

CATCHING THE UNIVERSE'S MOST
ENERGETIC PARTICLES



ULTRA-HIGH ENERGY COSMIC RAYS

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PENN STATE UNIV.

LECTURE 3

LA-CONGA PHYSICS - COURSES 21B

ASTROPARTÍCULAS Y COSMOLOGÍA

July 2023

LAST CLASS' SUMMARY

▶ EXTENSIVE AIR SHOWERS

▶ DETECTION TECHNIQUES

▶ THE PIERRE AUGER OBSERVATORY

TODAY'S PROGRAM

- ▶ MEASUREMENT OF THE COSMIC RAYS SPECTRUM
- ▶ SETTING LIMITS ON PHOTON & NEUTRINO FLUXES
- ▶ CORRELATION WITH NEAR-BY ASTROPHYSICAL SOURCES & INTERPRETATION
- ▶ MEASUREMENT OF THE ELONGATION RATE
- ▶ LOOKING AT THE BIG (BROKEN?) PICTURE
- ▶ FUTURE DETECTORS & UPGRADES

Summary of Auger Results

- The energy spectrum exhibits the ankle and the existence of a GZK-like flux suppression.
- At energies above 60 EeV the arrival directions of cosmic rays become anisotropic. In addition, a correlation between the arrival directions and Active Galactic Nuclei (AGN) listed in the Veron-Cetty and Veron catalogue has been found.
- There is no evidence for significant excess of cosmic ray arrival directions from the galactic center, for clustering on different angular scales at the highest energies and for correlations with BL Lac objects.
- We can infer the primary particle composition from the dependence of X_{max} on energy (the elongation rate), yielding a significant change from 'heavy' at 10^{18} eV to 'light' at $\geq 10^{19}$ eV.
- The photon fraction is less than 2 percent above 10^{19} eV with 95% confidence level; this limit restricts the so-called top-down, non-acceleration models for the origin of the most energetic particles.
- The Auger Observatory is sensitive to neutrinos in the EeV range and has set the currently best limit on the diffuse tau neutrino flux in this range as $E_\nu^2 dN_{\nu\tau}/dE_\nu < 1.3 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

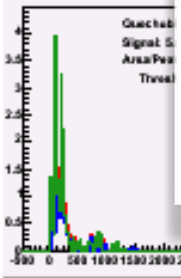
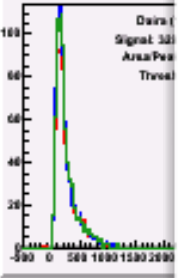
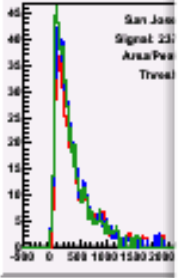
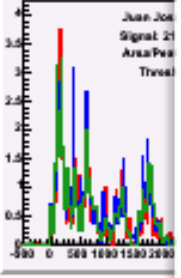
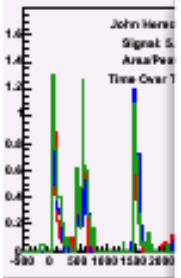
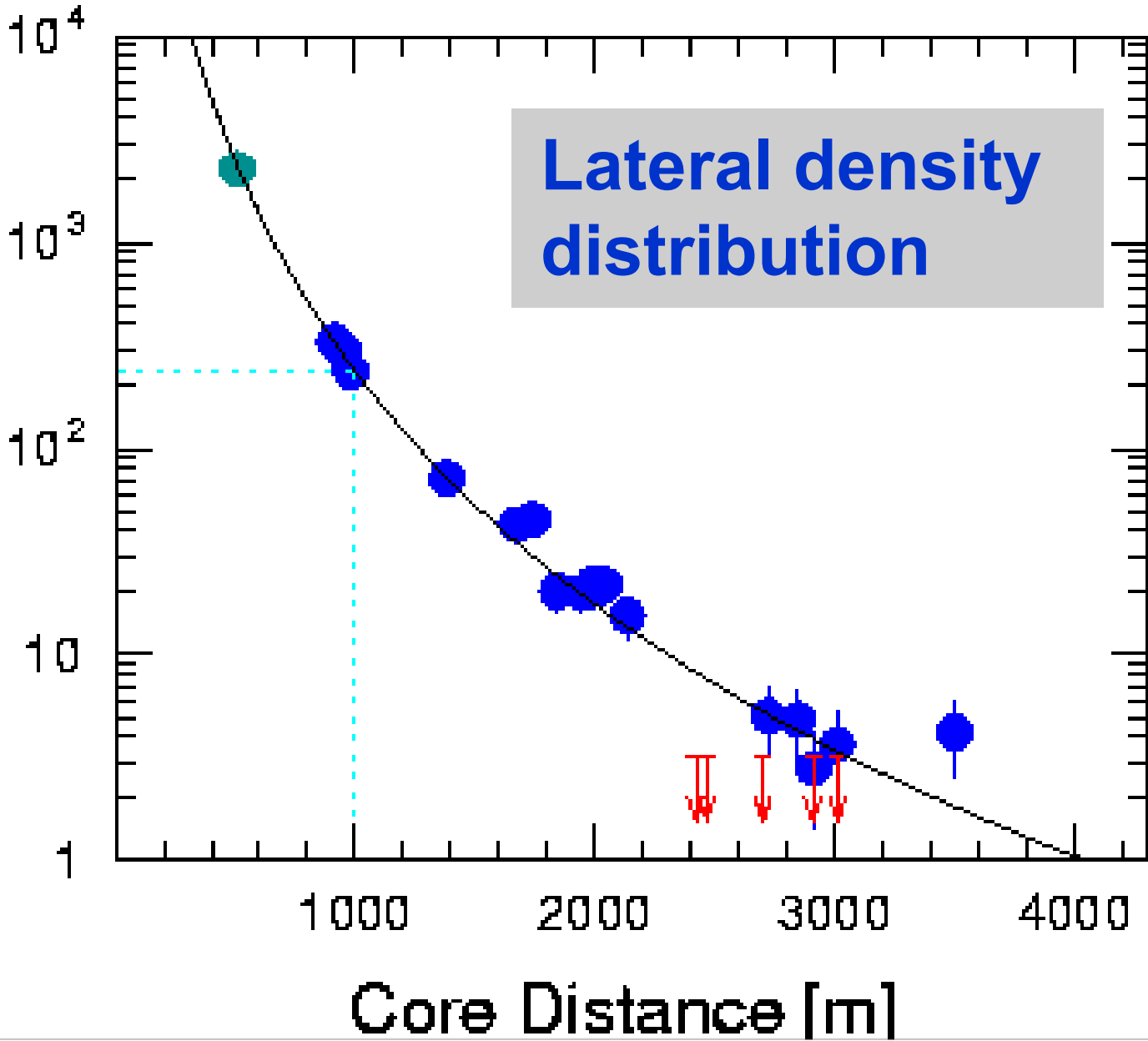
ENERGY

ENERGY SPECTRUM

ID 762238

Signal Size [VEM]

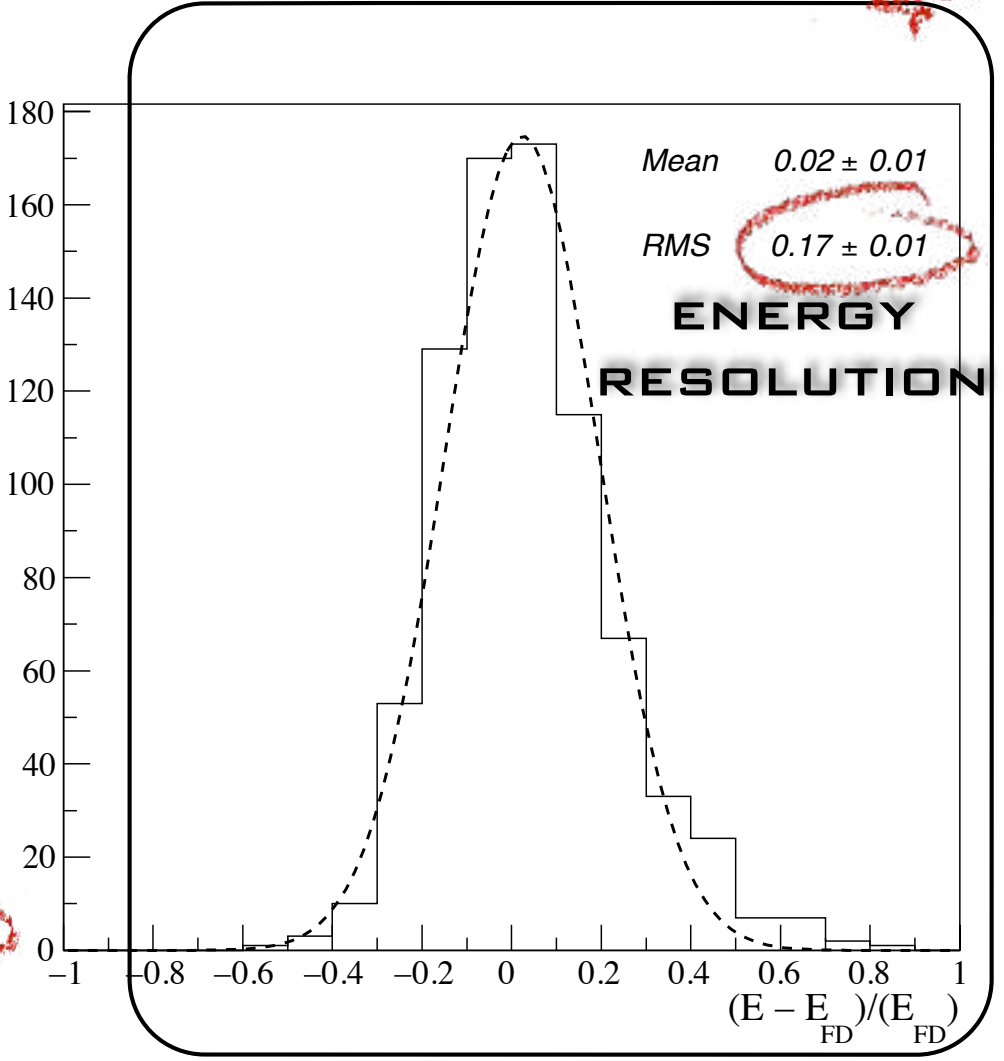
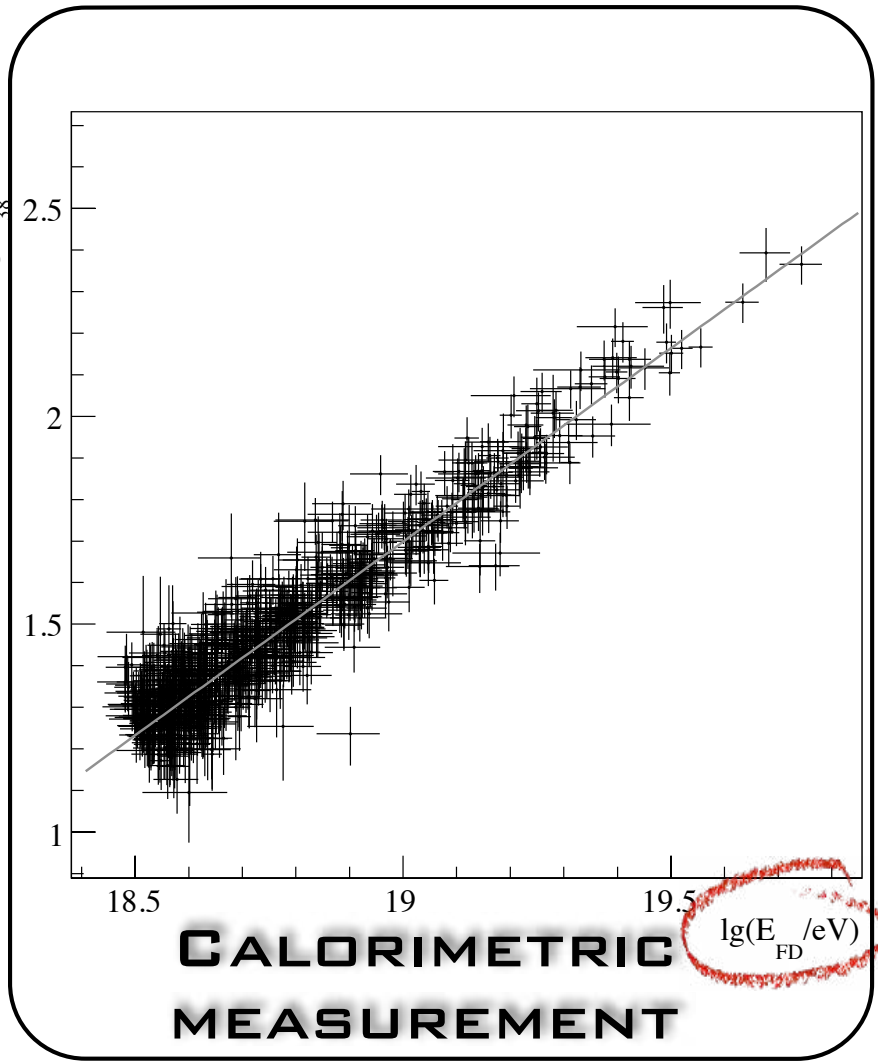
Lateral density distribution



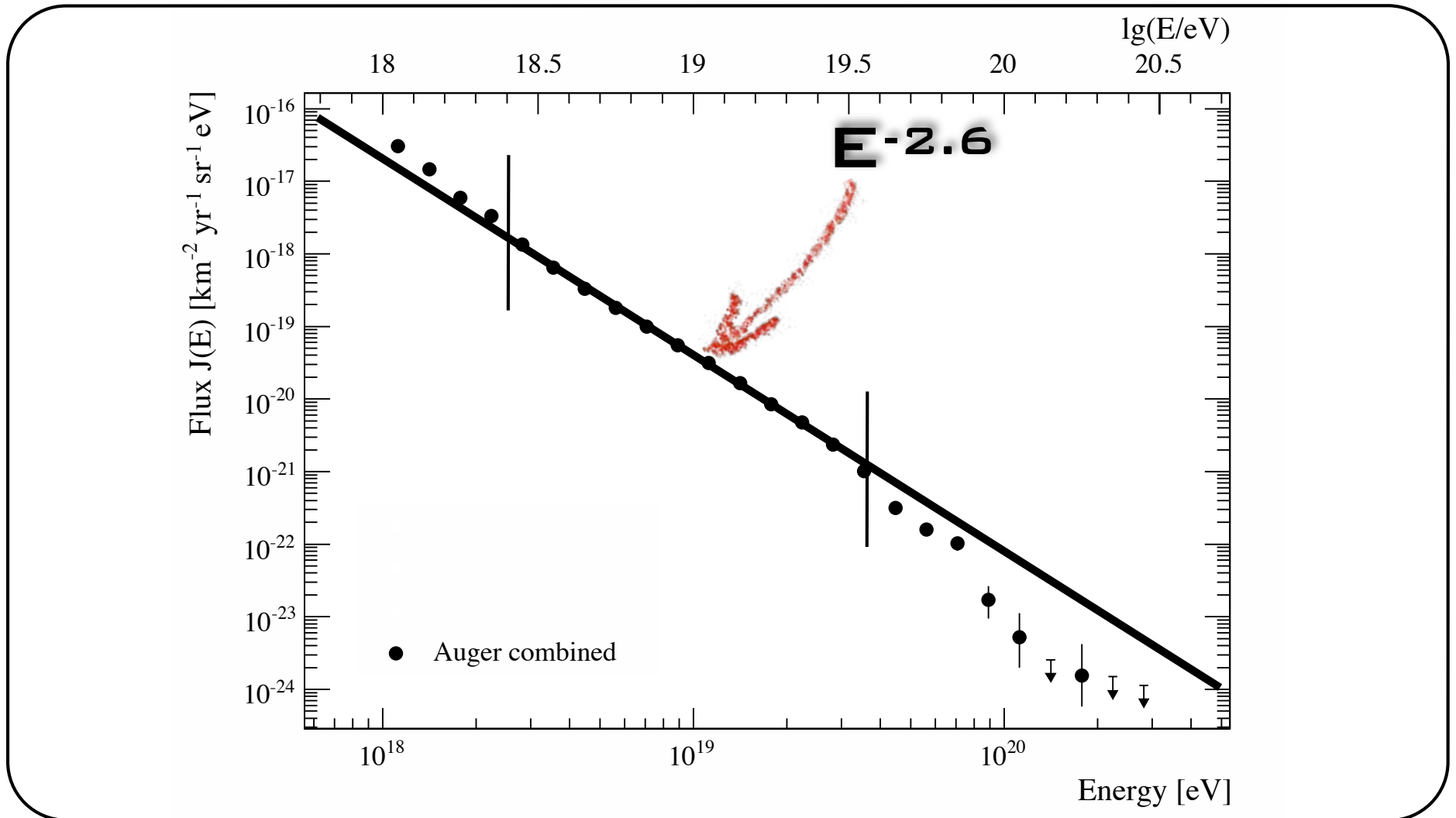
ENERGY MEASUREMENT

THE ABSOLUTE ENERGY SCALE IS DETERMINED FROM DATA.

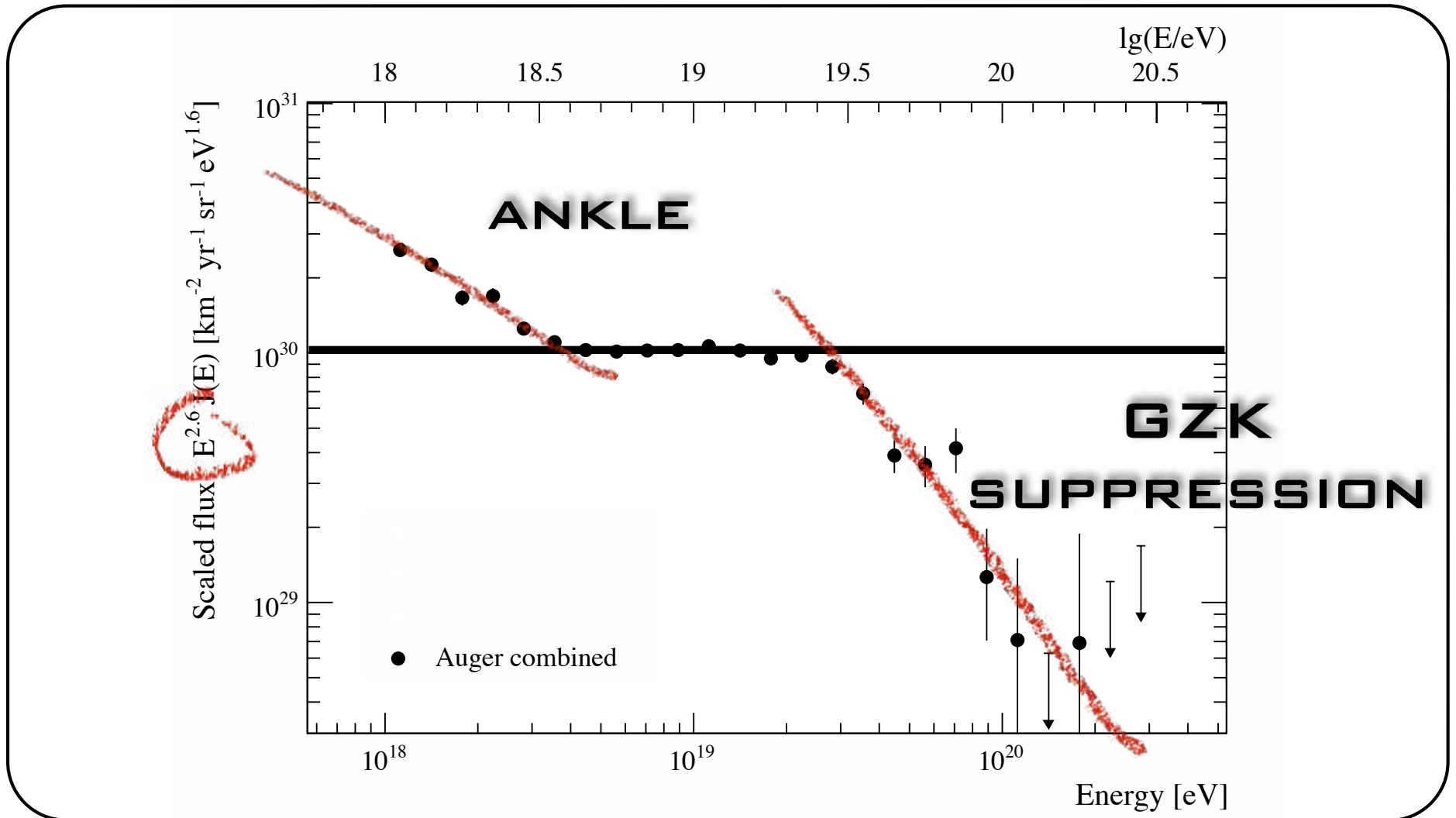
SIGNAL IN THE SURFACE DETECTORS
 $\lg(S_{38}/V_{EM})$



