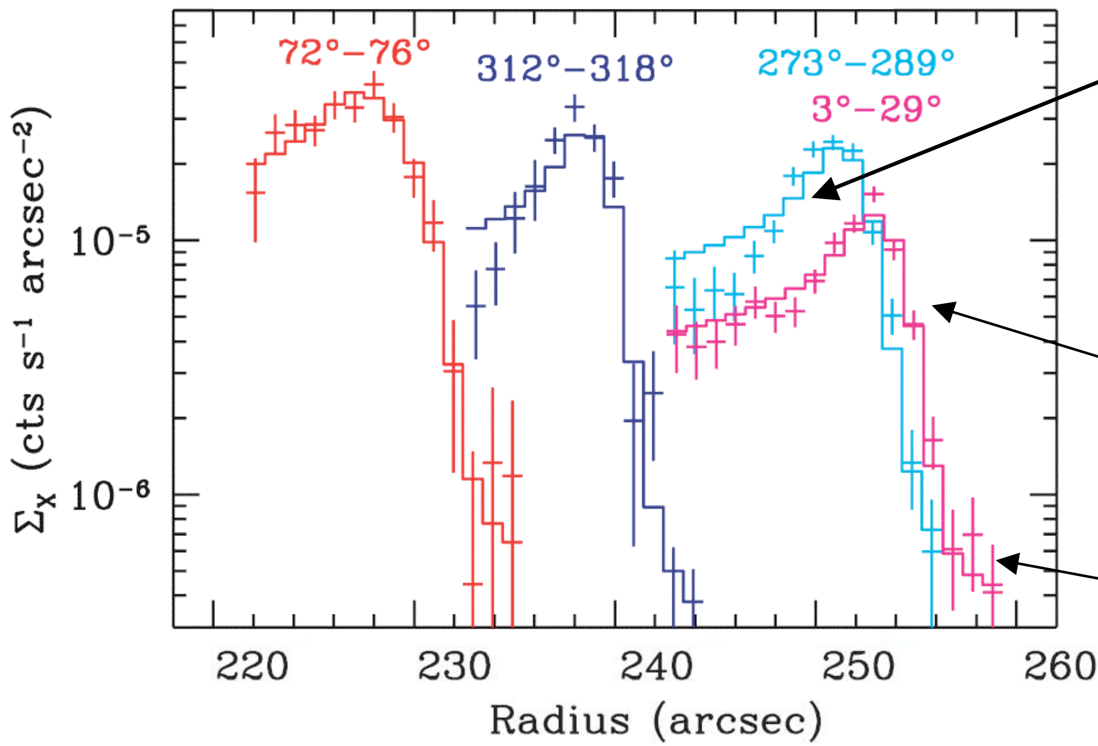
Non-thermal, X-ray synchrotron emission from TeV electrons

High B → large synch losses → short electron lifetime and short diffusion lengths → narrow X-ray structures. Imply B-fields ≥ $200\mu G$

Note: If simply compress B_{ISM}, expect $B_{sk} \sim 4 \times B_{ISM} \sim 10\text{-}40\ \mu G$

Sharp edges from various radial slices in Tycho's SNR:

Fig. 7 from Warren et al. 2005



Drop in brightness attributed to synchrotron losses in large B-field (note: poster by Cassam-Chenai shows RADIO emission doesn't fall off sharply)

line-of-sight projection effect, NOT precursor

Precursor in front of forward shock? (below Chandra sensitivity?)

Tycho's SNR, 4-6 keV surface brightness profiles at outer blast wave (non-thermal emission)

Additional constrains on magnetic field come from synchrotron emission in forward shock precursor → B must increase sharply at forward shock

