8TH ASTROPARTICLE PHYSICS SCIENTIFIC FAIR: 2021/2022

Tuesday 15th February 2022

UHECR physics at the Pierre Auger Observatory

Caterina Trimarelli*

* PhD Student at University of L'Aquila & INFN-LNGS

Pierre Auger Observatory 20th Anniversary

More than 400 members,
98 institutes, 17 countries

November 2019

Pierre Auger Observatory
Malargue, Mendoza, Argentina


Collaboration Meeting, November 2020

L'Aquila group (GSSI, UnivAq, LNGS):

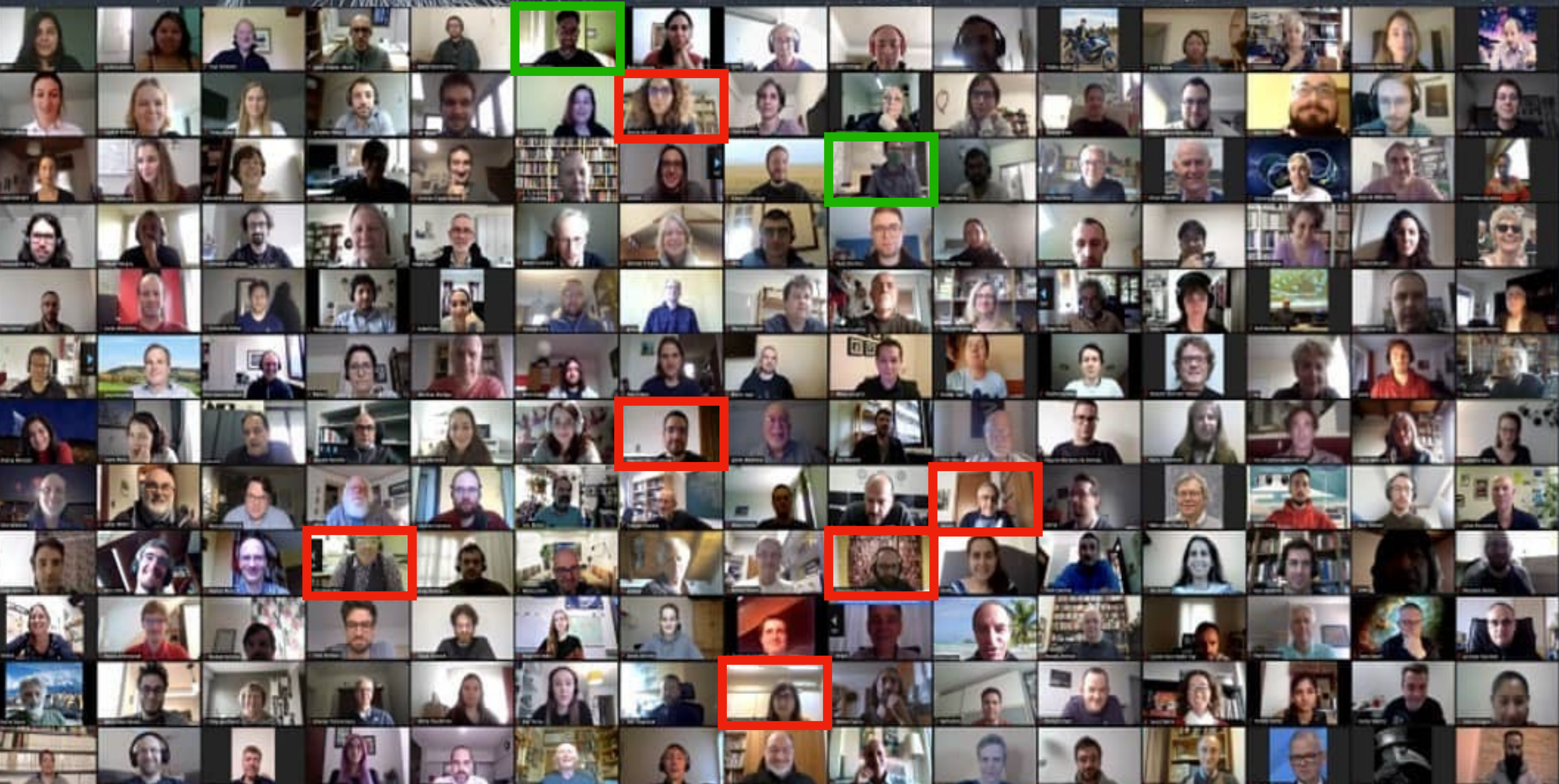
F. Barbato, I. De Mitri, S.Petrera — GSSI

E. Avocone, D. Boncioli, M. Mastrodicasa, C. Petrucci, V. Rizi, F. Salamida, C. Trimarelli — UnivAq

PHD Graduates - GSSI Alumni

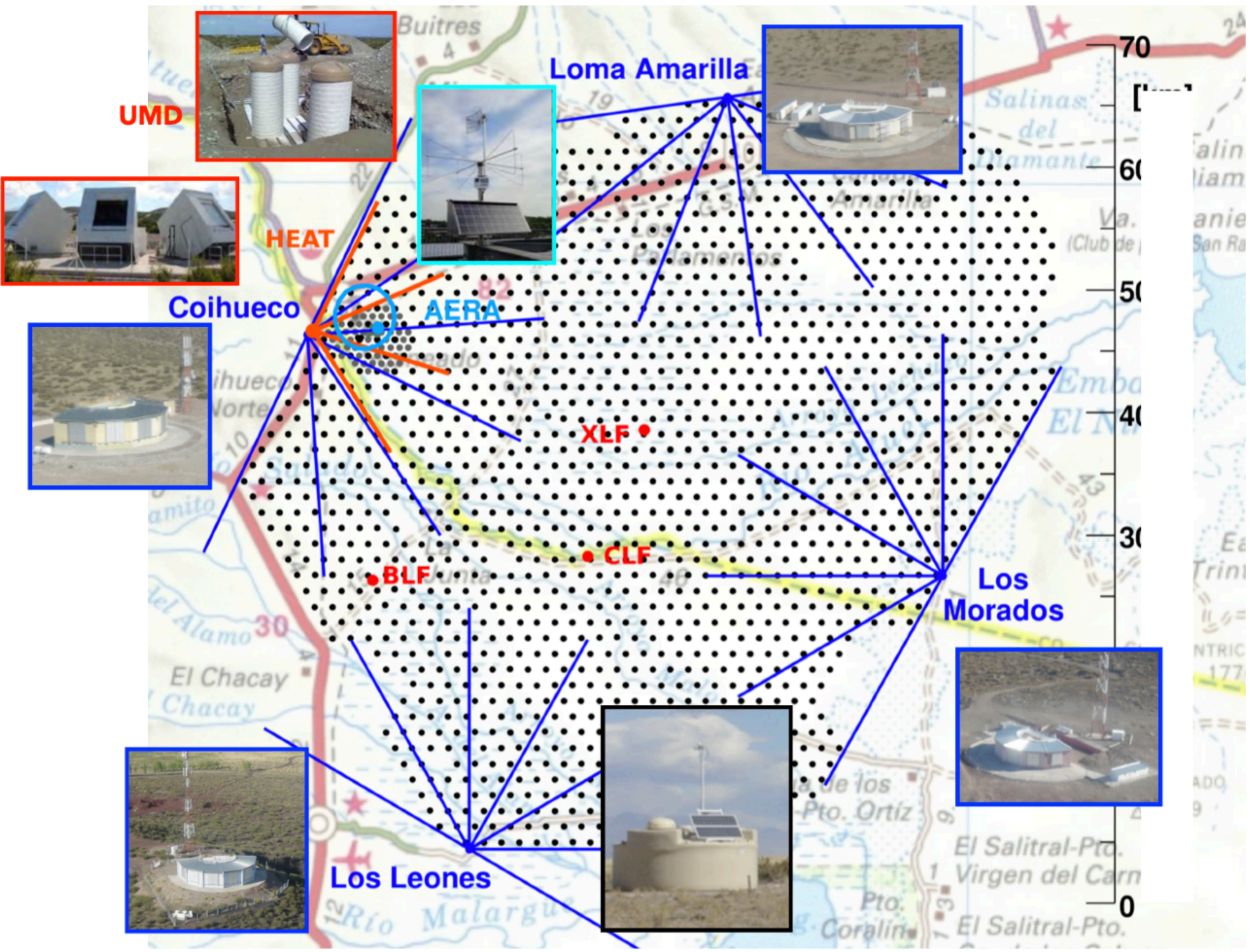
G. A. Anastasi — Università degli Studi di Torino

A. Condorelli — IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis



The Observatory

Located in the southern hemisphere is the largest air shower detector built so far



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km²
  - ➡SD750 : 61, 0.75 km grid, 25 km²
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30⁰ FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60⁰ FoV
    For reconstructing showers more reliably at ~10^{17}eV
- AERA radio antennas
  - ➡153 graded 17 km²

+Atmospheric monitoring devices
CLF, XLF, Lidars, …

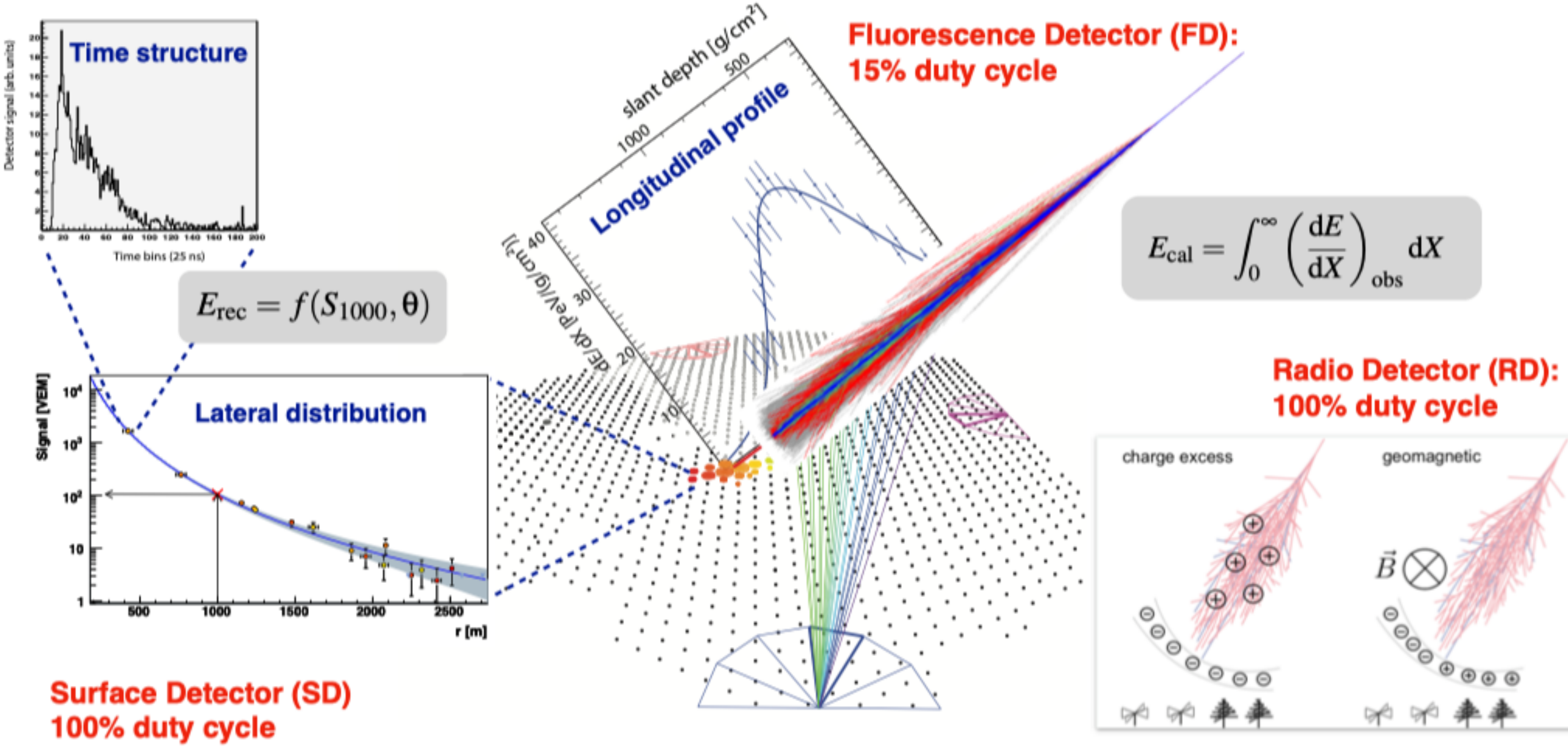
Hybrid Detection

The SDs measure photons and charged particles at ground level

The FDs observe longitudinal development of air showers in the atmosphere

The RDs complement this setup studying radio emission from air showers

AugerObservatory Phase I



Calibration of the SD risetime with X_{max} distributions measured with the FD

The Pierre Auger Observatory has been designed to investigate the highest energy cosmic rays with energy exceeding 10^{19}eV, combining a surface array of particle detectors with fluorescence telescopes for hybrid detection

