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Energy Agency

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SUMMER SCHOOL ON PARTICLE PHYSICS

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Astroparticle Physics - Part 3

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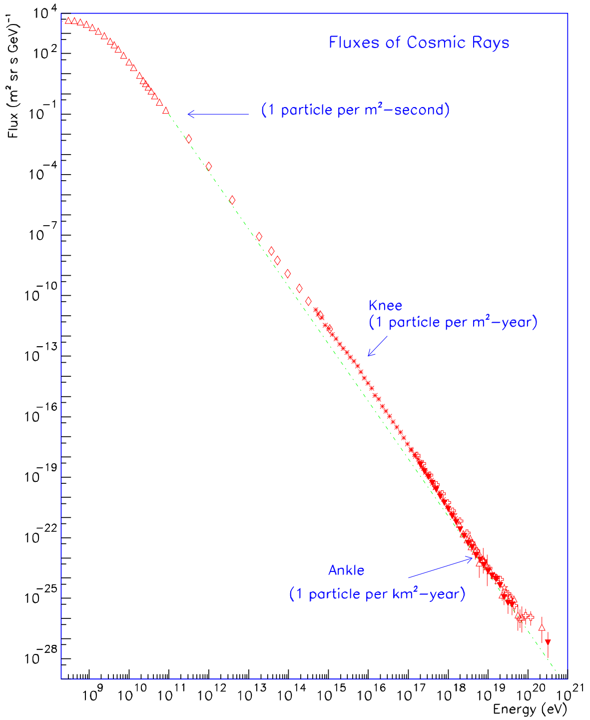
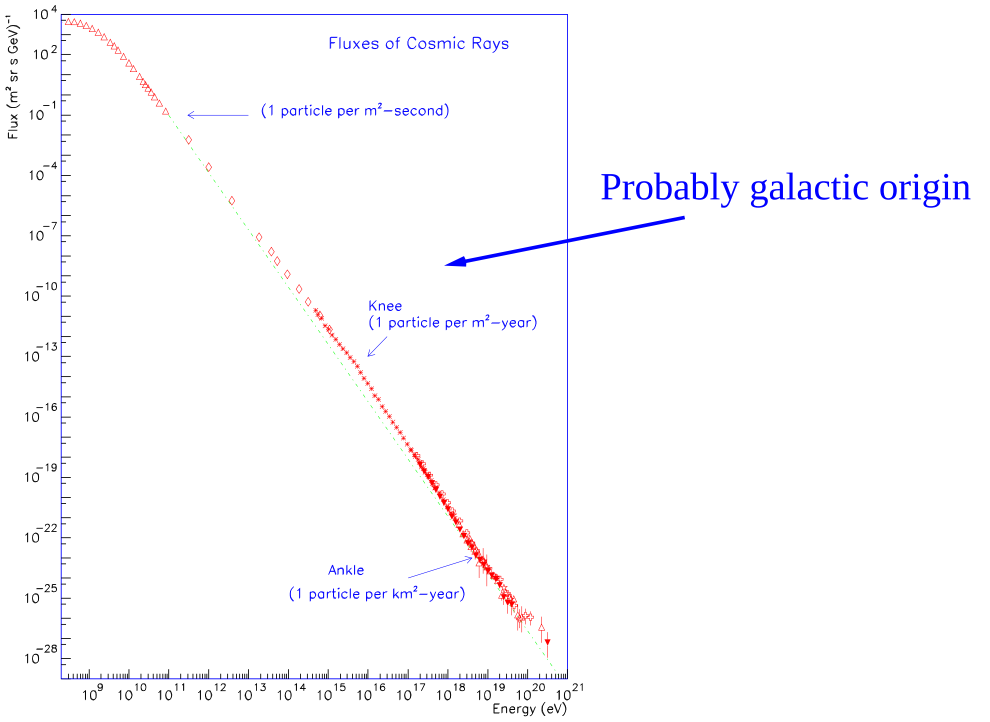
Physics of ultrahigh-energy cosmic rays

- Ultrahigh-energy cosmic rays
- Ultrahigh-energy neutrinos

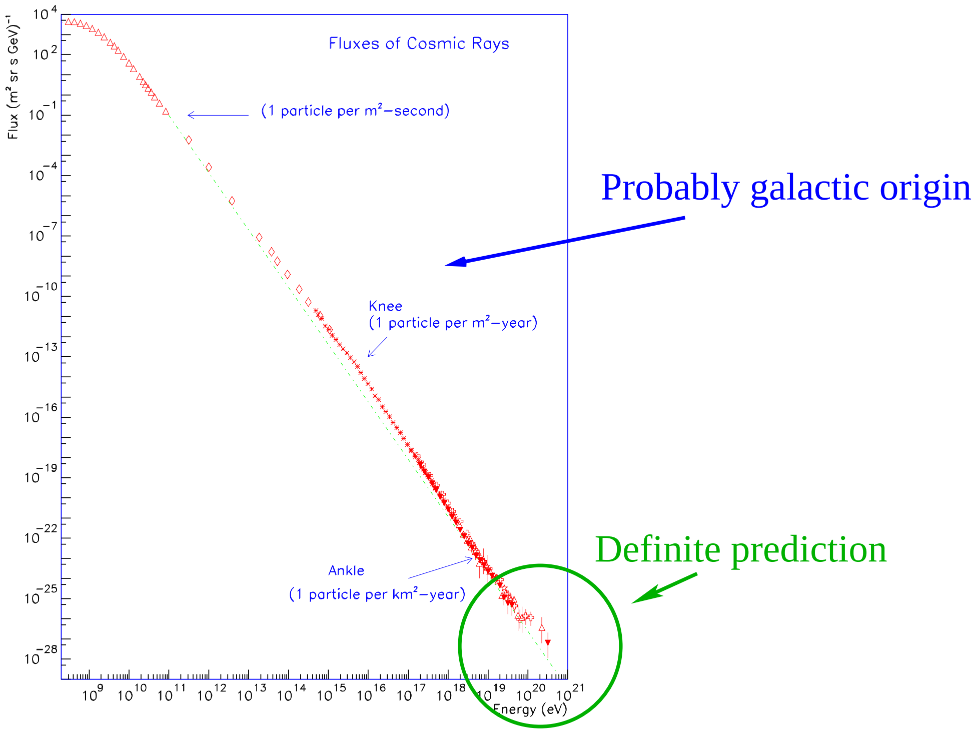
Spectrum of cosmic rays



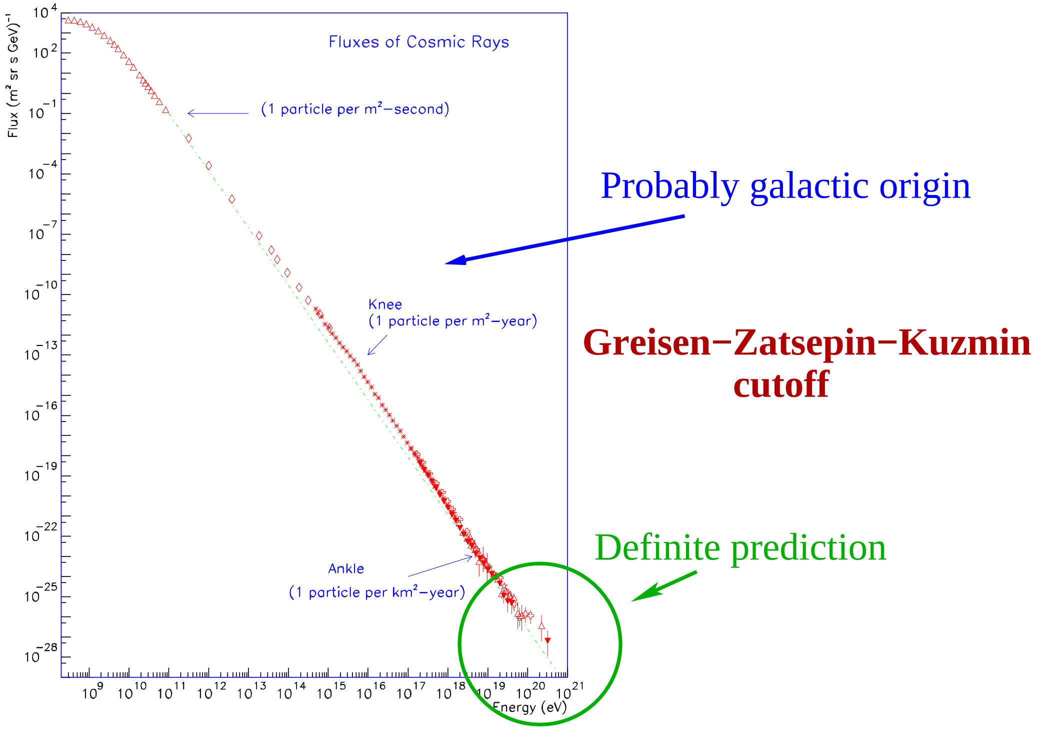
Spectrum of cosmic rays



Spectrum of cosmic rays



Spectrum of cosmic rays



Greisen-Zatsepin-Kuzmin cutoff

Cosmic microwave background radiation has temperature $2.7\text{K} = 10^{-4}\text{eV}$
Protons interact with the CMBR and lose energy to pion photoproduction:

$$p\gamma \longrightarrow n\pi^+, \; p\pi^0$$

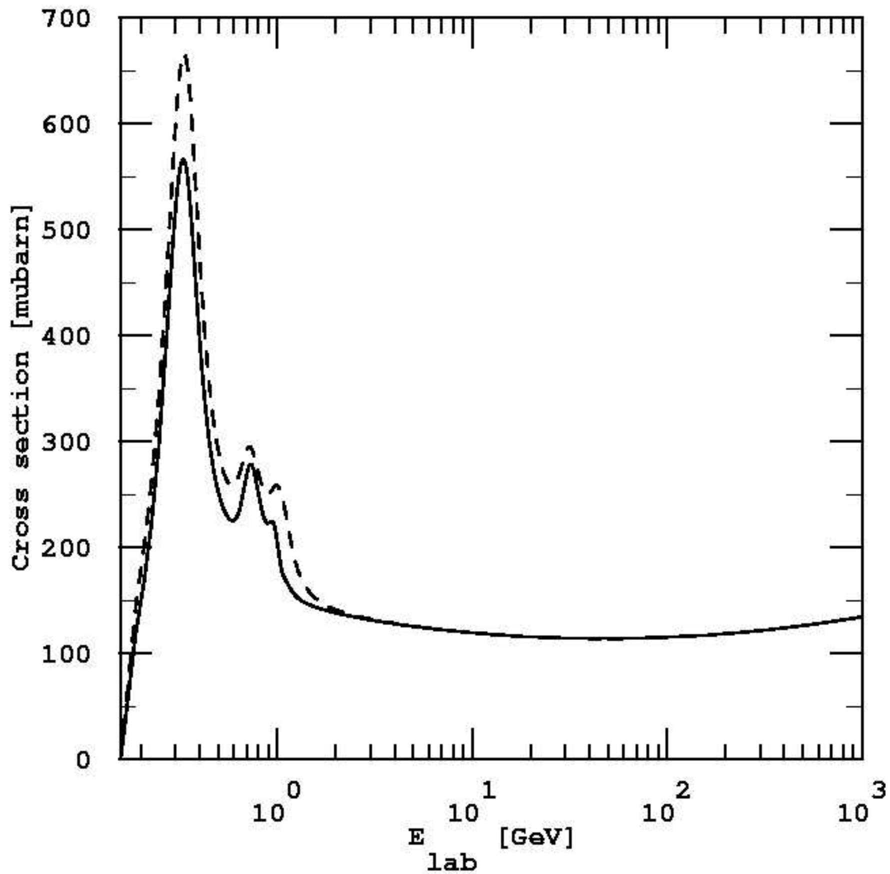
Threshold: $\sqrt{s} = \sqrt{m_p^2 + 2E_\gamma E_p} > m_p + m_\pi$ or

$$E_p > 5 \times 10^{19}\,\text{eV}$$

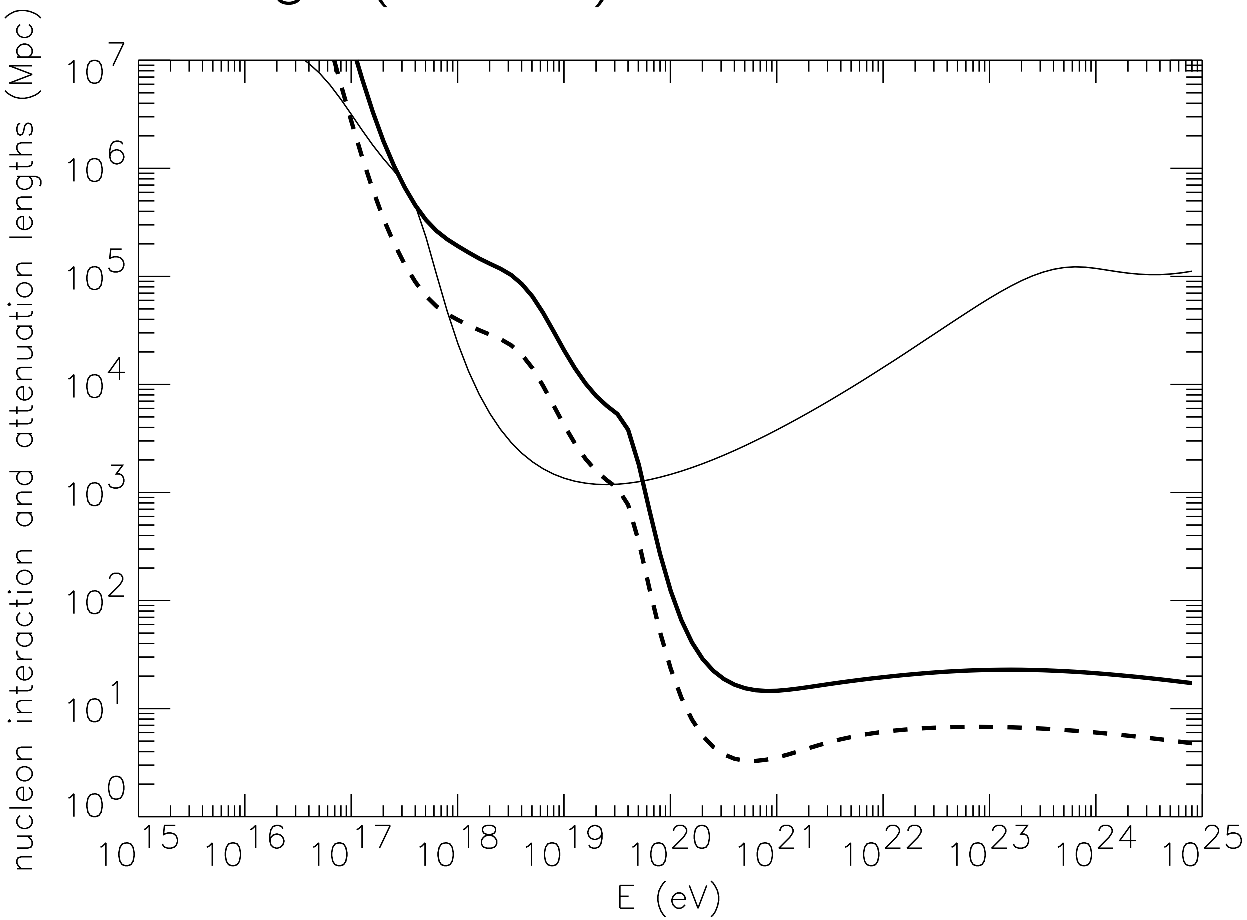
Nucleon loses about 20% of its energy in each interaction Energy attenuation length:

