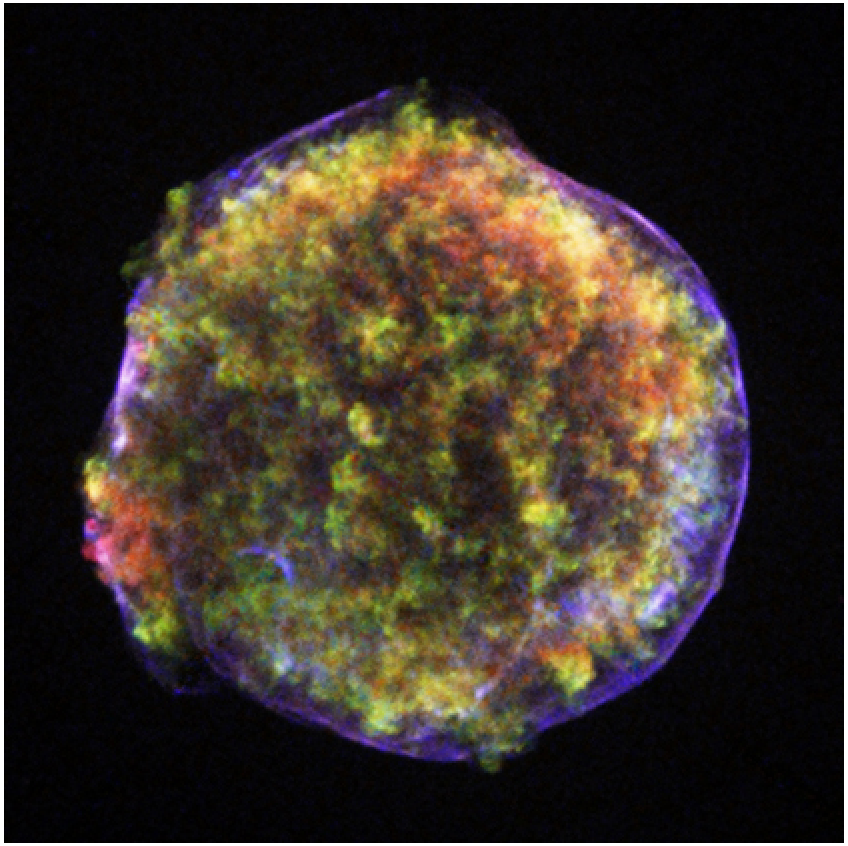
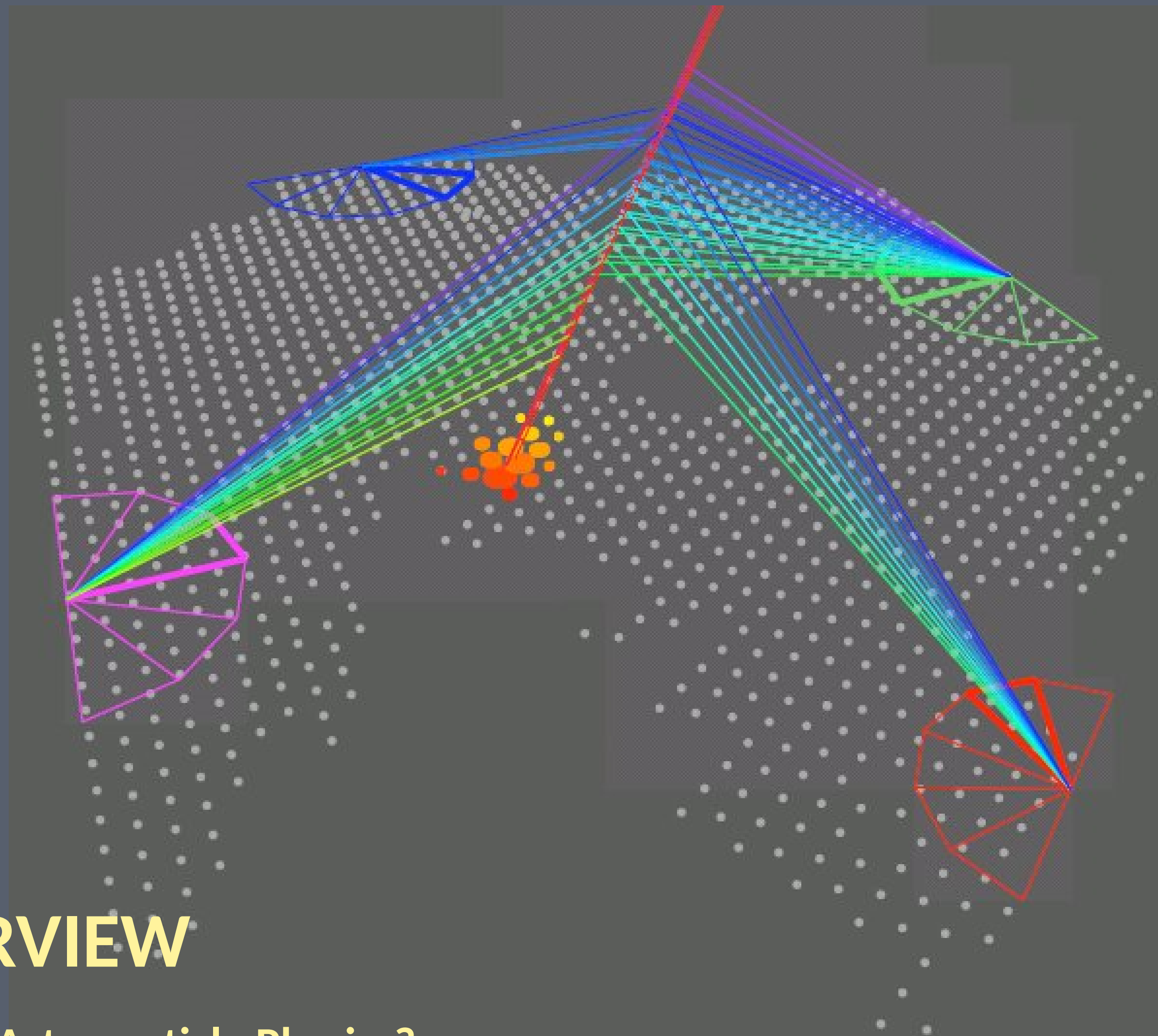


# ASTROPARTICLE PHYSICS LECTURE 1

Matthew Malek

University of Sheffield



# OVERVIEW

**What is Astroparticle Physics?**

# WHAT IS ASTROPARTICLE PHYSICS?

- Various definitions! Mine is
  **the use of particle physics technology to study astrophysical phenomena**
- Included:
  - neutrino astrophysics
  - gamma-ray astronomy
  - cosmic rays
  - dark matter
  - early-universe cosmology

coherent field with a lot of common factors

***High Energy Astroparticle Physics***

someone else's problem!

- Sometimes also included:
  - cosmic microwave background
  - gravitational waves
  - neutrino masses (especially $0\nu\beta\beta$)

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*

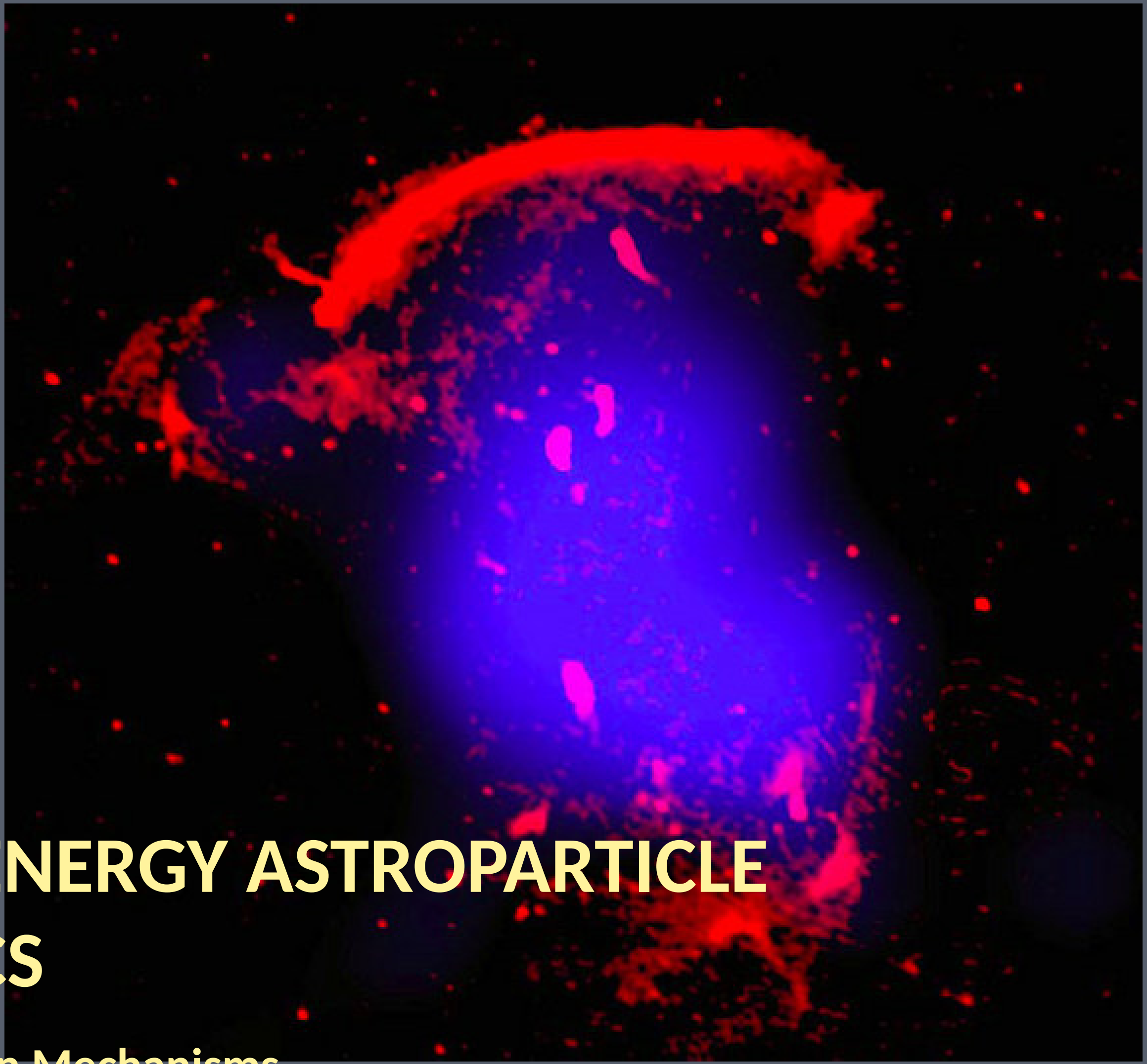
# RELATED FIELDS

- Neutrino physics
  - atmospheric neutrinos are "astroparticle physics" but have contributed more to understanding of neutrinos than to astrophysics
  - similar situation for solar neutrinos
  - long-baseline neutrino experiments can do low-energy neutrino astrophysics "for free" (and vice versa)
- Nucleon decay
  - many detector technologies useful for both
    - original purpose of Kamiokande (NDE = Nucleon Decay Experiment not Neutrino Detection Experiment!)
    - 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