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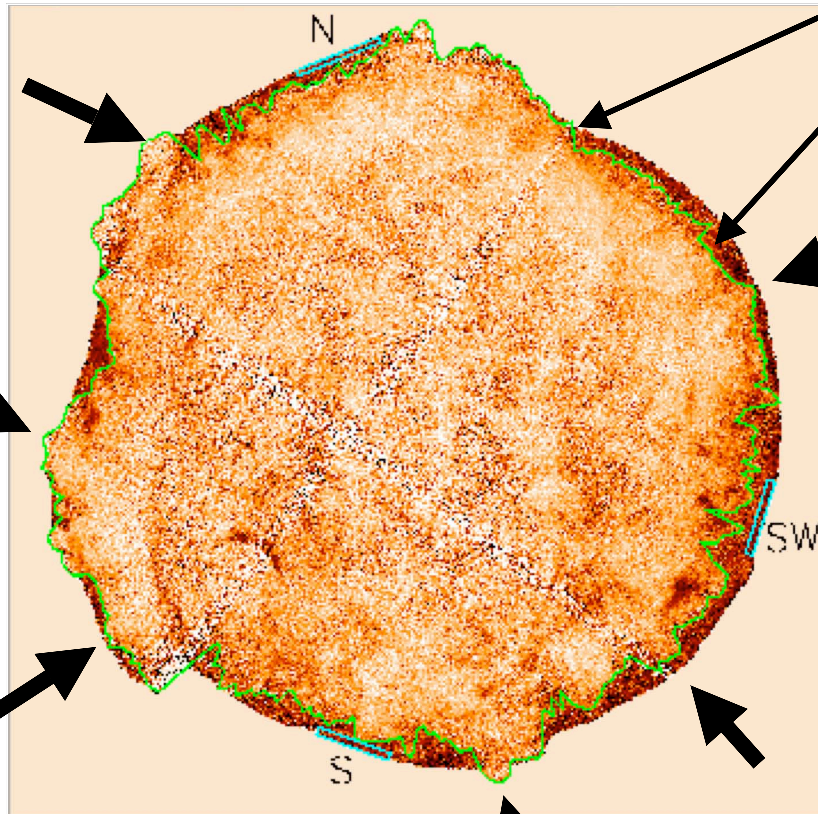
Also, evidence that diffusive shock acceleration is efficient and nonlinear at outer blast wave shocks in SNRs

Nonlinear effects from efficient acceleration allow shock compression ratios greater than 4

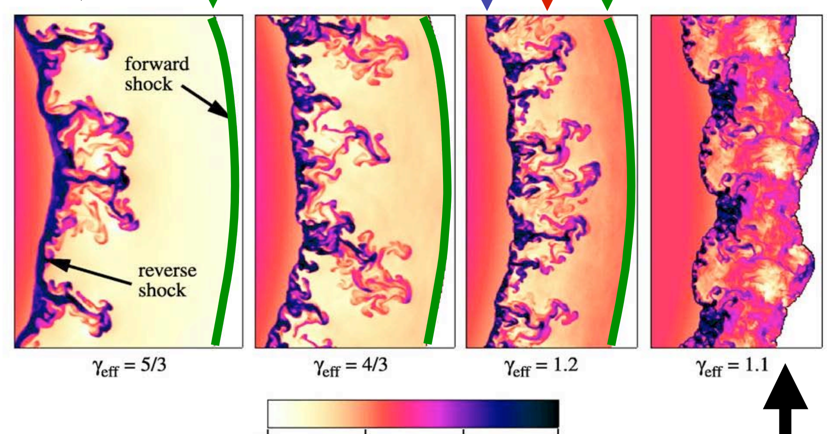
Chandra observations of Tycho's SNR
(Warren et al. 2005)



Green line is contact discontinuity (CD)

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

No acceleration



Efficient DSA acceleration

2-D Hydro simulation **Blondin & Ellison 2001**

Morphology: Strong evidence for Efficient production of cosmic ray ions at outer shock with compression ratio >> 4

Additional evidence exists for efficient shock acceleration & production of particles to ~10^{15} eV

