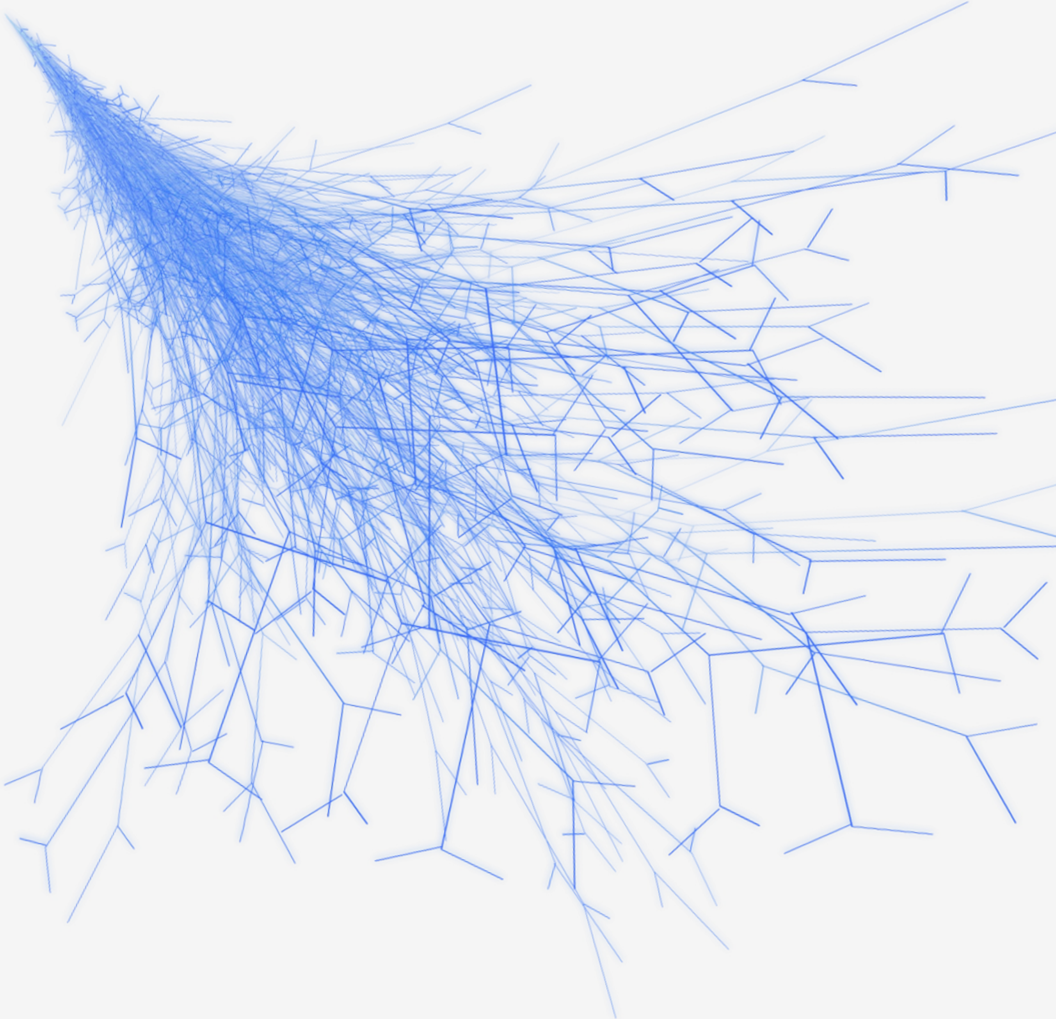


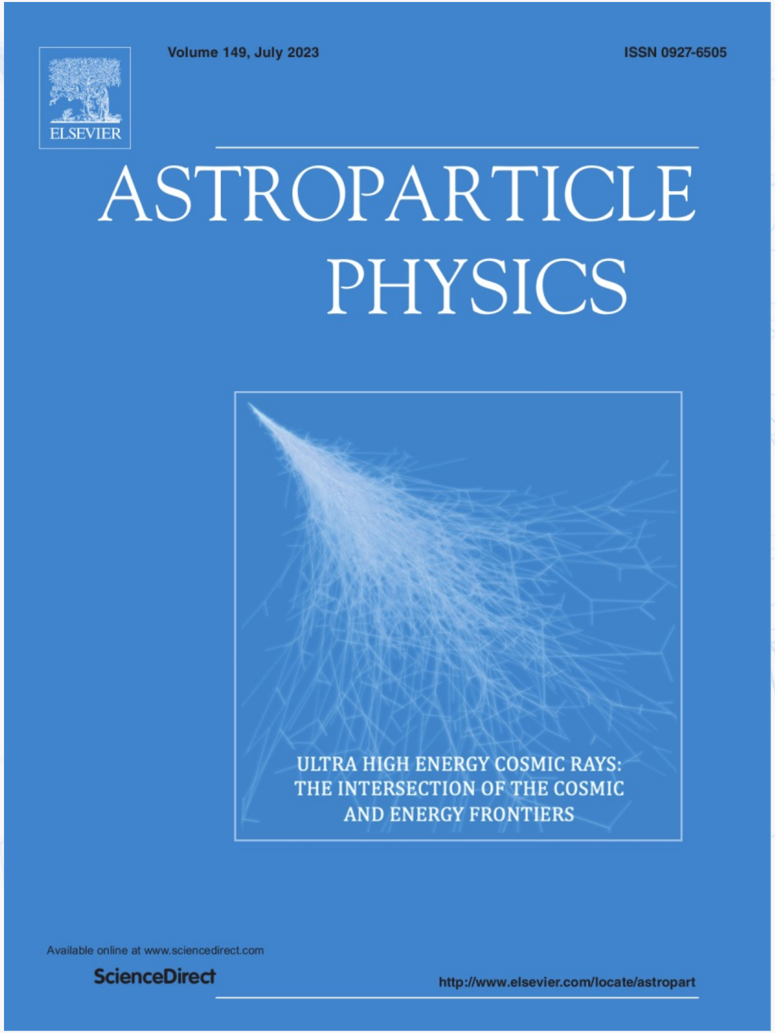
Observations of Ultra-High-Energy Cosmic Rays

TAUP XVIII

Friday, September 1st 2023

Eric Mayotte

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



Conveners

A. Coleman[1], J. Eser[2], E. Mayotte[3], F. Sarazin[†3], F. G. Schröder[†1,4], D. Soldin[1], T. M. Venters[†5]

Topical Conveners

R. Aloisio[6], J. Alvarez-Muñiz[7], R. Alves Batista[8], D. Bergman[9], M. Bertaina[10], L. Caccianiga[11], O. Deligny[12], H. P. Dembinski[13], P. B. Denton[14], A. di Matteo[15], N. Globus[16,17], J. Glombitza[18], G. Golup[19], A. Haungs[4], J. R. Hörandel[20], T. R. Jaffe[21], J. L. Kelley[22], J. F. Krizmanic[5], L. Lu[22], J. N. Matthews[8], I. Mariş[23], R. Mussa[14], F. Oikonomou[24], T. Pierog[4], E. Santos[25], P. Tinyakov[23], Y. Tsunesada[26], M. Unger[4], A. Yushkov[25]

Contributors

M. G. Albrow[27], L. A. Anchordoqui[28], K. Andeen[29], E. Arnone[10,15], D. Barghini[10,15], E. Bechtol[22], J. A. Bellido[30], M. Casolino[31,32], A. Castellina[15,33], L. Cazon[7], R. Conceição[34], R. Cremonini[35] H. Dujmovic[4], R. Engel[4,36], G. Farrar[37], F. Fenu[10,15], S. Ferrarese[10], T. Fujii[38], D. Gardiol[33], M. Gritsevich[39,40], P. Homola[41], T. Huege[4,42], K.-H. Kampert[43], D. Kang[4], E. Kido[44], P. Klimov[45], K. Kotera[42,46], B. Kozelov[47], A. Leszczyńska[1,36], J. Madsen[22], L. Marcelli[32], M. Marisaldi[48], O. Martineau-Huynh[49], S. Mayotte[3], K. Mulrey[20], K. Murase[50,51], M. S. Muzio[50], S. Ogio[26], A. V. Olinto[2], Y. Onel[52], T. Paul[28], L. Piotrowski[31], M. Plum[53], B. Pont[20], M. Reininghaus[4], B. Riedel[22], F. Riehn[34], M. Roth[4], T. Sako[54], F. Schlüter[4,55], D. Shoemaker[56], J. Sidhu[52], I. Sidelnik[19], C. Timmermans[20,57], O. Tkachenko[4], D. Veberič[4], S. Verpoest[58], V. Verzi[32], J. Vícha[25], D. Winn[59], E. Zas[7], M. Zotov[45]

- Started as a Snowmass Whitepaper on UHECR
- Over 100 authors contributed with 200 endorsers
- Aims to:
  - ➢ Review the current state of the field
  - ➢ Provide a 20-year roadmap for future

The past and future 20-years endeavor

for discovering origins of ultra-high energy cosmic rays

- Rapporteur of Cosmic Ray Indirect (CRI) -

Toshihiro Fujii (toshi@omu.ac.jp)

Graduate School of Science, Osaka Metropolitan University

Nambu Yoichiro Institute of Theoretical and Experimental Physics

OMU

Osaka Metropolitan University

NITEP

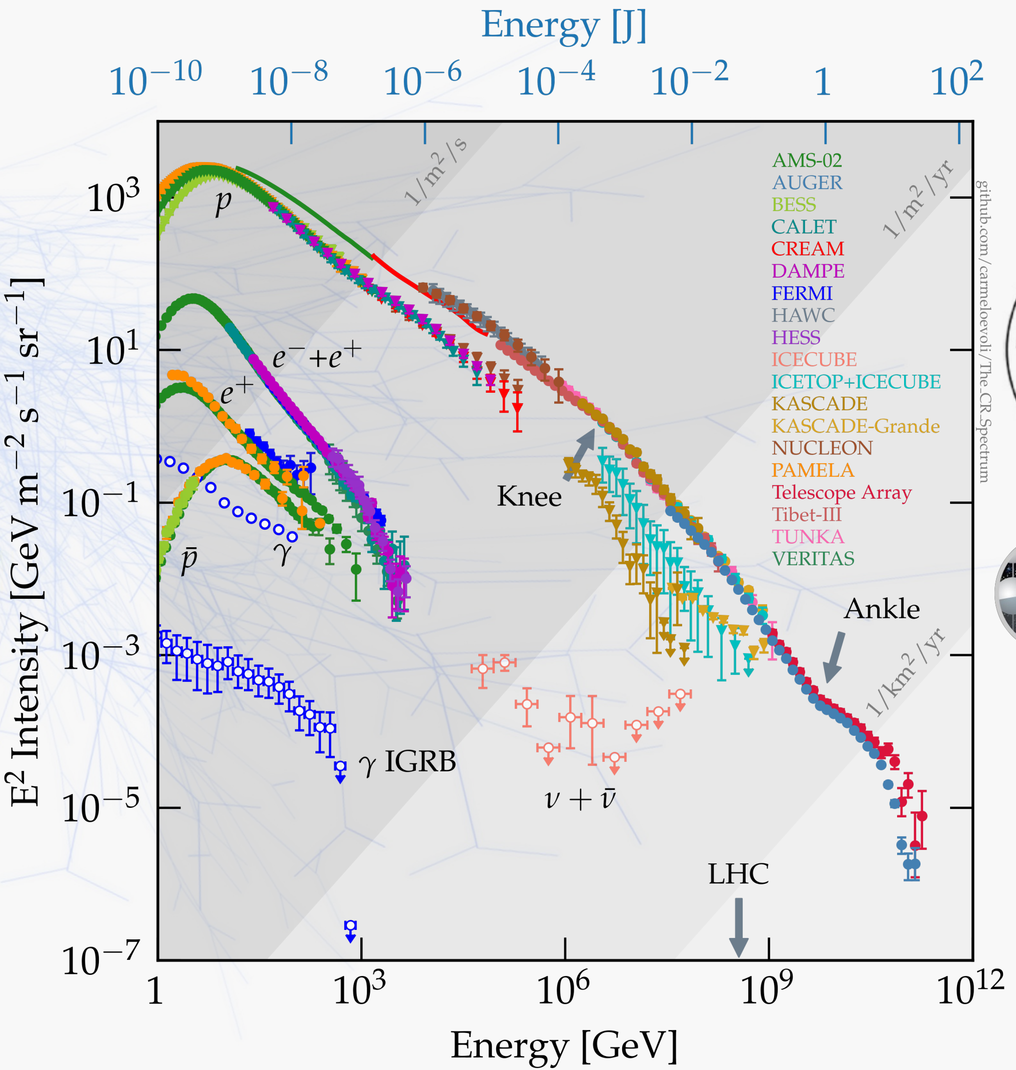
Nambu Yoichiro Institute of Theoretical and Experimental Physics

Auger Highlight
Francesco Salamida

TA Highlight
Jihyun Kim

Direct

Indirect



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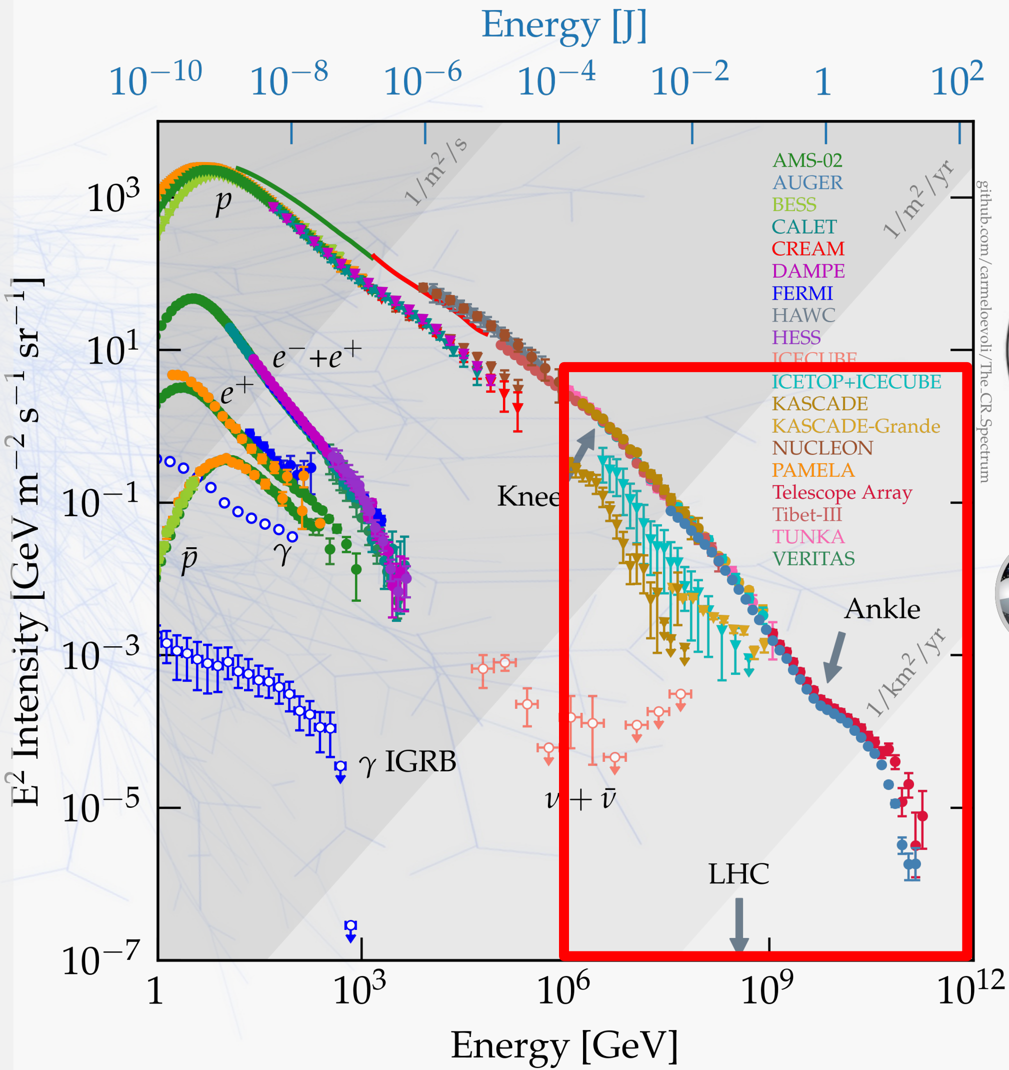
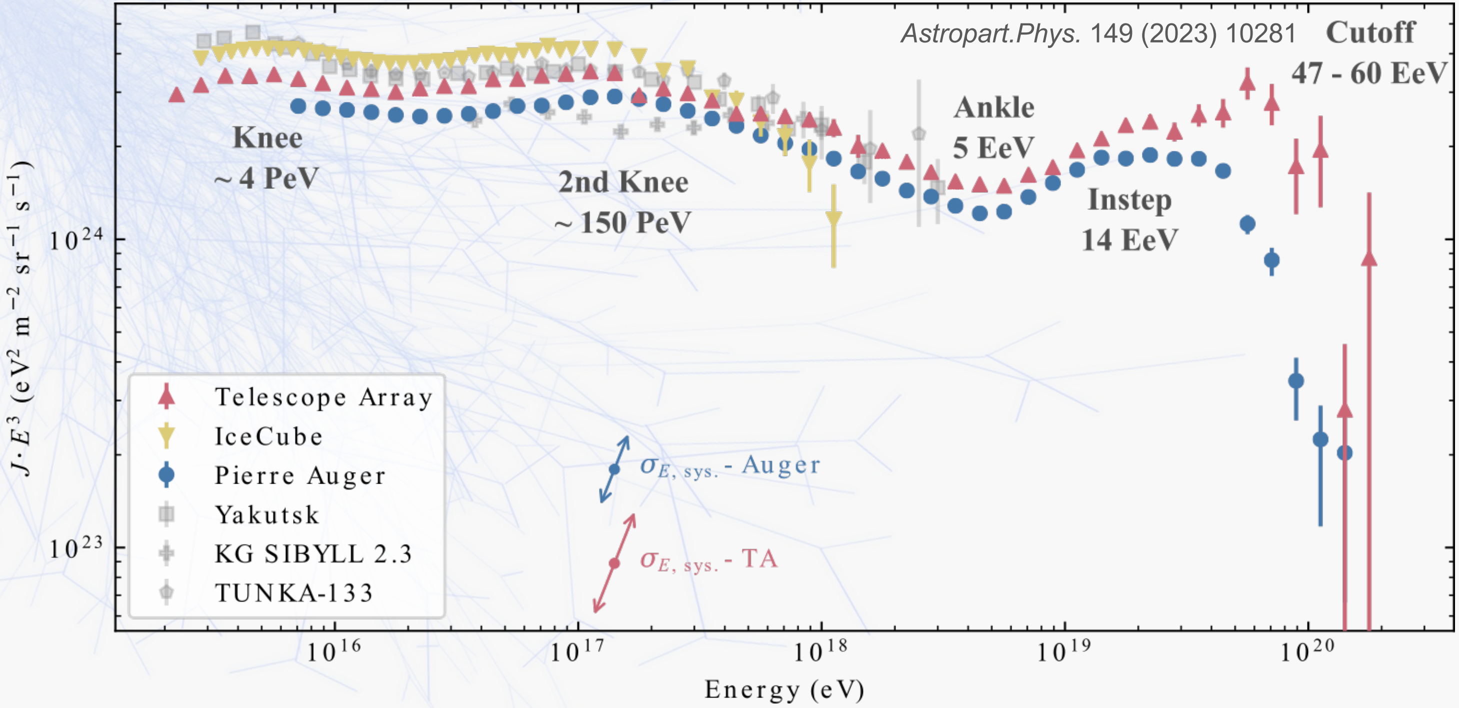
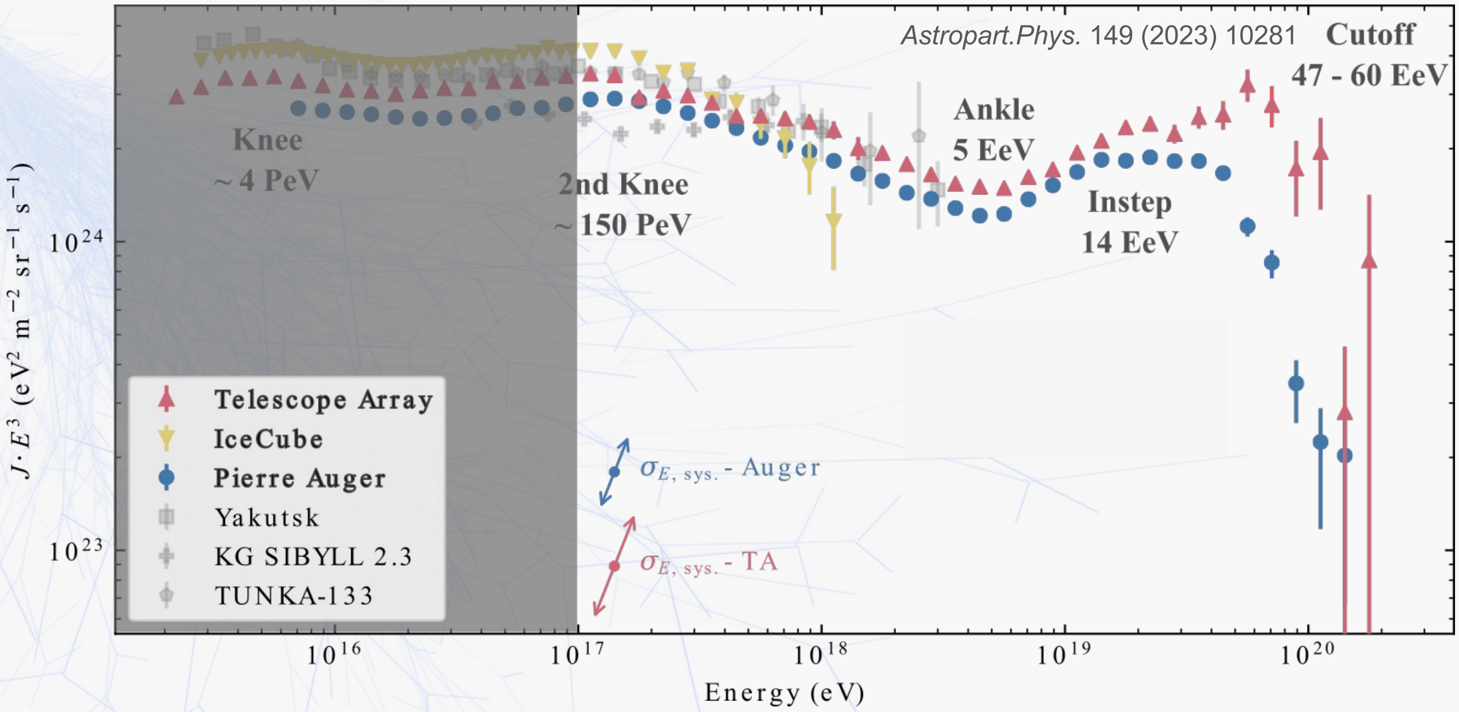


