Fourteenth Marcel Grossmann Meeting - MG14
University of Rome "La Sapienza" - Rome, July 12-18, 2015

CELEBRATING THE 100TH ANNIVERSARY OF THE EINSTEIN EQUATIONS

Ultra-High Energy Cosmic Rays:

What did we learn, where will we go?

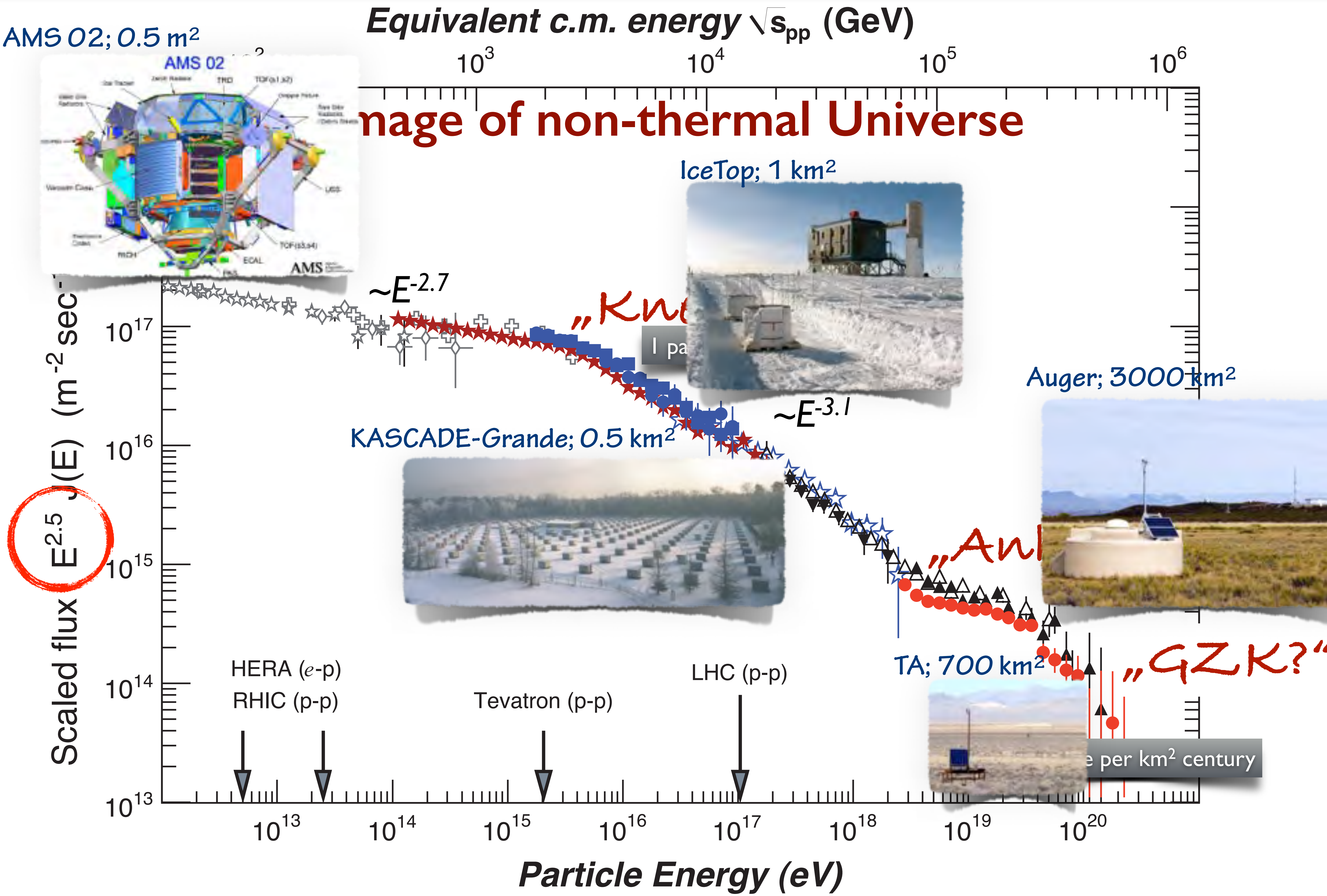
… a very selective review

Karl-Heinz Kampert, University of Wuppertal
on behalf of the Pierre Auger Collaboration

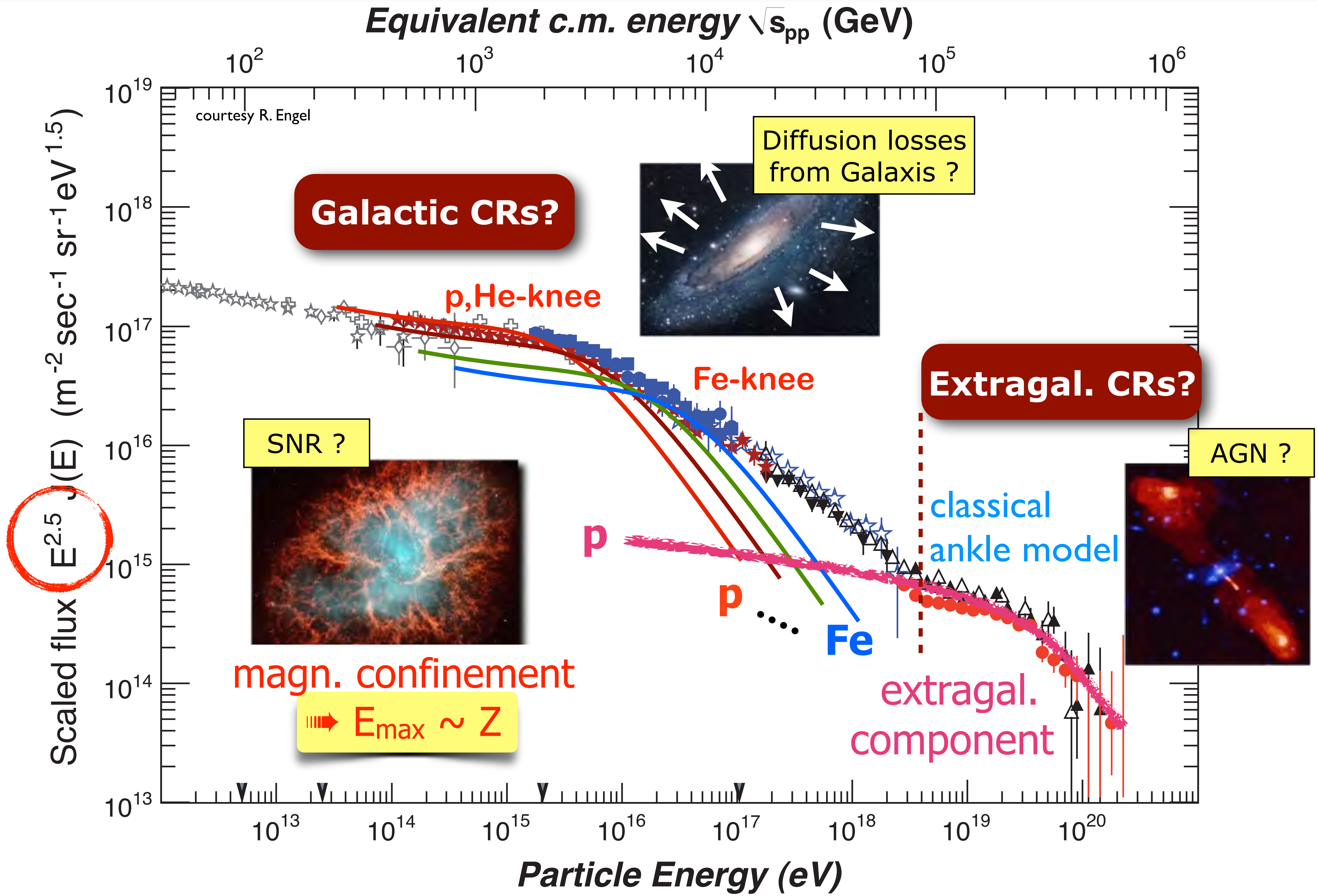
PIERRE AUGER OBSERVATORY

BERGISCHE UNIVERSITÄT WUPPERTAL

Features of CR spectrum



Features of CR spectrum



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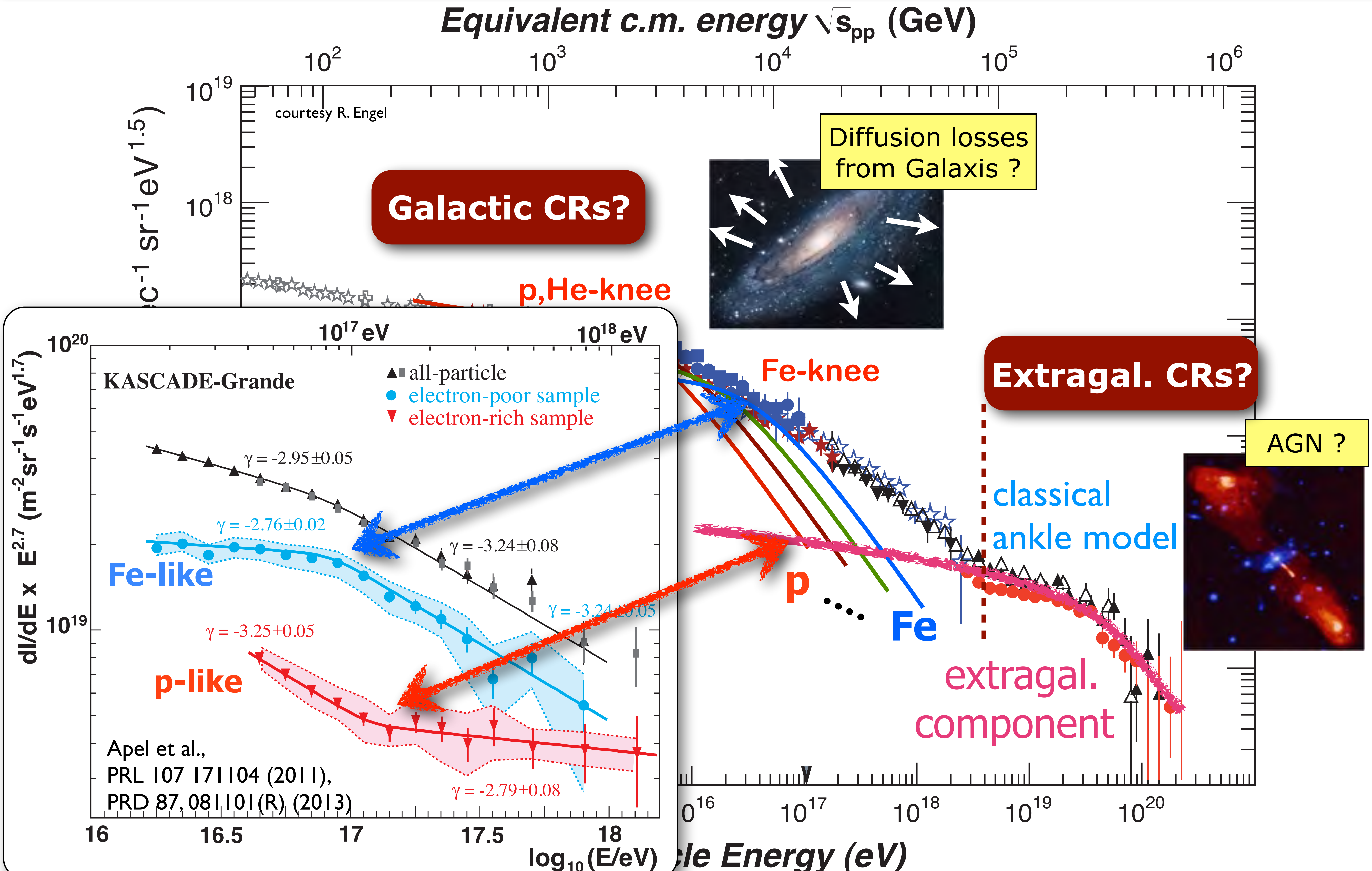

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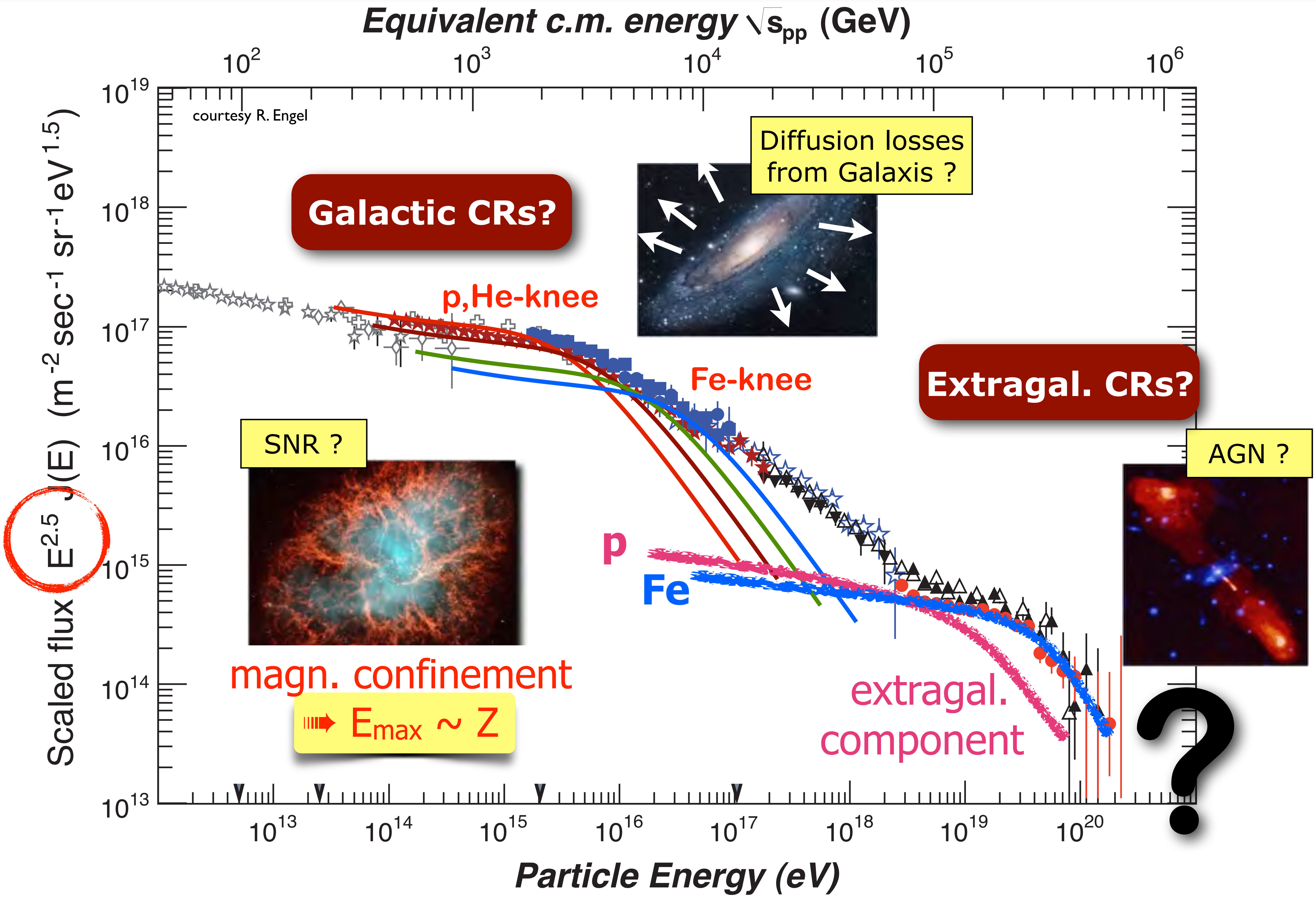
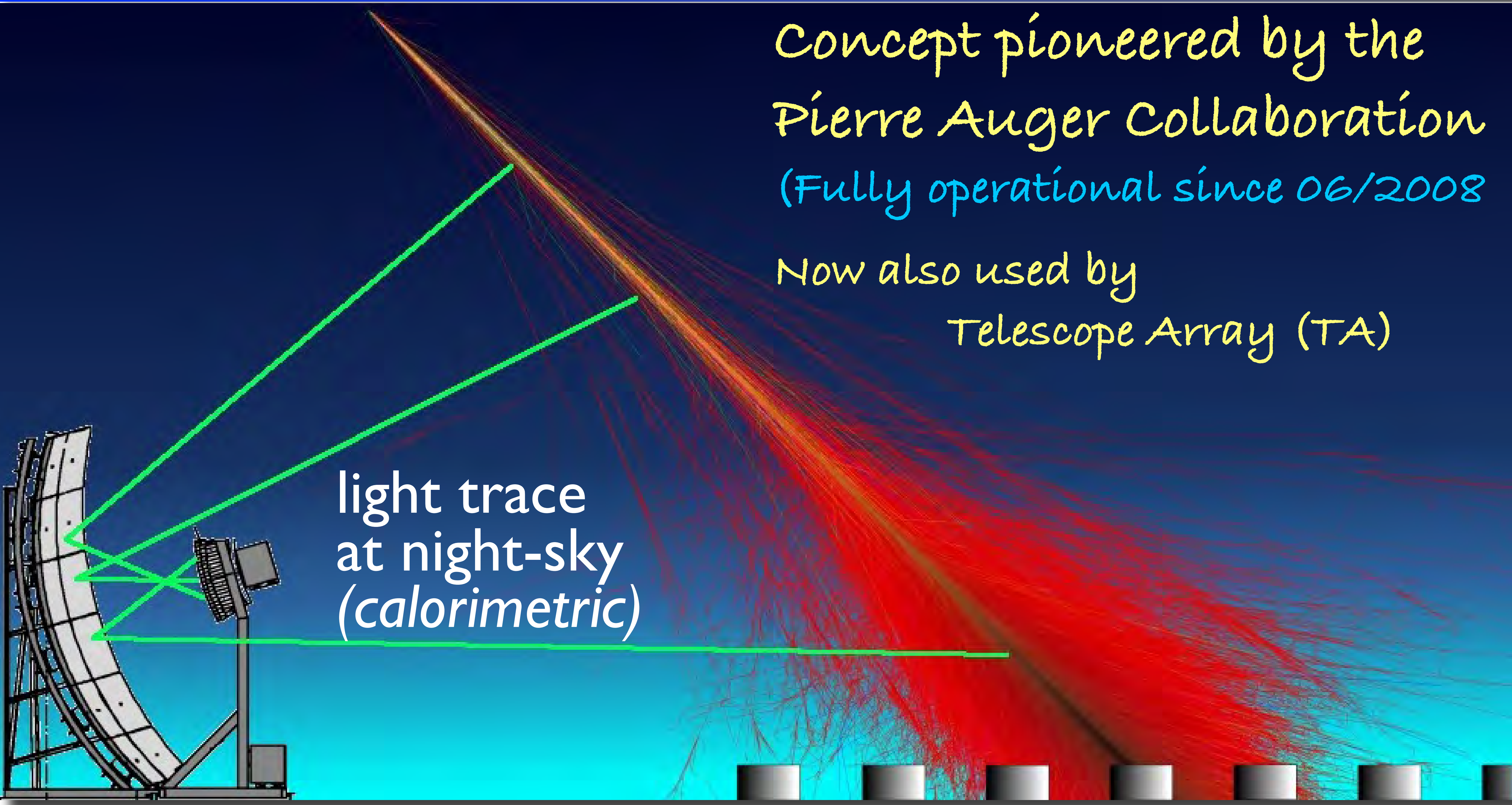


UHECR Menu

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

Hybrid Observation of EAS

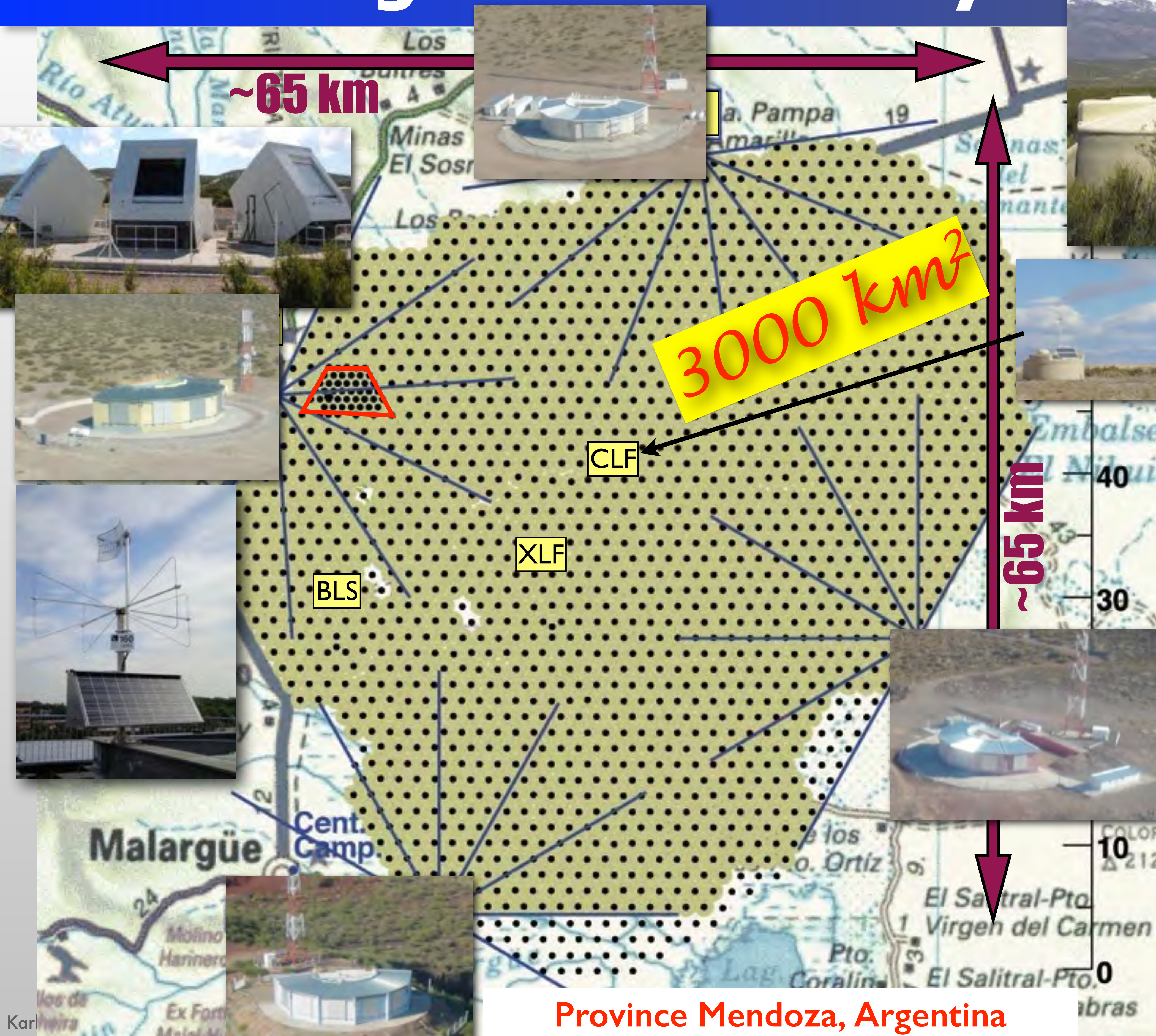


Fluorescence light

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

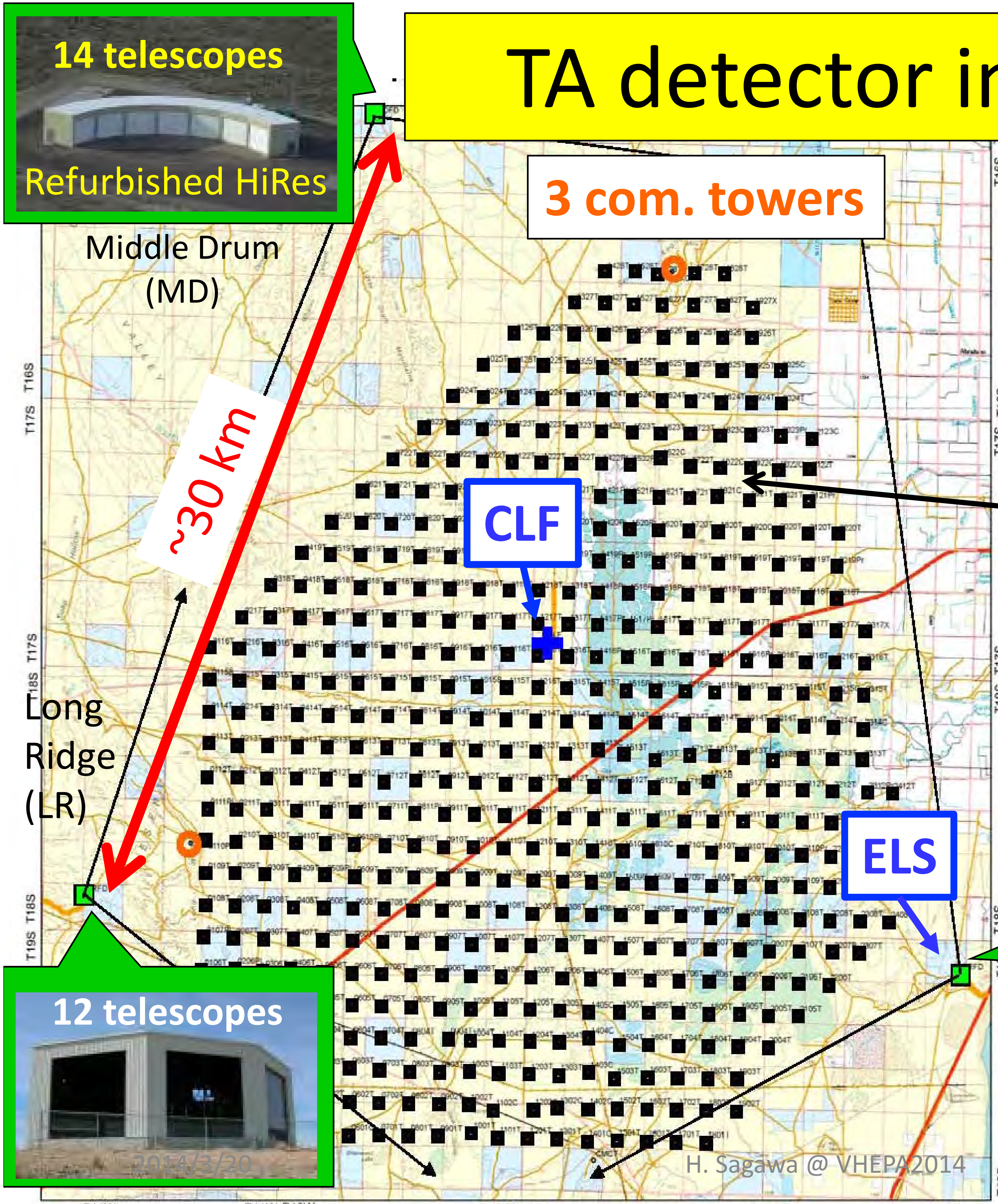
130 radio antennas

Auger Hybrid Observatory

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

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)

