# ULTRA-HIGH ENERGY COSMIC RAYS


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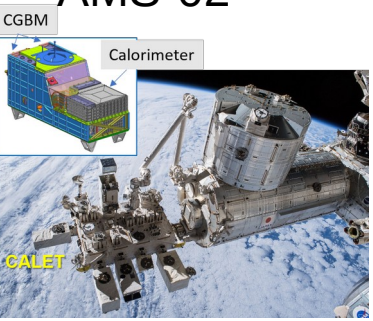
# SPECTRUM OF COSMIC PARTICLES

Direct detection from space

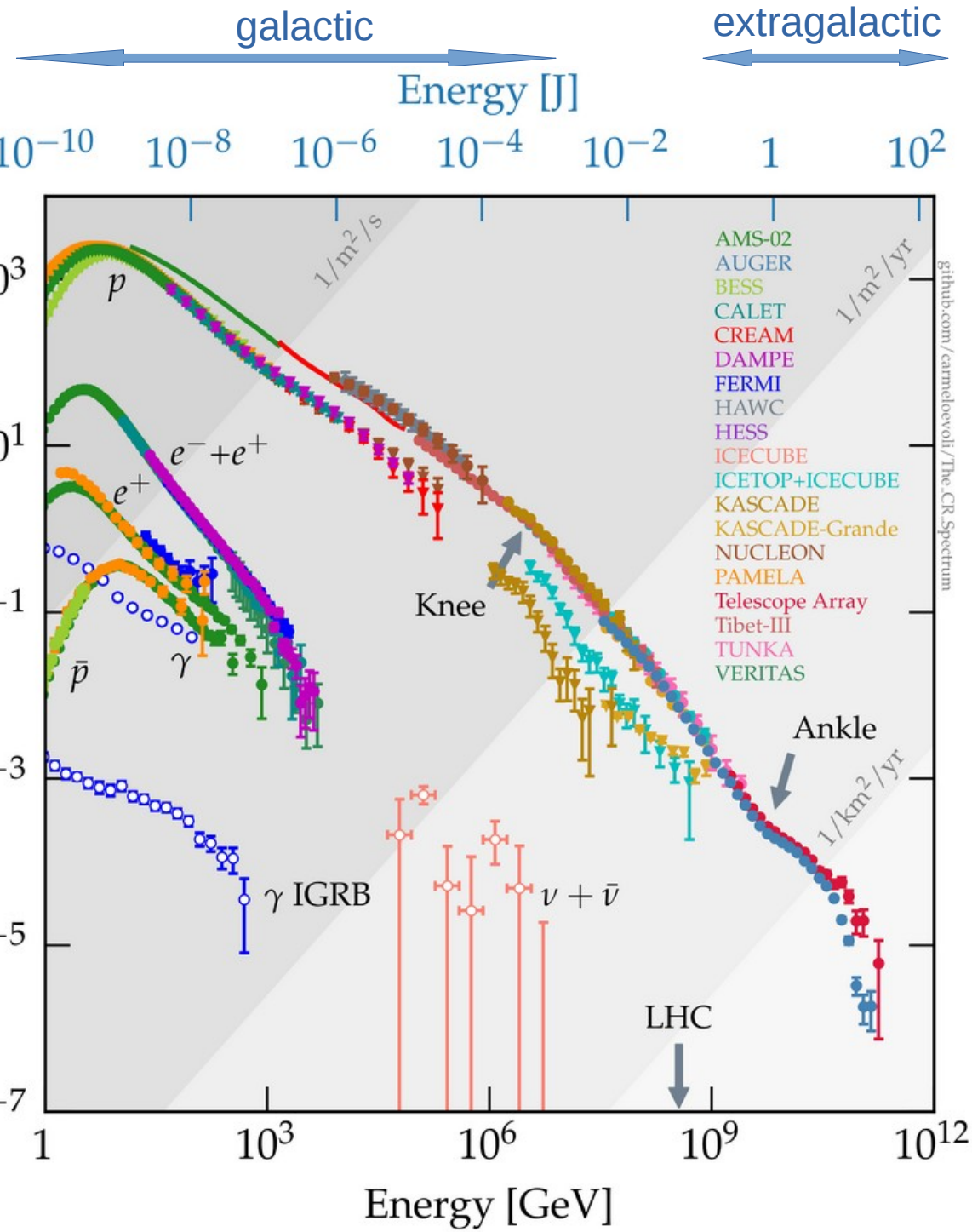
AMS-02

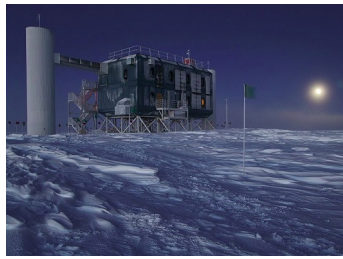



CALET

PAMELA

Fermi LAT



ICECUBE

HAWC

TA

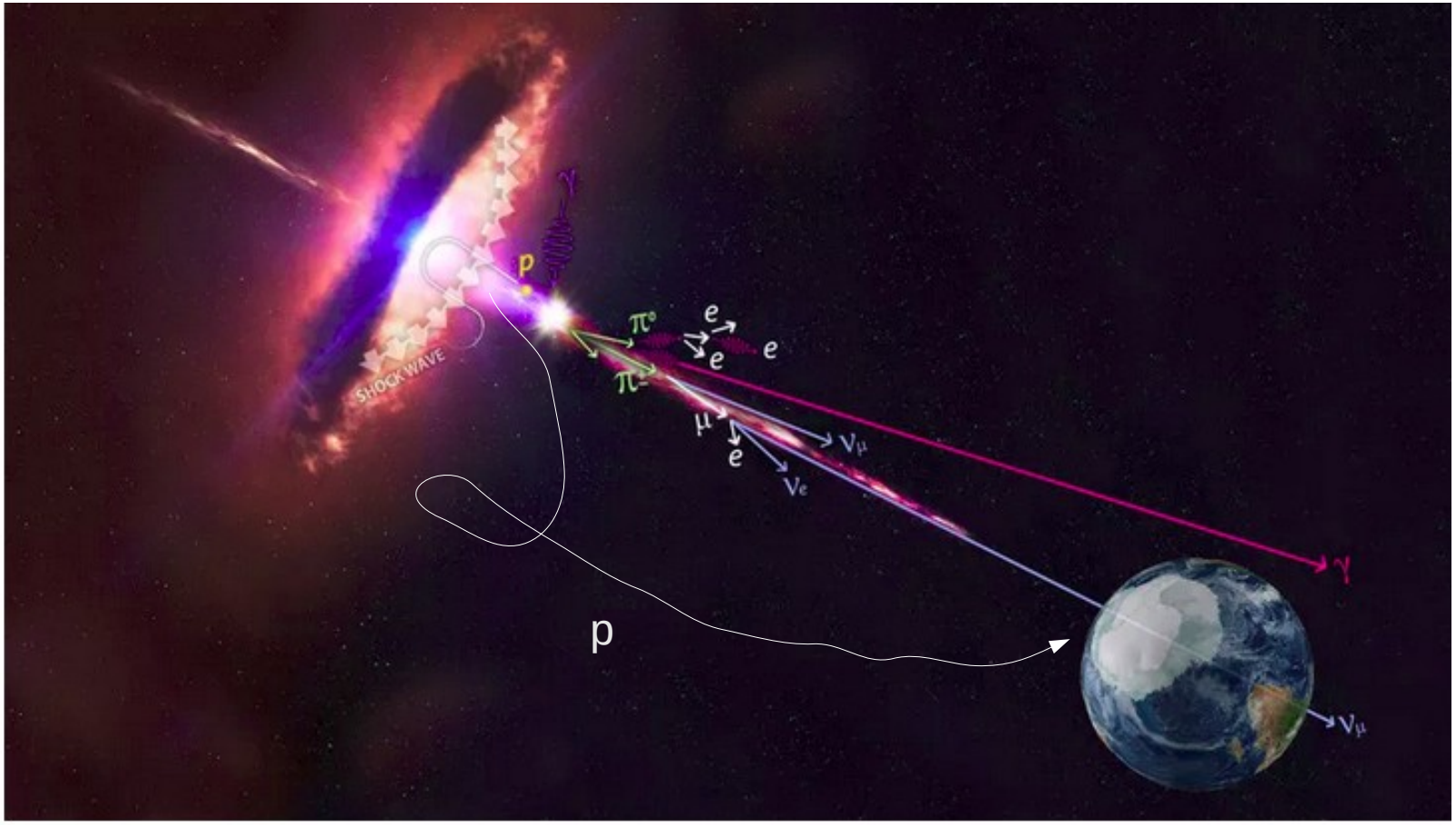
AUGER

Indirect detection from Earth: air-showers

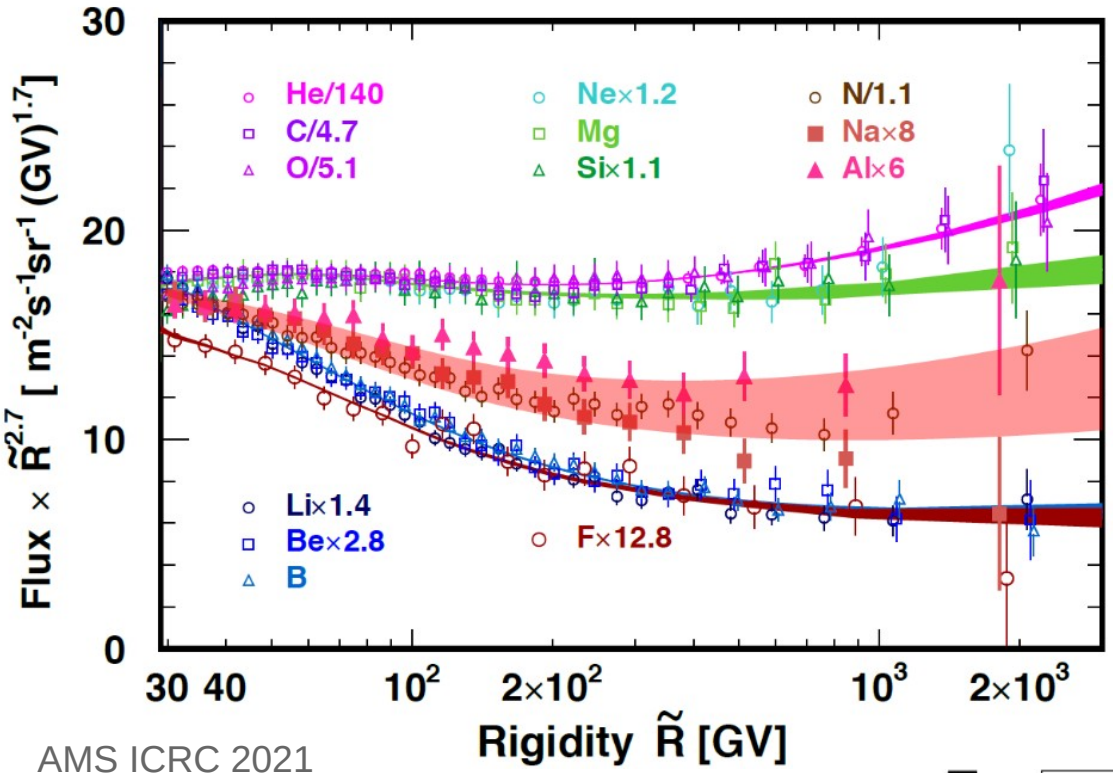
# Main questions:

Where and how are cosmic particles accelerated?
How is their propagation to the Earth?

e, p, nuclei: interact with gas & radiation and are deflected by magnetic fields
Photons: interact with gas & radiation, easy to be detected but attenuated
Neutrinos: weak interactions, difficult to detect but not attenuated




IceCube/NASA




AMS ICRC 2021

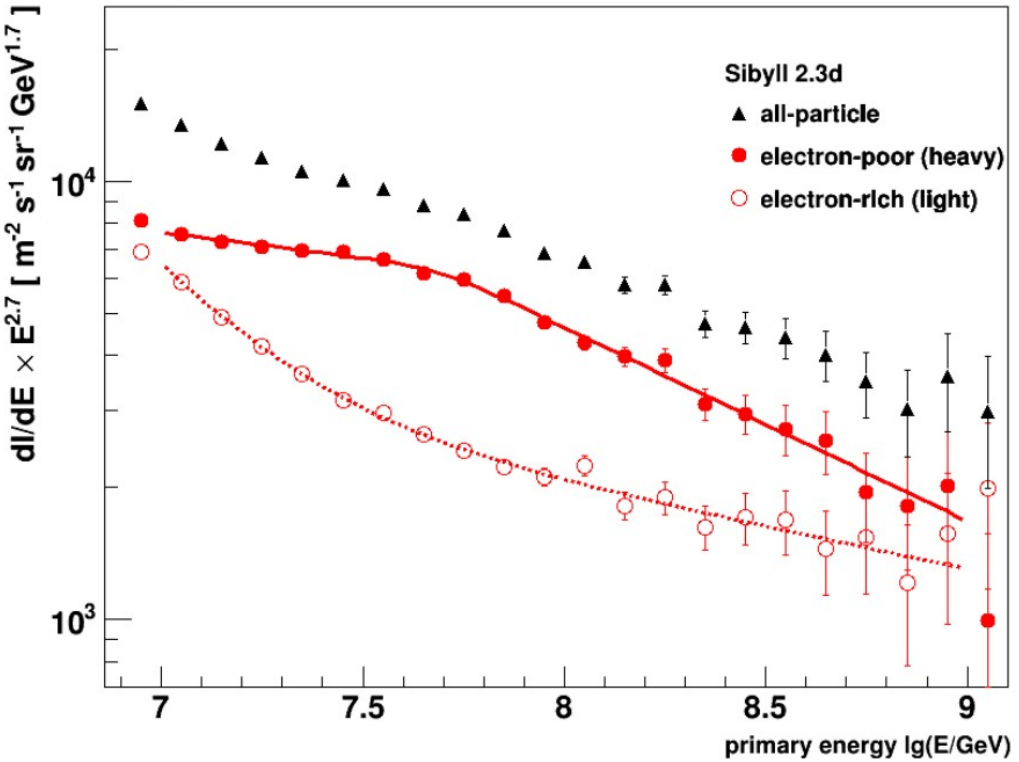
## GALACTIC COSMIC RAYS:

Very detailed measurements of spectrum of individual nuclei (and isotopes), $e^-$ and $e^+$
Explaining spectral features lead to lively interplay between experiments & theories: details of transport D(R), new astrophysical sources, DM signals?

