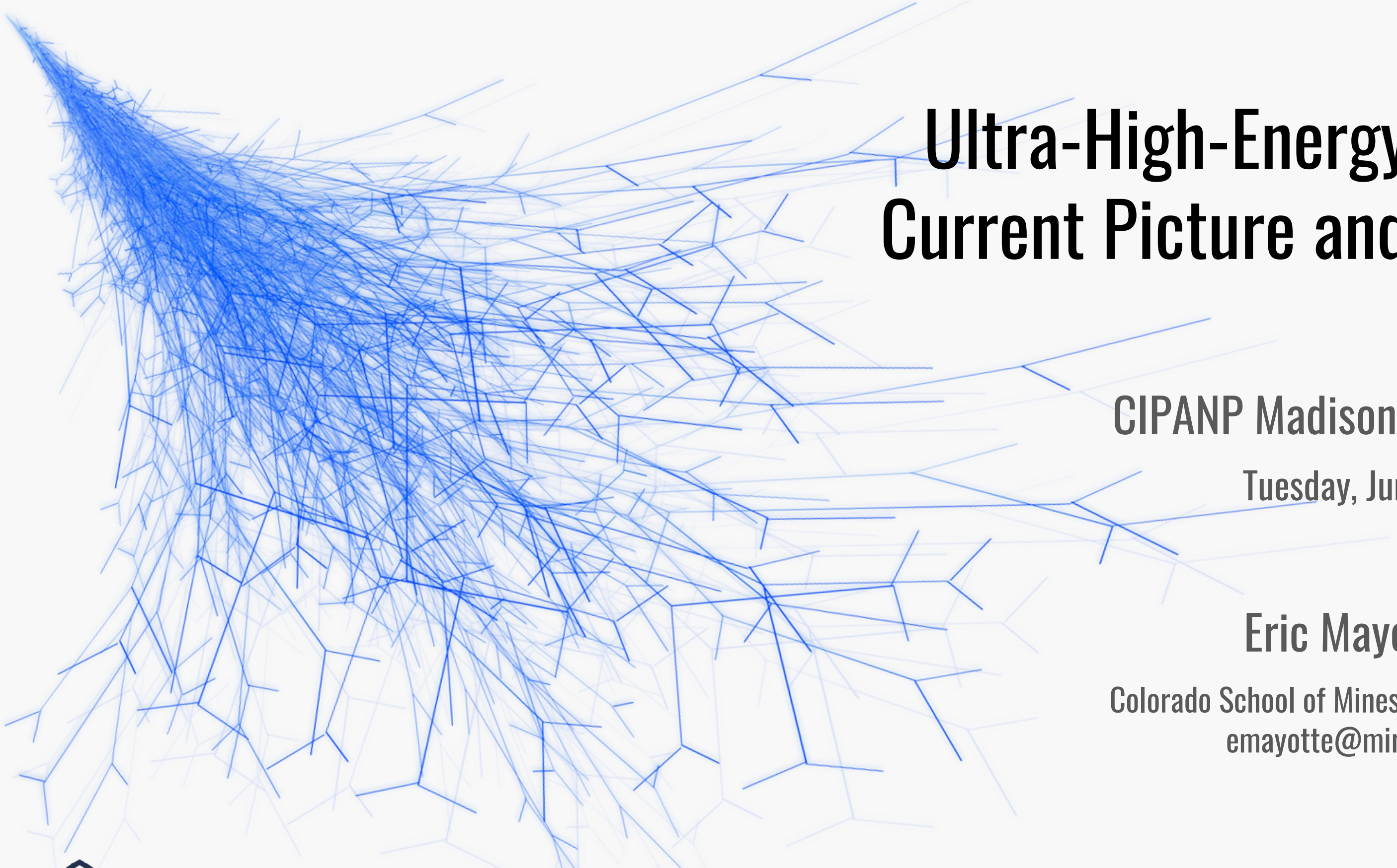


Ultra-High-Energy Cosmic Rays: Current Picture and Future Outlook

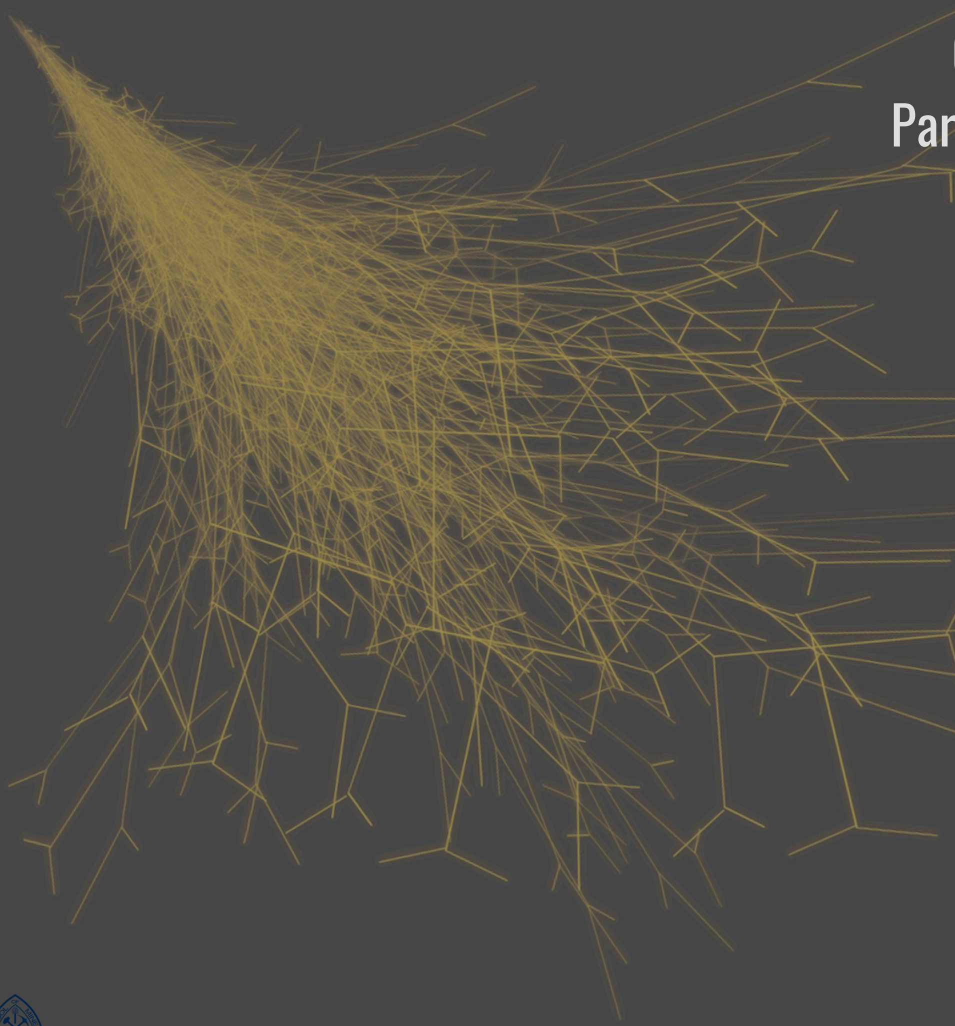
CIPANP Madison, Wisconsin

Tuesday, June 10th

Eric Mayotte

Colorado School of Mines, Golden CO, USA
emayotte@mines.edu

Funding



Chosen minimum UHECR definition:

Particles and nuclei with E ≥ 100 PeV from space

Material credit in order of quantity:

1. Pierre Auger Observatory
2. Telescope Array Project
3. EUSO Collaborations and Projects
4. Global Cosmic Ray Observatory (GCOS)

My Affiliations / Potential Biases

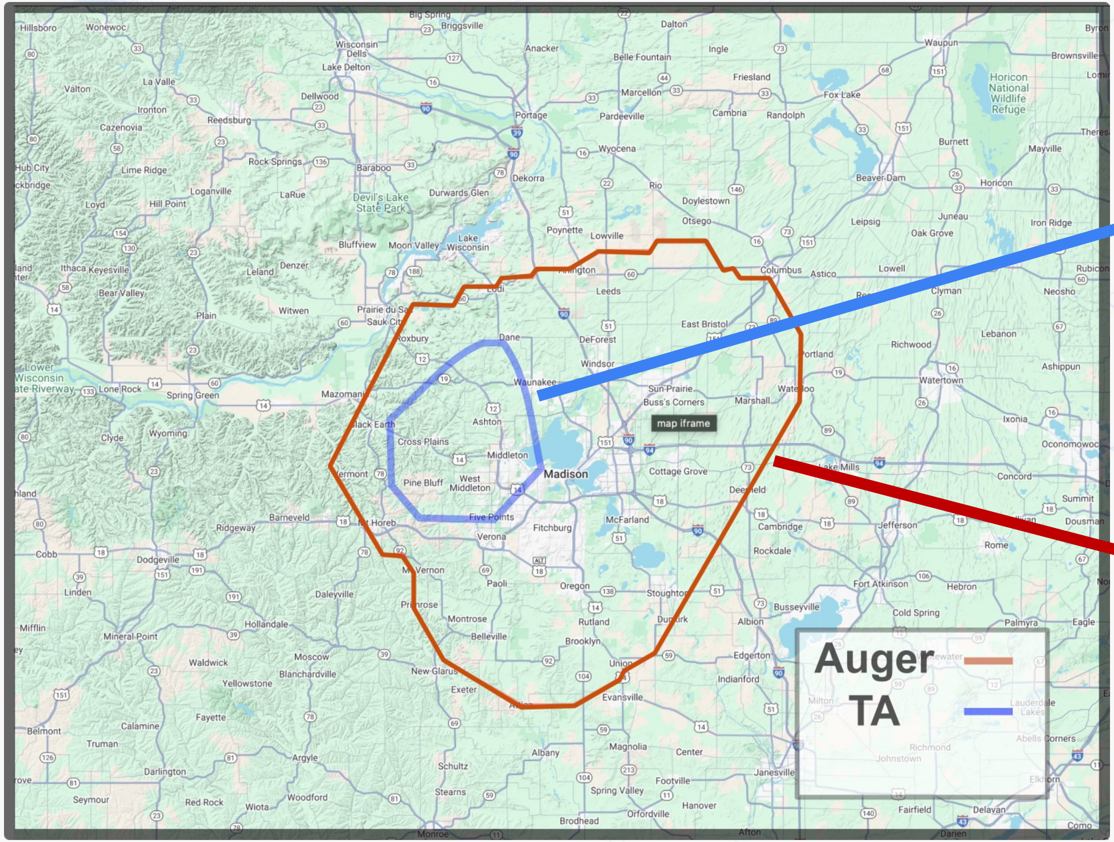
PIERRE AUGER OBSERVATORY

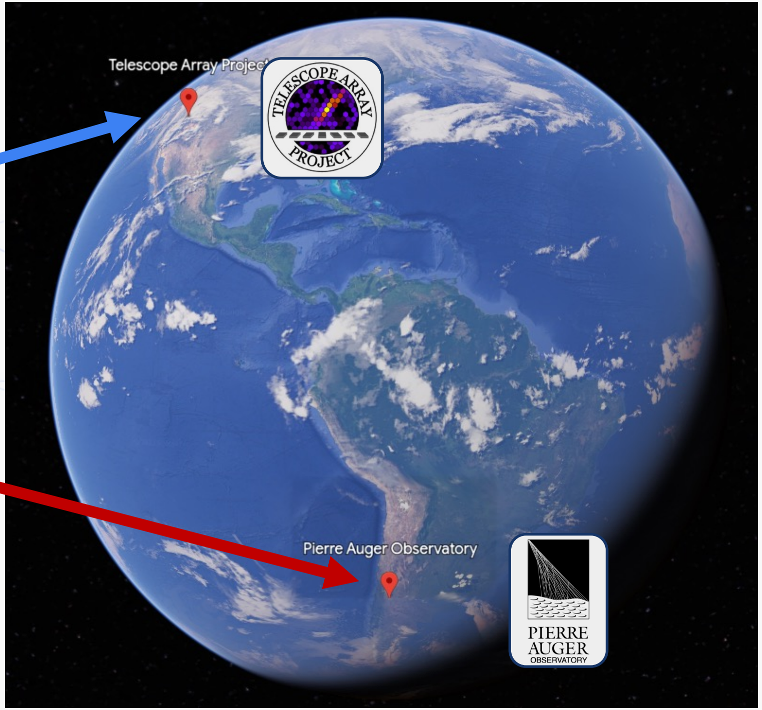
POEMMA BALLOON With RADIO

POEMMA

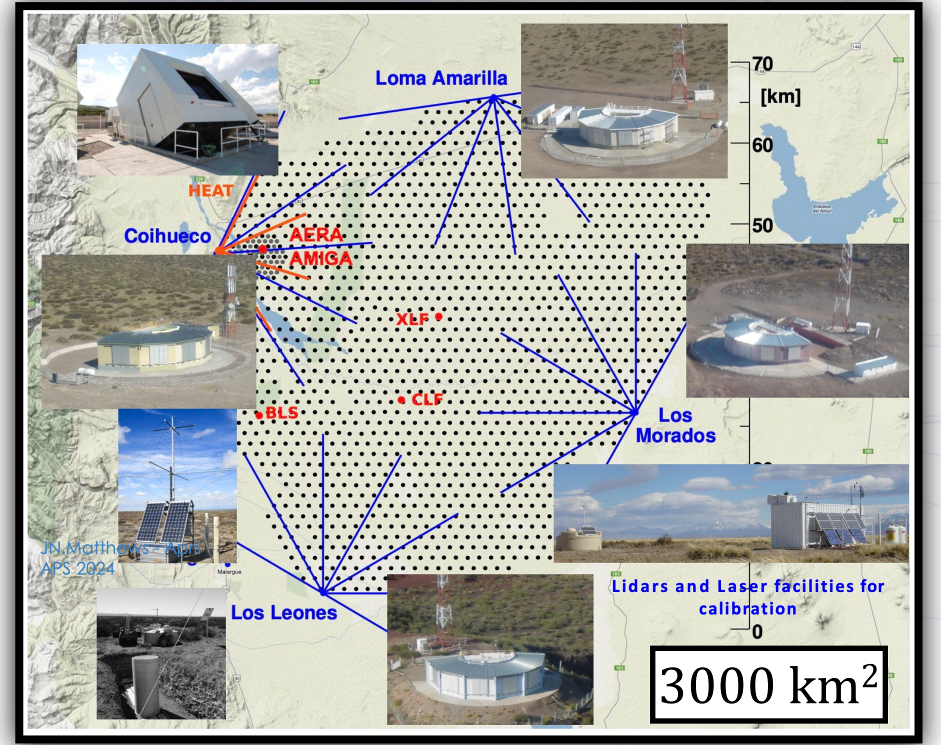
GCOS

The current generation of Ultra-High-Energy Cosmic Ray Detectors

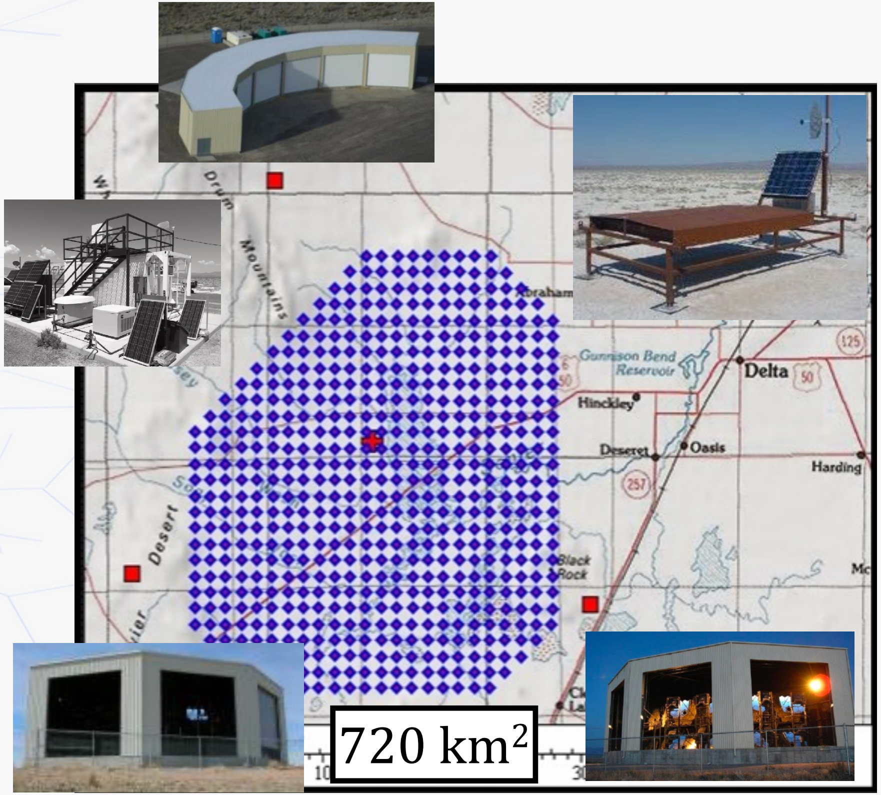




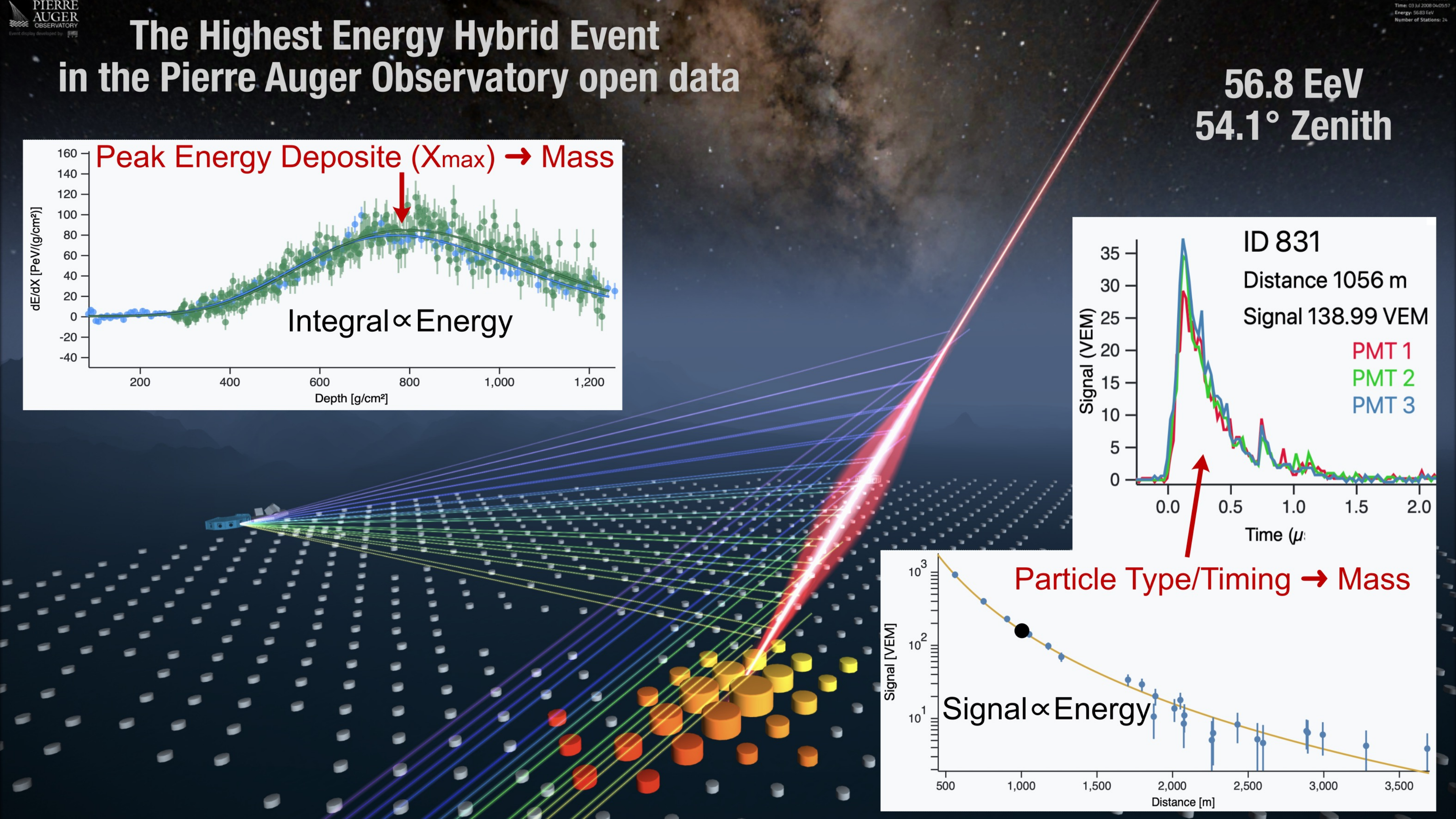
The Pierre Auger Observatory



The Telescope Array Project

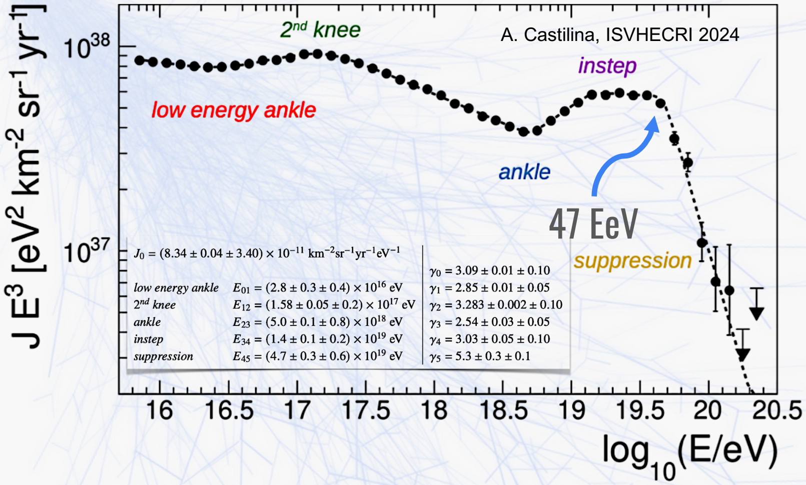


The Highest Energy Hybrid Event in the Pierre Auger Observatory open data

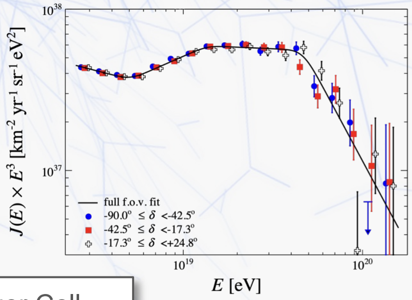


Current UHECR Spectrum

The Pierre Auger Observatory



No Significant Declination Dependence in the Auger Spectrum

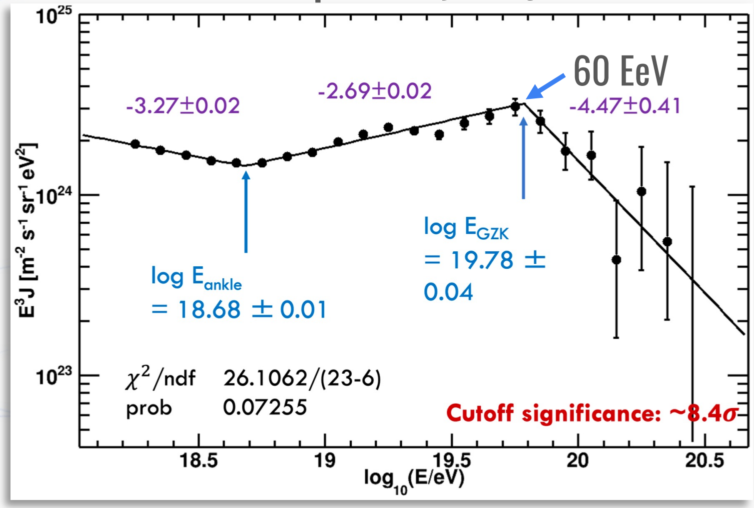


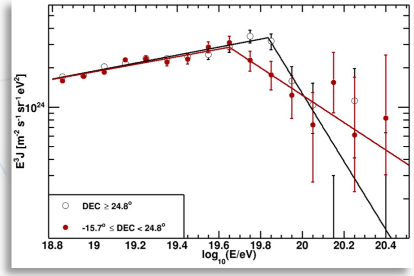
Pierre Auger Coll.
PRD 102 (2020) 062005

