ULB UNIVERSITÉ LIBRE DE BRUXELLES, UNIVERSITÉ D'EUROPE

PARTICLE ASTROPHYSICS

BND2013 Summer School
Université Libre de Bruxelles
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WHAT IS PARTICLE ASTROPHYSICS?

- New, old field: roots go back further than particle physics itself.
- 2012 was centennary of Victor Hess' paper on measurements of cosmic rays in balloon flights.
- Cosmic rays were sources of many early new particle discoveries until accelerator technologies finally outpaced them (Chadwick: neutron; Anderson: positron; Anderson and Neddermeyer: muons; Blackett, Anderson, Cowan: strange particles)
- Cosmic ray accelerators continue to produce the highest energy particles – cms energy of UHE cosmic rays still 10x LHC.
- Particle astrophysics continues to be study of Universe using elementary particles *and* study of elementary particles using natural accelerators found in the Universe.
- Shares detectors / data analysis techniques / mindset with particle physics.
- Note on terminology
  - Particle astrophysics: USAspeak
  - Astroparticle physics: Europe
  - Rest of world: ?

ASPERA's Six Questions

SCIENCE GOALS ADDRESSED

QUESTION 1

What is the Universe made of?

Only 4% of the Universe is made of ordinary matter. Following the latest measurements and cosmological models, 73% of the cosmic energy budget seems to consist of "dark energy" and 23% of dark matter. The nature of dark energy remains a mystery, probably intimately connected with the fundamental question of the "cosmological constant problem".

Direct DM Experiments:

DAMA, CDMS, Edelweiss, Xenon, Zeppelin, COUPP, CRESST, EURECA (Future)

Indirect DM Experiments:

EGRET, FERMI, PAMELA, AMS, MACRO, IceCube

QUESTION 2

Do protons have a finite lifetime?
Grand Unified Theories (GUTs) of particle physics predict that the proton has a finite lifetime. Proton decay is one of the most generic and verifiable implications arising from GUTs.

Past / Present Experiments:
IMB, Kamiokande, Super-K
Future Experiments:
LAGUNA (MEMPHYS, LENA, Glacier); Hyper-K; DUSEL megaton scale detector (Liquid Argon / Water Cherenkov)
MICA (extremely large IceCube infill array)

QUESTION 3

What are the properties of neutrinos? What is their role in cosmic evolution?

Neutrinos have provided the first reliable evidence of phenomena beyond the Standard Model of particle physics. In the Standard Model, neutrinos have no mass. A major breakthrough of the past decade has been the discovery that neutrinos, on the contrary, *are* massive.

Neutrino Oscillations:

Homestake Cl experiment, Gallex, Super-K, MACRO, SNO
IMB, Kamiokande, Super-K

Future NO Experiments:

LAGUNA (MEMPHYS, LENA, Glacier); DUSEL megaton scale detector (Liquid Argon / Water Cherenkov); PINGU

Neutrinoless Double Beta Decay:

NEMO, Heidelberg-Moscow, CUORE, EXO, GERDA, Kamland-Zen, SNO+, SuperNEMO

QUESTION 4

What do neutrinos tell us about the interior of Sun and Earth, and about Supernova explosions?
In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window on the Universe, specifically for the detection of neutrinos from the Sun and a Supernova. The observation that solar neutrinos change their identity on their way from the Sun to the Earth ("neutrino oscillations") has provided the first indications of massive neutrinos, i.e. of physics beyond the Standard Model of particle physics.

Past / Present Experiments:
IMB, Kamiokande, Super-K; IceCube; ANTARES
Future Experiments:
PINGU; Km3NeT; Lena (LAGUNA)

QUESTION 5

What's the origin of high energy cosmic rays? What's the sky view at extreme energies?

Nearly a century ago, the Austrian physicist Victor Hess discovered cosmic rays, charged particles that hit our atmosphere like a steady rain from space. Later, it turned out that some of these particles have energies a hundred million times greater than that achievable by terrestrial accelerators.

Gamma Ray Experiments:

EGRET/BATSE; FERMI, HEGRA; VERITAS, HESS, MILAGRO, HAWC, CTA

Cosmic Ray Experiments:

(Many here omitted) Pierre Auger, Telescope Array, AGASA, Fly's Eye, MACRO

Neutrino Observatories

ANTARES, Baksan, Baikal, IceCube, ANITA, ARA

QUESTION 6

Can we detect gravitational waves? What will they tell us about violent cosmic processes and basic physics laws ?
Gravitation governs the large scale behaviour of the Universe. Weak compared to the other macroscopic force, the electromagnetic force, it is negligible at microscopic scales. The main prediction of a field theory is the emission of waves. For electromagnetism this has been established through the discovery of electromagnetic waves in 1888.

Past / Present Experiments:
LIGO, VIRGO
Future Experiments:
Einstein

PRACTICAL APPLICATIONS

- Many people ask me why it's worthwhile studying cosmic rays and neutrinos – what is the benefit to mankind?
- See me later for my diatribe on necessity to pursue basic research.
- Nevertheless, there is industry awareness of importance of studying cosmic rays:
  - Space weather – solar storms et al.
  - Study of SEU in semiconductor devices at space, aeronautical, terrestrial levels becoming interesting

MESSENGER PARTICLES

Protons

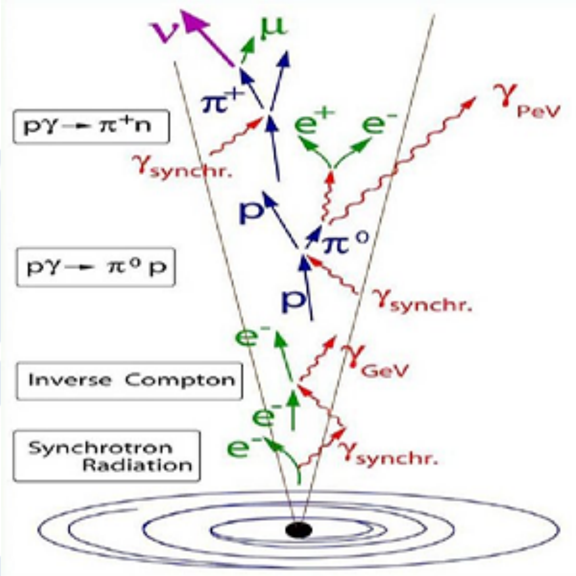
Protons (and heavier nuclei) accelerated at sources make up bulk of CR at top of atmosphere. They are easy to detect but bent by **B** fields or absorbed by scattering off of CMBR at 10^{19} GeV.

Gammas

Cosmic gamma radiation can be produced by either purely EM (synchrotron, bremsstrahlung, inverse Compton) or alongside the hadrons (π^0 decay mostly). They also could be signatures of dark matter annihilations. Gammas point back to source but interactions on CMBR limit TeV-γ to local neighborhood)

Neutrinos

Neutrinos are excellent cosmic messenger particles - ridiculously small cross sections mean you can look deep inside sources and the neutral neutrino is neither absorbed nor bent in flight so they carry pristine energy and point-of-origin information. The trouble comes in seeing them: you have to build a detector the size of a small city to have any hope of capturing a sizable sample.



Multi-wavelength / multi-messenger campaigns have begun combining satellites / radio and optical telescopes / neutrino observatories

OUTLINE OF LECTURES

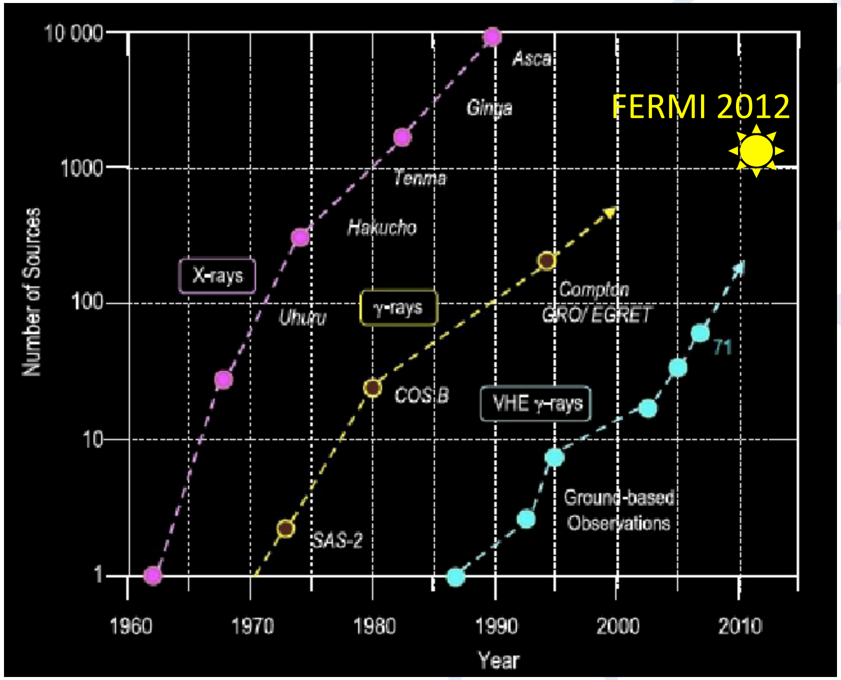
The main topics covered in these lectures concern research to answer question #5

- Part I
  - High energy gamma ray astronomy: just a brief treatment unfortunately …
  - Cosmic rays
    - Acceleration
    - Propagation
    - In the atmosphere
  - Muons and neutrinos underground
- Part II
  - Neutrino astrophysics
  - Detector Case Study #1: IceCube
  - Detector Case Study #2: ARA

Some brief words

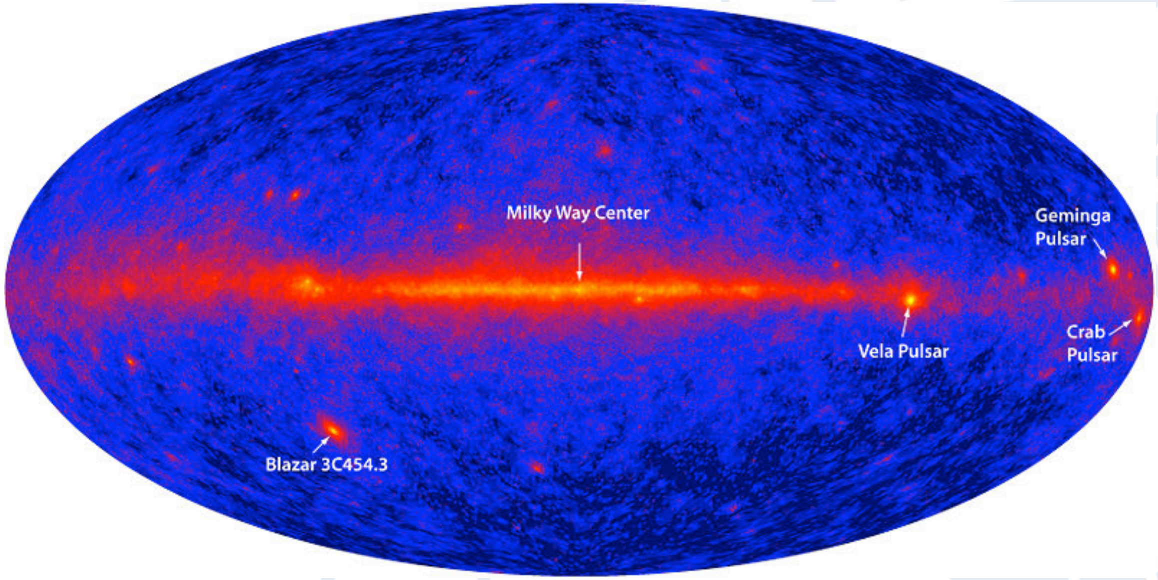
GAMMA RAYS

HISTORICAL PERSPECTIVE



- FERMI 2-year LAT catalog contains 1800 identified sources!
- Gamma rays explored from MeV up to TeV with ground based telescopes

