HIGH ENERGY PARTICLE ASTROPHYSICS

Introduction

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What is particle astrophysics?

- Particle astrophysics is the use of particle physics techniques (experimental or theoretical) to address astrophysical questions.
- Topics included:
  - early-universe cosmology
    - inflation (and alternatives), baryogenesis, dark energy
  - ***cosmic rays***
  - ***γ-ray astronomy***
  - ***high-energy neutrino astronomy***
  - low-energy neutrino astronomy
  - dark matter (*see PHY326/426*)
- I will focus on high-energy particle astrophysics

These form a coherent field with a lot of common factors—"high-energy particle astrophysics"

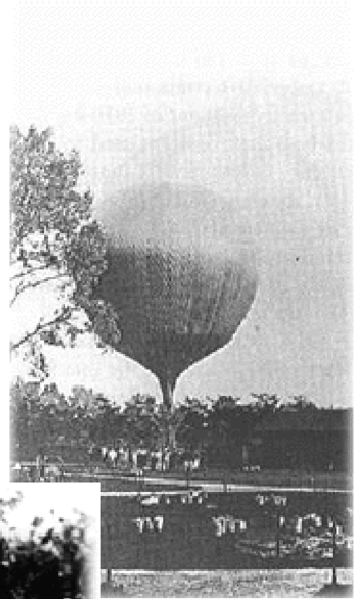
HIGH ENERGY PARTICLE ASTROPHYSICS

Cosmic Rays

COSMIC RAYS

Discovery

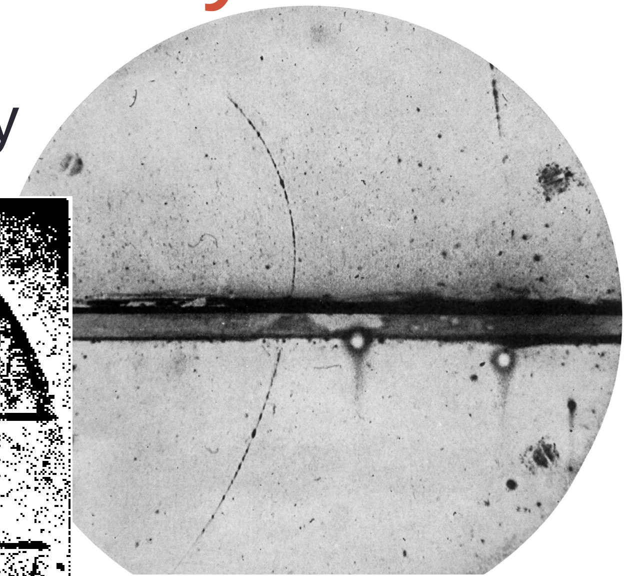
Discovery of cosmic rays

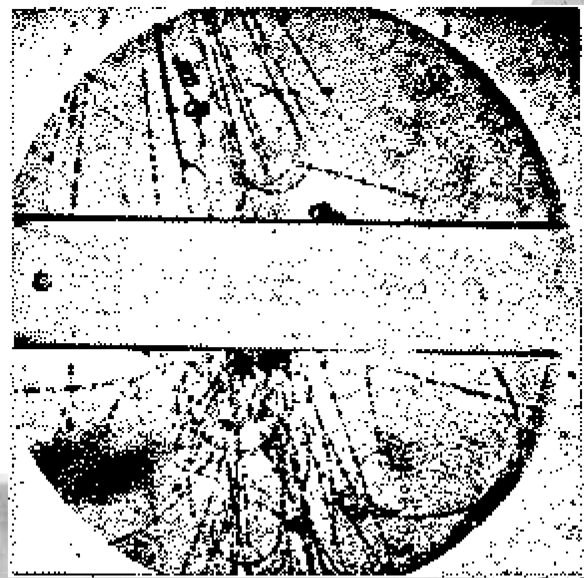


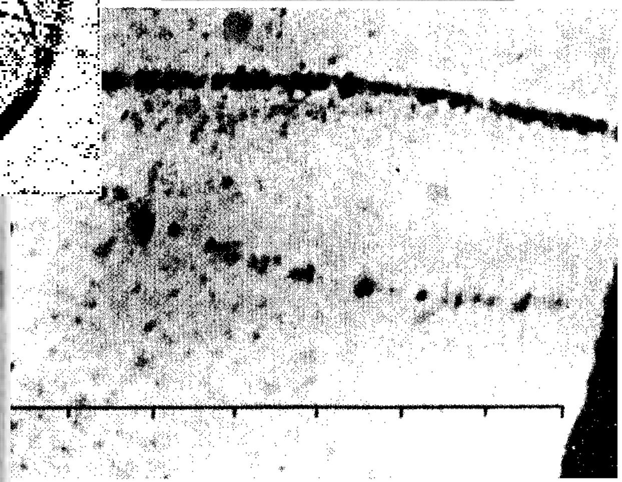

- Cosmic rays were discovered in 1912 by Hess
  - he showed that the intensity of penetrating radiation increased with altitude
  - therefore not due to natural radioactivity in rocks
- Shown to be charged particles by Compton in 1932
  - flux observed to vary with latitude as expected for charged particles deflected by Earth's magnetic field
- East-west asymmetry observed in 1933
  - showed particles were mainly positively charged (protons & ions)

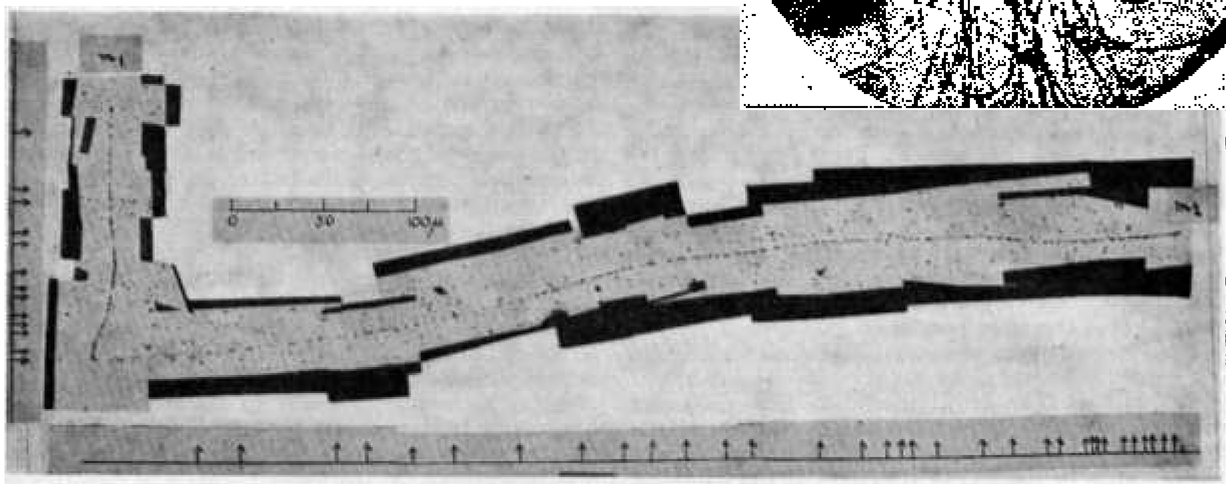
Early significance of cosmic rays

- Initial significance of cosmic rays mostly related to particle physics
  - e^+, μ, π and strange particles all discovered in cosmic rays
  - later superseded by accelerators







