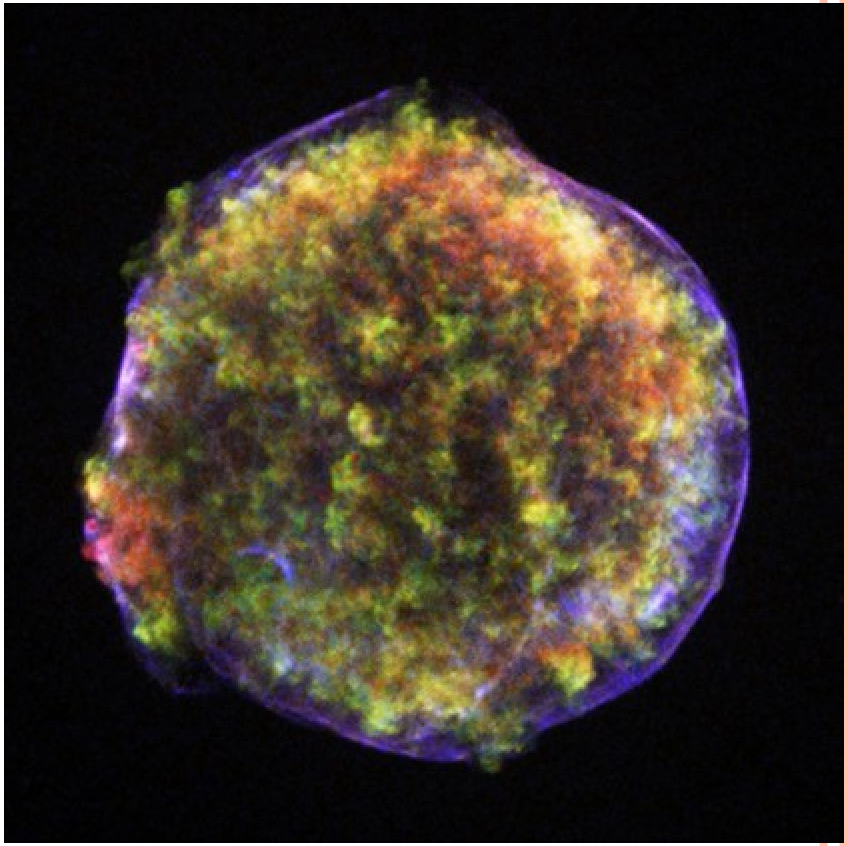
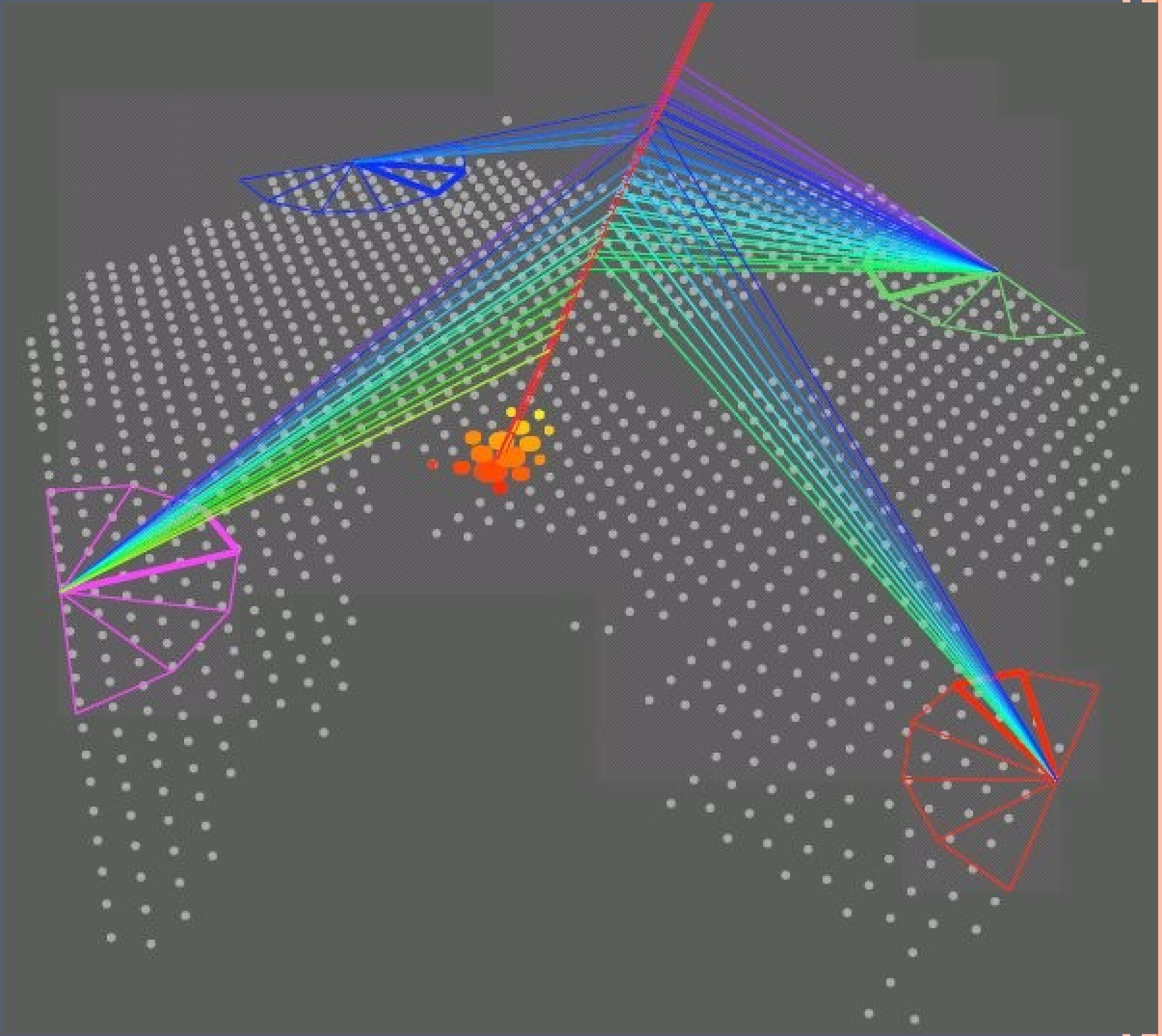


# ASTROPARTICLE PHYSICS LECTURE 1


Matthew Malek
University of Sheffield



# Overview

## What is Astroparticle Physics?

# What is Astroparticle Physics?

Various definitions! For this week, we use:

- **The use of particle physics technology to study astrophysical phenomena**
- Included:
  - neutrino astrophysics
  - gamma-ray astronomy
  - cosmic rays
  - dark matter
  - early-universe cosmology
- Sometimes also included:
  - cosmic microwave background
  - gravitational waves
  - neutrino masses (especially $0\nu\beta\beta$)

coherent field with a lot of common factors

***High Energy Astroparticle Physics***

someone else's problem!

not very particulate

not very astrophysical

# Common Issues

- Low rates
  - fluxes of high-energy particles are small
  - neutrinos and dark matter have weak interactions
- → *Need for large detectors*
- No control over "beam"
  - harder to control backgrounds
  - harder to calibrate, e.g., energy resolution
- → *Signals can be difficult to establish and/or characterise*
  - *cf. solar and atmospheric neutrino oscillation*

# Related Fields

- Neutrino physics
  - Atmospheric neutrinos are technically "astroparticle physics" but have contributed more to understanding of neutrinos than to astrophysics
  - Somewhat similar situation for solar neutrinos
  - Long-baseline neutrino experiments can do low-energy neutrino astrophysics "for free"

- Nucleon decay
  - many detector technologies useful for both original purpose of Kamiokande (NDE = **N**ucleon **D**ecay **E**xperiment before **N**eutrino **D**etection **E**xperiment!)
  - Planned noble-liquid detectors may be able to do both nucleon decay experiments and dark matter searches

