The Magnetic Bootstrap

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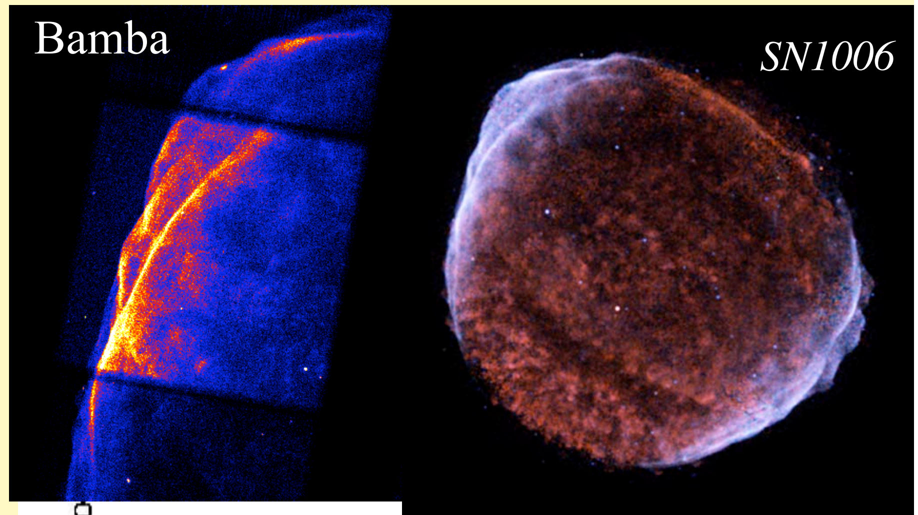
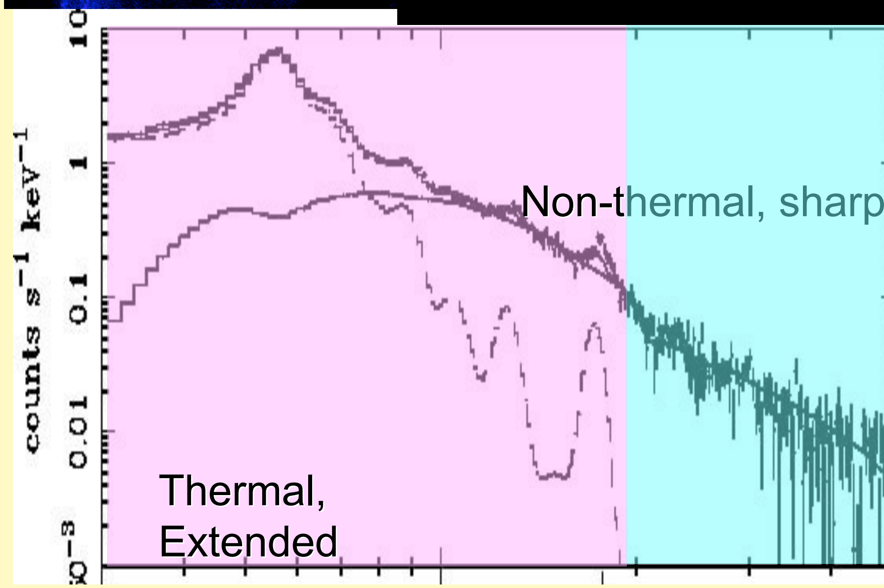
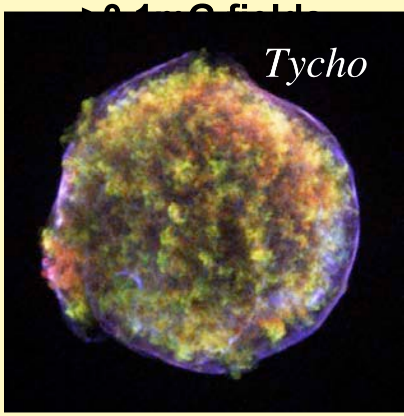
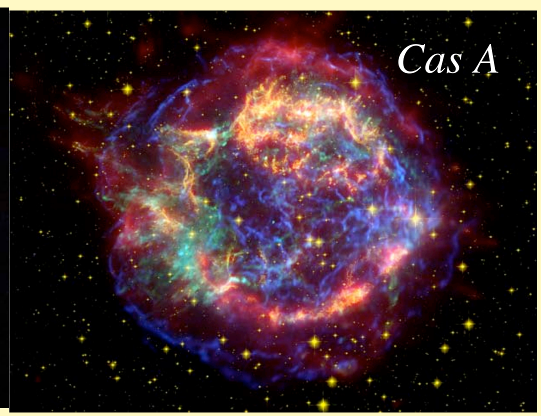
Nonthermal electron acceleration