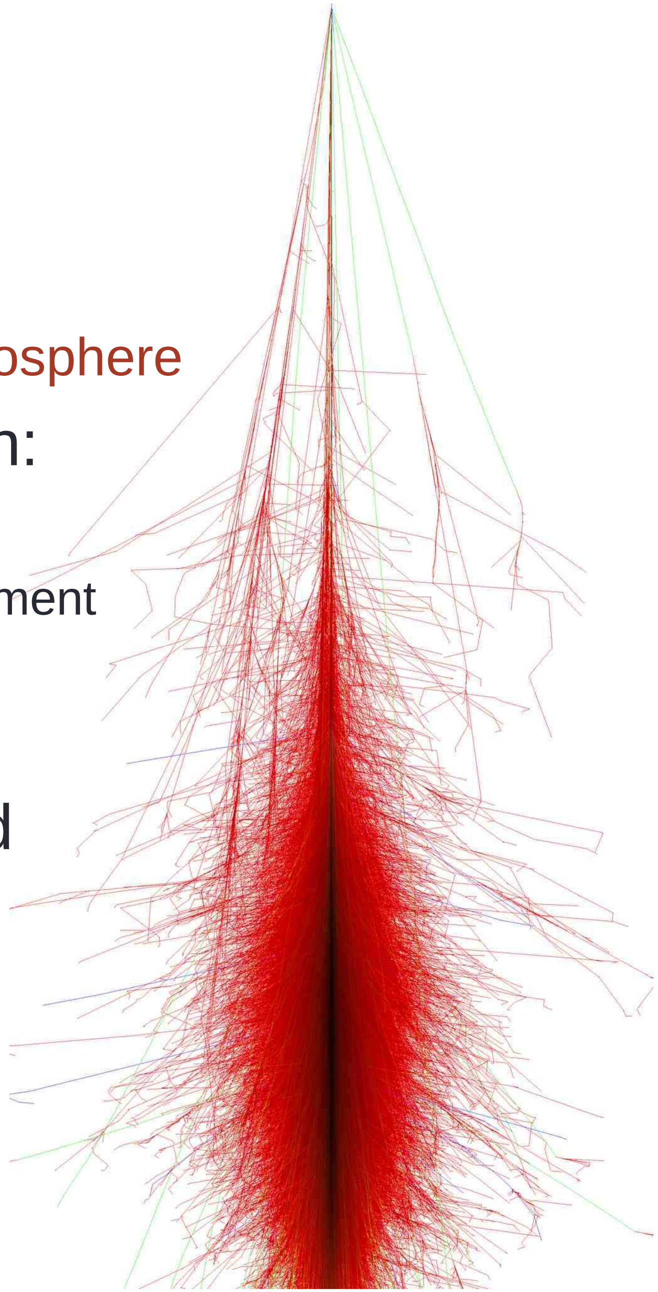


COSMIC RAYS

Detection

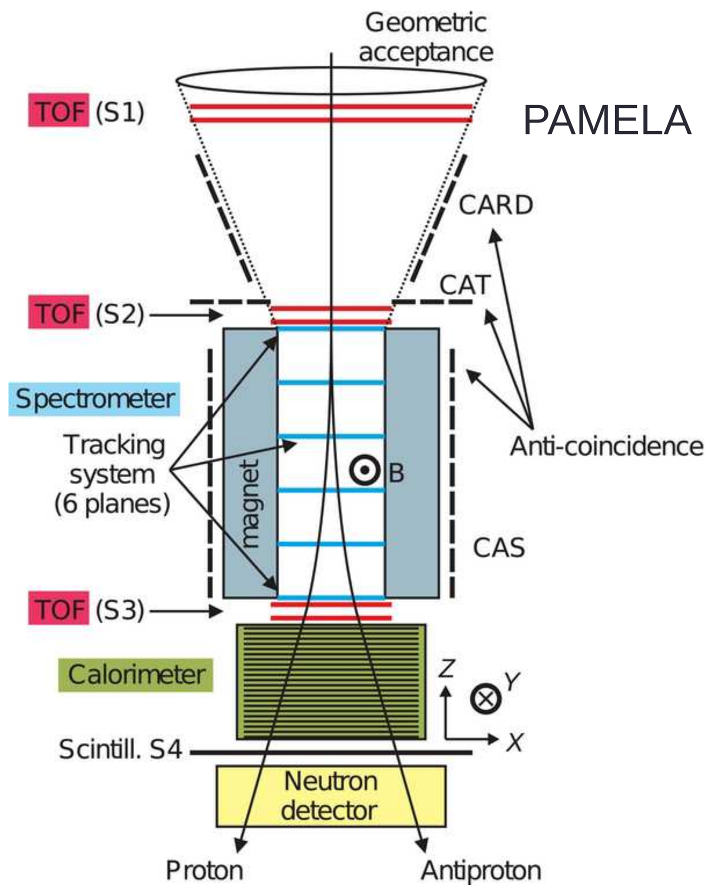
Detection of cosmic rays

- Cosmic rays are strongly interacting
  - primary cosmic rays shower high in the atmosphere
- Therefore, two approaches to detection:
  - detect primary particle at high altitude
    - requires balloon-borne or space-based experiment
  - detect shower products
    - can be ground-based, but loses information
- Typically, ground-based detection used for higher-energy cosmic rays
  - flux is too low for effective detection by experiments small enough to launch to high altitude



Detection of cosmic rays: primaries

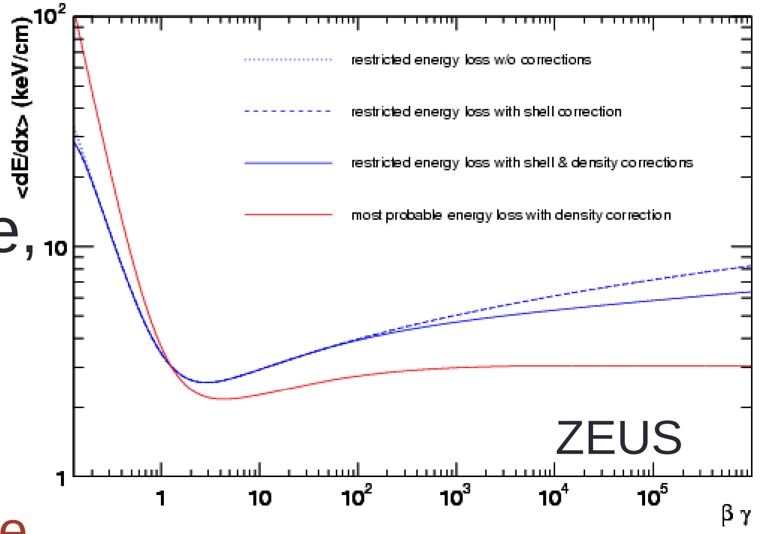
- Ideally, would like to know *energy* (or momentum), *direction* and *identity* of particle
  - energy can be measured by calorimetry
  - momentum by a magnetic spectrometer
  - direction requires tracking information
    - spark chambers, wire chambers, silicon strip detectors, CCDs, …
  - various techniques for particle identification
    - time of flight, d*E*/dx, threshold or ring-imaging Cherenkov
      - measure *mass*, but generally only for low-ish energies
    - charge measurement
      - measures *Z*, cannot separate isotopes