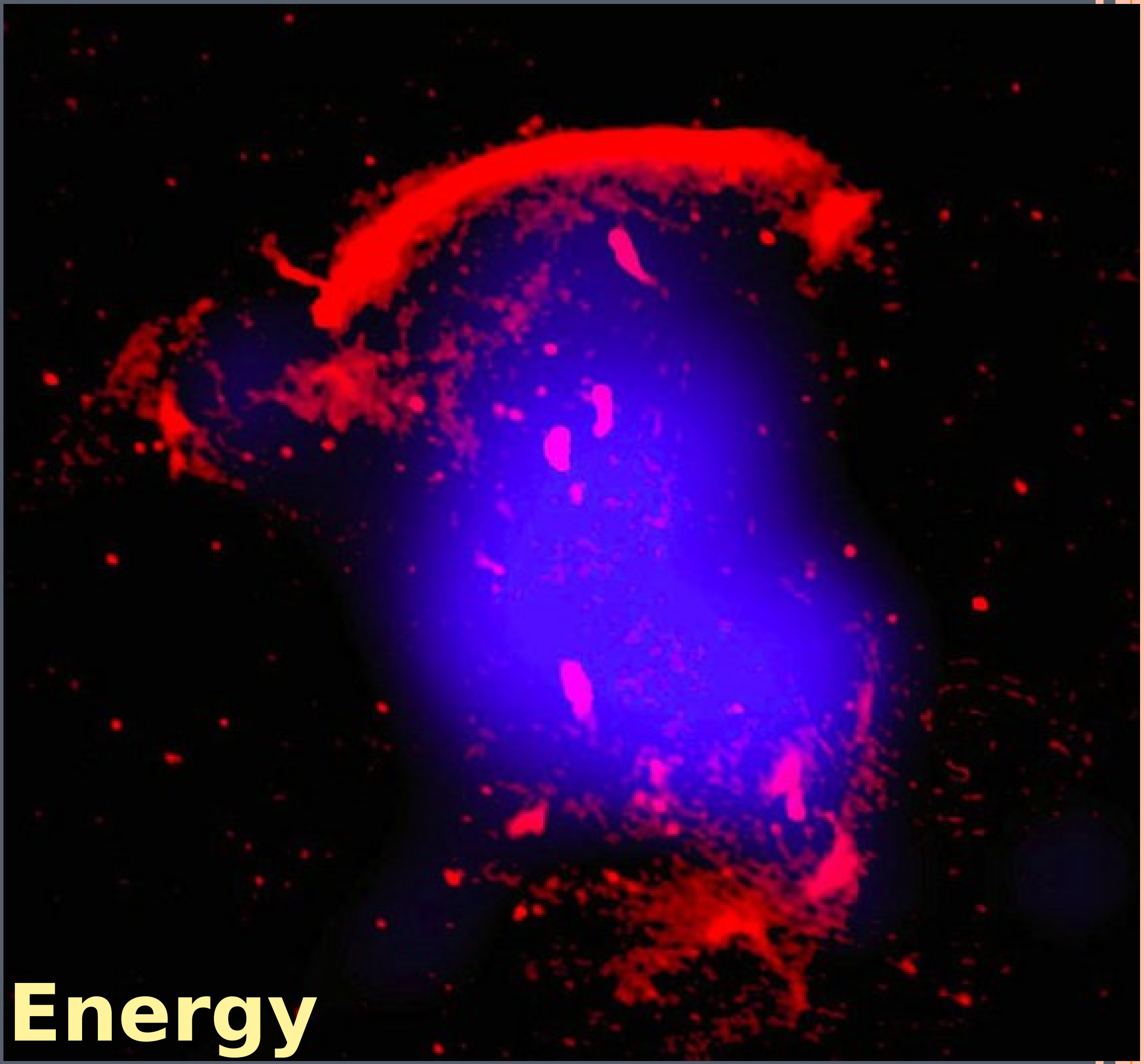
# Topics to be Covered

High energy astroparticle physics

- (cosmic rays, gammas, high-energy neutrinos)
  - sources
  - detection
  - results
  - prospects
- Dark matter
  - evidence
  - candidates
  - search techniques

Not Covering:

- solar neutrinos (SB)
- neutrino masses (SB)
- supernova neutrinos (no time)



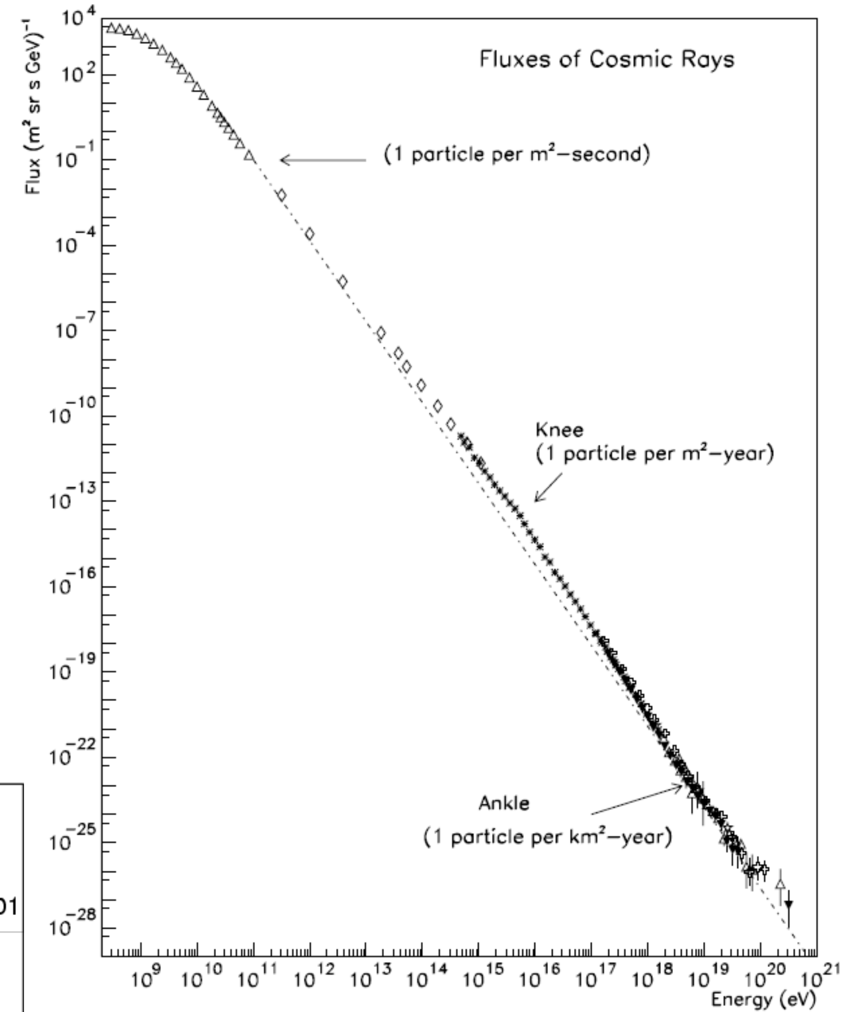
# High Energy Astroparticle Physics

<u>Acceleration Mechanisms</u>
Sources
Detection

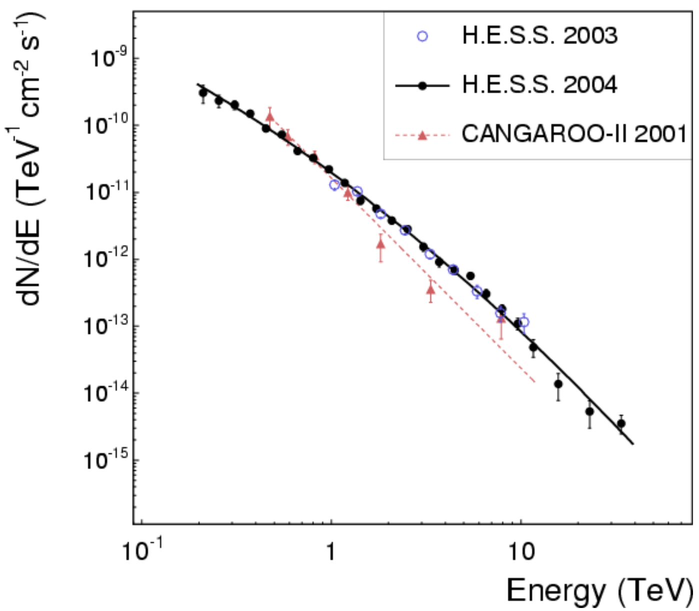
# Cosmic Accelerators

Cosmic rays and gamma rays are observed up to extremely

- high energies
- something must therefore
- accelerate them

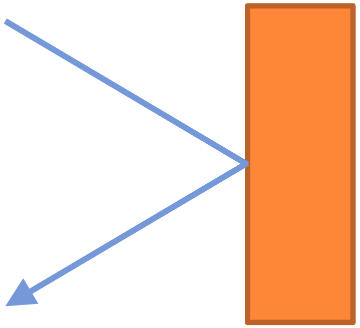



$10^9$ eV – $10^{21}$ eV




Note the power-law spectrum

# Acceleration Mechanisms



- Fermi Mechanism
  - energetic charged particles can gain energy by scattering off local magnetic turbulence (Fermi 1949)
  - Assume particle scatters off much more massive object moving with speed **u**.  Then in the c.o.m. frame (i.e., frame of massive object) its energy and momentum before the scatter are

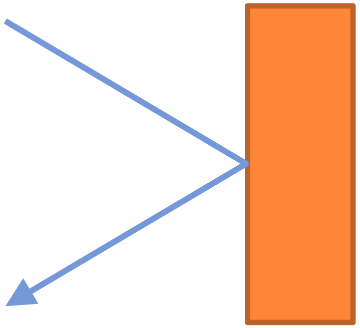
$$E' = \gamma_u (E + up\cos\theta)$$

$$p'_x = \gamma_u \left(p\cos\theta + uE/c^2\right)$$

- The particle scatters elastically: its energy is conserved and its *x*-momentum reversed.  In original (lab) frame

$$E_2 = \gamma_u (E' + up'_x) = \gamma_u^2 E \left[1 + \frac{2uv}{c^2}\cos\theta + \frac{u^2}{c^2}\right]$$

# Acceleration Mechanisms

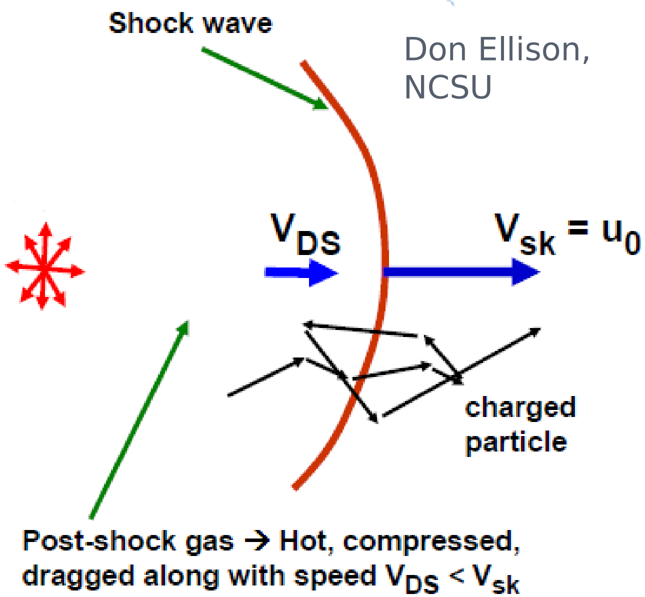


- Fermi Mechanism
  - energetic charged particles can gain energy by scattering off local magnetic turbulence (Fermi 1949)
  - We need to average over angle. Head-on collisions are slightly more likely than overtaking collisions, so middle term doesn't just go away. In relativistic limit we find:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{u}{c}\right)^2$$

