The science of ultra-high energy cosmic rays after 20 years of operation of the Pierre Auger Observatory

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July 6, 2025

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The Pierre Auger Observatory

1963 : 10^{20} eV !

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

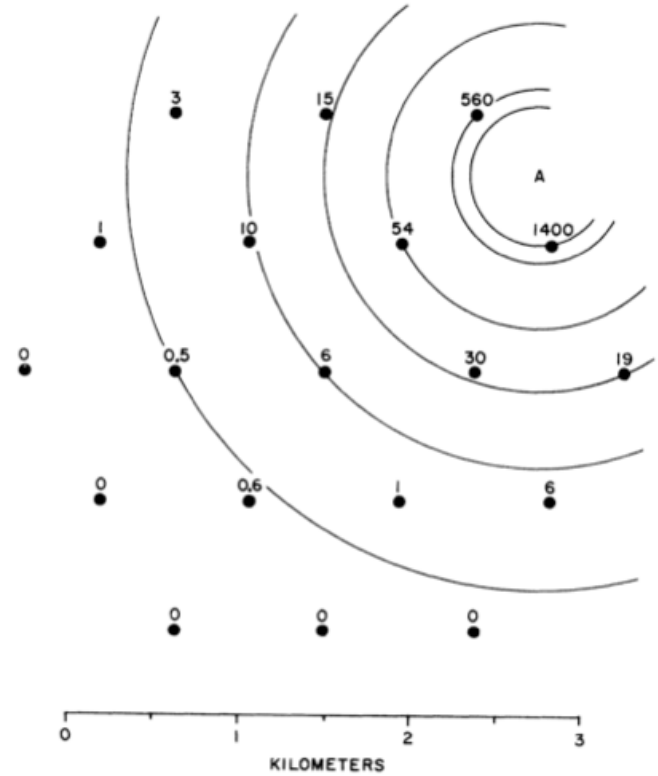
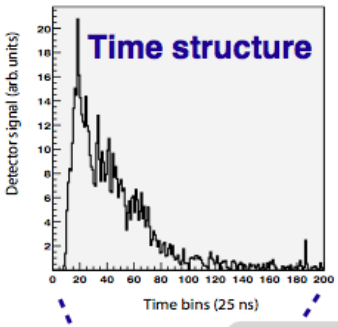
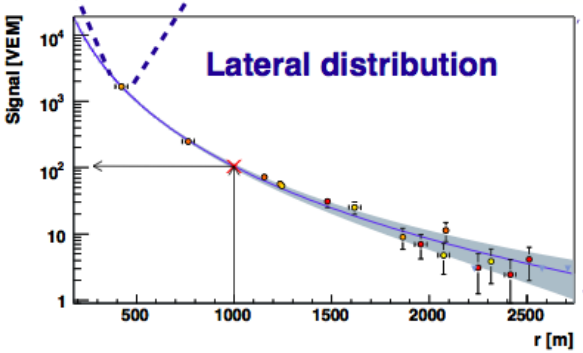


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

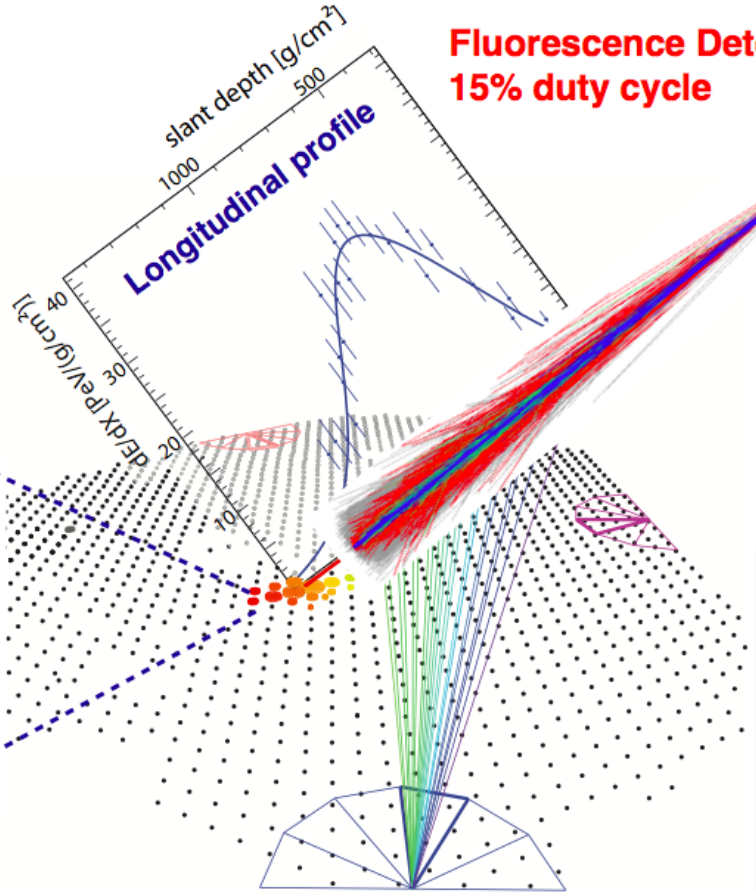
Air shower observables (hybrid observation)



