# FEATURES OF ULTRA-HIGH ENERGY COSMIC RAY SOURCES FOR HEAVY ENERGY TAIL

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# FEATURES OF UHECR SOURCES

The interactions during propagation in the cosmic space before their arrival to the Earth have a significant influence on the UHECR energy spectrum.

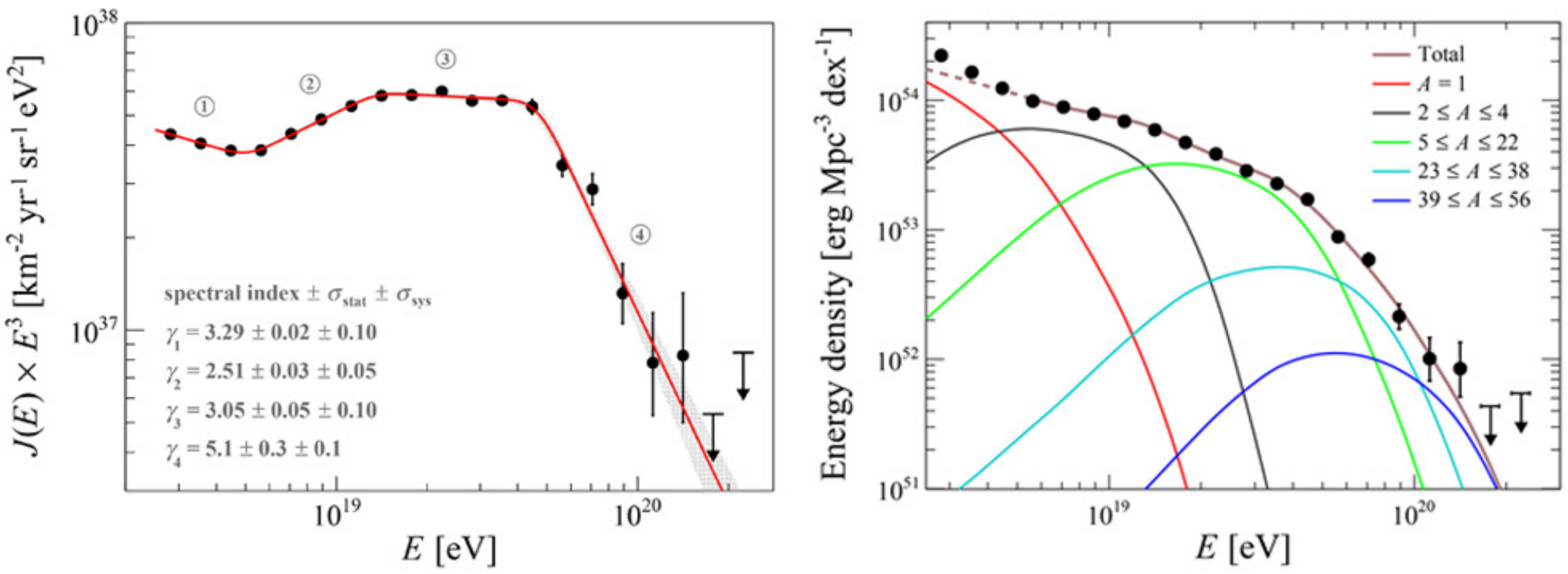
Such as:

- Direction smearing
- Mass composition

# COSMIC RAYS

Discovery of cosmic-rays is a standard example of ‘one man’s noise is another man’s signal’.

# ENERGY SPECTRA




*Left: Energy spectrum with superimposed the t function used to determine the spectral features.*
*Right: Energy spectrum reproduced in a model with energy-dependent mass composition [7].*

# XMAX

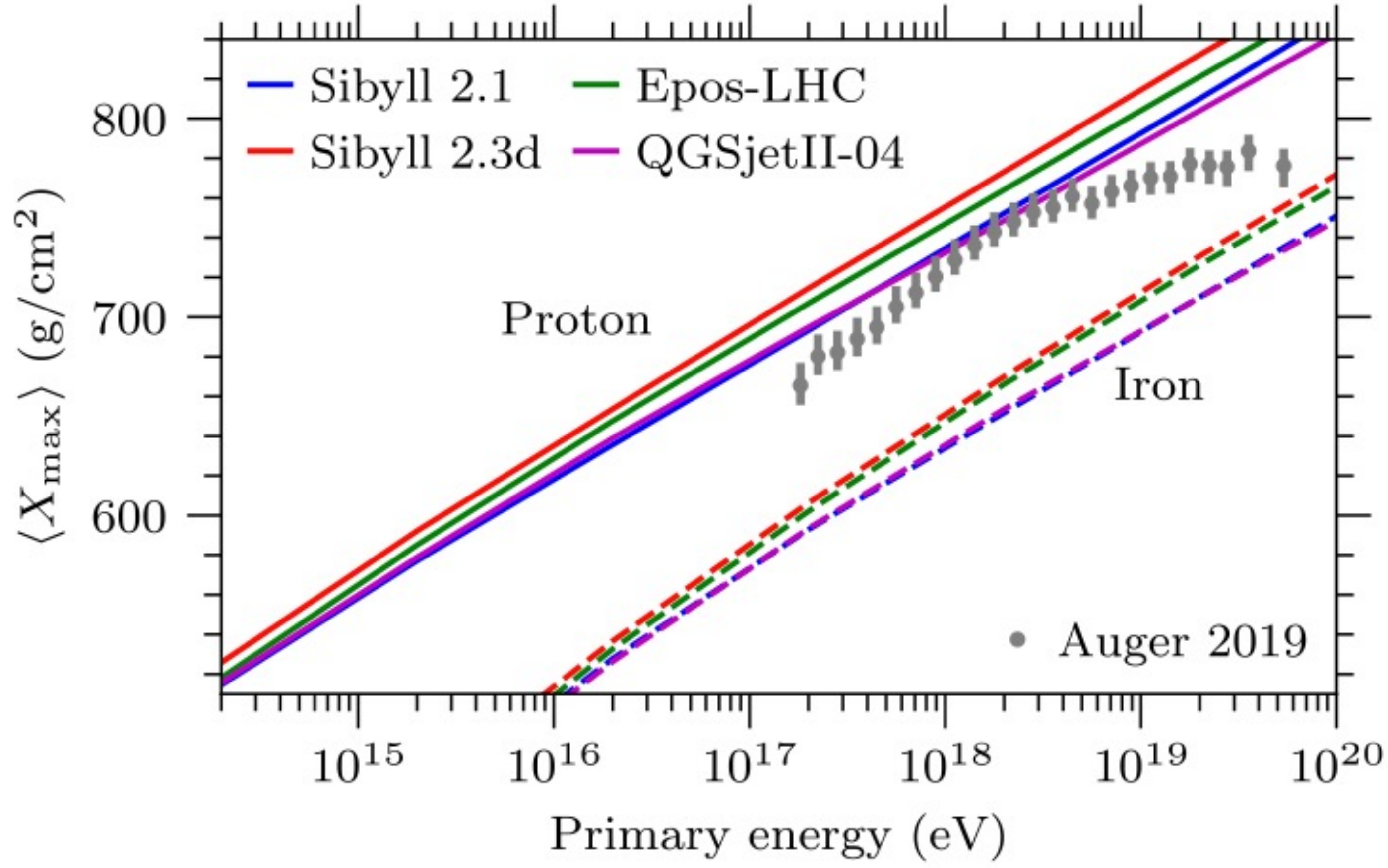
Penetration depth

Unique for each element

Good parameter to distinguish individual particles

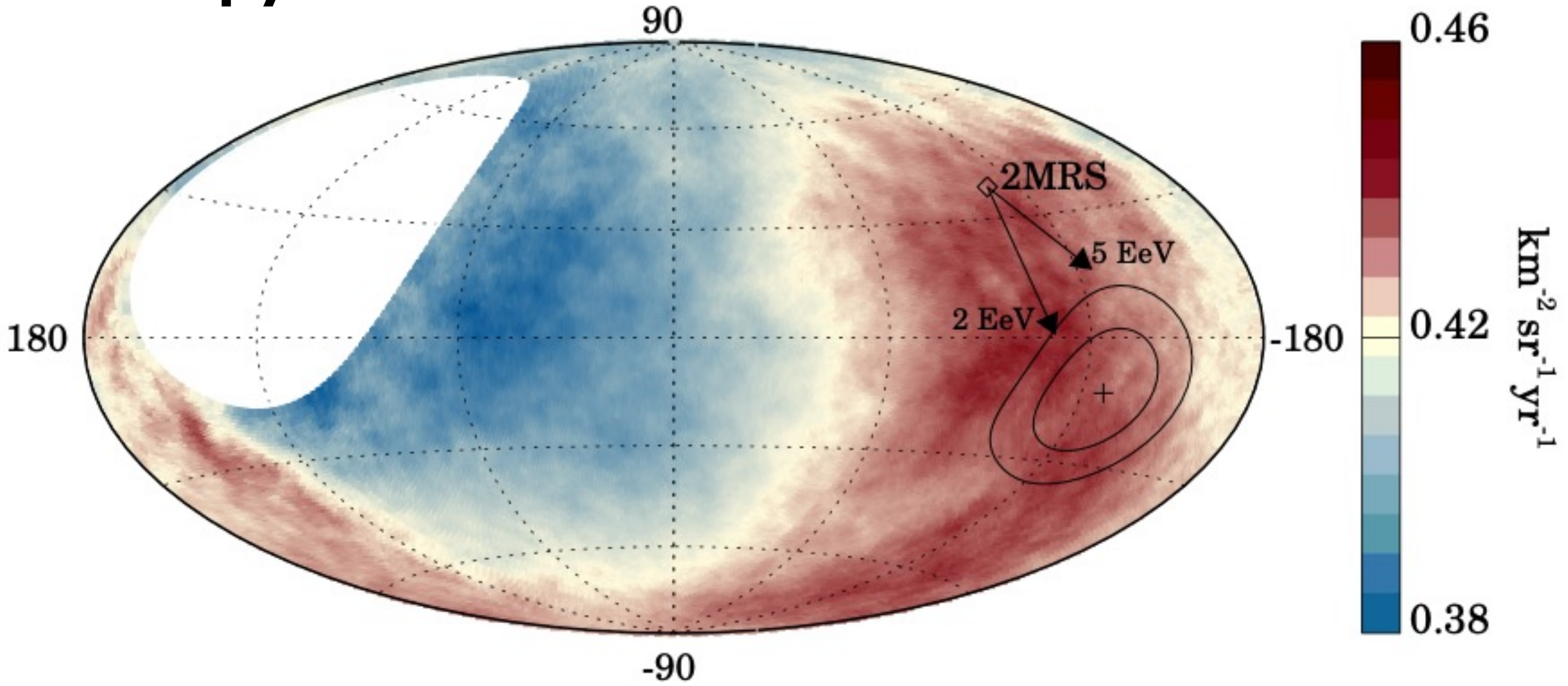
Often used in Astro particle physics field

# MASS COMPOSITIONS




Average depth of air-shower maxima $<X_{max}>$ for different models compared to recent data from the Pierre Auger Observatory [2].

# Dipole Anisotropy




**Map showing the fluxes of particles in Galactic coordinates.** Sky map in Galactic co- ordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45◦ top-hat function. The Galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence-level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for a particular model of the Galactic magnetic field on particles with $E/Z = 5$ EeV or 2 EeV [1].