Energy/momentum and direction

- Magnetic spectrometers measure *momentum* (actually, rigidity) from deflection of particle by magnetic field
  - this has the advantage that it measures charge *sign*, and thus distinguishes particles from antiparticles
- Calorimeters measure *energy* by causing particle to shower and then detecting deposited energy
  - this is usually more accurate than momentum above a certain threshold (depends on magnetic field) and measures photons (and other neutrals) as well as charged particles
- Other techniques include transition radiation (measures γ; convert to E by determining m)
  - calorimetry and transition radiation can both be used by non-magnetic detectors

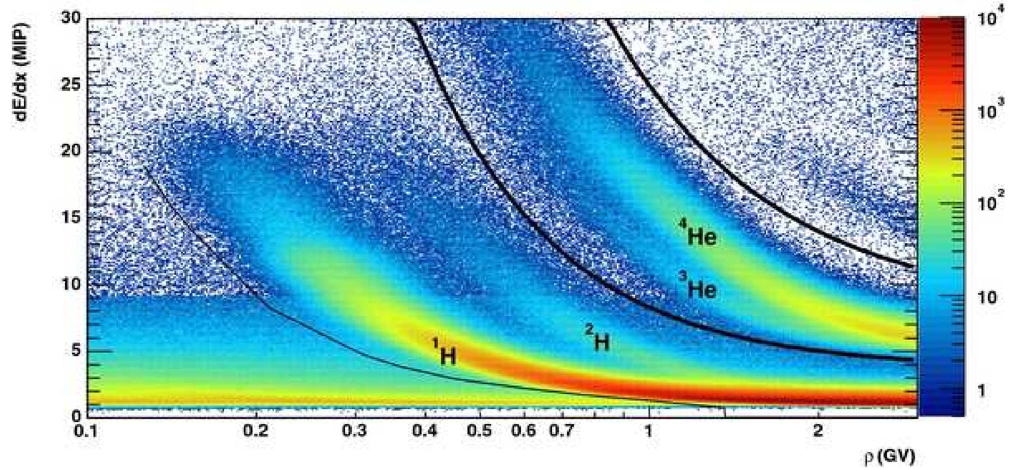
Particle identification

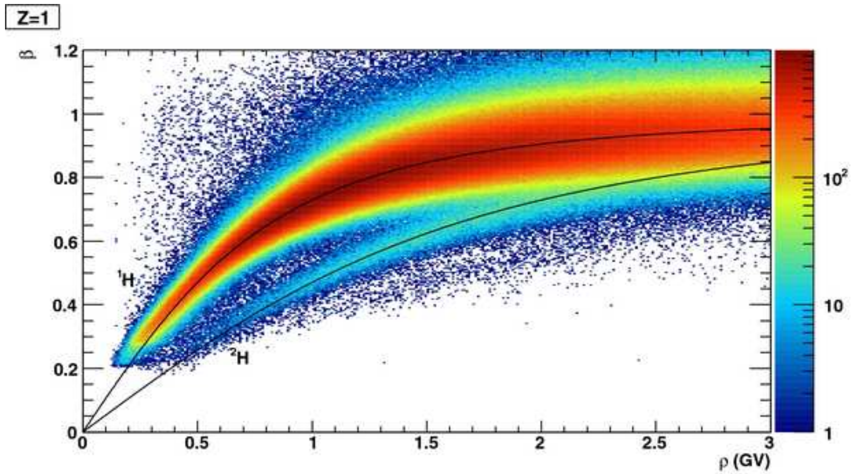


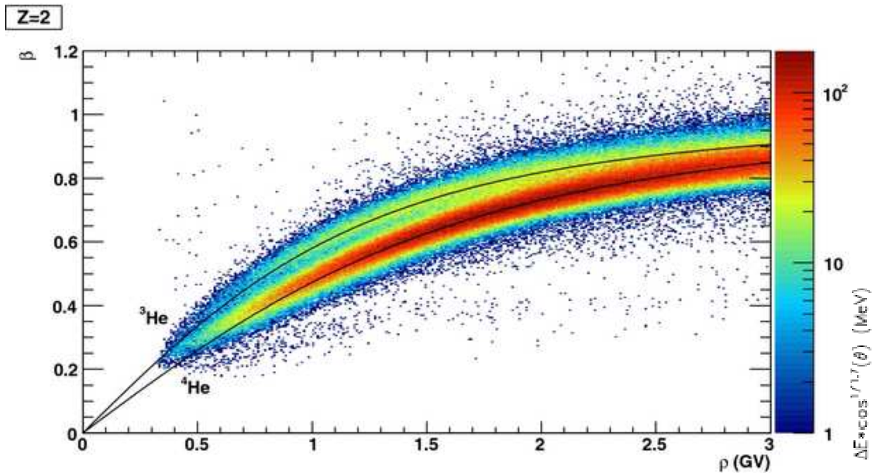
- d*E*/d*x* depends on βγ and therefore, for a known momentum, on the mass of the particle
  - the dependence is fairly complicated, and measurements do not generally use ⟨d*E*/d*x*⟩ itself but a truncated mean—therefore need to adjust formula
- TOF depends on β, hence on *m* if *p* known
- Cherenkov methods depend on β via $\cos\theta = 1/n\beta$
- *All these methods lose discrimination when particles become ultra-relativistic, so that m is negligible*
- Determining particle charge via ionisation produced works up to higher momenta, but does not give isotopic info

Particle identification

PAMELA dE/dx

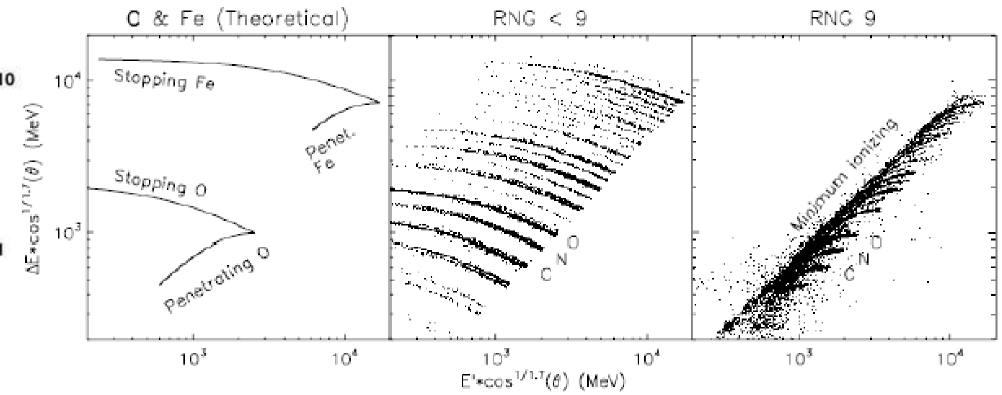






PAMELA time of flight

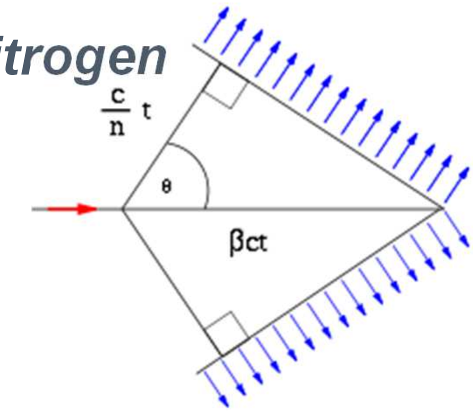
Note: ***rigidity*** *R* (or ρ) = *cp*/*Ze* is often used instead of momentum; it defines response of particle to magnetic field

