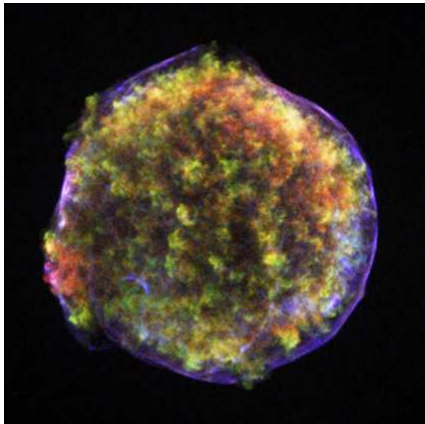



The
University
Of
Sheffield.






1

ASTROPARTICLE PHYSICS LECTURE 1

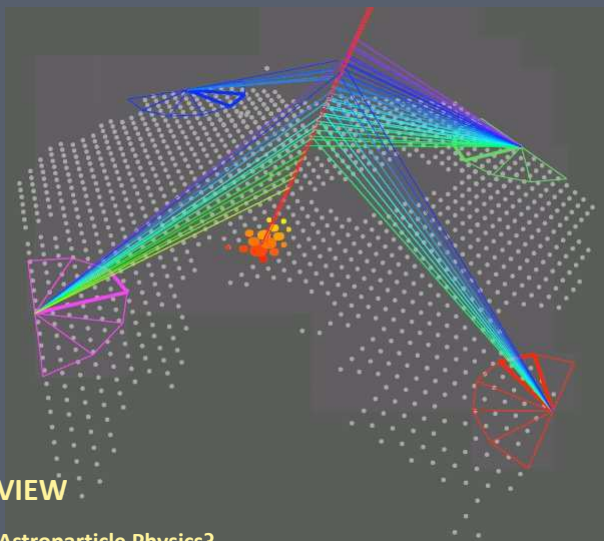
Susan Cartwright
University of Sheffield



2

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

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 $\text{Ov}\beta\beta$)

not very particulate

not very astrophysical

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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

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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

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TOPICS TO BE COVERED

○ High energy astroparticle physics

(cosmic rays, gammas, high-energy neutrinos)

