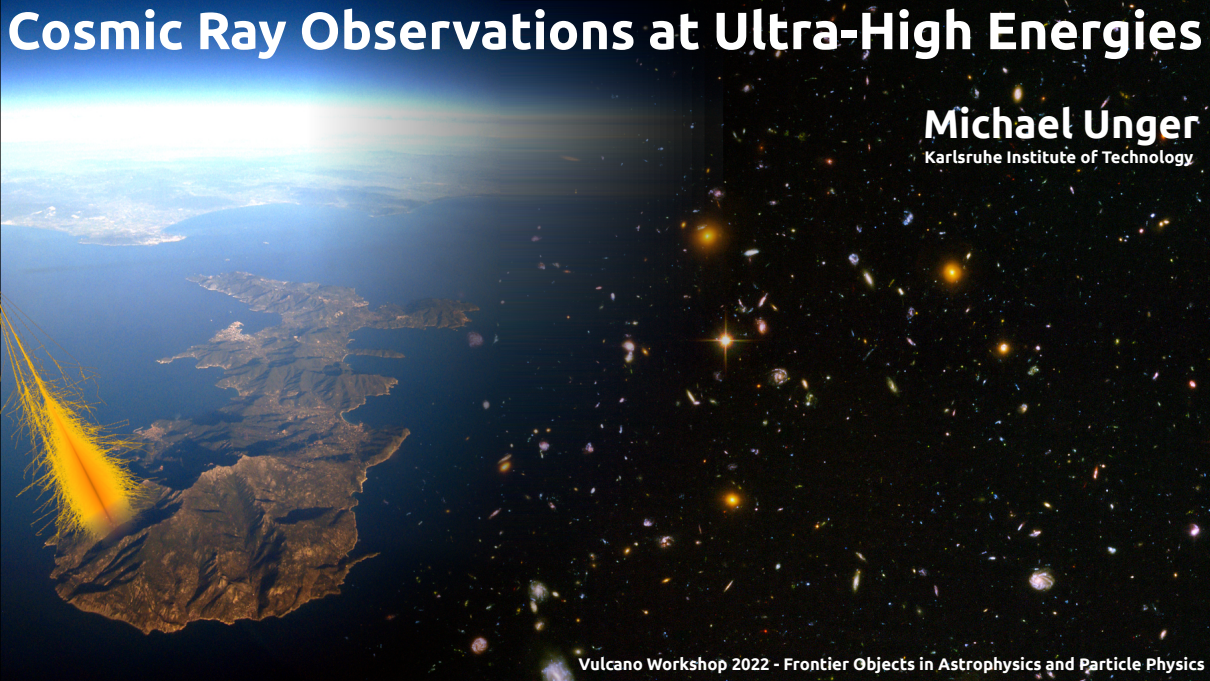
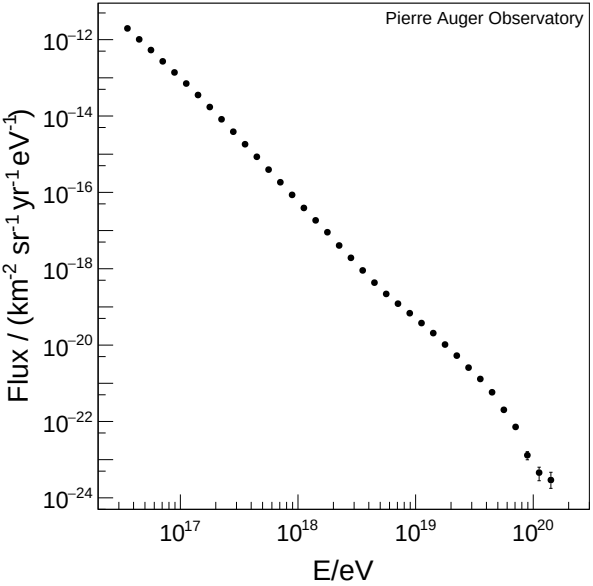
# Cosmic Ray Observations at Ultra-High Energies

**Michael Unger**
Karlsruhe Institute of Technology



Vulcano Workshop 2022 - Frontier Objects in Astrophysics and Particle Physics

# Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



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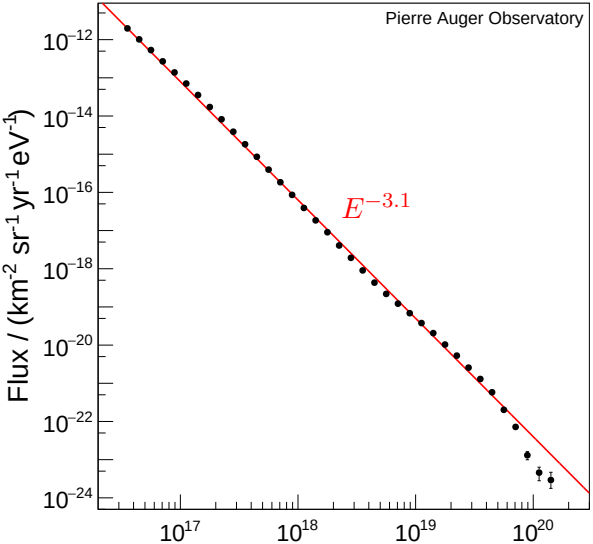
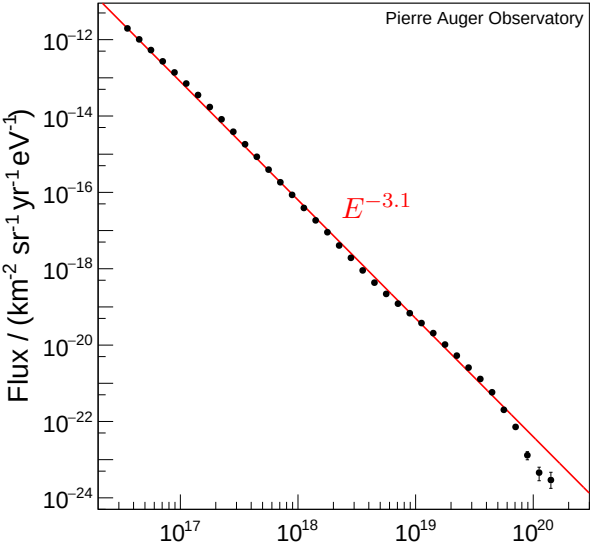



$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

$\sqrt{s_{\text{pp}}} = 450$ TeV

# Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)




$\sim$20 J!

