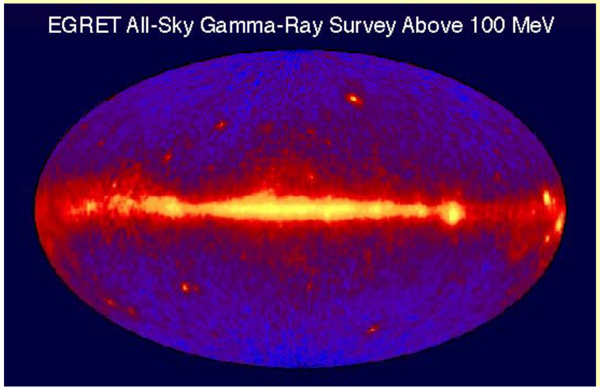
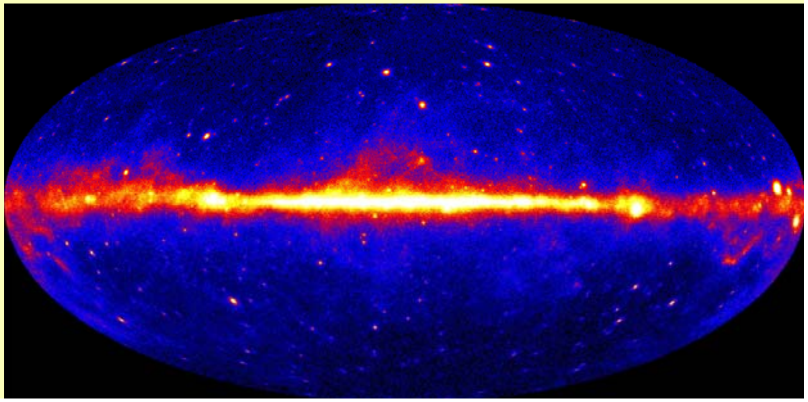
Particle Acceleration Results from Fermi (Higher Energy Astrophysics)

Roger Blandford
KIPAC
Stanford

Fermi

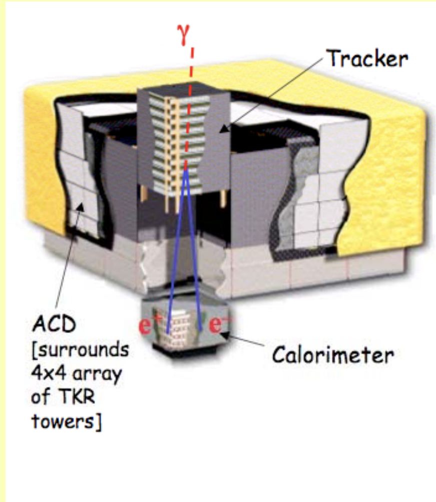
- Joint NASA-DOE-Italy- France-Japan-Sweden, Germany… mission
- Launch June 11 2008
  - Cape Canaveral
- LAT: 0.02-300 GeV
- All sky every 3hr
- ~100 x Compton Gamma Ray Observatory
- ~3 γ-rays per second





SLAC SSI

GLAST



LAT

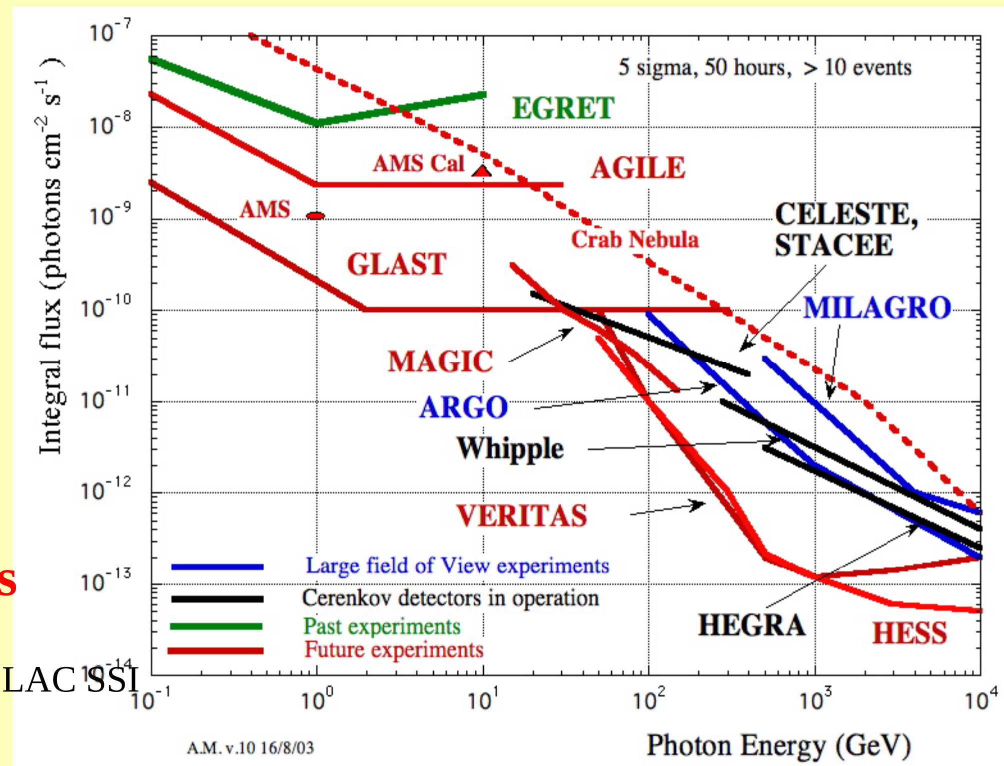
- 0.02 - 300 GeV
- 2.5 sr, 0.3 - 0.9m^2
- 5^o - 5'resolution
- Δln E ~ 0.1
- 3 x 10^{-9} cm^{-2} s^{-1} (>0.1 GeV, point source)
- 10^9 photons (3Hz)
- All sky every 3hr

GBM

- 0.01-30 MeV
- 9sr, 100 cm^2.
- 1^o resolution
- Δln E ~ 0.1
- Combine with Swift

Sources after a decade?

