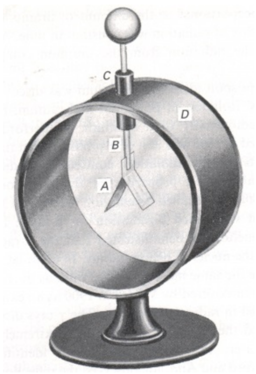
Ultra High Energy Cosmic Rays
and
Relic Neutrinos

PHYS 598NEU

Dec. 11, 2019

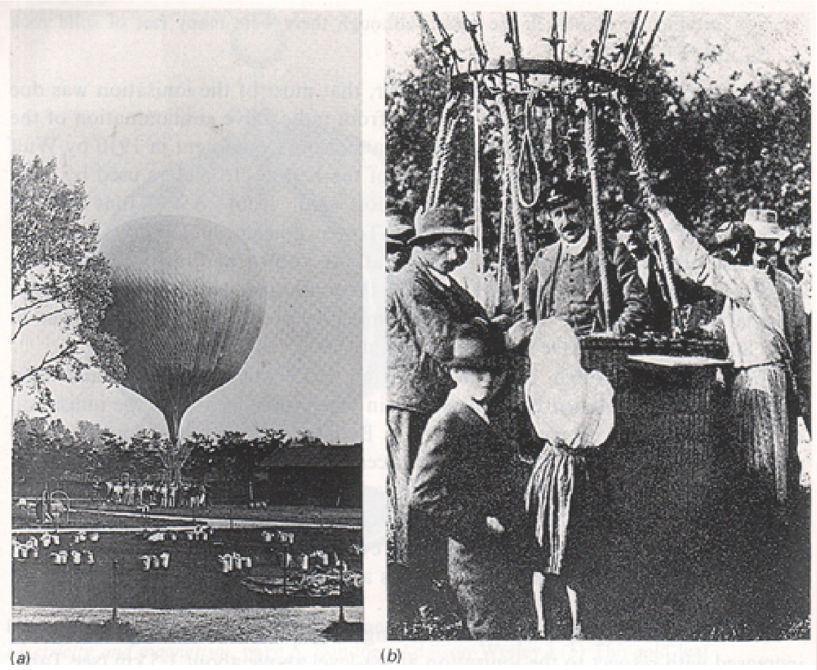
- Brief history
- Open questions and current status
- Future prospects and speculations

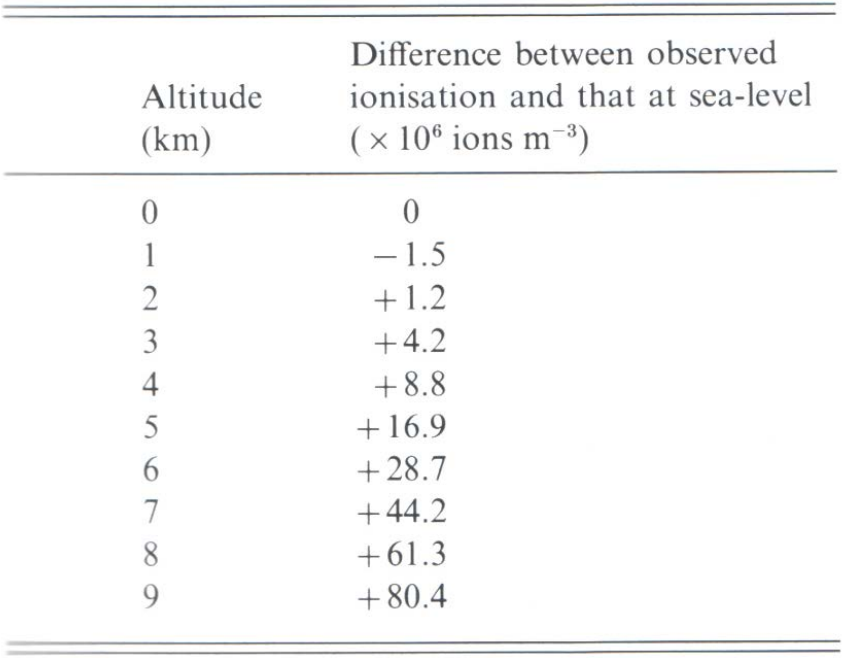
Ancient History



- ~1900 : Electroscopes were found to discharge even when they were heavily shielded.
- ~1910 : Wulf found the ionization fell from 6×10^6 ions/m^{-3} to 3.5×10^6 ions/m^{-3} as he ascended the Eiffel Tower (330m). This suggested a terrestrial origin of the ionization.
- ~1912-1914 : V. Hess and W. Kolhorster measured the ionization in open balloons ascending to height of 5 km and 9 km, respectively.

Ancient History



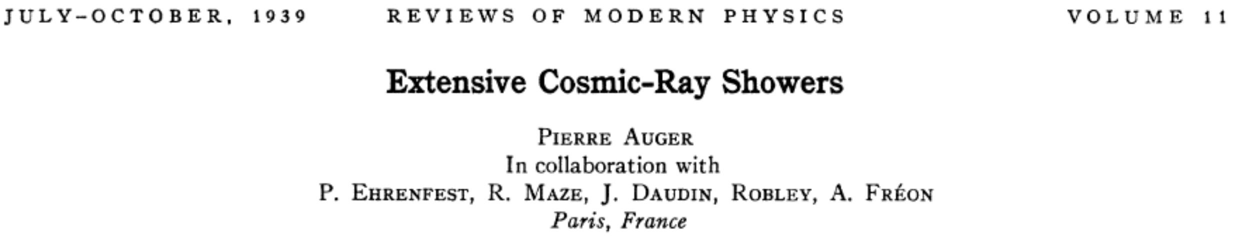


Altitude (km)	Difference between observed ionisation and that at sea-level ($\times 10^6$ ions m^{-3})
0	0
1	−1.5
2	+1.2
3	+4.2
4	+8.8
5	+16.9
6	+28.7
7	+44.2
8	+61.3
9	+80.4

Victor Hess returning from a balloon flight

- The ionization was found to have extra-terrestrial origin.
- Bitter debates regarding the nature of the ionization
  - Millikan: cosmic rays are gamma rays
  - Compton: cosmic rays are charged particles

Observation of air shower



JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

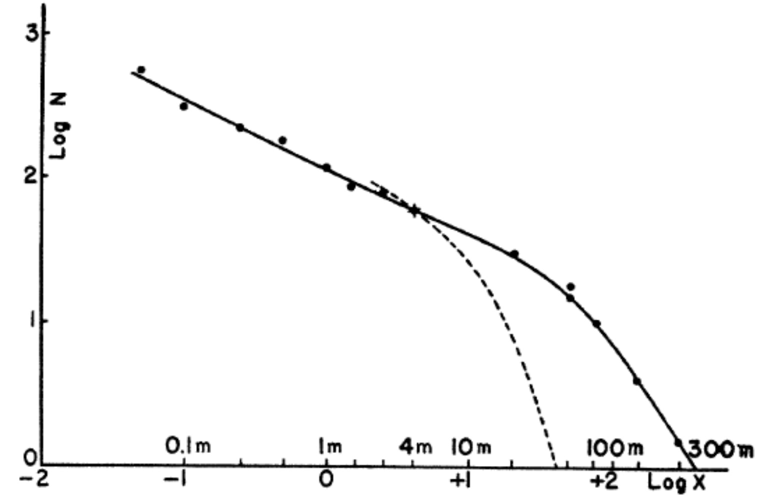
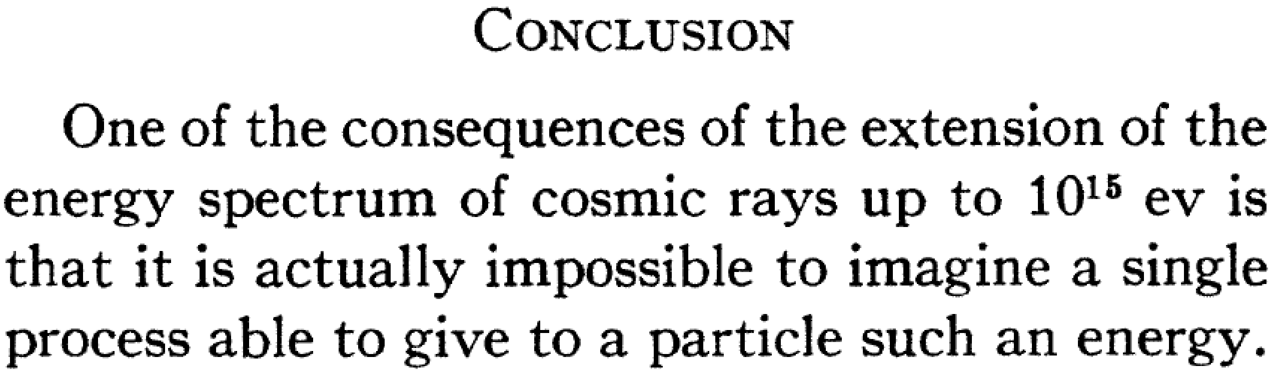


FIG. 1. Results with two parallel and horizontal counters.

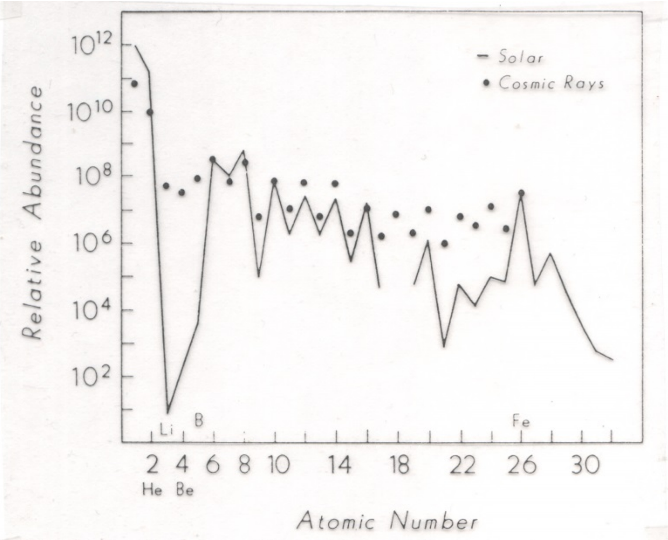
- Coincidence rates between two counters separated at a distance up to 300 meters
- The energies of the cosmic rays were estimated to be ~ 10^{15} ev.



