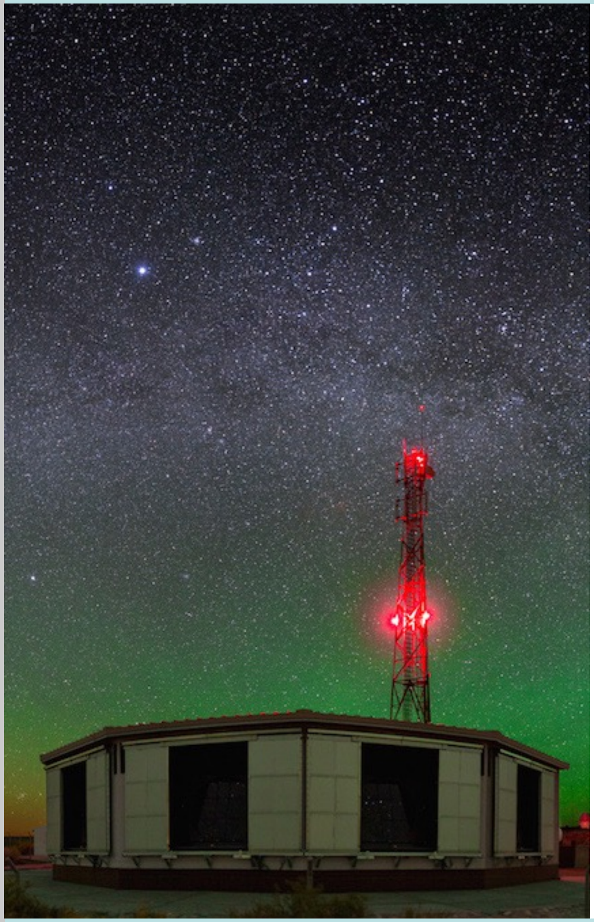

Latest results and the upgrade of the Pierre Auger Observatory

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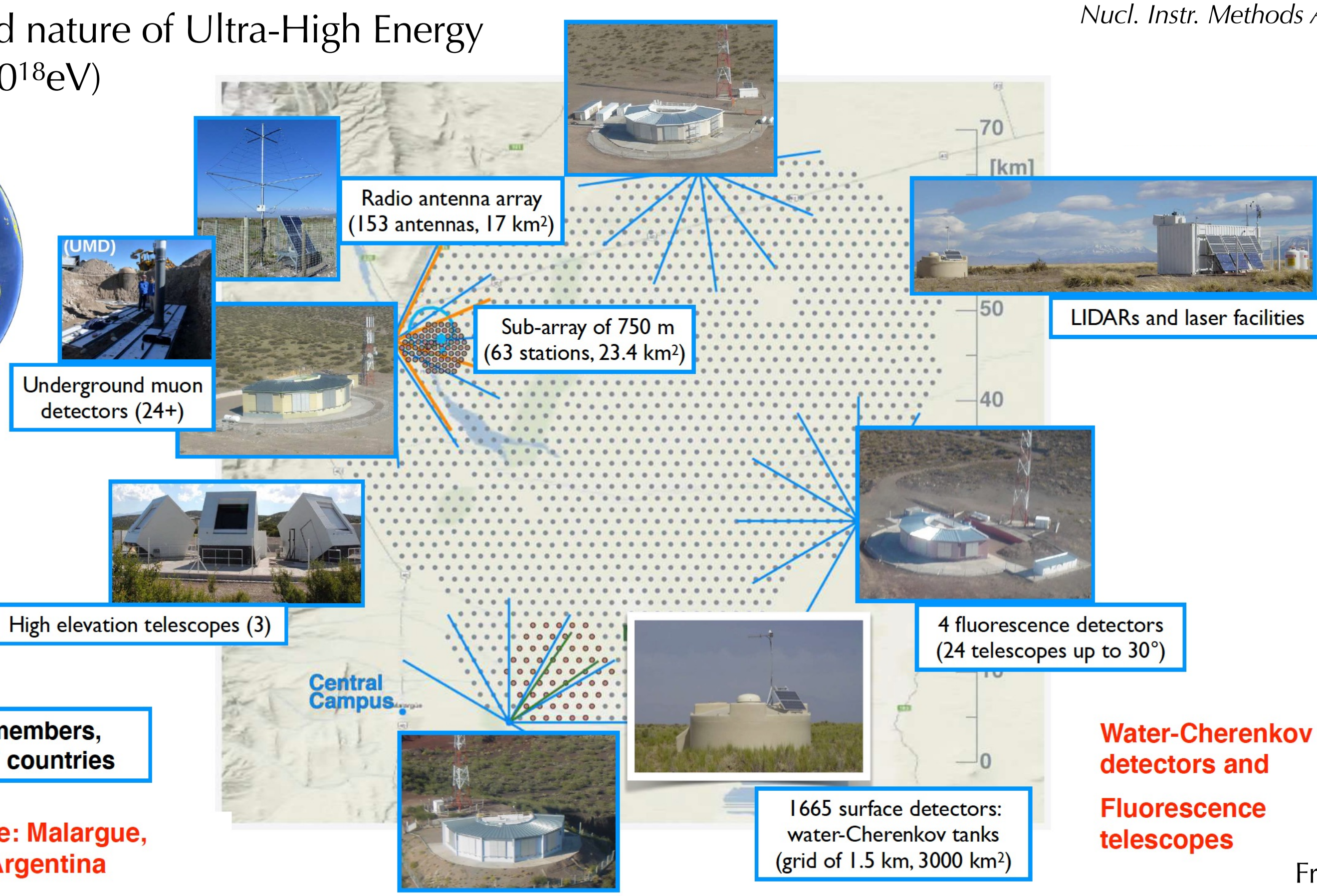
Funding acknowledgment:
Award #1506486

Nucl. Instr. Methods A 798 (2015) 172

Goal: Measure the origin and nature of Ultra-High Energy Cosmic-Rays (UHECR – $E>10^{18}$eV)

Pierre Auger Observatory
Province Mendoza, Argentina



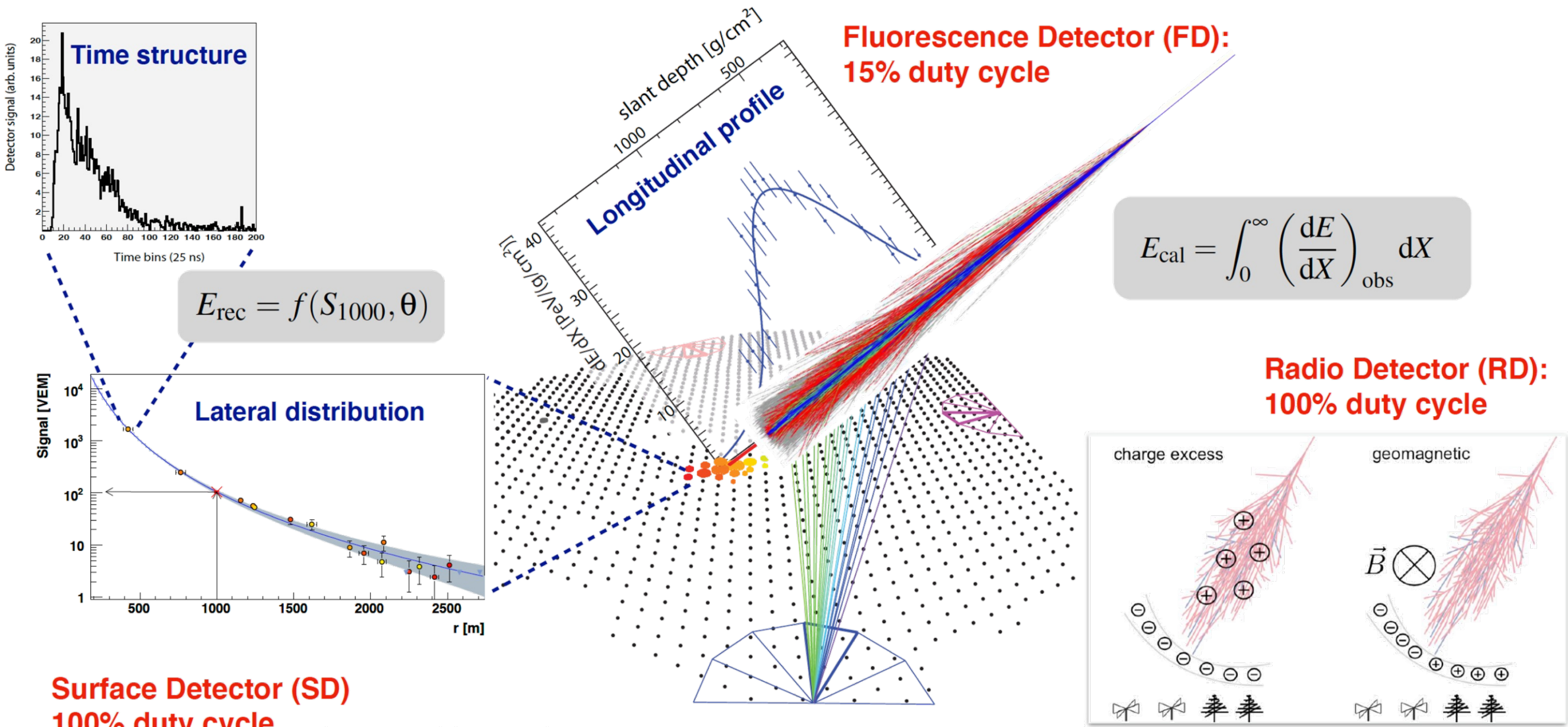
More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

