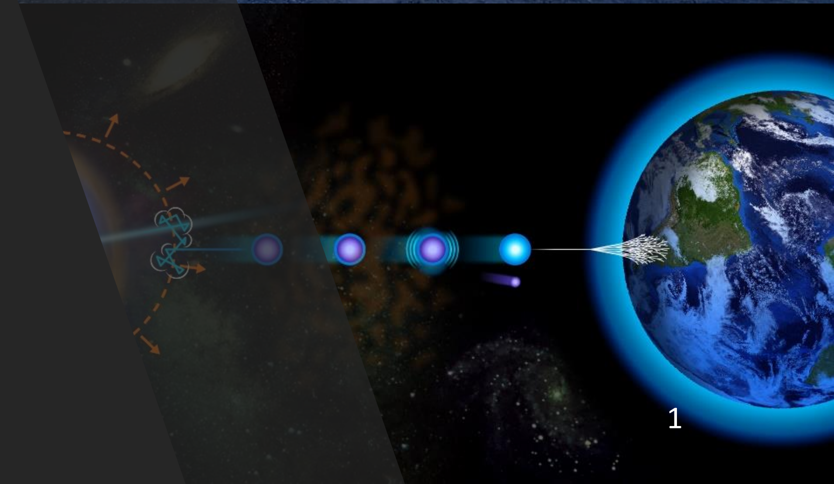
Eiji Kido

Riken, ABBL

# Observation of Ultra-High-Energy Cosmic Rays and photo-nuclear reactions for the interpretation



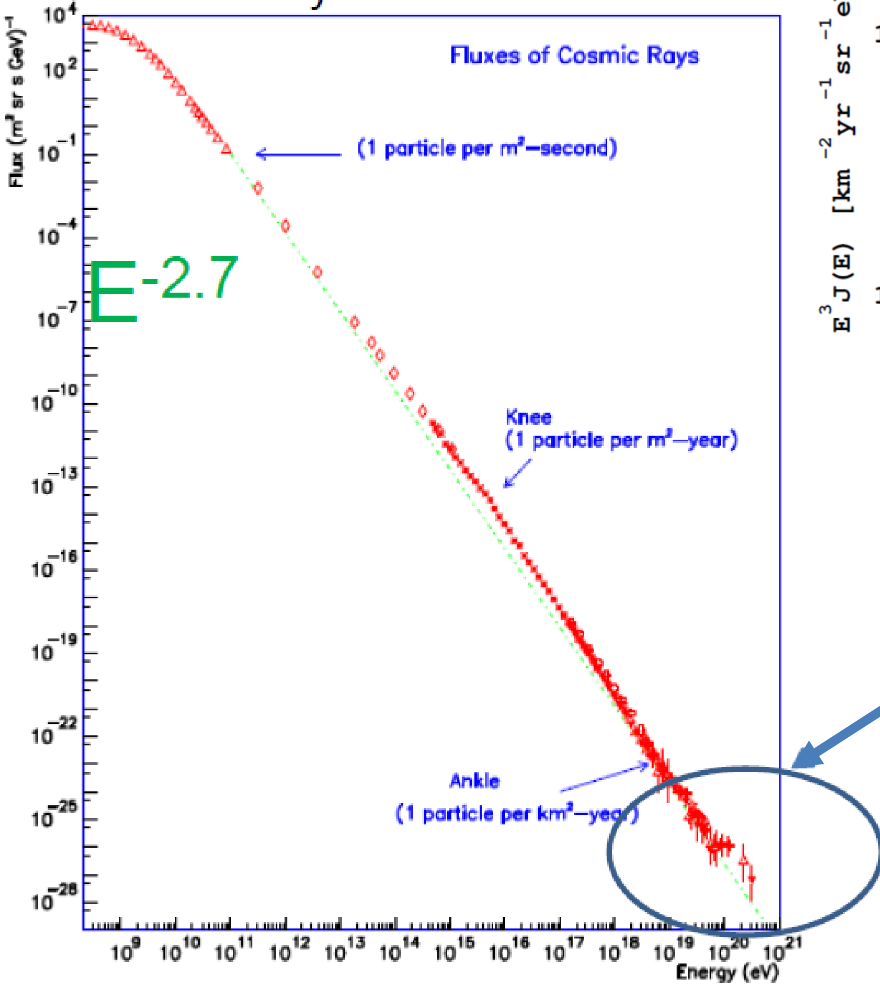
# Outline

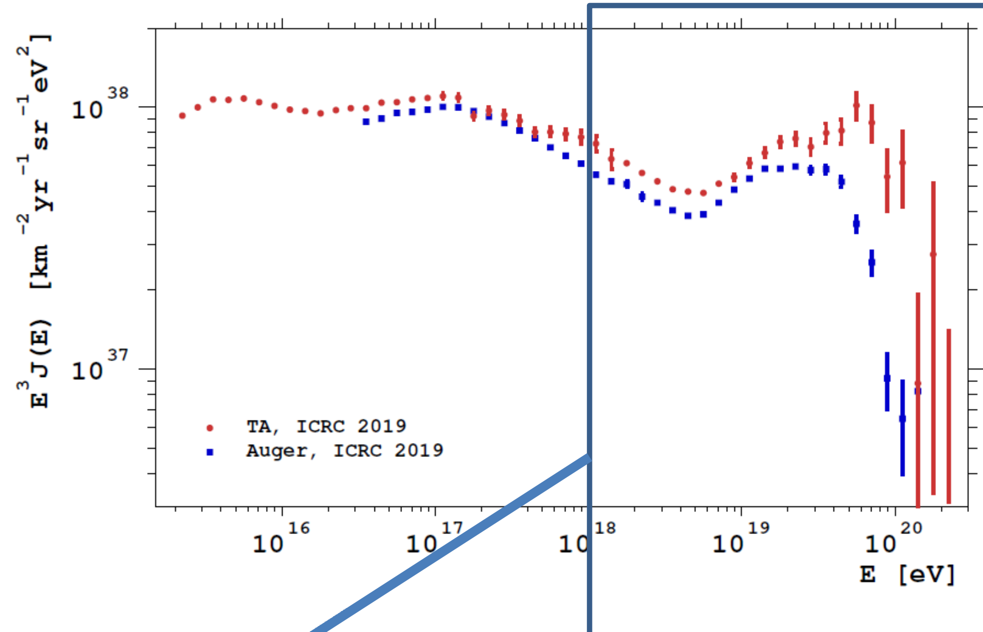
- Ultra-High-Energy Cosmic Rays (UHECRs)
- Observation of UHECRs
  - Telescope Array (TA)
  - Pierre Auger (Auger)
- Recent Results
  - Energy Spectrum
  - Composition
  - Anisotropy
- Ongoing Upgrades
  - TAx4
  - AugerPrime
- Interpretation of the Experimental Data
  - Review of the Interpretation
  - PANDORA Project
  - Impact of Photo-Nuclear Reactions on the Interpretation
  - Future Prospect
- Summary

# Ultra-High-Energy Cosmic Rays (UHECRs)

# Ultra-High-Energy Cosmic Rays

Differential energy spectrum of cosmic rays



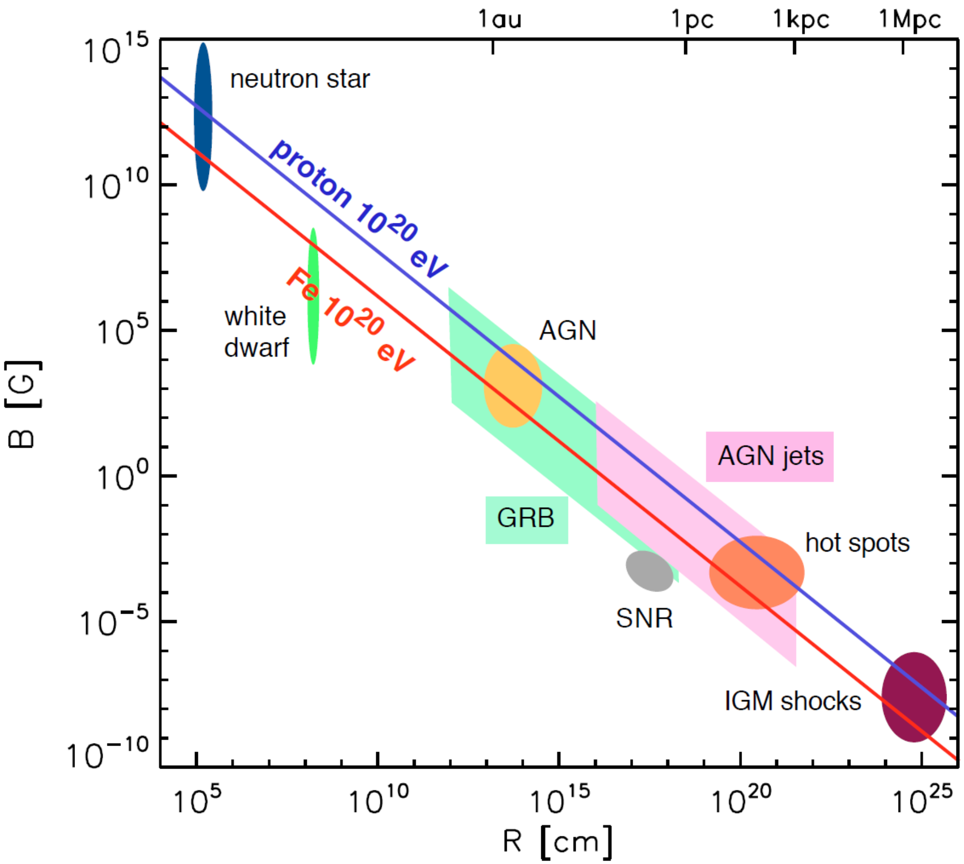

Energy > 1 EeV (1 EeV = $10^{18}$eV)

Small number of events:

$\sim 10^{-3}$ km$^{-2}$ yr$^{-1}$ (E > $10^{20}$ eV)

Cosmic ray sources are uncertain.

# Hillas Diagram




Kotera & Olinto, Annu. Rev. Astron. Astrophys (2010)

- Larmor radius

$R_L$ =

100 kpc (1/Z) (uG/B)(E/100 EeV)

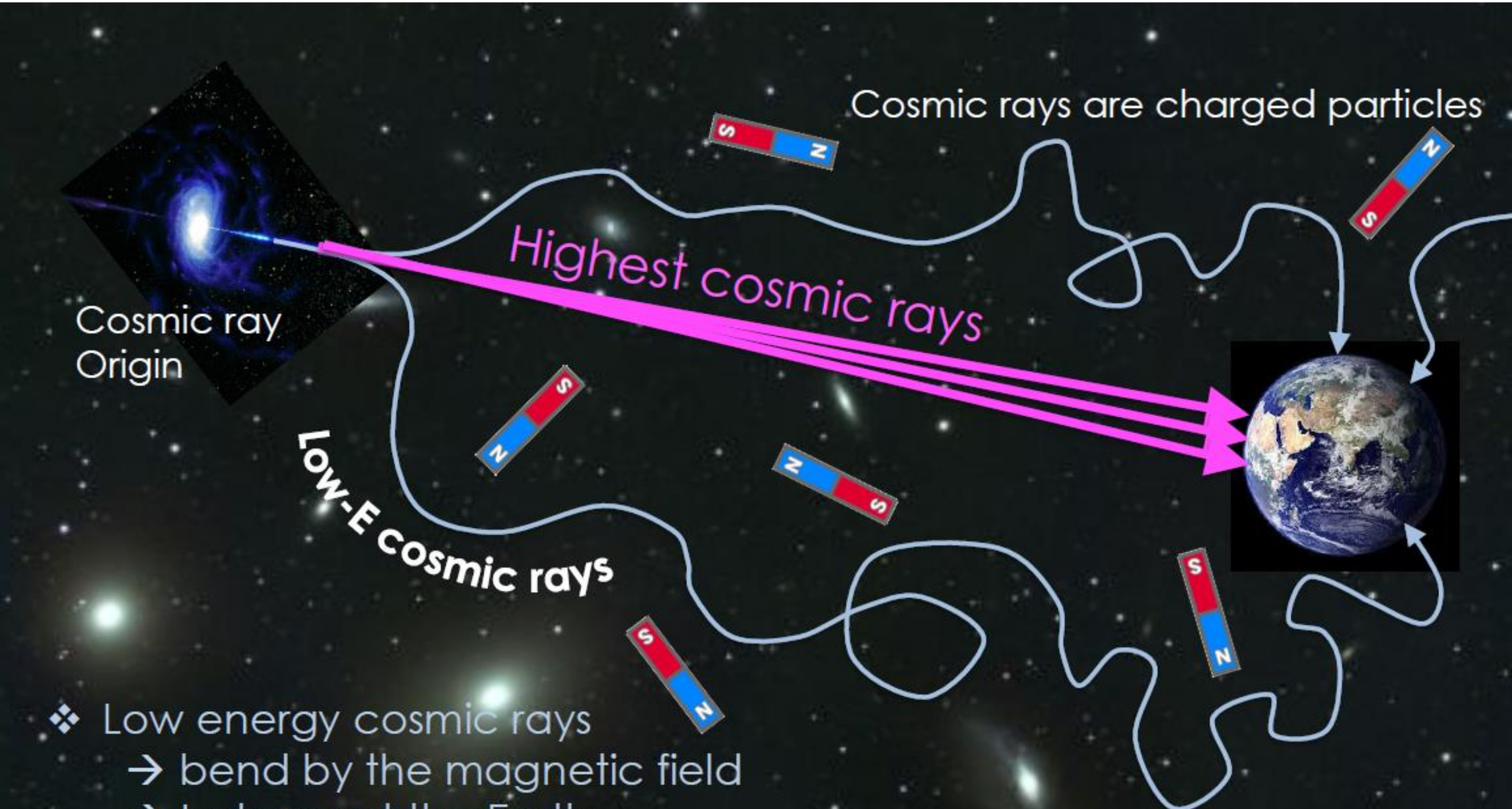
- Magnetic fields of the sources confine cosmic ray particles up to the energies

  (Blue: Emax = $10^{20}$ eV, Z=1)

  (Red: Emax = $10^{20}$ eV, Z=26)

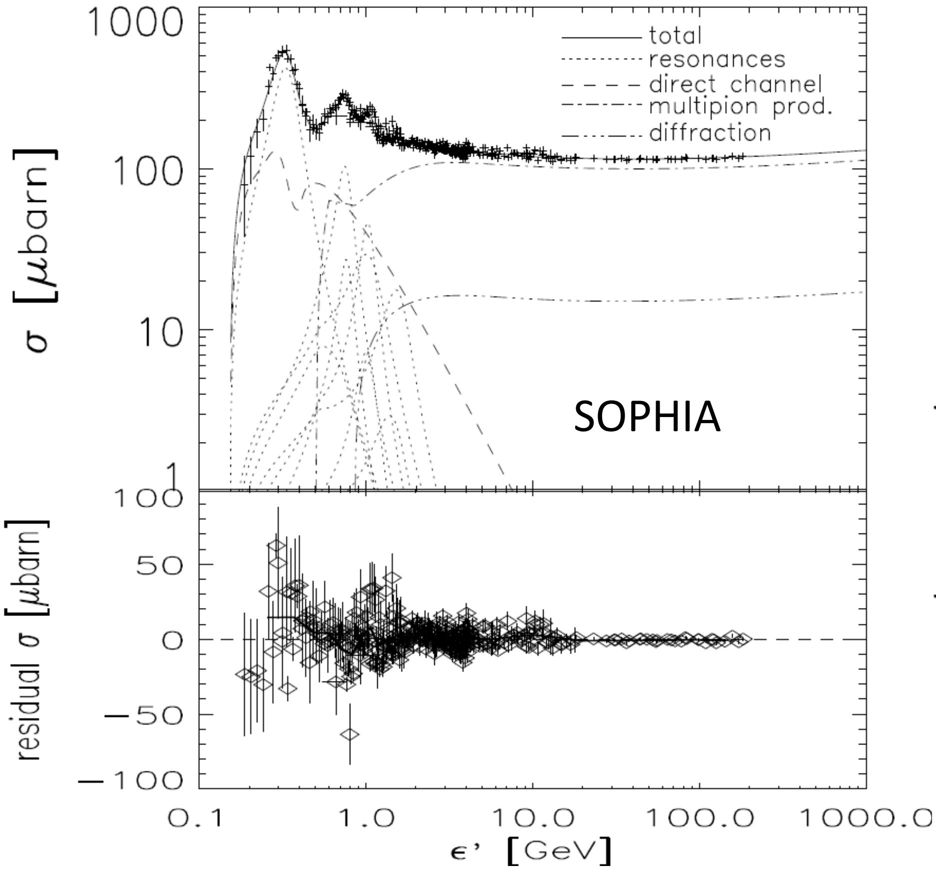
  → candidates of sources

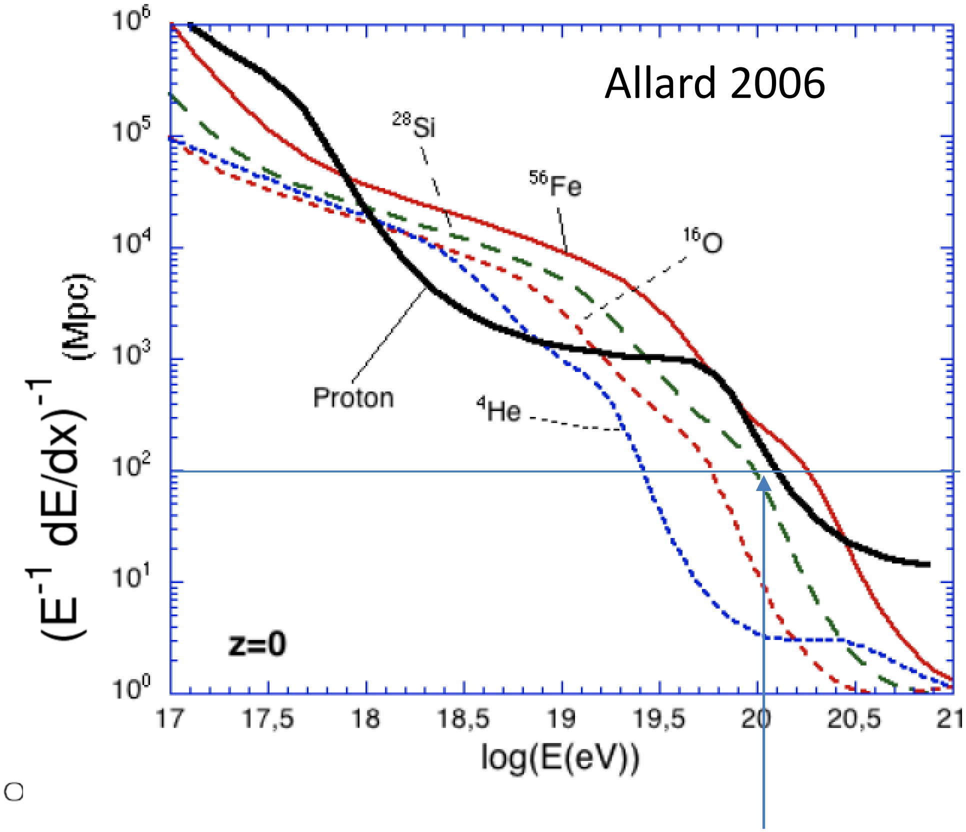
# Arrival Directions




- ❖ Low energy cosmic rays
  - → bend by the magnetic field
  - → Isotropy at the Earth
- ❖ Highest energy cosmic rays
  - → Almost go straight against magnetic field
  - → Possible to find cosmic-ray origin directly

# UHECR Proton Interactions



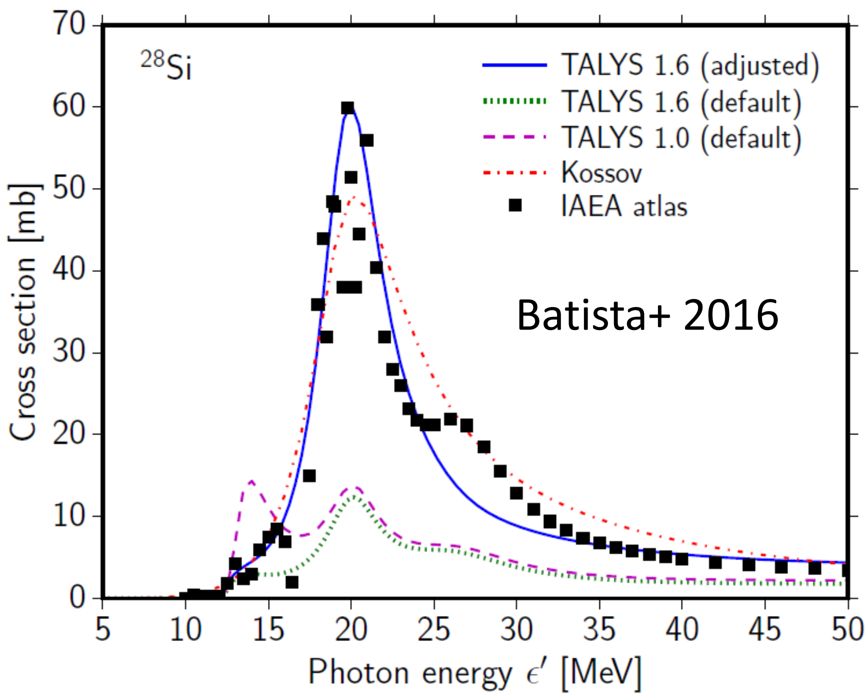

**GZK cutoff (photopion production)**

$\mathbf{p} + \gamma \rightarrow \mathbf{p}\ (\mathbf{n}) + \pi^0\ (\pi^+)$ cross section opens at $E_p > 7 \times 10^{19}$eV with $E_{\gamma,CMB} \sim 2.4 \times 10^{-4}$eV ($\Gamma_{proton} > 7\times10^9$)

Small energy loss length < 100 Mpc at the highest energies

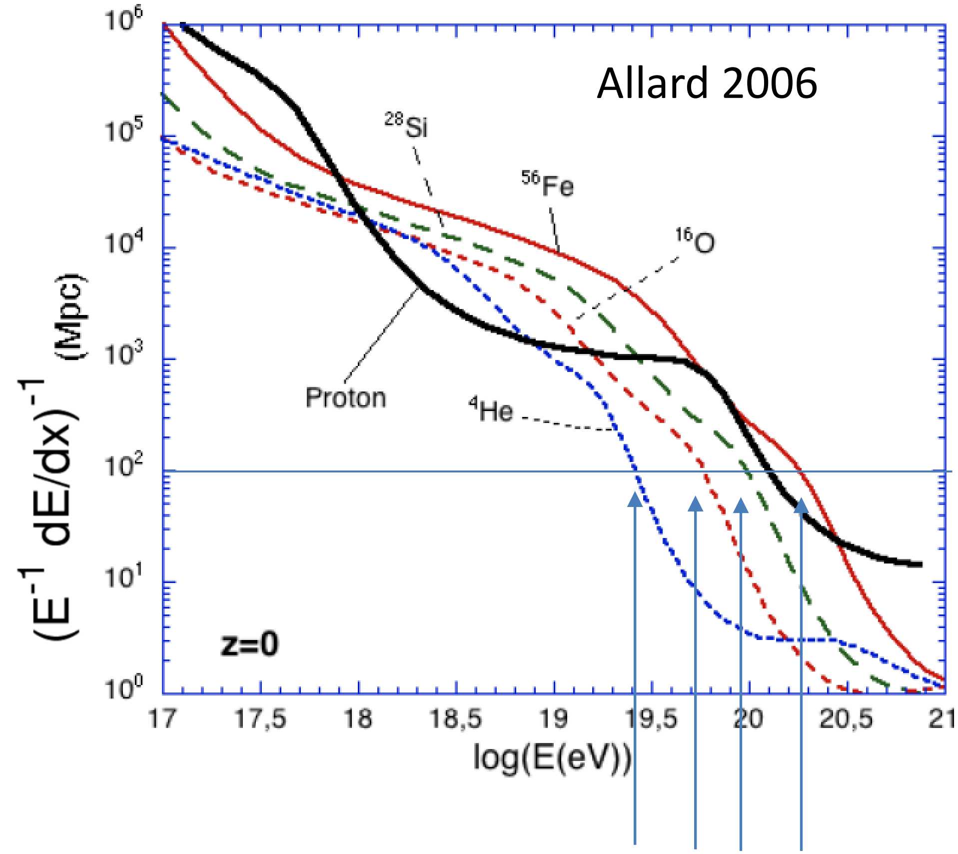
→ Sources are limited in the local universe.