- sources
- detection
- results
- prospects

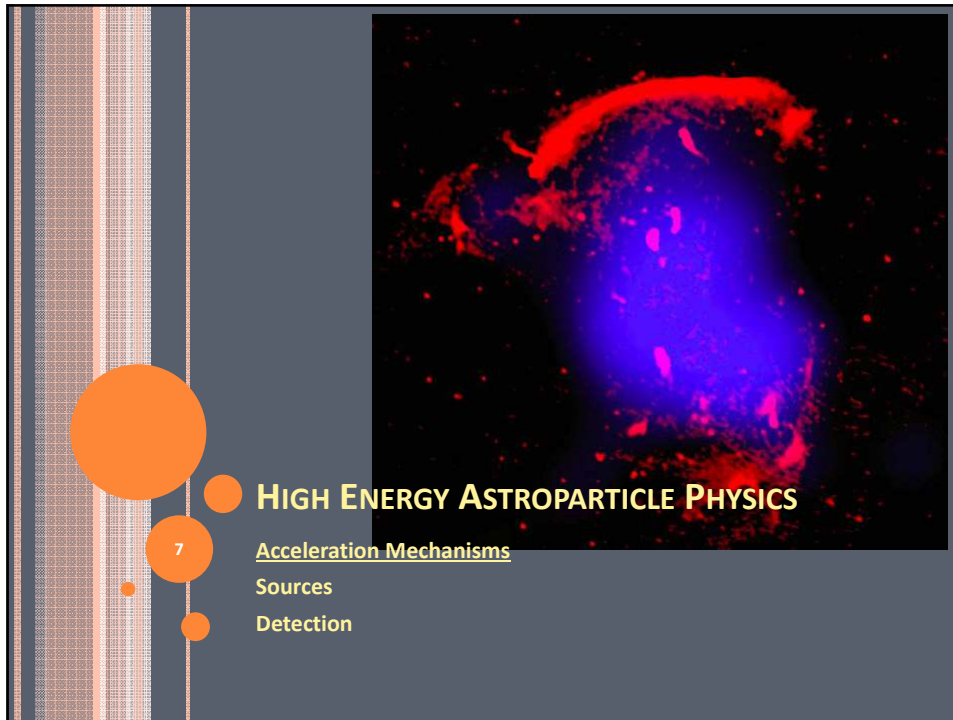
○ Dark matter

- evidence
- candidates
- search techniques

NOT COVERING:

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

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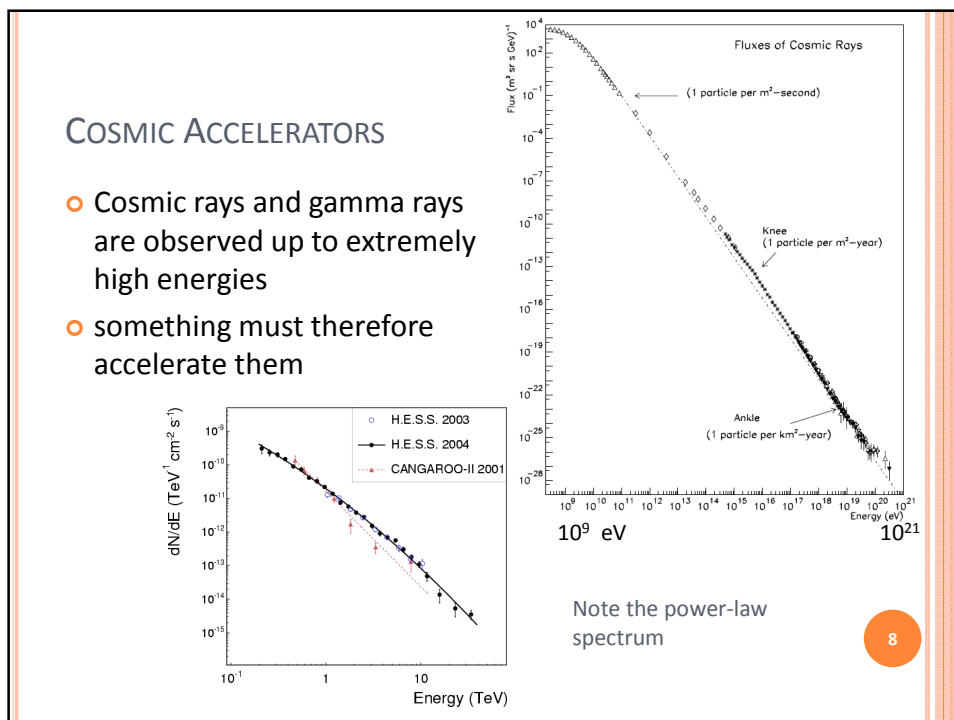
HIGH ENERGY ASTROPARTICLE PHYSICS

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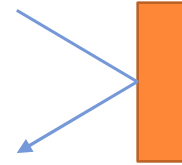
Acceleration Mechanisms

Sources

Detection



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

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

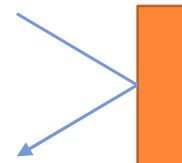
$$p'_x = \gamma_u (p \cos \theta + uE/c^2)$$

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

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

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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

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

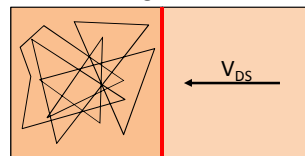
- Hence this process is known as **second-order Fermi acceleration**.
- The good news
 - this produces a power law energy spectrum: $N(E) \propto E^{-x}$ where $x = 1 + 1/\alpha\tau$, α is the rate of energy increase and τ is the residence time of the particle
- The bad news
 - since $u \ll c$, it's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