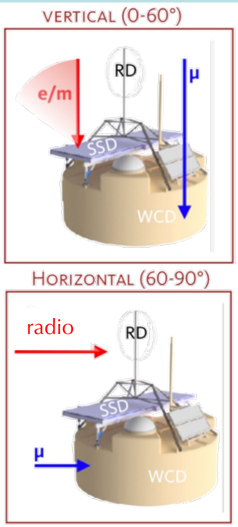
Fluorescence telescopes

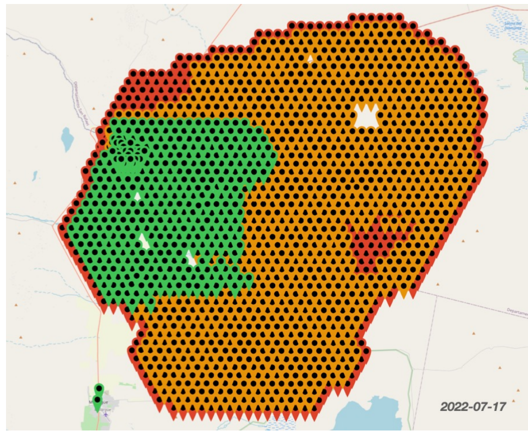
From Ralph Engel



The FD calibrates the SD

From Ralph Engel



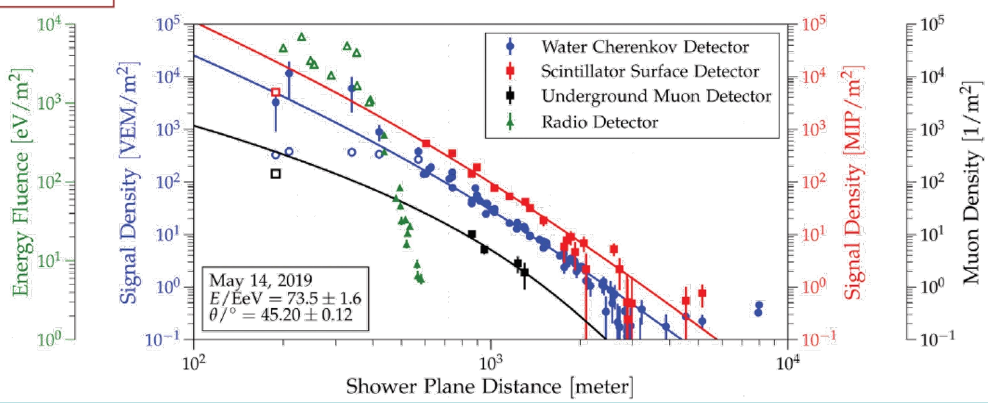


PHASE I: (ended in 2021)

- Exposure: 80,000 km^2.sr.yr (θ<60º)

PHASE II (8 years of operation starting 2022/23):

- Projected exposure: 40,000 km^2.sr.yr (θ<60º)
- Use the SD (100% duty factor) more effectively for mass composition information on an event by event basis



PHASE II detector upgrade:

- Two detector additions to every SD stations:
  - Scintillator detector (SSD) - θ<60º
  - Radio antenna – θ>60º
- Plus:
  - New electronics
  - Small PMT (1″ diameter) to increase the dynamic range of each WCD
  - Buried muon counters in the in-fill array

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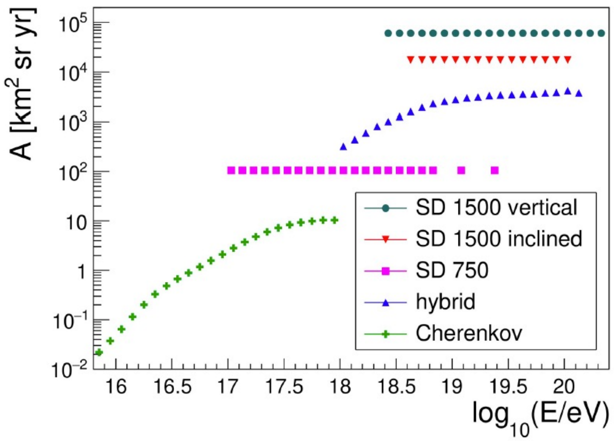
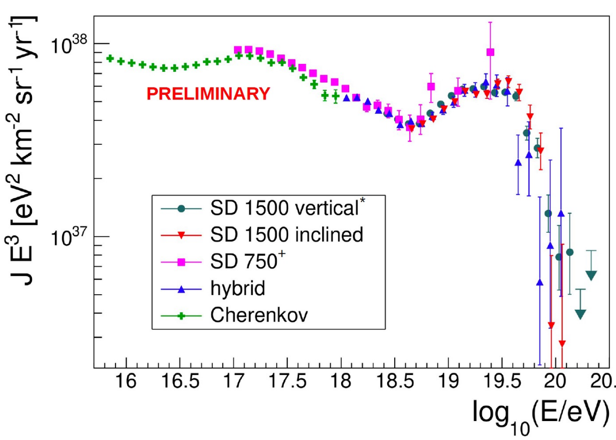
Energy spectrum

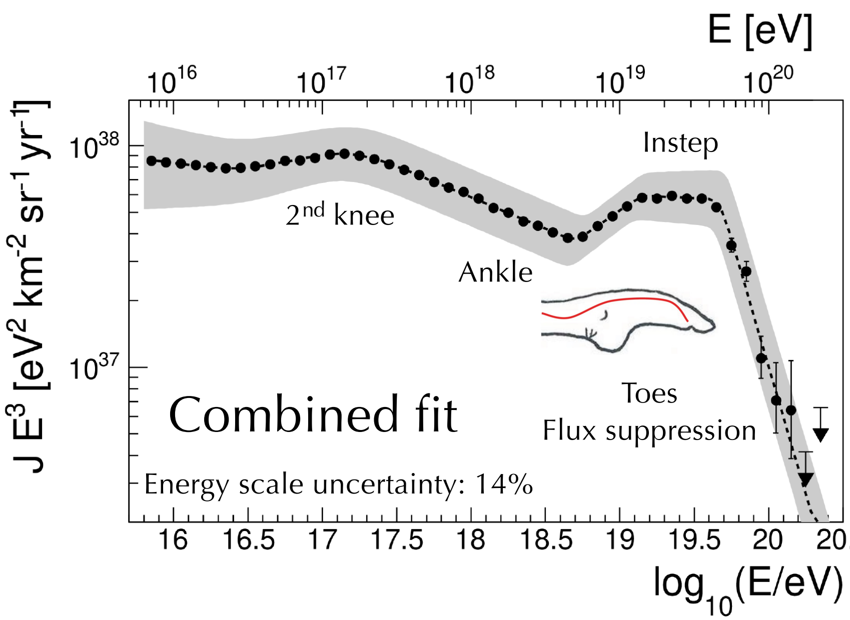
A.Aab et al., PRL 125, 121106 (2020)
A.Aab et al., PRD 102, 062005 (2020)
A.Aab et al., Eur. Phys. J. C81 (2021)
V.Novotny for the Pierre Auger Coll., ICRC 2021, #324





Contributions to total exposure at 10^{19}eV:

- SD 1500m vertical 74.8%
- SD 1500m horizontal 21.6%
- SD 750m 0.1%
- Hybrid 3.4%
- Cherenkov 0%



- Limited normalization between measurement methods [-2%,+7%]
- Spectrum features
  - 2nd knee
  - Ankle
  - Instep
  - Flux suppression
- Very small declination dependency consistent with measured dipole anisotropy
- **What can we learn from the shape of the spectrum?**

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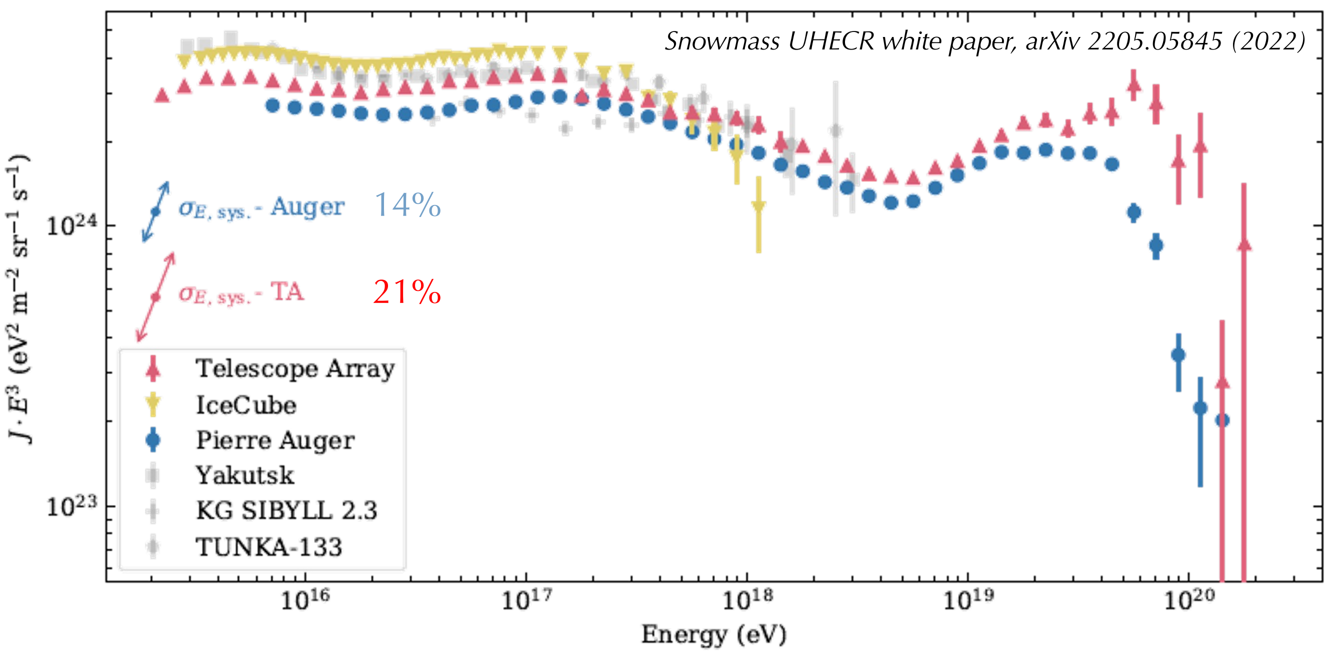
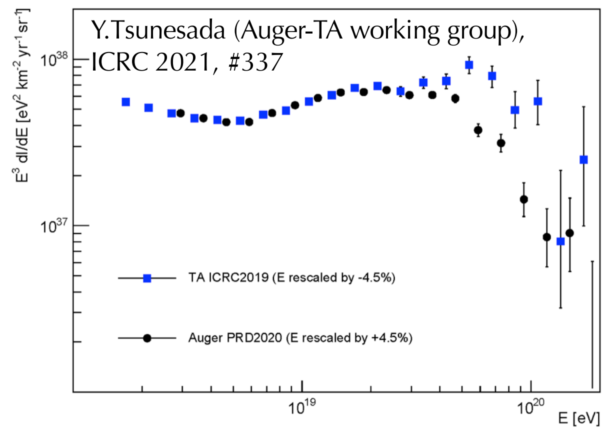
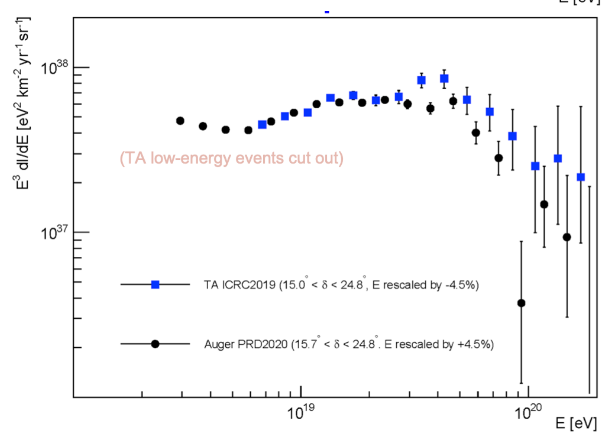
Spectrum: comparison with other data







