Cosmic Accelerators

2. Pulsars, Black Holes and Shock Waves

Roger Blandford
KIPAC
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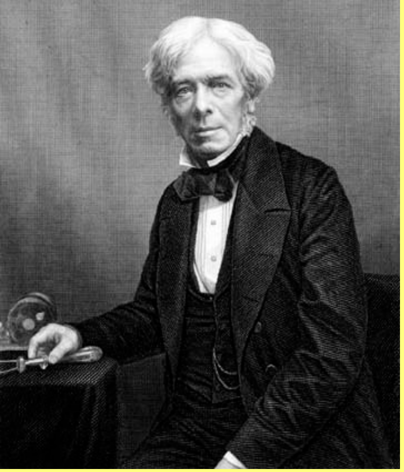
Particle Acceleration



Unipolar Induction

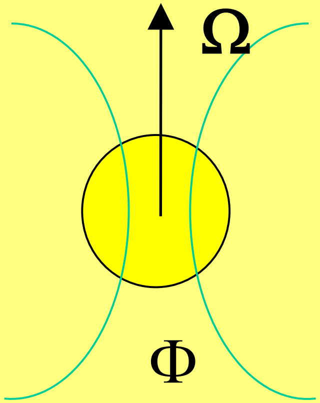
Stochastic Acceleration

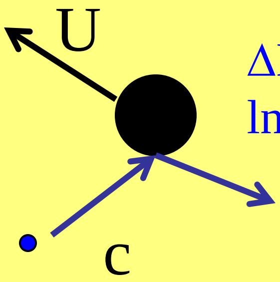
$V \sim \Omega\, \Phi$

$I \sim V / Z_0$

$Z_0 \sim 100\Omega$

$P \sim V I \sim V^2/Z_0$

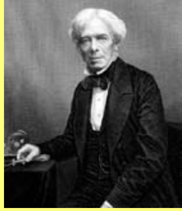




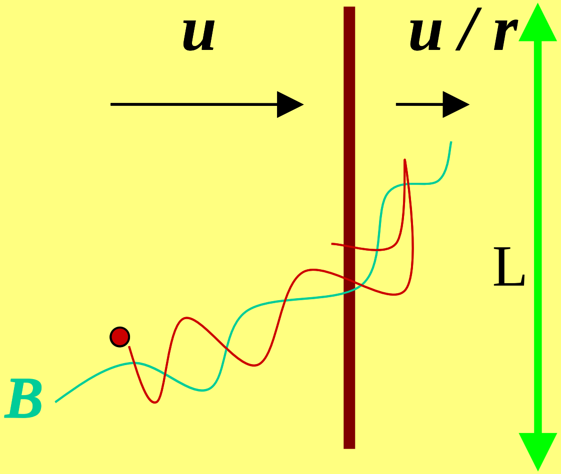
$\Delta E/E \sim +/-u/c$

$\ln(E) \sim u/c\ (Rt)^{1/2}$

Cosmic Accelerators



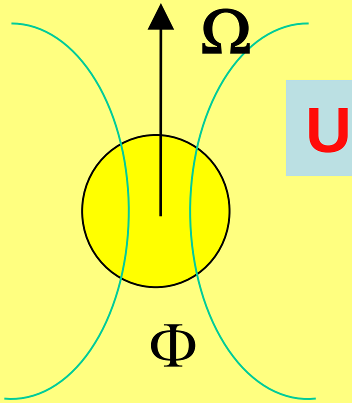
- **Stochastic acceleration**



Shocks transmit power law distribution
$f(p) \sim p^{-3r/(r-1)}$
Also second order processes; efficient when relativistic

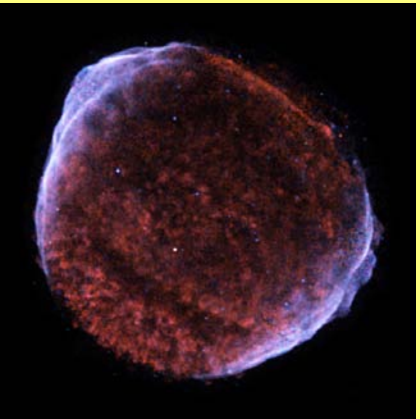
- **Unipolar induction**

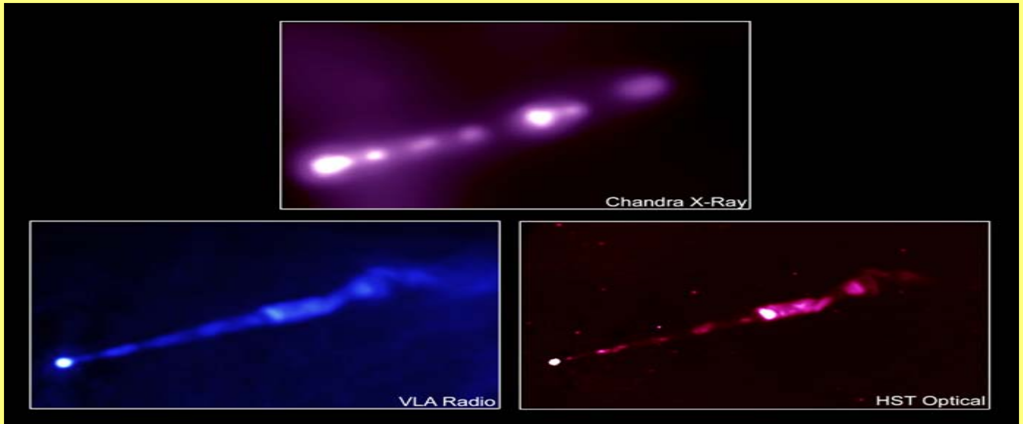
$V \sim \Omega\,\Phi$ ->1ZV
$I \sim V / Z_0$->10EA
$P \sim V\,I \sim V^2/Z_0$
$Z_0 \sim 100\Omega$

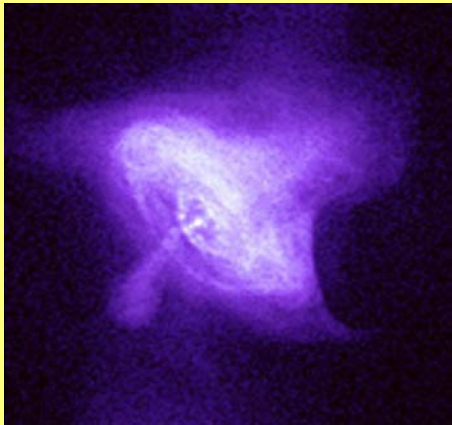


UHECR?

