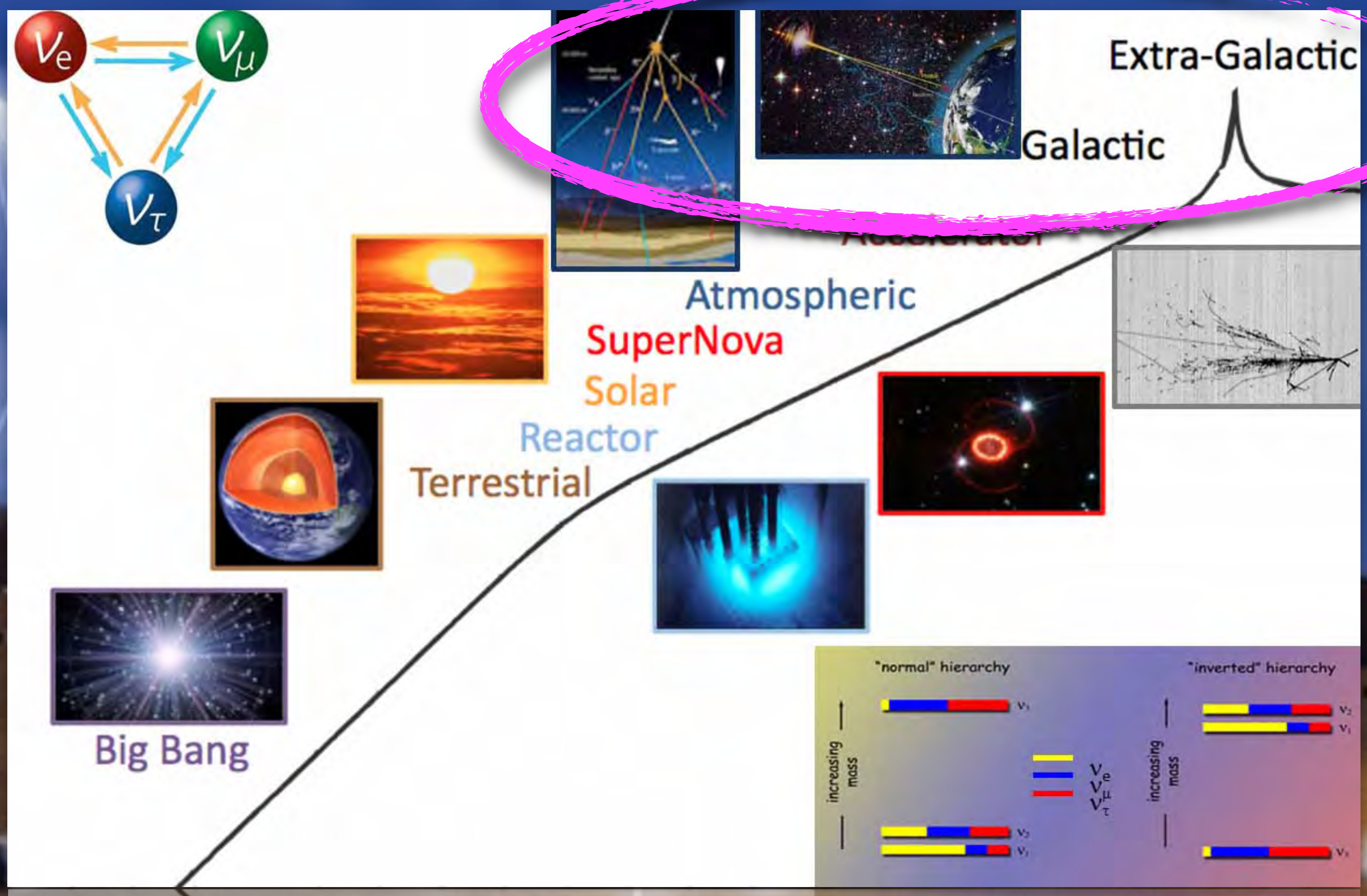
Ultra-High Energy Cosmic Rays: an Experimental Overview

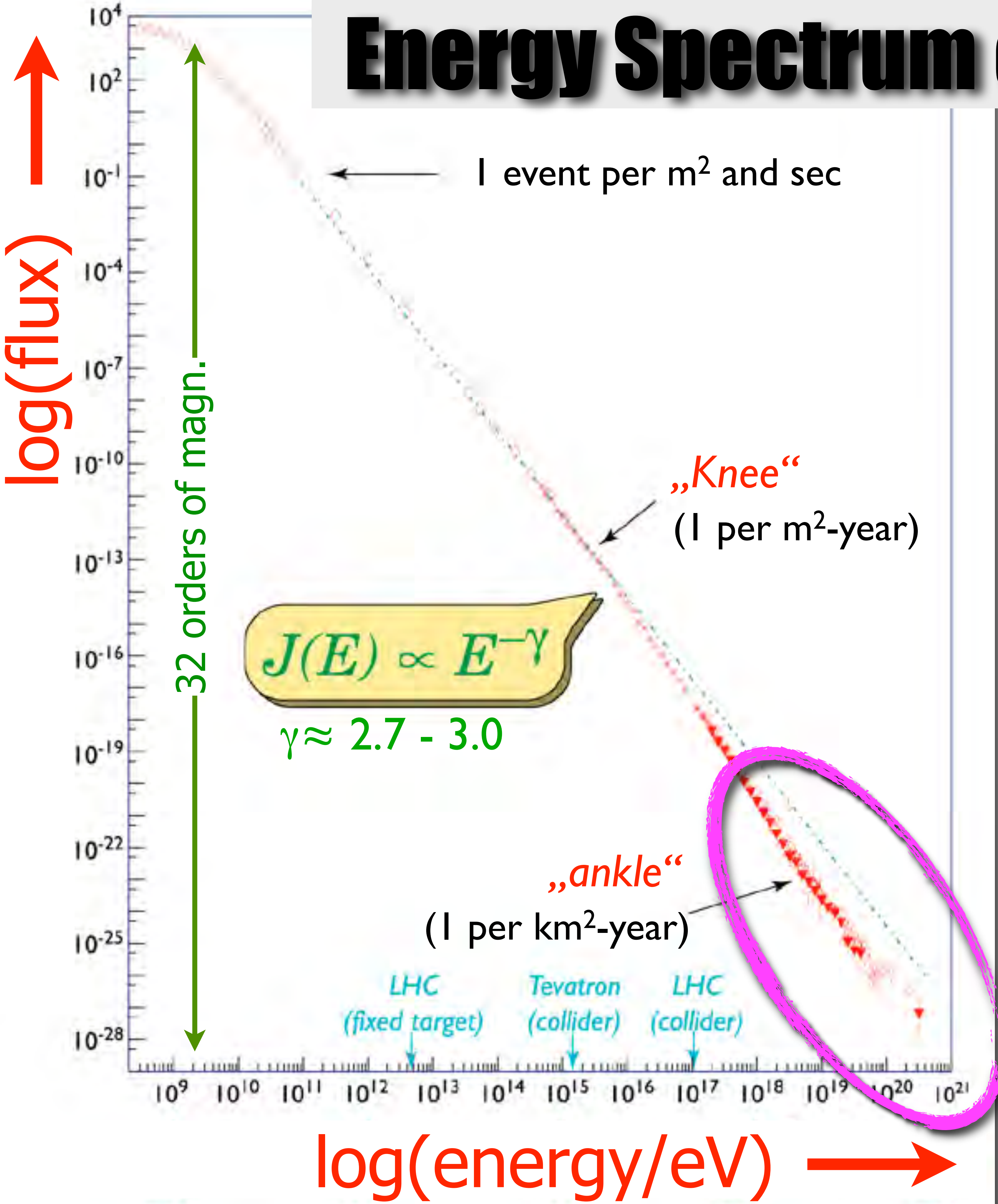
...and extension plans



BERGISCHE
UNIVERSITÄT
WUPPERTAL

Brussels, May 27-29, 2015

Energy Spectrum of Cosmic Rays

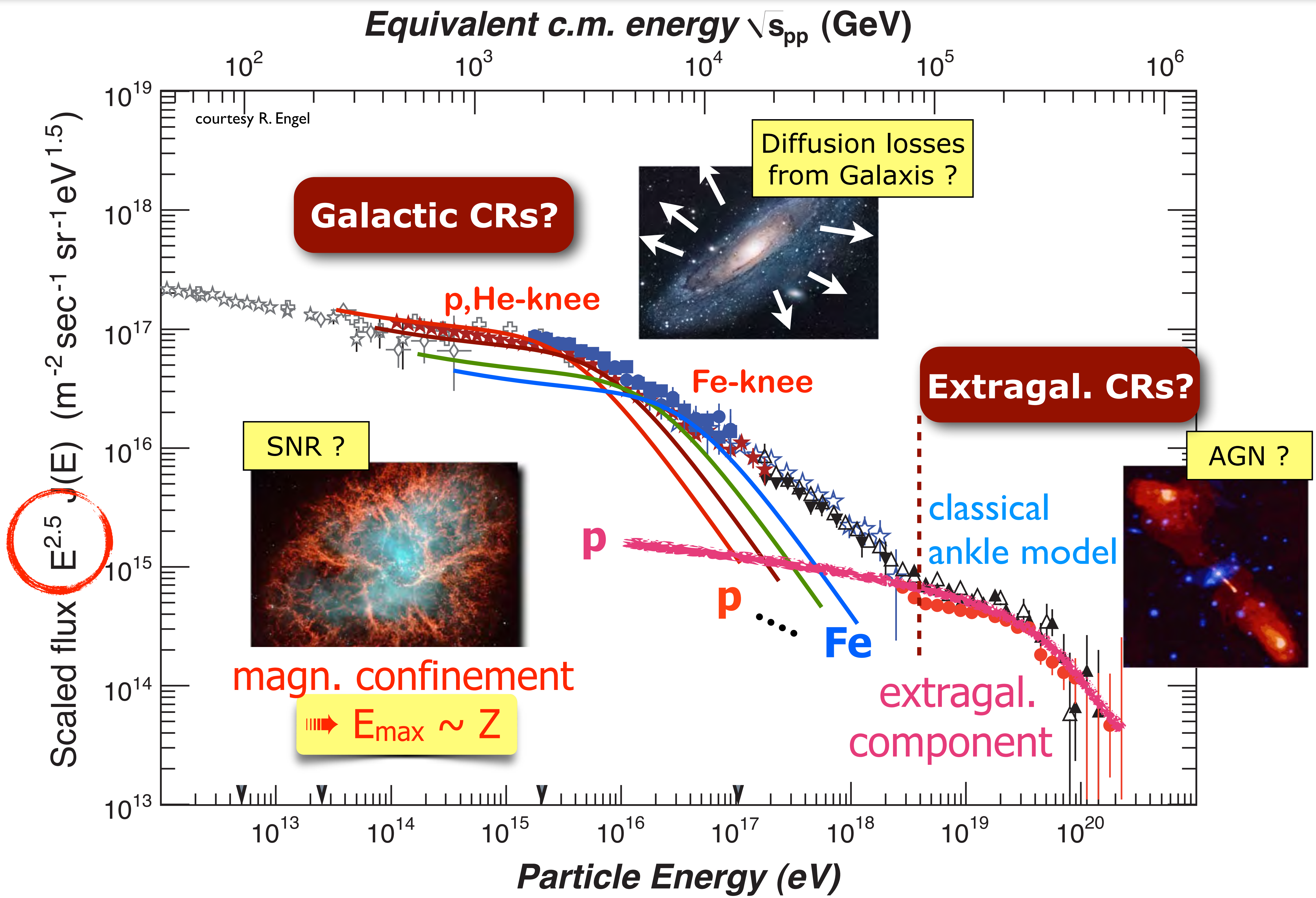


32 orders of magnitude:

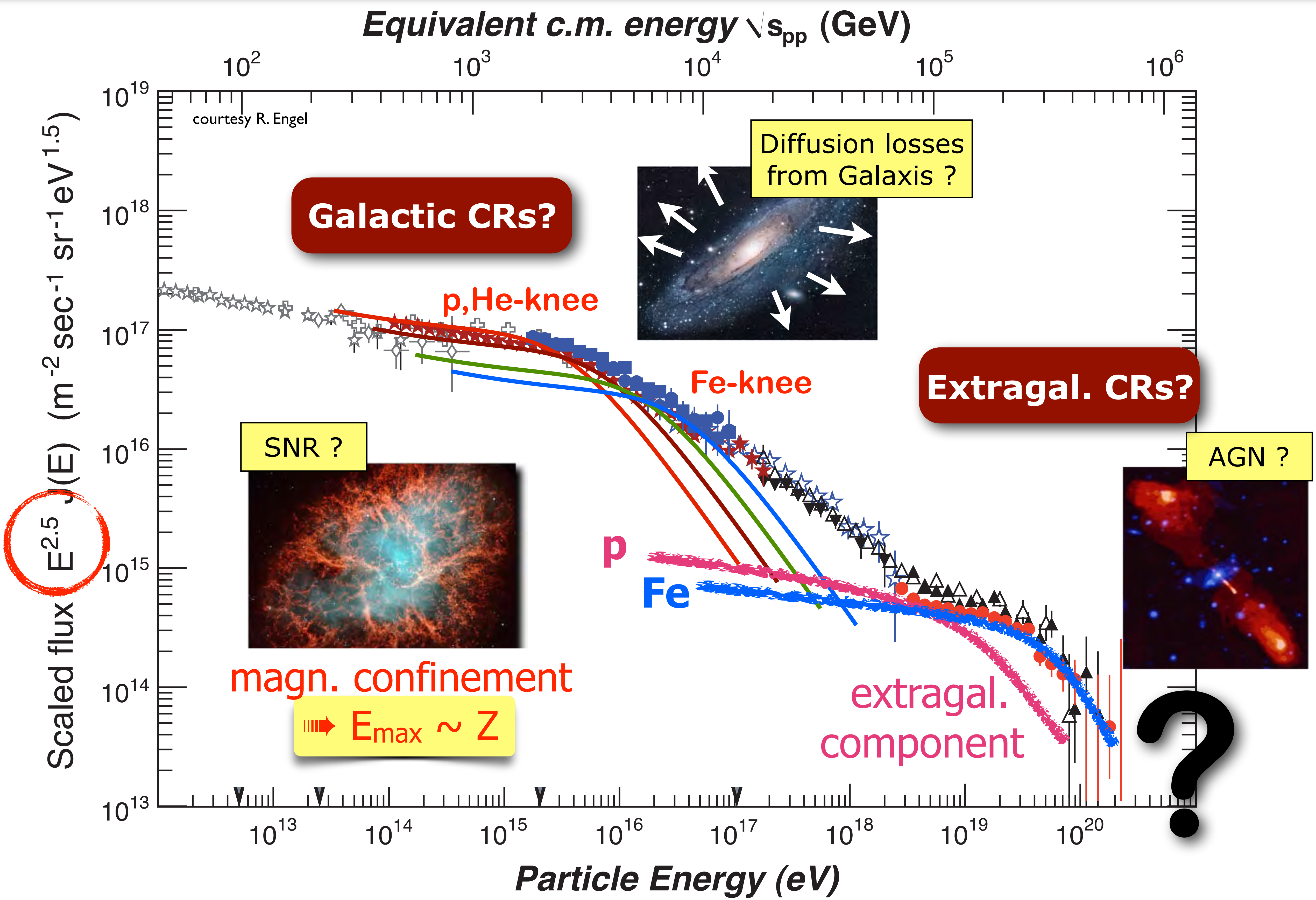
Outline

- **The End of the UHECR Energy Spectrum: GZK-effect or Exhaustion of Sources?**
- **Chemical Composition: getting heavier?!**
- **Arrival Directions: surprisingly isotropic**
- **EeV neutrinos and photons: smoking gun**
- **Further Searches: neutrons, monopoles, ...**
- **Future: Upgrades of Auger and TA**

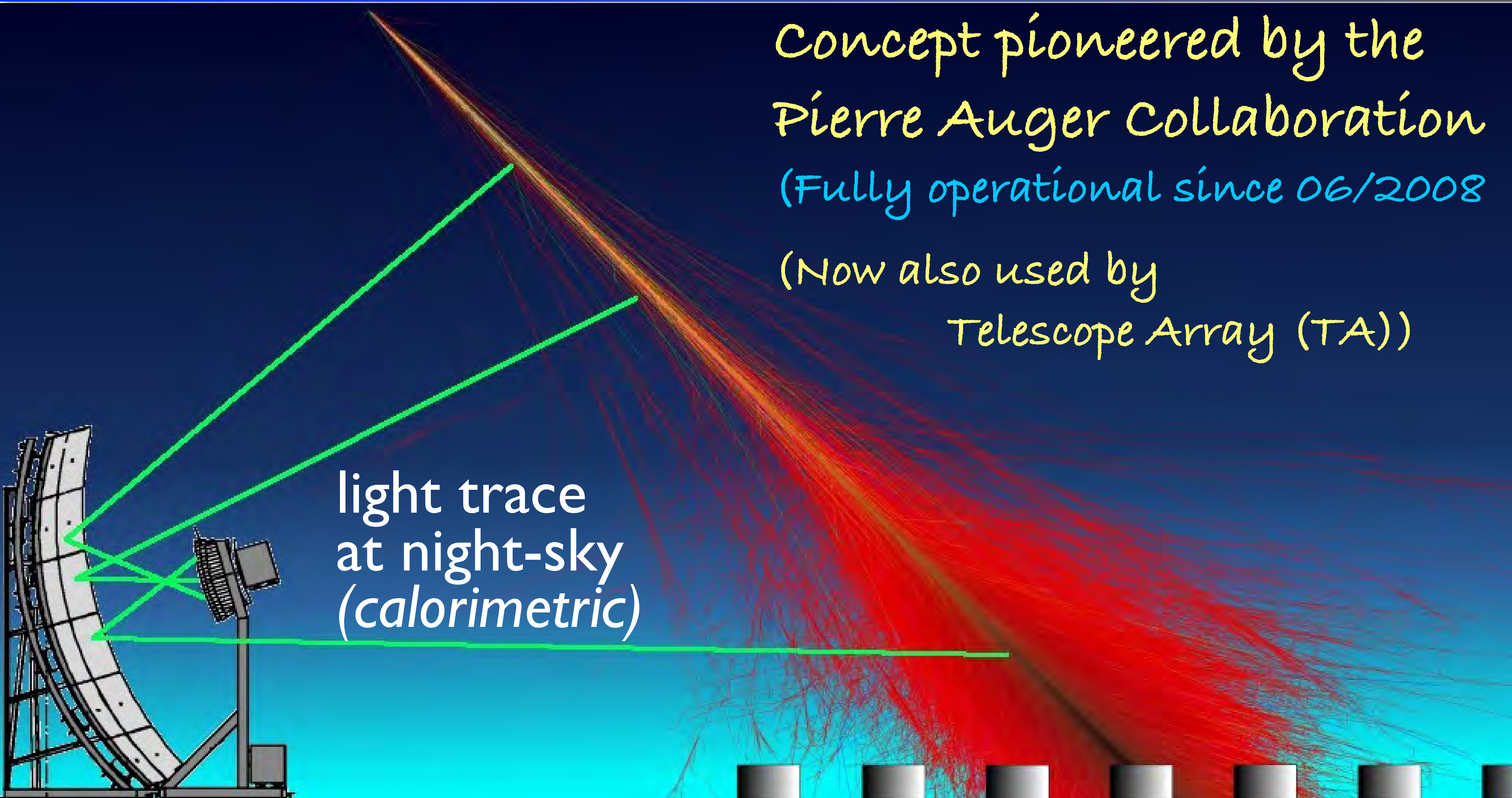
Features of CR spectrum



Features of CR spectrum



Hybrid Observation of EAS



Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radio- & Microwave-Signals

Pierre Auger Observatory

1660 detector stations on 1.5 km grid

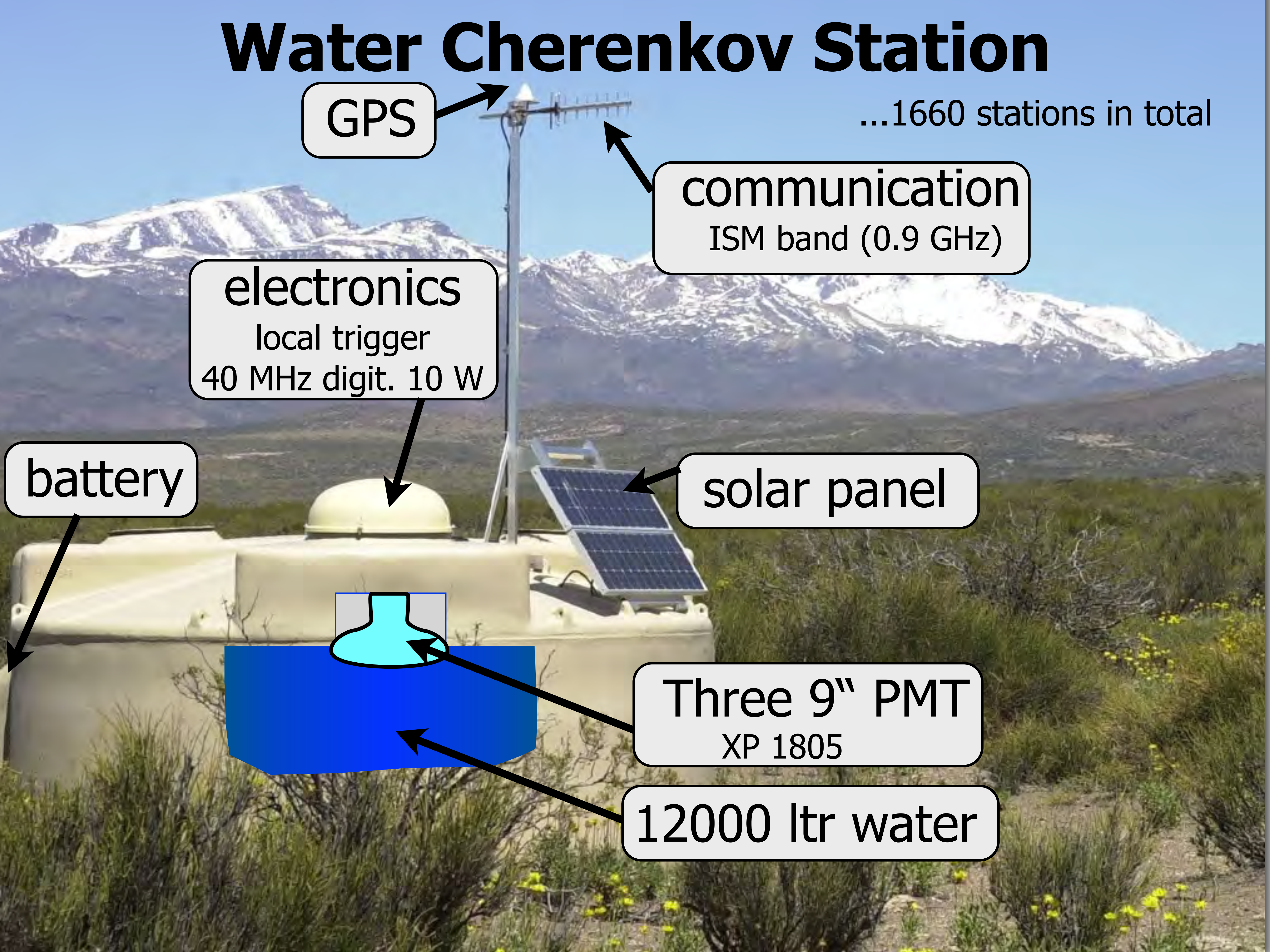
27 fluores. telescopes at periphery

130 radio antennas

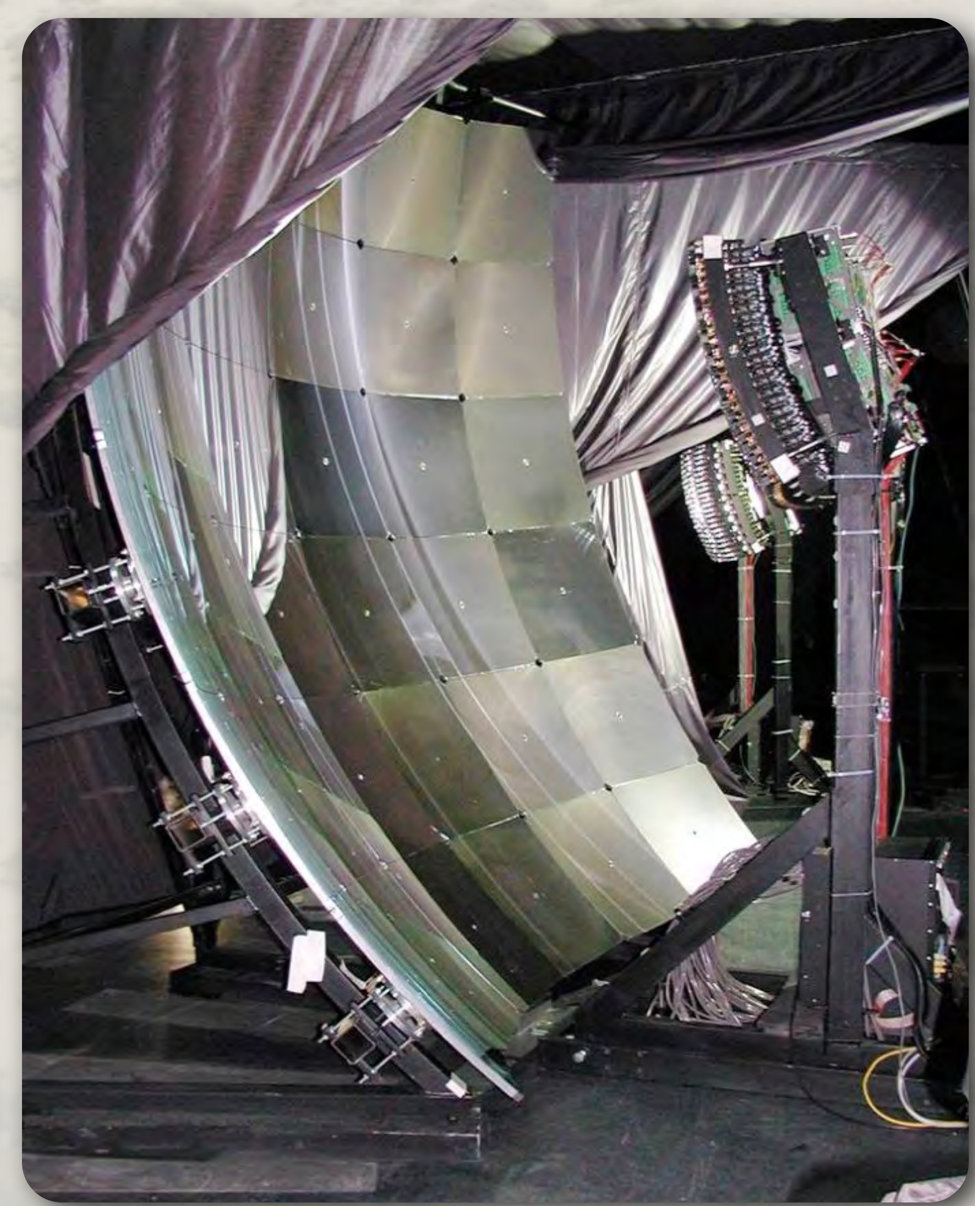
Province Mendoza, Argentina

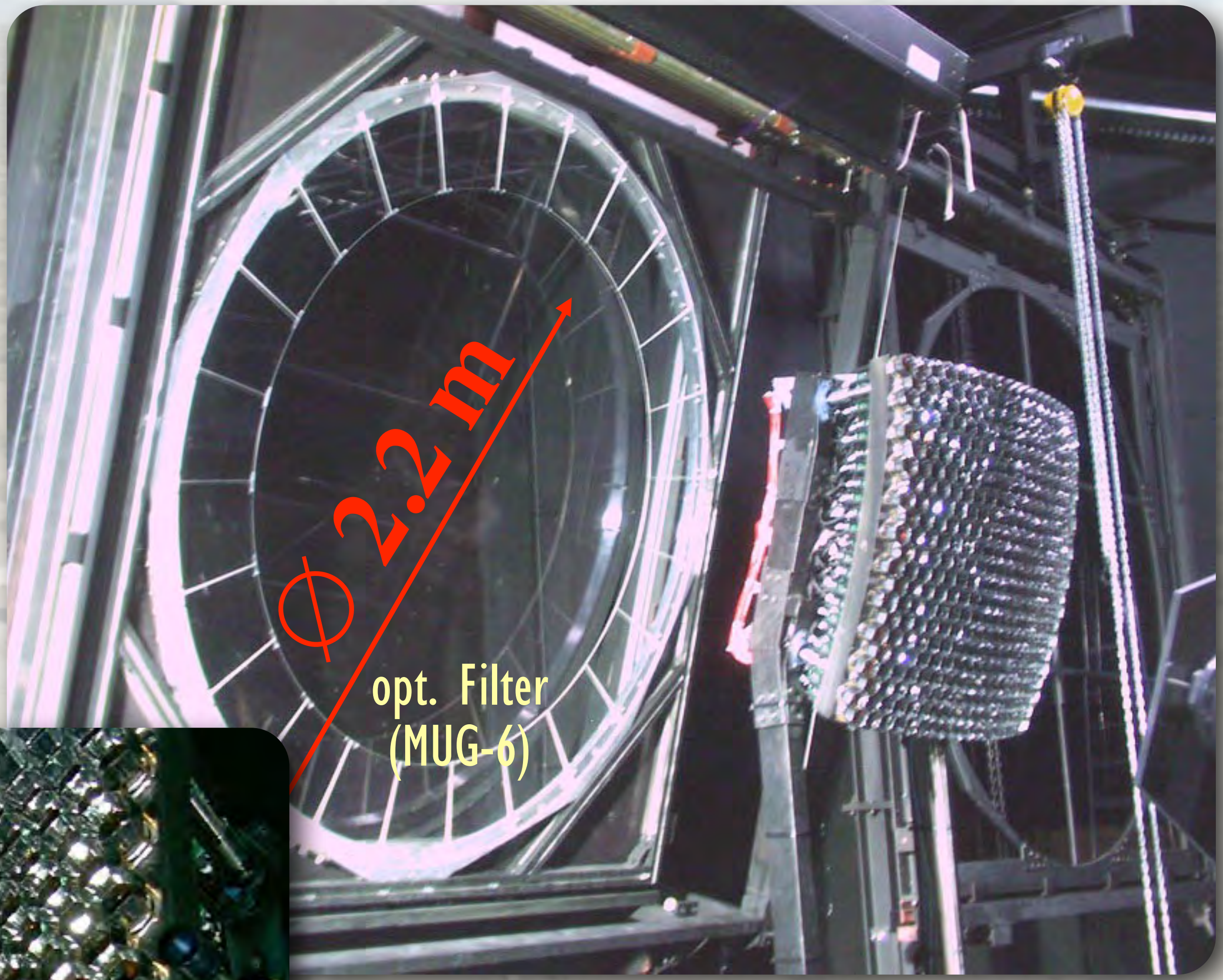
Auger Hybrid Observatory

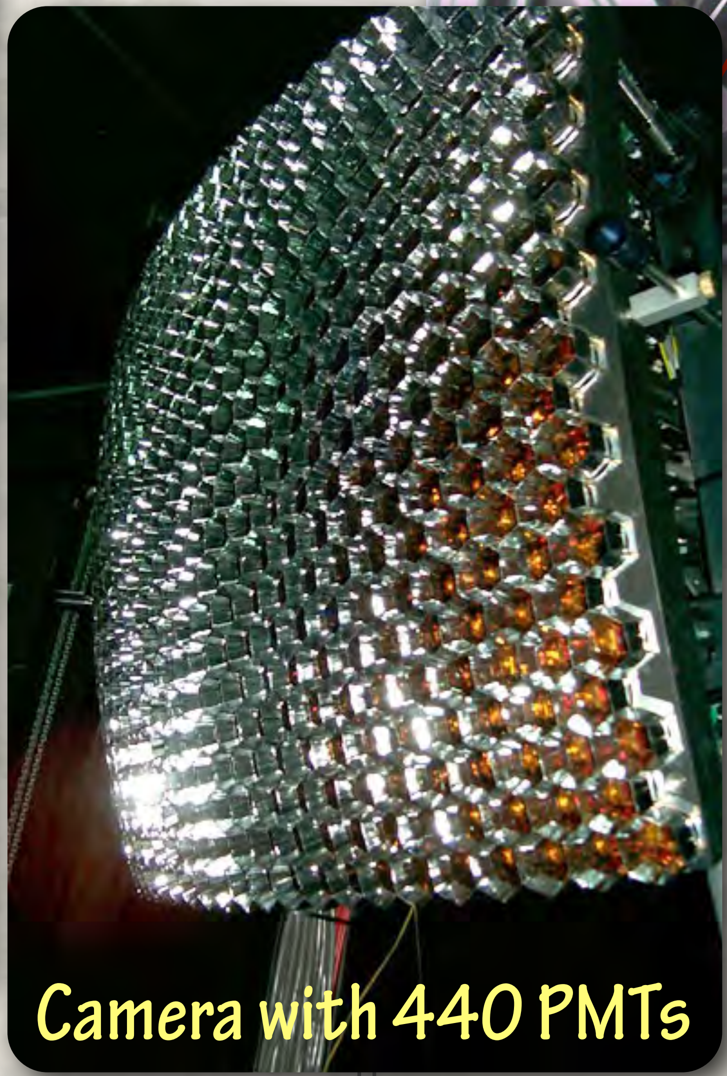
3000 km^2 area, Argentina
27 fluorescence telescopes plus
...1660 Water Cherenkov tanks

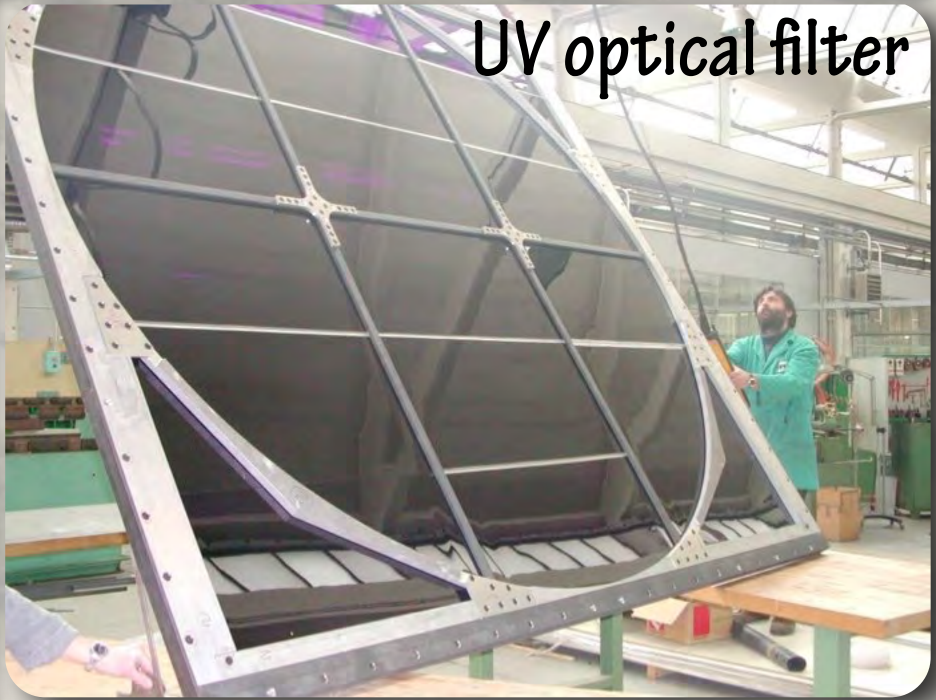

Water Cherenkov Station
GPS
...1660 stations in total
communication
ISM band (0.9 GHz)
electronics
local trigger
40 MHz digit. 10 W
battery
solar panel
Three 9" PMT
XP 1805
12000 ltr water

24 telescopes (6 per site)
12 m^2 mirrors, Schmidt optics
30°x30° deg field of view
440 PMTs/camera
10 MHz FADC readout



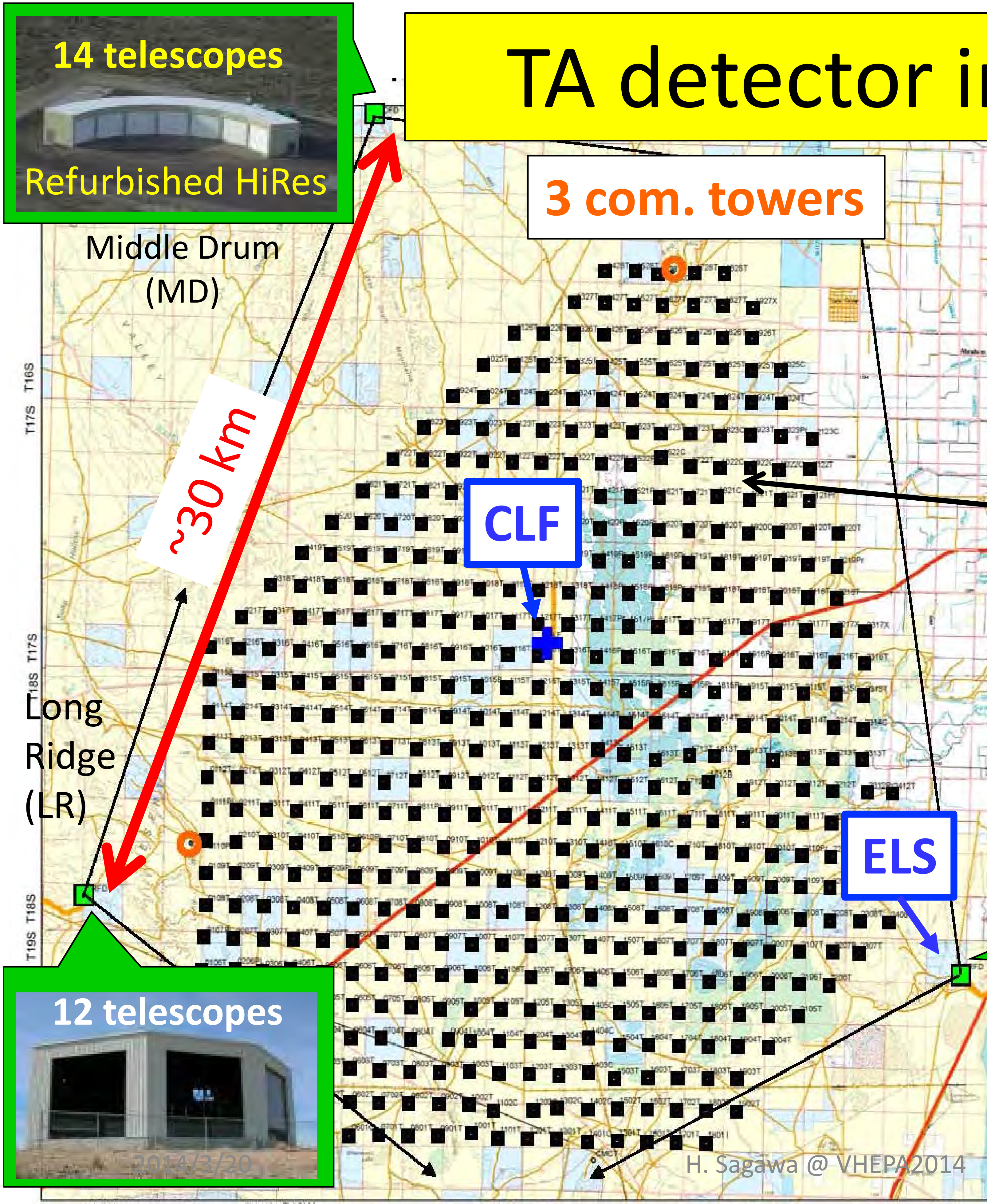






TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

~700 km²

Fluorescence Detector(FD)