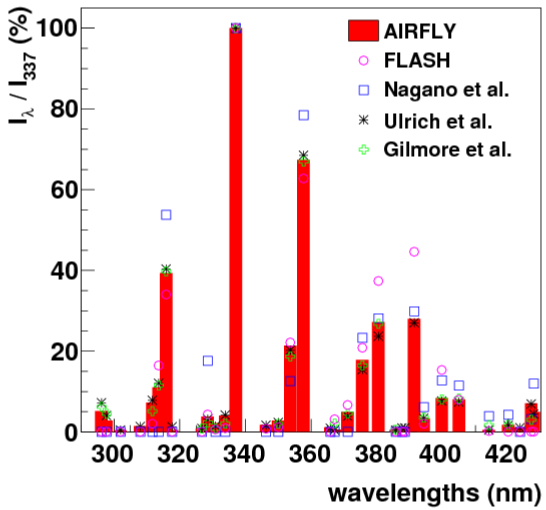


CRIS charge deposited

Detection of cosmic rays: showers

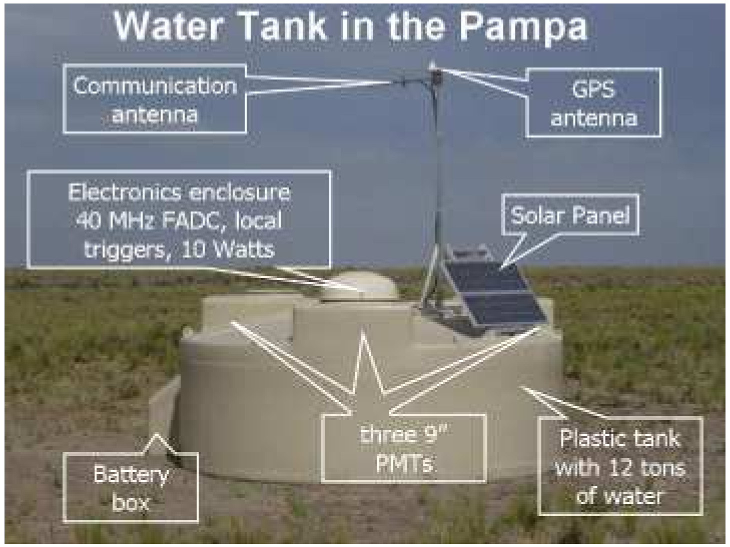
- Two possibilities: detect the shower in the air, or detect shower particles that reach the ground
  - Detection in air: either ***Cherenkov radiation*** or ***nitrogen fluorescence***
  - Cherenkov radiation: detect particles travelling at speeds > *c*/*n* (~25 MeV for electrons in air)
    - very forward peaked: cos θ = 1/*n*β ~ 1° in air
    - blue light
  - Nitrogen fluorescence: detect near-UV radiation from excited nitrogen molecules
    - also mostly sensitive to electrons, but isotropic
  - Light is very faint in both cases: require clear skies and very dark nights
    - poor duty cycle, but large effective area

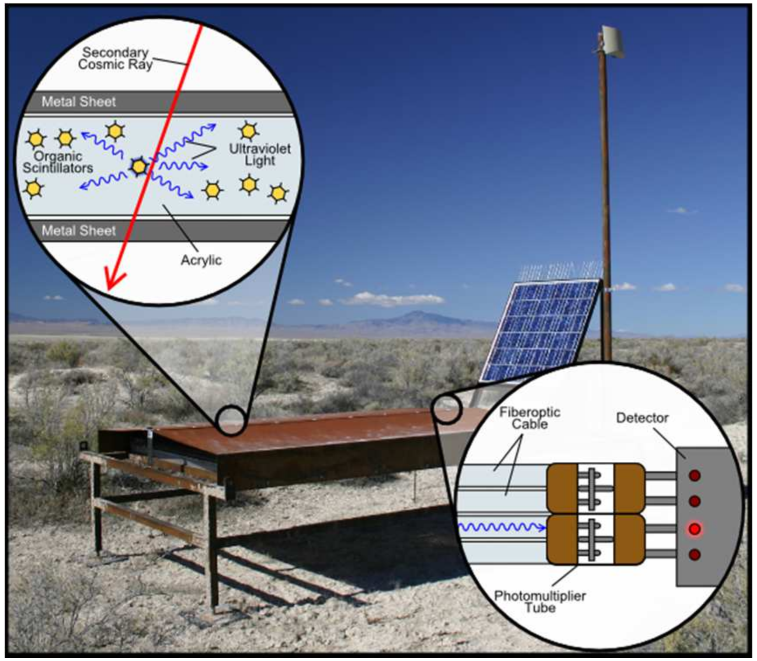




Detection of cosmic rays: showers

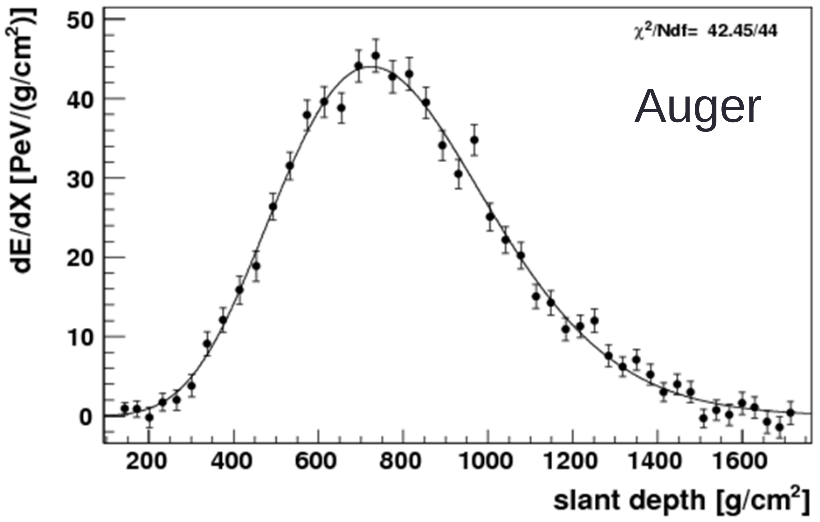
- Two possibilities: detect the shower in the air, or detect shower particles that reach the ground
  - Ground arrays: need large area coverage, so cheap, fairly autonomous array elements
    - technologies of choice: water Cherenkov or plastic scintillator
    - some arrays also have muon detectors (shielded from other particles)