Serena Williams' 2nd serve

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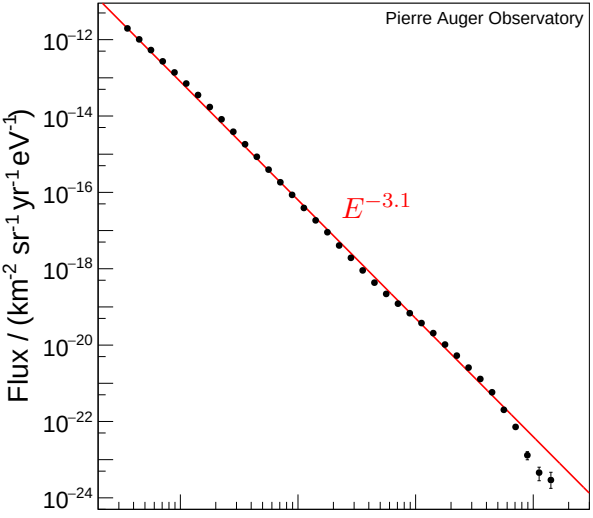



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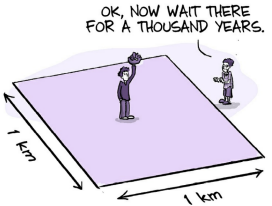
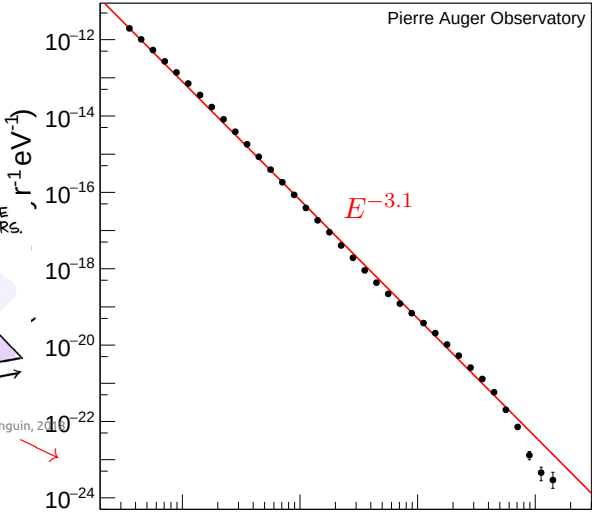



Cham&Whiteson "We have no idea", Penguin, 2018

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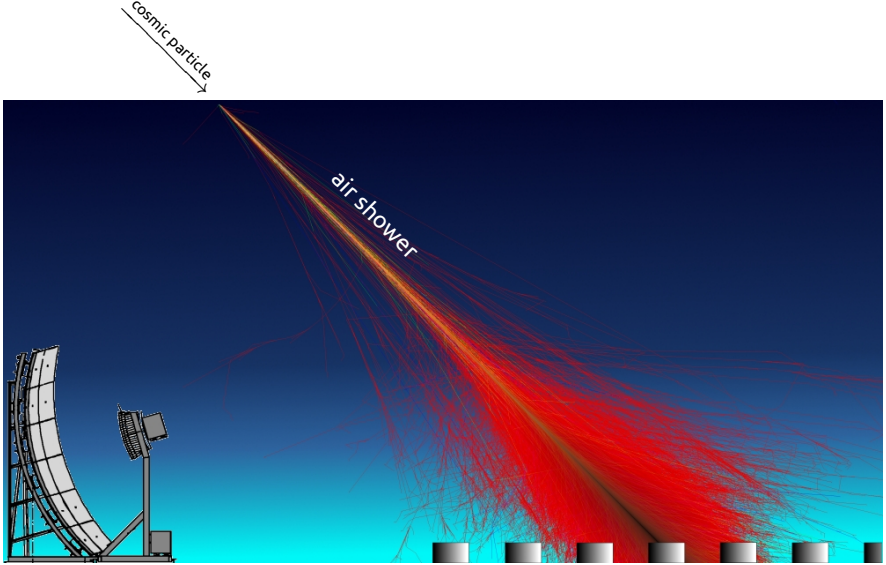
$\sqrt{s_{\text{pp}}} = 450$ TeV


Serena Williams' 2nd serve

# Detection of UHECRs: Air Showers

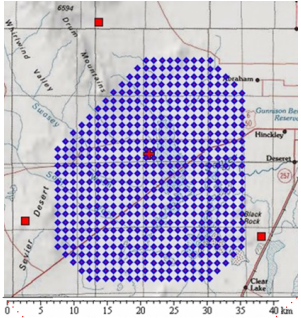


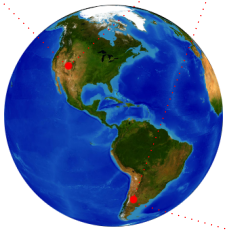

fluorescence telescope

particle detector

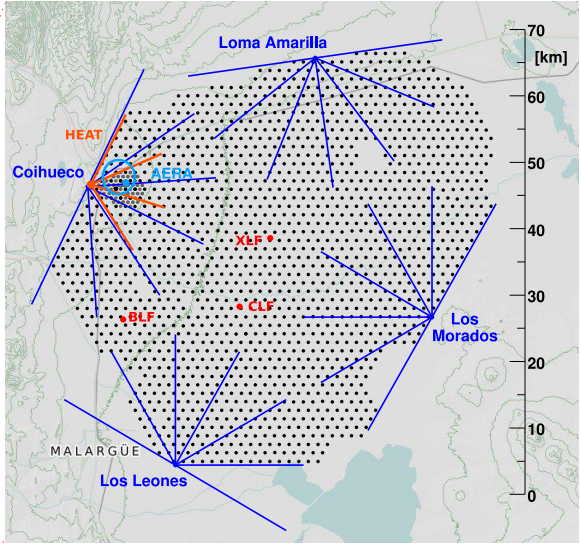
# UHECR Observatories

**Telescope Array**



**Pierre Auger Observatory**



# UHECR Observatories

**Telescope Array**

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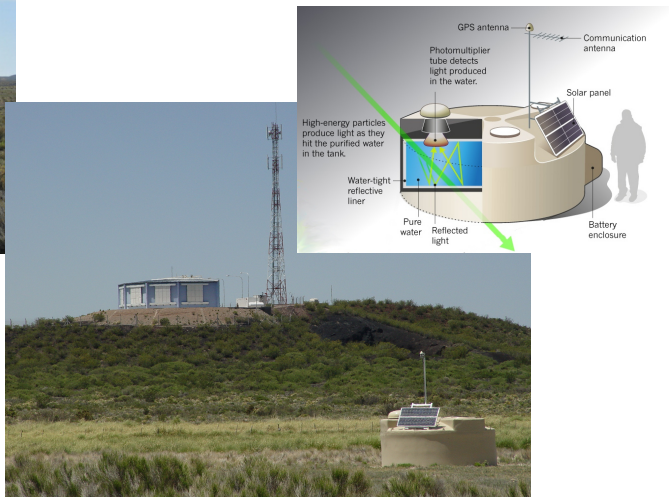
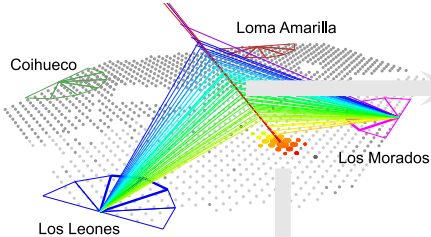
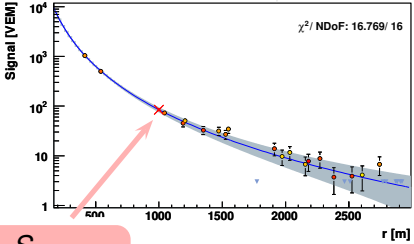
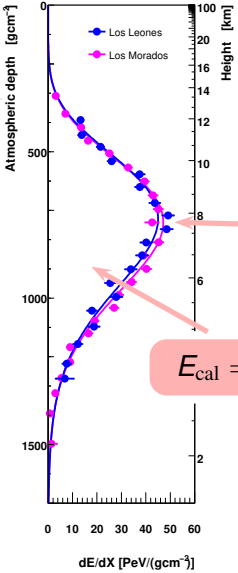