$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$



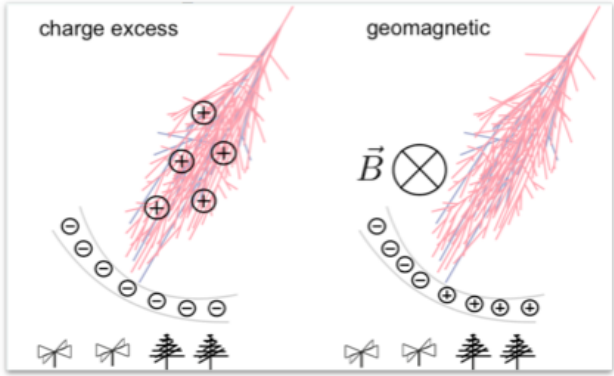
Surface Detector (SD)
100% duty cycle



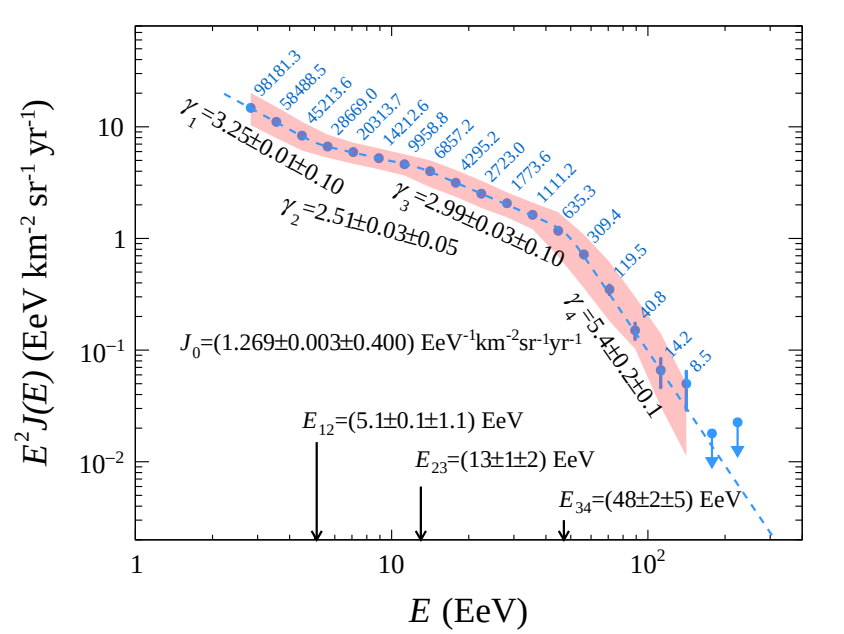
Fluorescence Detector (FD):
15% duty cycle

$$E_{\mathrm{cal}} = \int_0^{\infty} \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

Radio Detector (RD):
100% duty cycle



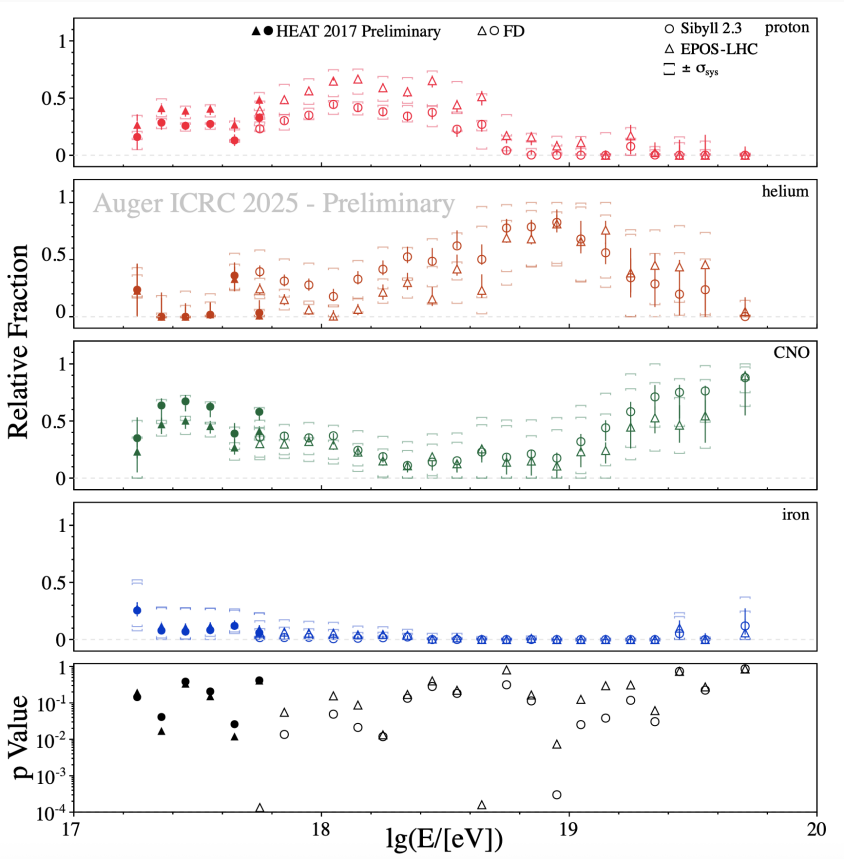
The two-step suppression of the energy spectrum



- $> 100{,}000$ km^2 sr yr
- Calorimetric energy estimate
- Combination of $[0, 60°]$ and $[60°, 80°]$ data streams
- New spectral feature uncovered: instep @10 EeV, 5.5 σ C.L.
- No dependences on declination but a small dipolar trend

[arXiv:2506.11688, submitted to PRL]

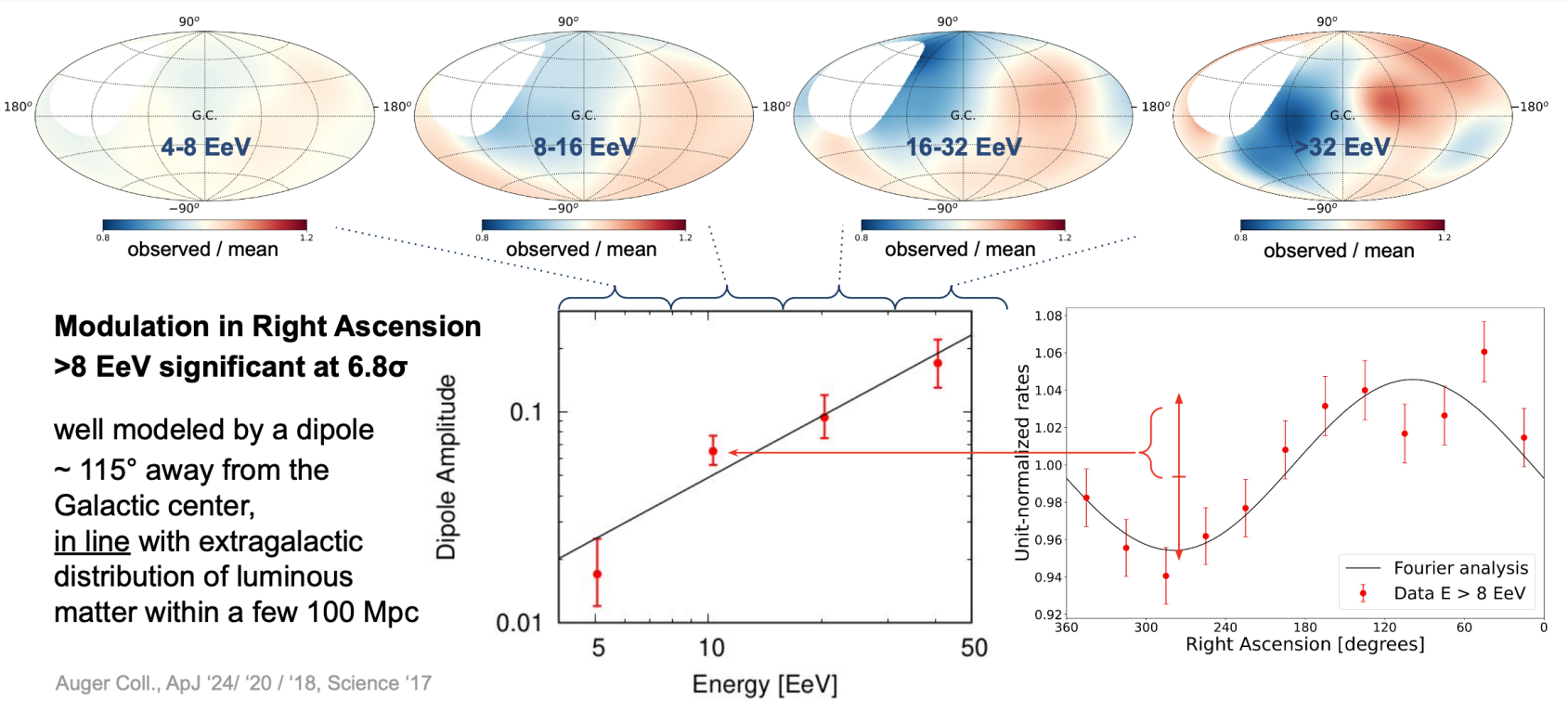
UHE Peters' cycle?