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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

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ACCELERATION MECHANISMS

- 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 γ is ratio of specific heats ($= 5/3$ for hydrogen plasma)
 - therefore expect $u_2/u_0 \approx 1/4$
 - gas approaches shock-crossing particle at speed $V = 3/4 u_0$
 - if high-energy particles move randomly, probability of particle crossing shock at angle ϑ is $P(\vartheta) = 2 \sin \vartheta \cos \vartheta d\vartheta$, and its energy after crossing shock is $E' \approx E(1 + pV \cos \vartheta)$ (if $V \ll c$)
- therefore average energy gain per crossing is

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

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ACCELERATION MECHANISMS

DSA spectrum

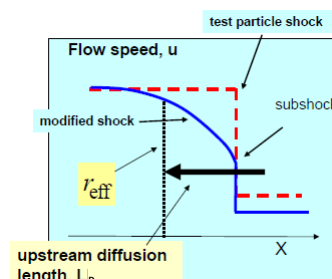
- if average energy of particle after one collision is $E_1 = fE_0$, and if P is probability that particle remains in acceleration region, then after k collisions there are $N_k = N_0 P^k$ particles with average energy $E_k = f^k E_0$.
- Hence $\frac{\ln(N/N_0)}{\ln(E/E_0)} = \frac{\ln P}{\ln f}$, or $\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P / \ln f}$
- 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

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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

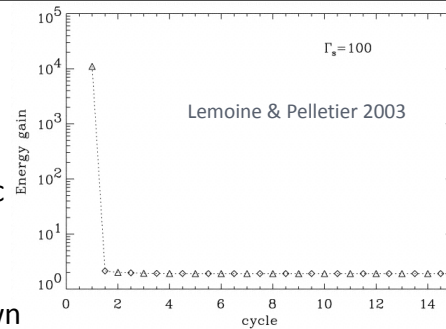


Don Ellison, NCSU

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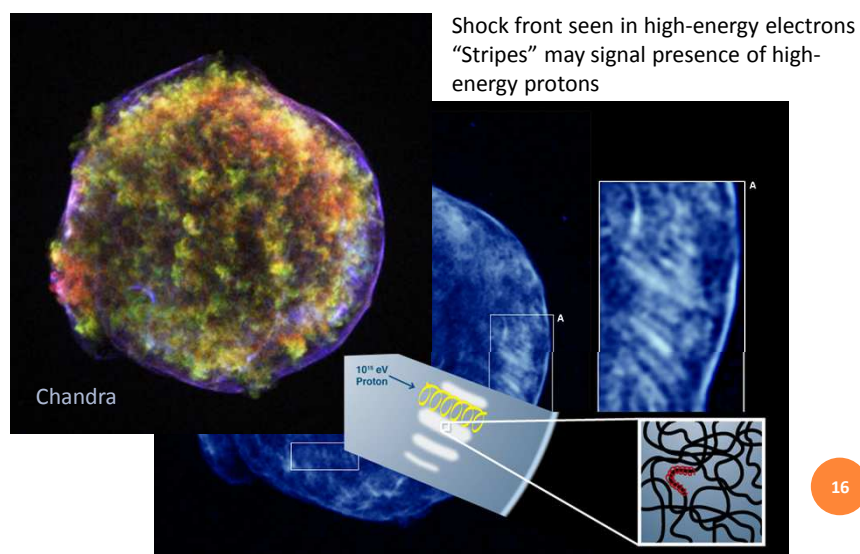
RELATIVISTIC SHOCKS

- DSA assumes non-relativistic shock
- Many astrophysical objects (γ -ray bursts, AGN) are known to host relativistic shocks ($\Gamma \sim 10$ for AGN, up to 1000 for GRBs)
 - these can produce much larger accelerations
 - first return crossing causes energy gain of order Γ^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



