Cosmic Rays and Magnetic Fields

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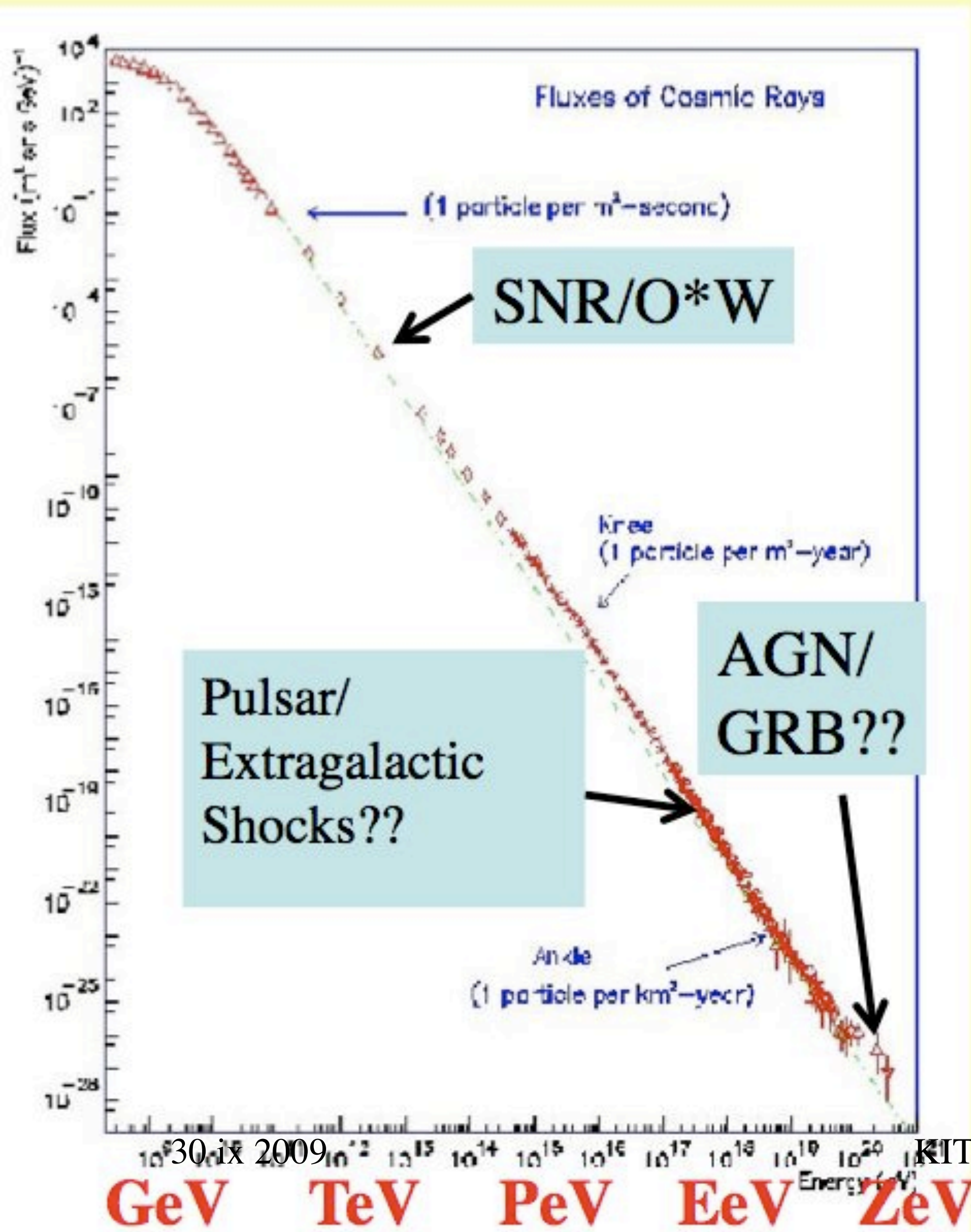
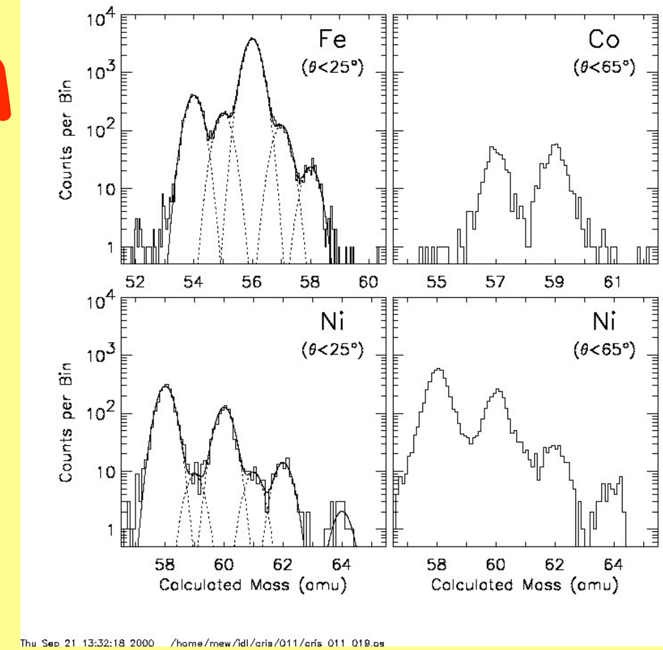
Cosmic Ray Spectrum