Latest Results and Perspectives

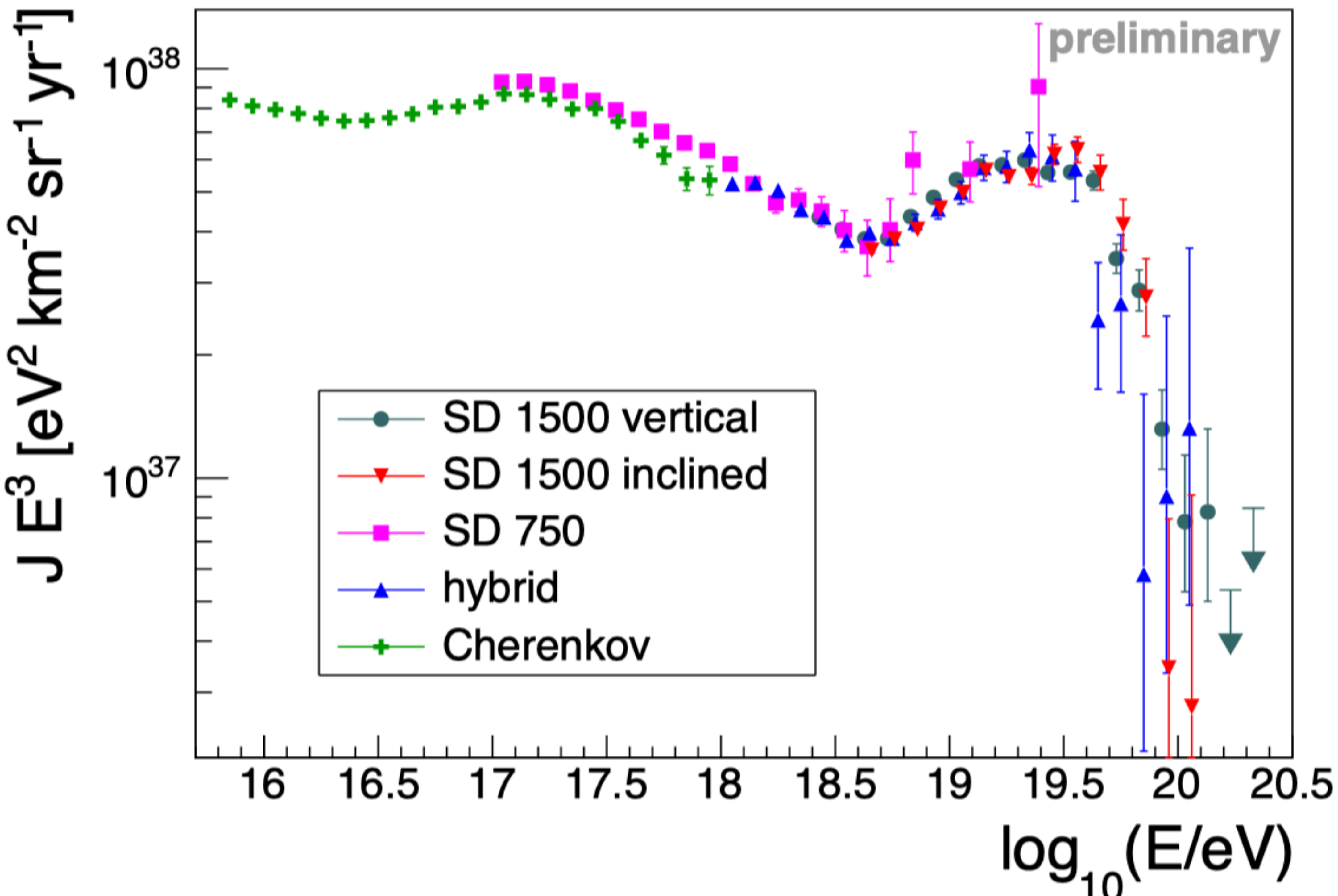
- Spectrum
- Mass Composition
- Large-Scale Anisotropy
- AugerPrime: status and motivation

INTRODUCTION
Spectrum
Mass Composition
Anisotropy
AugerPrime
CONCLUSIONS

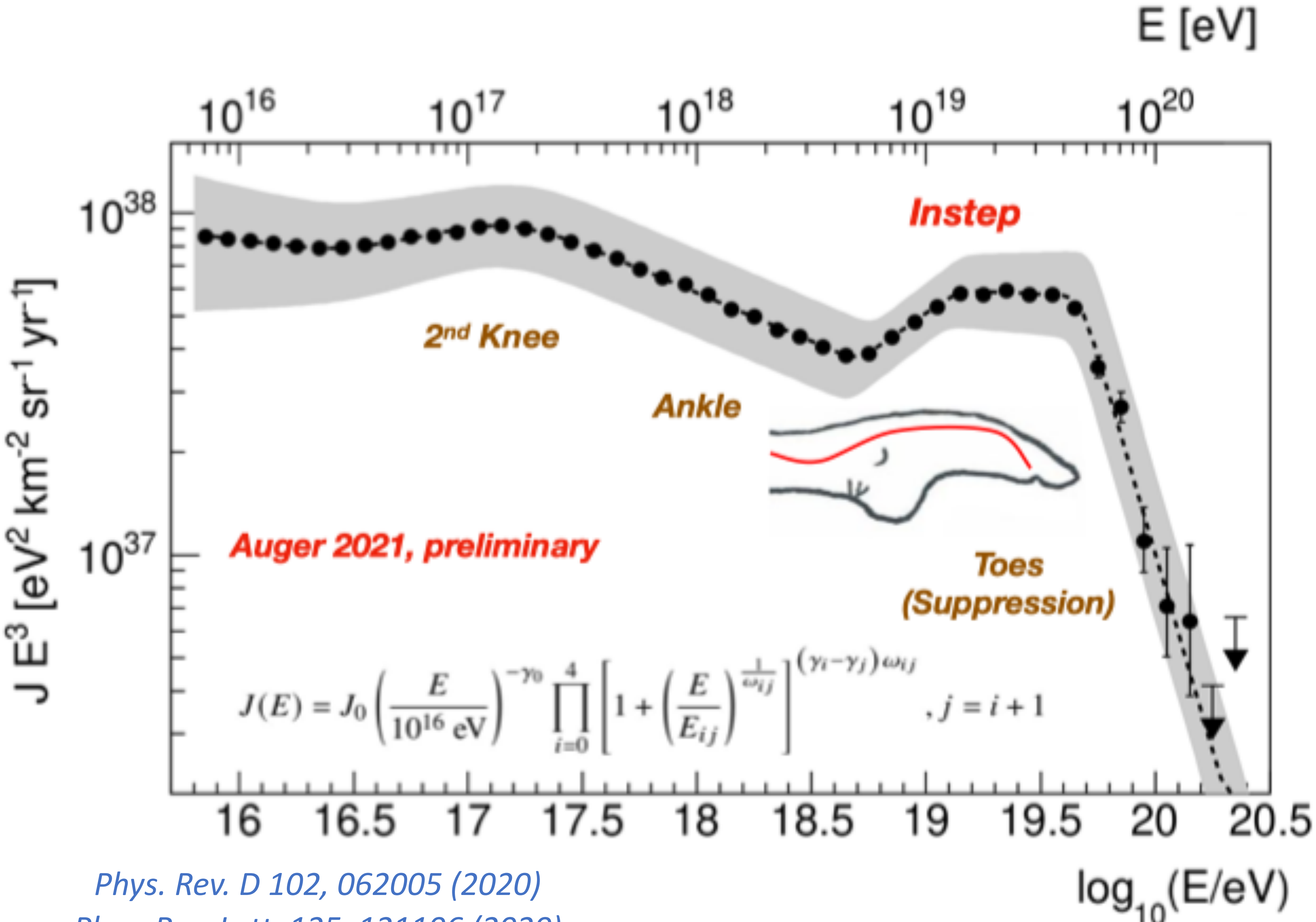
The Spectrum

Phys. Rev. D 102, 062005 (2020)
Phys. Rev. Lett. 125, 121106 (2020)

R. Engel, ICRC2021



The method to derive the spectrum is entirely data-driven



Phys. Rev. D 102, 062005 (2020)

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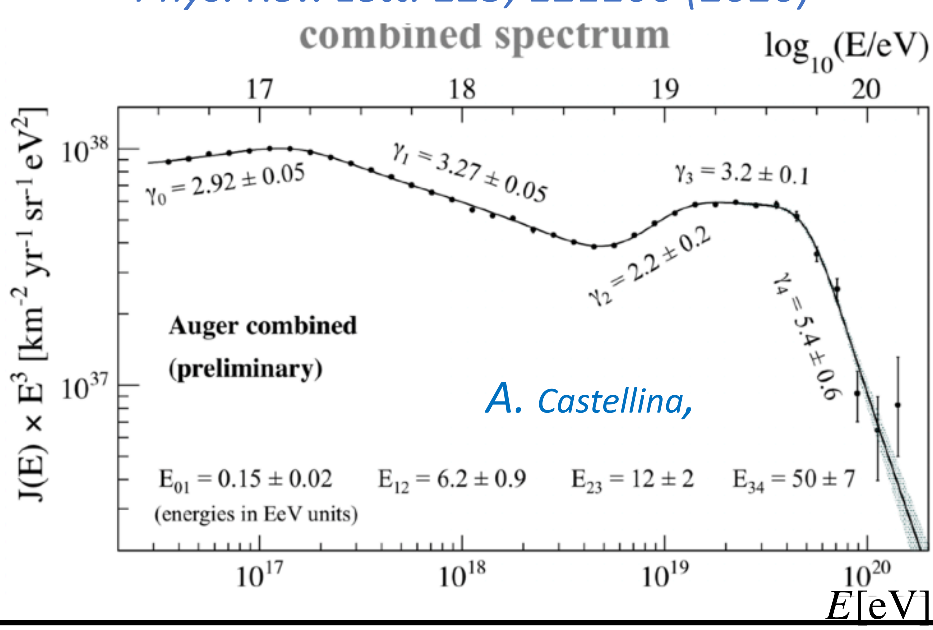
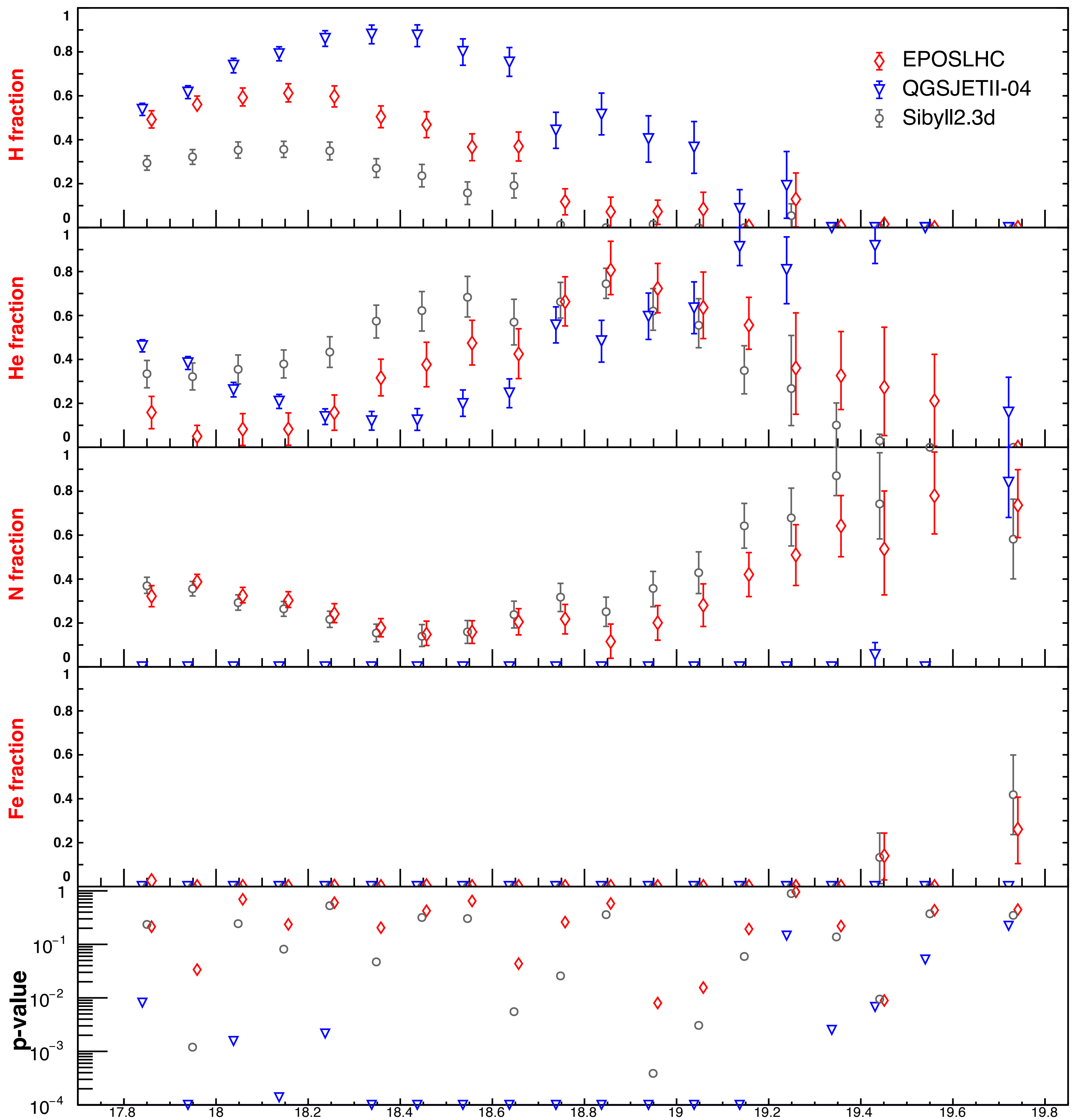
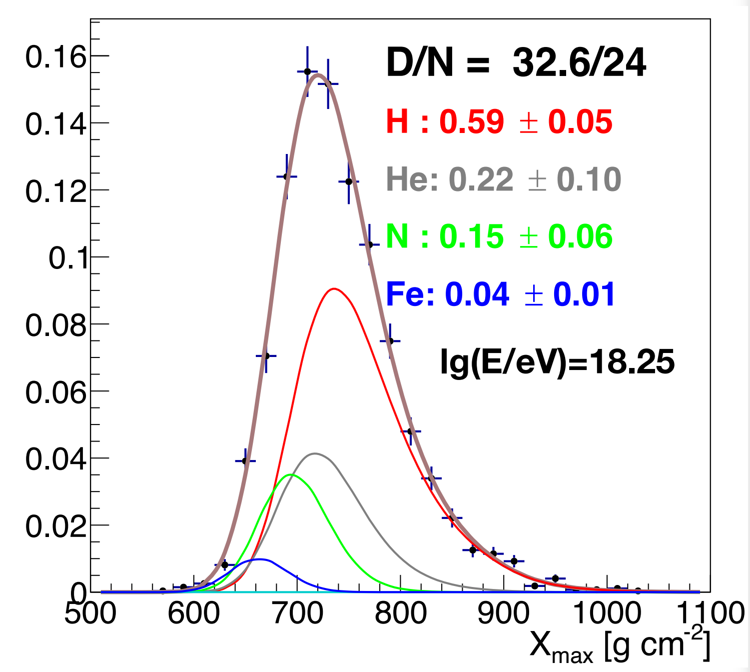