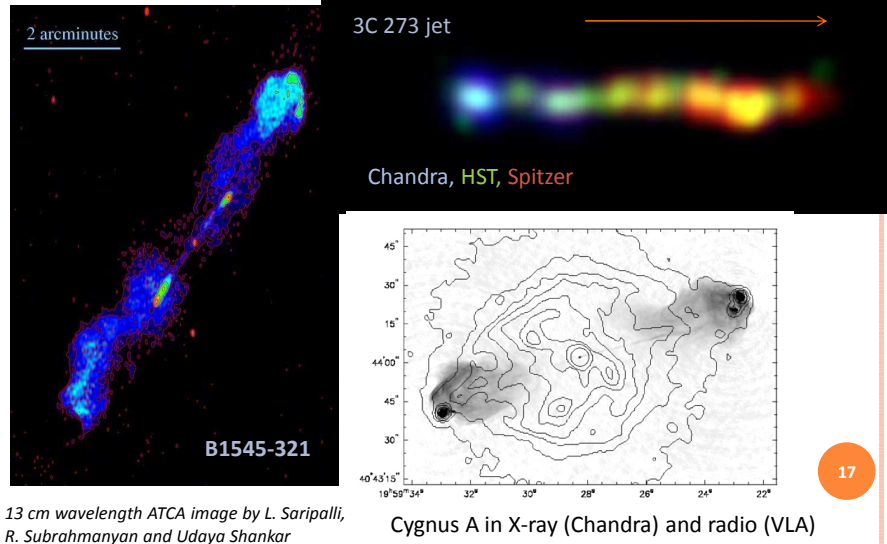
15

TYCHO'S SUPERNOVA (SN 1572)



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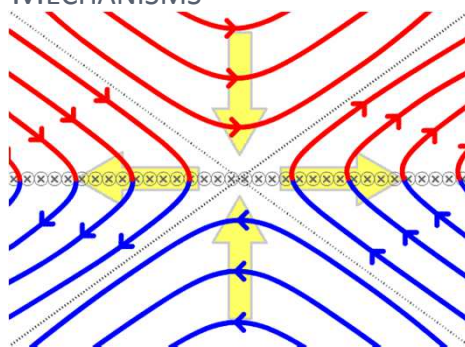
RADIO GALAXIES



ALTERNATIVE ACCELERATION MECHANISMS

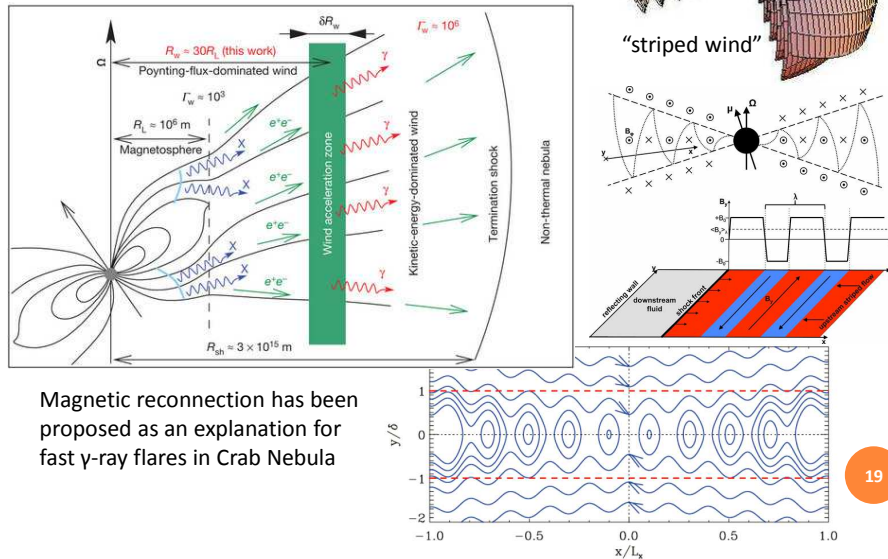
○ Magnetic reconnection

- occurs when two magnetic flows of opposite polarity are forced close together
- it is then energetically favourable for field lines to break and reconnect
- resulting release of energy could drive acceleration