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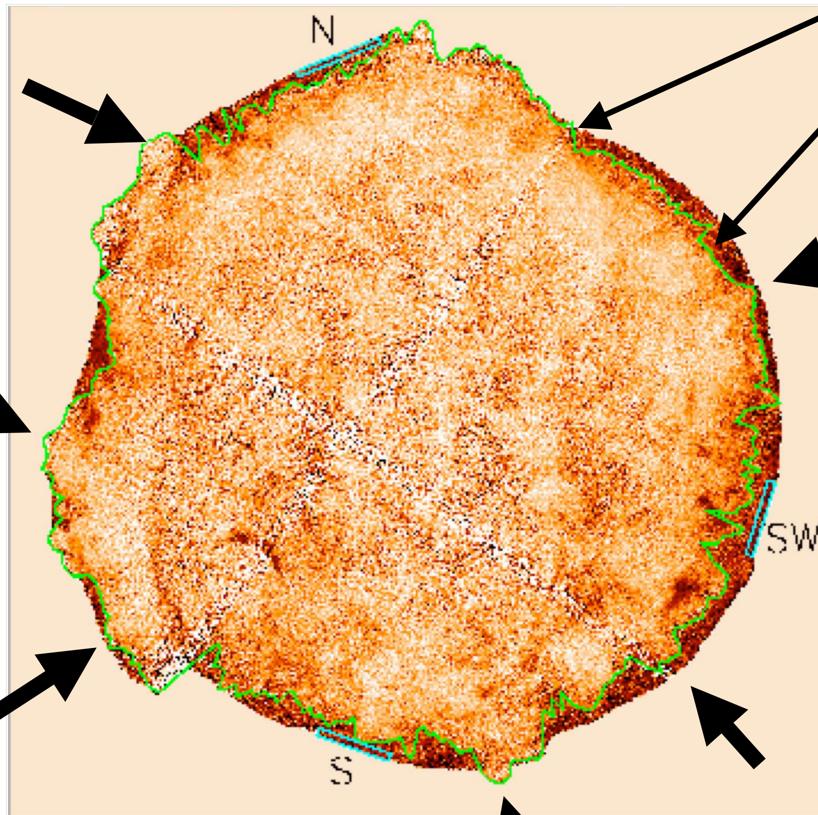

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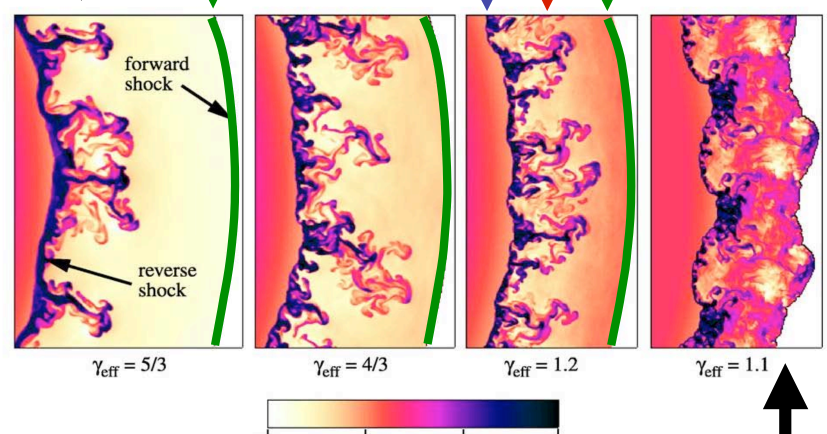
FS   RS CD FS



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How do you start with $B_{ISM} \sim 3\ \mu G$ and end up with $B \sim 500\ \mu G$ at the shock?

B-field Amplification:

Efficient diffusive shock acceleration (DSA) not only places a large fraction of shock energy into relativistic particles, but also amplifies magnetic field by large factors

Basic ideas:

1) **Large B-fields exist and shock acceleration produces them**
2) **Cosmic ray streaming instability must be responsible, but hard to model correctly → difficult plasma physics (e.g., non-resonant interactions etc)**
3) **Connected to efficient CR production, so nonlinear effects essential** ←
4) **Make approximations to estimate effect as well as possible**

Bell & Lucek 2001 → apply Q-lin theory when $\Delta B/B >> 1$

Amato & Blasi 2006; Blasi, Amato & Caprioli 2006; Vladimirov, Ellison & Bykov 2006 } **real calculations with nonlinear particle accel.**

See references for details

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Phenomenological approach:

Growth of magnetic turbulence driven by cosmic ray pressure gradient (so-called streaming instability) e.g., McKenzie & Voelk 1982

growth of magnetic turbulence energy density, $U(x,k)$, as a function of position, x, and wavevector, k

energetic particle pressure gradient as function of position, x, and momentum, p

$$\left[\frac{d}{dt}U(x,k)\right]_{\rm stream} = V_G \left[\frac{\partial P_p(x,p)}{\partial x}\frac{dp}{dk}\right]_{p=\bar{p}(k)}$$

$V_G(x,k)$ contains all of the complicated plasma physics that we don't understand