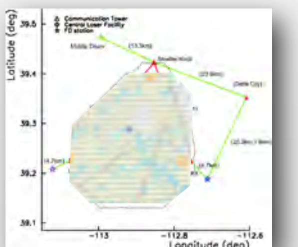
3 stations

38 telescopes

FD and SD: fully operational since 2008/May 4

Auger and TA

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

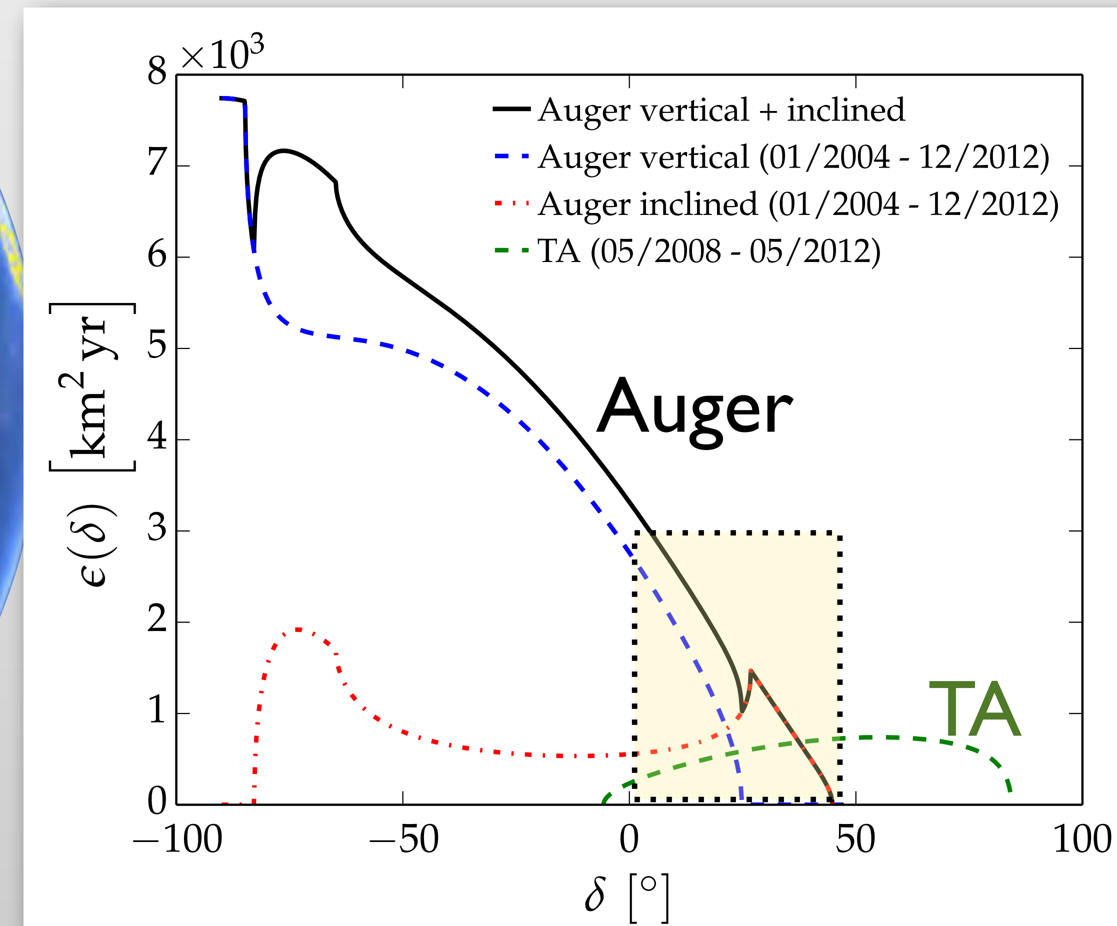


same
scale

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

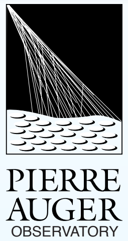
Auger and TA can see the same sky

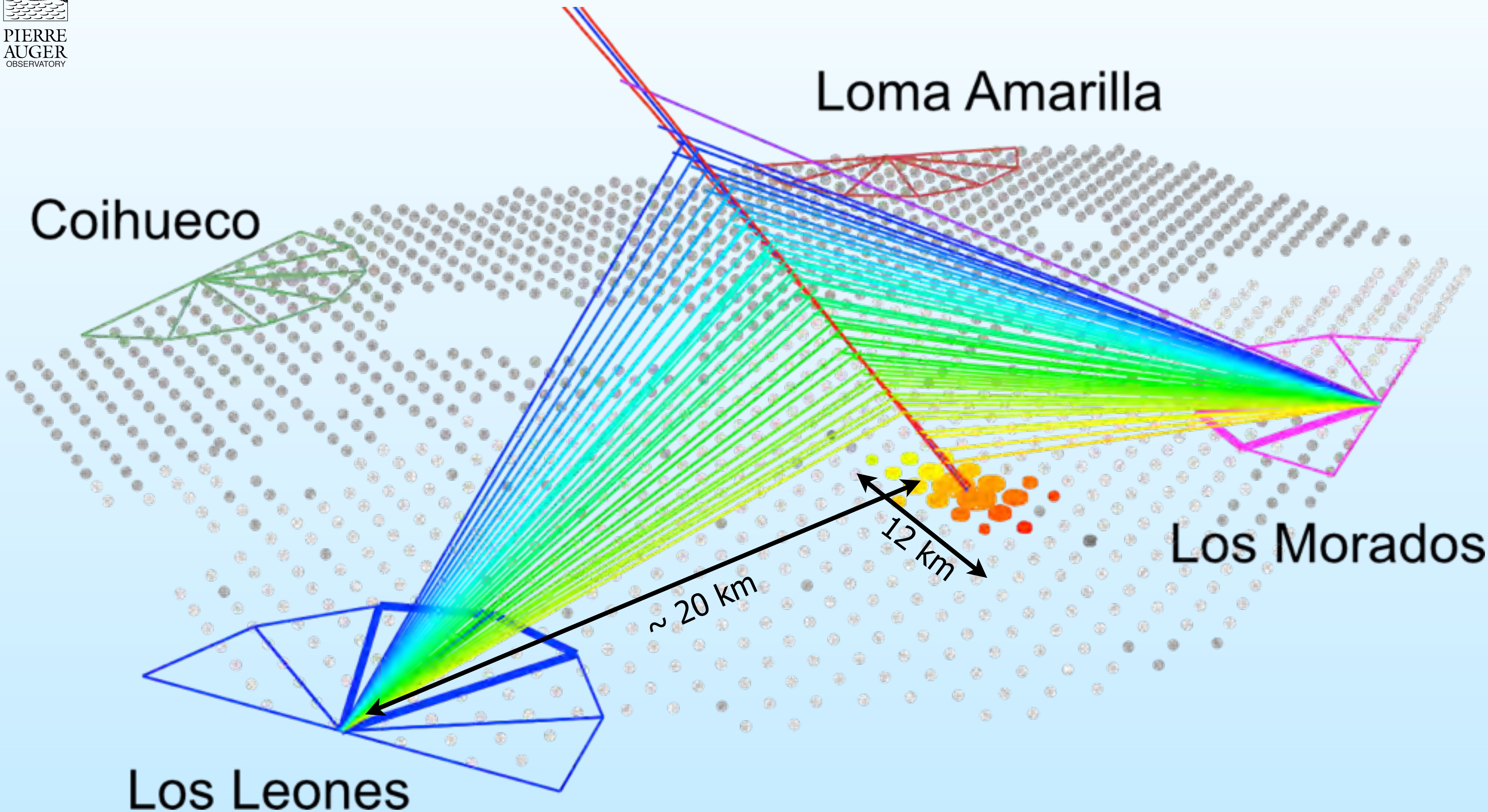
Auger: 01/2004 - 12/2012
TA: 05/2008 - 05/2012



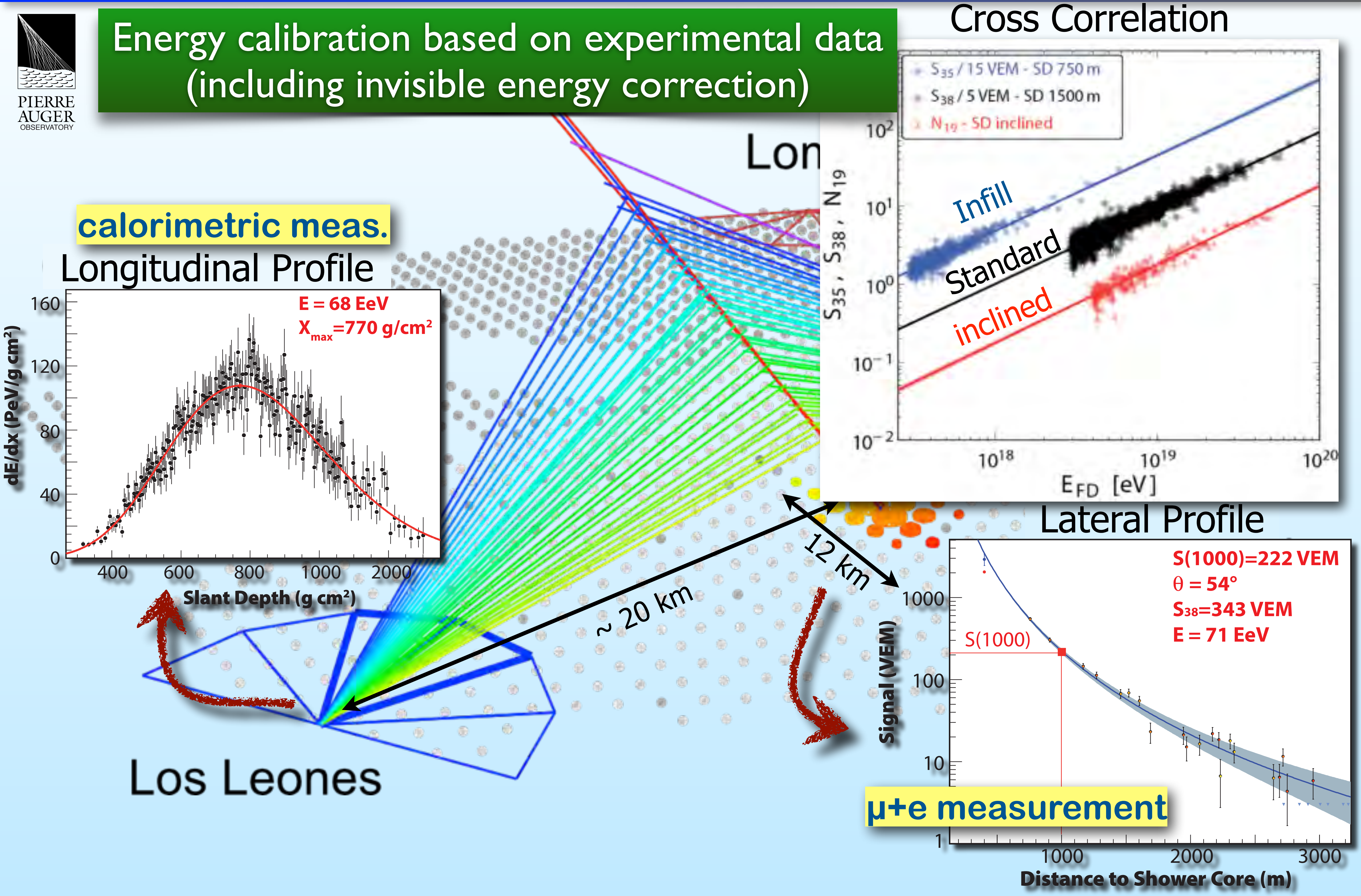
Auger exposure ~8 times that of TA

Event Example in Auger Observatory





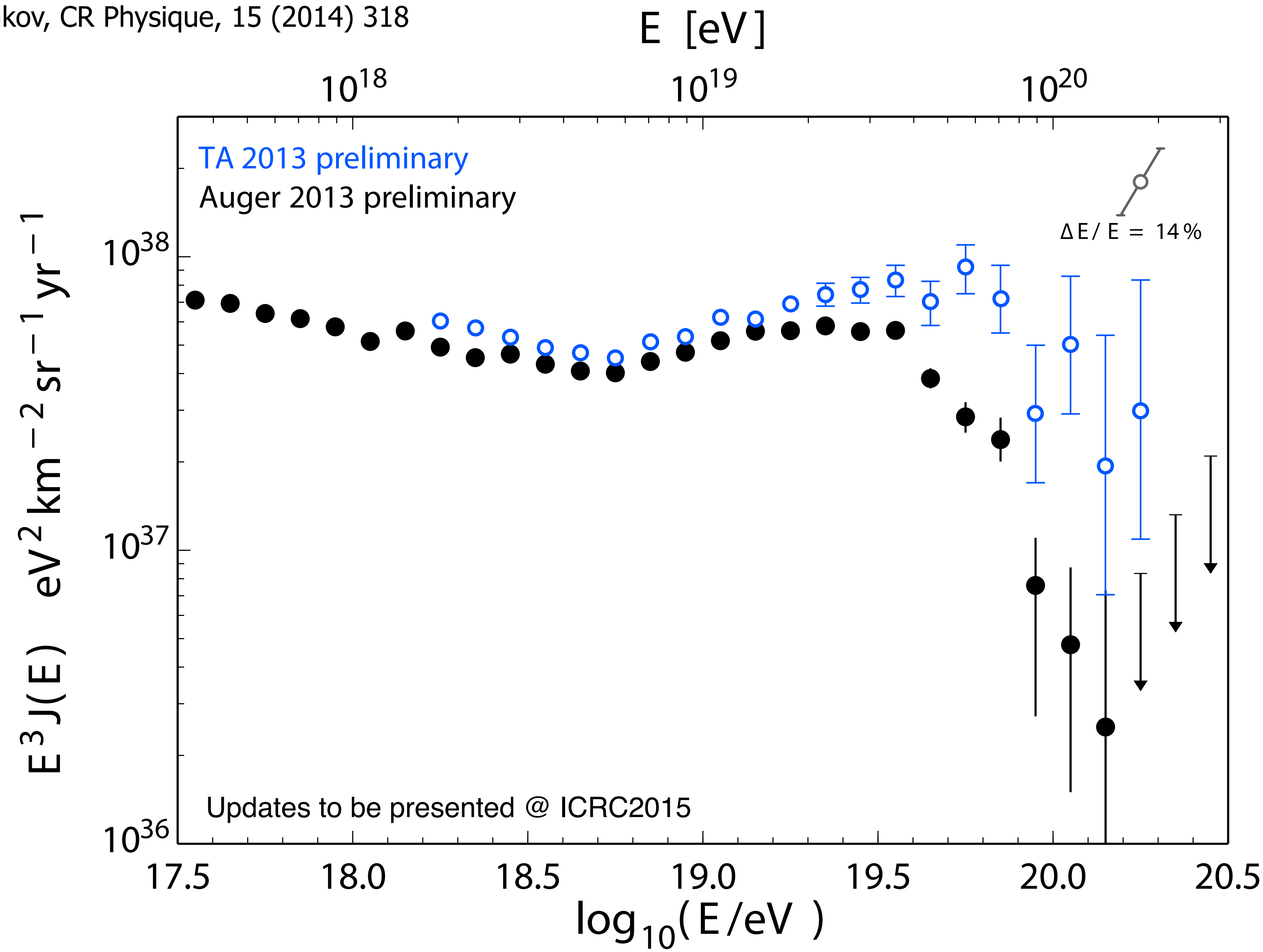
Event Example in Auger Observatory



UHECR Energy Spectrum

All Particle Energy Spectrum

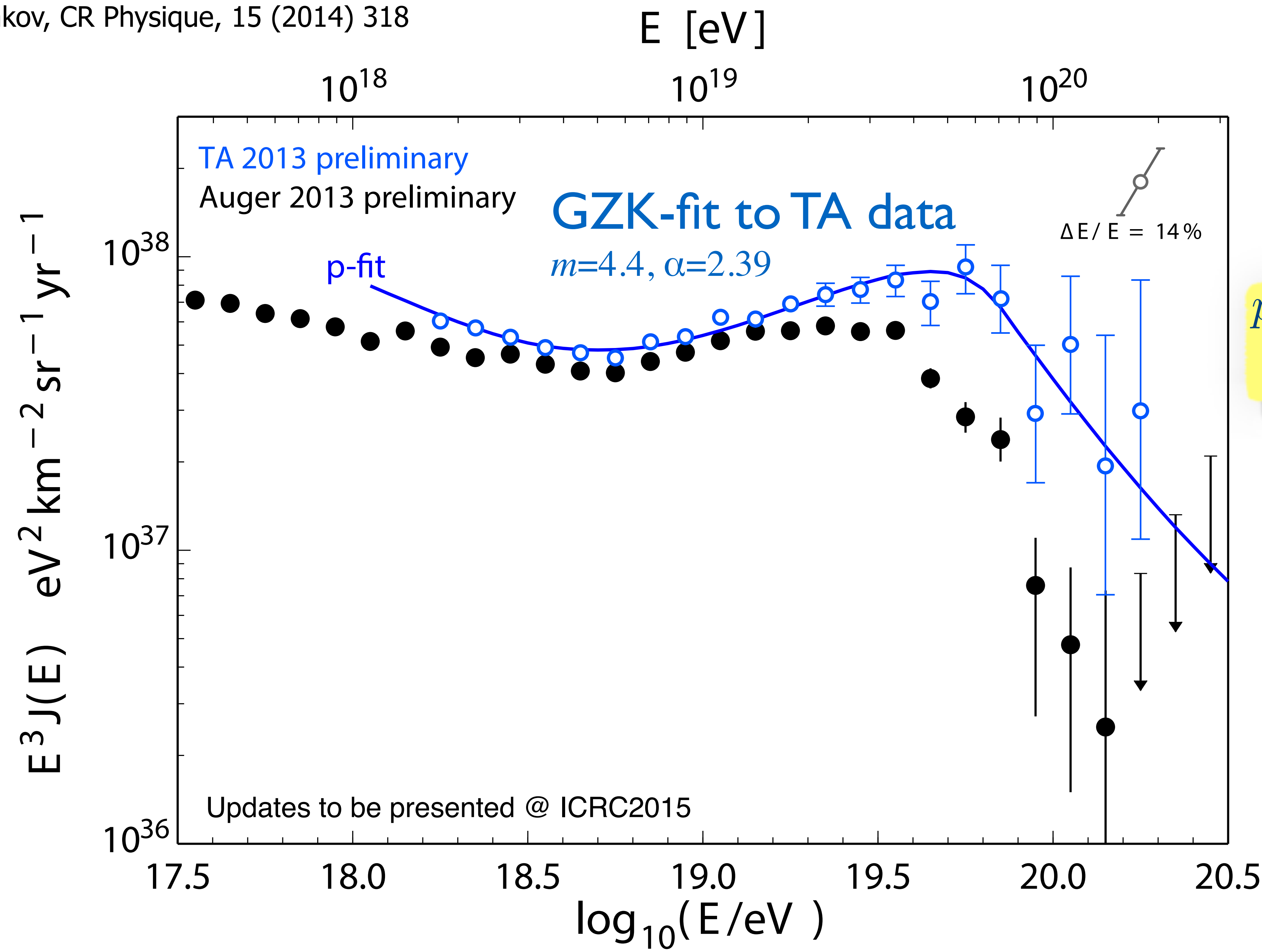
Kampert & Tiniakov, CR Physique, 15 (2014) 318