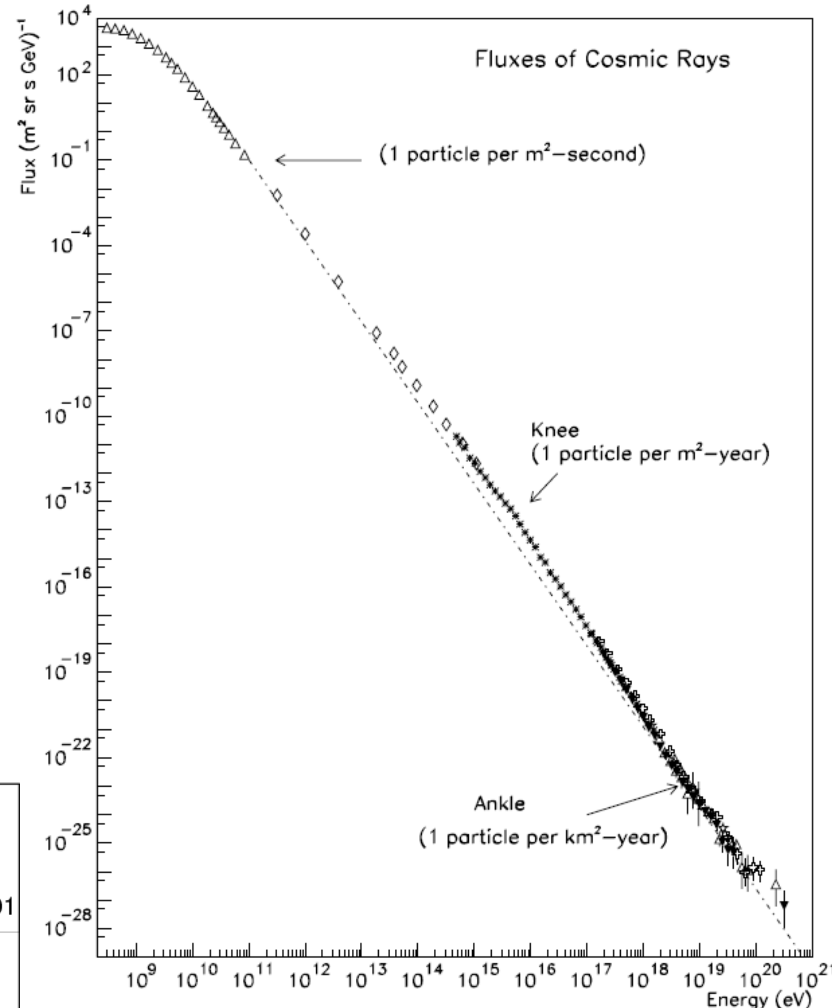
Acceleration Mechanisms

Sources

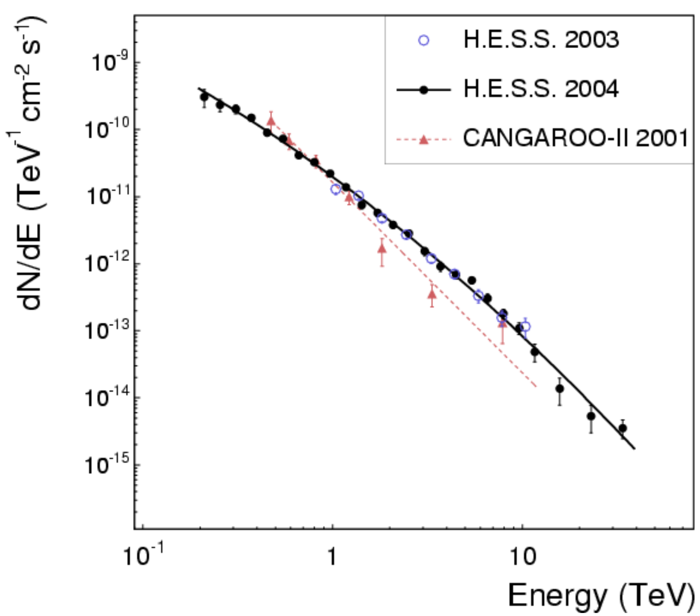
Detection

# COSMIC ACCELERATORS

- Cosmic rays and gamma rays are observed up to extremely high energies
- something must therefore accelerate them

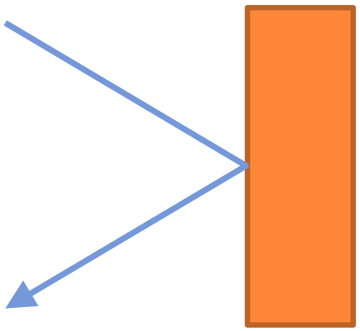



$10^9$ eV $10^{21}$




Note the power-law spectrum

# ACCELERATION MECHANISMS

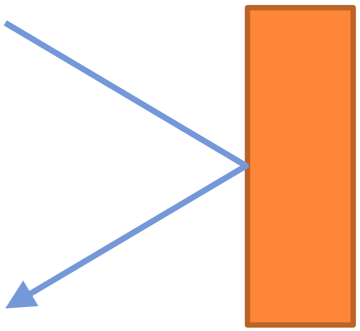


- Fermi Mechanism
  - energetic charged particles can gain energy by scattering off local magnetic turbulence (Fermi 1949)
    - Assume particle scatters off much more massive object moving with speed **u**. Then in the com frame (= frame of massive object) its energy and momentum before the scatter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

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



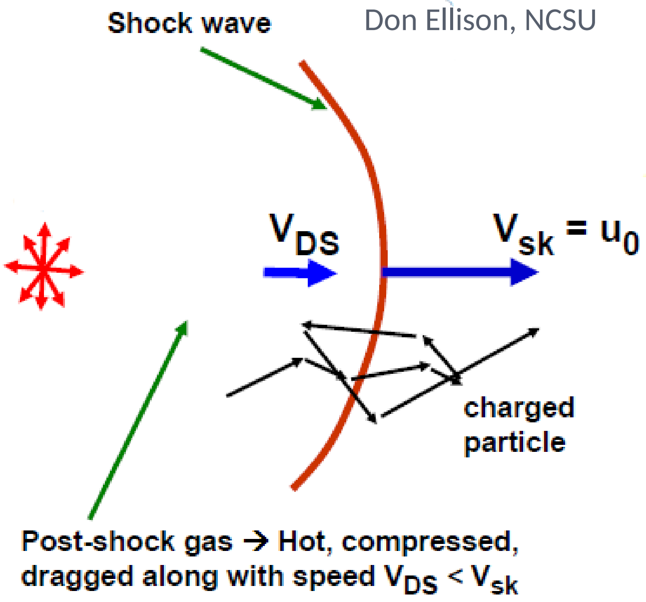
# ACCELERATION MECHANISMS

- 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

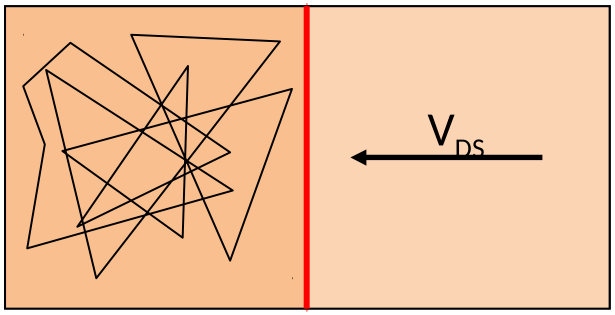
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{u}{c}\right)^2$$

    - 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 $x = 1 + 1/\alpha\tau$, α is the rate of energy increase and τ is the residence time of the particle
  - The bad news
    - since $u \ll c$, it's slow and inefficient

# ACCELERATION MECHANISMS



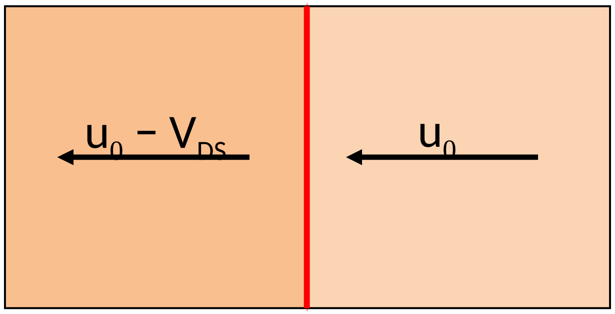

- First-order Fermi Mechanism (Diffusive Shock Acceleration)
  - *O*(*u*/*c*) term gets lost in integral over angles—we could retrieve this if we could arrange to have only head-on scatters
  - Consider shock wave as sketched above
    - high-energy particles will scatter so that their distribution is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




Rest frame of downstream 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 $\rho_2 > \rho_1$
  - in rest frame of shock, $\rho_1 u_0 = \rho_2 u_2$ where $u_2 = u_0 - V_{DS}$
    - for strong shock $\rho_2/\rho_1 = (\gamma + 1)/(\gamma - 1)$ where $\gamma$ is ratio of specific heats (= ⁵⁄₃ for hydrogen plasma)
    - therefore expect $u_2/u_0 \approx$ ¼
    - gas approaches shock-crossing particle at speed $V = \frac{3}{4} u_0$
    - if high-energy particles move randomly, probability of particle crossing shock at angle θ is $P(\theta) = 2 \sin\theta \cos\theta \, d\theta$, and its energy after crossing shock is $E' \approx E(1 + pV \cos\theta)$ (if $V << c$)
    - therefore average energy gain per crossing is