Mass Composition @ Earth

Measured considering the atmospheric depth at which the number of particles in an air shower reaches its maximum



$< X_{max} > \propto \lg(E/A)$



- **X_{max} distributions fitted with four-mass Gumbel function from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

FractionFit code

L'Aquila group

Anisotropy: Large scale

Combination of vertical and inclined showers

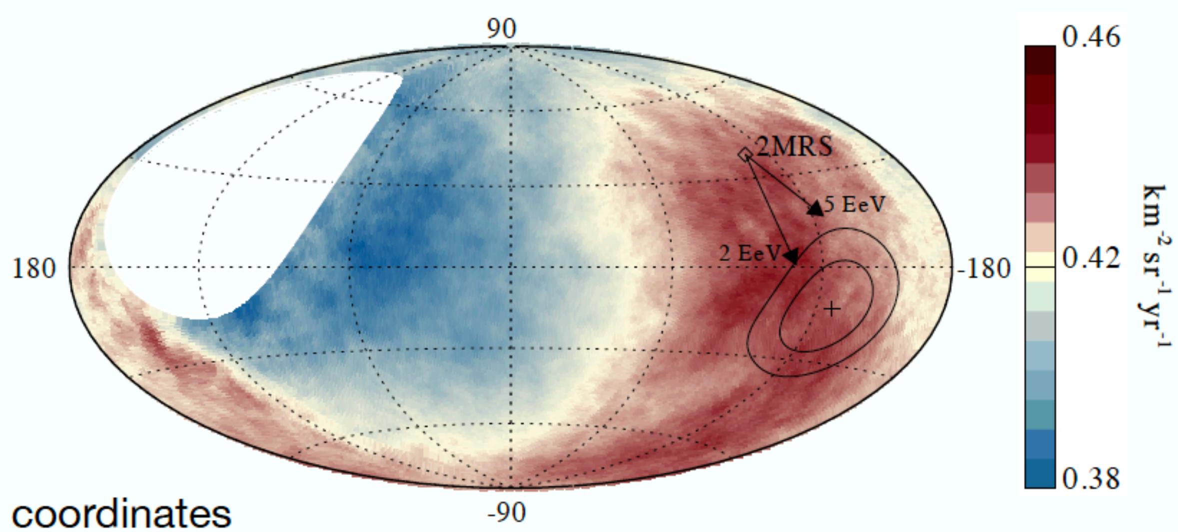
Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

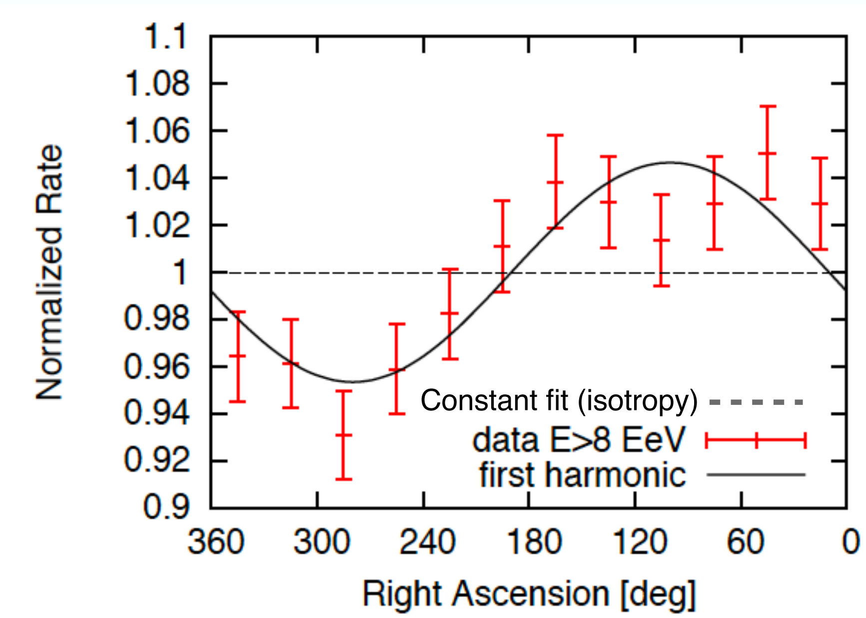
The amplitude of 3-d dipole above $8 \cdot 10^{18}$eV

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$ $(l, b) = (233°, -13°)$

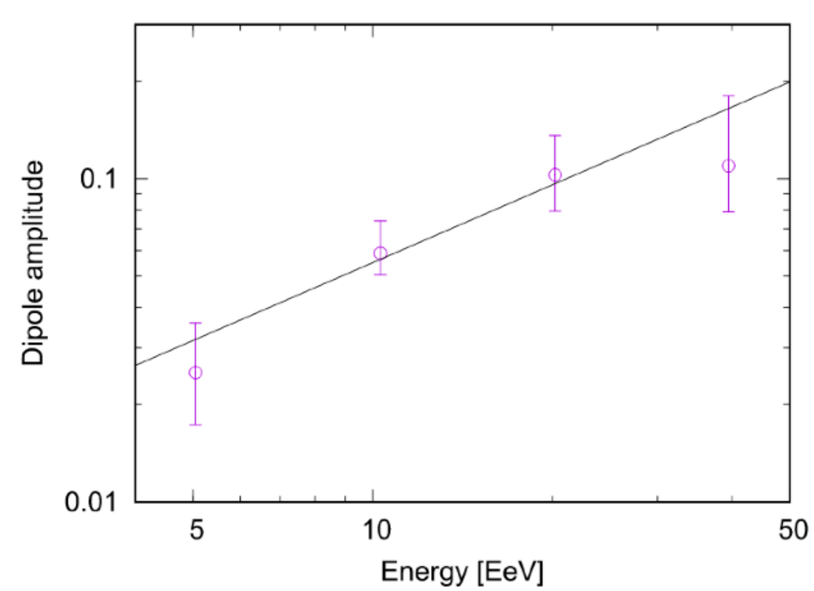


gal. coordinates

−90° < δ < 45°



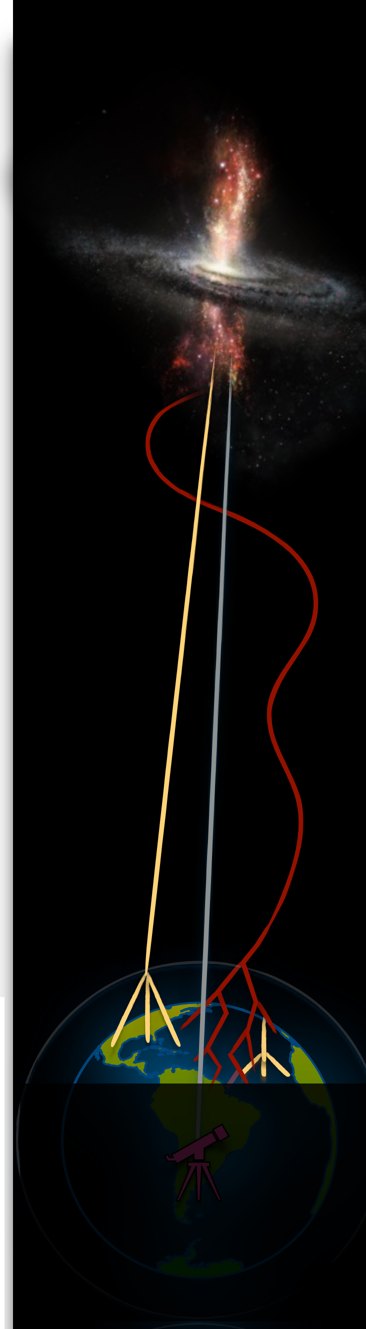
THE ASTROPHYSICAL JOURNAL, 868:4 (12pp), 2018 November 20



Auger Coll., Science (2017), APJ (2018)

physicsworld TOP 10 BREAKTHROUGH 2017

This direction is about 125° from the galactic center suggesting that the anisotropy has an extragalactic origin



Upgrade of the Pierre Auger Observatory

AugerPrime

Physics motivation

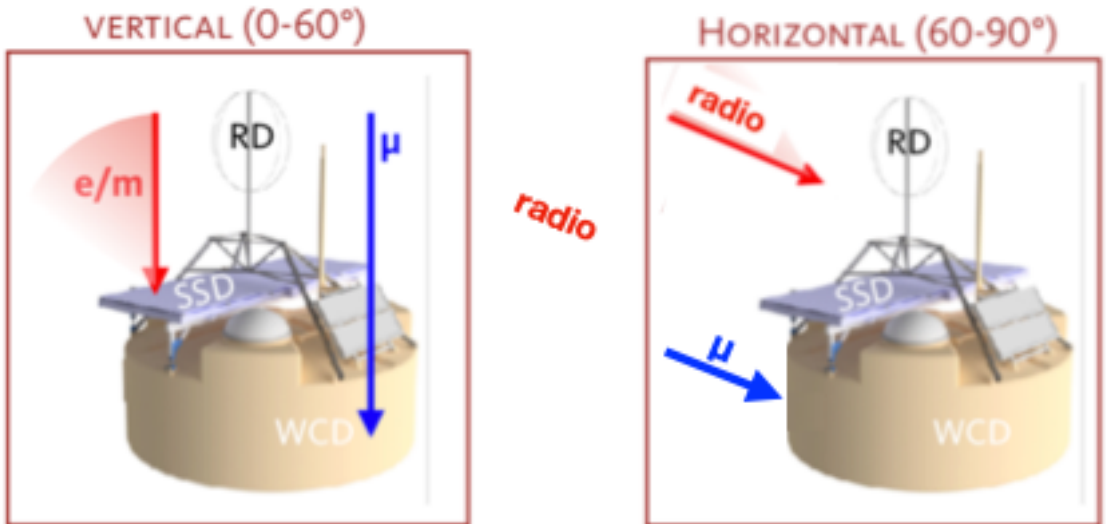
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle Physics with air showers (muon estimate)
- Much better understanding of new and old data

Auger Observatory Phase II

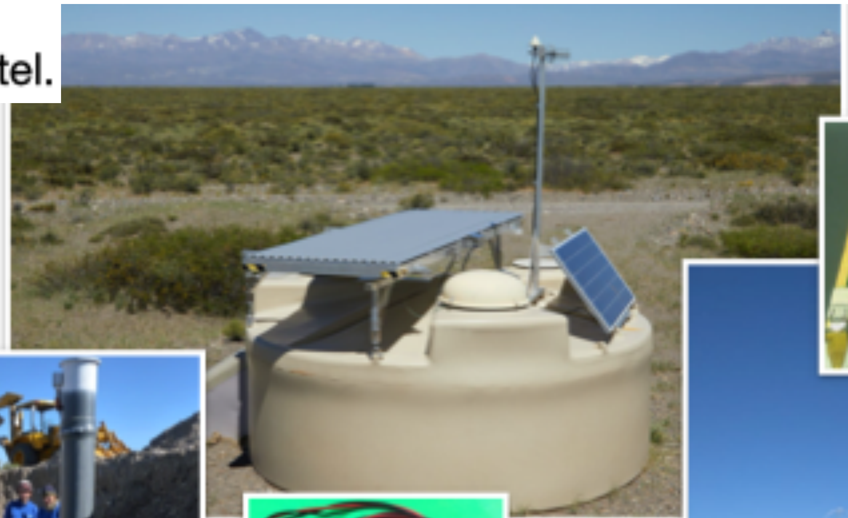
- Data taking 2022/23 – 2030
- AugerPrime (8 years, $\theta < 60°$): 40,000 km² sr yr (Phase II), 80,000 km² sr yr (Phase I)
- Re-analysis of old data set (deep learning)