# UHECR Nuclei Interactions




**Photodisintegration**
**A + $\gamma \rightarrow$ (A-1) + p (n)** cross section opens at $\Gamma_A \gtrsim 7\text{x}10^8$ with CMB
$E_A = \mathbf{A} \times m_p c^2 \Gamma_A$

Typical photon energy of Gian Dipole Resonance (GDR) peak in the nucleon rest frame is < 30-50 MeV.




Small energy loss length < 100 Mpc
at the highest energies
→ Sources are limited in the local universe.

# Motivation to observe highest energy cosmic rays

- Cosmic ray sources are uncertain
- Smaller deflection angles ($\propto 1/E$)
- Sources are limited in the local universe

  (～a few tens of Mpcs)

  → anisotropy in arrival directions

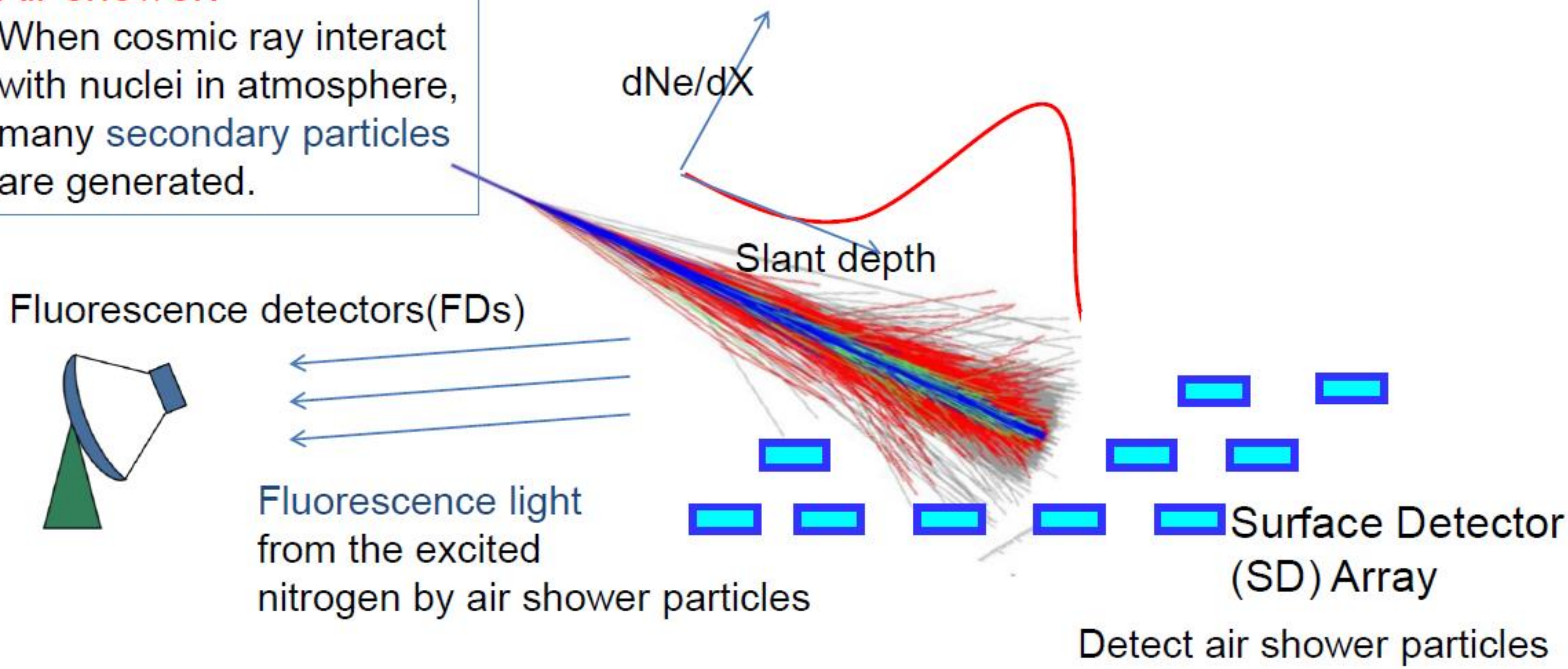
  → origin of cosmic rays
- Difficulty: To obtain

  high statistics (～$E_{th}^{-2}$ above $E_{th}$)

# Observation of UHECRs

# UHECR Detectors

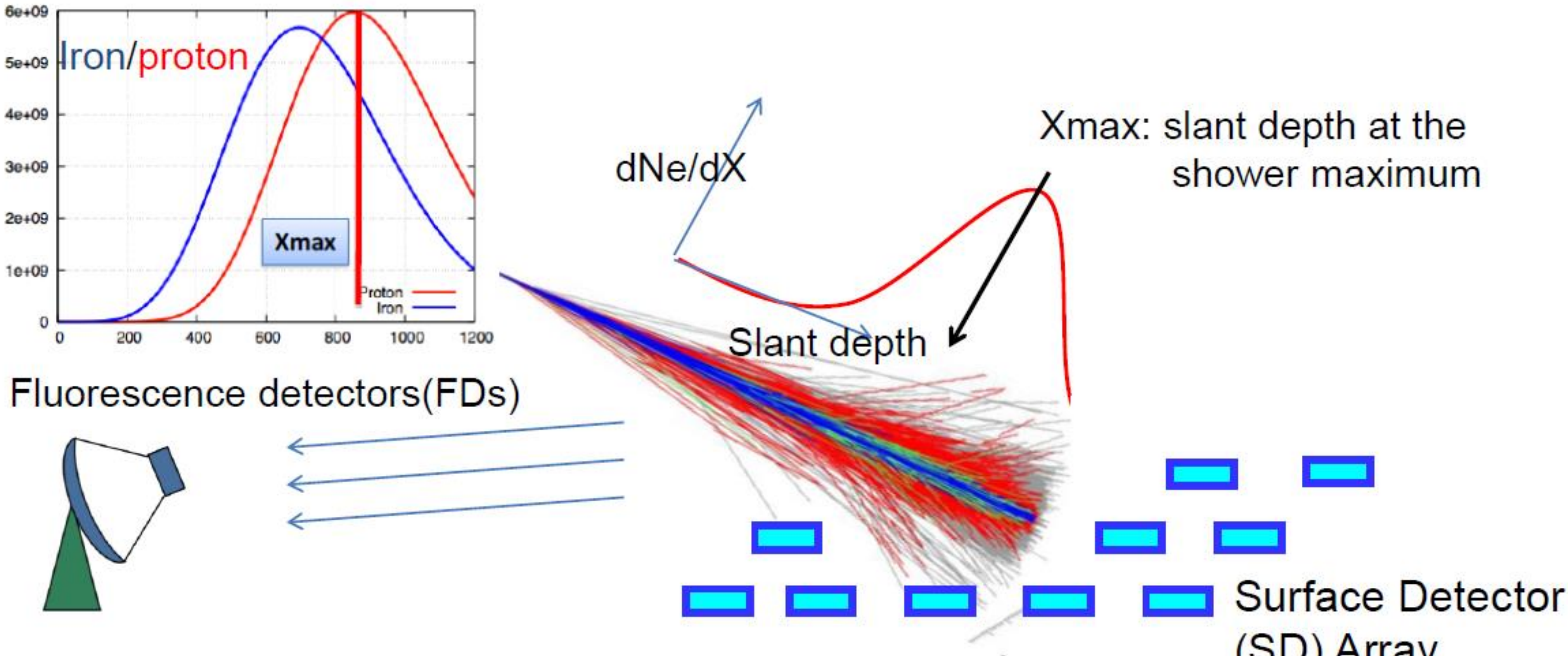
Air shower:
When cosmic ray interact with nuclei in atmosphere, many secondary particles are generated.




Surface Detector (SD) and Fluorescence Detector (FD) cover large area and detect the air shower.

→ Large detection area (~1000 $km^2$) is realized.

# UHECR Detectors

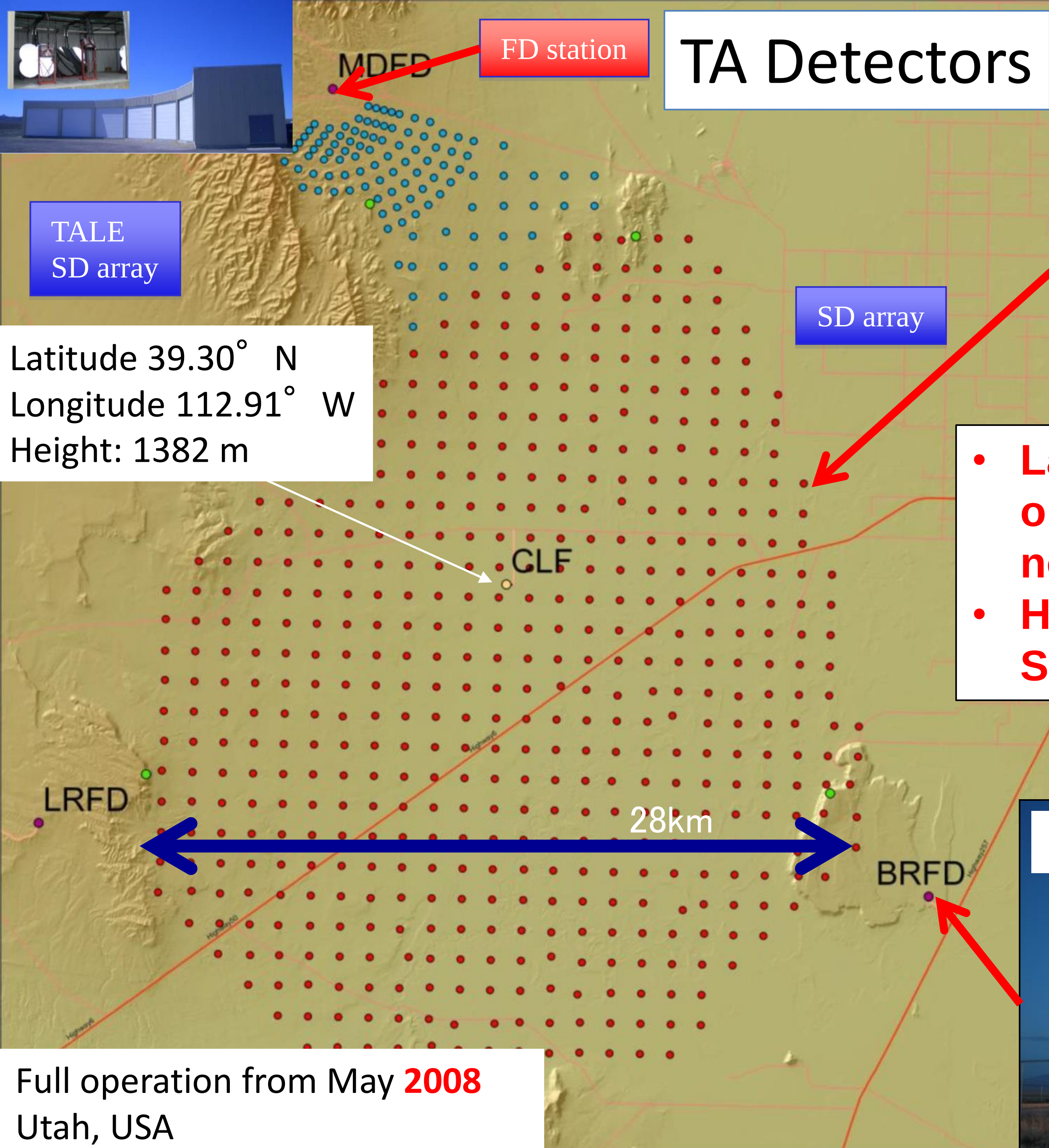



- SD: Regardless of weather condition, high duty circle and wide FoV → high statistics (～FDx10) → Anisotropy & Spectral shape
- FD: limited to clear moonless night.

  Longitudinal development of air shower→Mass composition (Xmax)

  Measure the energy deposit calorimetrically → absolute energy scale

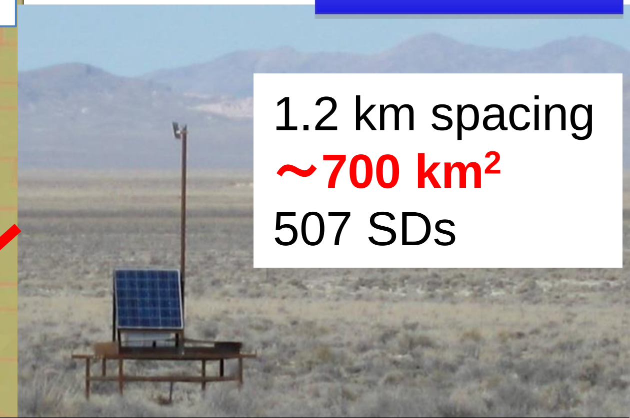
# TA Detectors




Latitude 39.30° N
Longitude 112.91° W
Height: 1382 m

Full operation from May **2008**
Utah, USA

Surface Detector (SD)



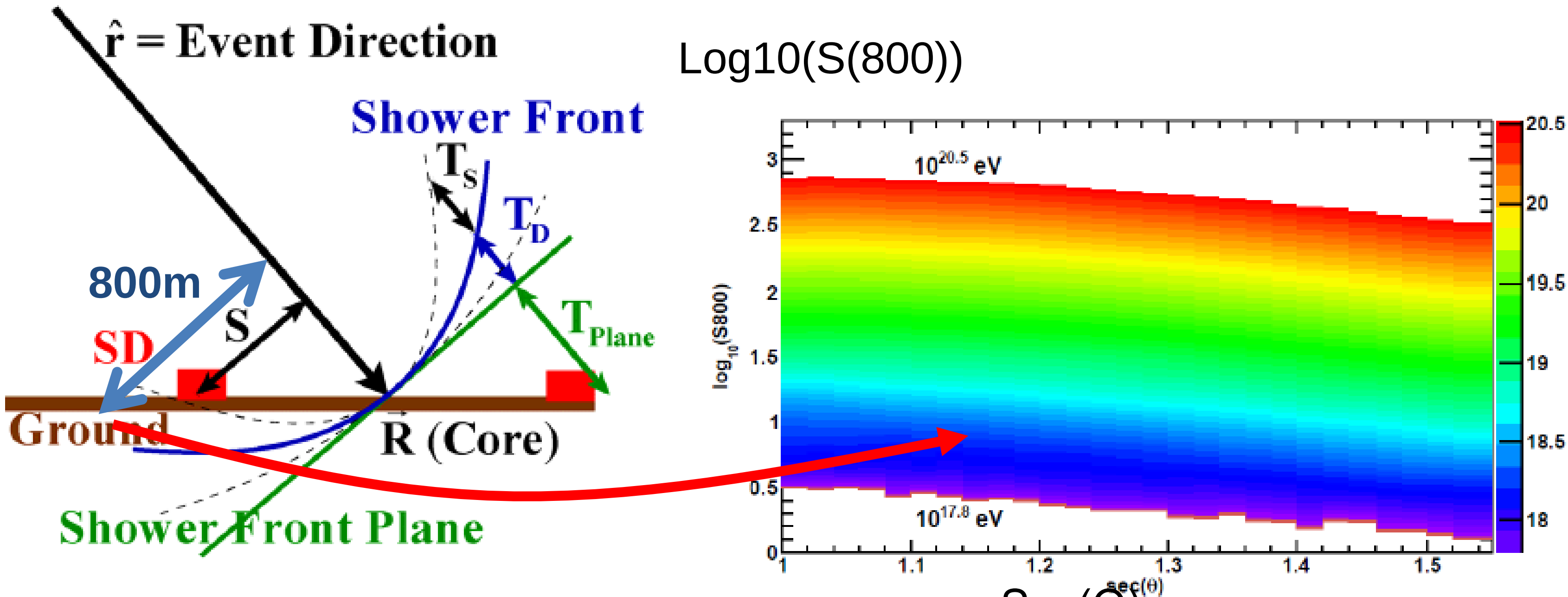
1.2 km spacing
**～700 km²**
507 SDs

- **Largest cosmic-ray observatory in the northern hemisphere**
- **Hybrid observation by SD and FD**

Fluorescence Detector (FD) station

12 telescopes

# Event Reconstructions with SDs




- Timing fit→Shower Geometry
- Lateral distribution fit →S(800)→Energy from MC

  → rescale to calorimetrically measured $E_{FD}$ using

  SD and FD hybrid events

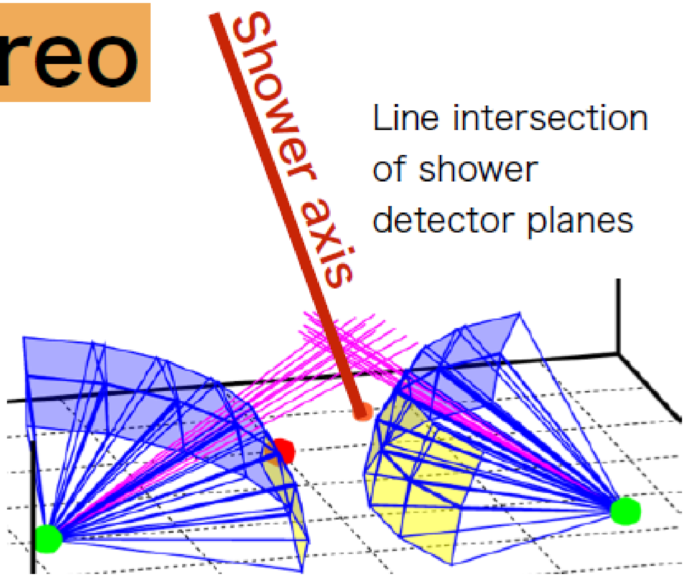


S(800): energy depositions which are converted in VEM unit.

