Observation of Ultra-High Energy Cosmic Rays (UHECRs)
- status and prospects -

CosPA 2013, Honolulu
November 15th, 2013
M. Fukushima
ICRR, Univ. of Tokyo
UHECRs Detector

- Pierre Auger Observatory (Auger) in Malargue, Argentina
- Telescope Array (TA) Experiment in Utah, USA
Ground Array + Air Fluorescence Telescope

- Total absorption calorimetry > Energy scale
- Imaging > Xmax > Particle Composition
- Duty ~ 10%

- Duty ~100%
- High Statistics > Spectral shape
- + ~Uniform sky sampling > Anisotropy
Auger

SD
Surface Detector

Water Tank
$S=10m^2, h=1.2m$
$\mu$ based sampling

Plastic Scint. 2-layer
$S=3m^2, t=1.2cm$
EM based sampling
FD
Fluorescence Detector
The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm²

1600 water Čerenkov detectors,
(a la Haverah Park)
1.5 km spacing, 3000 km²,
4 x 6 fluorescence telescopes
507 Surface Particle Detectors cover 680 km²

3 Fluores. Telescope stations overlook the array.

Utah, USA
39.3 ° N
112.9 ° W
Alt. 1400 m
Air Fluorescence: Reference model established

Reference Model proposed by B. Keilhauer & experimental groups at UHECR2012 @CERN.

- Spectrum at 1013 hPa and 293 K: AirFLY
- Extinction, T and humidity dep.: AirFLY, N. Sakaki et al.
- Normalization (AF Yield at 337nm): open

\[
Y_{\text{AFY}}^{\text{NEW2012}}(T, P, RH) (\text{ph/MeV}) = Y_{337\text{nm}}(T_r, P_r) \cdot I_A(T_r, P_r) \cdot \frac{1 + \frac{P_r}{P_{\text{air}}(T_0/T_r)^{1/2-\sigma}}}{1 + \frac{P}{P_{\text{air}}(T_0/RH)^{1/2-\sigma}}}
\]

\( T_r = T_0 = 293\text{K} \)
\( P_r = 800\text{hPa} \)
Air Fluorescence : 337nm Yield [photons/MeV]

AirFLY = 5.61 ± 0.06 (stat) ± 0.22 (sys) for 1013 hPa and 293 K

TA measured the AF yield in situ using
• 40 MeV electron beam from linac injected into the air.
• FD telescope with calib. database.
• Reference AF Model (spectrum, P-T-RH dependence)
• ∆E by GEANT-4 converted to photons with AirFLY yield.

ELS (data) / AirFLY (MC) = 0.96*) ± 0.01 (stat) ± 0.15 (sys) for ~860 hPa, -17° ~ 17° C

*) 0.99 with -3% correction not included in MC

Integrated Yield from Electron Beam relative to AirFLY yield.

TA weighed average=0.99

ELS DATA

Measurement in situ at TA.

Controlled laboratory measurement

Integrated Yield from Electron Beam relative to AirFLY yield.

TA weighed average=0.99

Measurement in situ at TA.

Controlled laboratory measurement
Energy Calibration $E'_{SD}$ ($S_{38}$ for Auger) vs $E_{FD}$ using hybrid events

- Auger E-scale updated (ICRC2013) using (nearly) reference model.
- Limited statistics for $10^{19.5}$ eV < $E$

- Good correlation (~linear) with particle density at 1000m (Auger), 800m (TA) from core for $10^{18.5}$ < $E$ < $10^{19.8}$ eV.

- Zenith attenuation of VEMs obtained from Constant Intensity Cut (CIC)

- $S_{800} = \#$ of particles at $D=800m$
- S-800($E'_{SD}$, th) map is obtained by air shower simulation.