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

All Particle Energy Spectrum

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

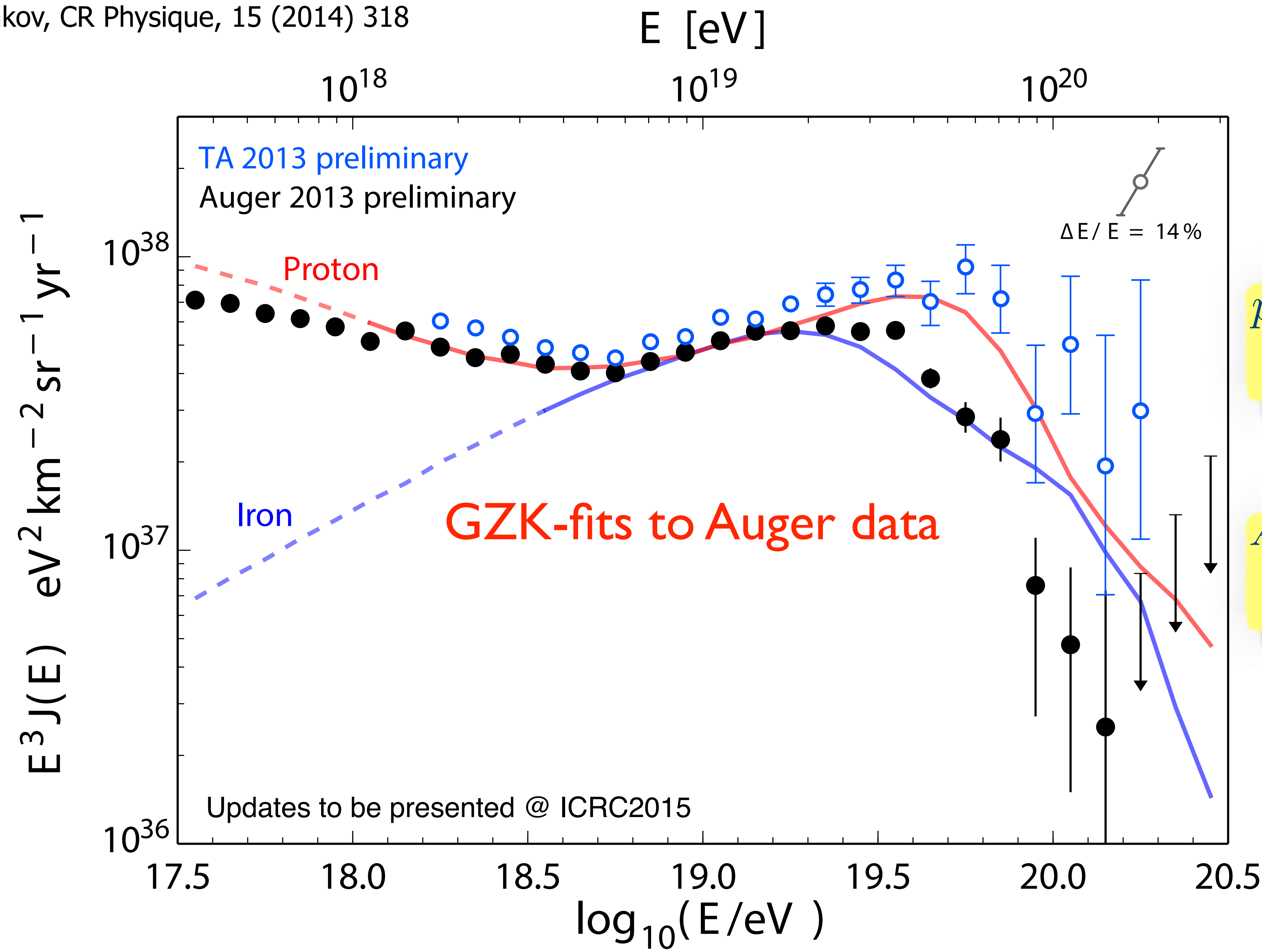


$$p + \gamma_{CMB} \to \Delta \to p + \pi$$

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

All Particle Energy Spectrum

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



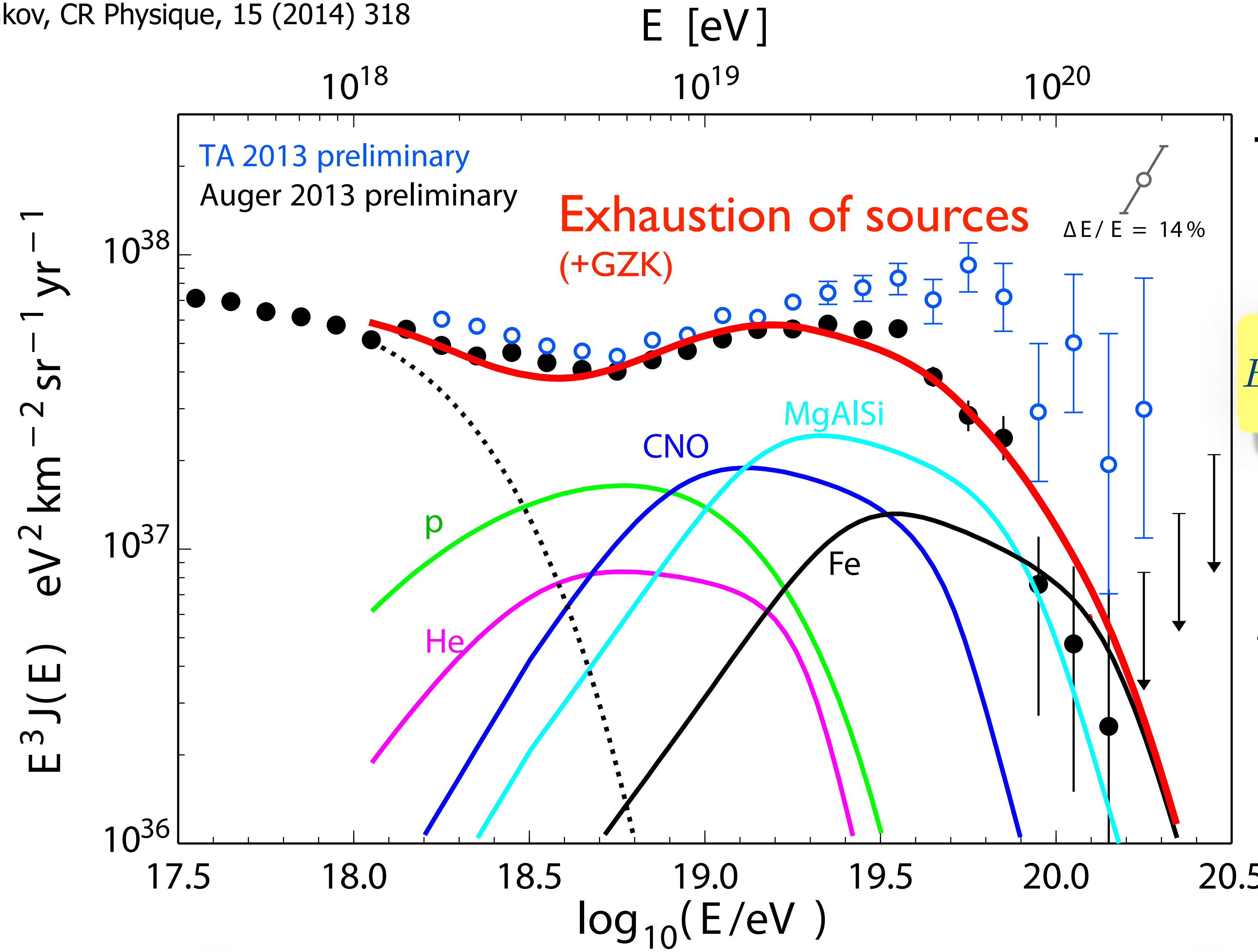
$p + \gamma_{CMB} \to \Delta$
$\to p + \pi$

$A + \gamma_{CMB}$
$\to (A-1) + n...$

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

All Particle Energy Spectrum

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



$$E^Z_{max} \propto E^p_{max} \times Z$$

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

Energy spectrum alone remains ambiguous concerning interpretations

Need

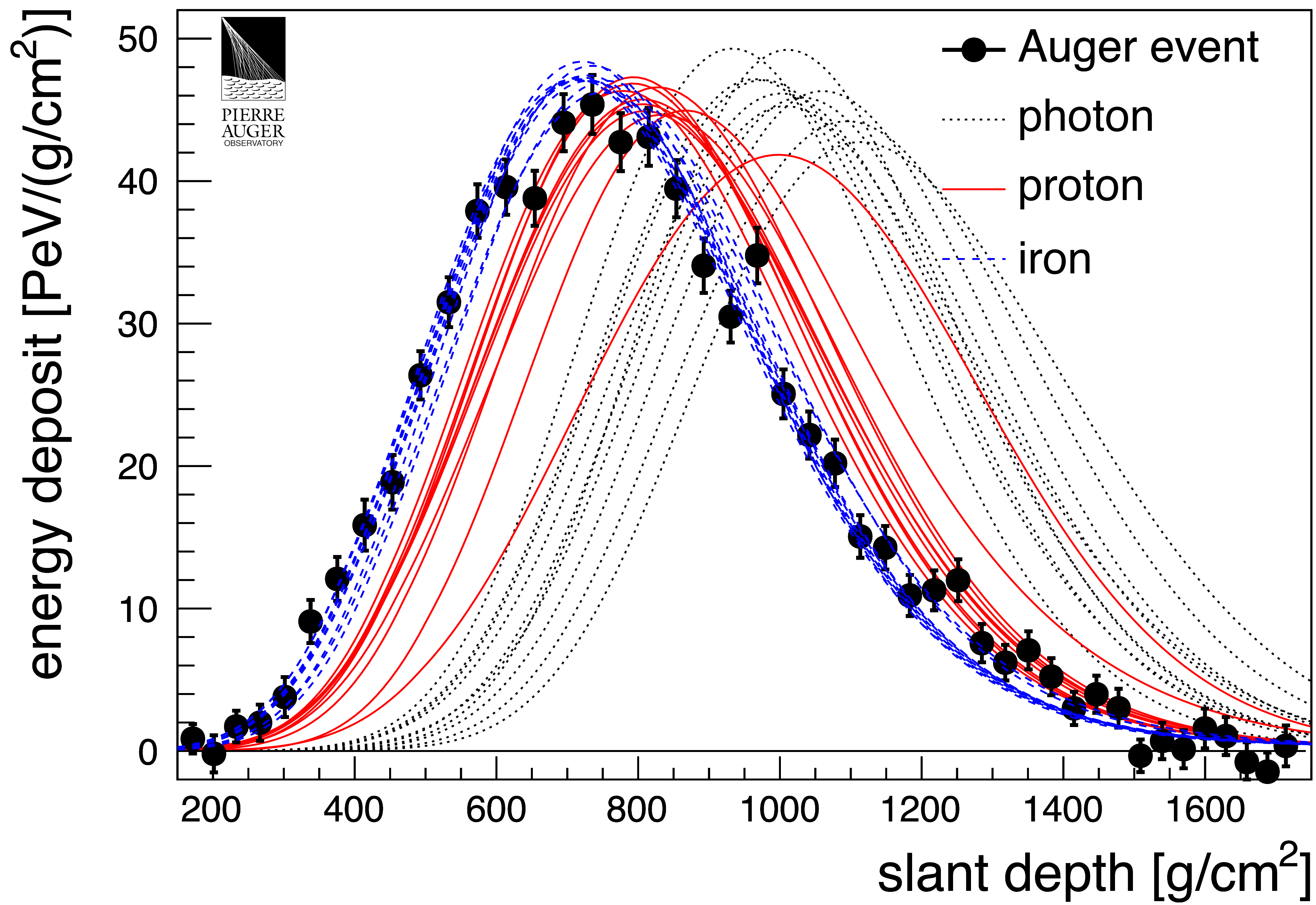
Mass Composition

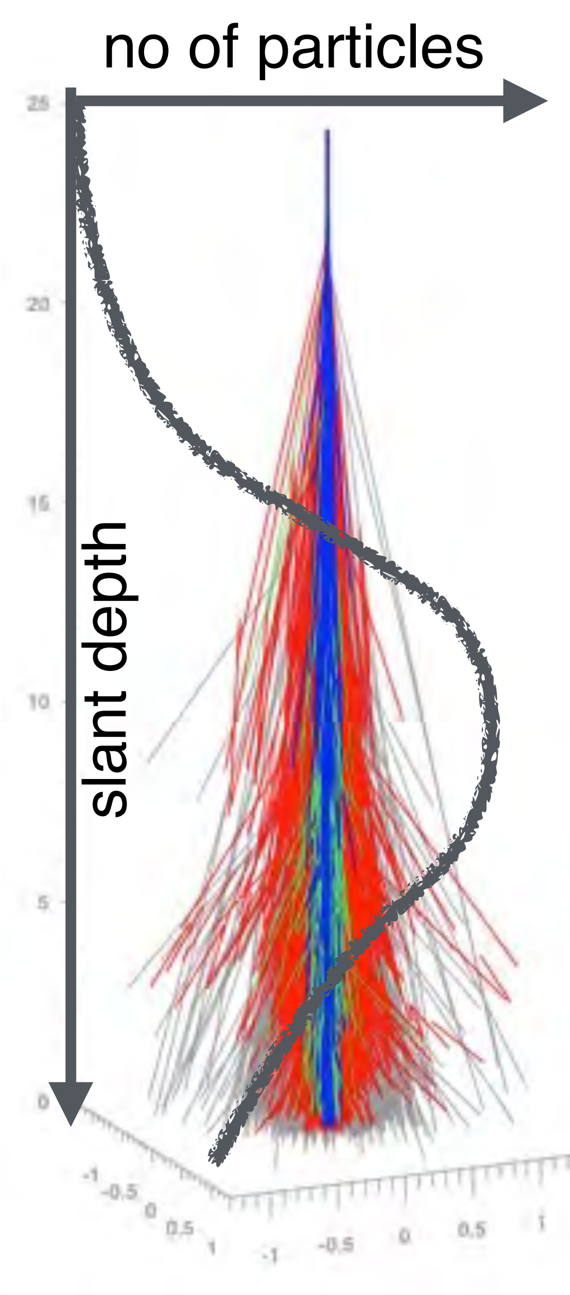
to disentangle GZK from maximum energy scenario

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

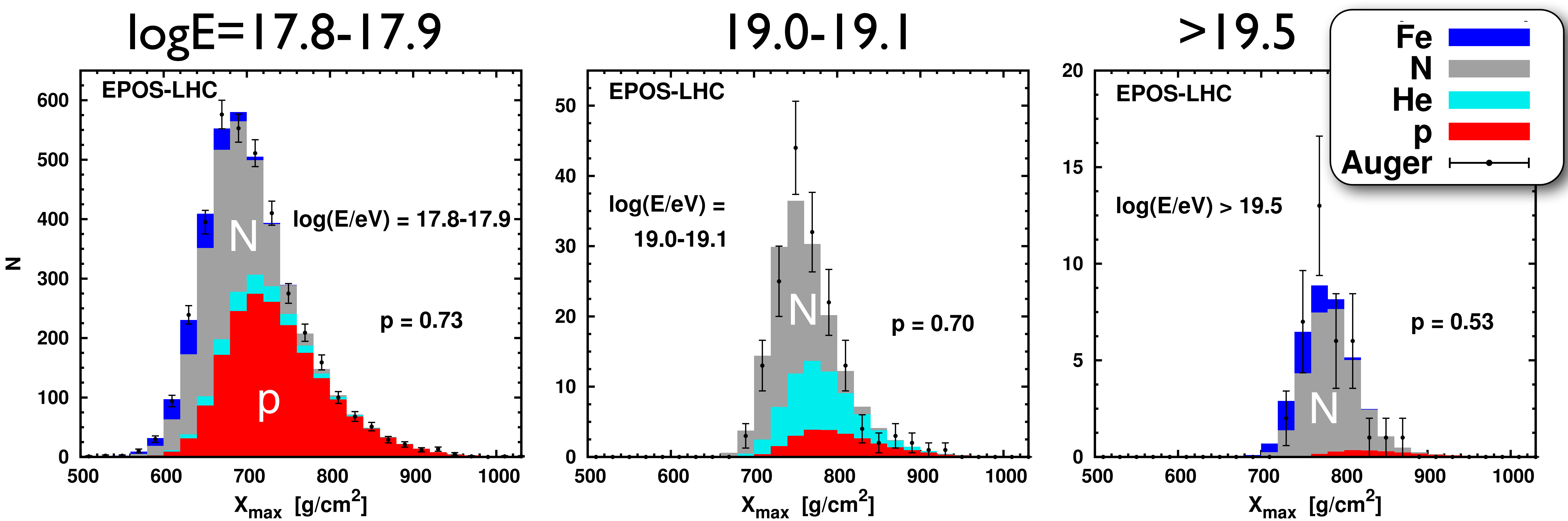




Fits to X_{max} Distributions

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

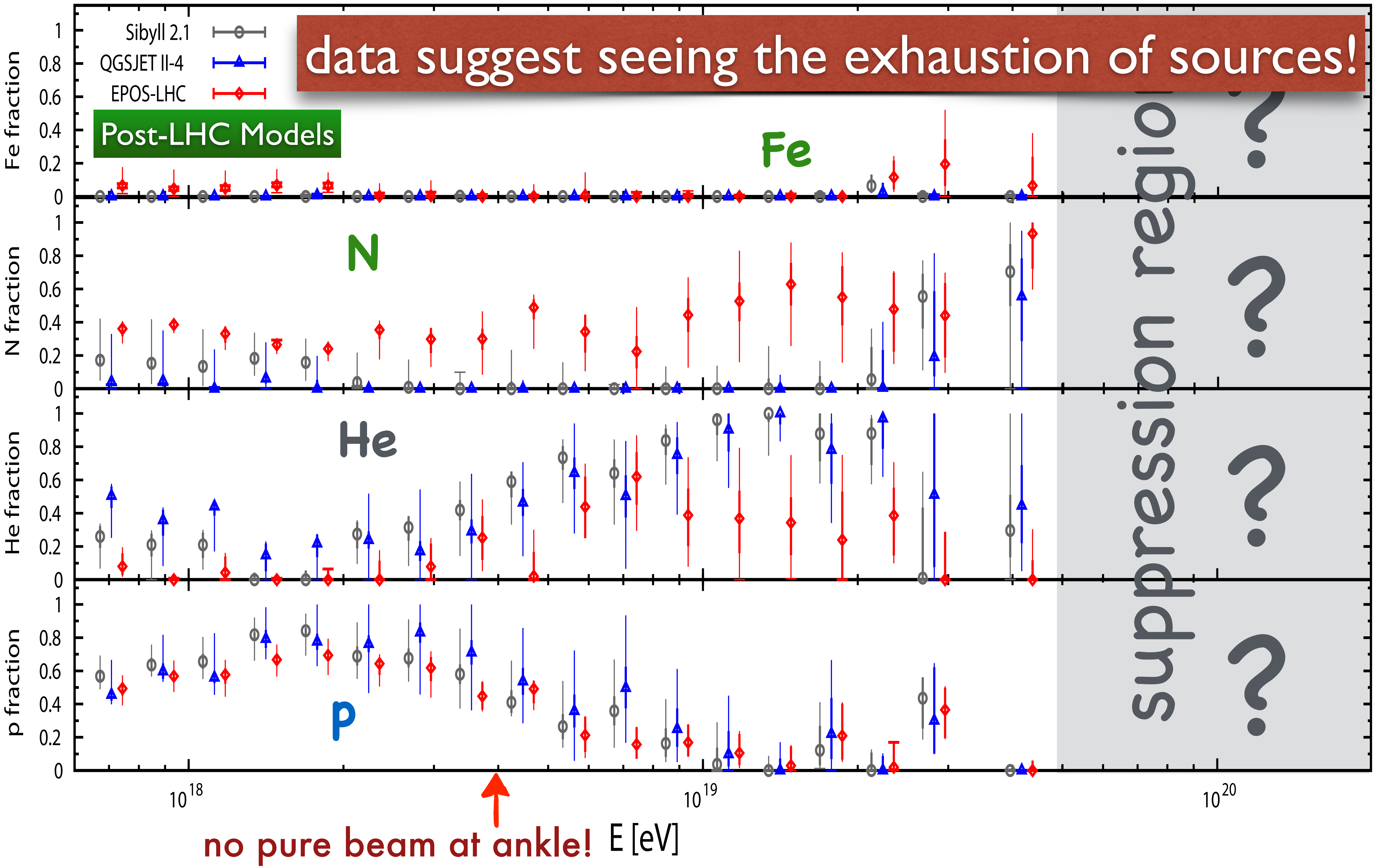
Here shown for EPOS-LHC



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

Decomposition of X_{max}-Distributions

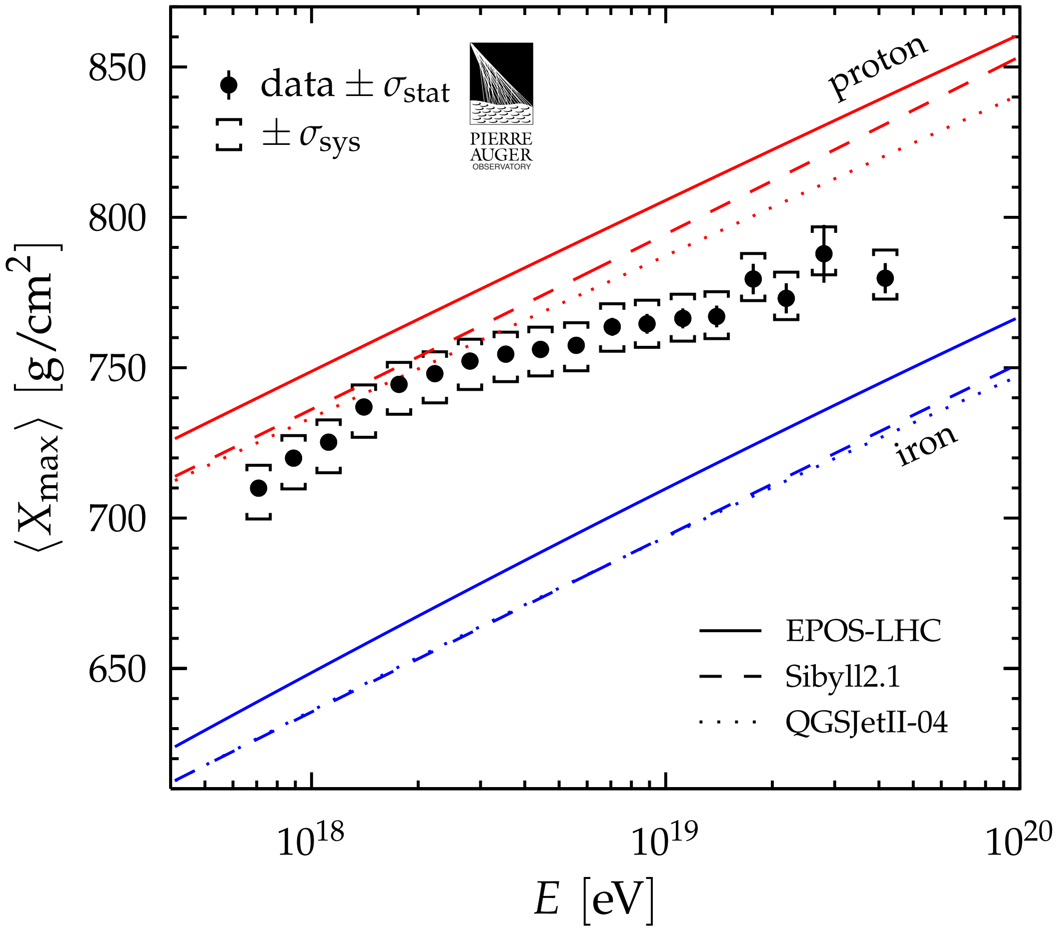
Auger collaboration, Phys. Rev. D 90, 122006 (2014)