    - Hence this process is known as **second-order Fermi acceleration**.
  - The good news
  - this produces a power law energy spectrum: $N(E) \propto E^{-x}$ where
    - $x = 1 + 1/\alpha\tau$, $\alpha$ is the rate of energy increase and $\tau$ is the residence time of the particle
  - The bad news
    - since $u << c$, it's slow and inefficient

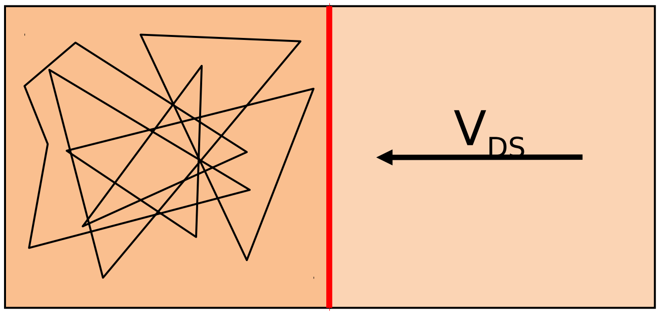
# Acceleration Mechanisms




Don Ellison, NCSU

## First-order Fermi Mechanism

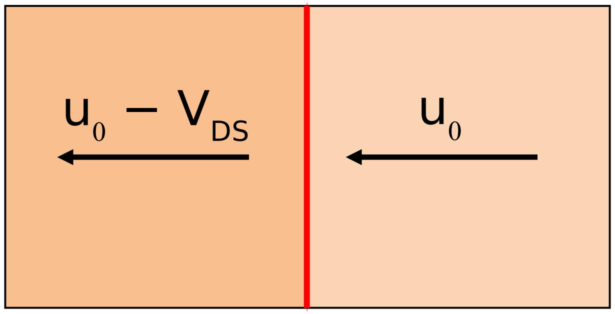
- (Diffusive Shock Acceleration)
- *O*(*u*/*c*) term gets lost in integral over
- angles—we could retrieve this if we
  - could arrange to have only head-on scatters
  - Consider shock wave as sketched above
  - high-energy particles will scatter so that their distribution is isotropic in the rest frame of the gas




Rest frame of dwnstream gas

- crossing shock **in either direction** produces head-on collision on average

# Acceleration Mechanisms




Rest frame of shock

- DSA, continued
- shock compresses gas, so density behind shock is $\rho^{2 > } \rho^{1}$

in rest frame of shock, ρ1u0 = ρ2u2 where u2 = u0 − VDS

for strong shock ρ2/ρ1 = (γ + 1)/(γ − 1) where γ is ratio of specific heats (= $^5/_3$ for hydrogen plasma); therefore

expect u2/u0 ≈ ¼

And gas approaches shock-crossing particle at speed *V* = ¾ u0

- if high-energy particles move randomly, probability of particle crossing shock at angle *θ* is *P*(*θ*) = 2 sin *θ* cos *θ* d*θ*, and its energy after crossing shock is *E'* ≈ *E*(1 + *pV* cos *θ*) (if *V* << *c*)
- therefore average energy gain per crossing is

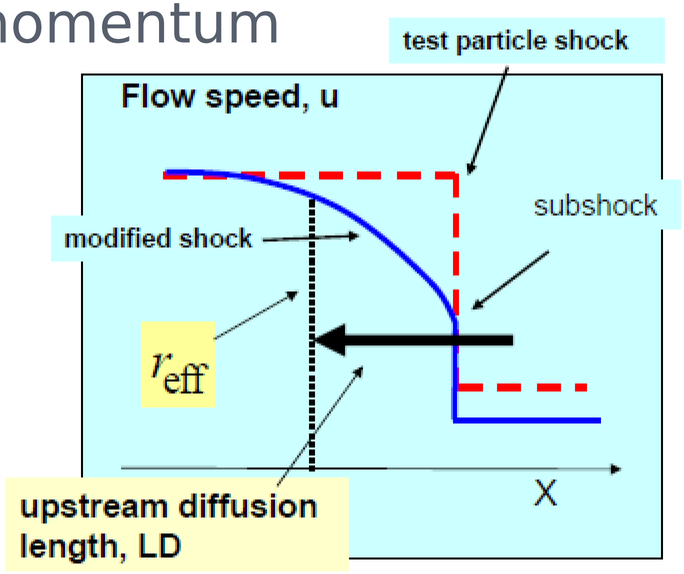
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{V}{c} \int_0^{\frac{\pi}{2}} 2\cos^2\theta \sin\theta \, d\theta = \frac{2}{3}\frac{V}{c}$$

# ACCELERATION MECHANISMS

- DSA spectrum
  - if average energy of particle after one collision is $E_1 = fE_0$, and if $P$ is probability that particle remains in acceleration region, then after $k$ collisions there are $N_k = N_0P^k$ particles with average energy $E_k = f^kE_0$.
  - Hence $\dfrac{\ln(N/N_0)}{\ln(E/E_0)} = \dfrac{\ln P}{\ln f}$, or $\dfrac{N}{N_0} = \left(\dfrac{E}{E_0}\right)^{\ln P/\ln f}$
  - This is the number of particles with $E \geq E_k$ (since some of these particles will go on to further collisions), so differential spectrum is $N(E)\,\mathrm{d}E \propto E^{(\ln P/\ln f)-1}\,\mathrm{d}E$
  - for DSA this comes to $N(E)\,\mathrm{d}E \propto E^{-(r+2)/(r-1)}\,\mathrm{d}E$, where $r = \rho_2/\rho_1$.
    - "universal" power law, independent of details of shock

# Additional Complications

- Above was a “test particle” approach, in which we assume most of the gas is unaffected
  - If acceleration is efficient, high momentum particles will modify the shock
  - Need a consistent treatment
  - which takes proper account
  - of this
    - mathematically challenging
    - but valid across very large
    - range of particle energies
    - Also need to allow for
  - possibility of relativistic shocks

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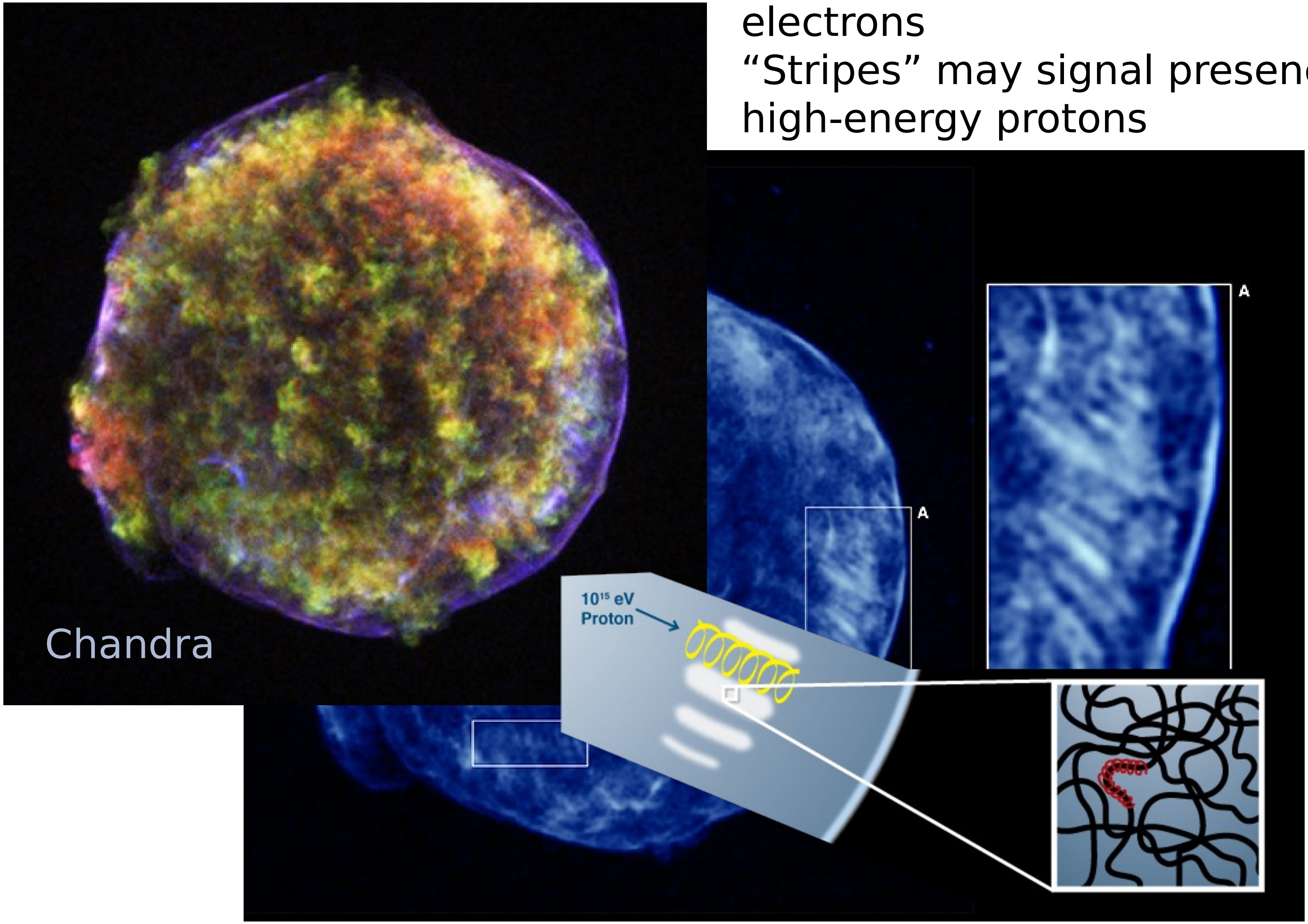
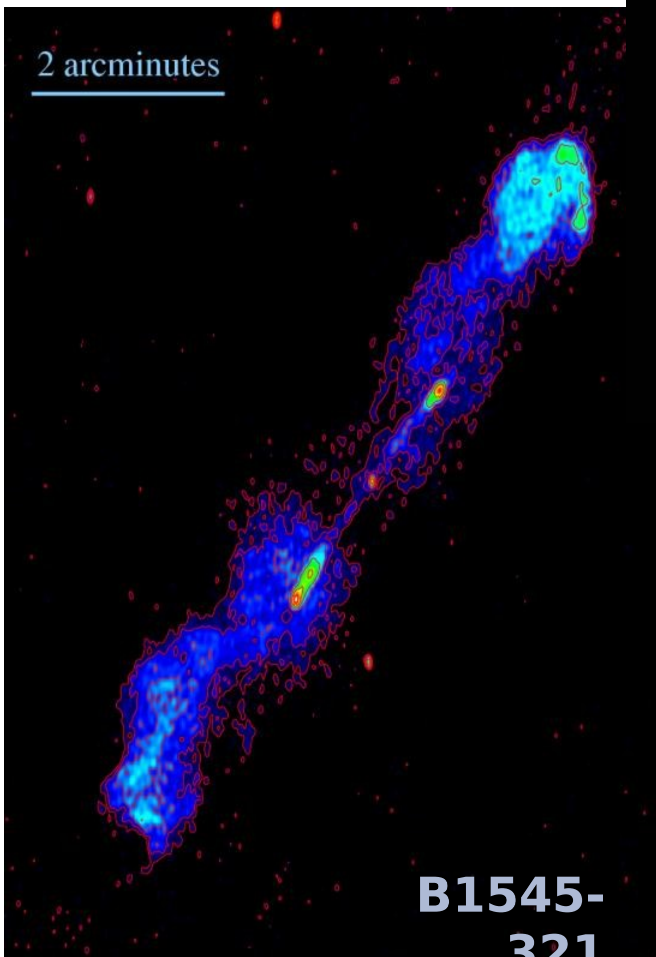
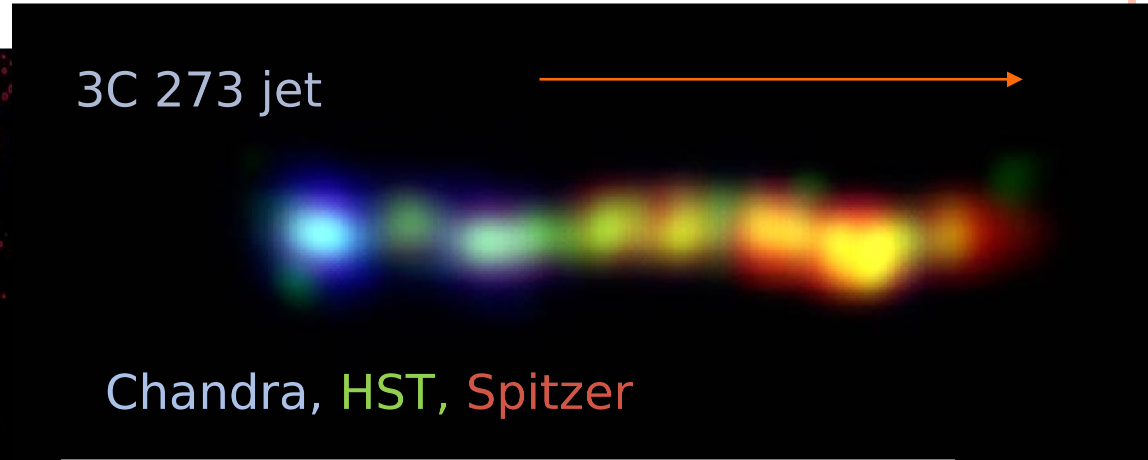
# Tycho’s Supernova (SN 1572)