$$R_{\text{GZK}} \sim 50\,\text{Mpc}$$

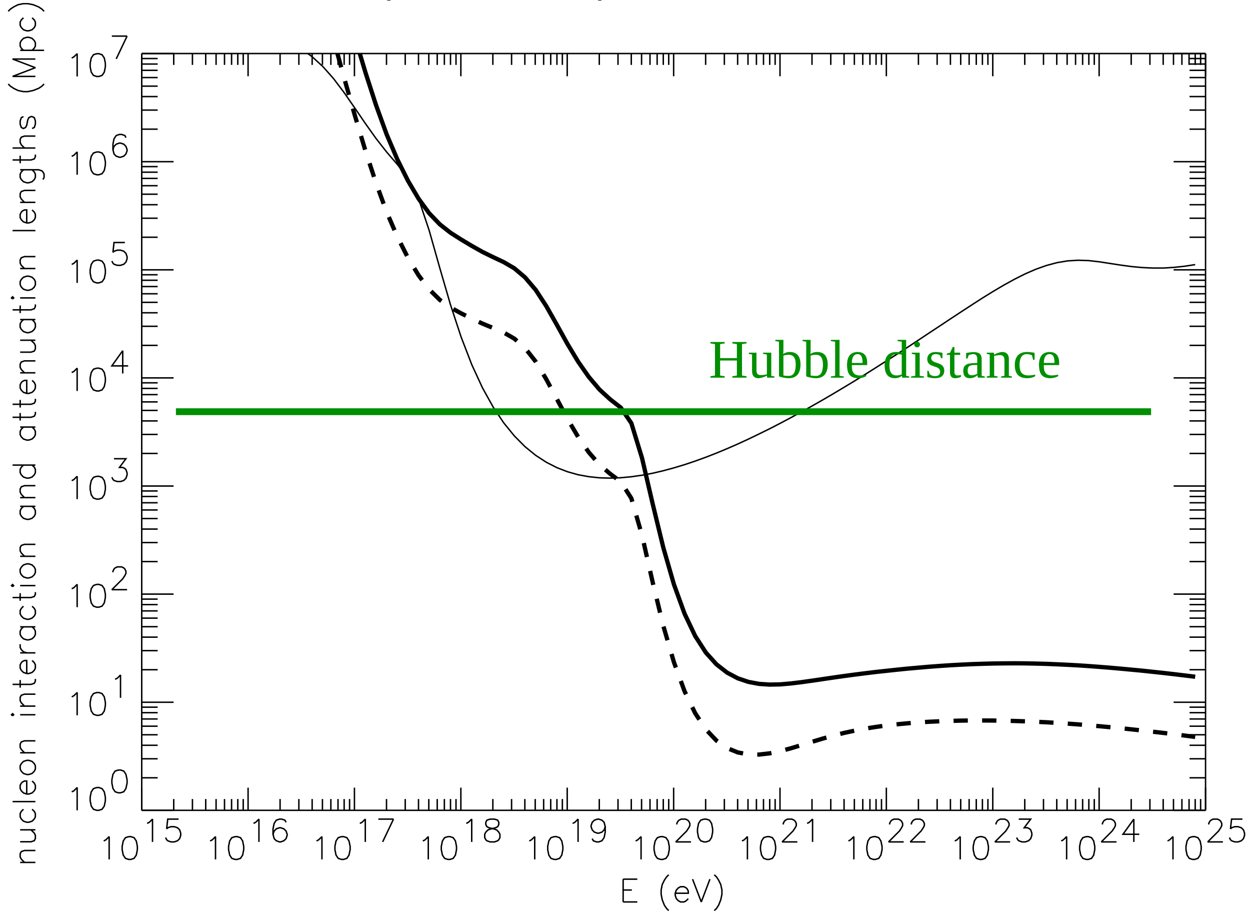
Cross section of $p\gamma \rightarrow N\pi$ rises rapidly at the Δ resonance



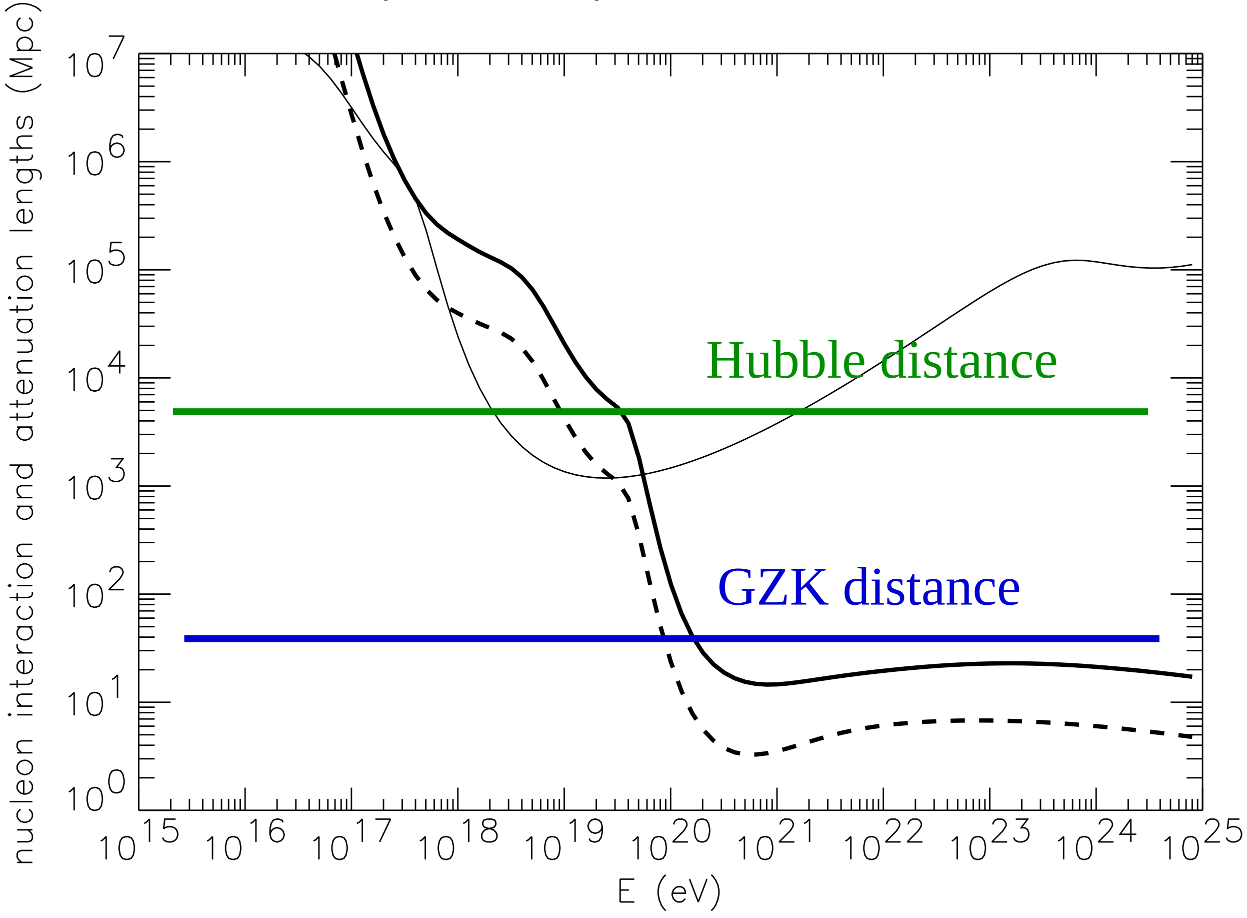
nucleon interaction length (dashed line) and
energy attenuation length (solid line)

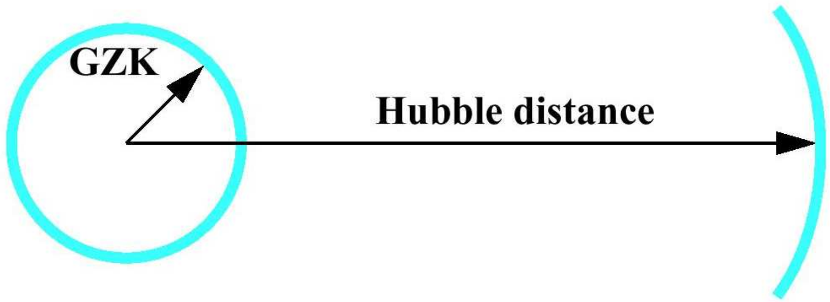


nucleon interaction length (dashed line) and
energy attenuation length (solid line)



nucleon interaction length (dashed line) and
energy attenuation length (solid line)



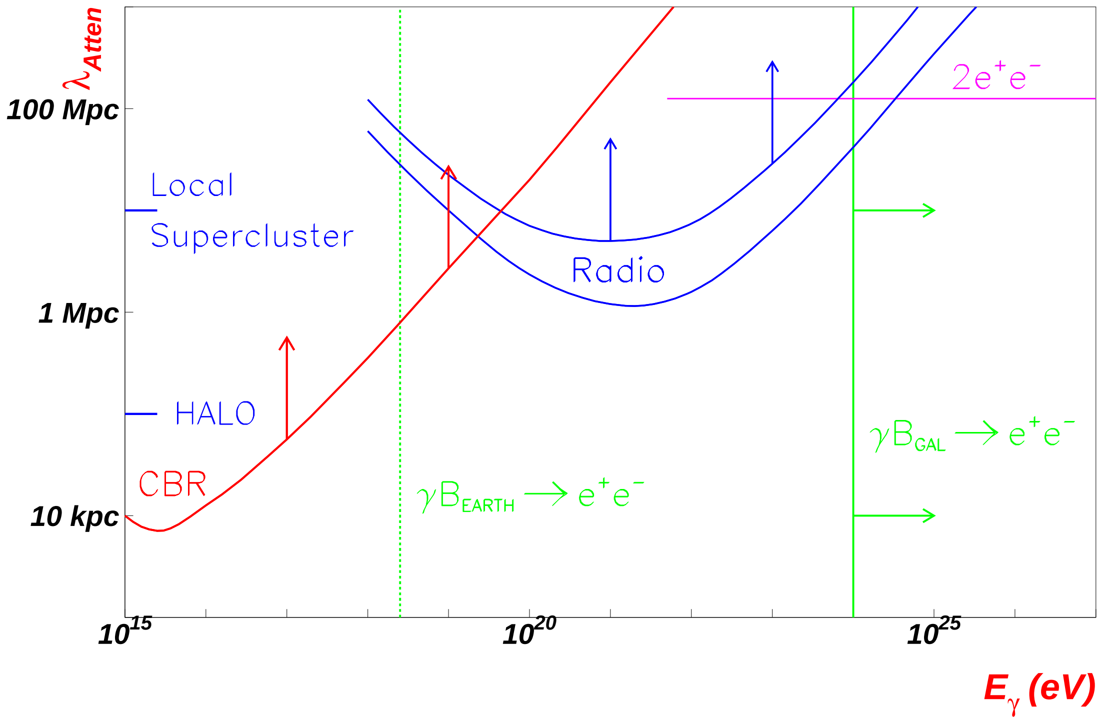


expect a sharp drop in the flux of cosmic rays:

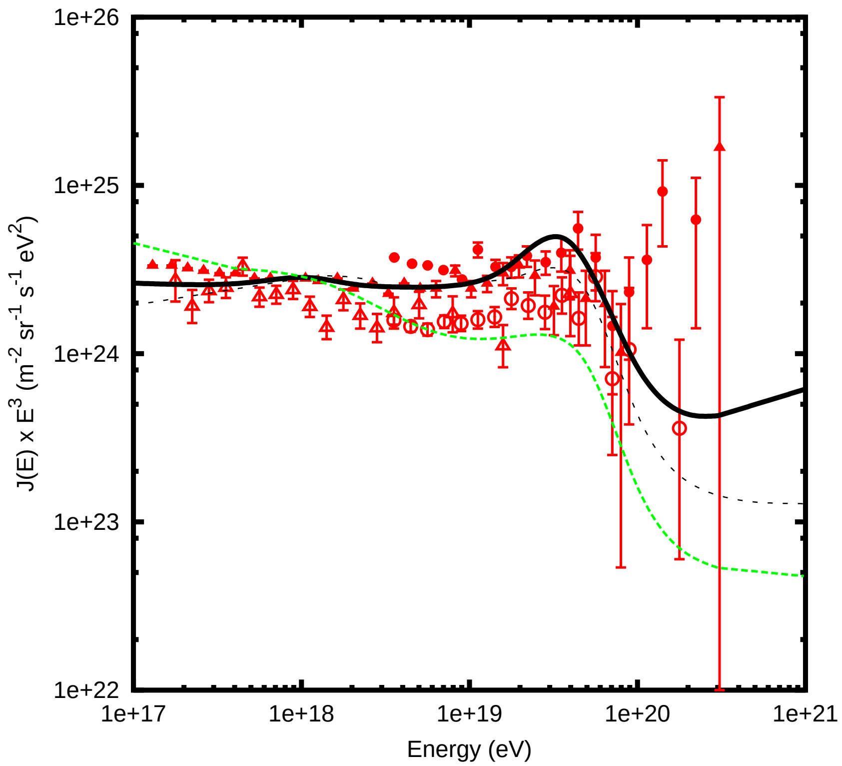
$E < 5 \times 10^{19}\mathrm{eV}$ – should see sources from entire universe

$E > 5 \times 10^{19}\mathrm{eV}$ – should see sources only within 50 Mpc

What about photons?

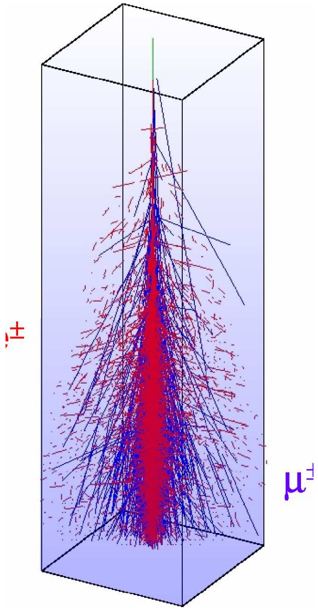


AGASA, HiRes experiments

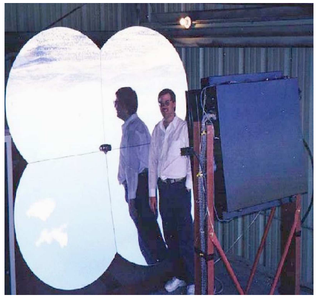


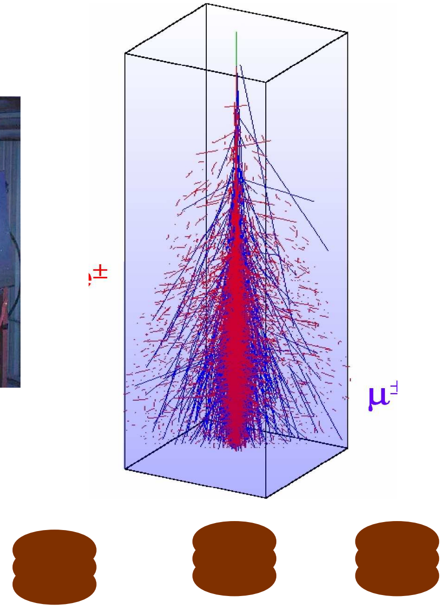
AGASA events beyond the cutoff...

