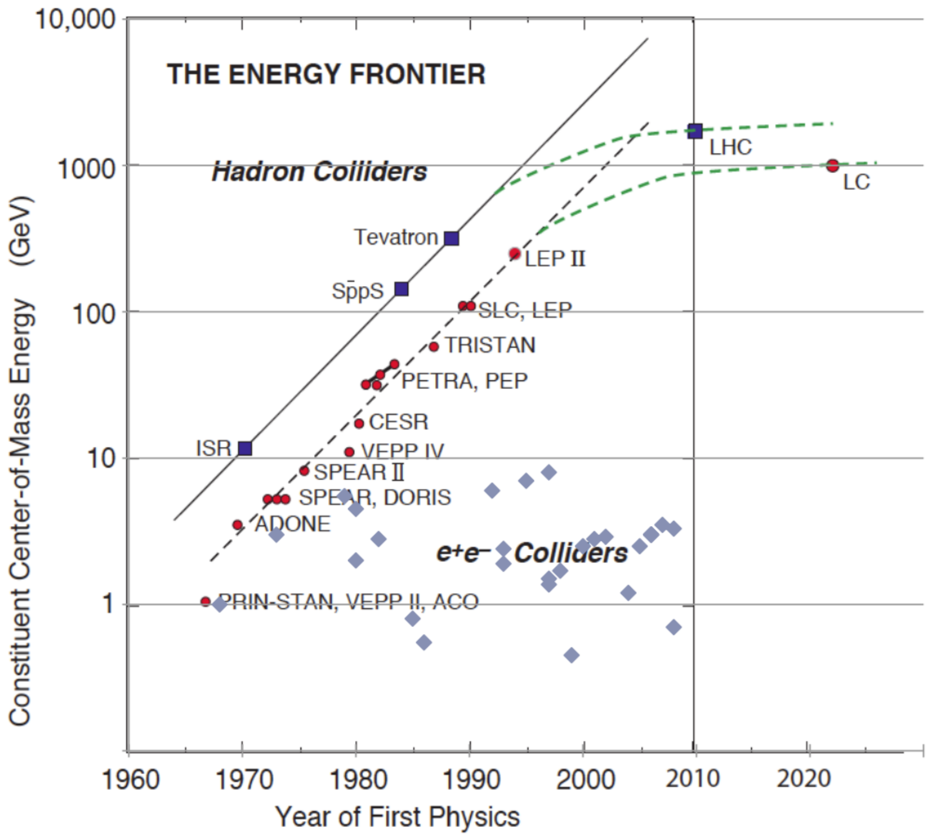
Observation of UHECR and air shower model

Xiangyun Long

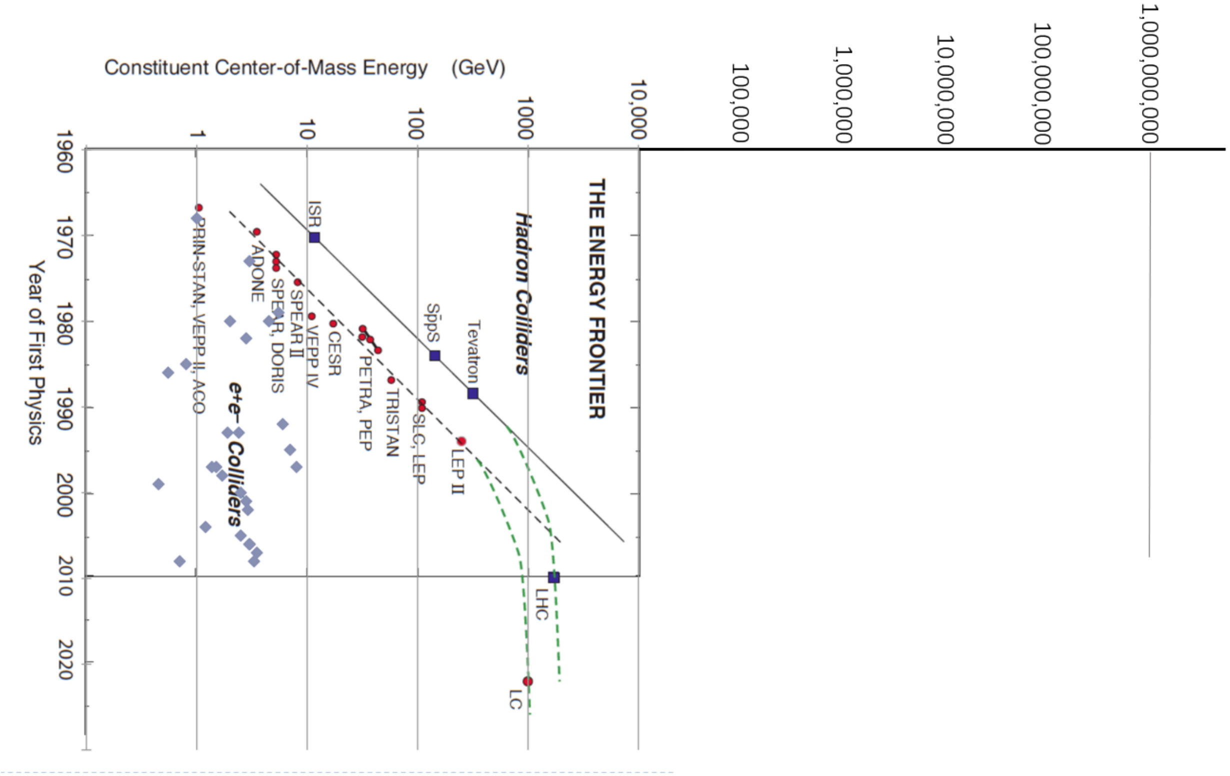
Contents

What is UHECR

Ultra-High-Energy Cosmic Rays



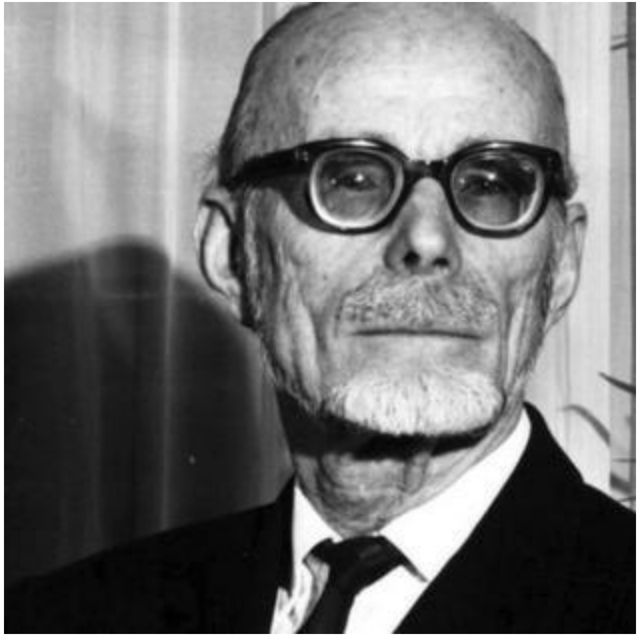
What is UHECR



energy of UHECR ≥ 10^9GeV =1EeV ≈0.16J

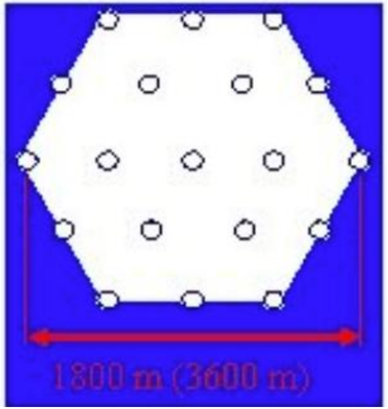
The history of HECR detection

1912 Hess



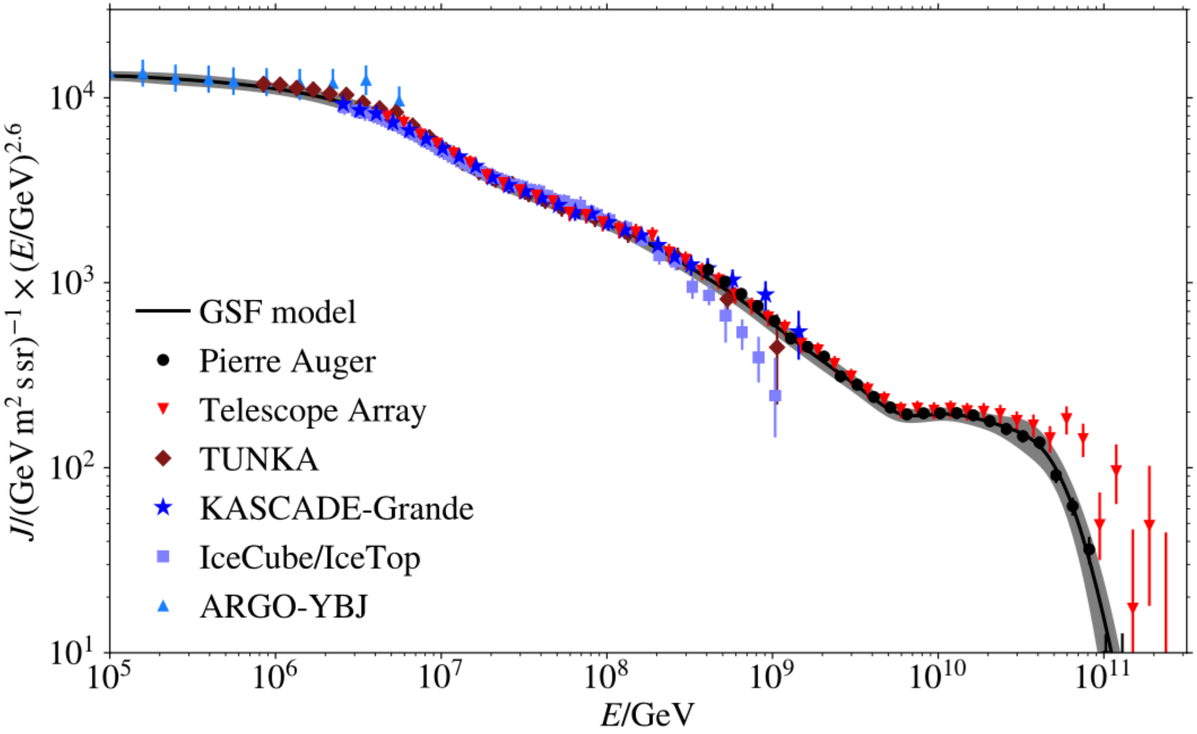
1938 Pierre Auger

1954 Agassiz Station

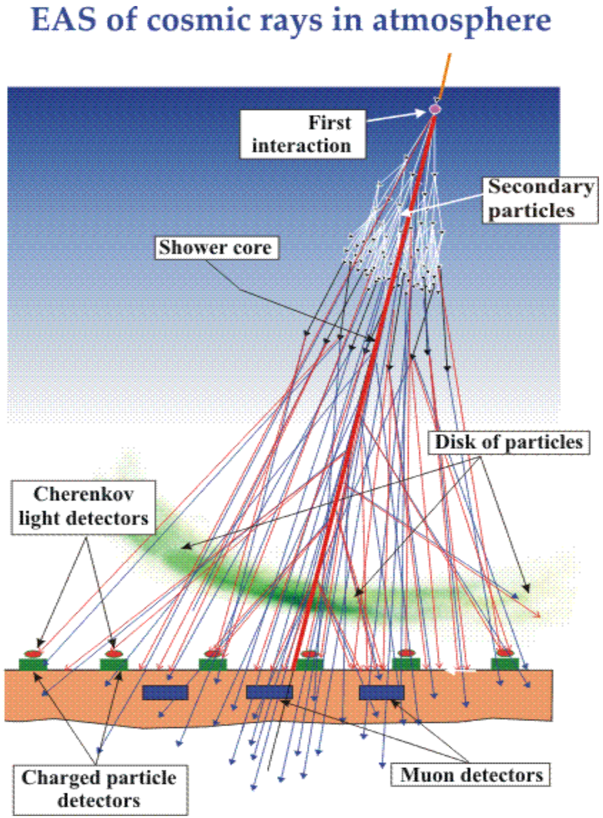


1962 Volcano Ranch

different energy different technique



How do we detect UHECR - extensive air showers



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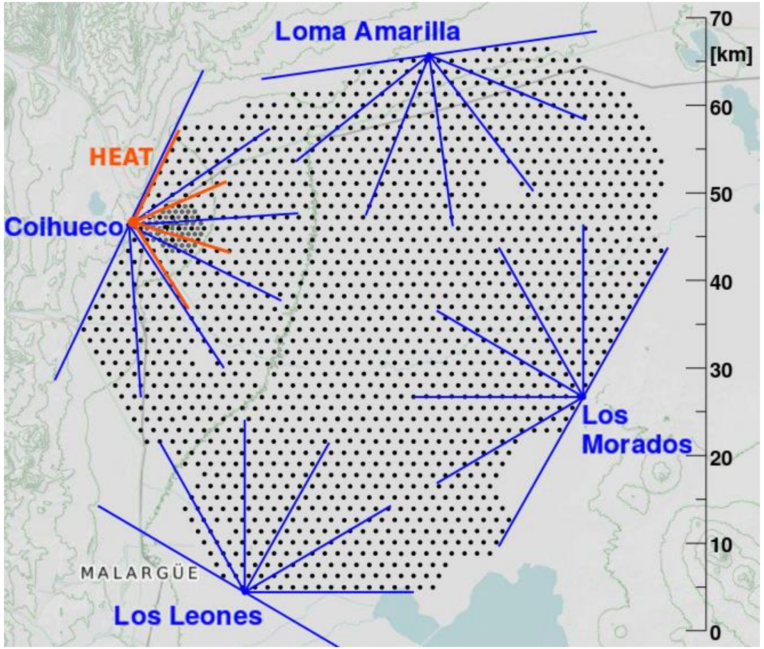
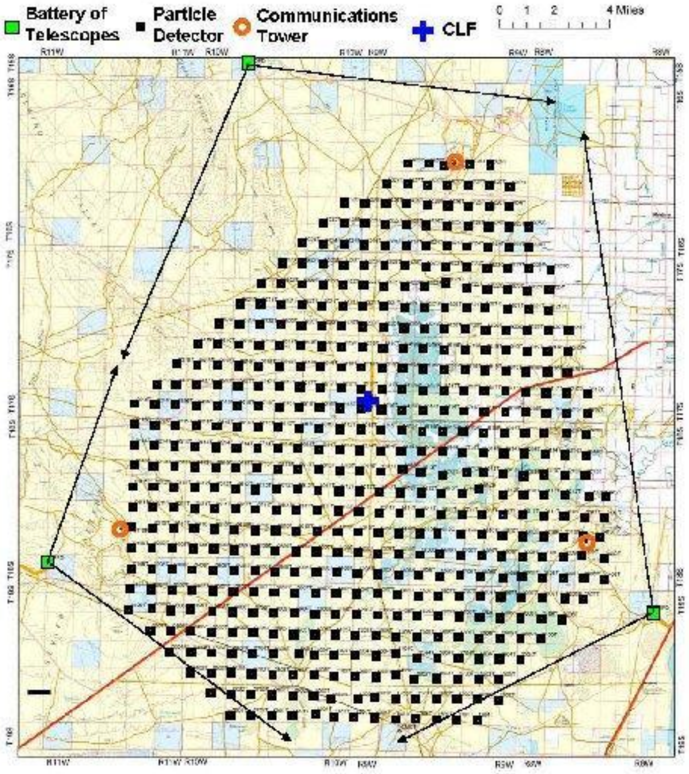
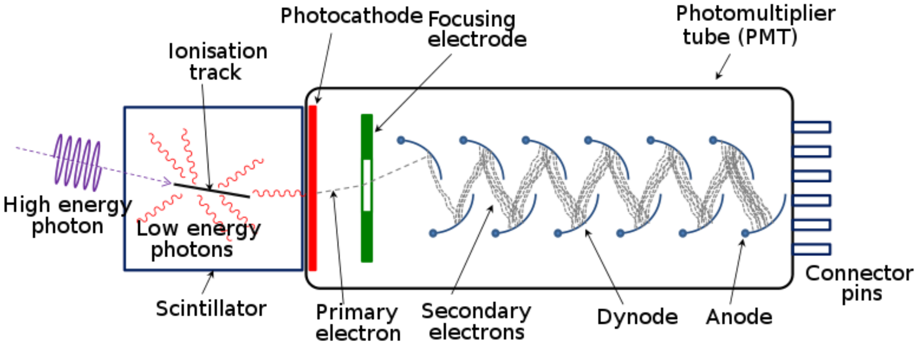


