OPEN DATA
AT THE PIERRE AUGER OBSERVATORY

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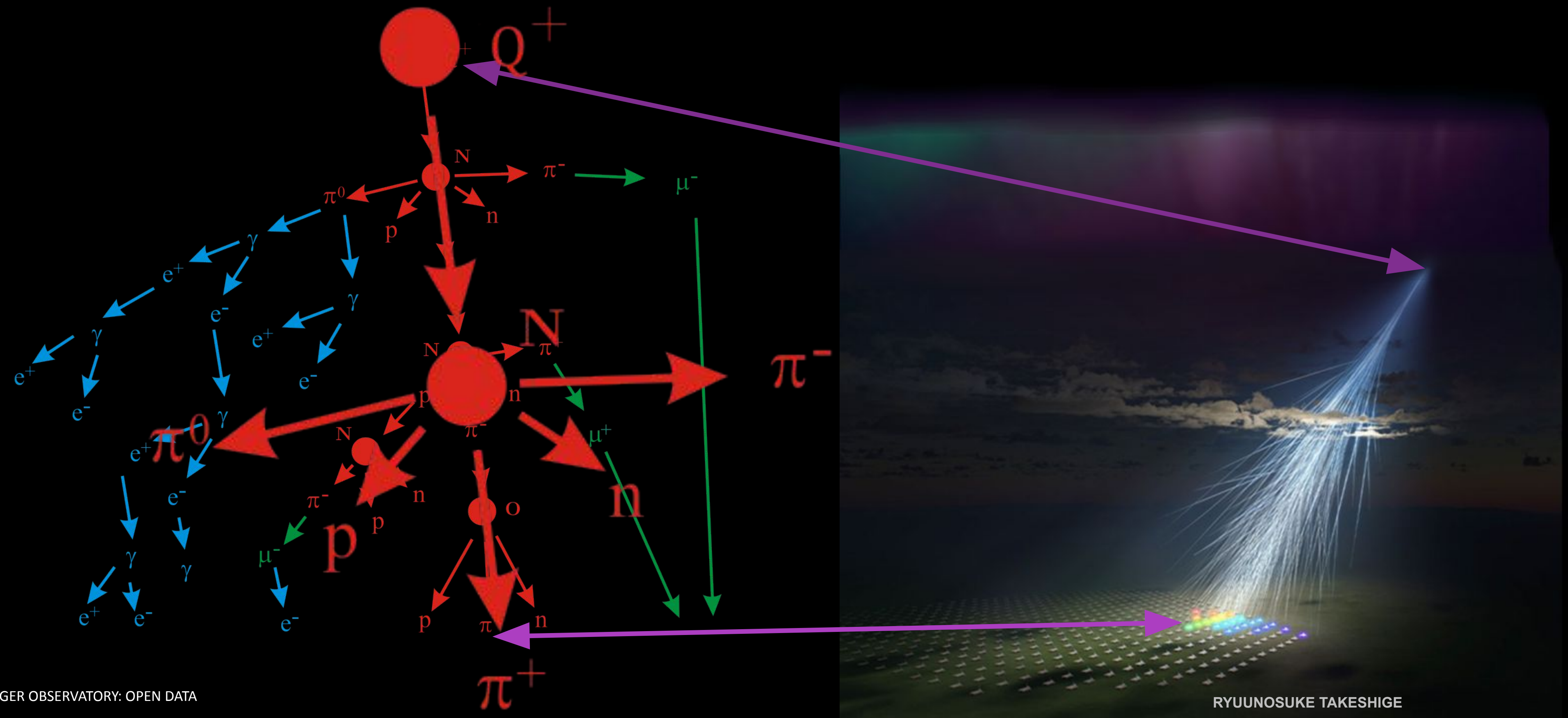
University of Nova Gorica

ULTRA-HIGH-ENERGY COSMIC RAYS

Astroparticle Physics: Unravelling the mysteries of the universe by exploring the *smallest phenomena*…



PIERRE AUGER OBSERVATORY: OPEN DATA

RYUUNOSUKE TAKESHIGE

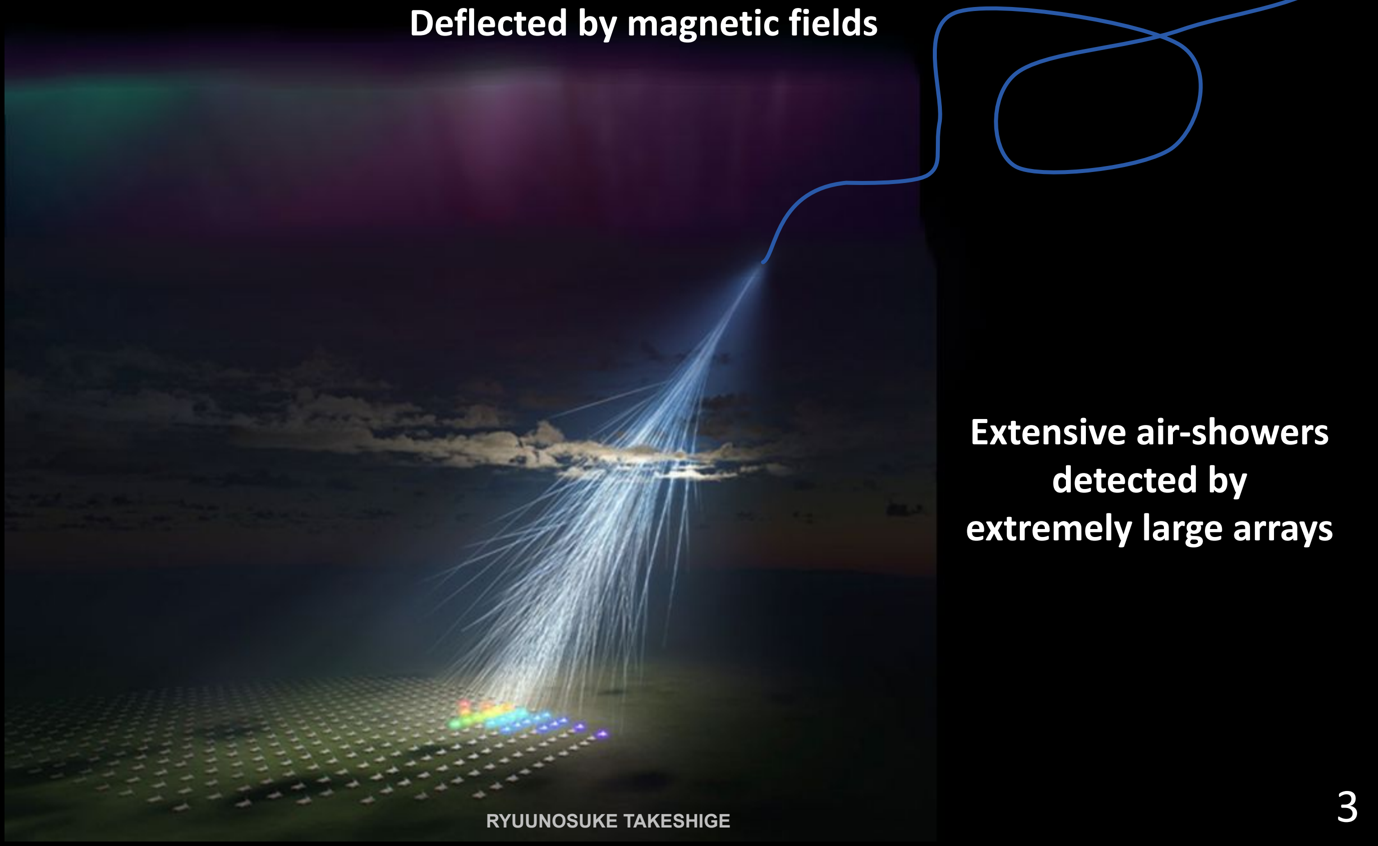
Extensive air-showers detected by extremely large arrays

ULTRA-HIGH-ENERGY COSMIC RAYS

Astroparticle Physics: Unravelling the mysteries of the universe by exploring the smallest phenomena *at cosmic scales*

Sources:
Most extreme galaxies in the universe

Atomic nuclei:
Deflected by magnetic fields



Extensive air-showers detected by extremely large arrays

Highest energy detected: "*Oh-My-God-Particle*"

$$E > 3 \times 10^{20}\ eV$$

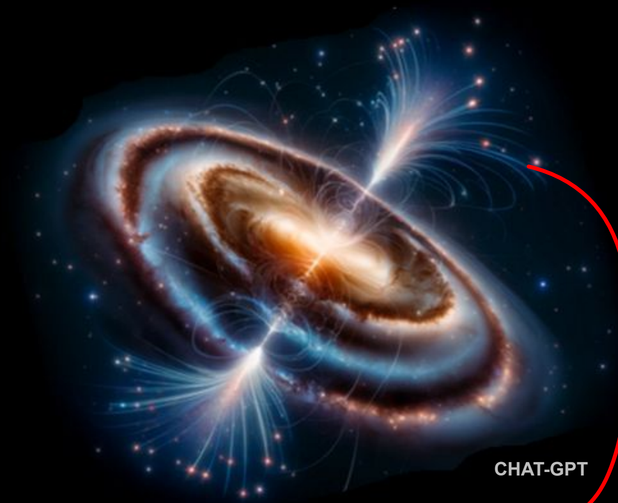
0.9999999999999999999999951 times light speed
(if proton)

ULTRA-HIGH-ENERGY COSMIC RAYS

THE BIGGEST QUESTION

Where do they come from?

Sources:
Most extreme galaxies in the universe



Atomic nuclei:
Deflected by magnetic fields

A complication…

ULTRA-HIGH-ENERGY COSMIC RAYS

THE BIGGEST QUESTION

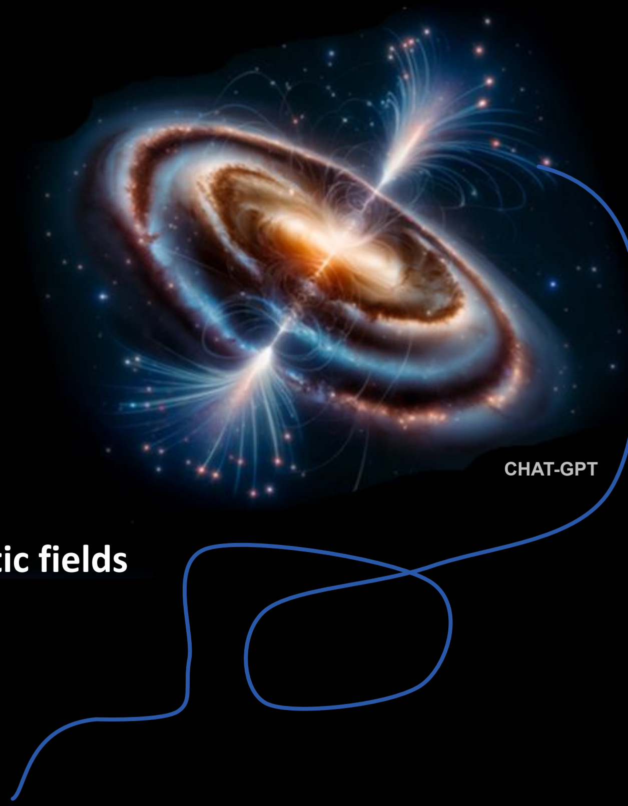
Where do they come from?

BIG QUESTIONS

What are they made of?

What are their energies?

Sources:
Most extreme galaxies in the universe



Atomic nuclei:
Deflected by magnetic fields

ULTRA-HIGH-ENERGY COSMIC RAYS

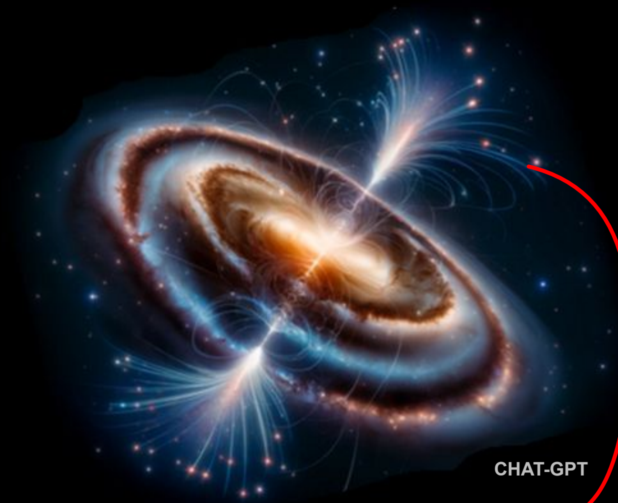
THE BIGGEST QUESTION

Where do they come from?

BIG QUESTIONS
What are they made of?
What are their energies?

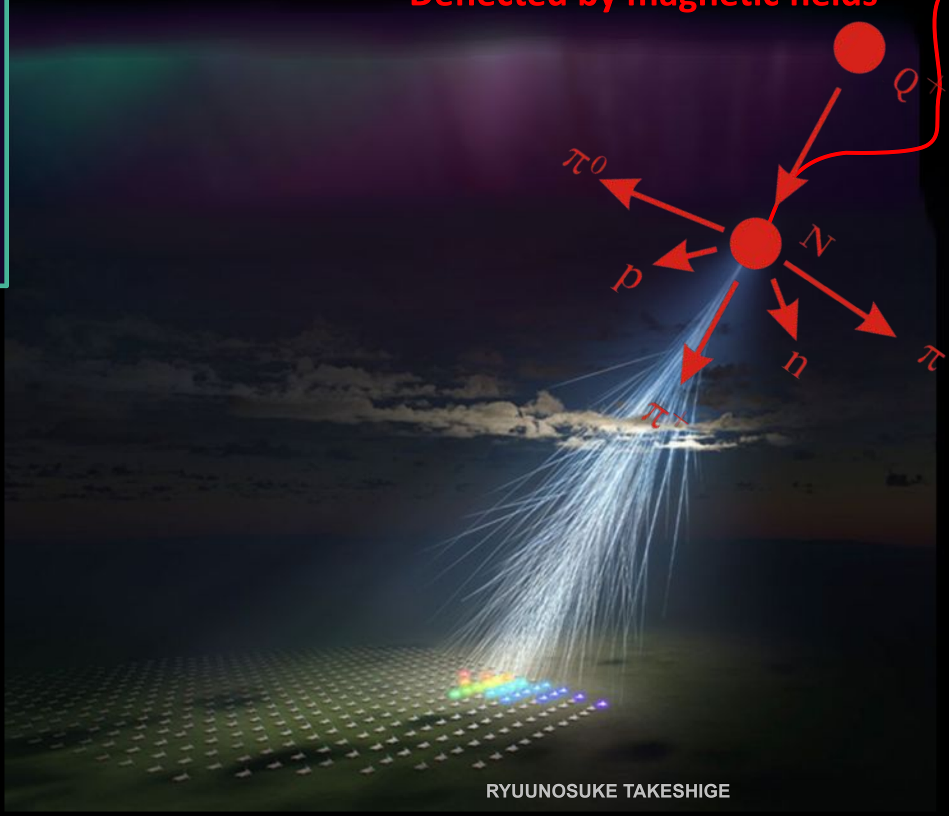
OTHER QUESTIONS
Magnetic Fields in the Universe
Fundamental Particle Interactions at extreme energies

Sources:
Most extreme galaxies in the universe



CHAT-GPT

Atomic nuclei:
Deflected by magnetic fields



RYUUNOSUKE TAKESHIGE

Extensive air-showers detected by extremely large arrays

ULTRA-HIGH-ENERGY COSMIC RAYS

THE BIGGEST QUESTION

Where do they come from?

BIG QUESTIONS
What are they made of?
What are their energies?

OTHER QUESTIONS
Magnetic Fields in the Universe
Fundamental Particle Interactions at extreme energies
Secondary and Accompanying Radiation (Multi-Messenger)
Violations of Relativity?

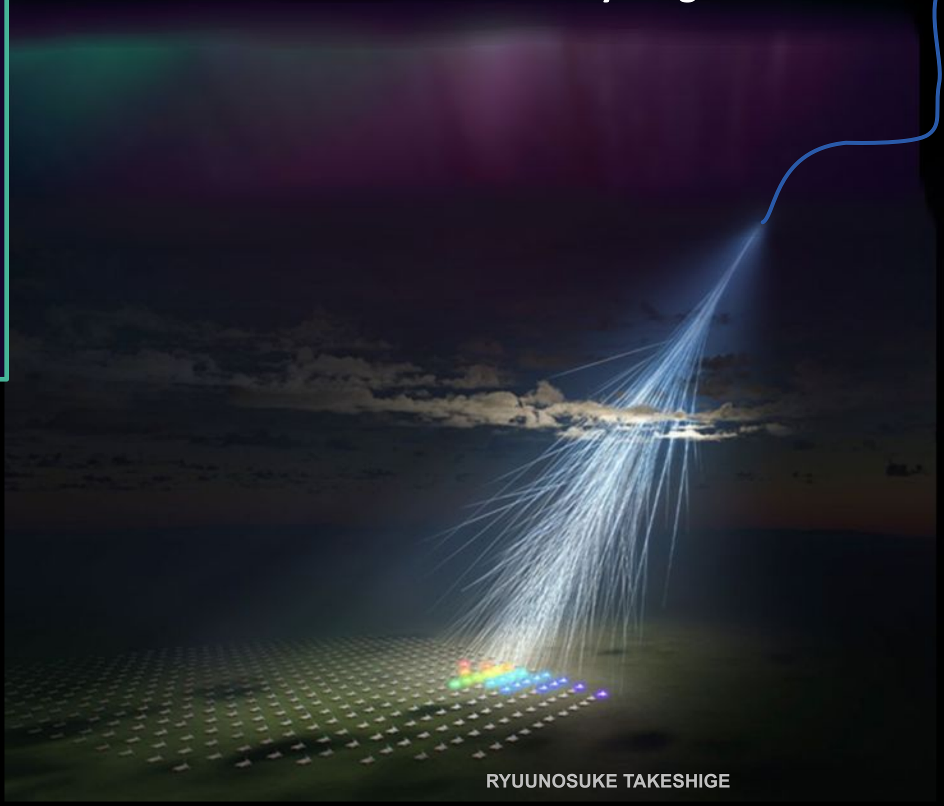
$$E^2 \neq m^2c^4 + p^2c^2 \; ?$$

$$\rightarrow E^2 = m^2c^4 + p^2c^2(1+\eta)$$

Sources:
Most extreme galaxies in the universe

CHAT-GPT

Atomic nuclei:
Deflected by magnetic fields



RYUUNOSUKE TAKESHIGE

Extensive air-showers detected by extremely large arrays

PIERRE AUGER OBSERVATORY: OPEN DATA

PIERRE AUGER OBSERVATORY

Highest energy multi-eye event

$3000\ \mathrm{km}^2$
18.5×Ljubljana

Ultra-High-Energy Cosmic Ray
Extensive Air-Shower
Particles

Four Fluorescence Detectors

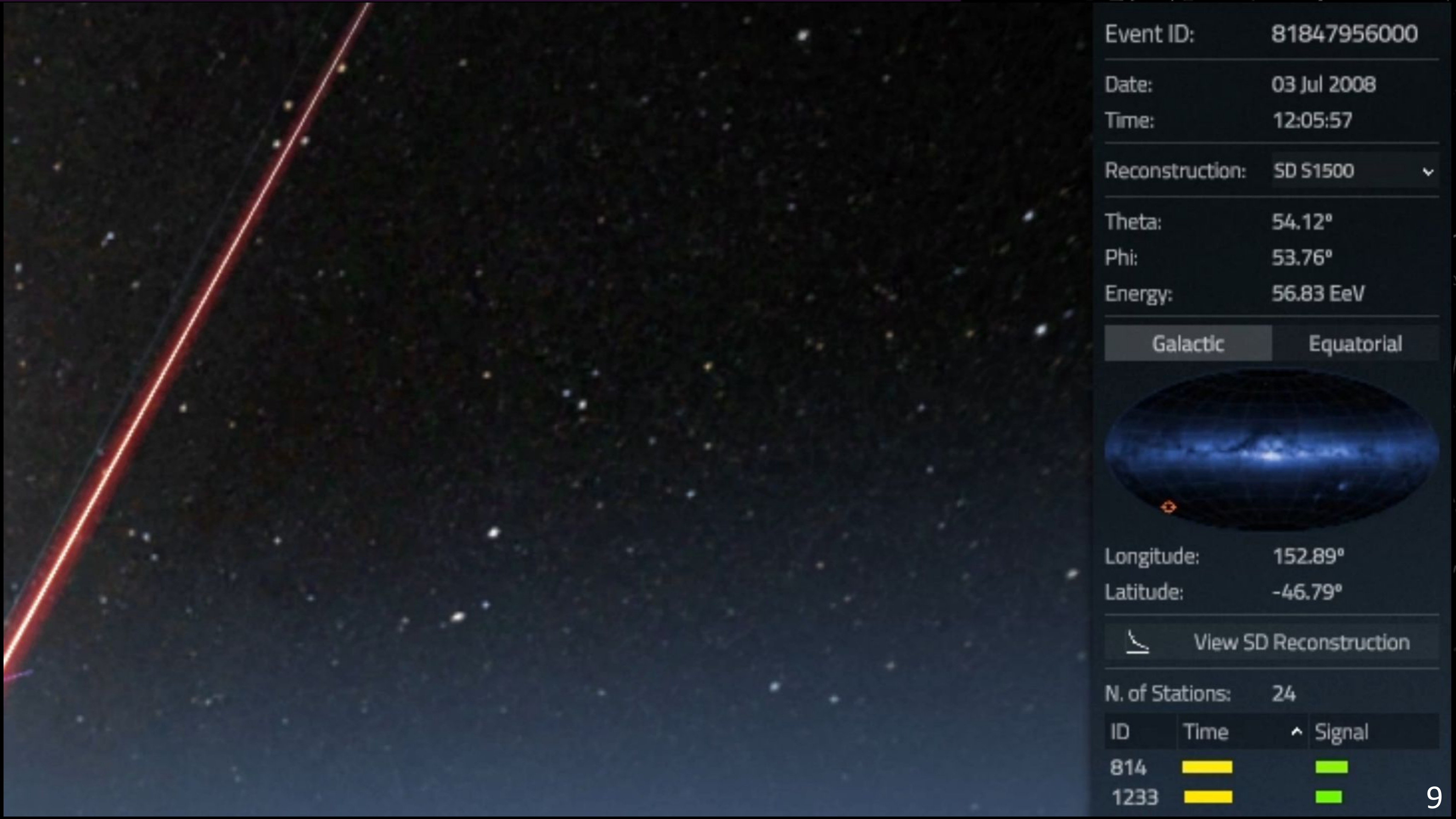
Open Data
3D Event Viewer

~1600 Surface Detectors

PIERRE AUGER OBSERVATORY

[Highest energy multi-eye event]