# Air Shower Detection in the Hybrid Era




$S_{1000}$




$X_{max}$

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

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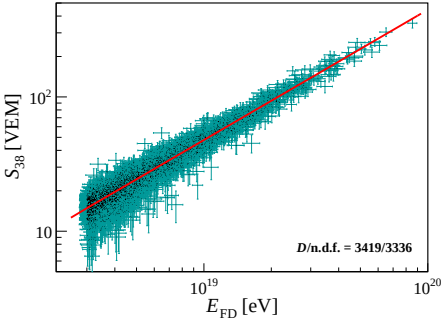


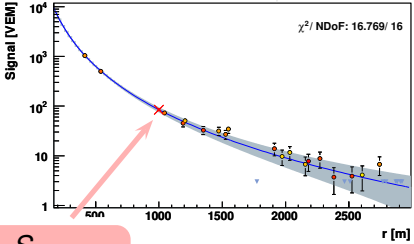


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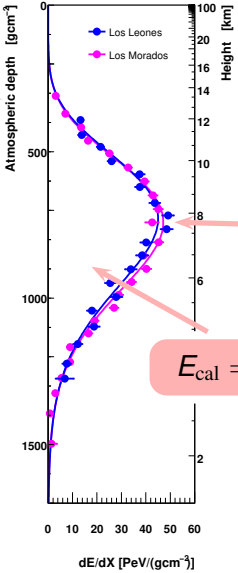


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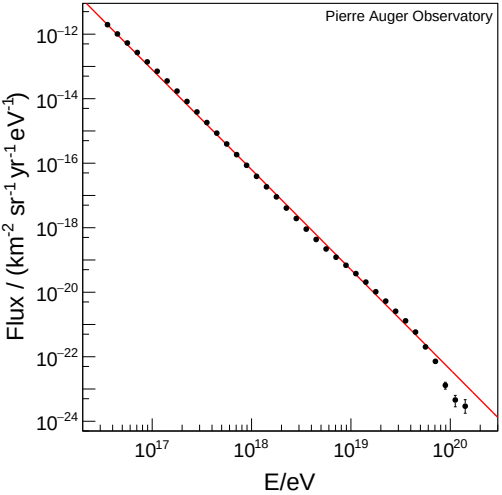
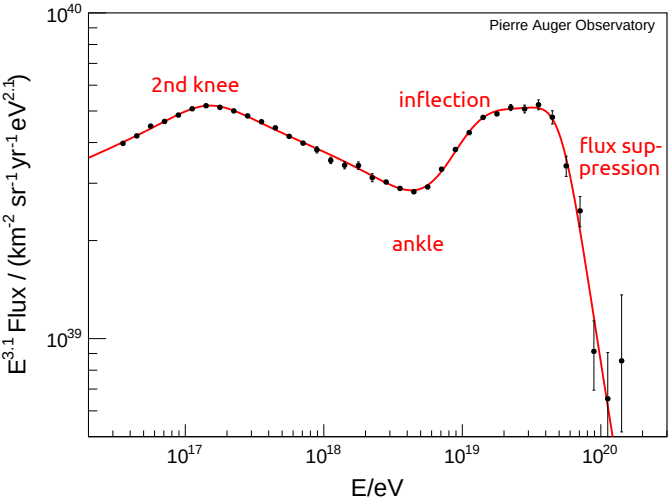
# Energy Spectrum

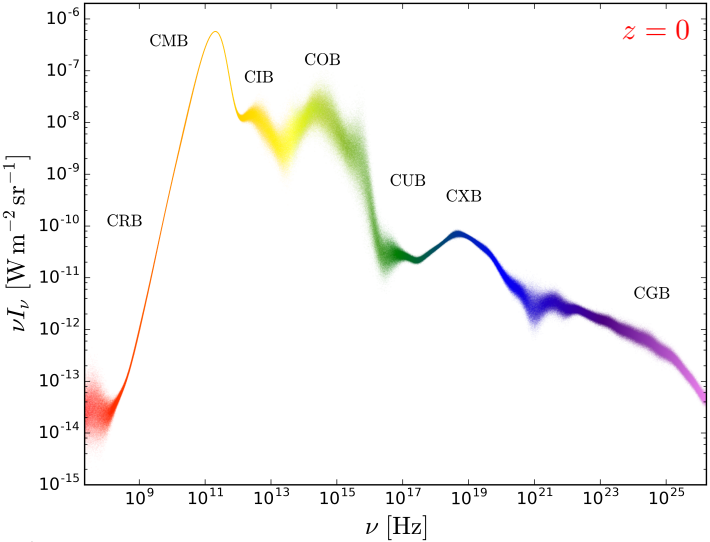


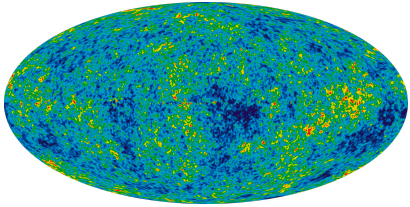

Pierre Auger Coll., ICRC19, PRD 2020, PRL 2020, EPJC 2021

Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

# Propagation of UHECRs in Photon Fields




CMB (WMAP)



$$p + \gamma_{\text{CMB}} \to p + e + +e^-$$
$$p + \gamma_{\text{CMB}} \to p/n + \pi^0/\pi^+$$
$$A + \gamma_{\text{CMB}} \to (A-1) + p/n$$