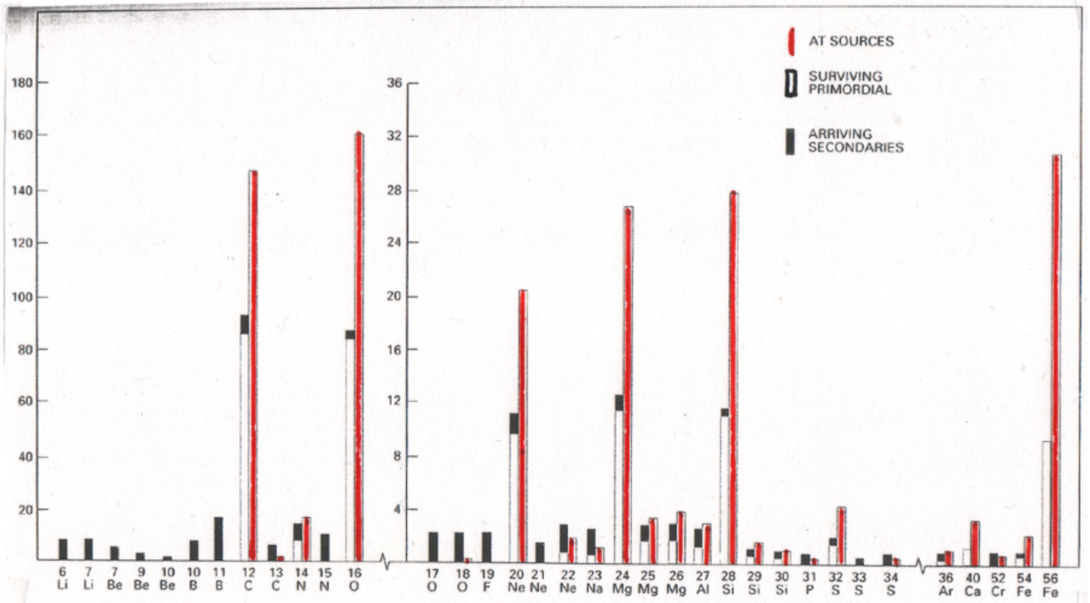
CONCLUSION

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy.

Isotope composition of the cosmic rays



- Abundance of Li, Be, B in cosmic rays. Why?
- Deficiency of H and He in cosmic rays relative to solar system. Why?

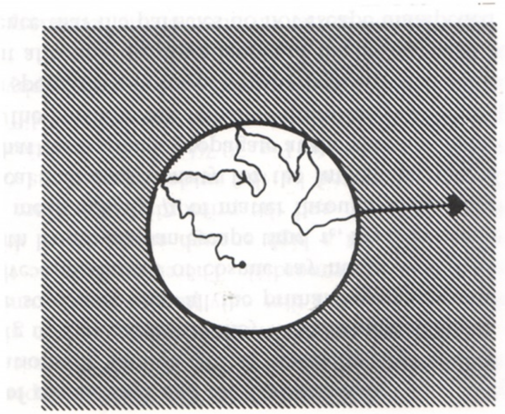


- Cosmic rays interact with interstellar gas.
- Observed isotope composition is the result of spallation.

Implication on the age of the cosmic rays

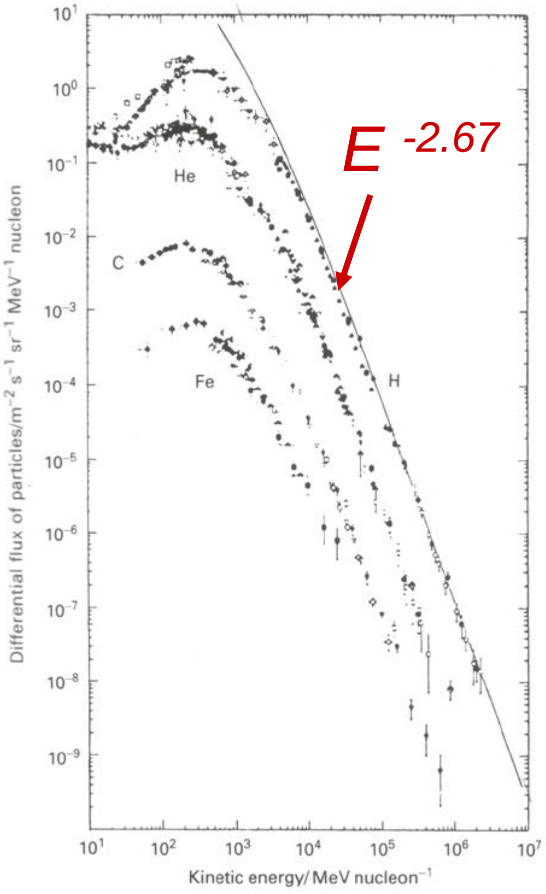
- ~ 5g/cm^2 of mass traversed by the cosmic rays.
- Average density for interstellar gas is 1 atom/cm^3 → ~ 3 x 10^6 years as the lifetime of cosmic rays.
- ^{10}Be as a "cosmic ray clock". Half-life of ^{10}Be is 3.9 x 10^6 years.
- ^{10}Be / (^{7}Be + ^{9}Be + ^{10}Be) = 0.028 implies "escape time" for cosmic ray ~ 10^7 years.

"Leaky Box" model



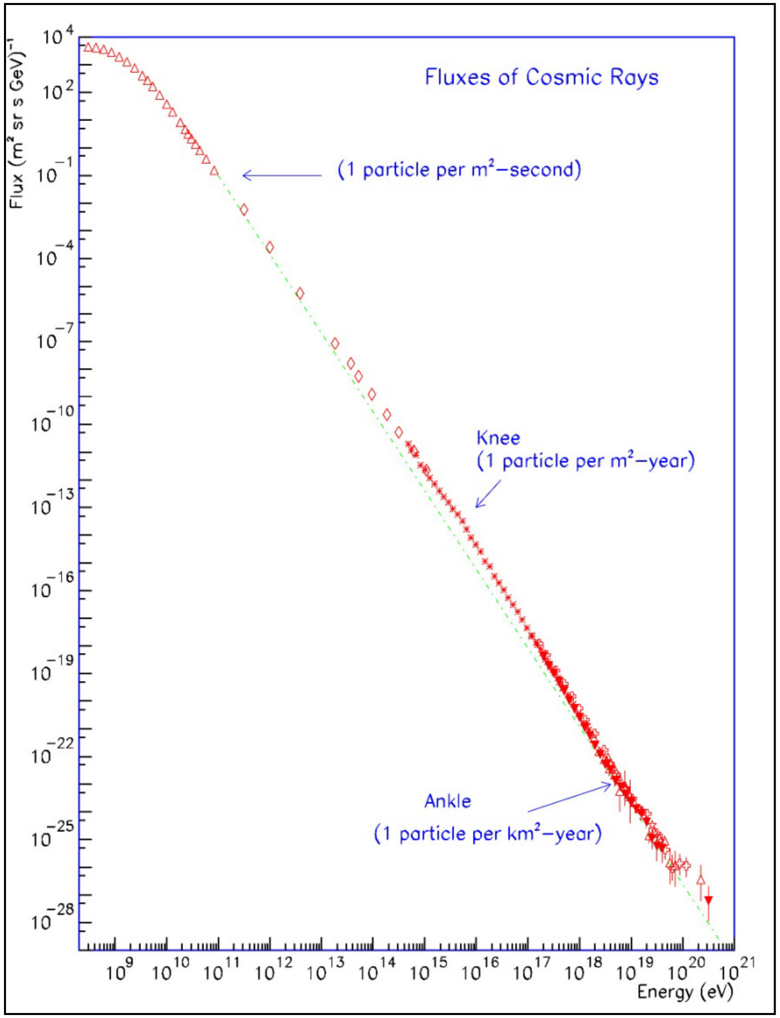
- Energetic cosmic rays in our galaxy can escape to other galaxies.
- Energetic cosmic rays from other galaxies can reach our galaxy.

Composition and energy spectrum of the cosmic rays



- Direct measurements with balloons or satellites
- “Low energy” part of the spectrum consists of proton (~87%), He (12%), Z>2 nuclei (~1%).
- Energy density:
  - – Cosmic rays: ~ 1 ev/cm^3
  - – Star light: ~0.3 ev/cm^3
  - – Interstellar B field: ~0.2 ev/cm^3
  - – Cosmic microwave background: ~0.3 ev/cm^3

Ultra high energy cosmic rays



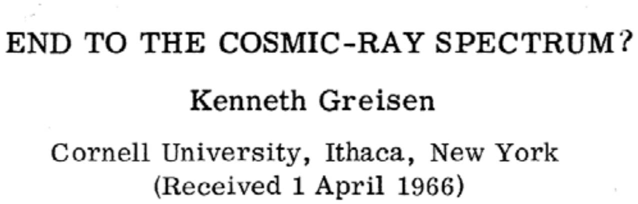
Flux ~ 1/cm^2/sec at 100 MeV

~ 1/km^2/century at 10^{20} eV

- Composition of the UHECR?
  - Proton, nucleus, gamma, neutron, exotics?
  - 10^{18} eV neutron travels a distance of 3 x 10^4 light years
- Sources of UHECR (Galactic, extra-galactic, AGN, GRB, …)?
- Mechanisms for producing UHECR?
- Origins of the “Knee”, “Ankle”, and the existence of the “GZK cut-off”?

The GZK cut-off (suppression)

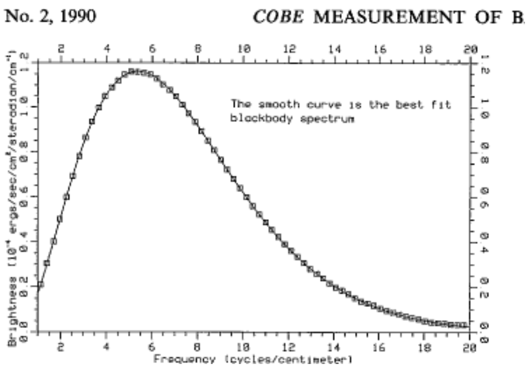
(Greisen, Zatsepin, Kuzmin)



END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)



2.73 K
CBR

- $p+\gamma \rightarrow p+\pi^0$

  $\text{threshold} = 5\times10^{19}\,\text{ev}$

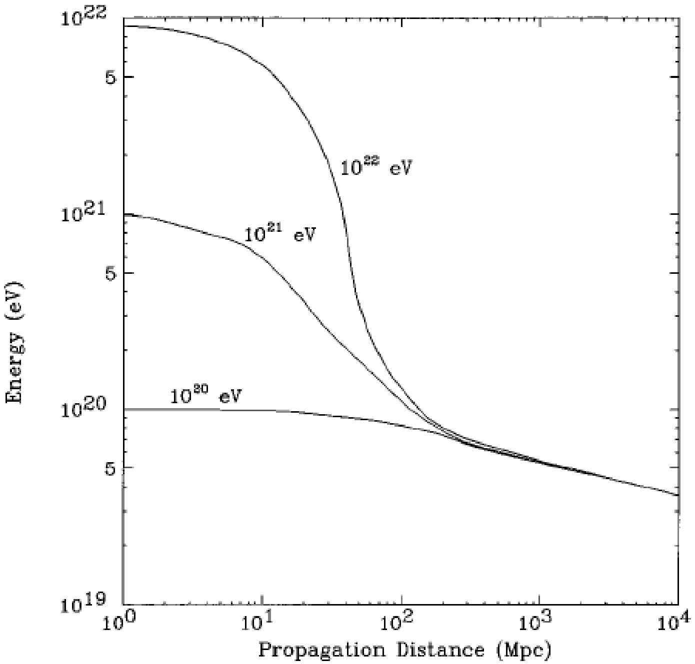
  for $6\times10^{-4}\,\text{ev}$ CMB photons

