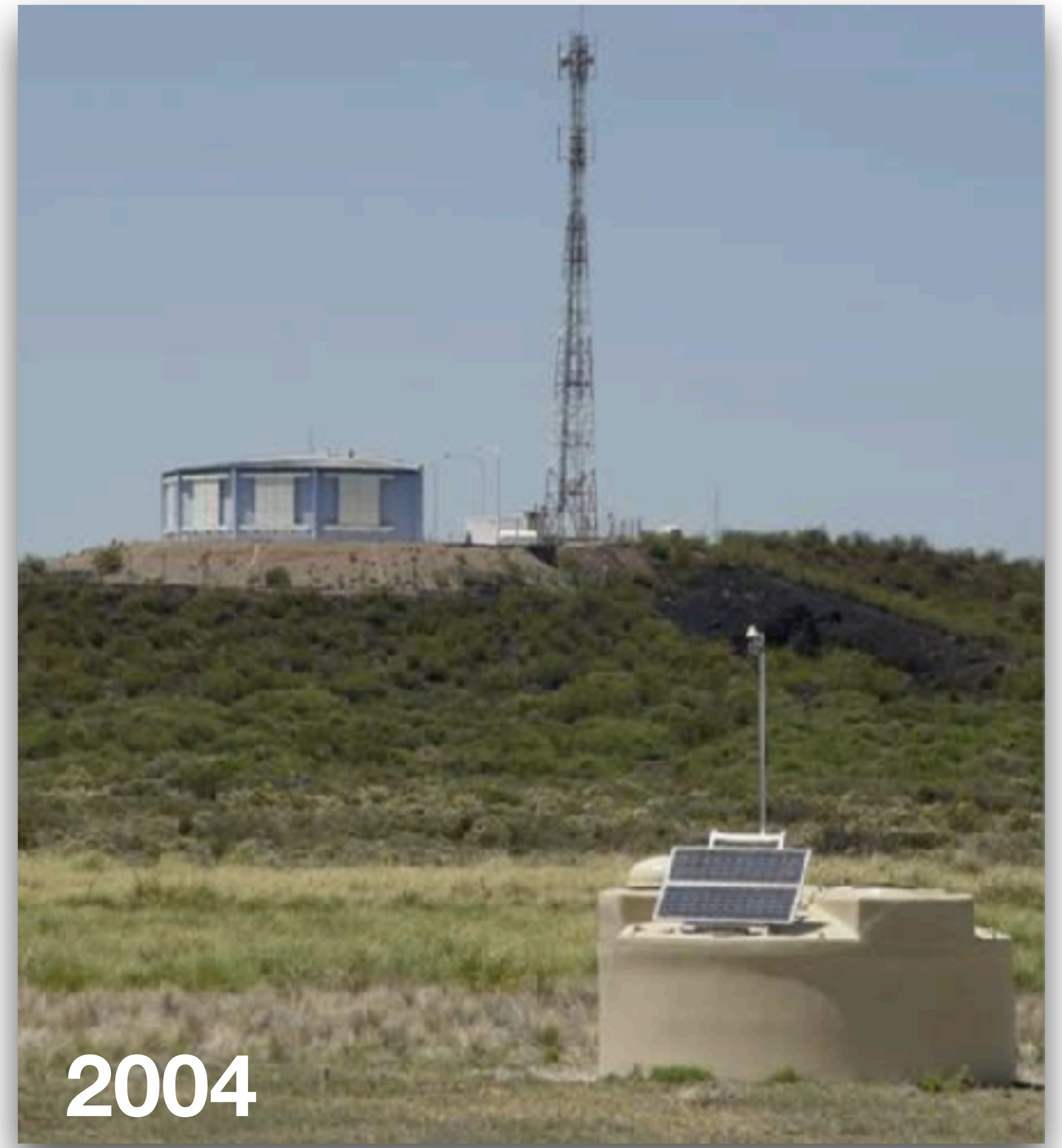
Pierre Auger Observatory
Status e risultati

Antonella Castellina

Napoli, 4 luglio 2025



Phase I
- 2000: Engineering Array
- 2004: start...
- 2008: ...end of construction of Auger
- 2022: start of data taking during AugerPrime deployment

Phase II
- 2024: end of construction of AugerPrime
- Data taking till > 2035

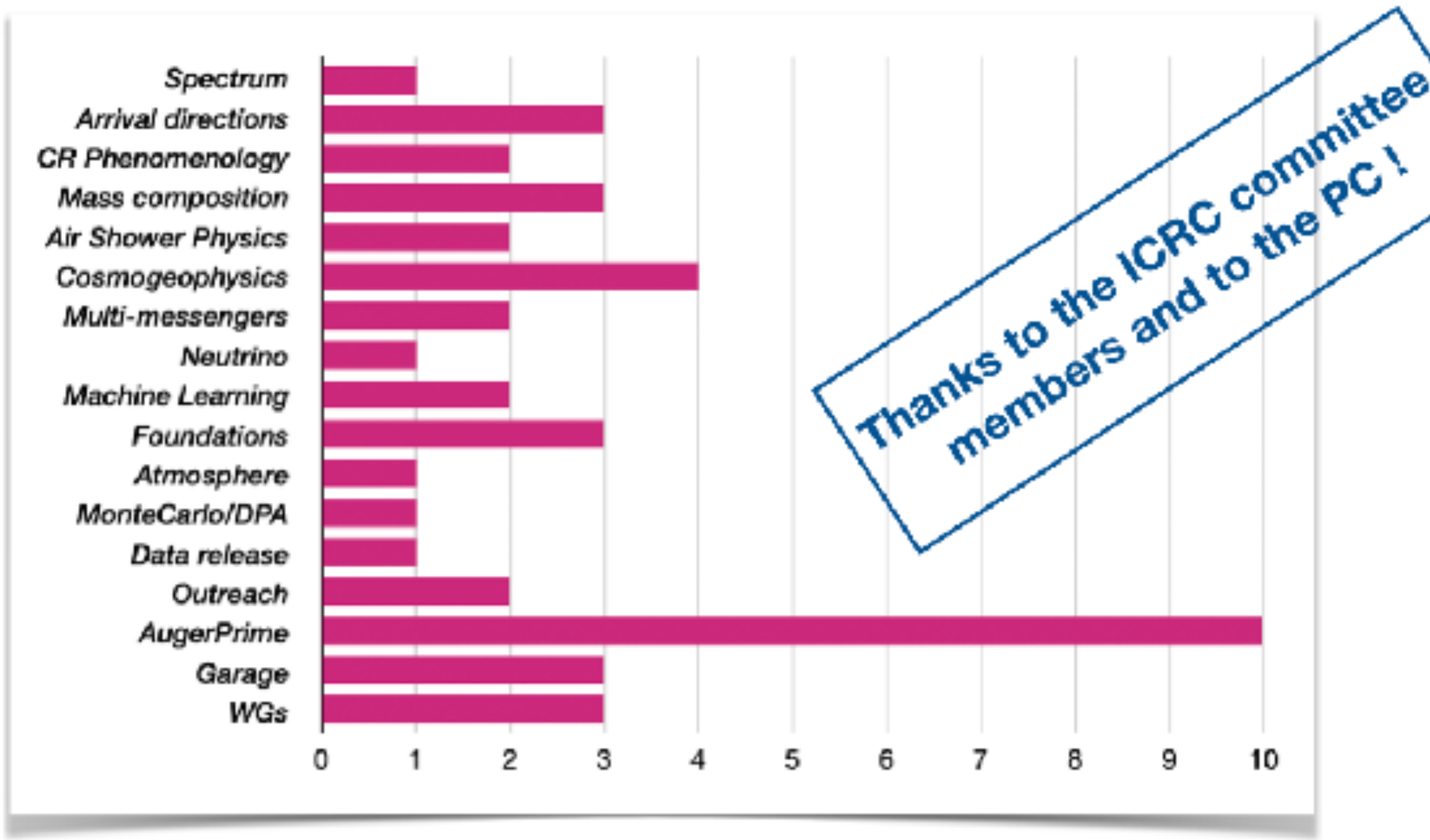
End of 2024:

➡ Collaboration meeting in Malargüe : 10-15 November
➡ Finance Board meeting in Malargüe (M.Pallavicini, O.Cremonesi attending)
➡ Celebration ceremony: extension of data taking for AugerPrime to 2035 [https://indico.nucleares.unam.mx/event/2235/]
➡ UHECR Symposium in Malargüe : 17-21 November

Activity since October 2024

2025: an ICRC year

➡ 1 Collaboration meeting in Malargüe : 9-14 March
➡ 1 AugerItalia meeting : 3-5 February
➡ 1 Analysis meeting in L'Aquila: 19-23 May in L'Aquila

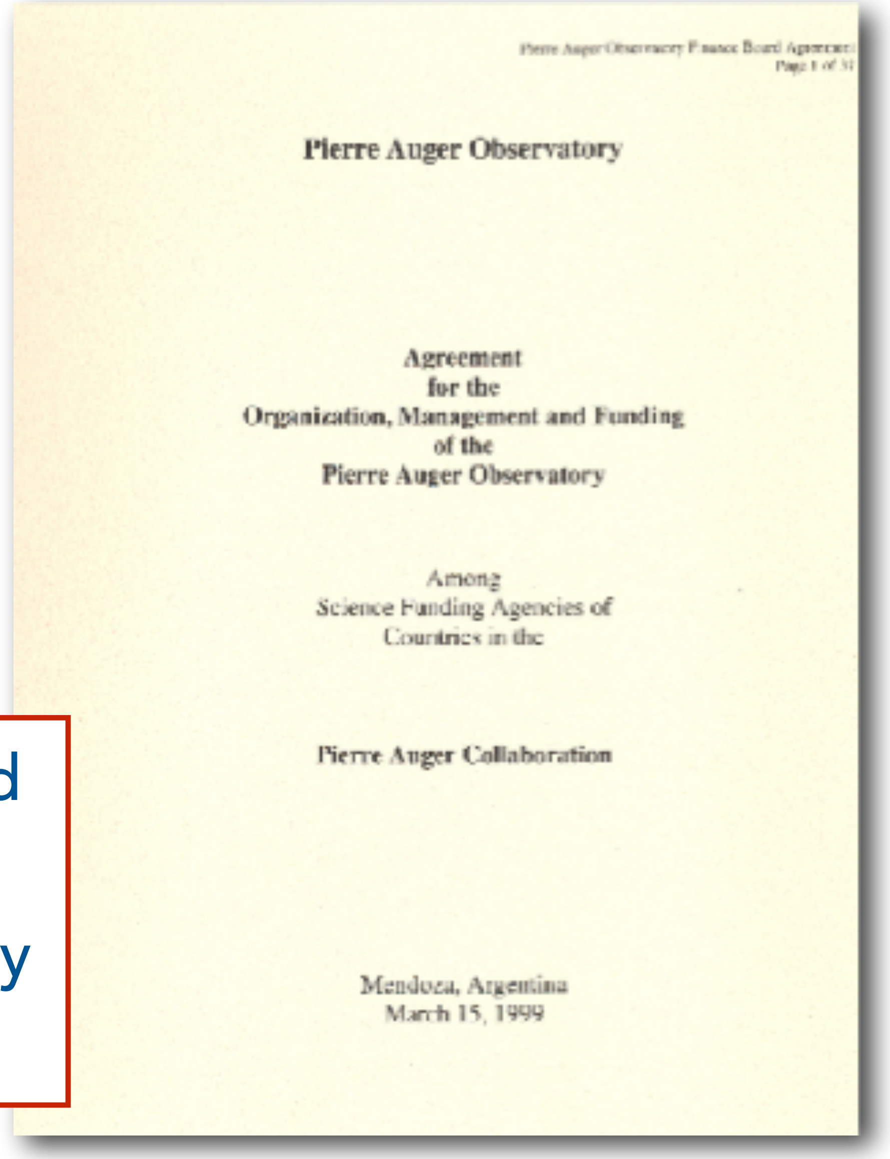


➡ ICRC (Geneva) : 15-24 July **44 contributions from Auger !**
➡ Next Collaboration meeting in Malargüe : 16-21 November

International agreements

1. First meeting of the starting collaboration held at CERN in 1995

2. First International Agreement finalized and approved at UNESCO, Paris in 1998
Signed in Mendoza March 1999 (chaired by H.Schopper)



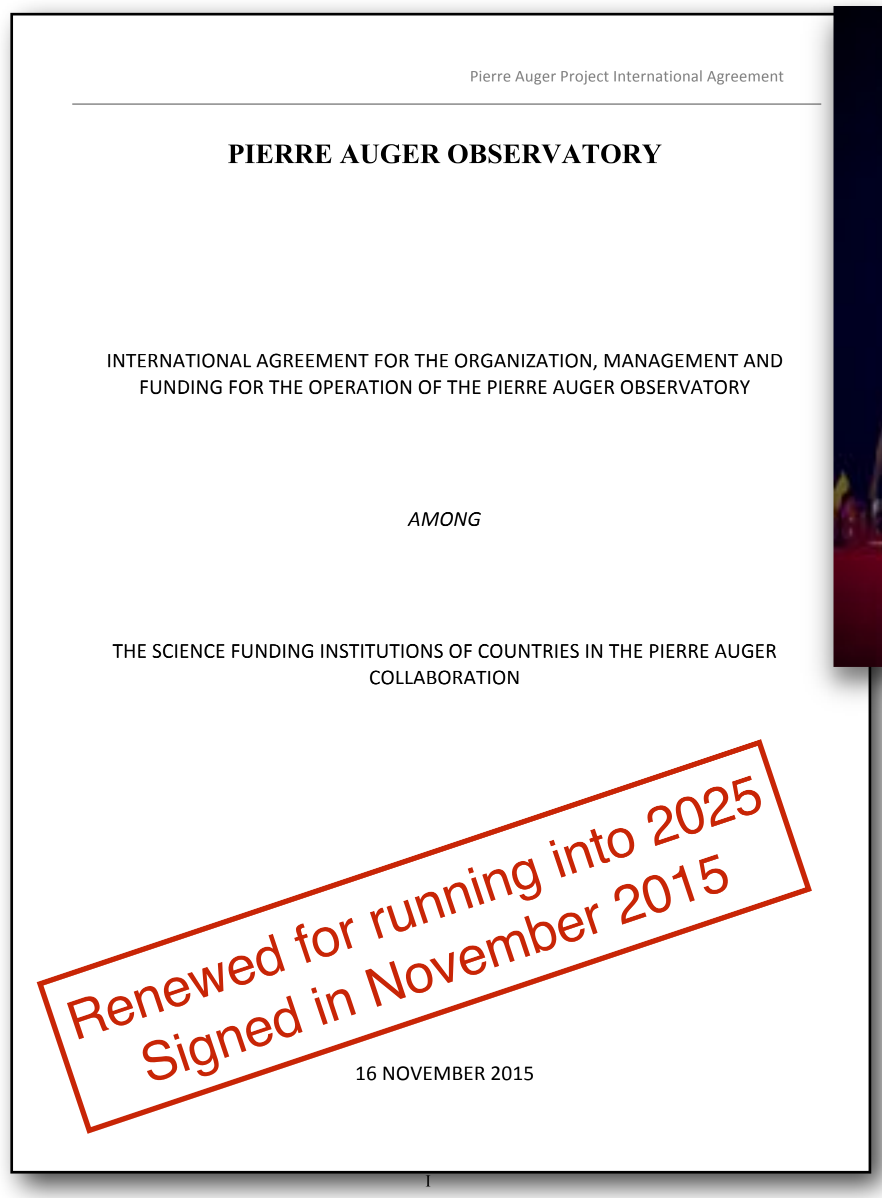
Pierre Auger Observatory

Agreement
for the
Organization, Management and Funding
of the
Pierre Auger Observatory

Among
Science Funding Agencies of
Countries in the

Pierre Auger Collaboration

Mendoza, Argentina
March 15, 1999



Pierre Auger Project International Agreement

PIERRE AUGER OBSERVATORY

INTERNATIONAL AGREEMENT FOR THE ORGANIZATION, MANAGEMENT AND FUNDING FOR THE OPERATION OF THE PIERRE AUGER OBSERVATORY

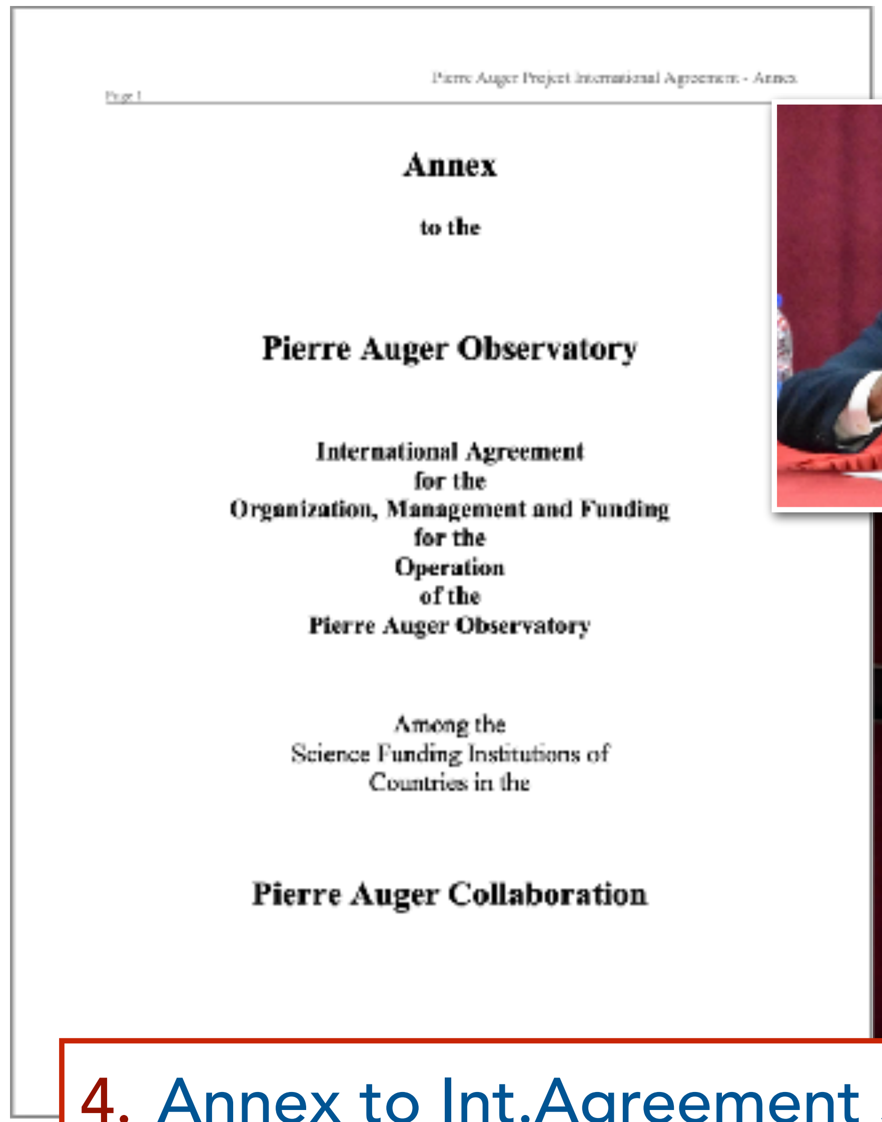
AMONG

THE SCIENCE FUNDING INSTITUTIONS OF COUNTRIES IN THE PIERRE AUGER COLLABORATION

16 NOVEMBER 2015

Renewed for running into 2025
Signed in November 2015

3. 2nd Int. Agreement signed in Malargüe in 2015 (chaired by F.Ferroni)



Pierre Auger Project International Agreement - Annex

Annex
to the

Pierre Auger Observatory

International Agreement
for the
Organization, Management and Funding
for the
Operation
of the
Pierre Auger Observatory

Among the
Science Funding Institutions of
Countries in the

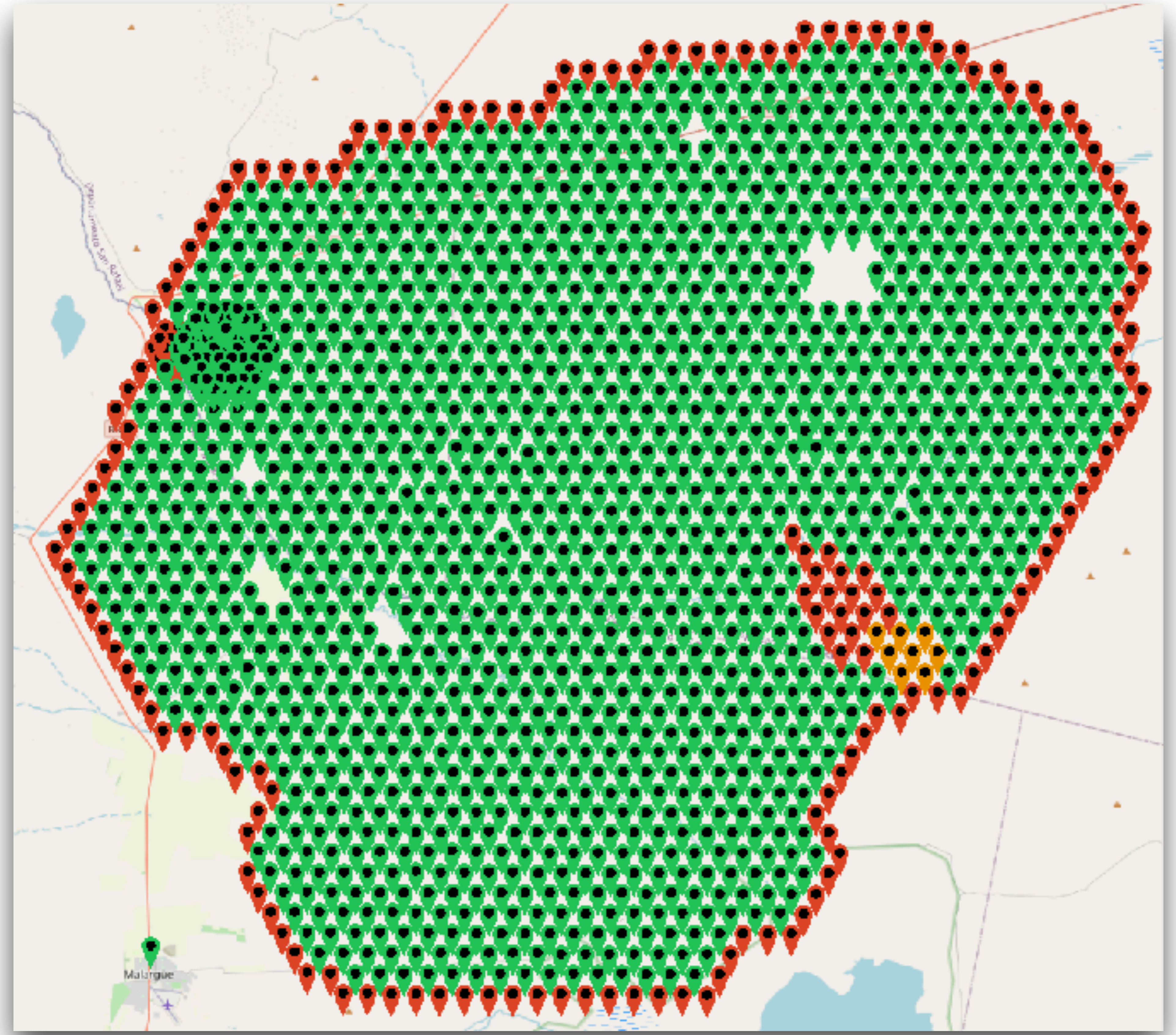
Pierre Auger Collaboration

Running until 2035 !
Signed in November 2024

4. Annex to Int.Agreement signed in Malargüe in Nov.2024 (chaired by S.Bentvelsen)

AugerPrime in the field

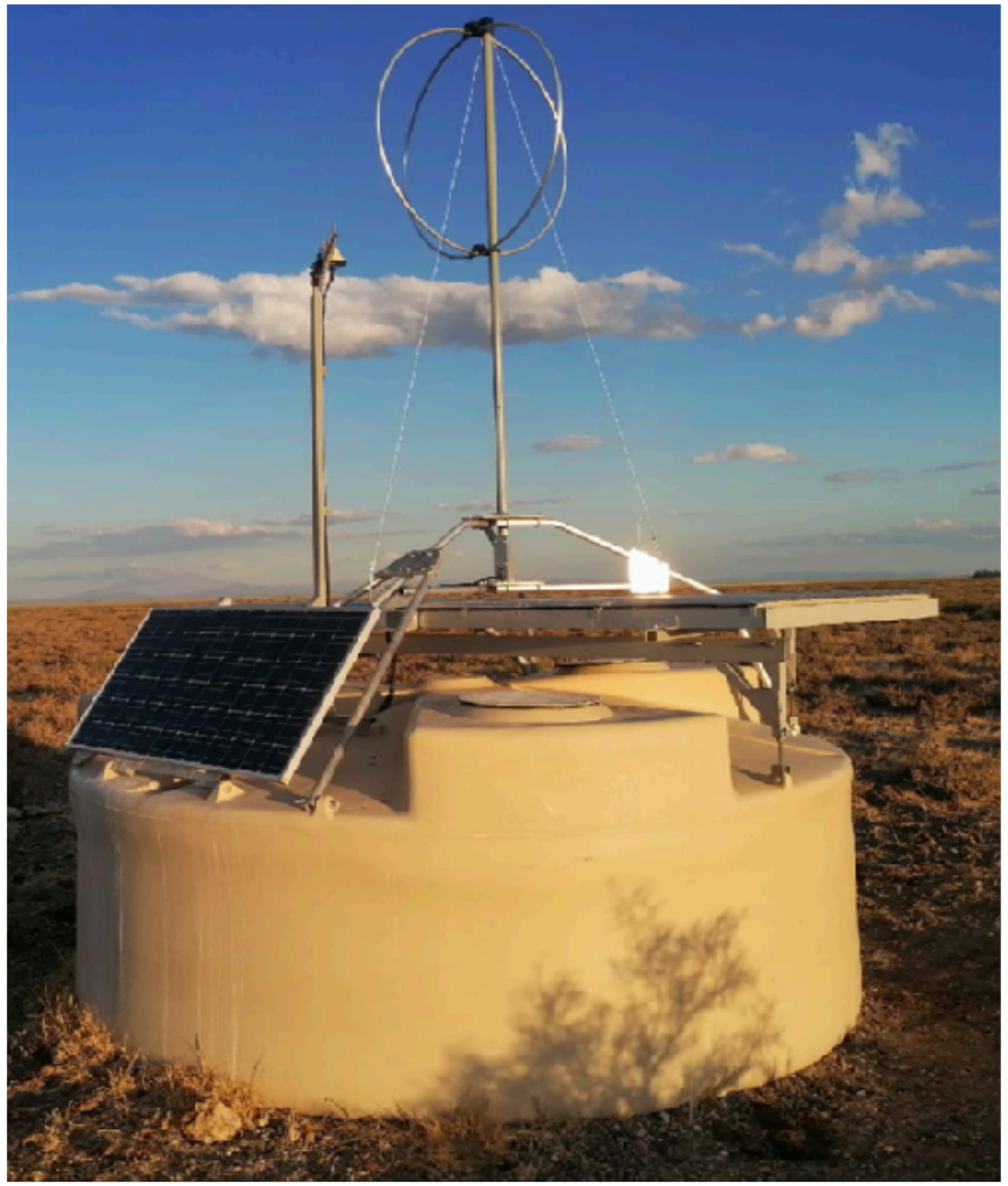
- WCD (UUB+SPMT) and SSD completed in summer 2023
- RD completed in December 2024
- UMD completion foreseen in mid 2025



➡ 1939 UUB delivered and working out of the 2000 ordered (+34 to be sent and 27 non working)

➡ 1480 SPMT working, only 31 missing (unaccessible regions).

➡ 1478 SSD, 10 without PMT, 31 missing (unaccessible regions).



AugerPrime in the field

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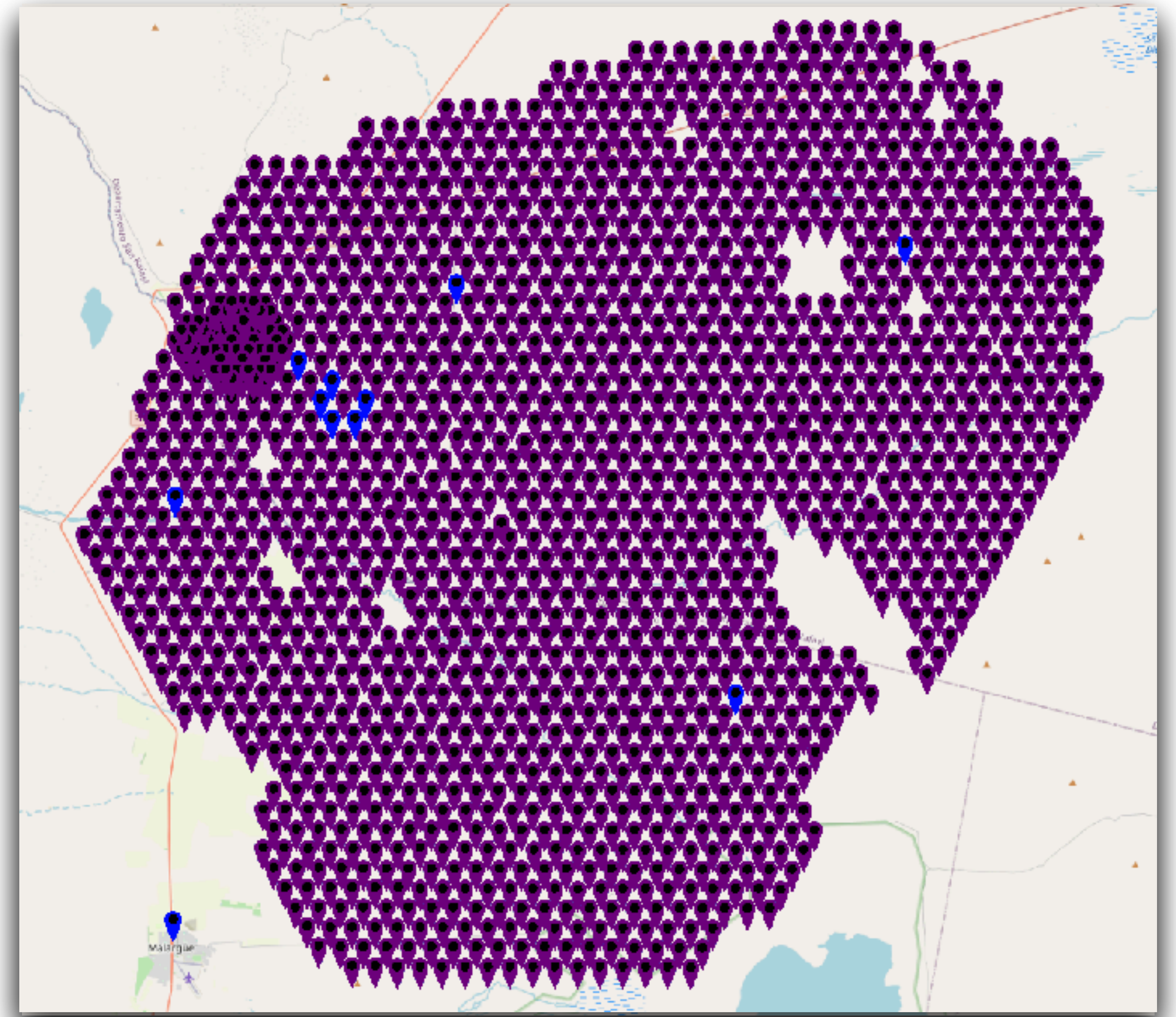
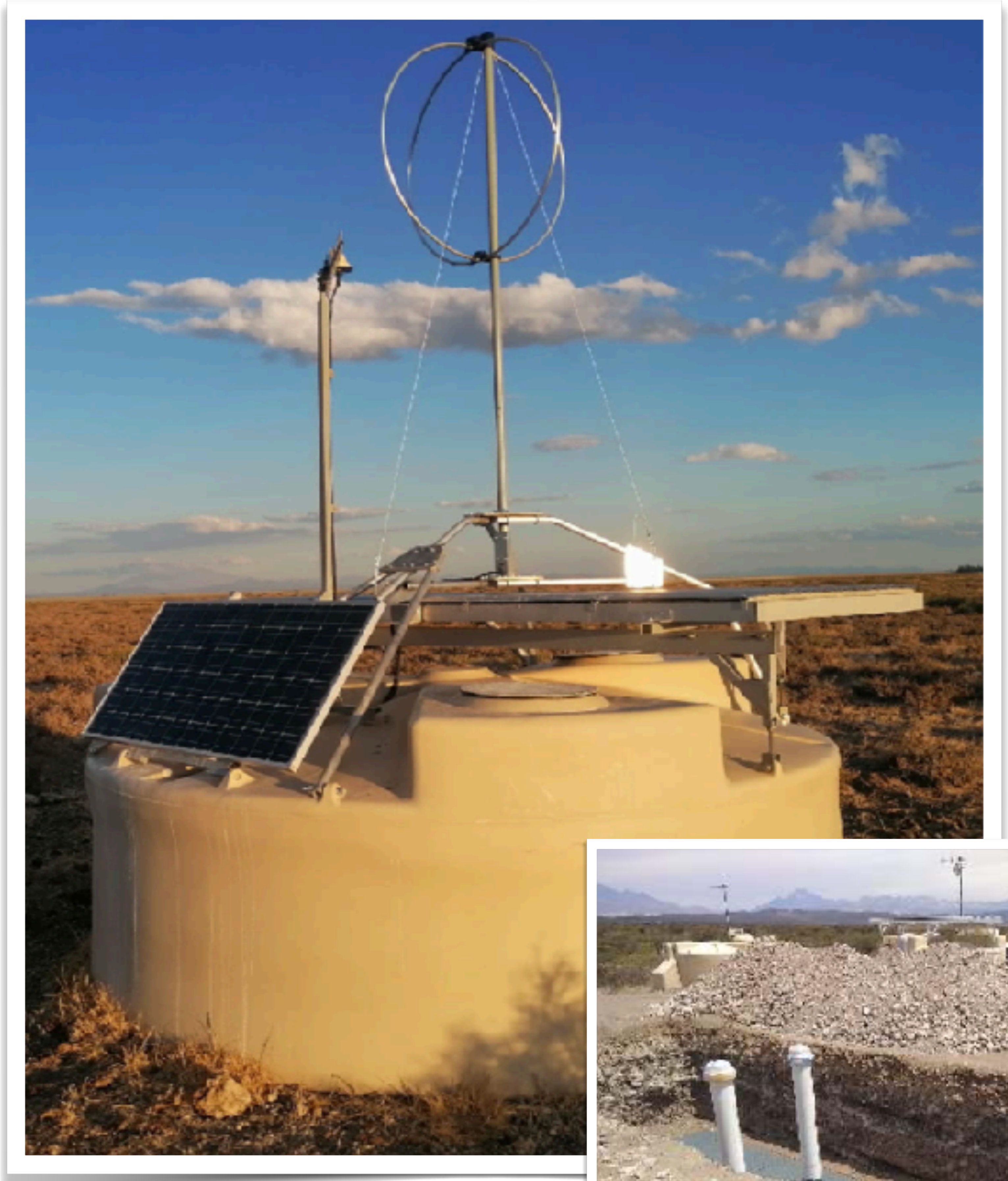


➡ 1605 antennas in place, with corresponding electronics

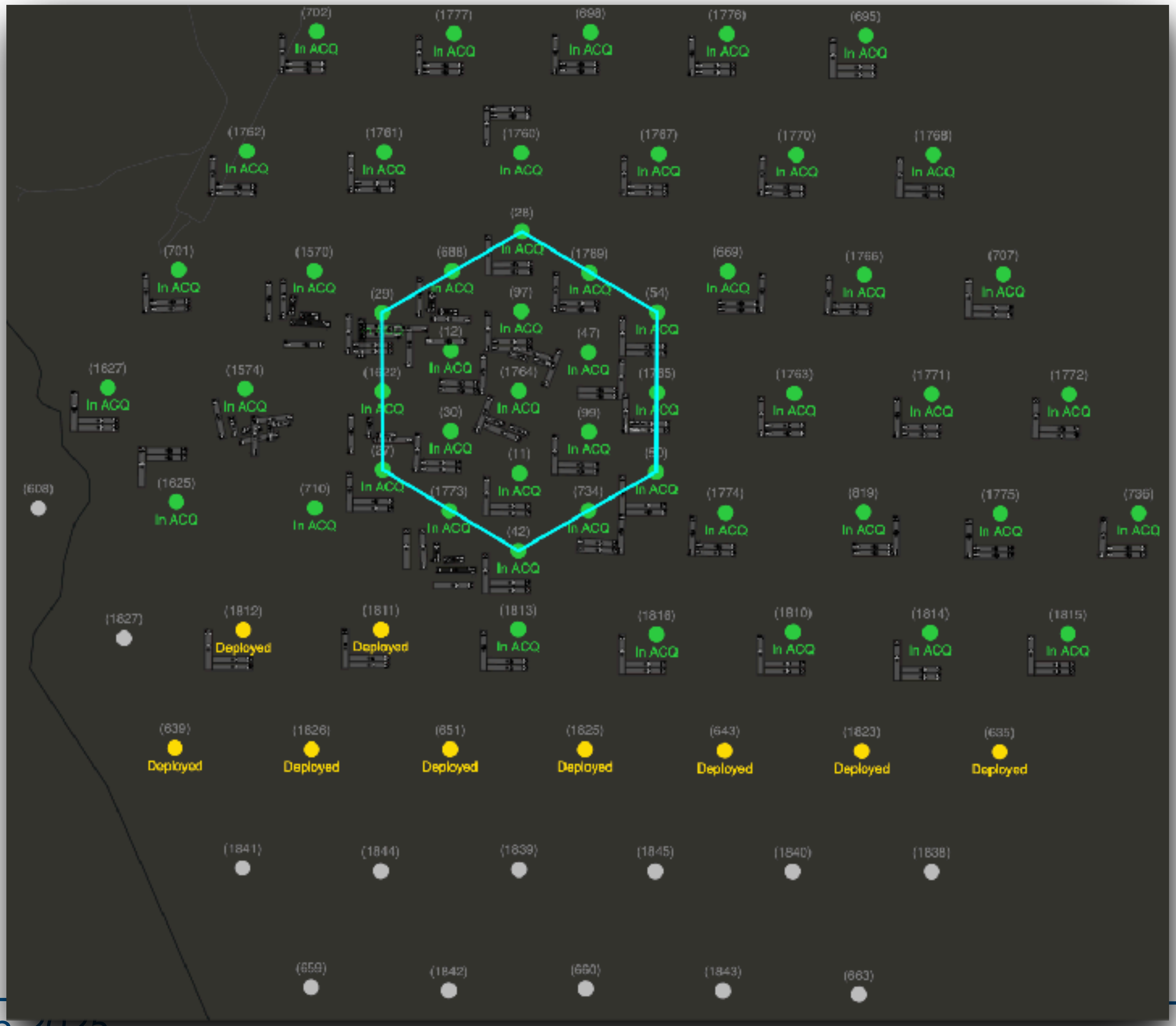
➡ Few positions missing, due to forbidden access, 12 without digitizer

➡ Commissioning ongoing



AugerPrime in the field

- WCD (UUB+SPMT) and SSD completed in summer 2023
- RD completed in December 2024
- UMD completion foreseen by 2025



➡ 100% of SD433 have UMDs

➡ 79% of SD750 have UMDs

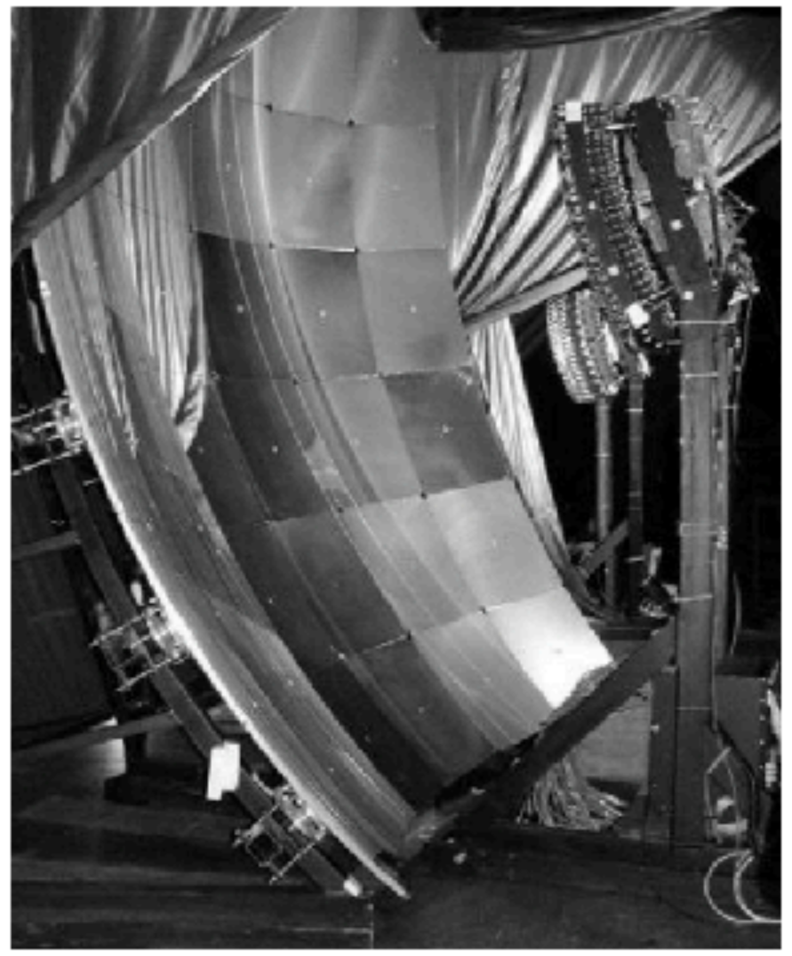
- 13 positions (39 modules) still to be deployed
- Second batch of scintillators arrived in Malargüe

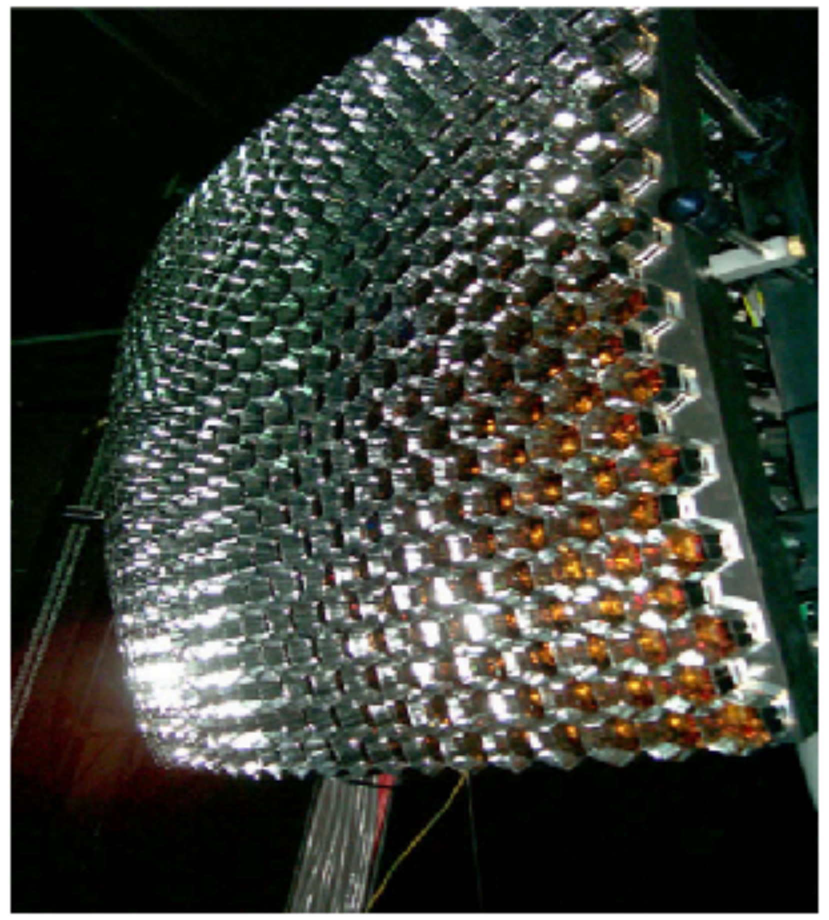
FD in AugerPrime

24+3 telescopes

$\sigma_E/E \approx 8\%$ $\quad$ $\sigma_{X_{max}} \leq 20\ g/cm^2$

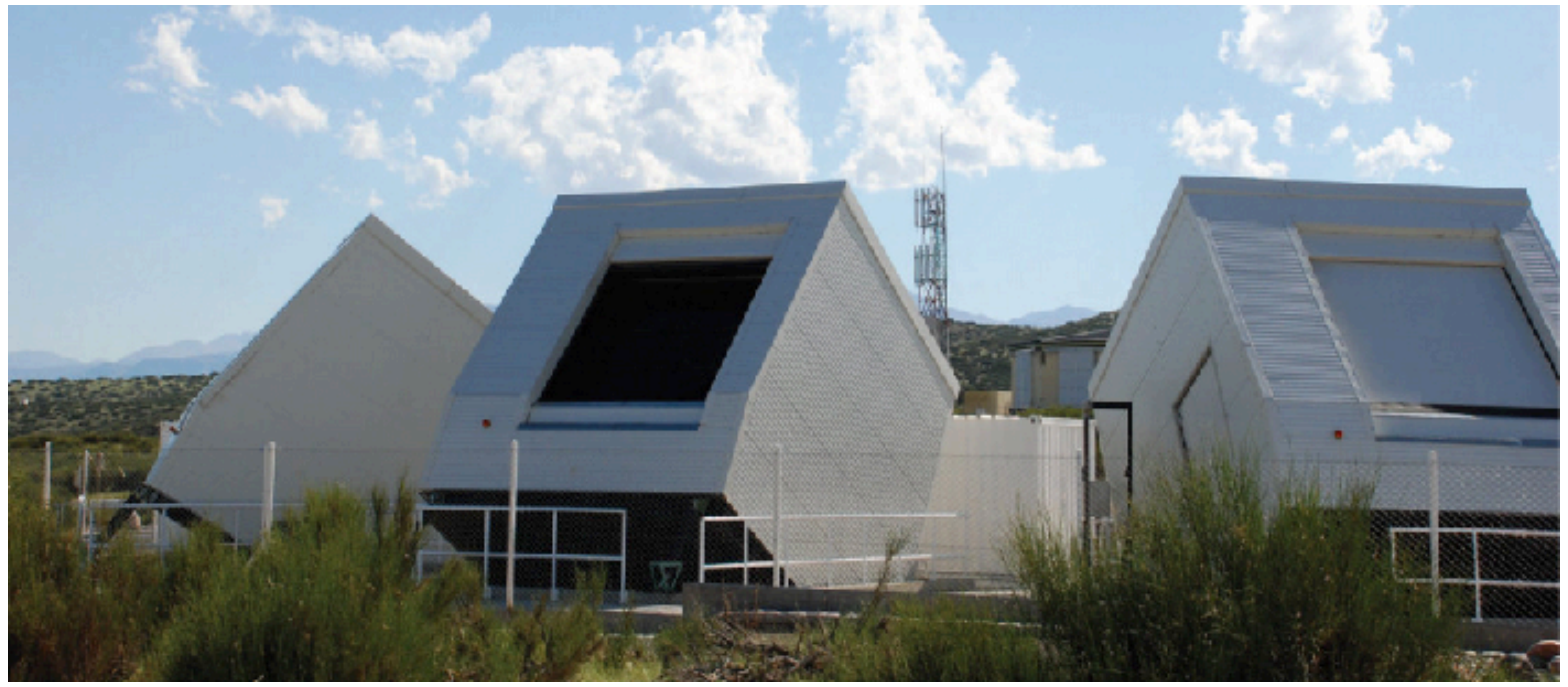
$\Delta_{sys} \approx 15\%$ $\quad$ $\Delta_{sys} \leq 10\ g/cm^2$



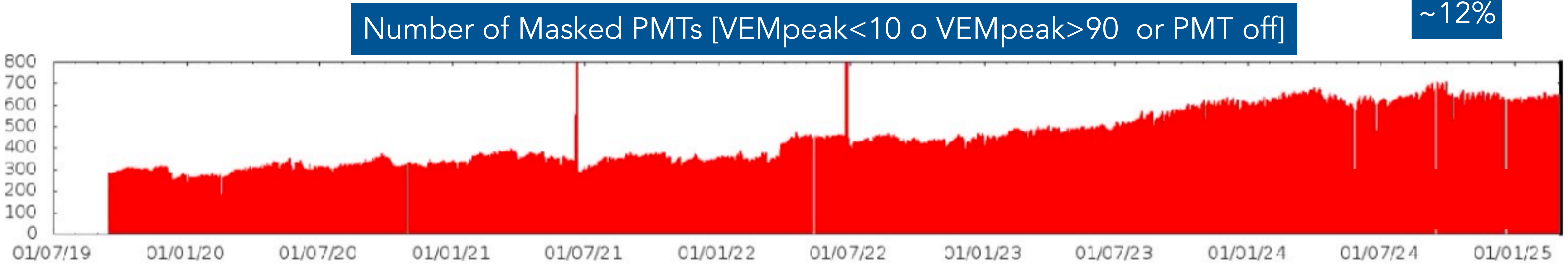


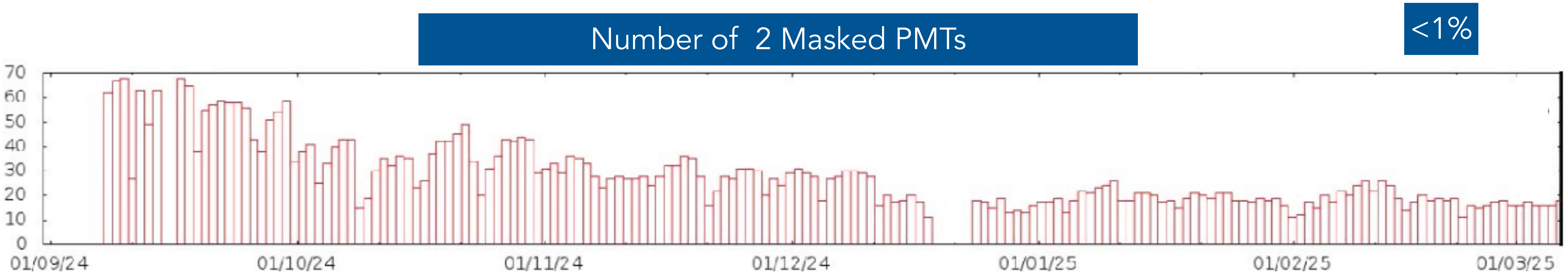
- energy and X_{max} scale provided to the Observatory
- most powerful evaluation of $<X_{max}>$ and $\sigma(X_{max})$ up to ~$10^{19.5}$ eV
- stereo measurements to evaluate X_{max} resolution and study the systematics
- Independent cross-checks for
  - energy calibration with Radio
  - $<X_{max}>$ and $\sigma(X_{max})$ from SD (DNN) and Radio

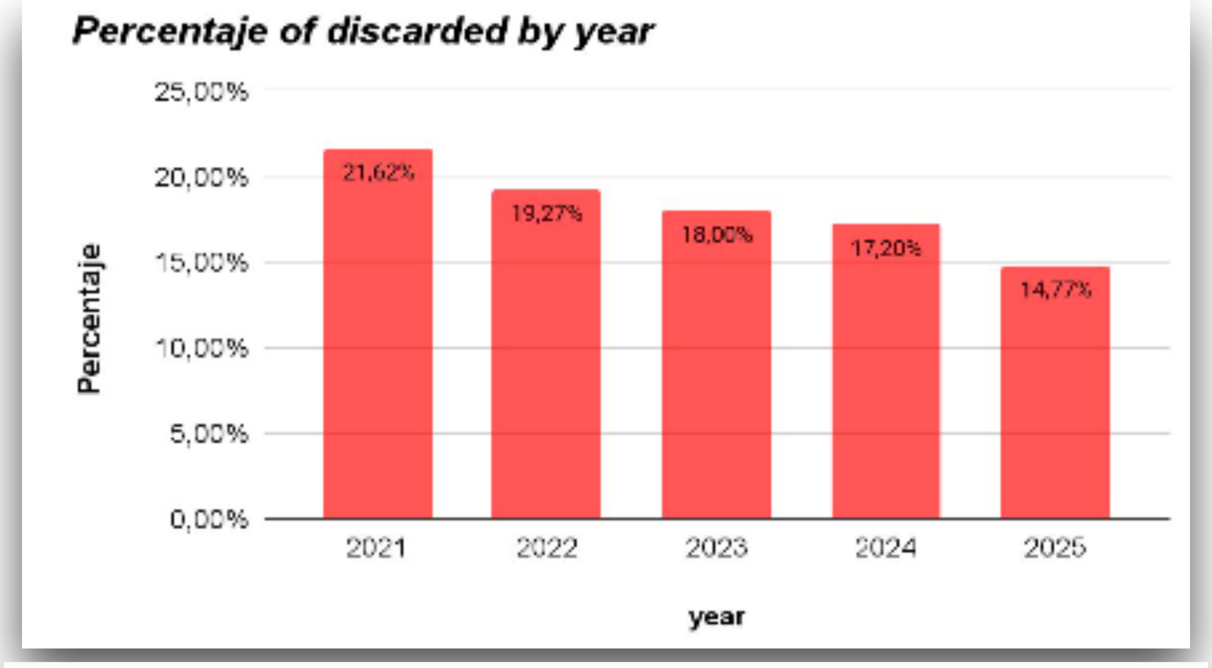
FD contribution in different analyses [μ excess with inclined and LE showers, up-going showers, anomalous profiles, …]



Maintenance





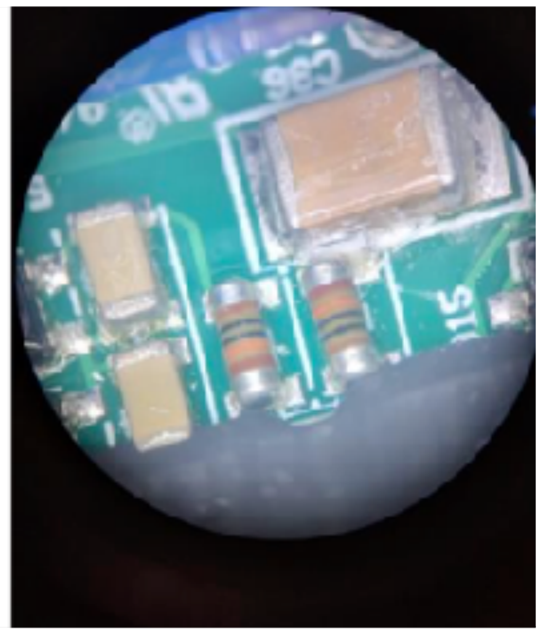


Large PMTs (3 x 5000) [IT/Torino, FR/Orsay + help from CZ/Prague]