- **Diffusive Shock Acceleration**
  - Transmit CR protons with $P_{CR} \sim E^2 N(E) \sim E^{-.2}$ $\sim 0.1 \rho u^2$
  - $P_e \sim 0.03\ P_p$
  - Accounts for GCR after including propagation
  - Observed in IPM
  - Generic - eg clusters of galaxies
- **Radio observations of SNR**
  - Relativistic electron spectrum
  - Tycho, Cas A….
- **X-ray observations of SNR**
  - 2-100 keV
  - 100TeV electrons





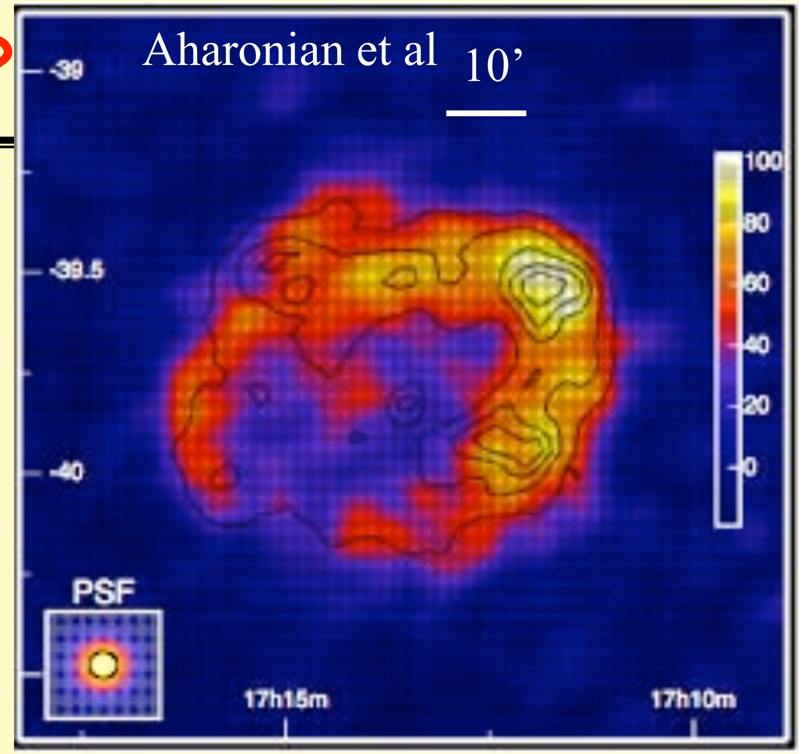


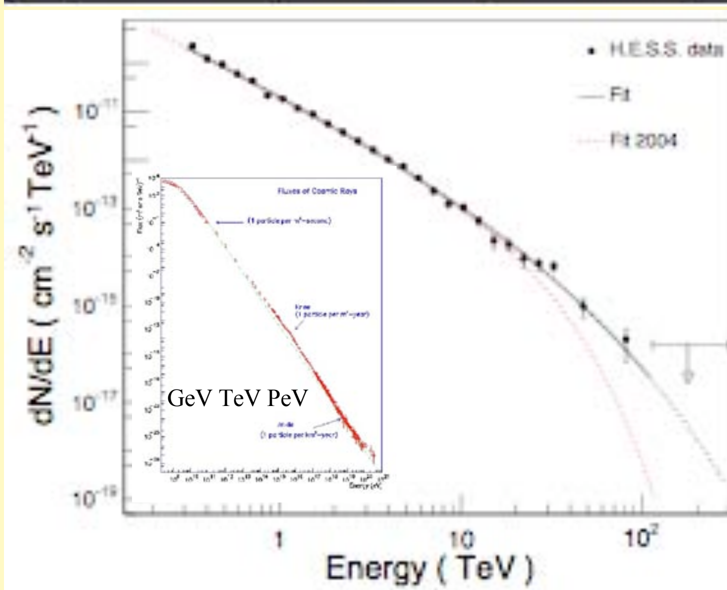


Nonthermal Proton Acceleration?