The High Energy End of the Cosmic Ray Spectrum



Ultra-High-Energy Cosmic Rays

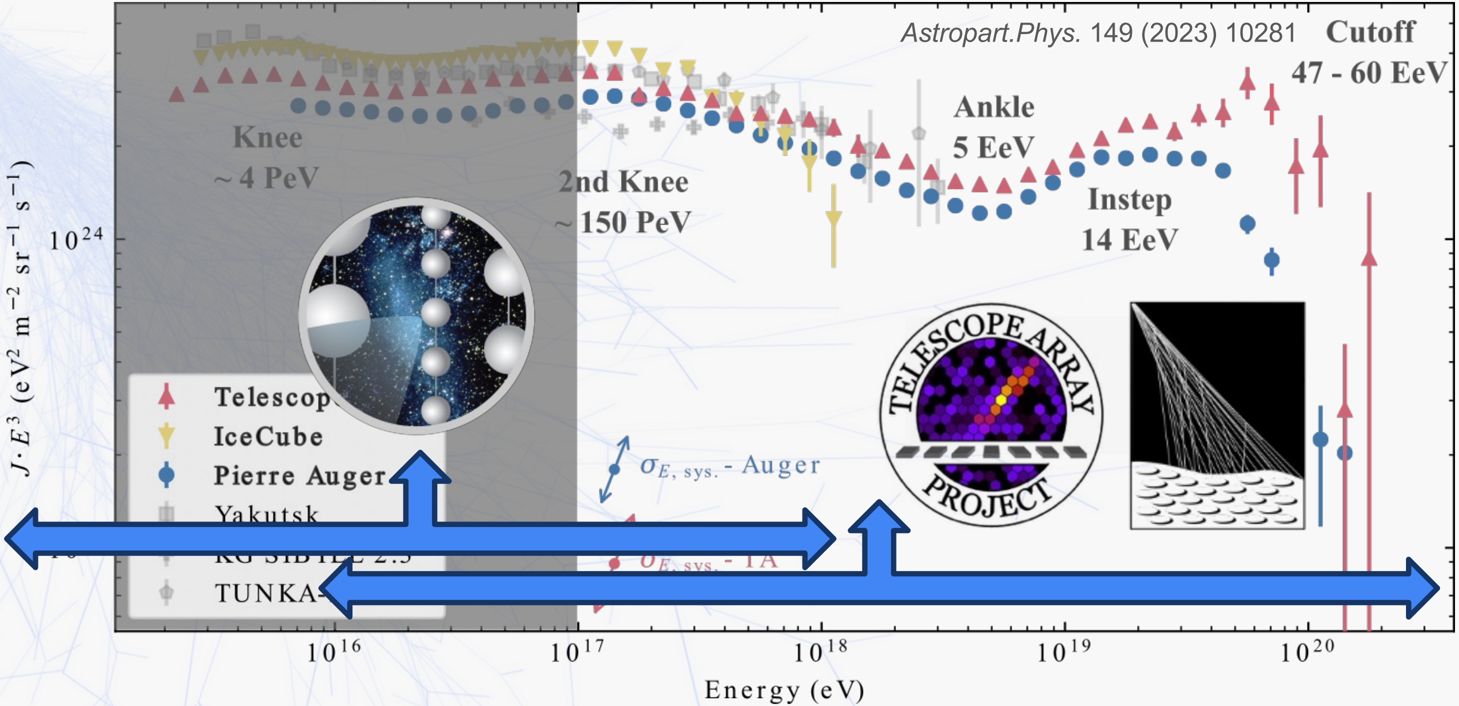


Adopting UHECR energy range of E > 100 PeV
from Snowmass Whitepaper

Open Questions

Astrophysics	What systems or phenomena are producing UHECR?
Astrophysics	What is the nature of the flux suppression at the highest energies?
Astrophysics	At what energy do galactic cosmic ray sources die out and extragalactic sources take over?
Particle Physics	Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?

Ultra-High-Energy Cosmic Rays Observatories



Due to the steeply descending flux,
measuring above the EeV range requires giant exposures

Era of Giant Arrays

The Telescope Array (TA):

Main Array 507 Scintillation Detectors (SD)
38 Fluorescence Telescopes (FD)
➢ Total Area ~700 km²

TA x 4 Expansion of SD and FD
➢ 500 new SDs
➢ 12-14 new FDs
➢ Total Area ~3000 km²

The Pierre Auger Observatory (Auger):

Phase 1 1660 water Cherenkov detectors (SD)
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AugerPrime Full Array upgrade adding:
➢ Scintillators to the full SD
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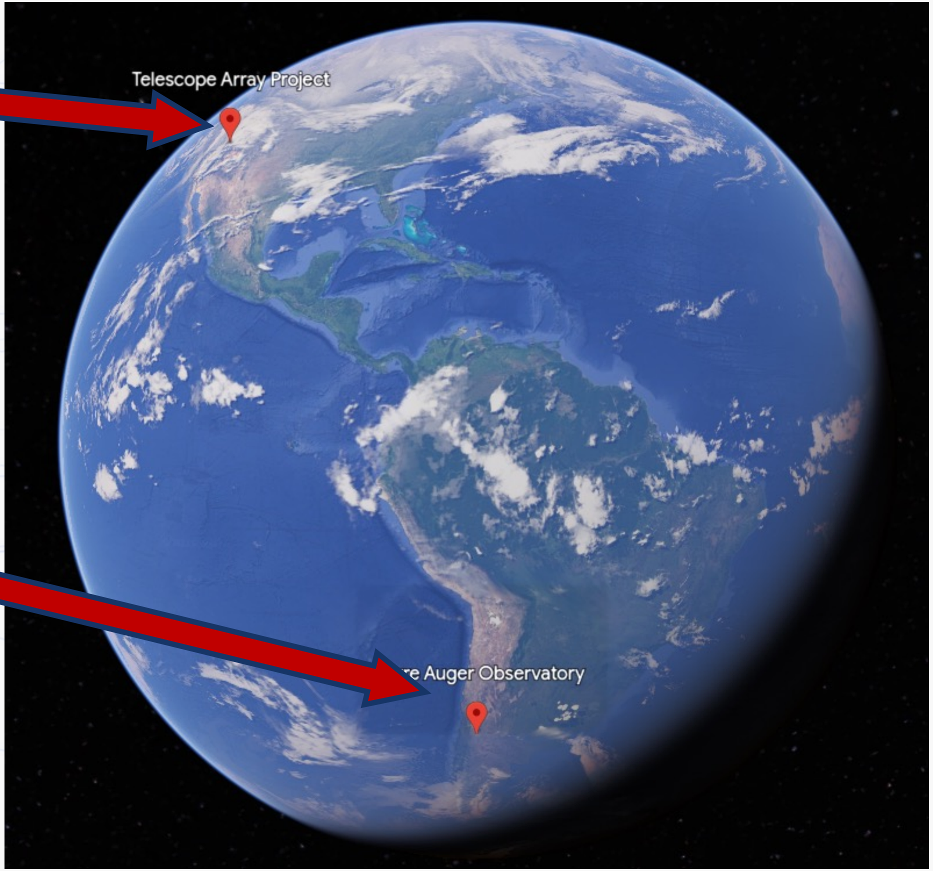
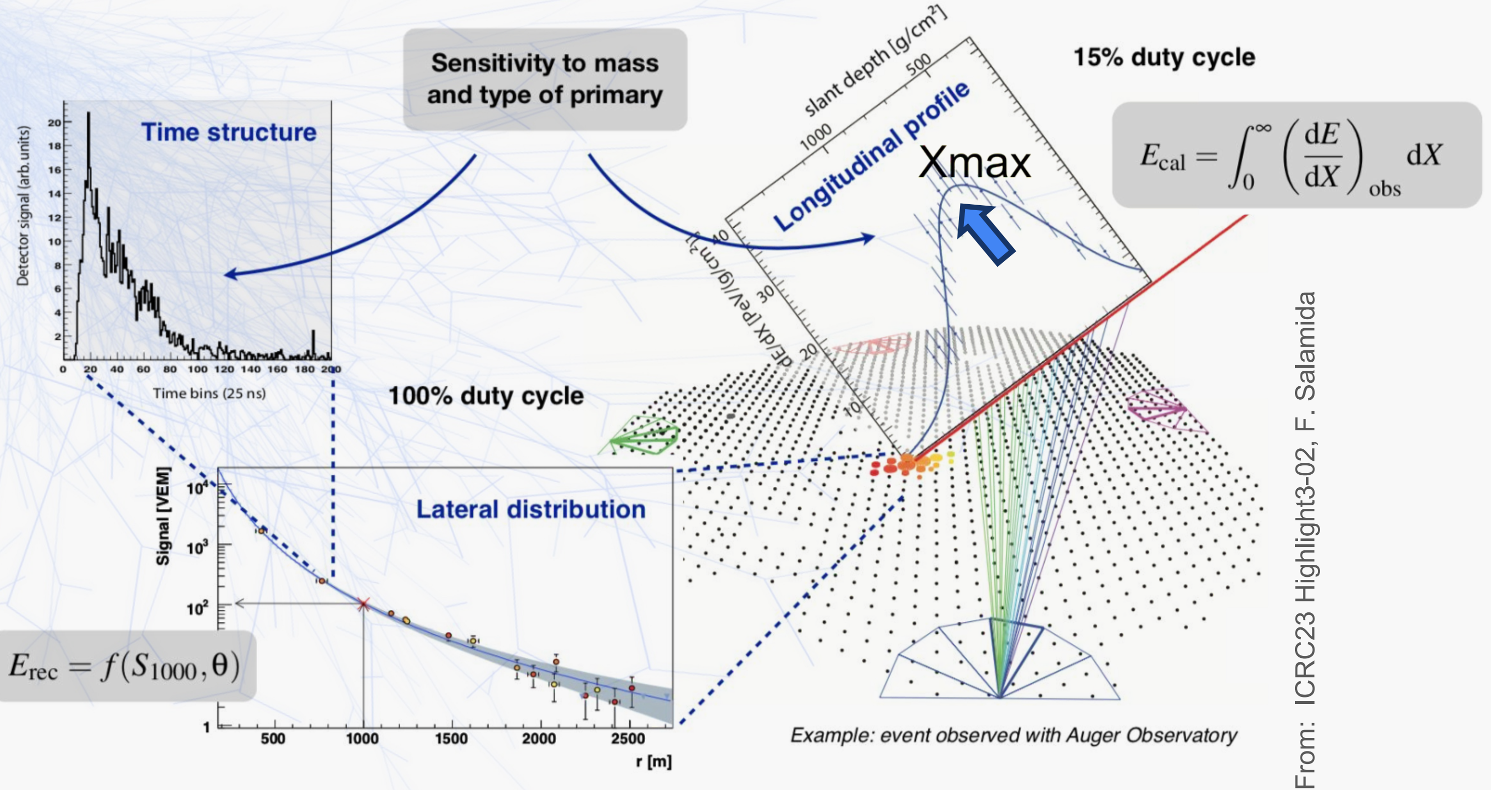


The Hybrid Observation Method



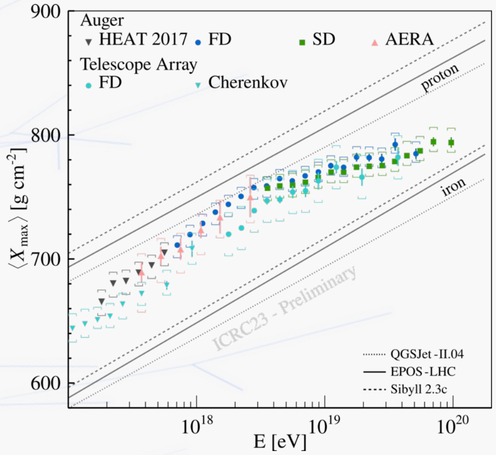
From: ICRC23 Highlight3-02, F. Salamida

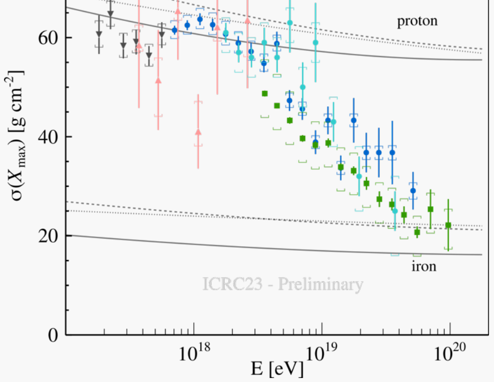
Composition of the UHECR Beam

PoS ICRC2023 (2023) 365

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:

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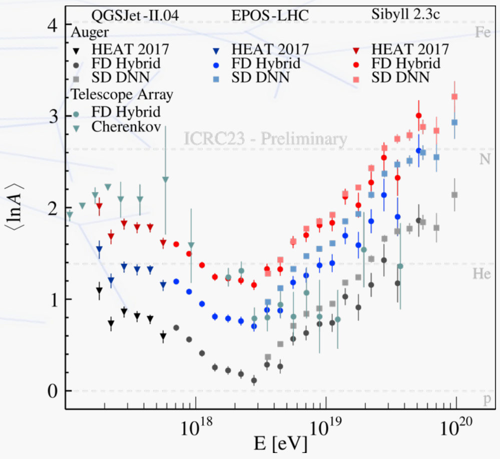

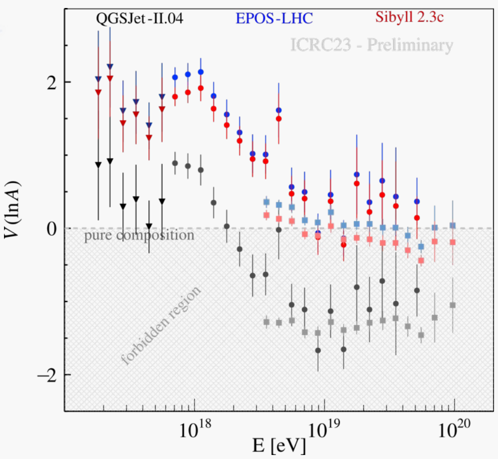

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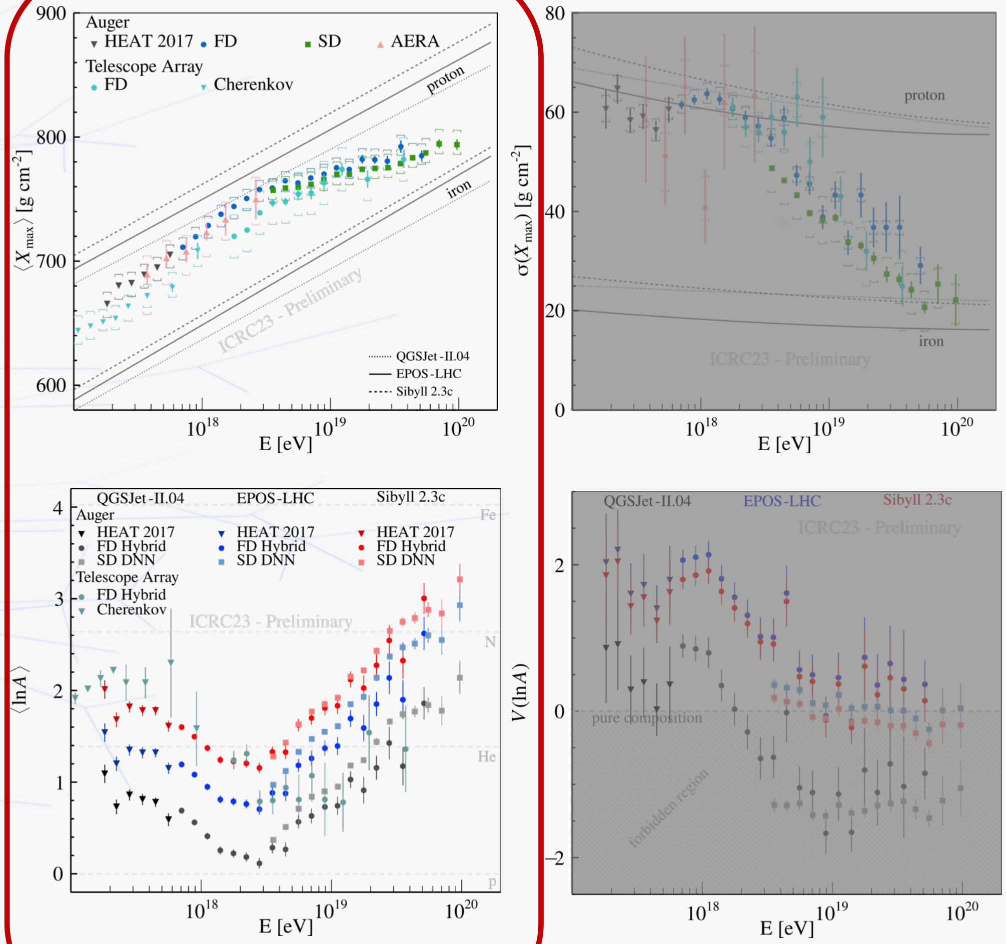

