Karlsruhe Institute of Technology

Ultra-High Energy Cosmic Rays

Status and plans

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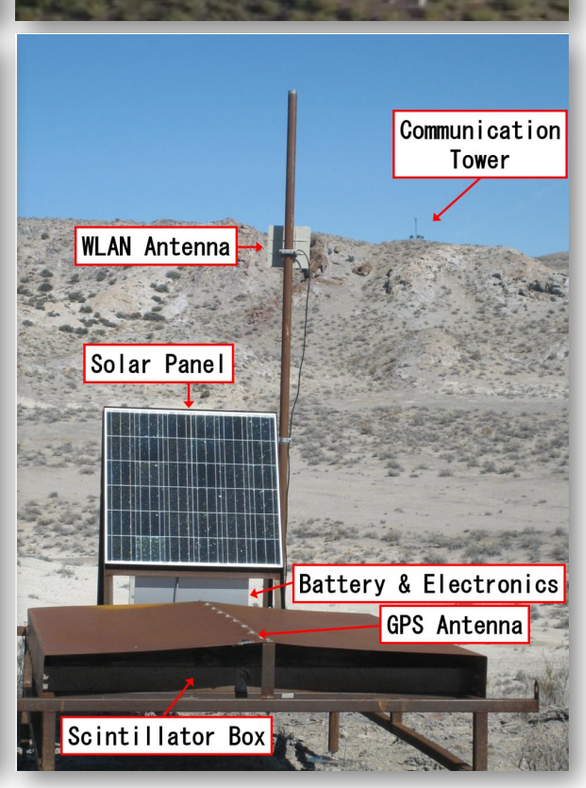
Outline — UHECR experiments

- TAx4
- AugerPrime
- EUSO
- And related:
  hadronic interactions



Existing CR detectors at highest energies

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

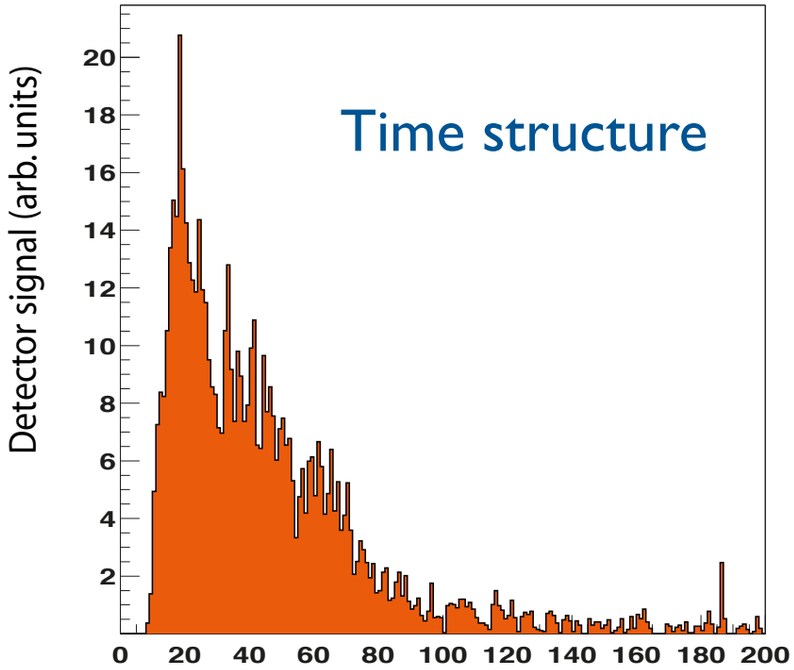
The Pierre Auger Observatory

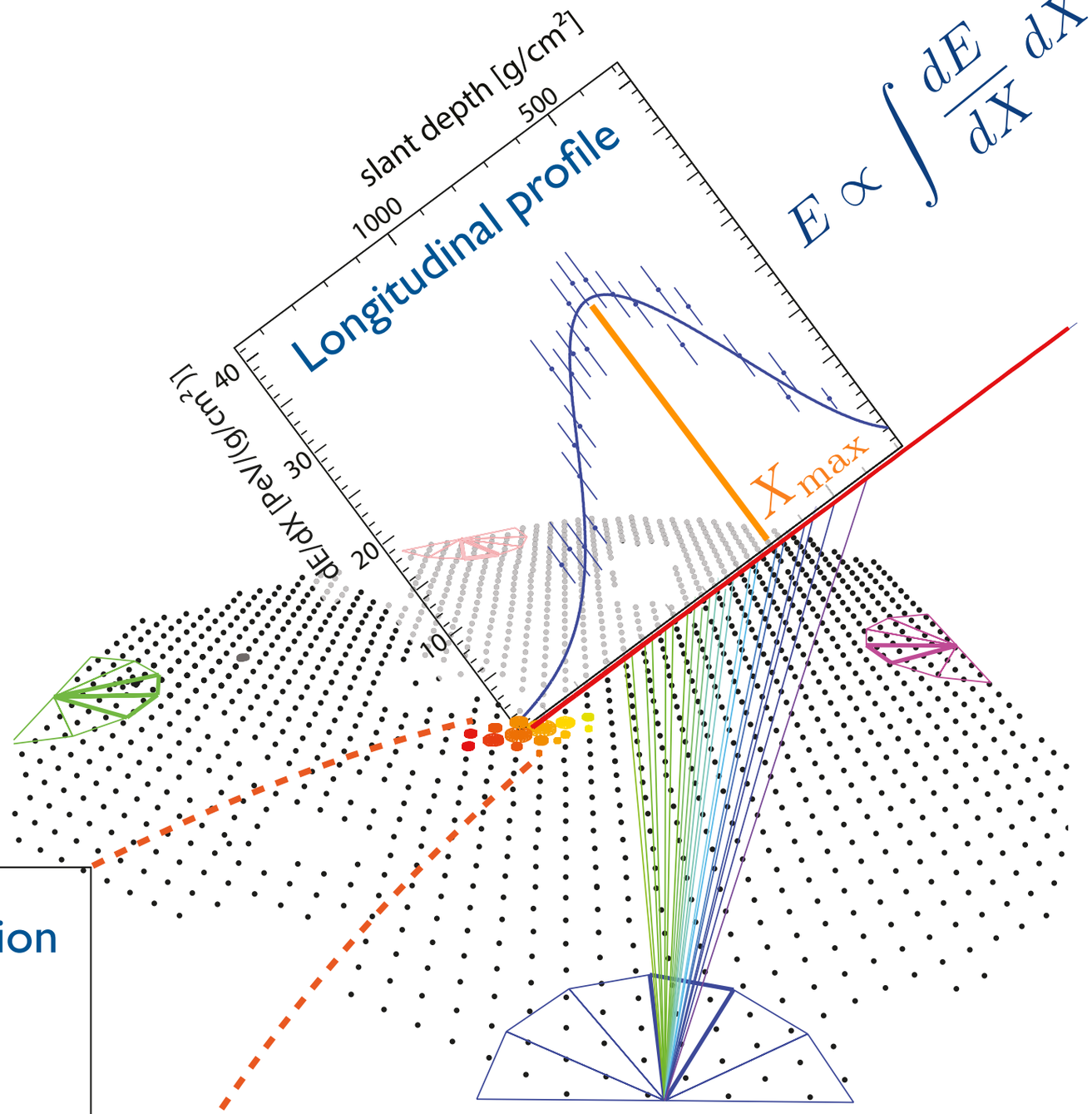
Fluorescence detector
- 4 sites: $E>10^{18}$ eV
- HEAT: $E>10^{17}$ eV

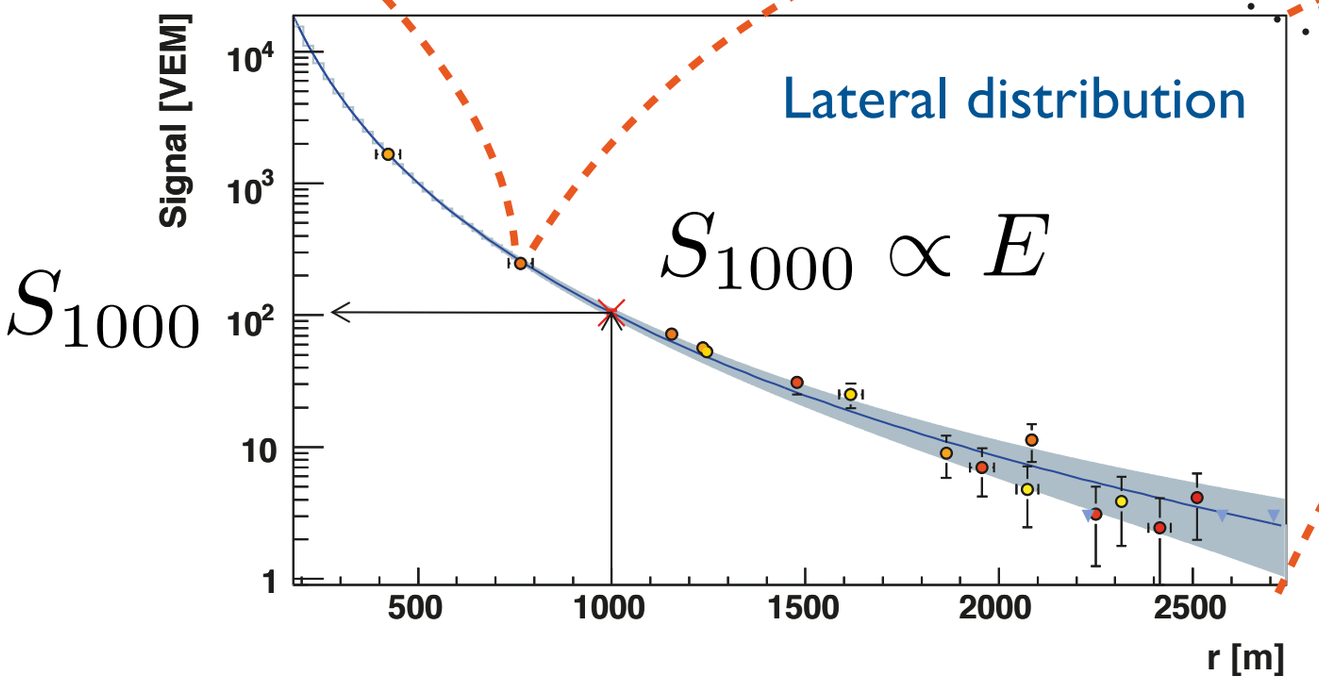
Surface detector array
- 1660 stations
- Grid of 1.5 km: 3000 km^2 $E>10^{18.5}$ eV
- Grid of 0.75 km: 24 km^2 $E>10^{17.5}$ eV

Radio detection
- AERA (MHz)
- AMBER (GHz)
- EASIER (MHz, GHz)
- MIDAS (GHz)

Shower observables recorded at Auger

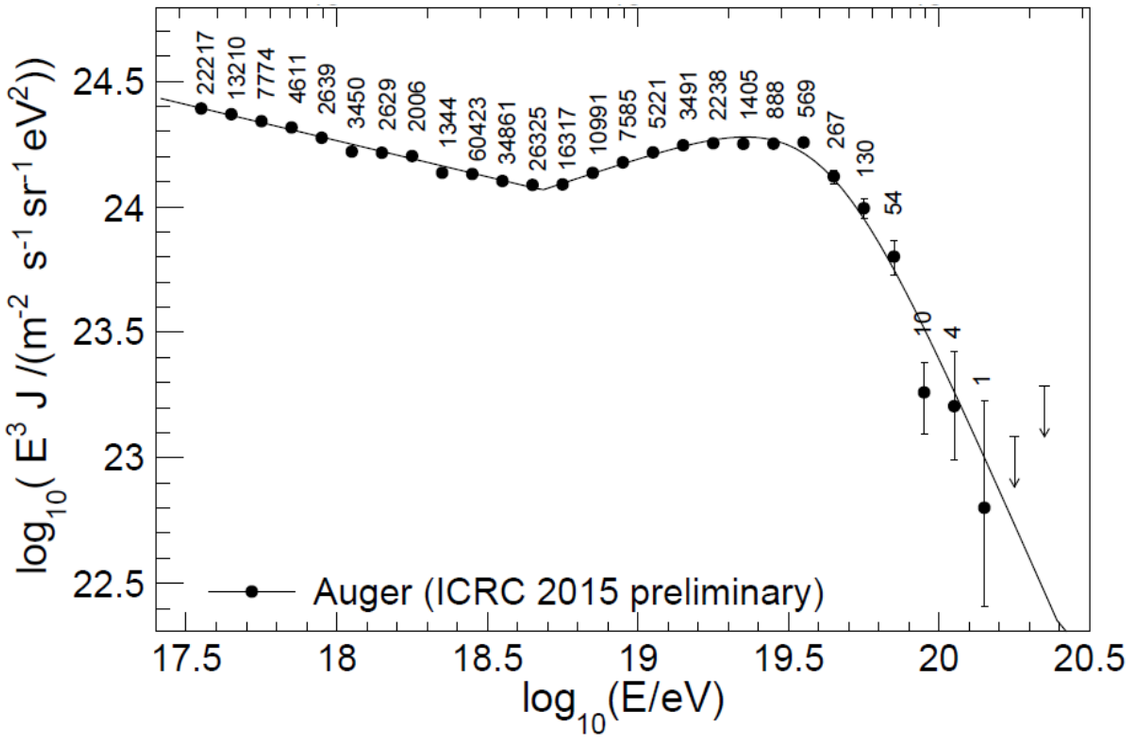


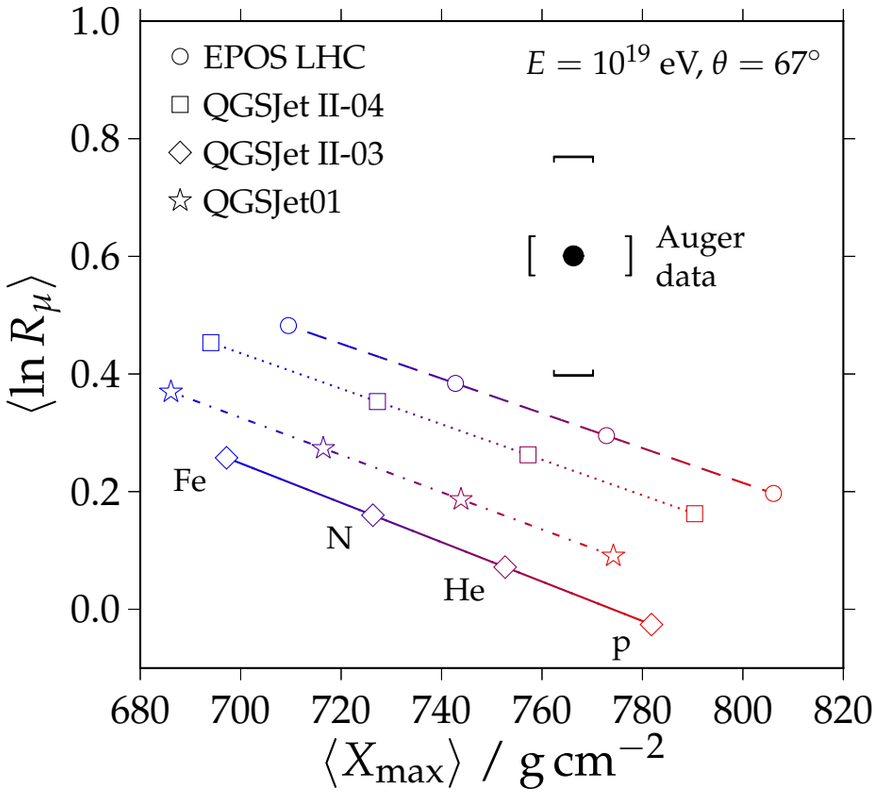


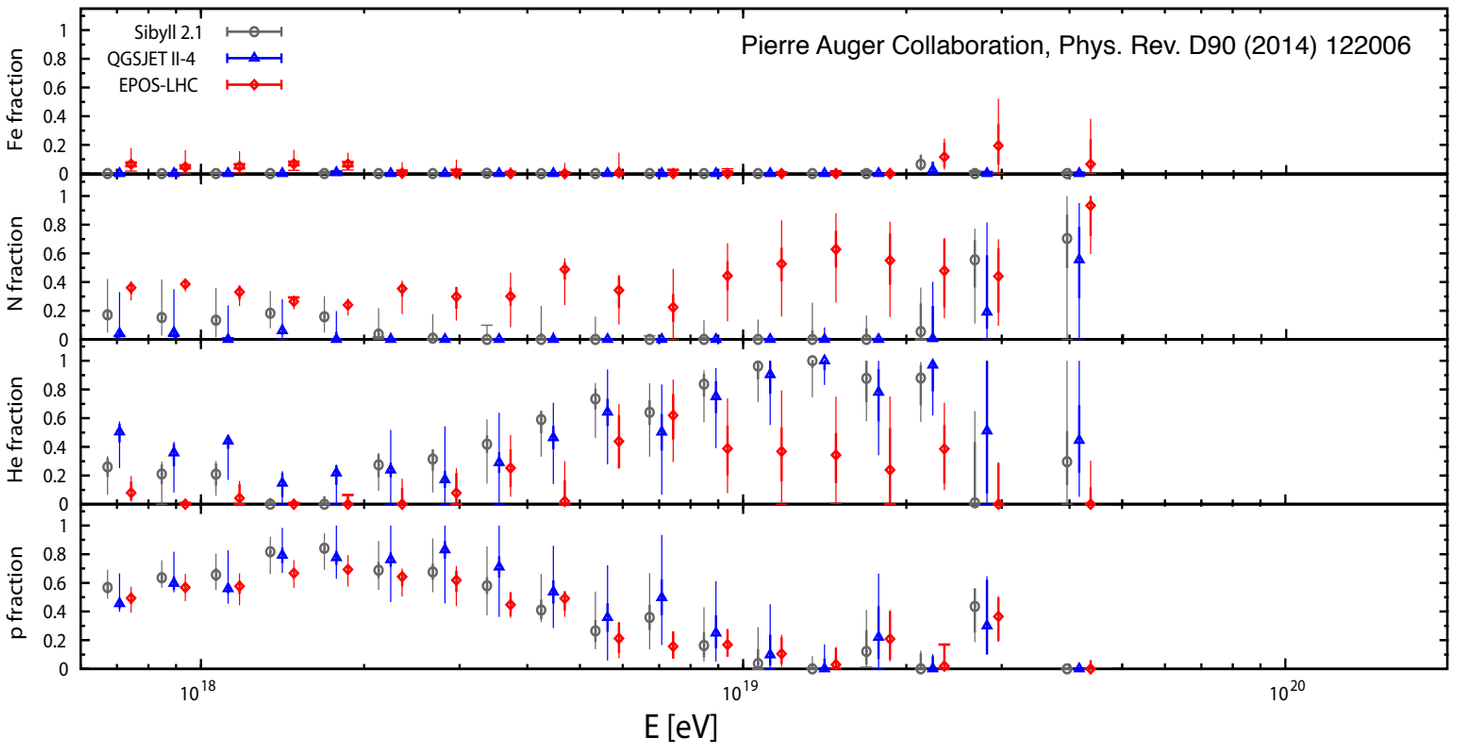


Key results of the Auger Observatory

1. Very strong flux suppression
2. Top-down scenarios ruled out
3. Challenging level of isotropy
   (but ~7% dipole at E > 8×10^{18} eV)
4. Unexpected mass composition or change of hadronic interactions for E > $10^{18.5}$ eV
5. Air showers have surprisingly high number of muons