Greisen, Zatsepin & Kuzmin (GZK) 1966

arXiv:1802.03694

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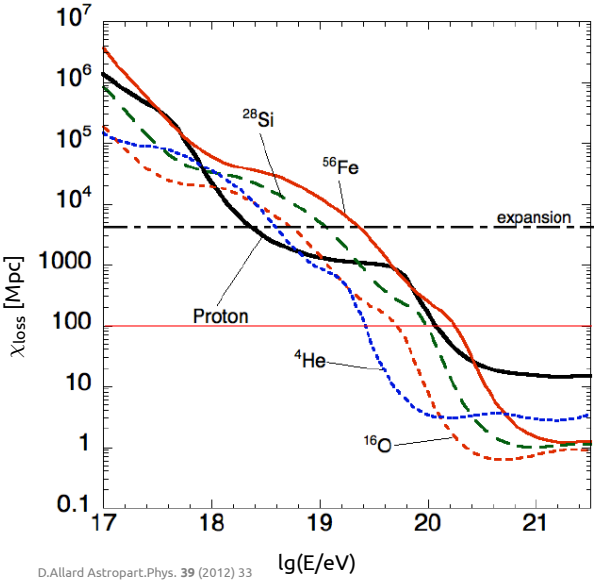
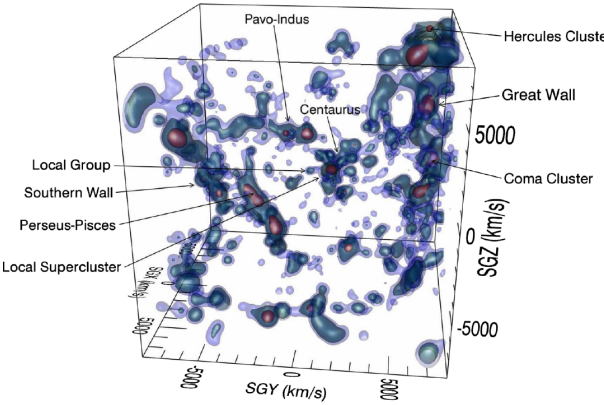


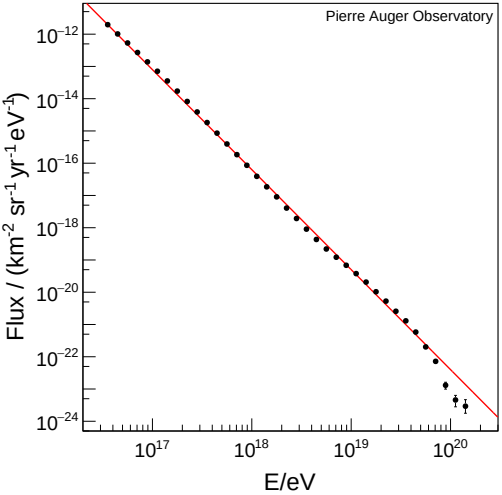

D.Allard Astropart.Phys. **39** (2012) 33




Y.Hoffman et al, Nat.Astron. **2** (2018) 680

local universe: inhomogeneous and anisotropic!

# Energy Spectrum




## Measurement of Local CR Energy Density

$$\rho = 4\pi/c \int_{E_{\rm ankle}}^{\infty} E\ \mathrm{Flux}(E)\ \mathrm{d}E$$
$$= (5.66 \pm 0.03 \pm 1.40) \times 10^{53}\ \mathrm{erg\ Mpc^{-3}}$$

$\rightarrow$ source luminosity density

$$\mathcal{L} \sim \rho / t_{\rm loss} = 2 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

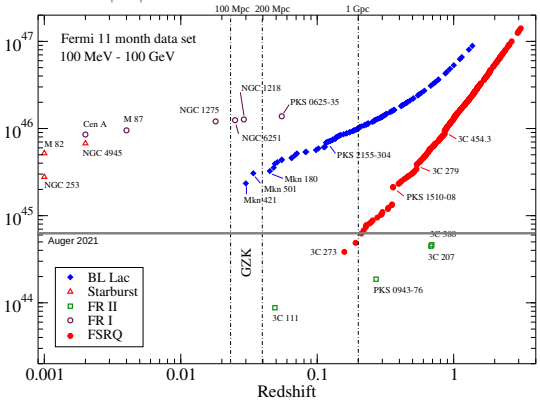
Typical energy loss time $t_{\rm loss} \sim 1\ \mathrm{Gpc/c}$ at $E_{\rm ankle} = 5 \times 10^{18}$ eV

Full calculation with SimProp gives $\mathcal{L} = 6 \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$)

Pierre Auger Coll., ICRC19, PRD 2020, PRL 2020, EPJC 202· Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

# Energy Spectrum

Dermer&Razzaque ApJ 2010

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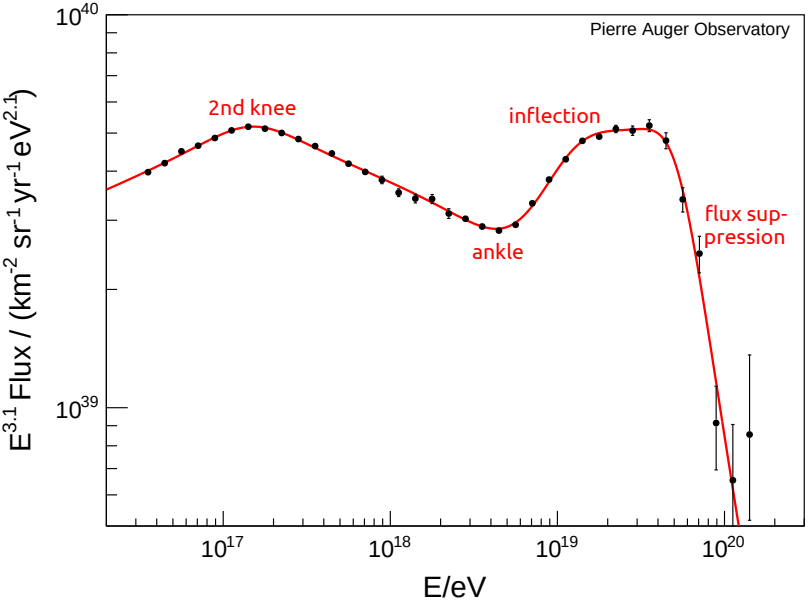
# Energy Spectrum – Interpretation of Spectral Features