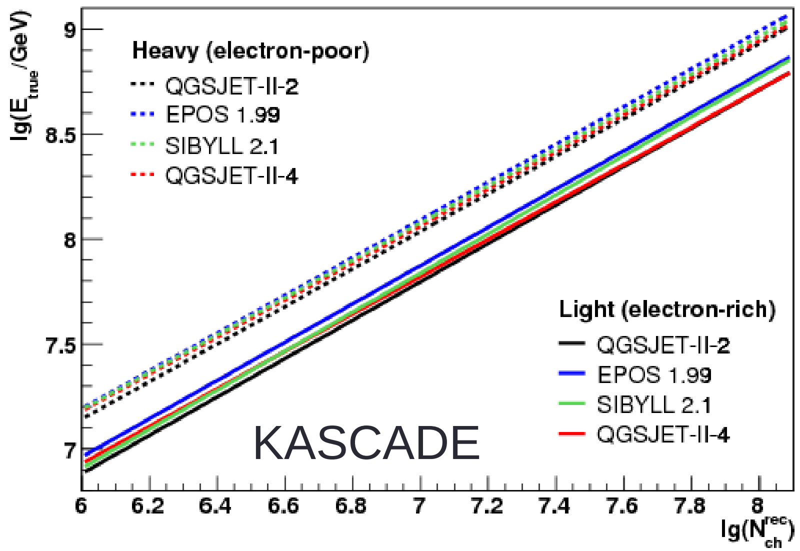




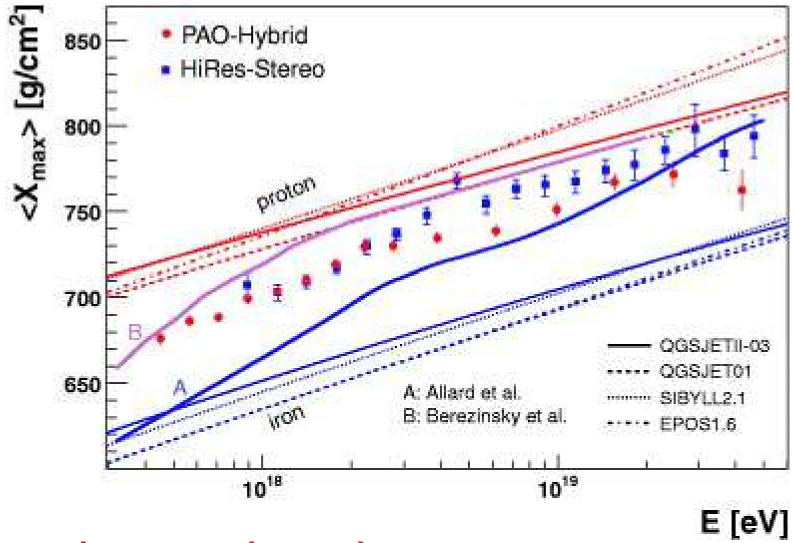
Energy measurement

- Fluorescence detectors measure light yield and longitudinal shower profile
  - a fit to this can be used to deduce energy of primary
- Ground arrays measure transverse shower profile at ground level
  - charged particle multiplicity or charged particle density at specified distance from shower axis can be used to deduce energy

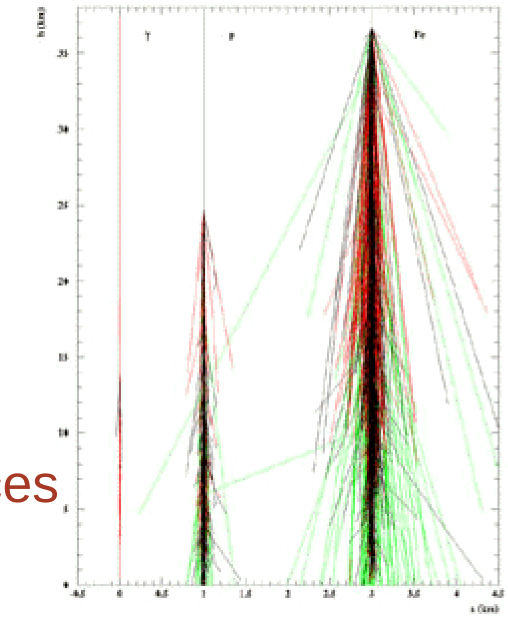




Particle identification



- Ground arrays cannot provide specific primary identification
  - “Heavy” and “light” primaries can be distinguished by the depth in the atmosphere at which they shower (X_{max})
  - Showers initiated by electrons/photons are narrower and contain only $e^{\pm}$ and γ
- At the highest energies there is some model dependence in this—no way to test models at these energies—and some disagreement between experiments
  - this is actually quite important as particle ID at highest energies has a bearing on possible sources