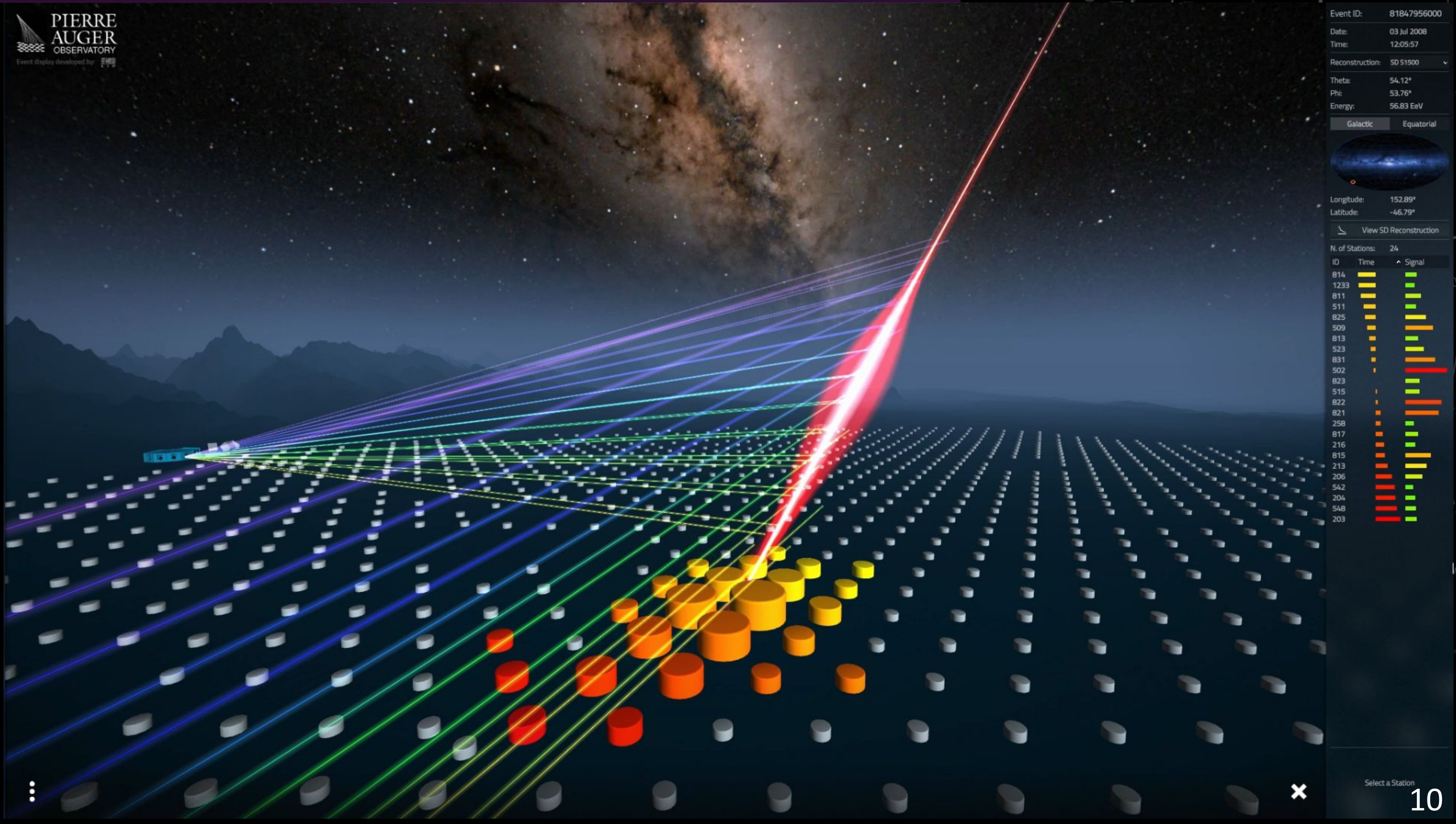
56.83 EeV or 9 J
47° off Galactic Plane
Extragalactic Source



PIERRE AUGER OBSERVATORY

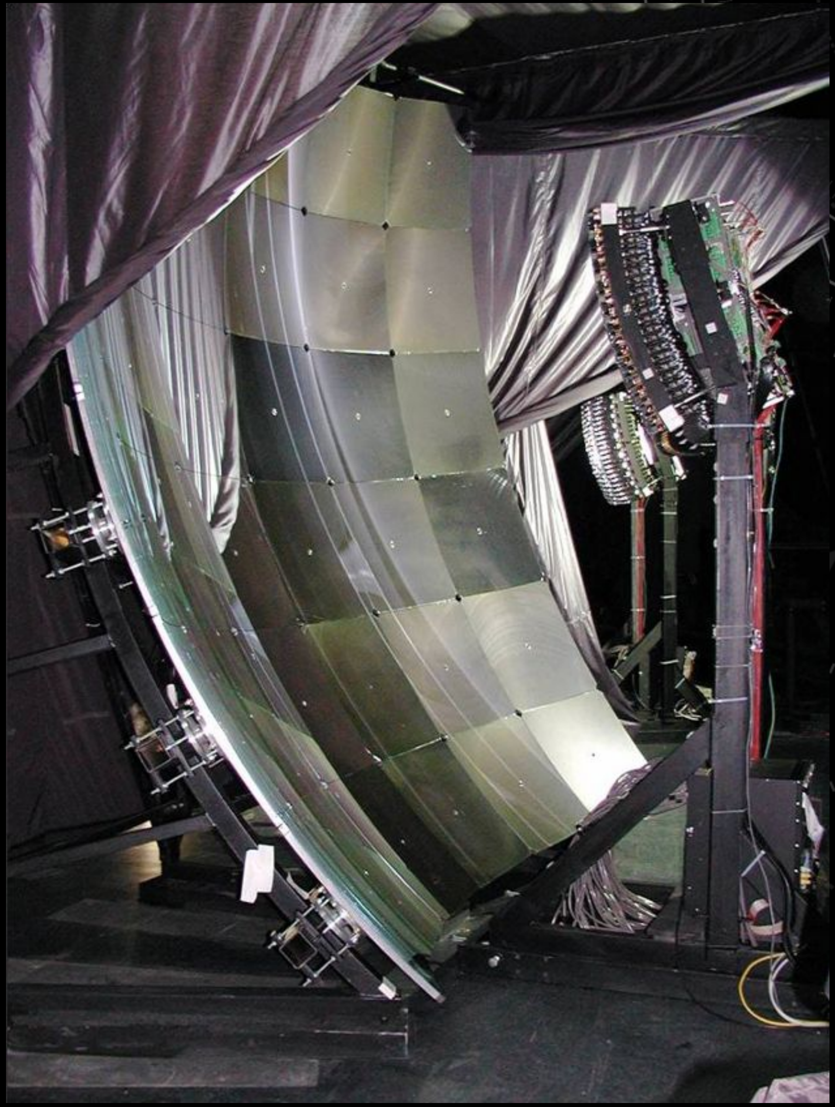
[Highest energy multi-eye event]

Triggered by 24 Surface and Two Fluorescence Detectors



EVENT RECONSTRUCTION

Highest energy multi-eye event

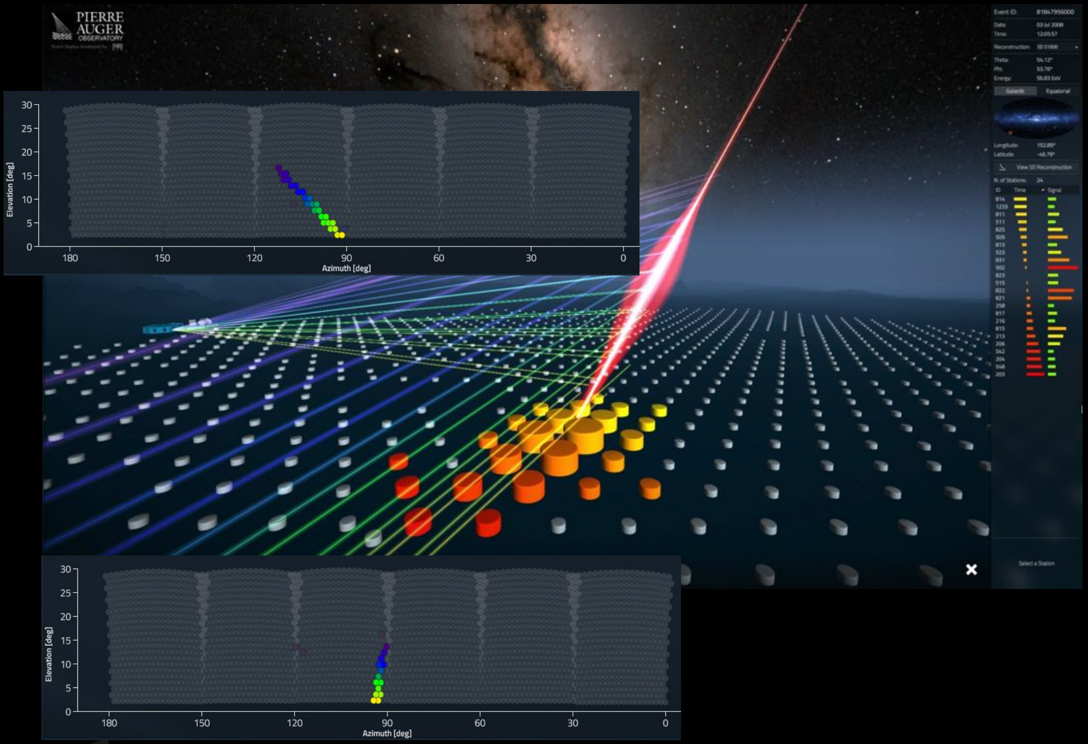


Mirror
and
PMT Array

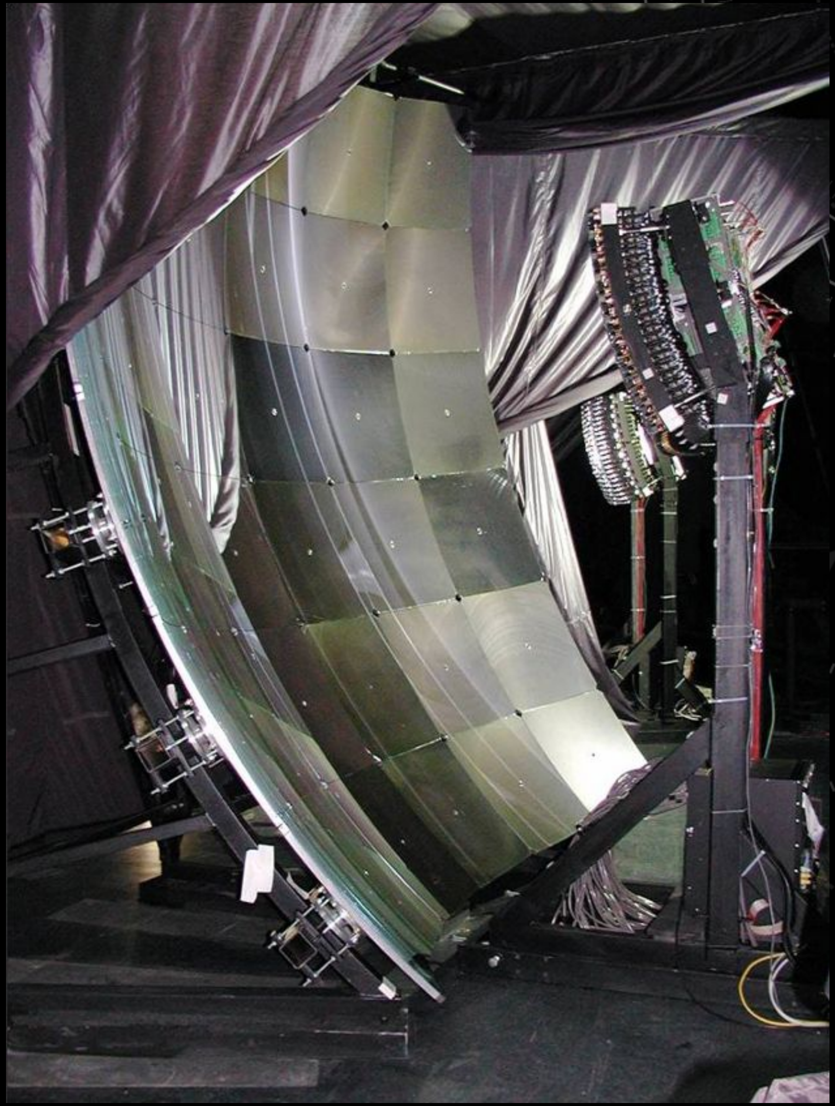
EVENT RECONSTRUCTION

[Highest energy multi-eye event]

Triggered by Two Fluorescence Detectors



Geometry Reconstruction:
FD Pointing Direction Timing

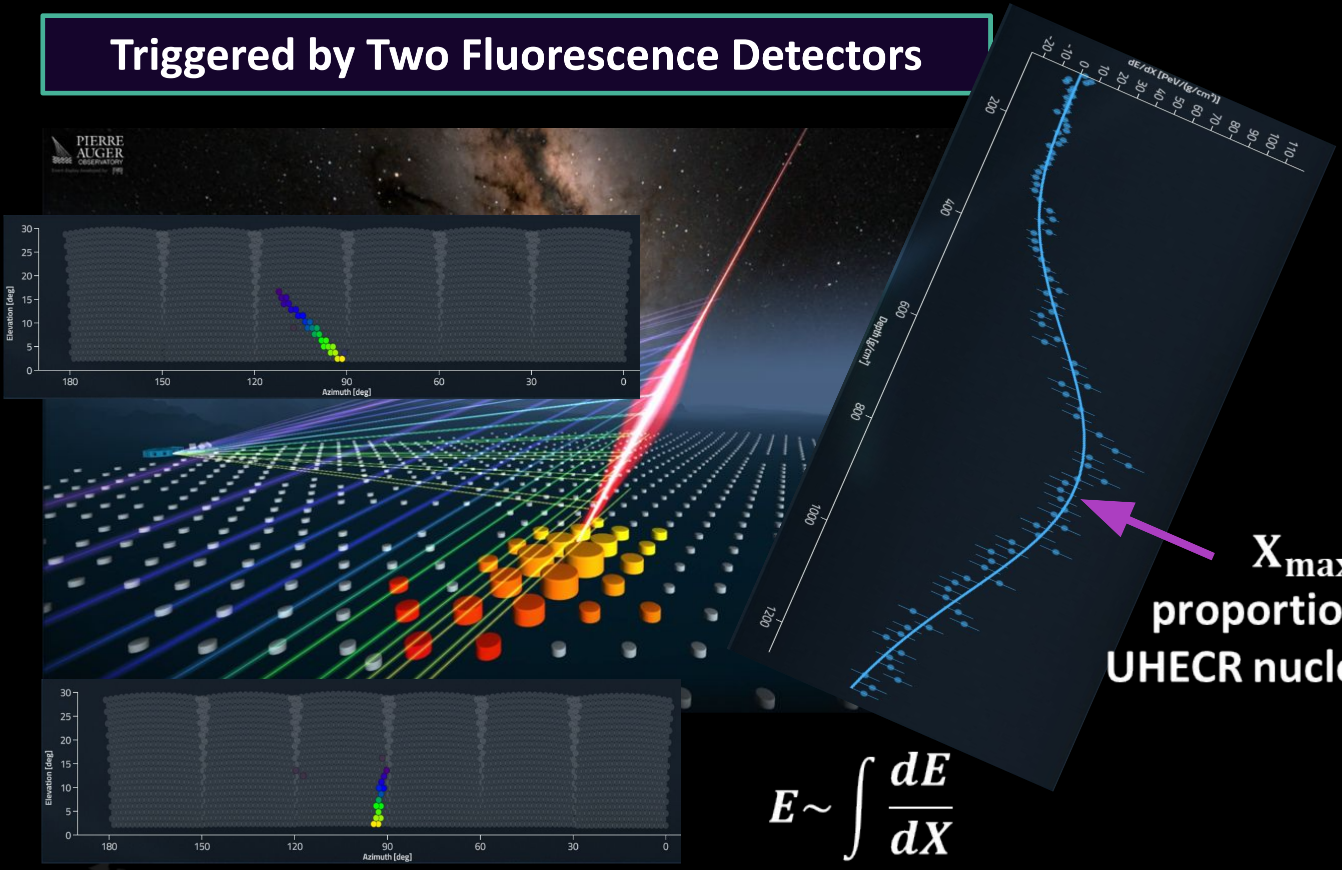


Mirror and PMT Array

EVENT RECONSTRUCTION

Highest energy multi-eye event

Triggered by Two Fluorescence Detectors



X_{max} proportional to UHECR nuclear mass

$$E \sim \int \frac{dE}{dX}$$

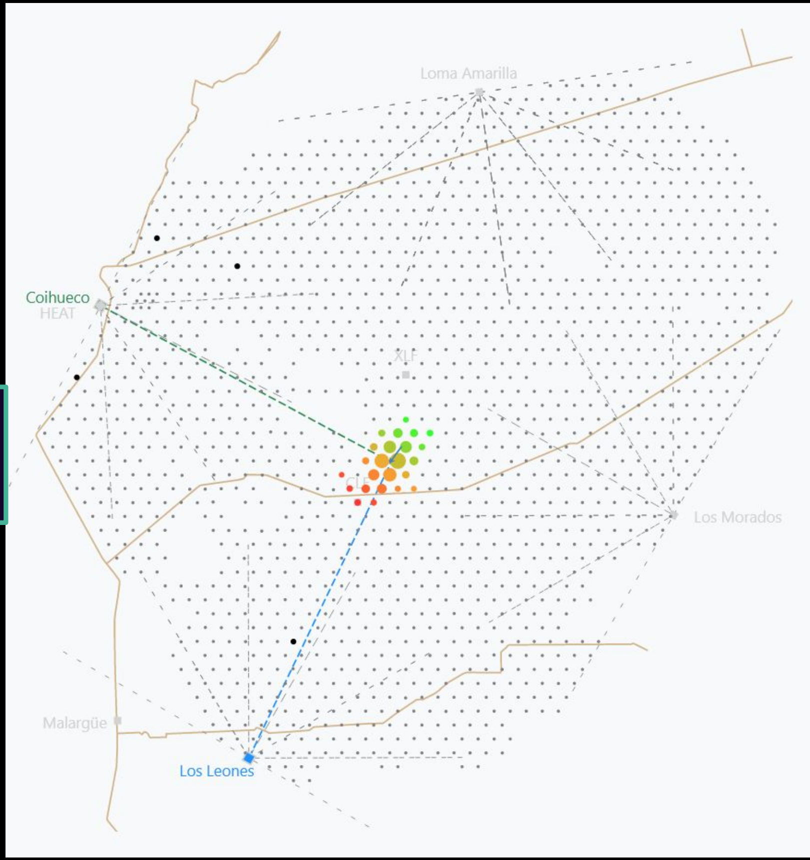
Geometry Reconstruction:
FD Pointing Direction Timing