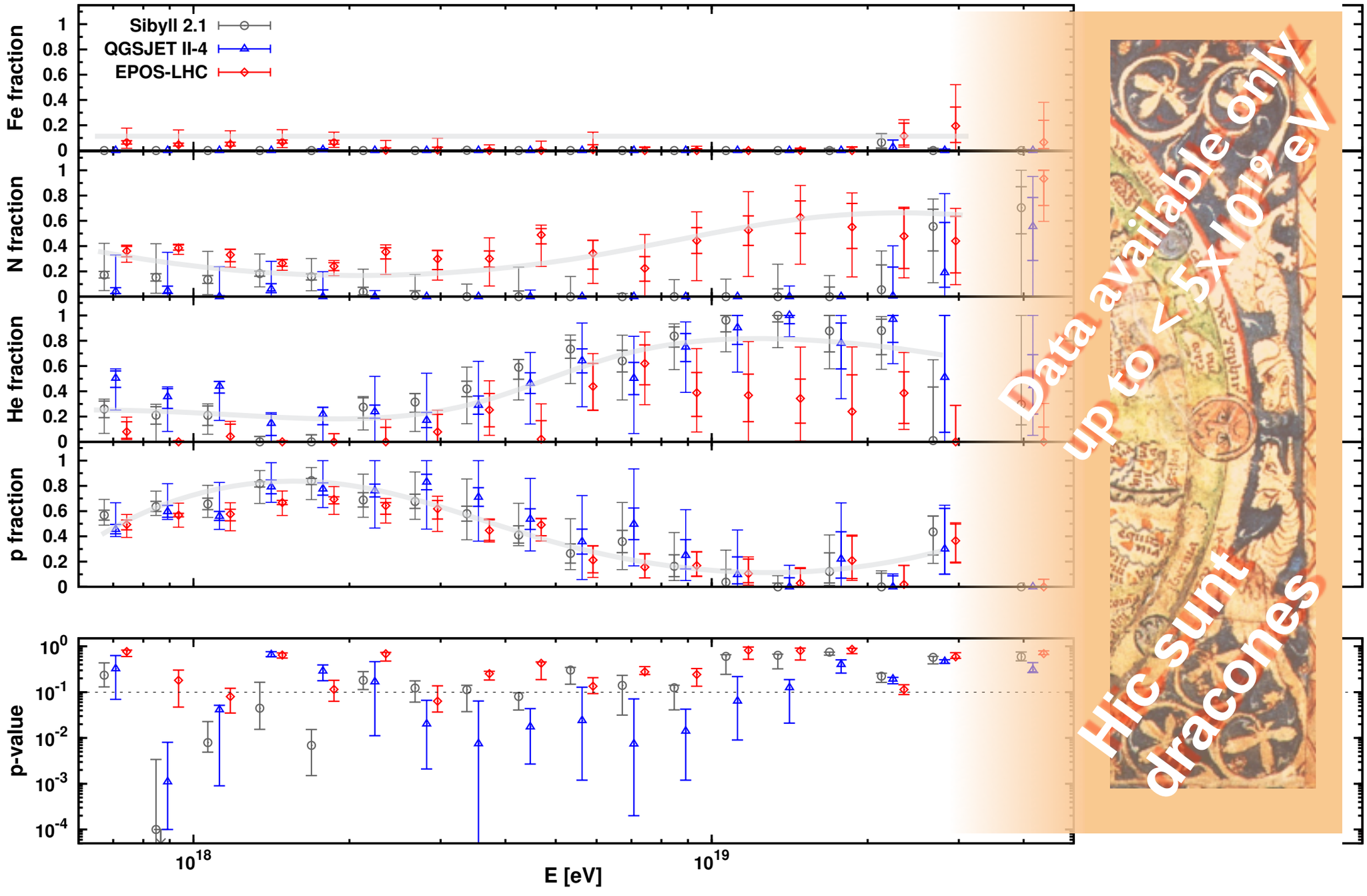




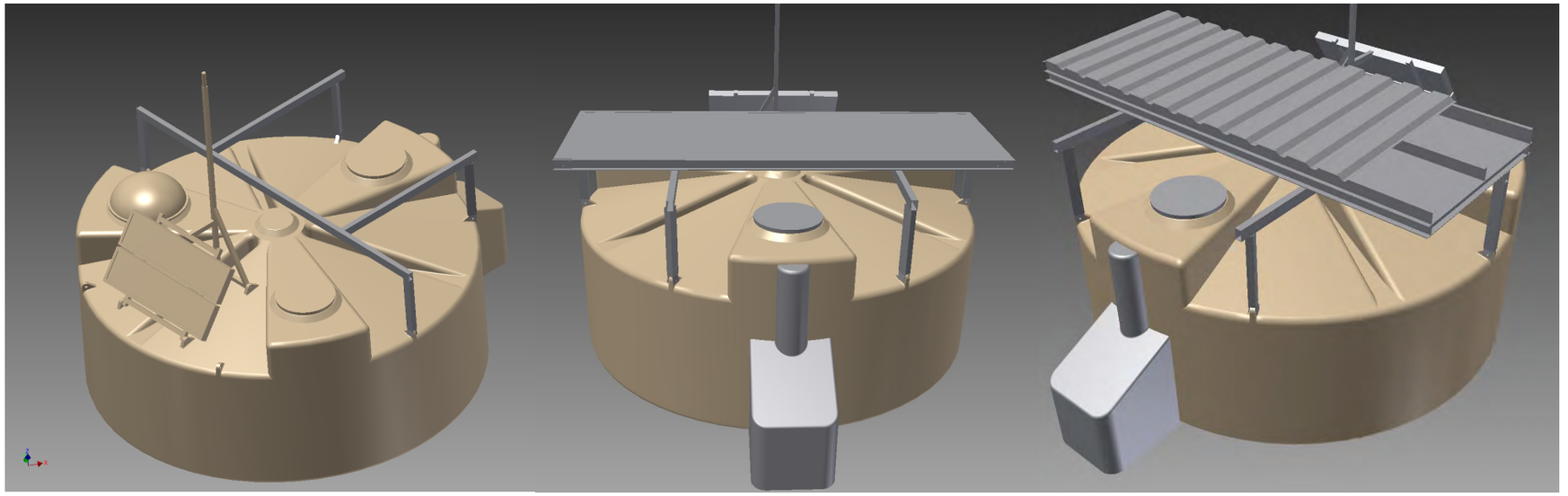


FD: Composition measurement of Auger

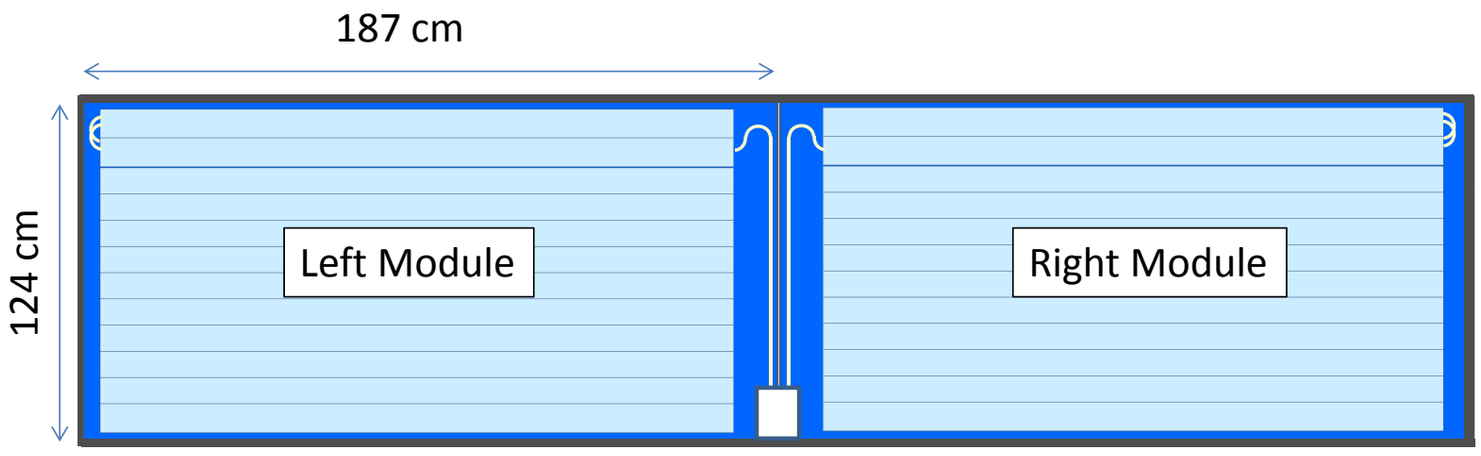
~13% duty cycle



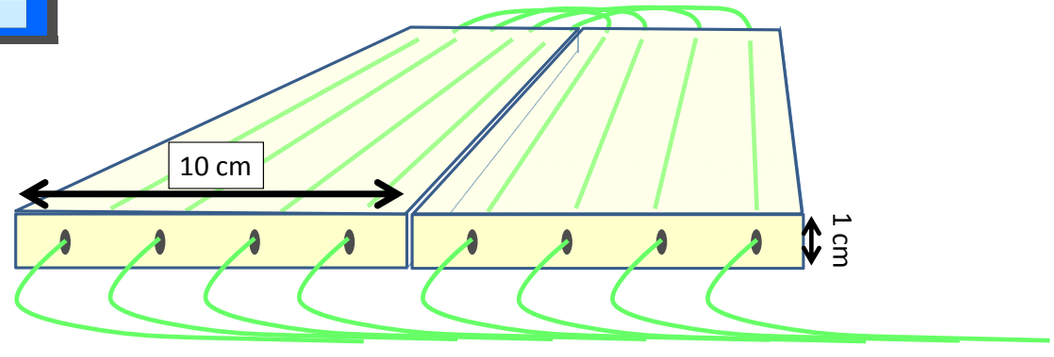
Schematic of the Scintillation Surface Detector (SSD)



Simple and robust construction of detector module and mounting frame, double roof for thermal insulation

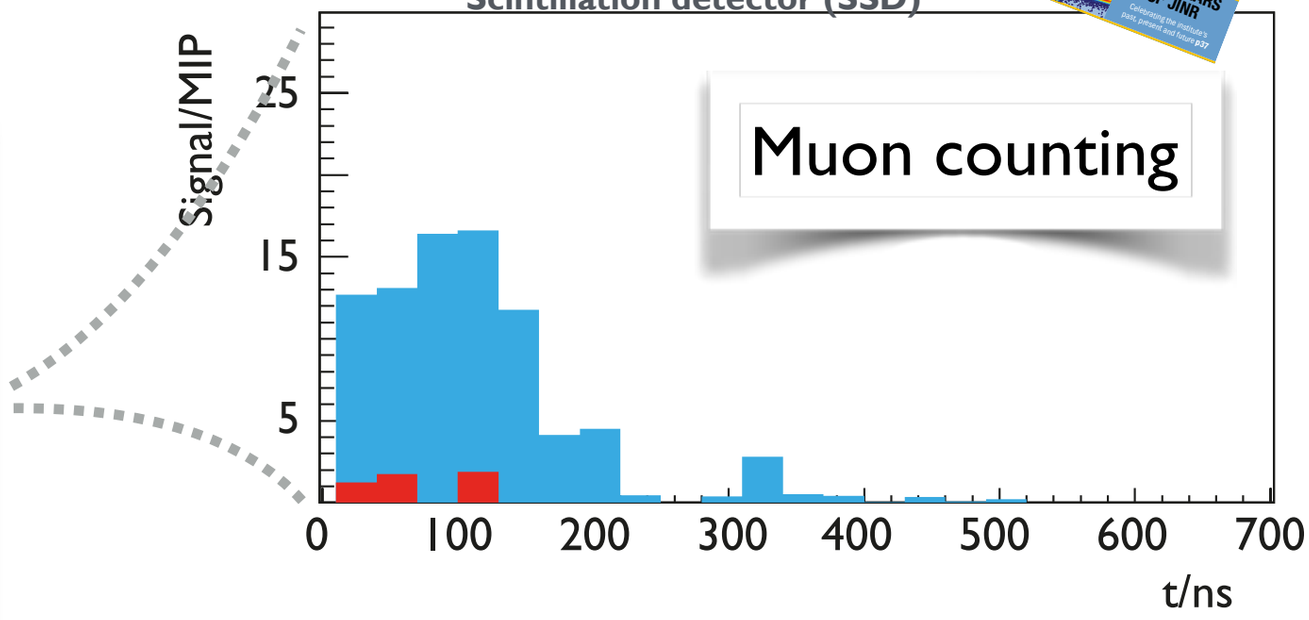


Two scintillator modules per box
read out by single PMT using WLS fibers
About 4 m^2 in total
Both detectors make use of
new 120 MHz electronics (IPE)



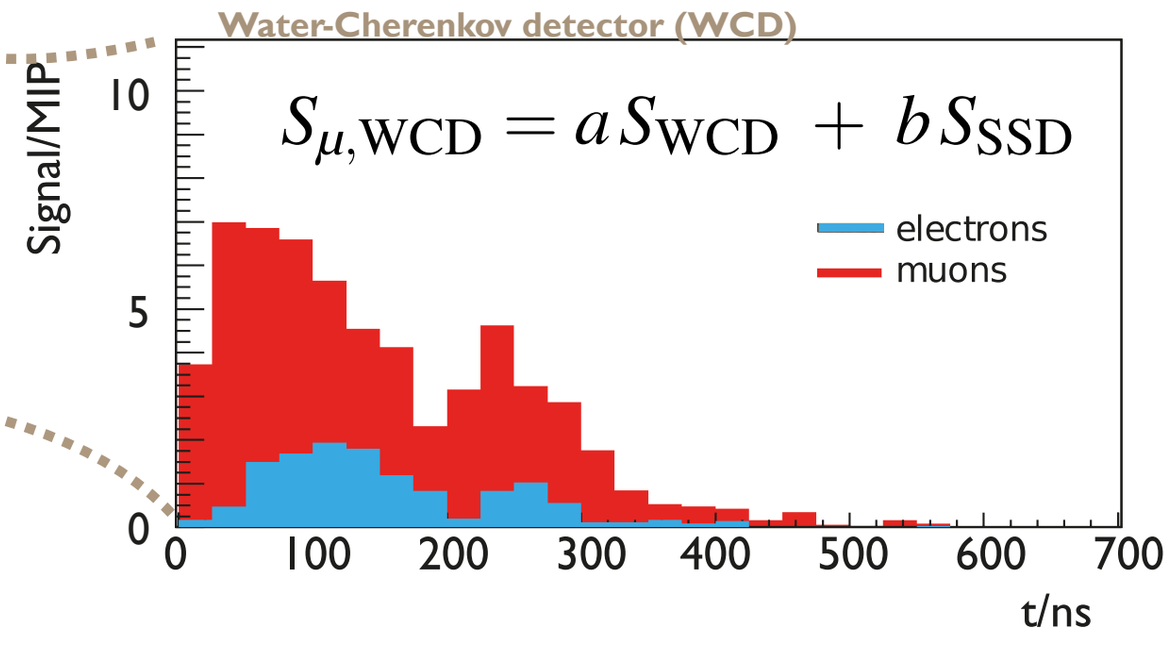
AugerPrime: Detection principle

Scintillation detector (SSD)



Muon counting

Water-Cherenkov detector (WCD)



Signals of both detectors used to extract muons and electrons/photons @100% duty cycle

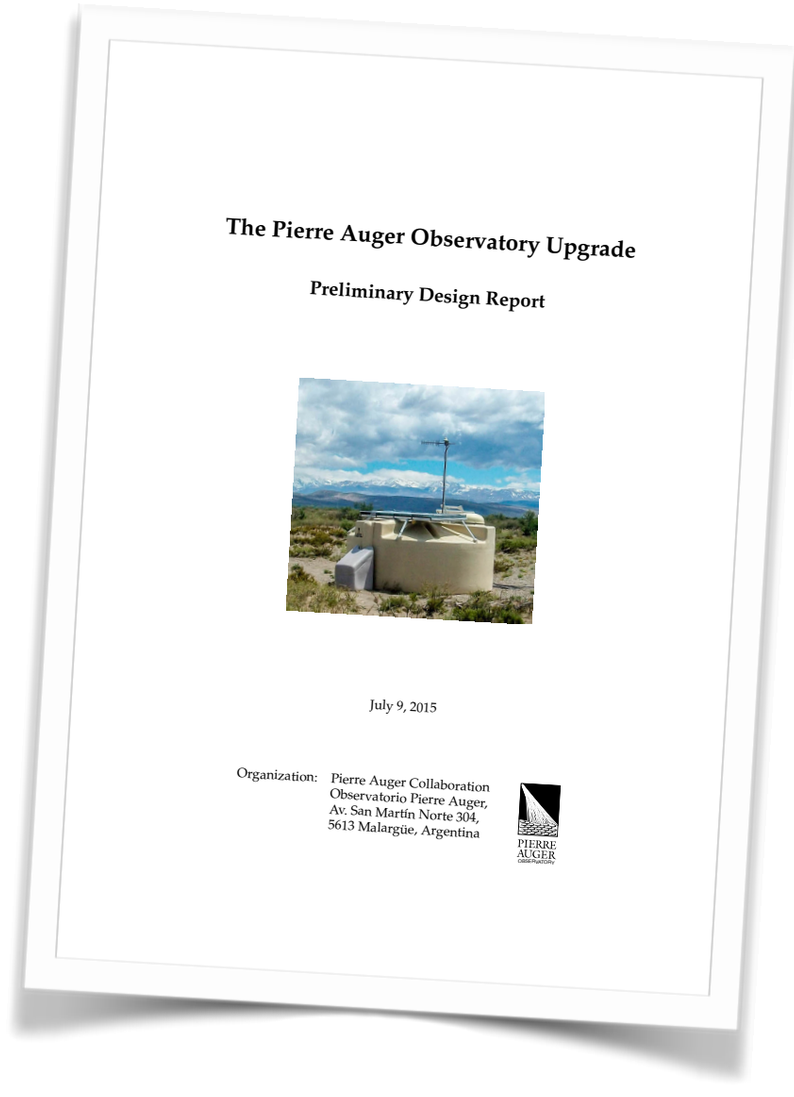
6 detectors ready
for deployment

First detector
in the field

Current status

- International Advisory board
  strongly recommended
  AugerPrime: total cost
  (WBS) 15 M$

- Design report available
  arxiv.org/pdf/1604.03637


The Pierre Auger Observatory Upgrade

Preliminary Design Report

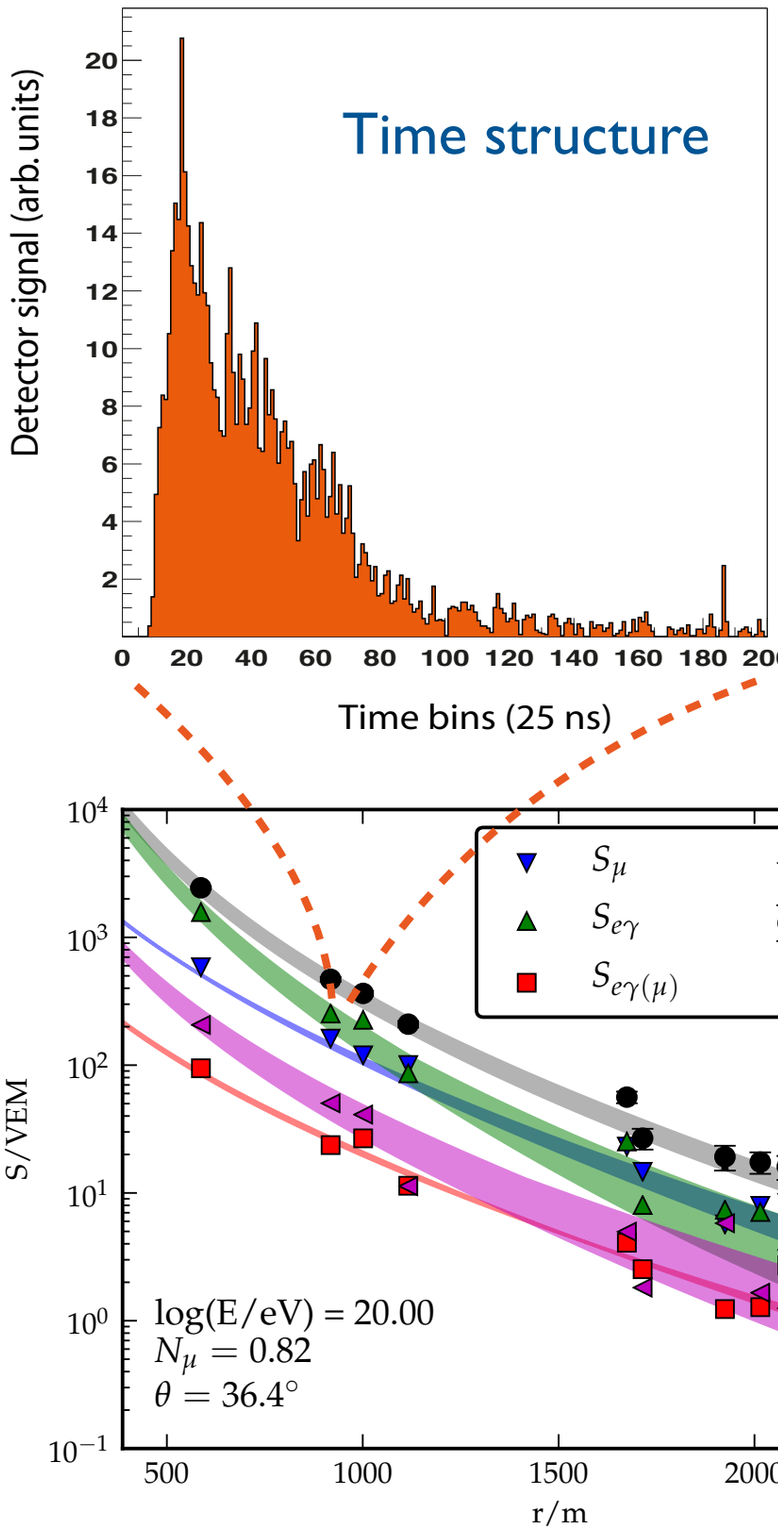
July 9, 2015

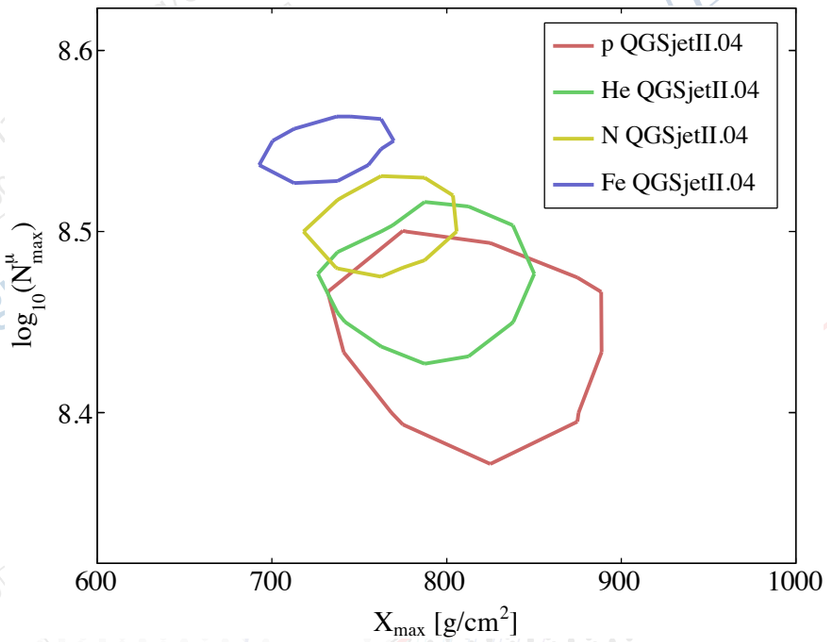
Organization: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

- Auger groups started to
  submit individual funding proposals

- Special BMBF proposal from german
  Universities approved (Aufstockungsantrag),
  which is complemented by a proposal
  within HGF/KIT granted

New analysis techniques: Shower universality





Extract

- X_{max}
- N_μ
- Energy

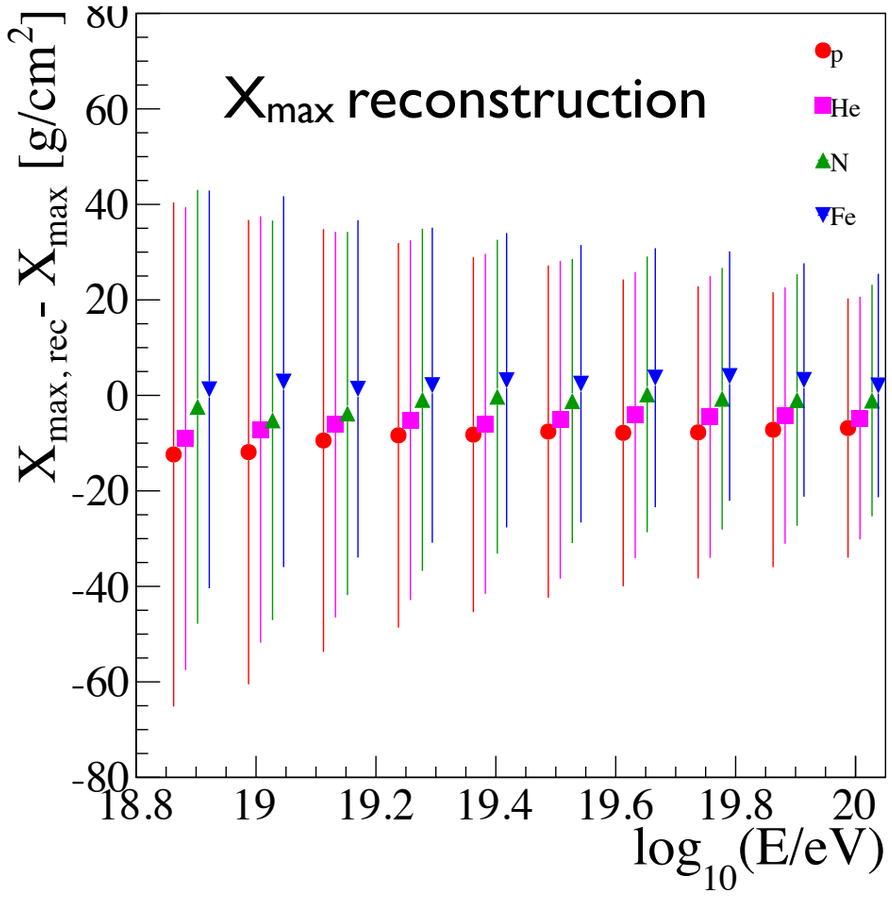
from surface detector only (AugerPrime)