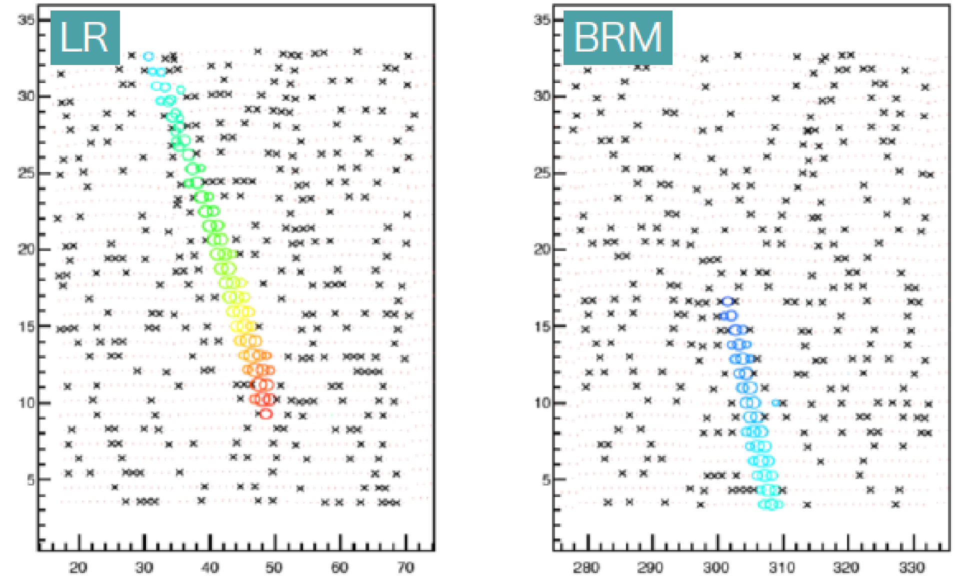
# Event reconstruction

*S. Ogio, ICRC2019*

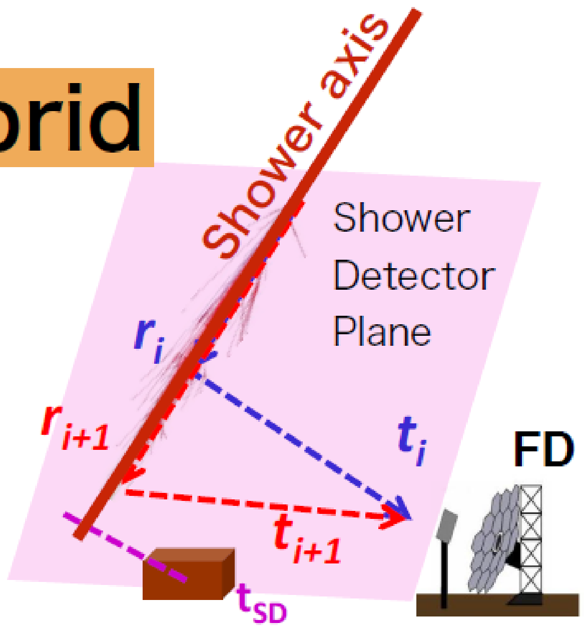
## Stereo



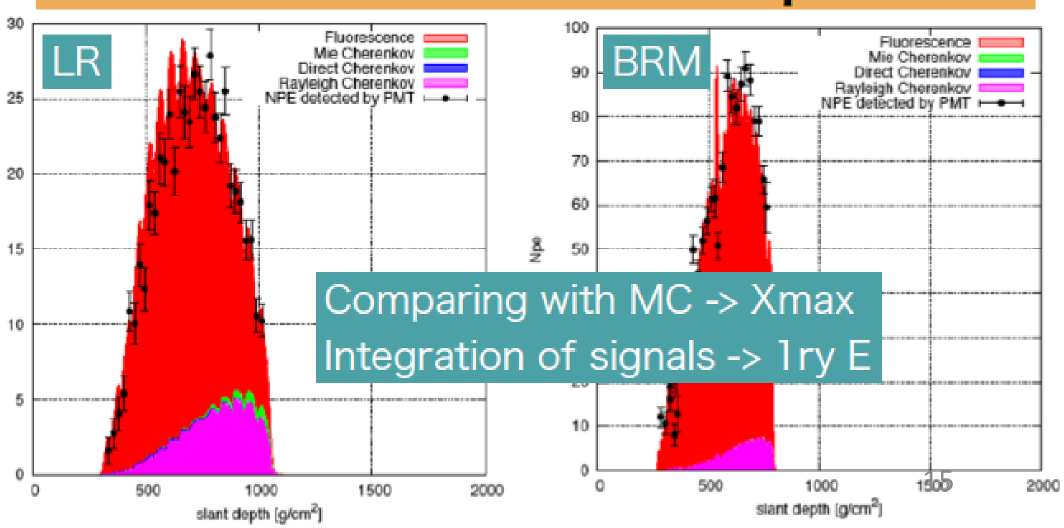

## observed images




## Hybrid



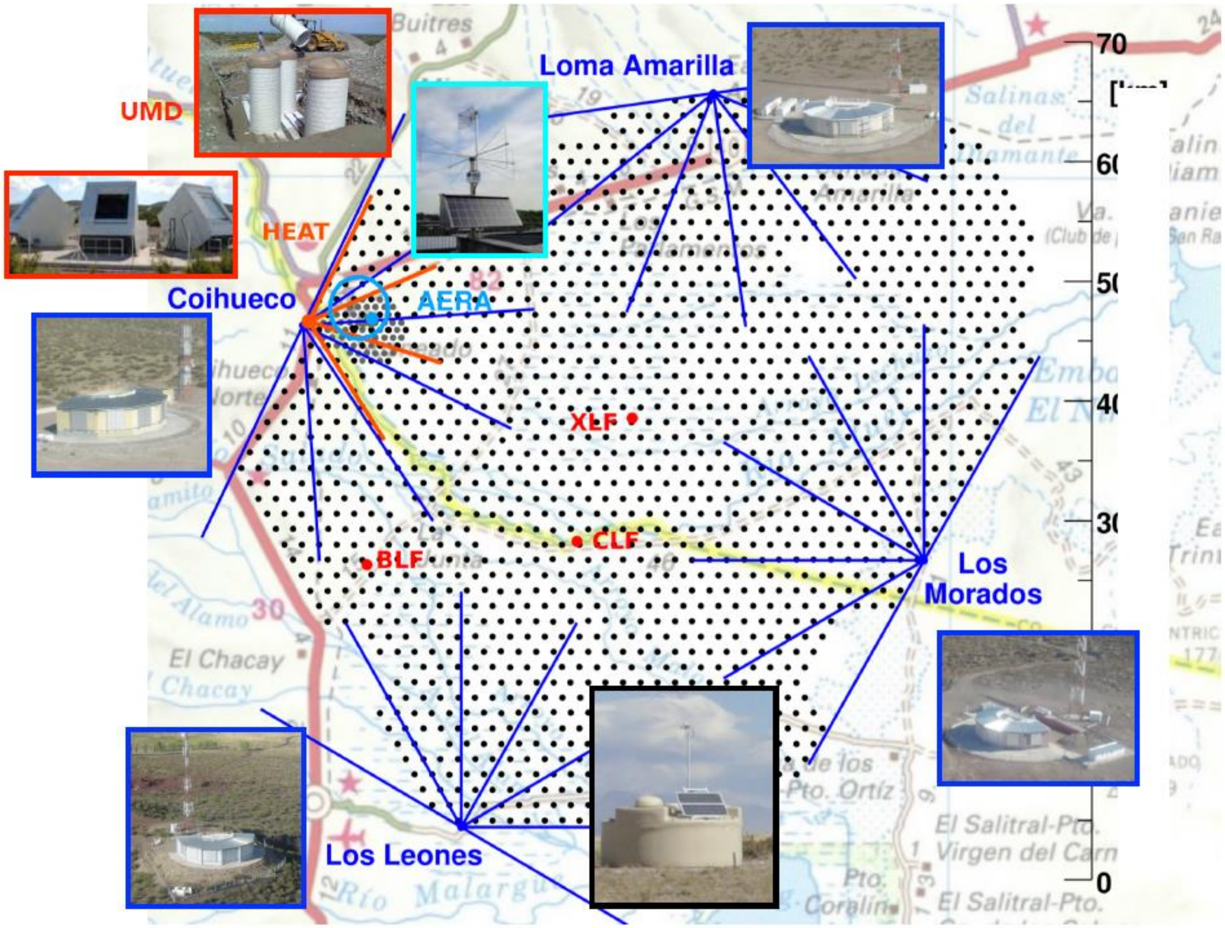

## reconstructed shower profiles




Comparing with MC -> Xmax
Integration of signals -> 1ry E

# The Pierre Auger Observatory

TeVPA2019 Dawson



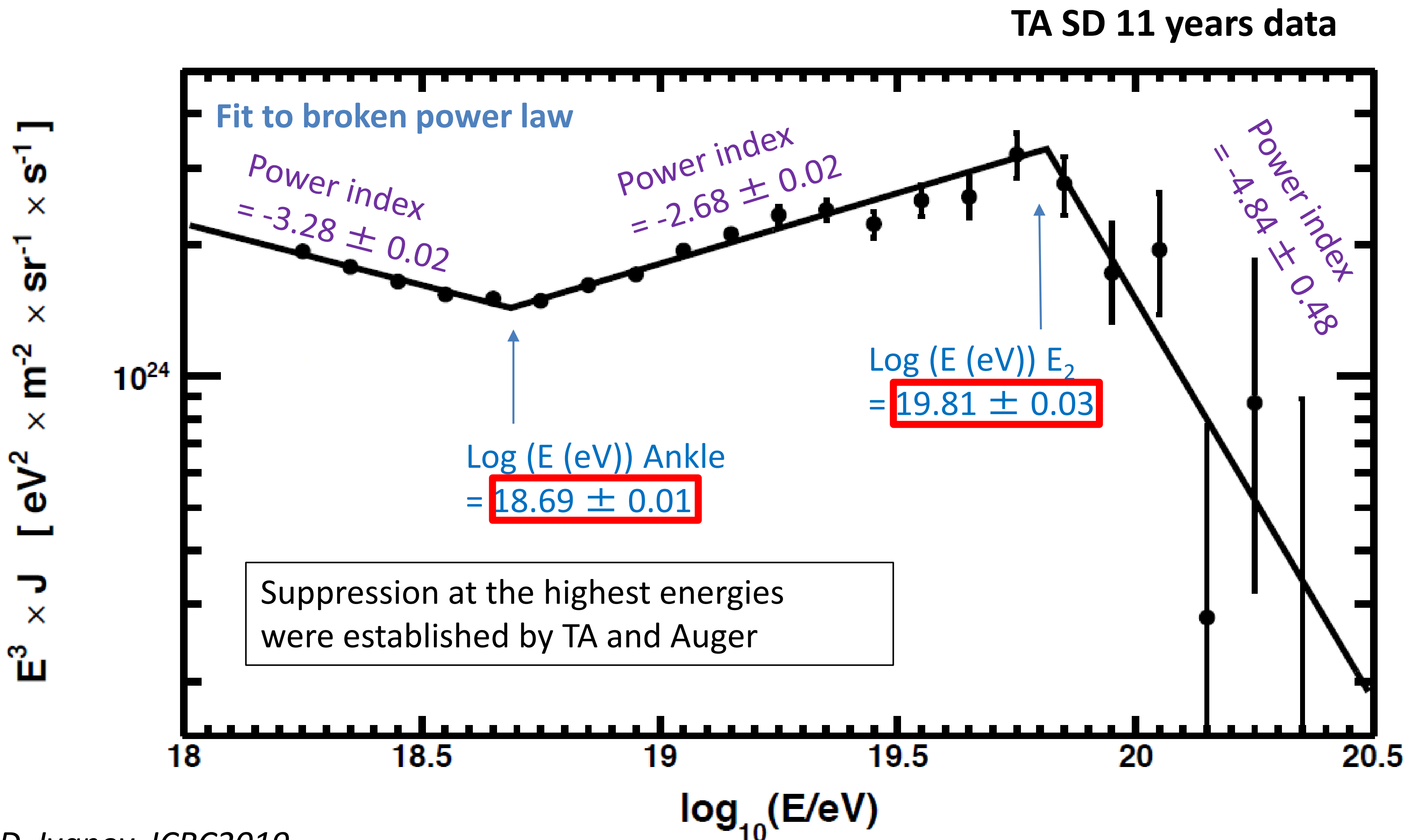

- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km²
  - ➡SD750 : 61, 0.75 km grid, 25 km²
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30⁰ FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60⁰ FoV
- AERA radio antennas
  - ➡153 graded 17 km²

+Atmospheric monitoring devices CLF, XLF, Lidars, …

1.5 km spacing 1600 SDs: cover **～3000 km$^2$**
4 FD sites
Operation in a stable mode from 2004

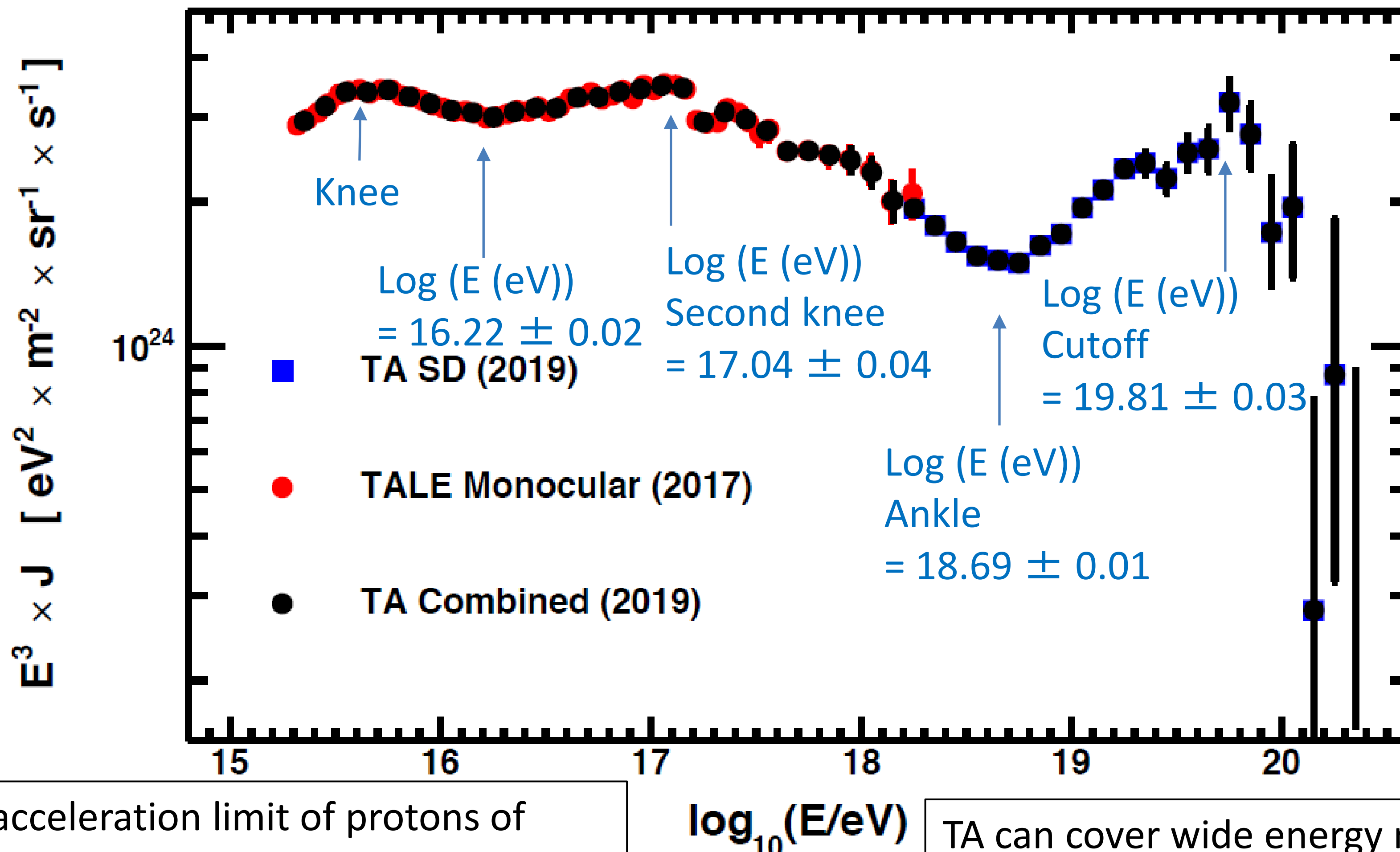
# Recent Results

# Energy Spectrum with TA SD




*D. Ivanov, ICRC2019*

# Combined Energy Spectrum with TALE FD Mono




Knee: acceleration limit of protons of galactic sources such as SNRs?
Second Knee: acceleration limit of irons?

*D. Ivanov, ICRC2019*

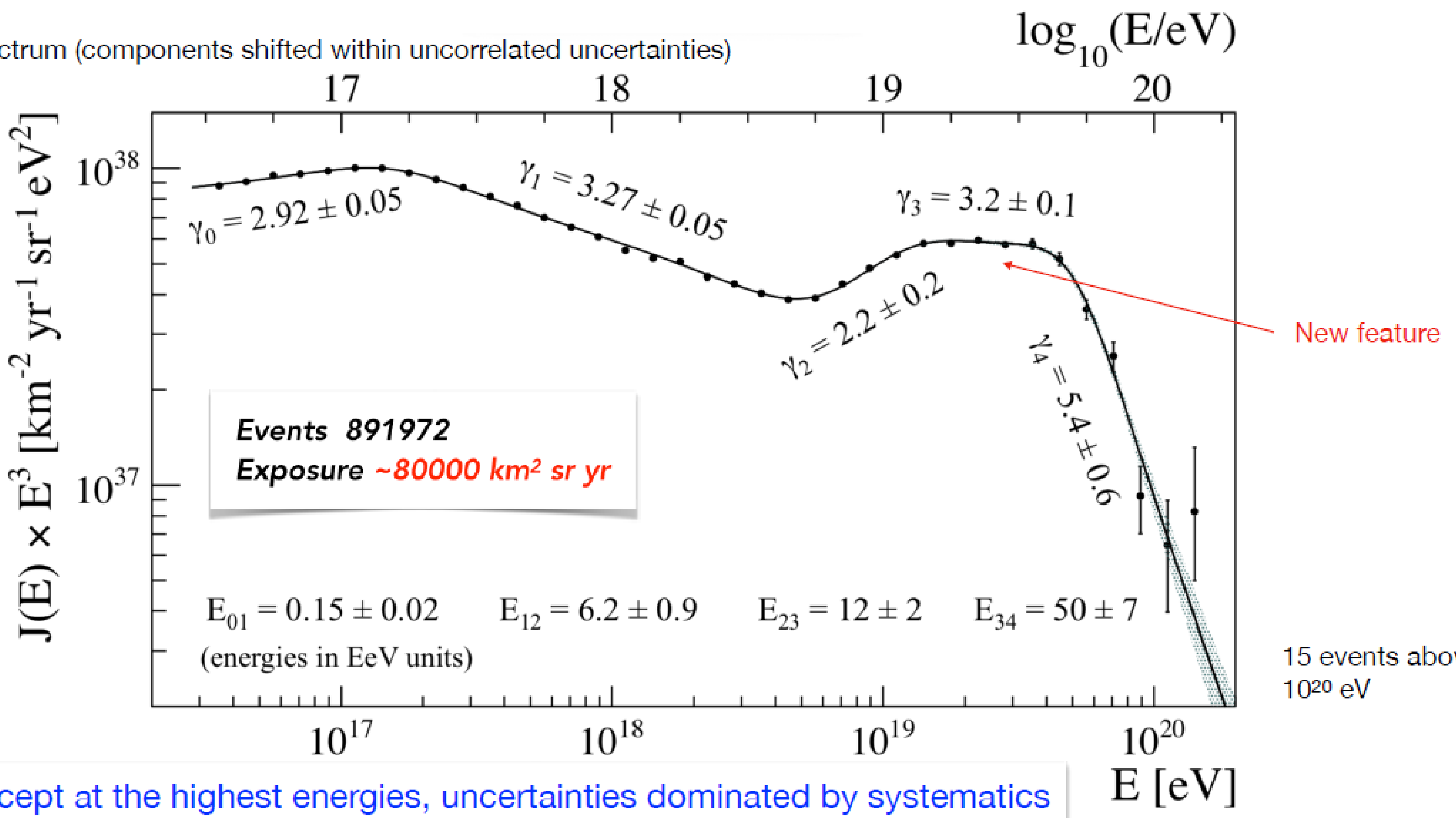
TA can cover wide energy range

Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

# Auger Energy Spectrum

TeVPA2019 Dawson

Combined spectrum (components shifted within uncorrelated uncertainties)



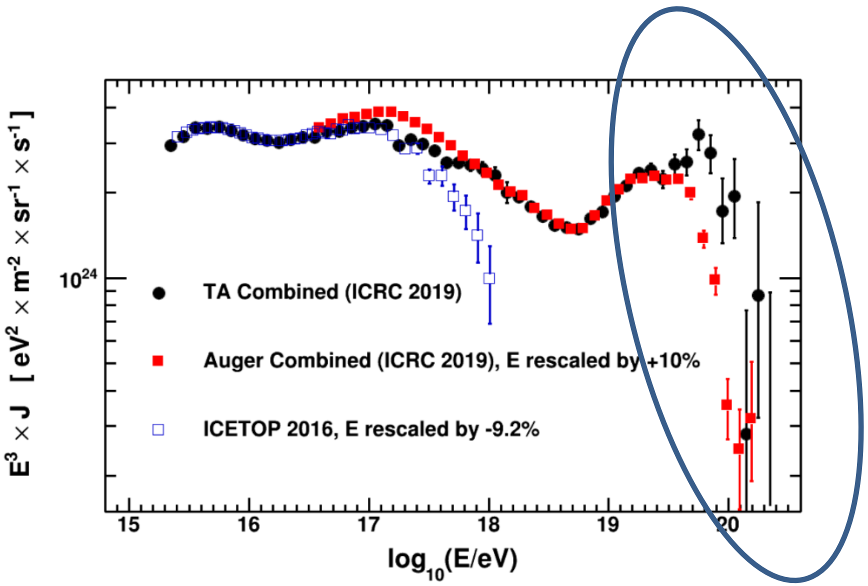

15 events above $10^{20}$ eV

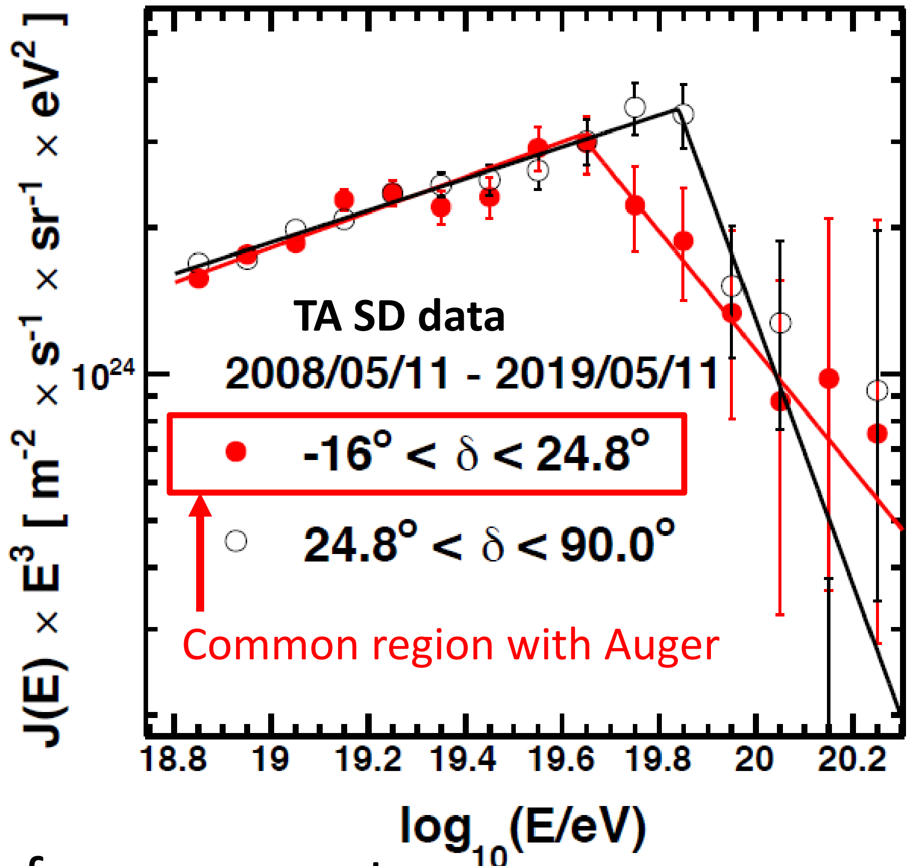
Except at the highest energies, uncertainties dominated by systematics