THE HIGH ENERGY SKY IN GAMMA RAYS

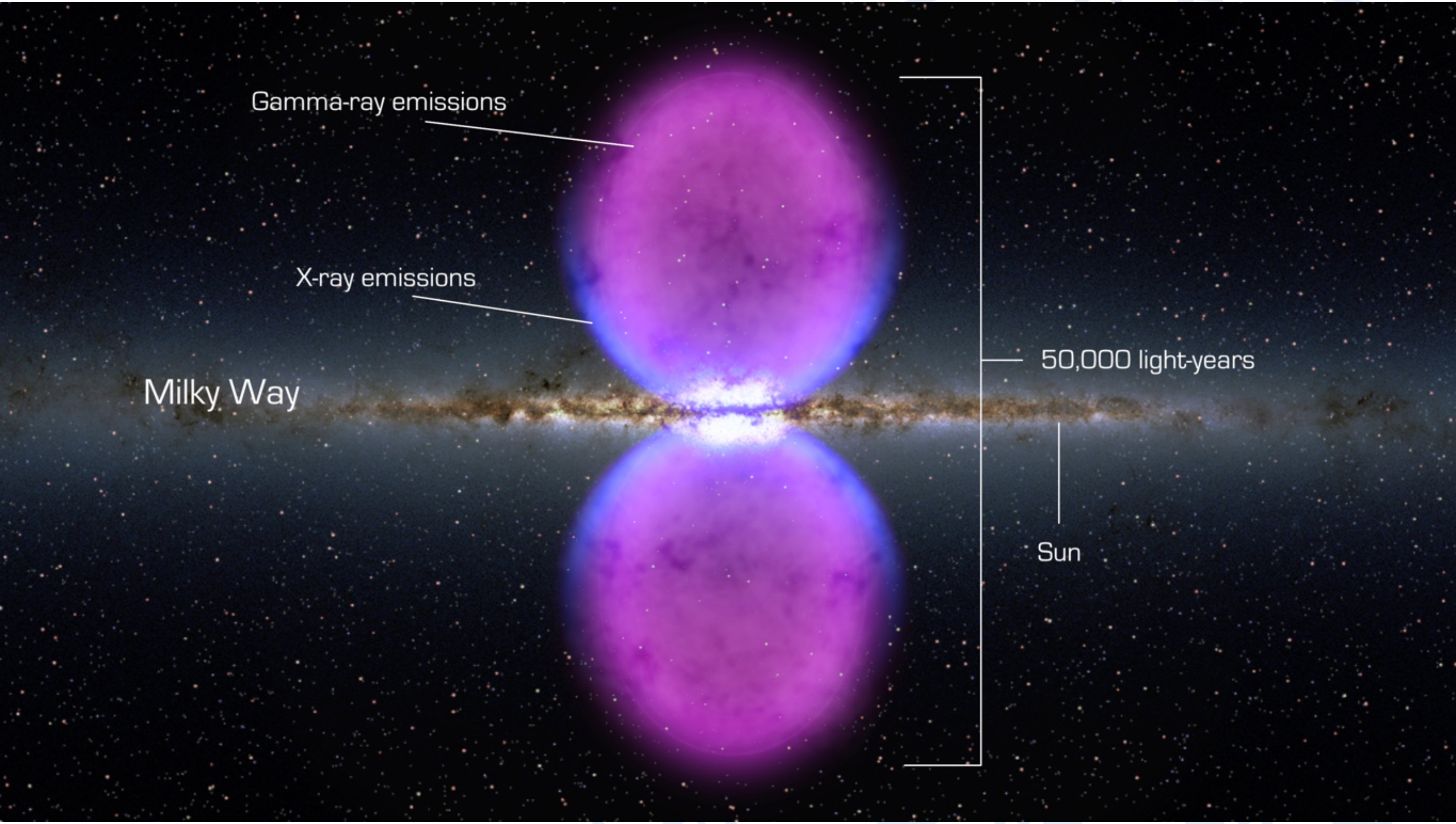


Diffuse extragalactic flux of gammas well described by power law with spectral index -2.4 and normalization given by:

$$\Phi_{\gamma,EB} = 1.5 \times 10^{-5}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

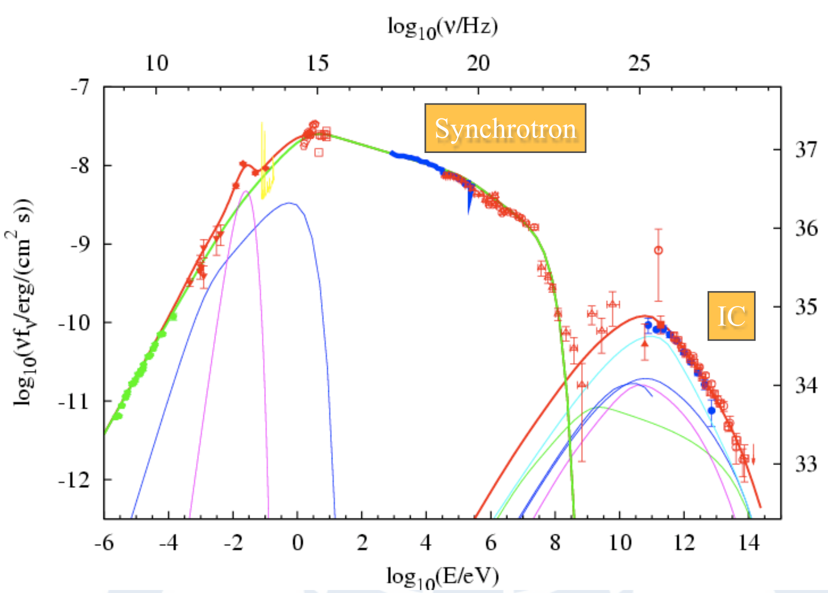
Diffuse galactic flux ~ 100 × this flux.

FERMI BUBBLES



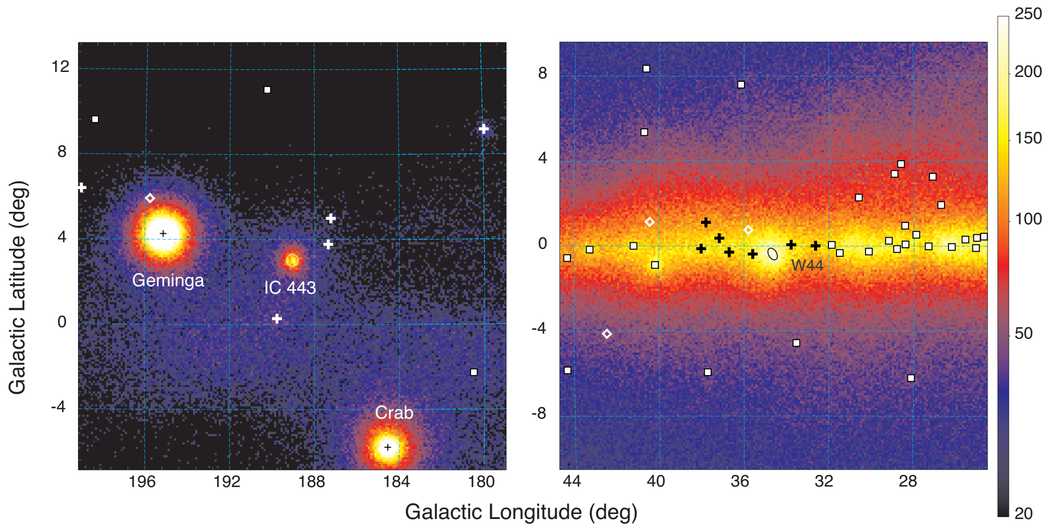
THE CRAB NEBULA

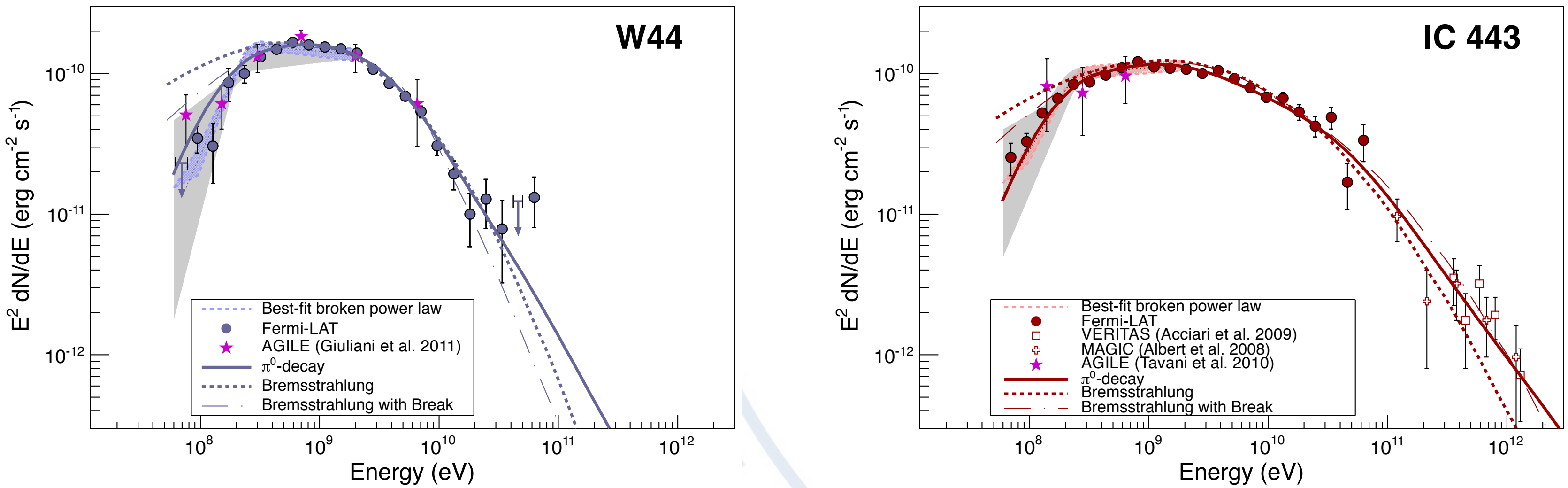
- The Crab Nebula is a class of supernova remnants called “plerions” (filled - referring to the center-filled morphology that the sources exhibit) - also called pulsar wind nebulae.
- It is close by, young (it comes from the historically recorded supernova explosion of 1054), and is the 2nd strongest DC source of HE gammas in the sky (Vela pulser - also plerion is strongest DC).
- Owing to its visibility, it has been the subject of intense study in the gamma rays, it is a calibration source (sources are oft quoted in “crab units”) but now that instruments are very sensitive it is now known that the Crab is a variable source.
- A composition of observations have confirmed that the Crab emission fits extremely well the hypothesis of synchrotron and inverse Compton production of high-energy gammas



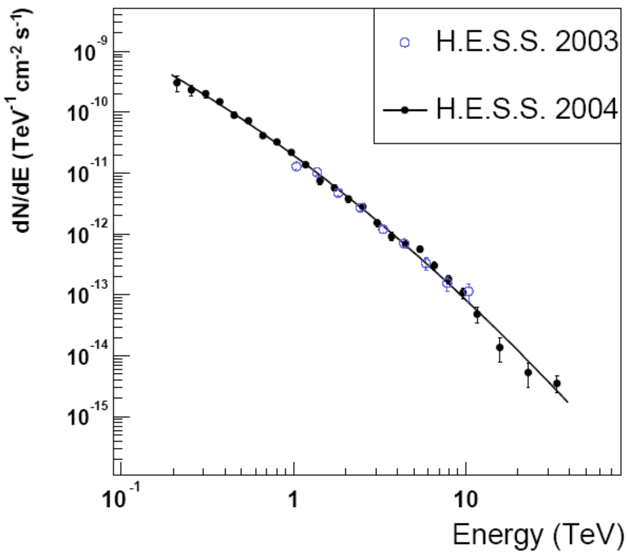
$$\Phi_{\rm crab} \equiv 2.83 \times 10^{-11} \left(\frac{E}{\rm TeV}\right)^{-2.62} \rm cm^{-2} \cdot s^{-1} \cdot TeV^{-1}$$

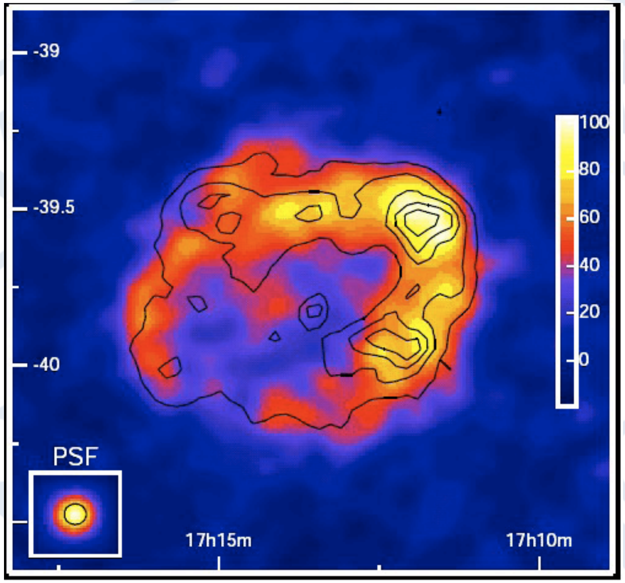
CR CONNECTION? IC443, W44



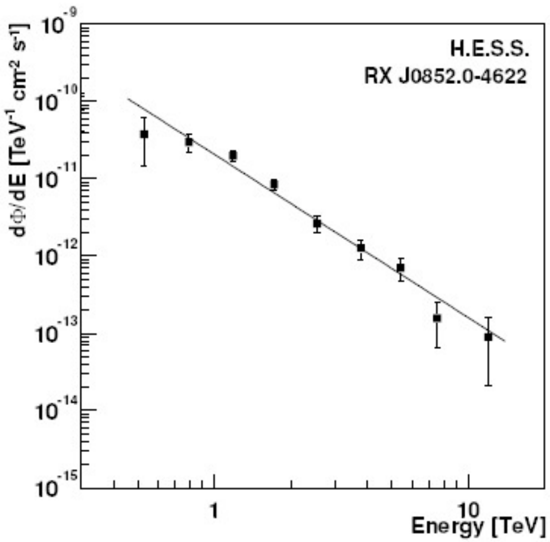


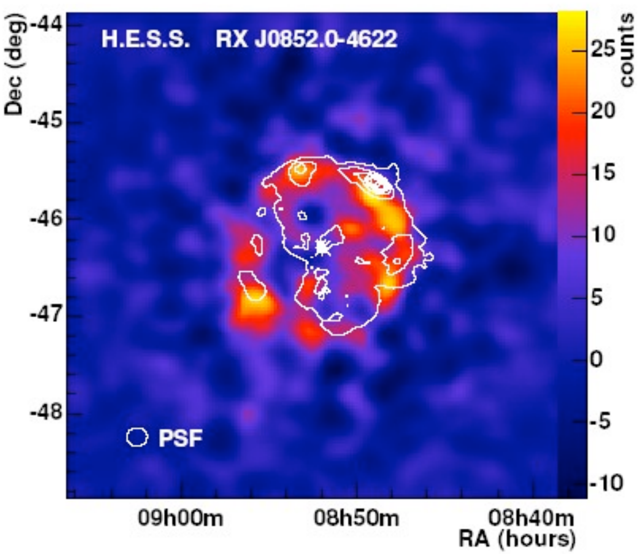
SOURCE MEASUREMENTS AT IACTS (HESS HERE)



