International Symposium on Very High Energy Particle Astronomy
- New Approach to PeV-EeV Universe -

Latest Results and Upgrade of Auger Observatory

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BERGISCHE UNIVERSITÄT WUPPERTAL

Taipei (Taiwan), April 8-9, 2015

Photo by Steven Saffi

Pierre Auger Observatory

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

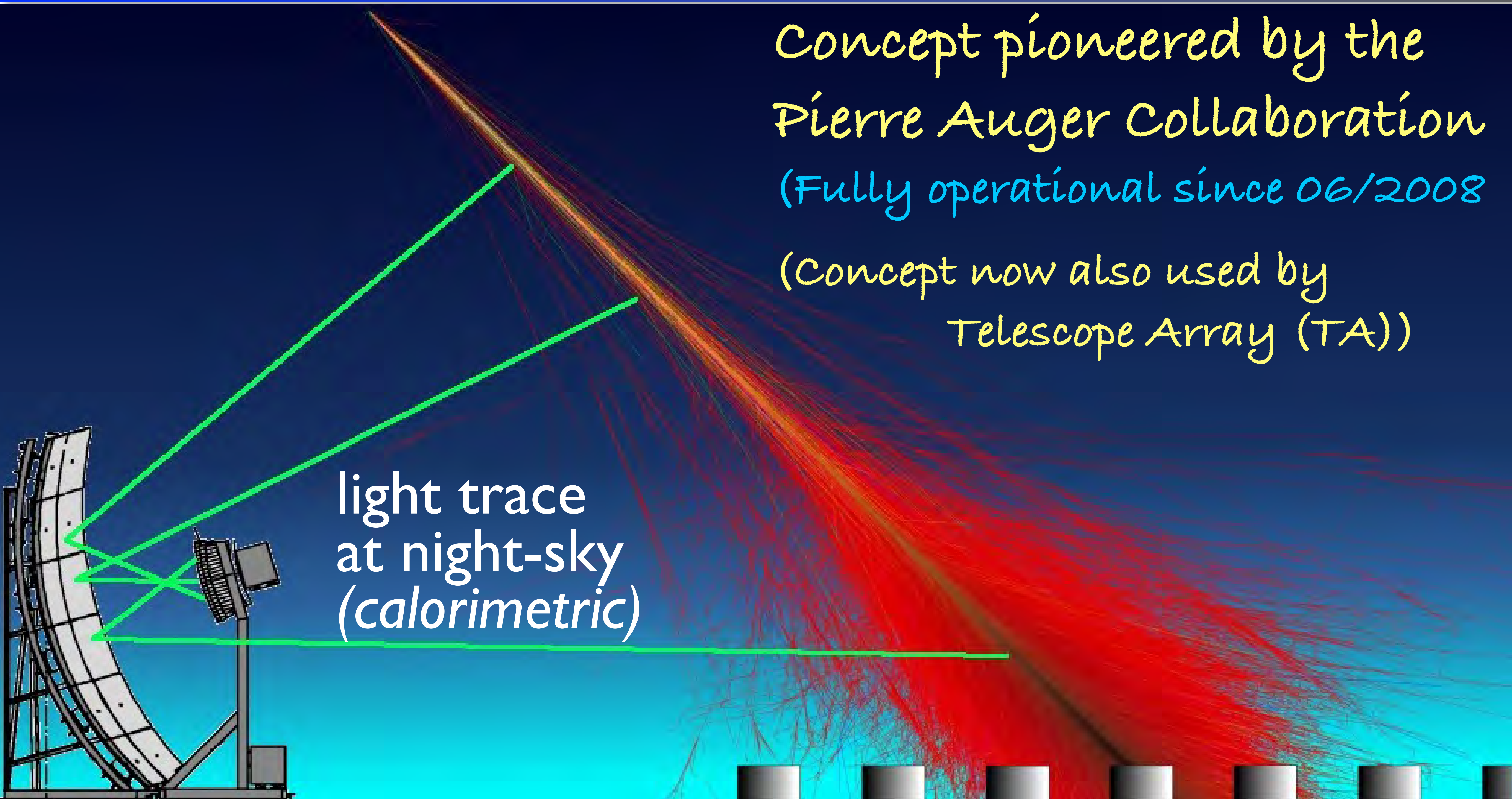
130 radio antennas

Province Mendoza, Argentina

Auger Hybrid Observatory

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

A New Generation: Hybrid Observation of EAS



Fluorescence light

Particle-density and -composition at ground

Also:
Detection of Radio- & Microwave-Signals

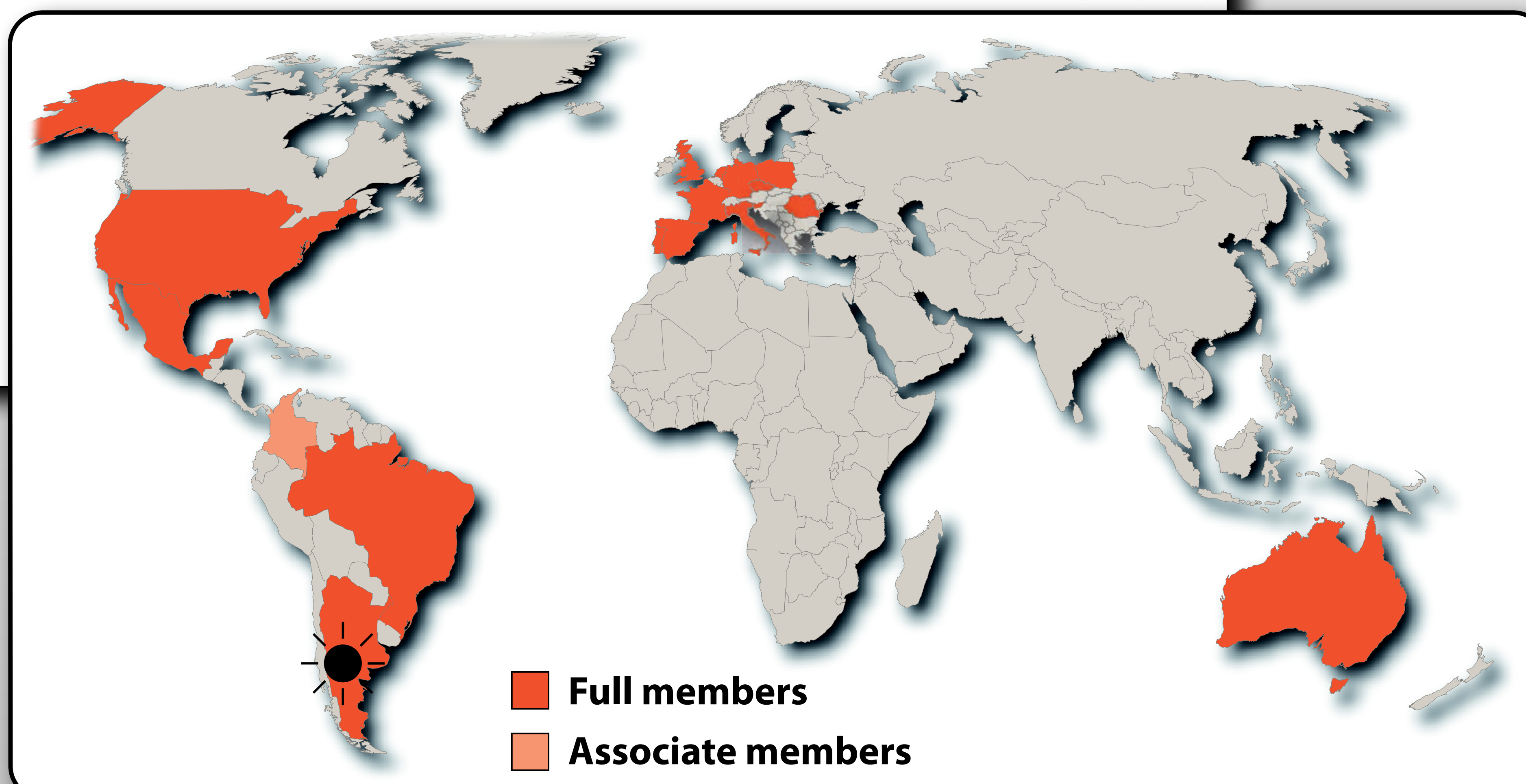
Pierre Auger Collaboration

~500 Collaborators; 88 Institutions, 17 Countries:

Argentina
Australia
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
UK
USA
Colombia*

New members are welcome!

*Associated



Outline

1. Brief Overview of Recent Results

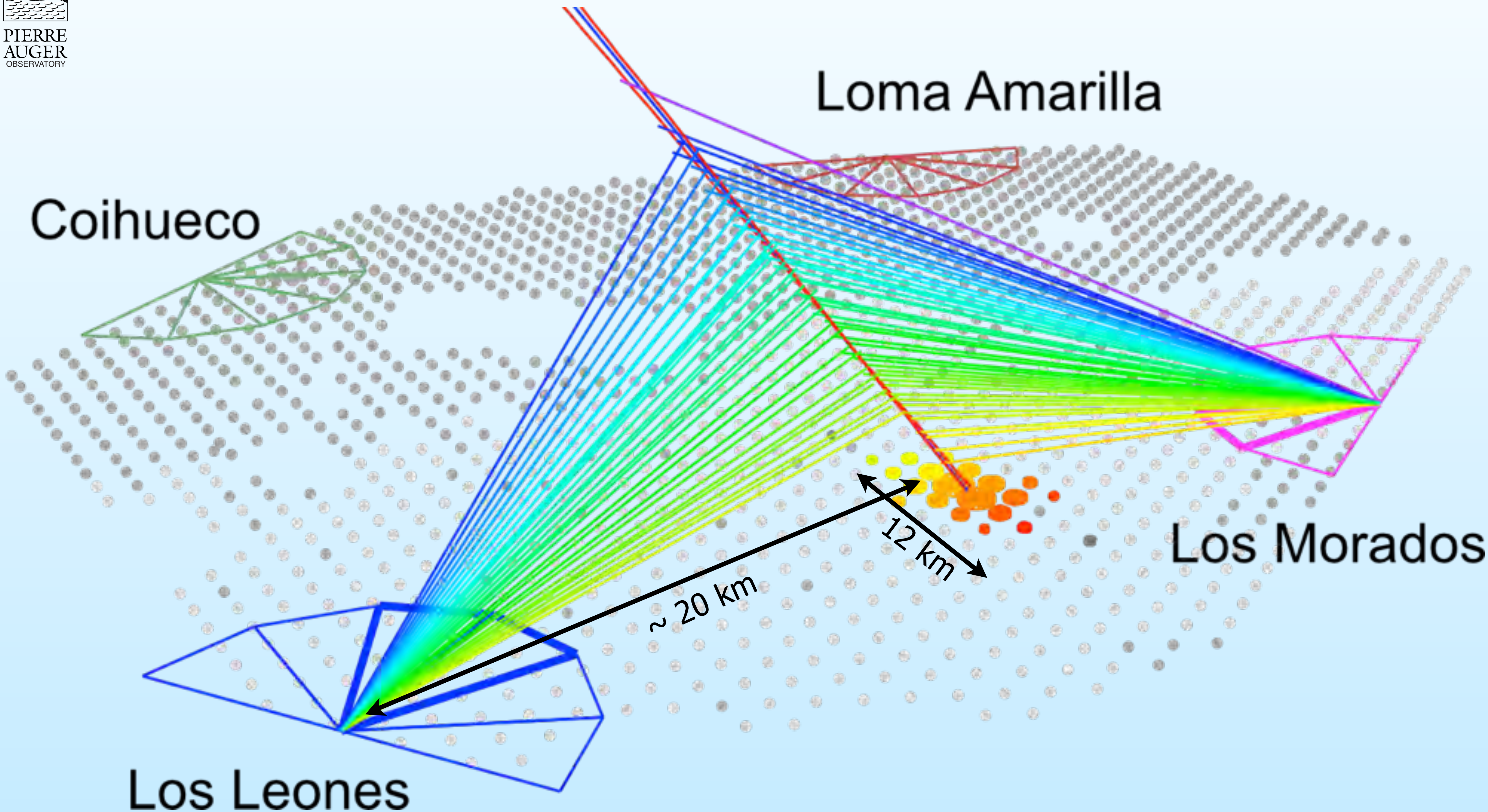
- energy spectrum
- mass composition
- anisotropies
- photons
- neutrinos
- particle & fundamental physics
- interdisciplinary science, ...