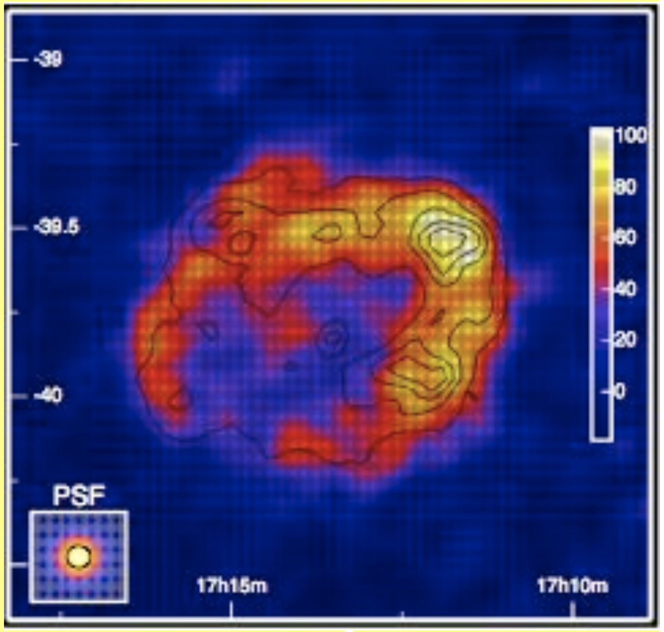


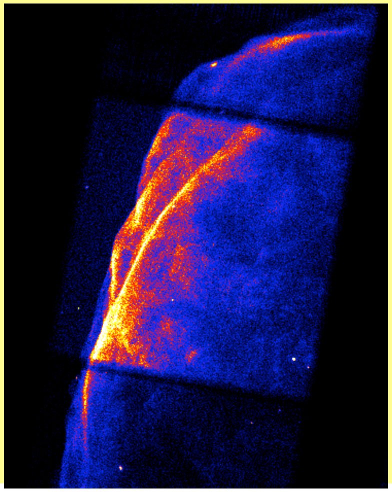


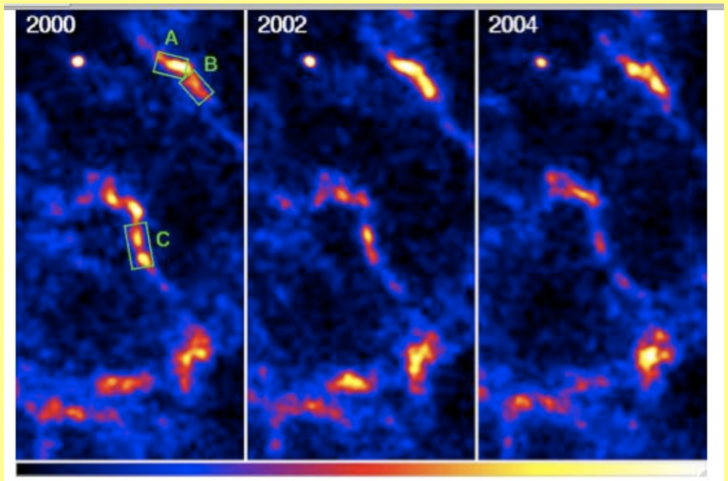
- $N \sim E^{-2.6}$ below "knee"
- $U_{CR} \sim U_{GeV} \sim U_{ISM} \sim U_{CMB} \sim U_{star}$
- 0.1 Myr < t < 15 Myr
- L/M $\lambda \sim 5\ E_9^{-.3}$ g cm^{-2}
- => $S \sim E^{-2.3}$
- $L_{CR} \sim U_{CR}\ M_{gas}\ c\ \lambda^{-1}$
  $\sim 3\times10^{33}$W $\sim 0.03 L_{SNR} \sim 10^{-3} L_{gal}$