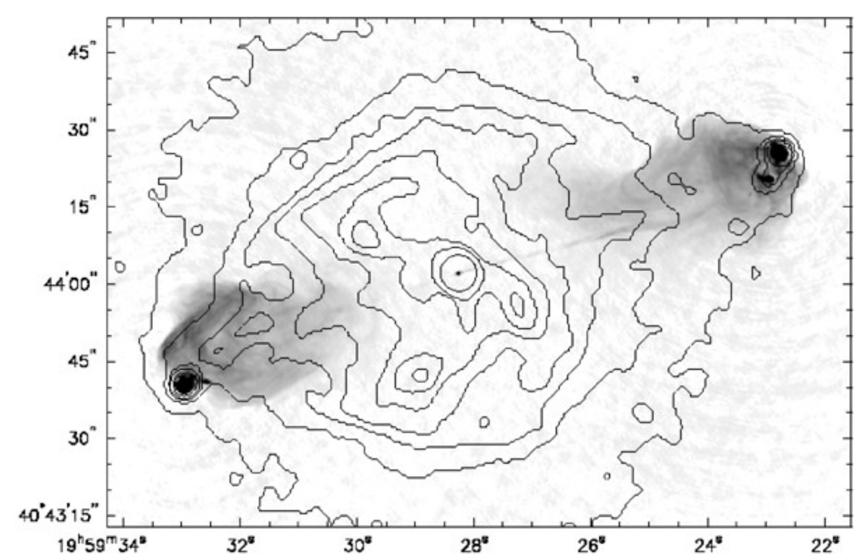
Shock front seen in high-energy electrons
“Stripes” may signal presence of high-energy protons



# Radio Galaxies




*13 cm wavelength ATCA image by L. Saripalli, R. Subrahmanyan and Udaya Shankar*

Cygnus A in X-ray (Chandra) and radio (VLA)

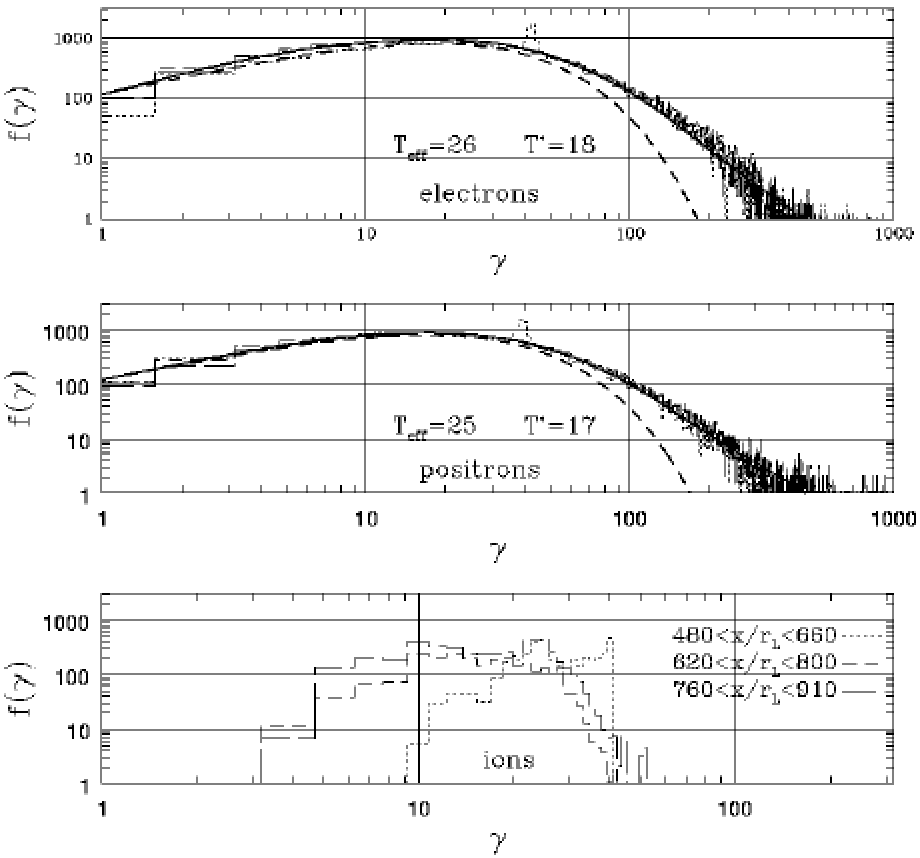
# Acceleration Mechanisms

- Resonant Cyclotron Scattering & Absorption (RSA)

acceleration of $e^+e^-$ in *relativistic* shock with magnetic field *perpendicular* to particle flow (so DSA doesn't work)

  - relevant to pulsar wind nebulae, e.g. Crab
- principle: consider relativistic plasma whose mass is dominated by ions ($m_i/m_{e\pm} >> 1$)
  - ions gyrate *coherently* in magnetic field
  - they therefore radiate ion cyclotron waves (Alfven waves) at shock front
  - positrons and electrons absorb these resonantly and are accelerated to high Lorentz factors with fairly high efficiency (few % of upstream energy density converted to non-thermal e±
- mechanism seems to account well for high-energy emission; not so clear that it deals with radio−IR emission
  - two different electron populations?
  - but consistency of spectra suggest otherwise

# RSA Simulations




- Simulation by Amato & Arons (*ApJ* **653** (2006) 325)
  - Input parameters:
    - $N_i/N_{e\pm} = 0.1$
    - $m_i/m_{e\pm} = 100$

72% of upstream energy density carried by ions

Result:

- 5% of upstream energy density winds up in accelerated e±

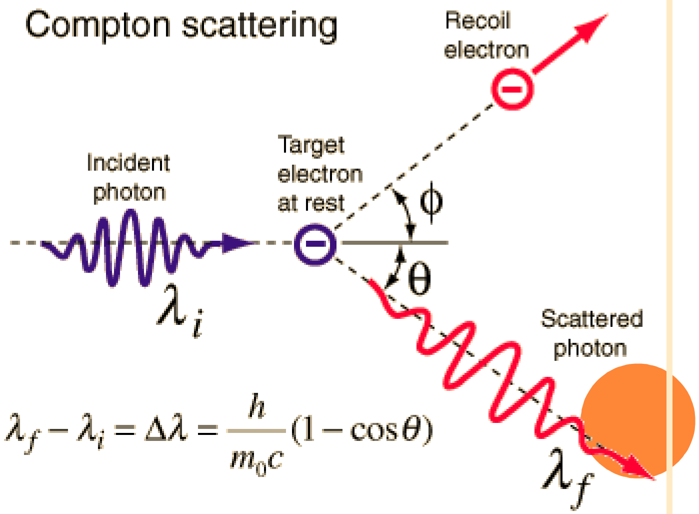
Less extreme ion loading, e.g., $m_i/m_{e\pm} = 20$, preferentially accelerates positrons

# Photons and Neutrinos

- High-energy photons and neutrinos are **secondary particles** produced by interactions of high-energy  primaries.
  - production mechanisms:
  - inverse Compton scattering (photons only)
  - Low-energy photon backscatters off high-energy electron.
  - In electron rest frame we have
  - $\Delta\lambda = h(1 - \cos\theta)/mc^2$.