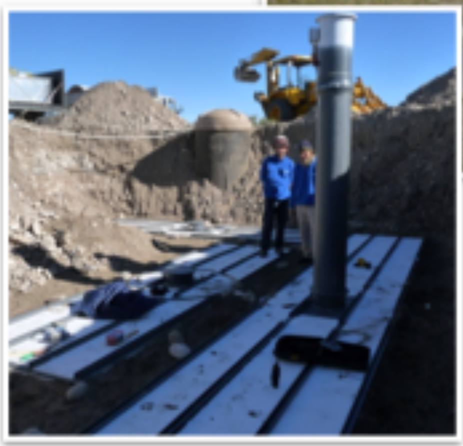
Components of AugerPrime

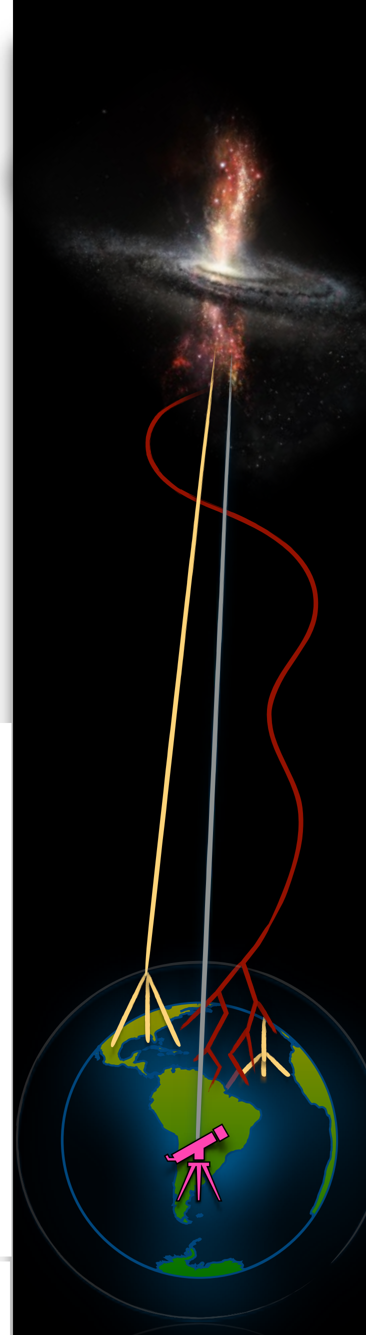
- 3.8 m² scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

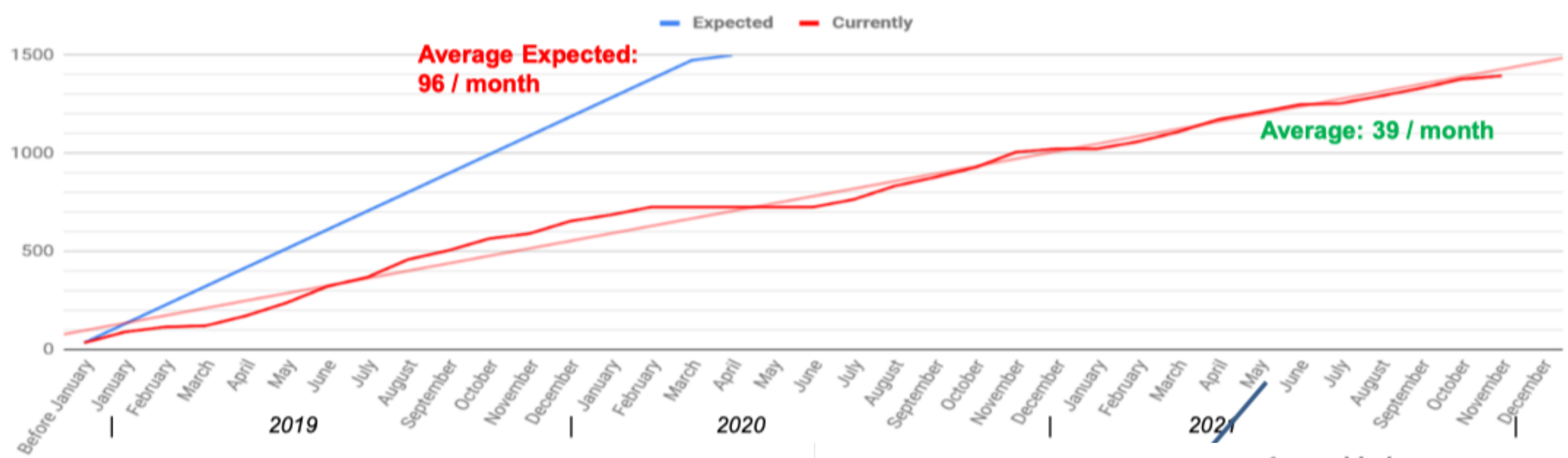


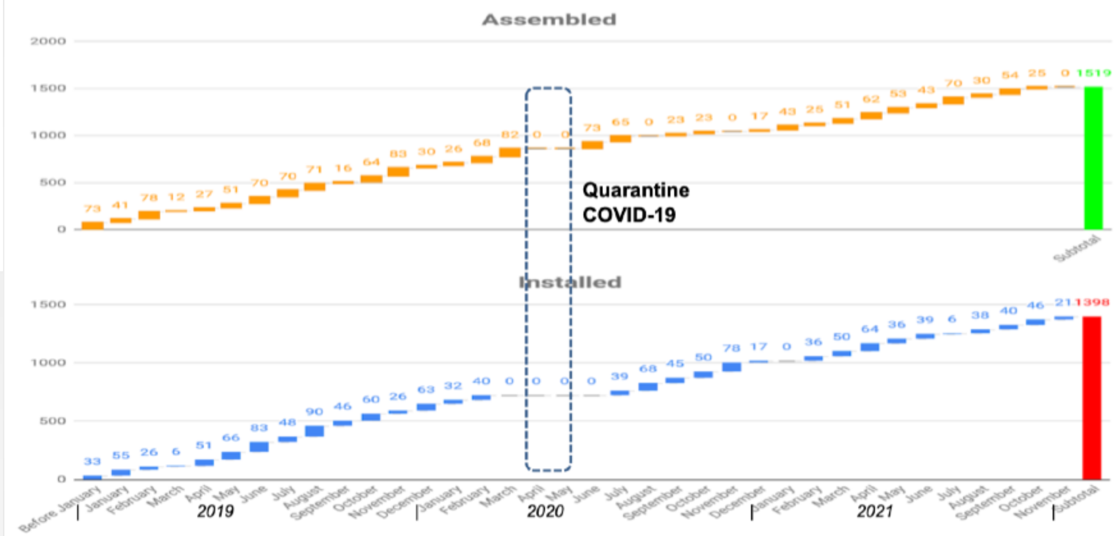
(AugerPrime design report 1604.03637)

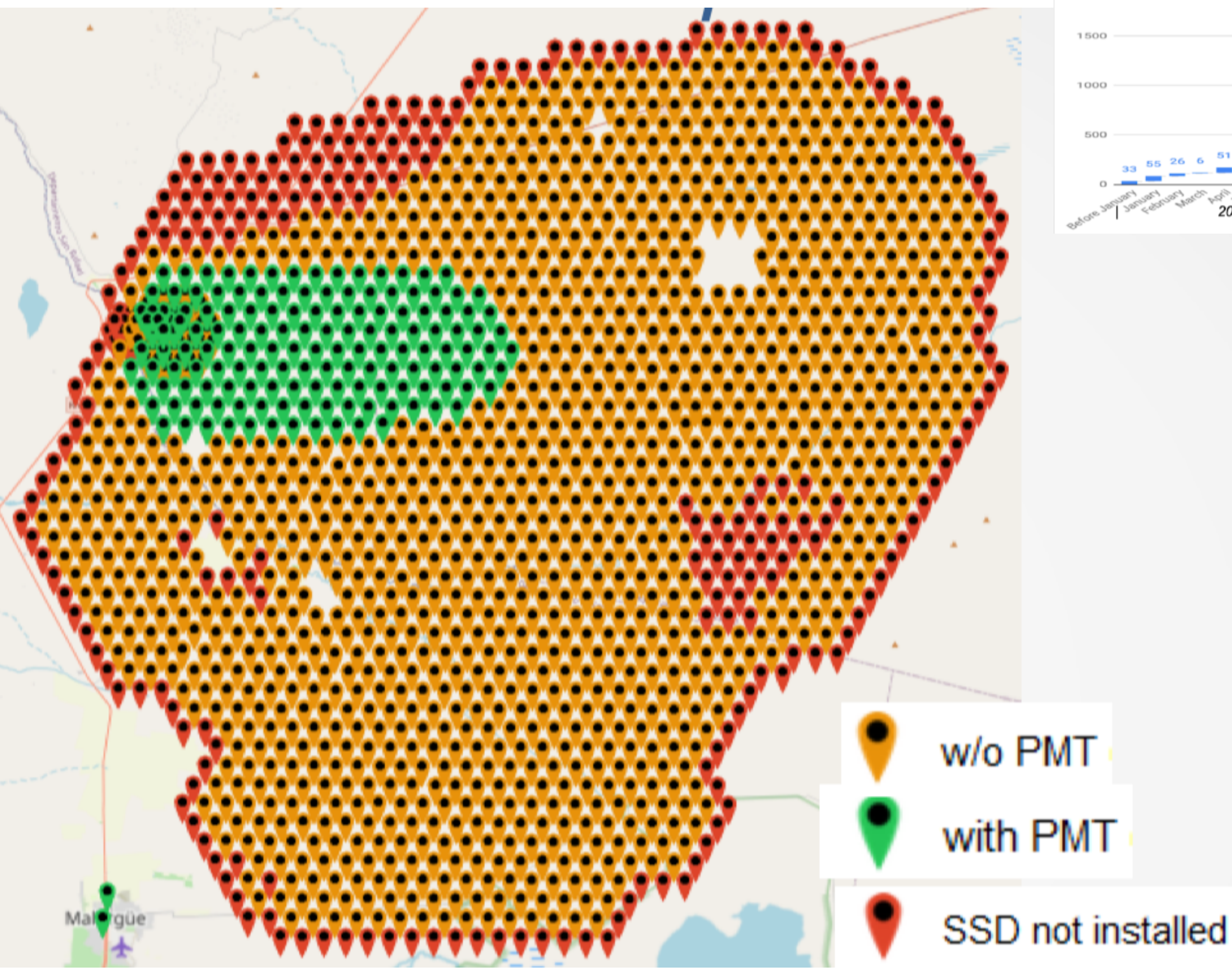








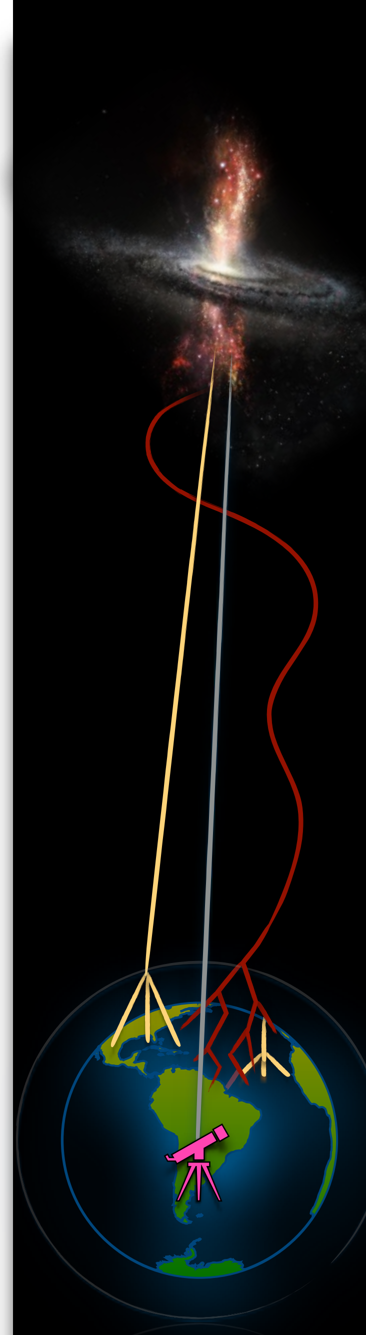




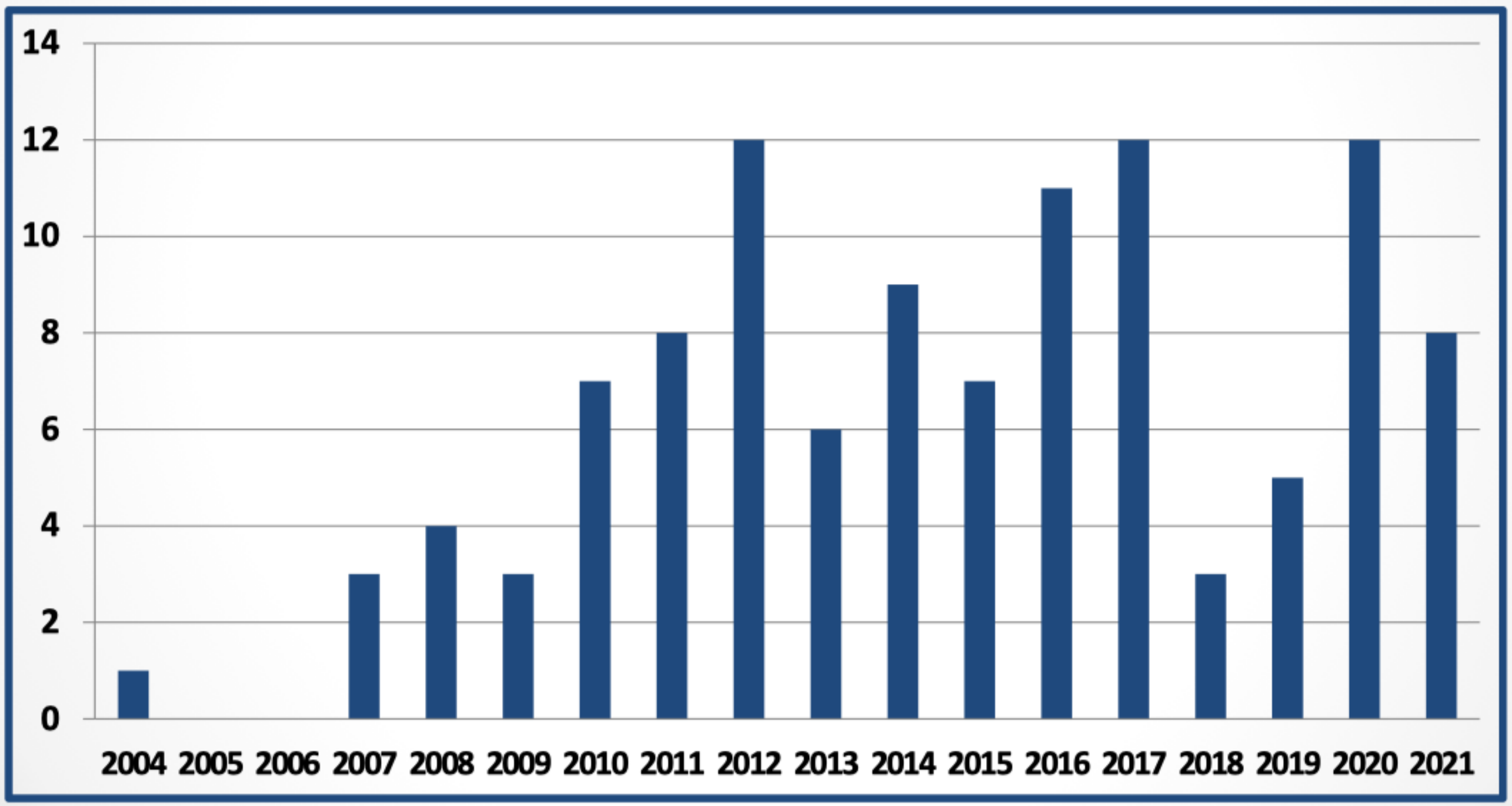
Total SSD to install: 1493
Installed: 1398 (93%)
To install: 99 (7%)