2. Puzzles to be solved; Rational of Upgrade

- transition galactic to extragalactic CRs
- origin of the flux suppression
- proton astronomy at the highest energies
- features of hadronic interaction @ $\sqrt{s}$~100 TeV

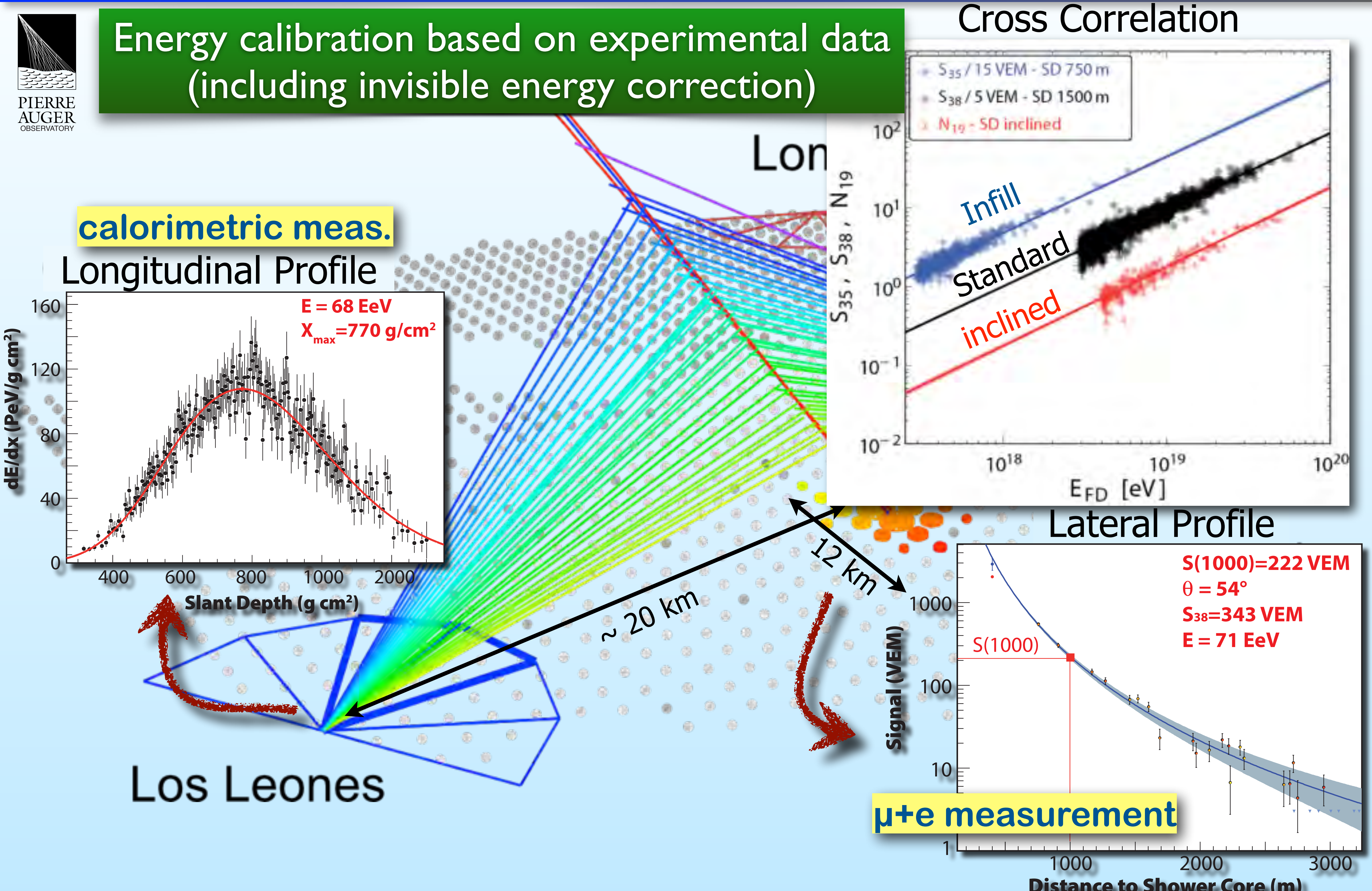
3. Cost Estimate, Timeline

Event Example in Auger Observatory

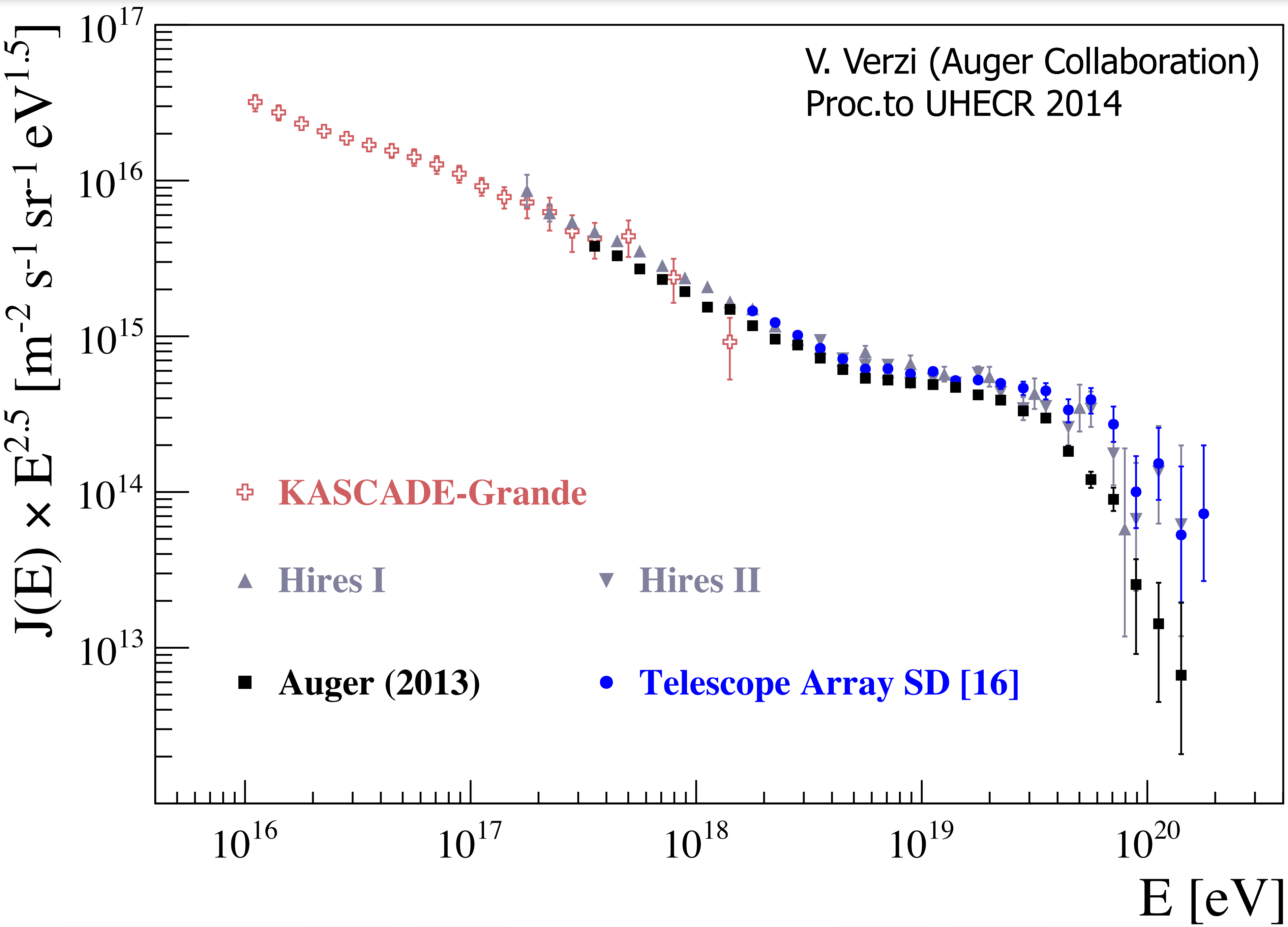


Event Example in Auger Observatory

Energy calibration based on experimental data
(including invisible energy correction)

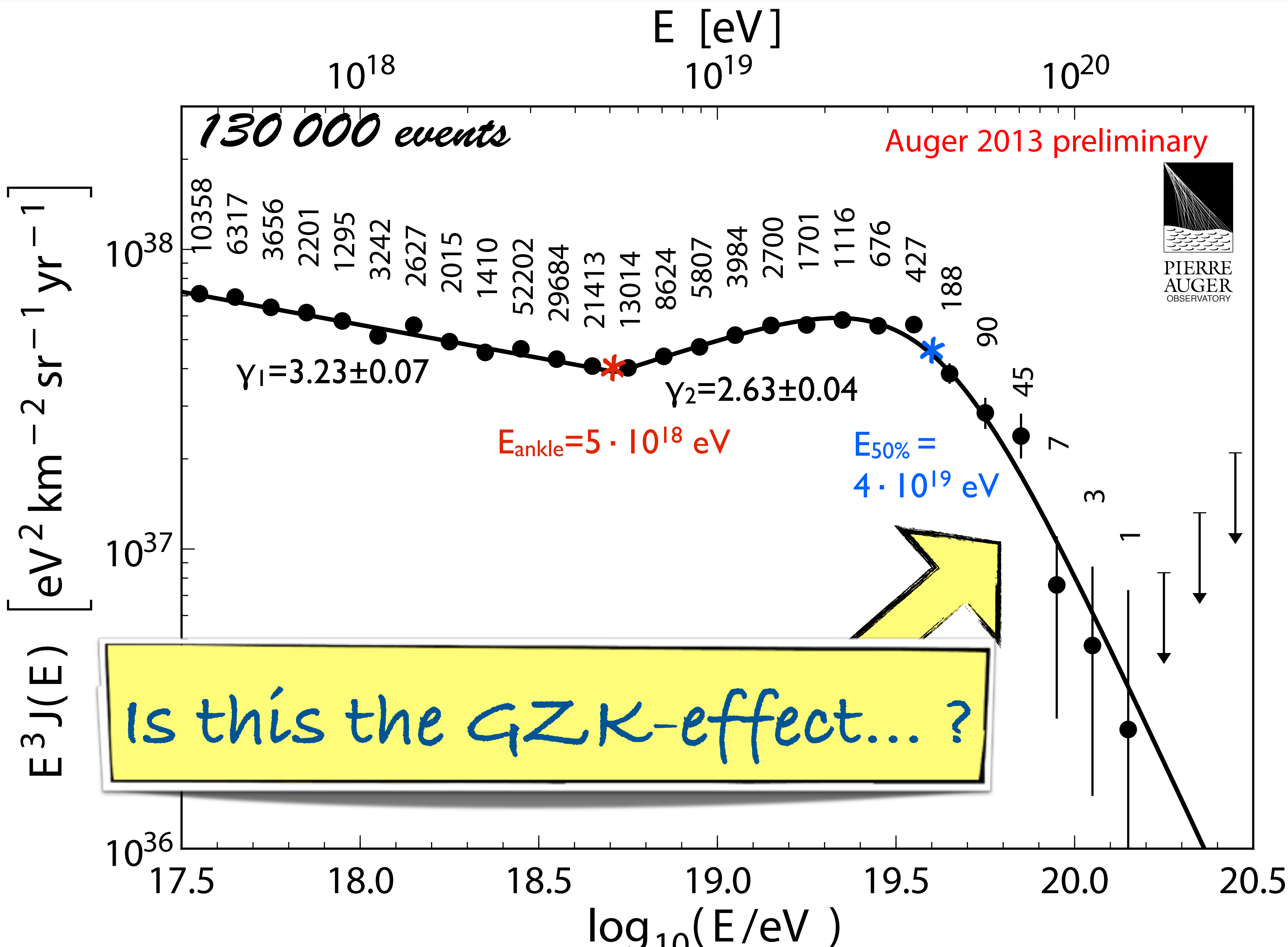


All Particle Energy Spectrum

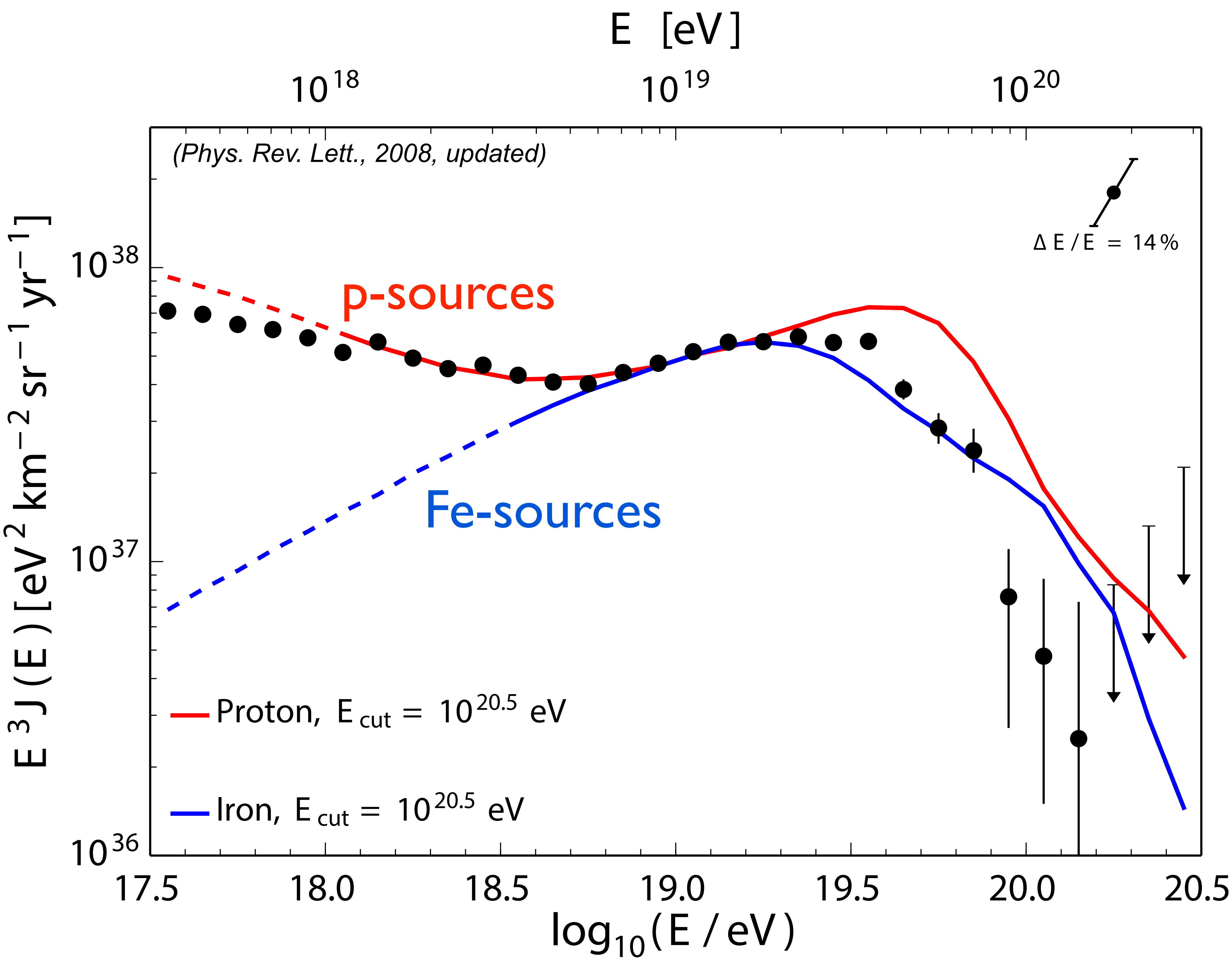


Good agreement between experiments
- some differences at the highest energies -

Auger Combined E-Spectrum (0°-80°)