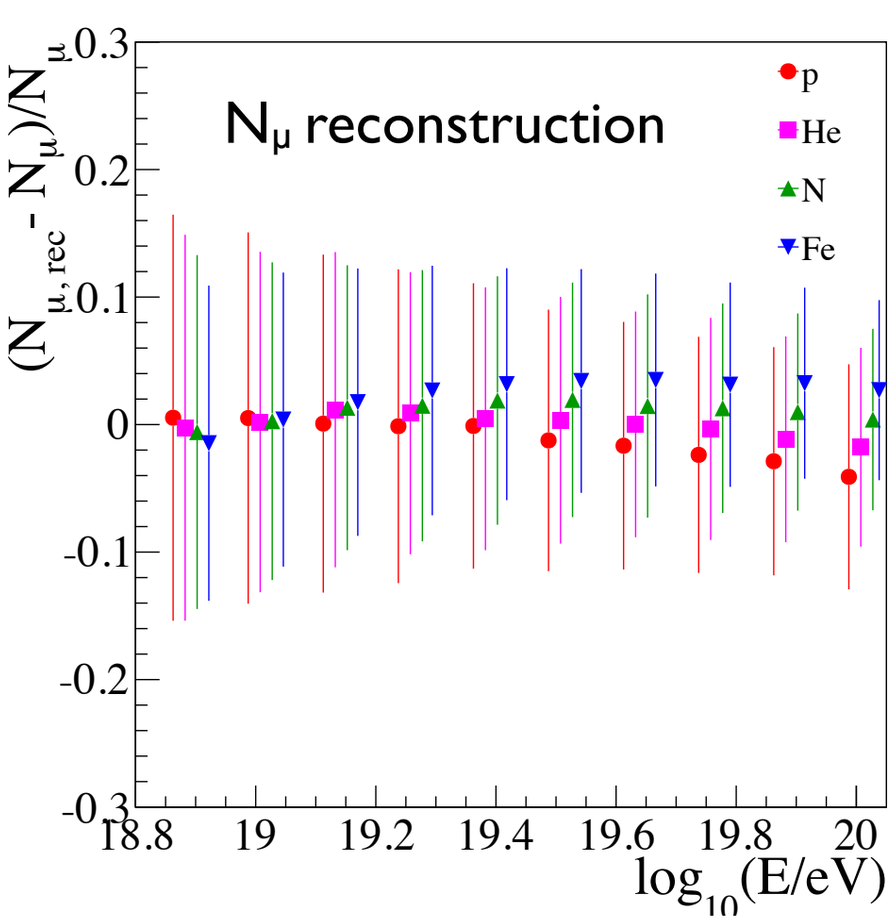
The additional detectors will add information on the

- eγ
- muon components

Upgrade of the Pierre Auger Observatory

- Additional scintillators (4 m^2)
- Event-by-event mass estimate with 100% duty cycle instead of 15% for FD
- Detection of proton fraction as low as 10%



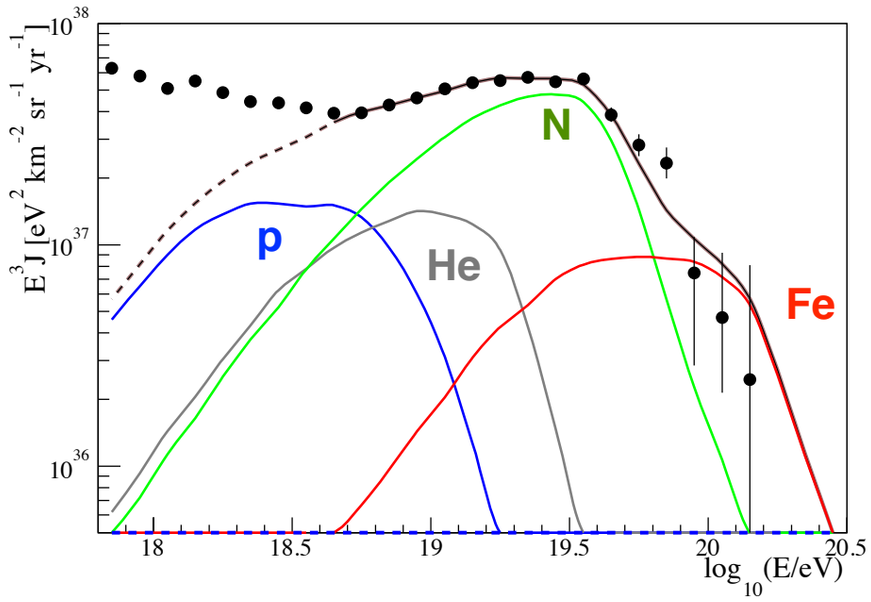


Physics reach: mass sensitivity & discrimination of scenarios

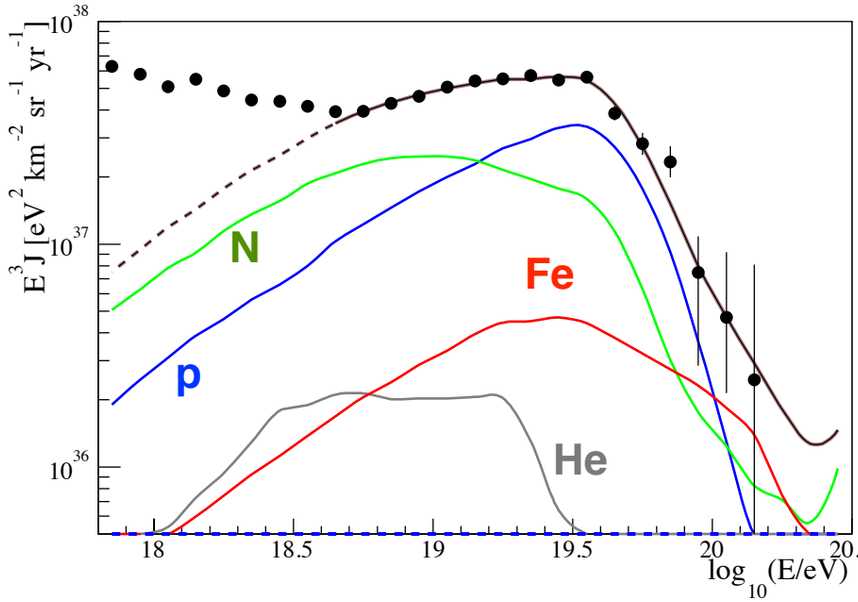
Illustration with two benchmark scenarios

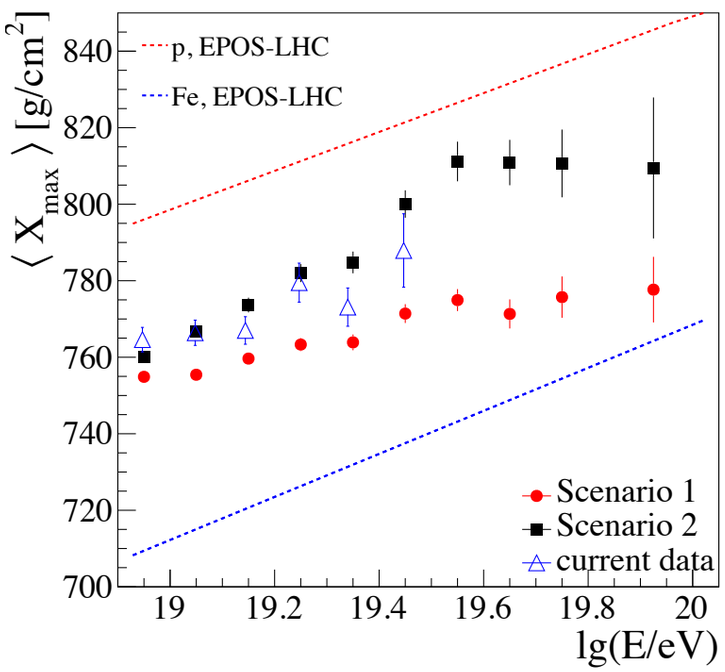
arxiv.org/pdf/1604.03637

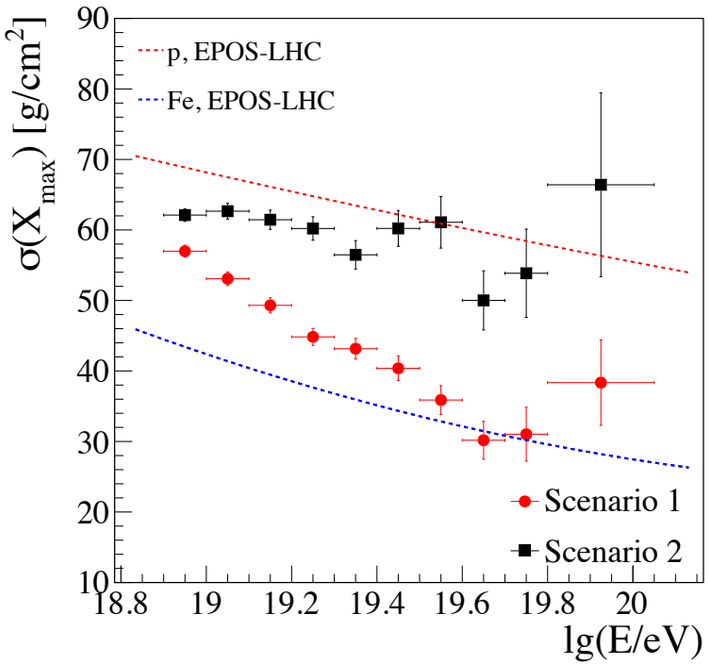
Scenario 1: maximum rigidity model

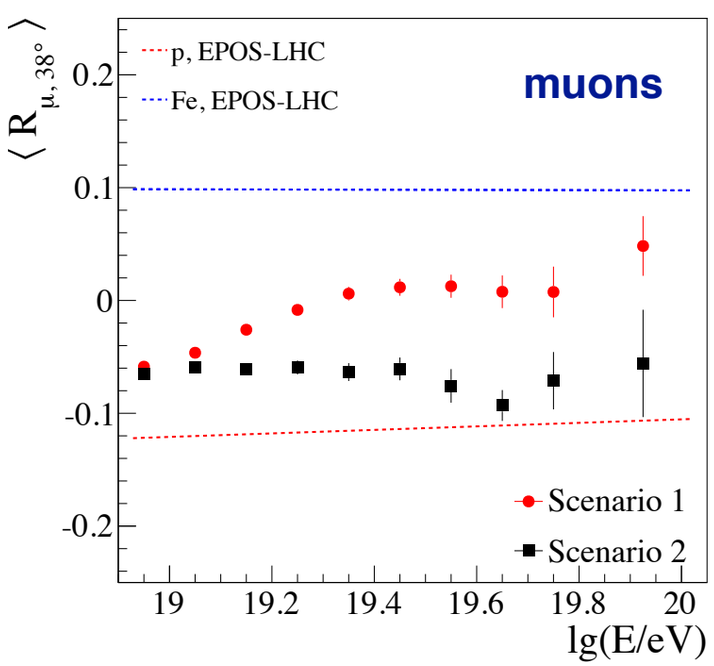


Scenario 2: photo-disintegration model



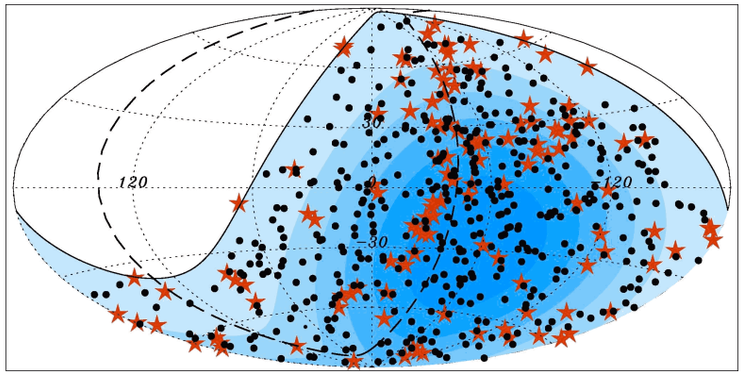


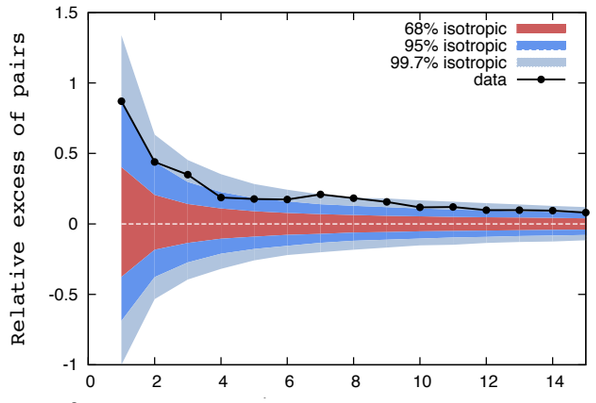




Physics reach: composition-enhanced anisotropy

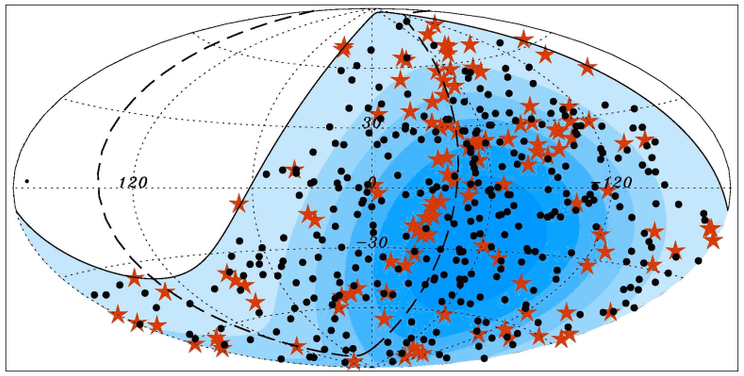
Modified Auger data set
(E > 4×10^{19} eV,
454 events)

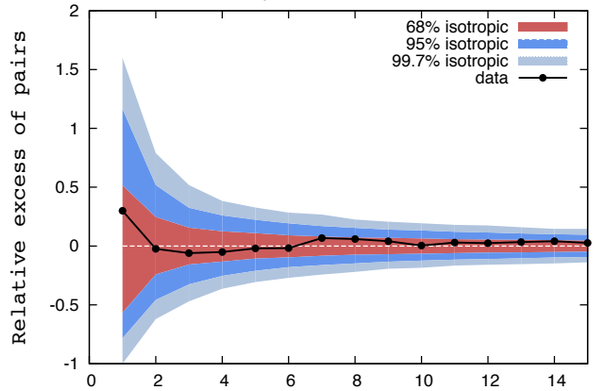




all 454 events

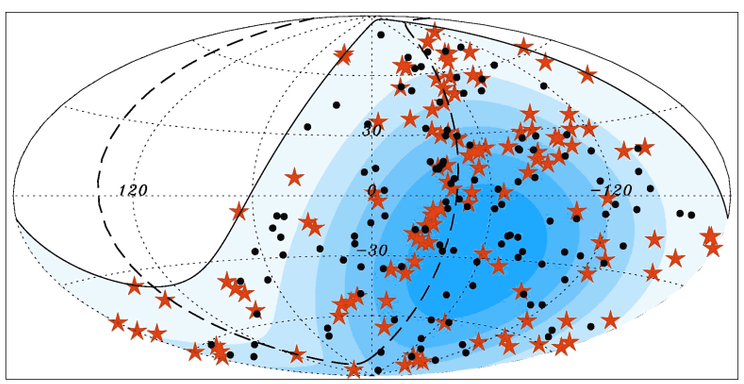
X_{max} assignment according to maximum rigidity scenario

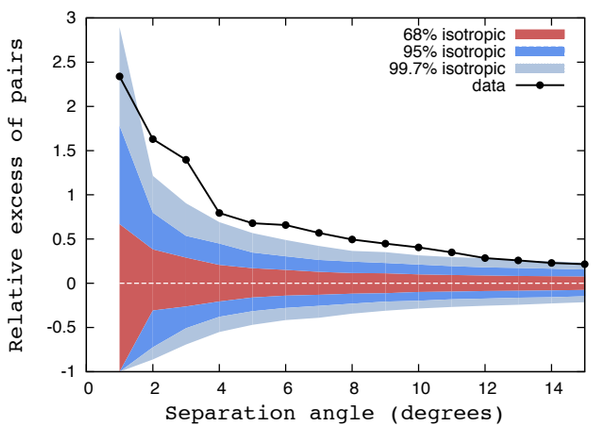




proton depleted data set (326)

10% protons added, half of which from within 3° of AGNs

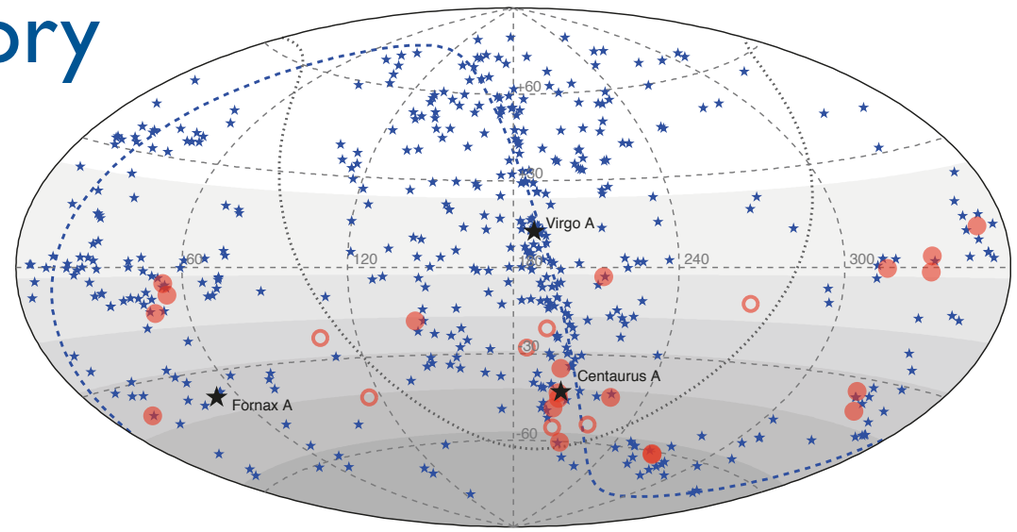




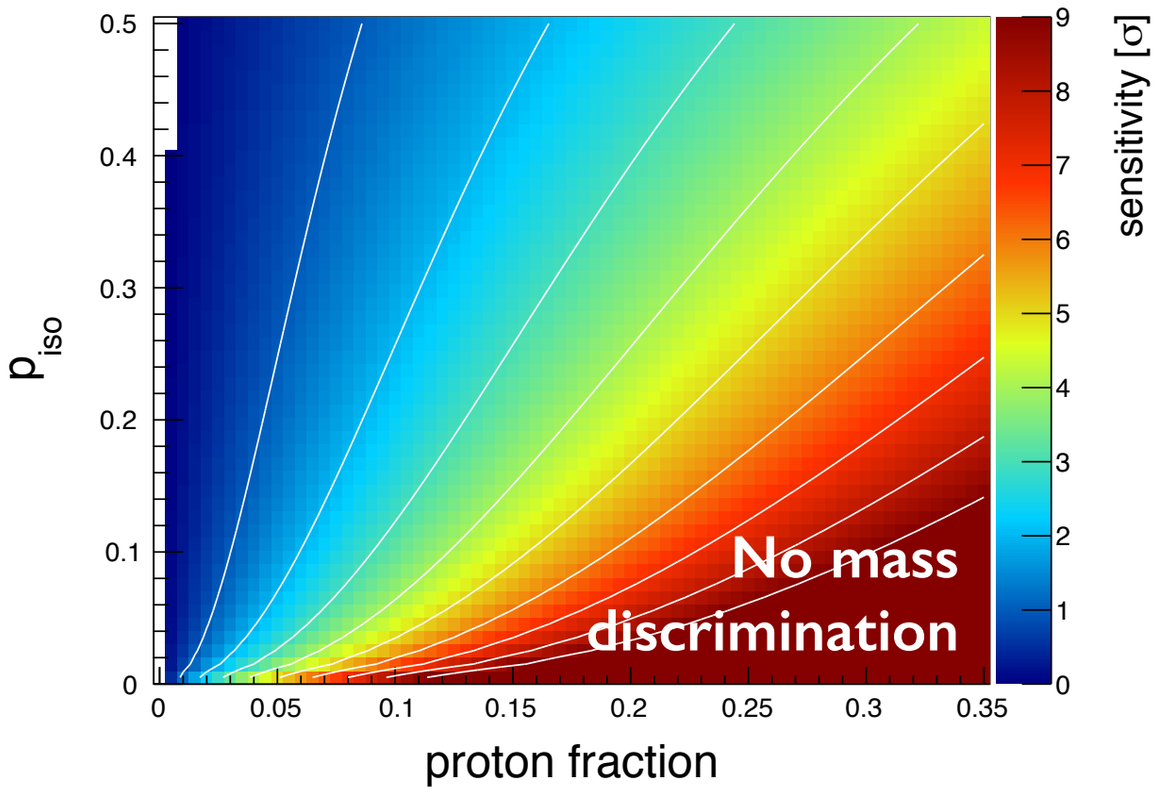
proton enhanced data set (128)

arxiv.org/pdf/1604.03637

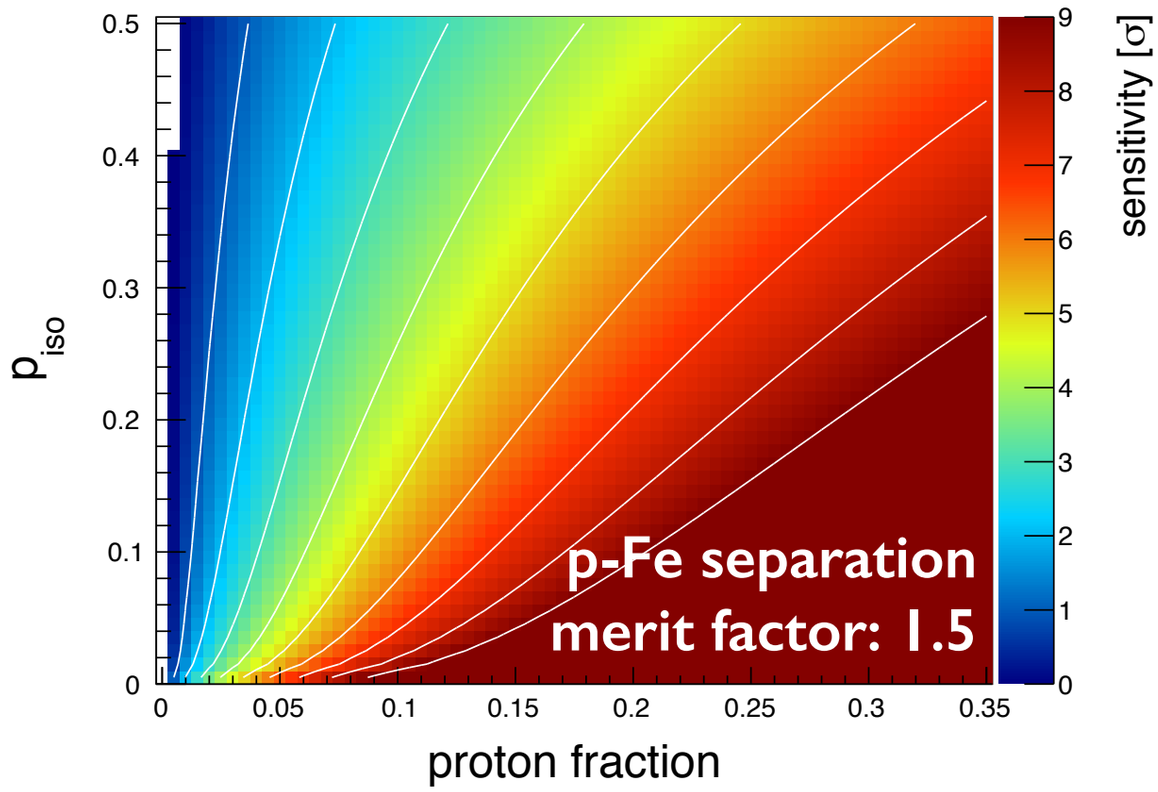
Upgrade of the Pierre Auger Observatory
Low-Z particle astronomy