- $p+\gamma \rightarrow p+e^+ + e^-$

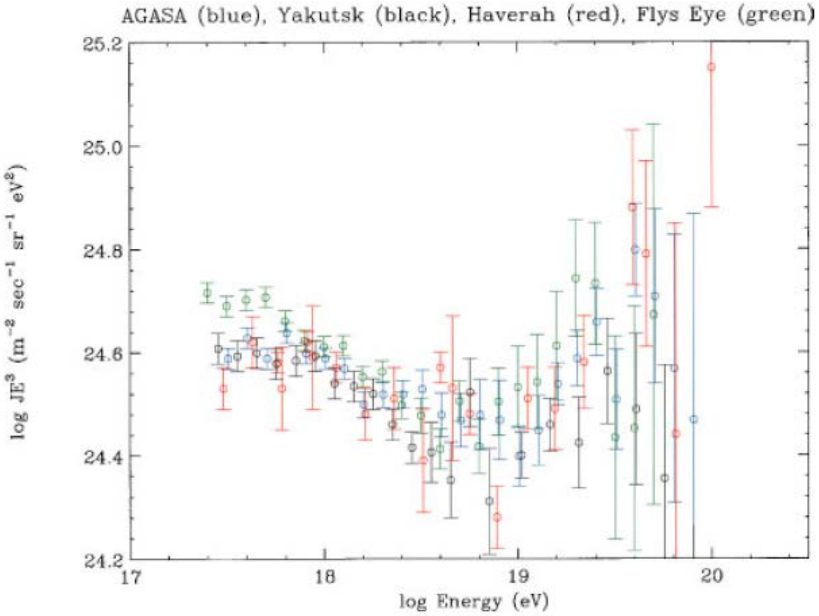
  $\text{threshold} = 5\times10^{17}\,\text{ev}$

- Attenuation length $=1/\rho\sigma$

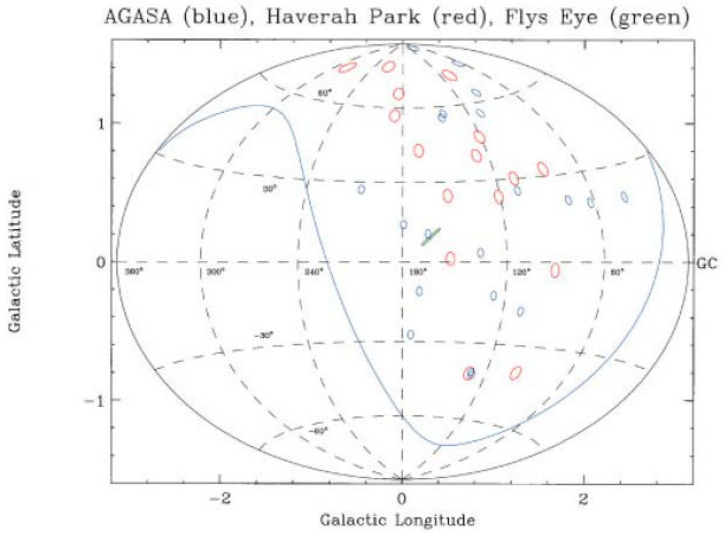
  $(\rho \simeq 500/cm^3)$

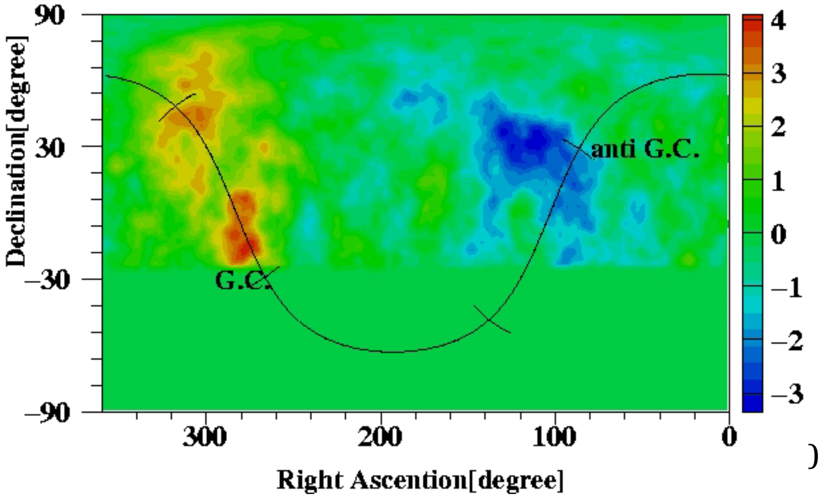


The GZK suppression or enhancement?



- From Cronin’s APS Centennial review paper in 1999.
- Energy is rescaled: Yakutsk (reduce by 20%), Fly’s Eye (raised by 10%), AGASA (reduced by 10%).
- The absence of GZK suppression suggested relatively close sources for the UHECRs.
- Clustering of sources (two pairs and one triplets)? Signs of anisotropy?
- 4 σ excess at the galactic center (from AGASA for events with E>10^{18}ev)





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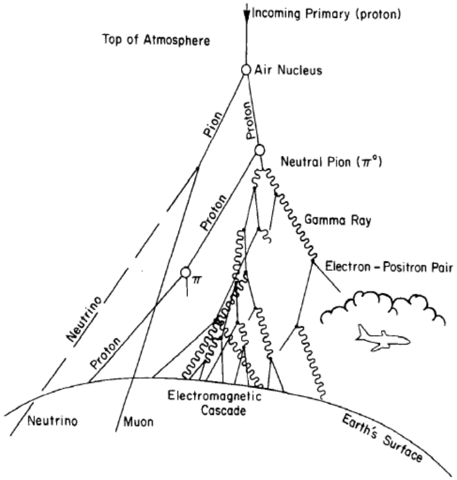
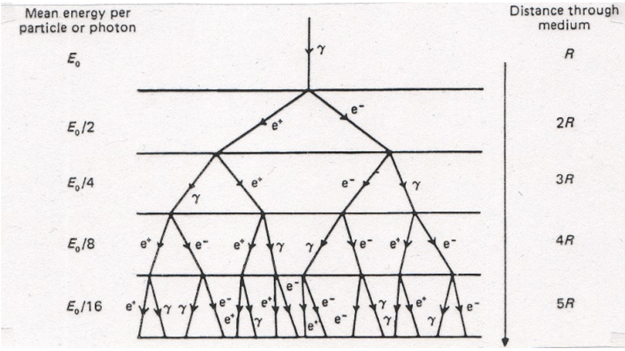
UHECR Detection – Ground Arrays

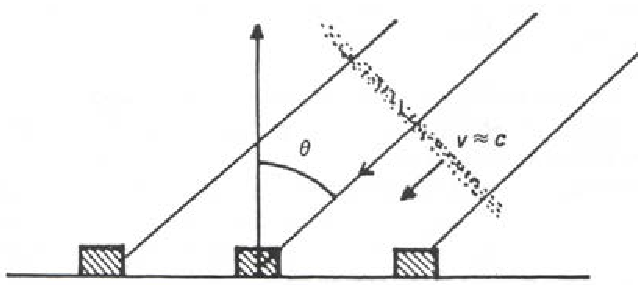
Hadronic shower



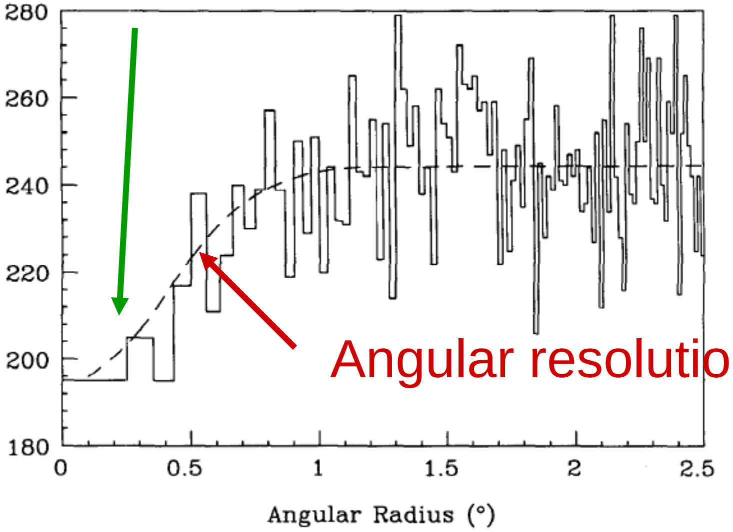
EM shower



- Hadronic shower contains EM showers.
- Muon content is very low for EM showers.
- Shower is only ~1-2 meters thick. Therefore, the arrival time and the direction can be well determined.

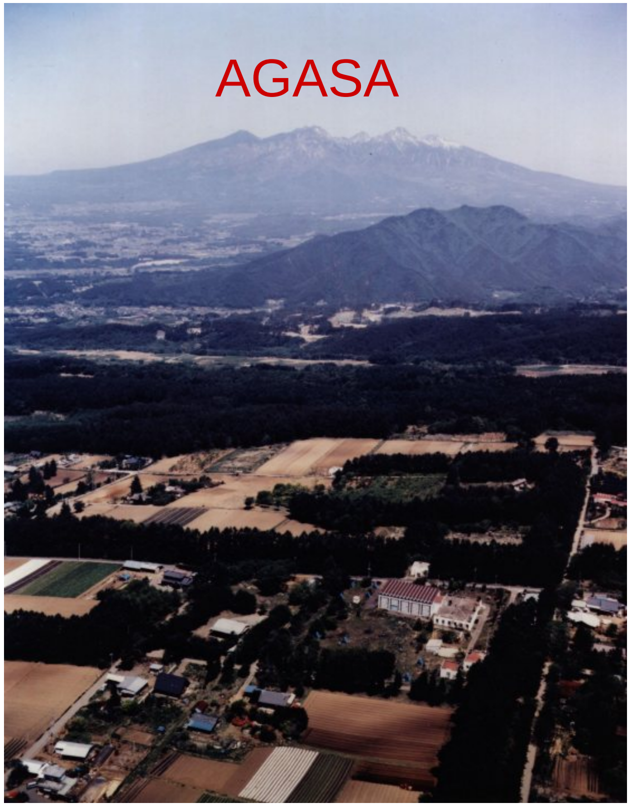


Shadowing from moon



Angular resolution ~ 0.35°

UHECR Detection – Ground Arrays



- 5 ground arrays were in operation during 40 years of measurements for UHECR detection.
  - Volcano Ranch, USA (1959-1963)
  - SUGRA, Australia (1968-1979)
  - Haverah Park, UK (1968-1987)
  - Yakutsk, Russia (1970-today)
  - AGASA, Japan (1990-2004)