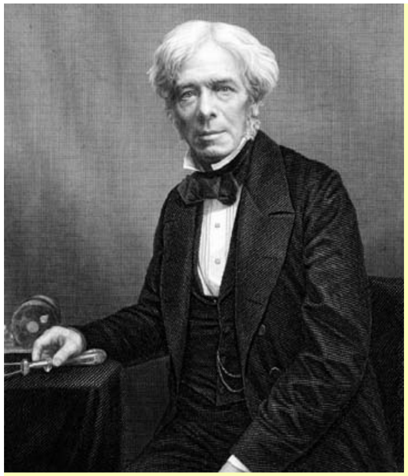
- 10,000 Active Galactic Nuclei
- 1000 Gamma Ray Bursts
- 100 Pulsars
- 100 Supernova Remnants
- 10 Galaxies
- 10 Clusters of Galaxies
- 10 X-Ray Binaries
- ? Unidentified Sources



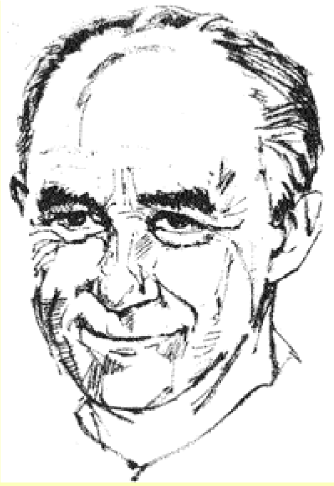
Fermi has greatly exceeded expectations

Fermi Particle acceleration

- Ellison, Hofmann, Sarazin lectures
  - **Observations of cosmic rays**
  - **Cosmic ray sources**
  - **Diffusive shock acceleration**
  - **Supernova remnant observations**
  - **Hadronic and leptonic models of gamma ray emission**
  - **Molecular and atomic hydrogen cloud emission**
  - **UHECR observations and phenomenology**

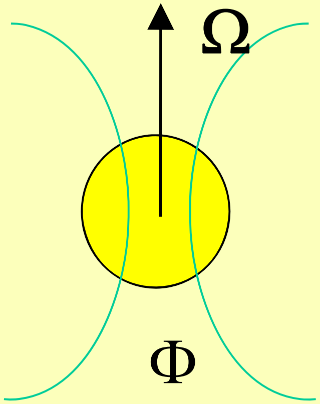


Particle Acceleration

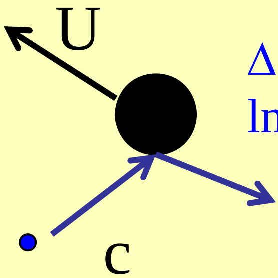


Unipolar Induction

$V \sim \Omega \Phi$
$I \sim V / Z_0$
$Z_0 \sim 100\Omega$
$P \sim V I \sim V^2/Z_0$

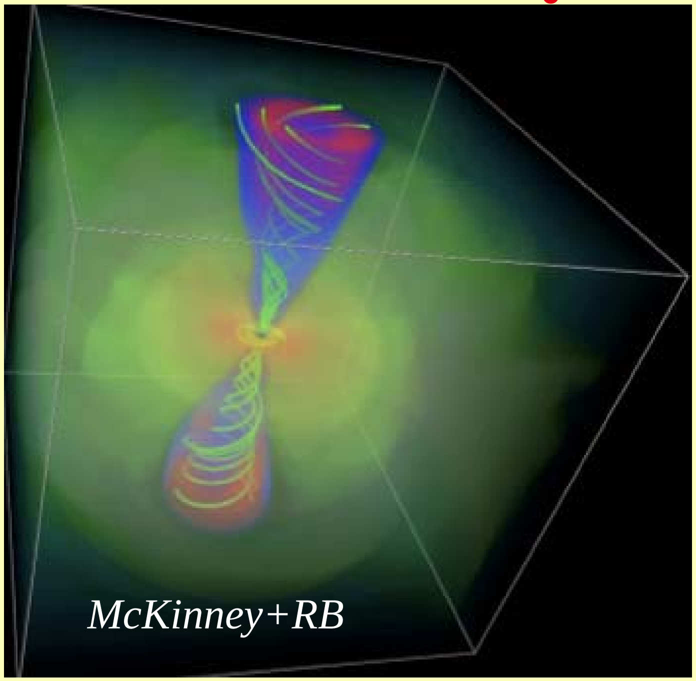


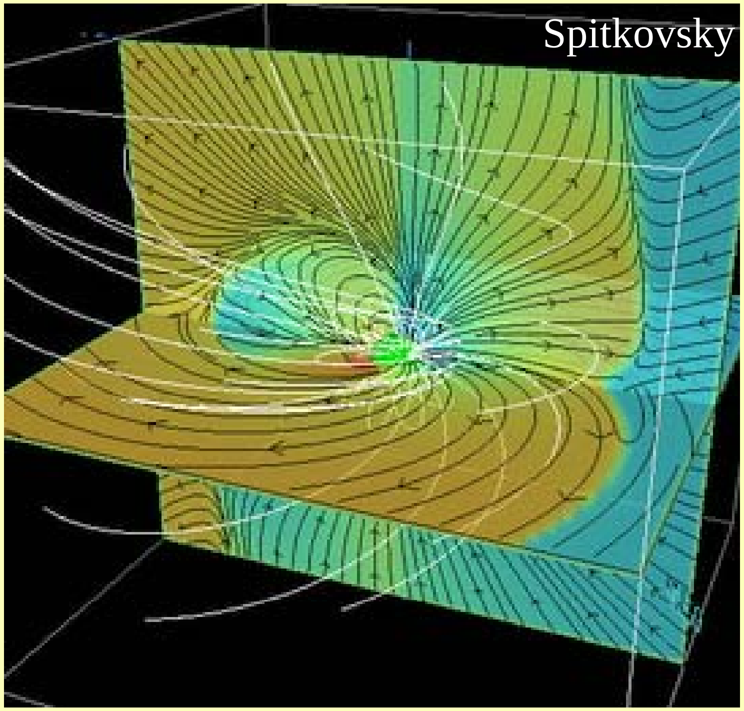
Stochastic Acceleration



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

Unipolar Inductors





- **Billion M_o Black Hole**
  - **B ~ 1T; $\Omega \sim 10^{-3}$ rad s^{-1}**
  - **V ~ 1ZV; I ~ 10EA**
  - **P ~ 10^{39}W**