V. Verzi [Auger Collaboration], ICRC 2019 arXiv:1909.09073

# Declination Dependence of Energy Spectrum

*D. Ivanov, ICRC2019*



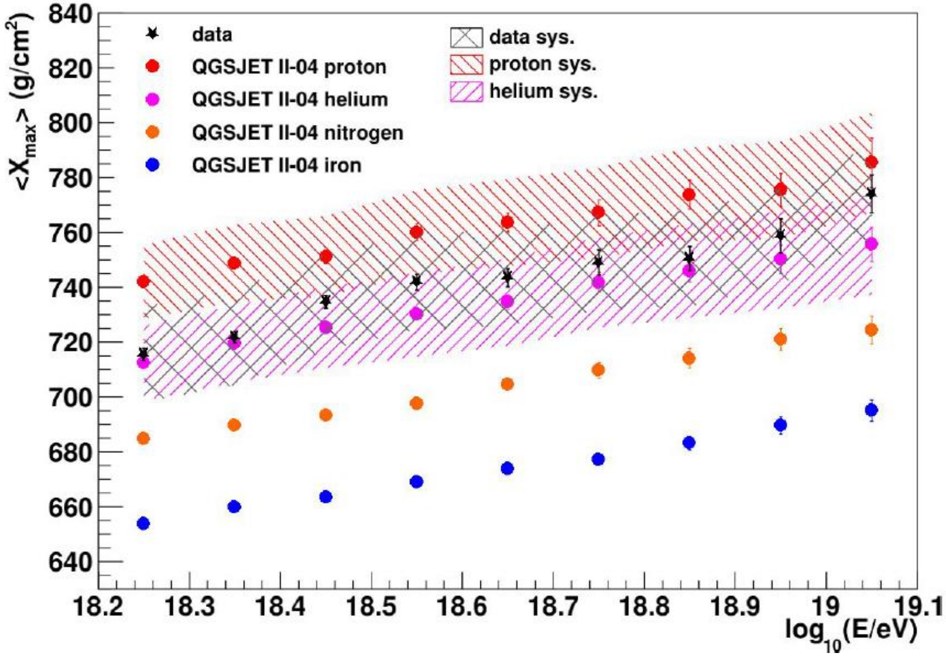

- Difference of the cutoff energies of energy spectra
  - log(E/eV) = 19.64 ± 0.04 for lower dec. band (-16° - 24.8°)
  - log(E/eV) = 19.84 ± 0.02 for higher dec. band (24.8° - 90°)
- The global significance of the difference was estimated to be **4.3σ**

# Composition Analysis with TA SDFD Hybrid Xmax

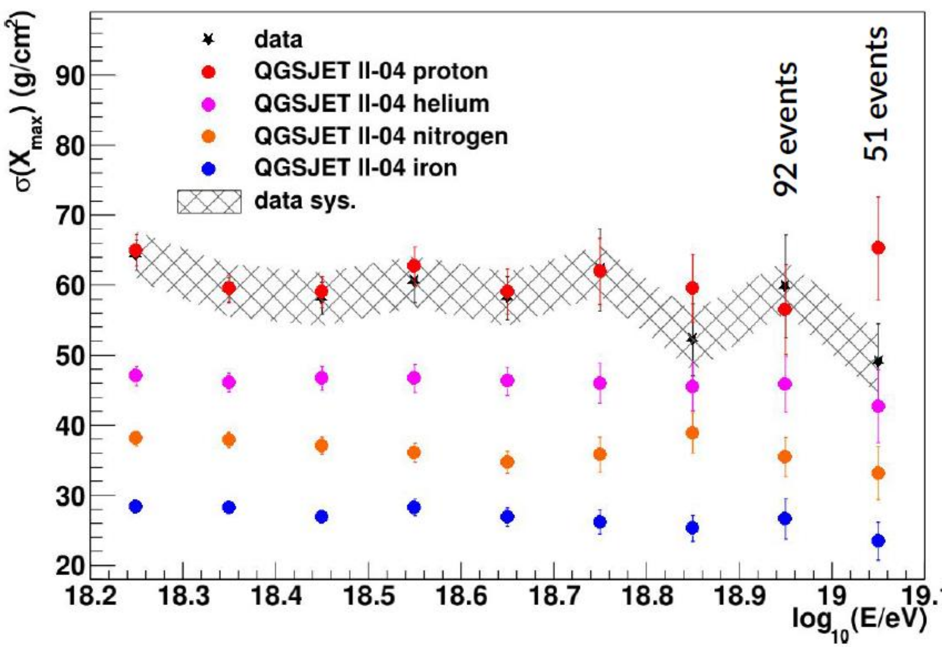
*W. Hanlon, ICRC2019*

10 years SD and FD hybrid data

Mean Xmax



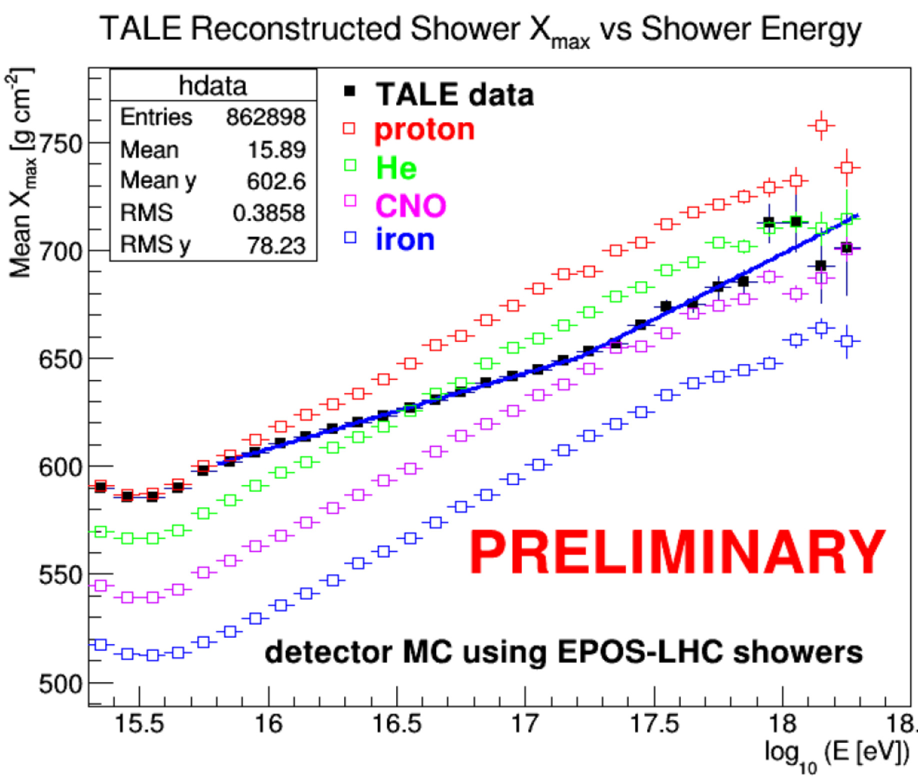

σ (Xmax)

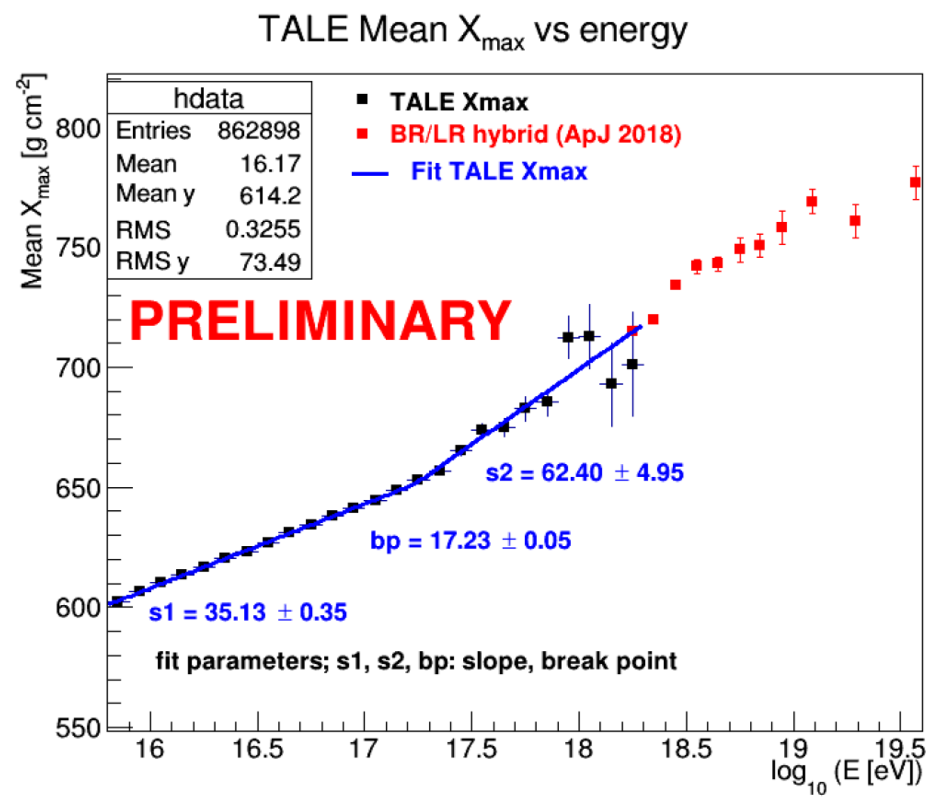



- Energy Range: $10^{18.2}$ eV – $10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 $g/cm^2$
- QGSjetII-04 interaction model was compared with the data
  → agreement with light composition
- More events are needed to study highest energies

# Composition Analysis with TALE FD Mono Xmax

*T. Abu-Zayyad, ICRC2019*



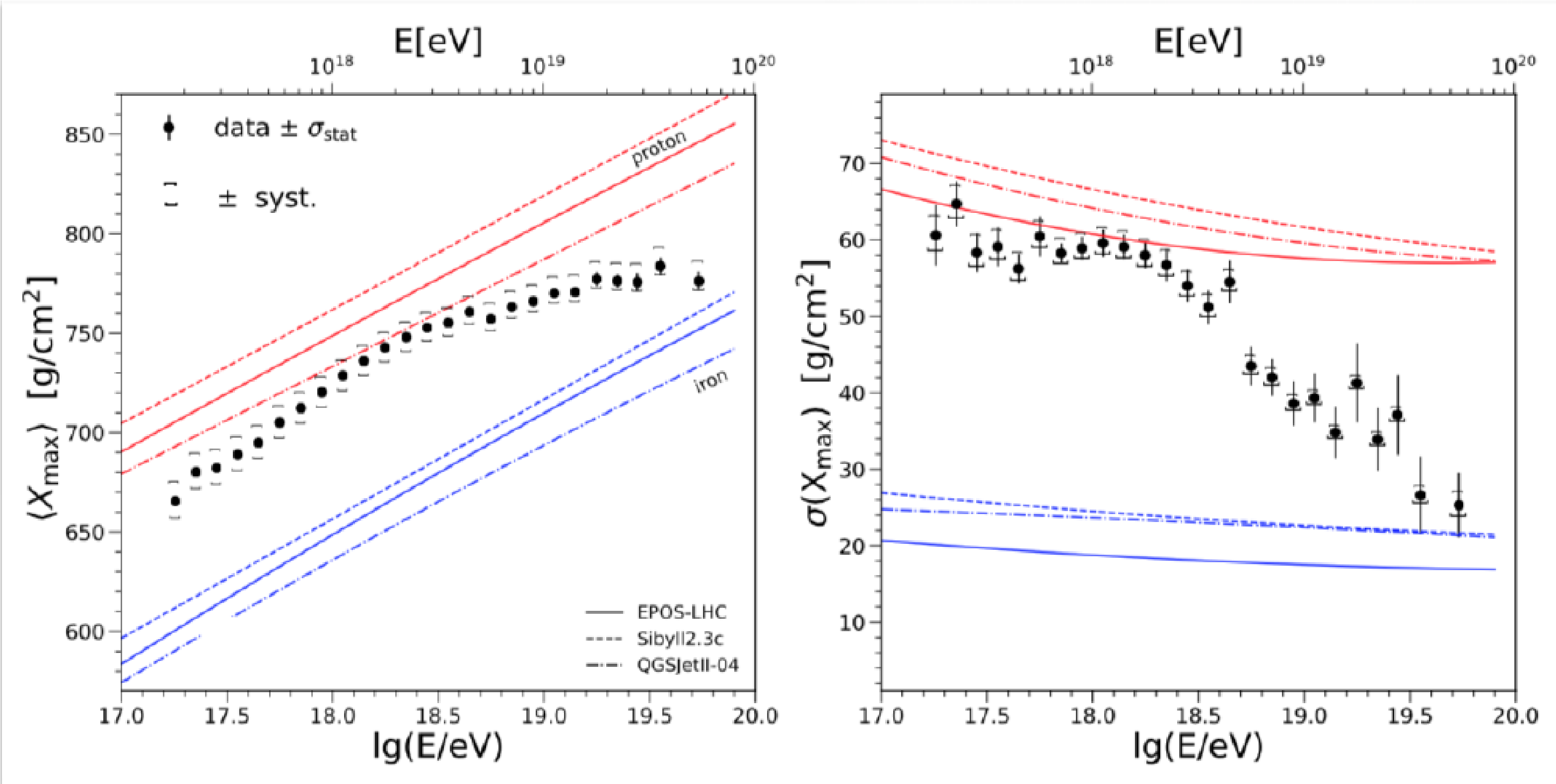




- Jun. 2014 – Nov. 2018 TALE FD mono data
- Energy Range: $10^{15.3}$ eV – $10^{18.3}$ eV
- Break point log (E/eV) = 17.23 ± 0.05

This result is expected to show the transition from galactic CRs to extragalactic CRs

# Mean Xmax and its fluctuations

TeVPA2019 Dawson




Composition becoming lighter up to $\sim 2 \times 10^{18}\,\mathrm{eV}$, heavier above this energy

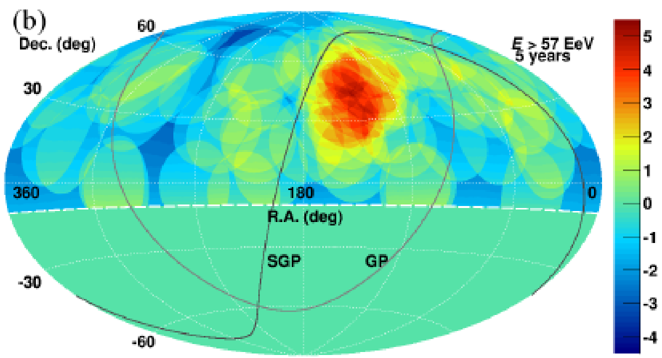
A. Yushkov [Auger Collaboration], ICRC 2019 arXiv:1909.09073

This result is expected to show the transition of compositions of extragalactic CRs at the highest energies.

# TA hotspot in the arrival directions of cosmic rays with E > 57 EeV

**Original hotspot reported in 2014, from 5 years of data**

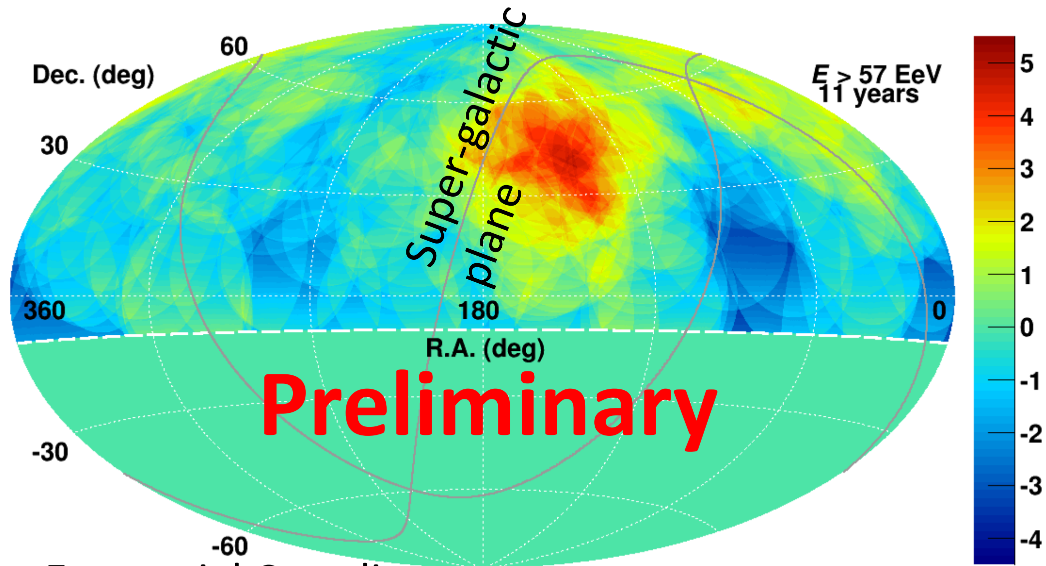
**Ap. J., 790, L21(2014)**
E > 57 EeV (Observed 72 events)
20° over-sampling circle
19 events fall in “Hotspot” centered at (146.7°, 43.2°)
(Expected = 4.5 events)
local significance 5.1σ, post trial significance 3.4σ




*K. Kawata, ICRC2019*

**TA SD 11 years data**

Significance map from isotropy expectation

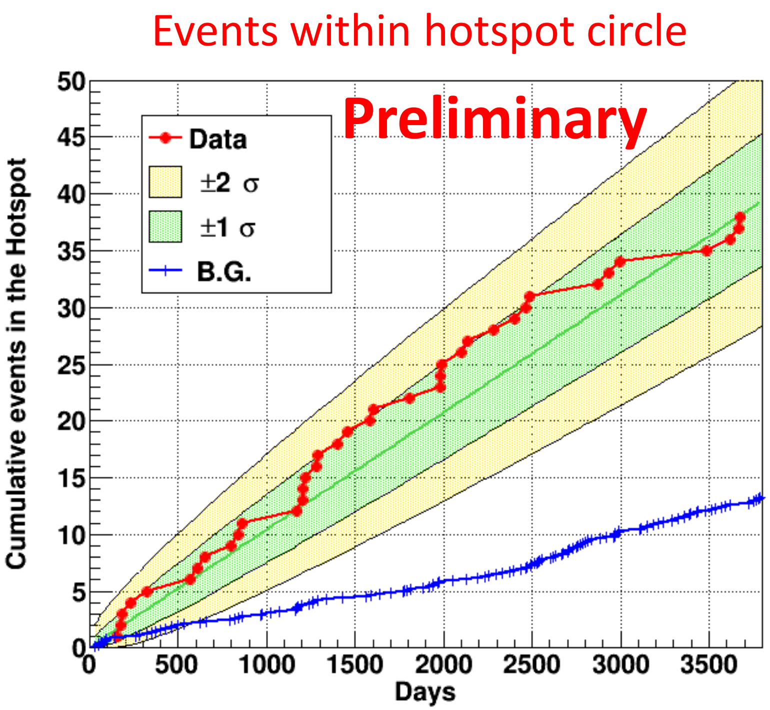


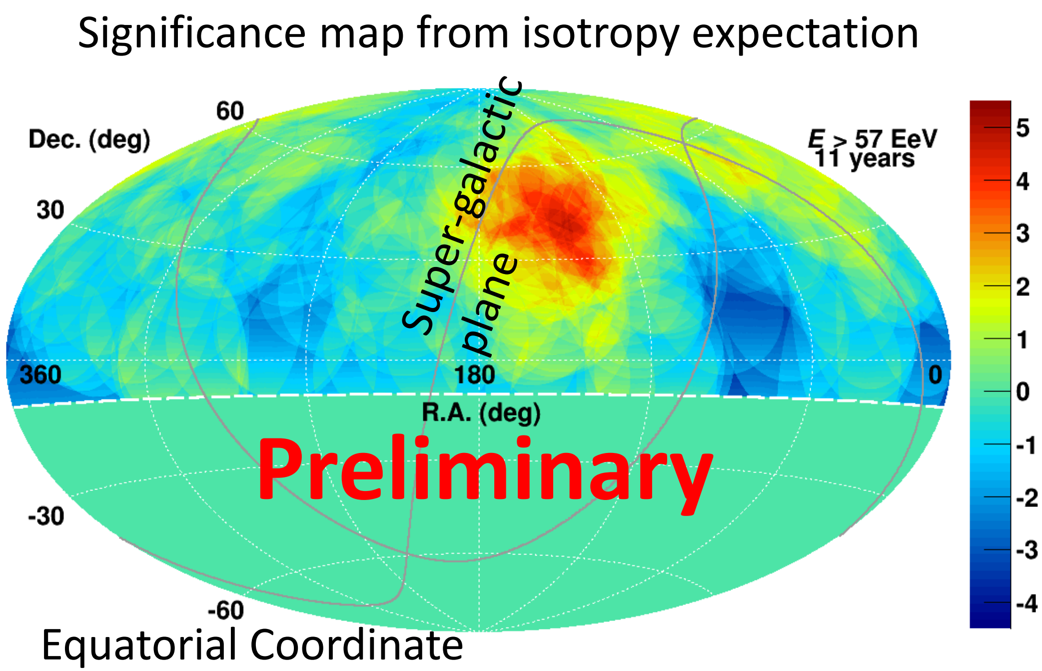

Equatorial Coordinate

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)

# TA hotspot in the arrival directions of cosmic rays with E > 57 EeV

*K. Kawata, ICRC2019*




The cumulative events inside the hotspot circle (25°-radius cirlce) defined by the 11-year.

The increase rate of the events inside the hotspot circle:

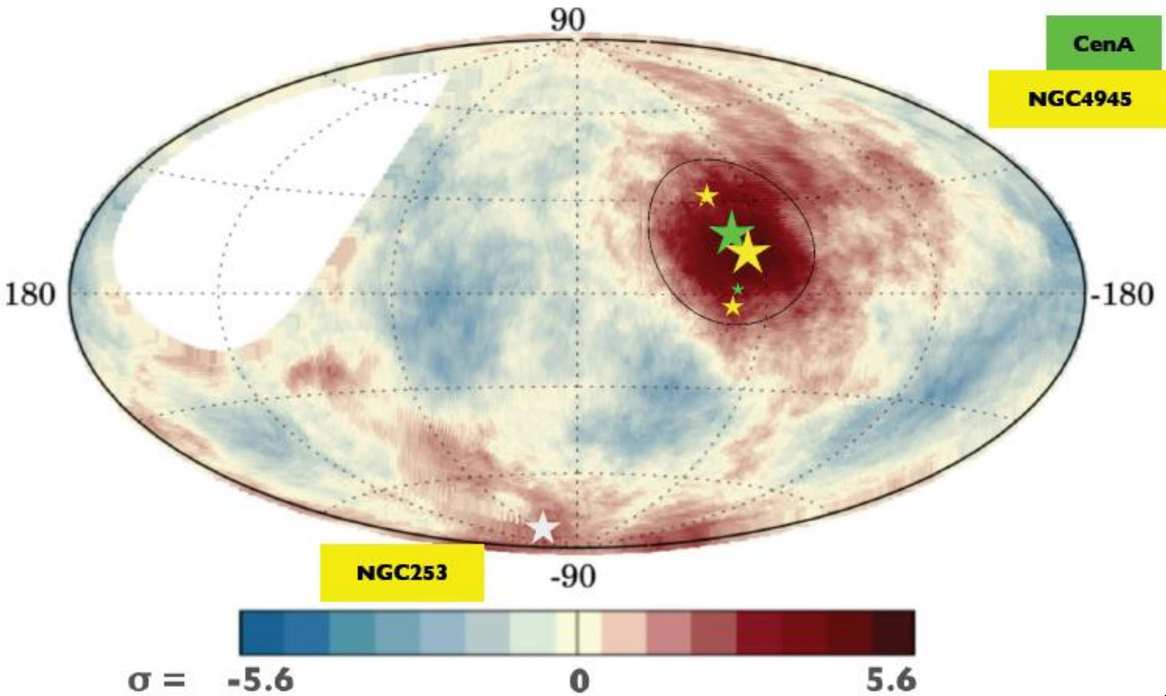
**Consistent with the linear increase within ~1σ**

Anisotropy in the arrival directions was not discovered before in this energy region.
This result would be the implication of the anisotropy.