- $S_{38} = \#$ of VEMs at $\theta=38^0$ and $D=1000m$
Energy Spectrum
Energy Spectrum of Cosmic Rays

Primary cosmic rays:
- proton, nucleus
- isotropic arrival (~0.1%)

\[ \propto E^{-3} \]

\~100 \text{ Hz/m}^2 \]

\~1 / (100 \text{ km}^2 \text{ Year}) \]
Energy Increased by 16% at $10^{18.0}$ eV and 10% at $10^{19}$ eV (mainly not by new AFY)

Dip and “Cutoff” confirmed.
5 year TA SD spectrum

Dip and “Cutoff” confirmed.

TA data
May, 2008 – May, 20013
Zenith angle < 45°
14787 ev. (E > 10^{18.2} eV)
Exposure 4500 km² sr yr

Broken power law fit

\[ \gamma_1 = -3.283 \pm 0.032 \]

\[ E_{\text{ankle}} = (5.04 \pm 0.27) \times 10^{18} \text{ eV} \]

\[ \gamma_2 = -2.685 \pm 0.030 \]

\[ E_{\text{GZK}} = (5.68 \pm 1.05) \times 10^{19} \text{ eV} \]

\[ \gamma_3 = -4.62 \pm 0.74 \]
Spectrum at UHE: Auger and TA

\[ I(E) E^3 \text{[eV}^2\text{m}^2\text{s}^{-1}\text{sr}^{-1}] \]

- **Auger combined**
- **Auger combined (x1.1)**
- **TA-SD**

\[ \log_{10}(E/\text{eV}) \]

From Y. Tsunesada
ICRC 2013
Rapporteur Talk
Spectrum at UHE: Auger and TA

Results of Broken Power Law Fit

<table>
<thead>
<tr>
<th></th>
<th>Auger</th>
<th>TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-1</td>
<td>$3.23 \pm 0.01$</td>
<td>$3.28 \pm 0.03$</td>
</tr>
<tr>
<td>$E_{\text{ANKLE}}$</td>
<td>$10^{18.72}$ eV</td>
<td>$10^{18.70}$ eV</td>
</tr>
<tr>
<td>$\gamma$-2</td>
<td>$2.63 \pm 0.02$</td>
<td>$2.69 \pm 0.03$</td>
</tr>
<tr>
<td>$E_{1/2}$</td>
<td>$10^{19.63}$ eV</td>
<td>$10^{19.74}$ eV</td>
</tr>
</tbody>
</table>

- **Spectral shape:** Auger and TA agree well for $E < \sim 10^{19.3}$ eV if overall $E$-scale shifted by 10%.
- **$E_{1/2}$:** $E_{\text{AUGER}} = 0.78 \times E_{\text{TA}}$ (w/o 10% rescale)
Astrophysical Scenario : AUGER

- Models calculated with CRPropa and validated with SimProp.
- Spectrum alone is not enough to Discriminate between scenarios.
- Cutoff by Acceleration limit is not excluded?

A. Schulz, ICRC 2013
Astrophysical Scenario: TA

**Fit with extra-galactic proton**

Source Distribution
- Uniform
- LSS (~2MASS XSCz)

Energy Loss with
- CMB
- Infra-Red
using CRPropa 2.0 simulation
checked with analytic $\Delta E$.
No magnetic field.

4-parameter fit
- Injection spectrum: $E^{-p}$
  $E_{\text{max}} = 10^{21}$ eV
- Evolution: $(1+z)^m$
- Flux normalization
- Energy scale

For LSS
- $P = 2.37 \pm 0.08 - 0.08$
- $m = 5.2 \pm 1.2 - 1.3$
- $\log E'/E = -0.02 \pm 0.04 - 0.05$
Particle Composition
Auger Xmax (updated at ICRC 2013)

- + statistics
- AFY updated.
- PSF updated.
- Calibration etc.