- ~100 PMT changed /year in the past, now doubled : ~balance between failure and recovery rate
- % discarded/year decreasing mainly thanks to new procedure to recover corroded pins
- Decreasing PMT stock

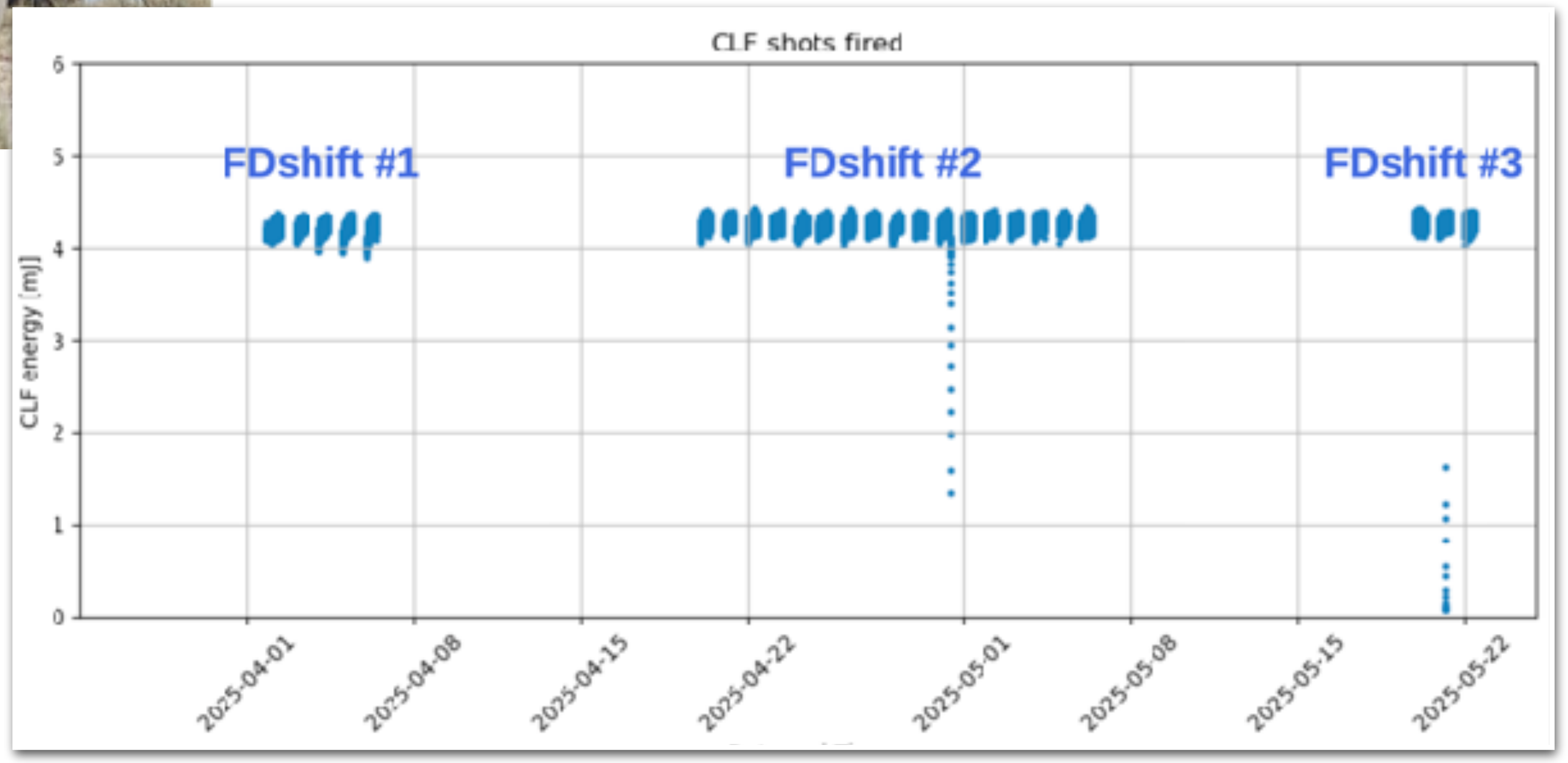
Bottleneck : SensTech HVPS

- ~120 Sens-Tech HV modules repaired in 2024, ~180 waiting to be repaired
- Purchase of new modules: quotation ~260 €/cad for at least 250 (5% decrease from 100 units)
- SensTech only provider - problems with past purchases after pandemic



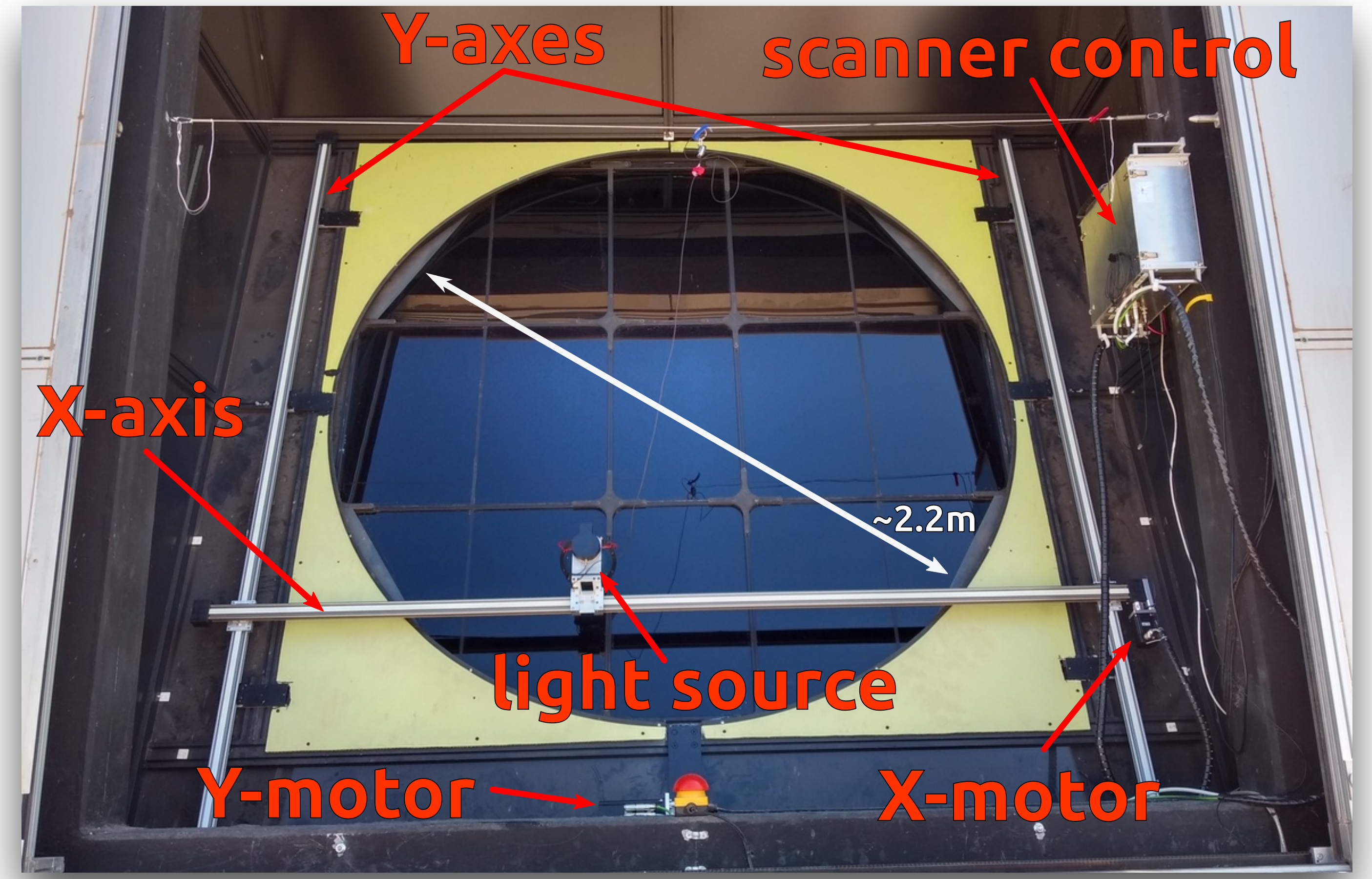
Maintenance

CLF stably running
(After 2 campaigns in November 2024 and March 2025)
XLF stably running



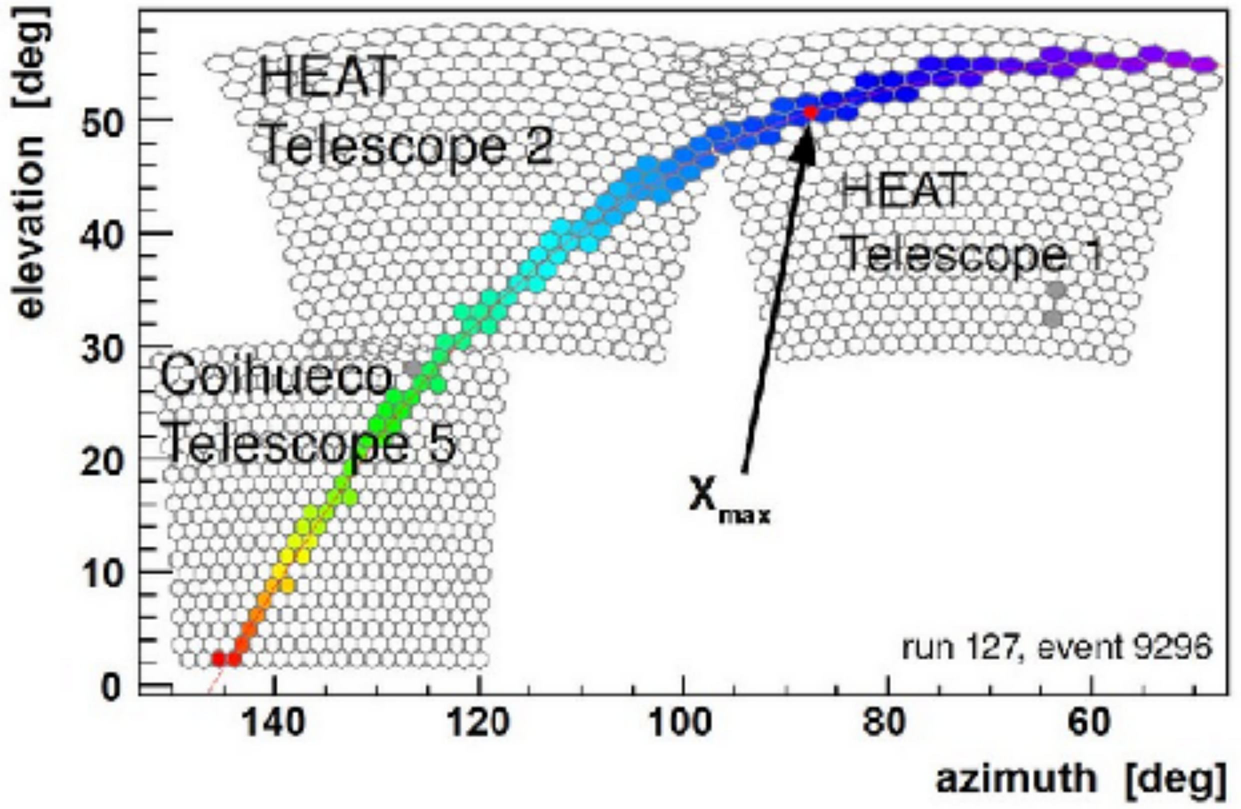
Raman Lidar and LA Lidar working fine
CO LIDAR PC replaced end of March
LL : spare HV/LV boards (CAEN A1738) will be provided by Catania group

Very active ***common working group of Calibration & Foundation***



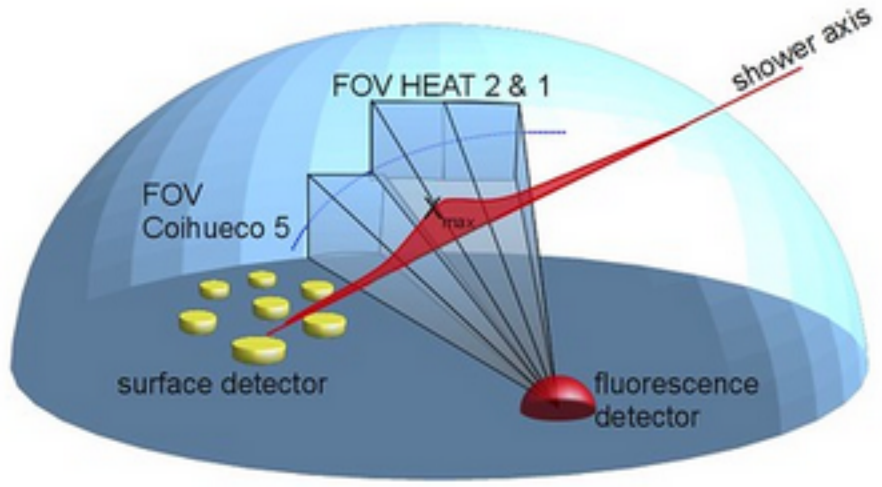
Absolute calibrations updated as of July 2024

X-Y scanner : differences with CalA are investigated

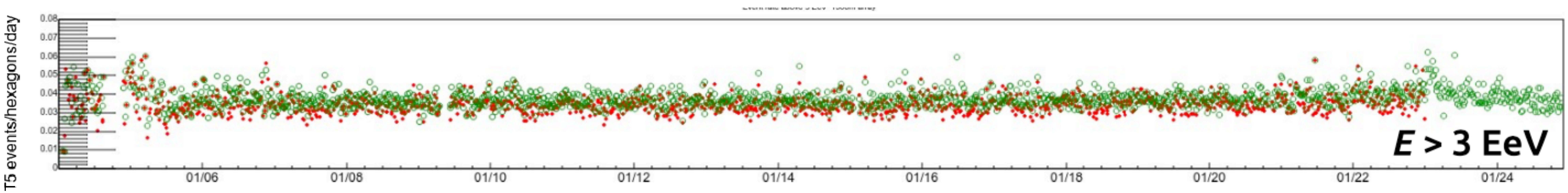


HEAT-Coihueco intercalibration

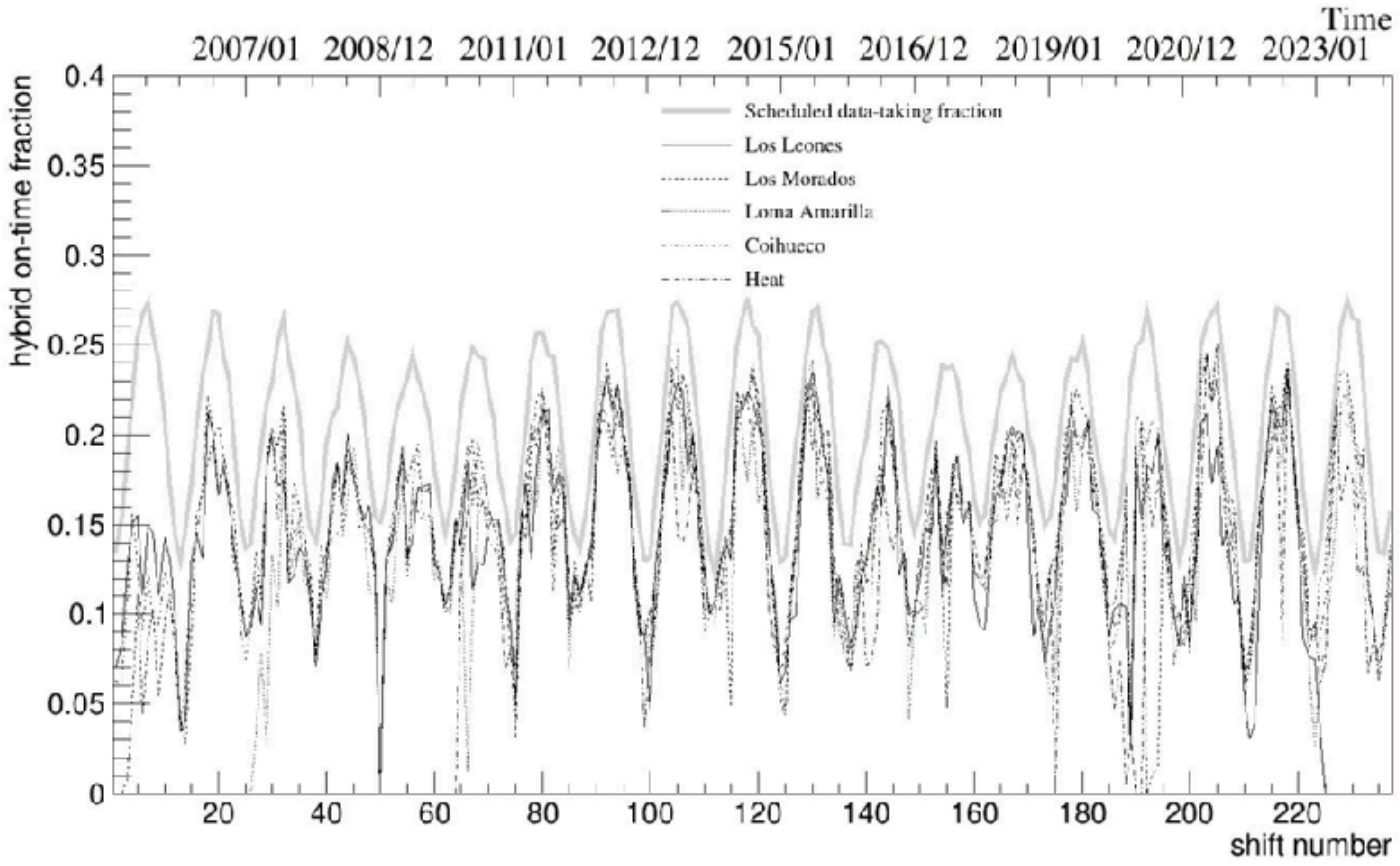
HEAT downward for a precise measure of the cross-calibration factors



Performance of data taking



- Two SD shifts/month online
- More than 300 FD shifts (15-20 days each), mostly on site + remote (20 remote rooms)



The largest worldwide exposure:

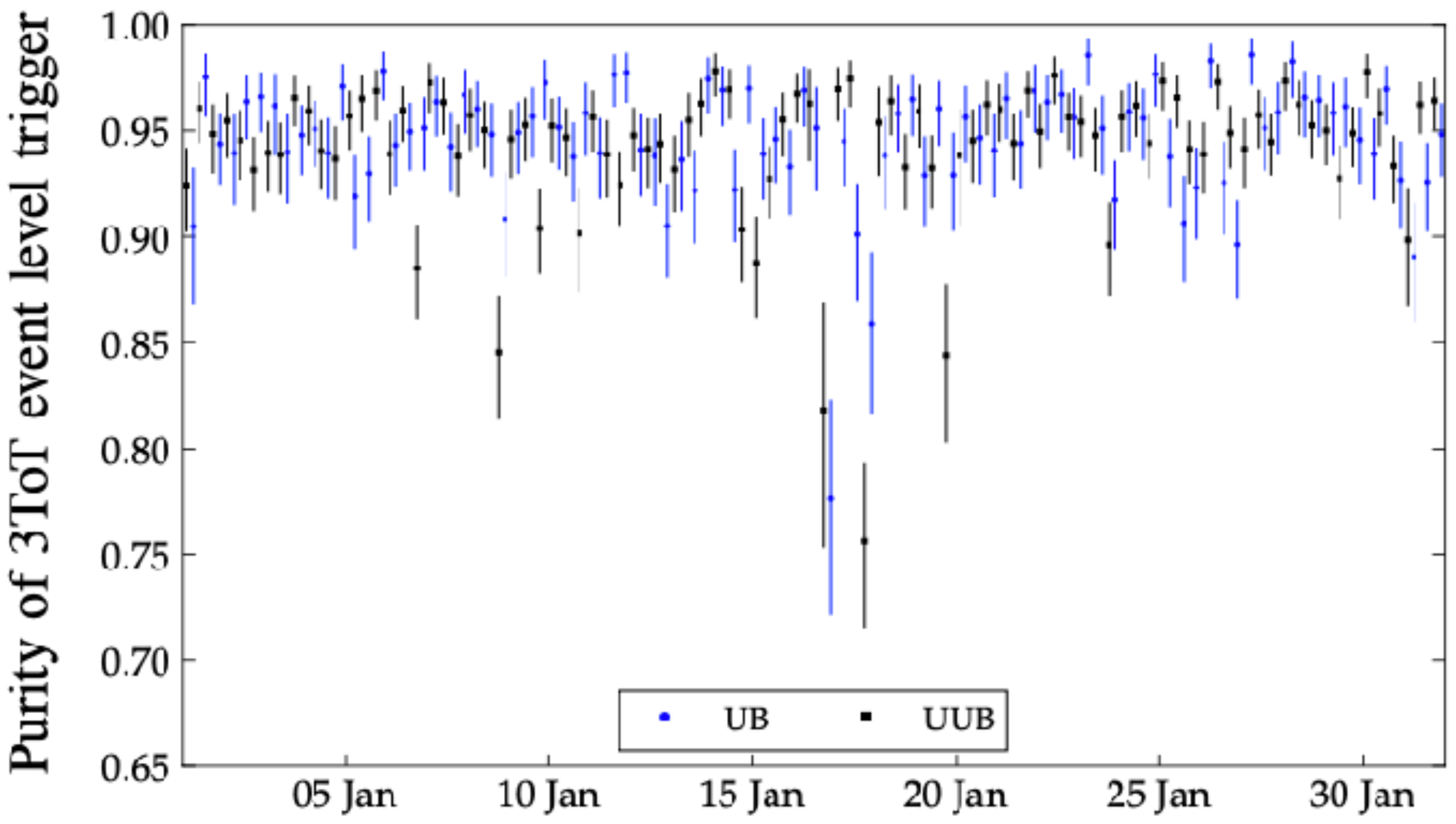
➡ ~105,000 km² sr yr for the measure of the spectrum by SD

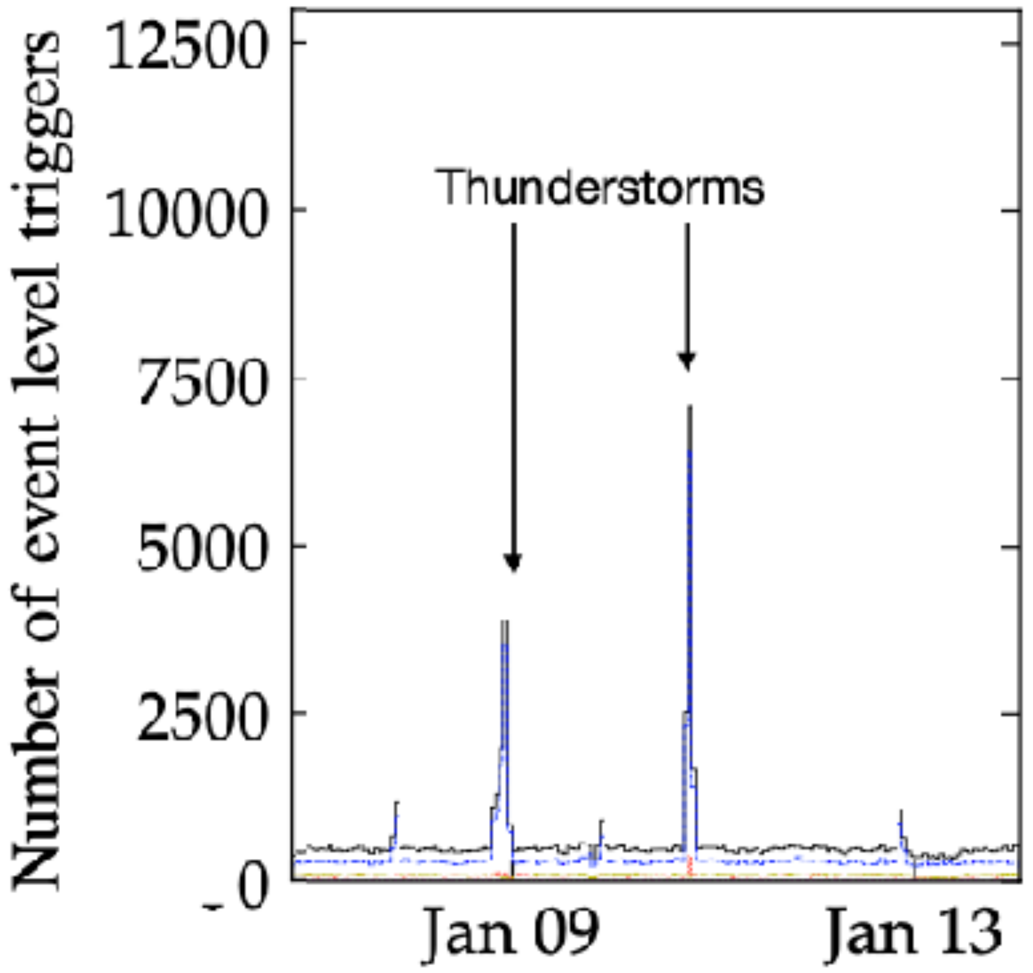
➡ ~ 5,000 km² sr yr for the measure of the spectrum by FD

➡ ~135,000 km² sr yr for the search of anisotropies

Commissioning of AugerPrime [“bring (something newly produced) into working condition”]

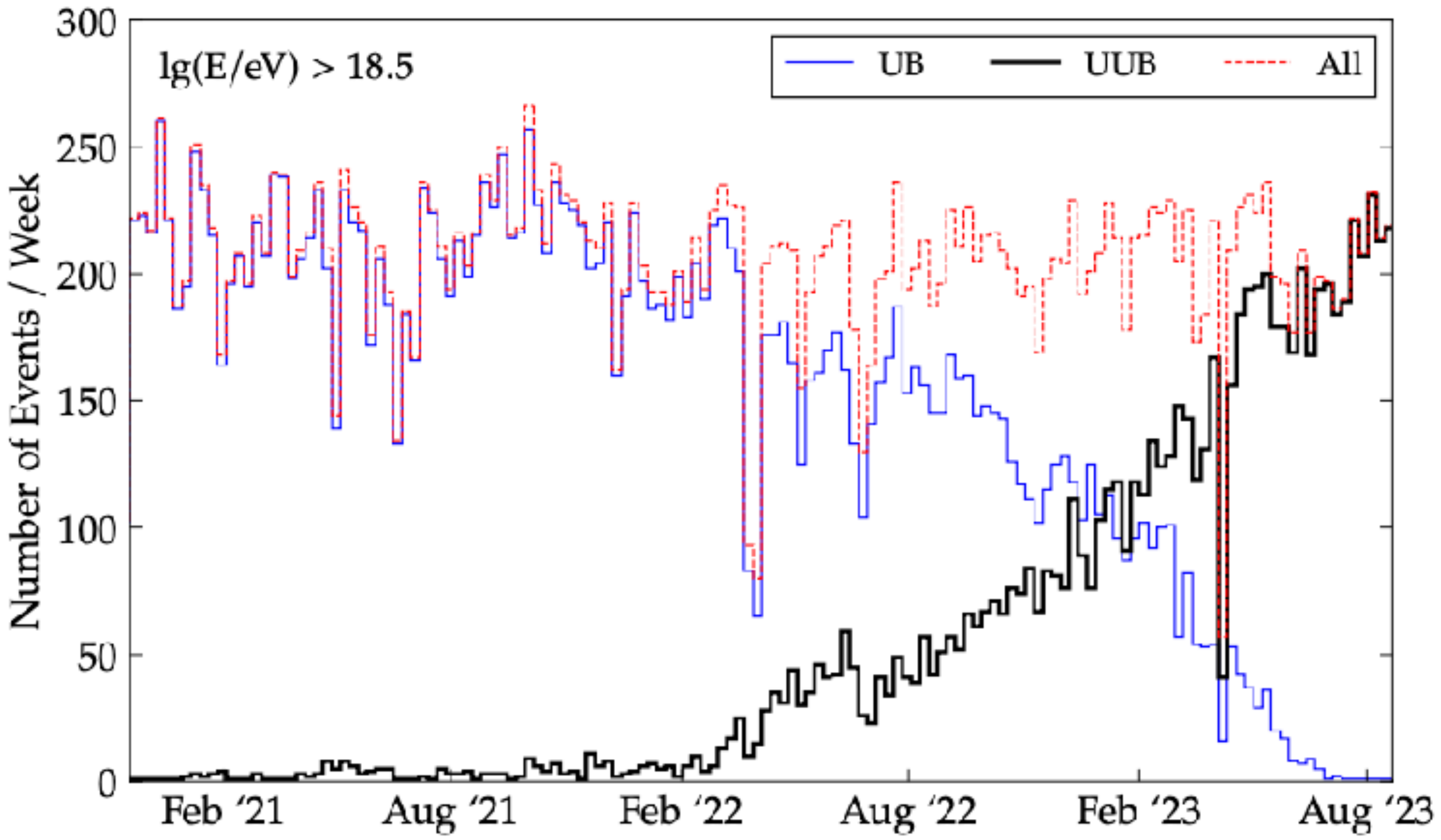
- Methods used for Phase I daily monitoring have been adpted to Phase II data
- Currently operating in compatibility mode with Phase I
- Purity of event-level triggers same as in Phase I
- *Over 99.9% of events (satisfying EAS triggers) can be reconstructed*
- Due to higher UUB sensitivity, bursts at station level appear during lightning periods: estimated 5% exposure loss/year





Currently finalizing
- Alarm settings
- Commissioning of triggers and calibration procedures
- Data processing anf reconstruction pipelines

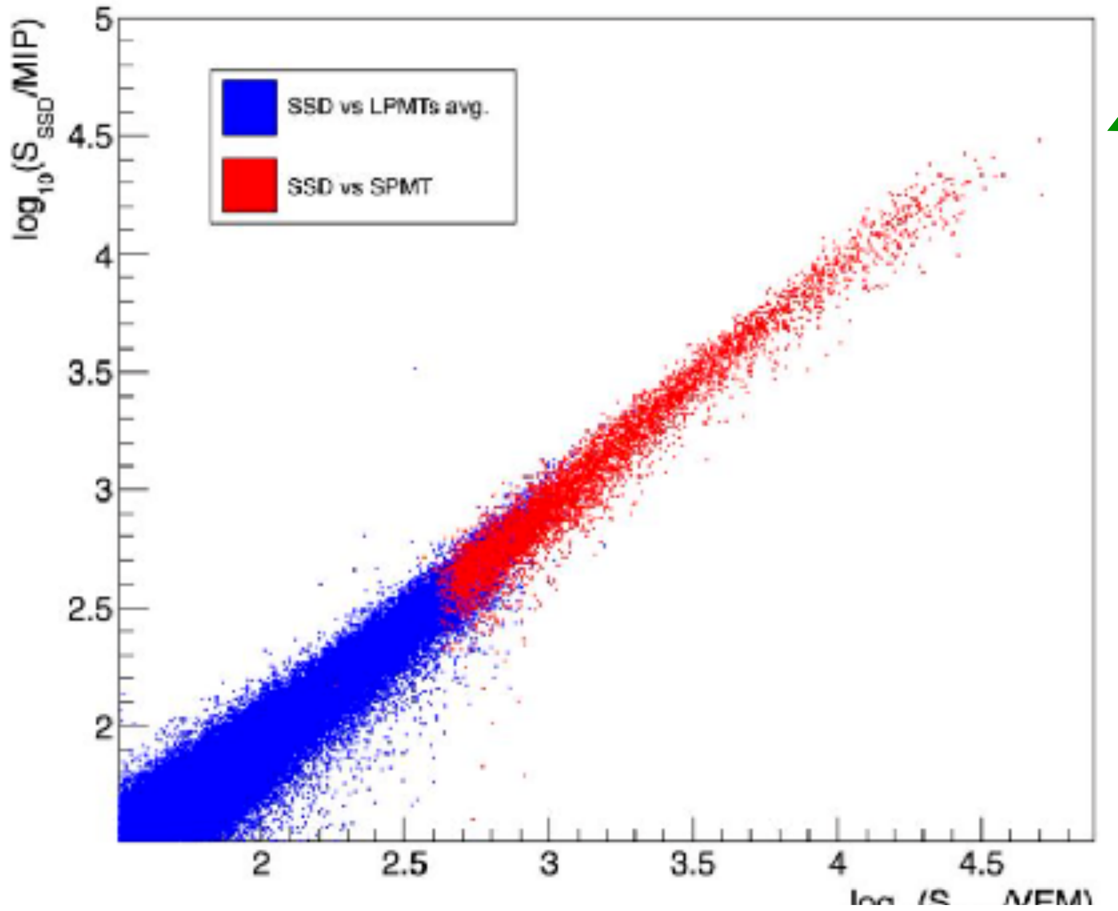
First analyses of physics quantities ongoing

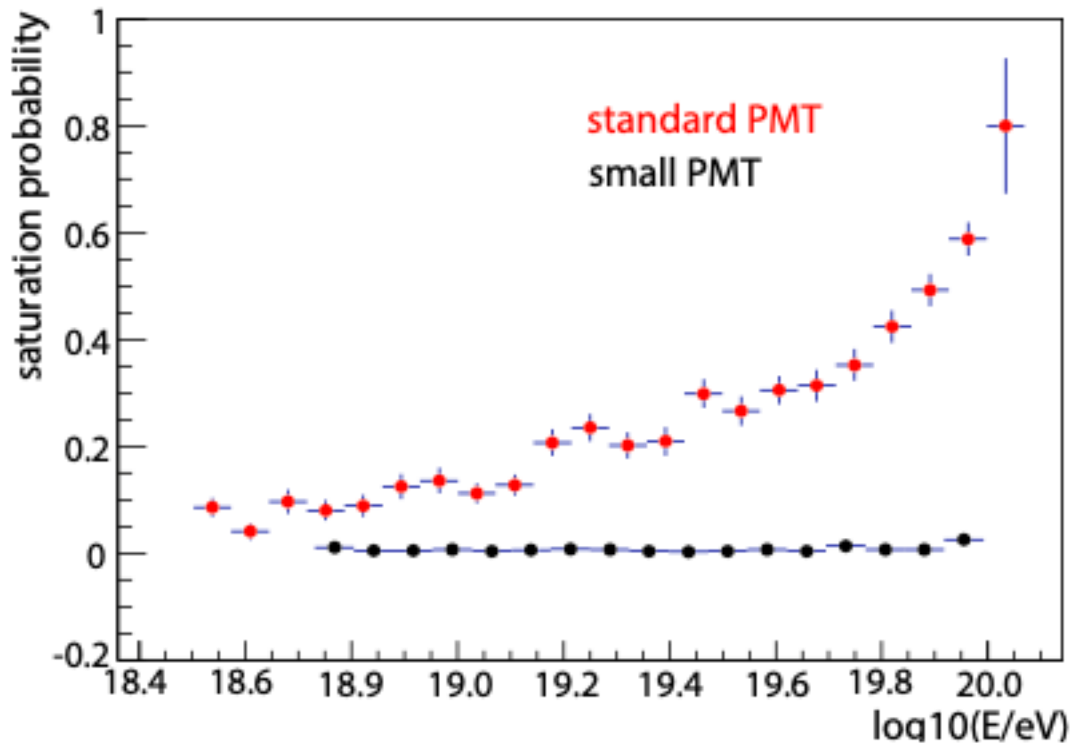


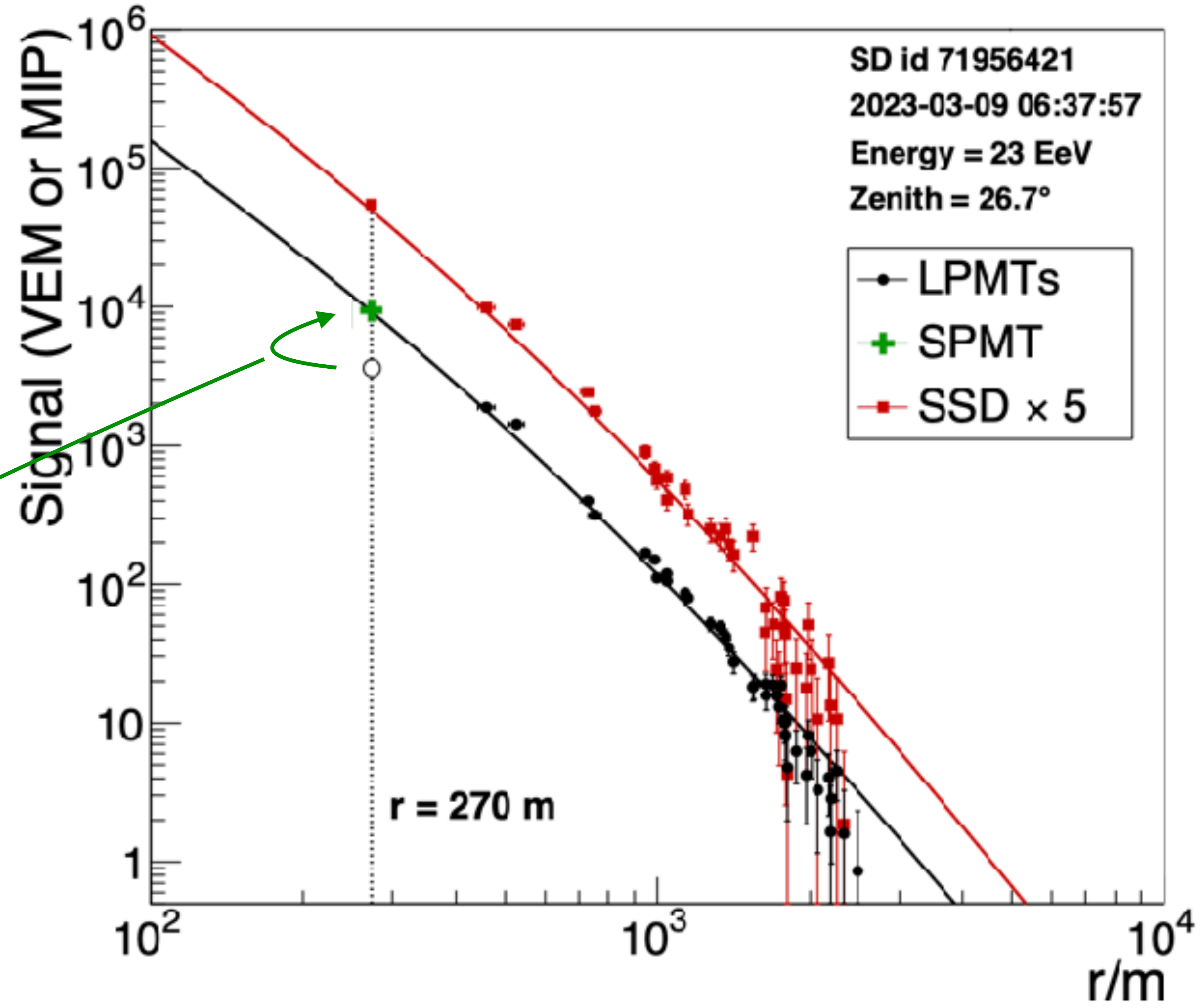
Commissioning of AugerPrime [*"bring (something newly produced) into working condition"*]

Dynamic range extended to >20,000 VEM thanks to the SPMT

Matched by SSD employing a highly linear PMT, gain-ratio set to 128

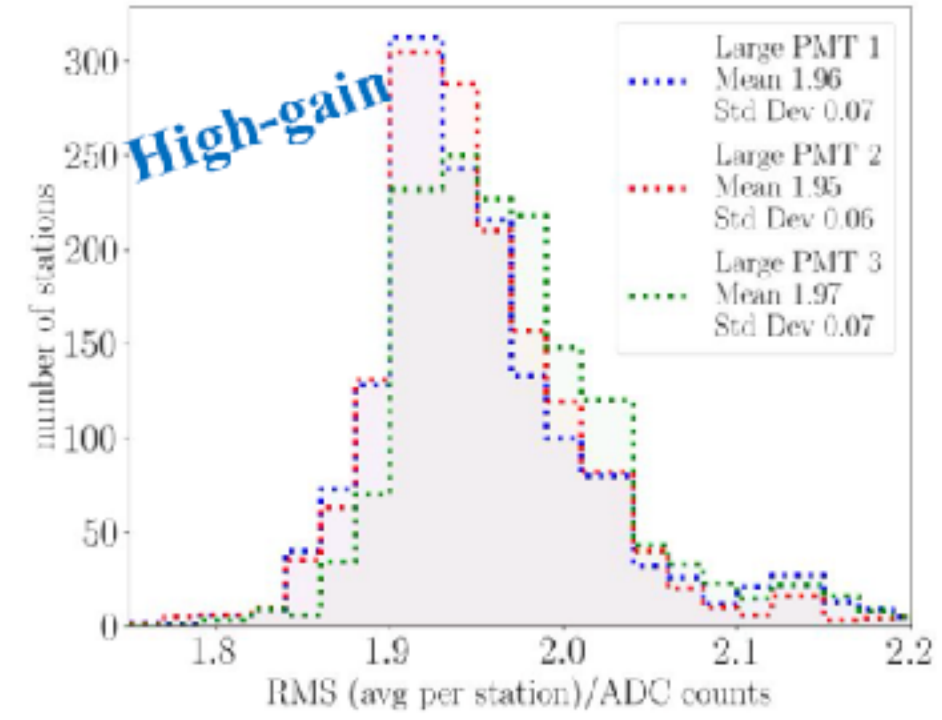


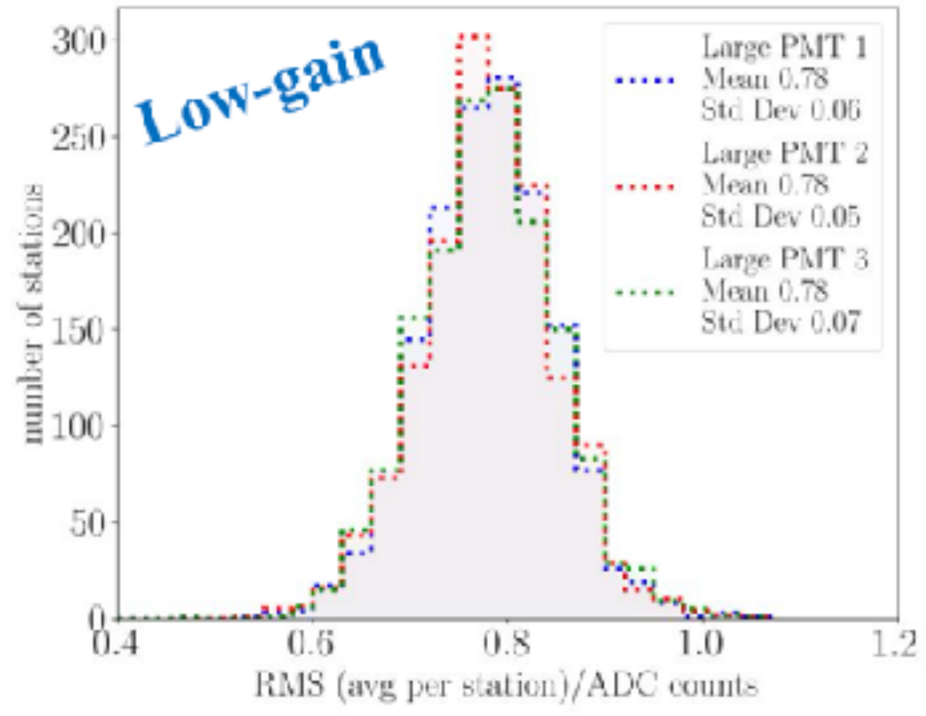




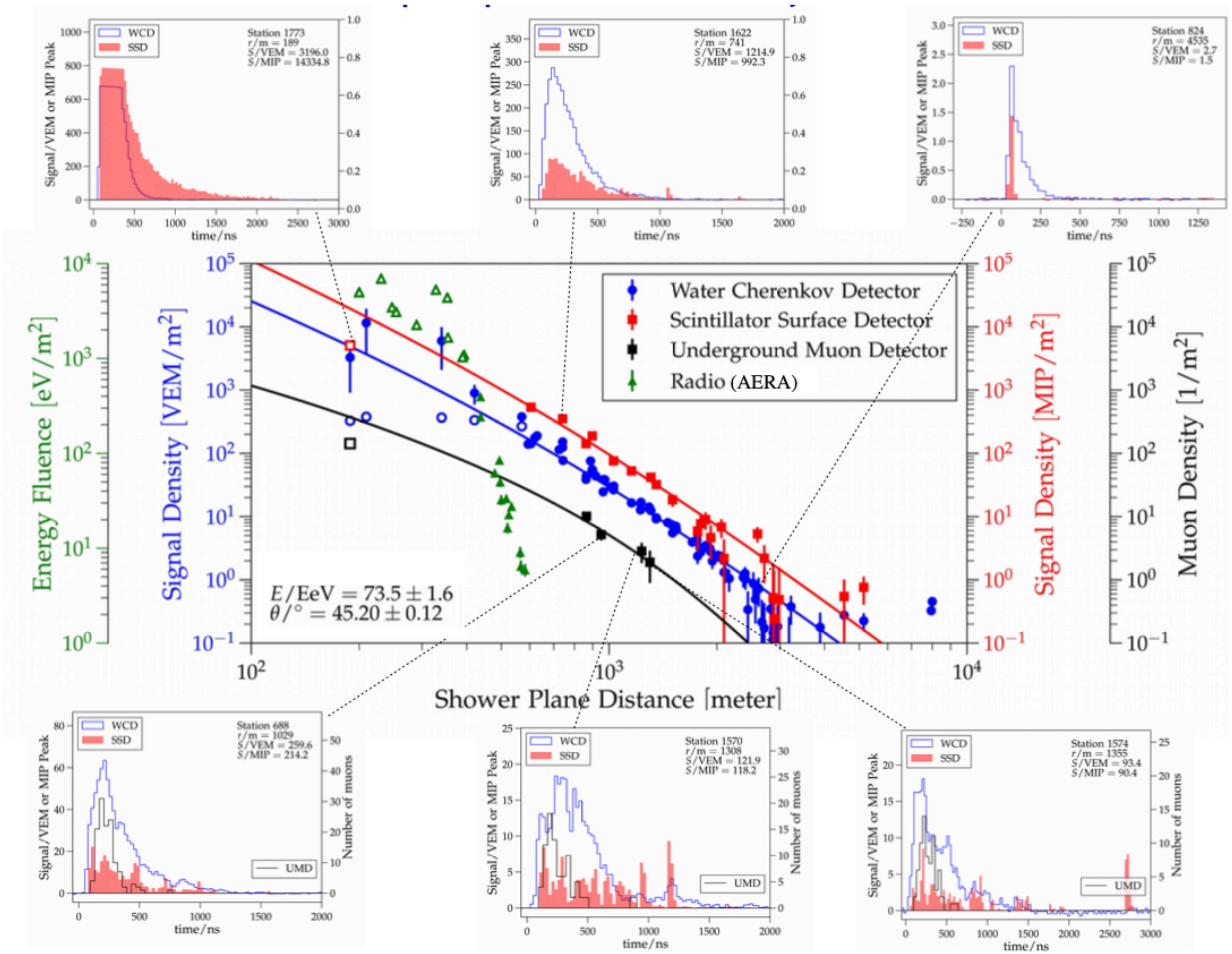
GPS timing accuracy measured
- in lab ~2 ns
- in the field ~ 5ns

Noise :
- HG channel ***<2 ADC counts***
- LG and SPMT channels <1 FADC count





AugerPrime - one multi-hybrid event



- Commissioning is ongoing
- It has to be strictly linked to maintenance
- The monitoring is fundamental

Publications

➡ ***SDEU: AugerPrime Surface Detector Electronics*** [JINST 18 (2023)]

➡ ***SSD:*** [submitted to JINST, 2025]

➡ ***UMD***: [JINST 16 (2021) T07008 nd P01026, JINST 12 (2017) P03002]

➡ ***RD***: in preparation

6 Contributions to ICRC2025

- UMD results
- RD Reconstruction
- Status and first results
- CDAS
- Electronics
- RD status

More info

Staff

Staff hired for AugerPrime (UUB, RD) completed their task

- 3 will remain in staff
- 1 payed from AugerPrime budget for 2025

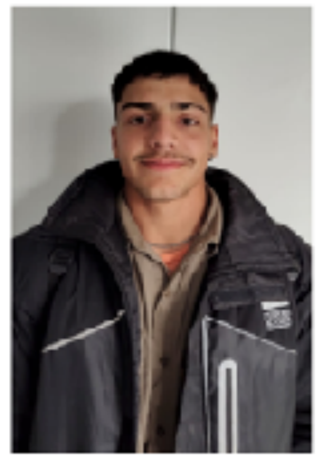
2 technicians from CNAE, part time

22 interns from Isazky School

Gabriel Díaz

Matías Rojas

Neiber Castro

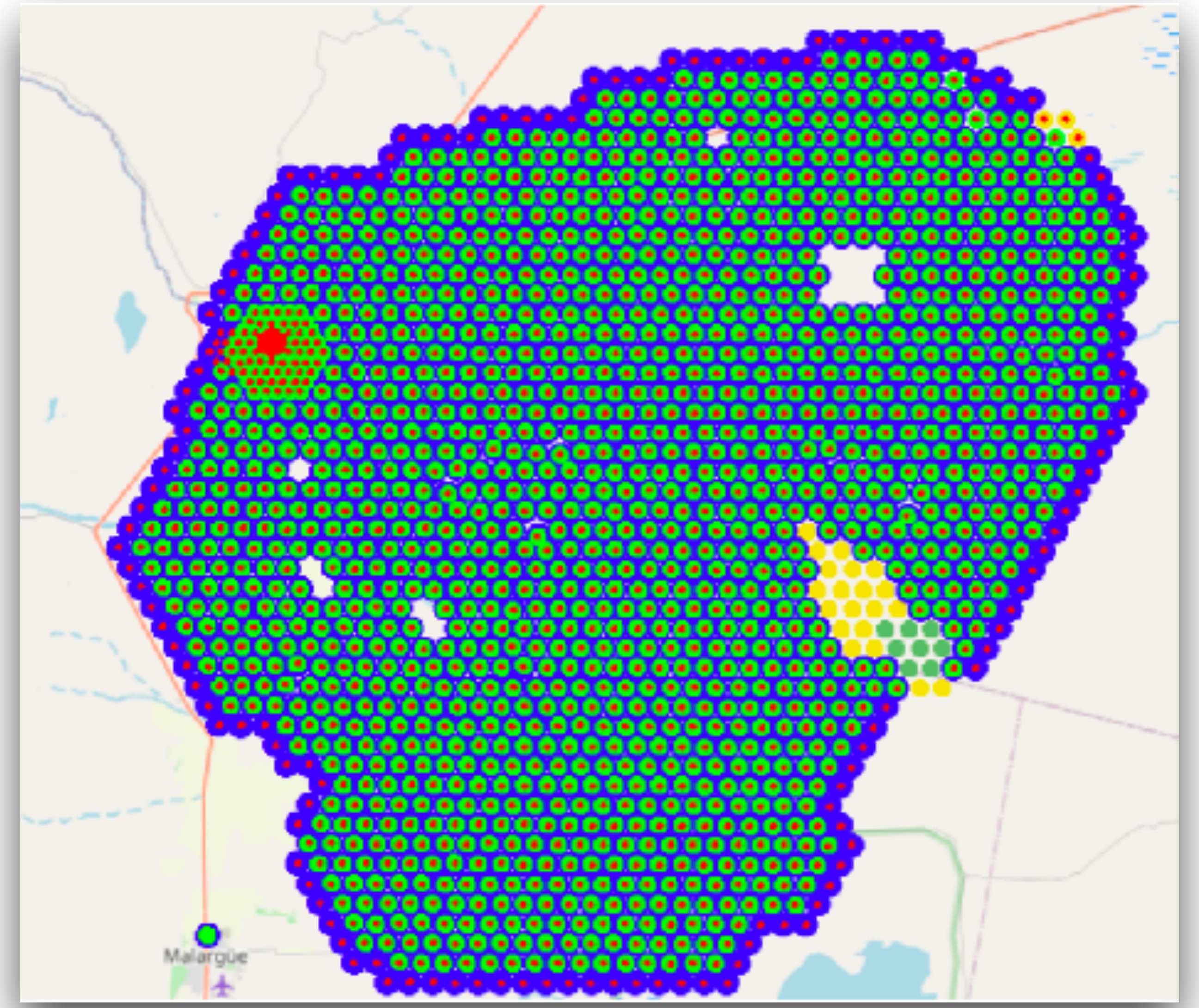


Sebastián Villar

New FD observer
Yosel Balibrea

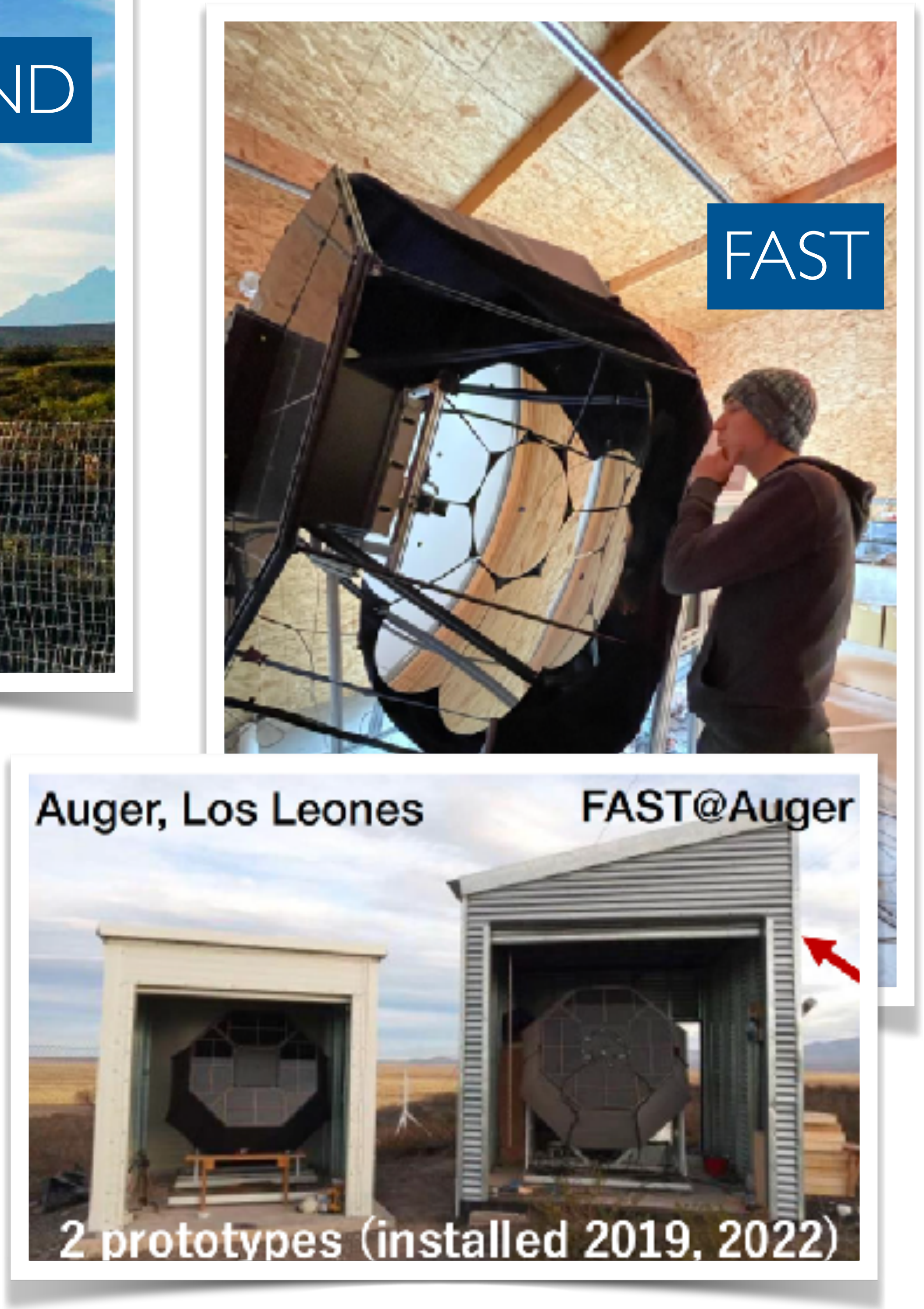
New computing expert
Juan Pablo Behler

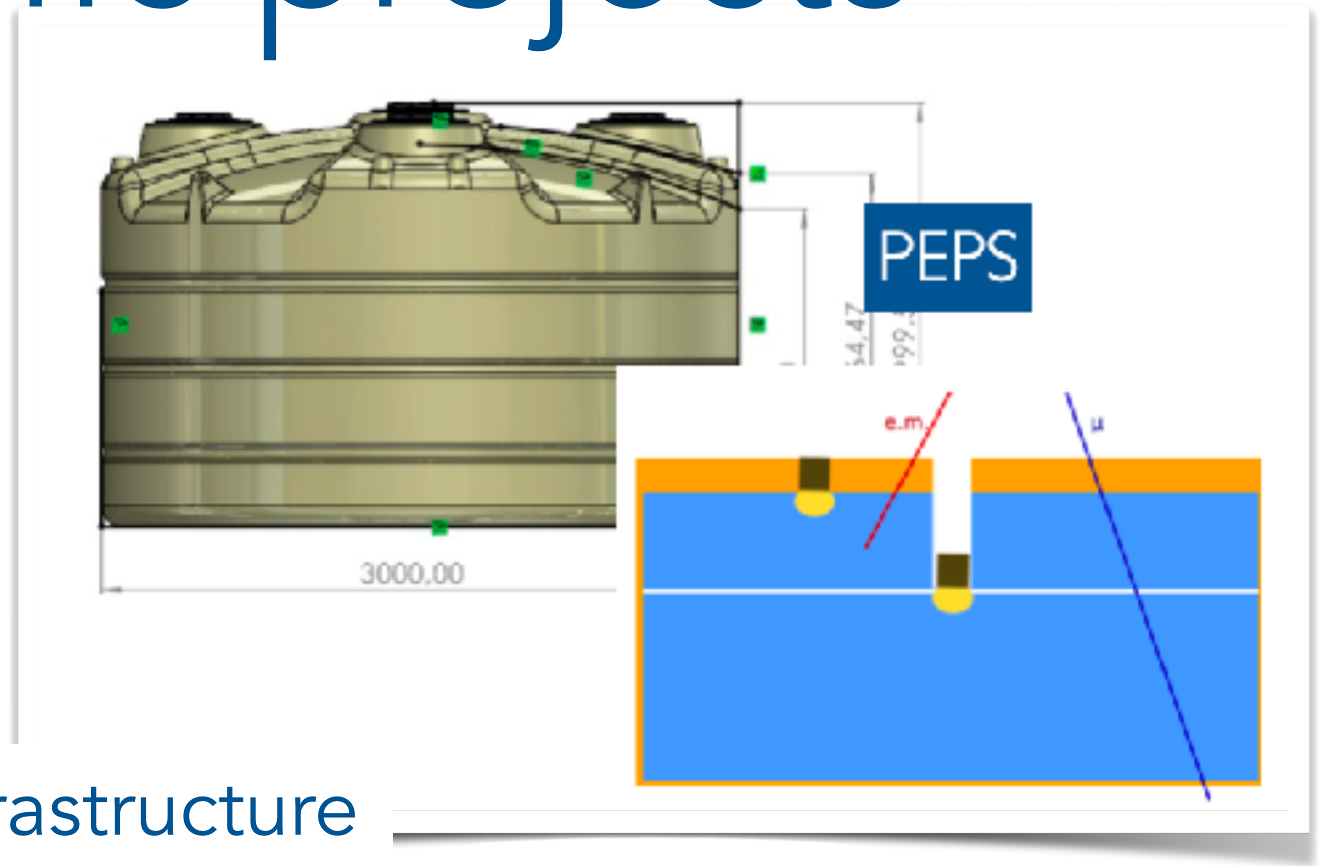
Landowners



Only 1 conflict on 101 properties
almost all renewed to cover AugerPrime data taking period
~20 USD/WCD/yr and ~400 USD/FD/yr

Auger as an infrastructure for other scientific projects





Pierre Auger Observatory: unique infrastructure providing deployment expertise from the local staff, good communication systems, a multitude of detectors for comparison of all techniques, a perfect playground!