Pierre Auger Coll.
PRL125 (2020) 121106

Pierre Auger Coll.
EPJ C 81 (2021) 966

The Telescope Array Project



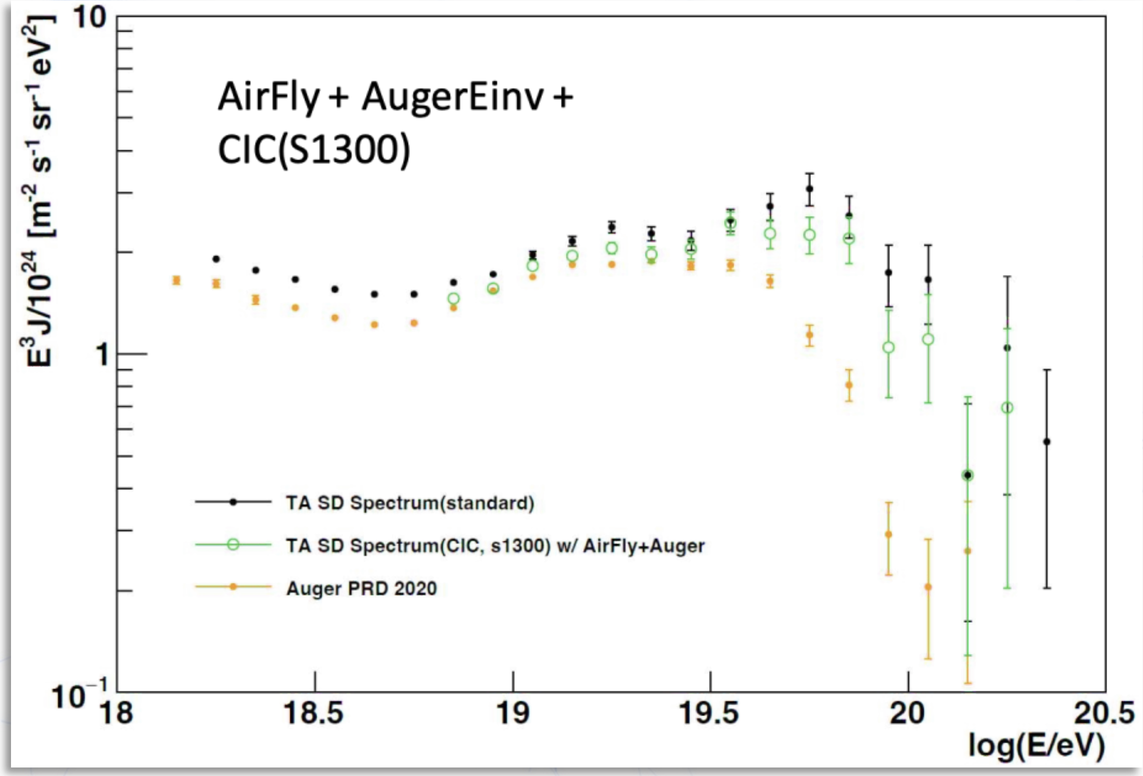


Declination dependence of Cutoff Energy at 4.4σ
δ < 24.8° $E_{break} = 10^{19.6}$ eV
δ > 24.8° $E_{break} = 10^{19.8}$ eV

J. N. Matthews | APS 2024
Invited UHECR Review

Hitoshi Oshima for T.A. Coll.
PoS ICRC2023 271

Spectrum Differences Between Northern and Southern Skies?



D. Bergman for Auger/TA
PoS ICRC2023 406

With original Calibration and Air fluorescence models:

TA / Auger Difference 9%
Well within the sys. uncert.

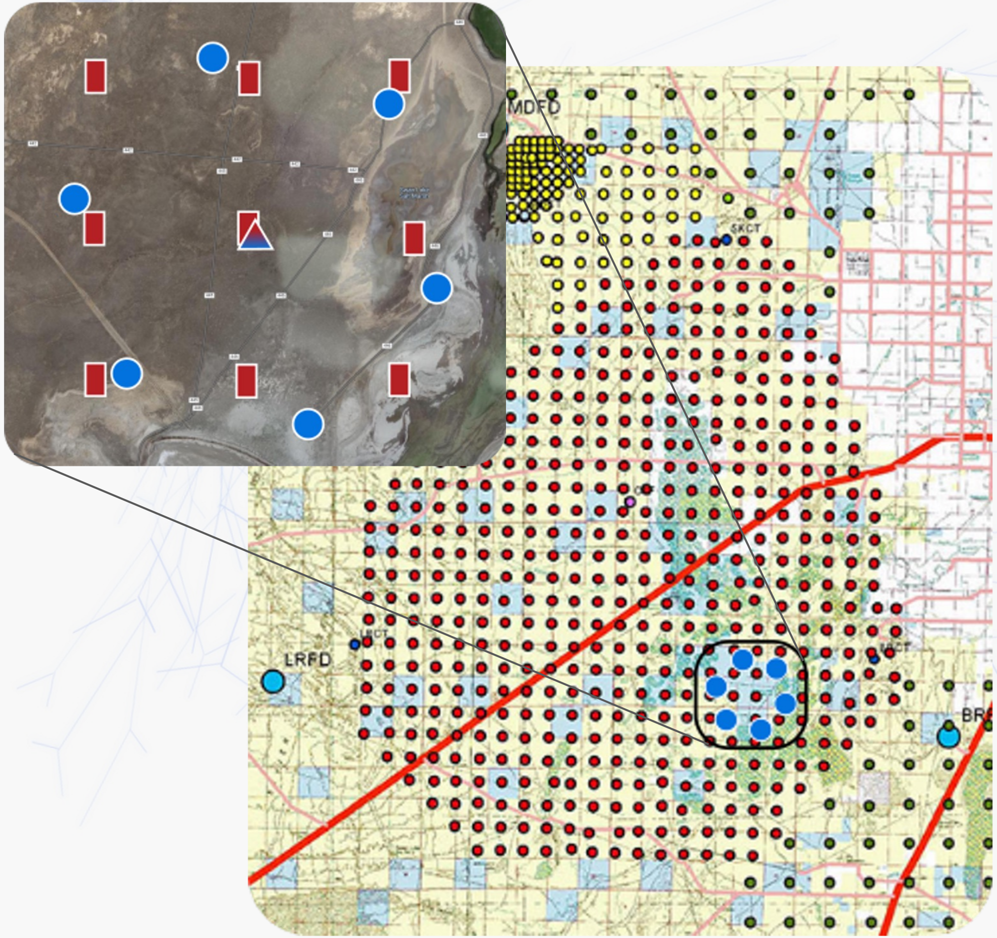
TA with Auger missing energy (CIC) and Airfly Air Fluorescence Model

TA / Auger Difference ~1%
in the common declination band

Difference remains at E > $10^{19.5}$ eV for TA's northernmost exposure

+ 10% per decade to Auger
- 10 % per decade TA needed

Probing Remaining Difference via Direct Comparison



In-situ cross-calibration of Auger and TA with an Auger-like SD Array

- Deployed in the south-east corner of TA array
- 9 Total Stations, 1 Hexagon, 1 Triplet
  - Hexagon of 7 (1 PMT) stations
  - 1 Auger South Station in Triplet
  - 1 TA Station in Triplet
  - All with Auger Prime SSDs
- Fully independent trigger and measurements

S. Mayotte for P.A. Coll.
Pos ICRC2023 368

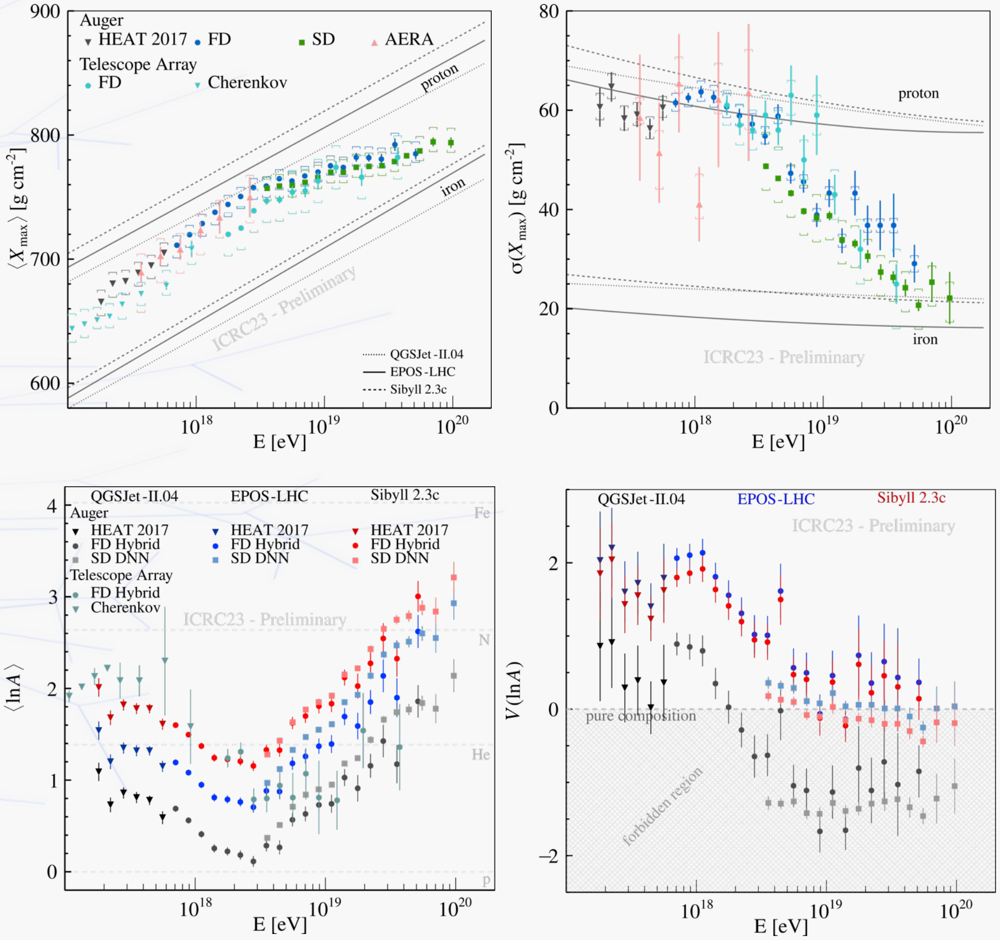
Measurments of UHECR Mass Composition

Xmax

The First and Second Moments
of the distributions of event Xmax
measured in each energy bin are used to
estimate mean composition for the Flux

ln*A*

The First and Second Moments of ln*A*
(the log of the mass of the primary)
can be derived from the Xmax moments
High Model Dependence

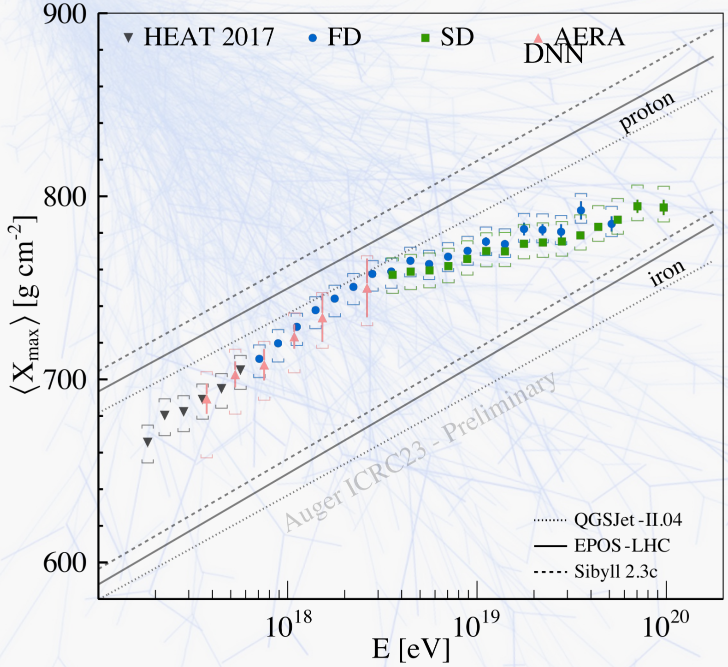


A. Coleman et al.
ApJ 149 (2023) 102819

E. Mayotte for Auger
Pos ICRC2023 365

Composition: Xmax Measurements

The Pierre Auger Observatory



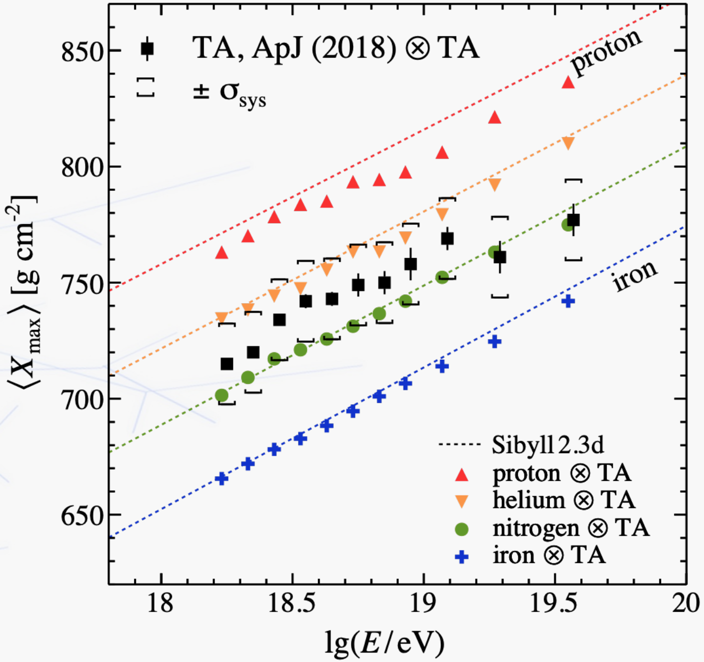
Pierre Auger Coll.
PRL 134 (2025) 2, 021001

T. Fitoussi for P.A. Coll.
Pos ICRC2023 438

Pierre Auger Coll.
PRL 132 (2024) 2, 021001

J. Bellido for P. A. Coll.
PoS ICRC2017 506

The Telescope Array Project



A. Yushkov for Auger/TA
Pos ICRC2023 249

Telescope Array Project
ApJ. 909 (2) (2021) 178

Telescope Array Project
ApJ. 858 (2) (2018) 76

Comparing TA and Auger Xmax Measurements

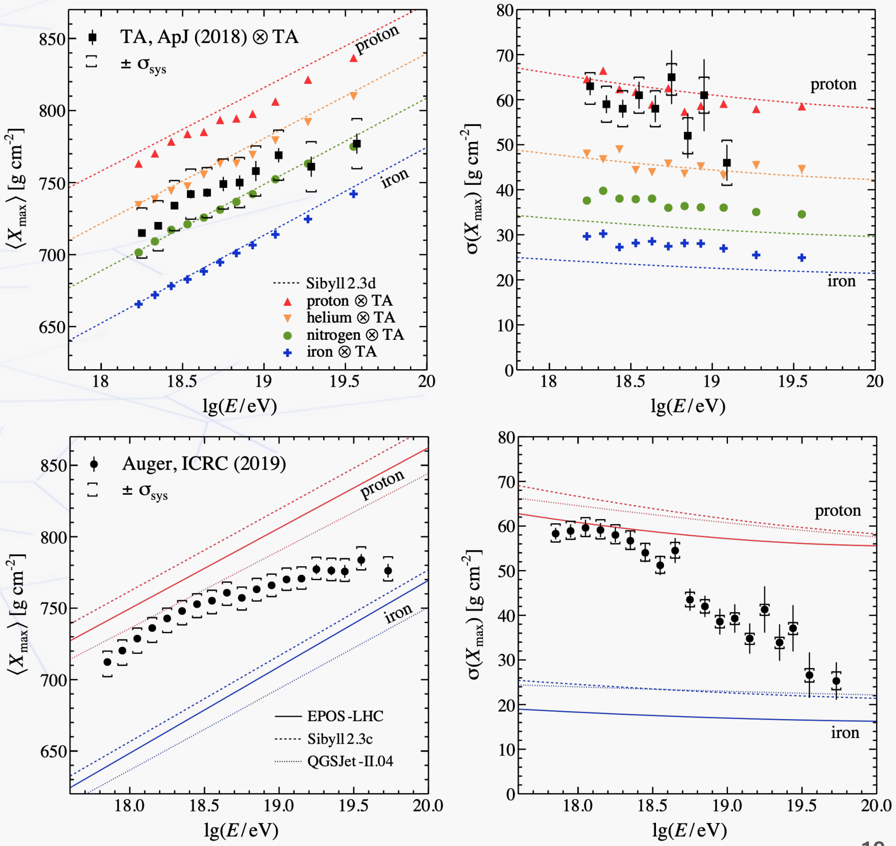
A. Yushkov for Auger/TA
Pos ICRC2023 249

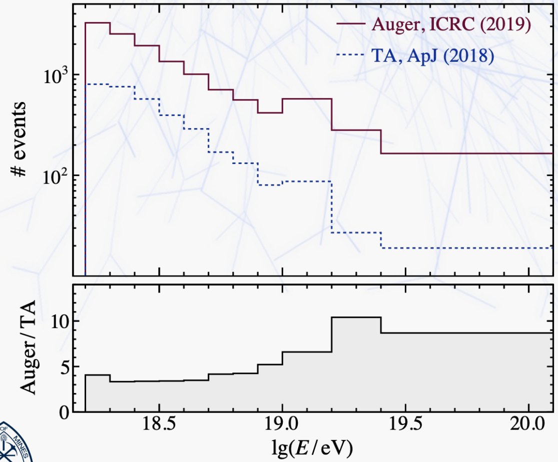
PRD in prep

Direct comparisons through Xmax are not possible:

Auger Detector effects are accounted for or removed from Xmax Moments.

TA Detector effects are folded into Xmax Moments and addressed in the interpretation.