Air showers



Detection techniques

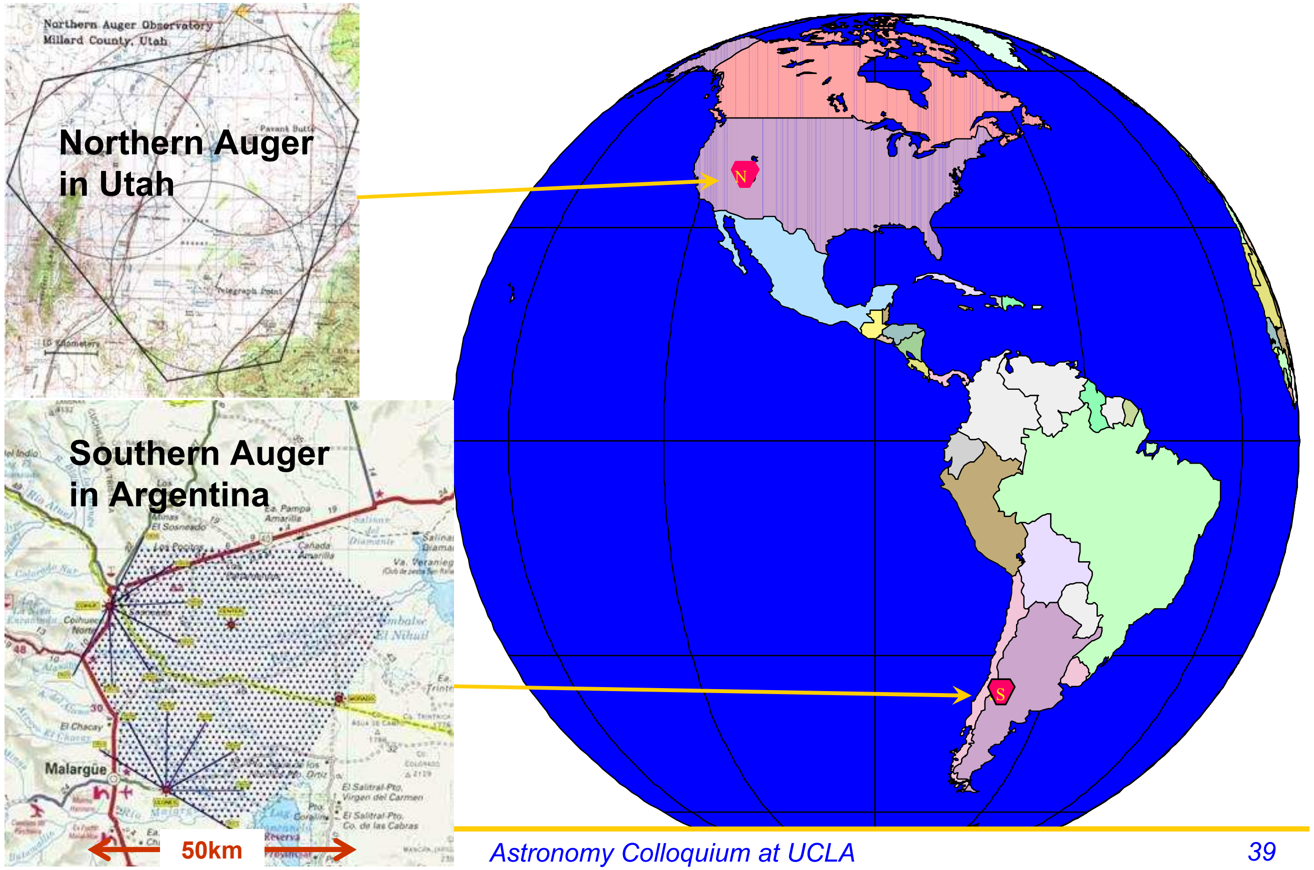


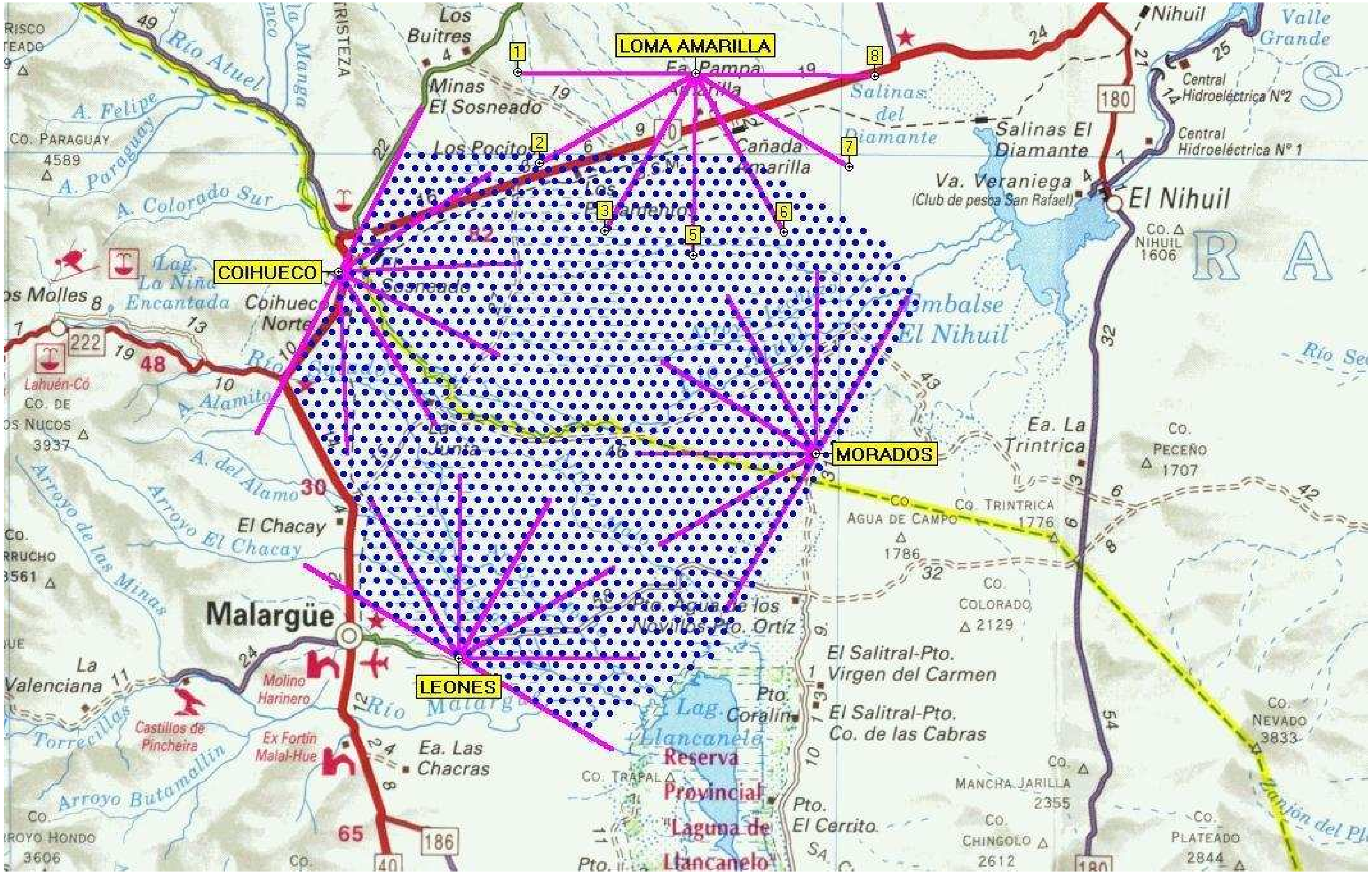


Fluorescent detection: Fly's Eye, Hi Res, EUSO
Surface array: AGASA
Both: Pierre Auger

Pierre Auger

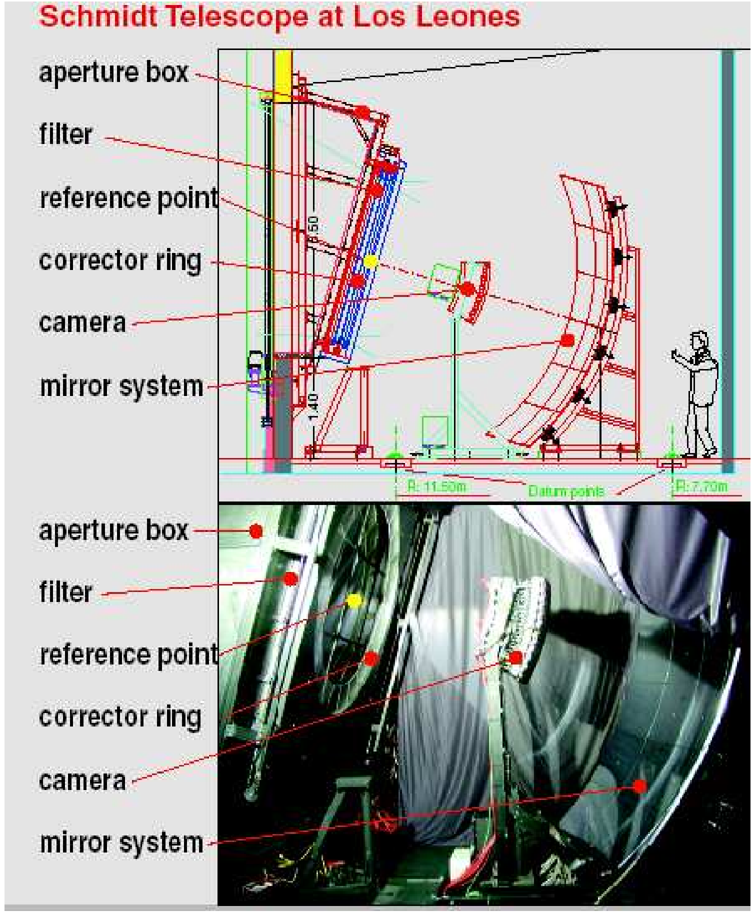
Pierre-Auger Observatory

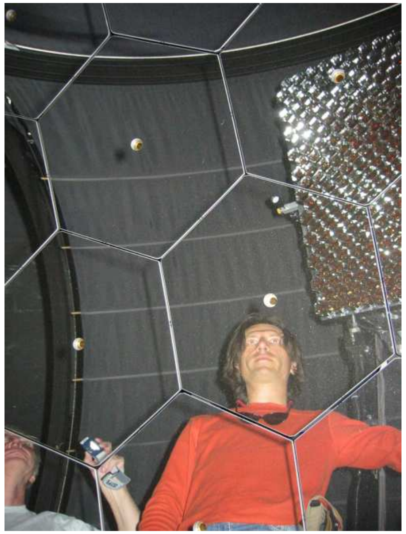



LOMA AMARILLA
COIHUECO
MORADOS
LEONES
1
2
3
4
5
6
7
8
Malargüe
Los Buitres
Minas El Sosneado
Los Pocitos
Cañada Amarilla
Salinas del Diamante
Salinas El Diamante
Va. Veraniega
(Club de pesca San Rafael)
El Nihuil
Central Hidroeléctrica N°2
Central Hidroeléctrica N° 1
Valle Grande
Nihuil
Embalse El Nihuil
Ea. La Trintrica
Co. Peceño 1707
Co. Trintrica 1776
Co. Agua de Campo 1786
Co. Colorado 2129
El Salitral-Pto. Virgen del Carmen
El Salitral-Pto. Co. de las Cabras
Pto. Coralino
Lag. Llancanelo
Reserva Provincial Laguna de Llancanelo
Pto. El Cerrito
Co. Trapal
Co. Mancha Jarilla 2355
Co. Chingolo 2612
Co. Nevado 3833
Co. Plateado 2844
Ea. Las Chacras
Molino Harinero
Ex Fortín Malal-Hue
Castillos de Pincheira
Arroyo Butamallin
Torrecillas
La Valenciana
El Chacay
Arroyo El Chacay
Arroyo de las Minas
A. del Alamo
A. Alamito
Lahuén-Có
Co. Paraguay 4589
A. Paraguay
A. Felipe
A. Colorado Sur
Río Atuel
Lag. La Niña Encantada
Coihueco Norte
Río Malargüe
Río Seco