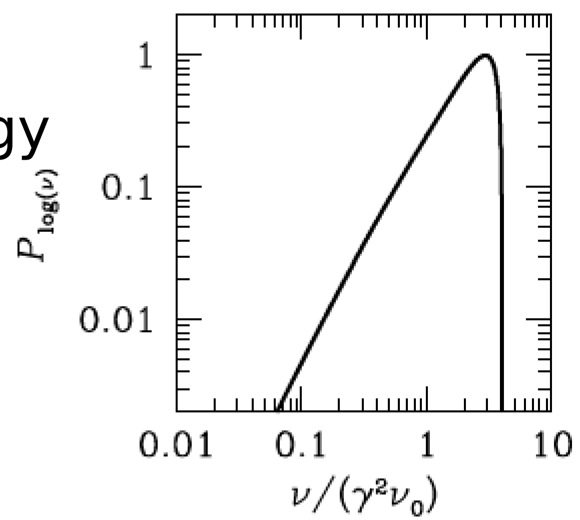
  - In lab frame, maximum energy gain
  - occurs in head-on collision:
  - $\nu \approx 4\gamma^2\nu_0$

  - Because of relativistic
  - aberration, spectrum is
    - sharply peaked near maximum

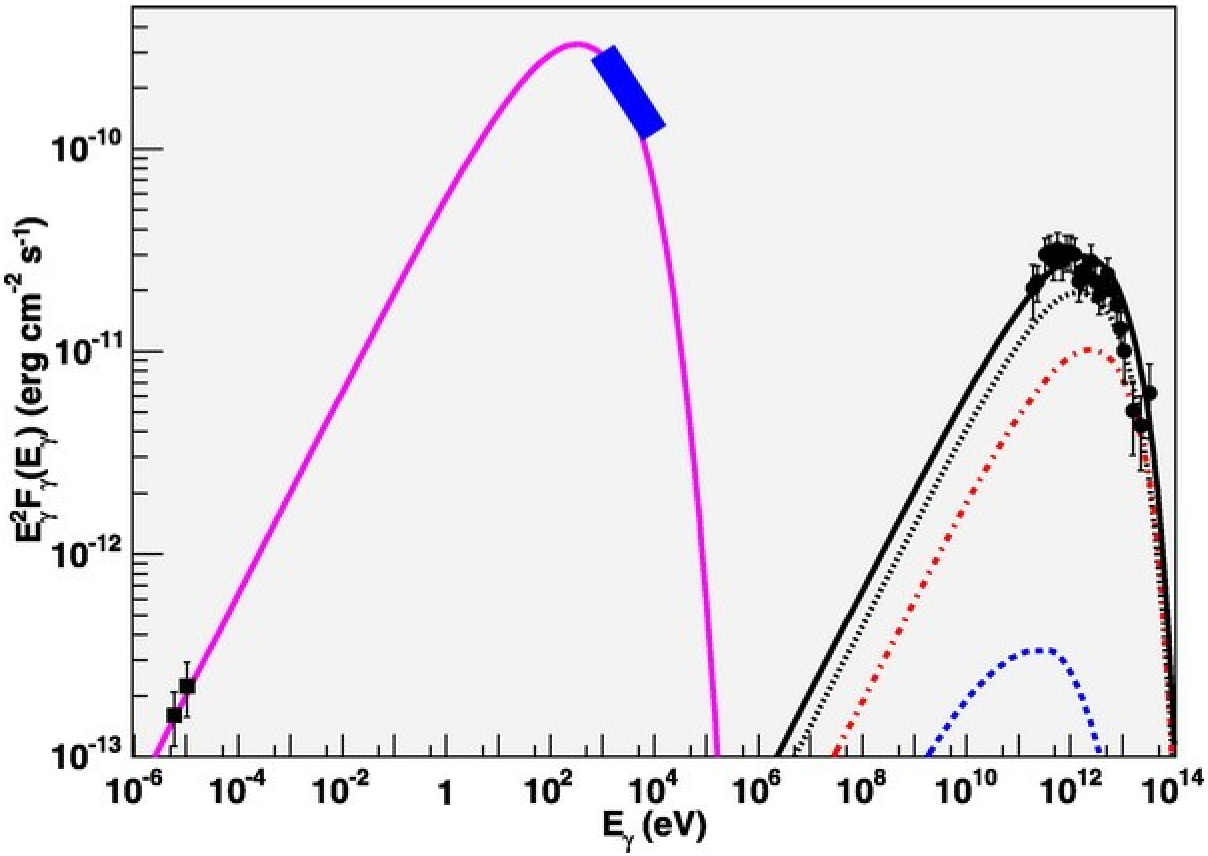


# Photons and Neutrinos

- inverse Compton scattering (continued)
- Plot shows calculated spectrum for
  - monoenergetic photons and electrons.
  - Plenty of potential sources of low-energy
  - photons to be upscattered:
  - synchrotron radiation produced by the
  - same population of fast electrons
    - (**synchrotron-self-Compton**, SSC)
    - cosmic microwave background
    - optical photons from source
  - For real objects, need to integrate over power-law spectrum of electrons and spectrum of photon source



# Spectrum of RXJ 1713.7−3946




Assumed distance 1 kpc, electron luminosity $1.5 \times 10^{30}$ W, B = 12 μG

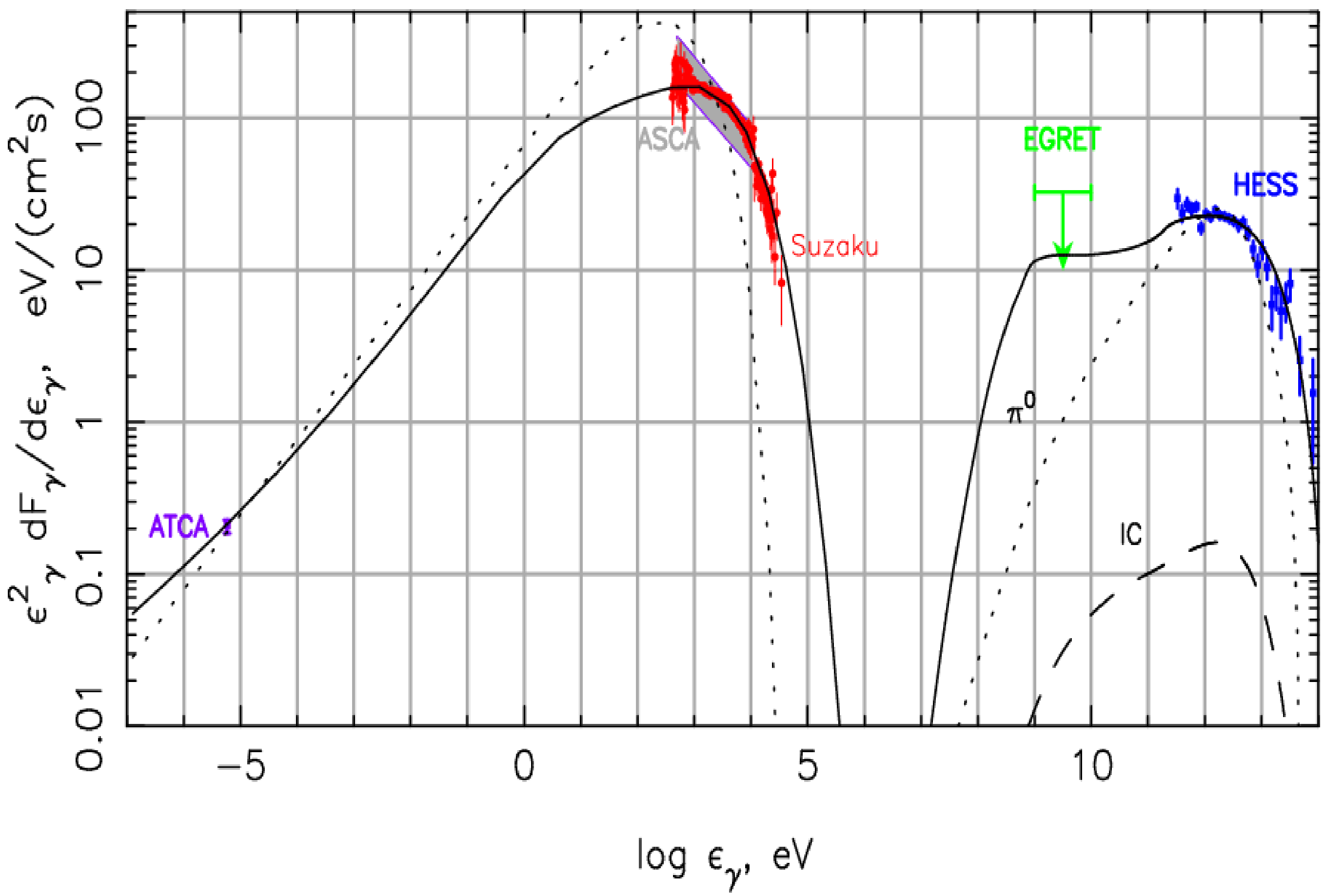
Source photons include optical, IR, CMB

Porter, Moskalenko & Strong, *ApJ* **648** (2006) L29-L32

# Photons and Neutrinos

- High-energy photons and neutrinos are **secondary particles** produced by interactions of high-energy  primaries.
  - production mechanisms:
  - pion decay (photons and neutrinos)
    - pions produced by high-energy proton colliding with either matter or photons (**pion photoproduction**)
    - neutral pions decay to γγ, charged to $\mu\nu_\mu$
      - mechanism produces both high-energy γ-rays and neutrinos
- Both mechanisms need population of relativistic charged particles
  - electrons for IC, protons for pion decay
- Unclear which dominates for observed TeV γ-ray sources