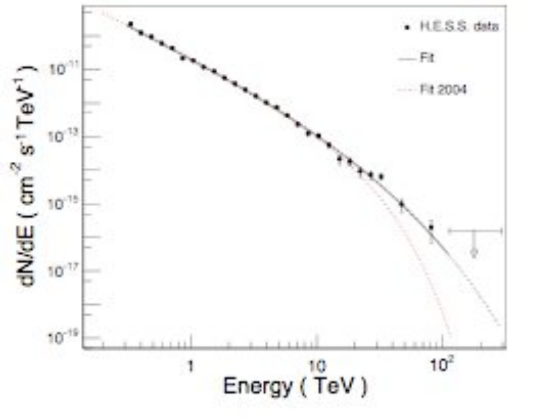
X-γ Observations

- E_γ ~ 100TeV
  - =>E_{CR} ~0.3 PeV
  - Hadronic vs leptonic?
    - Fermi?
- Variable X-rays
  - E_e ~ 100 TeV
  - B~100 μG
- => Shocks also amplify field
  - Details controversial









Acceleration

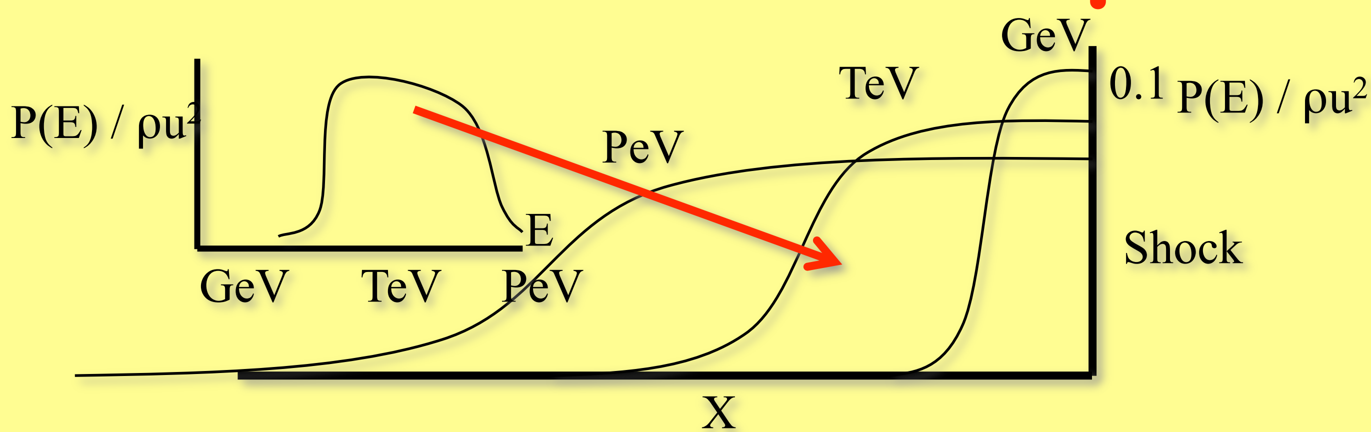
$$f = f_- + (f_+ - f_-)\exp[\int_0^x dx' u/D]; x < 0$$

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

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

=>N(E)~E$^{-2.2}$ for strong shock with r~3.5
Consistent with Galactic cosmic ray spectrum allowing for energy-dependent propagation

Diffusion and Escape



Magnetic Bootstrap

The can of worms (AV)

- Create turbulence at long wavelengths
  - $\lambda > r_L(E) \sim 3 \times 10^{16} E_{15}$cm
- Conjectured to saturate at large value
- "Background" field for lower energy particles that encounter it later
  - Quasi-linear theory of wave modes?
    - More bootstraps?
  - Inertial range? (Goldreich-Sridhar etc)
  - Limit cycle, intermittency, convective motion?
- What is the nature of the transport?
  - Reconcile with X-ray observations of SN1006?