Water tanks

Fluorescence detector



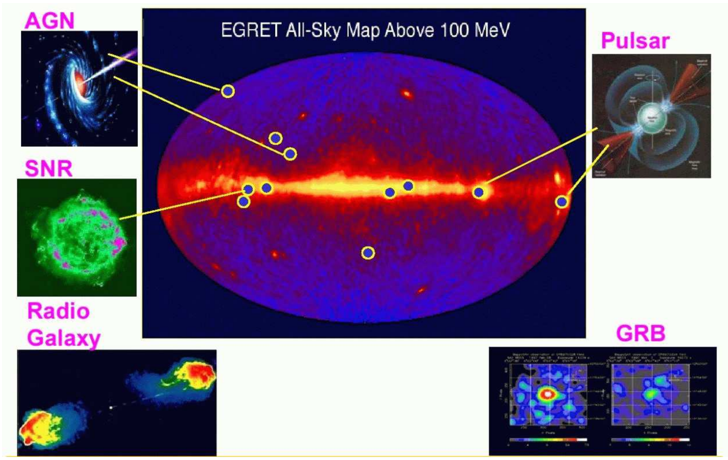


Lidar is used to monitor the atmosphere

The GZK puzzle is two-fold

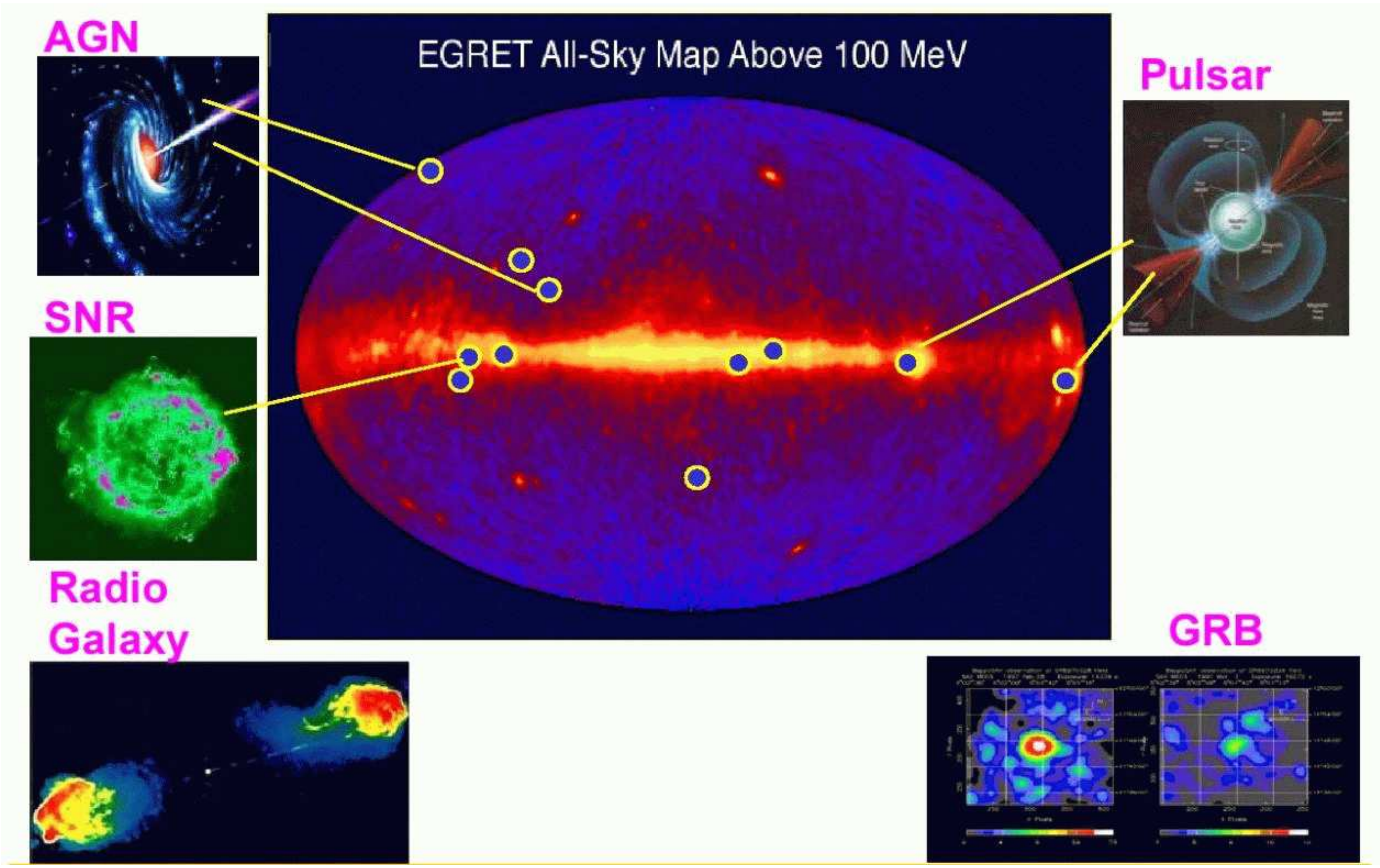
- what are the sources of UHECR?
- Why no GZK cutoff (assuming AGASA results are correct)?

Cosmic accelerators

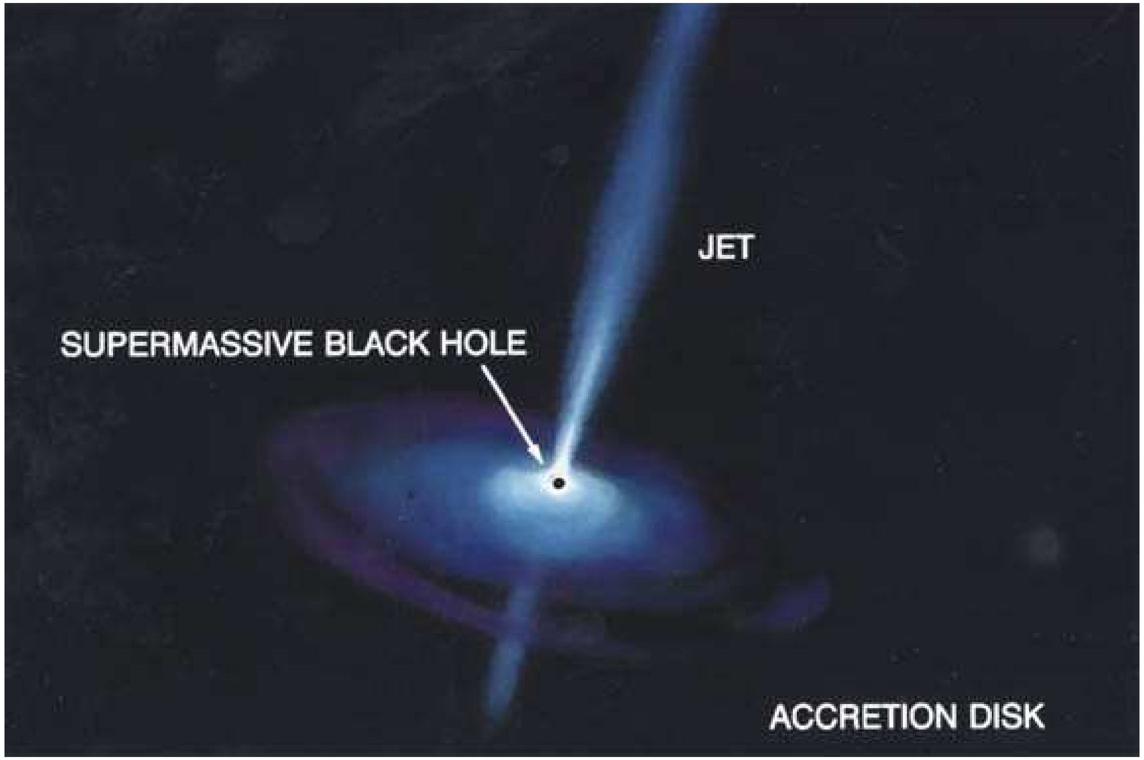


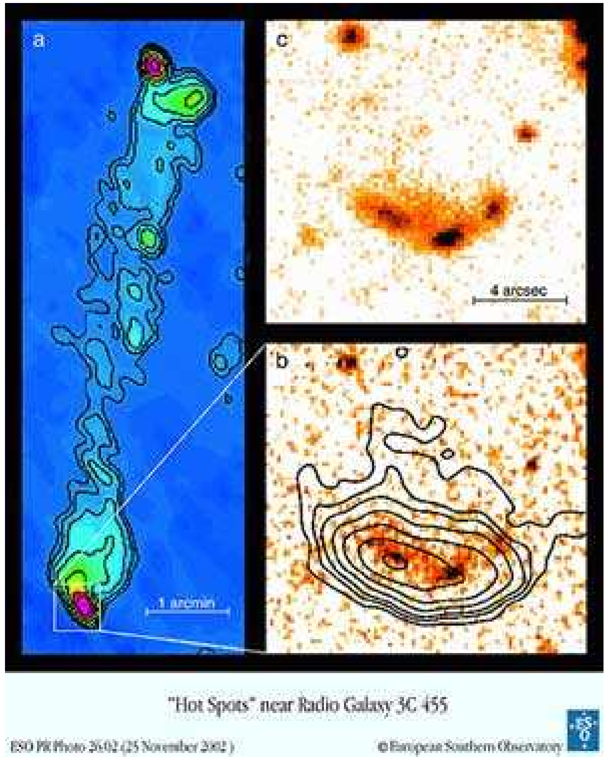
Can accelerate particles to 10^{20} eV ?

Cosmic accelerators

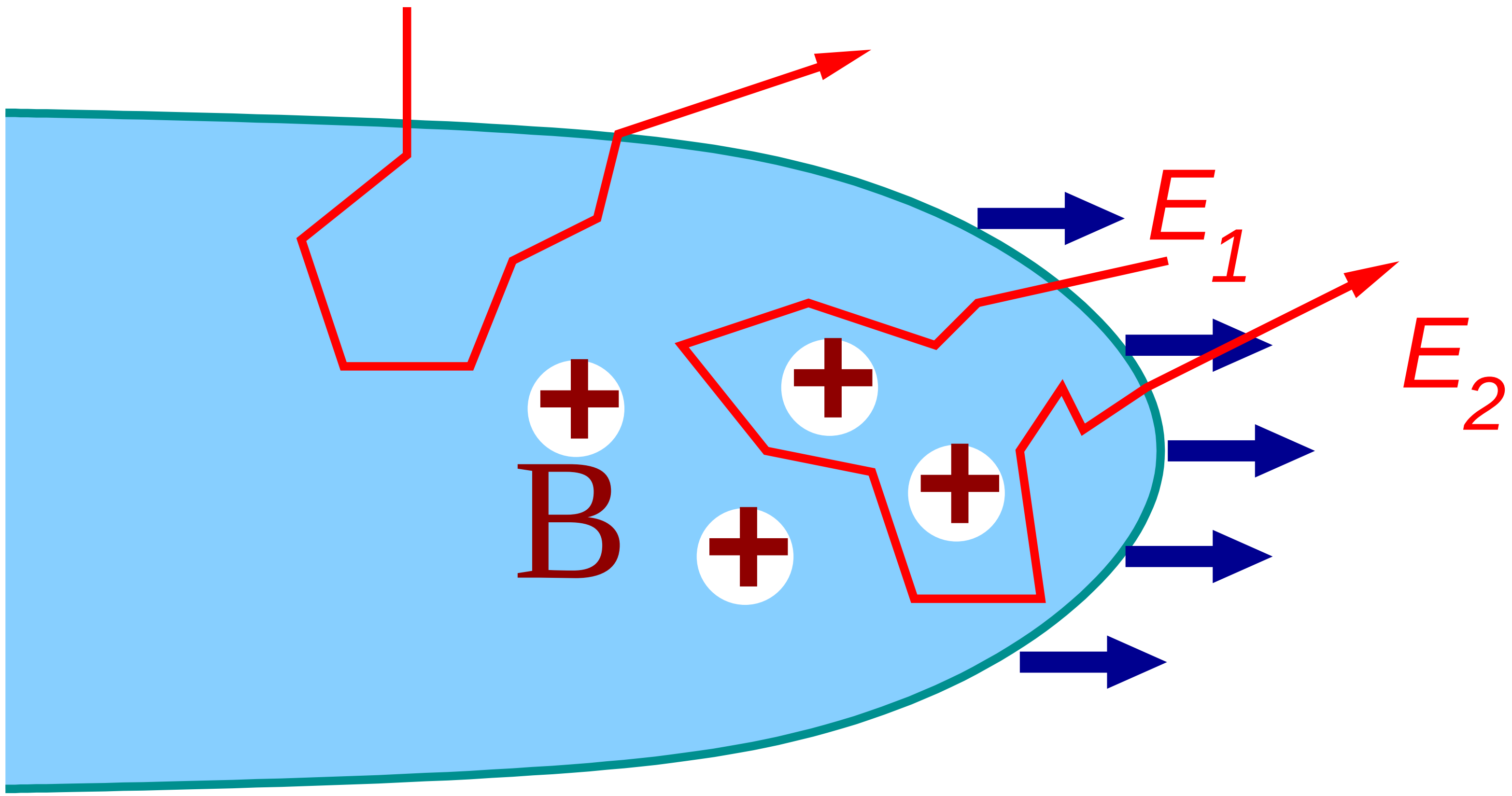


Acceleration in AGN and radio galaxies





Fermi acceleration



New physics?

- Supermassive relic particles
- Topological defects (cosmic strings, *etc.*)
- New exotic particles

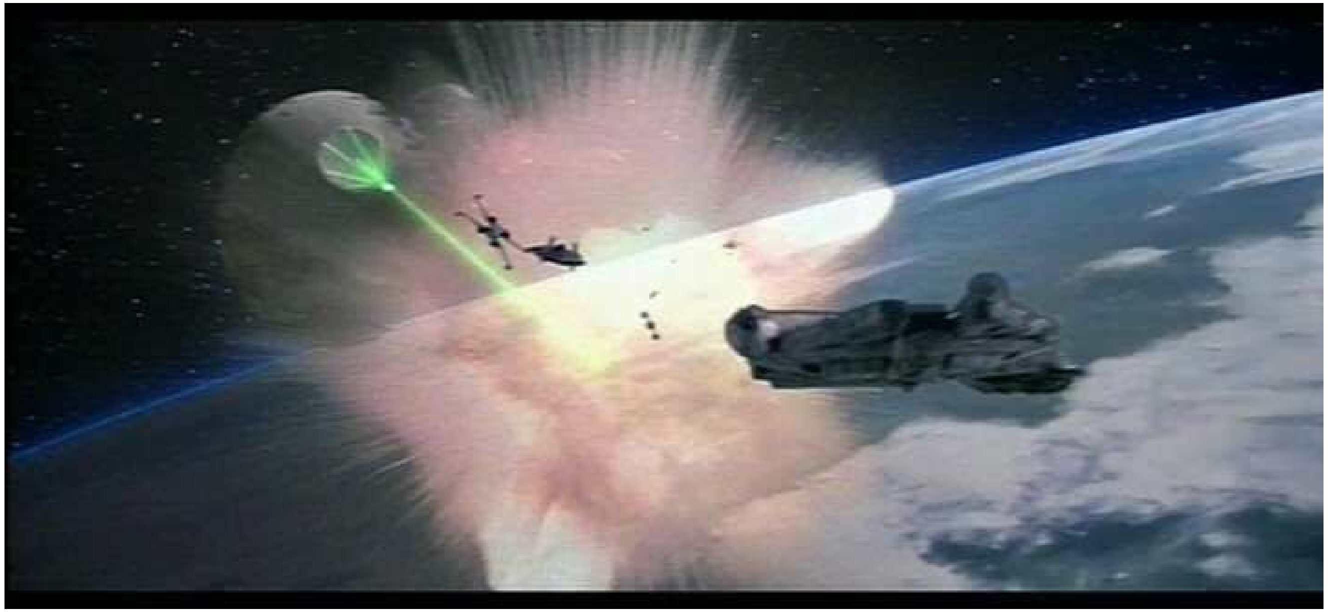
Supermassive relic particles

- Could be copiously produced at the end of inflation, during reheating, from gravity or other interactions at the high scale.