UHECR Detection – Florescence telescope

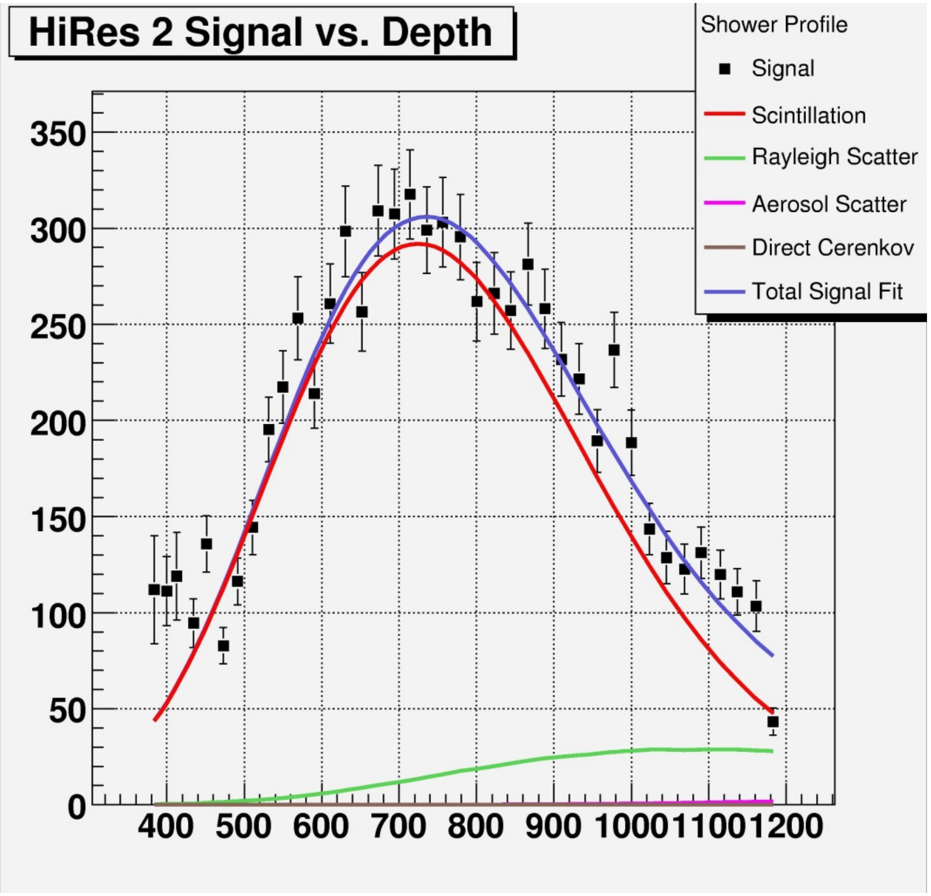
Fly’s Eye

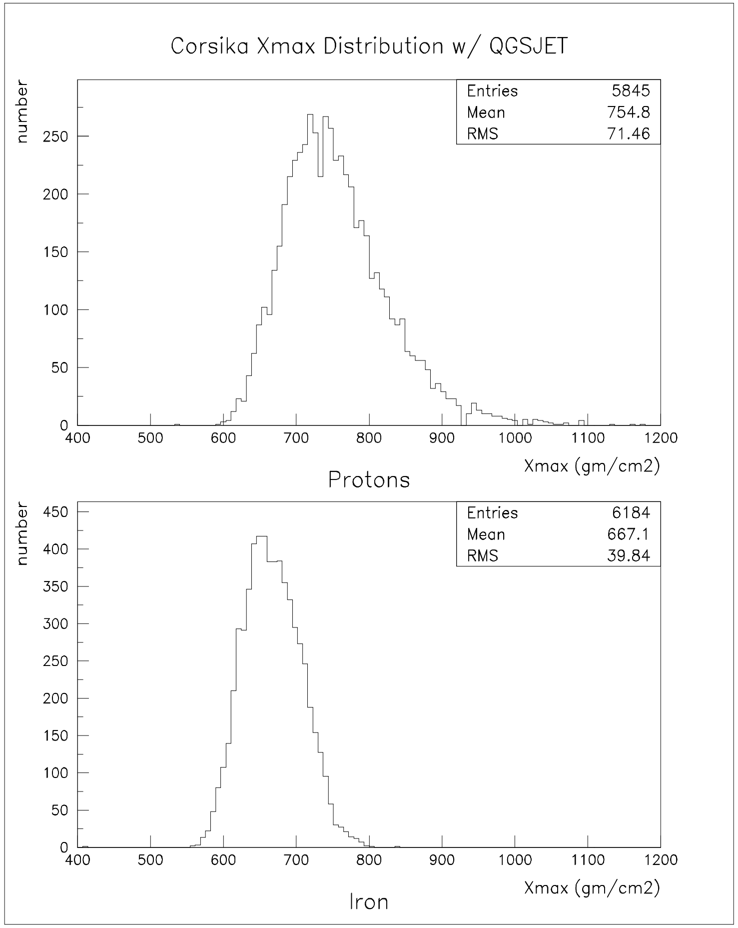
HiRes

- Optical photons in the range of 300 – 400 nm are produced by charged particles passing through the nitrogen of the atmosphere.
- An array of PMTs, each focused on a part of the sky, the shower development can be directly measured.
- The energy dissipation of the shower is directly measured.
- Limited to dark moonless nights.

- Fly’s Eye (1981-1992)
- HiRes-I (5/1997-6/2005)
- HiRes-II (12/1999-8/2004)

UHECR Detection – Florescence telescope

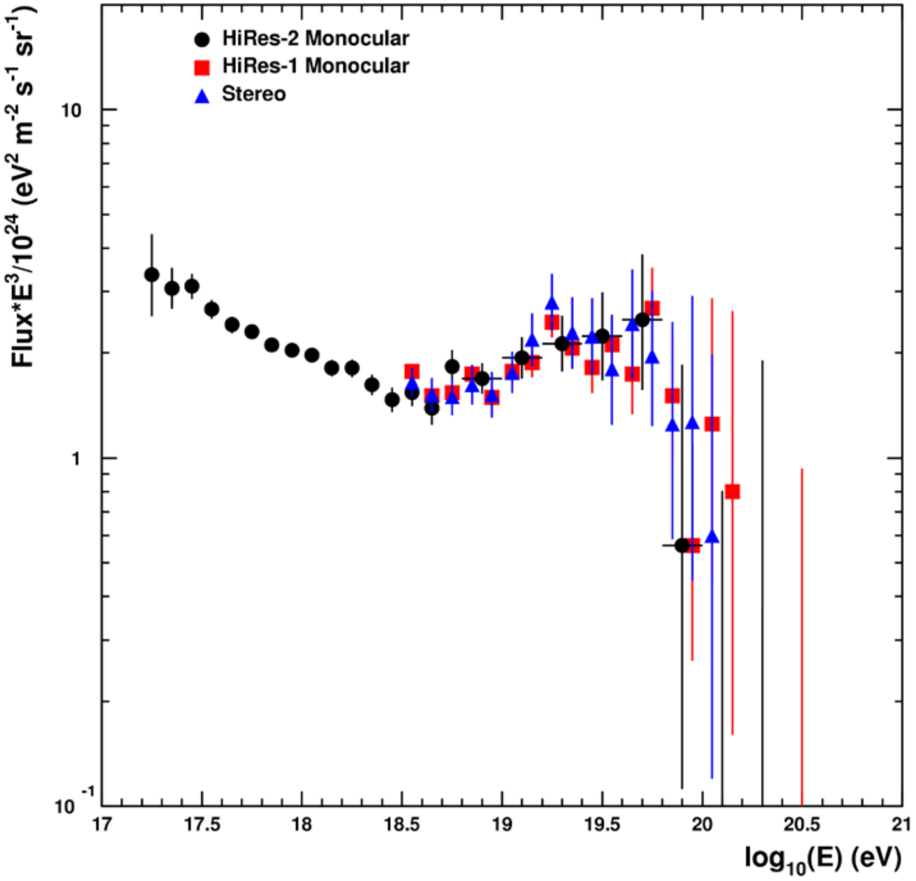




- Shower depth could be used to distinguish proton from nucleus, since shower depth ~ log(E/A).

Latest UHECR results from HiRes

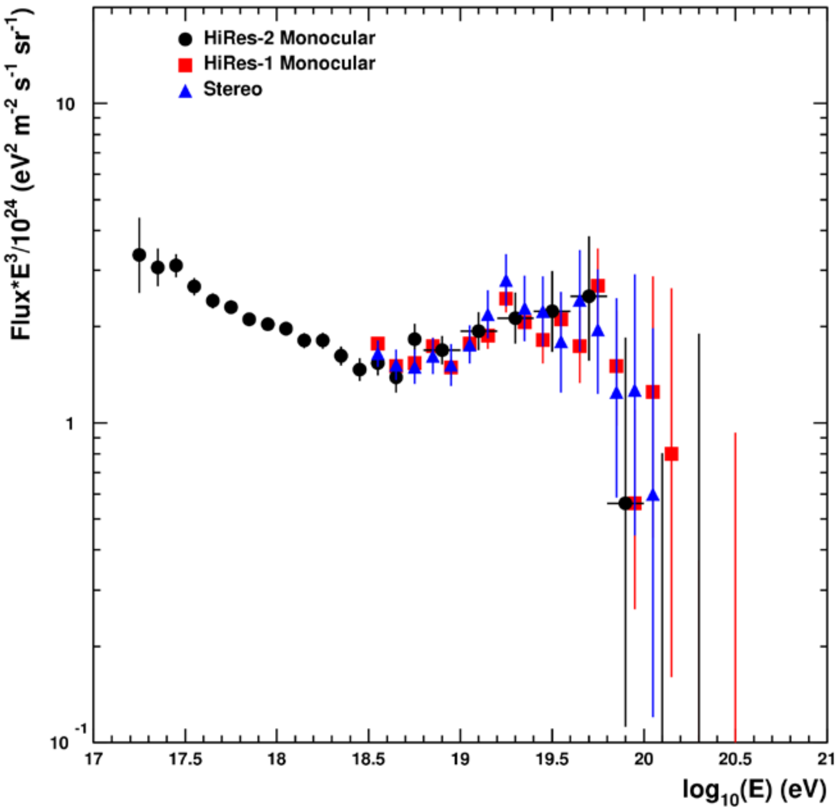
CIPANP2006 Talk by J. Mathews



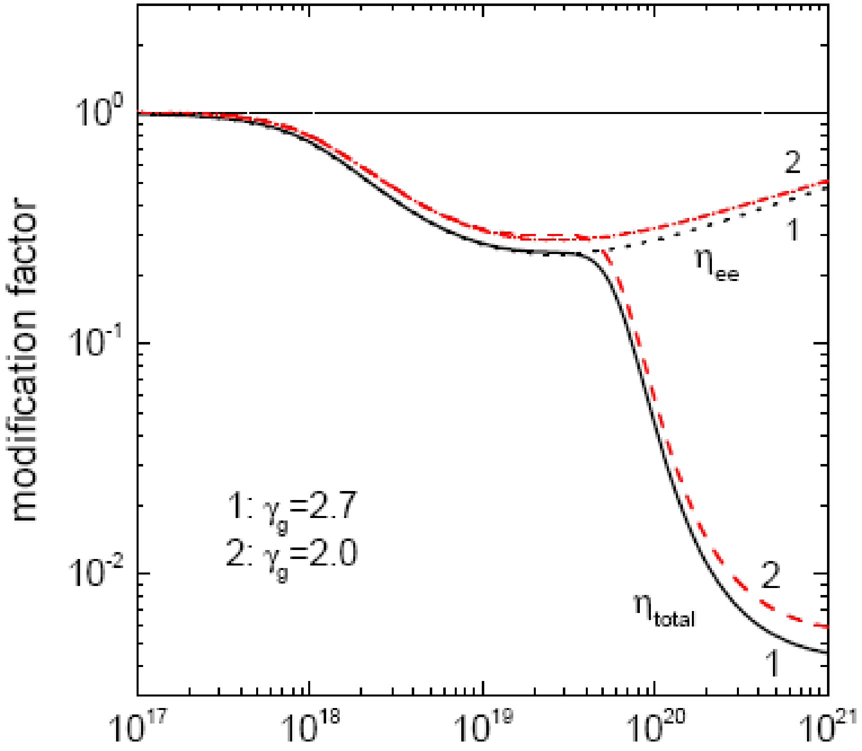
A “Dip” and a “Cut-off”?