# ENERGY LOSSES DURING PROPAGATION

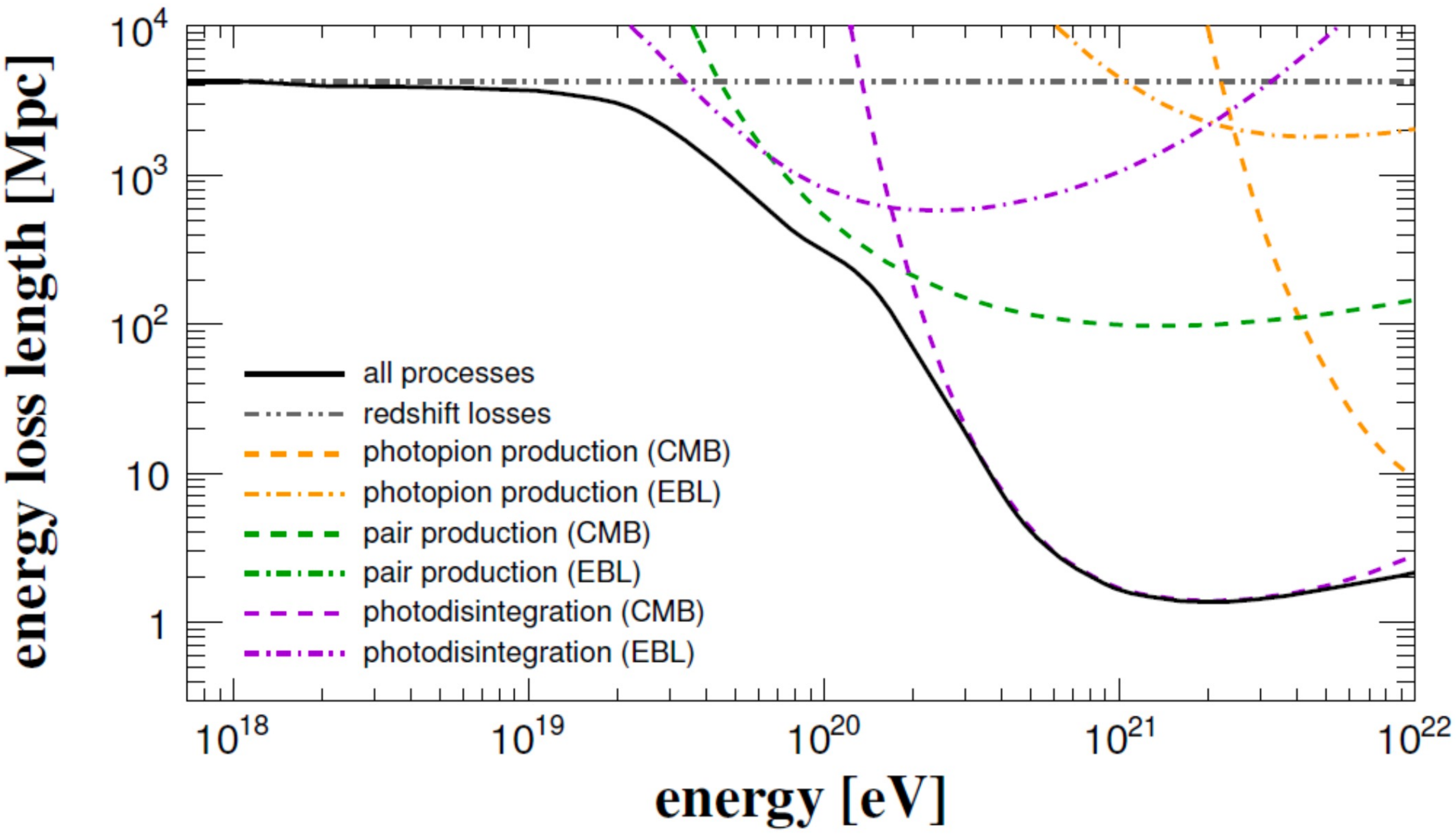
Distance travelled

Energy of the primary particle

Strength

Direction

Magnetic field




Energy loss length for 56Fe (a) at z = 0. Dotted-dashed lines correspond to interactions with the EBL, and dashed lines with the CMB [3]

# GALACTIC MAGNETIC FIELDS IN THE UNIVERSE

**Two common ways of measuring are:**

- Faraday Rotation
- Synchrotron radiation

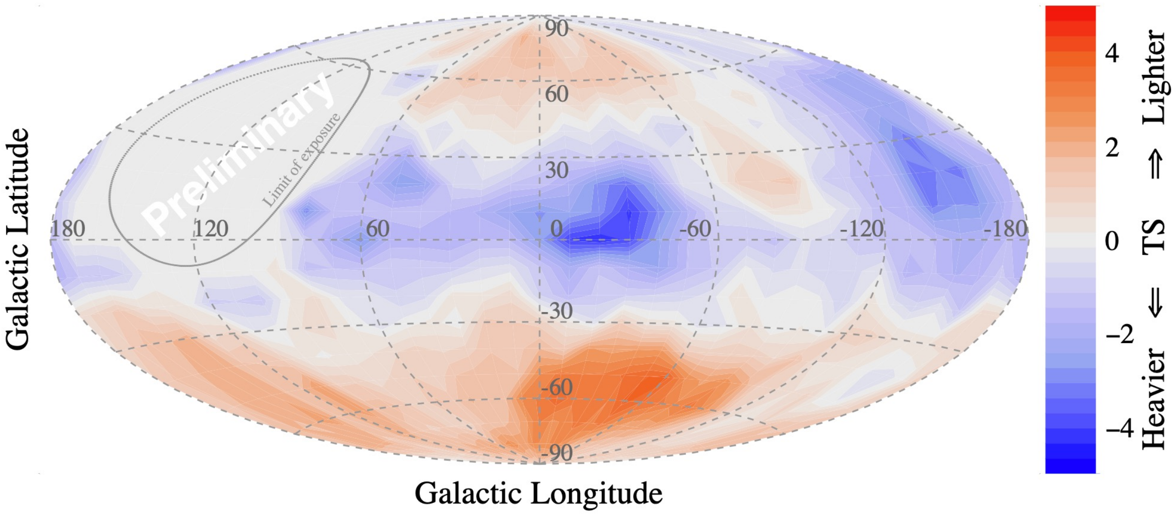
**Extragalactic Magnetic Fields is a weak filed,** estimated usually to be less than nG.

**Most used Galactic Field Model is the: JF12.**

# SIMULATION OF PROPAGATION OF COSMIC - CRPROPA

- CRPropa is a publicly available simulation framework.
- Can be used for 3D simulations.
- Version CRPopa3 was used.
- p, He, Ne, Fe – elements were simulated.
- Each element had a library of  200 000 particles.
- Each library was produced for direct simulations from the edge of Galaxy (negligible energy losses).

# PHYSICS MOTIVATION



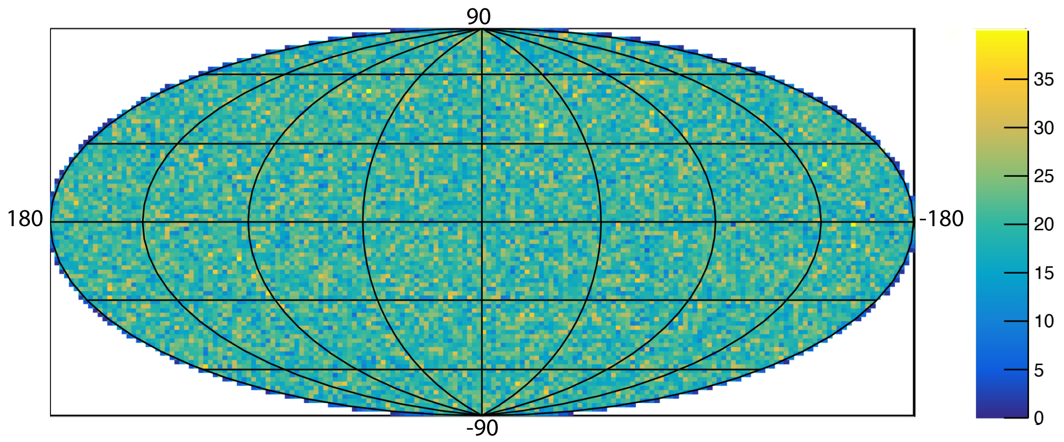

Sky map of comic ray composition for $E \geq 1018.7$ eV [1]

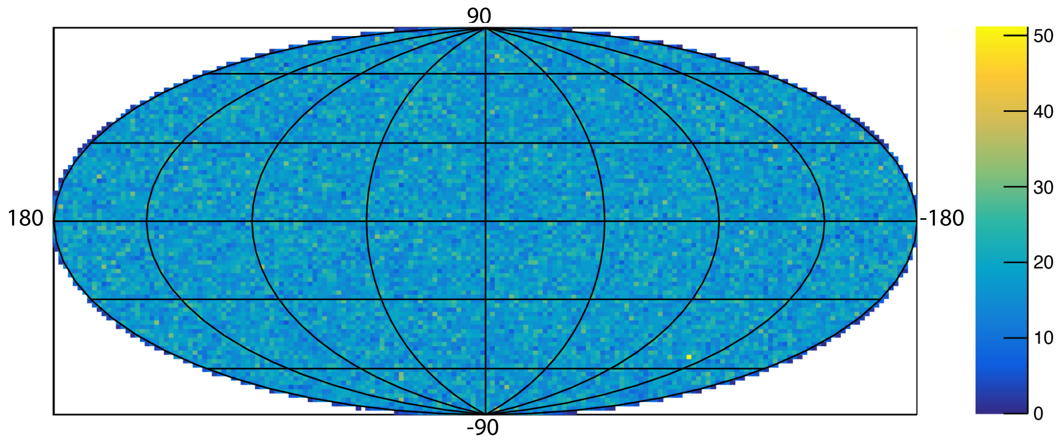
Eric Mayotte and Pierre Auger Observatory contributed very interesting Sky map of comic ray composition regarding its mass composition for particle arriving to Earth.

These findings together with the map, sparks a curiosity that motivated this project.

This project then try to answer question about the compositions, and or dipole distribution of arrival directions,, and what initial conditions it would take to simulate these observed results, what would happen if specific conditions are given, etc…

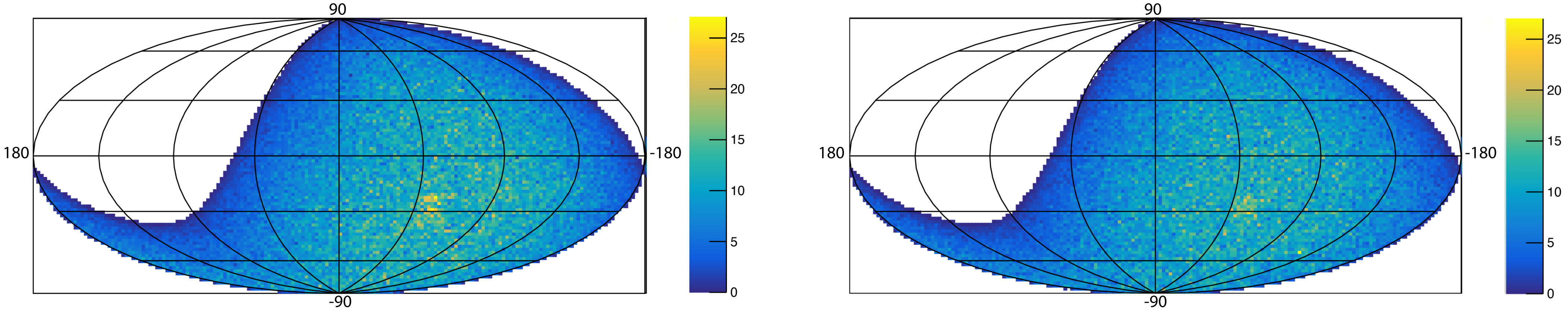
# RESULTS: EFFECTS OF GMF ON ARRIVAL DIRECTIONS




Mollweide projection with a distribution of arrival directions in galactic coordinates, isotropic flux with a mixing set to 100 % proton (p) left and iron (Fe) right.

# RESULTS: EFFECTS OF GMF ON ARRIVAL DIRECTIONS




Mollweide projection with a distribution of arrival directions in galactic coordinates, Auger-Dipole + exposure weight flux with a mixing set to 100 % proton (p) left and iron (Fe) right.

# GENERATION OF XMAX DISTRIBUTIONS

Each simulated primary generated using a Generalized Gumble Function

$$G(\mu, \sigma, \lambda) = \lambda^{\lambda} * e^{\frac{-\lambda(x-\mu)}{\mu} - \lambda e^{\frac{-(x-\mu)}{\sigma}}}$$

Tree parameters μ, σ, λ, from EPOS-LHC model.