A very welcoming environment for cross-calibration and testing detectors

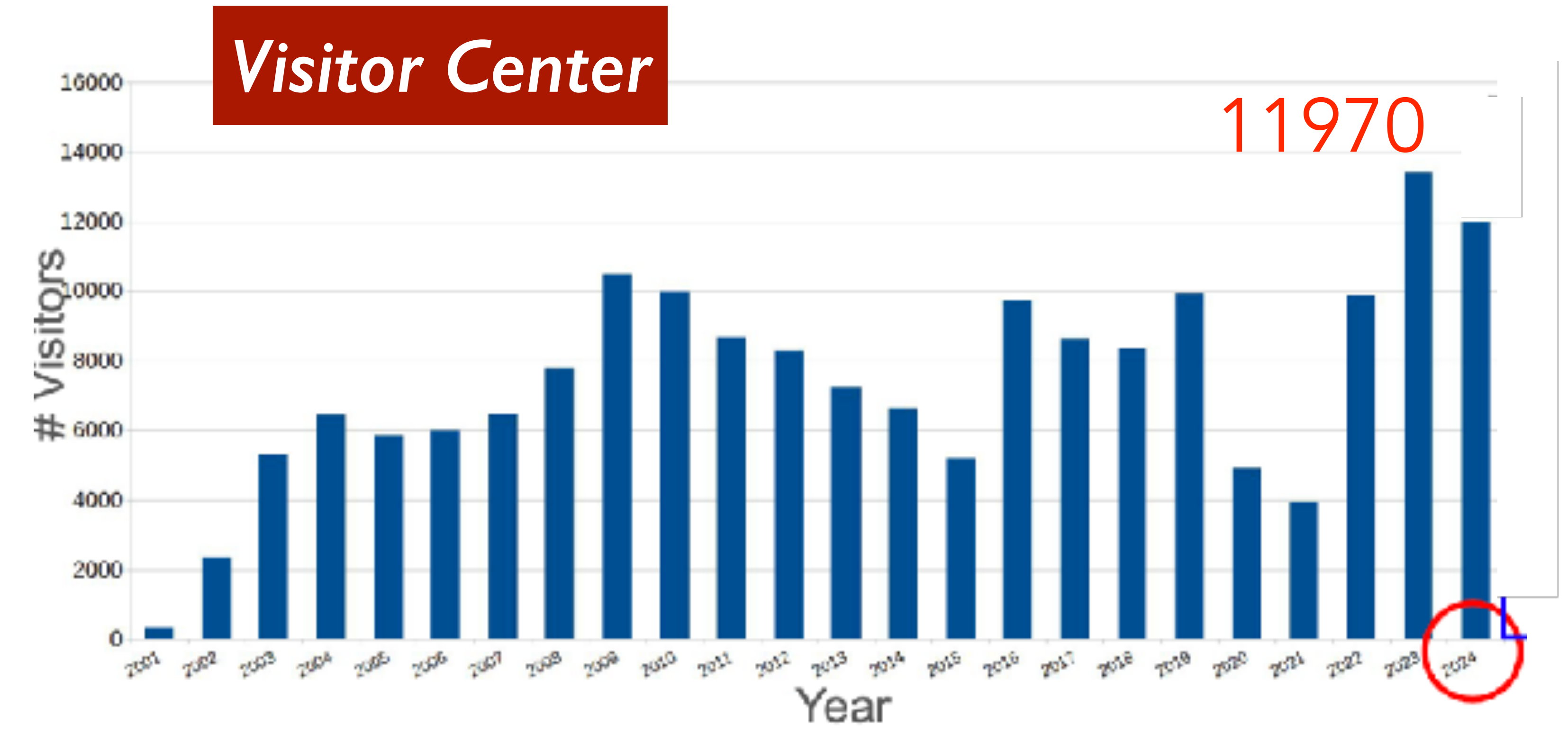
Excellent opportunities to learn from each other and test new ideas

…Andes Neutrino Telescope

Socio-economic impact of Auger

Local environment

- Close relation with municipality of Malargüe
- General public talks
- Visitor center (almost 12000 visits in 2024)
- Auger seat in the Strategic Planning Commission of Malargüe
- Ordinance for protection of night skies

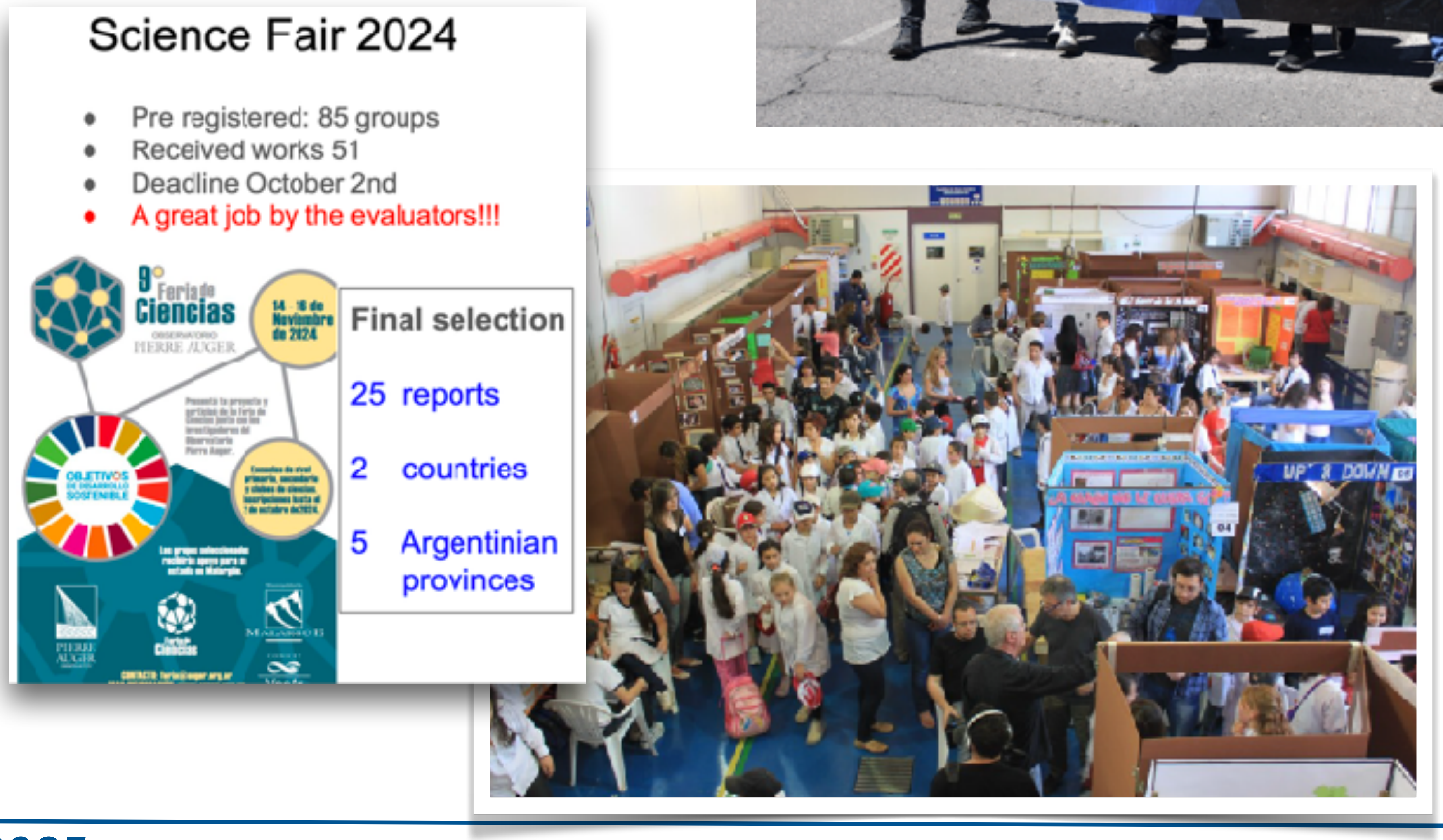


Landowners

- 101 owners, almost all contracts already extended to 20235
- Small increase in payment (20 USD/yr for WCD, 400 USD/yr for FD)

Science

- 140 papers
- Interdisciplinary researches (solar and atmospheric studies)
- Training: 419 PhD students, 27 double degree PhDs
- Infrastructures for other projects
- Technical training (Iszacky school)
- Science Fair



Economic impact

- >90% of operational budget is spent in town
- Use of Convention center
- Power line also used by local landowners
- Wi-fi provided to remote land inhabitants
- Donations to local schools

Outreach and Education

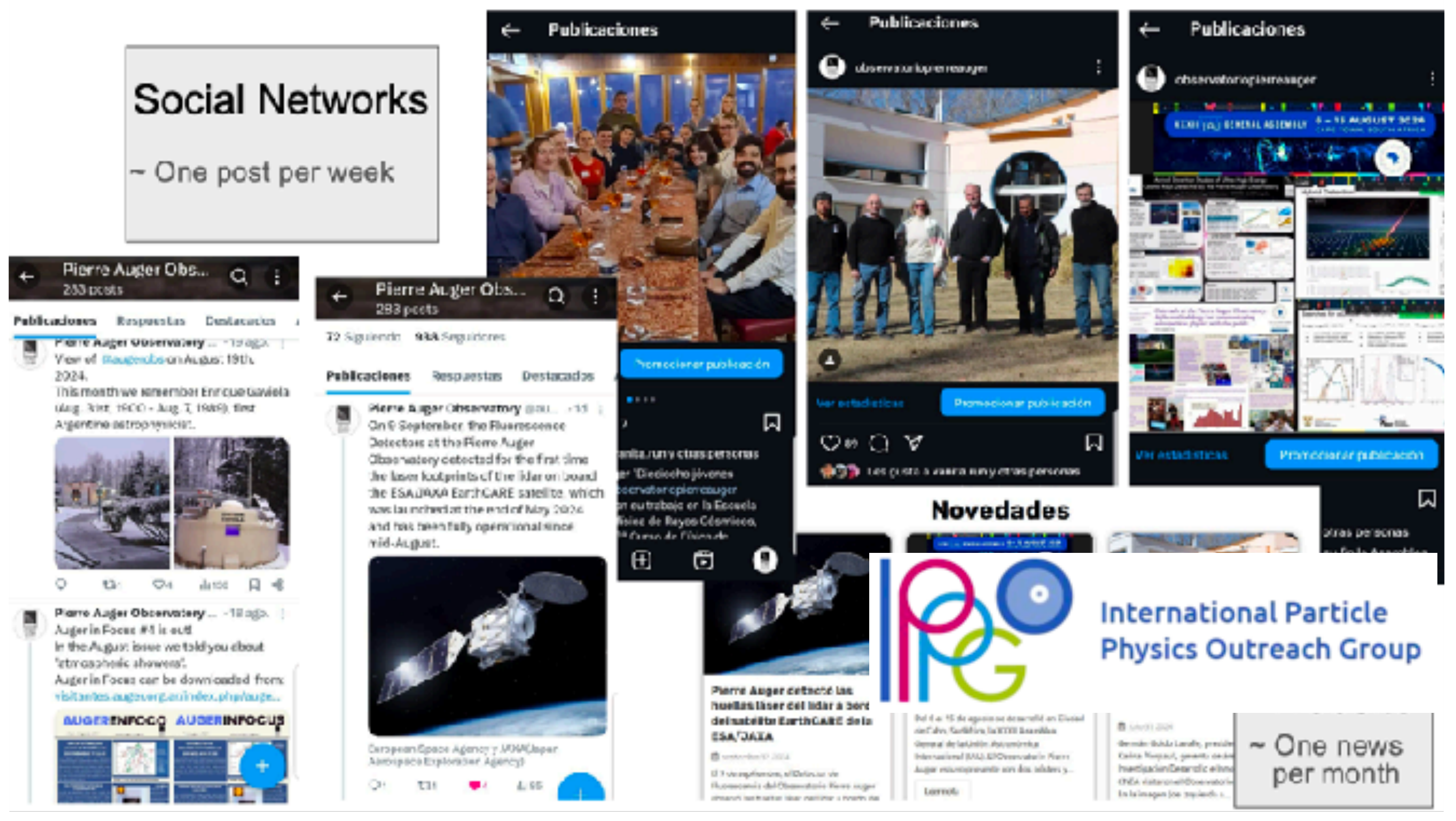
2012: 100 years of Cosmic Rays
2011: The Adventure of konwledge

Sep. 2024 - National High School - UNLP, La Plata

Women and Girls in Science Exhibitions 2024


IYL2016. Travelers of Light, educative transmedia. Planetario Malargue


GalileoMobile Project. Carapacho school

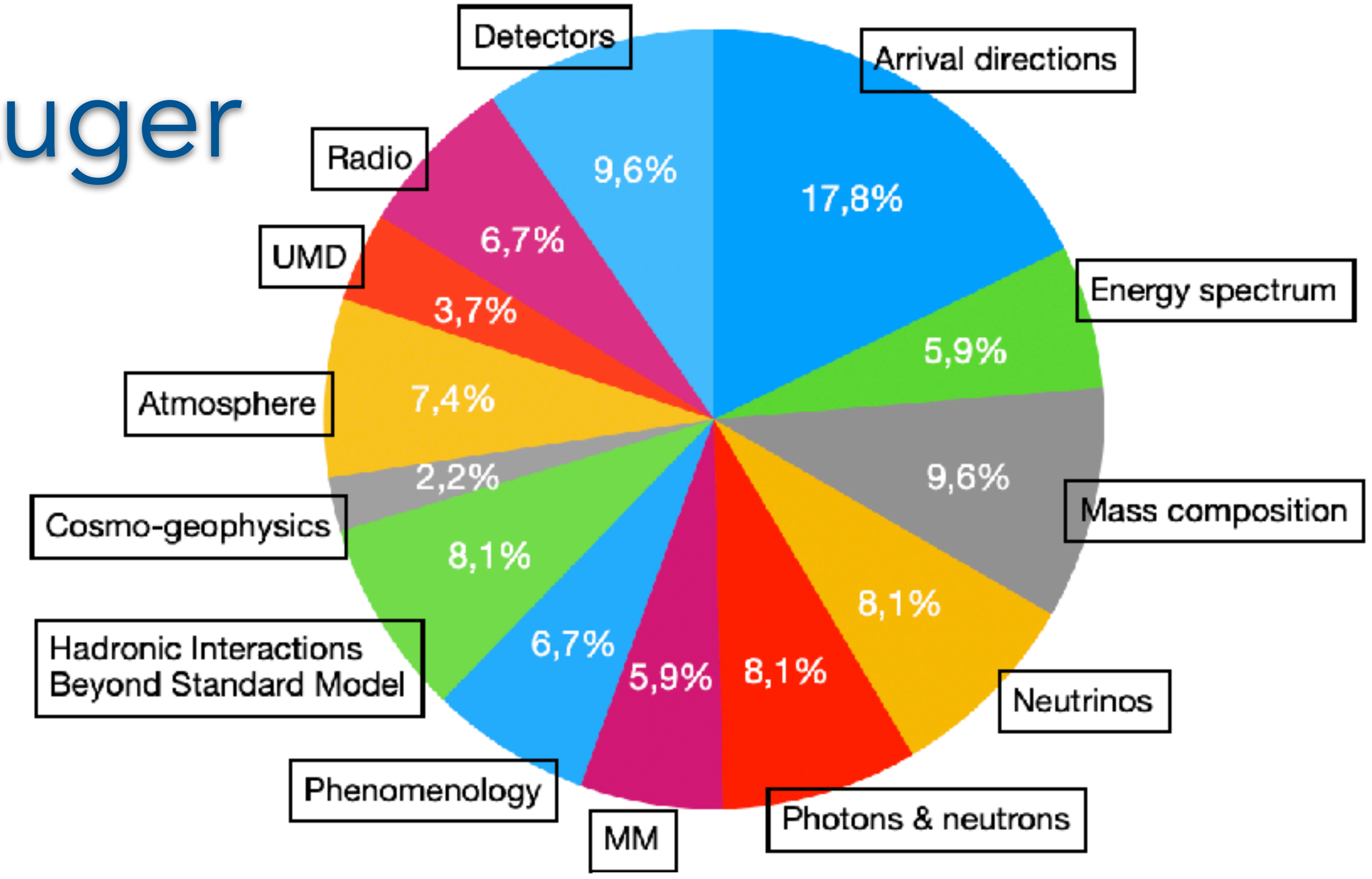


Phase I : the first 15 years of Auger

Unrivalled exposure and accuracy in measurements

140 journal publications

+ 3 already accepted



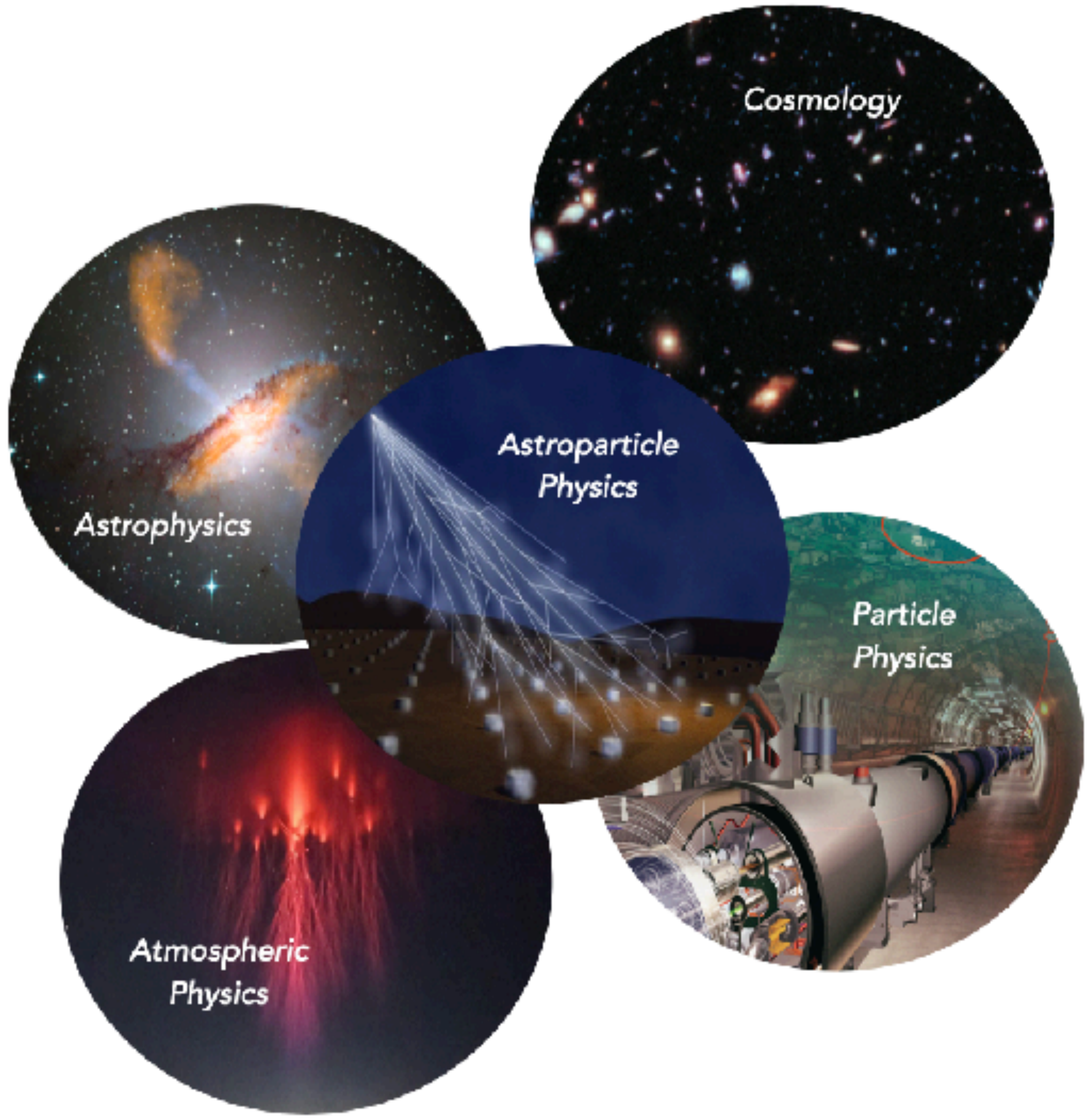
Take home message

A global, coherent view emerges from the analyses of the data collected at the Pierre Auger Observatory, dispelling the pre-existing UHECR picture

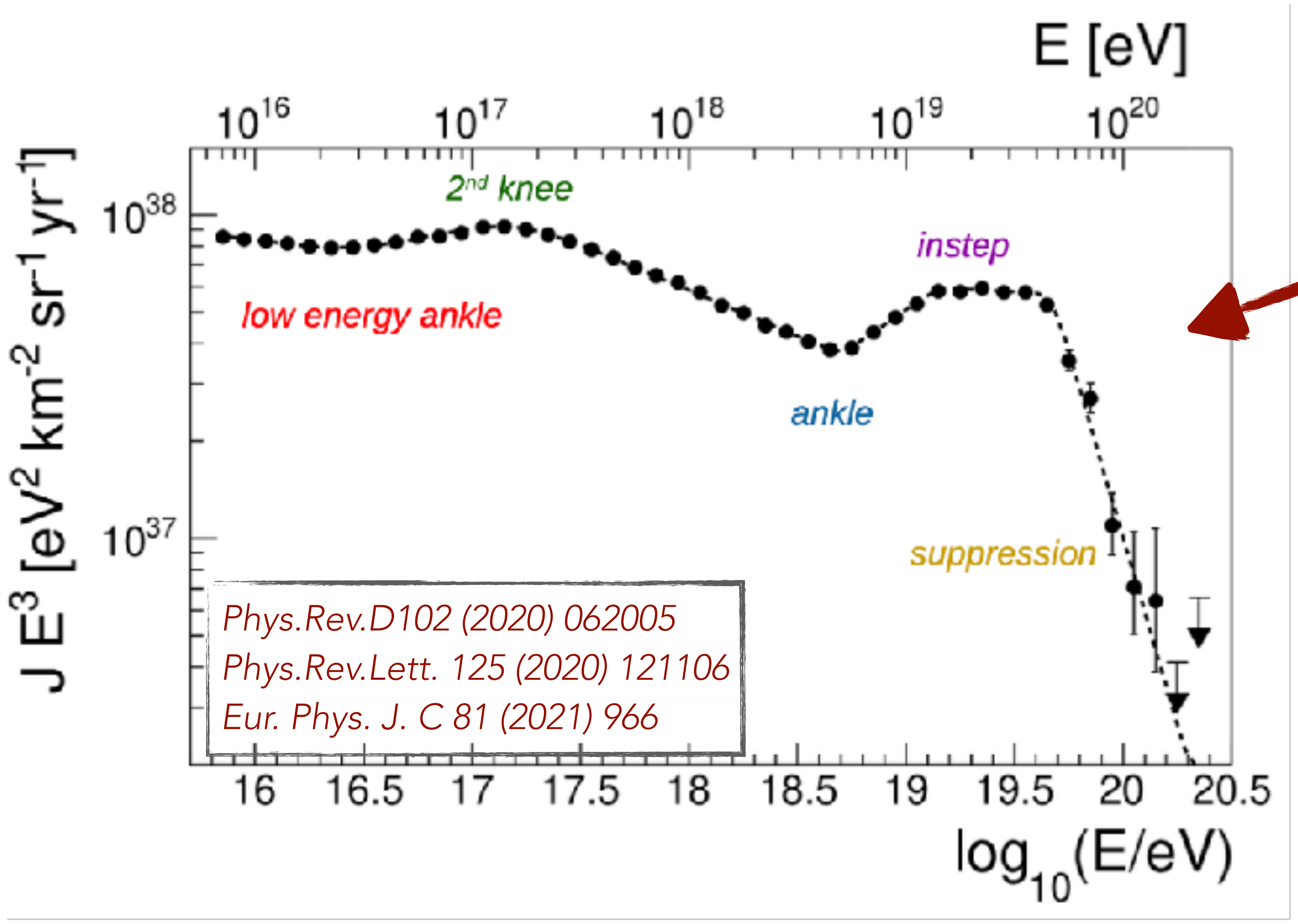
Valuable inputs to phenomenological models

Auger provides the only way to explore the UHE domain:

information about hadronic interactions and constraints on BSM effects



Energy spectrum

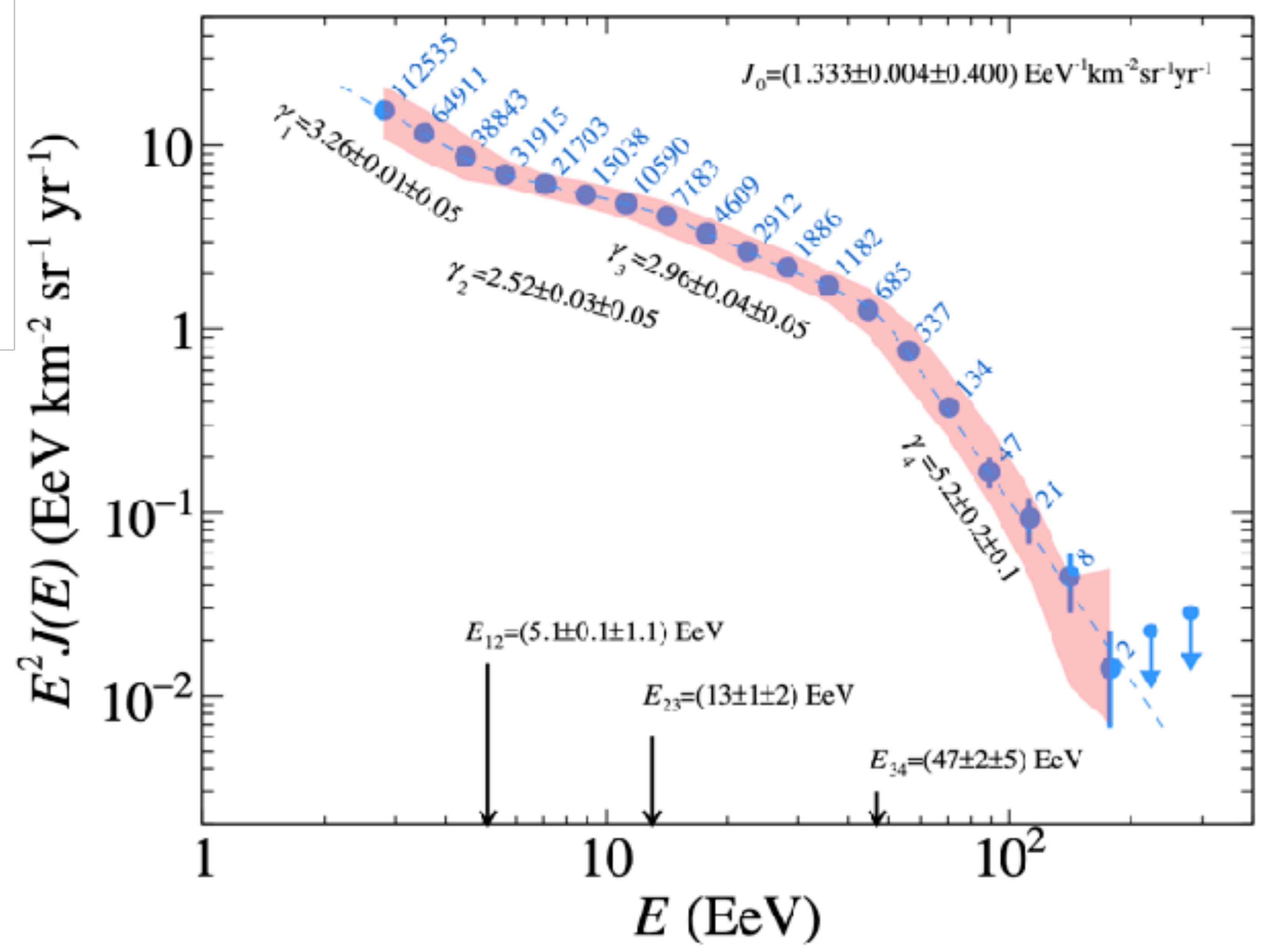


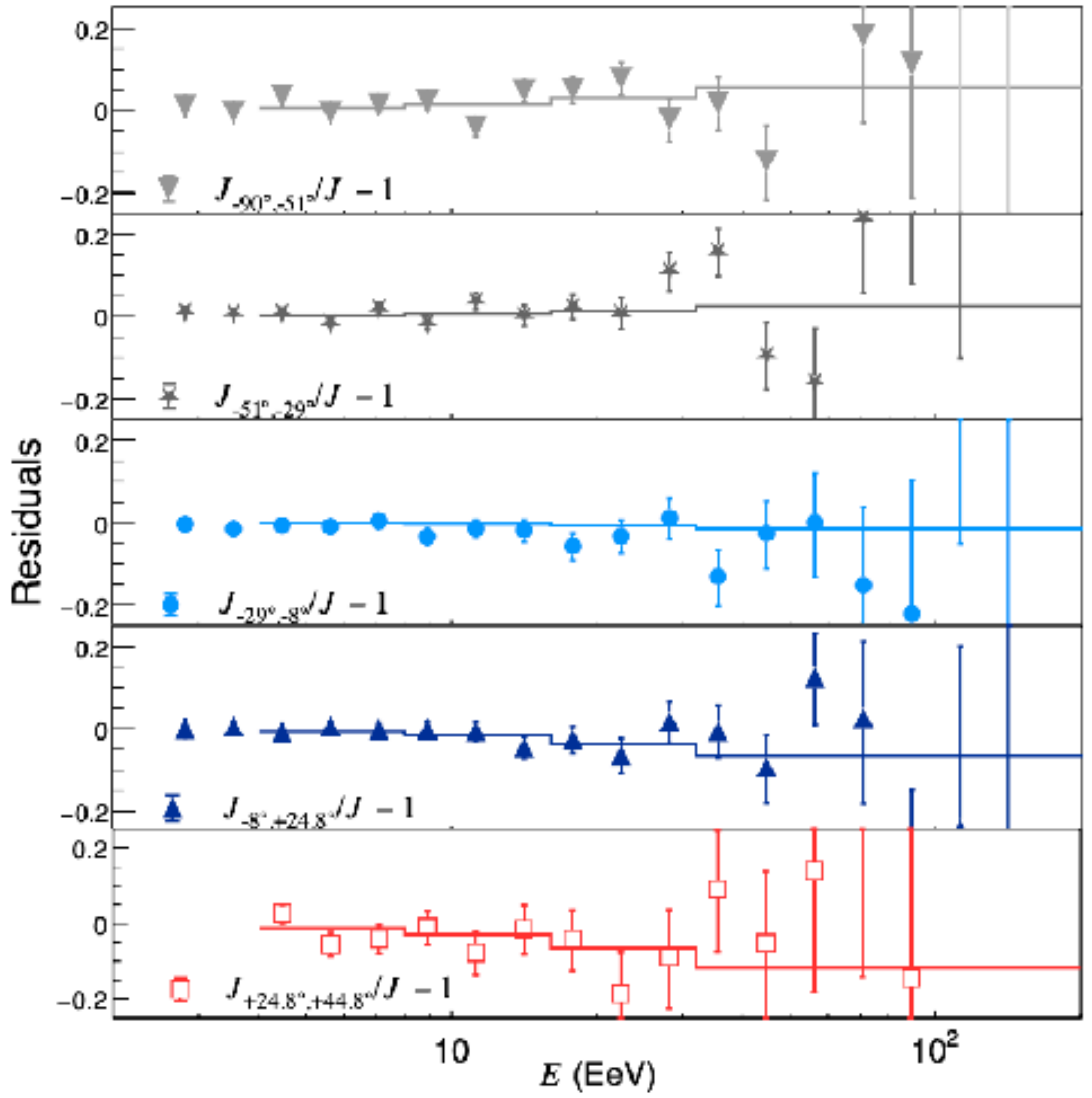
Largest available exposure, >80,000 km² sr yr, >920,000 events

First measurement of the instep feature

A measure completely independent of any assumptions on the primary mass

It provides constraints on source properties, injected masses, interactions/escape





NEW
submitted to ApJL
arXiv:2506.11688

D.Ravignani
PoS(ICRC2025) 268

- ➡ First measurement of the energy spectrum over the entire ***declination range -90⁰ to +45⁰ (104,575 km² sr yr)***
- ➡ ***No declination dependence*** up to δ= +45⁰ (apart from the modulation expected from the dipolar anisotropy) disfavoring the TA conclusion about a possible astrophysical contribution from the Northern sky [see slide SGP]
- ➡ I***nstep feature confirmed at 5.2σ***

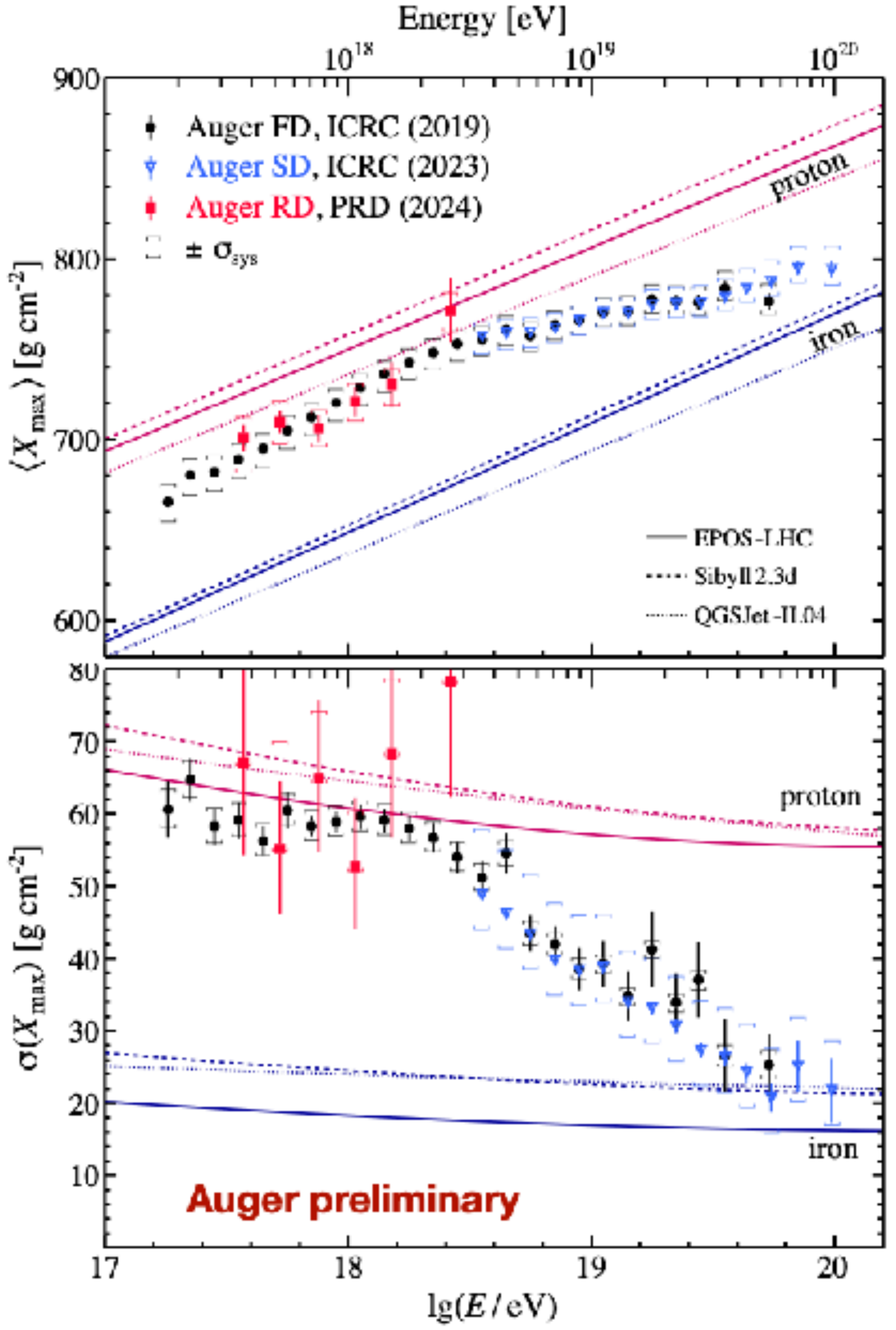
Mass Composition

FD, SD, AERA

Measurement from the

- longitudinal profile (FD, ~15% Duty Cycle) *PRD 90 (2014) 122005+122006*
- temporal and lateral distributions (SD, ~100% DC) *PRD 96 (2017) 122003*
- radio footprint (AERA, ~100% DC)

NEW
PRD 109 (2024) 022002
PRL 132 (2024) 021001
E.Mayotte, PoS(ICRC2025) 538



➡The <X_{max}> gets lighter up to ~2 10^{18} eV and heavier above this energy, incompatible with pure composition

➡The σ (X_{max}) at the highest energy

— excludes a large fraction of protons (DNN and FD)

— excludes the GZK as a dominant reason for the spectral cutoff

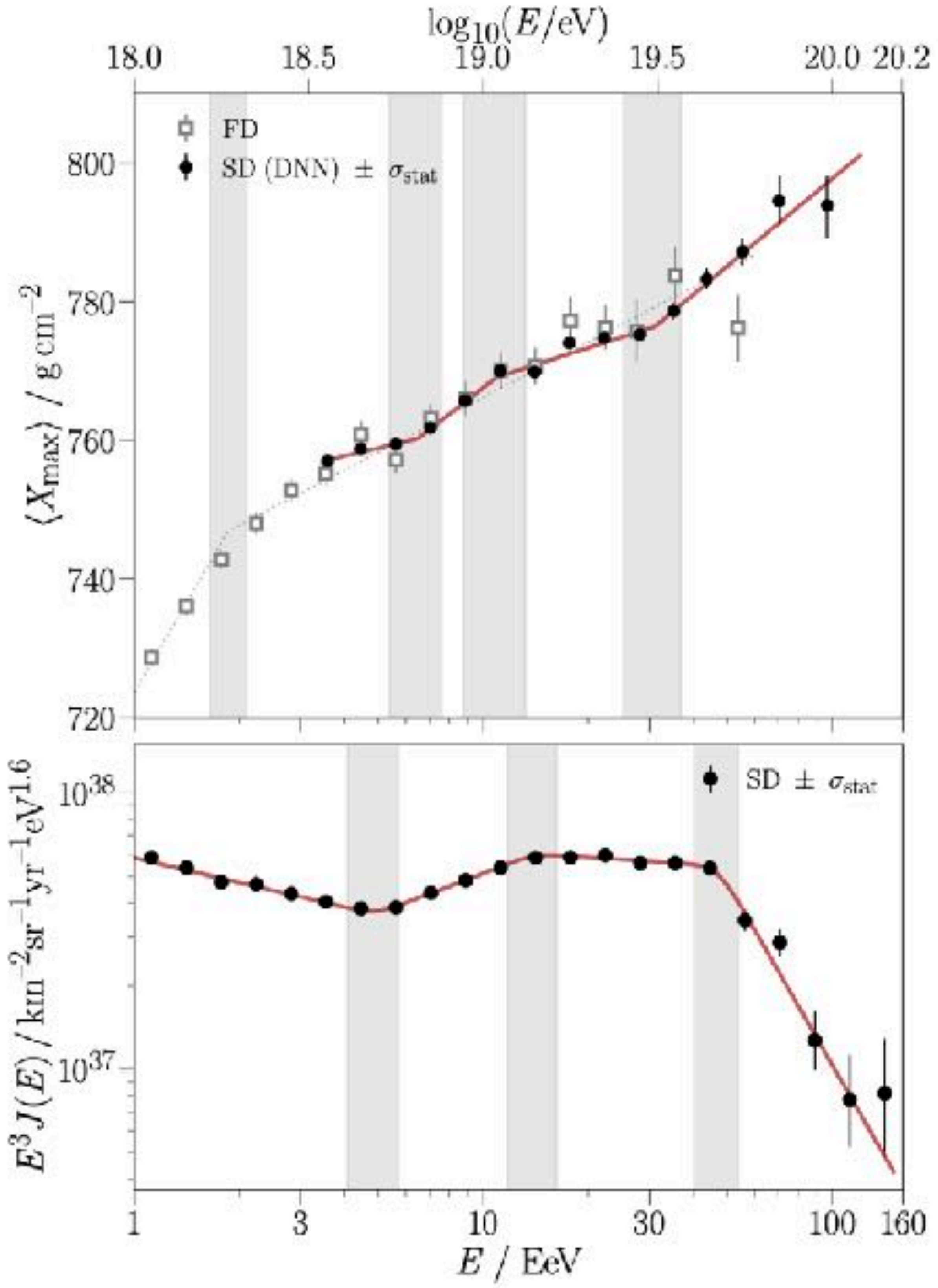
➡The radio measurement provides an independent confirmation

DNN analysis

Measurement from SD using DNN

- Elongation rate in agreement with that found with FD
- Clear evidence of a structure in ER, best described with a three-break model: constant ER rejected at 4.4σ

➡ *incompatible with pure composition*



NEW
PRD 111 (2025) 022003
PRL 134 (2025) 021001

➡ kinks resembling the spectrum features

➡ supported by independent SD-based measurements (Delta method)

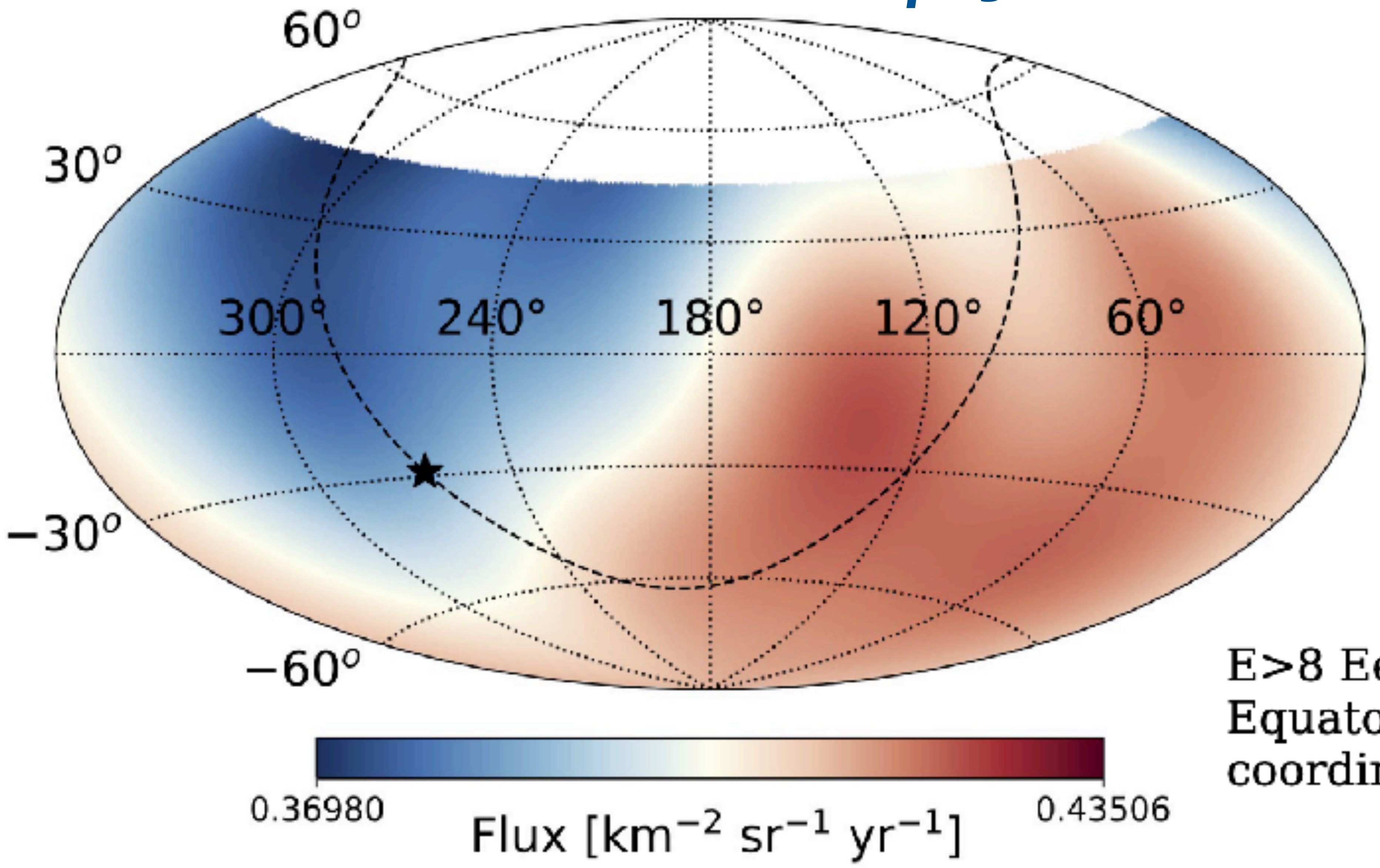
➡ in agreement with those predicted by a simplified astrophysical model

Composition informed search for large scale Anisotropy

Dipolar modulation in RA

at 6.8σ for E>8 EeV, at 5.7σ for 8<E<16 EeV

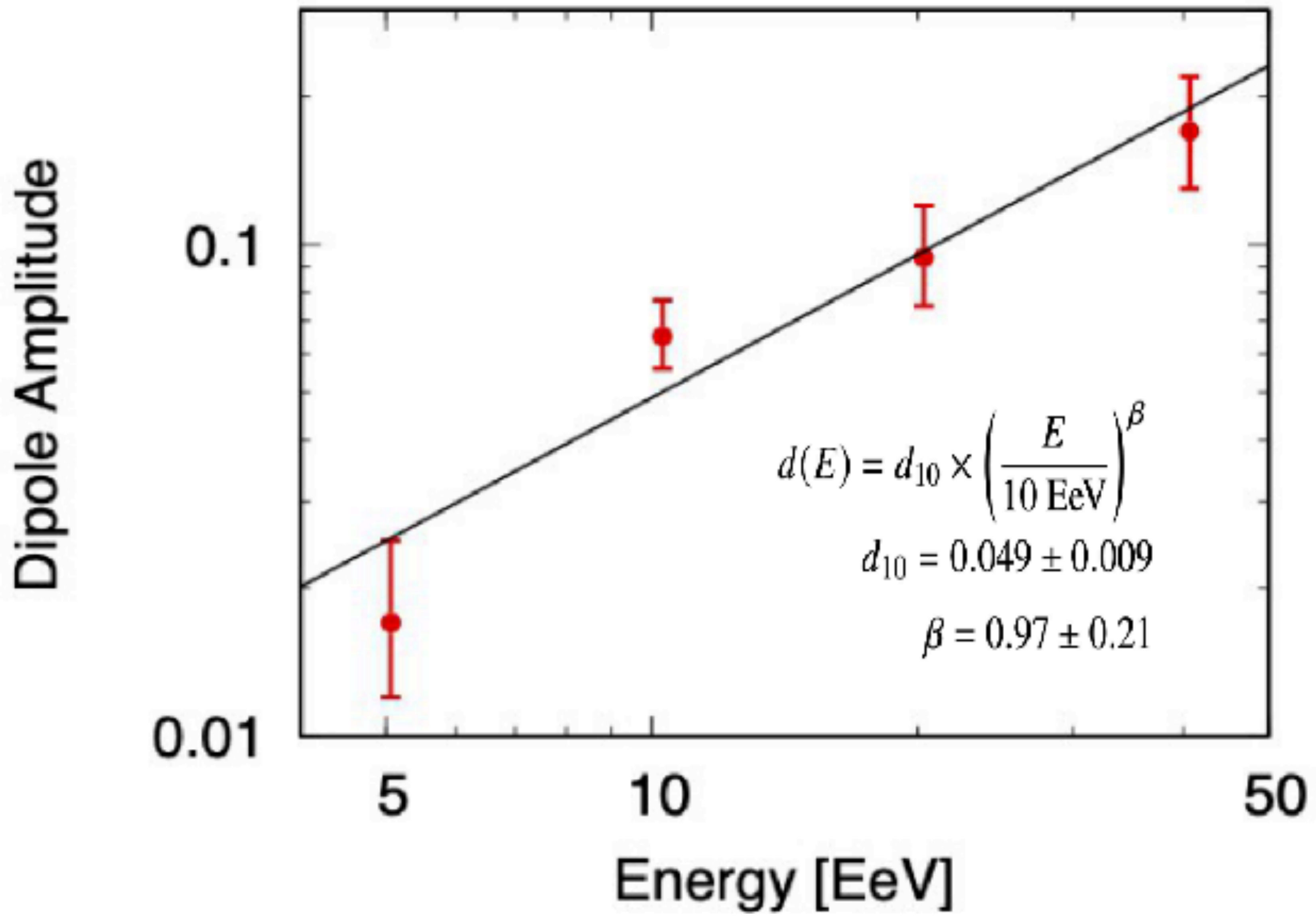
Science 357 (2017) 1266
ApJ 976 (2024) 48



E>8 EeV, Equatorial coordinates

Cosmic ray interactions with background radiation and magnetized regions depend on the cosmic-ray energy, charge and mass composition, giving rise to different horizons and deflections that are expected to lead to different anisotropies.