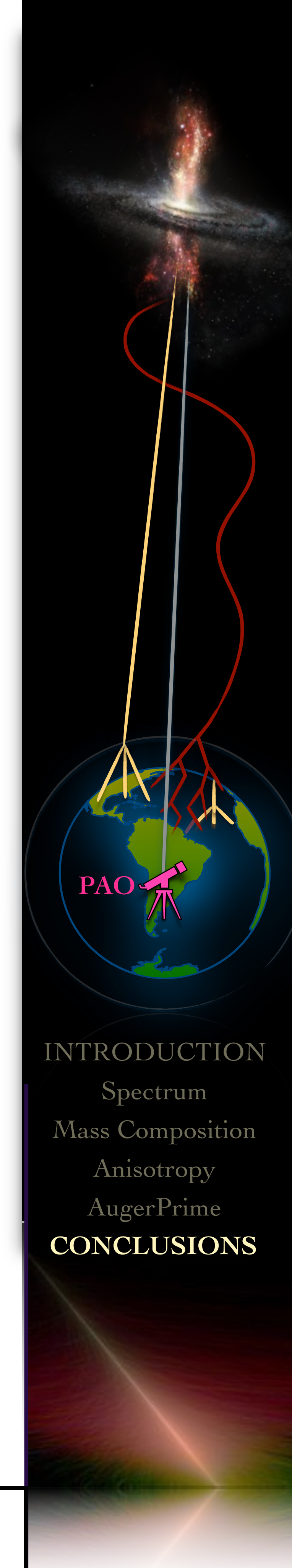
Total SSD with PMT :1493
Installed: 153 (10%)
To install: 1340 (90%)

Total SSD to assemble: 1519
Assembled: 1519 (100 %)
To assemble: 0 (0%)



111 Auger papers published
(cumulative up to 01 November 2021)





Working @L'Aquila Group

L'Aquila group (GSSI, UnivAq, LNGS):
F. Barbato, I. De Mitri, S.Petrera GSSI
E. Avocone D. Boncioli, M. Mastrodicasa, C. Petrucci, V. Rizi, F. Salamida, C. Trimarelli UnivAq

- Atmospheric monitoring;
- Combined fit of Spectrum and composition;
- Mass Composition at Earth;
- Inferring source scenarios from Spectrum+Composition

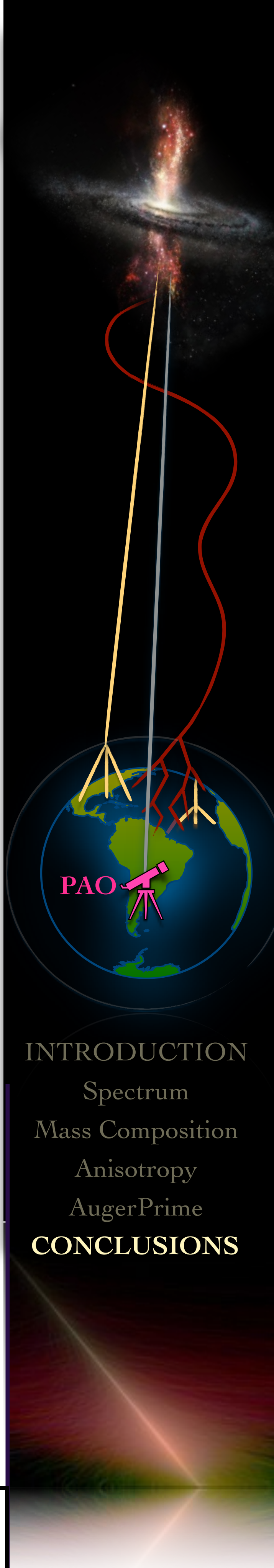
(**JCAP 04, 2017, 038**)

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

SimProp: a simulation code for ultra high energy cosmic ray propagation

R. Aloisio,[a,b] D. Boncioli,[c] A.F. Grillo,[a] S. Petrera[d] and F. Salamida[d,e]

- Lorentz Invariance Violation
  - Propagation constrains (**JCAP 01 (2022) 01, 023**)
  - Extensive air shower constrains (presented at ICRC2021)
- Multi-messenger studies (presented at ICRC2021)



Studying Cosmic Ray physics @ GSSI

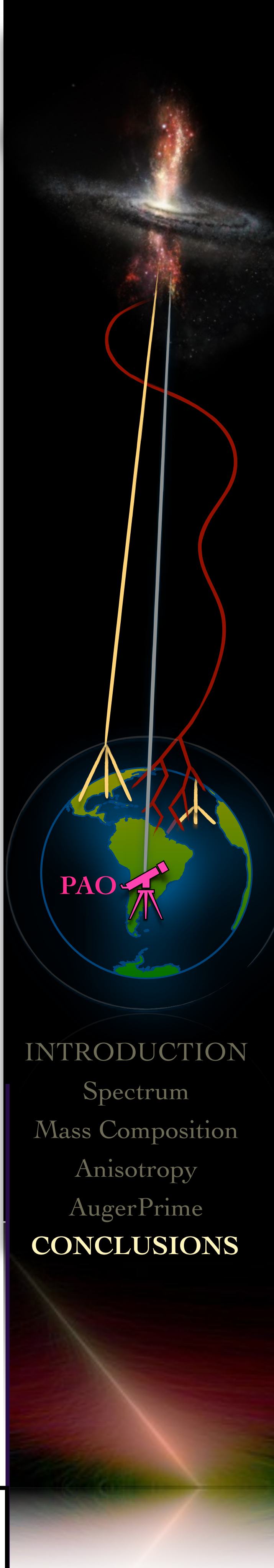
“Pillar” Courses :

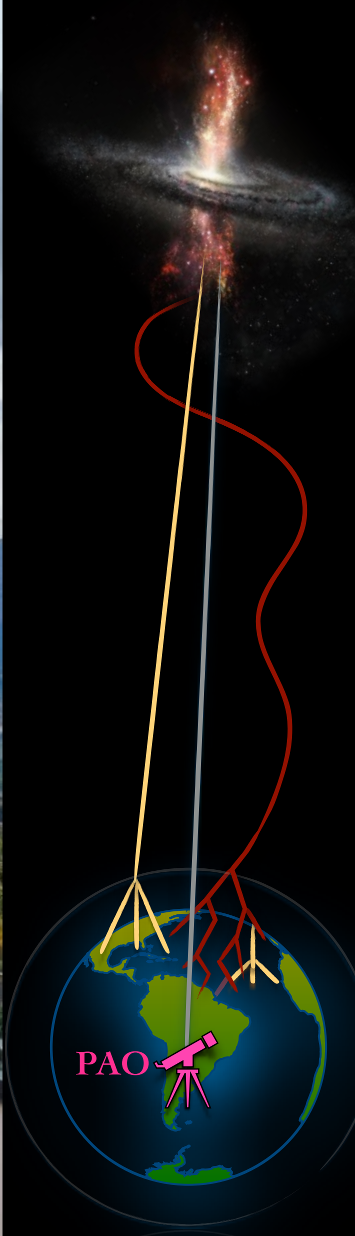
- **HE-TH:** High Energy Astroparticle Physics (**P. Blasi**)
- **HE-EXP:** High Energy Astroparticle Physics (**I. De Mitri**)

done.

“Short” Courses :

- **HE-7:** UHECR theory (**R. Aloisio**)
- **HE-2:** Data analysis techniques in HE Astroparticle Physics (**S. Petrera**)
- **HE-1:** Elementary processes for high energy Astroparticle Physics (**C. Evoli**)
- …….

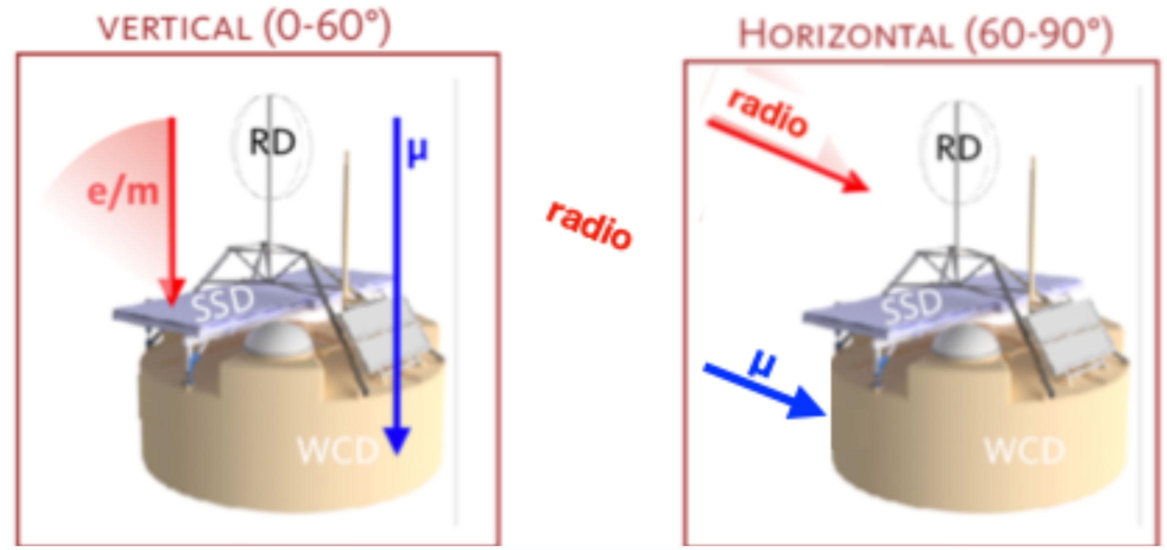




Thanks for your attention!

Backup

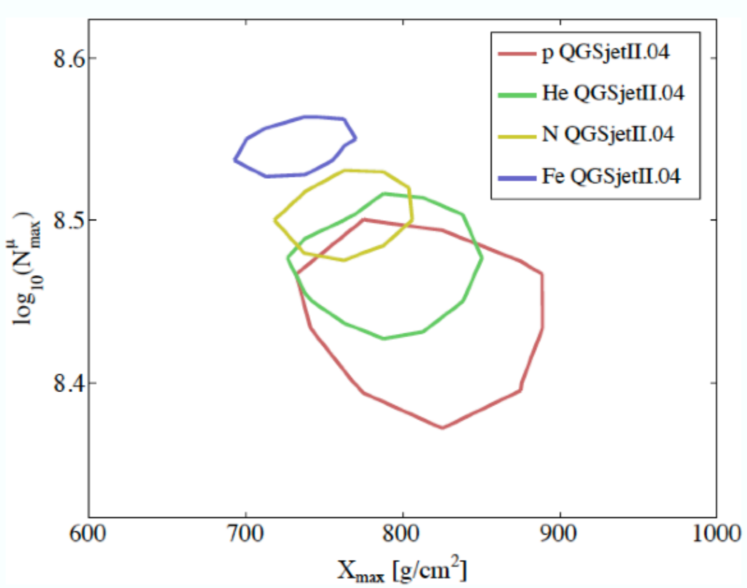
Upgrade of the Pierre Auger Observatory: *AugerPrime*



Composition sensitivity with 100% duty cycle

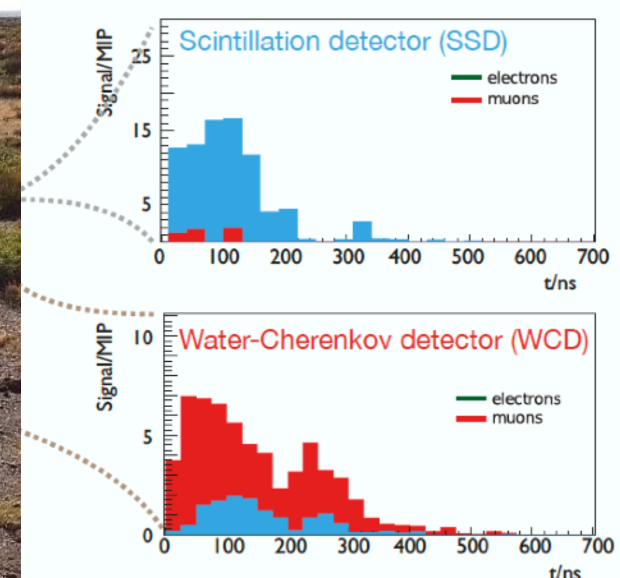
To increase exposure with composition sensitive data Surface array needed!