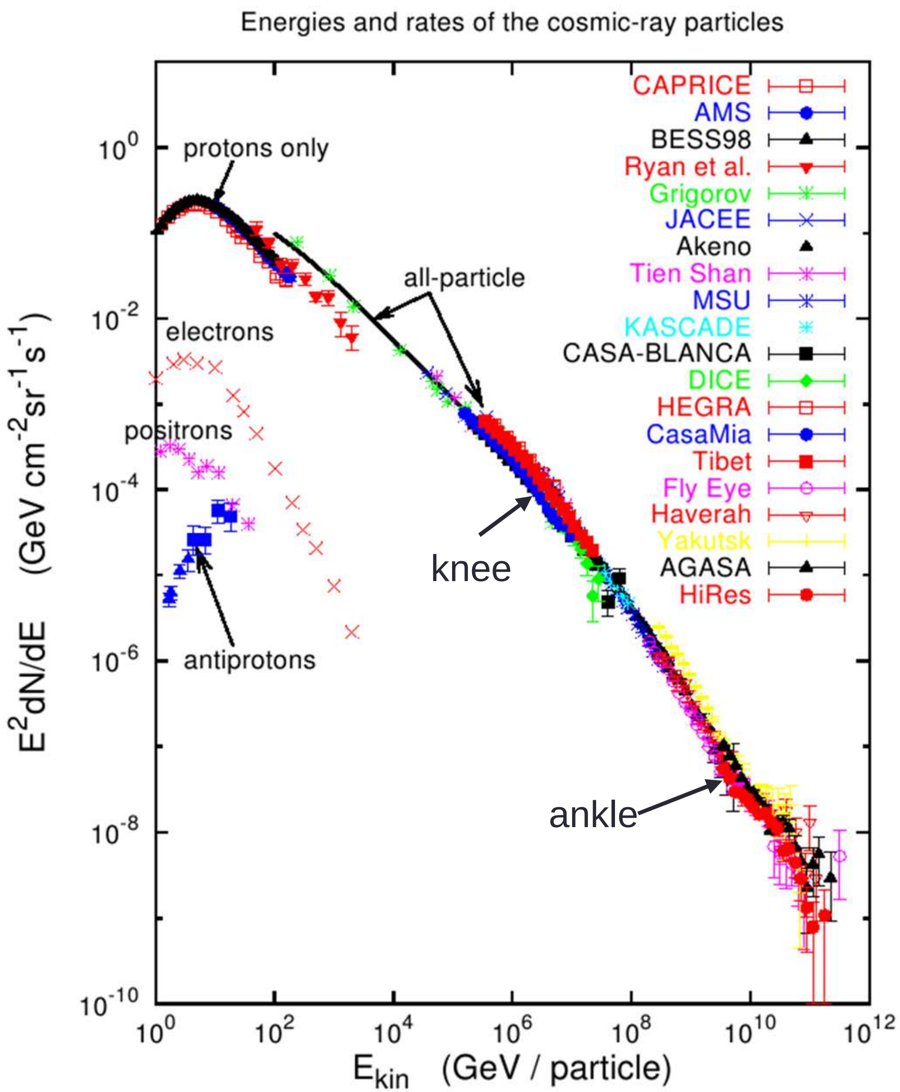


COSMIC RAYS

Properties

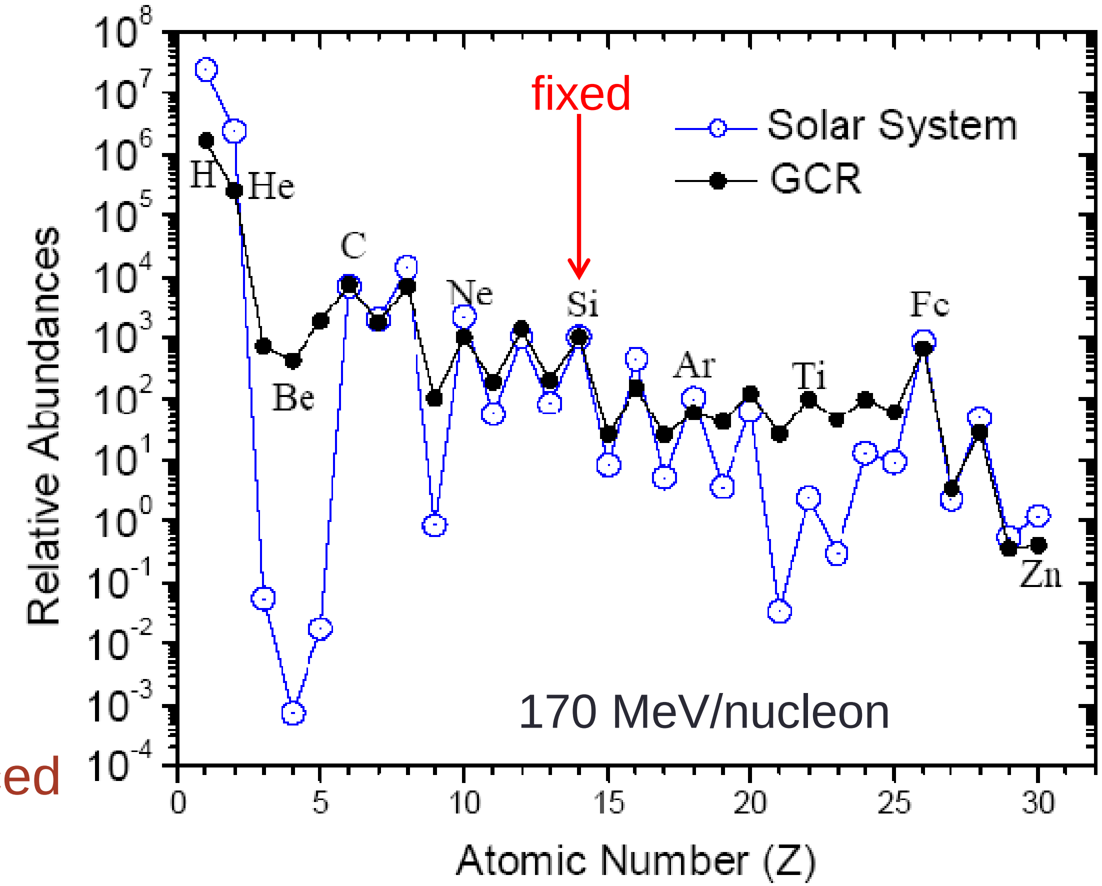
Properties of cosmic rays

- Energy spectrum is close to a power law with spectral index ~2.7
  - turn-over at low energies is due to solar magnetic field
  - two noticeable slope changes: “knee” at ~10^6 GeV and “ankle” at ~10^9 GeV
    - possibly due to changeover of sources



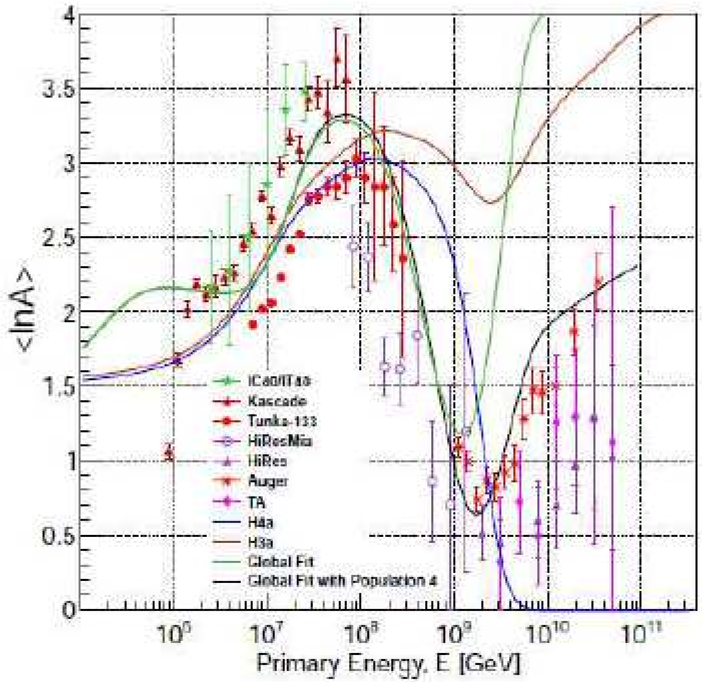
Composition

- Relative deficit of H and He (more easily deflected)
- Large excess of Li/Be/B and elements just below iron peak
  - these nuclei are produced in CRs by ***spallation***
  - also accounts for smaller odd/even modulation
- Note that detailed composition information is only available for fairly low-energy CRs



High energy composition

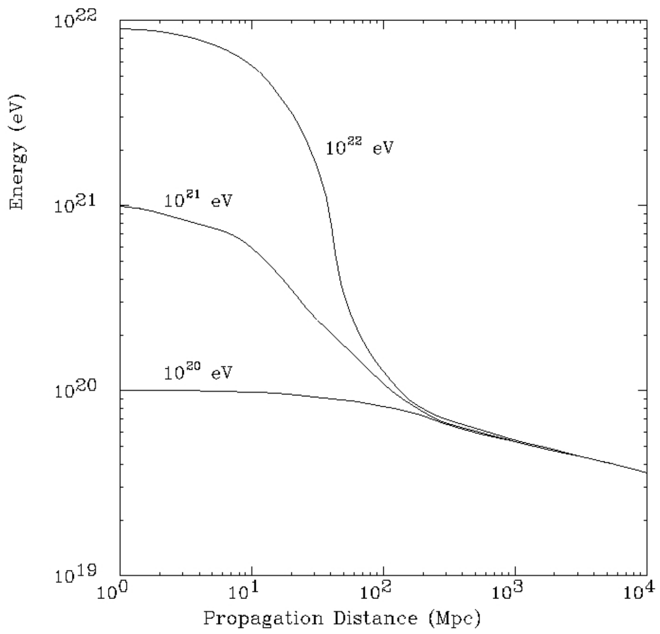
- Rigidity $R = cp/Ze$
  - particles of same rigidity behave in same way in Galactic magnetic field *and* in source magnetic field
  - if source can only confine particles up to rigidity R_{max}, then maximum particle *energy* $\propto Z$: composition will skew towards heavier species at cut-off