Data compared to GZK-effect

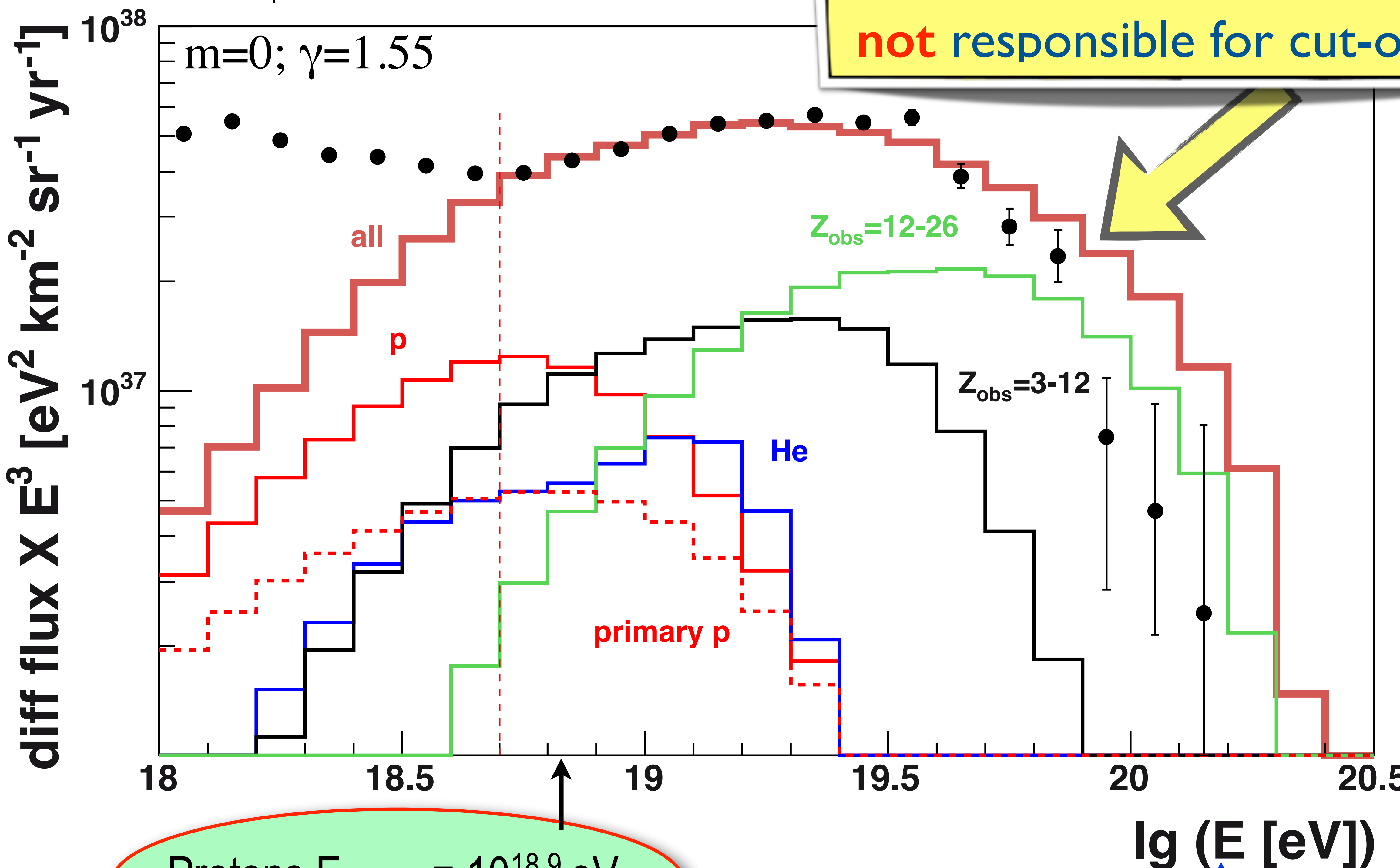


Limiting Energy of Sources (E_{max}~Z) + GZK

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!



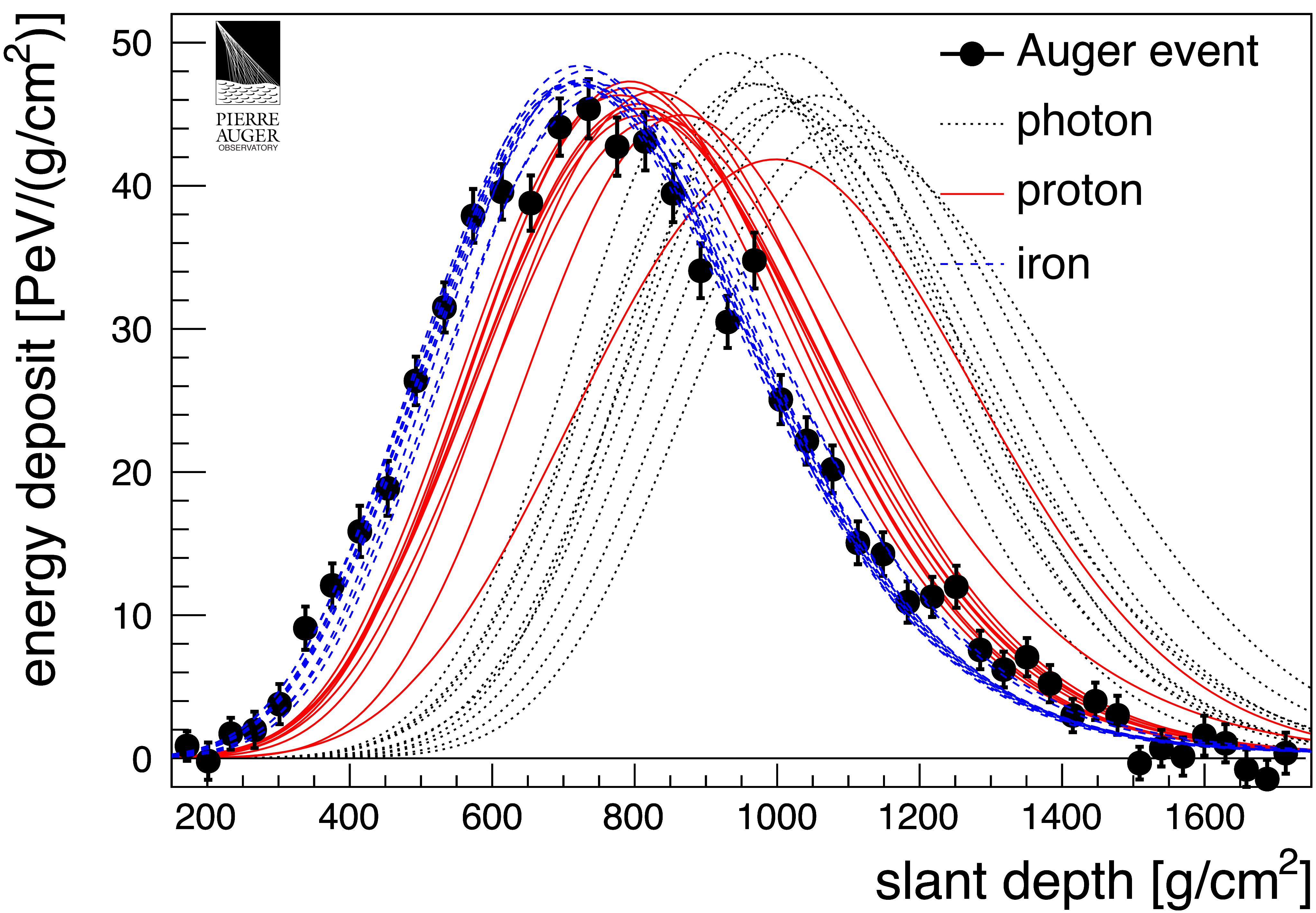
Protons $E_{max,p} = 10^{18.9}$ eV

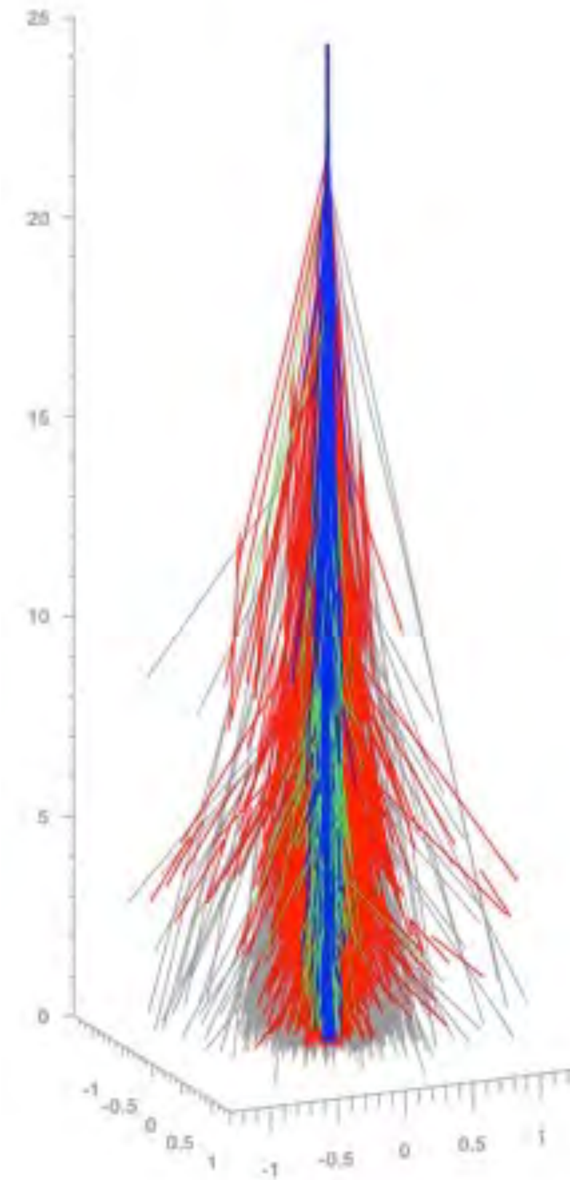
Iron $E_{max,\,Fe} = 26\ E_{max,p} = 10^{20.3}$ eV