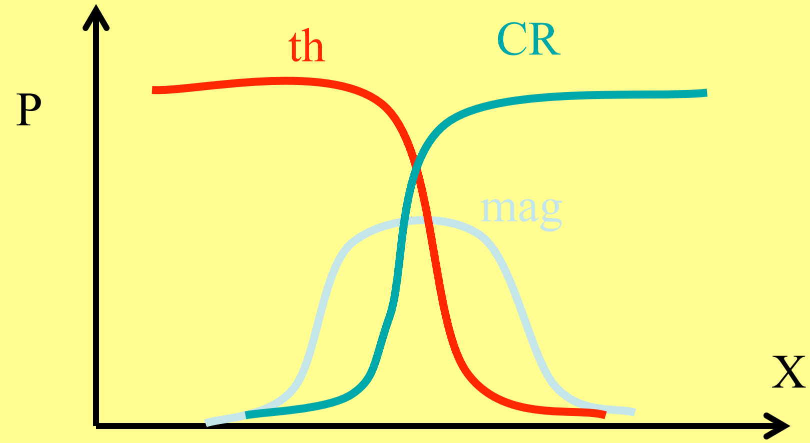
Magnetic Bootlaces

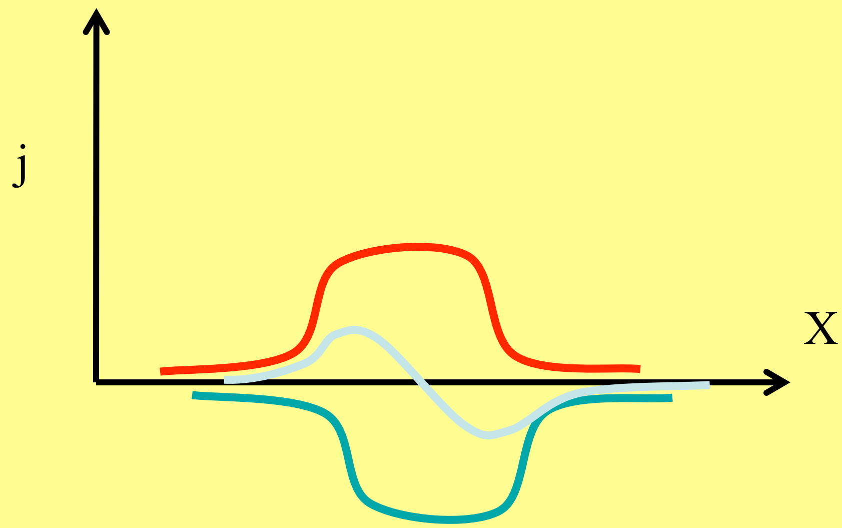
- How can a small magnetic pressure mediate the interaction between two particle "fluids"?

$$\nabla P_P = j_P B$$

$$\nabla P_{CR} = j_{CR} B$$

$$\frac{dB}{dX} = j_P + j_{CR}$$





Describing Cosmic Plasma

- **Fluid description**
  - P, ρ, **v, B…**
  - **Magneto Fluid Dynamics**
    - Flux-freezing, conservation of mass, momentum, energy
    - $P \sim \rho^{\gamma}$ – isotropic!
  - **Long wavelengths**
  - **Including cosmic rays is subtle**
- **Kinetic description**
  - **f(p,x,**t**), E, B…**
  - **Collisionless plasmas**
    - Vlasov equation for f
  - **Nonthermal distributions**
  - **Transport effects**
  - **Cosmic rays treated more confidently**