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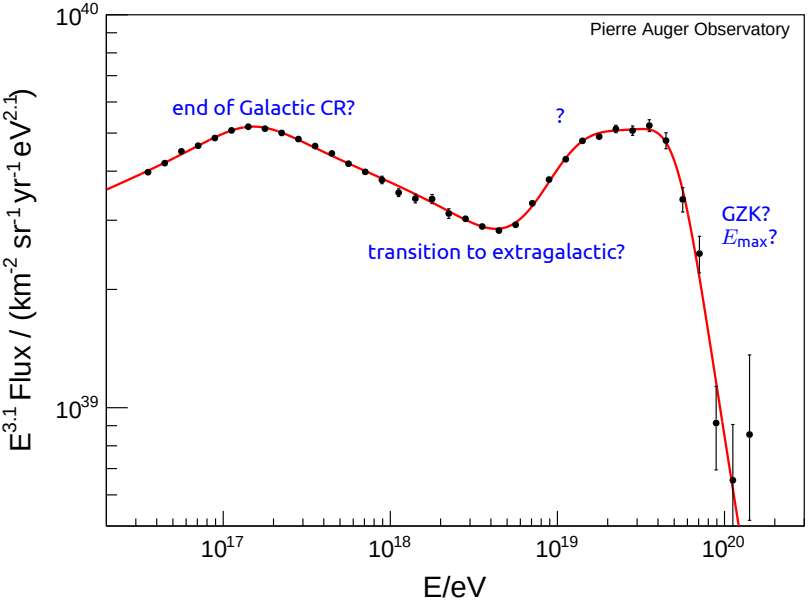
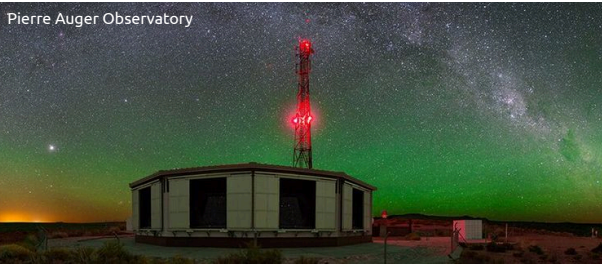
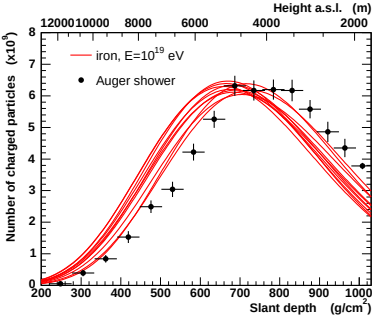
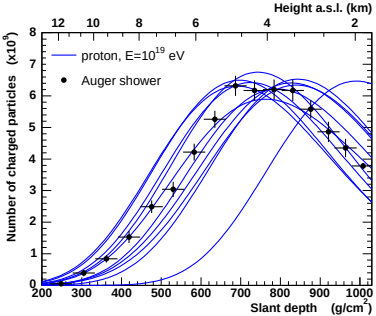


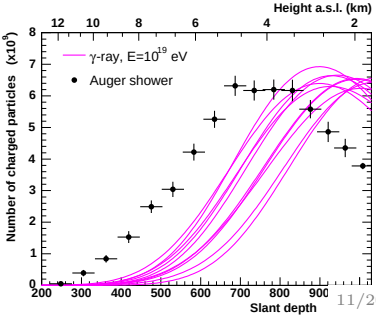
# Longitudinal Shower Development (Fluorescence Telescopes)



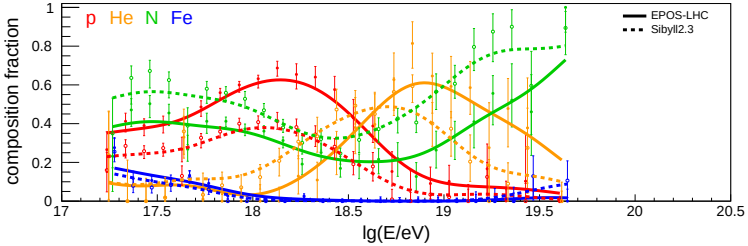




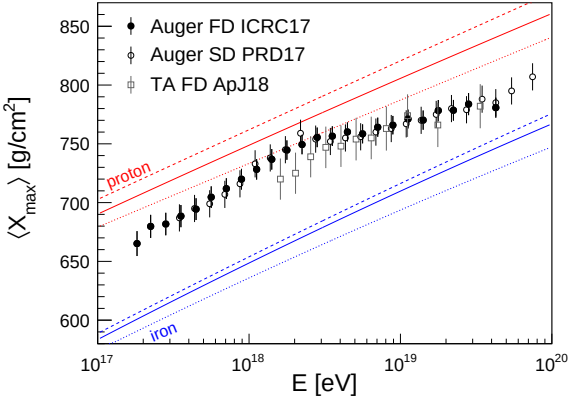



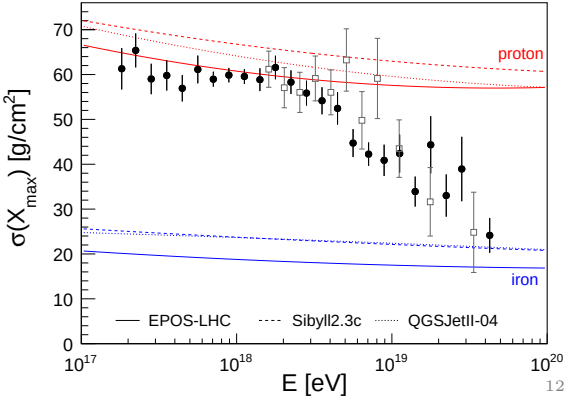



# UHECR Composition



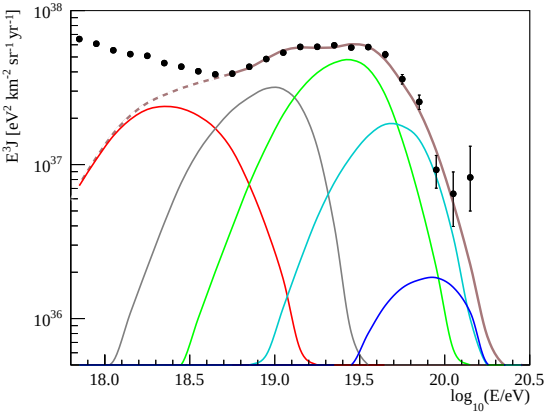

Telescope Array Coll. ApJ 858 (2018) 2
Pierre Auger Coll. PRD90 (2014) 12 and 1708.06592
A. Yushkov for the Auger and TA Coll. EPJ210 (2019) 01009
MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