Mirror and PMT Array

EVENT RECONSTRUCTION

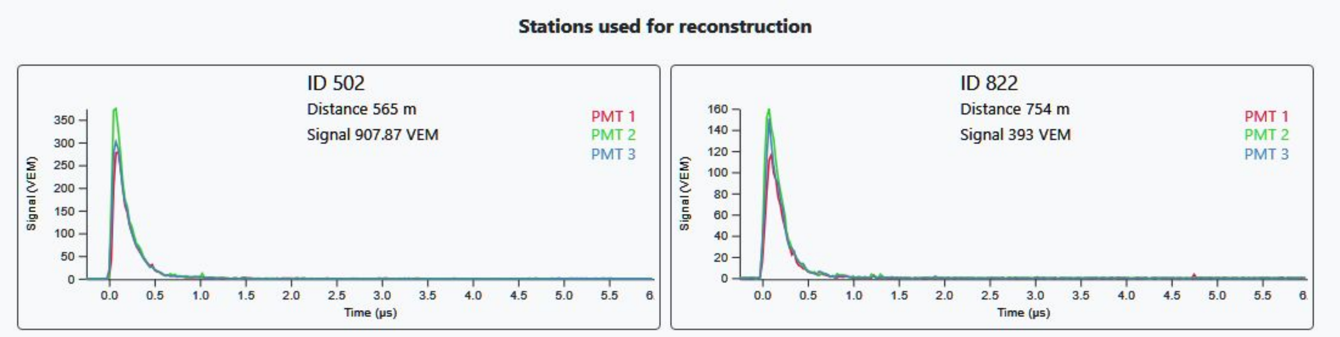
Highest energy multi-eye event

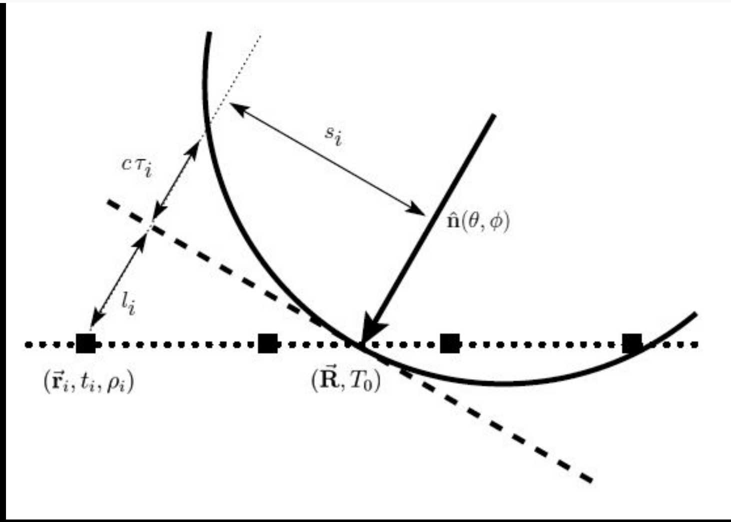
Triggered by 24 Surface Detectors



Color: Time of Arrival

Geometry Reconstruction: SD Location Timing

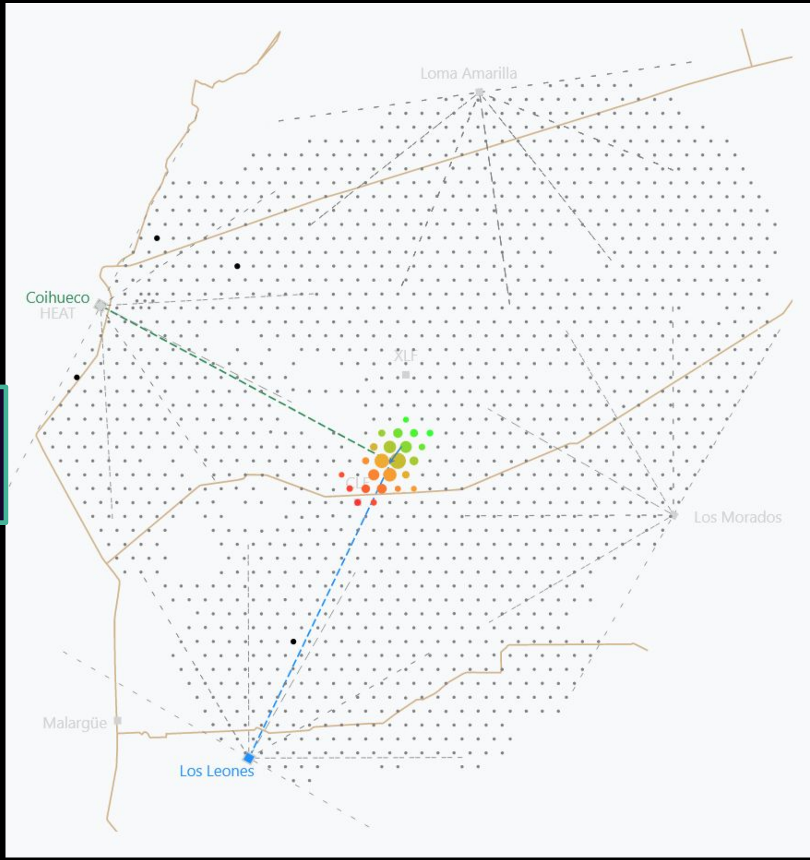




EVENT RECONSTRUCTION

[Highest energy multi-eye event]

Triggered by 24 Surface Detectors



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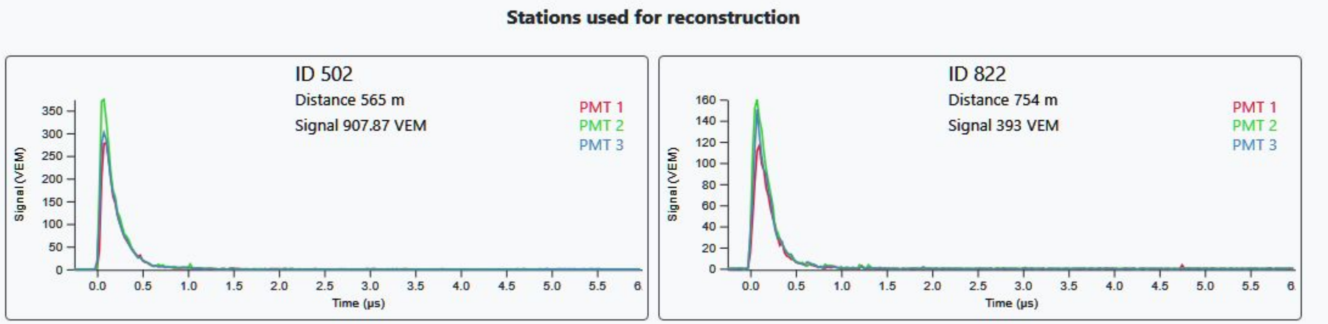
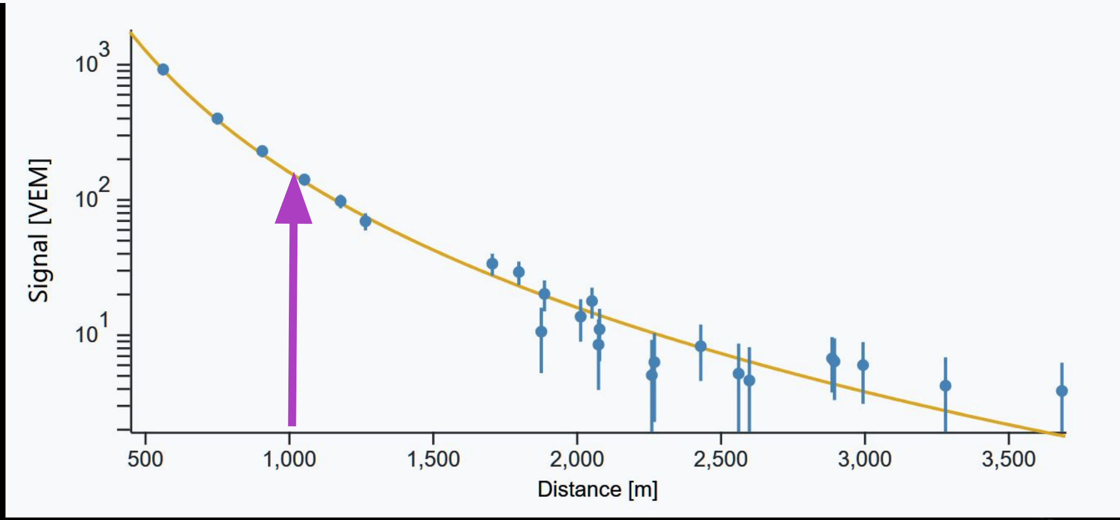


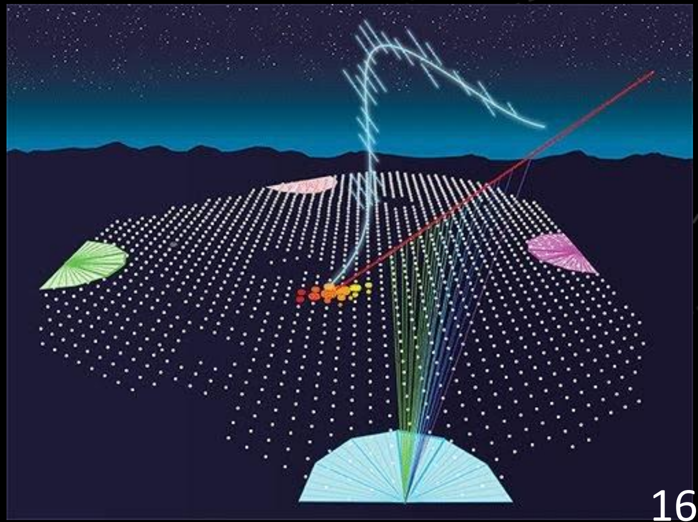


Energy Reconstruction: Signal at 1000 m

PIERRE AUGER OBSERVATORY OPEN DATA

opendata.auger.org

- 10% of Pierre Auger Observatory cosmic-ray surface detector (or hybrid) data from January 2004 to August 2018.



PIERRE AUGER OBSERVATORY OPEN DATA

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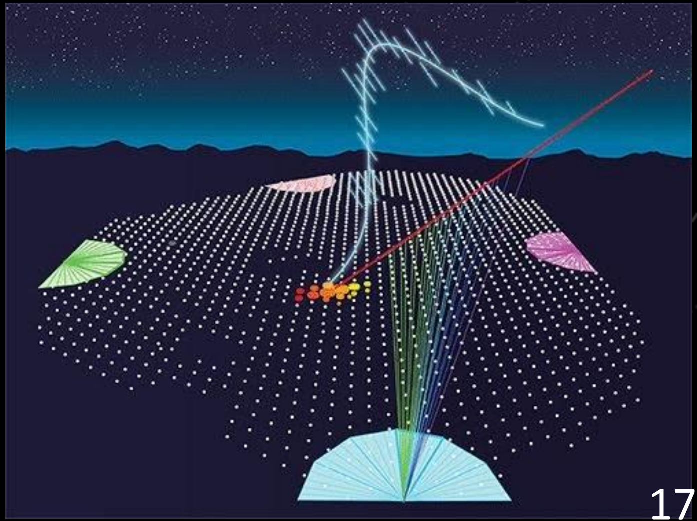
- 10% of Pierre Auger Observatory cosmic-ray data Jan. 2004 to Aug. 2018.

- 100% of weather data collected.
  - Atmosphere is the detectors giant calorimeter (energy absorber).



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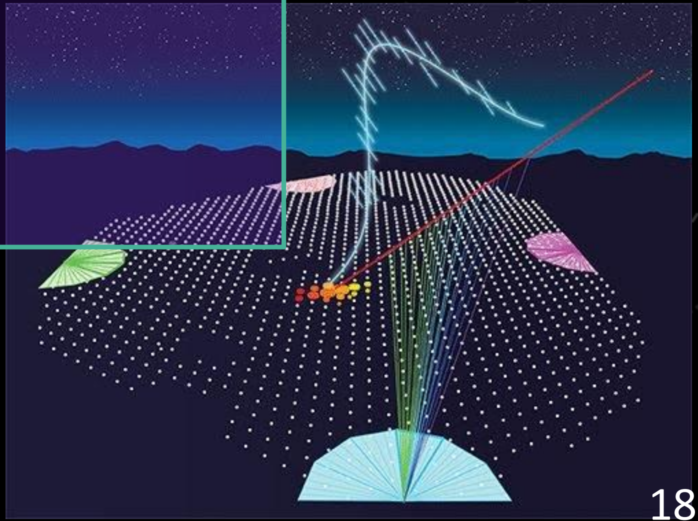
  - Atmosphere is the detectors giant calorimeter (energy absorber).
  - FD light emission:
    - Temperature, pressure and humidity measured on 5-10 minute intervals at four FDs and array center.
    - Aerosols and clouds measured by two laser facilities (15 minute intervals), LIDAR, and infrared cameras.
  - SD signal:
    - Air density affects lateral electromagnetic secondaries.
    - Pressure affects trigger probability.



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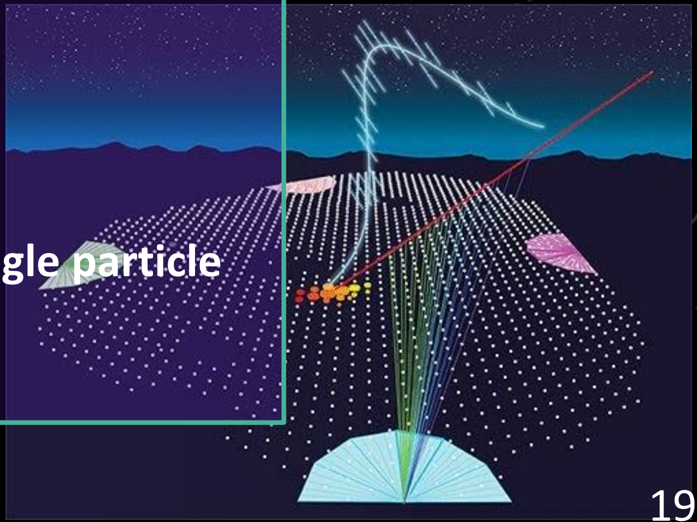
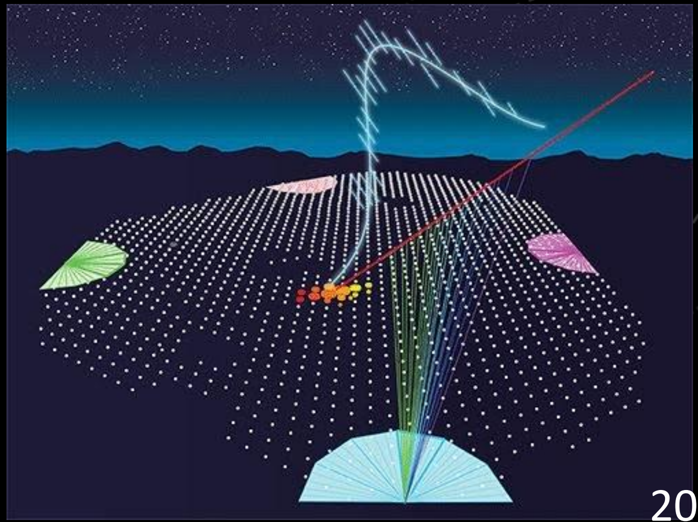
    - Temperature, pressure and humidity measured on 5-10 minute intervals at four FDs and array center.
    - Aerosols and clouds measured by two laser facilities (15 minute intervals), LIDAR, and infrared cameras.
  - SD signal:
    - Air density affects lateral electromagnetic secondaries.
    - Pressure affects trigger probability.
- 100% of space-weather (solar activity) measured by counting all single particle traces in Cherenkov tanks (SD).
  - CR 10^{10} eV < E < 10^{12} eV modulated by solar ejecta.



UHECR OPEN DATA

opendata.auger.org/data.php

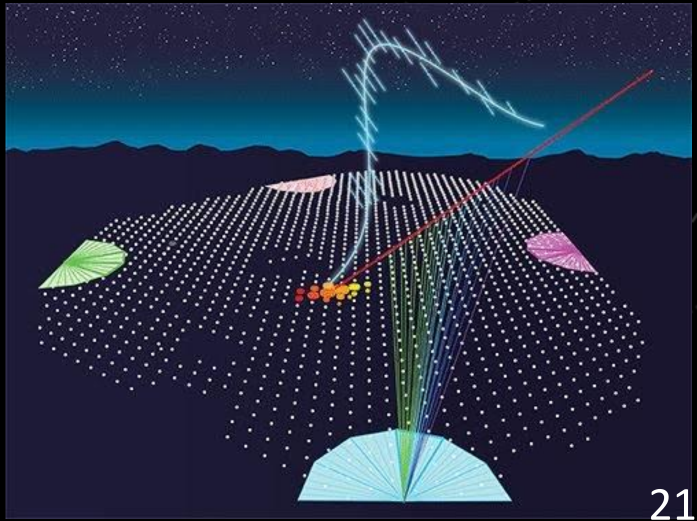
- Pierre Auger Observatory SD/Hybrid cosmic-ray data.
    - 81,121 showers pass high-level quality selection



UHECR OPEN DATA

opendata.auger.org/data.php

- Pierre Auger Observatory SD/Hybrid cosmic-ray data.
  - 81,121 showers pass high-level quality selection:
    25,086 measured by SD1500 array ($\log_{10} E/eV > 17.6$),
    54,481 by SD750 array (lower energies, $\log_{10} E/eV > 16.85$),
    3,348 *hybrid* (FD/SD).