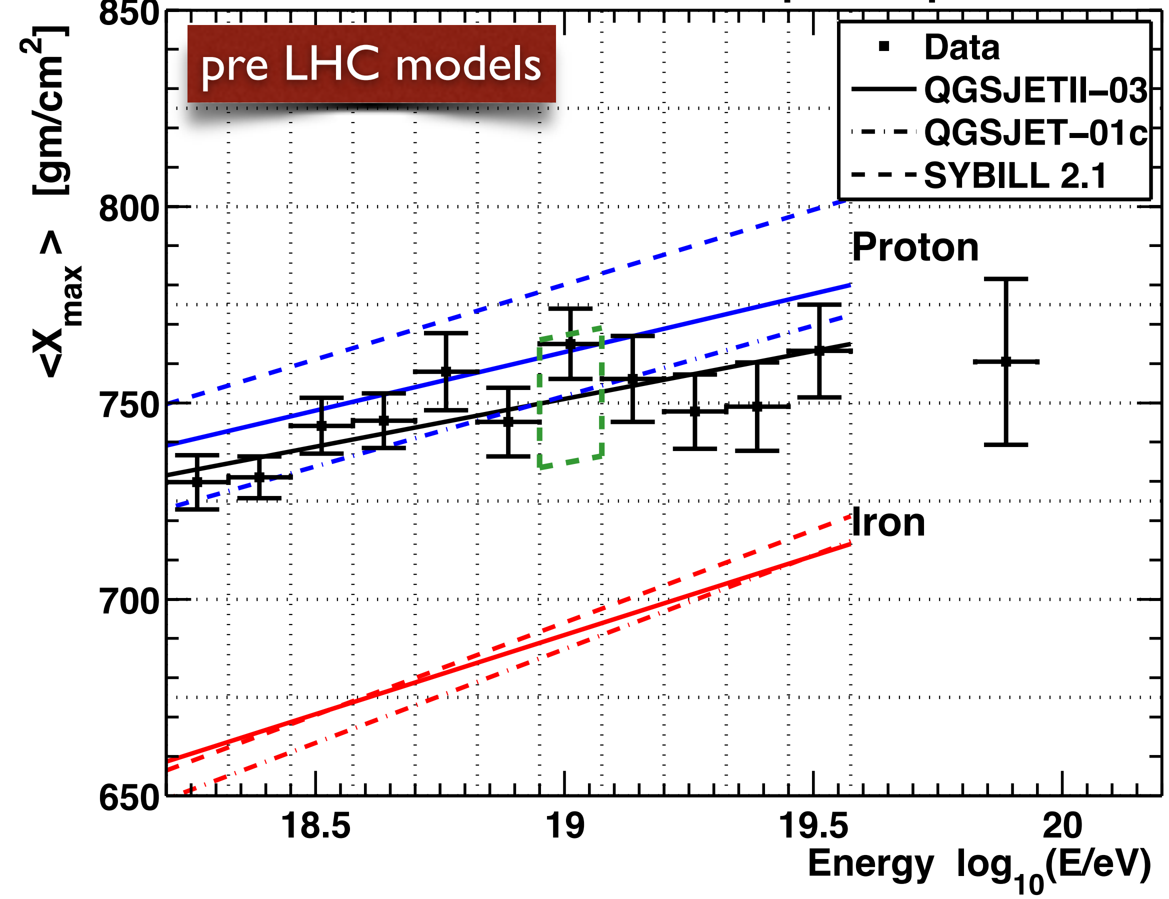
See also: Yushkov @ ICRC2015

Comparison of <X_{max}>: Auger vs TA

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

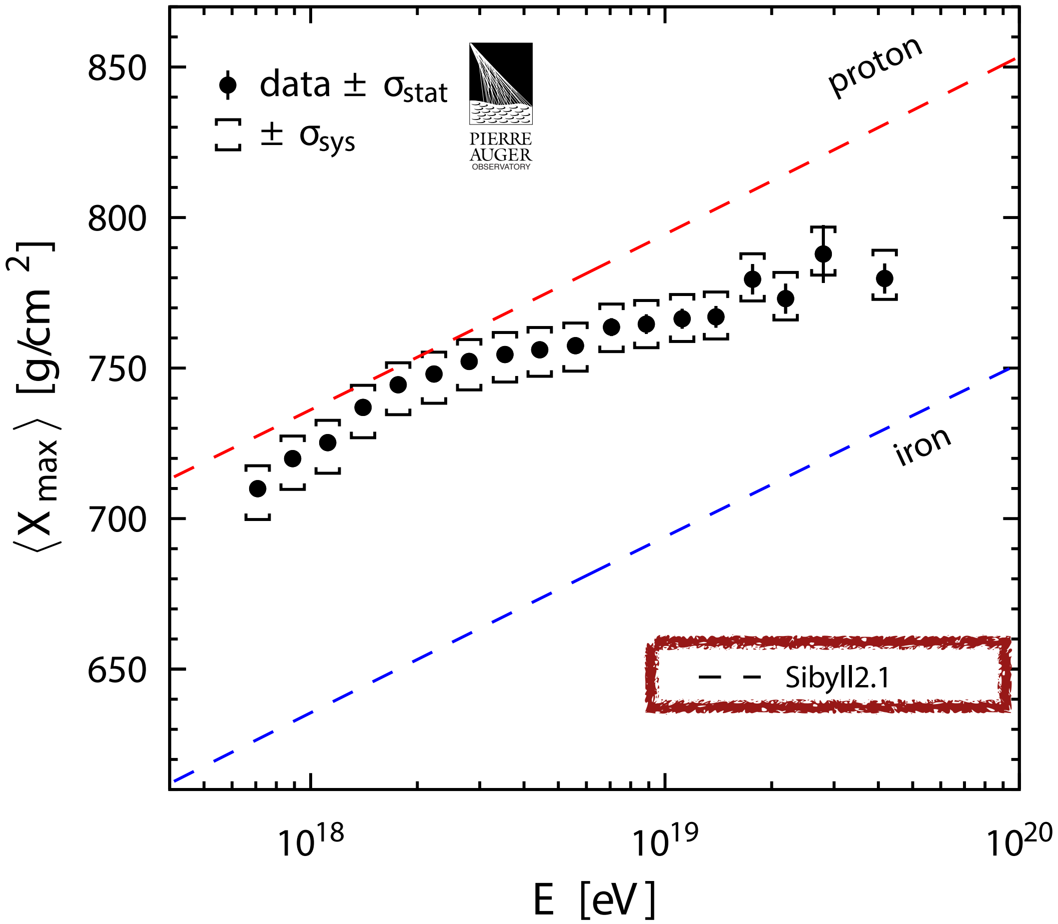


Telescope Array Collaboration, APP 64 (2015) 49
models are folded with exp. acceptance



Auger - TA Comparison

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



Telescope Array Collaboration, APP 64 (2015) 49
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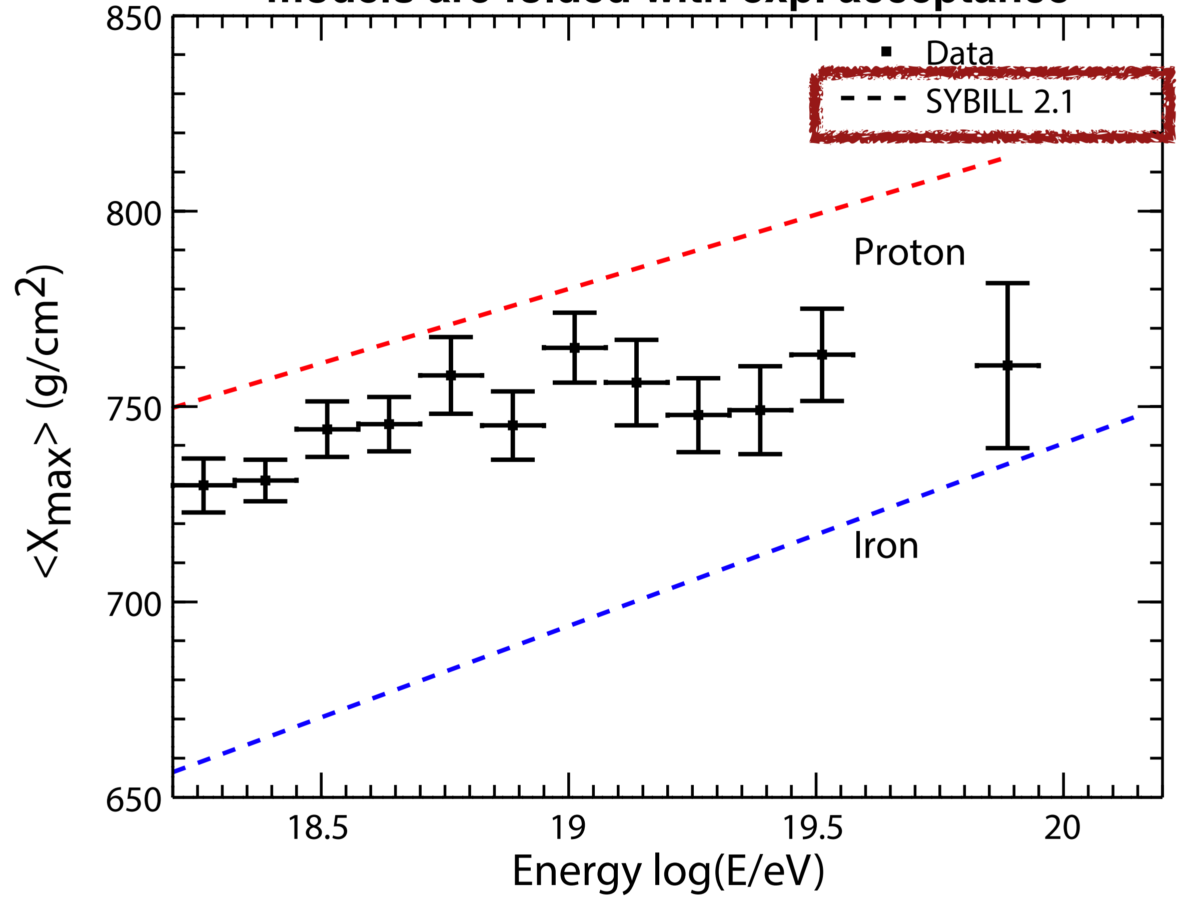
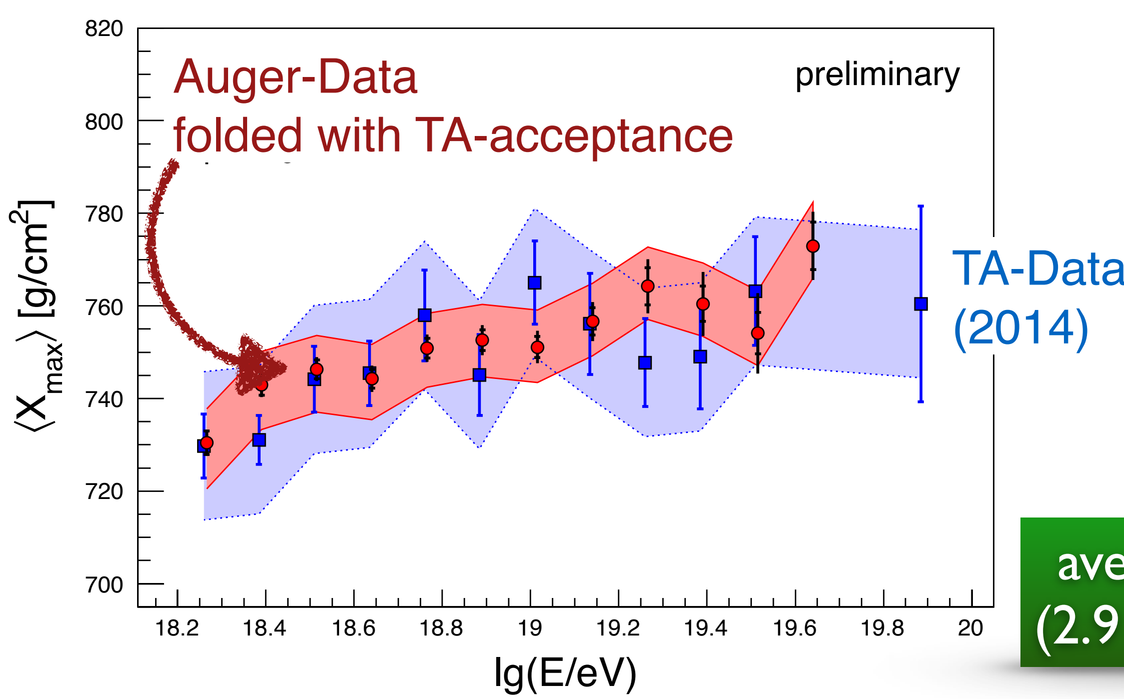




Joint Working Group (UHECR2014; arXiv:1503.07540)

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

average diff. between data points:
(2.9 ± 2.7 (stat.) ± 18 (syst.)) g/cm^2

Some

Interpretations...

Implications of a heavy composition

Astroparticle Physics 39-40 (2012) 33-43

Astroparticle Physics

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

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

UHECR composition models

Andrew M. Taylor *

On the ...

Dan Ho...

Frontiers ...

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

...uclei

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

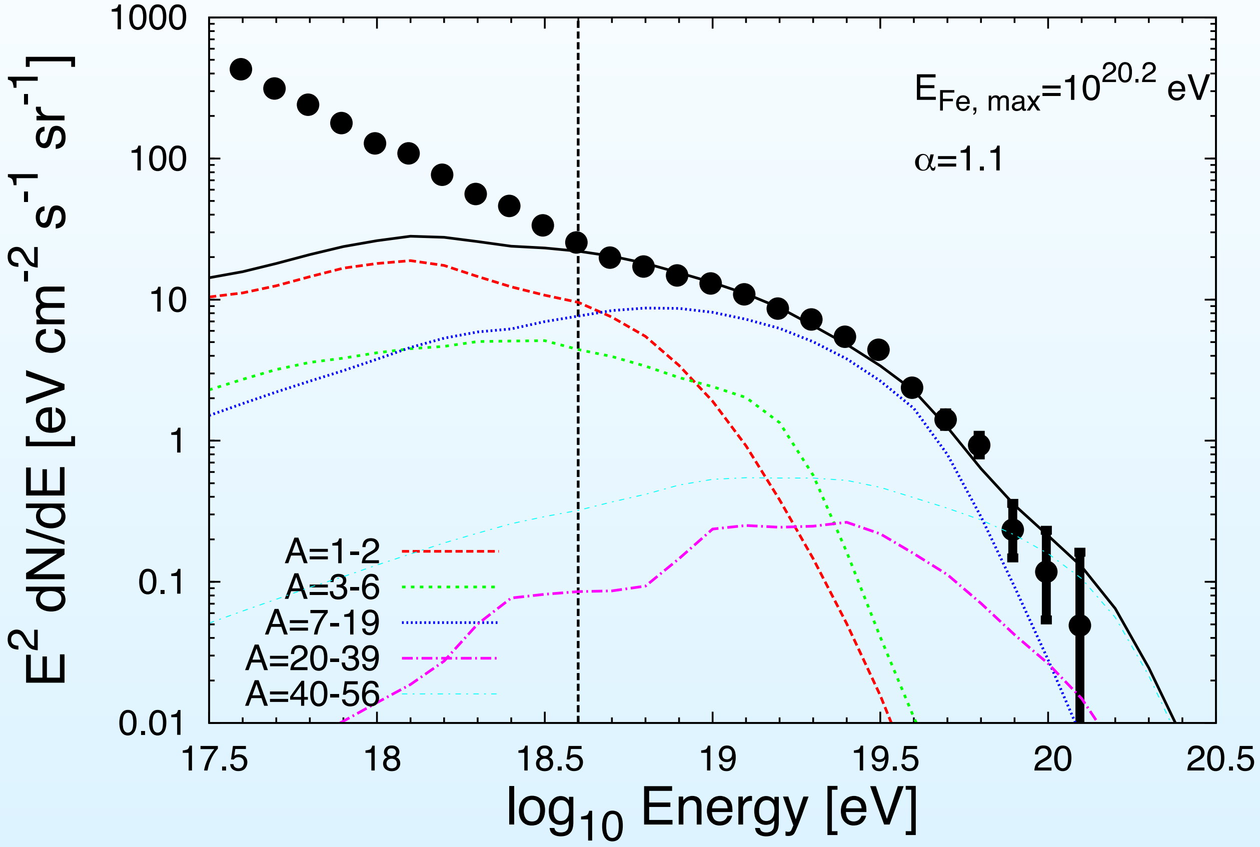
Subm. to JCAP 2013

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

...and many more papers of this type

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

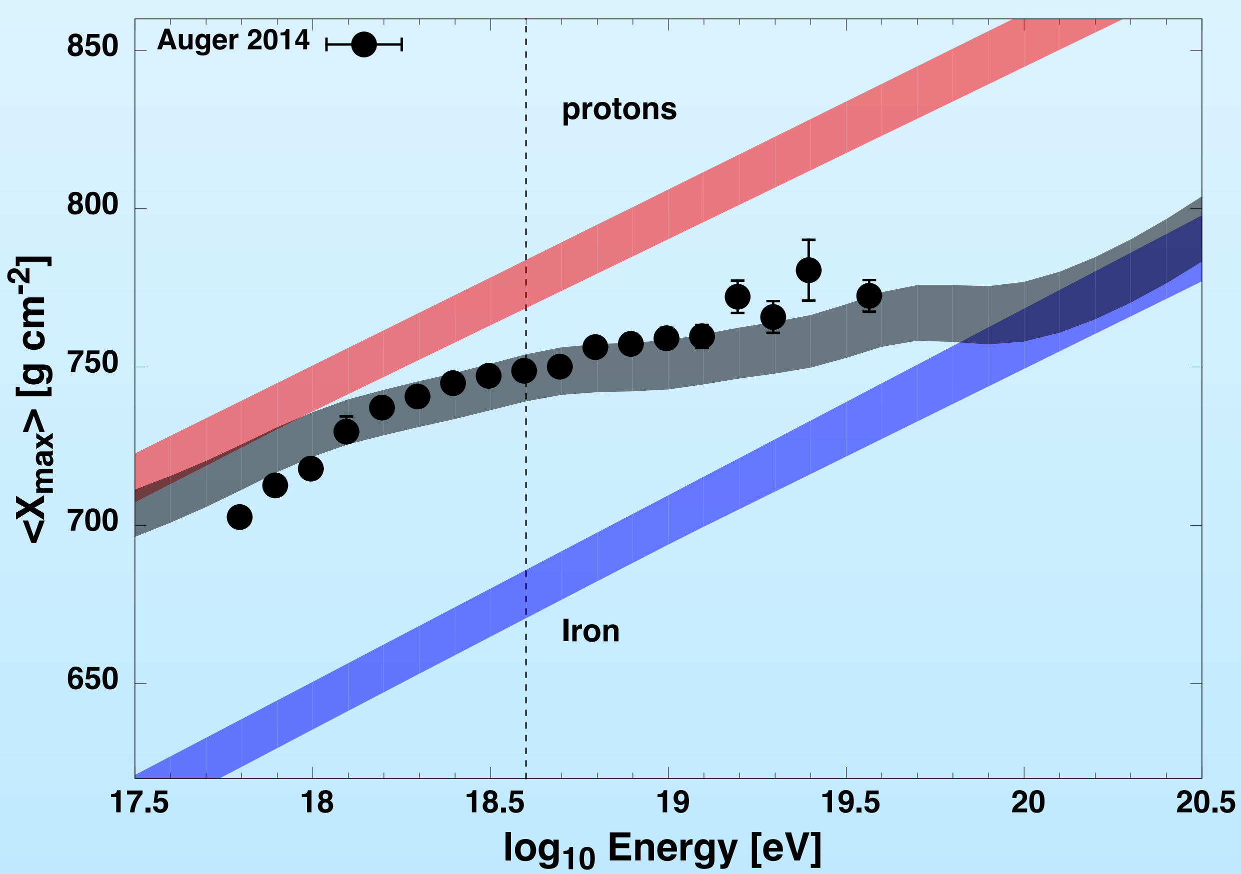
Comparison to Astrophys. Scenarios

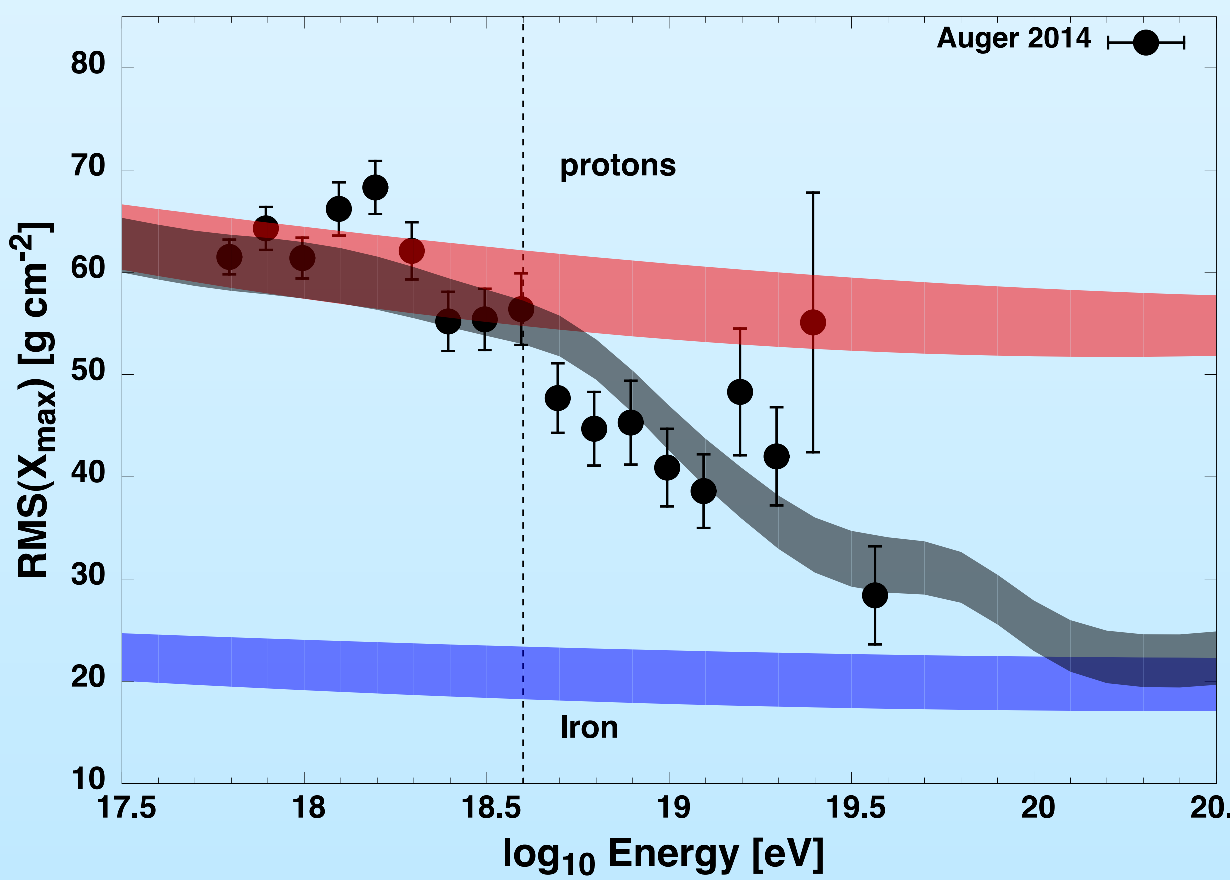


Taylor, Ahlers, Hooper; arXiv:1505.06090

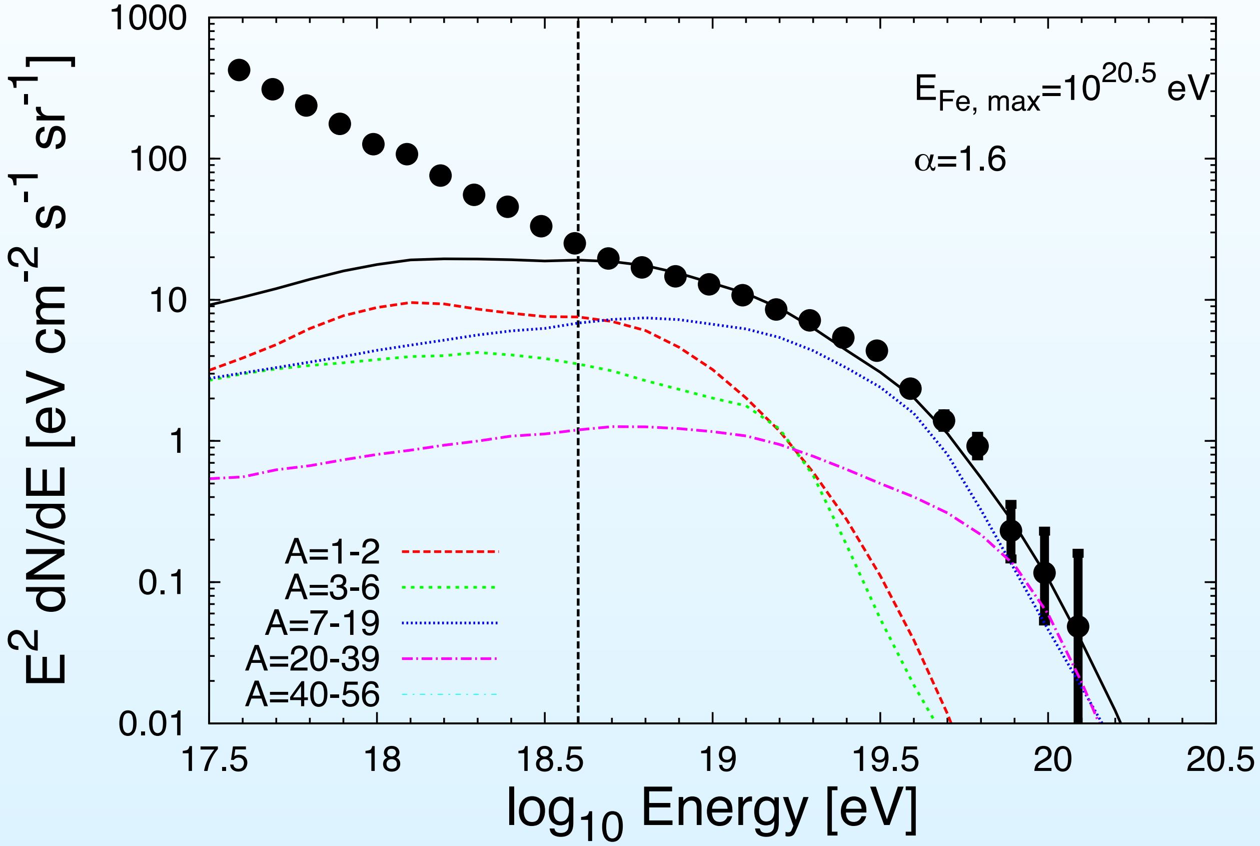
$E_{max}^{p}=10^{18.8}$ eV
index α=1.1
cosm. evolution: m=0