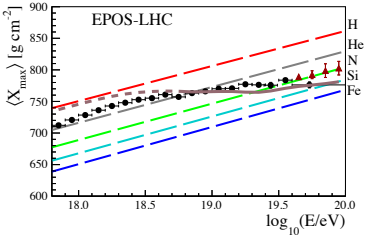


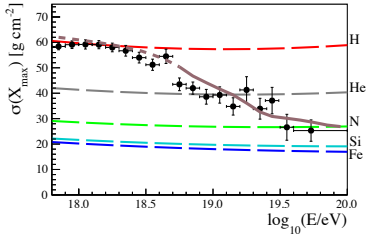



# Maximum Rigidity Model, Peters Cycle?

energy spectrum at source $\propto (E/Z)^{-\gamma}$

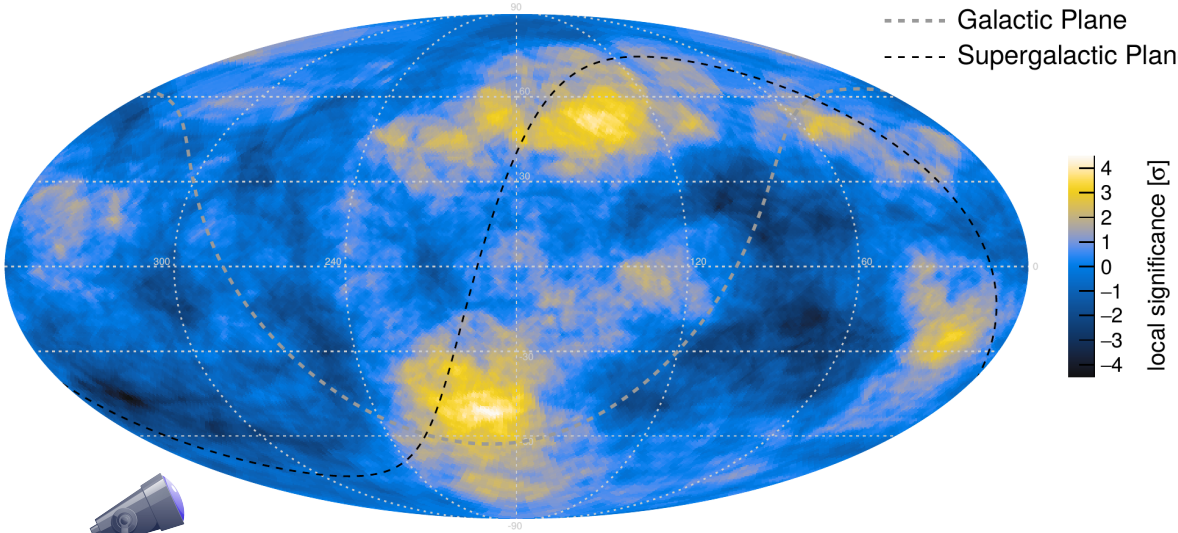


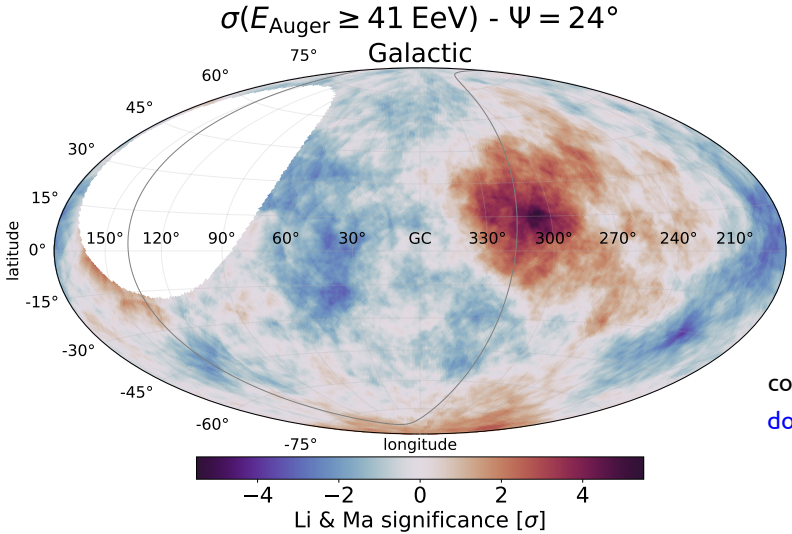

Pierre Auger Collaboration, E. Guido ICRC21, A. Castellina ICRC19 and JCAP **1704** (2017) 038

# Towards Charged Particle Astronomy




Cosmic ray sky above $5 \times 10^{19}$ eV (equatorial coordinates) Auger&TA UHECR18

# UHECR Sky as seen by the Pierre Auger Observatory



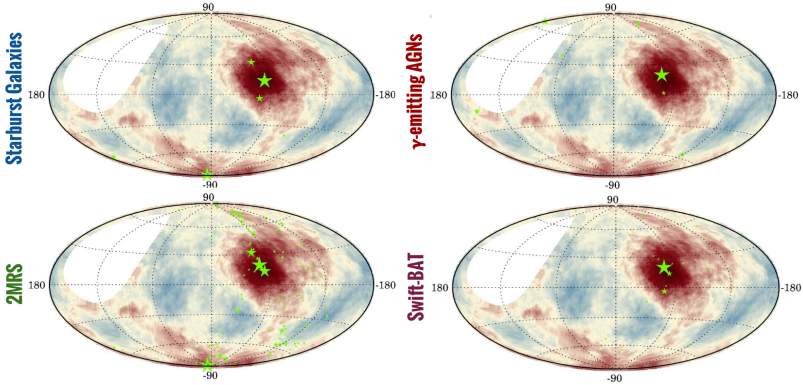

code and dataset available at

doi:10.5281/zenodo.6504276

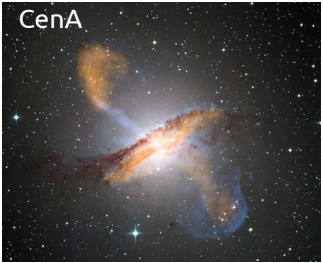
post-trial p-value is 3%

Pierre Auger Coll., ApJ 2022

# Correlation with Galaxy Catalogues (E$\gtrsim$ 40 EeV)



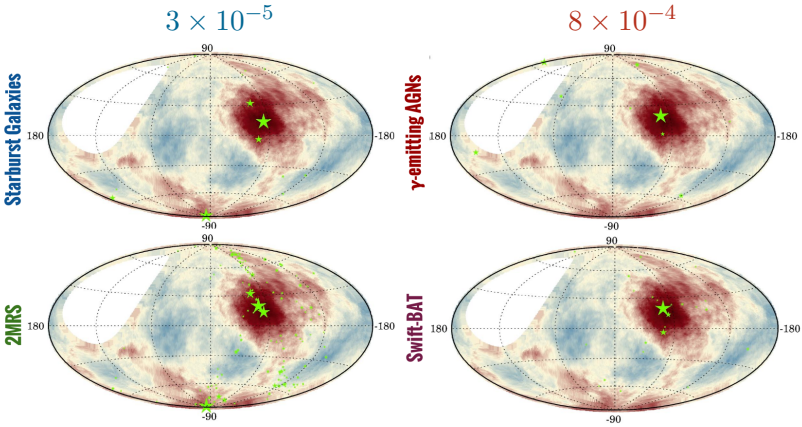


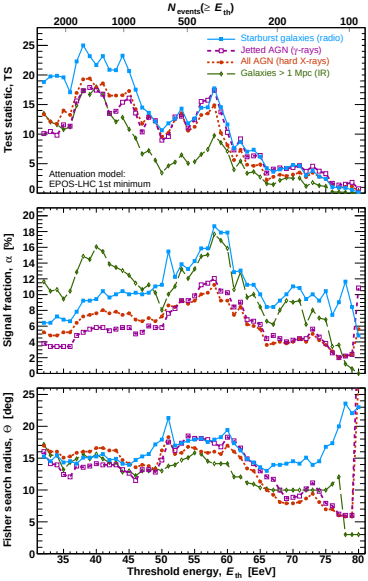



Pierre Auger Coll., ApJ 2022 (p-values) ICRC19 (plots)