- Well known to occur in solar flares and coronal mass ejections
- Good candidate for acceleration near pulsars

PULSAR MAGNETIC FIELDS



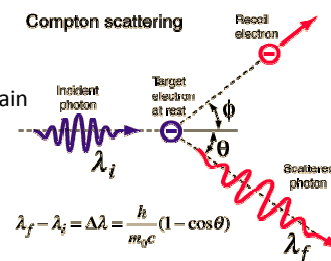
PHOTONS AND NEUTRINOS

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

In lab frame, maximum energy gain occurs in head-on collision:
 $v \approx 4\gamma^2 v_0$

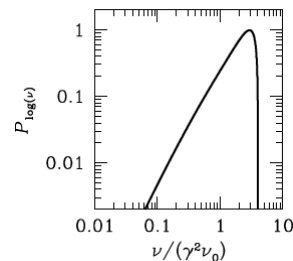
Because of relativistic aberration, spectrum is sharply peaked near maximum



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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



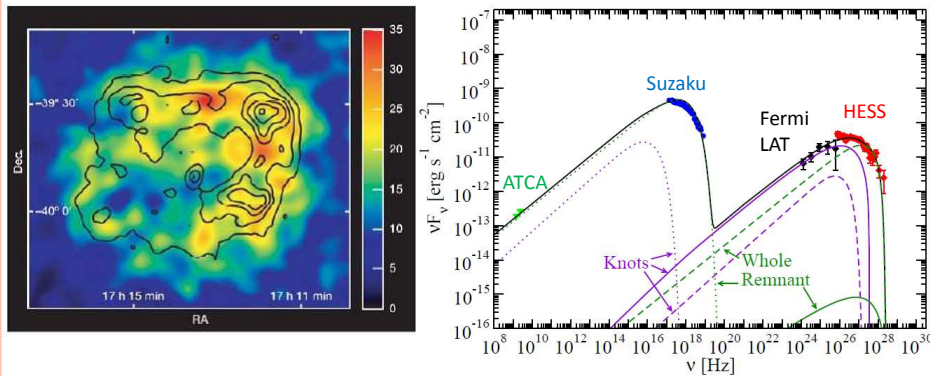
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PHOTONS AND NEUTRINOS

- 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 $\gamma\gamma$, 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

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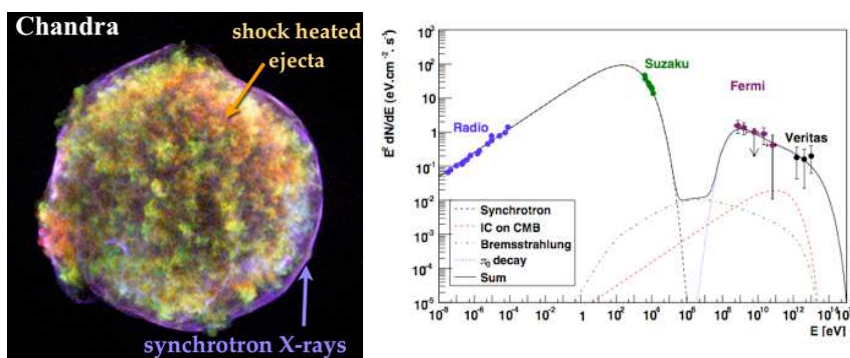
SPECTRUM OF SUPERNOVA REMNANT RXJ 1713.7–3946



Spectrum is consistent with high-energy electrons only: synchrotron radiation (radio \rightarrow x-ray) plus inverse Compton effect (γ -rays)
 Expect this SNR **not** to produce high-energy neutrinos

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SPECTRUM OF SN1572 (TYCHO'S SN)



