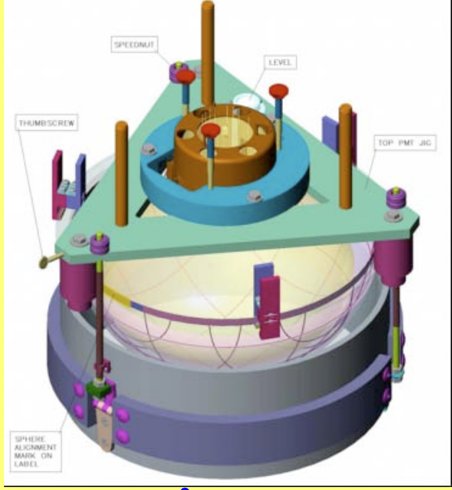
Cosmic Accelerators

1. General Principles

Roger Blandford
KIPAC
Stanford

Why build IceCube?

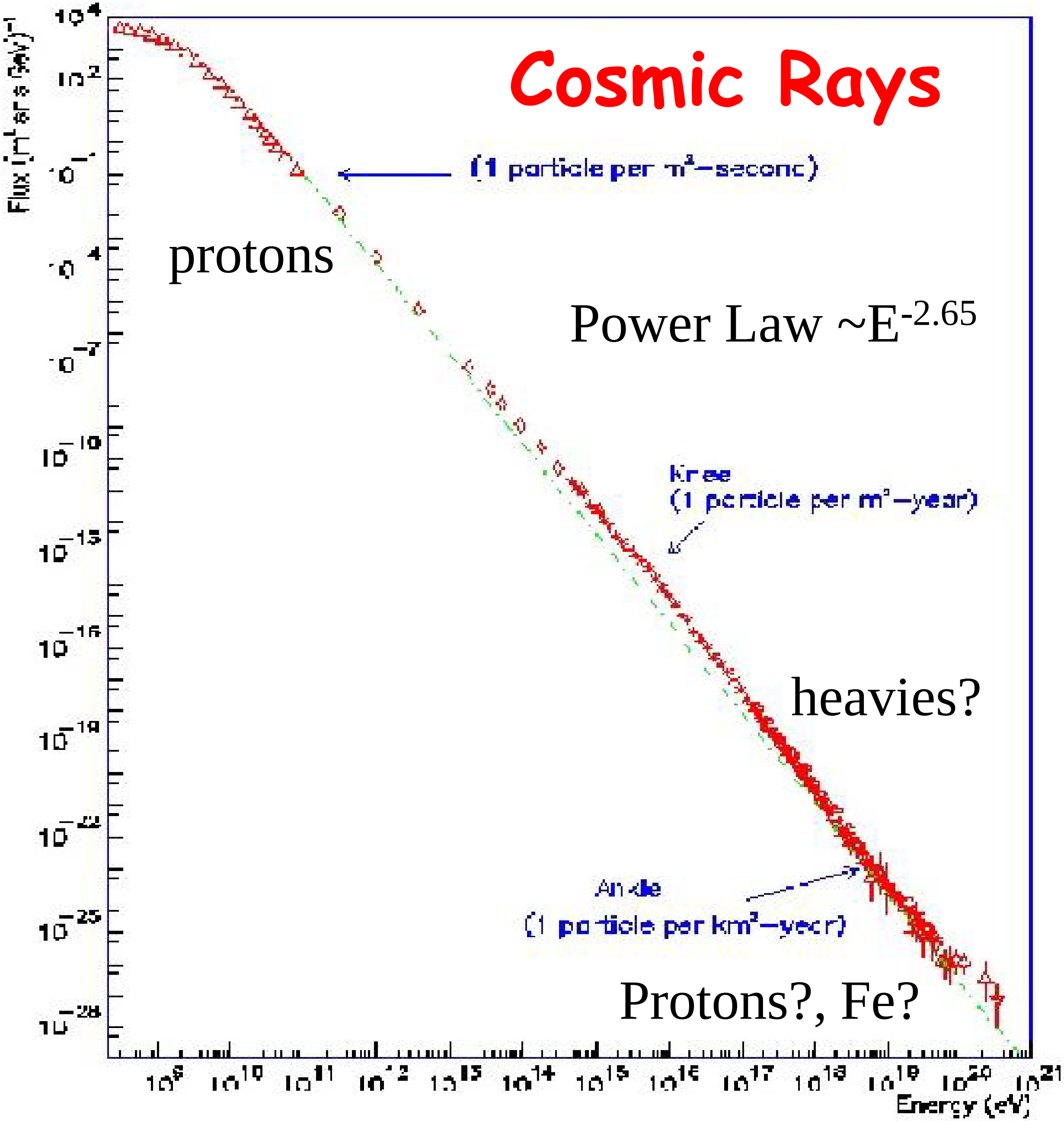


- **Cosmic ray protons? produced up to ~1 ZeV = 10^{21}eV = 10^{9} TeV = 160J!**
  - **At these energies p+p, p+γ… -> ν**
- **> 10 TeV γ-rays detected by ACTs from diverse sources**
  - **Higher energy γ-rays attenuated by pair production**
  - **Could be accompanied by protons and neutrinos**
- **Neutrinos escape from high energy density sources where protons and photons are trapped**
  - **Black Holes, Gamma Ray Bursts, Magnetars…**

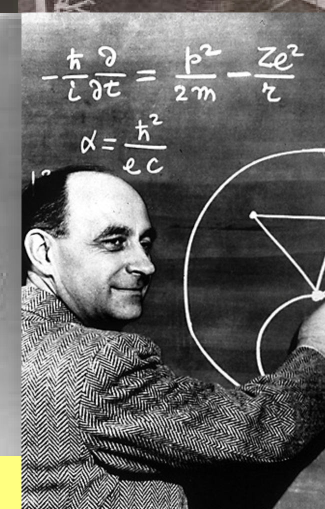
Even if we never find cosmic VHE neutrino sources, we still have to explain these enormous energies