Make approximations for V_G and proceed

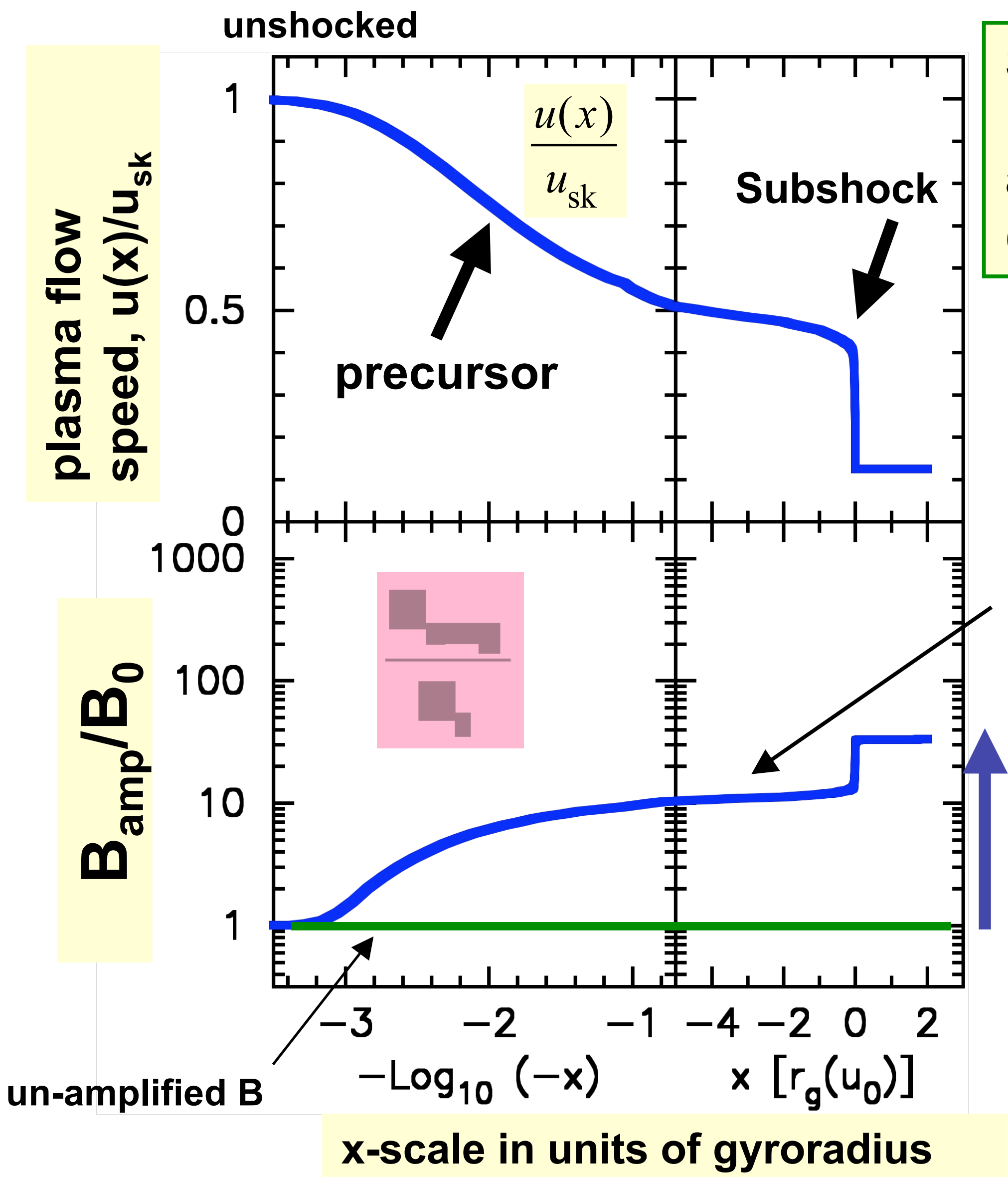
Determine diffusion coefficient, $D(x,p)$, from $U(x,k)$

In an iterative, Monte Carlo model of Nonlinear Diffusive Shock Acceleration (i.e., Vladimirov, Ellison & Bykov 2006)

We calculate - Self-consistently :

1) **The shock structure, modified by backpressure of accelerated particles**
2) **The amplified magnetic field structure**
3) **The injection of thermal particles into the acceleration mechanism**
4) **The increased compression ratio (r >> 4) that results from efficient particle acceleration**
5) **Maximum particle energy as a function of shock size (or age)**

