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Particle Astrophysics

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High energy particle astrophysics: the data

COSMIC RAYS
PHOTONS
NEUTRINOS
EXPECTED RELATIONSHIPS BETWEEN OBSERVABLES

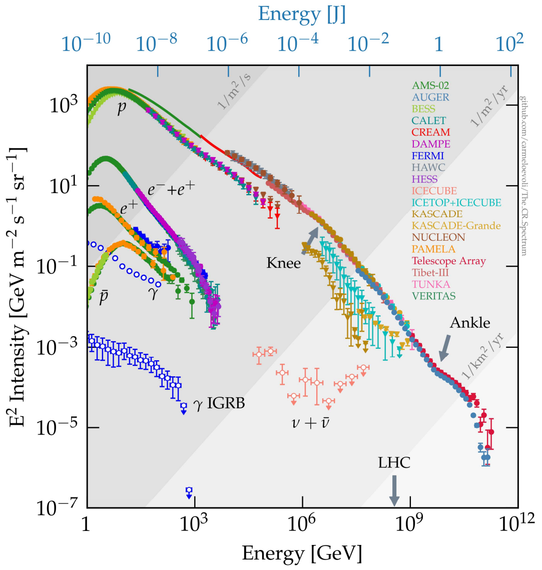
Cosmic rays

Cosmic rays were discovered about 1913 by Victor Hess.

- They consist mostly of protons and heavier ions, and have a power law spectrum with approximate spectral index 2.7.
  - There are two conspicuous slope breaks, the "knee" above 10^6 GeV and the "ankle" above 10^9 GeV, and an apparent cut-off around 10^{11} GeV.

Cosmic rays do not point back to their origin because of deflection by the Galactic magnetic field.

Diagram by Carmelo Evoli, doi:10.5281/zenodo.1468852

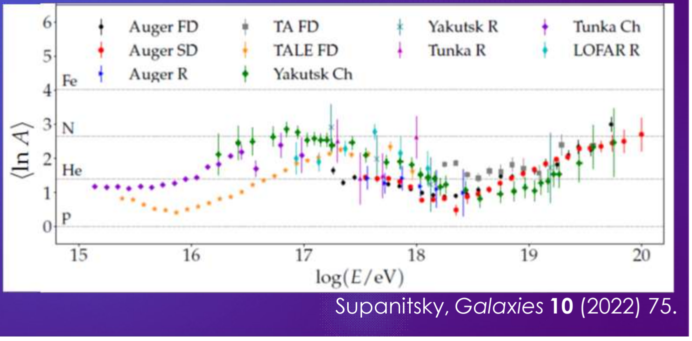


Composition, rigidity and sources

For cosmic rays to be accelerated, they must be confined within the accelerating region.

- This can't be done by gravity—it must involve magnetic fields.
- The response of a charged particle to a magnetic field is determined by its ***rigidity*** *cp*/*q*.
- Therefore the maximum energy attainable in a given source is higher for heavy ions than for protons.

Increasing mean mass is a signature for a source type cutting off.



Supanitsky, *Galaxies* **10** (2022) 75.

Cosmic ray origins

To identify the origins of cosmic rays we need a neutral messenger.

The possibilities are:

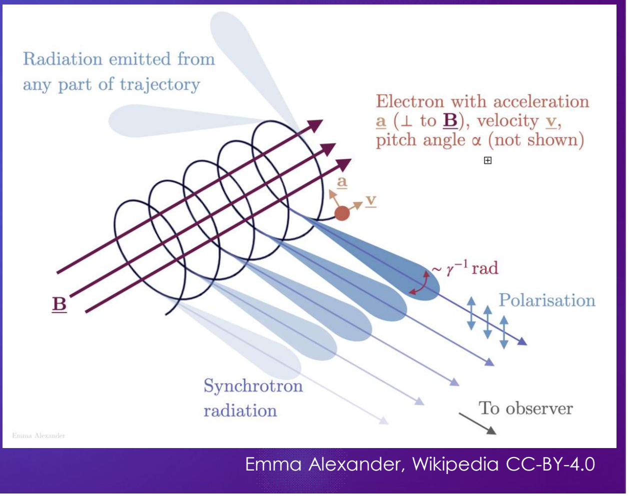
- Photons, if produced by a non-thermal mechanism that requires the presence of high-energy particles
  - examples: synchrotron radiation, inverse Compton scattering, π^0 decay.
- High-energy neutrinos
  - produced by $\pi^\pm$ decay (much higher energy than solar or supernova neutrinos).