Duty cycle: 100% (SD) vs 15% (FD)

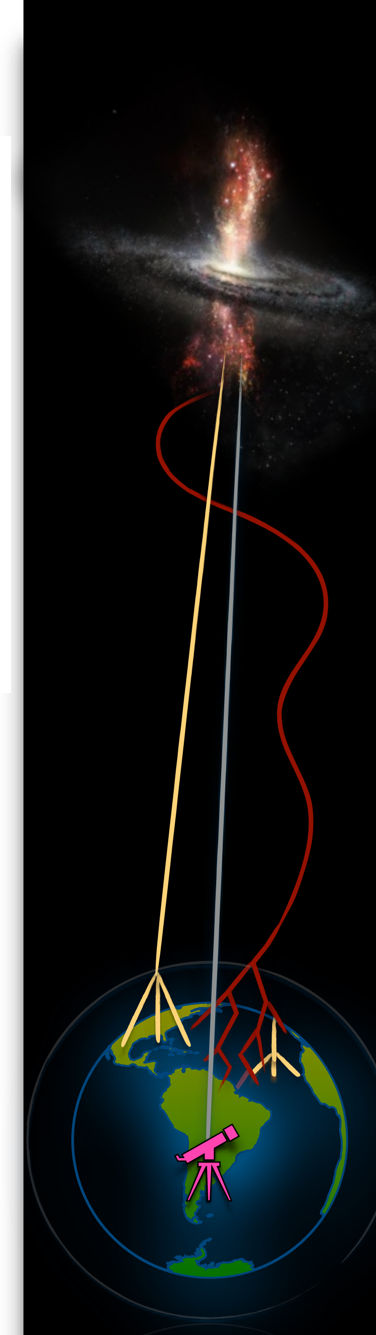


(AugerPrime design report 1604.03637)

complementarity of light responses used to discriminate e.m. and muonic component



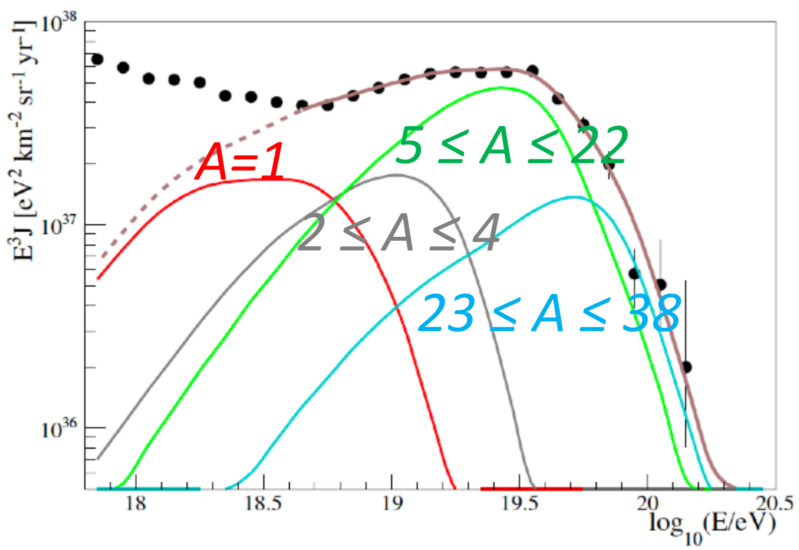
Moreover
- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

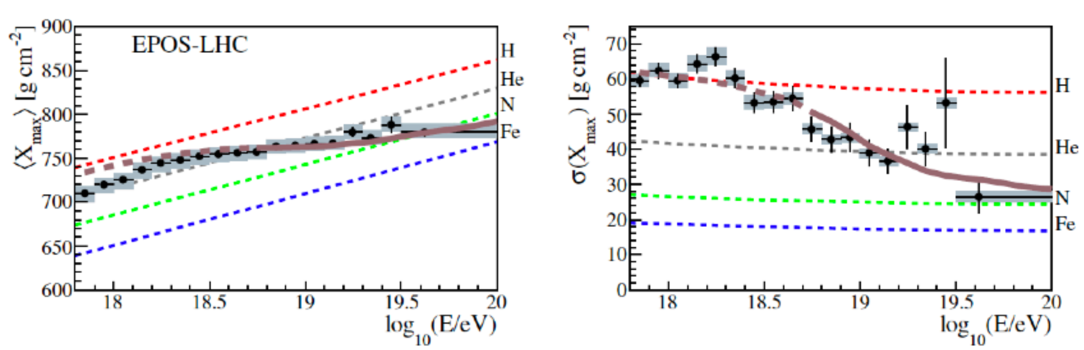


Inferring source scenarios from Spectrum+Compo

SPG (SimProp, PSB x-sect, Gilmore '12 EBL) + EPOS-LHC

$$\frac{dN}{dE} = J_0 \sum_{\alpha} f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{\text{cut}}\,, \\ \exp(1 - \frac{E_0}{Z_\alpha R_{\text{cut}}}) & \text{for} \quad E_0/Z_\alpha \geq R_{\text{cut}} \end{cases}$$





JCAP 04 (2017) 038

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

2012

SimProp: a simulation code for ultra high energy cosmic ray propagation

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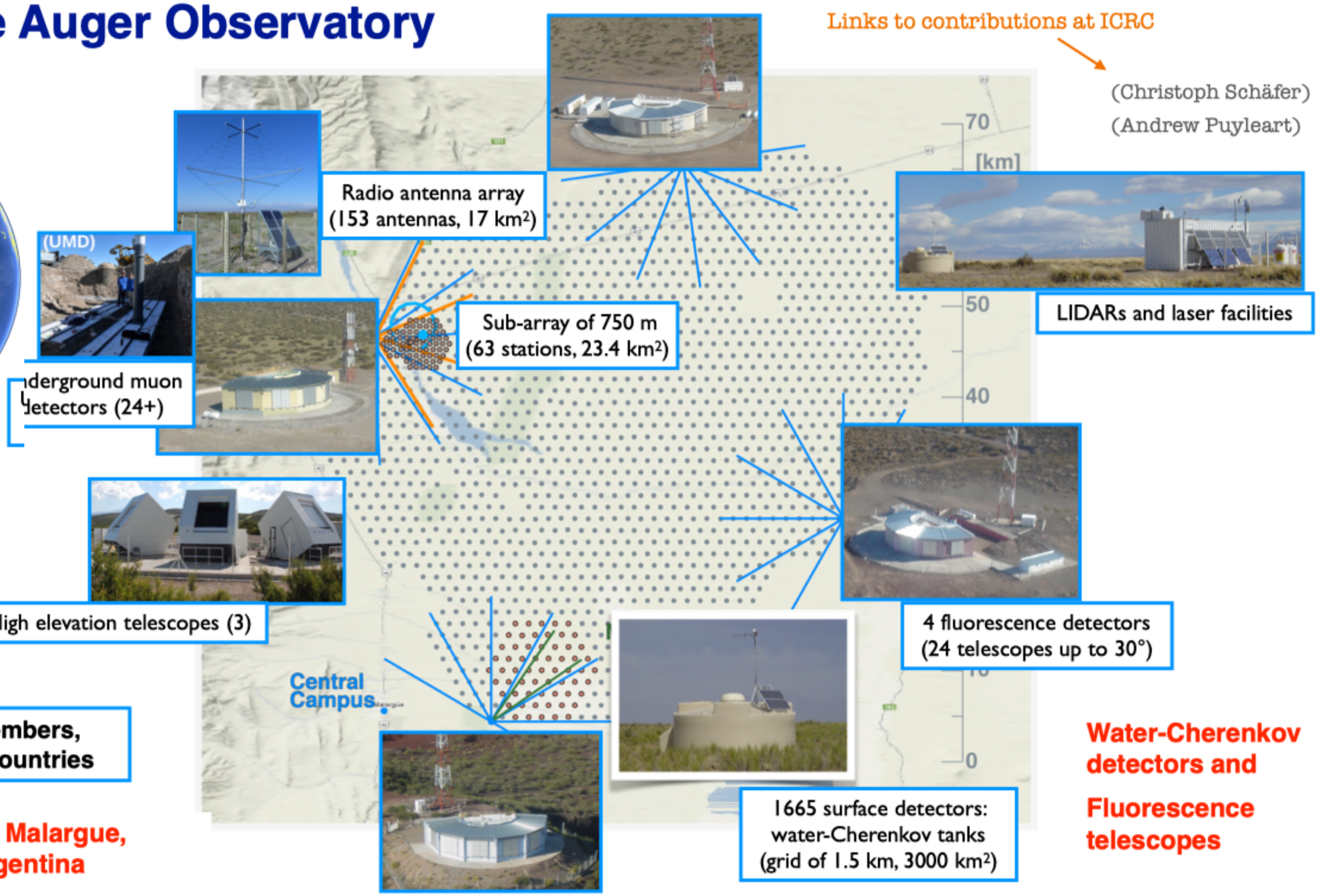
+ Cosmogenic photon & neutrino searches
(no event found > 10^{18} eV

+ Joint papers with Telescope Array
Energy spectrum, composition, anisotropies

+ Multimessenger studies
Icecube, Antares, Ligo/Virgo

The Pierre Auger Observatory



More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes

R. Engel, ICRC2021

INTRODUCTION
Spectrum
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CONCLUSIONS

Anisotropy: Large scale

Auger Coll., Science (2017), APJ (2018)

physicsworld TOP 10 BREAKTHROUGH 2017

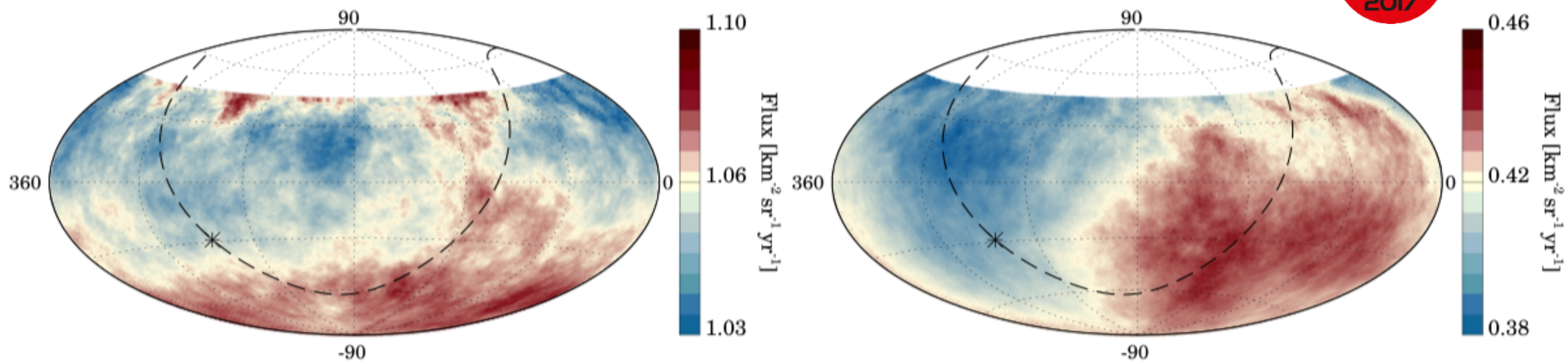


Figure 2. Maps in equatorial coordinates of the CR flux, smoothed in windows of 45°, for the energy bins [4, 8] EeV (left) and $E \geqslant 8$ EeV (right). The Galactic plane is represented with a dashed line, and the Galactic center is indicated with a star.