Our results go beyond those of Bell & Lucek (2001) but are similar to those of Amato & Blasi (2006); Blasi, Amato & Caprioli (2006) who use a semi-analytic technique → much broader dynamic range



Shock structure smoothed by backpressure of accelerated particles, compression ratio, r >> 4

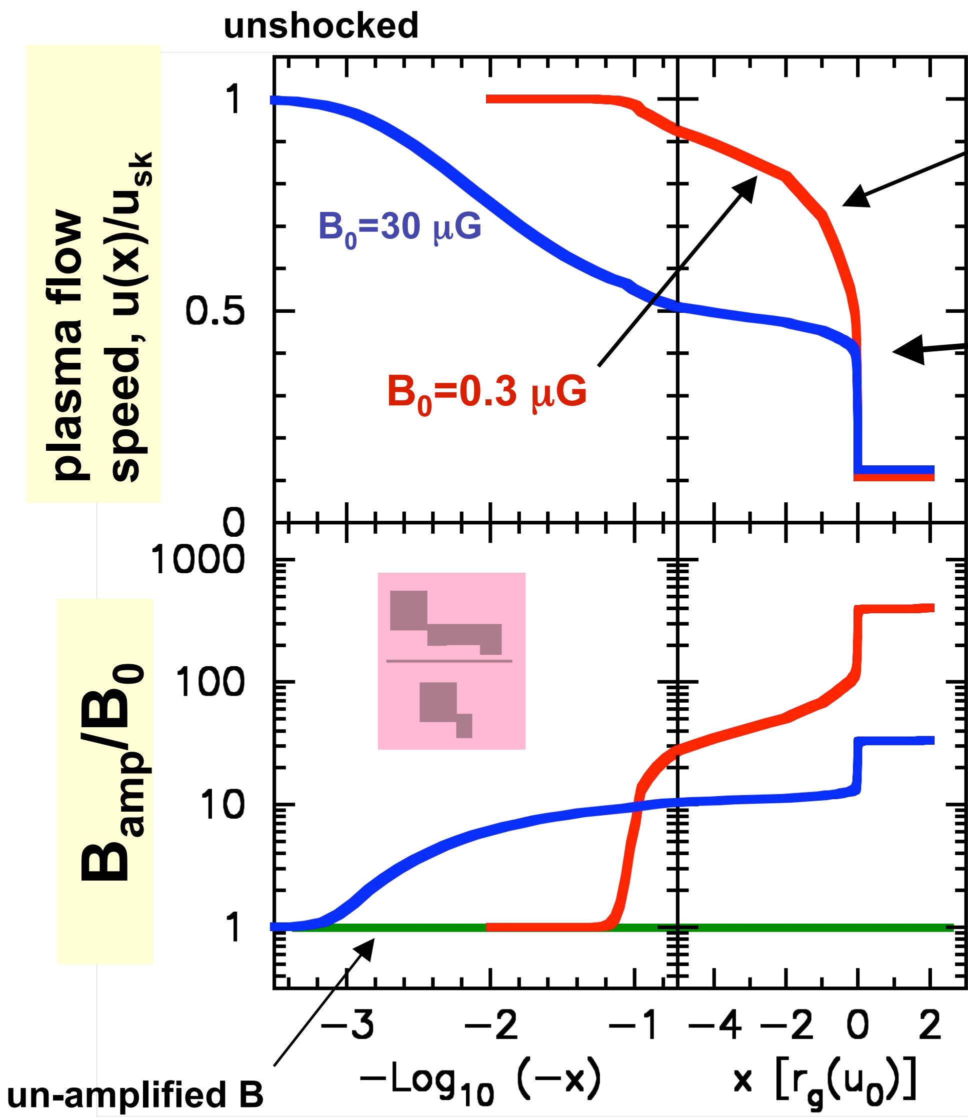
feedback

Magnetic field structure across shock

B_{amp} is 30 times far upstream field

(low Alfvén Mach # case, B_0=30 μG)

Vladimirov, Ellison & Bykov 2006



Keep physical size of shock the same, but reduce ambient B-field to B_0 = 0.3 μG

Subshock

x-scale in units of gyroradius

Now, magnetic field structure across shock is

400 times upstream field

(high Alfvén Mach # case, B_0=0.3 μG)