Neutron stars (>PeV)
Black holes (< ZeV)



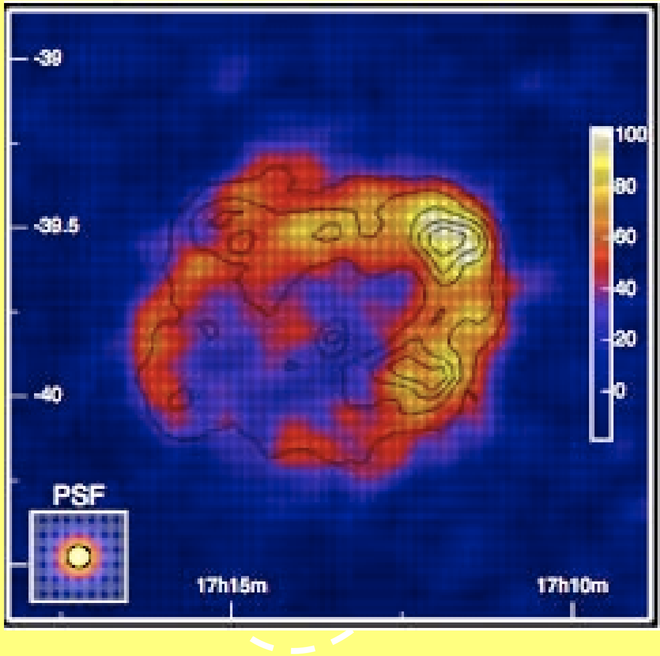


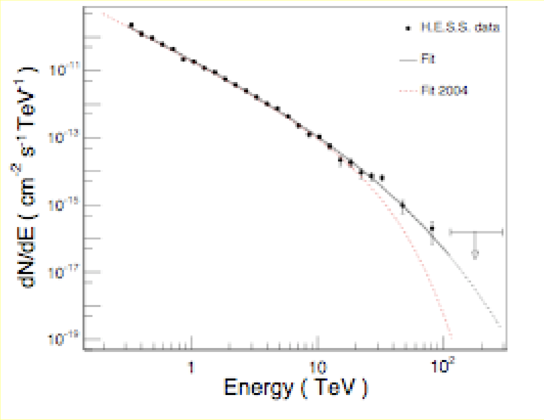


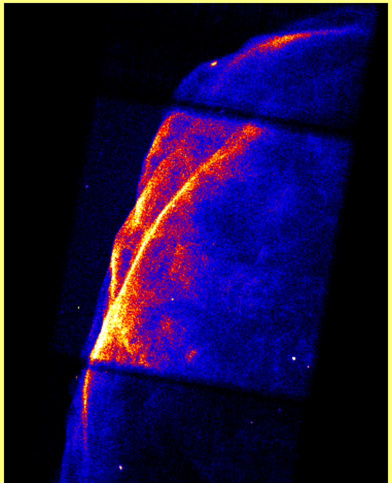
Particle acceleration in SNR

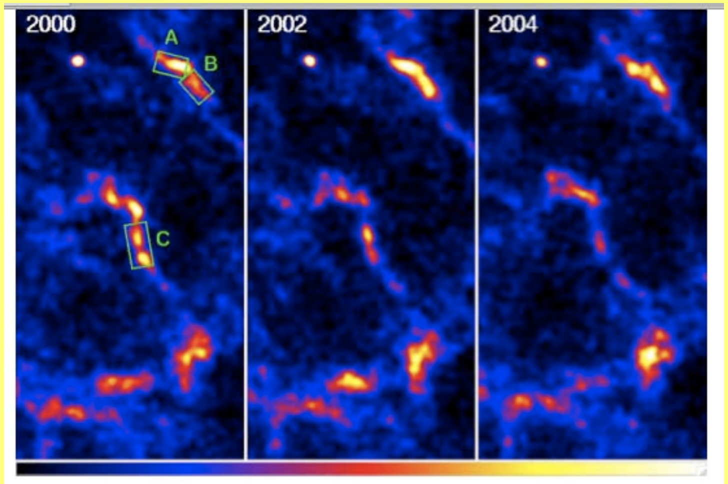
- ~ 100TeV gamma rays
  - ~0.3 PeV cosmic rays
  - Hadronic vs leptonic (Fermi)
- Variable X-rays
  - 100 TeV electrons
  - ~0.3 mG magnetic field
- Shocks also amplify magnetic field
  - Details controversial

Tycho









Convection-Diffusion Equation

- Consider nearly isotropic df in medium containing scatterers moving with fluid velocity u(x,t)
  - **eg Alfven waves with speed <<u**
  - **Stationary 1D flow**

$$u\frac{\partial f}{\partial x}-\frac{\partial}{\partial x}D_{xx}\frac{\partial f}{\partial x}=\frac{1}{3}\frac{du}{dx}\frac{\partial f}{\partial \ln p}$$