several talks by the AMS collaboration
M Paniccia
V Formato

## END OF GALACTIC COSMIC RAYS?

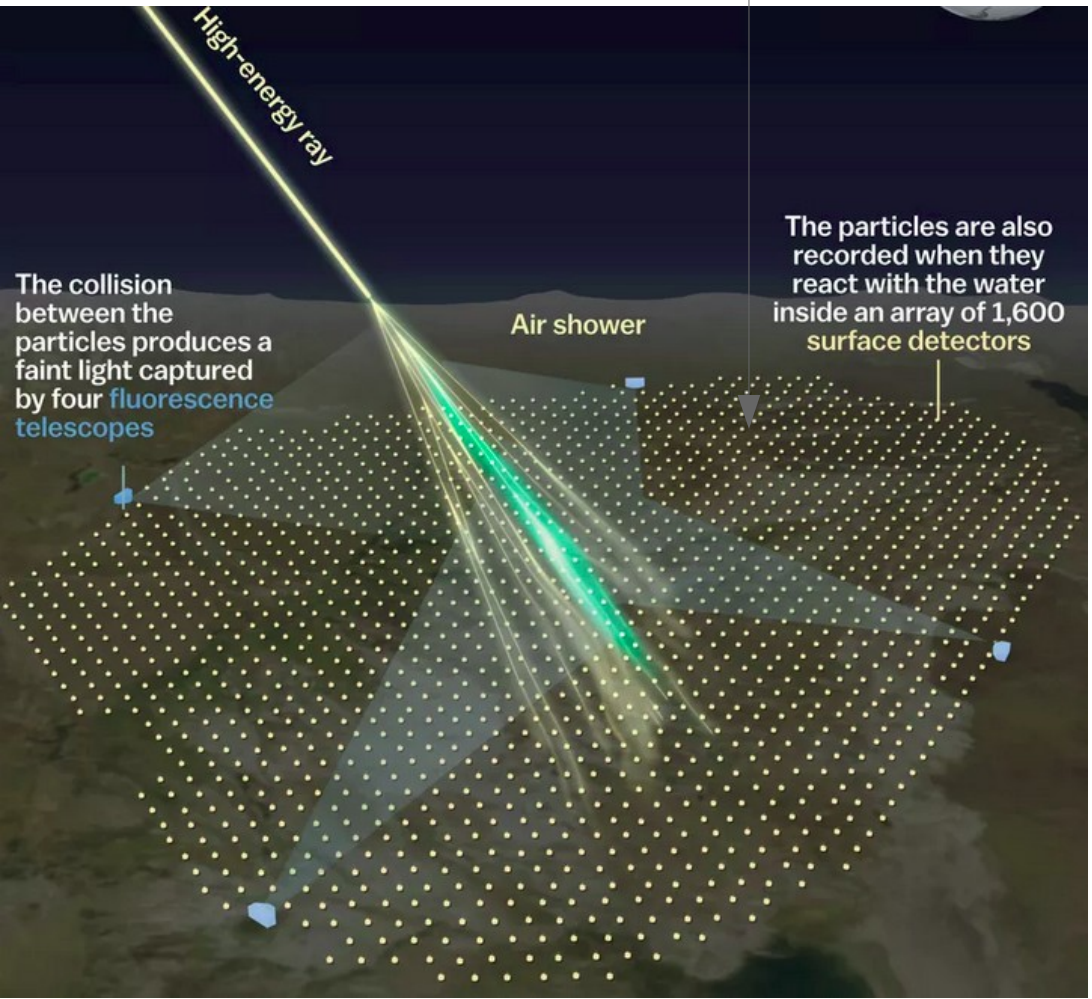
Knee @ 4 PeV: end of proton spectrum?
2nd knee @ 100 PeV: end of Fe?




KASCADE-Grande ICRC 2021

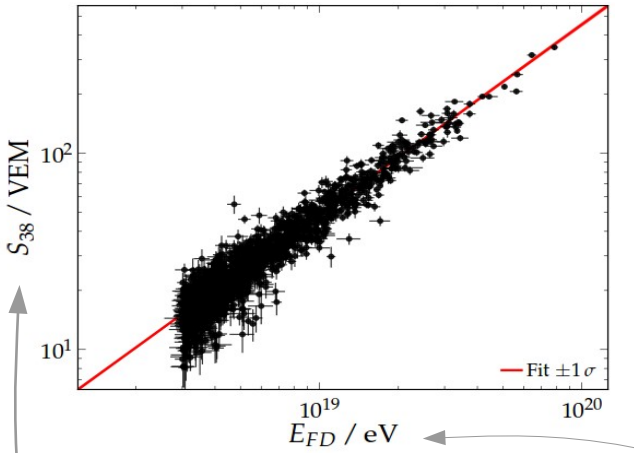
# EXTRAGALACTIC COSMIC RAYS: AIR SHOWERS DETECTION

**Pierre Auger Observatory**, Mendoza, Argentina
1660 water Cherenkov detectors, 1.5 km grid, 3000 km$^2$
27 fluorescence telescopes (15% duty cycle)
24 underground muon detectors
153 radio antenas




**Telescope Array (TA)**
Delta, UT, USA
507 scintillator detectors,
1.2 km grid, 700 km$^2$
36 fluorescence telescopes

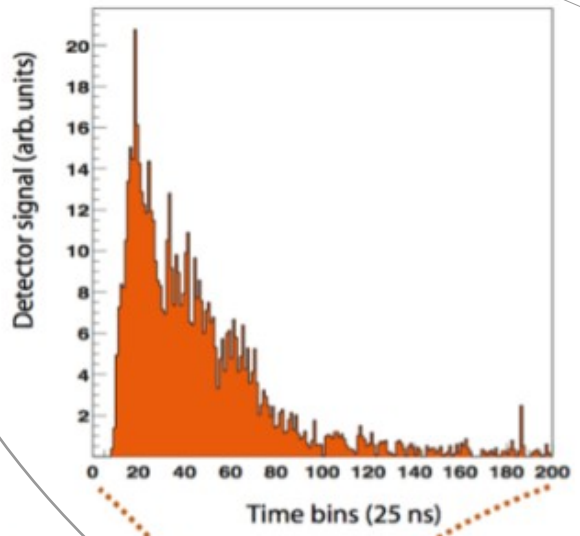
# AUGER HYBRID OBSERVATORY: ENERGY RECONSTRUCTION



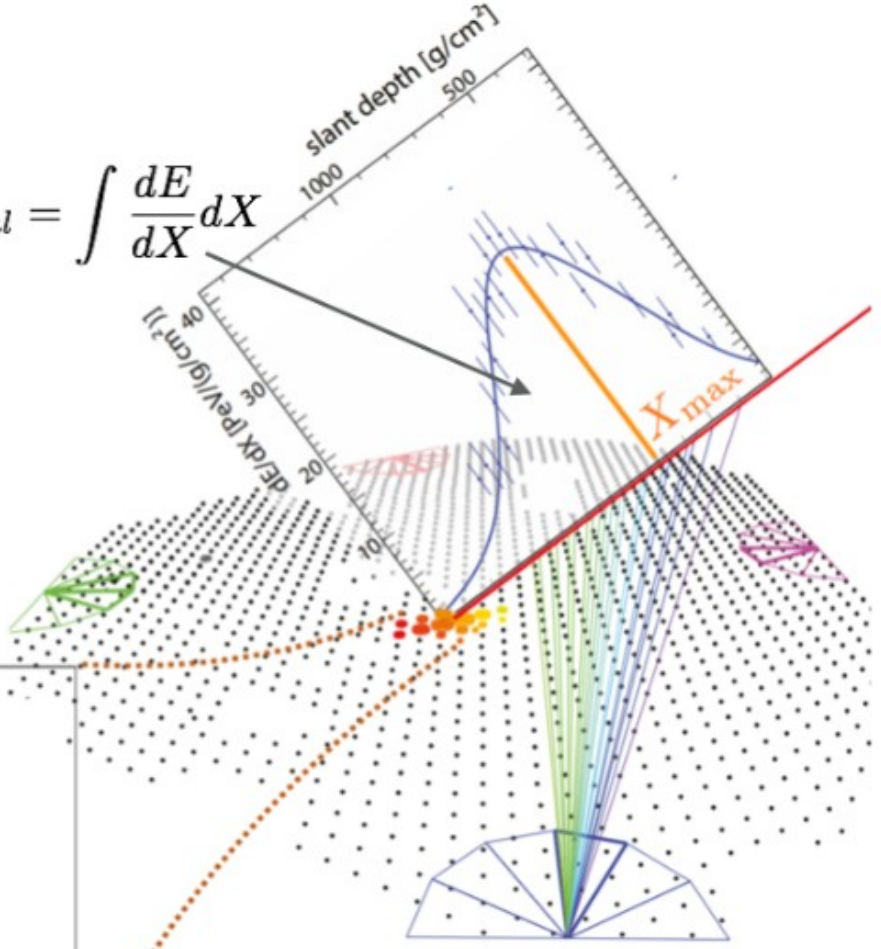

$E_{FD} = E_{cal} + E_{inv}$

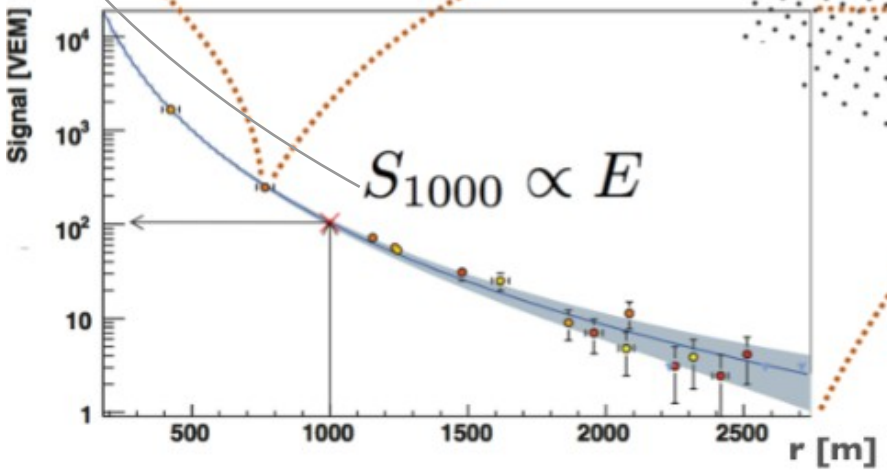
$\sigma(E_{FD})/E_{FD} \sim 7\%$

Systematic uncertainty 14%

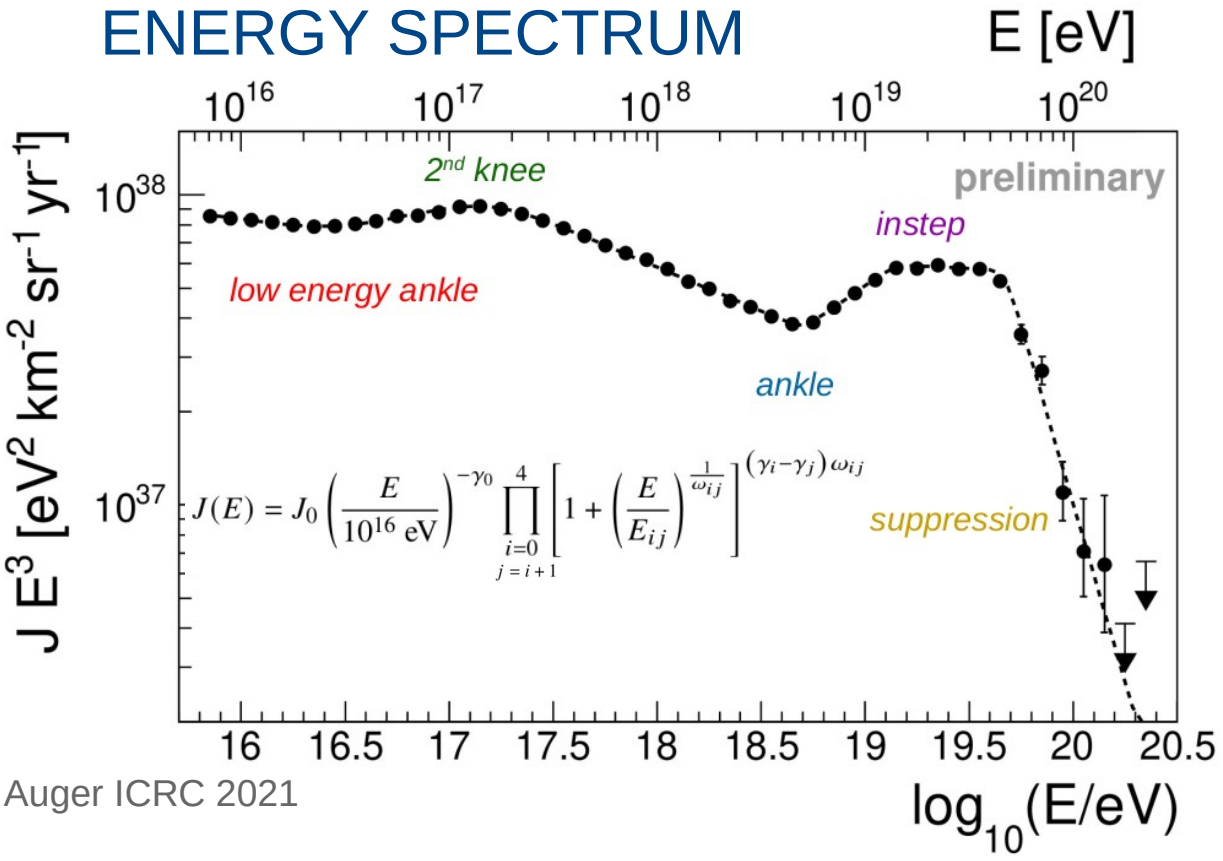



$$E_{cal} = \int \frac{dE}{dX} dX$$



# ENERGY SPECTRUM




Auger ICRC 2021

## Auger

**fit parameters (± stat. ± syst.)**

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

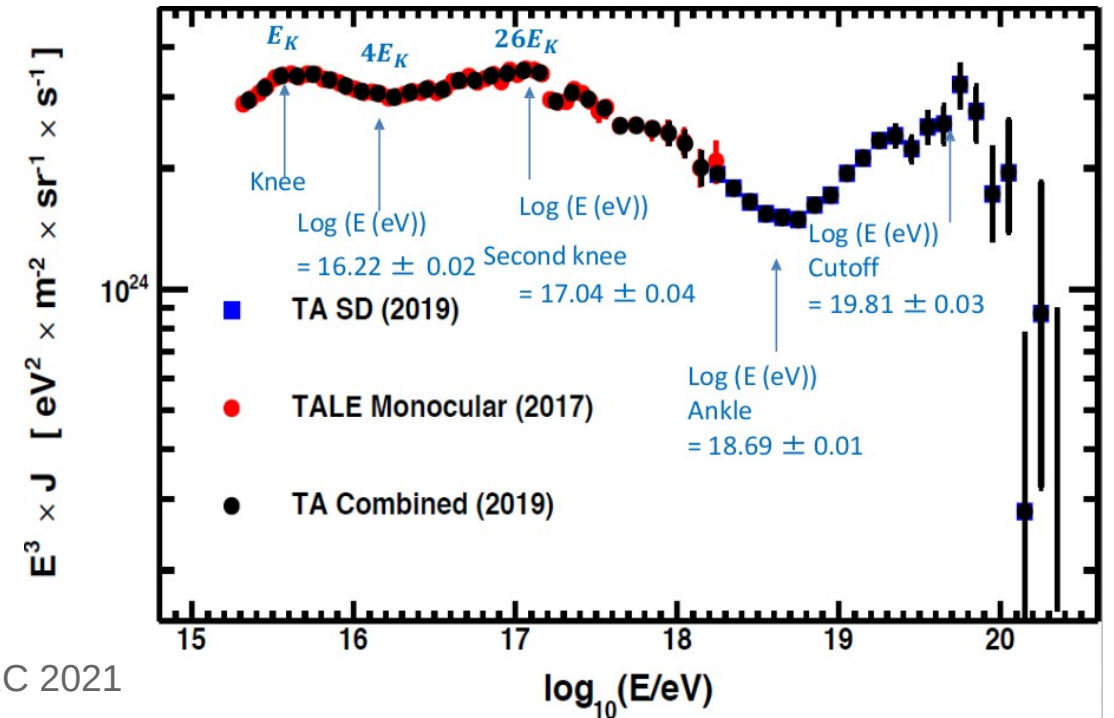
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km$^{-2}$ sr$^{-1}$ yr$^{-1}$ eV$^{-1}$