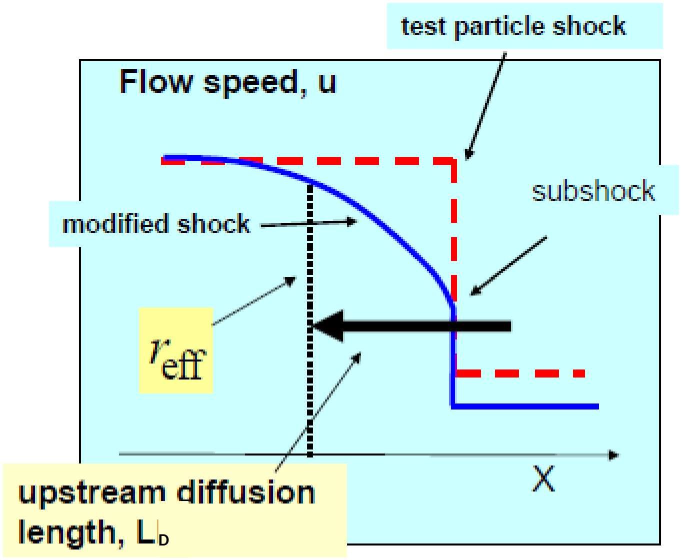
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{V}{c} \int_0^{\frac{\pi}{2}} 2\cos^2\theta \sin\theta \, d\theta = \frac{2}{3}\frac{V}{c}$$

# 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 $N_k = N_0 P^k$ particles with average energy $E_k = f^k E_0$.
  - Hence $\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln P}{\ln f}$, or $\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P/\ln f}$
  - 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 $N(E)\,dE \propto E^{(\ln P/\ln f)-1}\,dE$
  - for DSA this comes to $N(E)\,dE \propto E^{-(r+2)/(r-1)}\,dE$, where $r = \rho_2/\rho_1$.
    - "universal" power law, independent of details of shock

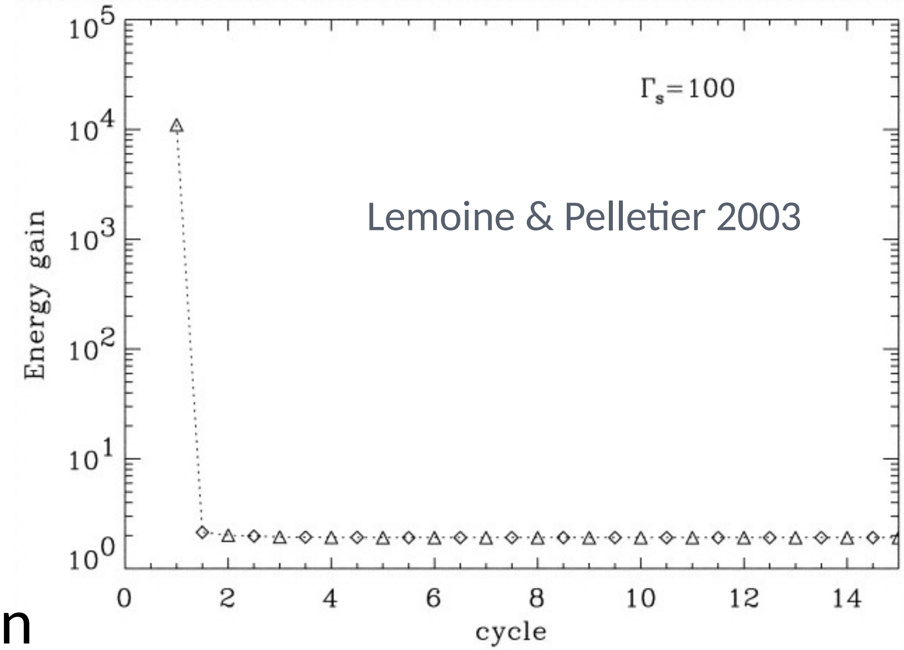
# ADDITIONAL COMPLICATIONS

- 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




Don Ellison, NCSU

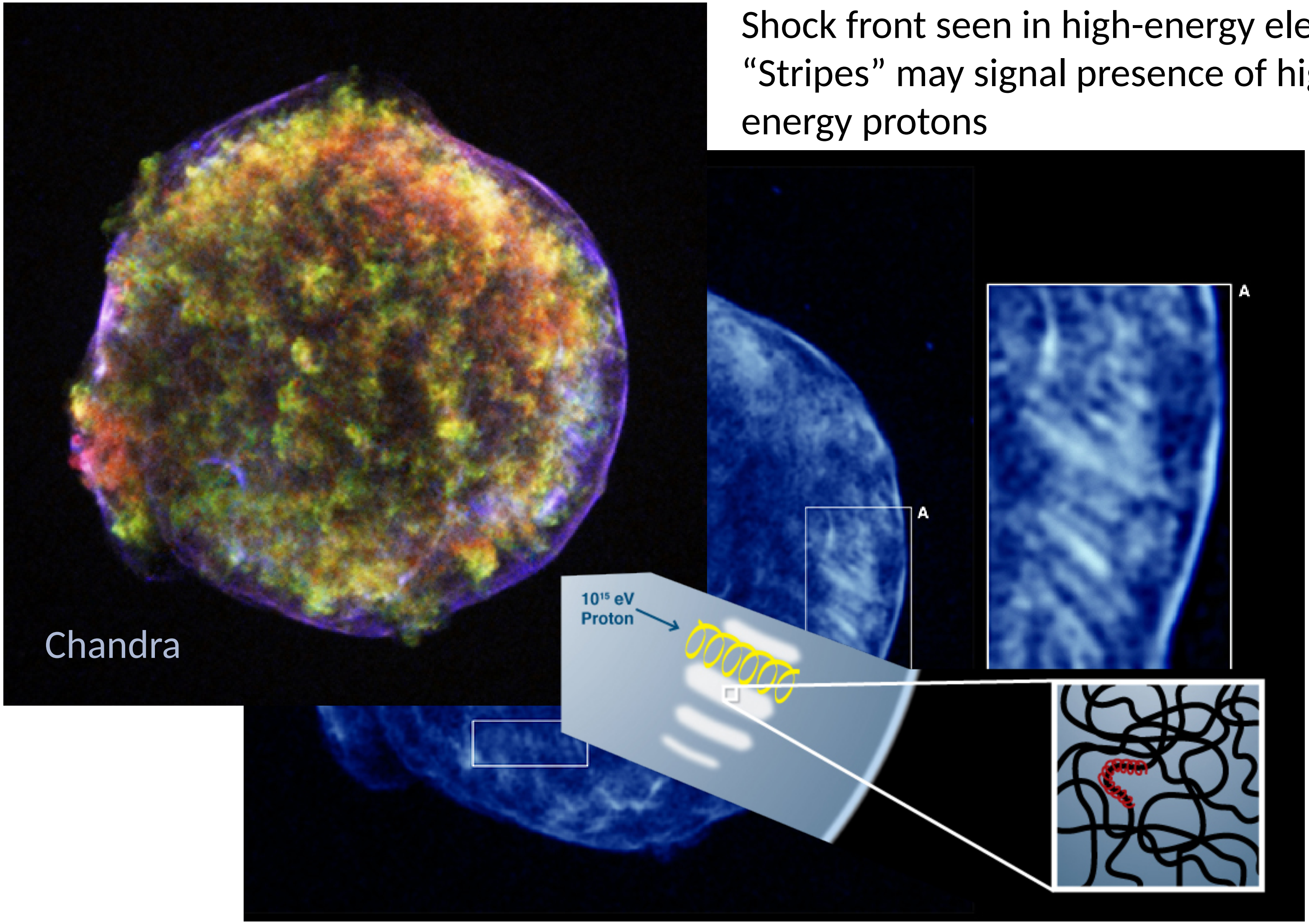
# RELATIVISTIC SHOCKS



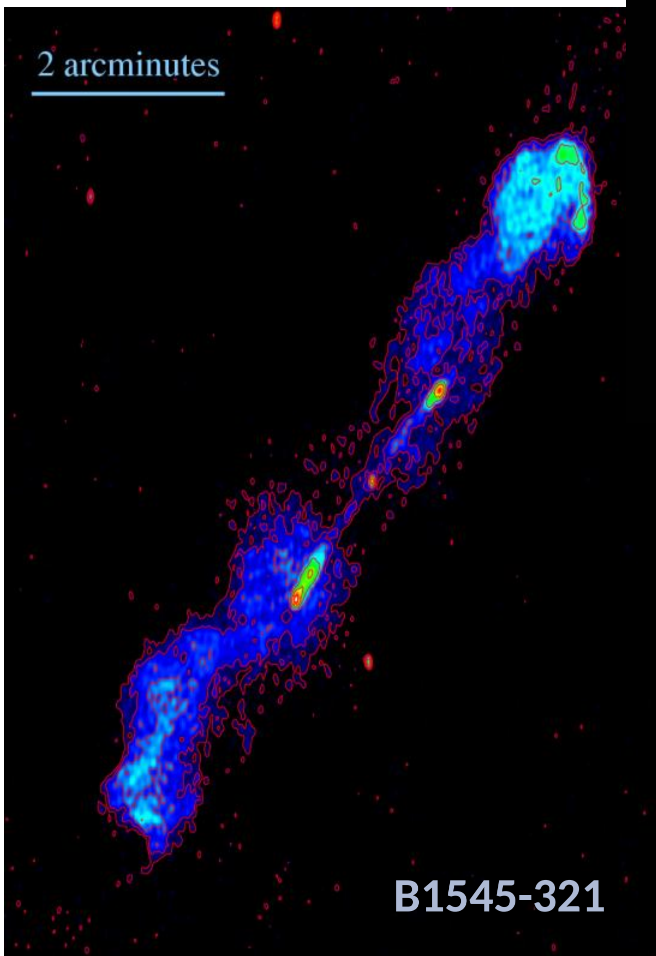

- DSA assumes non-relativistic shock
- Many astrophysical objects ($\gamma$-ray bursts, AGN) are known to host relativistic shocks ($\gamma$ ~ 10 for AGN, up to 1000 for GRBs)
  - these can produce much larger accelerations
  - first return crossing causes energy gain of order $\gamma^2$
    - second and subsequent crossings "only" factor 2, because particle does not have time to scatter to random orientation before shock overtakes it
  - produces a somewhat steeper spectrum, spectral index ~2.4