- **RX J1713.7-3946**
  - AD385, R ~ 10pc, u~3000 km s-1
  - $\rho \sim 10^{-25}$ g cm^{-3} ; $P_- \sim 10^{-12}$ dyne cm^{-2};
  - $P_+ \sim 10^{-8}$ dyne cm^{-2}; M ~ 150
- **~0.1 PeV γ-rays**
  - Inverse Compton by electrons?
  - Pion decay from protons?
  - Accelerate ~0.3 PeV protons?
  - Explain knee in GCR spectrum
- **L_x/L_γ ~ 3 => hadronic emission?**
  - $=> P_+(100\text{TeV}) \sim 10^{-10}$ dyne cm^{-2}
  - $=> P_+(\text{GeV}) \sim 10^{-9}$ dyne cm^{-2} ~0 1 P_+
  - $P_+(e) \sim 3 \times 10^{-11}$ dyne cm^{-2}
- **Particle transport**
  - $r_L \sim 4 \times 10^{12} E_{GeV} B_{\mu G}^{-1} Z^{-1}$cm
  - <u R/c

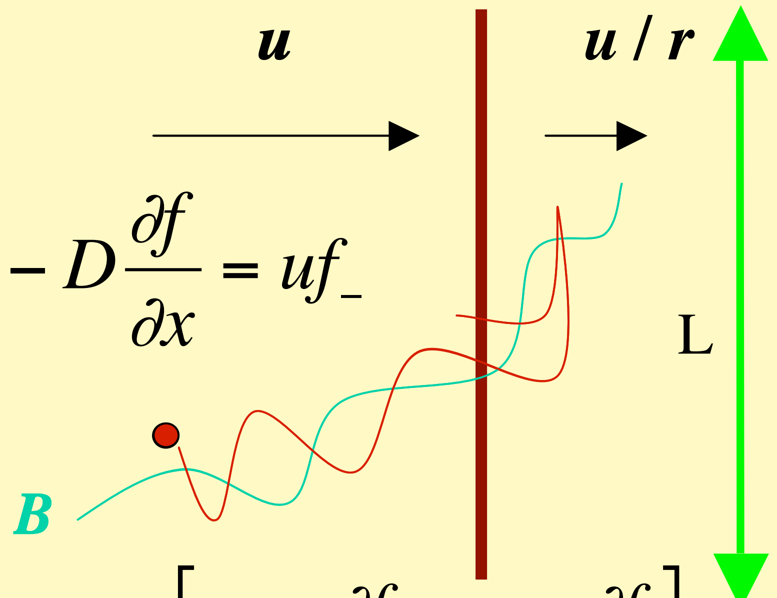
PeV CR => mG field





Diffusive Shock Acceleration

- **Non-relativistic shock front**
  - **Protons scattered by magnetic inhomogeneities on either side of a velocity discontinuity**
  - **Describe using distribution function f(p,x)**



$$f = f_-$$

$$uf - D\frac{\partial f}{\partial x} = uf_-$$

$$f = f_+$$

$$[f] = \left[-u\frac{\partial f}{\partial \ln p^3} - D\frac{\partial f}{\partial x}\right] = 0$$

Transmitted Distribution Function

$$f = f_- + (f_+ - f_-)\exp[\int_0^x dx' u/D]; x < 0$$

$$f = f_+; x > 0$$

$$f_+(p) = qp^{-q}\int_0^p dp' p'^{q-1} f_-(p'); q = 3r/(r-1)$$

=>N(E)~E^{-2} for strong shock with r=4
Consistent with Galactic cosmic ray spectrum allowing for energy-dependent propagation