Catalog based anisotropy search
Assuming current Auger exposure
(~155 events @ E>55 EeV)



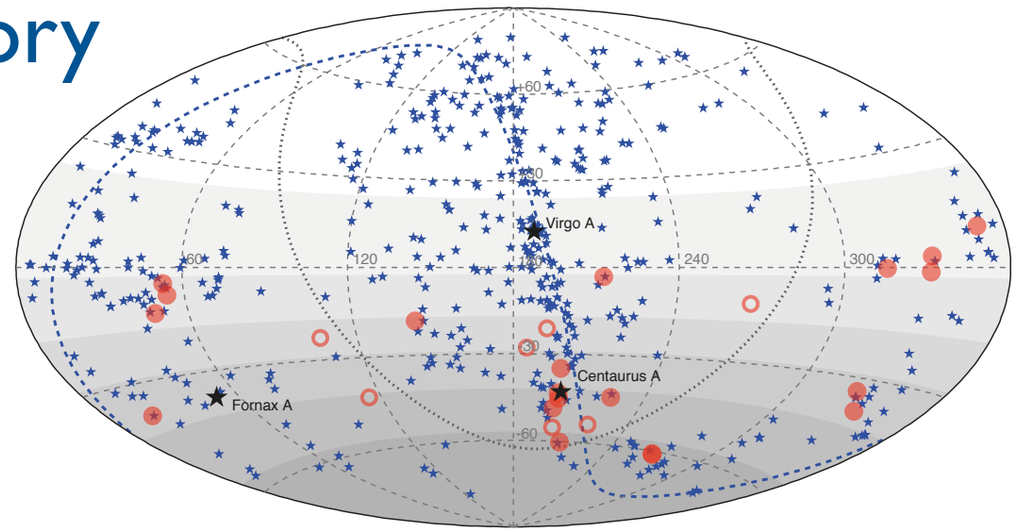
p_{iso}: Chance prob. to correlate with object from catalog



All protons correlating with objects from catalog

arxiv.org/pdf/1604.03637

Upgrade of the Pierre Auger Observatory
Low-Z particle astronomy



Catalog based anisotropy search
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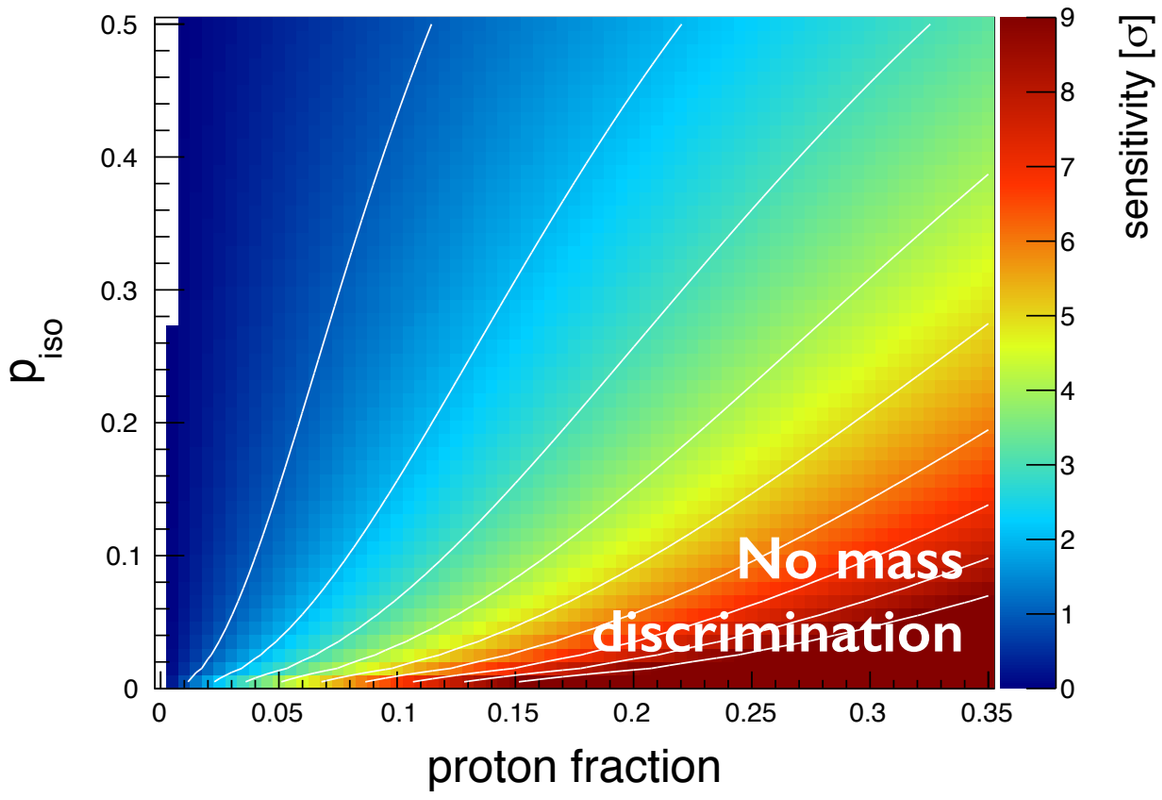
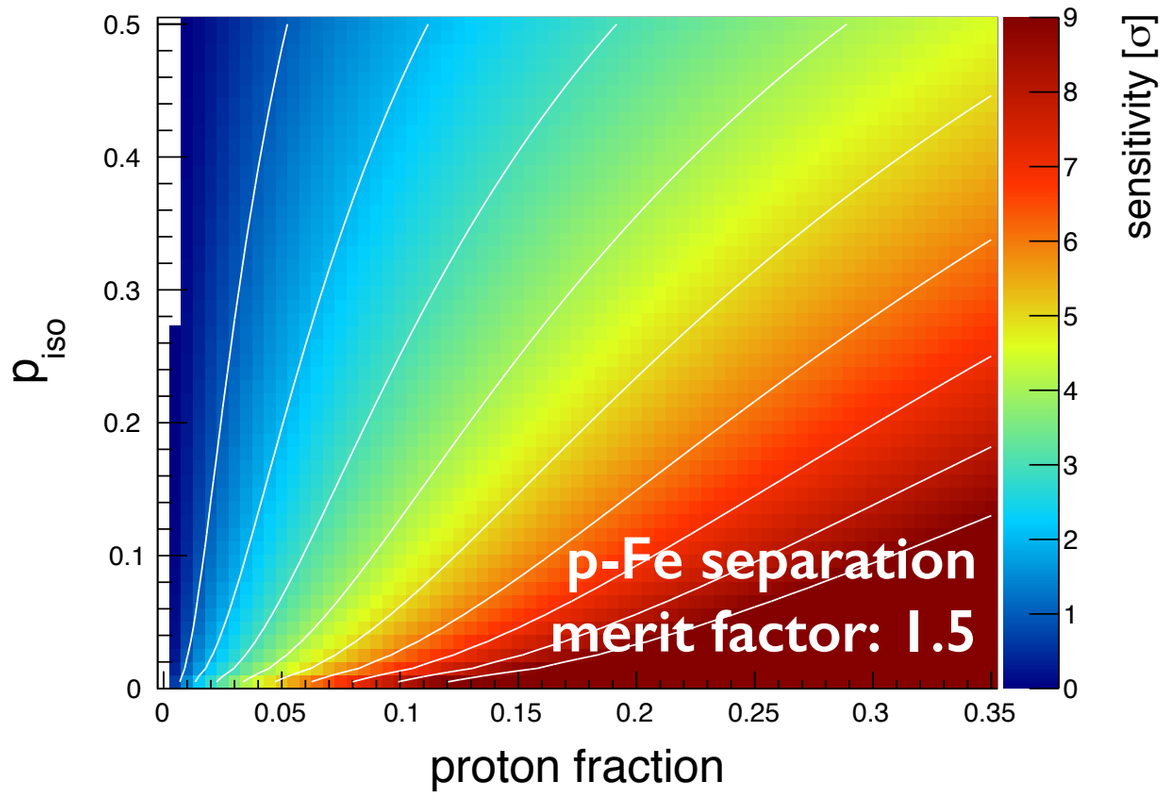




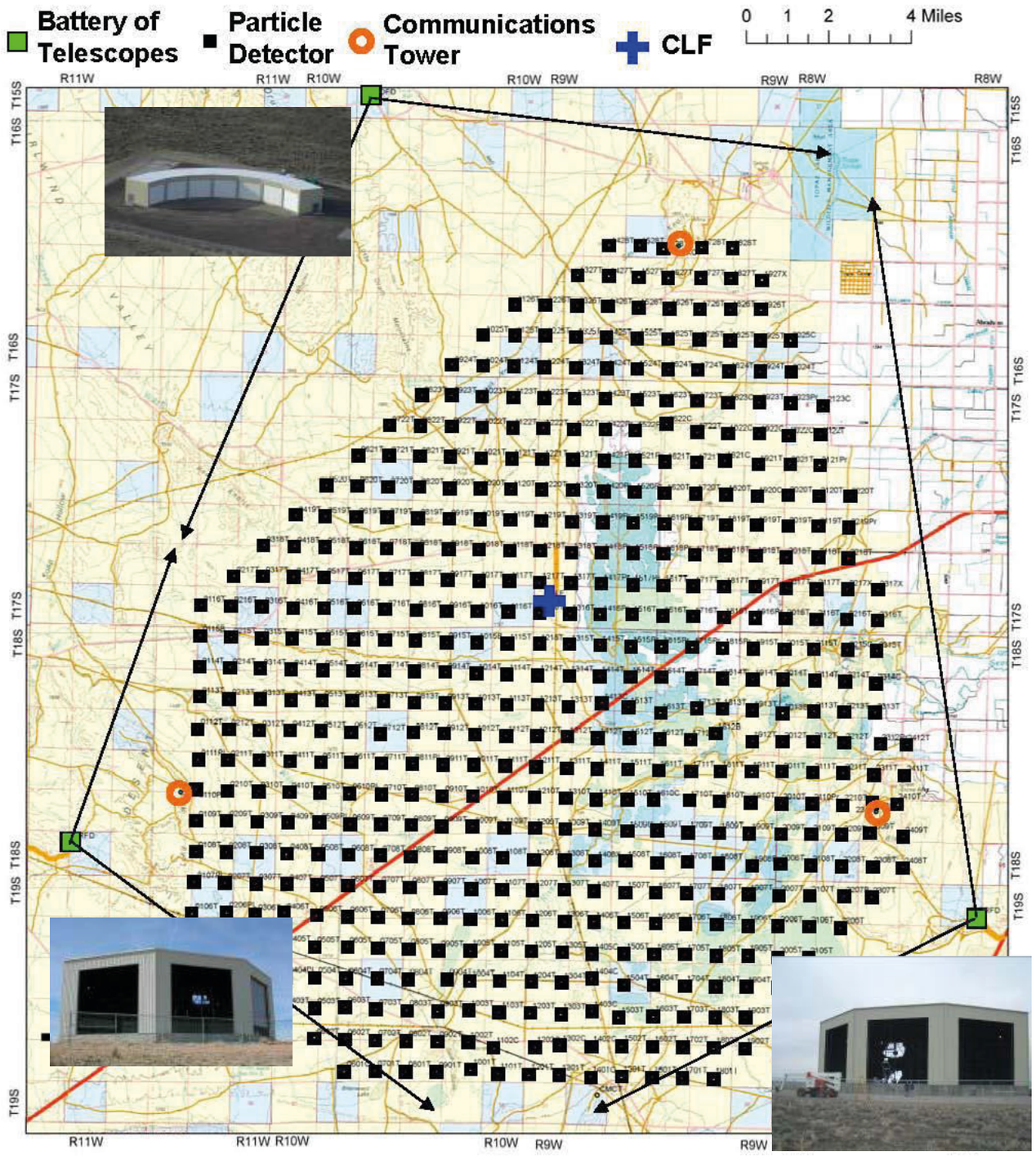
p_{iso}: Chance prob. to correlate with object from catalog

75% protons correlating with objects from catalog

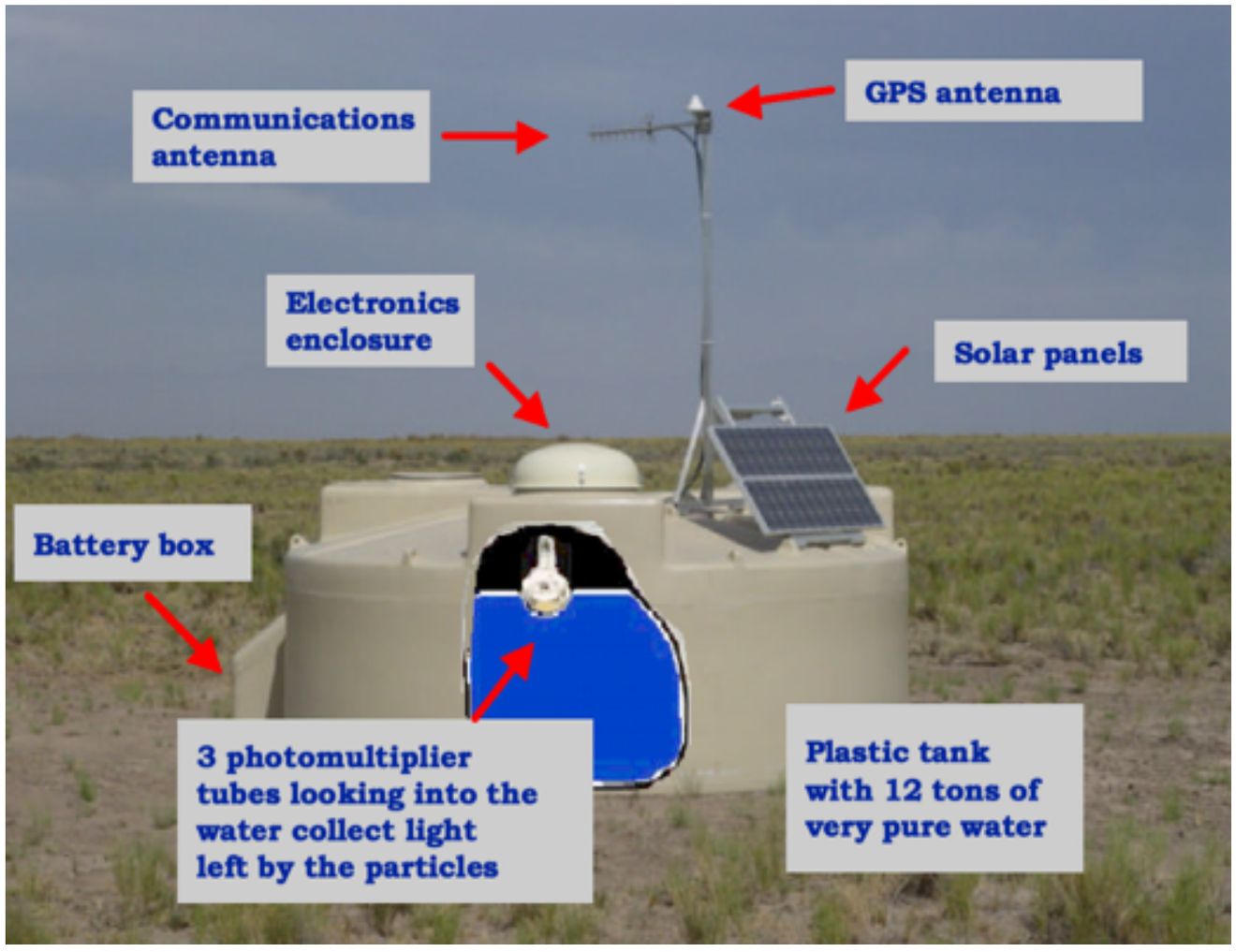
arxiv.org/pdf/1604.03637

Telescope array (TA)

- Northern hemisphere
- 507 surface detectors:
  double-layer scintillators
  (grid of 1.2 km, 680 km^2)
- 3 fluorescence detectors
  (2 new, one station HiRes II)
- Graded infill array and
  high elevation telescopes
  under construction



Comparison of surface detectors

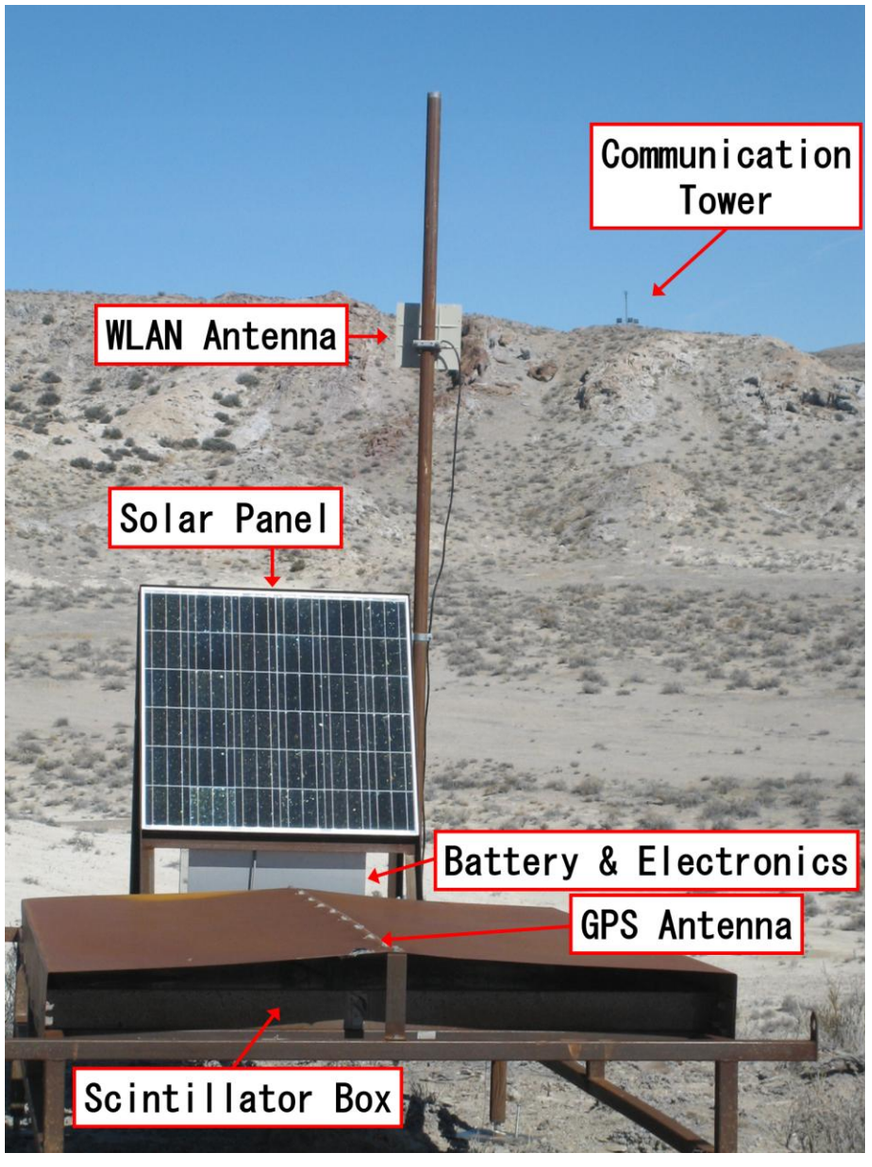


Auger: thick water-Cherenkov detectors

- large part of signal due to muons
- large acceptance to inclined showers

Telescope Array: thin scintillators

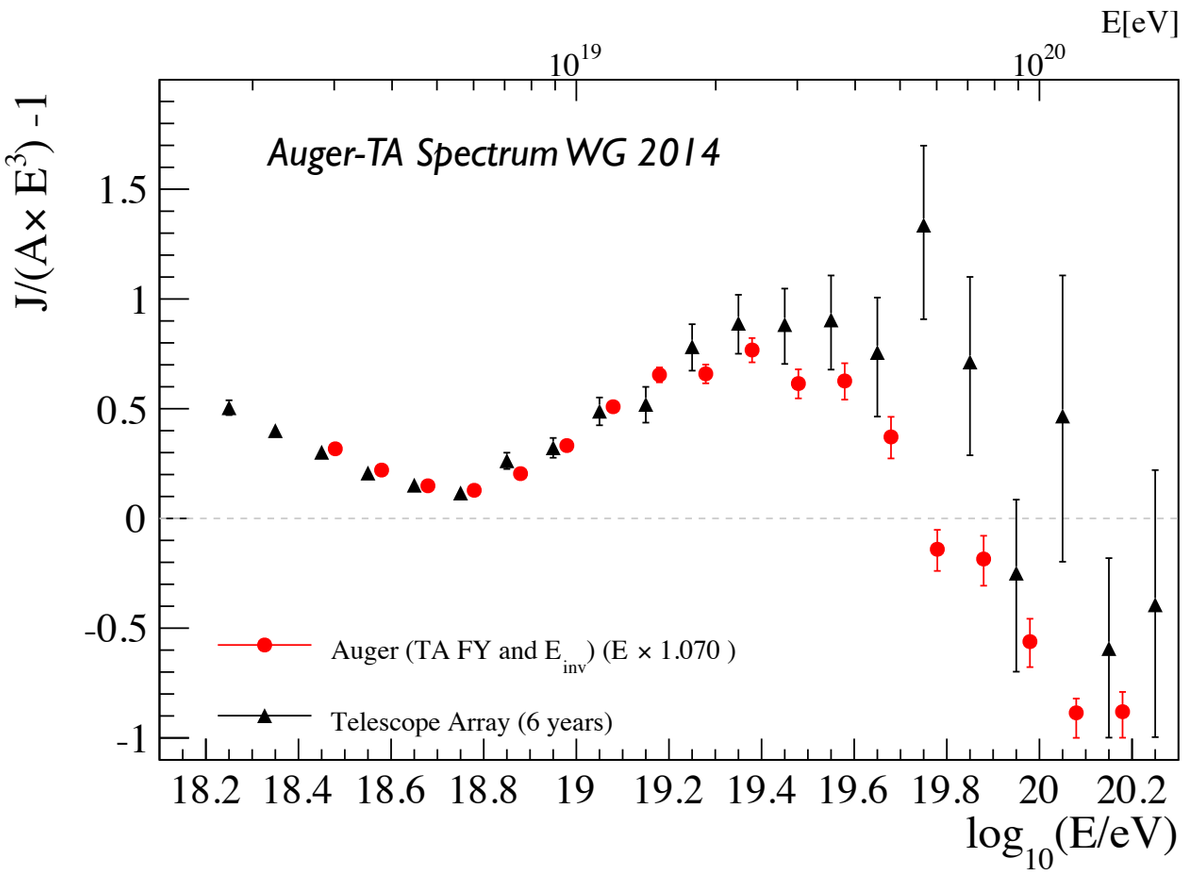
- main part of signal due to em. particles
- low sensitivity to muons