UHECR OPEN DATA

opendata.auger.org/data.php

- SD/Hybrid cosmic-ray data.
  - Pseudo-raw data (826 MB) for each event in JSON format files:

UHECR OPEN DATA

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  - Pseudo-raw data (826 MB) for each event in JSON format files:
    - *All* Auger_yydddsssssxx.json *files have* sections:
      - "meta": {"type", "release", "format", "reconstruction": {"software", "version"}}
      - "info": {"id", "sdid", "gpstime", "date"}

If you’re looking for a particular time frame start here

UHECR OPEN DATA

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Surface array used in construction: high energy or low energy

UHECR OPEN DATA

opendata.auger.org/data.php

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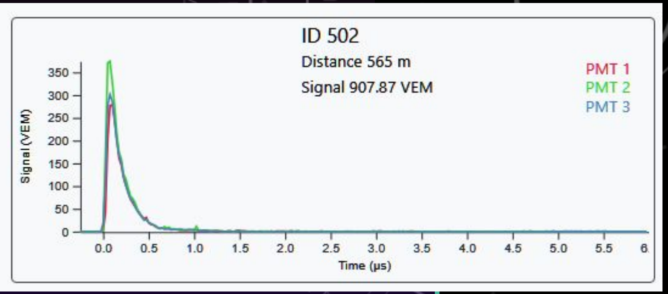
Used in Hybrid Event Analyses (0 or 1)

UHECR OPEN DATA

opendata.auger.org/data.php



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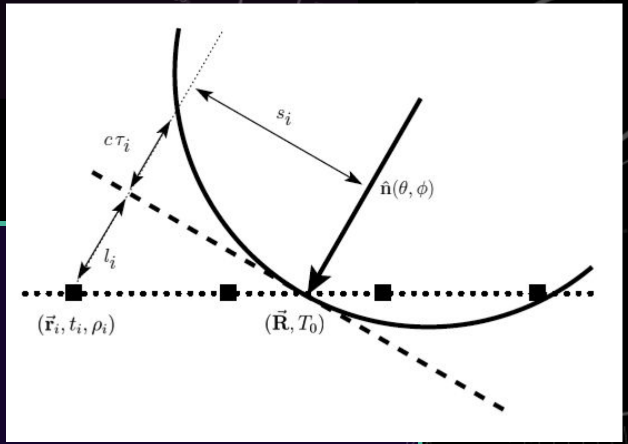
GPS time of event within the GPS second (combine with "gpstime")

UHECR OPEN DATA

opendata.auger.org/data.php



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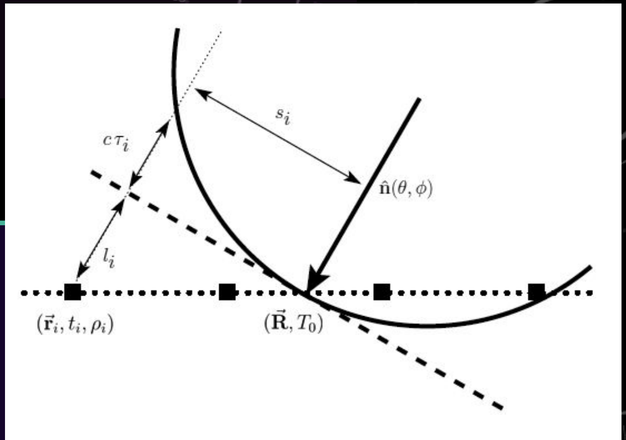
"Horizontal Coordinates"

reconstruct pointing direction in astronomical coordinates

(UTM coordinates system or relative to array center)

UHECR OPEN DATA

opendata.auger.org/data.php



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Uncertainties in zenith, azimuth, and core location to calculate pointing direction uncertainty

UHECR OPEN DATA

opendata.auger.org/data.php

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Reconstructed pointing direction:
galactic (l,b) and equatorial/TETE (ra, dec) coordinates

UHECR OPEN DATA

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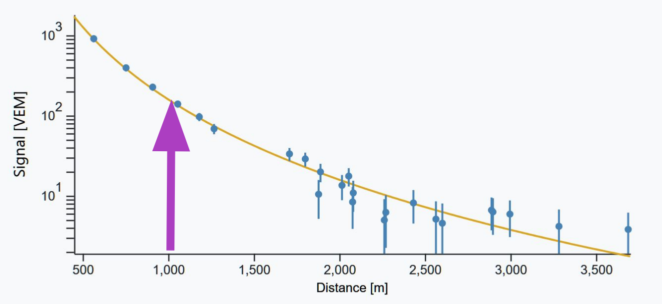

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      - "info": {"id", "sdid", "gpstime", "date"},
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Reconstructed energy in EeV (10^18 electronvolts) and uncertainty

UHECR OPEN DATA

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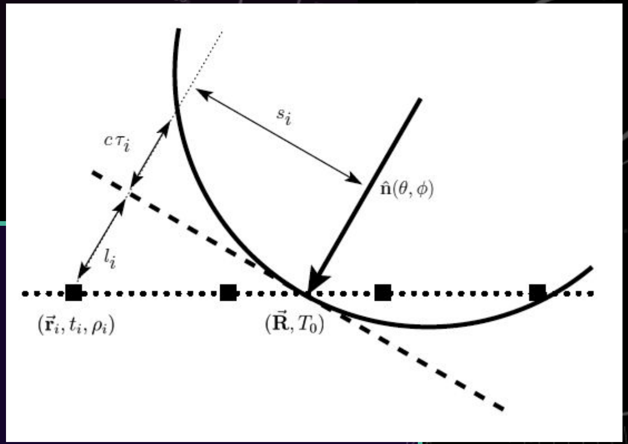

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Geometry goodness-of-fit: if you want to be pickier than Auger…

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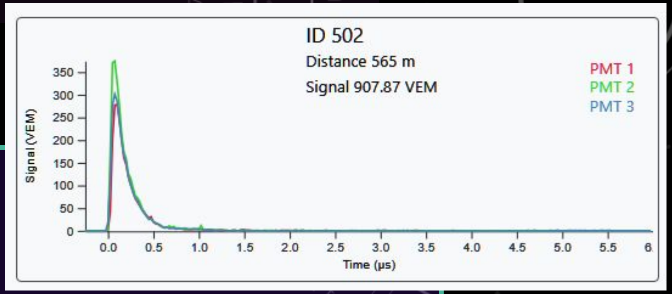

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    - All Auger_yydddsssssxx.json files have sections:
      - "stations": [
        {"id", "name", "x", "y", "z", "t", "dt", "signalStartBin", "signalStopBin", "signal", "dsignal", "sat", "isSelected", "spDistance", "dspDistance", "pmt1", "pmt2", "pmt3"},
        {…},
        …
        ]

Individual signal traces in each triggered surface detector

UHECR OPEN DATA

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    - *Hybrid event* Auger_yydddsssssxx.json files have sections:
      - "fdrec": [
        {"id", "gpsnanotime", "hdSpectrumEye", "hdCalibEye", "hdXmaxEye", "theta", "dtheta", "phi", "dphi", "l", "b":, "ra", "dec", "totalEnergy", "dtotalEnergy", "calEnergy", "dcalEnergy", "xmax", "dxmax", "heightXmax", "distXmax", "dEdXmax", "ddEdXmax", "x":, "dx", "y", "dy", "z", "easting", "northing", "altitude", "cherenkovFraction", "minViewAngle", "uspL", "duspL", "uspR", "duspR", "hottestStationId", "distSdpStation", "distAxisStation"},
        {…},
        …
        ]

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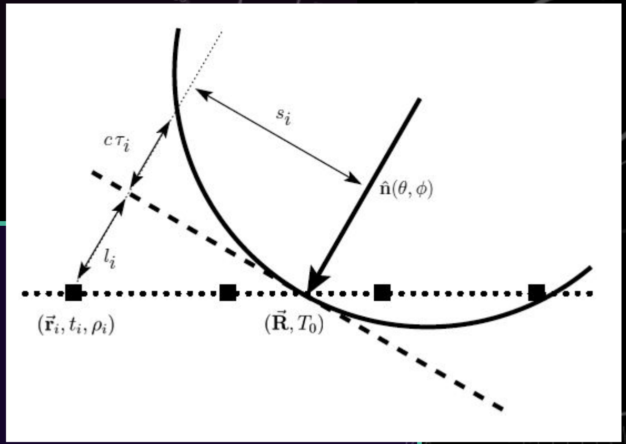
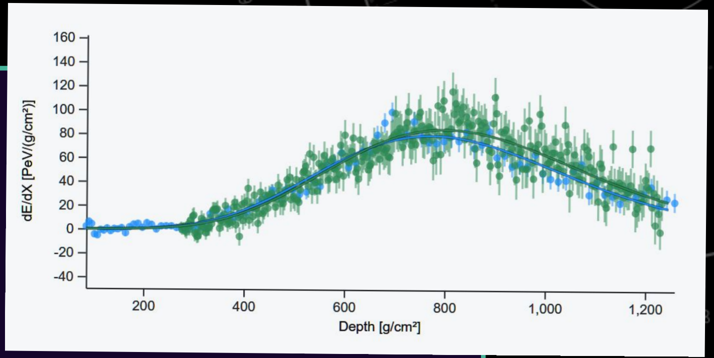


- SD/Hybrid cosmic-ray data.
  - Pseudo-raw data (826 MB) for each event in JSON format files:
    - *Hybrid event* Auger_yydddsssssxx.json files have sections:
      - "fdrec": [
        {"id", "gpsnanotime", "hdSpectrumEye", "hdCalibEye", "hdXmaxEye", "theta", "dtheta", "phi", "dphi", "l", "b":, "ra", "dec", "totalEnergy", "dtotalEnergy", "calEnergy", "dcalEnergy", "xmax", "dxmax", "heightXmax", "distXmax", "dEdXmax", "ddEdXmax", "x":, "dx", "y", "dy", "z", "easting", "northing", "altitude", "cherenkovFraction", "minViewAngle", "uspL", "duspL", "uspR", "duspR", "hottestStationId", "distSdpStation", "distAxisStation"},
        {...},
        …
        ]

More accurate pointing direction information

UHECR OPEN DATA

opendata.auger.org/data.php



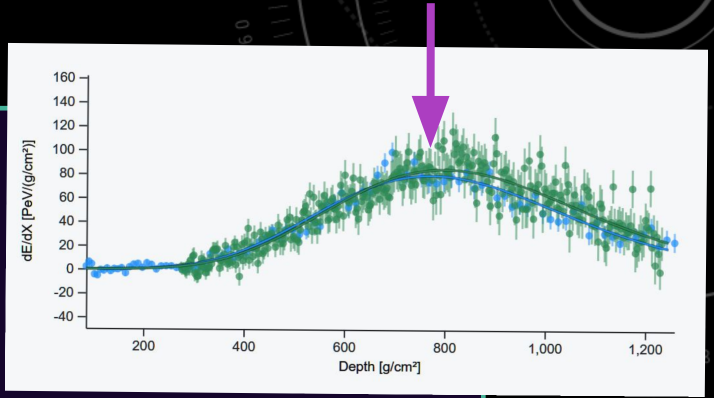
- SD/**Hybrid cosmic-ray data**.
  - Pseudo-raw data (826 MB) for each event in JSON format files:
    - *Hybrid event* Auger_yydddsssssxx.json files have sections:
      - "fdrec": [
        {"id", "gpsnanotime", "hdSpectrumEye", "hdCalibEye", "hdXmaxEye", "theta", "dtheta", "phi", "dphi", "l", "b":, "ra", "dec", "totalEnergy", "dtotalEnergy", "calEnergy", "dcalEnergy", "xmax", "dxmax", "heightXmax", "distXmax", "dEdXmax", "ddEdXmax", "x":, "dx", "y", "dy", "z", "easting", "northing", "altitude", "cherenkovFraction", "minViewAngle", "uspL", "duspL", "uspR", "duspR", "hottestStationId", "distSdpStation", "distAxisStation"},
        {...},
        ...
        ]

$$E \sim \int \frac{dE}{dX}$$

More accurate reconstructed energy and uncertainty

UHECR OPEN DATA

opendata.auger.org/data.php



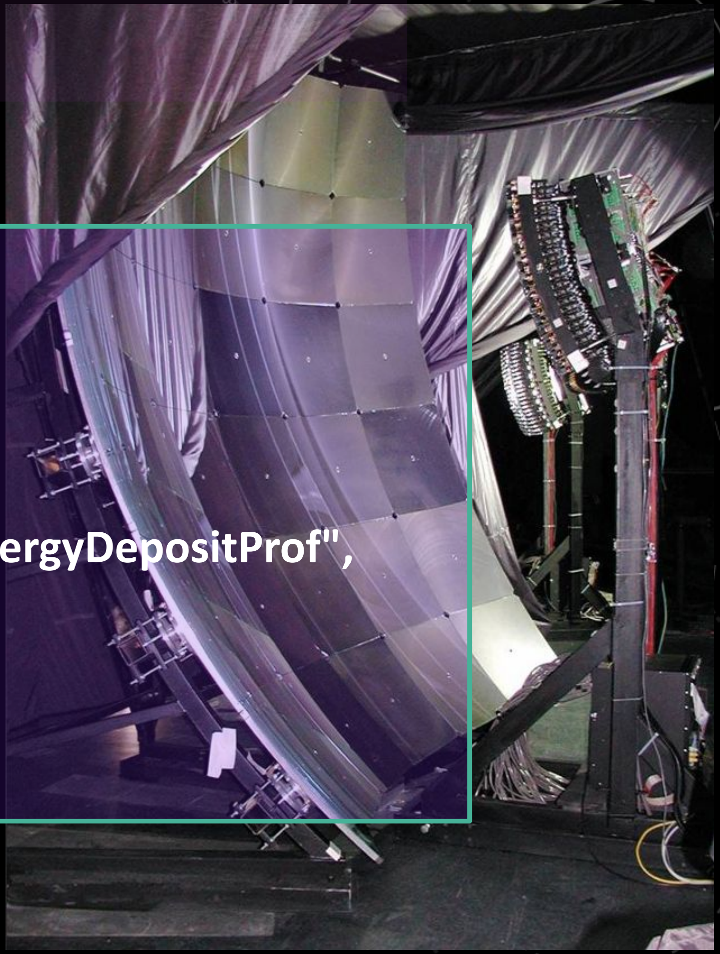
- SD/Hybrid cosmic-ray data.
  - Pseudo-raw data (826 MB) for each event in JSON format files:
    - *Hybrid event* Auger_yydddsssssxx.json files have sections:
      - "fdrec": [
        {"id", "gpsnanotime", "hdSpectrumEye", "hdCalibEye", "hdXmaxEye", "theta", "dtheta", "phi", "dphi", "l", "b":, "ra", "dec", "totalEnergy", "dtotalEnergy", "calEnergy", "dcalEnergy", "xmax", "dxmax", "heightXmax", "distXmax", "dEdXmax", "ddEdXmax", "x":, "dx", "y", "dy", "z", "easting", "northing", "altitude", "cherenkovFraction", "minViewAngle", "uspL", "duspL", "uspR", "duspR", "hottestStationId", "distSdpStation", "distAxisStation"},
        {…},
        …
        ]

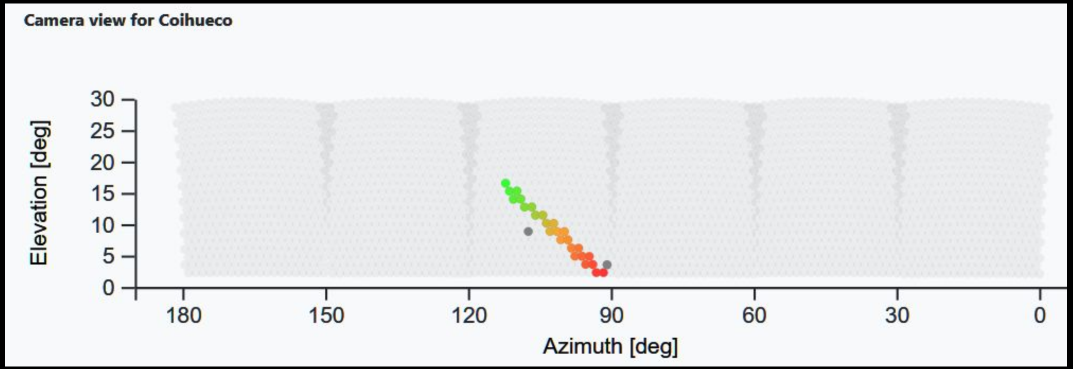
Depth of shower maximum X_{max} and uncertainty – correlated with primary nuclei mass

UHECR OPEN DATA

opendata.auger.org/data.php

- SD/Hybrid cosmic-ray data.
  - Pseudo-raw data (826 MB) for each event in JSON format files:
    - *Hybrid event* Auger_yydddsssssxx.json files have sections:
      - "eyes": [
        {"id", "name", "atmDepthProf", "energyDepositProf", "denergyDepositProf", "pixelID", "pixelTime", "pixelCharge", "pixelStatus"},
        {...},
        ...
        ]





Individual Camera Signals for Event Display

UHECR OPEN DATA

opendata.auger.org/data.php

- SD/Hybrid cosmic-ray data.
  - CSV Summary Files (8 MB) Comma Separated Matrix:
    - *Each event* has column variables:
      id, sdid, gpstime, sd1500, multiEye, sd_gpsnanotime, sd_theta, sd_dtheta, sd_phi, sd_dphi, sd_energy, sd_denergy, sd_l, sd_b, sd_ra, sd_dec, sd_x, sd_dx, sd_y, sd_dy, sd_z, sd_easting, sd_northing, sd_altitude, sd_R, sd_dR, sd_s1000, sd_ds1000, sd_s38, sd_gcorr, sd_wcorr, sd_beta, sd_gamma, sd_chi2, sd_ndf, sd_geochi2, sd_geondf, sd_nbstat, fd_id, fd_gpsnanotime, fd_hdSpectrumEye, fd_hdCalibEye, fd_hdXmaxEye, fd_theta, fd_dtheta, fd_phi, fd_dphi, fd_l, fd_b, fd_ra, fd_dec, fd_totalEnergy, fd_dtotalEnergy, fd_calEnergy, fd_dcalEnergy, fd_xmax, fd_dxmax, fd_heightXmax, fd_distXmax, fd_dEdXmax, fd_ddEdXmax, fd_x, fd_dx, fd_y, fd_dy, fd_z, fd_easting, fd_northing, fd_altitude, fd_cherenkovFraction, fd_minViewAngle, fd_uspL, fd_duspL, fd_uspR, fd_duspR, fd_hottestStationId, fd_distSdpStation, fd_distAxisStation, sd_exposure

All Previously Discussed Most Important Variables for Outside Auger Analyses

UHECR OPEN DATA

opendata.auger.org/data.php

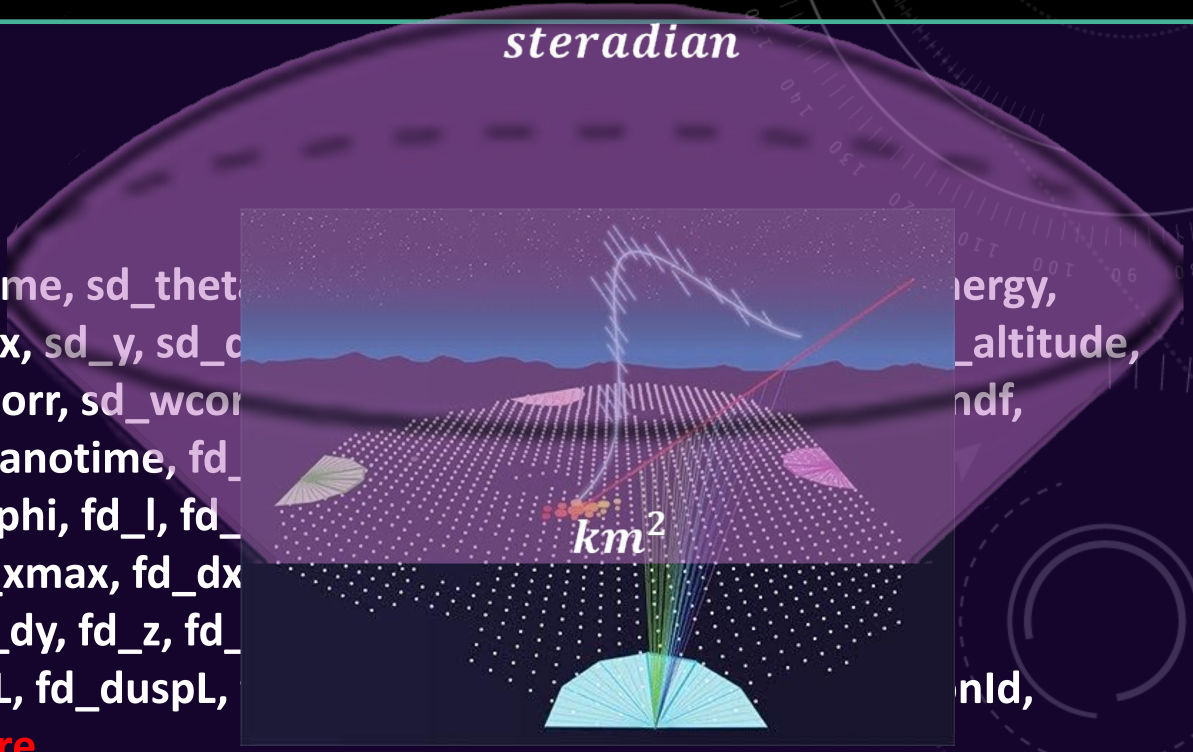
- SD/Hybrid cosmic-ray data.
  - CSV Summary Files (8 MB) Comma Separated Matrix:
    - *Multi-eye events* have repeated column variables for each eye:
      id, sdid, gpstime, sd1500, multiEye, sd_gpsnanotime, sd_theta, sd_dtheta, sd_phi, sd_dphi, sd_energy, sd_denergy, sd_l, sd_b, sd_ra, sd_dec, sd_x, sd_dx, sd_y, sd_dy, sd_z, sd_easting, sd_northing, sd_altitude, sd_R, sd_dR, sd_s1000, sd_ds1000, sd_s38, sd_gcorr, sd_wcorr, sd_beta, sd_gamma, sd_chi2, sd_ndf, sd_geochi2, sd_geondf, sd_nbstat, fd_id, fd_gpsnanotime, fd_hdSpectrumEye, fd_hdCalibEye, fd_hdXmaxEye, fd_theta, fd_dtheta, fd_phi, fd_dphi, fd_l, fd_b, fd_ra, fd_dec, fd_totalEnergy, fd_dtotalEnergy, fd_calEnergy, fd_dcalEnergy, fd_xmax, fd_dxmax, fd_heightXmax, fd_distXmax, fd_dEdXmax, fd_ddEdXmax, fd_x, fd_dx, fd_y, fd_dy, fd_z, fd_easting, fd_northing, fd_altitude, fd_cherenkovFraction, fd_minViewAngle, fd_uspL, fd_duspL, fd_uspR, fd_duspR, fd_hottestStationId, fd_distSdpStation, fd_distAxisStation, sd_exposure

Same Id for rows from each FD telescope. SD data is repeated.