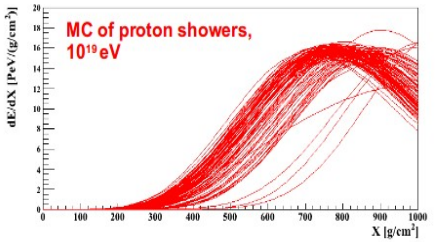
## Telescope Array

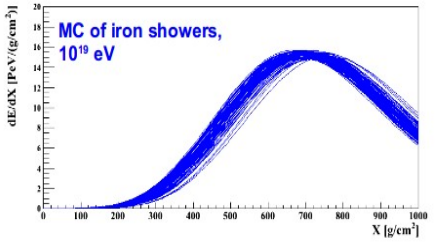


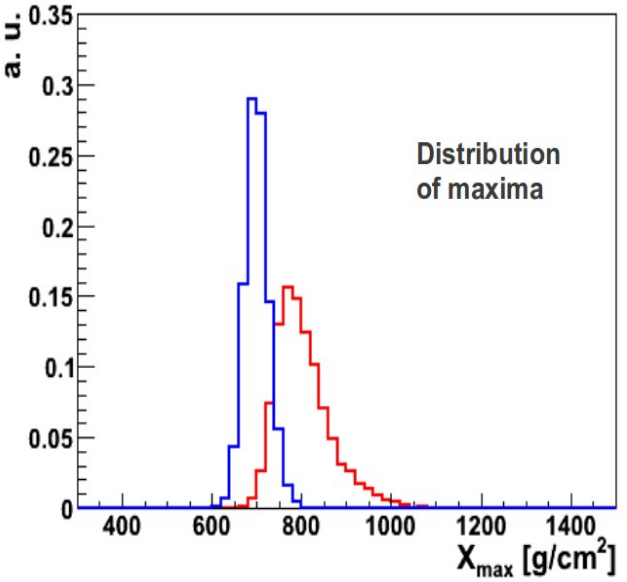

TA ICRC 2021

# MASS COMPOSITION

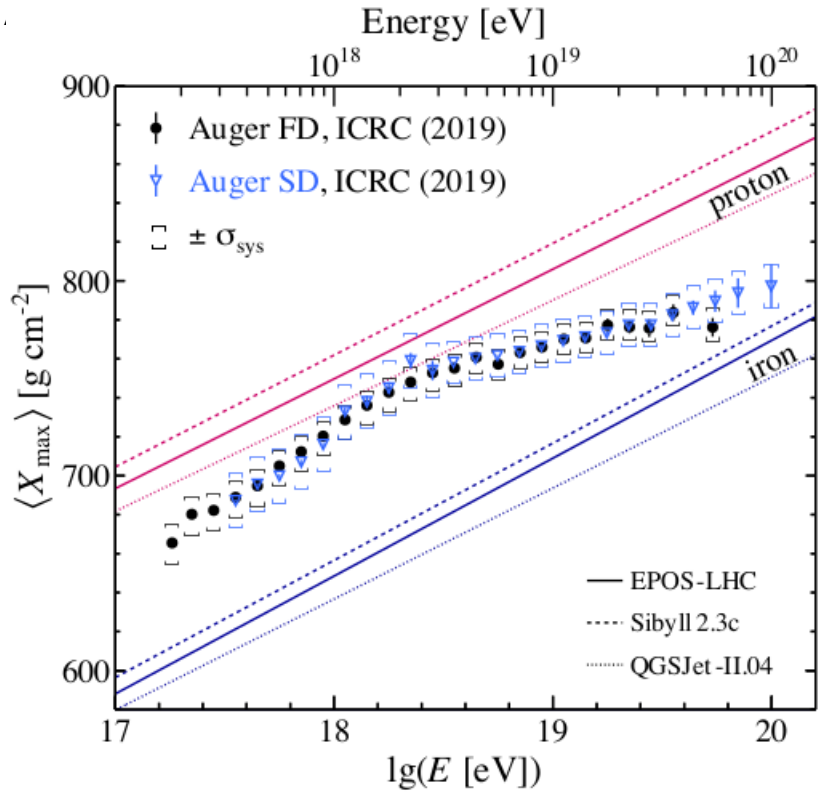
Indirect indicator of composition:
air column density traversed up to the shower maximum
Heavy nuclei showers develop higher in the atmosphere and have smaller fluctuations (superposition of nucleons)

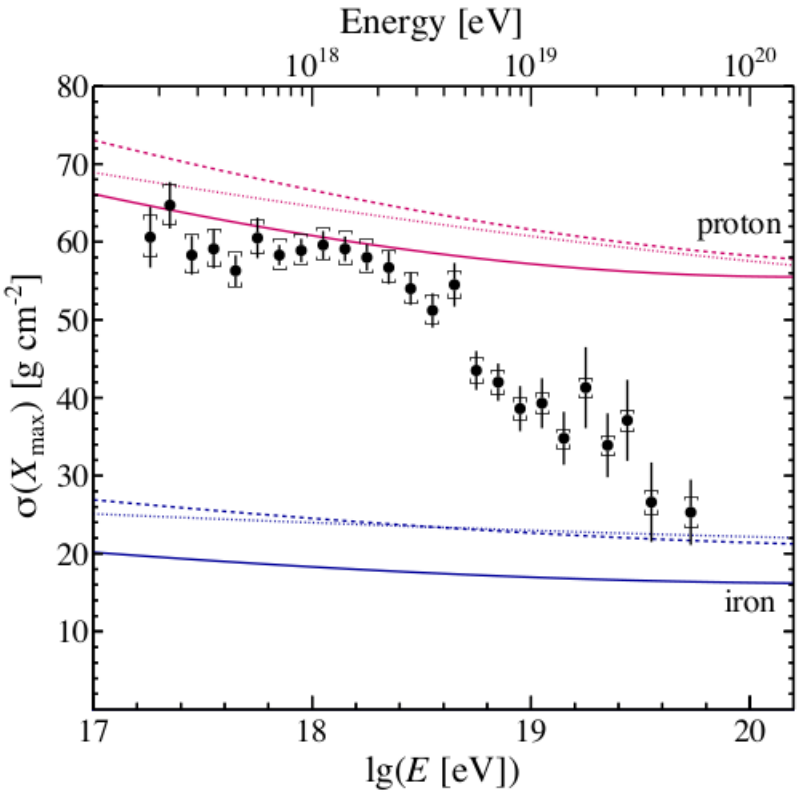



Auger ICRC 2019



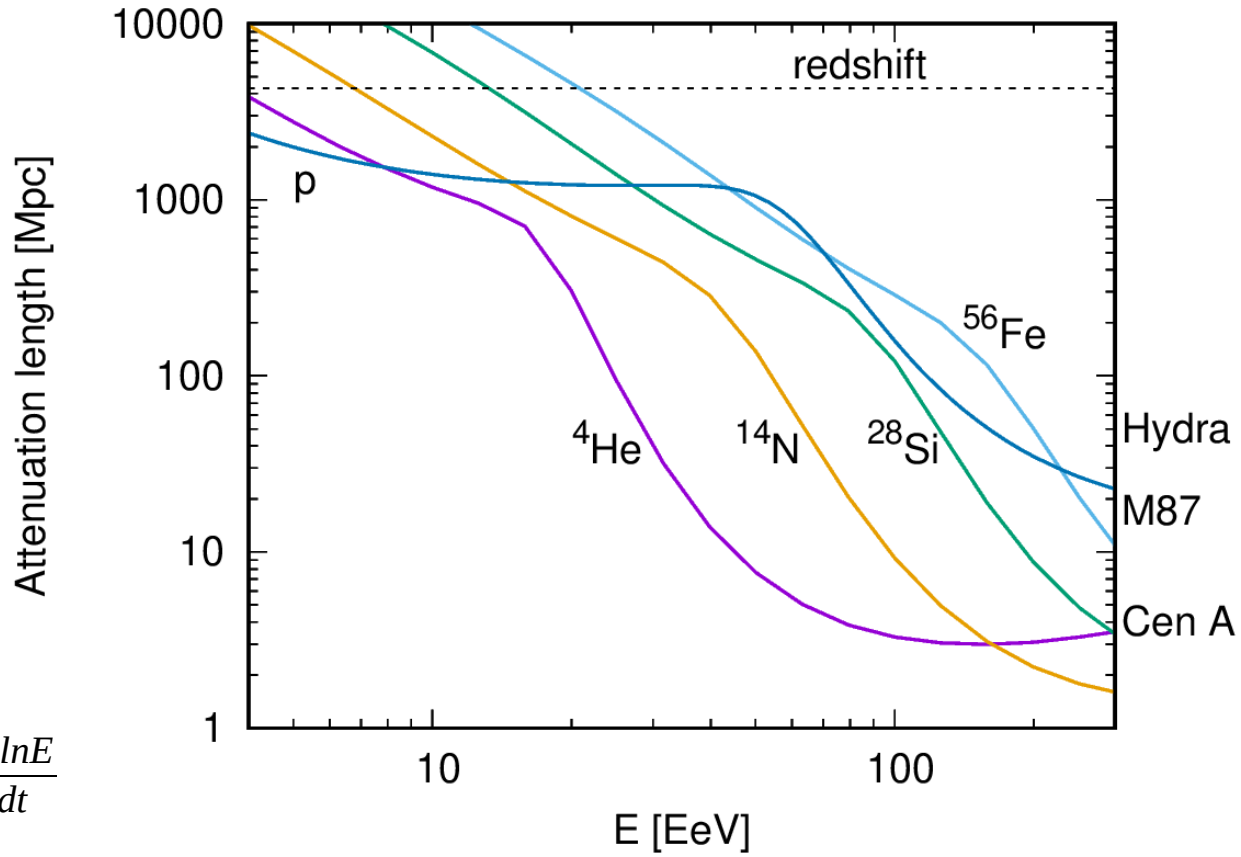

Composition becoming lighter up to 2 EeV and heavier above

# PROPAGATION FROM SOURCES TO EARTH

CRs are subject to interactions with radiation backgrounds (CMB and IR/visible/UV extragalactic background light) → energy losses, composition changes

- $e^-e^+$ pair production: $A+\gamma \rightarrow A+e^-+e^+$
- disintegration of nuclei: $A+\gamma \rightarrow (A-i) + i\ N$
- photopion production: $p+\gamma \rightarrow p+\pi^0$, $n+\pi^+$ or $n+\gamma \rightarrow n+\pi^0$, $p+\pi^-$

Greisen, Zatsepin & Kuz'min (1966)



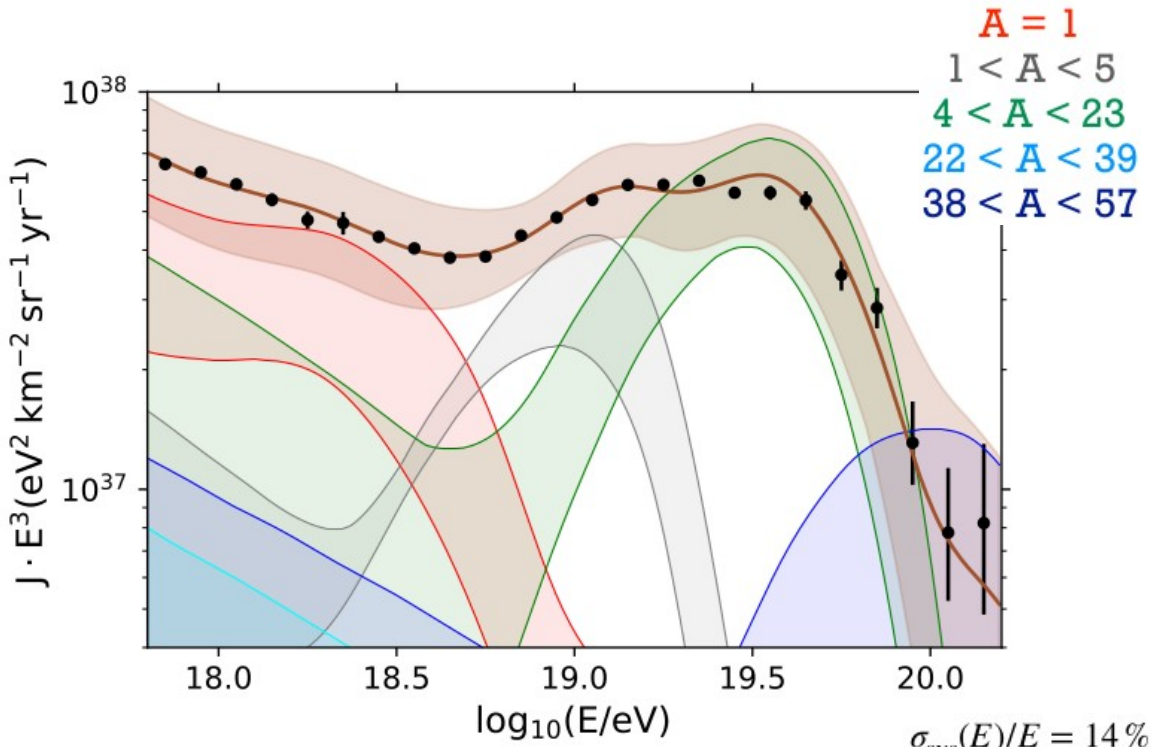

$$\lambda^{-1} = -\frac{1}{c}\frac{d\,lnE}{dt}$$

These processes also lead to the production of secondary particles: nucleons, $e^-e^+$ pairs, neutrinos, gamma rays

# INTERPRETATION OF SPECTRUM AND COMPOSITION DATA

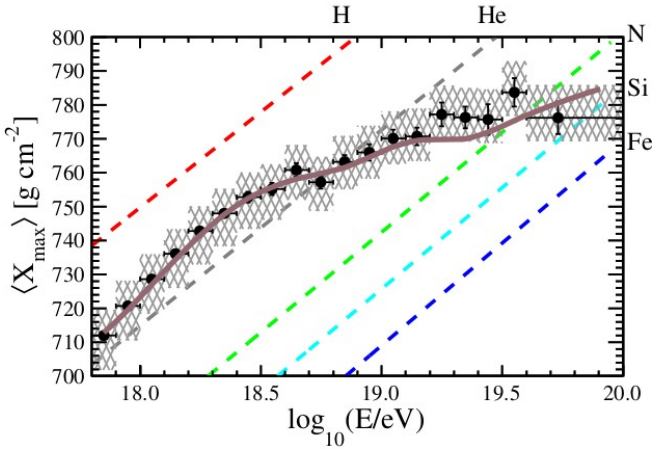
Simple model of sources continuously distributed and accelerating particles with rigidity dependent spectrum (power law with exponential cutoff)