These Lectures

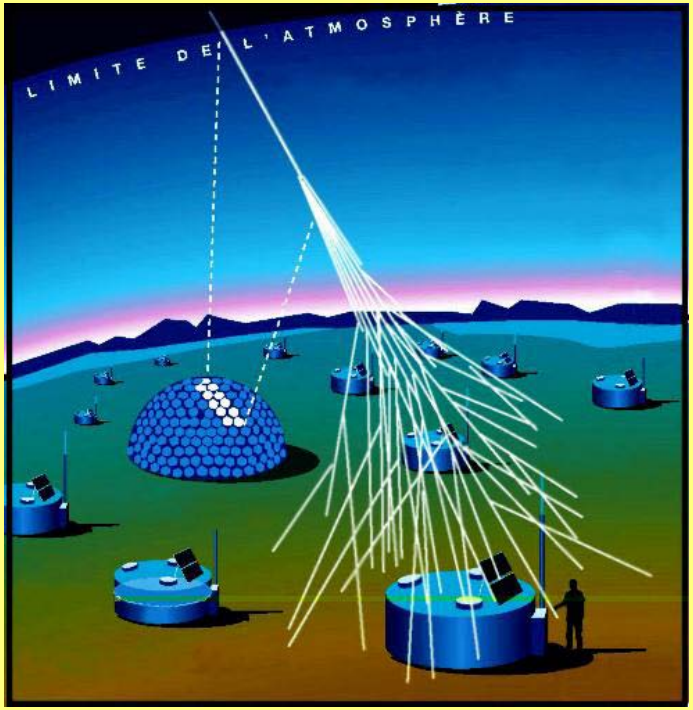
- First Lecture: Particle Acceleration
  - Principles, formalism, general deductions
- Second lecture: Detailed Mechanisms
  - Shocks, unipolar induction…
- Third lecture: Peter Meszaros
  - Specific sources, neutrino production, limits…



GeV TeV PeV EeV ZeV

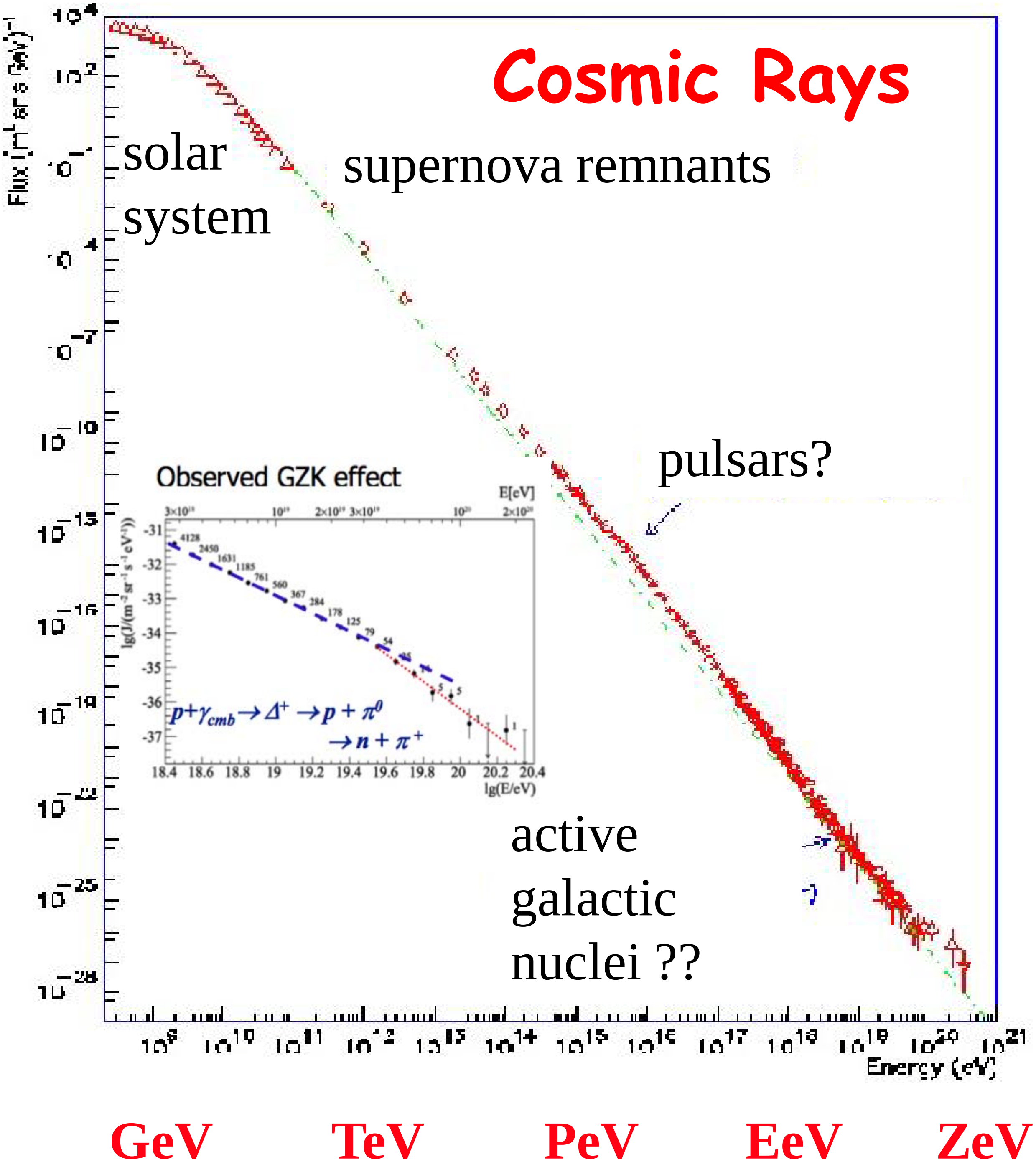


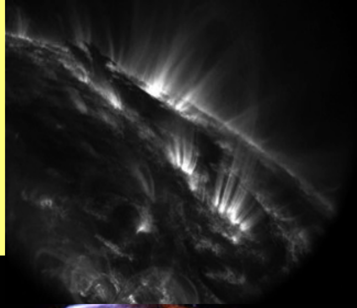
Pierre Auger Observatory

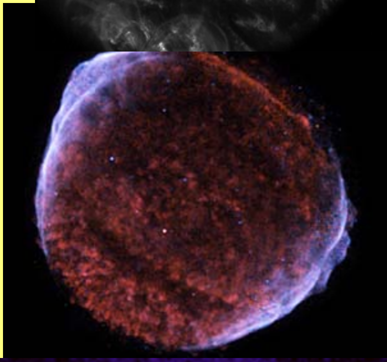


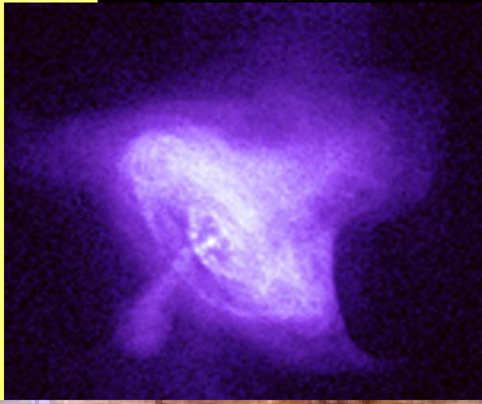
Measure UHECR using nitrogen fluorescence and water Cerenkov

Cosmic Rays


Flux (m^{-2} sr s GeV)$^{-1}$
solar system
supernova remnants
pulsars?
active galactic nuclei ??
Observed GZK effect
$p+\gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0$
$\rightarrow n + \pi^+$
E[eV]
lg(E/eV)
Energy (eV)
GeV
TeV
PeV
EeV
ZeV