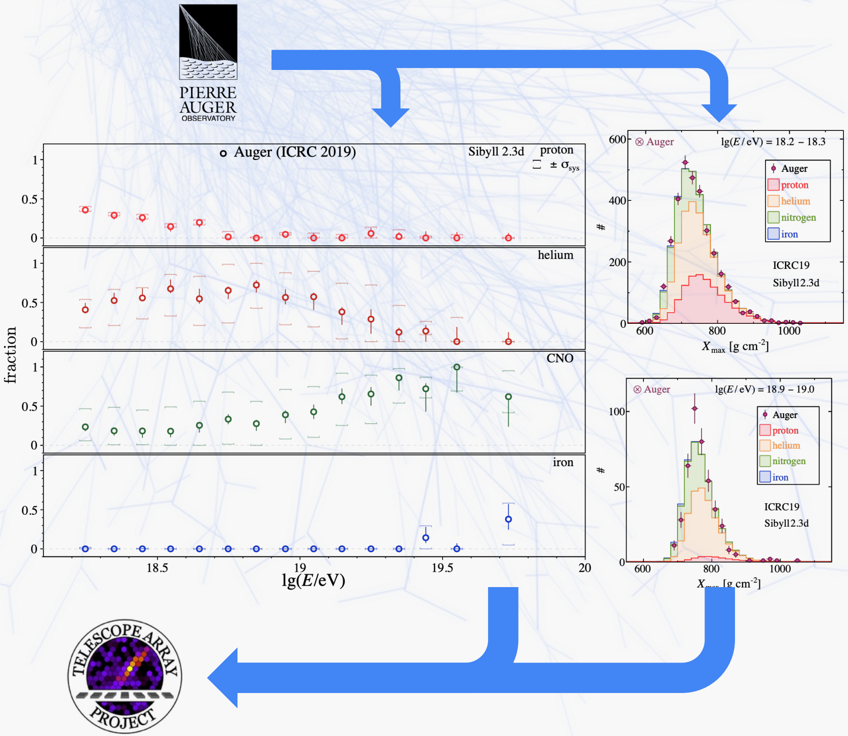
Auger and TA are meaningfully unequal in statistics, resulting in large uncertainties in joint comparisons

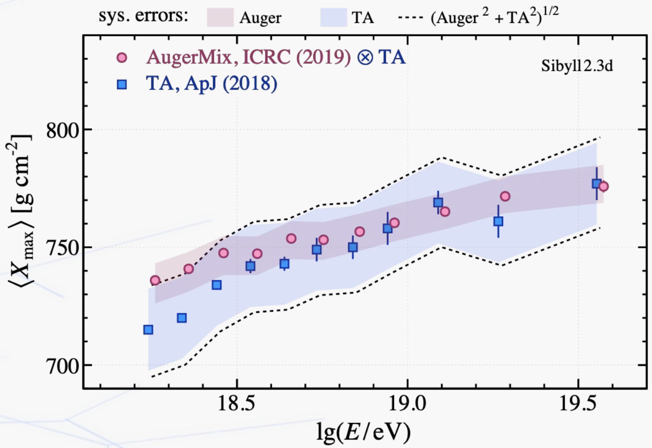
Comparing TA and Auger Xmax Measurements

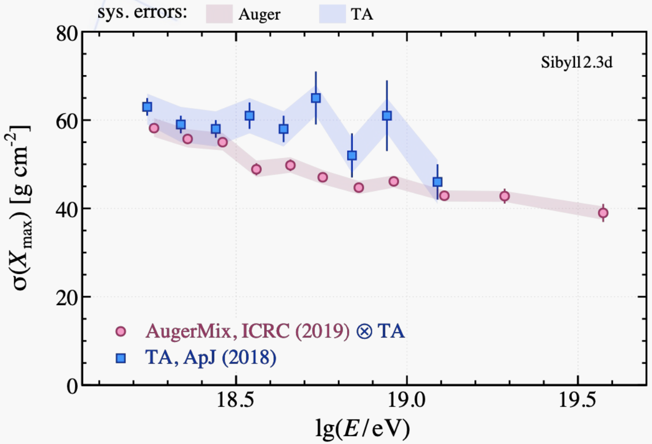
A. Yushkov for Auger/TA
Pos ICRC2023 249

PRD in prep

Solution: Bring Auger best fit mass fractions into TA detector simulations and then compare.







Comparing TA and Auger Xmax Measurements

A. Yushkov for Auger/TA
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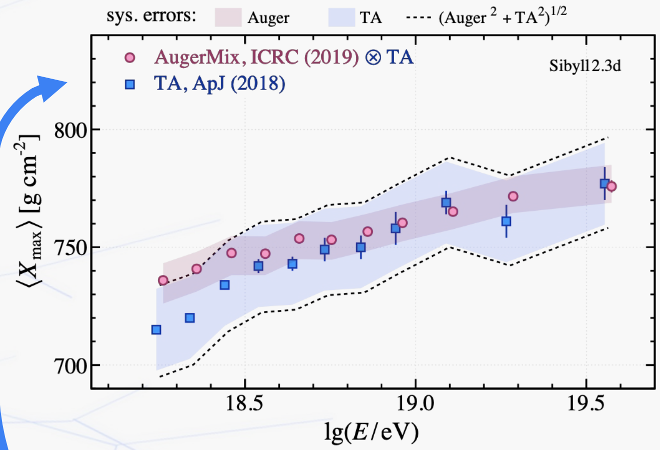
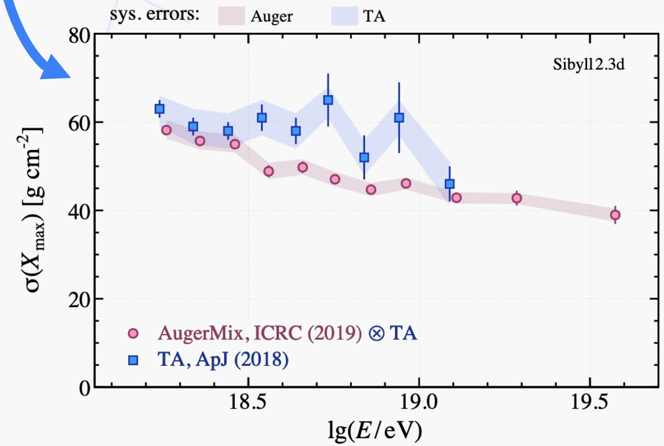
← PRD in prep

Solution: Bring Auger best fit mass fractions into TA detector simulations and then compare.

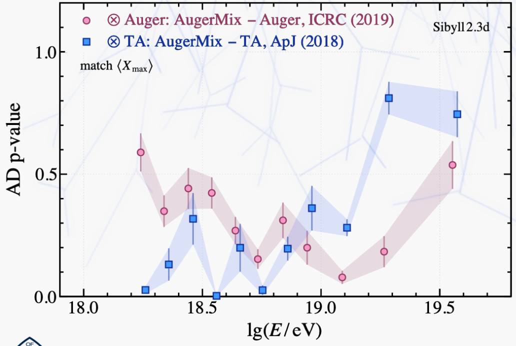
Result: Auger composition and TA Xmax Measurements are quite compatible for examined energy range.

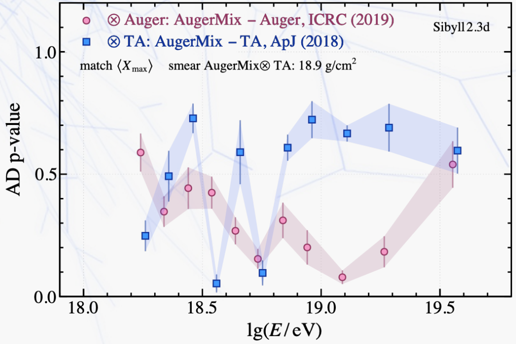




Additionally

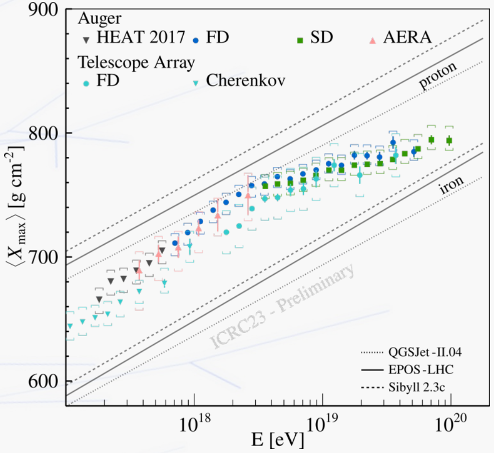
No clear differences in the shapes of the Xmax distributions could be resolved.

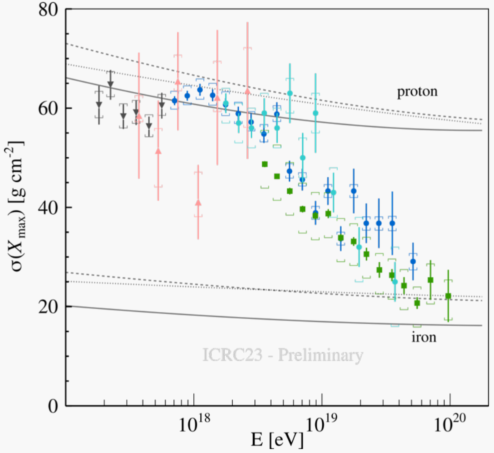




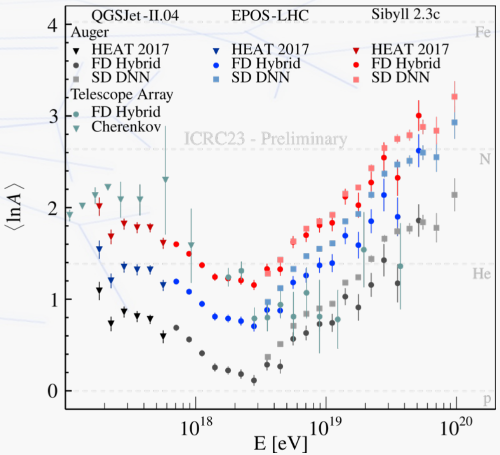
Current UHECR Mass Composition Picture

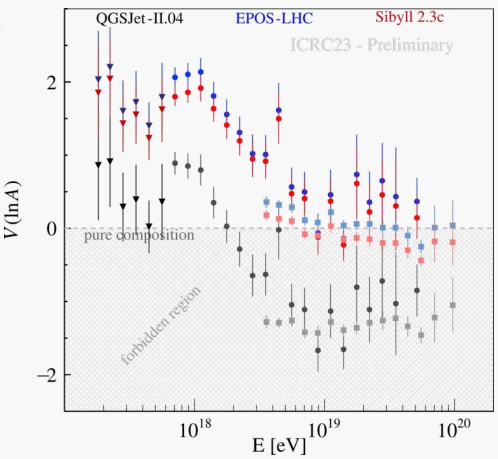
The First and Second Moments
of the distributions of event Xmax
measured in each energy bin





The First and Second Moments of ln$A$
(the log of the mass of the primary)
derived from the Xmax moments
High Model Dependence





A. Coleman et al.
ApJ 149 (2023) 102819

E. Mayotte for Auger
Pos ICRC2023 365

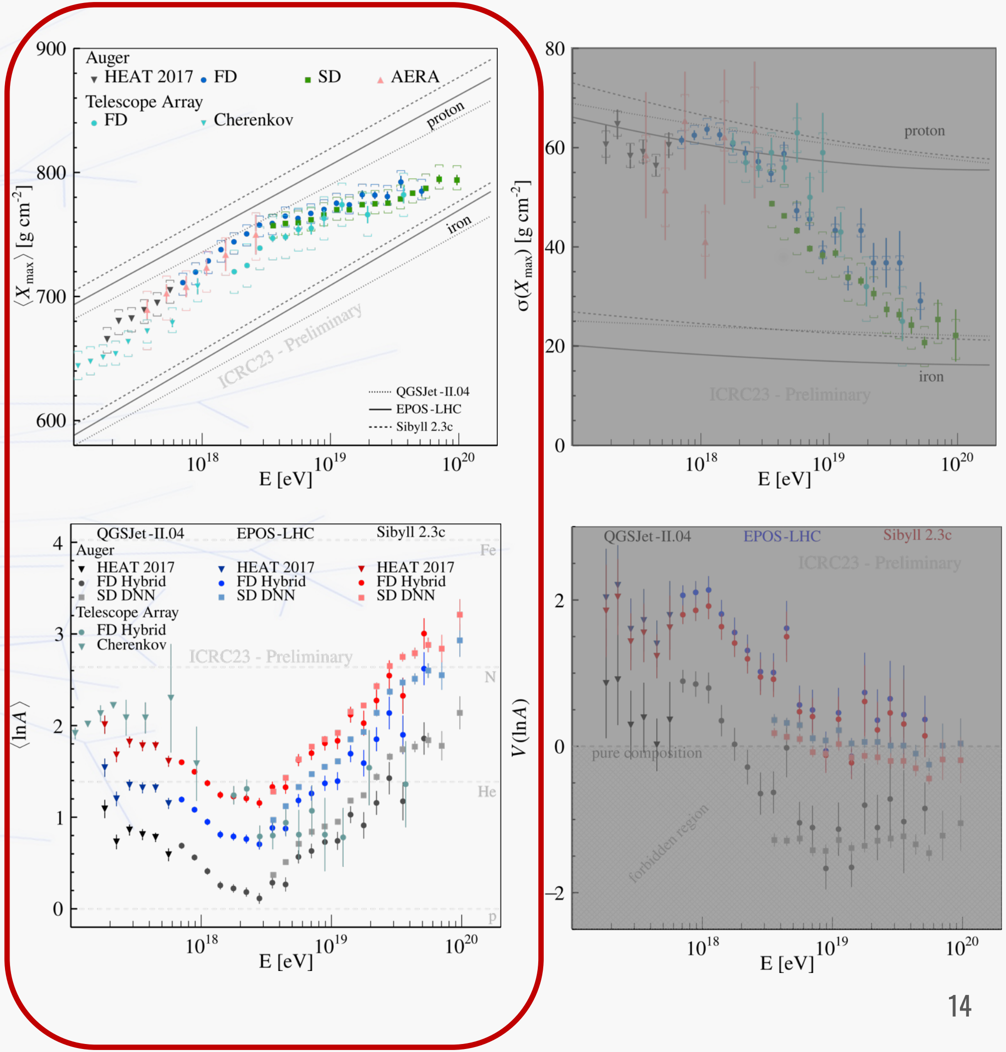
Current UHECR Mass Composition Picture

The mean mass of UHECR primaries:

E < 1 EeV	Moderately heavy composition becoming lighter
1 to 10 EeV	Lightest composition at 2-3 EeV
E > 10 EeV	UHECR composition becomes increasingly heavy with energy

The spread of UHECR primary masses:

E < 1 EeV	UHECR beam is highly mixed in composition until ~ 1 EeV
1 to 10 EeV	UHECR beam transitions from mixed to relatively pure
E > 10 EeV	Beam has only 1 or 2 components



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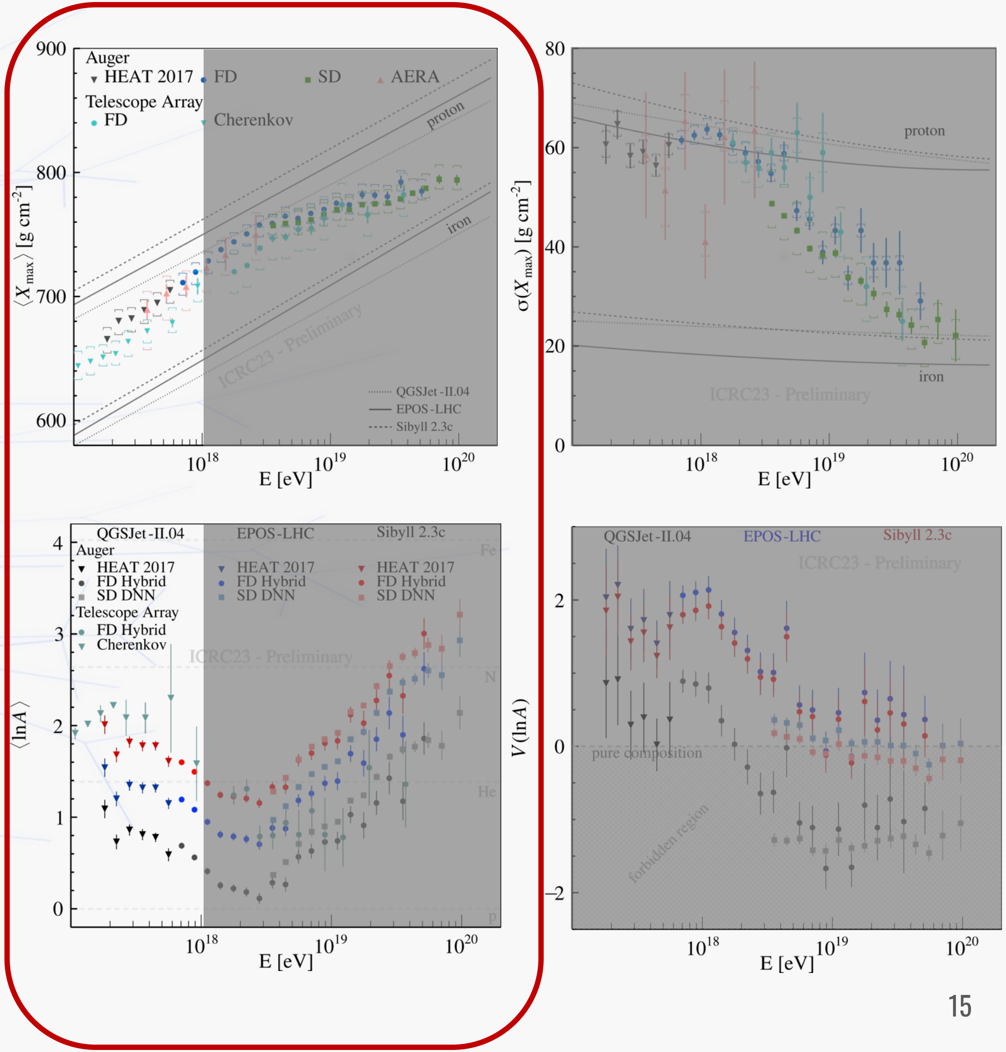

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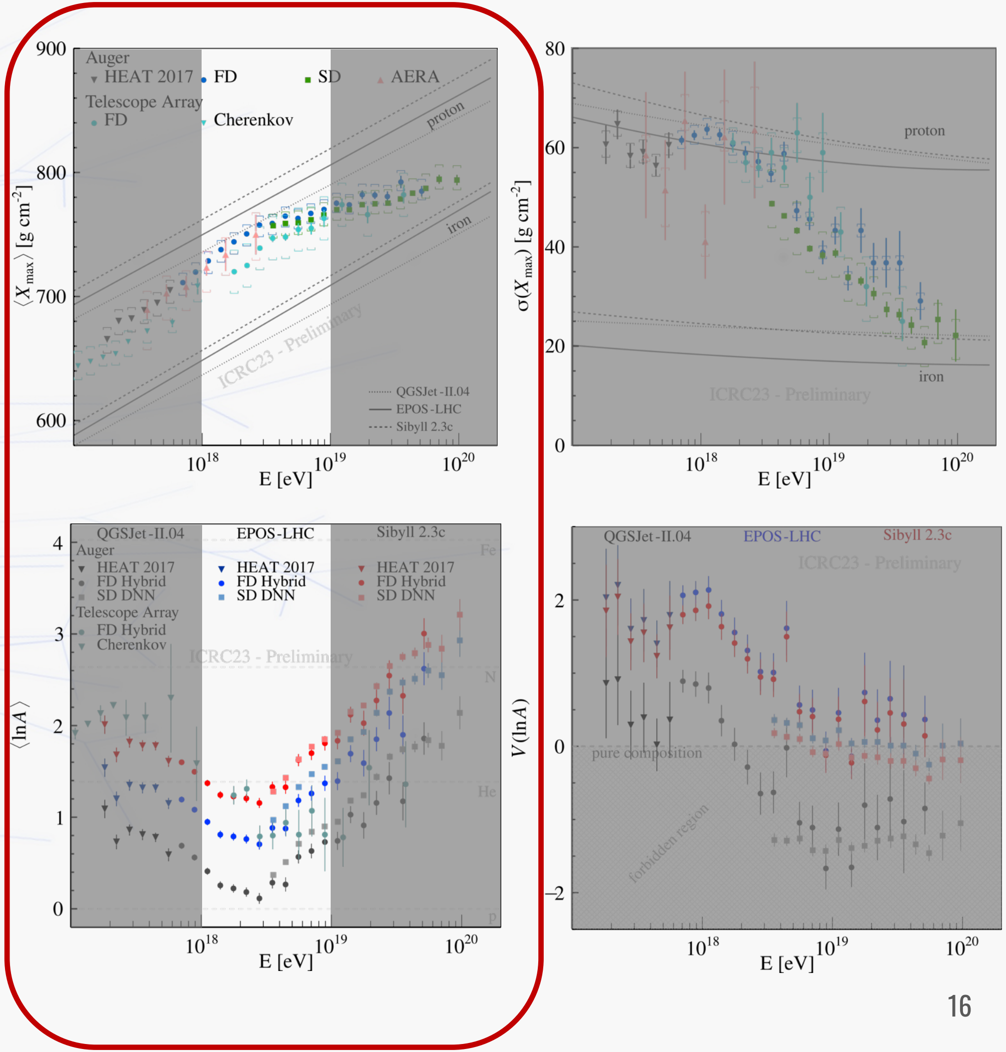