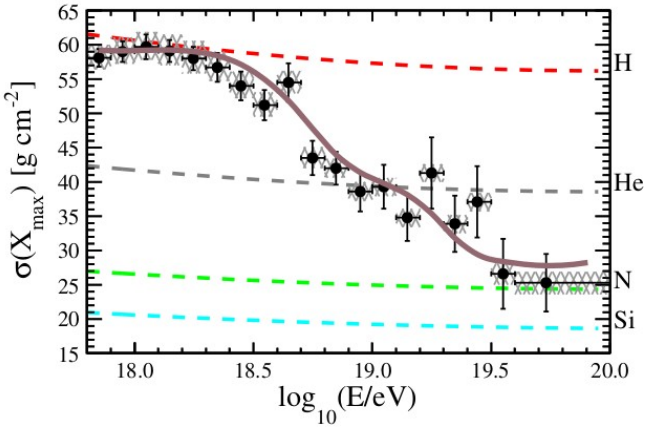
$$J(E) = \sum_A f_A \cdot J_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma} \cdot \begin{cases} 1, & E < Z_A \cdot R_{\rm cut} \\ \exp\left(1 - \frac{E}{Z_A \cdot R_{\rm cut}}\right), & E > Z_A \cdot R_{\rm cut} \end{cases}$$




$\sigma_{sys}(E)/E = 14\,\%$

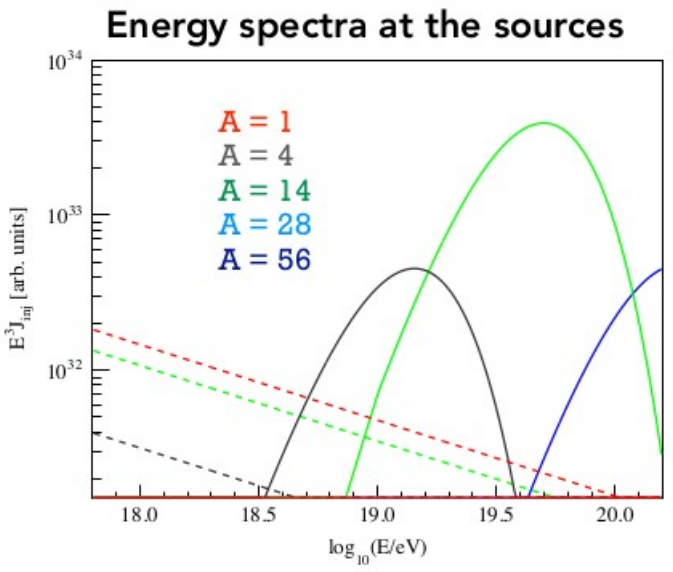
$\sigma_{sys}(X_{max}) = 6 \div 9\ g\ cm^{-2}$



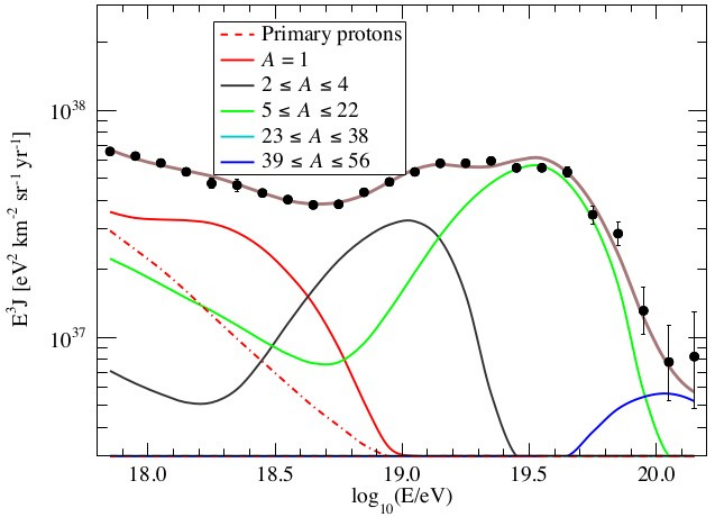



# INTERPRETATION OF SPECTRUM AND COMPOSITION DATA

| EG components (at the sources) | Low energy | High energy |
|---|---|---|
| $\mathcal{L}_0$ [erg Mpc$^{-3}$ yr$^{-1}$] | $1.7 \cdot 10^{46}$ | $4.5 \cdot 10^{44}$ |
| $\gamma$ | $3.49 \pm 0.02$ | $-1.98 \pm 0.10$ |
| $\log_{10}(R_{\rm cut}/{\rm V})$ | 24 (lim.) | $18.16 \pm 0.01$ |
| $I_{\rm H}$ (%) | 49.87 | 0.0 |
| $I_{\rm He}$ (%) | 10.92 | 28.60 |
| $I_{\rm N}$ (%) | 36.25 | 69.05 |
| $I_{\rm Si}$ (%) | 0.0 | 0.0 |
| $I_{\rm Fe}$ (%) | 2.96 | 2.35 |
| $D_J$ ($N_J$) | 60.1 (24) | |
| $D_{X_{\rm max}}$ ($N_{X_{\rm max}}$) | 554.8 (329) | |
| $D$ ($N$) | 614.9 (353) | |




**Energy spectrum at the Earth**



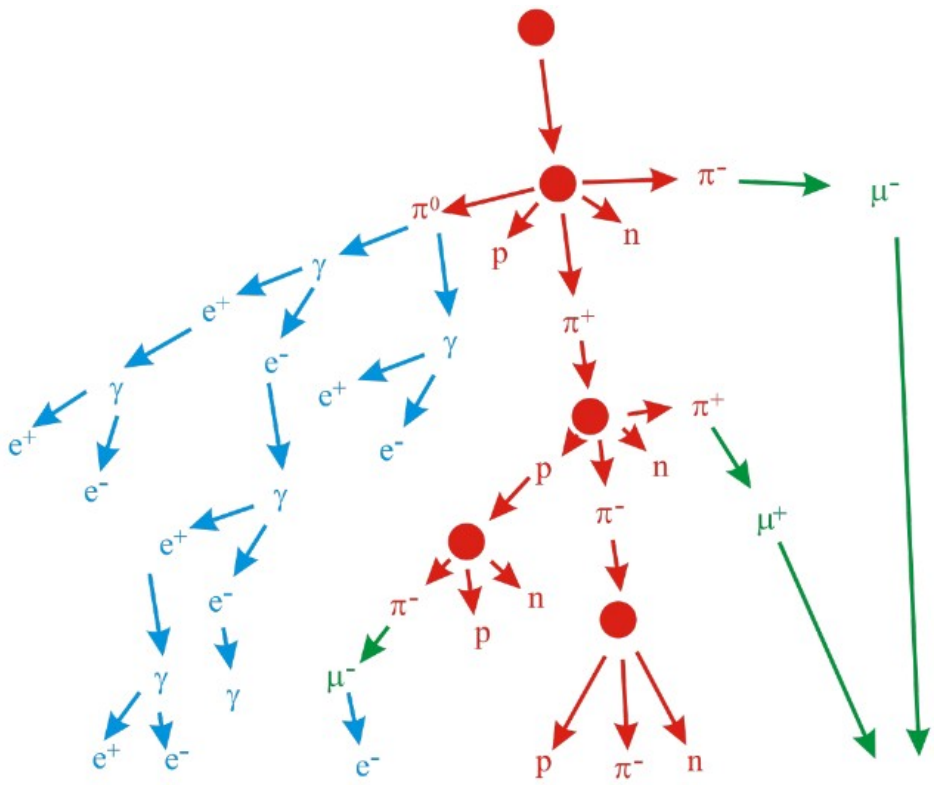

Two source populations needed to explain measurements above and below the ankle

- High energy: mixed composition with hard rigidity-dependent spectrum and low rigidity cutoff

- Low energy: lighter composition and soft spectrum extragalactic to agree with small observed anisotropies

Final steepening of the spectrum is a combination of propagation and maximum rigidity at the source

# HADRONIC INTERACTIONS IN AIR SHOWERS




Shower components

Electromagnetic (EM) from decay of neutral pions
+ from muon decay

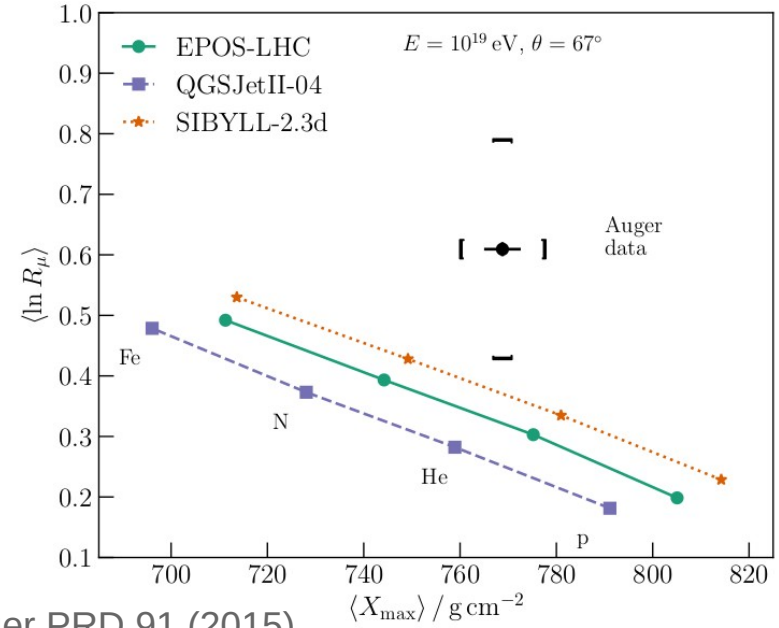
Muonic from decay of charged pions
+ from photo-production

Higher mass primaries produce more muons

A good theoretical model for the development of air showers should be able to describe consistently both the electromagnetic and the muonic components of the showers

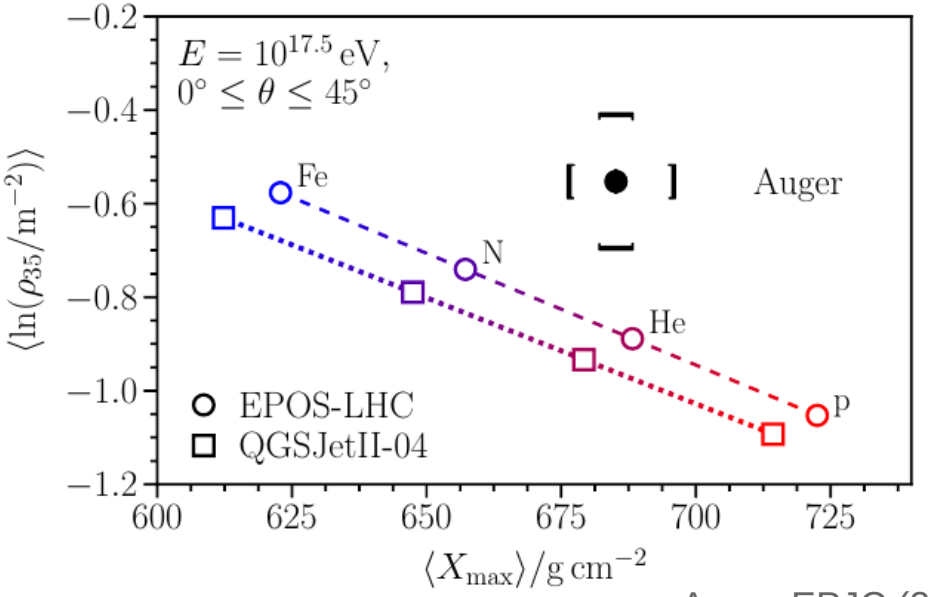
# MUON CONTENT MEASUREMENTS AT AUGER

Hybrid events and inclined showers

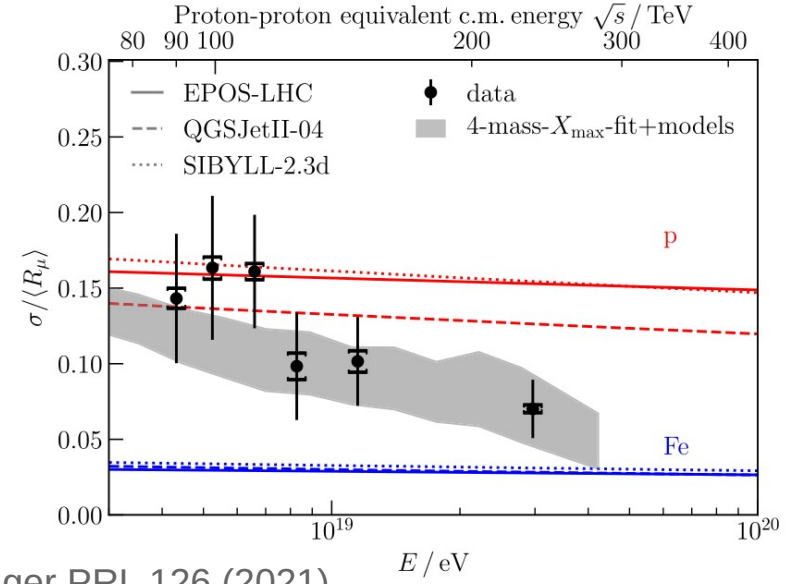



Auger PRD 91 (2015)

Underground muon detector and vertical showers




Auger EPJC (2020)




Auger PRL 126 (2021)