1 M_o Neutron Star

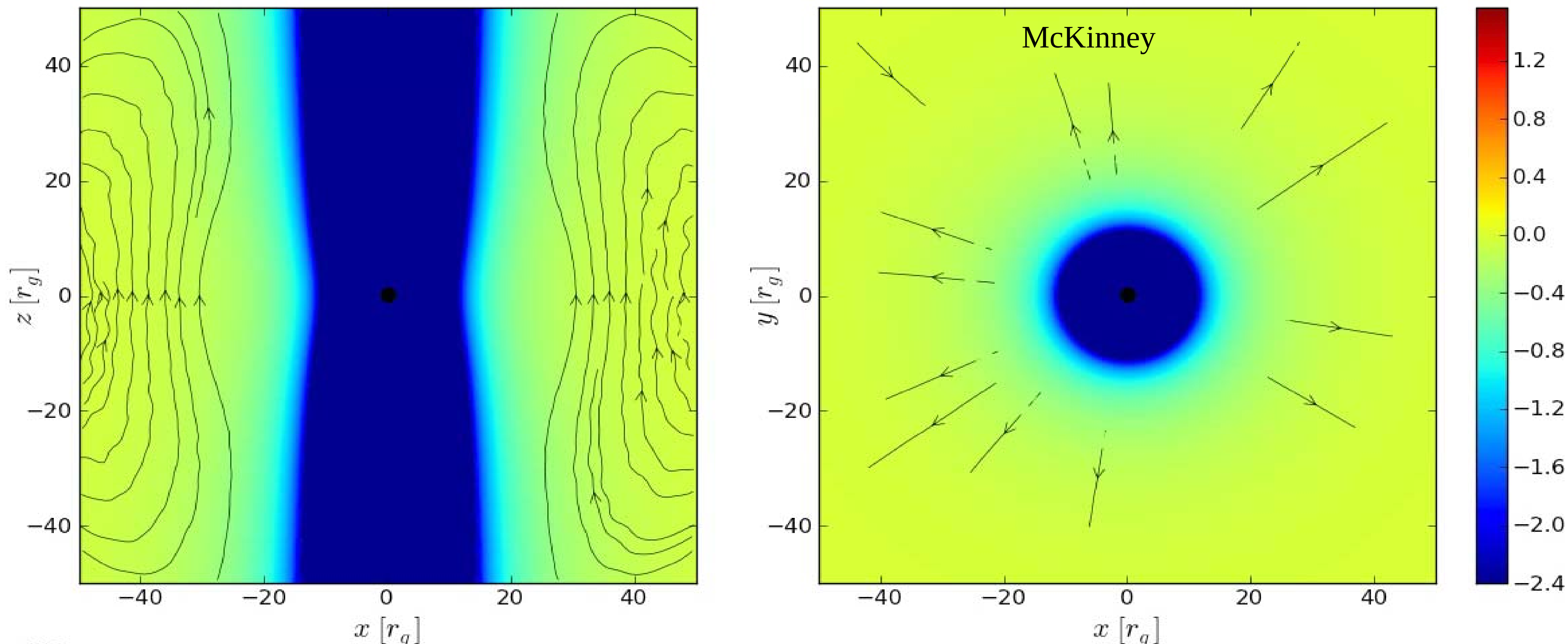
B ~ 10MT; Ω ~ 100 rad s^{-1}

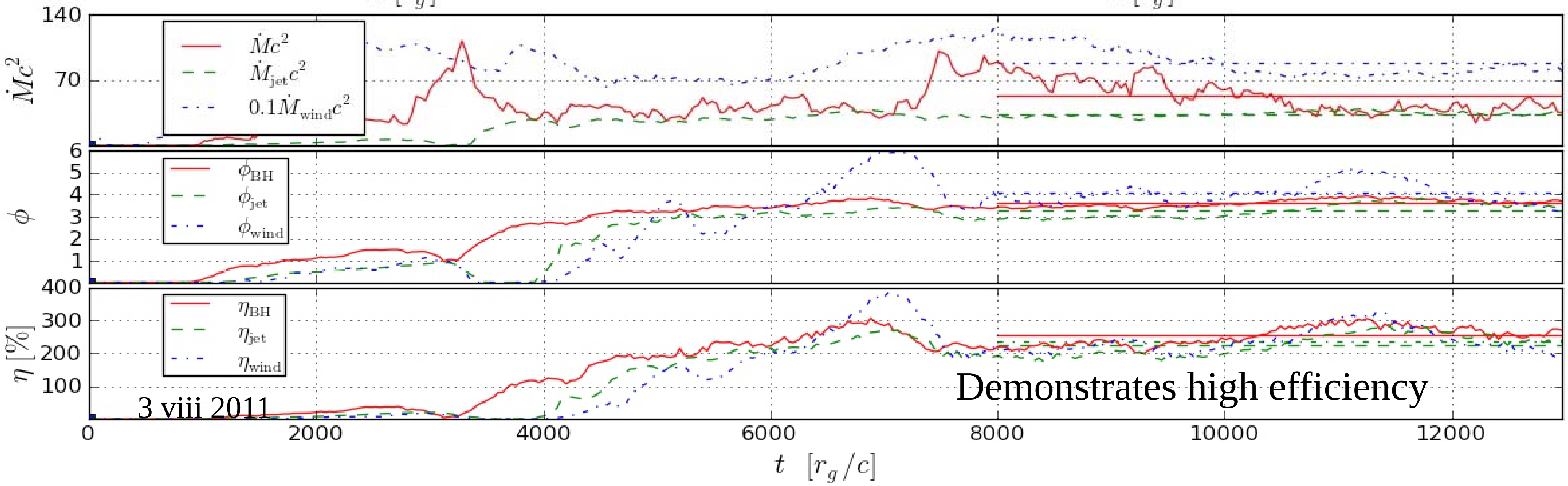
V ~ 30 PV; I ~ 300TA

P ~ 10^{31}W

Feature of UHECR sources?