  - **Spatial diffusion, p ~ L^{-1} De Broglie…**
  - **Much generalization**

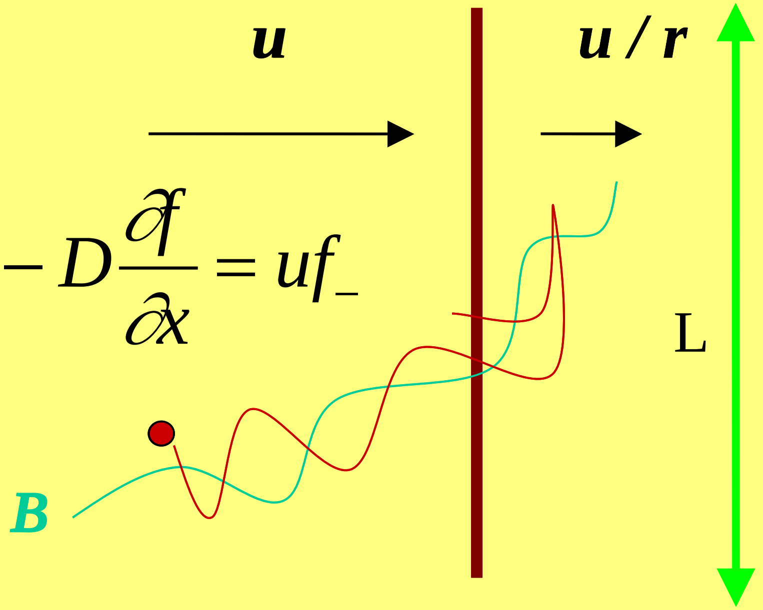
Diffusive Shock Acceleration

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

$$f = f_-$$

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

$$f = f_+$$



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

Transmitted Distribution Function

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

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

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

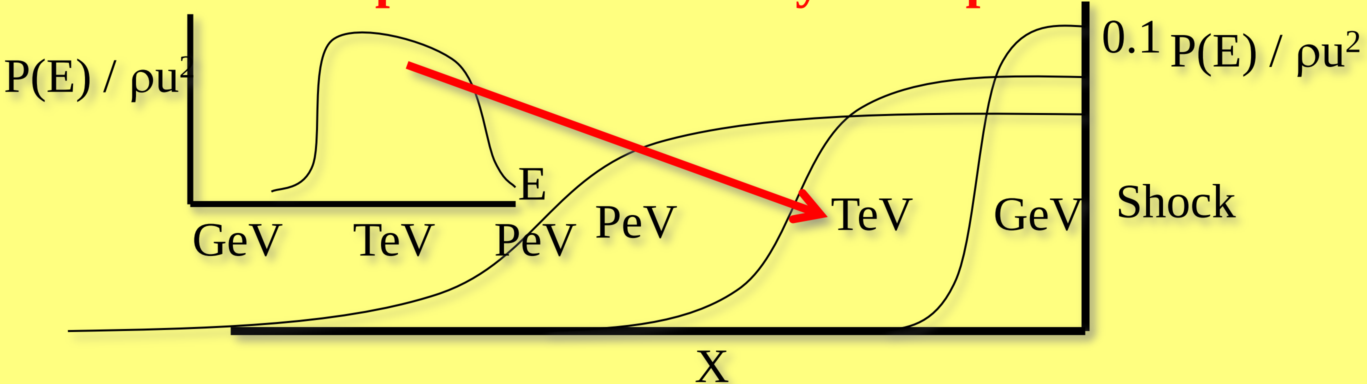
- **For strong shock with Mach number and monatomic gas (plasma),**
- **$q=4M^2/(M^2-1)$ => $r=4$ => $N(E)\sim E^{-2}$**
- **Consistent with Galactic cosmic ray spectrum allowing for energy-dependent propagation**

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 $v \sim u$?
  - Relativistic shocks
- Energy cutoff?
  - $E < euBR \sim$ PeV for mG magnetic field

Magnetic Bootstrap

- **Alfven waves scatter cosmic rays at supernova remnants**
  - **$\lambda \sim$ several $r_L(E)$**
  - **$D \sim c\lambda/3$; $L \sim D/u > 100\, E_{PeV} B_{\mu G}^{-1} Z^{-1}$pc**
  - **Requires magnetic amplification; B > 100 μG**
  - **Highest energy cosmic rays stream furthest ahead of shock**
  - **Distribution function is highly anisotropic and unstable**
  - **Conjecture that magnetic field created at radii ~ 2R by highest energy escaping particles**
  - **Cosmic ray pressure dominates magnetic pressure upstream**
  - **Lower energy particles transmitted downstream and decompress!**
  - **Magnetic field created upstream and locally isotropic**



Magnetic Field Amplification

Weibel

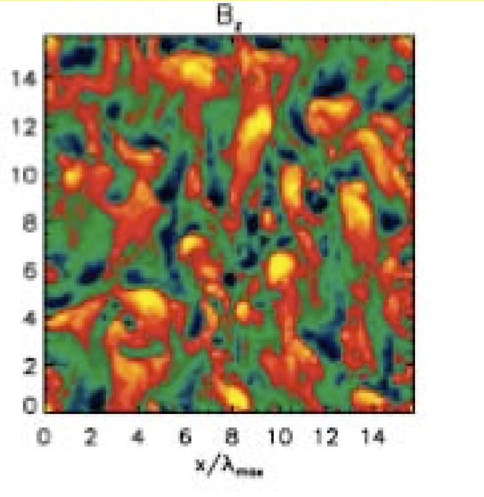
- Unmagnetized plasma
- Short wavelength - ion skin depth
- Saturates when magnetized

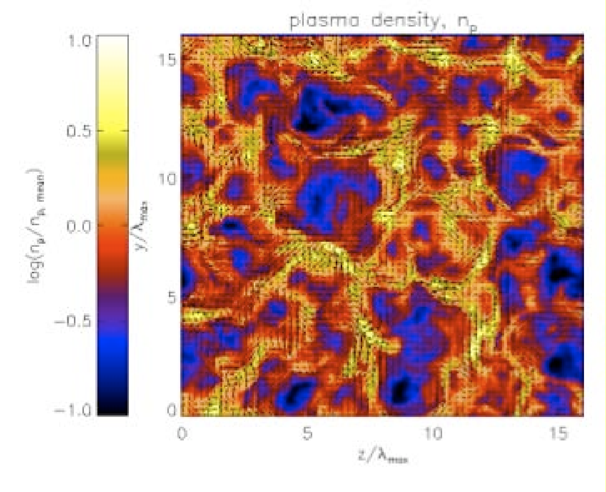
Bell-Lucek

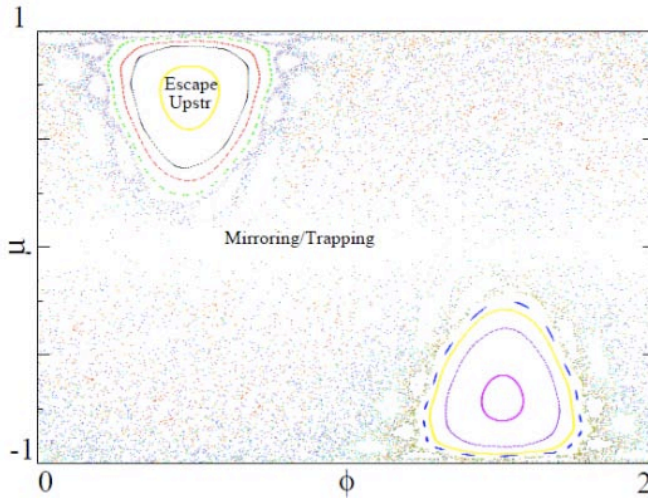
- GeV cosmic rays
- Cosmic ray and return current respond differently to perturbations
- Riquelme & Spitkovsky