[ICRC2025, cf. talk by B. Cermakova at this conference]

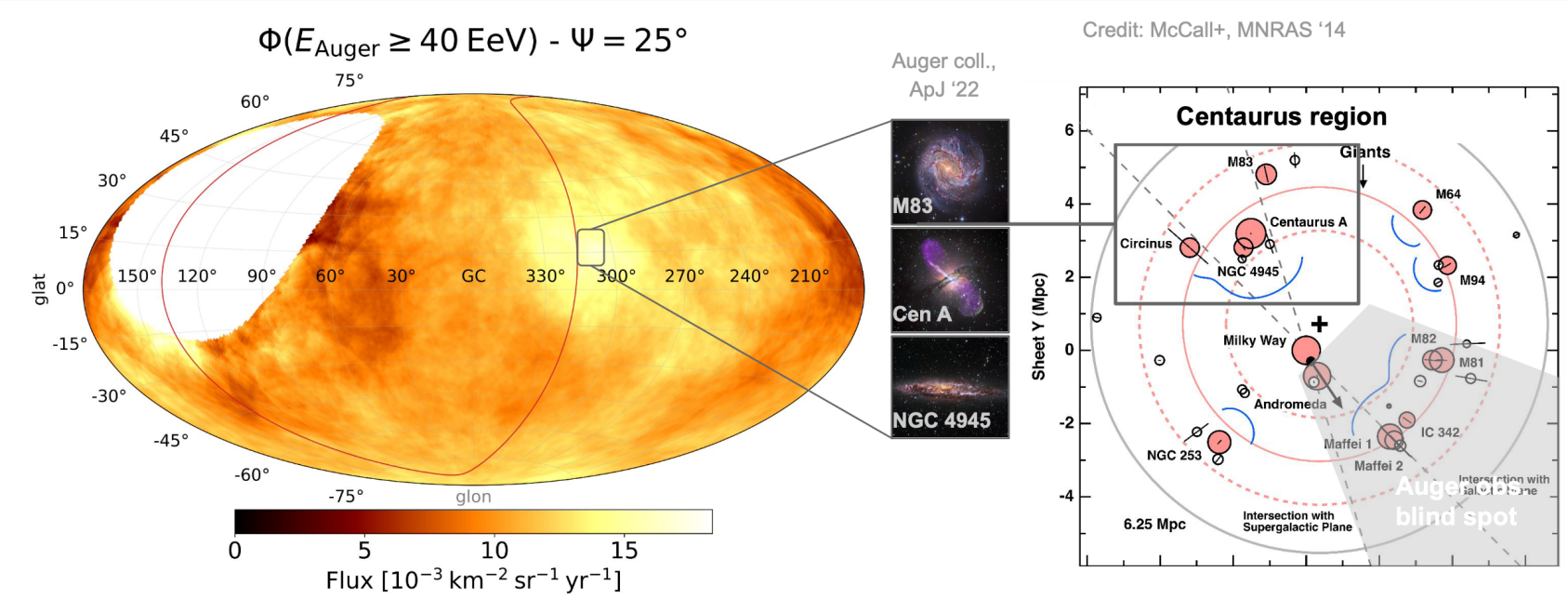
- Most sensitive observable: $X_{\max}$
- Directly observed by FD
- Expected distributions vs (E, A) from event generators
- p→He→CNO, extrapolation to heavier elements at UHE
- Little mix between elements
- Consistent picture with indirect measurements from SD (AI-based methods), with breaks in elongation rate

Extragalactic origin beyond the ankle energy



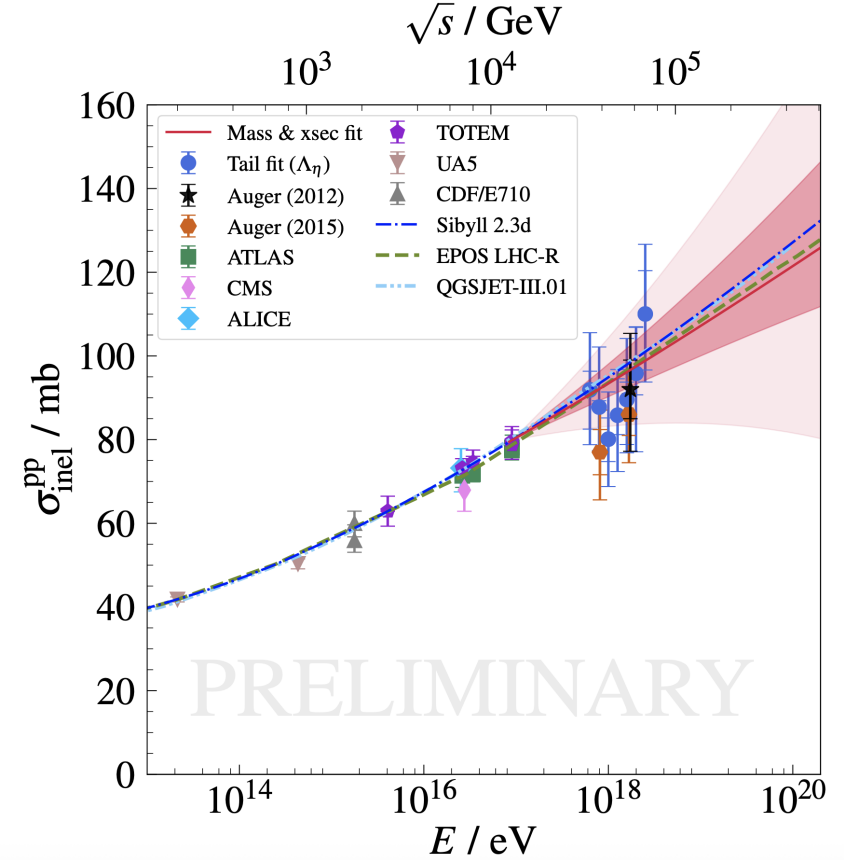
- Energy-loss length: cosmological horizon
- NB: Results confirmed with full-sky coverage (joint studies with the Northern-hemisphere observatory TA)