UHECR OPEN DATA

opendata.auger.org/data.php

- SD/Hybrid cosmic-ray data.
  - CSV Summary Files (8 MB) Comma Separated Matrix:
    - *Each event* has column variables:
      id, sdid, gpstime, sd1500, multiEye, sd_gpsnanotime, sd_theta ... ergy,
      sd_denergy, sd_l, sd_b, sd_ra, sd_dec, sd_x, sd_dx, sd_y, sd_d ... _altitude,
      sd_R, sd_dR, sd_s1000, sd_ds1000, sd_s38, sd_gcorr, sd_wcor ... ndf,
      sd_geochi2, sd_geondf, sd_nbstat, fd_id, fd_gpsnanotime, fd_
      fd_hdXmaxEye, fd_theta, fd_dtheta, fd_phi, fd_dphi, fd_l, fd_
      fd_dtotalEnergy, fd_calEnergy, fd_dcalEnergy, fd_xmax, fd_dx
      fd_dEdXmax, fd_ddEdXmax, fd_x, fd_dx, fd_y, fd_dy, fd_z, fd_
      fd_cherenkovFraction, fd_minViewAngle, fd_uspL, fd_duspL, ... nId,
      fd_distSdpStation, fd_distAxisStation, sd_exposure



...and the important

total surface detector exposure $(km^2 \cdot steradian \cdot year)$

summed for each event

UHECR OPEN DATA SET

opendata.auger.org/data.php

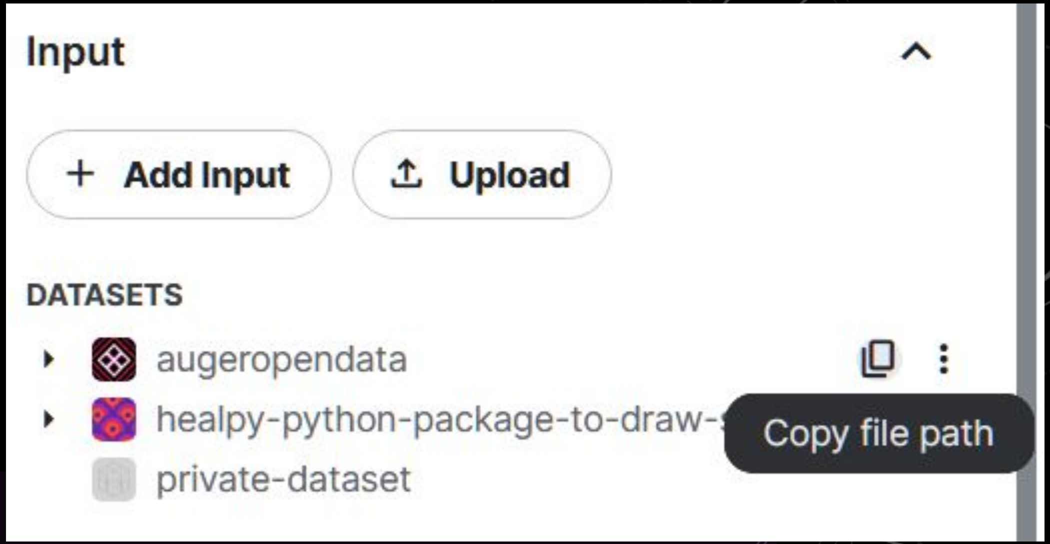
Auger Open Data release version 3, Mar 20 2024.

UHECR OPEN DATA

opendata.auger.org/data.php

Let's try a ChatGPT analysis real quick

"In this zip file there are some csv files. Please load the data from the csv file that has sd1500 in the name into a numpy structure."



OPEN DATA EXPLORATION

opendata.auger.org/outreach.php

Run a Kaggle example on new data

- Upload csv files as dataset.
- Change directory in “AugerLoad.”

Insert Web Page

This app allows you to insert secure web pages starting with https:// into the slide deck. Non-secure web pages are not supported for security reasons.

Please enter the URL below.

https:// opendata.auger.org

Note: Many popular websites allow secure access. Please click on the preview button to ensure the web page is accessible.

EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

EXAMPLE: LARGE-SCALE ANISOTROPY

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- SD cosmic-ray data analyses
  - Li-Ma Event Overdensity Analysis
    - Display arrival directions of UHECR ($E > E_{min}$).
    - Display detector exposure.
    - Calculate significance of excess/deficit of events from a sky location.

EXAMPLE: LARGE-SCALE ANISOTROPY

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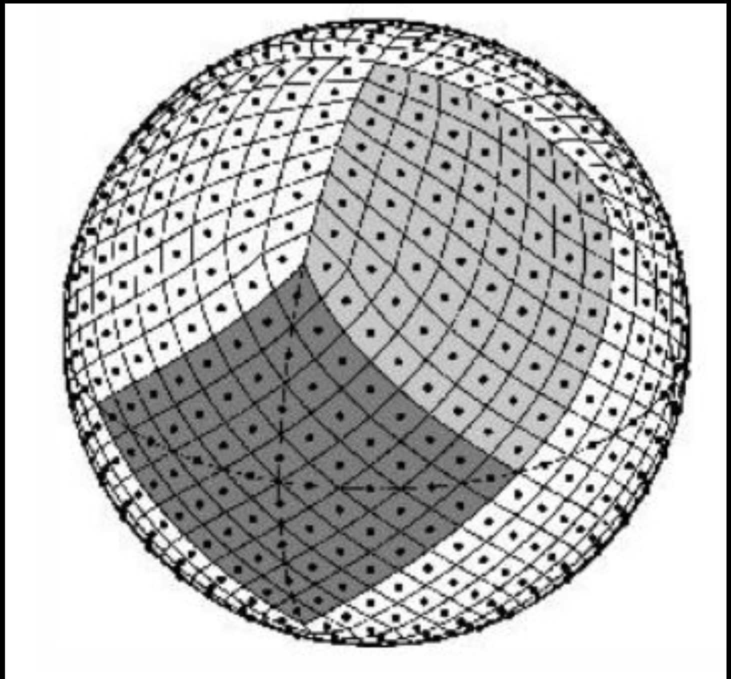
- SD cosmic-ray data analyses
  - Li-Ma Event Overdensity Analysis
    - Display arrival directions of UHECR ($E > E_{min}$).
    - Display detector exposure.
    - Calculate significance of excess/deficit of events from a sky location.
  - Rayleigh Right-Ascension Analysis
    - Find Fourier-series first-harmonic coefficients.
    - χ^2-minimization to cosine and uniform distributions.
    - Calculate significance of right-ascension modulation.

EXAMPLE: LARGE-SCALE ANISOTROPY

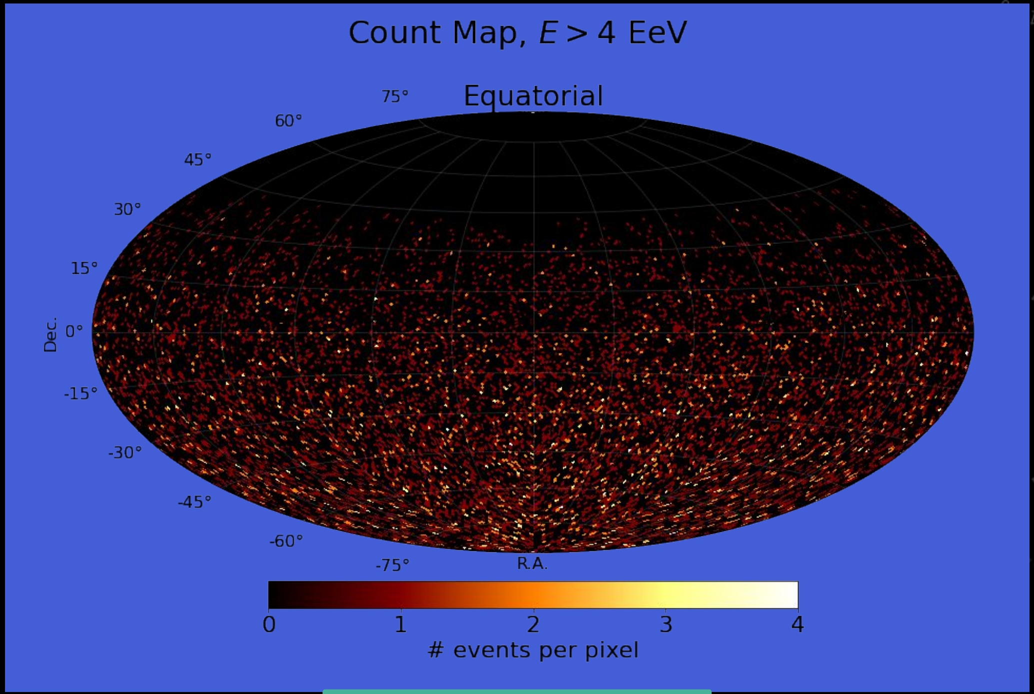
https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Event Overdensity Analysis

- Display **arrival directions** of UHECR.



Healpix: Equal Area Pixels



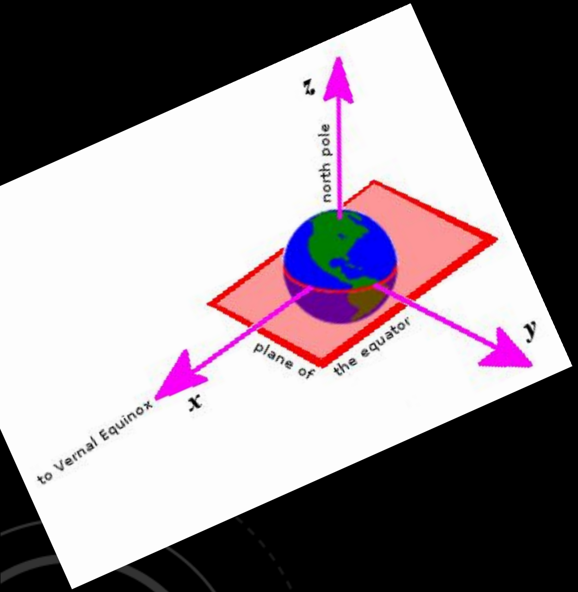
Event Count Map

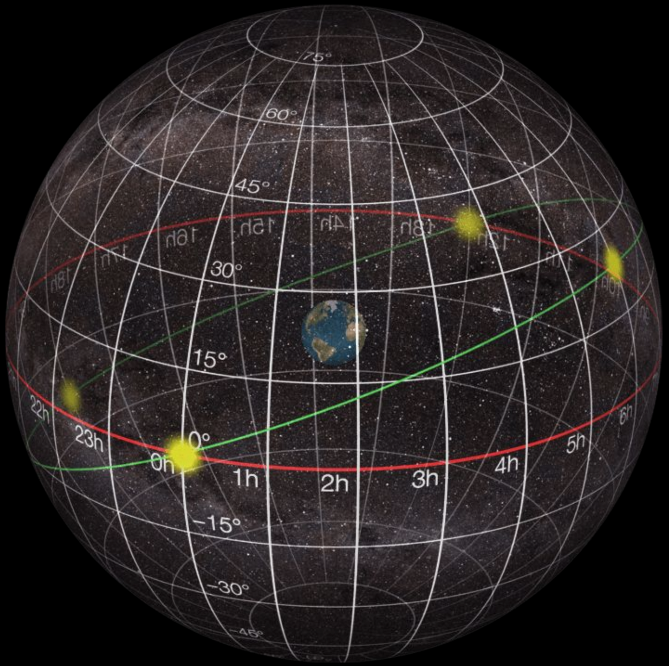
EXAMPLE: LARGE-SCALE ANISOTROPY

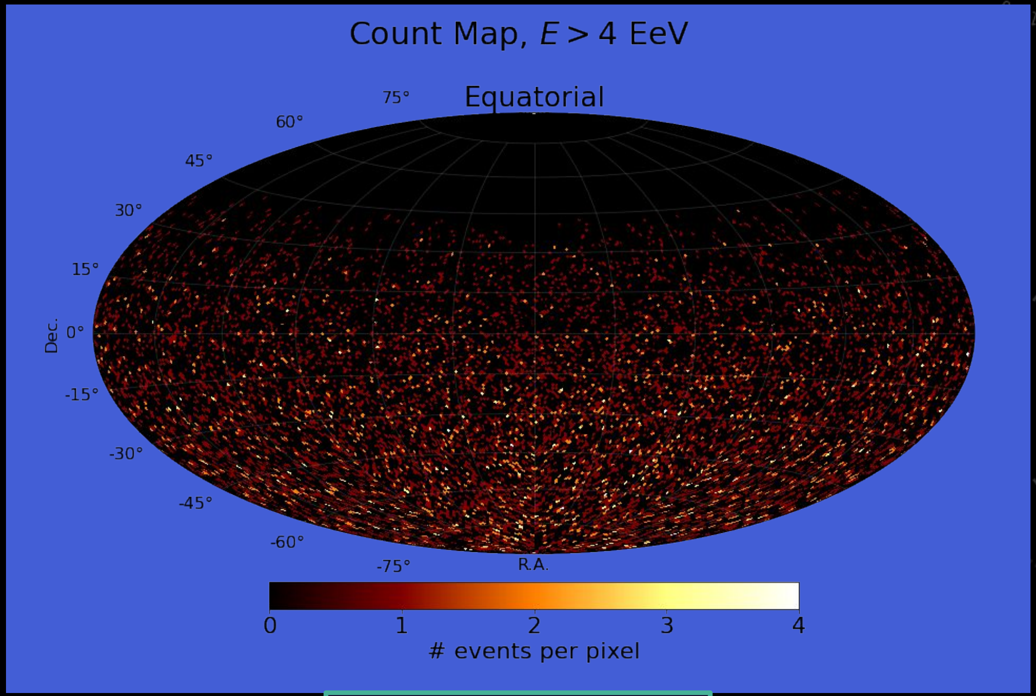
https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Event Overdensity Analysis

- **Display arrival directions of UHECR.**







Equatorial Coordinates

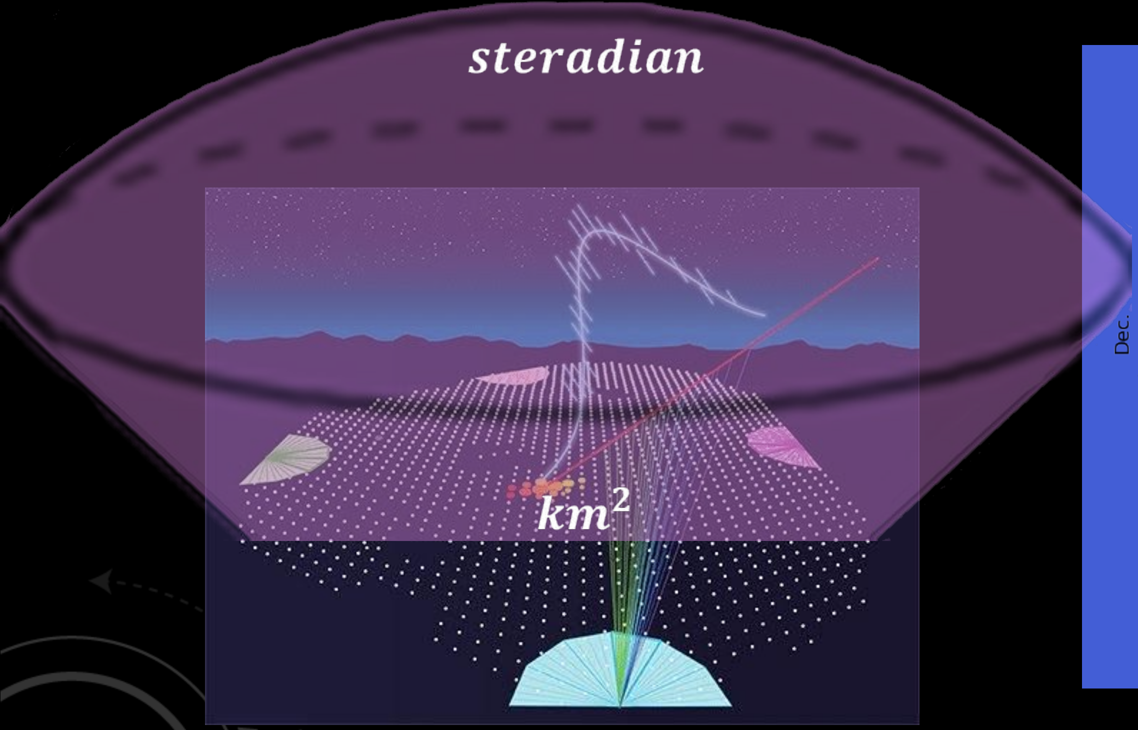
Event Count Map

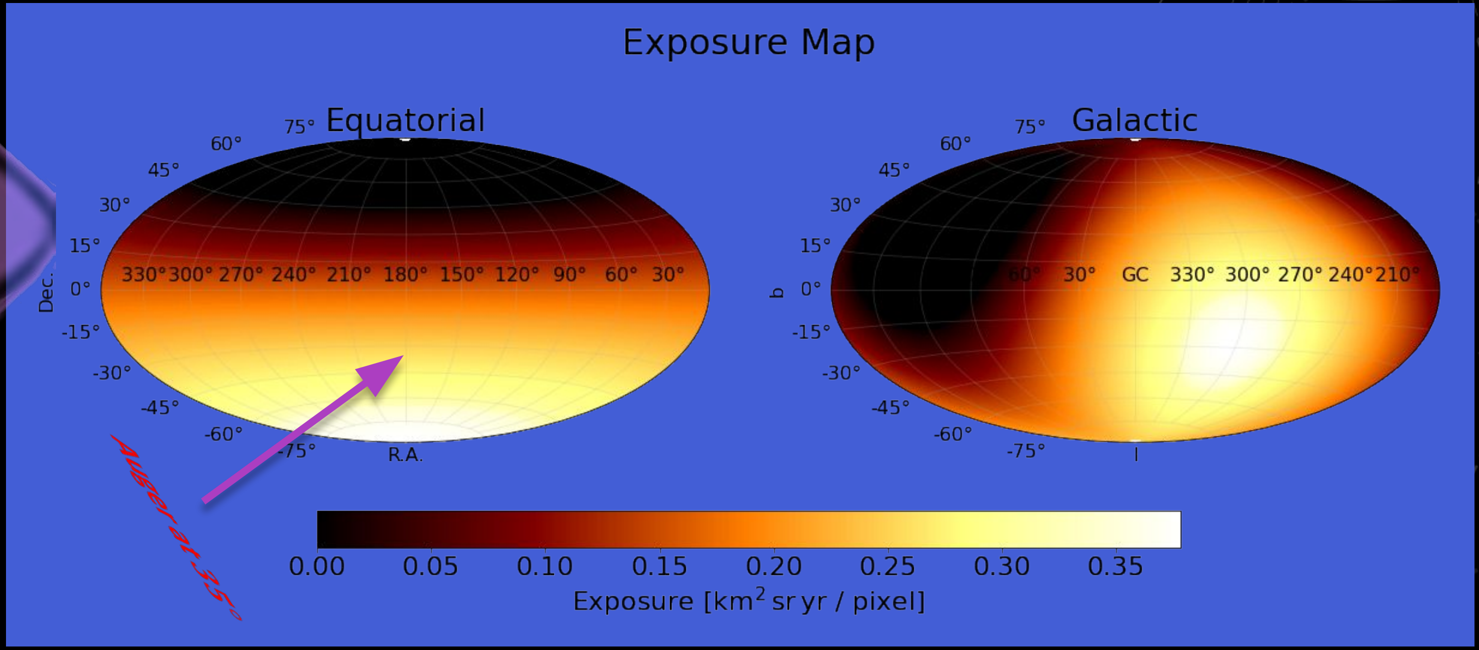
EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Event Overdensity Analysis