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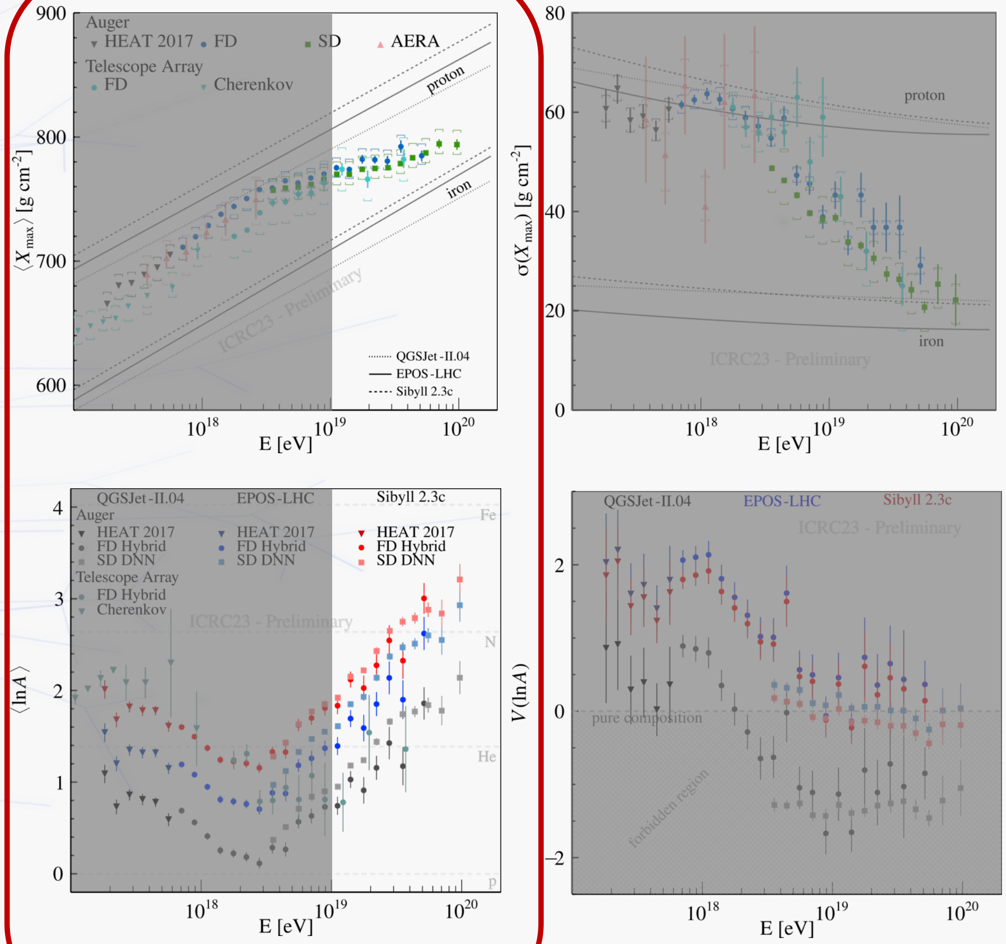

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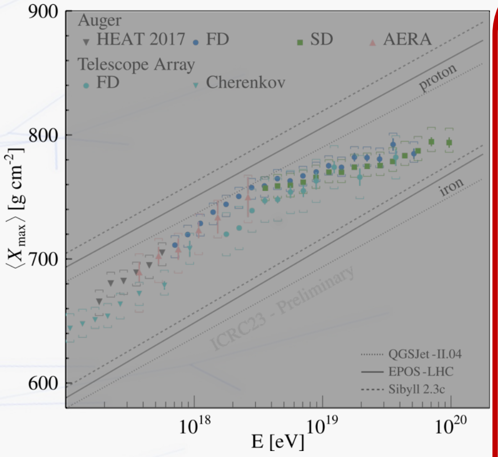

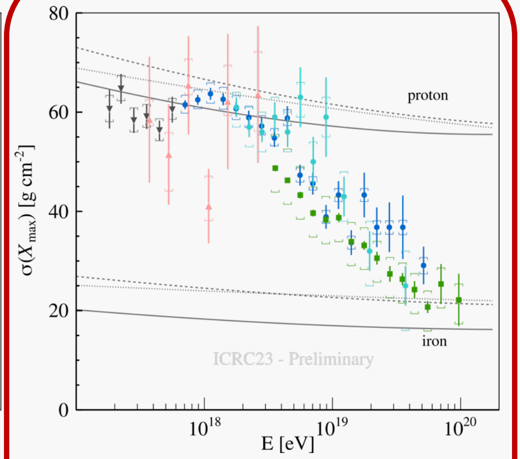

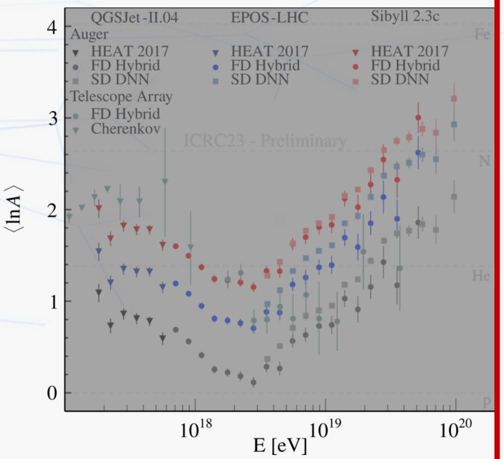

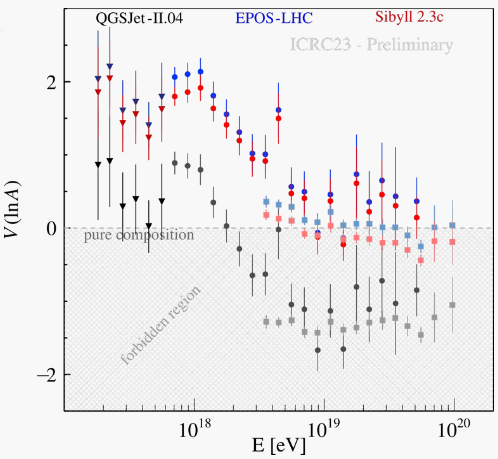

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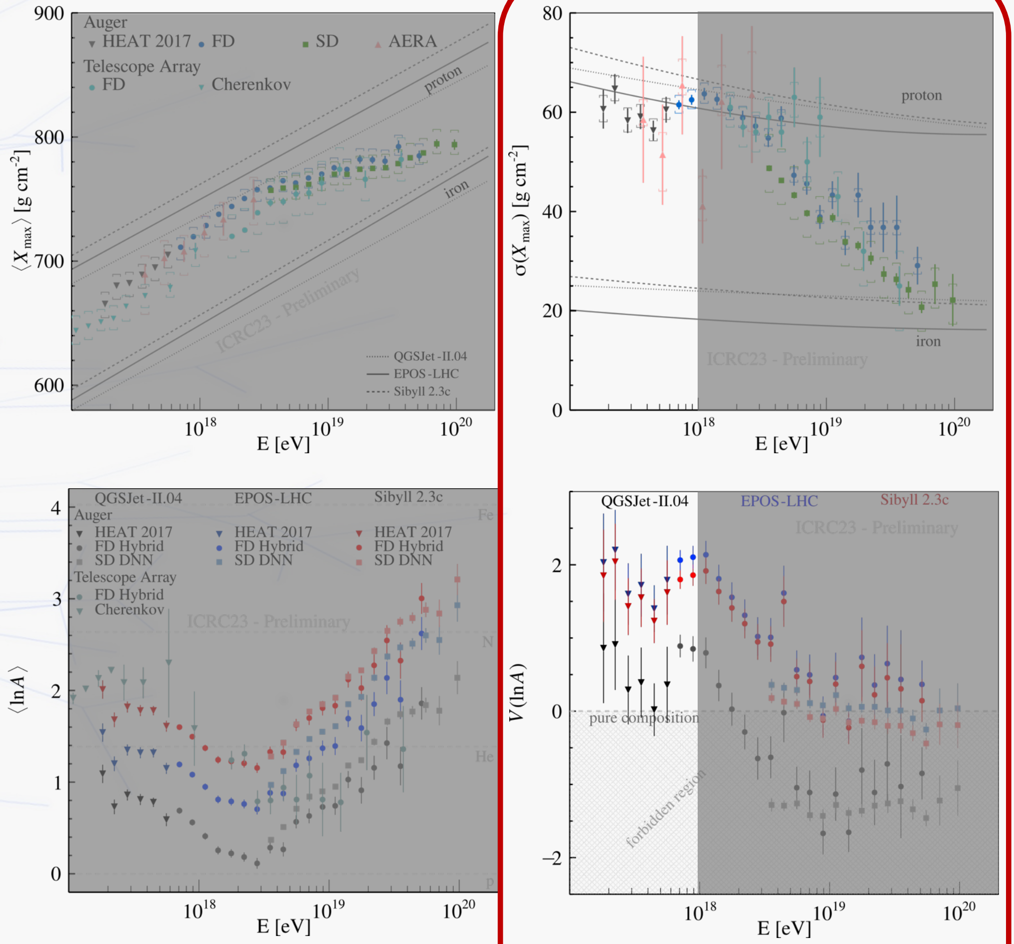

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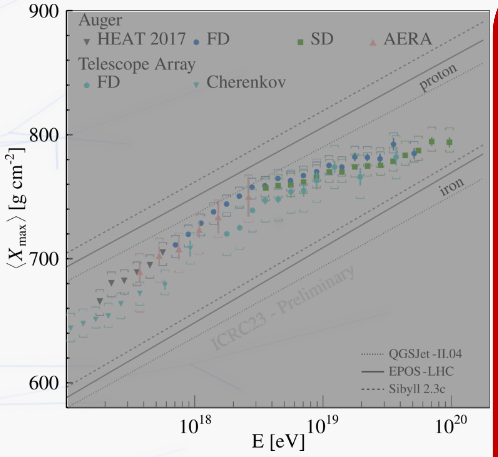

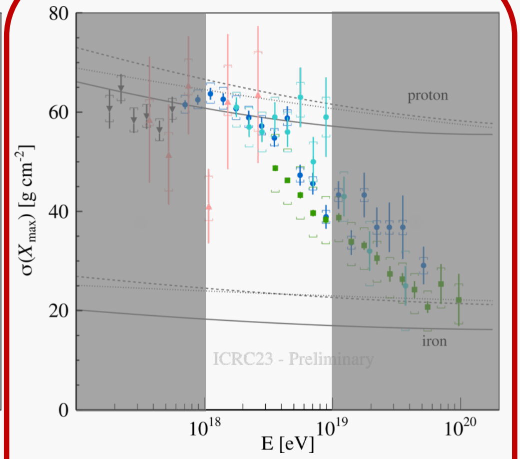

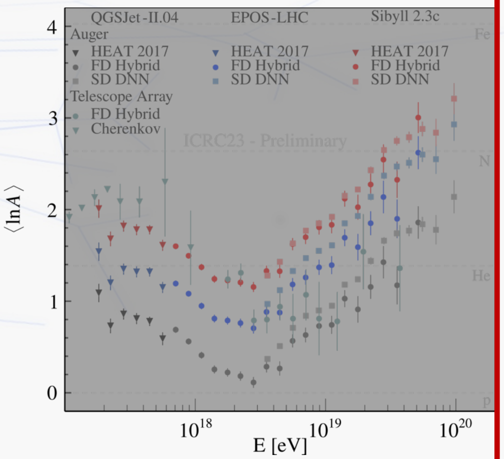

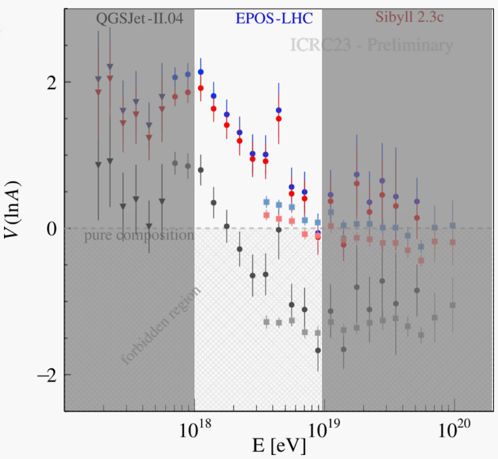

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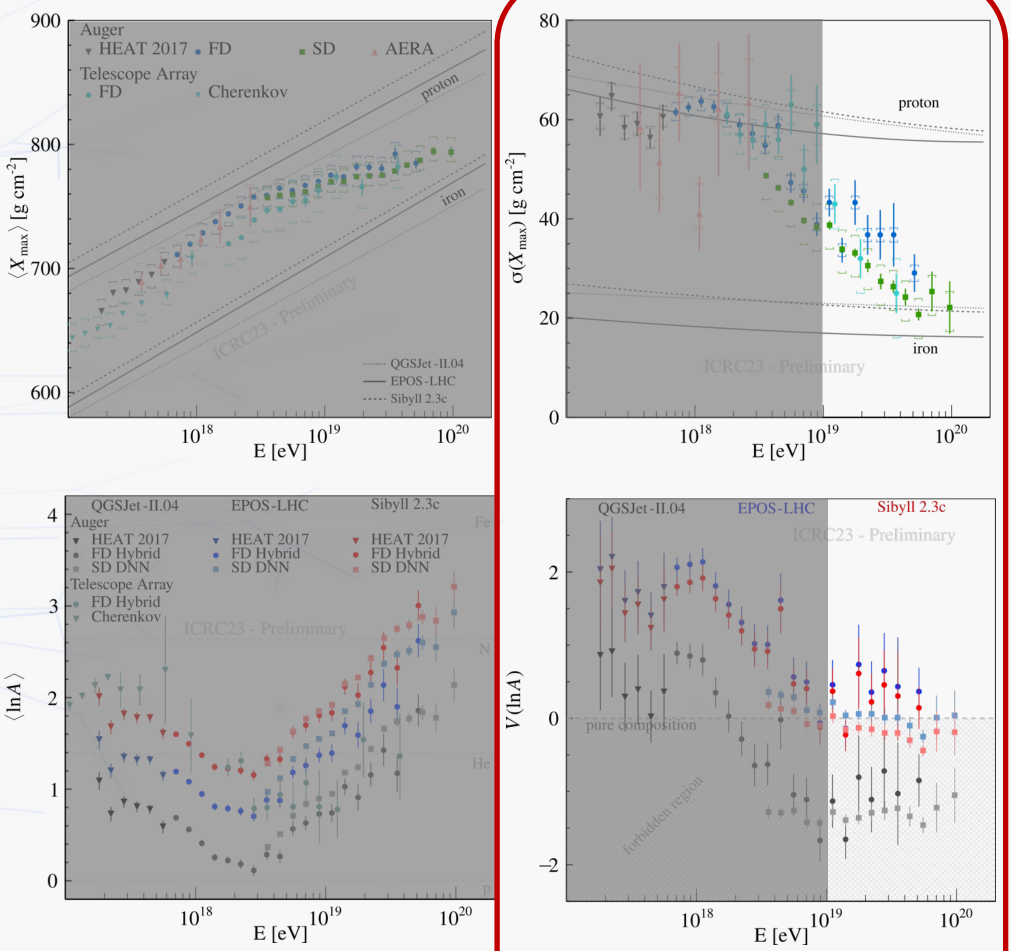


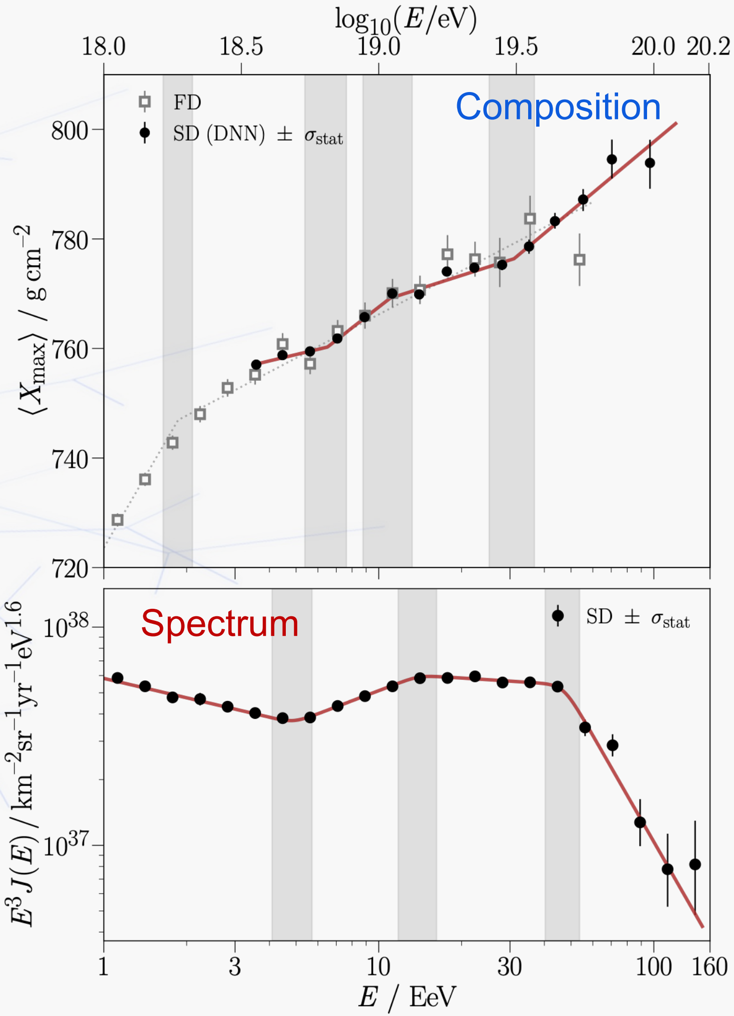
New Composition Feature: Fine structure

- With the new DNN-based SD Xmax, statistics are high enough to start testing for fine structure.
- A constant mass evolution above 3EeV can be rejected at greater than 4 σ
- 3-breaks produce the best fit with breaks at similar energies as the spectrum

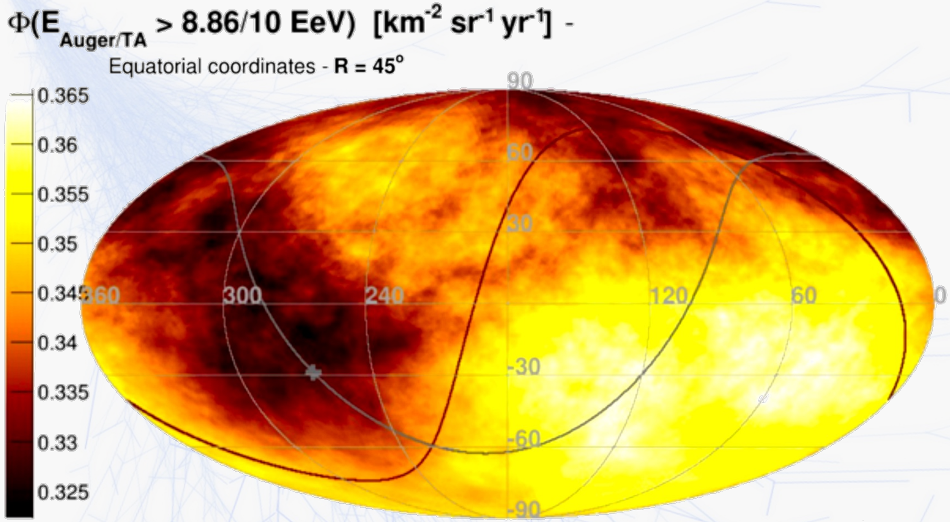
parameter val $\pm\sigma_{stat}\pm\sigma_{sys}$	3-break model val $\pm\sigma_{stat}\pm\sigma_{sys}$	energy spectrum val $\pm\sigma_{stat}\pm\sigma_{sys}$
b / g cm^{-2}	$750.5\pm3\pm13$	
D_0 / g cm^{-2} decade^{-1}	$12\pm5\pm6$	
E_1 / EeV	$6.5\pm0.6\pm1$	$4.9\pm0.1\pm0.8$
D_1 / g cm^{-2} decade^{-1}	$39\pm5\pm14$	
E_2 / EeV	$11\pm2\pm1$	$14\pm1\pm2$
D_2 / g cm^{-2} decade^{-1}	$16\pm3\pm6$	
E_3 / EeV	$31\pm5\pm3$	$47\pm3\pm6$
D_3 / g cm^{-2} decade^{-1}	$42\pm9\pm12$	

Pierre Auger Coll.
PRL 134 (2025) 2, 021001

Pierre Auger Coll.
PRD 11 (2025) 2, 022003



Large Scale Anisotropy: Dipole at E > 8EeV



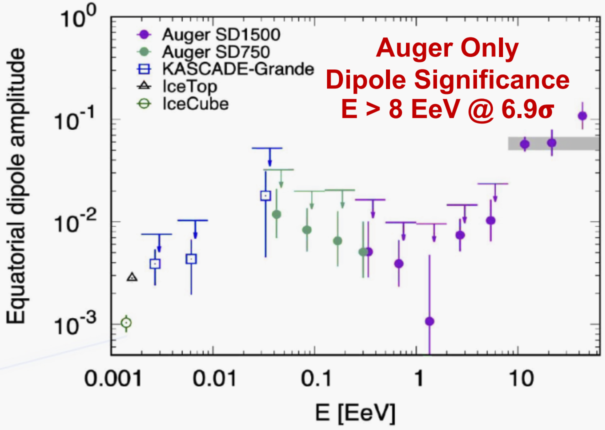
The above flux map is immediately interpretable

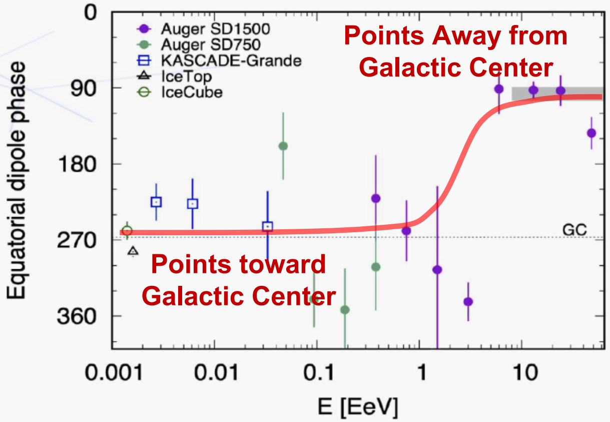
- ➢ equal sensitivity anywhere in the sky
- ➢ upper limits uniform over the sky
- ➢ no need for methods to re-weight individual exposures