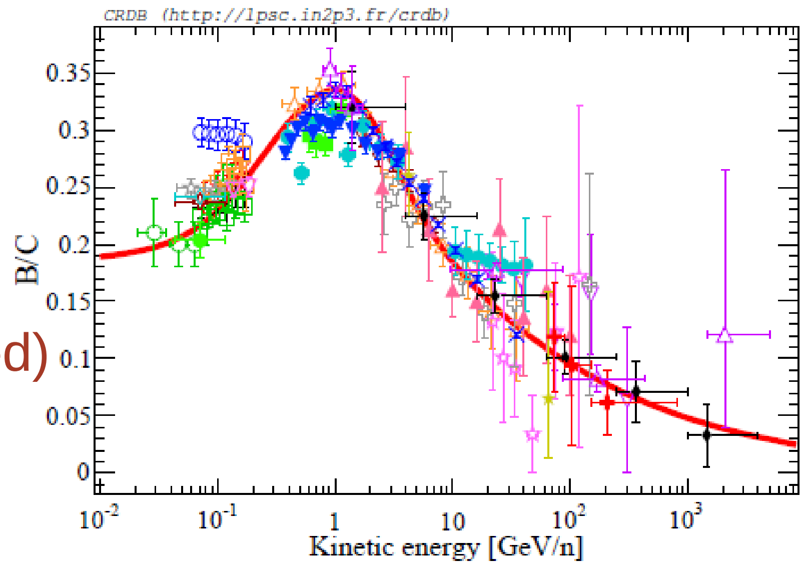
- Evidence for source change above knee, and perhaps also above ankle
  - latter is driven mainly by data from Auger—not much evidence of heavier composition from TA or HiRes

High energy composition: GZK

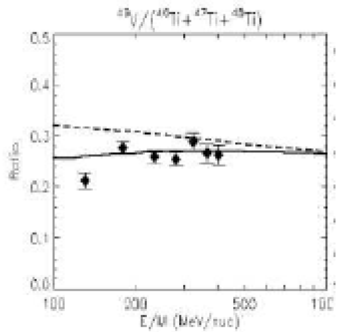
- An unavoidable cut-off at high energies arises from the interaction $p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0} (n + \pi^{+})$
  - at energies above ~5×10^{19} eV this reaction can take place with a CMB photon
    - this is unavoidable as these photons are everywhere
  - result is to reduce proton energy by ~3% owing to the production of the pion mass
    - repeated until proton energy drops below threshold
  - limits range of protons with *E* > 5×10^{19} eV to ~100 Mpc (~Coma cluster)
- It is *not* clear if observed cut-off at about this energy is GZK or not
  - if associated with shift to heavy nuclei, could be source cut-off instead

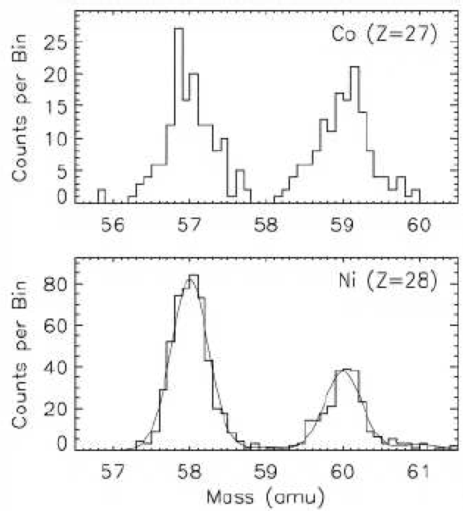


Isotopic composition



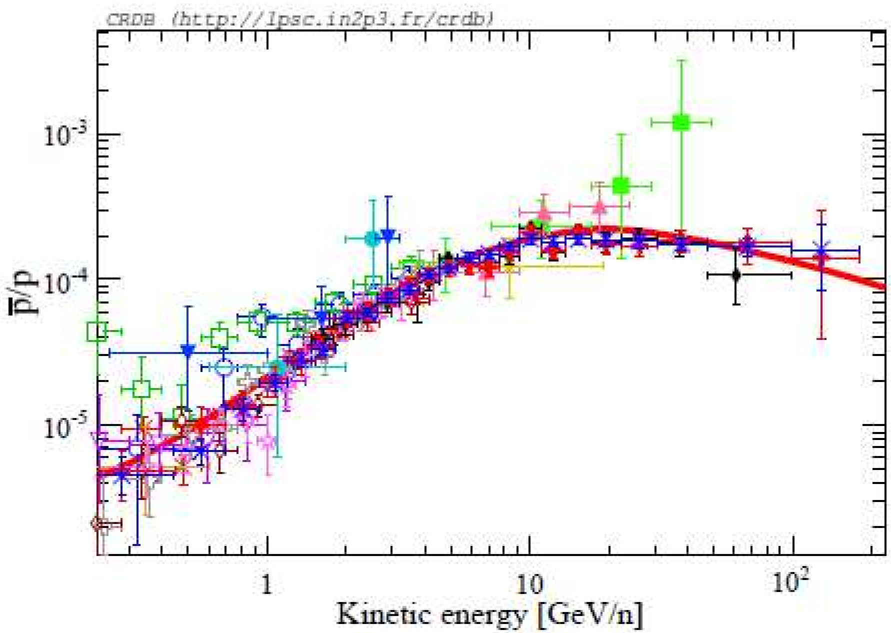
- Key issues:
  - ratio of secondary (spallation-produced) to primary nuclei
    - provides information about propagation of CRs in Galaxy
  - nuclei which are stable to β^+ decay ($X \rightarrow X' + e^+ + \nu_e$) but unstable to electron capture ($X + e^- \rightarrow X' + \nu_e$)
    - as long as such nuclei are *fully ionised* they are *completely stable*
    - absence of such isotopes among primary nuclei suggests that material that is accelerated is initially cold
    - (these isotopes *are* observed among secondary nuclei)