# Auger intermediate-scale anisotropy

TeVPA2019 Dawson

Total SD events with E>32 EeV : 2157
Total exposure 101,400 km² sr yr




L. Caccianiga [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Galactic coordinate

*Blind search*

Scan ranges:
32 EeV ≤ Eth ≤ 80 EeV (1 EeV steps)
1° ≤ ψ ≤ 30° (1° steps)

***Most significant excess for E>38 EeV***
***(α=202°, δ= -45°) ~2° from CenA***

2.5% post-trial chance probability

*Centaurus A*

***3.9 σ effect (post-trial)***
***for E>37 EeV, 28° window***

Cen A (3FHL catalog):
Gal. latitude: 309.5 deg.
Gal. longitude: 19.4 deg.

# Auger intermediate-scale anisotropy

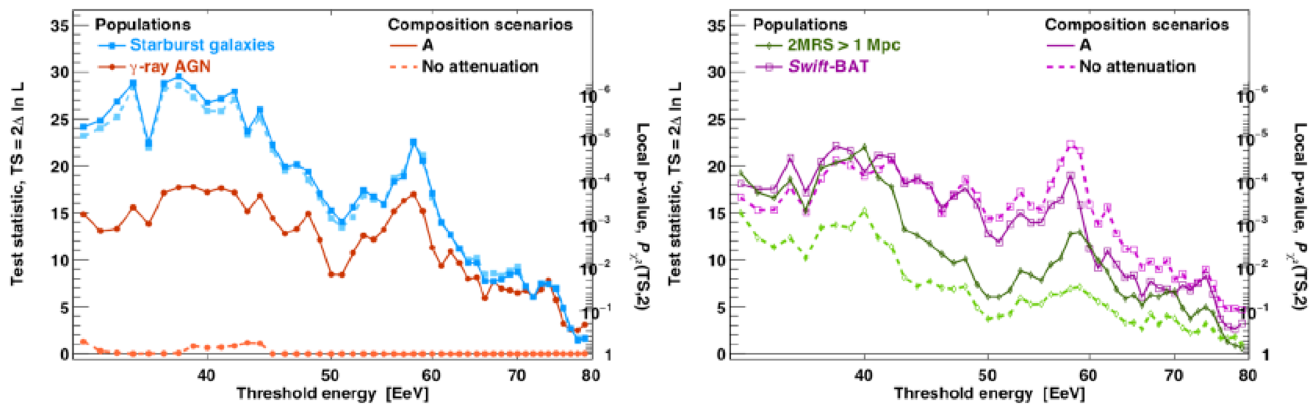
TeVPA2019 Dawson

**$\gamma$ AGNs**
- 3FHL catalog < 250 Mpc
- 33 sources (CenA, Fornax A, M87…)
- Flux proxy $\phi$(>10 GeV)

**Starburst Galaxies**
- 32 sources (Circinus, M82, M83,…)
- <250 Mpc
- Flux proxy $\phi$(>1.4 GHz), > 0.3 Jy

**Swift-BAT**
- >300 radio loud and quiet sources
- <250 Mpc
- $\phi$>13.4 $10^{-12}$ erg cm$^{-2}$ s$^{-1}$

**2MRS**
- ~$10^4$ sources with D>1 Mpc
- <250 Mpc
- Flux proxy K-band flux.




***Likelihood analysis*** $TS = 2Log\left[L(\psi, f_{anis})/L(f_{anis}=0)\right]$

| Catalog | $E_{\rm th}$ | TS | Local p-value | post-trial | $f_{\rm aniso}$ | $\theta$ |
|---|---|---|---|---|---|---|
| Starburst | 38 EeV | 29.5 | $4\times10^{-7}$ | 4.5 $\sigma$ | $11^{+5}_{-4}\%$ | $15^{+5}_{-4}{}^\circ$ |
| $\gamma$–AGN | 39 EeV | 17.8 | $1\times10^{-4}$ | 3.1 $\sigma$ | $6^{+4}_{-3}\%$ | $14^{+6}_{-4}{}^\circ$ |
| Swift-BAT | 38 EeV | 22.2 | $2\times10^{-5}$ | 3.6 $\sigma$ | $8^{+4}_{-3}\%$ | $15^{+6}_{-4}{}^\circ$ |
| 2MRS | 40 EeV | 22.0 | $2\times10^{-5}$ | 3.6 $\sigma$ | $19^{+10}_{-7}\%$ | $15^{+7}_{-4}{}^\circ$ |

(given source smearing, clearly some overlap between catalogs)

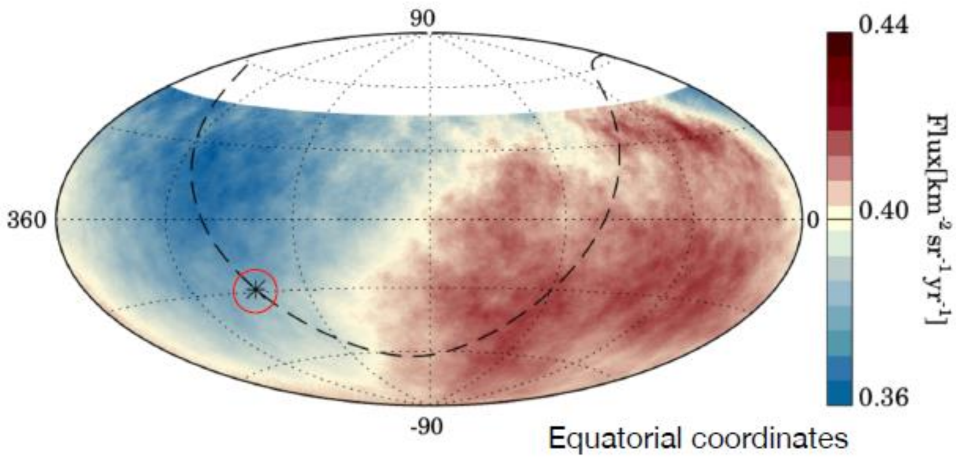
L. Caccianiga [Auger Collaboration], ICRC 2019 arXiv:1909.09073

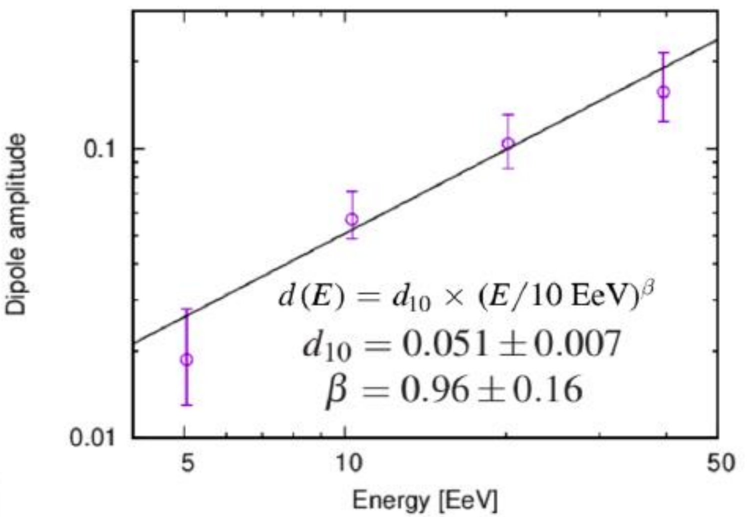
# Auger large-scale anisotropy

TeVPA2019 Dawson

| Energy [EeV] interval | median | $N$ | $d_\perp$ | $d_z$ | $d$ | $\alpha_d$ [°] | $\delta_d$ [°] |
|---|---|---|---|---|---|---|---|
| 4 - 8 | 5.0 | 88,317 | $0.010^{+0.007}_{-0.004}$ | $-0.016 \pm 0.009$ | $0.019^{+0.009}_{-0.006}$ | $70 \pm 34$ | $-57^{+24}_{-20}$ |
| $\geq 8$ | 11.5 | 36,924 | $0.060^{+0.010}_{-0.009}$ | $-0.028 \pm 0.014$ | $0.066^{+0.012}_{-0.008}$ | $98 \pm 9$ | $-25 \pm 11$ |

Exposure $> 92000\ \mathrm{km^2\ sr\ yr}$
for events with $\theta < 80°$




3D dipole above $8 \times 10^{18}$eV at $(\alpha, \delta) = (98°, -25°)$: $(6.6^{+1.2}_{-0.8})$ %
Amplitude increasing with energy

A. Aab et al. [Auger Collaboration], Science **357** 1266 (2017); E. Roulet [Auger Collaboration], ICRC 2019 arXiv:1909.09073

**Dipole E > 8 EeV** was discovered at **> 5.2σ** significance level in 2017

**Energy dependence** was also discovered at **5.1σ** significance in 2019

# Large-scale anisotropy

| Energy [EeV] interval | median | $N$ | $d_\perp$ | $d_z$ | $d$ | $\alpha_d$ [°] | $\delta_d$ [°] |
|---|---|---|---|---|---|---|---|
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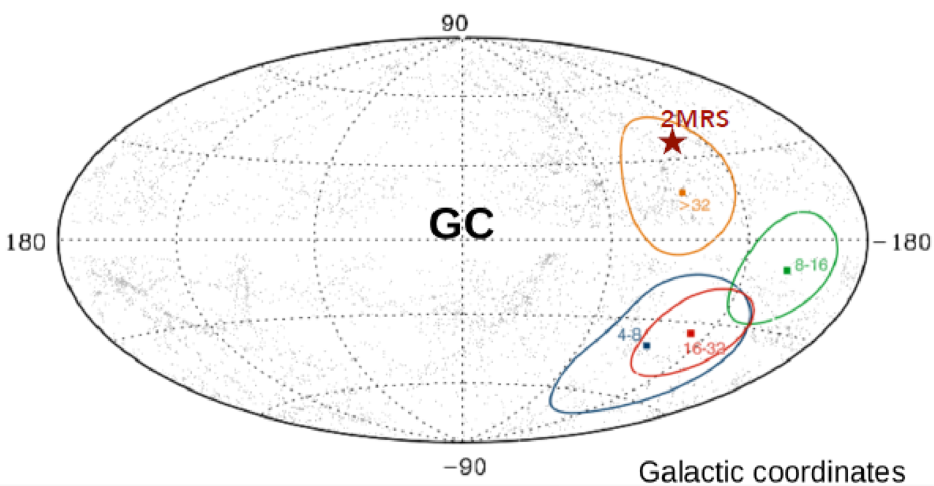


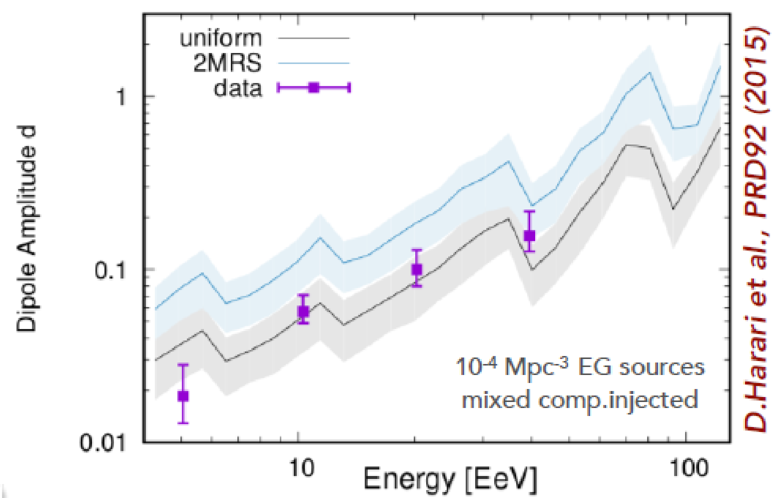


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A. Aab et al. [Auger Collaboration], Science **357** 1266 (2017); E. Roulet [Auger Collaboration], ICRC 2019 arXiv:1909.09073

18/30

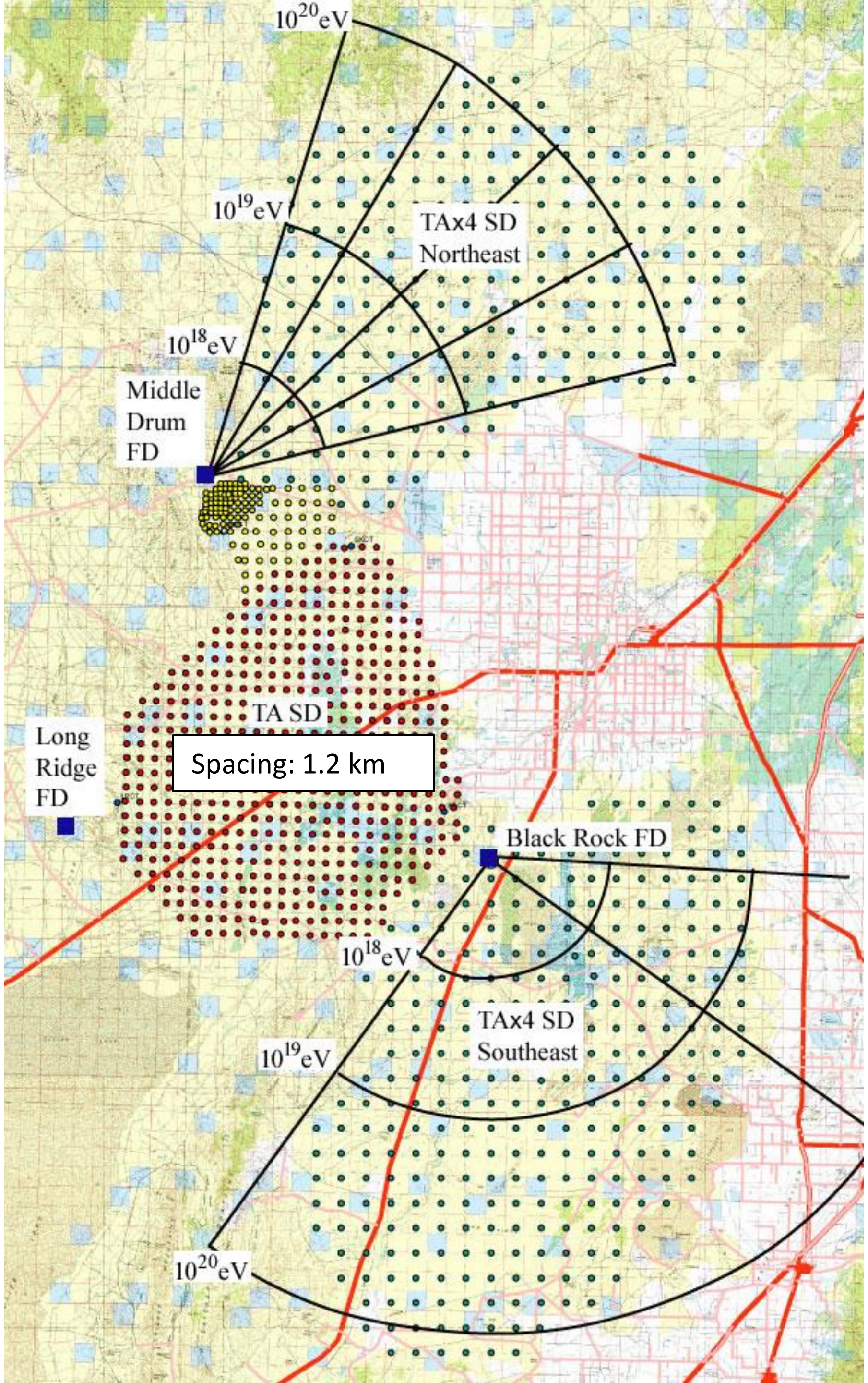
Anisotropy is expected to be come from nearby extragalactic sources by comparing with the distribution of nearby galaxies.

# Summary

- Energy Spectrum
  - TA: Declination dependence was claimed at **4.3σ** in the energy spectrum
  - Auger: New flattening feature was found in the spectral shape at the highest energies
- Composition
  - TA SD and FD hybrid: consistent with light composition with log (E/eV) > **18.2** and log (E/eV) < **19.1**
  - Auger: composition becoming lighter up to 2 $10^{18}$ eV and heavier than this energy
- Intermediate-scale anisotropy
  - TA: **2.9σ** hotspot, oversampling radius: 25° E > **57** EeV
  - Auger: **4.5σ** correlation with starburst galaxies, oversampling radius: 15° E>**38** EeV
- Large-scale anisotropy
  - Auger: dipole was detected in **>5.2σ**, E>8 EeV in 2017
- **Implications of anisotropy are showing up from both TA and Auger at the highest energies.**

# Ongoing Upgrades

# The TAx4 experiment




ICRC2019
Kido

To study more about the highest energies and examine the implications obtained by TA

**500 new** SDs with **2.08 km** spacing

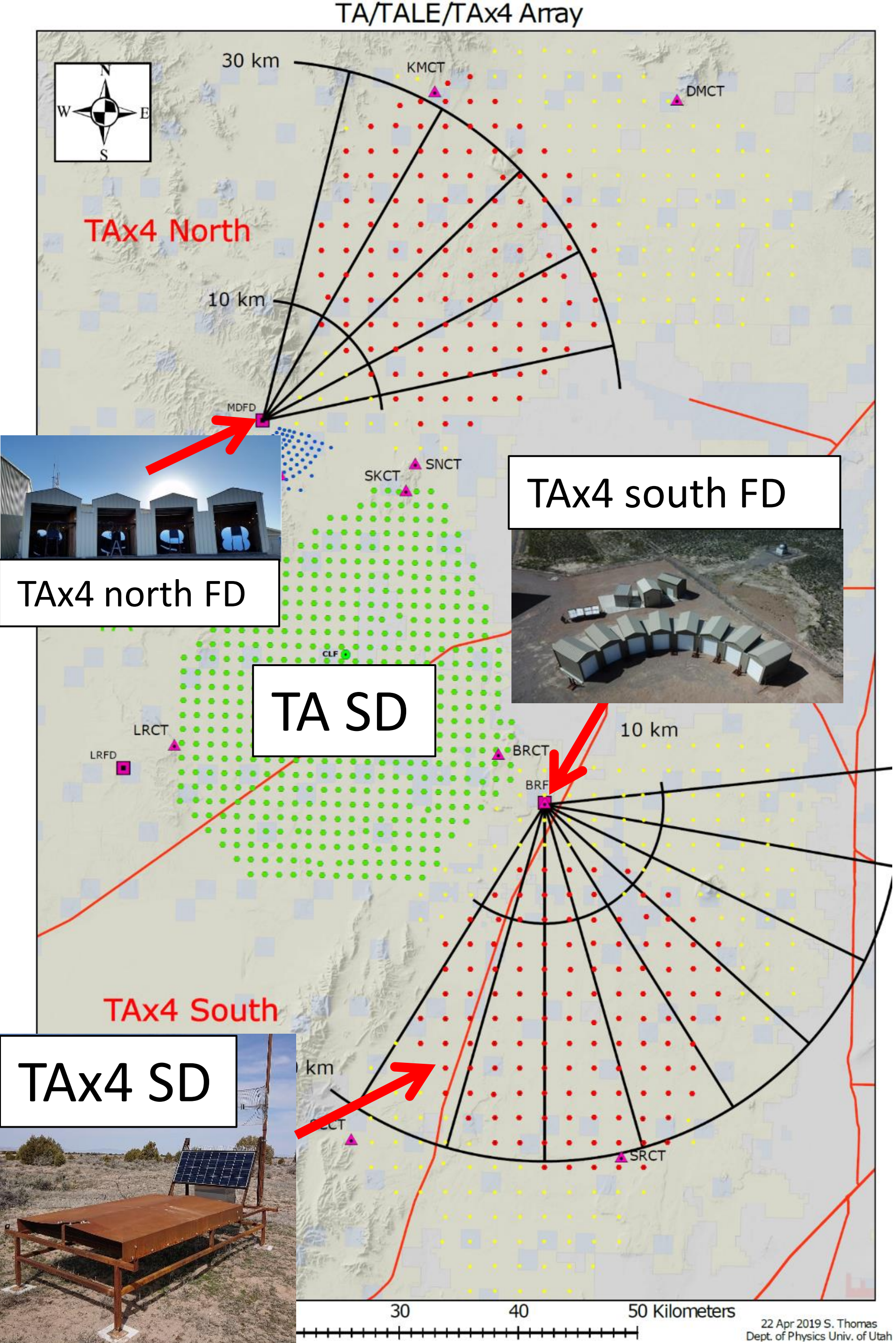
E > 57 EeV:

- Reconstruction efficiency > 95%
- Angular resolution: 2.2°
- Energy resolution: ～25%

and TA SDs cover

**4 × TA SD** detection area (~3000 km$^2$)

**2 new** Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)




# Deployed SDs and Communication Towers

- **More than half of SDs** (257 SDs) were deployed on 19 Feb. – 12 Mar. 2019.
- Locations of SDs were decided to optimize hybrid events above 10 EeV and consider practical conditions of wireless communications