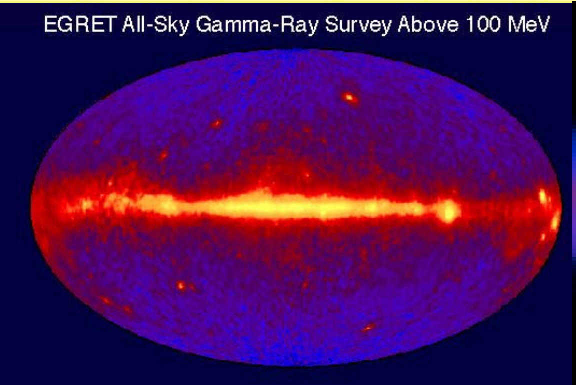


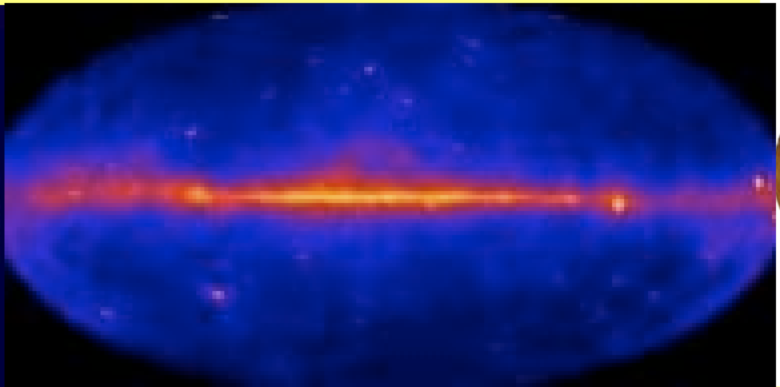
H.E.S.S., VERITAS…

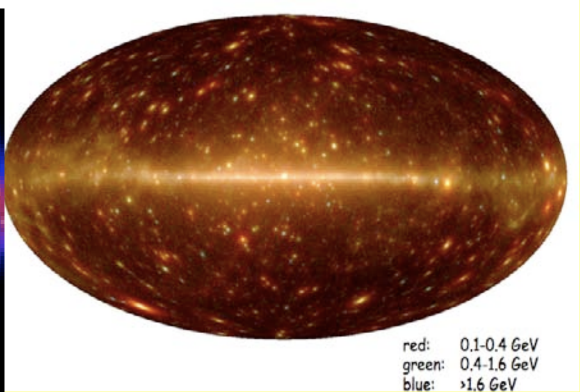
- **Measure ~ 0.1-10TeV gamma rays using atmospheric Cerenkov emission**

Fermi

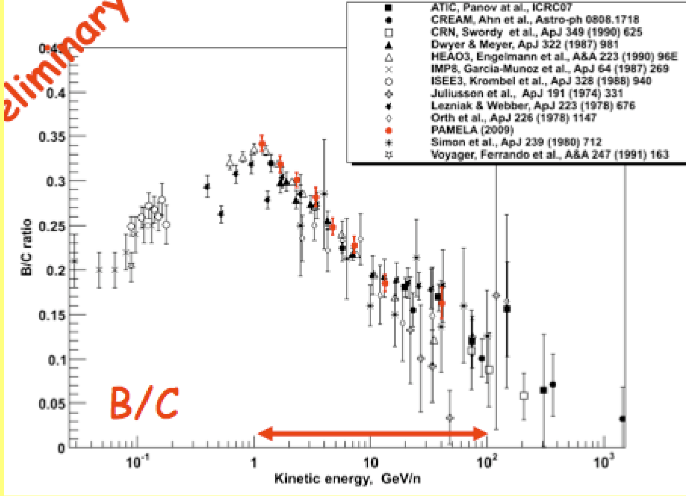
- Joint NASA-DOE-Italy- France-Japan-Sweden, Germany… mission
- Launch June 11 2008
  - Cape Canaveral
- LAT: 0.02-300 GeV
- All sky every 3hr
- ~100 x Compton Gamma Ray Observatory
- Nominal performance
- Discovering pulsars, GRBs, quasars…
- Measures gamma ray background, electron spectrum