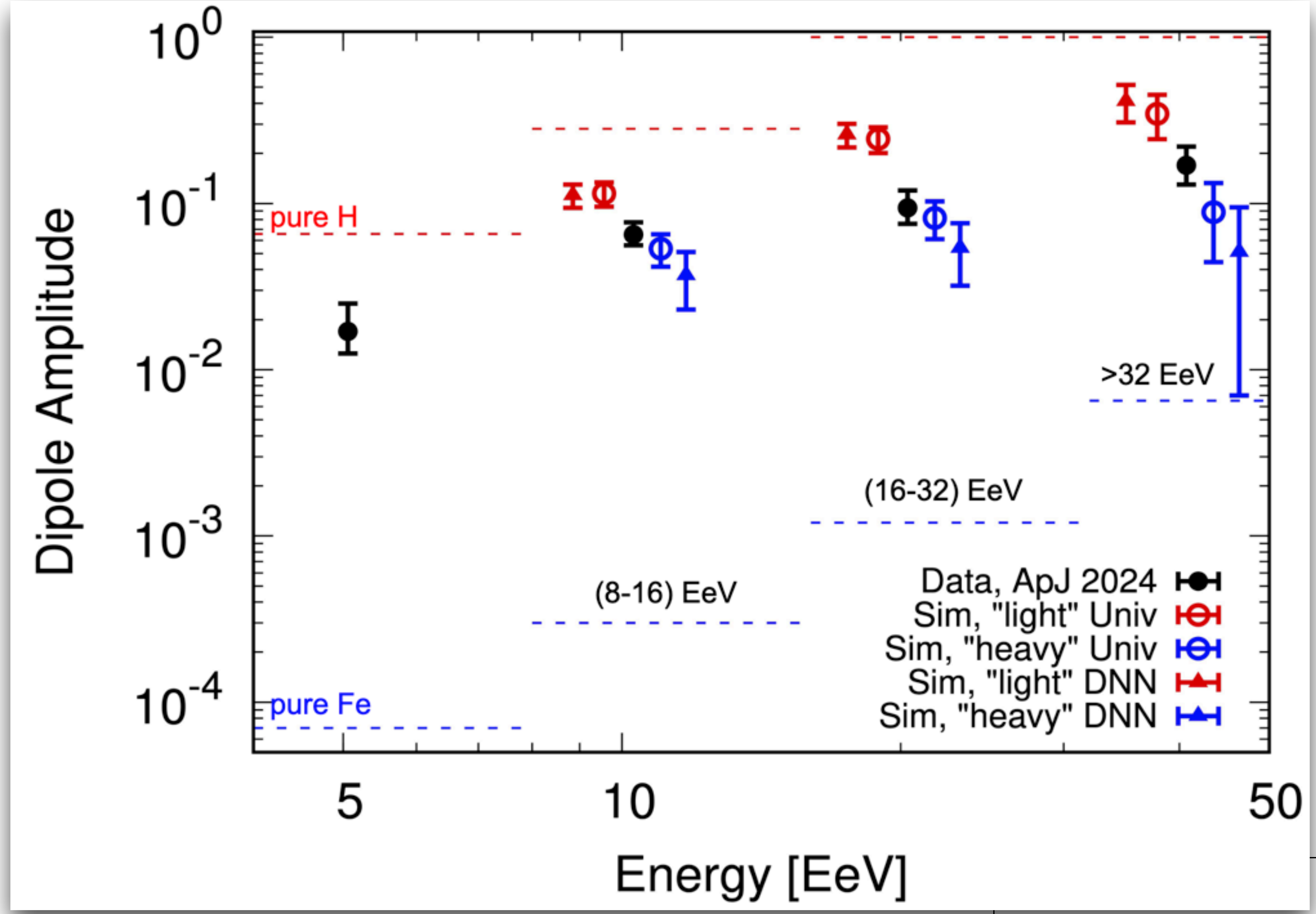
$$d(E,Z) = d_R\left(\frac{E/EeV}{Ze}\right)^{\beta_R}$$



events with zenith angle <80°

- Expected in models with a local dominant source emitting in the EGMF
- Expected in models with many inhomogeneously distributed sources

Composition informed search for large scale Anisotropy

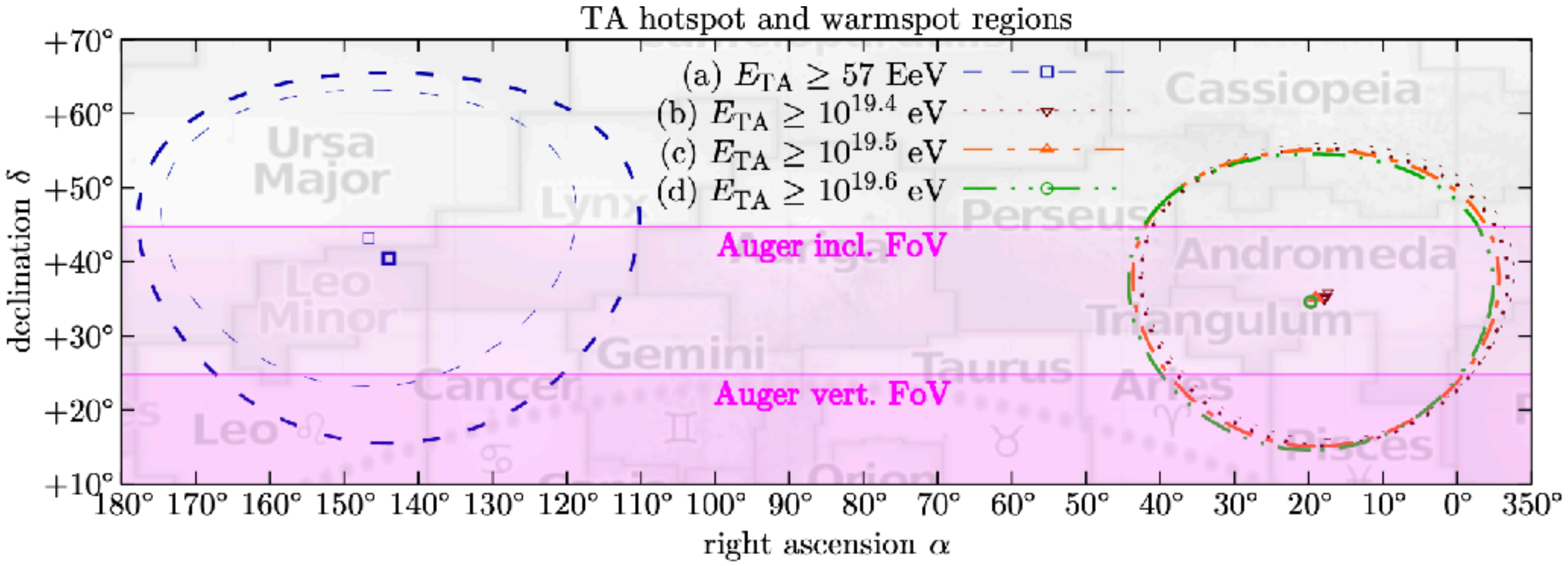


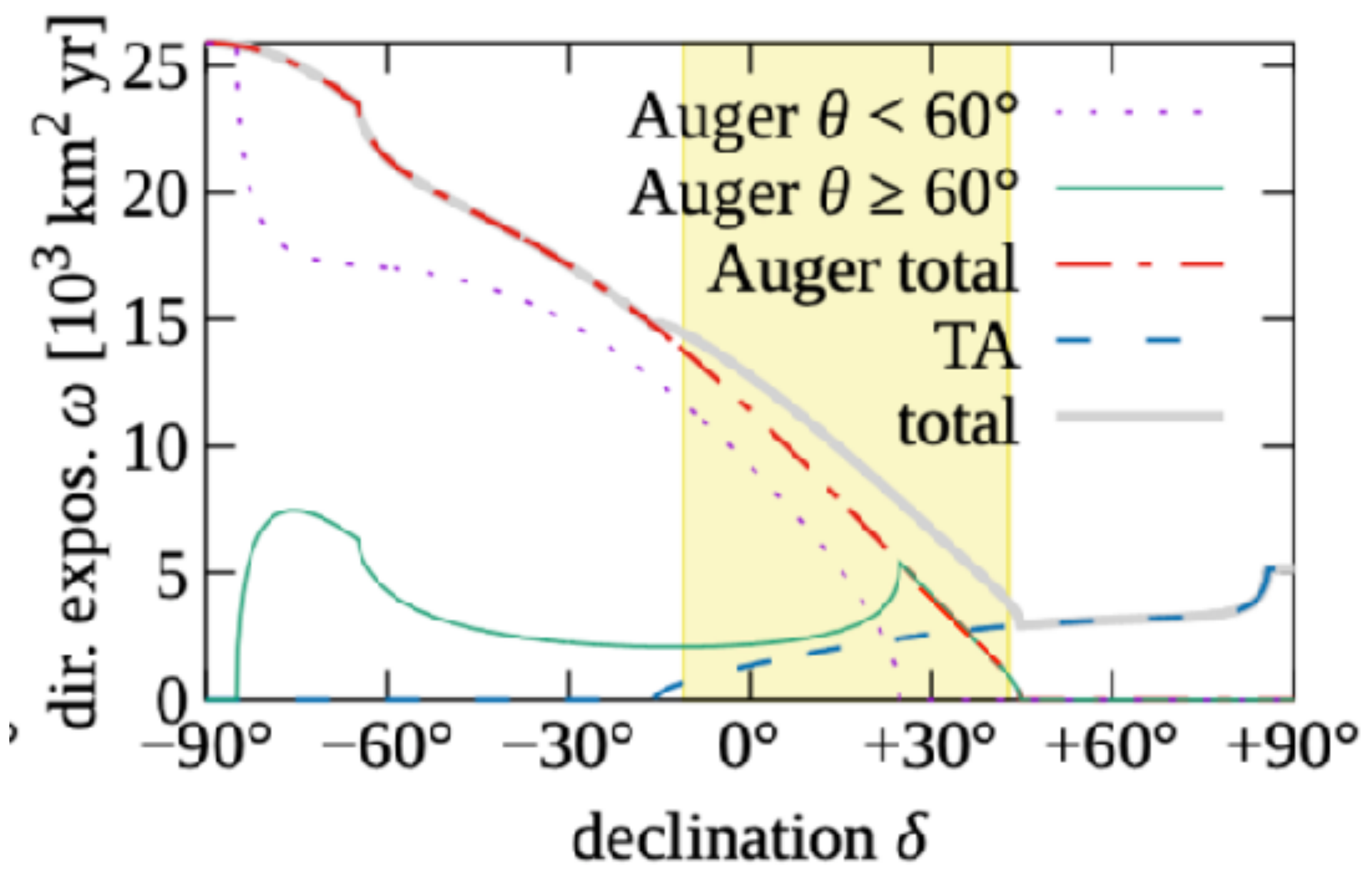
NEW
G.Golup, PoS(ICRC2025) 216

	Estimator	Resolution
FD	X_{max}	~ 15 g cm^{-2}
SD + Universality	$X_{max}^{Univ}, R_{\mu}^{Univ}$	~ 40 g cm^{-2}
SD + DNN	X_{max}^{DNN}	~ 25 g cm^{-2}

Differences between Northern and Sourthern sky?

Using vertical+inclined events we have partial coverage of the Northern sky





		Telescope Array (Telescope Array Collaboration 2023)									Pierre Auger Observatory (this work)							
		E_{min}	N_{tot}	$\frac{\mathcal{E}_{in}}{\mathcal{E}_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	Z_{LM}	99% L.L.	post-trial	E_{min}	N_{tot}	$\frac{\mathcal{E}_{in}}{\mathcal{E}_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	Z_{LM}	99% U.L.
TA hot spot →	(a)	57 EeV	216	9.47%	18.0	44	$2.44^{+0.44}_{-0.39}$	$+4.8\sigma$	1.60	2.8σ	44.6 EeV	1074	1.00%	10.7	9	$0.84^{+0.31}_{-0.25}$	-0.5σ	1.76
PPSC →	(b1)	$10^{19.4}$ eV	1125	5.88%	64.0	101	$1.58^{+0.17}_{-0.16}$	$+4.1\sigma$	1.22	3.3σ	20.5 EeV	8374	0.84%	70.1	65	$0.93^{+0.12}_{-0.11}$	-0.6σ	1.23
	(b2)	$10^{19.5}$ eV	728	5.87%	41.1	70	$1.70^{+0.22}_{-0.20}$	$+4.0\sigma$	1.25	3.2σ	25.5 EeV	5156	0.84%	43.5	39	$0.90^{+0.15}_{-0.14}$	-0.7σ	1.29
	(b3)	$10^{19.6}$ eV	441	5.84%	24.6	45	$1.83^{+0.31}_{-0.27}$	$+3.6\sigma$	1.23	3.0σ	31.7 EeV	2990	0.87%	26.0	27	$1.04^{+0.21}_{-0.19}$	$+0.2\sigma$	1.61

NEW
ApJ 984 (2025) 123

➡ confirmation of the Centaurus region as most significant excess (4.0σ post-trial), extended to lower energies (20 EeV)

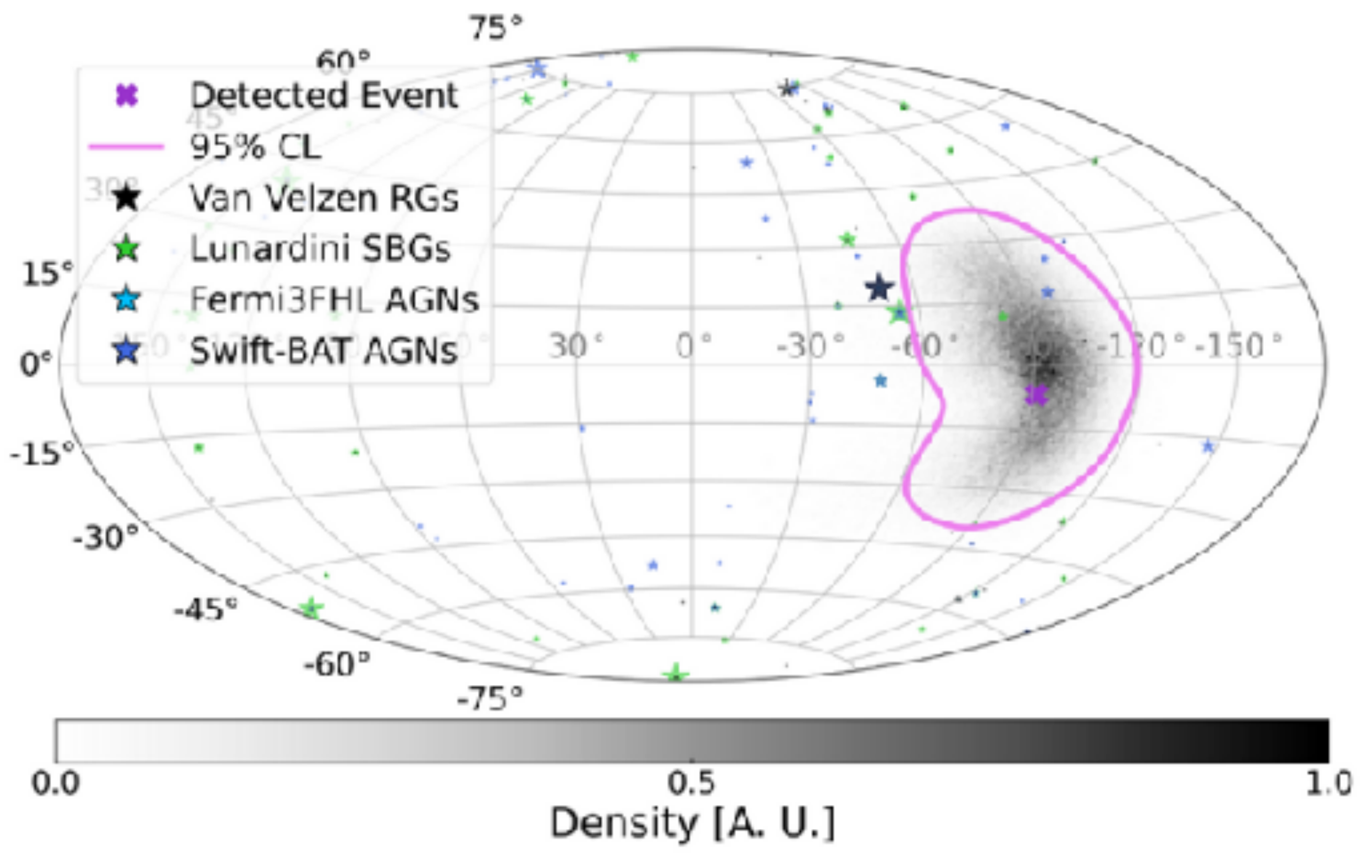
➡ no hints for excesses in the TA "spots" with data of comparable size —> at variance with the claim of TA that the declination dependence of the UHECR energy spectrum is due to the presence of excesses in particular regions of the Northern sky

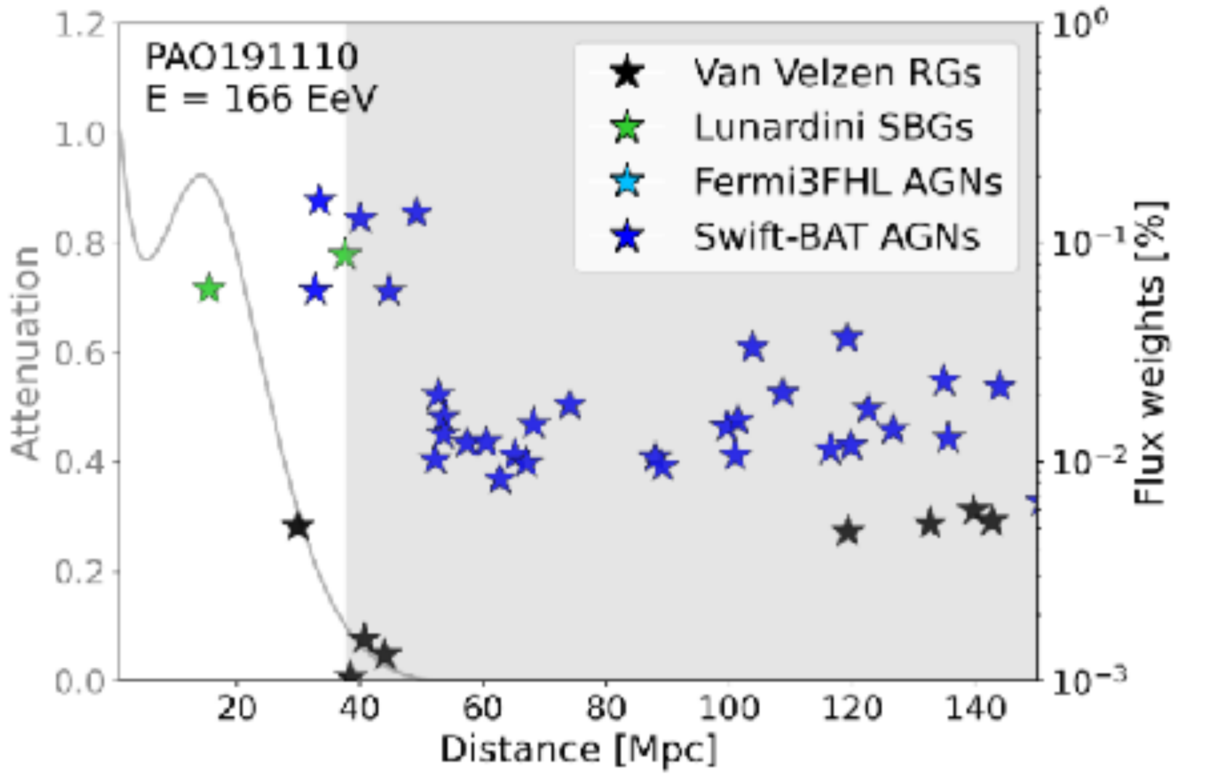
Galactic backtracking + limited UHECR horizon

Idea: apply GMF models backtracking UHE events above 100 EeV, taking into account the volume of the Universe responsible for them
8 GMF models, 6 different source catalogs

Single events analysis

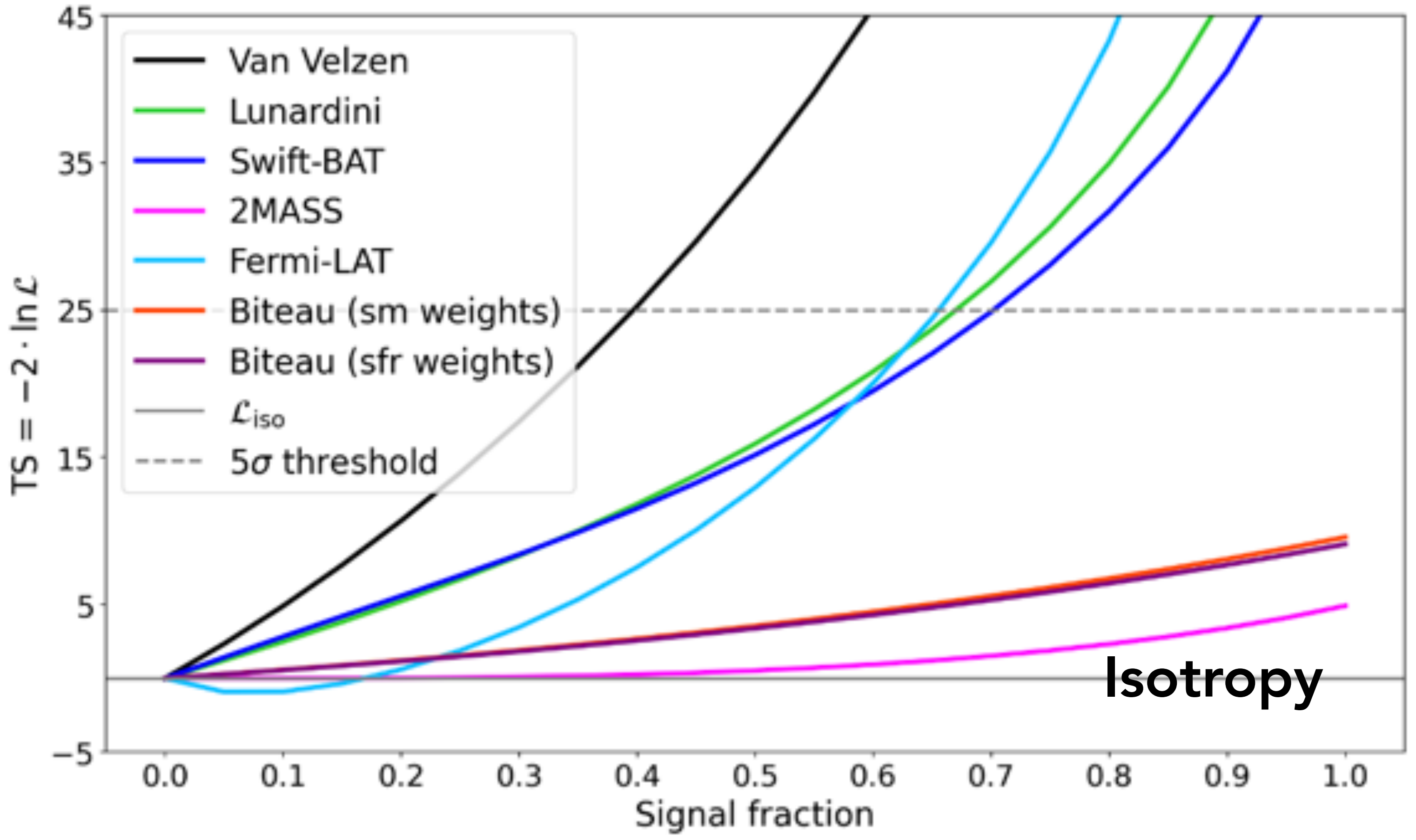
The backtracked position of 39 of 40 events above 100 EeV re compatible with more than one source of the SBG, Fermi-LAT, Swift-BAT or radio galaxies

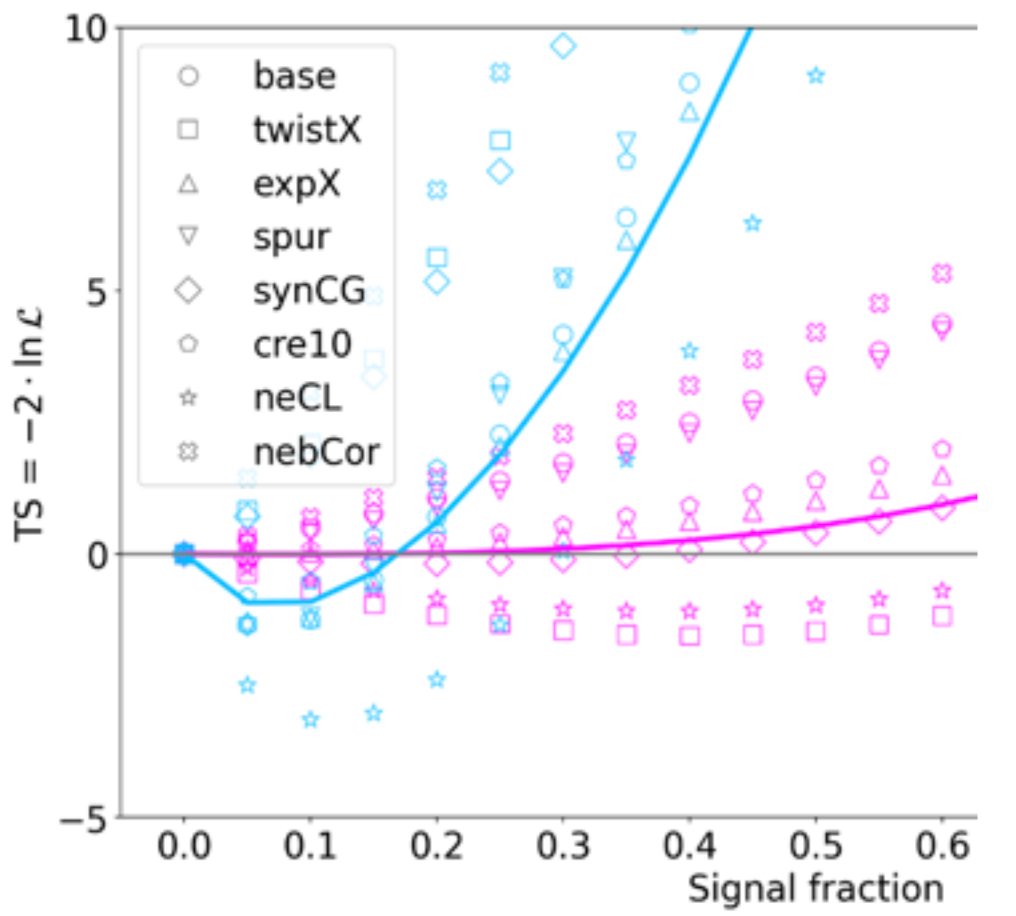




Likelihood based analysis

We can exclude at 5σ CL a contribution of >40% van Velzen, >65% Fermi-LAT, >67% Lunardini and 70% Swift-BAT
Only the Fermi-LAT catalog describes the data better than isotropy at low signal fraction (5-10%)





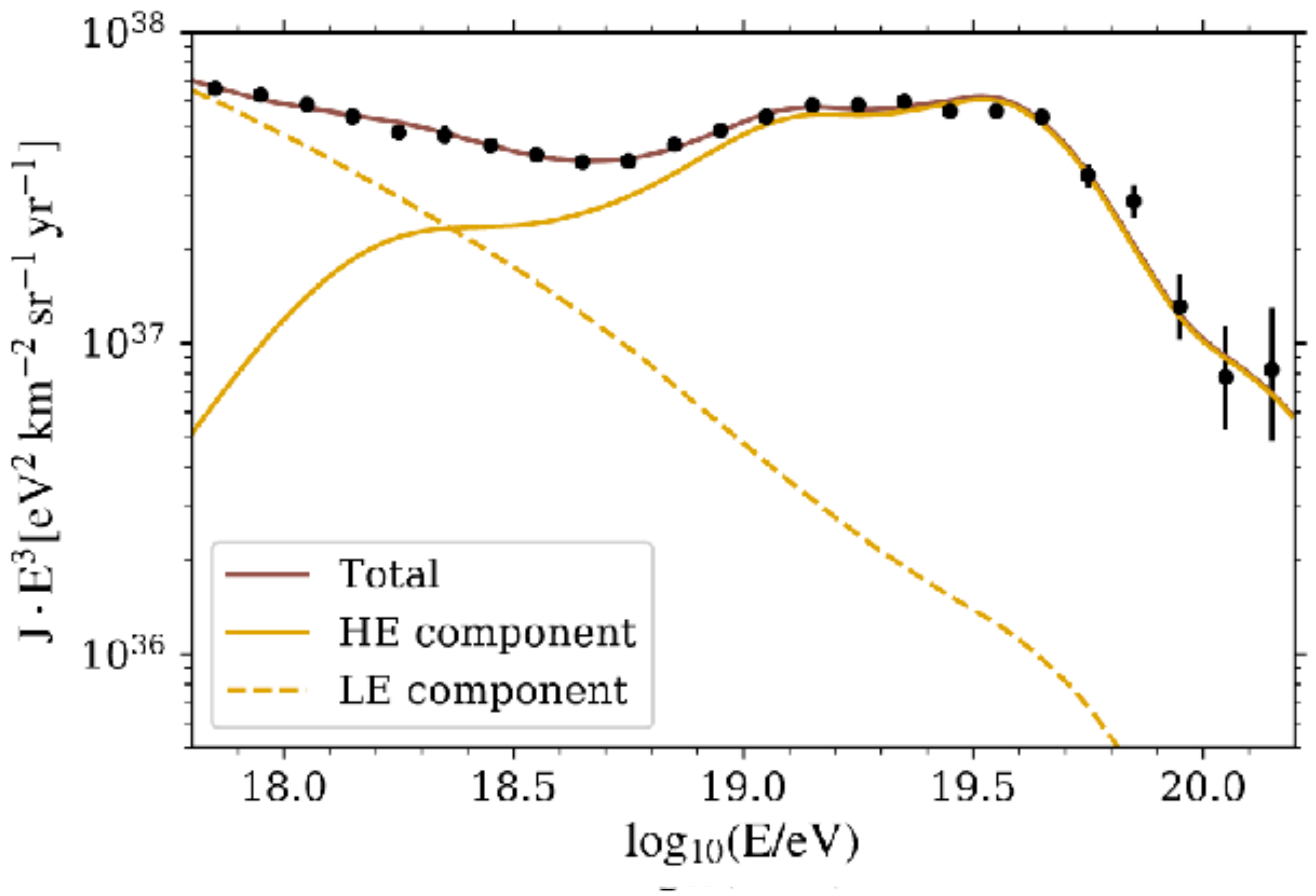
Inclusion of EGMF, UUHECR, newer GMF models can change the conclusion

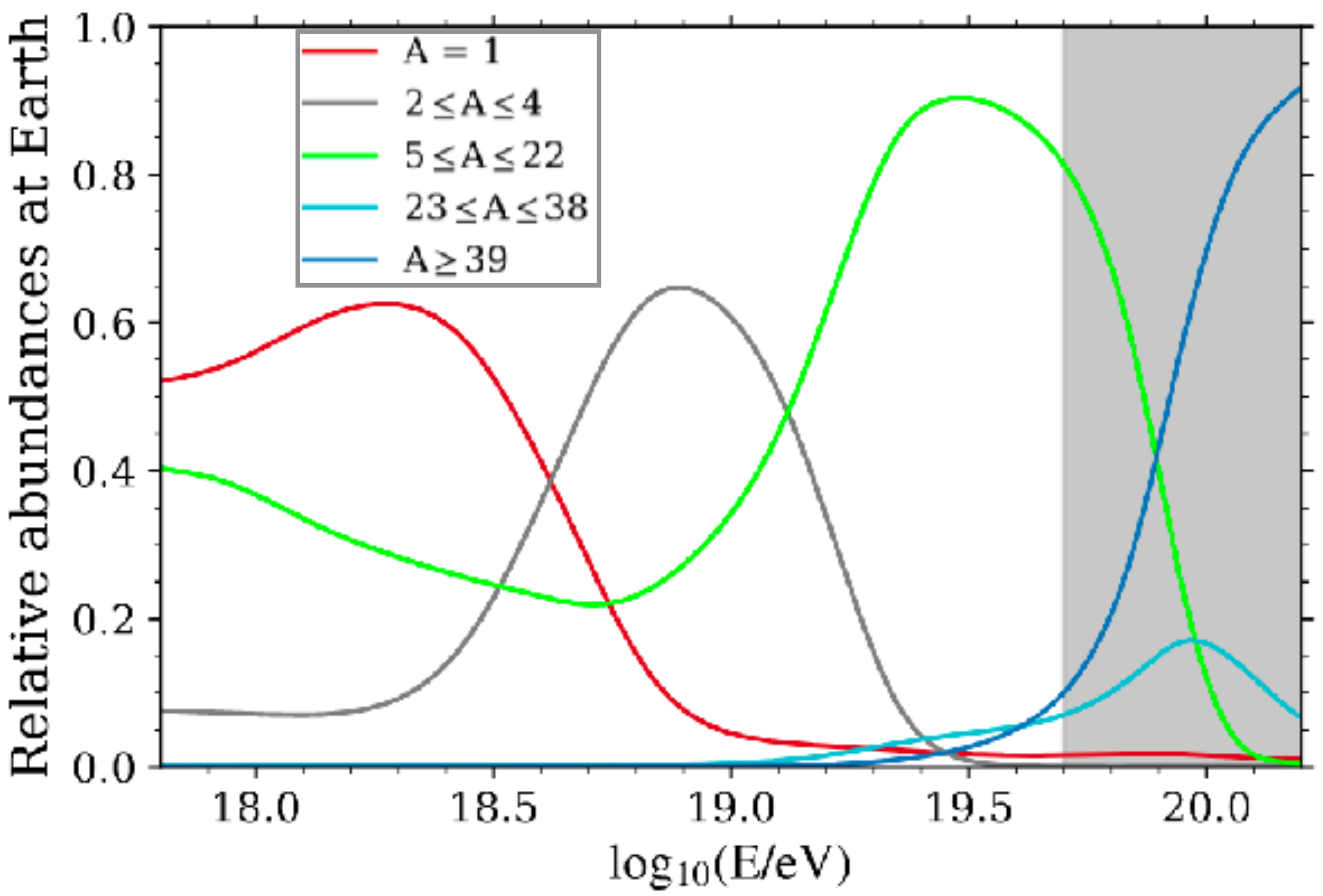
NEW
M.Bianciotto, PoS(ICRC2025) 188

Astrophysical interpretation (energy spectrum+mass composition)

Basic scenario:
— 2 populations of EG identical sources, uniformly distributed
— power law injected energy spectrum + rigidity cutoff
— ***propagation only*** (no in-source interactions considered)

Auger Coll., JCAP05 (2023) 024





➡*Ankle ~ 5 EeV: interplay between the two popolations*
➡*Instep ~ 10 EeV: interplay between He and CNO primary masses*
➡Luminosity density *~ 6 x 10^{44} erg Mpc^{-3} yr^{-1}* by continuously emitting sources to supply UHECR above the ankle

LE component

soft spectrum, unconstrained cutoff point to
➡interactions in-source or in the source environment indication
➡could be made of EG protons if a Galactic component is included

HE component

hard spectrum, low cutoff, limited mixing of different nuclear species point to
➡confinement of UHECR in the source, magnetic horizon
➡suppression mainly due to exhaustion of the sources
➡Limited source to source variations

The mass composition at UHE

From the global fit of the observed [X_{max},S_{1000}] distributions and from the most recent hadronic interaction models (EPOS LHC-R) → Heavier nuclei favored at the highest energies

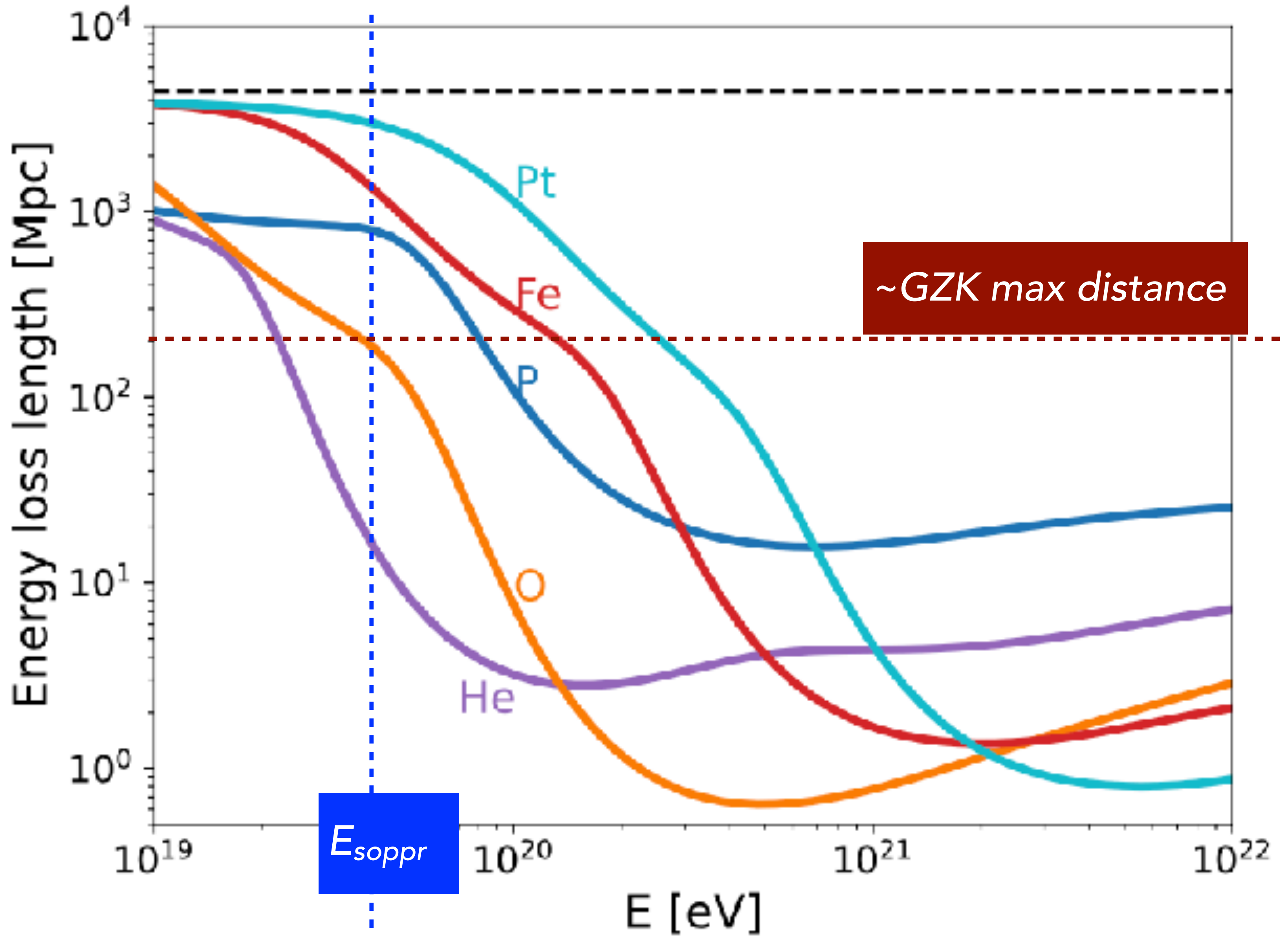


FIG. 1. Total energy loss lengths for various nuclei: p, He, O, Fe, and Pt. The black dashed line is the energy loss length due to the adiabatic expansion of the universe. CMB and EBL [60] are considered as target photons.

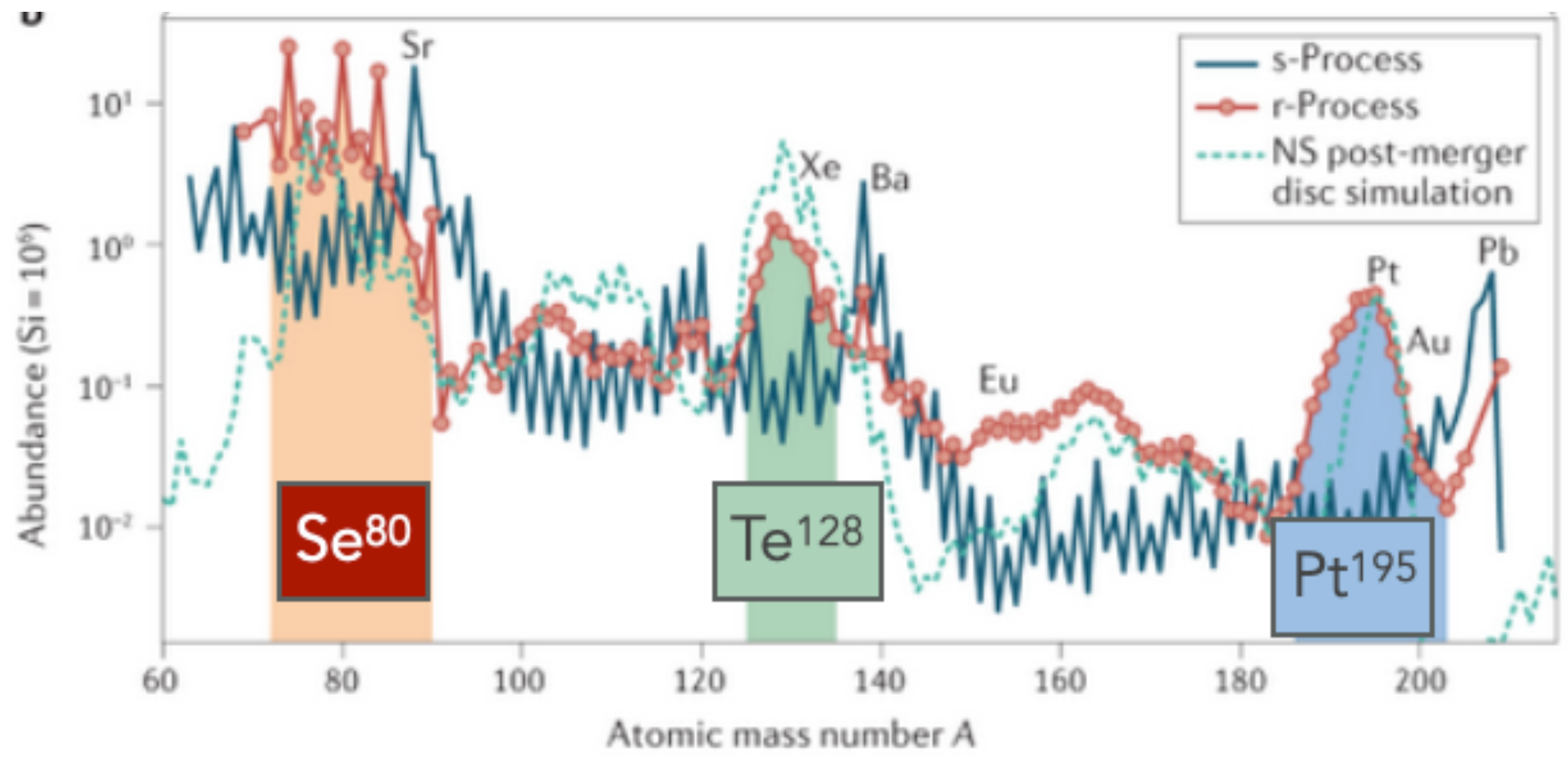
$$\mathrm{ELL} \approx A\left(\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty}\varepsilon'\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'\right)^{-1}$$

New questions:

— Are there astrophysical conditions for which ultra-heavy UHECR can exist?

Metal rich sources, r-processes = collapsars, BNS mergers

— What is the maximum A needed to explain our data?



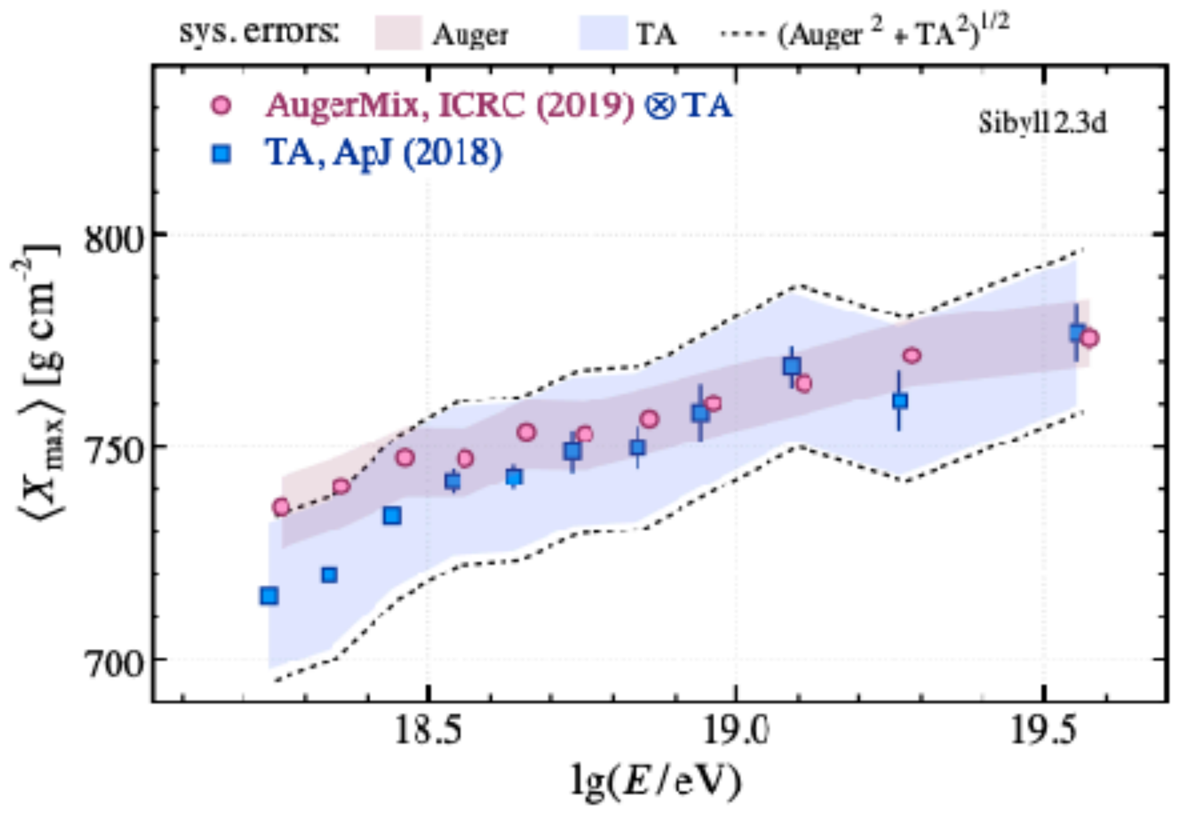
Auger  *Telescope Array*

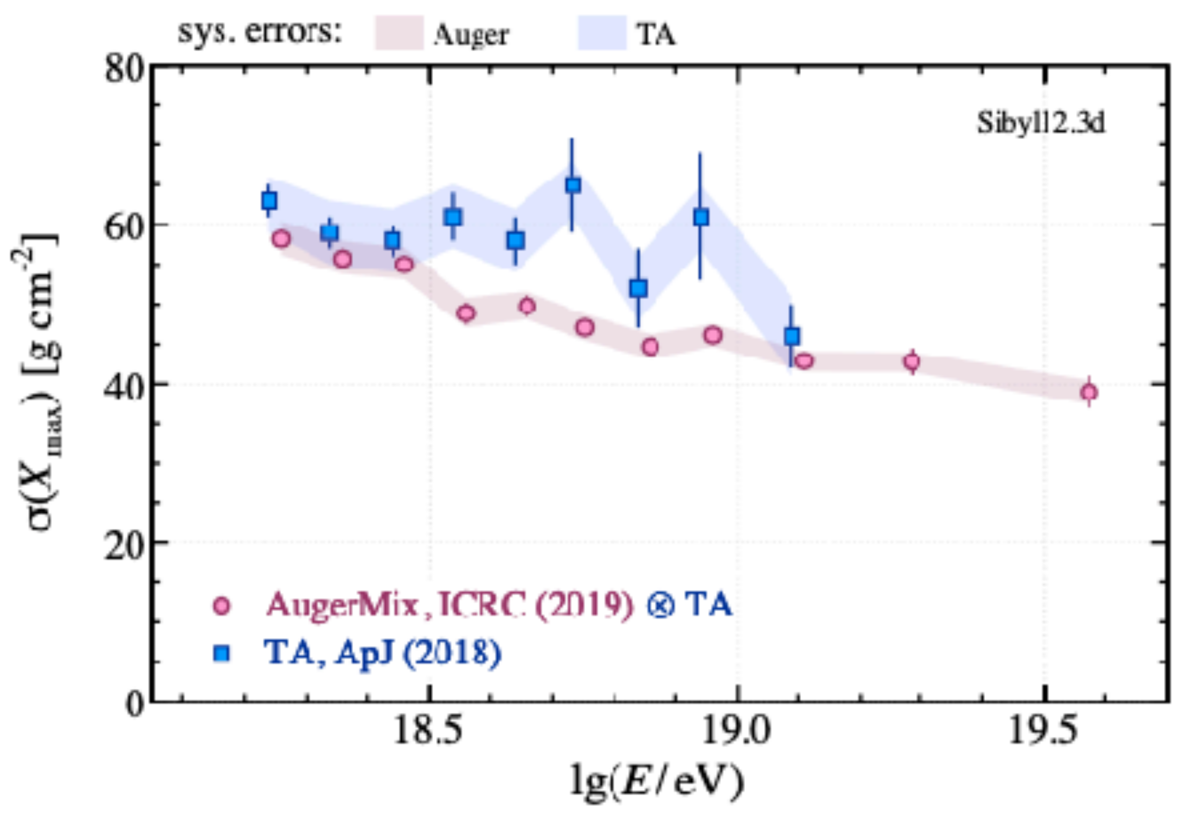
Mass composition

Comparison feasible only up to $10^{19.5}$ eV - no FD data above this energy

No direct comparison of X_{max} distributions is possible: Auger measurement unbiased, TA one folded with detector effects

Auger best fit composition as input to the TA simulations; the resulting distributions are compared to the TA X_{max} results



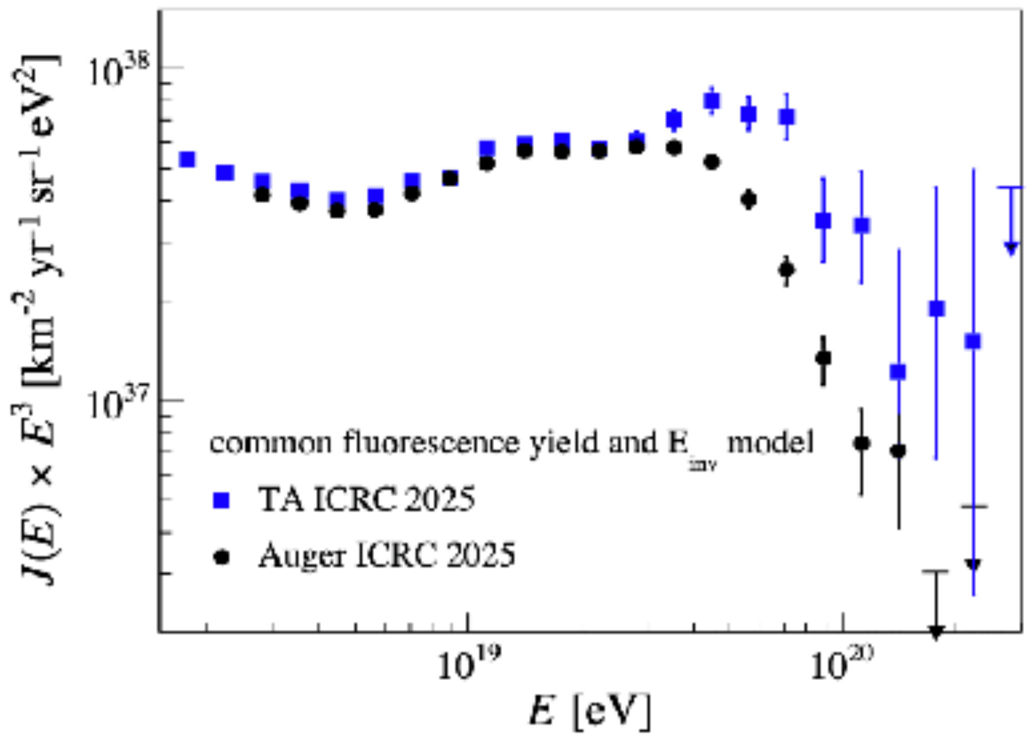


TA data consistent with proton and also with Auger-mix at least up to $10^{19.5}$ eV

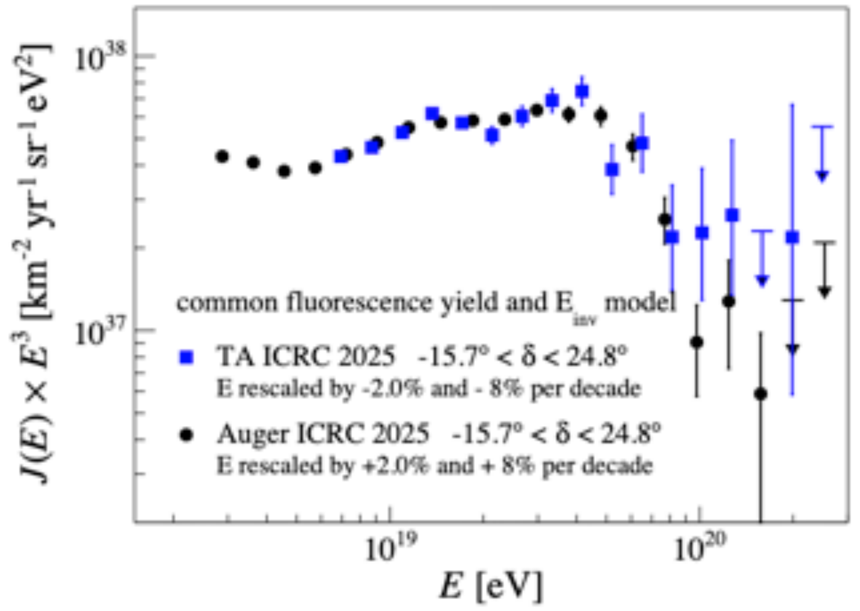
The opposite is NOT true, as Auger data are incompatible with pure composition (4.4σ exclusion of constant ER)