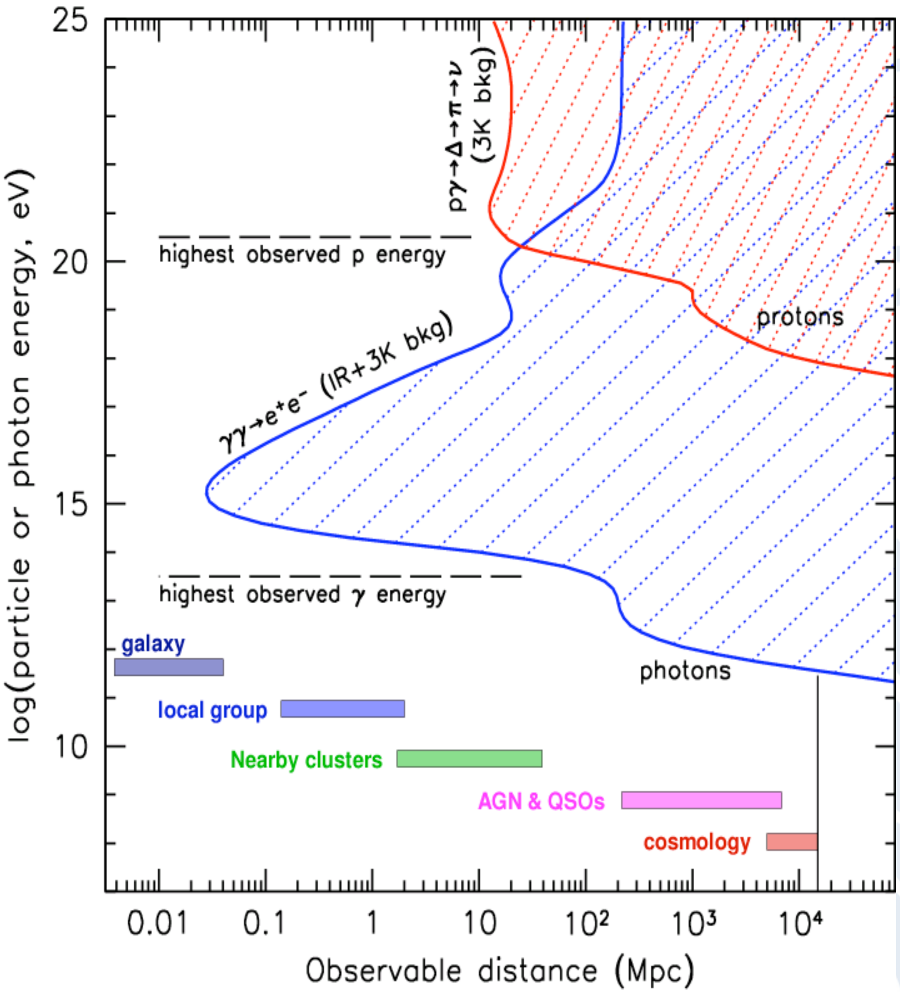


Vela Jr



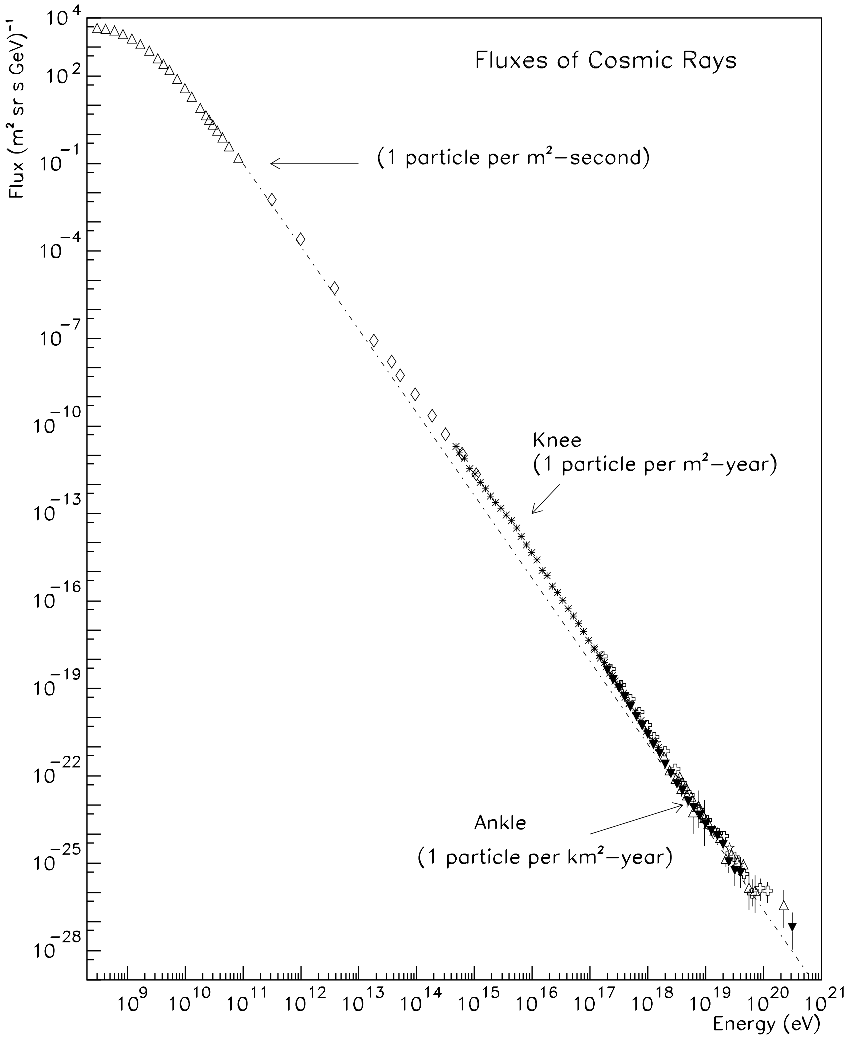


VHE GAMMA RAY HORIZON



THE COSMIC RAYS

OBSERVATIONAL FACTS



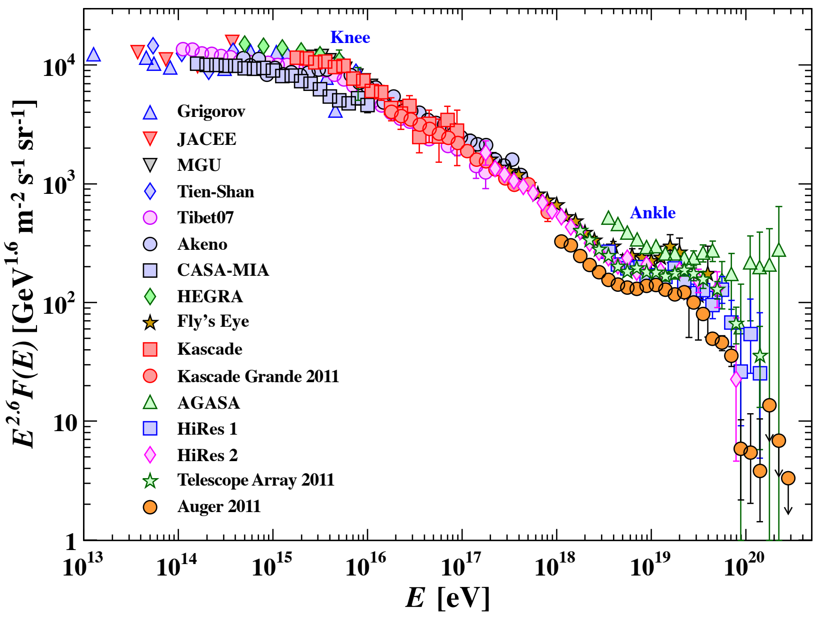
Low Energies (1 GeV – 4 PeV)

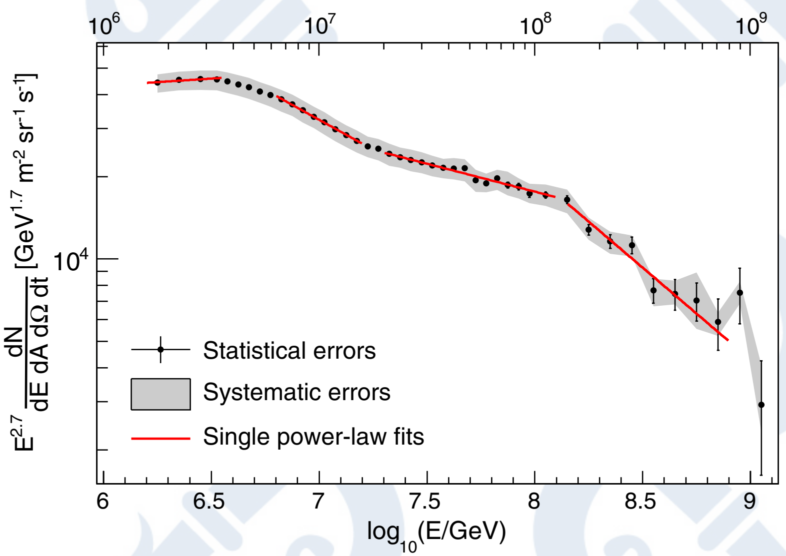
- Almost featureless power law spectrum with spectral index -2.7 from geomagnetic cutoff to ~4 PeV ("the knee")
- Flux at top of Earth's atmosphere is nearly isotropic and given by:
$$\frac{dN}{dE} = \frac{1.8 \times 10^4 (E/\mathrm{GeV})^{-2.7}}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{GeV}}$$
- Composition is dominated by protons (95%) with He all but 0.5% of the rest.
- Below 10's of GeV solar modulation effects are important and CR flux becomes time dependent.

OBSERVATIONAL FACTS (II)

Above the Knee (4 PeV – 30 EeV)

- Spectrum steepens to index of 3.0-3.1.
- Recent high statistics data from IceTop (PRD **88** (2013) 042004) indicates significant structure in this region → spectrum *not* well fit by simple power law.
- Composition tends to heavier elements.





LARMOR RADIUS

Larmor radius, or gyroradius, r_L, is the radius of the orbit of a charged particle moving in a uniform, perpendicular magnetic field, obtained by simply equating the Lorentz force with the centripetal force:

$$qvB = \frac{mv^2}{r_L} \Rightarrow r_L = \frac{p}{ZeB}$$

Some convenient reformulations for astrophysics are:

$$r_L = 33.36\,\mathrm{km}\left(\frac{p}{\mathrm{GeV/c}}\right)\left(\frac{1}{Z}\right)\left(\frac{G}{B}\right)$$

$$r_L = 1.081\,\mathrm{pc}\left(\frac{p}{\mathrm{PeV/c}}\right)\left(\frac{1}{Z}\right)\left(\frac{\mu G}{B}\right)$$

ACCELERATION

- Simple energetics arguments have long implicated galactic SNe as among principal sources of observed cosmic ray spectrum.
  - Find energy density of CR *fluid* by integrating all-particle flux over energy and solid angle and then dividing by c
  - Equate this to total power output by galactic supernova explosions assuming O(3) per century expel 10 M_{SUN} mass at speeds of 20000 km/s.
  - Assume some efficiency of order 1% to convert this kinetic energy to cosmic ray particle energy.
- So, how does this process work? Let's take a simple but compelling model…

- Fermi's original 2nd-order acceleration mechanism (ref dependence on β^2) involved randomly moving magnetic clouds sweeping up ISM particles and transferring kinetic energy. This mechanism not efficient at accelerating to even moderate energies.
- 1st-order acceleration in shock (e.g. expanding shocks of SNR): energy gain of CR proportional to β, a real win as $\beta \sim 0.05$ for typical shocks.