$<X_{\text{max}}>$ larger
+13 g/cm$^2$ at $10^{18}$ eV ~
+6 g/cm$^2$ at $10^{19.5}$ eV

RMS($X_{\text{max}}$) larger
< 10 g/cm$^2$
for $10^{18-19}$ eV

Updated models: EPOS-LHC and QGSJet-II-04 are used for MC rails.
Auger LnA Study

\[ \langle \ln A \rangle, \sigma(\langle \ln A \rangle) \rightarrow \langle \ln A \rangle, \sigma_{\ln A} \]

Using

\[ \langle X_{\text{max}} \rangle \approx \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle \]
\[ \sigma(X_{\text{max}})^2 \approx \langle \sigma_j^2 \rangle + D_p^2 \sigma(\ln A)^2 \]

DP: elongation rate
\( \sigma_j^2 \): mass averaged shower fluctuation

- \( \langle \ln A \rangle \) decreases until \( \sim 10^{18.3} \) eV
- increase of \( \langle \ln A \rangle \) at higher energies.
- small \( \sigma_{\ln A}^2 \lesssim 1 \) at high energies

Bottom Line of Auger Xmax study:

- showers at ultrahigh energies are shallower and fluctuate less than proton simulations
TA Xmax
(updated @ICRC2013)

- Hybrid Xmax added
- + statistics and Analysis updated for Stereo Xmax
- Analysis using QGSJET-II-03
  SIBYLL
  QGSJET-I

Hybrid Xmax (MD station)

Data
- $<X_{\text{max}}>$
- Proton MC
- Iron MC

MC: QGSJET-II-03

NO direct comparison with Auger Xmax

Both p/Fe expectation and data are affected by the selection bias.

QGSJET-II-03 is used for MC rails.
Both p/Fe expectation and data are affected by the selection bias.

K-S test: proton vs Fe

<Xmax> and Xmax distribution is consistent with proton by stereo and hybrid analyses.
Difference between Auger and TA on Xmax:

- For $10^{18.6} < E < 10^{19.4}$ eV, where Auger’s $\langle \text{LnA} \rangle$ analysis with QGSJET-II-04 simulation suggests a transition from proton to $\langle \text{Helium} \rangle$, TA’s $X_{\text{max}}$ and $X_{\text{max}}$ distribution are consistent with proton using QGSJET-II-03.
- Above $10^{19.4}$ eV, TA has no stat. power to separate p/Fe.
- Auger’s last point for $E > 10^{19.5}$ eV is somewhat singular suggesting pure Li or CNO depending on models.
UHE Gammas and Neutrinos

- No candidates found. Limits are updated.
- Some Top-down models are strongly constrained.
- Cosmogenic neutrinos maybe showing up soon.
- GZK gammas may be seen in next generation array.

\[ \text{PRELIMINARY} \]
Hadronic and Nuclear Interception above LHC

Air Shower Simulation
p-Air Cross Section by Auger \((10^{18} < E < 10^{18.5} \text{ eV})\)

\[
\Lambda_\eta = 55.8 \pm 2.3 \text{ g/cm}^2
\]

\[
\exp(-X_{\text{MAX}} / \Lambda_\eta)
\]

Observed \(\Lambda_\eta\) matched by tuning \(\sigma_{\text{p-Air}}\) in model

Inelastic \(\sigma_{\text{p-p}}\) obtained by Glauber model.

\[
\sigma_{\text{pp}}^{\text{inel}} = [92 \pm 7(\text{stat})^{+9}_{-11}(\text{syst}) \pm 7(\text{Glauber})] \text{ mb}
\]
Observed SD Signal vs Air Shower Simulation

Auger S(1000m)

SD signal is ~1.3 or more larger than Air Shower simulation at d=800-1000m, Water Tank (∼µ) or Scintillator (∼EM).

TA S(800m)

FD energy $E_{FD}$

Hybrid events

$E_{SD} = E'_{SD}/1.27$

- E~10^{19} eV
- MC events with $X_{max_{DATA}} = X_{max_{MC}}$ selected
Observed $\mu$ Signal vs Air Shower Simulation

Auger

- Separating $\mu$ and EM signal by waveform and timing.
- $E \sim 10^{19}$ eV and $d \sim 1000\text{m}$

Energy and $\mu$ rate of MC can be fitted
- Using Xmac_DATA $\sim$ Xmax_MC events.