Unipolar induction by a spinning black hole





Demonstrates high efficiency

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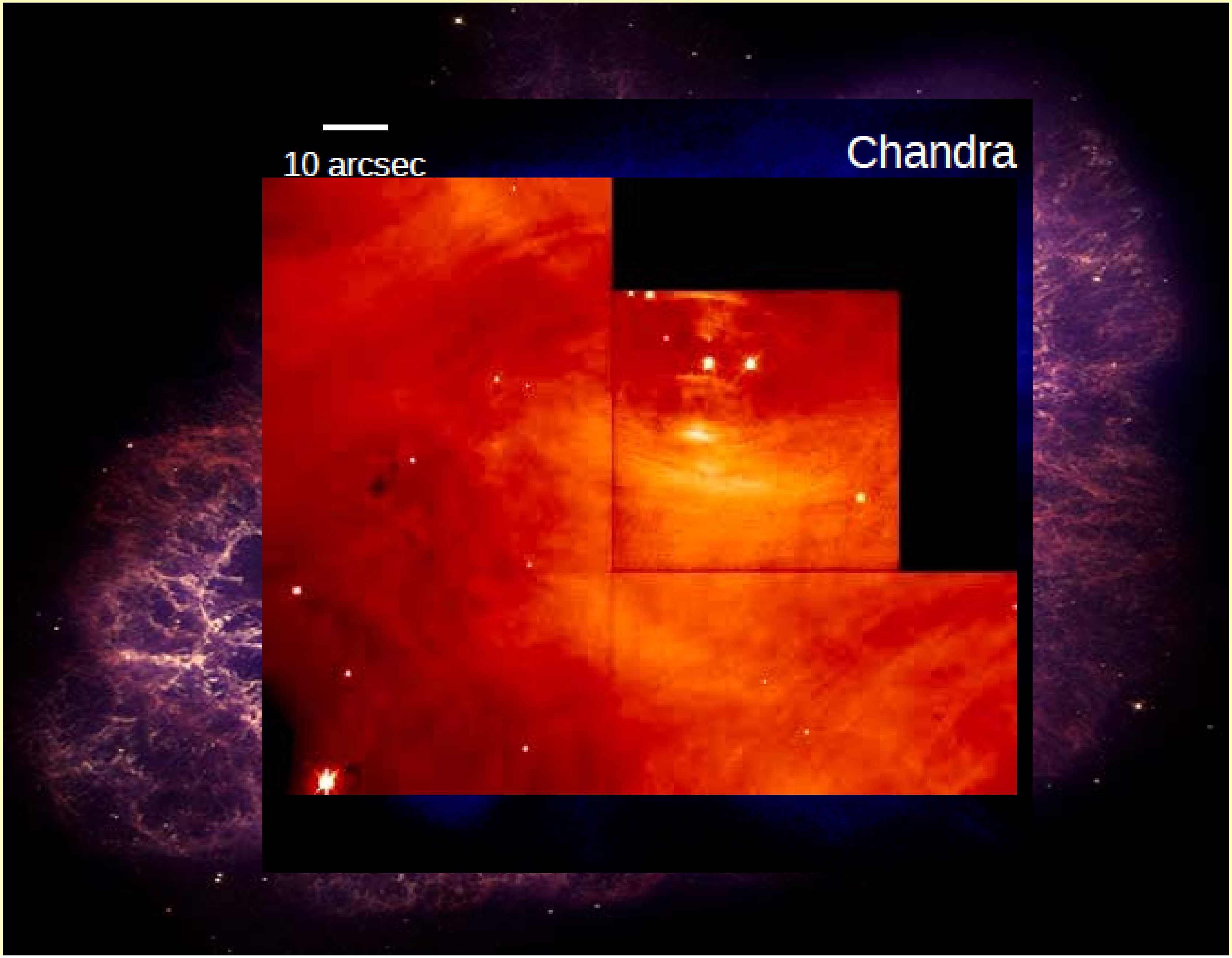
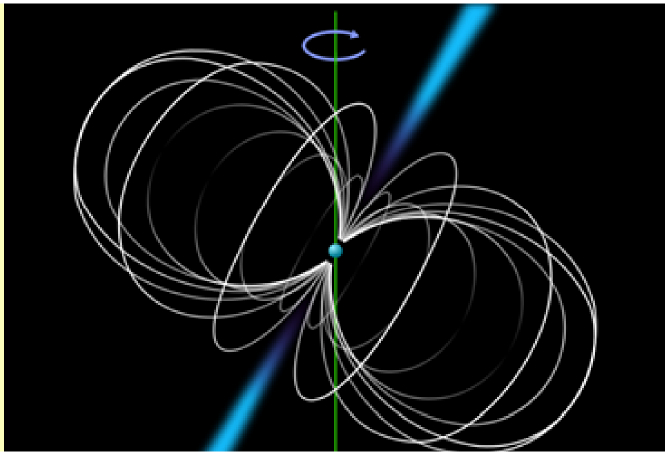
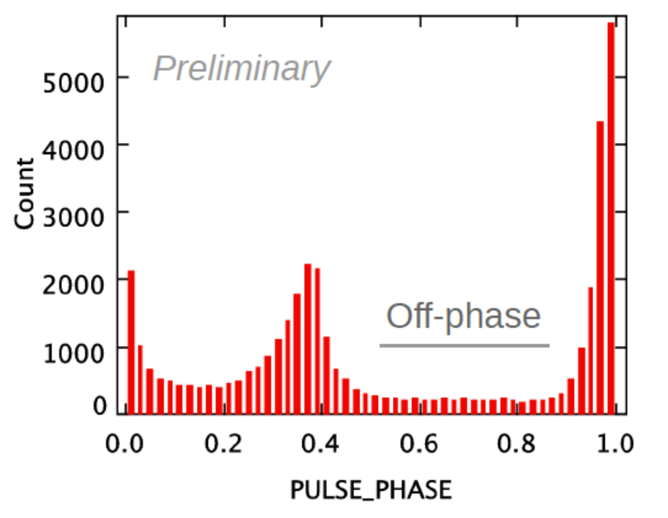
Crab Nebula

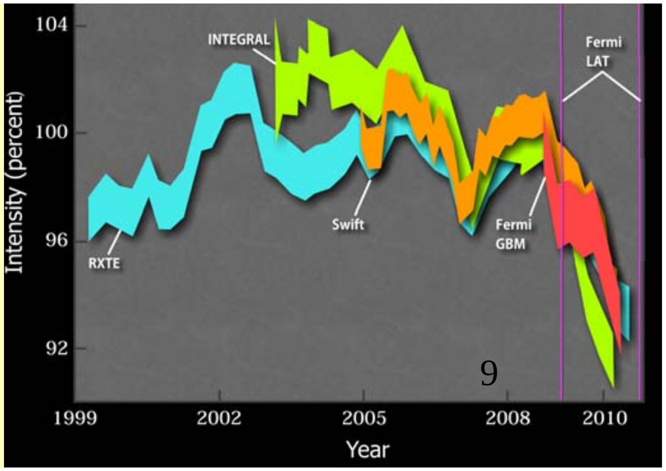


Crab Pulsar

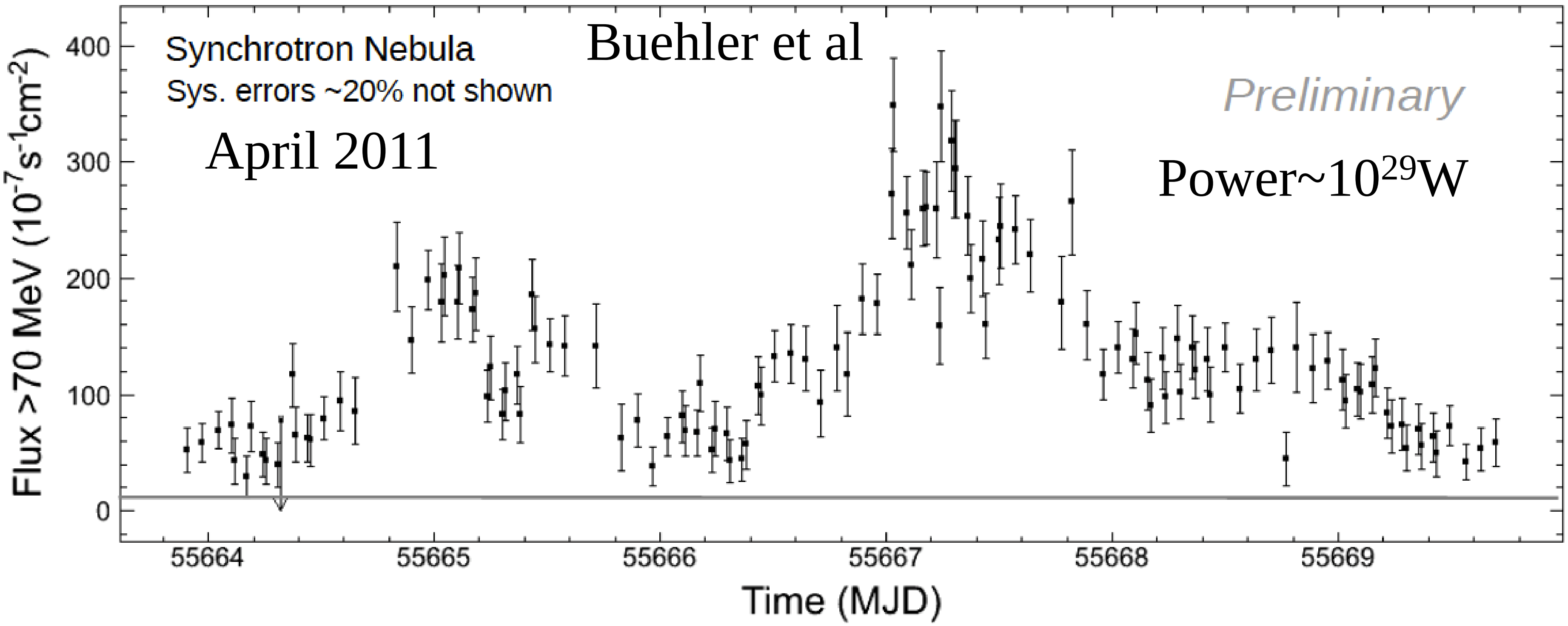
- Discovered in 1968
  - Turning point in history of astronomy
  - Predicted by Pacini
- Spinning, magnetized neutron star
  - 12km radius
  - 30 Hz spin frequency
  - 200 MT (2×10^{12}G) surface magnetic field
  - Radio through > 100 GeV γ-ray pulsation
- Giant electrical generator
  - ~ 50PV; 200TA; 2×10^{31}W ~ $-I\Omega\Omega'$
  - Powers nebula; large energy reservoir
  - Deceleration due to Maxwell stress applied to surface
    - Equivalently Lorentz force as current crossed B in star
  - Fate of EM energy and angular momentum flux?