THE MODEL

Particle "circulating" in region of shockwave due to magnetic field. In passes through the upstream region behind the shock front and the downstream region in from of the shock front, it picks up some fraction of energy, α (to be determined later). Thus after n cycles:

$$E_n = E_0(1+\alpha)^n$$

Or, equivalently, express the inverse

$$n = \frac{\ln(E_n/E_0)}{\ln(1+\alpha)}$$

Now assume that the probability of CR retention at each cycle is a fixed value, P. Then, after n cycles, the CR population remaining in the accelerator is:

$$N = N_0 P^n$$

$$n = \ln(N/N_0)/\ln P$$

CONTINUED

Equate the expressions in n to find that

$$\ln\left(\frac{N}{N_0}\right) = s\ln\left(\frac{E}{E_0}\right) \qquad s = \frac{\ln P}{\ln(1+\alpha)}$$

One obtains a power law spectrum (cf. observation) – the integral spectrum being

$$N(>E) \propto E^s$$

And the differential flux being one power steeper:

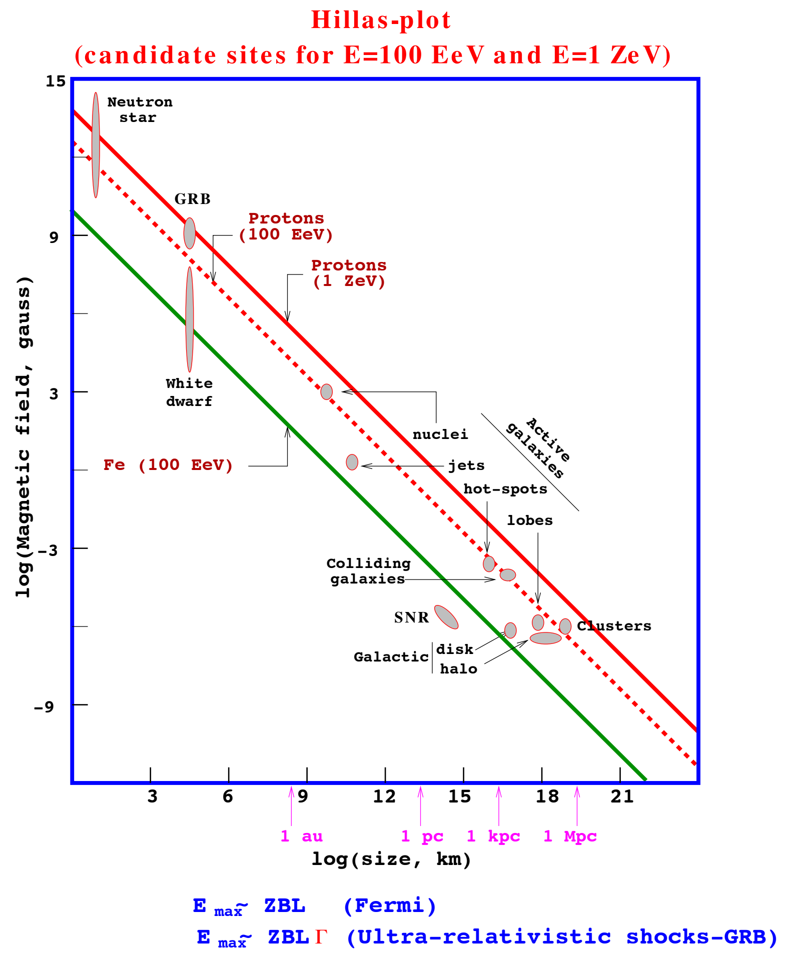
$$\frac{dN}{dE} \propto E^{-\gamma}, \gamma = 1 - s$$

$$\xi = 1 - P, \xi \ll 1, \Rightarrow s \simeq -\xi/\alpha$$

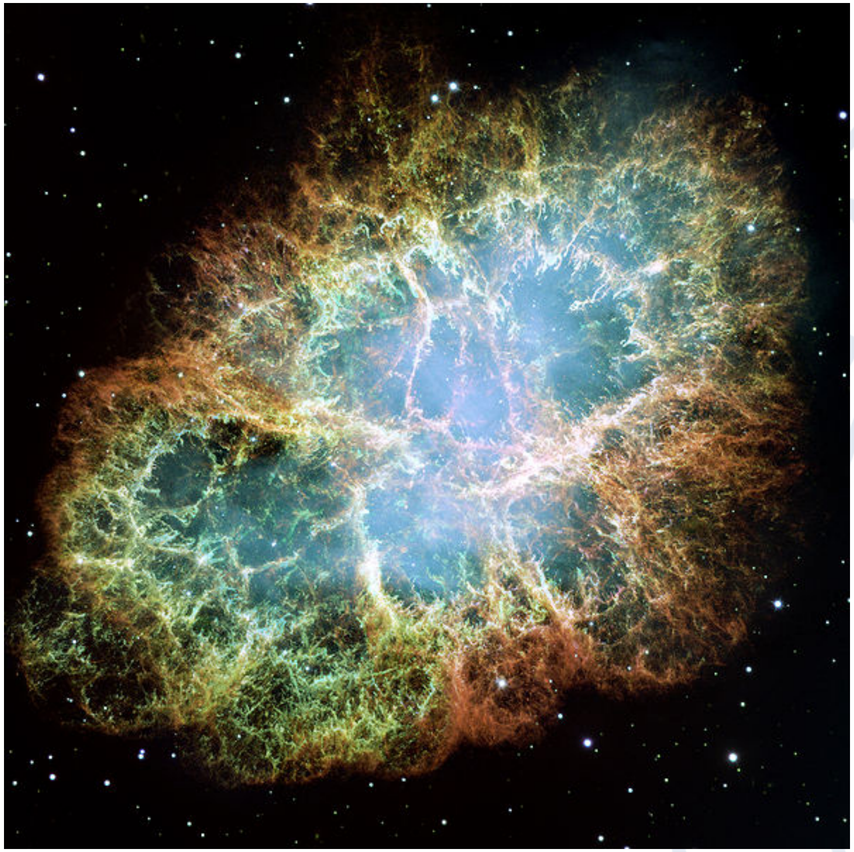
In the strong shock limit (see arXiV:0801.4376) it can be shown that shocks will tend to have s ~ -1 → FERMI 1st order predicts E^{-2} power flux for CR at source.

HILLAS PLOT

- There are a couple of problems with extending this model to infinity – most apparent is the tendancy of high energy particles to escape acceleration regions.
- Hillas argument: simple relation between maximum energy achievable by CR acceleration site, B field, size of object. Acceleration region must be at least 2 × Larmor radius.
- This yields Hillas Plot: objects above left OK



GALACTIC SOURCES

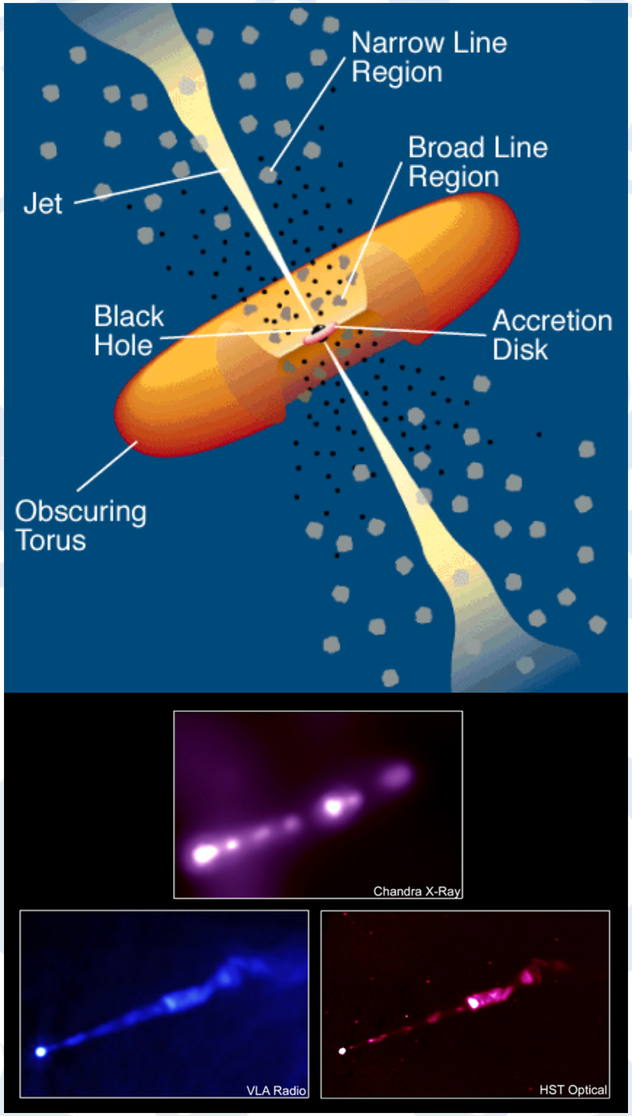


Supernova remnants (SNR) remain the most likely candidates for CR acceleration up to at least 10^{14} eV via Fermi shock mechanism.

Neutron stars Neutron stars, especially young fast-rotating pulsars and magnetars possess extreme magnetic fields (up to 1012G in the case of magnetars) with complex structure that could accelerate CR up to the highest energies. These objects are far rarer than SNRs, however, only a dozen magnetars are known in the Milky Way, although many could exist in the local neighborhood.

Microquasars are radio-intense X-ray binary stars with companion orbiting an accreting black hole. They are particularly interesting particle accelerators due to observation of VHE gamma ray emission and highly relativistic jets which could provide energy for UHECR.

- AGNs and blazars (AGNs pointed to us) are among prime candidates – extreme relativistic jets have right energetics to accelerate particles to extremely high energies
- M87, CenA two nearby objects (10's Mpc)
- GRBs suffered a hit from IceCube data but could still be significant player on cosmic scene.



PROPAGATION

On cosmological distance scales, a number of propagation effects distort the CR flux:

- There is always the issue of magnetic field deflection – you can calculate radius of curvatures yourself for typical IGMFs of nG.
- On scales where redshift is near unity or above, CR energies are redshifted down:

$$E \rightarrow \frac{E}{1+z}$$

- At energies above 10^{15} eV, the pair production process becomes possible:

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$$

Because the fraction of energy lost in each interaction is small, the effective interaction distance is still rather large:

$$R_{\mathrm{eff}} = \frac{m_p}{2m_e}\frac{1}{\sigma_{p\gamma}n_{\mathrm{CMB}}} \simeq 600\,\mathrm{Mpc}$$

INTERGALACTIC PROPAGATION: UHE

For heavier nuclei, dominant loss mechanism at UHE is photo-disintegration:

$$A + \gamma \to (A-1) + N$$

which, for He begins at 30 EeV and Fe at 80 EeV

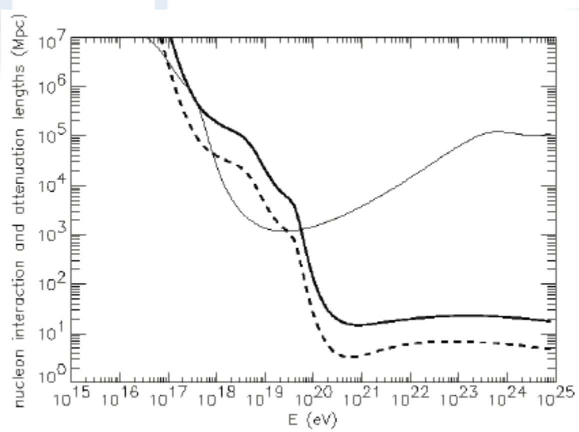
At energies ~ 10^{20} eV, pion production becomes possible

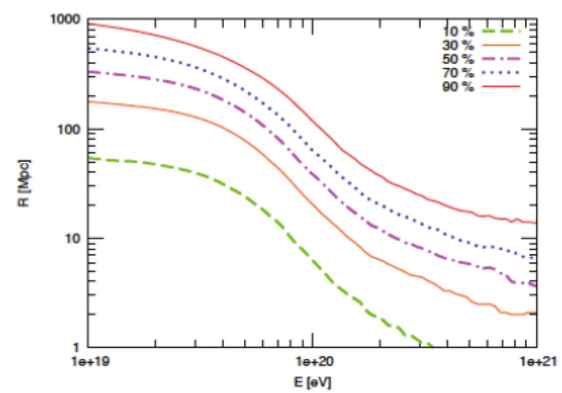
$$p + \gamma \to \Delta \to p/n + \pi^0/\pi + X$$

This interaction, called GZK, ultimately limits the observation of charged particles at extreme energies to horizons of

$$R = \frac{m_p}{2m_\pi}\frac{1}{\sigma_{p\gamma}n_{\mathrm{CMB}}} \simeq 100\,\mathrm{Mpc}$$

Charged particle (protons here) horizon plots shown at right. Thick / thin solid lines are pion / pair production processes

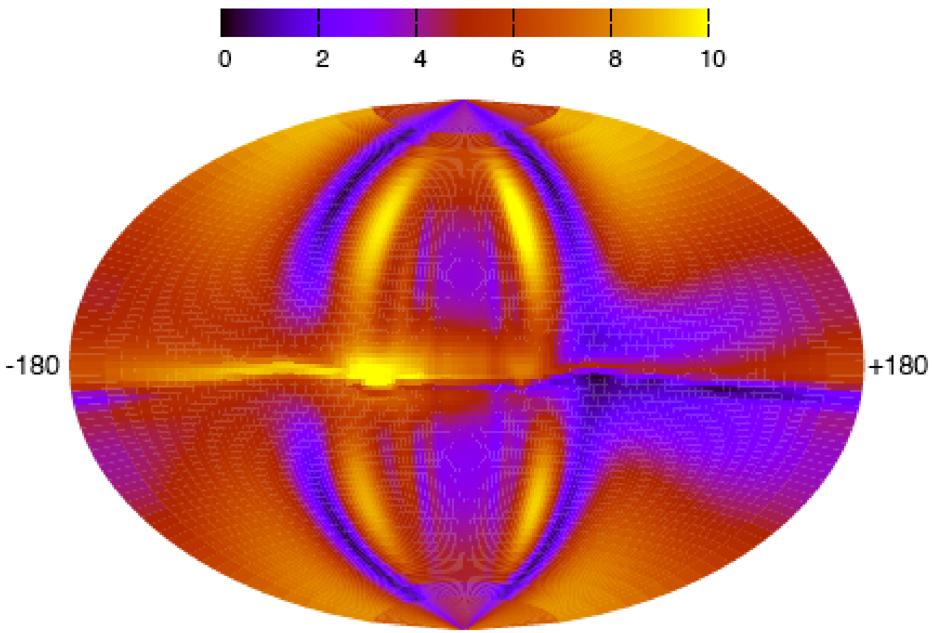




GALACTIC PROPAGATION

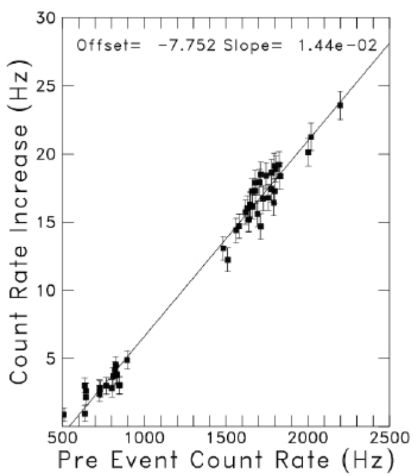
Galactic propagation for all but the highest energy CR particles is a diffusive process. It is here that the sources' E^{-2} raw spectra are shaped to the observed $E^{-2.7}$ observed at Earth.