# TYCHO'S SUPERNOVA (SN 1572)

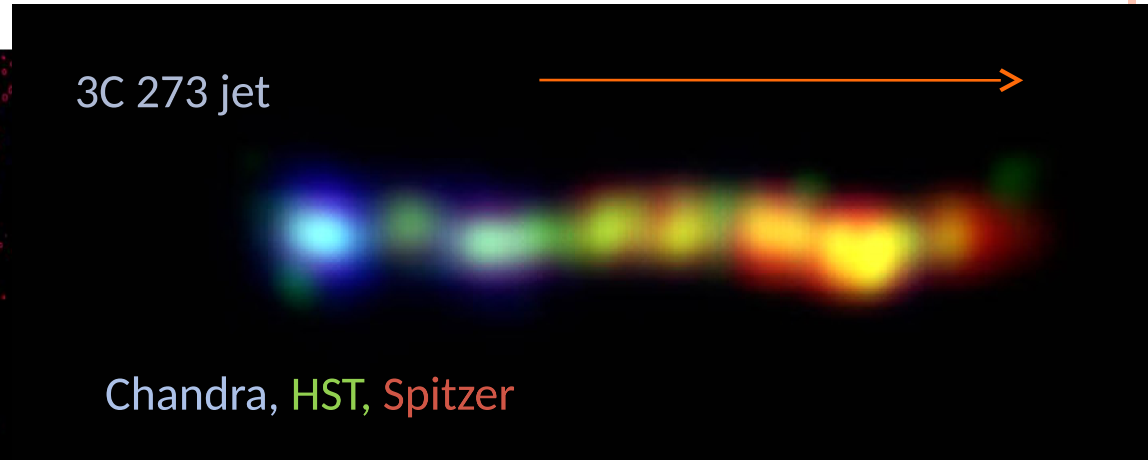
Shock front seen in high-energy electrons
"Stripes" may signal presence of high-energy protons

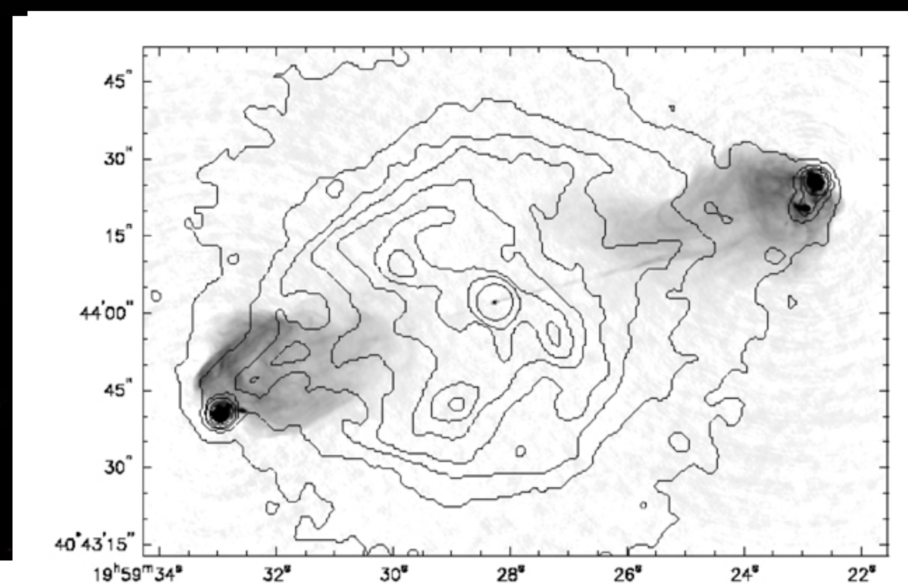


# RADIO GALAXIES



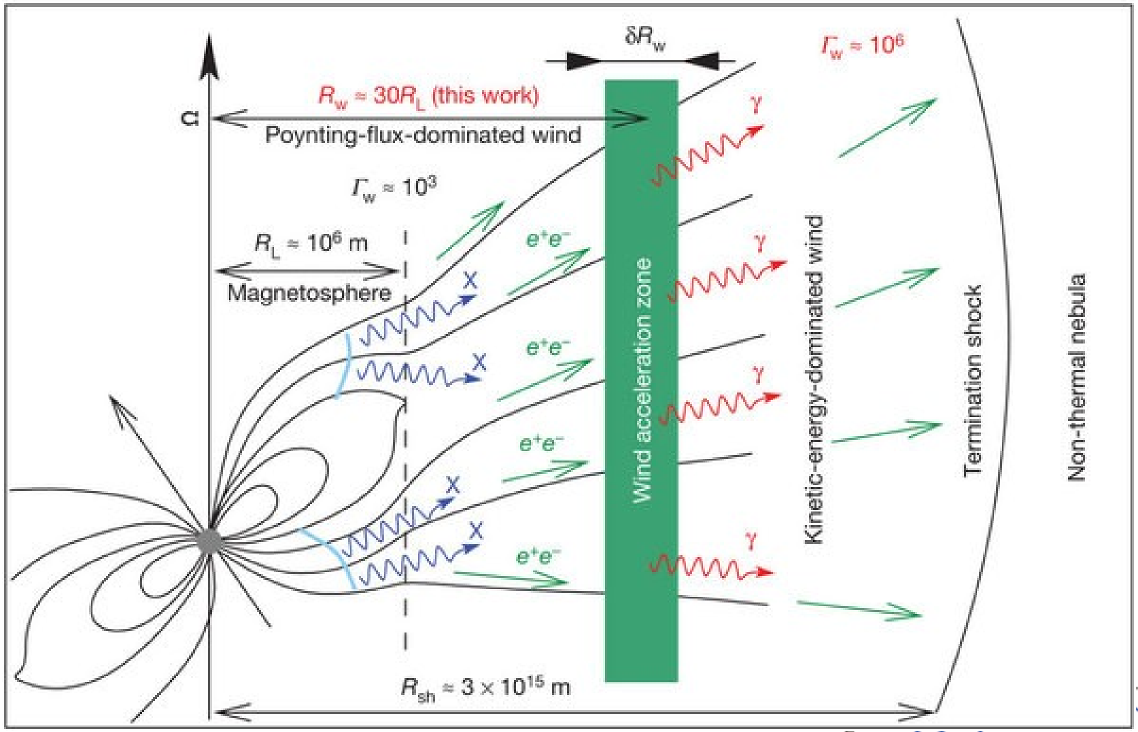

*13 cm wavelength ATCA image by L. Saripalli, R. Subrahmanyan and Udaya Shankar*

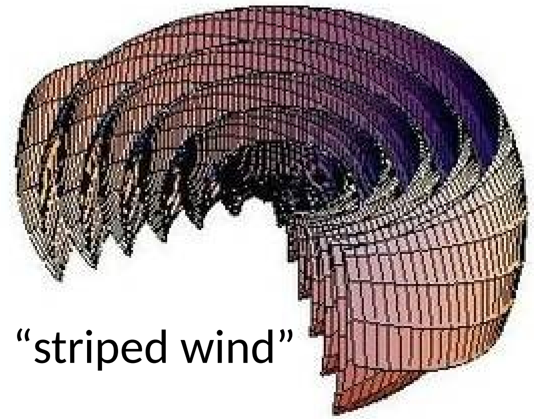


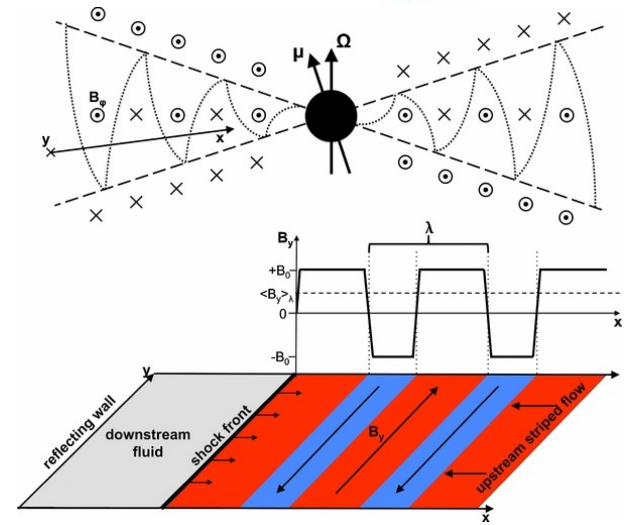

Cygnus A in X-ray (Chandra) and radio (VLA)

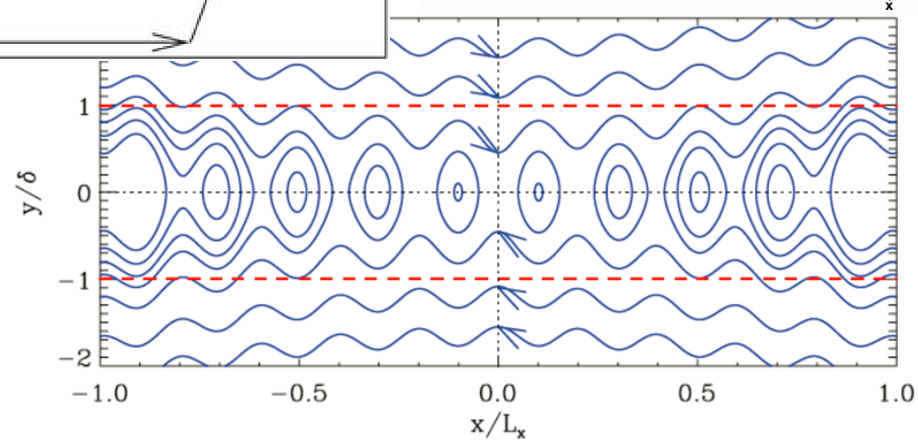
# PULSAR MAGNETIC FIELDS



"striped wind"



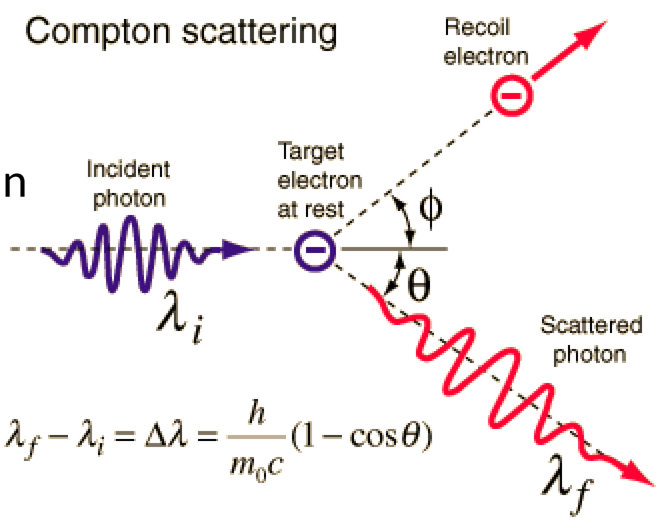

Magnetic reconnection has been proposed as an explanation for fast γ-ray flares in Crab Nebula