Confirm the presence of a dipole pointing away from the GC

L. Caccianiga for P.A. and T.A. Colls.
PoS ICRC2023 521

A. Castellina
ISVHECRI 2024

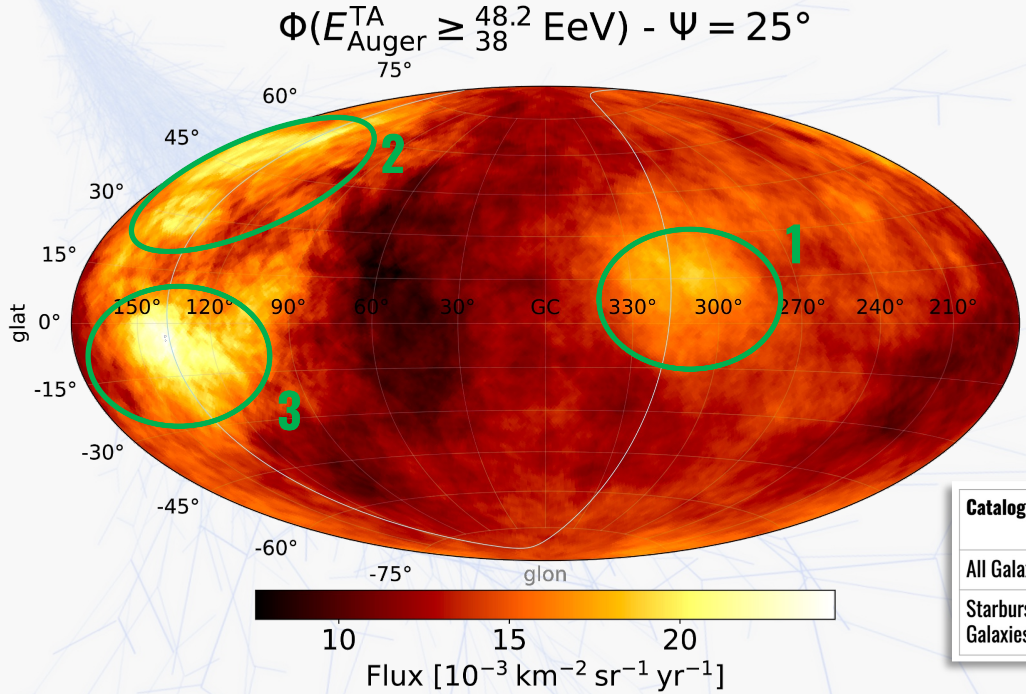


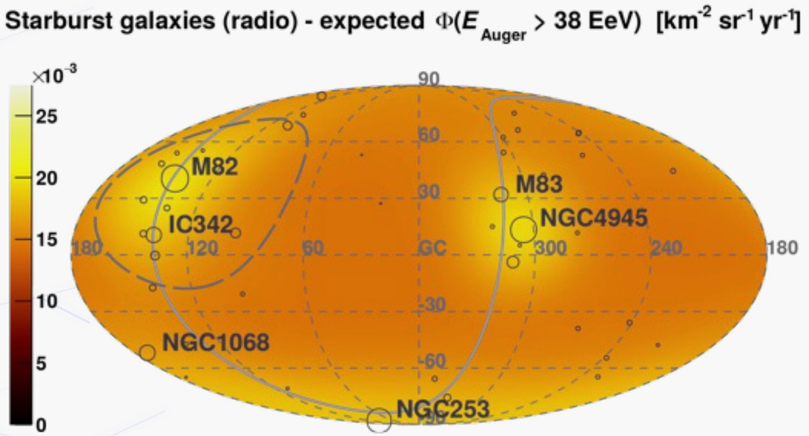


G. Golup for P.A. Coll.
PoS ICRC2023 252

Pierre Auger Coll.
Science 357 (2017) 6537

Intermediate Scale Anisotropy





Catalog	E_{Auger} threshold	E_{TA} threshold	Θ	f	TS	post-trial significance
All Galaxies	38 [40]	48.2 [51]	18.7 [29]	24.8 [41]	14.7 [14.3]	2.8σ [2.7σ]
Starburst Galaxies	38 [38]	48.2 [49]	15.4 [15.1]	11.7 [12.1]	30.5 [31.1]	4.6σ [4.7σ]

Exposure:
Auger 135,000 km² sr yr
TA 17,500 km² sr yr

Events: 3340 events
Auger 2004-2022
TA 2008-2022

Hot/Warm Spots found

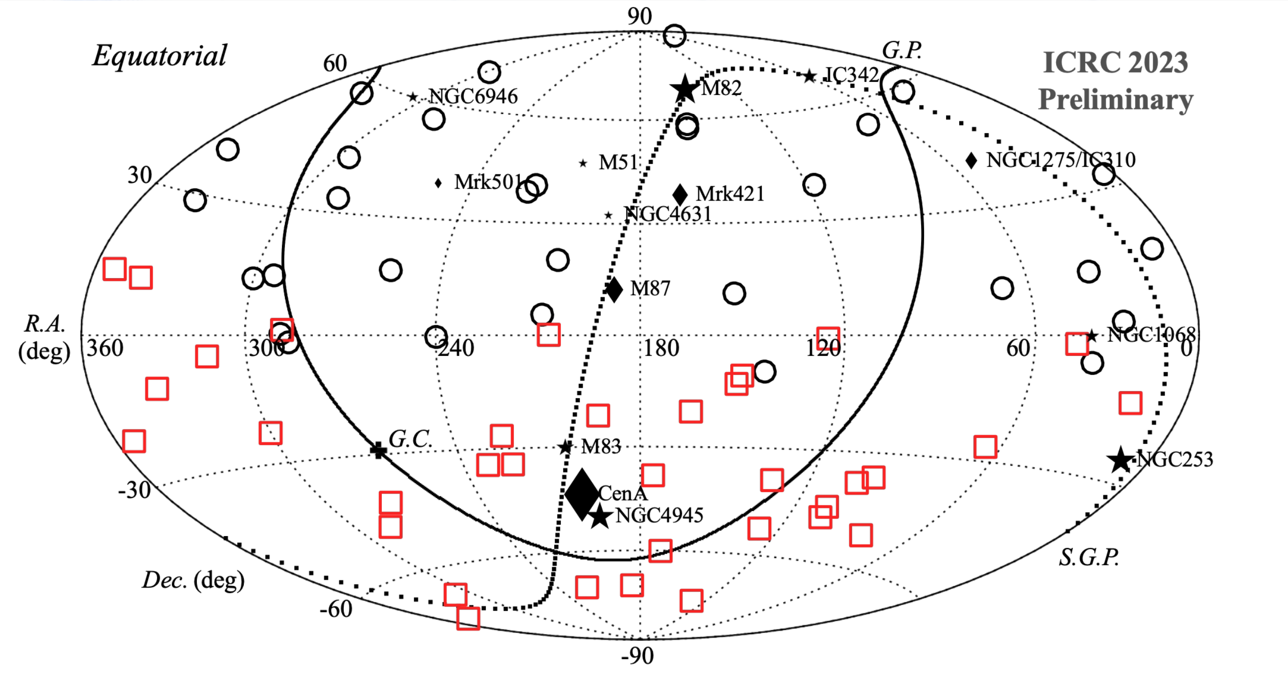
In the south: 1) Centaurus region and M253 (1)
In the north: 2) Ursa Major region
3) Perseus-Pisces regio

L. Caccianiga for P.A. and T.A. Colls.
PoS ICRC2023 521

A. Castellina
ISVHECRI 2024

Pierre Auger Coll.
ApJ. 935 (2022) 2, 170

UHECR Arrival Directions above 100 EeV



TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

No obvious sources or significant clustering above 100 EeV

This level of isotropy strongly disfavors Protons at the highest energies event at extremely high EGMF strengths.

Telescope Array Coll.
PRL 133 (2024) 4, 041001

J. N. Matthews | APS 2024
Invited UHECR Review

T. Fujii CRI Rapporteur
PoS ICRC2023 (2024) 031

Developing: Anisotropy in Mass

Using FD X_{max} (soon also SD X_{max}) , Anisotropy as a function of UHECR composition can be searched for

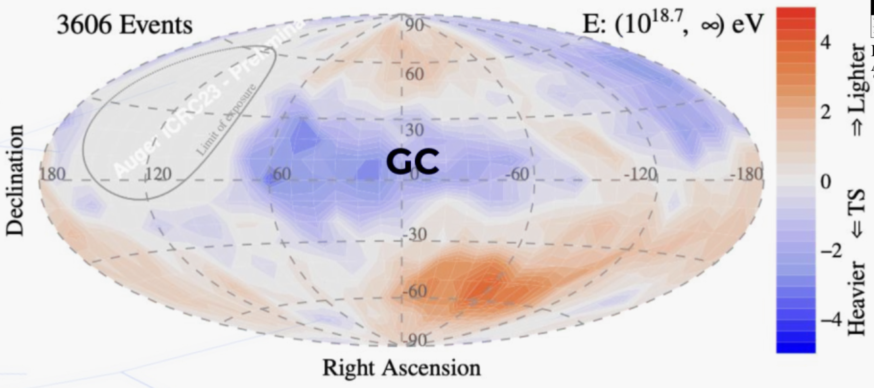
First result:

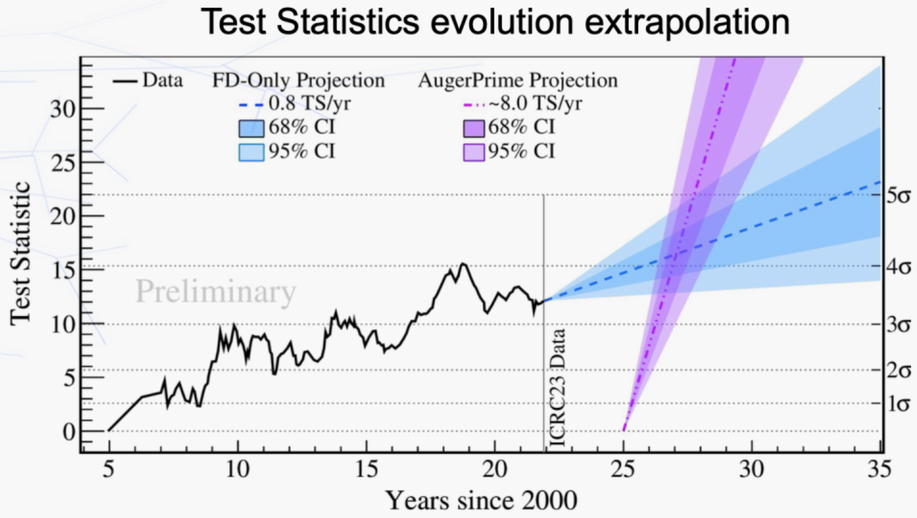
Above 5 EeV a slightly heavier mass was observed for UHECR arriving from within 30º of the Galactic Plane as compared to the rest of the sky

Current significance ~3**σ**

The current growth rate puts 5**σ** in 2034, with Upgraded Auger ➜ 2028.

E. Mayotte for Auger Pos ICRC2023 365





PoS ICRC2023 (2023) 365

The Next 10 Years: TAx4

Target ➜ Auger-like Statistics in FD and SD

TA×4

Expansion of the SD

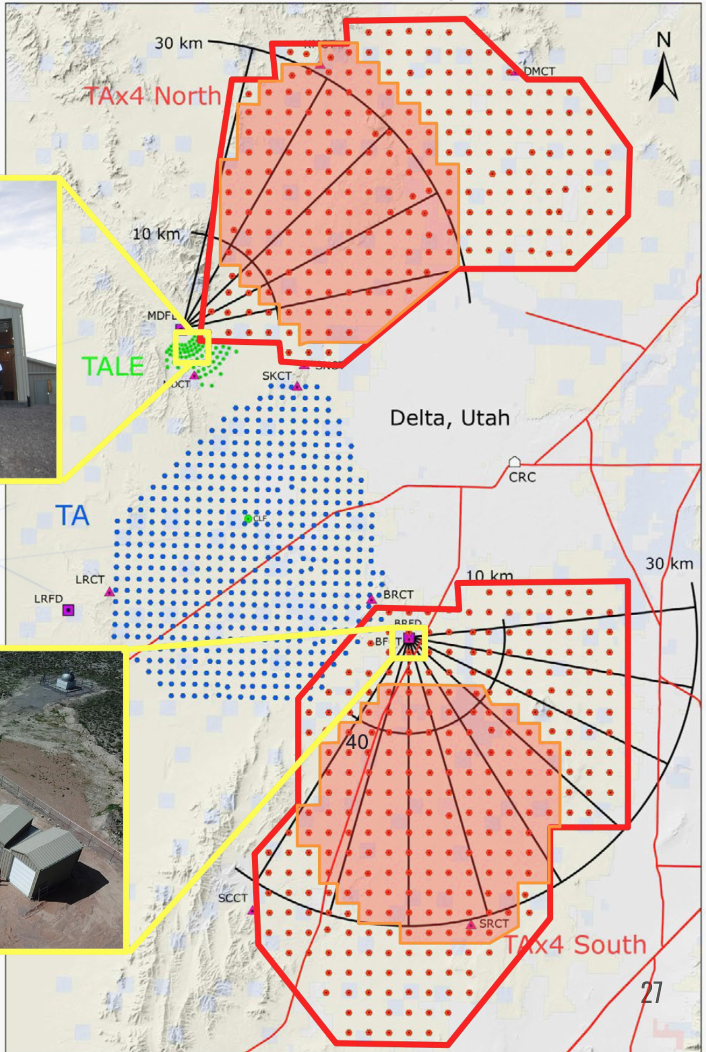
➢ 500 new SDs planned

➜ 230 So far deployed

Expansion of the FD

➢ 2 New FD Sites

- 4 North since 2018
- 8 South since 2020



- Already taking data
- First results already out!
- **Quickly accumulating the statistics required to resolve if Northern / Southern Sky differences are significant!**

The Next 10 Years: Auger Phase II

Target ➜ Improved Composition Sensitivity

- ➢ **Full SD:** Surface Scintillator detectors (SSD)
- ➢ **Full SD:** Radio Detectors (RD)
- ➢ **Dense Array:** Underground Muon Detectors (UMD)
- ➢ **Full SD:** Small PMT to expand dynamic range
- ➢ **Full SD:** New, faster electronics
- ➢ Increased FD duty-cycle

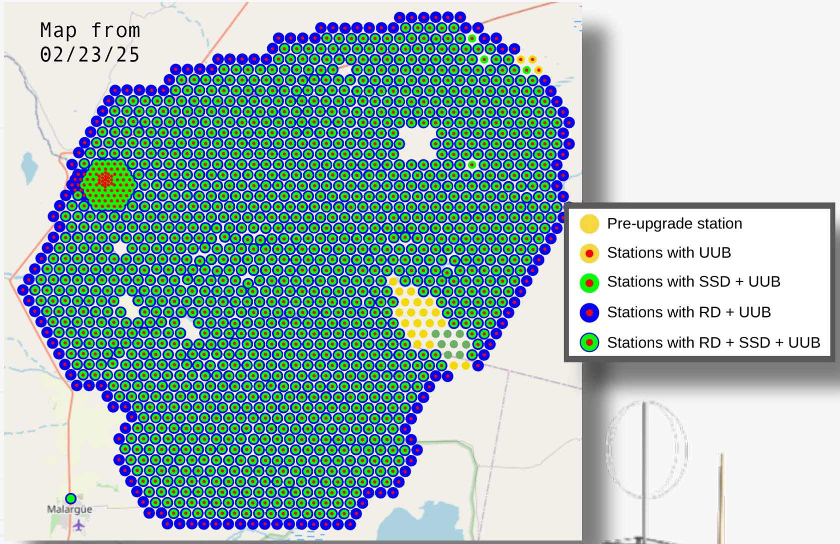
Upgrade hardware performs at or above spec

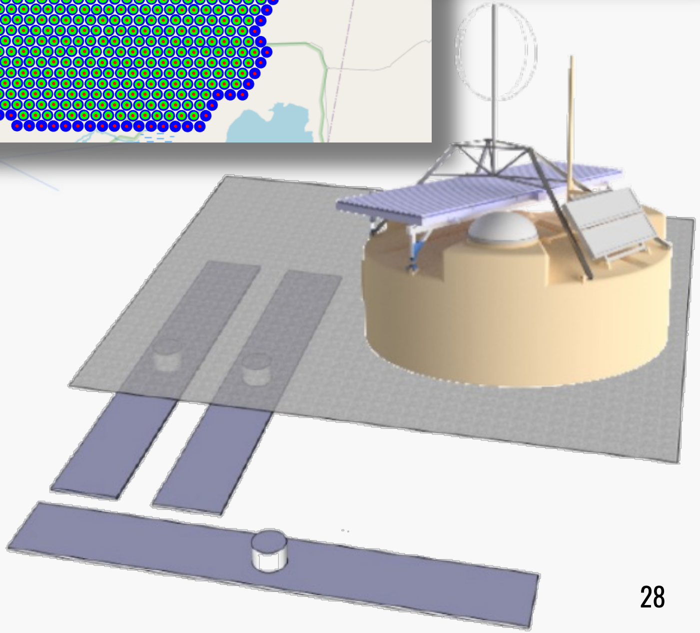
Auger Phase II science data has begun

First analyses underway

Operation of the Pierre Auger Observatory has been extended to **2035!**

NSF has recommended renewal of US participation





10-20 Years: The Global Cosmic Ray ObServatory GCOS

Current Gen:

TA	**Total Area ~700 km²**
TA x 4	**Total Area ~3000 km²**
Auger	**Total Area ~3000 km²**

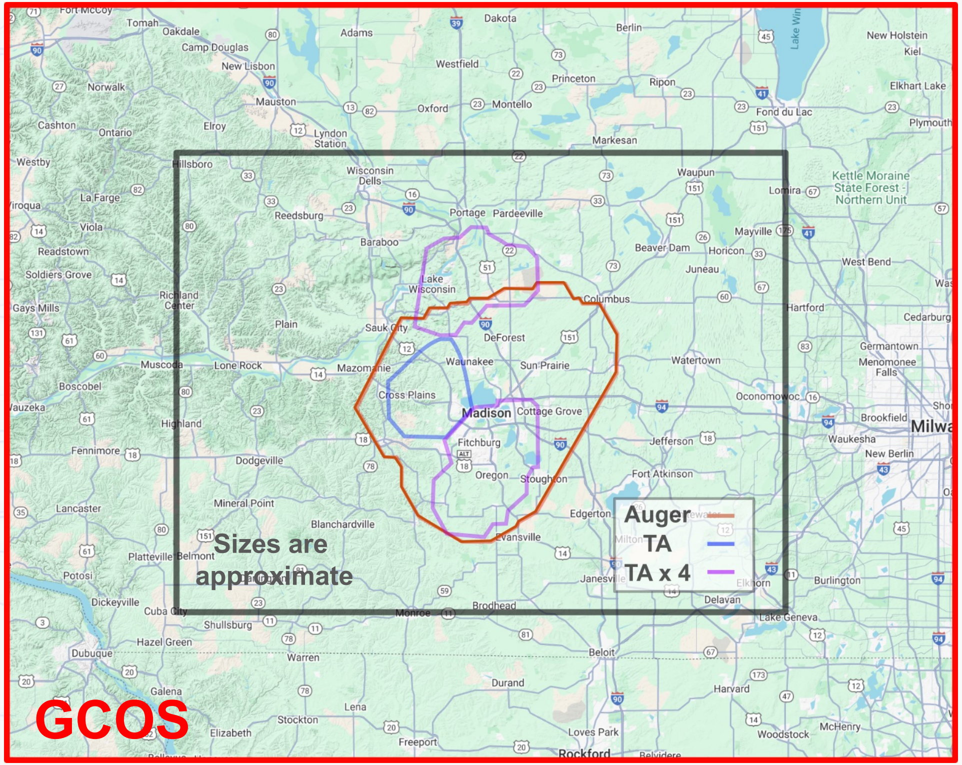
GCOS:

Total Area ➢ **> 40,000 km²**

Hybrid Detector Envisioned Target

- ➢ Next Gen Fluorescence Detectors
- ➢ Next Gen Surface Detectors
- ➢ Self - Triggering Radio Array
- ➢ Definitive identification of UHECR source

Full Sky Coverage ➜ Multi-Site



E. Mayotte for GCOS
APS Sacramento 2024

A. Coleman et. al
ApJ 149 (2023) 102819

10-20 Years: Probe Of Extreme Multi-Messenger Astrophysics POEMMA

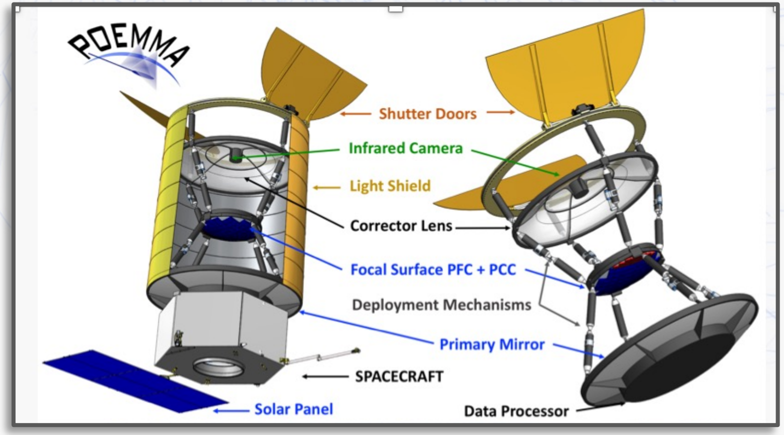
What ➢ Two co-flying Probe class satellites with hybrid Fluorescence/Cherenkov Telescopes