3 stations

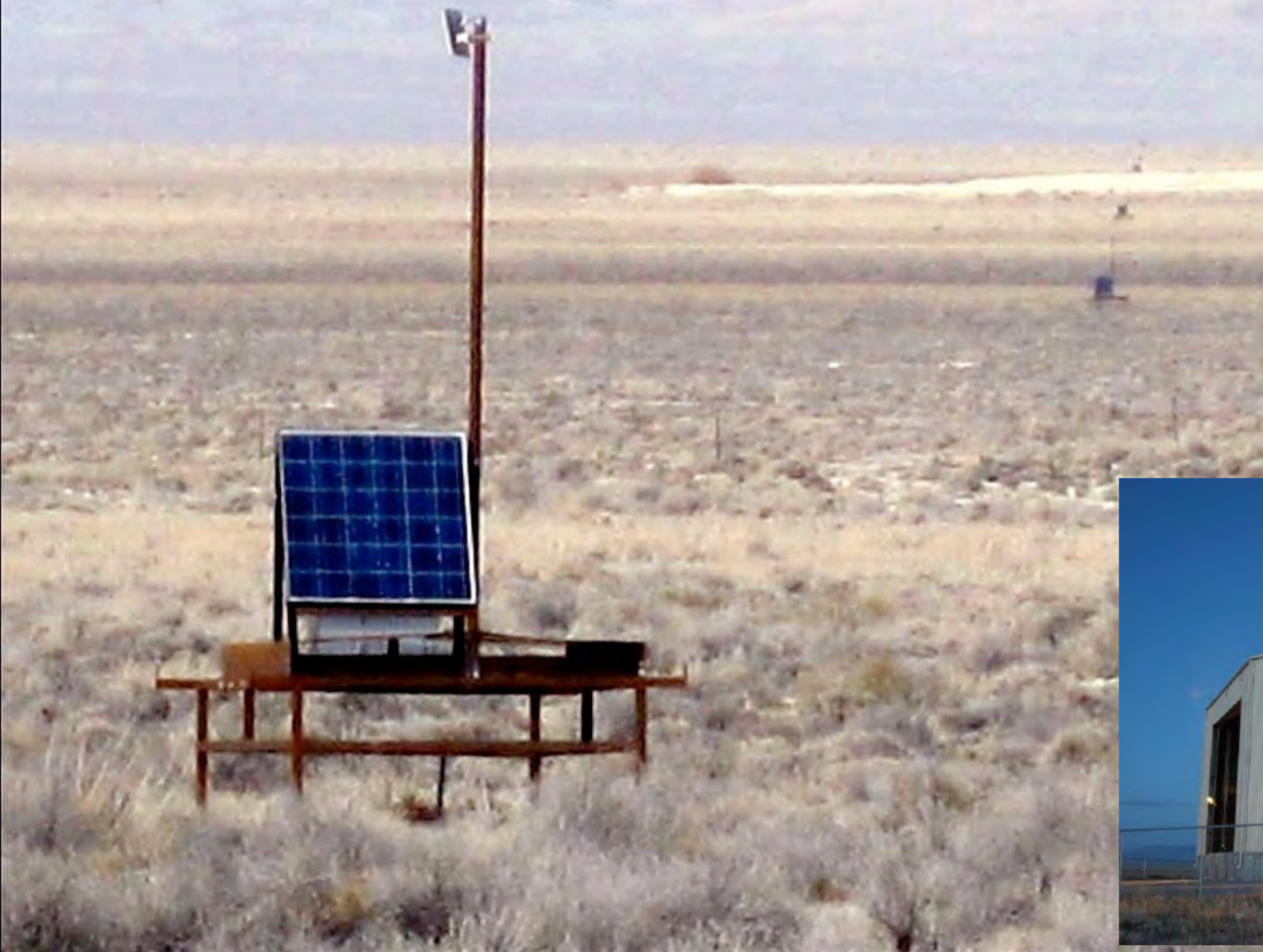
38 telescopes

FD and SD: fully operational since 2008/May

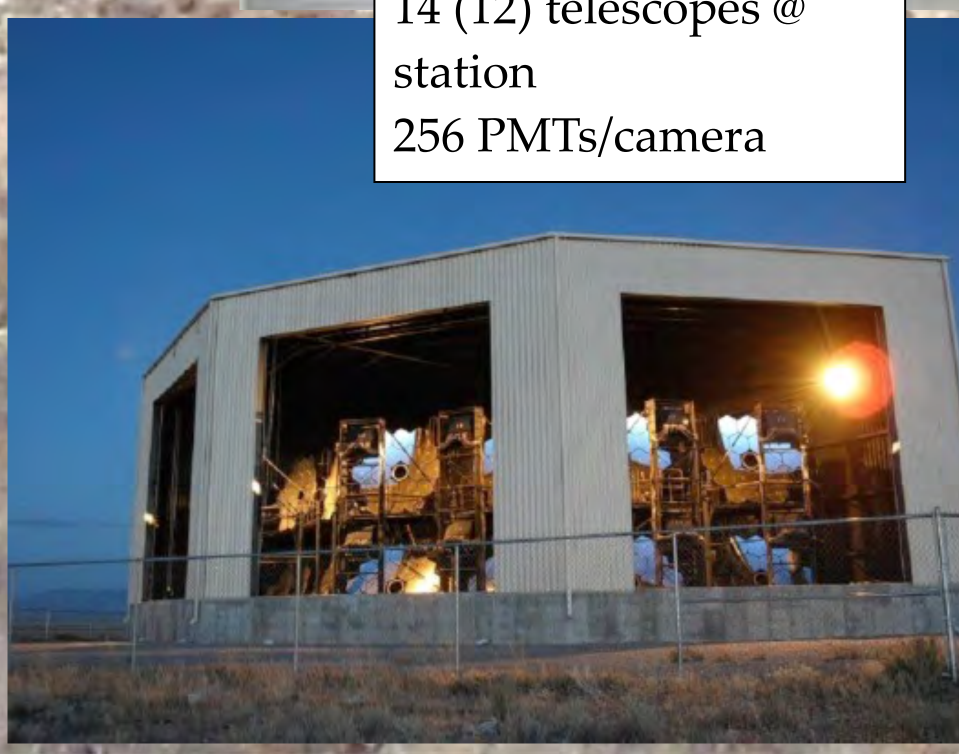
4

Telescope Array

700 km^2, Utah (USA)
3 m^2 Scintillator Detectors
on a 1.2 km square grid

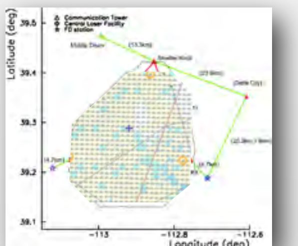


14 (12) telescopes @ station
256 PMTs/camera



Auger and TA

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

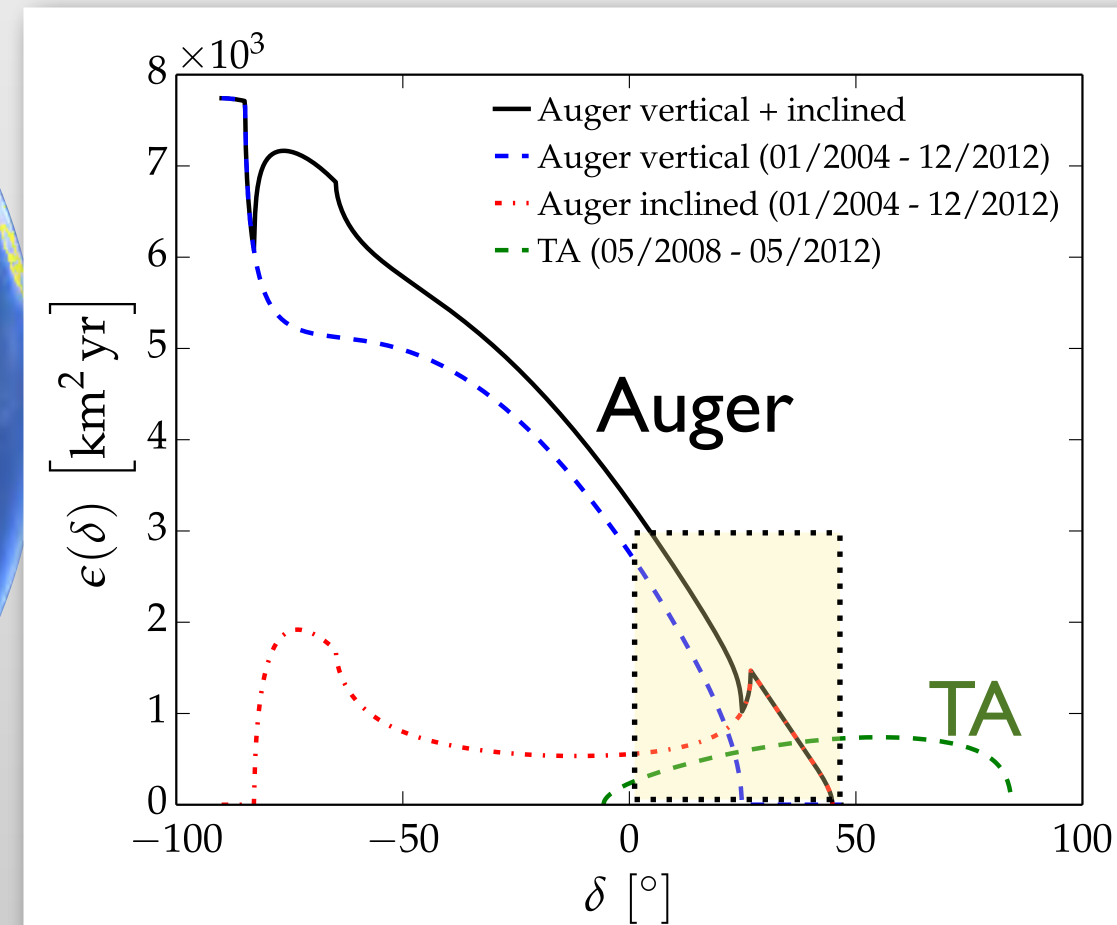


same scale

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

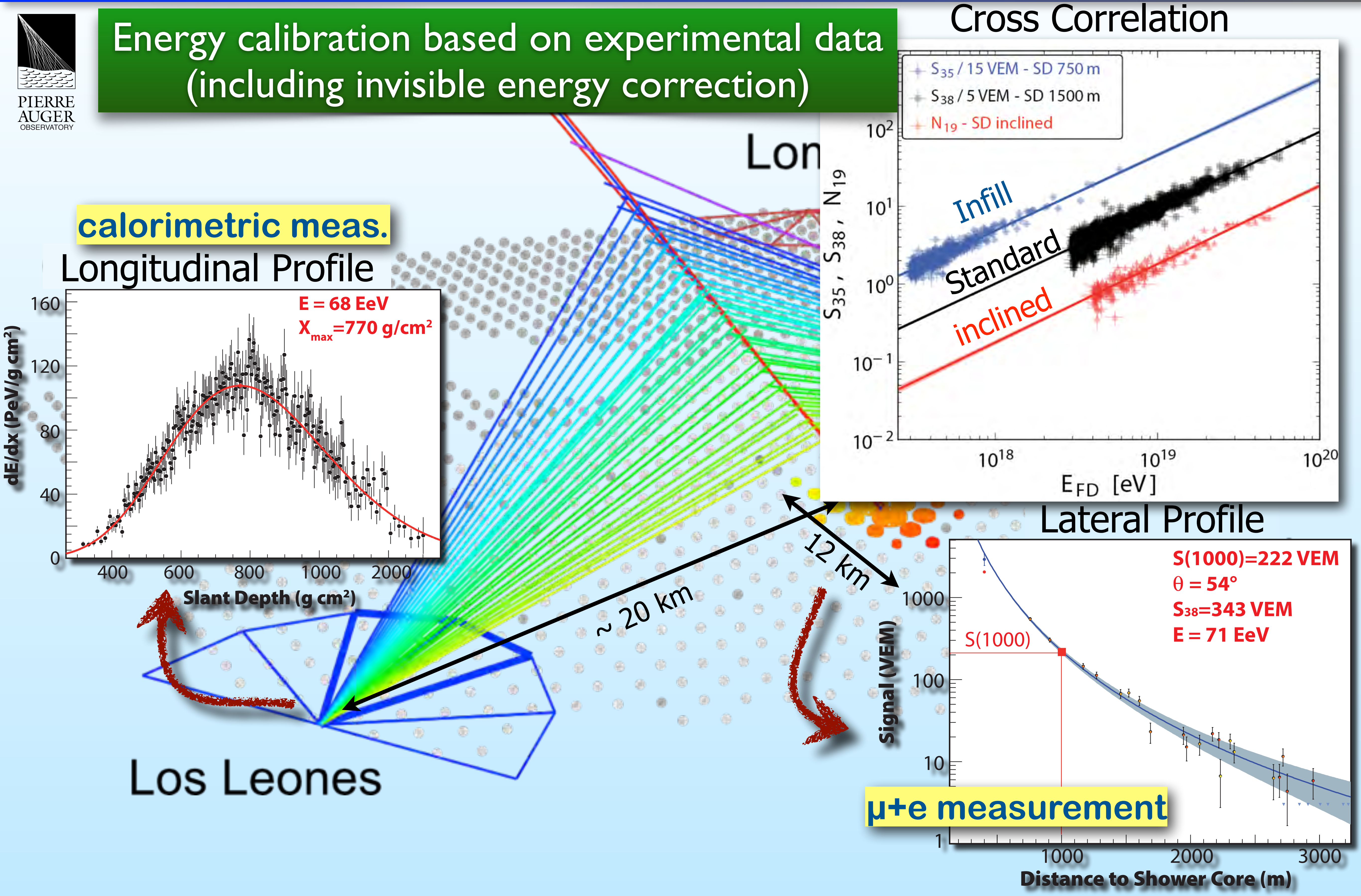
Auger and TA can see the same sky

Auger: 01/2004 - 12/2012
TA: 05/2008 - 05/2012



Auger exposure ~10 times that of TA

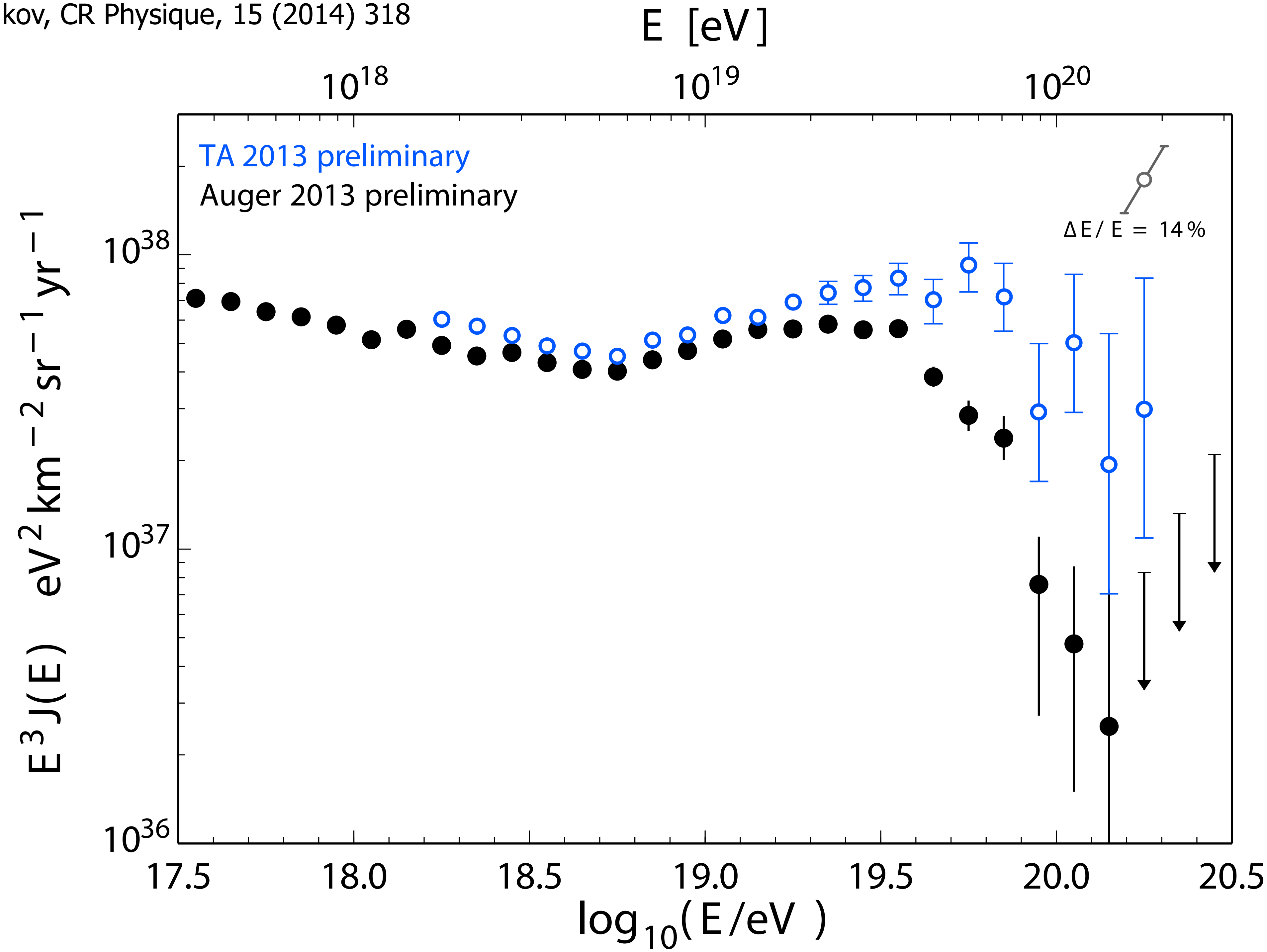
Event Example in Auger Observatory



Energy Spectrum

All Particle Energy Spectrum

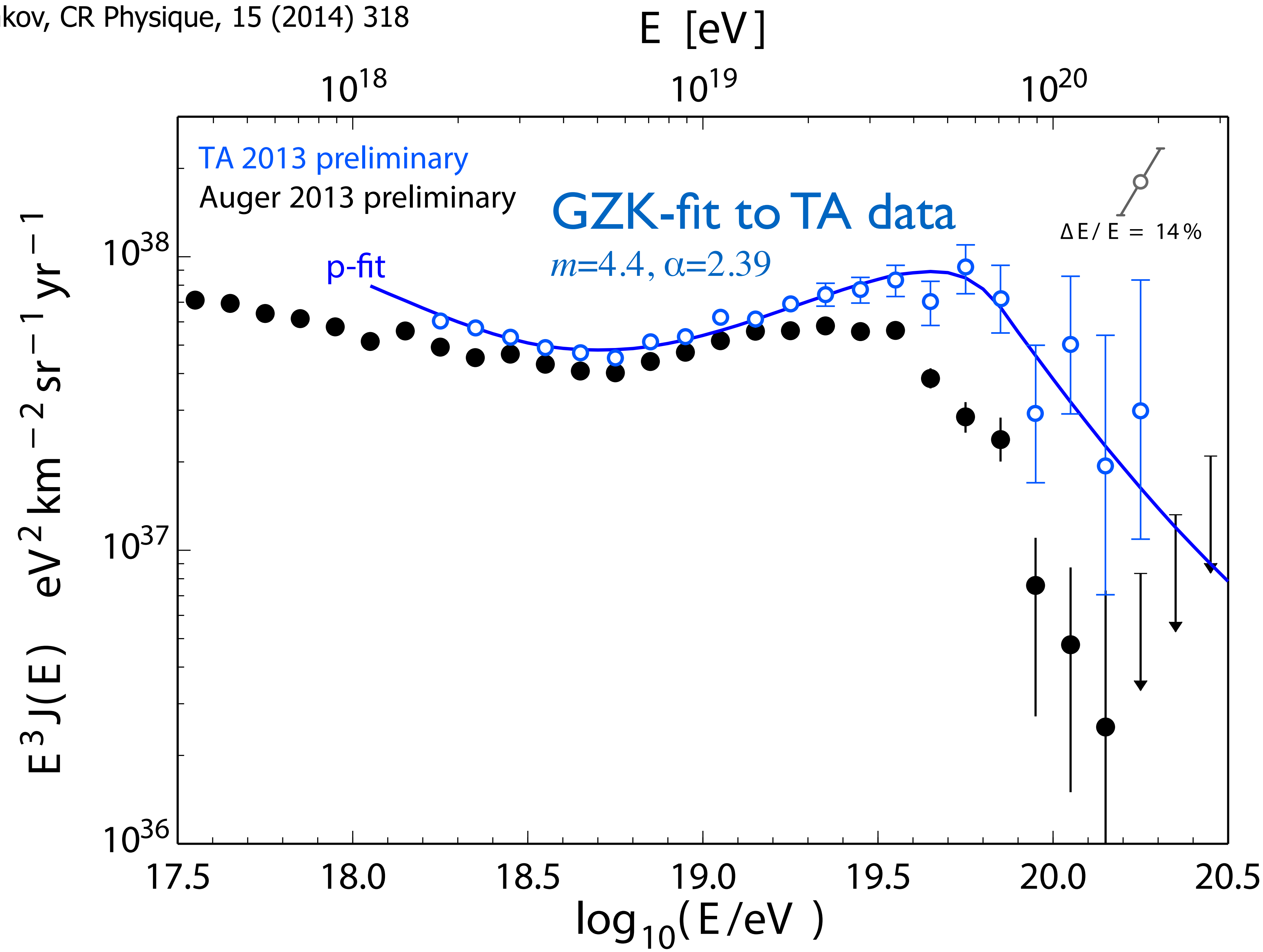
Kampert & Tiniakov, CR Physique, 15 (2014) 318



Good agreement between experiments
- some differences at the highest energies -

All Particle Energy Spectrum

Kampert & Tiniakov, CR Physique, 15 (2014) 318



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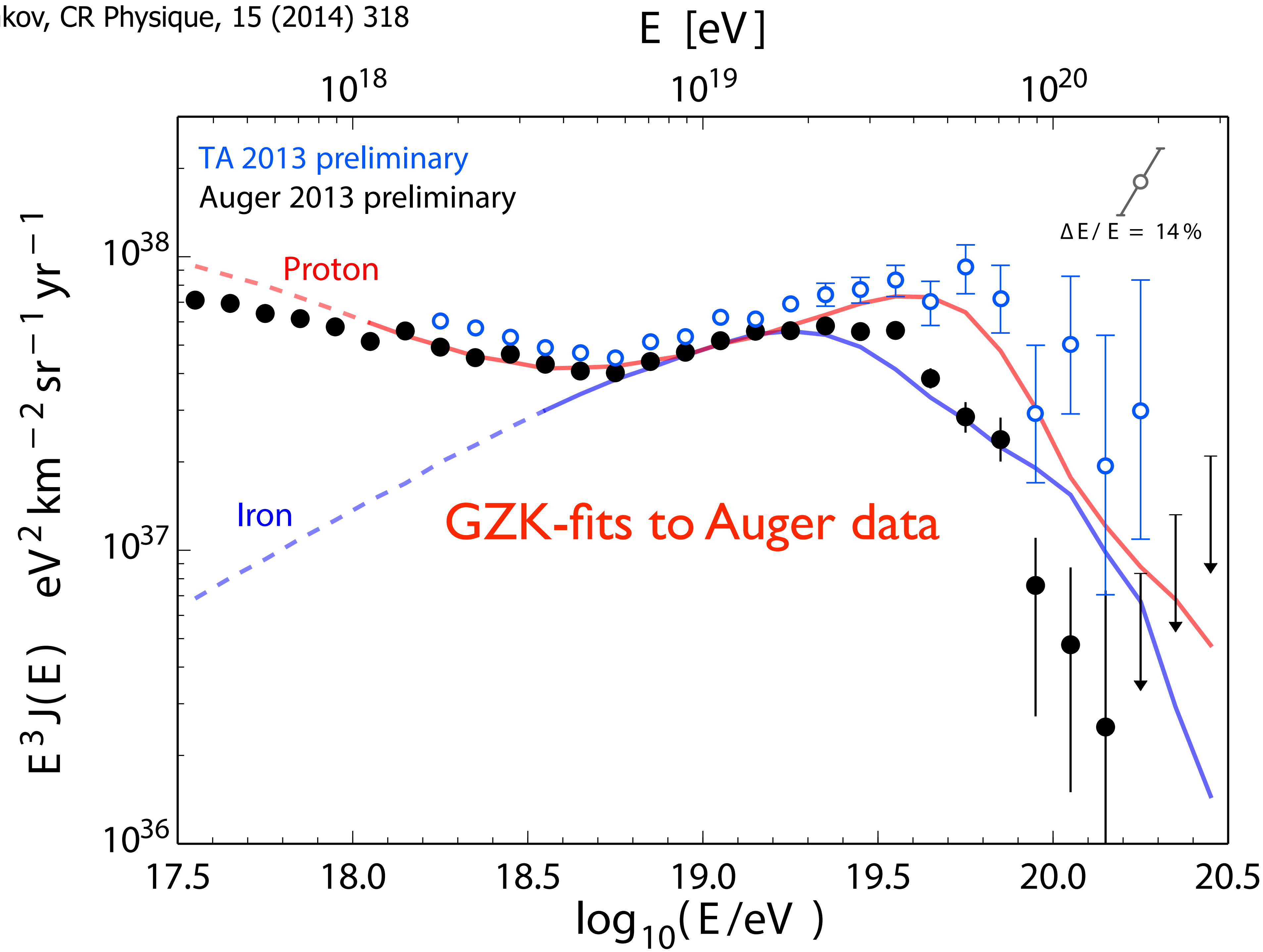
Kampert & Tiniakov, CR Physique, 15 (2014) 318



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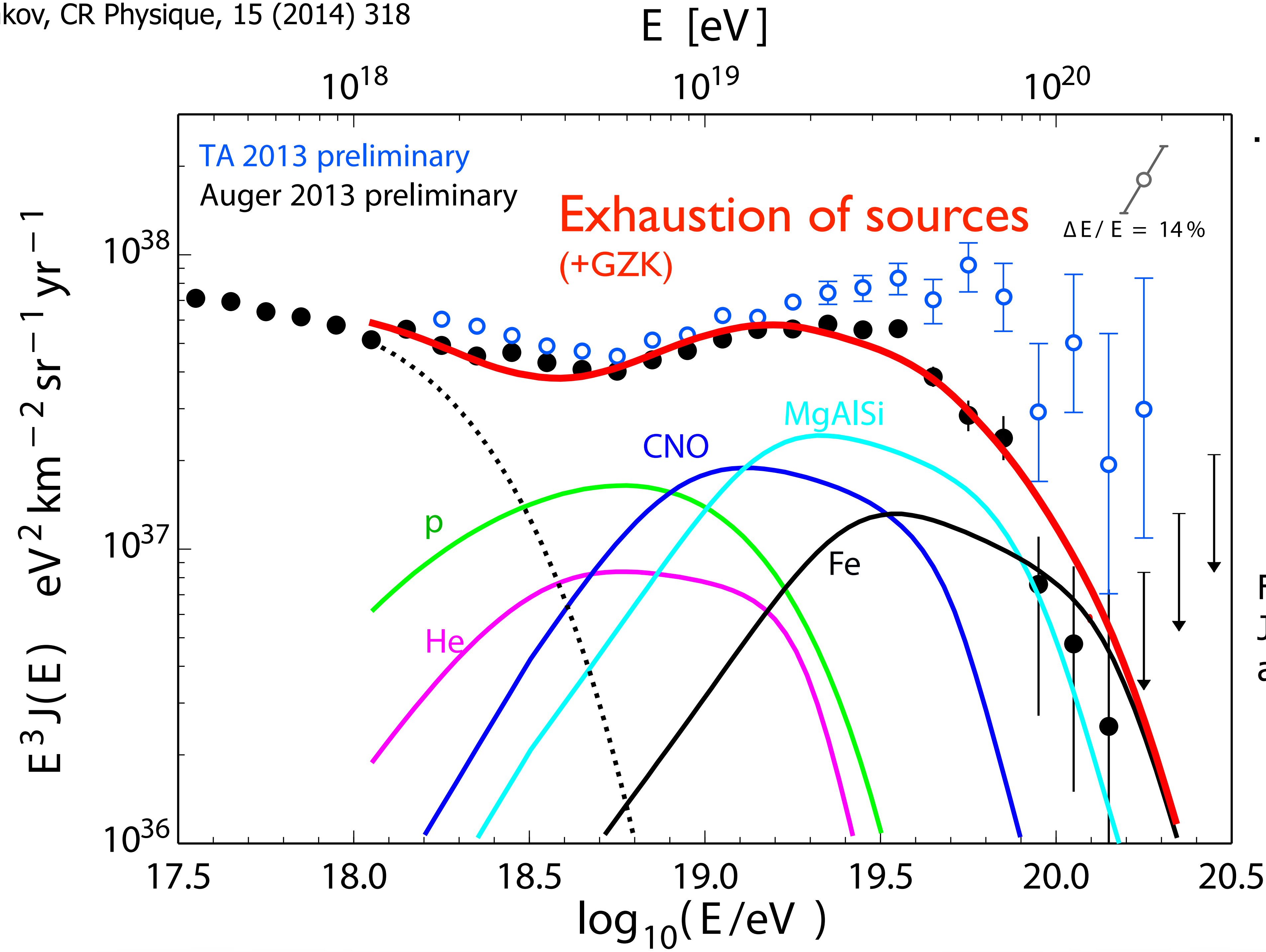


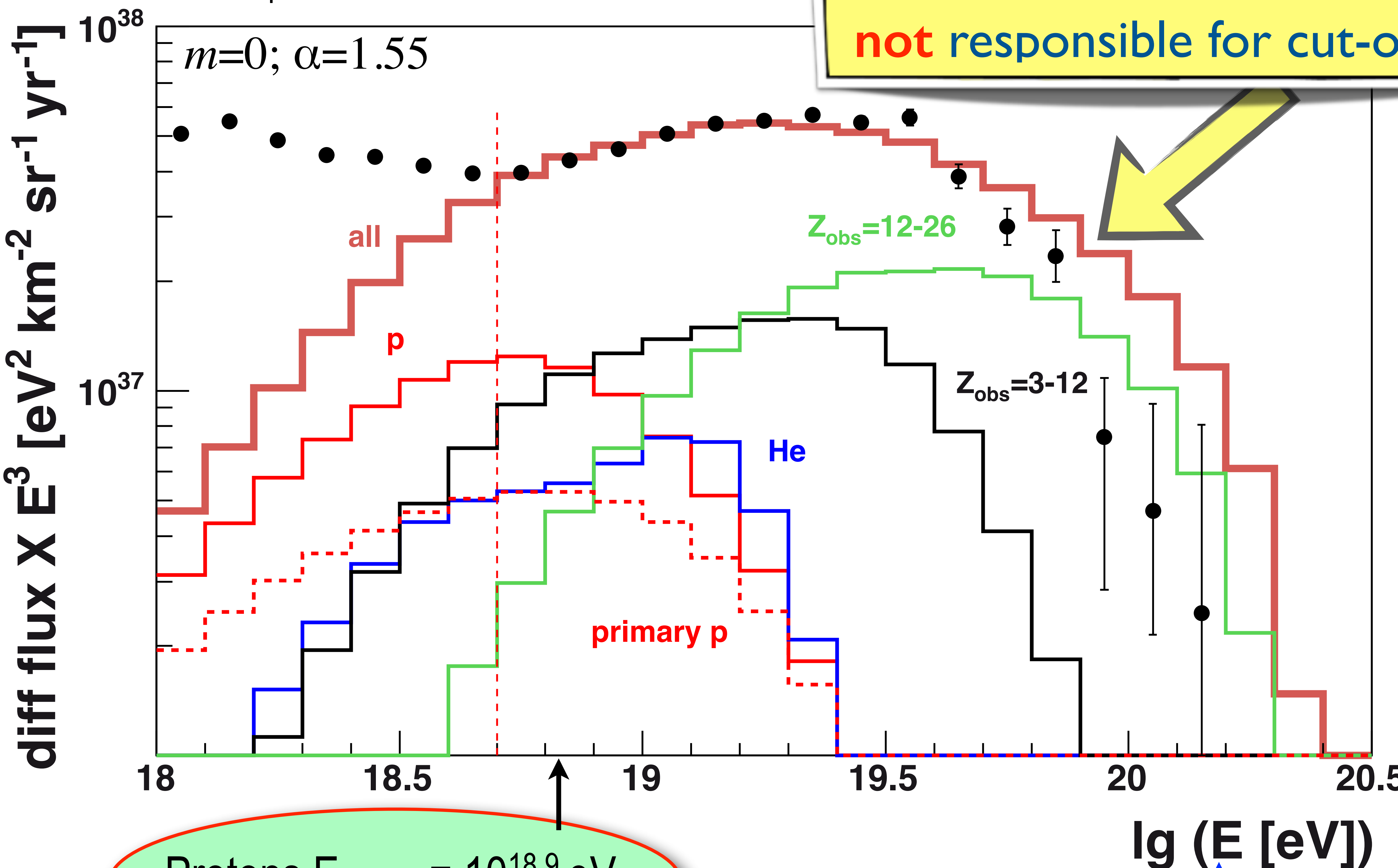
Fit by Blasi et al.
JCAP 2014
arXiv:1312.7459v1

Energy spectrum itself is ambiguous concerning interpretations

Limiting Energy of Sources (E_{max}~Z) + GZK

Model inspired by Allard, Astropart. Phys. 39-40, 2012

Simulations done with CRPropa 2.0



In this case GZK-effect is **not** responsible for cut-off!