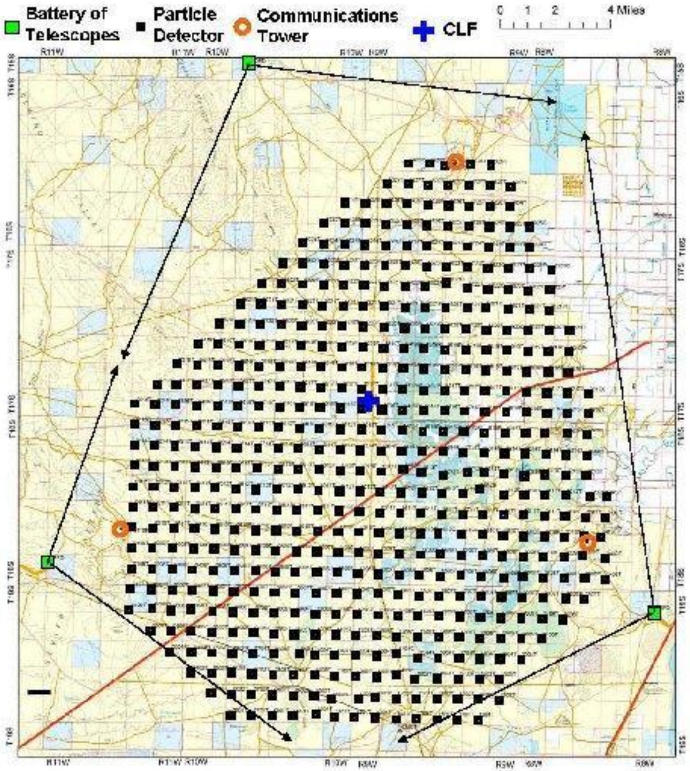
Pierre Auger Observatory



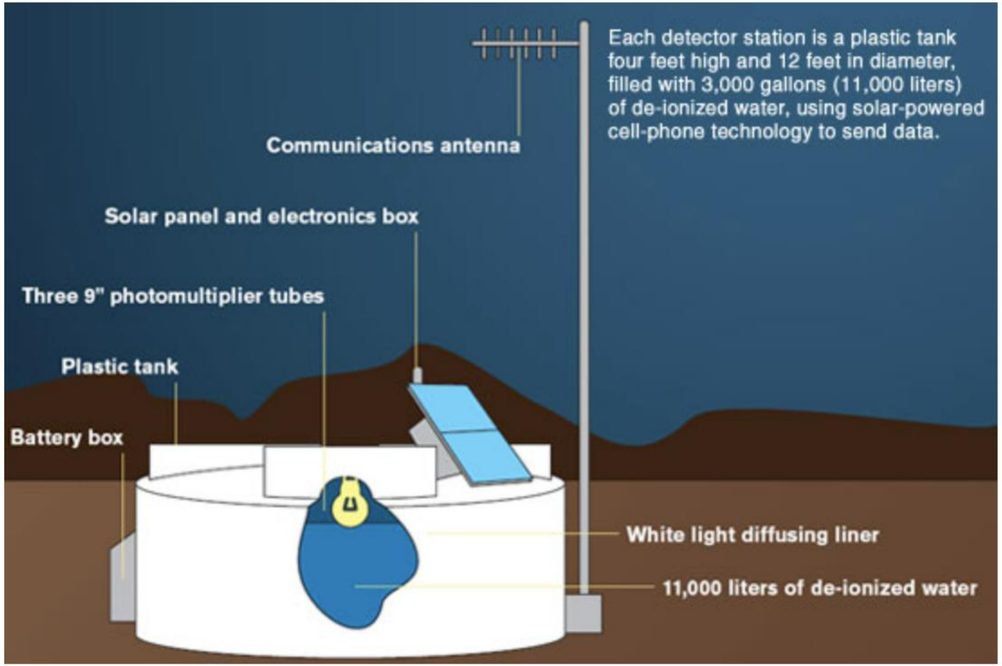
the TelescopeArray

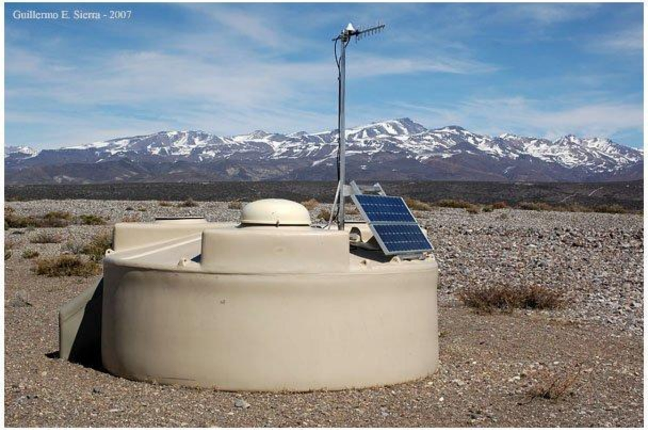
Scintillator



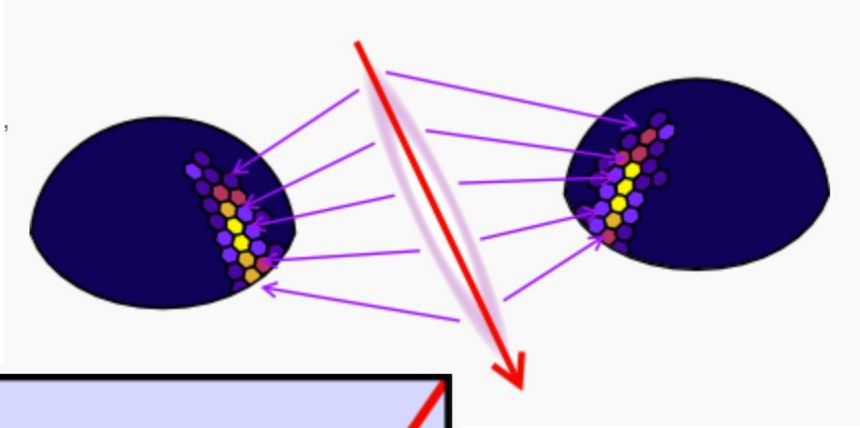


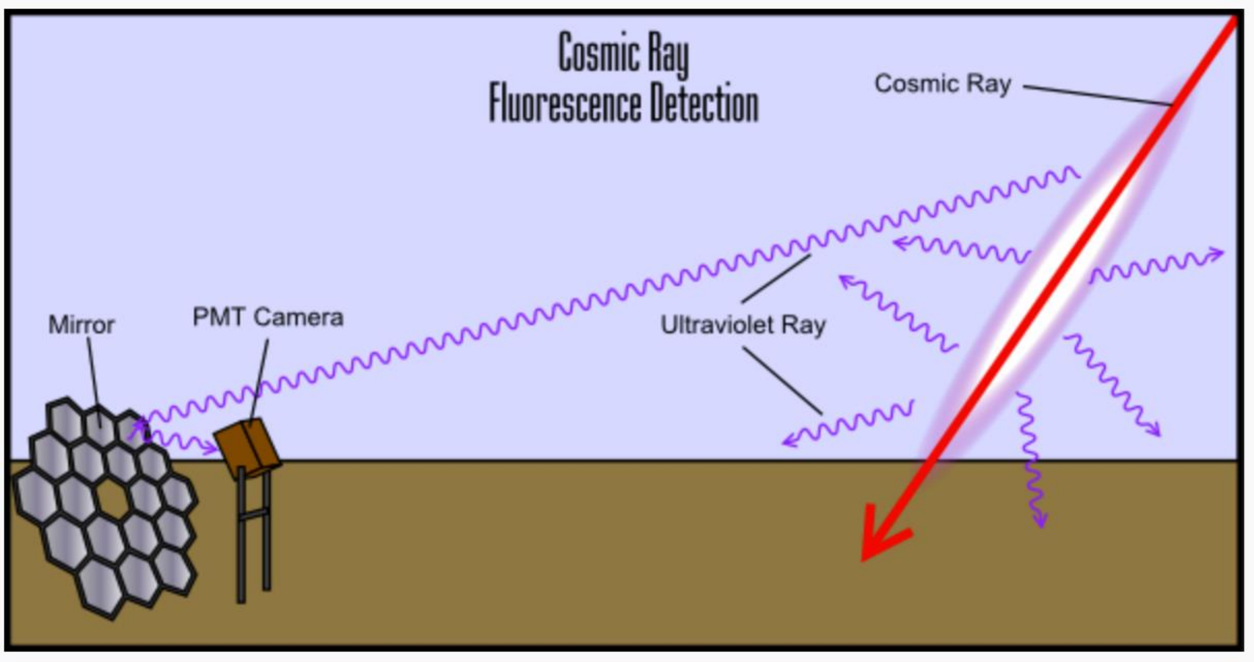
Cherenkov detector



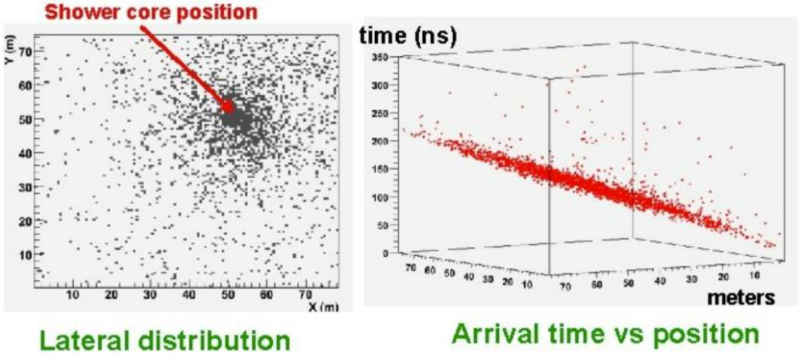


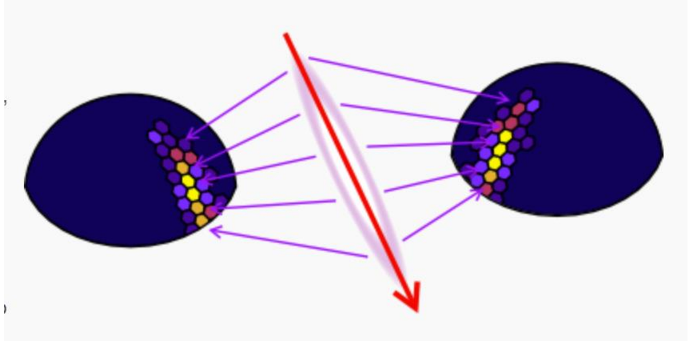
Fluorescence detector

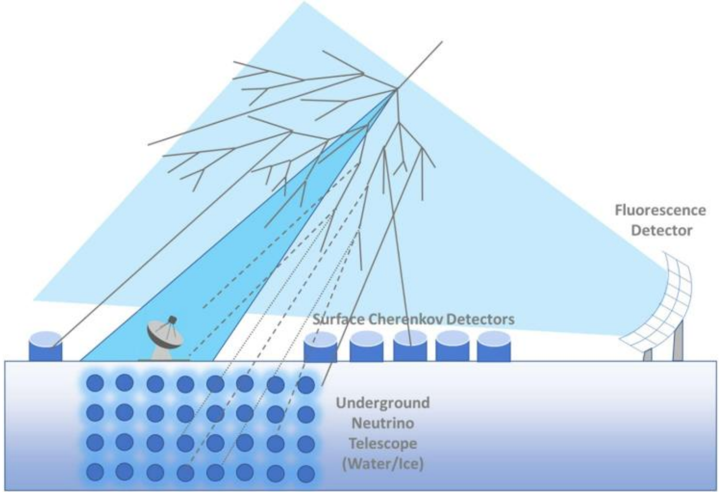




Air shower detection







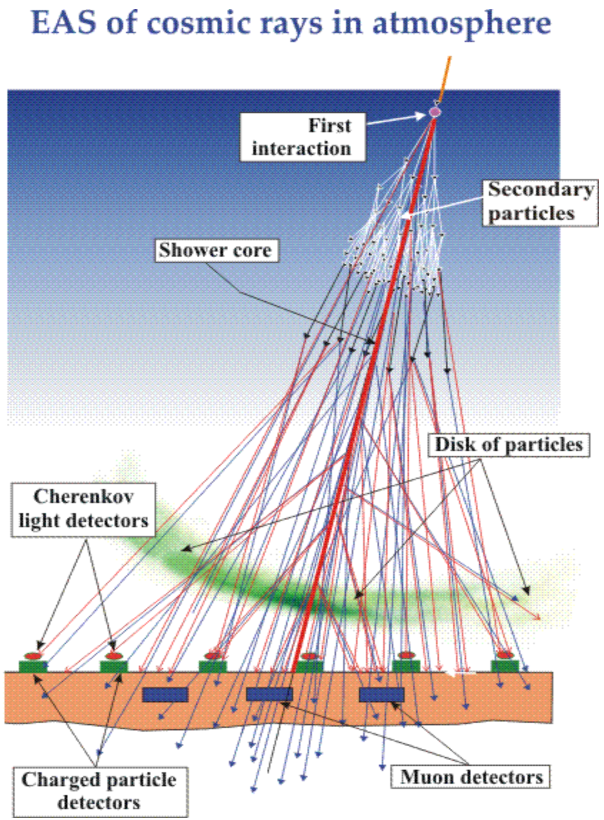
Systematical error of the detection

particle energy

can be determined

particle composition

?