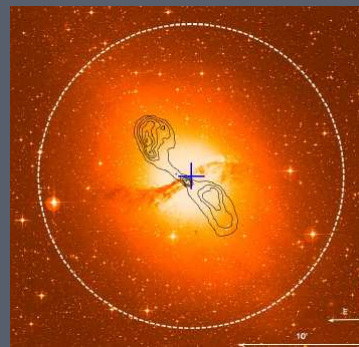
Spectrum seems to prefer π^0 decay—shape wrong for IC
 This SNR **should** produce high-energy neutrinos

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ACCELERATION: SUMMARY

- Observations made in high-energy astroparticle physics require that charged particles be accelerated to very high energies ($\sim 10^{20}$ 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 π^0 decay
 - latter will also make TeV neutrinos, not yet observed

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HIGH ENERGY ASTROPARTICLE PHYSICS

Acceleration Mechanisms

Sources

Detection

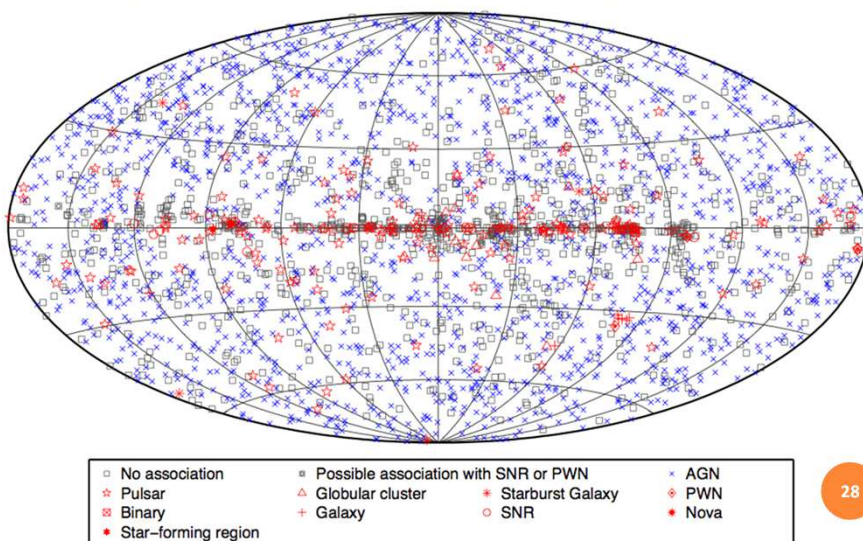
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GAMMA-RAY ASTRONOMY

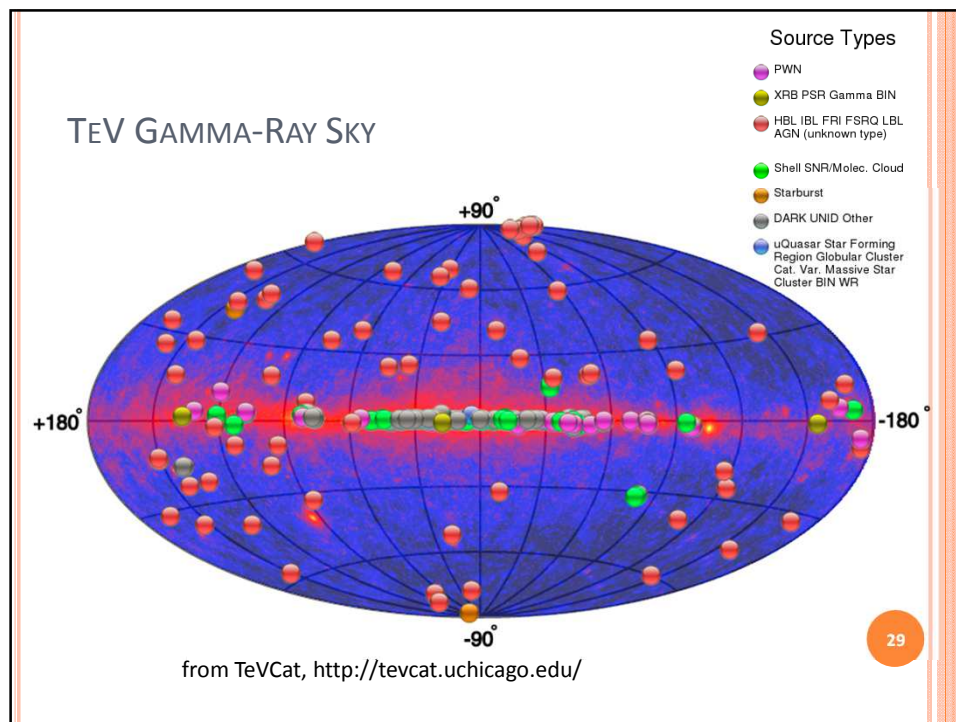
- Well-established branch of high-energy astrophysics
 - most work done at modest energies (few 10s of MeV)
 - some, e.g. EGRET, out to few 10s of GeV
 - this is not usually regarded as astroparticle physics
 - though EGRET catalogue sometimes used as list of candidates for, e.g., neutrino point source 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