HiRes data versus GZK cut-off calculation

HiRes data



GZK calculation
PRD 74 (2006) 043005

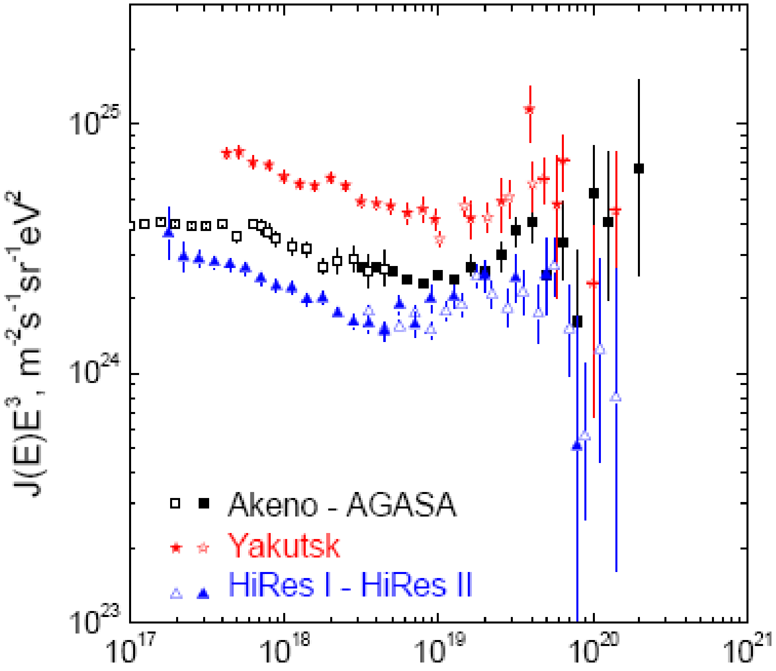


Dip is from $p + \gamma \rightarrow p + e^+ + e^-$

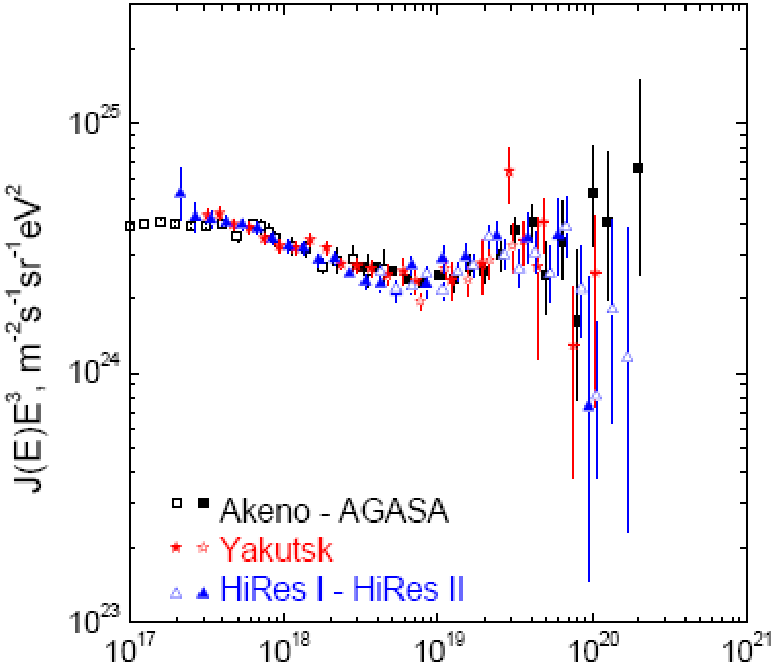
Cut-off is from $p + \gamma \rightarrow p(n) + \pi$

Are various UHECR data consistent?

Published Data



Energy Rescaled Data

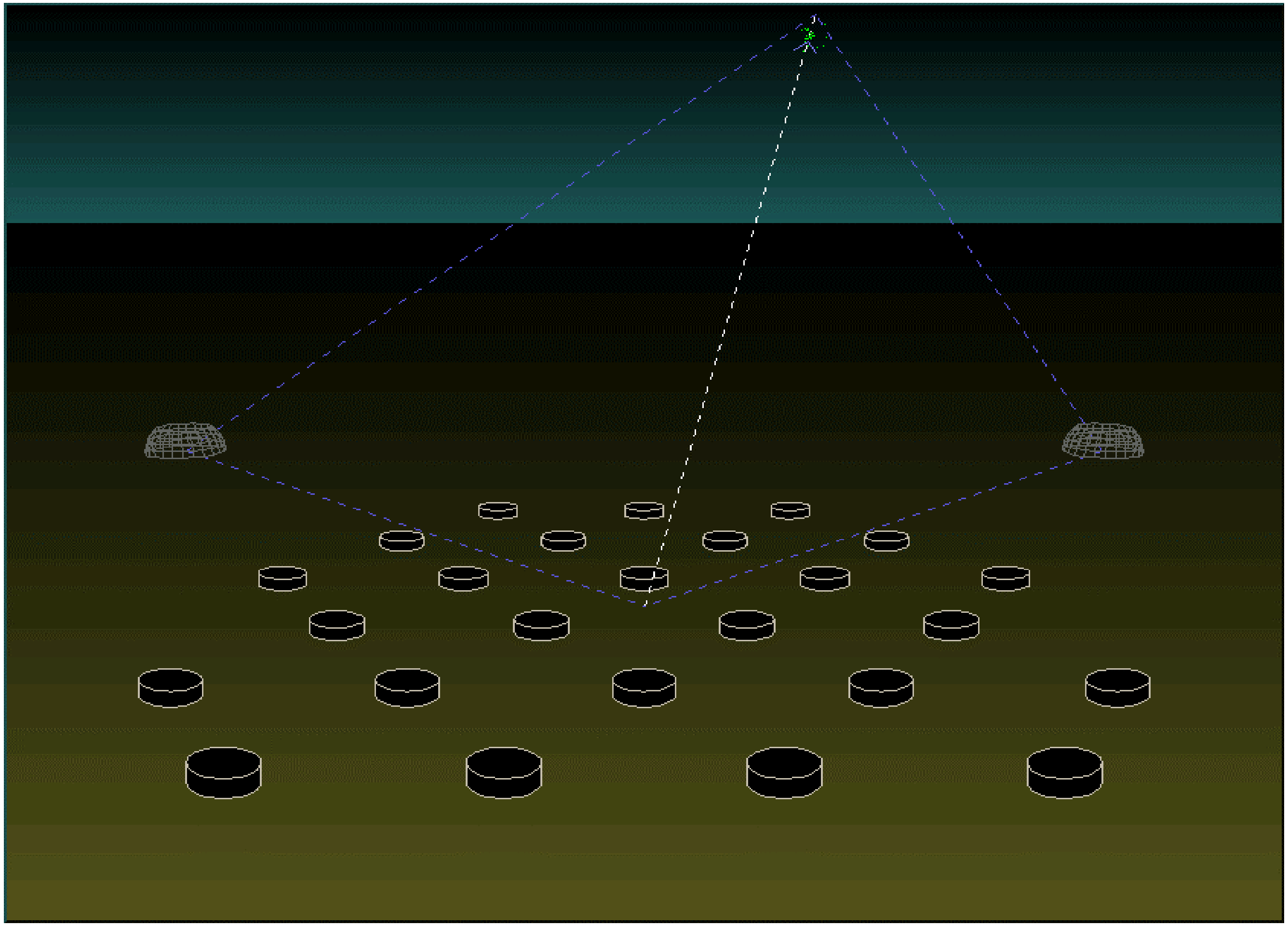


PRD 74 (2006) 043005

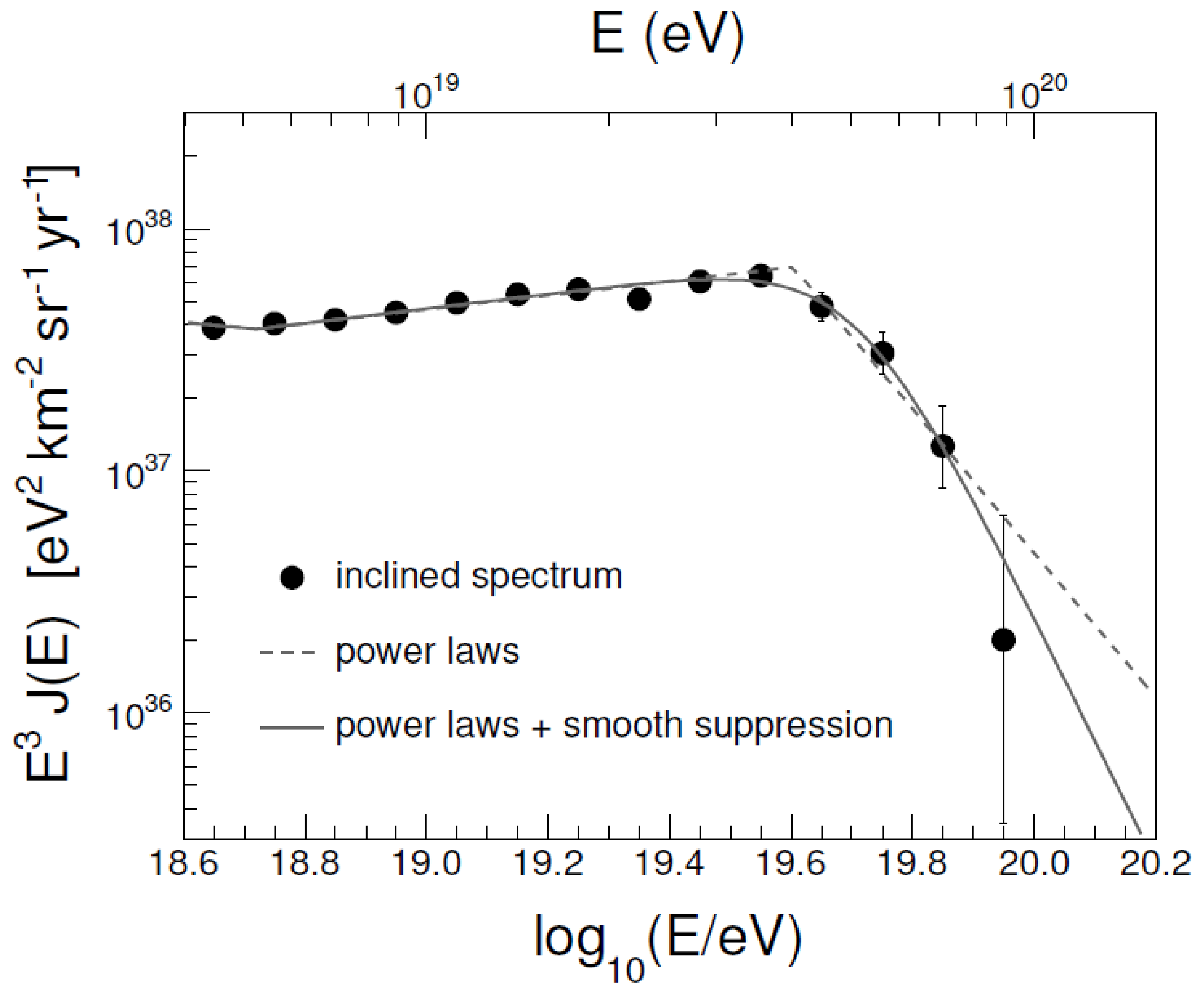
The Pierre Auger Observatory = hybrid detector of cosmic rays

- The array of surface Cherenkov detectors will be accompanied with system of fluorescence telescopes, which will observe faint UV/visible light during clear nights. This fluorescence light origins as by-product during the interactions of shower particles with atmosphere.