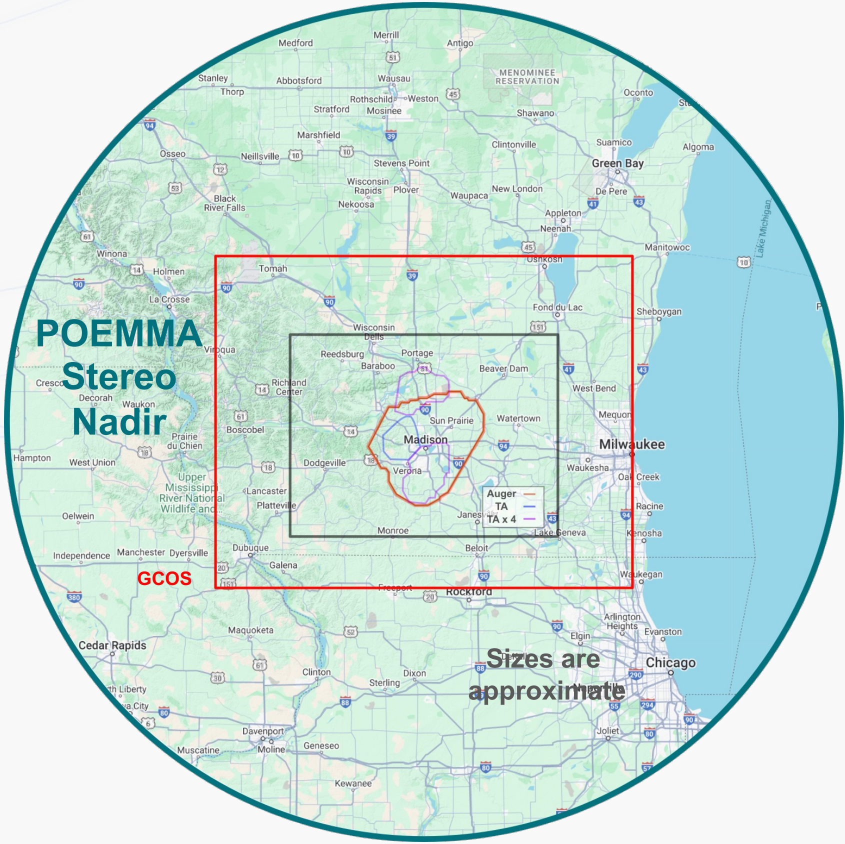
Exposure ➢ **Up to 160,000 km^2 sr yr per year**

Duty Cycle ➢ ~20% in FT higher for CT

Targets ➢ UHE Neutrinos & Post-cutoff UHECR flux

Full Sky Coverage ➜ Single-Site





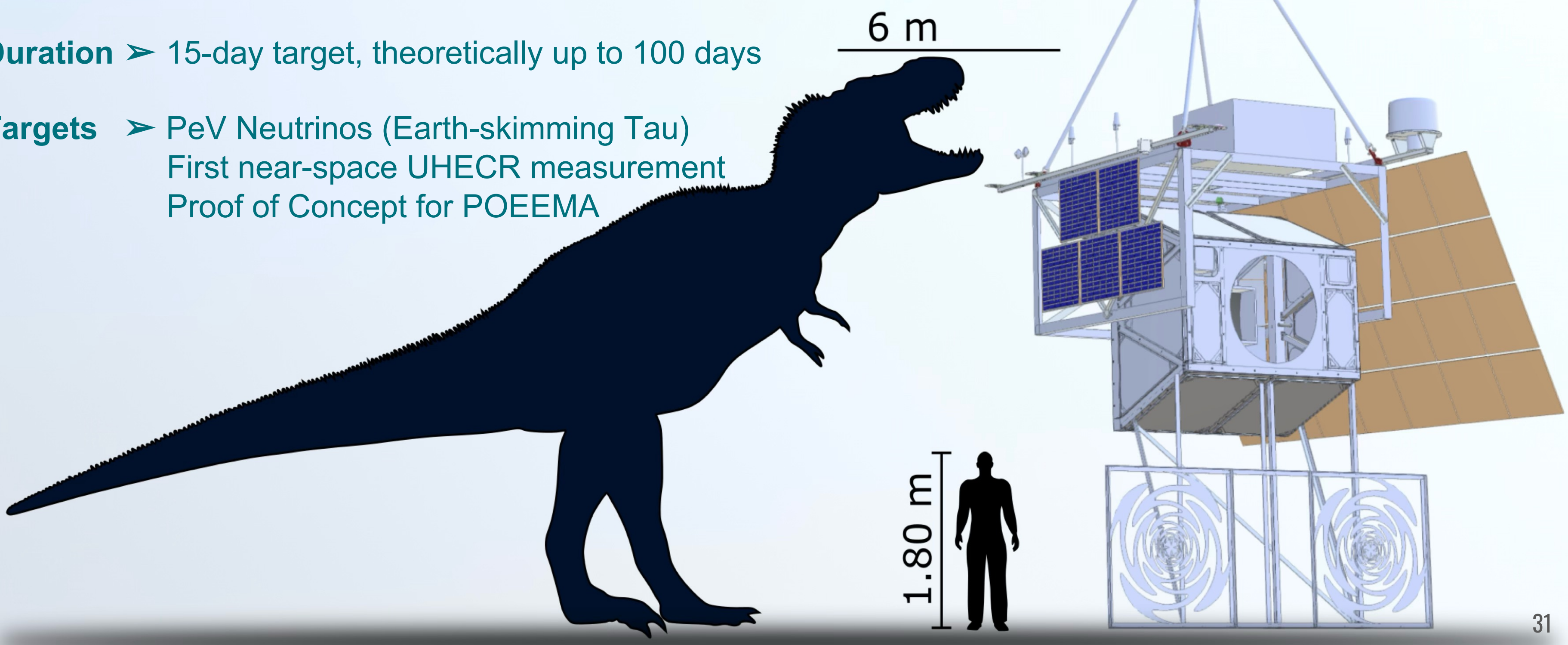
L. Anchordoqui et al.
PRD 101 (2020) 2, 023012

POEMMA Pathfinder Coming 2027: POEEMA Balloon with Radio PBR

What ➢ NASA super pressure Long-Duration Balloon experiment with hybrid Fluorescence/Cherenkov Telescope and 50-400 MHz Radio a la PUEO LF

Duration ➢ 15-day target, theoretically up to 100 days

Targets ➢ PeV Neutrinos (Earth-skimming Tau)
First near-space UHECR measurement
Proof of Concept for POEEMA



Talk Summary: The UHECR Picture

Spectrum:

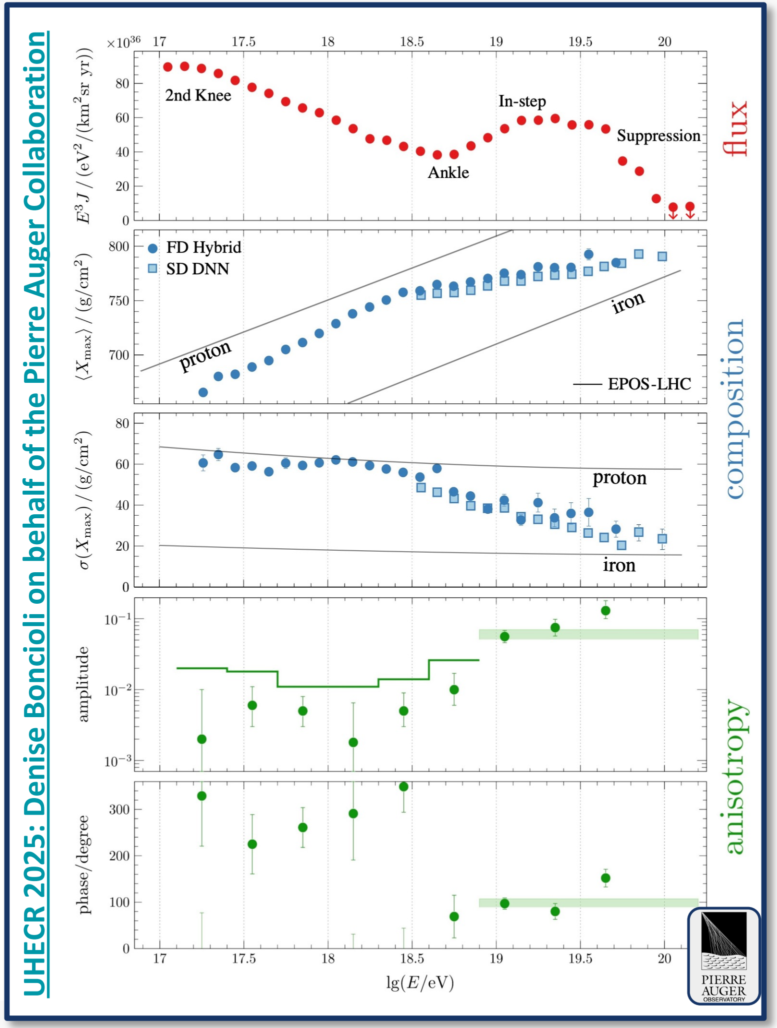
Before: Broken power law Knee, Ankle, maybe Cutoff
Now: New and old features resolved at high precision
With Upgrades: Full sky united with small differences
Far Future guess: Hints of new structure post-cutoff

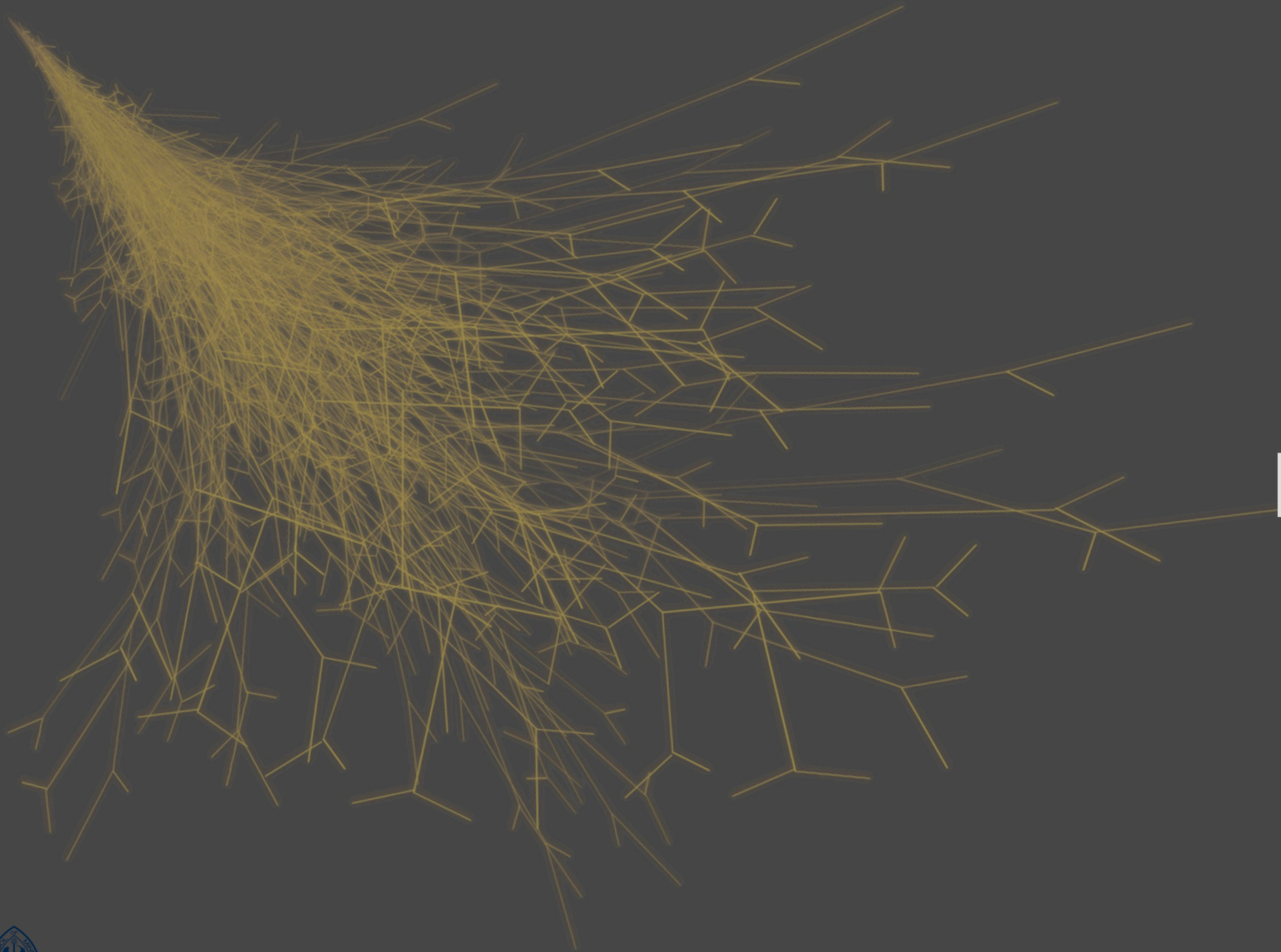
Composition:

Before: Uncertain, very high all proton expectation
Now: Composition is mixed and gets heavier with energy
→ Emerging fine-structured energy evolution
With Upgrades: Clear mass and charge ordering structures
Far Future guess: Fine detail mass group spectra

Anisotropy:

Before: Isotropic at all energies
Now: Not isotropic! Dipoles clear, source hints emerging
With Upgrades: 5 sigma source class correlations
Significant anisotropy in composition
Far Future guess: Clear targets for MM follow-up

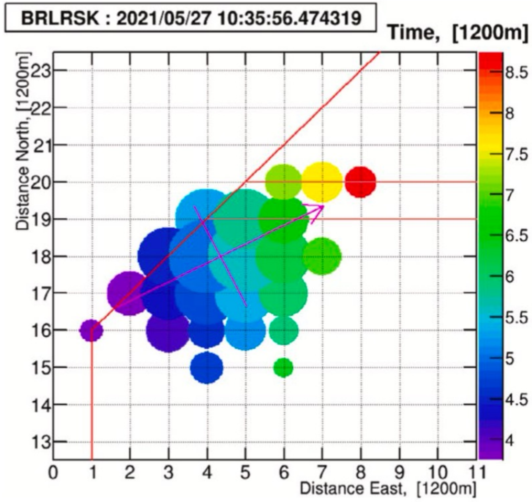


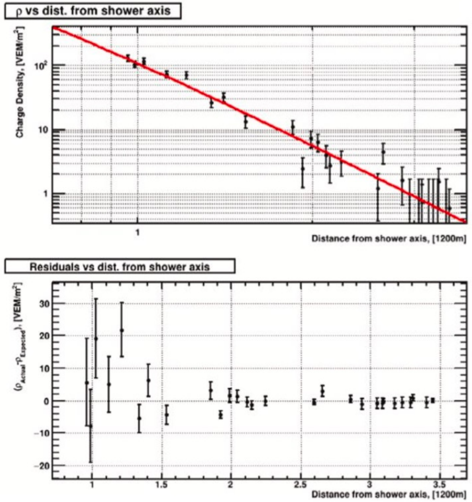


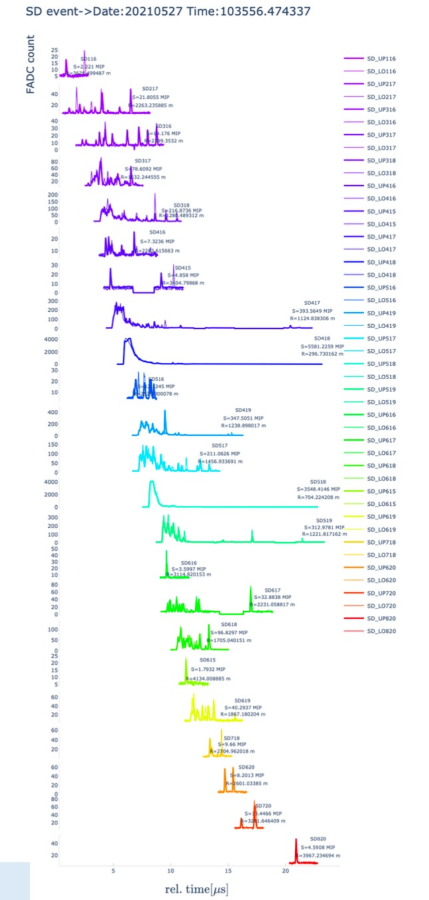
Backup

Highest energy event detected by Telescope Array...... Thus Far

- 2021-05-27 10:35:56.47, No FD observation
- E > ~240 EeV



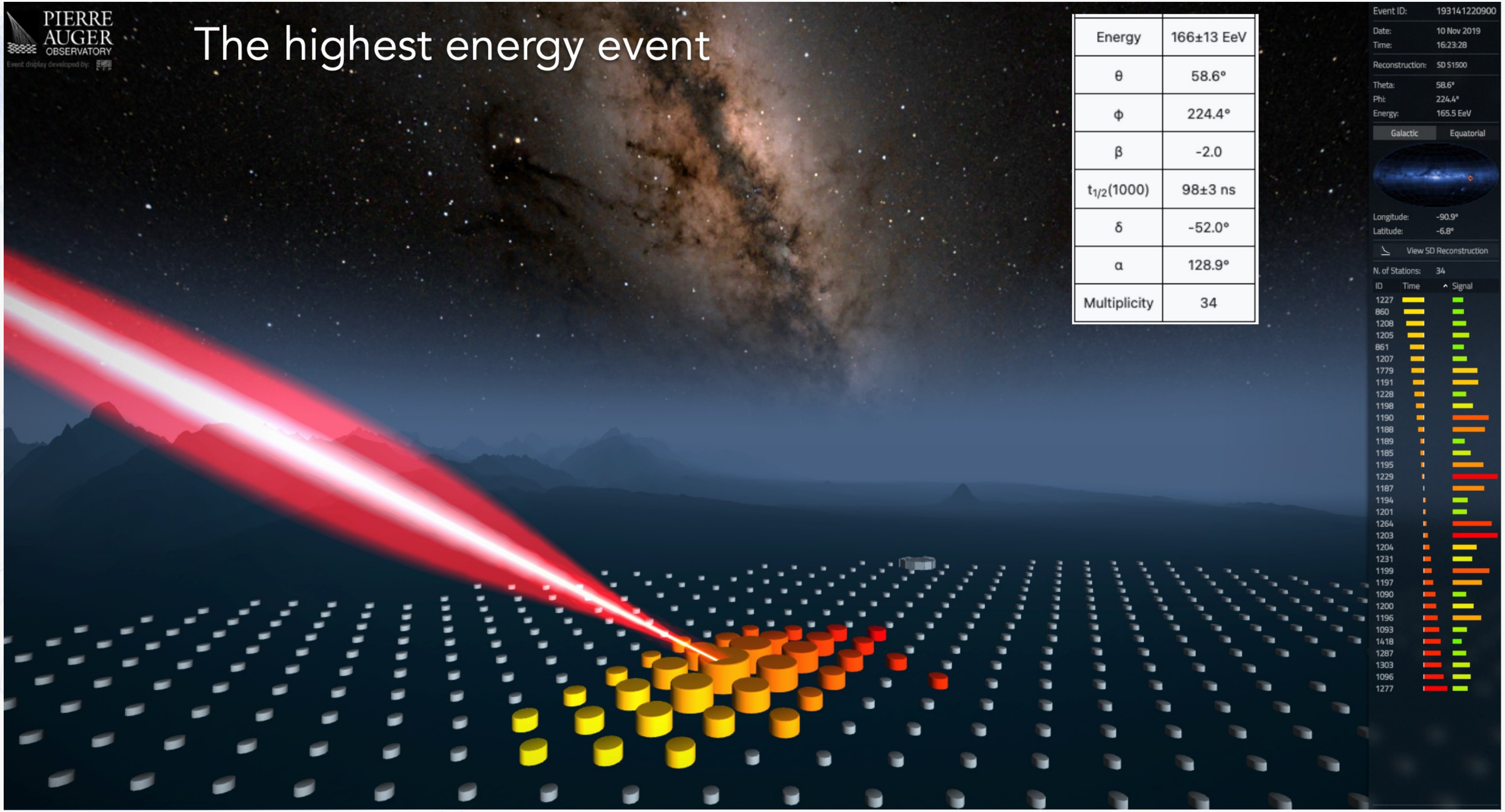




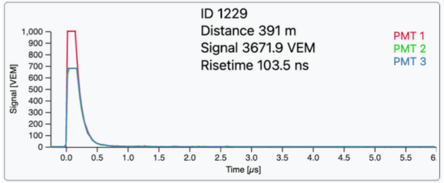
T.Fujii et al., Science Nov. 2023

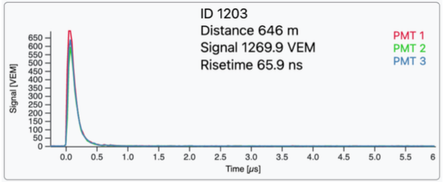
Despite suppression, really high energy events do exist