- At the highest energies, Auger and TA data can be brought to better agreement using a +/- 4.5% energy rescaling (well within systematics). However, some differences remain.
- Even when looking in the common declination band, an energy dependent shift is required to resolve the remaining discrepancies.

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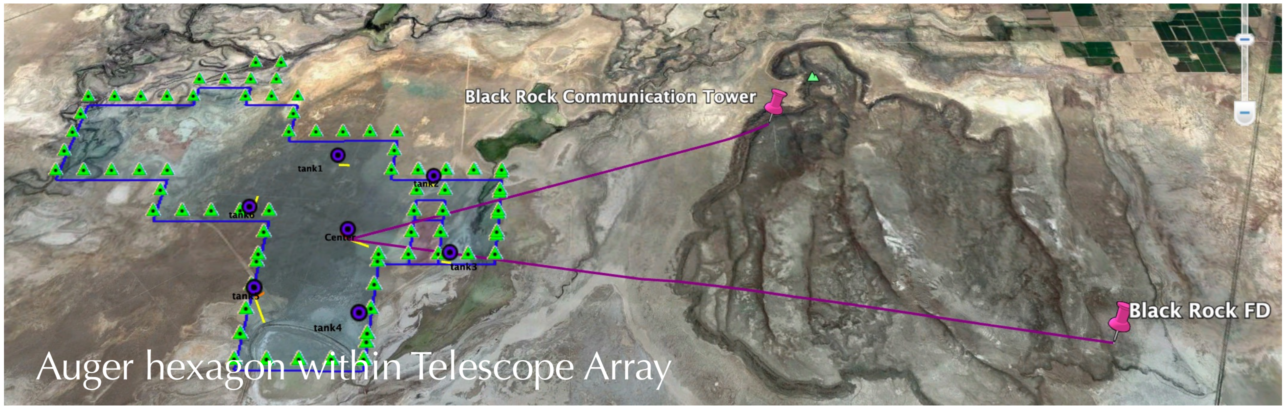
- **Deployment of an Auger hexagon within Telescope Array – Late Sept 2022**
  - Independent operation / reconstruction
  - Use the standard Auger reconstruction
  - Auger single-PMT SD station fitted with regular Auger electronics
  - Triplet set of detectors at the center for station-level comparisons
  - Will include Surface Scintillator Detector (SSD) Upgrade



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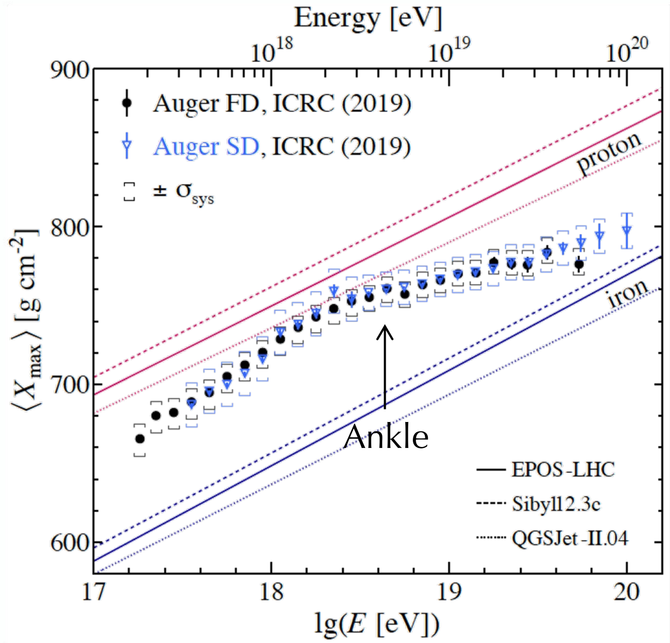
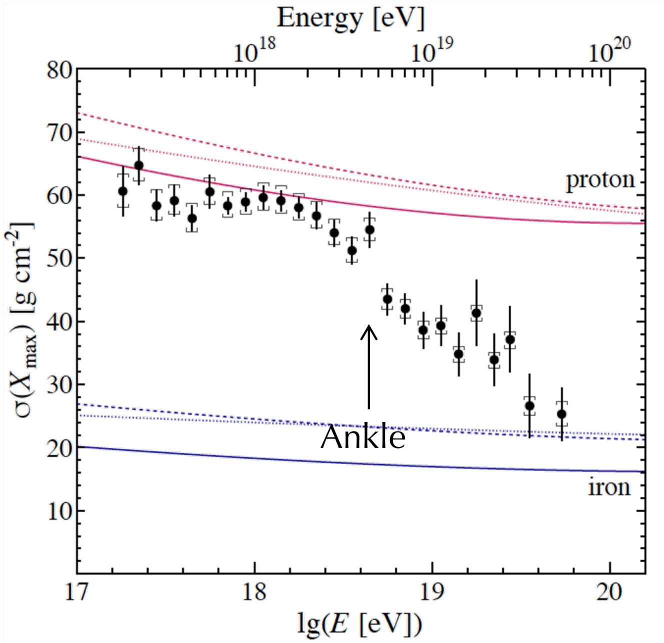
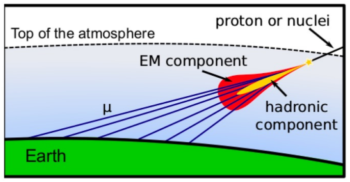
J.Bellido for the Pierre Auger Collaboration, ICRC 2017
A. Aab et al., Phys. Rev. D96 (2017) 122003
A.Yushkov for the Pierre Auger Collaboration, ICRC 2019



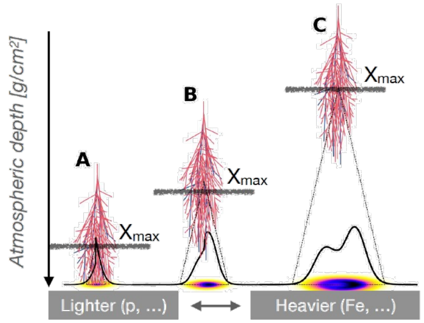


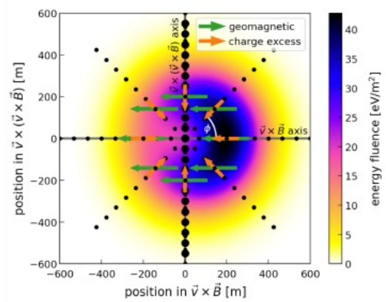
- Apparent transition towards heavier composition around 2 EeV
- Break in <X_{max}> behavior seems to occur below the Ankle energy
- Break in RMS(X_{max}) at roughly the same energy
- **Re-calibrated** SD data in very good agreement with FD and allow to extend the primary composition study to higher energies.