Longitudinal Shower Development → Primary Mass

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

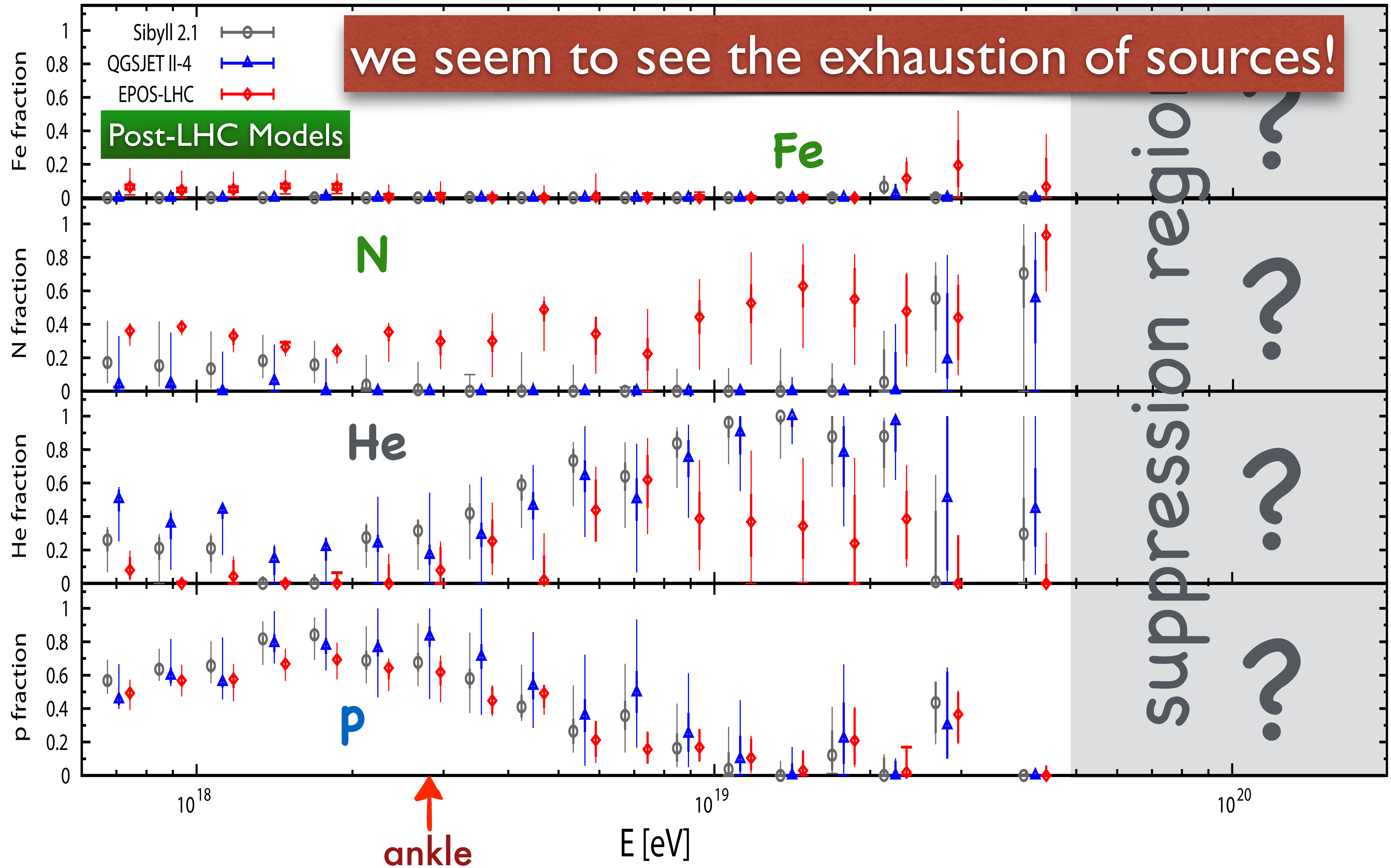
Example of a $3 \cdot 10^{19}$ eV EAS event in FD





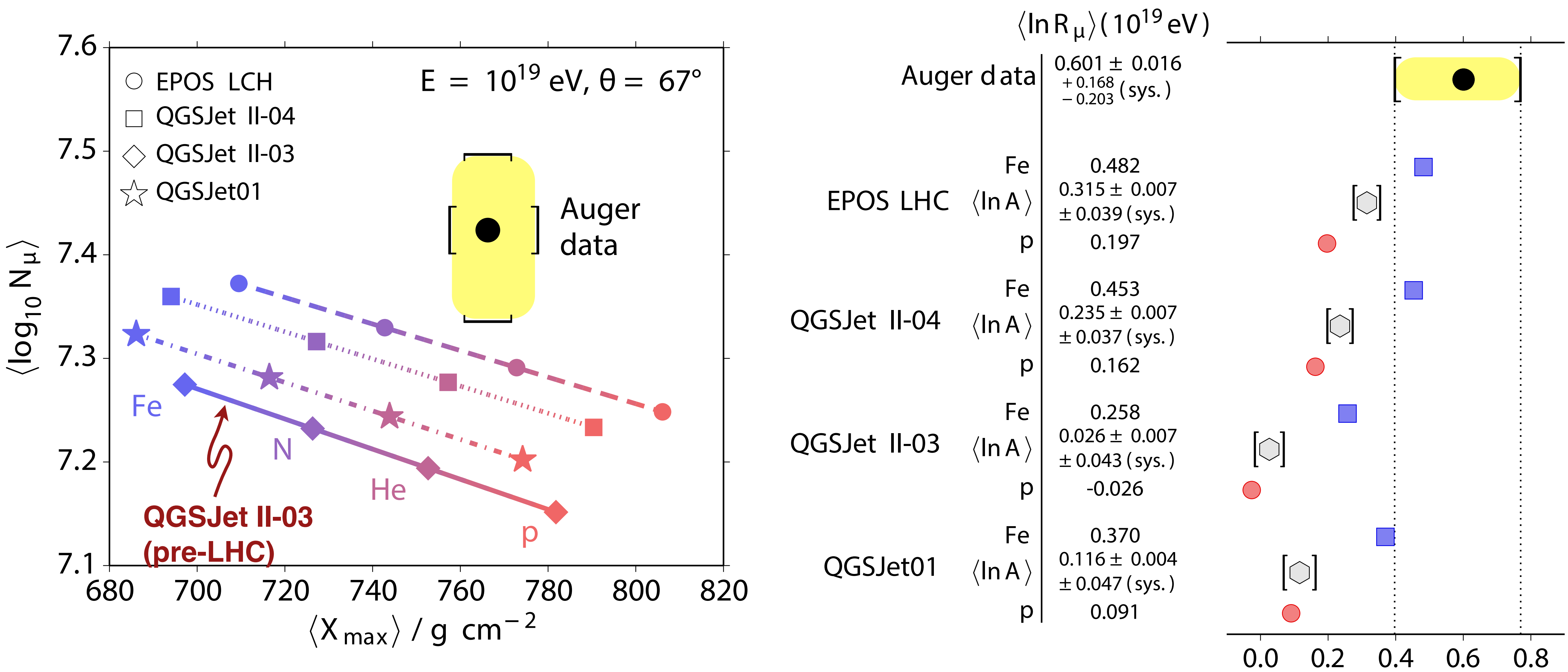
Decomposition of X_{max}-Distributions

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



Interaction Models lack Muons in EAS

Auger Collaboration, Phys. Rev. D 91, 032003 (2015); editors suggestion

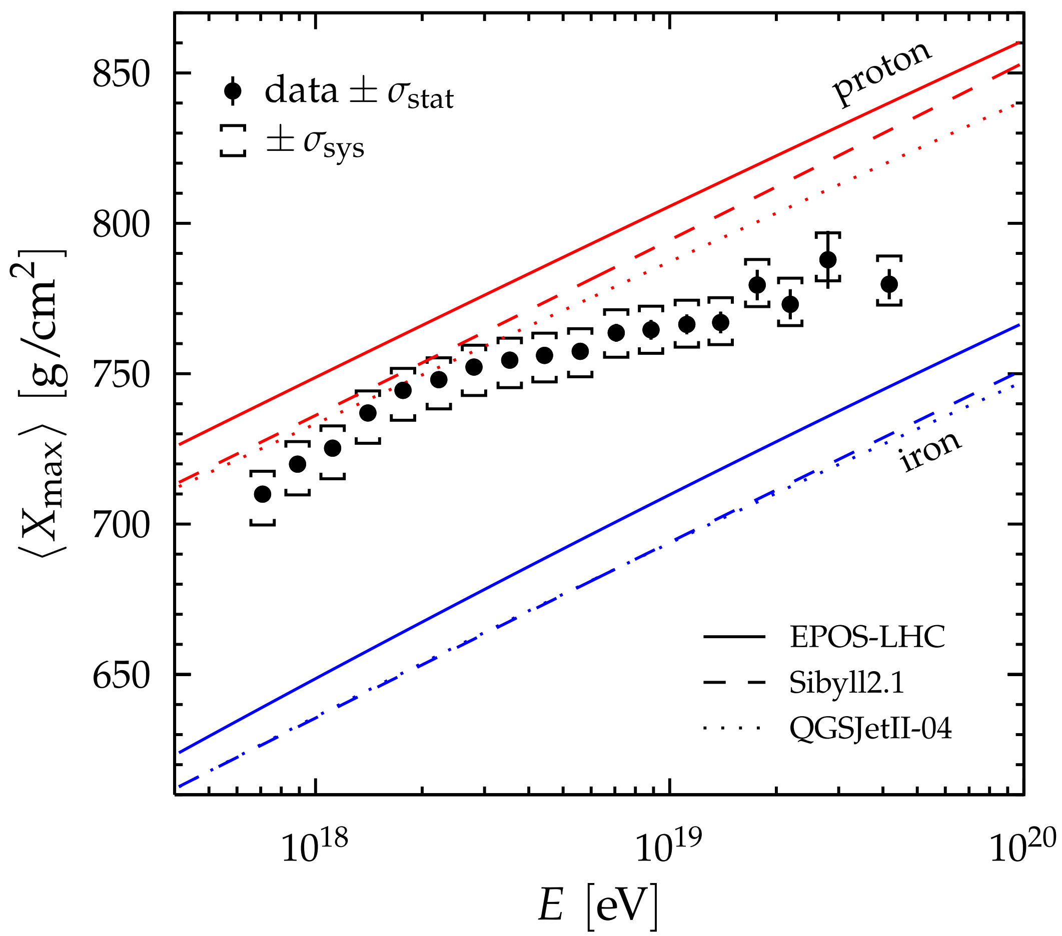


μ-deficit points to deficiencies of hadronic interaction models
LHC forward physics program highly relevant
joint efforts by people from both communities