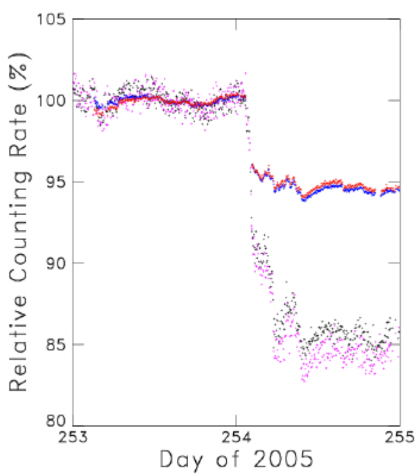
At very high energies, the magnetic deflections are near the point where CR astronomy can be attempted … shown at right is plot deflection angle versus galactic coordinates of incoming cosmic ray for rigidities of 40 EV.

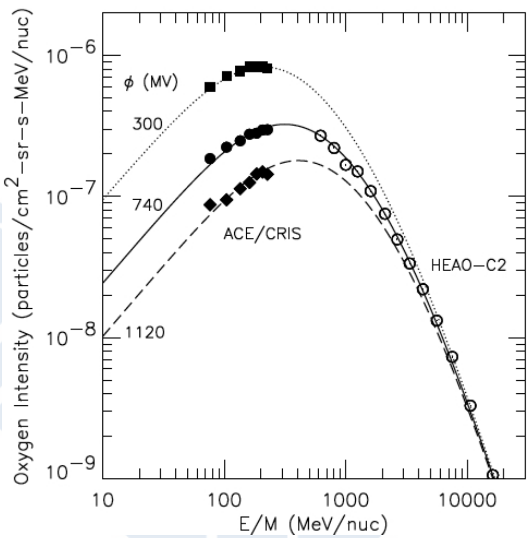


SOLAR MODULATION

- CR below several TeV are affected by solar wind which varies on 11-year solar cycle. At times of peak intensity the wind CR
- There is also dip in CR intensity following CME - the following plot demonstrates this "Forbush Decrease" following a solar flare event in 2006







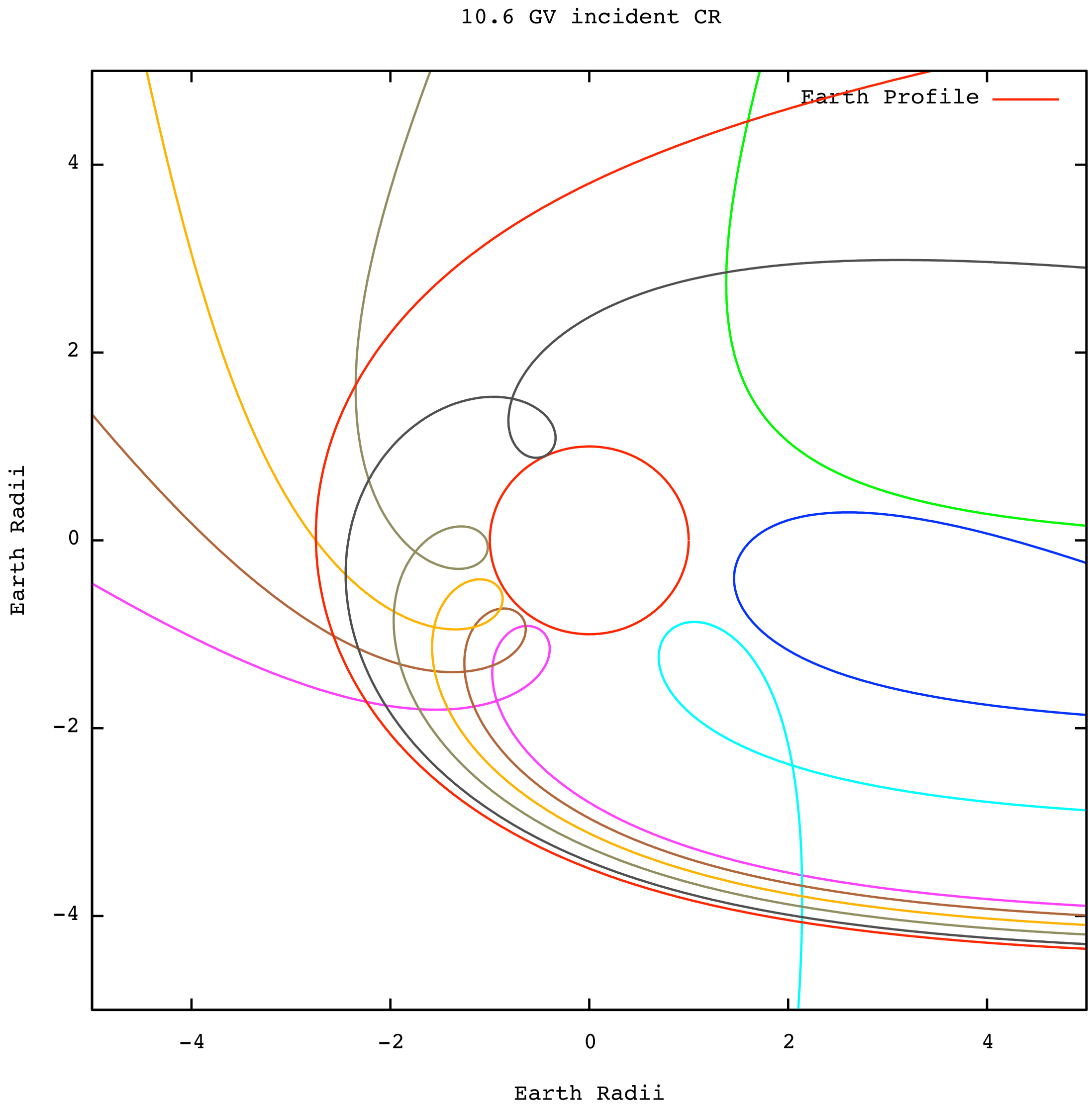
Intensity of Oxygen component of cosmic rays at different phases in solar cycle.

TERRESTRIAL EFFECTS

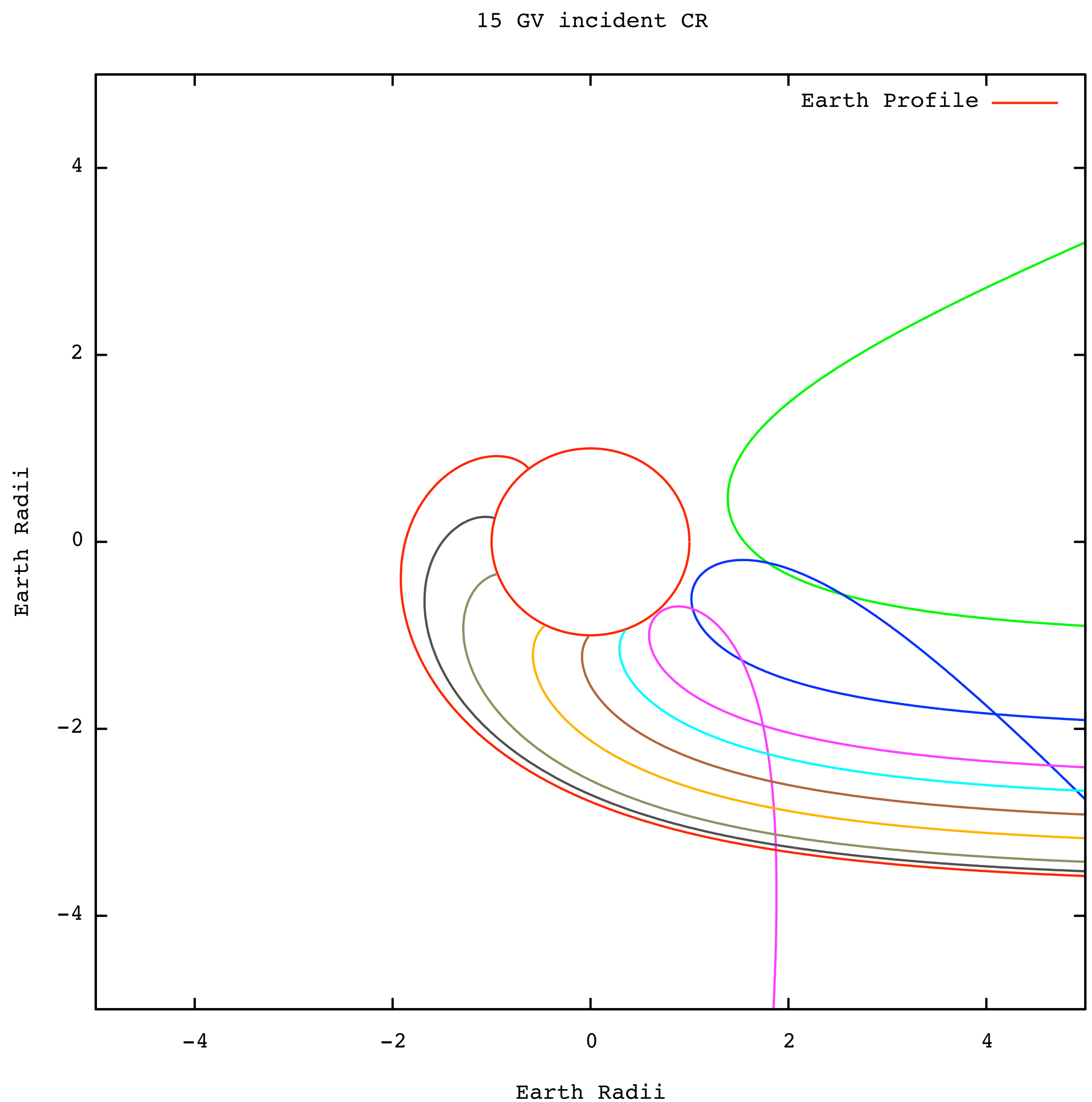
- Earth's magnetic field well-modeled as dipole of moment M = 8 × 1022 A · m, giving rise to equatorial field
$$B = \left(\frac{\mu_0}{4\pi}\right)\frac{M}{r^3}$$
of approximate intensity 0.5 G at surface.
- CR below several 10's of GV rigidity are affected by terrestrial **B** field: there is a cutoff which prevents CR particles from reaching ground level if they have rigidity less than
$$R_{\min} = \frac{59.6\cos^4\lambda}{[1+\sqrt{1-\sin\theta\cos^3\lambda}]^2}\mathrm{GV}$$
Where lambda is the magnetic latitude and theta is the so-called East-West angle (see Perkins' Particle Astrophysics books for nice graphic of coordinate system)
- Straightforward substitution of values for observer located at magnetic equator gives a rigidity cutoff of 59.6 GV from East, 10.2 GV from West and 14.9 GV for vertical incidence. This is the origin of the "East-West effect" used by Rossi and others to demonstrate predominance of positively charged particles in CR.
- In progressing toward magnetic poles, the cutoff is allayed – theoretically to zero – but this "latitude effect" still shows a cutoff of some 2-3 GeV due to atmospheric thickness.