Weak fields are amplified more than strong fields

Magnetic field varies strongly across precursor

These two shocks have same physical size

Vladimirov, Ellison & Bykov 2006

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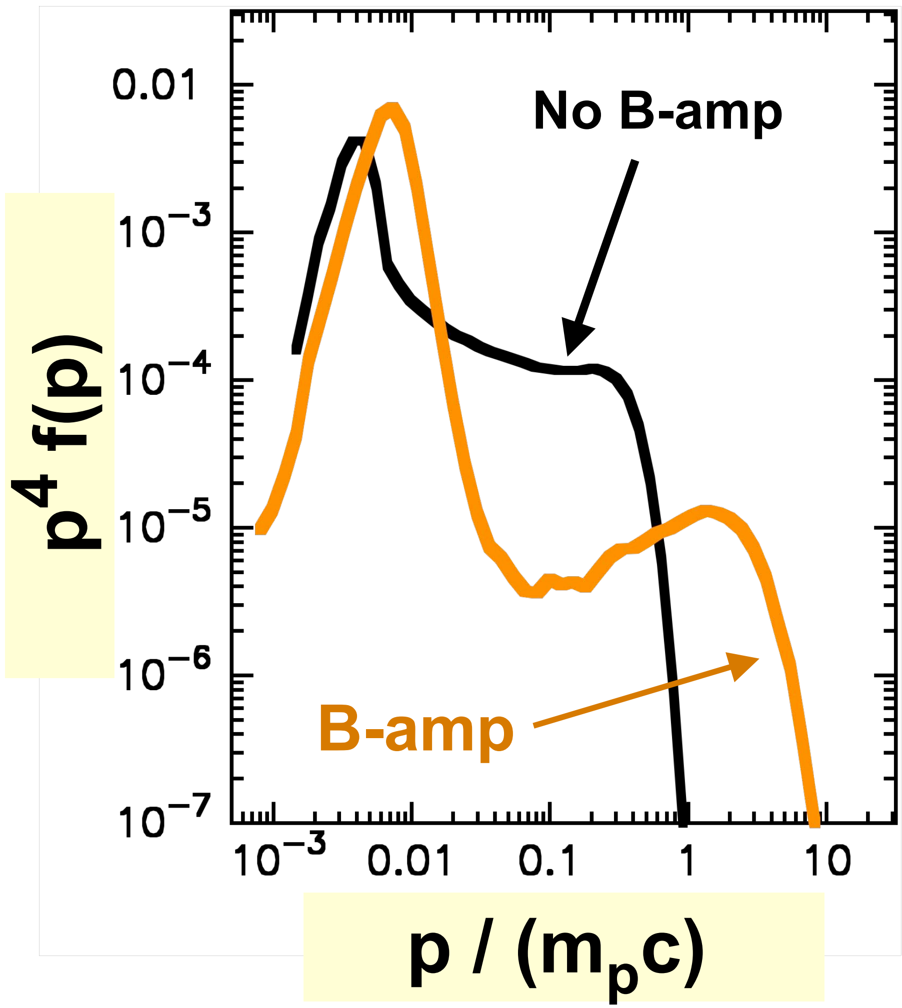
Particle distribution functions f(p) times p^4



Shocks with and without B-field amplification

The maximum CR energy a given shock can produce increases with B-amp

BUT

Increase is not as large as downstream B_{amp}/B_0 factor !!

Precursor structure of B-field is important for determining p_{max} and for synchrotron losses for electrons