- **Display detector exposure.**





Detector Geometric Exposure

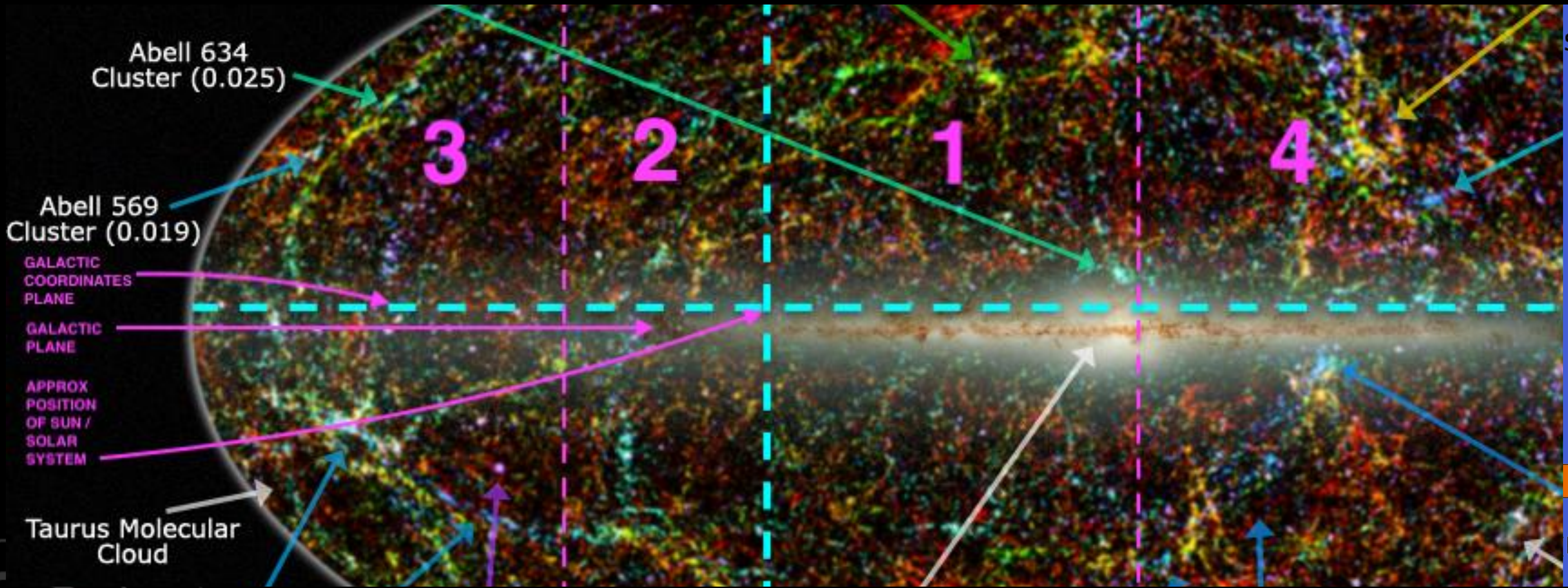
Exposure Map

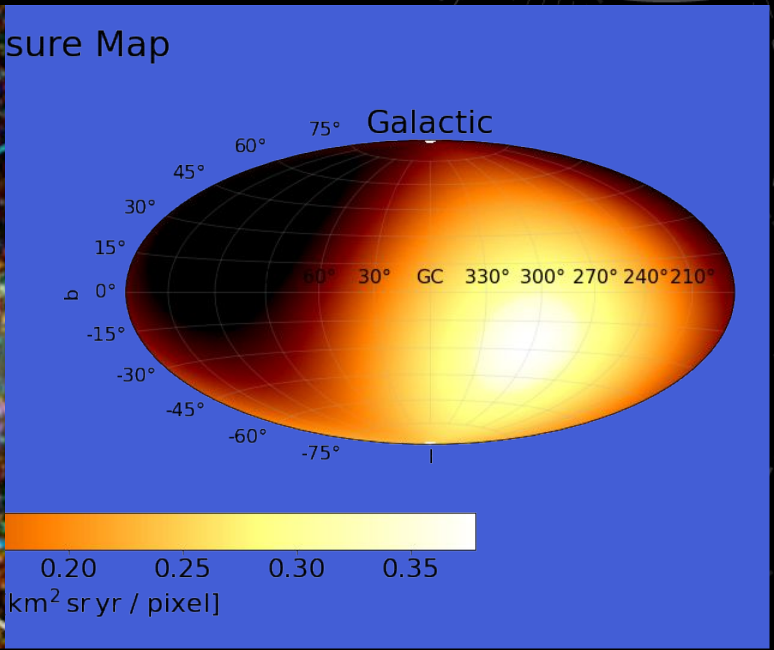
EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Event Overdensity Analysis

- Display detector exposure.



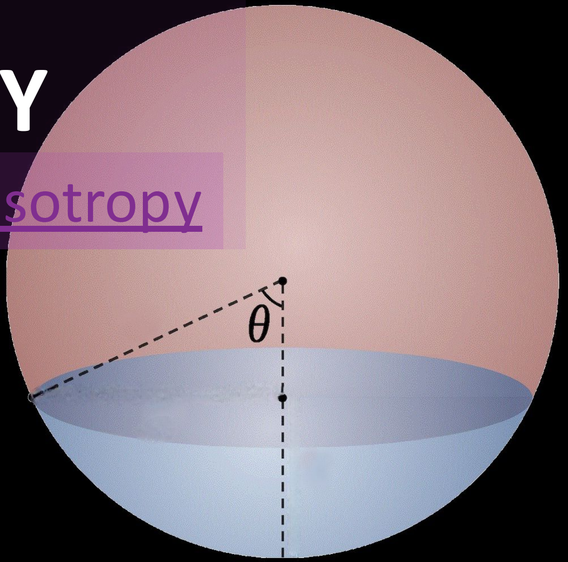


Galactic Coordinates

Exposure Map

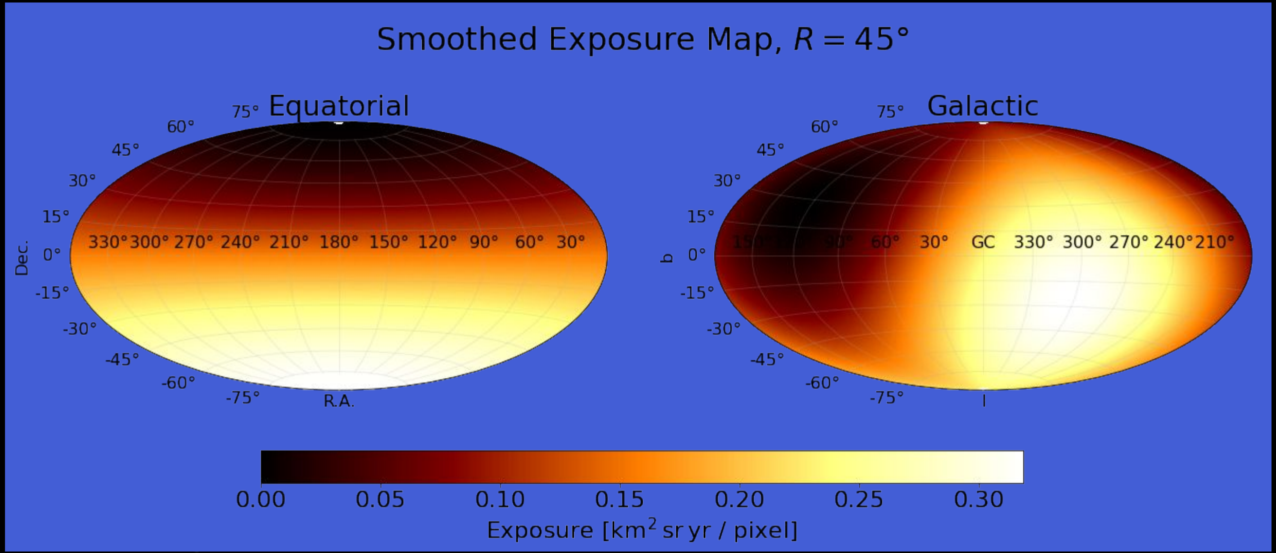
EXAMPLE: LARGE-SCALE ANISOTROPY

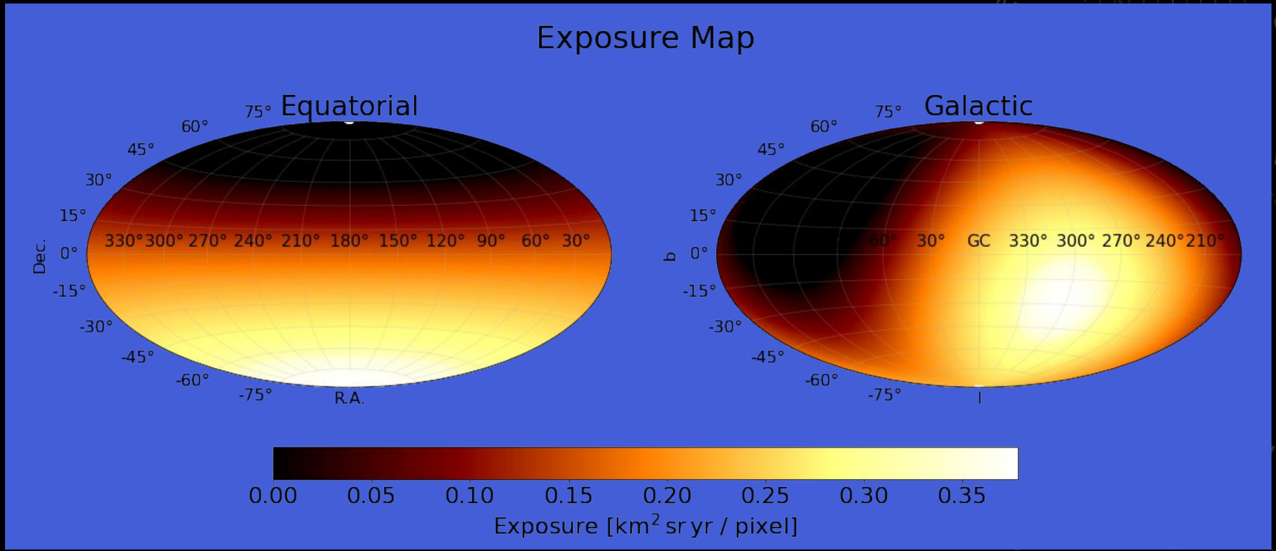
https://www.kaggle.com/code/augeropendata/large-scale-anisotropy



Li-Ma Event Overdensity Analysis

- **Display exposure.**
  - **Averaged in 45° spherical caps (“top-hat” filter).**



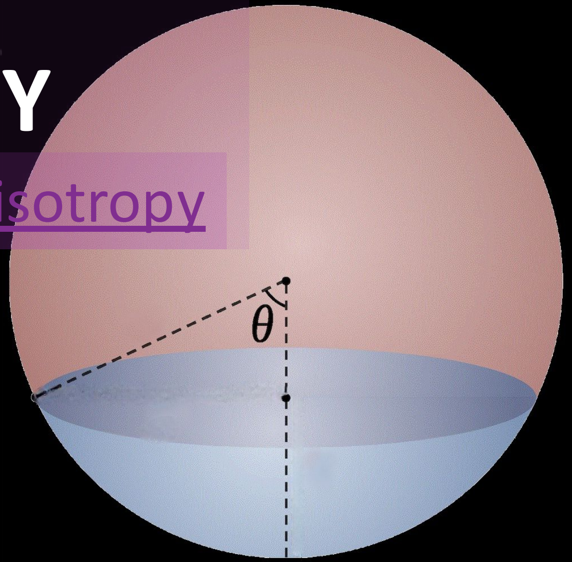


Smoothed Exposure Map

Exposure Map

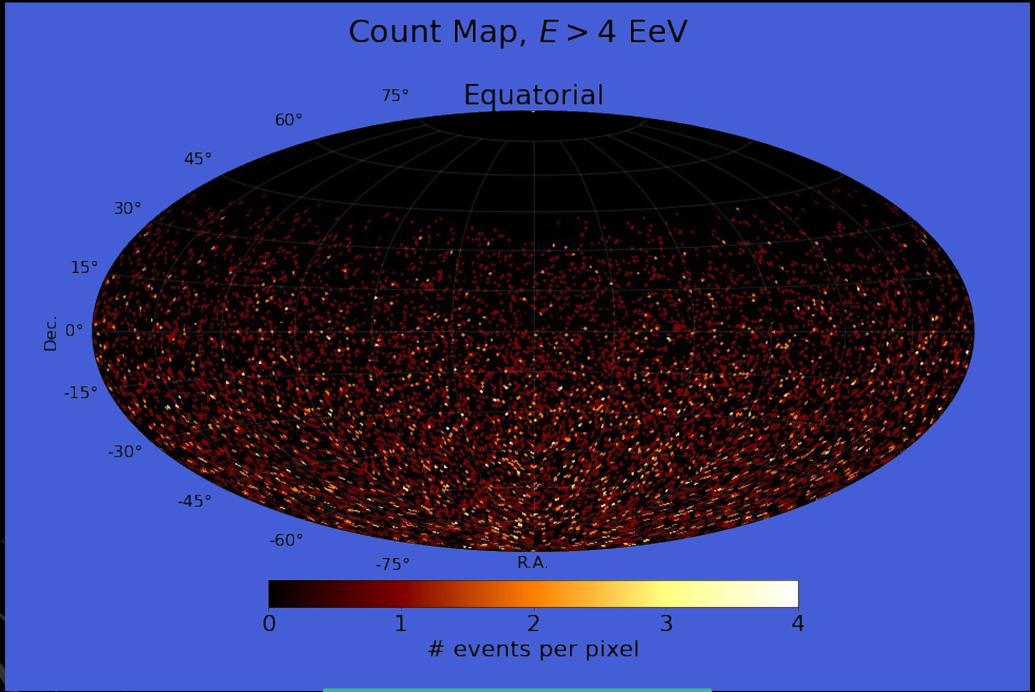
EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

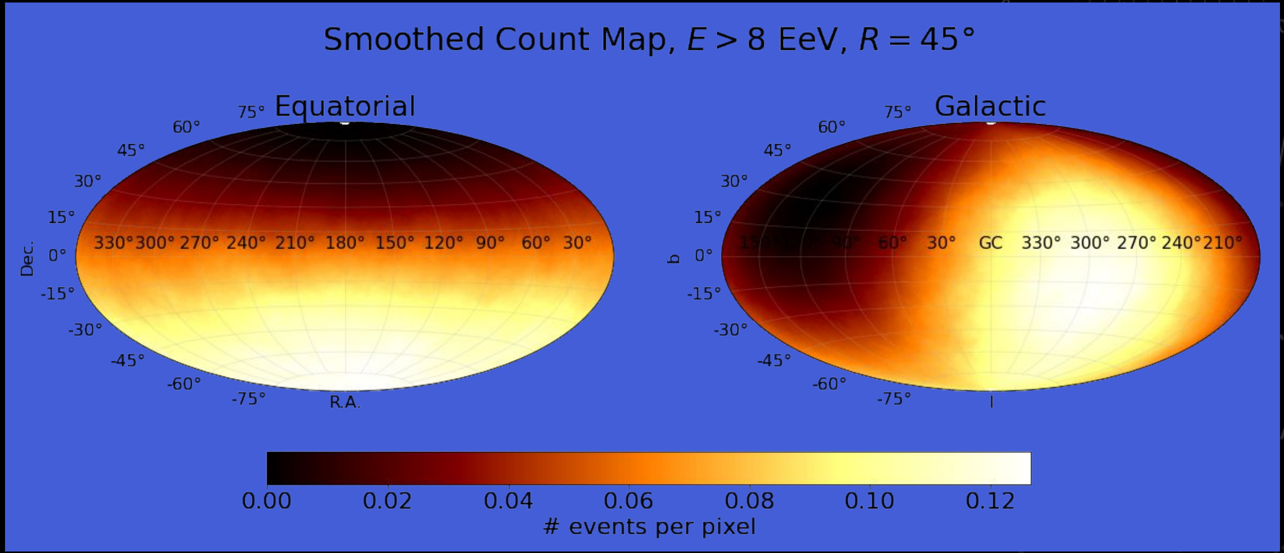


Li-Ma Event Overdensity Analysis

- **Display arrival directions of UHECR.**
  - **Averaged in 45° spherical caps ("top-hat" filter).**



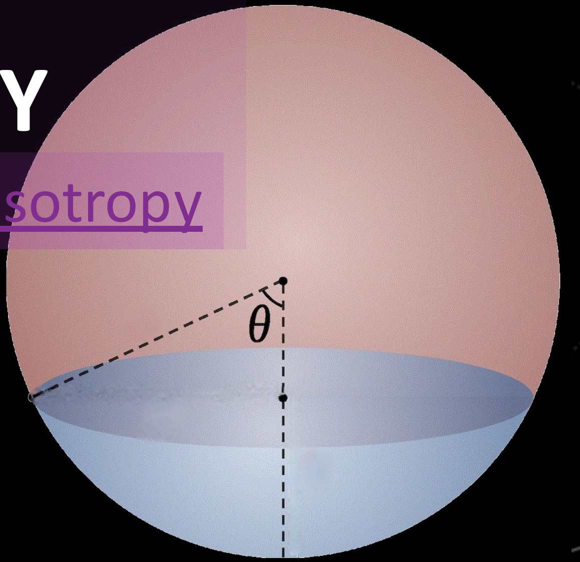
Event Count Map



Smoothed Count Map

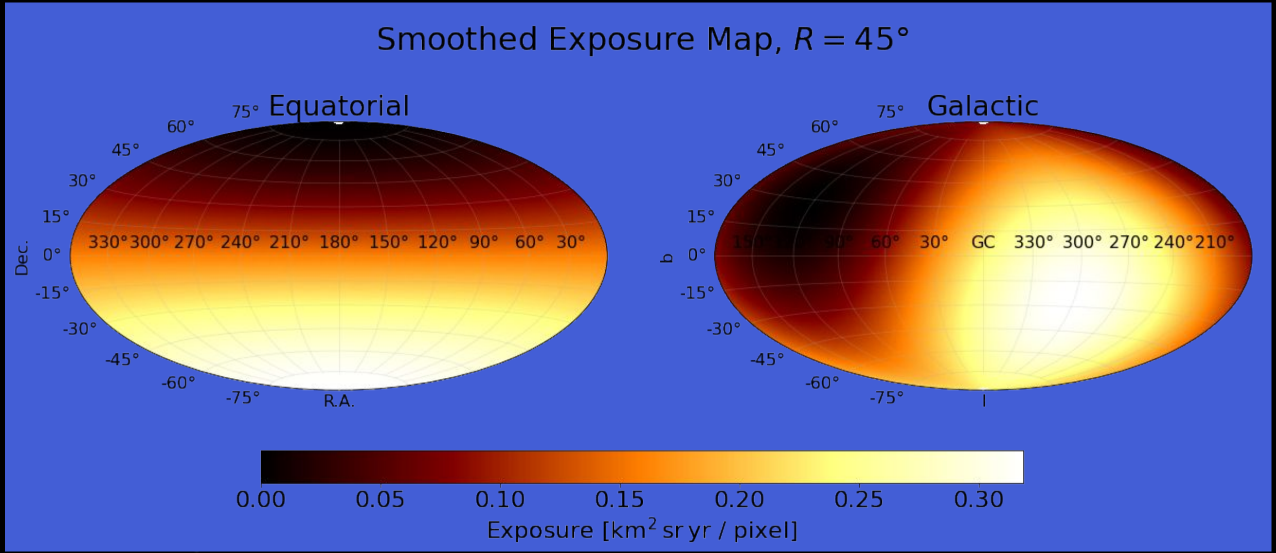
EXAMPLE: LARGE-SCALE ANISOTROPY

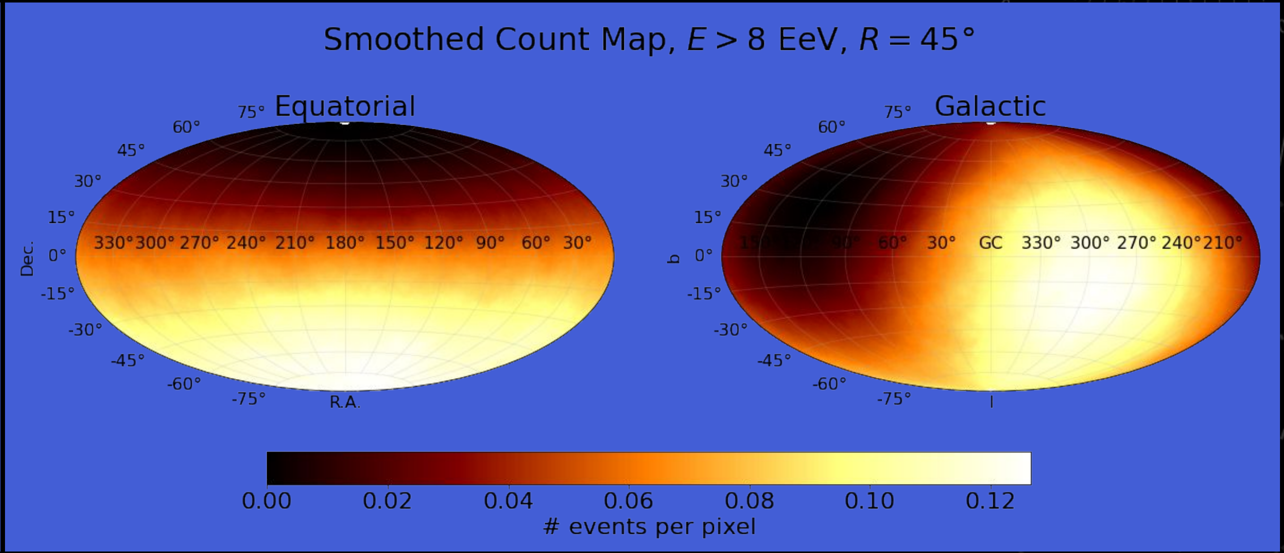
https://www.kaggle.com/code/augeropendata/large-scale-anisotropy



Li-Ma Event Overdensity Analysis

- **Arrival directions of UHECR and exposure.**





Smoothed Exposure Map

We generally see UHECR where/when we look for them!