# Spectrum of RXJ 1713.7−3946, take 2



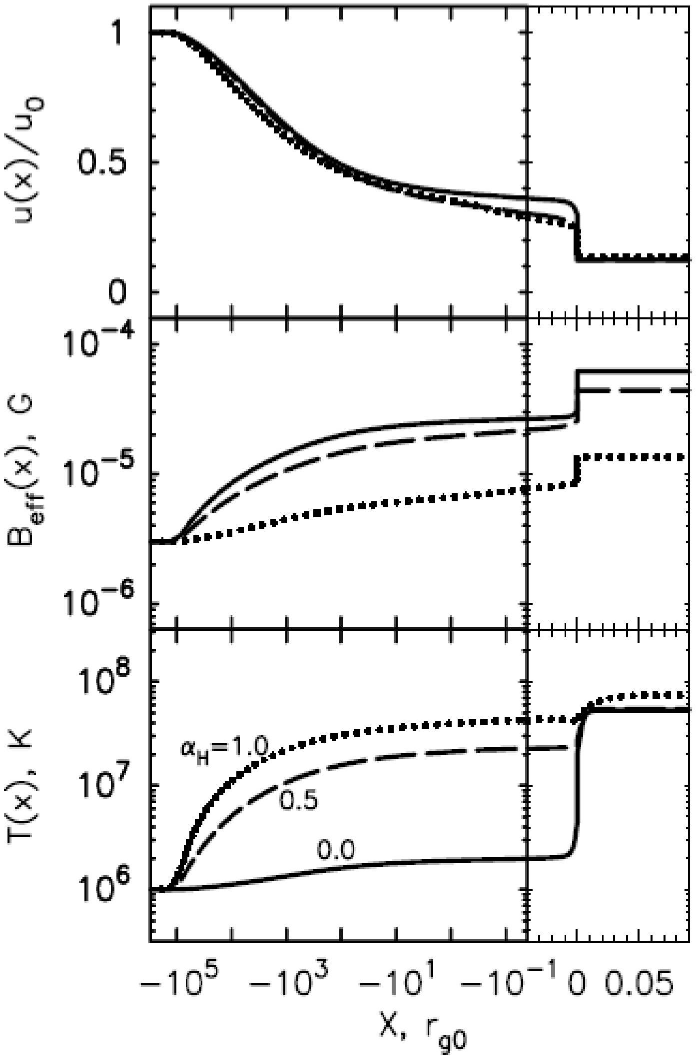

Uses DSA to accelerate protons.

B = 142 μG downstream of shock.

High B-field enhances synchrotron relative to inverse Compton

Berezhko & Völk, *A&A* **511** (2010) A34

# Are high magnetic fields plausible?




Vladimirov, Bykov, Ellison, *ApJ* **688** (2008) 1084

- Hadronic model fit to RXJ 1713 needs B > 100 μG
  - much larger than ambient Galactic B-fields
  - amplification required to make DSA fits self-consistent
  - fortunately modelling indicates that the interaction of the accelerated CRs with the magnetic field induces turbulence, resulting in amplification
- Direct observational evidence of high B-fields in some SNRs
- e.g. Cas A, B > 500 μG from comparing synchrotron & IC/ bremsstrahlung contributions
  - (Vink & Laming, *ApJ* **584** (2003) 758)

# Acceleration: Summary

- Observations made in high-energy astroparticle physics require that charged particles be accelerated to very high energies (~$10^{20}$ eV)
- Likely candidate is diffusive shock acceleration
  - requirement of shocks associated with magnetic fields found in many astrophysical objects, especially supernova remnants and AGN
  - synchrotron radiation from these objects direct evidence for population of fast electrons
  - much less evidence for presence of relativistic hadrons, but there must be some somewhere since we observe them in cosmic rays!
- TeV γ-rays can be produced by fast electrons using inverse Compton scattering, or by fast protons from $\pi^0$ decay
  - latter will also make TeV neutrinos, not yet observed

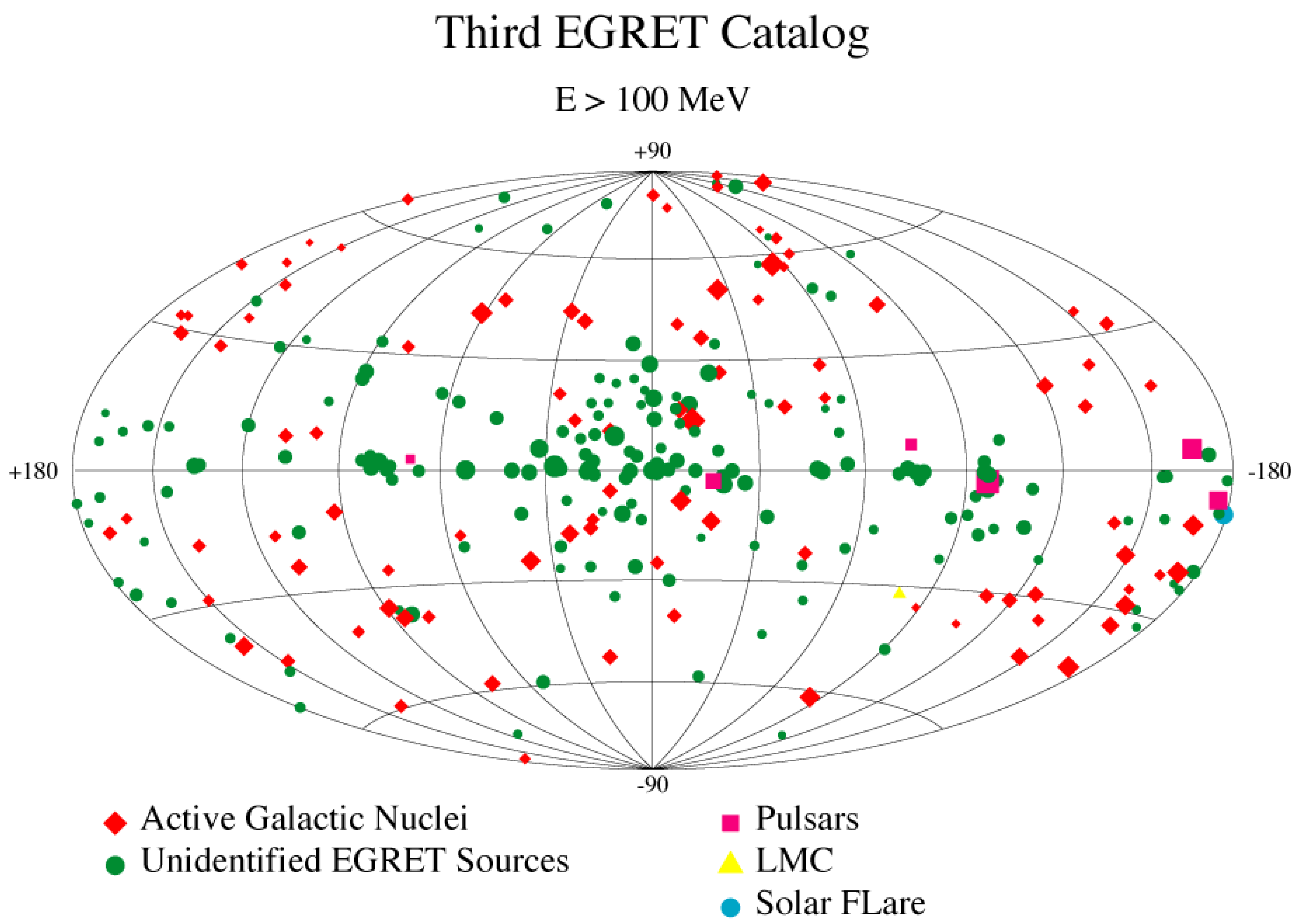
# High Energy Astroparticle Physics

**Acceleration Mechanisms**
**Sources**
**Detection**

# Gamma-Ray Astronomy

- Well-established branch of high-energy astrophysics
  - most work done at modest energies (few 10s of MeV)
    - some, e.g. EGRET, out to few 10s of GeV
  - this is not usually regarded as astroparticle physics
    - though EGRET catalogue sometimes used as list of candidates for, e.g., neutrino point source searches
- Atmosphere is not transparent to gamma rays
  - low and medium energy γ-ray astronomy is space-based
    - CGRO, SWIFT, GLAST, INTEGRAL, etc.
  - space platforms not suitable for TeV γ-ray astronomy
    - too small!
  - therefore very high energy γ-ray astronomy is a ground-based activity
    - detect shower produced as γ-ray enters atmosphere