Protons $E_{max,p} = 10^{18.9}$ eV

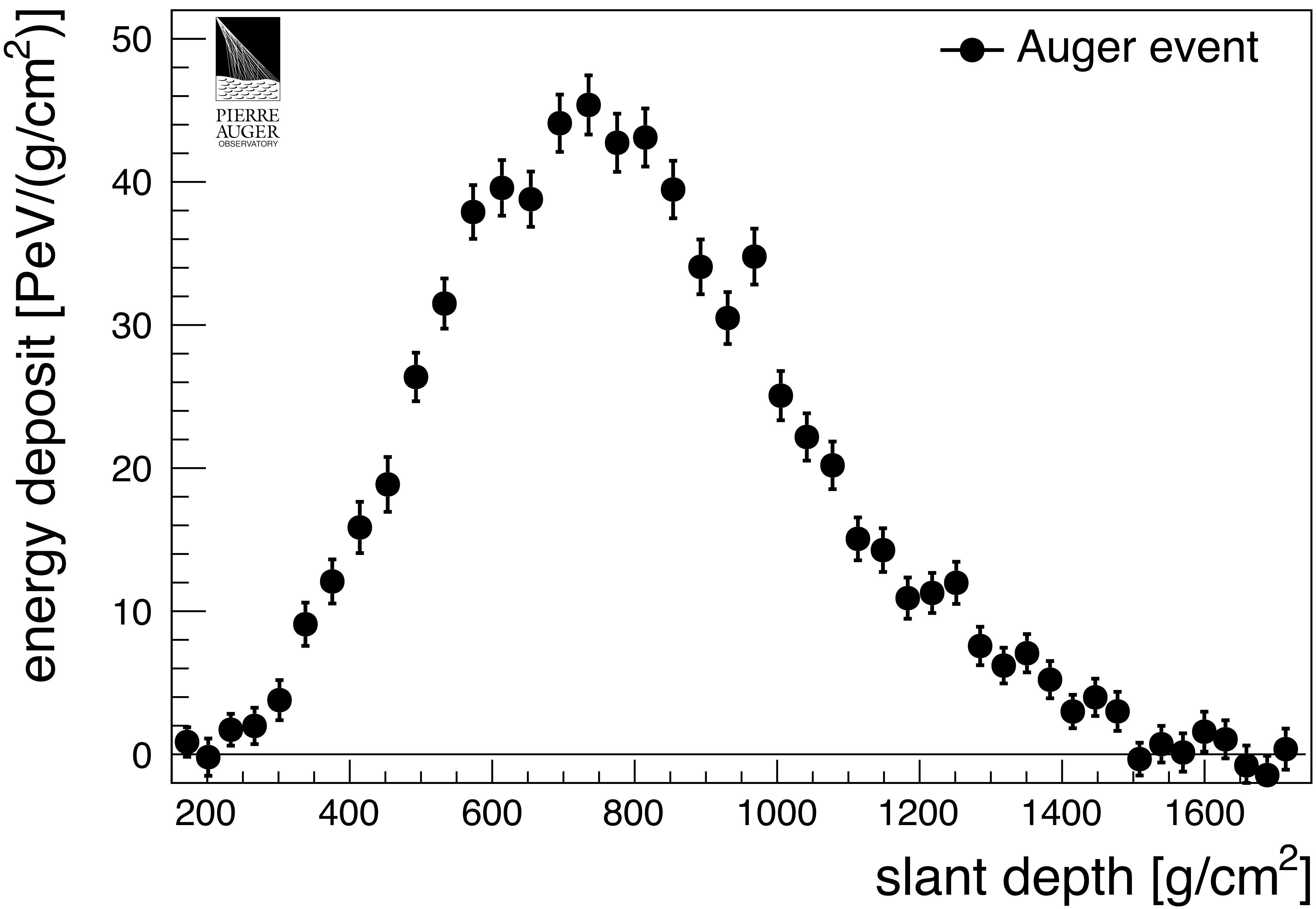
Iron $E_{max,\,Fe} = 26\ E_{max,p} = 10^{20.3}$ eV

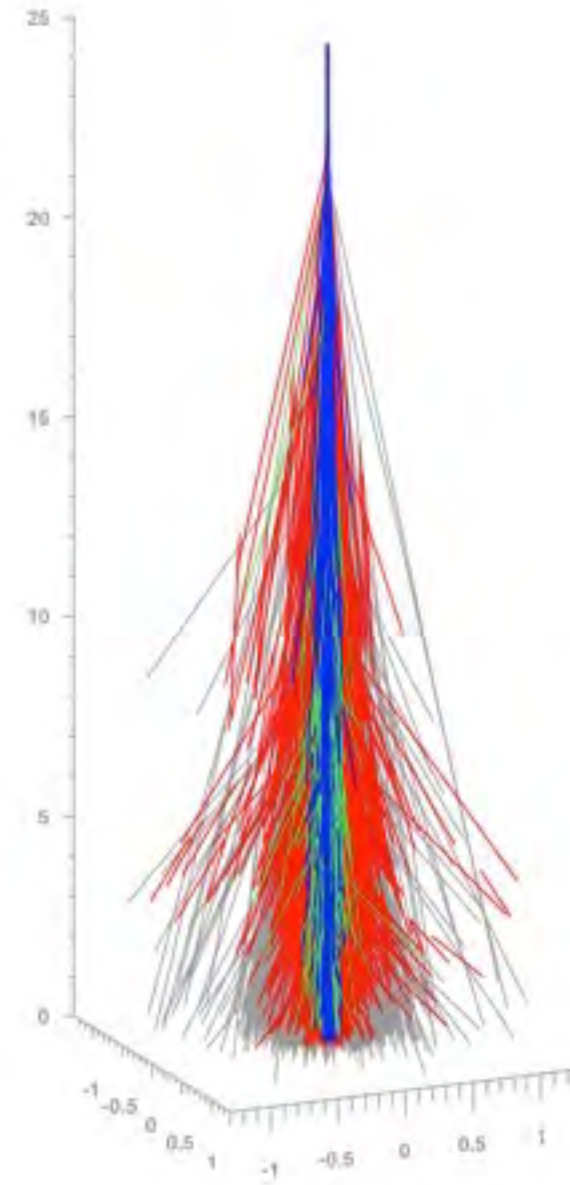
Mass Composition

Longitudinal Shower Development → Primary Mass

KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

Example of a $3 \cdot 10^{19}$ eV EAS event in FD





Longitudinal Shower Development → Primary Mass

KHK, Unger, APP 35 (2012)
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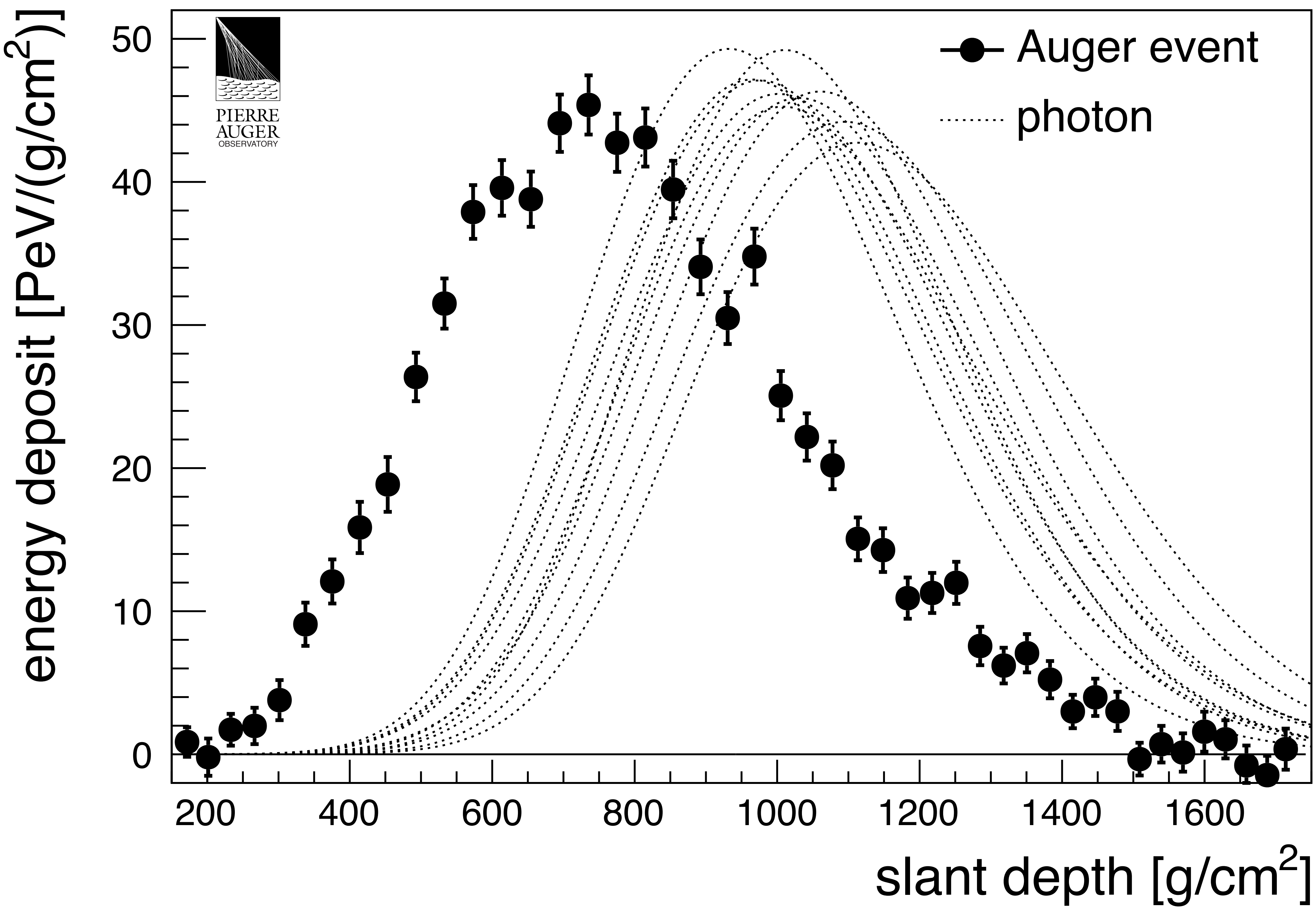

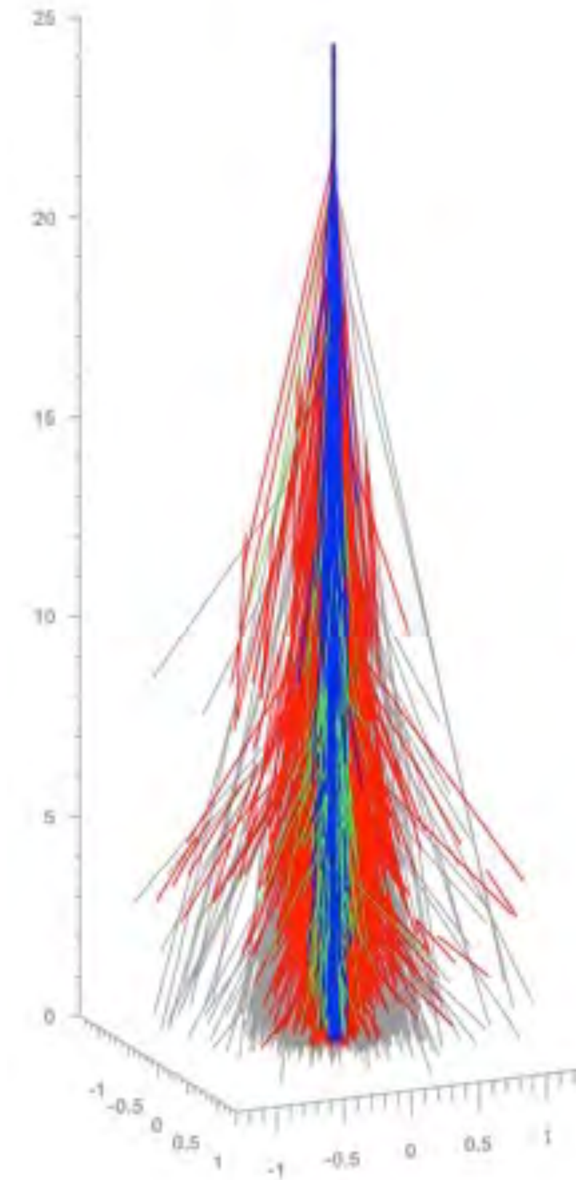

Longitudinal Shower Development → Primary Mass

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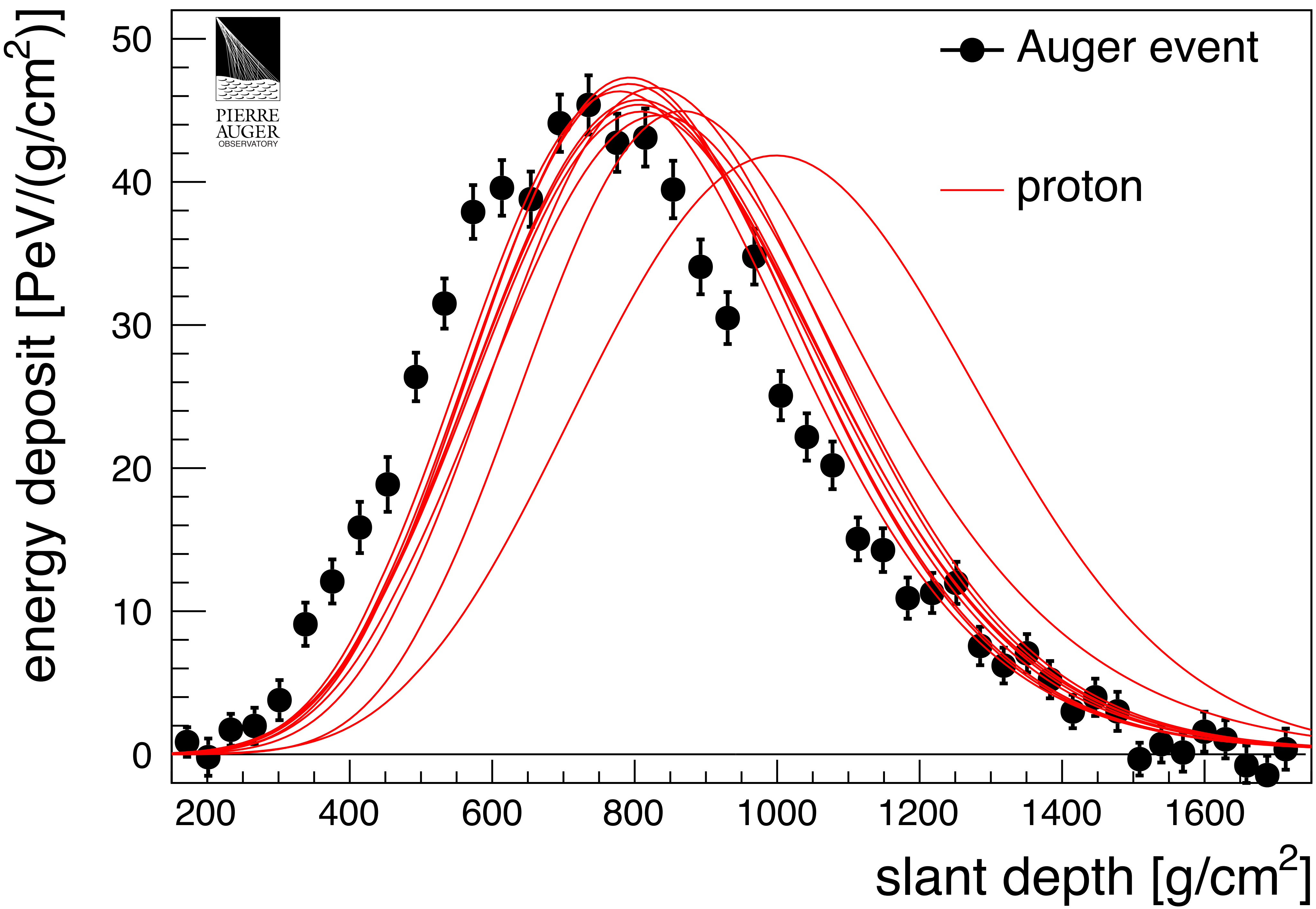

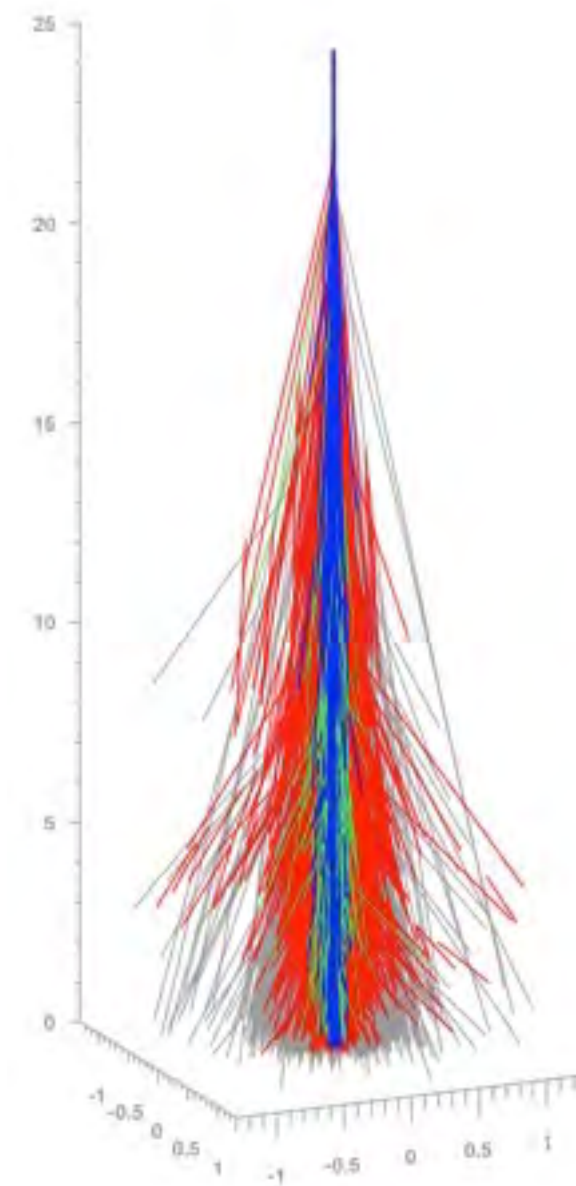

Longitudinal Shower Development → Primary Mass

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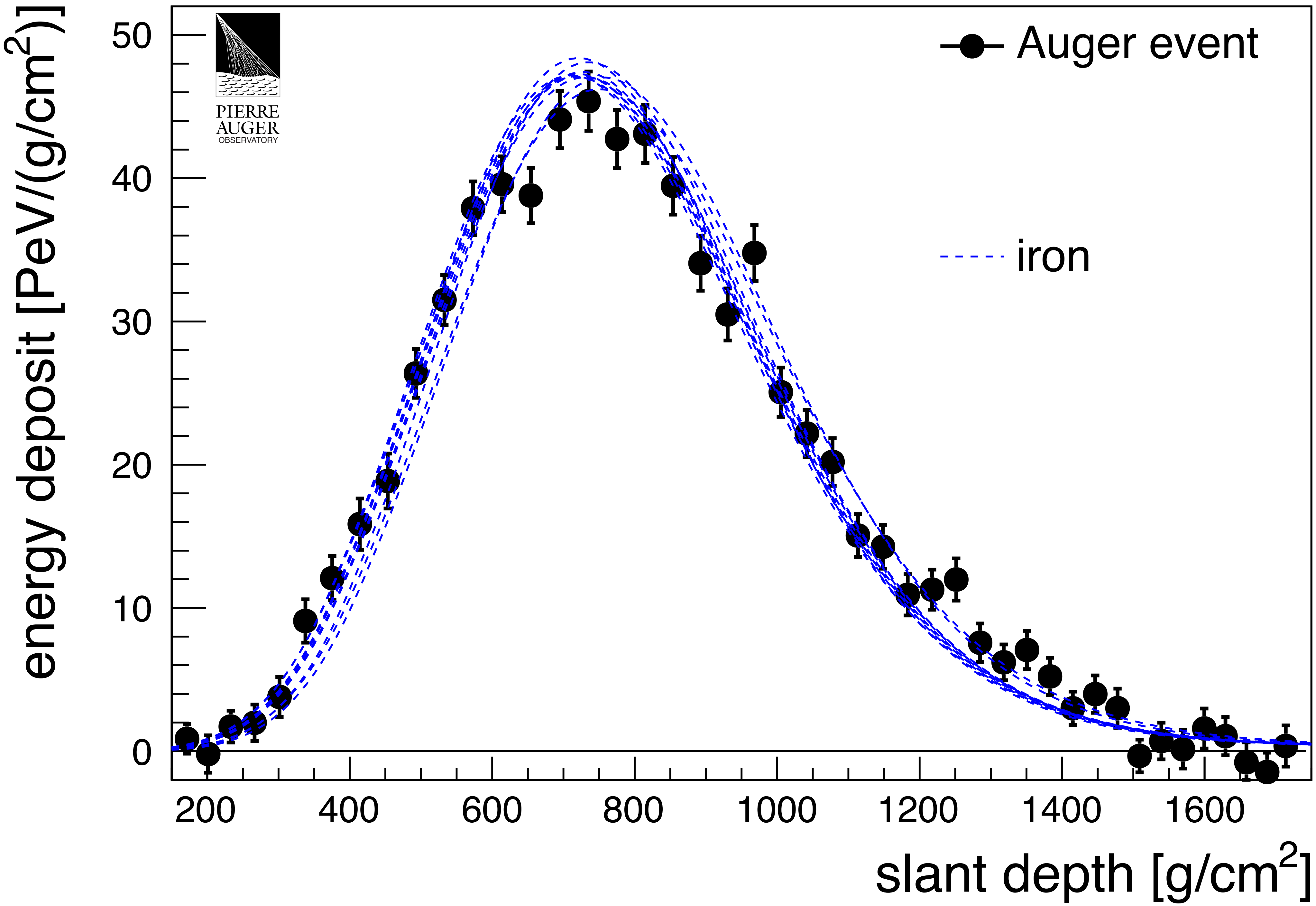

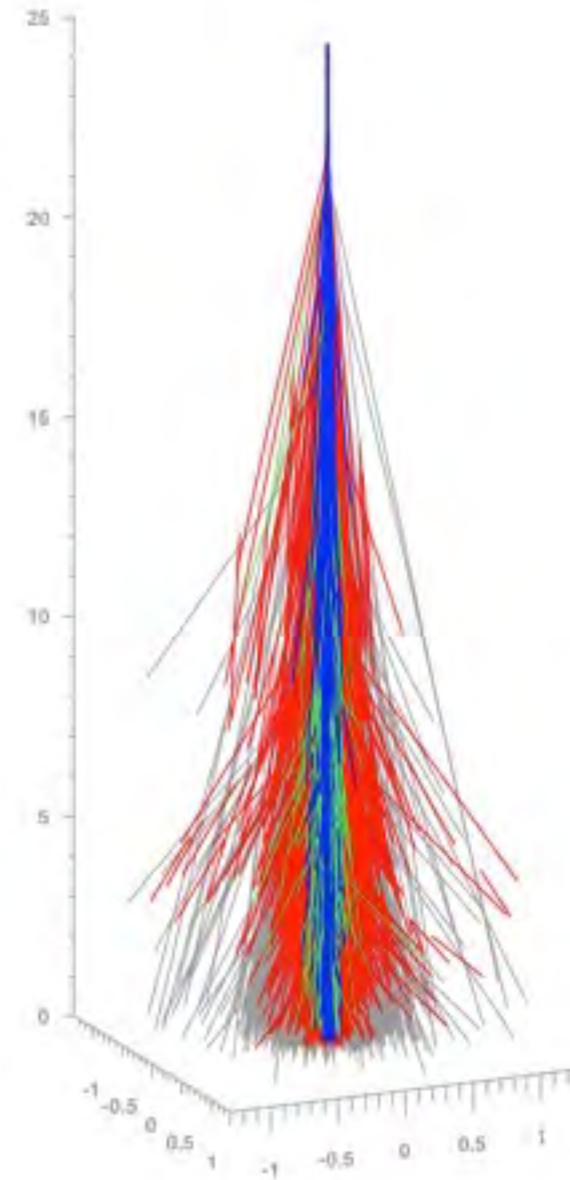

KHK, Unger, APP 35 (2012)
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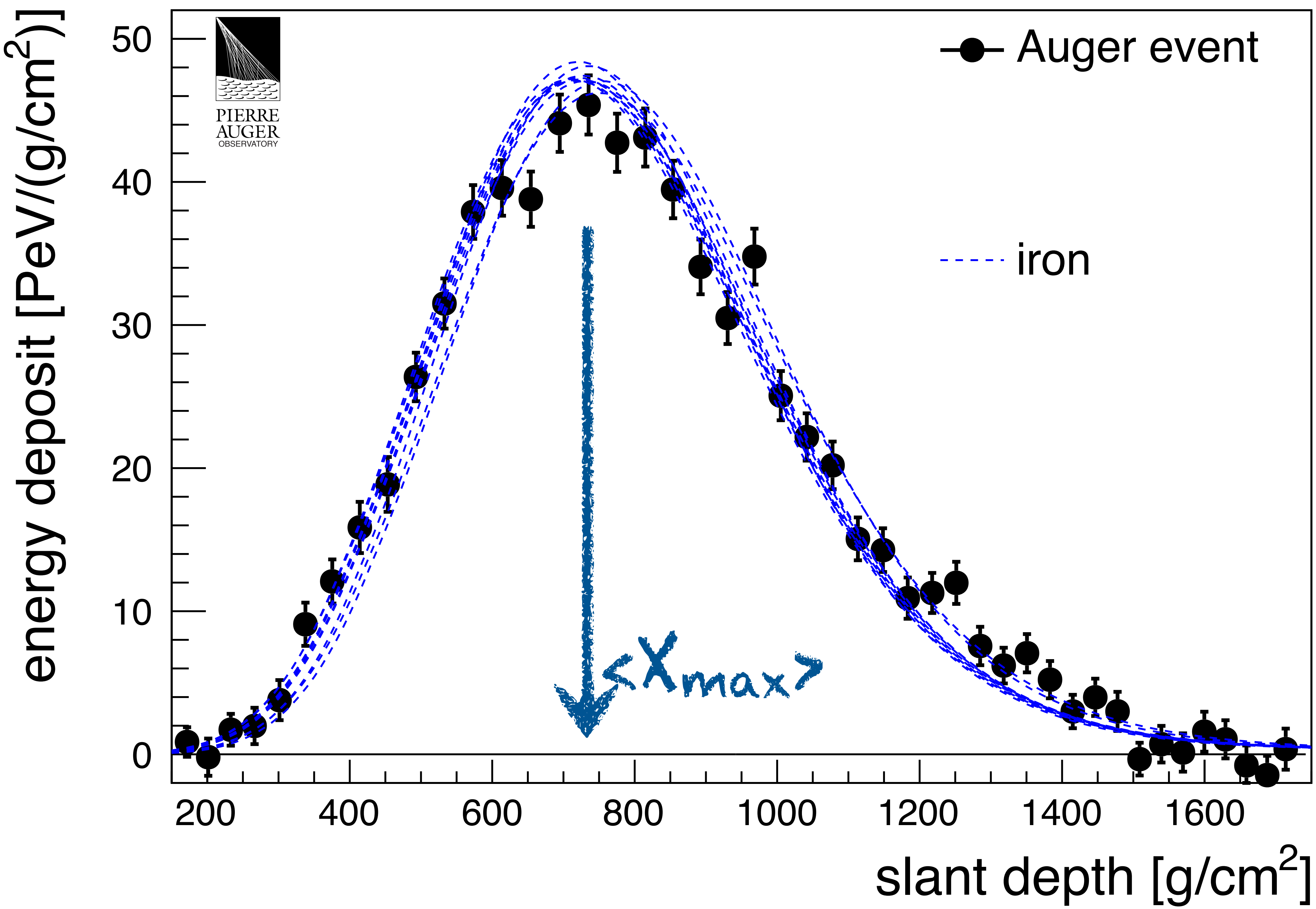

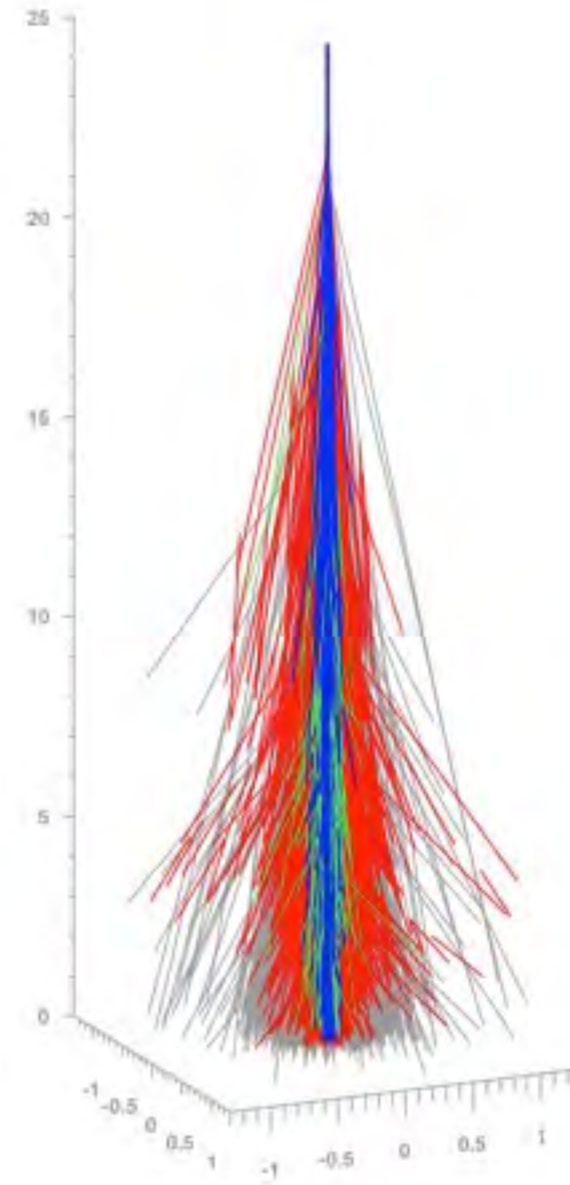

Longitudinal Shower Development → Primary Mass

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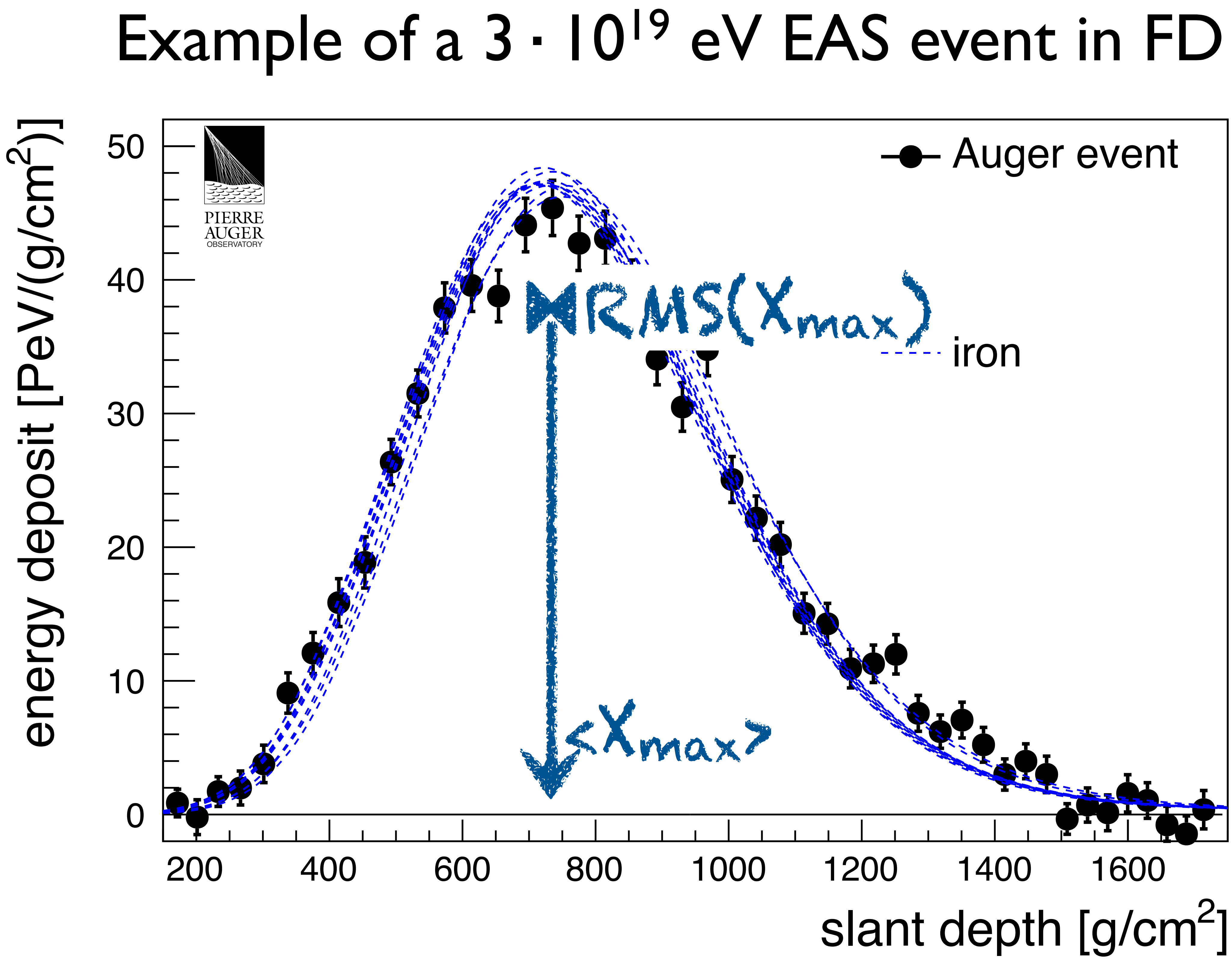
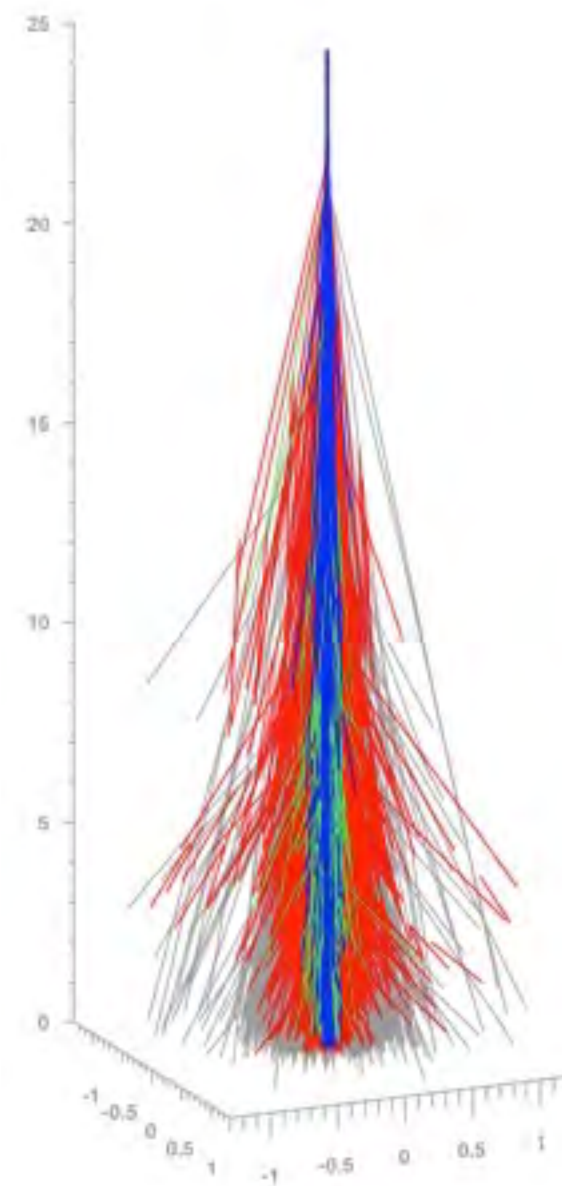
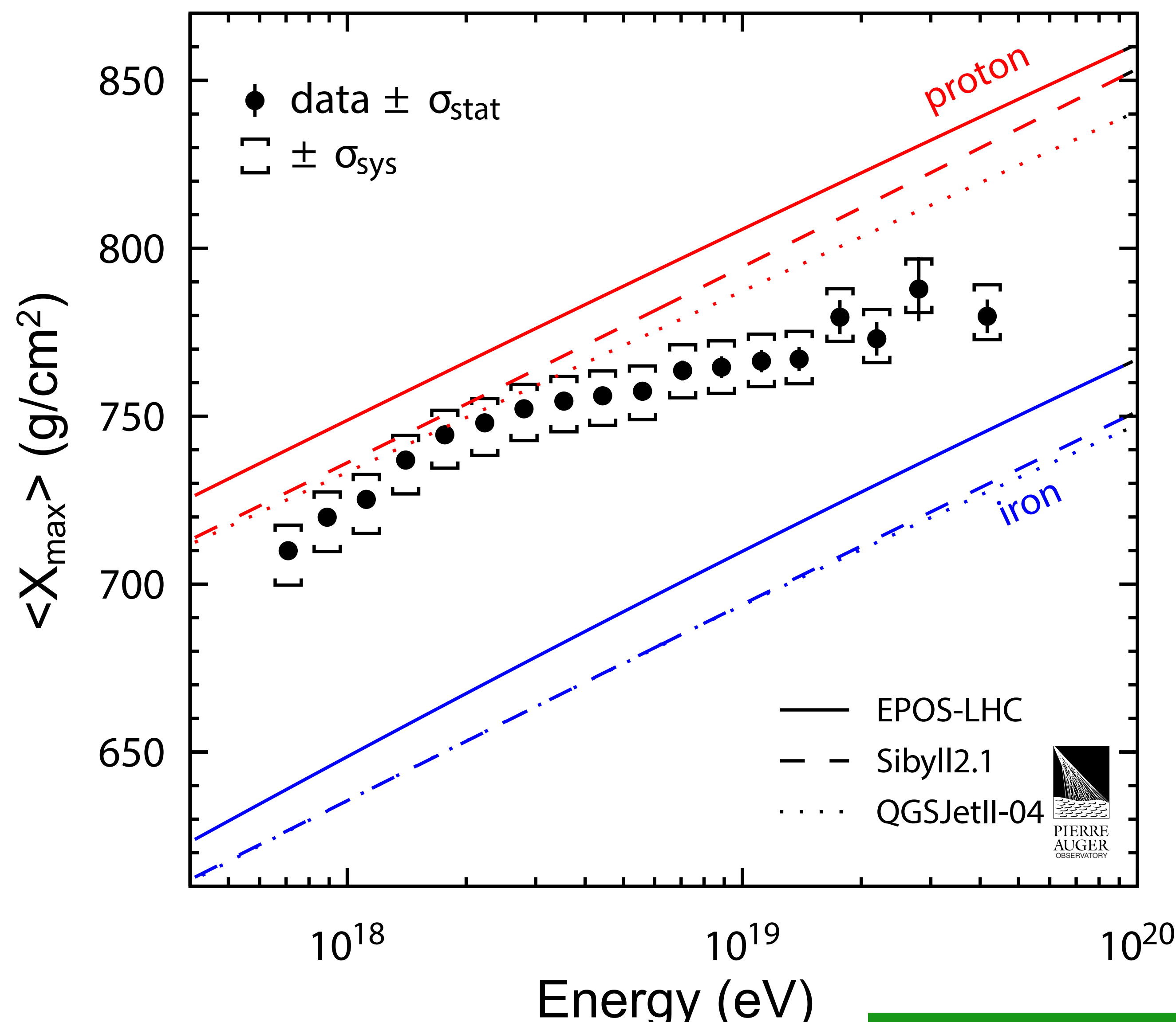
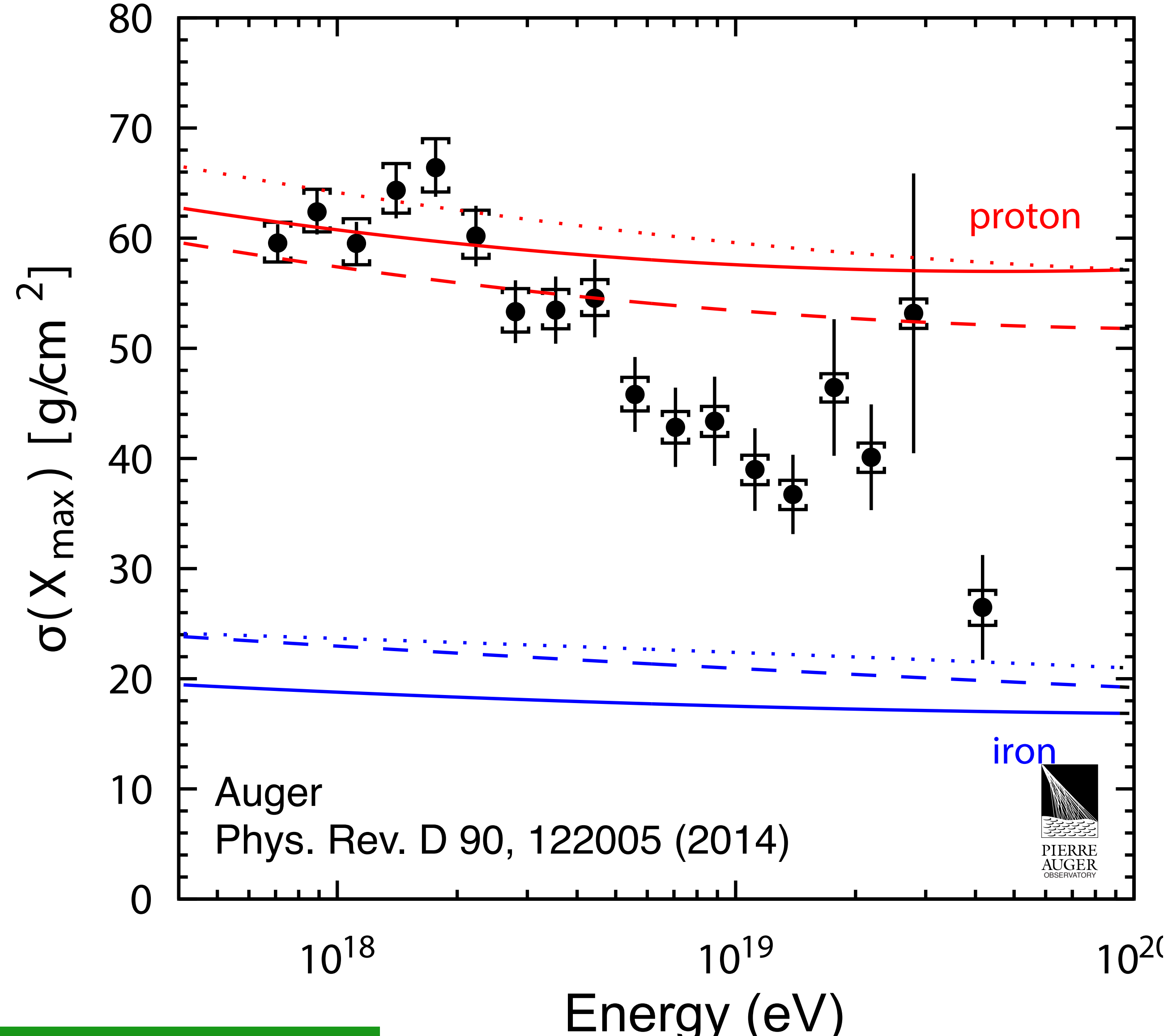