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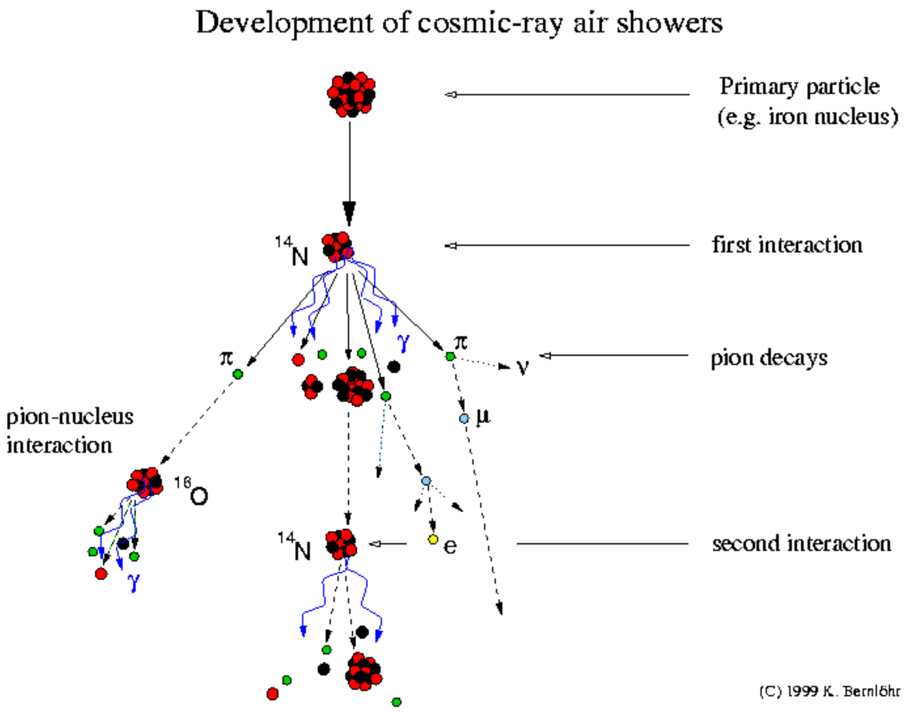


Current Observational Results

Ce Sui

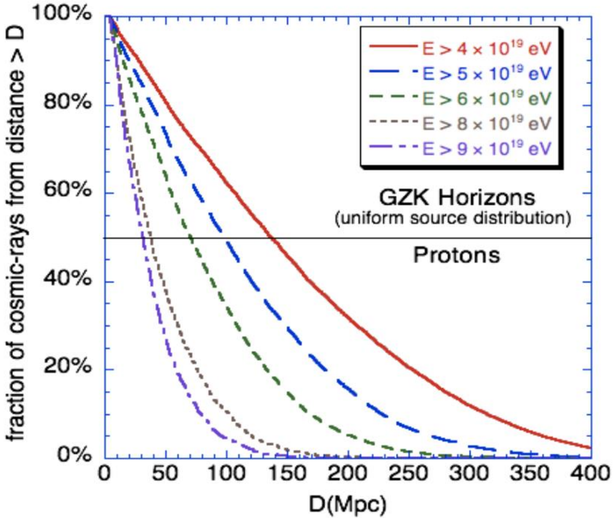
Contents

Important Effects

GZK(Greisen–Zatsepin–Kuzmin) effect: Cosmic rays with energies over some threshold energy would interact with cosmic microwave background photons.

$$\gamma_{\mathrm{CMB}} + p \to \Delta^{+} \to p + \pi^{0}$$

$$\gamma_{\mathrm{CMB}} + p \to \Delta^{+} \to n + \pi^{+}$$



(A.V.Olinto et al, 2009)

Important Effects

GZK effect: Cosmic rays with energies over some threshold energy would interact with cosmic microwave background photons.

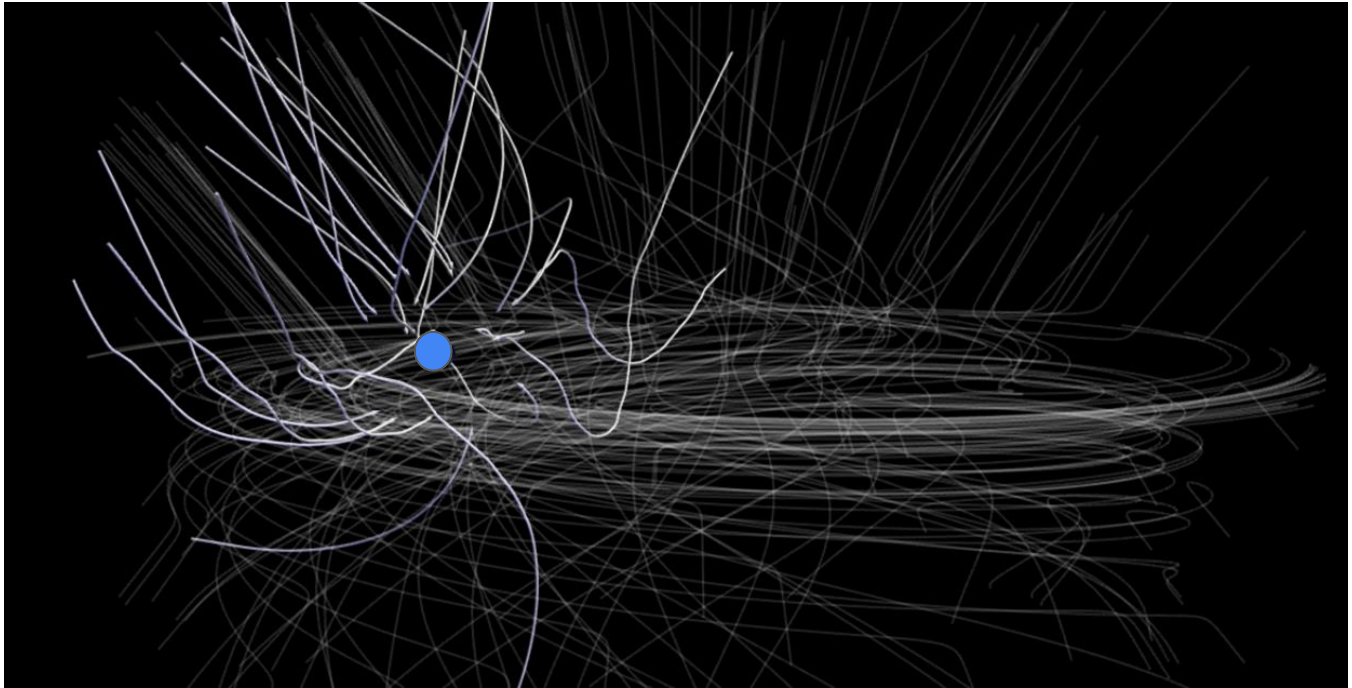
Suppression at high Energy

Local

Anisotropic

Important Effects

Deflections in Cosmic Magnetic Fields:
UHECRs are charged particles, their propagation is affected by extragalactic and Galactic magnetic fields.



UHECRs in a Galactic magnetic field model

(Glennys et al, 2015)

Important Effects

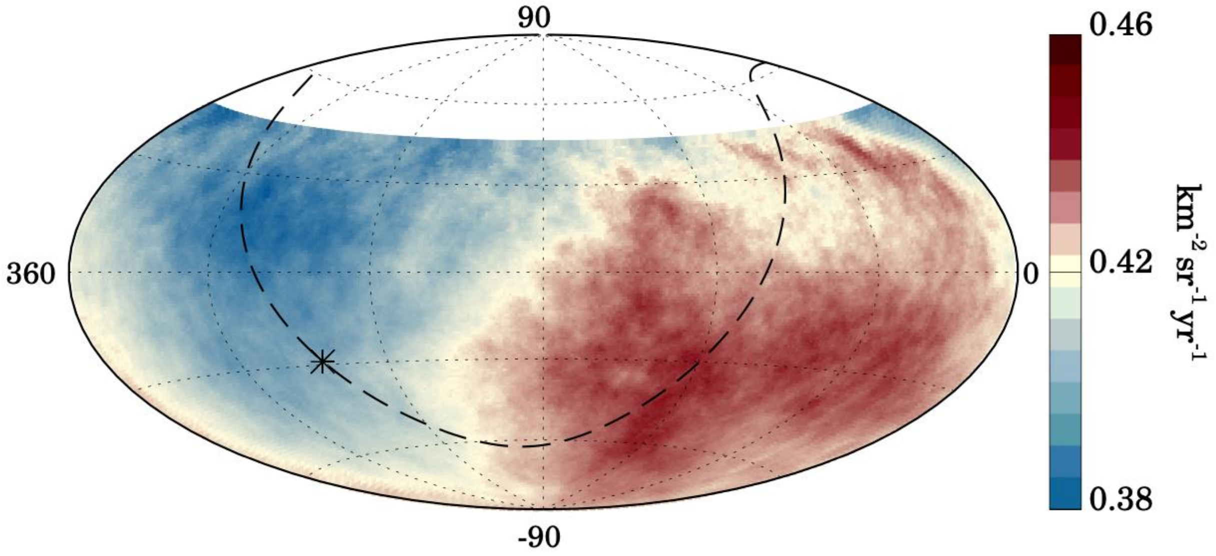
Deflections in Cosmic Magnetic Fields:
UHECRs are charged particles, their propagation is affected by extragalactic and Galactic magnetic fields.

↓

Large uncertainty at small scale

Model-dependent Source Identification

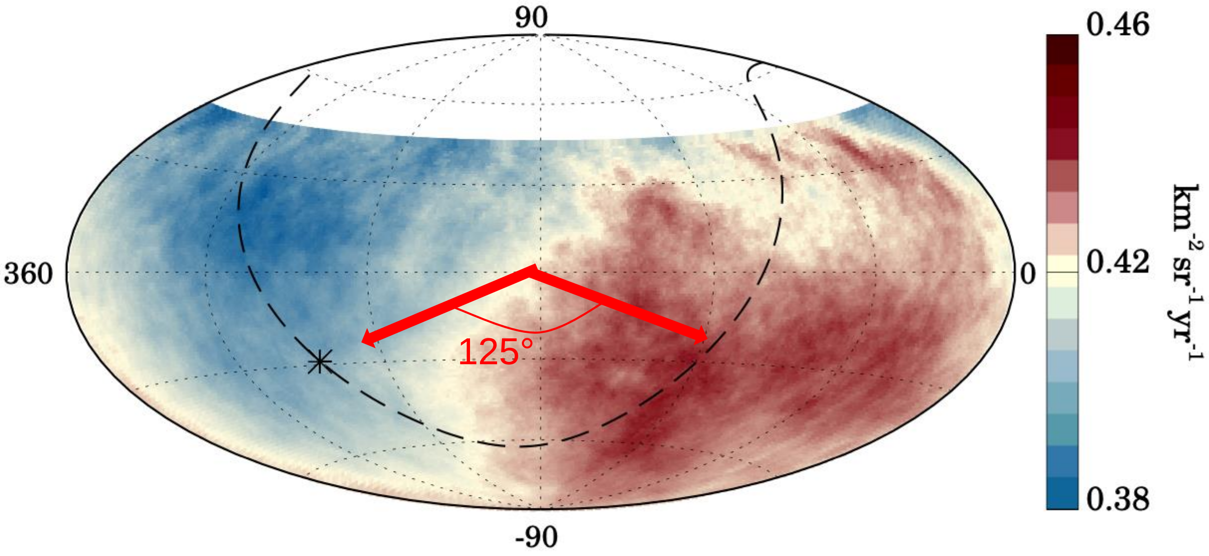
Anisotropy: Large Scale Dipole



Smoothed **cosmic-ray flux for E > 8 EeV** in Equatorial coordinates

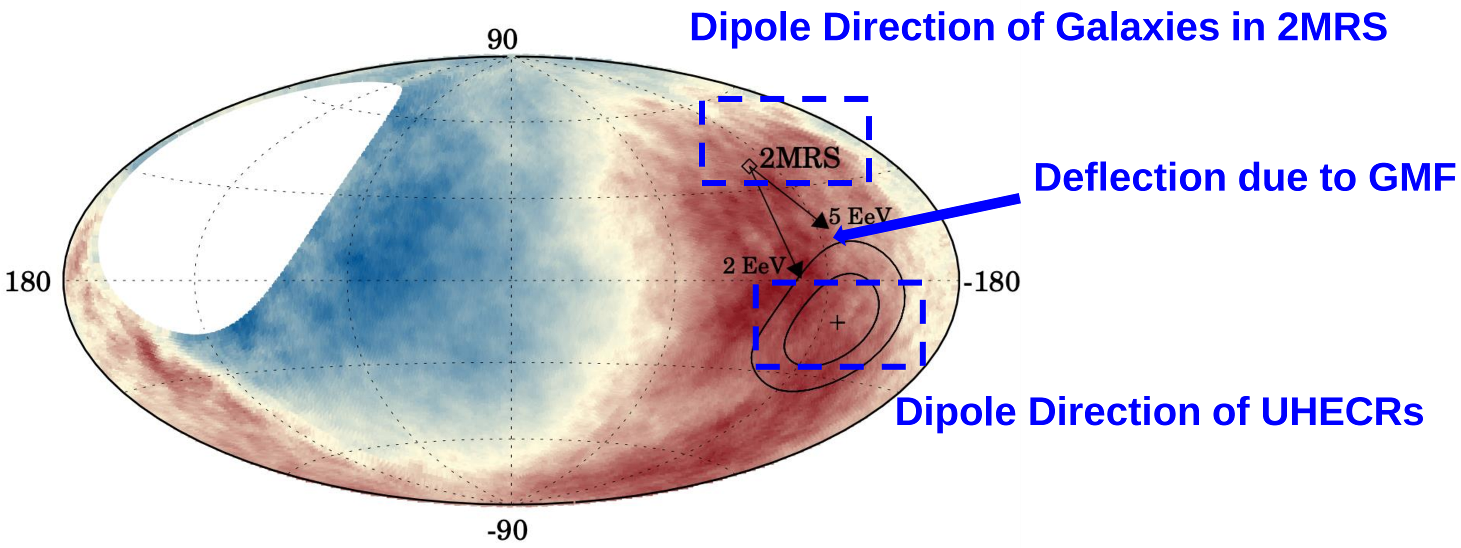
From Pierre Auger Collaboration

Anisotropy: Large Scale Dipole



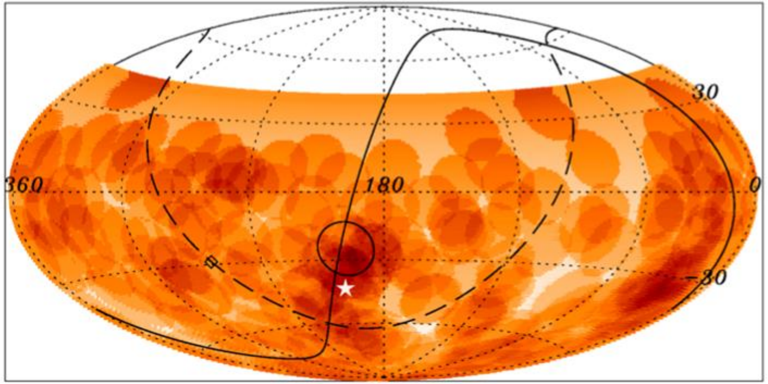
UHECRs that creates the anisotropy have an extragalactic origin

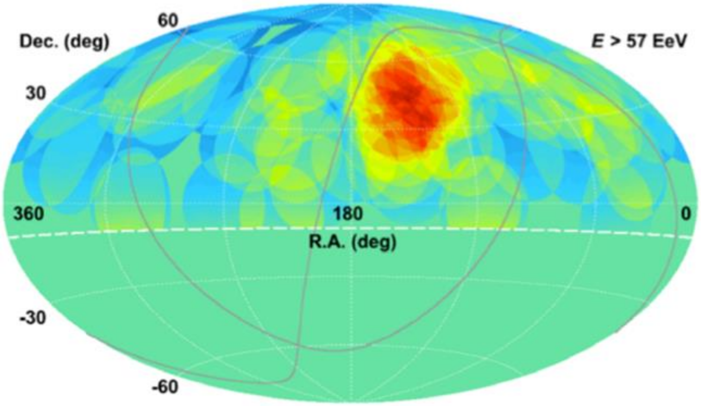
Anisotropy: Large Scale Dipole



Comparison with dipole from 2 Micron All-Sky Redshift Survey (2MRS)

Anisotropy: Small Scale “Hotspot”





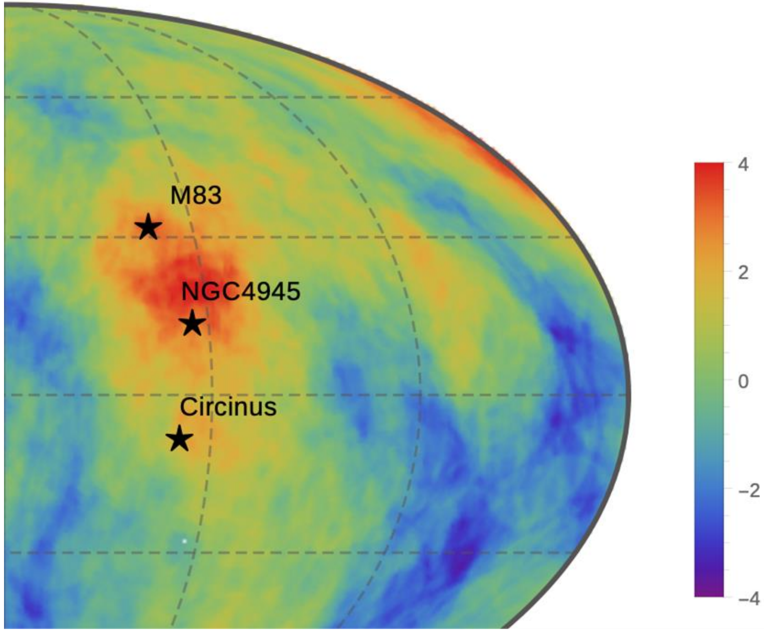
Auger Hotspots(E>54 EeV)