GEOMAGNETIC TOY SIMULATION

- A very simple model (magnetic dipole field) illustrates the basic trajectories
- Rays of rigidity 10.6 GV are launched with various impact parameters toward –x. You are looking at South Pole
- Detailed maps of terrestrial **B** field exist – slightly more effort will get you surprisingly rich simulation including magnetic mirroring of particles (Van Allen)



Same conditions but rigidity increased to 15 GV to allow vertically incident cosmic rays



COSMIC RAYS IN THE ATMOSPHERE

STRUCTURE OF THE ATMOSPHERE

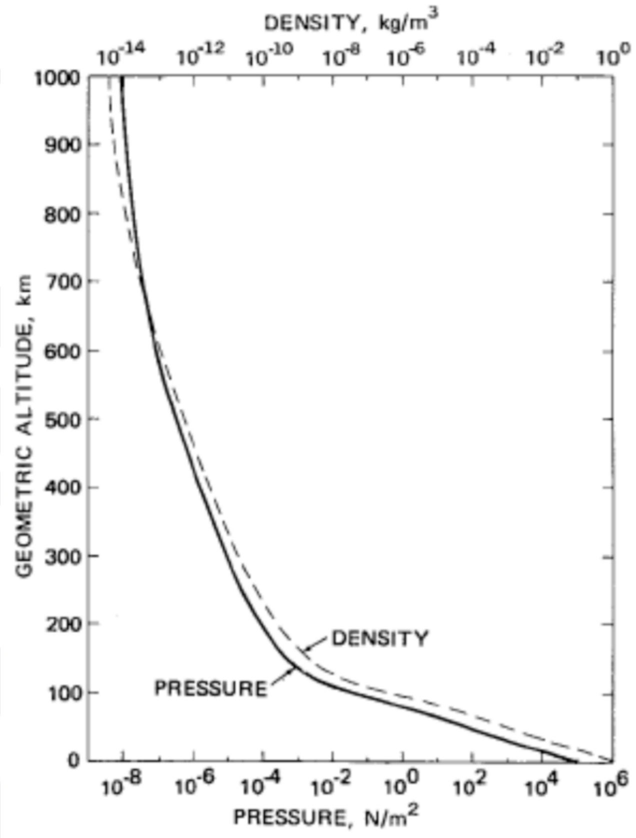
- Atmosphere below 86 km is to very good approximation an ideal gas composed of 0.78 N2 and 0.21 O2:

$$P = \frac{\rho R T}{M_0}$$

  where M0 is the mean molar mass of air: 28.5 g/mol and the ideal gas const R = 8.31 J/mol K
- In this model the pressure P(h) and the thickness X(h) are roughly exponential functions of the height:

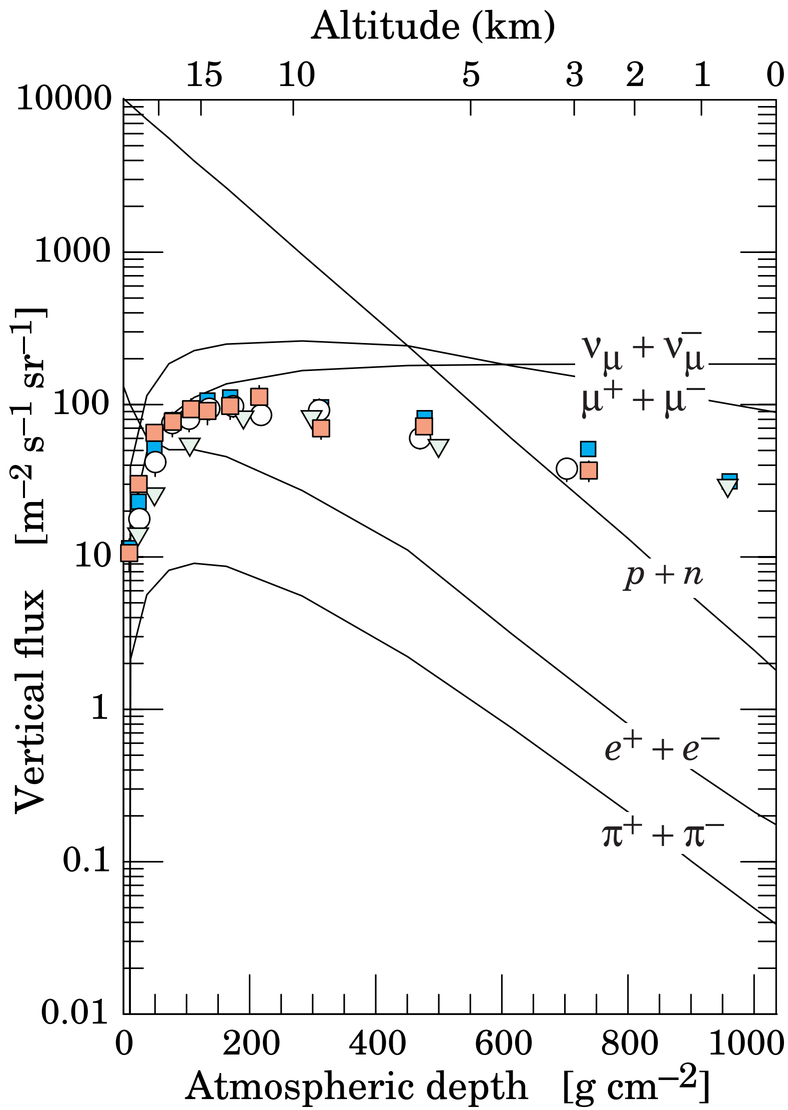
$$P(h) = P_0 \exp(-h/h_0)$$
$$X(h) = X_0 \exp(-h/h_0)$$

  where the **scale height** h_0 = 6.5 km, P_0 = 101 kPa, and X_0 = 1000 g/cm^2 (i.e., we are under 10 m.w.e. shielding)



U.S. Standard Atmosphere

PARTICLE FLUXES VERSUS ALTITUDE



EM SHOWER DEVELOPMENT

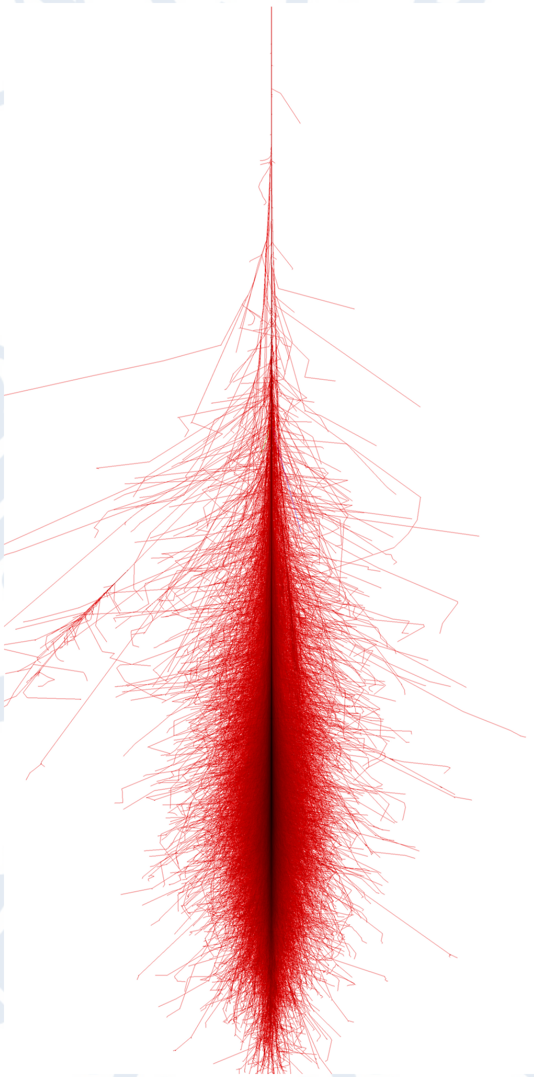
If EM particle such as photon or electron initiates shower in atmosphere ...

- Longitudinal development reaches maximum at depth

$$X_{\max} = \frac{\ln(E/E_c)}{\ln 2}$$

Where crictical energy $E_c \cong 100$ MeV and Xmax given in units of EM radiation length, X_0, approx 36 g/cm^2 in air.

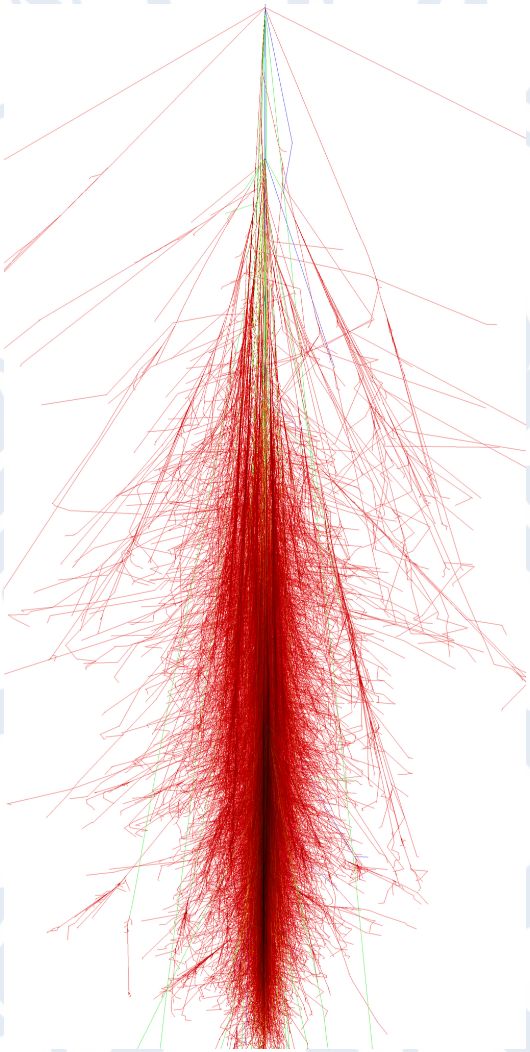
- Lateral development characterized by Molière radius, 0.2 X_0 = 100 m à MSL.
- Air is calorimetric, thus total charged particle track length gives good primary energy determination.



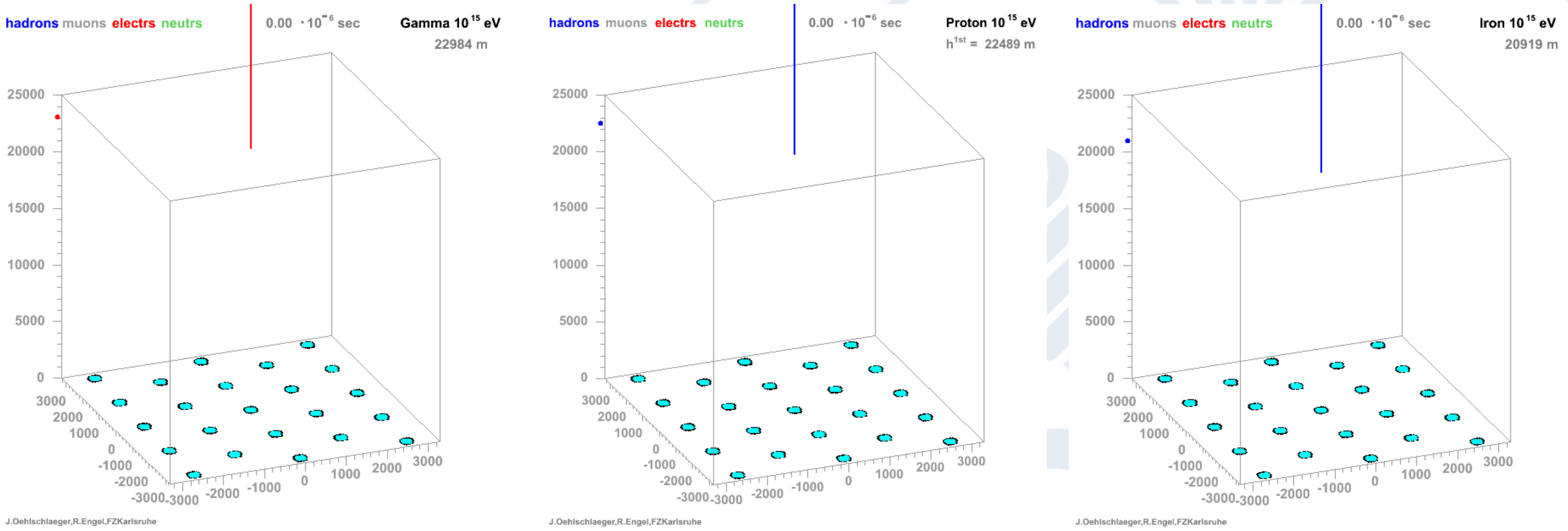
HADRON SHOWERS

If hadron initiates shower in atmosphere ...

- Longitudinal development also reaches shower maximum at depth given by EM formula with proviso that hadronic interaction length is 3x longer: 90 g/cm^2
- Hadron showers typically muon rich – muon count is related to Z of primary
- Lateral development is typically broader with sizes reaching km for UHE cosmic ray primaries.
- **Superposition model**: Heavier nuclei A act as A independent nucleons with energy E/A. This is exploited for CR composition study.



EXTENSIVE AIRSHOWERS



PARTICLE FLUXES AT SEA LEVEL AND UNDERGROUND

MUONS AND NEUTRINOS FROM MESON DECAY

Reaction is following cascaded chain of interactions and decays:

$$p + N \rightarrow \pi^+ + X$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu}$$

Plus charge conjugation and π → K/D mesons. Note that the ratio of electronic to muonic neutrinos is 1:2.

Pions dominate at lower energies but evetually muons from K mesons (and then D mesons) dominate due to pion energy loss in atmosphere (whereas K/D decay more rapidly). The energy scales for each regime of dominance are set by *critical energies*:

$$\epsilon_{c,i} = m_i c^2 \left(\frac{h_0}{c\tau_i} \right), \; i = \pi, K, D, ...$$

SEASONAL VARIATION

- Seasonal variations in the flux of muons at sea-level or underground due to density variations in the upper atmosphere from seasonal temperature change.
- The rarefied atmospheres in the summer months (note - January at S. Pole) enhance the probability for meson decay at higher energies due to weaker dE/dX.