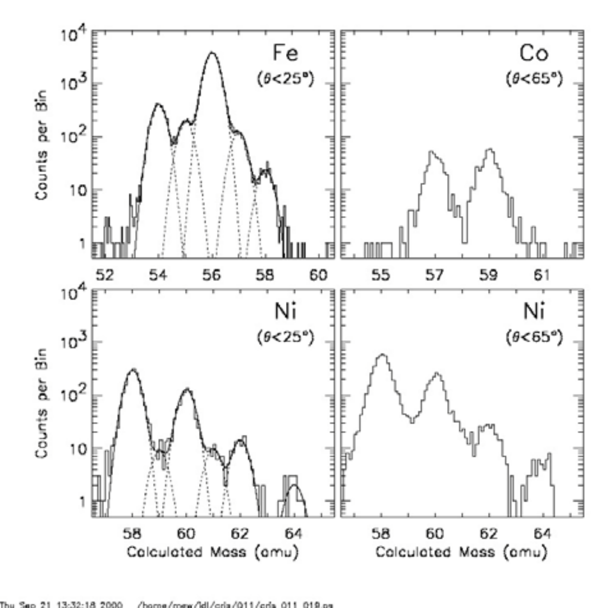


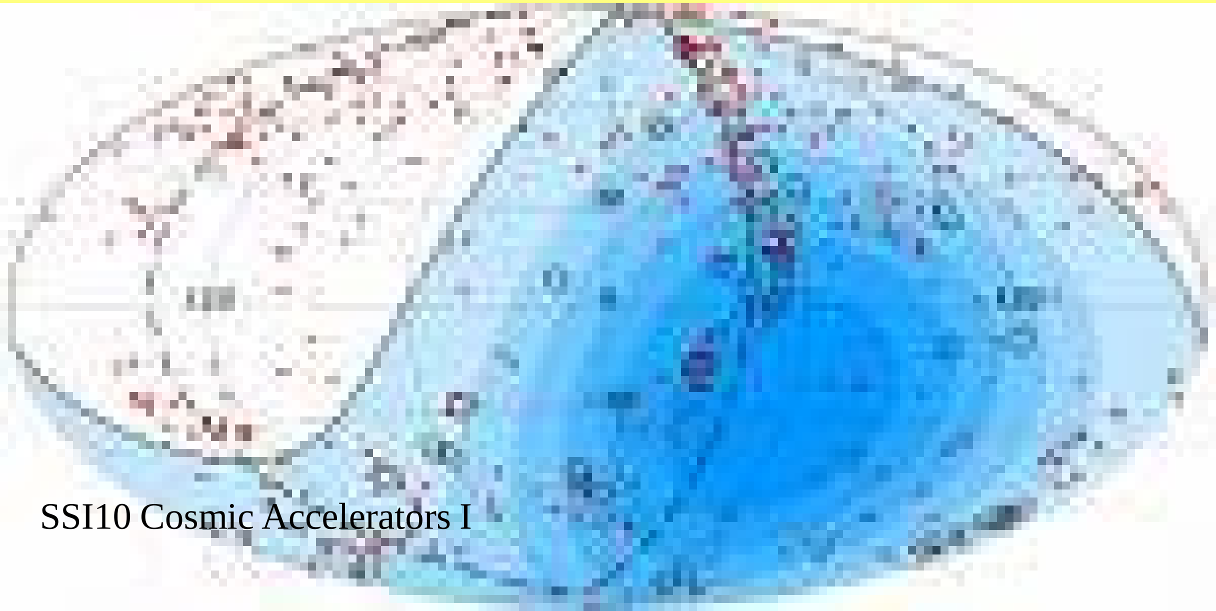


Some Deductions



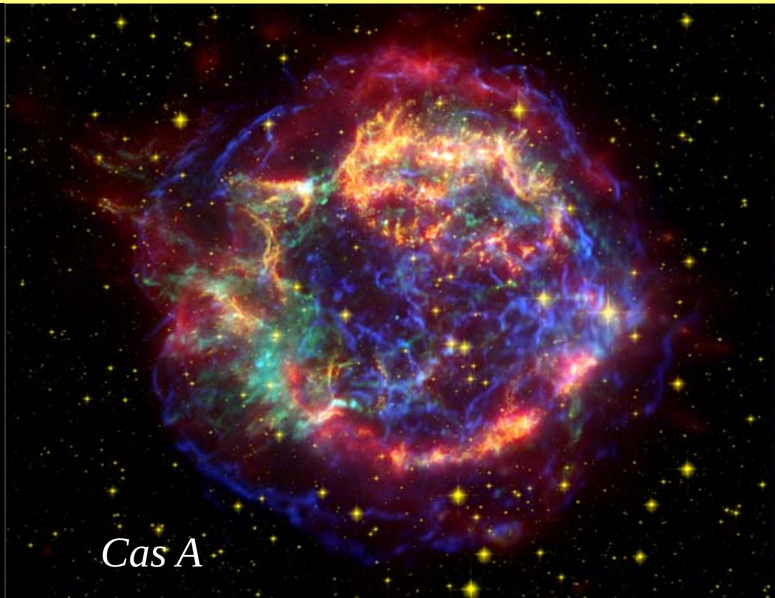
- $U_{GCR} \sim U_{GeV} \sim U_{ISM} \sim U_{CMB} \sim U_{star}$
- 0.1 Myr < t < 15 Myr
- $L_{CR} \sim U_{CR} M_{gas} c \lambda^{-1} \sim 3\times10^{33}$W $\sim 0.03 L_{SNR} \sim 10^{-3} L_{gal}$
- UHECR extragalactic $\mathcal{L} \sim 3 \times 10^{-5} \mathcal{L}_{gal}$
- Cosmic ray astronomy??