Scheme of hybrid detector function



Measurement of the cosmic ray spectrum above 4×10^{18} eV using inclined events detected with the Pierre Auger Observatory



Can one detect the relic neutrinos using UHECR?

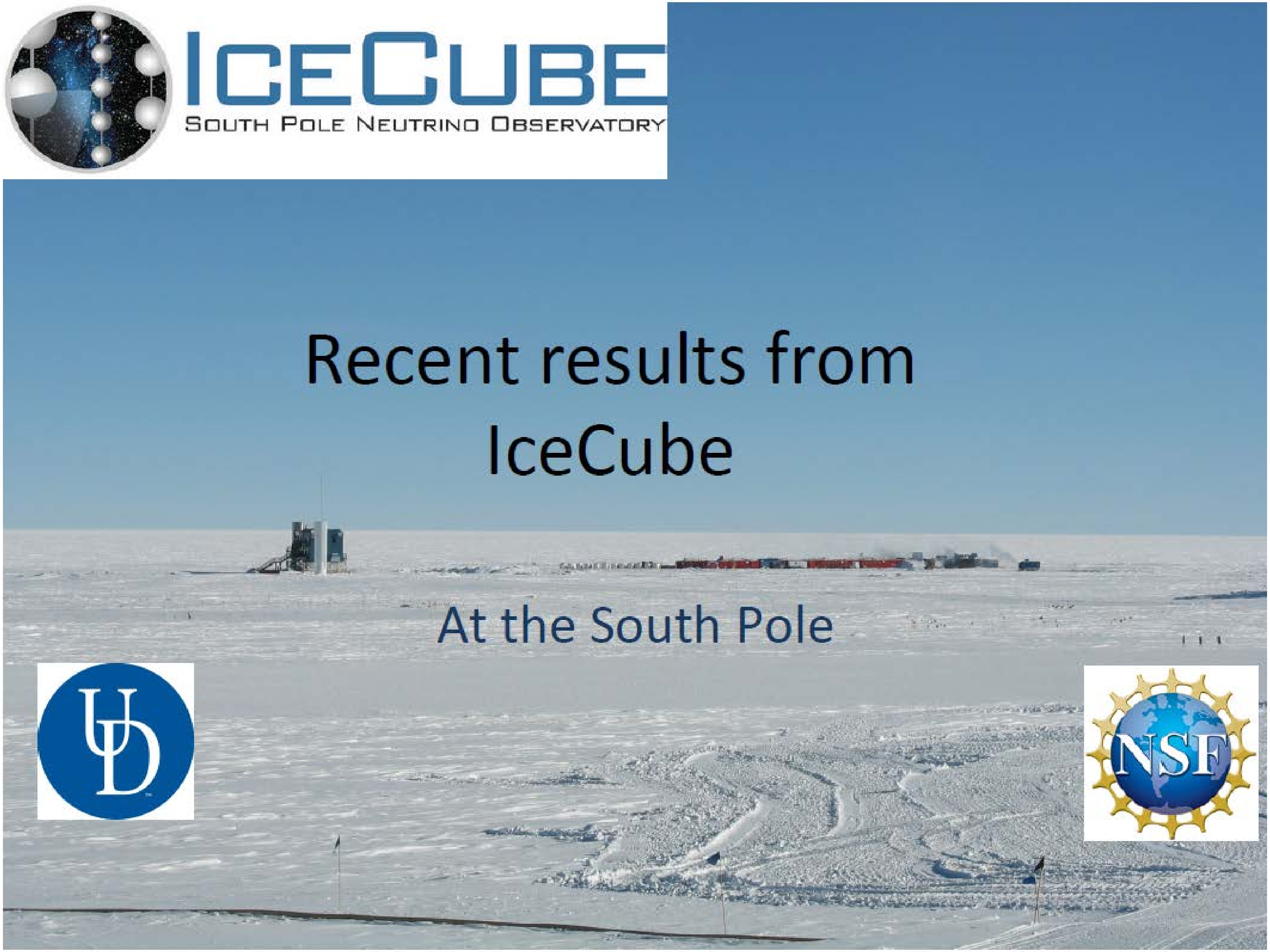
- The GZK Dip and Cut-off could be viewed as evidence for the CMB photons
- Are there UHECR reactions sensitive to the CMB neutrinos?

  * $\nu + \overline{\nu} \to Z \to e^{+} + e^{-}$

  * $p + \overline{\nu}_{e} \to n + e^{+}$

  * $e^{-} + \overline{\nu}_{e} \to W \to \mu^{-} + \overline{\nu}_{\mu}$
- Thresholds depend on the mass of ν
- Cross sections are too low?

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



Recent results from IceCube

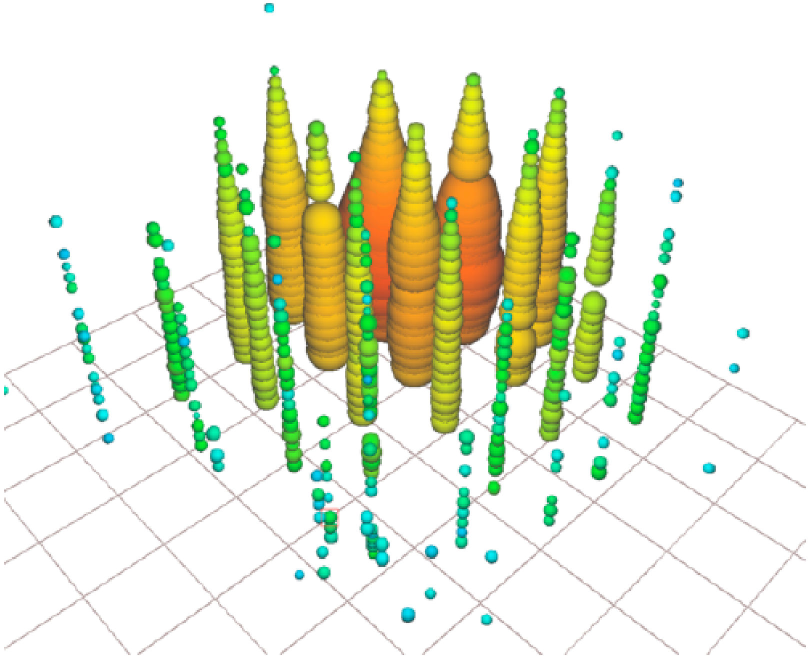
At the South Pole

Glashow event candidate in IceCube

$$\overline{\nu}_e + e^- \rightarrow W^- \rightarrow \text{cascade}$$

- Discovered in a study of partially contained large cascades
- Visible energy consistent with the 6.3 PeV resonance energy
- PoS(ICRC2019)945

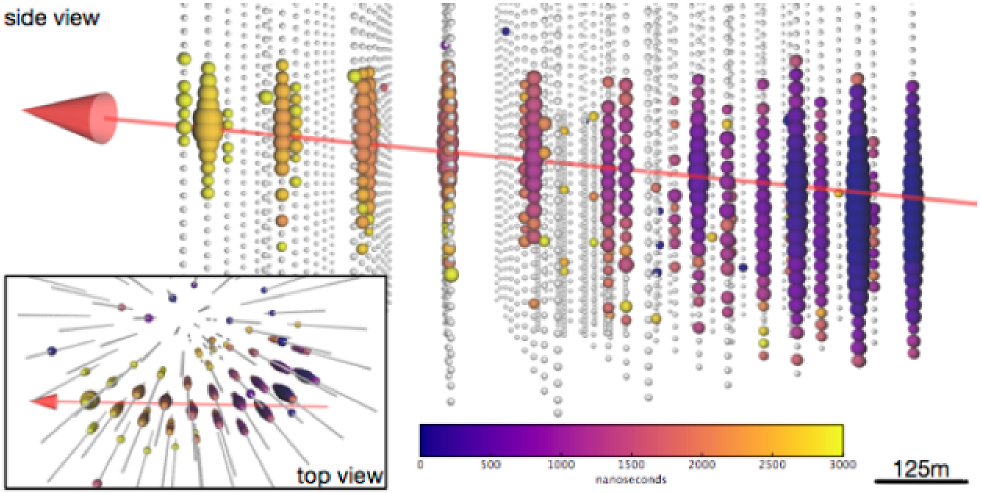
Lu Lu for IceCube



Publication in *Science,* 13 July 2018

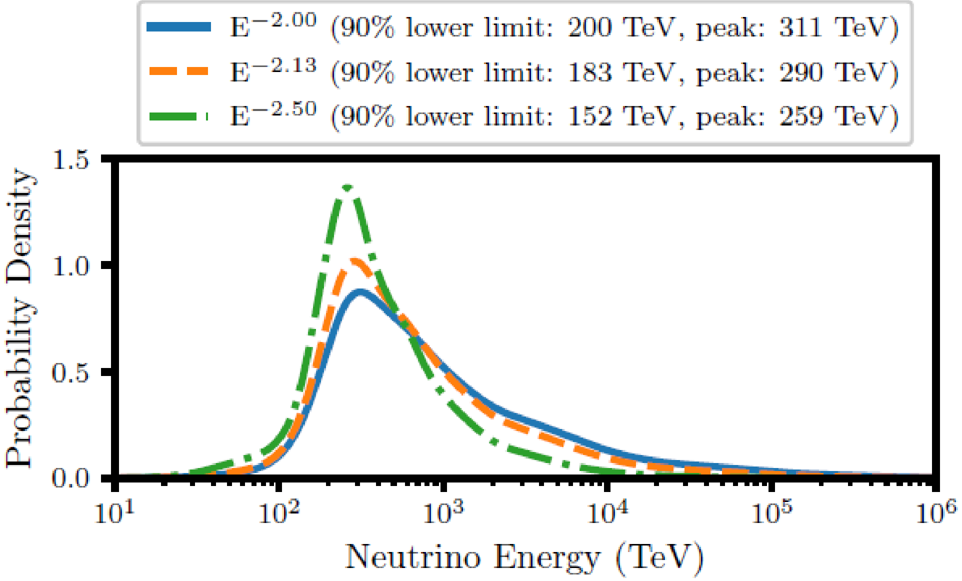
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†