☞ Phase II: designed to learn more about primary mass composition with 100% duty factor

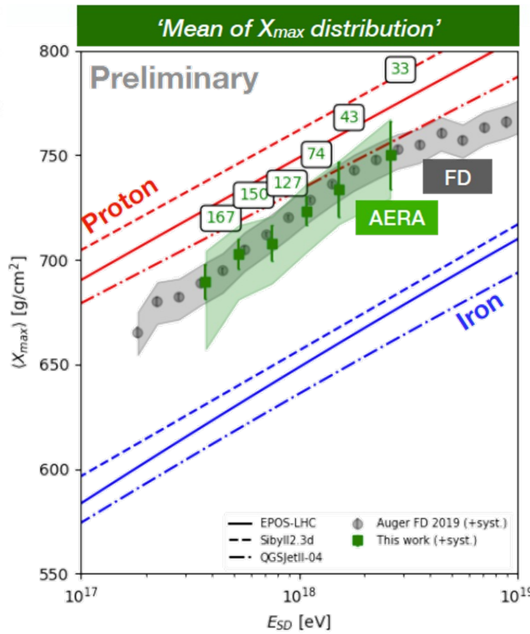
B.Pont for the Pierre Auger Collaboration, ICRC 2021, #387
PRL / PRD combo paper to be submitted

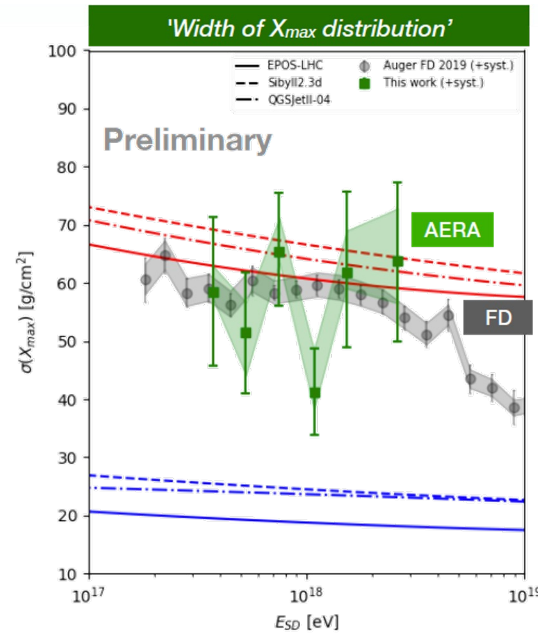




Auger
Engineering
Radio
Array

(17 km²)





- Resolution: 15g/cm² above a few EeV (comparable to FD)
- Systematics: different than FD

☞ Phase II: 100% duty factor / different systematics than FD resulting in a tighter energy scale

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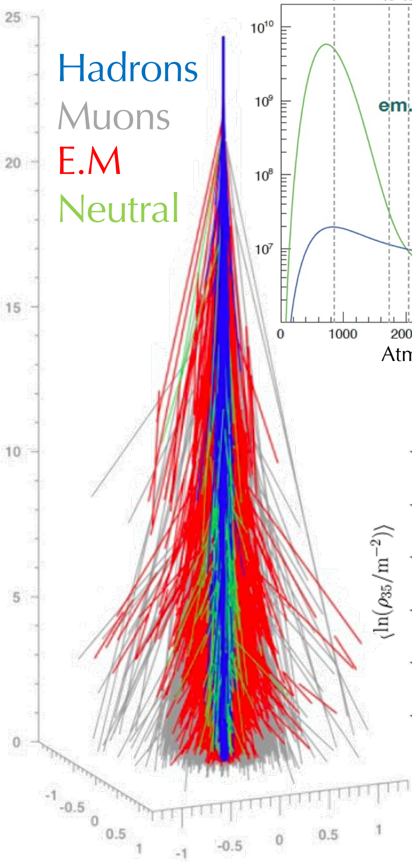
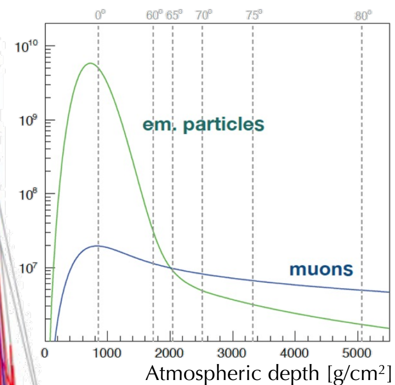
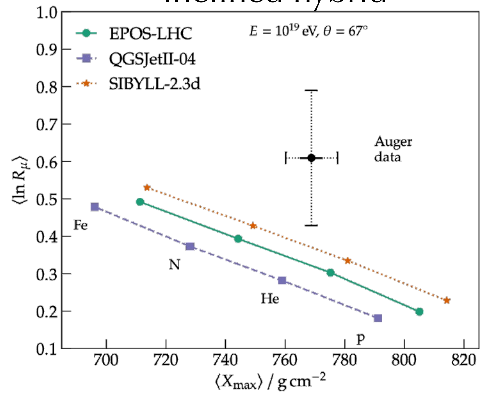
Muon excess in EAS compared to hadronic models





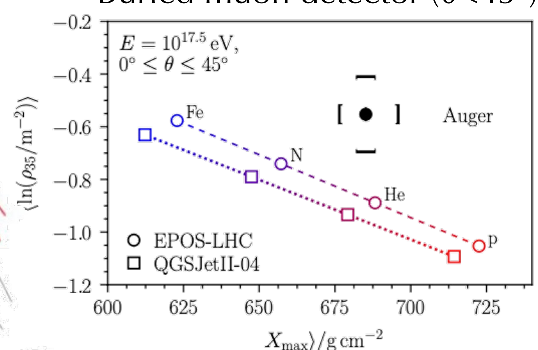
Inclined hybrid

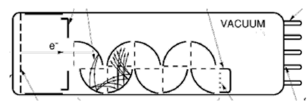


A.Aab et al., PRL 126 (2021) 152002
Pierre Auger Collaboration, Eur. Phys. J. C80 (2020)

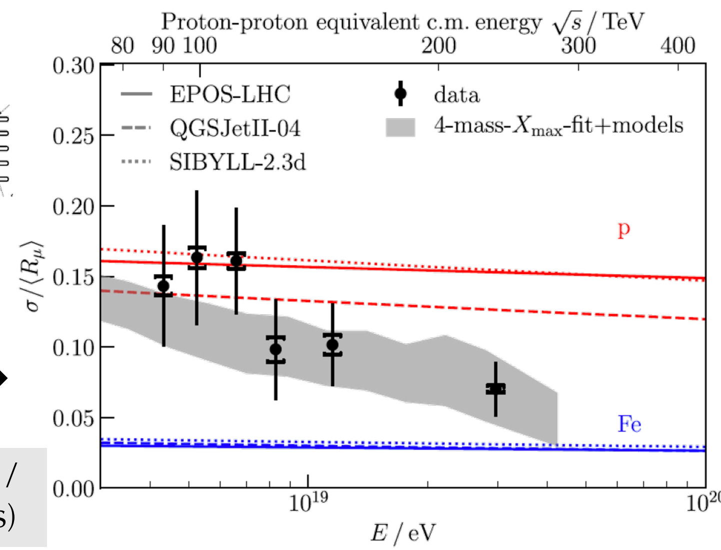
- Well documented muon excess (up to 30%) observed in data compared to all hadronic interaction models.
- What is the origin of the muon puzzle? See Dennis Soldin's presentation on Friday and recent discussion in the Snowmass UHECR WP (arXiv:2205.05845).

Buried muon detector (θ<45°)





First interactions in PMT analogy



☞ Phase II: extract muon information using SSD / WCD combination for all showers (high statistics)

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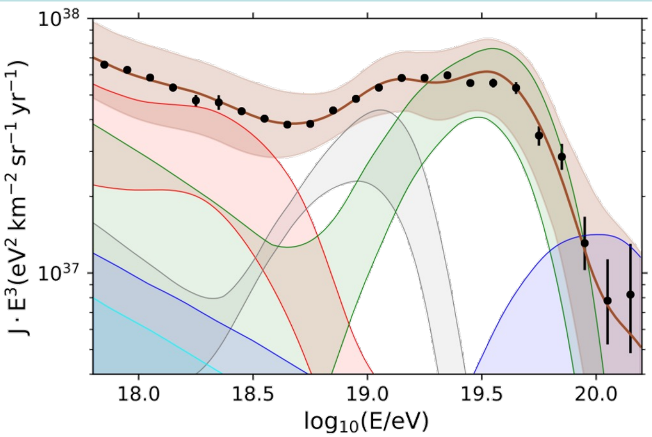
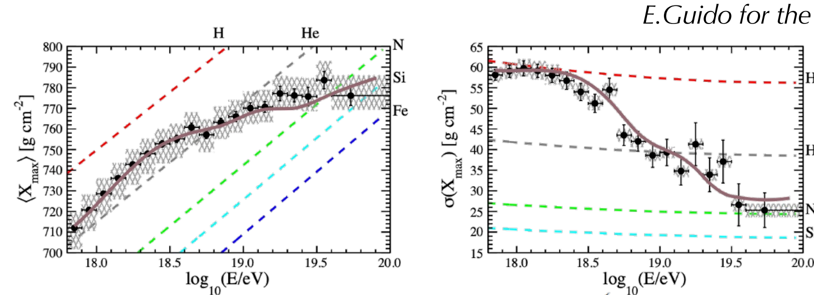
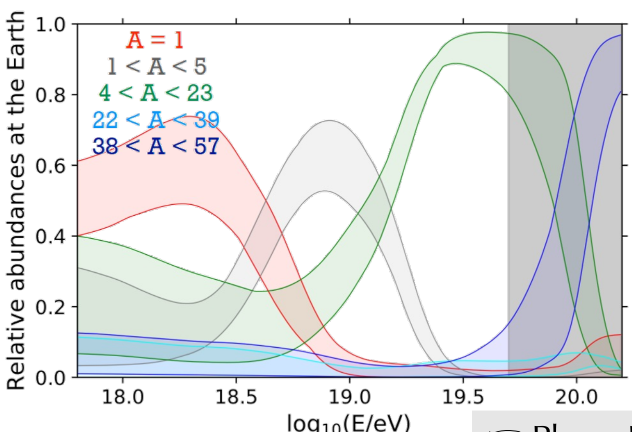
Combined fit: spectrum + composition

A.Aab et al., PRL 125, 121106 (2020)
E.Guido for the Pierre Auger Collaboration, ICRC2021 #311
Paper to be submitted to JCAP