Photons may only signal the presence of high-energy electrons; neutrinos definitely require high-energy hadrons.

Photons: synchrotron radiation

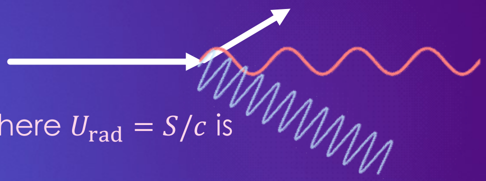
Synchrotron radiation is produced by relativistic particles gyrating in a magnetic field.

- Averaging over the pitch angle α, power emitted is
  $$P_{\text{rad}} = \frac{4}{3} c \sigma_{\text{T}} U_{\text{mag}} \beta^2 \gamma^2$$
  where $\sigma_{\text{T}} = \frac{e^4}{6\pi\epsilon_0^2 c^4 m_e^2}$ and $U_{\text{mag}} = \frac{B^2}{2\mu_0}$.
- The typical photon energy is $\frac{3}{2}\gamma^2 h\nu_g \sin\alpha$ where $\nu_g = eB/(2\pi m)$.



Emma Alexander, Wikipedia CC-BY-4.0

Photons: inverse Compton scattering



A low-energy seed photon backscatters off a high-energy electron.

- Power radiated is $P_{\mathrm{rad}} = \frac{4}{3} c\sigma_{\mathrm{T}} U_{\mathrm{rad}} \beta^2 \gamma^2$ where $U_{\mathrm{rad}} = S/c$ is energy stored in radiation field
- Typical photon energy is $\frac{4}{3}\gamma^2 h\nu_0$ where ν_0 is the seed photon frequency.

The dependence on the electron energy is the same for both synchrotron and inverse Compton, but $\nu_0 \gg \nu_g$.

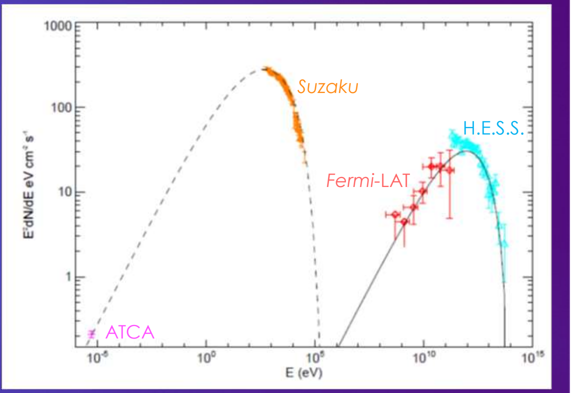
- Therefore we expect the same shape of spectrum, but at higher energies.
- The relative normalisation depends on the magnetic field.

Example: SNR RX J1713.7–3946

Fit to data using synchrotron radiation (dashed line) plus inverse Compton (solid line).

- Note that for a power-law electron spectrum $N(E_e) \propto E_e^{-\delta}$ we expect a synchrotron radiation spectrum $j_\nu \propto B^{(\delta+1)/2} \nu^{-(\delta-1)/2}$.
- Because $P_{\mathrm{rad}} \propto \gamma^2$ the electron power law will cut off at high energies owing to rapid energy loss in the high-energy tail, so expect similar cut-off in the photon spectrum, as seen.

Chuyuan Yang and Siming Liu *ApJ* **773** (2013) 138



Observed photon energy spectrum is roughly $E^2 \frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{0.5} \Rightarrow j_\nu \propto \nu^{-0.5} \Rightarrow N(E_e) \propto E_e^{-2}$.

Photons and neutrinos: pion decay

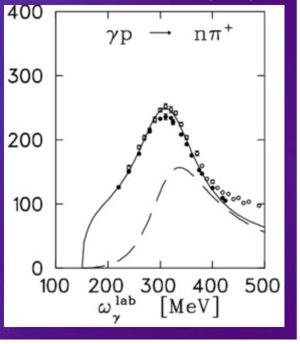
Cosmic rays are predominantly protons, with some heavier nuclei.

High-energy protons colliding with ambient gas or photons will produce both π± and π^0, and therefore ν_μ and photons.

- Muon decay will then produce more ν_μ and ν_e.
  - Oscillation will change the mix of flavours.
- The photon spectrum from π^0 decay differs from the inverse Compton spectrum, so we can distinguish cases where high-energy photon emission is *dominated* by pion decay.

There is no realistic way to produce a detectable neutrino flux without high-energy hadrons.