Need a hybrid approach to tackle global problem

Double Adiabatic Theory

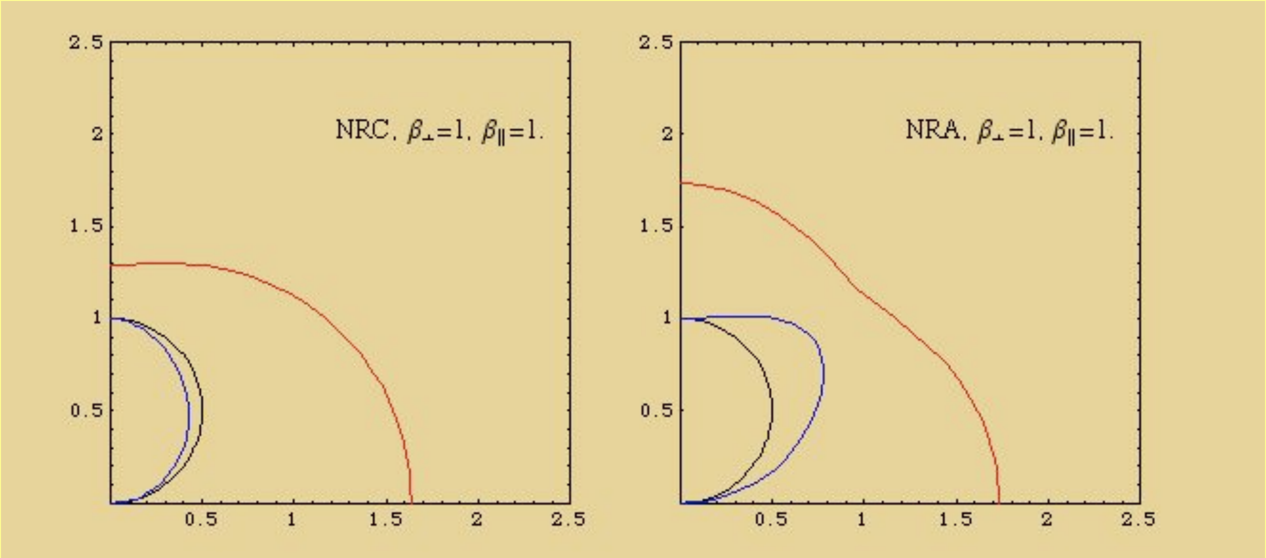
Chew Goldberger & Low (1955)

- **Adiabatic invariants**

$$P_\perp = \tfrac{1}{2}\int dp p_\perp v_\perp f \propto \rho p_\perp^2 \propto \rho B \quad (NR)$$

$$P_\parallel = \int dp p_\parallel v_\parallel f \propto \rho p_\parallel^2 \propto \rho^3 B^{-2} \quad (NR)$$

- **Second invariant requires rapid mirroring**
  - **Ignores heat flux (Kulsrud)**