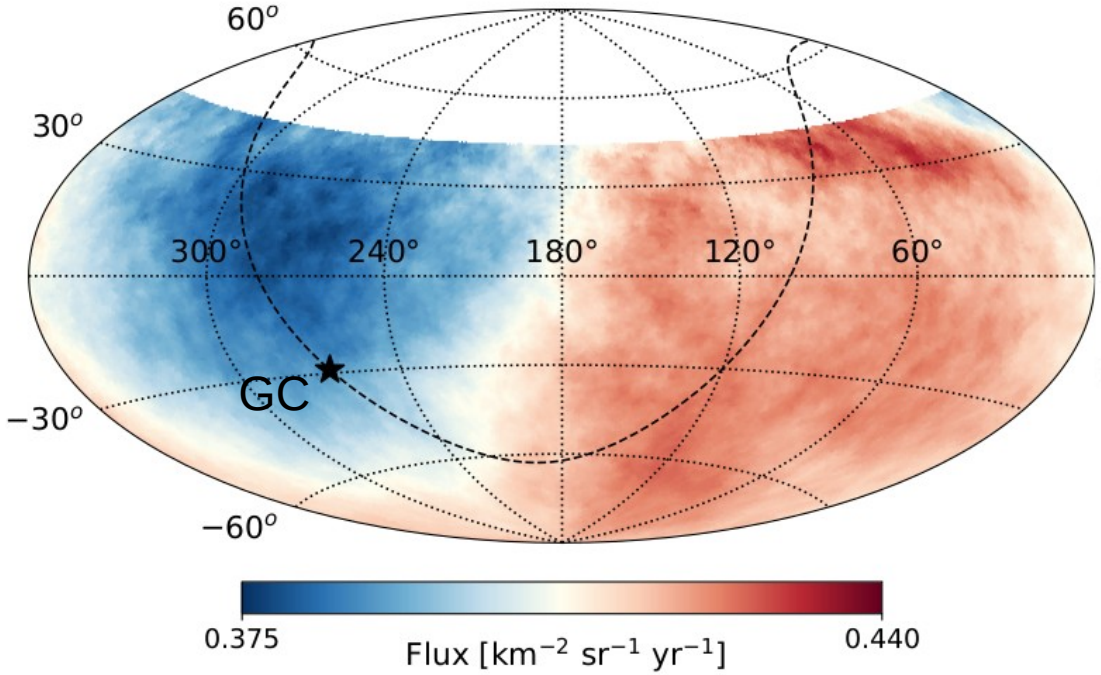
- MC simulations of EAS predict a muon density at ground smaller than observed considering the mass composition inferred from $X_{max}$ measurements

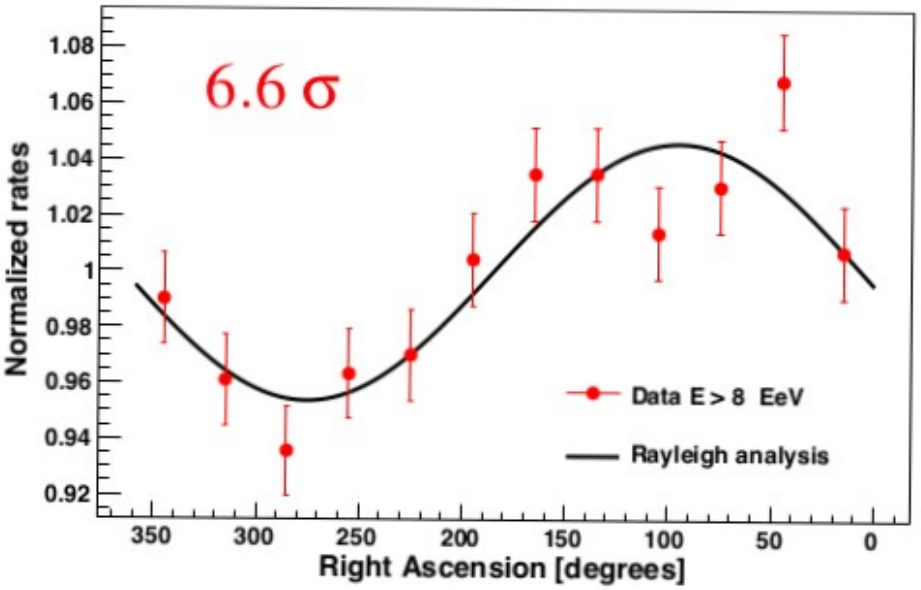
- Relative fluctuations in agreement

→ compatible with muon deficit originating from small deviations in predictions from hadronic interaction models that accumulate as the showers develop

# LARGE SCALE ANISOTROPIES

E> 8 EeV

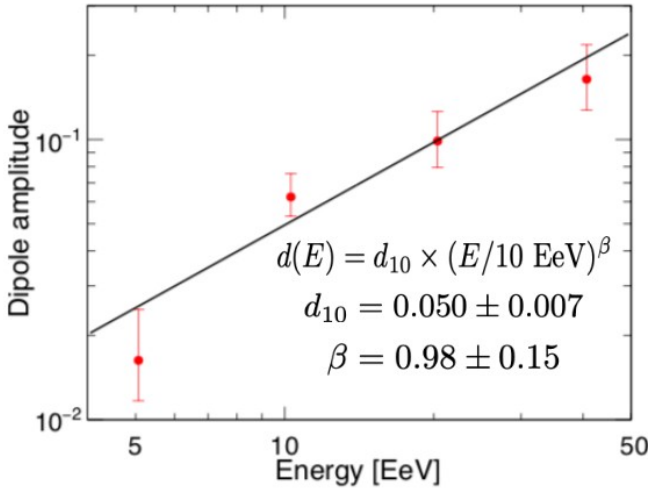


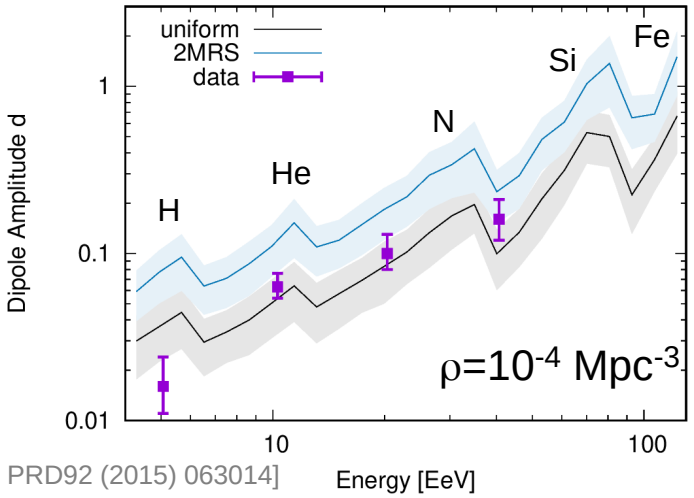




Dipole amplitude $d=0.073^{+0.011}_{-0.009}$ pointing to $(\alpha,\delta)=(95^{o},-36^{o})$

→ at 115$^{o}$ from the GC → evidence of extragalactic origin

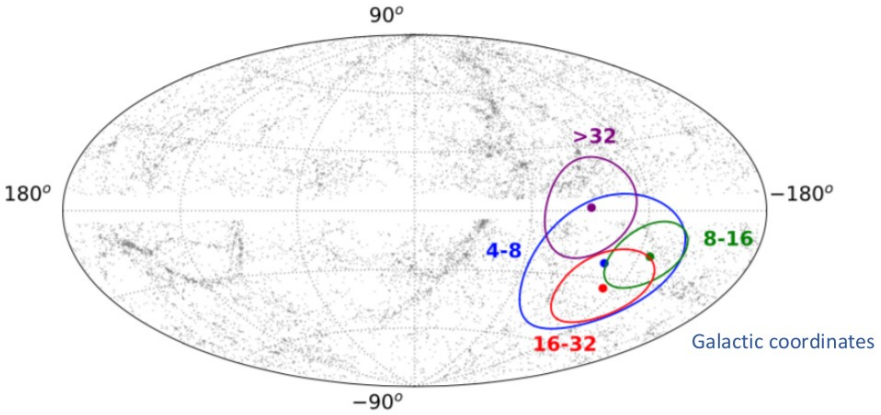
## Amplitude increases with energy



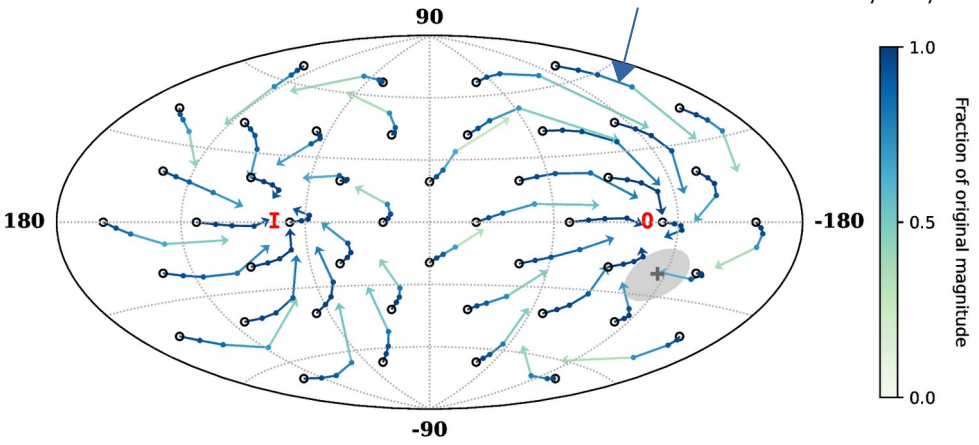




PRD92 (2015) 063014]

## Directions close to the outer spiral arm




JF12 B field for E/Z = 32, 16, 8 and 4 EeV




Extragalactic dipole direction gets shifted toward spiral arms by Galactic B field

## ORIGIN OF THE DIPOLE

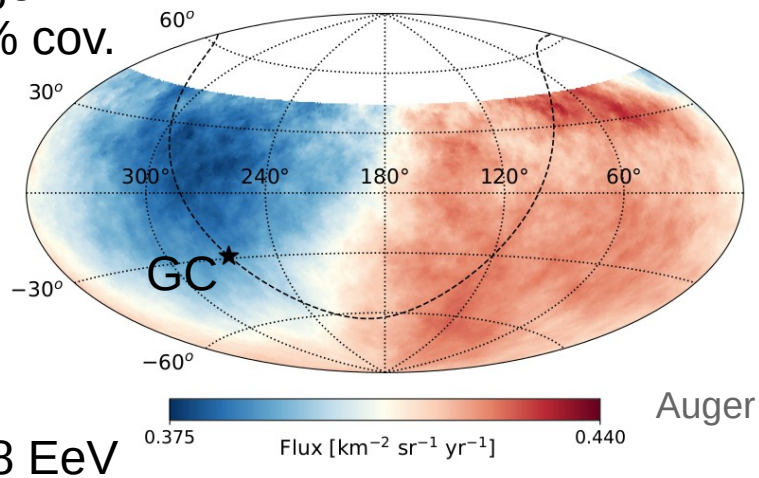
- Too large amplitude to be Compton-Getting

- CR dipole may arise from inhomogeneous distribution of nearby galaxies

- If XGMF large enough CR may propagate diffusively even from closest source(s)

# LARGE SCALE ANISOTROPIES: FULL SKY

Auger
85% cov.

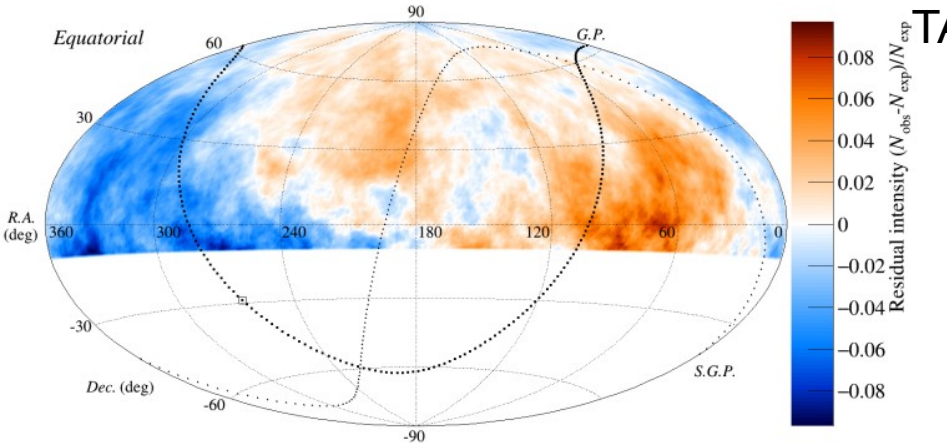



Auger ICRC 2021

E> 8 EeV

$d_\perp = 0.059 \pm 0.009$ $\alpha = 95° \pm 8°$

TA




TA ICRC 2021

$r = 0.031 \pm 0.018$ $\alpha = 134^o \pm 34^o$

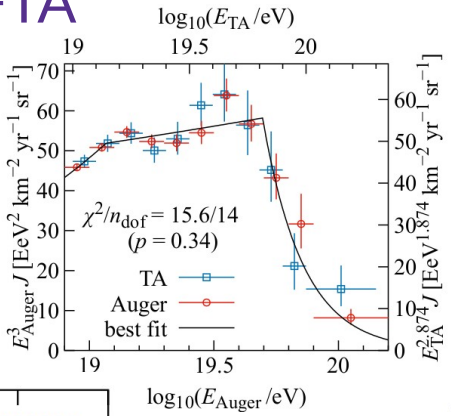
compatible with Auger dipole and with isotropy

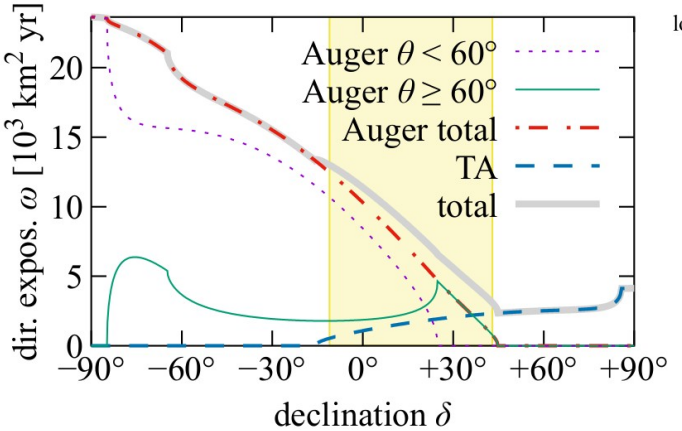
$d_\perp = r/\langle\cos\delta\rangle \sim 1.3\ r \sim 0.04 \pm 0.02$

## Combined Auger +TA

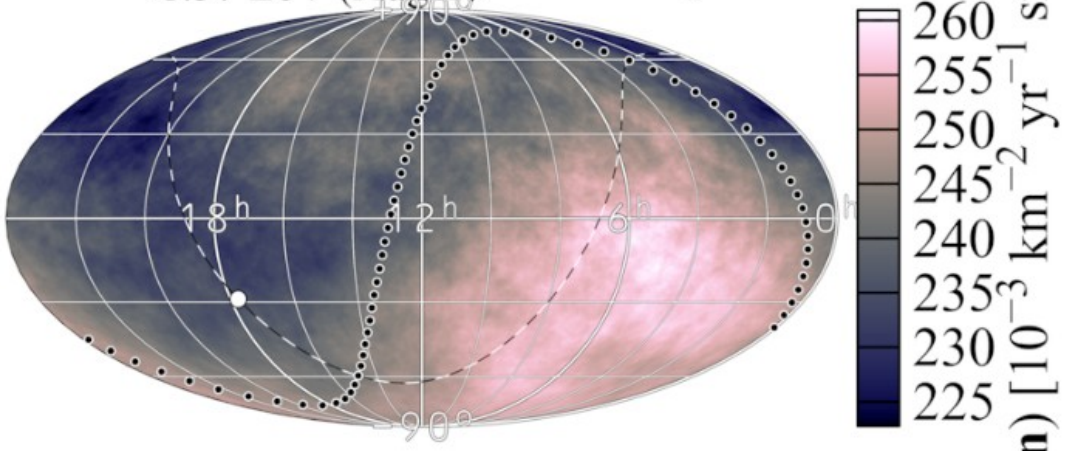
$$\frac{E_{\rm Auger}}{10\ {\rm EeV}} = 0.857 \left(\frac{E_{\rm TA}}{10\ {\rm EeV}}\right)^{0.937}$$

energy calibrated to match spectra in common band




$E \geq \begin{cases} 10\ {\rm EeV\ (TA)} \\ 8.57\ {\rm EeV\ (Auger)} \end{cases}$, 45°-r. top-hat