0.4σ

TA Hotspots(E>57 EeV)

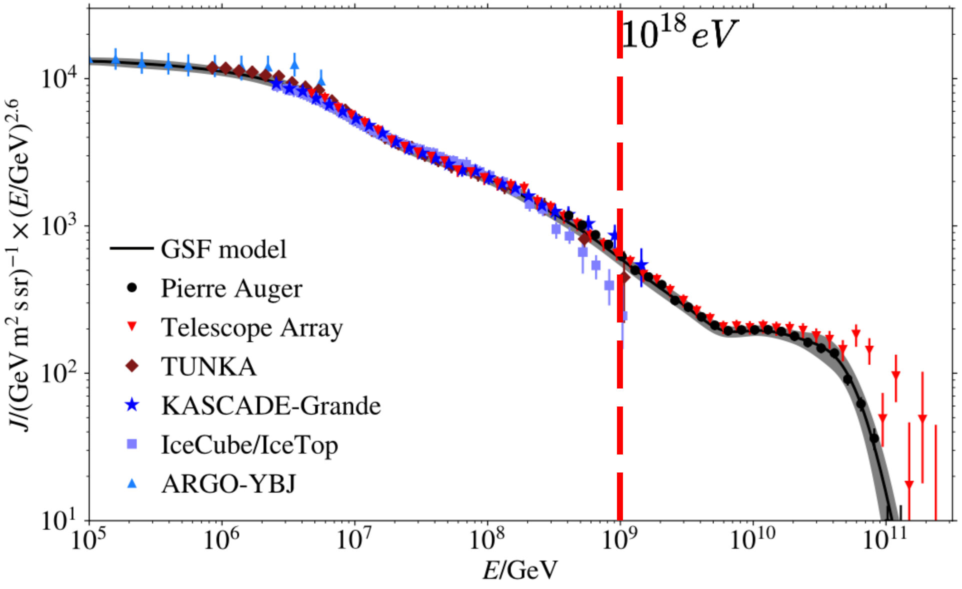
3.4σ

Anisotropy: Small Scale “Hotspot”



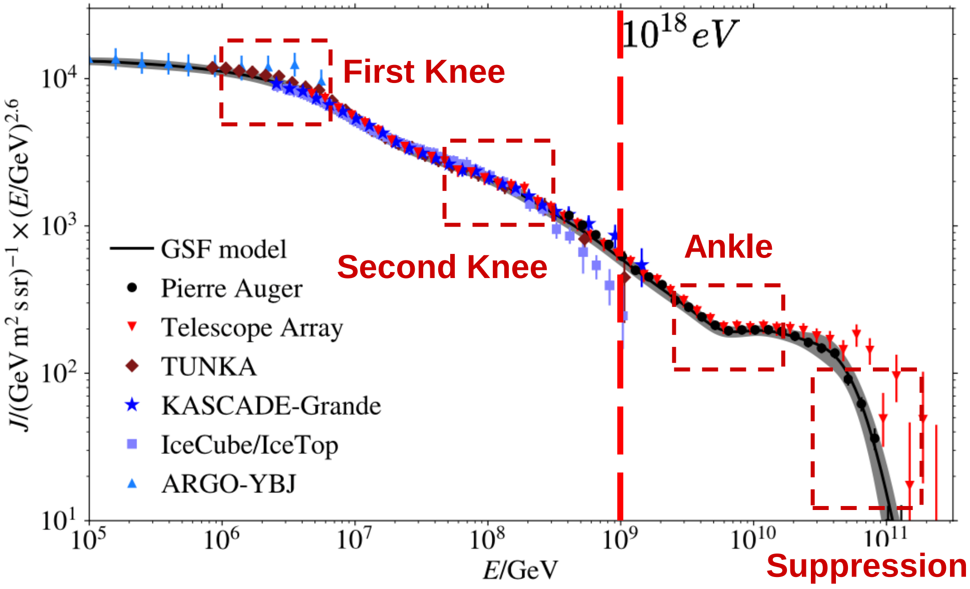
SBGs around TA Hotspots(E>57 EeV)

Spectrum and Mass Composition



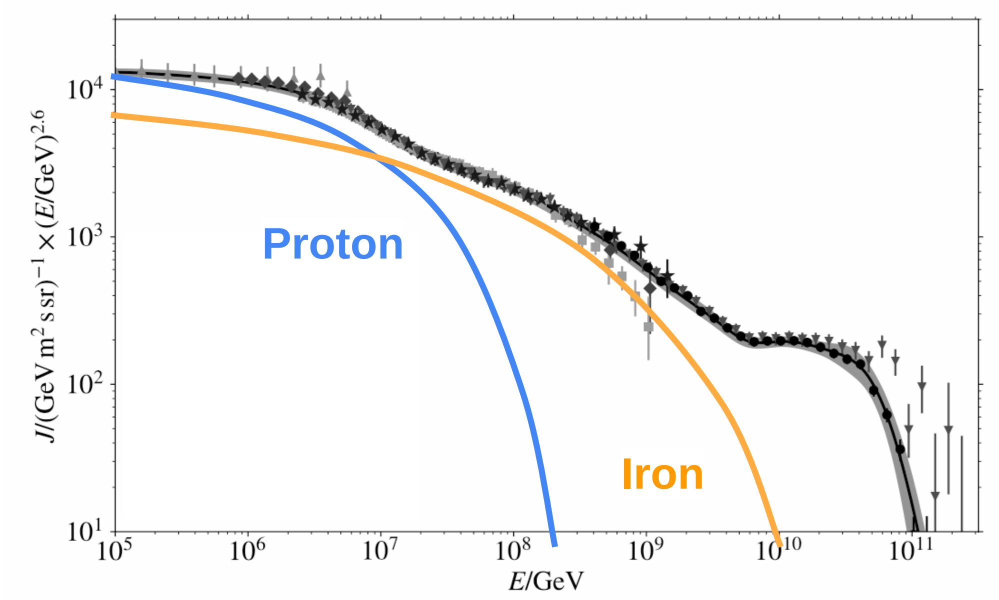
Energy Spectrum of Cosmic Ray

Spectrum and Mass Composition



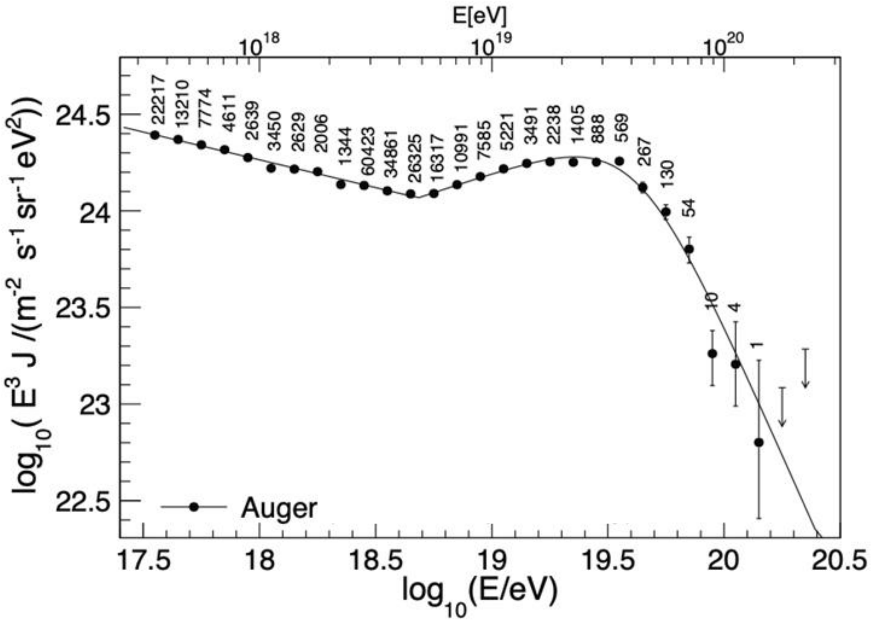
Energy Spectrum of Cosmic Ray

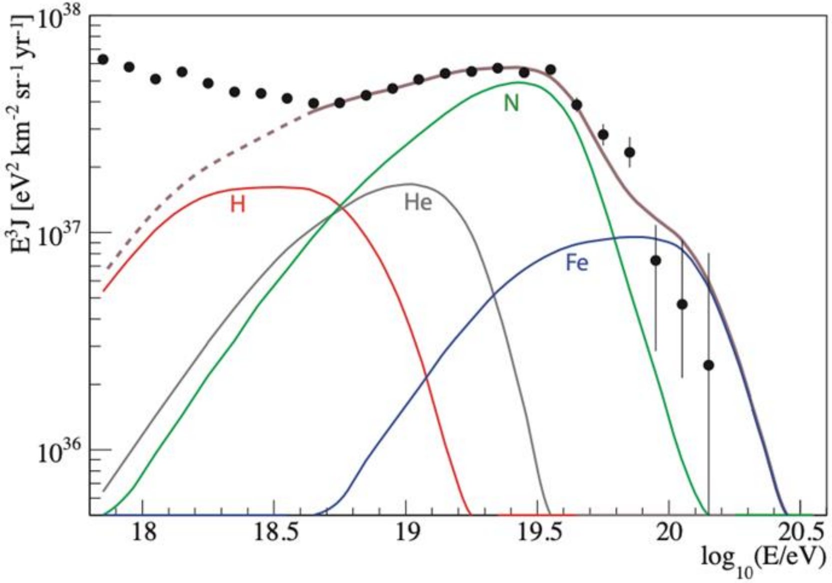
Spectrum and Mass Composition



Proton Knee and Iron Knee caused by Galactic Sources

Spectrum and Mass Composition at Ultra-high Energy

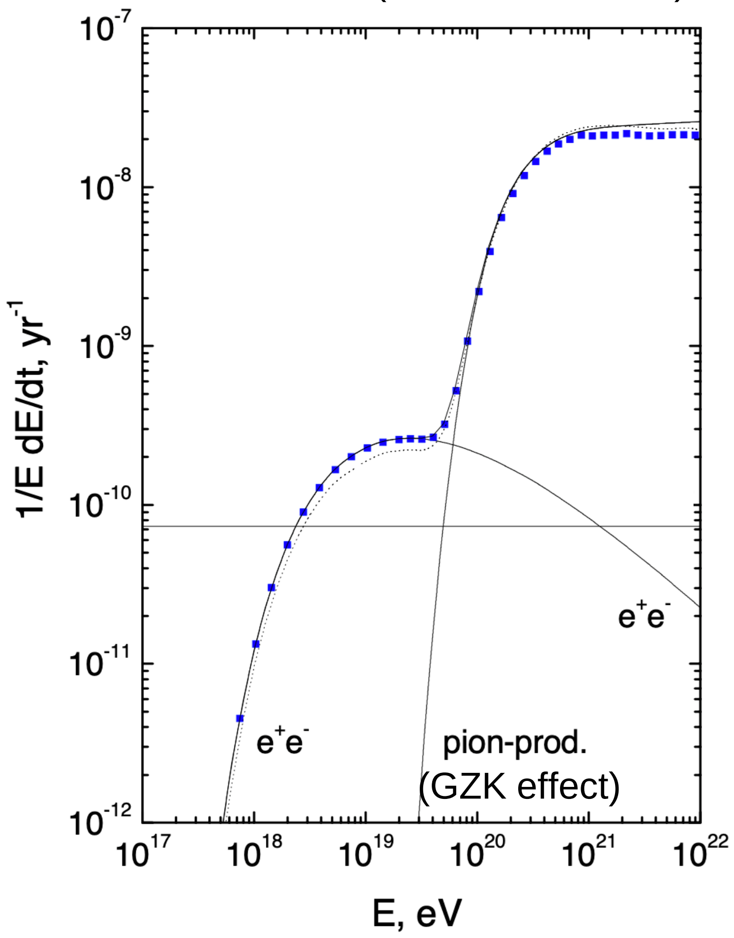




Spectrum amd Composition measured by the Auger Observatory

Explanation of the Spectrum Using Pure Propagation Effects

(Askhat et al 2007)



Electron-Positron Production:

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

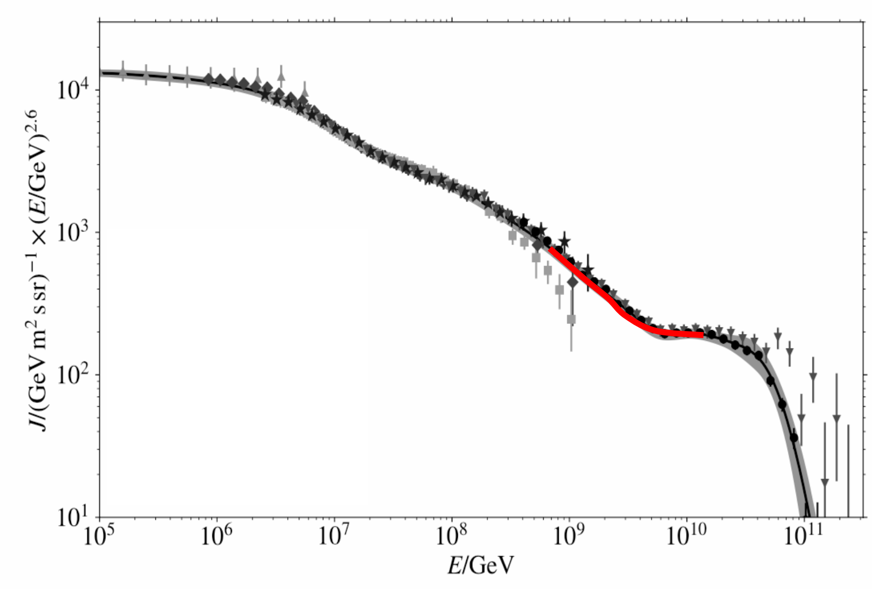
GZK effect

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

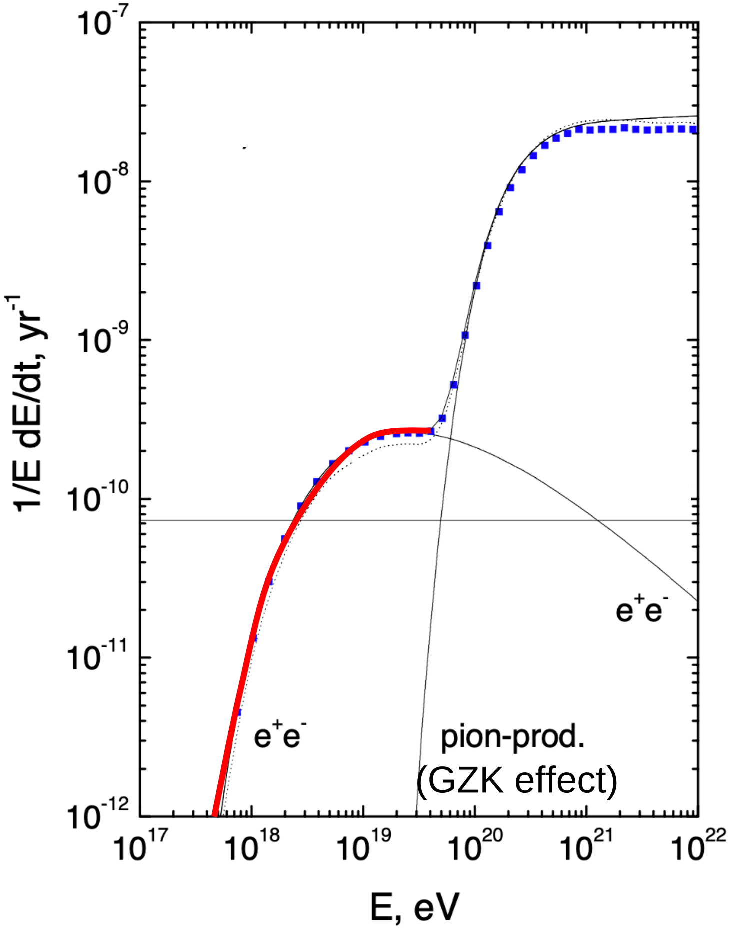
Explanation of the "Ankle"