Closing the net at the highest energies



- > 40 EeV : Contrasts of ~ 10–15% at intermediate angular scales
- Energy-loss length: few dozens of Mpc
- Angular scale consistent with He/CNO vs p
- Correlations at ~ 4σ with Centaurus region and starburst galaxies [ApJ 853 (2018) L29; ApJ 935 (2022) 170]

Cross section at $\sqrt{s} > 14$ TeV



[ICRC2025]

- From a simultaneous fit of mass composition, cross-section and a shift in $X_{\max}$ scale
- Cross section rescaled by

$$f(E) = 1 + H(E - E_0)(f_{19} - 1)\frac{\lg(E/E_0)}{\lg(E_1/E_0)}$$

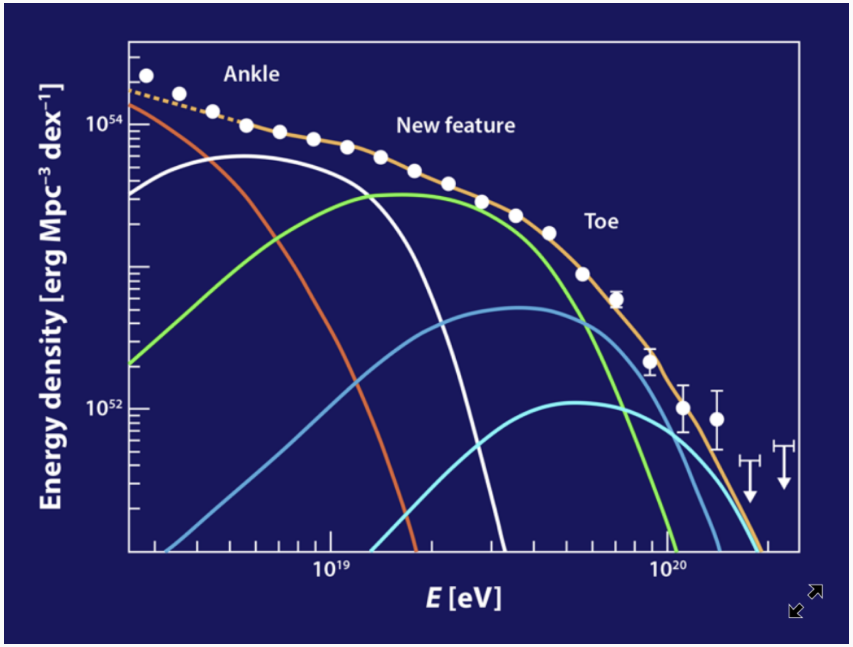
- $f_{19} = 1$ for Sibyll2.3d model
- Consistent with model predictions within uncertainties

UHECR physics – Minimal benchmark after 20 years of Auger

Minimal benchmark

☛ One single (extragalactic) component > 5 EeV [JCAP 04 (2017) 038; PRL 125 (2020) 121106]

[September 16, 2020 Physics 13, 145]

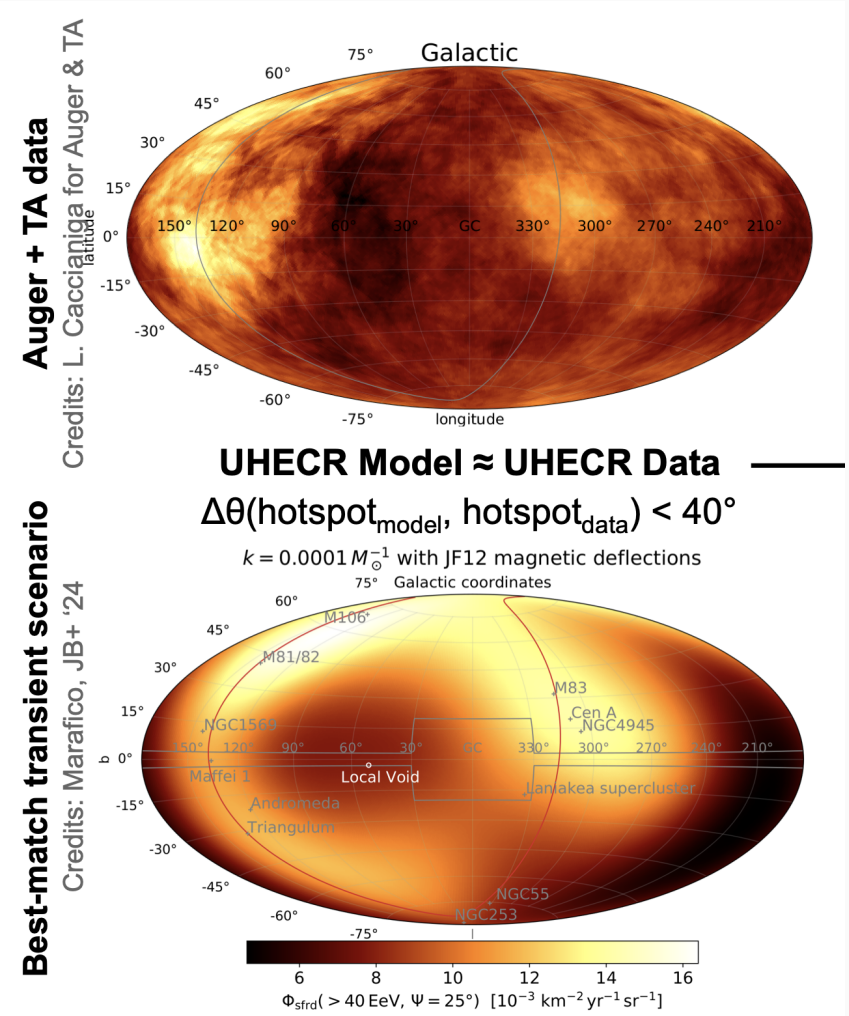


- Intermediate/heavy elements
- Max. acceleration:
  $E_{\rm max}(Z) = Z \times E_{\rm max}(p)$, with
  $E_{\rm max}(p) \simeq 5$ EeV
- Emission at sources :

$$\frac{dN}{dE} \propto E^{\pm 1}$$

- Reservoir of intermediate/heavy elements?
  - Accelerators located close to exceptional sources of metal, e.g. of nucleosynthesis or direct synthesis
  - Re-acceleration of PeV CRs
- Escape/Environment at sources: $E^{-2} \rightarrow E^{\pm 1}$