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





Comparison to Astrophys. Scenarios

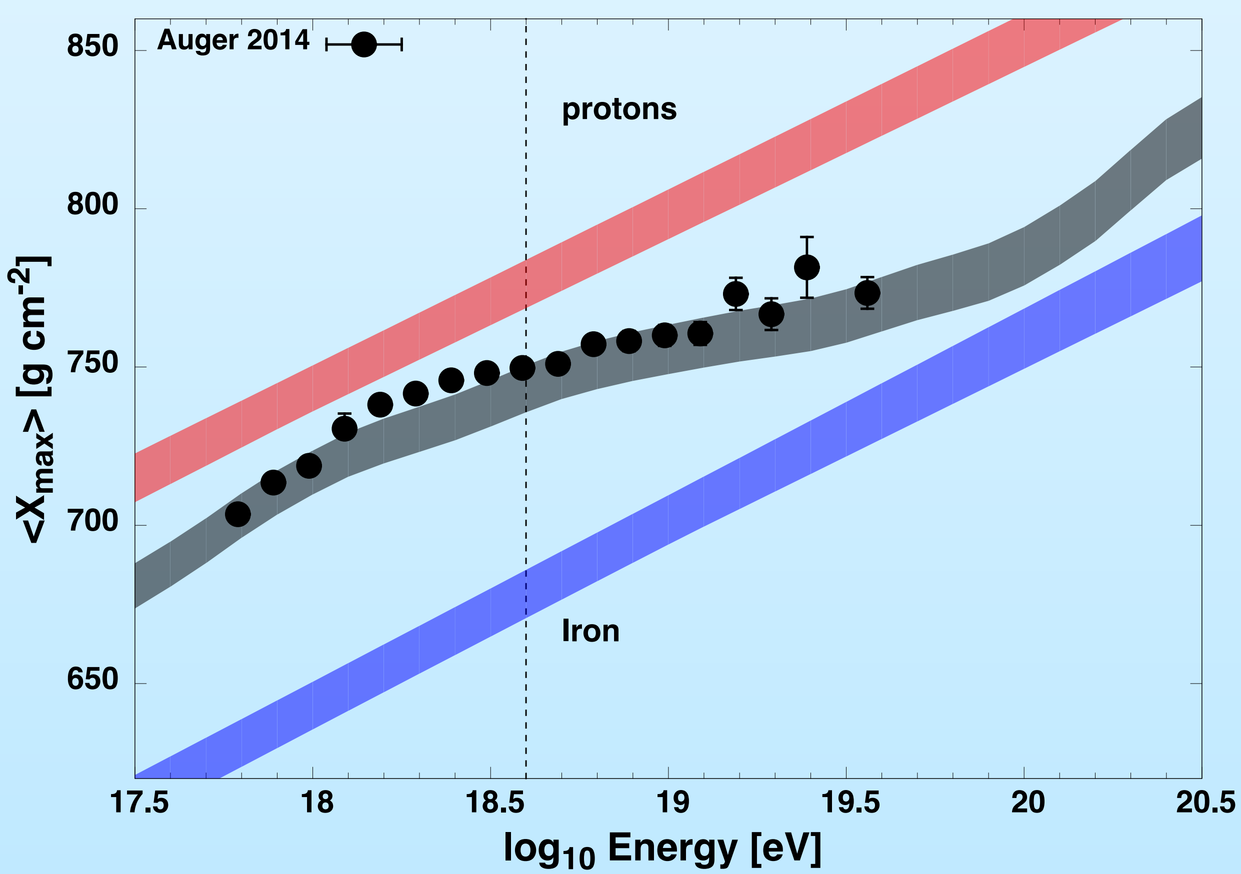


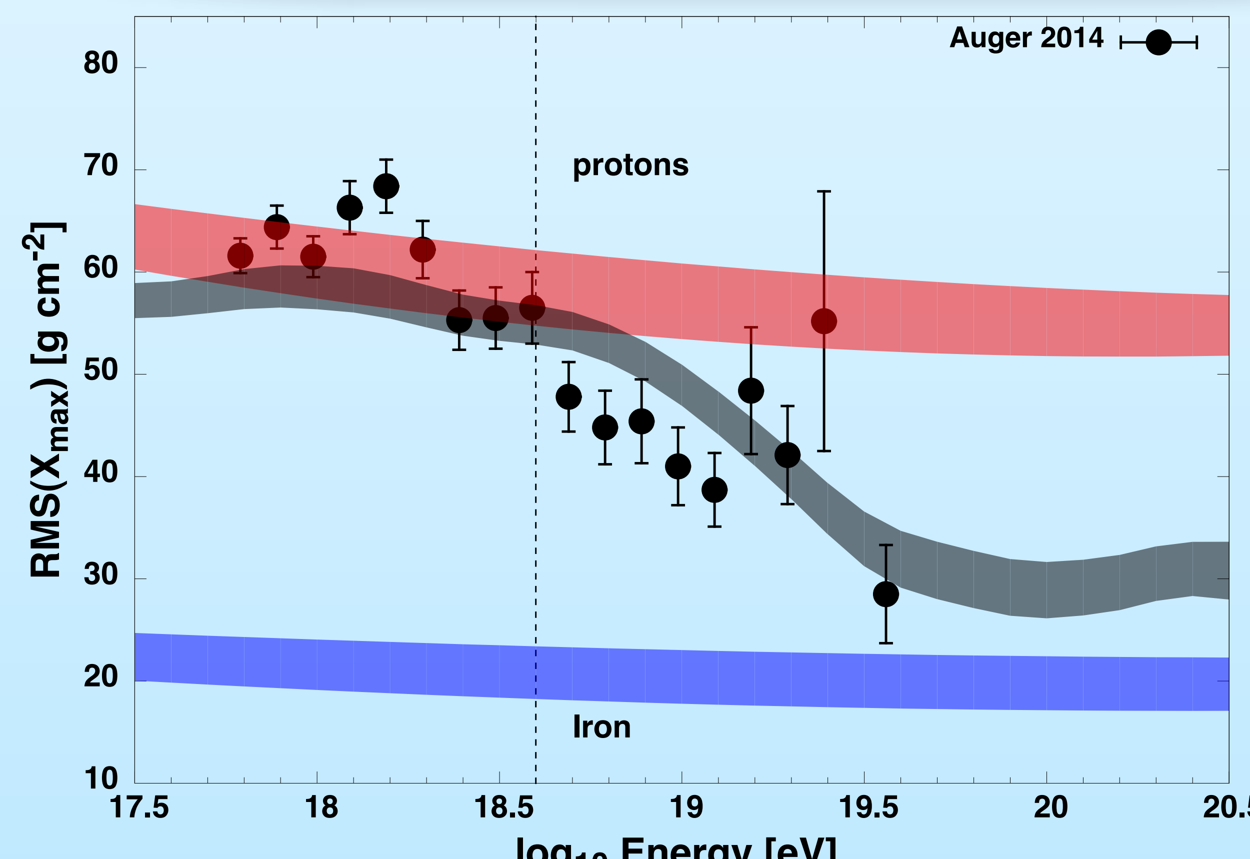
Taylor, Ahlers, Hooper; arXiv:1505.06090

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

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

if local sources ➥ low luminosity

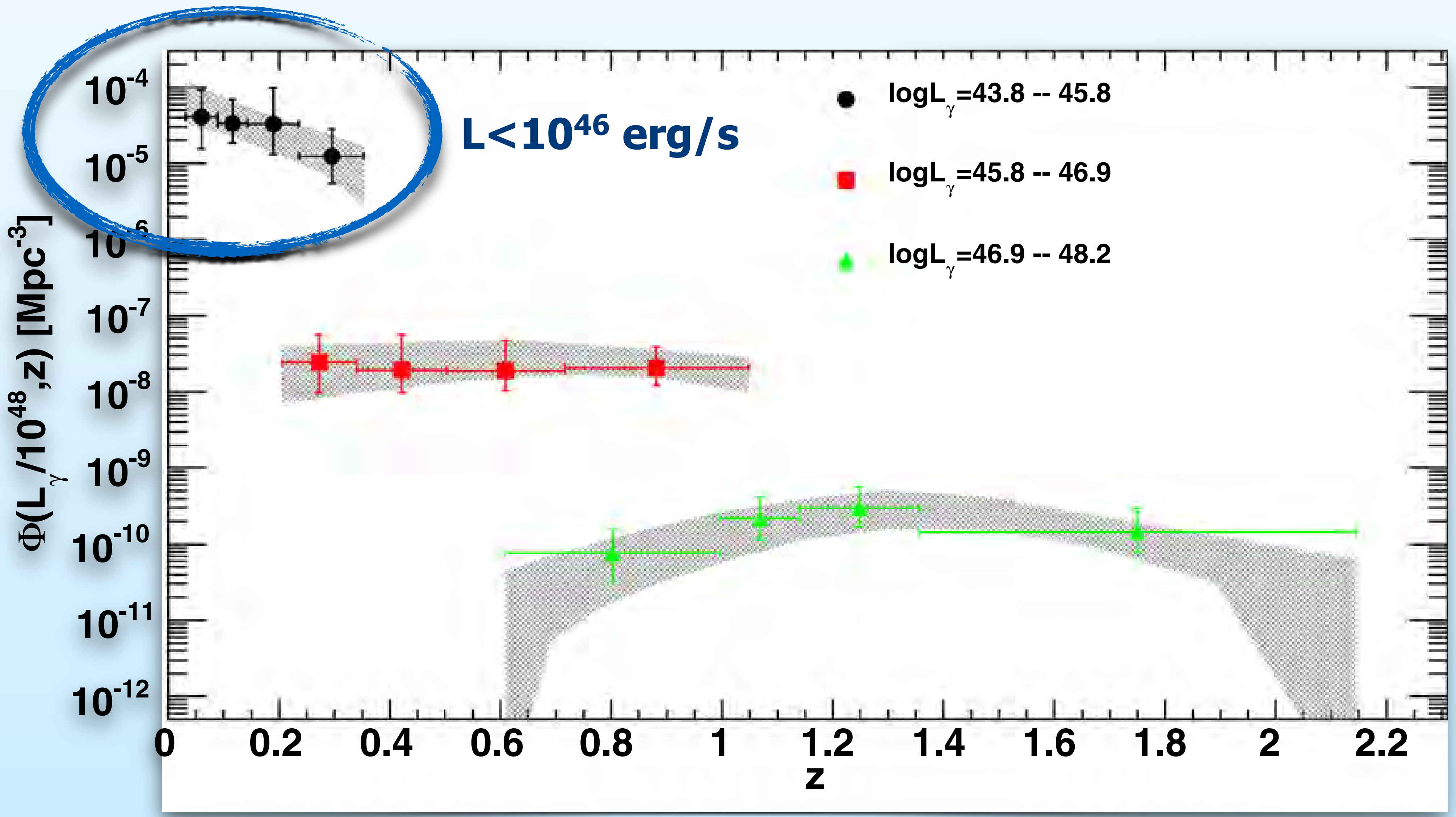




Negative Cosmological Evolution?

A strong <u>negative</u> 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



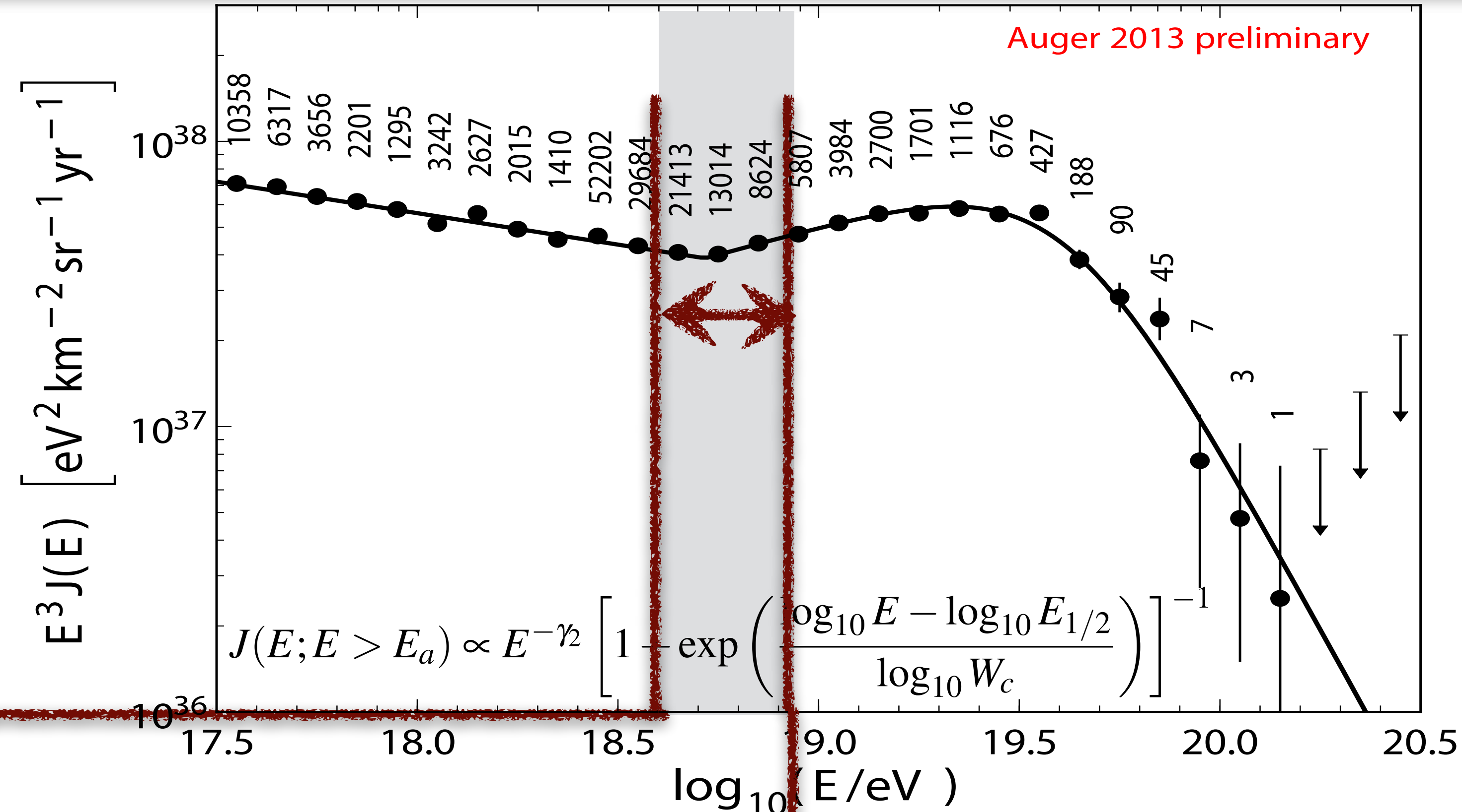
We may see mostly nearby low-power sources !

Same conclusion independently: I. Dutan & L. Caramete; Astroparticle Physics 62 (2015) 206–216

Anisotropies

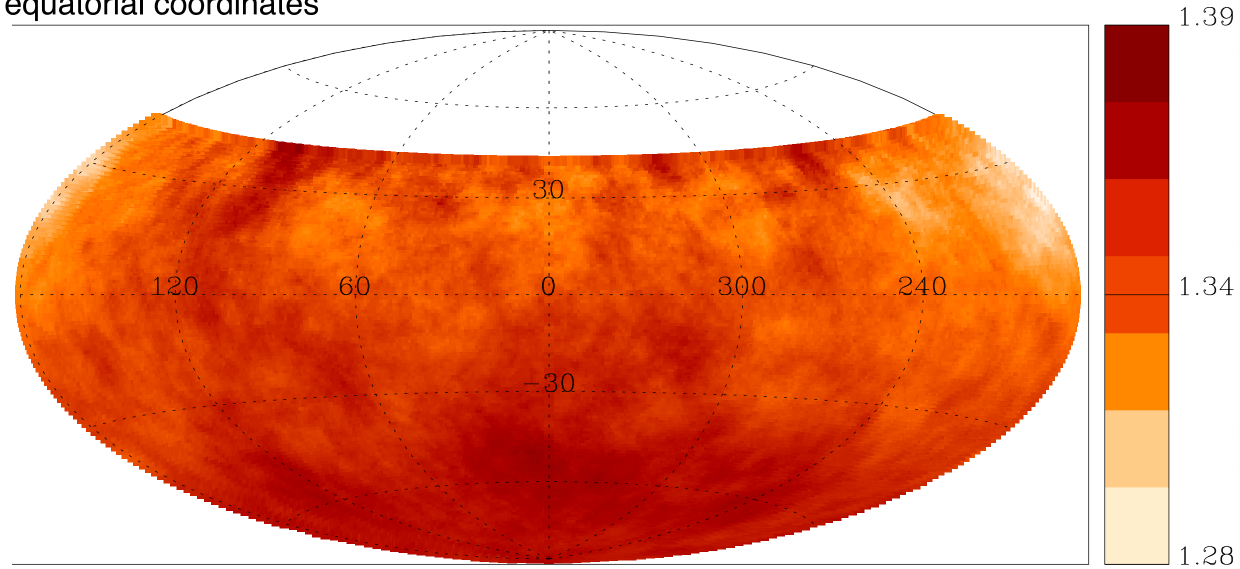
may tell us more

UHECR Sky surprisingly isotropic



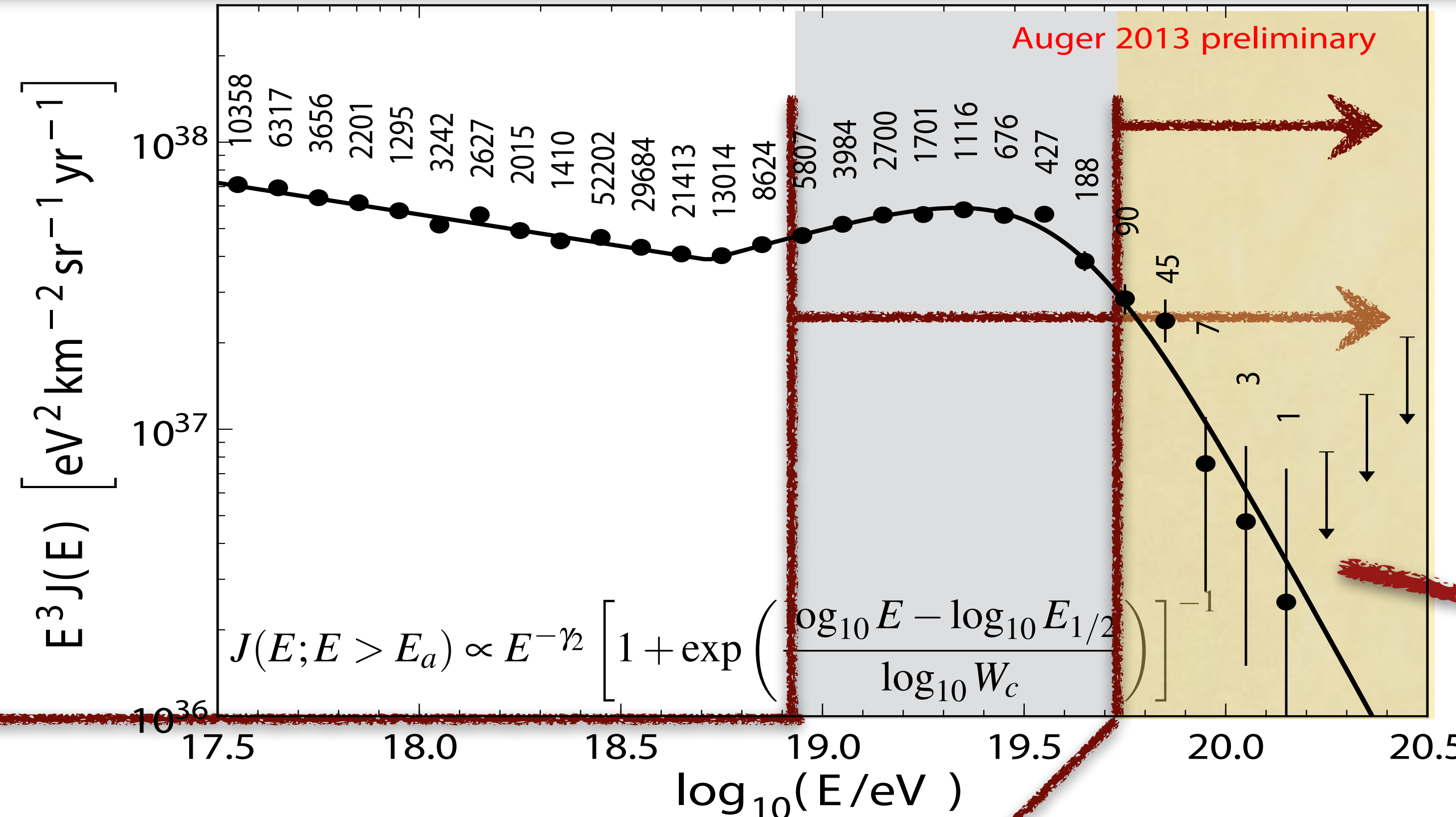
isotropic distribution

E=4-8 EeV



Auger Collaboration ApJ 802:111 (2015)