Number of muons is 1.3 $\sim$ 1.5 larger than Air Shower Simulation at $\sim 10^{19}$ eV.
Arrival Directions

- Anisotropy
- Association with Astronomical Objects
- Clusters of events
Correlation with AGN in VCV Catalogue within 75Mpc

- \( E > 55 \text{ EeV} \) in 2011 E-scale
- 28/84 (tot) correlated
- \( P = 0.006 \) from isotropy

**Auger** data until July 2011

Cen A

Separation Angle from Cen A

AGN 3.1° circle

UHECR events

Correlation with VCV in the north

- Data until May 2013
- Same condition as Auger

- $E > 57$ EeV in TA's E-scale
- $17/42$ (tot) correlated
- $P = 0.014$ from isotropy
E > 10 EeV
in TA’s E-scale
θ < 55°
2130 events

E > 57 EeV
52 events

E > 40 EeV
132 events

Galactic Coordinate

Shades: expectation from 2MASS XSCz

Compatibility with LSS expectation (shades)

Compatibility with Isotropy: p ~ 0.001 for 6° smearing
A Cluster of Events in Hotspot

Looser cuts:
- No 1.2 km boarder cut
- $\theta < 55^0$
- $E > 57$ EeV

2008 May – 2013 May:
A Total of 72 events selected.

Oversampling with $r = 20^0$ circle

Background from 72 random isotropic events estimated by MC

Maximum significance in hot spot is $5.1\sigma$ by Li-Ma method

Post-trials chance probability is being estimated.
Summary

• Pierre Auger Observatory
• Telescope Array
Summary of Auger

- SD/SD calib.
  - 1018.45
  - 1018.7
  - 1019.6 (E^{1/2})

AUGER AGN correlation
- 28/84 correlated
- P = 0.006 from randoms
- Cluster at Cen A?

TA with same selection
- 17/42 correlated
- P = 0.041

Summary of Auger
Summary of TA

PAO break point

SD/FD calib.

E > 57 EeV

LSS correlation (60 smearing)
- P = 0.1 from LSS
- P = 0.001 from isotropy
- Cluster of ~20° radius near the SG plane
Auger and TA run for next 10 years with
◆ Auger extension for efficient mu-tag at each SD and
◆ TA extension for x4 acceptance (+500 SDs and +1 FD)
Collaboration started on
◆ S+N all sky coverage, common anisotropy analysis
◆ understand differences in composition and E-scale
  by exchanging calib, analysis, simulation, tank/scint...
Both are harboring RD projects for
◆ Radio detection (MHz, GHz, Radar,...)
◆ Testing and calibrating JEM-EUSO prototype
◆ High performance SD/FD/RD for future super-Ground-Array
◆ Earth and atmospheric science

JEM-EUSO on ISS (2017 - )
super-Ground-Array
TAX4: Near Future Operations of TA

- Anisotropy and Hotspot: ~5σ confirmation by 2019.
Common Isotropy Analysis using Auger and TA data

Upper limit on 1st harmonic amplitude (Auger), but change of phase seen?

- Auger/TA acceptance matching
- E > $10^{19}$ eV in TA scale
- Fitting with spherical harmonics

O. Deligny, ICRC 2013
Octocopter of Auger flew twice in 2012 and 2013 over TA’s night sky with calibrated UV-LED light source.
ELVES observed by Auger FD

Burst of particle showers observed by TA SD associated with lightning

- Example of one burst
- 2 particle showers within 1ms.
- ~10^{-4} event from randoms.