- Can be the dark matter.
  Long lifetime is difficult to explain,
  but models exist [*e.g.*, Kuzmin, Rubakov]

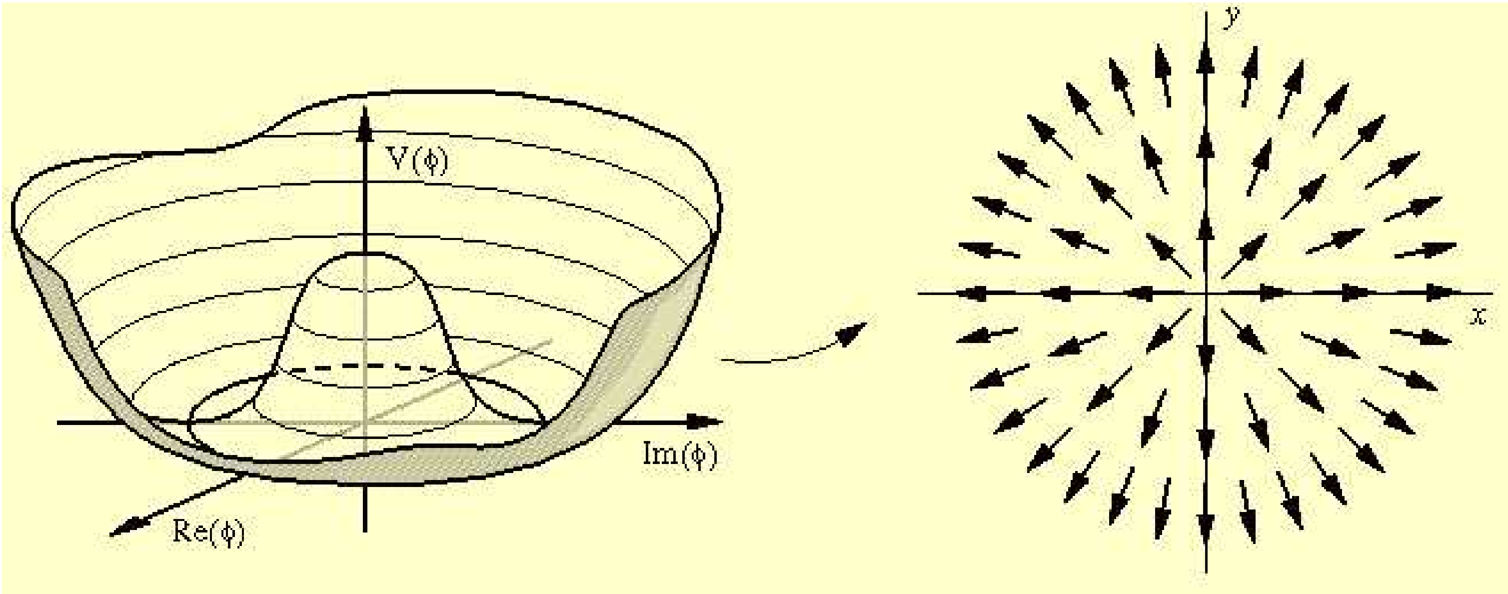
- Decays can produce UHECR in our galactic halo, hence no GZK cutoff

Superheavy dark-matter particles producing UHECR



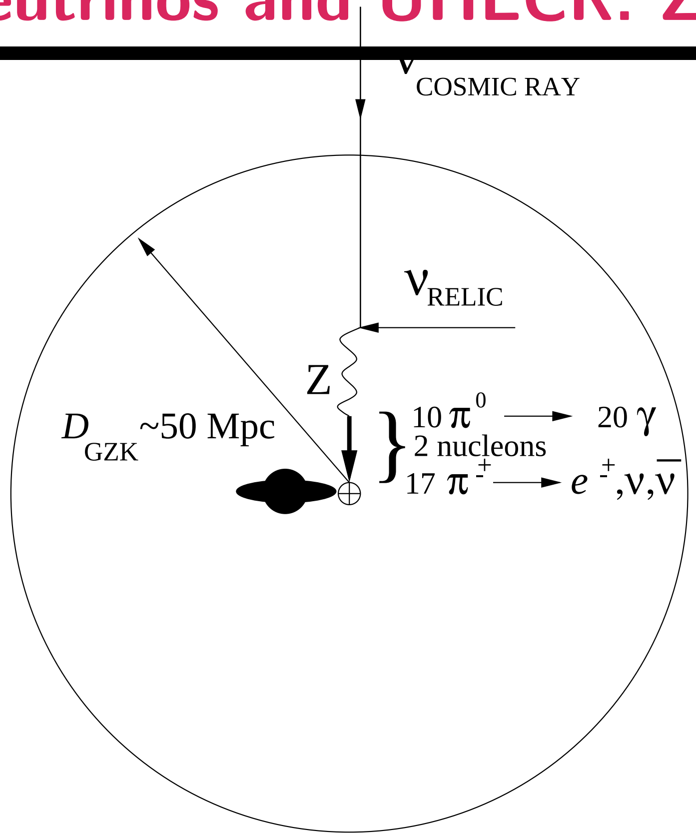
Observational signature: **North-South asymmetry.**

Topological defects



High energy density in the core. Decays can produce high-energy particles. Long lifetimes.

UHE neutrinos and UHECR: Z-bursts



Cross section $\nu\bar{\nu}$ is strongly peaked at Z resonance, where $\mathbf{2E_\nu m_\nu \approx M_Z^2}$.

Z-bursts

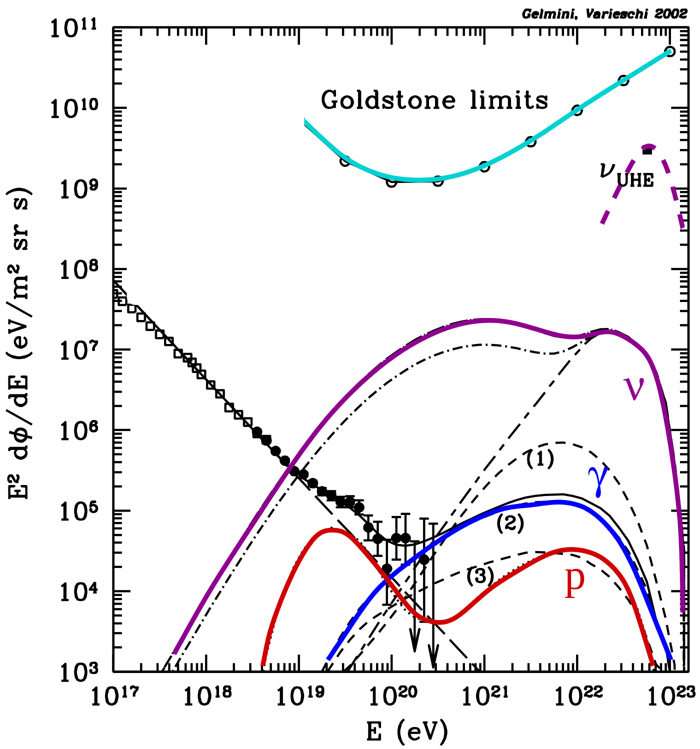
- Can explain the events beyond the Greisen-Zatsepin-Kuzmin cutoff [Weiler]

- the energy scale is *natural*:

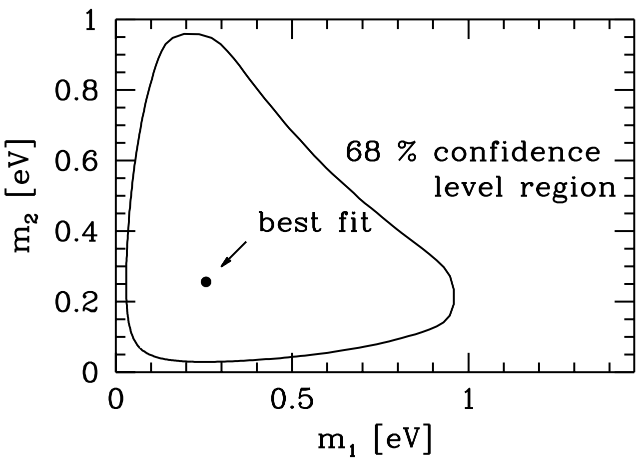
$$E \sim 10^{-2} \frac{M_Z^2}{2m_\nu} \sim 10^{21} \mathrm{eV}$$

- If Z-bursts take place, one can probe the clustering [Chung-Pei Ma] of relic neutrinos and measure their masses [Weiler; Ringwald *et al.*]

UHECR spectrum from Z-bursts



If the Z-burst scenario is right, one can **measure the mass of a relic neutrino**.



[Weiler; Fodor, Katz, Ringwald]

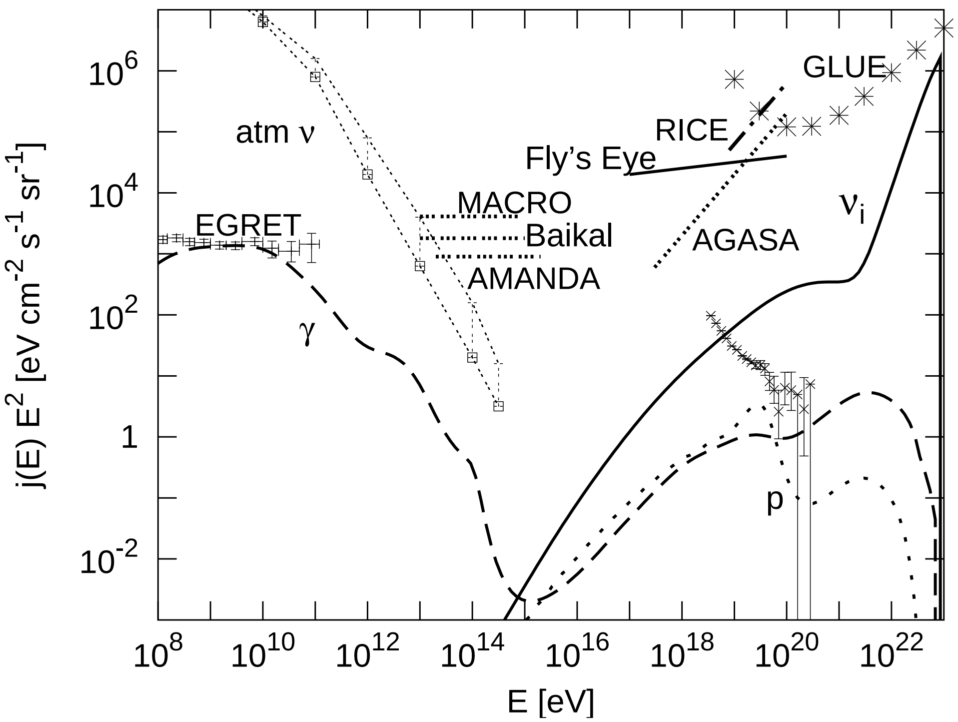
Z-problems

- lack of plausible sources

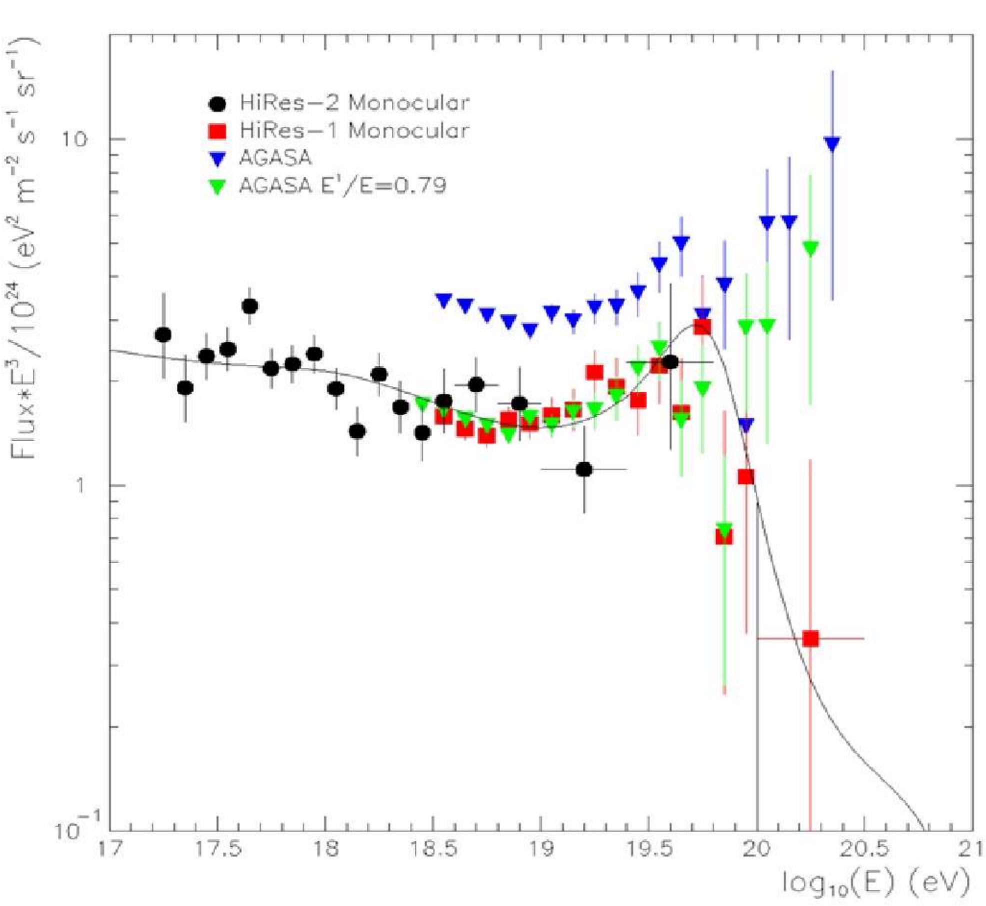
- most proposed sources generate too many GeV photons, in excess of the EGRET bound

An apparently photonless source, a relic particle decaying into neutrinos, may, in fact, produce photons through weak loops that are "strong" at this energy [Berezinsky *et al.*].

The EGRET bound

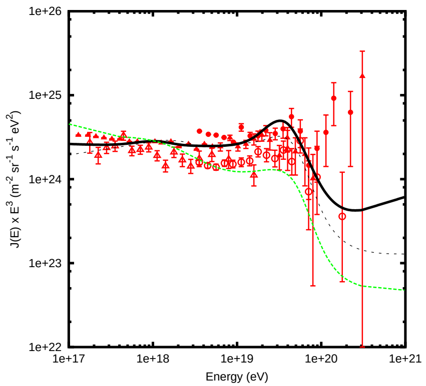


AGASA vs HiRes



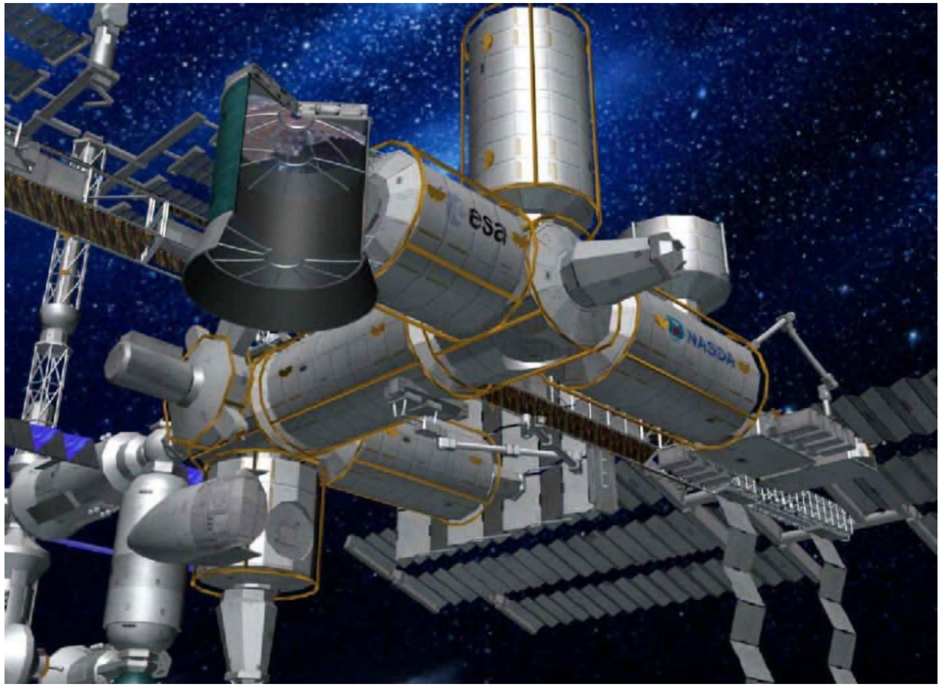
Pierre Auger will clarify the experimental situation

Fitting even HiRes data alone might require exotic nearby sources



However, regardless of whether the GZK cutoff is there, there is great physics one can do with detectors like Pierre Auger and EUSO.