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

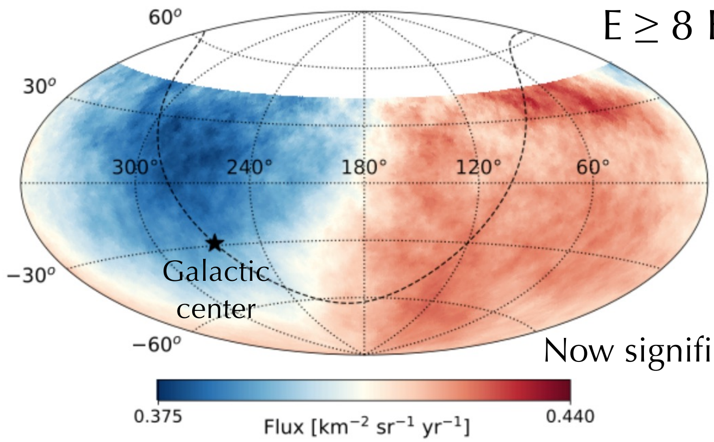


- Extension of the previous work to below the ankle. Two scenarios considered, but little effect on mass composition predictions.
- Maximum rigidity scenario with $R_{cut} \sim 1.5\times10^{18}$V (sources run out of steam) and very hard spectral index $\gamma < 1$ (although not strongly constrained)
- Chance of a significant proton fraction at the highest energy appears dim
- Similar work also including anisotropy under development (T.Blister, ICRC 2021, #368)

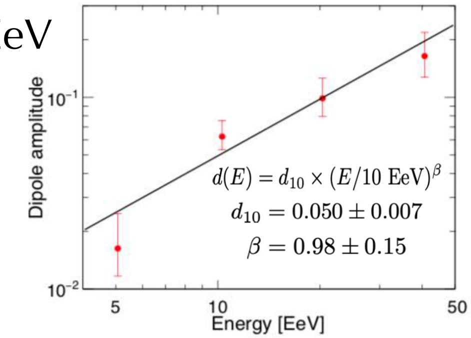
☞ Phase II: event by event primary mass information will help better identify the spectrum features

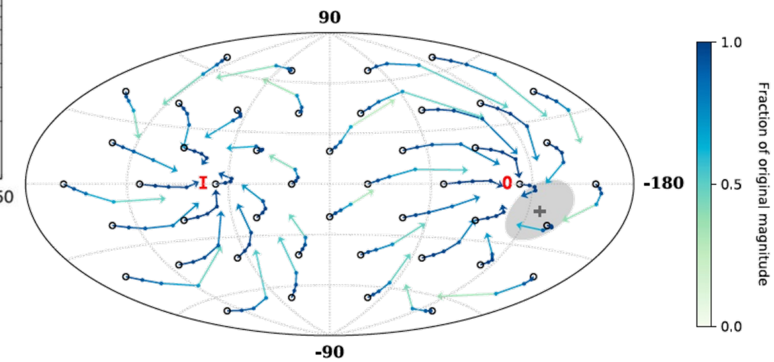
The Pierre Auger Collaboration, Science 357 (2017) 1266
The Pierre Auger Collaboration, ApJ (2020)
R.M.de Almeida for the Pierre Auger Collaboration, ICRC 2021, #335

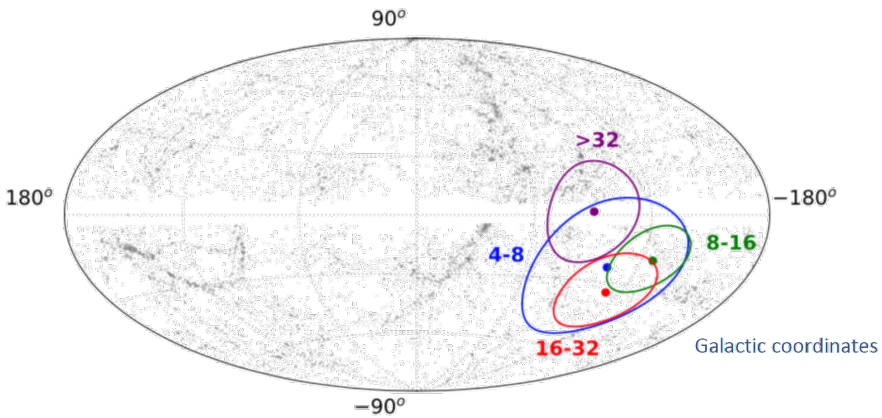
$E \geq 8$ EeV



Now significant at 6.6σ



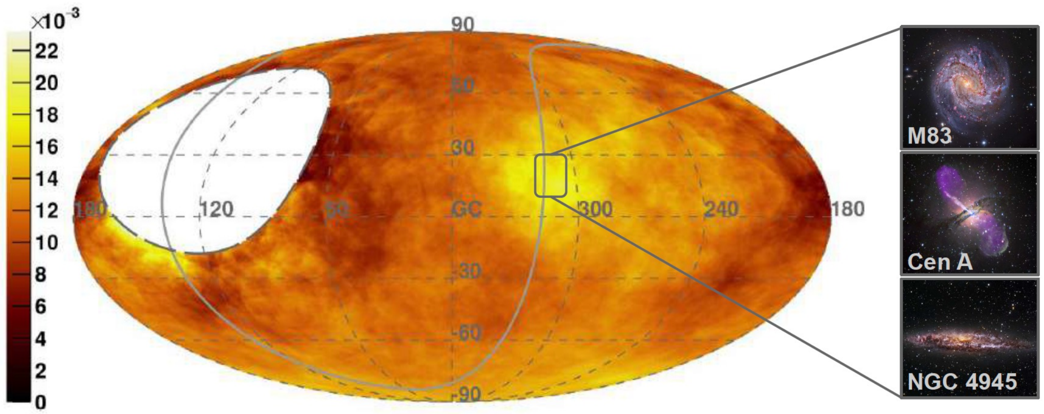




- Increase of the dipole amplitude as a function of energy. No evidence for quadrupolar structure.
- Dipole structure remains centered in the same region.
- Location of the dipole is consistent with mixed composition deflected by galactic magnetic fields.

Anisotropy at the highest energies

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



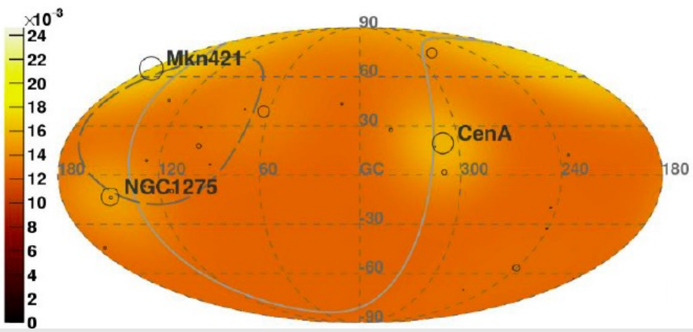
Exposure: 120,000 km^2.sr.yr

J.Biteau for the Pierre Auger Collaboration, ICRC2021 #307
A.Aab et al., Ap. J. Lett 853 L29 (2018)
Paper accepted to ApJS (2022)

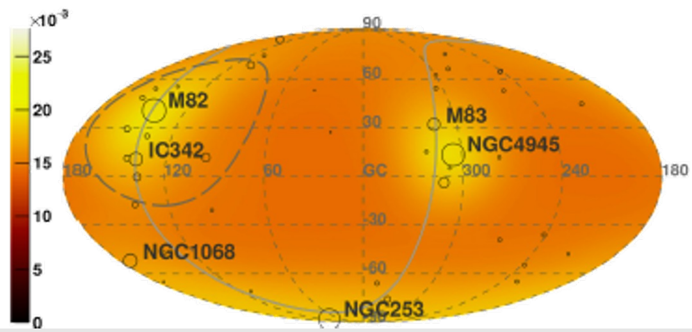
Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}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

Search parameters:
- $1° \leq \psi \leq 30°$
- 32 EeV $\leq$ E $\leq$ 80 EeV

Jetted AGN (γ-rays) - expected $\Phi(E_{Auger} > 40\ \text{EeV})$ [km^{-2} sr^{-1} yr^{-1}]



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



Whole sky blind search:
- Most significant excess:
  - $\psi = 24°$ & E = 41 EeV
  - 2.2σ post trial

Fixed direction (CenA):
- Most significant excess:
  - $\psi = 27°$ & E = 41 EeV
  - 3.9σ post trial

Catalog searches (see table)

☞ Phase II: event-by-event primary mass information – composition enhanced anisotropy studies