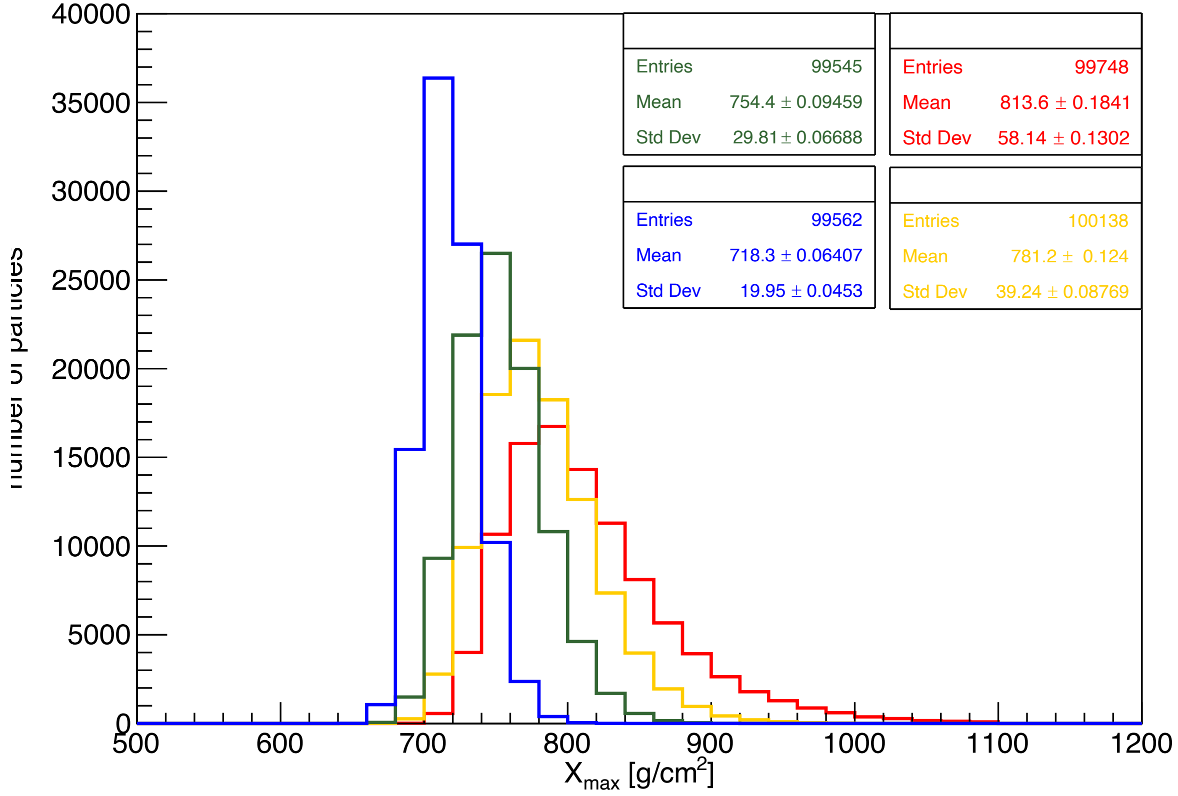
$$\mu(A, E) = p_{0\mu} + p_{1_\mu} log_{10}(E/E_0) + p_{2_\mu} log_{10}^2(E/E_0)$$

$$\sigma(A, E) = p_{0_\sigma} + p_{1_\sigma} log_{10}(E/E_0)$$

$$\lambda(A, E) = p_{0_\lambda} + p_{1_\lambda} log_{10}(E/E_0)$$

Further parameters that are required can found in paper [4].

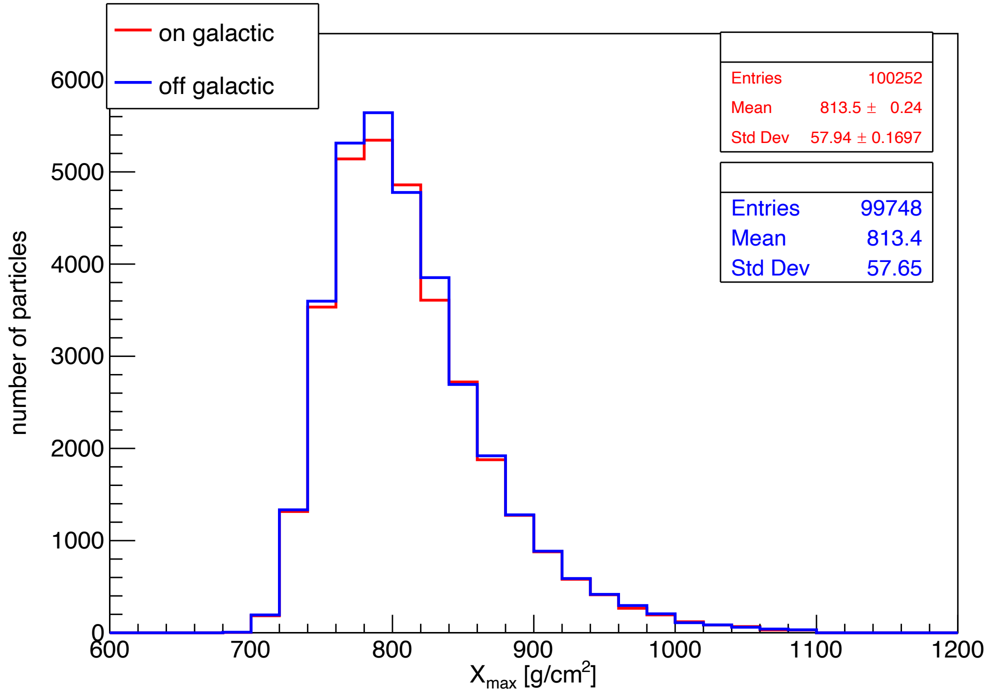
# Results: Xmax distribution of all four primaries



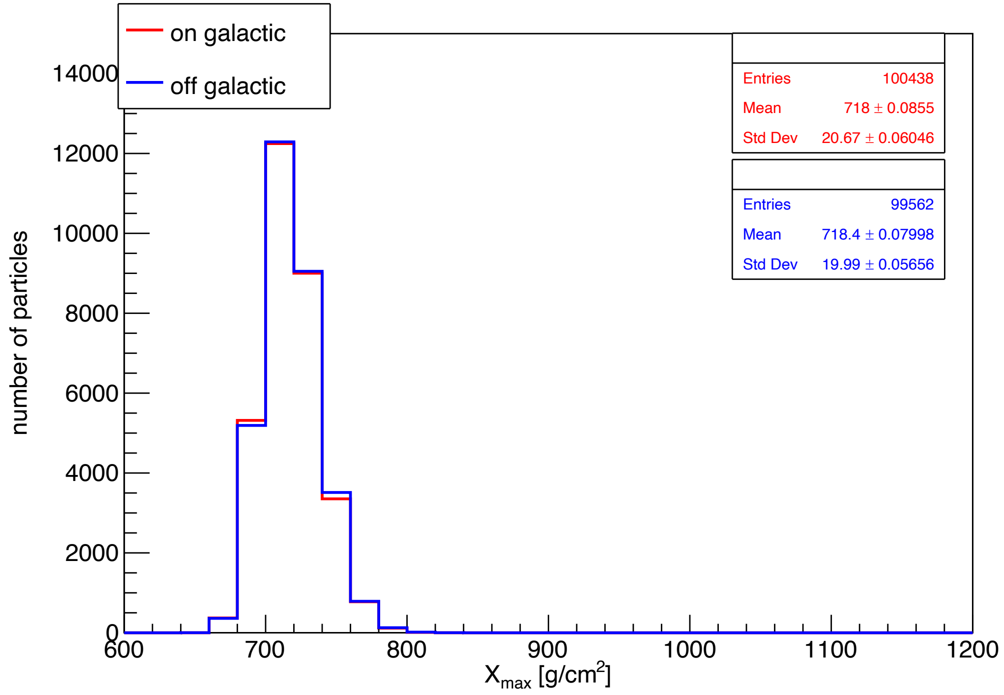

Histogram displaying all Xmax distribution for all primaries (p, He, N, Fe) with Auger-Dipole + exposure weight flux.

# RESULTS:XMAX DISTRIBUTION OF THE TWO ENDS (P) & (FE )

- Pure proton and Iron



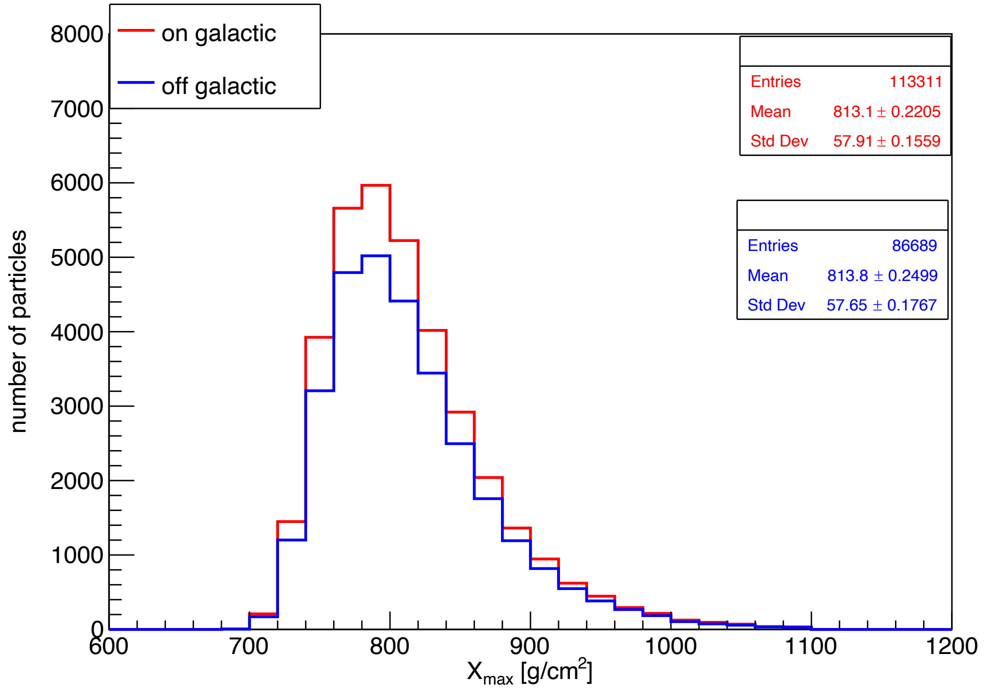

The on-and off-plane distributions of shower Xmax using the galactic latitude for Auger-Dipole + exposure weight flux of pure proton (p).



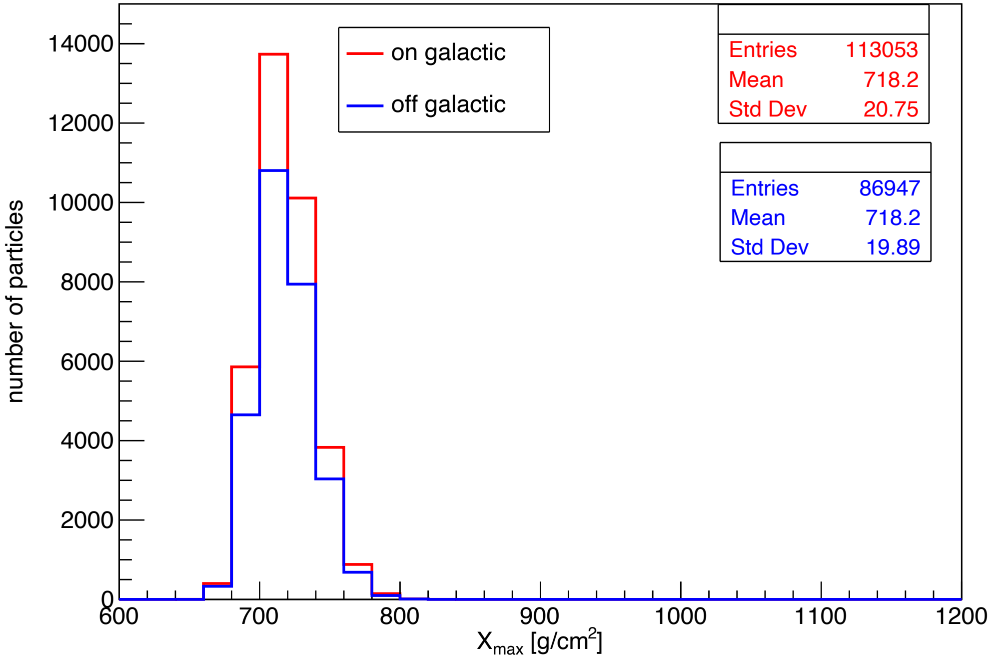

The on-and off-plane distributions of shower Xmax using the galactic latitude for Auger-Dipole + exposure weight flux of pure Iron (Fe).