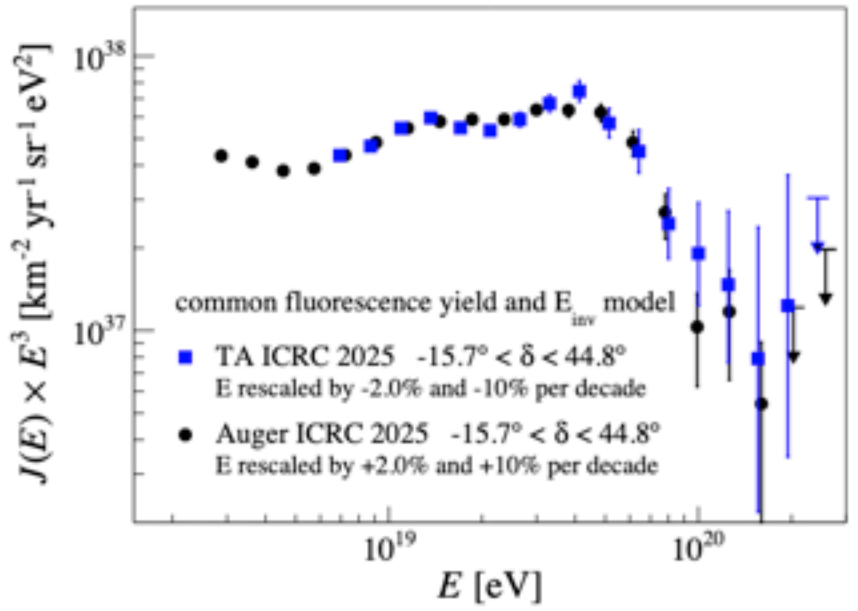
Energy spectrum

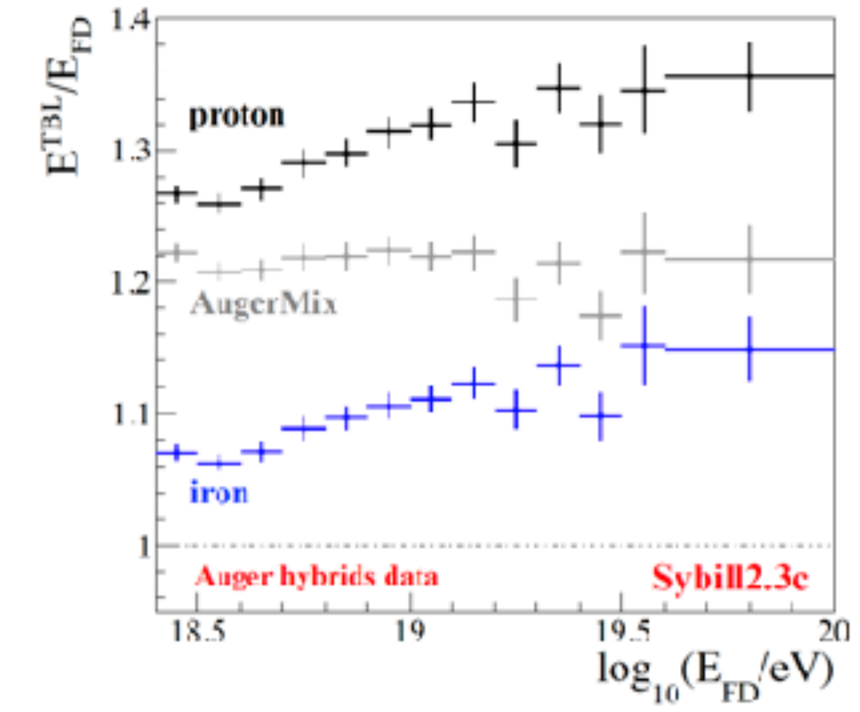
Full declination band
[-90^0, +44.8^0] Auger
[-5.7^0, +90^0] TA



Overall shift with same FY and E_{inv} of 4%, well within uncertainties in energy scales, up to 10 EeV





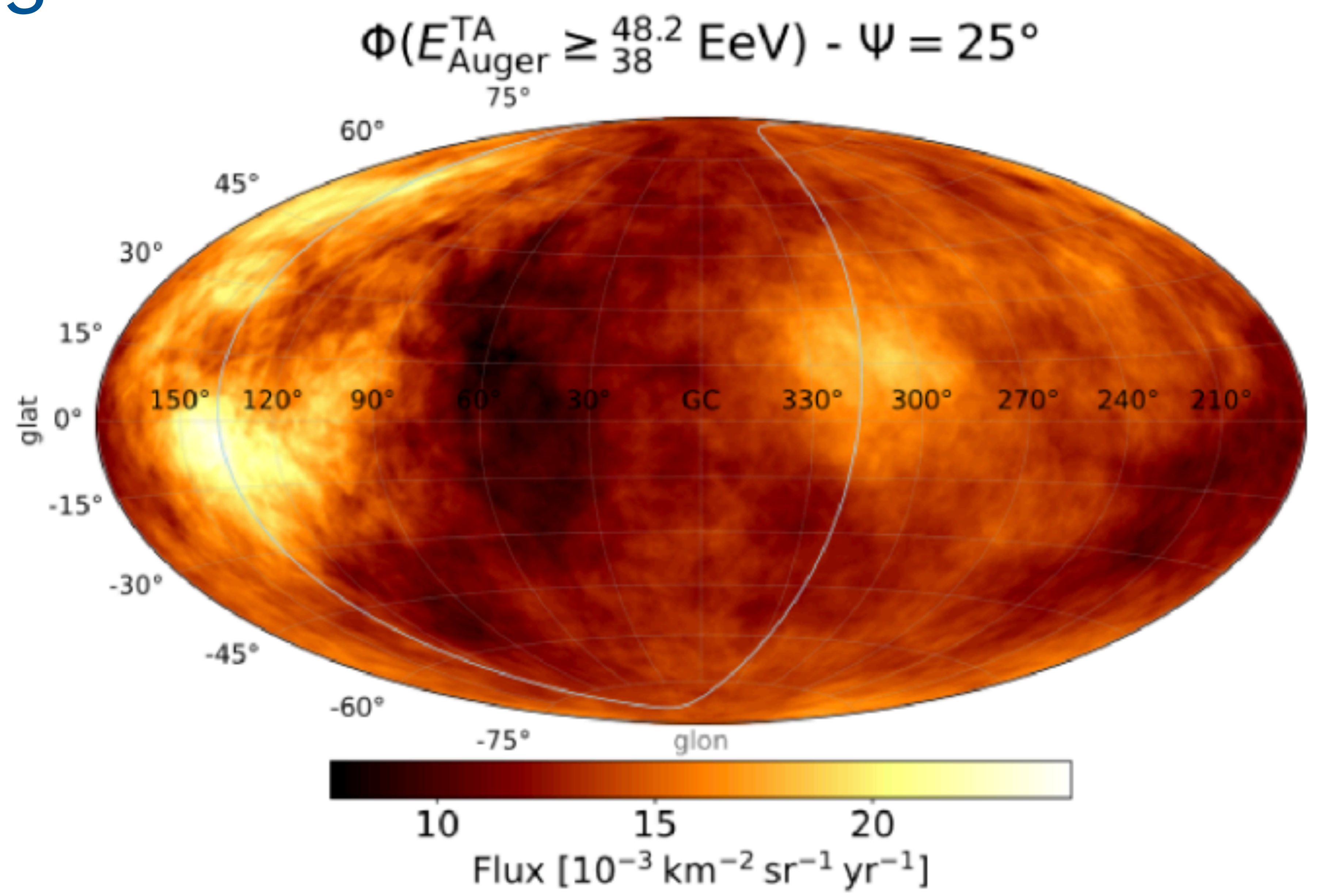


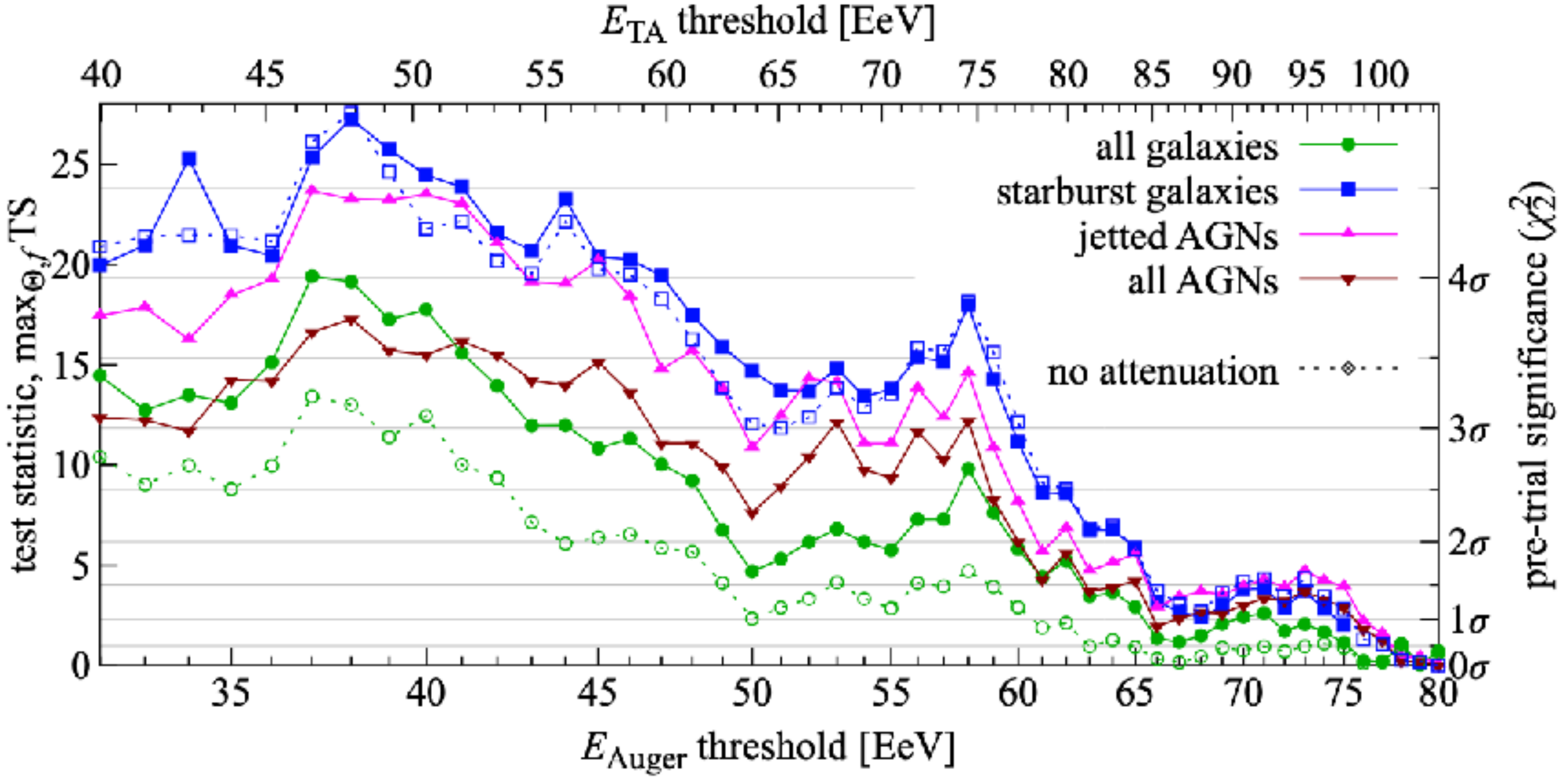
Auger conclusioin:
Unbiased calibration ONLY if evolution of the mass composition is accounted for

NEW
F.Salamida, PoS(ICRC2025) 480

Auger and TA WG - full sky search for anisotropies

	$E_{\min}$	TS	f/%	Θ/°	post-trial
All galaxies	37 EeV$_{\text{Auger}}$ ≈ 47 EeV$_{\text{TA}}$	19.3	$13.1^{+4.7}_{-3.6}$	$15.5^{+6.1}_{-3.6}$	3.4σ
Starburst galaxies	38 EeV$_{\text{Auger}}$ ≈ 48 EeV$_{\text{TA}}$	27.3	$10.6^{+56.6}_{-3.2}$	$17.6^{+26.6}_{-4.1}$	4.2σ
All AGNs	38 EeV$_{\text{Auger}}$ ≈ 48 EeV$_{\text{TA}}$	17.6	$4.8^{+1.6}_{-1.4}$	$15.4^{+3.5}_{-2.8}$	3.3σ
Jetted AGNs	37 EeV$_{\text{Auger}}$ ≈ 47 EeV$_{\text{TA}}$	22.9	$8.8^{-2.6}_{-2.3}$	$17.4^{+3.4}_{-2.8}$	3.8σ
All gal. (no atten.)	37 EeV$_{\text{Auger}}$ ≈ 47 EeV$_{\text{TA}}$	13.5	$33.6^{+26.3}_{-19.4}$	$29.2^{+12.9}_{-17.5}$	2.8σ
Starburst gal. (no atten.)	38 EeV$_{\text{Auger}}$ ≈ 48 EeV$_{\text{TA}}$	27.3	$10.6^{+4.0}_{-2.7}$	$15.0^{+4.8}_{-2.9}$	4.2σ



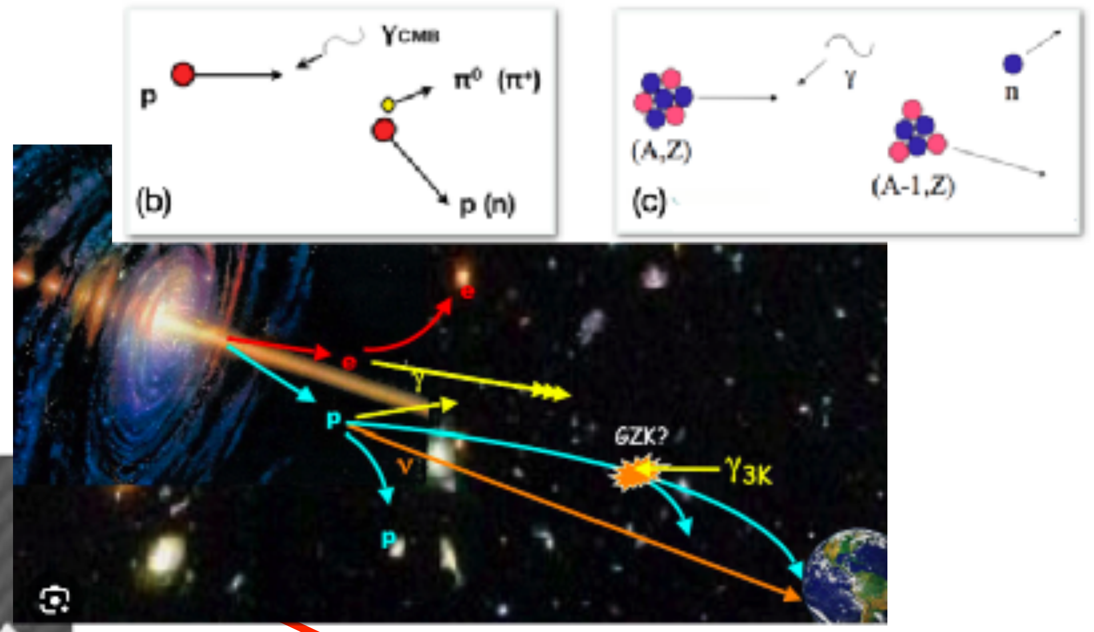


	ℓ	$E_{\min}$	pre-trial	post-trial
Auto-Correlation	2	41 EeV$_{\text{Auger}}$ ≈ 51.8 EeV$_{\text{TA}}$	4.2σ	2.1σ
All galaxies	2	37 EeV$_{\text{Auger}}$ ≈ 46.5 EeV$_{\text{TA}}$	3.2σ	—
Starburst galaxies	2	38 EeV$_{\text{Auger}}$ ≈ 47.8 EeV$_{\text{TA}}$	4.5σ	2.7σ
All AGNs	2	38 EeV$_{\text{Auger}}$ ≈ 47.8 EeV$_{\text{TA}}$	4.7σ	3.0σ
Jetted AGNs	2	38 EeV$_{\text{Auger}}$ ≈ 47.8 EeV$_{\text{TA}}$	4.1σ	2.0σ

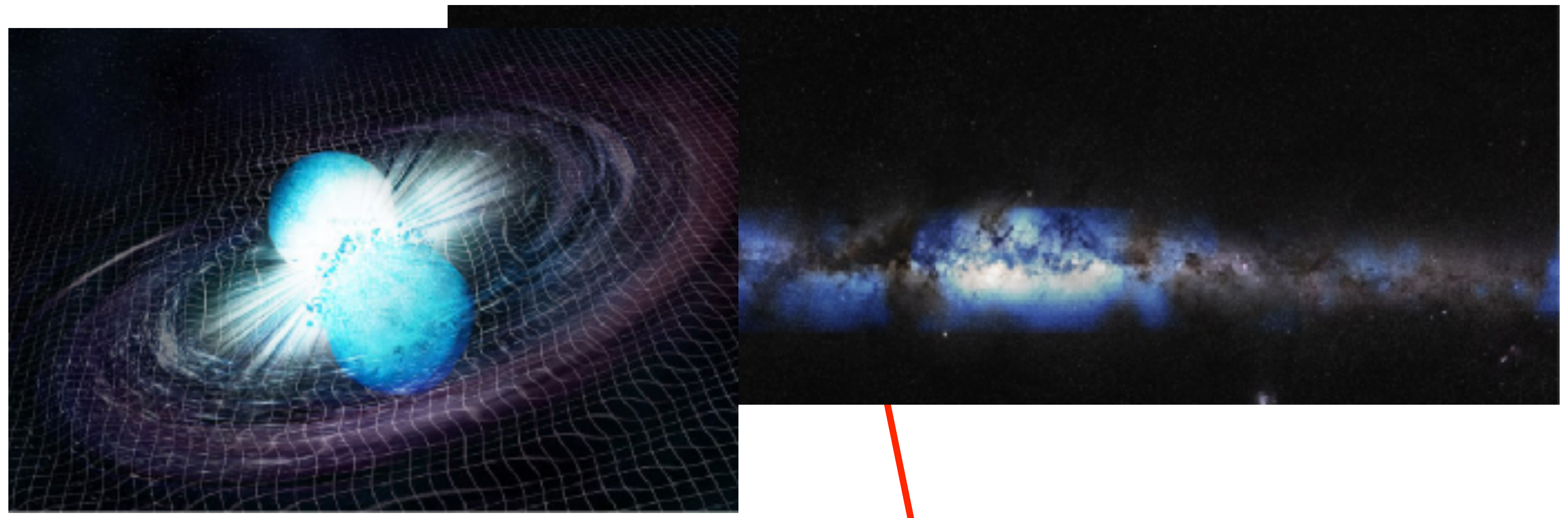
NEW
A.Galvez Urena, PoS(ICRC2025) 185

The science case

The origin of the flux suppression above $10^{19.5}$ eV

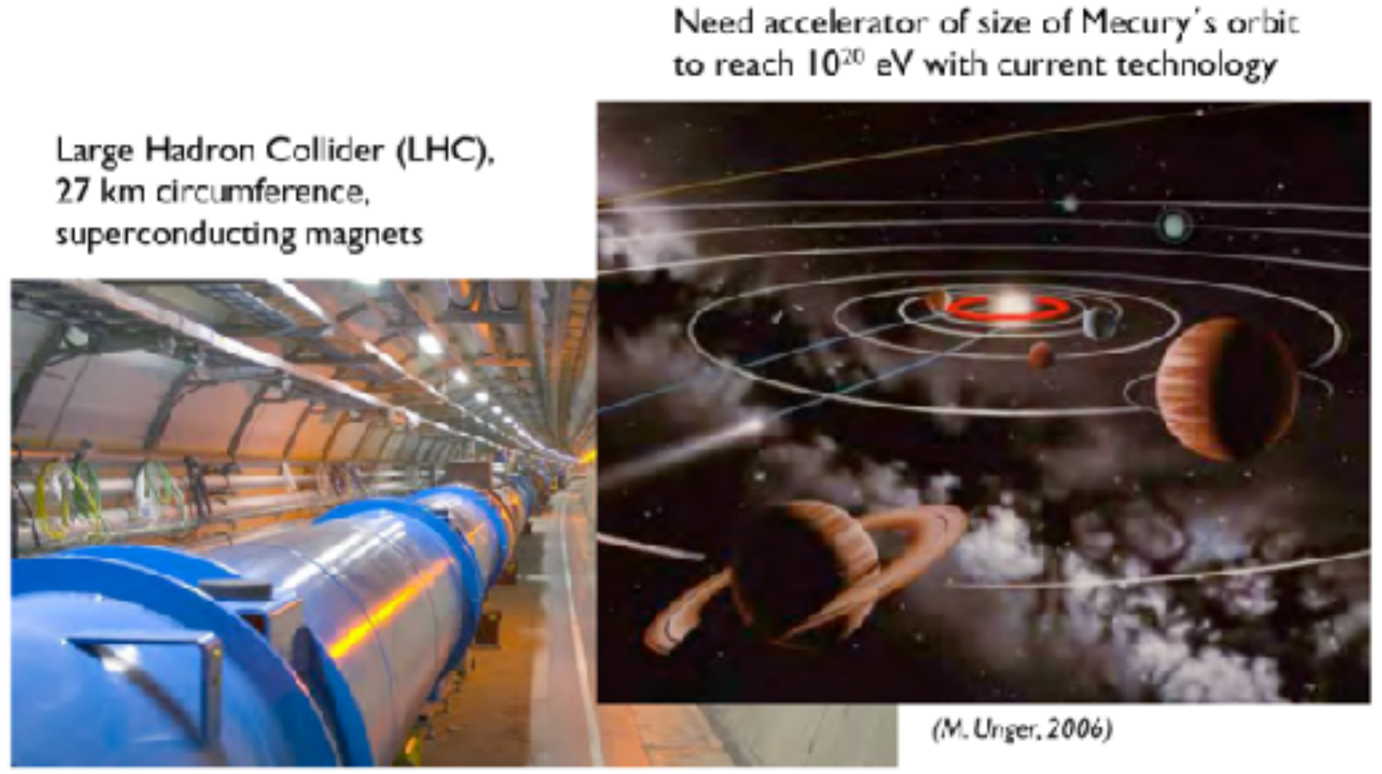


Do UHE photons and neutrinos exist?
Transients / steady sources



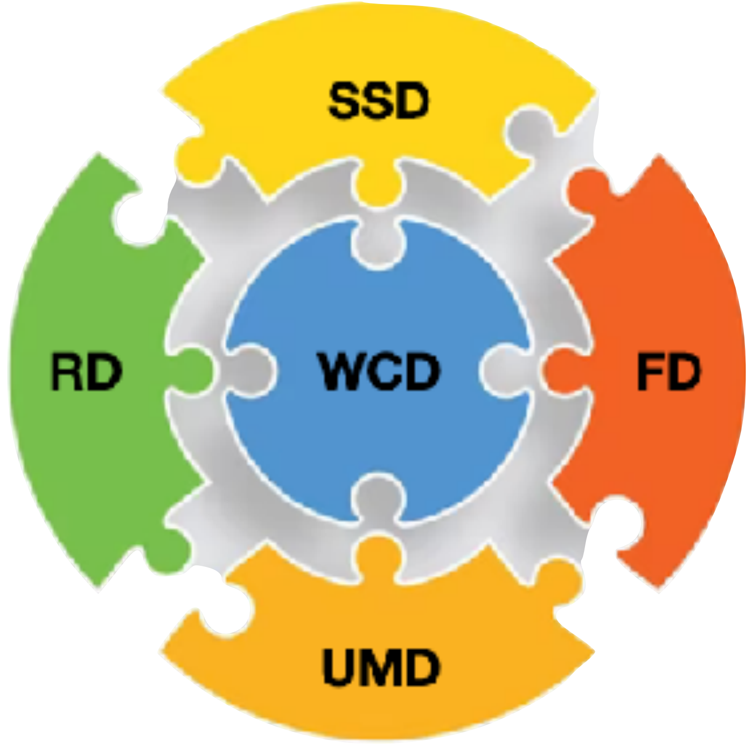
The identification of the sources

Particle interactions at UHE
Hints for new physics?



The nuclear composition at UHE

Multi-hybrid events in AugerPrime



WCD/SSD/RD can collect multi-hybrid events with a 100% duty cycle

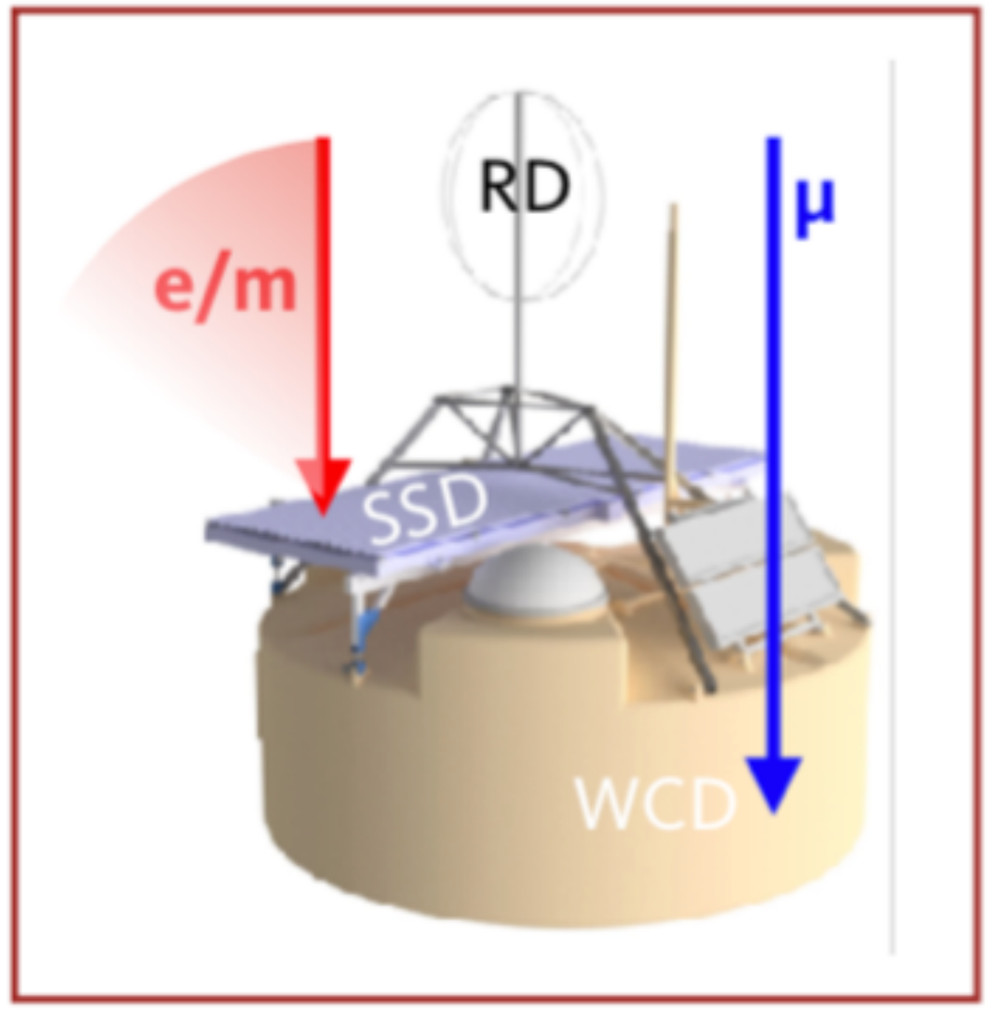
Separation of shower components can be obtained

- by WCD/SSD for events up to ~60^0
- by WCD/RD for inclined events >60^0
- by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving the photons/hadrons discrimination

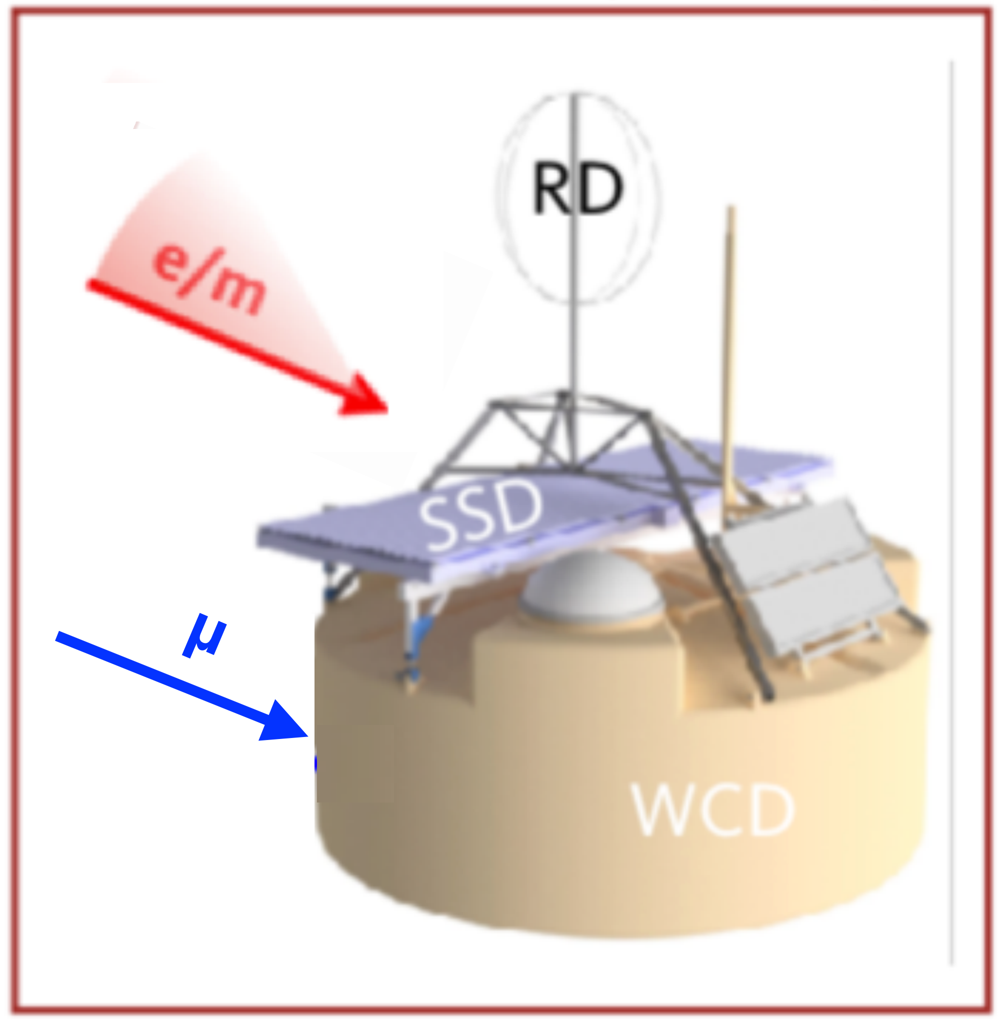
Hadronic interactions can be studied

- By WCD/RD simultaneously measuring energy and muon content of EAS up to the UHE with 100% duty cycle
- By exploiting different muon populations (WCD and UMD)

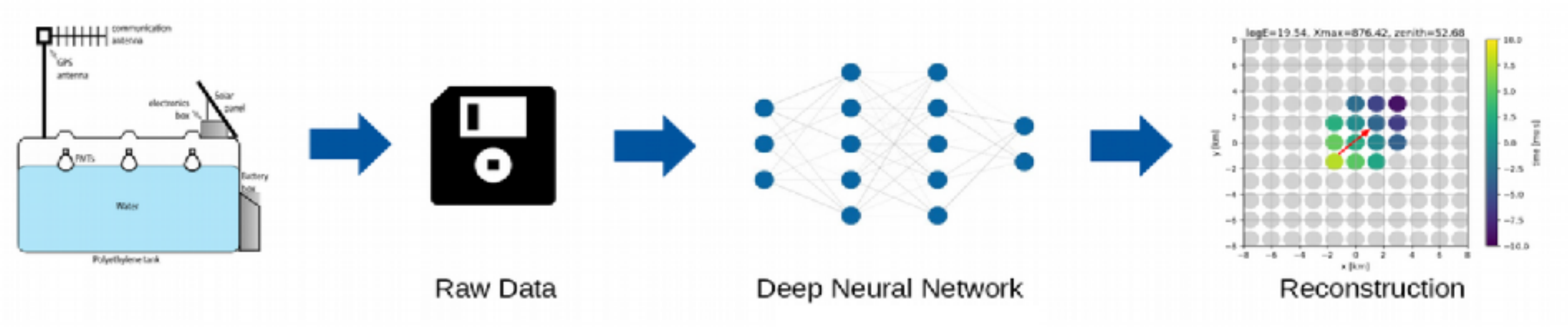
VERTICAL (0-60°)

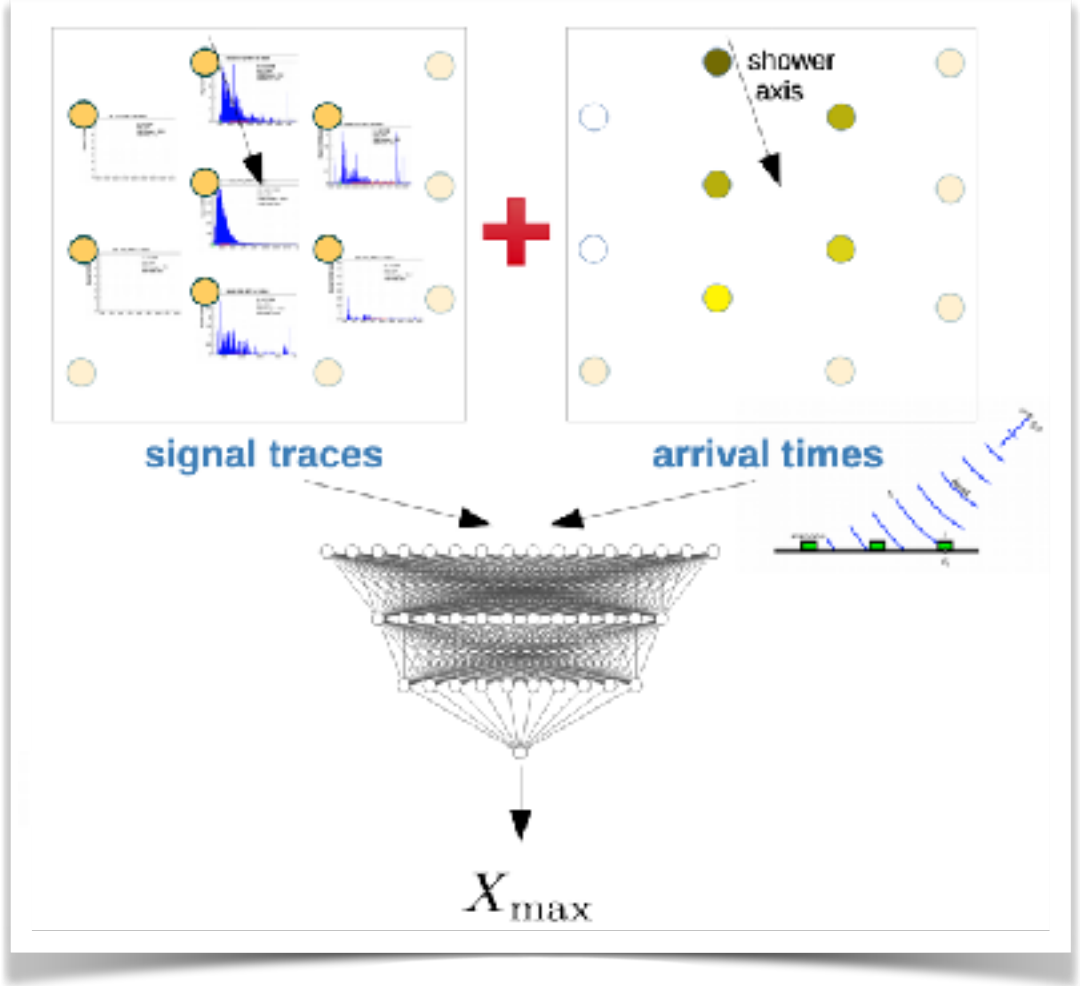


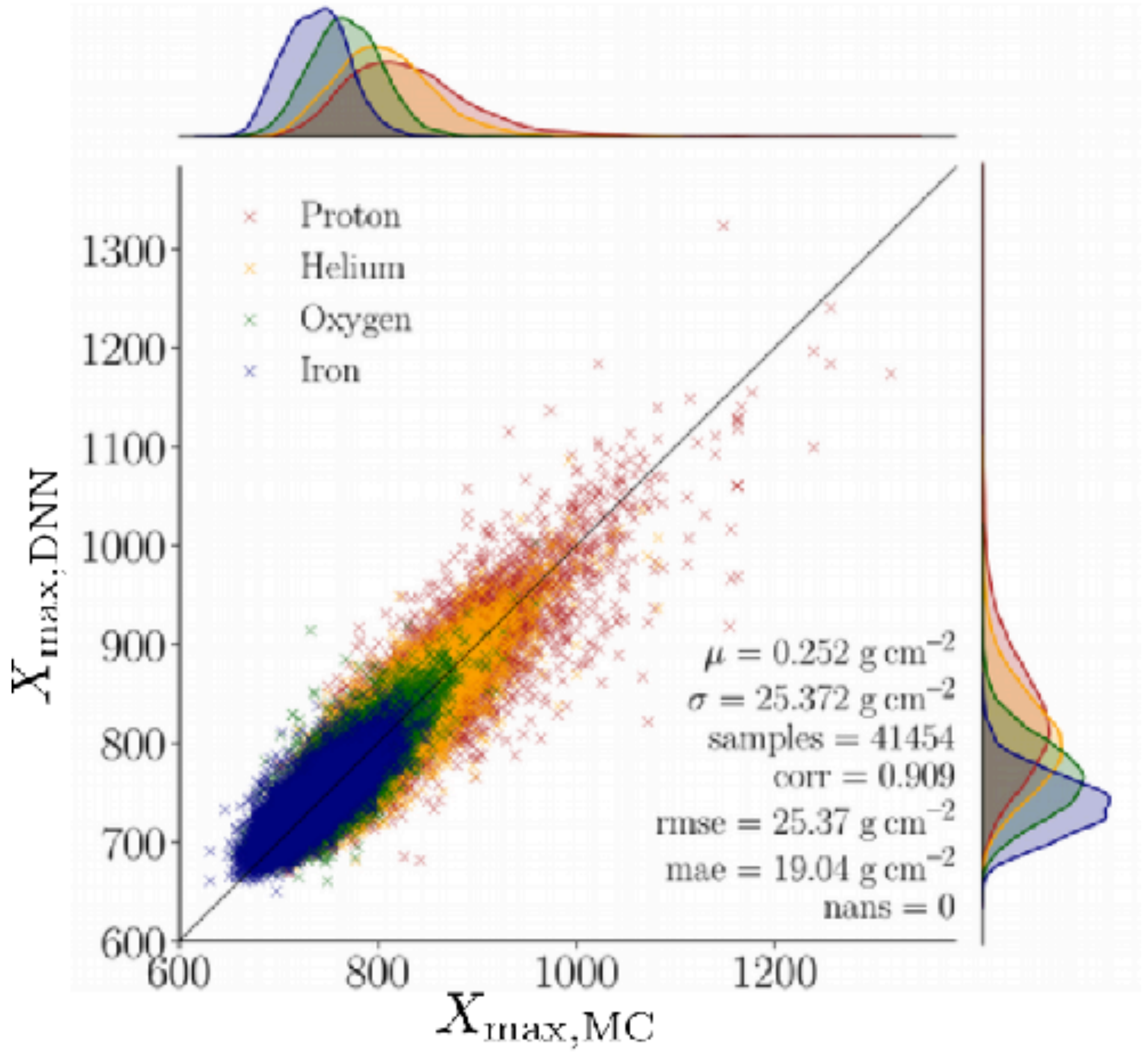
HORIZONTAL (60-90°)

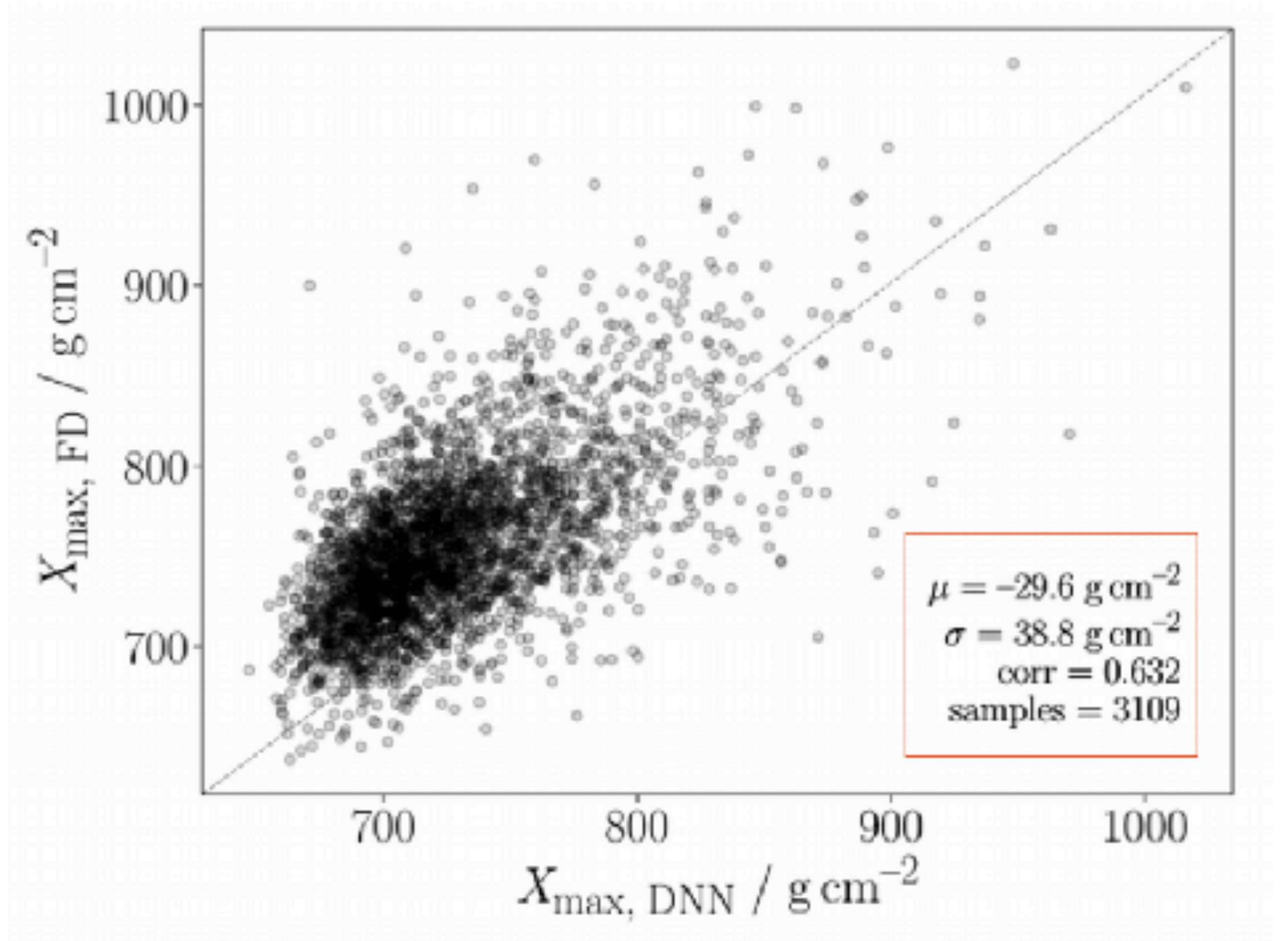


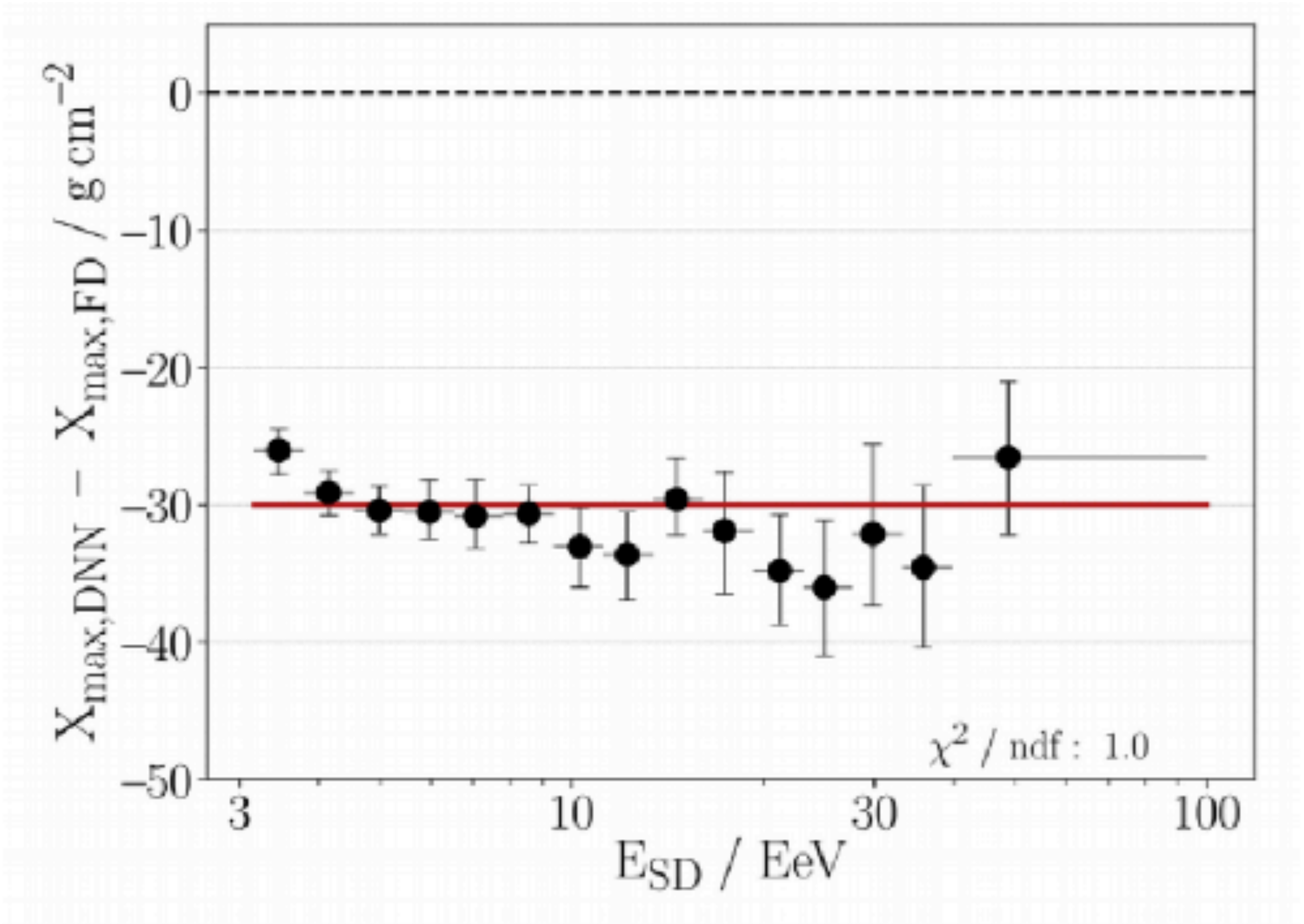
Multi-hybrid events and Machine learning





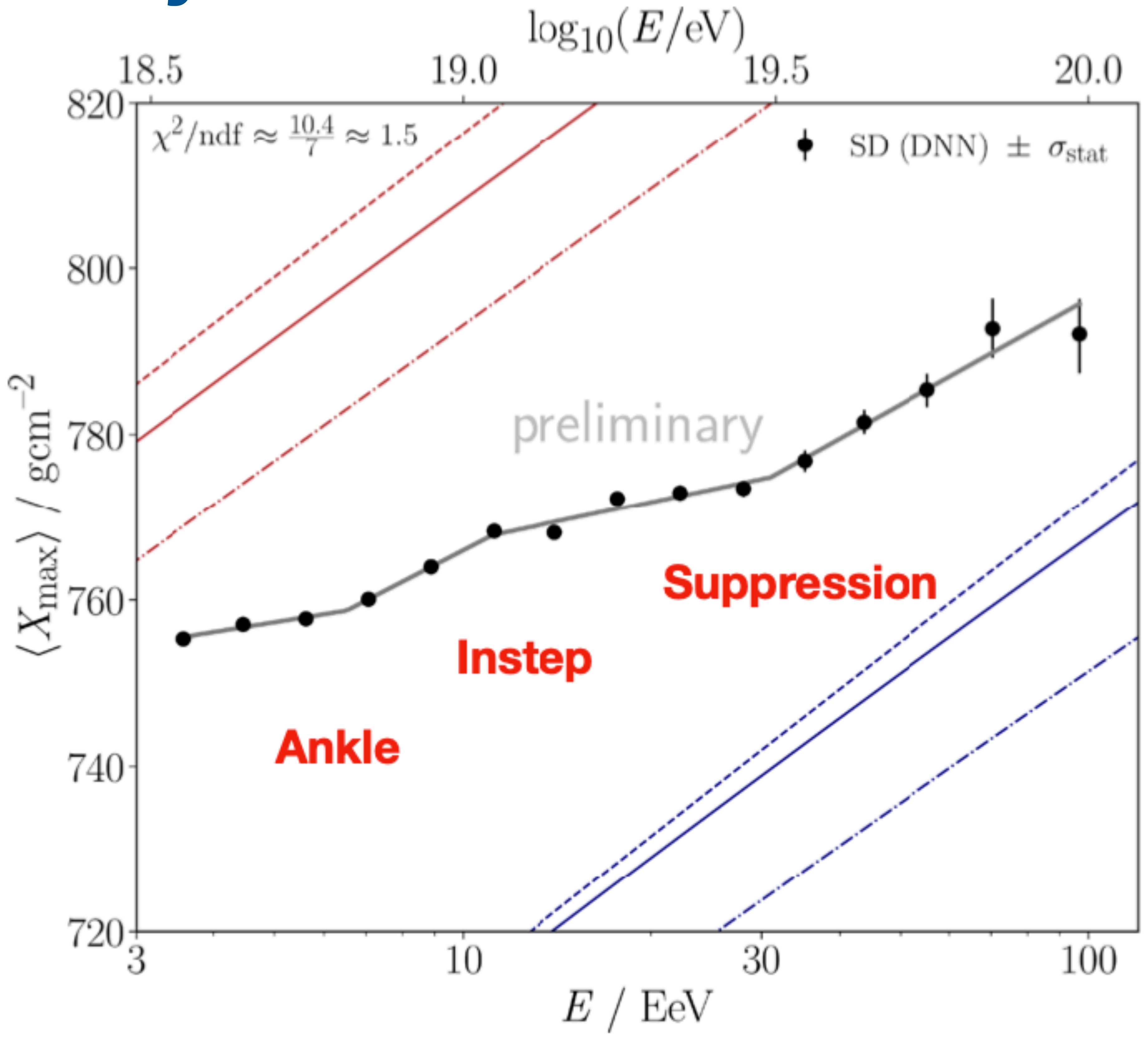


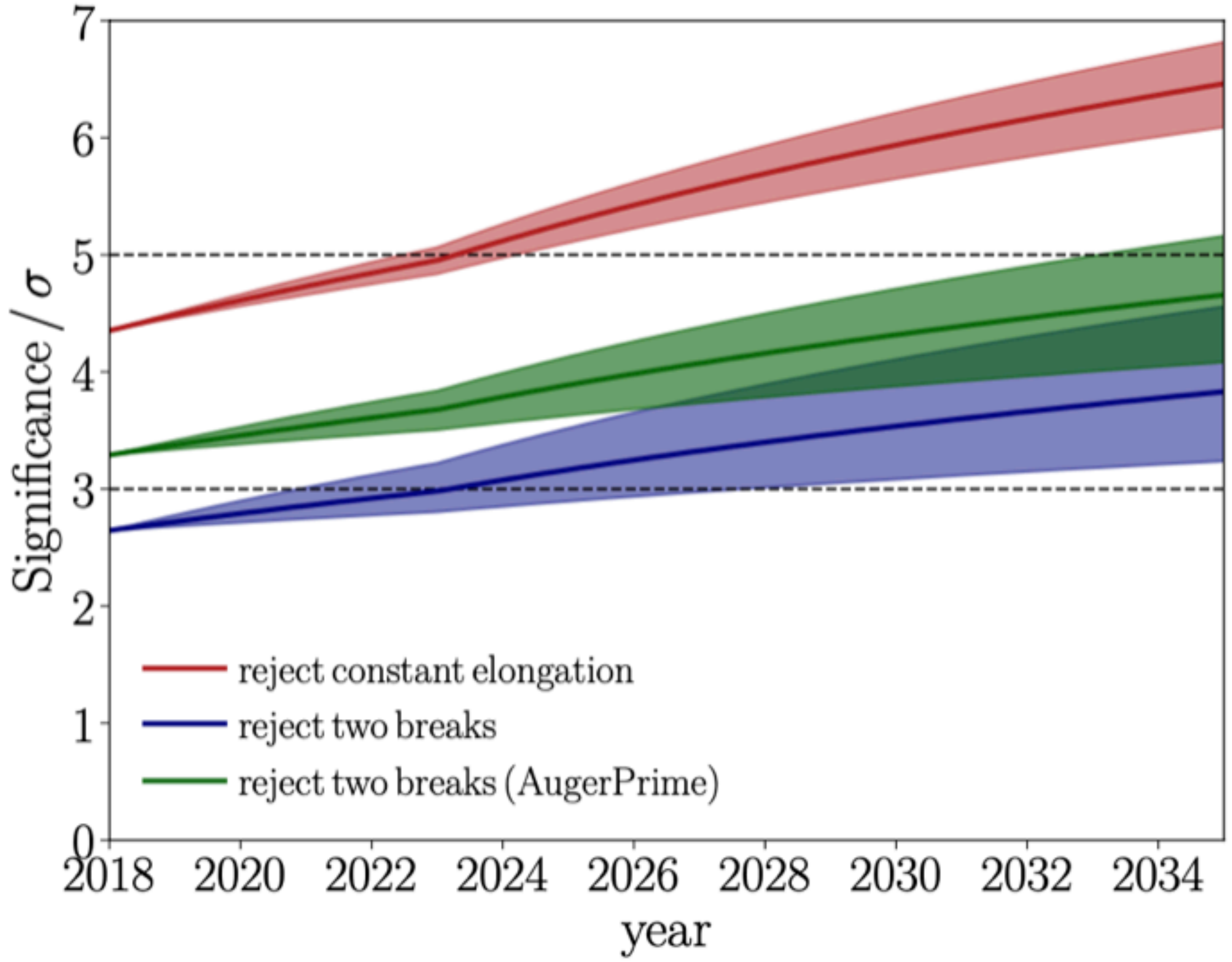




powerful Machine Learning techniques need to be cross-checked by means of multi-hybrid measurements!