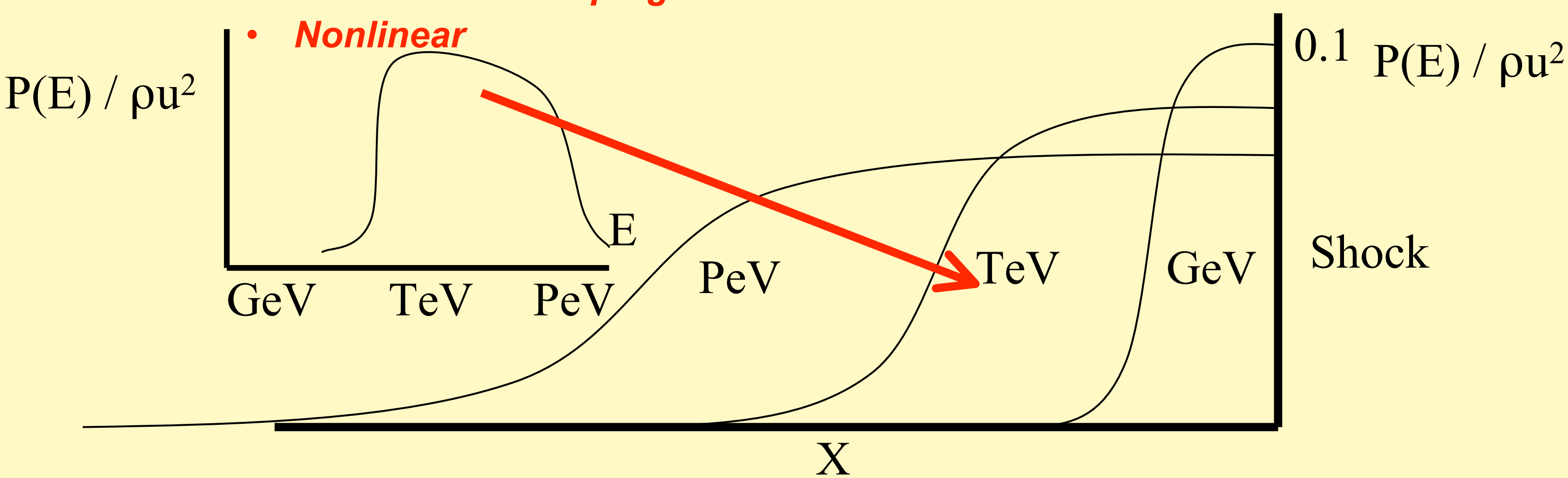
Too good to be true!

- Diffusion: CR create their own magnetic irregularities ahead of shock through instability if <v>>a
  - Instability likely to become nonlinear - Bohm limit
  - What happens in practice?
  - Parallel vs perpendicular diffusion?
- Cosmic rays are not test particles
  - Include in Rankine-Hugoniot conditions
  - u=u(x)
  - Include magnetic stress too?
- Acceleration controlled by injection
  - Cosmic rays are part of the shock
- What happens when v ~ u?
  - Relativistic shocks
- How do you accelerate ~PeV cosmic rays?
  - E < euBR ~ TeV for μG magnetic field

Particle Transport

- **Alfven waves scatter cosmic rays**
  - $\lambda \sim (B/\delta B)^2 r_L$
    - *Bohm?*
  - $D \sim c\lambda/3$
    - *Parallel vs perpendicular*
  - $L \sim D/u > 100 r_L \sim 100\ E_{PeV} B_{\mu G}^{-1} Z^{-1}$ pc
    - *$R_{SNR} < 10$pc*
  - Highest energy cosmic rays stream furthest ahead of shock
    - *L ~ E ?*
  - Wave Turbulence spectrum
    - *3, 4 Wave processes.*
    - *Transit time damping?*
    - *Nonlinear*

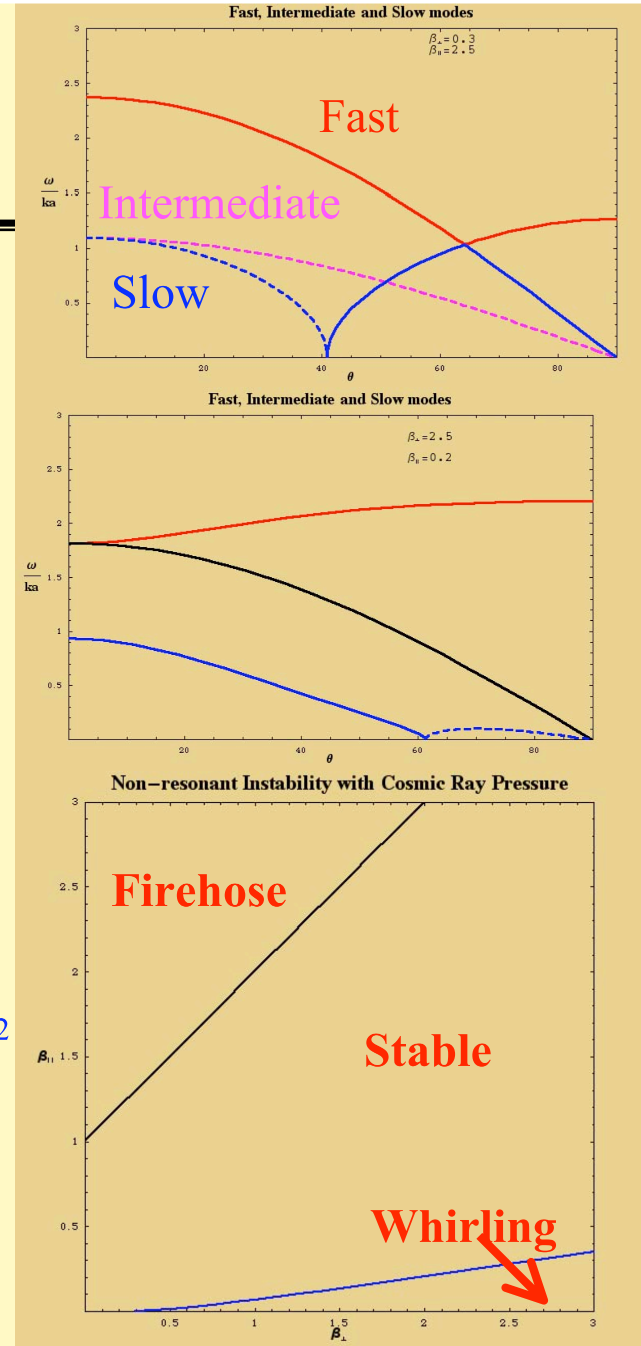
Cosmic Ray Pressure dominates
Magnetic and Gas Pressure
far ahead of Shock