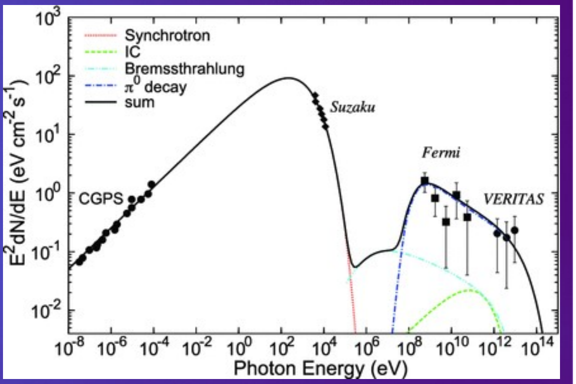
Schmidt et al., *Z. Phys. A* **355** (1996) 421



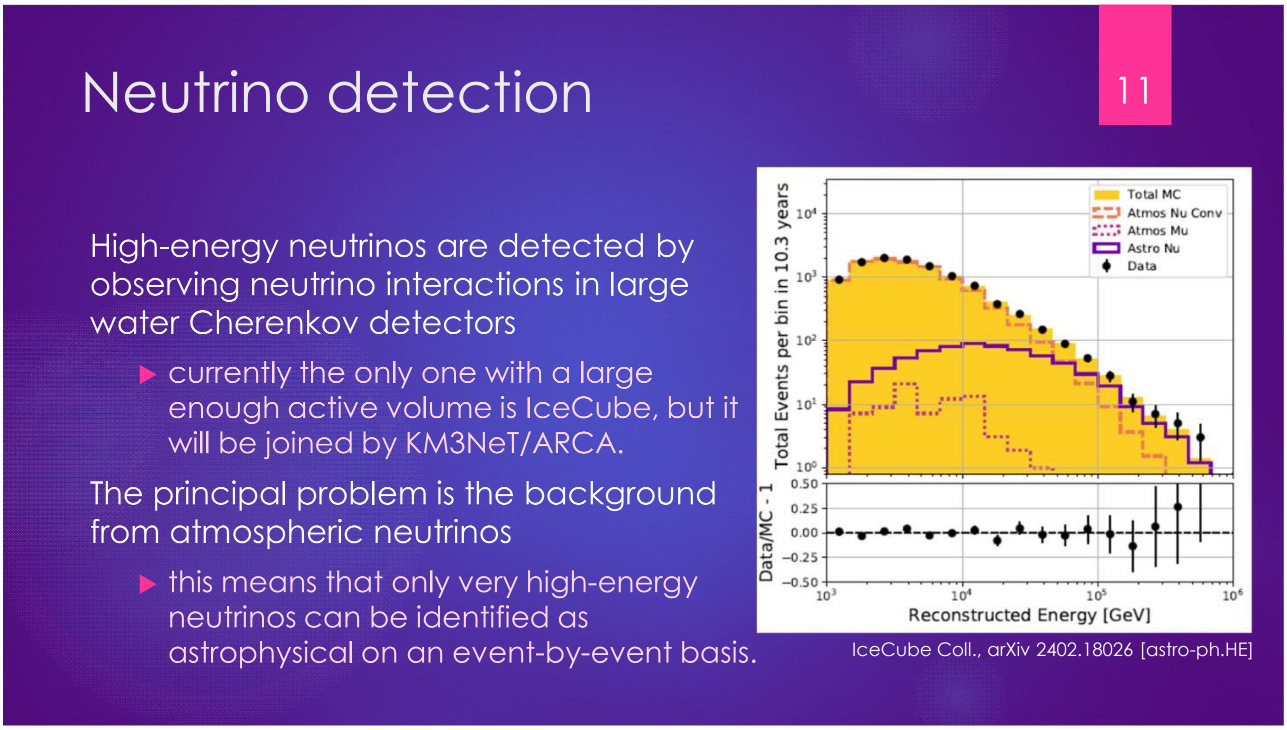
Example: Tycho's supernova

The remnant of the supernova observed by Tycho Brahe in 1572.

- Known to have been Type Ia from reflected spectrum observed in 2008.
- Shape of high-energy spectrum quite different from the synchrotron spectrum, so not inverse Compton.
- Can be well fitted by π^0 decay.



Zhang et al., *MNRAS* **429** (2013) L25.