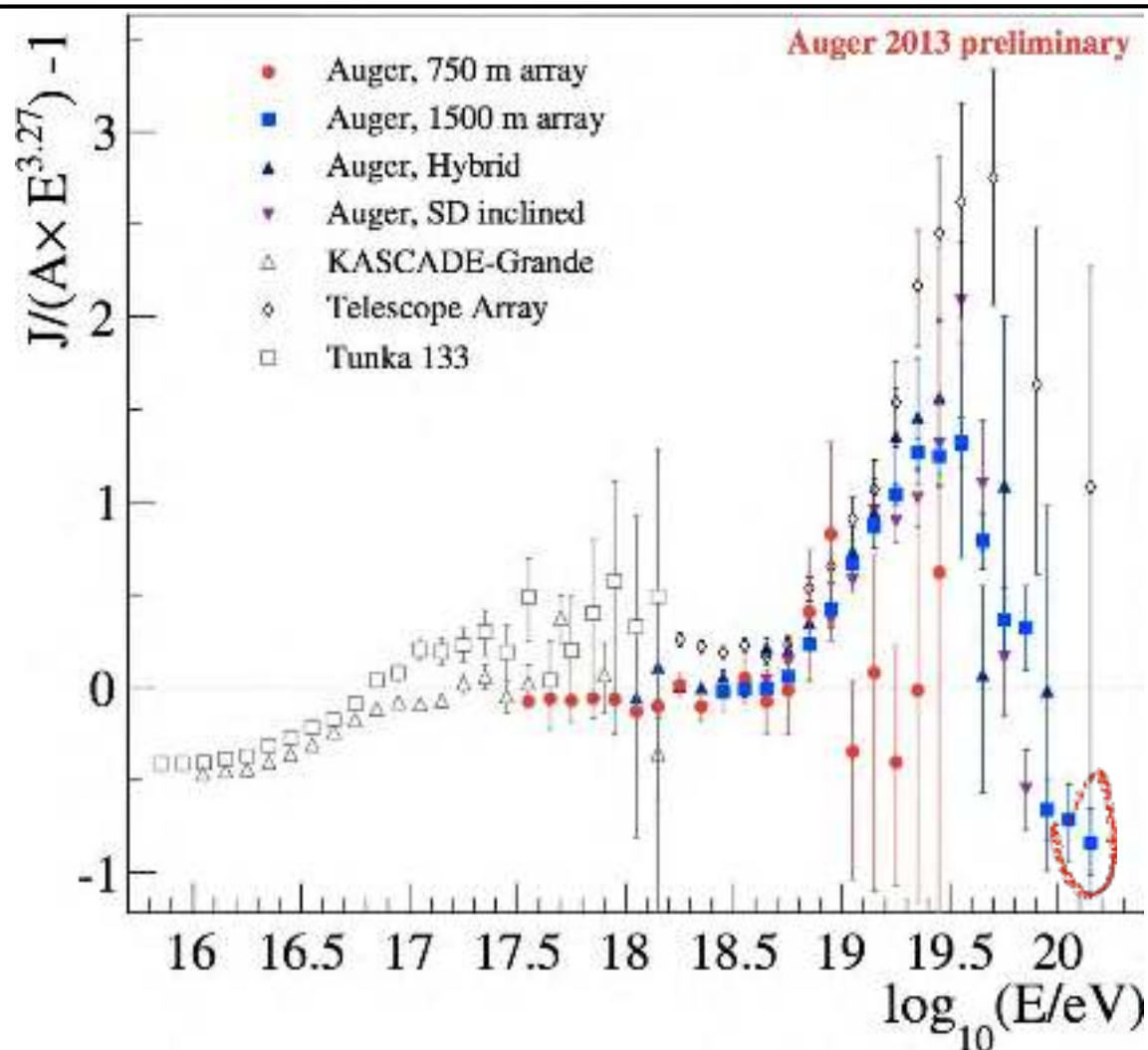
CR ENERGY SPECTRUM



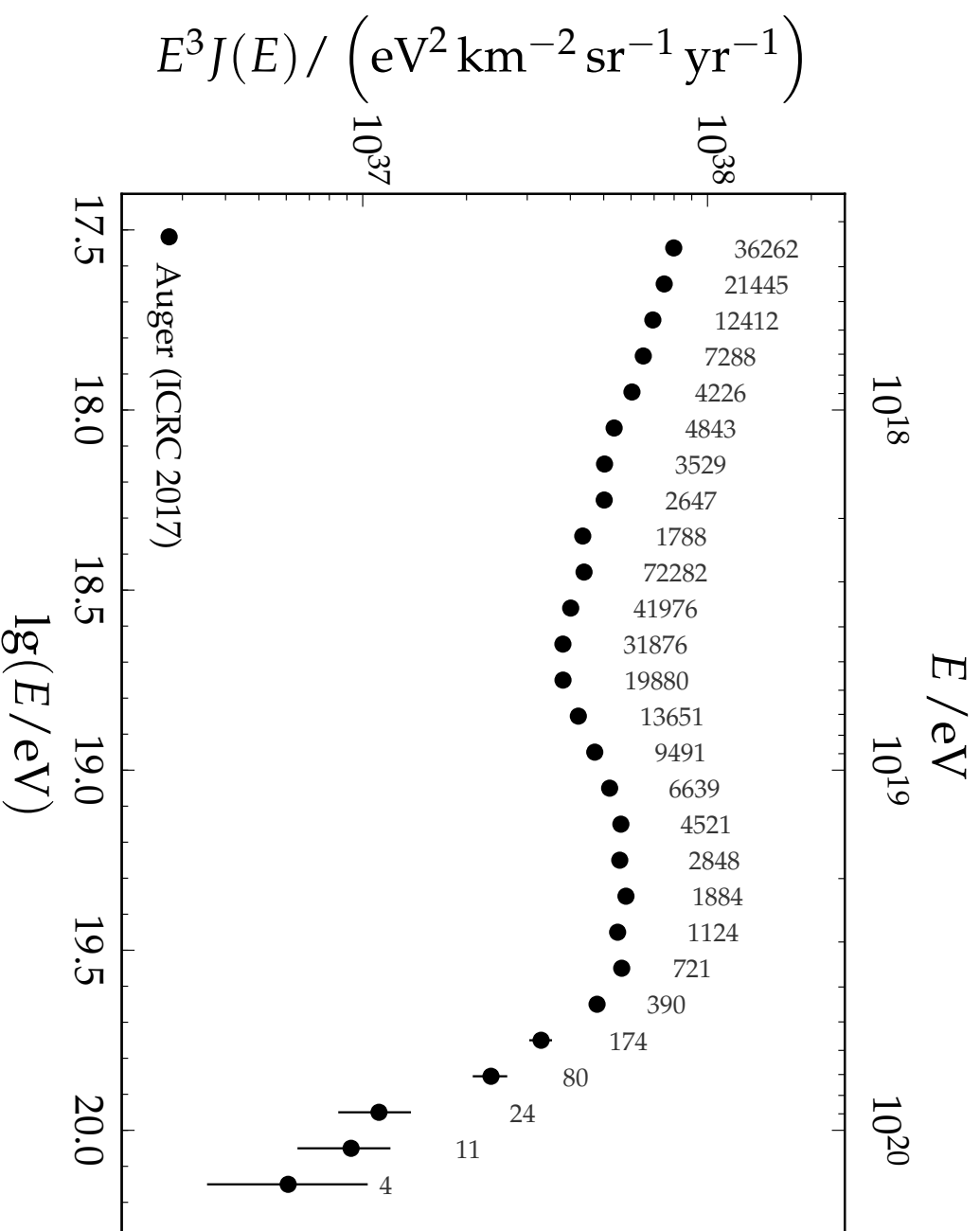
CR ENERGY SPECTRUM



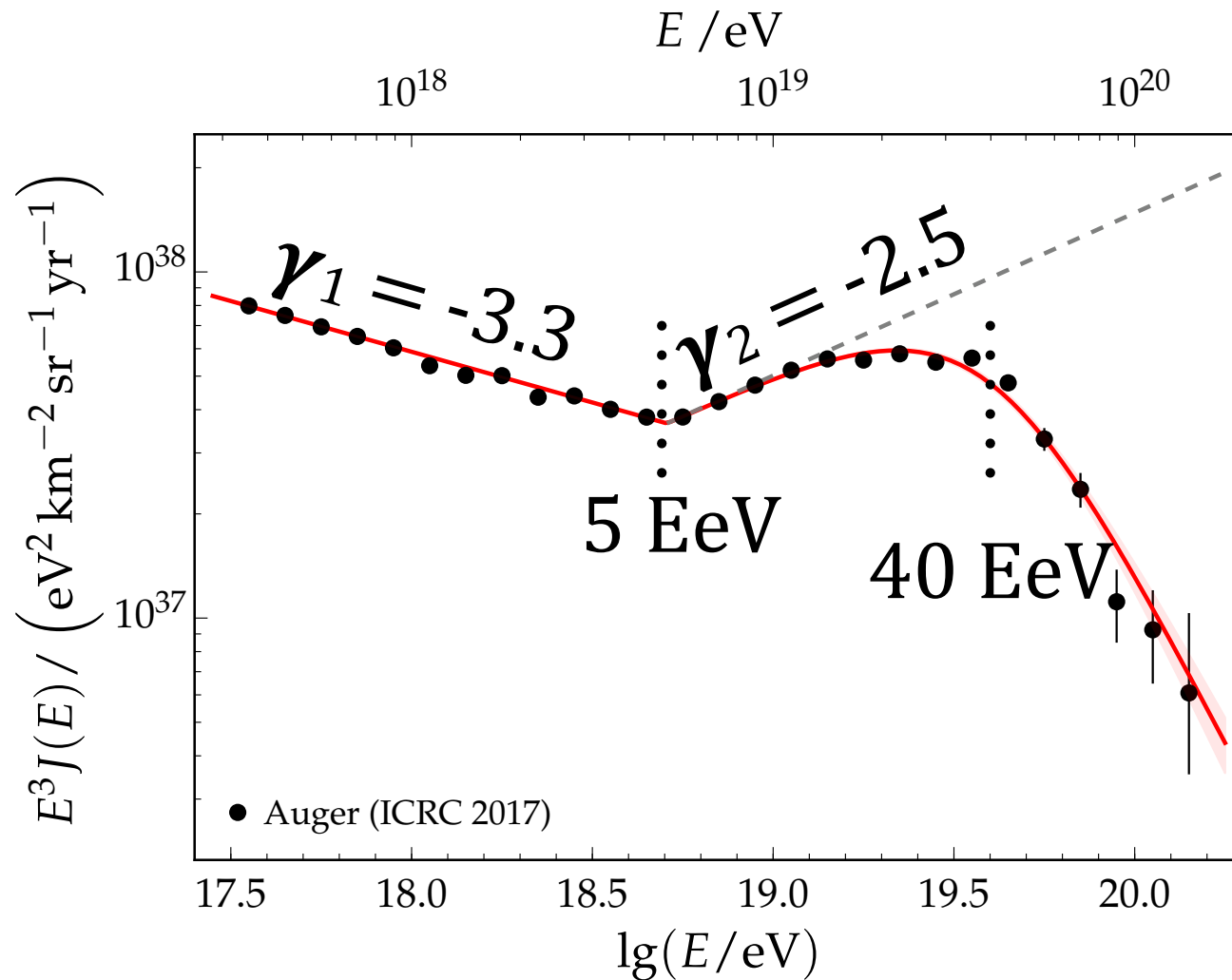
STATS @ THE HIGHEST E



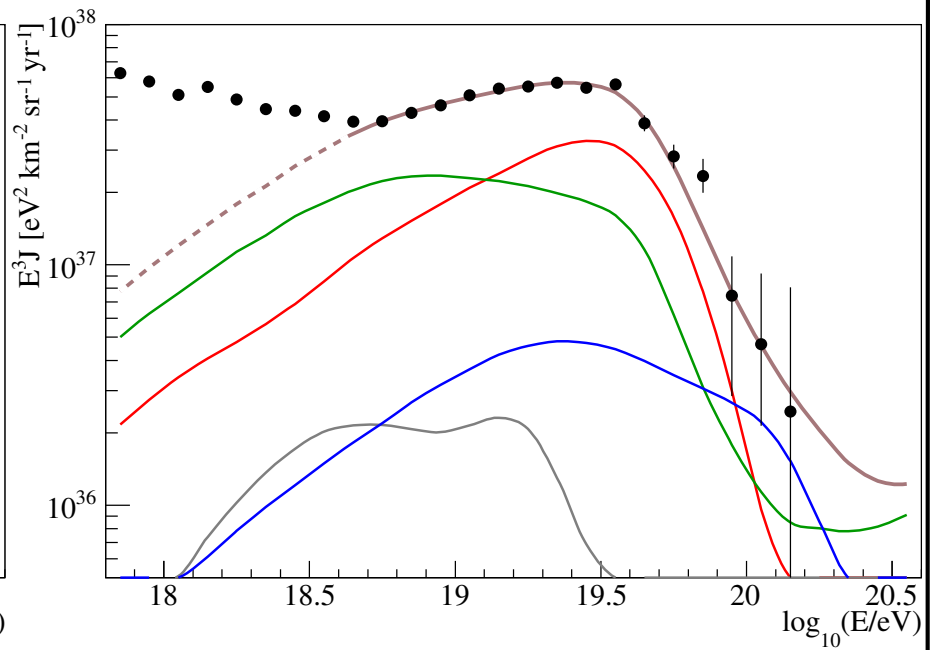
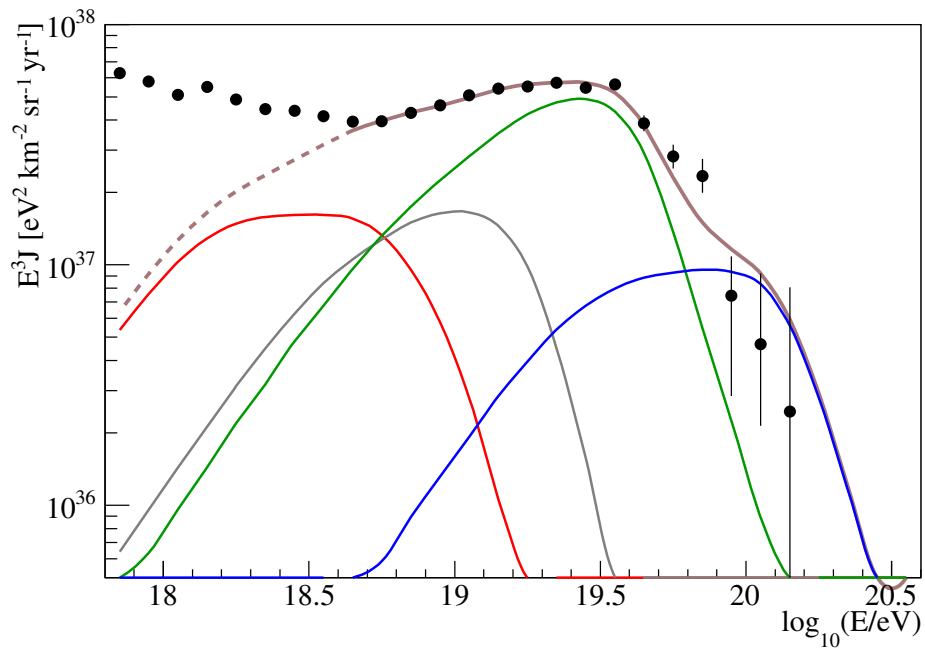
UHECR SPECTRUM



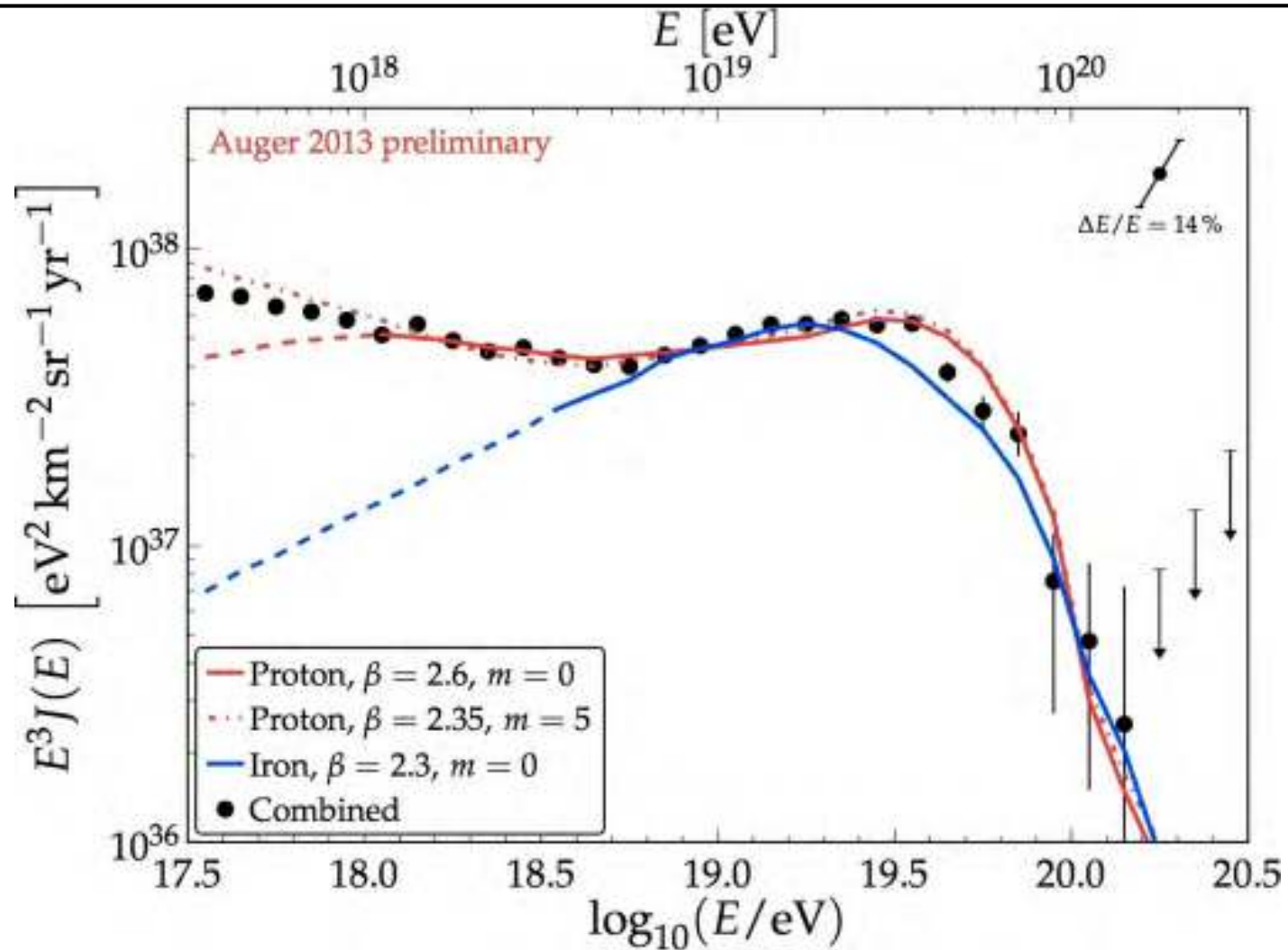
UHECR SPECTRUM



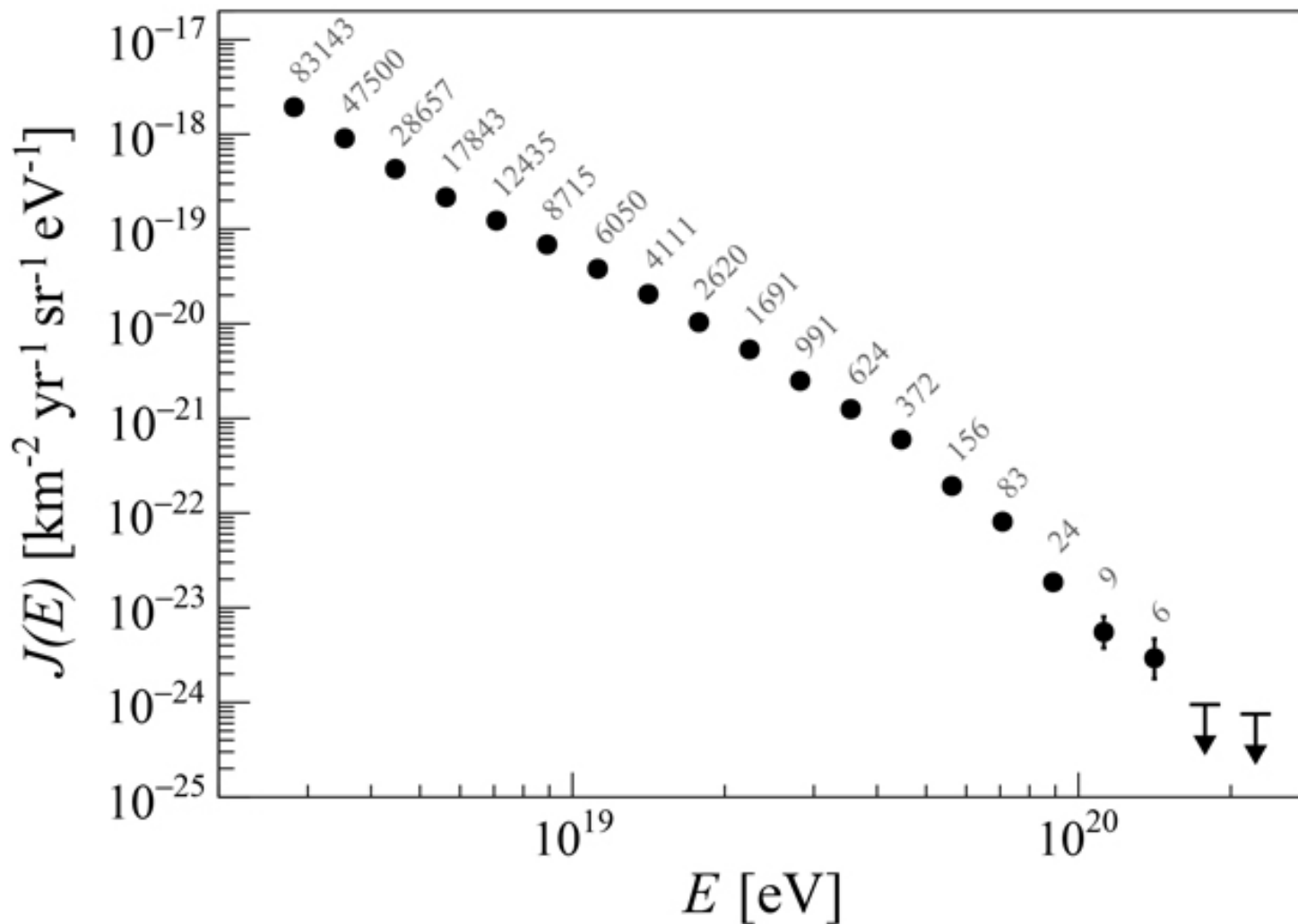
FITTING THE SPECTRUM



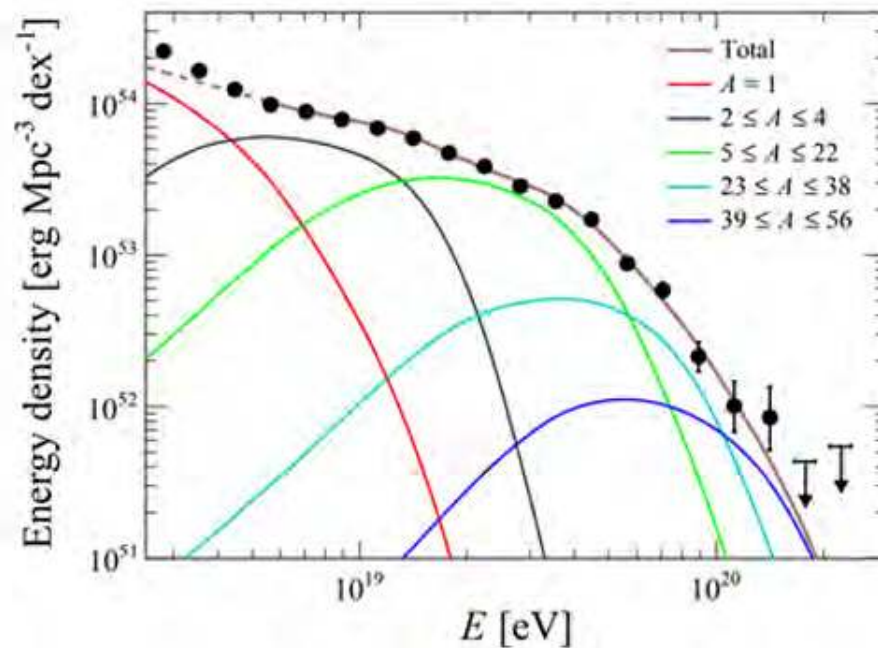
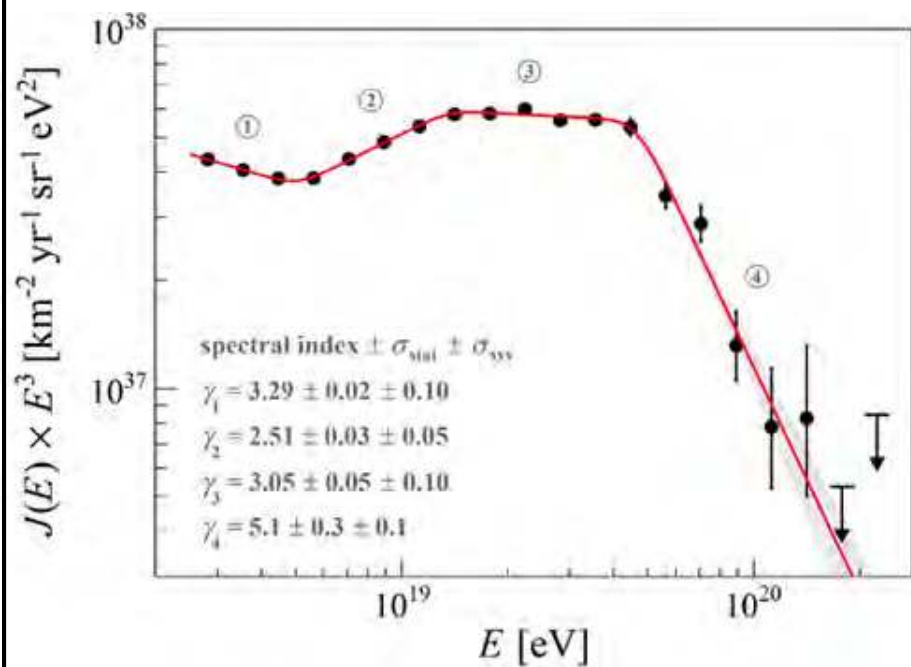
TAKE HOME MESSAGE



LATEST RESULT



LATEST RESULT

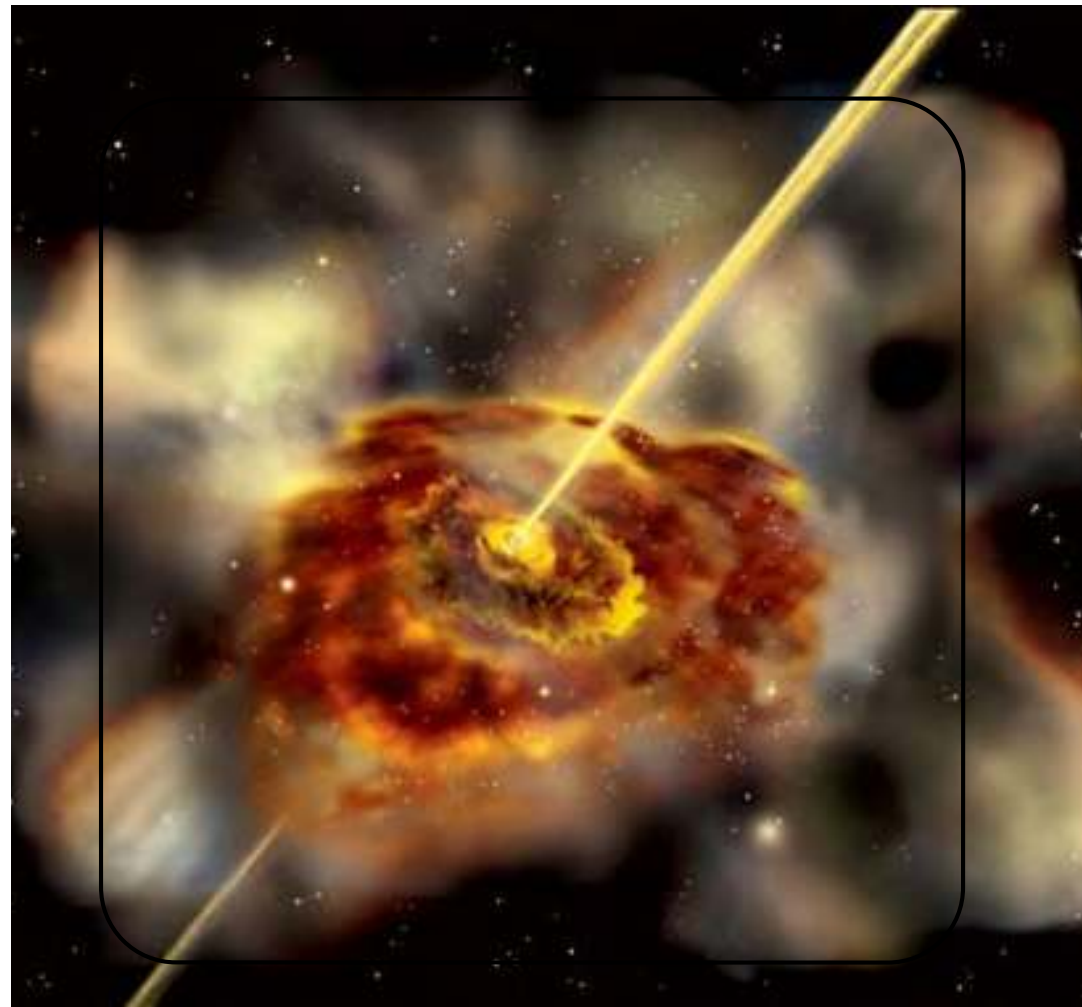


ANISOTROPY

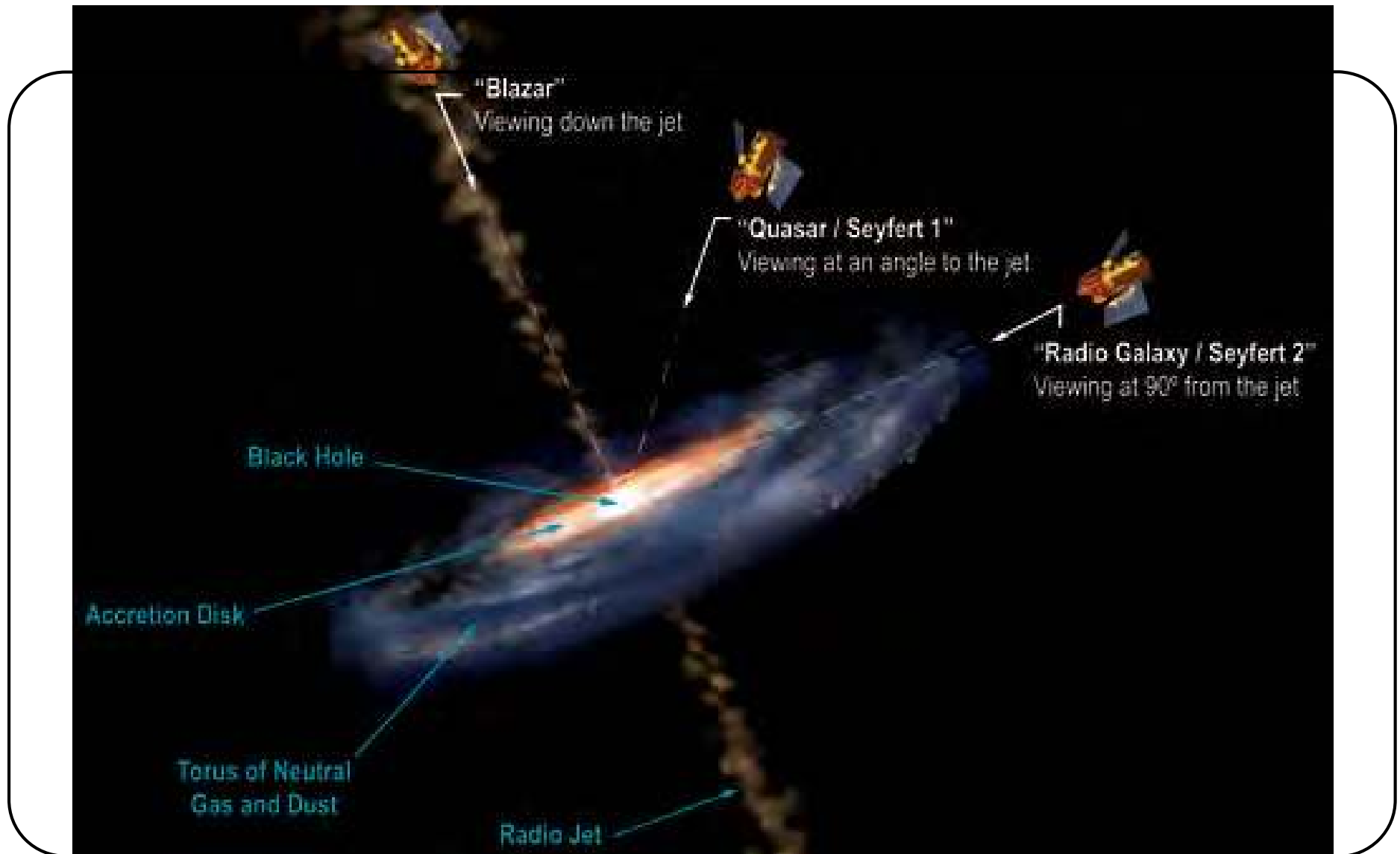
SEARCHING FOR “SOURCE(S)”

WHY LOOK @ AGN?