Magnetic Bootstrap

- Operates far ahead of shock front and enables PeV acceleration





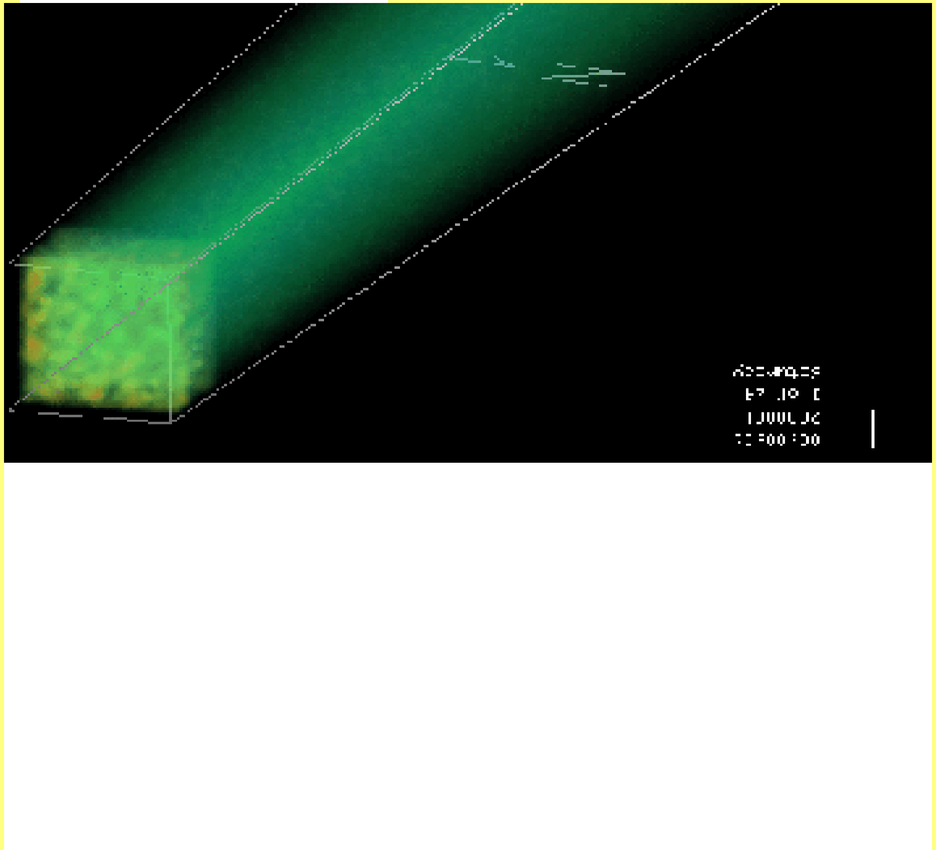


PIC Simulations of collisionless shocks

Why does a collisionless shock exist?

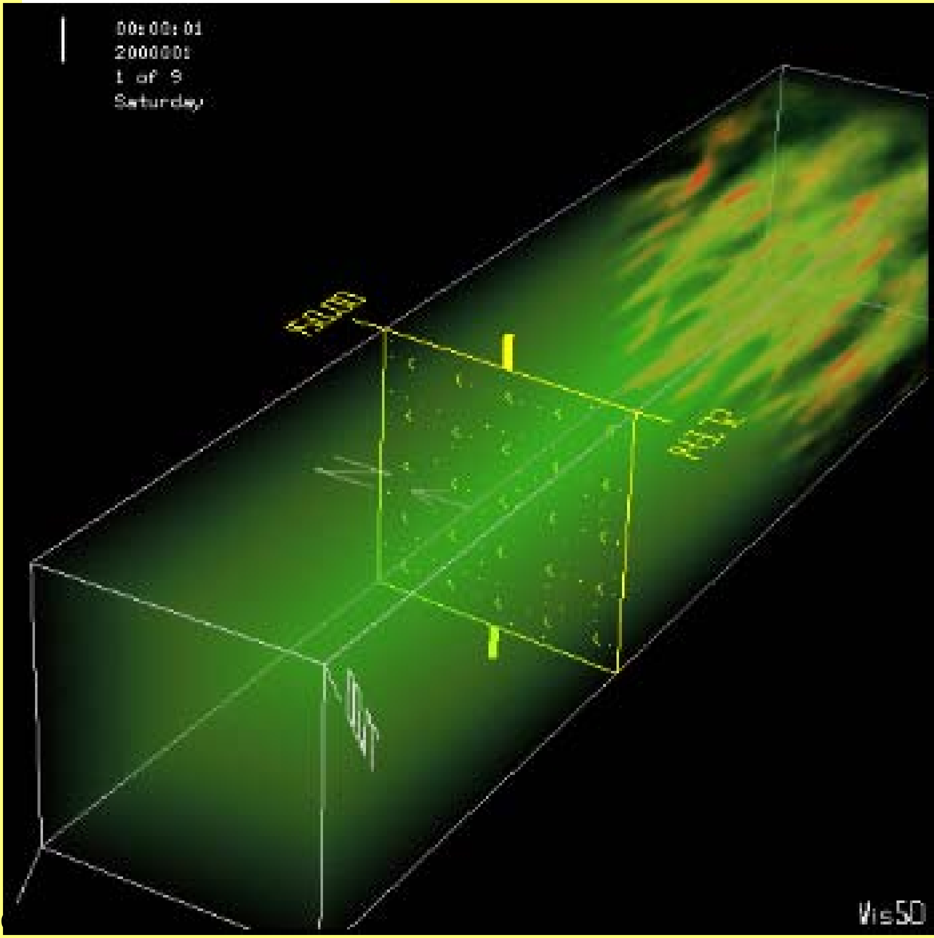
Particles are slowed down either by instability (two-stream-like) or by magnetic reflection.
Unmagnetized shocks are mediated by Weibel instability, which generates magnetic field:

Plasma density



Field generation

Spitkovsky



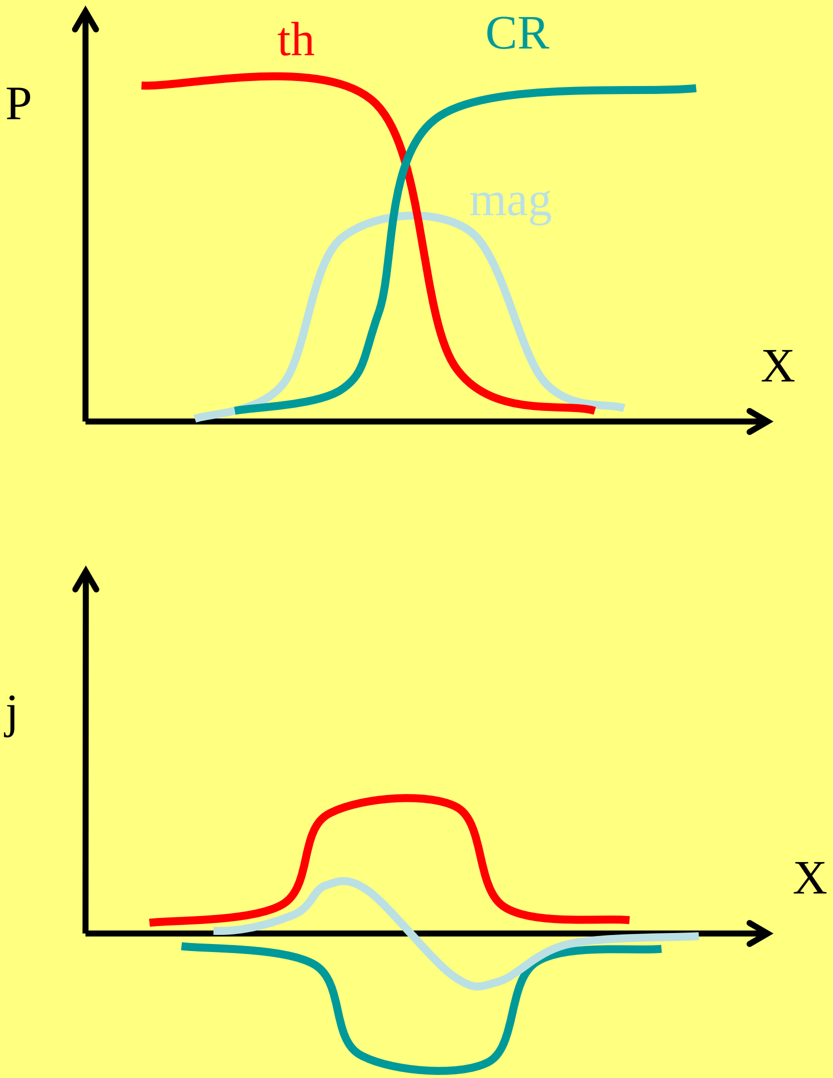
Magnetic Bootlaces

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

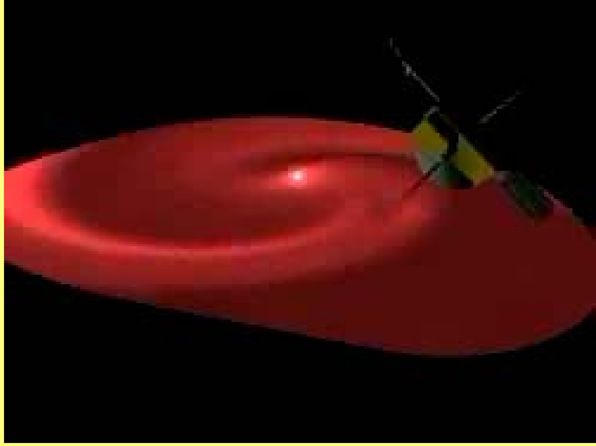
$$\nabla P_P = j_P B$$

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

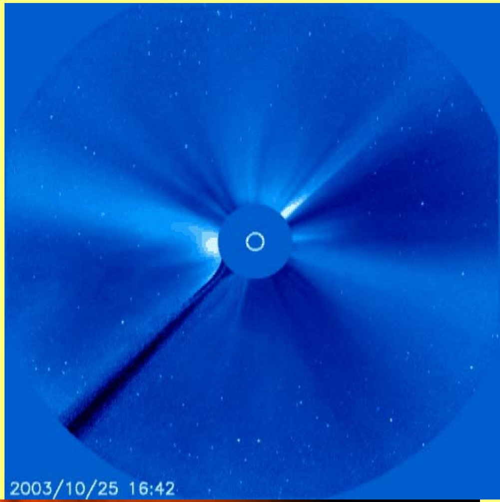
$$\frac{dB}{dX} = j_P + j_{CR}$$

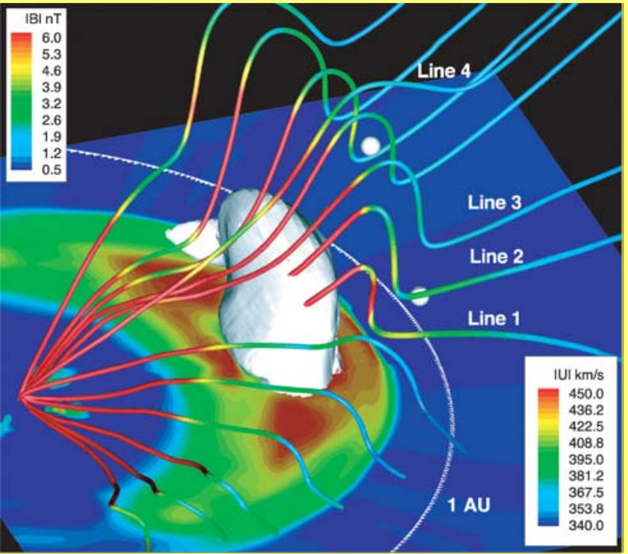


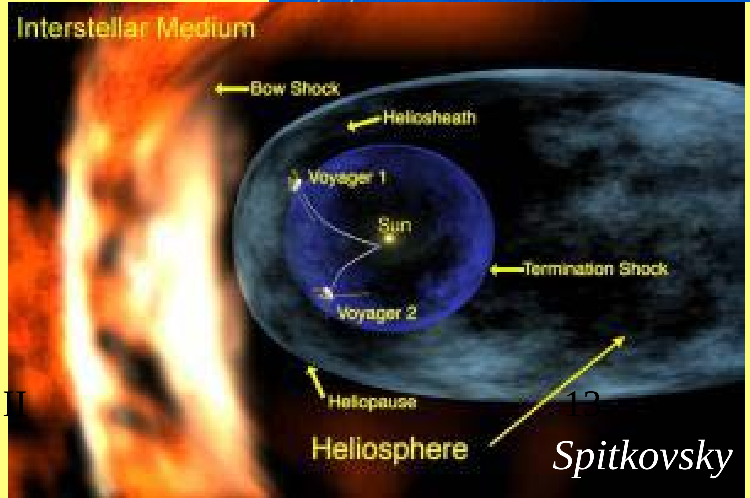
Solar system shocks



- Observations of planetary bow shocks
- Voyager observations of solar wind termination shock
- Numerical simulations