Neutrino detection

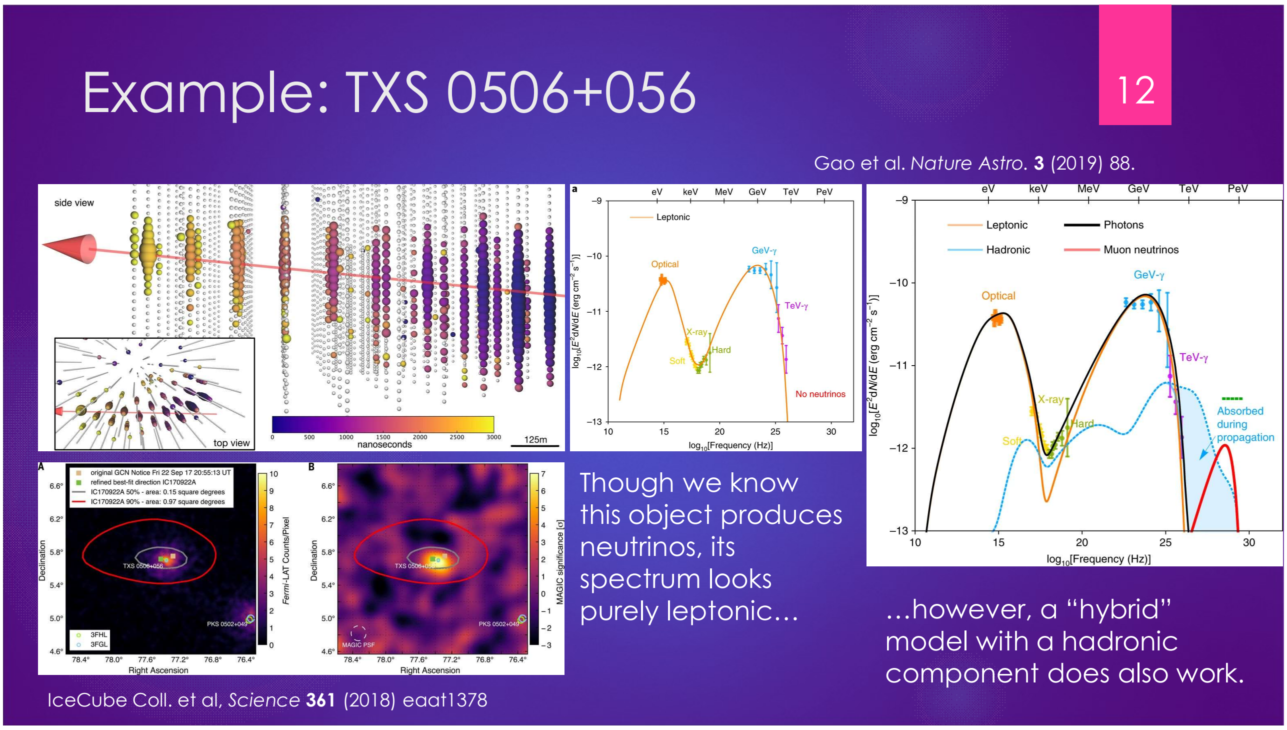
High-energy neutrinos are detected by observing neutrino interactions in large water Cherenkov detectors

- currently the only one with a large enough active volume is IceCube, but it will be joined by KM3NeT/ARCA.

The principal problem is the background from atmospheric neutrinos

- this means that only very high-energy neutrinos can be identified as astrophysical on an event-by-event basis.

IceCube Coll., arXiv 2402.18026 [astro-ph.HE]



Example: TXS 0506+056

Gao et al. *Nature Astro.* **3** (2019) 88.

Though we know this object produces neutrinos, its spectrum looks purely leptonic…

…however, a "hybrid" model with a hadronic component does also work.

IceCube Coll. et al, *Science* **361** (2018) eaat1378

Expected correlations

High-energy neutrinos should be accompanied by high-energy photons, as $\pi^{\pm}$ production should imply π^0 production

- but if the source region (or its surroundings) is very dense, the photons might not escape.

High energy photons from π^0 decays should be accompanied by neutrinos, for the same reason

- but the neutrino signal may be too weak to see, or buried in the atmospheric neutrino background

Most acceleration mechanisms should accelerate all charged particles, so high-energy electrons should imply high-energy hadrons

- but they might not, if the seed material is mostly e^+e^- pair plasma (which it may be in some environments).