Pinpointing minimal-benchmark sources



- Metallicity poorly constrained (p secondaries/primaries?)
- Material from (high-mass) stars He/Heavy nuclei:

$$\frac{M(\mathrm{He})}{M(\mathrm{C-He})} = 0.21 \pm 0.05_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}$$

(18 ± 2 for ISM material)

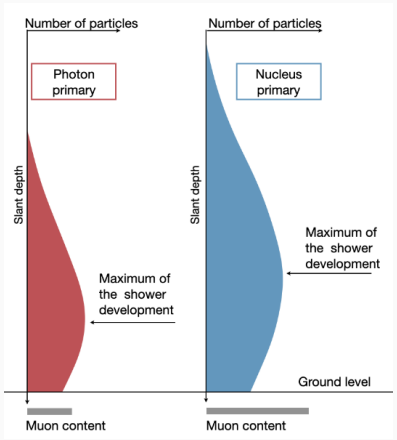
- Transient rate: $50 - 30,000\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Local Sheet $B_{\mathrm{rms}} = 0.5 - 20$ nG

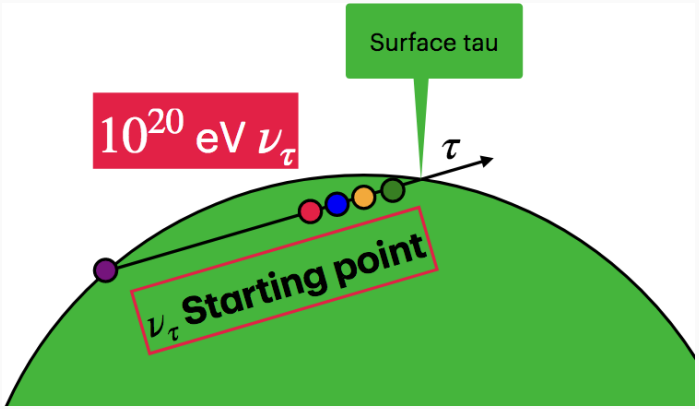
- Stellar-sized transients satisfying energetics and burst rate: long GRBs

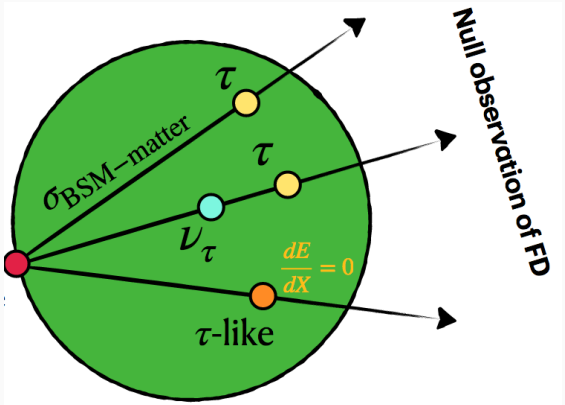
[Marafico et al., ApJ 972, 1 (2024)]