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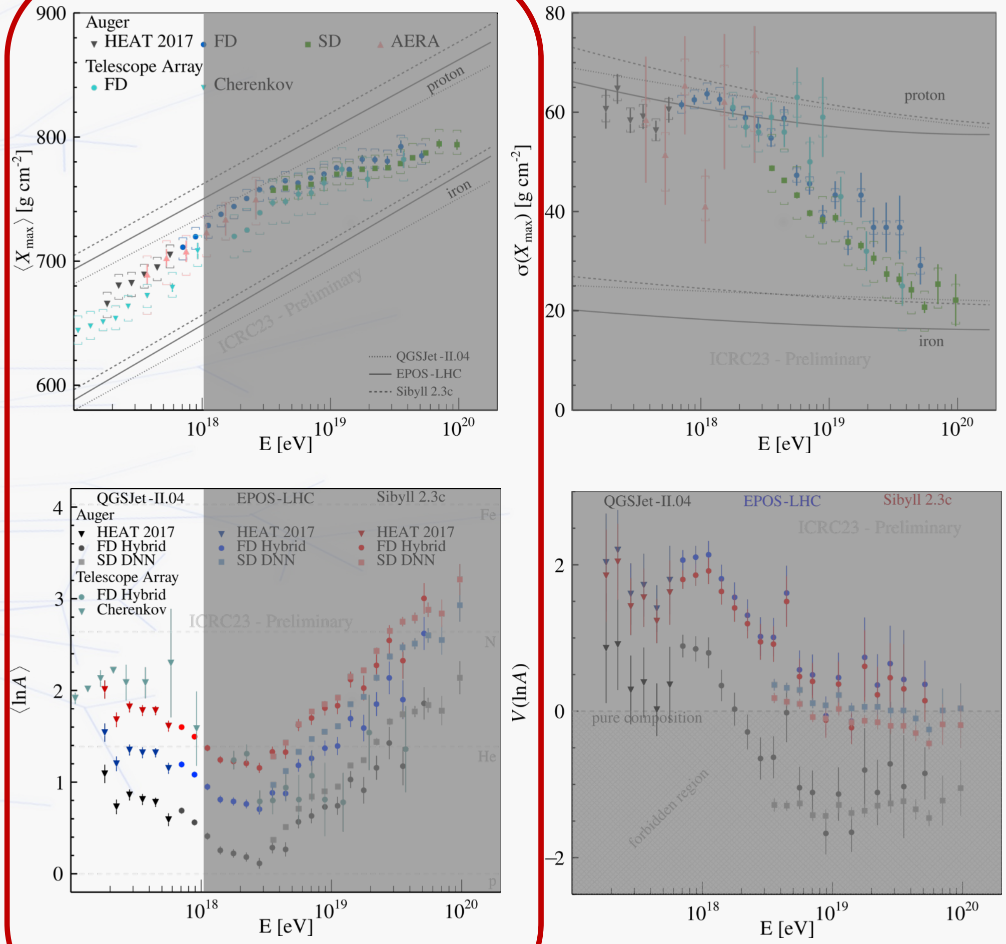

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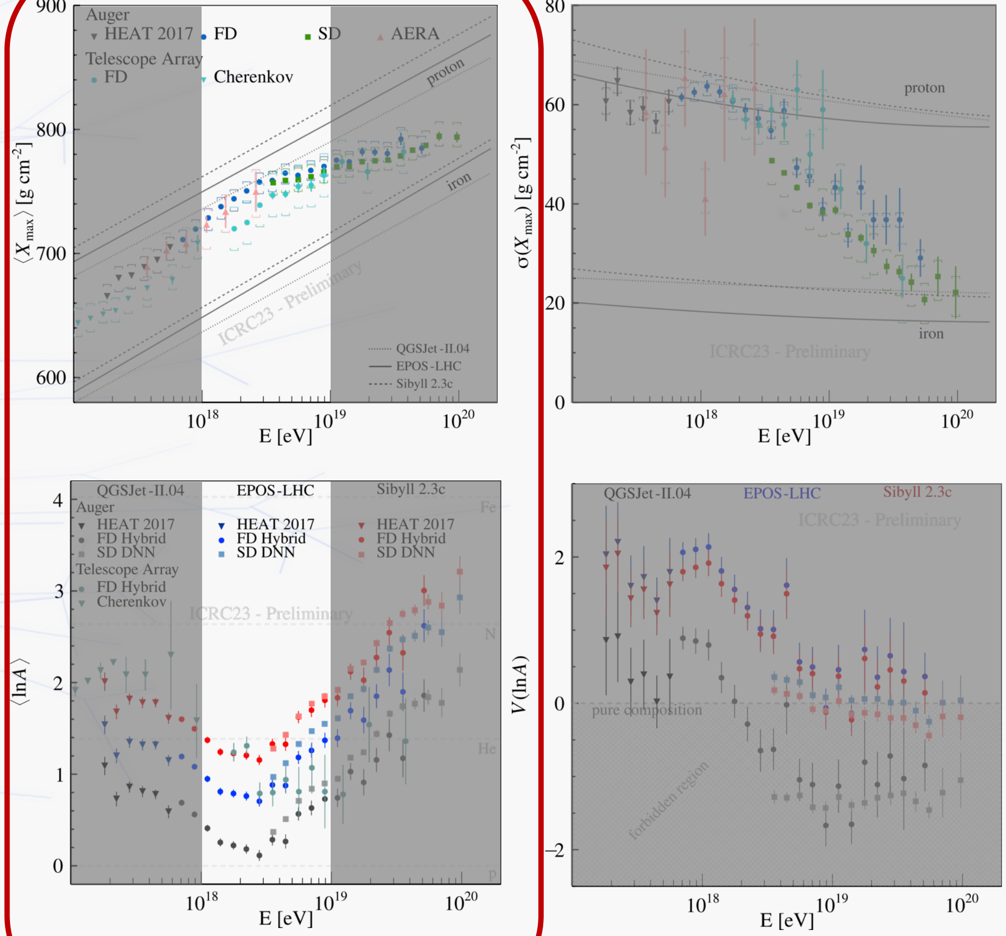

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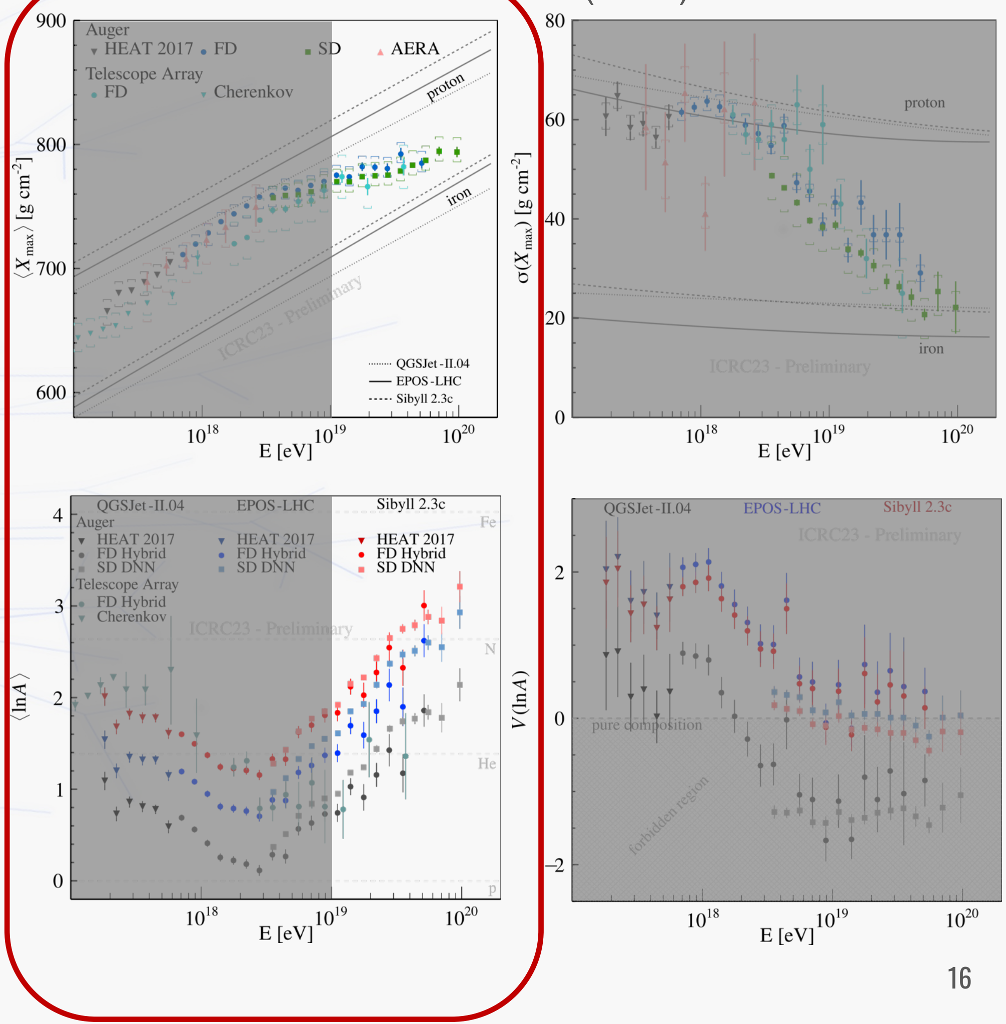

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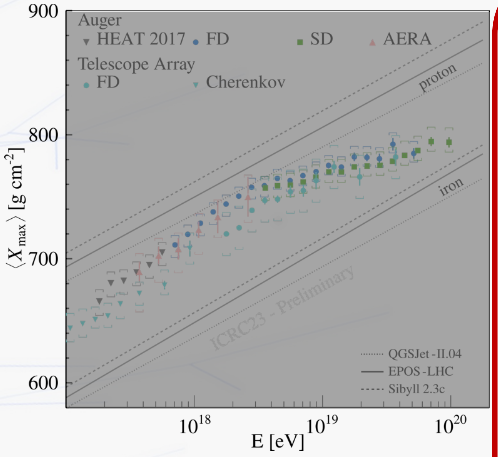

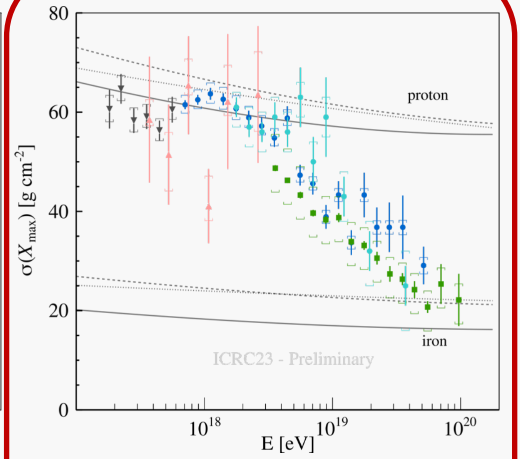

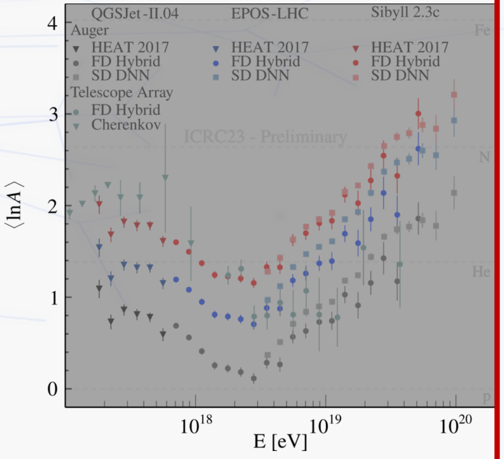

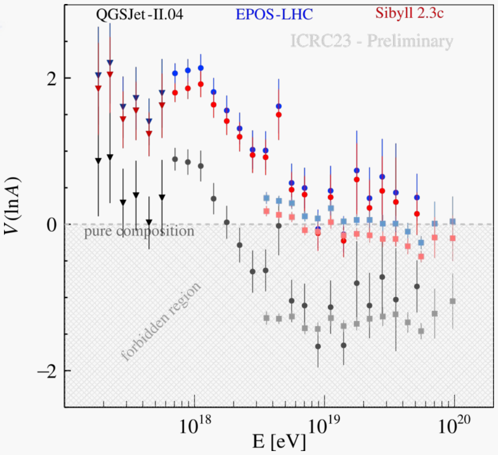

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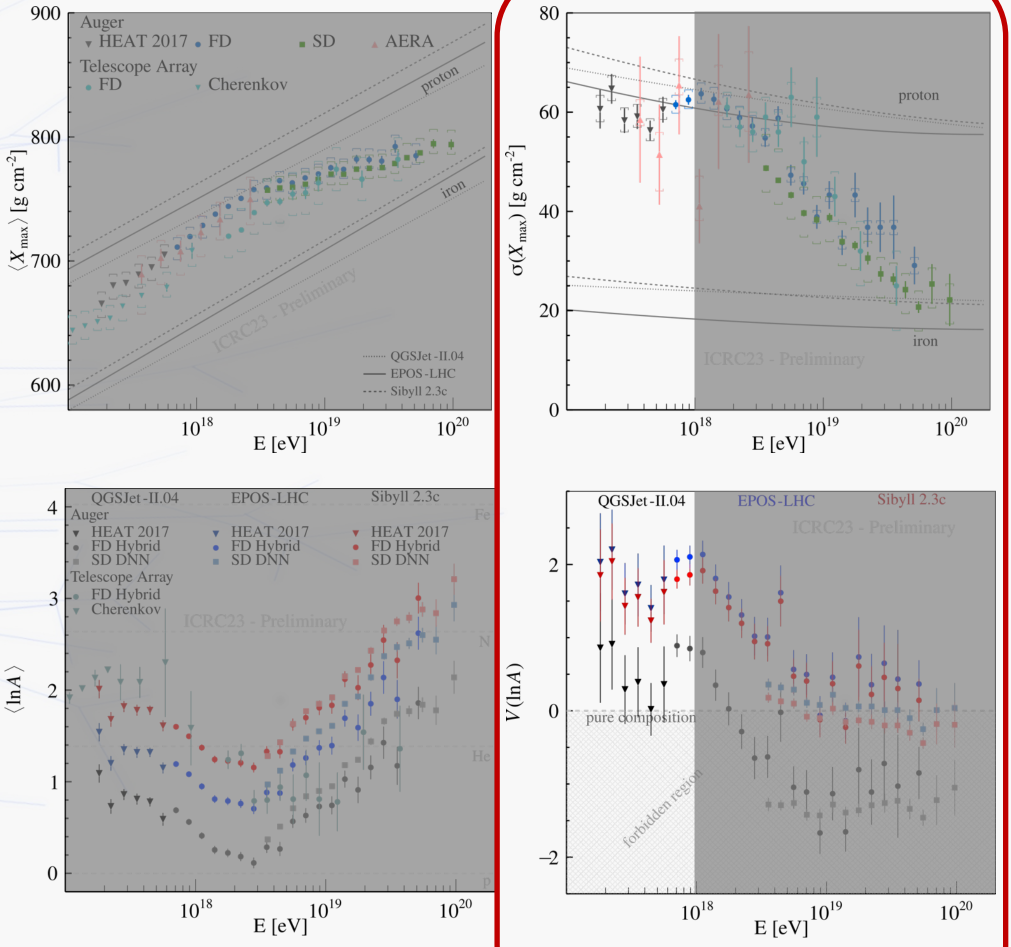

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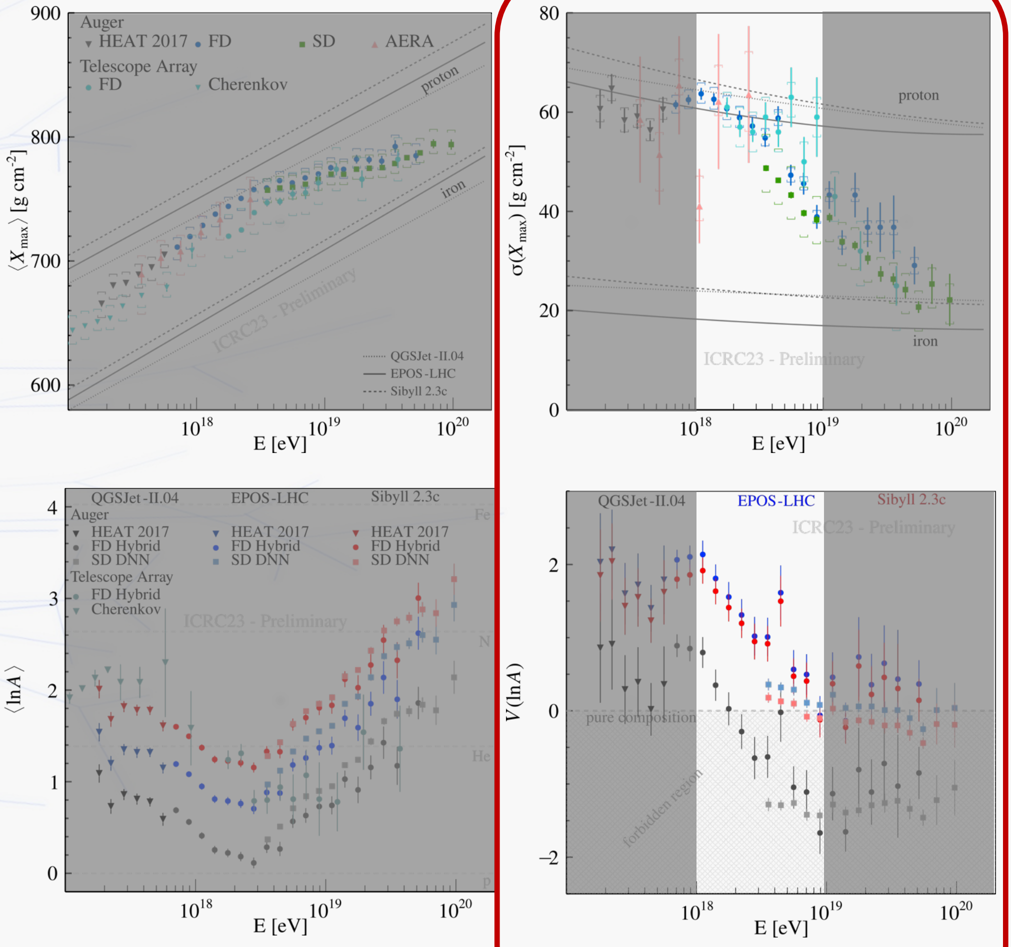

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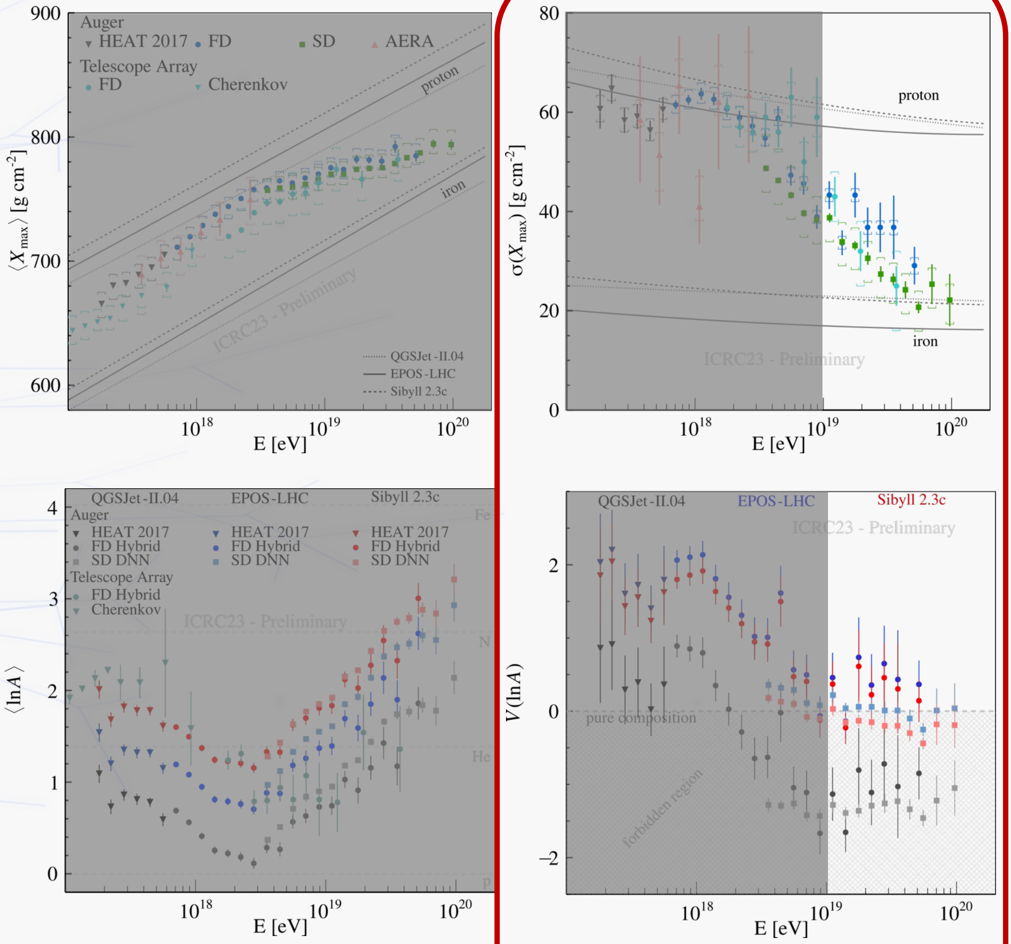