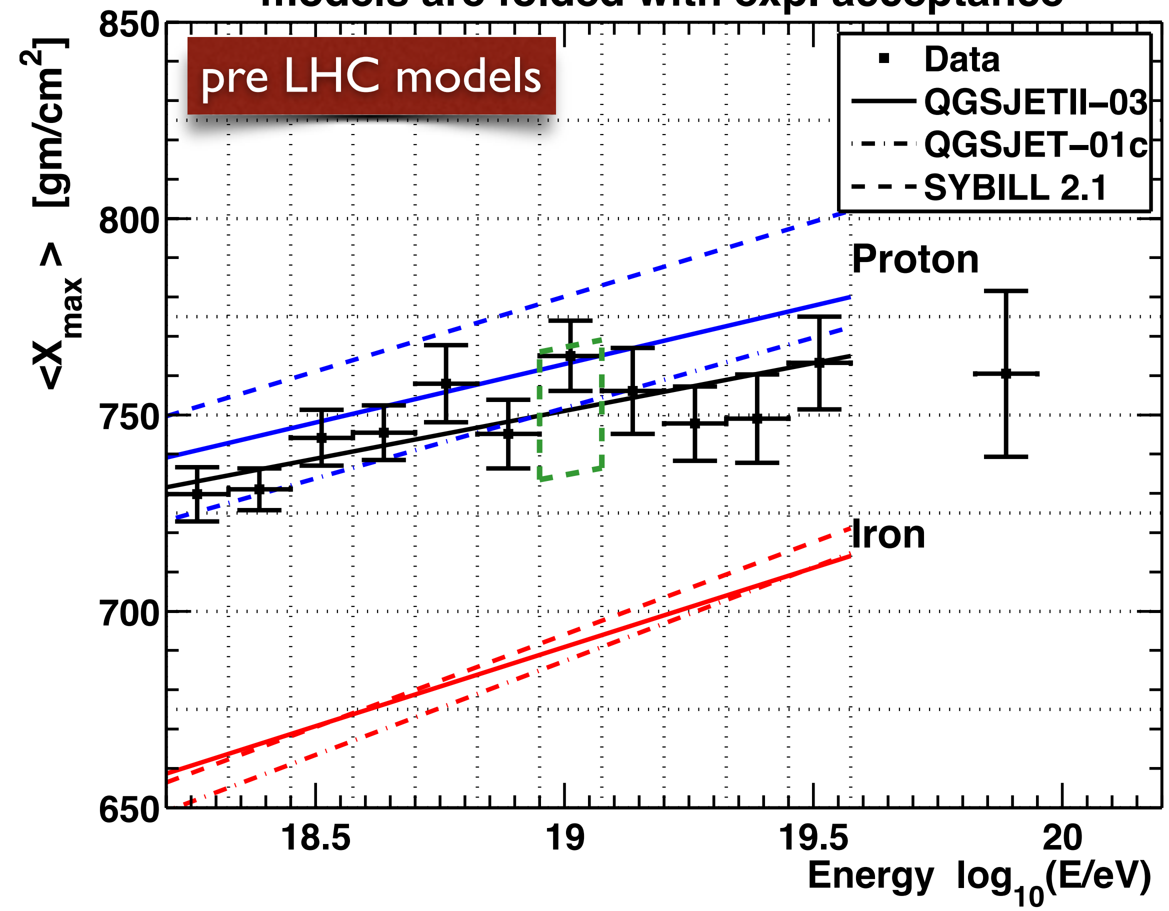
Auger - TA Comparison

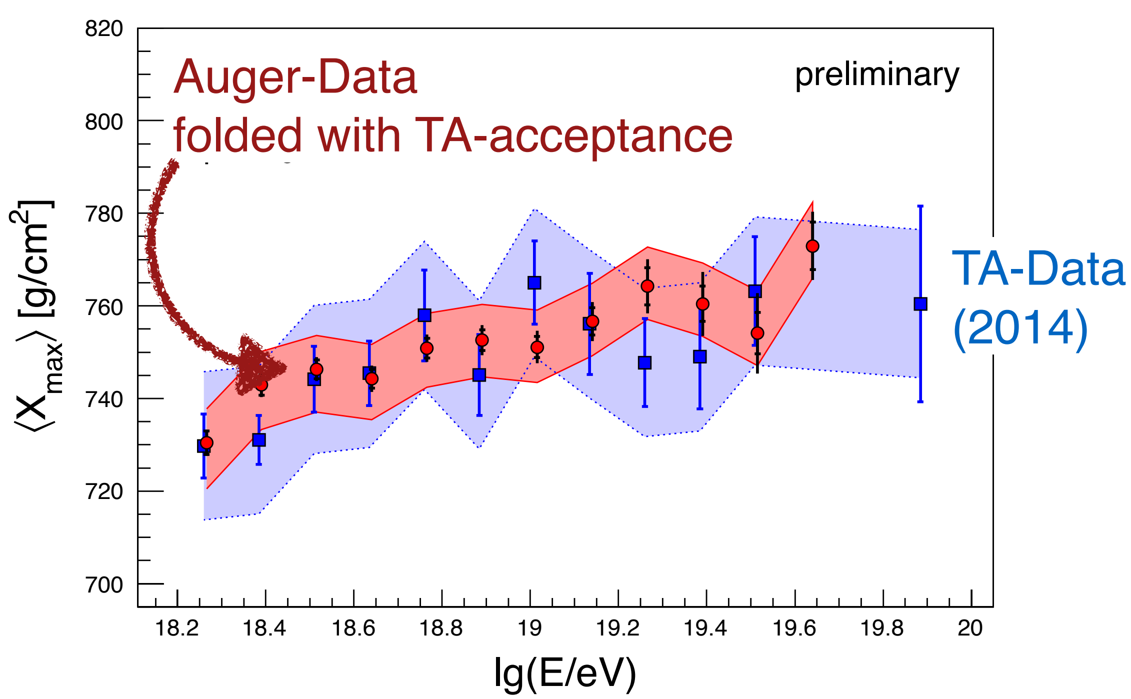
Joint Working Group (UHECR2014; arXiv:1503.07540)

bias-free due to anti-bias cuts



models are folded with exp. acceptance



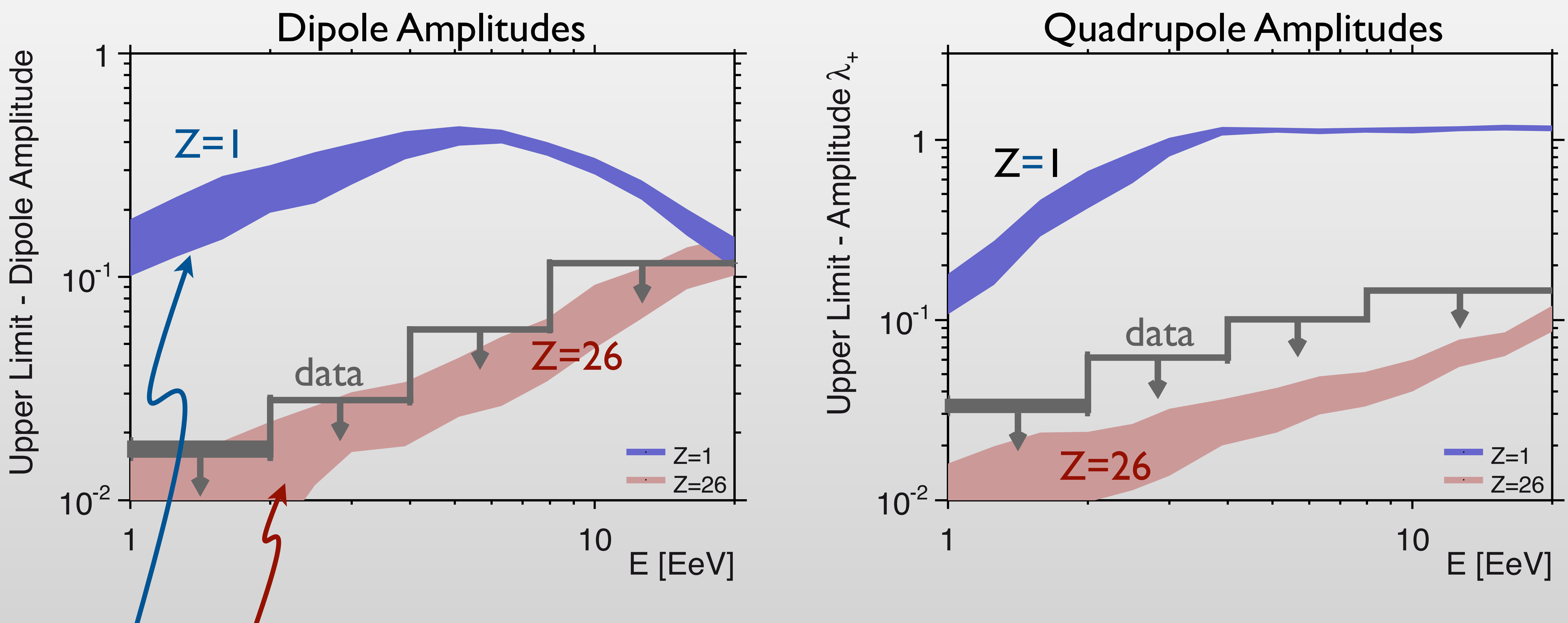


„Two data sets are in excellent agreement, even without accounting for the respective systematic uncertainties on the X_{max} scale.“

…and surely both TA and Auger agree on seeing a p (He) dominated composition in the ankle range

Large Scale Anisotropies

Auger Collaboration: ApJL, 762, L13 (2012), ApJS 203,34 (2012)



expectations from stationary galactic sources distributed in the disk

light CR component seen at 10^{18} eV cannot originate from stationary sources in the galactic disk

Large Scale Anisotropies

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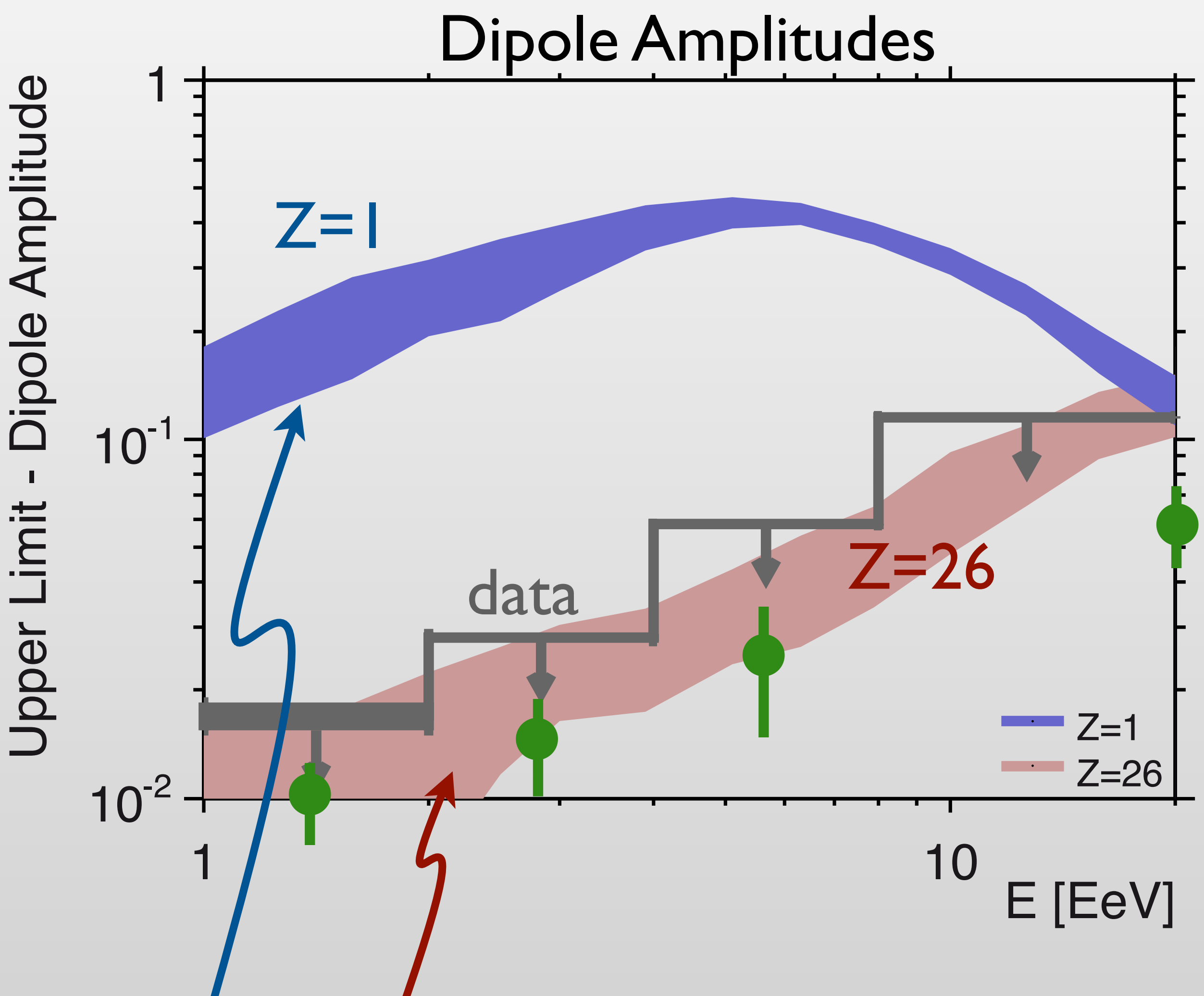


Auger Collaboration: ApJ 802:111 (2015)

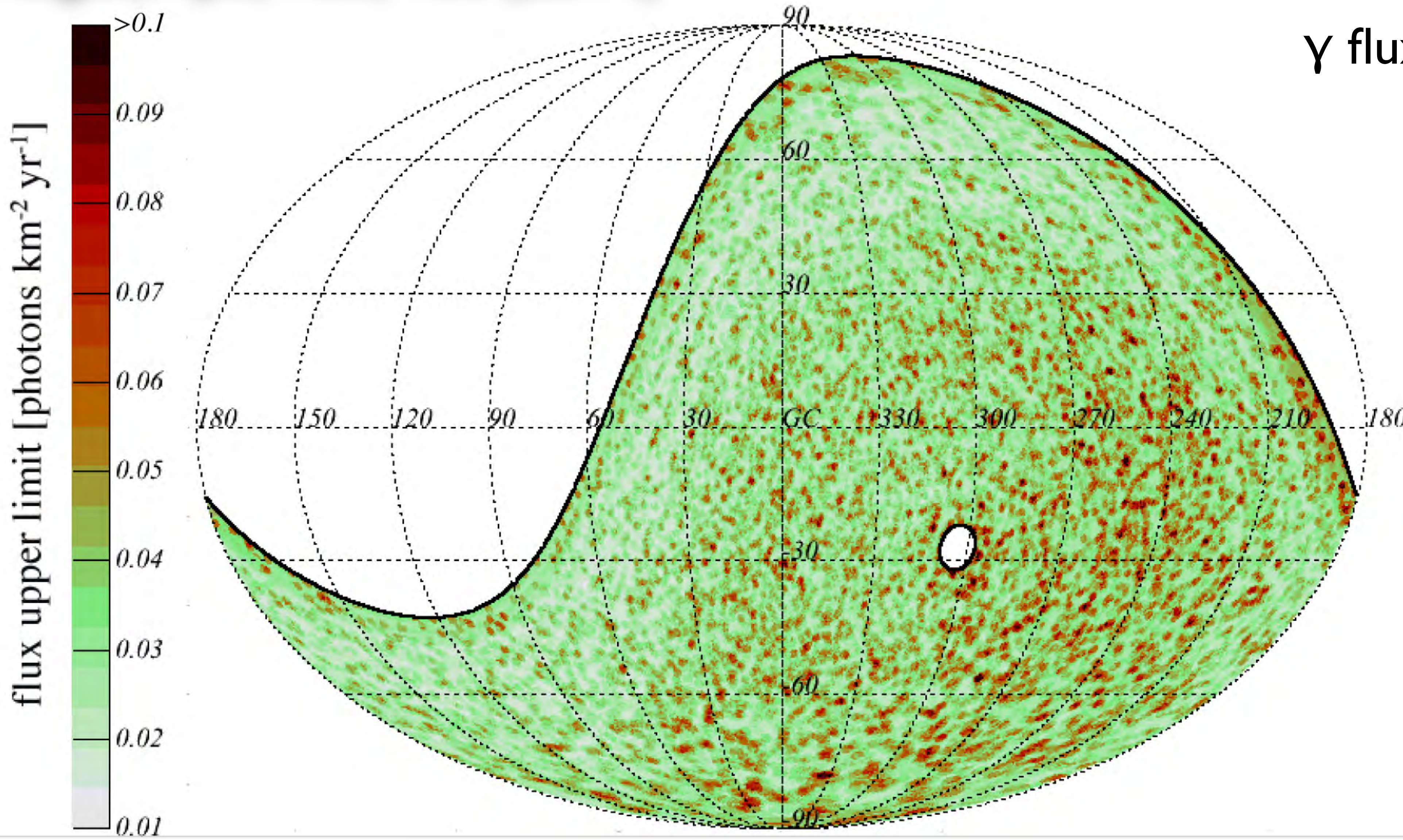
Largest departure from isotropy:
E > 8EeV: $r^{\alpha}=(4.4\pm1)\cdot10^{-2}$;
$p< 6.4\cdot10^{-5}$ isotropic