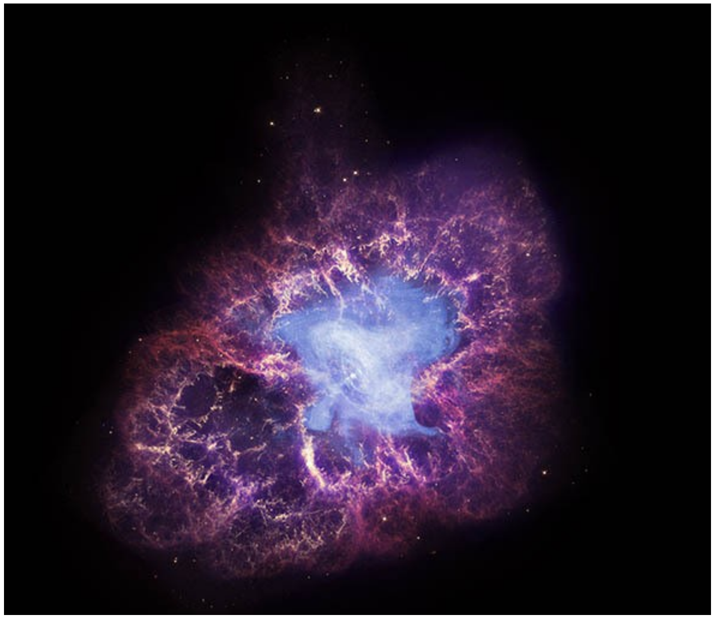
# EGRET Point Sources

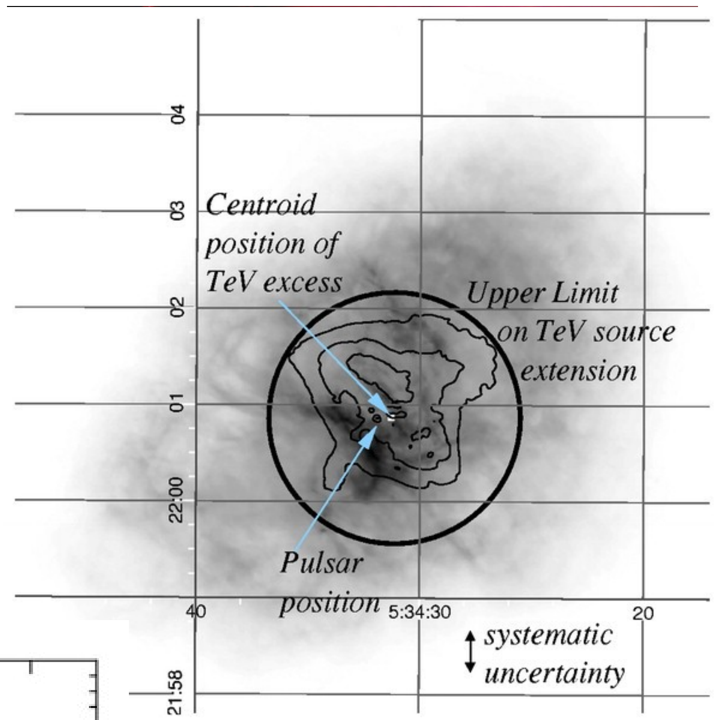


# Gamma-Ray Sources

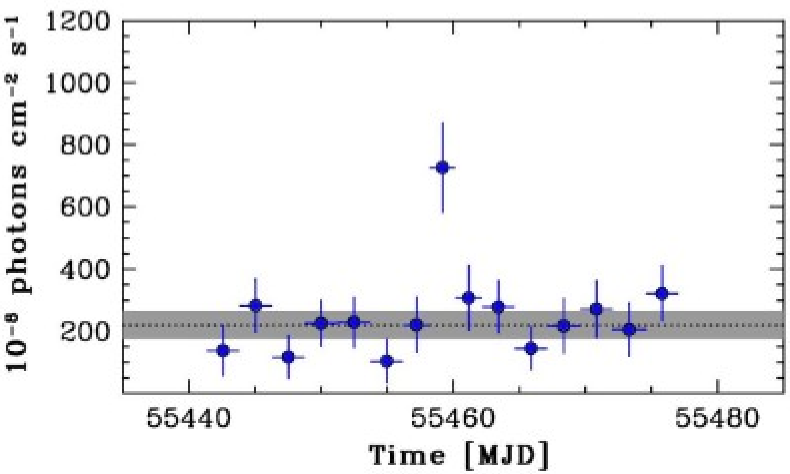
- From maps, clearly mixed Galactic and extragalactic
  - extragalactic sources of TeV γs are mostly blazars (a class of AGN where we are looking down the jet)
  - identified Galactic sources are SN-related (supernova remnants and pulsar wind nebulae), plus a few binary compact objects
  - dark/unidentified objects associated with Galactic plane, therefore presumably Galactic
- SNRs and AGN are suitable environments for particle acceleration
  - shocks, magnetic fields, synchrotron emission

# Pulsar Wind Nebula: The Crab



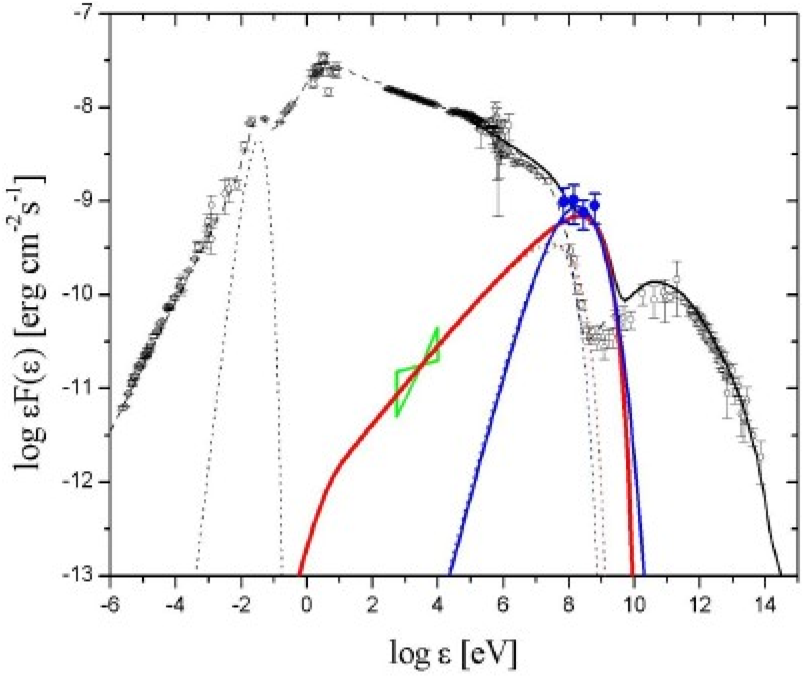



TeV gamma-ray signal as observed by HEGRA (Aharonian et al. 2004)



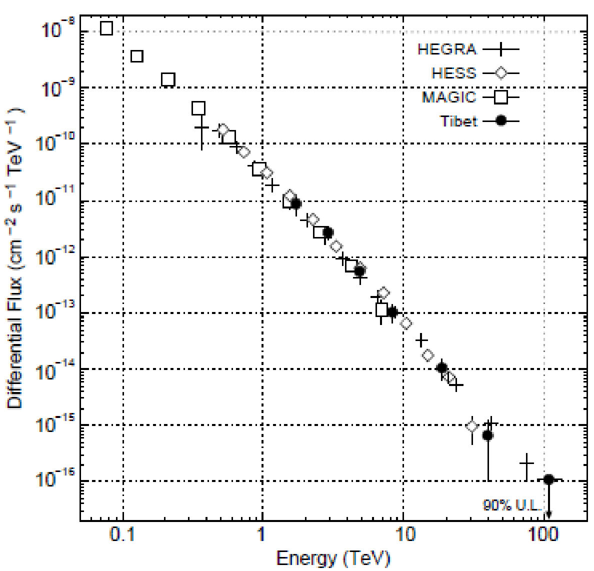

Medium-energy γ-ray flare observed by AGILE (Tavani et al. 2011)