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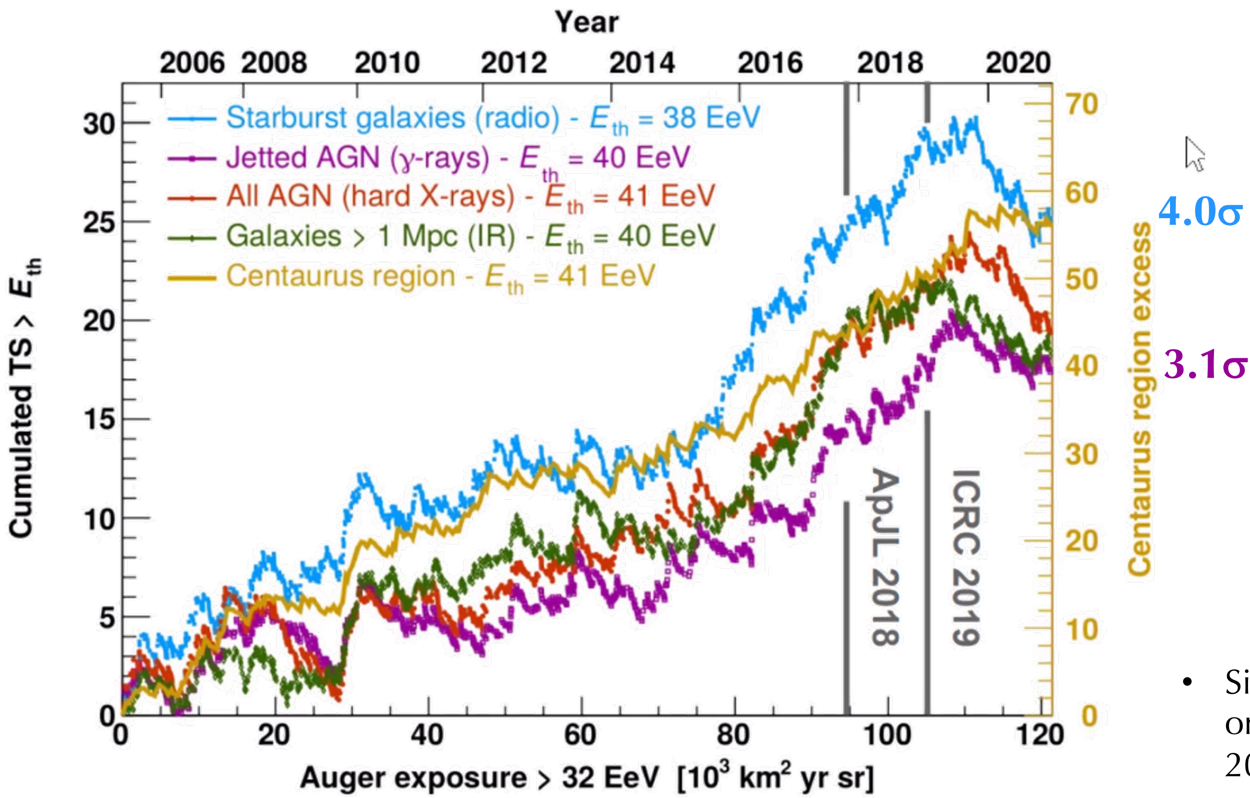
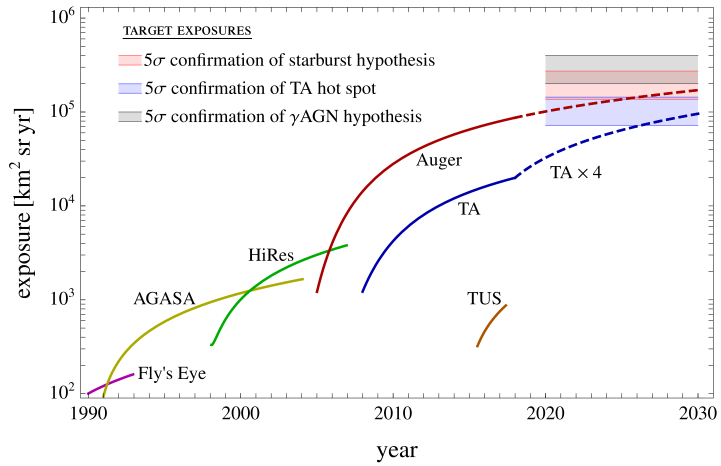




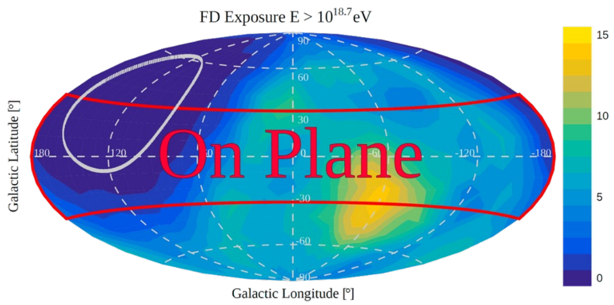
F.Sarazin, L.Anchordoqui et al.
2020 Decadal Survey UHECR white paper
arXiv:1903.04063

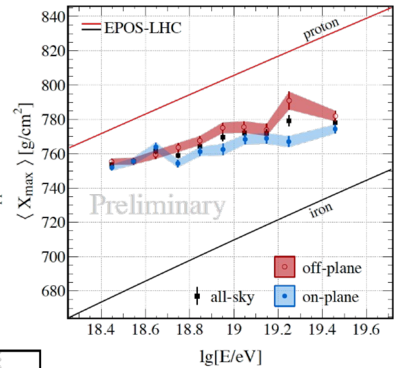
- Signal growths consistent with the discovery of one or more classes of UHECR sources by 2025-30.

☞ Phase II: event-by-event primary mass information – identify and learn more about the UHECR source classes

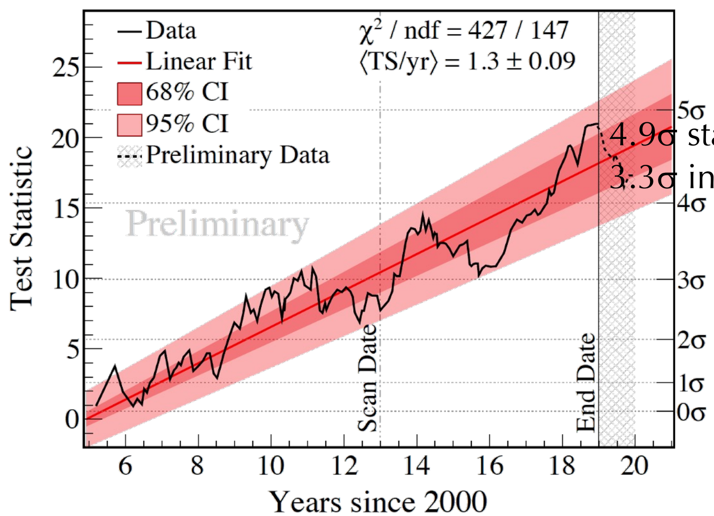
Composition enhanced anisotropy studies

E. Mayotte for the Pierre Auger Collaboration, ICRC 2021 #321



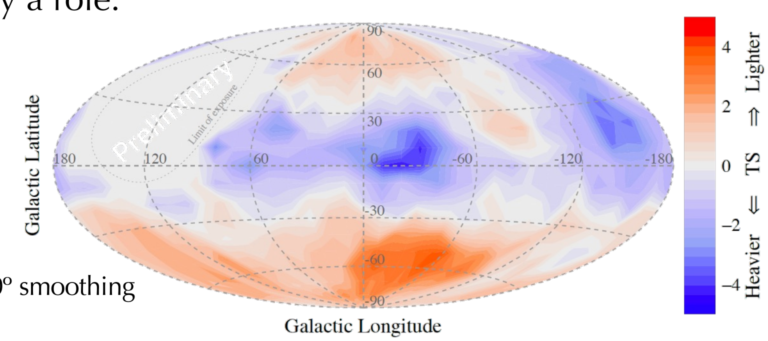


- Is the sky uniform in primary composition or are there differences that are potentially correlated with magnetic field strengths and therefore the Galactic plane?
- Scan of data before Jan 1, 2013 (54% of the data). Highest TS for Log(E_{min}/eV)=18.7 and b_{split}=30º.
- Indication of a lighter composition far from the galactic plane
- Interpretation is likely complex. Local source distribution, mass-dependent horizons and propagation effects may all play a role.



4.9σ statistics only

3.3σ including systematics



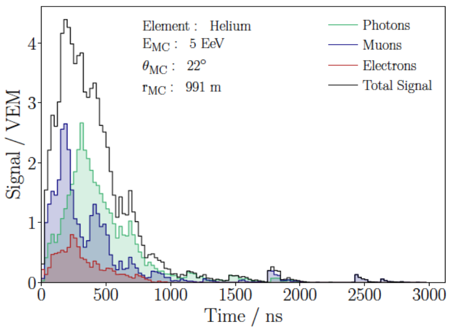
30º smoothing

☞ Phase II: event-by-event primary mass information – more studies like this

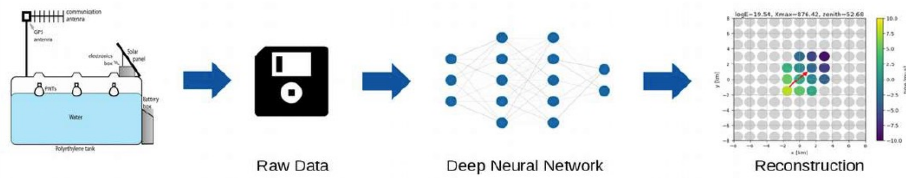
A very promising approach: Machine Learning

X_{max}: Pierre Auger Collaboration, JINST 16 (2021) P07019
Muon: Pierre Auger Collaboration, JINST 16 (2021) P07016

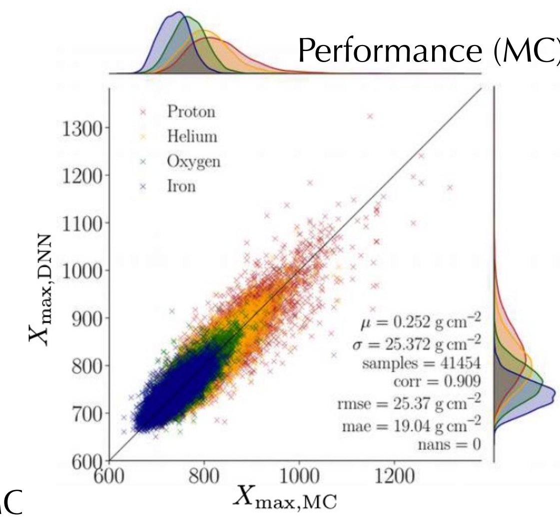
Simulated SD traces



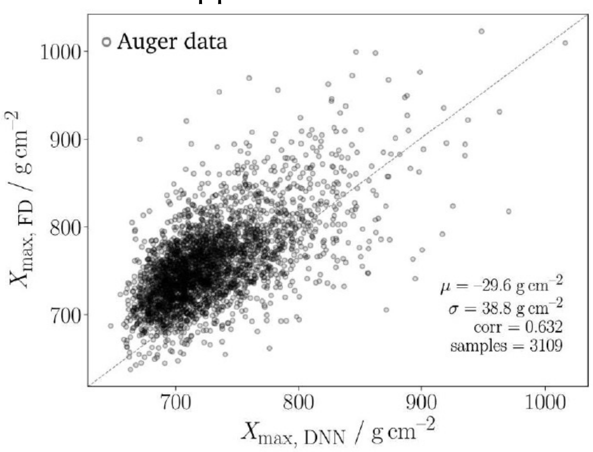
Machine Learning (DNN)