Extreme Universal Space Observatory (EUSO)



EUSO is designed to observe fluorescent air showers initiated by extremely high energy cosmic rays - and neutrinos

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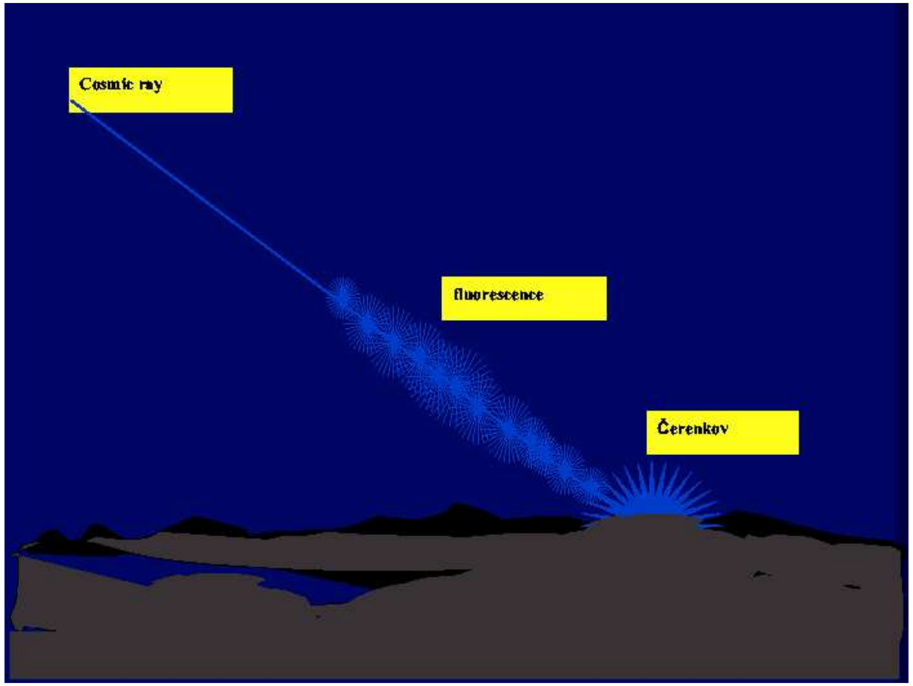
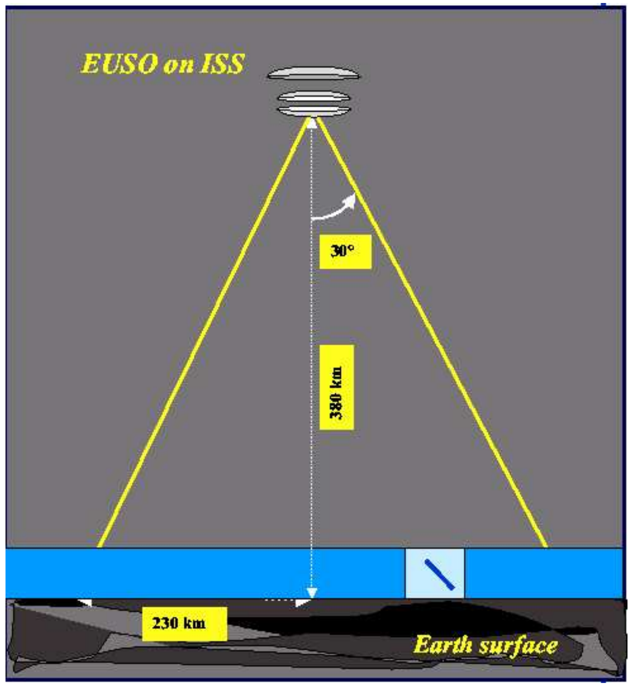




Ultrahigh-energy neutrinos

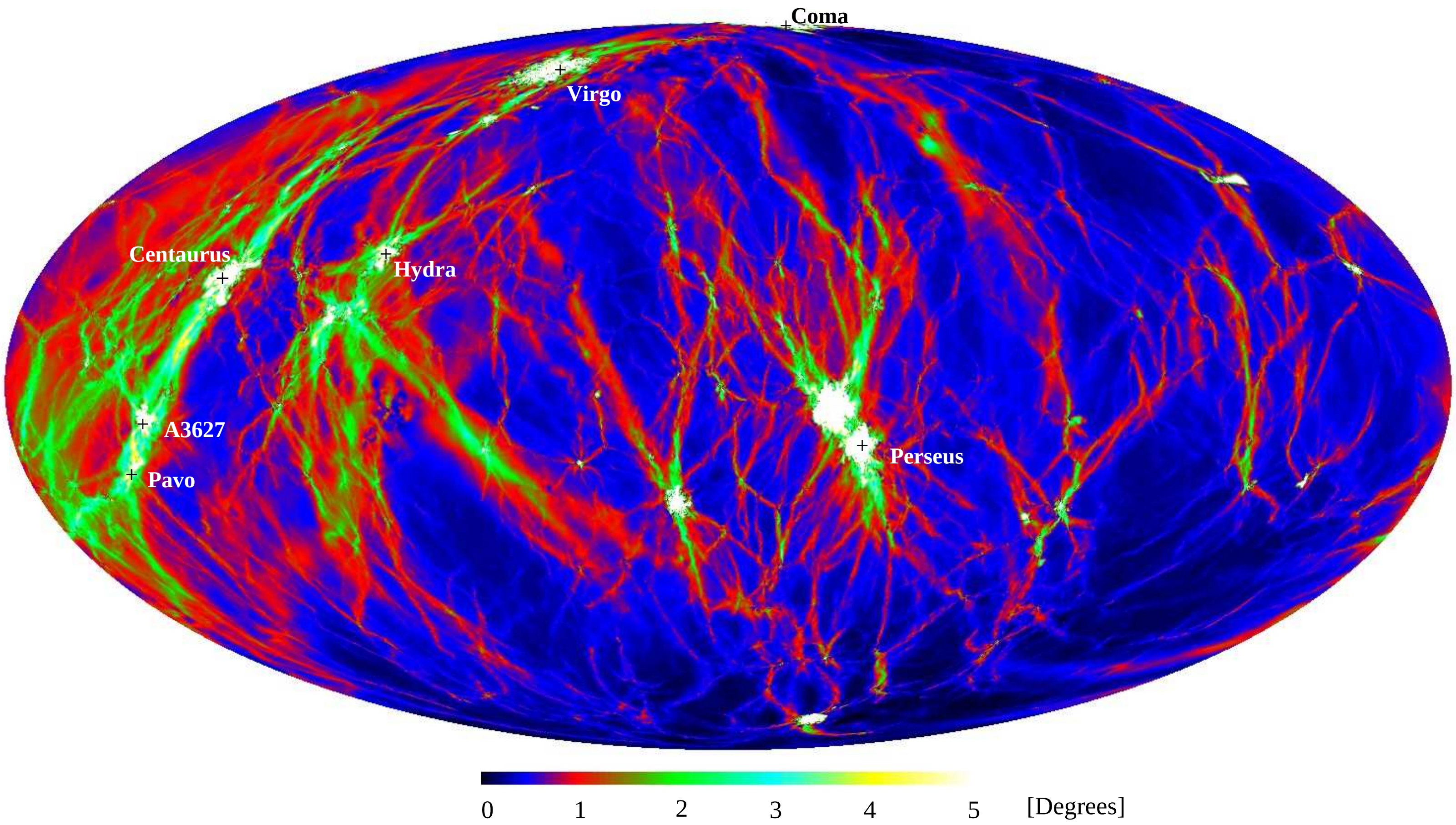
UHE neutrinos are out there!

- Astrophysical sources
- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.
- Additional sources can provide additional flux. (*e.g.* Z-bursts)

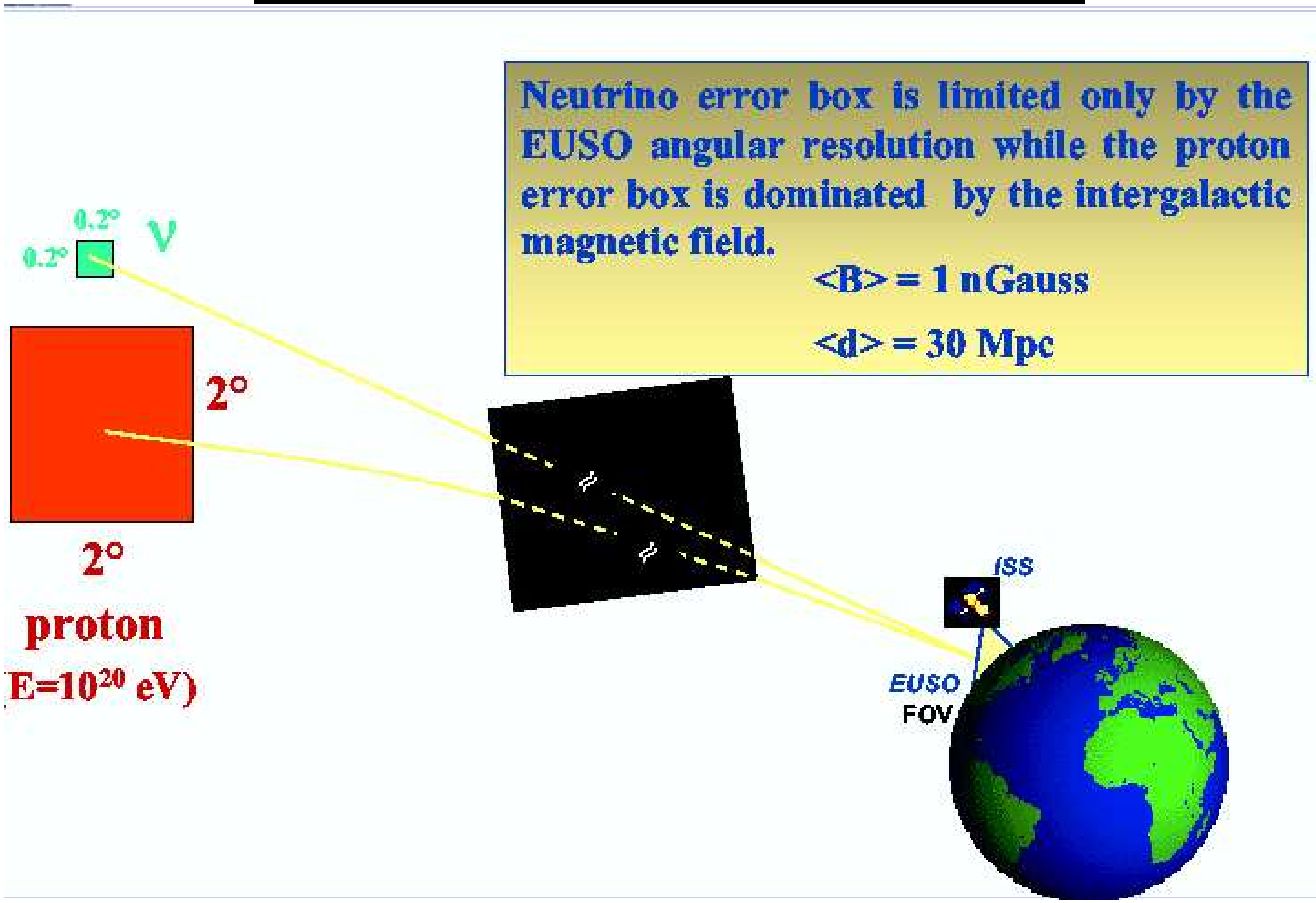
Hopefully, they will be discovered in the near future

Pierre Auger, AMANDA, ANITA, ICE CUBE, EUSO, OWL,...