# RESULTS:XMAX DISTRIBUTION OF THE TWO ENDS (P) & (FE )

- Pure proton and Iron



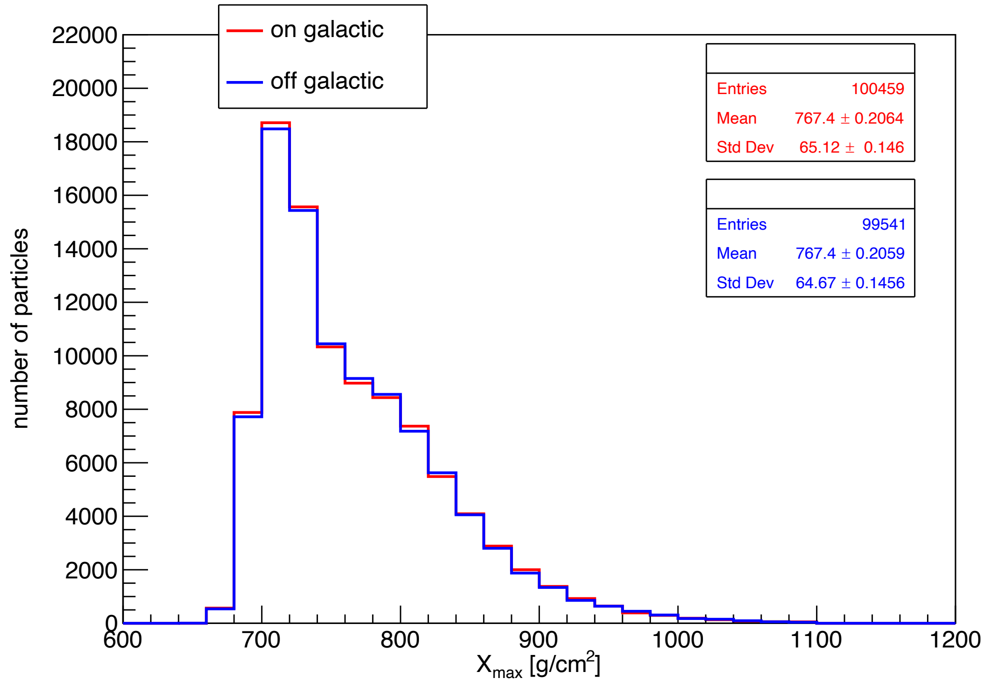

The on-and off-plane distributions of shower Xmax using the equatorial Right Ascension for Auger-Dipole + exposure weight flux of pure proton (p).



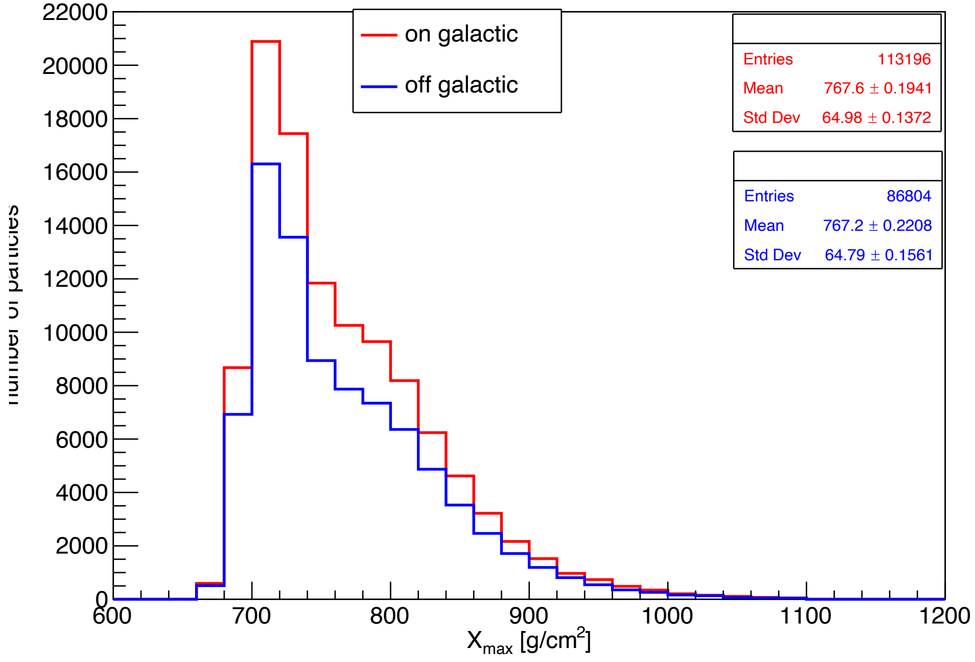

The on-and off-plane distributions of shower Xmax using the equatorial Right Ascension for Auger-Dipole + exposure weight flux of pure Iron (Fe).

# RESULTS:XMAX DISTRIBUTION OF THE TWO ENDS (P) & (FE )

- proton Iron Mix 50/50




The on-and off-plane distributions of shower Xmax using the galactic latitude for isotropic flux of 50/50 mix of protons (p) and Iron (Fe).




The on-and off-plane distributions of shower Xmax using the equatorial Right Ascension for isotropic flux 50/50 mix of protons (p) and Iron (Fe).

# RESULTS:XMAX DISTRIBUTION OF THE TWO ENDS (P) & (FE )

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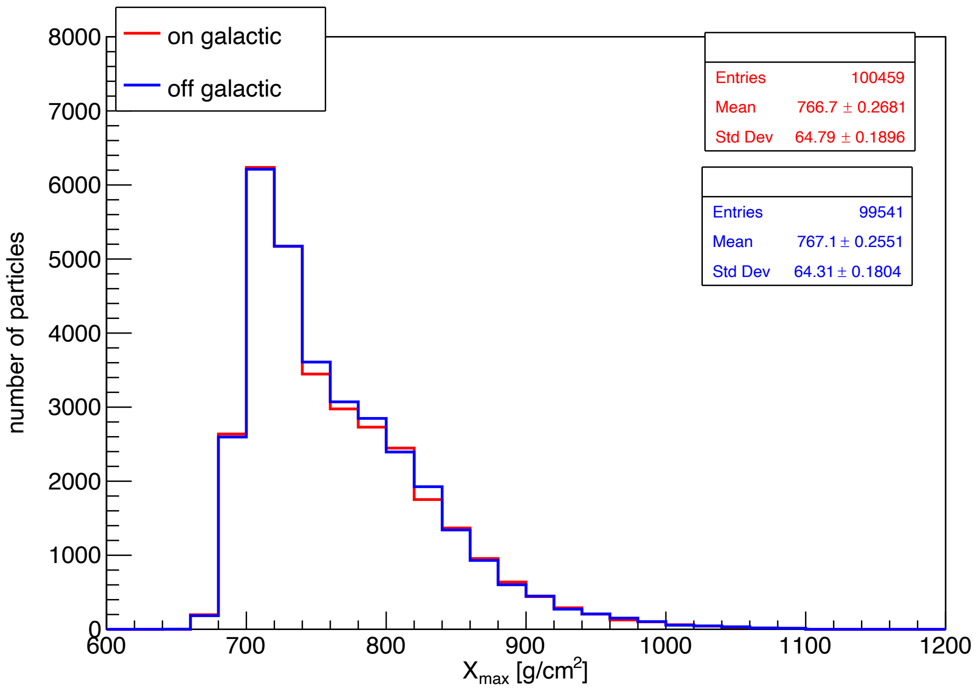
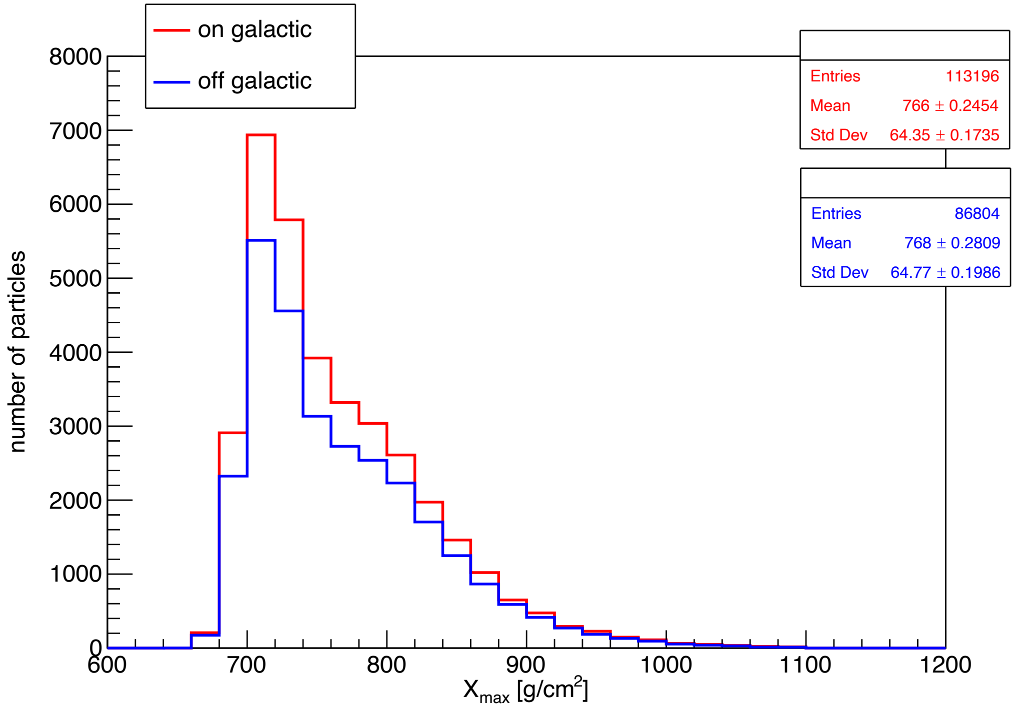


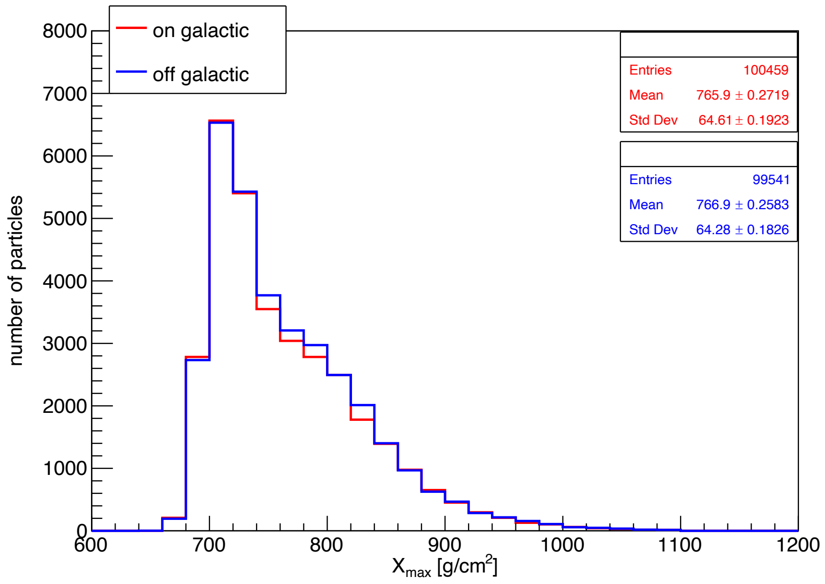

The on-and off-plane distributions of shower Xmax using the galactic latitude for isotropic flux of 50/50 mix of protons (p) and Iron (Fe).