The IceCube Collaboration et al., Science 361, eaat1378 (2018) 13 July 2018

170922 neutrino energy ≈ 300 TeV



- Monte Carlo of ν_μ interaction, μ propagation
- Peak of distribution: 290 TeV with high energy tail
- 90% of area has E > 180 TeV

References

- Malcom S. Longair, “High Energy Astrophysics” Cambridge University Press, 2nd Edition, 1994, two volumes.
- James W. Cronin, “Cosmic rays: the most energetic particles in the universe”, Rev. Mod. Phys, 71 (1999) S165.
- G.B. Thomson, “Observation of the GZK Cutoff by the HiRes Experiment”, arXiv:astro-ph/0609403.
- V. Berezinsky, A. Gazizov, S. Grigorieva, “On astrophysical Solution to Ultrahigh Energy Cosmic Rays”, Phys. Rev. D 74 (2006) 043005.
- John N. Matthews, “Ultra High Energy Cosmic Rays in the North” (HiRes), Talk at CIPANP 2006.
- Michael Prouza, “First Cosmic-ray Grapes Ripen in Argentina” (Pierre Auger Observatory), Talk at CIPANP 2006.

Prospects for Observing Cosmic Neutrino Background

- Properties of the cosmic neutrino background (relic neutrinos)
- Brief review of previous proposed ideas for detection
- Recent development

Expected properties of the (yet unobserved) cosmic neutrino background (CNB) versus the cosmic microwave background (CMB)

	CMB	CNB	Relation
Temperature	2.73K	1.9 K (1.7×10^{-4} ev)	$T_\nu / T_\gamma = (4/11)^{1/3}$ $=0.714$
Decouple time	3.8×10^5 years	~ 1 sec	
Density	~ 411 / cm^3	~ 56 / cm^3 (per flavor, $n_\nu = n_{\nu\text{-bar}}$)	$n_\nu = (3/22)\, n_\gamma$

- CNB took a snapshot of the Universe at a much earlier epoch than CMB n_ν
- Since $\Delta m_{21}^2 = (8.0 \pm 0.3) \times 10^{-5}$ ev^2, and $|\Delta m_{32}^2| = (1.9 \rightarrow 3.0) \times 10^{-3}$ ev^2, at least two of the three neutrinos have masses higher than 10^{-2} ev, and these two types of CNB are non-relativistic ($\beta \ll 1$)

Non-standard cosmic neutrino background

- In inflationary models, CNB density depends on the "reheating temperature" T_R :

  $T_R \geq 8\text{MeV} \Rightarrow n_\nu$ agrees with standard prediction

  $T_R = 5\text{MeV} \Rightarrow n_\nu$ drops to ~90% of the standard prediction

  $T_R = 2\text{MeV} \Rightarrow n_\nu$ drops to ~3% of the standard prediction

- Non-standard models allow

  $n(\nu) \neq n(\overline{\nu})$

- Non-standard models also allow

  $n(\nu_e) \neq n(\nu_\mu) \neq n(\nu_\tau)$ at production

  (flavor oscillation would have removed this asymmetry)

Incomplete list of proposed searches for CNB

1) Coherent ν-nucleus scattering (effect of order G_F^2)

(Zeldovich and Khlpov, 1981; Smith and Lewin, 1983; Duda, Gelmini, Nussinov, 2001)

For CNB, $T_\nu \simeq 10^{-4}\,\text{ev}, \quad \lambda_\nu \simeq 2.4\,\text{mm}$

$$\sigma(\nu\text{-nucleon}) \sim \mathrm{G}_\mathrm{F}^2 E_\nu^2/\pi \simeq 5\times10^{-63}\,cm^2\,\text{(Relativistic)}$$

$$\sim \mathrm{G}_\mathrm{F}^2 m_\nu^2/\pi \simeq 10^{-56}\left(\frac{m_\nu}{ev}\right)^2 cm^2\,\text{(Non}-\text{Relativistic)}$$

- $\nu-$nucleus coherent scattering $\Rightarrow$ enhancement factor of $\mathrm{A}^2 \approx 10^4$
- coherence over CNB wavelength $\Rightarrow$ enhancement factor of $\sim 10^{20}$

  (coherence over a volume of $(\lambda_\nu)^3$ containing $\sim 10^{20}$ nuclei)

Isotropic CNB flux $\Rightarrow$ net force = 0

From COBE dipole anisotropy $\Rightarrow$ $v_{sun} = 369 \pm 2.5\,\text{km/s}$ (CNB is non-isotropic, just like the dark matter)

$\Rightarrow$ net acceleration due to "neutrino wind" $\sim 10^{-26}\,\text{cm/s}^2$ on grain of size λ_ν

2) “Neutrino Optics” (effect linear in G_F)

(R. Opher, 1974; R. Lewis, 1980)

Total reflection or refraction of CNB on a flat surface

Index of refraction, $n = p'/p$, and $n-1 \sim G_F$

Later, Cabibbo and Maiani showed that

$$\vec{F} \sim G_F \int d^3x \rho_A(x) \vec{\nabla} n_\nu(x)$$

Effect is only due to the gradient of $n_\nu(x)$,

and again negligible

3) Torque exerted on a polarized target (effect linear in G_F)

(Stodolsky, 1974)

For a polarized target (magnetized iron), there is an energy split of the two spin states of electron in the sea of the CNB

The split is proportional to $n_\nu - n_{\bar{\nu}}$

(no effect for $n_\nu = n_{\bar{\nu}}$)

4) Astrophysical search with ultra-high energy neutrinos (Z-resonance)

(T. Weiler, 1982, 1999)

$\nu + \overline{\nu} \rightarrow Z^0$ resonance formation from interaction of ultra-high energy incident neutrinos with CNB

$$E_\nu^{res} = \frac{m_Z^2}{2m_\nu} = 4.2\times10^{21}\left(\frac{1\text{ev}}{m_\nu}\right)\text{ev}$$

(Energy depends on the rest masses of neutrinos)

$$\sigma(\nu + \overline{\nu} \rightarrow Z^0) \simeq 4\times10^{-32}\,cm^2$$

Signatures:

a) Dip in the UHE neutrino energy spectrum at energy $E_\nu \geq 10^{22}$ ev (A possible dip in UHE proton could also come from $p + \overline{\nu}_e \rightarrow e^+ + n$, see W. Hwang and B.Q. Ma, astro-ph/0502377)

b) "Z-burst"

Observation of UHE p, n, γ, and ν from decay of Z^0

However, sources of UHE neutrinos with $E_\nu \geq 10^{22}$ ev might not exist.

5) Capture of CNB on radioactive nuclei

A very old idea: S. Weinberg, 1962

Consider tritium beta-decay:

$$a)\ {}^3H \to {}^3He + e^- + \bar{\nu}_e$$

This is a 3-body β-decay with Q-value of

$$Q_a = M({}^3H) - M({}^3He) - M(e^-) - M(\bar{\nu}_e)$$

where $M(x)$ refers to mass of particle x

Now consider the CNB capture reaction:

$$b)\ \nu_e + {}^3H \to {}^3He + e^-$$

This is a 2-body reaction with the Q-value of

$$Q_b = M(\nu_e) + M({}^3H) - M({}^3He) - M(e^-)$$

It follows that

$$Q_b = Q_a + 2M(\nu)$$

5) Capture of CNB on radioactive nuclei (continued)

For massless neutrinos, $M(\nu) = 0$, and we have

$$Q_a = Q_b$$

Note that the conventional definition of Q-value for the β-decay, Q_β, assumes $M(\nu) = 0$, hence

$$Q_\beta = Q_a + M(\nu)$$

The maximal energy for electrons from the

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

β-decay is the end-point energy (ignoring recoil energy)

$$T_a = Q_a = Q_\beta - M(\nu)$$

Electrons from CNB capture reaction are mono-energetic:

$$T_b = Q_b = Q_\beta + M(\nu)$$

(Q_β = 18.6 KeV for tritium β-decay)

It follows that

$$T_b = T_a + 2M(\nu)$$

5) Capture of CNB on radioactive nuclei (continued)

To check the feasibility of separating the CNB capture peak from the end-point, one need to consider

- Neutrino masses
- Experimental energy resolution
- Any local clustering of CNB due to gravity?
- Capture cross section on radioactive nuclei
- Size of the tritium source

Capture rate per tritium atom:

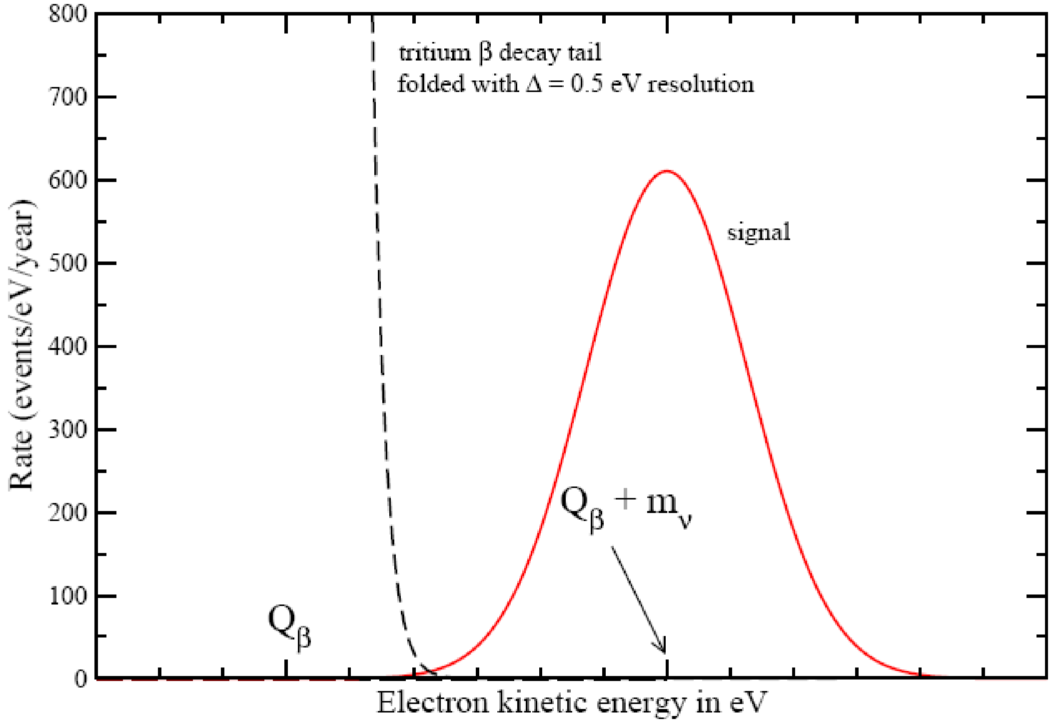
$$R = \sigma \times v_\nu \times n_\nu \simeq 10^{-32} / s$$