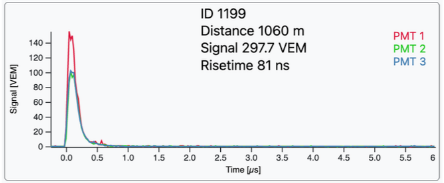
The highest energy event

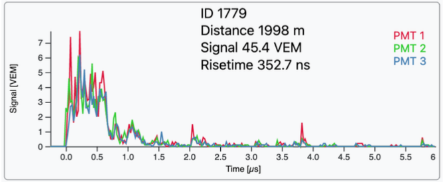


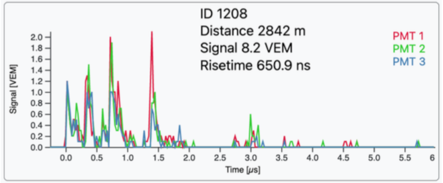
Energy	166±13 EeV
θ	58.6°
ϕ	224.4°
β	-2.0
$t_{1/2}(1000)$	98±3 ns
δ	-52.0°
α	128.9°
Multiplicity	34

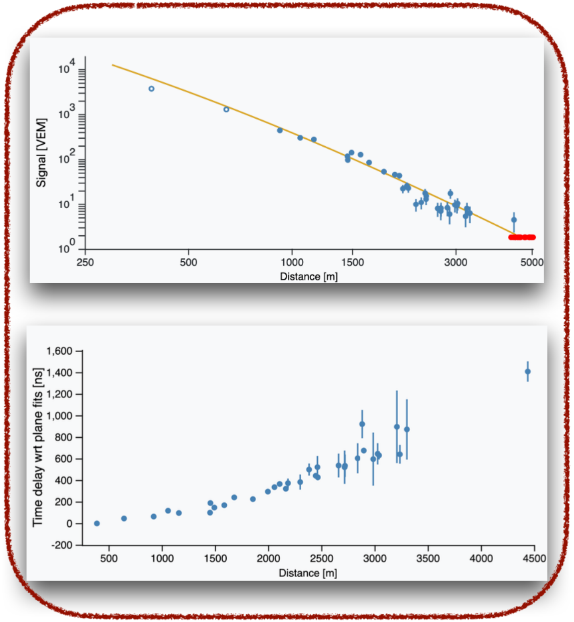












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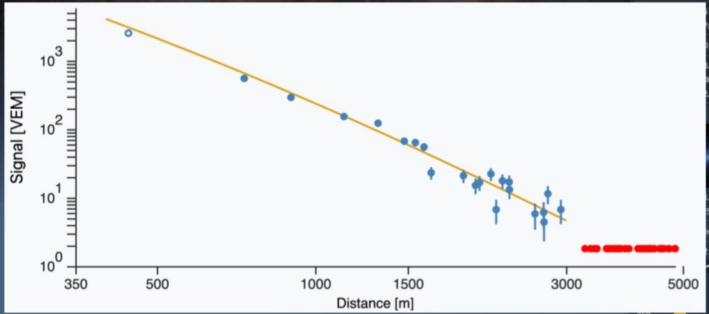
The highest energy hybrid event

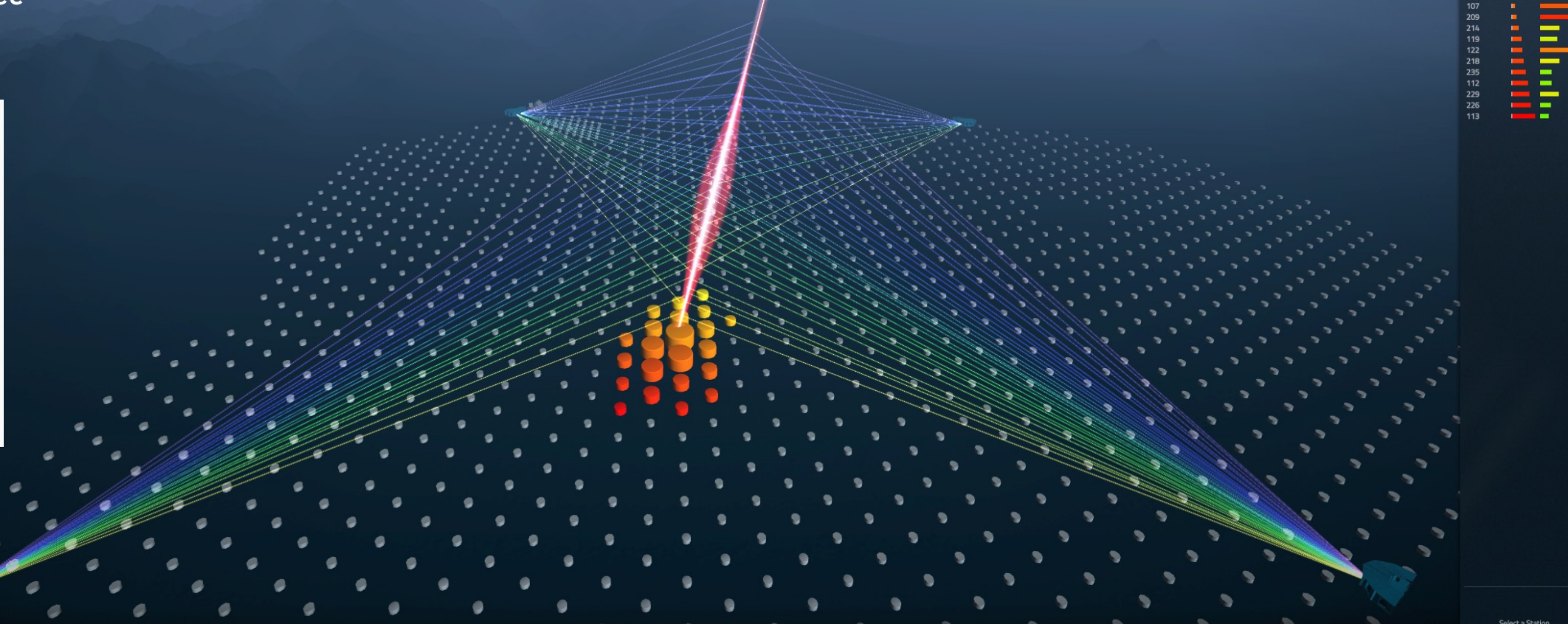
FD site	Energy [EeV]	X_{max} [g cm^{-2}]	θ [deg]	ϕ [deg]
1	86.0 ± 8.1	767.1 ± 31.9	53.7 ± 0.7	100.4 ± 0.4
2	79.9 ± 6.9	768.7 ± 21.0	53.9 ± 0.5	101.0 ± 0.4
3	91.5 ± 9.0	753.4 ± 12.5	52.3 ± 0.3	100.6 ± 0.8
4	87.7 ± 8.1	771.1 ± 13.5	52.8 ± 0.3	101.1 ± 0.5

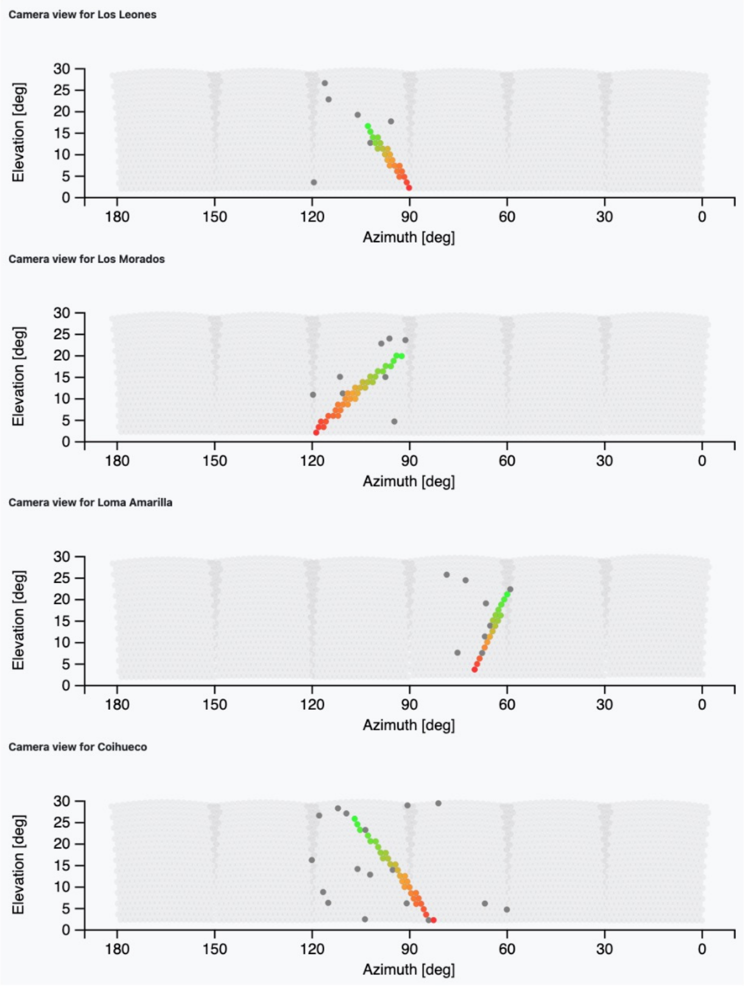
Hybrid rec

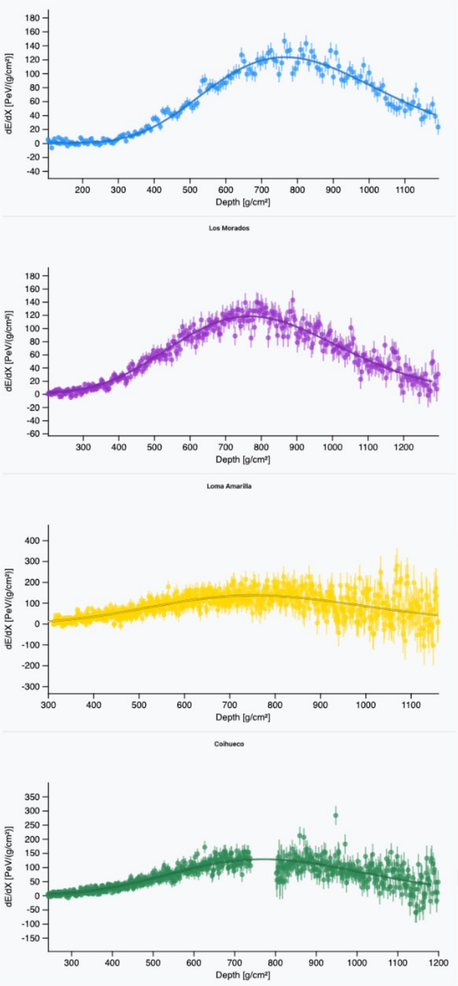


SD rec

Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22







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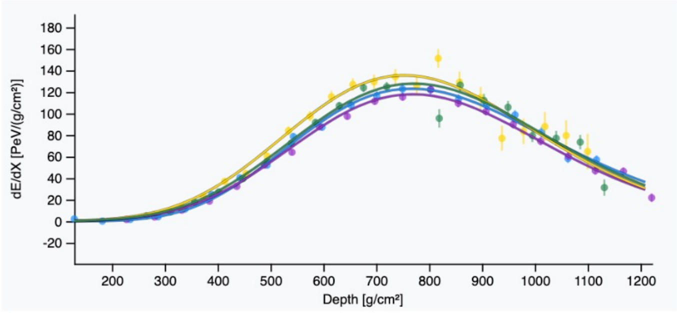
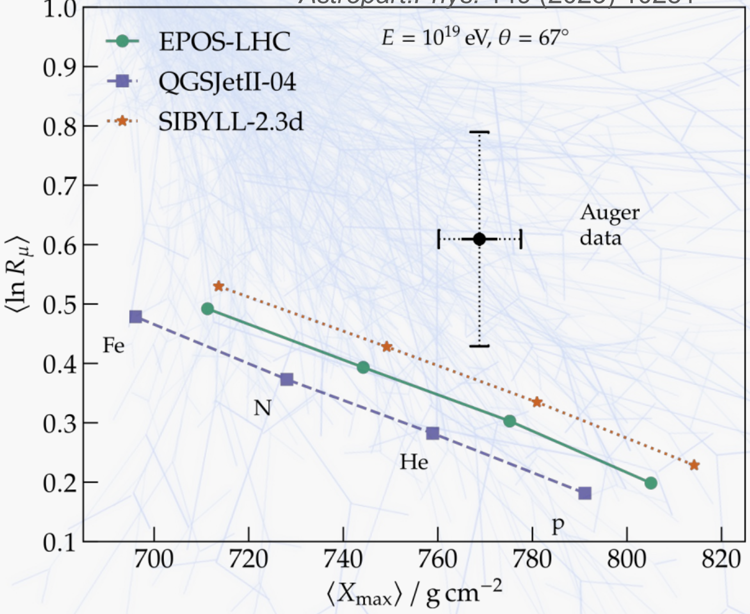
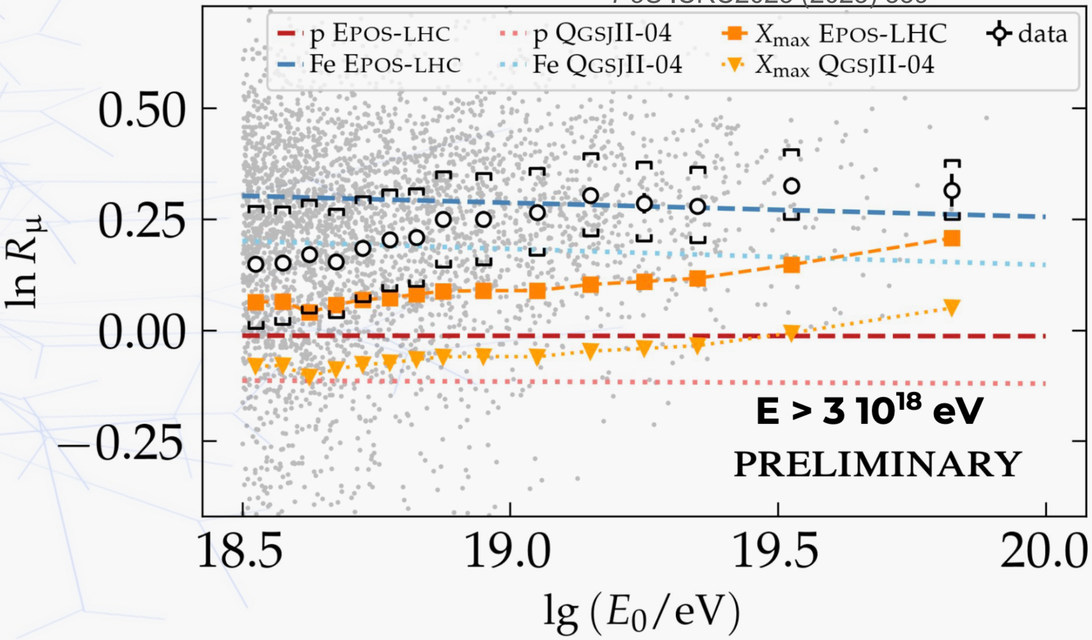


The Muon Puzzle

Astropart.Phys. 149 (2023) 10281

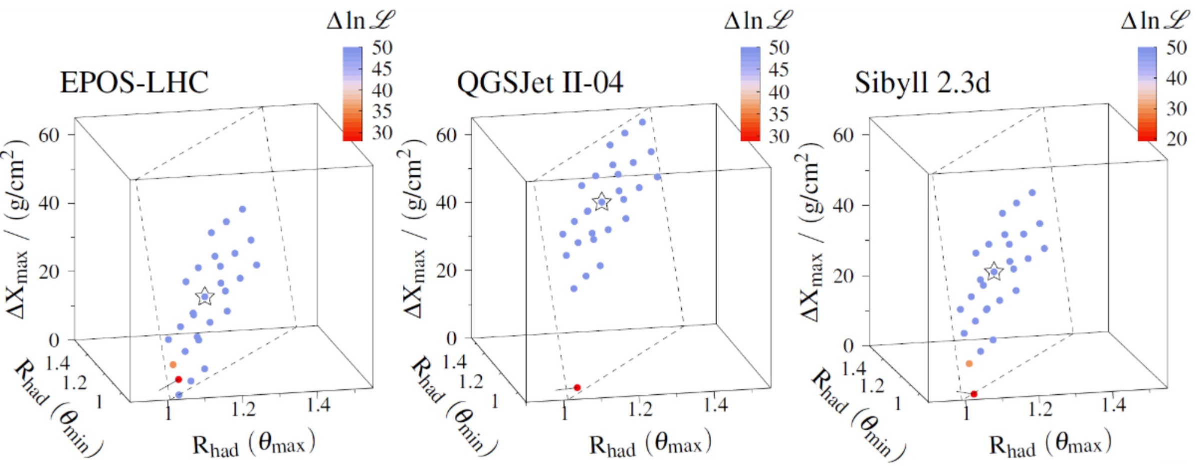


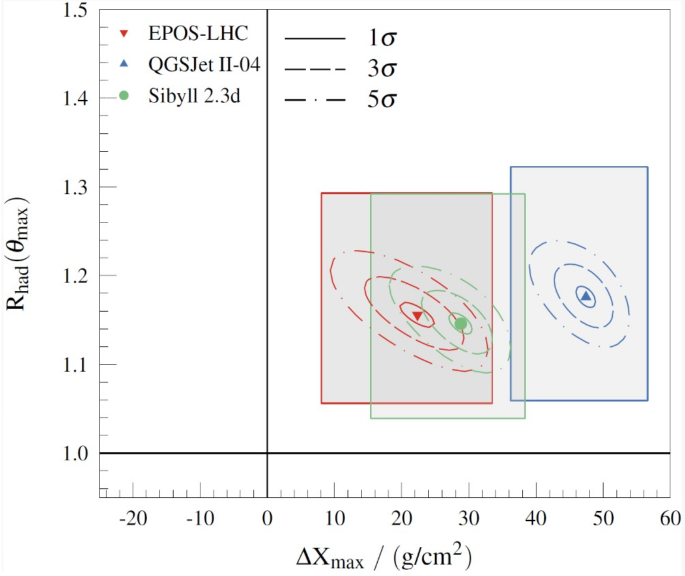
PoS ICRC2023 (2023) 339



Analyses of shower data from both Auger and TA see a large excess in muons as compared to expectations from LHC informed hadronic interaction models.

The Muon Puzzle

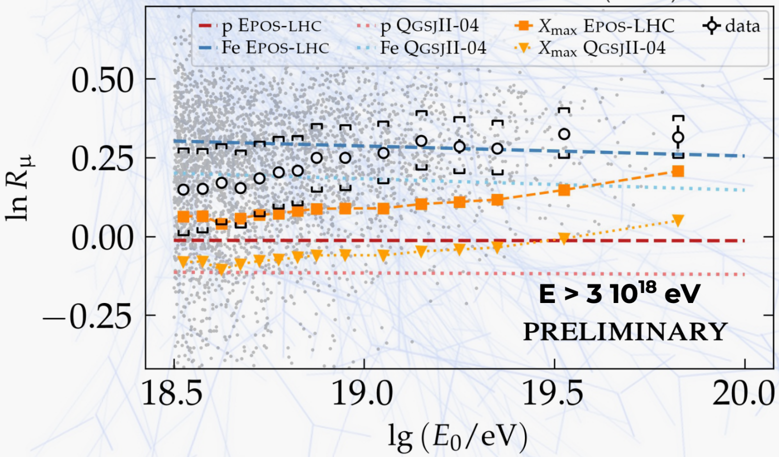


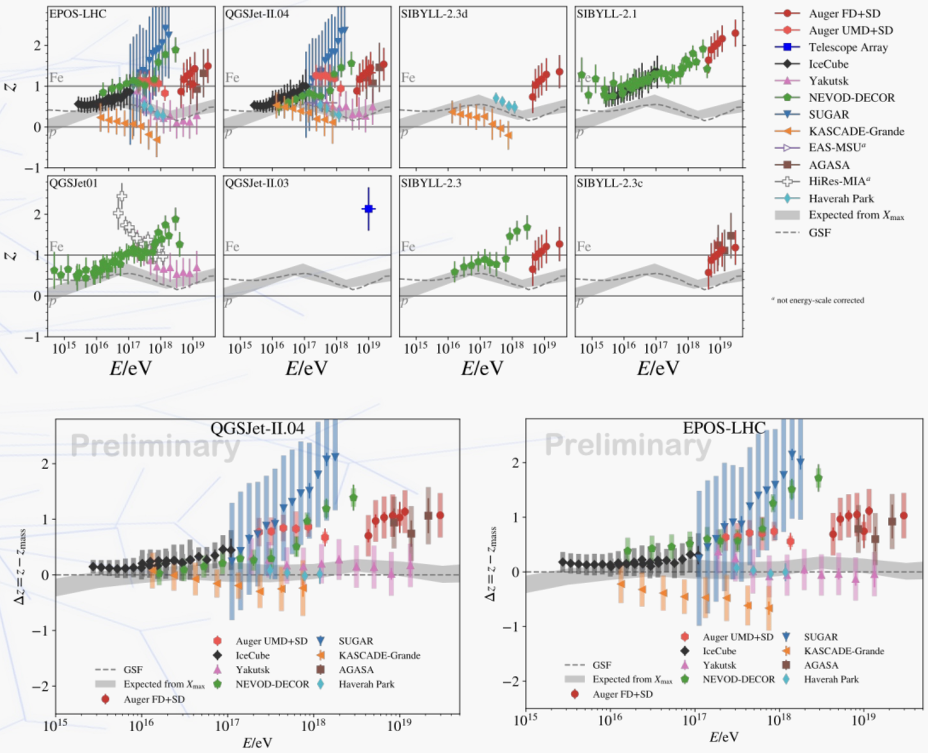


The Pierre Auger Collaboration,
Phys. Rev. D 109, 102001 (2024)

New physics in UHECR interactions?