▶ ARTIST'S IMPRESSION
OF AN AGN

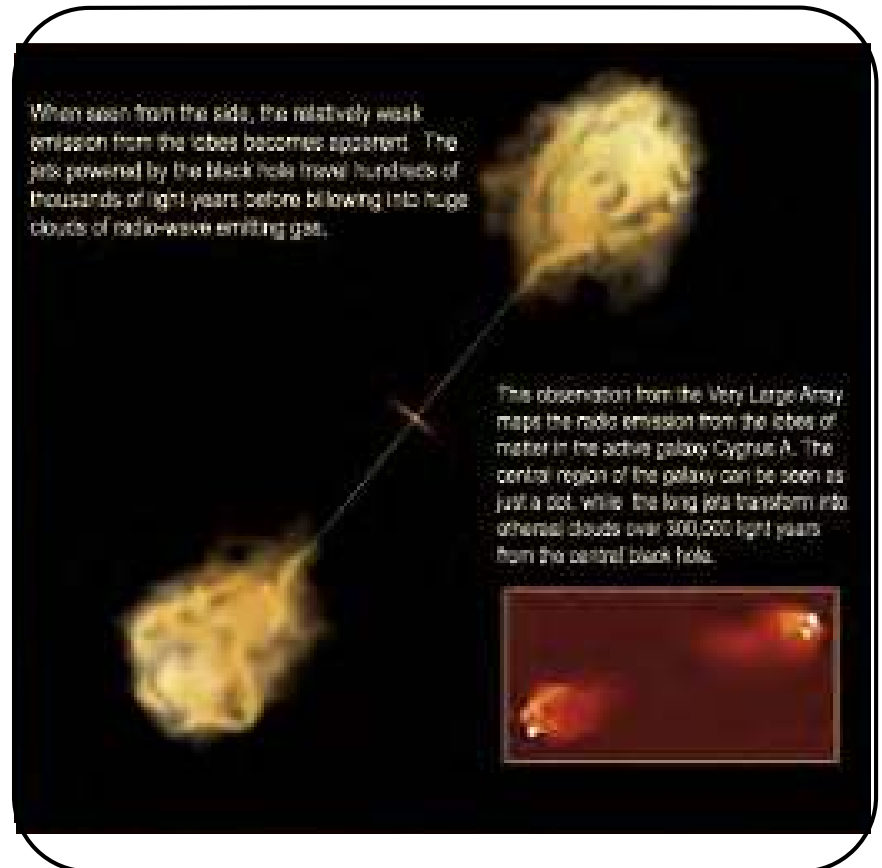


ACTIVE GALAXIES



POINTS OF VIEW...

- ▶ **DIFFERENT ANGLES ON A GALAXY WITH JETS:**
 - ▶ **VIEWING DOWN THE JET**
 - ▶ **VIEWING AT AN ANGLE**
 - ▶ **VIEWING AT 90 DEGREES FROM THE JET**



CENTAURUS A



Credits

X-ray

NASA/CXC/M. Karovska et al.

Radio 21-cm image

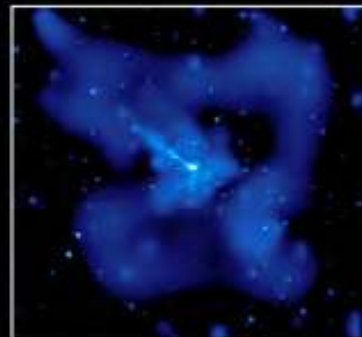
NRAO/AUI/NSF/J. Van Gorkom/
Schminovich et al.

Radio continuum image

NRAO/AUI/NSF/J. Condon et al.

Optical

Digitized Sky Survey U.K. Schmidt
Image/STScI



CHANDRA X-RAY



DSS OPTICAL



NRAO RADIO
CONTINUUM



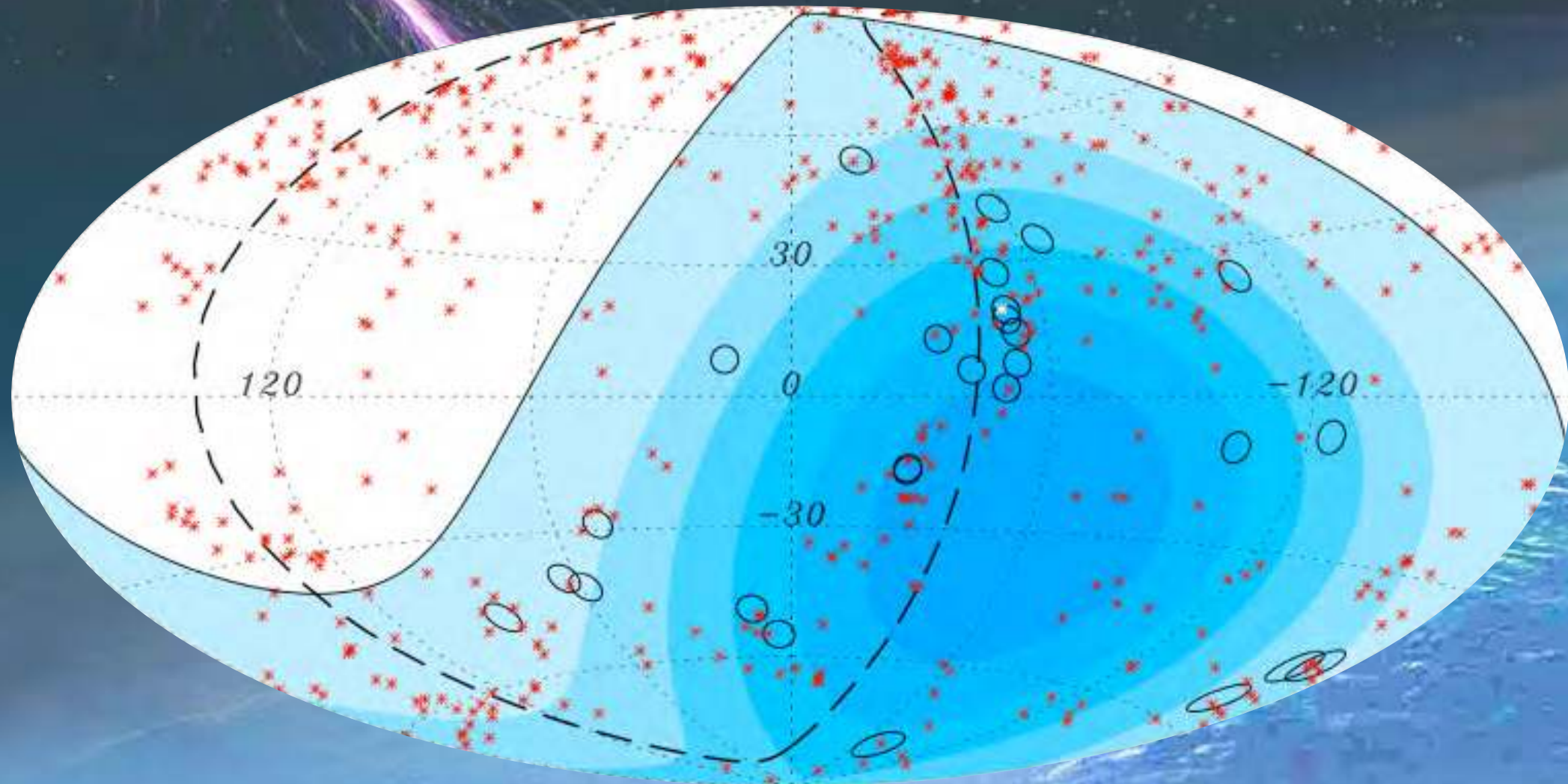
NRAO RADIO
(21-CM)

Pierre Auger Observatory

studying the universe's highest energy particles

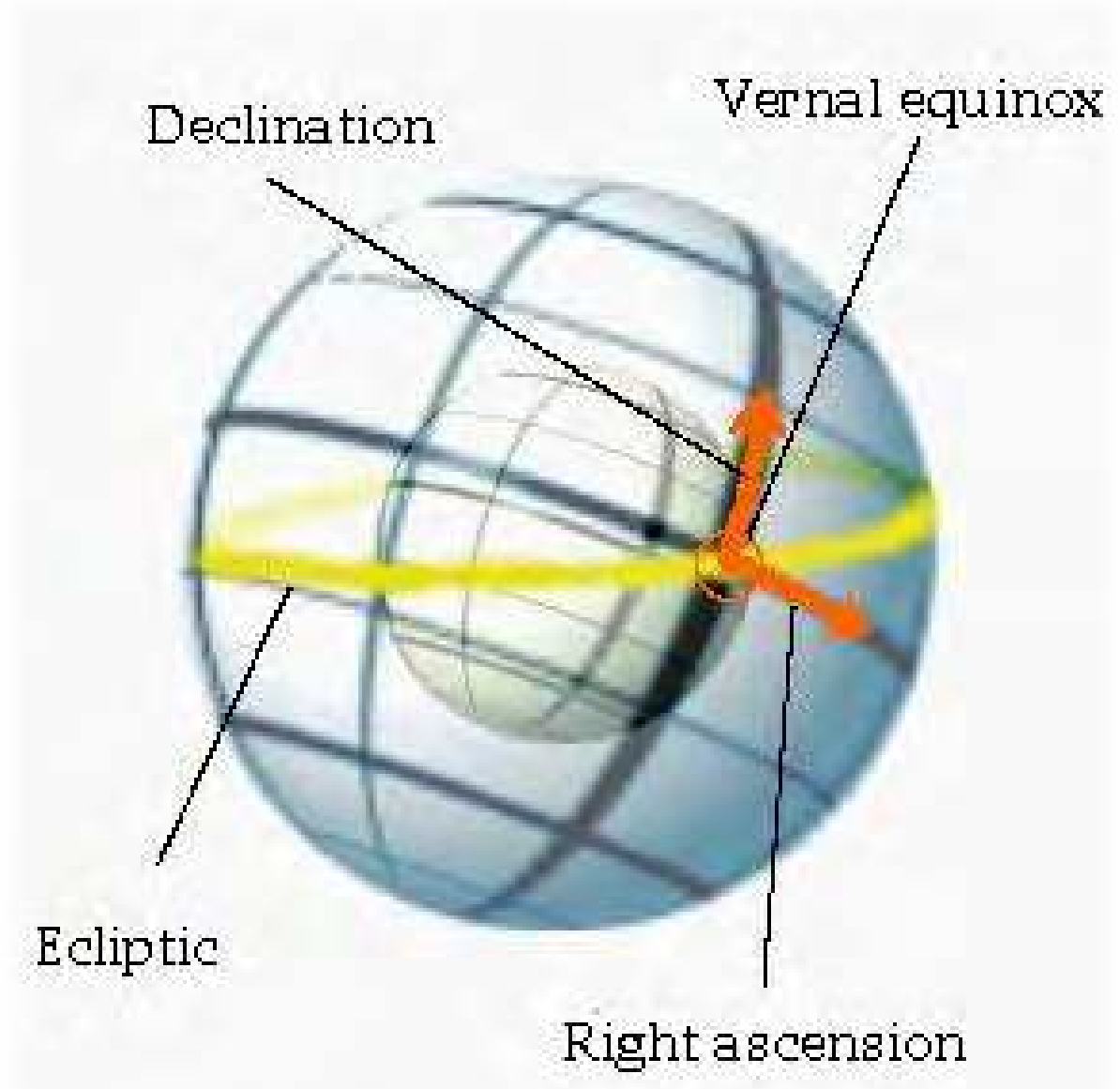


PIERRE AUGER COLLABORATION SCIENCE 318 (2007) 939



COORD. SYSTEM

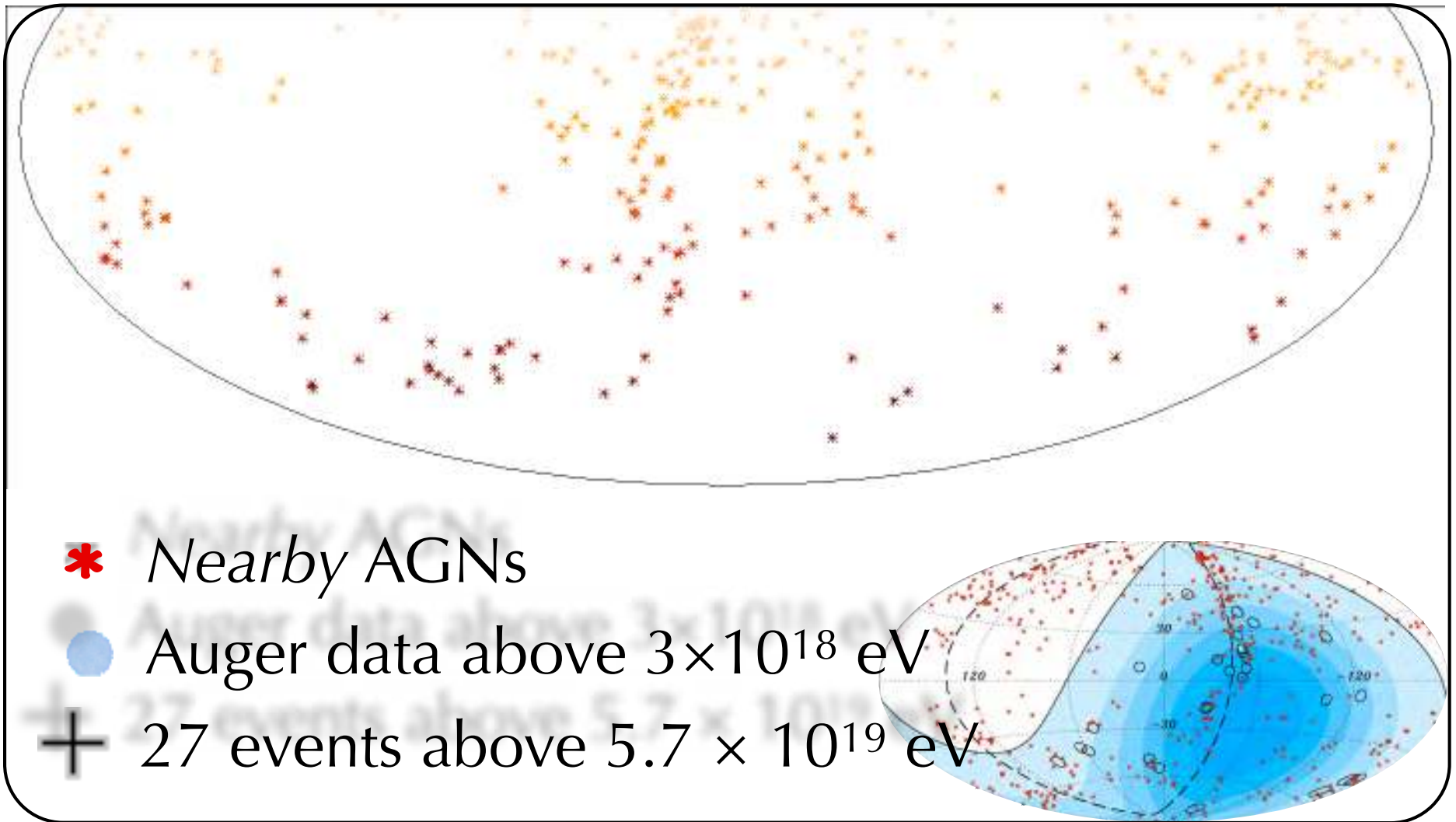
► CHANGE TO
EQUATORIAL
COORDINATES



EQUAL AREA MAP (MOLLWEIDE)