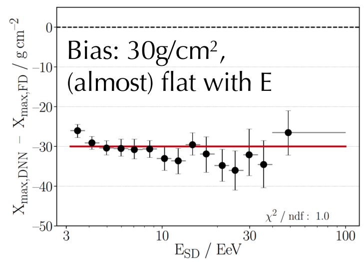


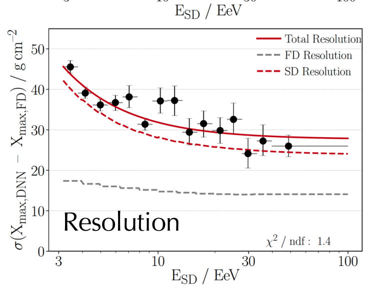
Performance (MC)



DNN applied to data





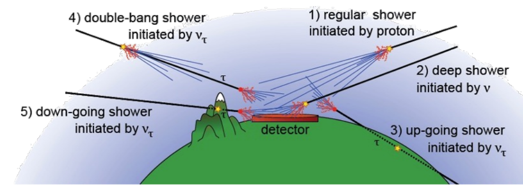


- Works very well in MC
- Observed bias with the data. $X_{max,DNN}$ is predicted to be shallower than the data (heavier composition). Likely related to the muon excess in EAS.
- Similar effort underway to extract muon number from SD traces (especially in conjunction with Phase II)

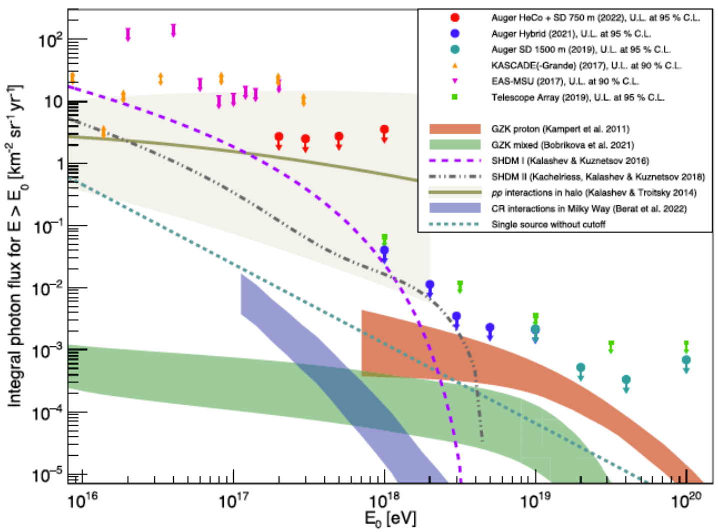
☞ Phase II: use of ML to extract better primary mass information

Photons: Pierre Auger Collaboration, Astrophys. J. 933 (2022)
Neutrinos: Aab et al., JCAP 10 (2019), JCAP 11 (2019)

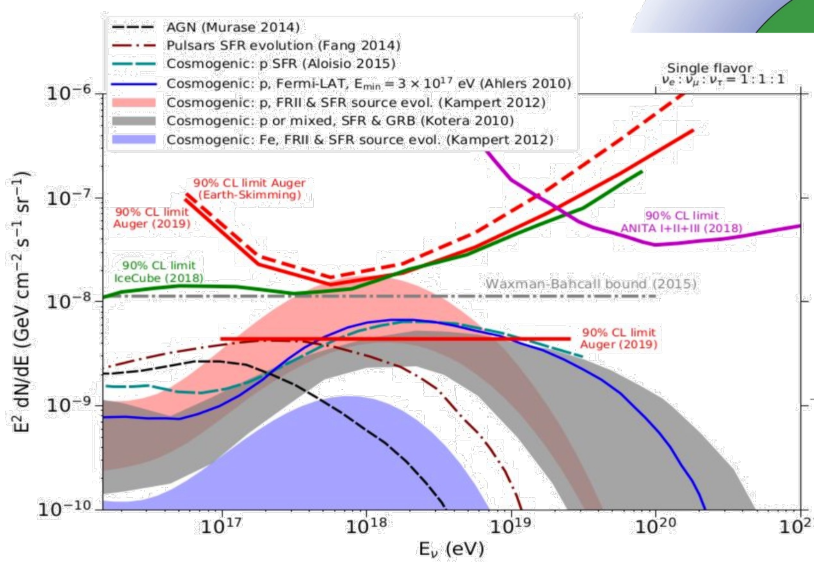
- Auger is also a UHECR photon and neutrino detector able to place very competitive limits
- Unambiguous detection of one UHECR photon or neutrino can be a game changer.
- Photon and neutrino limits strongly constrain pure proton models in particular.



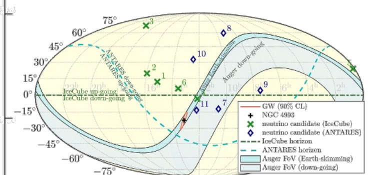
Photons:



Neutrinos:

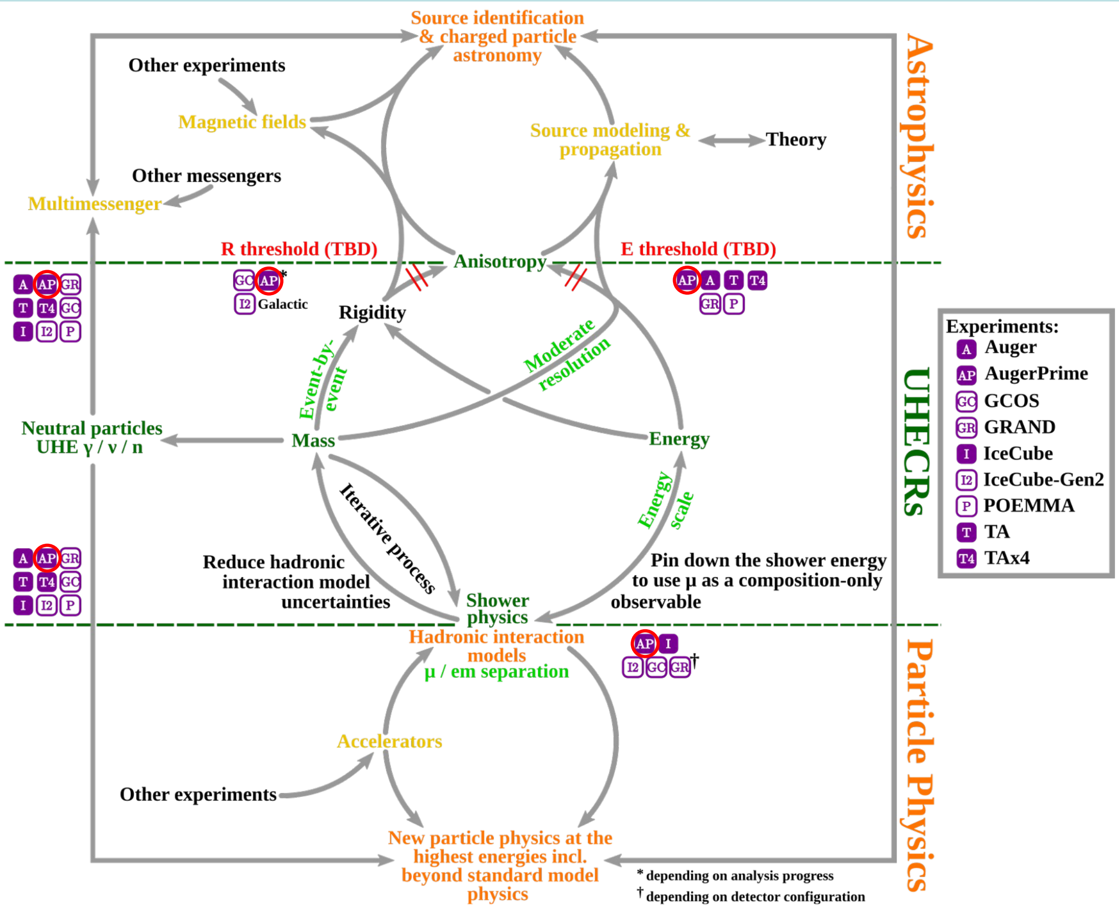


Also MM!



☞ Phase II: event-by-event primary mass information allows for tighter cuts for photons especially

Ultra High Energy Cosmic Rays: at the intersection of the Cosmic and Energy frontiers



Snowmass UHECR white paper, arXiv:2205.05845 (2022)

Wide community involvement:

- 7 conveners
- 29 topical conveners
- 62 contributors
- 200+ endorsers

Document:

- 190+ pages of content and discussion (283 with front- and back-matter)
- Spread over 8 chapters, 38 sections and 78 subsections
- 132+ figures, 25+ of which are unique
- 1,114 unique references cited