# Pulsar Wind Nebula: The Crab

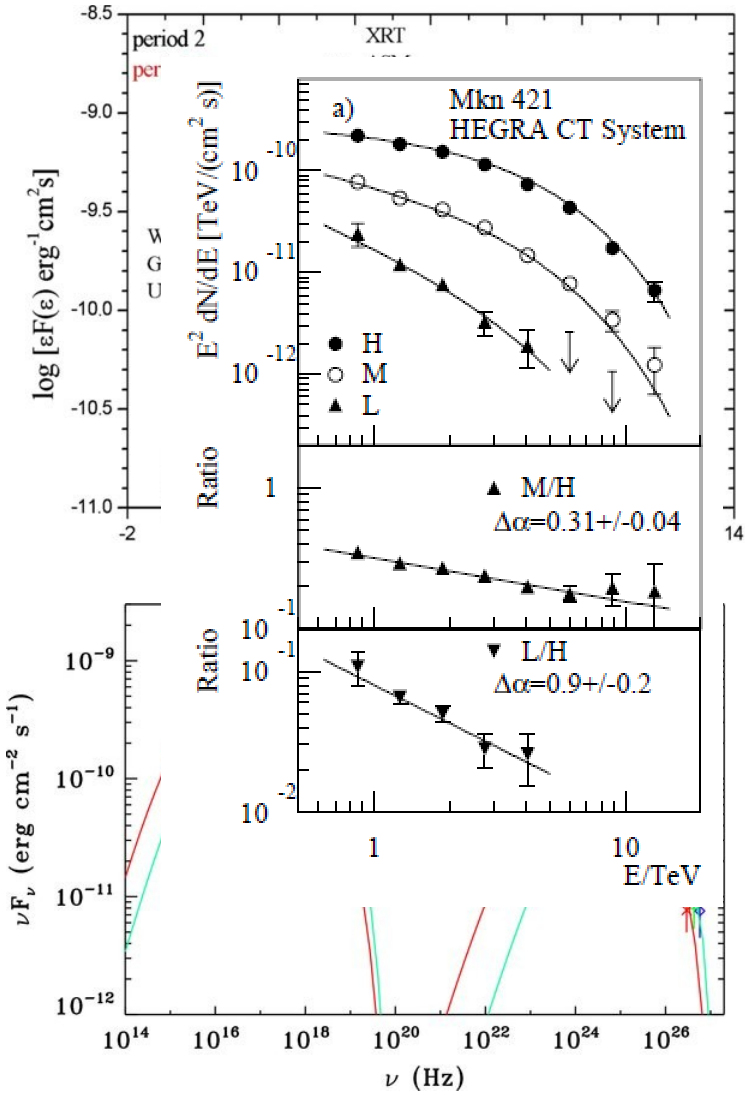


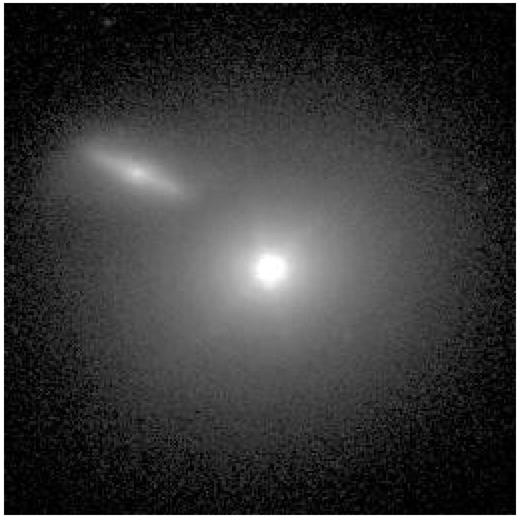

Crab spectral energy distribution showing September 2010 flare

TeV energy spectrum



# Blazar: Mkn 421



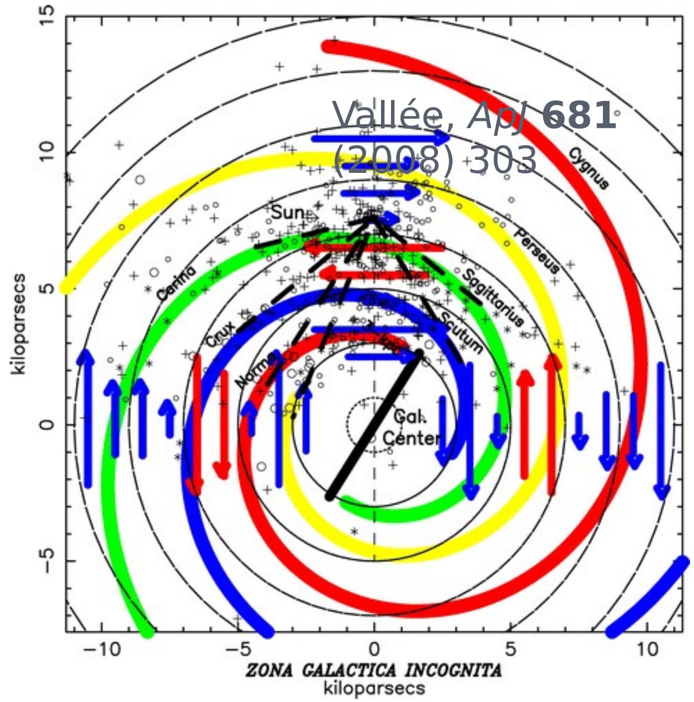



Mkn 421 and companion galaxy.
Aimo Sillanpaa, Nordic Optical Telescope.
(Above: very boring X-ray image by Chandra)

Highly variable (typical of blazars)
Spectrum varies according to state

# Cosmic Ray Sources

- Observations of cosmic rays now span about 100 years
- However, sources are not definitively established
- Galaxy has a complex magneticfield which effectively
- scrambles direction of
  - charged particles
  - Gamma ray luminosity
  - requires fast particles,
  - but maybe only electrons
  - therefore, observation of
  - γ-rays does not definitively
  - establish source as a cosmic
    - ray factory



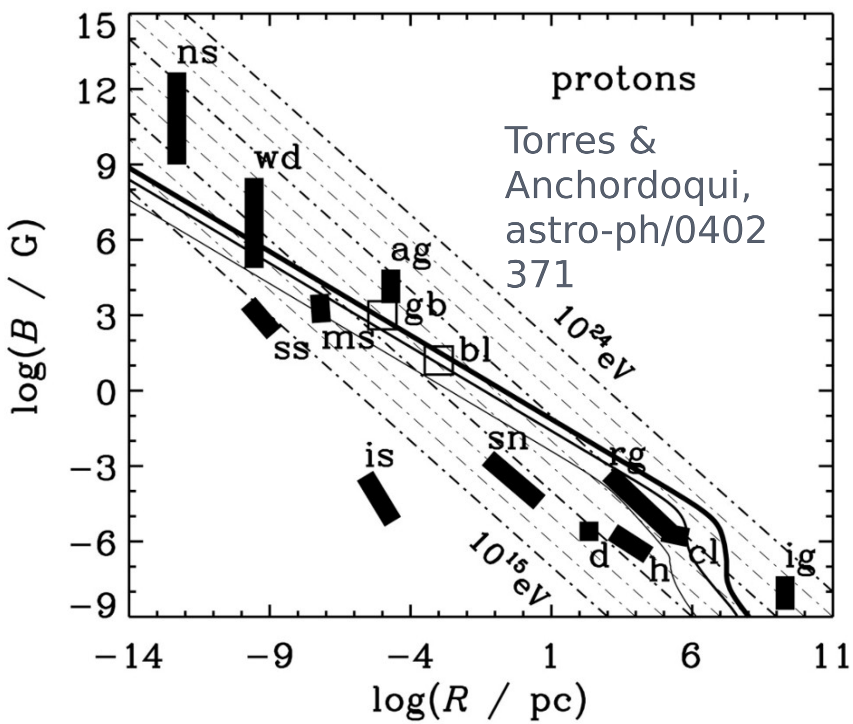

Vallée, *ApJ* **681** (2008) 303

  - Neutrino luminosity *does* require fast hadrons
  - but no neutrino point sources yet to be correlated with cosmic rays

# Cosmic Ray Sources

General dimensional analysis suggests

- $E$max [GeV] ≈ 0.03 $\eta^{-1}$ $Z$ $R$[km] $B$[G] (Hillas condition)
  - basically requires particles to remain confined in accelerating region
  - quite difficult to satisfy for highest-energy CRs
  - plot shows
    - neutron stars
    - white dwarfs
    - sunspots
    - magnetic stars
    - active galactic nuclei
    - interstellar space
    - supernova remnants
    - radio galaxy lobes
    - disc and halo of Galaxy
    - galaxy clusters
    - intergalactic medium
    - gamma-ray bursts
    - blazars
    - shock-wave velocities



# Cosmic Ray Sources

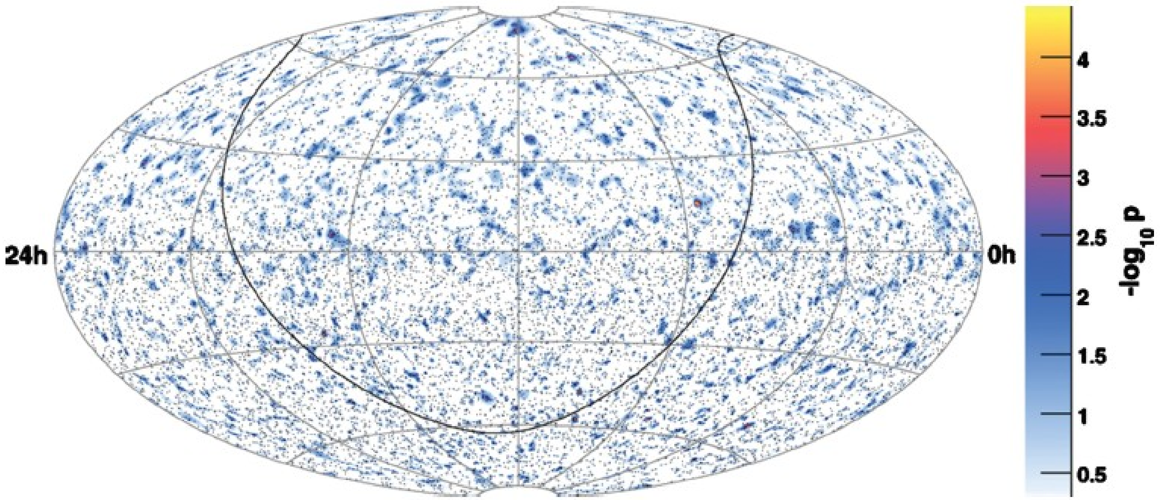
- Amount of magnetic deflection decreases with increasing energy
  - highest energy events might remember where they came from...
  - Pierre Auger Observatory observes significant correlation between arrival directions of CRs above 55 EeV and a catalogue of AGN
    - 38±7% of events within 3.1° of a catalogued
    - nearby AGN, cf. 21% expected for intrinsically isotropic distribution
    - similar results found for SWIFT catalogue—data do however require significant isotropic component (40−80%)

# Cosmic Ray Sources: Summary

- CRs up to about 1015 eV or so assumed to come from SNRs
  - but they don't provide good directional information, so this remains to be confirmed
    - neutrino observations, or definitive proof that some SNR $\gamma$-rays originate from $\pi^0$ decay
- Ultra-high energy CRs may come from local AGN
  - statistically significant (but partial) correlation
  - note that intergalactic space is not completely transparent to UHECRs—see later—so *distant* AGN (beyond ~100 Mpc) are assumed not to contribute

# Neutrino Sources

- Known sources of low-energy (0.1−100 MeV) neutrinos:
  - Sun
  - SN 1987A
- Known sources of high-energy neutrinos:
  - Starting to develop (since 2018) → see third lecture




IceCube search for point sources.

# Sources: Summary

- TeV gamma rays are observed from a variety of sources, primarily SNRs within the Galaxy and blazars outside
  - clear evidence of charged particles accelerated to very high energies, but whether electrons or hadrons is unclear
- Cosmic ray sources are difficult to pinpoint because CRs are strongly deflected by the Galactic magnetic field
  - SNRs suspected to be source of CRs at $<10^{15}$ eV
  - some hints that local AGN may be responsible for highest energy CRs
- Observations of high energy neutrinos would solve the mystery, but need more statistics