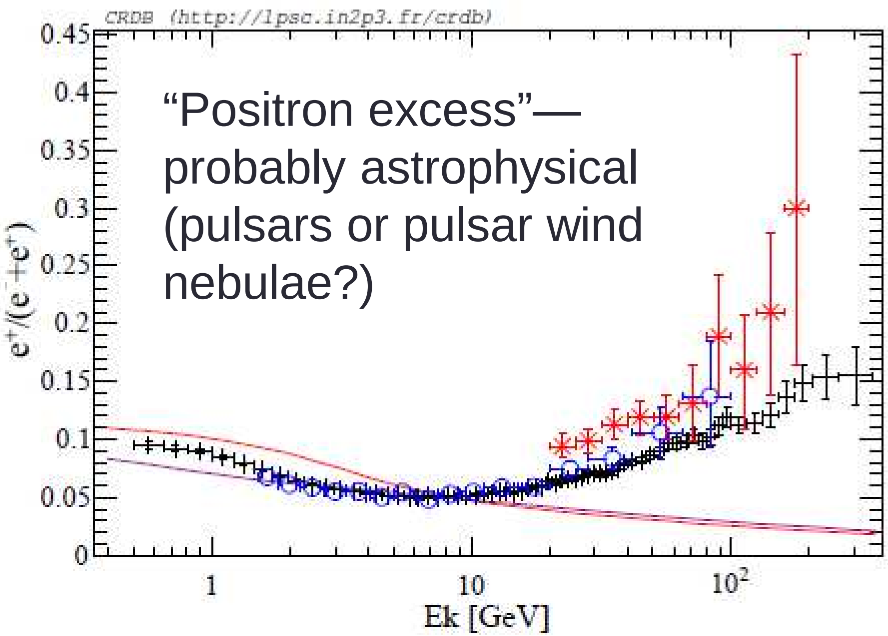




Antiparticles

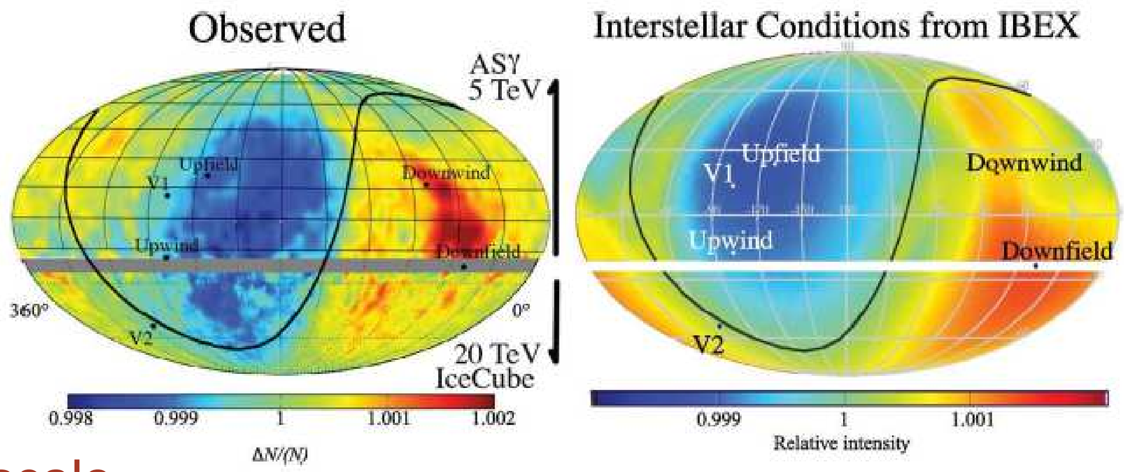
- Antiprotons and—especially—positrons can be produced as secondaries by energetic interactions
  - also possibly by dark-matter annihilation
- Antinuclei would imply existence of antistars

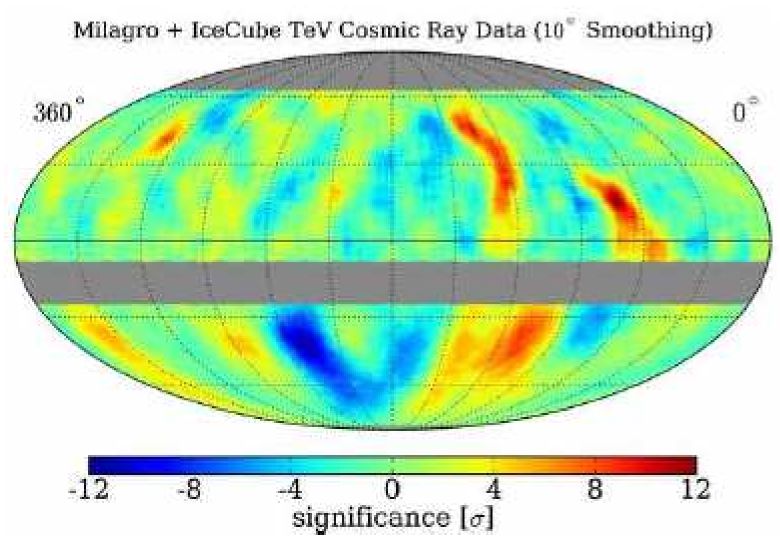




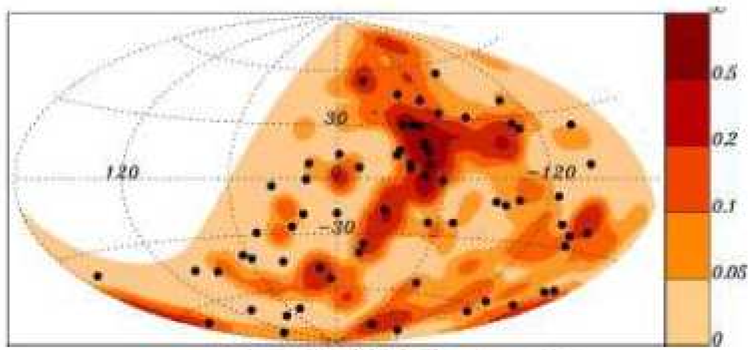
Directional information

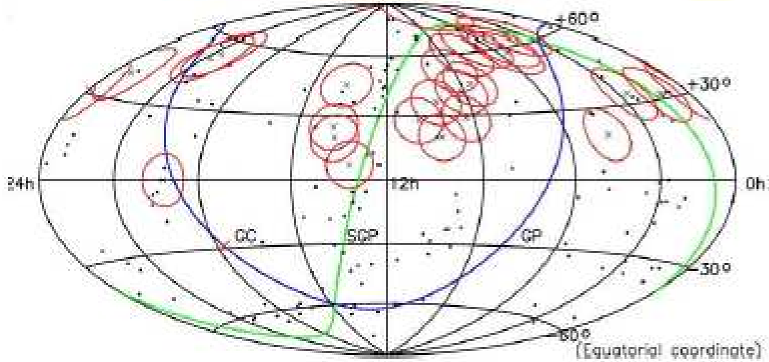
- Cosmic ray directions are scrambled by Galactic magnetic field
  - small-amplitude large-scale anisotropies are well accounted for by local magnetic fields
  - smaller-scale anisotropies may be due to source distribution or magnetic field variations
    - in fact, level of anisotropy is much *lower* than theoretically expected





Directional information: high energies





- At very high energies directions should not be so severely affected—might find correlations with sources
  - results so far not very impressive
    - Auger see weak correlation with nearby AGN, but more data have weakened, not strengthened, result
    - Auger also see slight increase in flux in direction of Cen A; both these are 2σ
    - TA sees "hot spot" near 6^h RA, 60° Dec (3.6σ)—but this is broad and not obviously correlated with a potential source
  - if high-energy CRs are heavy ions as suggested by Auger data, this is easier to understand, as they are deflected more for same *p*

Summary

You should read section 2.2 of the notes.

You should know about

- *the discovery of cosmic rays*
- *detection techniques*
- *basic properties (energy spectrum, composition, anisotropies)*

- Cosmic rays consist mostly of protons and heavy ions
  - primary cosmic rays are detected by balloon-borne and space-based platforms
  - products of air showers are detected by ground-based experiments
- Detectors aim to measure energy, direction and particle ID
  - energy by magnetic spectrometers, calorimeters, transition radiation (primaries) or by shower profile, light yield and particle counting (showers)
- Observed properties:
  - energy spectrum is a power law with spectral index ~2.7
  - elemental composition shows evidence for spallation
  - isotopic composition implies accelerated material is initially cool
  - directions are broadly isotropic, no direct evidence for particular sources

Next: radio emission

- radiation from an accelerated charge
- bremsstrahlung
- synchrotron radiation

Notes section 2.3