→ **~3×TA SDFD** equivalent hybrid events will be collected

# Construction of TAx4 SDs

# Deployment of Assembled SDs

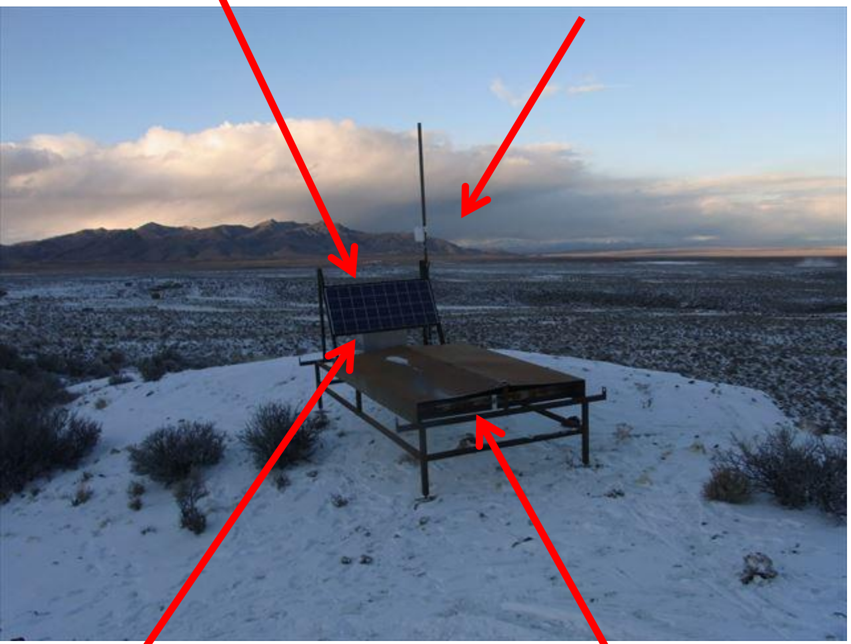
https://www.flickr.com/photos/142880279@N06/albums/72157689940402503

Helicopter for the transportation of SDs

# Design of SDs

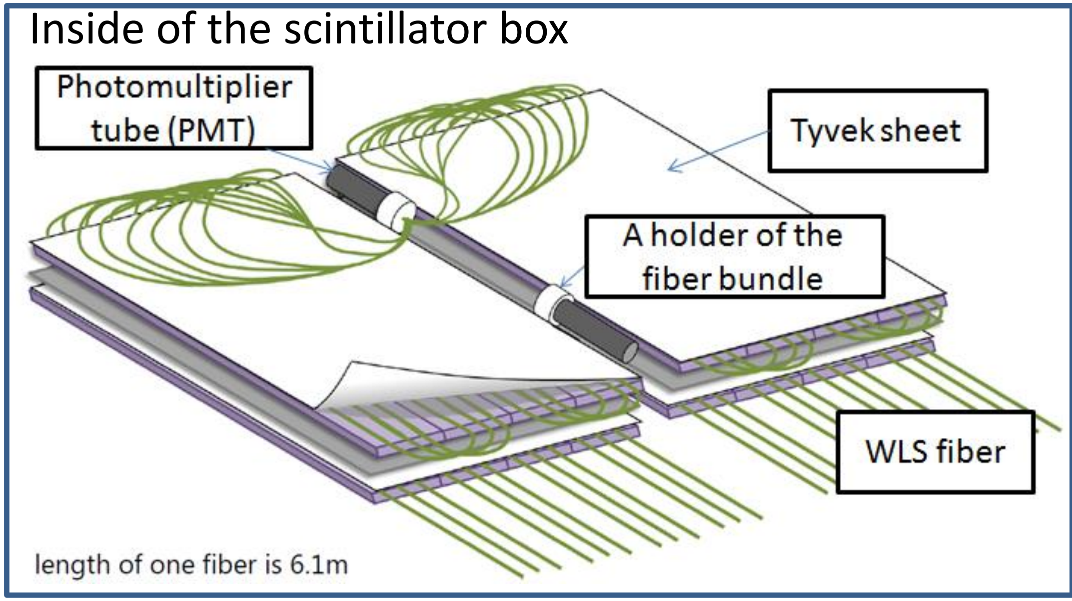
Solar panel

Planar antenna for wireless communication



Stainless steel box for the electronics and a battery

Scintillator box




- **2 layers 3 m² 1.2 cm thick plastic scintillators**

→ Calibration of signals using single muons

- DAQ with 2.4 GHz wireless communication

PMT and arrangement of WLF fibers (**33%** of TA SDs) was changed from TA SD for the cost reduction

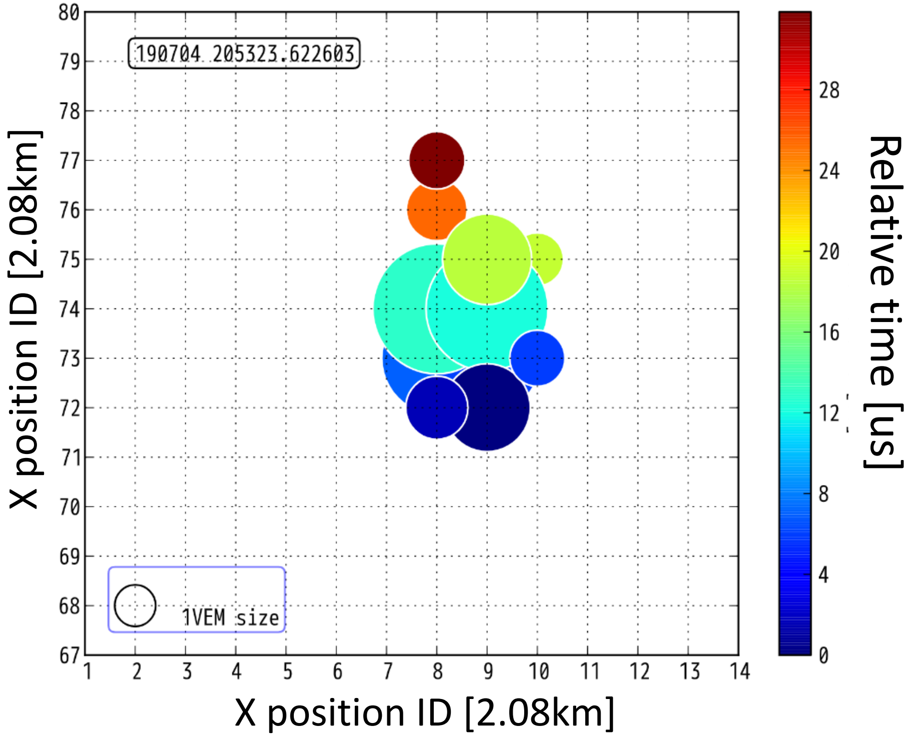
Single peak: **21 p.e.** in average **(∼ TA SDs)**

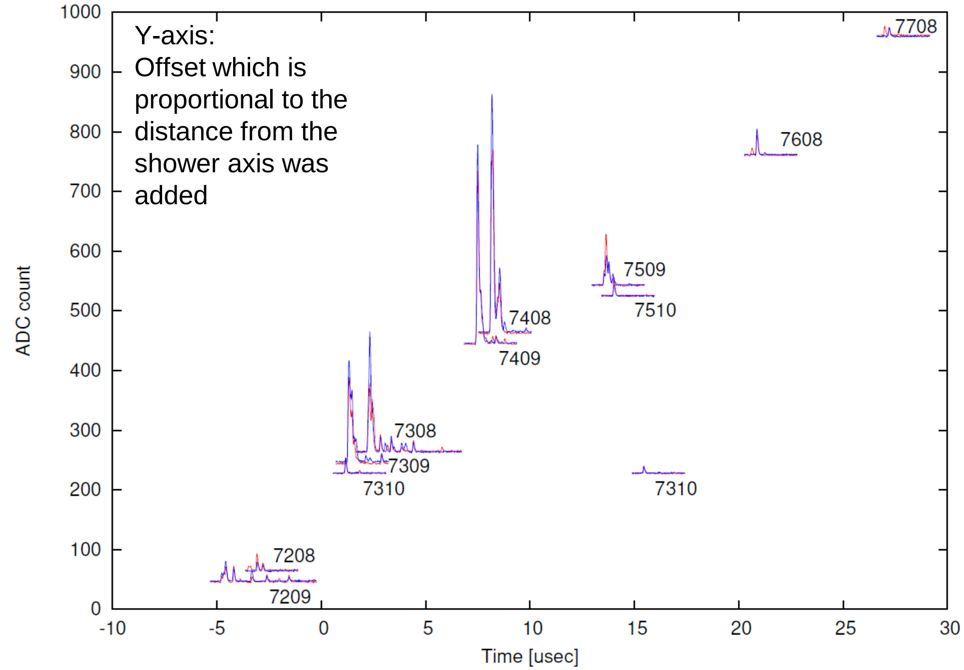
Non-uniformity: **< 15 %** (**∼1/2 x TA SDs**)

Pulse linearity: 50 mA (∼**2 x TA SDs**)

ICRC2019
Kido

# Cosmic Ray Event (E > 57 EeV)




We started stable observation

SD: from 2019 Nov. , FD(north): from 2018 Jun. FD(south): from 2020 Sep.

# Expectation of Hotspot in next 5 years

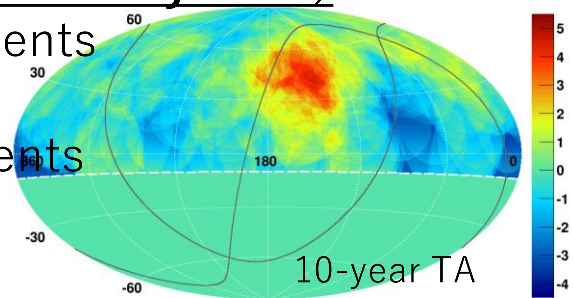
**<u>Hypothesis (10-yr observation from May 2008)</u>:**

- Total # of events: 157 events

  → 15.7 events/yr

- Hotspot # of events: 36 events (25° radius circle)

  → 3.6 events/yr




10-year TA Data

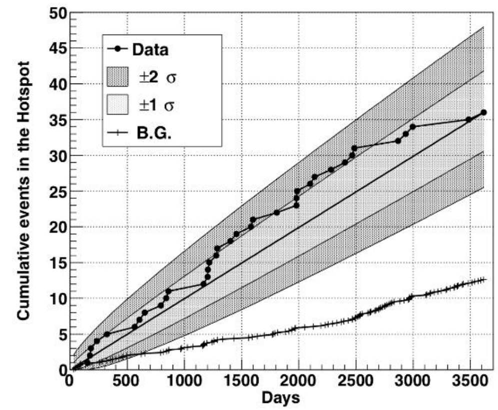
Simple extrapolation

**<u>Expectation (as of May 2025)</u>:** 12-yr TA + 5-yr TAx2.5 = 24.5-year TA

- Total # of events: 384 events
- Hotspot # of events: 88 events (25° radius circle)

→ Local Li-Ma Significance: 7.8σ

Global Significance: 7.8σ − 2σ = ~6σ



# Auger upgrade (AugerPrime)

$4\ m^2$ thickness: 1cm plastic scintillator

Auger water tank

ICRC 2015
Engel #686

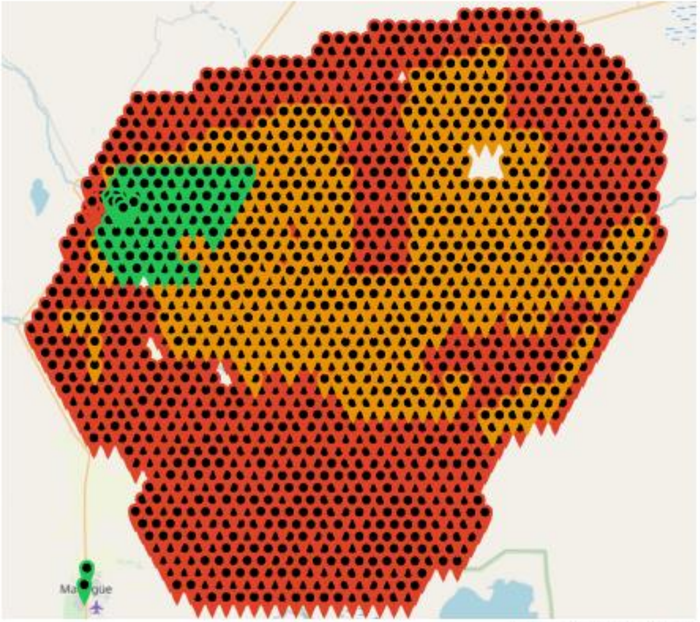
SD statistics ～10 × FD statistics
Plastic scintillator is added to the water tank SD:
measure electromagnetic component, muon component
→R&D of the method to determine
the mass composition of cosmic rays using only SD
→ Mass composition at the highest energies with large statistics
(operation: 2018-)

TeVPA2019 Dawson

# AugerPrime - deployment underway

Mass-composition information for all events, including the very highest energies.

- Engineering array (12 stations) since 2016, scintillator (SSD), new electronics (faster sampling, increased dynamic range)
- Pre-production SSD array (80 stations) since March 2019.
- 559 SSD stations installed up to now (Nov 2019)
- Underground muon detector (UMD) construction continues
- New: 3000 km$^2$ radio detector



November 17, 2019

Water-Cherenkov detector (WCD) with new surface scintillator detector (SSD) and new radio antenna.

# Interpretation of the Experimental Data

Heinz 2019
CRPropa meeting

# Sources – Generic model

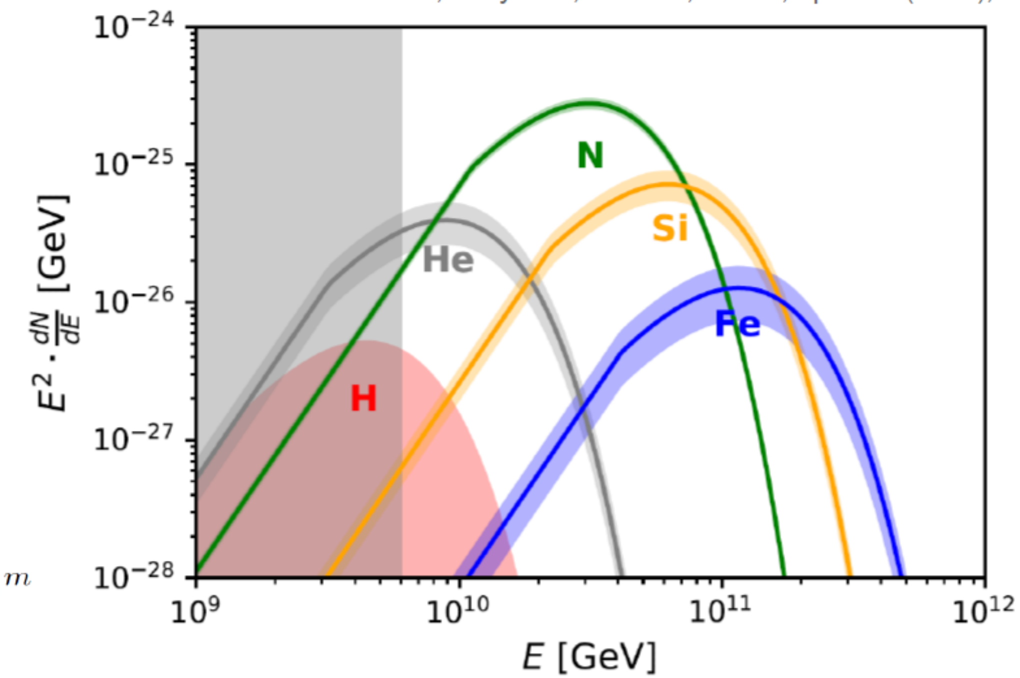
**Generic assumptions**

- Choices following Auger Combined Fit
  …extended to source evolution
  Auger Collaboration, JCAP04(2017)038
- Only five injection elements:
  $H, He, N, Si, Fe$
- Simple Power-law with rigidity dependent cut-off

$$J_A(E) = \mathcal{J}_A \left(\frac{E}{10^9\ \mathrm{GeV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A, R_{\mathrm{max}}) \times n_{\mathrm{evol}}(z)$$

- Source evolution locally as $n_{\mathrm{evol}}(z) = (1+z)^m$

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88




**Total of 8 free parameters** → Fit observed energy spectrum and Xmax

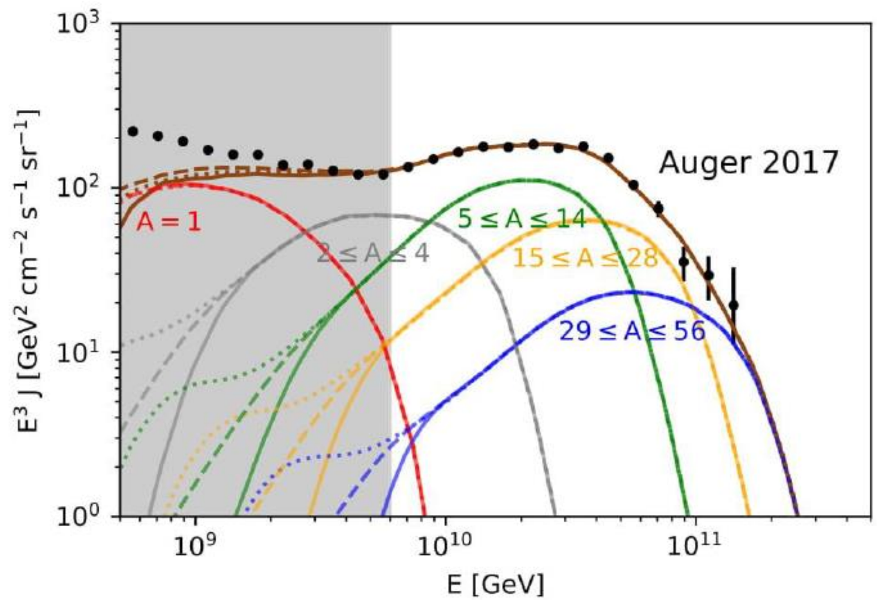
DESY.

Heinz 2019
CRPropa meeting

# Results: Best fit spectrum

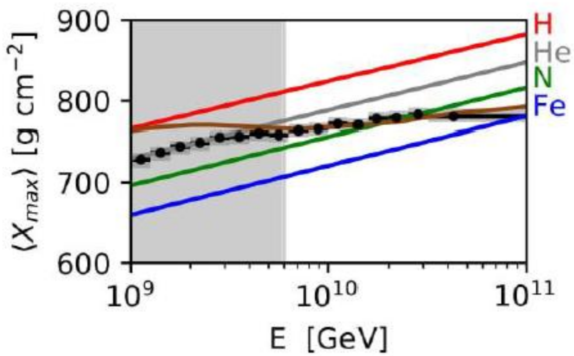
**For combination Talys – Sibyll 2.3**

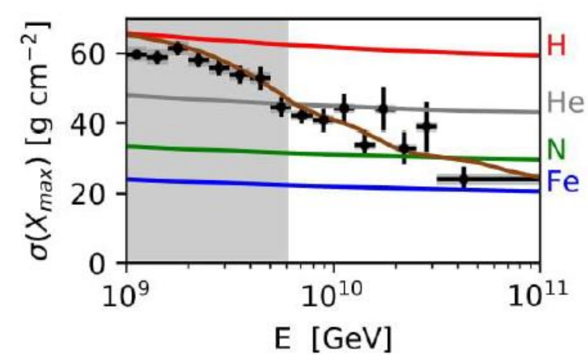
- Fit mainly sensitive to envelope of cutoffs
- Fit-range insensitive above z = 1!
- Composition below ankle proton dominated (by construction) …
- … additional heavy component needed (galactic)




JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

| | best fit (•) | | |
|---|---|---|---|
| $\gamma$ | | | $-0.80^{+0.27}_{-0.23}$ |
| $R_{\max}$ (GV) | | | $(1.6 \pm 0.2) \cdot 10^9$ |
| $m$ | | | $4.2^{+0.4}_{-0.6}$ |
| $\delta_E$ | | | $0.14^{+0.00}_{-0.03}$ |
| $f_A(\%)$ | H | He | N |
| | $0.0^{+42.6}_{-0.0}$ | $82.0^{+3.8}_{-6.4}$ | $17.3^{+1.0}_{-1.1}$ |
| | Si | Fe | |
| | $0.6 \pm 0.1$ | $(2.0 \pm 0.8) \cdot 10^{-2}$ | |
| $I^9_A(\%)$ | H | He | N |
| | $0.0^{+1.2}_{-0.0}$ | $9.8^{+2.8}_{-2.9}$ | $69.2^{+1.5}_{-1.6}$ |
| | Si | Fe | |
| | $17.9^{+3.2}_{-3.5}$ | $3.2^{+1.2}_{-1.3}$ | |
| $\chi^2$ / dof | | | 27.0 / 21 |




DESY.