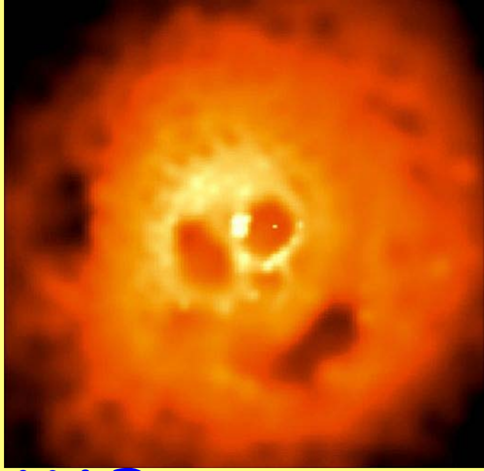






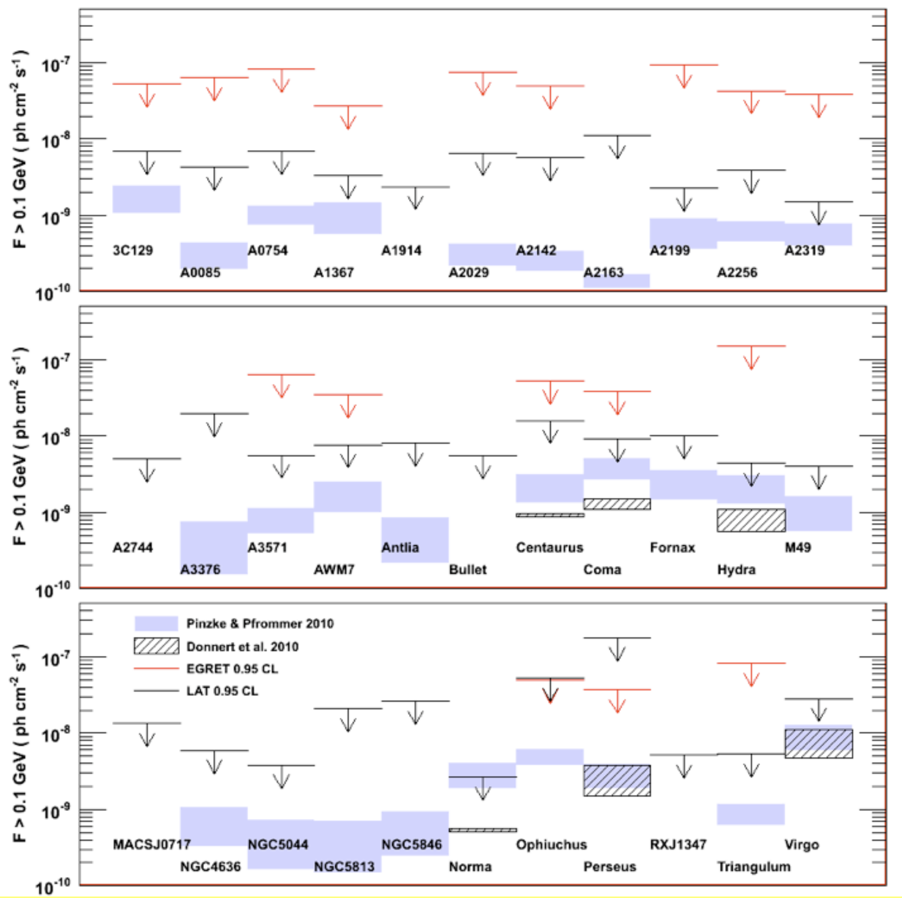
Spitkovsky

Cluster of Galaxies



- eg Perseus Cluster
- Observe using X-rays, lensing, CMB, simulations and gamma rays
- High entropy gas in outer regions. Requires ~10Mpc strong accretion shock
  - Simulations concur
- Accelerate UHECR if Fe!
- Unlikely to make observable neutrinos

GeV γ-rays from Clusters of Galaxies



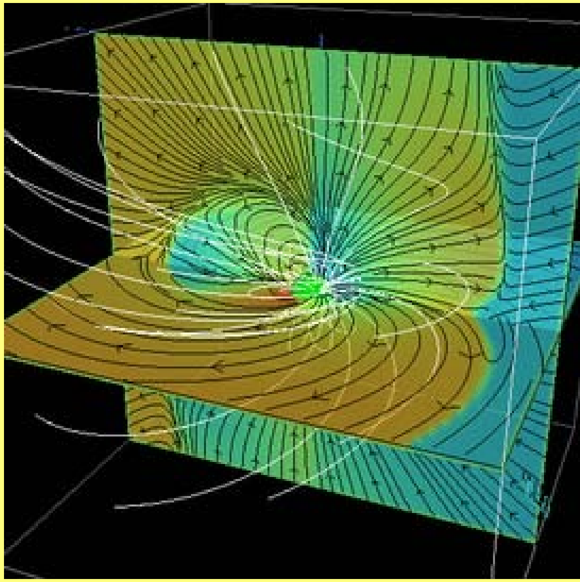
Keith Bechtol

- Active Galactic Nuclei
- Primordial cosmic rays
- Dark Matter Annihilation

Upper limits are interesting!

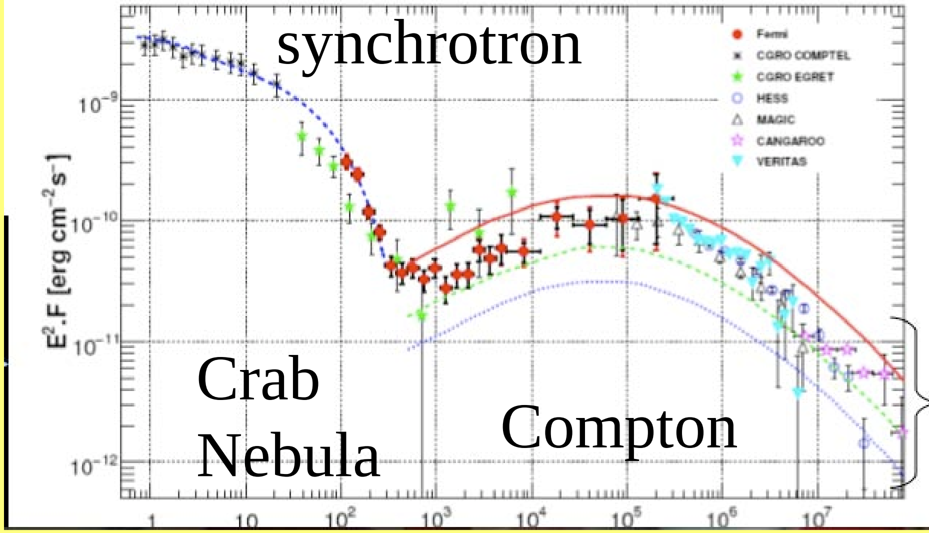
Unipolar Inductors

- **Neutron star magnetospheres**
  - **Mapping of pulsar magnetospheres**
  - **Plerions and relativistic shocks**
  - **Force-free models**
  - **Typically B~ 10^{12} G, P~ 100ms, Φ ~ PV**
  - **Millisecond magnetars**
  - **B~ 10^{15} G, P~ 3ms, Φ ~ ZV**