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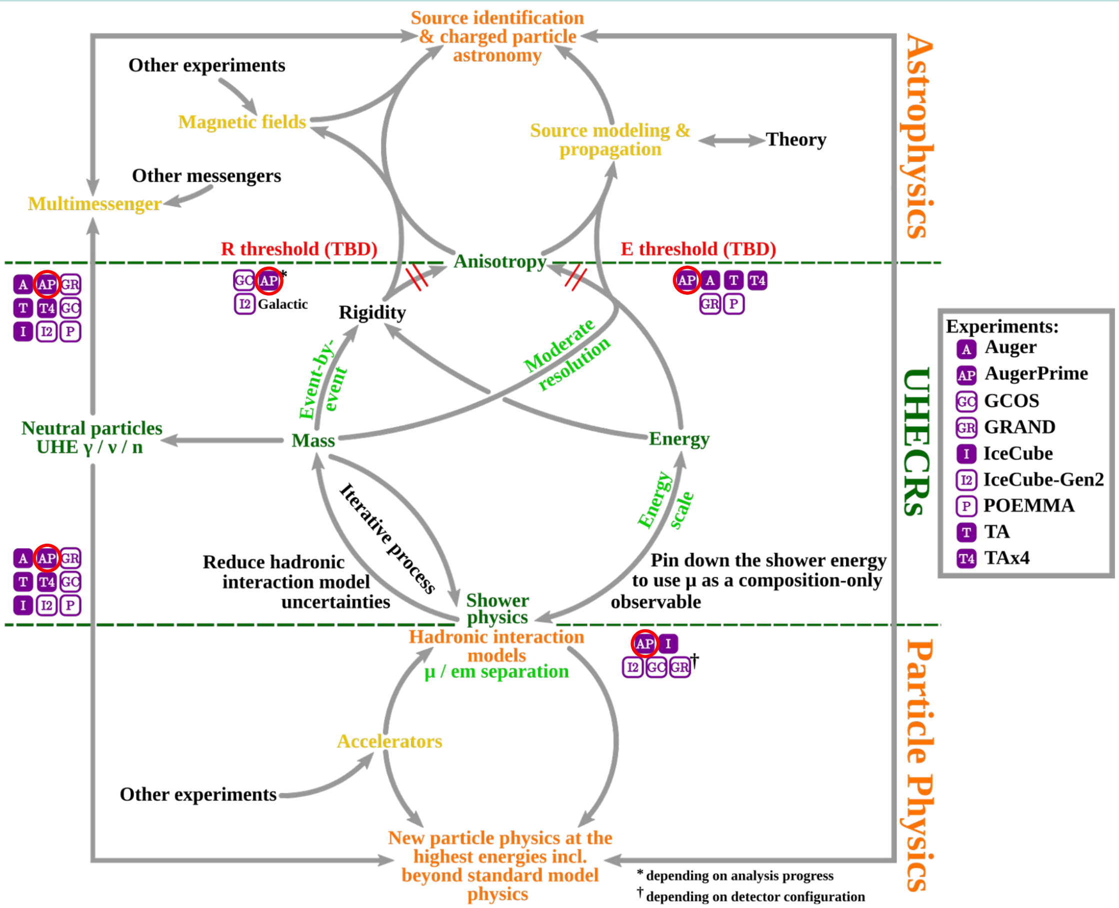

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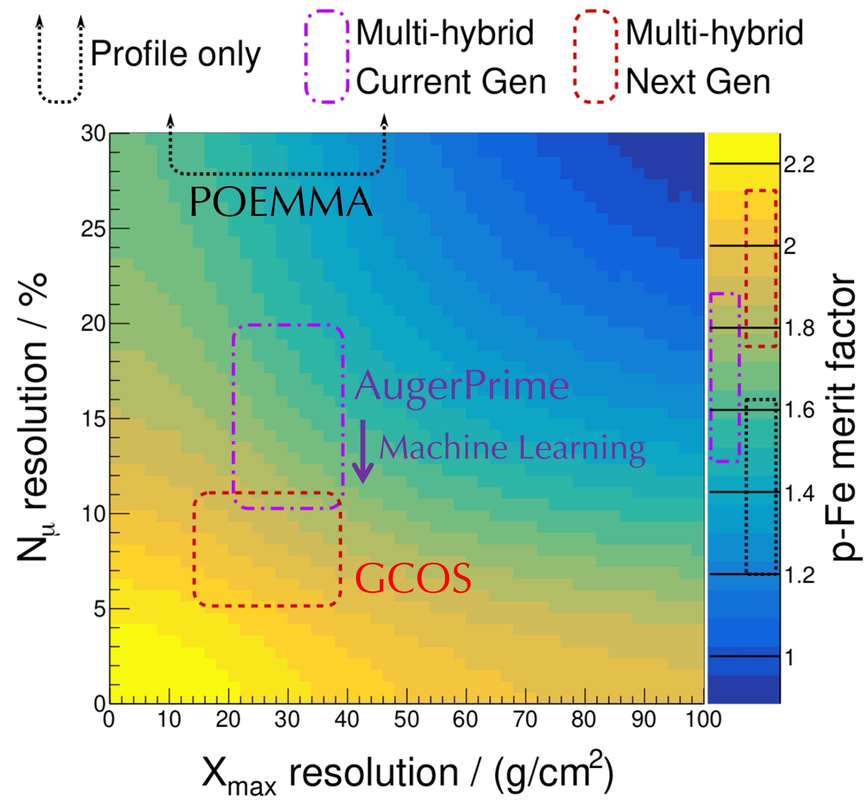

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TeVPA 2022, Kingston (ON, Canada), August 2022

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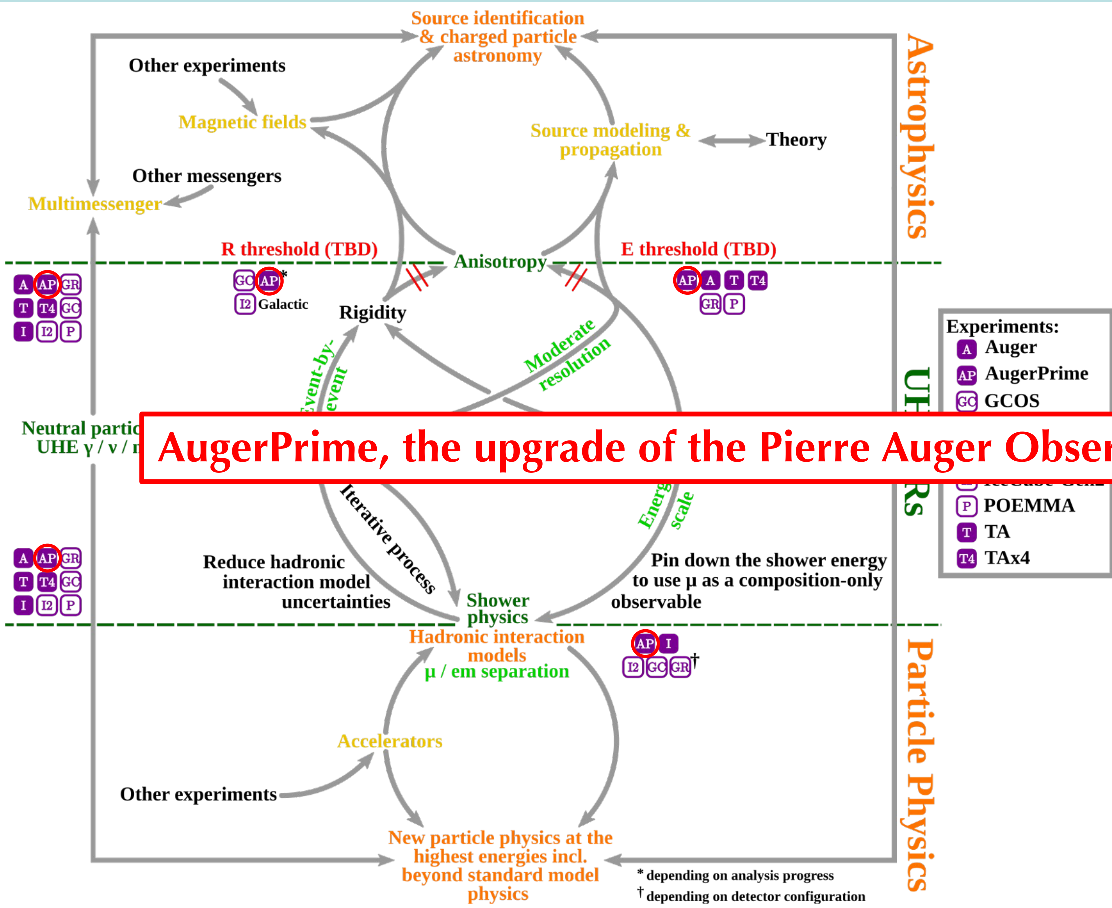

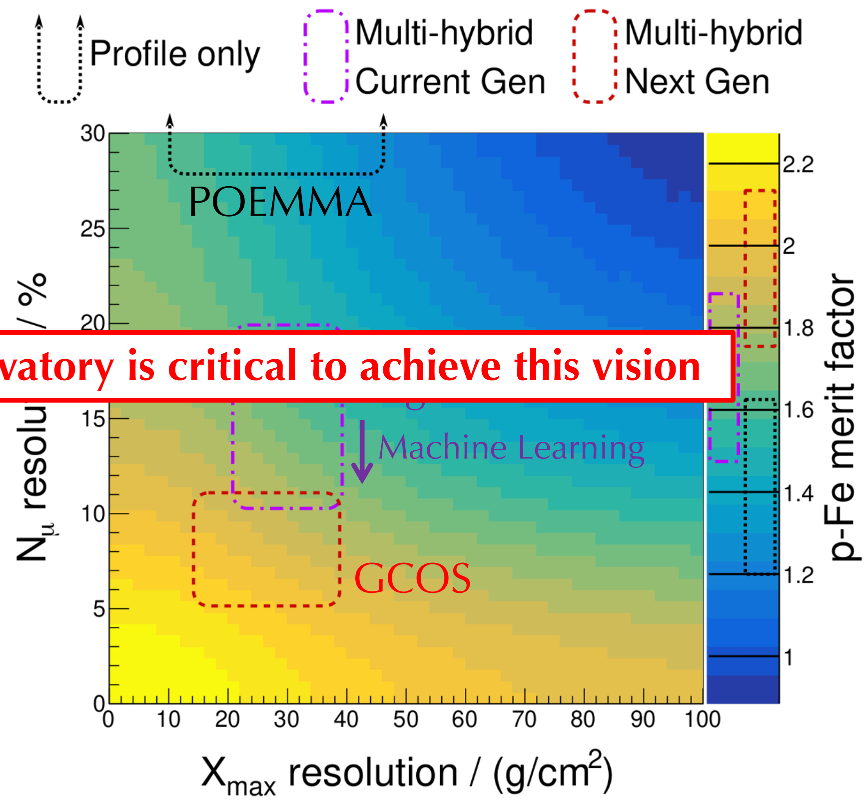

AugerPrime, the upgrade of the Pierre Auger Observatory is critical to achieve this vision

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THANK YOU!