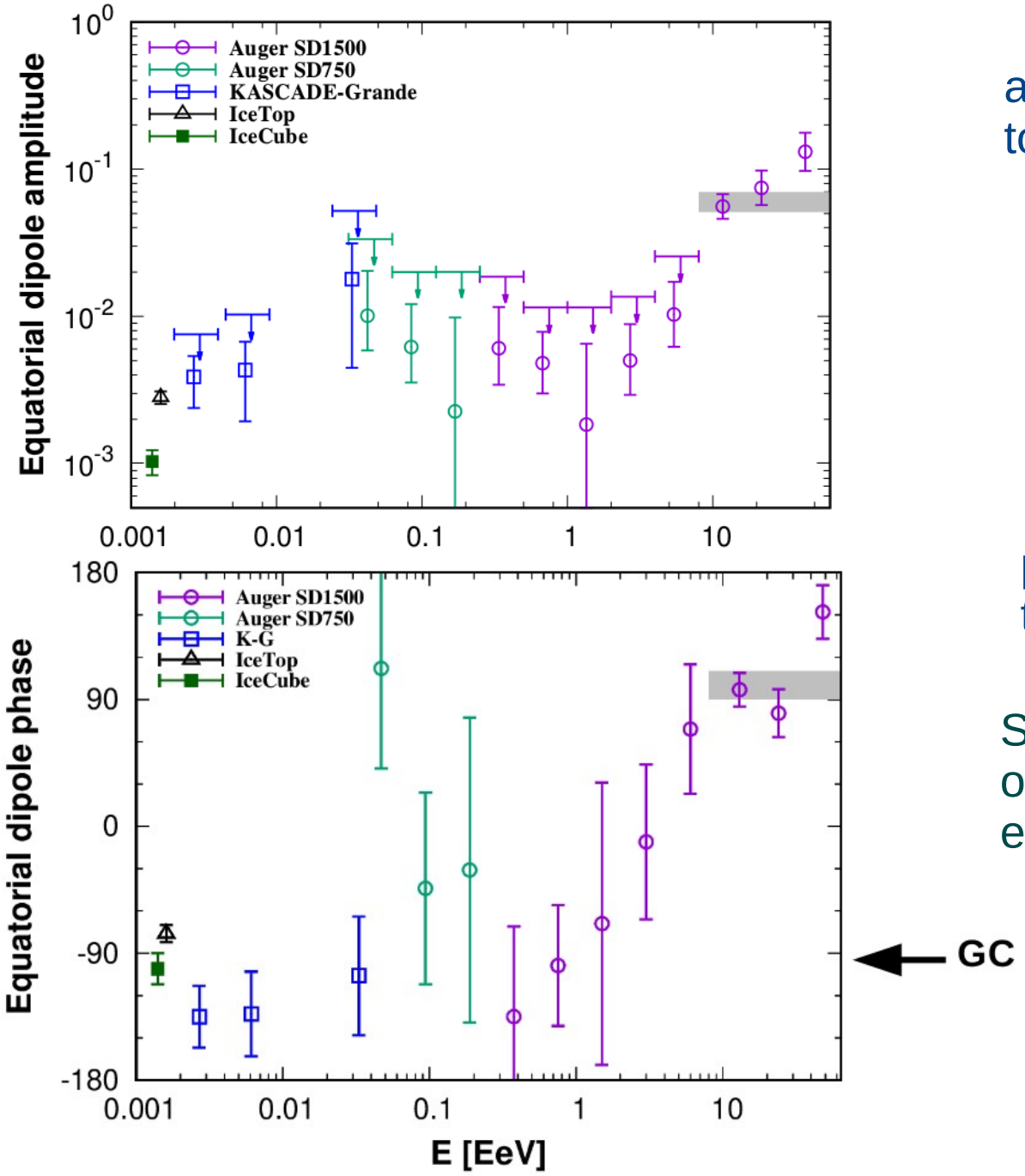



$d = 0.059 \pm 0.020$

Compatible with Auger only results

Auger + TA ICRC 2021

# EQUATORIAL DIPOLE FROM 1 PeV TO 100 EeV




amplitudes grow, from below 1% to above 10%

phases shift, from ~ GC to ~ opposite direction

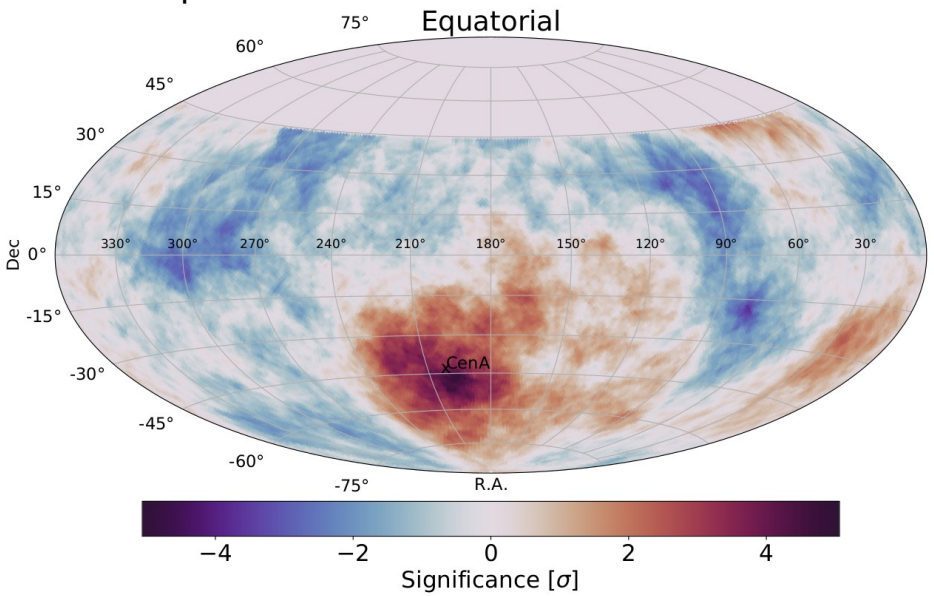
Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Auger coll, ApJ 891(2020)

# MEDIUM-SCALE ANISOTROPIES AT THE HIGHEST ENERGIES

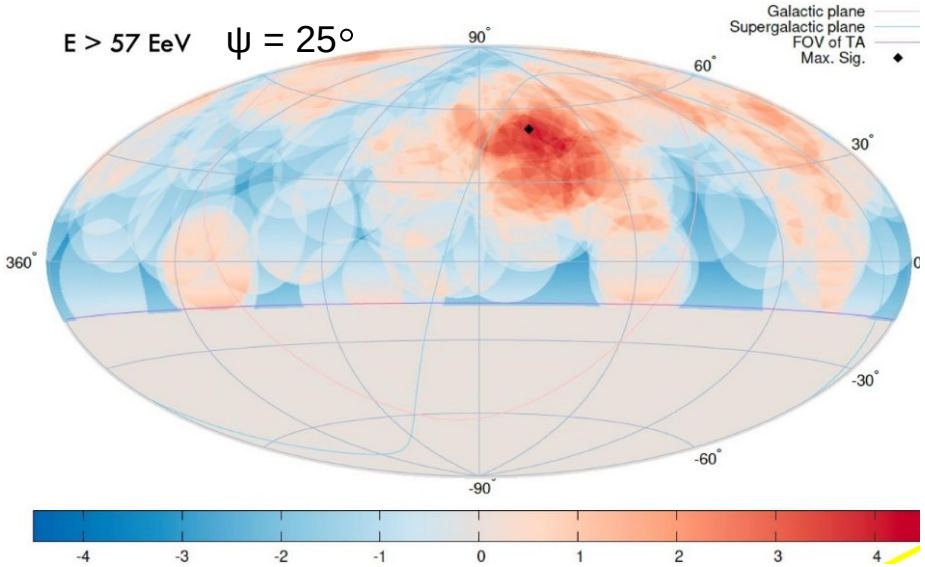
Auger ICRC 2021

E > 41 EeV  ψ = 24°

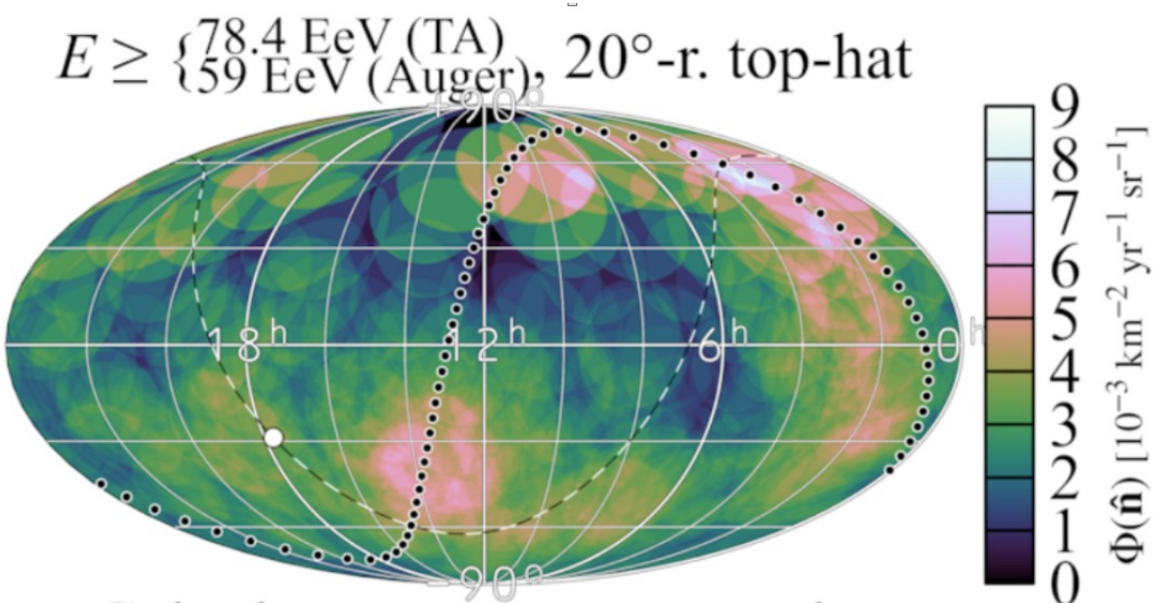



post-trial significance 2.2σ, obs/exp = 156/98

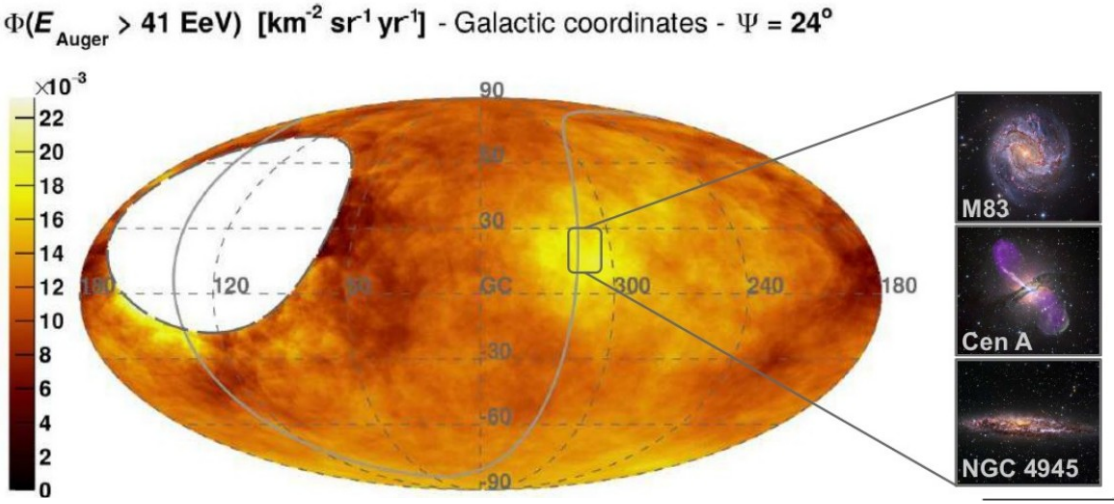
TA ICRC 2021




post-trial significance 3.2σ, obs/exp = 40/14.6



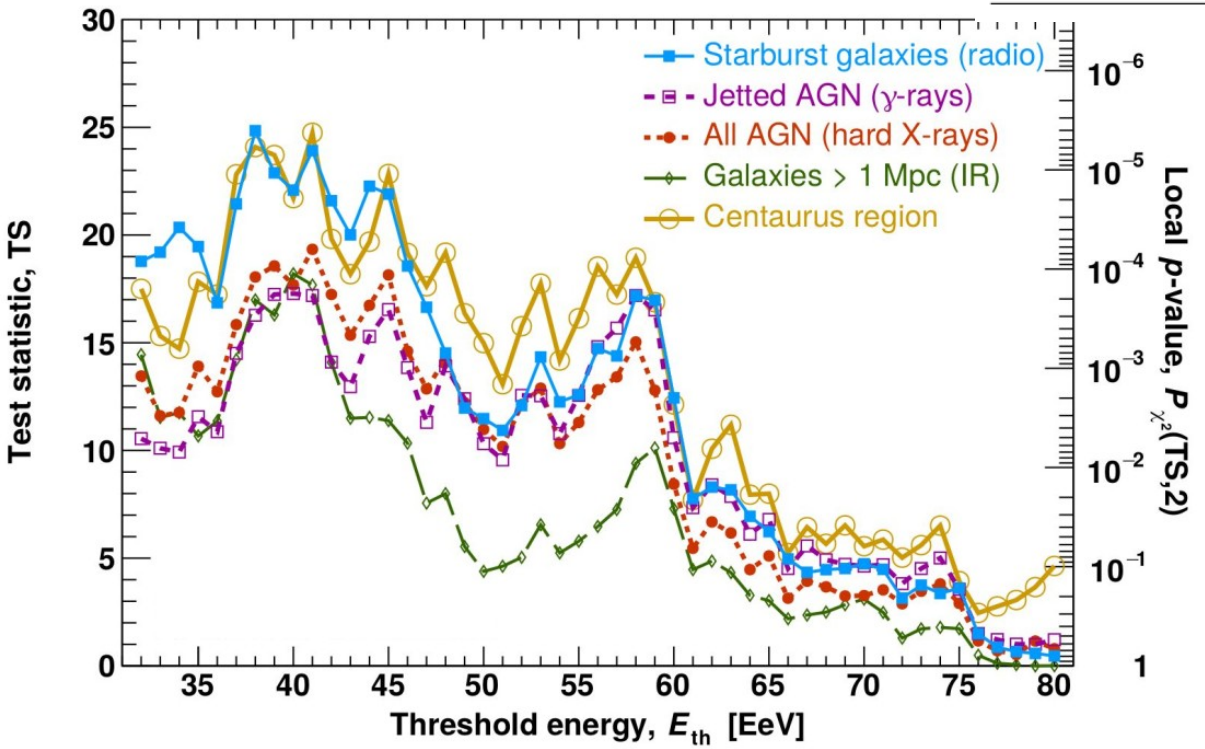
# ANISOTROPIES AT THE HIGHEST ENERGIES: CATALOGS