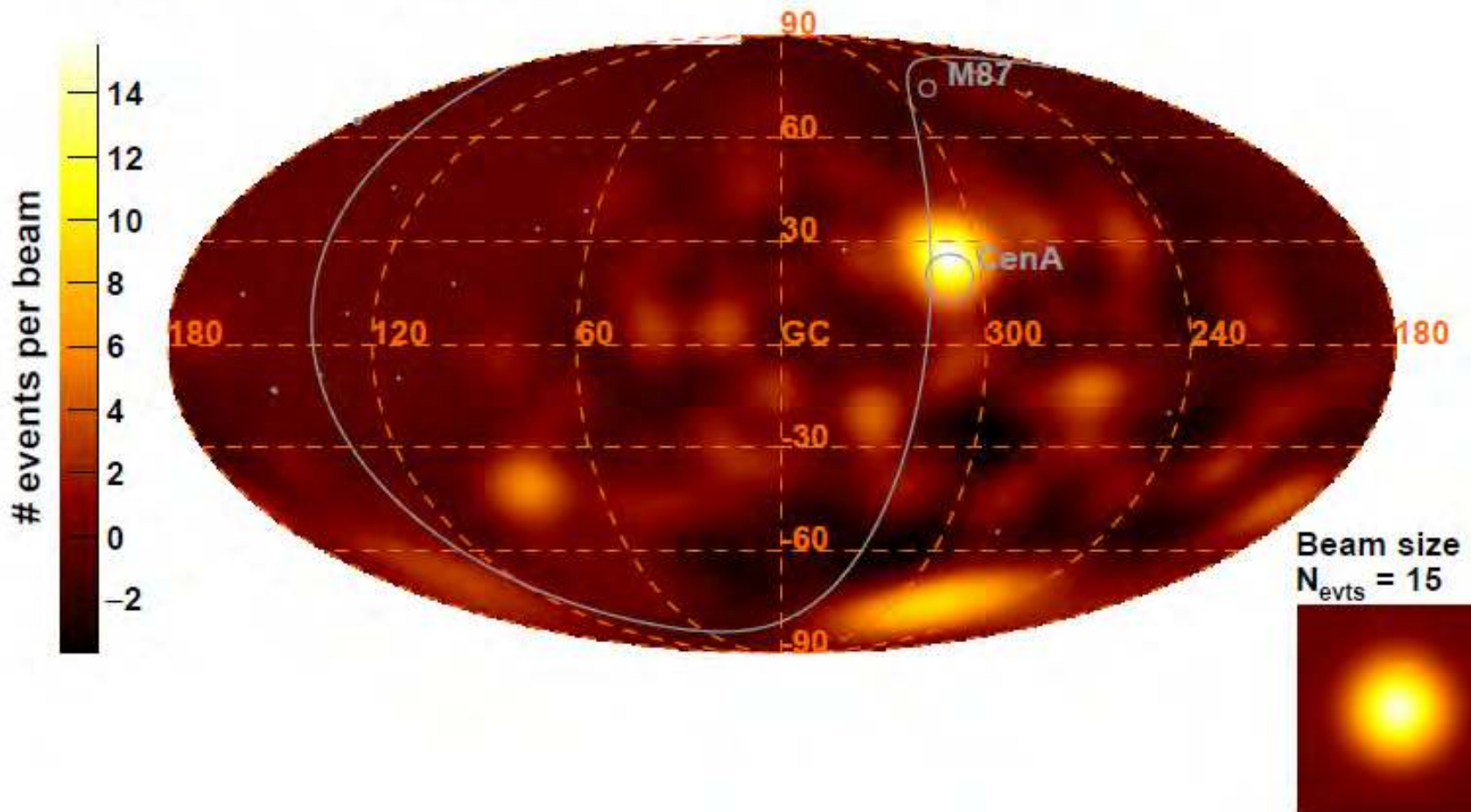


CORRELATION



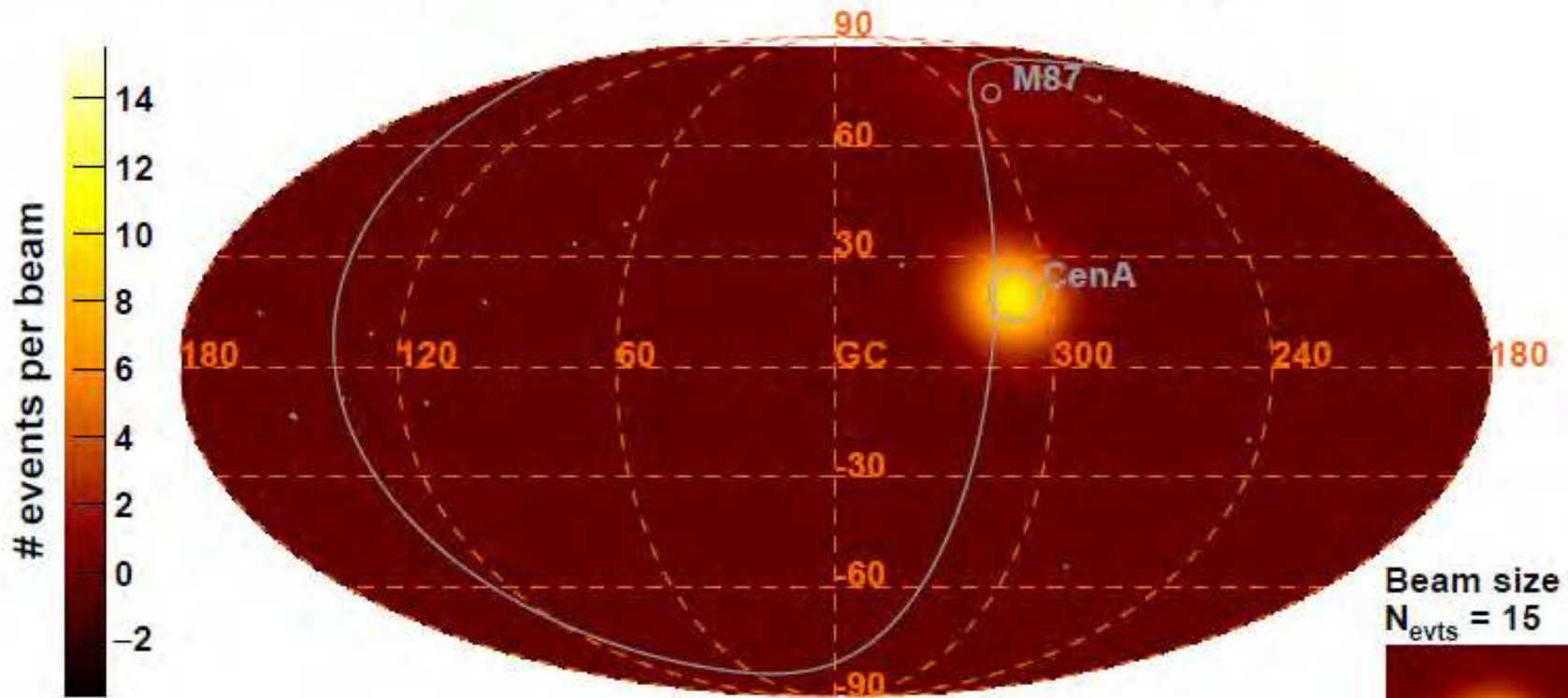
“SMALL” SCALES

Observed Excess Map - $E > 60$ EeV



“SMALL” SCALES

Model Excess Map - Active galactic nuclei - $E > 60$ EeV



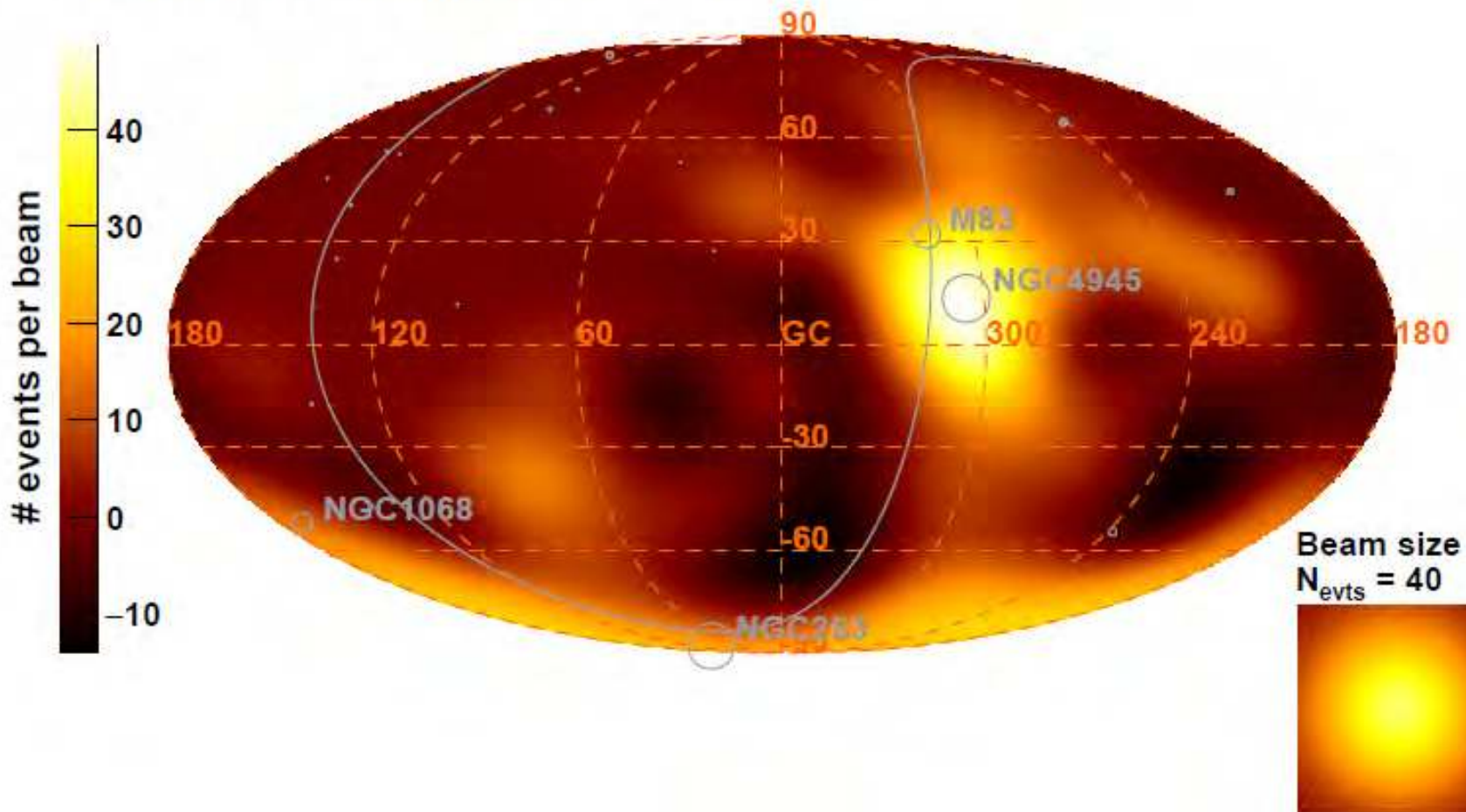
$$f = 7\%; \psi = 7^\circ$$

“pre-trial” p-value = 5×10^{-4}

“post-trial” significance = 2.7σ

“SMALL” SCALES

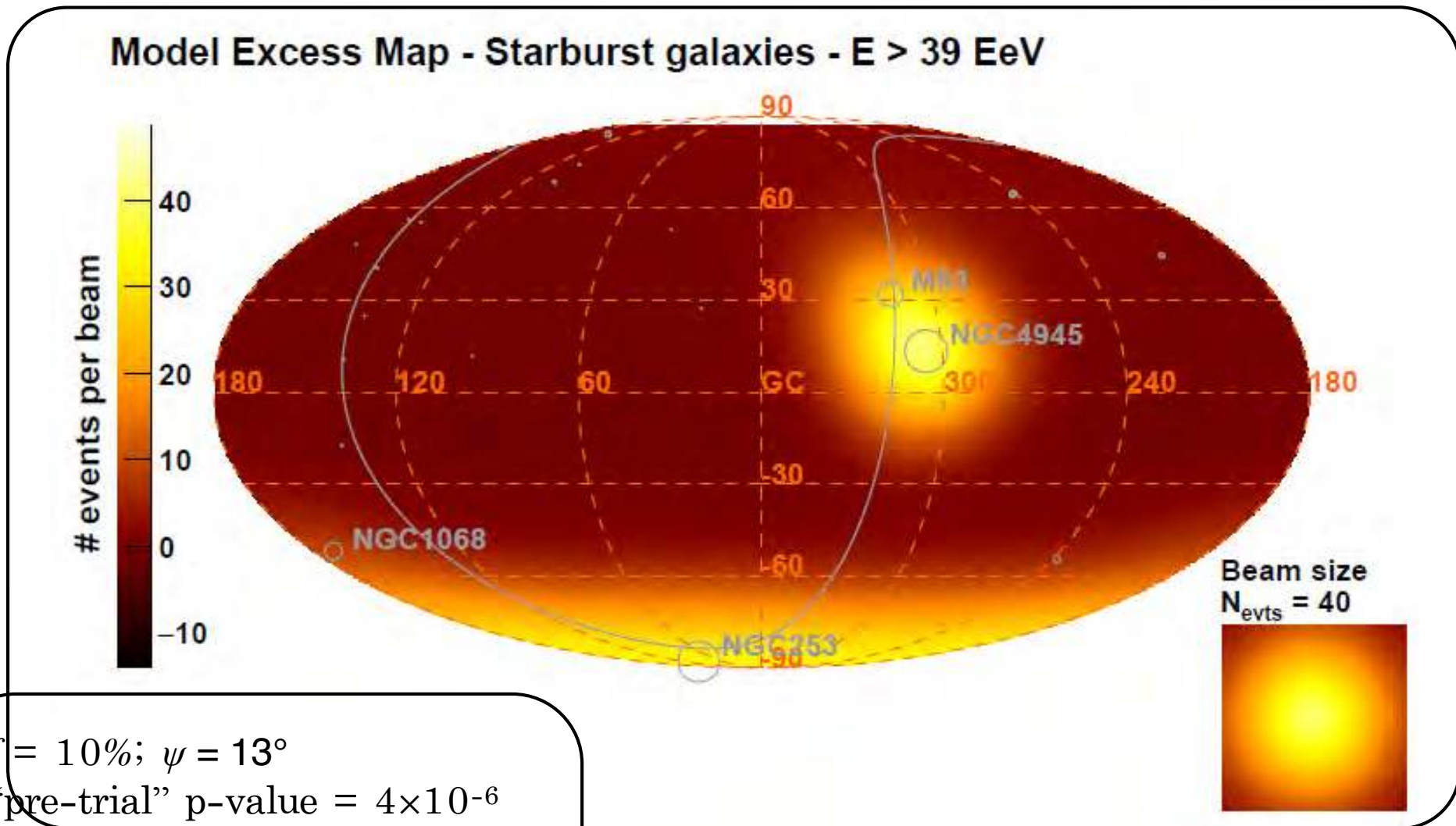
Observed Excess Map - $E > 39$ EeV



Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources

The Pierre Auger Collaboration, The Astrophysical Journal Letters 853 (2018) L29

“SMALL” SCALES

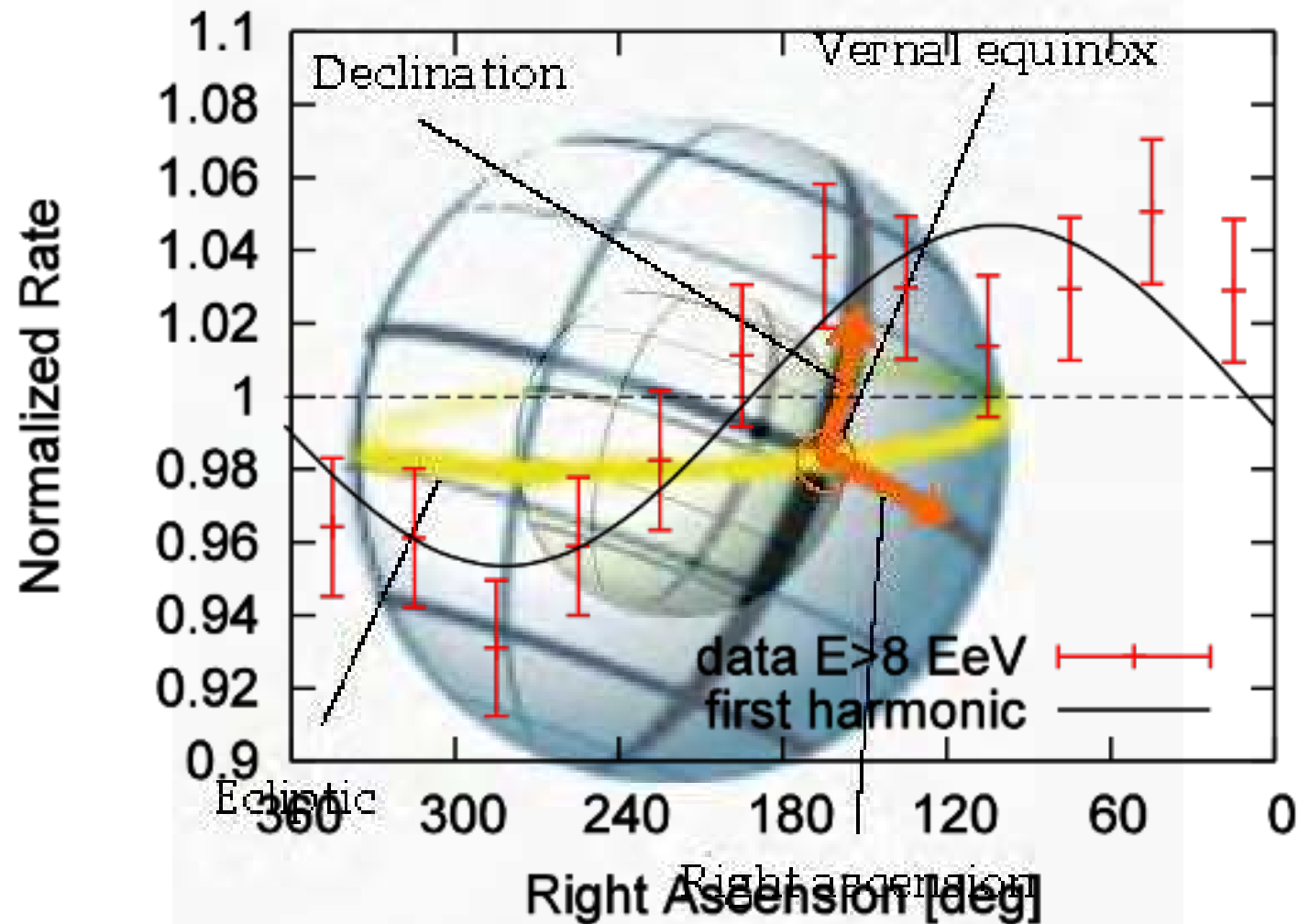


$$f = 10\%; \psi = 13^\circ$$

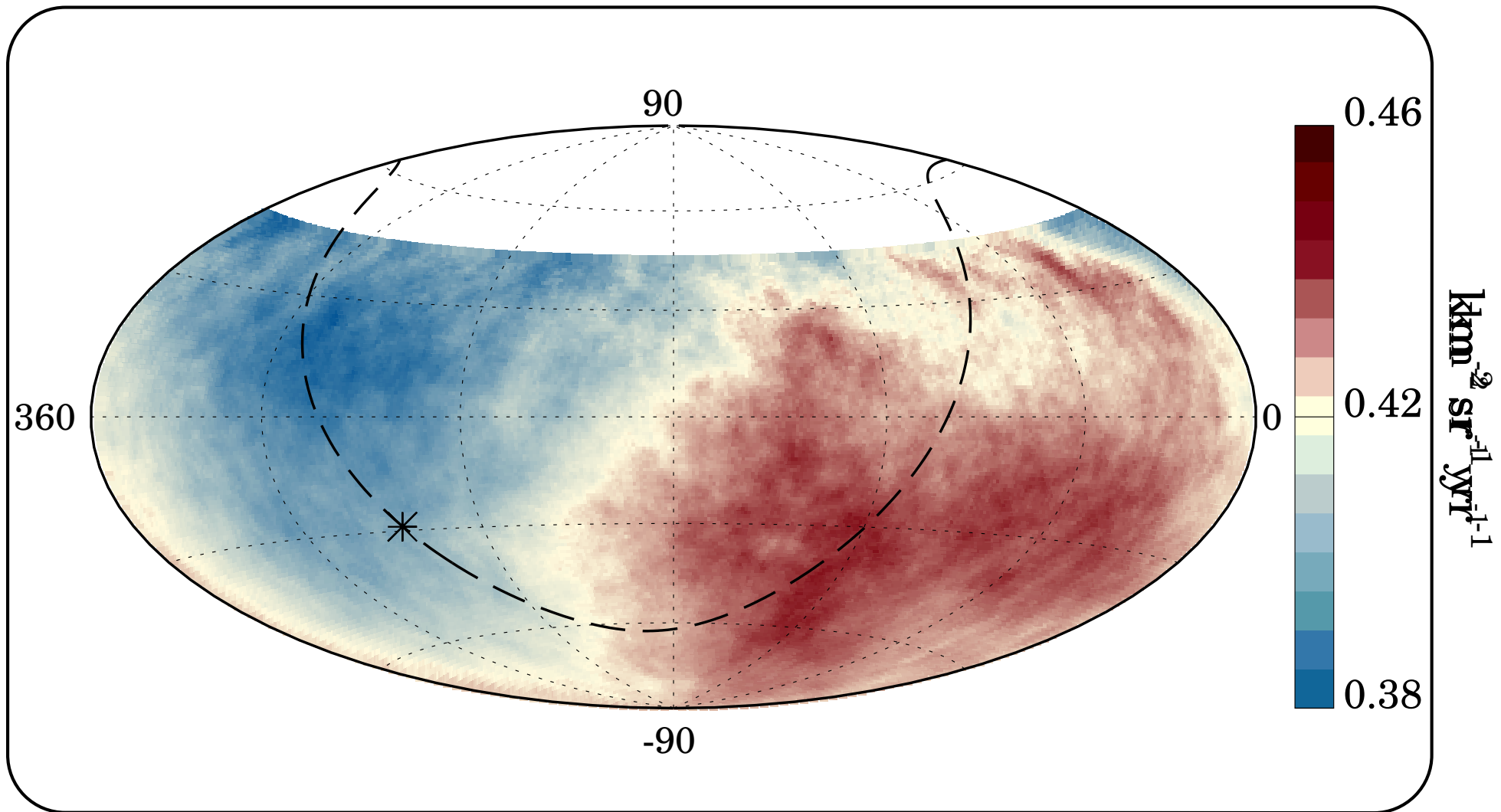
“pre-trial” p-value = 4×10^{-6}

“post-trial” significance = 3.9σ

LARGE SCALES

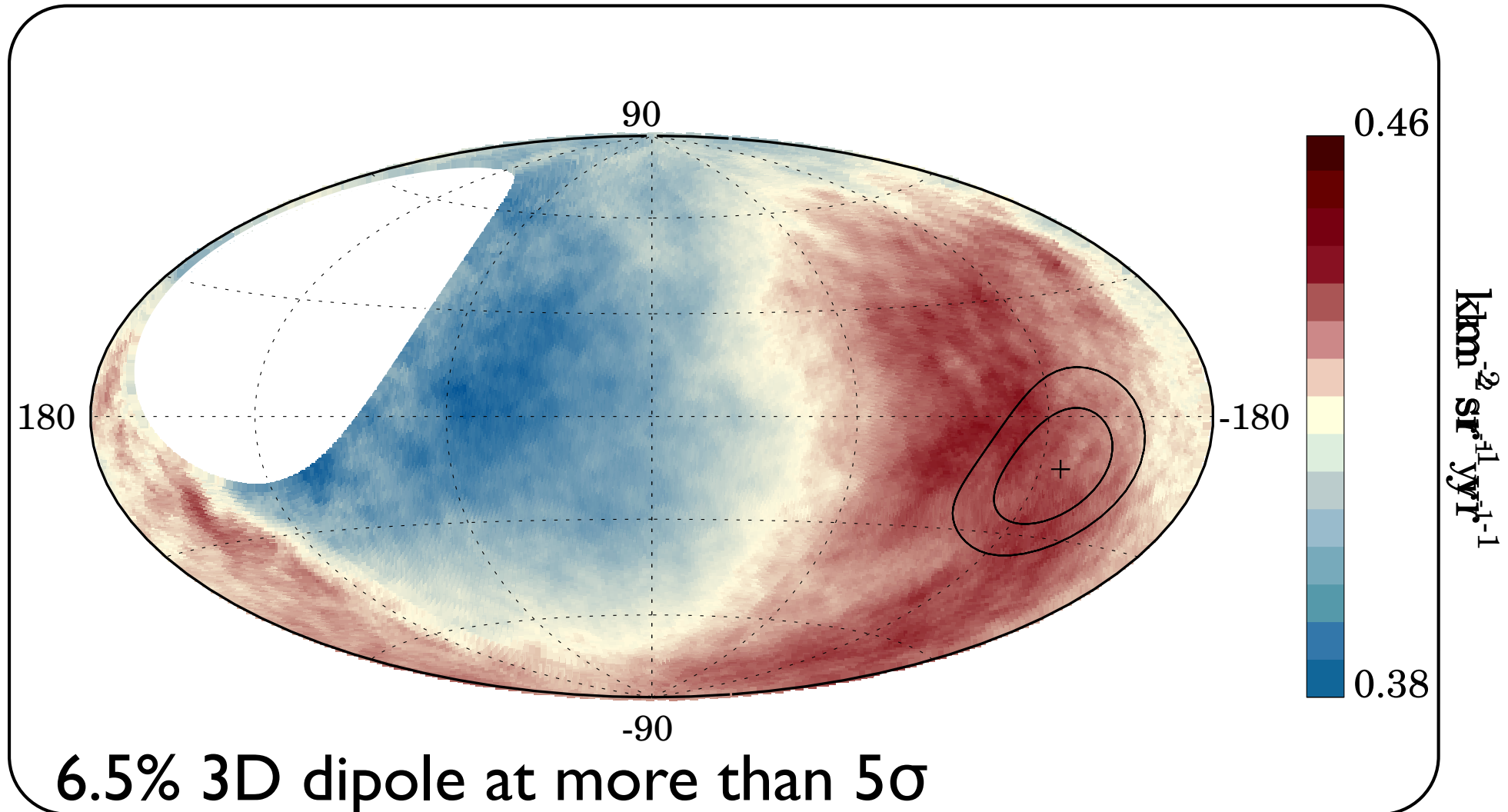


LARGE SCALES



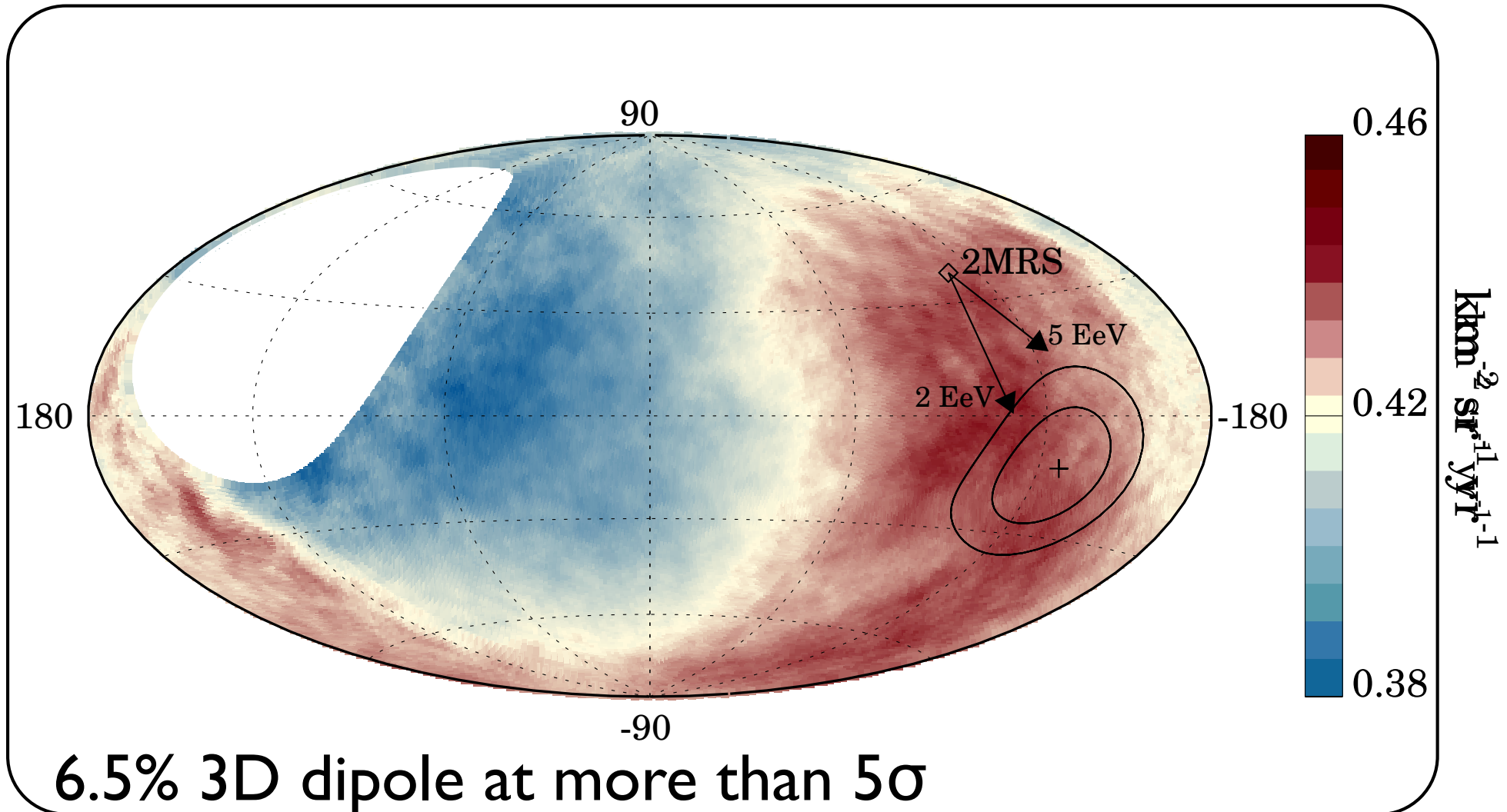
LARGE SCALES

Galactic coordinates

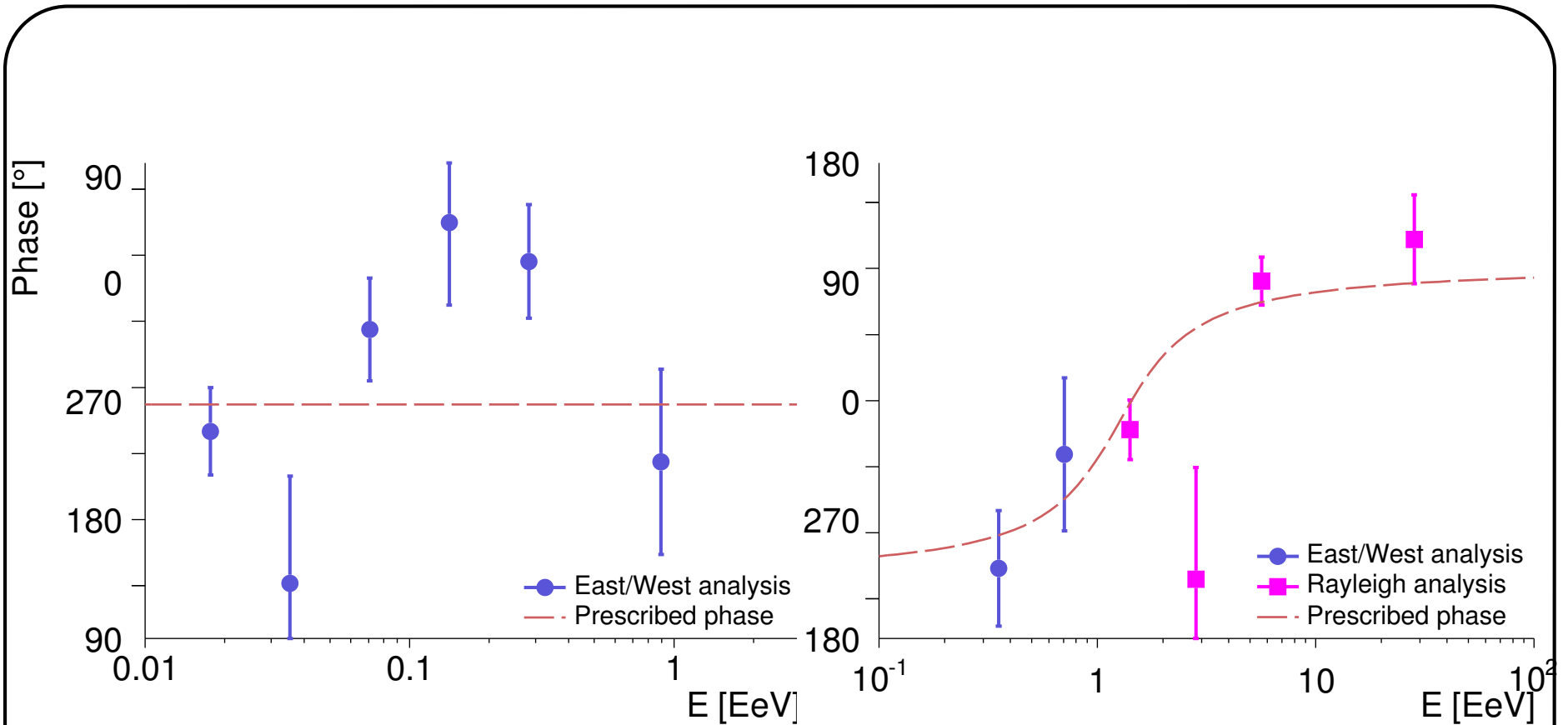


LARGE SCALES

Galactic coordinates

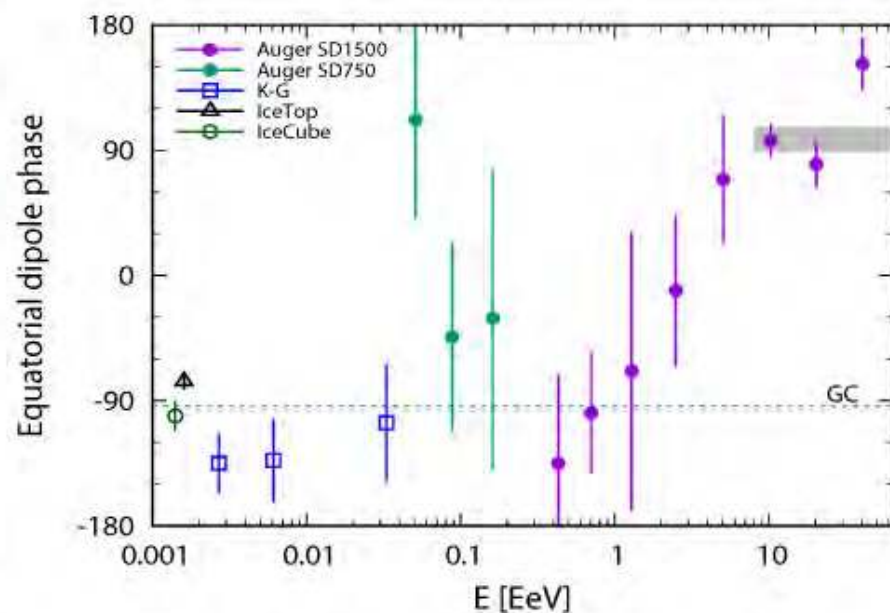
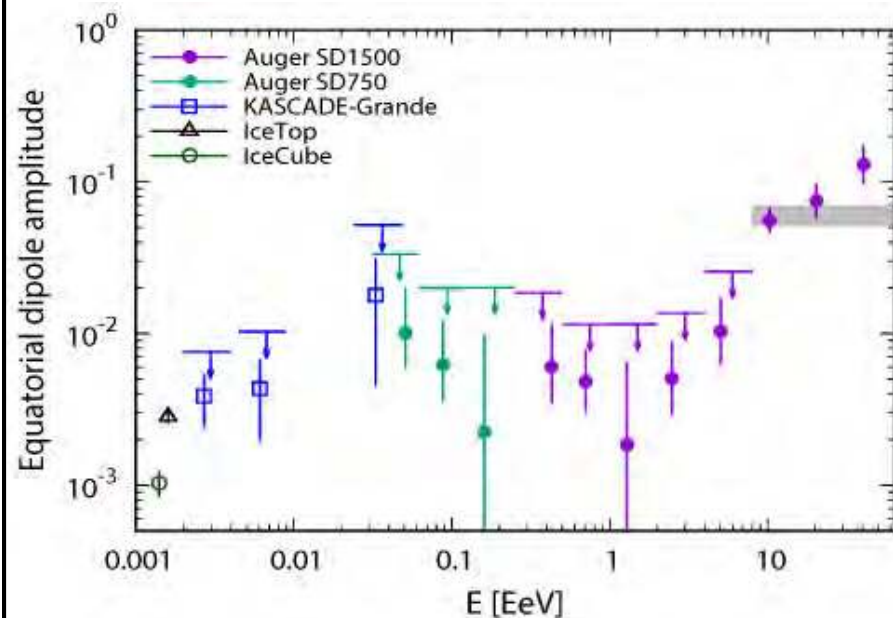