Electron-Positron Production:

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



(Askhat et al 2007)

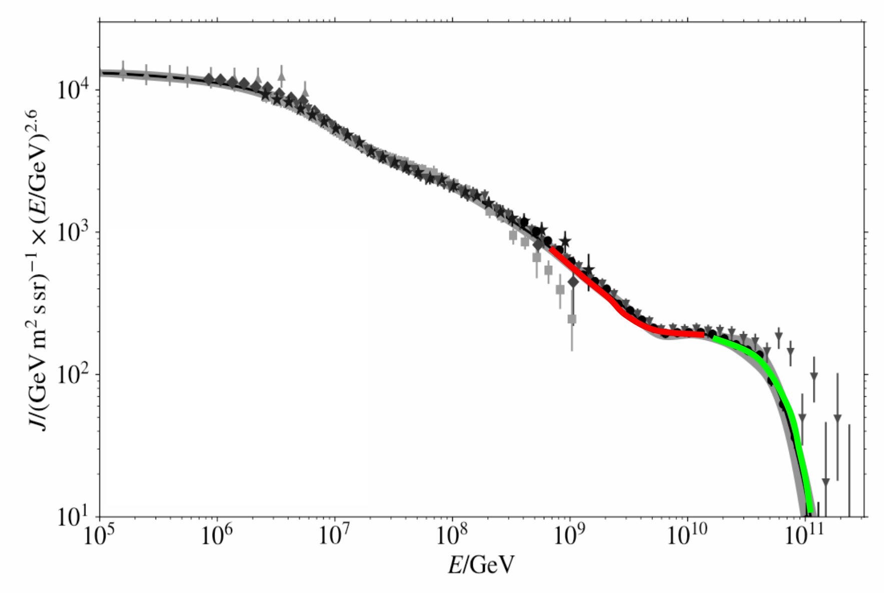


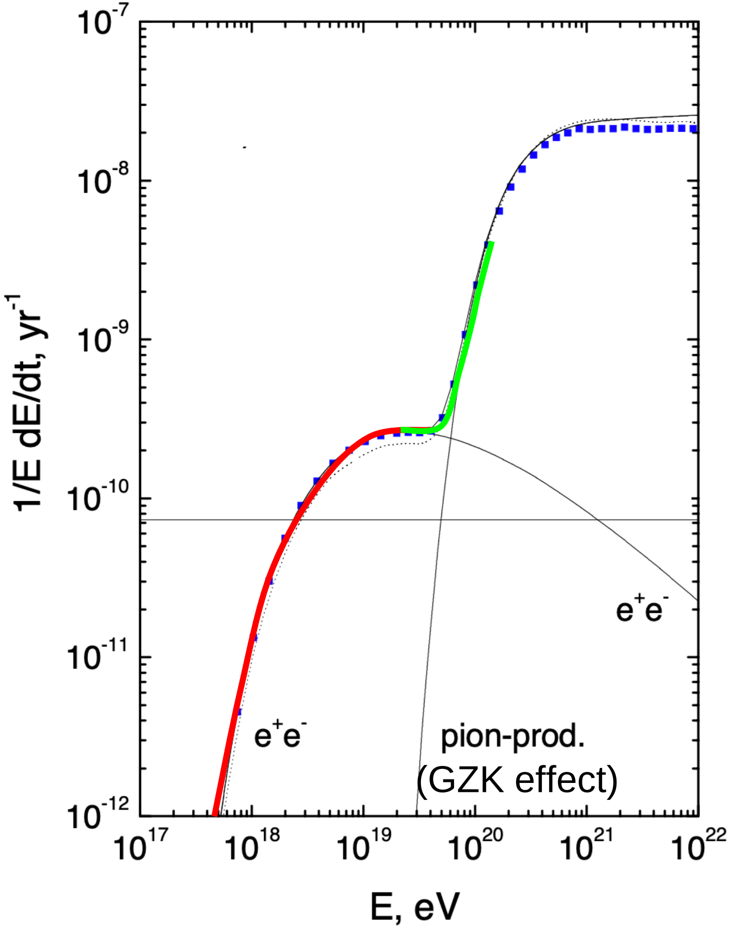
Explanation of the Suppression

(Askhat et al 2007)

GZK effect

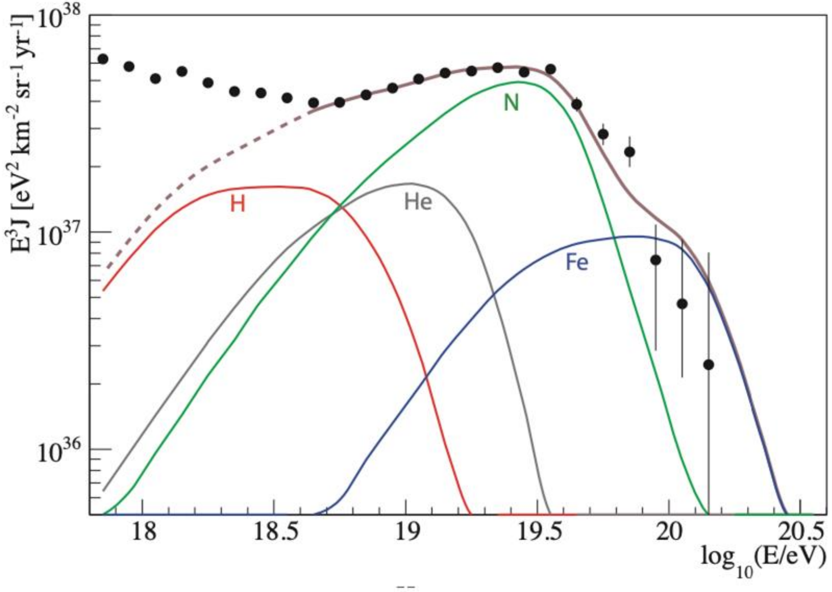
$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$





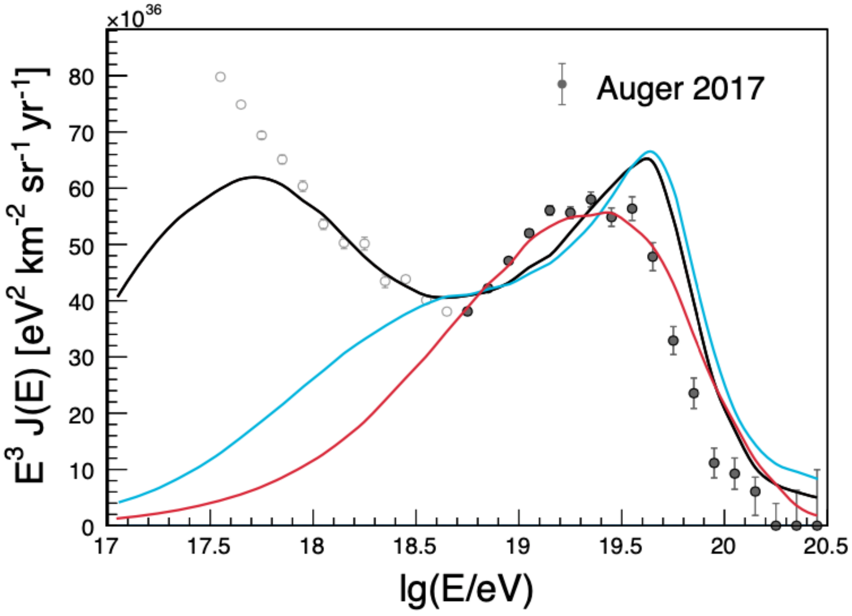
Problem of Pure-Propagation Explanation

1. It requires an almost **pure proton composition** at the ankle.



Problem of Pure-Propagation Explanation

2. GZK alone **can not fit the suppression** very well.



Possible Constrain for Sources

1. **Rigidity-dependent acceleration mechanism** Mass Composition

2. **Maximum Acceleration Energy** Suppression

3. **“High-Pass filter” Source Environment** Ankle

Summary of Part II

1. The observed dipole structure suggests an **extragalactic origin of UHECRs** and indicates they are correlated with Galaxies distribution.

2. Search of small-scale anisotropy is promising method for source identification, but **current statistics are not sufficient**.

3. **Observed spectrum and mass composition can only be partly explained by current theory.** More study of the acceleration mechanism and propagation effects are needed.

Acceleration Mechanism & Plausible Sources

Jiani Chu

outline

Hillas plot

second order Fermi acceleration

first order Fermi acceleration

plausible sources

summary

- UHECRs: >1e18 eV
- LHC : 1.4e13 eV

=>How to accelerate particles to such high energy?

Larmor motion/ Gyromotion

Equation of motion :

$$m\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v}\times\vec{B}) + m\vec{g}$$

assuming $\vec{B} = B\vec{e}_z$

simple harmonic oscillator solution: circular motion

Larmor radius/Gyroradius

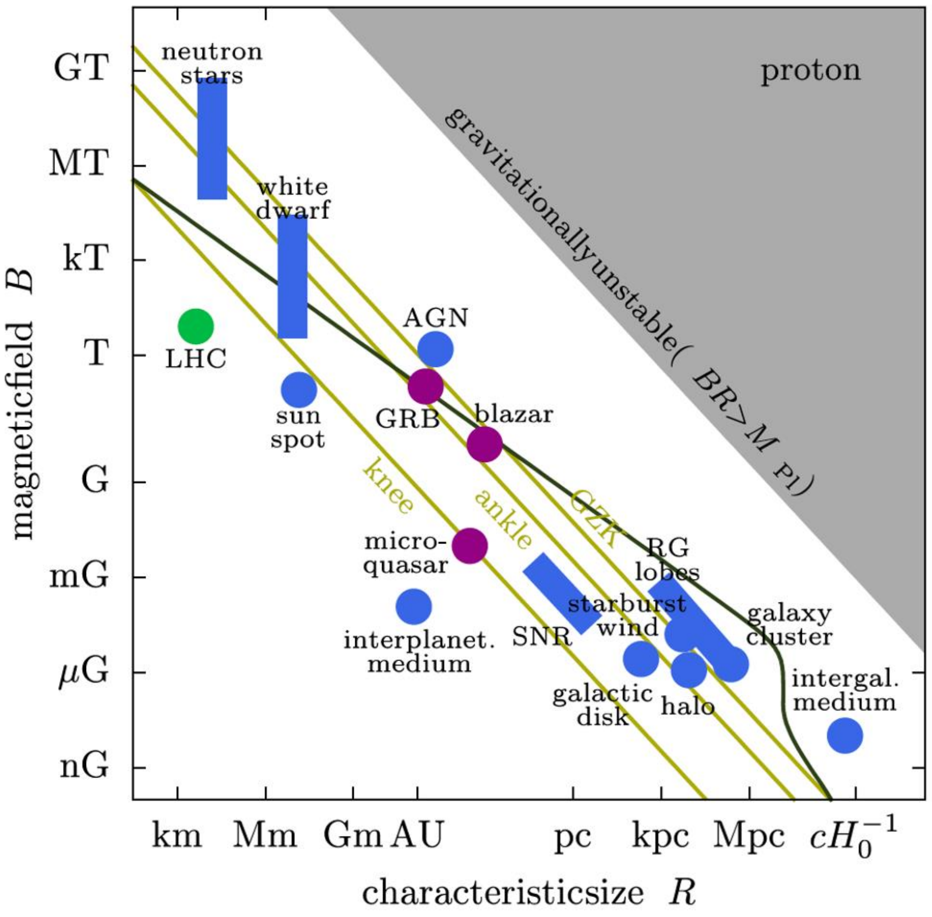
$$r_L = \frac{v_\perp}{\omega_c} = \frac{mv_\perp}{|q|B}$$

relativistic

$$r_L = \frac{1}{\sqrt{4\pi\alpha}}\frac{E}{ZB} = 1.1\,\frac{1}{Z}\left(\frac{E}{10^9\,\mathrm{GeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1}\mathrm{kpc}\,;$$

Hillas plot

$$E \lesssim Z \left(\frac{R}{\text{kpc}}\right)\left(\frac{B}{\mu\text{G}}\right) \times 10^9\ \text{GeV}\,.$$



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Fermi acceleration

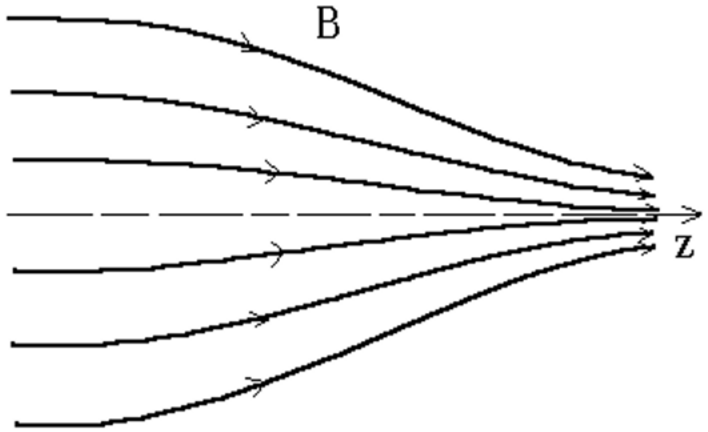
magnetic mirror : $\nabla B // \overrightarrow{B}$

reflecciton → magnetic trap

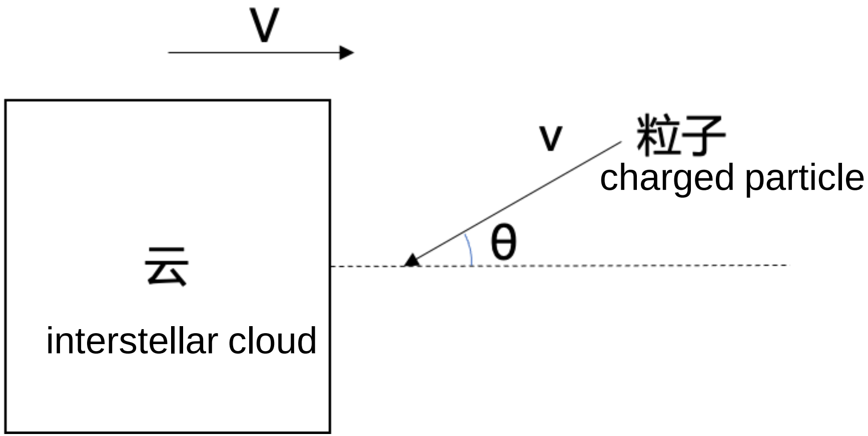
1 geomagnetic field

2 Tokamak

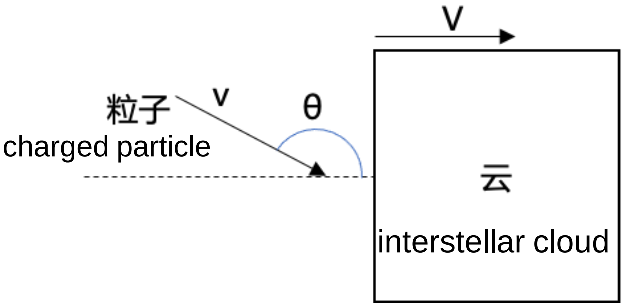
…



Fermi first proposed magnetic mirror as a mechanism to accelerate cosmic ray



head-on collision   gain energy



tail-end scattering   lose energy

For a particle, the probability of collision at $\theta \propto (v + V cos\theta)$