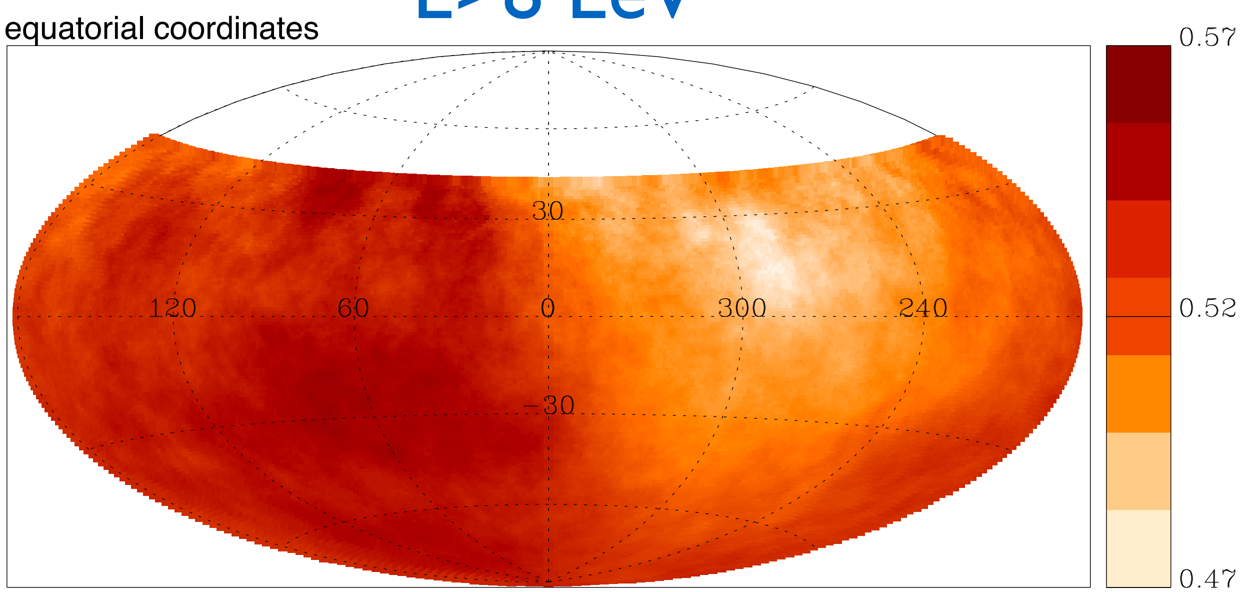
UHECR Sky surprisingly isotropic



hot/warm spot

dipole like anisotropy

E>8 EeV

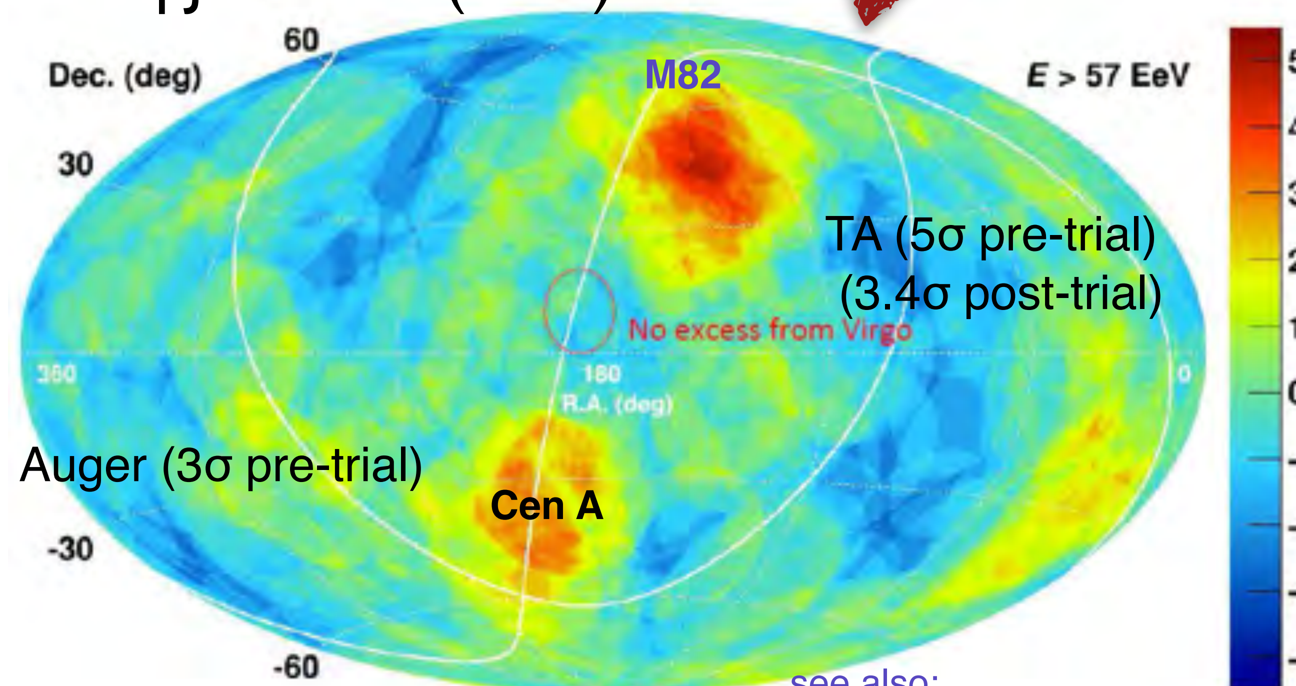


Auger Collaboration ApJ 802:111 (2015)

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

E>57 EeV

TA: ApJ 790:L21 (2014)

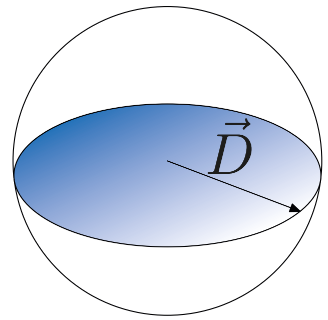


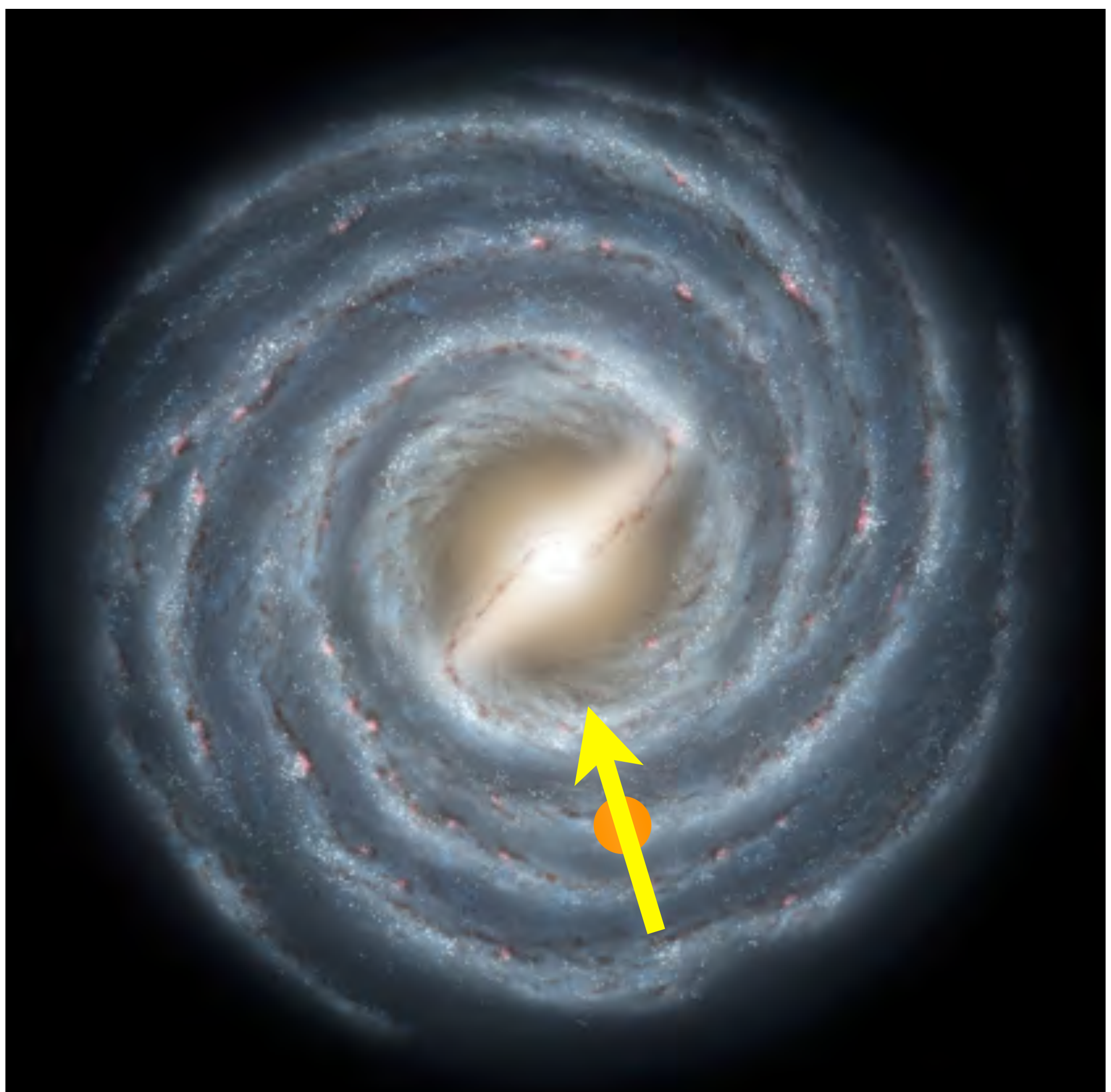
Auger: APP 34(2010) 314

see also:
D. Fargion; arXiv:1412.1573

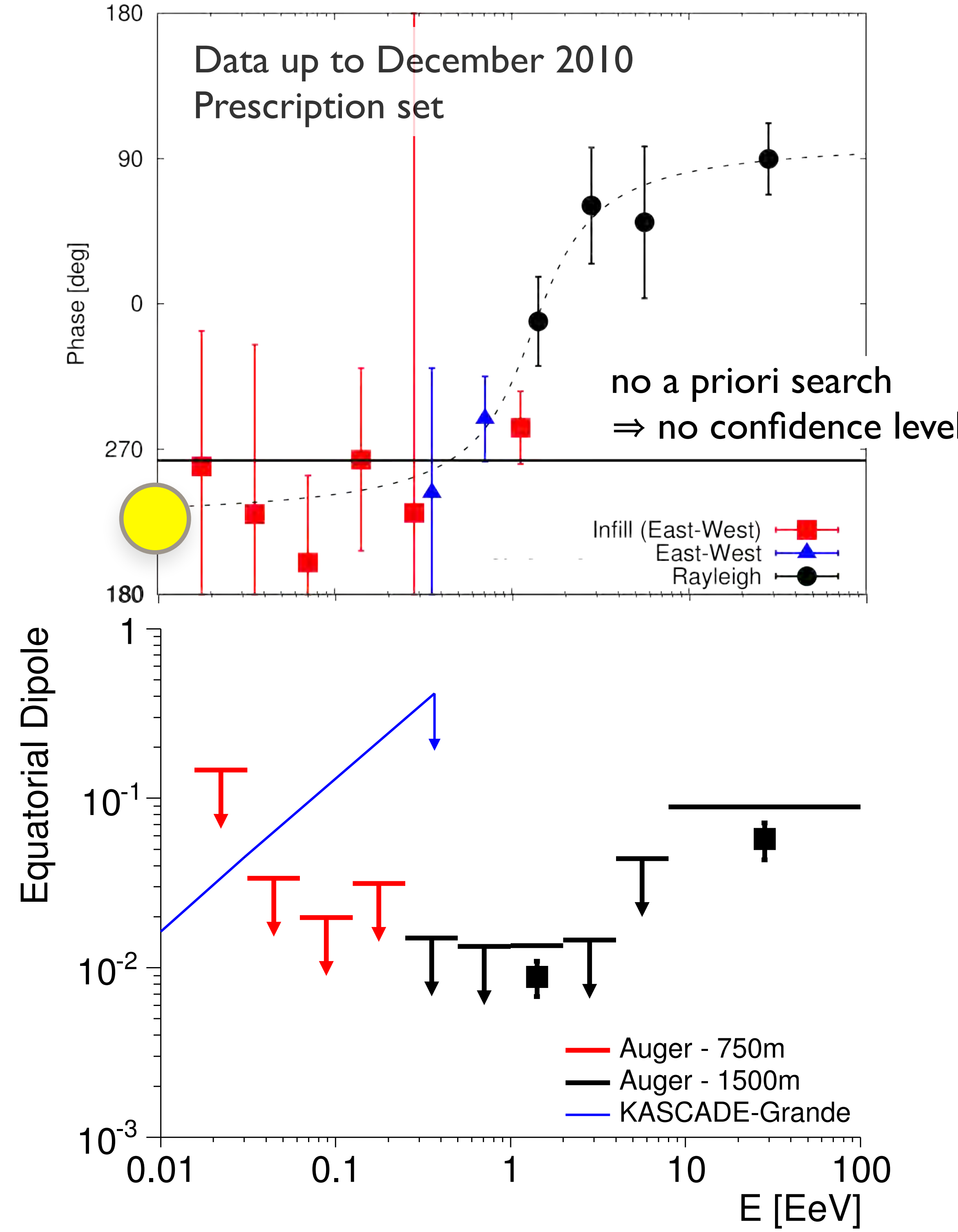
Large scale analysis: First harmonic

Amplitude and phase
of first harmonic
in right ascension: dipole $\vec{D}$



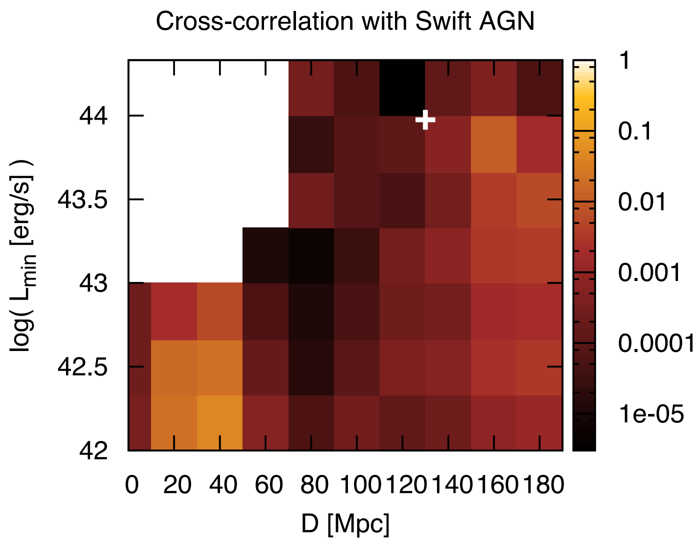


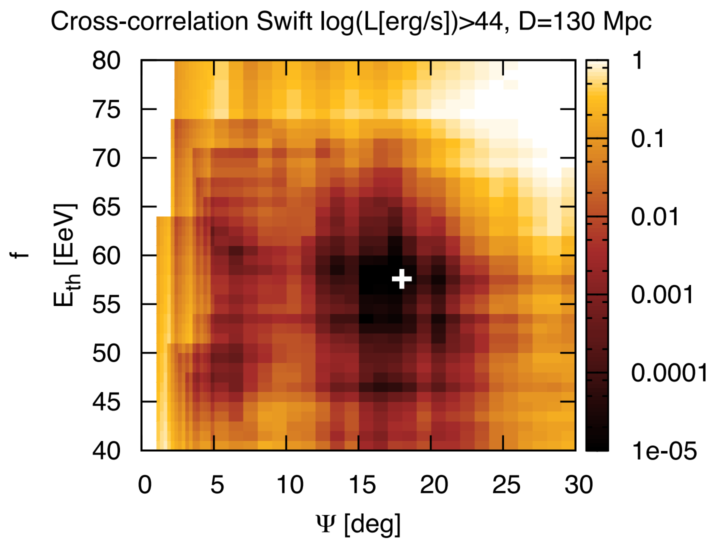
courtesy by Markus Roth (KIT)

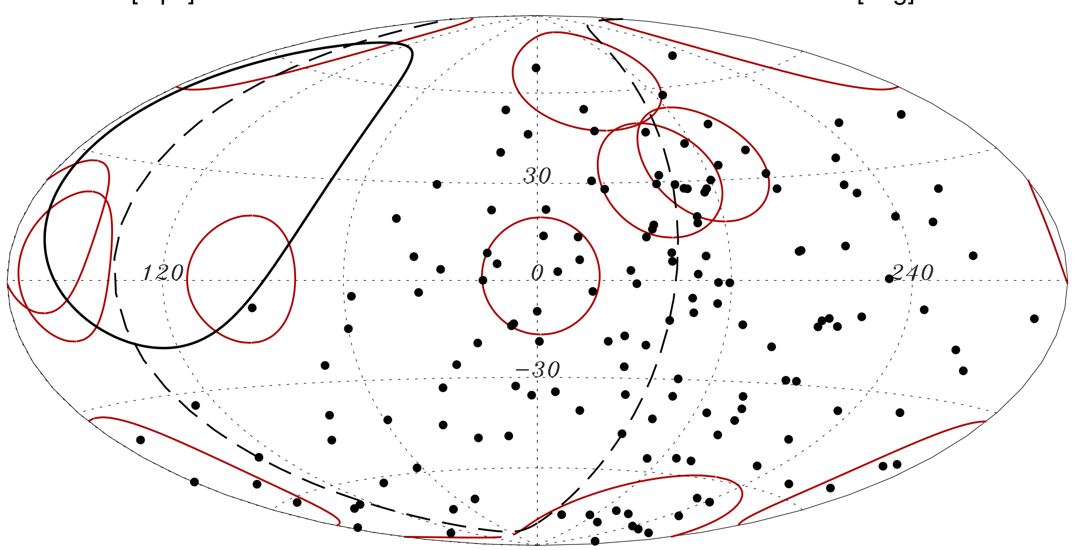


if prescription is confirmed, clear signal of transition from galactic to extra-galactic CRs

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) Observed change of phase in RA-analysis and absence of significant correlations to Galactic Center and Galactic Plane

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

2) Only small deviations from overall isotropic sky

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

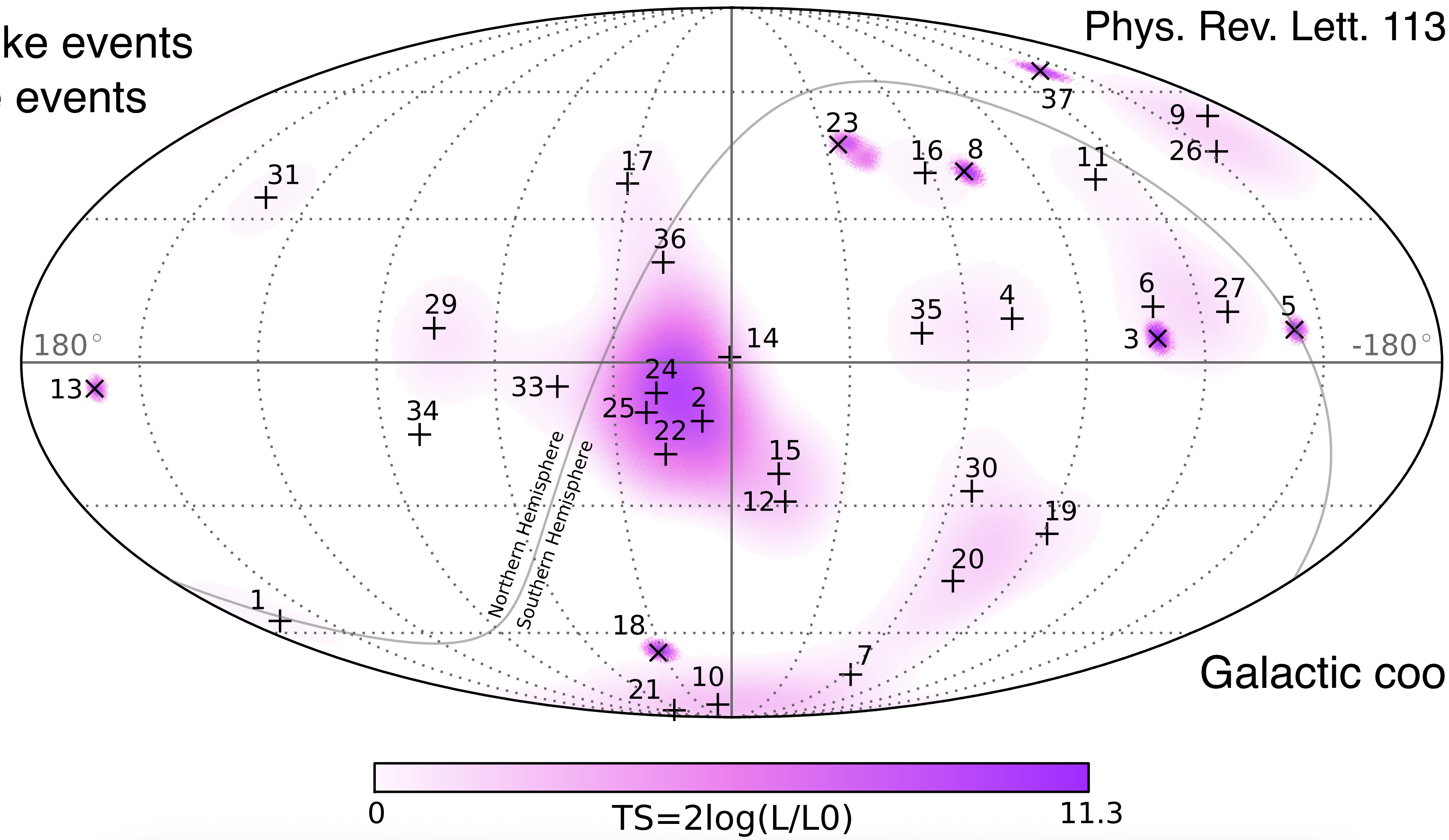
➪ **or number of sources is very large (and luminosity low)** (bounds by Auger from lack of autocorrelations: $\rho \gtrsim 10^{-4}\ \mathrm{Mpc}^{-3}$)