LARGE SCALES



6.5% 3D dipole at more than 5σ

LATEST RESULT



TAKE HOME MESSAGE

- ▶ **HAVE WE FOUND THE SOURCES OF UHECRs?**
- ▶ **THE RESULTS ARE CERTAINLY INTERESTING IF NOT (YET!) STATISTICALLY COMPELLING.**
- ▶ **IF/WHEN OUR CORRELATIONS ARE STATISTICALLY COMPELLING, WE WILL HAVE (ARGUABLY) THE FIRST EXPERIMENTAL FEEDBACK ON MAGNETIC DEFLECTIONS OF EXTRA-GALACTIC CRs.**
- ▶ **WE WILL CONTINUE OUR ANALYSIS ON THE EVER-INCREASING AUGER DATA SET.**

COMPOSITION

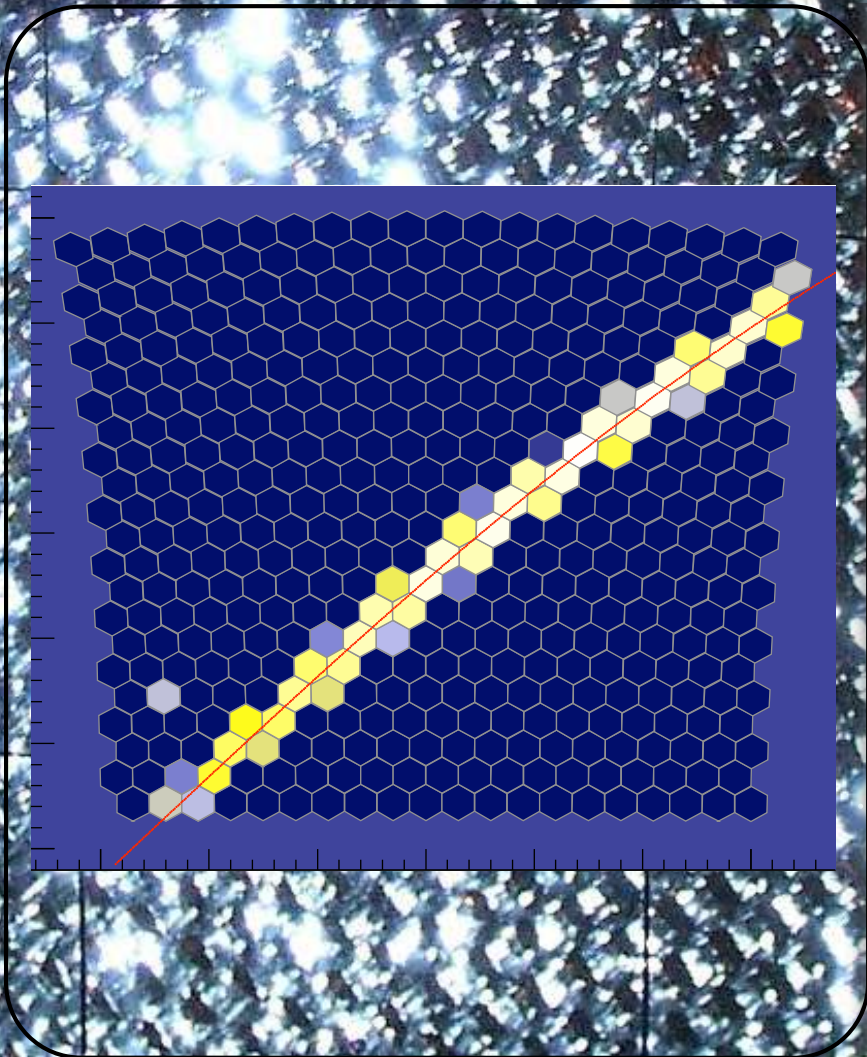
ELONGATION RATE

LATEST RESULTS

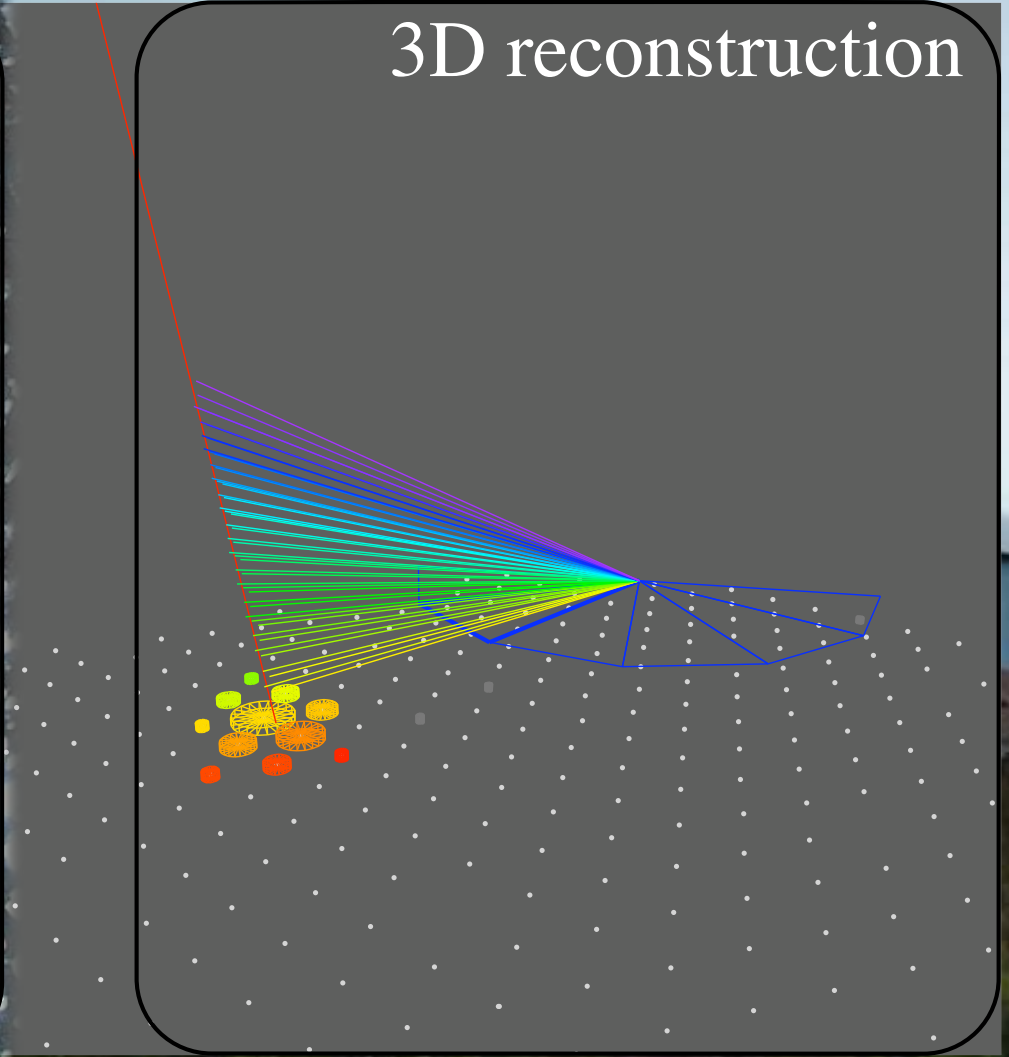
COMPOSITION - INFERRING THE IDENTITY OF THE PRIMARY CR



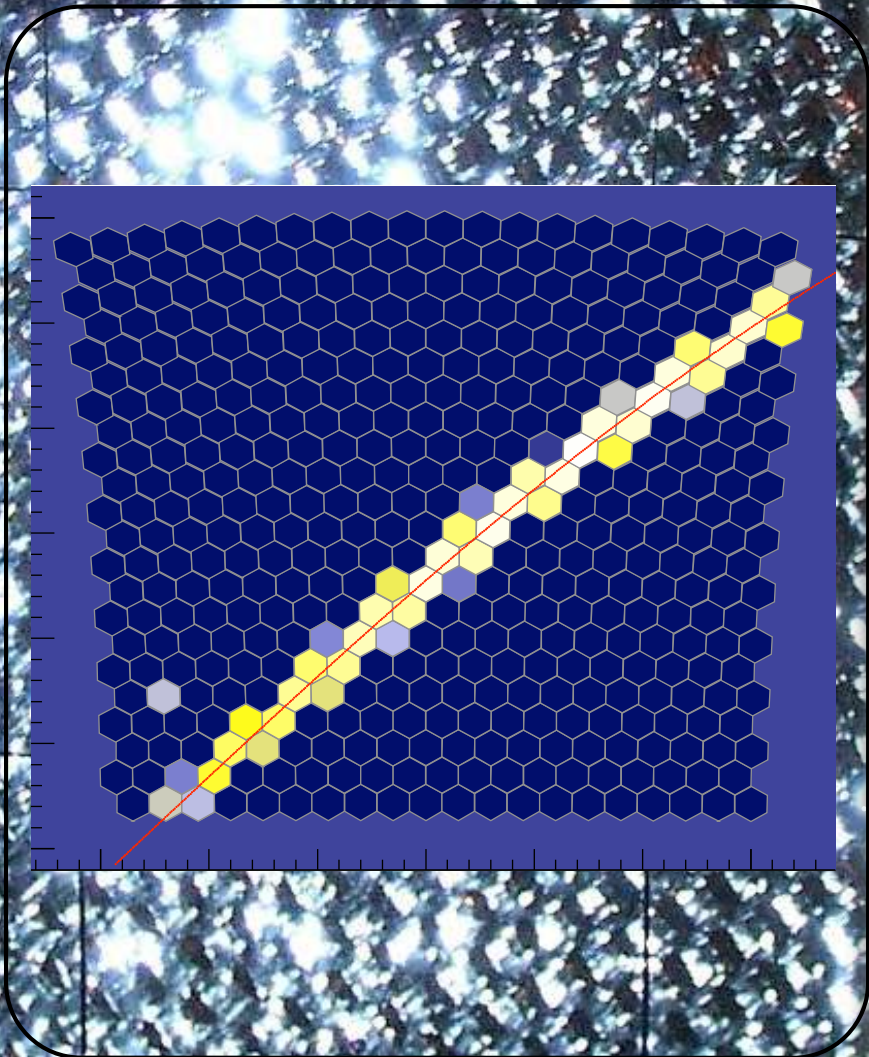
SHOWER PROPERTIES



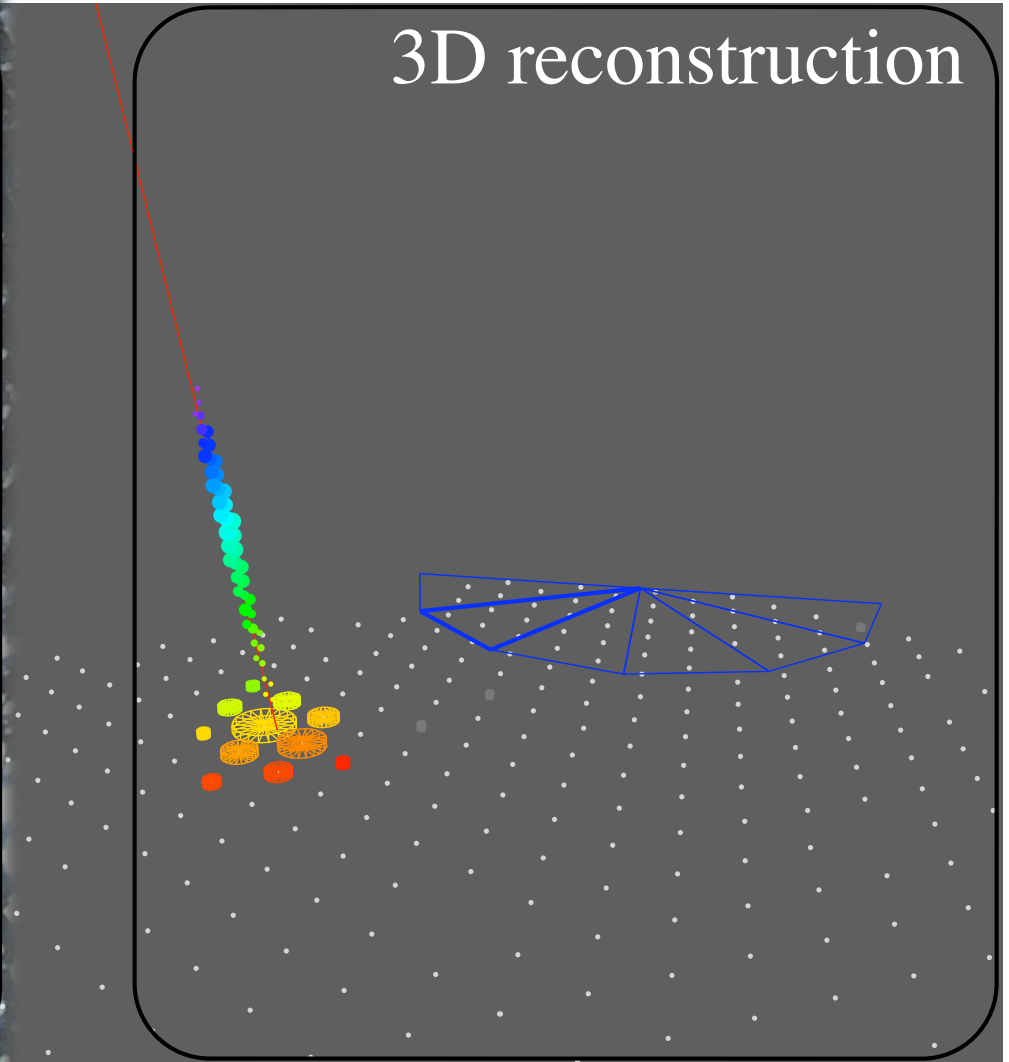
3D reconstruction



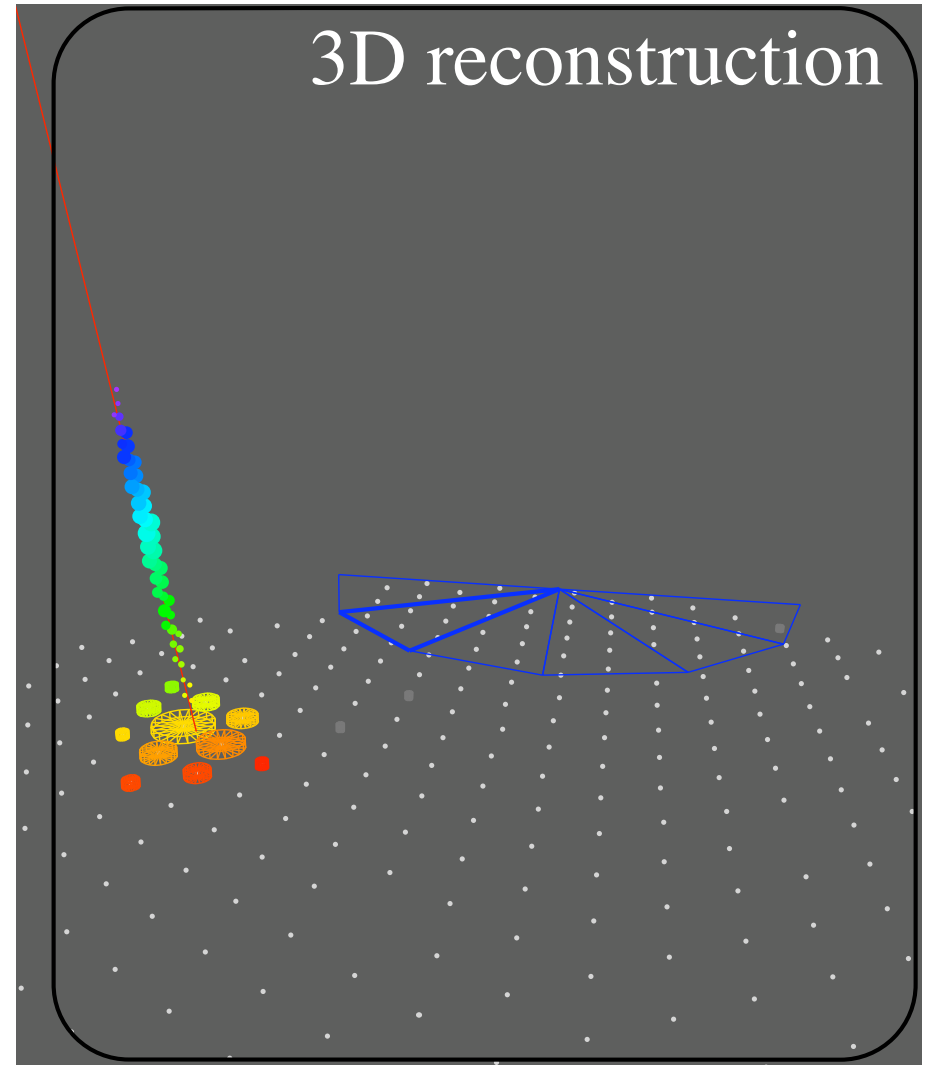
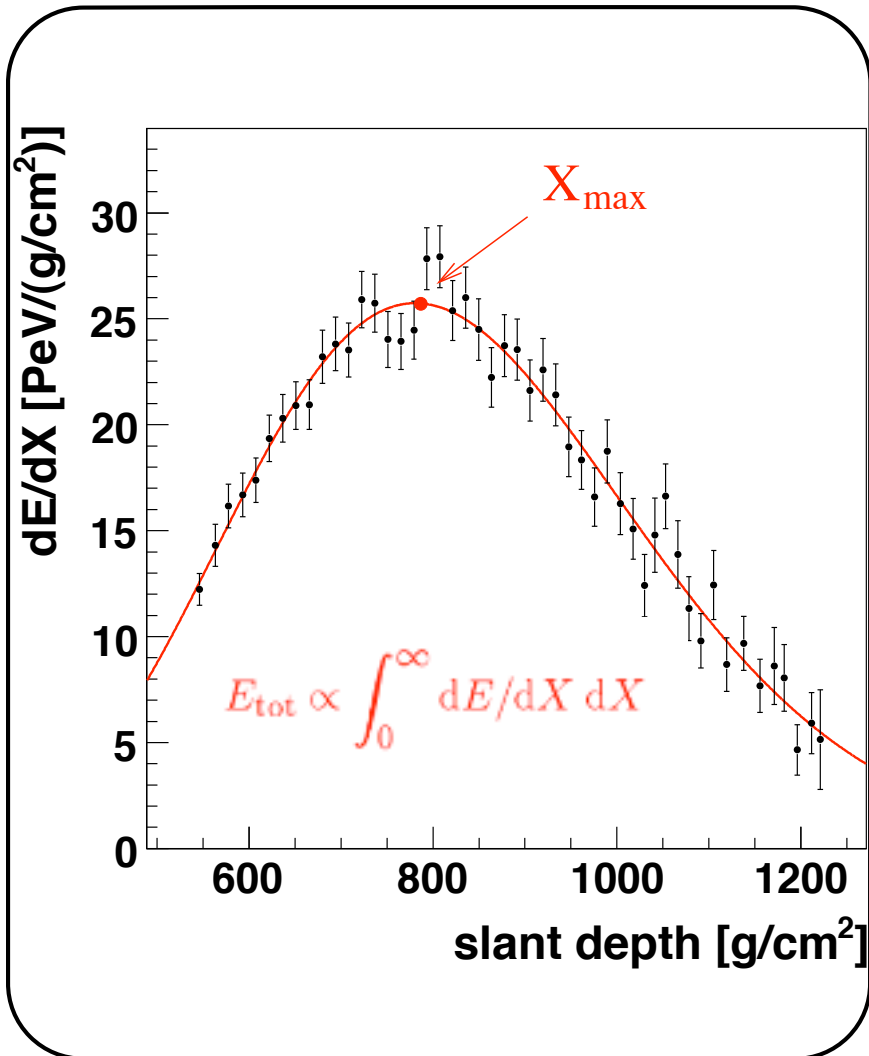
SHOWER PROPERTIES