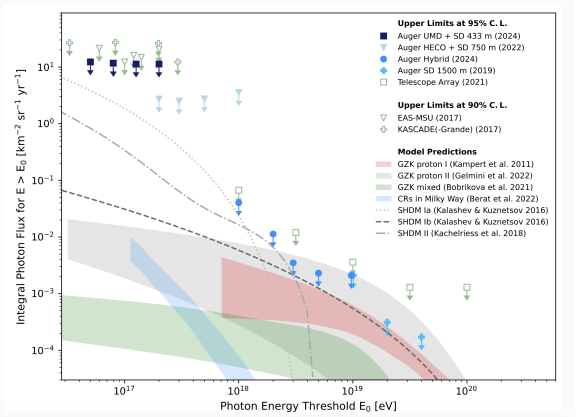
Multi-messenger & BSM physics

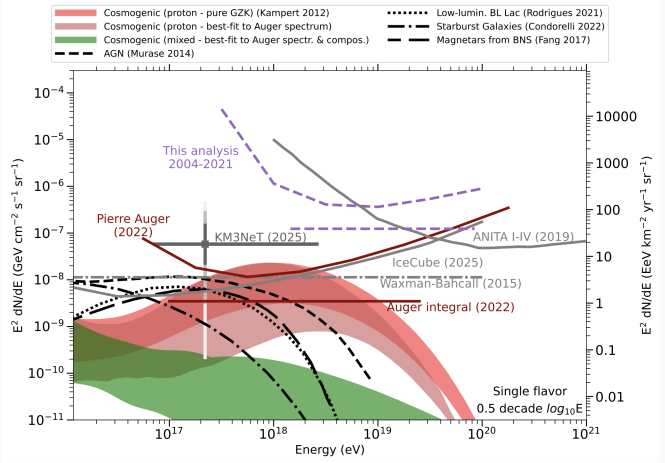
UHE multi-messengers

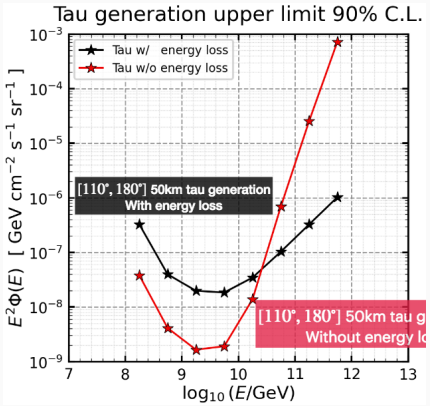






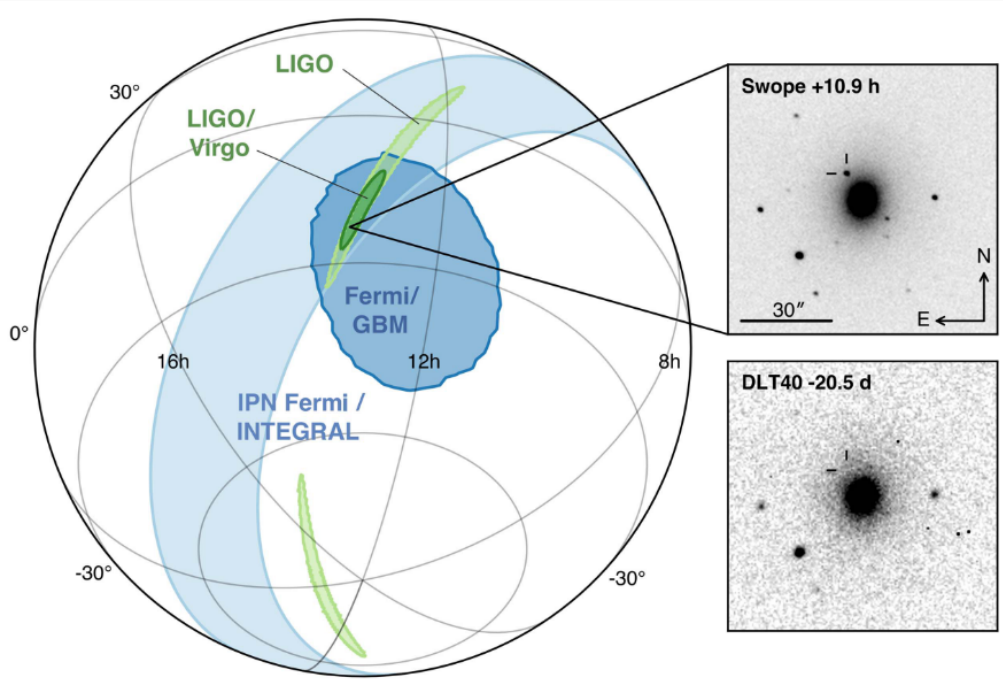




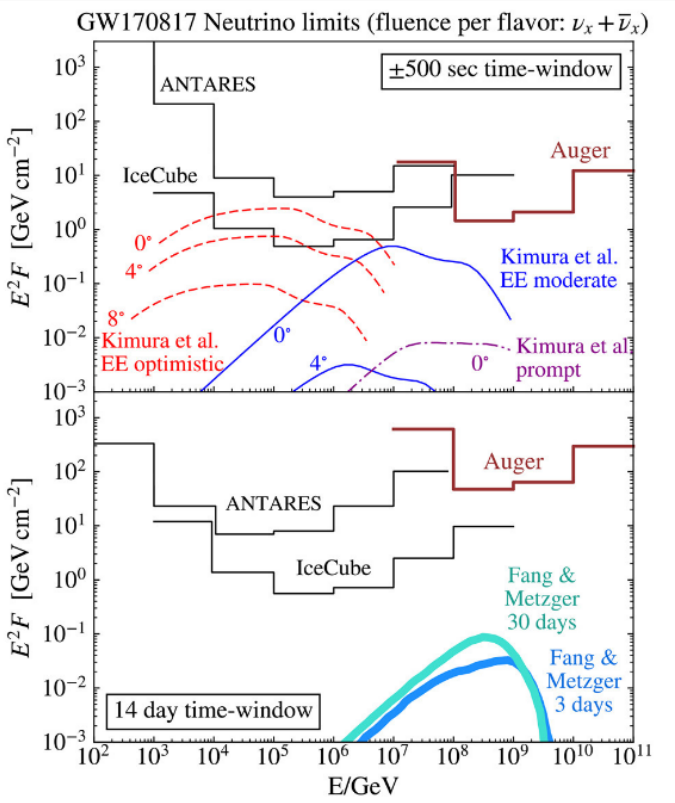


- UHE gamma rays [Auger, TA]: Horizon limited to a few Mpc **cf. talk by N. Gonzalez at this conference**
- Neutrinos [IceCube, KM3NET, Auger, ANITA]: Cosmological horizon
- Leptons τ [Auger, ANITA, ...]: BSM tests of neutrino production

Multi-messenger astrophysics

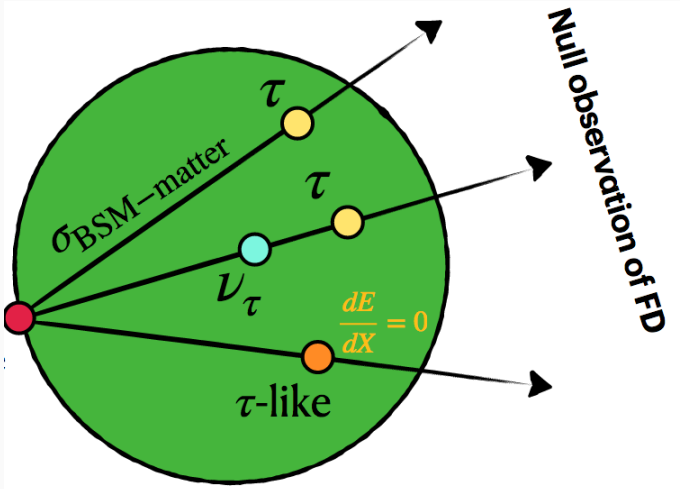


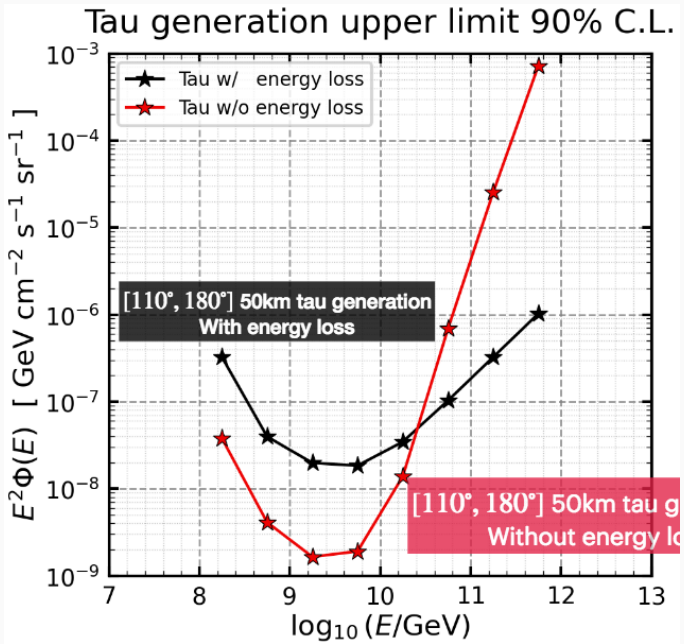
[ApJ 848:L12 (2017)]



- γ/ν follow-up of gravitational waves [PRD 94 122007 (2016); ApJ 848:L12 (2017); ApJ 952:91 (2023)]
- UHEν follow-up of UHE phenomena [ApJ 902:105 (2020)]