X_{max} and RMS(X_{max}) as a fct of E

Auger; Phys. Rev. D 90, 122005 (2014)



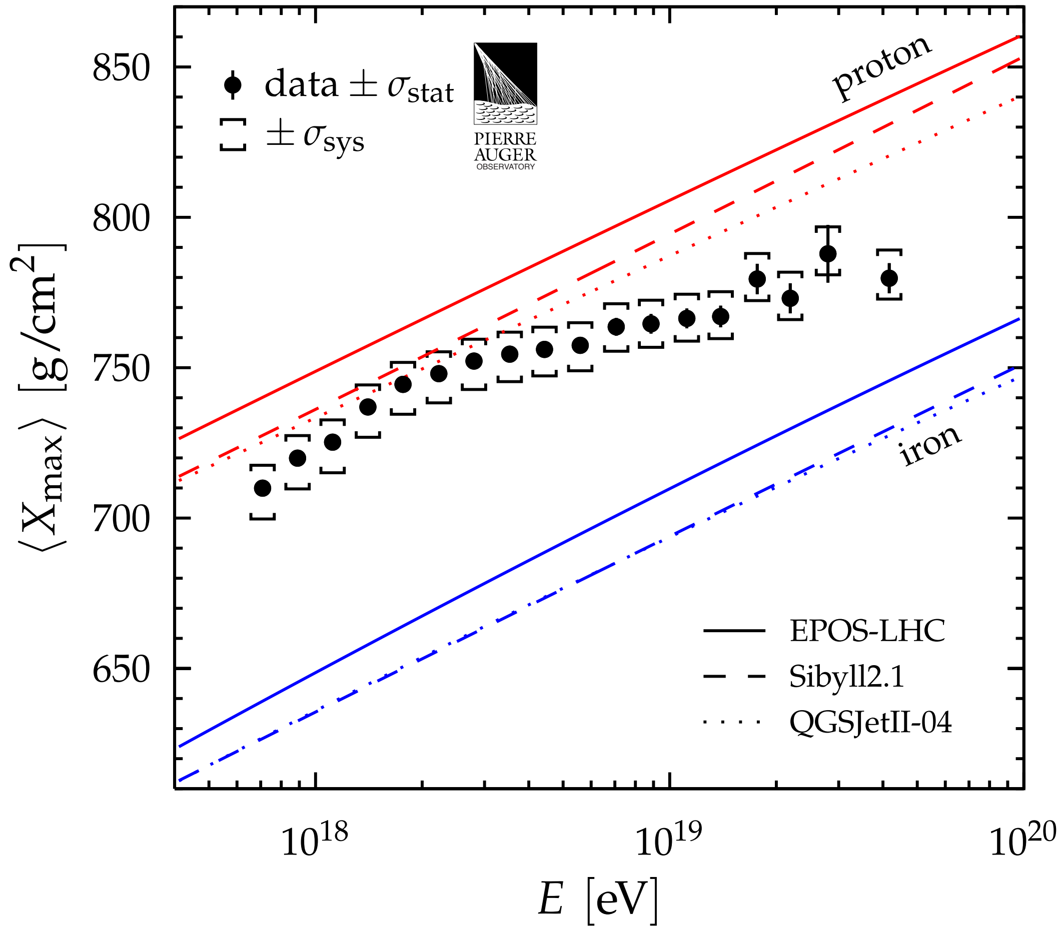


using post-LHC models

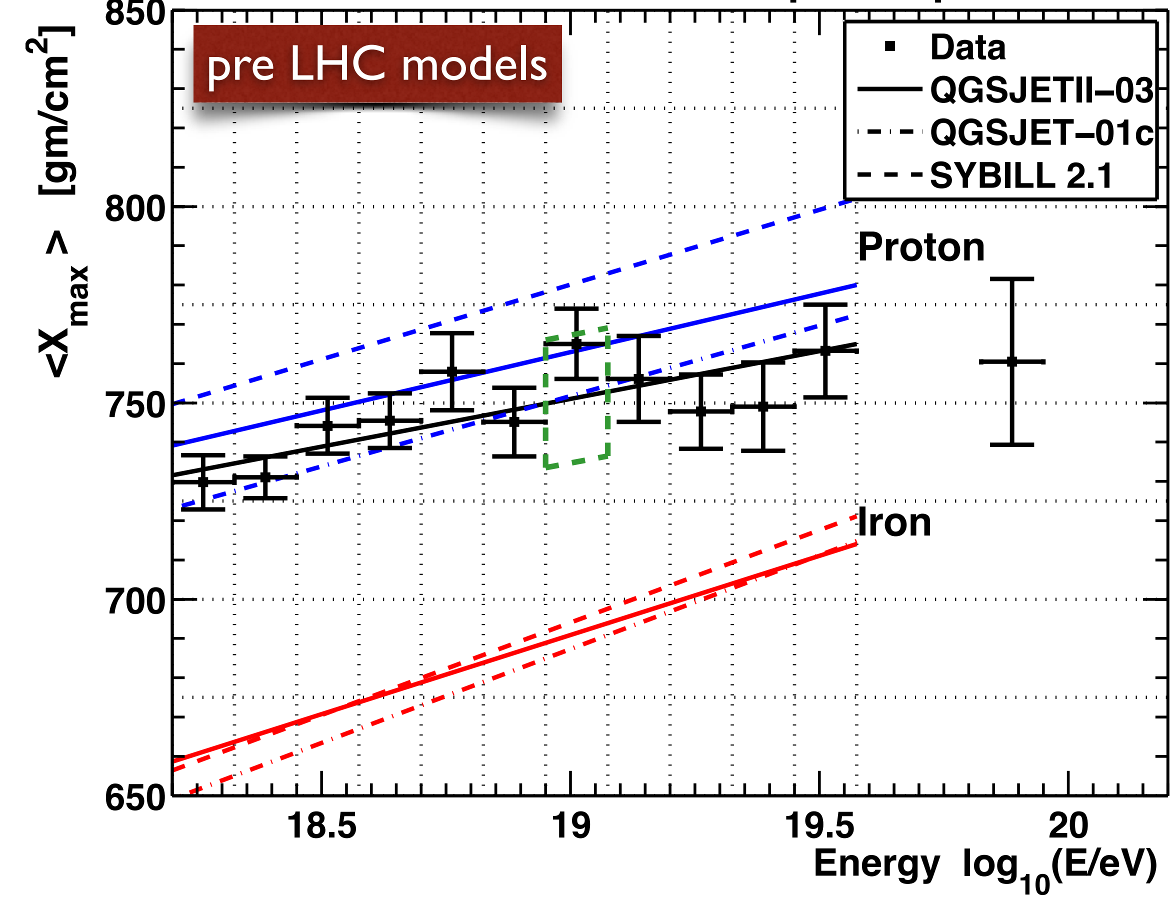
Auger data show a smooth change to a heavier composition above 5 EeV

Auger - TA Comparison

Auger; Phys. Rev. D 90, 122005 (2014)
bias-free due to anti-bias cuts



Telescope Array Collaboration, APP 64 (2015) 49
models are folded with exp. acceptance



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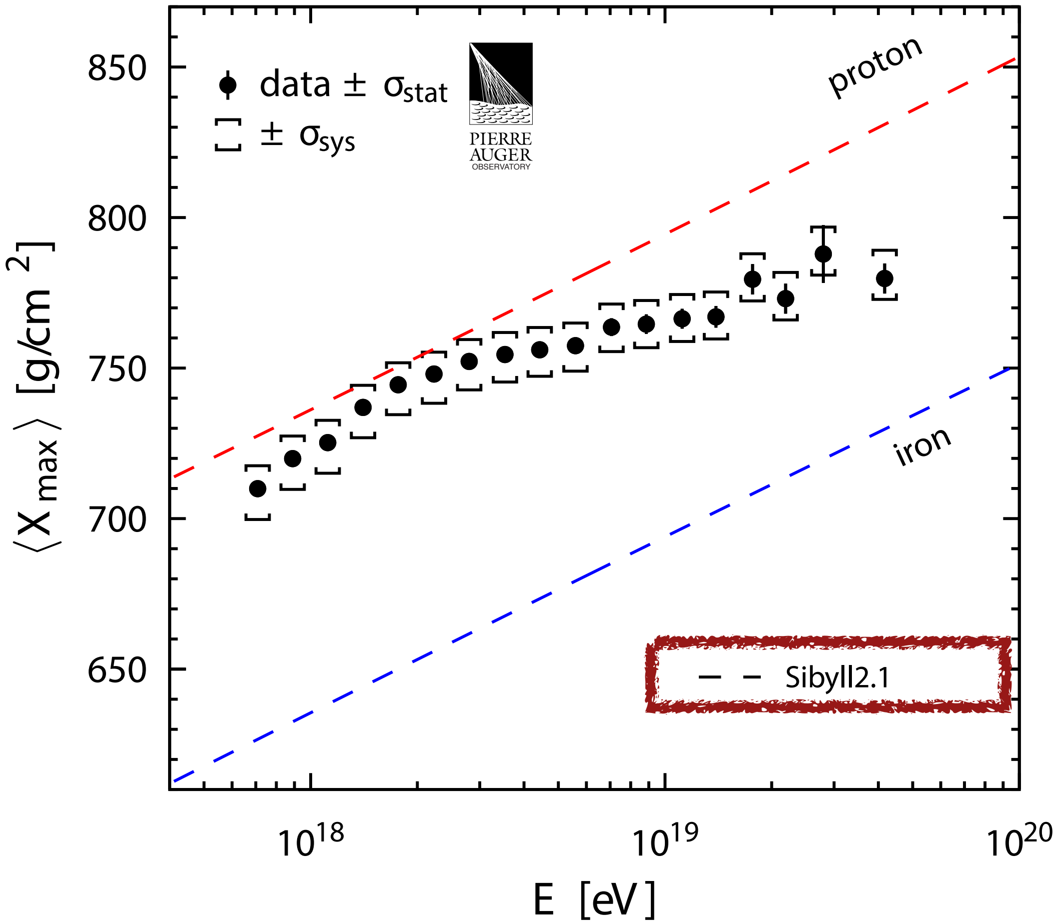

Telescope Array Collaboration, APP 64 (2015) 49
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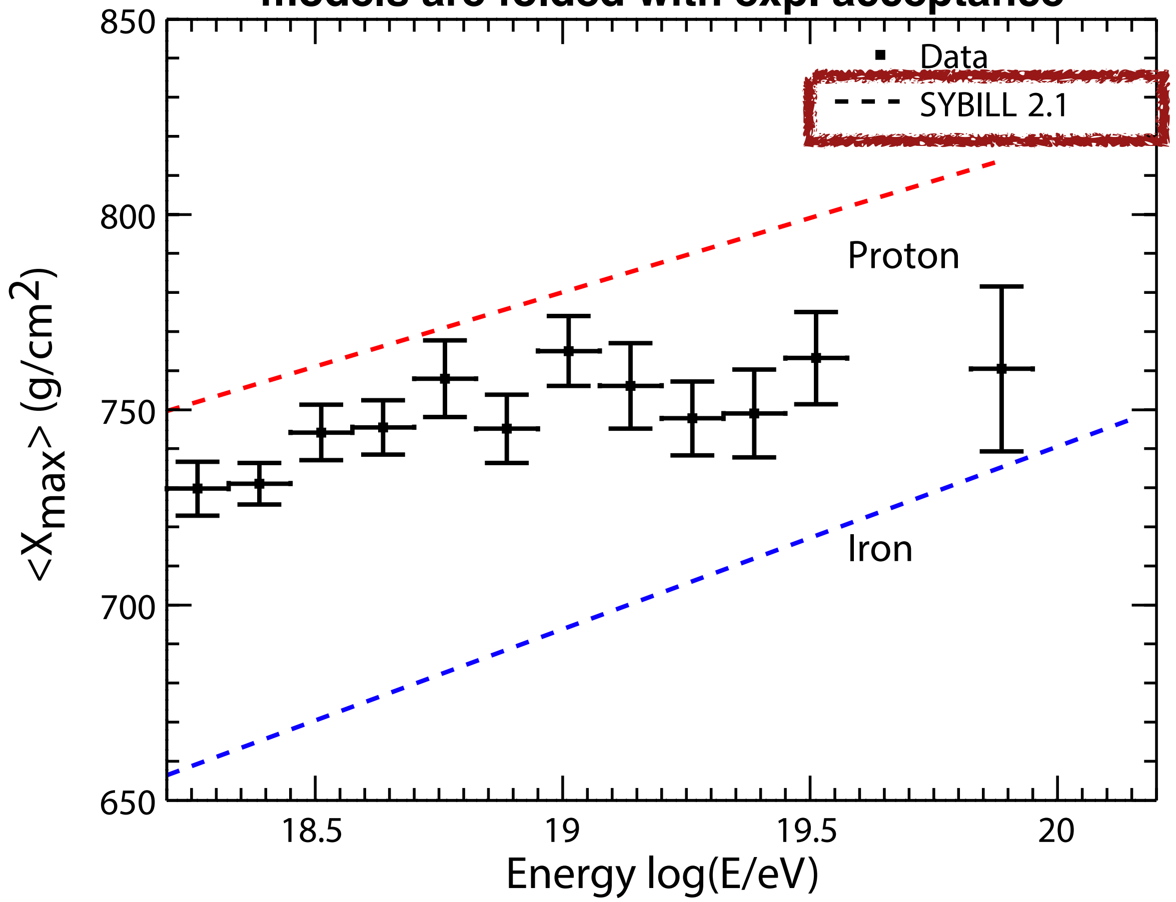
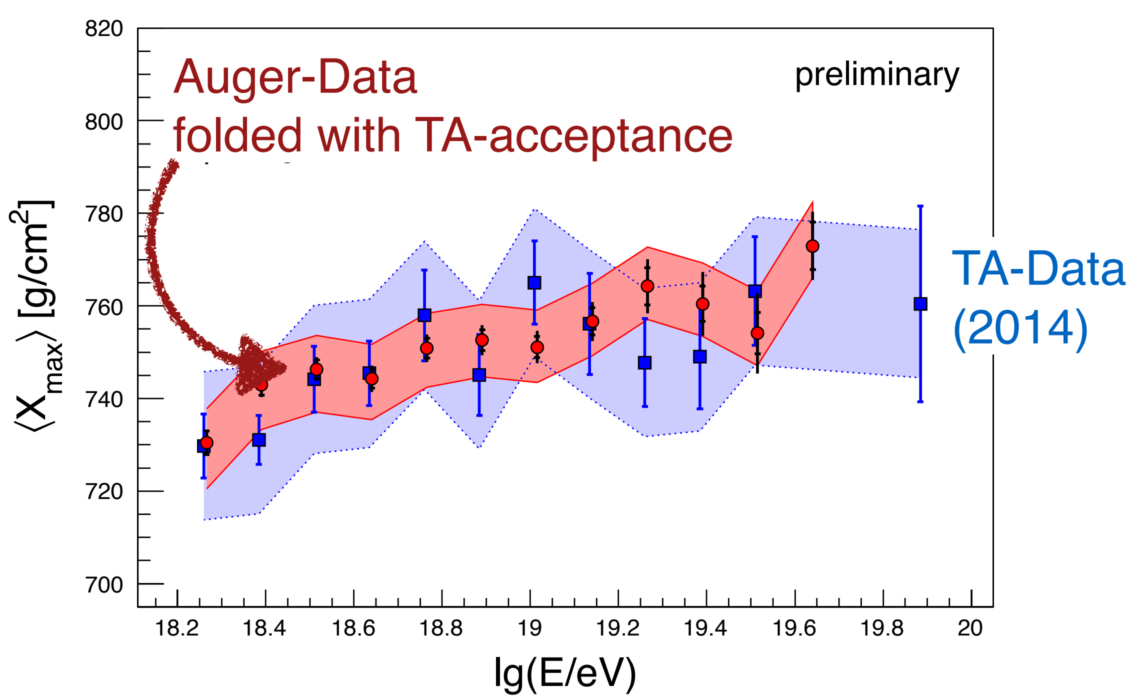


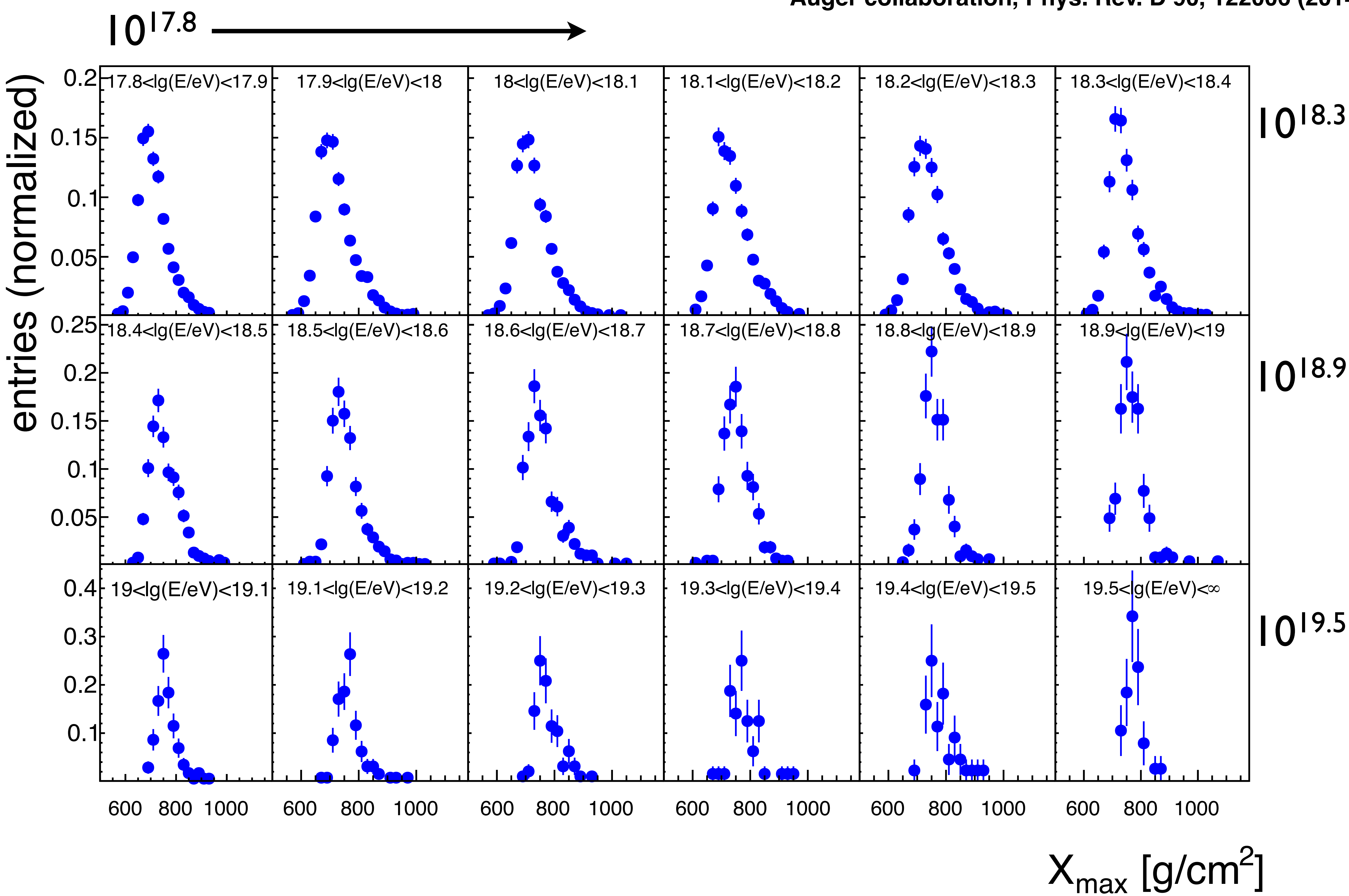


Joint Working Group (UHECR2014; arXiv:1503.07540)

„Two data sets are in excellent agreement, even without accounting for the respective systematic uncertainties on the X_{max} scale.“

X_{max} Distributions

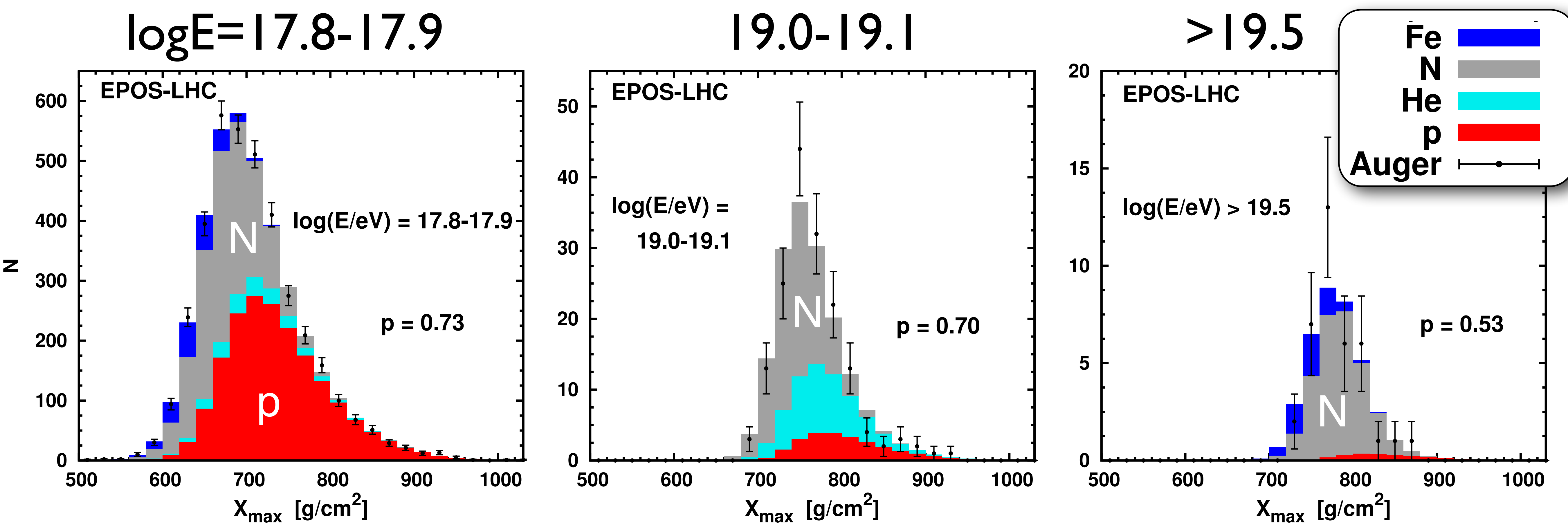
Auger collaboration, Phys. Rev. D 90, 122006 (2014)



Fits to X_{max} Distributions

Auger collaboration, Phys. Rev. D 90, 122006 (2014)

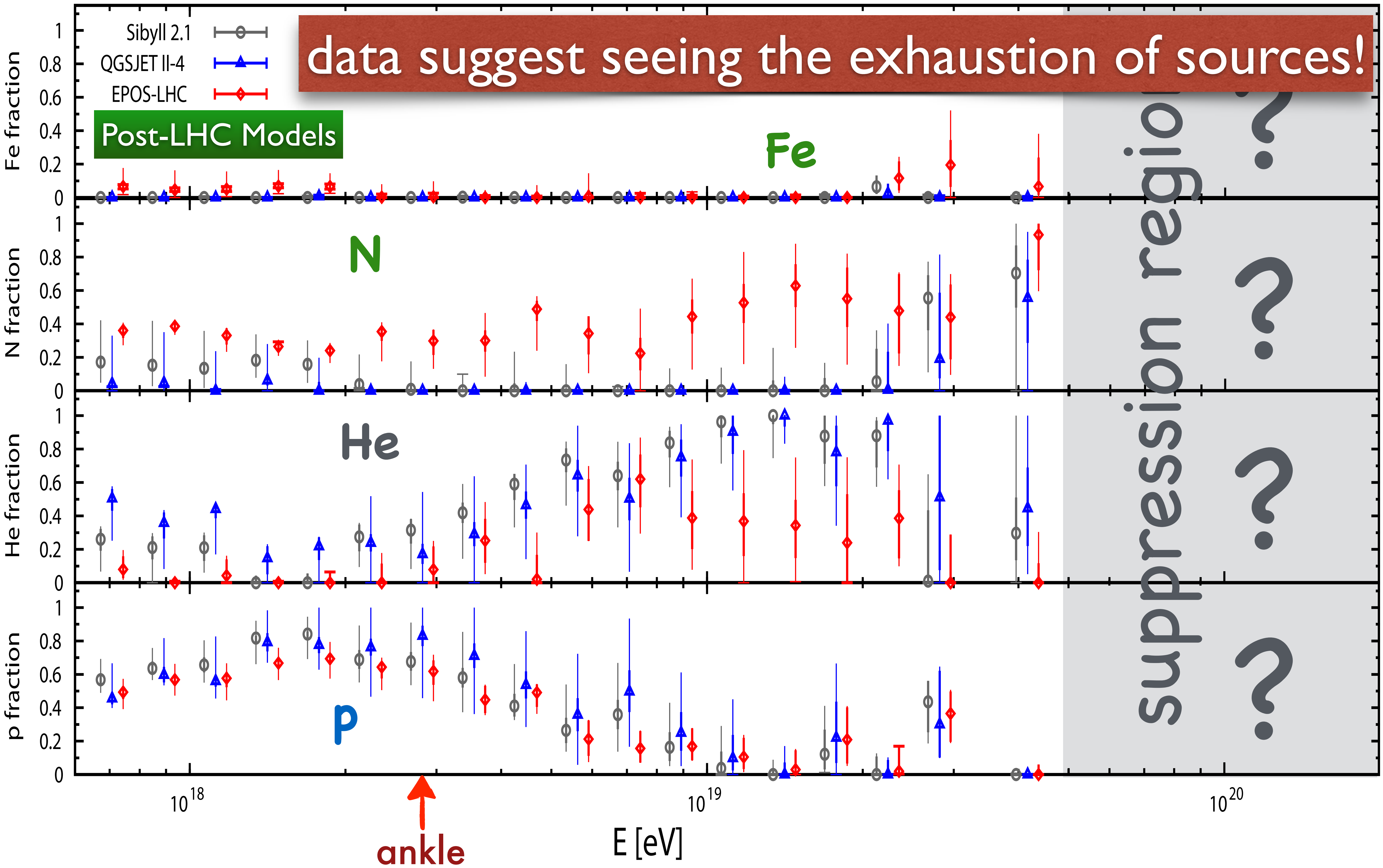
Here shown for EPOS-LHC



above 10^{19} eV p,He components diminish for N, Fe to take over

Decomposition of X_{max}-Distributions

Auger collaboration, Phys. Rev. D 90, 122006 (2014)



Interpretation

Implications of a heavy composition

Astroparticle Physics 39–40 (2012) 33–43
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

Extragalactic propagation of ultrahigh energy cosmic-rays ☆

Denis Allard
Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

Astroparticle Physics 54, 48 (2014)
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

UHECR composition models

Andrew M. Taylor *
Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

Astroparticle Physics 33 (2010) 151–159
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

On the heavy chemical composition of the ultra-high energy cosmic rays

Dan Hooper[a,b], Andrew M. Taylor[c,d,*]

PHYSICAL REVIEW D **84**, 105007 (2011)

Need for a local source of ultrahigh-energy cosmic-ray nuclei

Andrew M. Taylor,[1] Markus Ahlers,[2] and Felix A. Aharonian[3,4]

Frontiers of Physics
December 2013, Volume 8, Issue 6, pp 748-758

Cosmic ray energy spectrum from measurements of air showers

T. K. Gaisser, T. Stanev, S. Tilav

Ultra high energy cosmic rays: implications of Auger data for source spectra and chemical composition

Subm. to JCAP 2013

R. Aloisio[1,2], V. Berezinsky[2,3] and P. Blasi[1,2]

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journal homepage: www.elsevier.com/locate/astropart

UHECR composition models

Andrew M. Taylor *

...and many more papers of this type

all require very hard injection spectra unless a nearby source (population) is assumed

Frontiers

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Cosmic ray energy spectrum from measurements of air showers

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cosmic rays: implications of Auger data for source spectra and chemical composition

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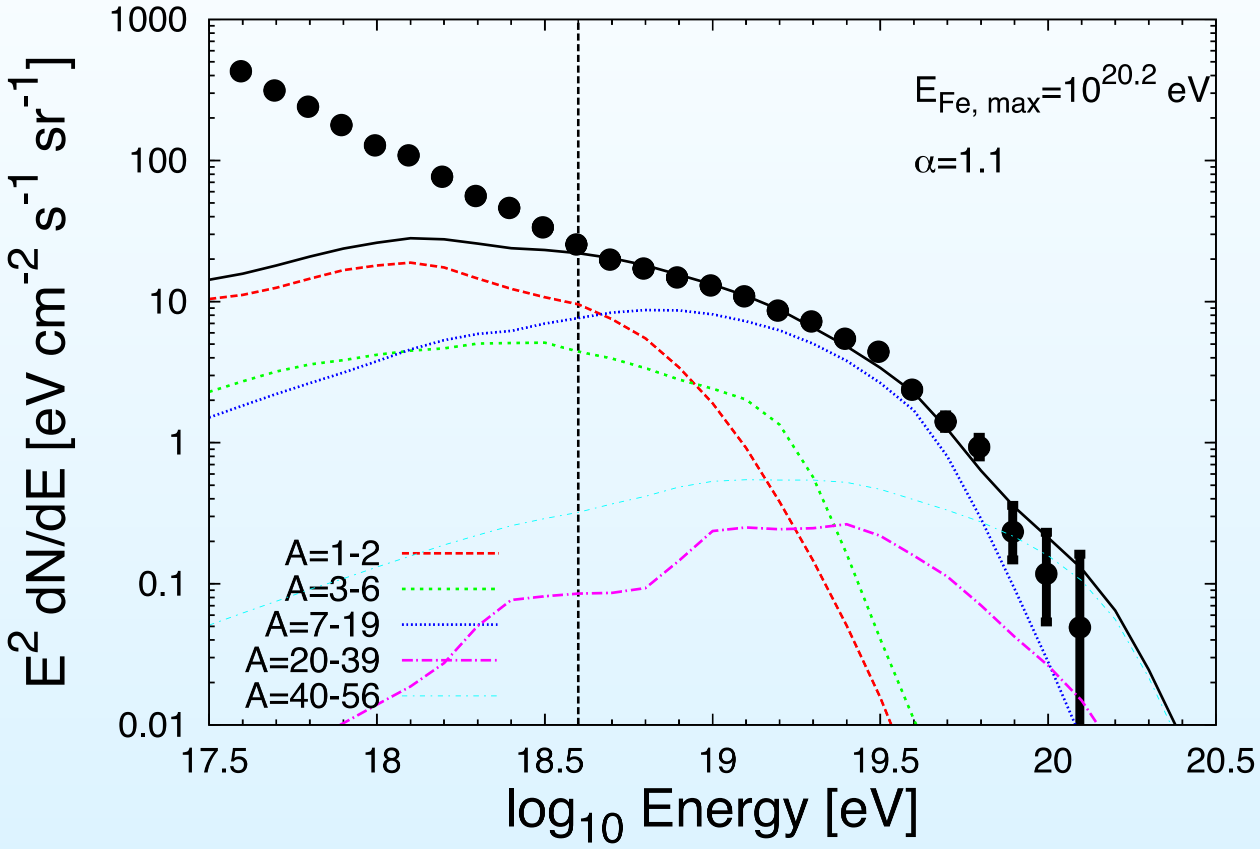
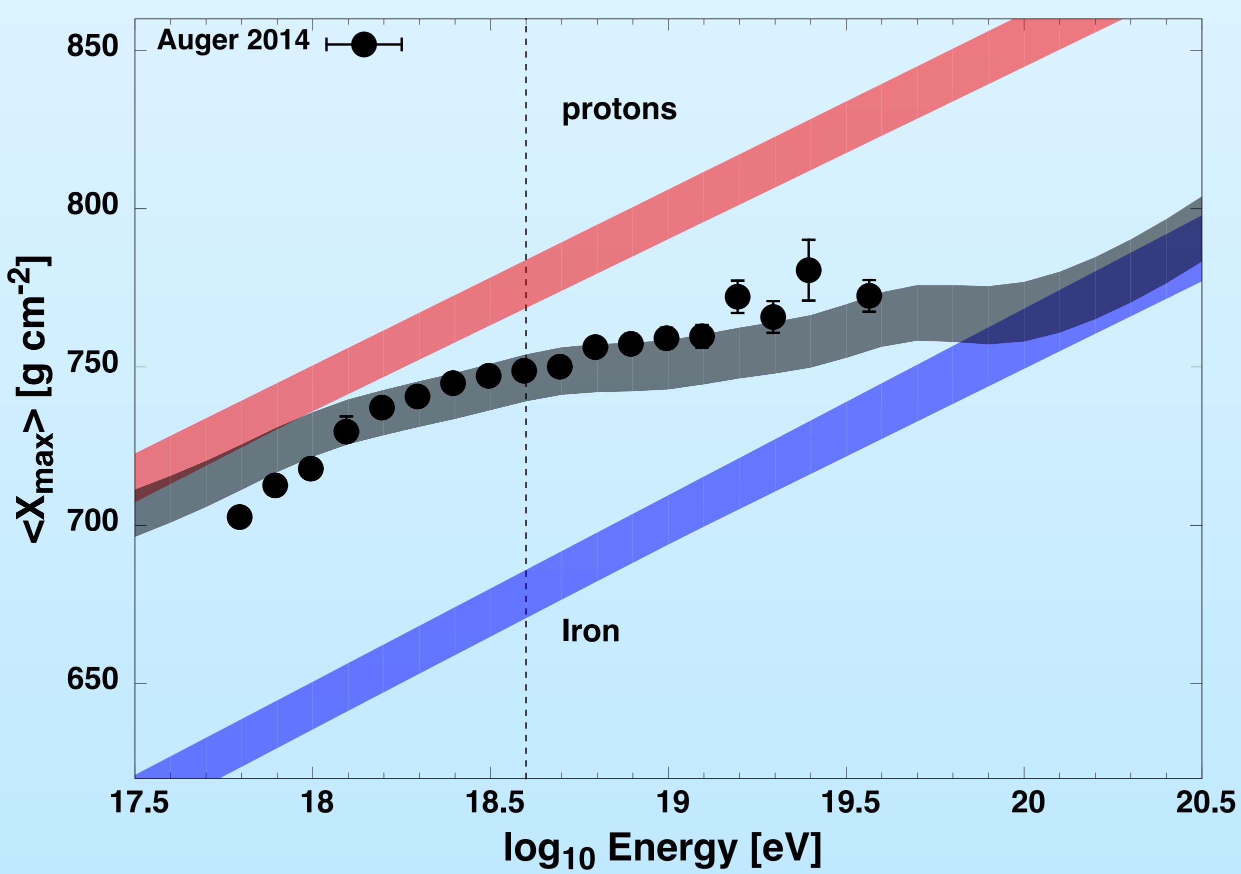
Comparison to Astrophys. Scenarios