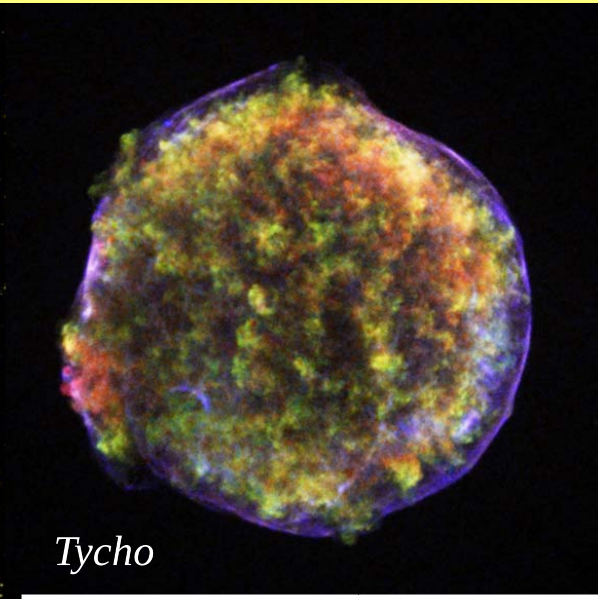


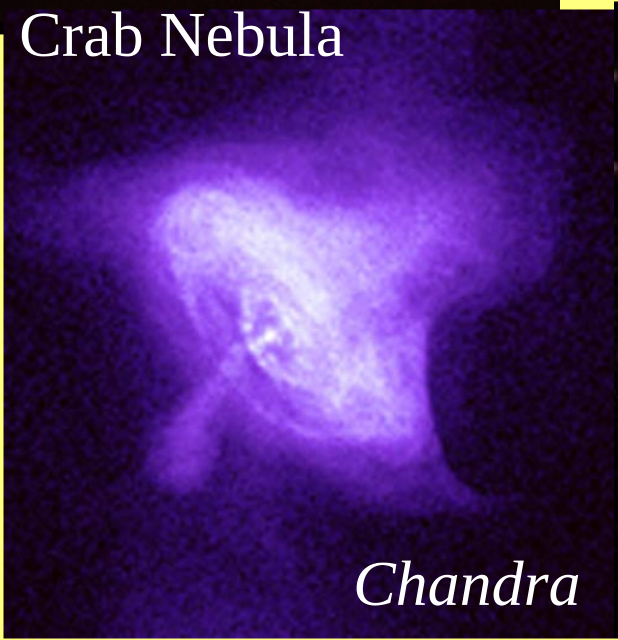


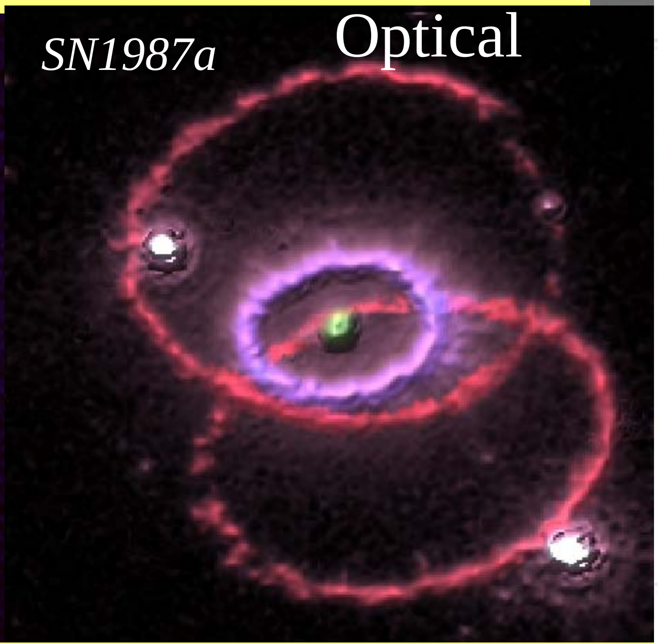
Supernova remnants

Power Law ~E^{-2}

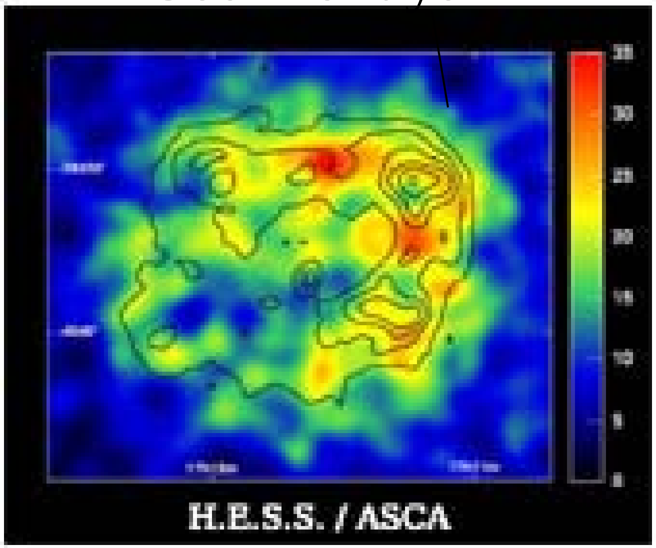




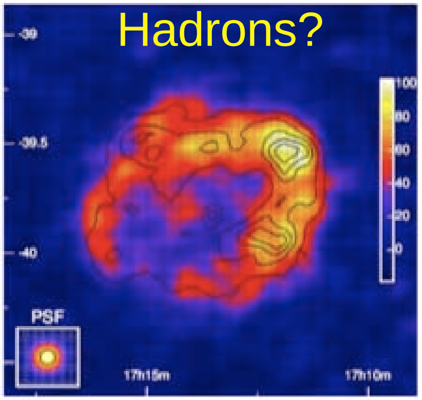


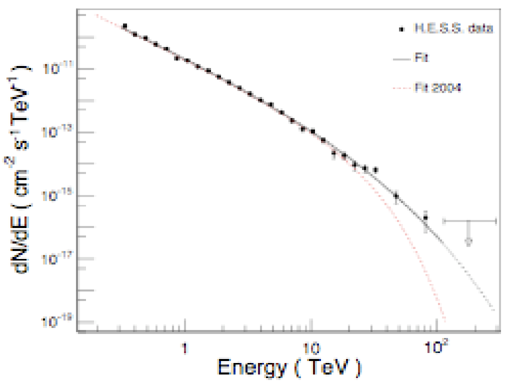


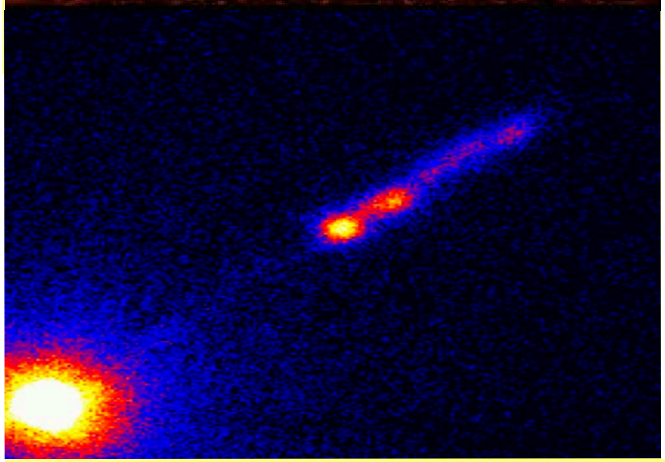
Cosmic rays

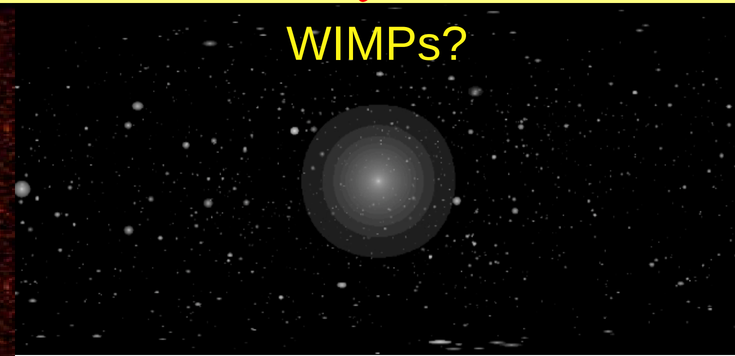


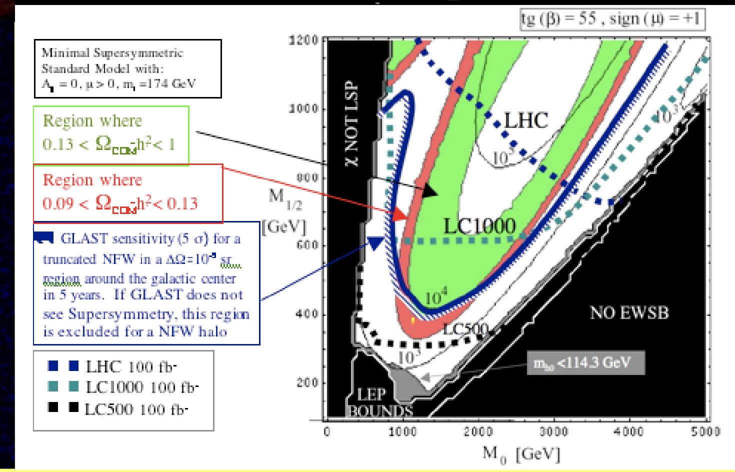
Hadrons vs Leptons vs WIMPS
(Pions vs Compton vs Annihilation)