Astrophysical 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

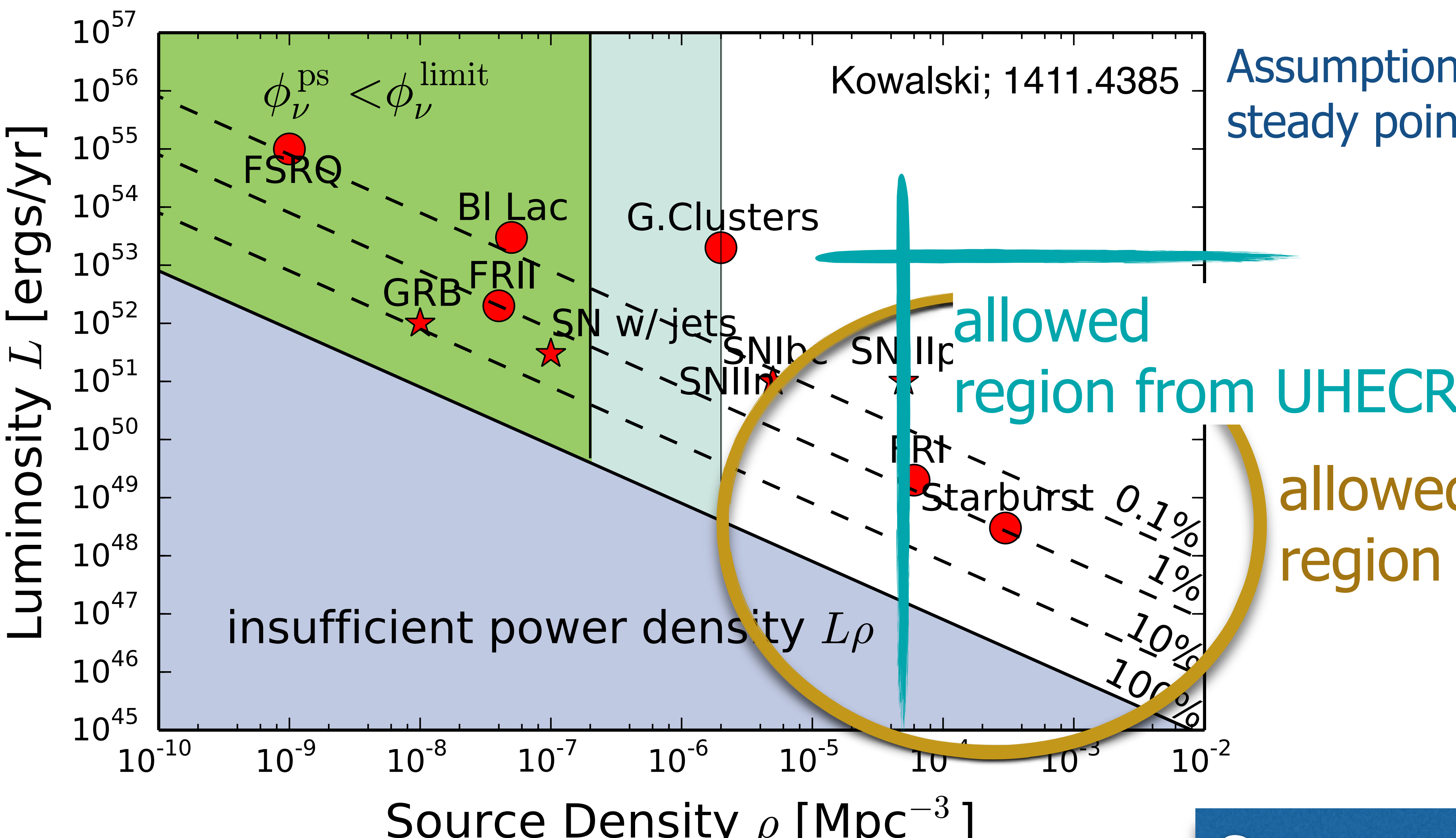
No significant clustering seen (p=84%)

cross correlations to catalogs ⇒ no signal yet

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**



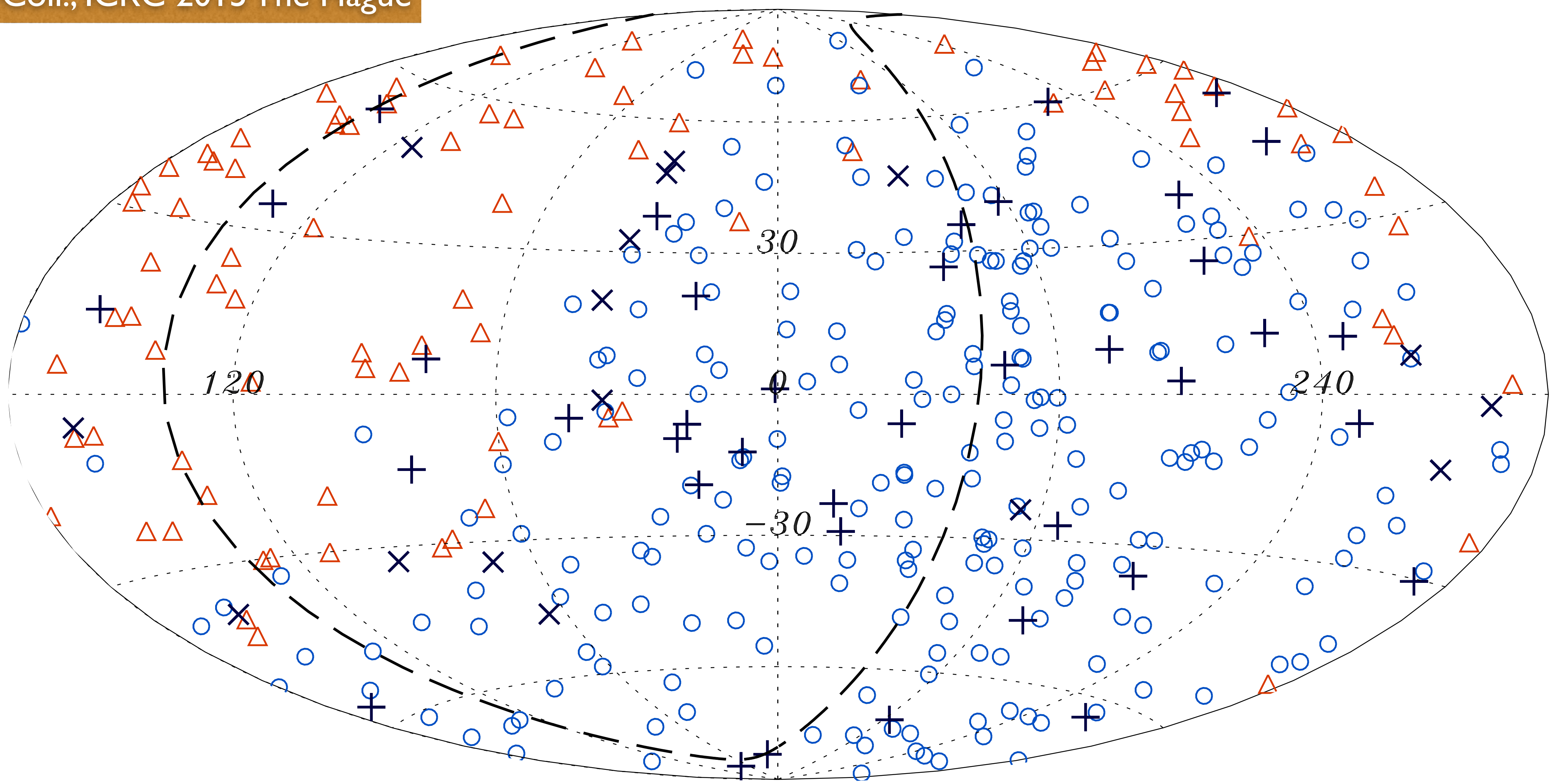
Assumption: steady point sources

Density & Luminosity compare very well to UHECRs !

Same sources for UHECR and ν's ?

UHECR-Neutrino correlations?

IC+ Auger+TA-Coll., ICRC 2015 The Hague



△ TA >57EeV ; ○ Auger >52EeV; × IceCube cascades ; + IceCube tracks

- cross correlation analysis
- stacking analysis done
- 3°, 6°, 9° UHECR angular smearing at 100 EeV around neutrino direction

This analysis: no significant correlations (p-values ≃ 2-4 %)

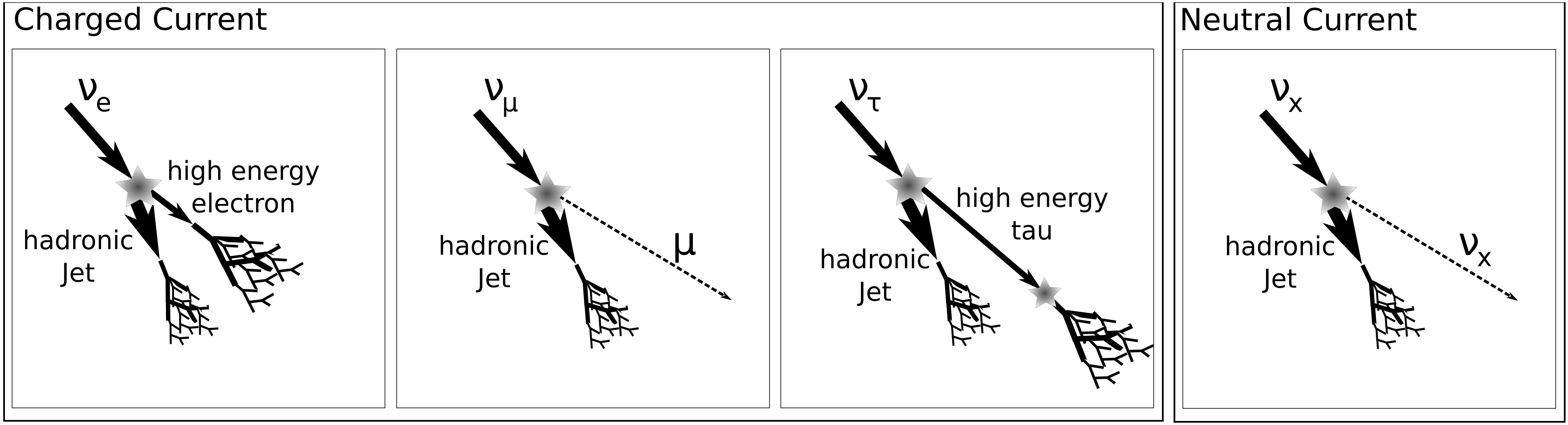
with 4-year IC data to be presented @ ICRC ⟹ interesting to pursue

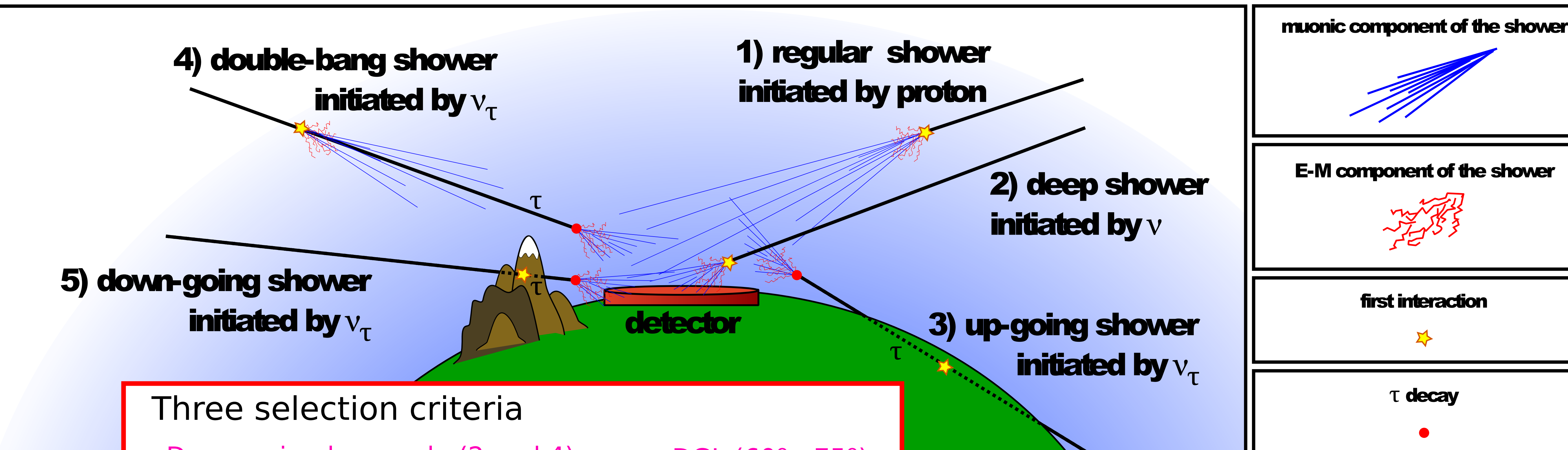
Cosmogenic Neutrinos

Recall:

- If flux suppression above $5 \cdot 10^{19}$ eV is due to GZK-effect: expect cosmogenic neutrinos & photons
- If due to source exhaustion: neutrinos & photons strongly suppressed

EAS are sensitive to all ν flavors and channels

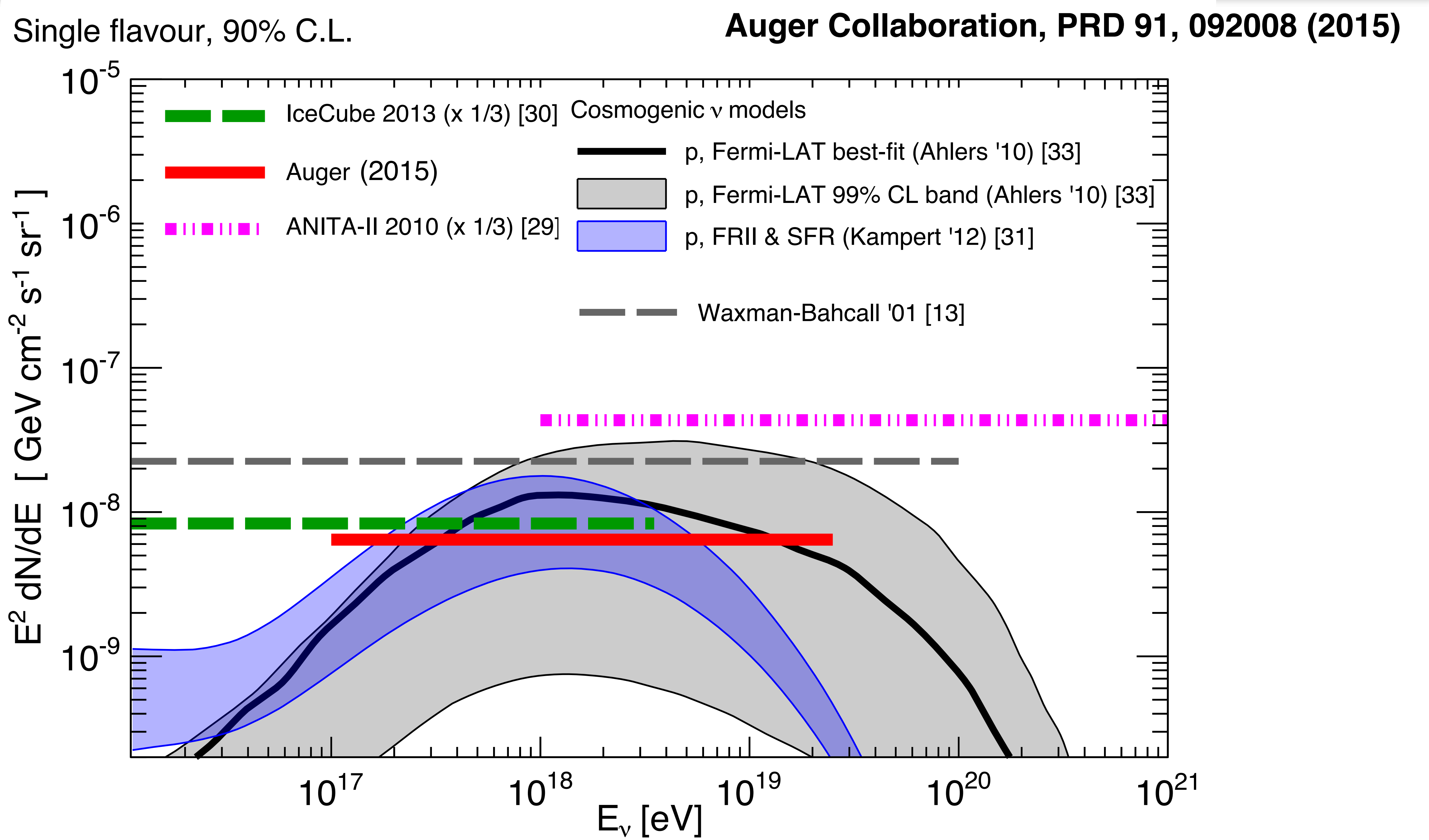




Three selection criteria

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)

EeV Neutrino Limits

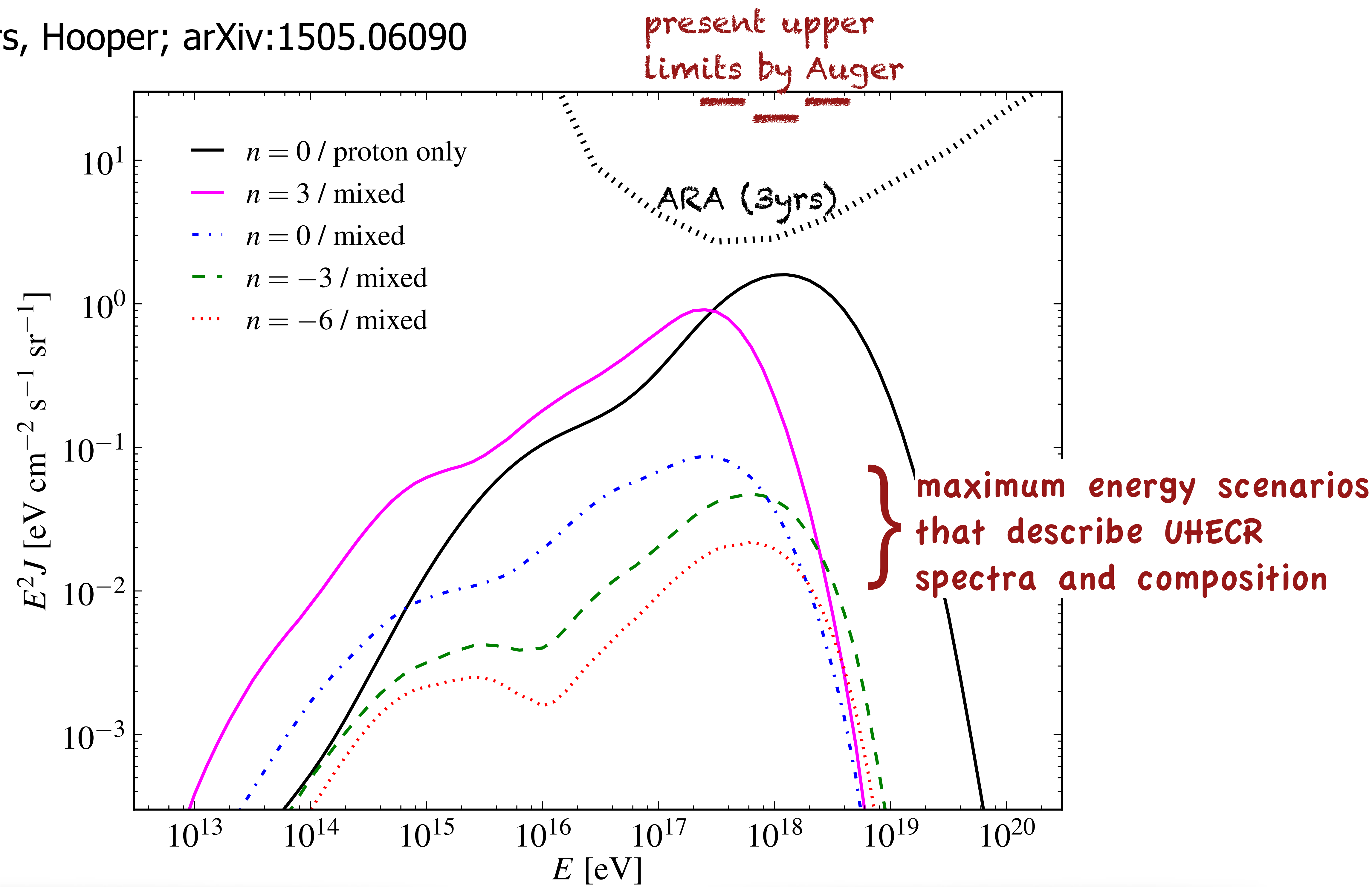


Would have expected to see 1-7 GZK neutrinos (for different models), have seen none

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

Exhausted UHECR Sources

Taylor, Ahlers, Hooper; arXiv:1505.06090



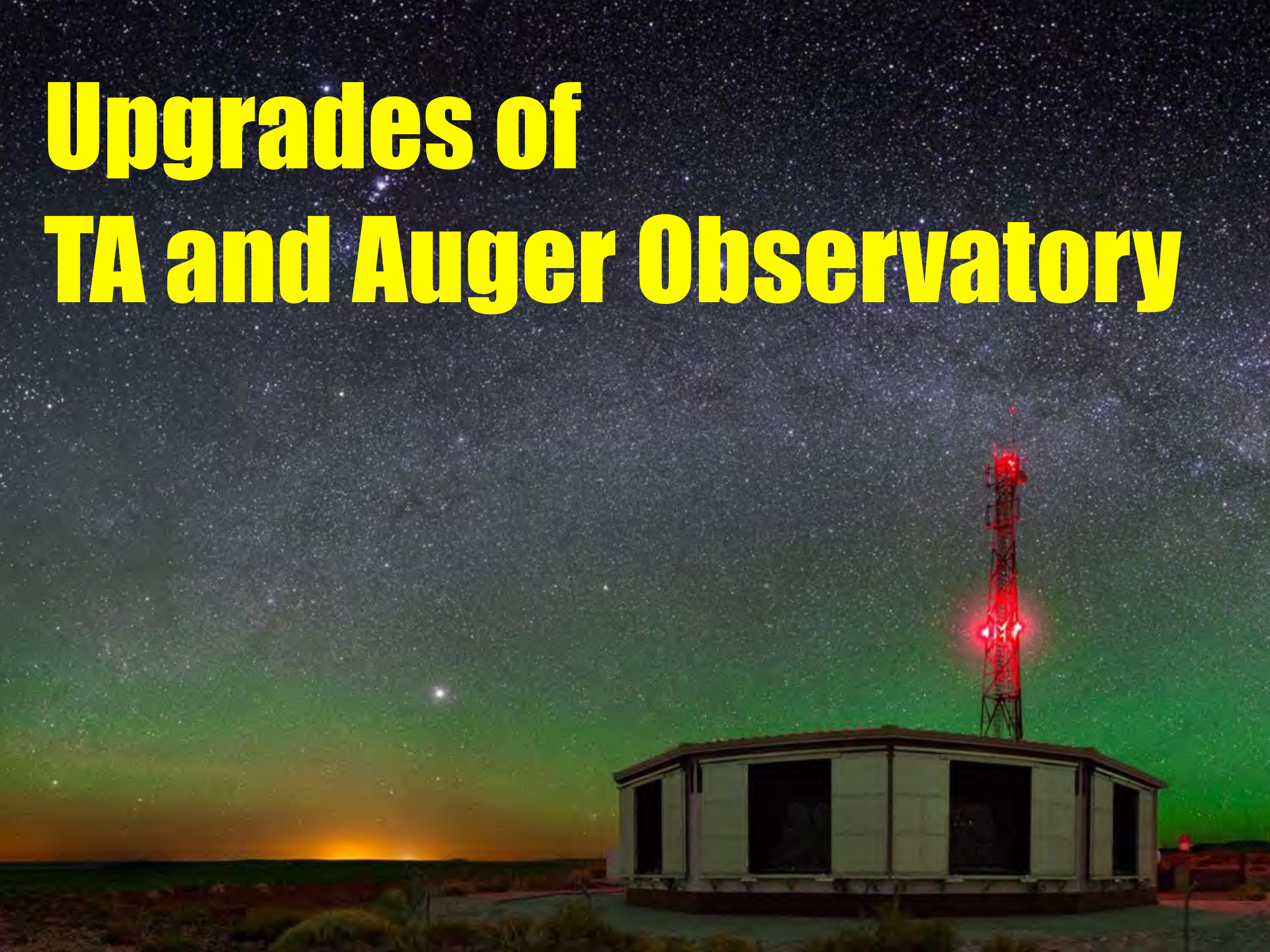
Cosmogenic neutrino fluxes may be down by ~2-3 orders of magnitudes for exhausted sources !!

Enormous progress in last 8 years

8 years ago...	Now...
• did not know whether flux suppression exists	• beyond any doubt
• thought composition is purely protons	• appears to become heavier (unless new physics at E_{cm} ~ 50 TeV)
• no signatures of anisotropies (on any angular scale)	• LS anisotropies seen, but no point sources yet
• no relevant bounds on cosmogenic ν's and γ's	• cosmogenic ν's and γ's being constrained
	• particle physics: σ(pp)
	• smoothness of space-time
	• unexpected geophysical effects (elves, ...)