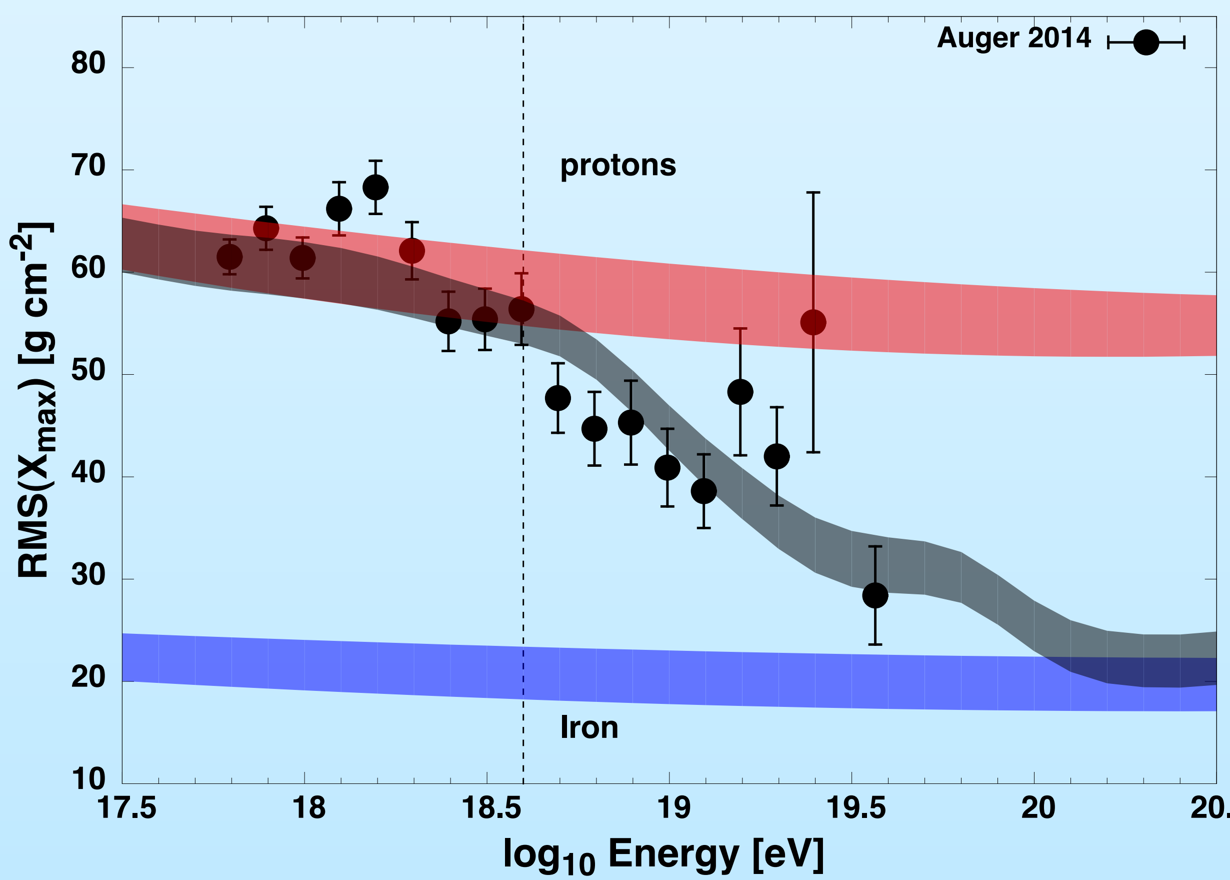


Taylor, Ahlers, Hooper; arXiv:1505.06090

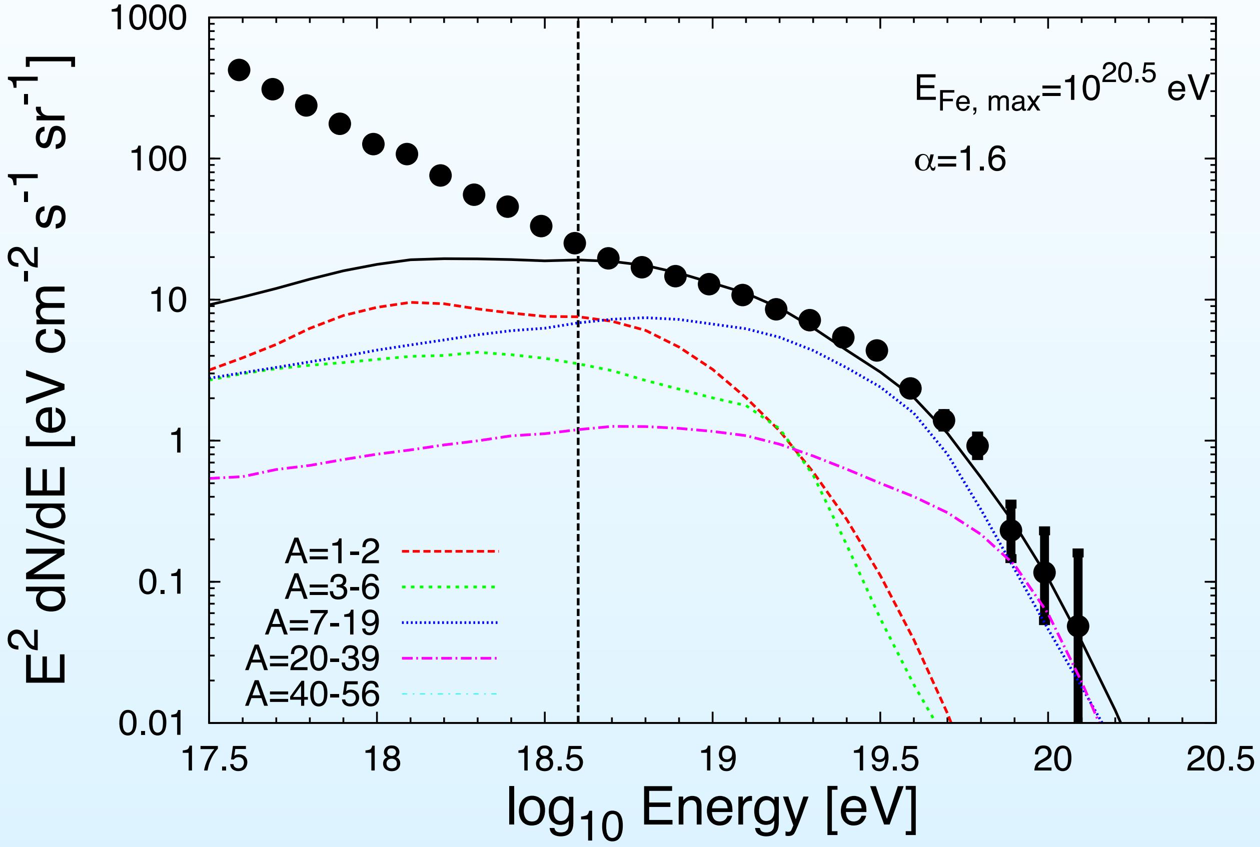
$E_{max}^{p}=10^{18.8}$ eV
index α=1.1
cosm. evolution: m=0

maximum energy scenario requires very hard (non-Fermi like) injection spectra





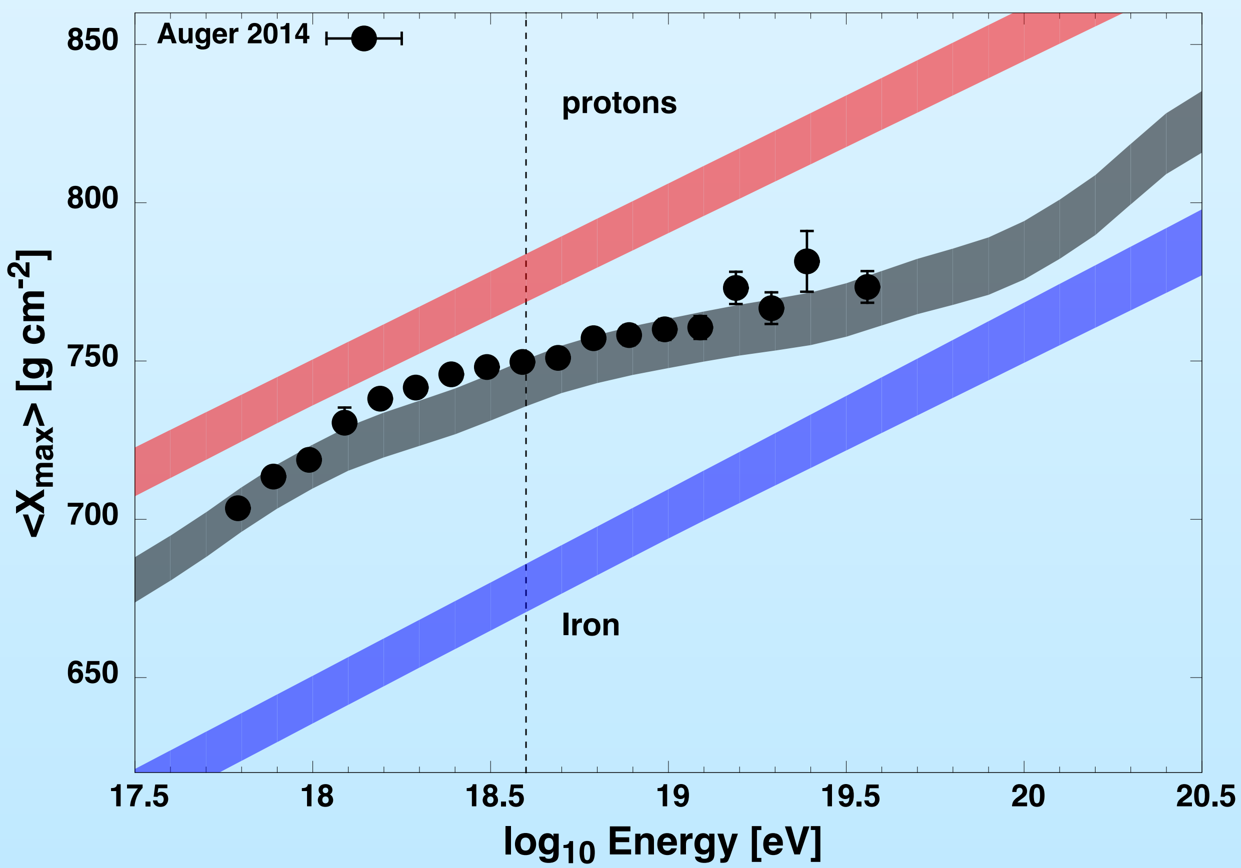
Comparison to Astrophys. Scenarios

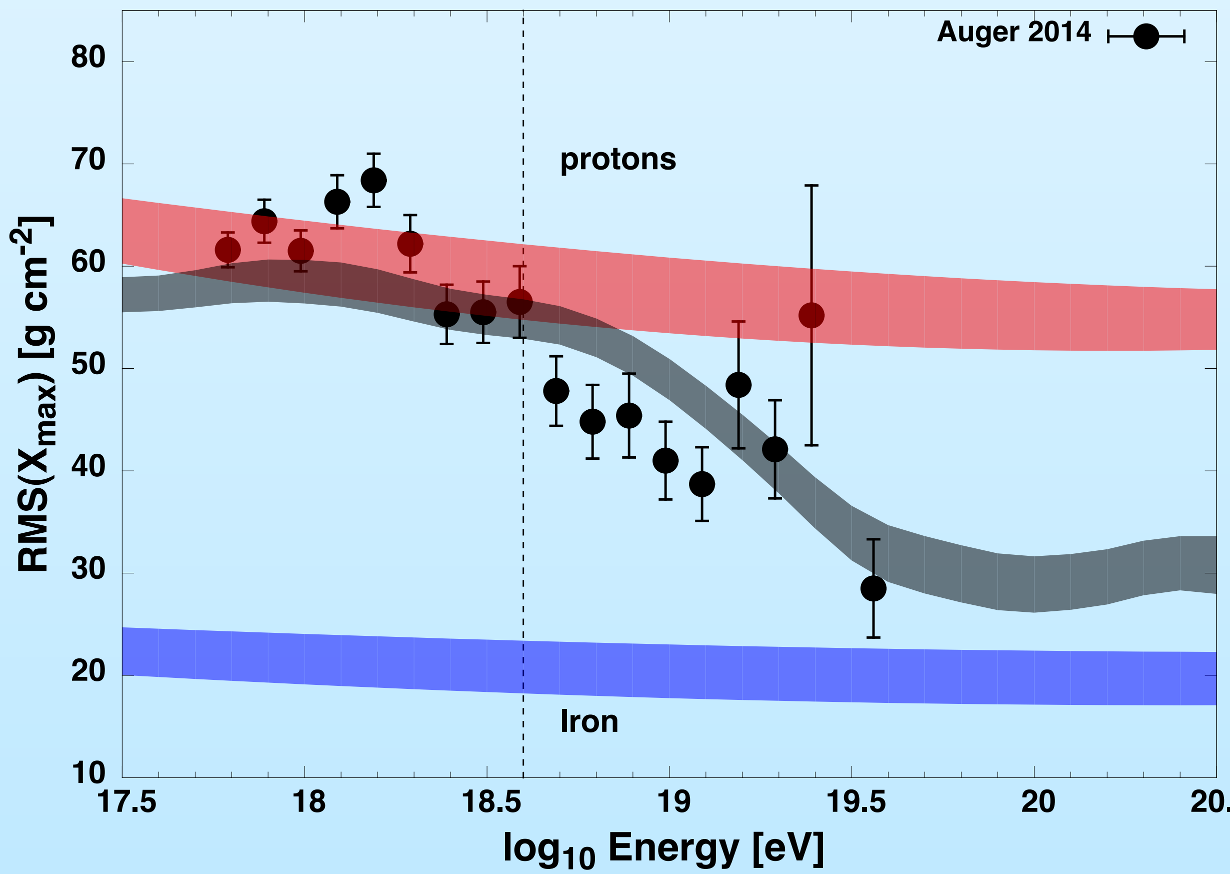


Taylor, Ahlers, Hooper; arXiv:1505.06090

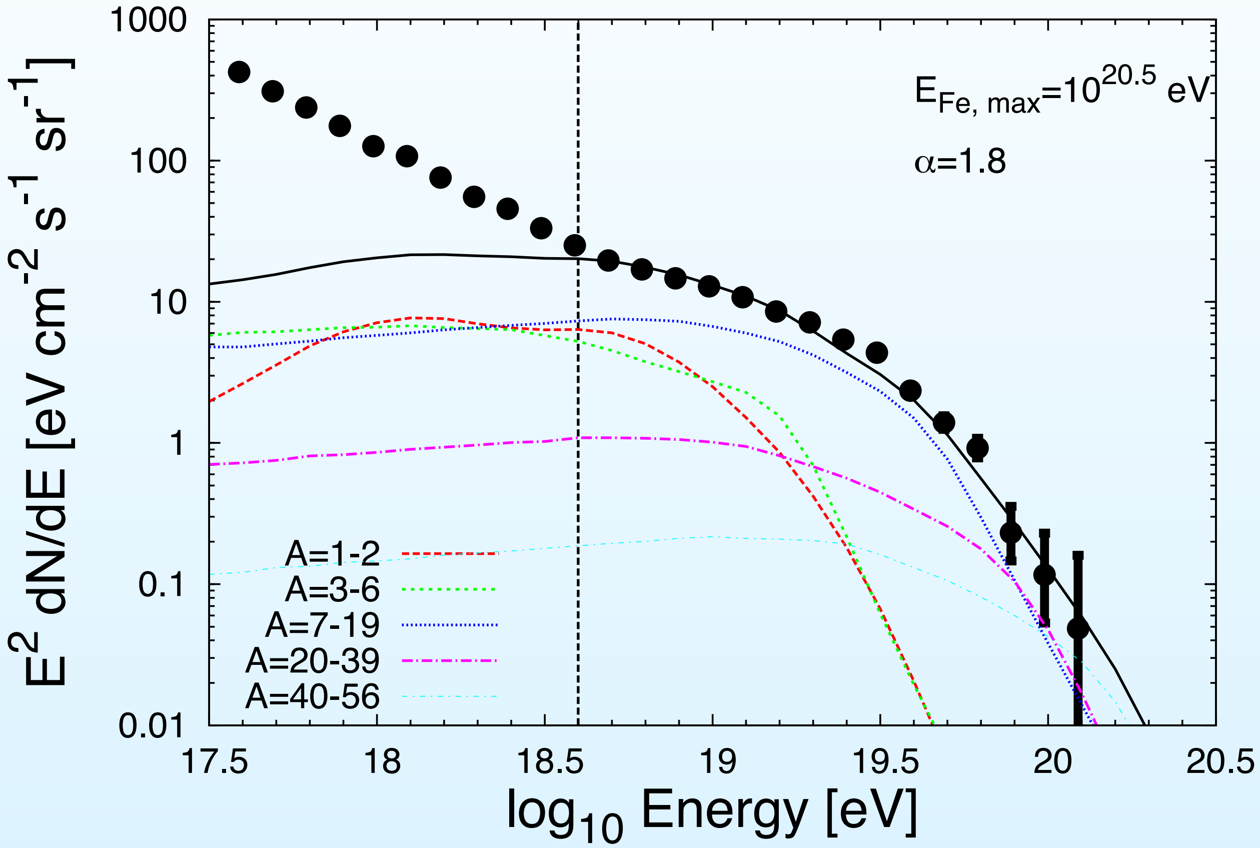
$E_{max}^p=10^{19.1}$ eV
index α=1.6
cosm. evolution: m=-3

maximum energy scenario requires very hard (non-Fermi like) injection spectra or local sources





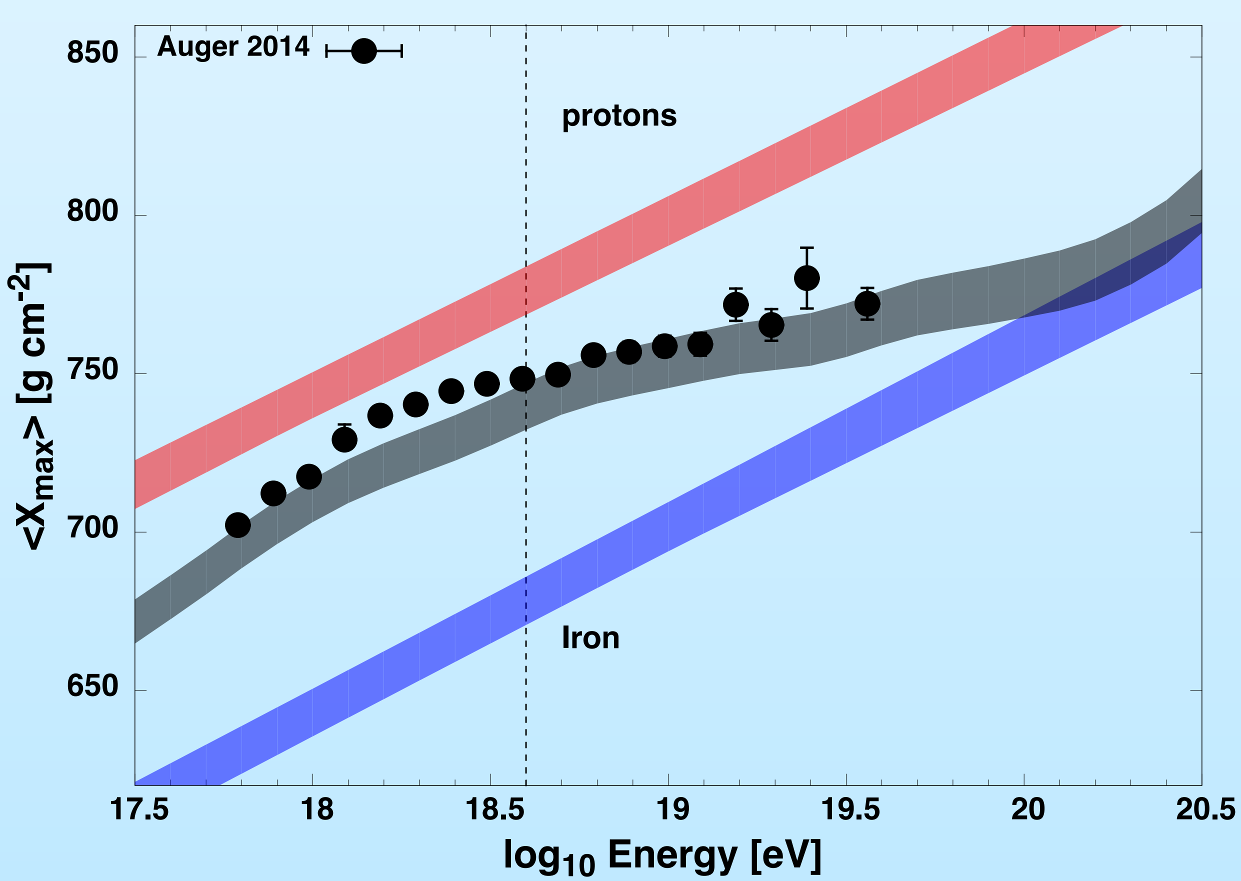
Comparison to Astrophys. Scenarios

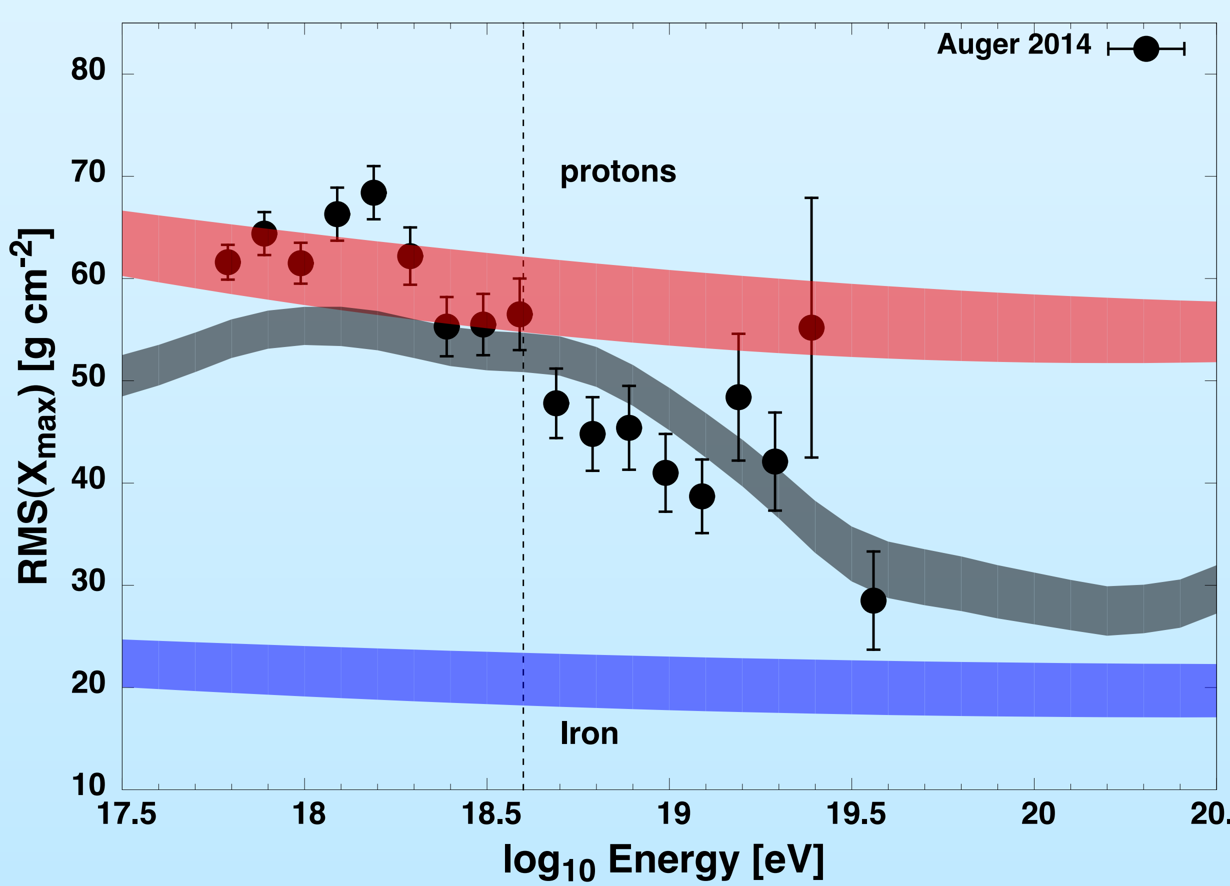


Taylor, Ahlers, Hooper; arXiv:1505.06090

$E_{max}^p=10^{19.1}$ eV
index α=1.8
cosm. evolution: m=-6

maximum energy scenario requires very hard (non-Fermi like) injection spectra or local sources

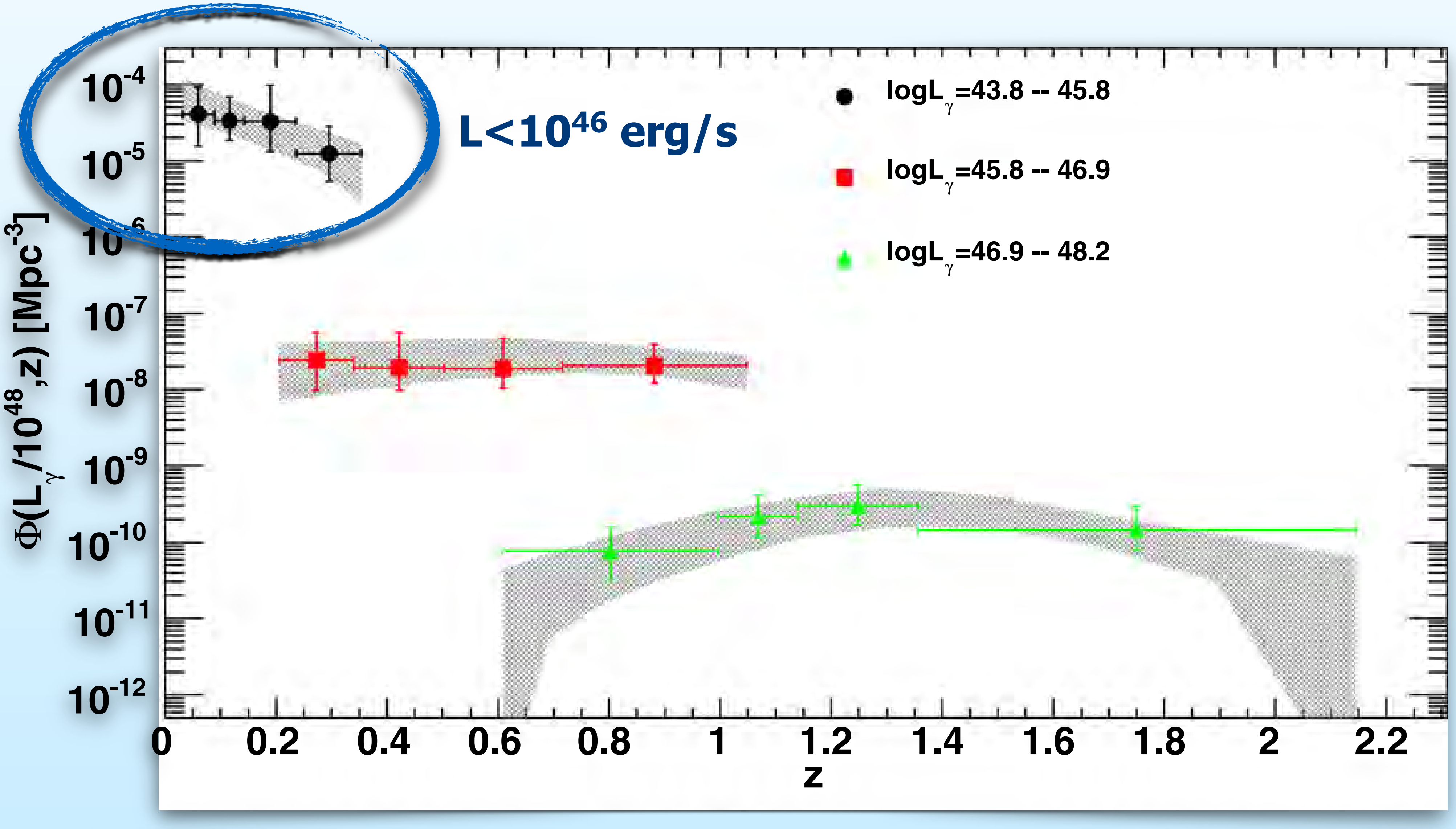




Negative Cosmological Evolution?

A strong negative cosmological evolution has been found in low-luminosity, high-synchrotron–peaked (HSP) BL Lac objects based on Fermi data

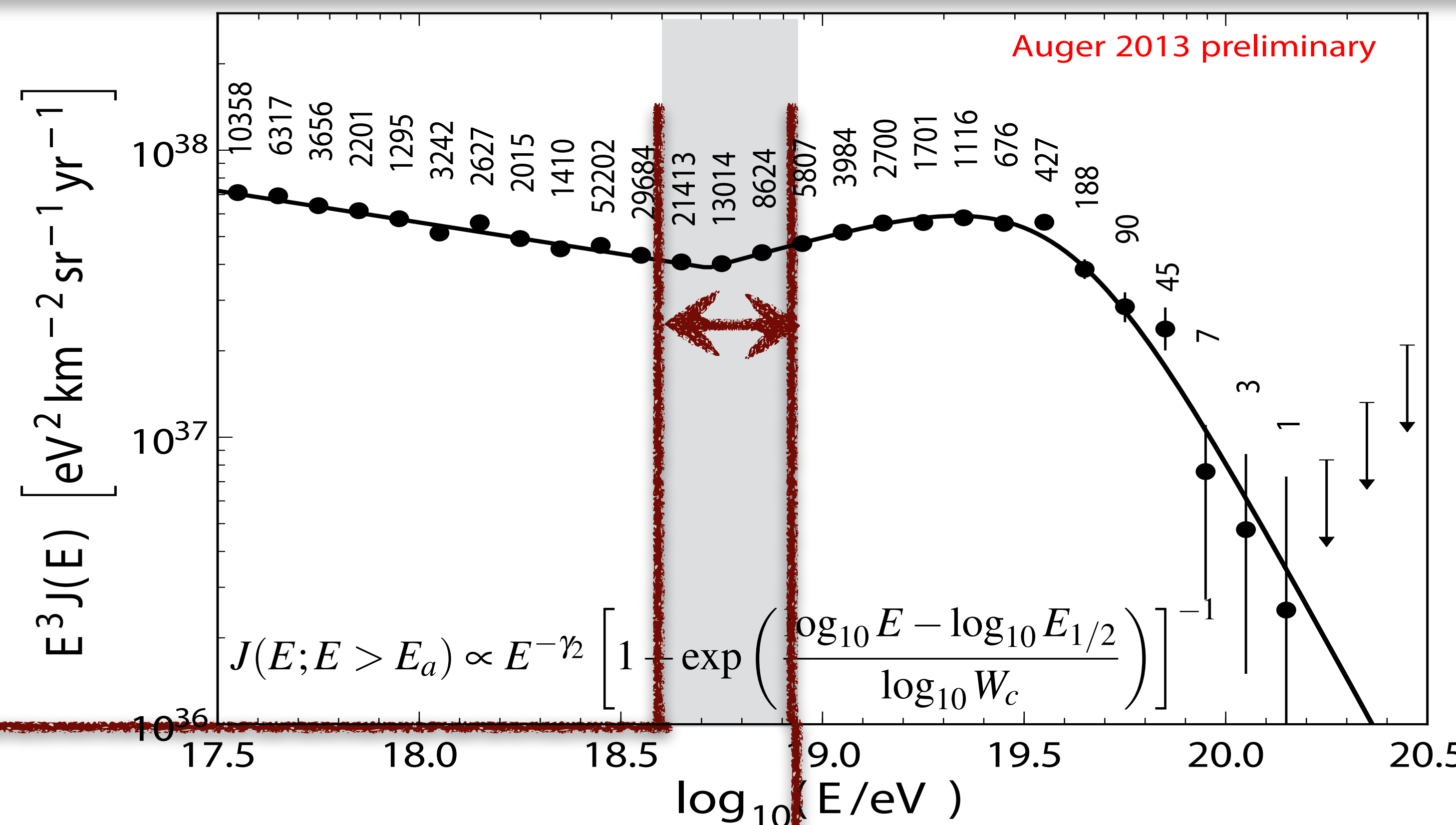
M. Ajello et al., ApJ, 780:73 2014



We may see mostly nearby low-power sources !

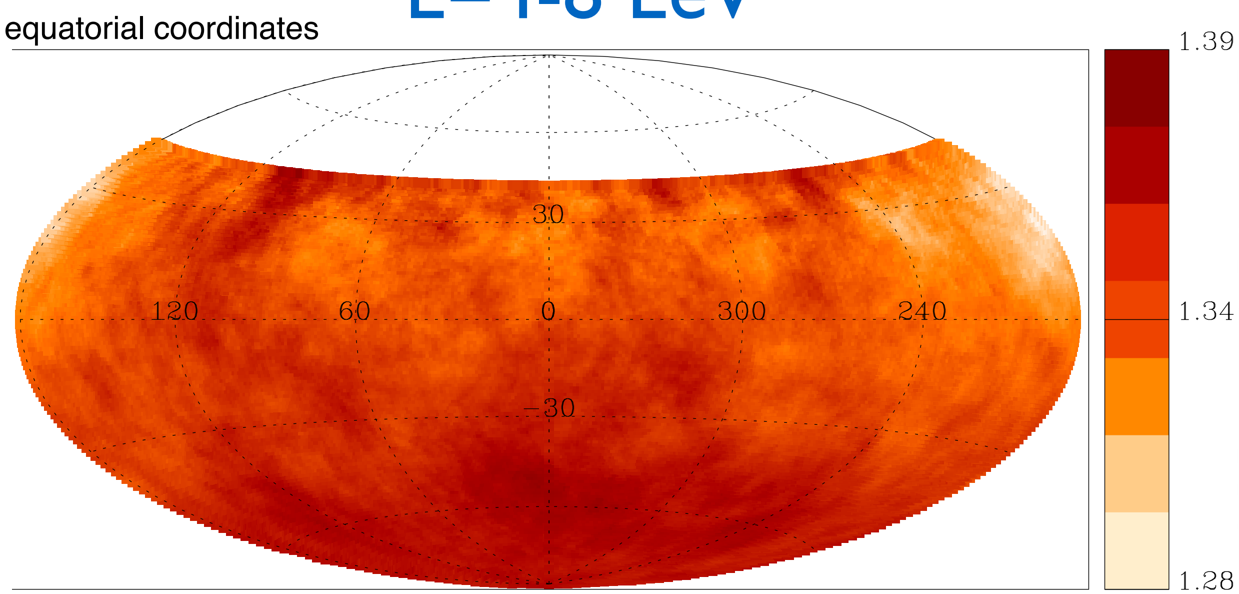
Anisotropies

UHECR Sky surprisingly isotropic



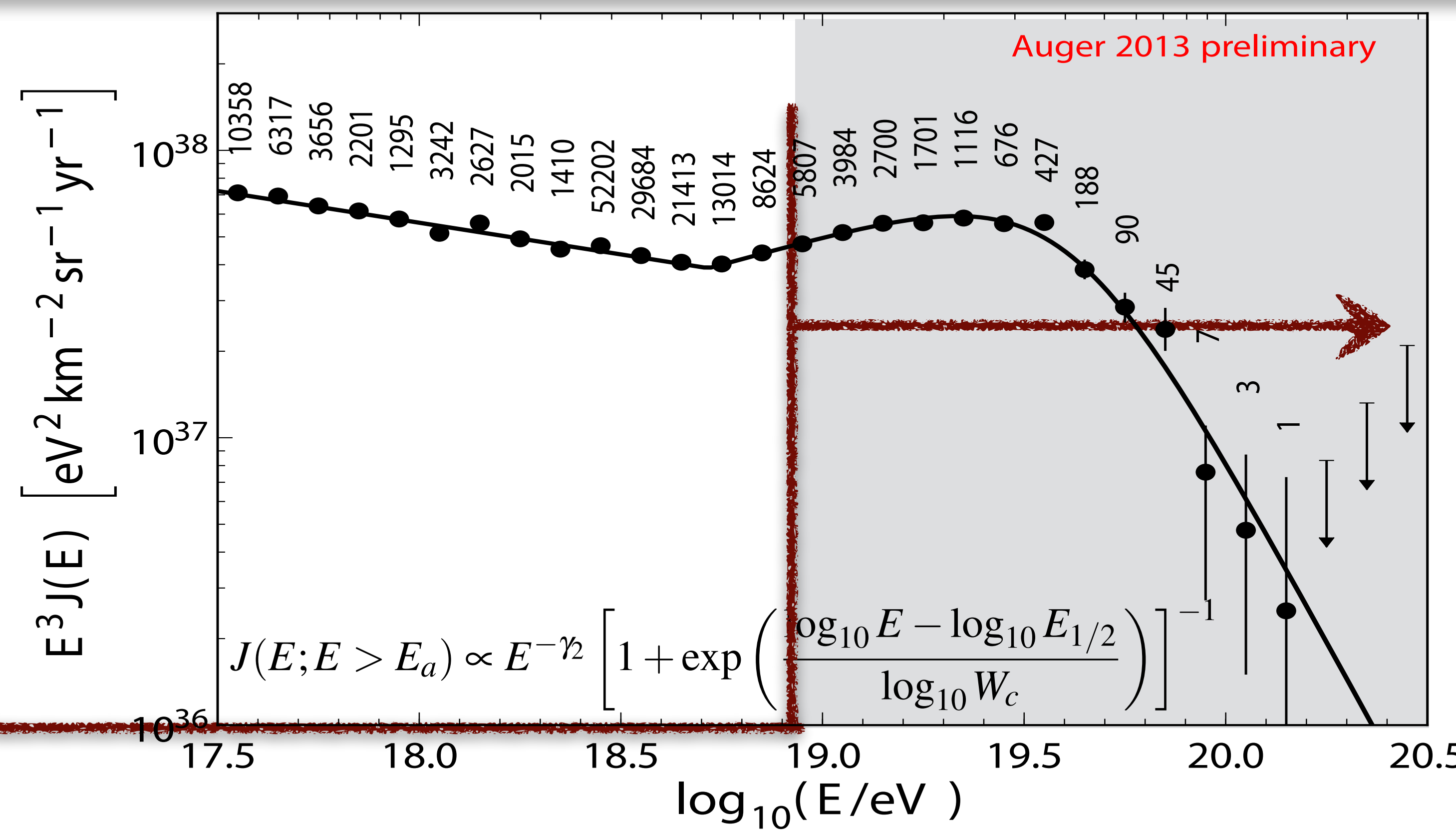
isotropic distribution

E=4-8 EeV



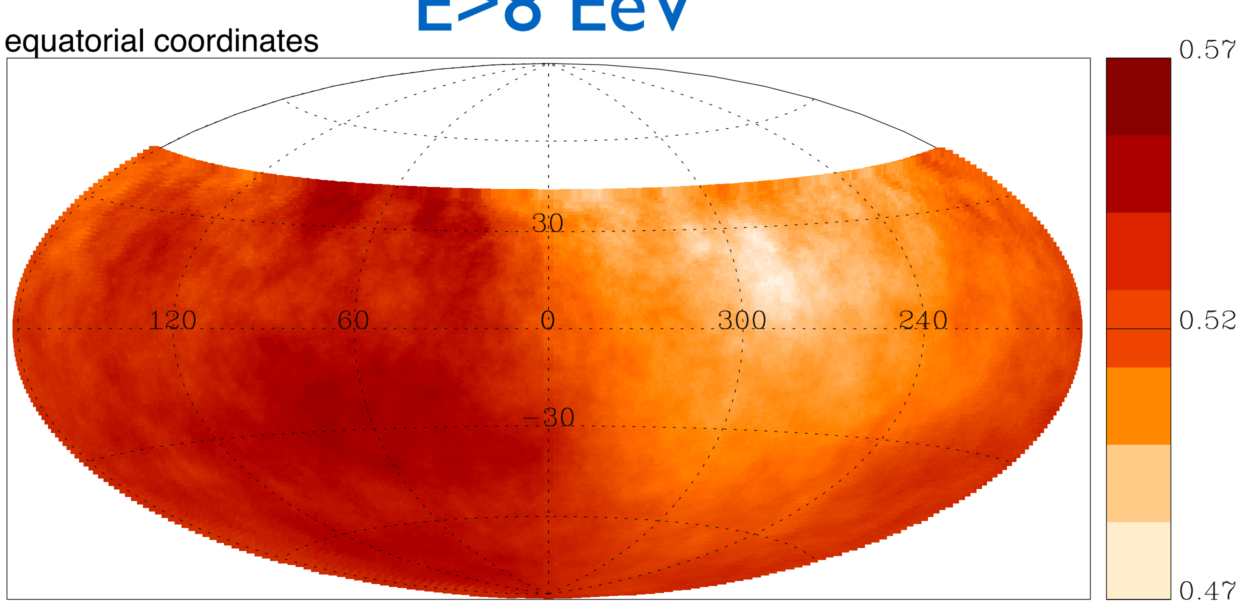
Auger Collaboration ApJ 802:111 (2015)