Multi-hybrid events and composition





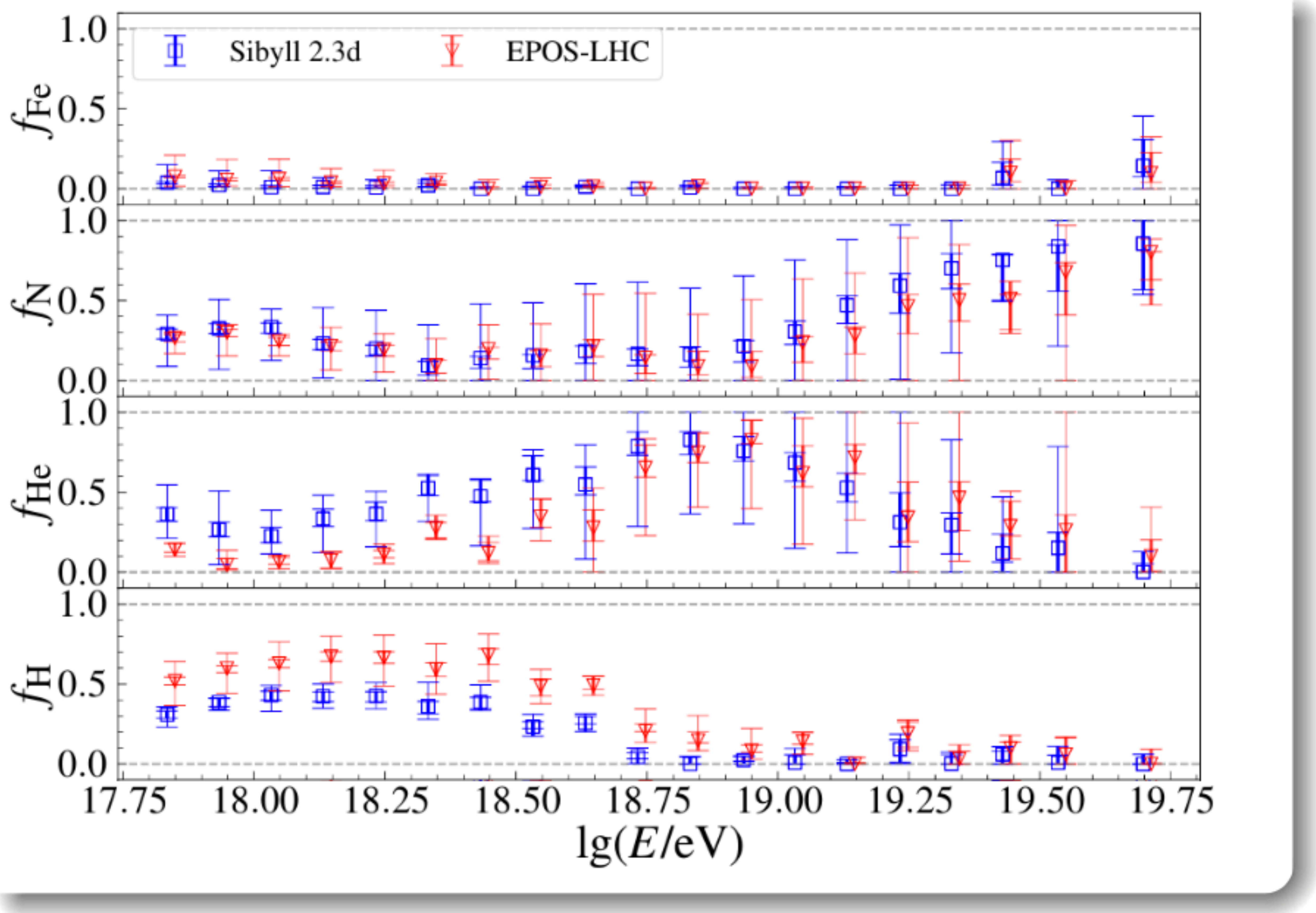
Composition features (DNN, current result, bias-corrected with FD) :

➡ energy independent elongation rate excluded at 4.4σ,

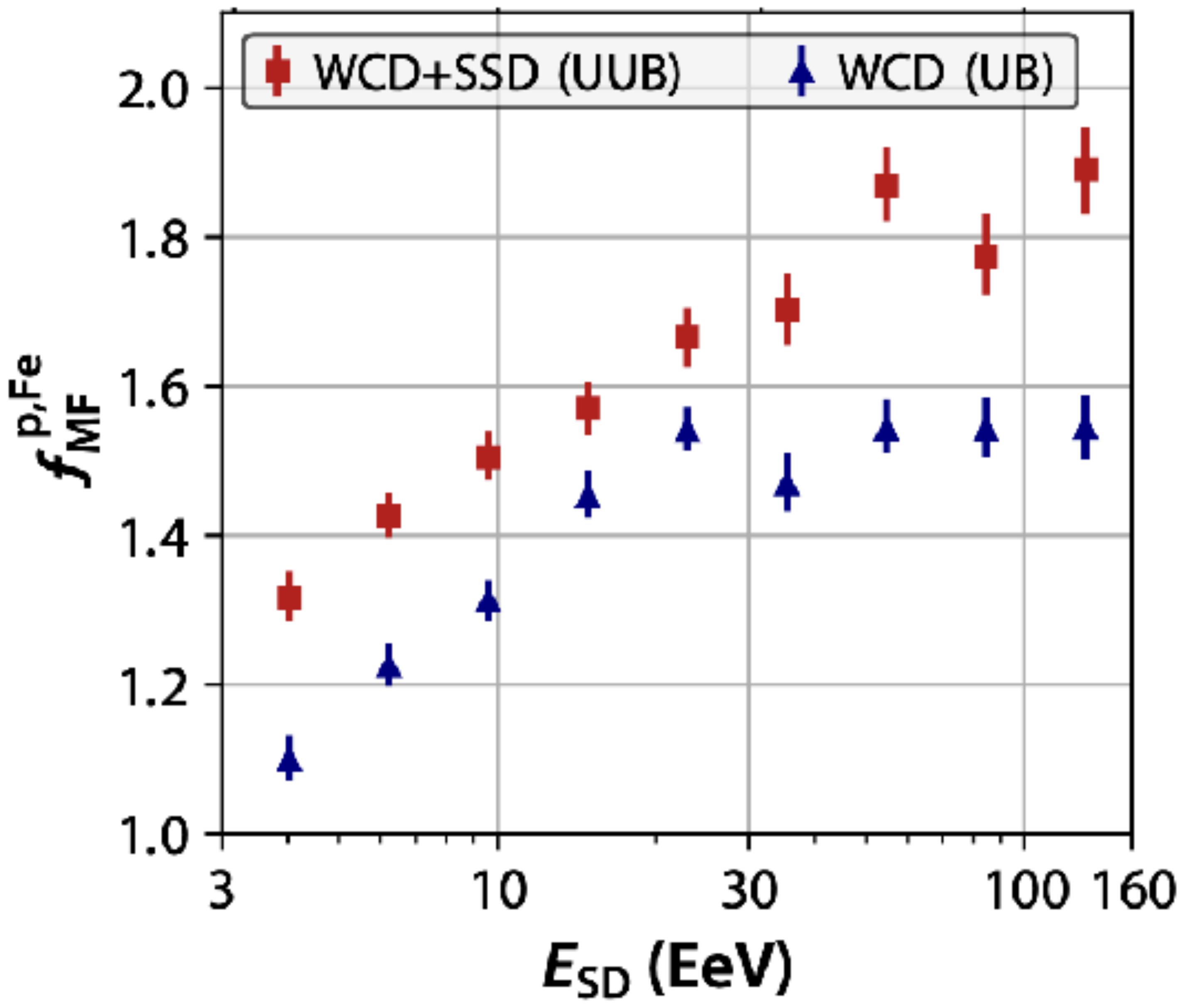
➡ two breaks rejected at ~2σ

5σ reachable in 10 years from now with AugerPrime

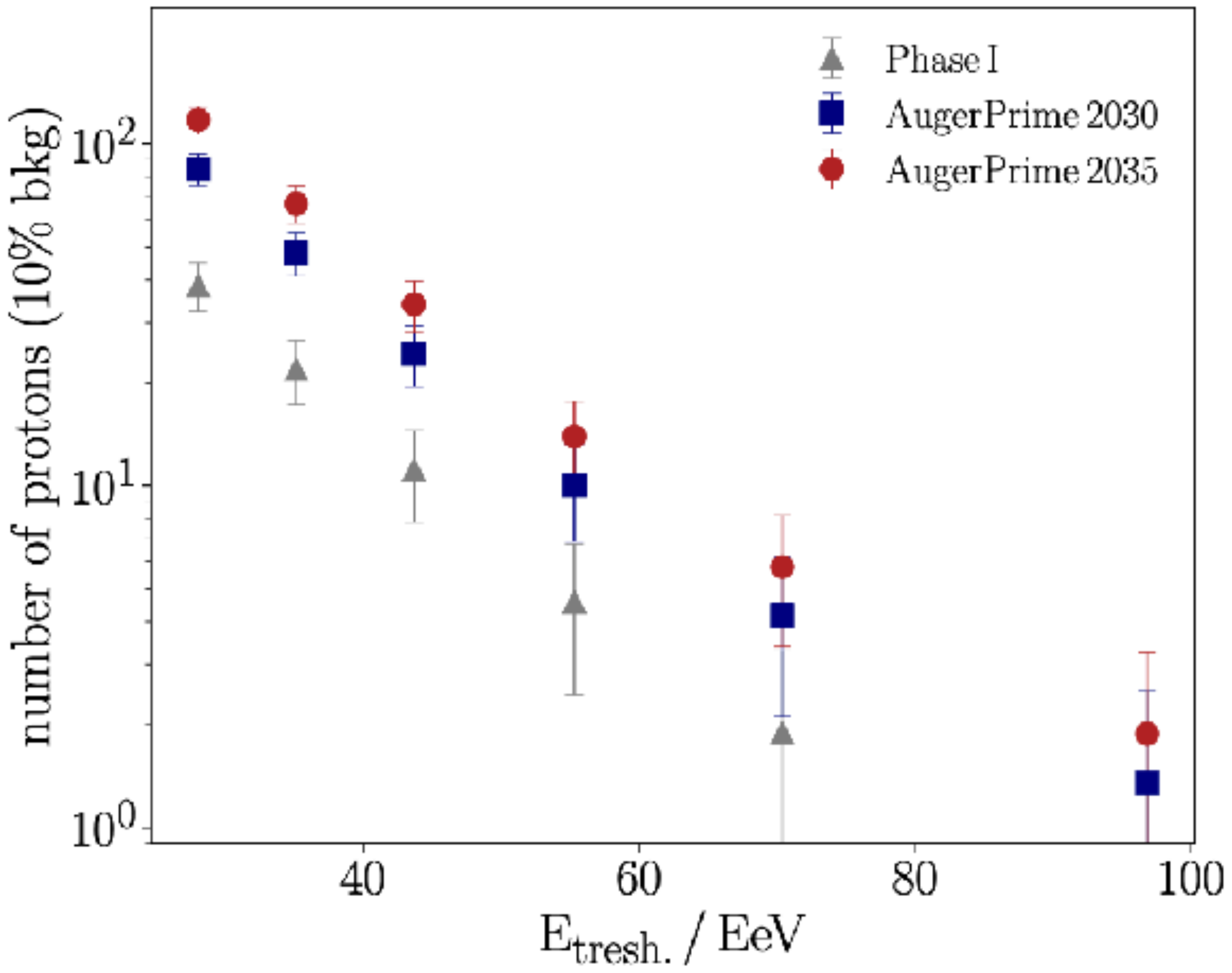
Multi-hybrid events and composition



merit factor MF: difference in units of std-dev



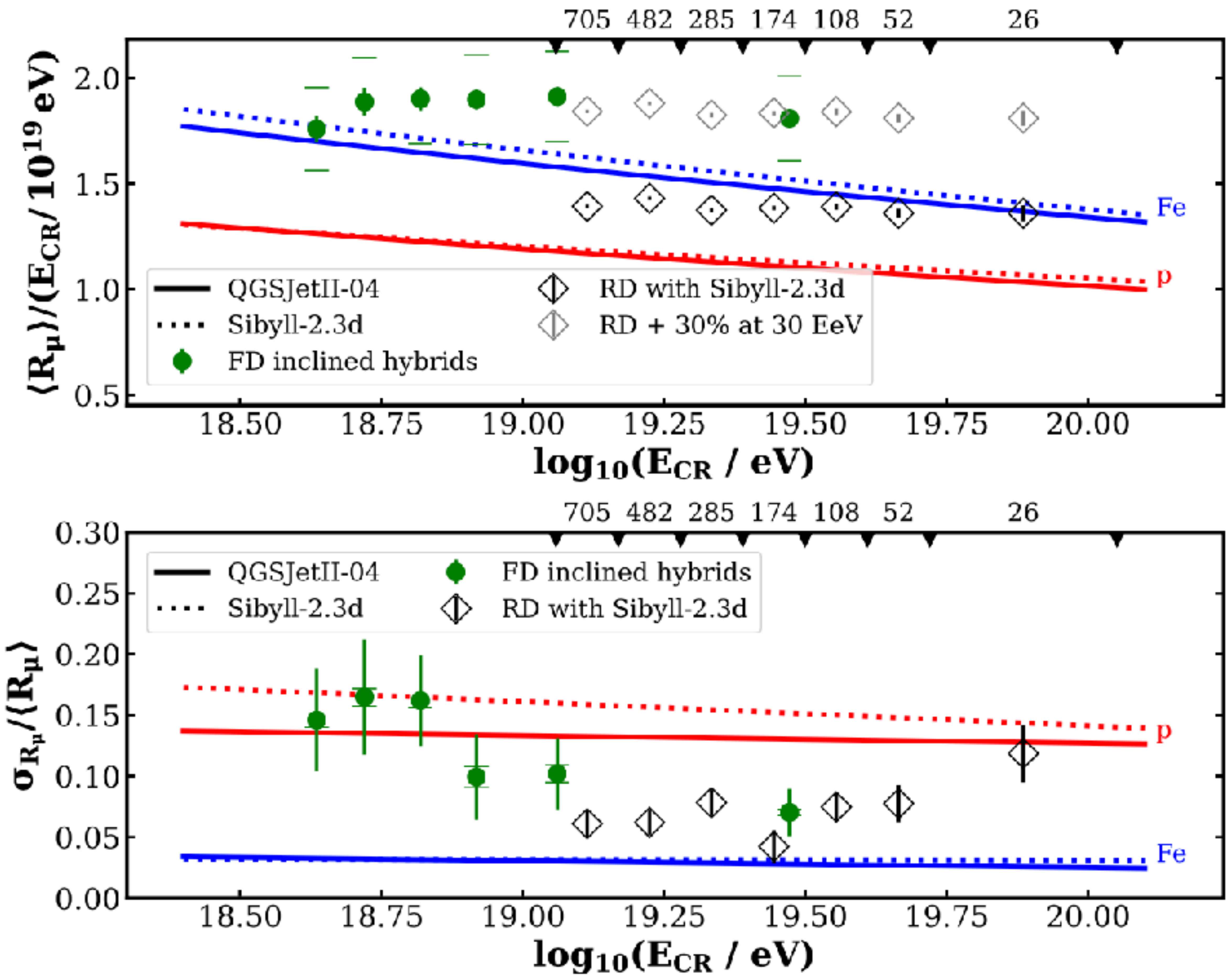
if UHE composition mix is 5%p and 95% Fe



What is the fraction of protons at UHE ?

WCD + SSD

Multi-hybrid events and hadronic interactions



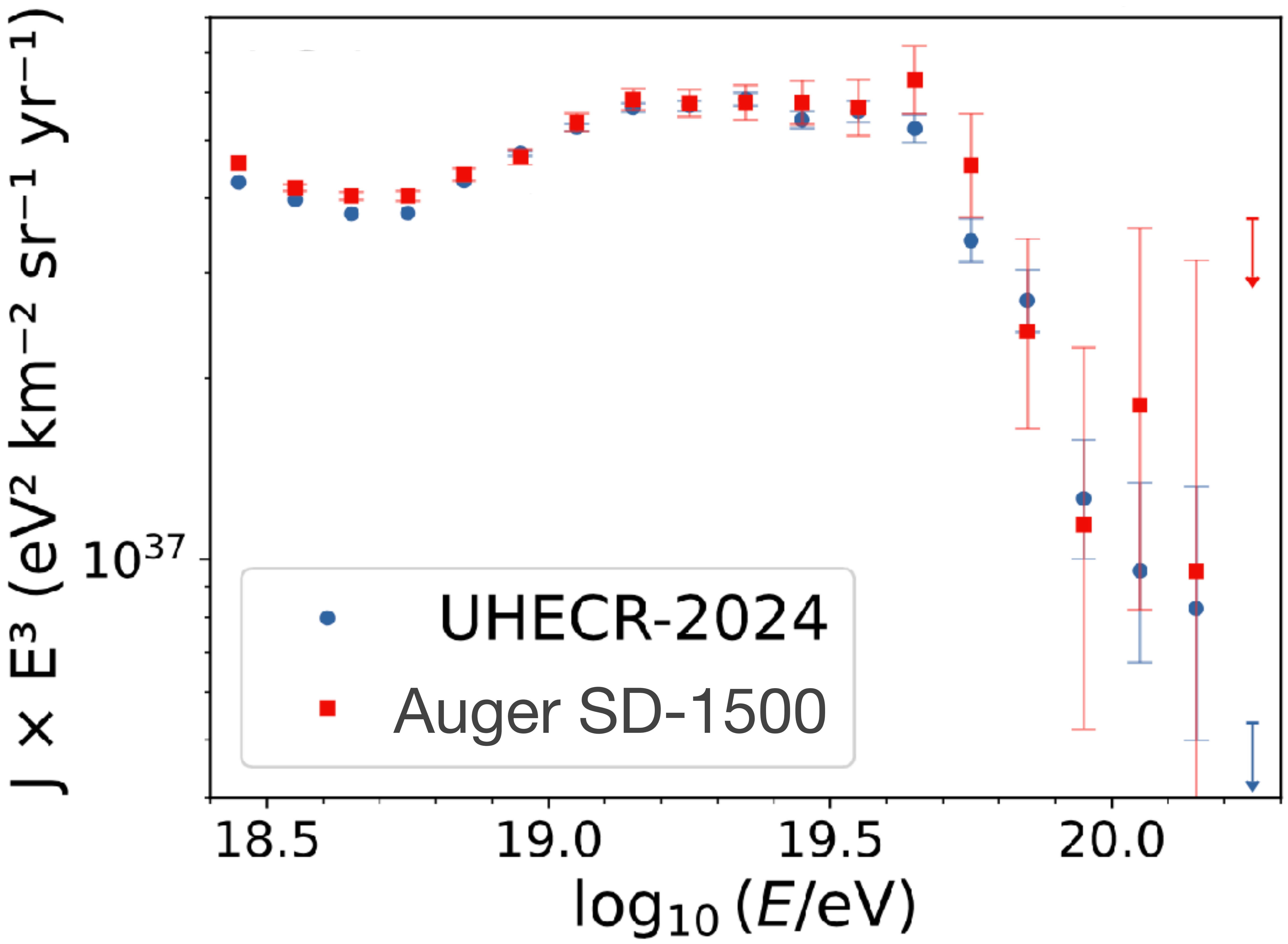
What is the muon number at UHE ?

WCD + RD - inclined events

RD+WCD, simulations - 10 years. (mass composition mixed)
ad-hoc correction for the muon deficit in simulation for the mean R_μ

Phase II : the first preliminary results

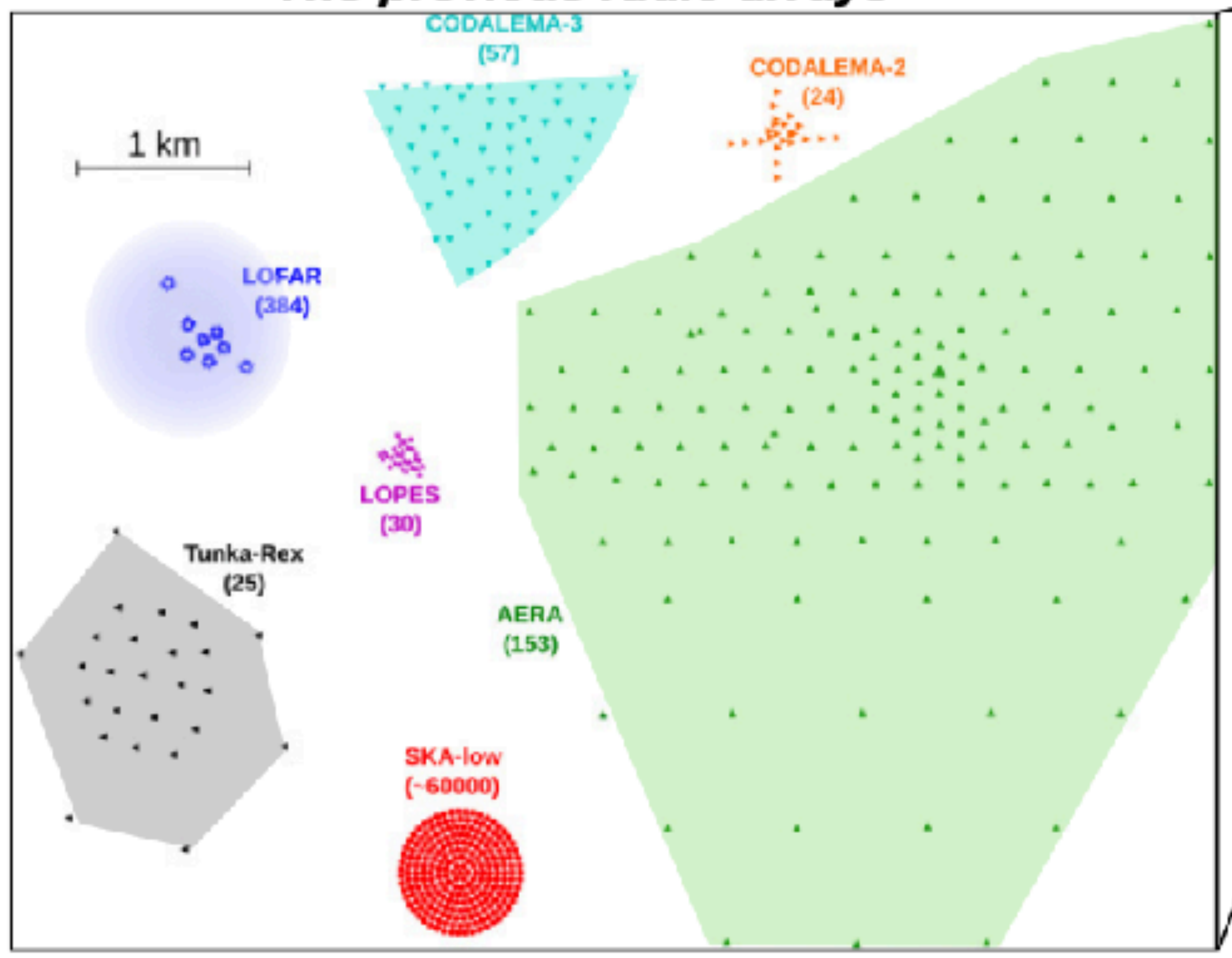
- ➡ First preliminary measurement of the energy spectrum (SD-1500, $\vartheta < 60^0$) with the data of Phase II
- ➡ Very good agreement with Phase I result !



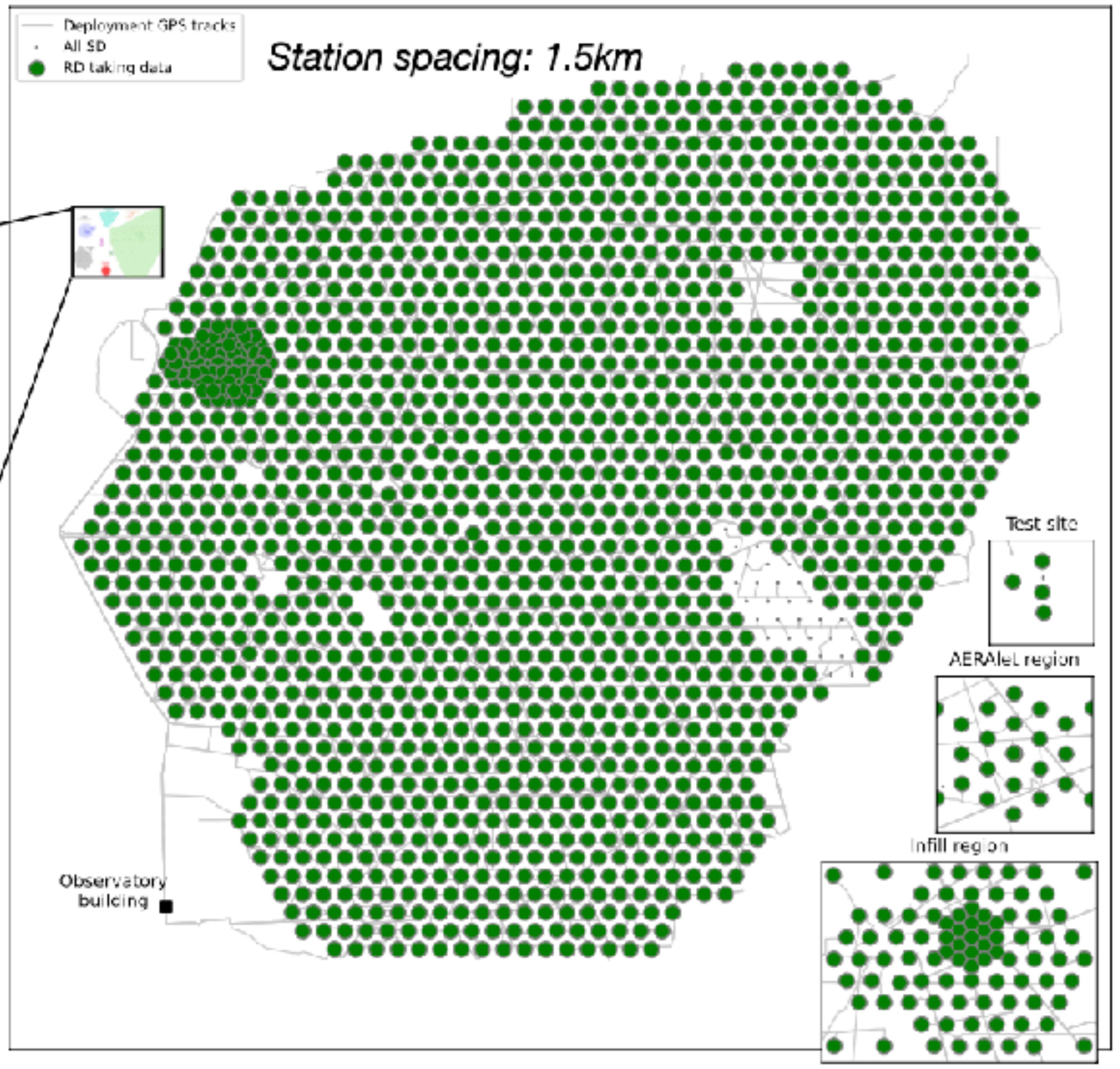
The largest radio array for cosmic rays by far.

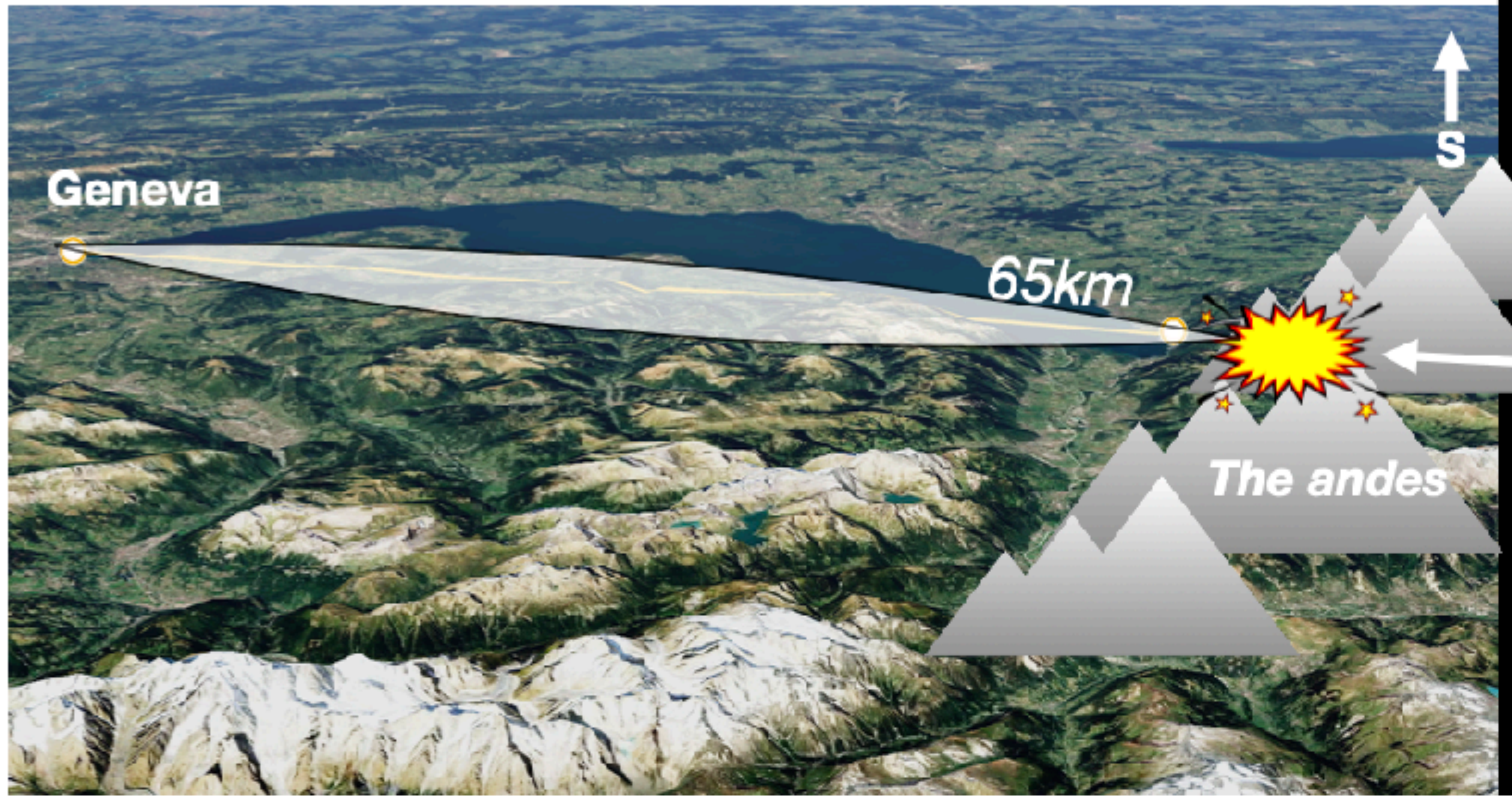
- Allows to measure the highest energies >$10^{18\text{-}21}$ eV
- Smaller denser grids (SKA) do high precision at $10^{16\text{-}18}$ eV

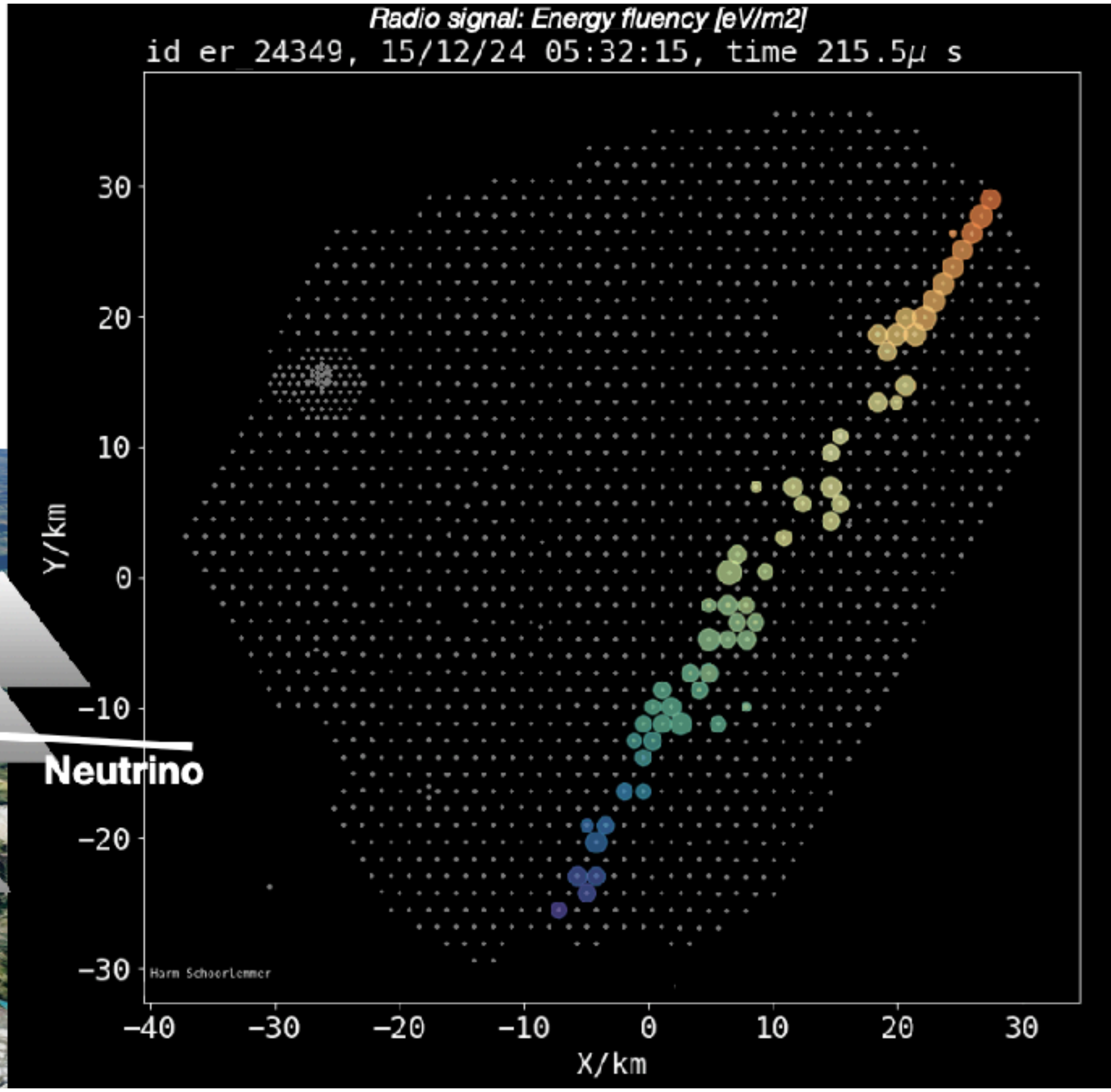
The previous radio arrays



T. Huege, Physics Reports, 620 (2016)







RD :

Measured event at 89^0, 20 EeV

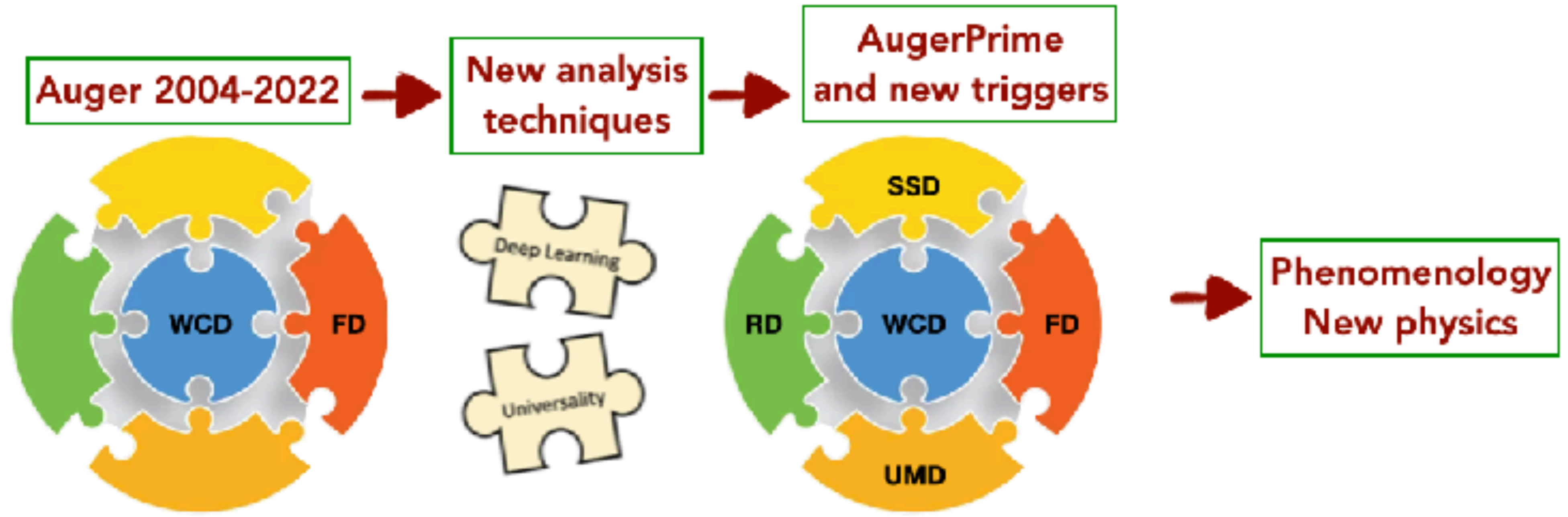
Science roadmap - From our coordinators (D.Boncioli, L.Cazon)

Mass composition at UHE is the key; together with the spectrum info

- ➡ what are the nuclear species ?
- ➡ up to which mass are our data described at the highest energies?
- ➡ which components do we need to explain the Galactic to extragalactic transition?
- ➡ Input to hadronic interaction models

+ Arrival directions

- ➡ exploration of the most interesting regions (CenA)
- ➡ Study of mass-informed dipolar amplitude
- ➡ UHECR-informed studies of models of GMFs and EGMFs



Neutral particles

- ➡ Cosmogenic νs and γs observation/non observation provide more info on the possible sources - strong connection to proton fraction at UHE
- ➡ Astrophysical νs and γs can be studied, down to which energy?
- ➡ Info on BSM effects (LIV, SHDM, upping showers)

Open Data

Started in 2007 with 1% of CR data, portal opened in 2021

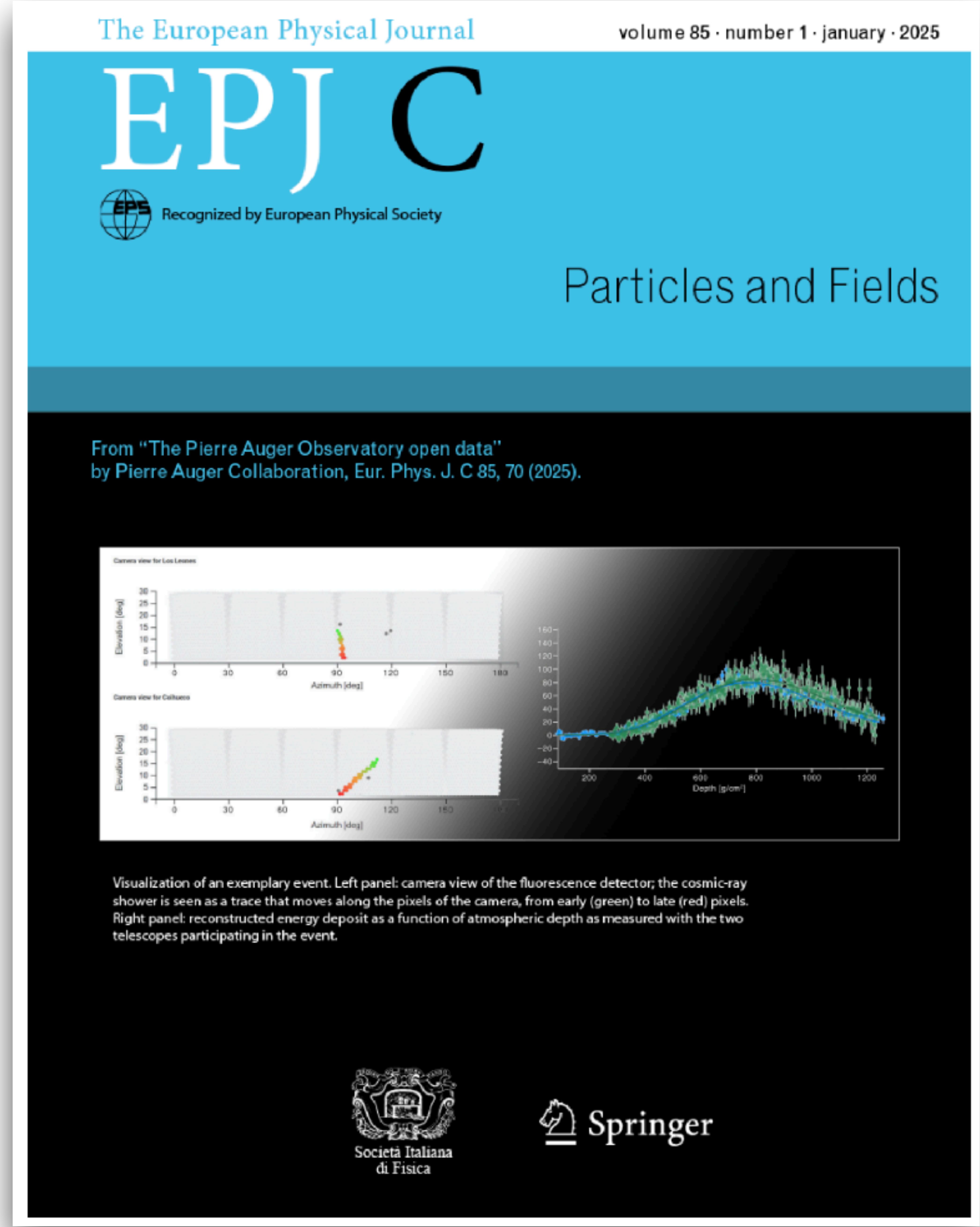
Table 1 List of specific releases on the open data portal [19] with the corresponding DOIs

Release tag	Date	Content	Specific DOI
Release 3.0	March 20, 2024	10% cosmic-ray data, low energy sample	https://doi.org/10.5281/zenodo.10488964
Release 2.0	Dec 22, 2022	10% cosmic-ray data, inclined sample (60°–80°), Outreach section with different languages	https://doi.org/10.5281/zenodo.6867688
Release 1.1	Oct 26, 2021	100% atmospheric data and scaler data	https://doi.org/10.5281/zenodo.5588460
Release 1.0	Feb 15, 2021	10% cosmic-ray data, vertical sample (0°–60°) and auxiliary files, ready-to-use event display, analysis examples	https://doi.org/10.5281/zenodo.4487613

➡ March 2024: >54000 SD750 + 197 HeCo hybrid events
100 highest energy events

➡ Next release : 30% of Phase I data (2004-2021) vertical SD + Hybrids,
100% atmo+scaler

NEW
EPJC 85 (2025) 70
V.Scherini, PoS(ICRC2025) 646



New data center at CNAF

The storage and computing resources required for 2025 have arrived at CNAF.

Storage:
The /sps/pauger will be increased from 150 T → 300 T

Computing:
about 3000 HS06 (similar computing power as in Lyon) has also be given as requested. The access to the pauger users will be provided through a HTCondor batch system

TAPE: the tape is also available at this endpoint : xfer-archive.cr.cnaf.infn.it:8443/pauger-tape/

https://www.auger.unam.mx/AugerWiki/CNAF

Synchronization between Malargue and CNAF:
Testing new software tools : very advanced **[Lorenzo Perrone**, Juan Pablo Behler]
A new software tool - *Mirage* - based on rclone has been created for this task

<u>Key points</u>:
→ optimize the usage of bandwidth and CPU through continuous and parallel processes replacing the current rsync-based procedure executed twice a day.
→ Filtering options (you can activate/deactivate specific targets)
→ More efficient diagnostic

The Pierre Auger Observatory

Phase I [2004-2022]: a radical change in our view of UHECRs

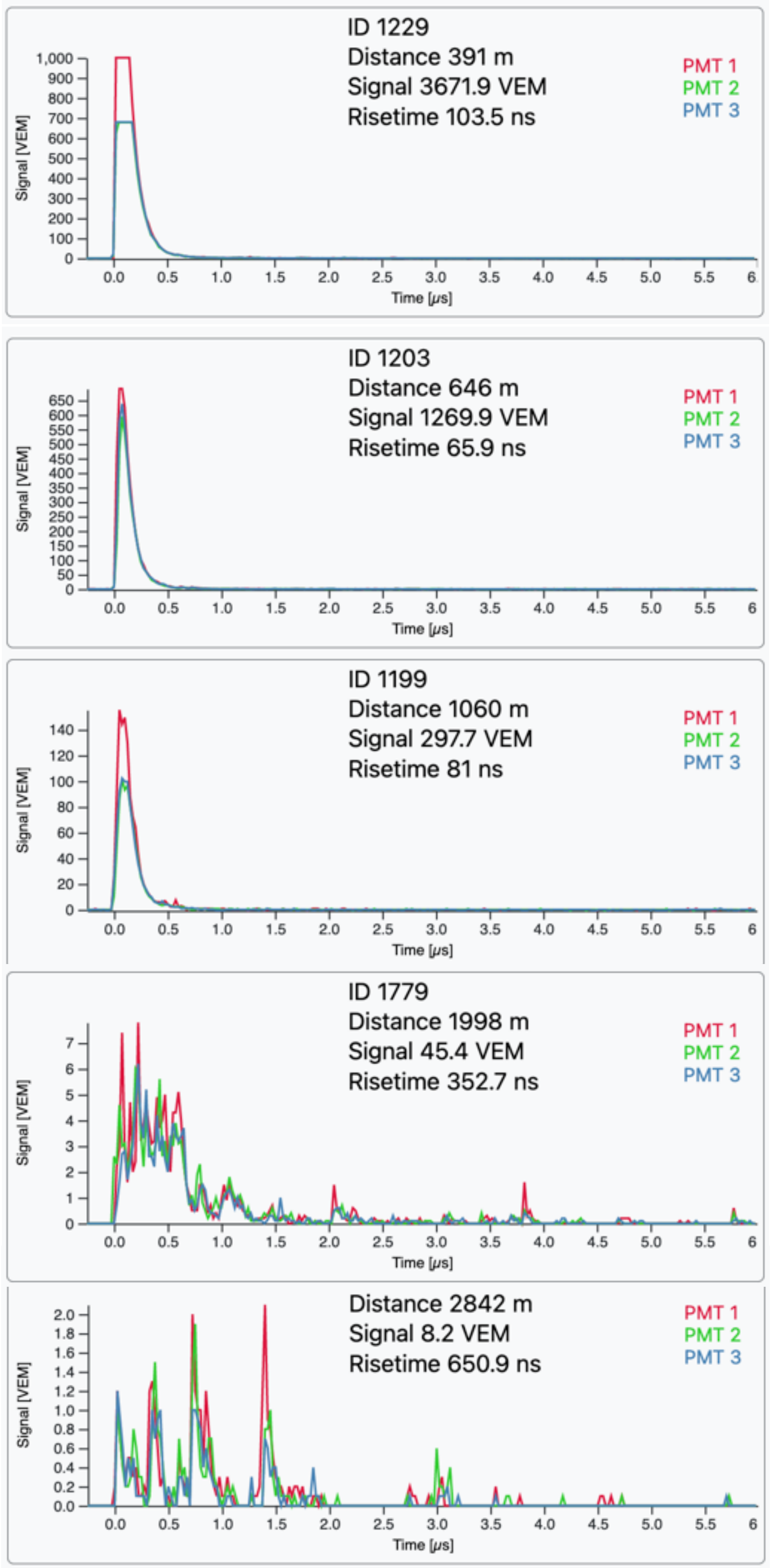
↓

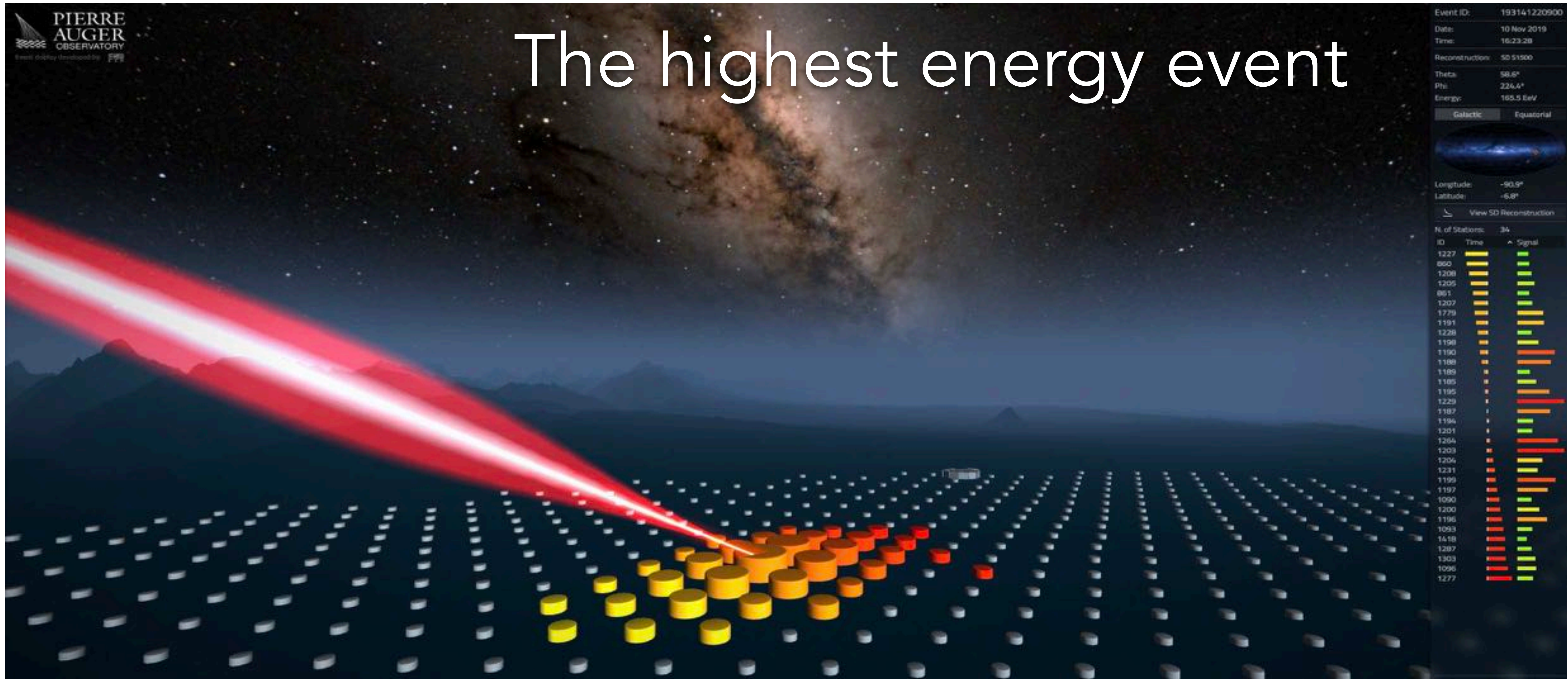
Phase II [2025-2035]: more statistics and more insight on the UHECR nuclear mass composition

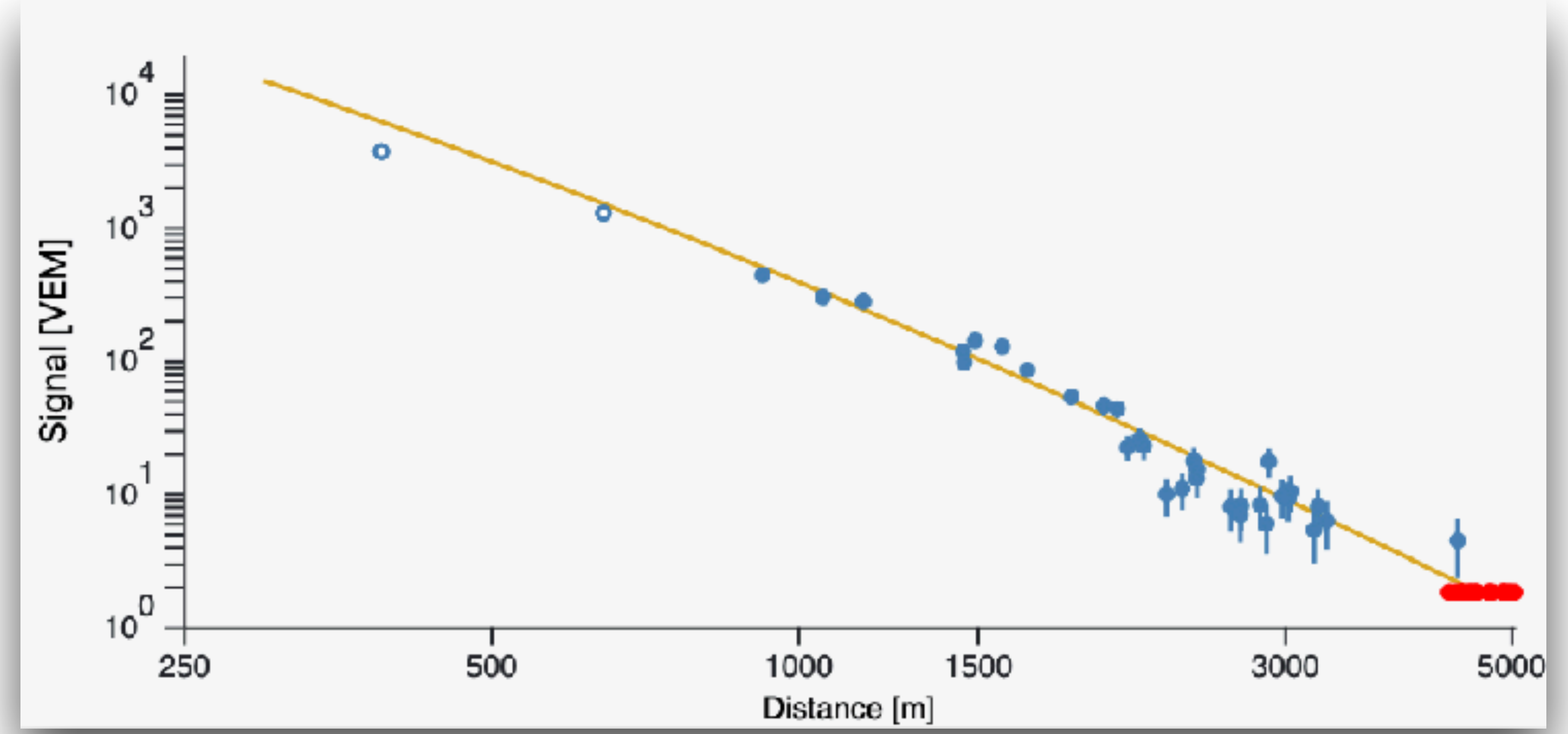
➡human-power: need to increase number of contracts for post-Docs and number of PhD students
➡our responsibilities in the maintenance and services should be supported