Note that for exothermal reaction, $\sigma \times v_\nu$ is constant for small v_ν

$$(\sigma \times v_\nu \simeq 7.6 \times 10^{-45} cm^2 \cdot c)$$

5) Capture of CNB on radioactive nuclei (continued)

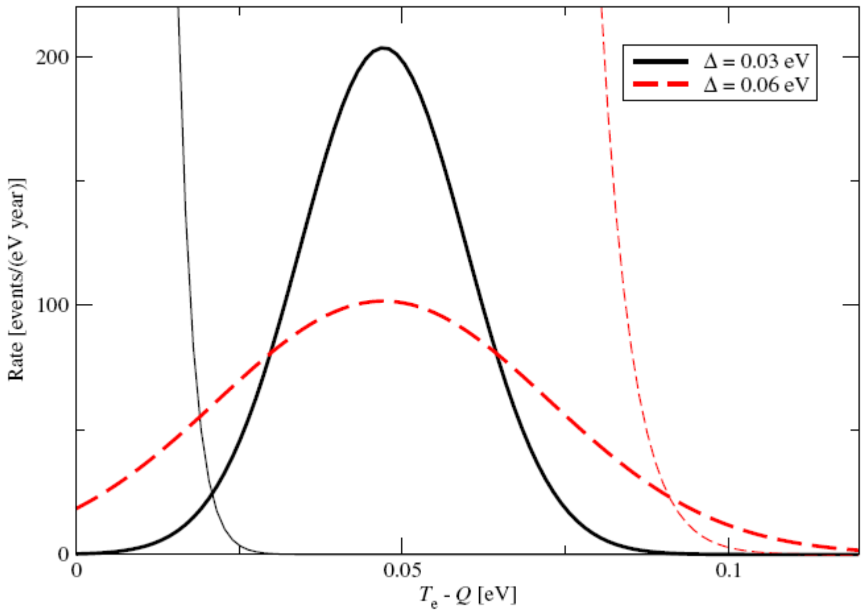
- Neutrino masses: $M(\nu)$=1ev (mass degeneracy of three neutrinos)
- Experimental energy resolution : Δ=0.5ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu > = 50$
- Size of the tritium source: 100 grams



Lazauskas, Vogel, Volpe, J. Phys. G. 35 (2008) 025001

5) Capture of CNB on radioactive nuclei (continued)

- Neutrino masses: $M(\nu)$=0 ev (for the lightest neutrino, assuming inverted mass hierarchy, the other two massive neutrinos are nearly degenerate)
- Experimental energy resolution : Δ=0.03 (0.06) ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu >= 1$
- Size of the tritium source: 100 grams



M. Blennow, Phys. Rev. D 77 (2008) 113014

Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

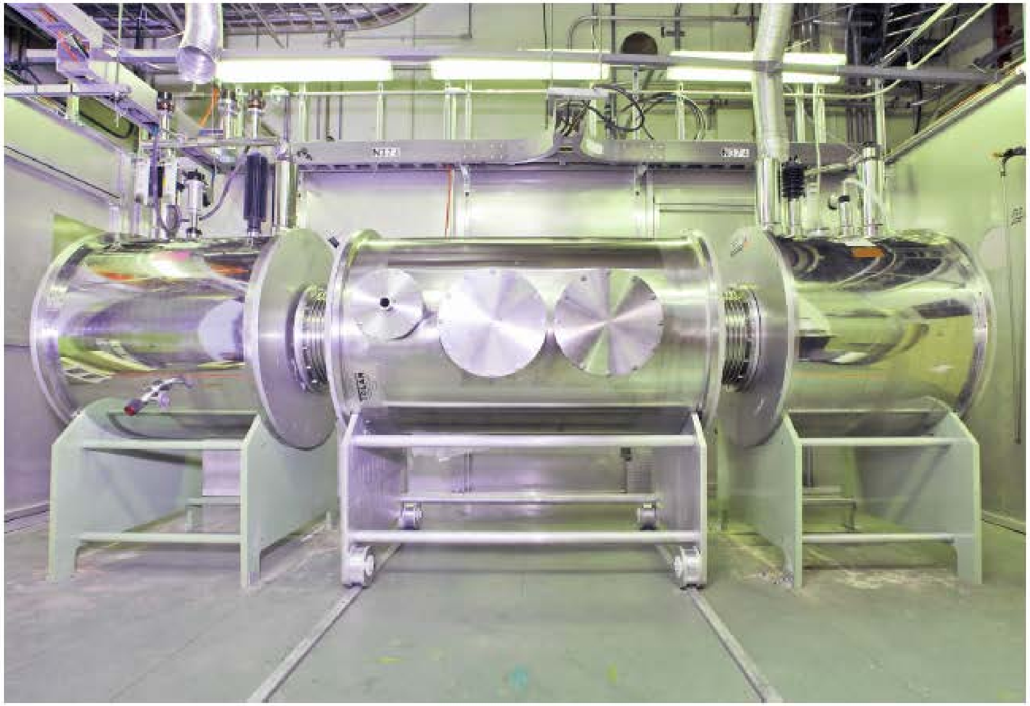


Figure 2: The small-scale PTOLEMY prototype installed at the Princeton Plasma Physics Laboratory (February 2013). Two horizontal bore NMR magnets are positioned on either side of a MAC-E filter vacuum tank. The tritium target plate is placed in the left magnet in a 3.35T field, and the RF tracking system is placed in a high uniformity 1.9T field in the bore of the right magnet with a windowless APD detector and in-vacuum readout electronics.

5) Capture of CNB on radioactive nuclei (continued)

- Is there a way to INCREASE the energy separation between the electrons from the β-decay background and the CNB capture signals?
- How about boosting the momentum of the tritium relative to the sea of CNB? (by accelerating the tritium)?
- Now consider a tritium accelerated to an energy corresponding to $E({}^3H)/m({}^3H)=\gamma$. It is simple to show that in the center-of-mass frame of ${}^3H+\nu$, the total energy is equal to $\sqrt{s}=m({}^3H)+\gamma\cdot m(\nu)$
- This means that electron emitted from the CNB capture would have an energy larger by $\gamma\cdot m(\nu)$ relative to case when a tritium is at rest.
- On the other hand, electrons from the tritium β-decay would still have the same end-point energy in the tritium rest frame.
- This implies the separation between the energy of CNB capture electron and β-decay end-point is now increased by an amount $\sim\gamma\cdot m(\nu)$.

5) Capture of CNB on radioactive nuclei (continued)

- We need to boost the electrons back to the lab frame, since the detectors will only measure the electron energy in the lab frame.
- It is interesting that one would gain another important factor for electrons emitted along the direction of the tritium momentum. Consider the Lorentz transformation:

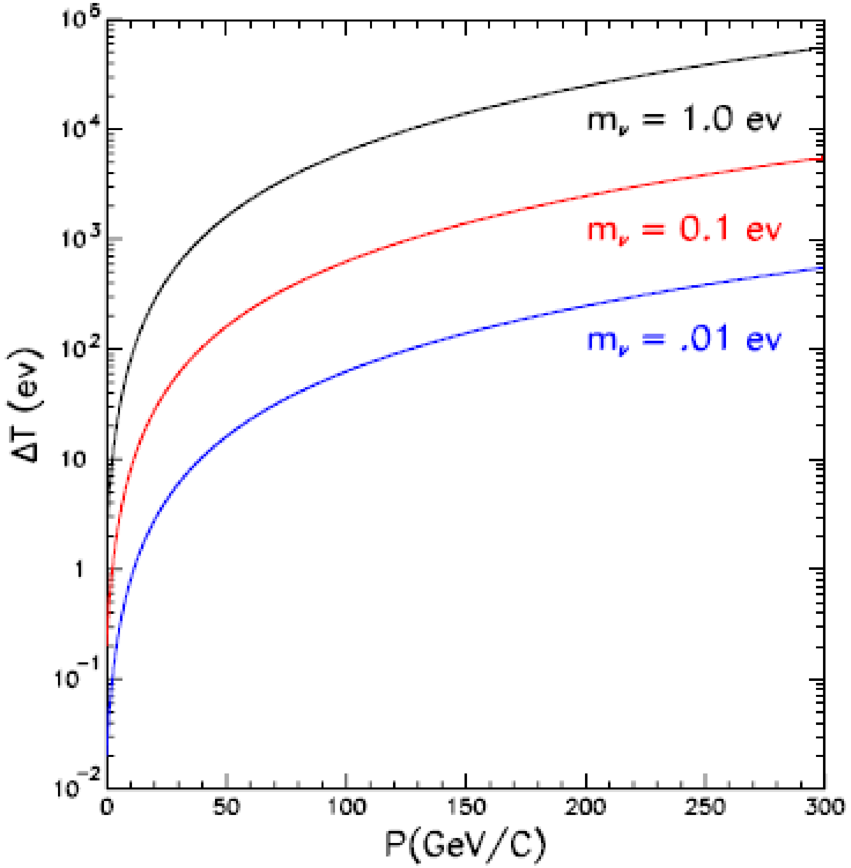
  $E_1' = \gamma E_1 + \beta\gamma P_1; \quad E_2' = \gamma E_2 + \beta\gamma P_2$

  where E and E' are the electron energies in the c.m. frame and the lab frames ,respectively. The subscripts 1 and 2 refer to electrons emitted in the CNB capture and β-decay, rspectively. We have

  $E_1' - E_2' = \gamma(E_1 - E_2) + \beta\gamma(P_1 - P_2) \sim 2\gamma(E_1 - E_2)$ for $\beta \to 1$
- This shows that the energy separation between electrons emitted in the forward angles from the CNB capture and the electrons from the β-decay is further increase by a factor of $\sim 2\gamma$!! This amounts to a separation of $\sim 2(1+\gamma)\gamma m_\nu$ in the relativistic limit.

5) Capture of CNB on radioactive nuclei (continued)

- We have carried out calculations for various neutrino masses over a wide range of tritium momentum:



ΔT is the separation of the kinetic energy for electrons emitted at forward angle from the CNB capture and electrons at end-point from the tritium β-decay.

The figure shows that ΔT becomes very large for high energy tritium beam. Note that P=300 GeV/c can be achieved at the RHIC accelerator.

Summary

- Observation of Cosmic Neutrino Background would have tremendous impact on our knowledge of Universe at the very early stage.
- It would also have important impact on our knowledge on neutrino physics (mass hierarchy, Dirac versus Majorana), as well as developing techniques to detect very low energy neutrinos from other sources (solar, supernova, geo, reactor…).
- Many interesting ideas have been proposed in the past. None of them proved to be viable.
- The recent proposal of “capture on radioactive nuclei” seems promising. More study is required.
- It remains a great challenge to come up with new idea for observing the CNB.

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