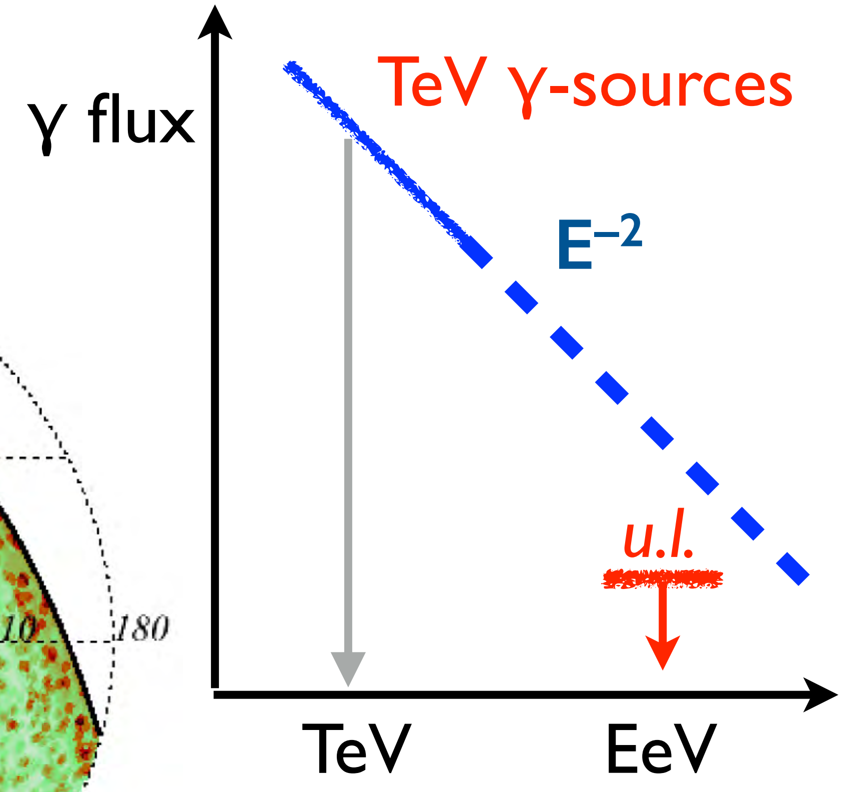
expectations from stationary galactic sources distributed in the disk

light CR component seen at 10^{18} eV cannot originate from stationary sources in the galactic disk

Search for EeV γ-point sources

Auger, ApJ, 789, 160 (2014)



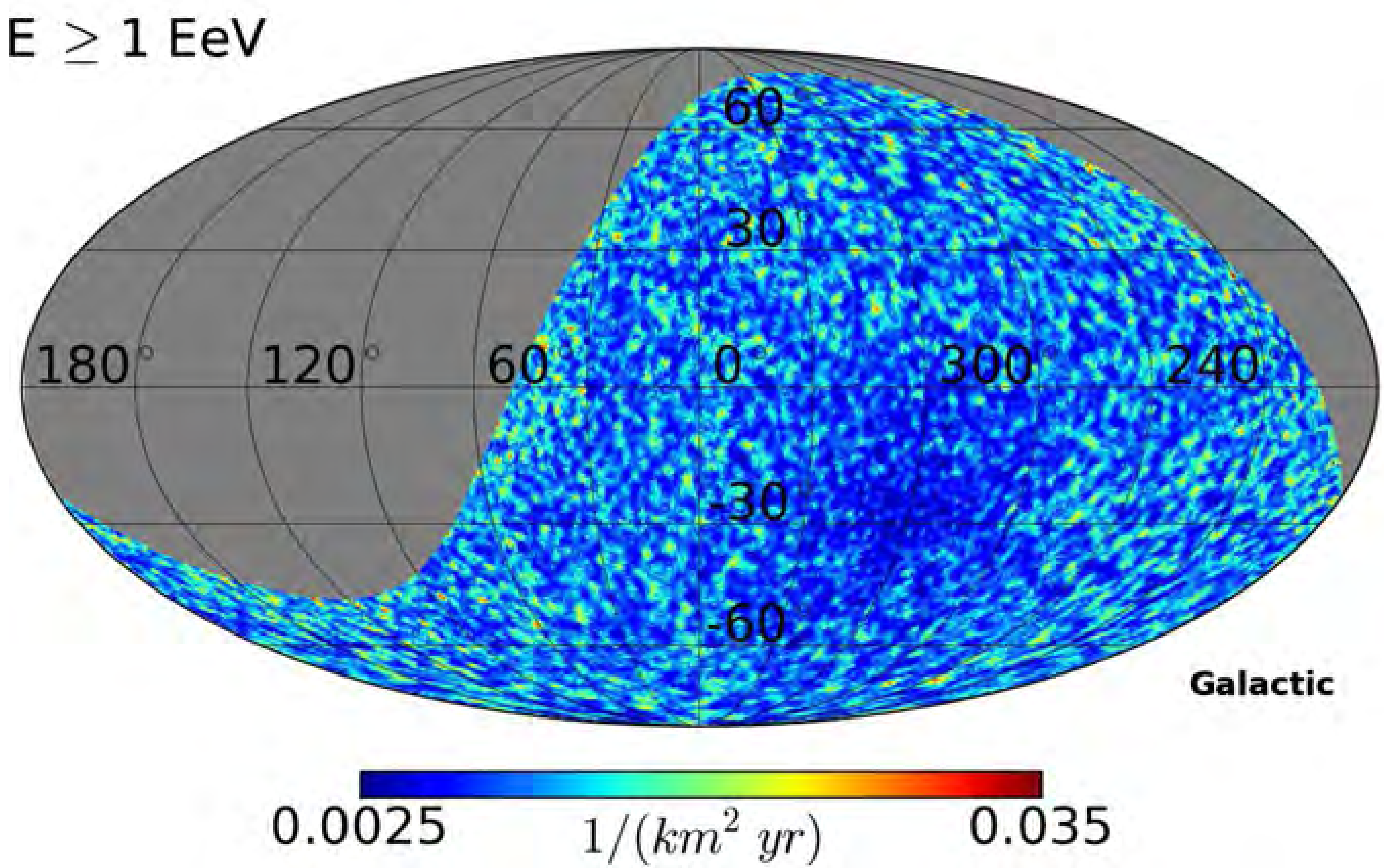


Energy flux of 0.25 eV/cm^{2}s would yield a 5σ excess (assuming E^{-2} spectr.)
Note, some Galactic TeV sources exceed 1 eV/cm^{2}s !

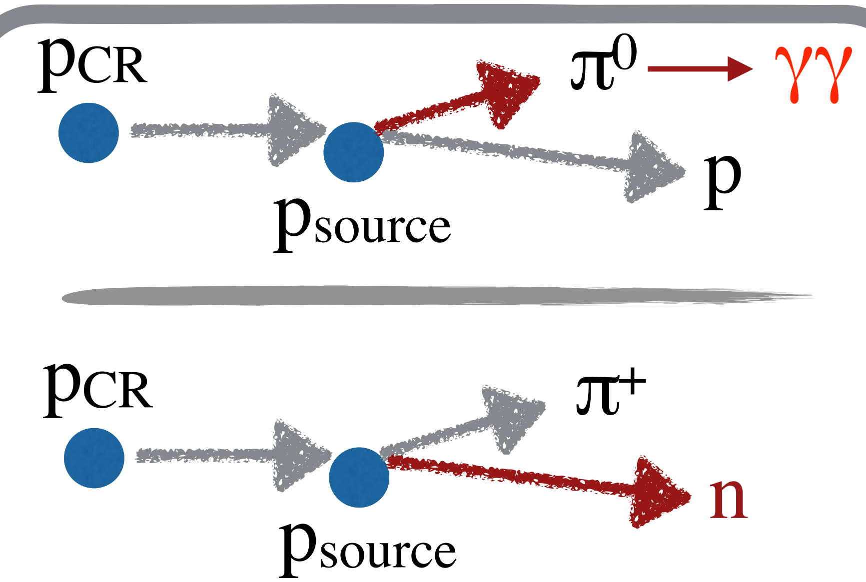
⇒ Galactic TeV γ-sources don't stick out to EeV energies

Search for EeV neutron-point sources

Auger, ApJ, 760:149 (2012), ApJ 789:L34(2014)



If TeV γ-flux of 1 eV/cm²s would originate from π^0 decay, neutron flux would even exceed that value:



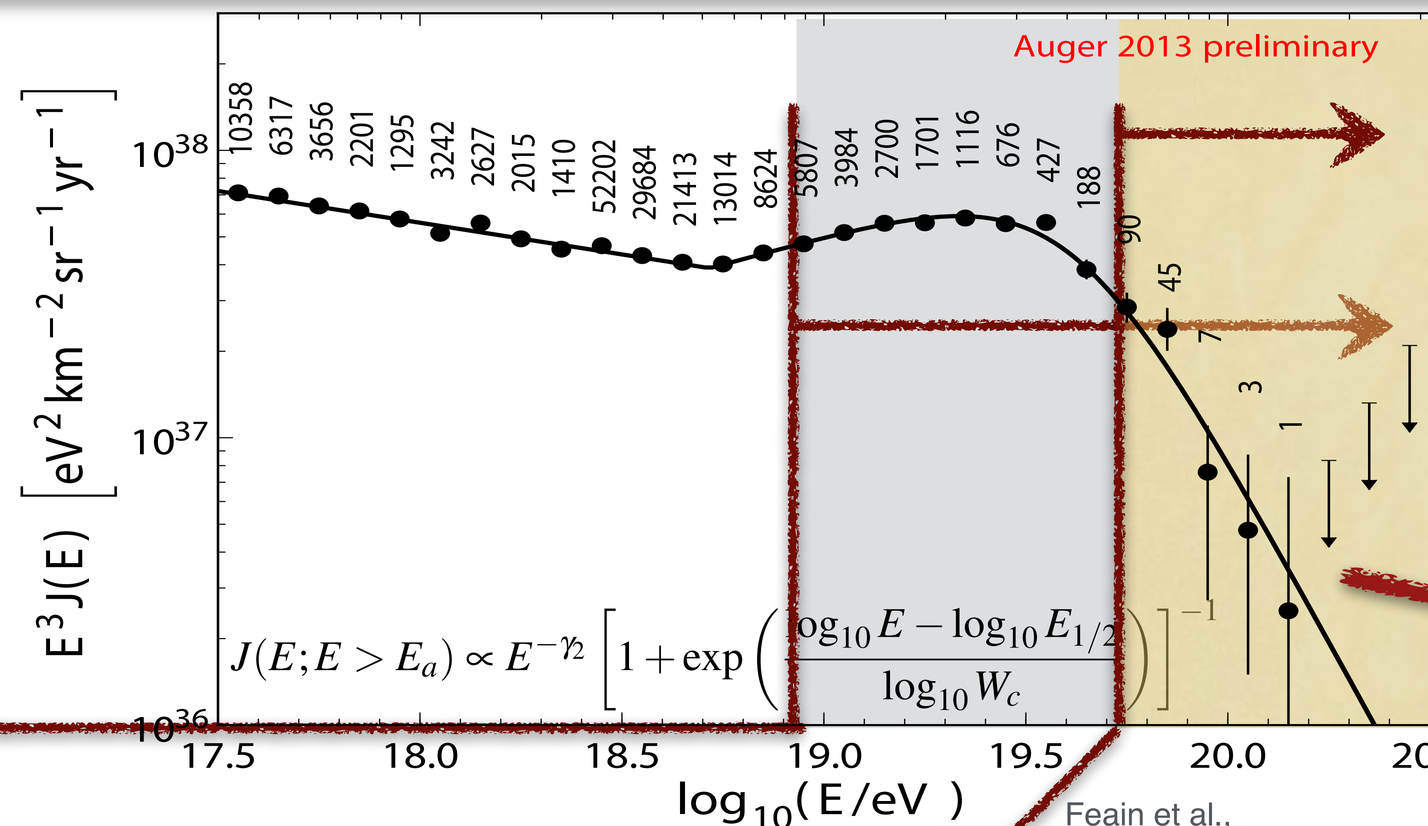
Charge exchange interaction

$$\tau_{\rm decay} = 9.2\ {\rm kpc} \times E({\rm EeV})$$

Energy flux of neutrons F_n <0 .083 eV/cm²s (assuming E^{-2} spectr.)
None of HESS source candidates shows any significance of n-emission!