# 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 $\Delta\lambda = h(1-\cos\theta)/mc^2$.

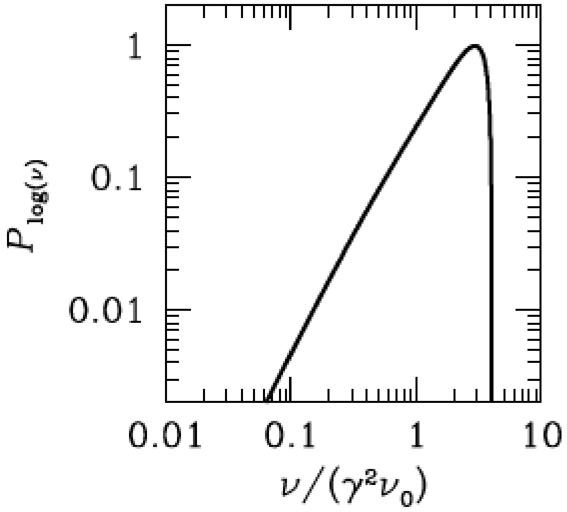
      In lab frame, maximum energy gain occurs in head-on collision: $\nu \approx 4\gamma^2\nu_0$

      Because of relativistic aberration, spectrum is sharply peaked near maximum



# PHOTONS AND NEUTRINOS

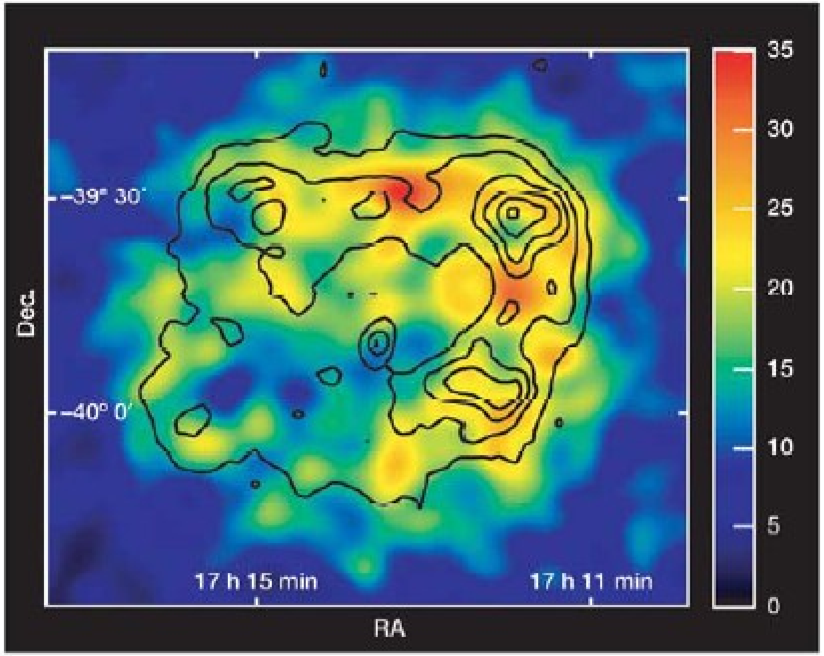
- inverse Compton scattering (continued)
  - Plot shows calculated spectrum for monoenergetic photons and electrons.
  - Plenty of potential sources of low-energy photons to be upscattered:
    - synchrotron radiation produced by the same population of fast electrons (**synchrotron-self-Compton**, SSC)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

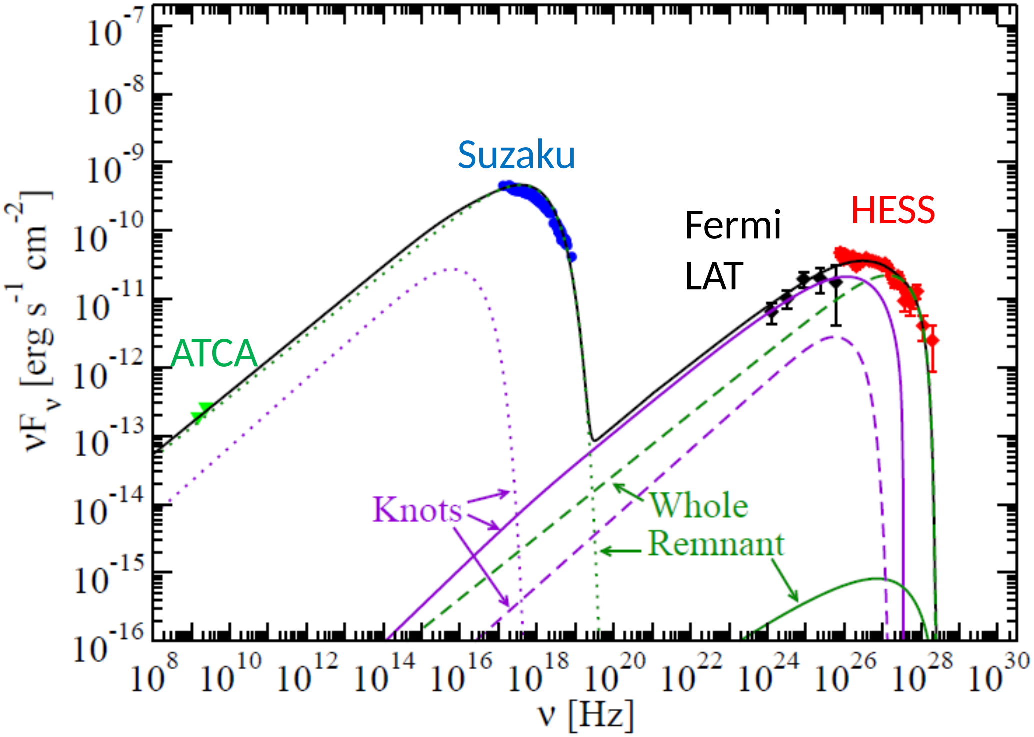


# PHOTONS AND NEUTRINOS

- 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 SUPERNOVA REMNANT RXJ 1713.7−3946

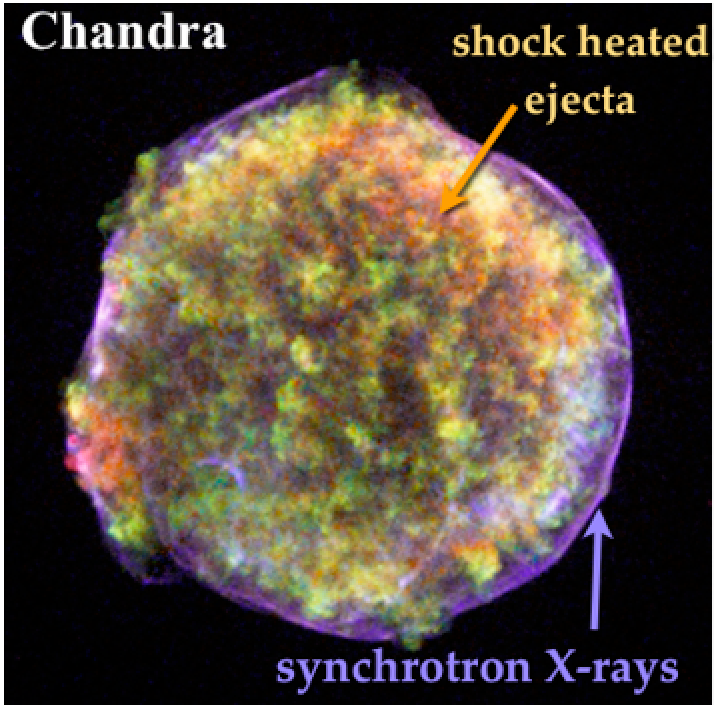


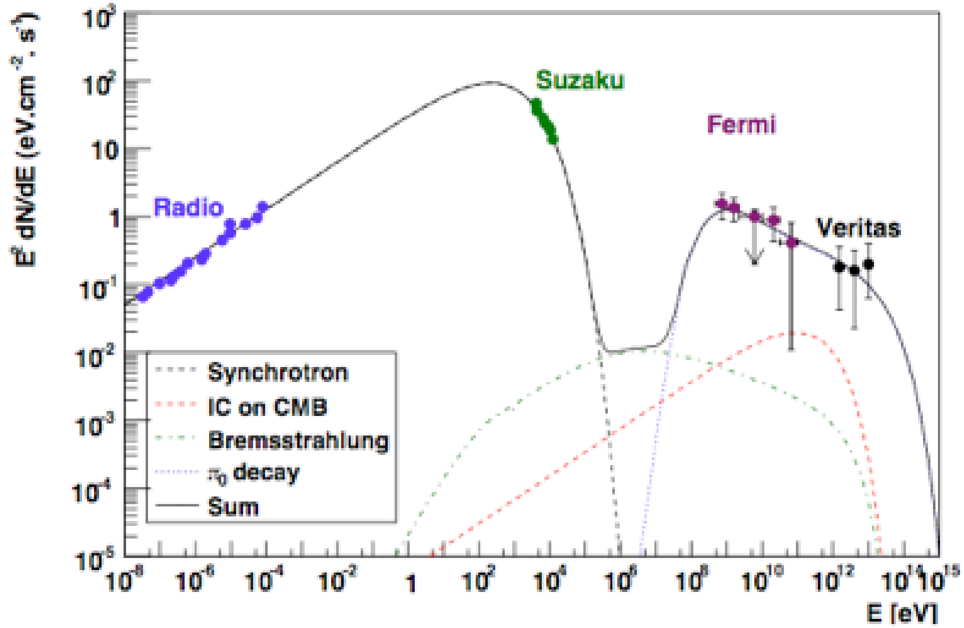




Spectrum is consistent with high-energy electrons only: synchrotron radiation (radio → x-ray) plus inverse Compton effect (γ-rays)