BACKUP

The highest energy event







Date	2019-11-10
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

SD-PMT maintenance

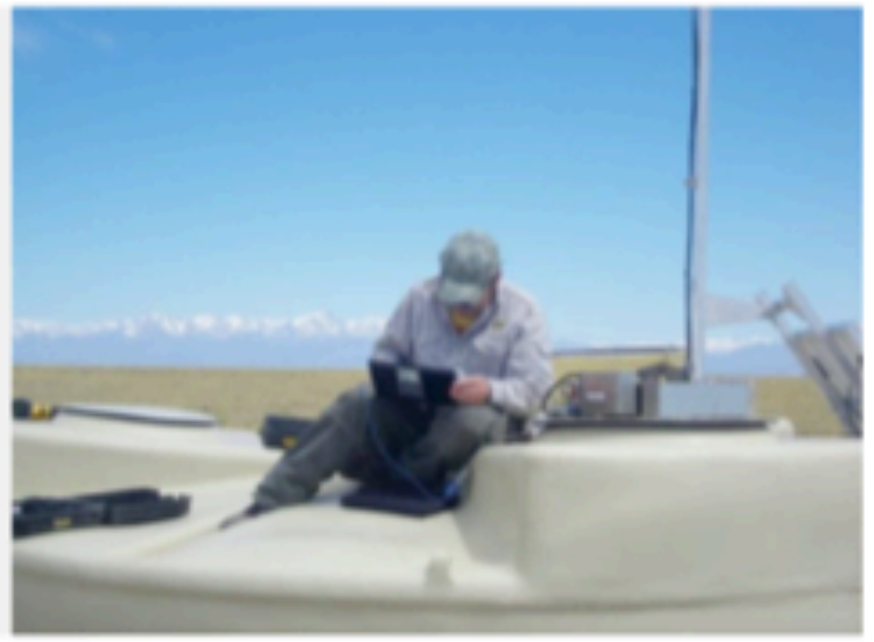
In the field

to repair or change PMTs with failures

- PMT weeks: special SDE shifts dedicated to the PMT maintenance in the field

twice/year for 2 weeks
2-3 teams in the field at the same time

40 to 60 PMTs fixed



INFN-Torino in charge of SD-PMTs
[M.Aglietta, A.Gorgi, A.Zampieri]

In the LAB

to repair PMTs, bases and HVPS returned from the field

- *reconditioning of PMTs in SdeCO*
  - *PMT cleaning*
  - *removal of PVC support*
  - *new flying leads welding*
  - *new base installation*
  - *PMT full test*
  - *potting (need many PMTs ready)*
  - *packing*
- *reconditioning of the bases in SdeCO*
  - *base cleaning*
  - *fast HV module test (~88% ok)*
  - *LTT 1 week   (~80% ok)*
  - *HV capacitors replacement*
  - *other actions (e.g. cure for raining, short pins…)*
  - *full functional test (automatic system)*
- *HVPS repaired in INFN-Torino*

QUOTATION

Sens-Tech Ltd.
18 The Avenue
Egham
Surrey
TW20 9AB
United Kingdom

Telephone: 01784 624410
E Mail: info@sens-tech.com

SENS - TECH

Customer	Quotation	
Karlsruher Institut fur Technology (KIT)	**Quote Number:**	100691
Finanzmanagement	**Date:**	24/06/2025
Hermann-von-Helmholtz-Platz	**Sens-Tech Contact:**	Paul Hurtado
Eggenstein-Leopoldshafen	**Valid To:**	08/07/2025
Germany	**Customer Reference:**	
Contact Name:	**Payment Terms:**	30 Days from Date of Invoice
Contact Email:	**Currency:**	Euros

Line No.	Sens-Tech Part No.	Product Description	Quantity	Unit Price	Lead Time	Total Price
1	PS2010/12	POWER SUPPLY	25	€293.39		€7,334.75
2	PS2010/12	POWER SUPPLY	50	€281.14		€14,057.00
3	PS2010/12	POWER SUPPLY	100	€268.89		€26,889.00
4	PS2010/12	POWER SUPPLY	250	€256.64		€64,160.00
5	EM33	EM33 ISSUE 3	25	€233.61		€5,840.25
6	EM33	EM33 ISSUE 3	50	€202.93		€10,146.50
7	EM33	EM33 ISSUE 3	100	€192.78		€19,278.00
8	EM33	EM33 ISSUE 3	250	€173.50		€43,375.00

More info

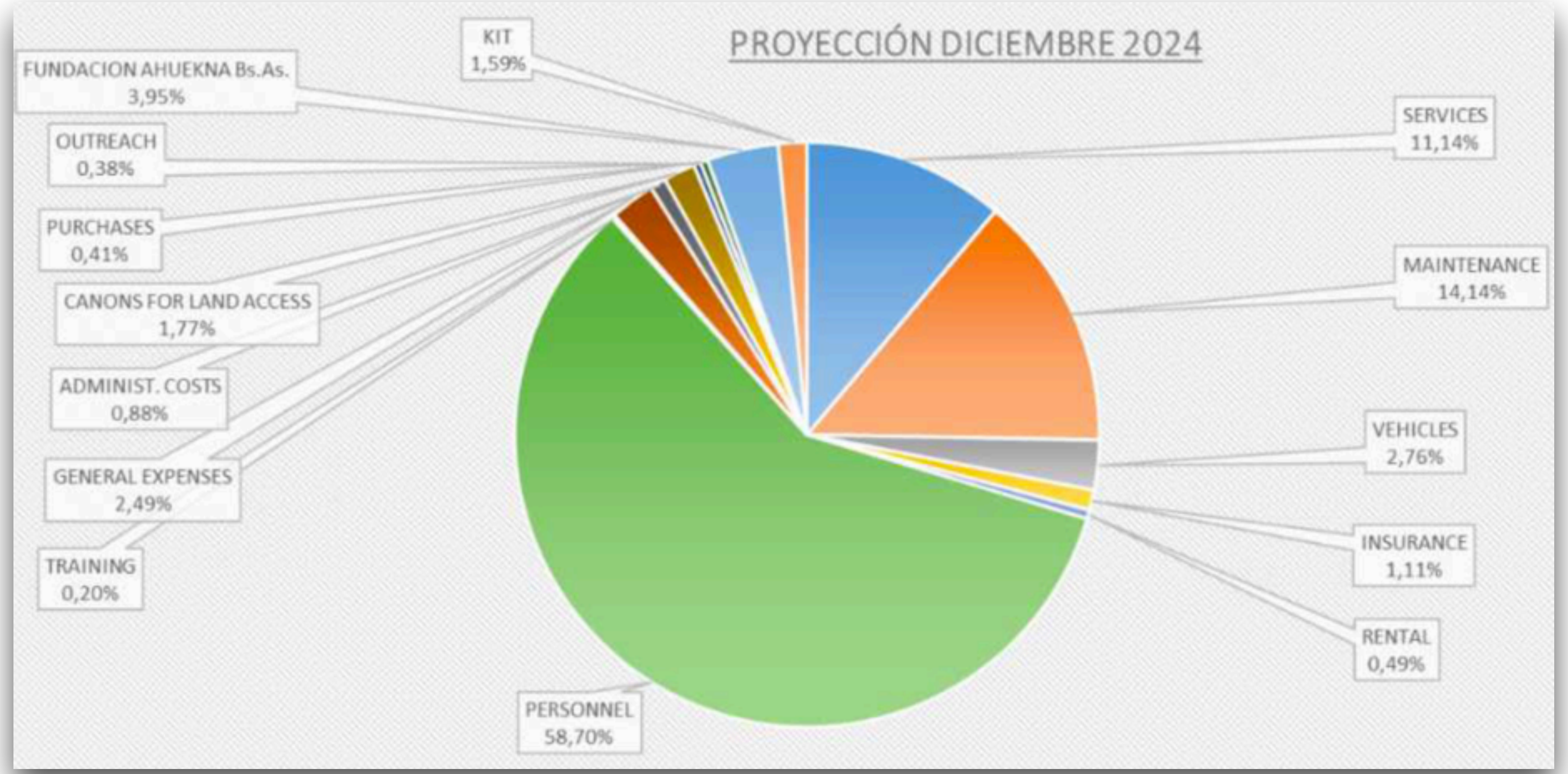
SUMMARY: In 2025

REQUEST: 1,716 KUSD (Operating) + 85 KUSD (Reserve) + C-O until 2023 = 1,801 KUSD + C-O

OCL PER PERSON: 9,529.10 USD

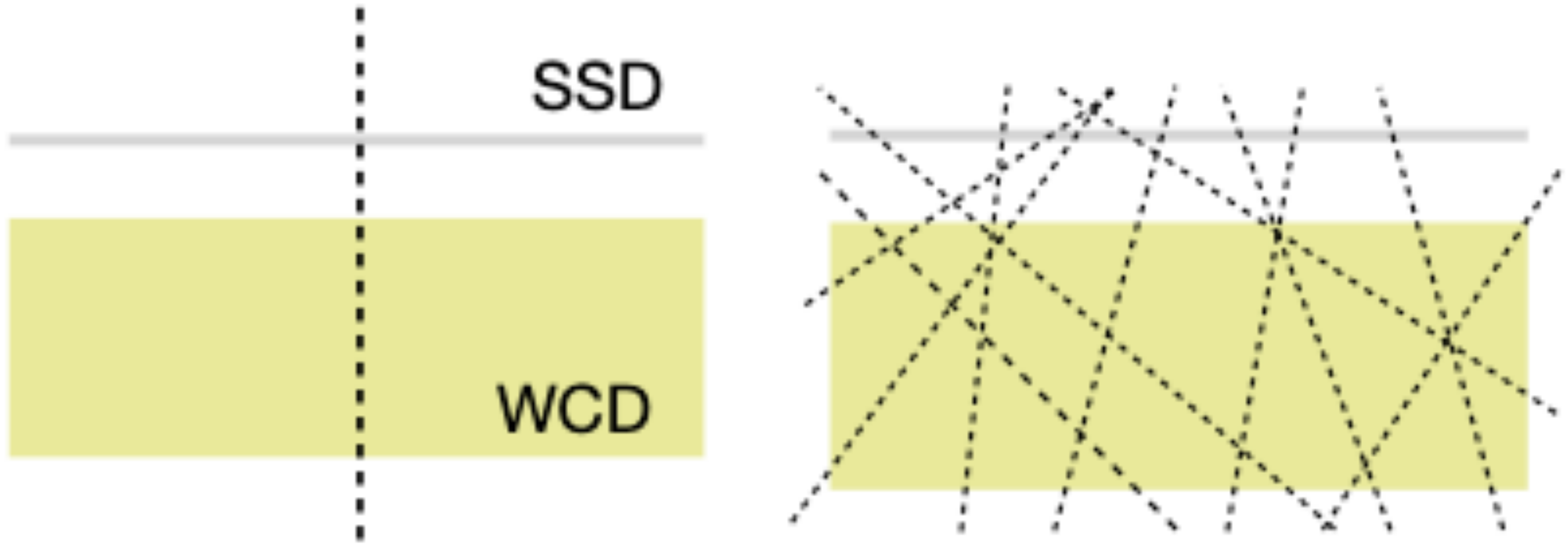
10,800 USD for 2026. VERY CONSERVATIVE

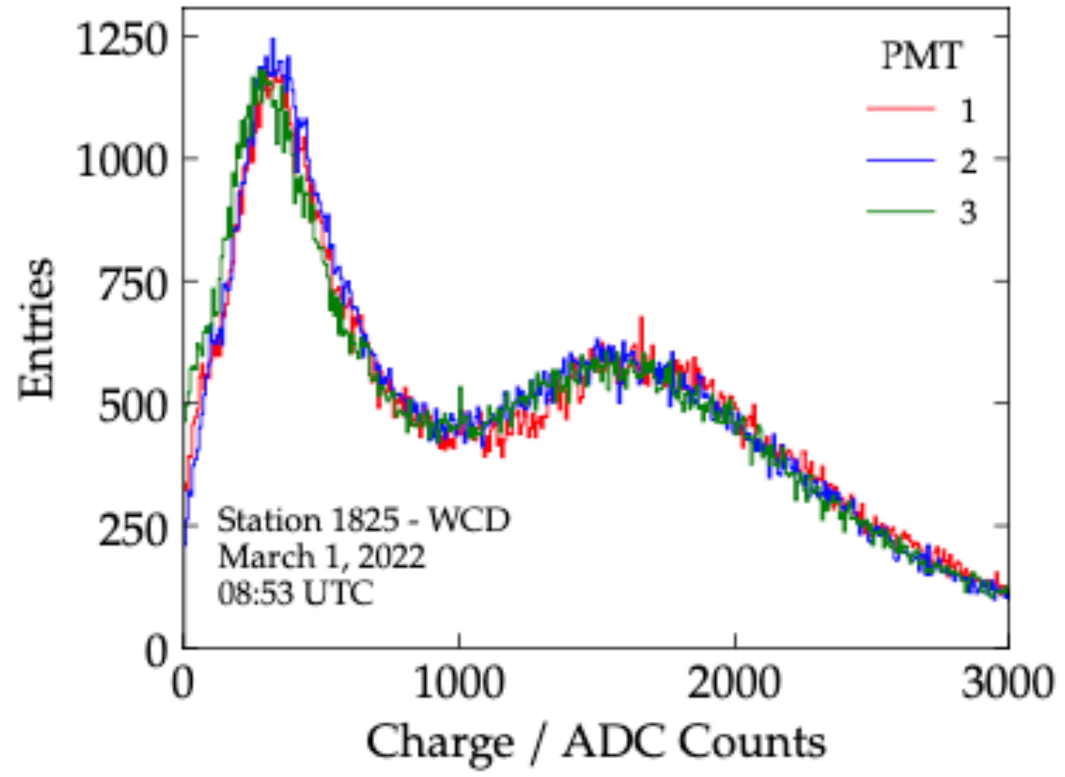
Includes Mexico paying their full share for 9 people and does not include funds for the reserve

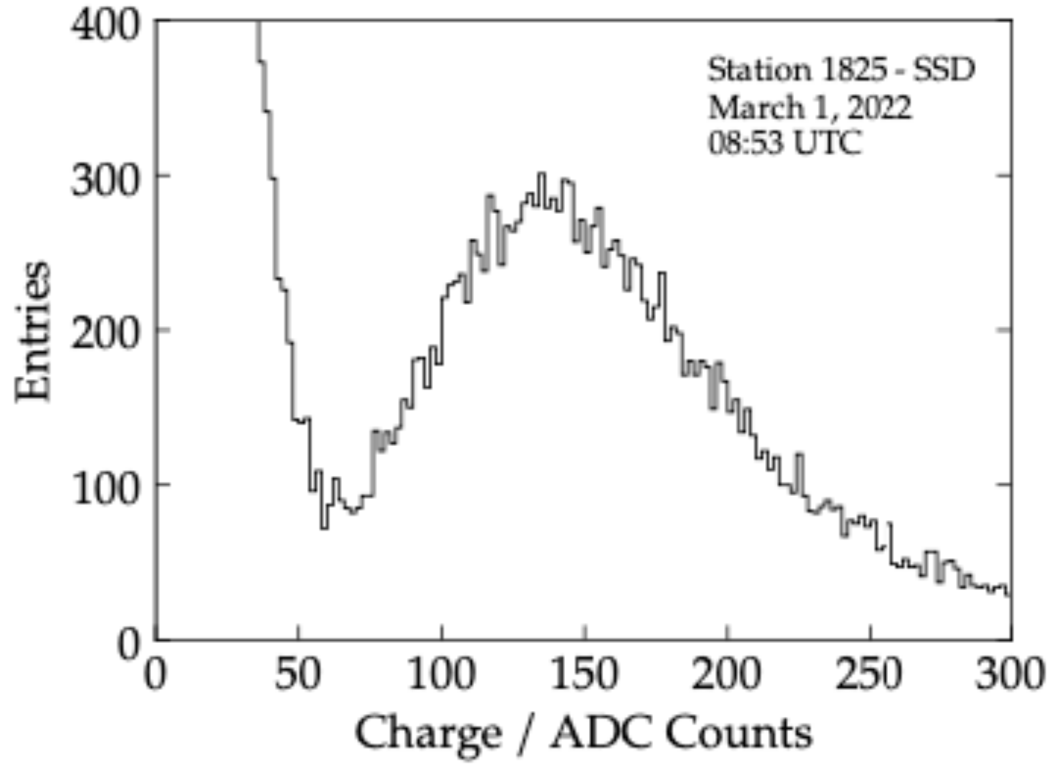


Calibration - WCD+SSD

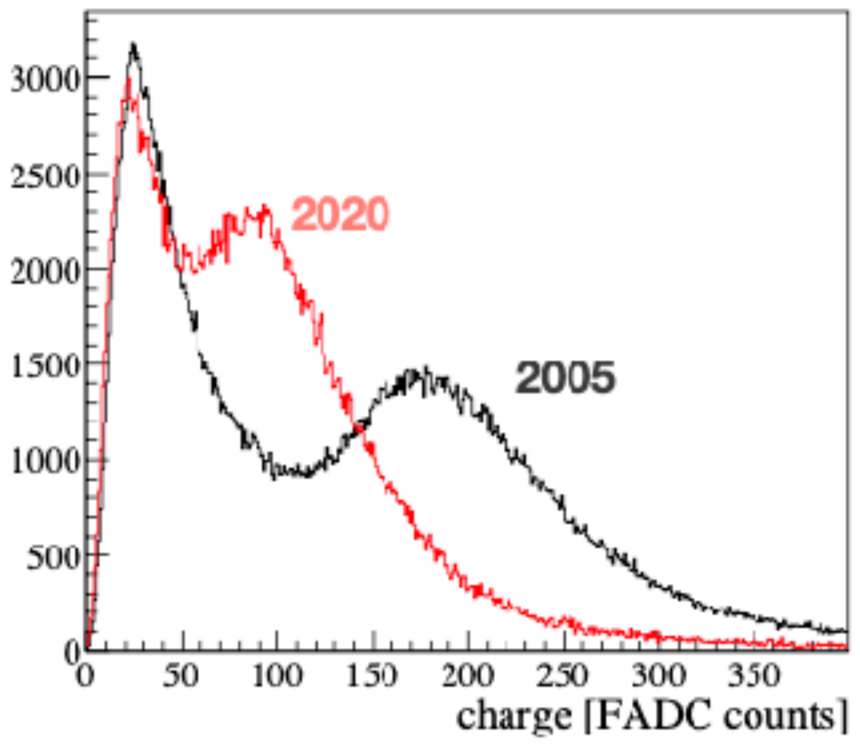
- ➡ Vertical Equivalent Muon (VEM) for WCD
- ➡ Minimum Ionizing Particle (MIP) for SSD
- ➡ ***In >99% of cases muon hump well determined***
- ➡ Day/night fluctuations: ~3% for VEM and 15% for MIP
- ➡ Uniformity across the array ~13% (VEM) and 6% (MIP)

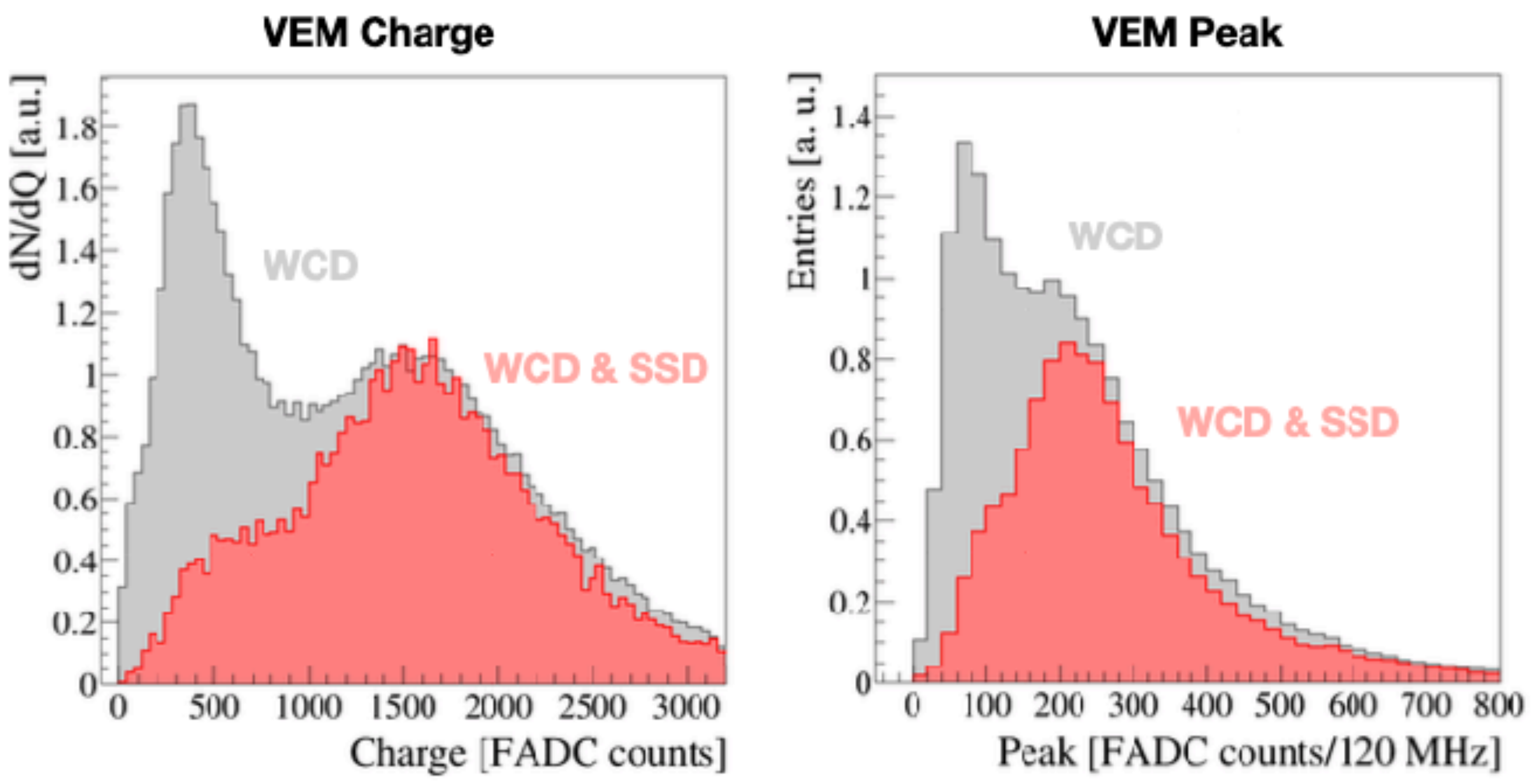






WCD+SSD coincidence allows calibration of aged WCD :





smallPMT cross-calibration

Calibration not feasible with single muons:
only ~1 photoelectron per muon in the sPMT
(vs ~90 in the Large PMTs).

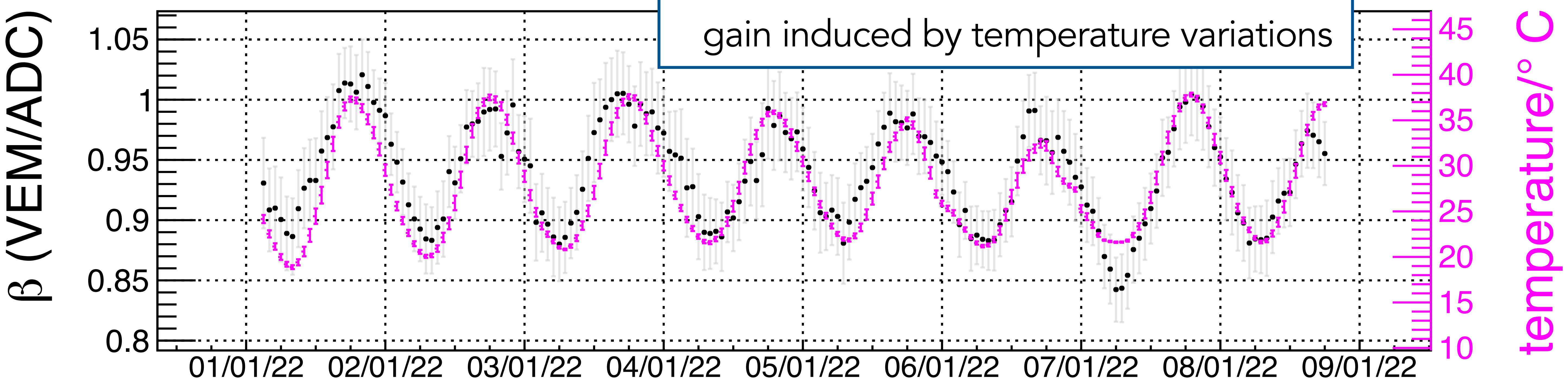
Cross-calibration with Large PMTs signals expressed in VEM to find factor β such as

$$S_{\mathrm{SPMT}}/\mathrm{VEM} = \beta\, Q_{\mathrm{SPMT}}/(\mathrm{ADC\ counts})$$

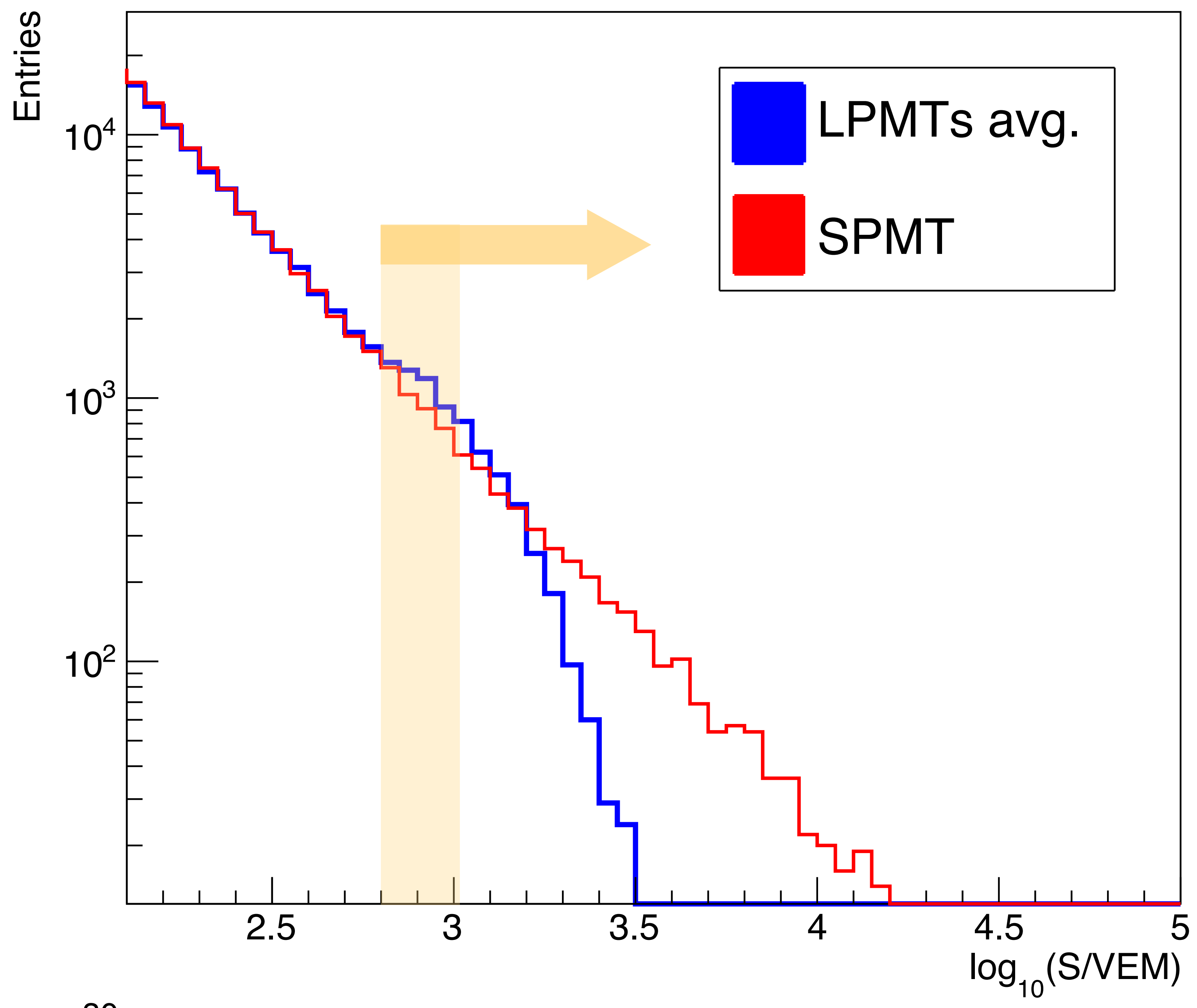
- Dataset: signals from low-energy showers, selected locally at each station
- Method: minimization of the differences between the signal distribution of Large WCD PMTs vs sPMT

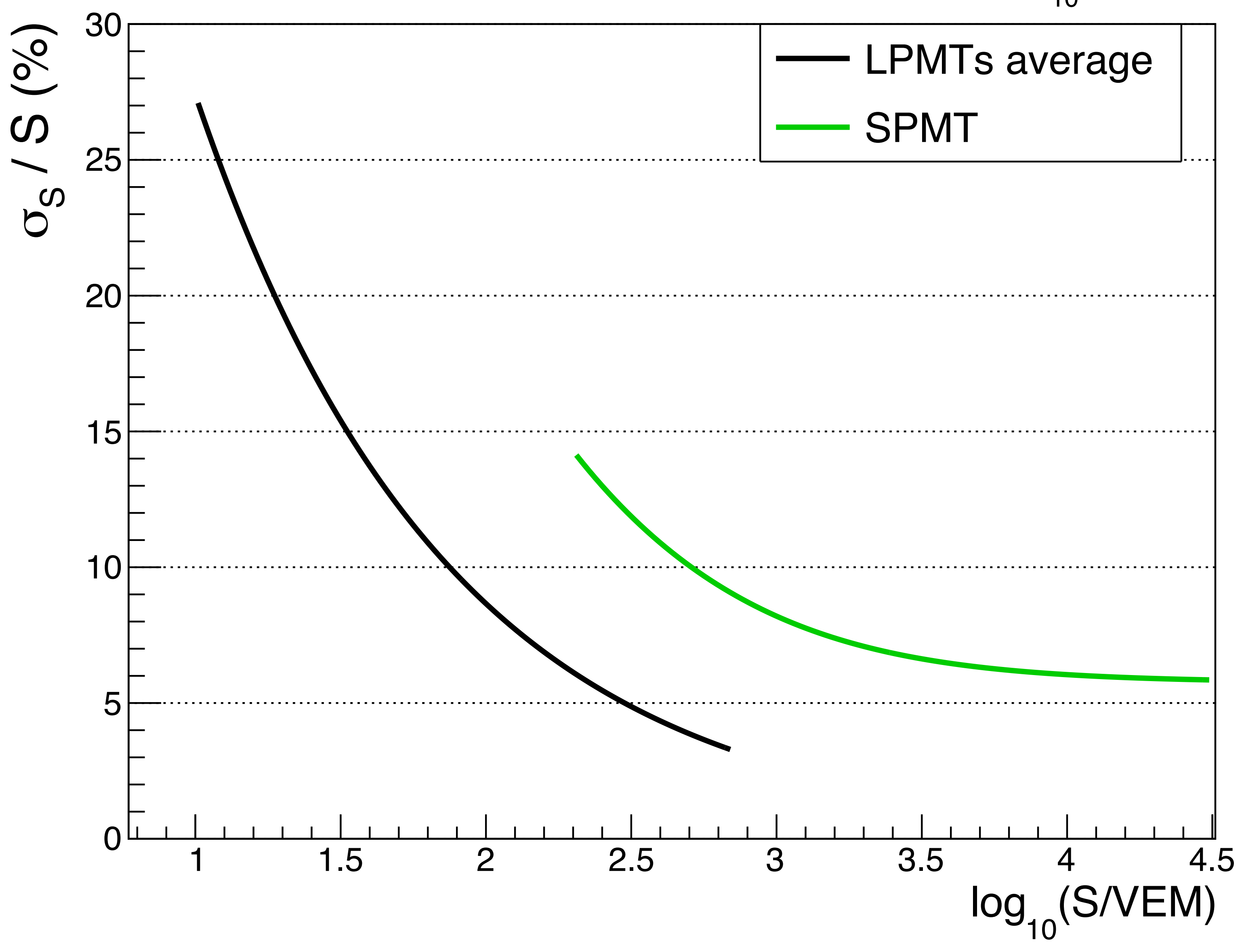
✓ **Precision ~2.2%**

✓ Performed in an 8-hour sliding window to follow daily evolution of the SPMT gain induced by temperature variations



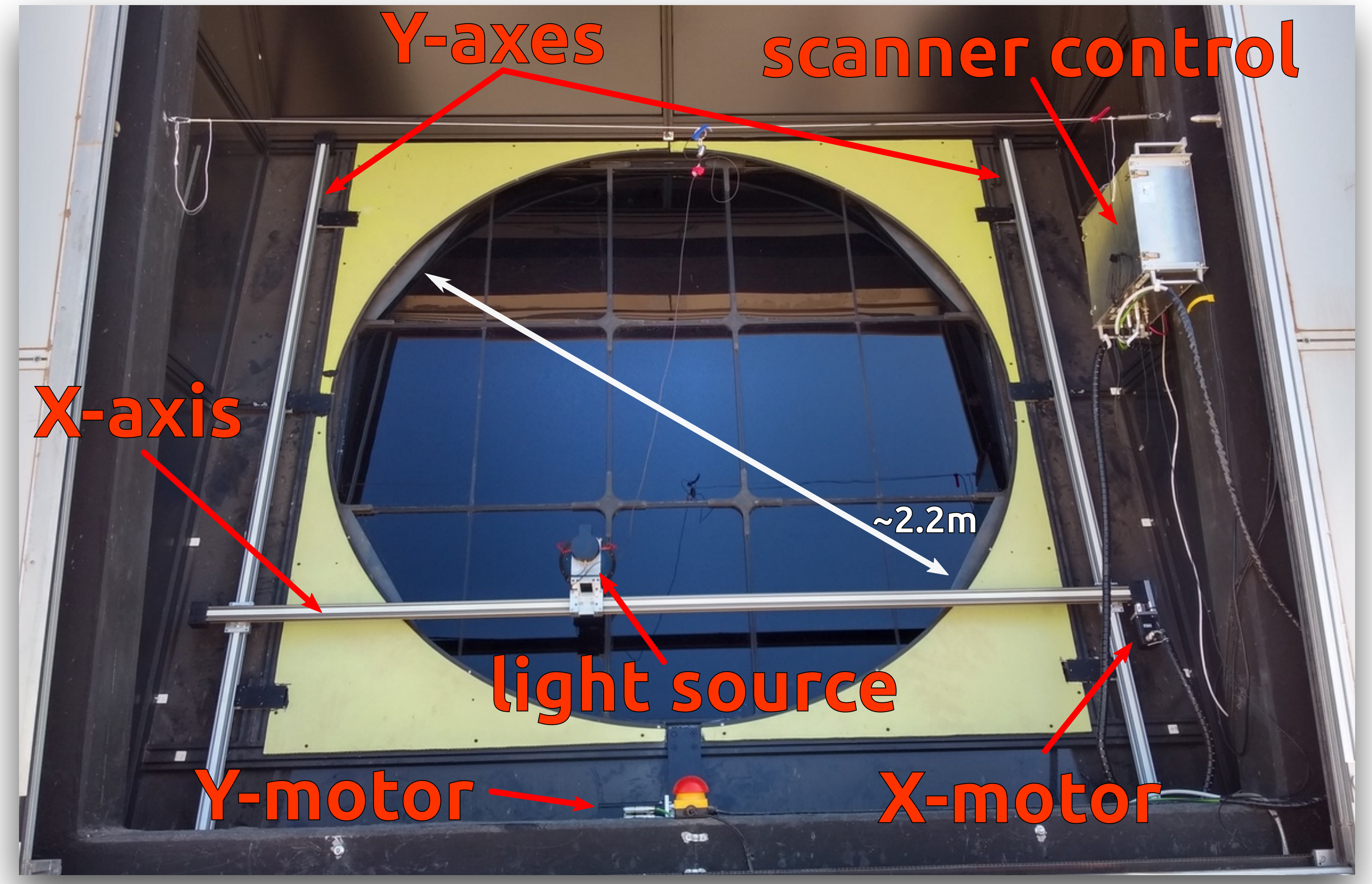
Cross-calibration factor β for a typical SPMT, calculated hourly using 8h of data

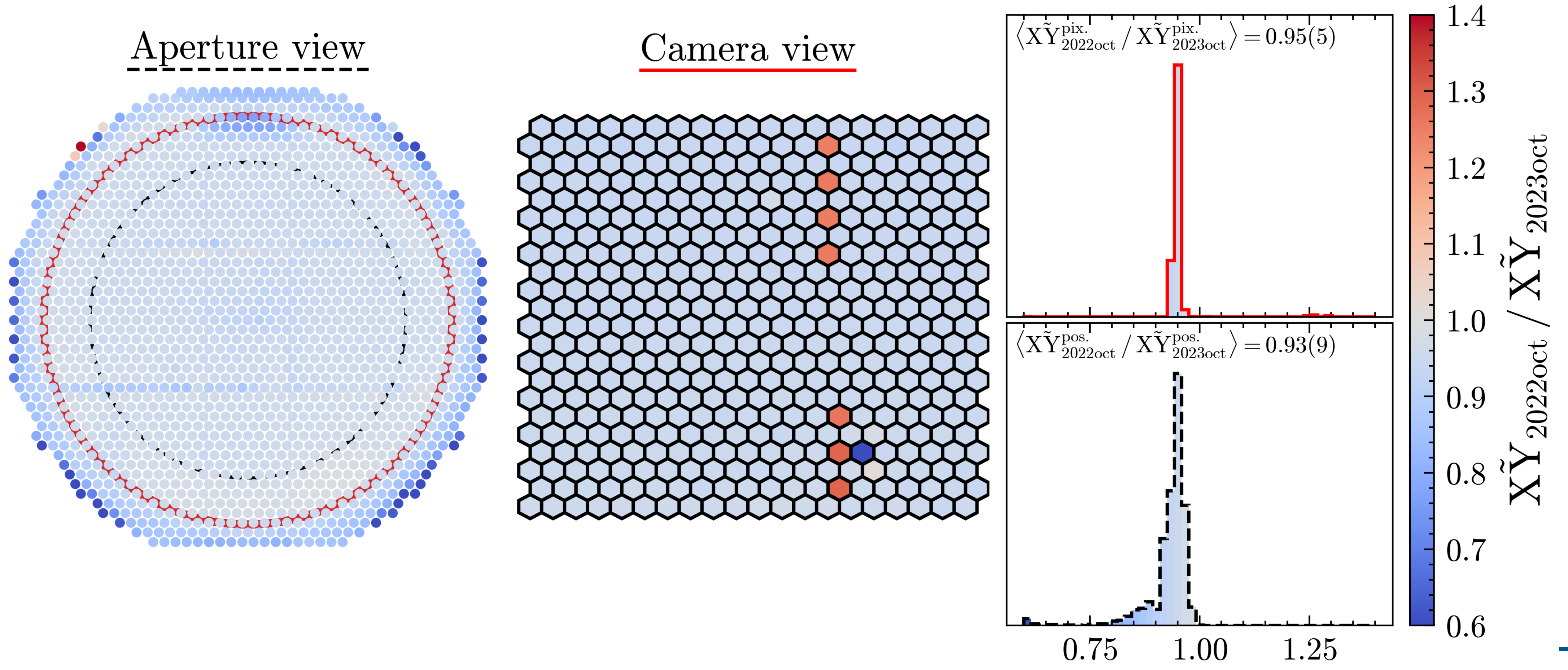


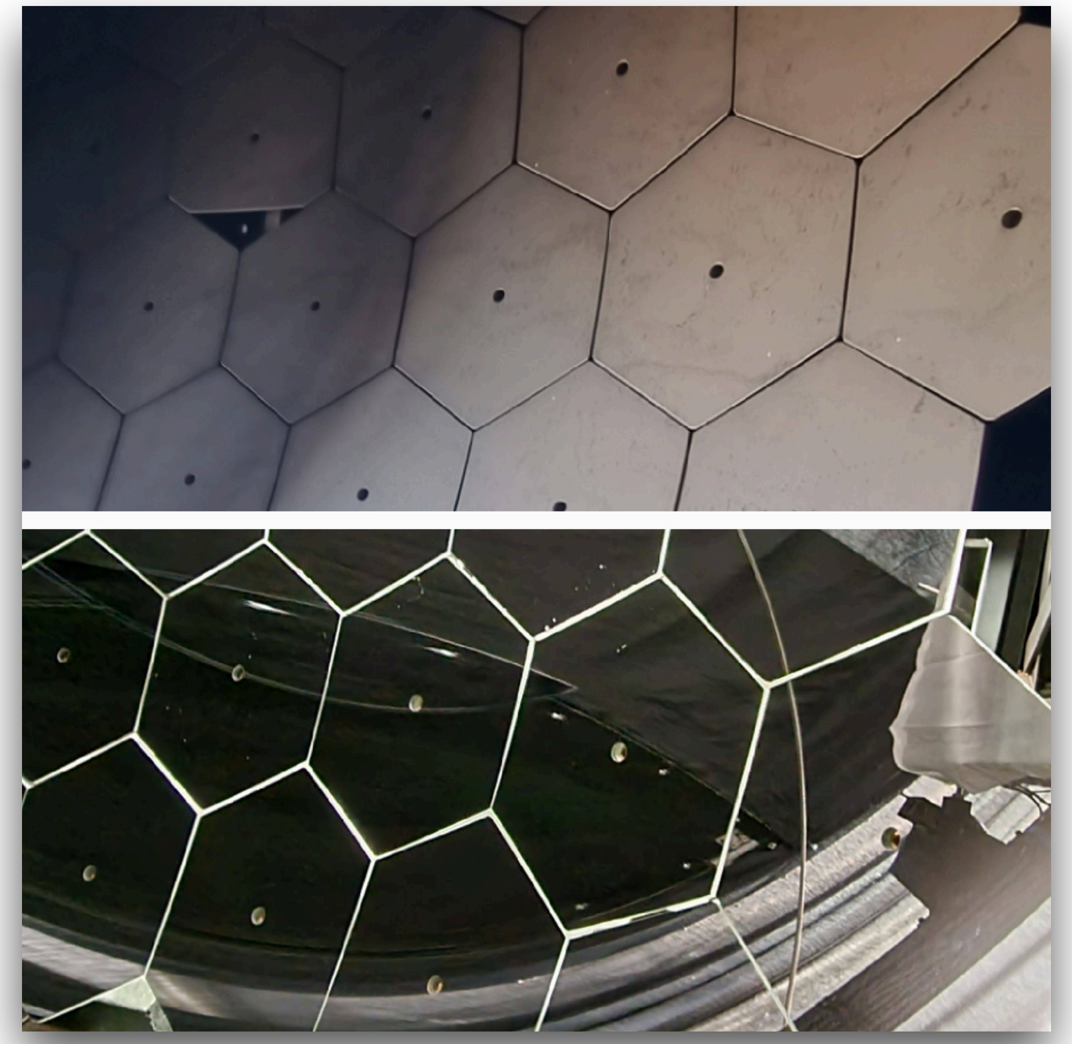


FD calibration: the XY scanner

- Scan complete telescope aperture (~1700 positions) with uniformly emitting, absolutely calibrated light source on rail system
- Permanent infrastructure installed at all telescopes
- all telescopes measured at least once
- Systematic uncertainty in absolute calibration of the fluorescence detectors of 6%
  (as compared to 9% with former large-diameter source)
- Comparison with CalA past calibration under study (Roma/KIT)

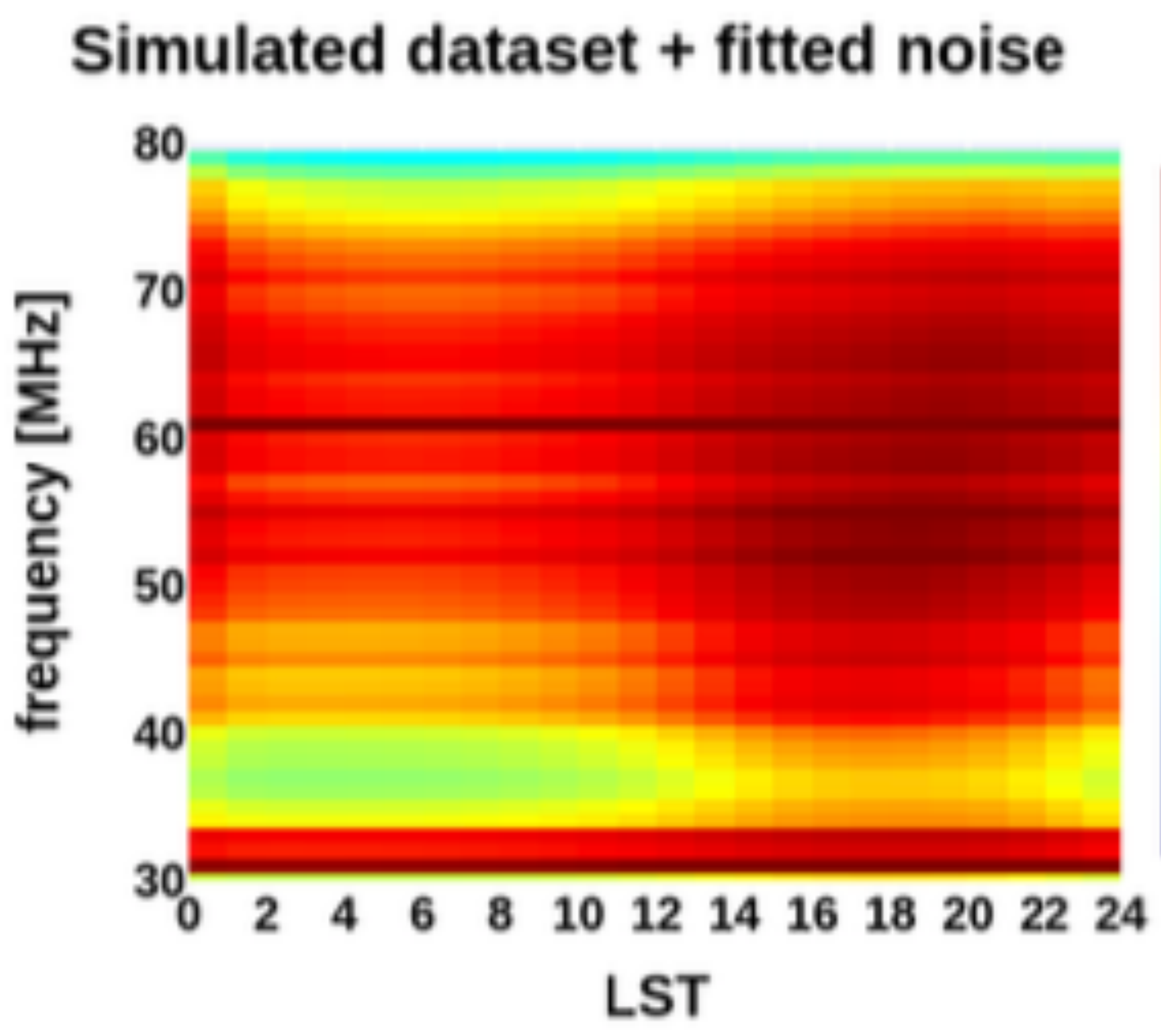


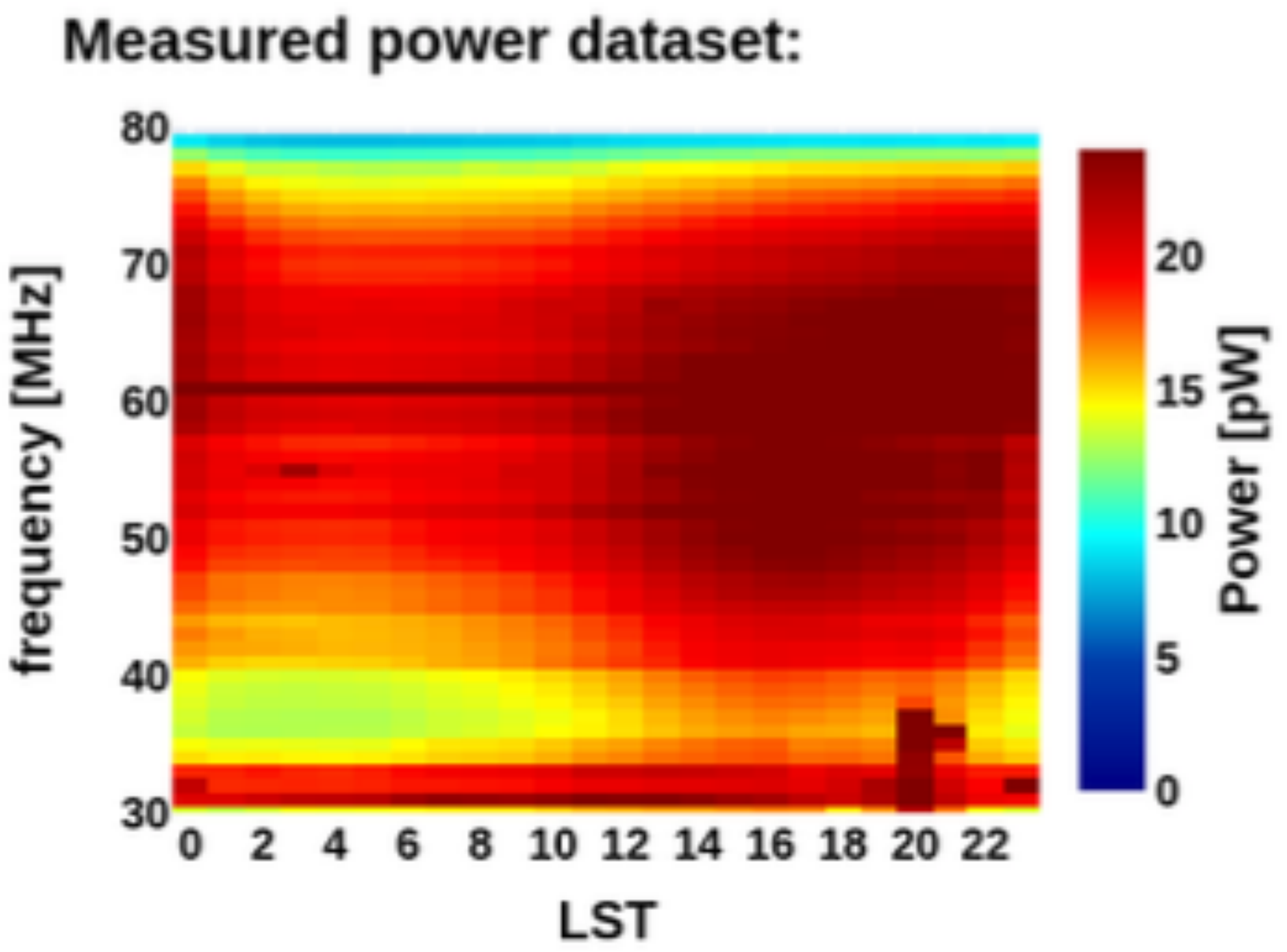




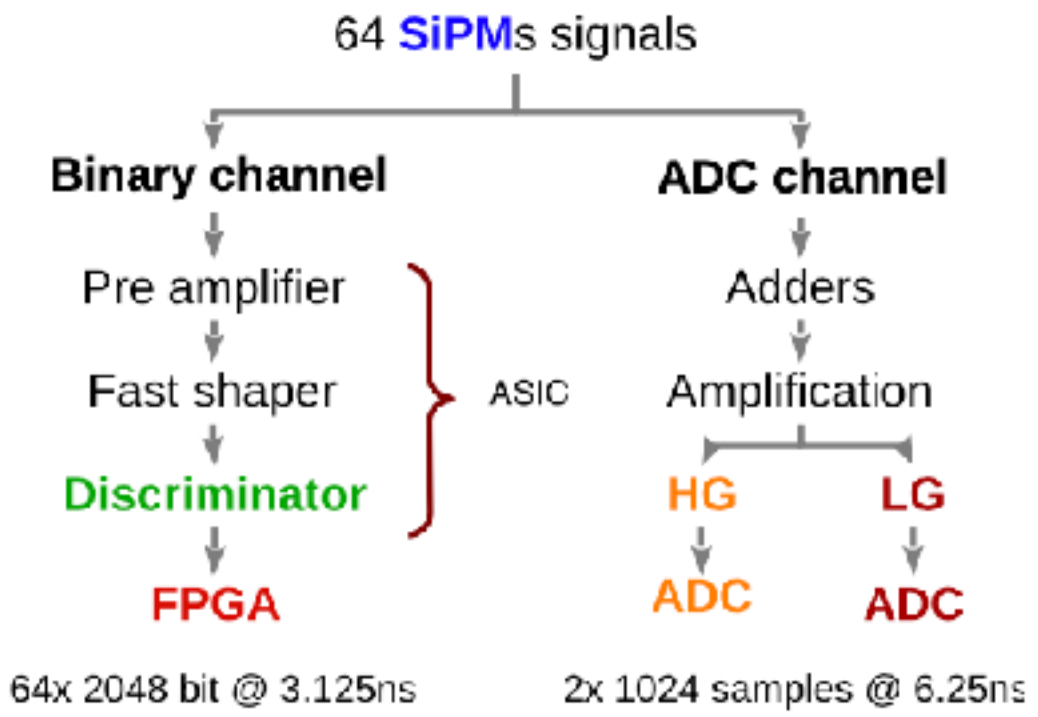
Calibration - RD

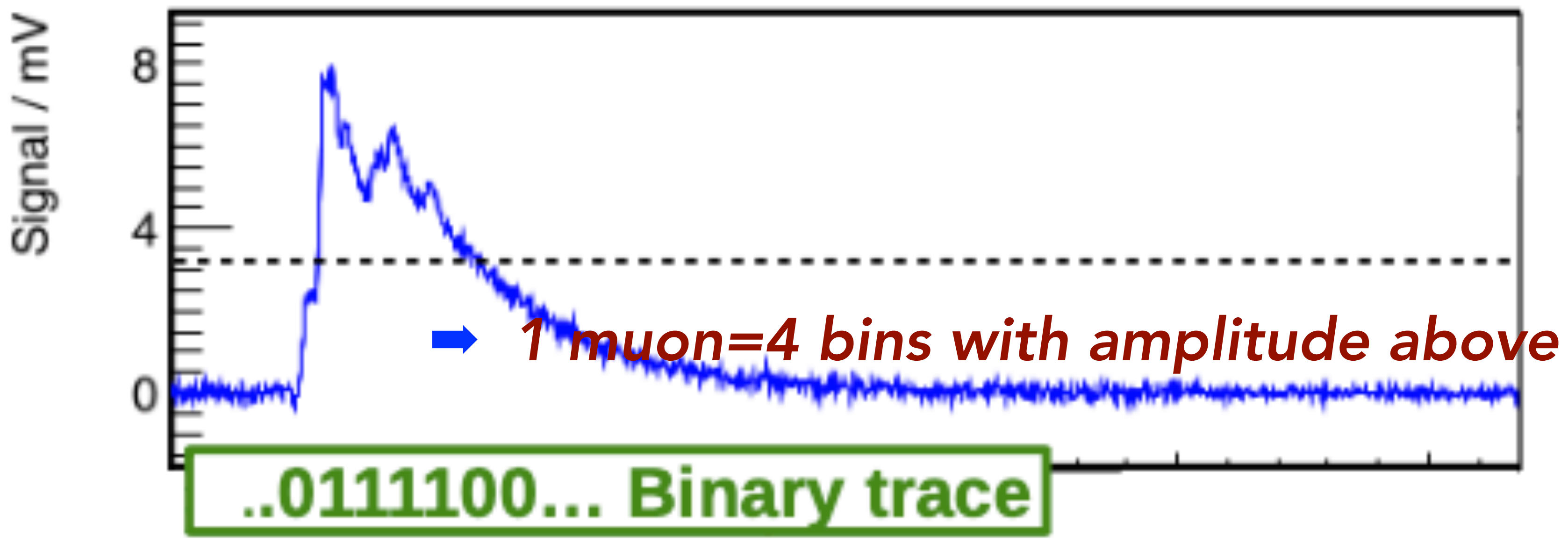
- ➡ Measure of the response of hardware components (in laboratory)
- ➡ Relative calibration: drone measurements
- ➡ Absolute scale: measure of the Galactic modulation in the 30-80 MHz frequency band
- ➡ ***Uncertainty in energy scale :   Goal: <10%***
  [with AERA: 14%]