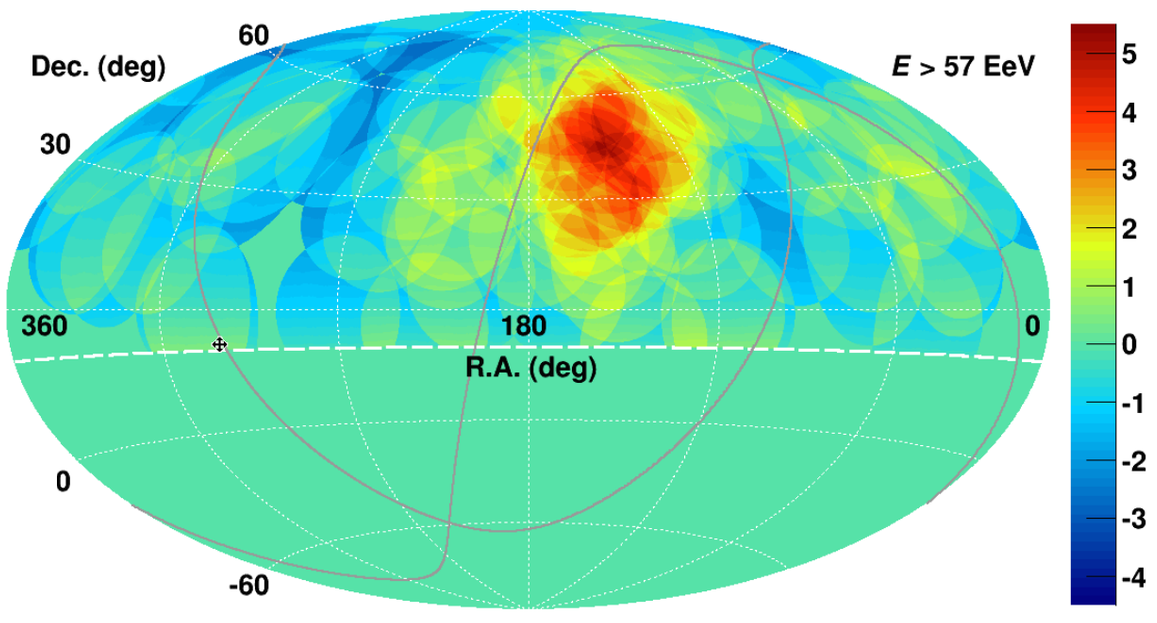


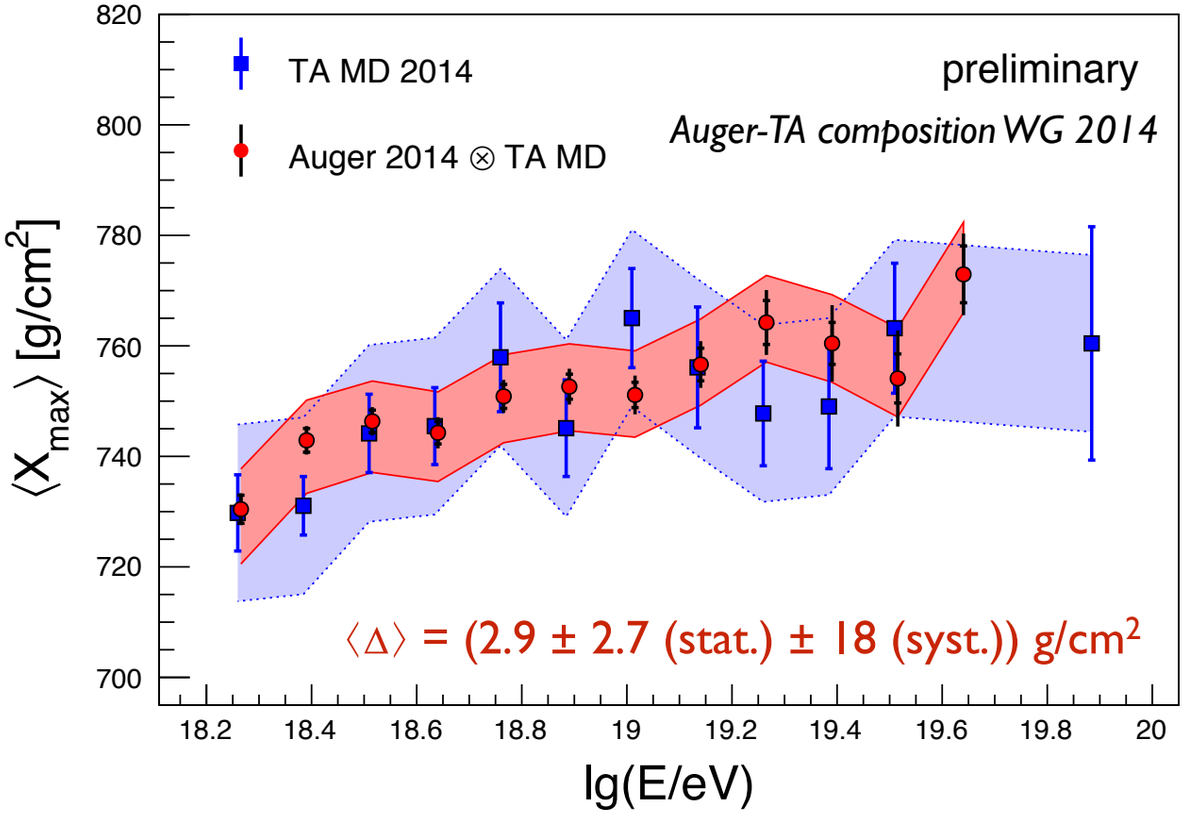
Complementary surface detector arrays

Results

- Flux differences at highest energies due to
  - Physics or
  - Instrumental effects?
- Hot spot seen at E > 57 EeV
  - Pre-trial 5.1 σ
  - Post-trial 3.4 σ

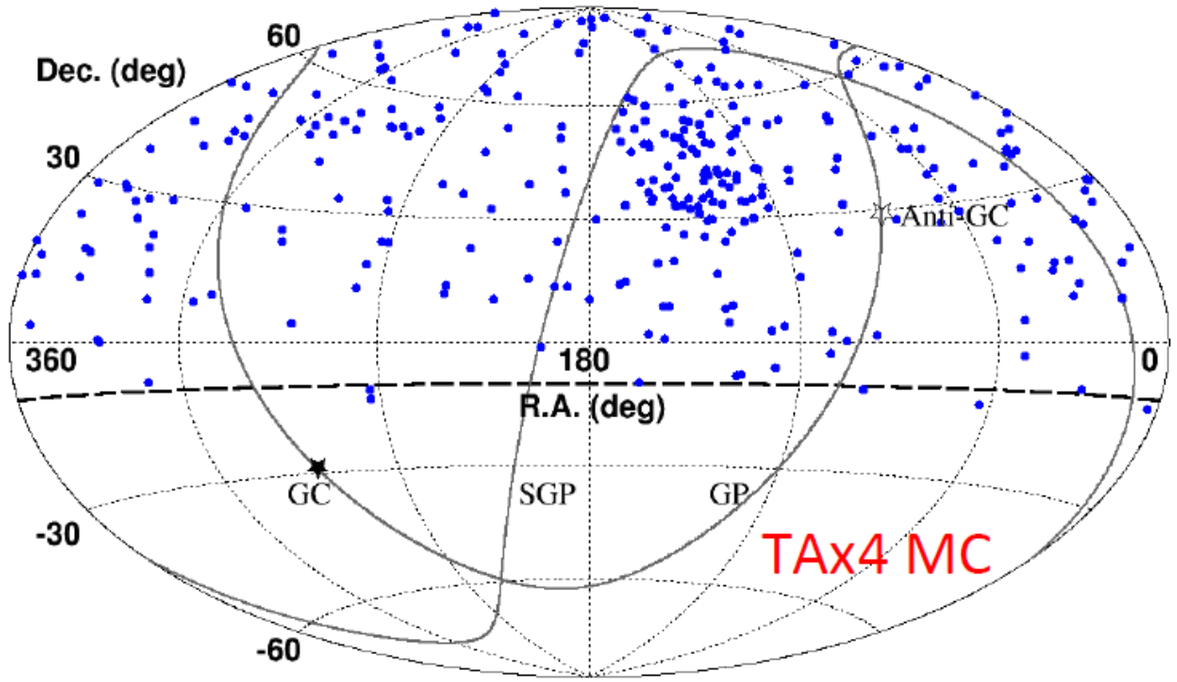






TAx4 mission: Clarify the nature of the hotspot

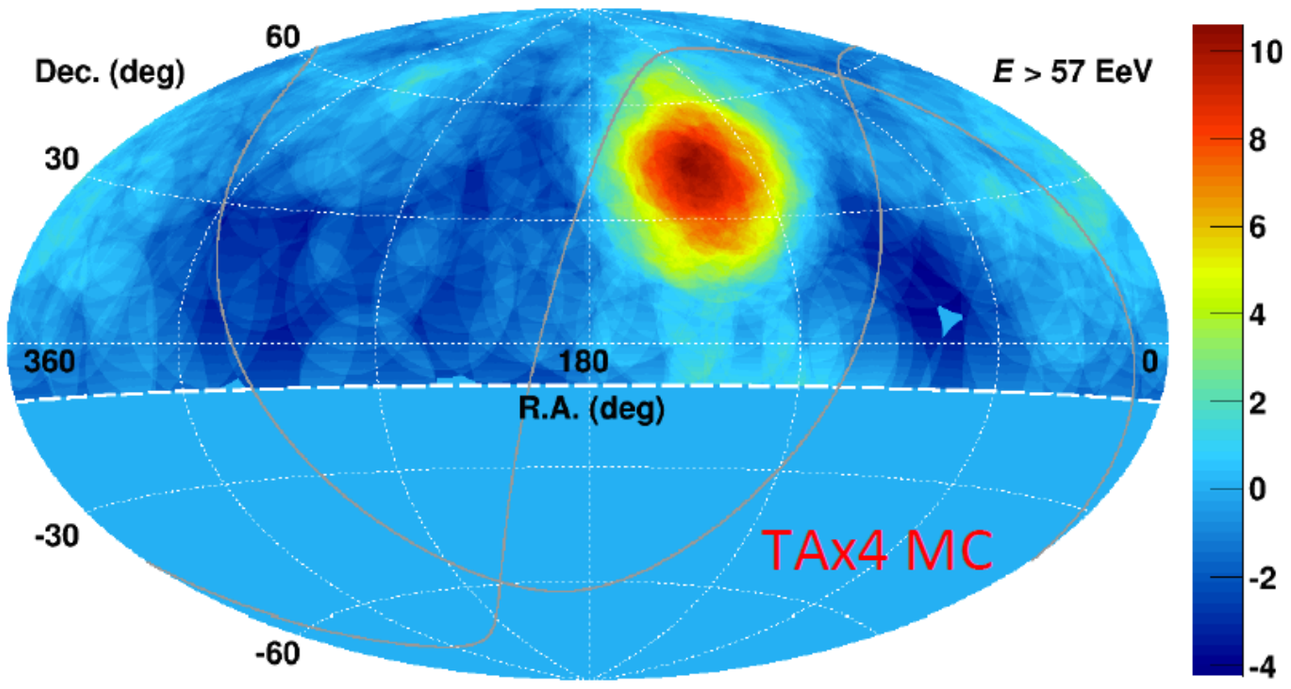
(1) One Hotspot



Hotspot Signal
80-18.9=61events
(RA, Dec)=(145°,45°)
Gaussian σ=10°

Isotropic B.G.
305-61=244events

Oversampling
20° radius circle



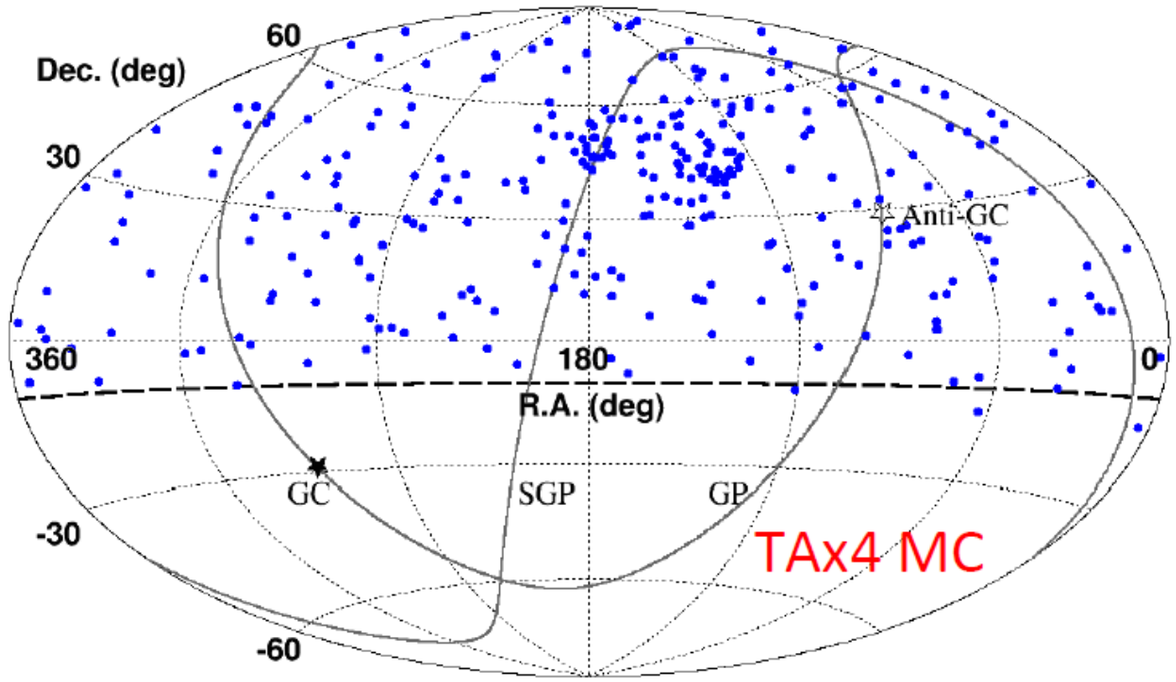
TAx4 mission: Clarify the nature of the hotspot

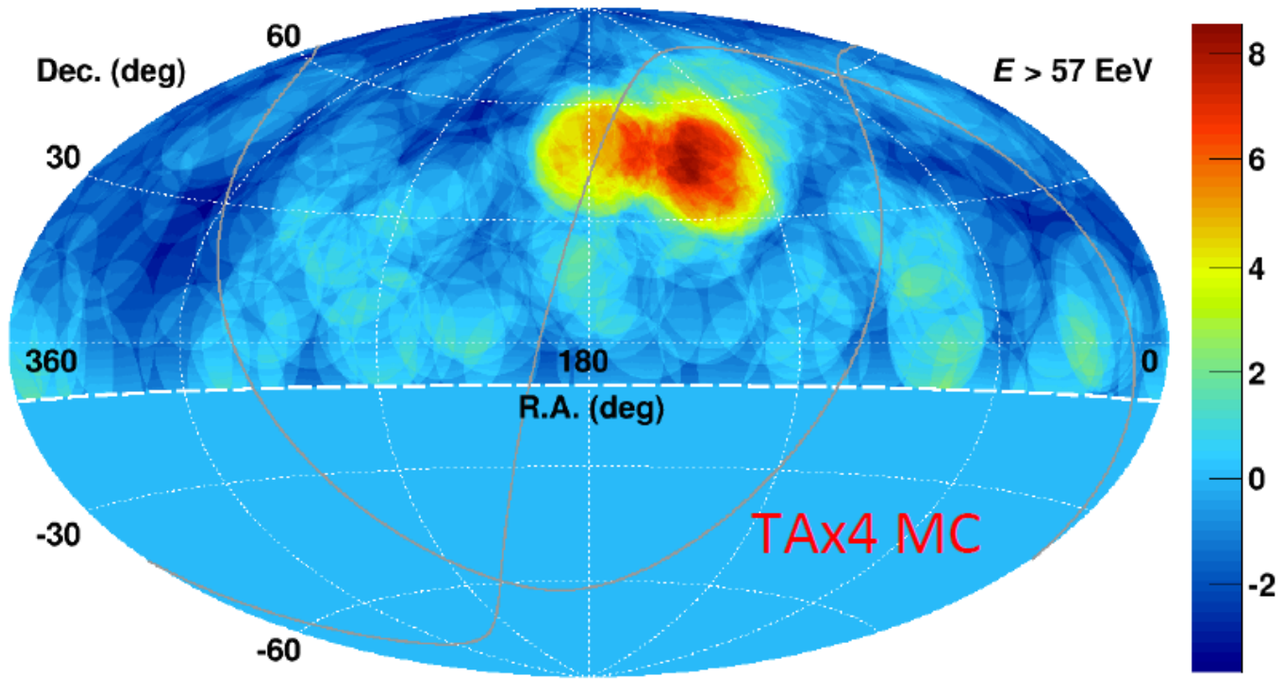
(2) Double Hotspot

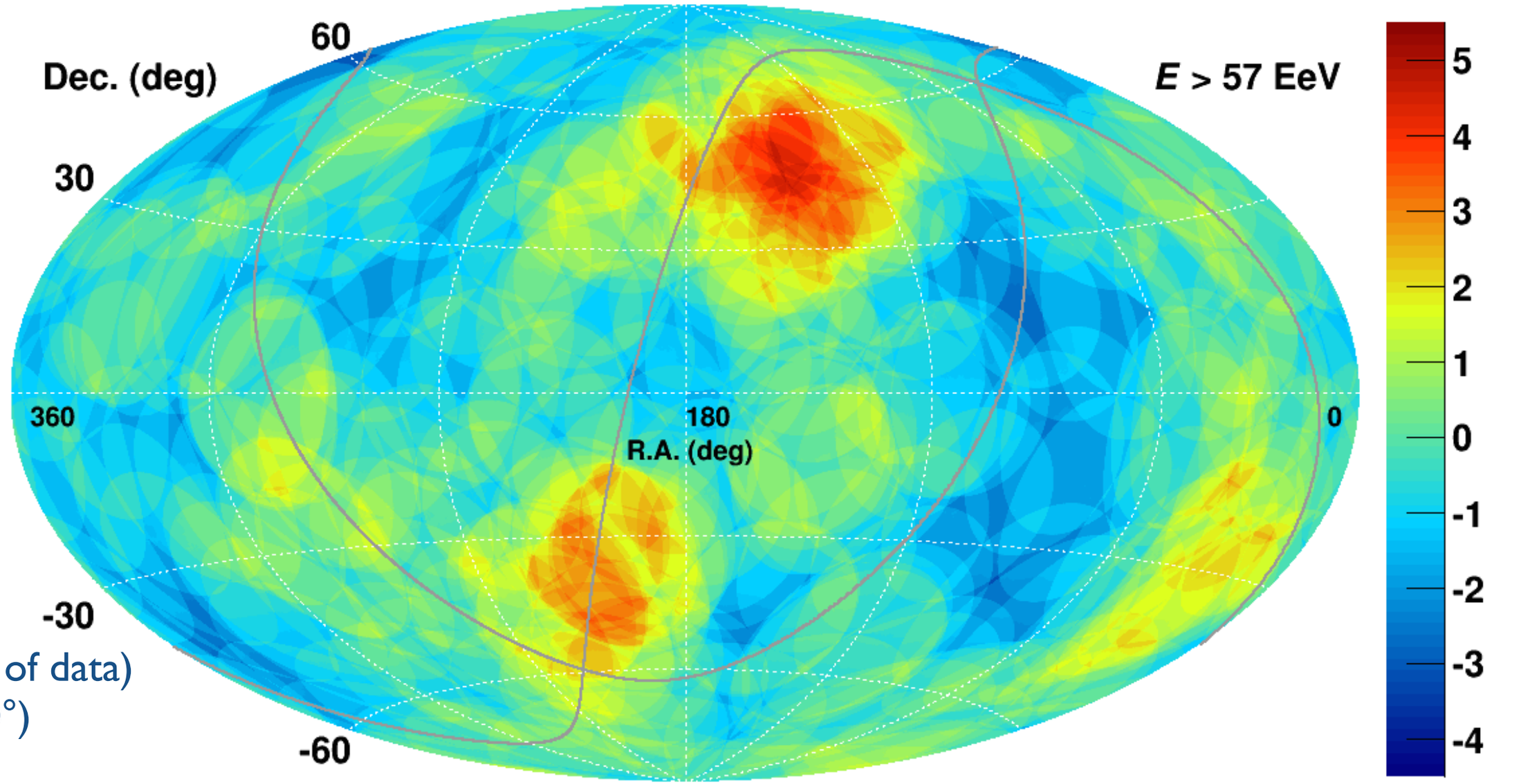
Hotspot Signal
Total 61 events
1. 41events
   (RA, Dec)=(145°,40°)
   Gaussian σ=10°
2. 20events
   (RA, Dec)=(175°,40°)
   Gaussian σ=5°

Isotropic B.G.
305-61=244events

Oversampling
15° radius circle







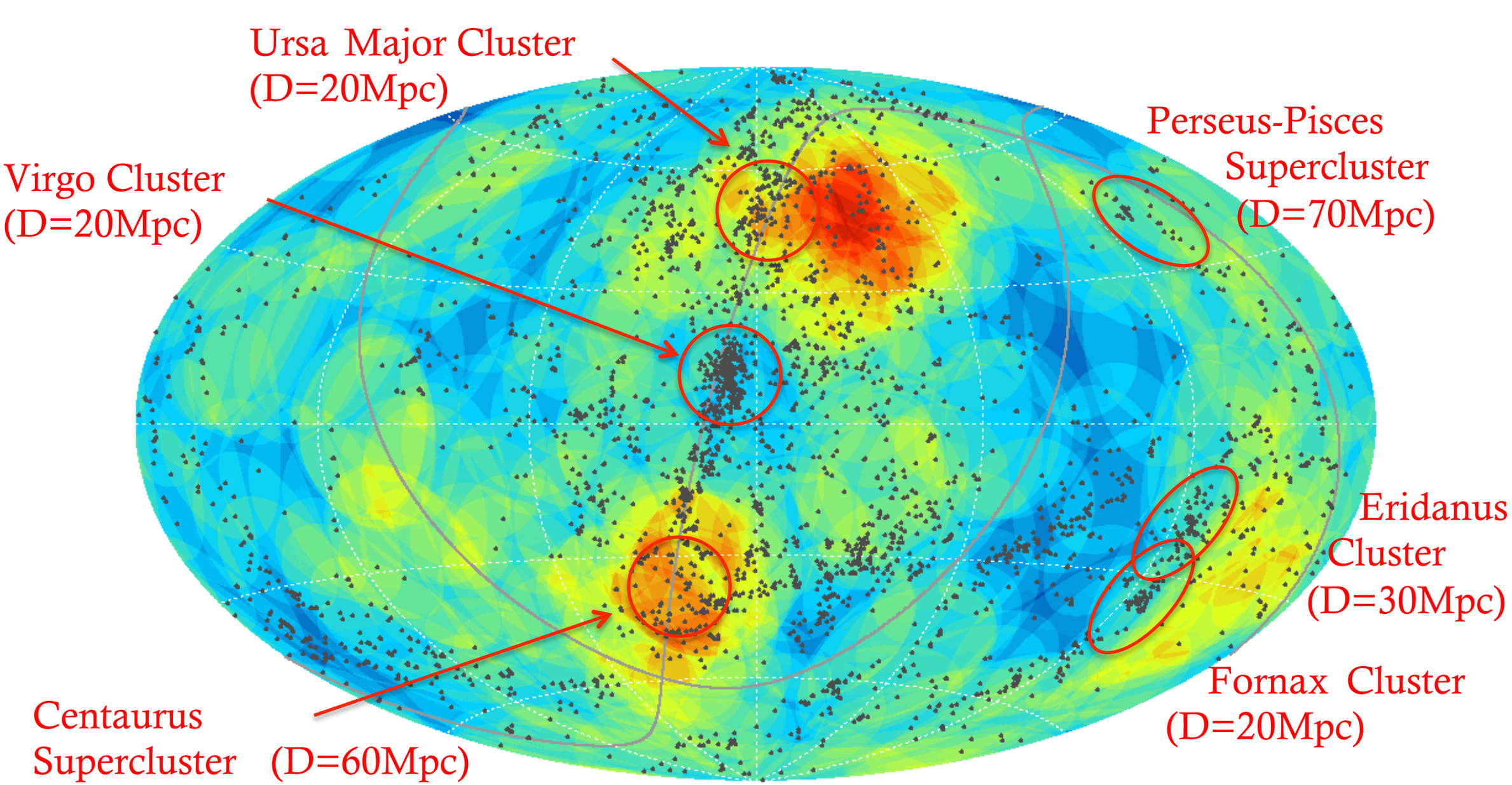
TA (6 year of data)
hotspot (20°)