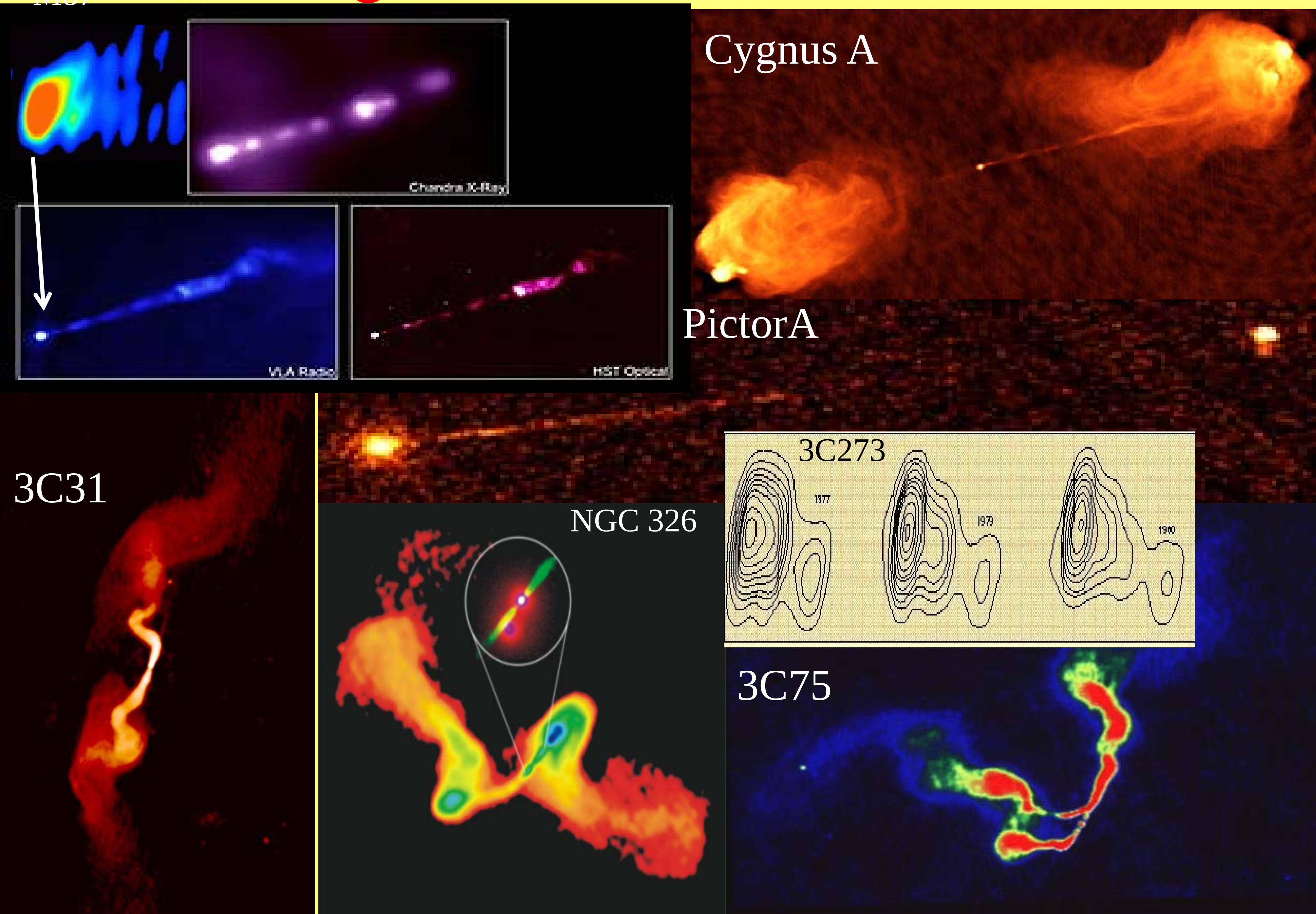
X-ray vs TeV
Fermi acceleration at shocks
Magnetic field amplification
Origin of cosmic rays?
Many puzzles remain
Fermi will interpolate

Relativistic jets created by massive black hole in galactic nuclei
Gamma ray emission at small radii
Inverse Compton radiation
2 min variability?
EM -> L -> H ? RFF?
UHECR?

If DM is cosmologically-generated, weakly interacting massive particle, there may be detectable annihilation from Galactic center and dwarf galaxies.
Constraints will be combined with results from LHC and underground direct searches.
Must understand diffuse background!