Pulsar Wind Nebulae

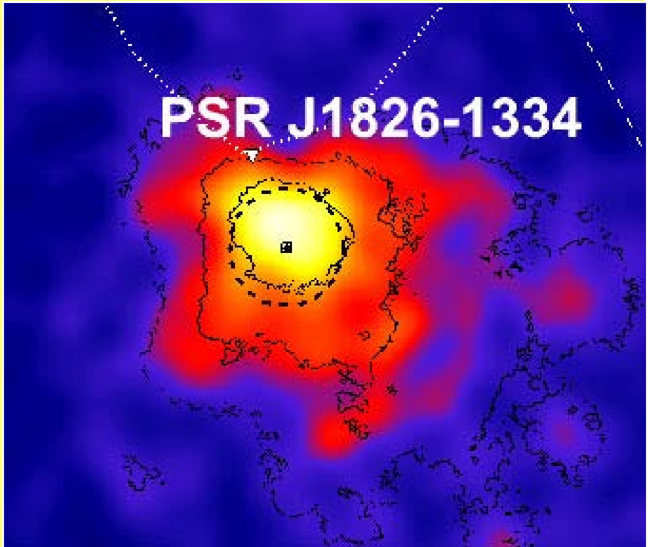
- Common sources especially at TeV
- Displaced from pulsar
- Synchrotron nebulae
- Compton -CMB/synchrotron
- Accelerating >10PeV electrons
- Larmor radius – ~0.1pc
  - Cooling length - ~0.01pc
  - Requires E>~B!!
  - Pulsar wind –relativistic beaming?
  - Pulsar magnetosphere – ground-states of gyration

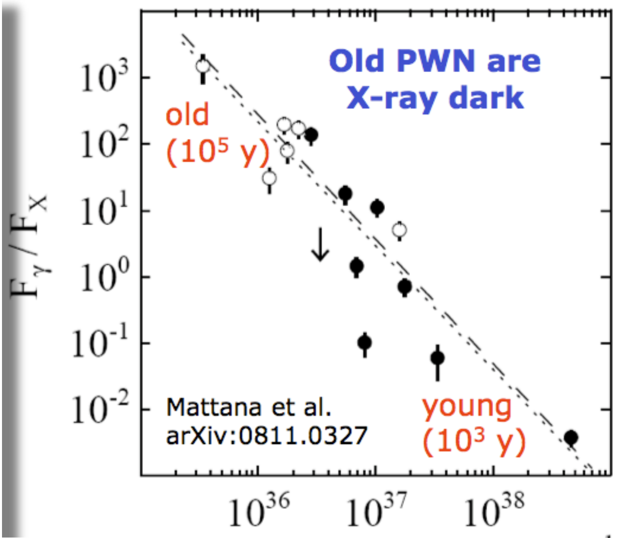

synchrotron

Crab Nebula

Compton

P



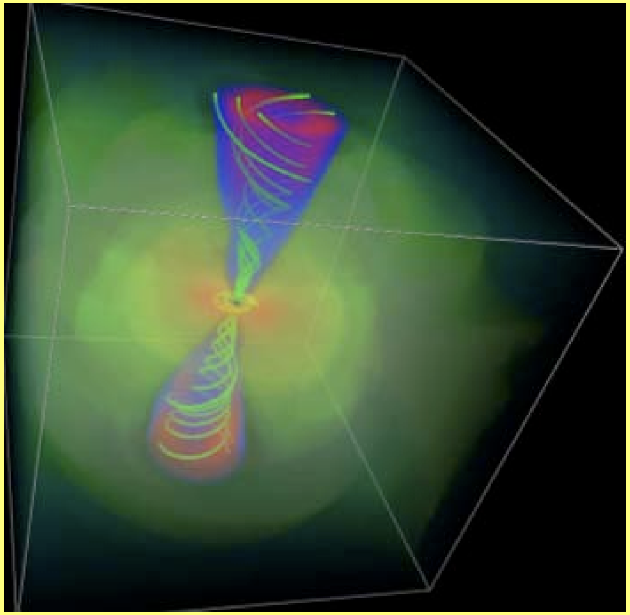

Old PWN are X-ray dark

old (10⁵ y)

young (10³ y)