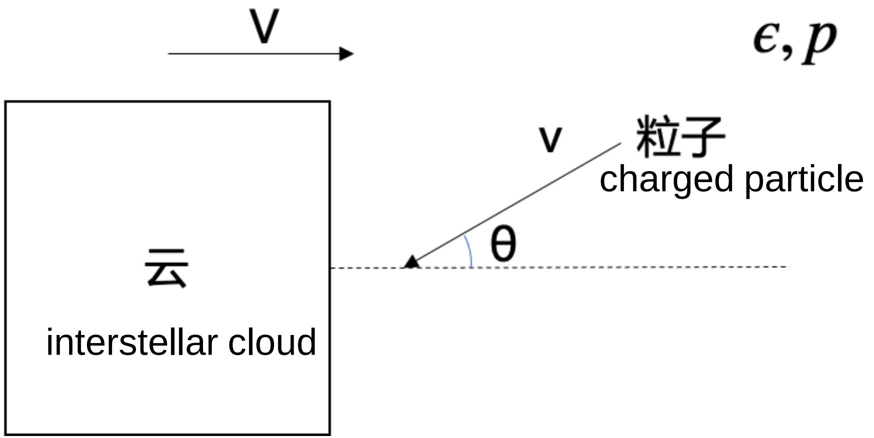
A collision is more likely a head-on collision.

in cloud'frame

$$\epsilon' = \gamma(\epsilon + Vp cos\theta)$$

$$p'_x = \gamma(p cos\theta + \frac{V\epsilon}{c^2})$$

$$\gamma = \sqrt{1 - \frac{V^2}{c^2}}$$



after collision: p'_x changes to $-p'_x$, ϵ is conserved

in rest frame

$$\epsilon'' = \gamma(\epsilon + Vp'_x) = \gamma^2 \epsilon \left[1 + \frac{2Vv cos\theta}{c^2} + \left(\frac{V}{c}\right)^2\right]$$

$$\Rightarrow \Delta\epsilon = \epsilon'' - \epsilon = \epsilon \left[\frac{2Vv cos\theta}{c^2} + \left(\frac{V}{c}\right)^2\right]$$

Second order Fermi Acceleration

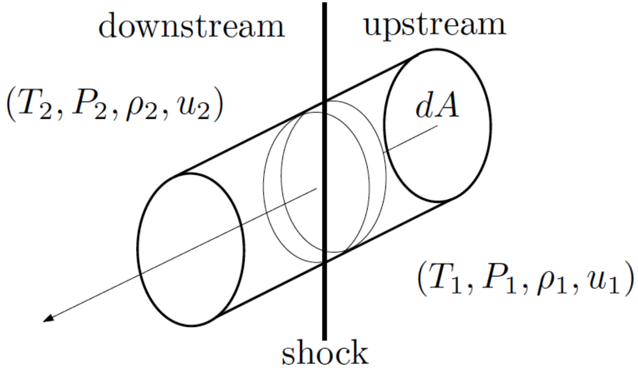
if assuming the clouds in the universe have a completely random direction of motion, $P(\theta \sim \theta + d\theta) \propto sin(\theta)$

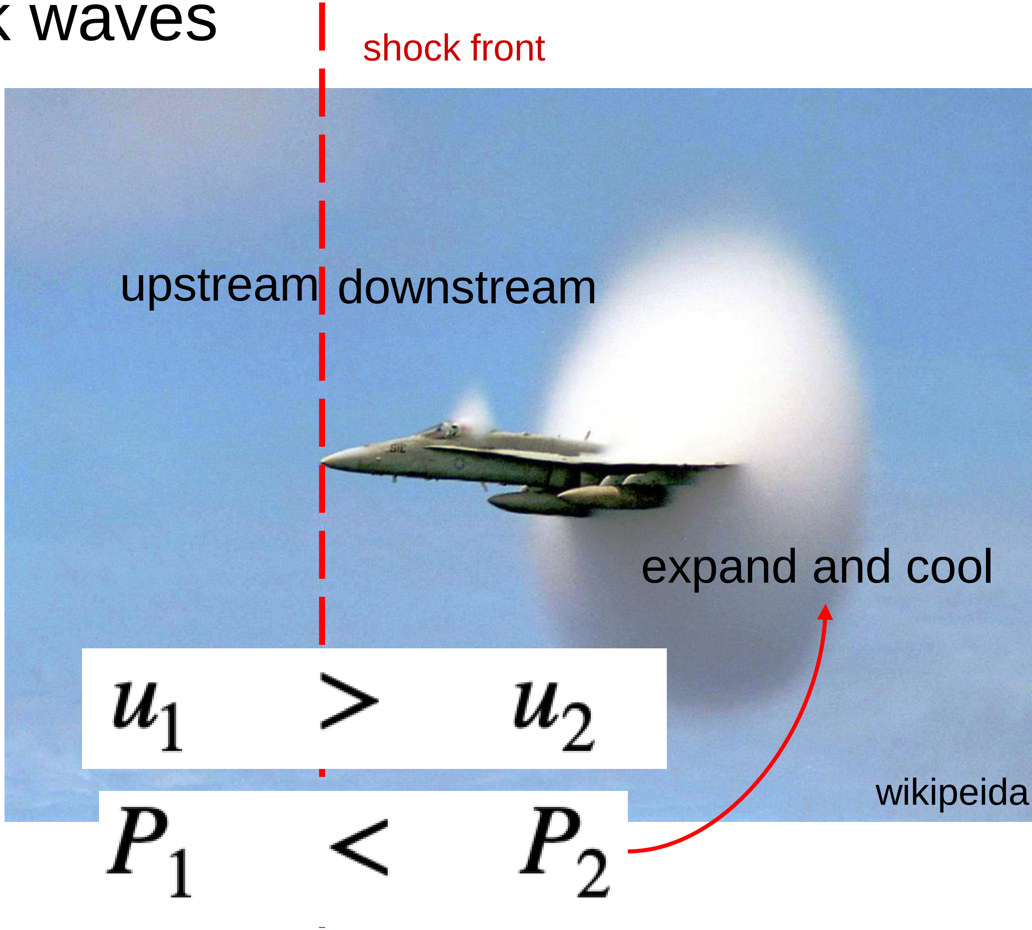
net effect: $$\langle \Delta\epsilon \rangle = \frac{2\epsilon V v}{c^2} \langle \cos\theta \rangle = \frac{2\epsilon V v}{c^2} \frac{\int_0^\pi \cos\theta [v + Vcos\theta] \sin\theta \, d\theta}{\int_0^\pi [v + Vcos\theta] \sin\theta \, d\theta}$$
$$= \frac{2\epsilon}{3} \left(\frac{V}{c}\right)^2$$

Fermi acceleration at shock waves

shock wave： like *supersonic aircraft*

in astrophysics: supernova remanent etc.





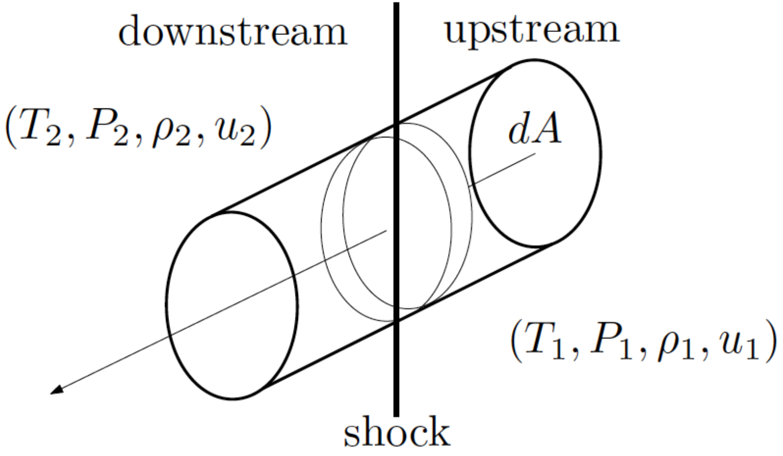
Fermi acceleration at shock waves

downstream frame: $E' = \gamma_u (E + u\, p \cos\theta)$

upstream → downstream $\dfrac{\delta E}{E} = u \cos\theta$

assuming isotropy $dP = 2 \sin\theta \ \cos\theta \ d\theta$

upstream → downstream $\dfrac{\Delta E}{E} = \dfrac{2}{3} u$



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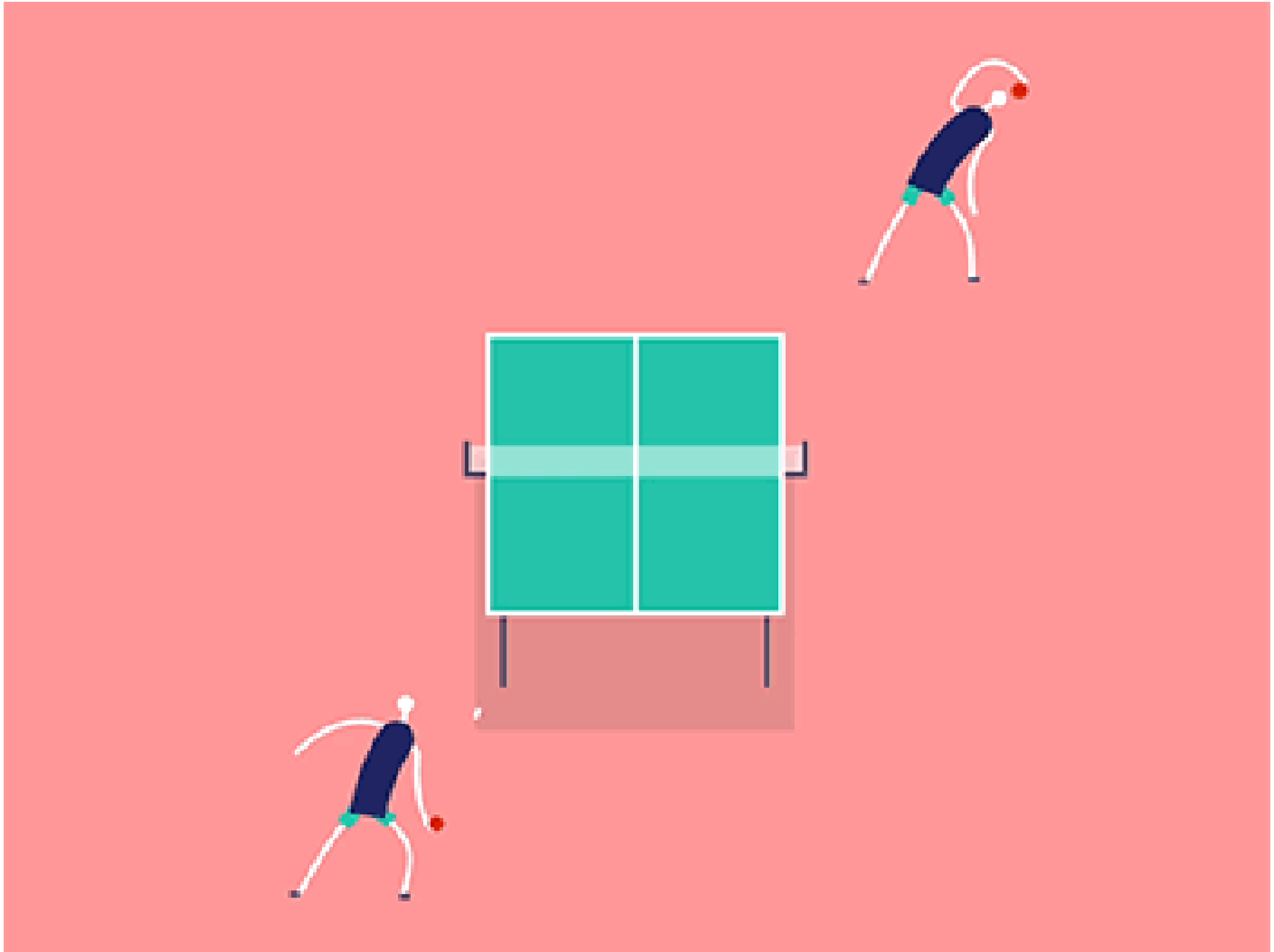
$$\langle \delta E \rangle / E|_{\mathrm{up}\to\mathrm{down}} = \langle \delta E \rangle / E|_{\mathrm{down}\to\mathrm{up}}$$

net effect: $\dfrac{\langle \Delta E \rangle}{E} = \dfrac{4}{3} u = \dfrac{4}{3} (u_1 - u_2)$

first order: more efficient !

shock wave direciton→ first order contribution



plausible sources: gamma AGN

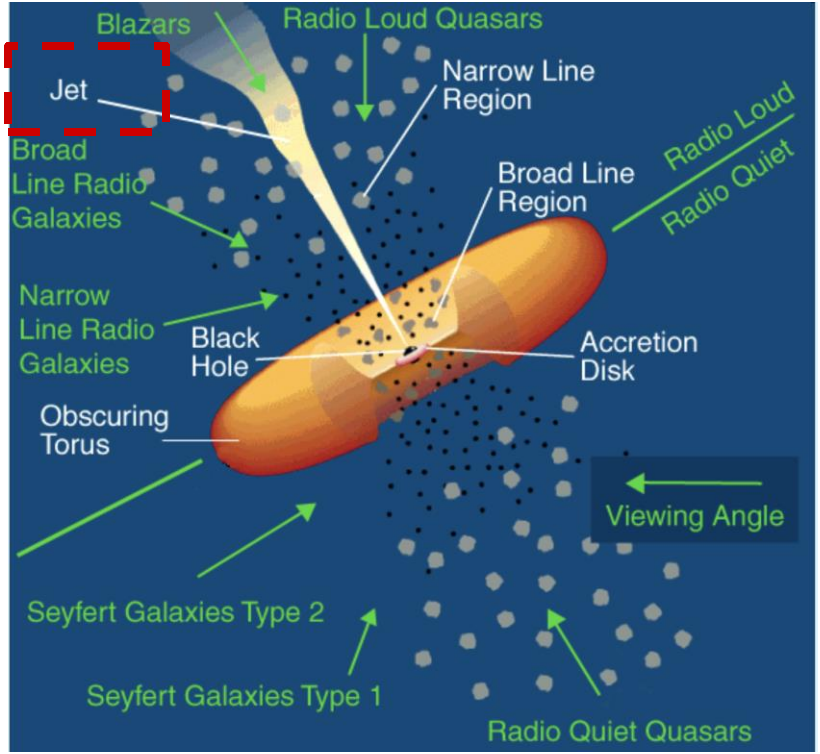
hotspots, jet: strong collisionless shock

→ environment for acceleration

observation :