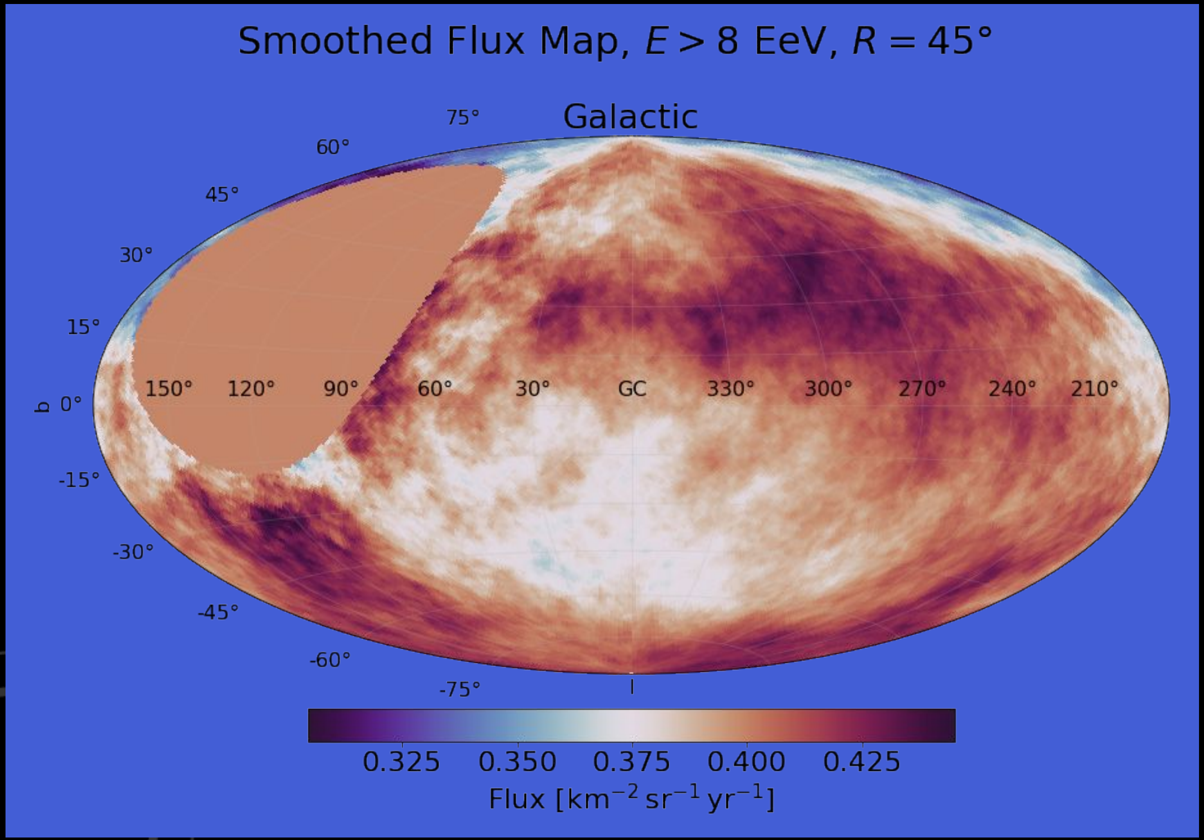
Smoothed Count Map

EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Event Overdensity Analysis

- **Arrival directions of UHECR flux.**



Smoothed Flux Map:
Count/Exposure = Flux

EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

Li-Ma Significance:

"Analysis methods for results in gamma-ray astronomy"

$$S = \sqrt{2} \times \sqrt{N_{\text{on}}\, log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}}\right)\right] + N_{\text{off}}\, log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}}\right)\right]} \times \text{sign}(\text{XS})$$

EXAMPLE: LARGE-SCALE ANISOTROPY

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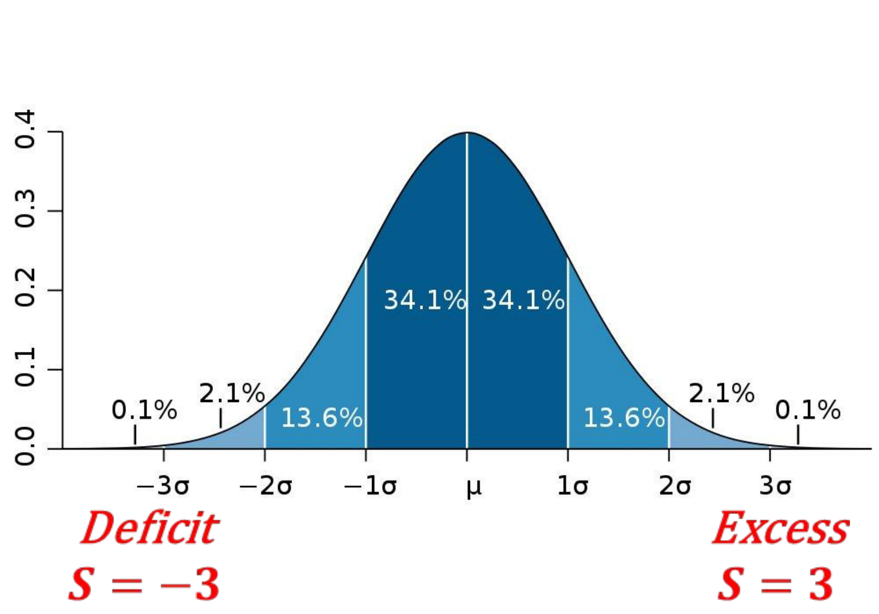
“Sigma Significance” is number of standard deviations away from the average result of random noise.



EXAMPLE: LARGE-SCALE ANISOTROPY

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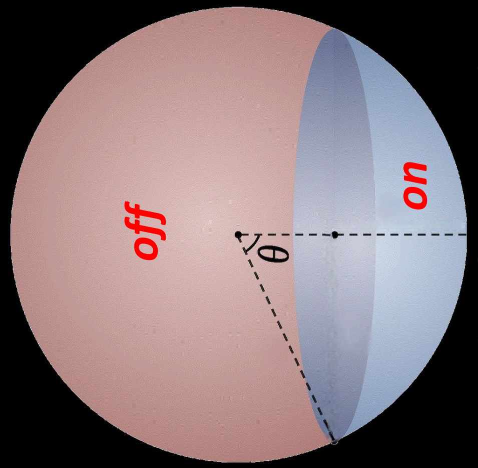
"Local" significance:
Does not account for scanning



EXAMPLE: LARGE-SCALE ANISOTROPY

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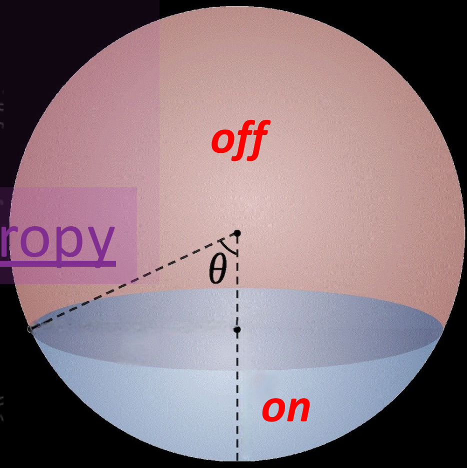
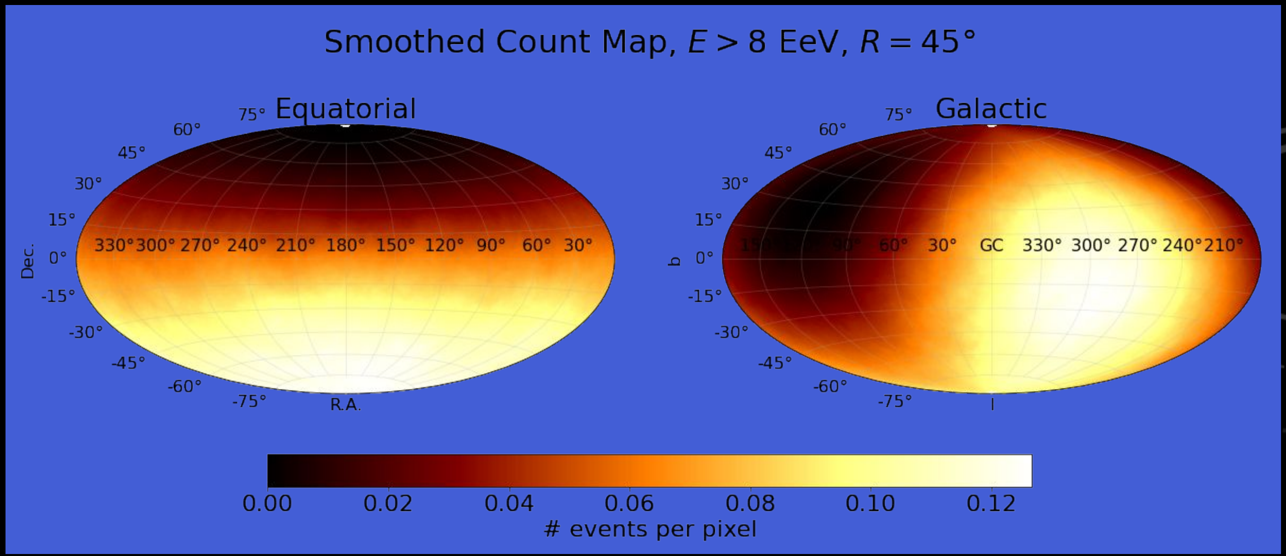


Li-Ma Significance:
"Analysis methods for results in gamma-ray astronomy"

$$S = \sqrt{2} \times \sqrt{N_{\text{on}}\, log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N}\right)\right] + N_{\text{off}}\, log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N}\right)\right]} \times \text{sign}(\text{XS})$$

- $N = N_{on} + N_{off}$

Total Number of Events



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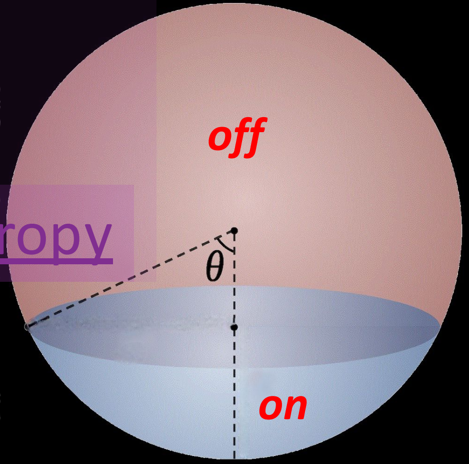
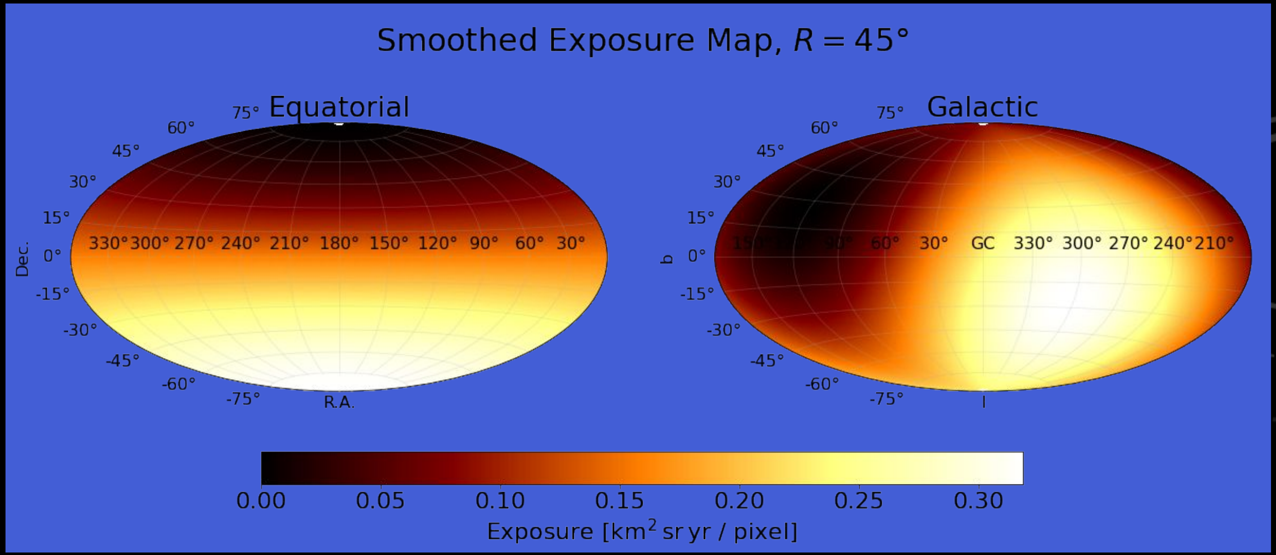


Li-Ma Significance:
"Analysis methods for results in gamma-ray astronomy"

$$S = \sqrt{2} \times \sqrt{N_{\text{on}}\, log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N}\right)\right] + N_{\text{off}}\, log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N}\right)\right]} \times \text{sign}(\text{XS})$$

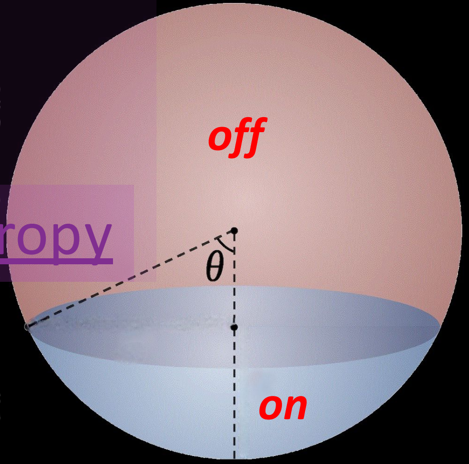
- $N = N_{on} + N_{off}$
- $\alpha = \frac{exposure(on)}{exposure(off)} = \frac{\omega_{on}}{\omega_{off}}$

Exposure Ratio



EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy



Li-Ma Significance:
"Analysis methods for results in gamma-ray astronomy"

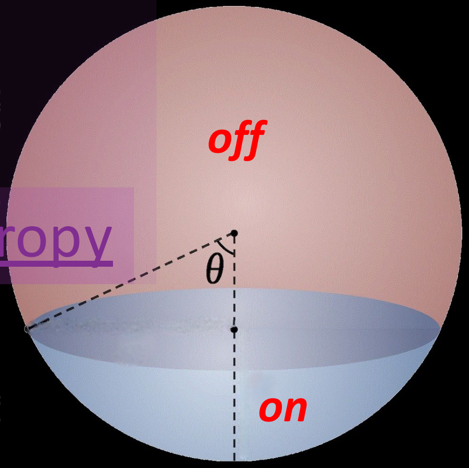
$$S = \sqrt{2} \times \sqrt{N_{\text{on}}\, log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N}\right)\right] + N_{\text{off}}\, log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N}\right)\right]} \times \text{sign(XS)}$$

- $N = N_{on} + N_{off}$
- $\alpha = \frac{exposure(on)}{exposure(off)} = \frac{\omega_{on}}{\omega_{off}}$
- $N_{bg} = \alpha N_{off}$

"On" Region Expected Events

EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy



Li-Ma Significance:
"Analysis methods for results in gamma-ray astronomy"

$$S = \sqrt{2} \times \sqrt{N_{\text{on}}\, log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N}\right)\right] + N_{\text{off}}\, log\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N}\right)\right]} \times \text{sign(XS)}$$

- $N = N_{on} + N_{off}$
- $\alpha = \frac{exposure(on)}{exposure(off)} = \frac{\omega_{on}}{\omega_{off}}$
- $N_{bg} = \alpha N_{off}$
- $N_{sig} = XS = N_{on} - N_{bg} = N_{on} - \alpha N_{off}$

N Signal Events Deviation from Background

EXAMPLE: LARGE-SCALE ANISOTROPY

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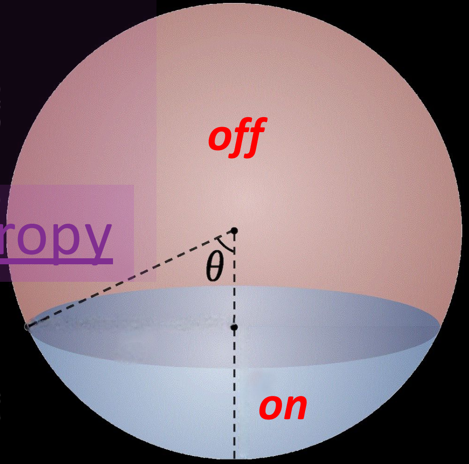

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Maximum Likelihood Ratio

Null Hypothesis:

$N_s = 0,$

Measured N_{on} and N_{off} are fluctuations

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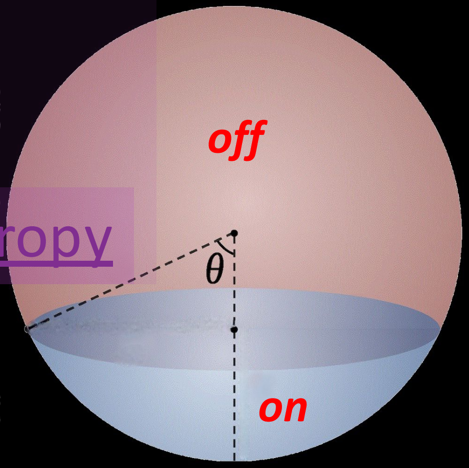

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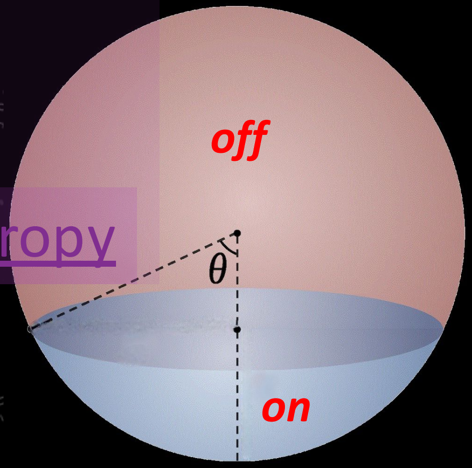

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Alternative Hypothesis:

$$N_s = N_{on} - \alpha N_{off}, \quad N_{bg} = \alpha N_{off},$$

Measured N_{on} and N_{off} means real signal

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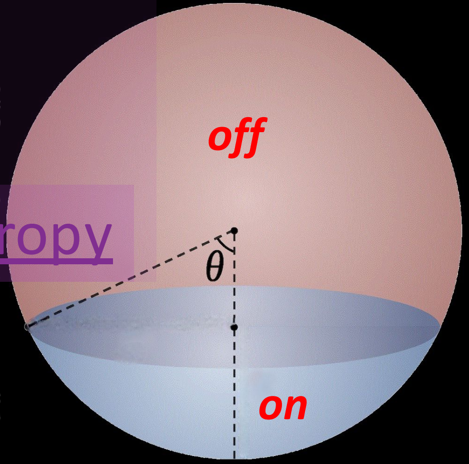

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$$P_k = \frac{\lambda^k e^{-\lambda}}{k!}$$