Heinz 2019
CRPropa meeting

# Model dependence of the Fit

**Compared in $\gamma - m$ space**

### Disintegration model

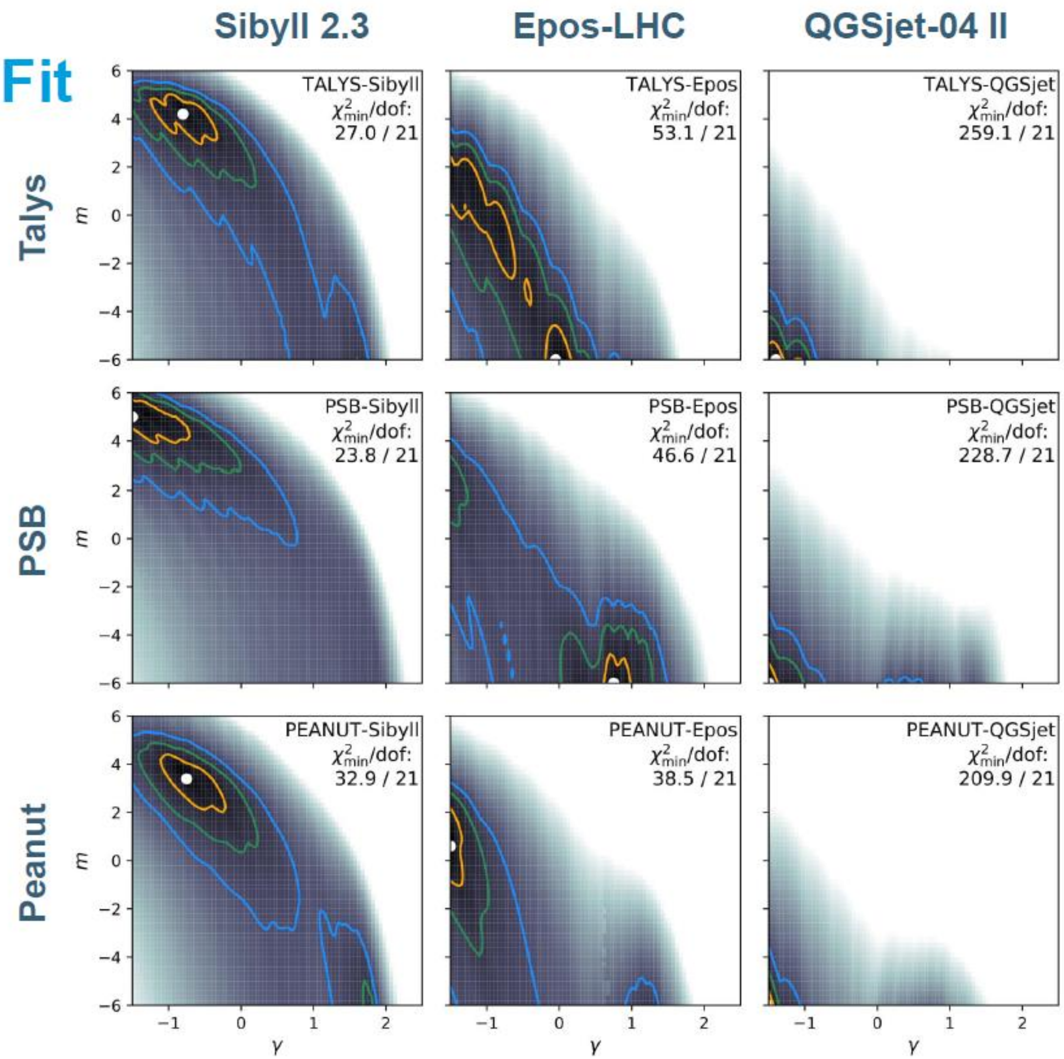
- Qualitatively similar fits
- PSB: Ligher injection
- Peanut/Talys: Heavier injection

### Shower model

- Epos-LHC: Two distinct minima
  avoids disintegration
- Sibyll 2.3: Larger allowed space
  prefers disintegration
- QGSjet 4 II: Overall rather bad fit

*See also: Auger Collaboration JCAP02(2013)026*
*Auger Collaboration JCAP04(2017)038*

**The shower model has a stronger qualitative impact!**




JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

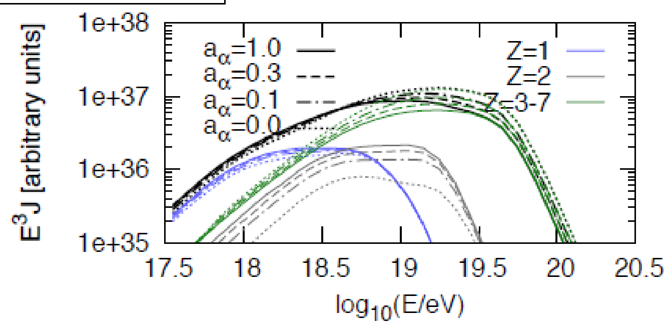
DESY.

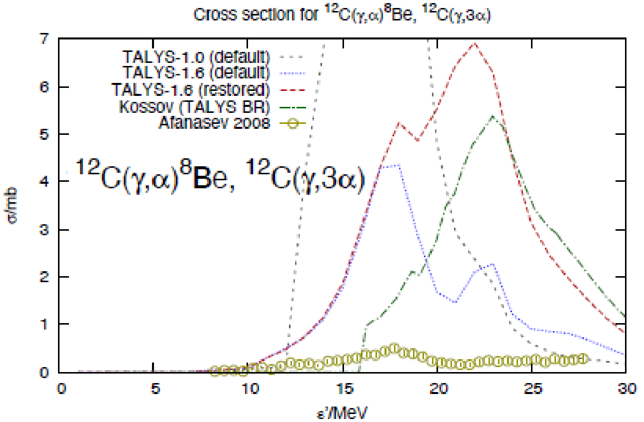
Sako
JPS meeting 2020

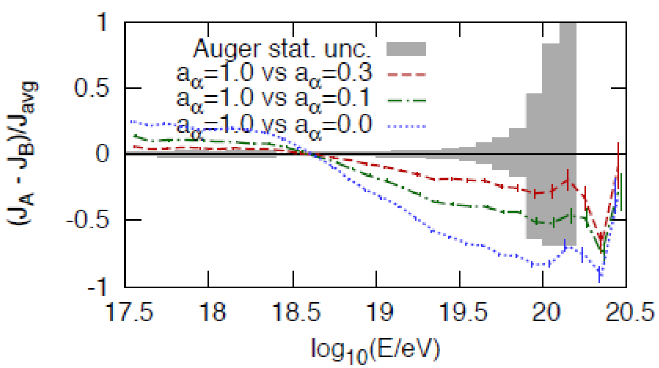
# Forward-folding analysis : Propagation, model dependence

R.A. Vatista et al., JCAP10(2015)063

$a_\alpha$ = 1.0 : TALYS original
$a_\alpha$ = 0.0 : No $\alpha$ production




- >50% effect of ***α* production rate**, which is poorly constrained by the laboratory experiments, or poorly modeled for existing data (plot above)

$$dN/dE \propto E_{\rm inj}^{-\gamma} \exp(-E_{\rm inj}/ZR_{\rm cut})$$

$$0 < z < 1$$

$\gamma = 1$, $R_{cut} = 5\times10^{18}$ V

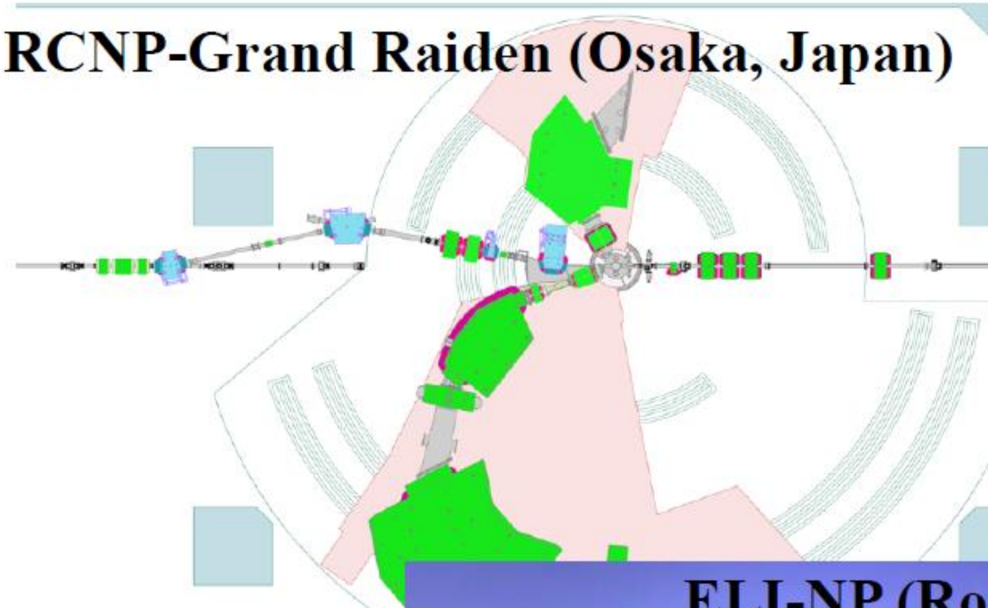
# PANDORA Project

**P**hoto-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

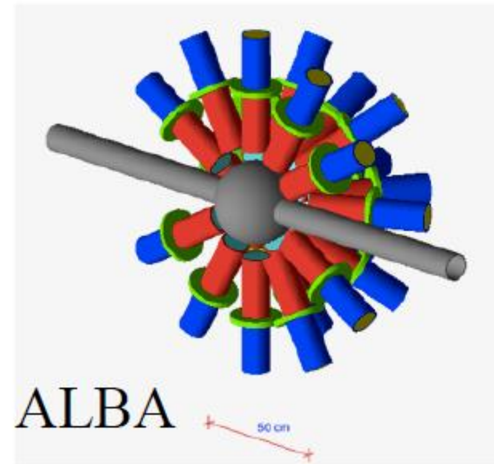
XSCRC2019 Tamii

Joint project among three experimental facilities with nuclear theories and astrophysical simulations

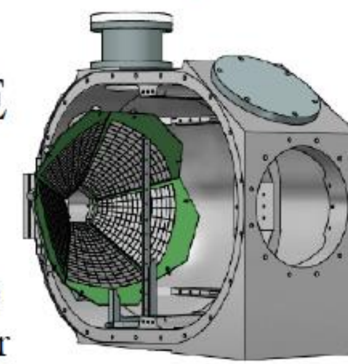
## RCNP-Grand Raiden (Osaka, Japan)



## iThemba LABS South Africa




ALBA



CAKE

decay charge particle detector array

## ELI-NP (Romania)

complementary experimental techniques

# Schedule of the Measurements

Virtual Photon Exp.

JPS2020 Tamii

**RCNP** 2022-

Total strength distribution up 32 MeV

γ-decay

multipole decomp. analysis (ang. dep. and polarization transfer)

**iThemba LABS** 2021-

Beam time approved for the first cases: $^{12}C$, $^{27}Al$
$\sigma_{abs}$ and *p*,α,γ decays

Total strength distribution up 24 MeV

p,α,γ-decays

multipole decomp. analysis (ang. dep.)

Real Photon Exp.

LoI submitted

Good systematic data
Consistency among three facilities
Reference target: $^{27}Al$.

**ELI-NP** 2023-

absolute c.s.

model independent separation of E1 and M1

n,p,α,γ-decays up to 20 MeV

# Target Nuclei

Measurements on 10-20 nuclei in 5-10 years
with theoretical model developments

JPS2020 Tamii

Cross section accuracy:
5-10%

Candidate target nuclides

- $^{12}C$, $^{16}O$, and $^{27}Al$ — first cases, alpha decay, reference target
- $^{6}Li$, $^{7}Li$, $^{9}Be$ — light nuclei
- ($^{20}Ne$), $^{24}Mg$, $^{28}Si$, $^{32}S$, ($^{36}Ar$), $^{40}Ca$ — N=Z nuclei, α-cluster effect, deformation
- $^{26}Mg$, $^{48}Ca$, $^{56}Fe$ — N>Z nuclei
- $^{13}C$, $^{14}N$, $^{51}V$ — odd and odd-odd nuclei
- (γ,xn) on $^{18}O$, $^{48}Ca$, $^{64}Ni$

Sensitivity test and selection of important nuclei are under discussions.

# PANDORA Project: Organization

JPS2020 Tamii

## Nuclear Experiments

| | |
|---|---|
| RCNP | *Osaka Univ.*<br>**A. Tamii, N. Kobayashi, T. Sudo**, Z. Yang, T. Furuno, M. Murata, A. Inoue, H. Mori |
| ELI-NP | *ELI-NP*<br>**P.-A. Söderström**, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu |
| iThemba LABS | *iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.*<br>**L. Pellegri**, R. Neveling, F.D. Smit, J.A.C. Bekker, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, K.C.W. Ki, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya |
| TU-Darmstadt | P. von Neumann-Cosel, N. Pietralla, J. Isaak, J. Kleemann, M. Spall |
| U. Milano / INFN | A. Bracco, F. Camera, F. Crespi, O. Wieland |

## Nuclear Theory

| | | |
|---|---|---|
| AMD | **M. Kimura, Y. Taniguchi**, H. Motoki | **Antisymmetrized Molecular Dynamics** |
| NRFT | **E. Litvinova**, P. Ring, H. Wibowo | **Nuclear Relativistic Field Theory** |
| RPA / DFT | **T. Inakura** | |
| TALYS | **S. Goriely, E. Khan** | |

## UHECR Theory

| | |
|---|---|
| Propagation and production | **D. Allard**, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff<br>**S. Nagataki, E. Kido**, J. Oliver, H. Haoning |

## NC Neutrino Detection

**Y. Koshio, M. Sakuda, M.S. Reen**,

# PANDORA Project: Organization

JPS2020 Tamii

## Nuclear Experiments

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| RPA / DFT | **T. Inakura** | |
| TALYS | **S. Goriely, E. Khan** | |

Theoretical models are needed to include the experimental data in the simulations of the propagation of UHECRs → Kido started to compare models with collaborators

## UHECR Theory

| | |
|---|---|
| Propagation and production | **D. Allard**, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff<br>**S. Nagataki, E. Kido**, J. Oliver, H. Haoning |

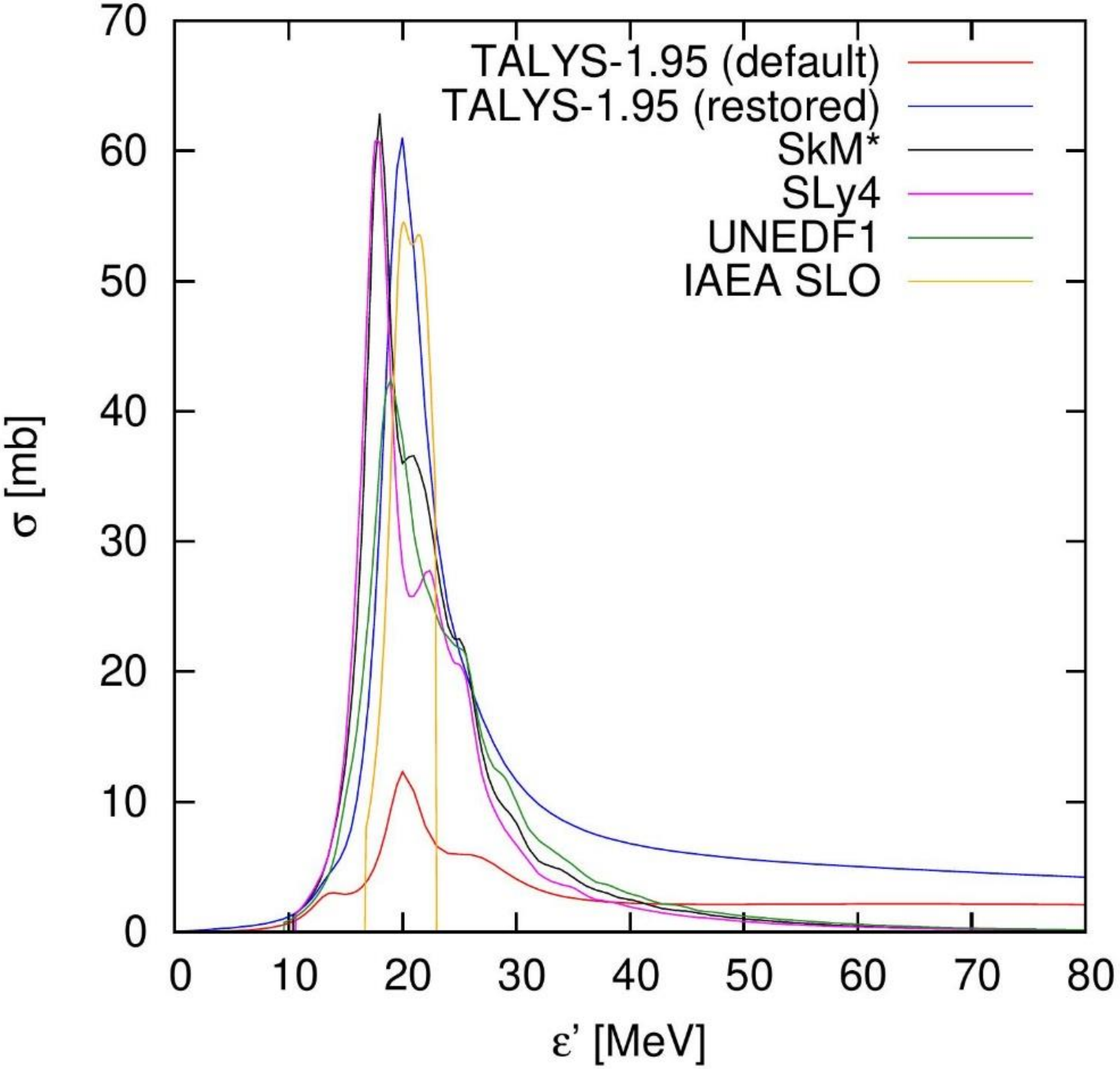
## NC Neutrino Detection

**Y. Koshio, M. Sakuda, M.S. Reen,**

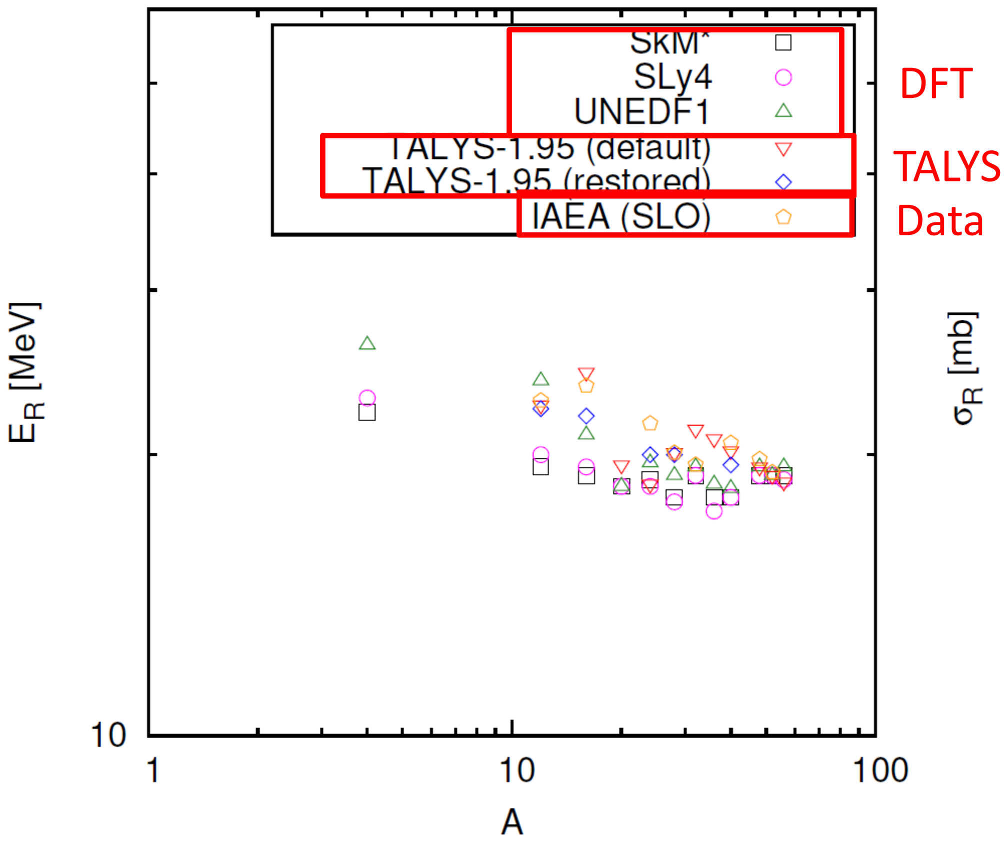
# Comparison of Photoabsorption Cross Sections

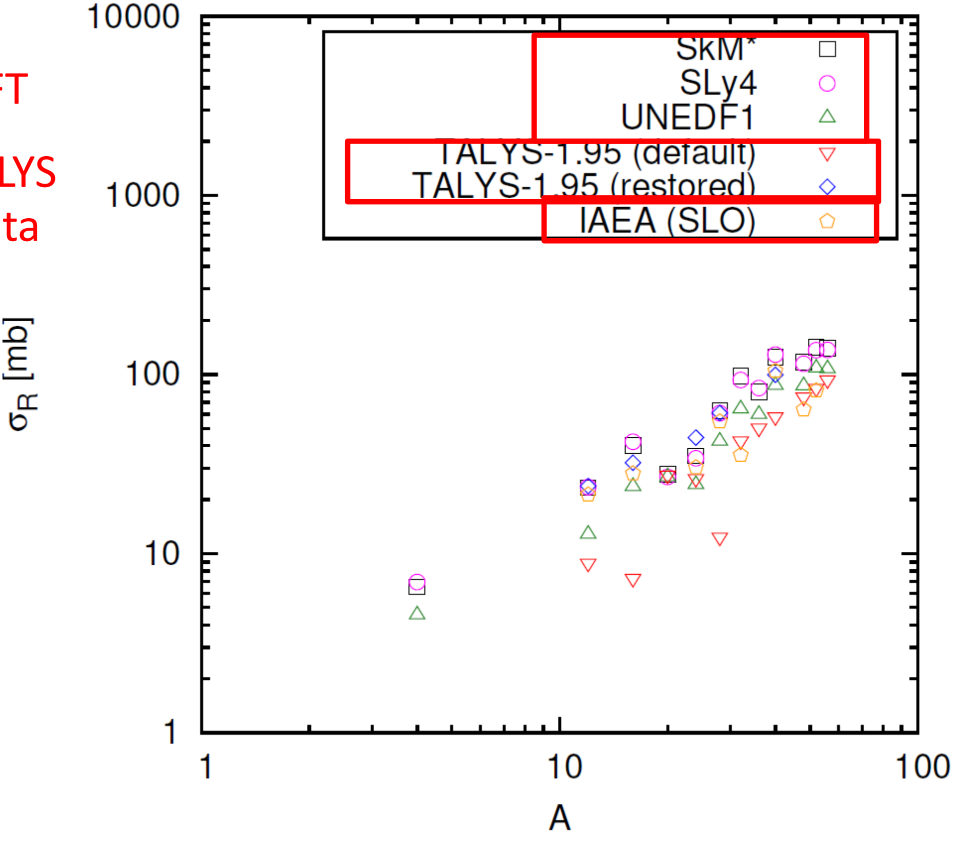
- T. Inakura *et al.*, *PHYSICAL REVIEW C* **80**, 044301 (2009) and T. Inakura *et al.*, *PHYSICAL REVIEW C* **84**, 021302(R) (2011).
  - Density Functional Theory (DFT) calculation
  - $\sigma_{GDR}$ (GDR: Giant Dipole Resonance)
  - 12 nuclei (4He 12C 16O 20Ne 24Mg 28Si 32S 36Ar 40Ca 48Ti 52Cr 56Fe)
  - 3 interaction models
    - SkM* : J. Bartel *et al., Nucl. Phys.* ***A*** **386**, 79 (1982).
    - SLy4 : E. Chanbanat, P. Bonche, P. Haensel, J. Mayer, and R. Schaeffer, *Nucl. Phys.* **A627**, 710 (1997).
    - UNEDF1 : M. Kortelainen *et al., Phys. Rev. C* **85**, 024304 (2012).
- TALYS-1.95 https://tendl.web.psi.ch/tendl_2019/talys.html
  - Statistical Hauser-Feshbach theory
  - $\sigma_{GDR} + \sigma_{QD}$ (QD: Quasi Deuteron)
  - Default : 11 nuclei
    (12C 16O 20Ne 24Mg 28Si 32S 36Ar 40Ca 48Ti 52Cr 56Fe)
  - Restored (E1-strength function was changed for CRPropa and SimProp) )
    : 5 nuclei (12C 16O 24Mg 28Si 40Ca)
- Data
  - IAEA Photonuclear Data Library 2019 T. Kawano *et al.*
  - Table III Recommended Experimental GDR parameters in the certain energy range
  - Standard Lorentzian (SLO): $$\sigma_{\mathrm{GDR}}(E_\gamma) = \sigma_R \frac{E_\gamma^2 \Gamma_R^2}{(E_R^2 - E_\gamma^2)^2 + E_\gamma^2 \Gamma_R^2}$$