UHECR Sky surprisingly isotropic



dipole like anisotropy

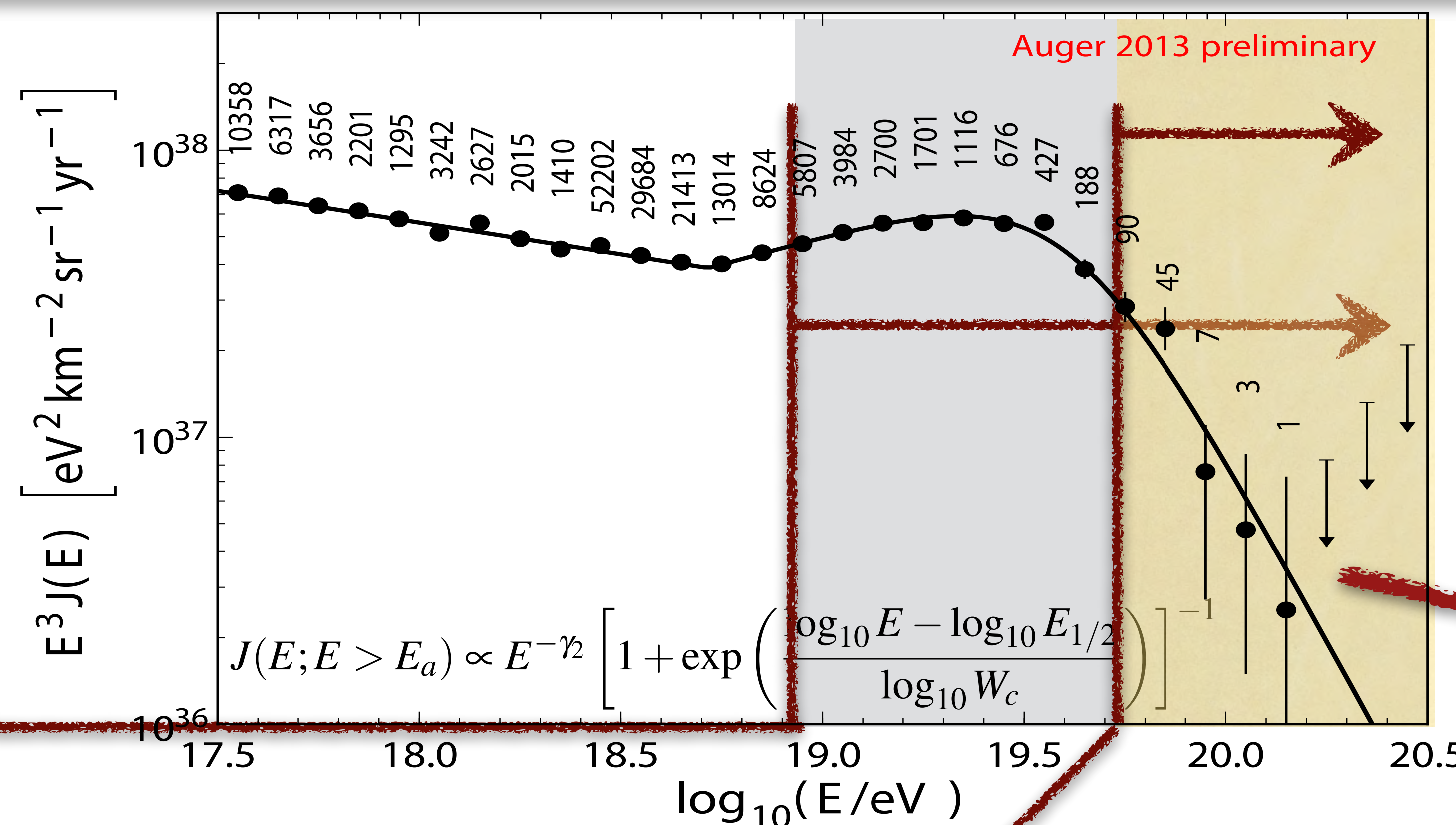
E>8 EeV



Auger Collaboration ApJ 802:111 (2015)

Amplitude: (4.4±1.0)%; $p=6.4 \cdot 10^{-5}$

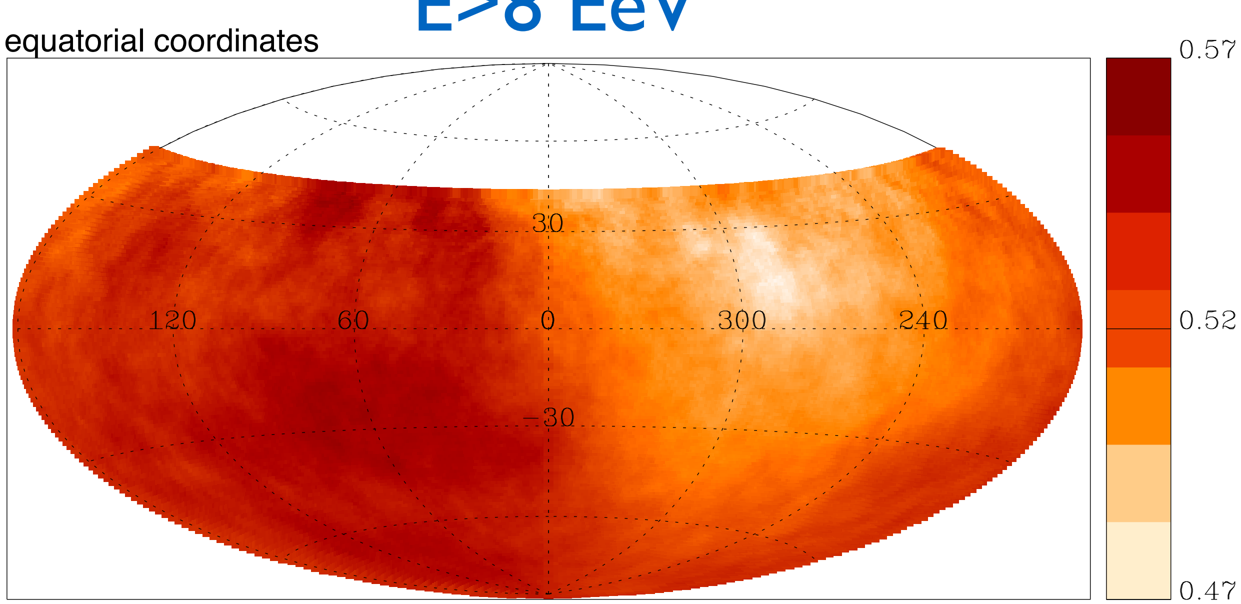
UHECR Sky surprisingly isotropic



hot/warm spot

dipole like anisotropy

E>8 EeV

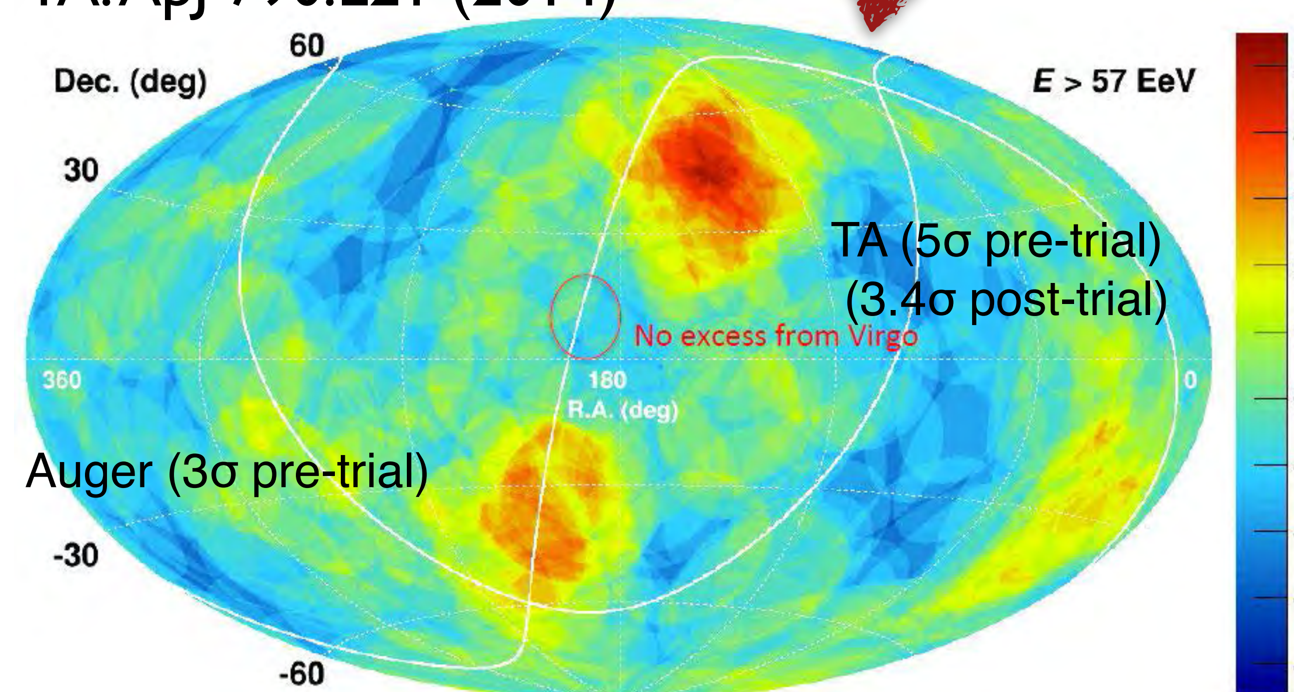


Auger Collaboration ApJ 802:111 (2015)

Amplitude: (4.4±1.0)%; p=6.4 · 10^{-5}

E>57 EeV

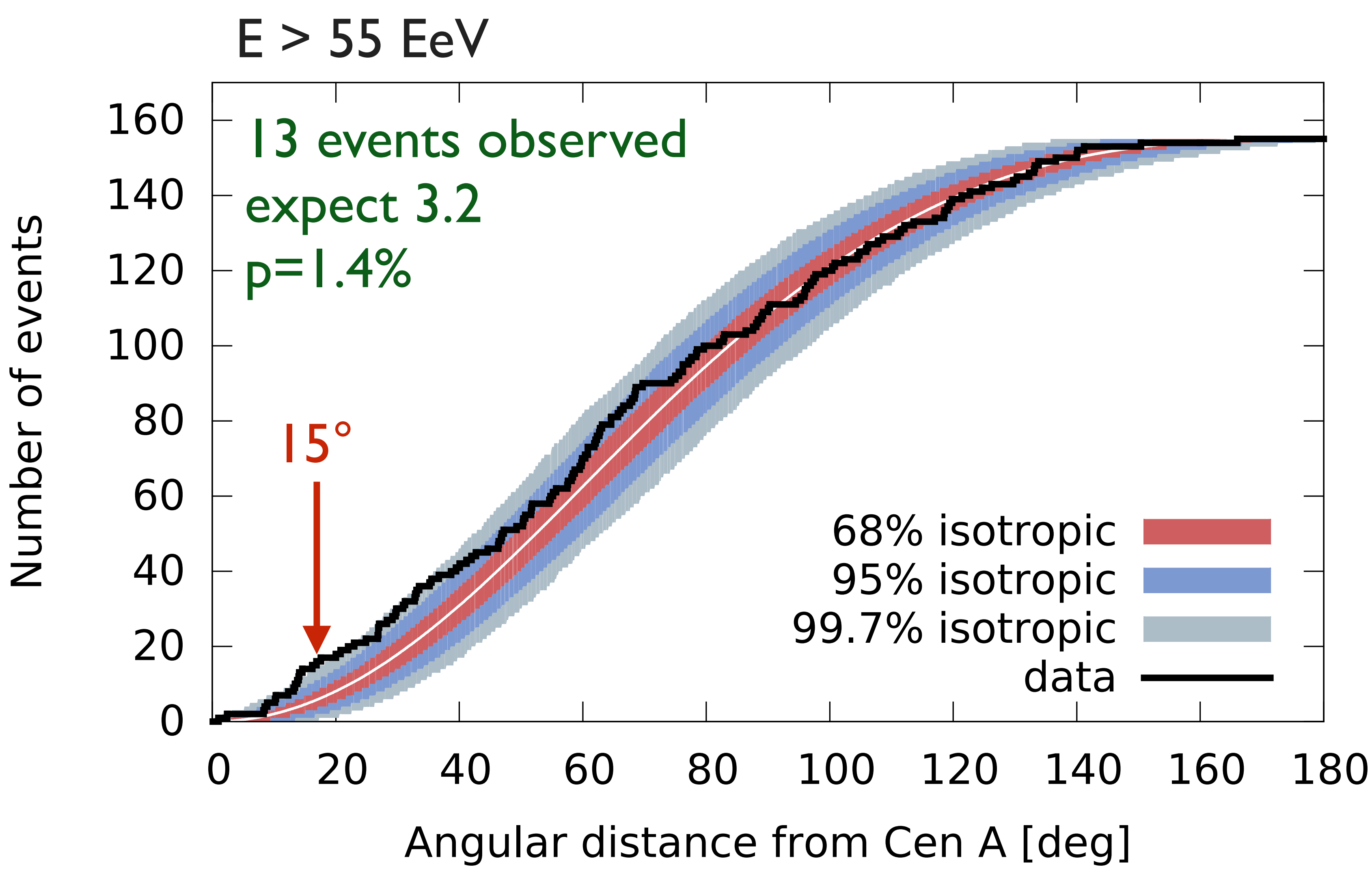
TA: ApJ 790:L21 (2014)



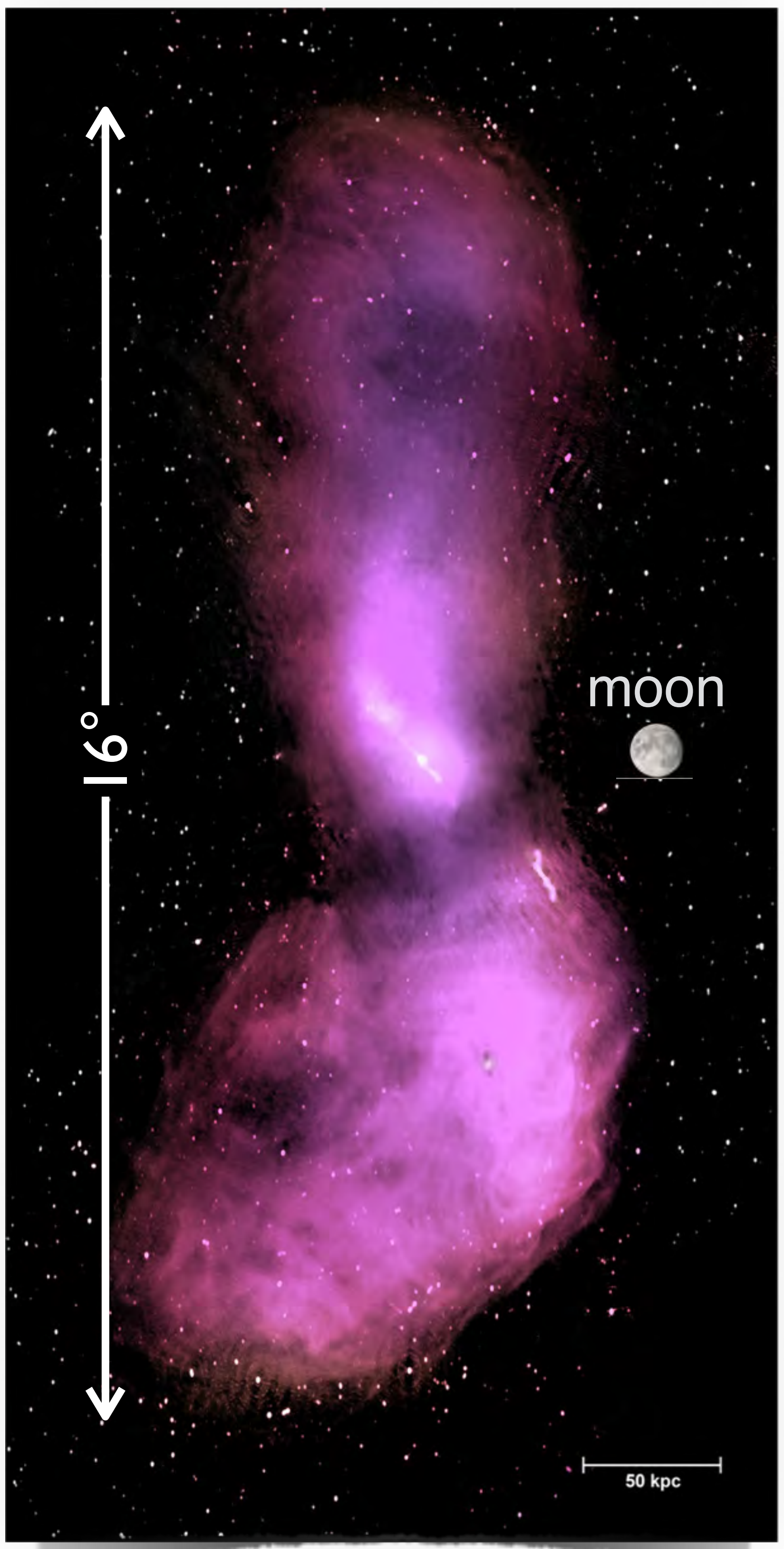
Auger: APP 34(2010) 314

Weak excess of events around Cen A

giant lobes ~ 280 kpc
physical age ~ 560 Myr
distance ~ 3.8 Mpc

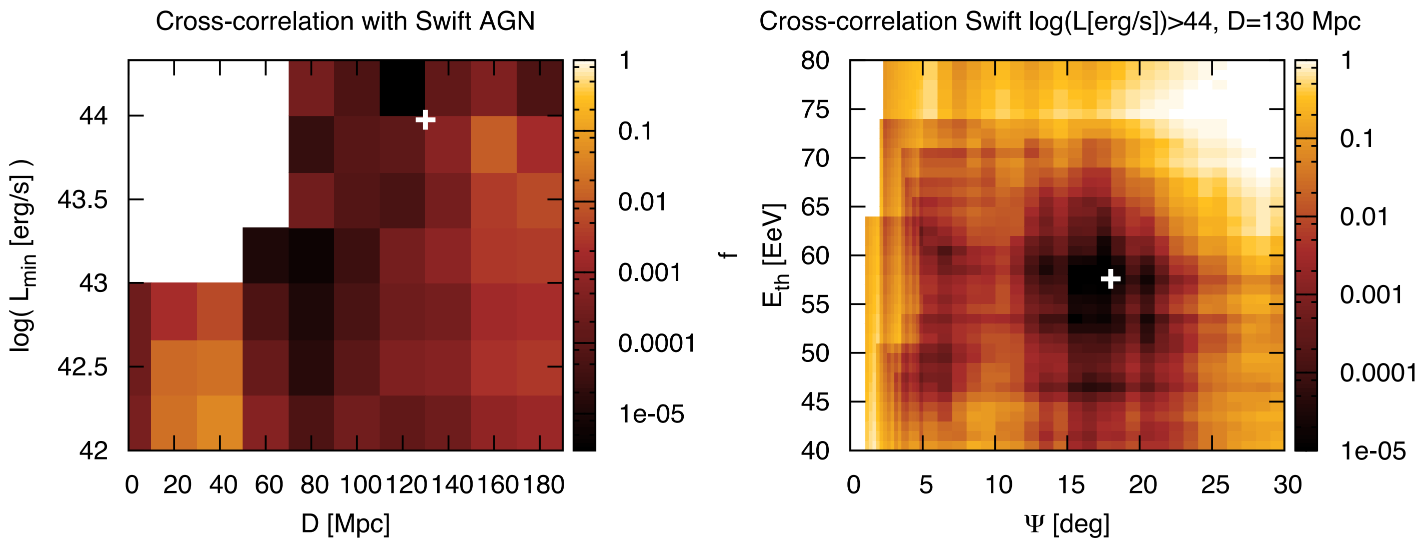


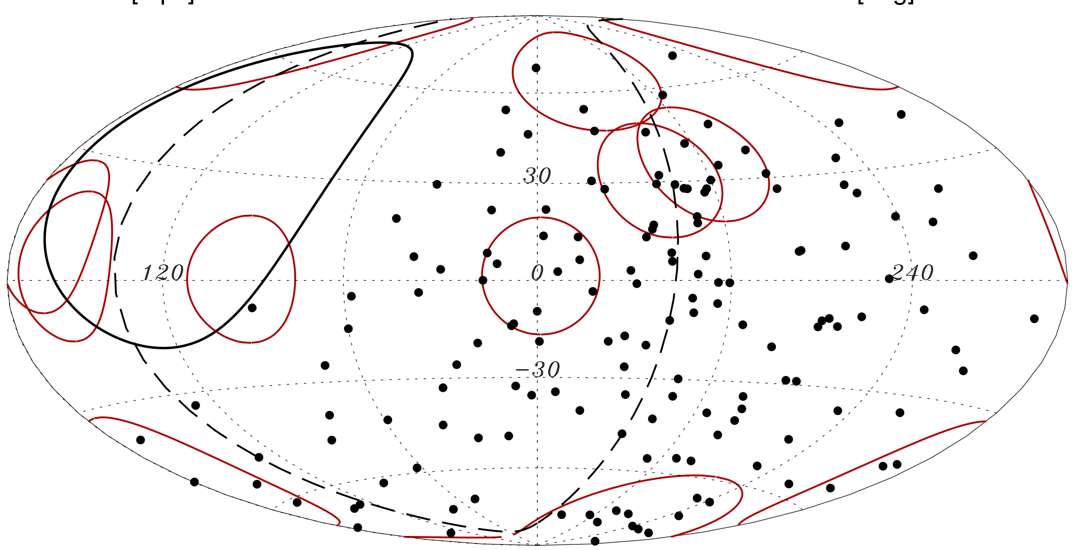
Auger Collaboration: ApJ 802:111 (2015)



Feain et al., ApJ 740 (2011) 17

Point Source Searches





Example:

Correlation to bright SWIFT AGN

best for:

D < 130 Mpc

L > 10^{44} erg/s

Ψ < 18°

➠ 62 pairs correlate with the 10 AGN, for 32.8 expected

p = 1.3%

Auger Collaboration
ApJ 804:15 (2015)

Summary of searches

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathcal{L}_{min}$ [erg/s]	f_{min}	$\mathcal{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	58	12	90	$10^{39.33}$	5.6×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%

No significant excesses were found around the Galactic Center, the Galactic Plane, or the Super-Galactic Plane.

Conclusions from CR Anisotropy Studies

1) Absence of significant correlations to Galactic Center and Galactic Plane

➪ **10 EeV sources are unlikely of Galactic origin**

2) Only a small deviation from overall isotropic sky

➪ **either large deflections by B-fields, e.g. due to heavy primaries**
(supported by Auger composition studies)

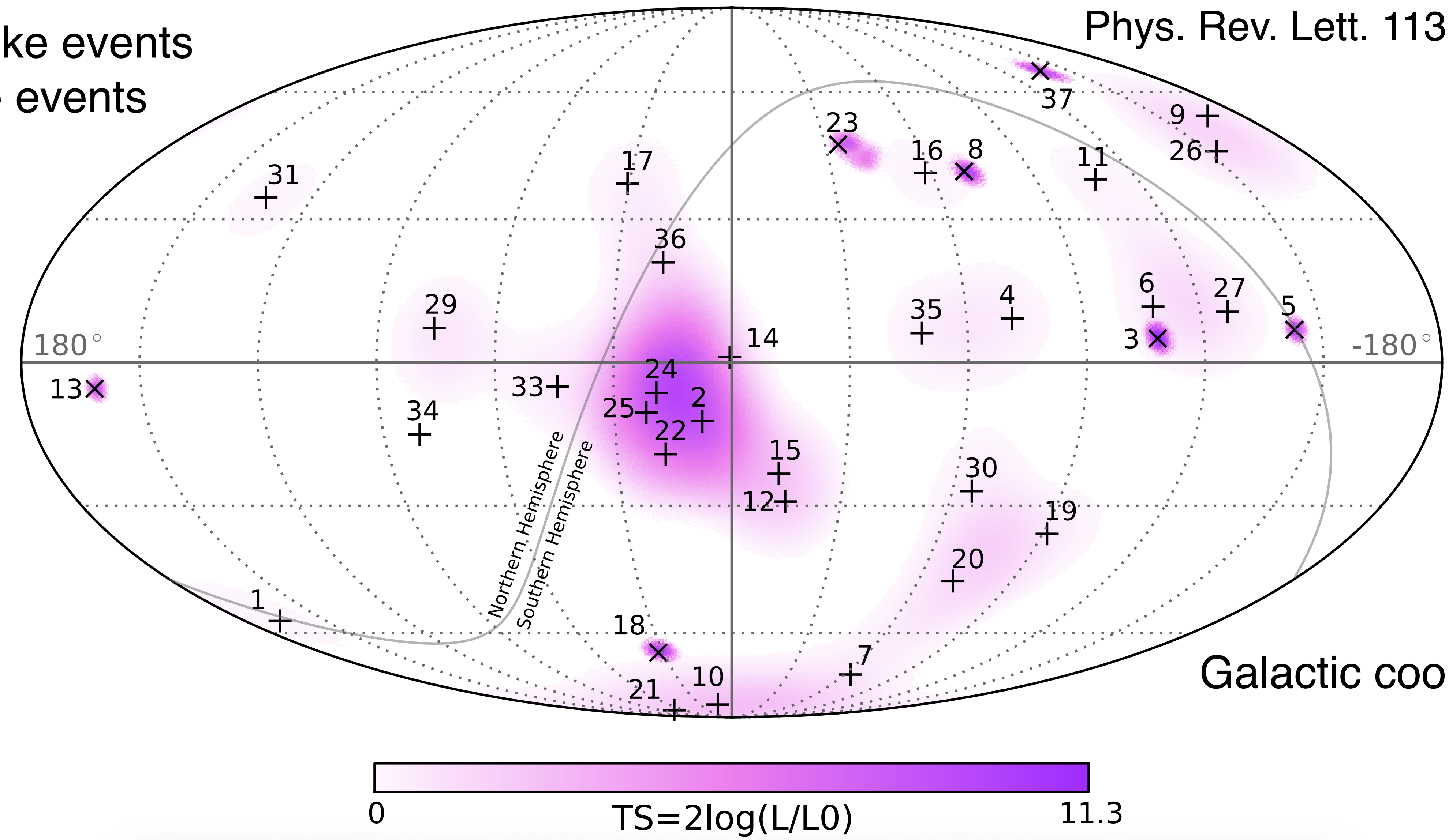
➪ **or number of sources is very large**
(bounds by Auger from lack of autocorrelations: $\rho \gtrsim 10^{-4}$ Mpc^{-3})

Neutrinos

A look to the PeV Neutrino Sky

IceCube Collaboration:
Phys. Rev. Lett. 113 (2014) 101101

+: Shower like events
x: Track like events



Galactic coordinates

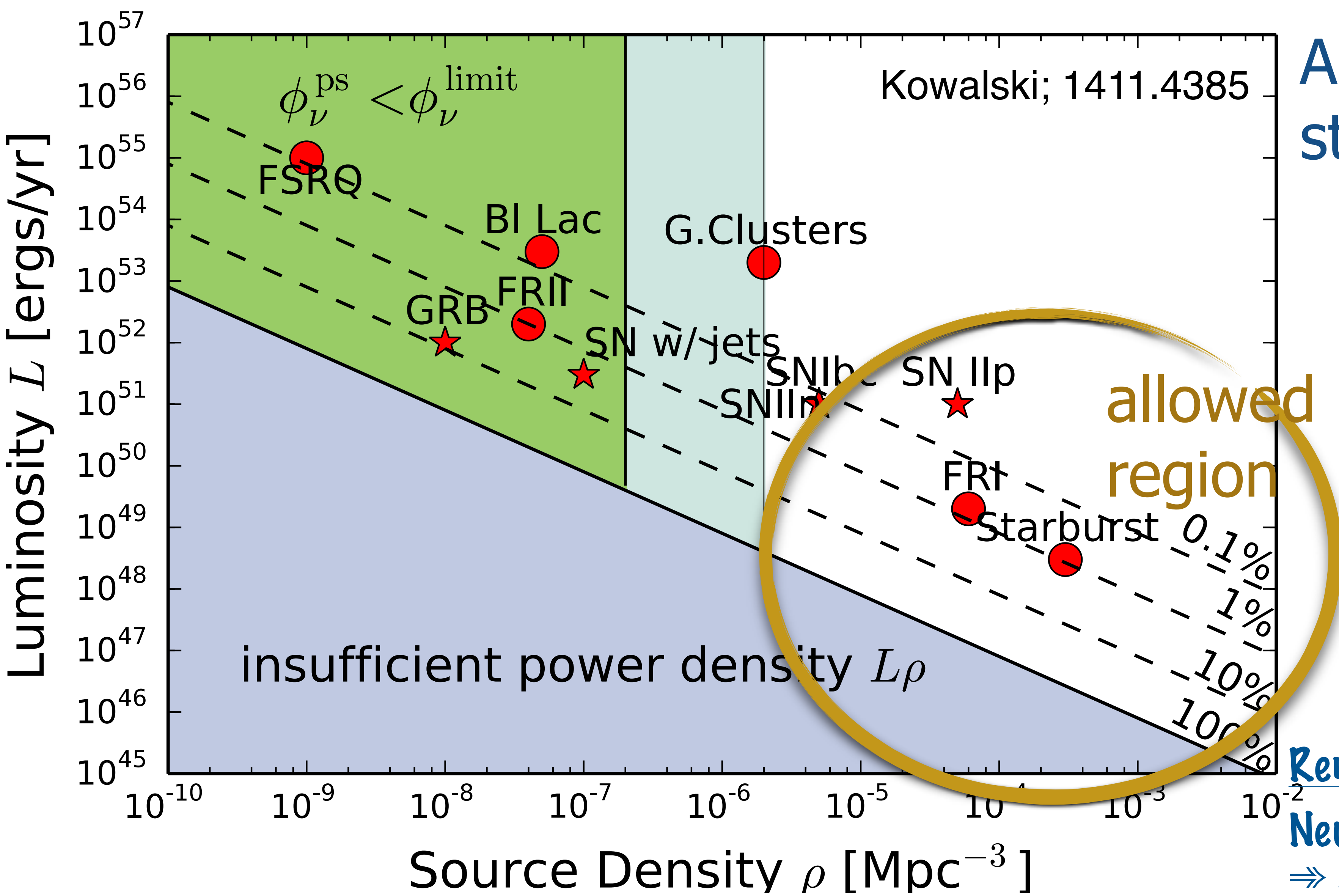
No significant clustering seen (p=84%)

cross correlations to catalogs ⇛ no signal yet
cross correlations to UHECR (Auger+TA) ⇛ ongoing

Constraints from Neutrino-Isotropy

High level of Isotropy ⇛ **source density** must be fairly **high**

Int. Flux F=ρ·L is known ⇛ Mean **Luminosity** per source must be **low**



Assumption:
steady point sources

Density & Luminosity compare well to UHECRs !

Remark:

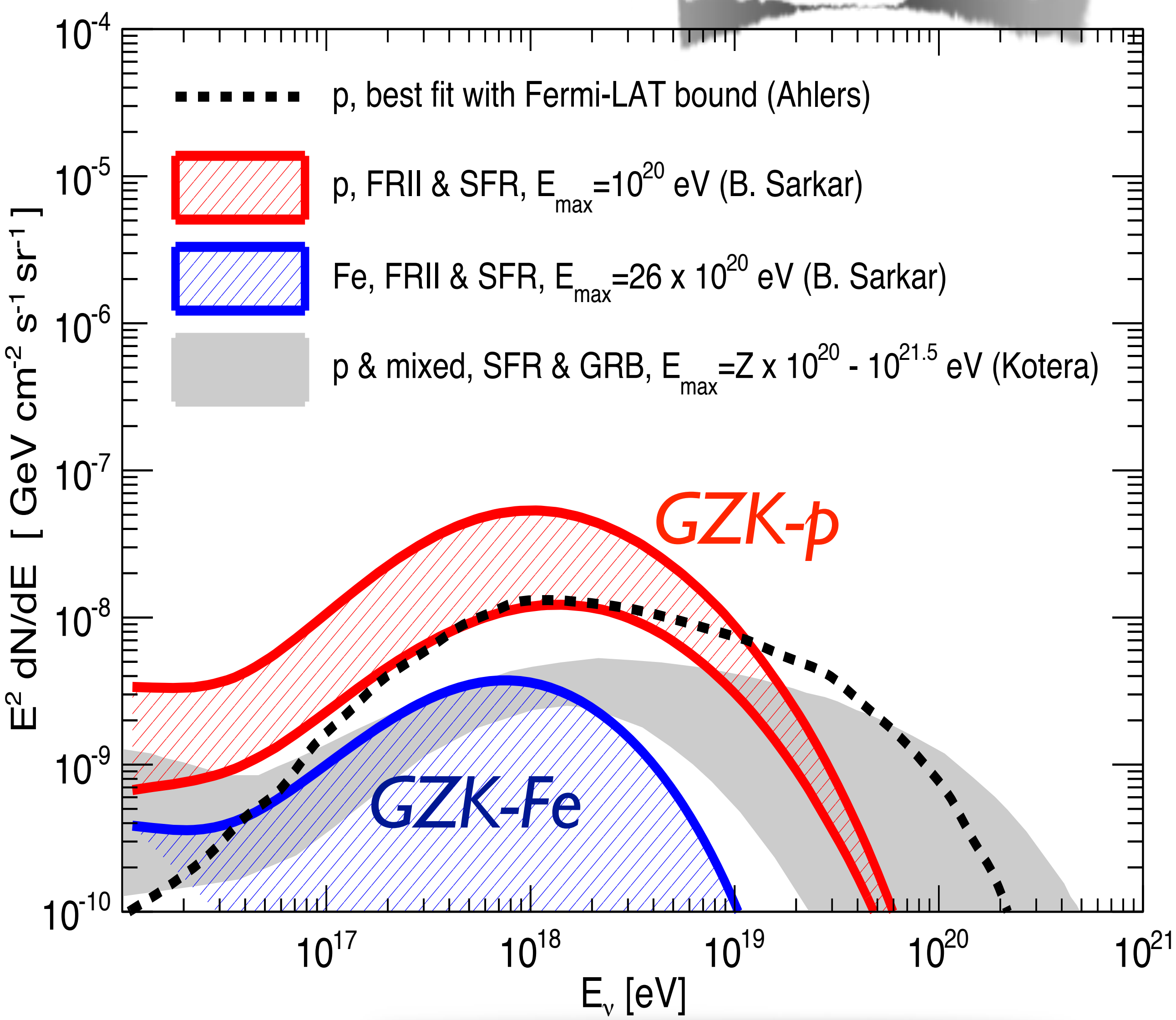
Neutrinos can come from far away
⇛ sky may remain isotropic

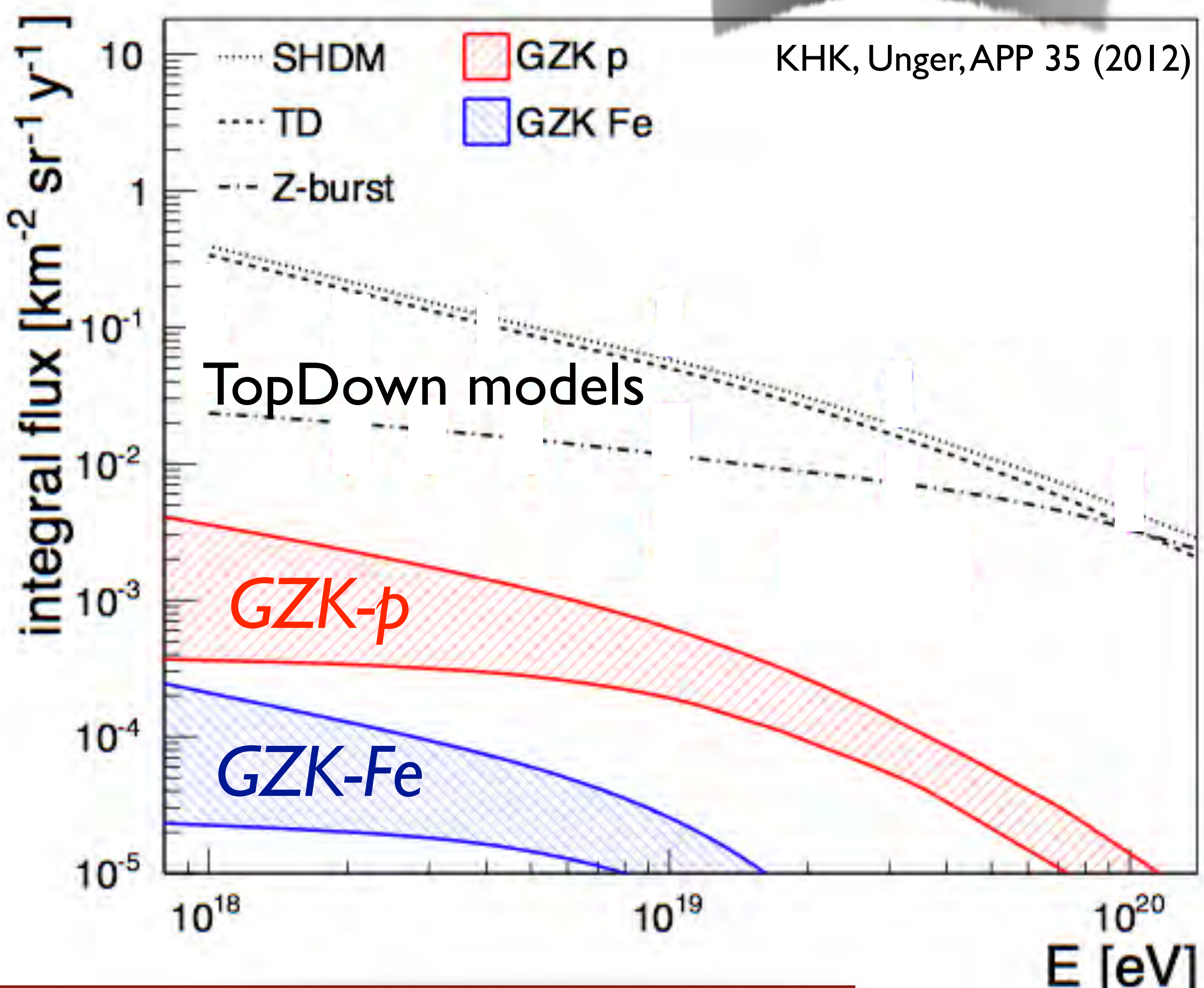
UHECRs come from within GZK sphere
⇛ limited number of sources
sky needs to become anisotropic

...Back to the GZK-Question:
– smoking gun signals by EeV ν's and γ's –

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow$$

$$\rightarrow n + \pi^{+} \rightarrow \nu_{\mathrm{EeV}} \qquad \rightarrow p + \pi^{0} \rightarrow \gamma_{\mathrm{EeV}}$$