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FERMI-LAT 3RD POINT SOURCE CATALOGUE



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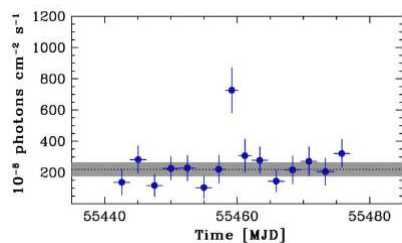
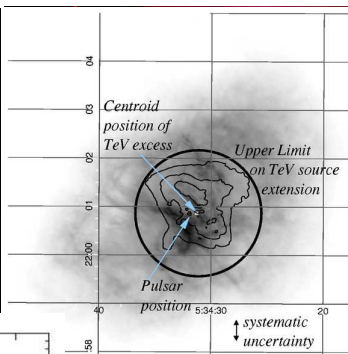
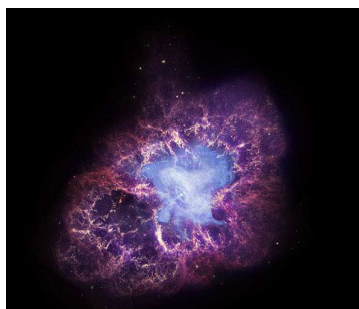


GAMMA-RAY SOURCES

- From maps, clearly mixed Galactic and extragalactic
 - extragalactic sources of TeV γ s 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

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PULSAR WIND NEBULA: THE CRAB

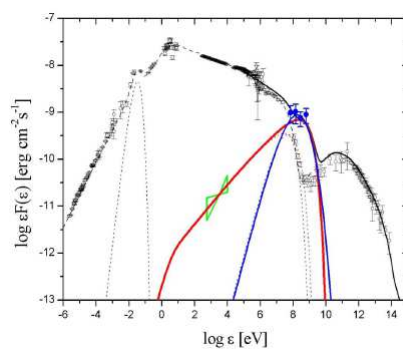


TeV gamma-ray signal as observed by HEGRA (Aharonian et al. 2004)

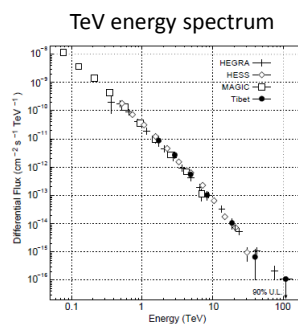
Medium-energy γ -ray flare observed by AGILE (Tavani et al. 2011)

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PULSAR WIND NEBULA: THE CRAB