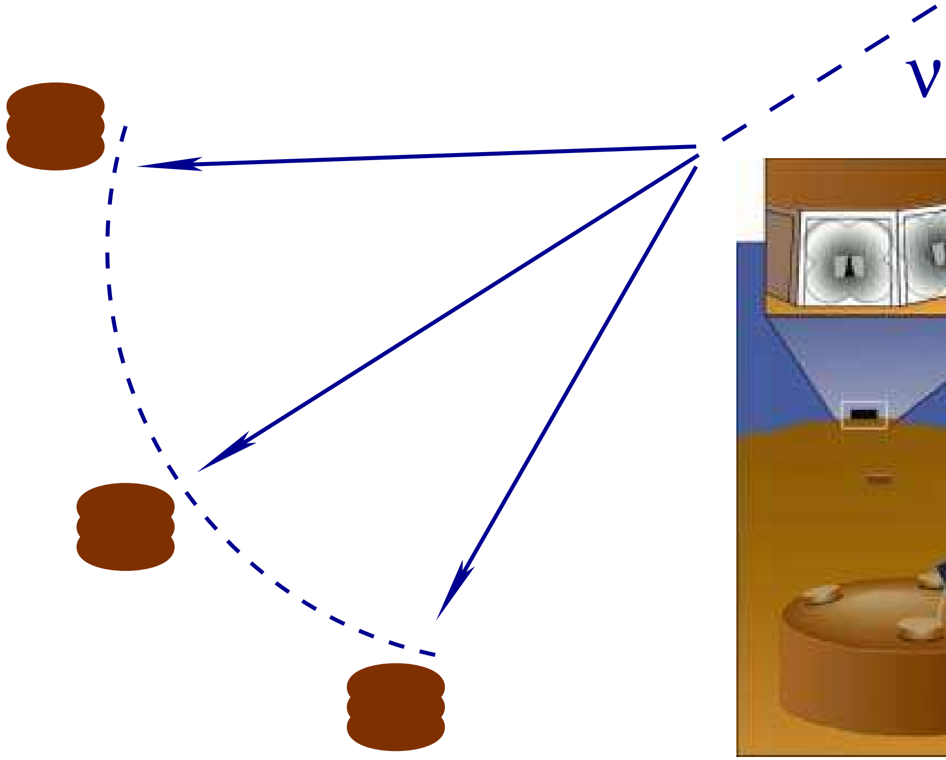
UHECR are deflected by magnetic fields

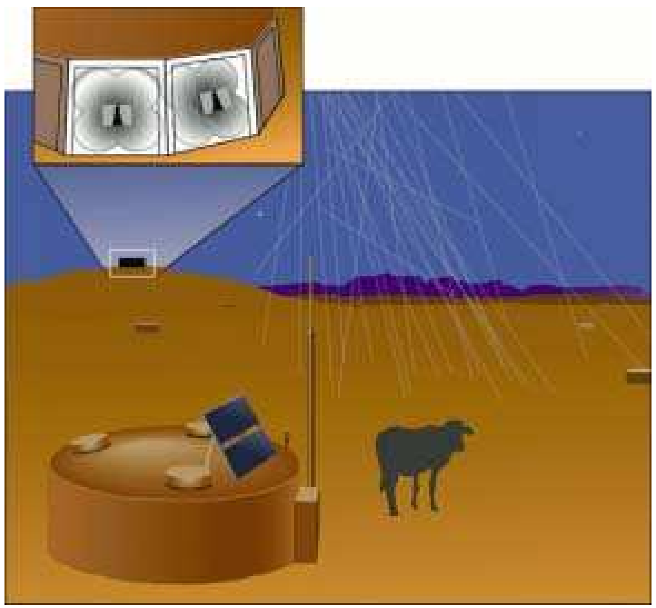


UHE neutrino astronomy

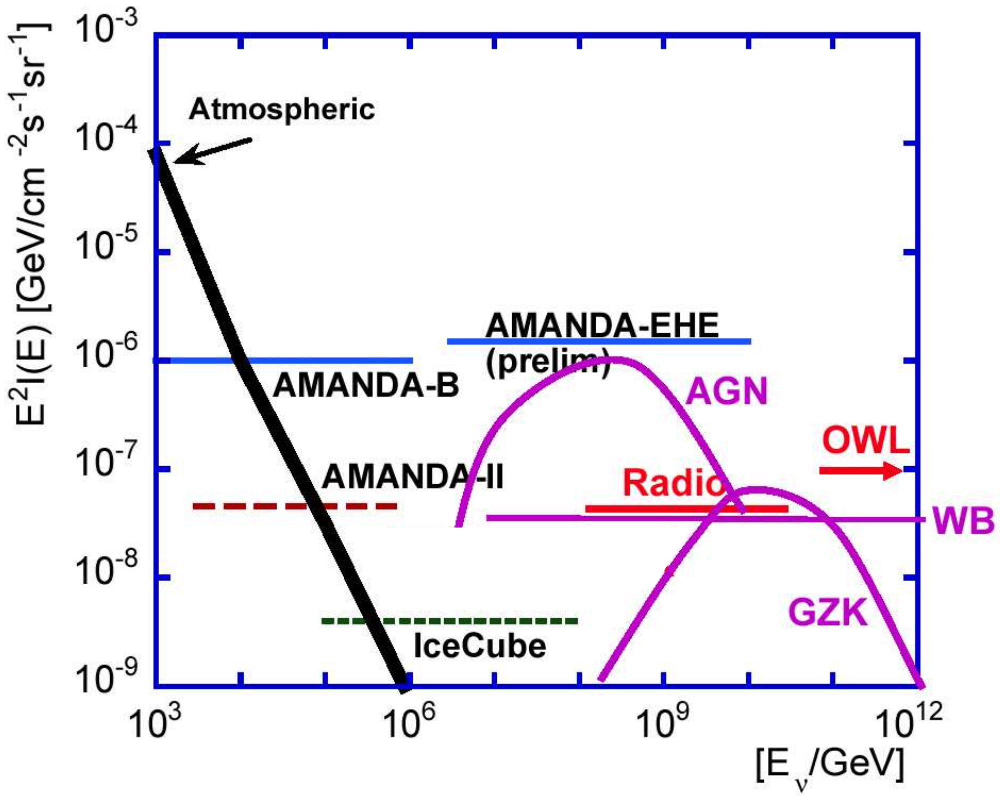


Pierre Auger can detect UHE neutrinos

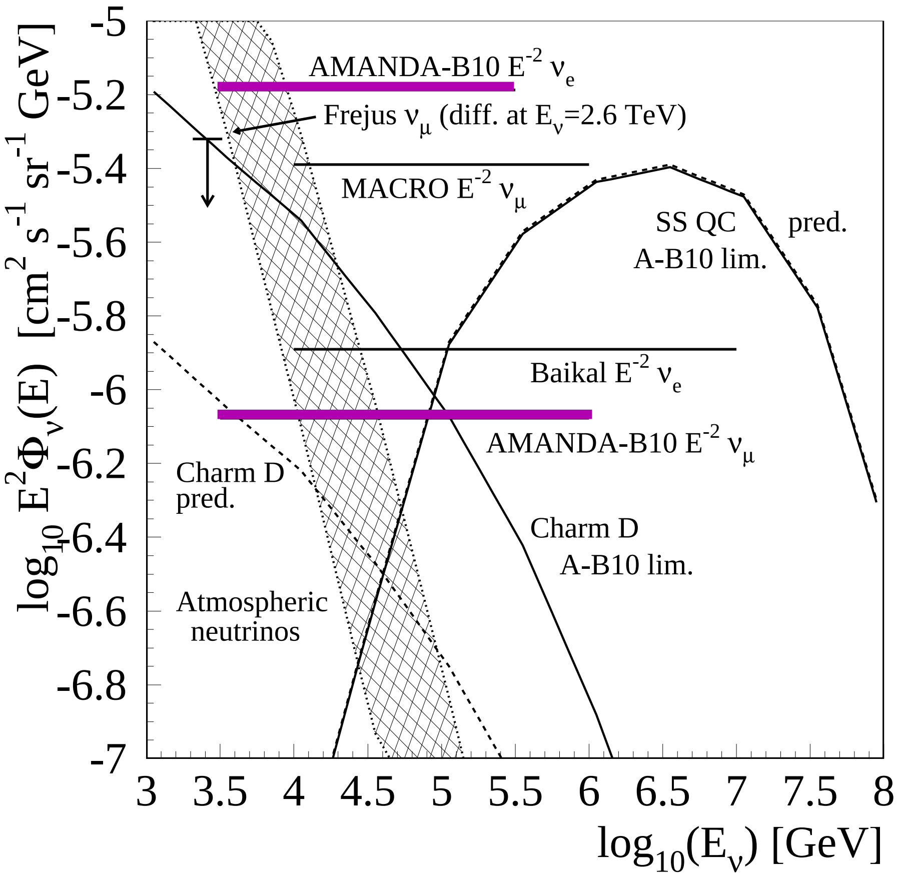




"Certain" predictions and limits

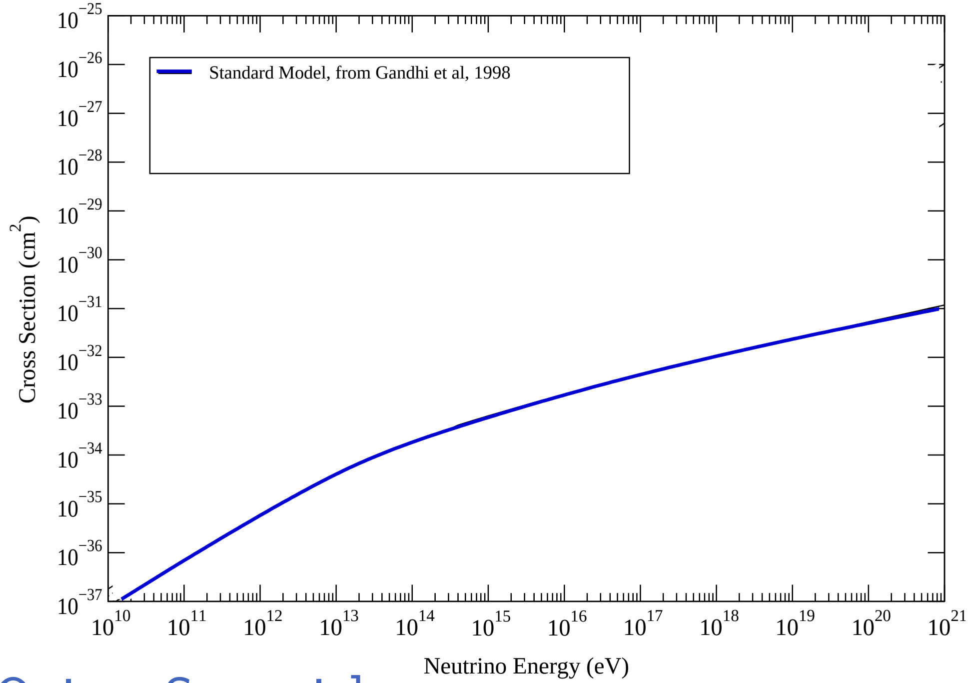


Limits from AMANDA-B



Detection strategy relies on the knowledge of the neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



[Gandhi, Reno, Quigg, Sarcevic]

Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

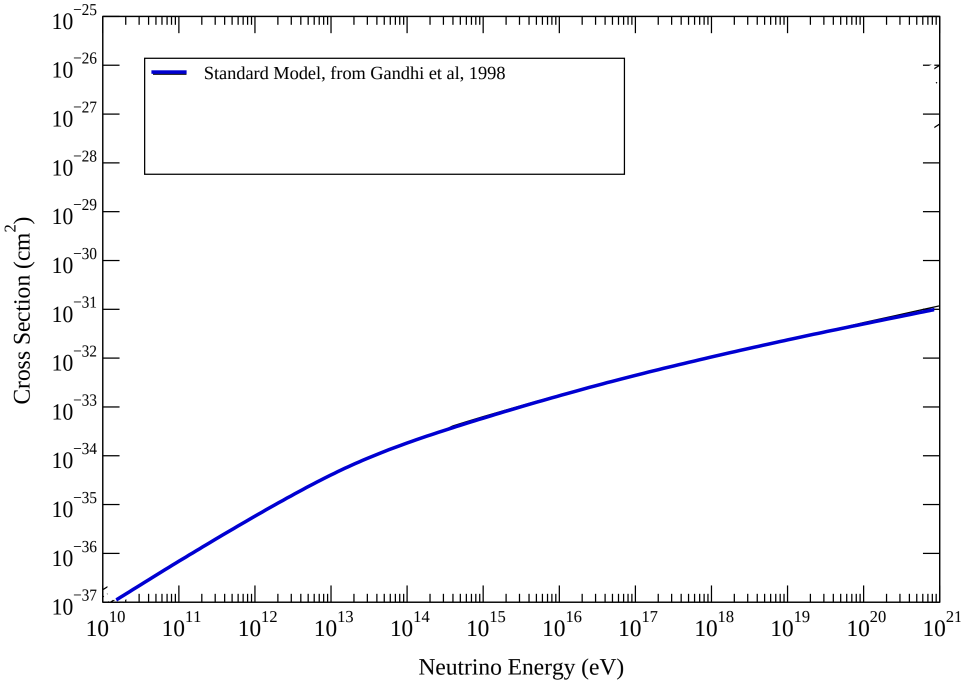
Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

How well do we know the neutrino-nucleon cross section? New physics contributions? Can saturation affect the cross section at high energy?

Is it possible to **measure** the neutrino-nucleon cross section at these energies?

Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



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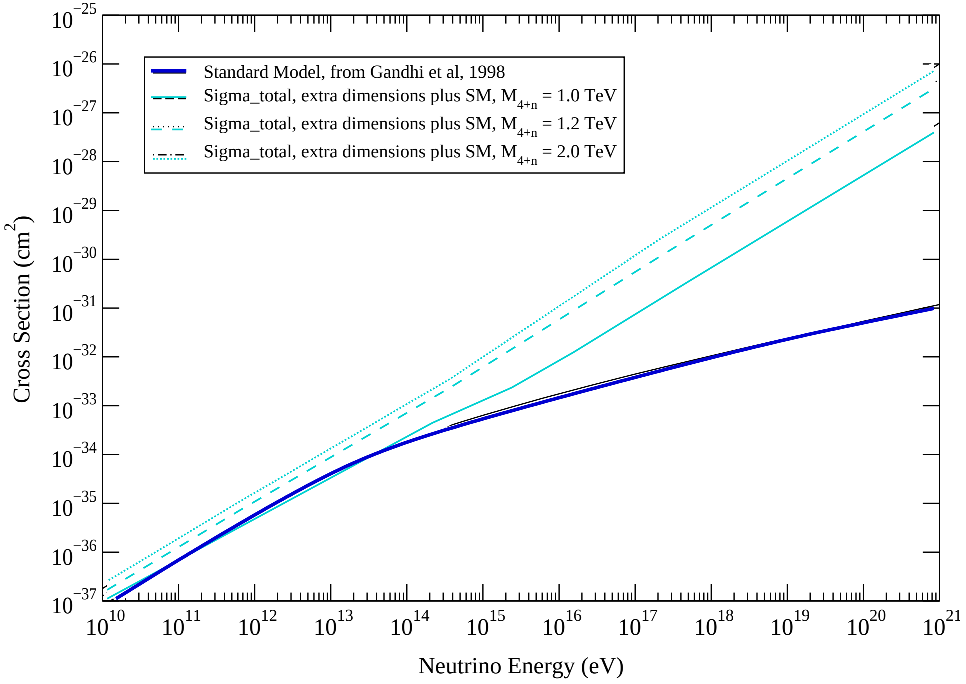

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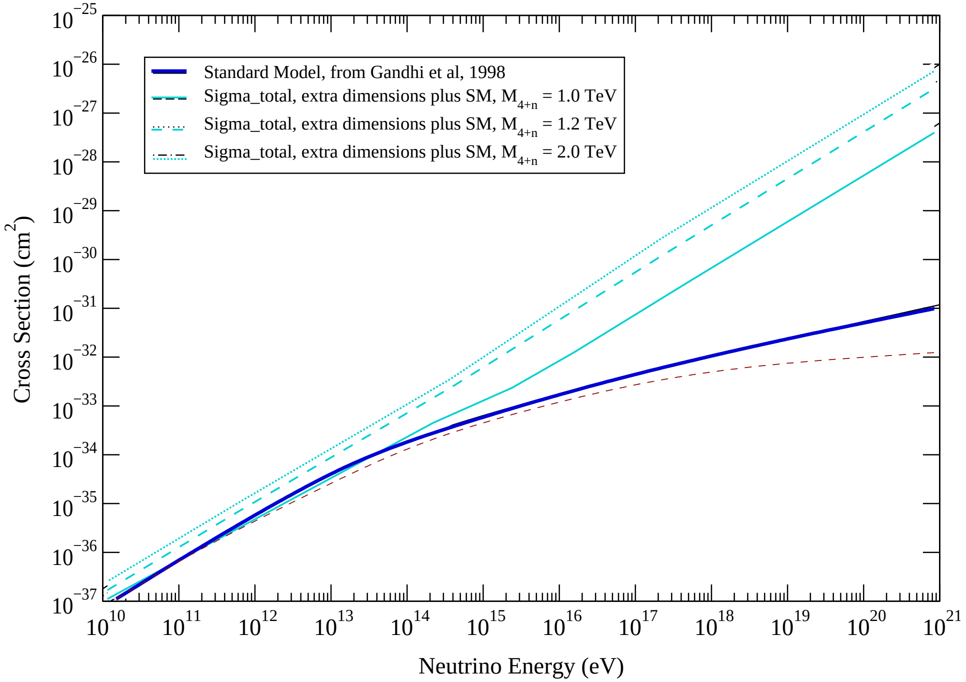
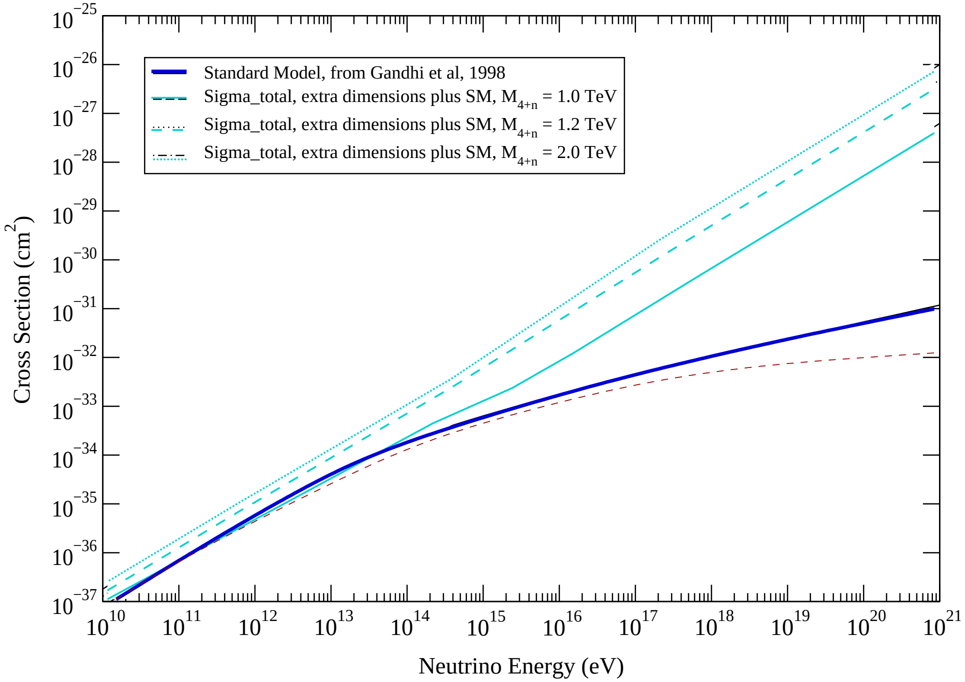


Neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations necessarily use extrapolations of PDF and standard model parameters.