Expect this SNR **not** to produce high-energy neutrinos

# SPECTRUM OF SN1572 (TYCHO'S SN)



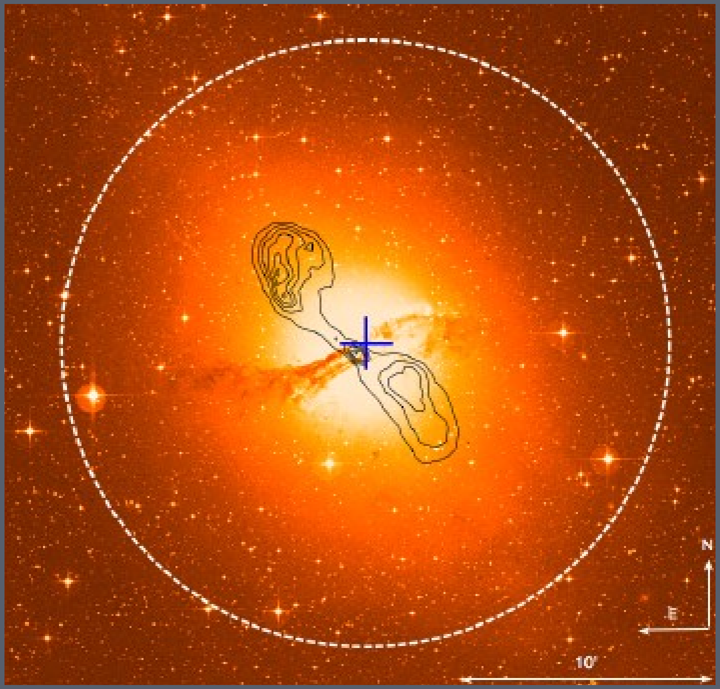




Spectrum seems to prefer $\pi^0$ decay—shape wrong for IC

This SNR **should** produce high-energy neutrinos

# 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

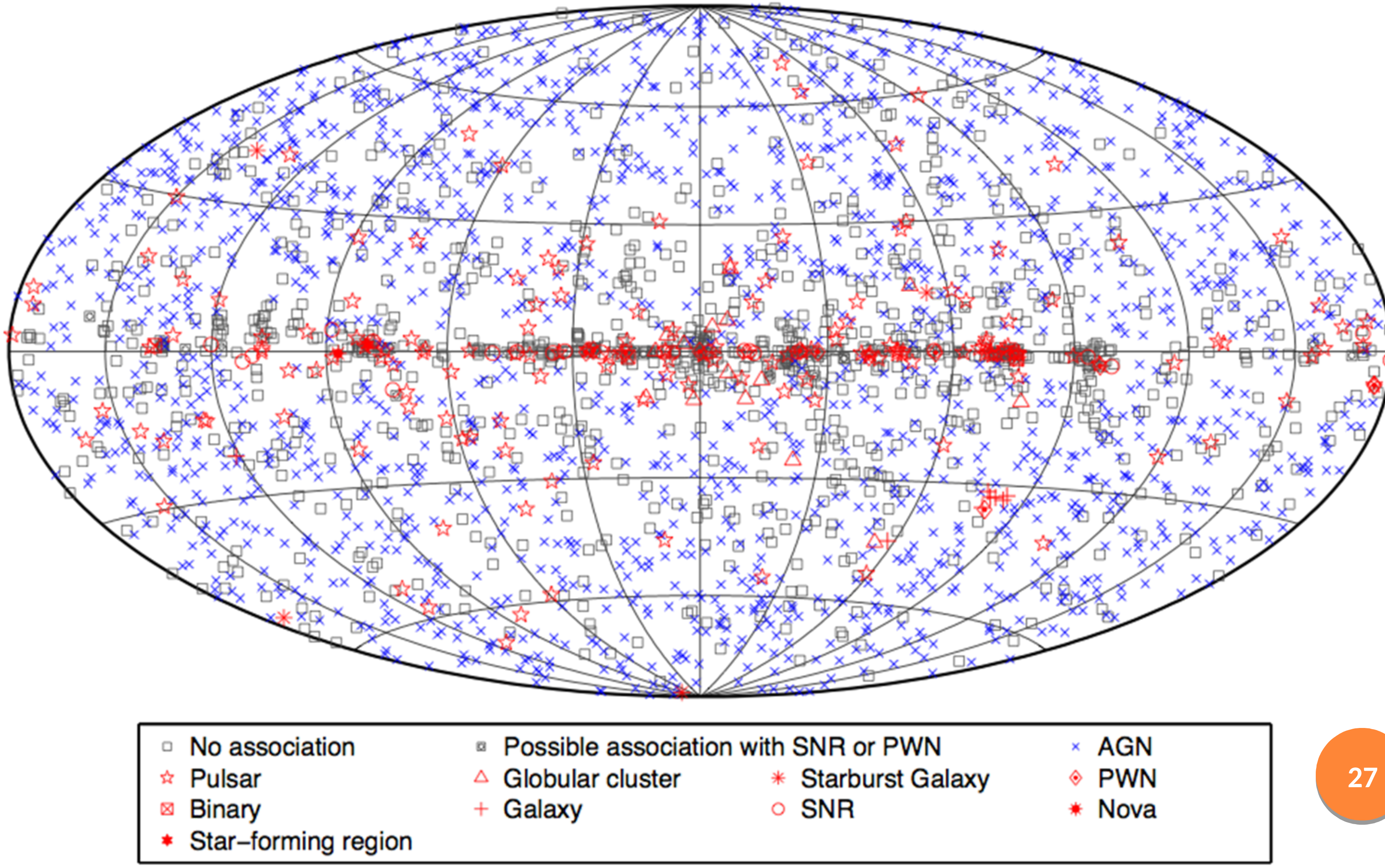
Sources

Detection

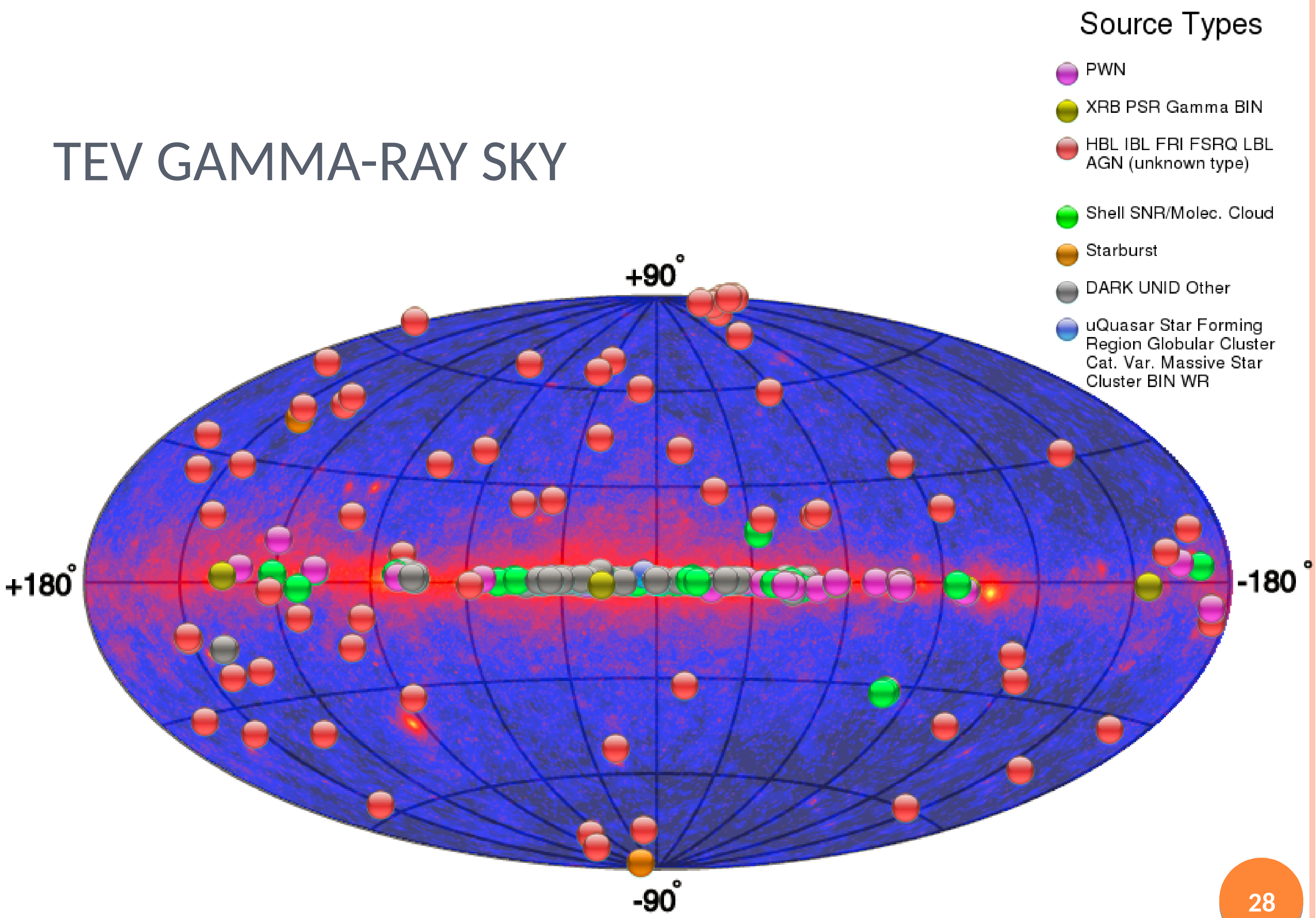
# GAMMA-RAY ASTRONOMY

- 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

# FERMI-LAT 3RD POINT SOURCE CATALOGUE



# TEV GAMMA-RAY SKY

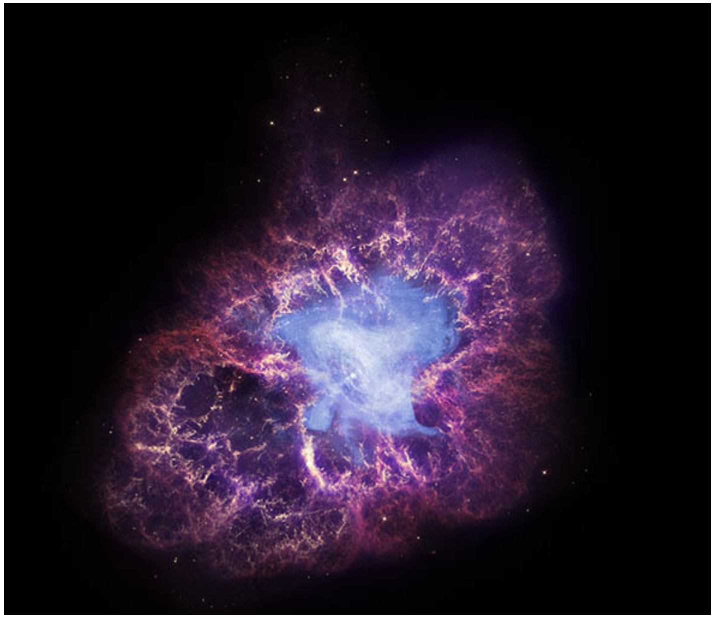


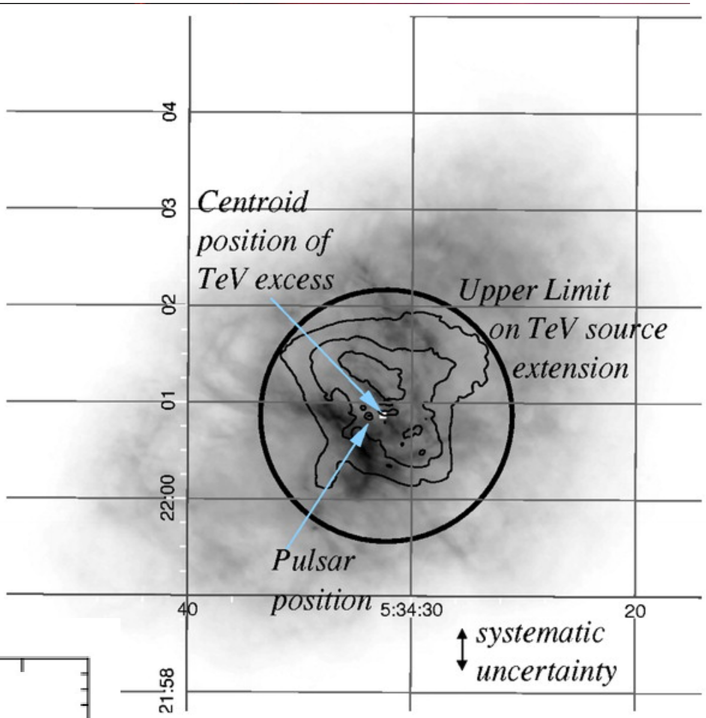

from TeVCat, http://tevcat.uchicago.edu/