# $^{28}$Si Photoabsorption Cross Sections

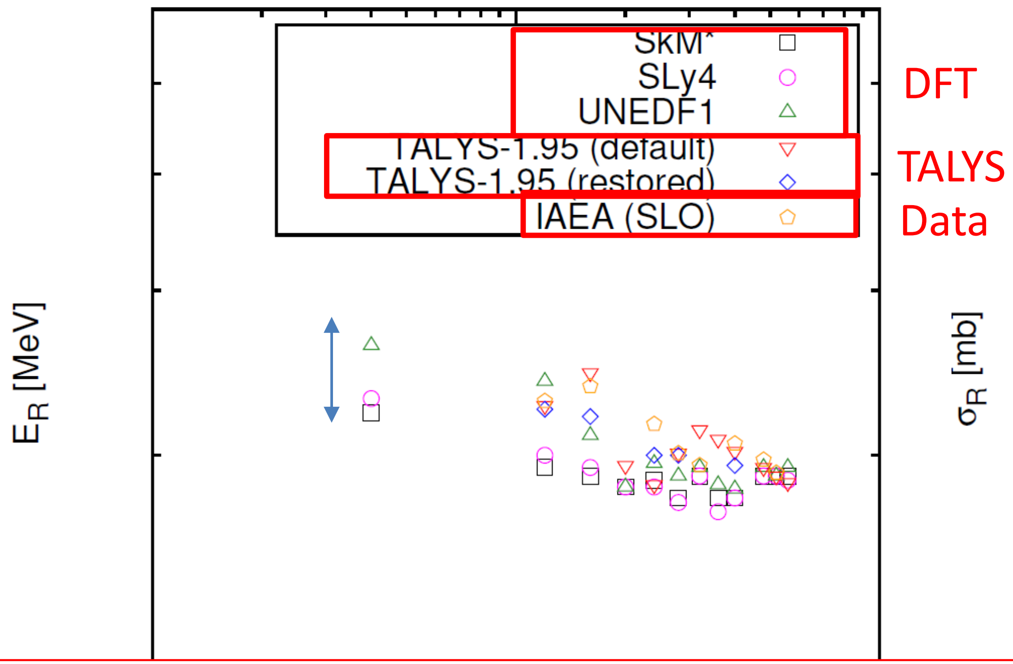


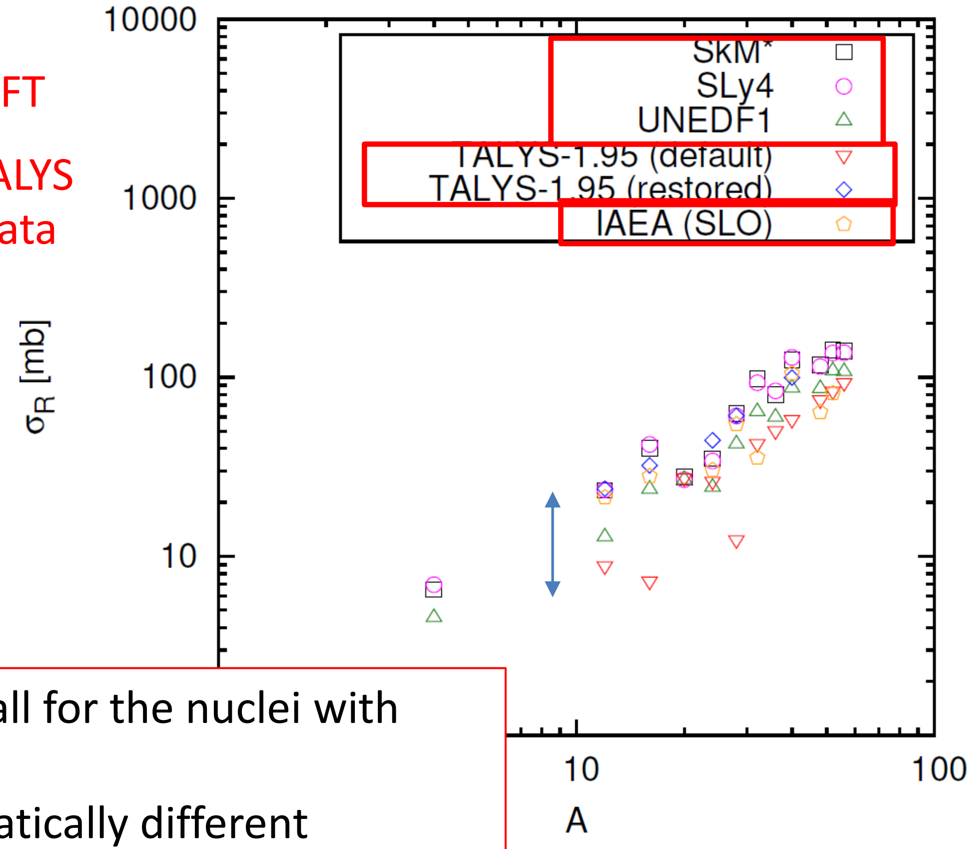
# Comparison of Peak Energies and Cross Sections



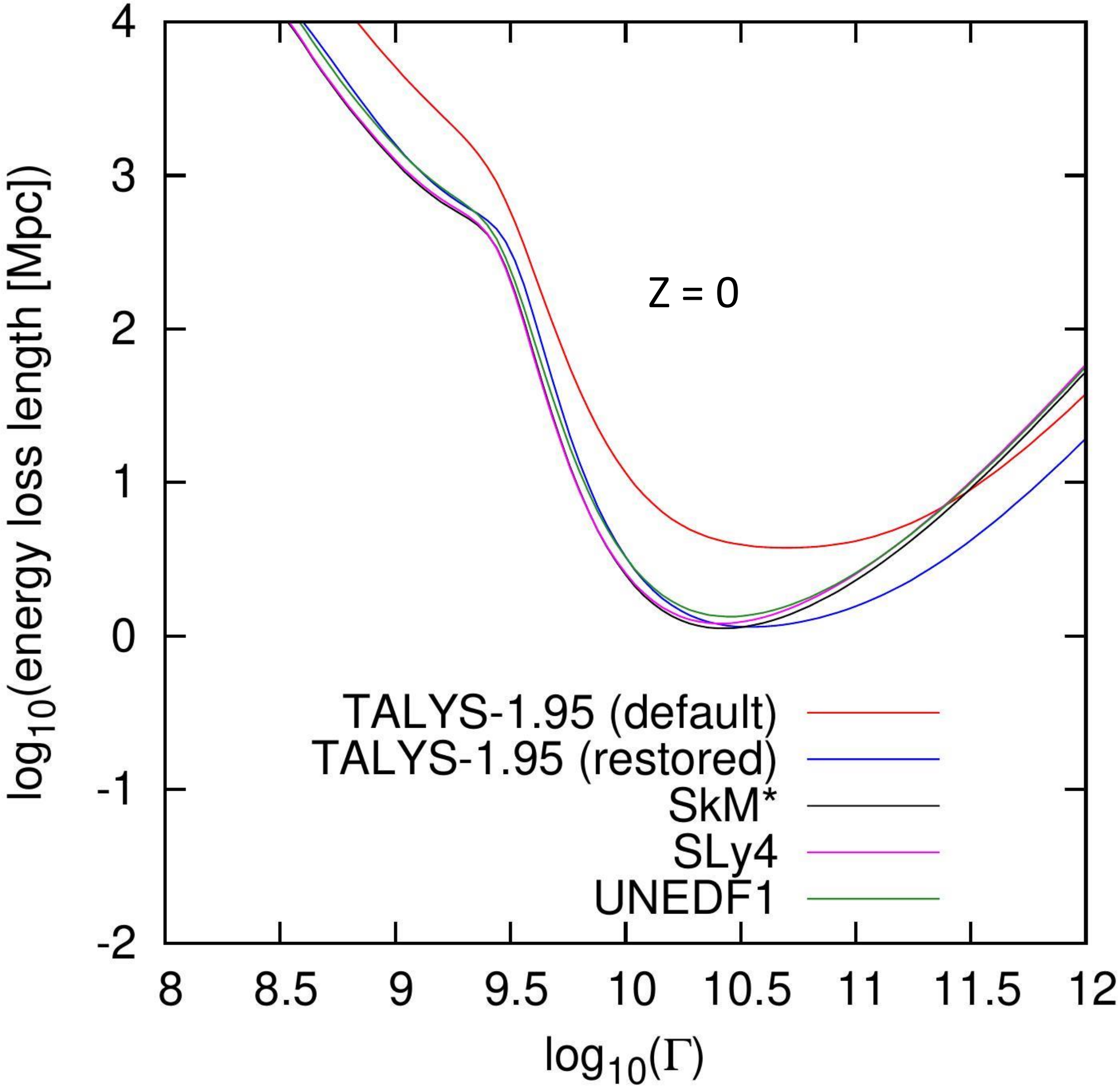
# Comparison of Peak Energies and Cross Sections




- Model dependence of DFT calculation is small for the nuclei with large mass numbers.
- Peak energies and cross sections are systematically different depending on the models.

# $^{28}$Si Energy Loss Length of Photodisintegration (CMB + IRB(Gilmore+, 2012))



# Simulations of Propagation of UHECRs

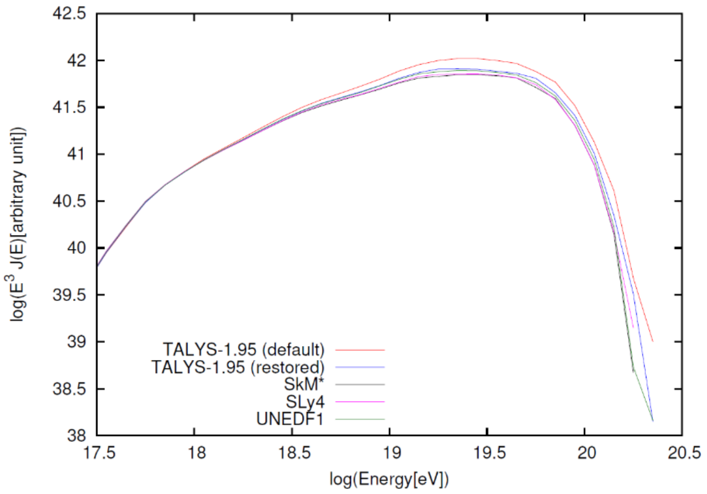
$$dN/dE \propto E_{\mathrm{inj}}^{-\gamma} \exp(-E_{\mathrm{inj}}/ZR_{\mathrm{cut}})$$

$$0 < z < 1$$

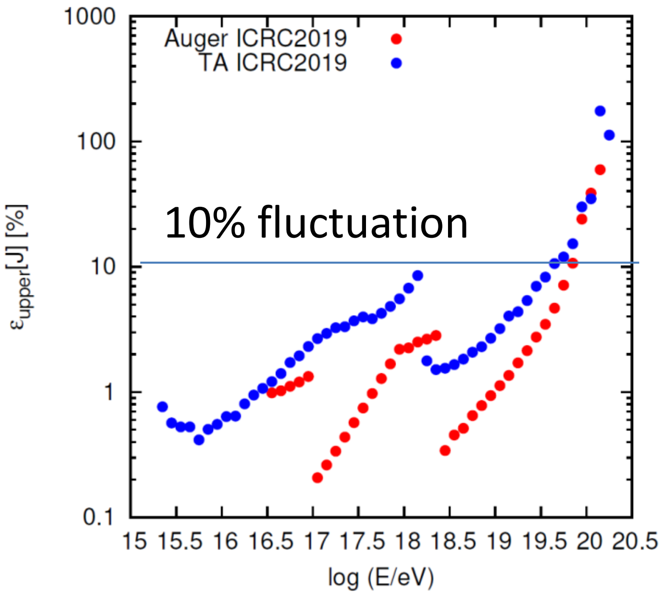
- $\gamma = 1$,   $R_{\mathrm{cut}} = 5\times10^{18}$ V
- Sources are uniformly distributed in comoving volume.
- CRPropa3
- IRB: Gilmore+ 2012
- 1 dimensional propagation
- We replaced the default mean free path tables (TALYS (restored)) with other models (TALYS (default), SkM*, SLy4, UNEDF1).
- We did not change the tables of the branching ratios.

# Energy Spectrum from 28Si source

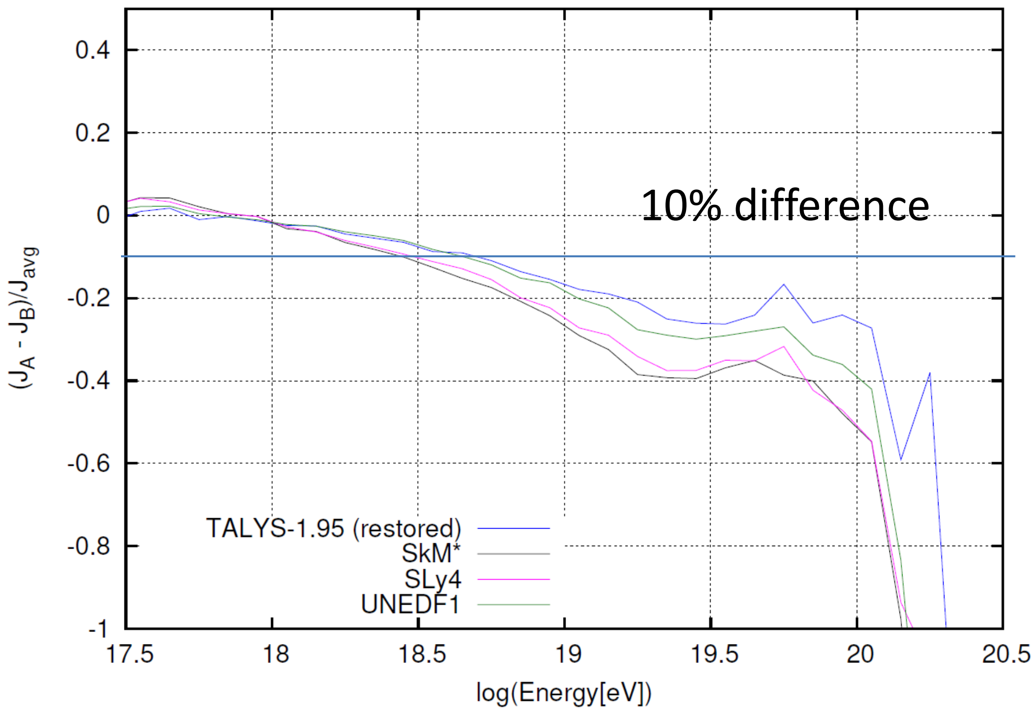
Normalization: total number of events




σ[J]/E[J] statistical fluctuation of the data

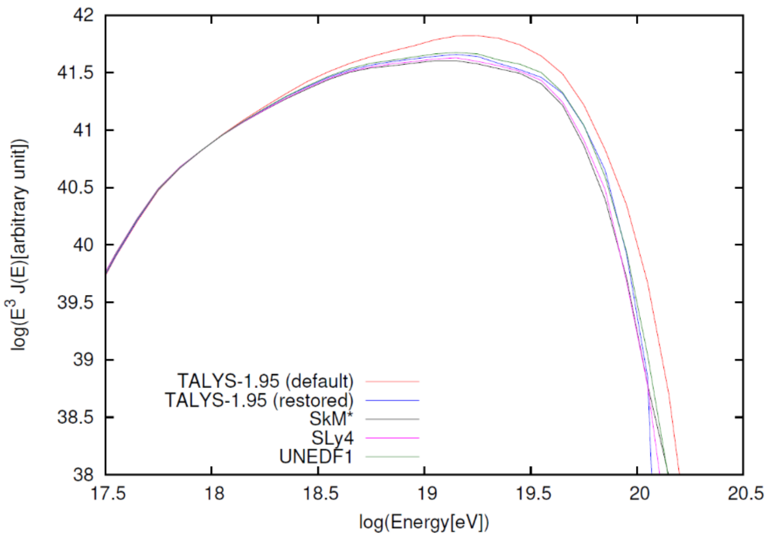



Comparison of the simulated spectrum with TALYS-1.95 (default) model

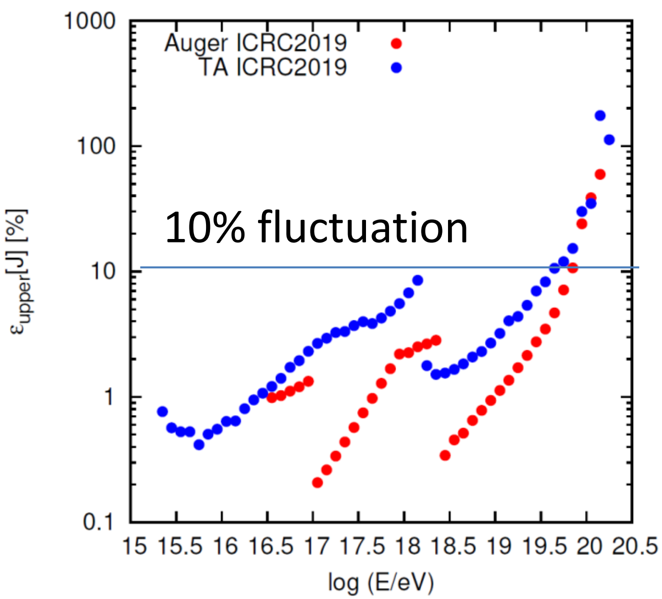


# Energy Spectrum from 16O source

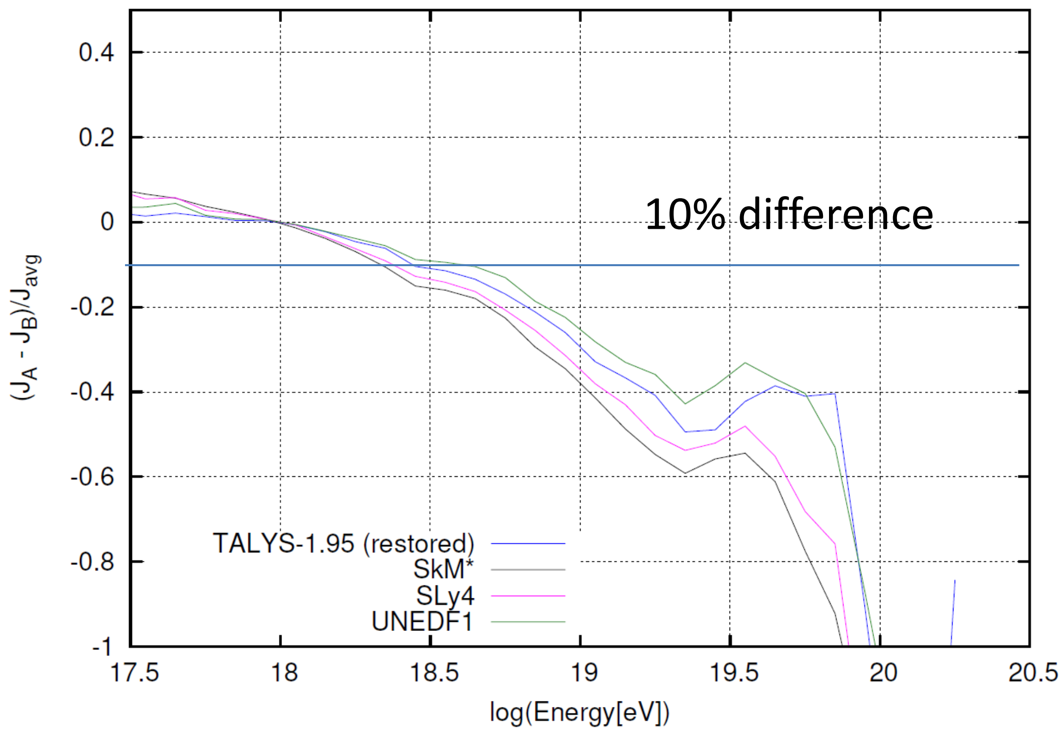
Normalization: total number of events




σ[J]/E[J] statistical fluctuation of the data




Comparison of the simulated spectrum with TALYS-1.95 (default) model



# Summary

- Uncertainty of Xmax is the dominant factor for the interpretation of the experimental data.
- Model dependence of the photo-nuclear interaction models were searched, and especially the uncertainty of the alpha particle production ratio was pointed out by Batista+ 2016.
- PANDORA project will start their measurements in the near future.
- Model dependence of nuclear theories are being studied for the implementation of the measurements in the simulation of propagation of UHECRs.
- Ongoing update from nuclear theorists
  - Cross sections using DFT calculation will by updated by T. Inakura.
  - Cross sections and alpha particle production ratio will be provided using AMD calculation by M. Kimura.

# Summary 2

- Intermediate-scale anisotropy
  - TA: **2.9σ** hotspot, oversampling radius: 25° E > **57** EeV
  - Auger: **4.5σ** correlation with starburst galaxies, oversampling radius: 15° E>**38** EeV
- Large-scale anisotropy
  - Auger: dipole was detected in **>5.2σ**, E>8 EeV in 2017
- Composition
  - TA SD and FD hybrid: consistent with light composition with log (E/eV) > **18.2** and log (E/eV) < **19.1**
  - Auger: composition becoming lighter up to 2 $10^{18}$ eV and heavier than this energy
- Energy Spectrum
  - TA: Declination dependence was claimed at **4.3σ** in the energy spectrum
  - Auger: New flattening feature was found in the spectral shape at the highest energies
- TAx4 detectors partially started to run.
  - More than half of TAx4 SDs were deployed, and 2 TAx4 FD stations were constructed.
  - Data acquisition was started. SD: from **Apr. 2019**, FD: from **Jun. 2018.** Cosmic ray events are being collected.
  - Prospects
    - **~4×TA SD** equivalent cosmic ray events with E > 57 EeV will be collected when the full operation is started.
    - **~3×TA SDFD** equivalent hybrid events will be collected especially for Xmax at the highest energies when the full operation is started.
- AugerPrime detectors also partially started to run. → more composition sensitivity from SDs

- UHECR source are still uncertain.
- More information of UHECR sources will be obtained with upgraded experiments!