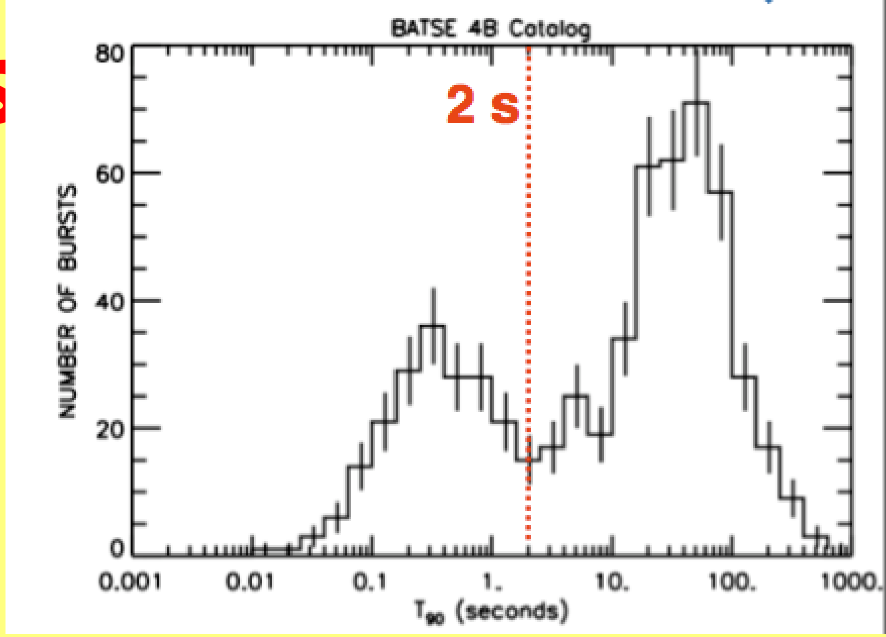
Extragalactic Jets

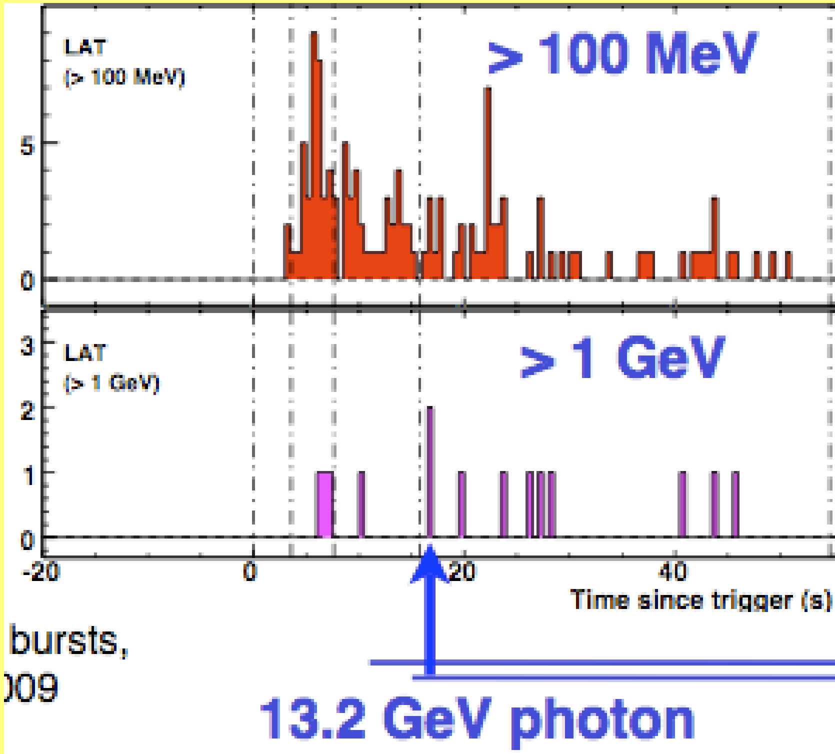
Power Law ~$E^{-2.4}$



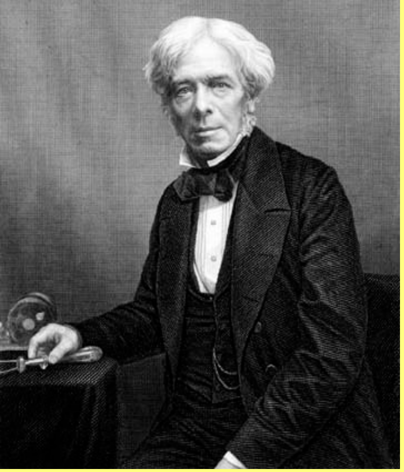
Gamma Ray Bursts

- Three types
  - Short -- NS coalescence
  - Long – Collapse of massive
  - Magnetars _ 0.3PG neutron
- Fermi (Swift)
  - 240 GBM
    - Broad spectral coverage
  - 9 LAT (7 long, 2 short)
    - 5 solar mass isotropic energy
    - GeV photons -> Γ~1000
    - Late emission (2000s)
    - Short bursts also SN??



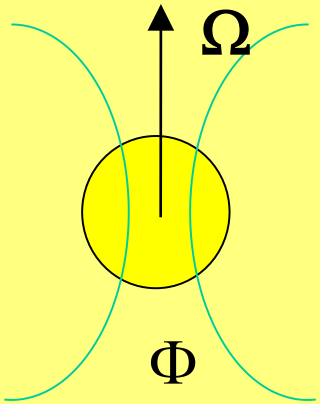


Particle Acceleration

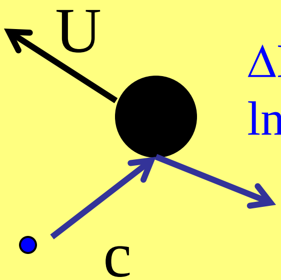


Unipolar Induction

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



Stochastic Acceleration



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

Particle Distribution Function

- MHD = Fluid mechanics (u, P, ρ), jxB,Maxwell
- Collisionless non-Maxwellian
- Details of velocity distribution matter
- dN=f(**p**,**x**,t)d**p**d**x**
- Lorentz invariant
- If isotropic, $$\frac{dN}{dE} = \frac{4\pi pE}{c^2} f$$

Vlasov Equation

- **Collisionless plasmas**

$$\frac{\partial f}{\partial t}+\nabla\cdot vf+\nabla_p\cdot\frac{dp}{dt}f=\frac{\partial f}{\partial t}+v\cdot\nabla f+\frac{dp}{dt}.\nabla_p f=0$$

where

$$\frac{dp}{dt}=e(E+v\times B)$$

and $\rho=e\int dpf;\quad j=e\int dpvf$ **+ Maxwell**

Fokker-Planck Equation

- **Markov Process. PDF depends upon where you just were; no long term memory**

$$\frac{\partial f}{\partial t} + \ldots = \nabla_p \cdot [-\frac{\Delta p}{\Delta t} f + \frac{1}{2}\nabla_p \frac{\Delta p \Delta p}{\Delta t} f] = \frac{1}{2}\nabla_p \cdot \frac{\Delta p \Delta p}{\Delta t} \cdot \nabla_p f$$

- **Second inequality applies if no recoil**
- **Diffusion in momentum space**
- **cf** $\frac{\partial V}{\partial t} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + rS\frac{\partial V}{\partial S} - rV = 0.$ **Black-Scholes!**

Fermi/stochastic acceleration

- Proton gains energy thorough collisions with something heavy
- Gas cloud, wave…
- Momentum kick ~ p

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}p^2\frac{p^2}{\tau_a}\frac{\partial}{\partial p}f - \frac{f}{\tau_e} = S\delta(p) \Rightarrow f \propto p^{-q}; \quad q(q-3) = \frac{\tau_a}{\tau_e}$$

- Why special q; injection?

Wave scattering

- eg Alfven waves, $v_A \sim B/\rho^{1/2}$
- Wavelength ~ Larmor radius
  - $\omega - k_{\|} v_{\|} = n\Omega_g$; $\Omega_g \sim E^{-1}$
- Pitch angle scattering $D_{\phi\phi} \sim \Omega_g (dB/B)^2$
- $L_{mfp} \sim v/D_{\phi\phi}$; $D_{xx} \sim v l_{mfp}$
- $D_{pp} \sim p^2 \omega (v_A/v)^2 (dB/B)^2$
- VERY SLOW, Magnetosonic waves better
  - Landau damping
- Much better in relativistic plasmas, $v_A \sim c$

Compton Scattering

- Photons Compton scatter off electrons

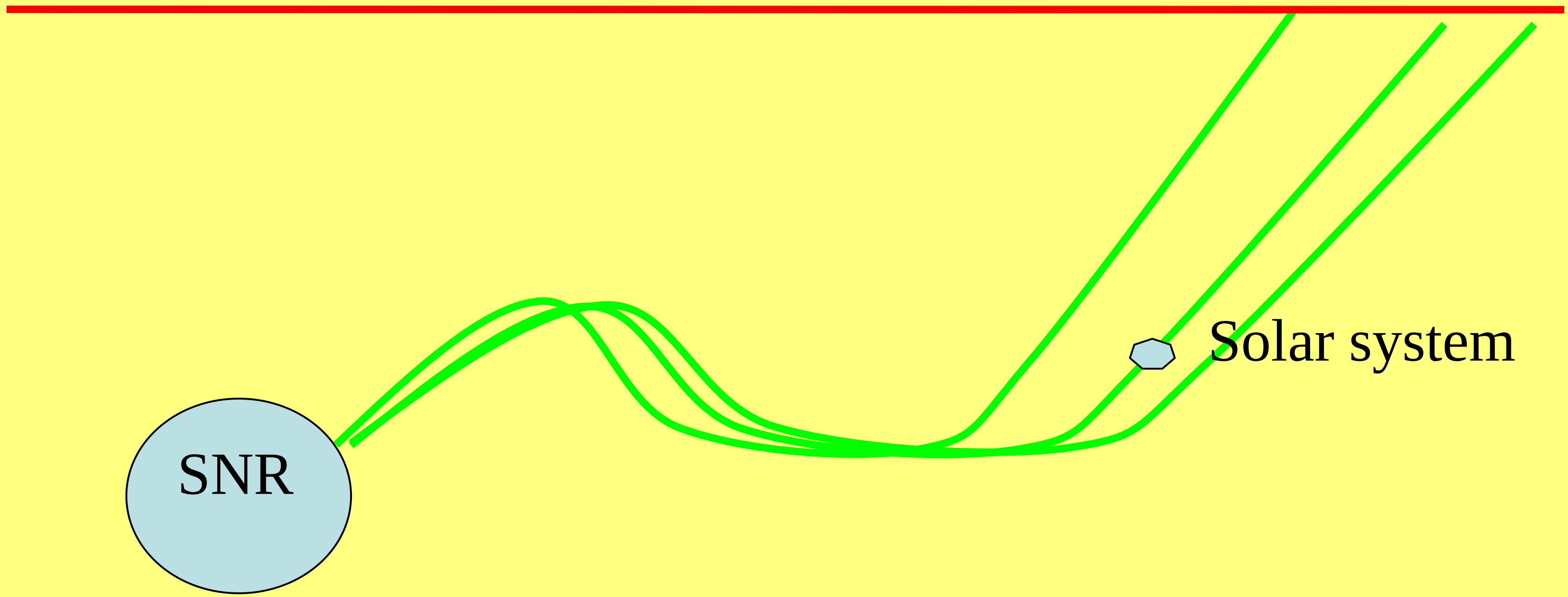
$$\frac{\partial n}{\partial y} = \left(\frac{1}{x^2}\right)\cdot\frac{\partial}{\partial x}\left[x^4\left(\frac{\partial n}{\partial x}+n+n^2\right)\right] \quad x \equiv \frac{h\nu}{k_B T} \quad y \equiv \left(\frac{k_B T}{m_e c^2}\right) N_e \sigma_T c t$$