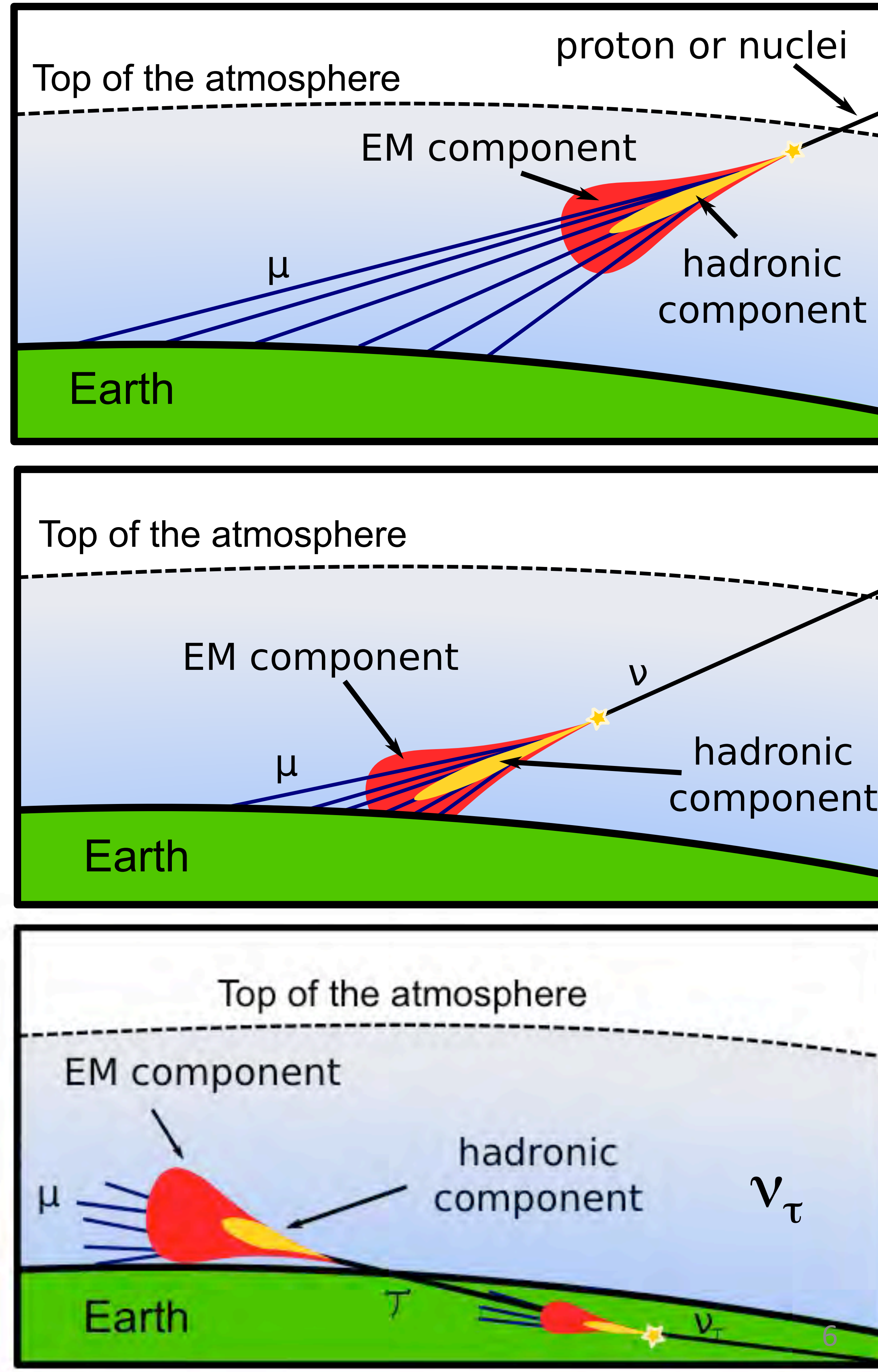




Note, these calculations assume that the flux suppression is caused solely by the GZK-effect

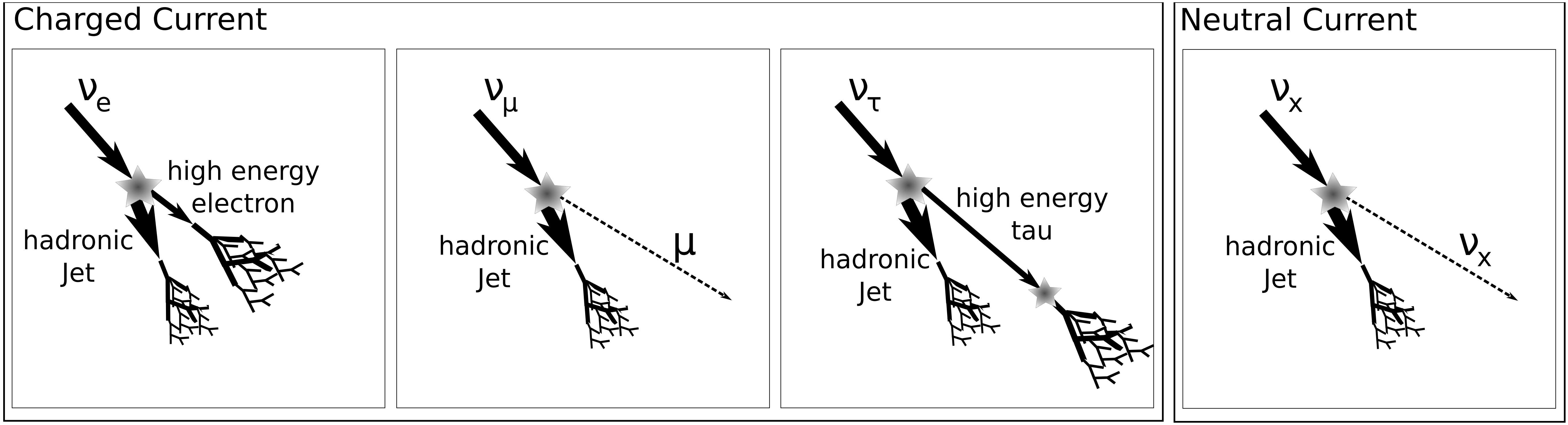
Search for EeV Neutrinos in inclined showers

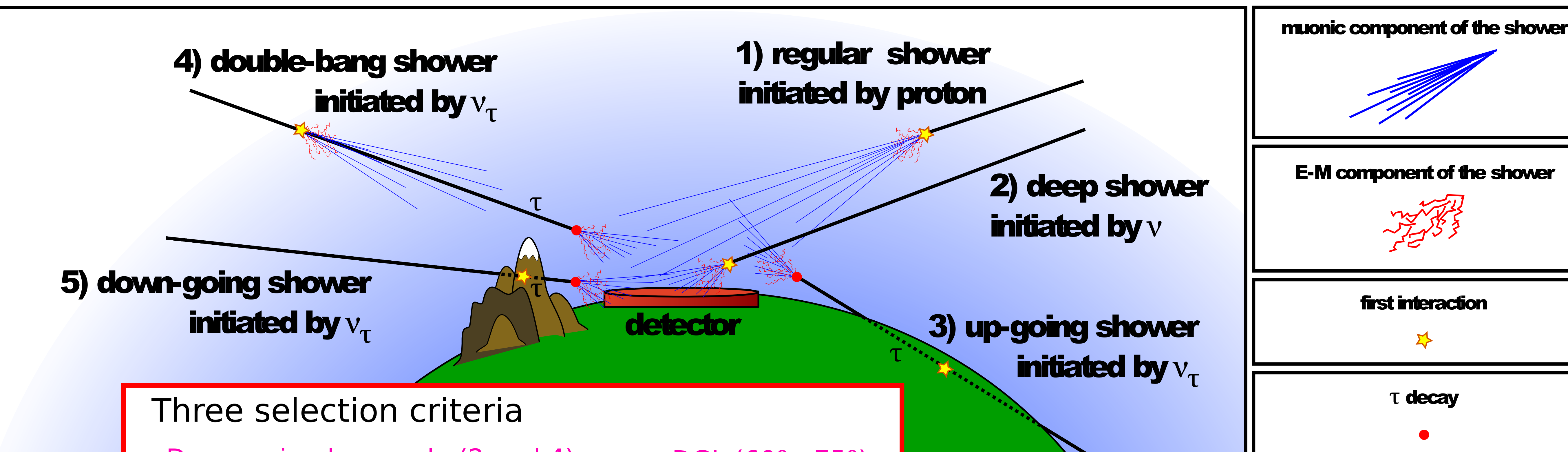
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

Sensitivity to all ν flavors and channels



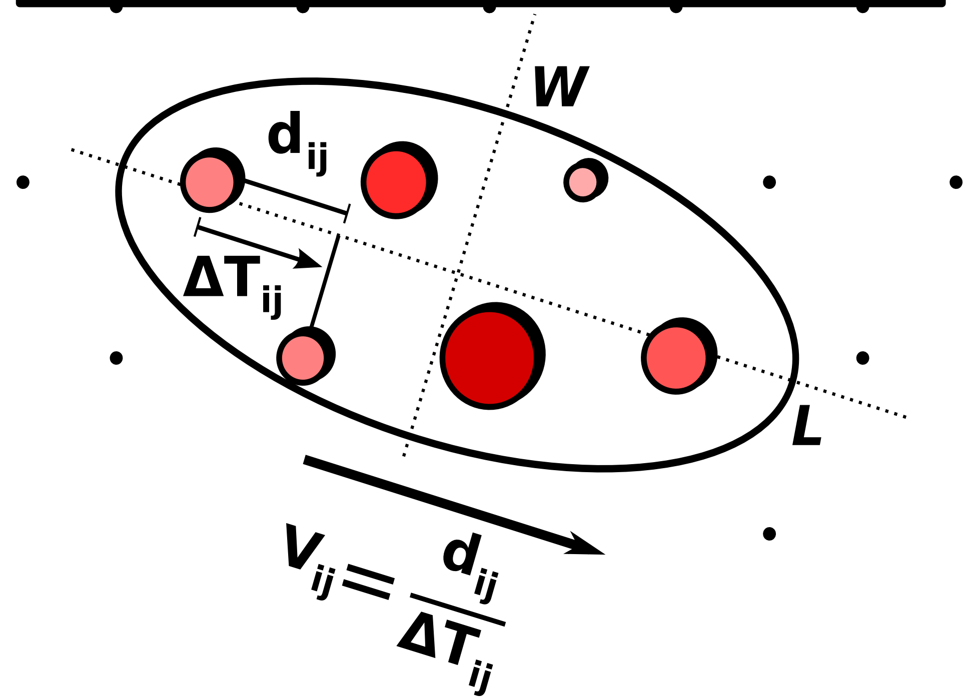


Three selection criteria

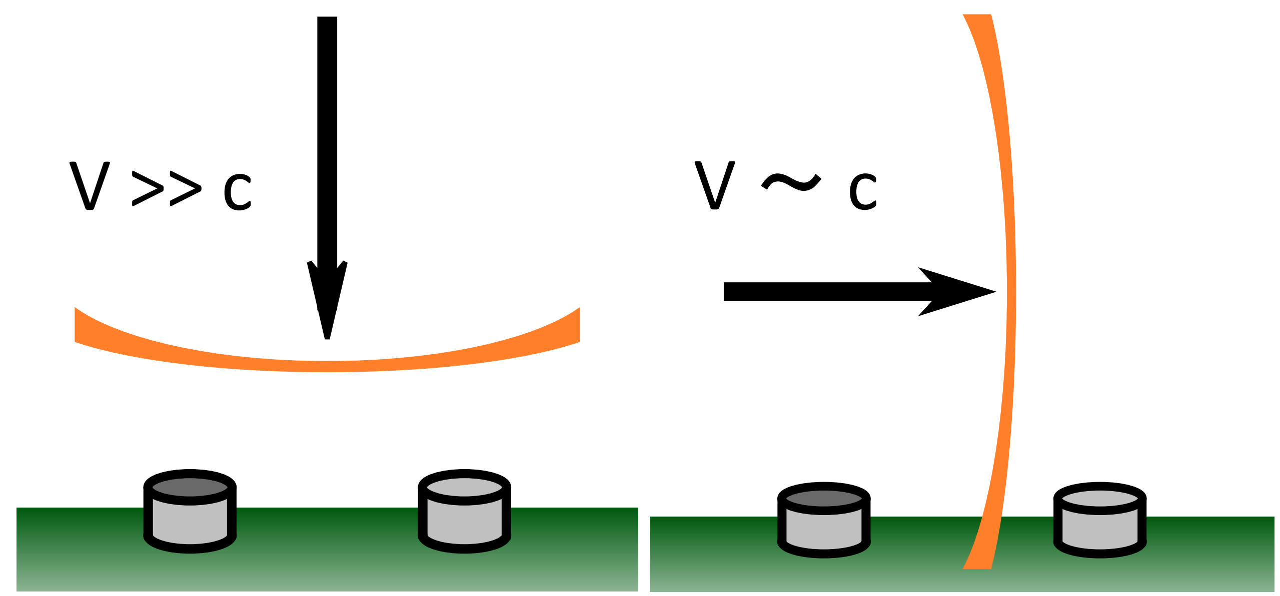
- Down-going low angle (2 and 4) ⟶ DGL (60º - 75º)
- Down-going high angle (2, 4 and 5) ⟶ DGH (75º - 90º)
- Earth-skimming (3) ⟶ ES (90º - 95º)

(1) Selection of inclined showers

(1) Elongated footprint



(2) Apparent velocity V of propagation of shower front at ground along major axis L

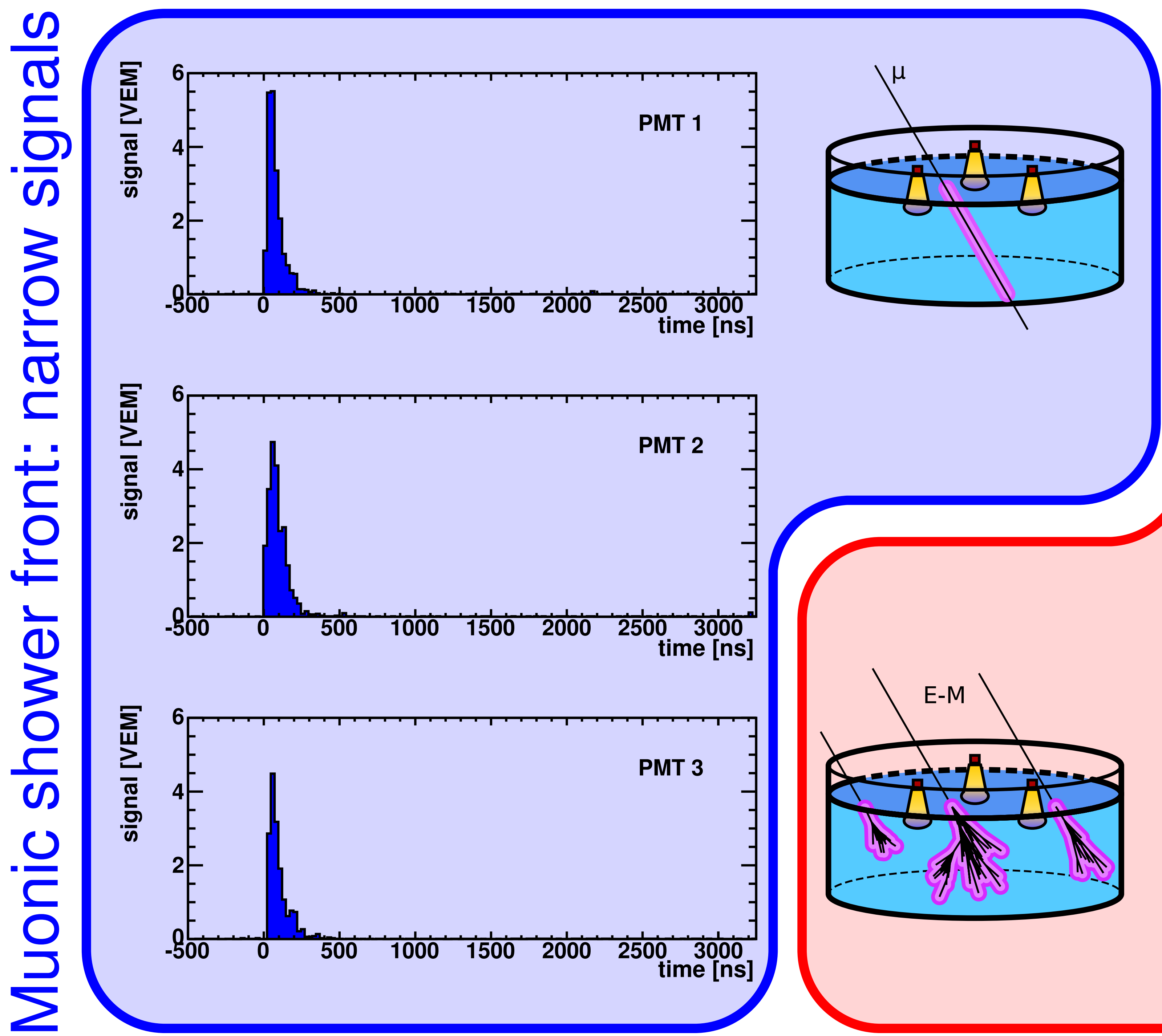


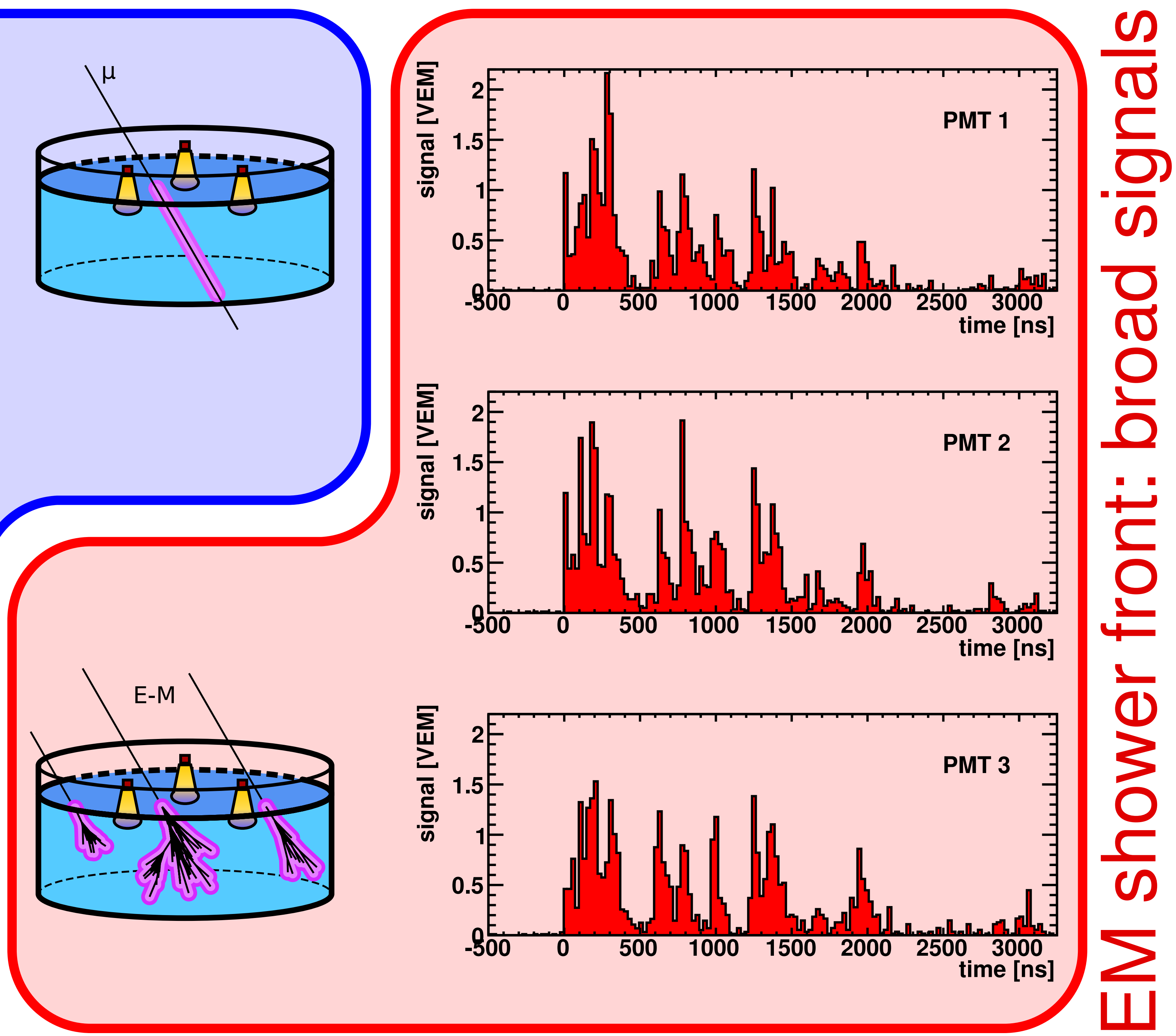
(3) Reconstructed θ

Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
$L/W > 5$	$L/W > 3$	–
$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
$\mathrm{RMS}(V) < 0.08$ m ns^{-1}	$\mathrm{RMS}(V)/\langle V \rangle < 0.08$	–
–	$\theta_{rec} > 75°$	$\theta_{rec} \in (58.5°,\ 76.5°)$

(2) Identifying νs in surface detector data

With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signals in the water Cherenkov stations).





(2) Identifying νs in surface detector data

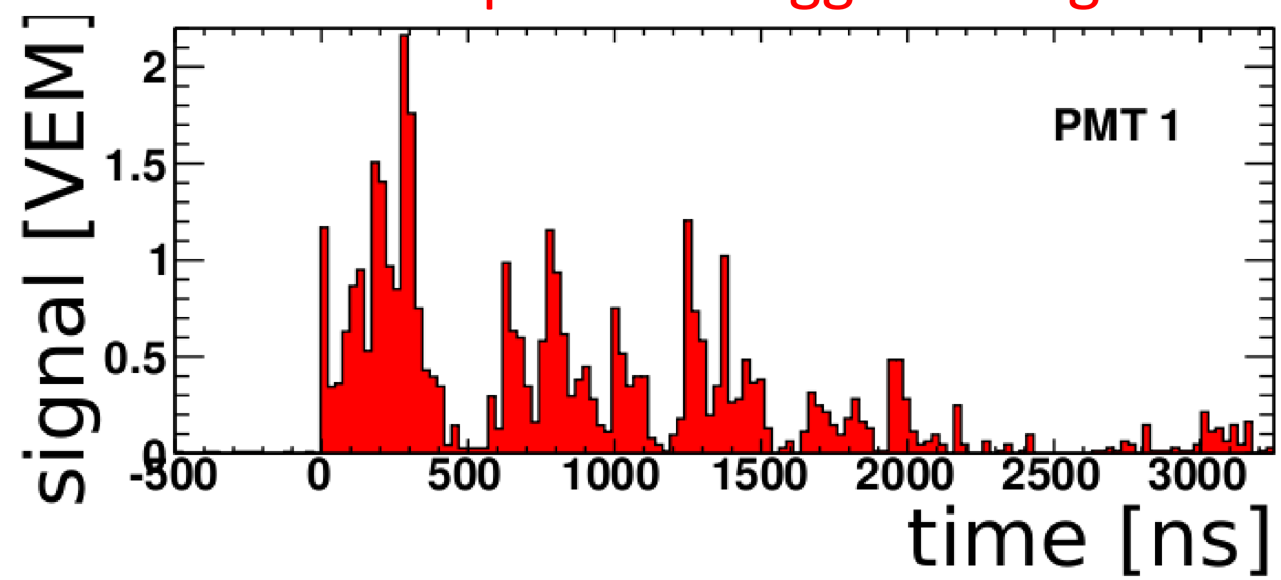
From the observational point of view, signals extended in time:

- Induce Time-over-Threshold (ToT) triggers in the SD stations

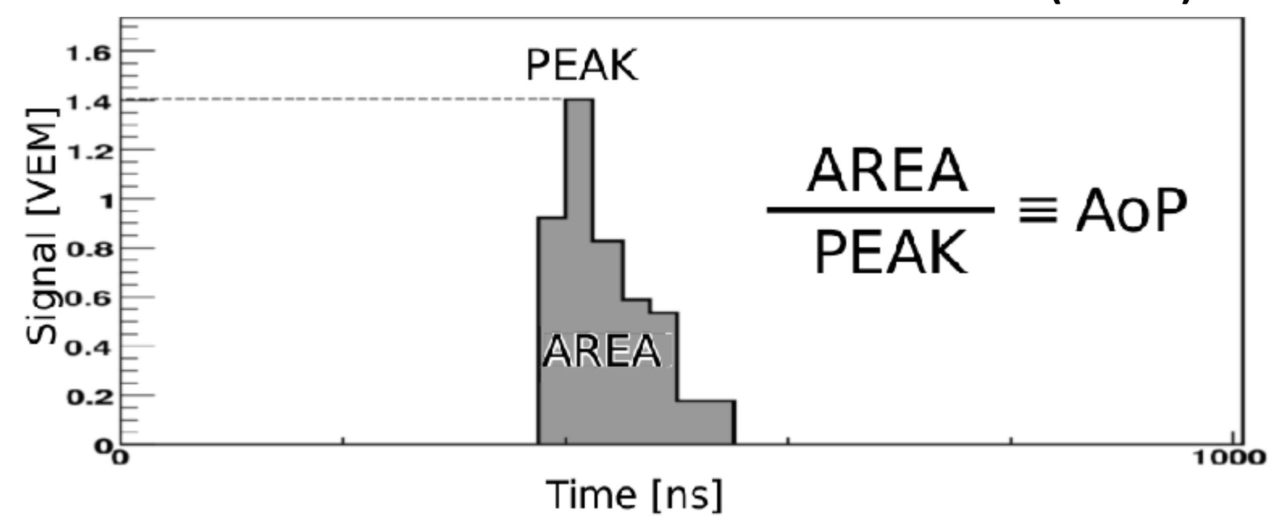
and/or

- Have large Area-over-Peak value (AoP ∼ 1 muonic front)

Trace example: ToT trigger & large AoP



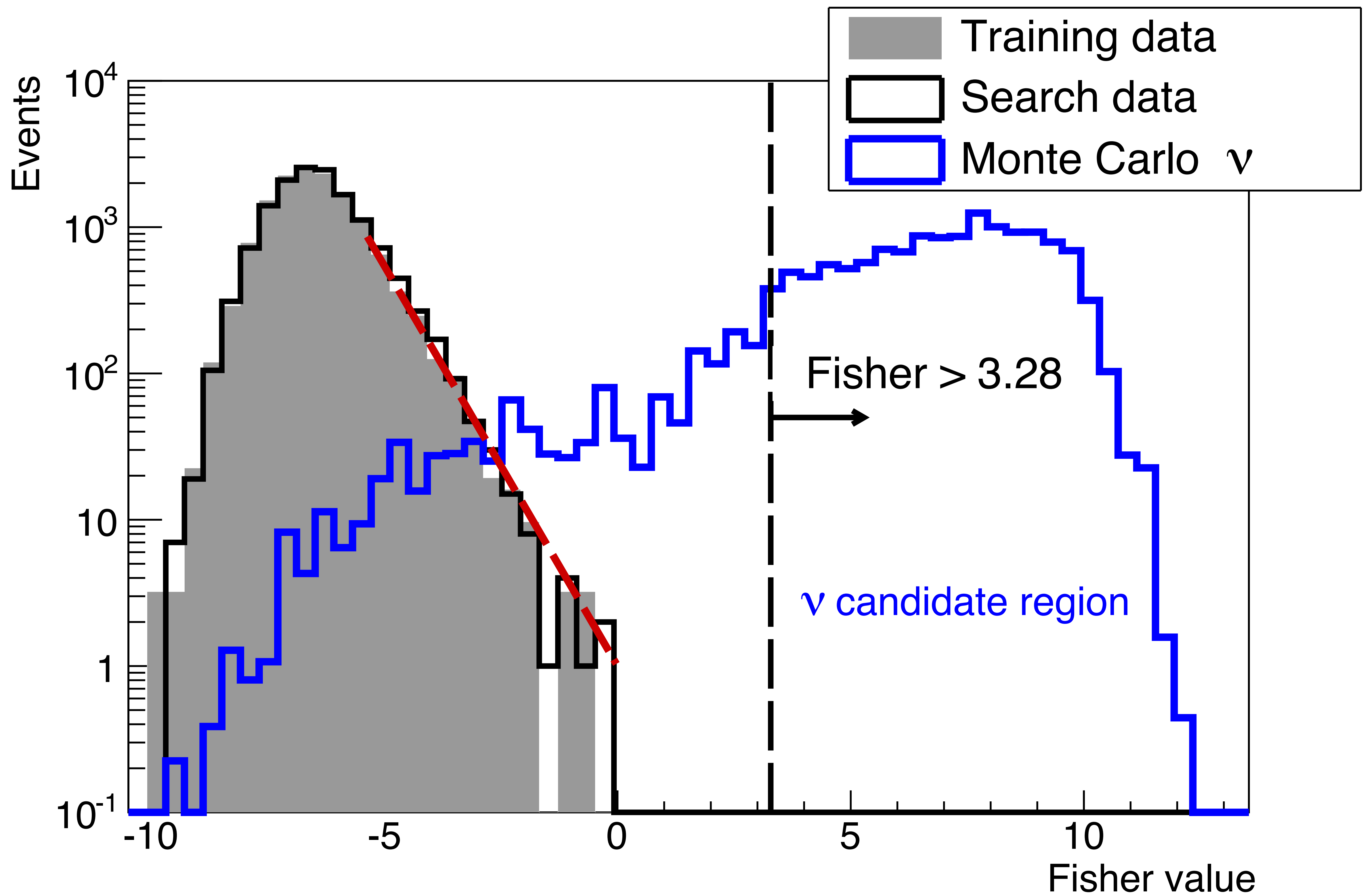
Definition of Area-over-Peak (AoP)



$$\frac{\text{AREA}}{\text{PEAK}} \equiv \text{AoP}$$

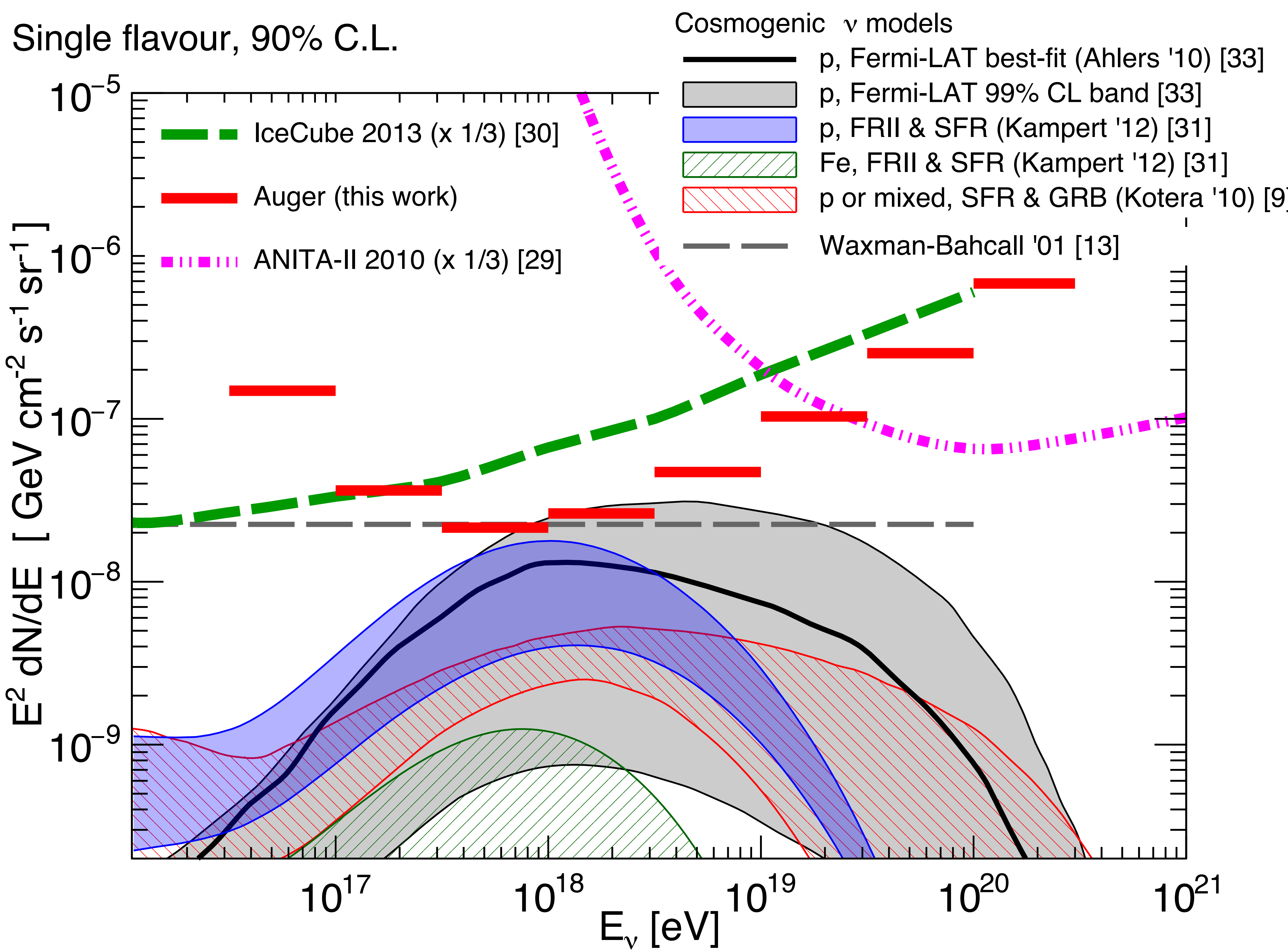
Searching for neutrinos ⇒
Searching for inclined showers with stations with ToT triggers and/or large AoP

Combined Fisher Discriminant

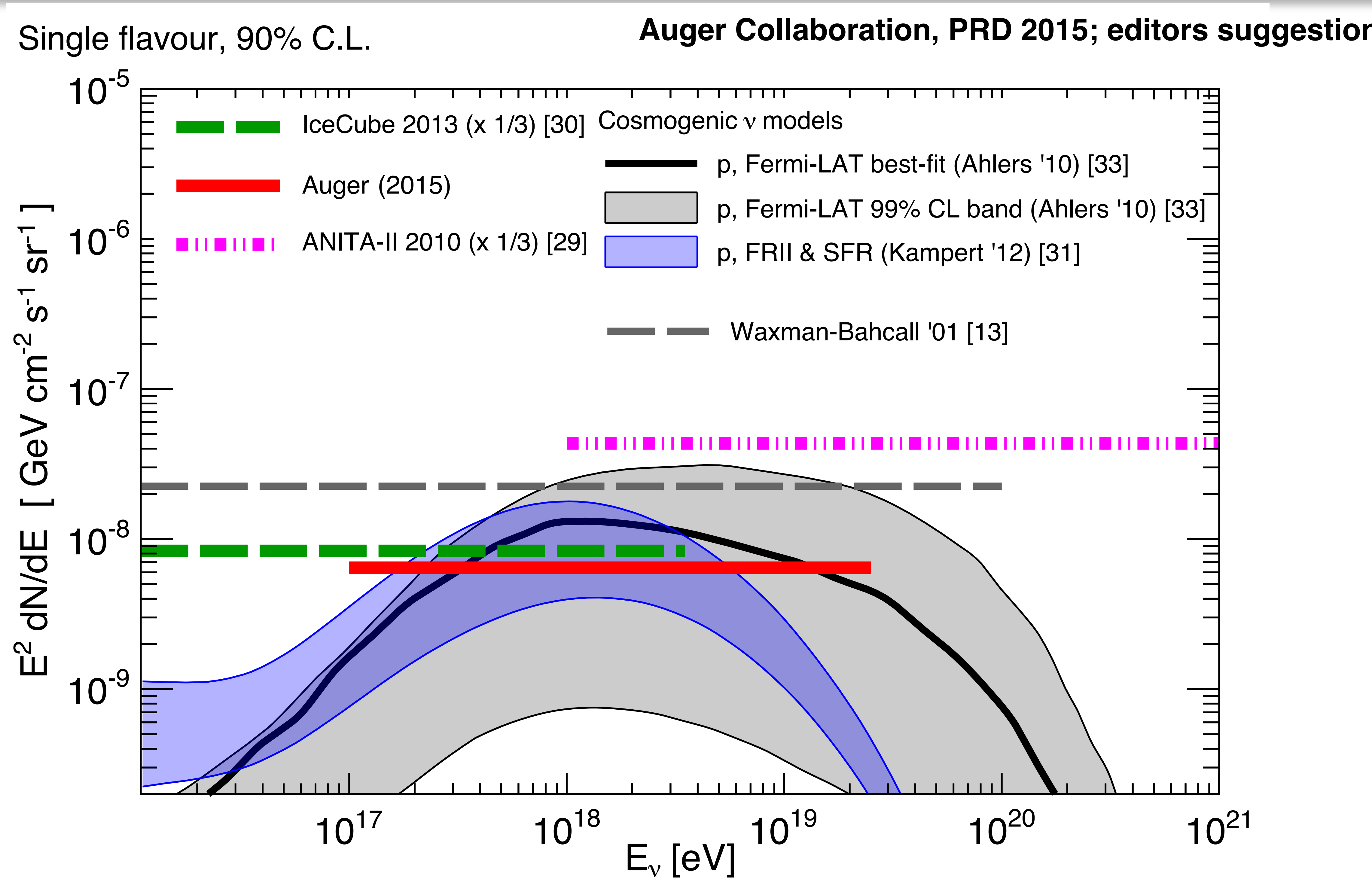


EeV Neutrino Limits

Auger Collaboration, PRD 2015; editors suggestion

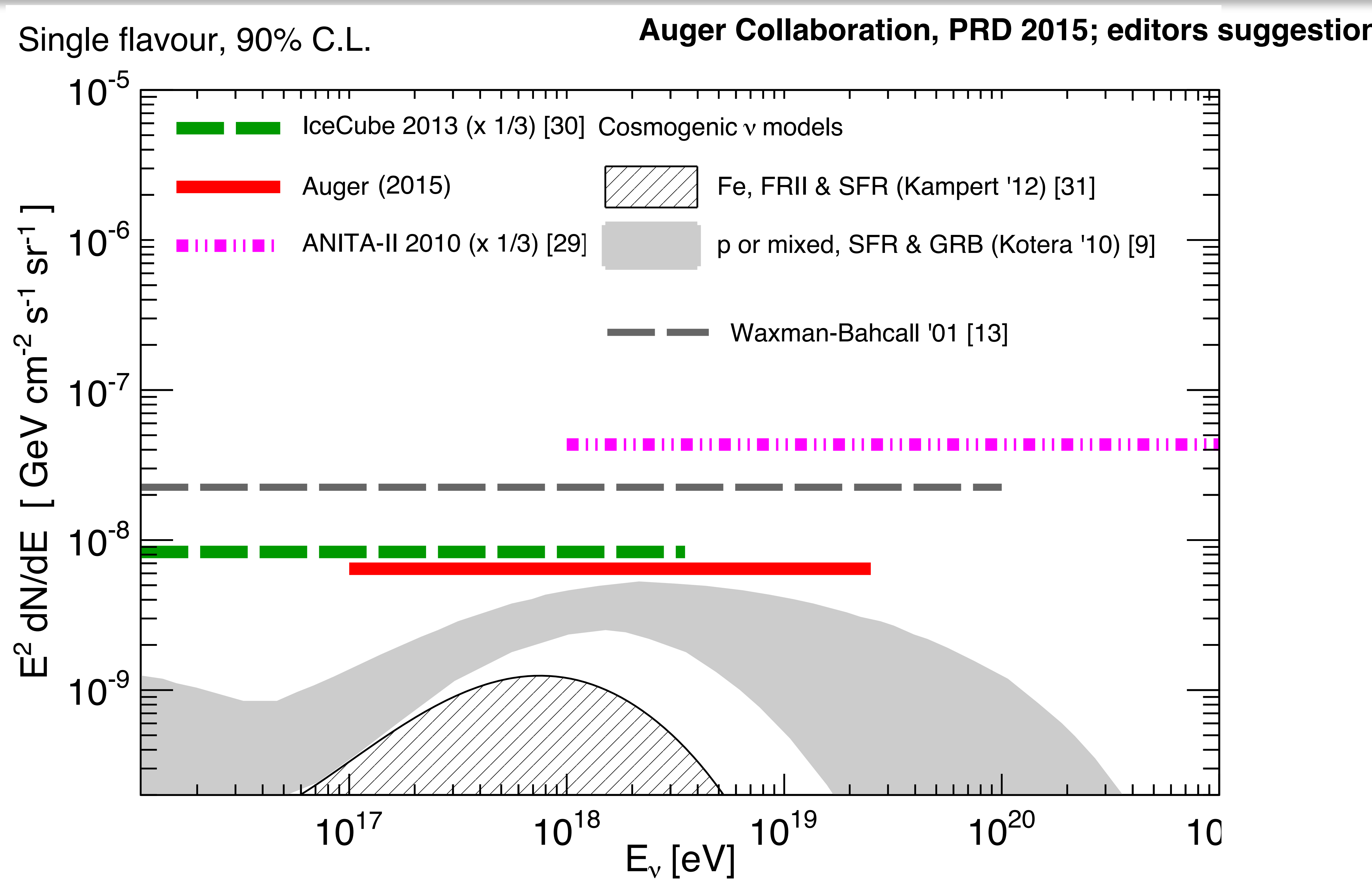


EeV Neutrino Limits



Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources

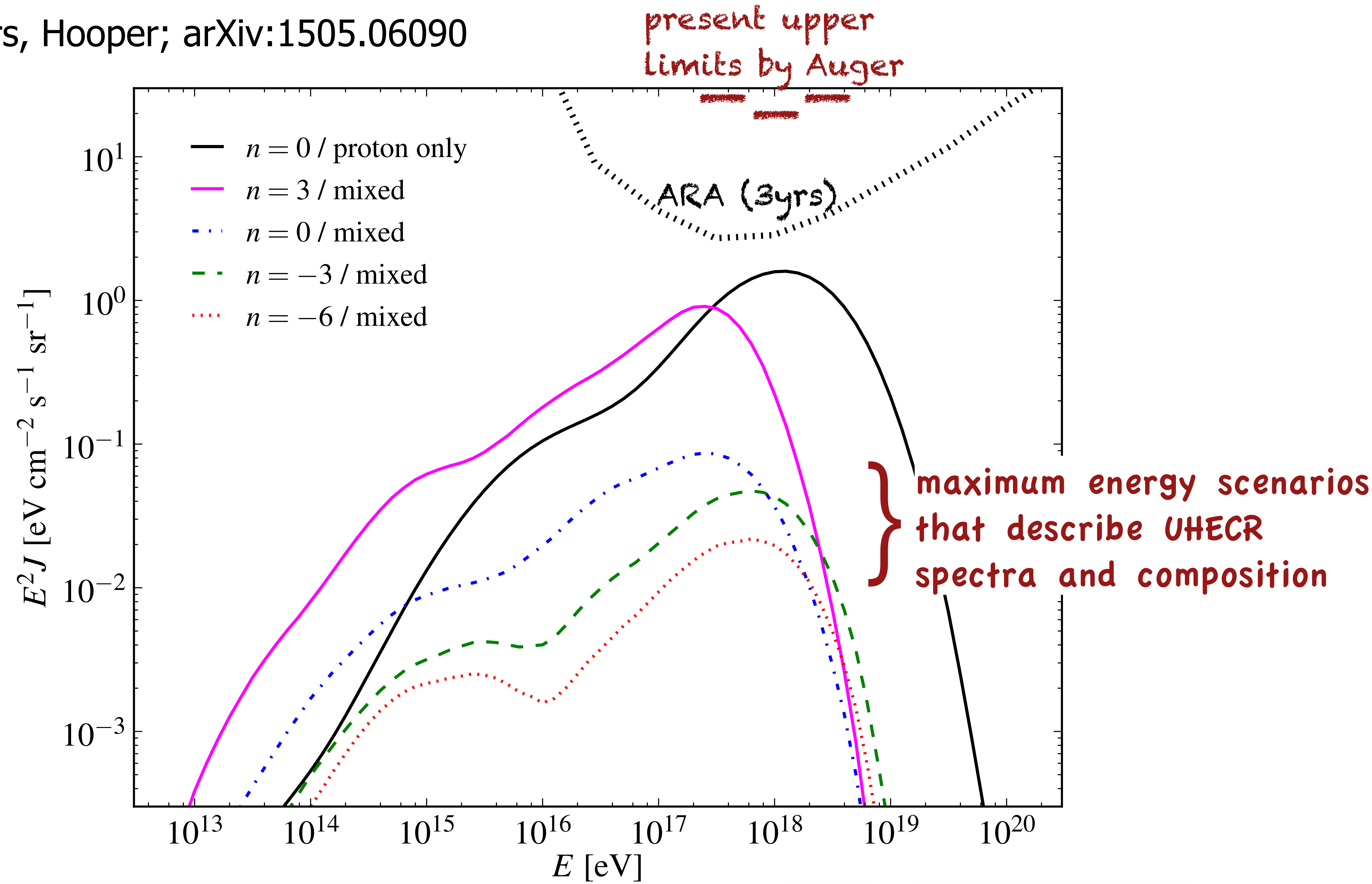
EeV Neutrino Limits



Neutrino upper limits start still above cosmogenic neutrino fluxes for Fe-sources

Cosmogenic Neutrinos Expectations

Taylor, Ahlers, Hooper; arXiv:1505.06090



Cosmogenic neutrino fluxes may be ~2 orders of magnitudes lower than generally expected !!