The mirage of neutrinos coming from Antartica





cf. talk by E. de Vito at this conference

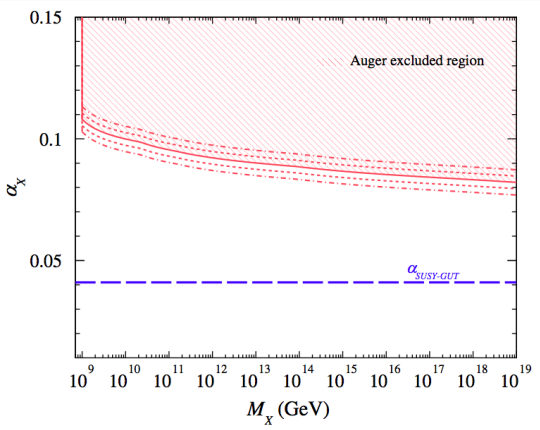
- "Anomalous ANITA events"
- Stringent limits from Auger:

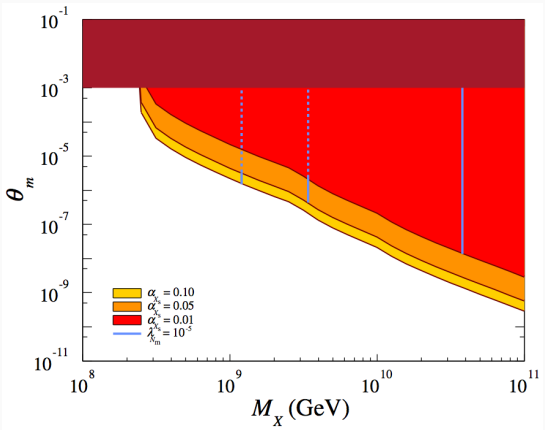
  [PRL 134 (2025) 12, 121003]

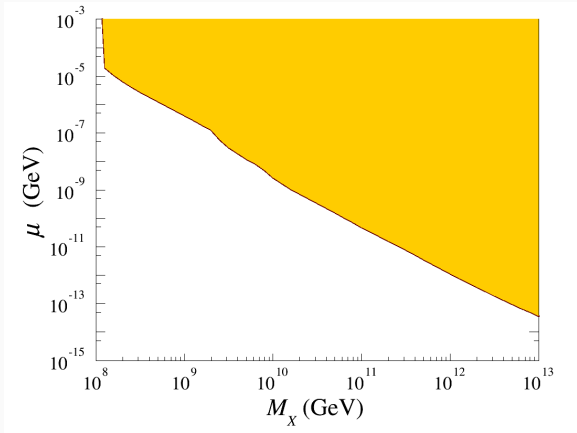
  - 1 obs. vs 0.24 exp. (bkg)
  - ~ 30 exp. (signal)
- Strong constraints on scenarios with input fluxes of BSM particles
- e.g. DM$\rightarrow \overline{N}_R N_R$ with seesaw-like mixing regulated by a mixing angle θ_{mix}

Superheavy dark matter

- ☛ Superheavy particles? Inflationary sector, sterile neutrinos, instability scale of SM: hidden/dark sector at high scale?
- ☛ DM production by "freeze-in" mechanism through s-channel
- ☛ SHDM? $\tau > 10^{22-23}$ yr





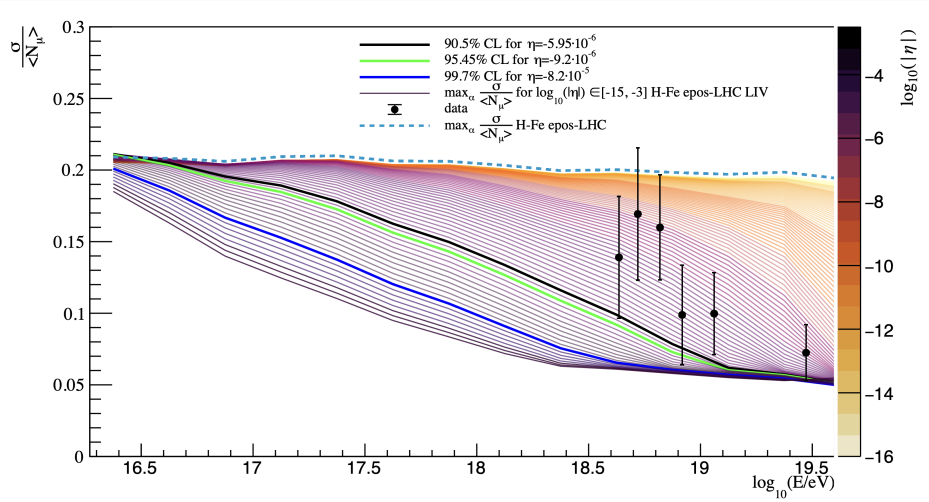


- Hidden sector with gravitational couplings alone : decay through instantons **[PRL 130 (2023) 061001 ; PRD 107 (2023) 042002]**
- Couplings to ultra-light sterile neutrinos mixed with active ones **[PRD 109 L081101 (2024)]**
- SUSY broken at high scale with R-parity violation **[in preparation]**

Lorentz Invariance Violation

- Standard Model Extension framework: Lorentz- and CPT-violating terms *not* violating gauge symmetries
- High energy-momentum eigenstates different from low-energy mass eigenstates, leading to velocity-mixing effects and different maximum attainable velocities
- Dispersion relations modified at high E: $E_i^2 - p_i^2 = m_i^2 + \sum \frac{\eta_{i,n}}{M_{\mathrm{Pl}}^n} E_i^{2+n}$

- Modification of reaction thresholds for non-zero $\eta_{i,n}$
- For $\eta < 0$, π^0 decay suppressed above E_{crit}
- π^0 interacting before decaying: decrease of e.m. component, increase of muon number