MUON FLUX AT SEA LEVEL

For cases when muon decay can be neglected (E_μ > 100 GeV/cos θ) and Earth curvature is not important (θ < 70°) the following parameterization due to Gaisser is convenient for calculation of muon flux at sea level:

$$\frac{dN_\mu}{dE_\mu d\Omega} = \frac{0.14}{\mathrm{cm}^2\ \mathrm{s\ sr\ GeV}} \left(\frac{E_\mu}{\mathrm{GeV}}\right)^{-2.7} [F_\pi(E_\mu, \theta) + F_K(E_\mu, \theta)]$$

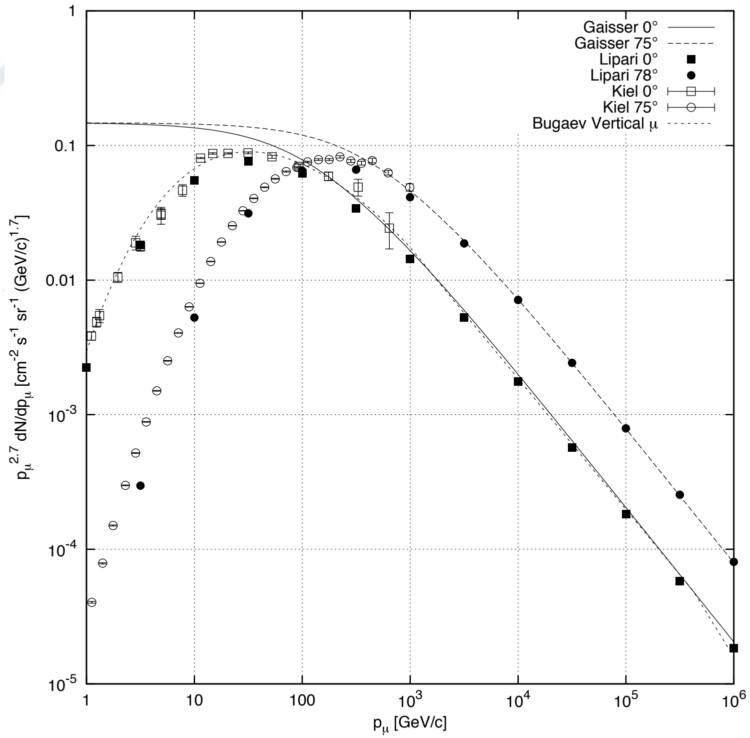
Where F_π and F_K represent the contributions from pions and kaons as discussed previously:

$$F_\pi(E_\mu, \theta) = \frac{1}{1 + \frac{1.1 E_\mu \cos\theta}{115\,\mathrm{GeV}}}$$

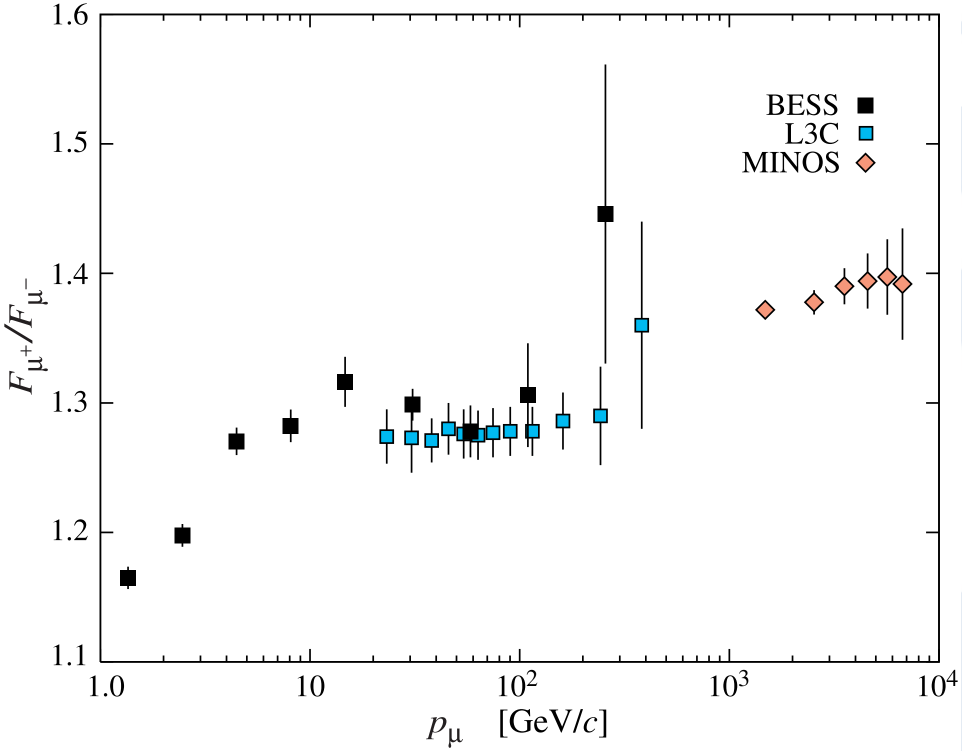
$$F_K(E_\mu, \theta) = \frac{0.054}{1 + \frac{1.1 E_\mu \cos\theta}{850\,\mathrm{GeV}}}$$

FLUX COMPILATION

- Compilation of theoretical and measured fluxes of multiple authors
- Theoretical models dominated by lack of knowledge of nucleon structure functions in low x region - overall errors could be as high as 30%.
- High slant angles dominate upper energy regimes as decay becomes more favorable over interaction at large angle (more time in less dense atmosphere)



MU+/MU- RATIO



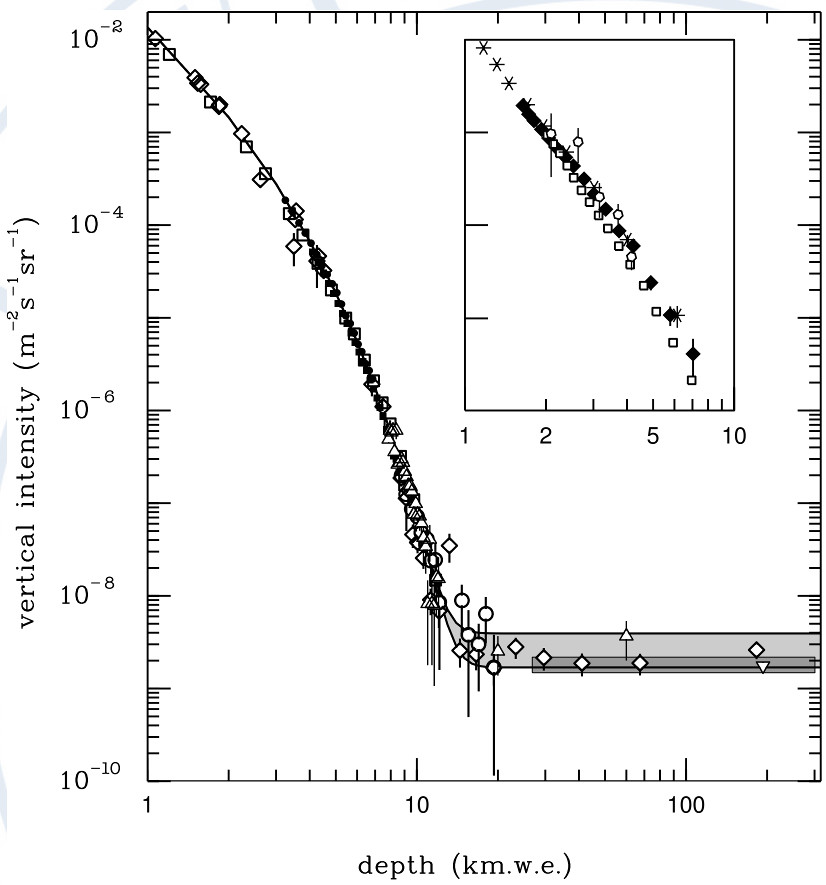
Excess of μ^+ relative to μ^- taken from PDG. The measurement of this ratio demonstrates the predominance of p CR primaries and moreover is important as input to MC models of CR primary induced air showers.

MUON FLUXES DEEP UNDERGROUND

Muons are found underground from two sources:

- "Punch-through" atmospheric muons exist to depths of several km.w.e. due to penetrating nature - 1 TeV muon has range of approx. 2.5 km in rock.
- Neutrino-induced muons : atmospheric neutrinos penetrate to deepest depths - thus at all points in Earth interior one will find muons from CC interactions:

  $\nu_\mu N \rightarrow X + \mu$



MUON DE/DX AT HIGH ENERGIES

The Beta-Bloch equation (see PDG, for example) for muons (and taus too but they have 10× smaller radiative losses) becomes dramatically simplified at high-energy:

$$-\frac{dE}{dX} = a + b(E)E$$

where a = 0.002 $GeVg^{-1}cm^2$ is the more or less constant energy loss due to ionization and the b term is due to radiative processes which take precendence at high energies:

$$b_{\mathrm{tot}} = b_{\mathrm{brems}} + b_{\mathrm{pair}} + b_{\mathrm{nucl}}$$

See http://pdg.lbl.gov/AtomicNuclearProperties for further data.
Data for water and standard rock are given below in units of 10^{-6} $g^{-1}cm^2$:

	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV
Water	1.439	2.279	2.959	3.313	3.497
Rock	1.840	3.028	3.934	4.365	4.563

MUON RANGE

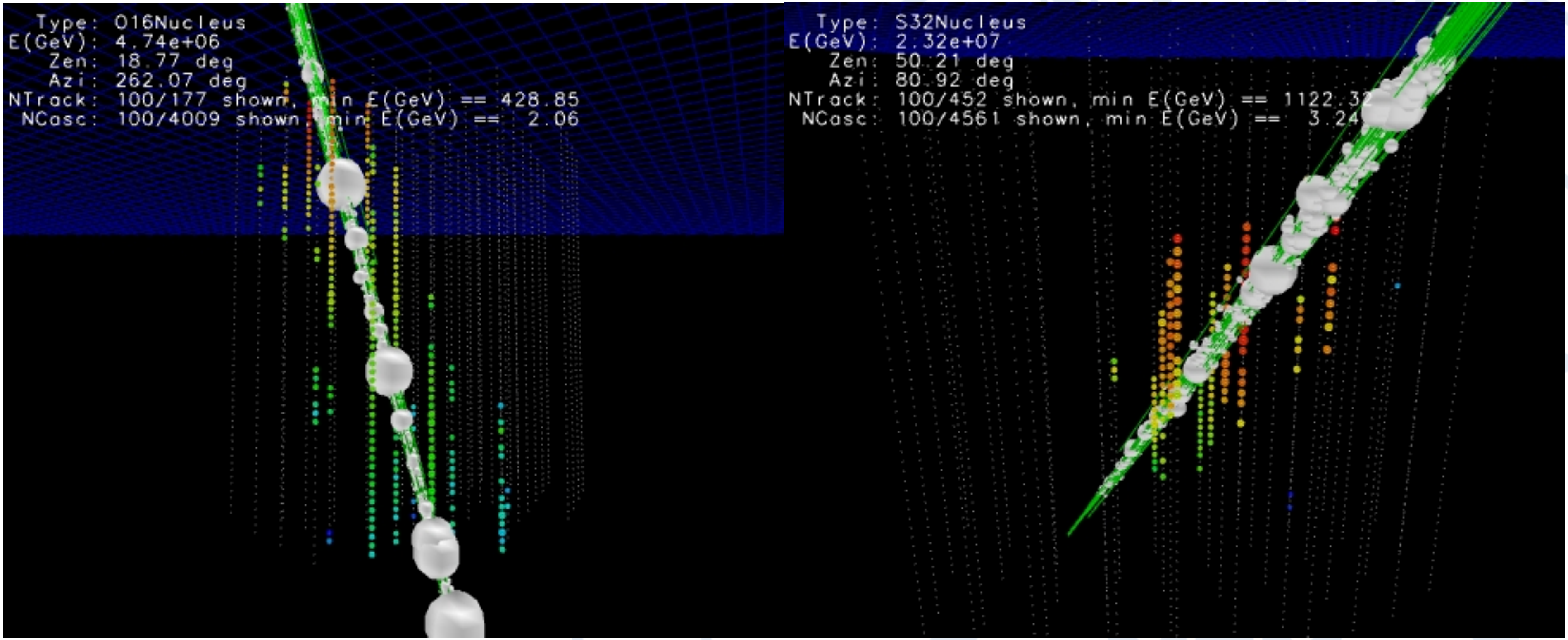
The muon range can be expressed as

$$R(E) \approx \frac{1}{b}\ln(1+\frac{E}{E_c})$$

where $E_c \equiv a/b(E)$ and where b(E) has been approximated to be constant versus energy.

This can be inverted to express the energy as a function of the range which then may be used with the Gaisser parameterization to obtain a flux of atmospheric muons deep underground

STOCHASTIC LOSSES



Two Monte Carlo CR muon bundle events from IceSim. The “clumpy” nature of the stochastic losses is particularly evident in the figure at right. These losses dominate at high energy, thus the muon dE/dX and range formulae are only statistically applicable at HE.