- Core locations ~2km apart.
- Common “origin” ~3km above Ground.
  (highly curved shower front r~3km)
- Lightning found within 1ms (NLDN-db)
- Lightning location ~ core location

Tonachini, K.H. Kampert  
ICRC 2011  
T. Okuda  
CosPA 2013
End
090122-225422
TH~38°

Event “Side” View

Zenith ~ arcsine (ΔT / ΔX)

SD Event

Event Top View

X,Y = counter #
number = MeV energy deposit (av U+D)
~ 2.5 MeV for vertical mu
FD Event

![Graphs showing BRM and LR data with labeled lines for different processes: Fluorescence, Mie Cherenkov, Direct Cherenkov, Rayleigh Cherenkov, and NPE detected by PMT.](image)
<table>
<thead>
<tr>
<th></th>
<th>HiRes</th>
<th>Auger</th>
<th>TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>10%</td>
<td>9.9%</td>
<td>③ 10%</td>
</tr>
<tr>
<td>Fluorescence yield</td>
<td>6%</td>
<td>3.6%</td>
<td>① 11%</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>5%</td>
<td>6.2%</td>
<td>② 11%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>10%</td>
<td>6.5%</td>
<td>④ 10%</td>
</tr>
<tr>
<td>Invisible energy</td>
<td>5%</td>
<td>3.0%</td>
<td>(Included above)</td>
</tr>
</tbody>
</table>

**Total Systematic Uncertainty**

- Calibration: 17%
- Fluorescence yield: ~14%
- Atmosphere: 22%
- Reconstruction: 21%

Auger updated energy scale in ICRC 2013

Energy Increased by 16% at $10^{18.0}$ eV and 10% at $10^{19}$ eV

FD Energy Scale

1. Fluorescence yield
2. Atmosphere
3. Calibration
4. Event reconstruction

V. Verzi, ICRC2013
A. Lettessier-Selvon, ICRC2013
$SD_{1500m}$ - $SD_{inclined}$ - $SD/FD$ Hybrid & $SD_{750m}$ Spectra

Consistent among Different methods
SD - FD_{monocular} - SD/FD Hybrid Spectra

Consistent among Different methods.

Statistics limited Below $10^{19.6}$ eV.
EAS with Old CR Models: $X_{\text{max}}$

- HiRes-MIA
- HiRes (2005)
- Yakutsk 2001
- Fly’s Eye
- Yakutsk 1993
- Auger (2010)
- QGSJET01

- EPOS 1.99
- SiBYLL 2.1
- QGSJETII-03

Energy (eV) vs. $<X_{\text{max}}>$ (g/cm$^2$) for different models and data sets.
EAS with Re-tuned CR Models: $X_{\text{max}}$
SD Analysis

\[ \log_{10} \left( \frac{S800}{(\text{VEM m}^{-2})} \right) \]

- \(10^{17.8} \text{ eV}\)
- \(10^{20.5} \text{ eV}\)

sec(\(\theta\))
$S(1000)$ attenuation function

- Empirical correction with 3rd deg. polynomial
  
  $CIC(\theta) = 1 + ax + bx^2 + cx^3 \ (x = \cos^2 \theta - \cos^2 38^\circ)$

- Zenith angle independent energy estimator $S_{38} = S(1000)/CIC(\theta)$

\[ \chi^2/n_{d.o.f} = 6.5/11 \]
\[ S_{38}^{\text{fit}} = 49.72 \pm 0.44 \]
\[ a = 0.98 \pm 0.06 \]
\[ b = -1.68 \pm 0.12 \]
\[ c = -1.30 \pm 0.67 \]

- In case of SD 750 m array: $S(450) \Rightarrow S_{35}$. Separate attenuation function.
Air Fluorescence: 337nm Yield by TA electron beam calibration
Air Fluorescence Yield using ELS beam

DATA

- Error of each point < 0.2%
- Weighed average = 1.22

**ELS (data) / TA (MC)**

= \(1.18^*\) ± 0.01 (stat) ± 0.18 (sys)