Cen A: gamma ray emmission+enhanced activity ~100Myr→ can accelerate 1e20 eV

→ neutrino→future multi messager obervation



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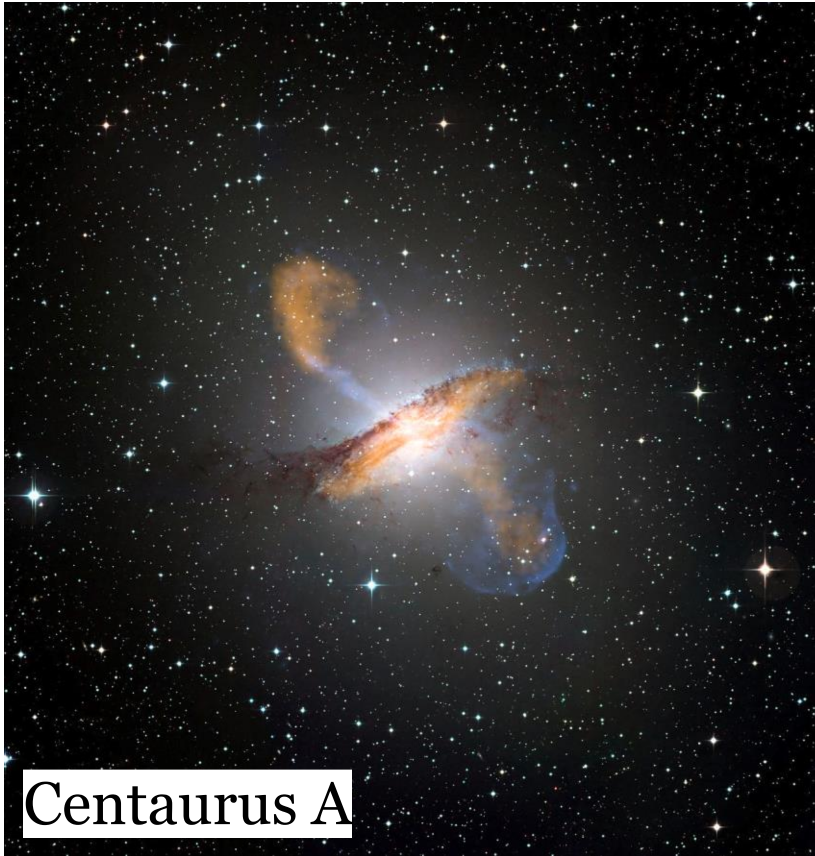


plausible sources: SBGs

stellar winds ,supernova remanent

→ encironment for acceleration

observation:

- correlation of UHECRs and SBGs

  M82: leading correlation

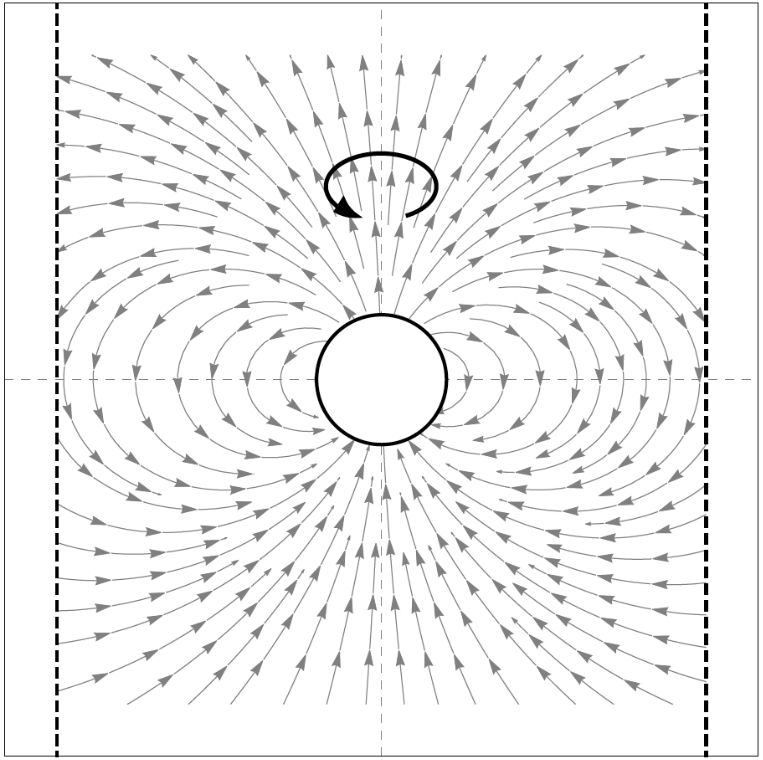
  IC342:second relative contribution

Unipolar induction

rotating neutron star
subpbermassive BH

rotating magnetic filed → potential difference
→ acceleration

many opportunities for energy loss exits



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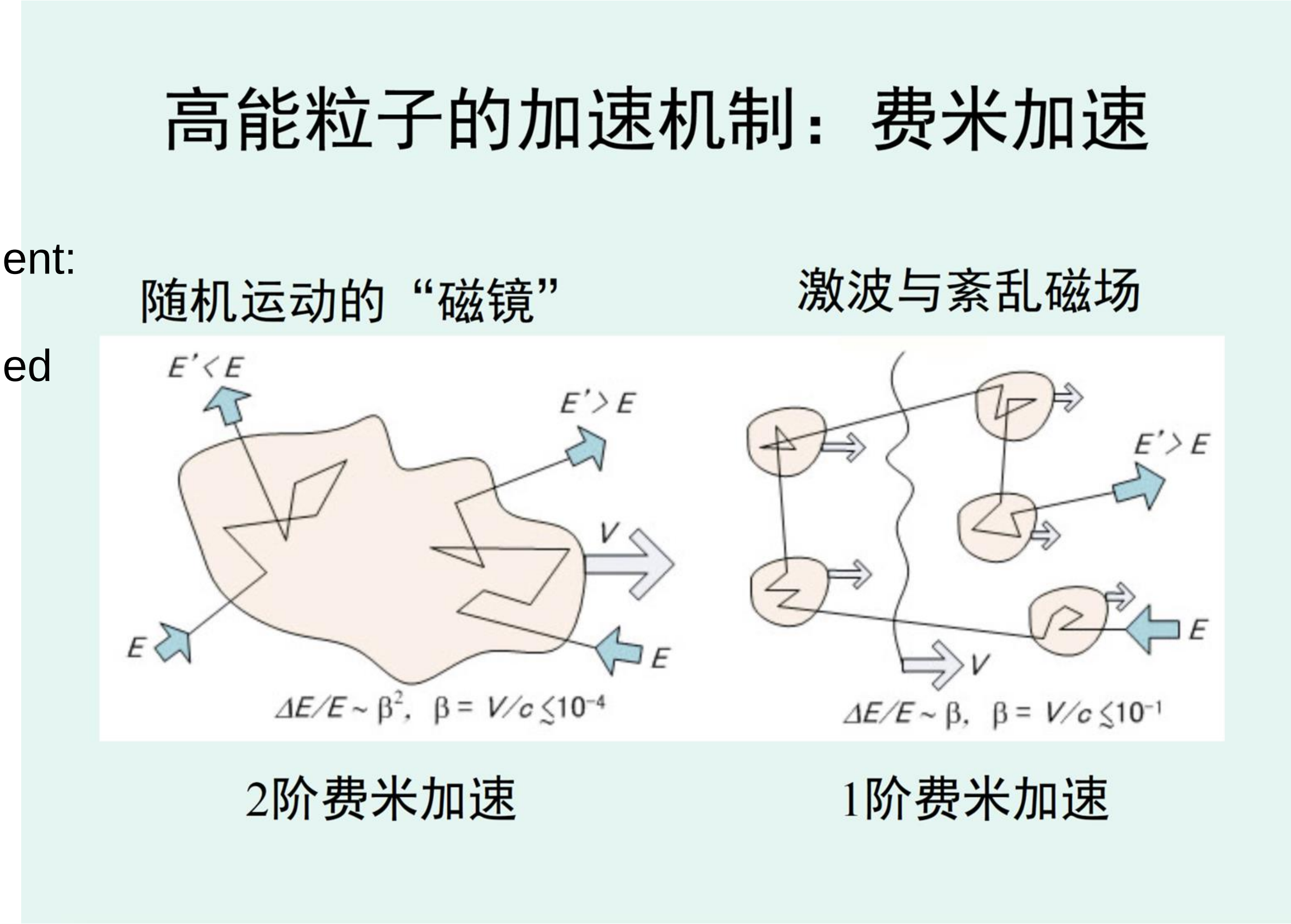
summary

acceleration enviroment:
shock wave
turbulent magnetic filed

sourece:
gamma AGN
SBGs
……



Search for UHECR Sources

Zitao Hu

Contents

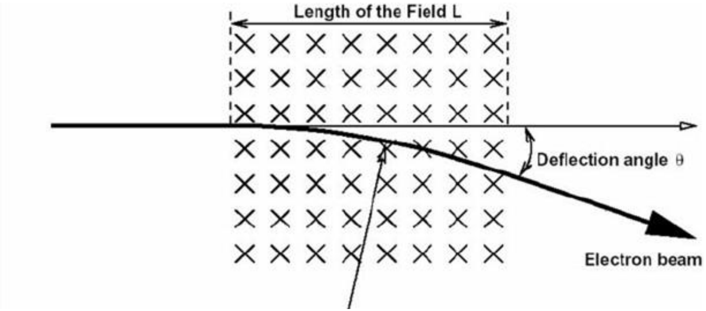
1. Multi-messenger detection for UHECR

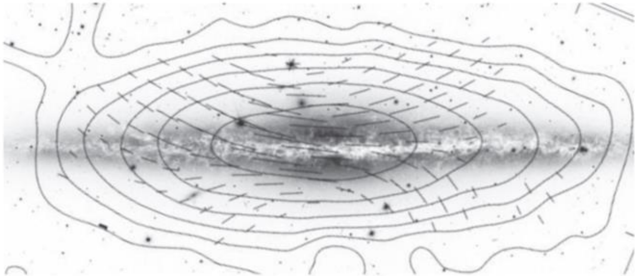
2. Detectors in the future

3. Meaning of UHECR study

Magnetic Deflections

- UHECRs are deflected in galactic and in extragalactic magnetic fields (GMF/EGMF) by a non-negligible amount
- Little is known about
  - the strength and correlation length of the extragalactic magnetic fields
  - the distance of the UHECR sources





the magnetic structure of Milky Way, Krause (2009)

Origins of UHECRs

- UHE gamma rays
  - interactions with the CMB make the Universe opaque to UHE gamma rays
    - they do not reach Earth from beyond 10 Mpc.
  - cascade down to GeV–TeV
- UHE neutrinos
  - travel unimpeded
  - energies unaffected by interaction
  - point back directly at their points of production

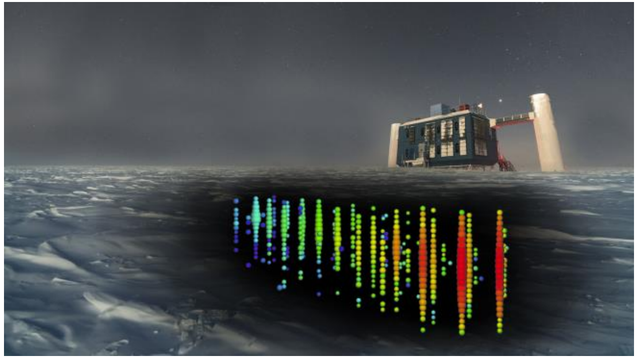
Origins of UHECRs

- UHE neutrinos & UHECR sources
  - neutrinos may also be produced by UHECRs interacting inside their sources
  - neutron star:
    - 0.1-1 EeV neutrinos (Fang et al., 2013)
  - starburst superwind:
    - neutrino energy < 0.1 EeV (Loeb & Waxman, 2006)

Multi-Messenger Approach

Image: Jack Pairin/IceCube/NSF.

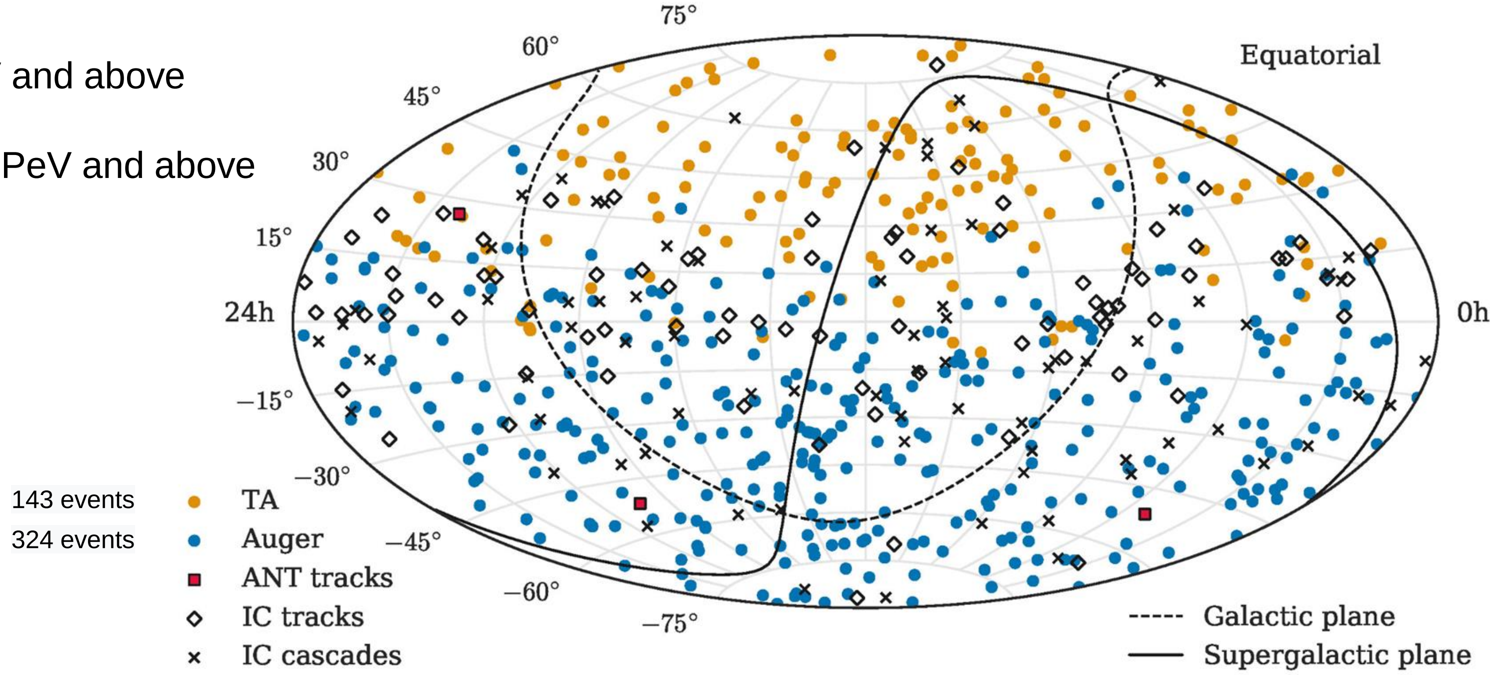
ANTARES Neutrino telescope



IceCube Neutrino Observatory, *Image: ESA*

Multi-Messenger Approach

UHECR:
    near 50 EeV and above
neutrino:
    hundreds of PeV and above



Credit: The ANTARES, IceCube, Pierre Auger and Telescope Array collaborations

Analysis Methods

1. Search for excesses of neutrinos clustering in the vicinity of UHECR directions.

2. Searches for an excess of UHECRs in the direction of the highest-energy neutrinos.

3. Searches for an excess of pairs of UHECRs and highest-energy neutrinos on different angular scales.

Analysis Methods

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All three yield the same main result:

they did not find a correlation between UHECRs and neutrinos.

Possible Reasons

1. Nearby UHECR sources are not efficient neutrino emitters

2. The neutrino flux of sources in the local universe is too small to be detected with IceCube and ANTARES with the analyses presented here

3. Intergalactic magnetic fields would scramble the direction of cosmic rays and delay their arrival at Earth, thus losing any correlation with neutrinos produced in the same source.