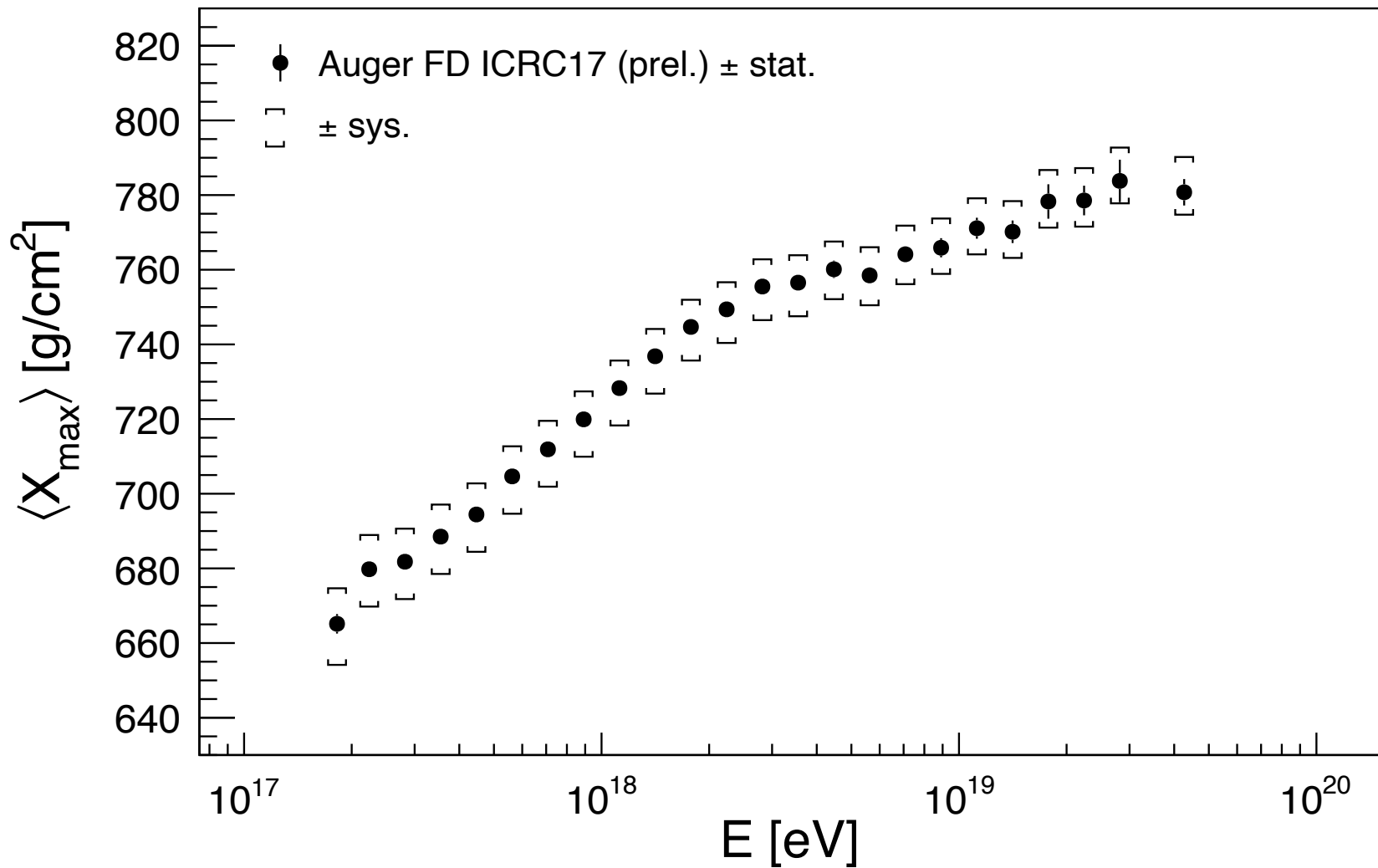
3D reconstruction



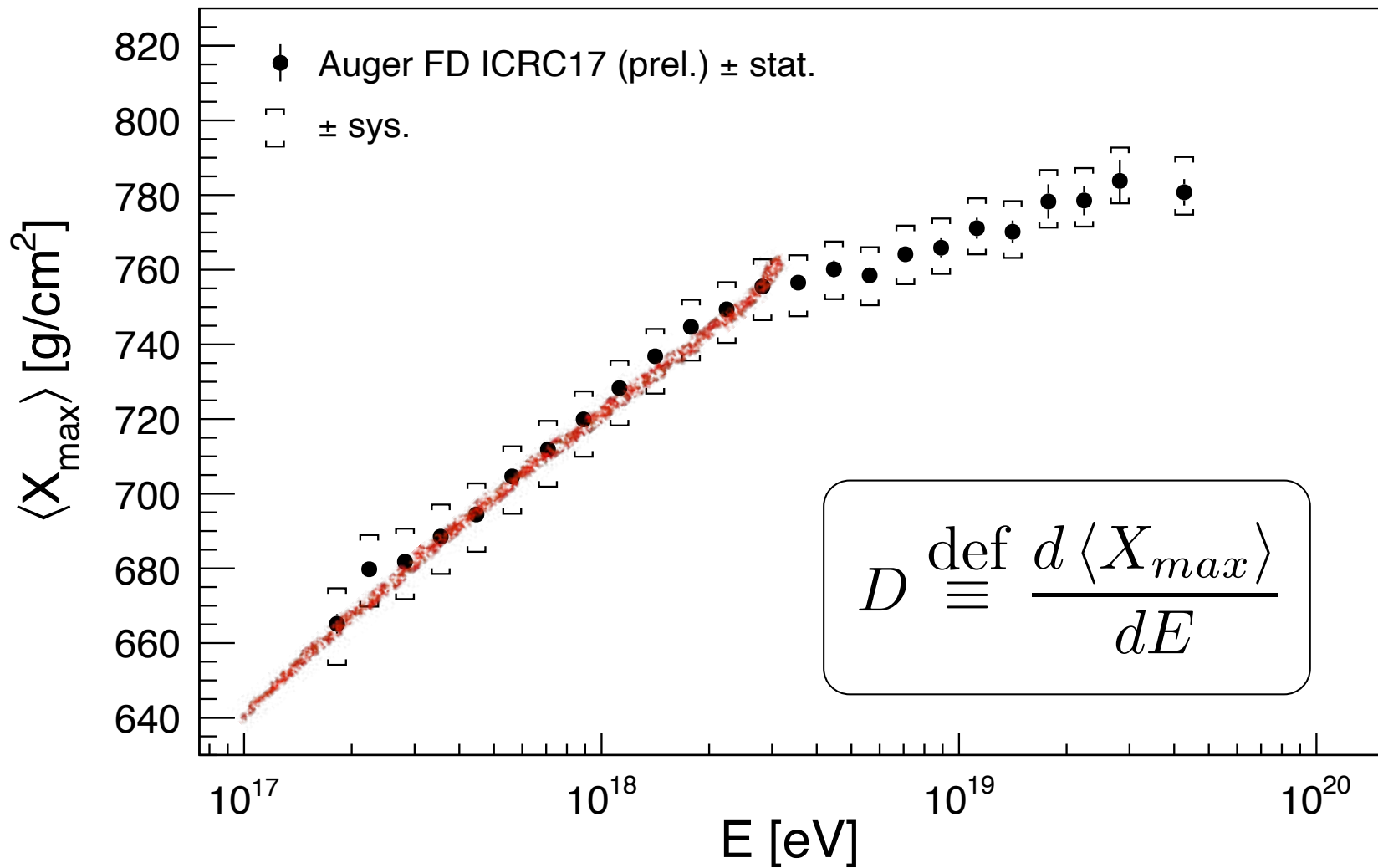
SHOWER PROPERTIES



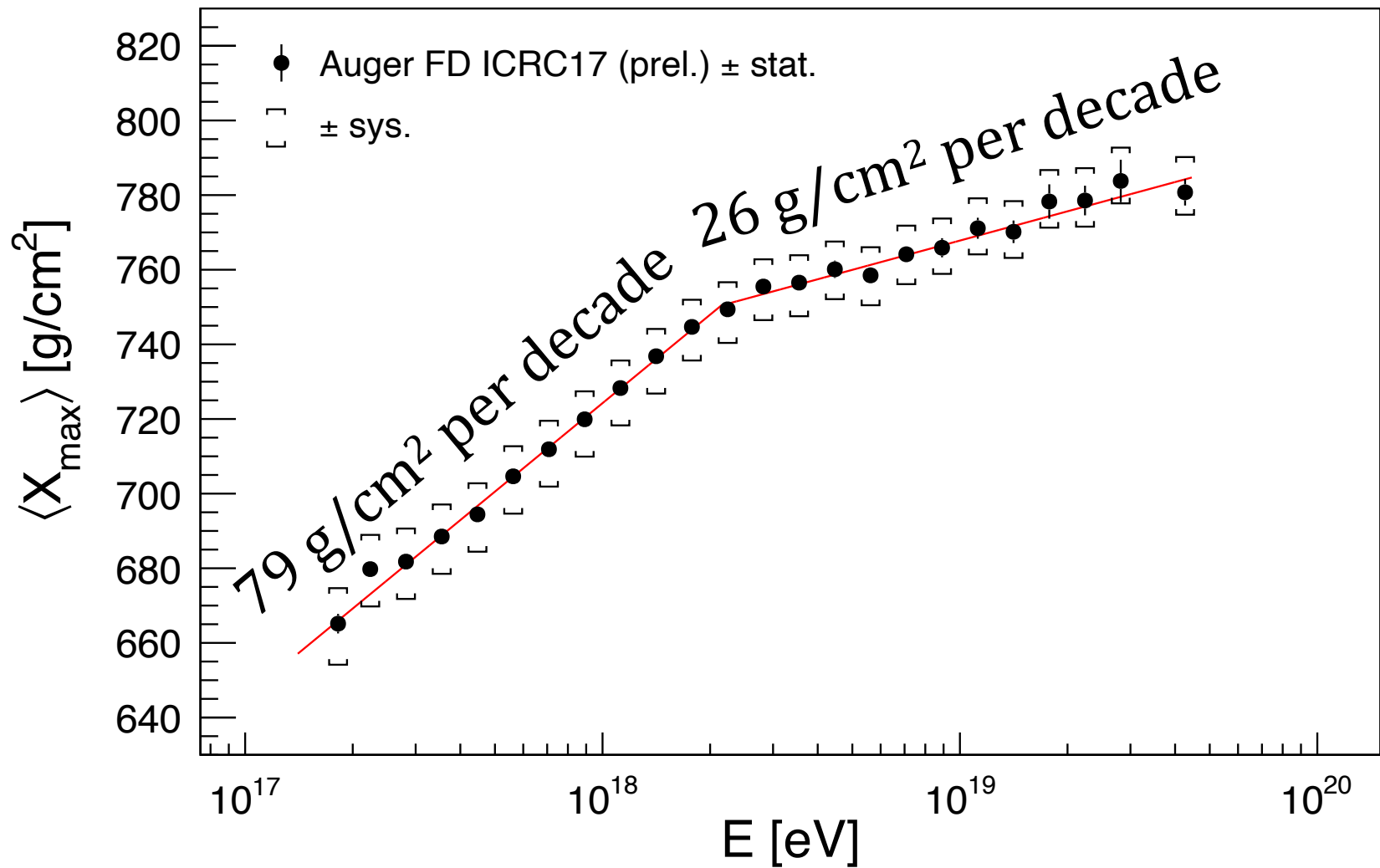
PROPERTIES OF SHOWER MAX



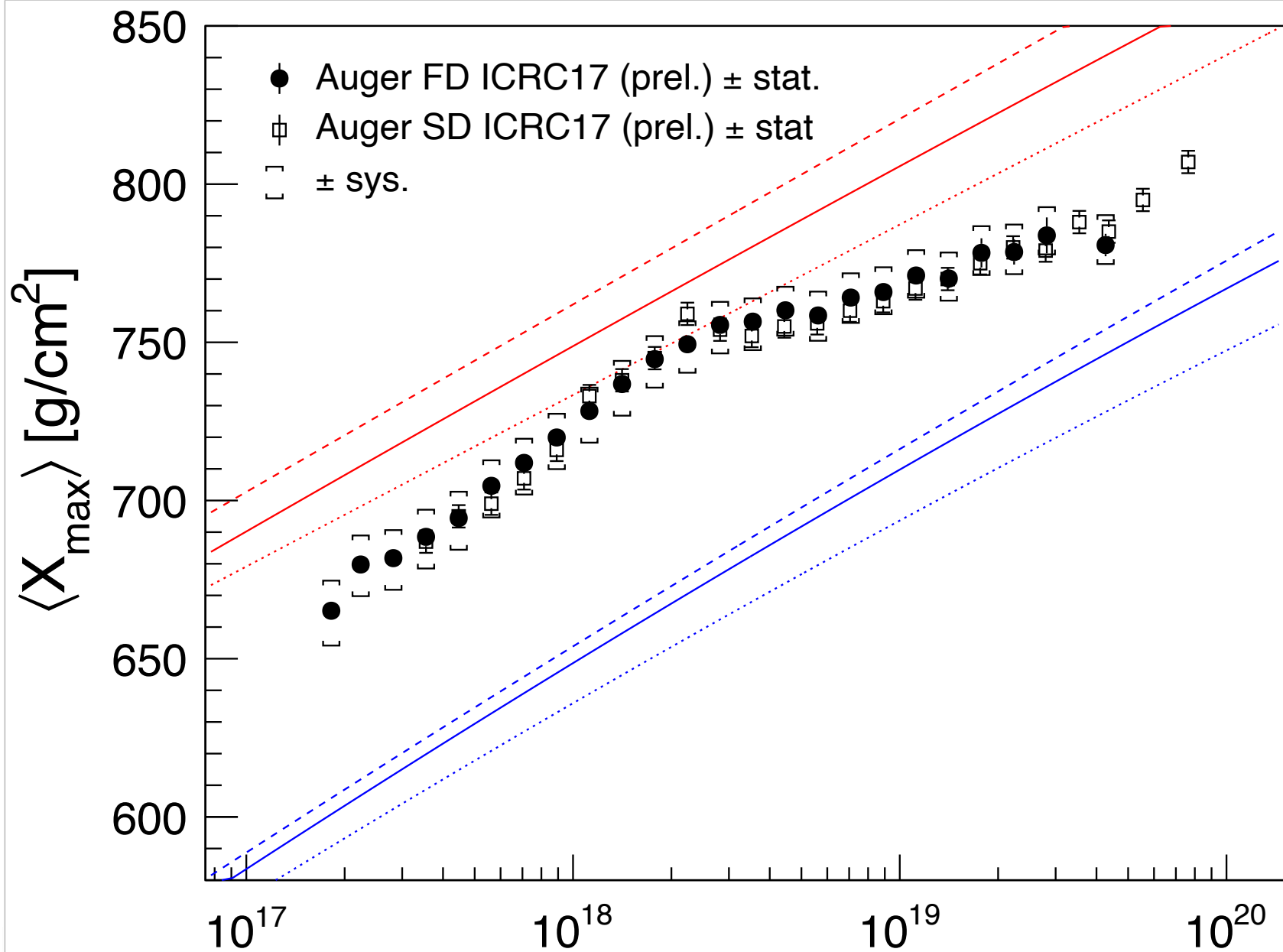
PROPERTIES OF SHOWER MAX



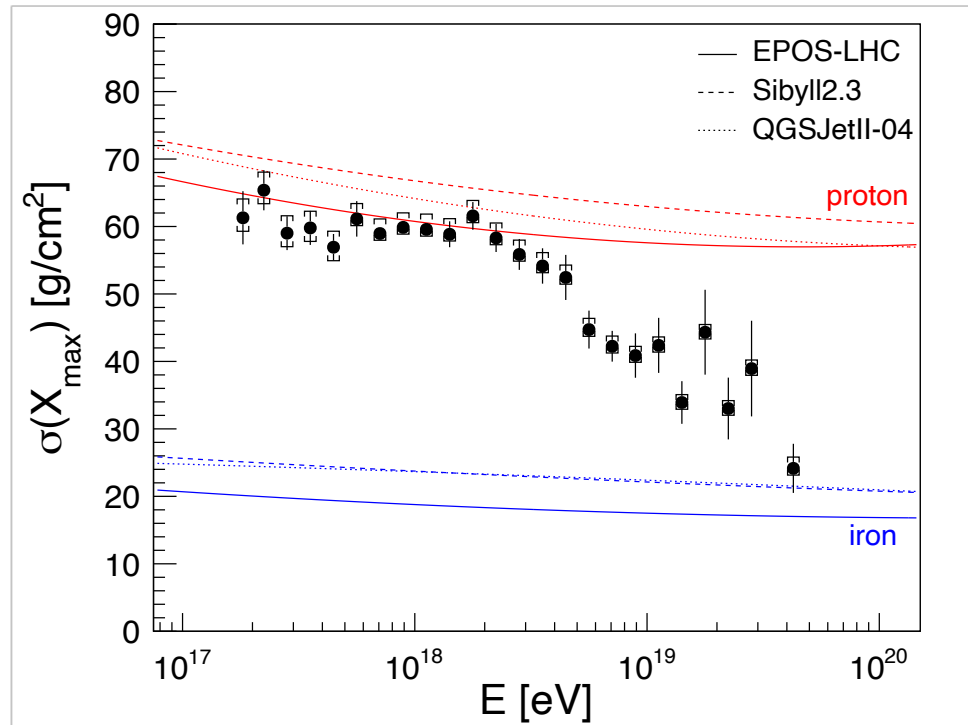
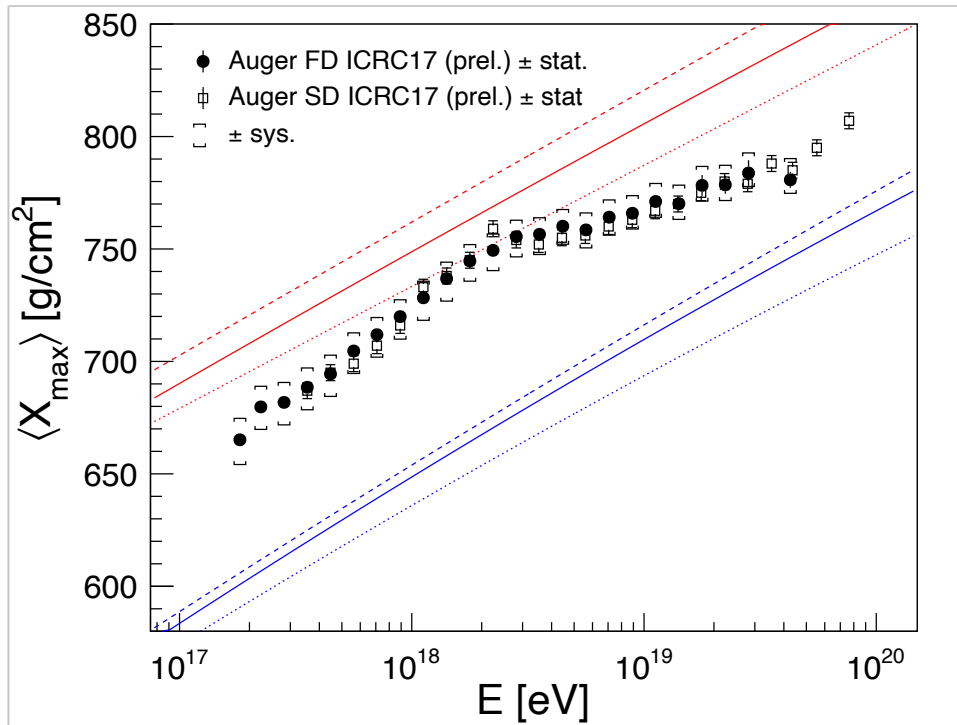
ELONGATION RATE



ELONGATION RATE



COMPOSITION

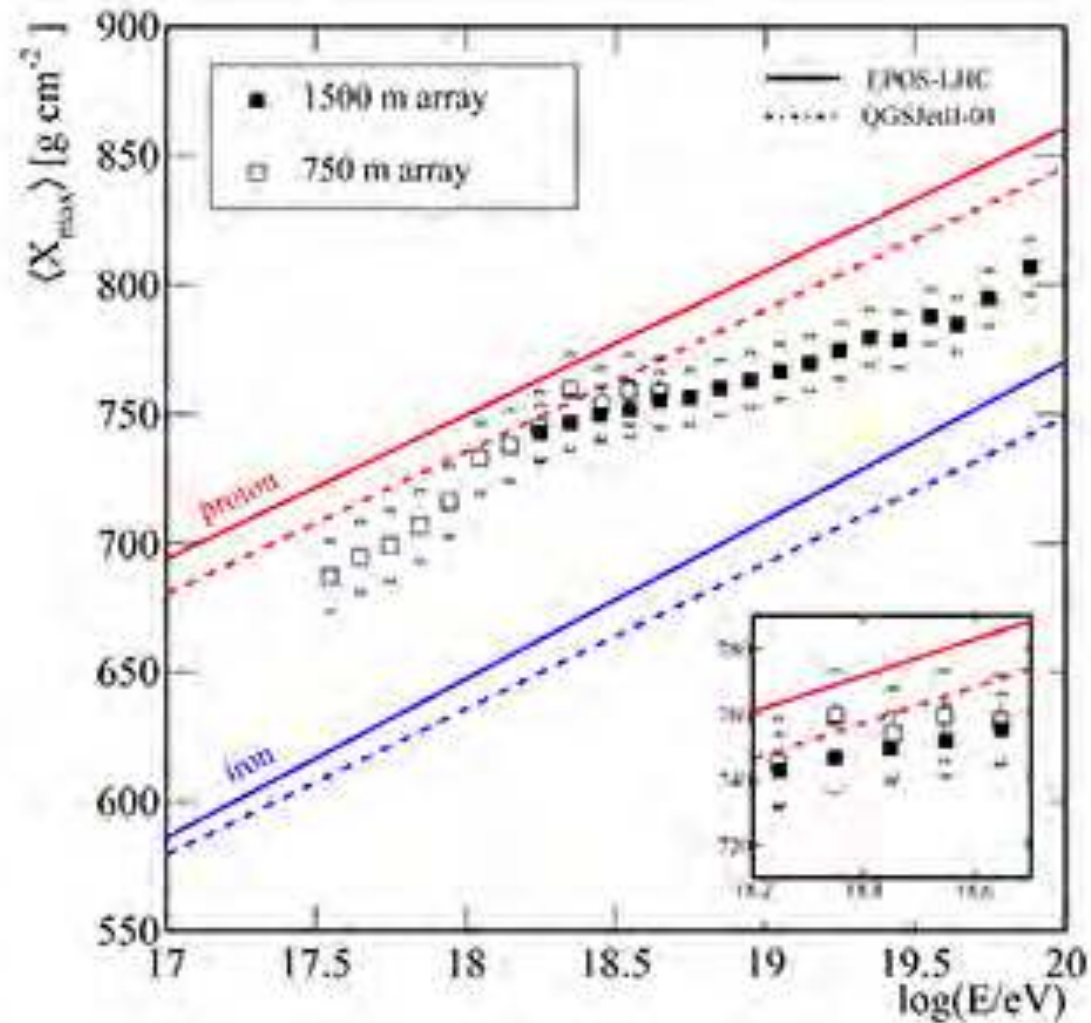


Lines: air-shower simulations using post-LHC hadronic interaction models

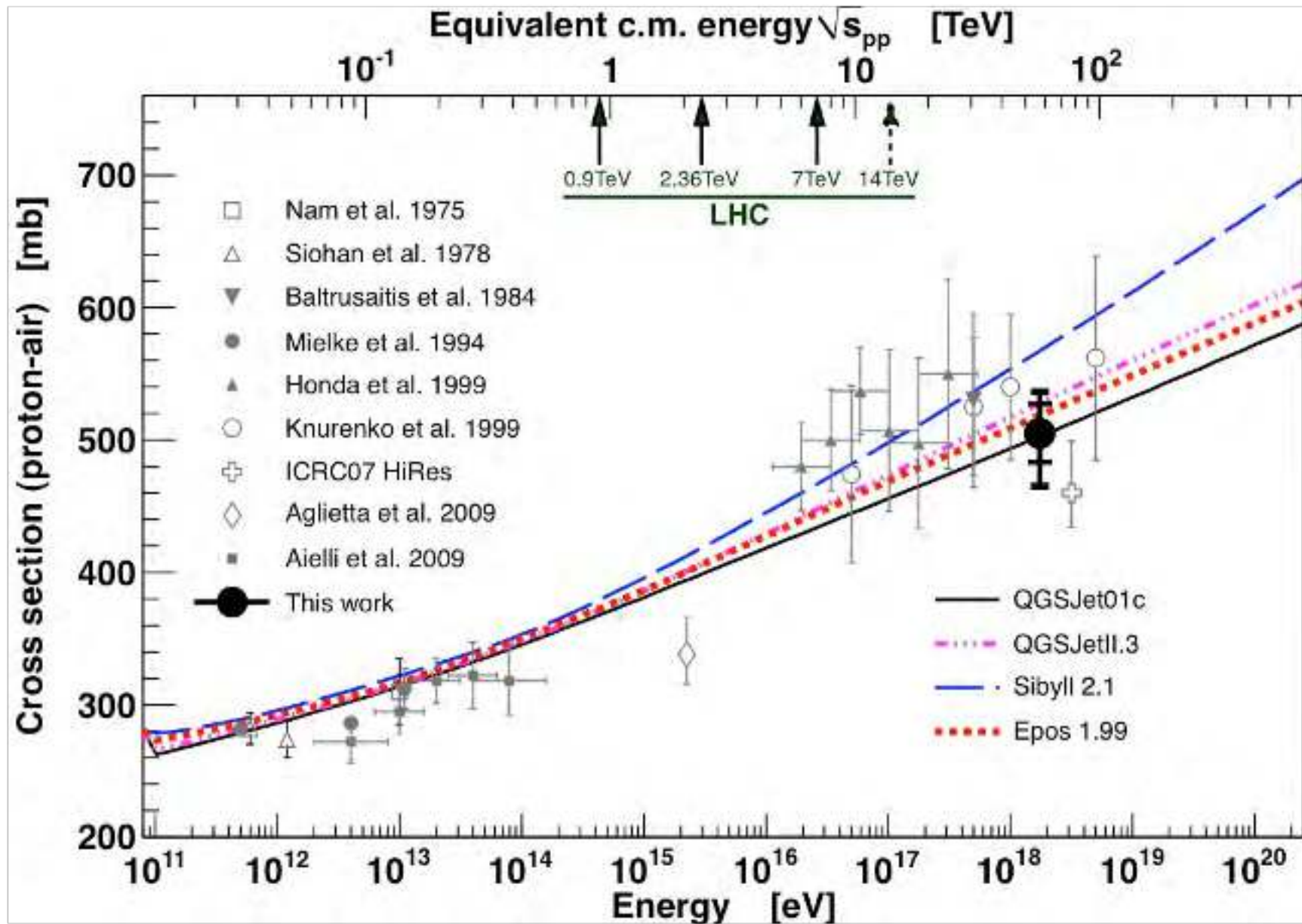
Inferences on Mass Composition and Tests of Hadronic Interactions from 0.3 to 100 EeV using the water-Cherenkov Detectors of the Pierre Auger Observatory

The Pierre Auger Collaboration, Phys. Rev. D **96** (2017) 122003

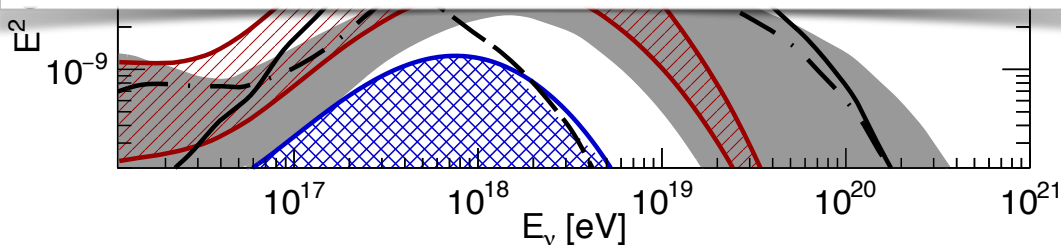
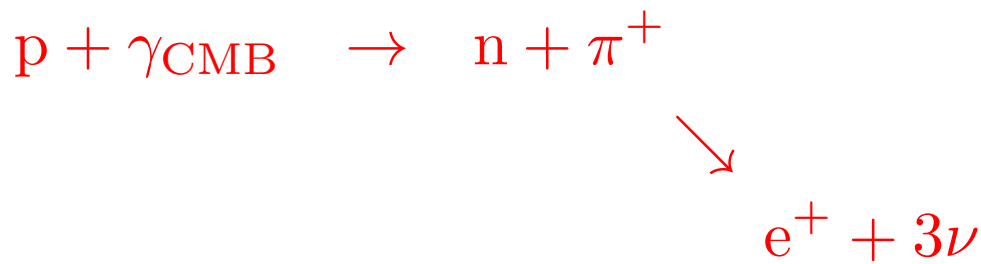
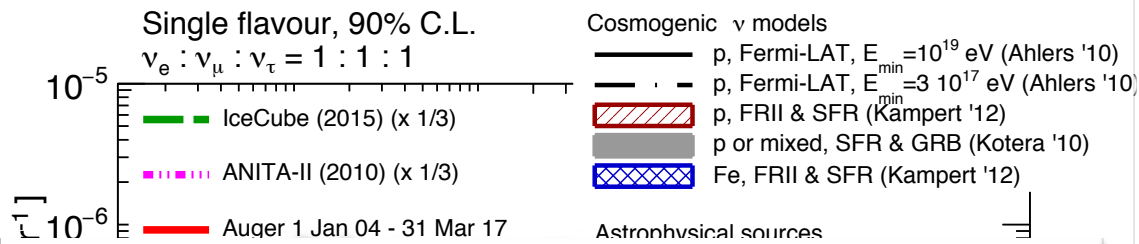
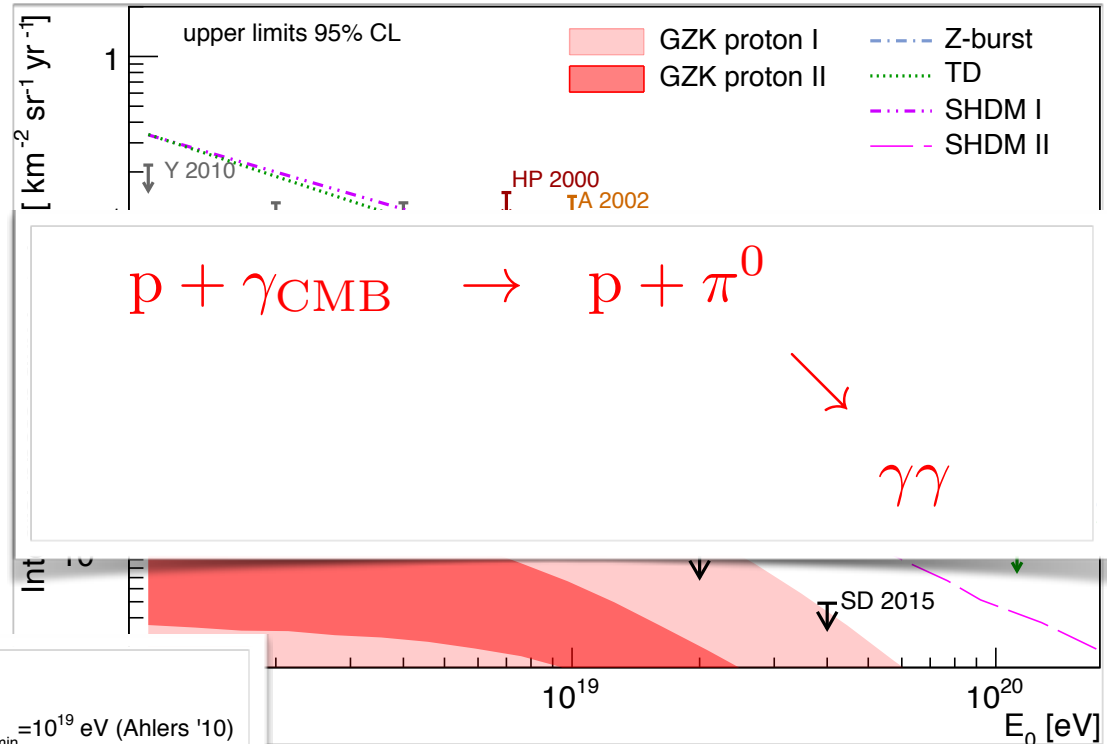
LATEST RESULT