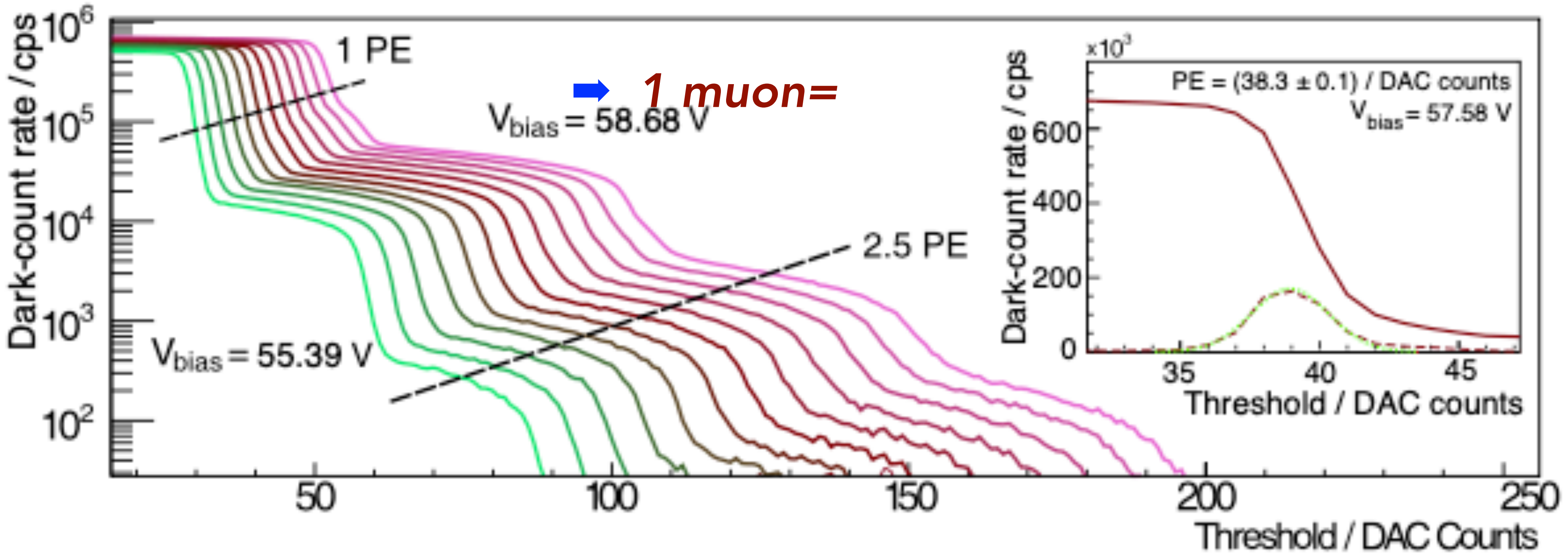


Calibration - UMD





➡ *1 muon=4 bins with amplitude above the*

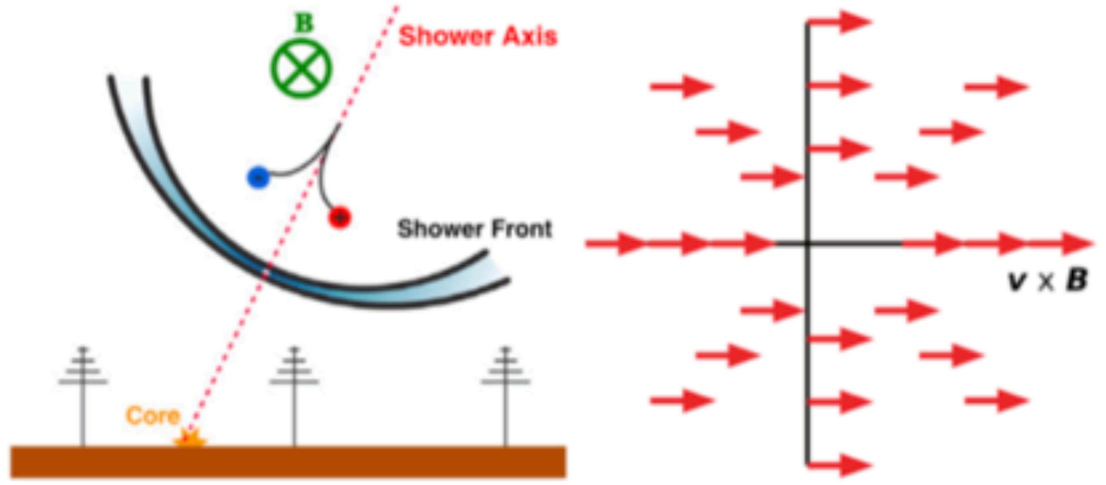


➡ *1 muon=*

- ➡ Measure of the rate of SiPM signals as a function of threshold for different bias voltages
- ➡ ***Threshold for the binary mode set at 2.5 photoelectrons.***
- ➡ The gain stability has been measured to be within 1% (3 years of data)

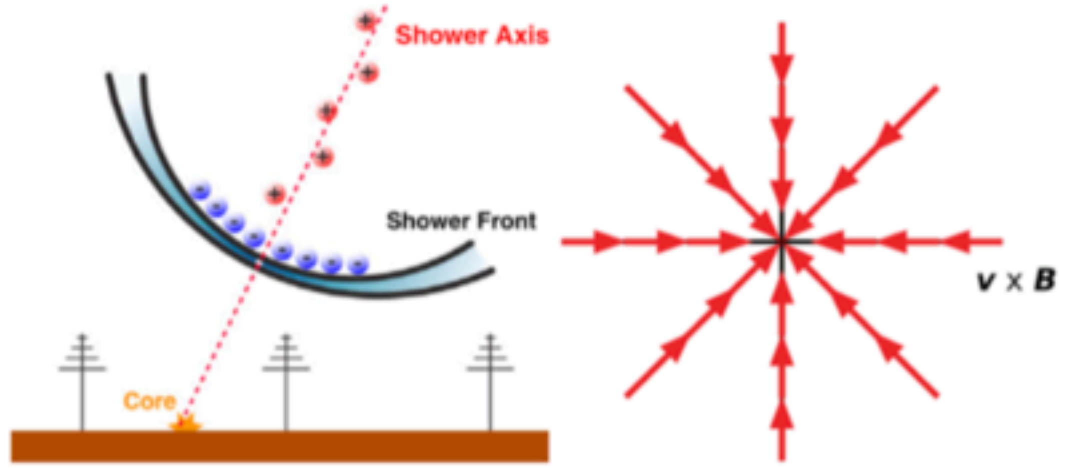
Radio emission in EAS

Geomagnetic emission



- acceleration of e± by the geomagnetic field
- they continuously interact with air molecules
- linear polarisation of the radiation (E aligned along the Lorentz force)
- propagation along the shower axis

Charge excess emission (Askaryan effect)



- ionisation of ambient medium by EAS particles: excess of ionisation e- following a longitudinal development
- linear polarisation of the radiation (E radially oriented wrt EAS axis
- sub-dominant in EAS, unless EAS arrive parallel to MF

Emission mechanism

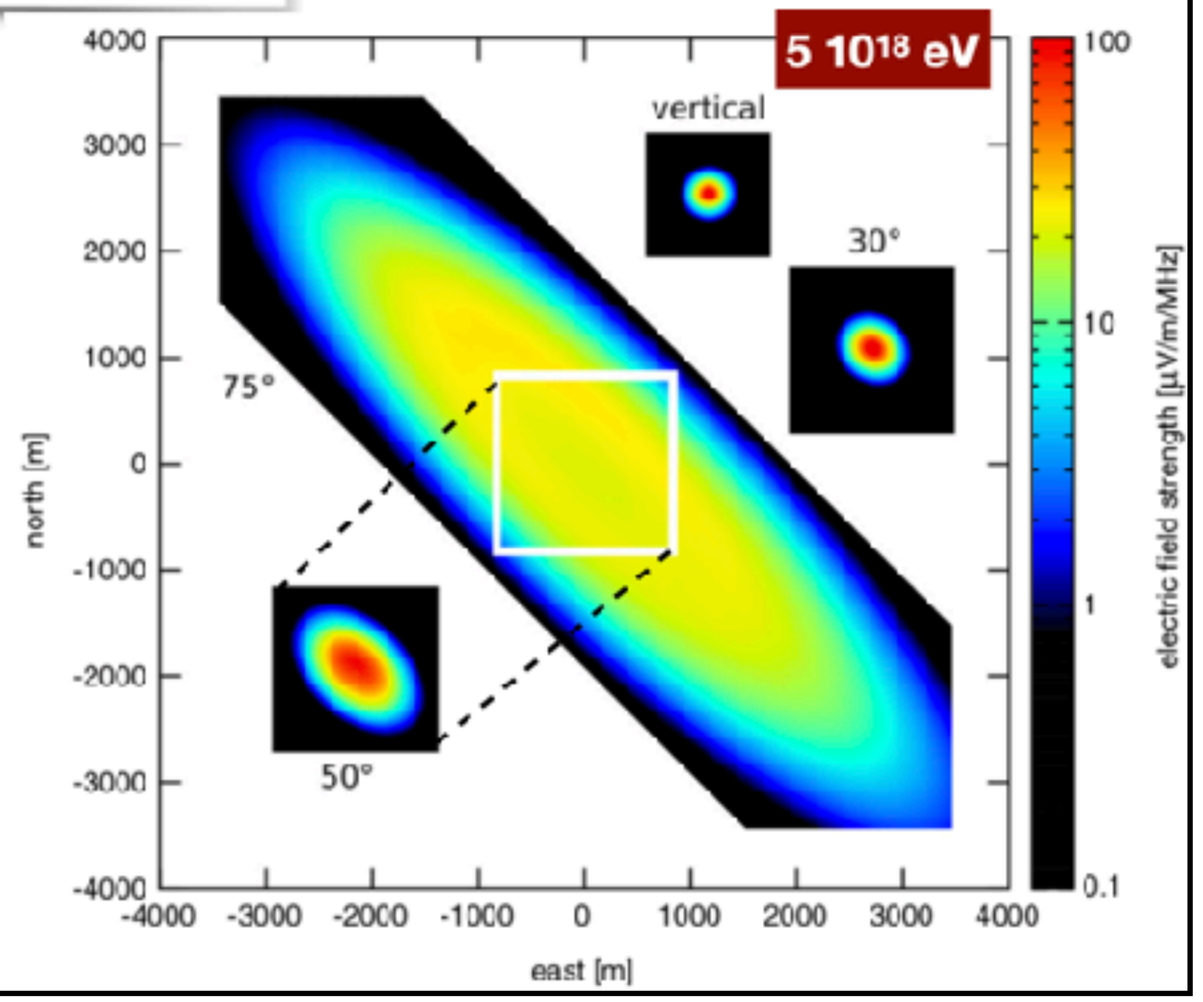
Superposition of the two effects :

- asymmetric footprint: it depends on relative weight of the 2 effects (i.e. on the geomagnetic and EAS angles)
- total polarisation is elliptical
- radiation strongly forward-beamed into a cone of few degrees
- Δn(z) influences the radiation by compressing or stretching it
- if the E add up coherently

Amplitude(E) $\propto N_{particles} \propto E_{primary}$
received power $\propto (E_{primary})^2$

- as it is not absorbed in atmosphere, the radio emission depends on the source distance and not on the amount of traversed matter

inclined air showers can be detected by a sparse antenna grid
- lower $\vec{E}$ amplitude
- larger footprint
- less steep LDF



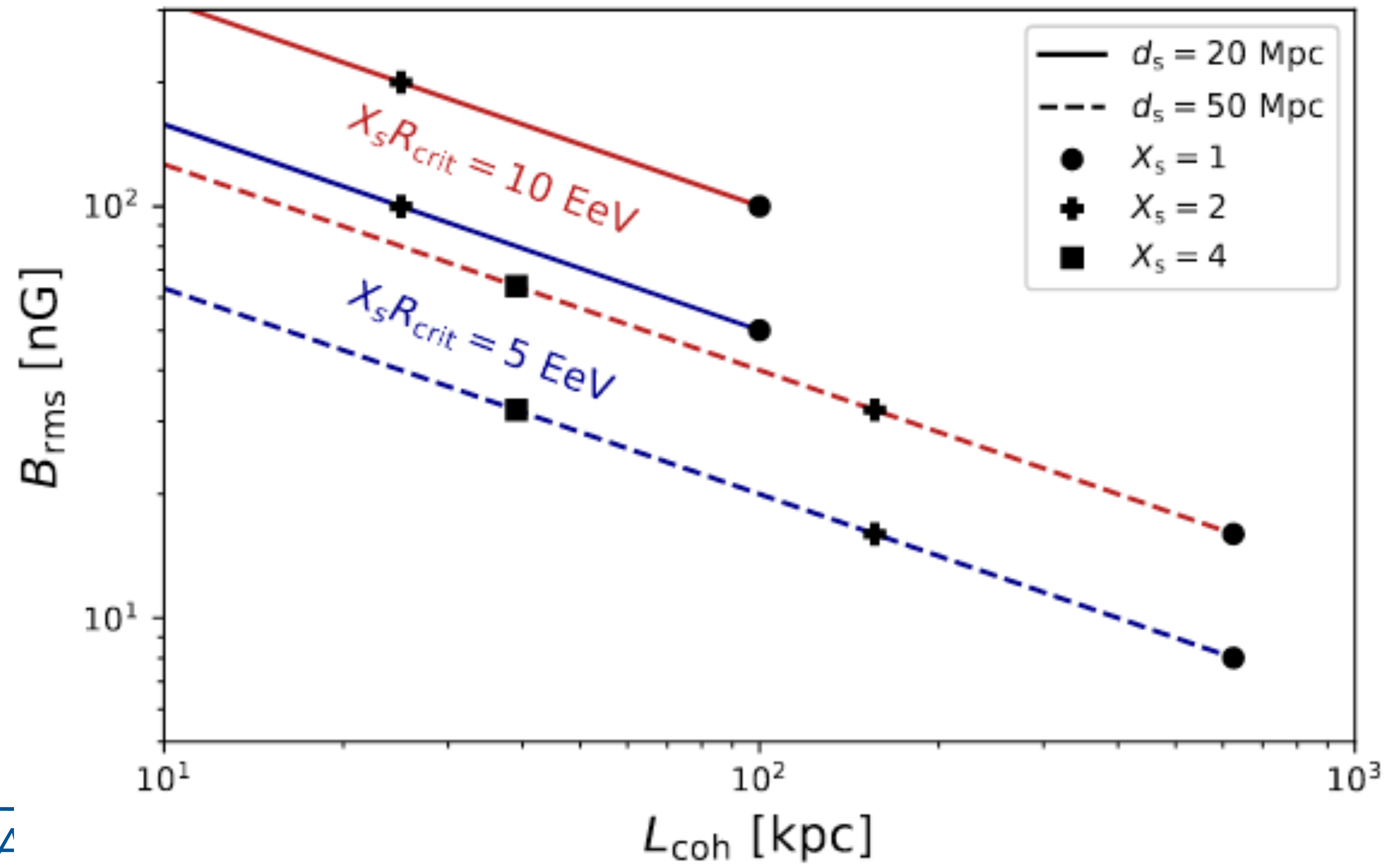
Astrophysical interpretation - the magnetic horizon effect

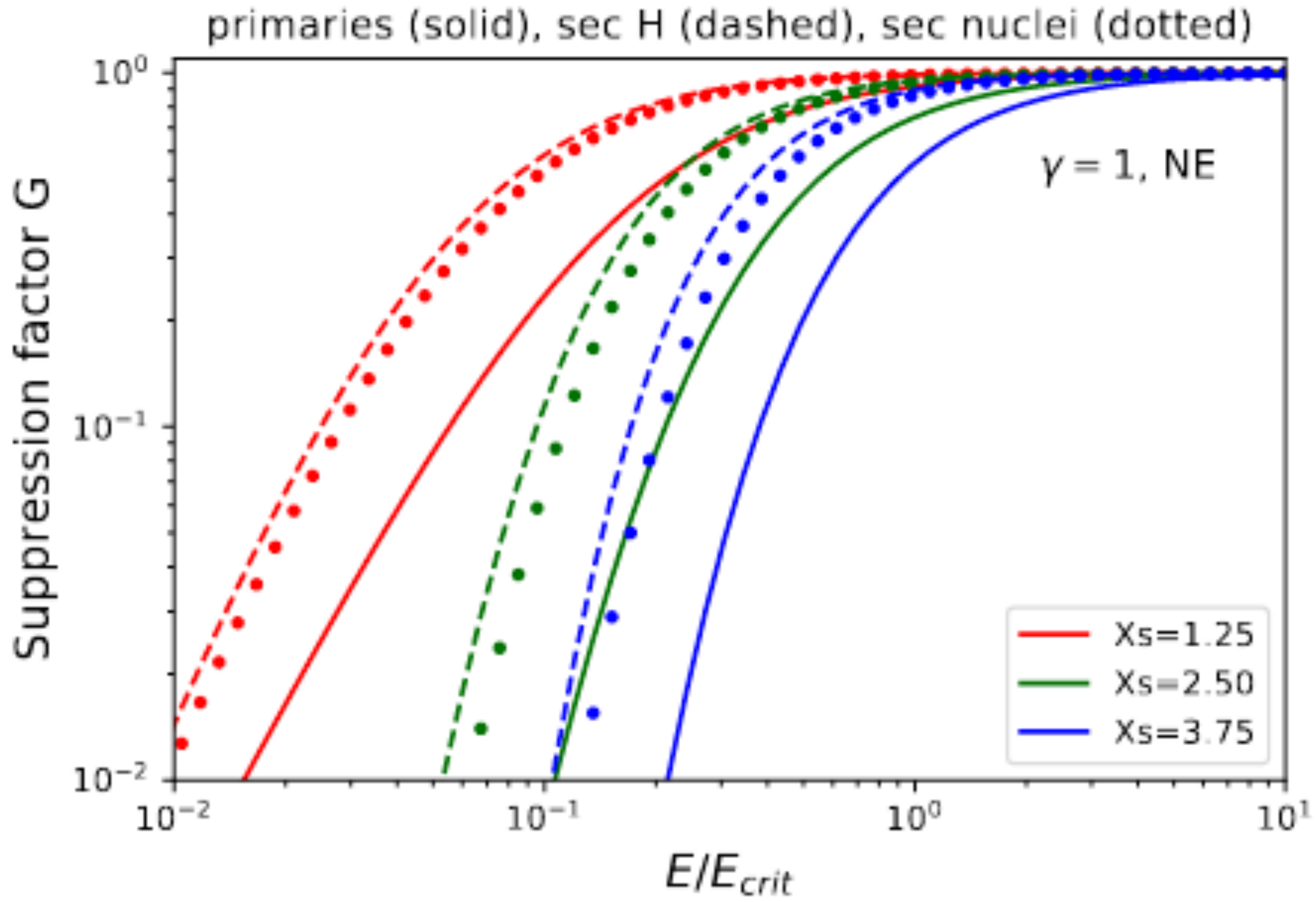
NEW
JCAP 07 (2024) 094

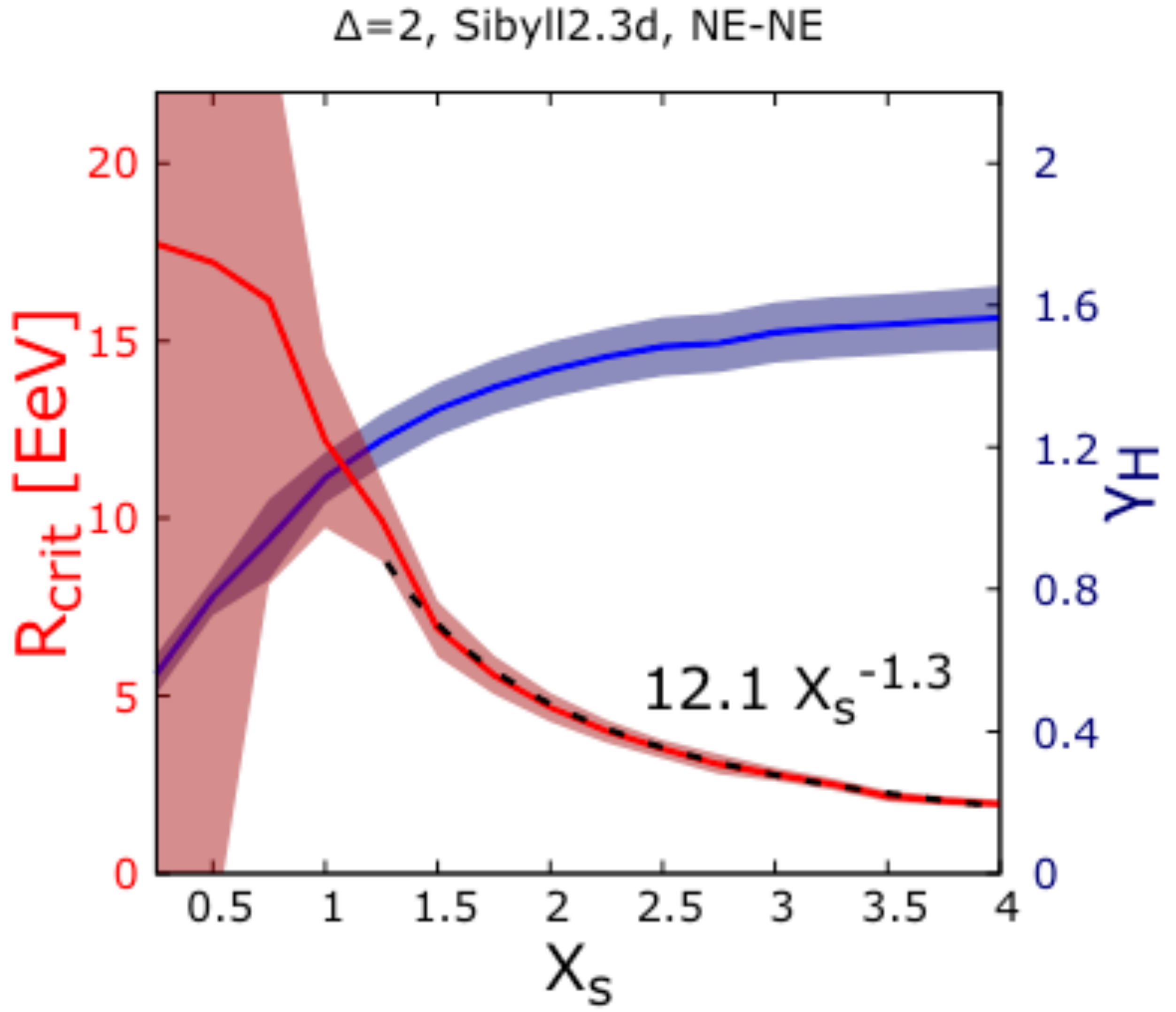
EG magnetic fields between Earth and the closest sources can affect the observed spectrum, reducing the low-rigidity particle flux

Suppression factor $G(E) \equiv \dfrac{J(E)}{J(E)_{d_S \to 0}}$

Normalized intersource distance $X_s \simeq \dfrac{d_s}{10\ Mpc}\sqrt{\dfrac{25\ kpc}{L_{coh}}}$







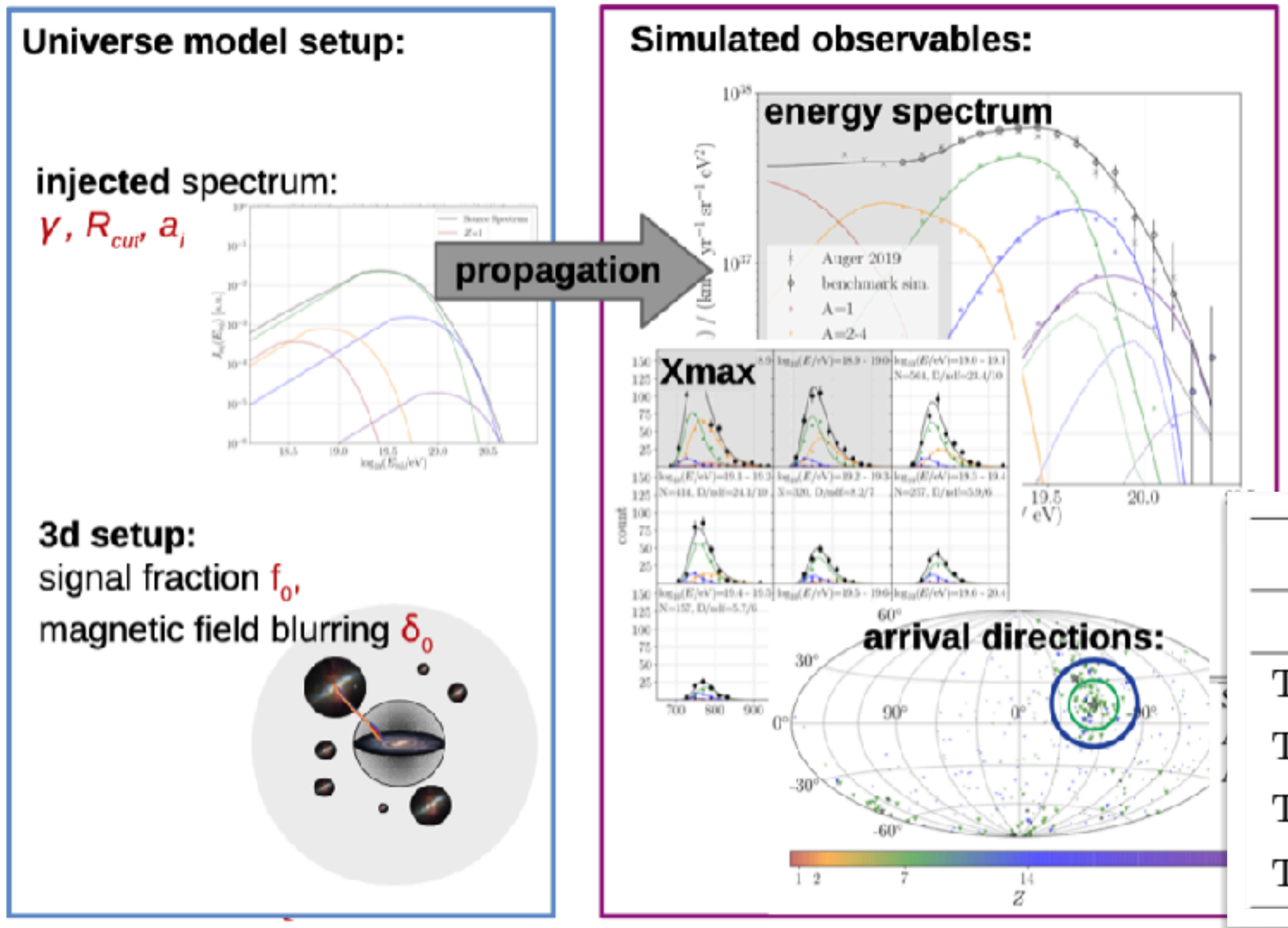
➡ The spectrum is softer for larger R_{crit} (E_{crit}= Z R_{crit})

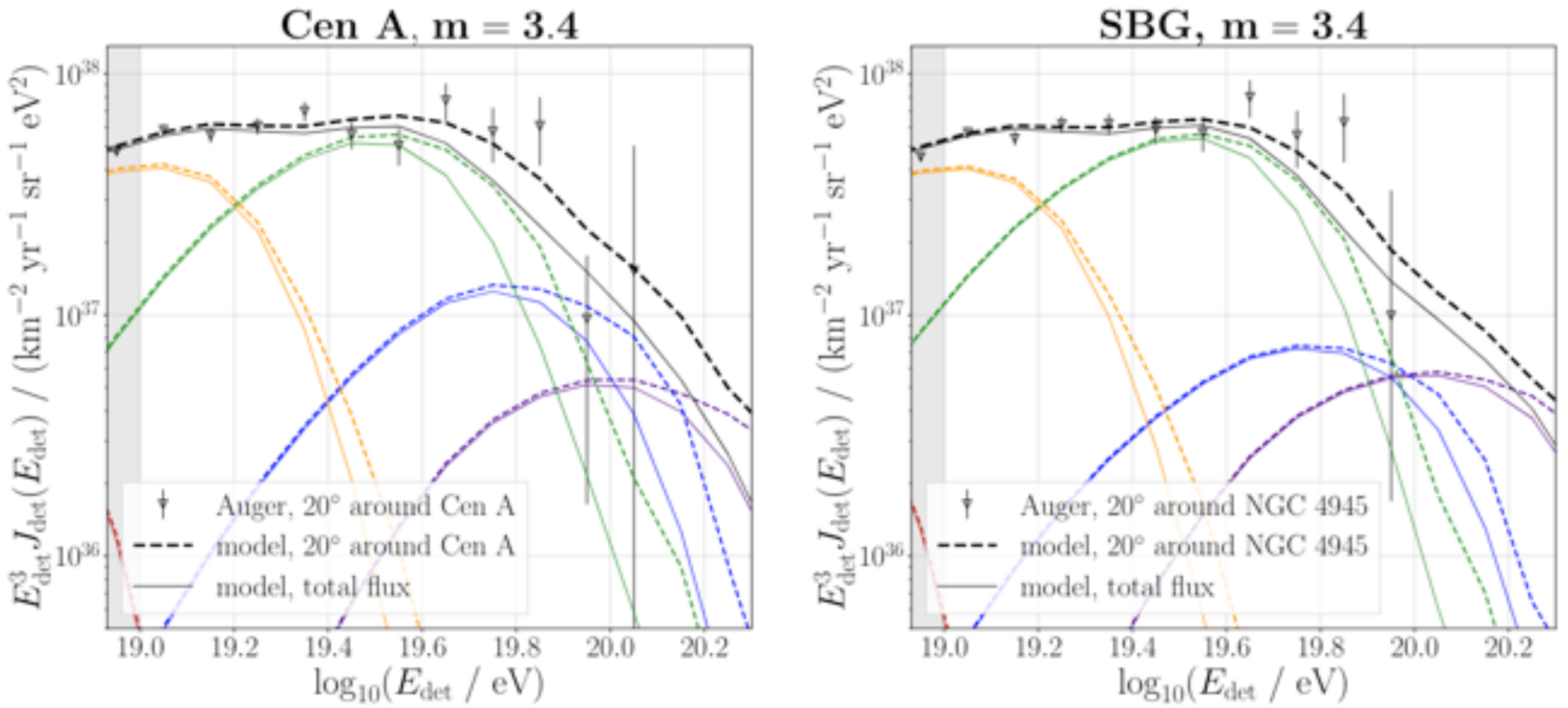
➡ The magnetic horizon plays a role if

$$X_s R_{crit} \simeq 5 \text{ to } 10 \text{ EeV}$$

Implying strong EGMF $\mathcal{O}$(10-200) nG in the Local Supercluster

Astrophysical interpretation
(energy spectrum+mass composition+arrival directions)



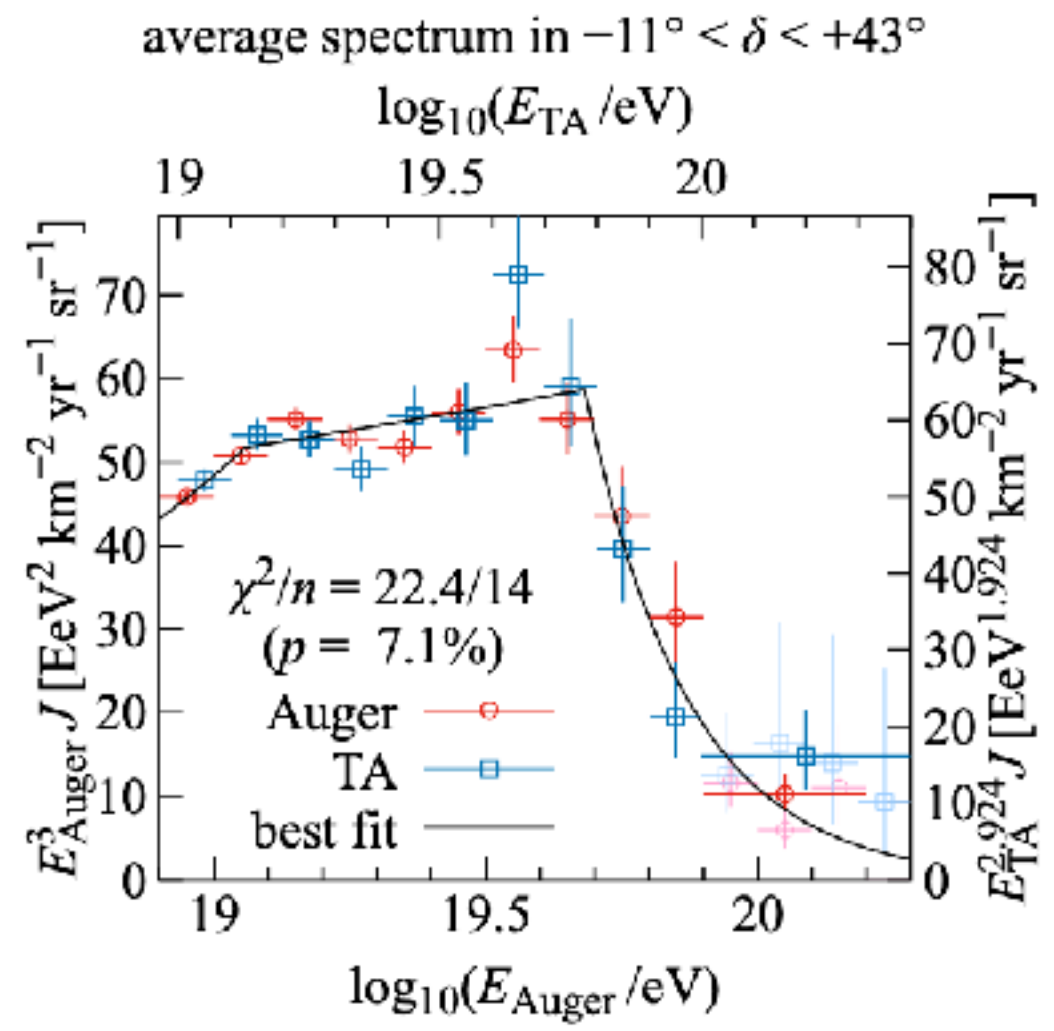


	Cen A, $m = 0.0$		Cen A, $m = 3.4$		SBG, $m = 3.4$		γAGN, $m = 5.0$	
		+ syst		+ syst		+ syst		+ syst
TS_{tot}	22.8	17.3	22.2	19.1	27.6	25.6	23.9,[a]	9.8,[a]
TS_E	−0.1	−1.4	−0.4	−1.1	−5.2	−4.5	26.8	3.9
$TS_{X_{max}}$	1.9	0.2	1.8	1.0	6.2	2.0	−0.8	6.4
TS_{ADs}	20.9	18.7	20.8	$\boxed{19.0}$	26.6	$\boxed{27.1}$	−2.1	−3.0

- Data well described by a model with f ~ 20% from SBGs and δ~20⁰ at 40 EeV, N-dominated hard injection spectrum
- Significance of SBG model ~4.5σ, contribution of Centaurus A dominant (~80%)
- **γ-AGN sources disfavoured** (not possible when considering only energy and mass composition)

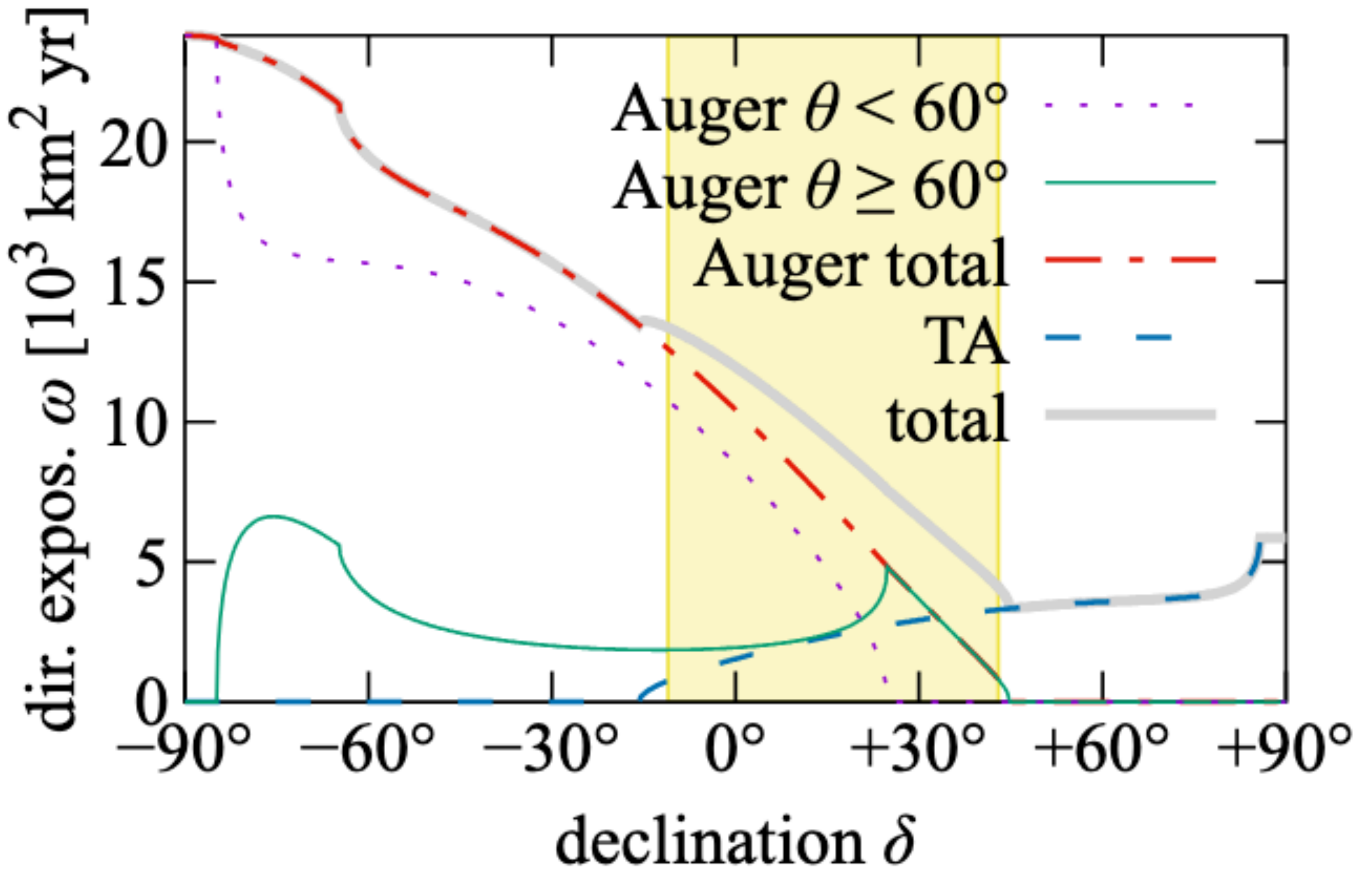
NEW
JCAP 01 (2024) 022

Auger and TA WG - full sky search for anisotropies



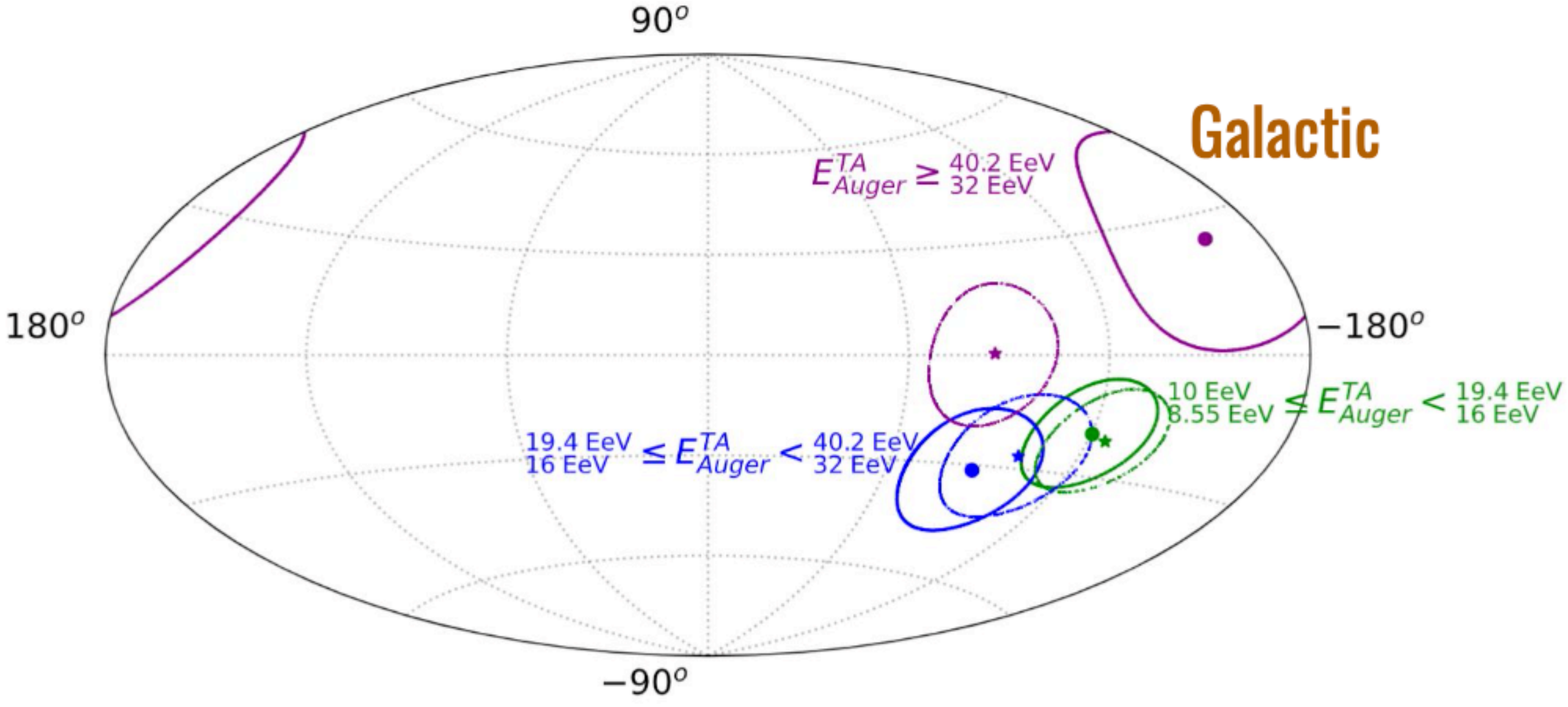
Energy scale systematic uncertainties
±14% for Auger ±21% for TA

Cross-calibration of the datasets in the common declination band



- scatter plots of arrival directions immediately interpretable
- equal sensitivity anywhere in the sky
- upper limits uniform over the sky

Confirm the presence of a dipole pointing away from the GC



Testing the predictions of hadronic models

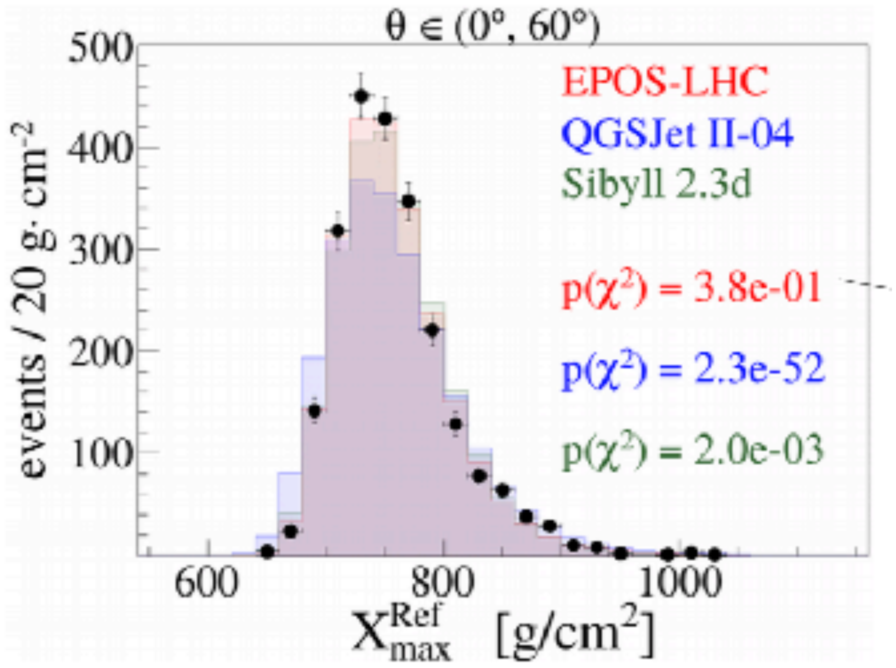
NEW
PRD 109 (2024) 102001

Global fit of the observed [X_{max},S_{1000}] distributions with templates of free mass composition and different hadronic interaction models

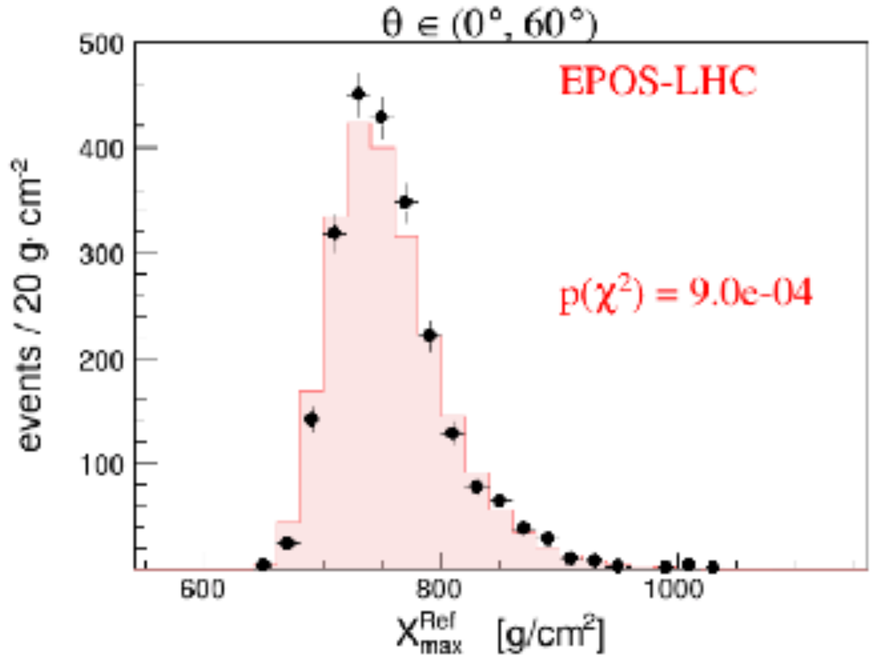
ad-hoc adjustments

$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

$$S_{Had}(\theta) \rightarrow S_{Had}(\theta) \cdot R_{Had}(\theta)$$

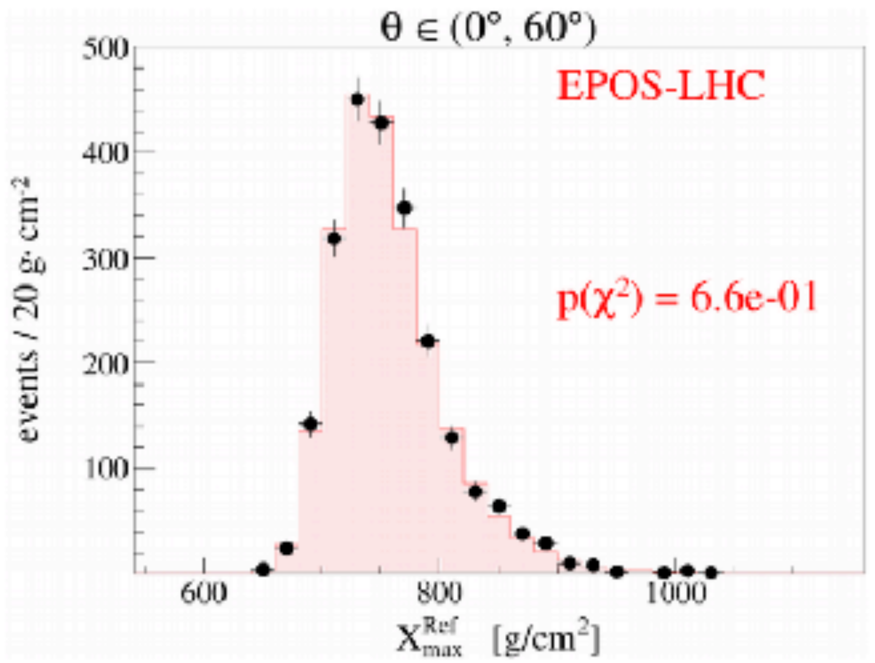


Combined fit of the [X_{max},S_{1000}] distributions without any adjustments



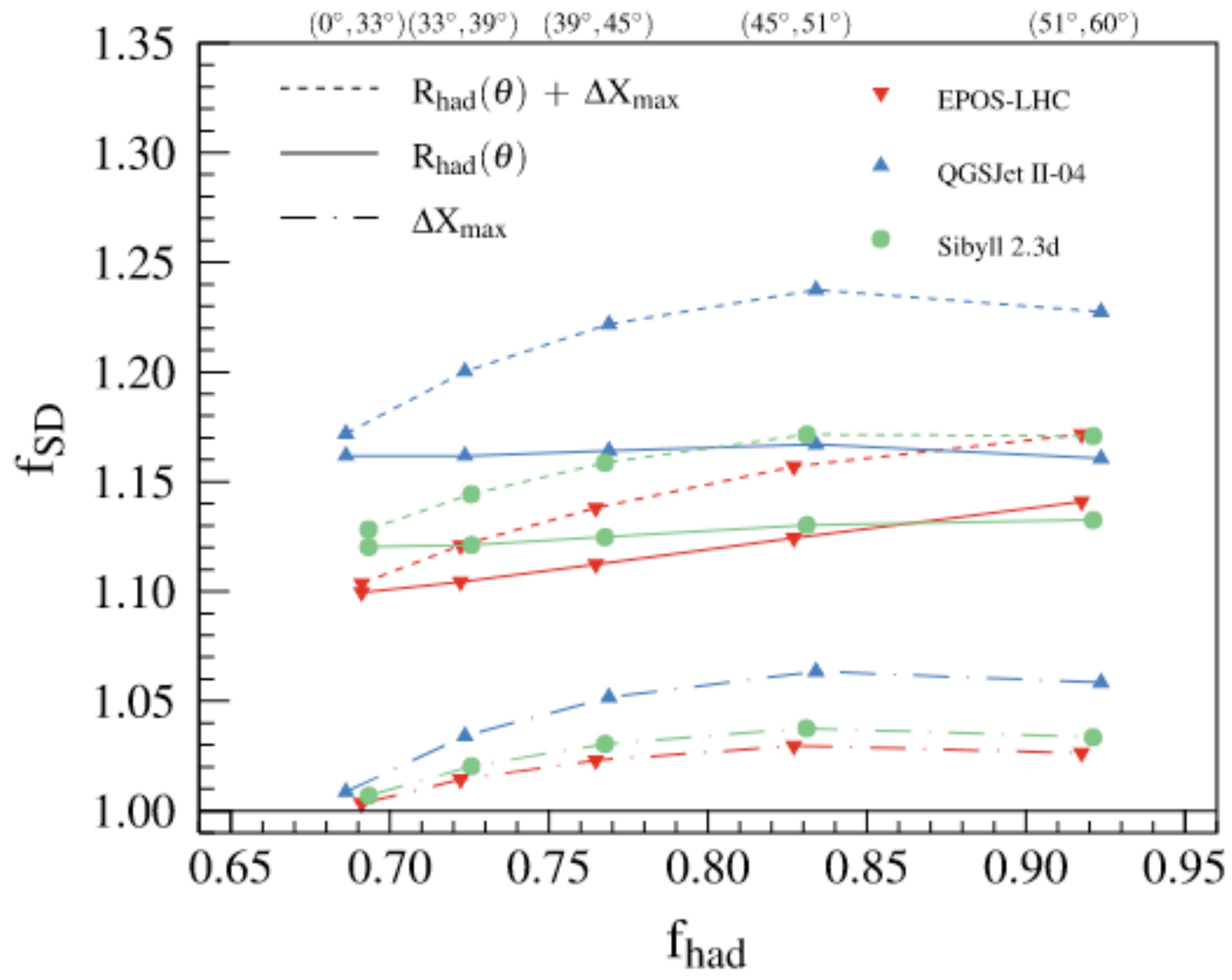
Combined fit of the [X_{max},S_{1000}] distributions with angular dependent muon rescaling $R_{had}(\vartheta)$

largest improvement



Combined fit of the [X_{max},S_{1000}] distributions with angular dependent muon rescaling $R_{had}(\vartheta)$ and shift of X_{max}

further improvement -> heavier composition



*Best description of data **if models modified** such that :*

X_{max} deeper by 20-50 g cm^{-2}

S_{had} increased by 15-25%

KM3NeT event

Assuming the estimated neutrino flux central value ~ 29 events should have been detected with Auger SD1500...

(~ 1.5 events assuming central value minus 2 sigma)