- Kompaneets equation
- n is photon occupation number
- nonlinear term; Dirac-Kaptiza, induced Compton effect
- Purely classical; =>wave kinetic theory

Wave Kinetics

- Plasma turbulence
  - Wave-wave interaction; energy->shorter wavelength
  - Interact with a range of particle energies
- Waves also created by instabilities of velocity distribution function
  - Landau damping negative when $\frac{\partial f}{\partial p} > 0$
  - Stream instability when $v > v_A$
- Governs spatial transport of cosmic rays

Halo

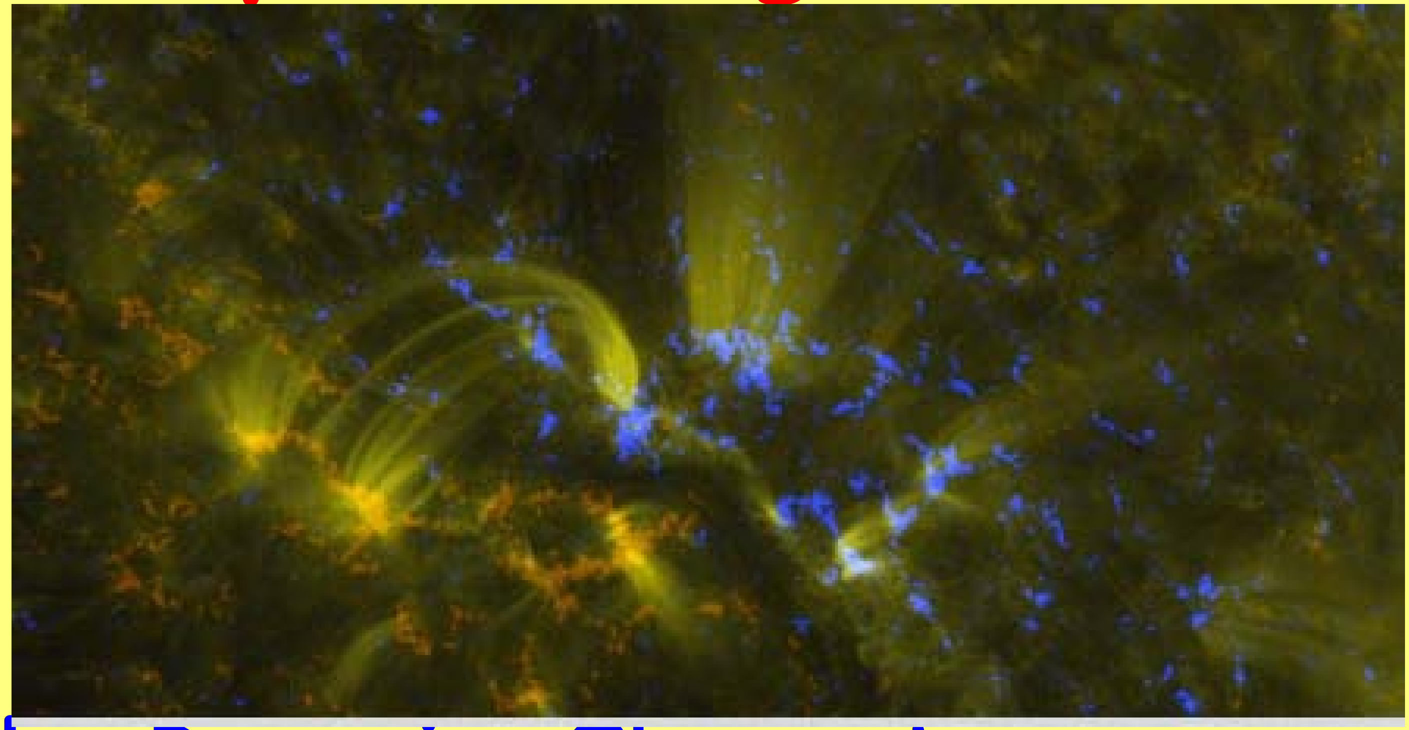


- **100Gev CR scatter off waves with $\lambda \sim r_L \sim 10^{14}$cm**
  - **Waves are part of local turbulence spectrum**
  - **Waves are self-generated by escaping particles $\langle v \rangle < V_A$**
- **CR escape times are energy-dependent**

C Violation

- **Protons create and scatter off RF waves**
  - **Protons are abundant**
  - **Protons create much turbulence**
  - **Protons diffuse slowly**
  - **Proton intensity relatively high**
- **Electrons create and scatter off LF waves**
  - **…Electron intensity relatively low**
  - **Effects are energy-dependnet**
- **Positrons create and scatter off RF waves**
  - **Follow the protons at the same rigidity**

Solar system is great laboratory



- Solar Dynamics Observatory
- Particle Acceleration in Solar Corona
- Solar flares involve explosive reconnection
  - Generally quite inefficient but relativistic promising

Summary

- Cosmic particle acceleration common, efficient and effective => Zevatrons
- Power laws common and a challenge to explain
- Electrostatic (unipolar induction) promising
- Stochastic (Fermi) accleleration also promising but only efficient in relativistic plasma
- Data improving rapidly
- Good motivation for seeking VHE neutrinos