P-AIR X-SECTION



UHE NEUTRINOS & GAMMAS

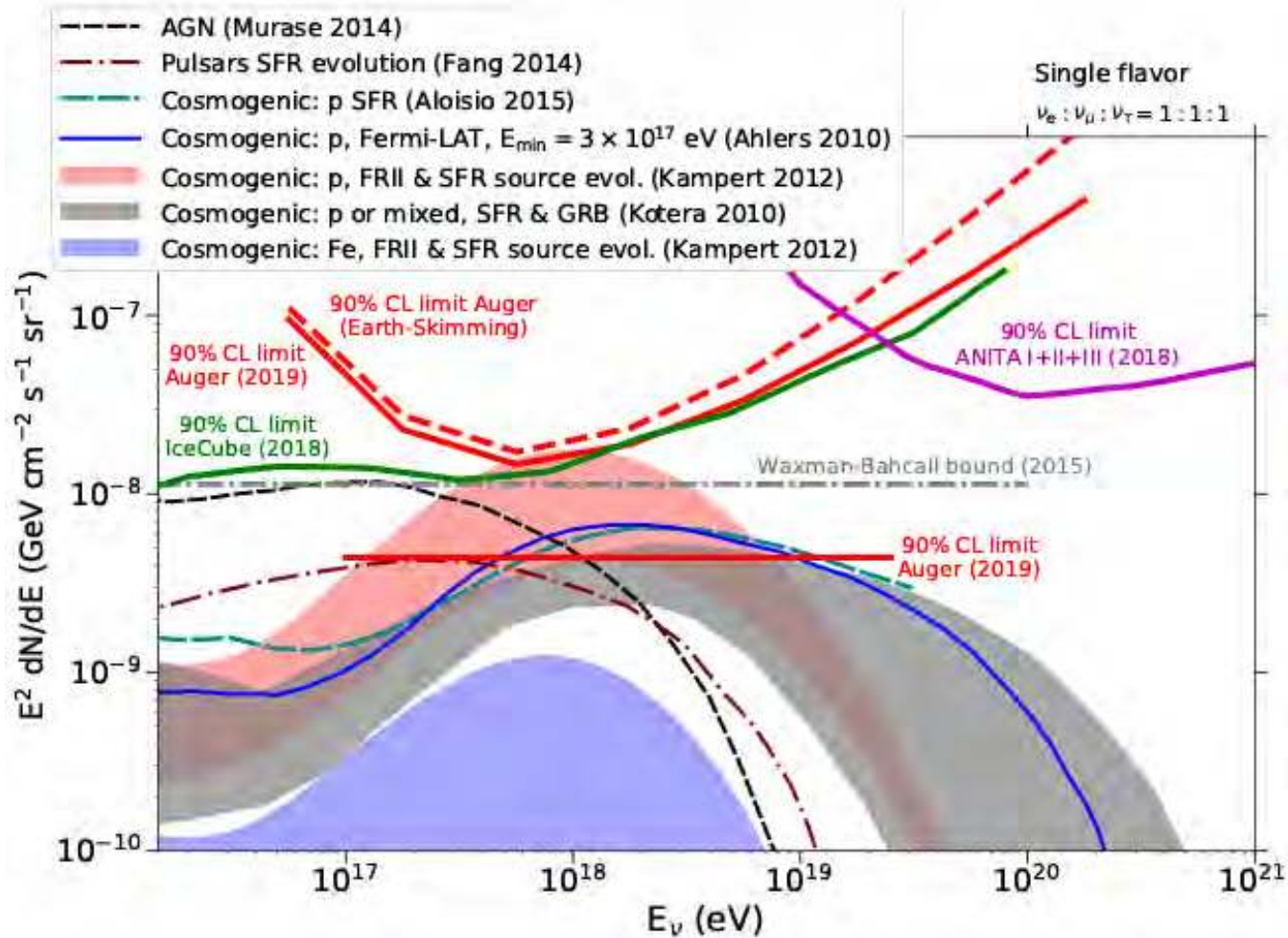


**EXOTIC SOURCES
DISFAVORED**

Probing the origin of ultra-high energy cosmic rays with neutrinos in the EeV energy range at the Pierre Auger Observatory

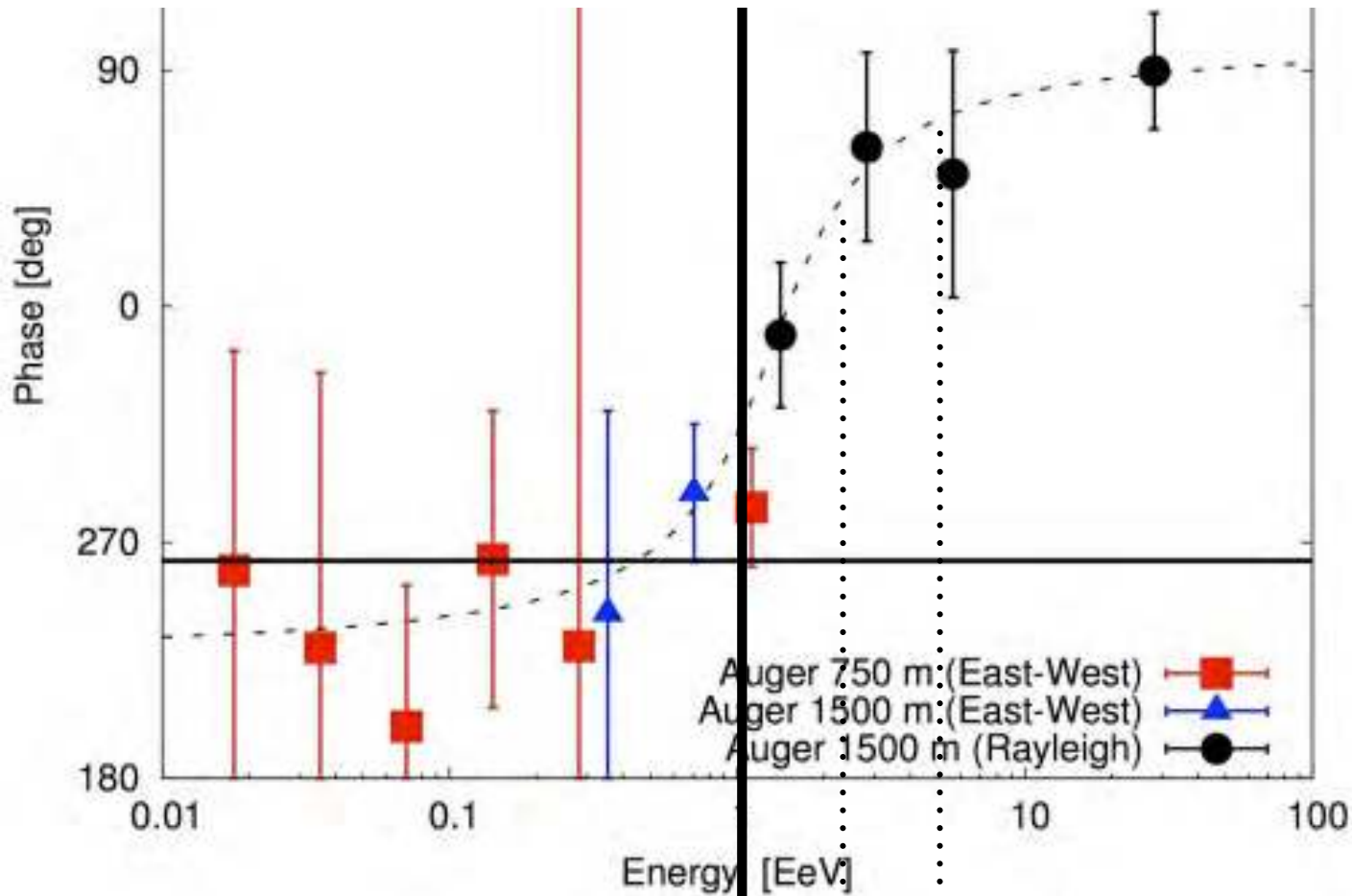
The Pierre Auger Collaboration, JCAP 10 (2019) 022

LATEST RESULT



THE BIG PICTURE

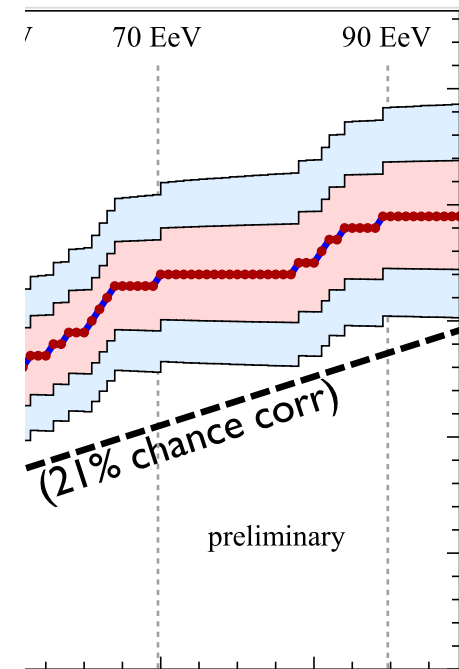
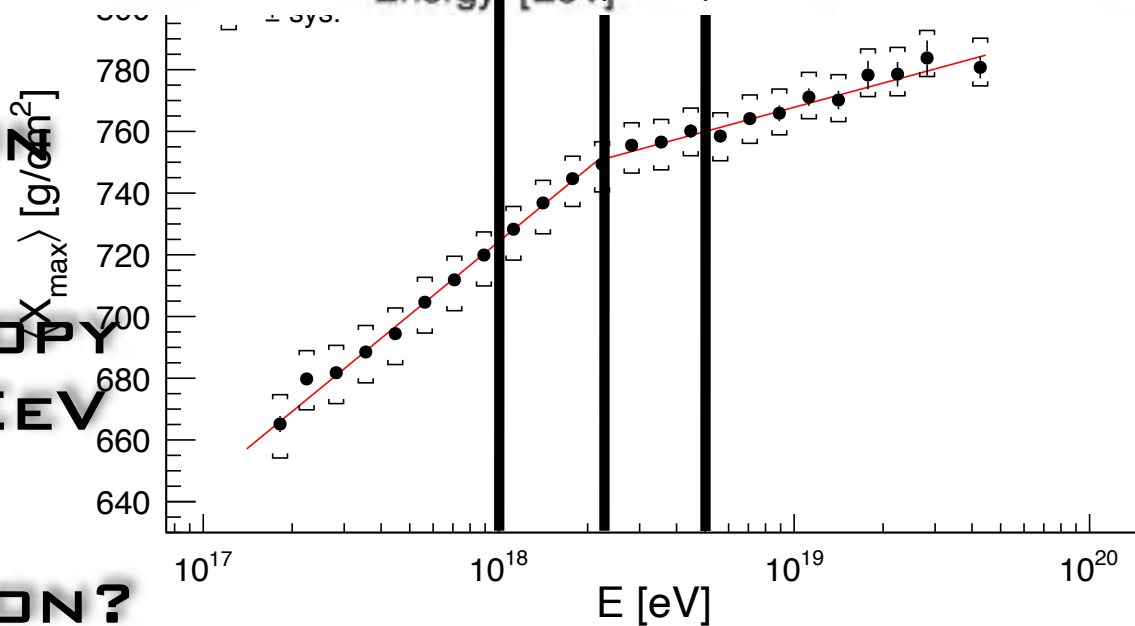
- ▶ UHECR ARE PRODUCED BY NEAR-BY EXTRAGALACTIC OBJECTS
- ▶ VERY LOW FLUXES OF PHOTONS AND NEUTRINOS
- ▶ STRONG FLUX SUPPRESSION @ GZK ENERGIES
- ▶ “AGN” CORRELATION AT “SMALL” ANGULAR SCALE (CONSISTENT WITH CNO PRIMARIES?)



**1. FLUX
SUPPRESSION**

**2. ANISOTROPY
ABOVE 60 EeV**

3. TRANSITION?



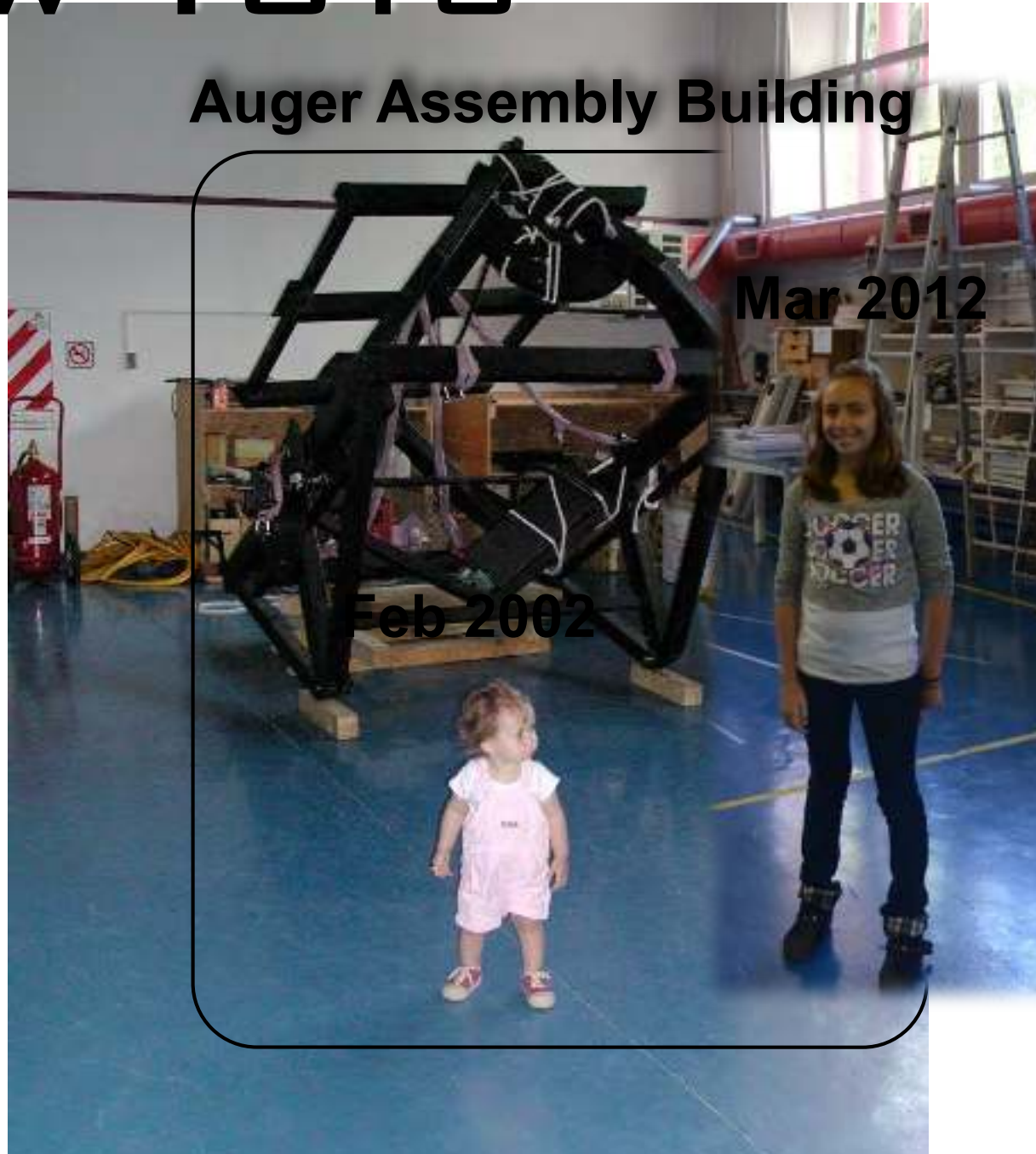
NEW TOYS

ENHANCEMENTS
&
UPGRADE

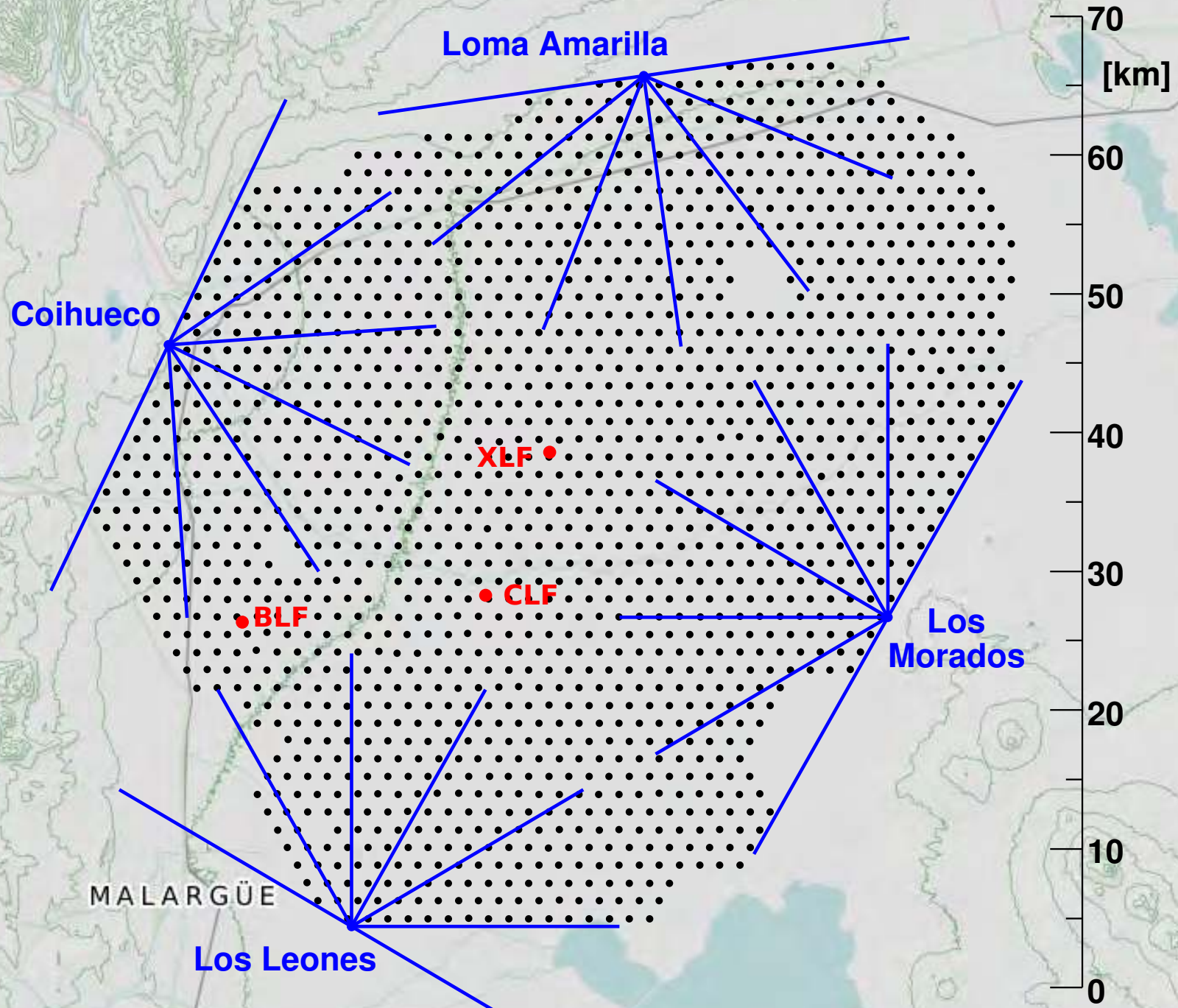
Auger Assembly Building

Mar 2012

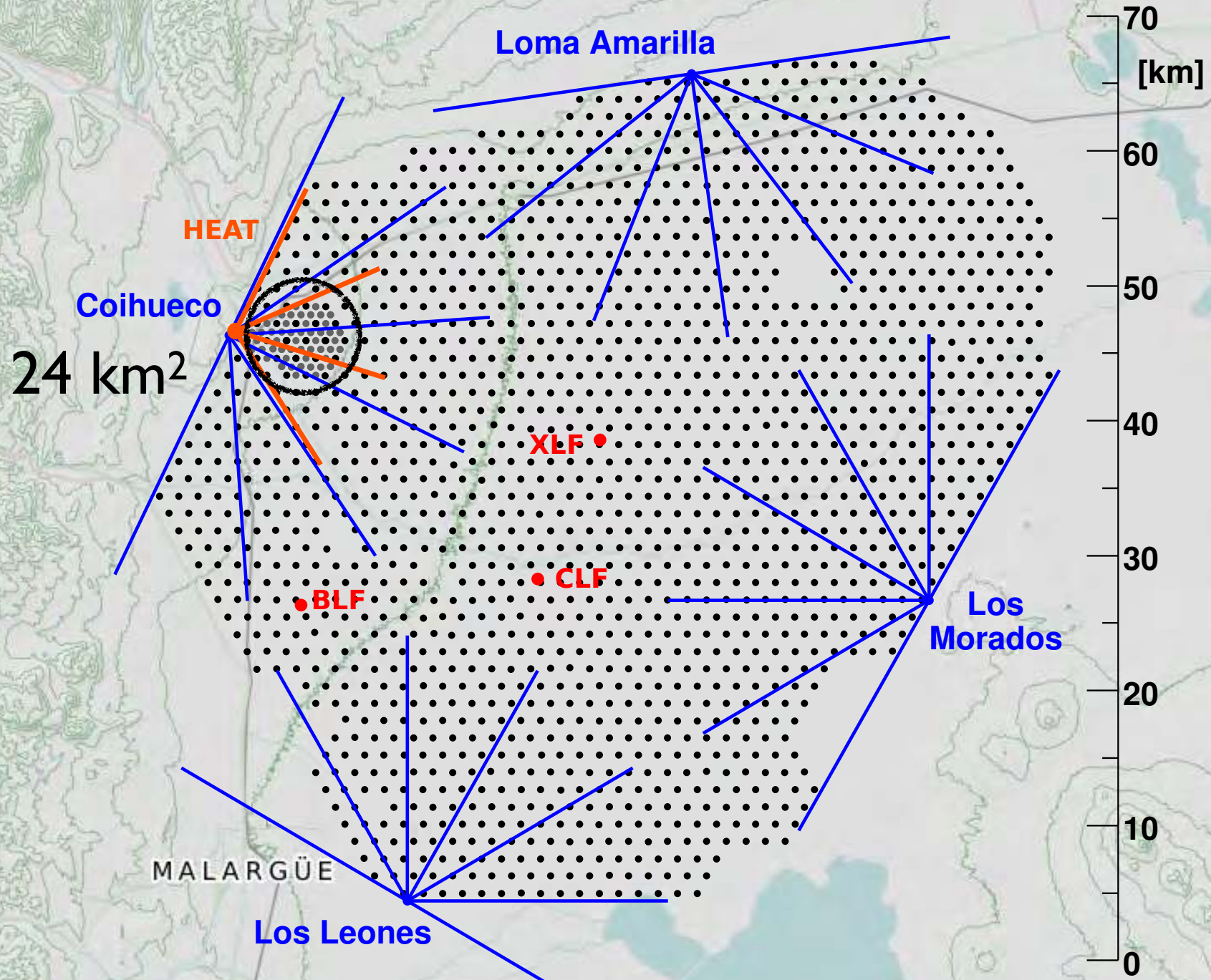
Feb 2002



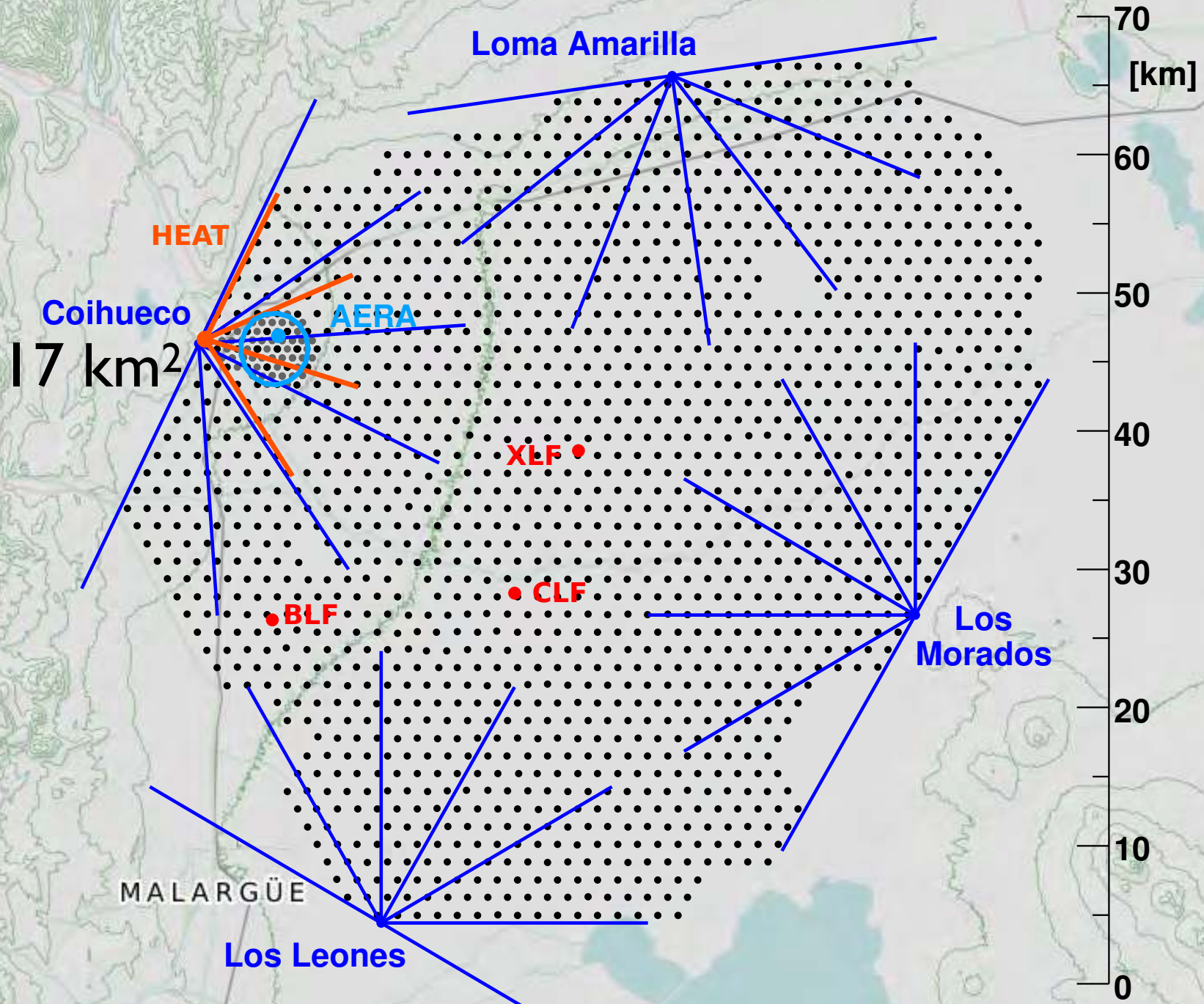
ENHANCING AUGER



ENHANCING AUGER



ENHANCING AUGER



AUGER UPGRADE

- ▶ 4 M² SCINTILLATORS ON EACH STATION
- ▶ UPGRADED ELECTRONICS
- ▶ NEW SMALL PMT
- ▶ BURIED MUON COUNTERS UNDER EACH INFILL STATION
- ▶ INCREASE FD UPTIME