Atmospheric and Extra-Terrestrial

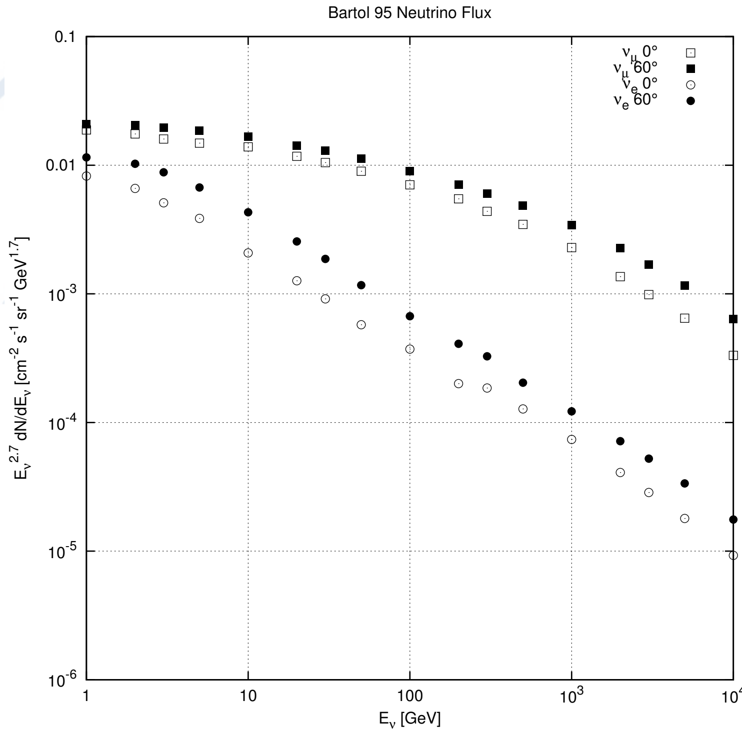
THE NEUTRINOS

ATMOSPHERIC NEUTRINO FLUXES

- All comments about uncertainties of theoretical fluxes made for muons apply equally to the case of neutrinos.
- Muons begin with E–2.7 spectrum which steepens at large E due to enhancement of interactions over decays of parent mesons.
- Electrons mostly from muon decays:

$$B(\pi \to e\nu) \simeq 10^{-4}$$
$$B(K \to e\nu) \simeq 0.05$$

- No good parameterizations that I know of – best to resort to tables published by many authors (Bartol, Honda, …)



NEUTRINO CROSS SECTIONS (I)

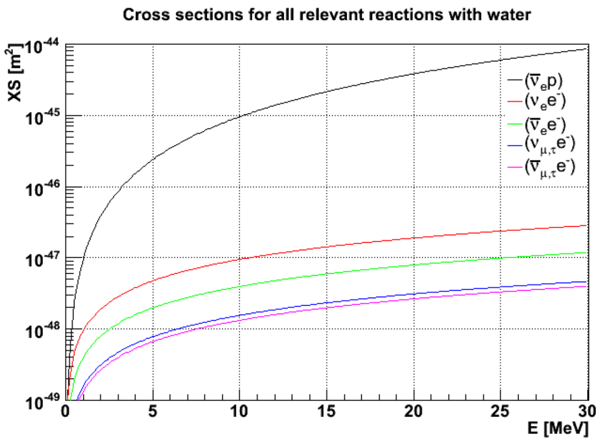
- Neutrinos feel only the weak force thus interactions with matter mediated by W and Z bosons with cross-sections typical of weak processes (pb - but see later).
- Feynman diagrams factor along two lines
  - Neutral current (NC) interactions - exchange of Z
  - Charged current (CC) interaction - exchange of $W^{\pm}$
- Neutrinos scatter from electrons as well as nucelons
- Pheno complex - resort to MC package such as C++-based GENIE package (arXiV: 0905.2517)

LOW ENERGY

At low energy of interest for supernova neutrino detection neutrino / matter interactions are dominated by the **inverse beta** reactions:

$$\bar{\nu} + p \rightarrow n + e^{+}$$

with a cross-section that scales as the square of the neutrino energy.



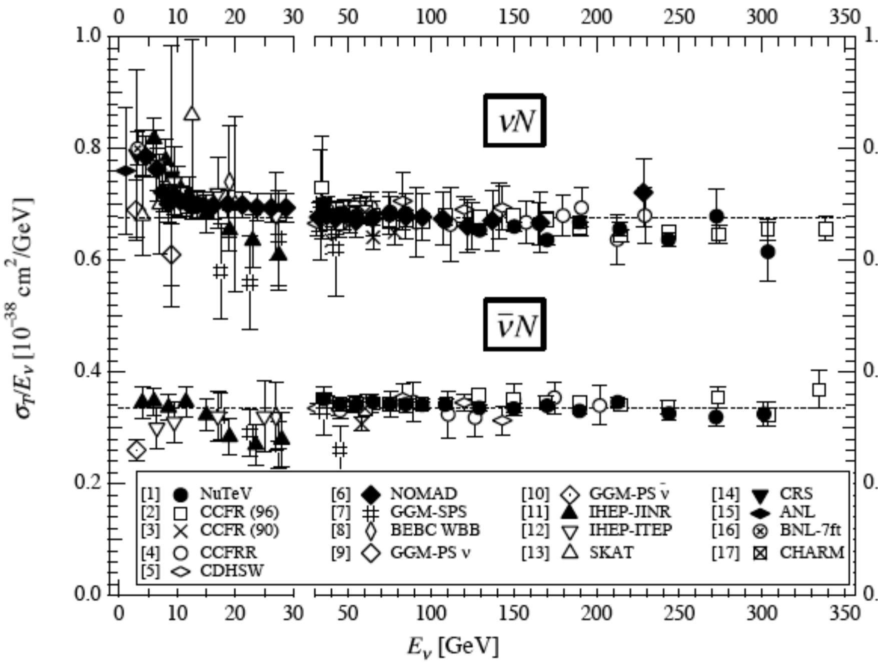
Neutrino-electron and coherent neutrino-nucleus interactions can also be important for some materials. In water usually IBD strongly dominates.

GEV SCALE

- Below 1 GeV range of **elastic** or **quasielastic** scattering : GENIE MC tuned for this range of energies
- At E >> 1 GeV deep inelastic scattering is dominant – here cross sections are tractable:

$$\sigma_{\nu p} \simeq 0.69 \times 10^{-38} E_\nu \text{ cm}^2$$

$$\sigma_{\bar{\nu} p} \simeq 0.35 \times 10^{-38} E_\nu \text{ cm}^2$$



THE EARTH IS TRANSPARENT TO NEUTRINOS!

Take the number of nucleons inside the Earth:

$$N_N = \frac{M_E}{m_N} = \frac{5.97 \times 10^{24}\,\mathrm{kg}}{1.67 \times 10^{-27}\,\mathrm{kg/nucleon}} = 3.57 \times 10^{51}\ \mathrm{nucleons}$$

Then divide by Earth volume:

$$V_E = \frac{4}{3}\pi r_E^3 = 1.09 \times 10^{21}\,\mathrm{m}^3$$

To obtain the mean nucleon density in Earth:

$$= 3.28 \times 10^{24}\,\mathrm{nucleons/cm}^3$$

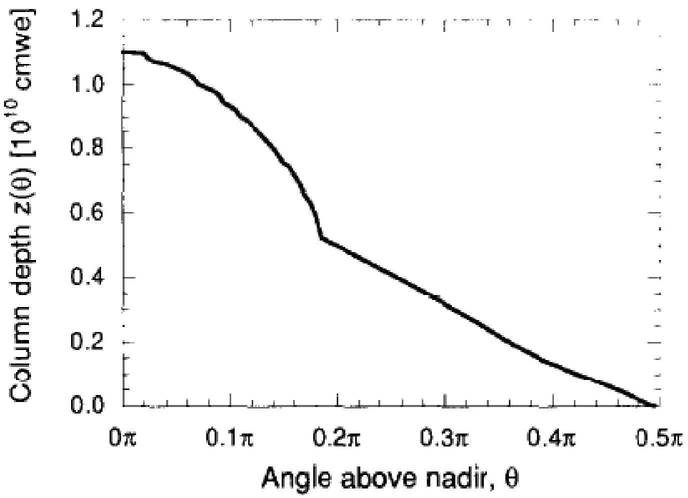
The mean interaction length is >> Earth radius for GeV / TeV neutrinos:

$$\mathcal{L}_{\mathrm{int}} = (\sigma n_N)^{-1} = 10^9\,\mathrm{km!}$$

PRELIMINARY EARTH MODEL

The PREM (ref GQRS article next slide) defines the Earth density as a function of the radial distance from center:

$$\rho(r) = \begin{cases} 13.0885 - 8.8381x^2, & r < 1221.5, \\ 12.5815 - 1.2638x - 3.6426x^2 - 5.5281x^3, & 1221.5 < r < 3480, \\ 7.9565 - 6.4761x + 5.5283x^2 - 3.0807x^3, & 3480 < r < 5701, \\ 5.3197 - 1.4836x, & 5701 < r < 5771, \\ 11.2494 - 8.0298x, & 5771 < r < 5971, \\ 7.1089 - 3.8045x, & 5971 < r < 6151, \\ 2.691 + 0.6924x, & 6151 < r < 6346.6, \\ 2.9, & 6346.6 < r < 6356, \\ 2.6, & 6356 < r < 6368, \\ 1.02, & r \le R_\oplus, \end{cases}$$



As a function of angle the total amount of material in cm.w.e. (centimeter of water-equivalent – equivalent to g/cm^2)

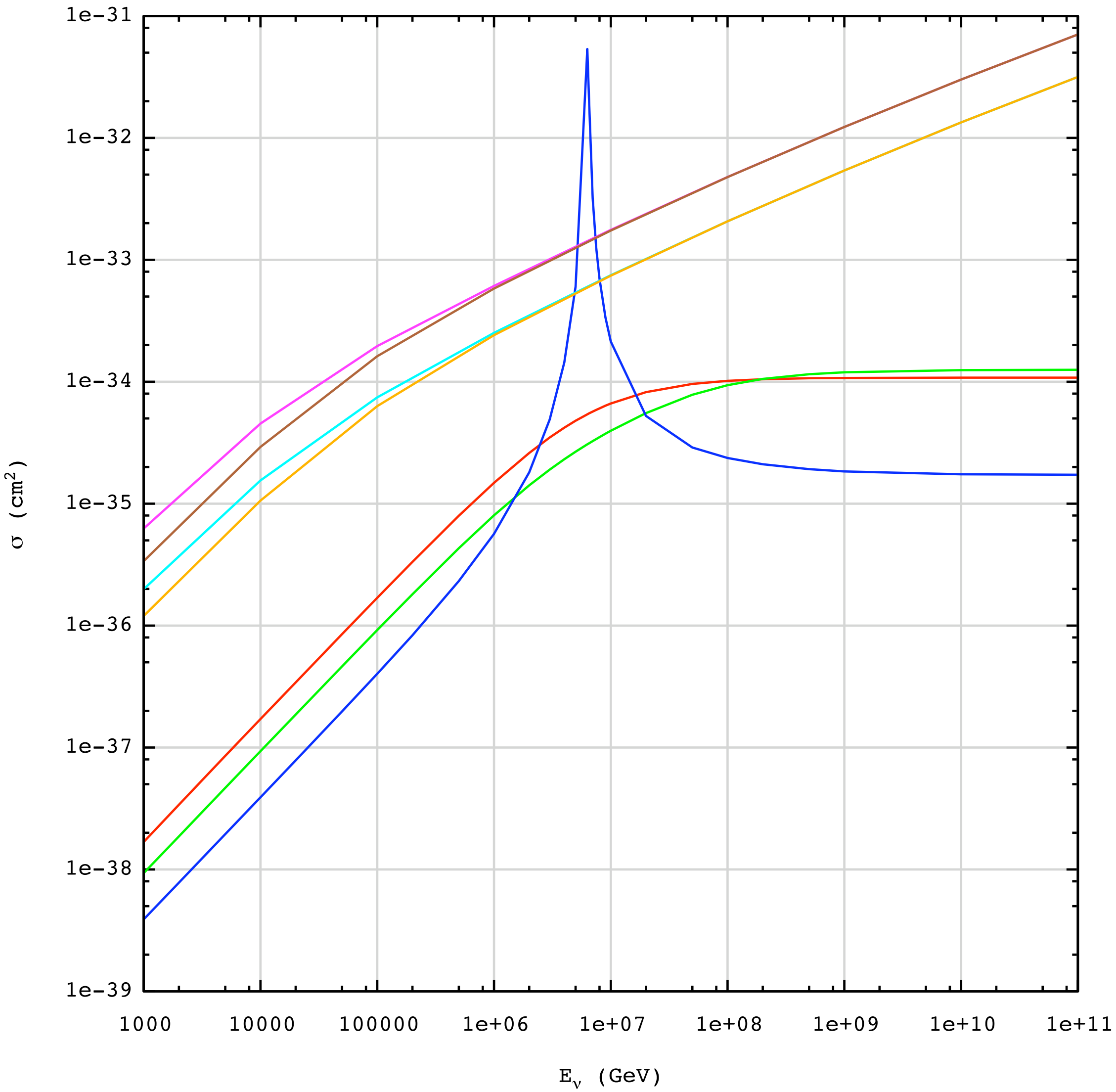
UHE NEUTRINO CROSS SECTIONS

At UHE the neutrino cross-sections continue to rise but less than linearly. The paper by GQRS (Gandhi, Quigg, Reno, Sarcevic, Astropart. Phys. 5 81-110 (1996)) discusses the topic at length. Summarizing for the neutrino-nucleon reactions (dominant except where noted):

$$\sigma = A\left(\frac{E_\nu}{\mathrm{GeV}}\right)^{\alpha} \times 10^{-36}\mathrm{cm}^2$$

	A		α	
	NC	CC	NC	CC
$\nu + N$	1.06	2.69	0.408	0.402
$\bar{\nu} + N$	0.98	2.53	0.410	0.404

UHE NEUTRINO CROSS SECTIONS



NO WAIT! THE EARTH IS OPAQUE TO NEUTRINOS!

- About about 100 TeV the mean free path for neutrino-nucleus scatters is about 10^{10} c.m.w.e which is about the matter thickness encountered in passing the Earth along the diameter.
- This means that for UHE observatories such as IceCube, the rate of such high-energy events from below the horizon is strongly suppressed!
- There is an important exceptional case: ν_τ . A very high energy beam of ν_τ at one side of theE arth $E \gg 1$PeV can end up at the other side as lower energy flux of ν_τ and ν_e and ν_μ through the tau regeneration effect.

SUMMARY

- Thus concludes the section on cosmic rays.
- We will continue with a more in-depth look at neutrino astrophysics and take a look at the detailed design and data from two HE/UHE neutrino observatories in the next module:
  - IceCube
  - ARA