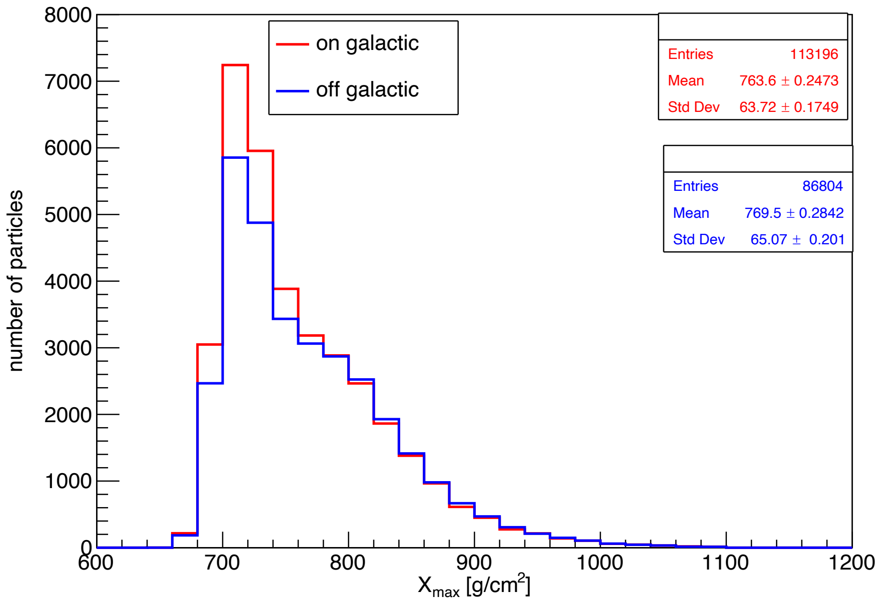

The on-and off-plane distributions of shower Xmax using the equatorial Right Ascension for isotropic flux 50/50 mix of protons (p) and Iron (Fe).

# RESULTS:XMAX DISTRIBUTION OF THE TWO ENDS (P) & (FE ) AMPLITUDE ON 30%

- proton Iron Mix 50/50

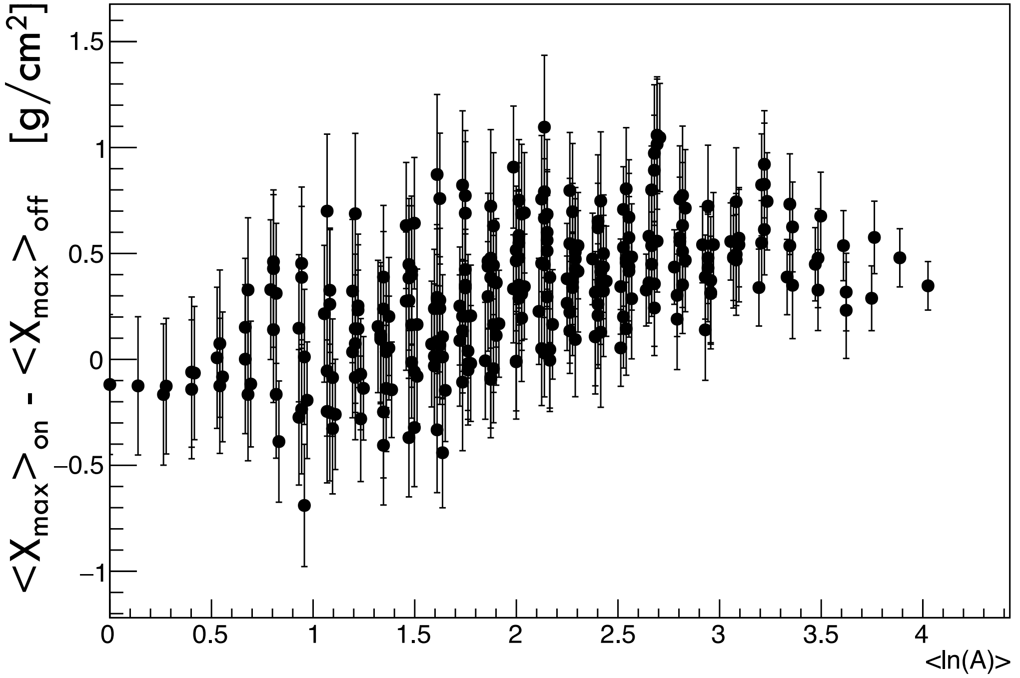



The on-and off-plane distributions of shower Xmax using the galactic latitude for Auger-Dipole + exposure weight flux of 50/50 mix with amplitude 30% for protons (p) and Iron (Fe).

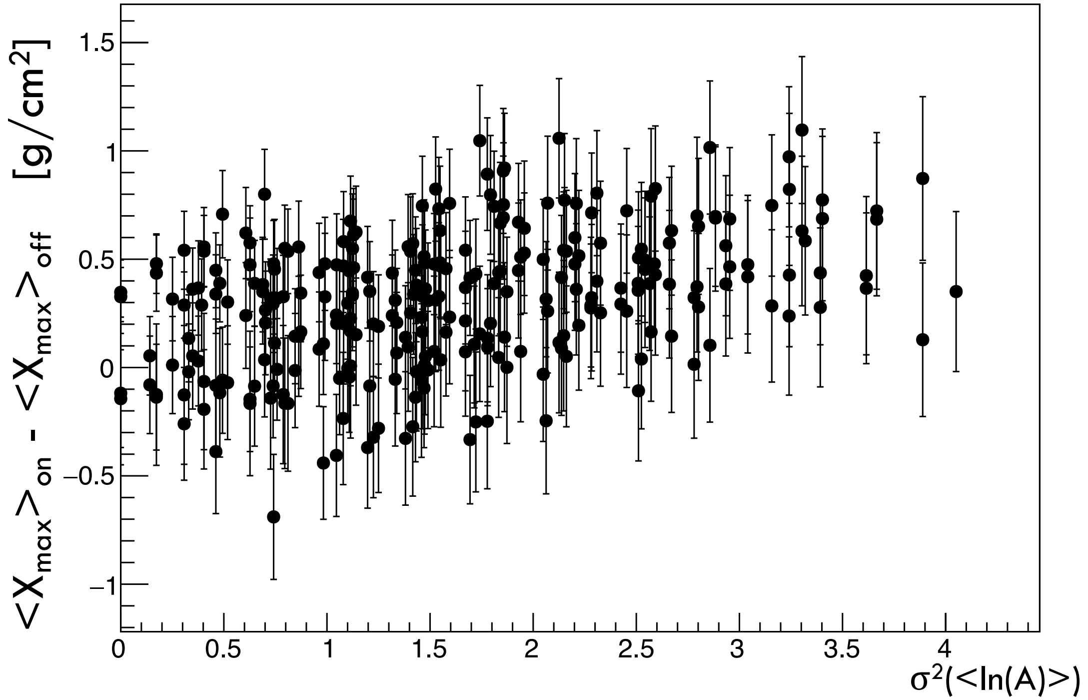



The on-and off-plane distributions of shower Xmax using the equatorial Right Ascension for Auger-Dipole + exposure weight flux with amplitude 30% for 50/50 mix of protons (p) and Iron (Fe).

# Δ ⟨XMAX⟩ OF ALL POSSIBLE COMBINATIONS OF THE FOUR PRIMARIES




Mean $X_{max}$ vs ln(A) in dipole for Latitude




Mean $X_{max}$ dipole vs $\sigma^2$(ln(A)) in dipole for LAtitude

ln(A) values corresponds to:

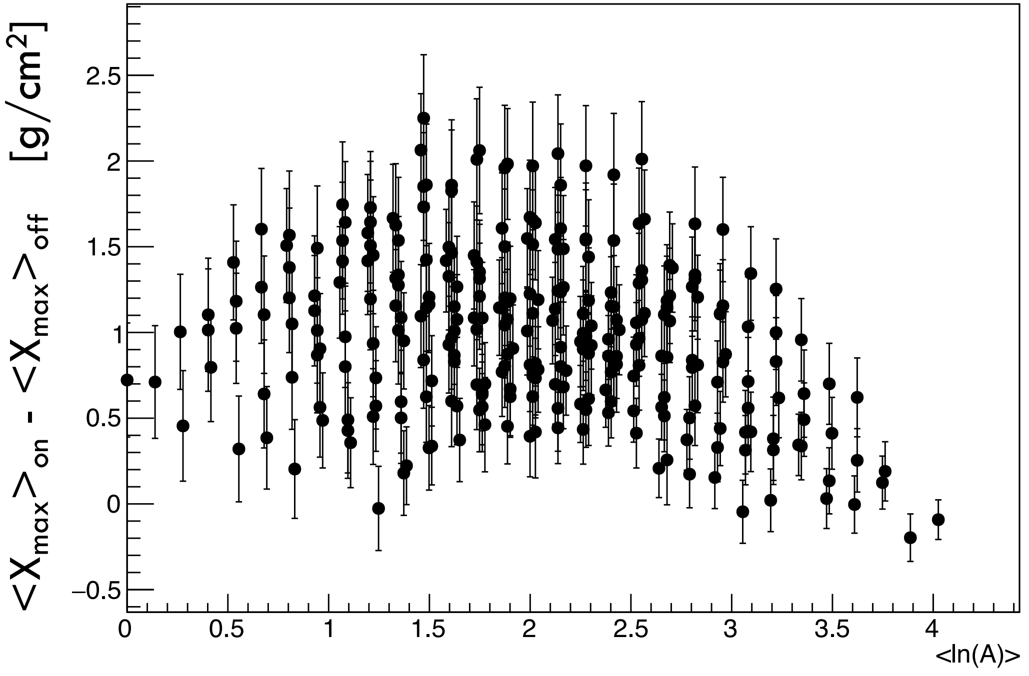
pure p = 0

Pure He = 1

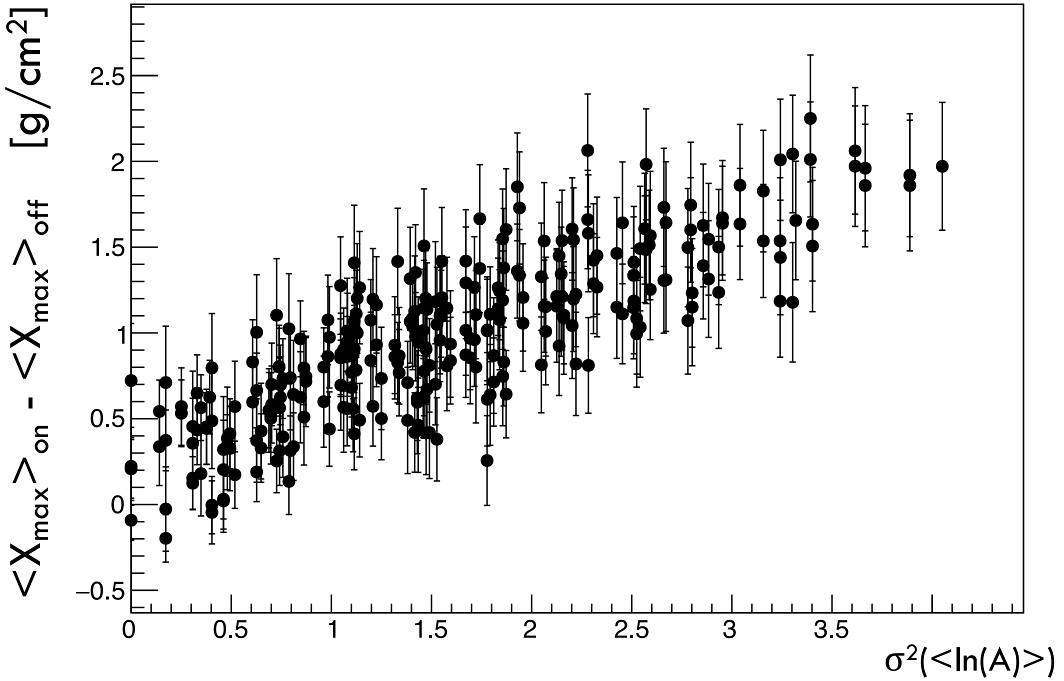
Pure N = 3

Pure Fe =4

# Δ ⟨XMAX⟩ OF ALL POSSIBLE COMBINATIONS OF THE FOUR PRIMARIES




Mean $X_{max}$ vs ln(A) in dipole for RA




Mean $X_{max}$ dipole vs $\sigma^2$(ln(A)) in dipole for RA

ln(A) values corresponds to:

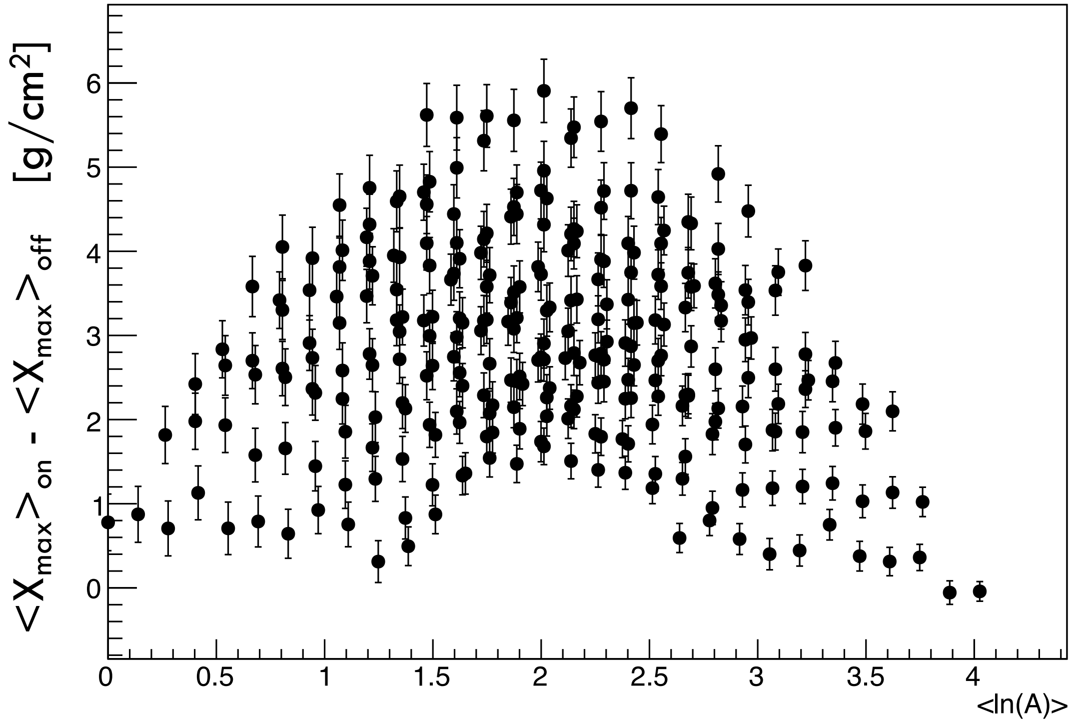
pure p = 0

Pure He = 1

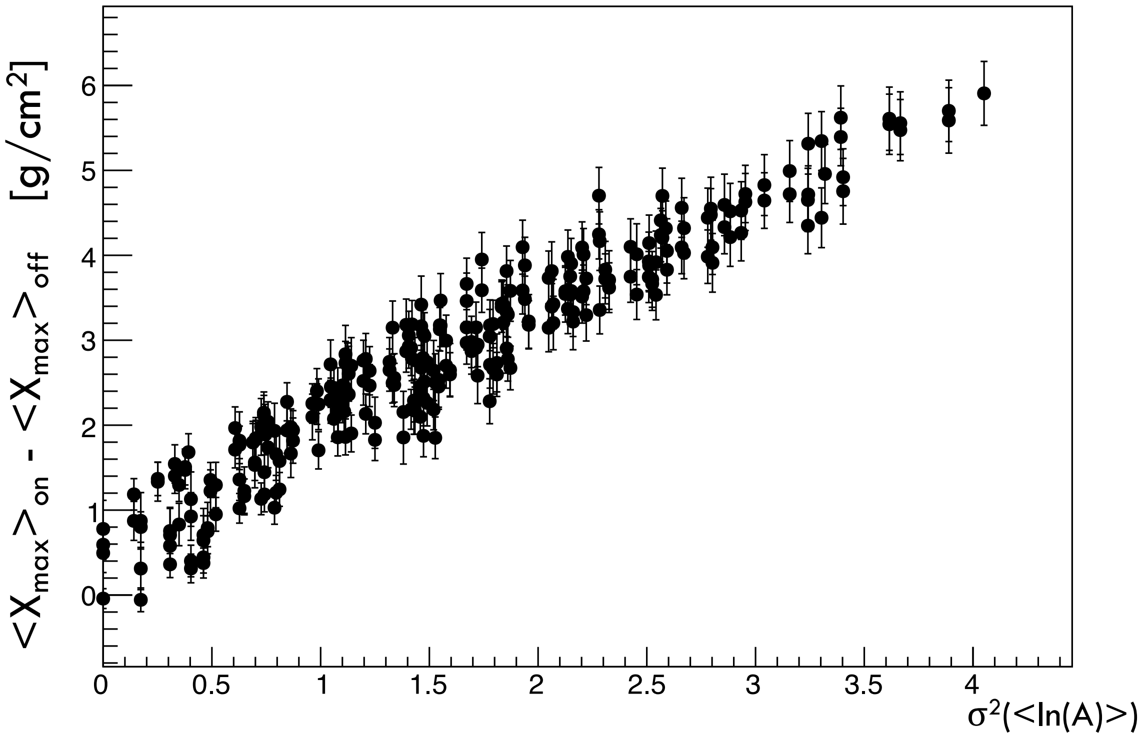
Pure N = 3

Pure Fe =4

# Δ ⟨XMAX⟩ OF ALL POSSIBLE COMBINATIONS OF THE FOUR PRIMARIES FOR AMPLITUDE 30%




Mean $X_{max}$ vs ln(A) in dipole for RA




Mean $X_{max}$ dipole vs $\sigma^2$(ln(A)) in dipole for RA

ln(A) values corresponds to:
pure p = 0
Pure He = 1
Pure N = 3
Pure Fe =4

# SD VS FD

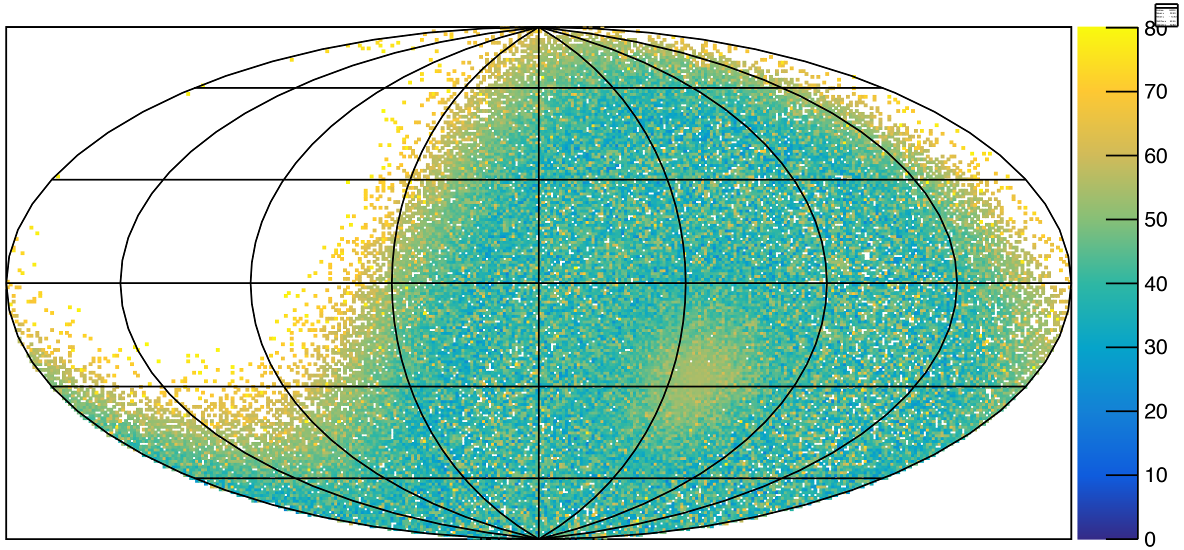
The SD stations are self-powered water-Cherenkov cylindrical tanks

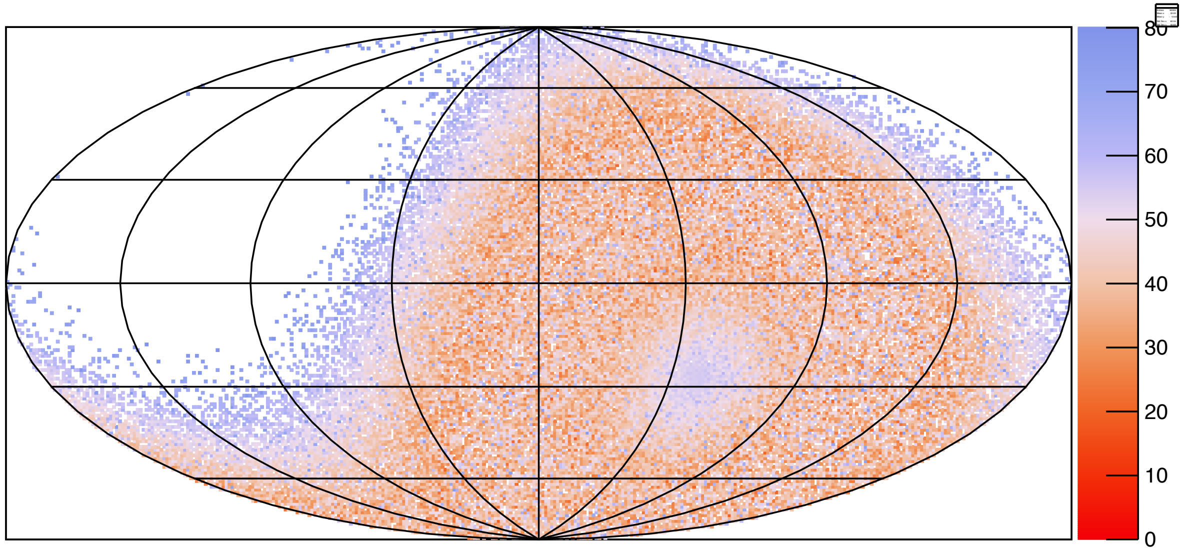
The FD stations work by a charged particles created during the development of cosmic-ray shower in the atmosphere excite and ionise the nitrogen atoms that afterwards emit the fluorescence light

SD – for reconstruction has a geometry that can be used,  which is super however we won't find the difference In SD.

→ Need to change to FD

# FD-RESULT BY REAL MC SIMULATIONS

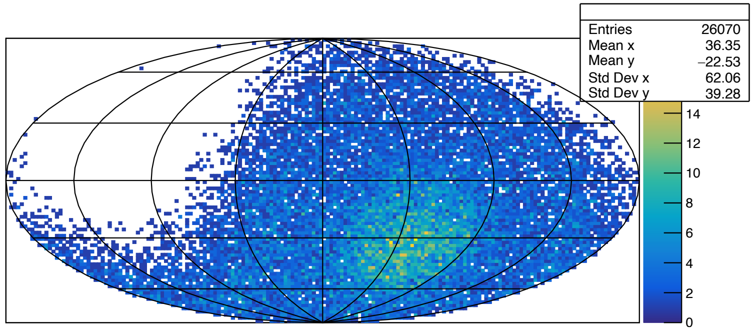


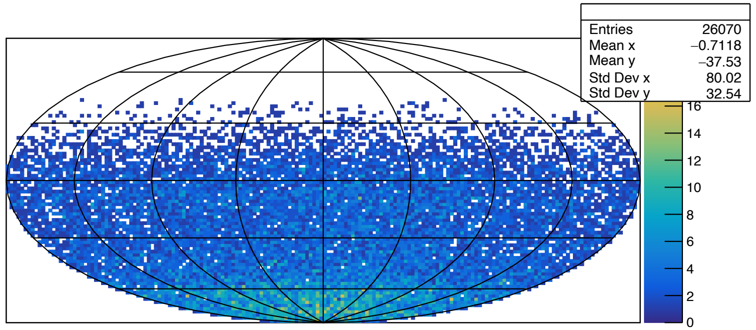
# USED LIBNOVA

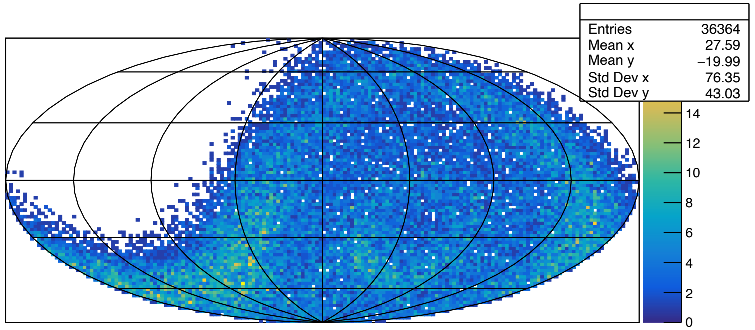
libnova is a general purpose, double precision, Celestial Mechanics, Astrometry and Astrodynamics library.