Probability of measuring k counts with λ expected

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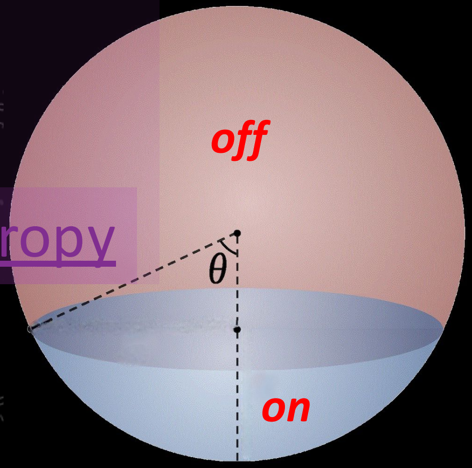

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Wilk's Thei

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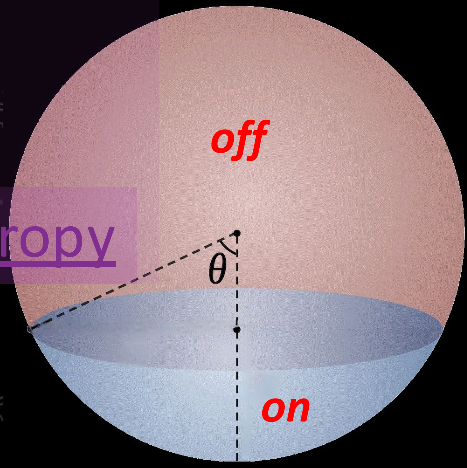

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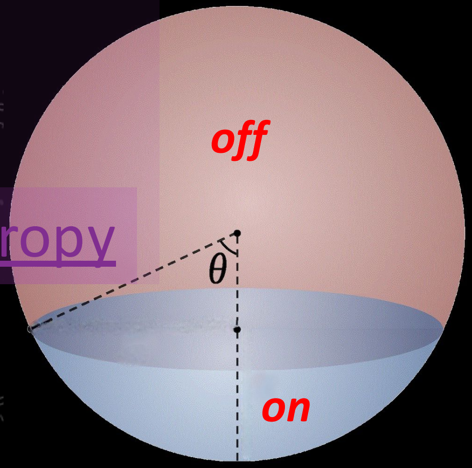

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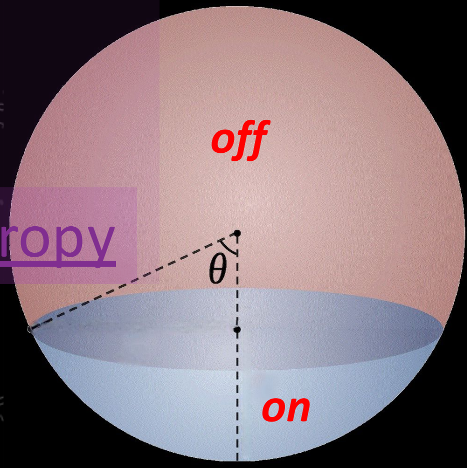

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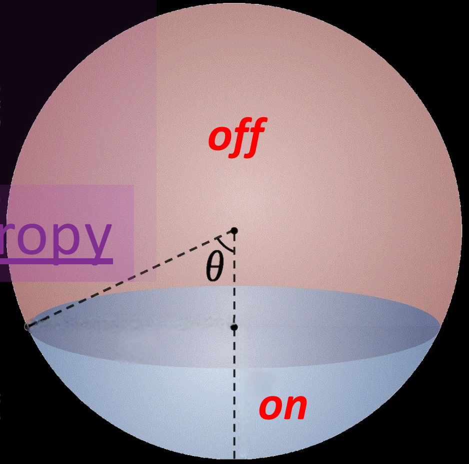

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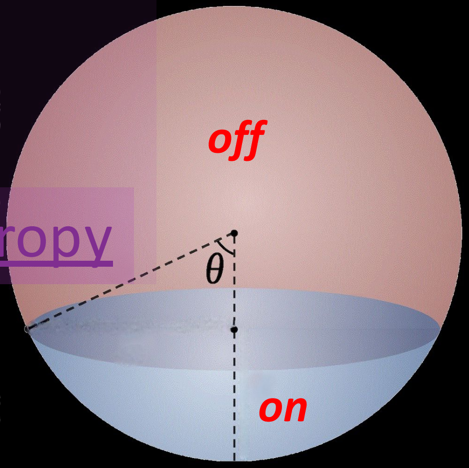

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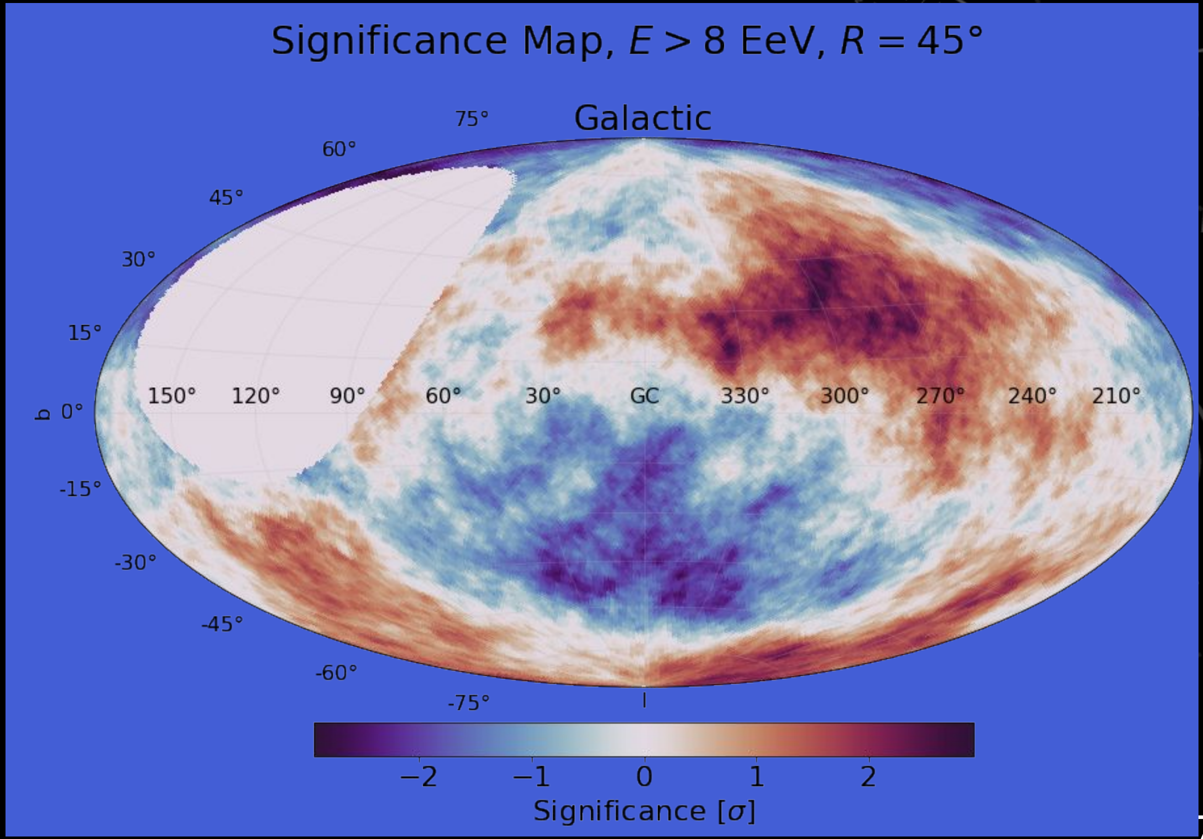
...and do a bunch of algebra

EXAMPLE: LARGE-SCALE ANISOTROPY

https://www.kaggle.com/code/augeropendata/large-scale-anisotropy

- **Li-Ma Event Overdensity Analysis**
  - **Local significance of UHECR flux compared to isotropy.**

Smoothed "Local" Significance Map



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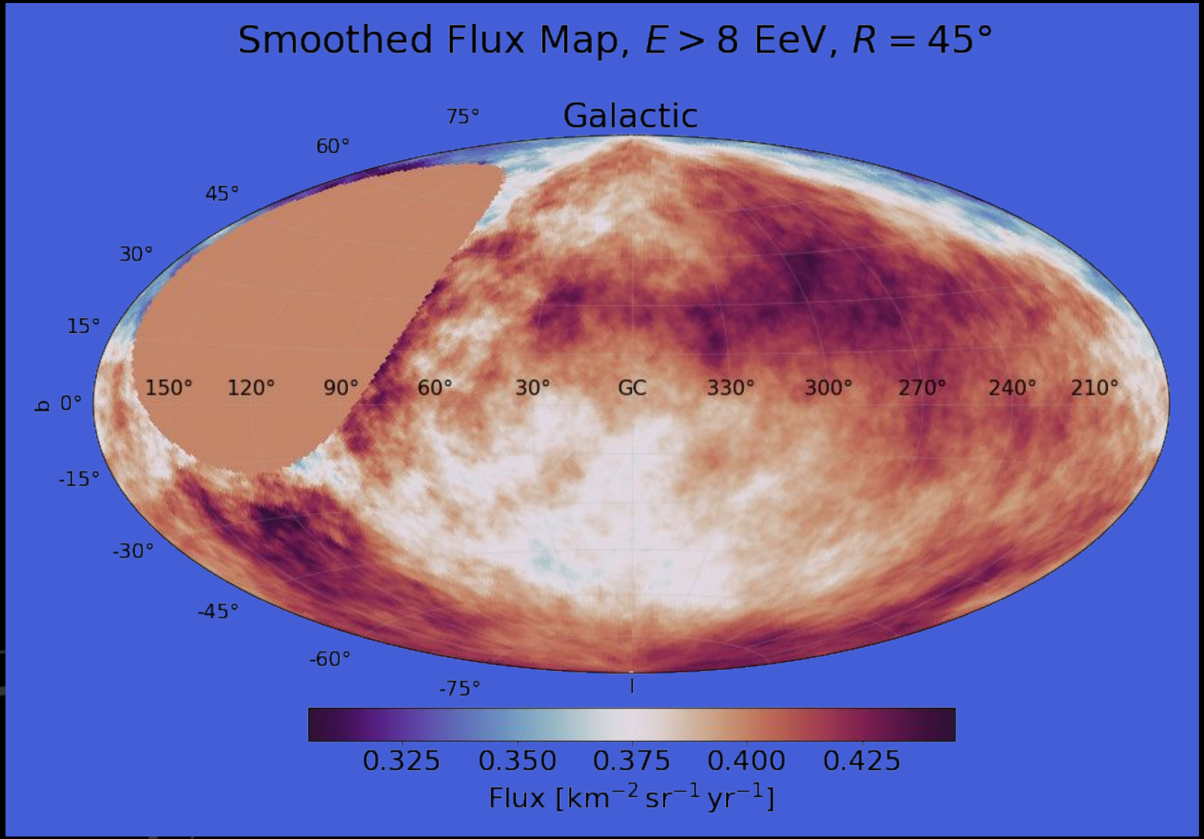
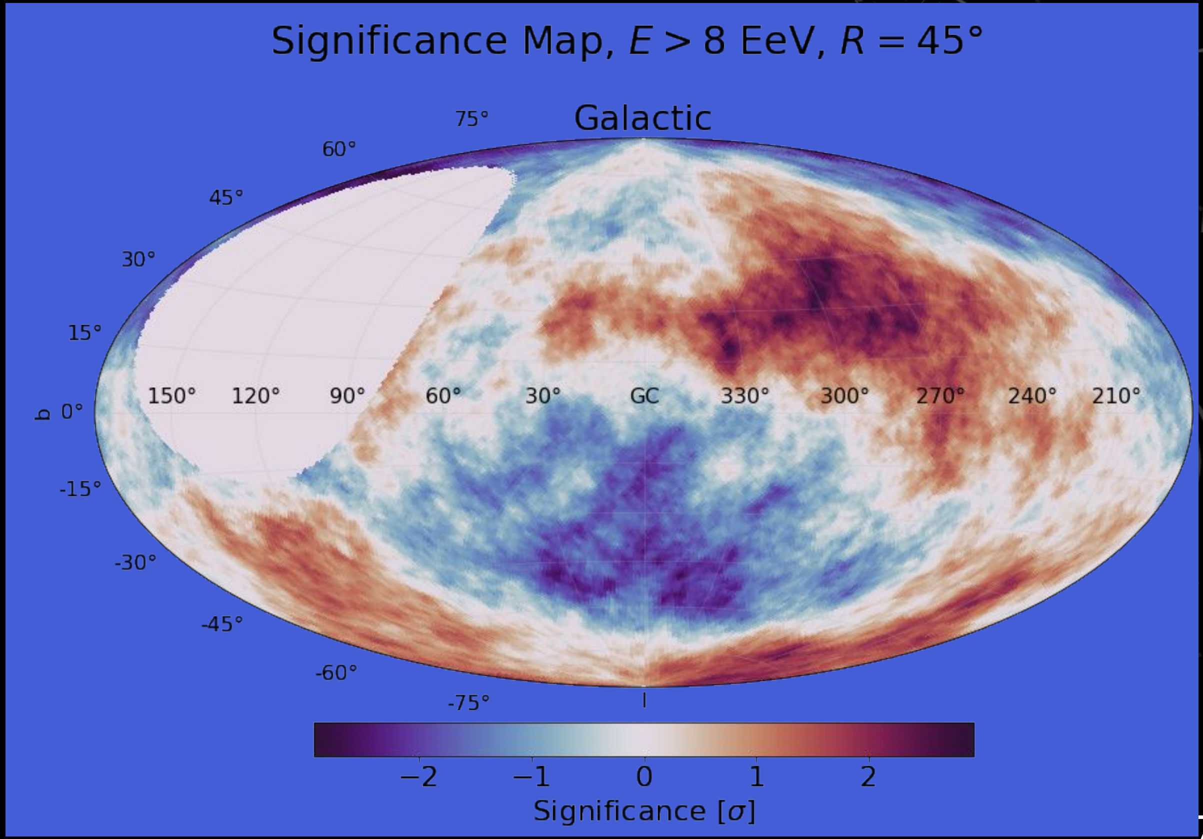
- **Li-Ma Event Overdensity Analysis**
  - **Flux and its local significance.**
  - **No high significance due to 10% of data available.**

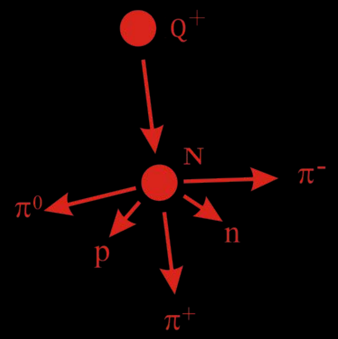




ADDITIONAL

ULTRA-HIGH-ENERGY COSMIC RAYS

Astroparticle Physics: Unravelling the mysteries of the universe by exploring the smallest phenomena…



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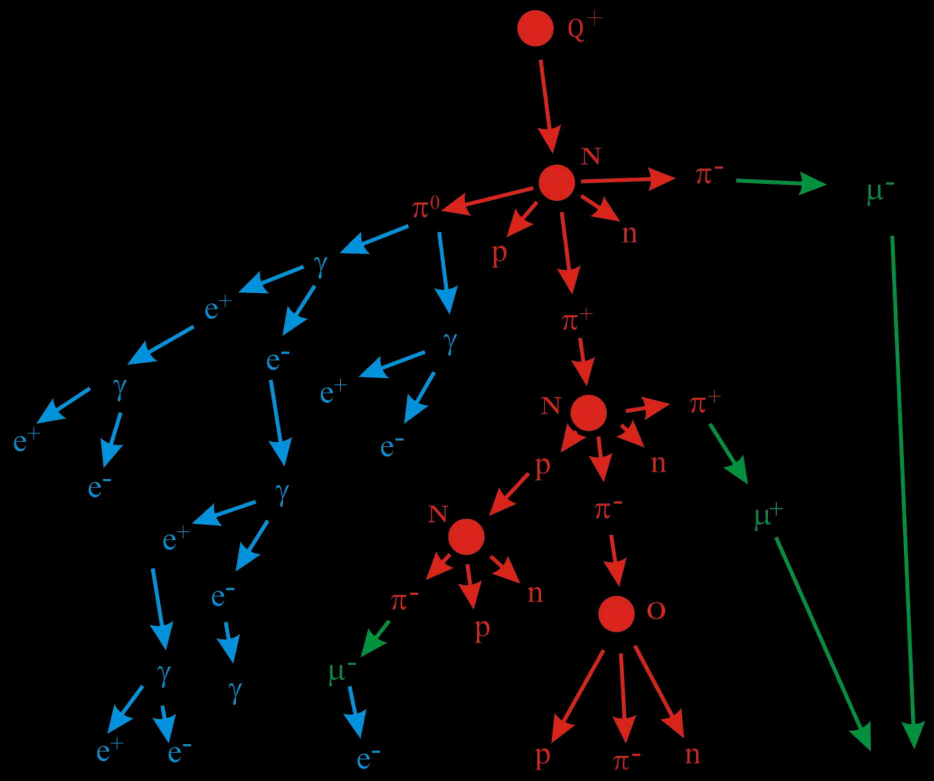

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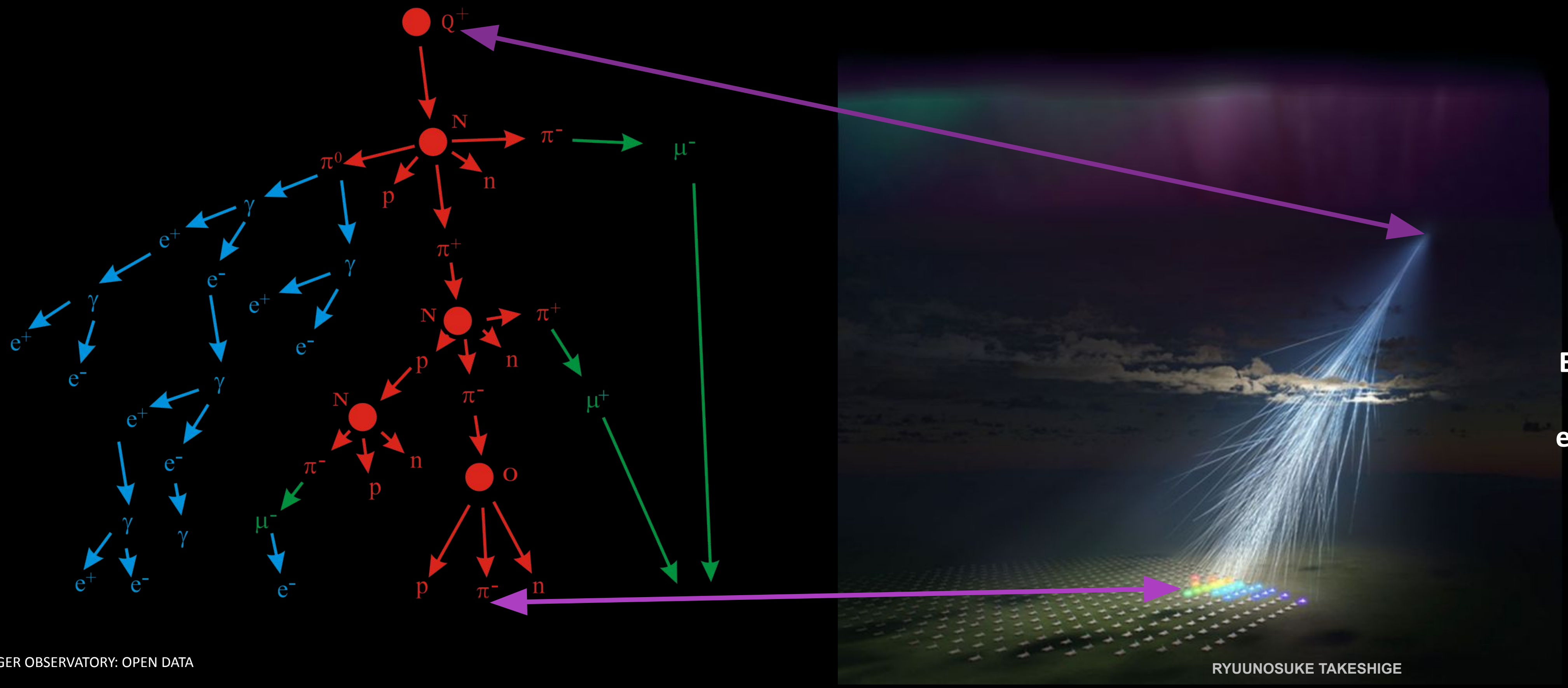

Extensive air-showers detected by extremely large arrays

PIERRE AUGER OBSERVATORY: OPEN DATA