All parameters are the same in these cases except one has B-amplification

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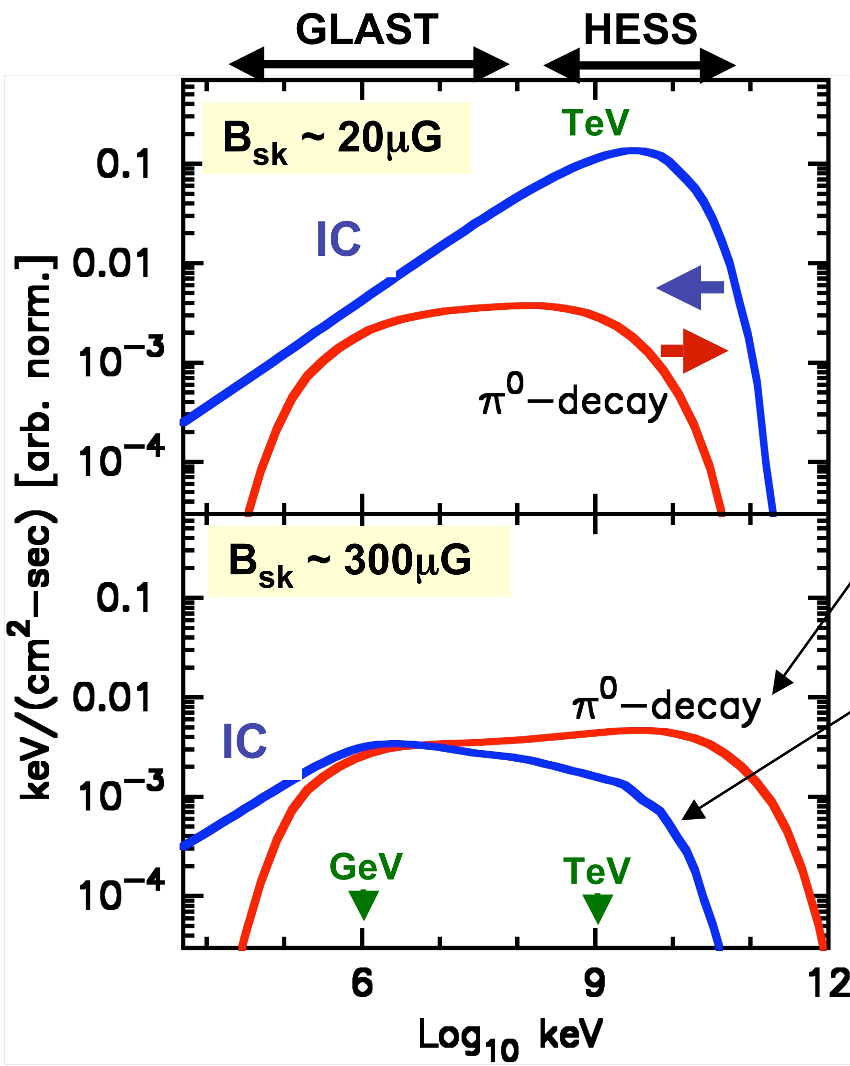
GeV-TeV Observations (IC/p-p) ratio :

Inverse-Compton (IC) and pion-decay emission from SNR with large shocked B-fields



Only difference in models is assumed B-field

Large magnetic fields :

Higher maximum energy for protons. Large B can extend pion-decay gamma-rays to beyond HESS detectable range