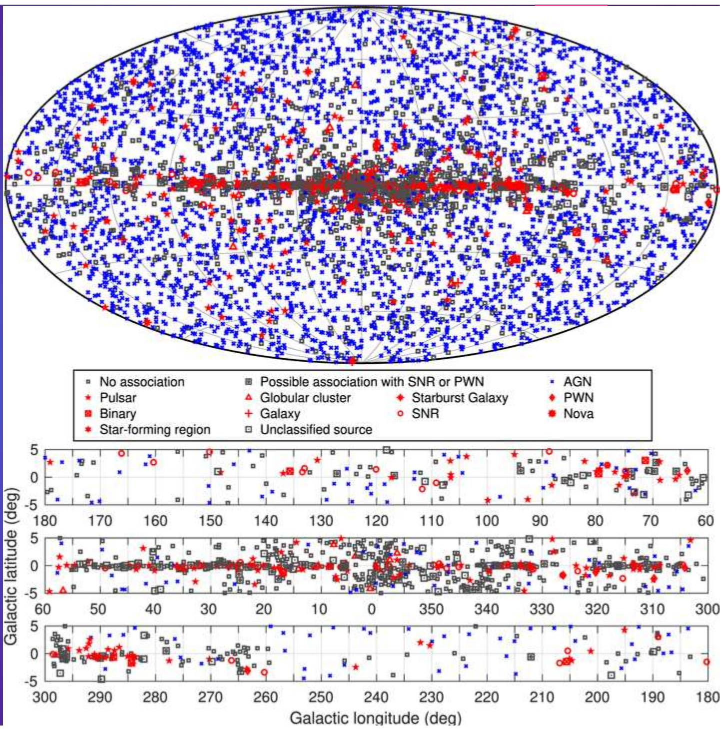
S. Abdollahi *et al* *ApJS* **247** (2020) 33

Photon sources

High-energy photon sources in our Galaxy are mainly pulsars and supernova remnants.

Extragalactic sources are mainly blazars.

In addition, there are also transient sources of MeV γ-rays, i.e. gamma-ray bursts (GRBs).

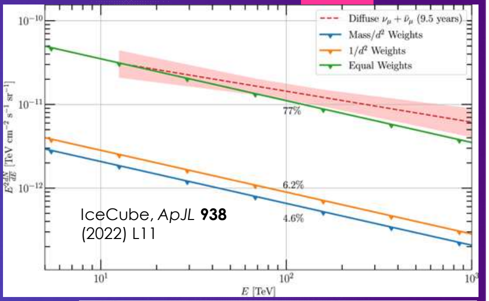


Not neutrino sources!

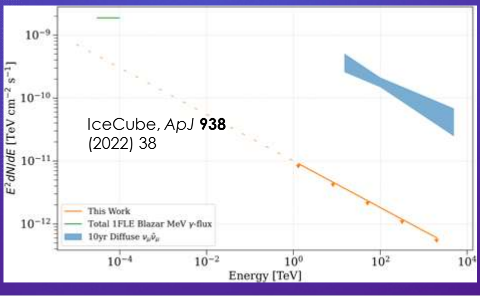
IceCube has conscientiously searched for correlations between high-energy neutrinos and various source catalogues. They find:

- GRBs are *not* neutrino sources (<1%)
- though at least one blazar is a neutrino source, blazars do *not* account for the vast majority of the neutrino flux.
- Nor do galaxy clusters.

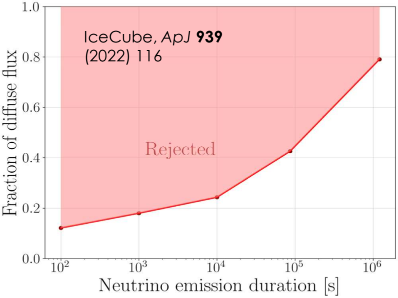
But AGN in general could do so.



IceCube, *ApJL* **938** (2022) L11



IceCube, *ApJ* **938** (2022) 38



IceCube, *ApJ* **939** (2022) 116

Summary

Cosmic rays, consisting primarily of protons and heavier ions, are observed to have a power-law energy epctrun extending out to ~10^{20} eV.

- This implies the existence of extremely powerful astrophysical accelerators.
- Cosmic rays do not pinpoint these directly because their trajectories are deflected by the Galaxy's magnetic field.

Acceleration of hadrons should be accompanied by γ-ray and neutrino emission from pion decay, and of electrons by photons from synchrotron radiation (radio to X-rays) and inverse Compton (γ-rays).

- These are all seen, but a complete explanation is still lacking
- in particular, the origins of astrophysical neutrinos are not yet established.