Fit attenuated flux pattern + isotropy to data with variable signal fraction α and smoothing scale above $E_{th}$ = {32, 33, …, 80} EeV

| Catalog | $E_{th}$ [EeV] | Ψ [deg] | $\alpha$ [%] | TS | Post-trial $p$-value |
|---|---|---|---|---|---|
| All galaxies (IR) | 40 | $24^{+16}_{-8}$ | $15^{+10}_{-6}$ | 18.2 | $6.7 \times 10^{-4}$ |
| Starbursts (radio) | 38 | $25^{+11}_{-7}$ | $9^{+6}_{-4}$ | 24.8 | $3.1 \times 10^{-5}$ |
| All AGNs (X-rays) | 41 | $27^{+14}_{-9}$ | $8^{+5}_{-4}$ | 19.3 | $4.0 \times 10^{-4}$ |
| Jetted AGNs ($\gamma$-rays) | 40 | $23^{+9}_{-8}$ | $6^{+4}_{-3}$ | 17.3 | $1.0 \times 10^{-3}$ |

Cen A direction (fixed), free $E_{th}$ and ψ
$E_{th}$ > 41 EeV, ψ = 27°: 3.9 σ post-trial

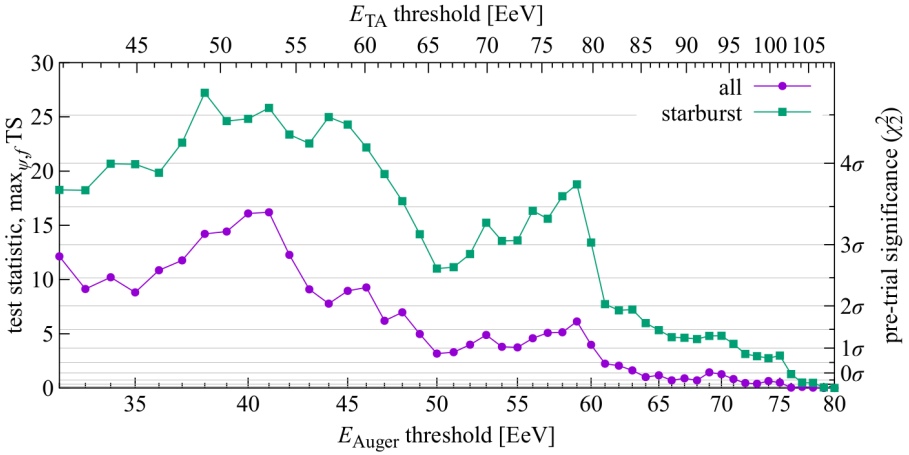



Post-trial deviation from isotropy:
from 3.1σ (jetted AGN)
up to 4.0σ (starbursts)

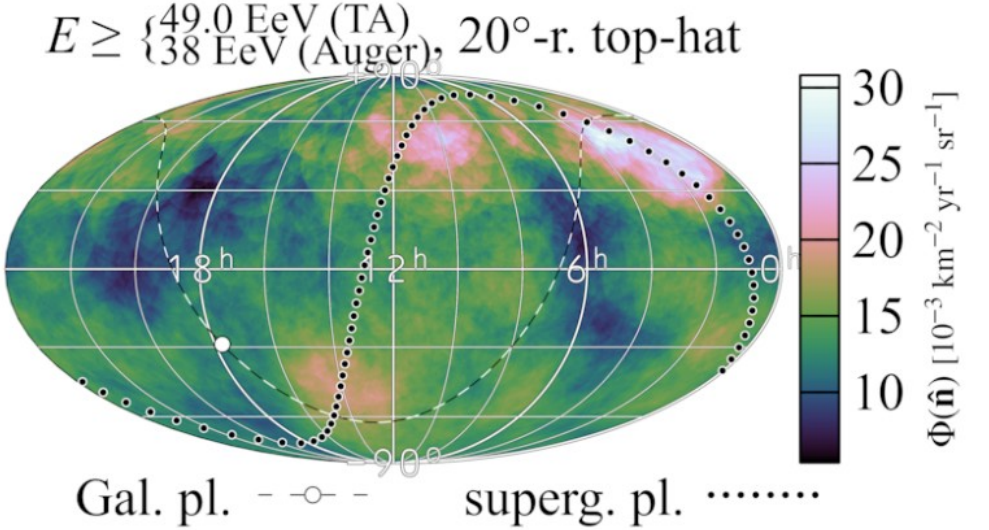
# AUGER + TA: CORRELATION WITH CATALOGS

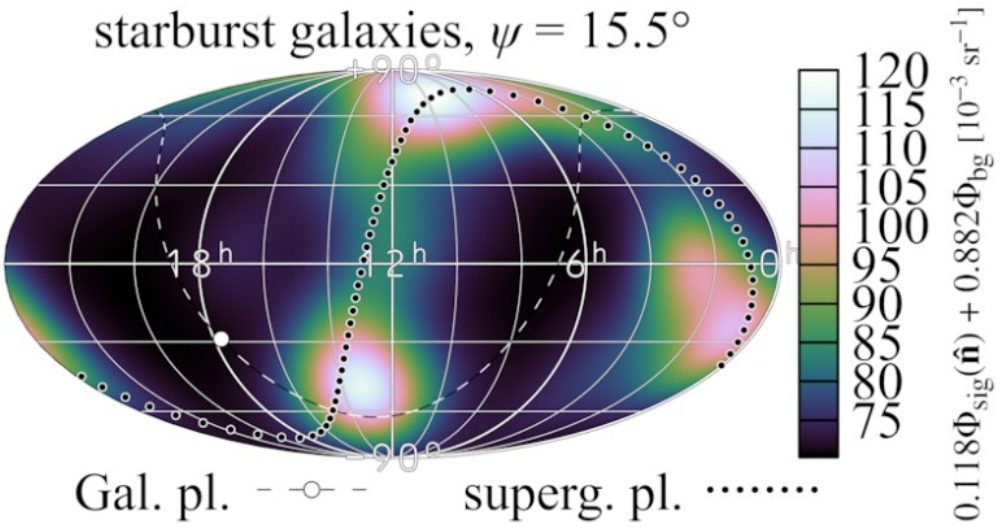
2 models:

- all galaxies closer than 250 Mpc from 2MASS
- starburst galaxies




| catalog | $E_{min}$ (Auger) | $E_{min}$ (TA) | $\psi$ | equiv. top-hat radius | $f$ | TS |
|---|---|---|---|---|---|---|
| all galaxies | 41 EeV | 53 EeV | $24^{\circ}{}^{+13^{\circ}}_{-8^{\circ}}$ | $38^{\circ}{}^{+21^{\circ}}_{-13^{\circ}}$ | $38\%^{+28\%}_{-14\%}$ | 16.2 |
| starburst galaxies | 38 EeV | 49 EeV | $15.5^{\circ}{}^{+5.3^{\circ}}_{-3.2^{\circ}}$ | $24.6^{\circ}{}^{+8.4^{\circ}}_{-5.1^{\circ}}$ | $11.8\%^{+5.0\%}_{-3.1\%}$ | 27.2 |




**starburst galaxies:**

**TS = 27.2 → 4.2 σ post-trial significance**

all-galaxy model:

TS = 16.2 → 2.9 σ post-trial significance

# ANISOTROPIES SEARCH SUMMARY:

- Significant dipolar modulation of 7.3 % amplitude for E > 8 EeV

- Hints of Intermediate angular scale anisotropy at ~40 EeV:
  ~ 4σ from Centaurus region
  catalogs: largest signal from starbursts - no compelling evidence for catalog preference

- No evidence of small scale anisotropies

→ PROBABLY INDICATING LARGE DEFLECTIONS IN GALACTIC AND/OR INTERGALACTIC B FIELD (consistent with heavy composition at highest energies)

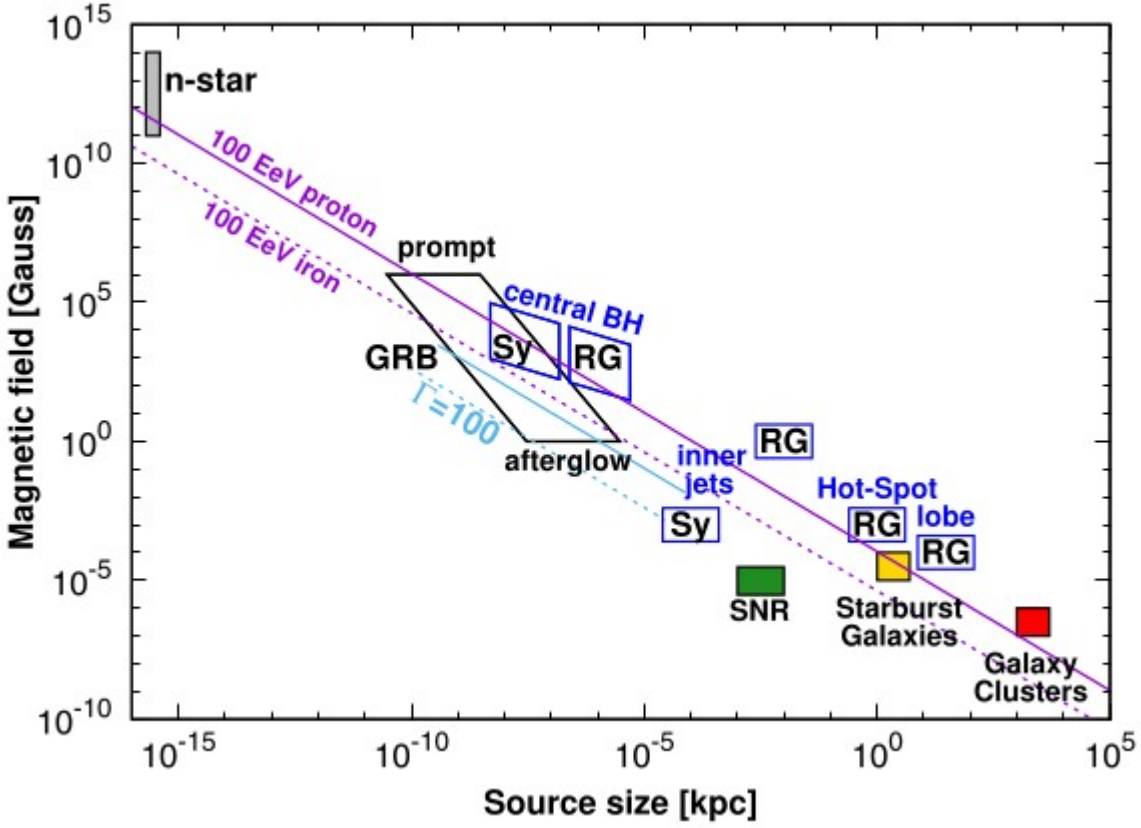
**Main difficulty to identify UHECR sources: magnetic deflections**

Regular B field: $\delta \simeq 10^{\circ} \frac{10\,\mathrm{EeV}}{E/Z} \left| \int_0^L \frac{\mathrm{d}\vec{x}}{\mathrm{kpc}} \times \frac{\vec{B}}{2\,\mu\mathrm{G}} \right|$ Turbulent B field: $\delta_{\mathrm{rms}} \simeq \frac{BZe}{E} \sqrt{\frac{Ll_c}{2}} \simeq 4^{\circ} \frac{B}{\mathrm{nG}} \frac{10\,\mathrm{EeV}}{E/Z} \frac{\sqrt{Ll_c}}{\mathrm{Mpc}}$

Problem: Galactic/extragalactic magnetic fields and composition of individual CRs are poorly known

# WHERE ARE UHECRs ACCELERATED?

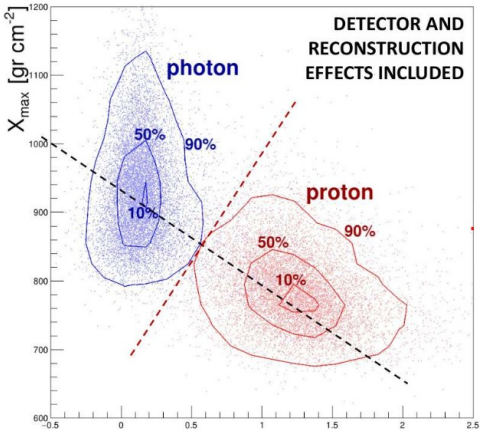
Few proposed candidates meet minimal conditions for accelerator sites: AGNs, Starburst galaxies, GRBs, magnetars




But identification is difficult since arrival direction of CRs do not point to their sources

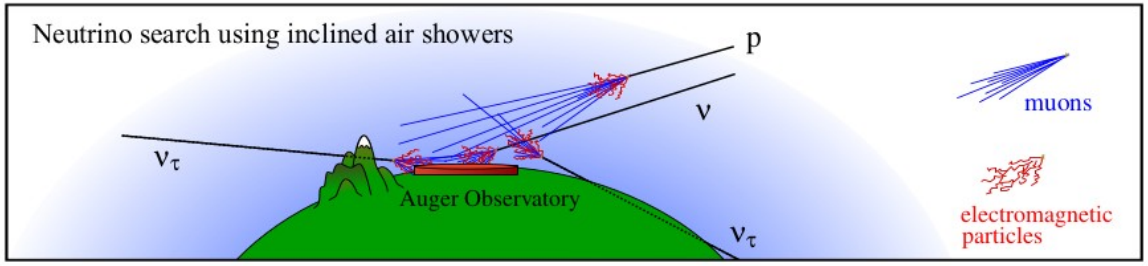
# SEARCHES FOR UHE PHOTONS AND NEUTRINOS