# GAMMA-RAY SOURCES

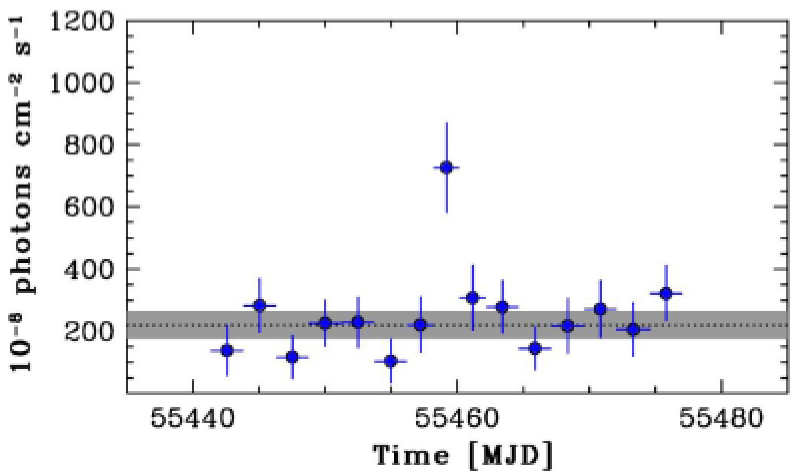
- From maps, clearly mixed Galactic and extragalactic
  - extragalactic sources of TeV γs are mostly blazars (a class of AGN where we are looking down the jet)
  - identified Galactic sources are SN-related (supernova remnants and pulsar wind nebulae), plus a few binary compact objects
  - dark/unidentified 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



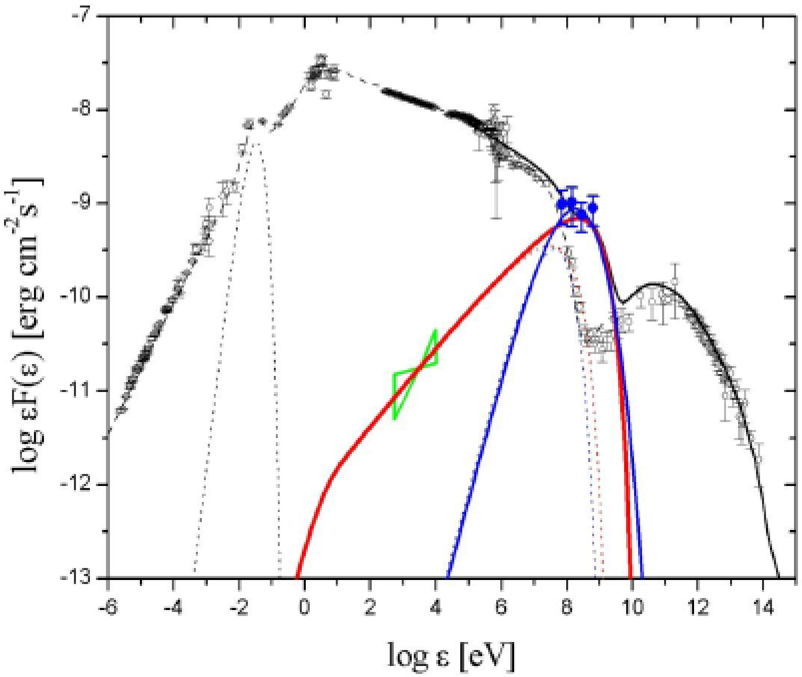



TeV gamma-ray signal as observed by HEGRA (Aharonian et al. 2004)



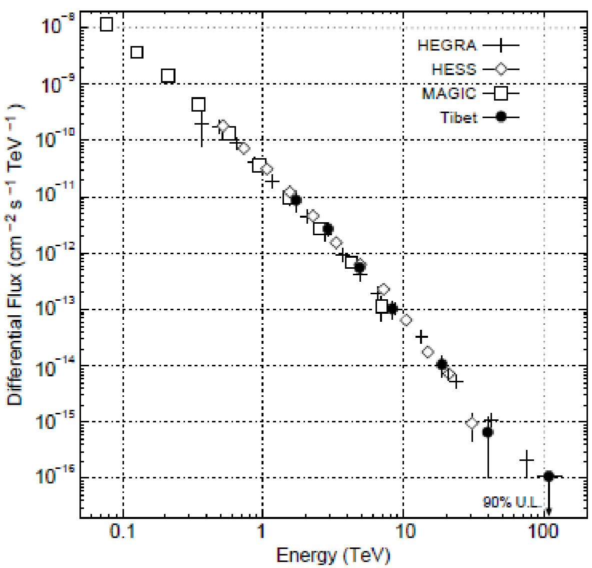

Medium-energy γ-ray flare observed by AGILE (Tavani et al. 2011)