Flaring behavior

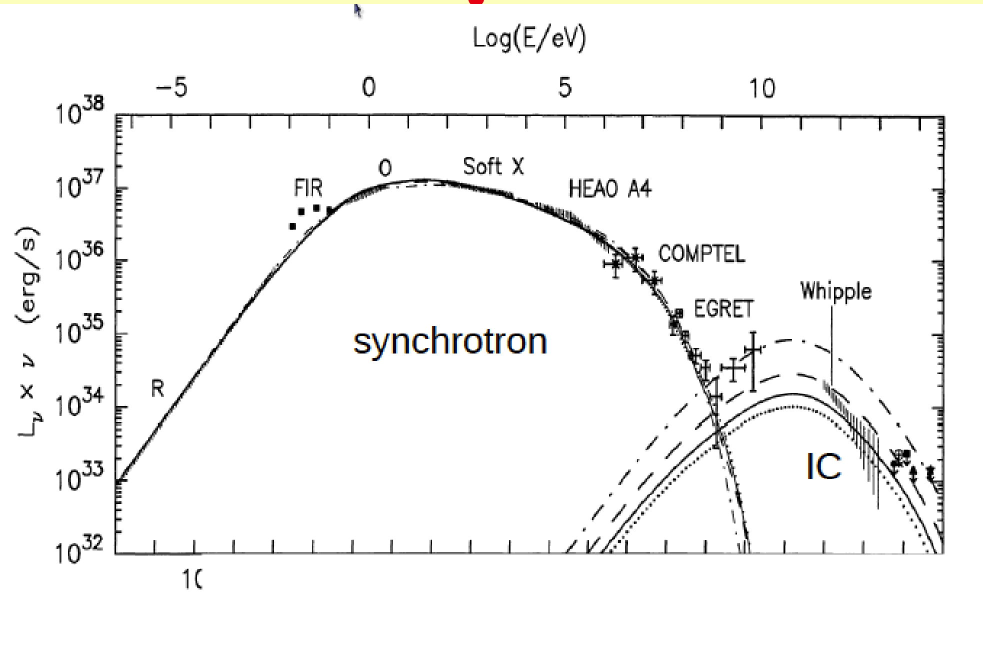


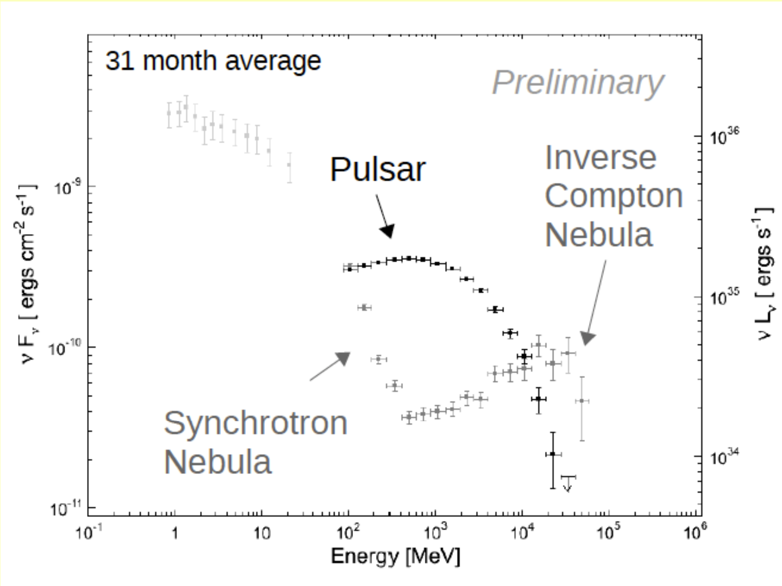
Singular events or power spectrum?

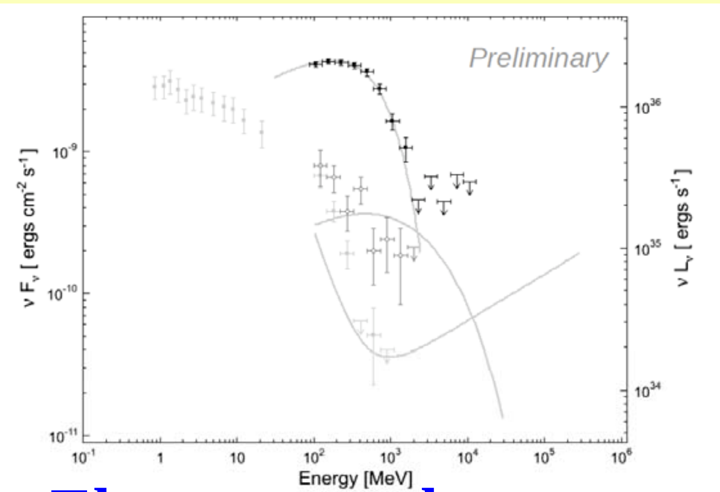
No variation seen in other bands

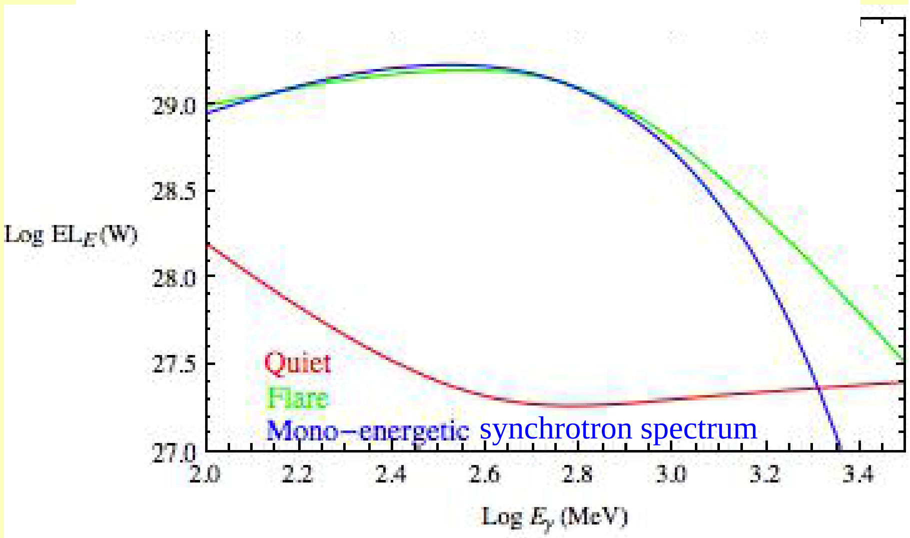
Rapid flux variability <1h

Spectrum of "Flare"