⇒ Galactic TeV γ-sources don't stick out to EeV energies

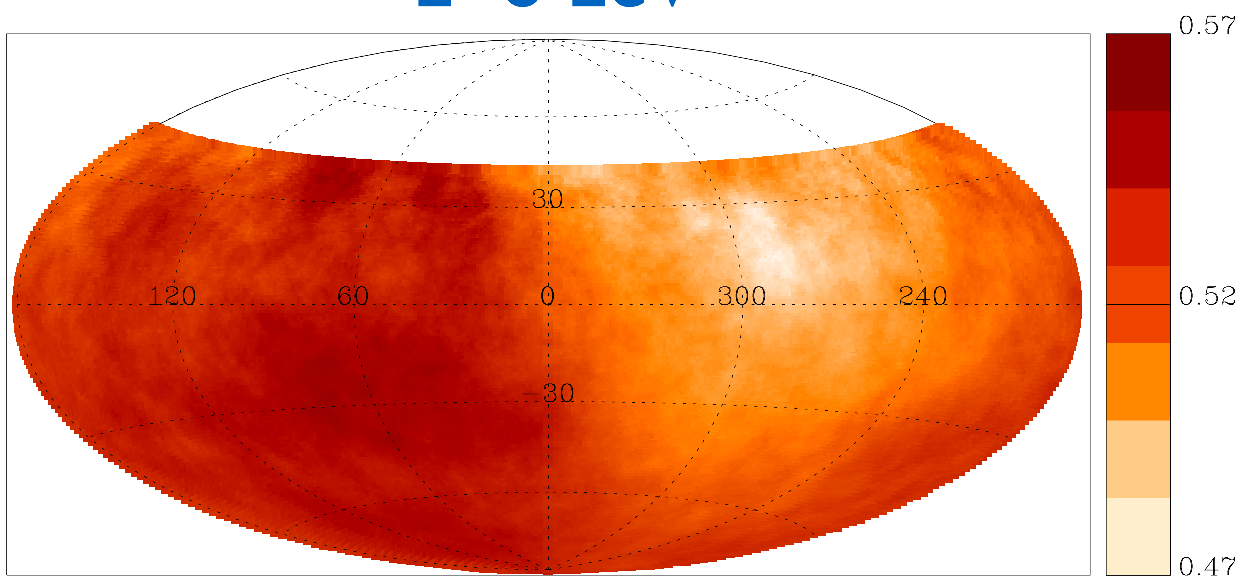
UHECR Sky surprisingly isotropic



hot/warm spot

dipole like anisotropy

E>8 EeV

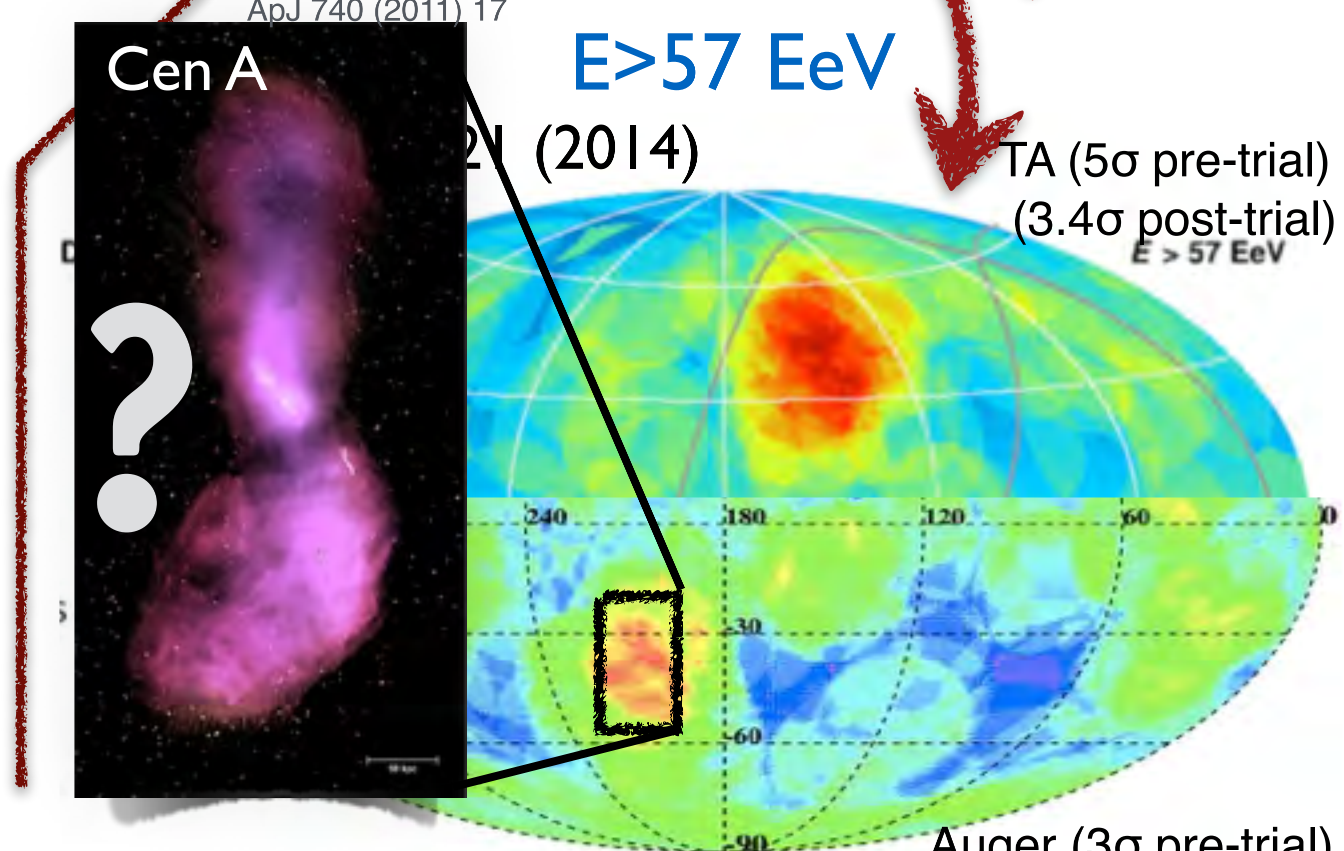


Auger Collaboration ApJ 802:111 (2015)

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

Feain et al.,
ApJ 740 (2011) 17

E>57 EeV



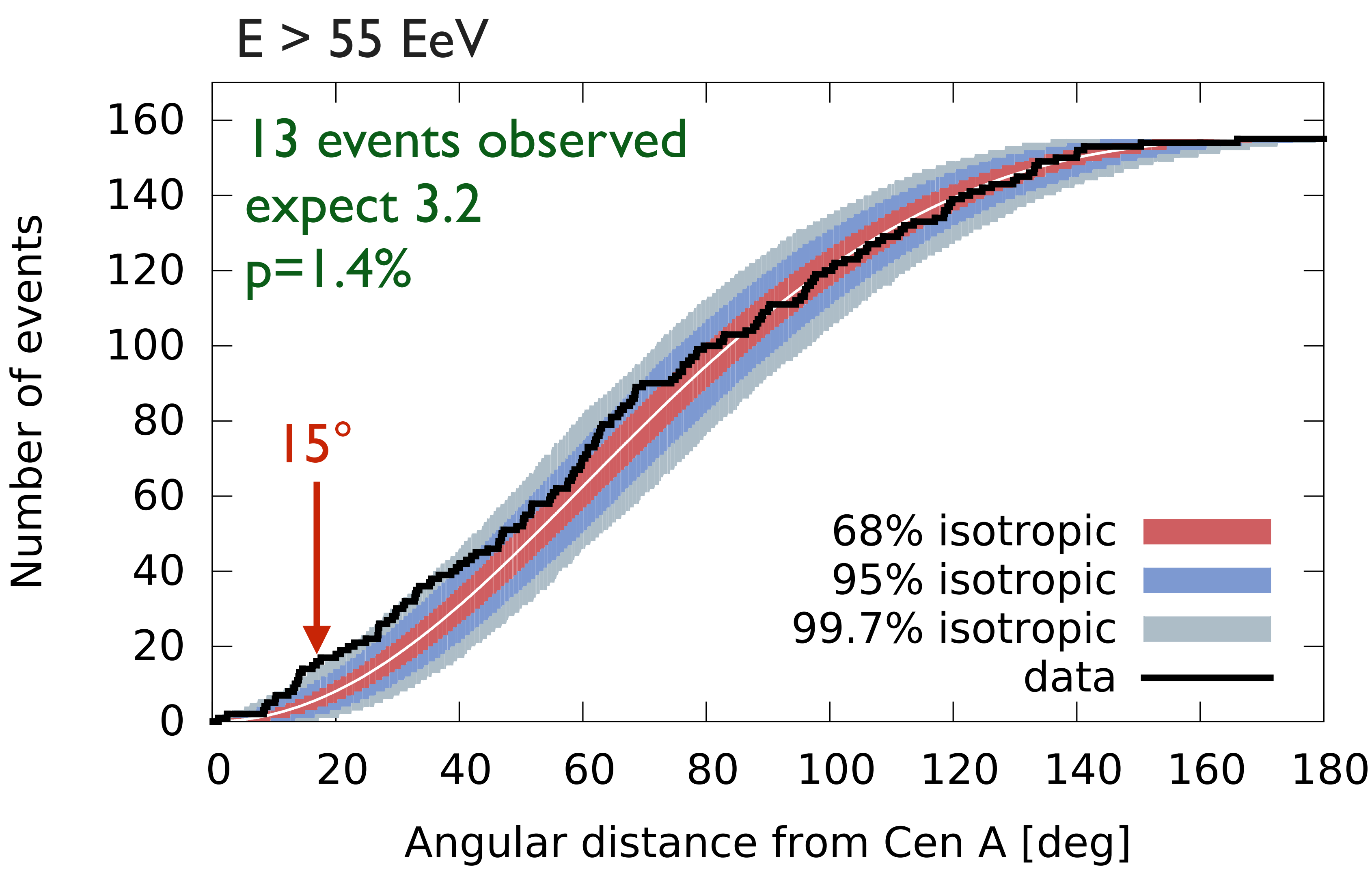
TA (5σ pre-trial)
(3.4σ post-trial)

Auger (3σ pre-trial)