- **Scan:**
  - r =15°- 35°, Δr =15°
  - E ≥ 57 EeV
- **Result:**
  - r =20°, E = 57 EeV
  - n_{obs}/n_{exp} = 27/6.59
  - pre-trial: 5.5σ
  - post-trial: P = 4σ

AUGER (2004-2014)
warm spot (12°)

- **Scan:**
  - r =1°- 30°, Δr =1°
  - E = 40-80 EeV, ΔE = 1EeV
- **Result:**
  - r =12°, E = 54 EeV
  - n_{obs}/n_{exp} = 14/3.23
  - post-trial: <3σ

P. Tinyakov et al.



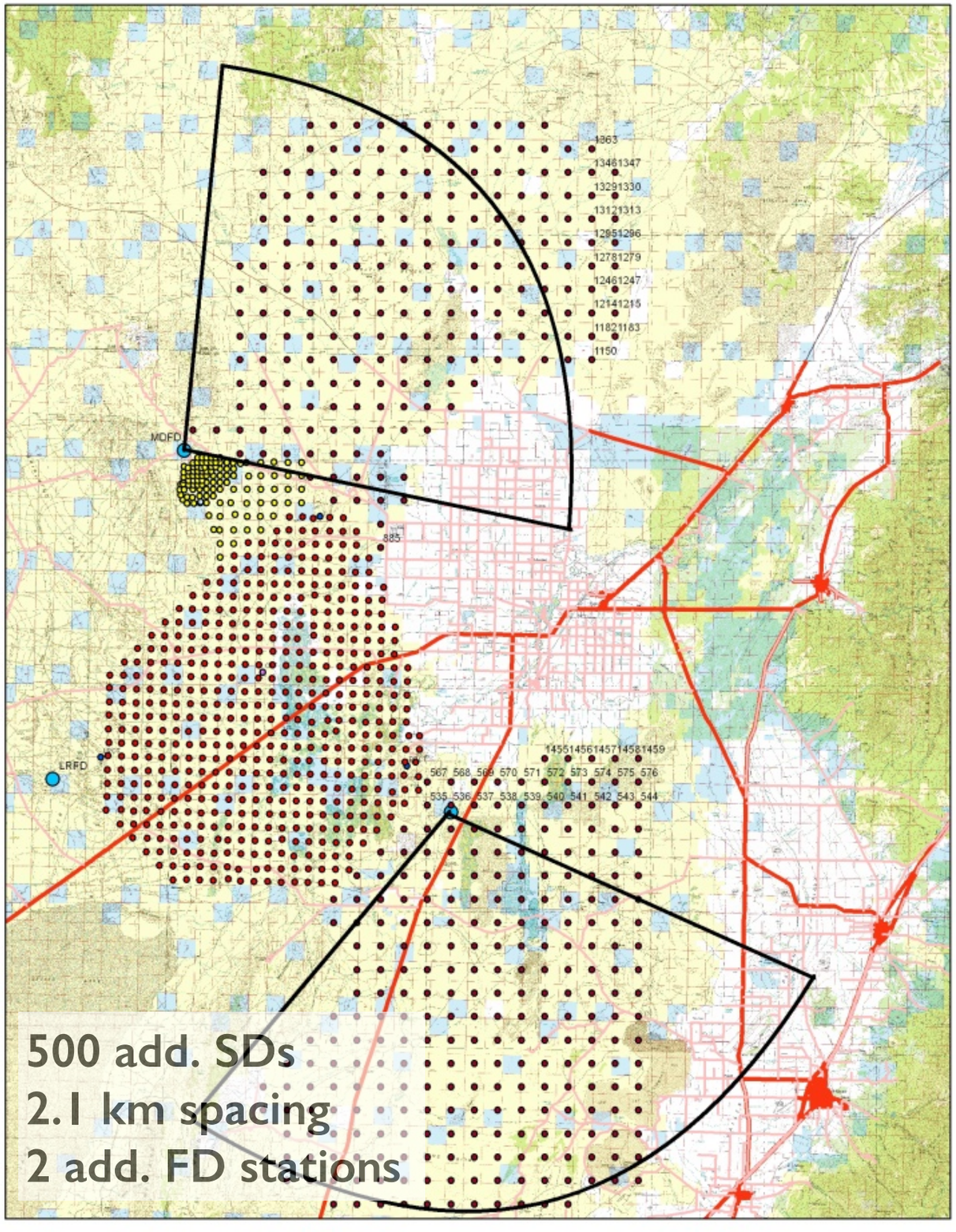
Black dots :
2MASS catalog
Heliocentric velocity <3000 km/s
D < ~45 Mpc

Huchra, et al, ApJ, (2012)

TA hotspot is found near the Ursa Major Cluster
TA & PAO found no excess in the direction of Virgo.

P. Tinyakov et al.

Tale and Telescope array x 4



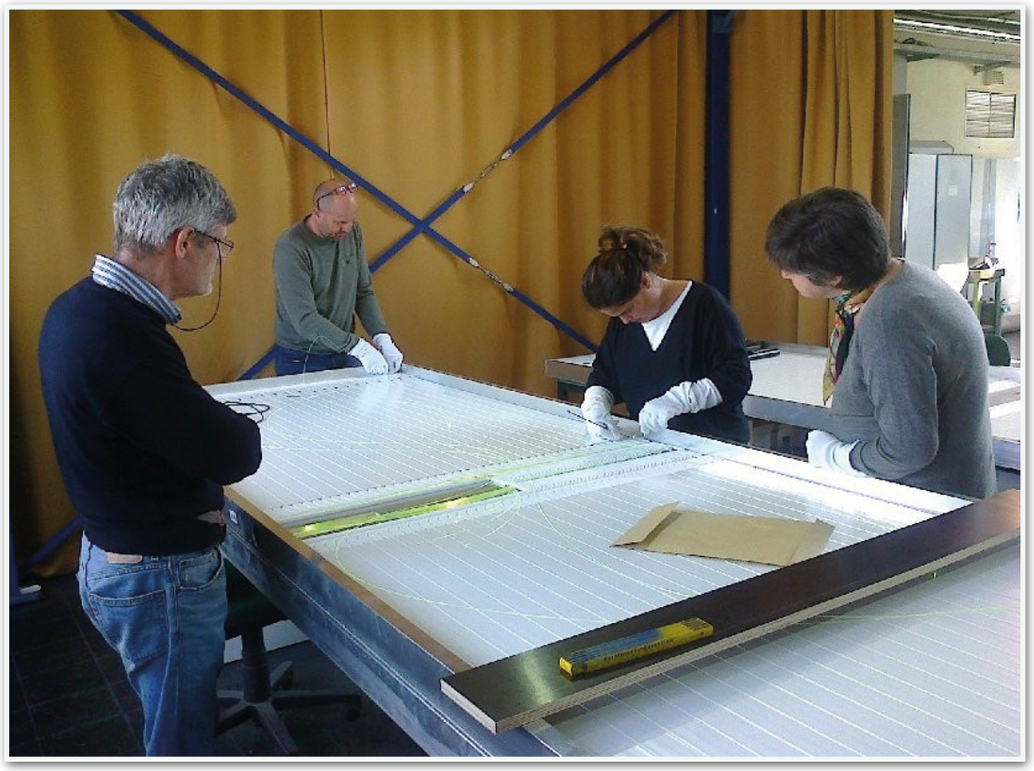
TALE

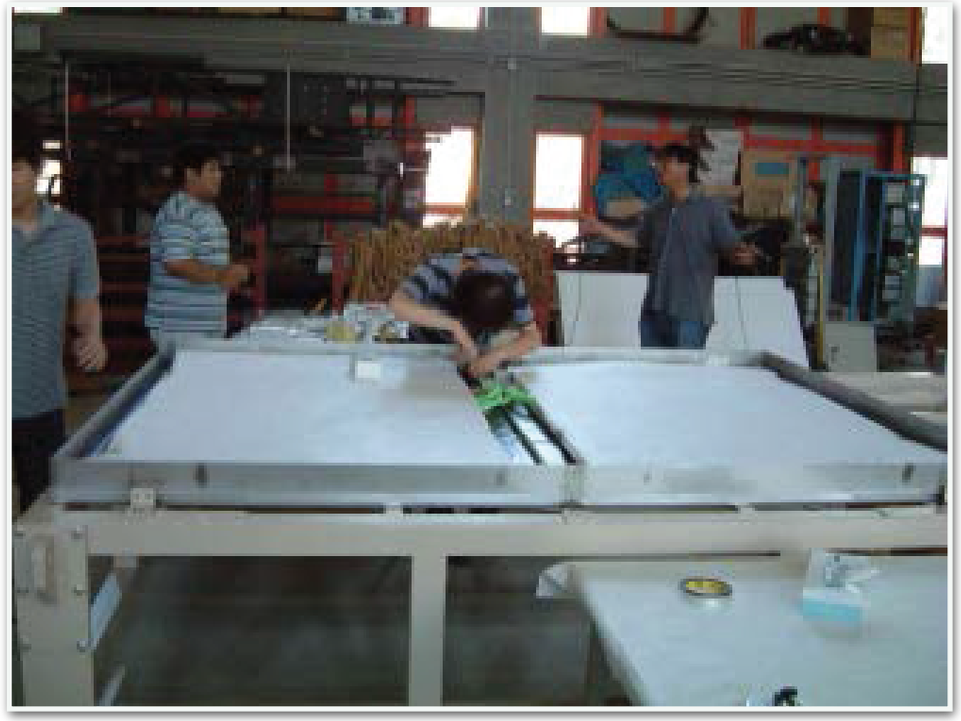
- 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operating in conjunction with TA Middle Drum FD
- $10^{16.5} < E < 10^{20.5}$ eV
- Infill array is being deployed

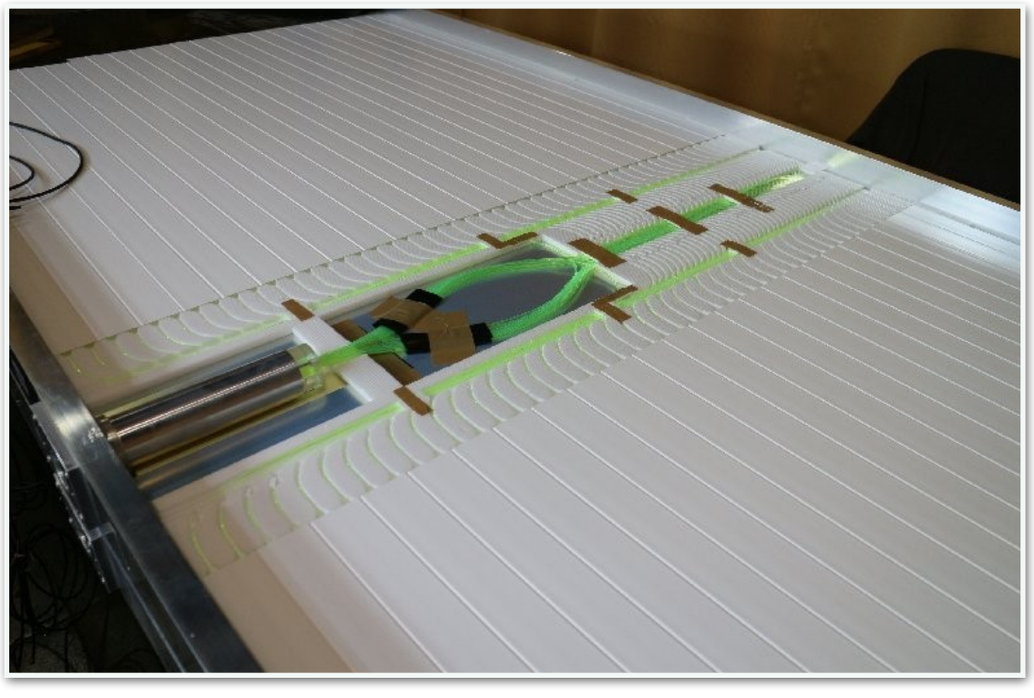
TAx4

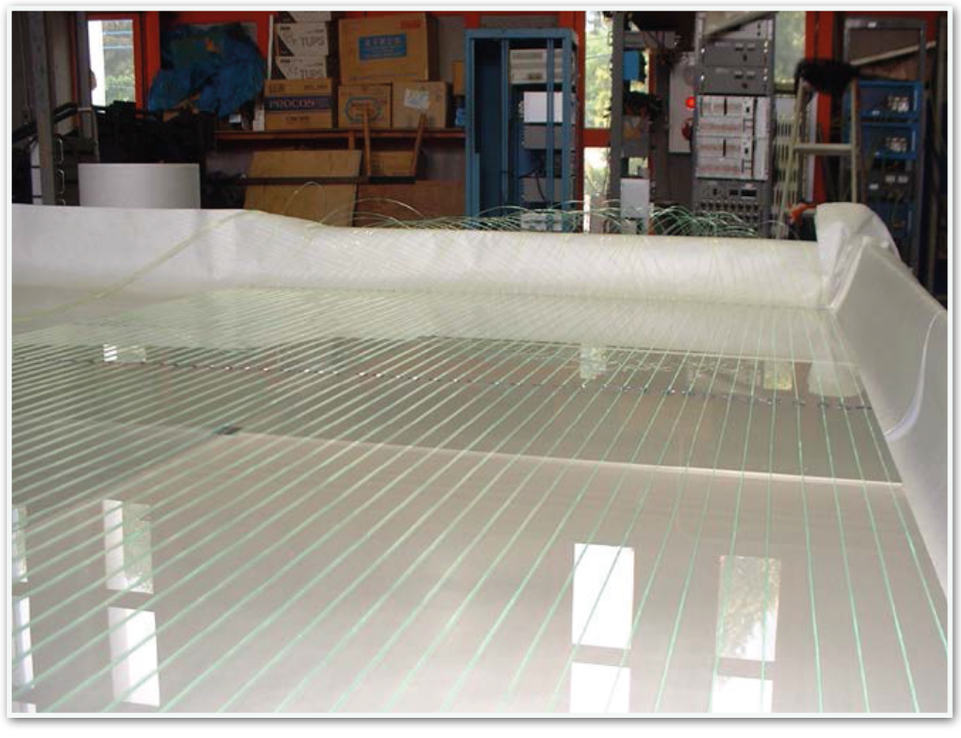
- Fourfold increase in size of TA SD
- Add 500 SD counters, at 2.1 km spacing
- Add 2 FD sites, 28 telescopes

- Get 21 TA-years by 2020
- Proposals:
  - SD = Japan (successful)
  - FD = U.S.



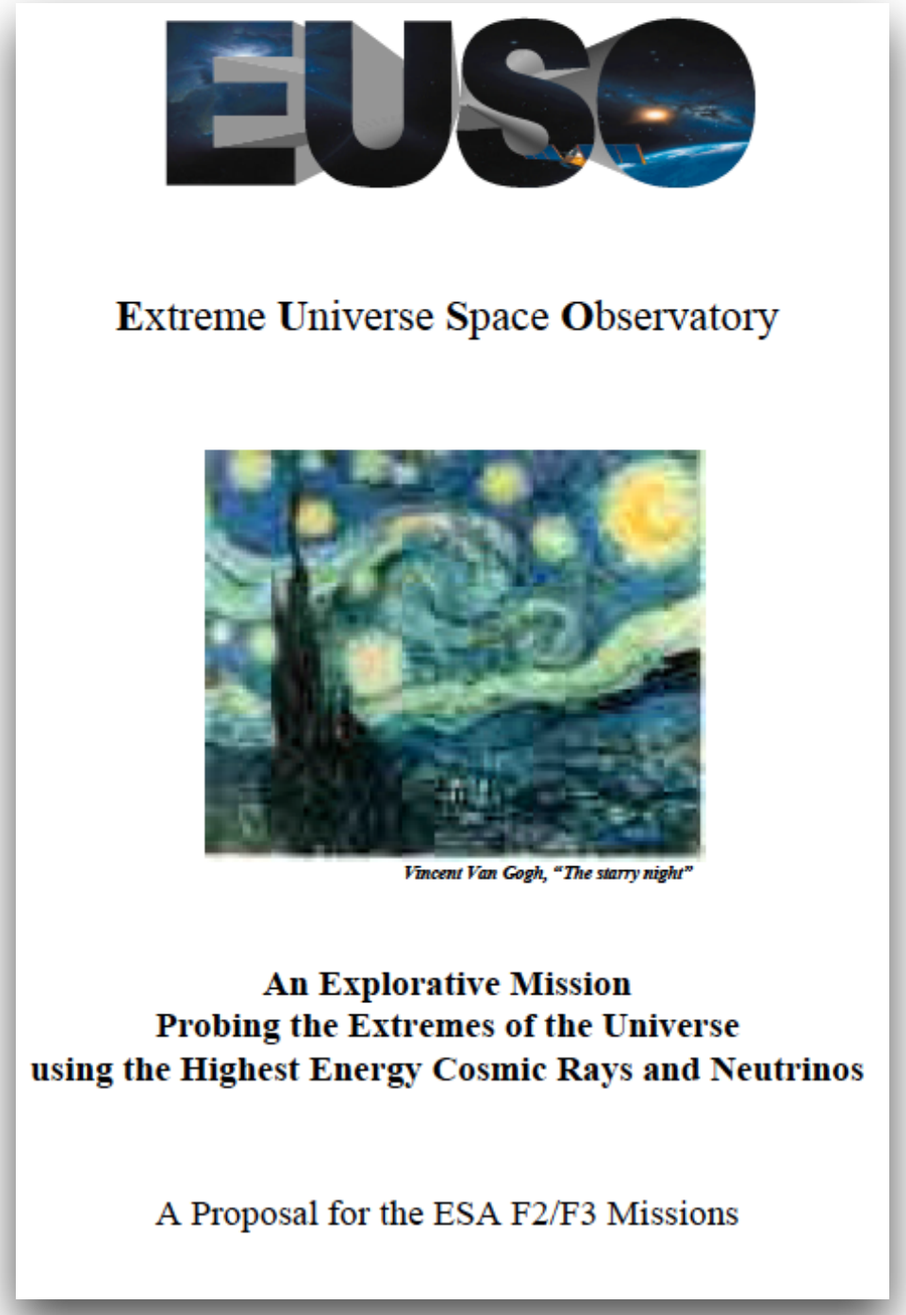






EUSO —
Extreme Universe Space Observatory

A glimpse at the "origins"



Extreme Universe Space Observatory

Vincent Van Gogh, "The starry night"

An Explorative Mission
Probing the Extremes of the Universe
using the Highest Energy Cosmic Rays and Neutrinos

A Proposal for the ESA F2/F3 Missions

Original proposal for ESA F2/F3, submitted January 2001

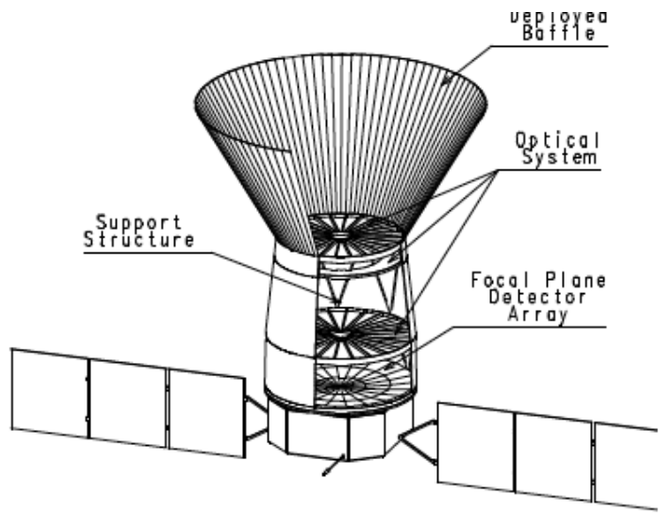


Fig.4.1 – ***EUSO*** in the operative configuration.

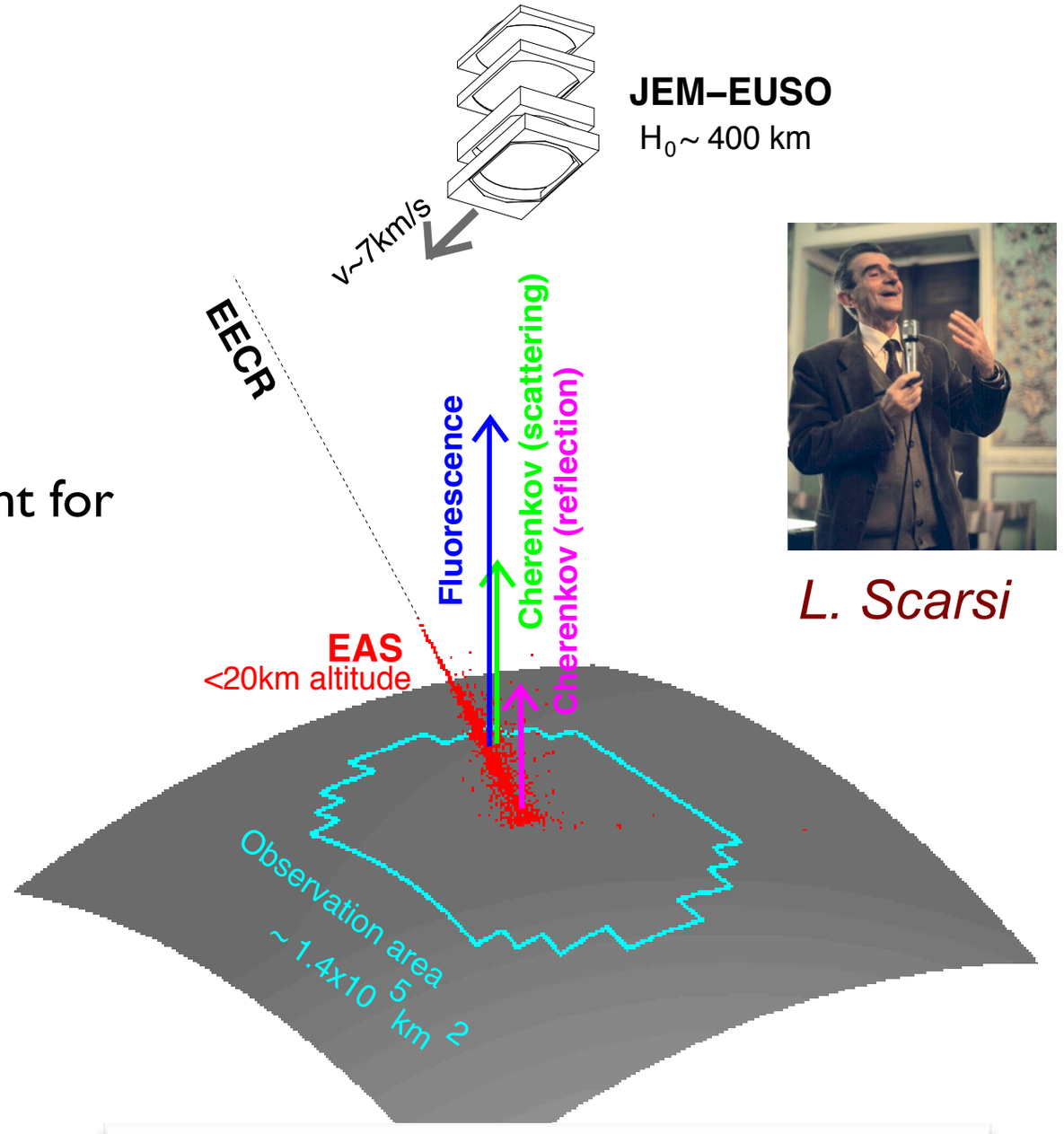
Field of View	60°
Entrance Pupil Diameter	2.6 m
Operating wavelengths	330-400 nm
Angular resolution	~ 0.1°
Pixel diameter (and spot size)	~ 6 mm
Number of pixels	~ 2.5×10^5
Pixel size on ground	1 km

Basic ***EUSO*** payload characteristics.