ENHANCING AUGER SOUTH

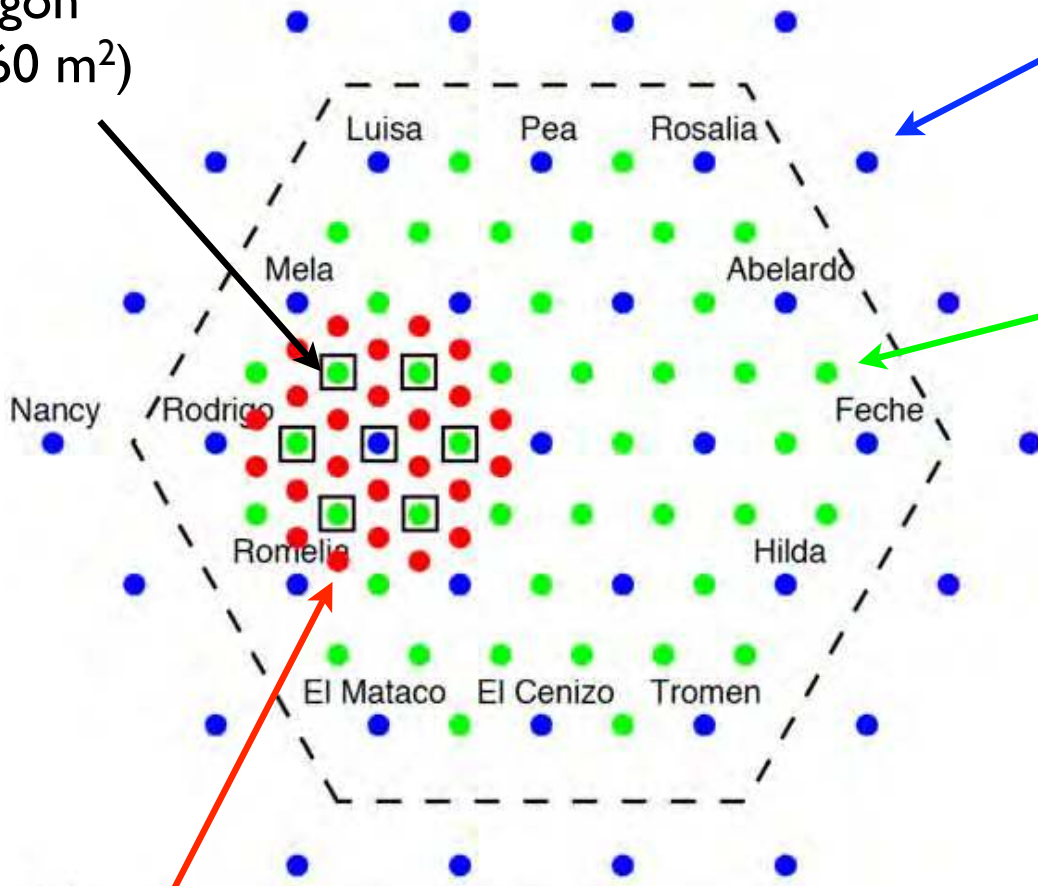
Hexagon
(7 x 60 m²)

Existing tank array 1500m

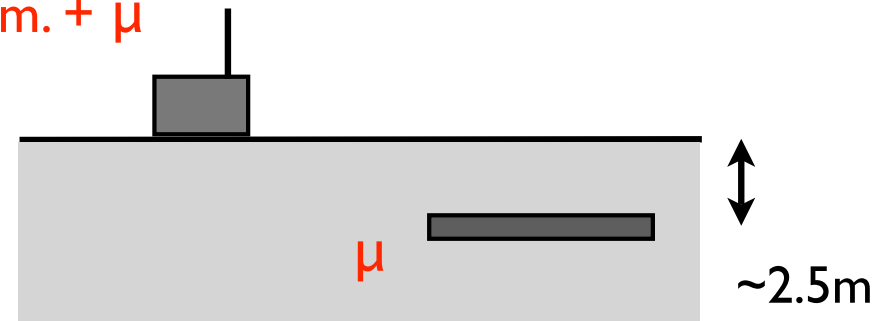
Infill array 750m

Muon detectors:
54 (30m²) + 7 (60m²)
Cherenkov tanks: 61
Area ~ 23 km²

Infill array 433m
Area ~ 5.9 km²

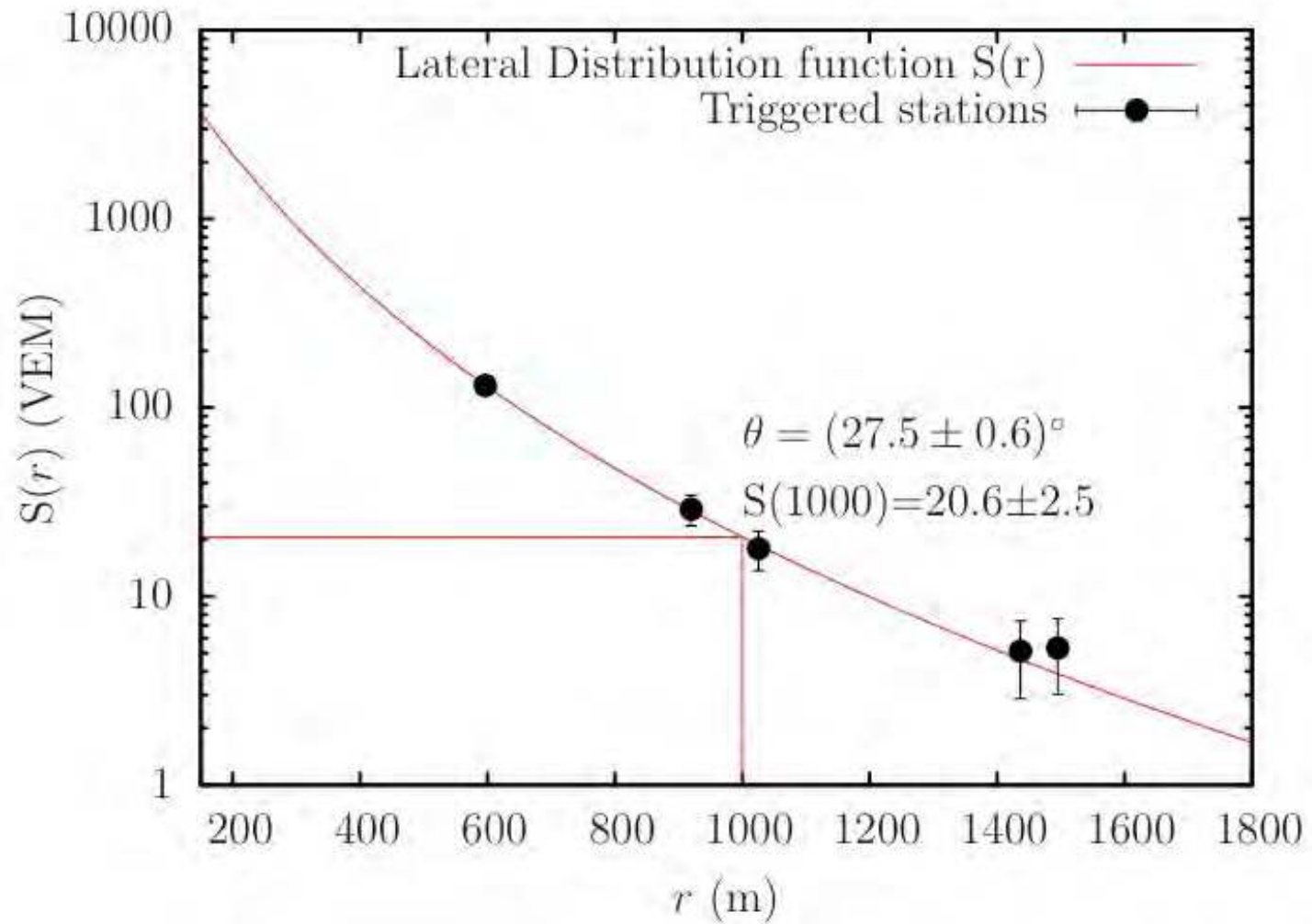


em. + μ



Detector pairs

IN-FILL ARRAY



AMIGA STATUS

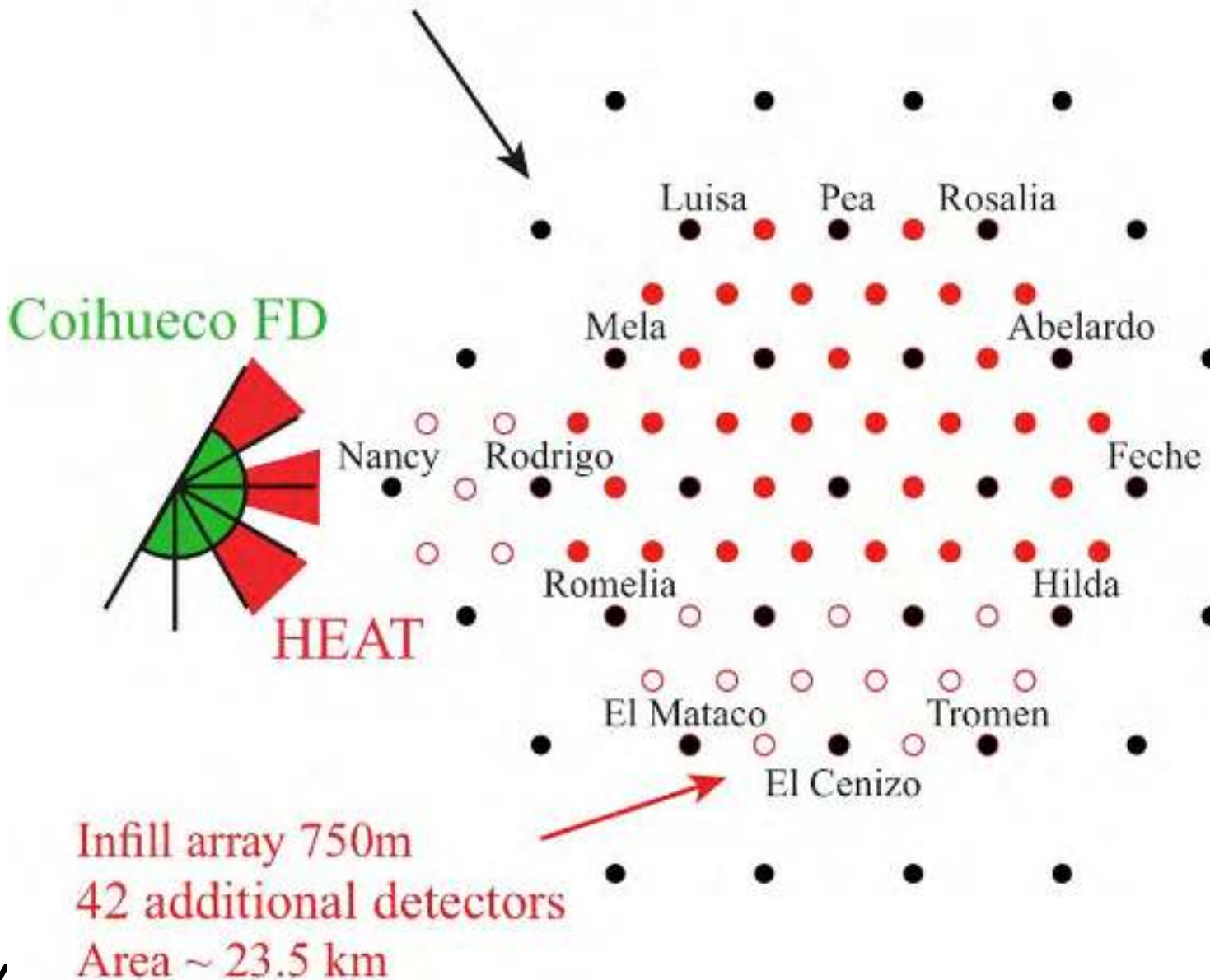


SSD DEPLOYMENT



ENHANCING AUGER SOUTH

Existing tank array 1500m

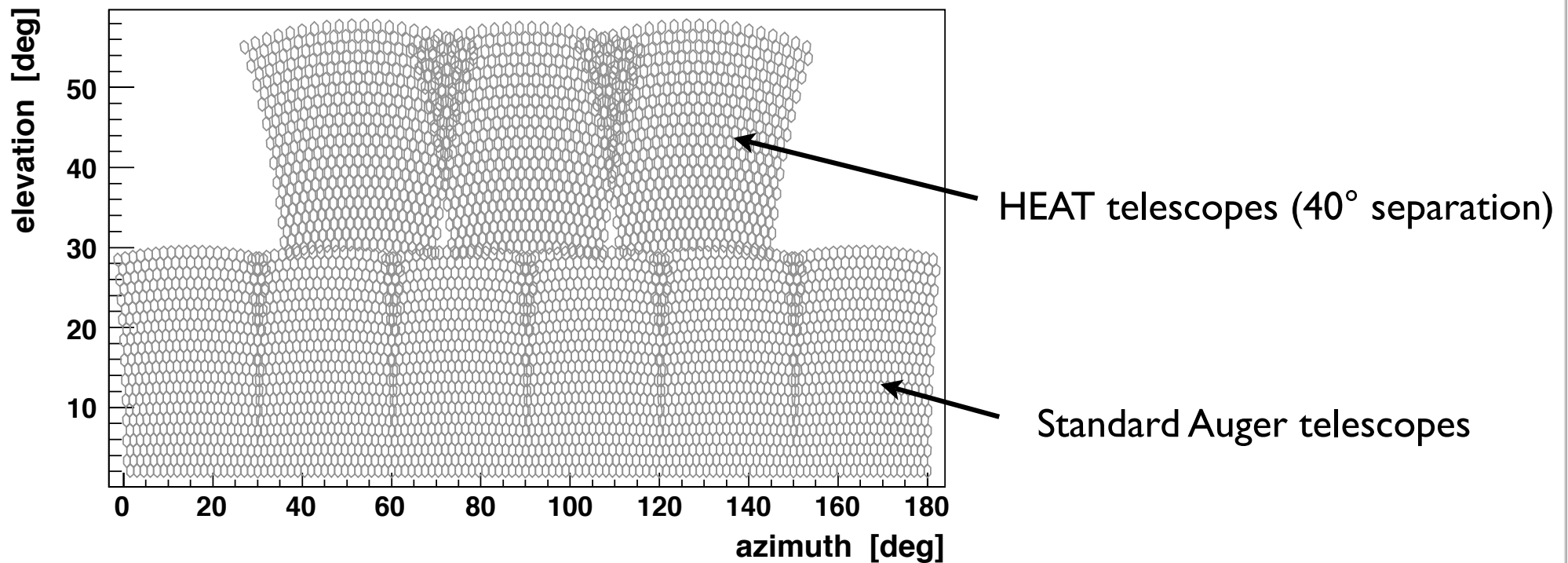


Infill array 750m

42 additional detectors

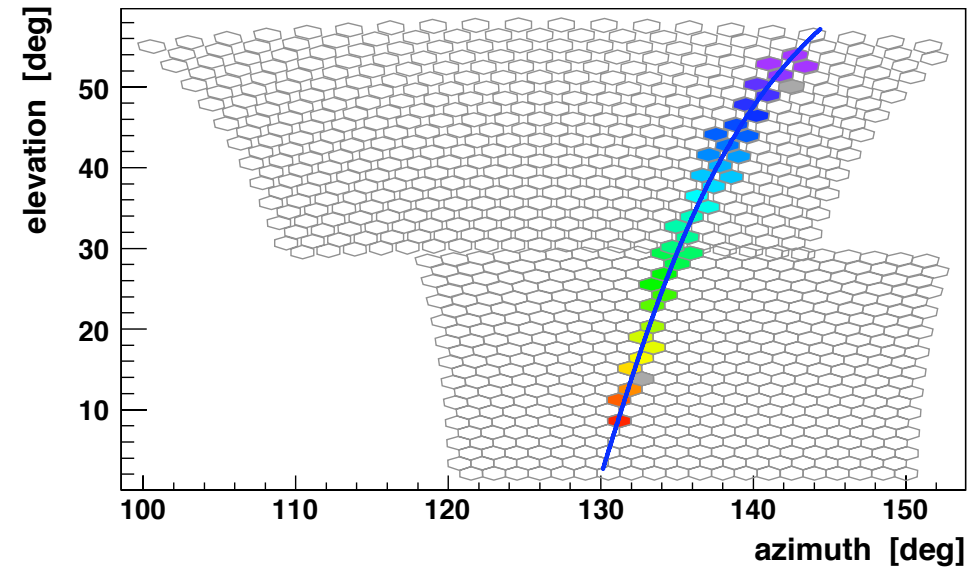
Area ~ 23.5 km

LOW(ER)-ENERGY FD

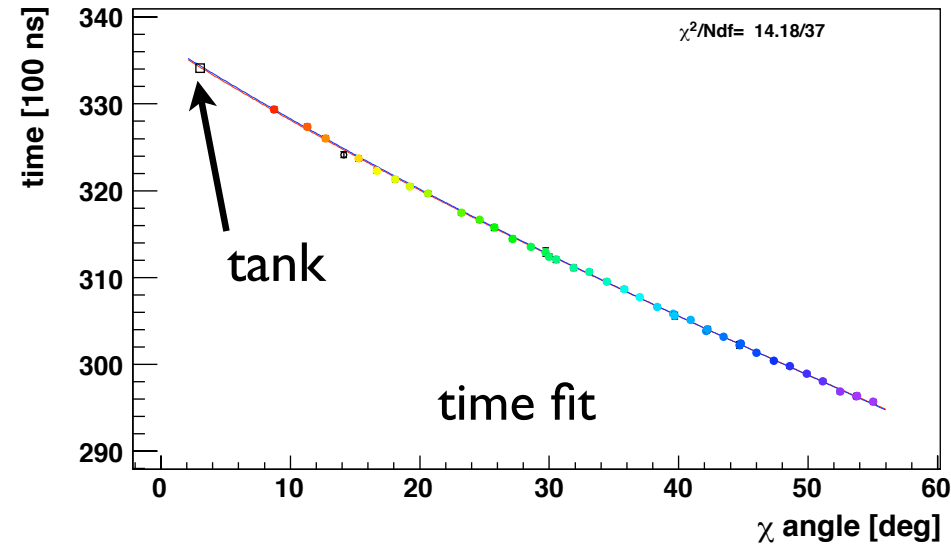
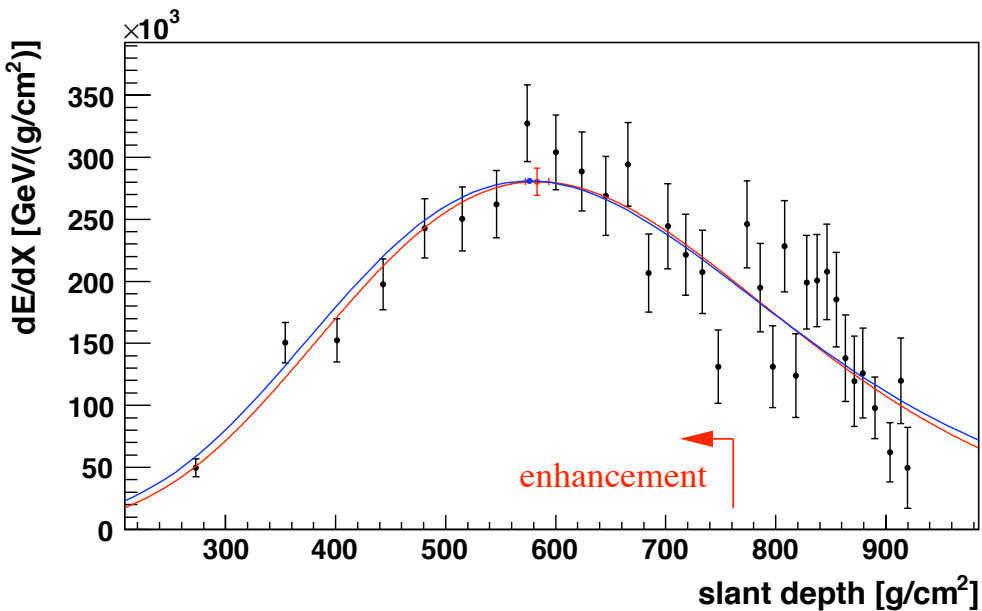


Hybrid event rate with AMIGA (750m):
~200 high quality events / year in energy region $\sim 10^{18}$ eV

LOW-ENERGY FDS



Simulated shower with core distance
 $R_p = 1.2 \text{ km}$, $E = 10^{17.25} \text{ eV}$

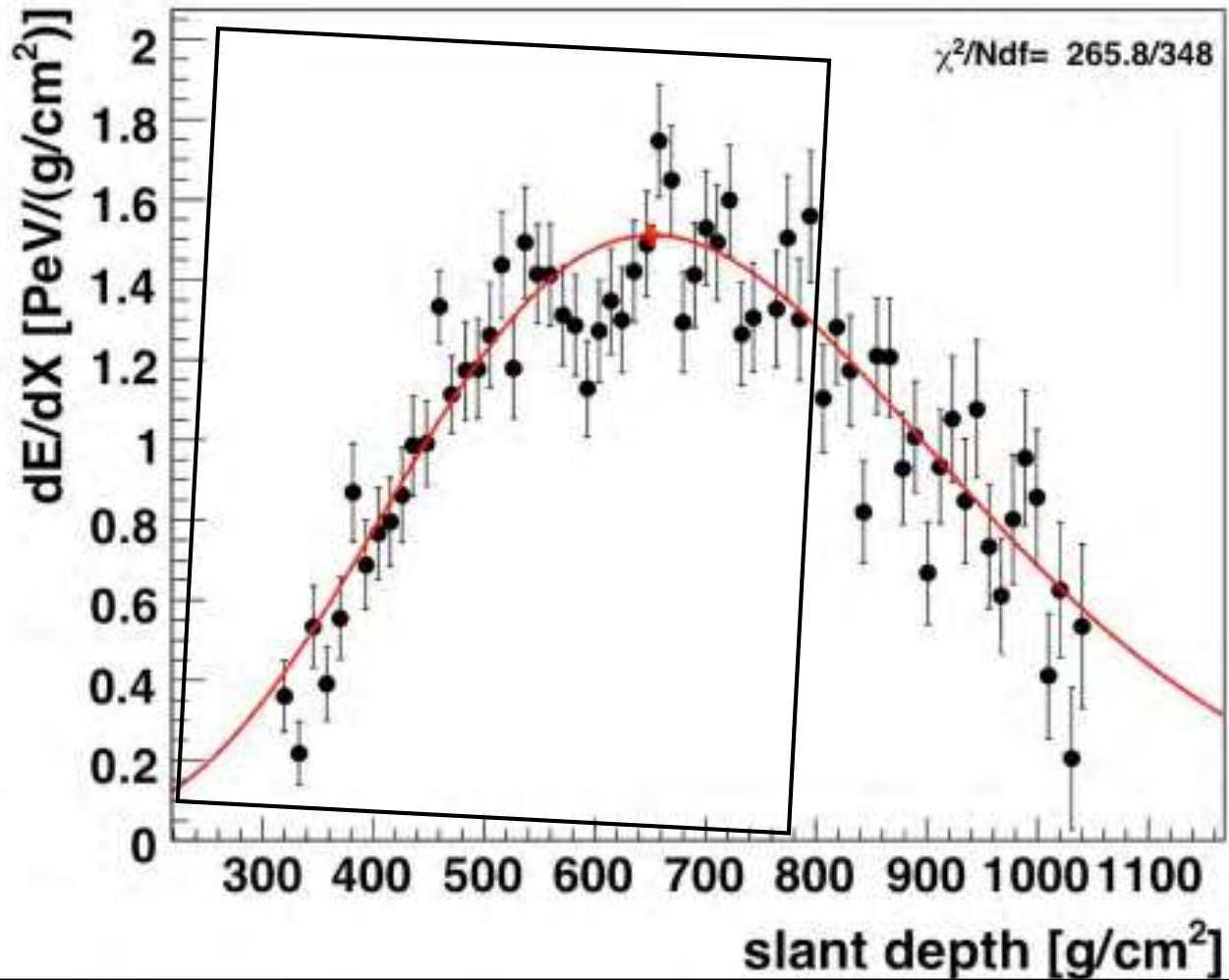


- simulated profile
- reconstructed profile

HEAT STATUS



HEAT STATUS



OTHER IDEAS

- ▶ **ON-GOING PROTOTYPES:**
- ▶ **RADIO DETECTION**
- ▶ **RADAR DETECTION**
- ▶ **LIGHTENING DETECTION**
- ▶ **...**



AUGER PRIME



SUMMARY

- ▶ INTRODUCTION TO COSMIC RAYS
- ▶ DETECTION TECHNIQUES
- ▶ THE LATEST RESULTS IN UHECRs
- ▶ CURRENT UPGRADES & OUTLOOK

**COSMIC RAYS - MIGUEL MOSTAFA
LA-CONGA PHYSICS 2023**

THANK YOU!