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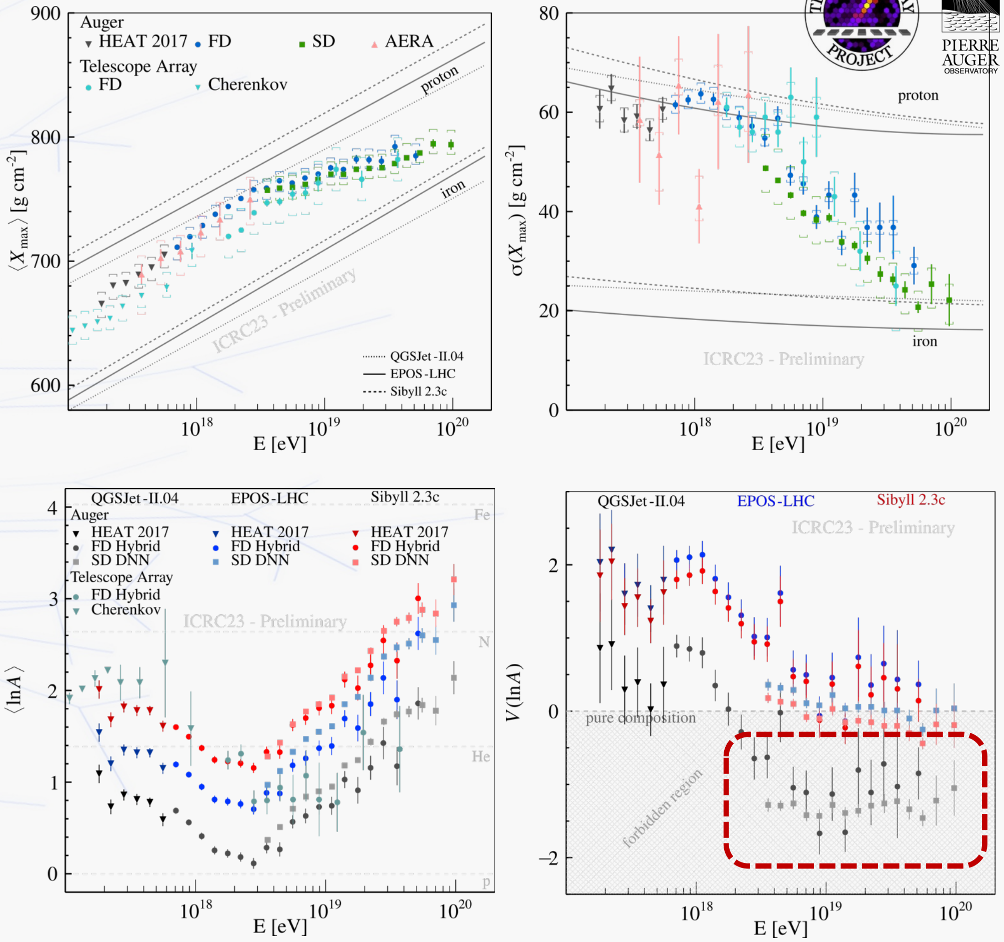

QGSJET-II.04 model predictions in tension with data and should be used with caution!

Fractional Composition of the UHECR Beam

PoS ICRC2023 (2023) 365
PoS ICRC2023 (2023) 438

Protons: as expected from ln*A*, peak around 2-3 EeV.
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CNO: fraction continues to climb up to ~ 50 EeV and may continue beyond

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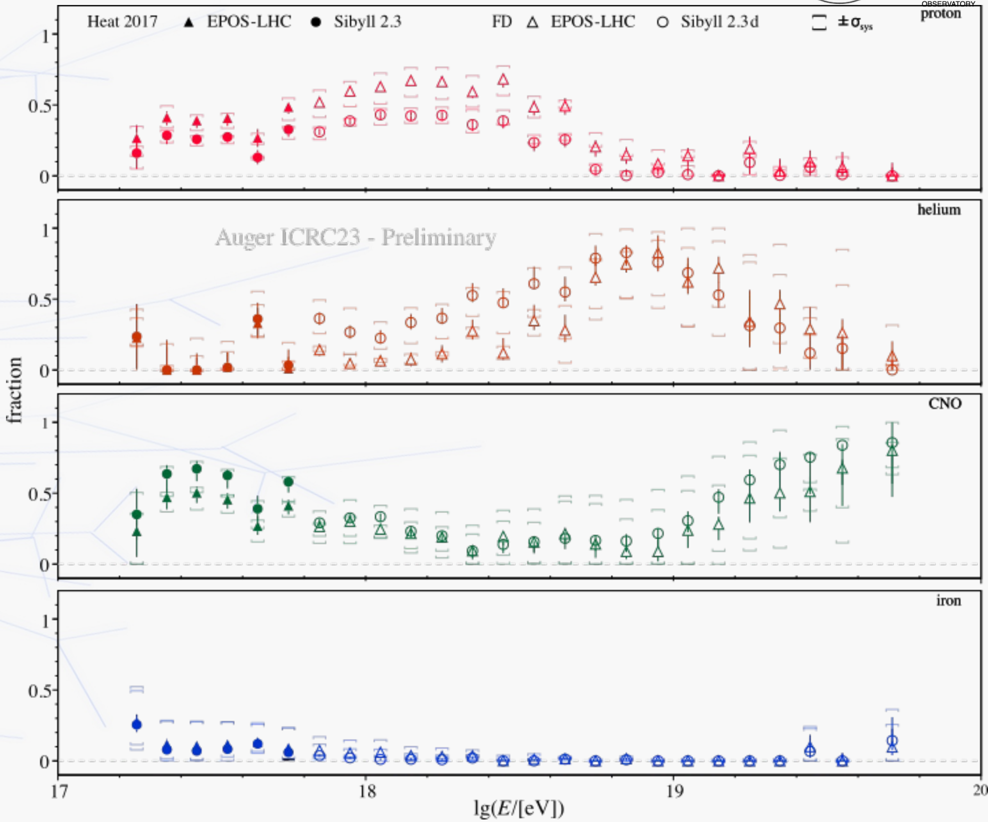

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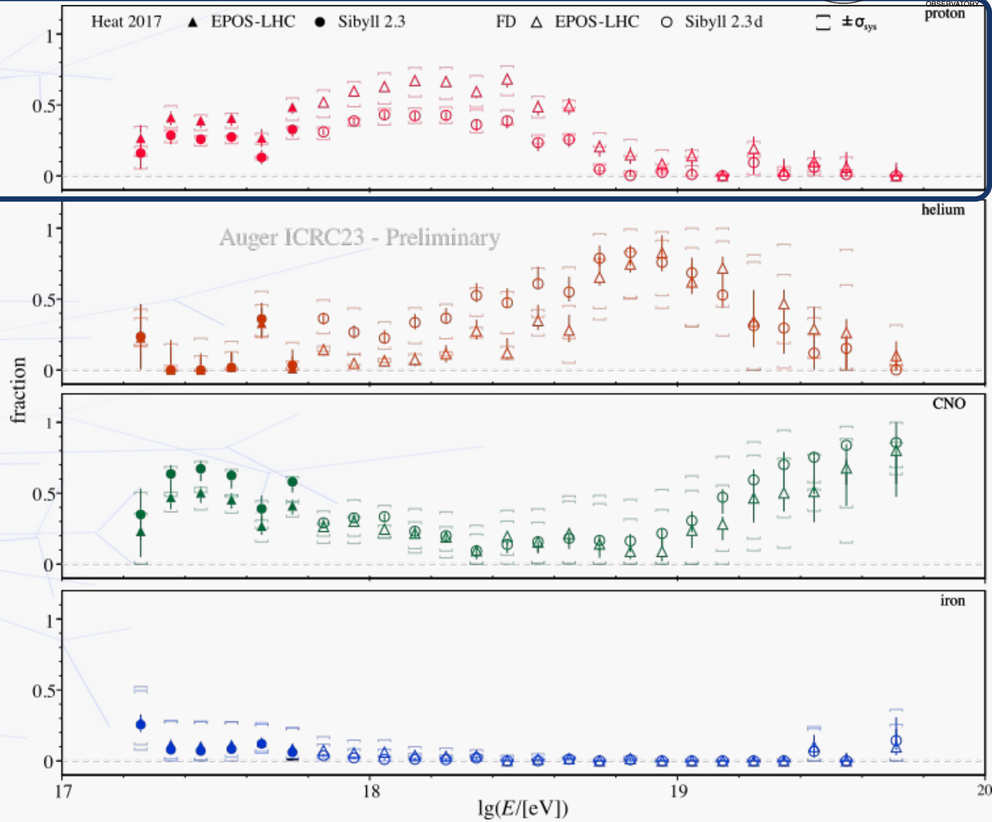

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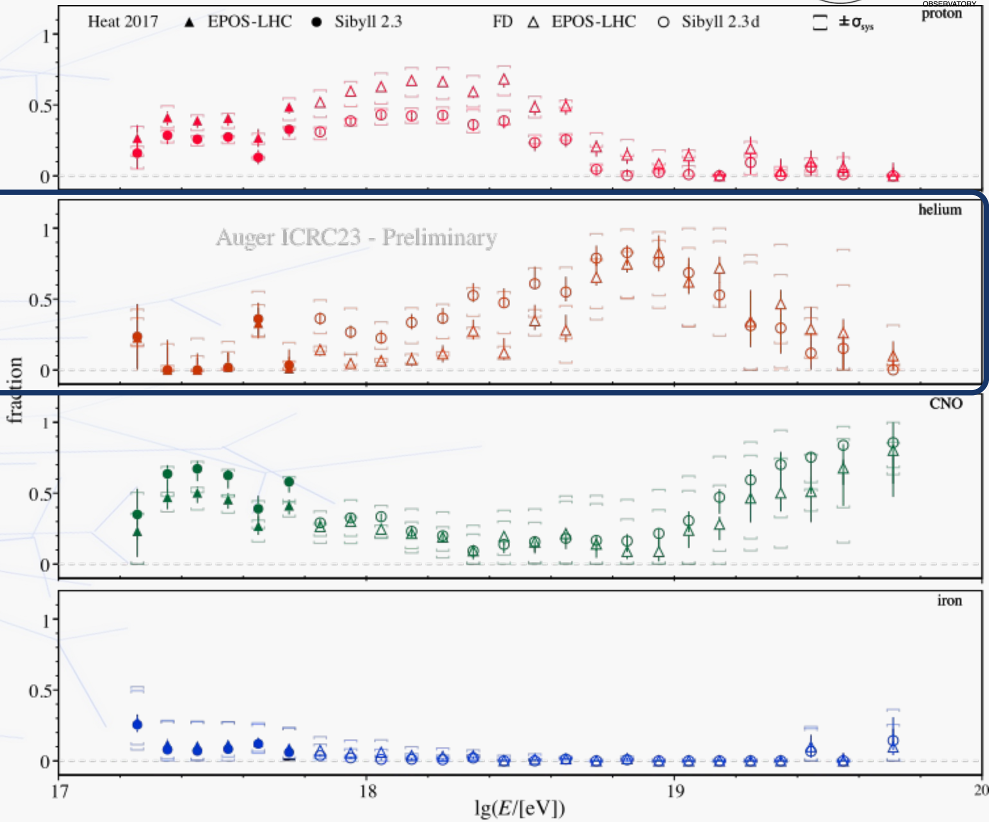

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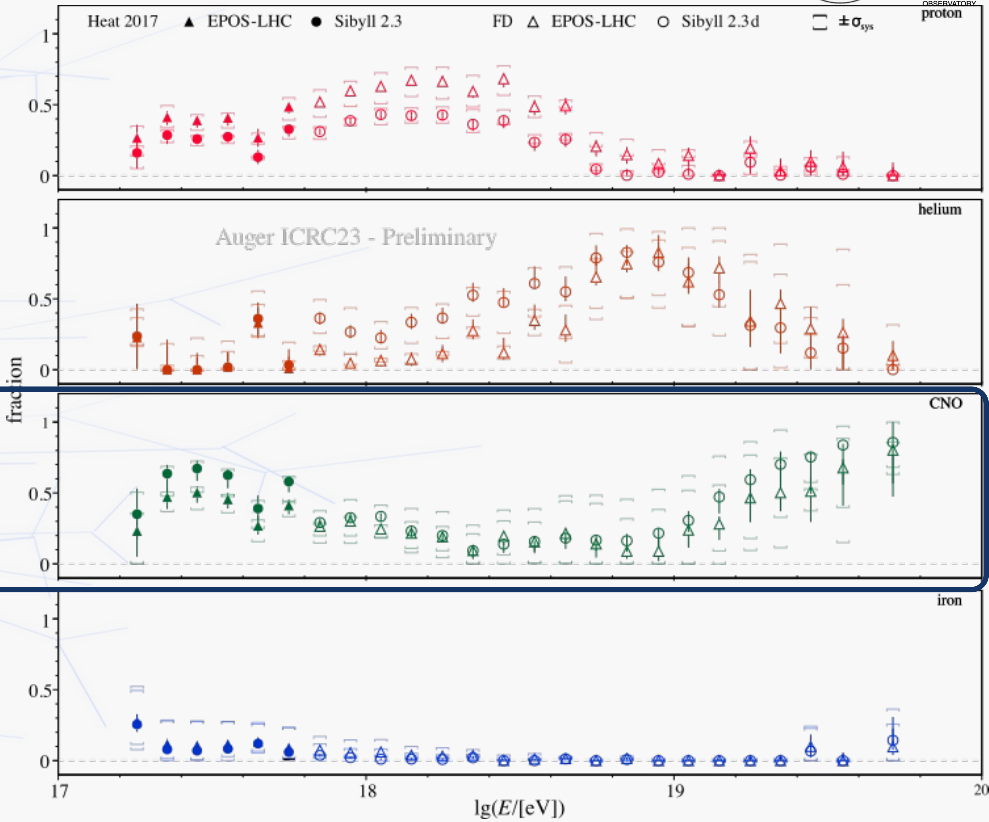

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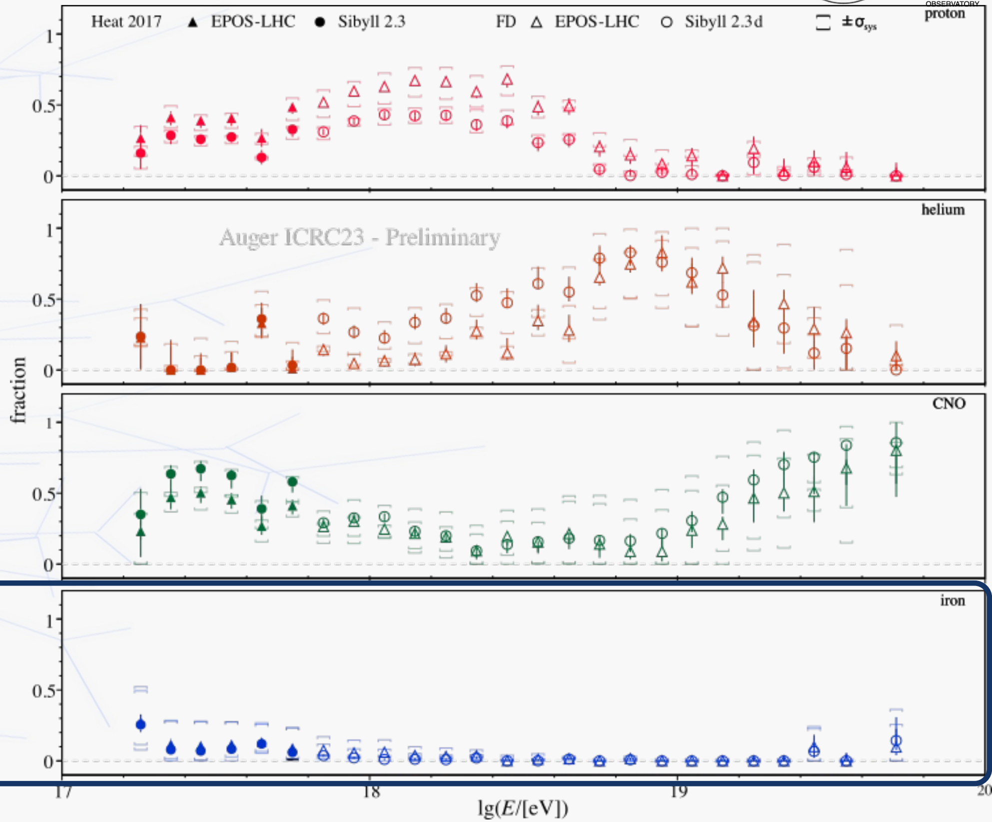

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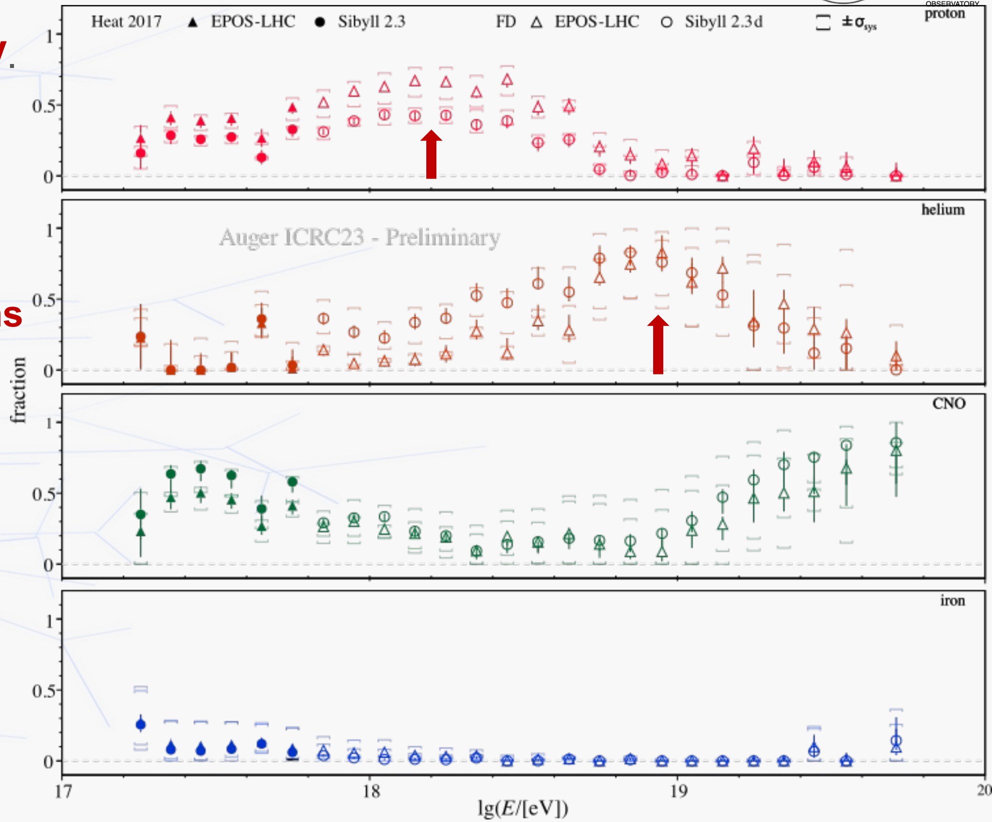