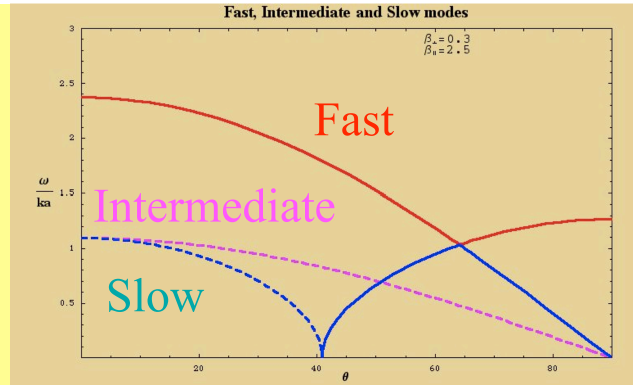


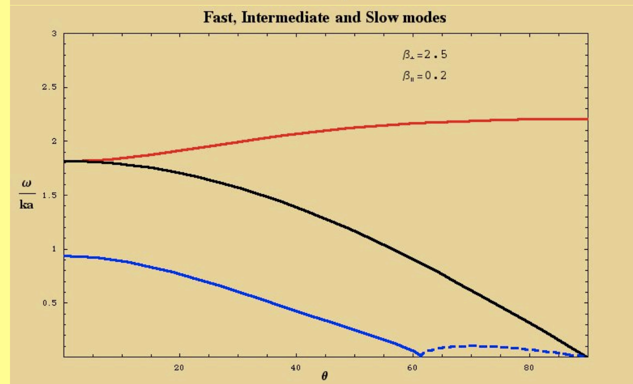
Wave Growth

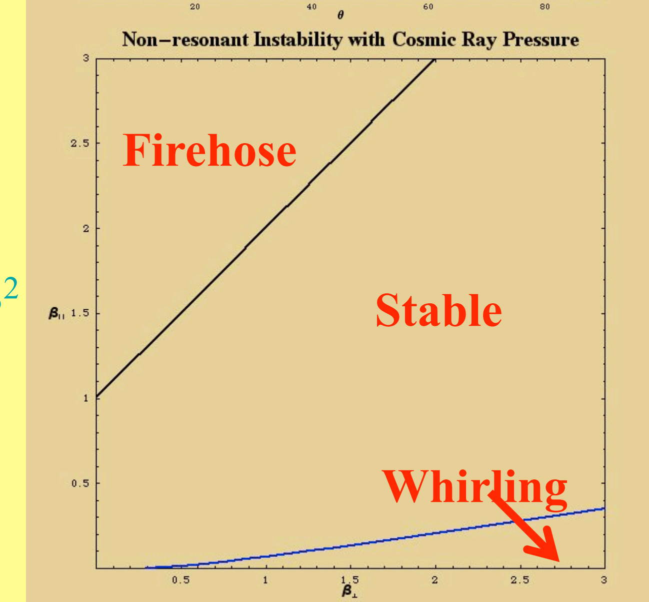
- **Streaming instability**
  - Kinetic treatment $P_1(\mu)$
  - $\langle V \rangle > a$
  - Resonant; $\lambda \sim r_L$
  - $\sigma \sim P_{res}\, u / \rho\, c\, a\, r_L$
  - Creates scattering waves at low energy
  - Ineffective at high energy
- **Firehose instability**
  - Fluid treatment $P_2(\mu)$
  - Parallel pressure dominant
  - $P_z > P_x + B^2$
  - Non-resonant; $\lambda > r_L$
  - $\sigma_{max} \sim [(P_z - P_x)/\rho]^{1/2} / r_L$
  - $\sigma\, t_3 \sim 30\, E_{15}^{-1}\, (\Delta P/P)^{.5}\, B_{-4}\, n^{-.4}\, t_3^{-.2}$

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

- **Whirling (mirror) instability**
  - Slower than Firehose
- **Energy – magnetic moment formalism**