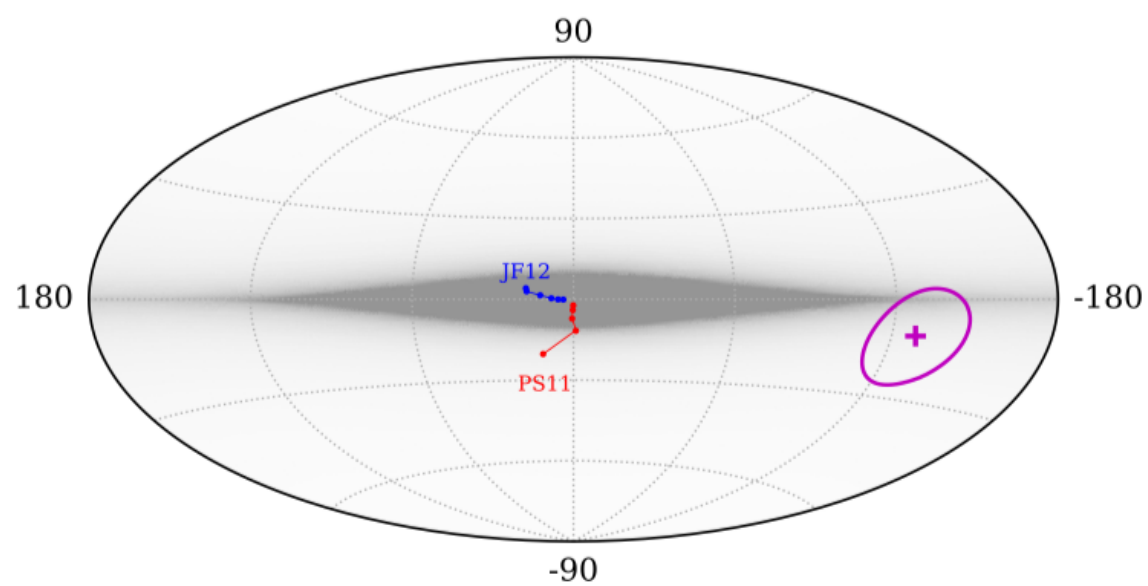
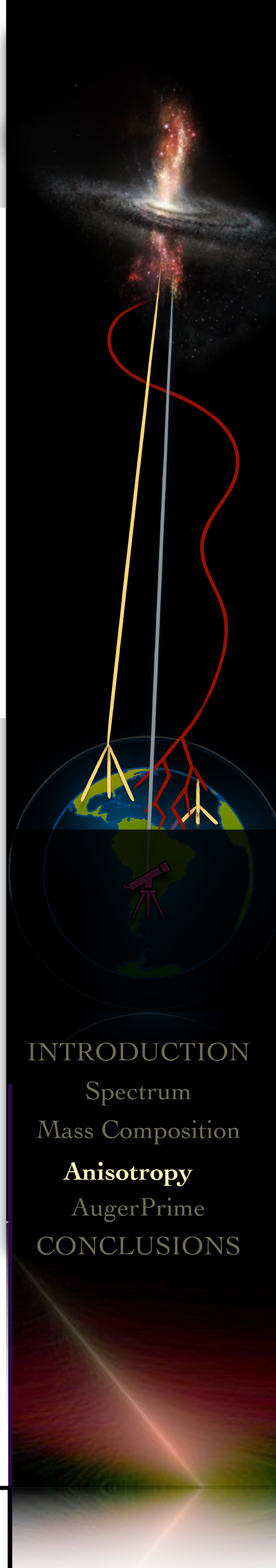
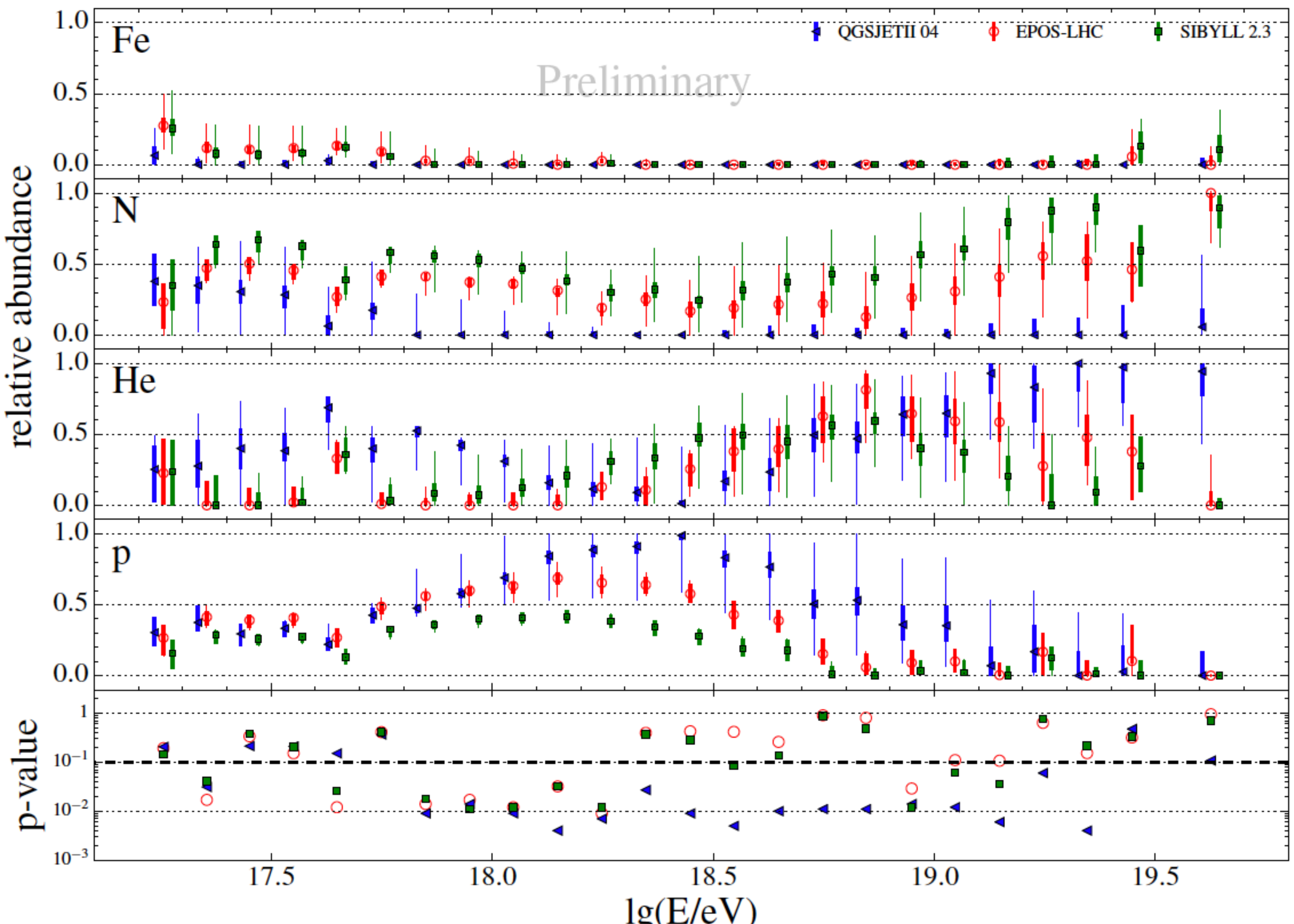


Figure 5. Map in Galactic coordinates of the direction of the dipolar component of the flux for different particle rigidities for CRs coming from Galactic sources and propagating in the Galactic magnetic field model of Jansson & Farrar (2012) (blue points) and the bisymmetric model of Pshirkov et al. (2011) (red points). The points show the results for the following rigidities: 64, 32, 16, 8, 4 and 2 EV (with increasing distance from the Galactic center). We also show in purple the observed direction of the dipole for $E \geqslant 8$ EeV and the 68% CL region for it. The background in gray indicates the integrated matter density profile assumed for the Galactic source distribution (Weber & de Boer 2010).

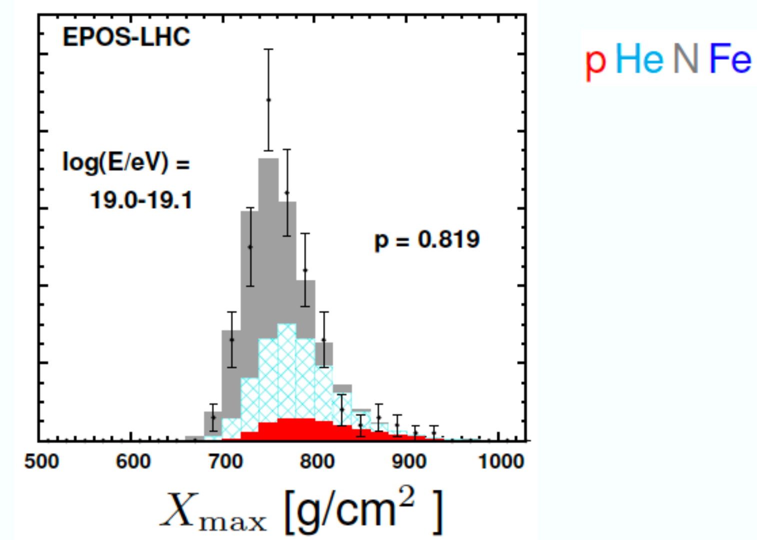


Mass Composition @ Earth

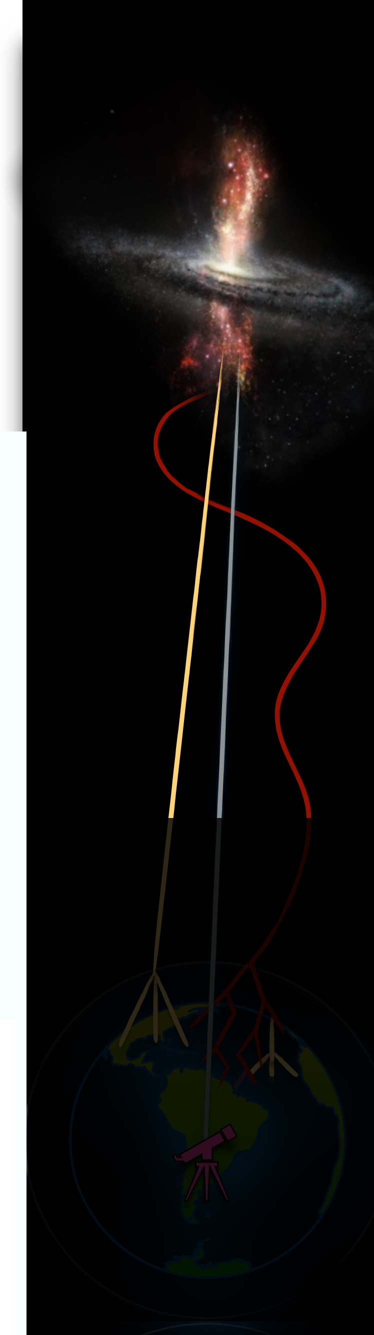
Mass composition @ Earth (top of the atmosphere)



(Bellido ICRC 2017)



- **Xmax distributions fitted with four-mass CONEX showers from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

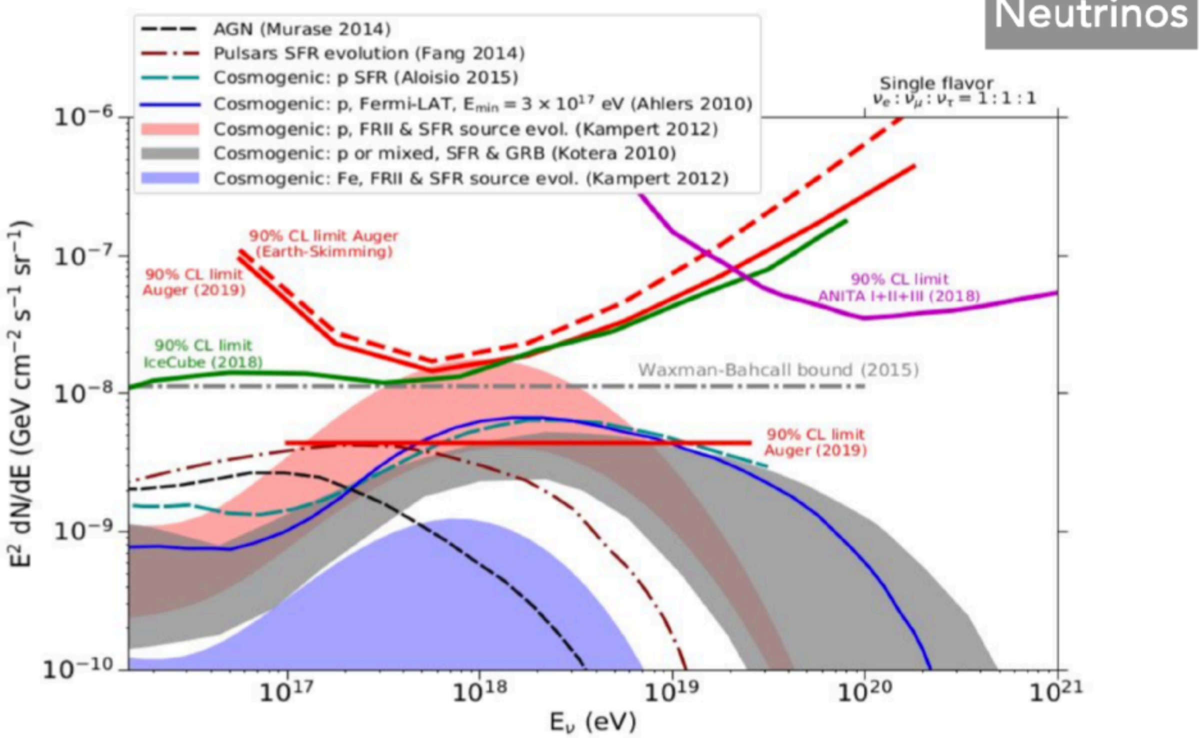


Cosmogenic neutrino and photon fluxes

$p + \gamma \rightarrow n + \pi^+$
$\rightarrow \mu^+ + \nu_\mu$
$\rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