Energies of the proton and Helium peaks suggest dependence on mass rather than rigidity
→ implies propagation effects play an important role in arriving composition ←

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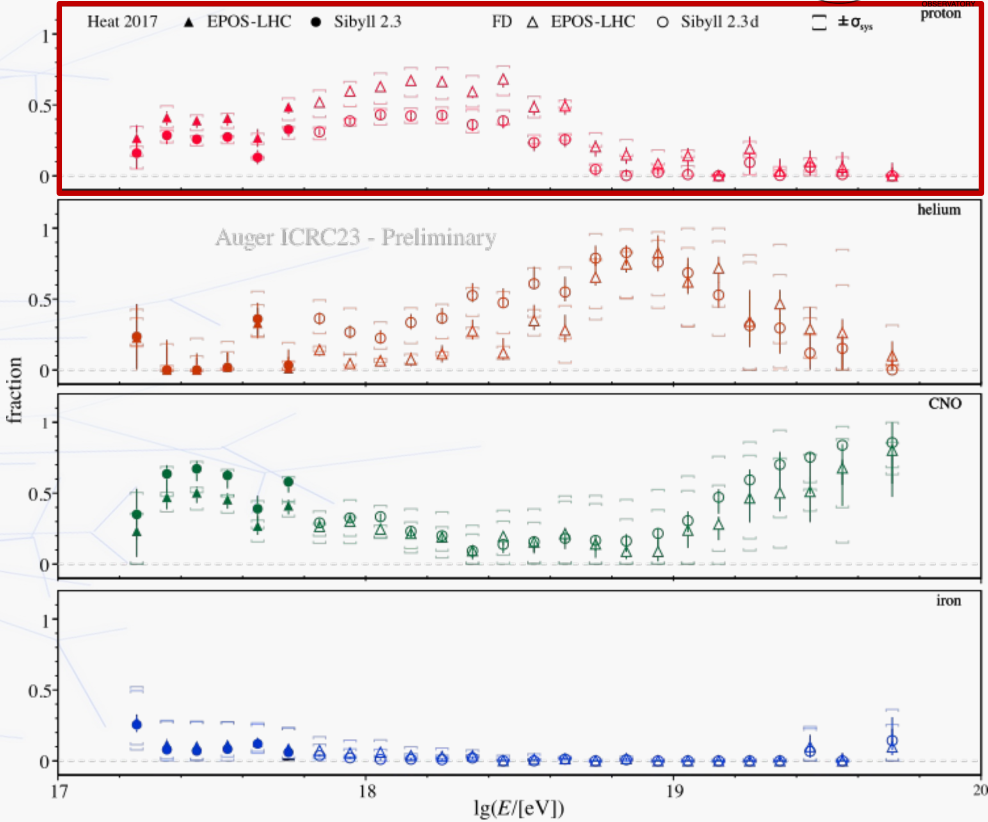

Non-dominance of protons at ankle and high energies constrains a proton-pile-up scenario and strongly constrains photo-pion GZK as a cause for the cutoff at the highest energies.

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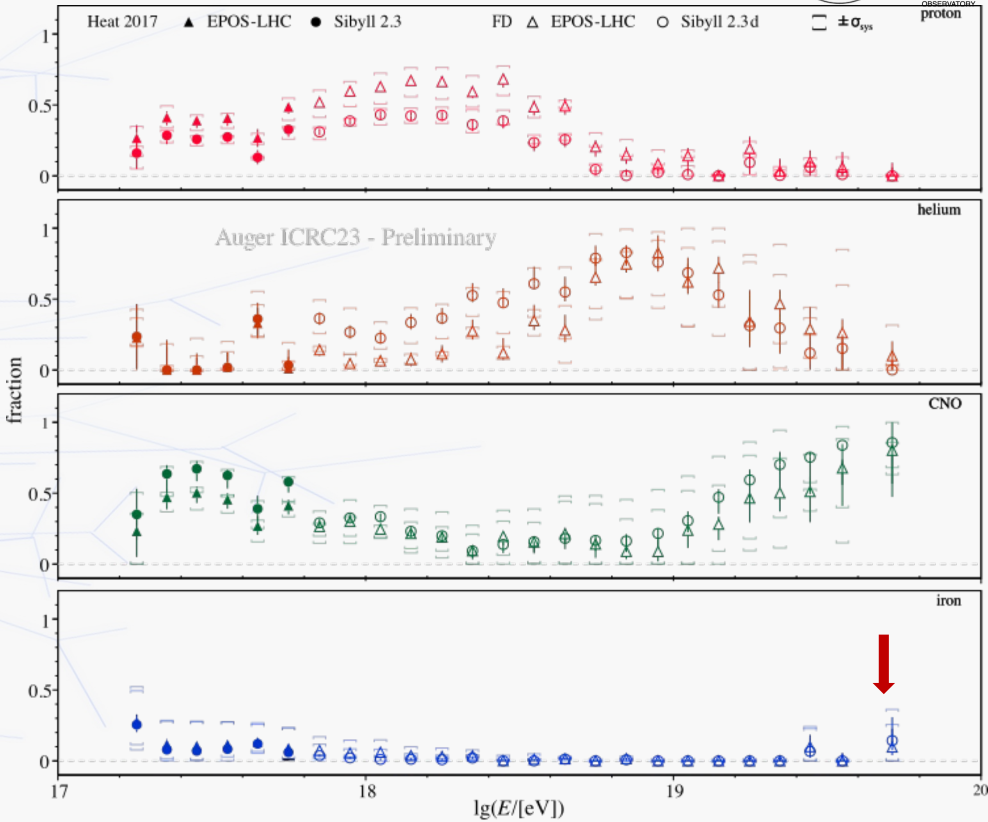


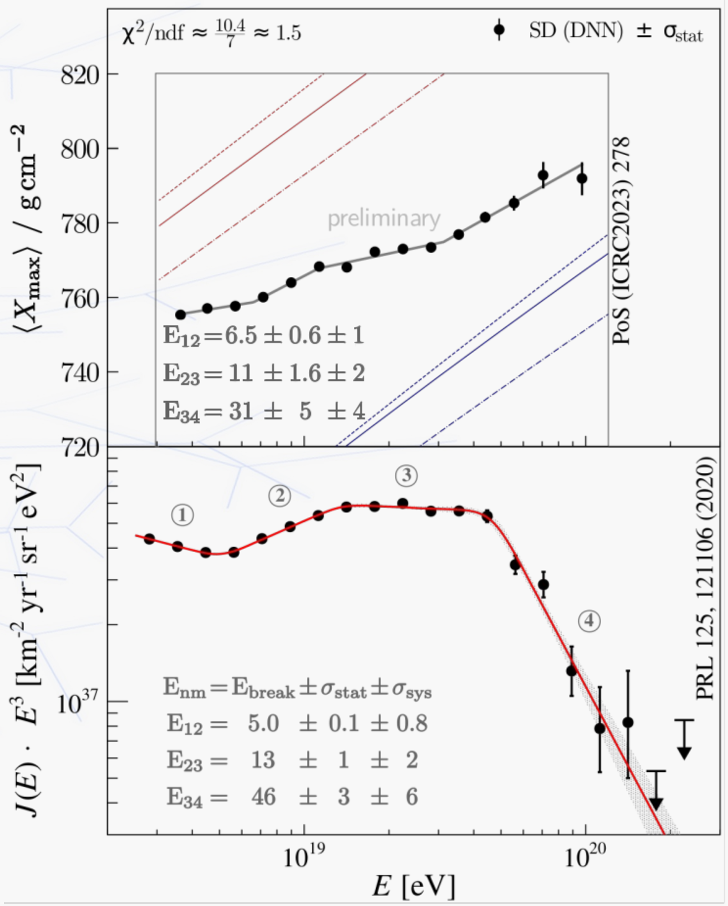
Small allowable Iron fraction hints the flux may trend towards iron at highest energies
Fitting fractions to SD X_{max} will illuminate UHECR composition up to 100 EeV

New possible Cross-correlation! – Mass and Spectrum

With the new DNN based SD X_{max} 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 produces the best fit with breaks at similar energies as the spectrum



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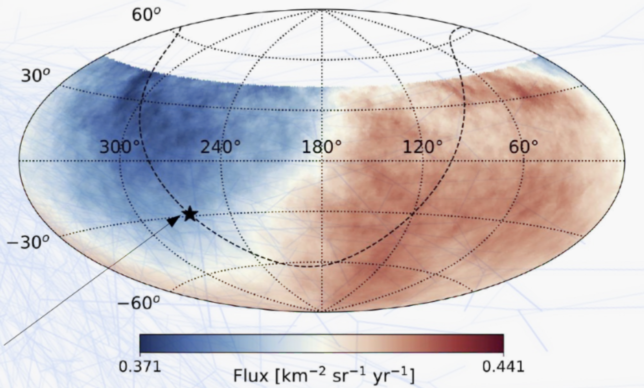
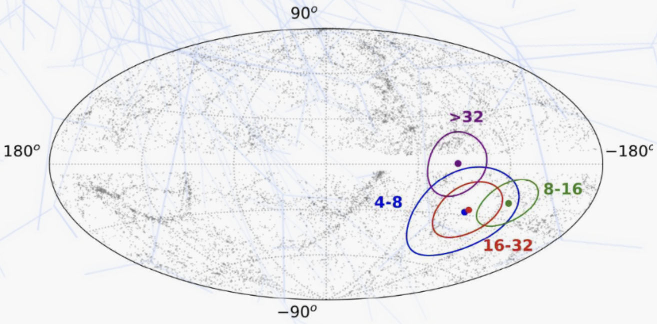
Dipole in UHECR Arrival Directions above 8 EeV

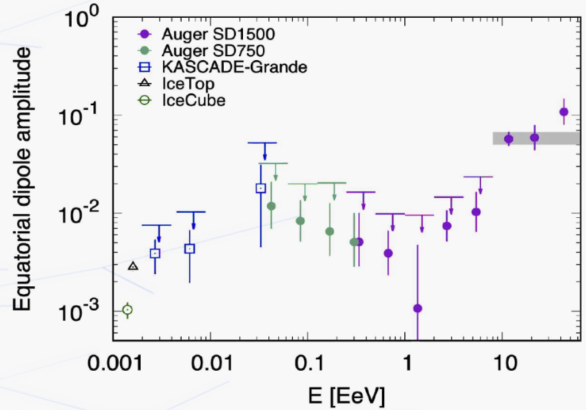
Dipole direction ~113° away from the GC

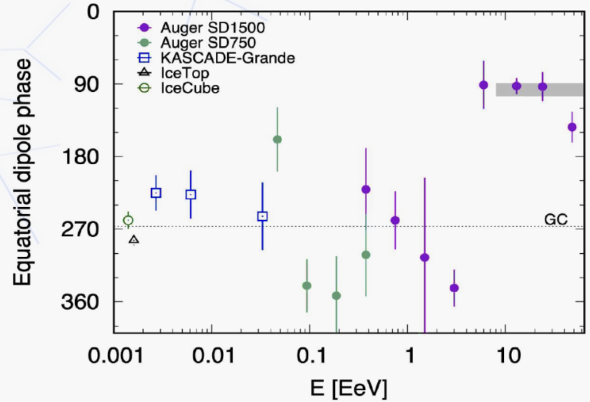


Equatorial coordinates, smoothed by a top-hat window of 45°.



Evolution of the dipole direction with E
(Galactic coordinates)





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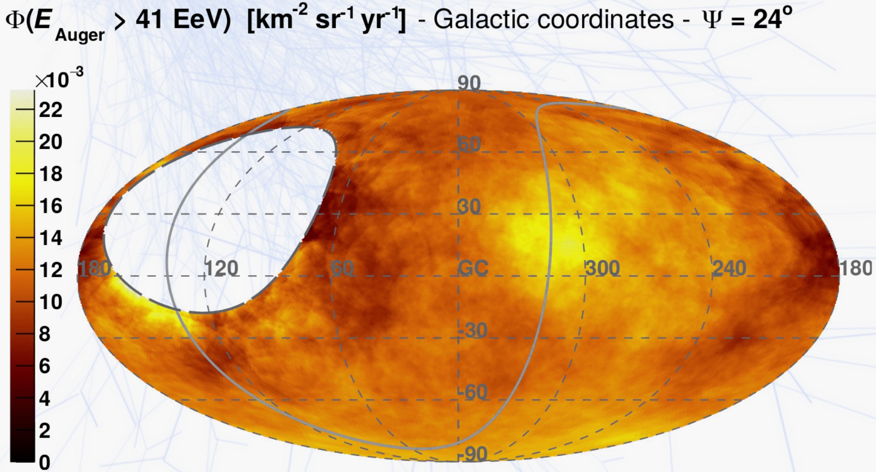
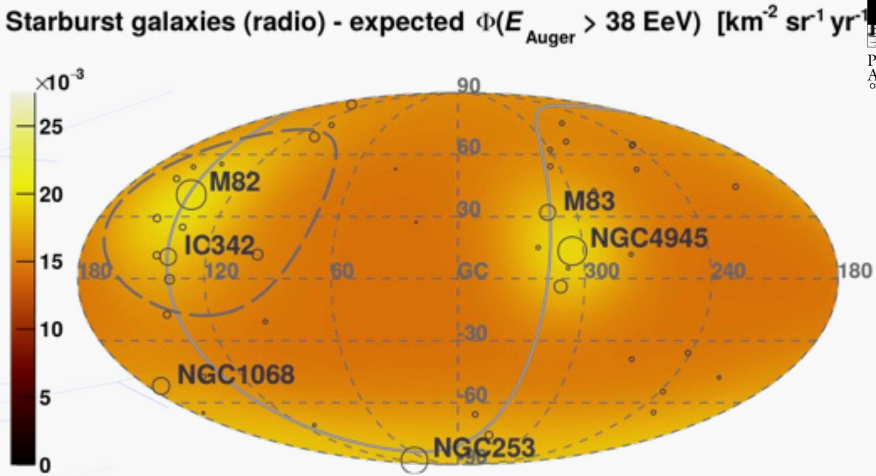
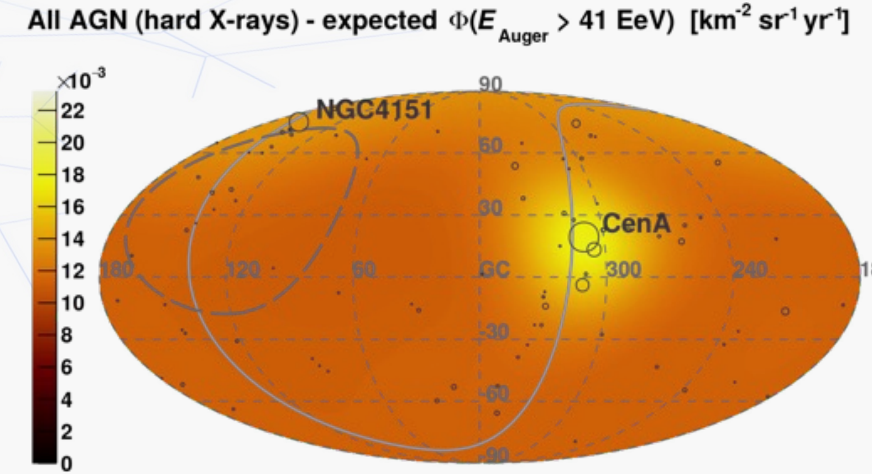
Narrowing down Source Candidates In Southern Sky



Starburst Galaxies?

AGN?





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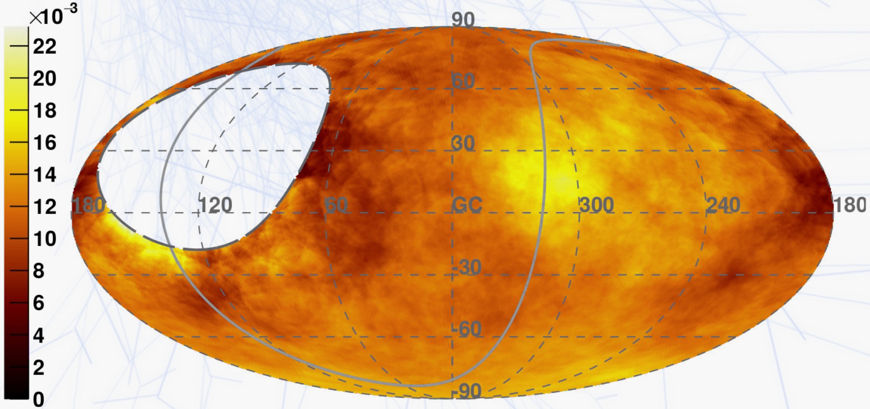
Narrowing down Source Candidates In Southern Sky

3.8 σ

Starburst Galaxies?

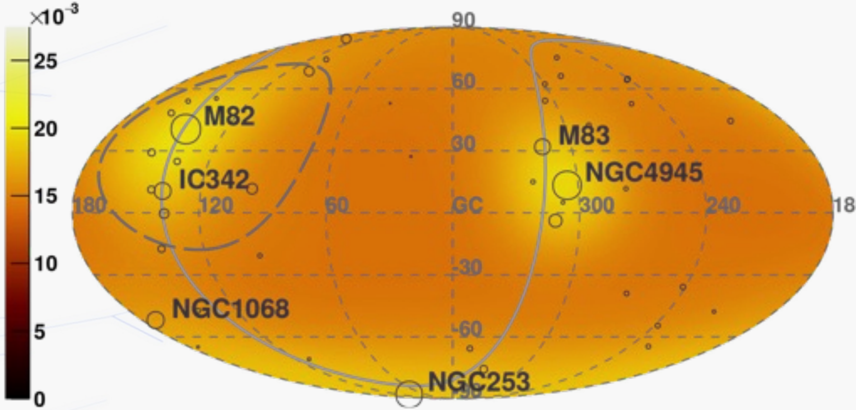
$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24^{o}$



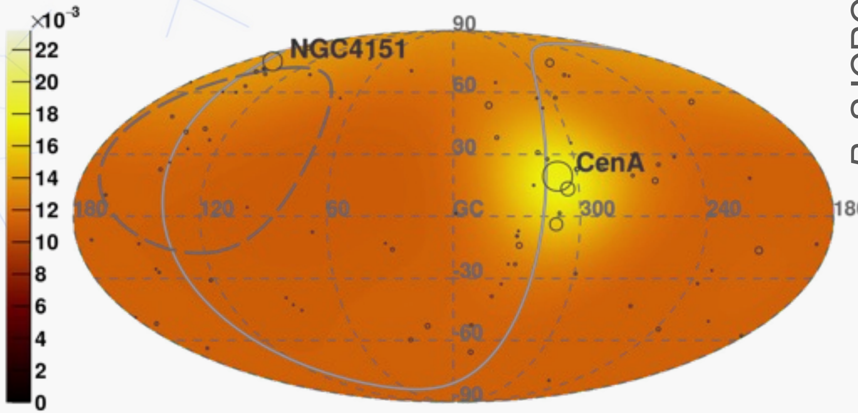
AGN?