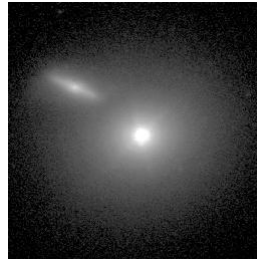
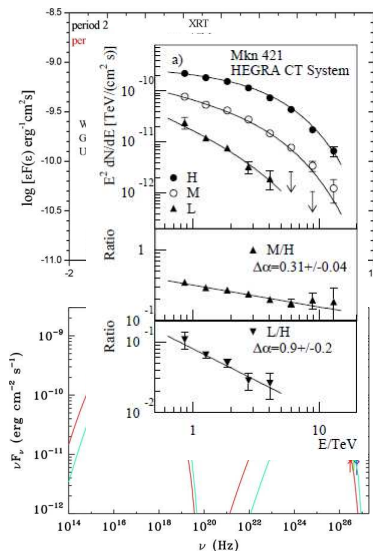


Crab spectral energy distribution showing September 2010 flare



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BLAZAR: MKN 421



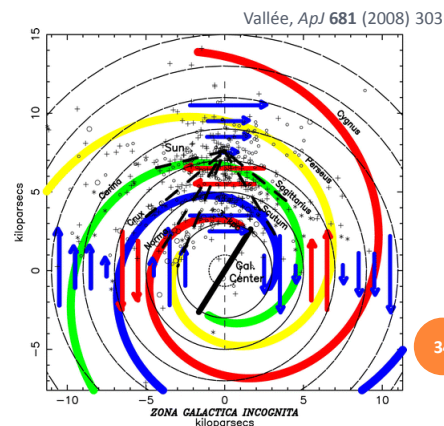
Mkn 421 and companion galaxy.
Aimo Sillanpaa,
Nordic Optical
Telescope.
(Above: very boring
X-ray image by
Chandra)

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

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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



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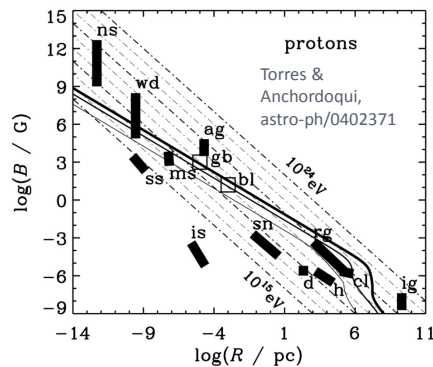
COSMIC RAY SOURCES

General dimensional analysis suggests

$$E_{\text{max}} [\text{GeV}] \approx 0.03 \eta Z R [\text{km}] B [\text{G}] \text{ (Hillas condition)}$$

- 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

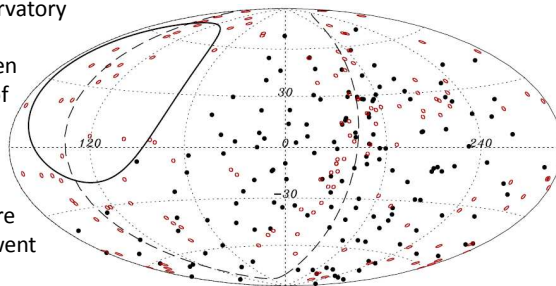


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COSMIC RAY SOURCES

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 (2014), no statistically significant correlation with galaxy surveys, nearby AGN/radio galaxies, or Centaurus A



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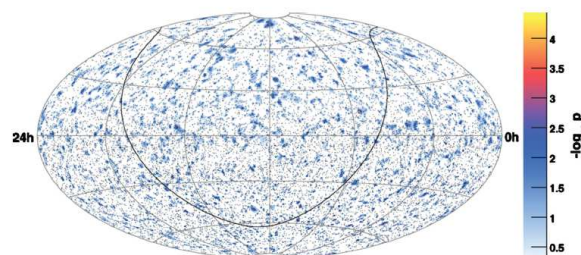
COSMIC RAY SOURCES: SUMMARY

- 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 π^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

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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. (Halzen & Klein 2010)

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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