Wave Growth

- **Short Wavelength Instabilites**
  - Weibel
  - Bell-Lucek
- **Streaming instability**
  - Kinetic treatment $P_1(\mu)$
  - $\langle V \rangle > a$
  - Resonant; $\lambda \sim r_L$
  - $\sigma \sim P_{res}\, u / \rho\, c\, a\, r_L$
  - Creates scattering waves at low energy
  - Ineffective at high energy
- **Firehose instability**
  - Fluid treatment $P_2(\mu)$
  - Parallel pressure dominant
  - $P_z > P_x + B^2$
  - Non-resonant; $\lambda > r_L$
  - $\sigma_{max} \sim [(P_z - P_x)/\rho]^{1/2} / r_L$
- **Whirling (mirror) instability**
  - Perpendicular pressure dominant
  - $P_x > 6\, P_z,\, B^2$
  - Non-resonant; $\lambda > r_L$
  - $\sigma_{max} \sim a / r_L$
  - Slower than Firehose

$$P_{x,z} \propto \rho^{\gamma_{x,z}} B^{\delta_{x,z}}$$



Magnetic Bootstrap

- Assume:
  - Cosmic rays accelerated by DSA at shock front to ~PeV energy
  - $P_{CR} \sim 0.1\rho u^2 E_9^{-0.2}$
  - Magnetic field amplified upstream
- Ignore dynamical effect of cosmic rays on flow speed.
  - Small correction
- Wave turbulence maintained at Bohm level by resonant streaming instability at wavelengths for which particles are present if
  - $P_{CR} > 0.1 \rho u a$
  - Marginally satisfied
  - "Uniform" field is turbulent field created by higher energy particles streaming ahead of the shock with larger Larmor radii and longer wavelengths
- Maximum cosmic ray energy (~PeV) determined by equating diffusion length to shock radius
  - $E_{max} \sim \rho_{-25}^{1/2} u_8^2 R_{19}$ PeV
- Cosmic rays with energy ~ E_{max} stream away from the shock in its frame with $P_{1,2}(\mu)$ anisotropy
  - Magnetic field grows if $\sigma > u / R$
  - Firehose dominates if $u > (a_{ISM}\, c)^{1/2} (P_{CR}/\rho u^2)^{-1/4}$ ~1000 km s^{-1}

Summary

- Good evidence that supernova (and other) shock fronts generate magnetic field as well as accelerate cosmic rays
  - Accelerate to > 0.3 PeV
  - =>B> 0.3 mG
- Diffusive Shock Acceleration
  - ~PeV cosmic rays first
    - *Pressure >> ambient magnetic pressure*
  - Linearly unstable distribution function?
    - *Resonant streaming Instability*
    - *Non-resonant firehose Instability*
    - *Non-resonant whirling (mirror) Instability*
- Nonlinear magnetic field growth?
  - Precursor field convected downstream
  - Uniform for successively lower energy particles
- GLAST prospects
  - Observe Cas A, Tycho, Kepler…;
  - Detect pion feature ~ 0.1 - 1GeV
  - Quantitative check/calibration of theory
- Modify magnetosonic theory for collisionless plasma
  - Wave speeds, shocks, magnetosonic turbulence

Summary

Numerical Simulations
GLAST