3.5 σ

Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38$ EeV) [km^{-2} sr^{-1} yr^{-1}]



All AGN (hard X-rays) - expected $\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}]



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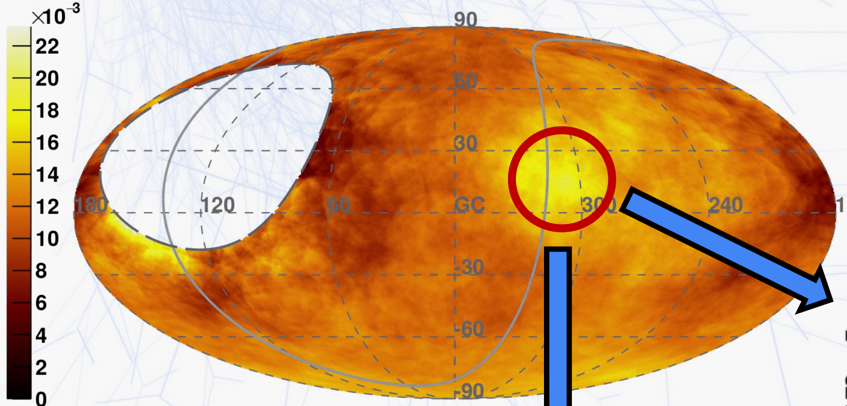
Narrowing down Source Candidates in Southern Sky

3.8 σ

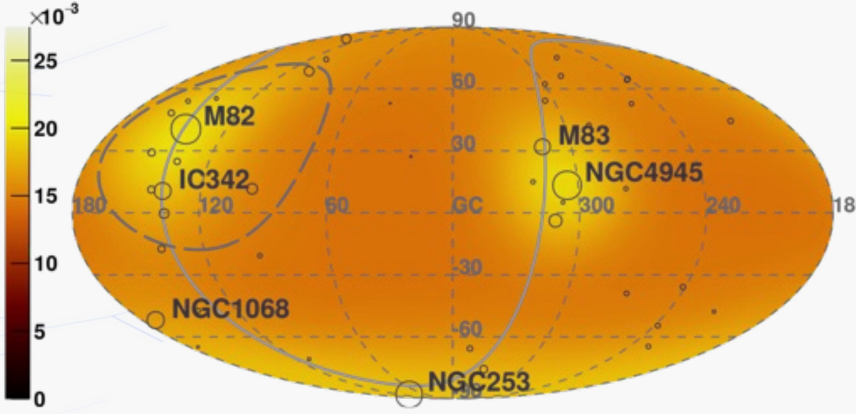
Starburst Galaxies?

$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24^{\circ}$

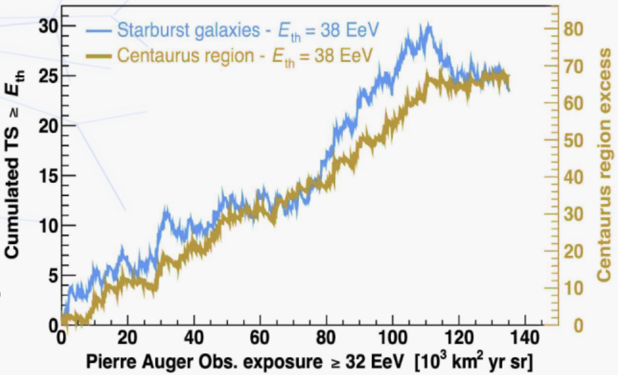


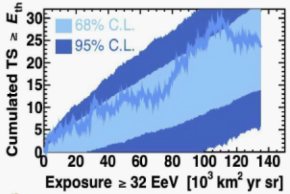
CenA region alone is as significant as SBGs

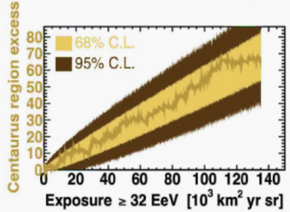
Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38$ EeV) [km^{-2} sr^{-1} yr^{-1}]



~90% isotropic distribution







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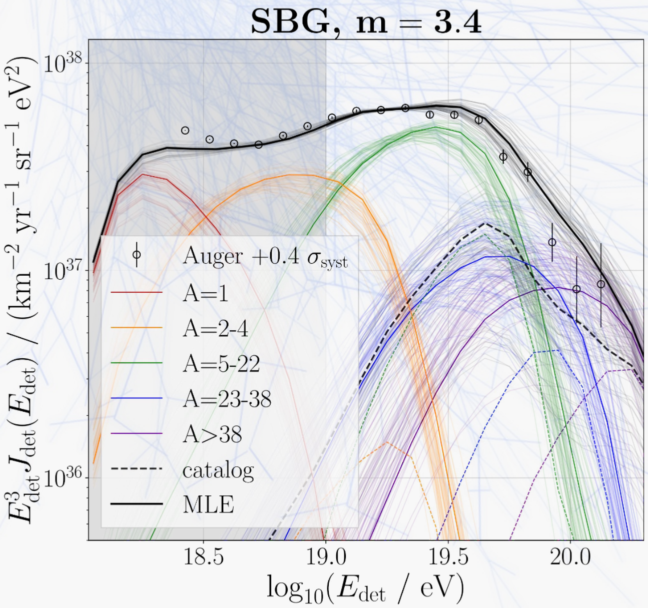
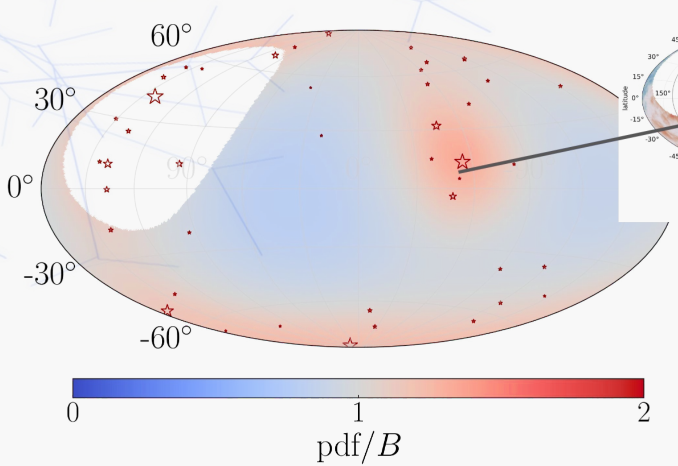
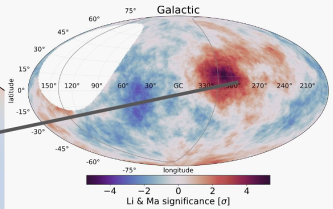
Fit combining Anisotropy, Composition and Spectrum accounting for Magnetic Fields and Source Distribution

Can we break the tie?



- SBG signal fraction of 20%
- Main contribution from CenA region
- Results compatible with standard combined fit
- Significance of 4.5 σ
  → 4.0 σ with only arrival direction





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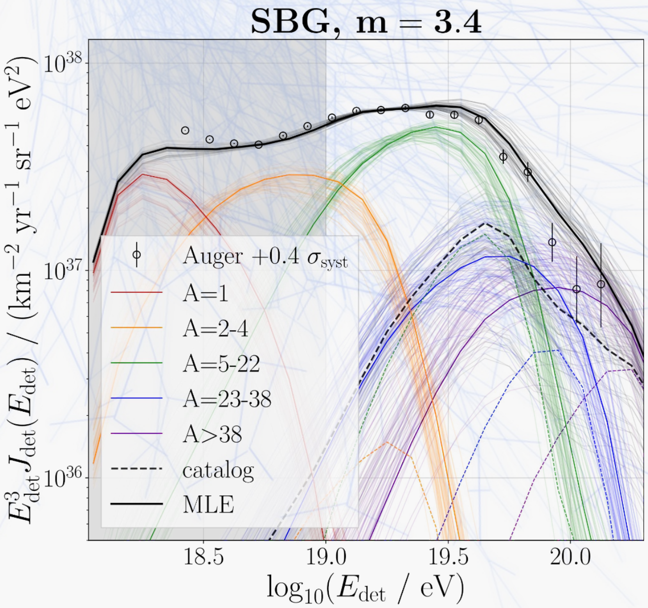
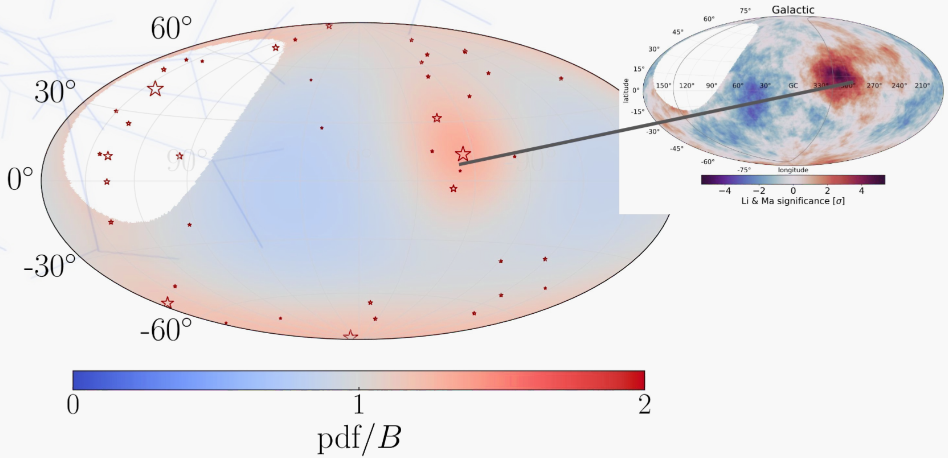
Fit combining Anisotropy, Composition and Spectrum accounting for Magnetic Fields and Source Distribution

Starburst Galaxy Catalog favored



- SBG signal fraction of 20%
- Main contribution from CenA region
- Results compatible with standard combined fit
- **Significance of 4.5 σ**
  → 4.0 σ with only arrival direction



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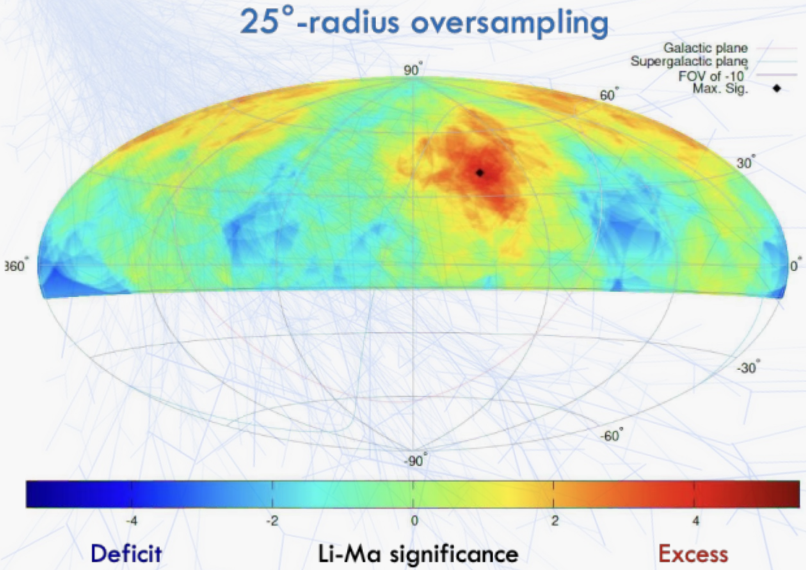
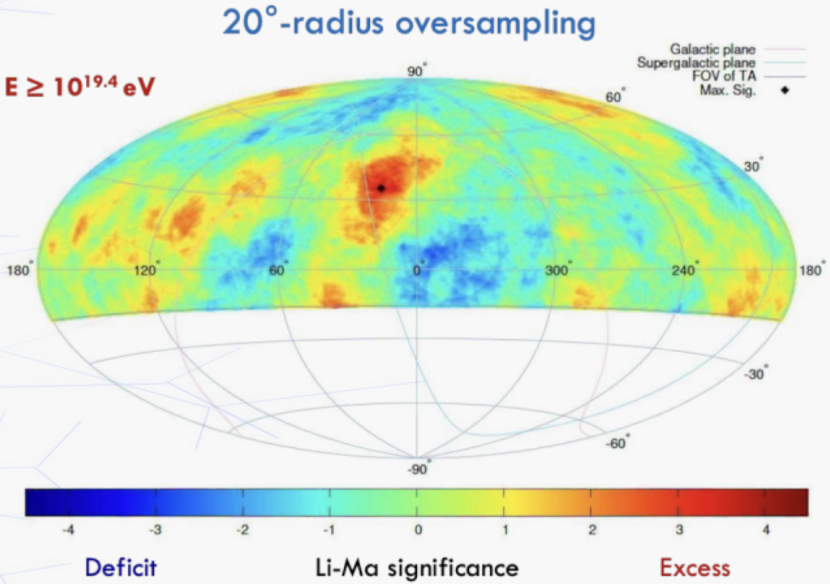
Narrowing down Source Candidates in the Northern Sky





Localized excess observed in UHECR E > 57 EeV

Excess around Perseus–Pisces Supercluster observed for E > 25 EeV

Current Significance 2.8σ

Current Significance 3.3σ

dd

New possible Cross-correlation!

Mass and Arrival Direction

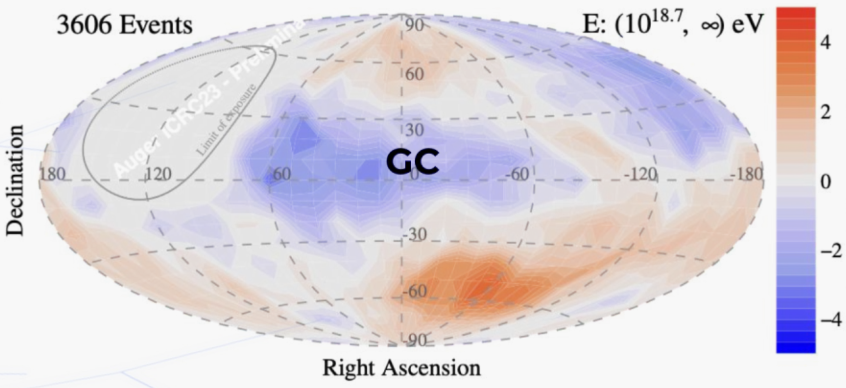
Using FD X_{max} (soon also SD X_{max}) Anisotropy as function of UHECR composition can be searched for

First result:

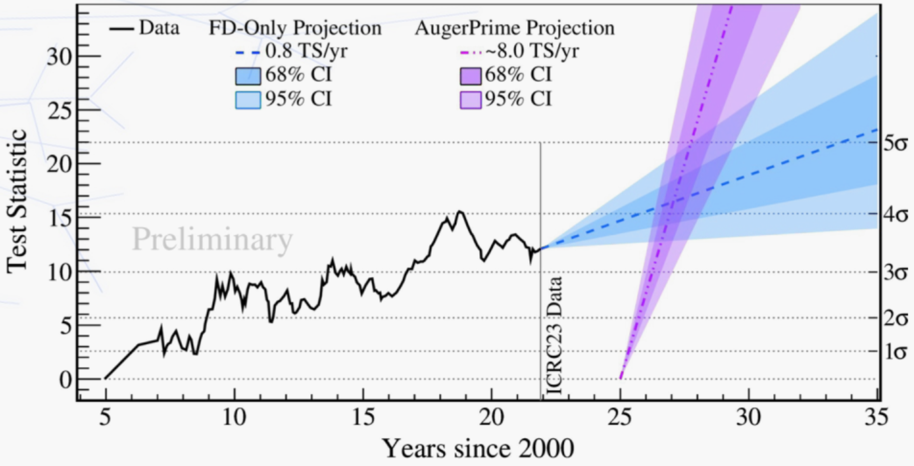
Above 5 EeV a slightly heavier mass observed for UHECR arriving from within 30º of the Galactic Plane as compared to the rest of the sky

Current significance 2.5**σ**

Current growth rate puts 5**σ** in 2034, with AugerPrime 2027.



Test Statistics evolution extrapolation



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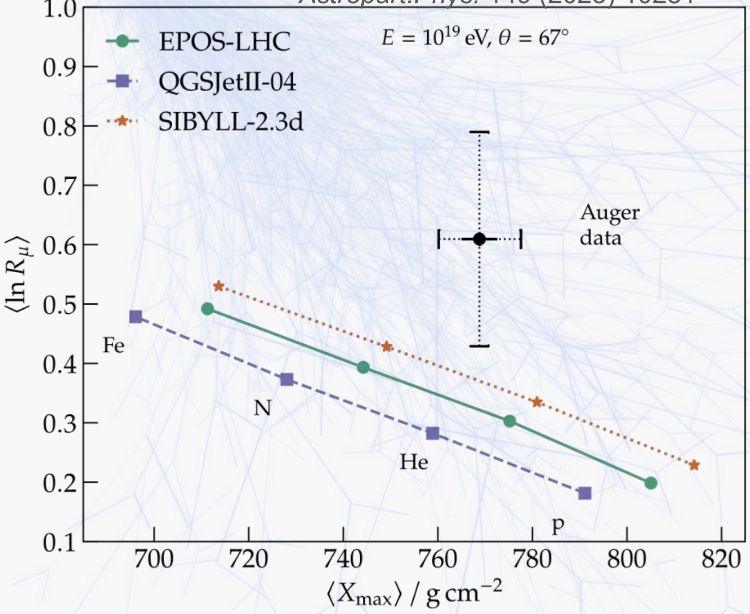
PIERRE AUGER OBSERVATORY

The Muon Puzzle

Astropart.Phys. 149 (2023) 10281



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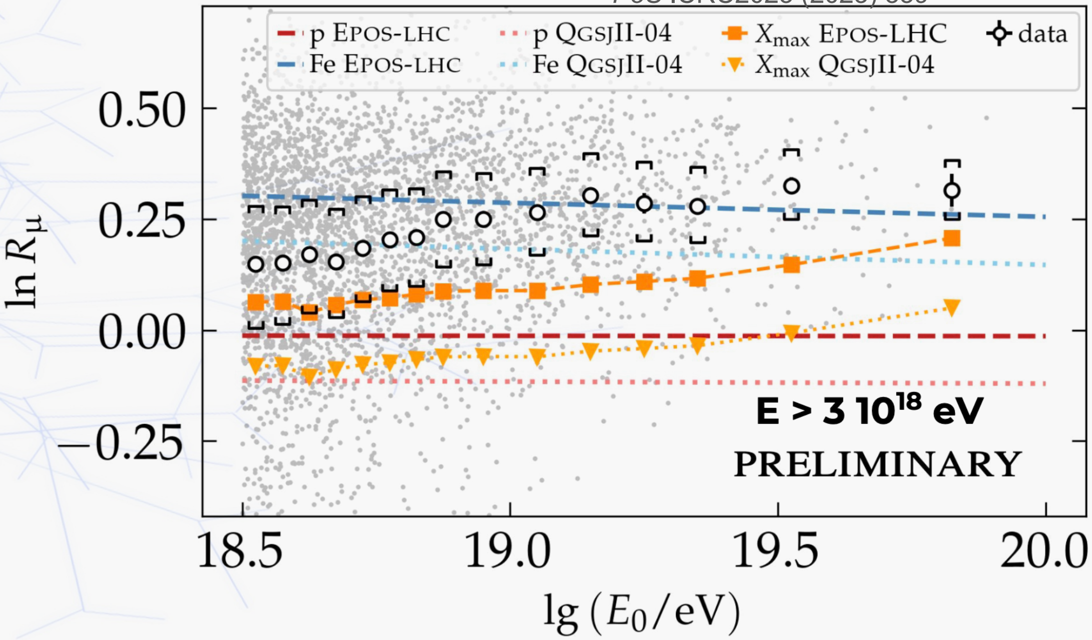
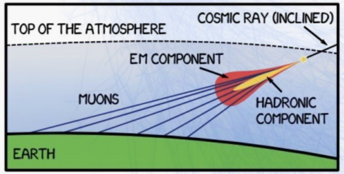
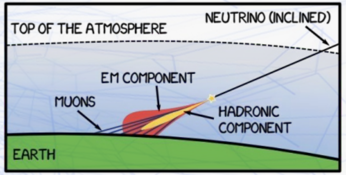


Analyses of shower data from both Auger and TA see a large excess in muons as compared to expectations from LHC informed hadronic interaction models.

Neutrino Search → Limits

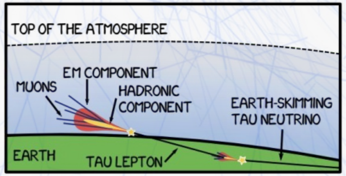


vs.