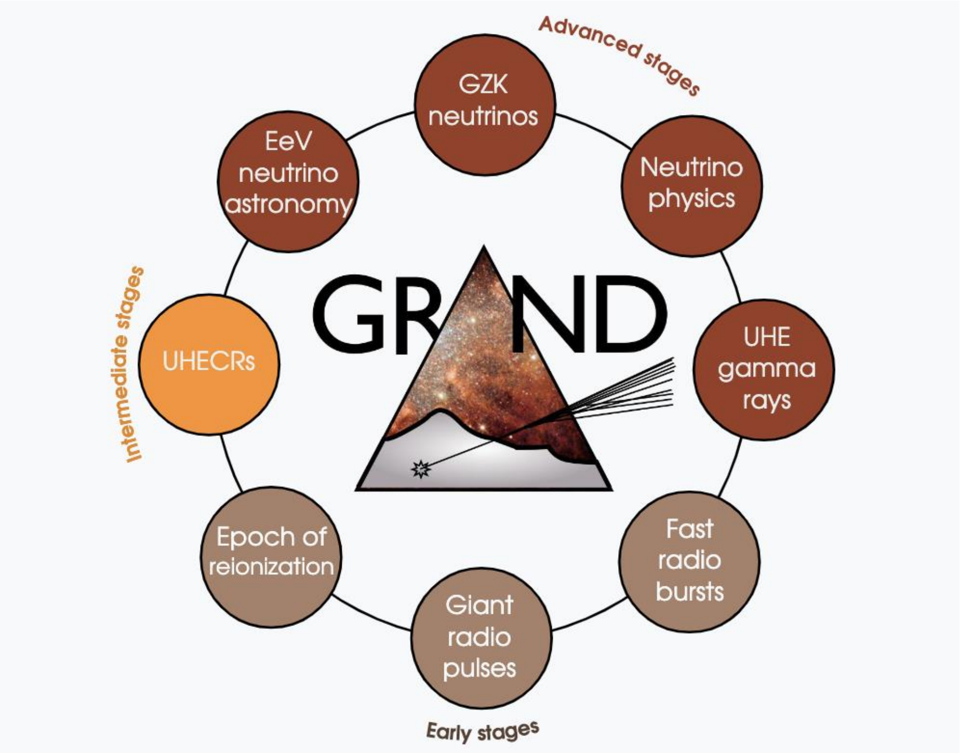
   The deflection in the EGMF causes a time delay on the order of a thousand years (Davoudifar, 2011)

What’s Next?

- Improving the simulation of galactic magnetic fields
- Better UHECR observatories
- Better knowledge of the proton/nuclei composition of cosmic rays
- Next-generation neutrino observatories
- ……

Future Detectors

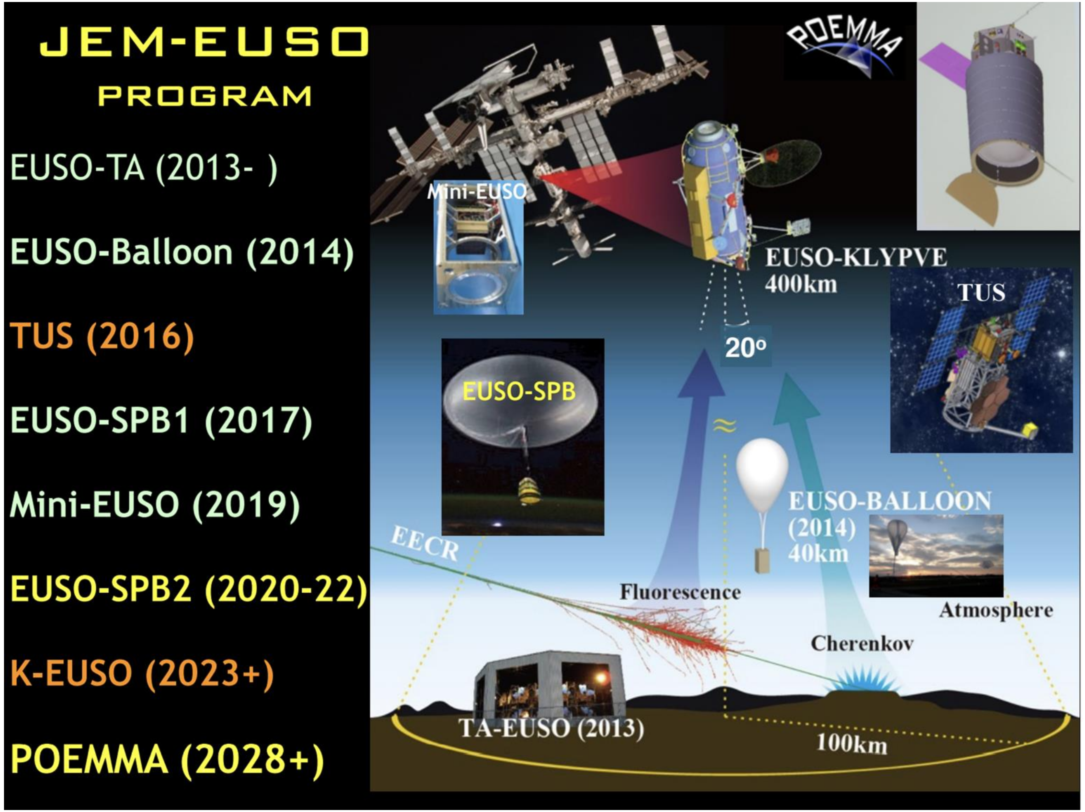
- Earth-based detectors
  - Upgrade of Auger and TA
  - GRAND, Giant Radio Array for Neutrino Detection



Future Detectors

- Space experiments
  - JEM-EUSO program, Extreme Universe Space Observatory
  - EUSO-KLYPVE will measure about 170 events at E>57EeV per year.

Extreme Universe Space Observatory



Bertaina, 2018

Multi-Messenger Approach

UHECR:

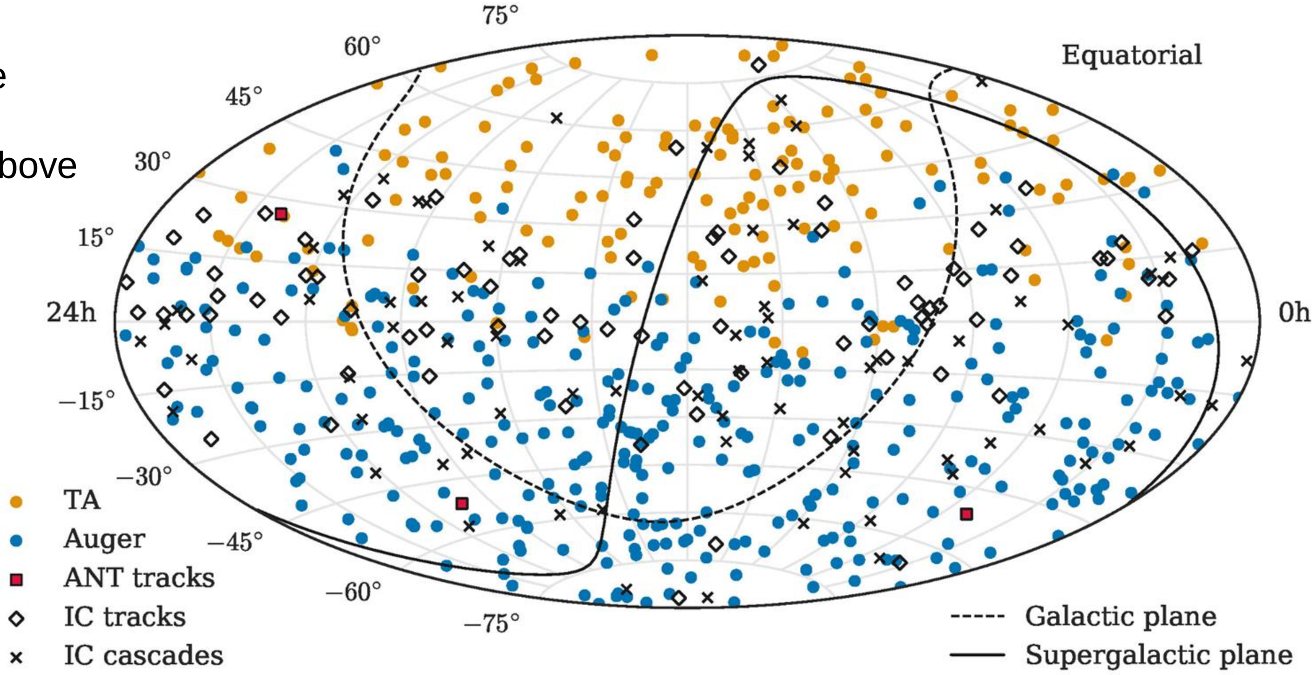
near 50 EeV and above

neutrino:

hundreds of PeV and above

143 events

324 events



Credit: The ANTARES, IceCube, Pierre Auger and Telescope Array collaborations

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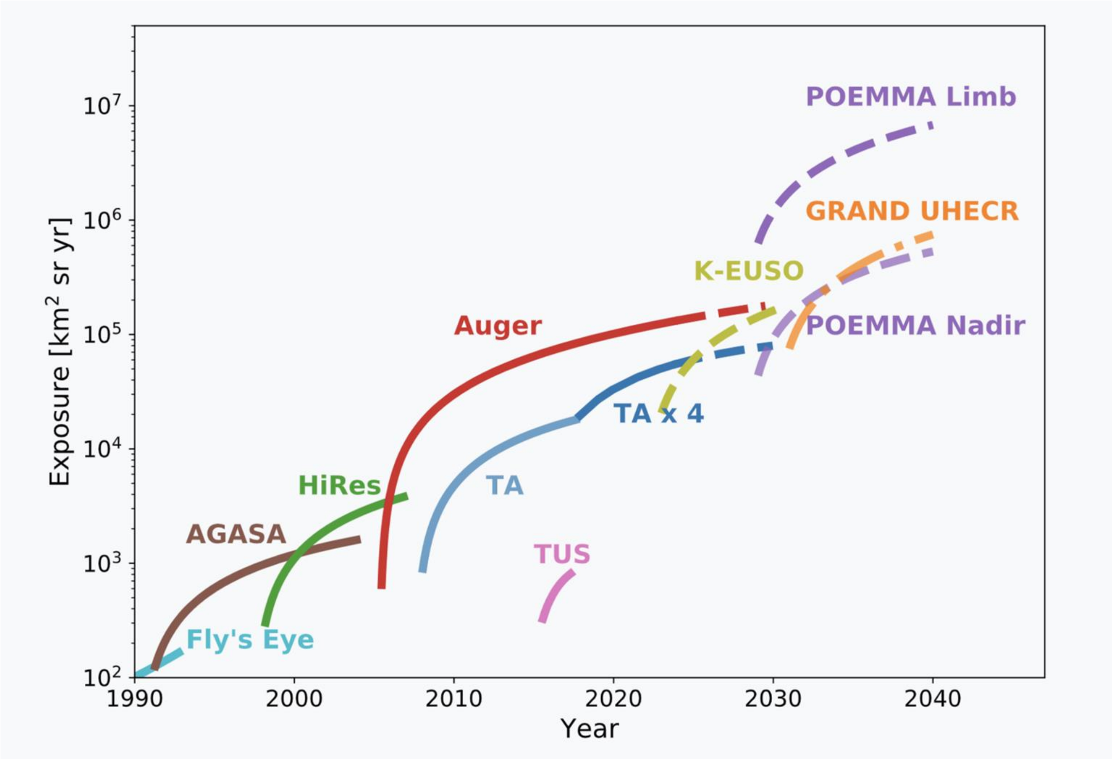
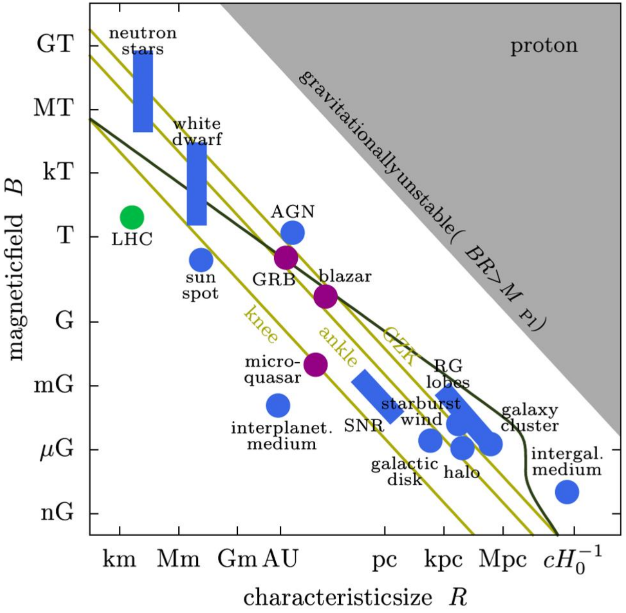


Batista et al., 2019

UHECR and New Physics

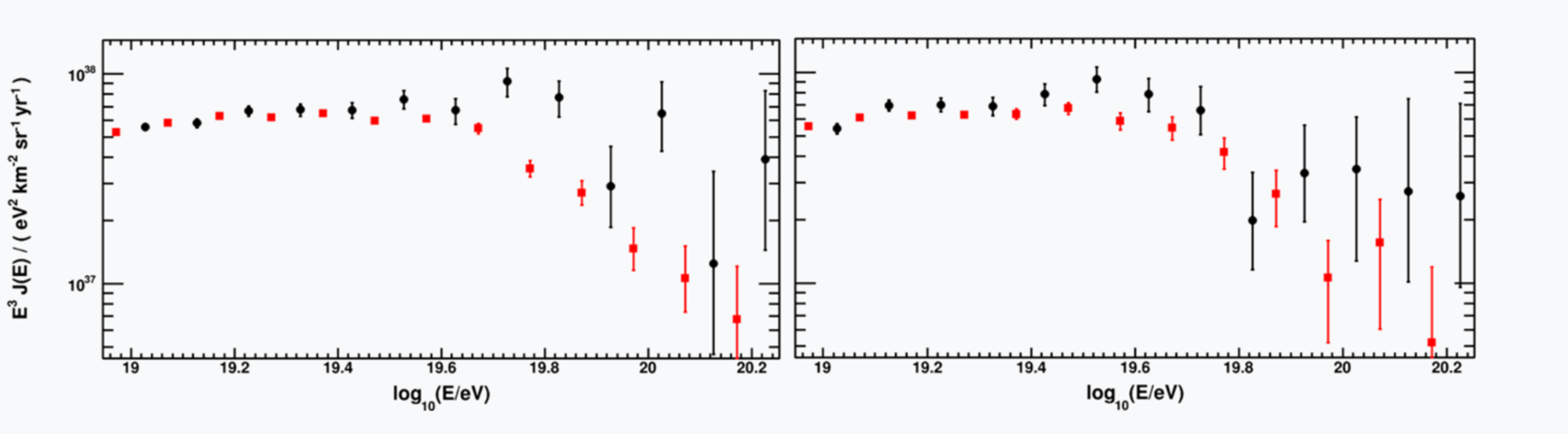
- Search for unknow astrophysical sources
  - > 1000 EeV CR or > 100 EeV neutrino



UHECR and New Physics

- Search for unknow astrophysical sources
  - > 1000 EeV CR or > 100 EeV neutrino
- Search for Lorentz invariant breaking effects
  - GZK energy thershold (~60EeV) is based on Lorentz invariant

$$E^2 = \mathbf{p}^2(1 + 2\delta) + m^2$$



Batista et al., 2019

UHECR and New Physics

- Search for unknow astrophysical sources
  - > 1000 EeV CR or > 100 EeV neutrino
- Search for Lorentz invariant breaking effects
  - GZK effect is based on Lorentz invariant
- UHECRs are the only particles with energies exceeding those available at terrestrial accelerators.
  - CR collisions center-of-mass energy: range up to 250TeV
  - LHC: 14TeV

Summary

- ***Neutrinos are a direct probe of hadronic interactions of UHECRs, but no correlation between neutrinos and UHECRs has been found yet.***
- ***Space-based detectors for UHECR research has the advantage of a very large exposure and a uniform coverage of the celestial sphere.***
- ***UHECRs can be used as probes of beyond standard model physics models.***

Appendix: Spectrum