for \(\sim860\) hPa, \(-17^0 \sim 19^0\) C

*) 1.22 with -3% correction not included in MC

TA and HiRes use

- FLASH spectrum
- Modified Yield of Kakimoto et al.
The fluorescence yield

1 EeV 10 EeV

The atmosphere

The absolute calibration of the telescopes

Reconstruction of the longitudinal profile of the showers

The invisible energy

Changes in FD energies at $10^{18}$ eV

<table>
<thead>
<tr>
<th>Change Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airfly fluorescence yield (sec. 2)</td>
<td>-8.2%</td>
</tr>
<tr>
<td>New optical efficiency</td>
<td>4.3%</td>
</tr>
<tr>
<td>Calibr. database update</td>
<td>3.5%</td>
</tr>
<tr>
<td>Sub total (FD calibration - sec. 4)</td>
<td>7.8%</td>
</tr>
<tr>
<td>Likelihood fit of the profile</td>
<td>2.2%</td>
</tr>
<tr>
<td>Folding with the point spread function</td>
<td>9.4%</td>
</tr>
<tr>
<td>Sub total (FD profile reconstr. - sec. 5)</td>
<td>11.6%</td>
</tr>
<tr>
<td>New invisible energy (sec. 6)</td>
<td>4.4%</td>
</tr>
<tr>
<td>Total</td>
<td>15.6%</td>
</tr>
</tbody>
</table>

Systematic uncertainties on the energy scale

<table>
<thead>
<tr>
<th>Uncertainty Description</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>Absolute fluorescence yield</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fluor. spectrum and quenching param.</td>
<td>1.1%</td>
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<tr>
<td>Sub total (Fluorescence yield - sec. 2)</td>
<td>3.6%</td>
</tr>
<tr>
<td>Aerosol optical depth</td>
<td>3% ± 6%</td>
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<tr>
<td>Aerosol phase function</td>
<td>1%</td>
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<tr>
<td>Wavelength depend. of aerosol scatt.</td>
<td>0.5%</td>
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<tr>
<td>Atmospheric density profile</td>
<td>1%</td>
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<tr>
<td>Sub total (Atmosphere - sec. 3)</td>
<td>3.4% ± 6.2%</td>
</tr>
<tr>
<td>Absolute FD calibration</td>
<td>9%</td>
</tr>
<tr>
<td>Nightly relative calibration</td>
<td>2%</td>
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<tr>
<td>Optical efficiency</td>
<td>3.5%</td>
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<tr>
<td>Sub total (FD calibration - sec. 4)</td>
<td>9.9%</td>
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<tr>
<td>Folding with point spread function</td>
<td>5%</td>
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<td>Multiple scattering model</td>
<td>1%</td>
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<tr>
<td>Simulation bias</td>
<td>2%</td>
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<tr>
<td>Constraints in the Gaisser-Hillas fit</td>
<td>3.5% ± 1%</td>
</tr>
<tr>
<td>Sub total (FD profile reconstr. - sec. 5)</td>
<td>6.5% ± 5.6%</td>
</tr>
<tr>
<td>Invisible energy (sec. 6)</td>
<td>3% ± 1.5%</td>
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<tr>
<td>Stat. error of the SD calib. fit (sec. 7)</td>
<td>0.7% ± 1.8%</td>
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<tr>
<td>Stability of the energy scale (sec. 7)</td>
<td>5%</td>
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<tr>
<td>Total</td>
<td>14%</td>
</tr>
</tbody>
</table>
Update of $X_{\text{max}}$ Results

accumulated effect of **improved reconstruction and calibration**: 

most important change:

convolution of point spread function\(^\S\) with lateral shower width

$\rightarrow \Delta X_{\text{max}} \sim +10 \text{ g/cm}^2$ at low energies

\(^\dagger\)V. Verzi for the Auger Collab., ICRC #0926, \(^\ddagger\)J. Baum for the Auger Collab., ICRC #0806
Expectation from LSS

• Sources:
  with \(5 < D < 250\) Mpc: 2MASS galaxy redshift catalog (XSCz)
  Apparent magnitude < 12.5 and
  extrapolate with luminosity density function
  Galactic center is extrapolated from surroundings
  with \(D > 250\) Mpc: uniform distribution

• Propagation:
  proton with \(E^{-2.4}\) at origin
  -dE with CMB interactions (average energy loss)

• Magnetic Field:
  Gaussian smearing (6° for shown plots)
  No regular GMF deflection is introduced