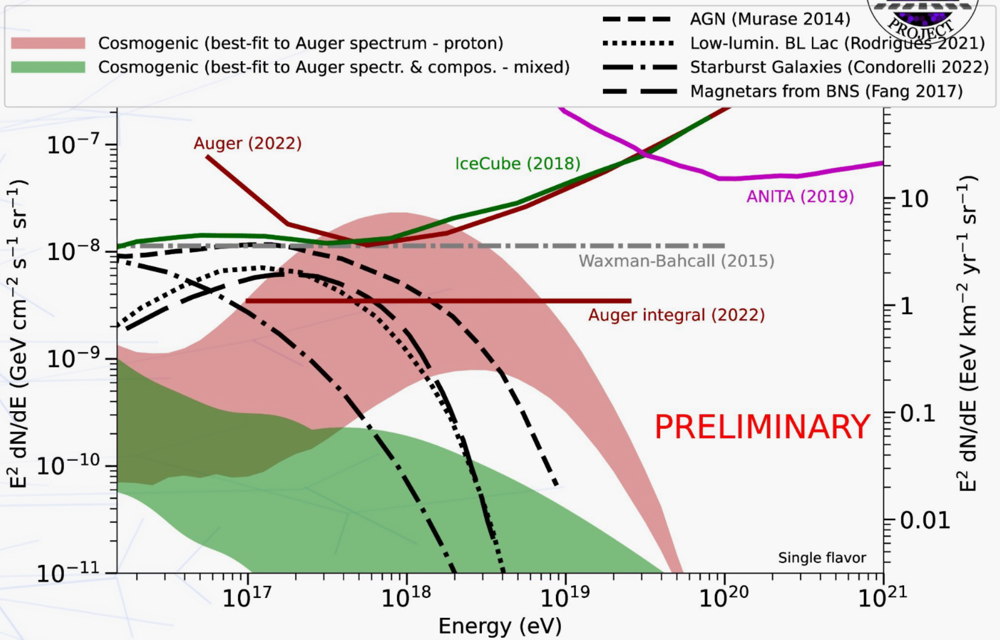


Look for highly inclined showers with high EM component,

or



Look for upward-going showers which come from below the horizon.



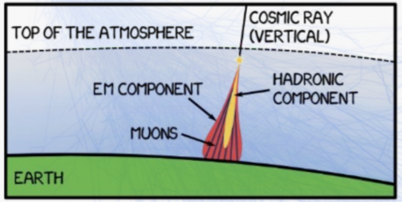
Neutrino limits used to:

- Set neutrino fluence limits in NS-NS / BH-BH mergers
- Limit Photo-Pion GZK and proton only accelerators
- Limit UHE-neutrino point sources
- Put overall constraints on UHECR sources

UHE-Photon Search → Limits

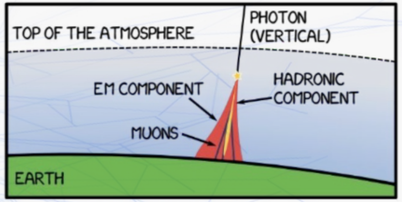
Super Heavy Dark Matter

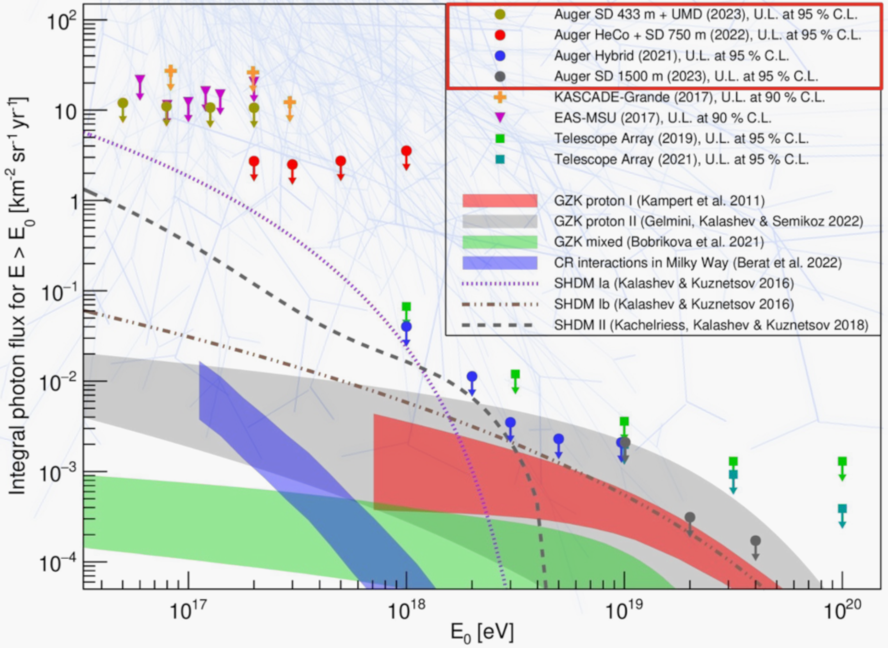
Cosmic Ray = lots of μ



vs.

Photon = lots of e ±



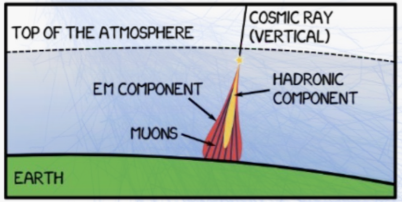


UHE-Photon Search → Limits

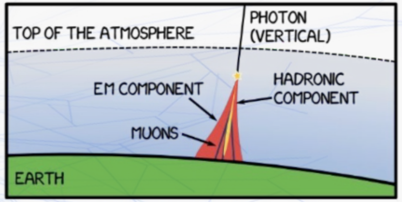
Super Heavy Dark Matter Limits

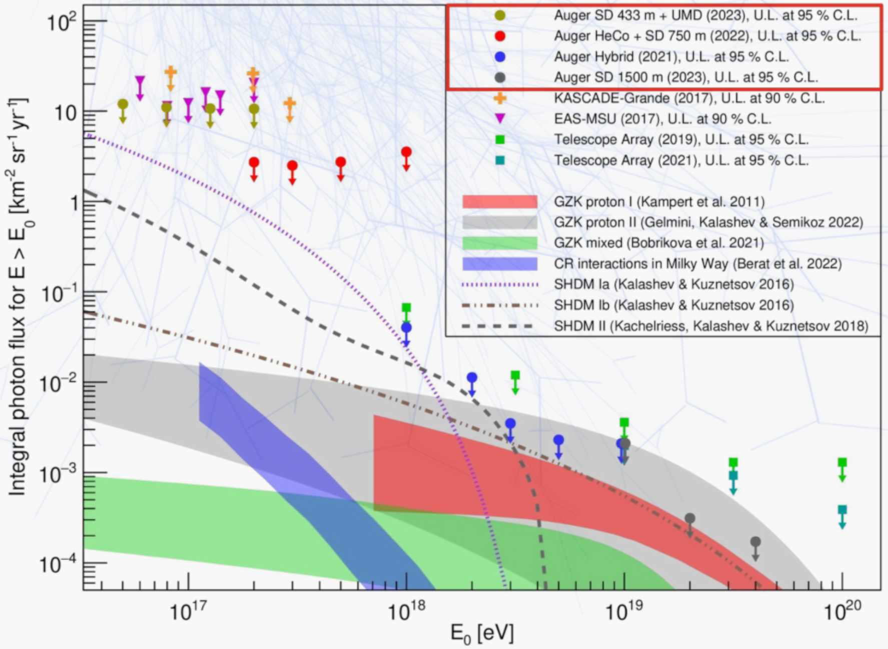
Cosmic Ray = lots of μ

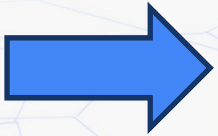
Photon = lots of e ±

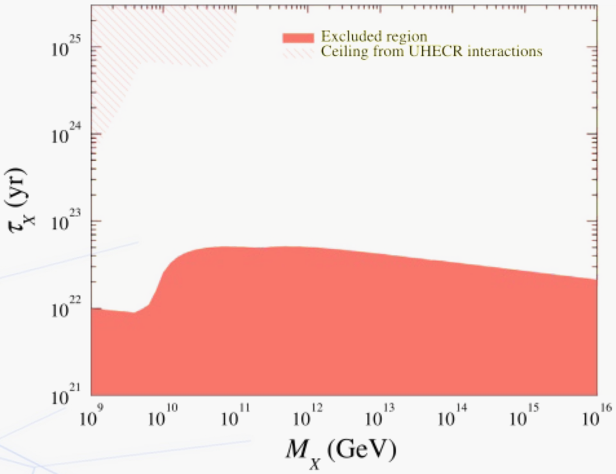


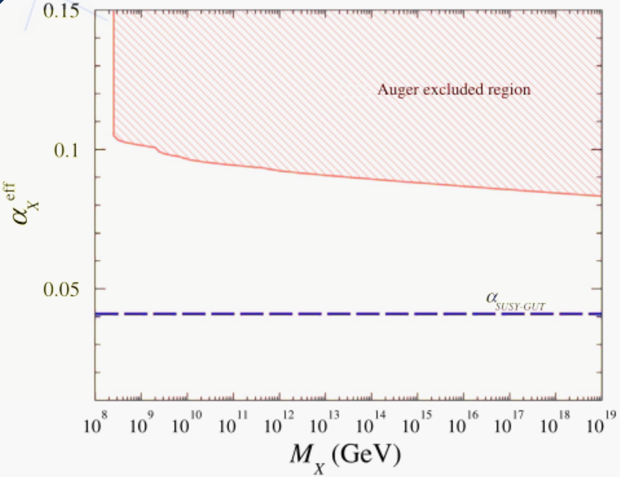
VS.



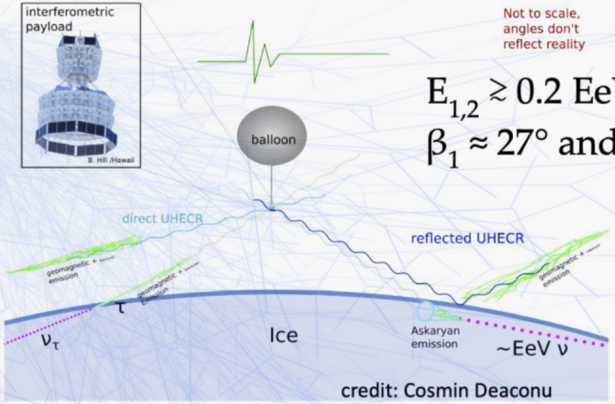






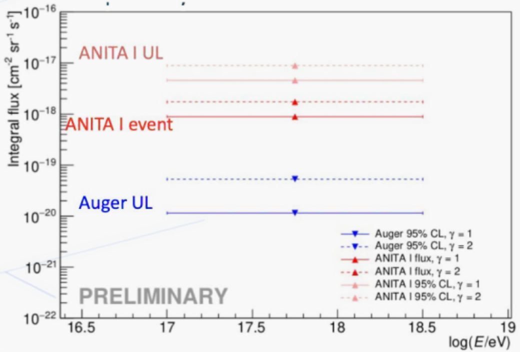


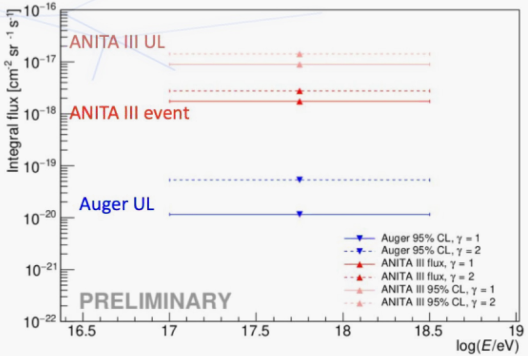
Follow up of anomalous steeply up-going ANITA Events



$E_{1,2} \gtrsim 0.2$ EeV $\approx 10^{17.8}$ eV
$\beta_1 \approx 27°$ and $\beta_2 \approx 35°$

(ANITA, Phys. Rev. Lett. 121 (2018) 161102)





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- ➢ Auger performed search for up-going air showers with zenith > 110º with the FD
- ➢ Due to large exposure 100s were expected
  1 event was found (consistent with background)
- ➢ Set limit on flux of such events 2 OoM lower than required flux from ANITA observations.

Effectively rules out up-going CR-like events as cause for ANITA observations.

Open Questions

Astrophysics	What systems or phenomena are producing UHECR?
Astrophysics	What is the nature of the flux suppression at the highest energies?
Astrophysics	At what energy do galactic cosmic ray sources die out and extragalactic sources take over?
Particle Physics	Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?

UHECR Sources?

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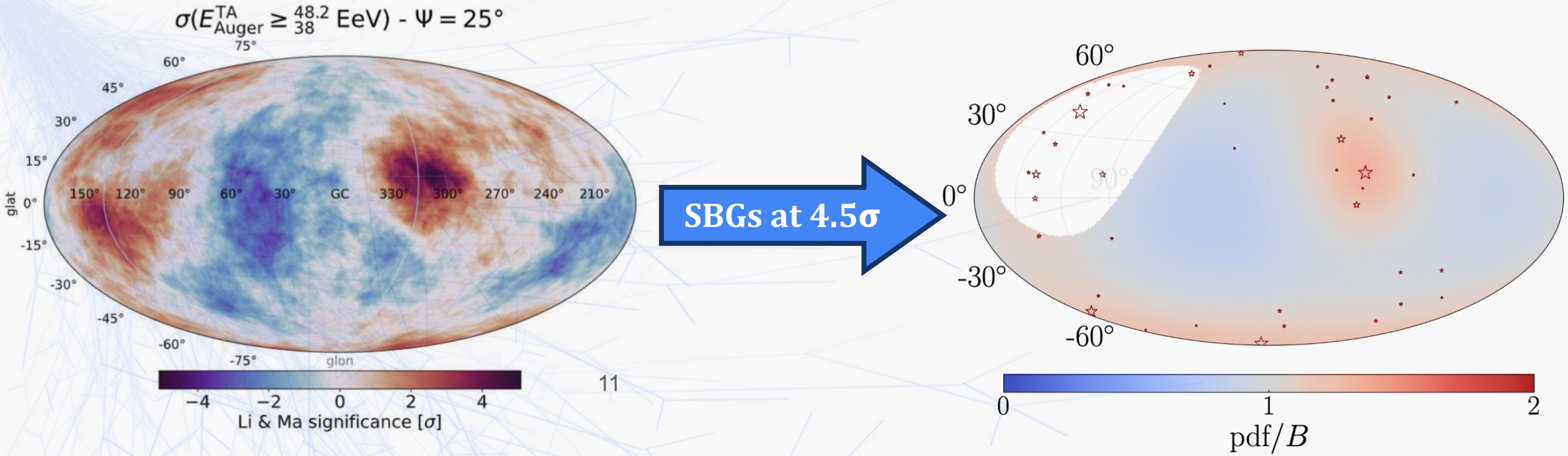


By combining composition, spectrum and arrival direction a strong association with starburst galaxies is forming.

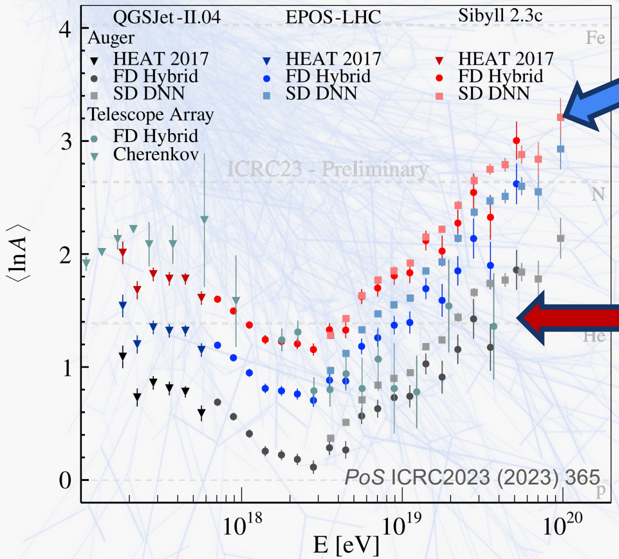
However, this is dominated by dense regions of many objects. An association with a sources class is far from a positive identification of accelerating phenomena.

Getting farther will require multiple messengers and clever composition games.

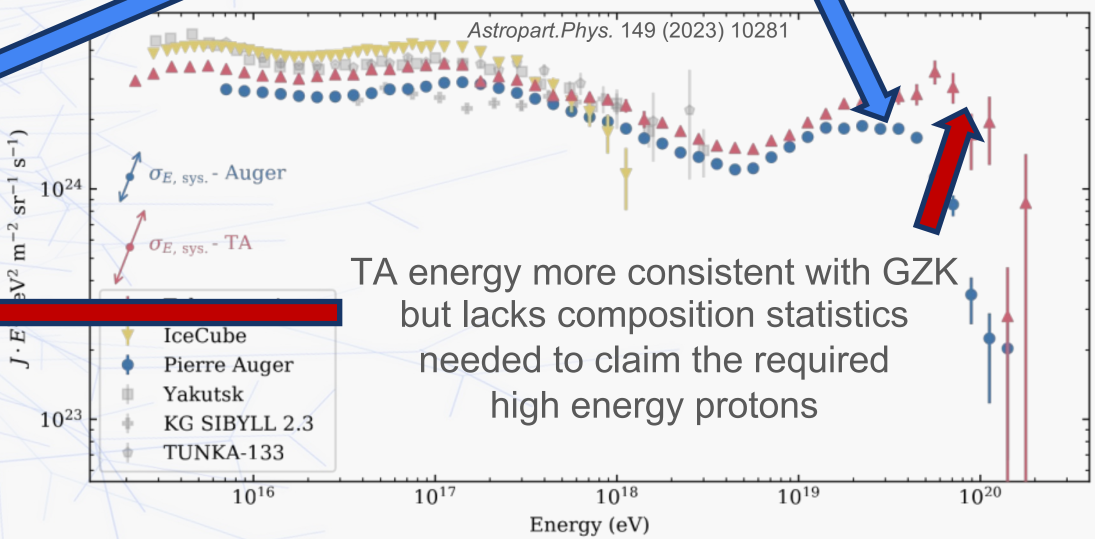
Open Questions

Astrophysics	What systems or phenomena are producing UHECR?
Astrophysics	**What is the nature of the flux suppression at the highest energies?**
Astrophysics	At what energy do galactic cosmic ray sources die out and extragalactic sources take over?
Particle Physics	Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?

Nature of high energy suppression?



Auger cutoff energy, composition
And neutrino limits are
clearly inconsistent with GZK



TA energy more consistent with GZK
but lacks composition statistics
needed to claim the required
high energy protons

For Auger is it photodisintegration, or the maximum power of sources?

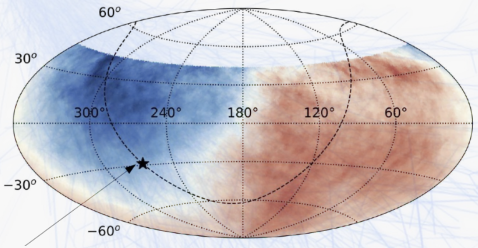
Is the answer different in the Northern sky?

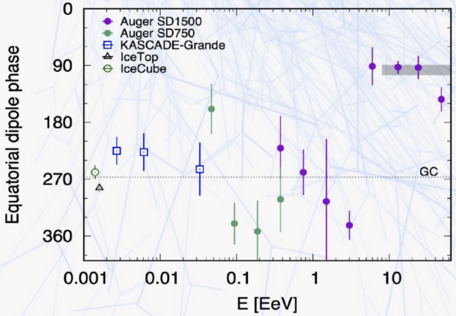
Is the suppression actually a cutoff, or will the flux continue?

Open Questions

Astrophysics	What systems or phenomena are producing UHECR?
Astrophysics	What is the nature of the flux suppression at the highest energies?
Astrophysics	**At what energy do galactic cosmic ray sources die out and extragalactic sources take over?**
Particle Physics	Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?

Galactic to Extragalactic Transition?