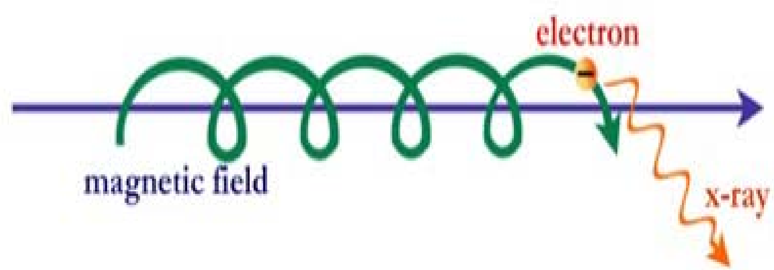






Electron synchrotron radiation: E~PeV, γ~10^9; B~100nT

Equations of Motion



0.011photons emitted in turning through aberration angle γ^{-1}

$$\frac{d\vec{u}}{dt} = \vec{a}_L - \frac{2r_e}{3c}\gamma^2 a_{L\perp}^2 \hat{\vec{u}}, \quad \frac{d\vec{x}}{dt} = \hat{\vec{u}} \qquad \vec{a}_L = \frac{e}{m}\left(\frac{\vec{E}}{c} + \hat{\vec{u}} \times \vec{B}\right)$$

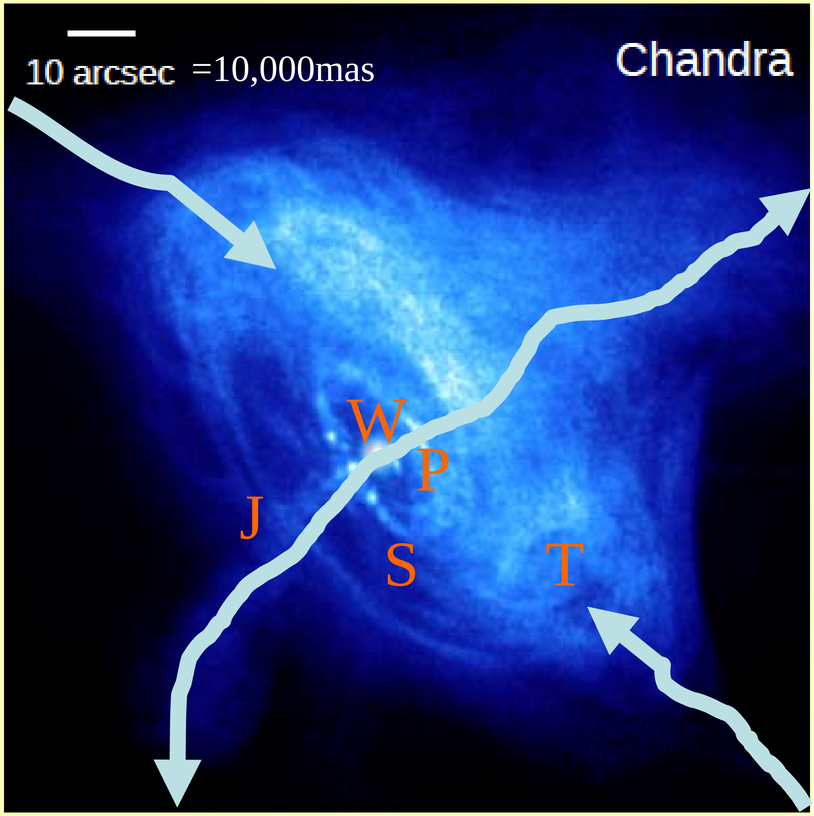
$$a_{L\perp}(\vec{x}, \hat{\vec{u}}) = \frac{e}{m}B_e = \frac{e}{m}\left[B_\perp^2 + \left(\frac{E_\perp}{c}\right)^2 - 2\frac{\vec{E}\times\vec{B}.\hat{\vec{u}}}{c}\right]^{1/2}$$

$\gamma_9{}^2 B_{e-7} = (E_{peak}/23\text{MeV})$
Radiation reaction dominates when $E_\gamma > \alpha^{-1} m_e c^2$
If only uniform magnetic field, electron cools in 12^o
If add electric field, E>5cB to avoid energy loss
If as likely, E>B, not just relativistic beaming

Where does the variation originate ?

- Long term variation of nebula likely due to changes in magnetic field
- Peak power is ~ 3 percent of nebular power
- Flare energy equals that stared in a region of size

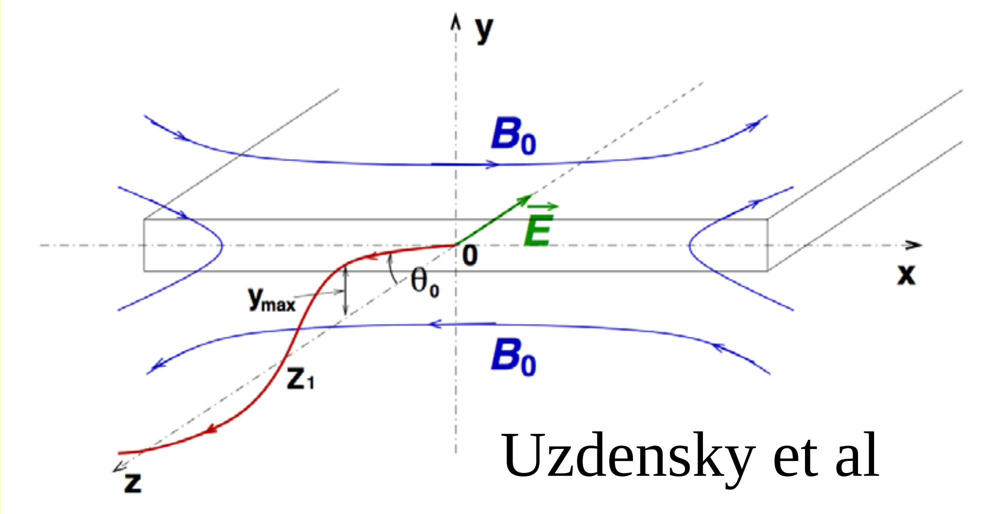
  $L \sim 20 B_{-7}^{1/2}$ lt d ~ $2 B_{-7}^{1/2}$ arcsec
- We want to learn where and how nature accelerates particles to high energy
- Not the Pulsar
  - No correlation with rotation frequency
- Wind shocks when momentum flux equals nebular pressure
- Wind, Shock, Jet, Torus are all possibilities