# PULSAR WIND NEBULA: THE CRAB

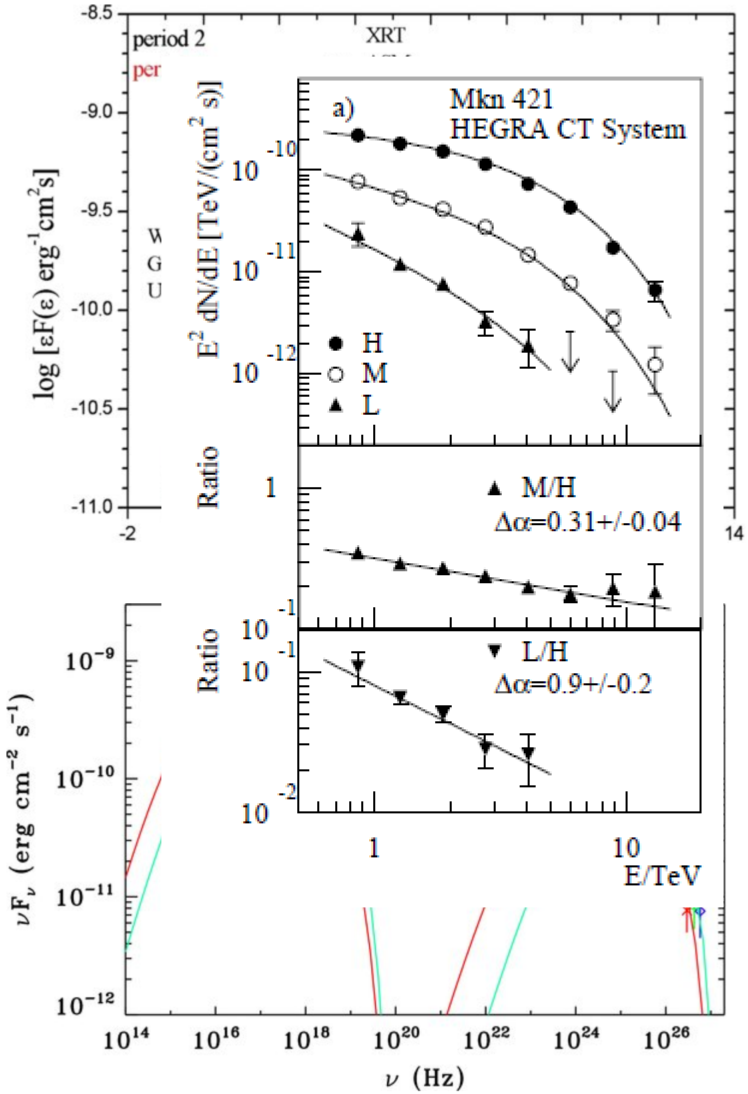


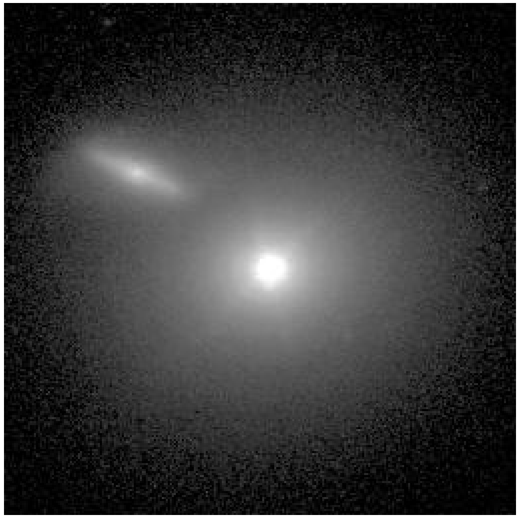

Crab spectral energy distribution showing September 2010 flare

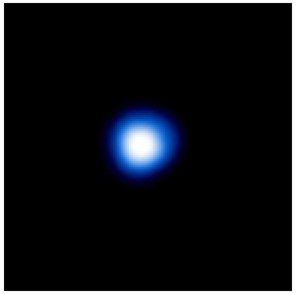
TeV energy spectrum



# BLAZAR: MKN 421





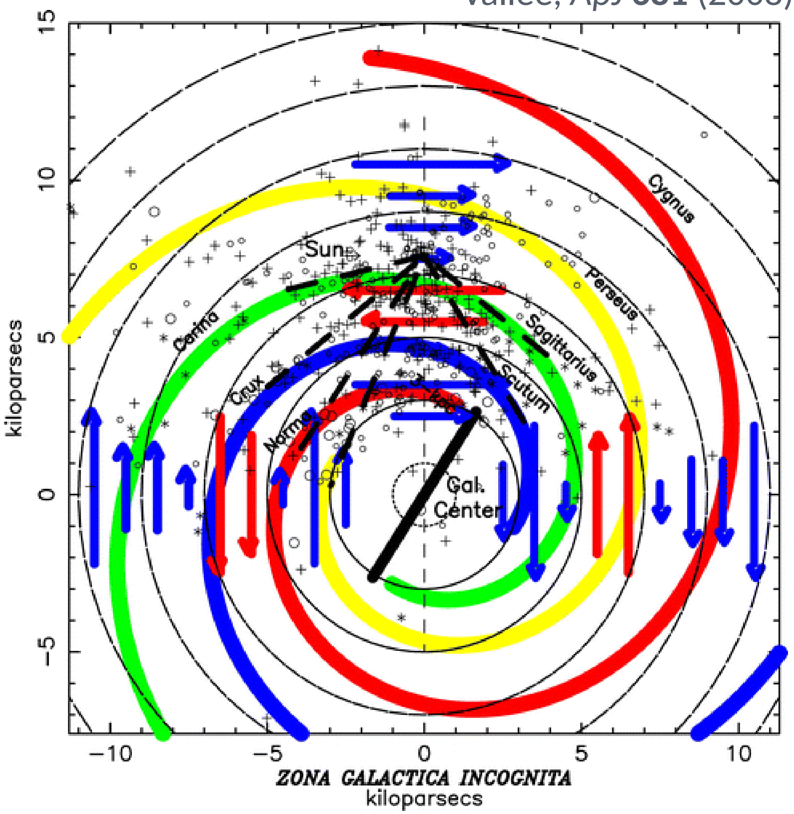
Mkn 421 and companion galaxy. Aimo Sillanpaa, Nordic Optical Telescope.
(Above: very boring X-ray image by Chandra)

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

# COSMIC RAY SOURCES

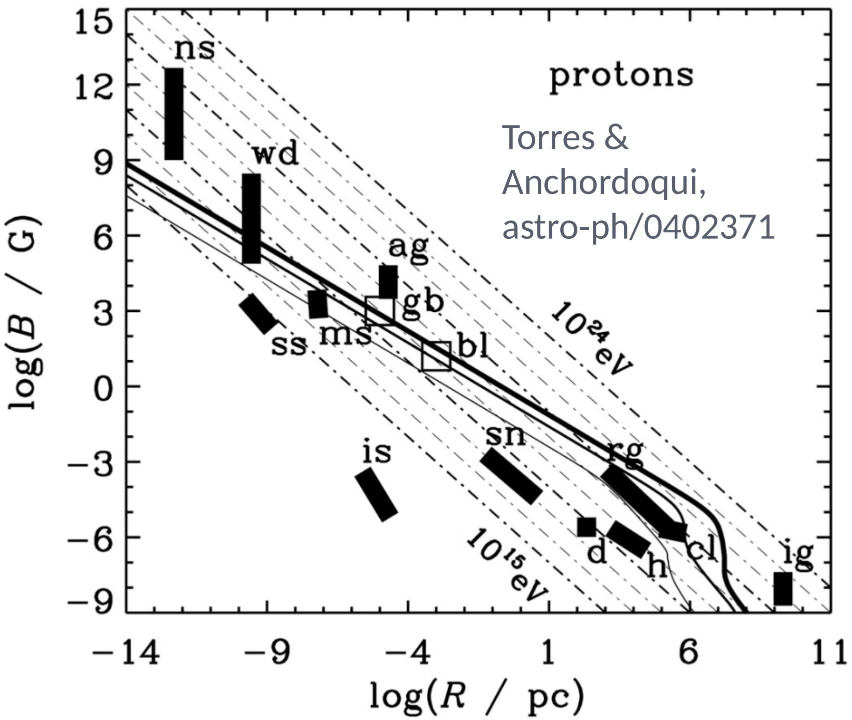
- Observations of cosmic rays now span about 100 years
- However, sources are not definitively established
  - Galaxy has a complex magnetic field which effectively scrambles direction of charged particles
  - Gamma ray luminosity requires fast particles, but maybe only electrons
    - therefore, observation of γ-rays does not definitively establish source as a cosmic ray factory
  - Neutrino luminosity *does* require fast hadrons
    - but no neutrino point sources yet

Vallée, *ApJ* **681** (2008) 303



# COSMIC RAY SOURCES

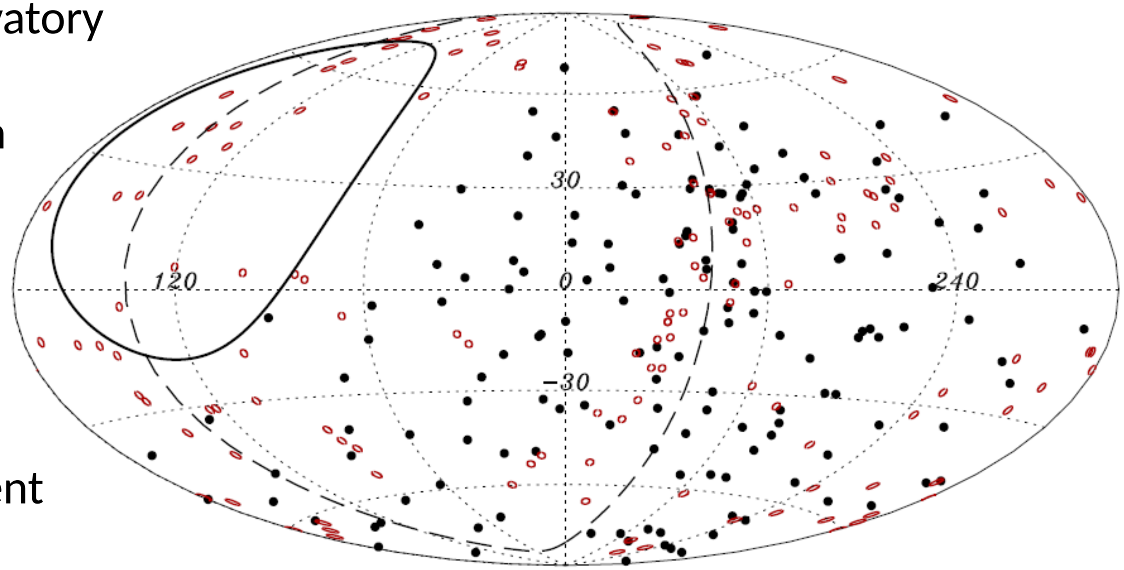
- General dimensional analysis suggests
  $E_{max}$ [GeV] ≈ 0.03 η $Z$ $R$[km] $B$[G] (Hillas condition)
  - basically requires particles to remain confined in accelerating region
  - quite difficult to satisfy for highest-energy CRs
    - plot shows
      neutron stars
      white dwarfs
      sunspots
      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




Torres & Anchordoqui, astro-ph/0402371

# COSMIC RAY SOURCES

- Amount of magnetic deflection decreases with increasing energy
  - highest energy events might remember where they came from…
    - Pierre Auger Observatory initially observed correlation between arrival directions of CRs above 55 EeV and a catalogue of AGN
    - however, with more data significance went down (not up!)



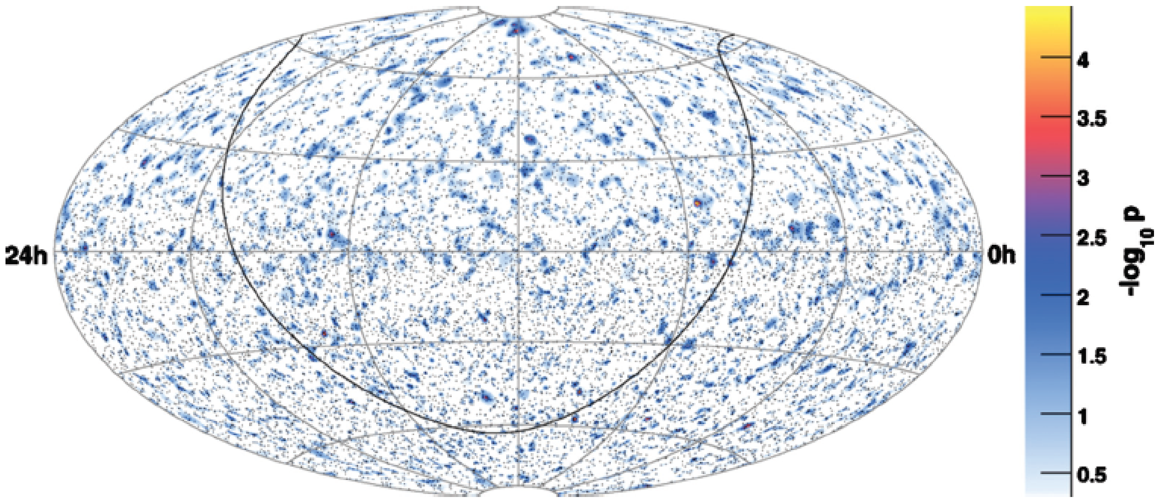

  - currently (2018), no statistically significant correlation with galaxy surveys, nearby AGN/radio galaxies, or Centaurus A

# COSMIC RAY SOURCES: SUMMARY

- CRs up to about $10^{15}$ 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 γ-rays originate from $\pi^0$ decay
- Ultra-high energy CRs may come from local AGN
  - however, arrival directions do not show significant correlation
    - this is not unexpected if UHEC CRs are heavy nuclei, as higher charge implies more deflection by magnetic fields
    - composition of UHE CRs is currently unclear, as experiments disagree
  - 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 point sources of high-energy neutrinos:
  - None (some events, but no significant clusters)
    - to be fair, this is as expected for current exposure times




IceCube search for point sources. No significant excess found yet.

# 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
  - local AGN *may* be responsible for highest energy CRs
- Observations of high energy neutrinos would solve the mystery, but no clear point sources yet
  - situation should improve after a few more years of IceCube running