# Correlation with Galaxy Catalogues ($E \gtrsim 40$ EeV)

post-trial p-value



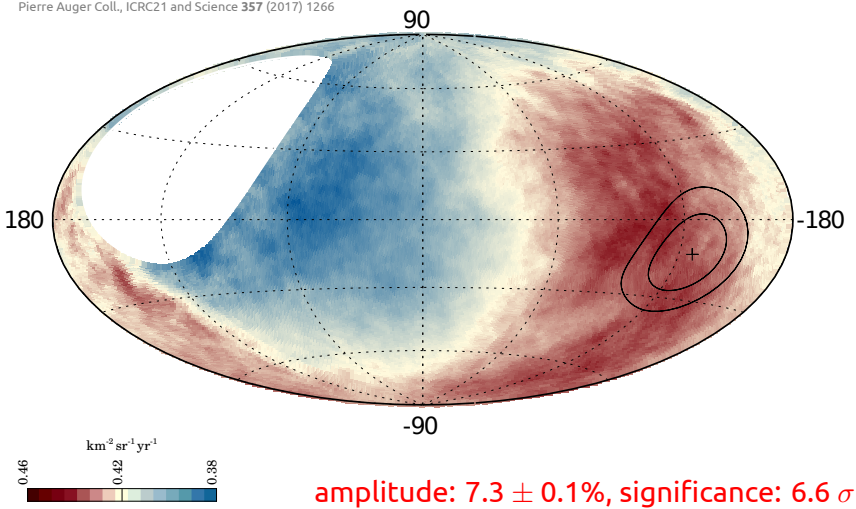



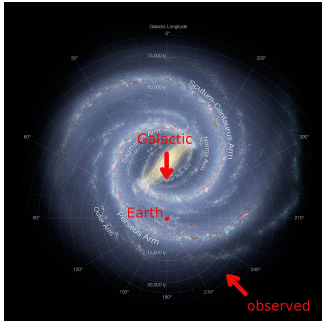

isotropy rejected at $\sim 3.3 - 4.2\,\sigma$

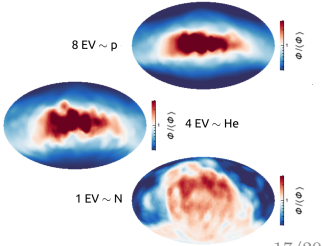
Pierre Auger Coll., ApJ 2022 (p-values) ICRC19 (plots)

# Observation of a Dipolar Anisotropy of UHECRs (E> 8 EeV)

Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266




amplitude: 7.3 $\pm$ 0.1%, significance: 6.6 $\sigma$

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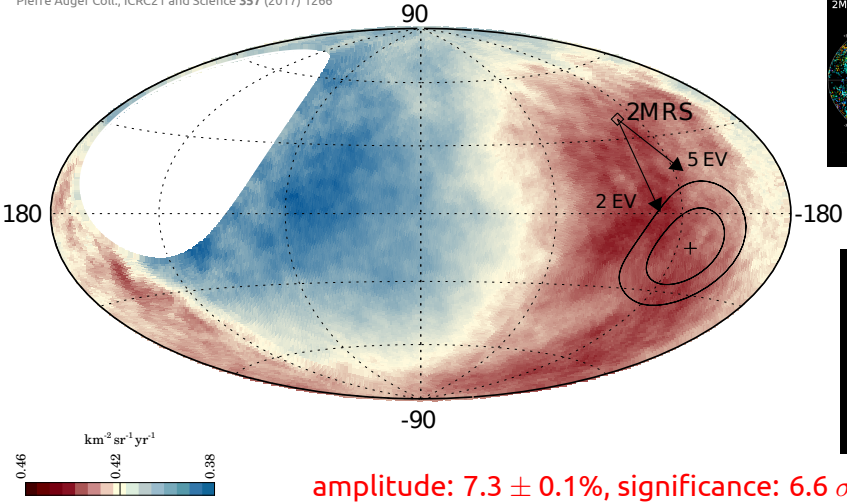
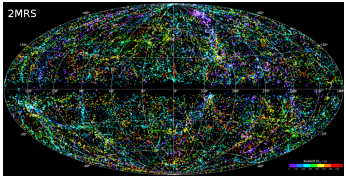
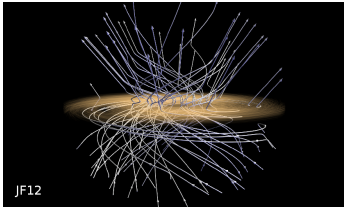


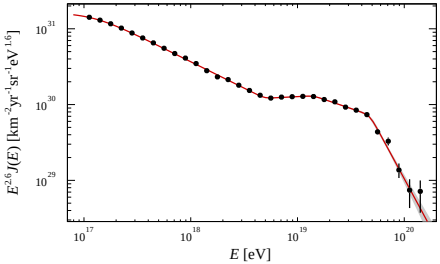



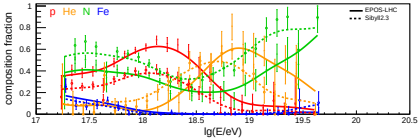

amplitude: 7.3 $\pm$ 0.1%, significance: 6.6 $\sigma$

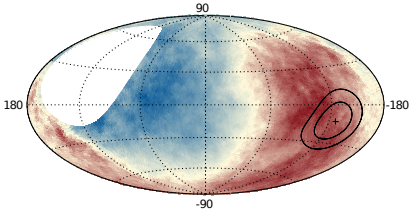
# Summary

## Golden Age of UHECR Research

- high-precision flux measurement
- unexpected mass composition
- large-scale anisotropy at $> 5\,\sigma$
- indication of intermediate-scale anisotropy
- maximum energy of source discovered?
- $\nu$ and $\gamma$ limits constrain UHECR sources
- mass-dependent anisotropy
- hadronic interactions at UHE
- search for LIV, SHDM at UHE
- transient follow-ups (GWs, TXS 0506+056,...)
- ...