JEM-EUSO onboard of ISS

Aims

- Physics and Astrophysics at E>5×10^{19} eV
- Highest statistics, thus largest exposures at extreme energies E ≈10$^{20-21}$eV with uniform coverage
- „Lower energies“ (E < 5×10^{19} eV) important for overlapping with current generation observatories with significant statistics…
- Perform anisotropy studies with UHECRs, and study the evolution of anisotropies with energy ⇒ flux, cut-off, angular size...
- Identify sources in the sky and study their spectra
- Constrain the composition of the UHECRs at the highest energies



L. Scarsi

Will NOT be onboard of ISS in 2017

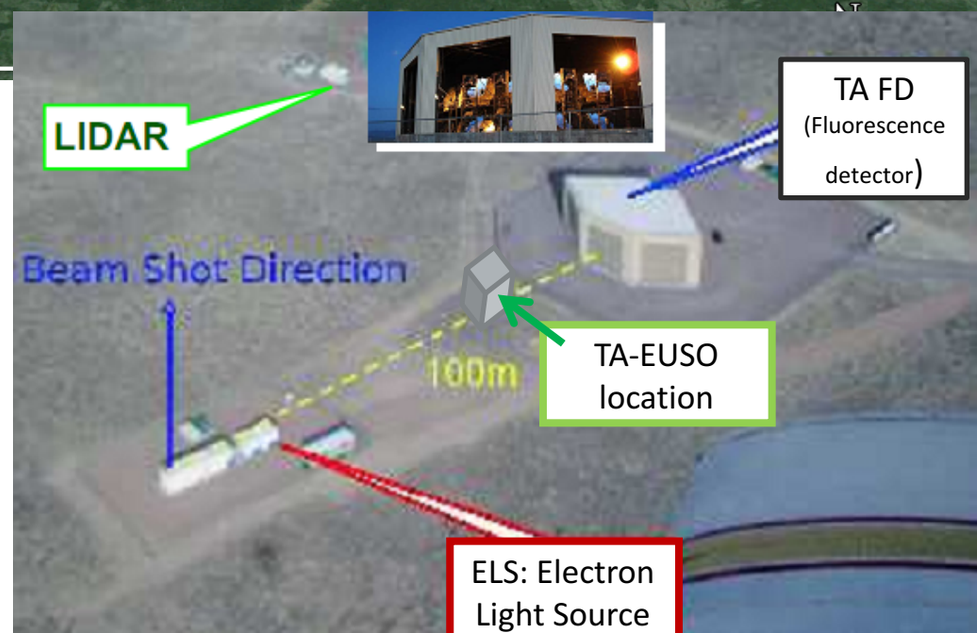
Near term program

- EUSO Balloons
  (First flight completed,
  New flights In preparation,
  Superpressure balloons)

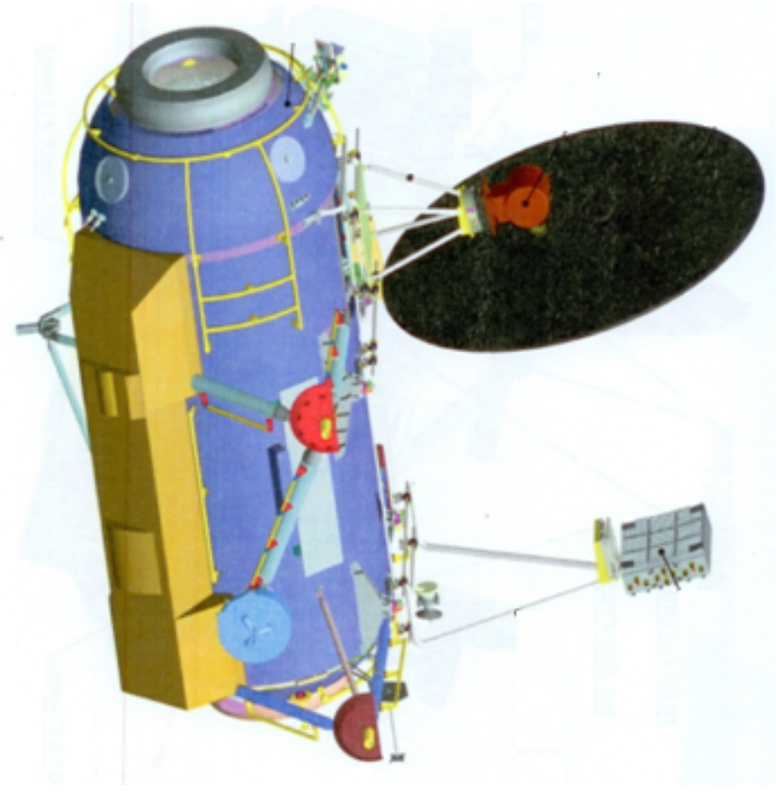
- MINI-EUSO
  (on the ISS, approved
  by ROSCOSMOS and ASI)

- EUSO-TA (On-ground, operating)

- TUS (In space,
  operating, UV light, aurora)



KLYPVE-EUSO



In 2014:

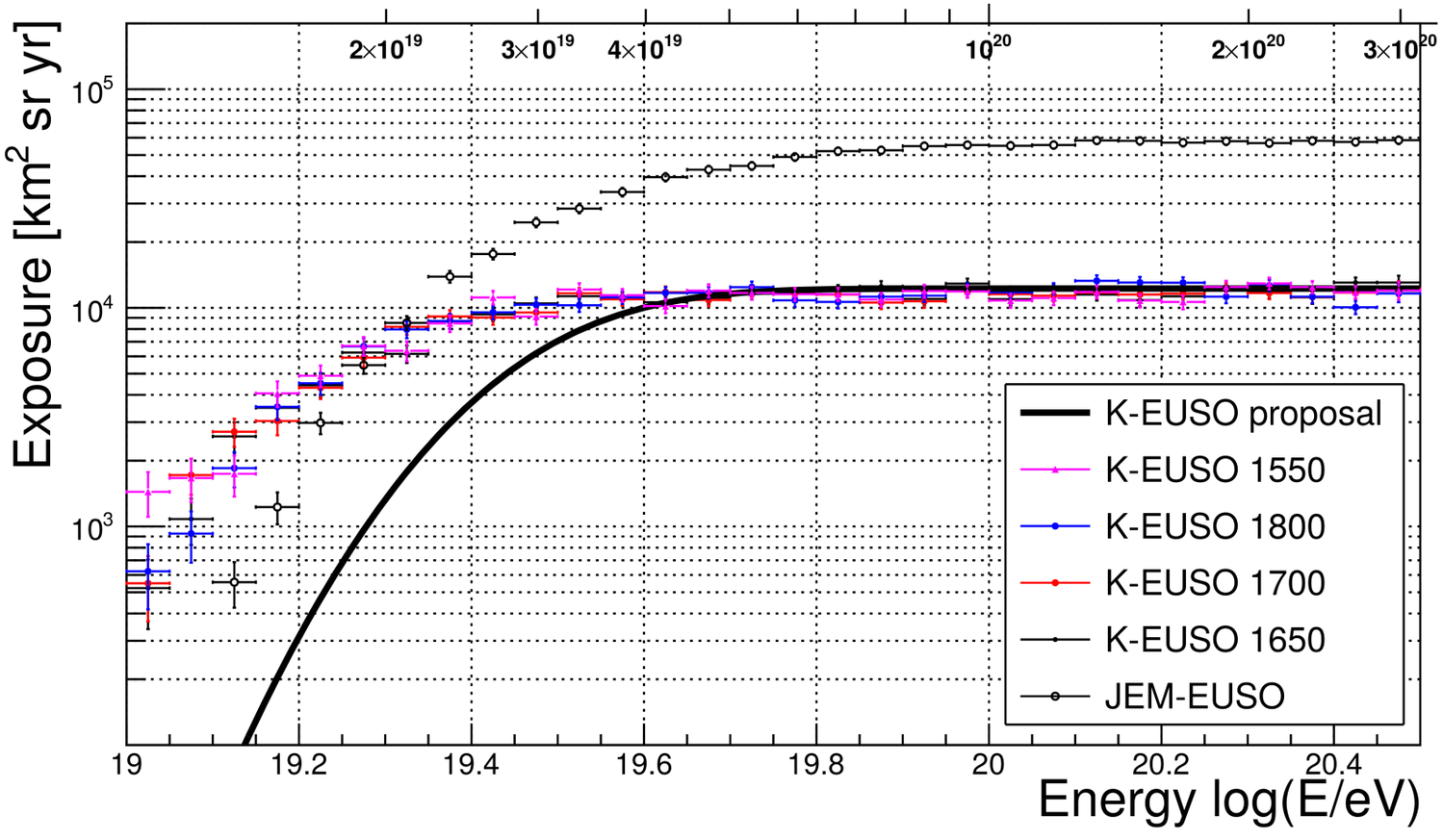
- Improved version of the KLYPVE mission

- Hosted onboard the Mini Research Module-1 module of the Russian ISS segment

- The KLYPVE study is led by MSU and ROSCOSMOS

- The study passed the preliminary design stage (pre- phase A study)

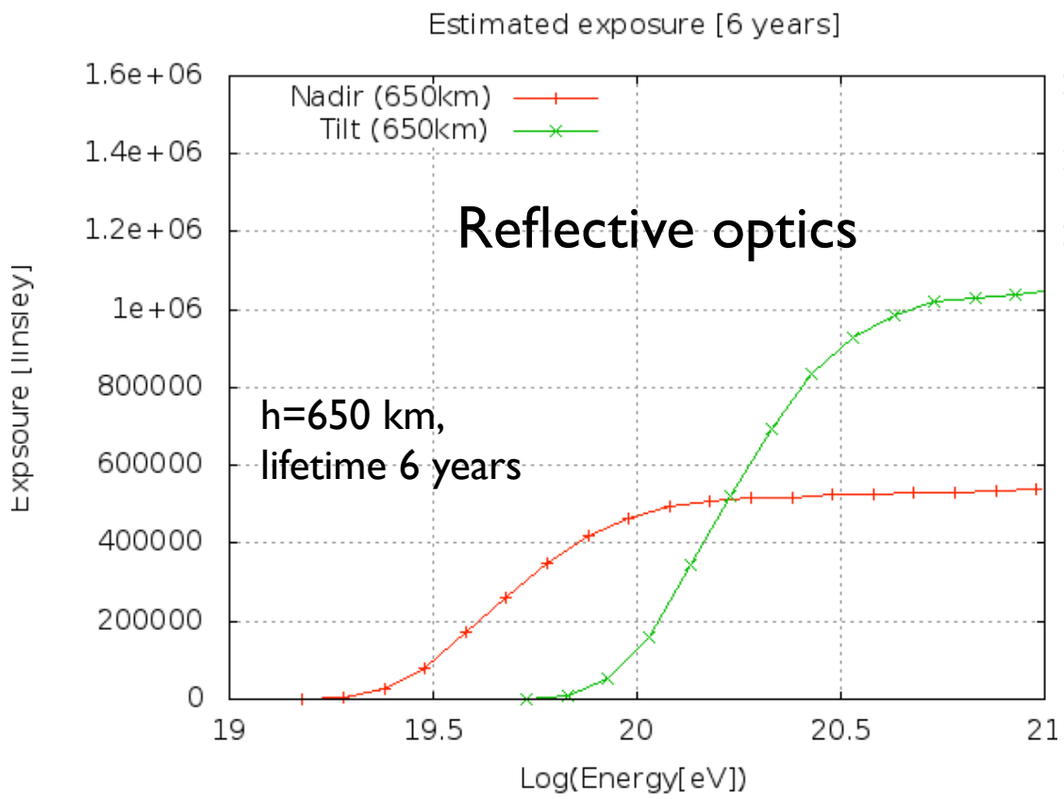
- Technical Requirements have been defined.

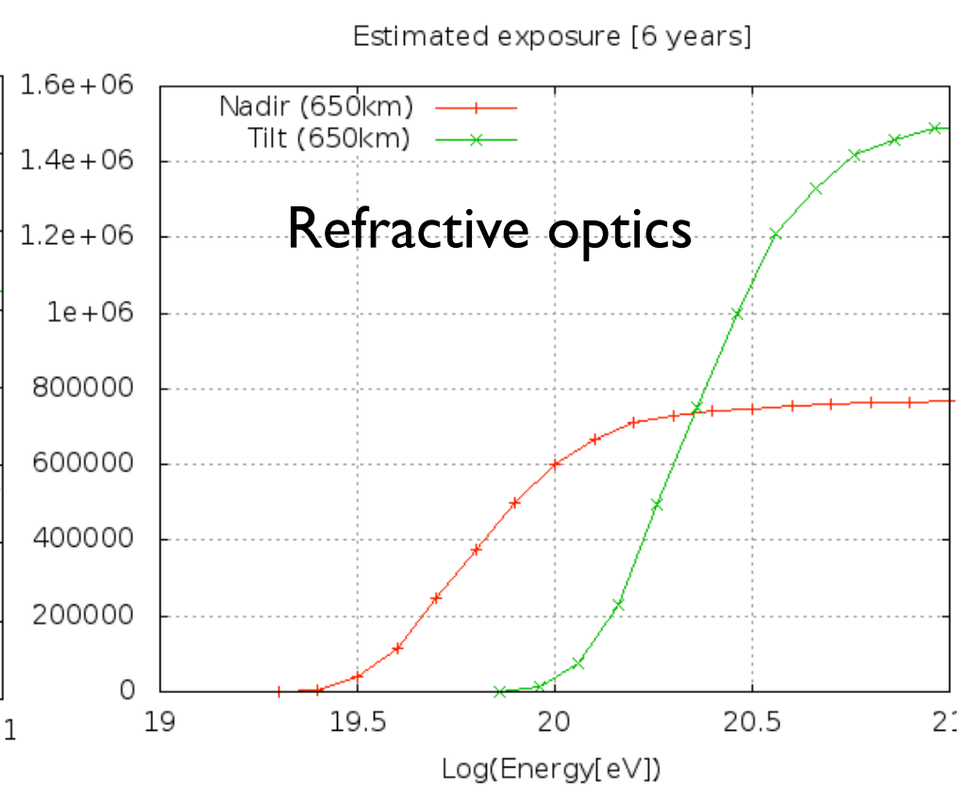


EUSO-FF

- Proposal to be submitted to ESA in response of the Announcement of Opportunity for *the fifth cycle (M5) of medium missions* of the Programme "Cosmic Vision 2015-2020".
- Submission is early October 2016.
- Ariane 6 Fairing limiting factor.
- Refractive and reflective optics considered.

Parameter	Requirement value
Exposure at 100 EeV*	10^6 km^2 sr yr
at 50 EeV*	0.5 × 10^6 km^2 sr yr
Angular res. at 50 EeV	≤5°
at 200 EeV	≤2°
Energy res. at 50 EeV	≤30%
at 100 EeV	≤20%
****X_{max} res.**	≤100 g/cm^2
*****<X_{max}> res.** at 50 EeV	≤20 g/cm^2
at 100 EeV	≤30 g/cm^2





Hadronic interactions: Extrapolation and LHC Results

Source of uncertainties:

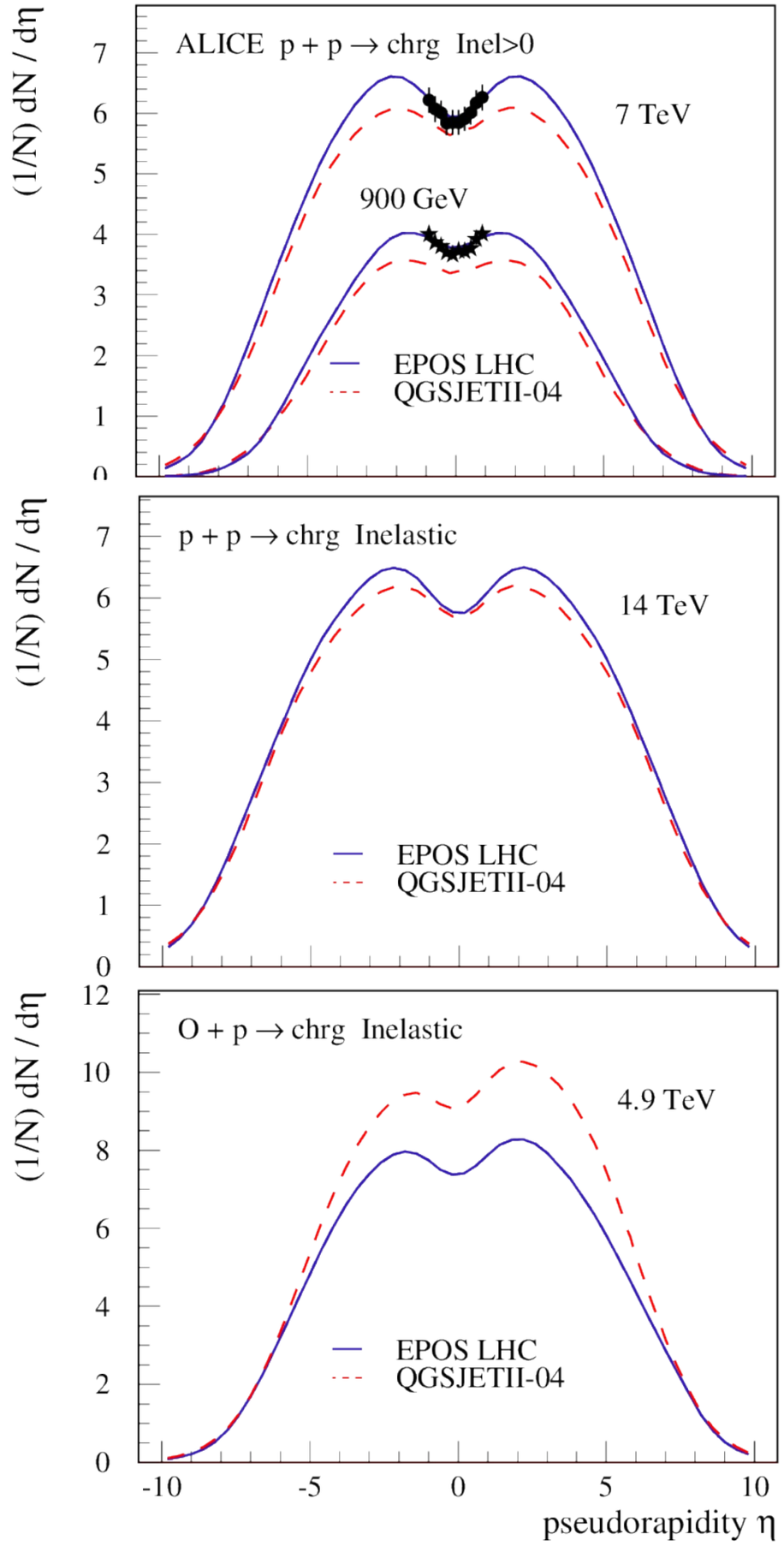
- extrapolation to higher energies
- extrapolation from p-p to p-Air and pi-Air (currently main source of uncertainty)

Need to better take into account recent LHC results:

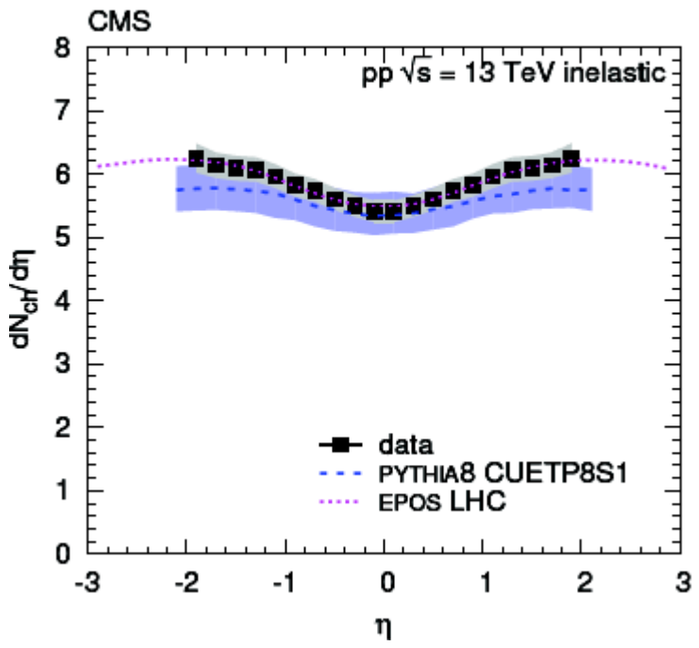
- hard scale saturation
- collective effects in small systems
- detailed diffractive measurements
- particle correlations