PoS ICRC2023 (2023) 339





PoS ICRC2023 (2023) 466

Work in progress to confirm an excess in muons and investigate its nature.

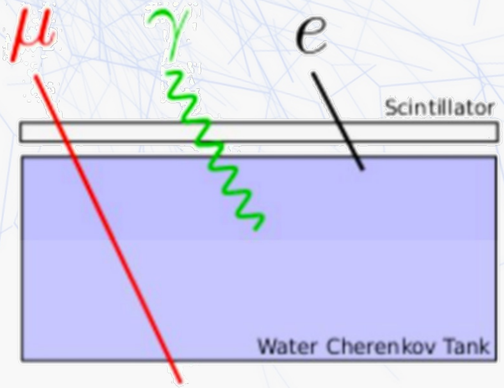
Precision measurements with event-by-event composition info might be needed

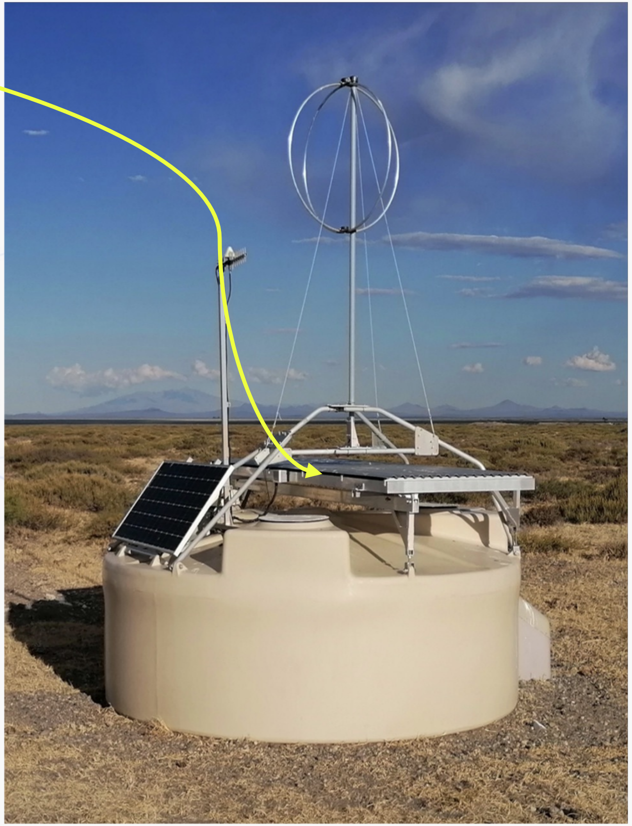
The AugerPrime Upgrade

Surface Scintillator Detector (SSD):

- Measure mass composition in combination with the WCD
  - 3.8 m^2 area, 1 cm thick
  - Muons and electrons deposit about the same amount of energy
  - Sensitive to charged particle density

➞ Disentangling different components of shower possible with multi-parametric analyses





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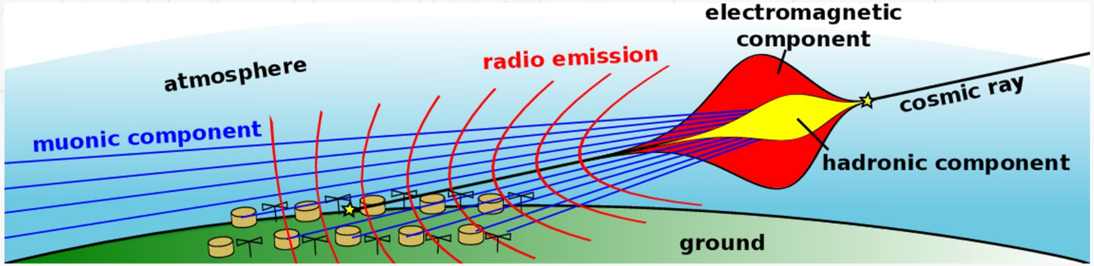
Radio Detector (RD):

- Measure radio emission of showers in atmosphere (30-80 MHz)
  - Radio emission not absorbed in atmosphere
    → Depends on source distance not amount of traversed matter
  - Inclined air showers can be detected by a sparse antenna grid



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Underground Muon Detector (UMD):

- Directly measure muon component of LE showers
  - Buried scintillators with A_{tot}=30 m^2, 2.3 m underground
  - Cross-check of muon evaluation with SD
  - Enhance photon/hadron discrimination

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+

Additional Enhancements:

Upgraded Unified Board (UUB)

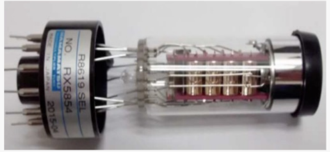
➞ Processes signals of WCD, SSD and RD detectors and increases resolutions and data processing capabilities

small PMT (SPMT):

➞ Increases dynamic range of the WCD to match SSD

Fluorescence Detector (FD):

➞ Increased duty cycle and improved calibration



AugerPrime - Expected Performance

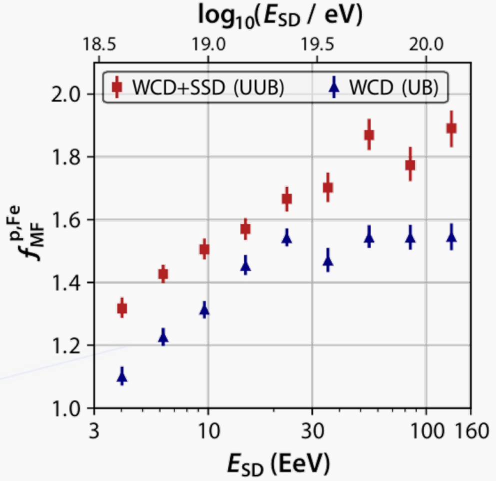
SSD mass composition improvements:

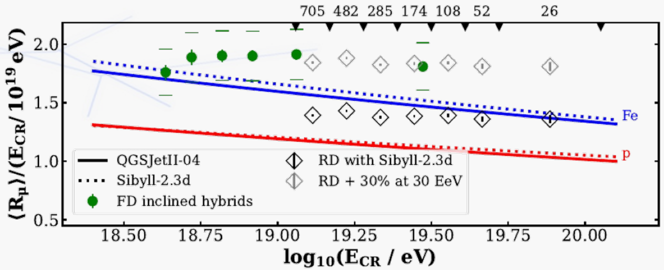
- Merit factor of current measurements reaches maximum of 1.5
- WCD+SSD+UUB enables increase of at least 0.2 in merit factor across full energy range

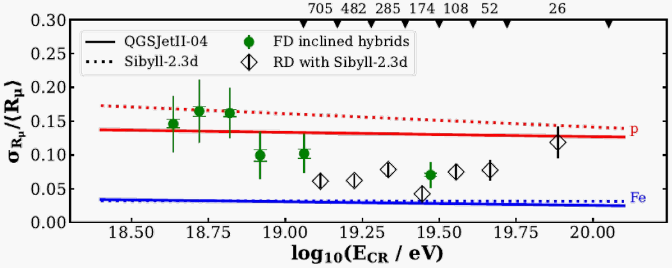
➞ AugerPrime could reach a merit factor of almost 2 at the highest energies

RD mass composition improvements:

- The RD will provide ~6% resolution on E_{em}
- Using $\langle R_\mu \rangle$ and $\sigma_{R\mu}$ from WCD + E_{em} from RD
  - Simulated period of 10 years (with and without scaling MC simulations by 30%)
  - Strong improvement in mass composition sensitivity for highly inclined showers



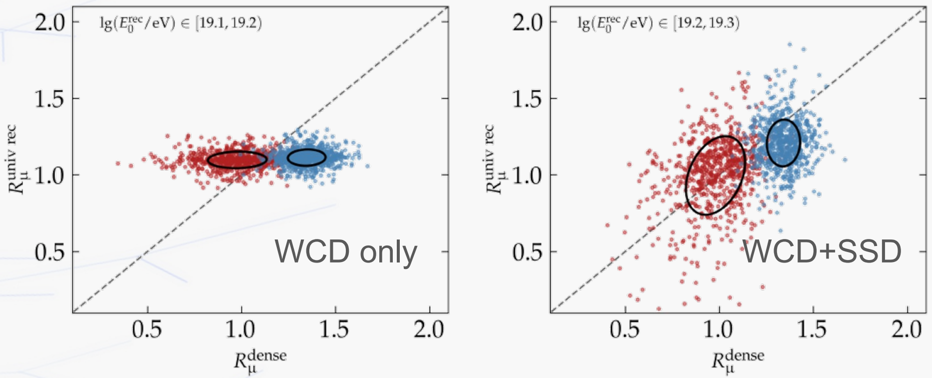




AugerPrime - Expected Performance

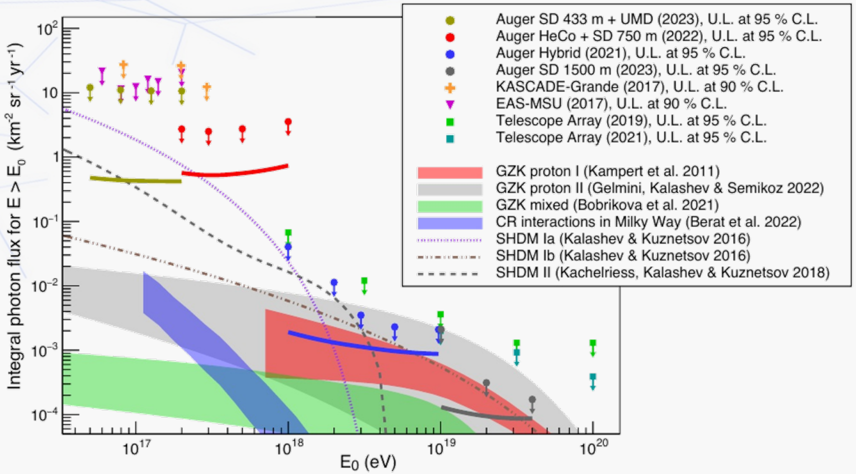
The muon puzzle:

- UMD directly counting muons gives valuable information for
  - Calibrating muon reconstruction methods
  - Probing the muon energy spectrum
- Reconstructed R_{μ} from shower universality:
  - Addition of SSD increases correlation with “MC” R_{μ}

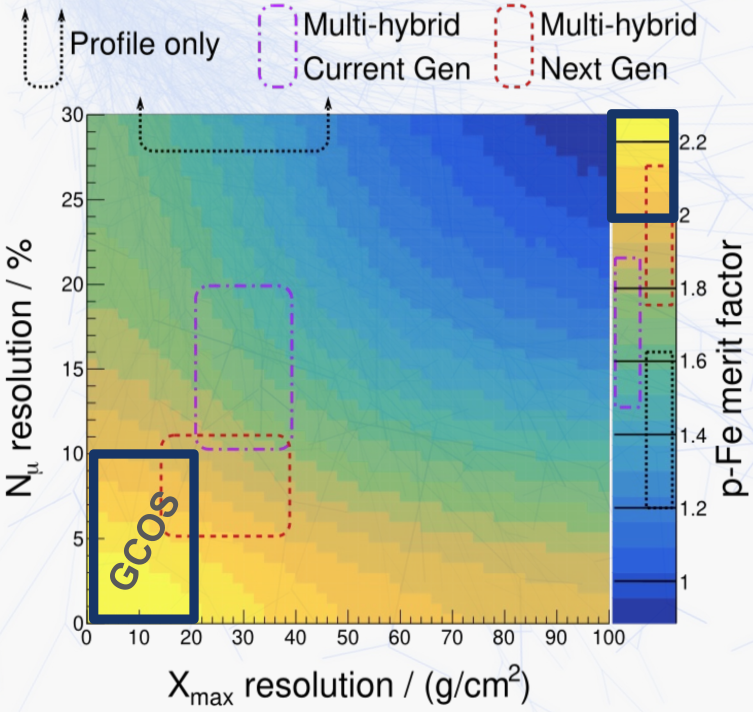


Search for UHE photons:

- With 10 year extrapolation, photon limits will benefit from
  - Increased exposure
  - Better photon-hadron discrimination
  - New/improved trigger algorithms possible with new electronics

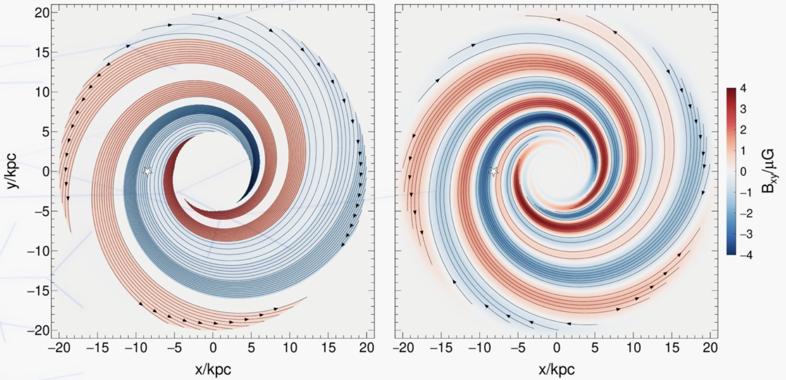


Aiming for High Resolution in Composition to Enable Charged Particle Astronomy



Next Generation Composition Resolution

Double Liner WCDs, Radio, FDs, and Neural Networks together will unlock unprecedented event-by-event composition resolution.



Magnetic Field Backtracking

Combining this composition resolution with high energy resolution and advanced GMF models may enable true charged particle astronomy

E. Mayotte for GCOS *APS Sacramento 2024*

A. Coleman et. al ApJ 149 (2023) 102819

Unger, Farrar *ApJ.* 970 (2024) 1, 95

GCOS Design Goals

A next-generation Ultra-High-Energy observatory

- ➢ Full sky coverage with a single design (multi-site)
- ➢ Total area 40,000 - 80,000 km^2
- ➢ Targeted at 10 EeV to ZeV energies

Next-generation sensitivity

Energy Resolution: better than 10%

Muon Number Resolution: better than 10%

Xmax Resolution: better than 20 gcm^{-2}

Angular Resolution: better than 1°

A. Coleman et. al
ApJ 149 (2023) 102819

R. A. Batista for GCOS
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GCOS Progression

Community-Driven Effort

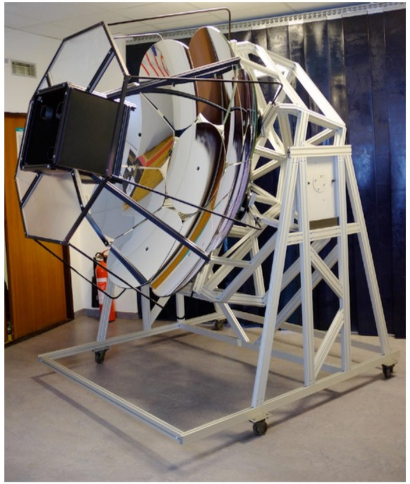
1st Workshop
17-21 May 2021
Nijmegen NE

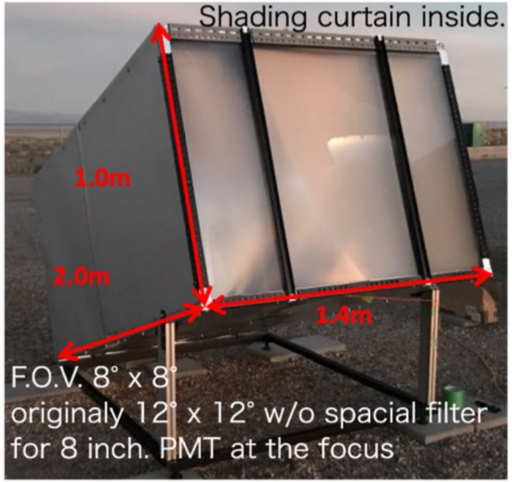
2nd Workshop
13-15 July 2022
Wuppertal DE

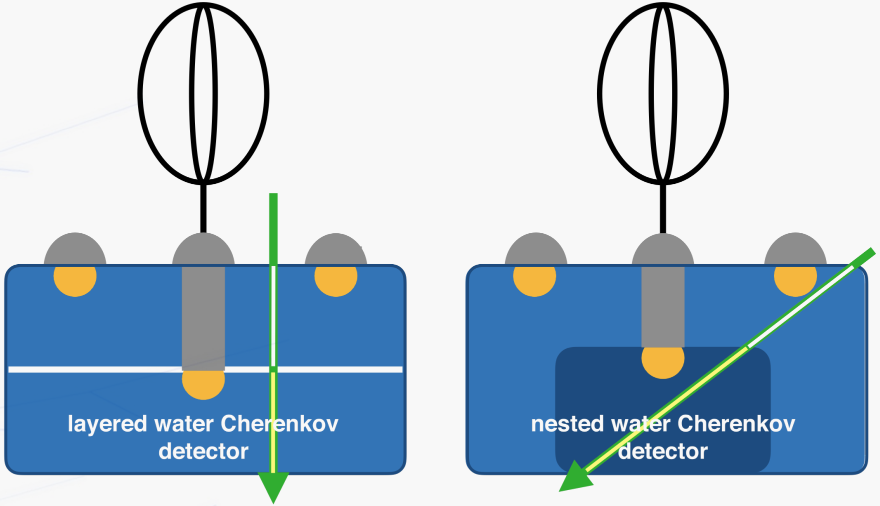
3rd Workshop
10-11 June 2023
Brussels BE

4th Workshop
9-11 Sept 2025
Tokyo JP

GCOS Detector Design







Fluorescence Detector Candidates:

Goal: 100% efficiency at above 30 EeV, low cost

Options under R&D:
FAST (**F**luorescence Detector **A**rray of **S**ingle-pixel **T**elescopes)
CRAFFT (**C**osmic-**R**ay **F**luorescence **F**resnel **L**ens **T**elescope)
MACHETE (A design adaptation of Trinity)

Surface Detector Spacing, Count and Design:

Goal: 100% efficiency around 10 EeV

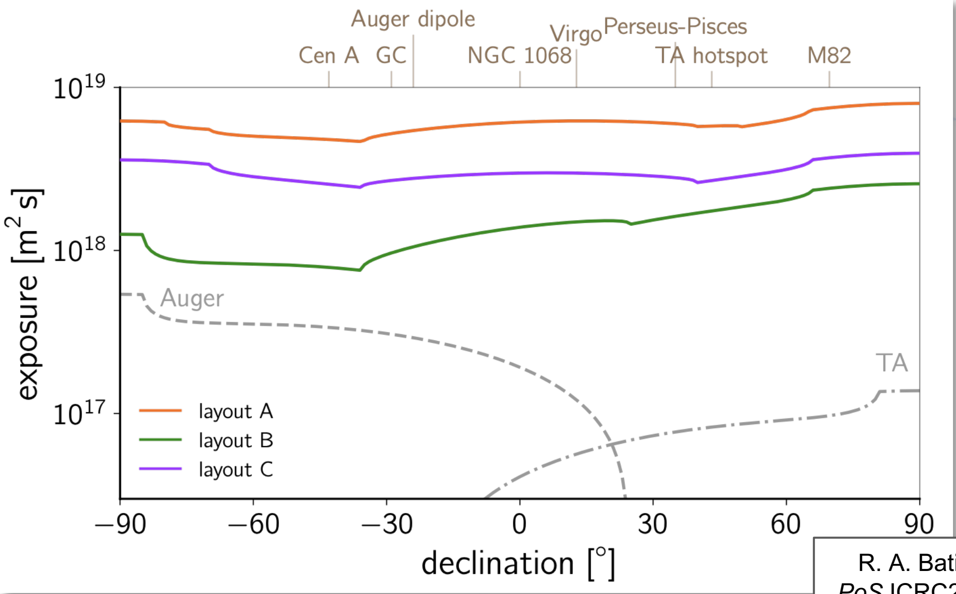
- **Example total area:** 60000 km^2
- **Spacing (R):** ~2.5 km
- **Number of detectors**: 15k stations or less
- **Detector in R&D**: PEPS WCD, AugerPrime RD
- **Maximize Muon Resolution**: Double Liner + Radio

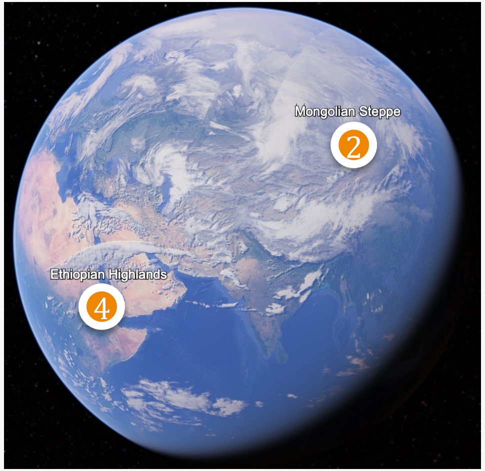
RDA ➜ PEPS (Probing **E**xtreme **P**eVatron **S**ources)

M. Malicari et al. *ApJ.* 119 (2020) 102430	Y. Tameda et al. PTEP (2019) 4, 043F01	A. Nepomuk PRD 99 (2019) 8, 083012	A. Coleman et. al ApJ 149 (2023) 102819	I. Mariş *PoS* ICRC2023 718	R. A. Batista for GCOS *PoS* ICRC2023 (2023) 281

Example Global Observatory Site Layout

layout	A_1 [km²]	A_2 [km²]	A_3 [km²]	A_4 [km²]	θmax
A	20k	20k	20k	20k	75°
B	7	-	13	-	60°
C	20k	-	20k	-	75°





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