1 lt hr = 3 mas

Larmor radius= $60\gamma_9 B_{-7}^{-1}$mas

Reconnection

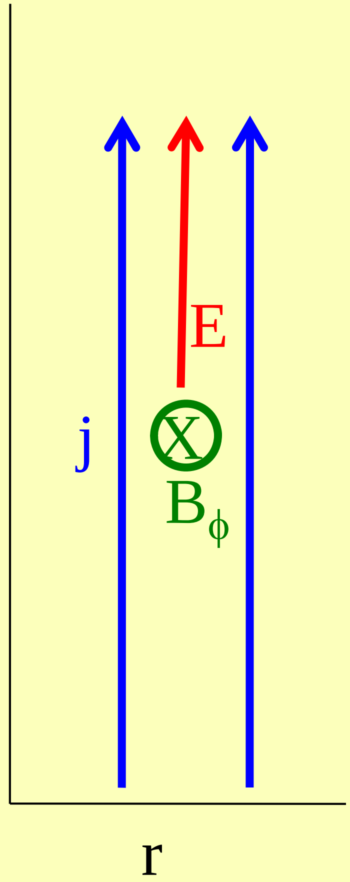


Uzdensky et al

- Oppositely-directed field lines "change partners" through resistive region containing electric field
- High energy particles can be accelerated in field where curvature is low
- Hard to radiate GeV photons, however
- Hard to make efficient in equatorial current sheet

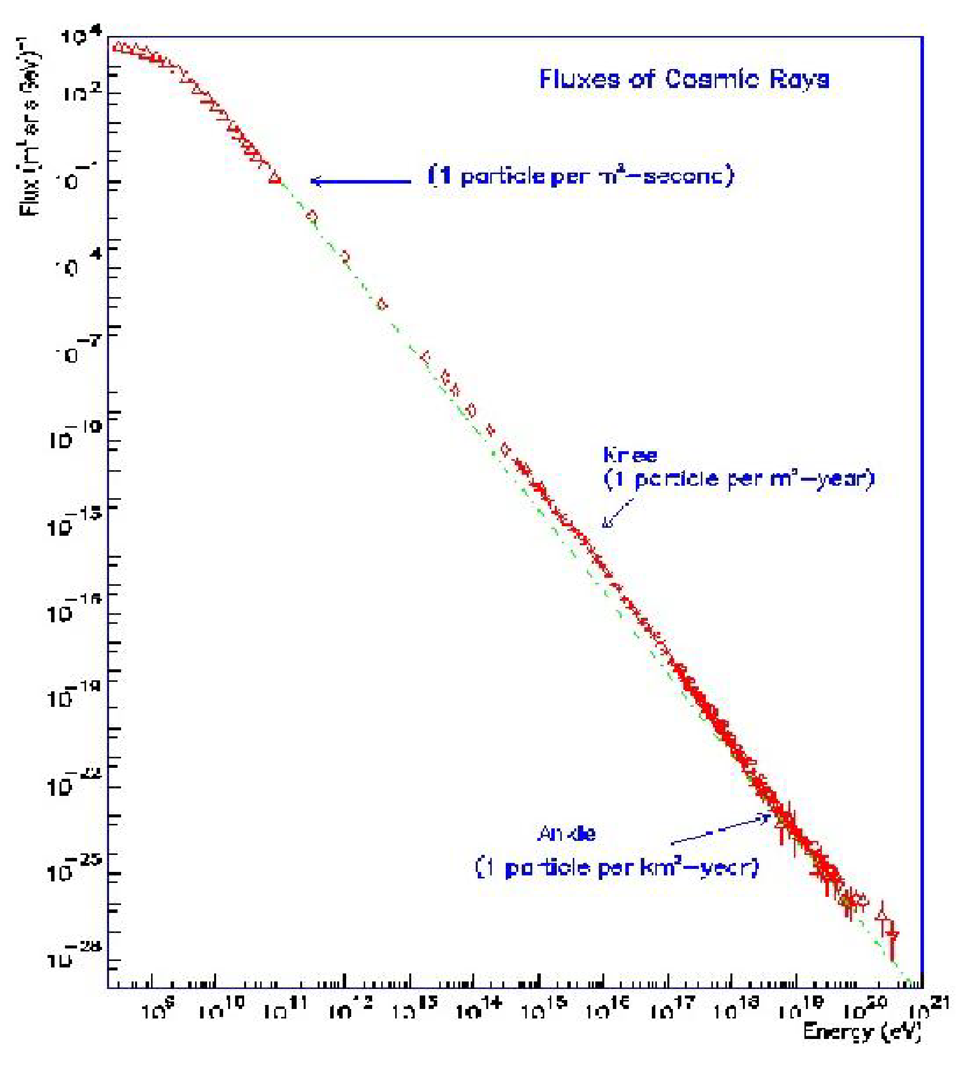
Pinch?

- **Resistance in line current**
  - **Current carried by PeV pairs**
  - **Resistance due to radiation reaction**
  - **Pairs undergo poloidal gyrations which radiate in all directions**
  - **Relativistic drift along direction of current**
  - **Compose current from orbits self-consistently**
  - **Illustration of Poynting’s theorem!**
  - **Variation due to instability of pinch**
    - Like a “slinky”
    - Observed in other nebulae