Allows me to check the phenomena

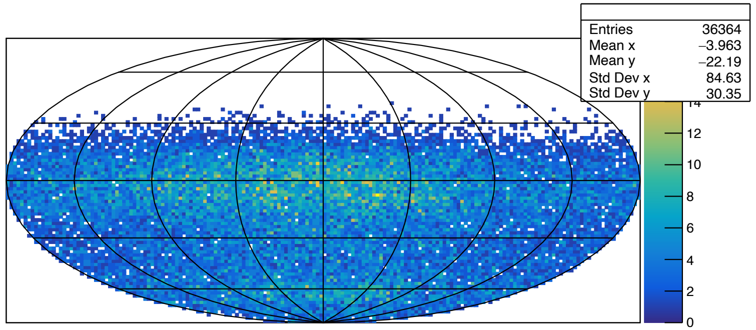


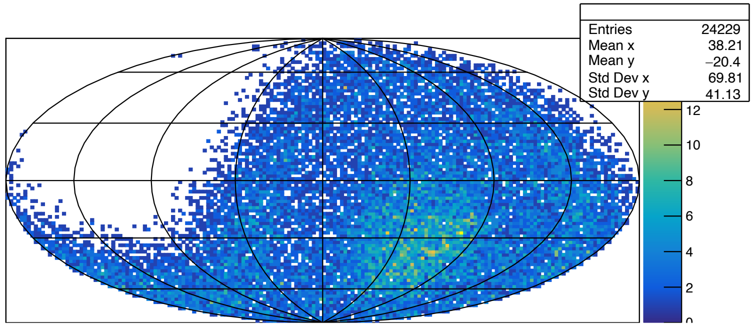

EYE 1



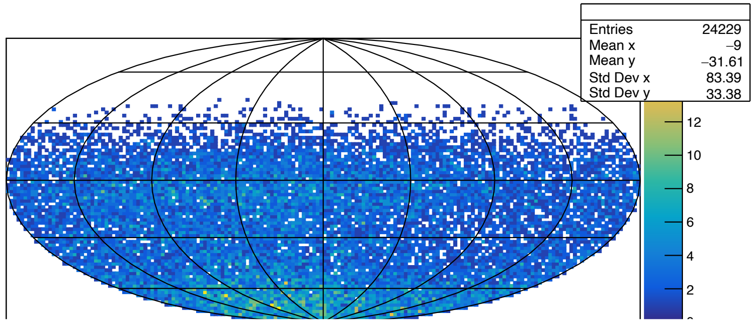



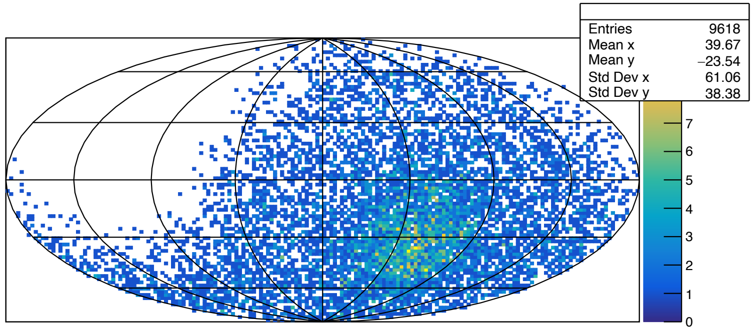

EYE 2



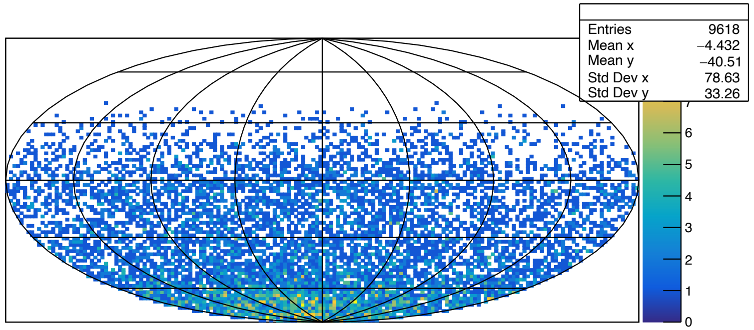




EYE 3




EYE 4



# CREATE MASK --> USE IT FOR CRPROPA

CRPropa

# CONCLUSION

Region in RA are more reliable data and showed the phenomena better.

- Liouville's theorem -> Isotropic cosmic ray flux entering the Galaxy remains isotropic for any observer inside the Galaxy was shown.
- Show anisotropy is present.
- Very interesting results that the anisotropy is not depended only on the mean ln(A) but on how much is mixed.
- SD not working FD does
- Map of all 4 eyes proven

What's for the future?

- Changing the direction of the dipole, changing the amplitude, changing the composition so that it matches the real observed data, just to name few.
- Account for observation effects (resolution, biases, acceptance).
- Second topic: relations between mass composition, energy spectrum and anisotropies with source features (propagation in extragalactic fields with energy losses)

# SOURCES


[1] Collaboration, T. P. A. *et al.* (2017) 'Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8 $\times 10^{18}$ eV'. doi: 10.1126/science.aan4338.

[2] Riehn, F. *et al.* (2019) 'Hadronic interaction model Sibyll 2.3d and extensive air showers'. doi: 10.1103/physrevd.102.063002.

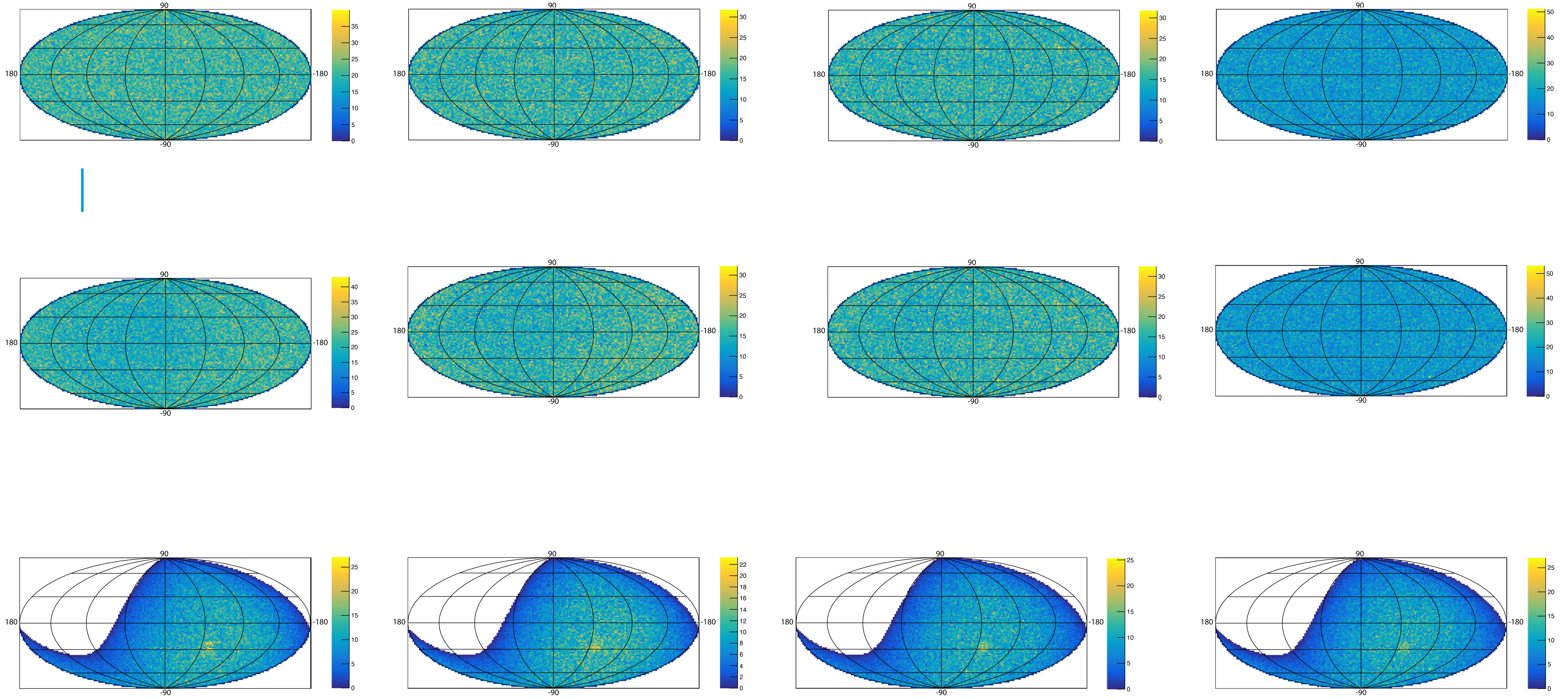
[3] Batista, R. A. *et al.* (2015) 'Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp', *Journal of Cosmology and Astroparticle Physics*, 2015(10), pp. 063–063. doi: 10.1088/1475-7516/2015/10/063.

[4] De Domenico, M. *et al.* (2013) 'Reinterpreting the development of extensive air showers initiated by nuclei and photons'. doi: 10.1088/1475-7516/2013/07/050.

[5] Batista, R. A. *et al.* (2016) 'CRPropa 3 - a Public Astrophysical Simulation Framework for Propagating Extraterrestrial Ultra-High Energy Particles'. doi: 10.1088/1475-7516/2016/05/038.