Next logical Step

Now...	Next...
• beyond any doubt	• understand origin of flux suppression
• appears to become heavier (unless new physics at E_{cm} ~ 50 TeV)	• measure composition into flux suppression region
• LS anisotropies seen, but no point sources yet	• composition enhanced anisotropies, p-astronomy
• cosmogenic ν's and γ's being constrained	• improve limits by better triggers
• particle physics: σ(pp)	• particle physics at 100 TeV
• smoothness of space-time	• …
• unexpected geophysical effects (elves, …)	


Upgrades of
TA and Auger Observatory

TAx4 SD Upgrade

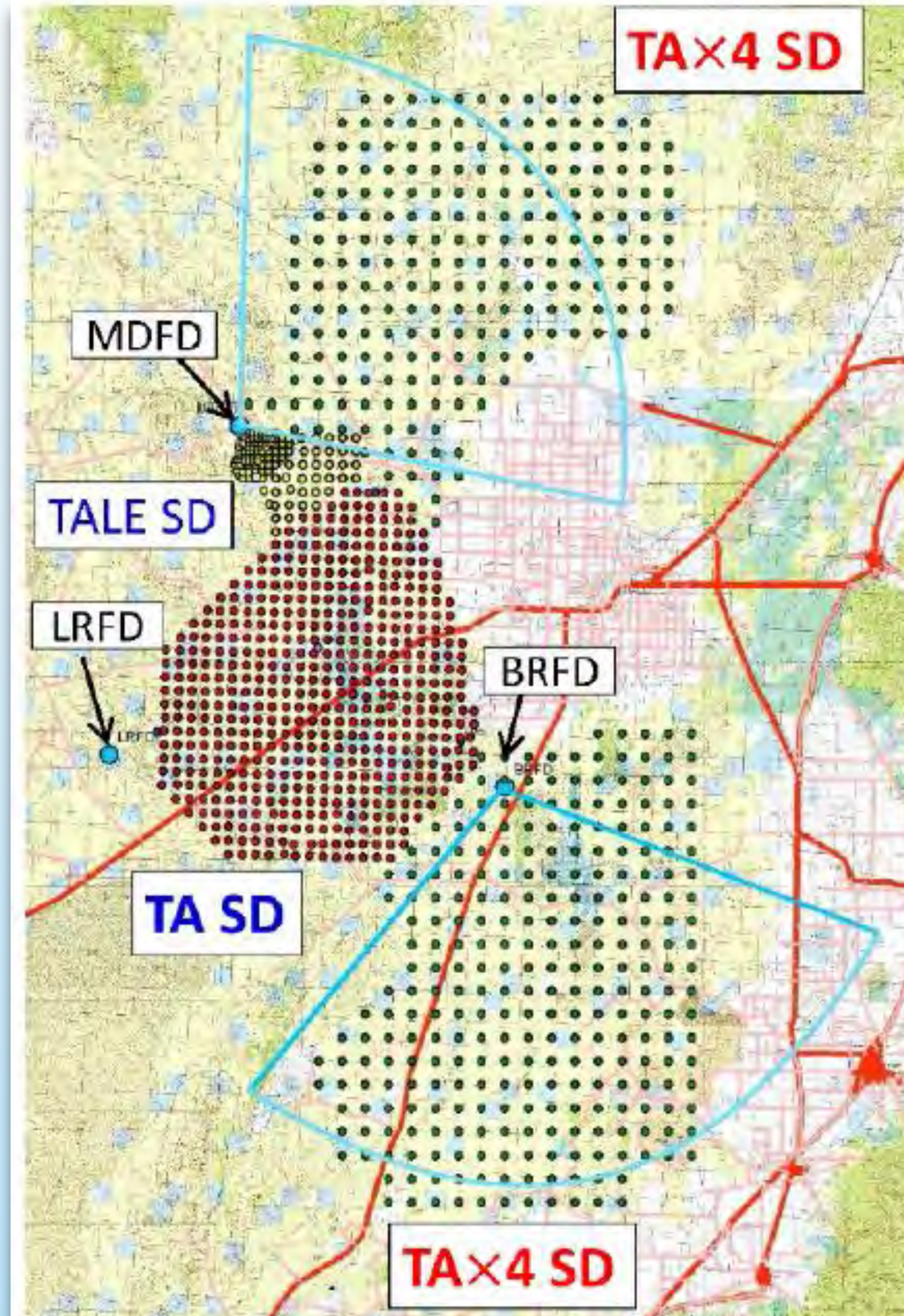
500 more SDs

2 more FD stations

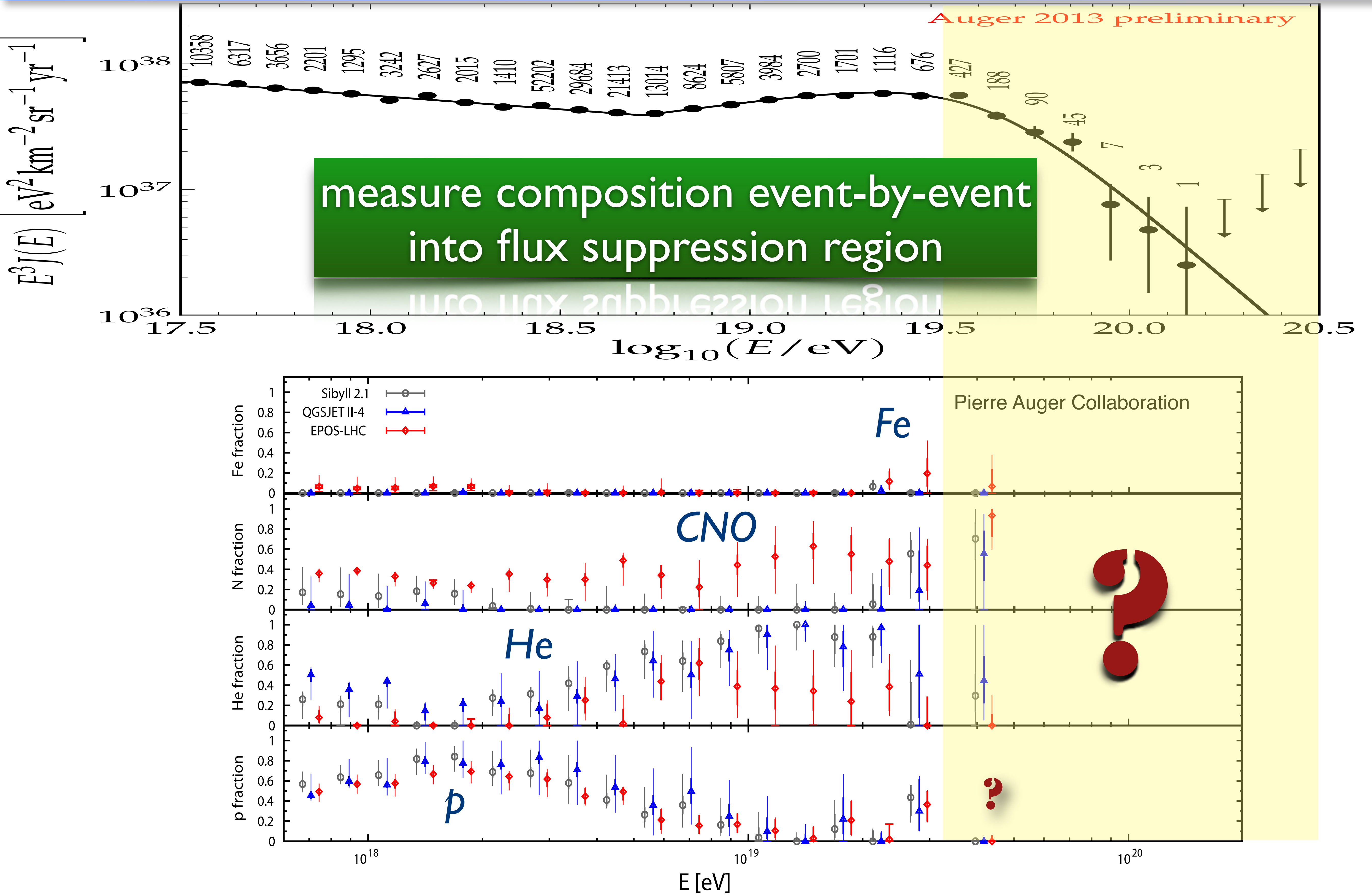
- SD: 700 → **2800 km²**
- Hybrid: x3 acceptance
- Optimized for UHECR above cutoff (fully efficient above ~60 EeV)

collect statistics more rapidly

funding of array



Auger Upgrade

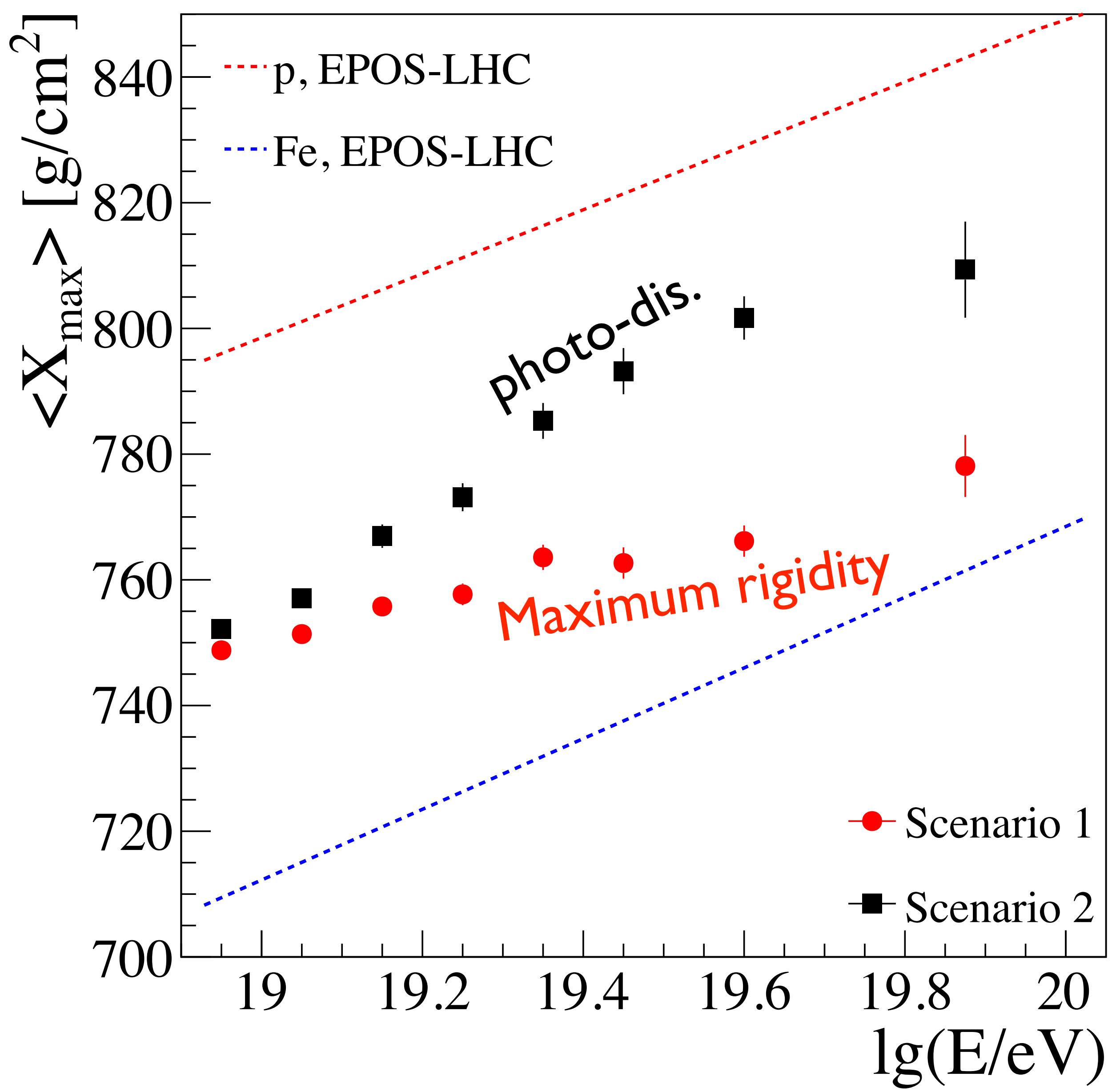


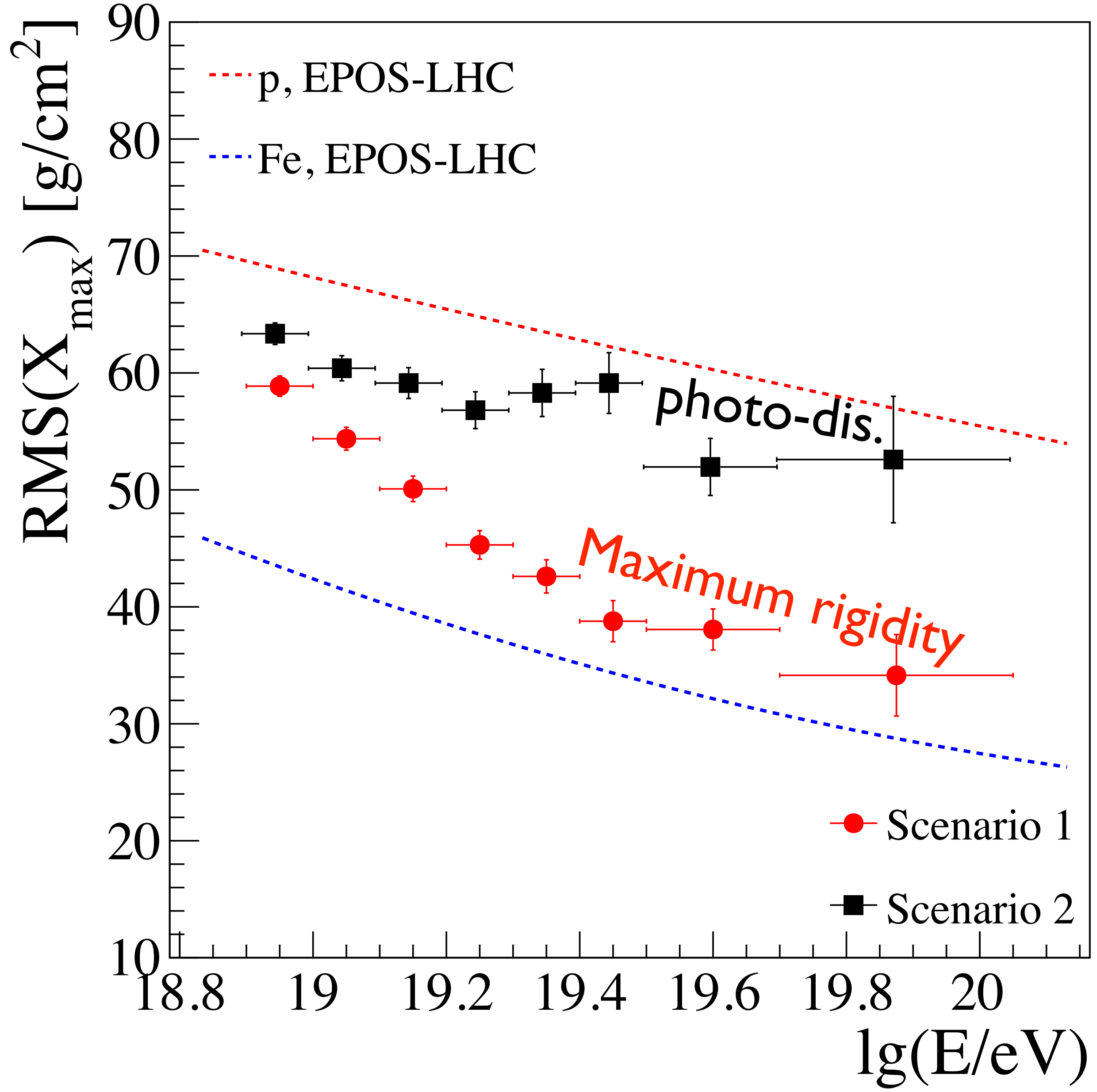
Auger Upgrade

Scintillators on top of each Water Cherenkov Tank

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

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



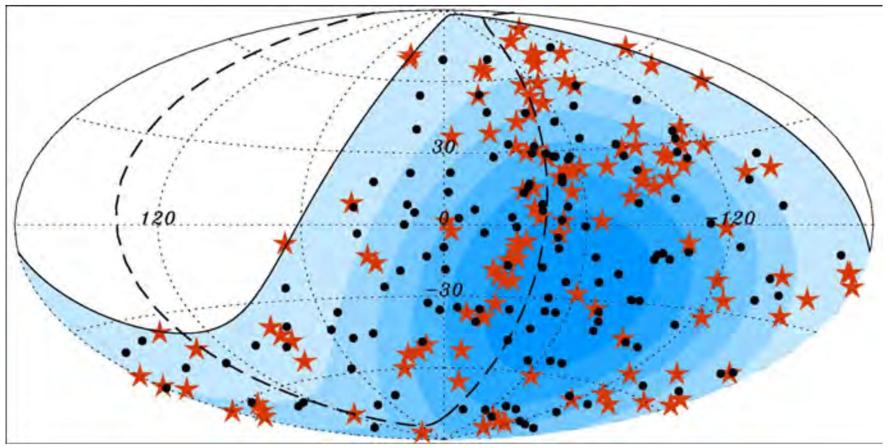


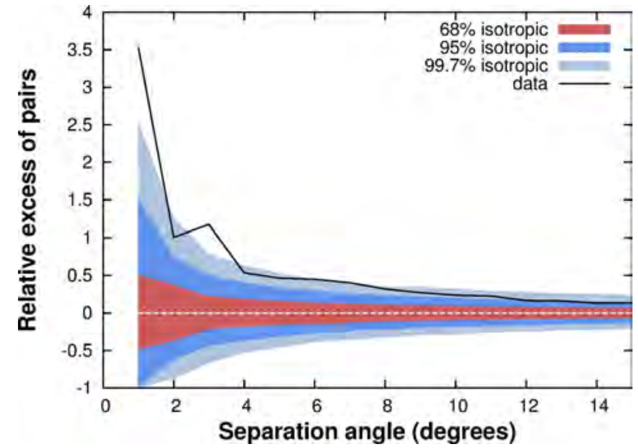
Shower fluctuations and detector resolutions included

scenarios can be distinguished with high significance

p-Astronomy

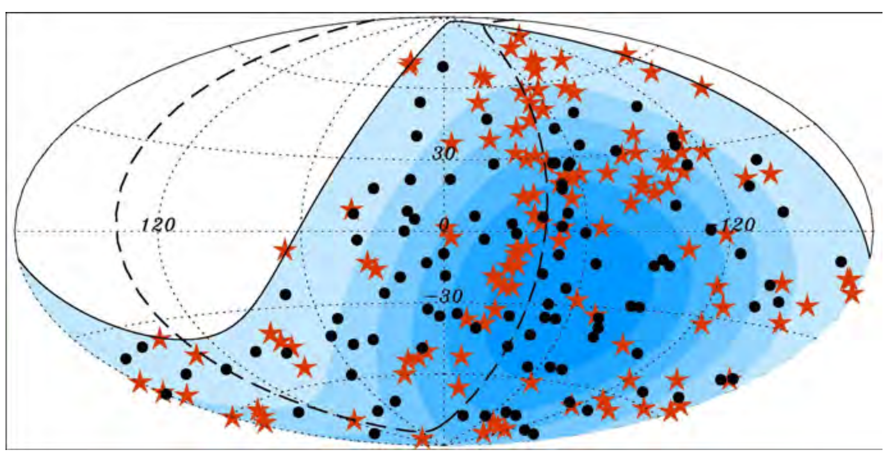
use arrival directions of 141 measured events with $\theta < 60°$ and $E > 5.5 \cdot 10^{19}$ eV and randomly assign X_{max} according to maximum rigidity model with 10% p-like at high E and let 50% of p-like events correlate with Swift-BAT sources

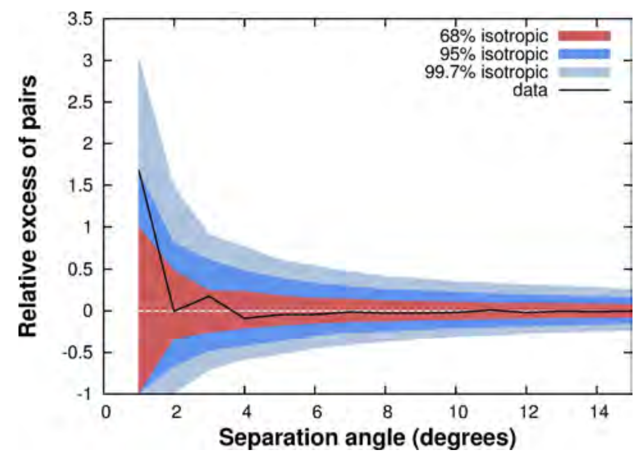




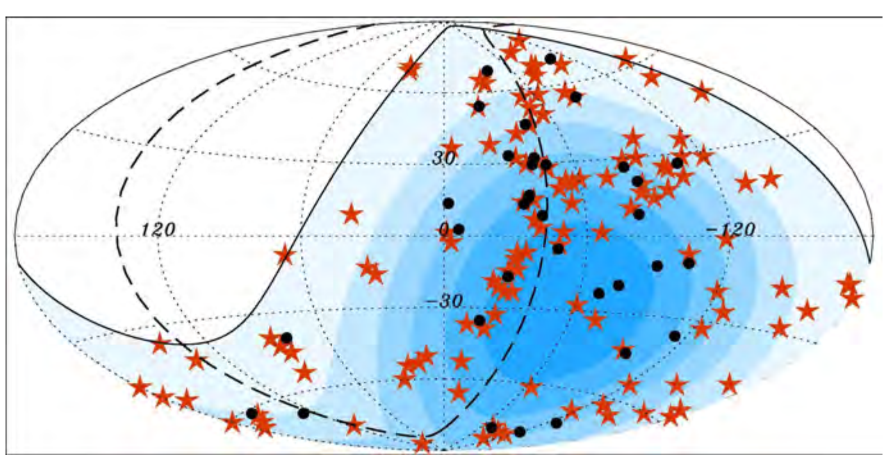
this reproduces well the present situation

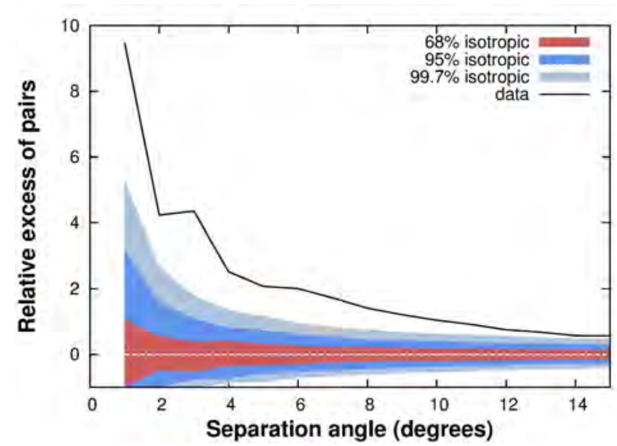
~ 3σ effect





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: some positive signs, but not yet approved

Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

~500 Collaborators; 88 Institutions, 17 Countries:

- Argentina
- Australia
- Brazil
- Czech Republic
- France
- Germany
- Italy
  - Milano
  - Napoli
  - Rome
  - Catania
  - Torino
  - Lecce
  - L'Aquila
  - Gran Sasso
- Mexico
- Netherlands
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- UK
- USA

Colombia Associated

Peru
Bolivia EoI

New members are welcome!