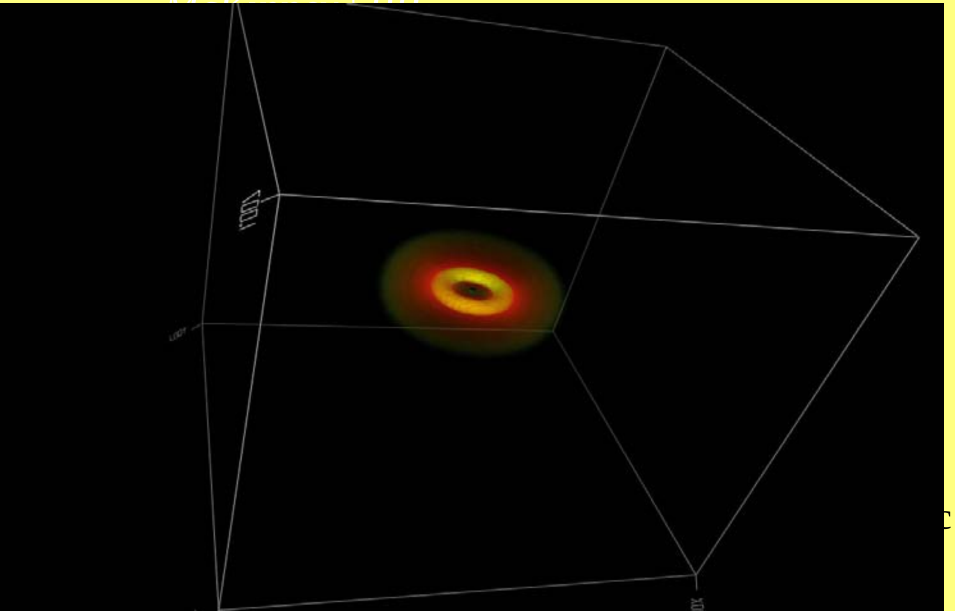
Mattana et al. arXiv:0811.0327

Black Hole Accelerators

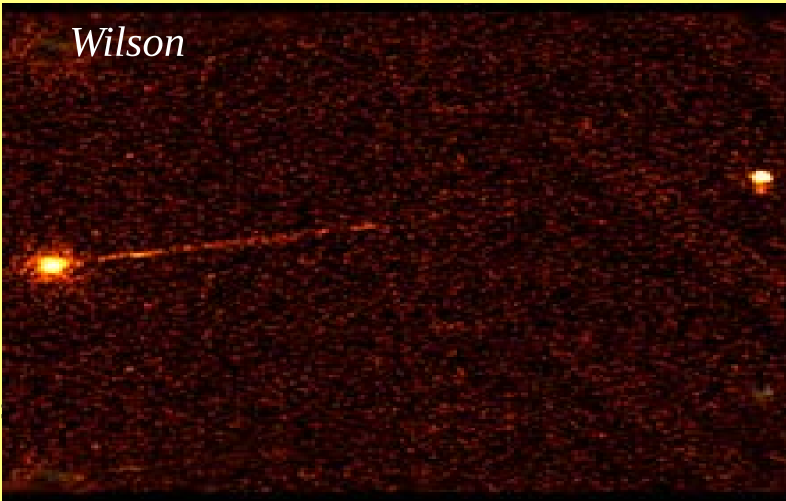


- 10^9 M_o AGN hole
    - B ~ 1T; $\Omega \sim 10^{-3}$ rad s^{-1}
    - V ~ 1ZV; I ~ 10EA
    - P ~10^{39}W
- 10 M_o GRB hole
    - P~10^{44}W

McKinney + RB



Co-ax or hosepipe?



Wilson

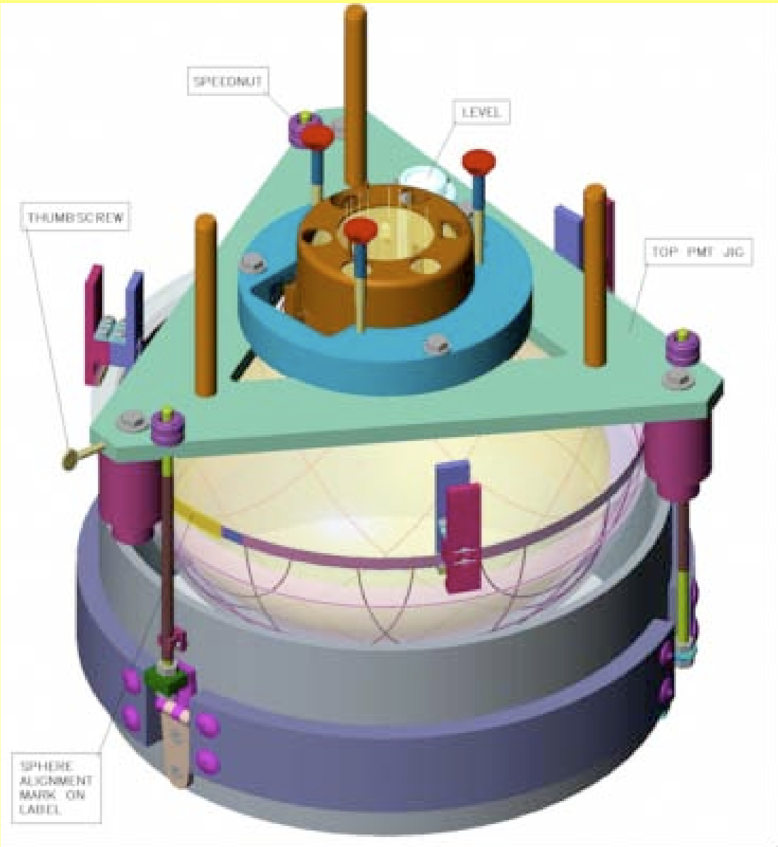
Losses

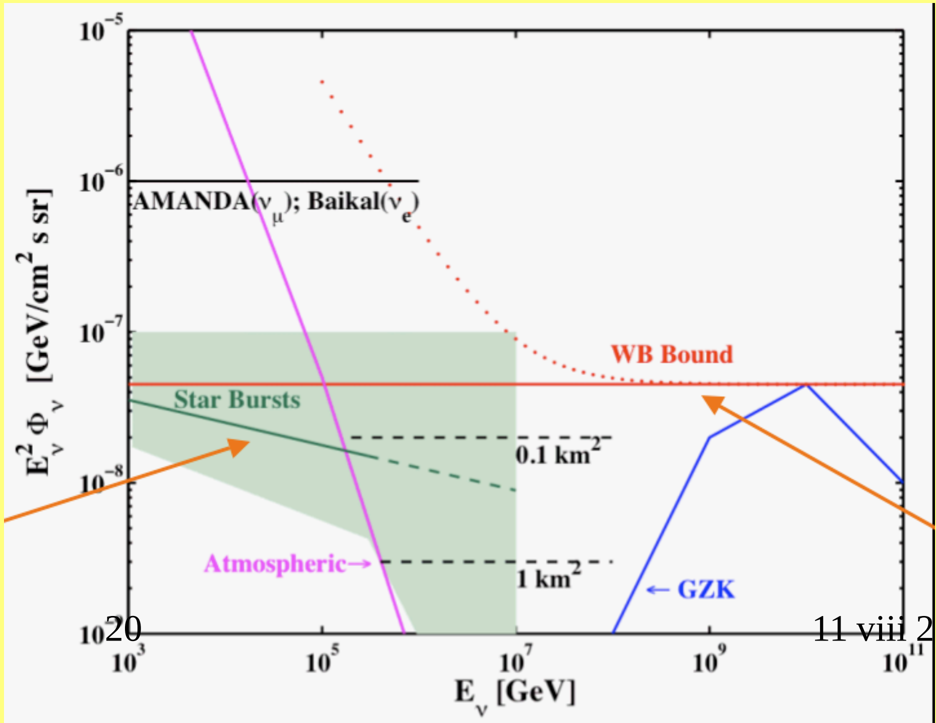
- Radiative losses
  - Synchrotron, Compton losses
  - $P \sim E^2 M^{-4}$; irrelevant for protons
- Photo-pion production
  - Dark accelerators
- Collisional losses
  - Source of gamma rays

Good for VHE neutrinos; bad for UHECR!

VHE Neutrinos

- Ice Cube deployed and working well
- No sources yet
- **Leptonic** vs hadronic jets
- GZK neutrinos (unless Fe)
- Cosmic ray detector
- Geophysics…
- Radio, sonic detection





PM will explain!

Summary

- Cosmic shocks are efficient accelerators
  - Solar system, SNR, clusters..
- Accelerate protons/electrons to higher energy than expected
- This implies that they also strech magnetic field lines. Many competing plasma instabilities
- Unipolar induction associated with millisecond magnetars, black holes in AGN, GRB can induce ZV.
- Neutrino observations can distinguish leptonic from hadronic sources