Photons: larger $X_{max}$ and less muons than hadronic primaries

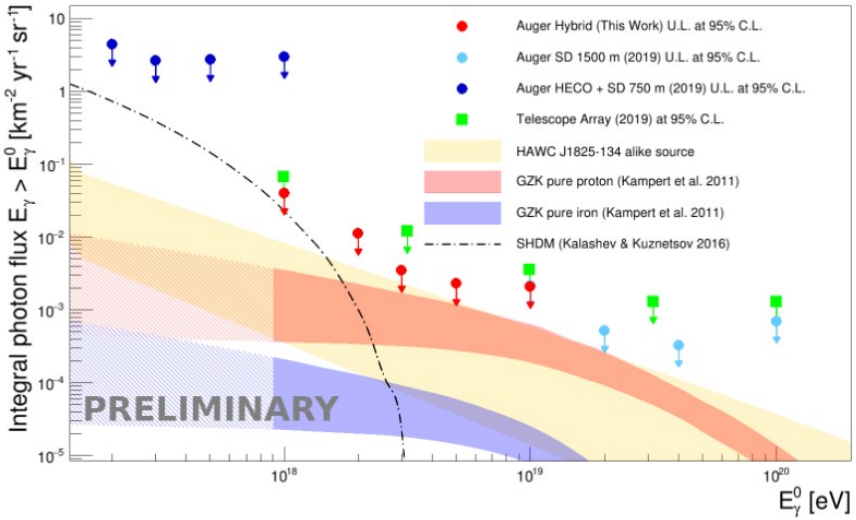


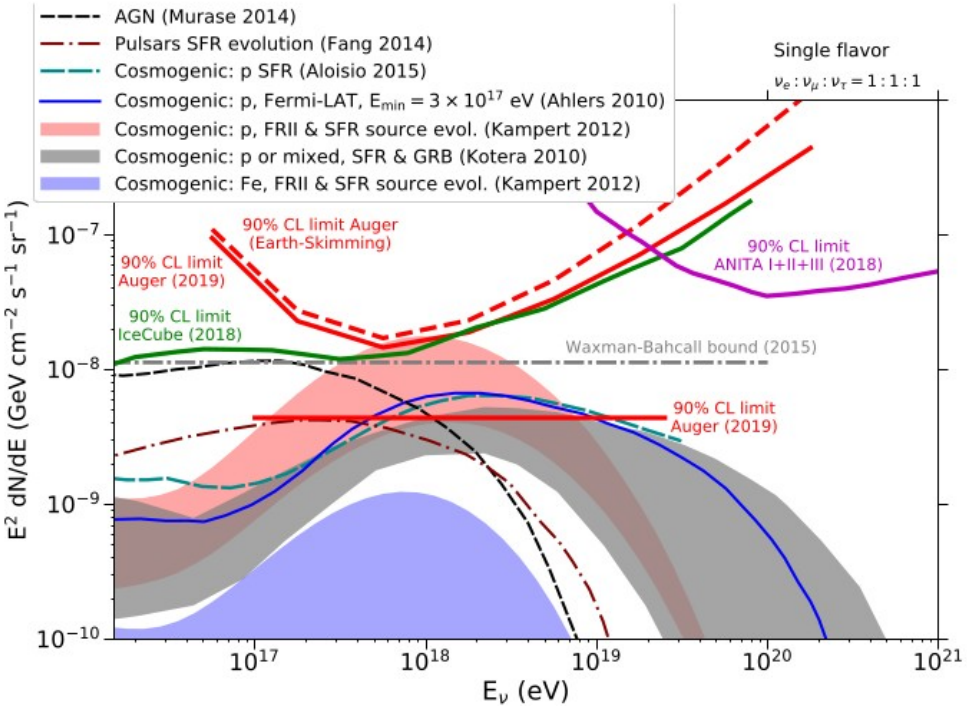

Muon signal by shower universality

Auger ICRC 2021




# candidates compatible with background



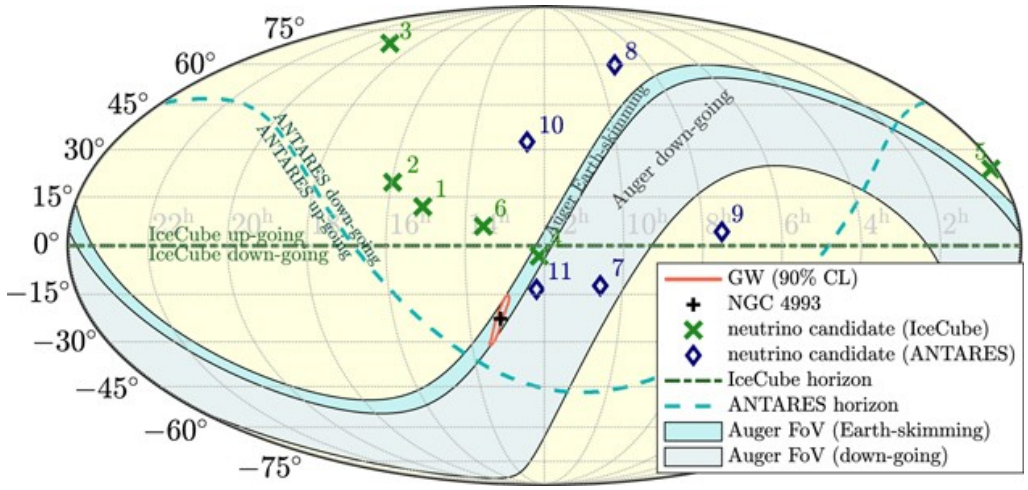

(G Parente)

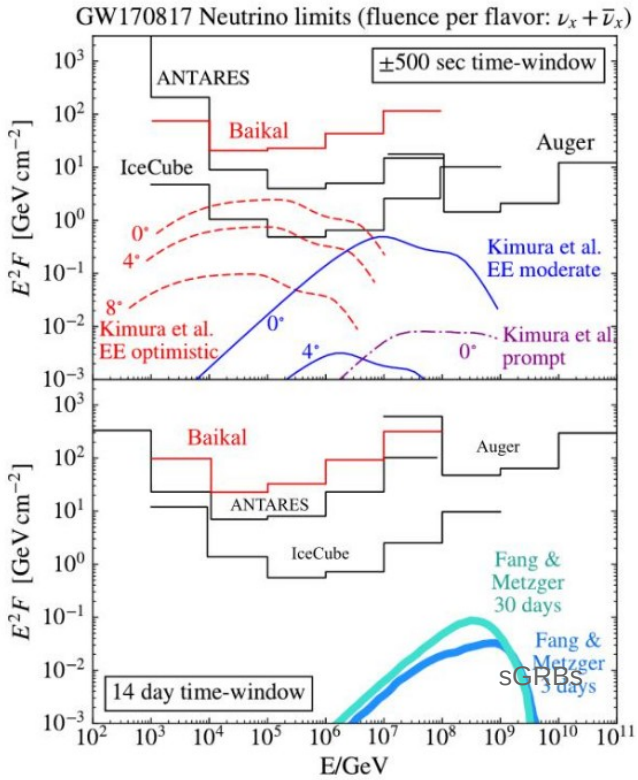
Multi-messenger: searches for photons in coincidence with GW events (P Ruehl)

Also MM searches of v in coincidence with GW events → upper bounds

# MULTIMESSENGER ASTRONOMY

Search for HE neutrinos in coincidence with a GW event: BNS merger GW170817 (LIGO+Virgo) + short GRB (Fermi-GBM, INTEGRAL)



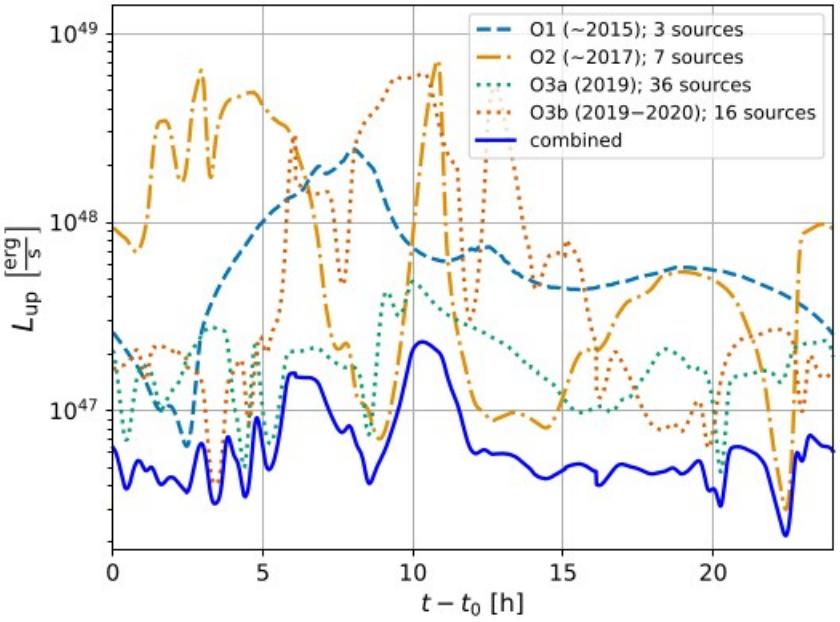




no significant neutrino counterpart within a ±500 s window, nor in the next 14 days

Antares, IceCube & Auger
ApJ, 850, L35 (2017)

Combined search for UHE neutrinos from GW events:

No candidate found →
upper limits to the luminosity



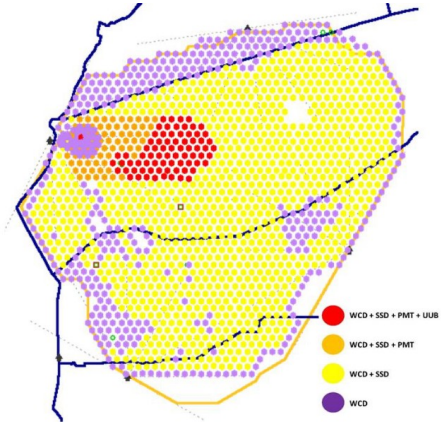

(P Ruehl)

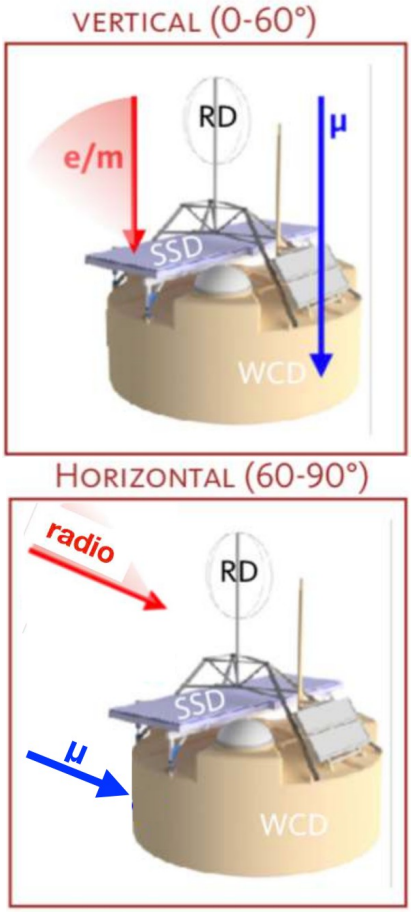
# THE (very near) FUTURE

## AugerPrime Upgrade

sensitivity to mass composition of SD
(100% duty cycle)

- 3.8 m$^2$ scintillator panels (SSD)
- Radio antennas for inclined showers
- Underground muon counters
- New electronics (40 MHz → 120 MHz)
- Small PMT (dynamic range WCD)

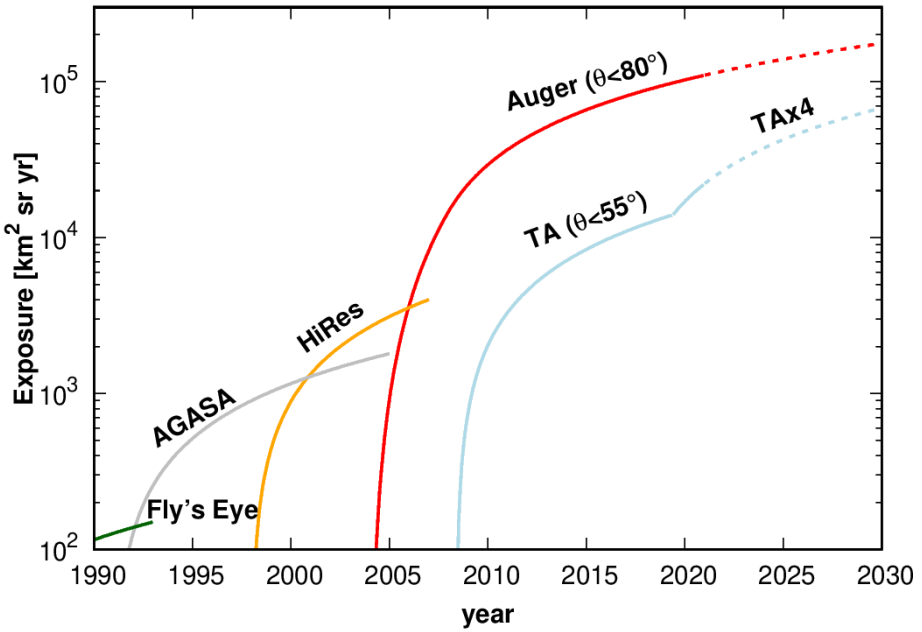



## Telescope Array: TAx4

(257 of 500 already deployed)

→ cover 3000 km$^2$

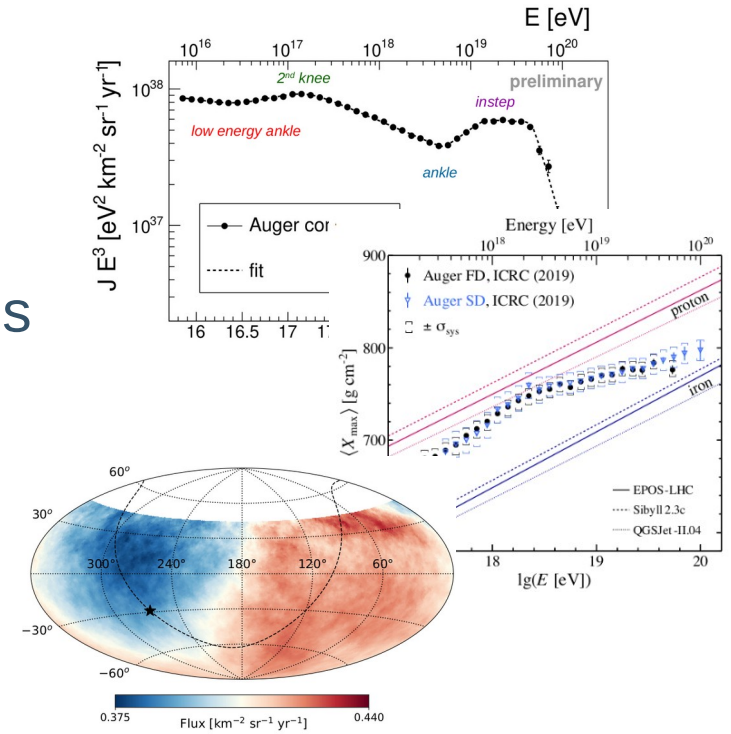


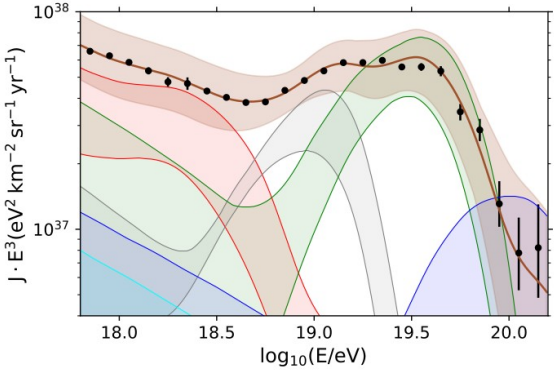
# SUMMARY

Many recent advances in understanding UHECRs

- Very detailed spectrum measurement
- Composition change to heavier elements with increasing energy
- Dipolar anisotropy above 8 EeV established

→ consistent picture starting to emerge




Major improvements in the observatories

Still many open questions

- sources and acceleration?