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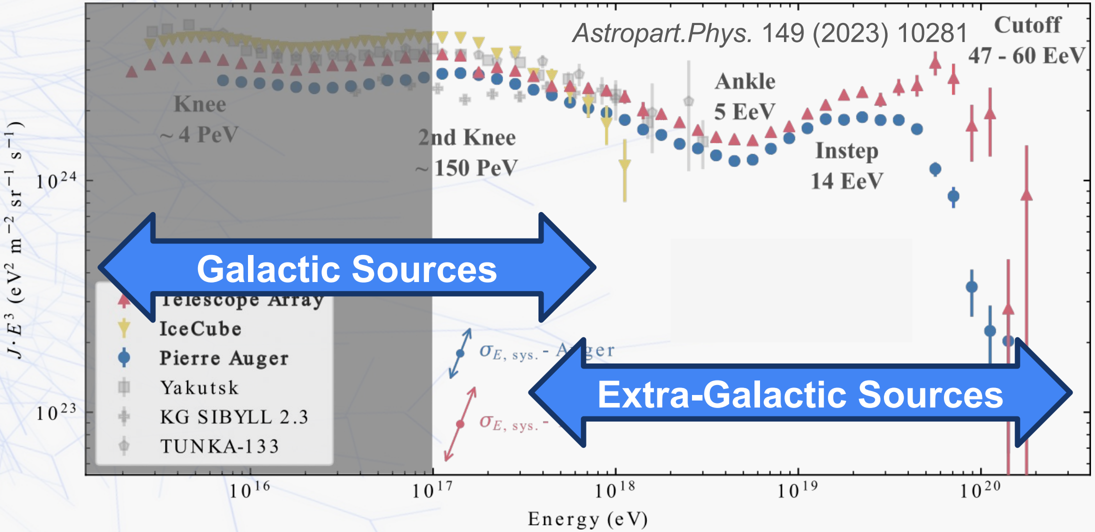

The exact nature of the transition is not yet known.

However, composition, spectrum and anisotropies hint to a transition in the 100PeV – 1 EeV range

Open Questions

Astrophysics	What systems or phenomena are producing UHECR?
Astrophysics	What is the nature of the flux suppression at the highest energies?
Astrophysics	At what energy do galactic cosmic ray sources die out and extragalactic sources take over?
Particle Physics	**Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?**

New physics in UHECR interactions?

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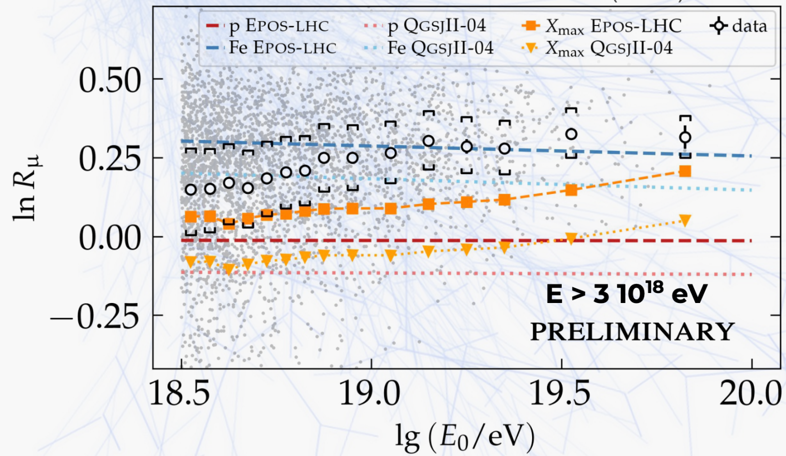

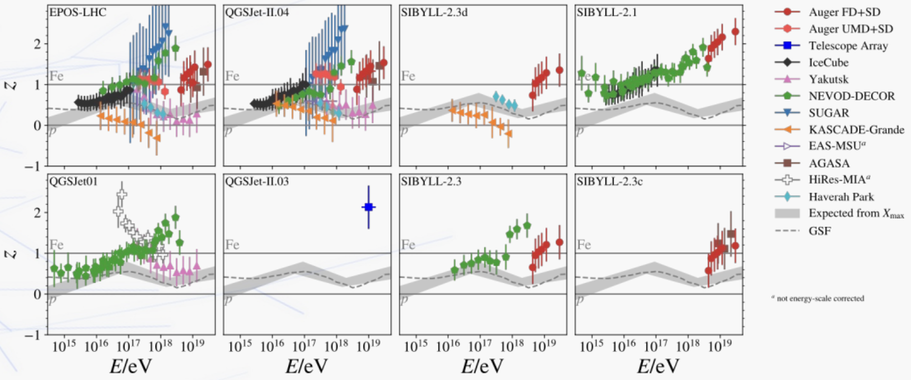

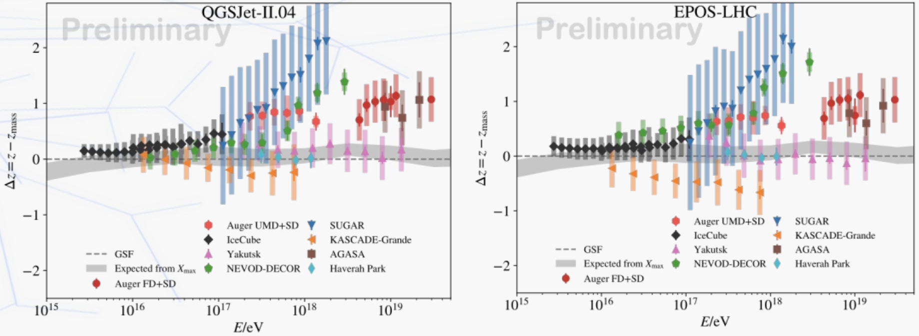

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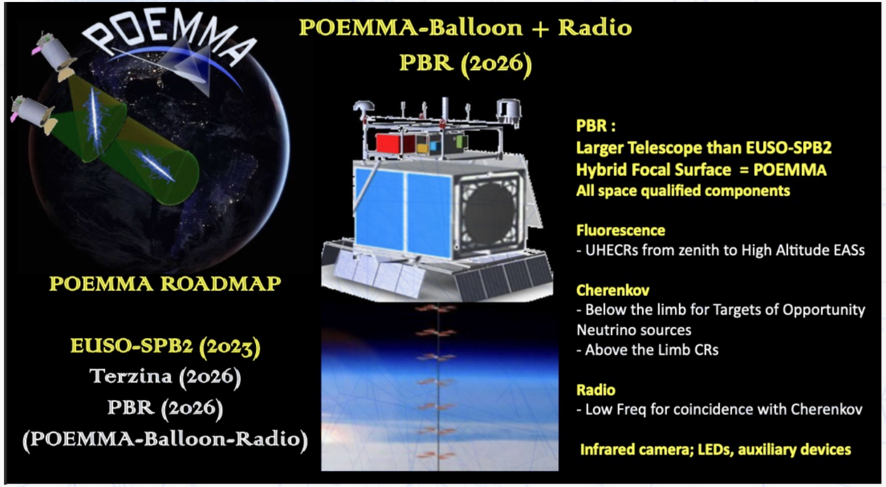
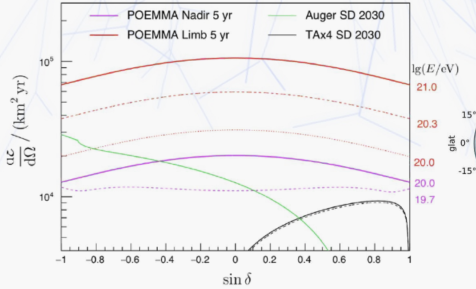
Work in progress to confirm an excess in muons and investigate its nature.

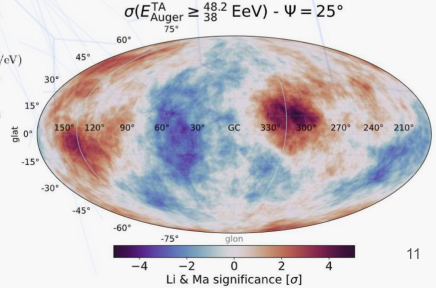
Precision measurements with event-by-event composition info might be needed

Up next: the Era of Global Arrays

Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)







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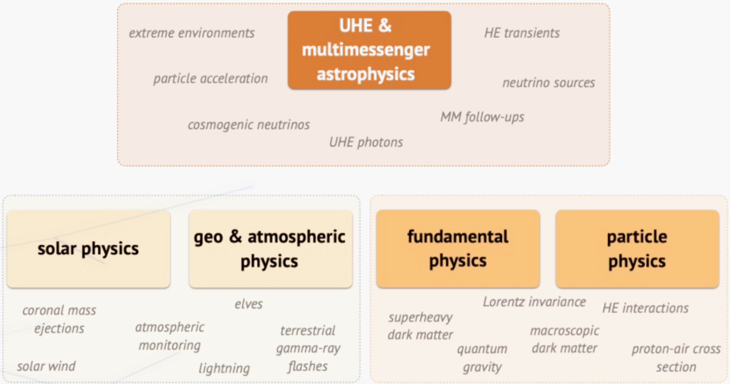
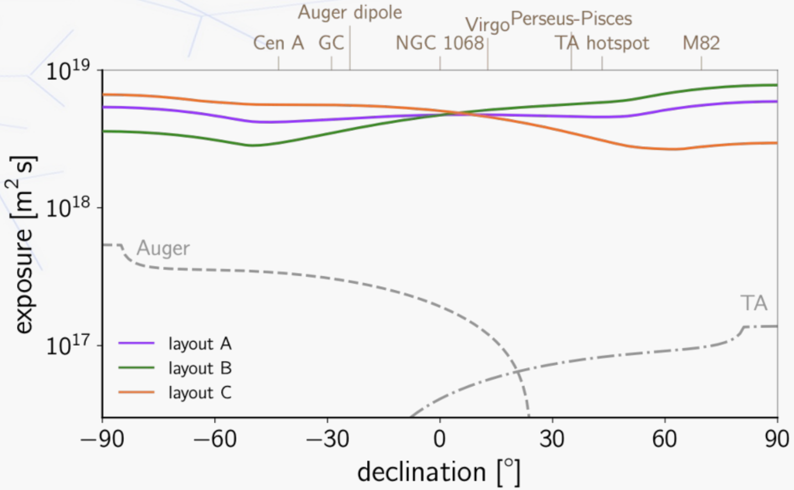
The Global Cosmic Ray Observatory (GCOS)





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Future Outlook

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Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	EUSO program → POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites

Timeline: 2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Backup Slides

Testing the Dipole across the Full Sky

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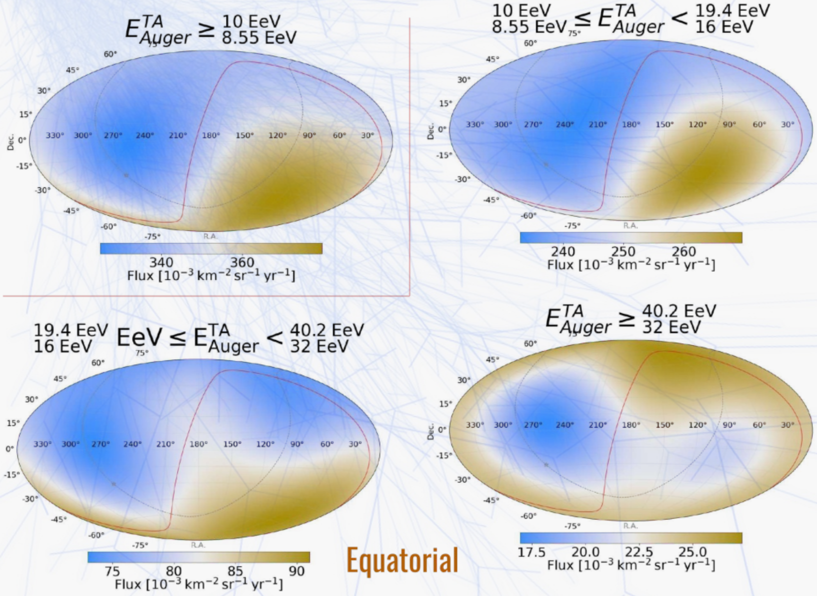
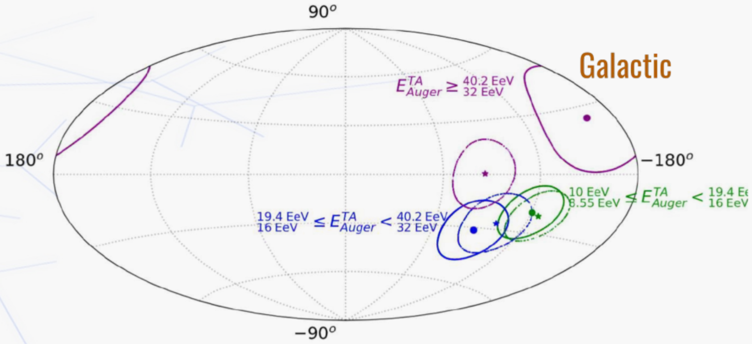
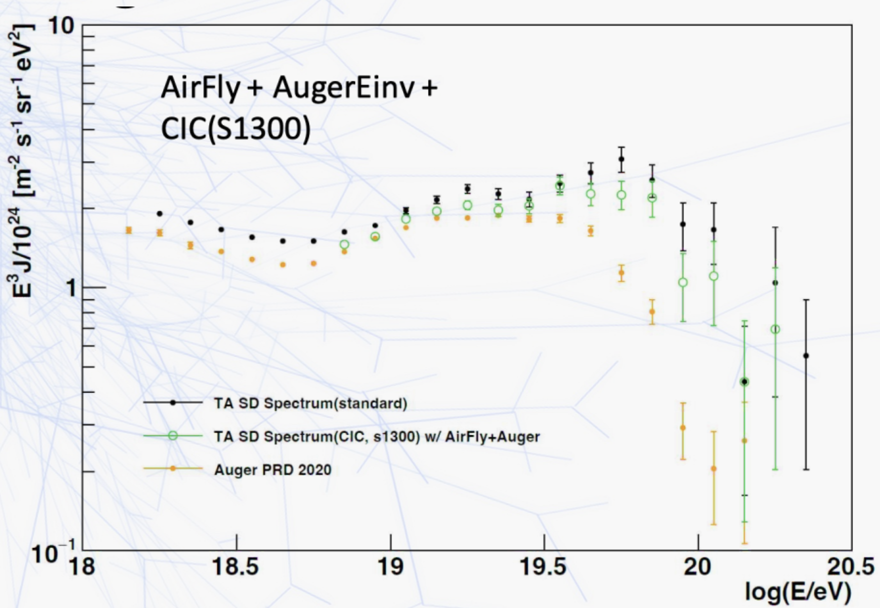
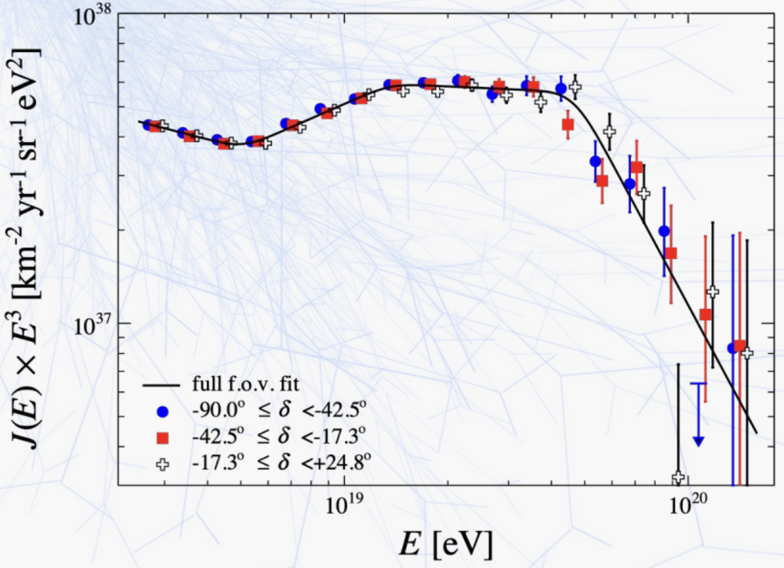


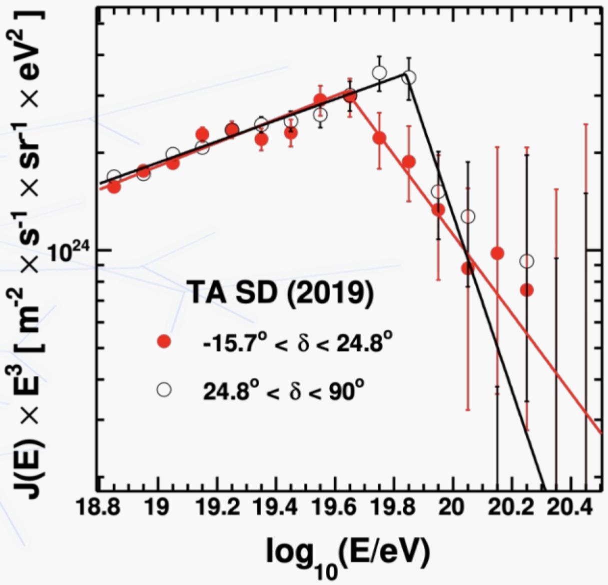


Auger / TA Spectrum Agreement

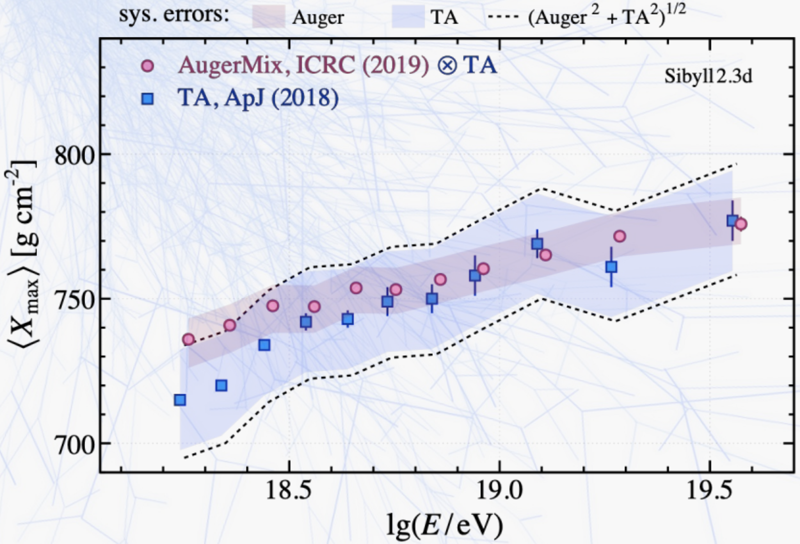


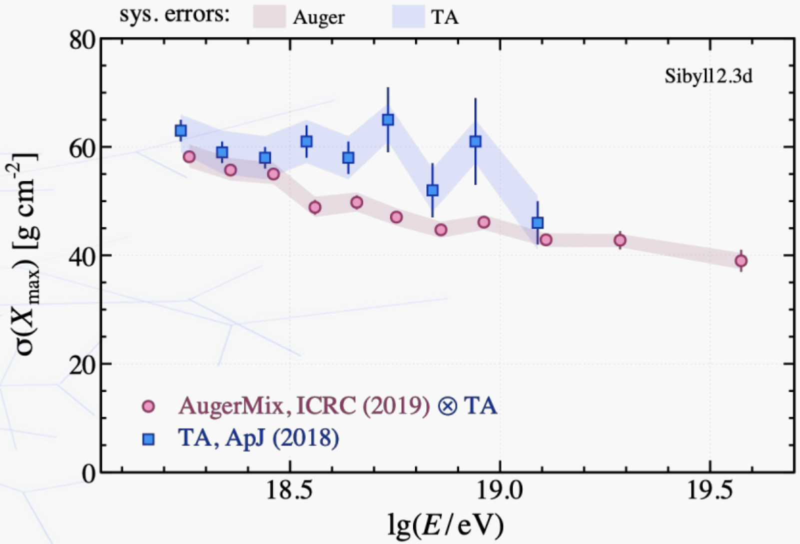
Declination dependence of Auger and TA Specra





Auger / TA Composition Agreement





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