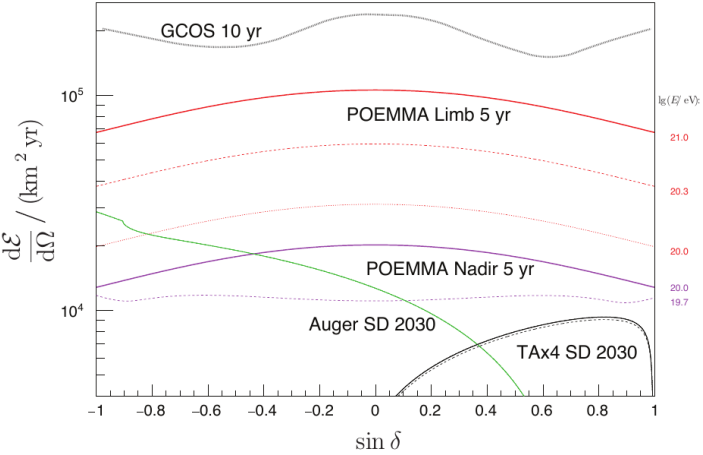
# Next Up: Charge Sensitivity and Full-Sky Equal Exposure

Under Construction: **AugerPrime**

Under Construction: **TAx4**

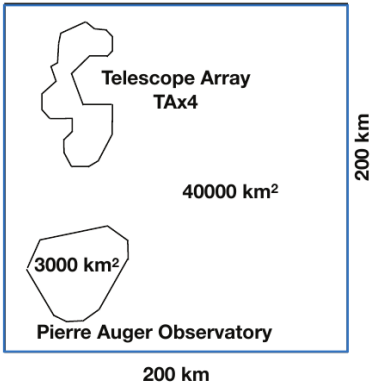
- composition/protons at UHE?
- charged-particle astronomy?
- $E_{\text{max}}$ or GZK?
- muon-puzzle at UHE

# Future Zevatron Hunters




fluorescence detection from space?

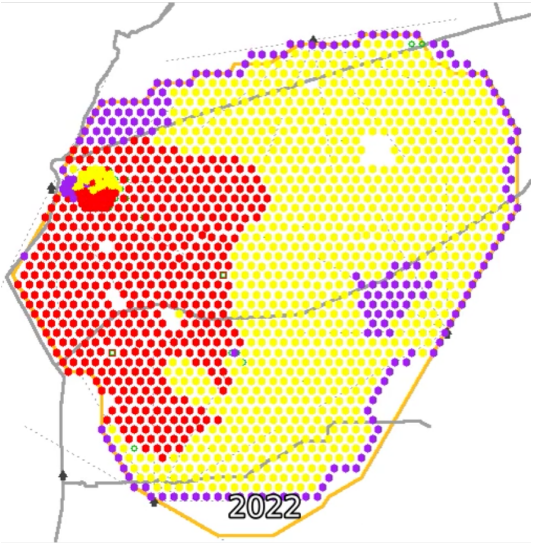
large hybrid ground array?




POEMMA PRD **101** (2020) 023012
GCOS PoS(ICRC2021)027
UHECR Snowmass white paper arXiv:2205.05845

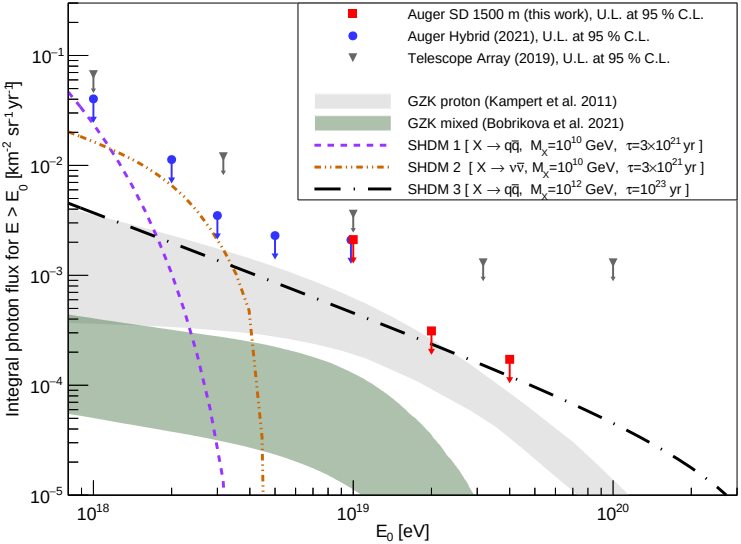
# backup slides

# AugerPrime Deployment Status 09/2022




- WCD sending T2
- with SSD
- pre-production array
- with UUB

# Photon Limits



# Comparison of TA and Auger Energy Spectra

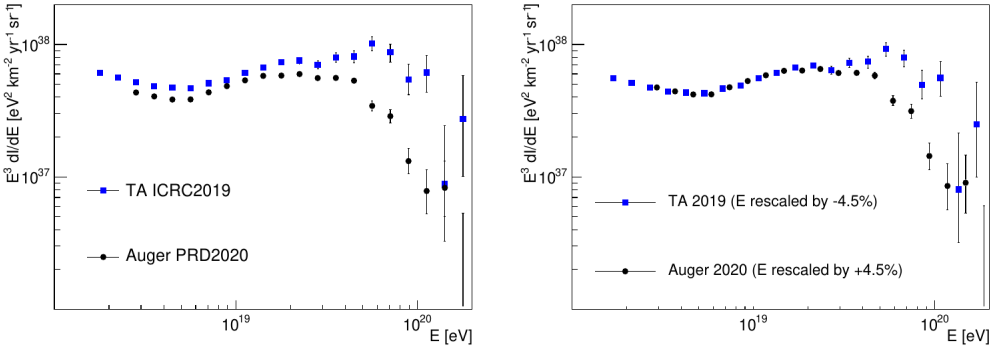



**Figure 1:** Left: Auger and TA energy spectra in the full fields of view ($-90° < \delta < +24.8°$ and $-15.7° < \delta < +90°$, respectively). Right: energy-rescaled spectra by the same amount ($\pm 4.5\%$) and in opposite directions.

# Comparison of TA and Auger Energy Spectra

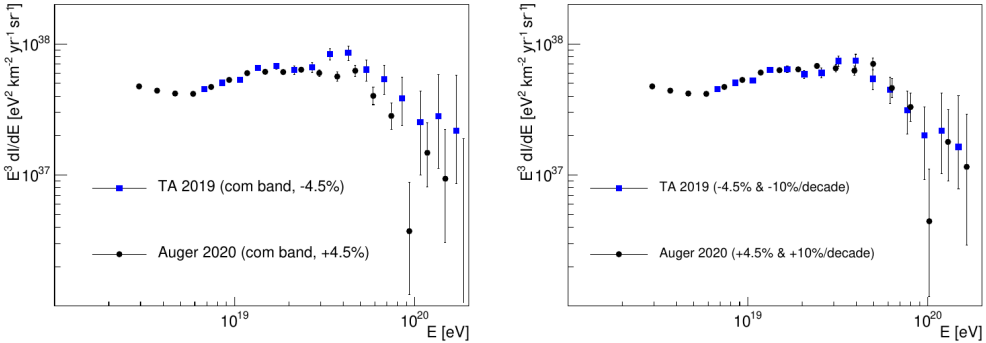



**Figure 2:** Left: Auger and TA spectra in the common declination band ($-15.7° < \delta < 24.8°$) with a constant shift $\pm 4.5\%$, Right: with an energy-dependent shift $\pm 10\% \times \log_{10}(E/10^{19}\ \mathrm{eV})$ for $E > 10^{19}$ eV.