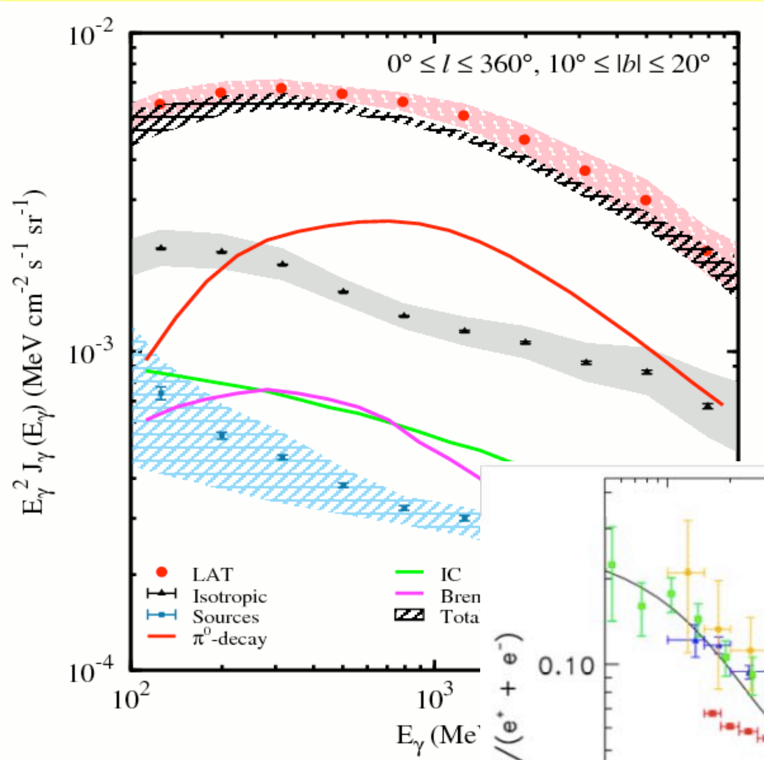


P_z/B^2

P_x/B^2

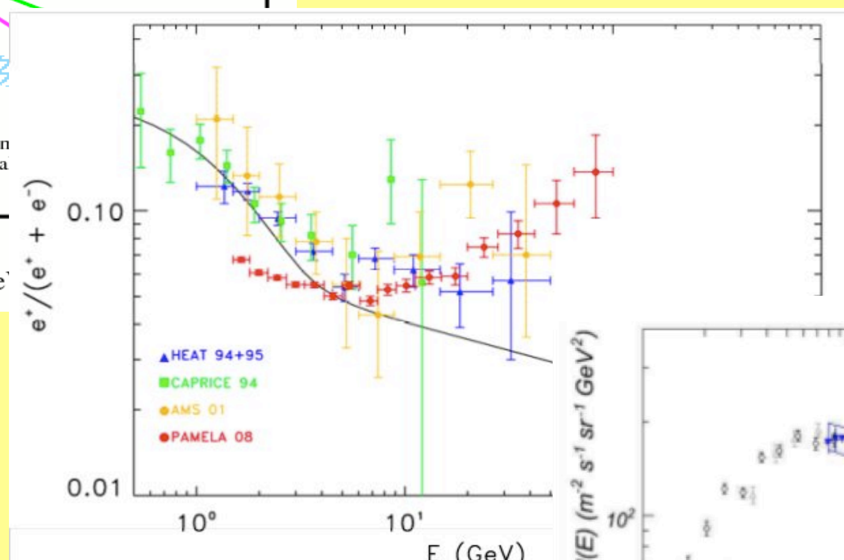
The Unobservable Lightness of Being

Fermi γ-rays

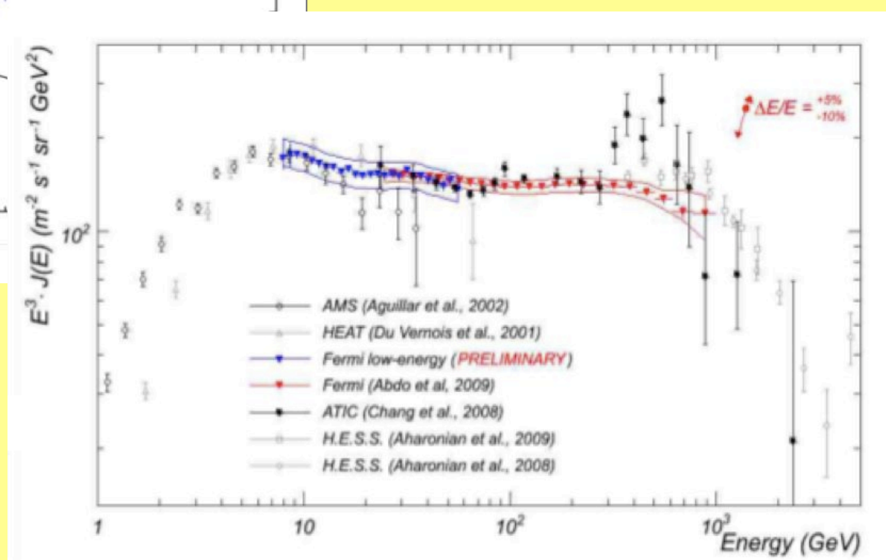


- •Fermi sees no GeV γ-ray excess
- •PAMELA sees 100 GeV positrons
- •Fermi sees <TeV electron mini bump
- •HESS sees >TeV γ-ray + e excess