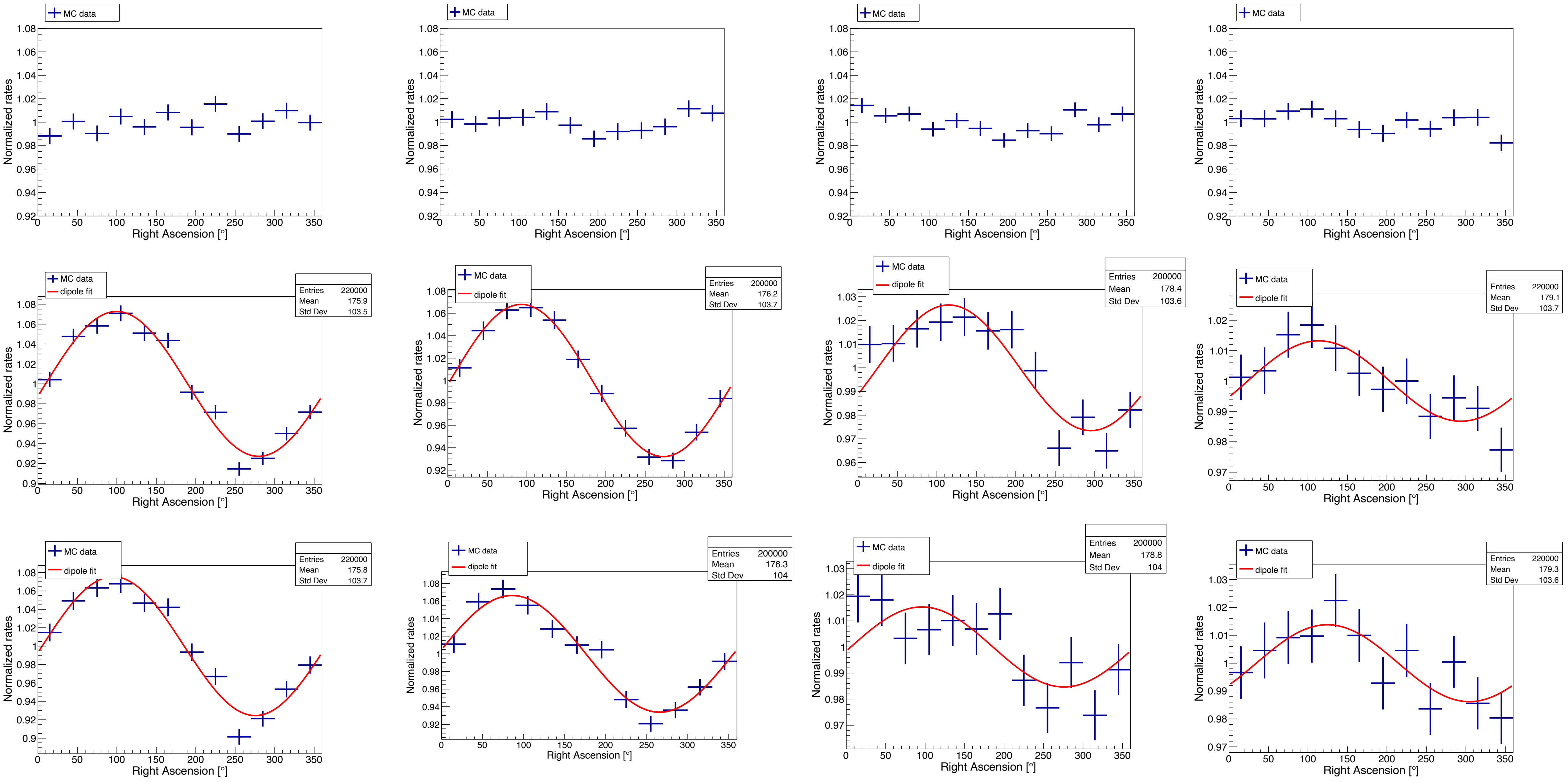
[6] Jansson, R. and Farrar, G. R. (2012) 'A New Model of the Galactic Magnetic Field'. doi: 10.1088/0004-637x/757/1/14.

[7] Collaboration, T. P. A. *et al.* (2020) 'Features of the energy spectrum of cosmic rays above $2.5{\times} 10^{18}$ eV using the Pierre Auger Observatory'. doi: 10.1103/physrevlett.125.121106.




1st row – isotropic, 2nd - Dipole, 3rd – Dipole plus exposure (all pure elements)

1st and 2nd column proton and Helium respectively, 3rd and 4th column Nitrogen and Iron respectively

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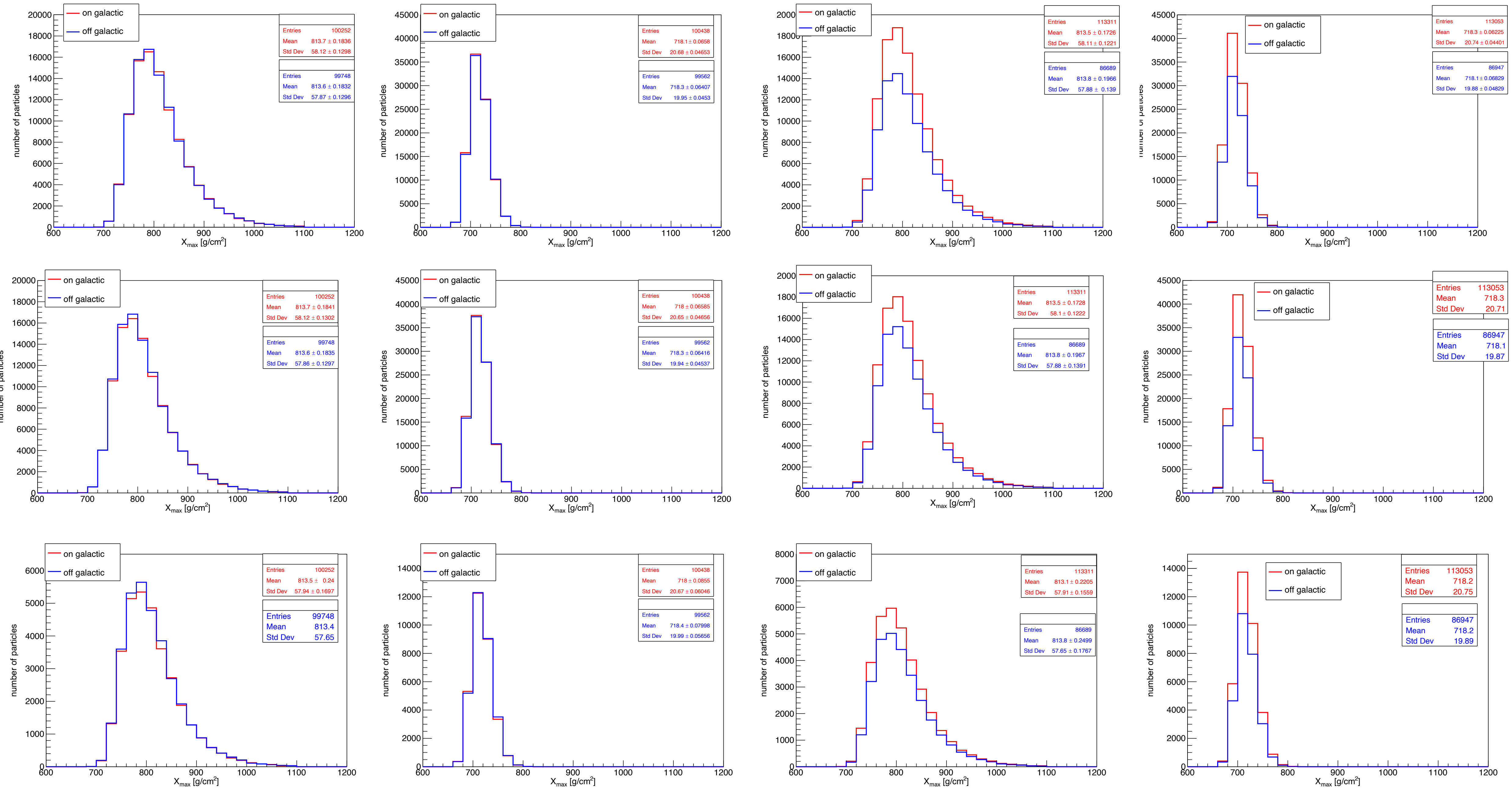
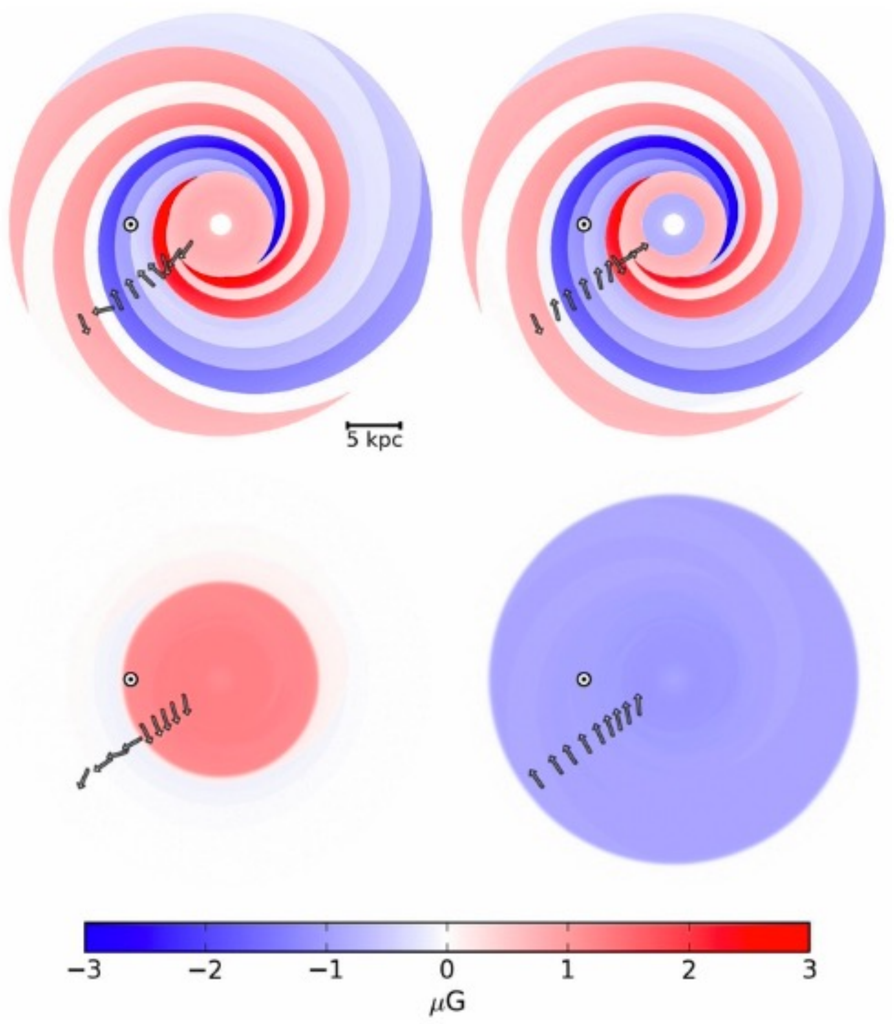



1[st] row – isotropic, 2[nd] - Dipole, 3rd – Dipole plus exposure (all pure elements)
1[st] and 2[nd] column proton latitude and RA respectively, 3[rd] and 4[th] column proton latitude and RA respectively

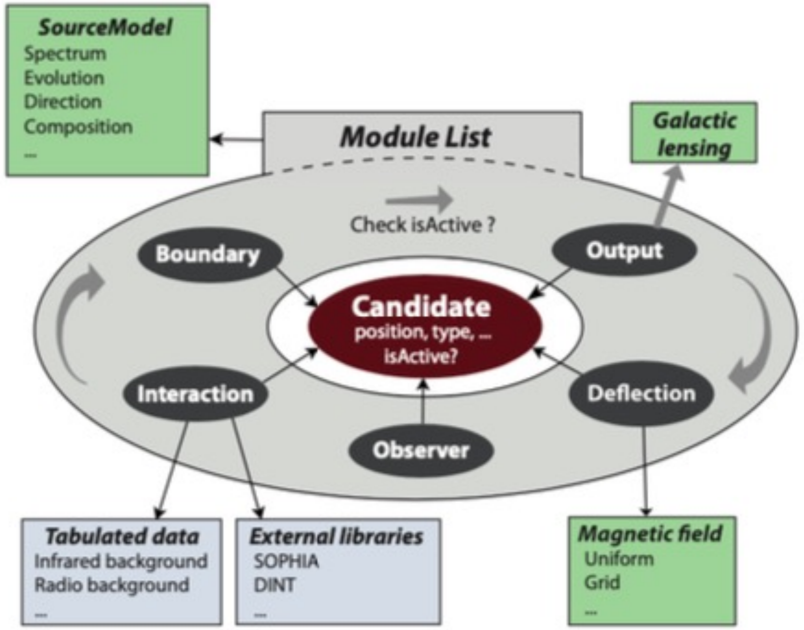
# JANSSON FARRAR GMF MODEL

This model is based on Faraday rotation and polarised synchrotron light measurements. It composes of a large-scale regular component, striated random components which are defined over large-scale features, and turbulent small-scale random fields which are arising from astronomical objects like supernovae. The necessity to separate disk and halo prompts the inclusion of an out-of-plane field component. Thus, the model is constructed as a large-scale regular GMF with three separate components.




Top view of slices in the x − y plane of the JF12 GMF mode model. [6]

# MORE FOR CRPROPA3




See source [5]