Lower maximum energy for electrons, due to severe synch losses

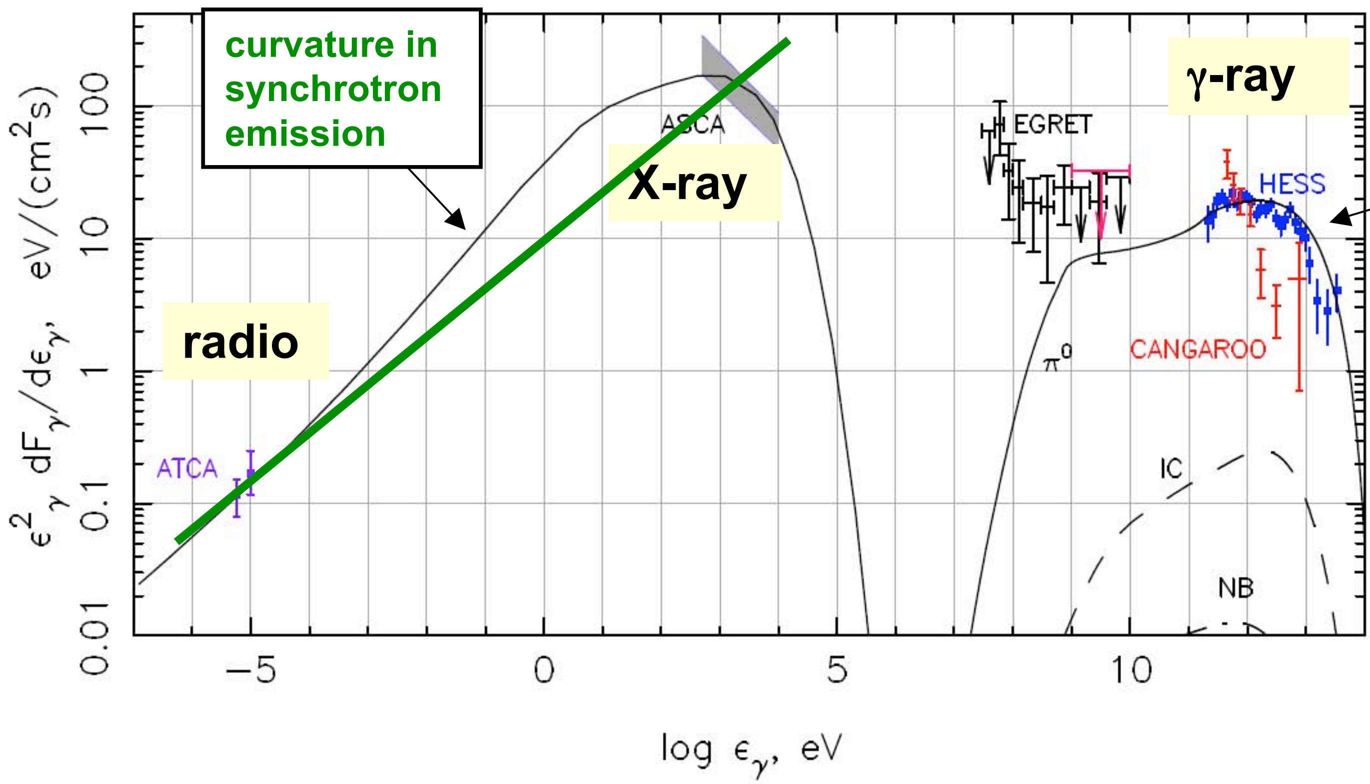
Shape of IC emission in GLAST range can be modified by strong losses in large magnetic fields in evolving SNR

Need broad-band fits

Example with preliminary results for one particular set of input parameters: adapted from Ellison, Patnaude, Slane, Blasi & Gabici et al. 2007 (Note: B-amp. NOT calculated in these models)

Broad-band continuum emission from SNRs

Berezhko & Voelk (2006) model of SNR J1713



HESS data fit with pion-decay from protons.

Assumes large B-field

Fig. 3. Spatially integrated spectral energy distribution of RX J1713.7-3946 . The ATCA radio data (cf. Aharonian et al. 2005), ASCA X-ray data (cf. Aharonian et al. 2005), EGRET spectrum of 3EG J1714-3857 (Reimer & Pohl 2002), CANGAROO data (Enomoto et al. 2002), in red color) and H.E.S.S. data (Aharonian et al. 2005), in blue color) are shown. The EGRET upper limit for the RX J1713.7-3946 position (Aharonian et al. 2005) is shown as well (red colour). The solid curve at energies above 10^7 eV corresponds to π^0-decay γ-ray emission, whereas the dashed and dash-dotted curves indicate the inverse Compton (IC) and Nonthermal Bremsstrahlung (NB) emissions, respectively.

So,

Magnetic field most important parameter in Diffusive Shock Acceleration (DSA)

a) **Controls injection, acceleration efficiency, and E_{max} through self-generated diffusion coefficient**

b) **B-field determines synchrotron emission for electrons**

Evidence in SNRs that magnetic fields can be amplified by large factors (x 100s) and that shock acceleration is nonlinear

B-field amplification ↔ efficient particle acceleration

If B amplified in SNR shocks, it will be amplified in lobes of radio jets, shocks in galaxy clusters, etc

ISSUES (not Conclusions):

- **How does B-amplification influence maximum particle energy, Emax?** **Not one-to-one relation**

- **What is shape of particle distribution near Emax? Depends on momentum dependence of self-consistent diffusion coefficient near Emax**

- **Emax, and shape near Emax, critical for X-ray synchrotron fits in 0.1-10 keV range, and for fits to GeV-TeV gamma-ray observations**

- **How does B-amp influence injection of electrons vs. protons?**

- **Structure of B-field in shock precursor: Influences electrons and protons differently.** (**Maximum proton energy set by weak B far upstream. Maximum electron energy set by synch losses in strong downstream B**)
  → critical for distinction between IC and pion-decay at GeV-TeV energies

- **Heating of shock precursor by dissipation of magnetic turbulence?**

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