PAMELA positrons



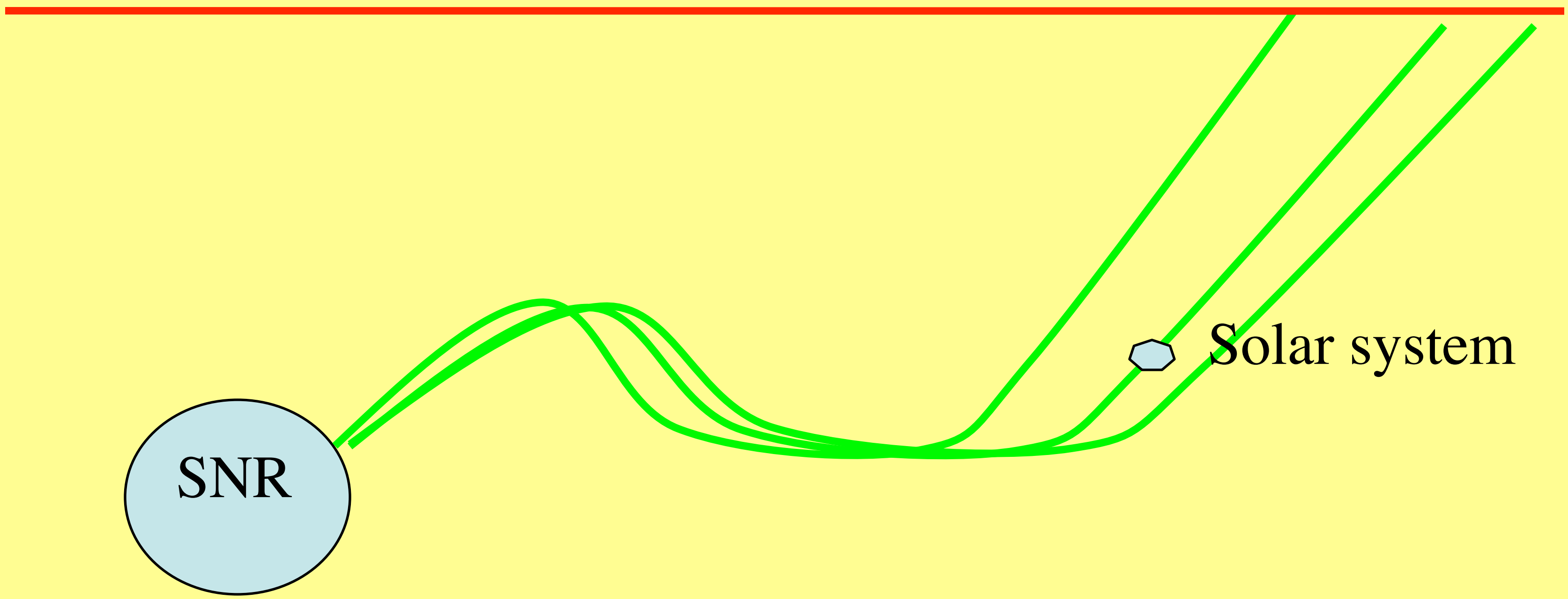
Fermi electrons
HESS γ-rays



Could be pulsars
Constrains dark matter
The hunt is on!

KITP

Halo



- 100Gev CR scatter off waves with $\lambda \sim r_L \sim 10^{14}$cm
  - **Waves are part of local turbulence spectrum**
  - **Waves are self-generated by escaping particles so that $\langle v \rangle < V_A$**
- CR escape times are energy-dependent

Active Propagation

- **Protons create and scatter off RF waves**
  - **Protons are abundant**
  - **Protons create much turbulence**
    - $\langle v\rangle \sim 1000 E_{12}^{.3}$ km s^{-1} $> v_A$ => instability
  - **Protons diffuse slowly**
  - **Proton intensity enhanced**
- **Electrons create and scatter off LF waves**
  - **…Electron intensity diminished**
  - **Effects are energy-dependent**
- **Positrons create and scatter off RF waves**
  - **Follow the protons at the same rigidity**

Passive Propagation

- Disturbances created on outer scale
  - L~100pc, I~0.1?
  - I ~ $\lambda^{.6?}$
  - Inner scale could be 1000km!
- If waves on outer scale possess helicity, is this preserved in cascade?
  - If so, propagation could be charge-dependent

Summary

- Shocks appear to accelerate cosmic rays and amplify magnetic field very efficiently
- Highest energy particles create field far ahead of shock
- Firehose may be of interest at shocks
- Interstellar propagation may be active or passive
- Positrons follow protons and may propagate differently from electrons
- Fermi, PAMELA, CREAM….