$$k = \frac{N_{up}}{\int_{E_\nu} E_\nu^{-2} \epsilon_{tot}(E_\nu) dE_\nu}$$

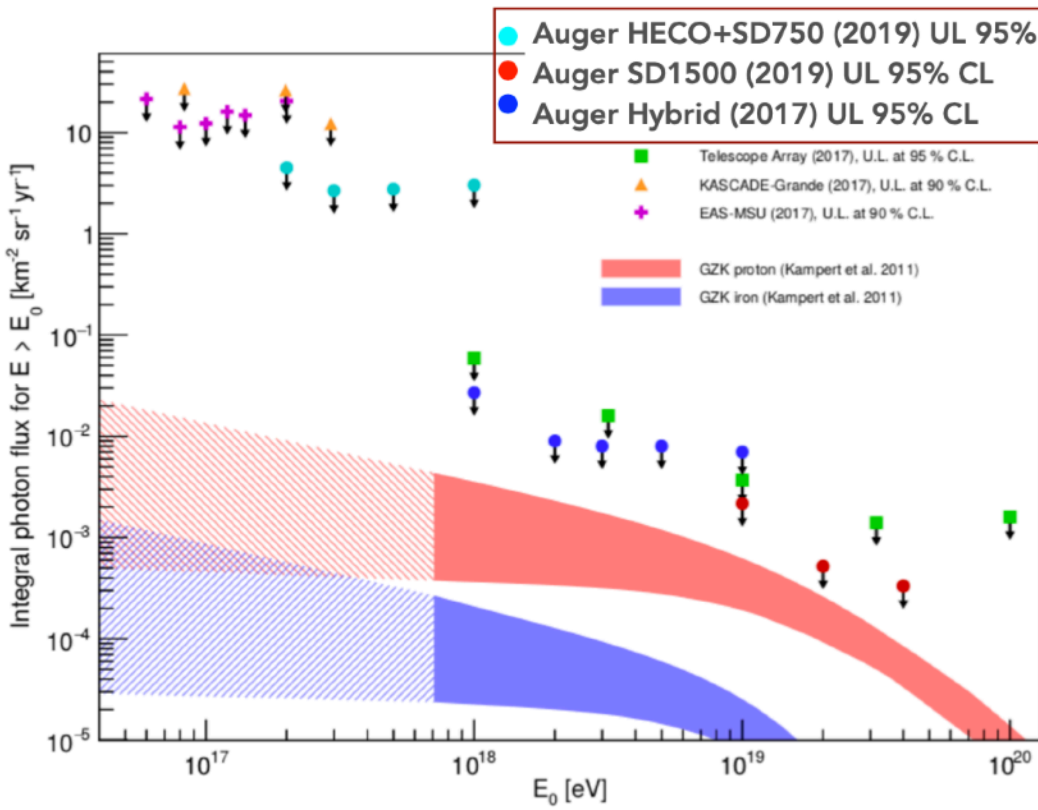
Neutrinos



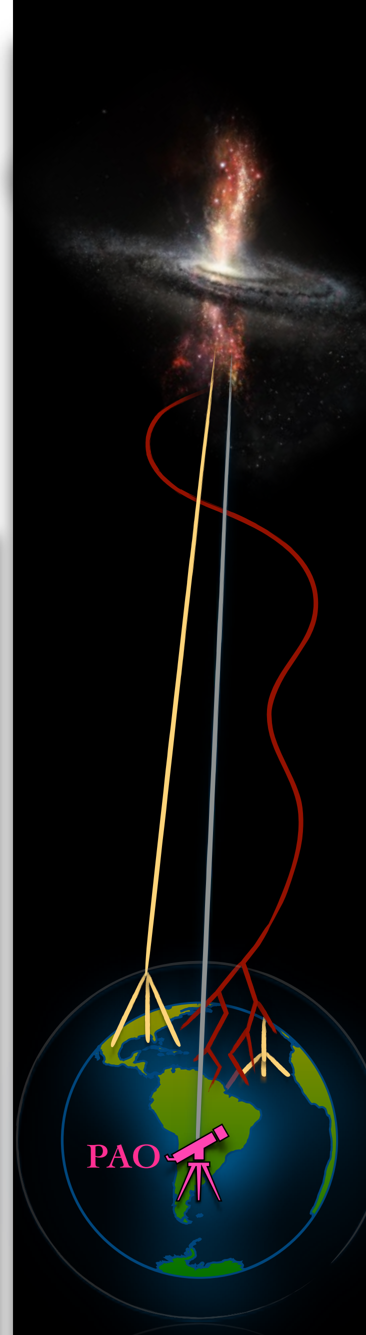
Maximum sensitivity around EeV
k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

$p + \gamma \rightarrow p + \pi^0$
$\rightarrow \gamma + \gamma$

Photon

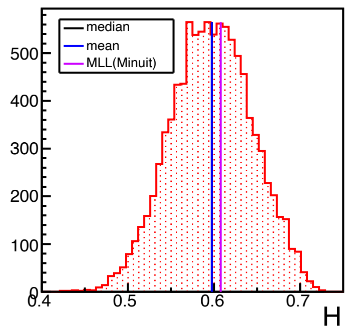


Most sensitive EAS detector for E_γ>0.2 EeV



Mass Composition @ Earth

FractionFit code

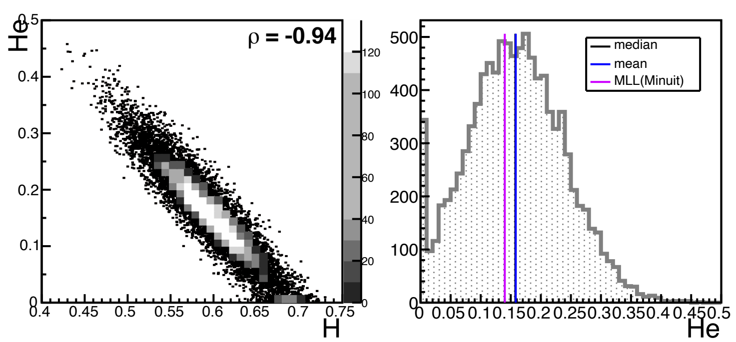


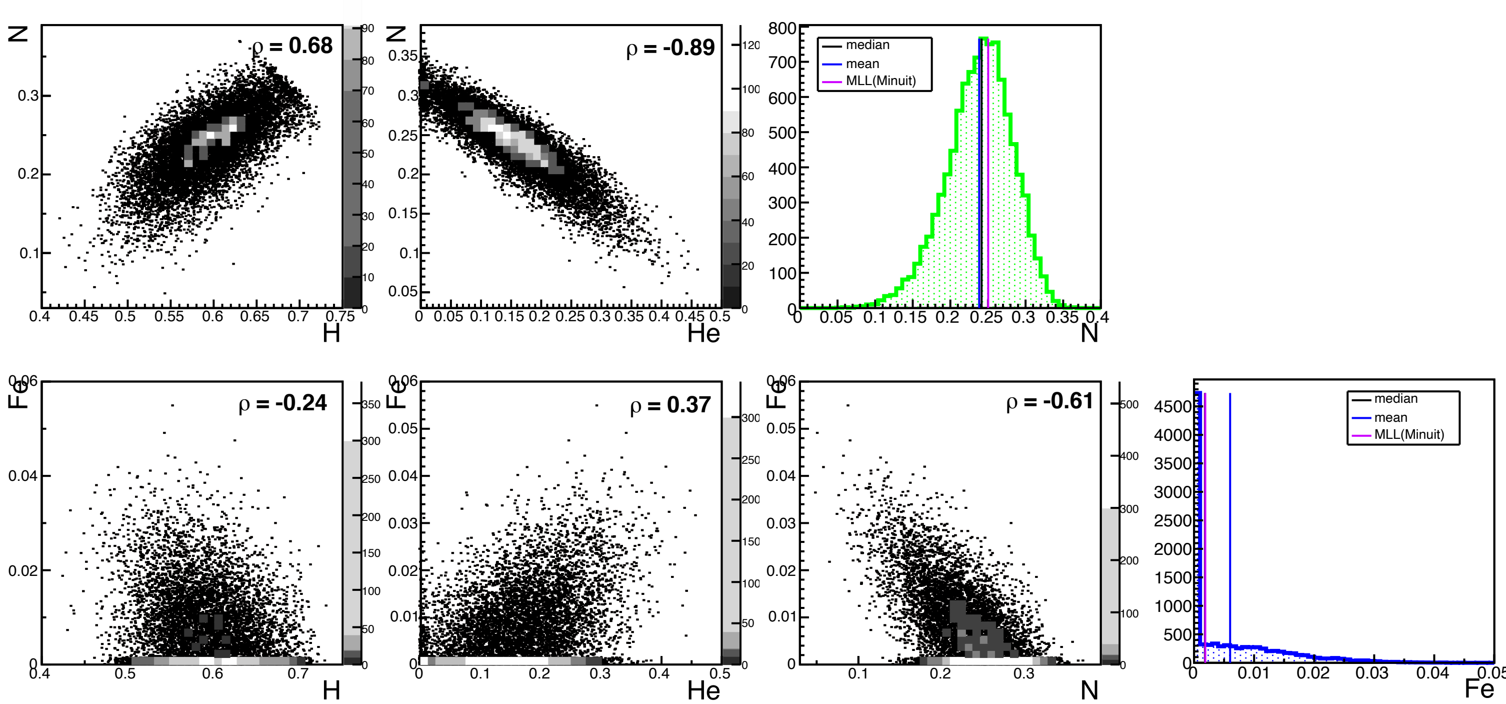
ICRC2019 EPOS-LHC

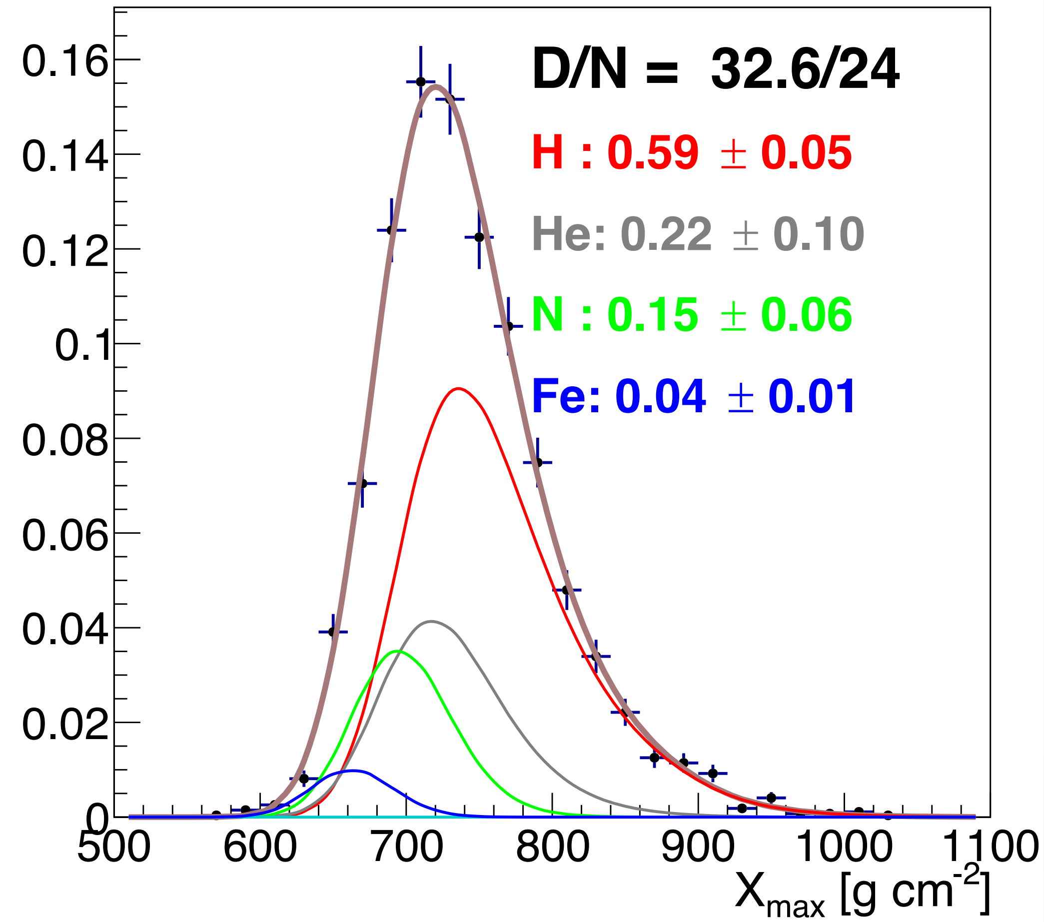
log(E/eV) = 18.25

p He N Fe

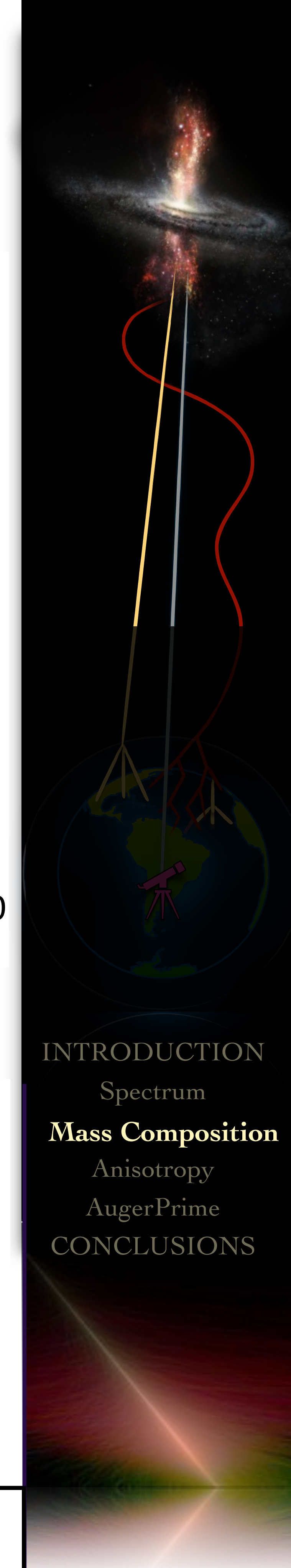
	mean ± std.dev.	68% C.L.
$f_{\rm H}$	0.5896 ± 0.0534	$0.6031^{+0.0403}_{-0.0675}$
$f_{\rm He}$	0.2224 ± 0.0946	$0.2466^{+0.0716}_{-0.1199}$
$f_{\rm N}$	0.1525 ± 0.0570	$0.1670^{+0.0431}_{-0.0717}$
$f_{\rm Fe}$	0.0355 ± 0.0130	$0.0387^{+0.0099}_{-0.0161}$







- The distributions of the mass fractions from 10,000 mock realizations
- the two-fraction correlations with the corresponding correlation coefficient reported in each plot.



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