Quest about origin of UHECR flux suppression of fundamental importance

- for understanding UHECR sources and
- prospects of future EeV neutrino experiments


Answering these questions requires
Upgrades of
TA and Auger Observatory

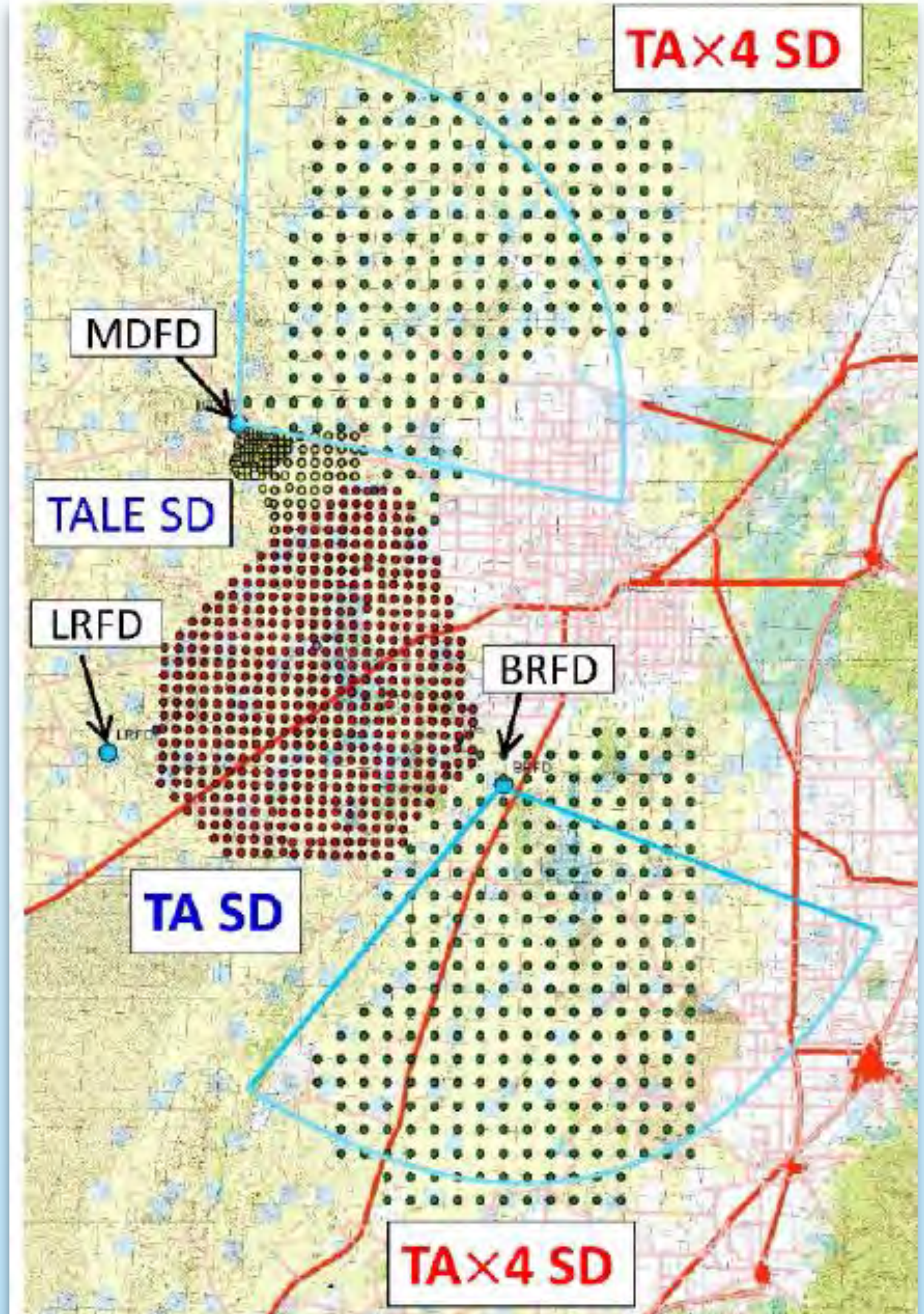
TAx4 SD Upgrade

500 more SDs
2 more FD stations

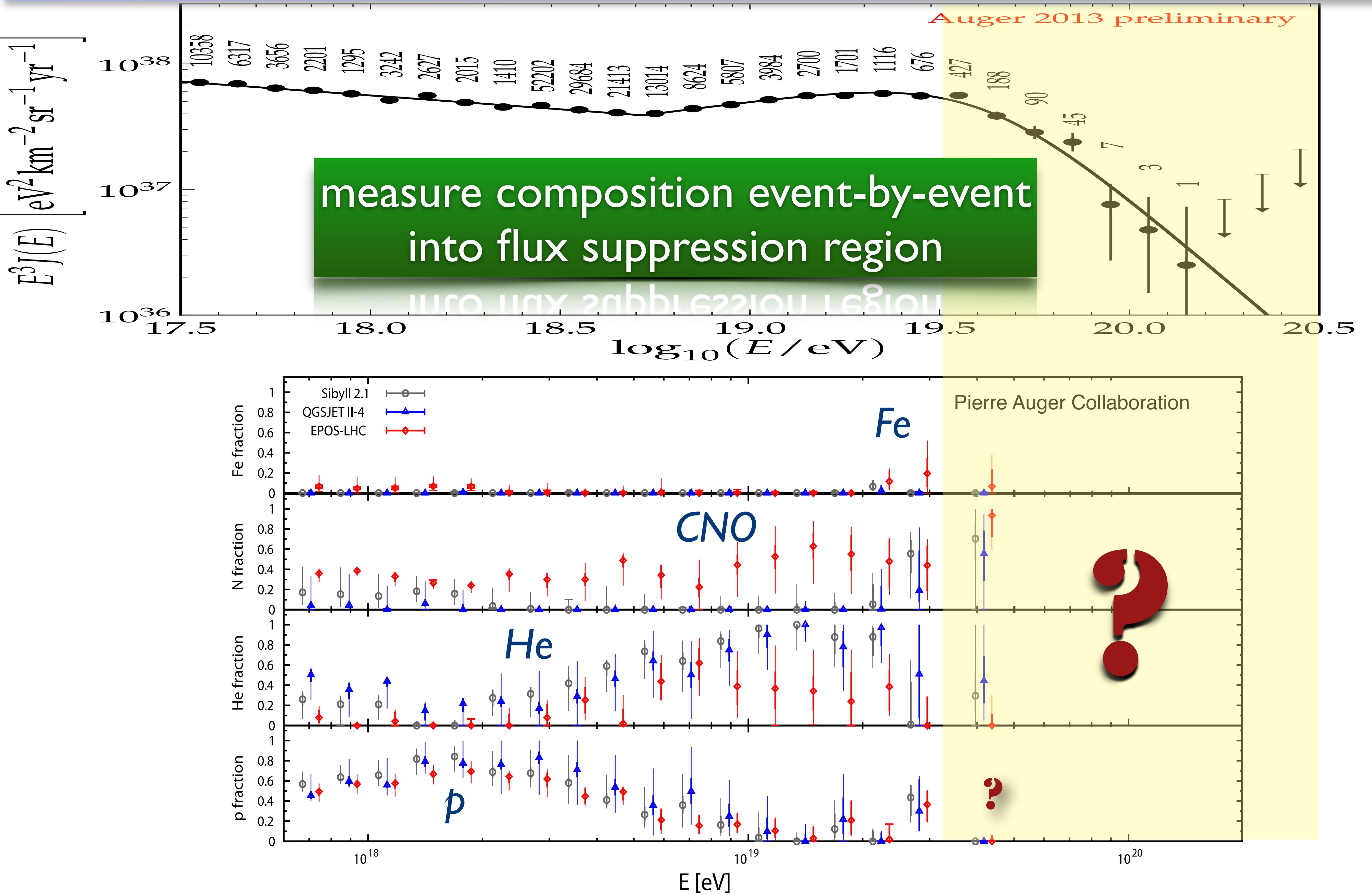
- SD: 700 -> **3000 km²**
- Hybrid: x3 acceptance
- Optimized for UHECR above cutoff (fully efficient above ~60 EeV)

collect statistics more rapidly

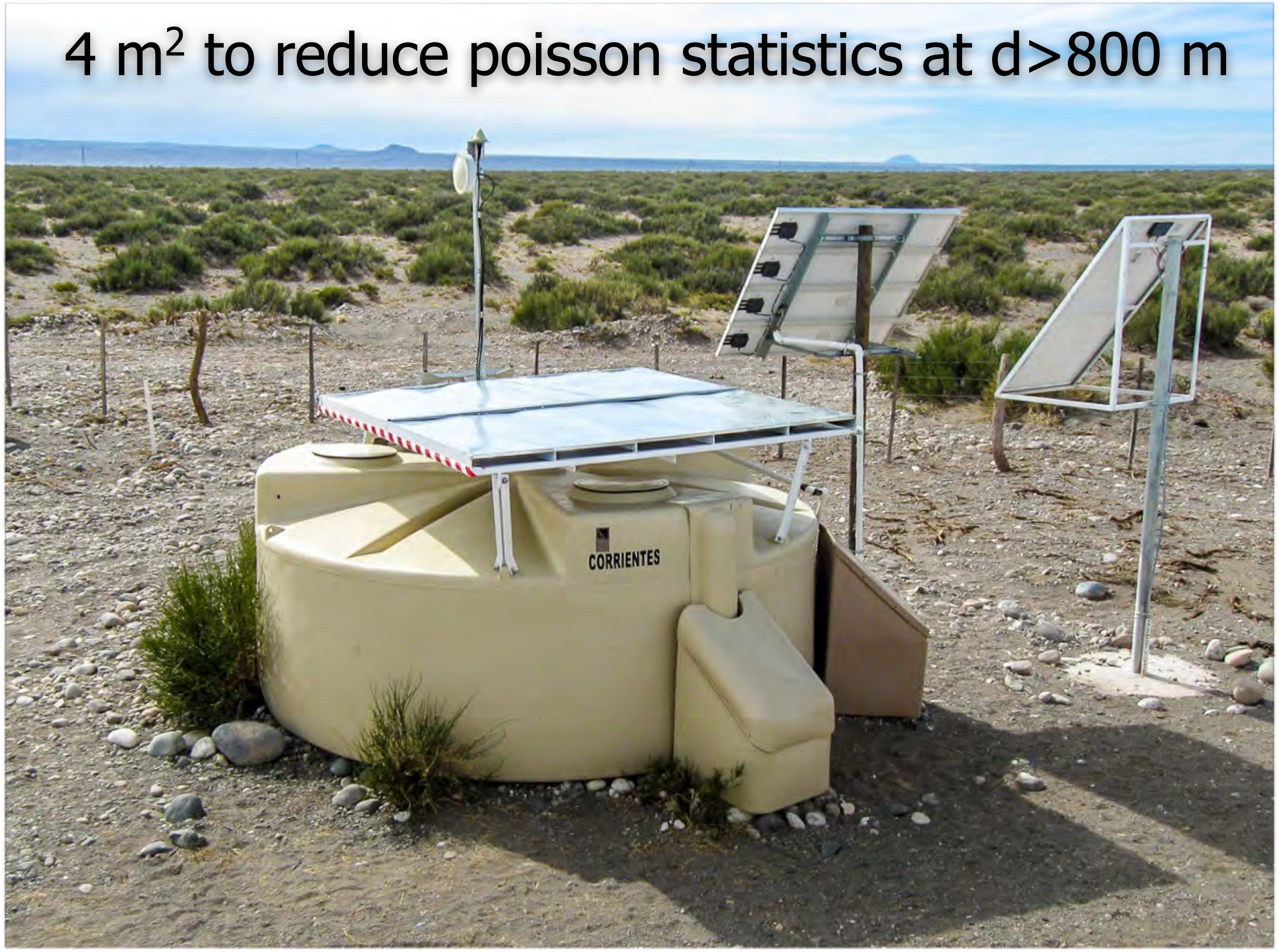
funding approved by JSPS



Auger Upgrade



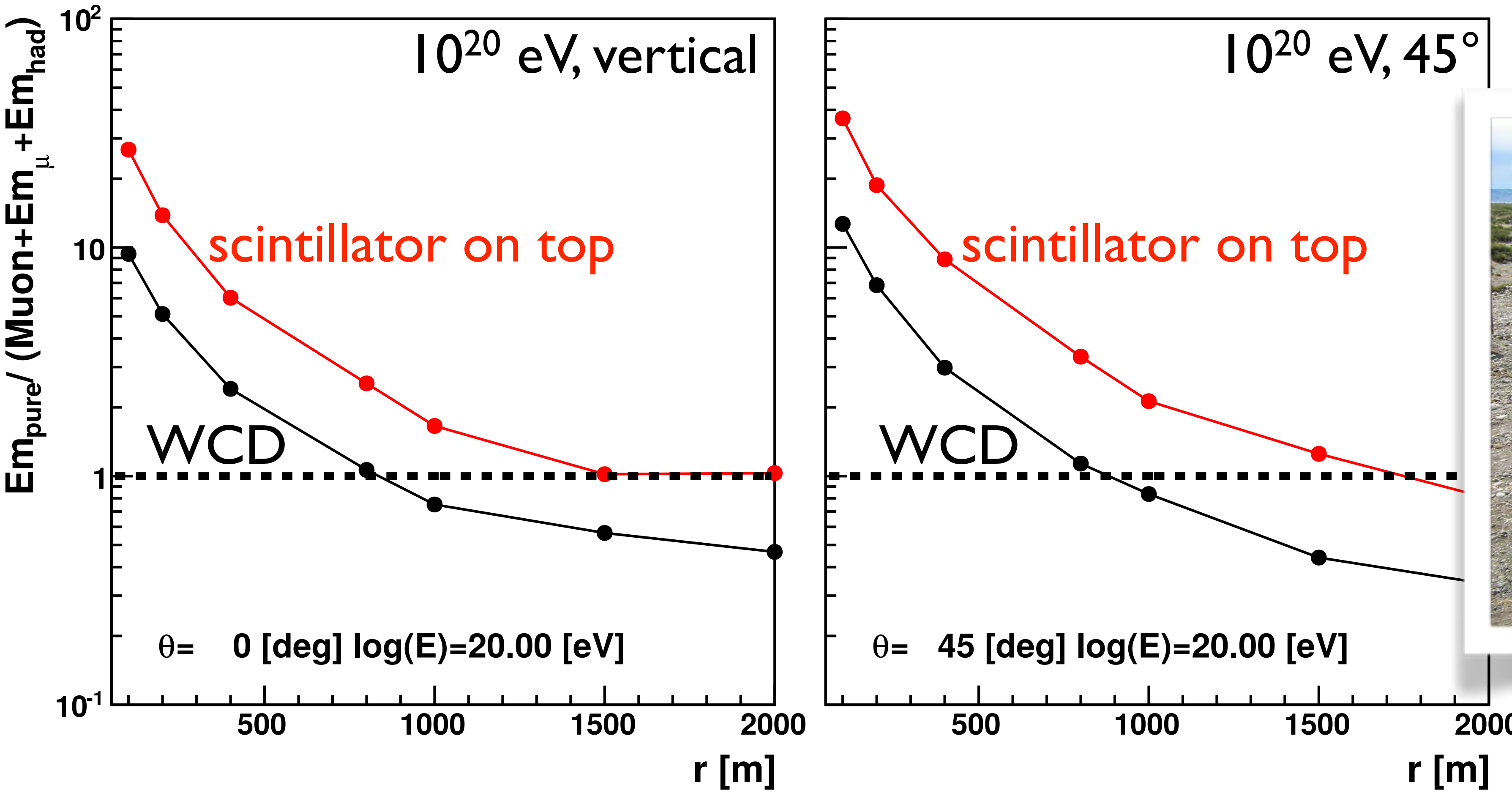
Auger Upgrade



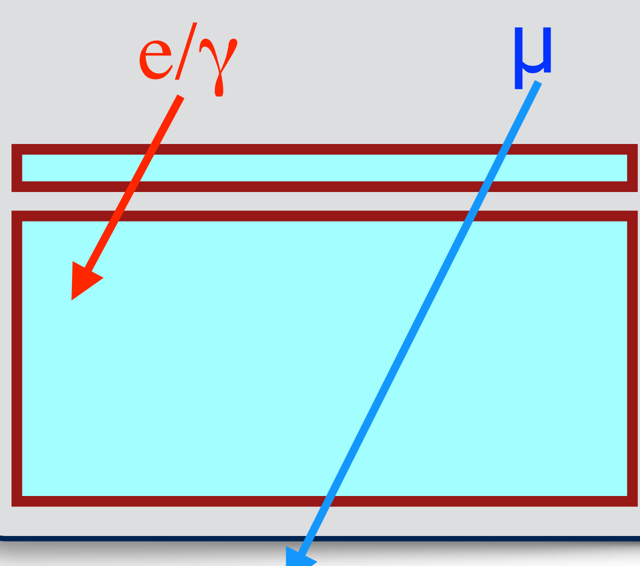
Scintillators on top of each Water Cherenkov Tank

(non invasive, fast to install, robust technology, relatively inexpensive)

Scintillator Signals dominated by e+γ



signal contribution from electrons and muons in EAS significantly different in scintillator and water Cherenkov tank



Linear system of equations solved by matrix inversion

$$\begin{pmatrix} S_{SSD} \\ S_{WCD} \end{pmatrix} = \begin{pmatrix} \lambda\, A_{SSD} & A_{SSD} \\ \beta\, A_{WCD} & A_{WCD} \end{pmatrix} \begin{pmatrix} \mathcal{F}_{em} \\ \mathcal{F}_{\mu} \end{pmatrix}$$

➡ $S_{WCD,\mu} = \delta \cdot S_{WCD} - \gamma \cdot S_{SSD}$

alternative approach: shower Universality

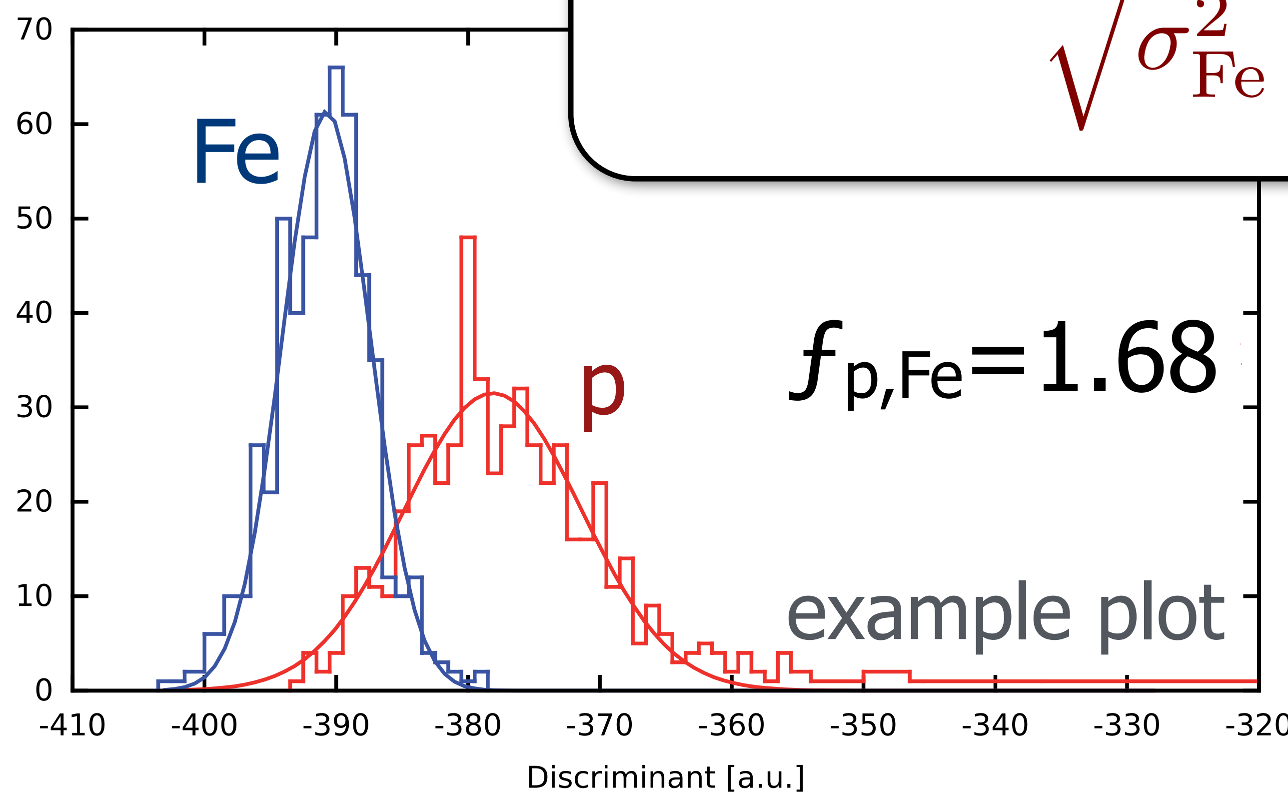
Primary Identification on Shower-by-Shower Basis

CORSIKA Shower libraries were generated with different
– energies (fixed and continuous)
– primaries
– zenith angles
– interaction models

Merit Factor (discrimination power):

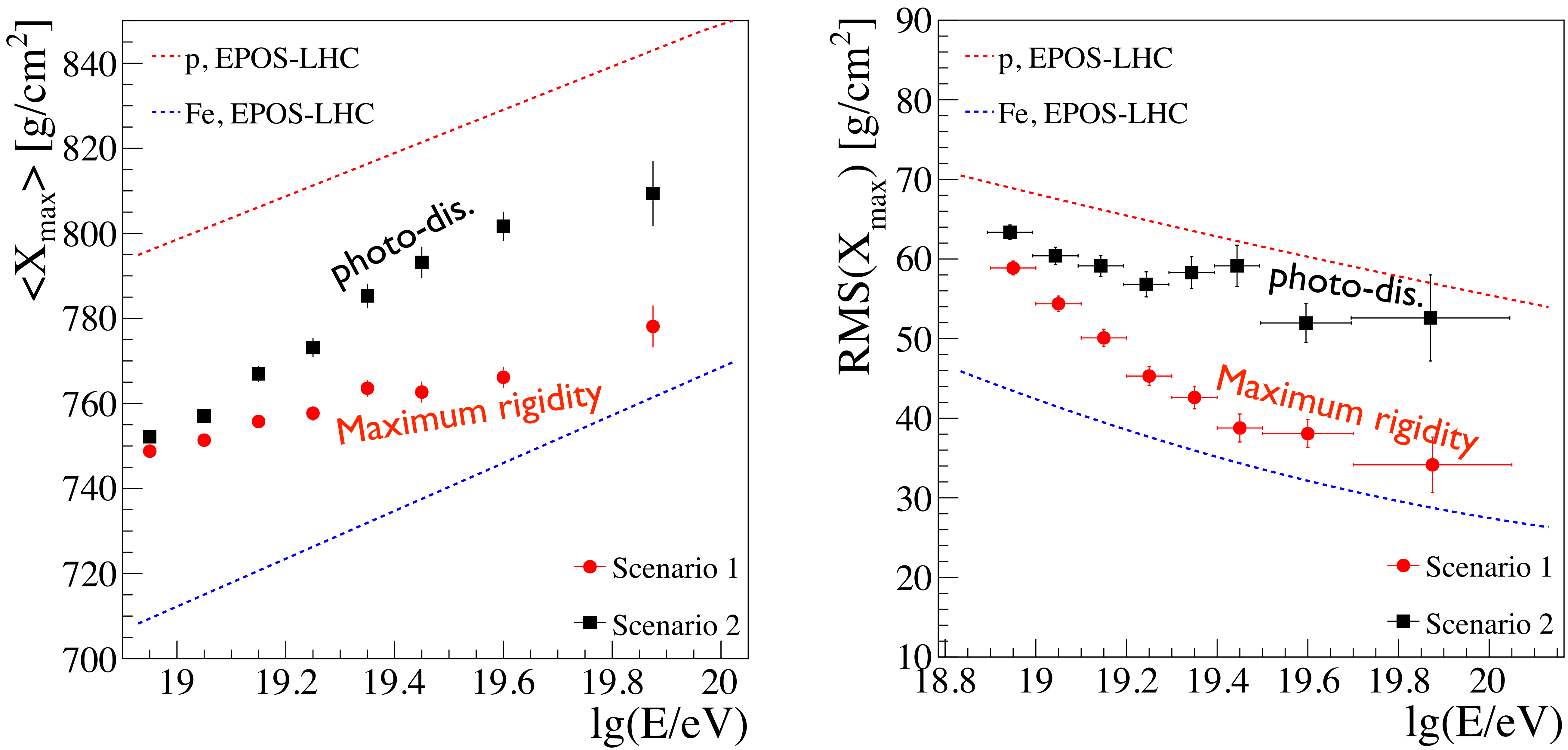
$$f_{p,\mathrm{Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_p\rangle|}{\sqrt{\sigma^2_{\mathrm{Fe}} + \sigma^2_p}}$$

performance then studied
– per station and
– per event



Note: enhanced SD helps also improving photons and neutrino detection

Reconstructed ⟨X_{max}⟩ and σ(X_{max})

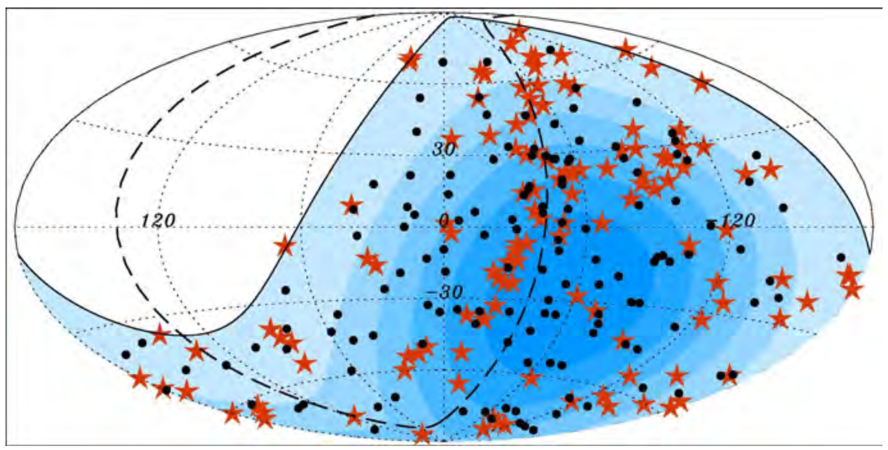


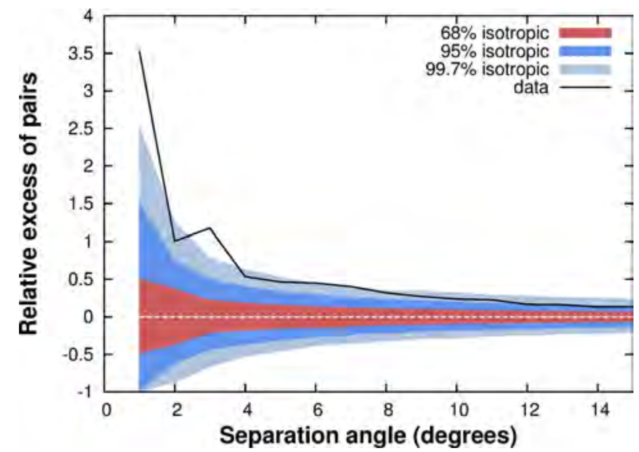
Shower fluctuations and detector resolutions included

models can be distinguished with high significance

p-Astronomy

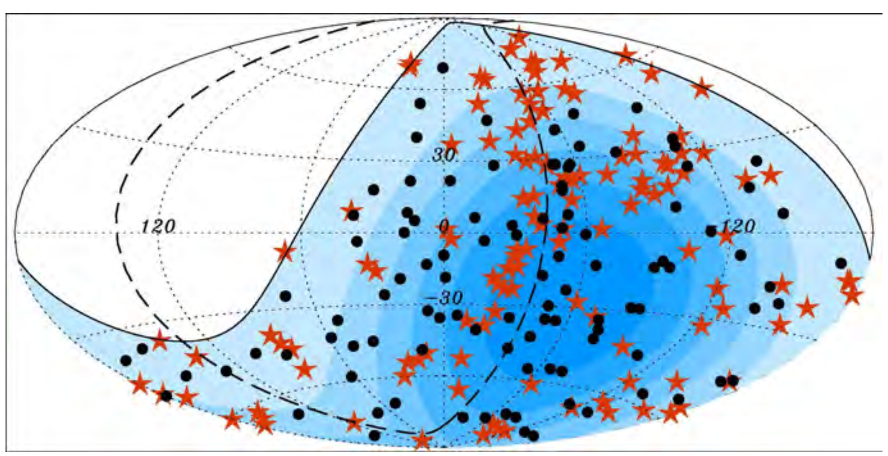
use arrival directions of 141 measured events with $\theta < 60°$ and $E > 5.5 \cdot 10^{19}$ eV
and randomly assign X_{max} according to maximum rigidity model with 10% p-like at high E
and let 50% of p-like events correlate with Swift-BAT sources

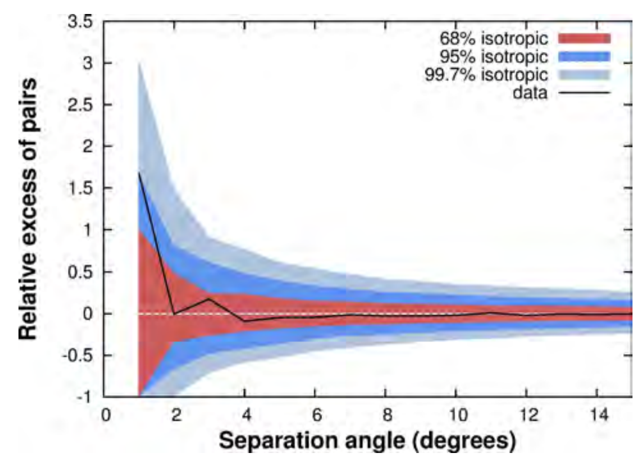




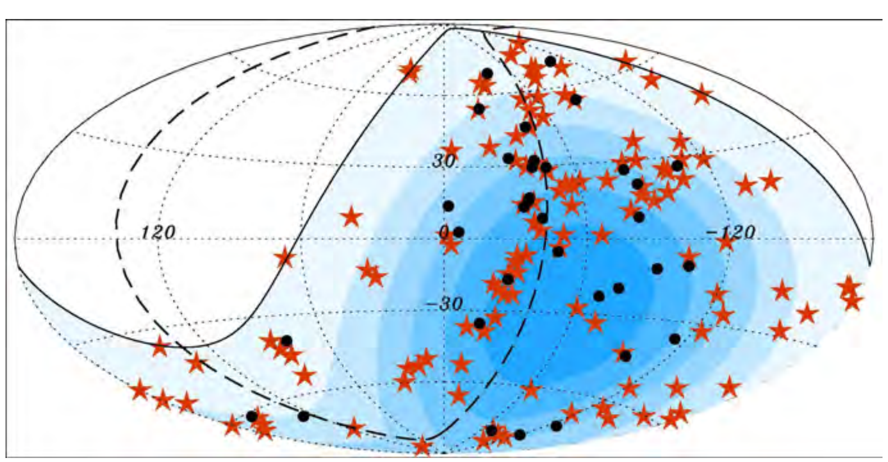
this reproduces well
the present situation

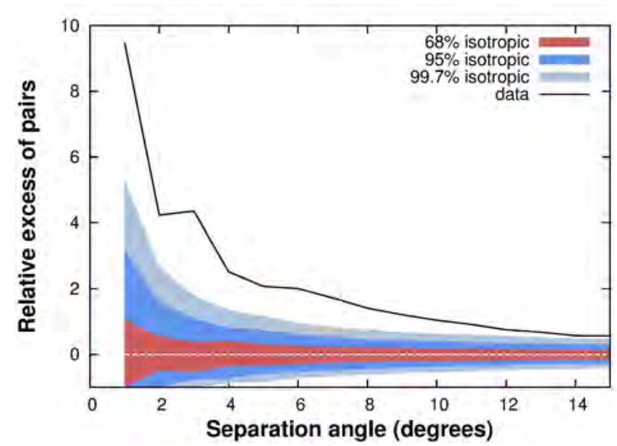
~ 3σ effect





p-like events are removed





only p-like events included

~ 5σ effect

Auger Upgrade: Status

The Pierre Auger Observatory Upgrade

Preliminary Design Report

April 17, 2015

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

PIERRE AUGER OBSERVATORY

- positively evaluated by International Advisory Committee
- endorsed by International Finance Board
- R&D well advanced, prototypes running
- engineering array 03/2016
- construction 11/2016 - 2018
- data taking into 2024
- costs: 12.5 M€
- funding: positive signs, but not yet approved

Major Achievements in the last ~7 years

- Clear observation of flux suppression, origin unknown
- Relevant bounds on cosmogenic ν and γ
- First evidence for large scale anisotropies
- First hints on directional correlations to nearby matter
- Increasingly heavier composition above ankle
- pp cross section at ~10*E_{LHC}, LIV-bounds, ...
- muon deficit in models at highest energies
- geophysics (elves, solar physics, aerosols...)