⇒ EPOS 3

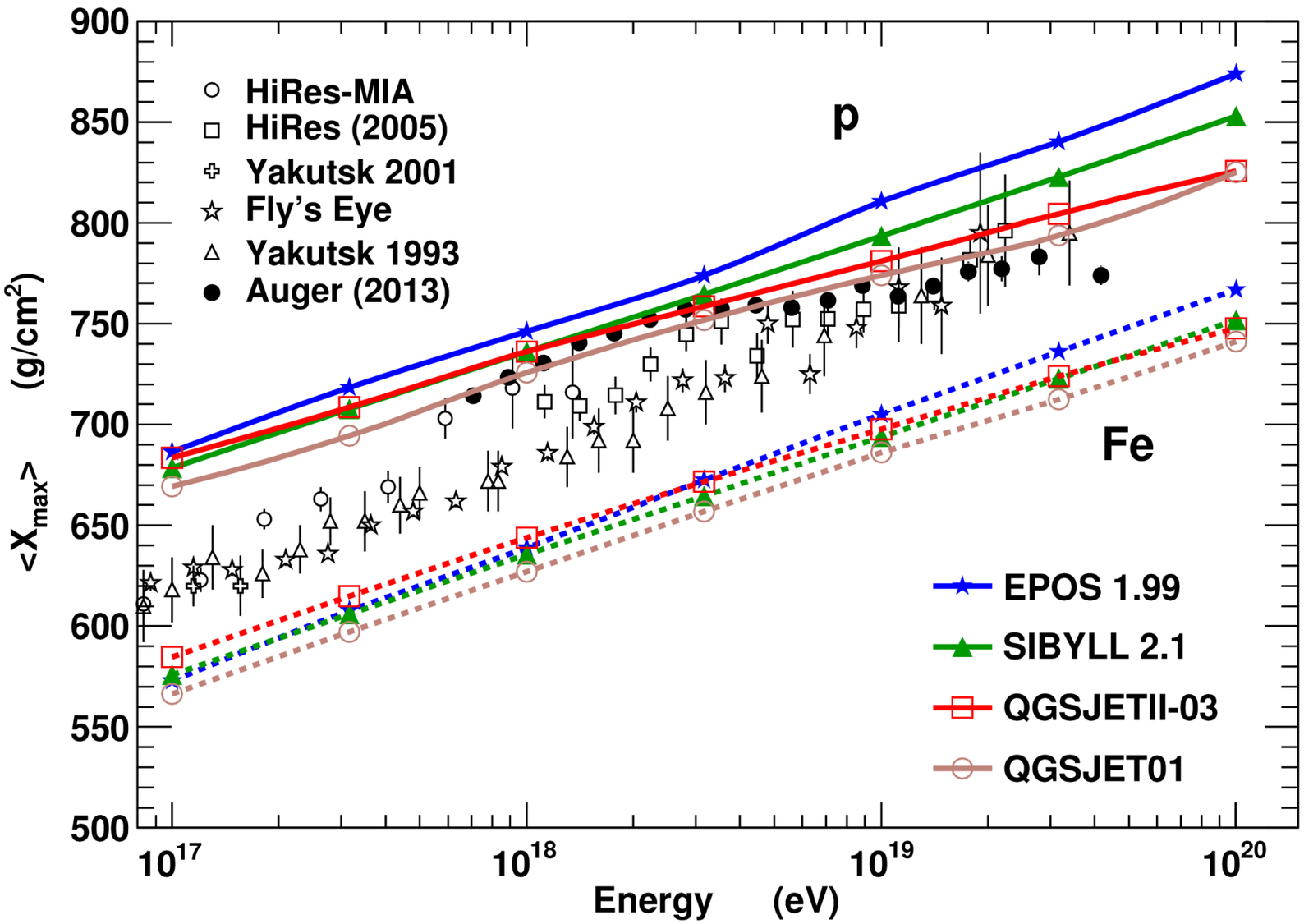
⇒ QGSJETxxx



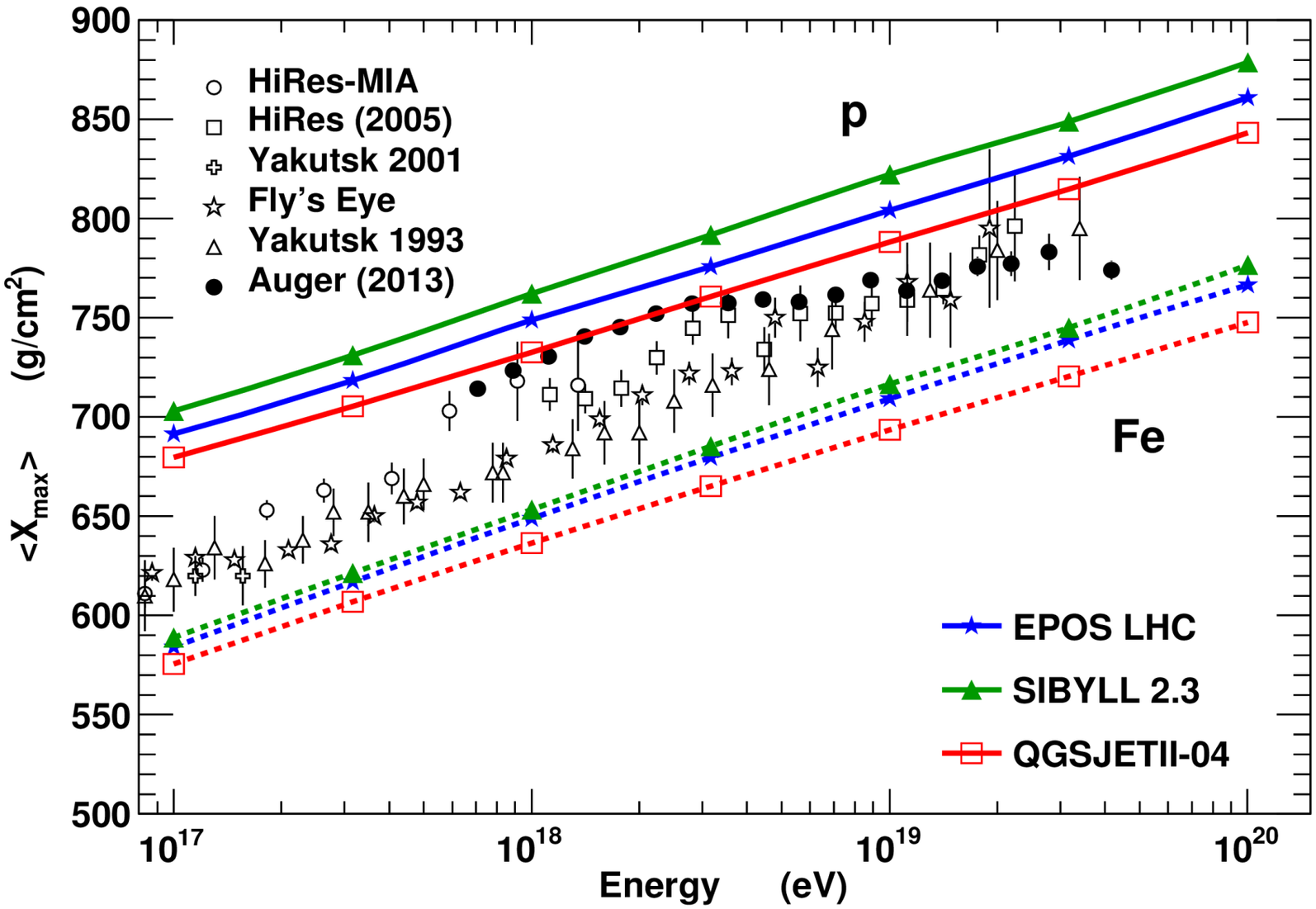
(CMS, 1507.05915)



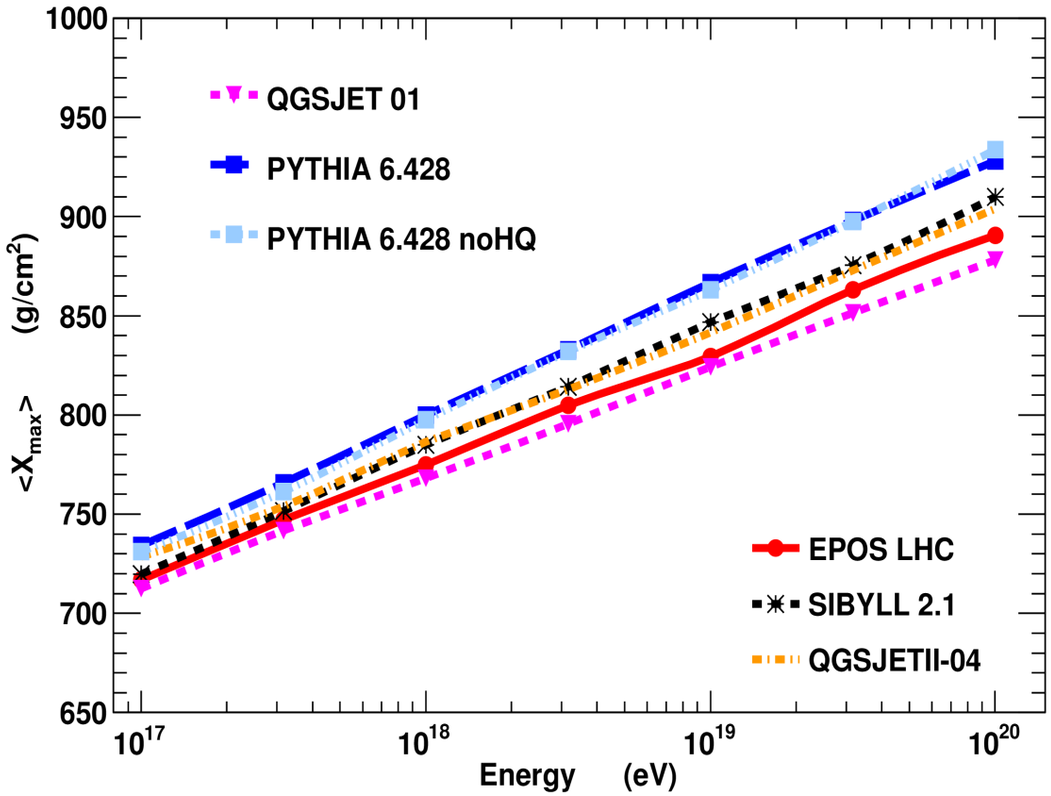
Pre-LHC models: X_{max}

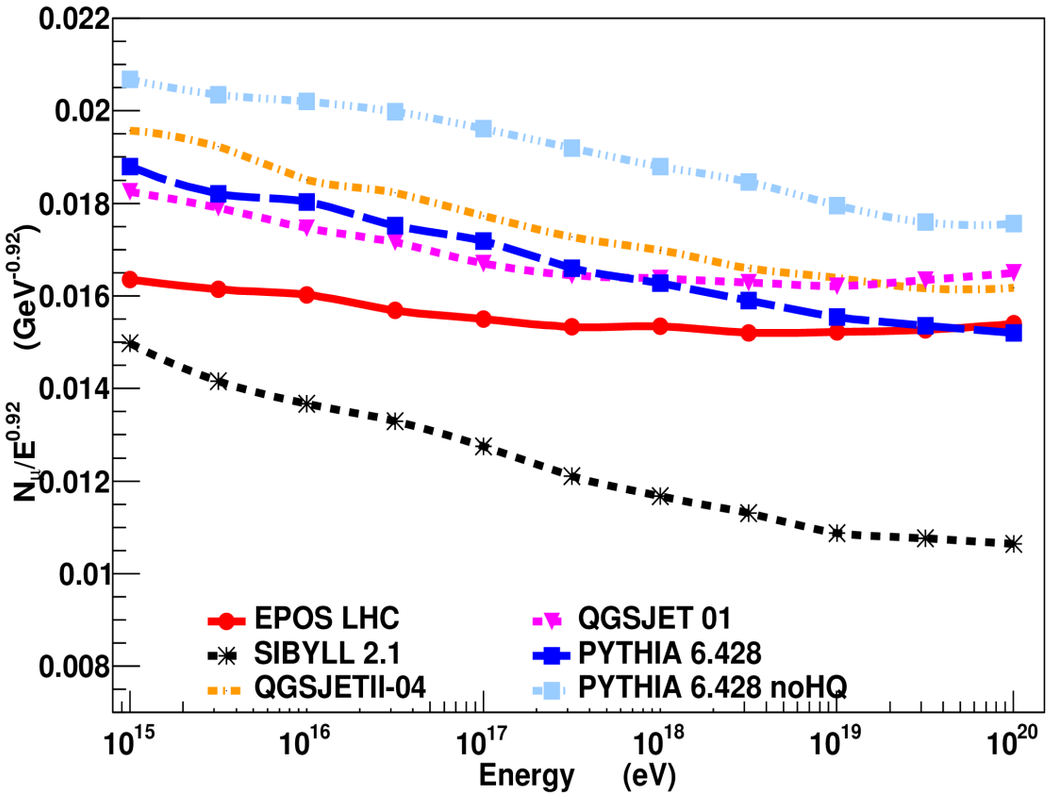


Post-LHC models: X_{max}



Tests using hydrogen atmosphere





Test of Pythia event generator

David D'Enterria (CERN), Sun Guanhao and Tanguy Pierog

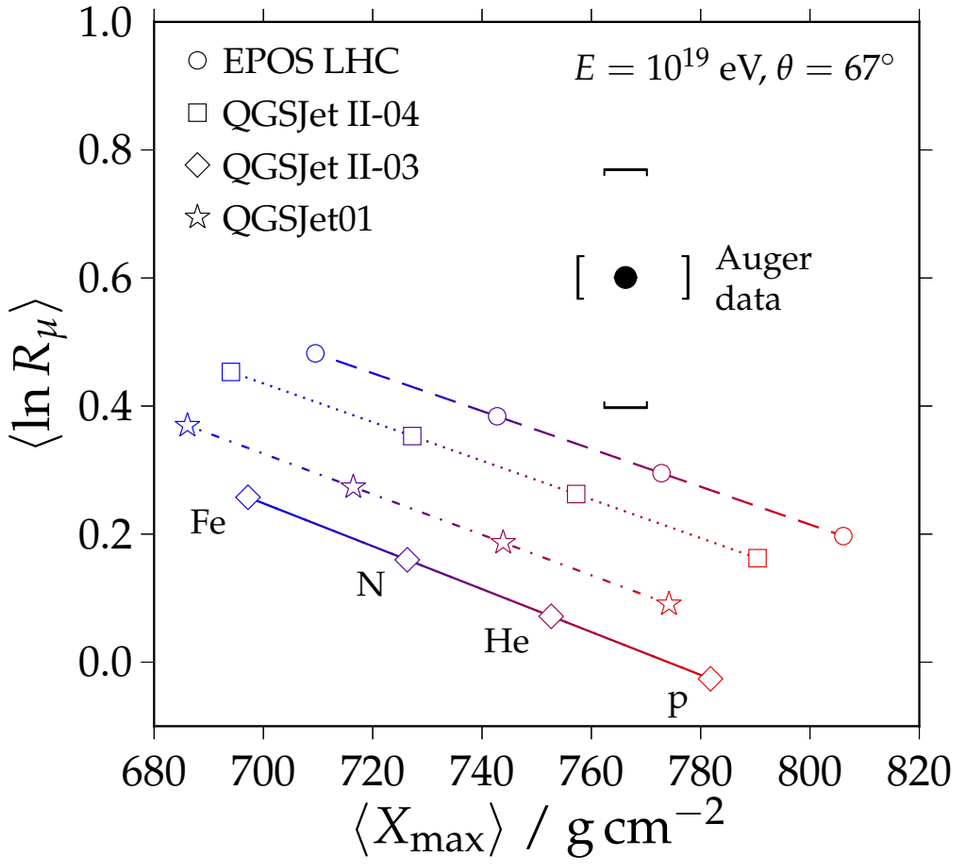
Modified air shower simulations
with air target replaced by hydrogen
for interactions only
(no change in density)
⇒ no nuclear effect

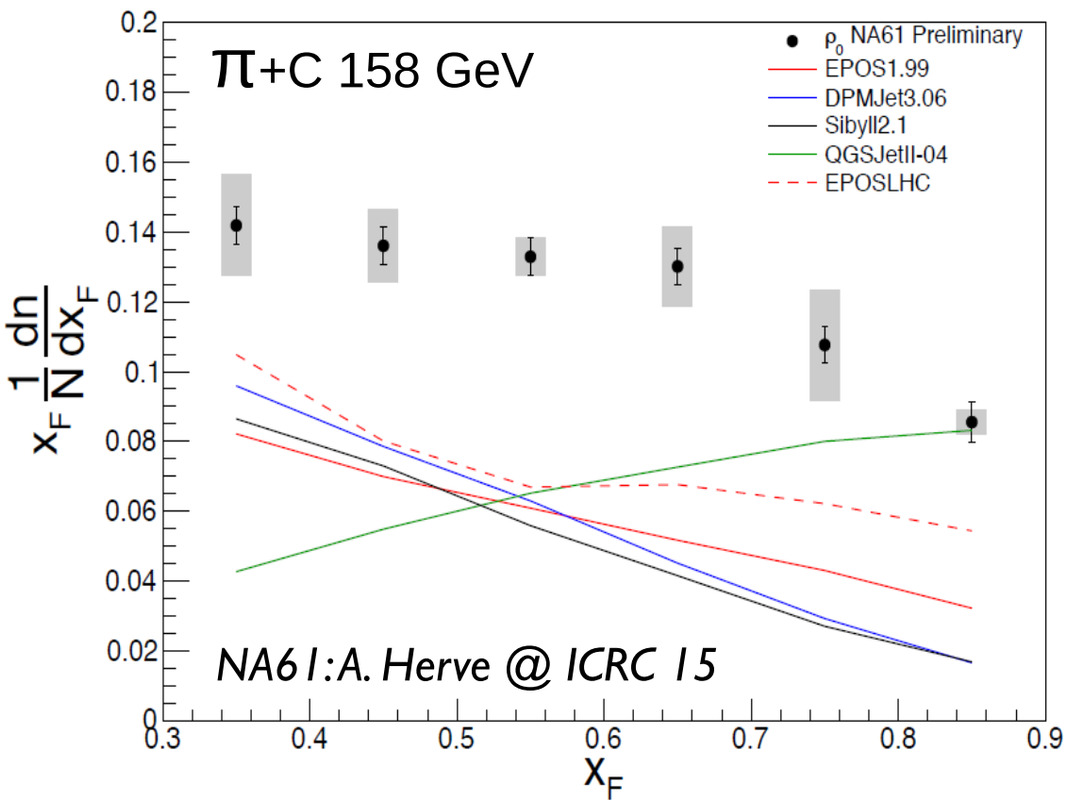
Strong effect of nuclear target on model predictions !

(cross section, absorption in target, diffraction, saturation scale, collective effects …)

Main source of uncertainty for first interaction and thus X_{max}

Hadronic interactions — Muon problem





Large discrepancy for ρ^0 production in π-A

Room for improvement on muon production

Test with p-O@LHC ?
LHCf@LHCb with SMOG (fixed target p-A and (π-A) at 6.5 TeV !)

Smart centrality selection in p-Pb (and LHCf+ATLAS or CMS+TOTEM) ...

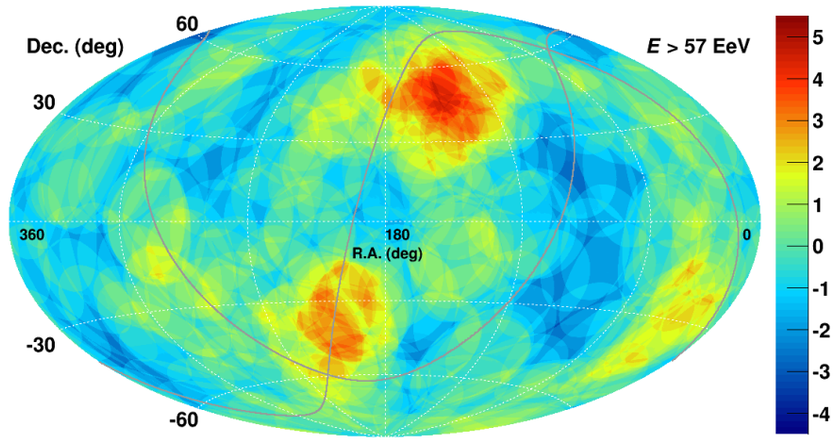
Summary

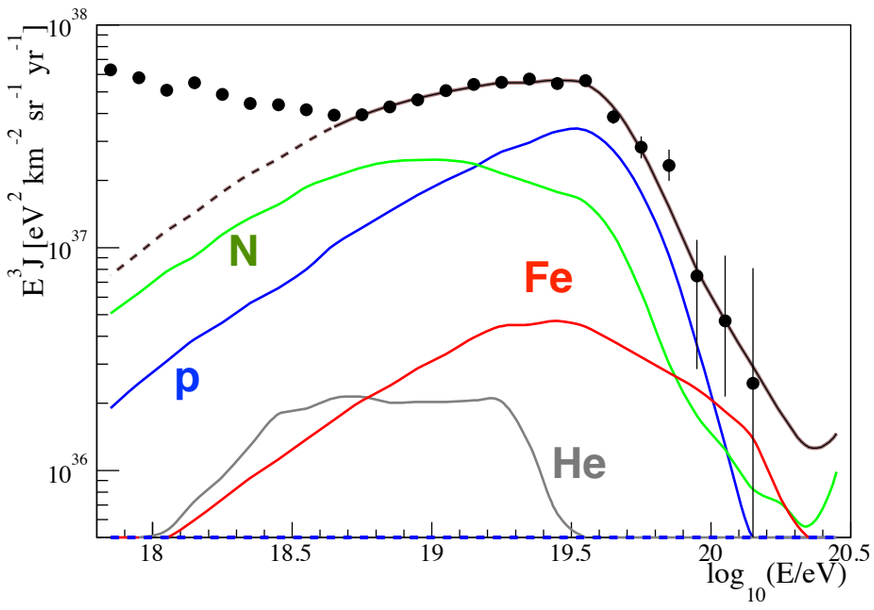
Interactions
- Support initiatives such as „Physics beyond colliders“

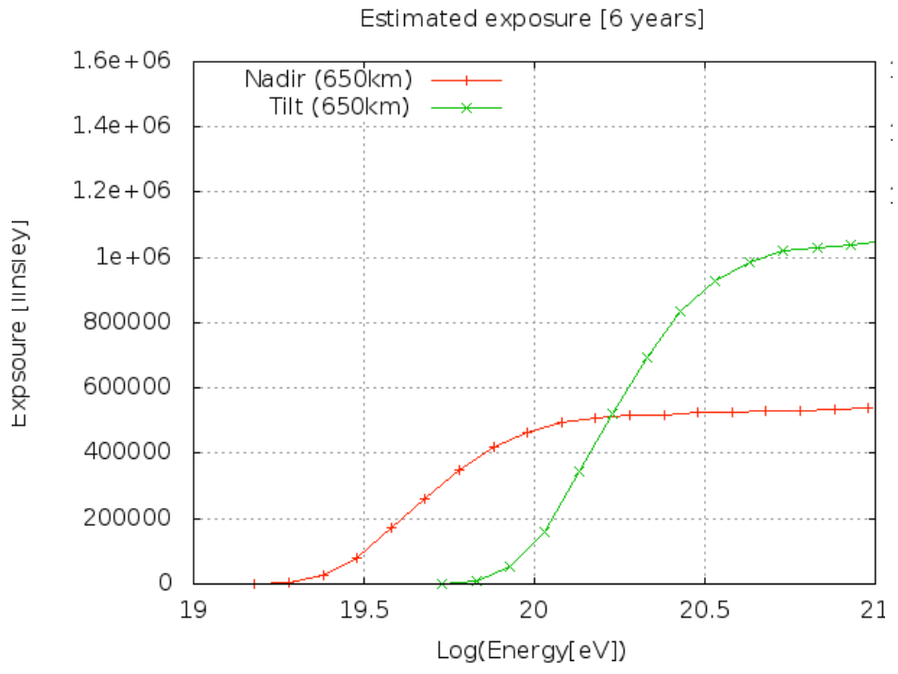
TA
- Extension of existing array by factor 4
- Clarify nature of the hotspot by 2020

Auger
- Upgrade of detector array to be operated 2017 – 2025
- Similar event statistics as collected so far
- Composition up to highest energies, anisotropy studies
- Study of had. interactions (muon counting)

EUSO
- 2 paths into the future:
  - EUSO-FF
  - KLYPVE EUSO







Summary

TA

- Extension of existing array by factor 4
- Clarify nature of the hotspot by 2020

Auger

- Upgrade of detector array to be operated 2017 – 2025
- Similar event statistics as collected so far
- Composition up to highest e… anisotropy studies
- Stud…

EU…

…ature:

…SO-FF

- KLYPVE EUSO

Interactions

- Support initiatives such as „Physics beyond colliders“

Precise measurements of Auger will shape the future development of the field