☛ $\eta > -5.95 \times 10^{-6}$ (90% C.L.) **[in preparation]**

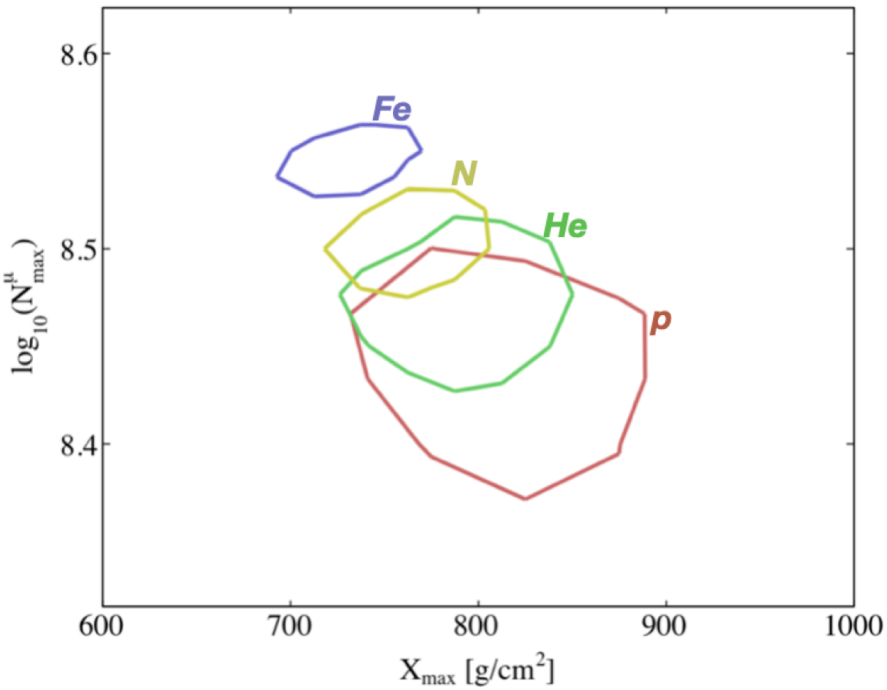
Phase II of the Observatory

AugerPrime - the detectors

- ***Surface Scintillator Detector (SSD)***
  to measure the mass composition in combination with the WCD (3.8 m^2, 1 cm thick)
- ***Upgrade of the WCD: small PMT (sPMT)***
  to increase the dynamic range of the WCD (≳ 20,000 VEM)
- ***Radio Detector (RD)*** to measure the radio emission of showers in atmosphere (30-80 MHz)
- ***Underground Muon Detector (UMD)***
  to have a direct muon measurement (infill area, 30 m^2, 2.3 m underground)
- ***SD Upgraded Unified Board (UUB)***
  to process the signals of all detectors (40 MHz -> 120 MHz, better GPS timing)

➡ AugerPrime: the Pierre Auger Observatory Upgrade EPJ Web of Conf. 210 (2019) 06002.
➡ Report for the AugerPrime Review (2023)

- Sensitivity to primary mass at UHE
  - X_{max} with FD : 10% duty cycle
  - X_{max} and N_μ with SD

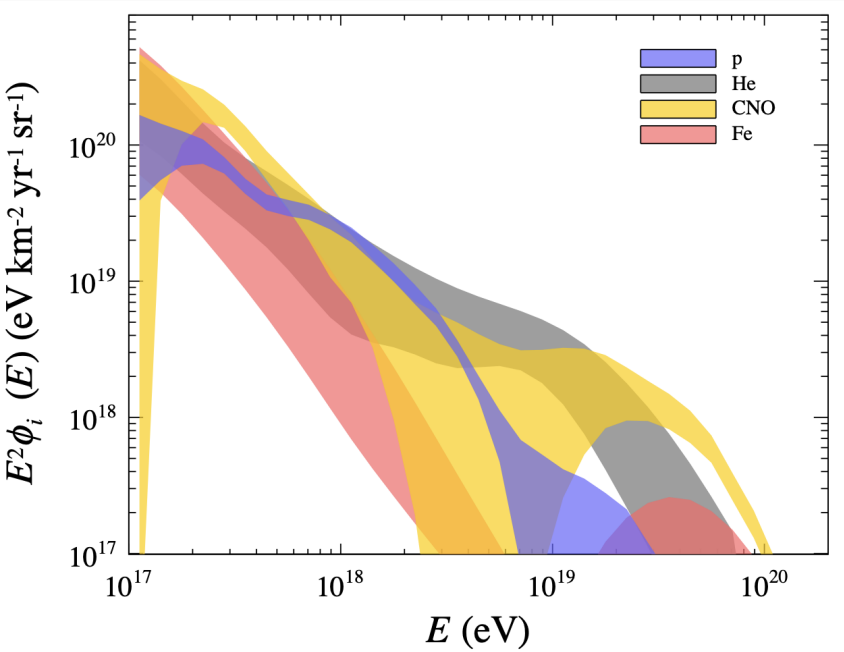


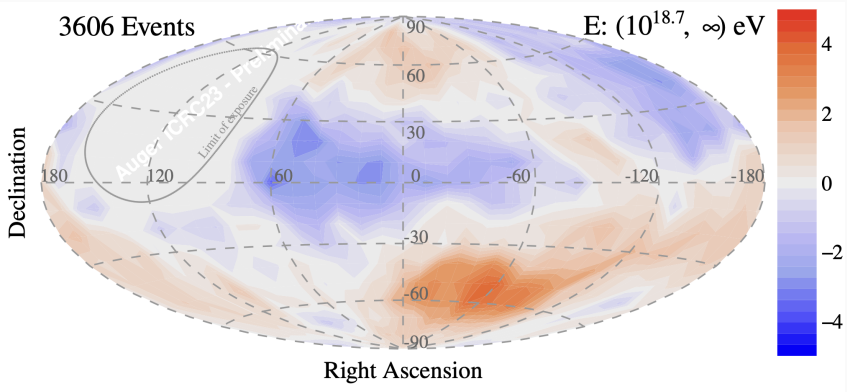
lg(E/eV)	SD 433	SD 750	SD 1500	FD hybrid	FD Cherenkov	RD
16.8	118000				48000	
17.5	3700	81000			4400	
18.0	270	5600		13000		
18.5	24	460	106000	3000		
19.0	5	88	13400	650		3000
19.5			1000	50		310
19.8			100	~ 5		23
20.0			12	~ 1		~3

With 10 years of data taking
~1000 events above $10^{19.5}$ eV

Conclusions

New questions on UHECRs





- Which model ?
  - Minimal model ? p→He→CNO→Si/Fe
  - Non-minimal model: sub-dominant component of protons at UHE?
- Sources?
  - Resolve anisotropies as a function of mass composition
  - UH-UHECRs?
- Photons/Neutrinos ?
  - Minimal vs non-minimal model
  - BSM

Conclusions/Perspectives

- UHECRs: Ultimate laboratory of high-energy physics
- Future of UHECRs?

☛ Confirmation of the minimal model

- High-energy astrophysics : origin, dynamics, energetics of relativistic jets, compact objets ; astrophysics of magnetised plasmas in motion, strong gravity environments

☛ Non-minimal model

- Several (two at least) populations of sources
- BSM?
- Dark matter
- Phase Transitions and cosmic strings