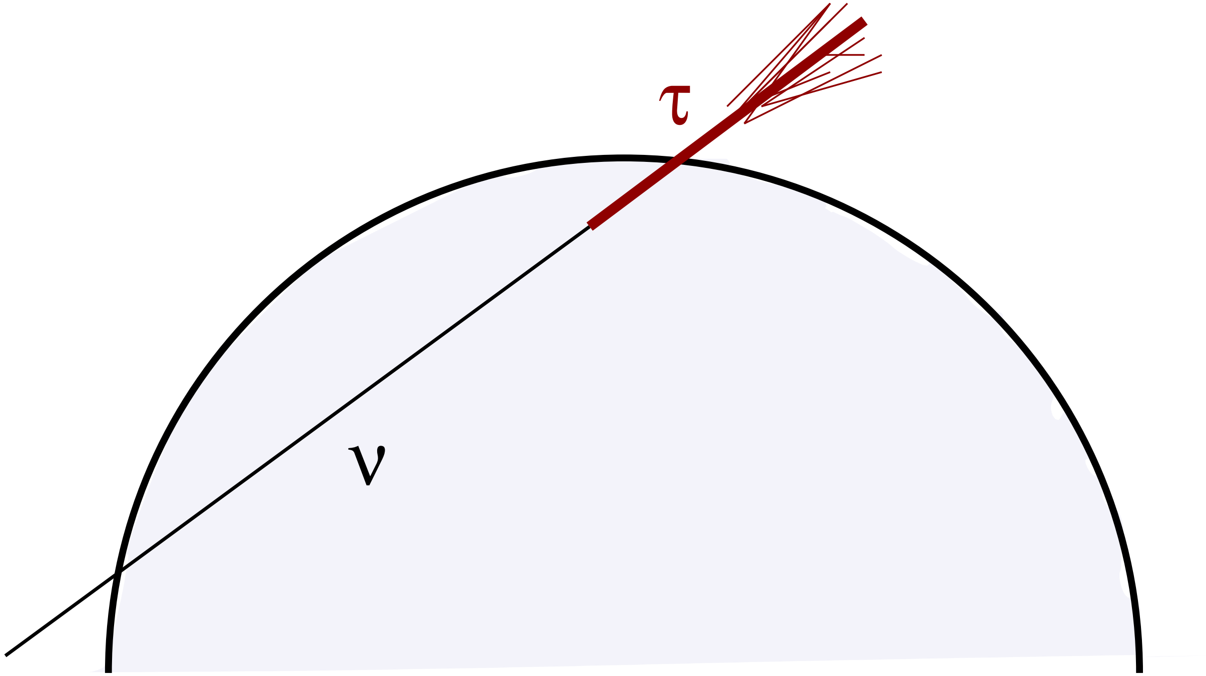
SM calculation [Quigg et al.] is most likely right, but we want to **measure** this cross section.

If the cross section is smaller, the Earth becomes more transparent to neutrinos. More neutrinos can get through the Earth, interact just below the surface and produce a charged lepton that originates an **up-going air shower (UAS)** .

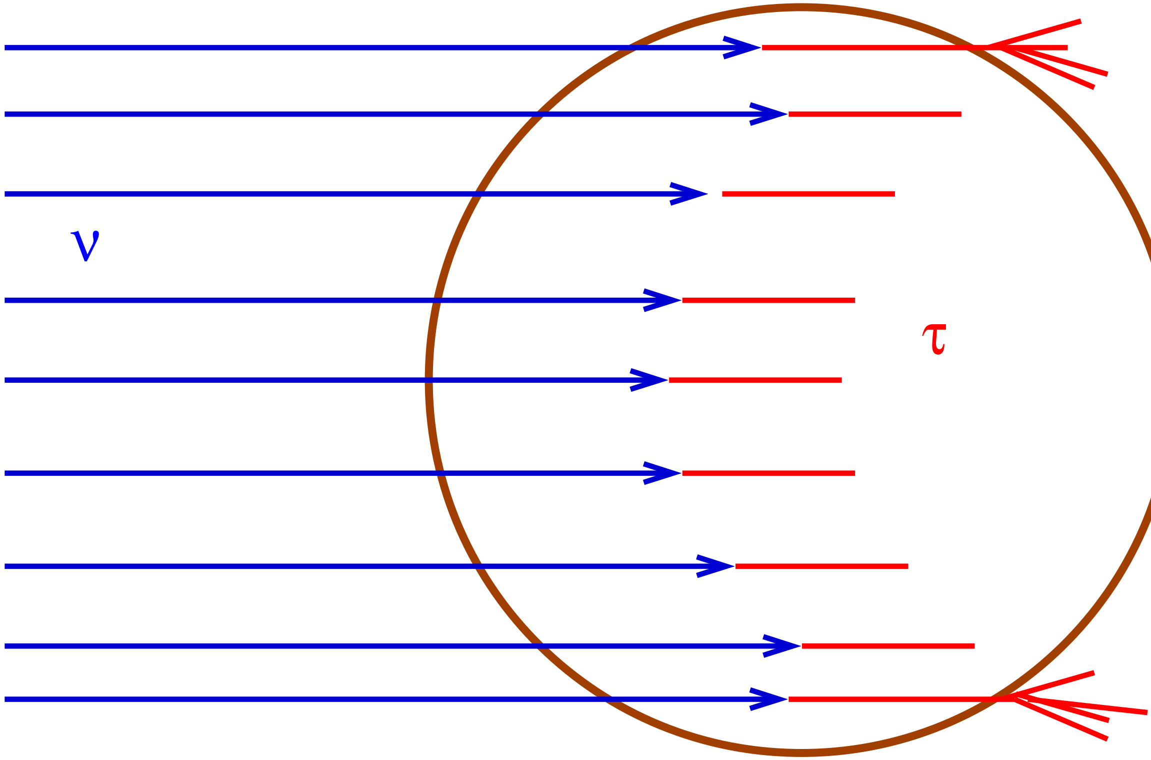
- **The increase in UAS rate compensates for the decrease in HAS.**

- **The comparison of the two rates allows a measurement of the cross section at 10^{11}GeV**

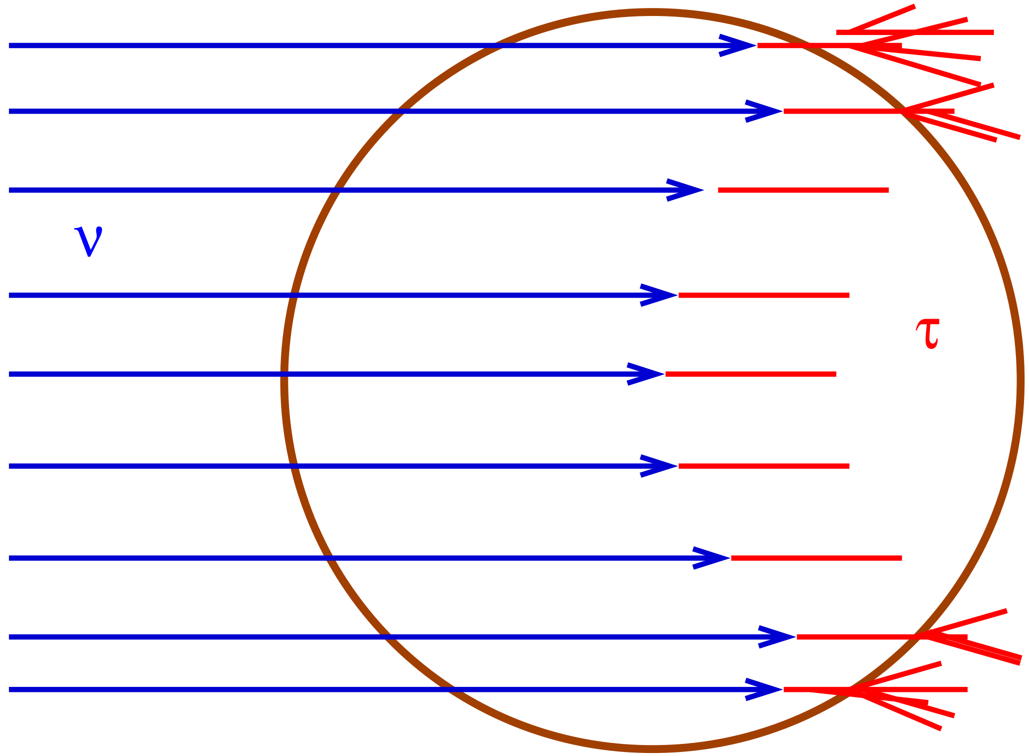
- **Angular distribution of UAS can provide an additional independent information about the cross section**



The probability of a neutrino conversion into an up-going τ grows with the mean free path λ_ν, for $\lambda_\nu < R_\oplus$, because the shadowing by the Earth decreases.

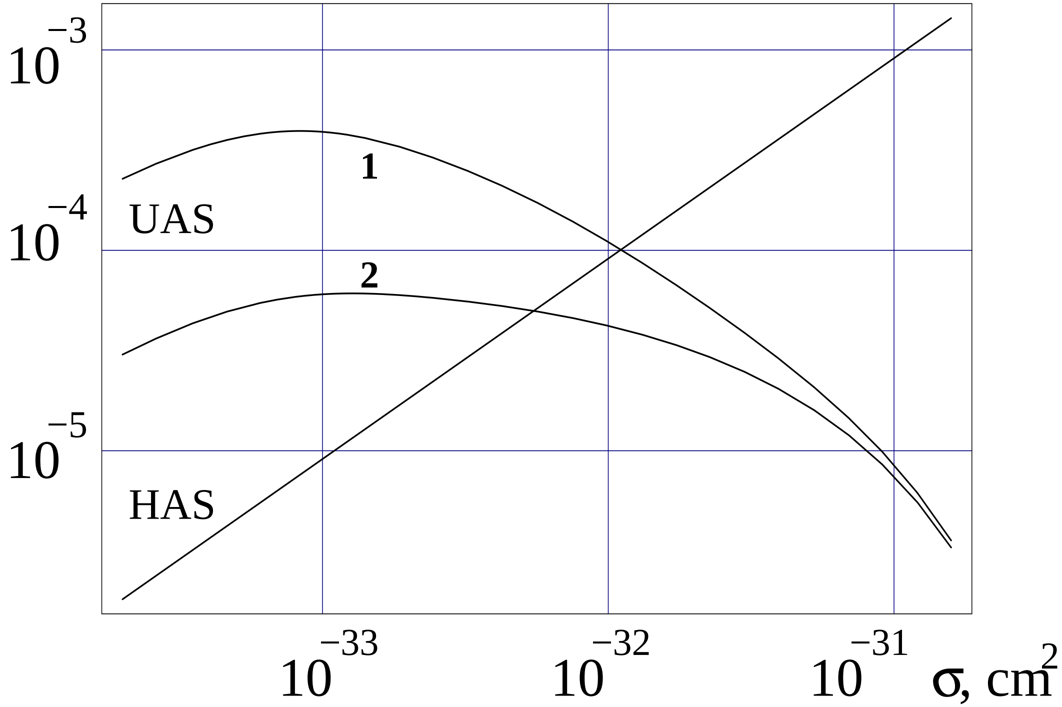


UAS requires a neutrino to interact and produce a τ below the surface.



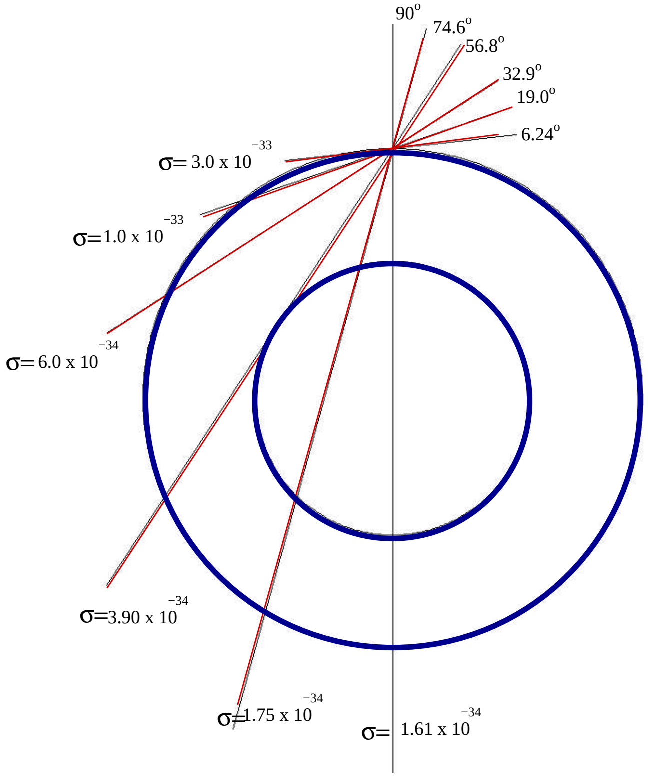
UAS requires a neutrino to interact and produce a τ below the surface.
The number of UAS is higher for a smaller cross section.

The shower probability per incident neutrino:



The energy threshold for detection of UAS was assumed $E_{\rm th} = 10^{18}$eV for curve 1 and $E_{\rm th} = 10^{19}$eV for curve 2. Additional UAS events, not included here, can be detected by EUSO or OWL via Cerenkov radiation of tau leptons.

In addition, the angular distributing depends on the cross section.



Most probable UAS corresponds to chord length close to mean free path

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto \boldsymbol{F_\nu \sigma_{\nu_N}}$

Rate of UAS: $\propto \boldsymbol{F_\nu / \sigma_{\nu_N}}$

Angular distribution: $\cos \boldsymbol{\theta}_{\rm peak} \propto 1/\boldsymbol{\sigma_{\nu_N}}$

$\Rightarrow$ **can determine $\sigma_{\nu N}$ and F_ν independently**

All one needs is enough statistics. Need neutrino telescopes.

Possible to do particle physics experiments using cosmic ray detectors

Conclusion

- There are some $\left(\mathbf{10^{28}cm}\right)^{4}$ worth of data flying at us at a speed of light. One can use these data, combined with those from collider experiments, to learn new physics.
- Dark matter and one's inability to explain the baryon asymmetry in the Standard Model both show that new physics is out there to be discovered.
- Anticipated discoveries.