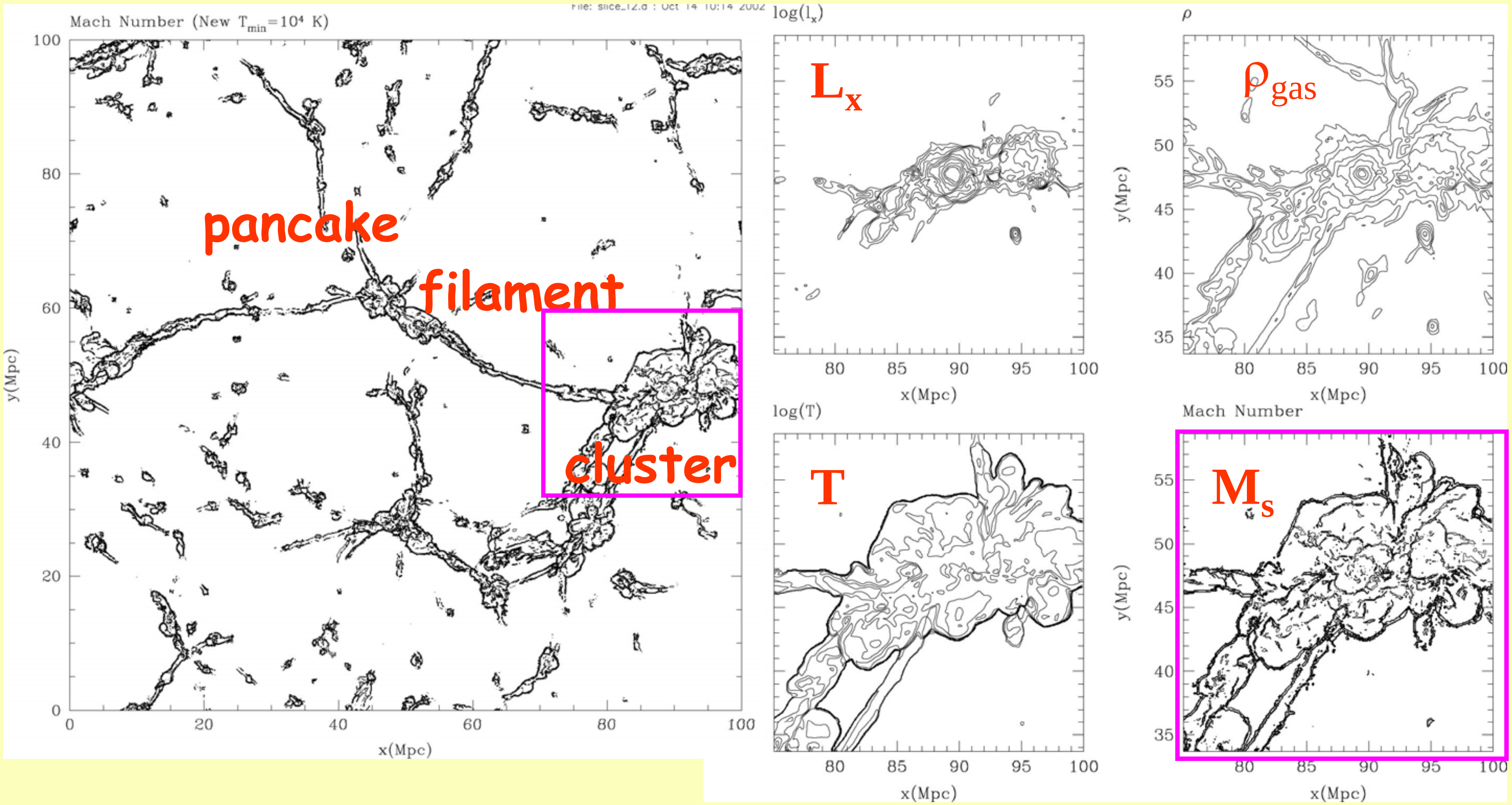


Ultra High Energy Cosmic Rays

- **Zevatrons?**
  - **Top down exotica**
    - GZK cutoff
    - EM channel not seen and hard to avoid
  - **Massive BH in AGN (~30-50 Mpc)**
    - AGN may be too weak
    - Acceleration must be remote from BH
  - **Gamma-Ray Bursts**
    - Stellar BH or millisecond magnetar?
    - Too distant? Too much radiation?
  - **Cluster Shocks (Norman,Ryu,Bohringer…)**
    - High Mach accretion shocks
    - Hard to accelerate p to ZeV energy
    - Heavy elements may be predicted
    - e.g. Fe; range ~ 10 Mpc?
    - Composition controversial
    - Analysis should be aided by LHC



Shocks in Structure Formation Simulations (Ryu et al 2003)



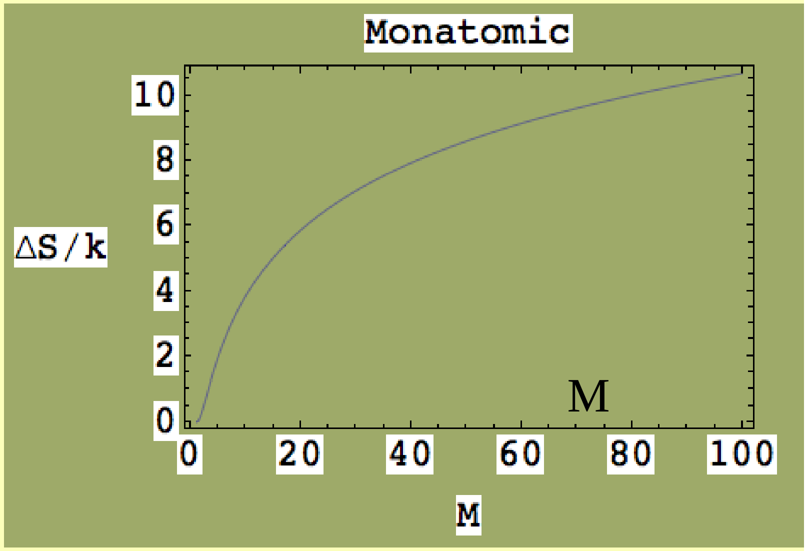
(100 Mpc/*h*)^2 2D slice

Simulations exhibit high M shocks

LCDM simulation with 1024^3 cells, computational box: $(100h^{-1}\ \text{Mpc})^3$, TVD: grid-based Eulerian hydro code

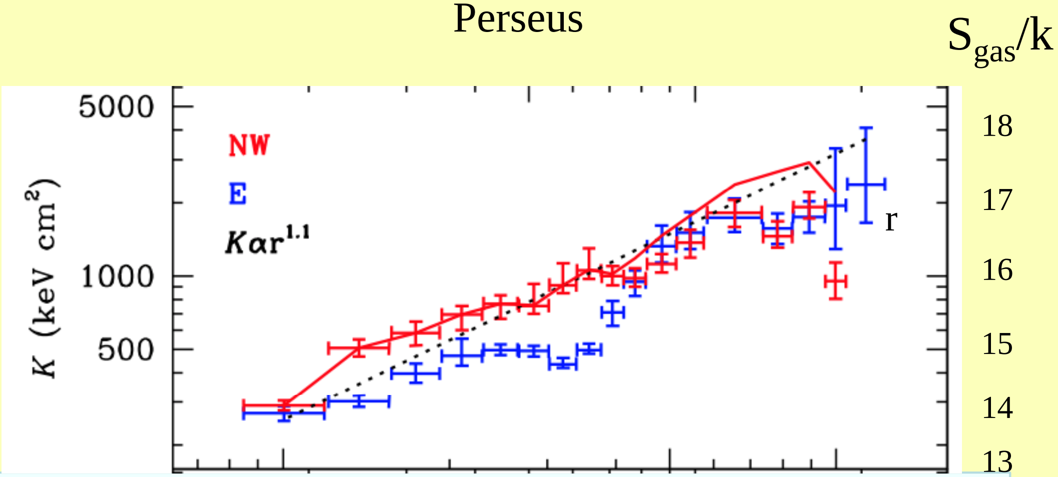
Entropy Matters

- S_{gas}=1.5 ln[(T/T_{rec})(n/n_{rec})$^{-2/3}$]k (relative to recombination)
  - Much more in CMB
- Shocks create gas entropy
  - $\Delta S[M]=1.5\ln[(5M^2/4-1/4)(1/4+3/4M^2)^{5/3}]k$



- Before reionization
  - Weak shocks M ~ 1-3
  - ΔS < k
- During reionization (z~10)
  - Ionization entropy
  - Moderate shocks M ~1-20
  - ΔS <3k

Simionescu et al
Perseus



- After reionization
  - May need ΔS as large as 10k
  - Would imply M~100
    - e.g. V~1000, s~10 km s^{-1}

Recent strong evidence for presence of high M accretion shocks around clusters

Summary

- Fermi is a great success
- Supernova shocks accelerate protons and electrons to >100 TeV AND create 100nT field
- Pulsar Wind Nebulae accelerate are efficient accelerators and create ~10PeV electrons?
- Accretion shocks surrounding clusters are good candidates to accelerate ~1 ZeV Fe nuclei
  - **Are they Fe (or lower z nuclei)?**
- Higher energy astrophysics provides impressive illustrations of high energy physics