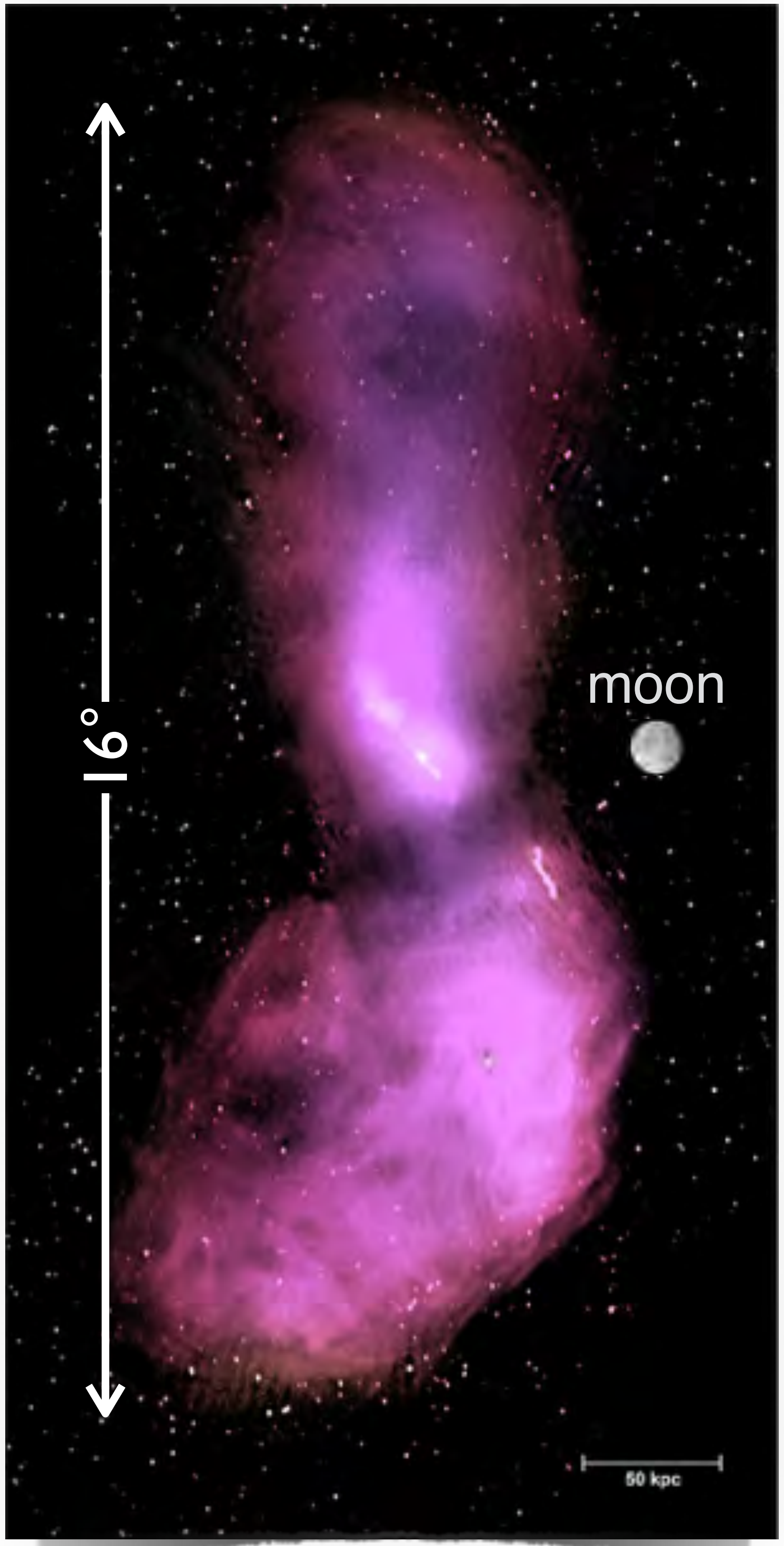
Auger: APP 34(2010) 314

Weak excess of events around Cen A

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

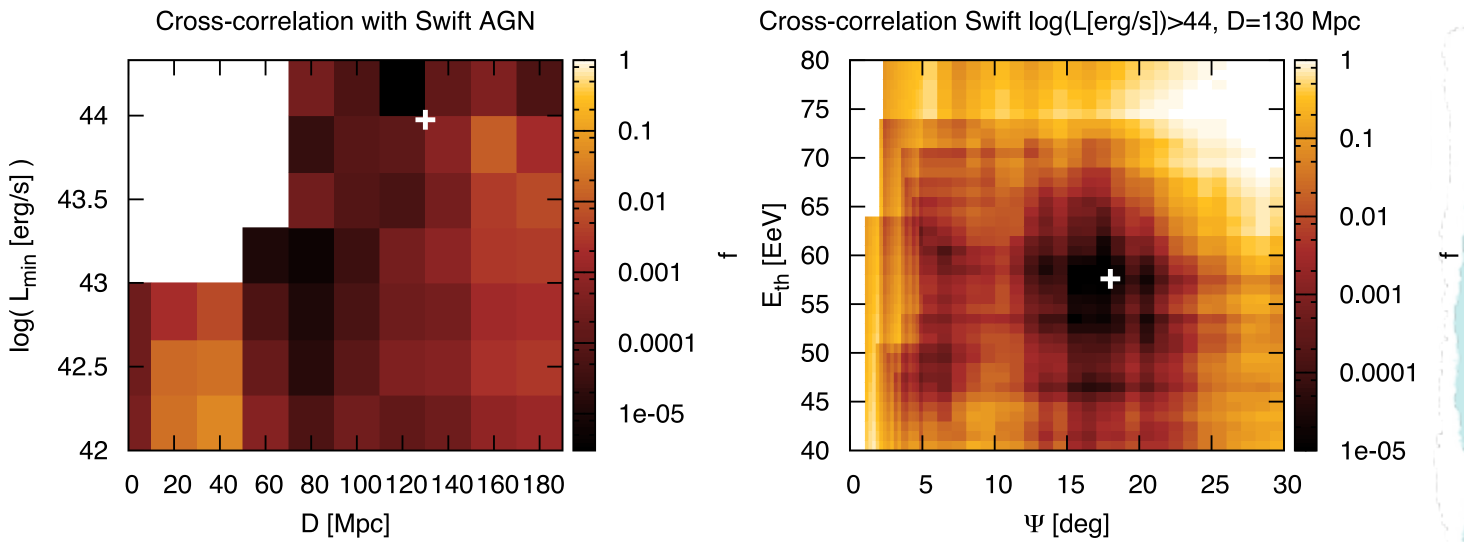


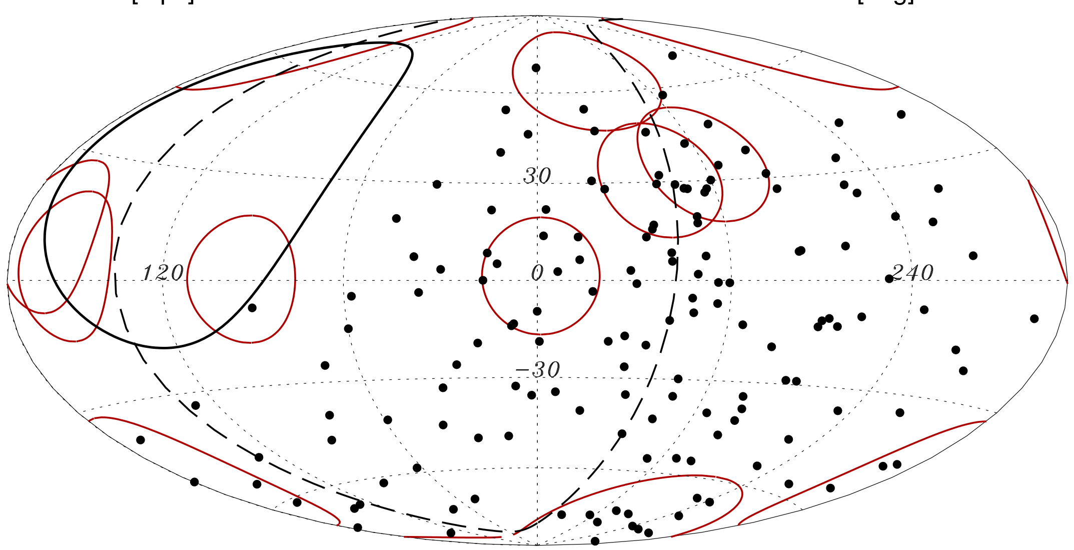
Auger Collaboration: ApJ 802:111 (2015)



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
arXiv: 1411.6111

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 small deviation from overall isotropic sky

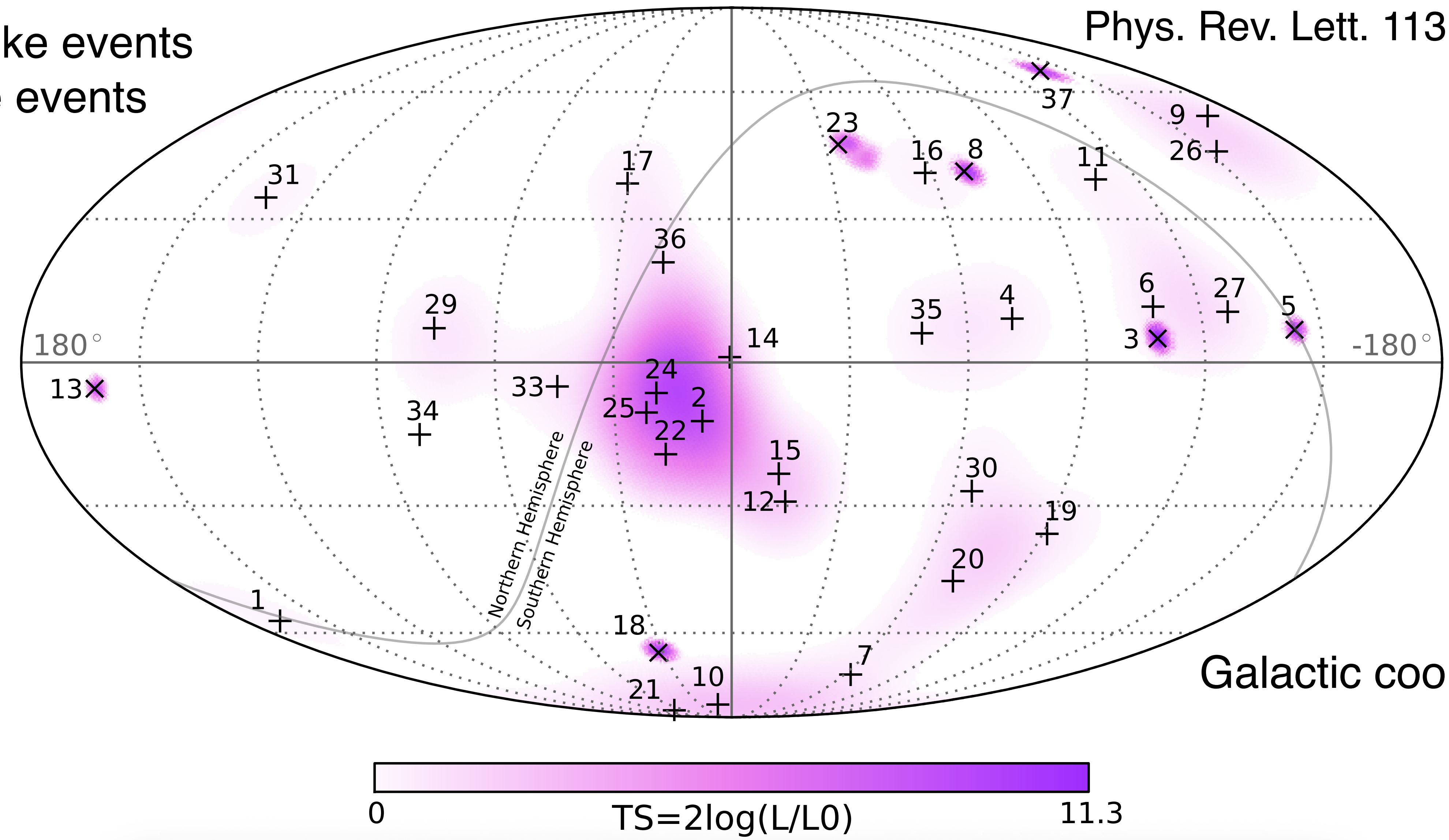
➪ **either large deflections by B-fields, e.g. due to heavy primaries**
(supported by Auger composition studies)

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

A look to the PeV Neutrino Sky

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

+: Shower like events
x: Track like events



Galactic coordinates

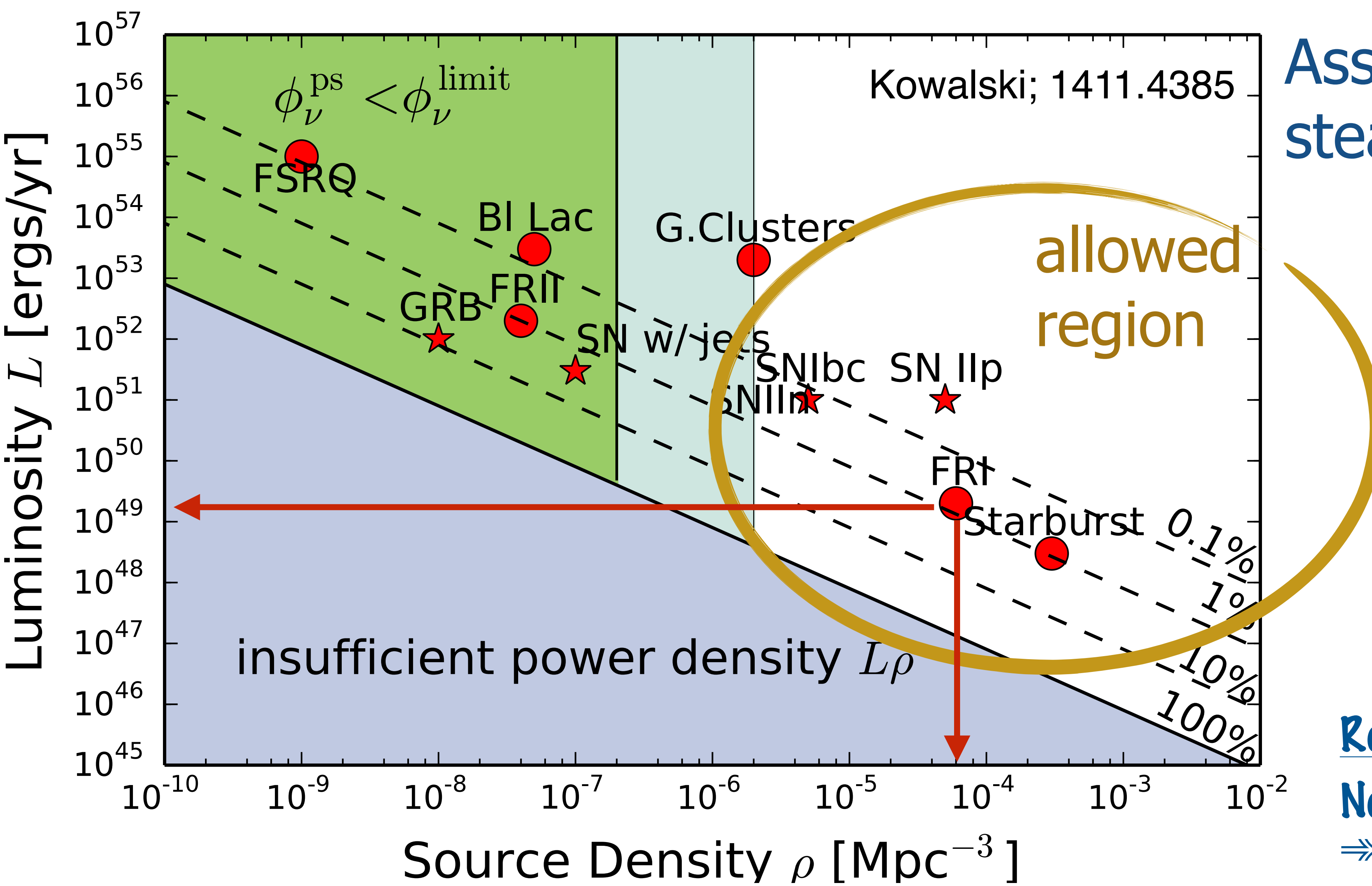
No significant clustering seen (p=84%)

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

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



Assumption:
steady point sources

Remark:

Neutrinos can come from far away
⇛ sky may remain isotropic

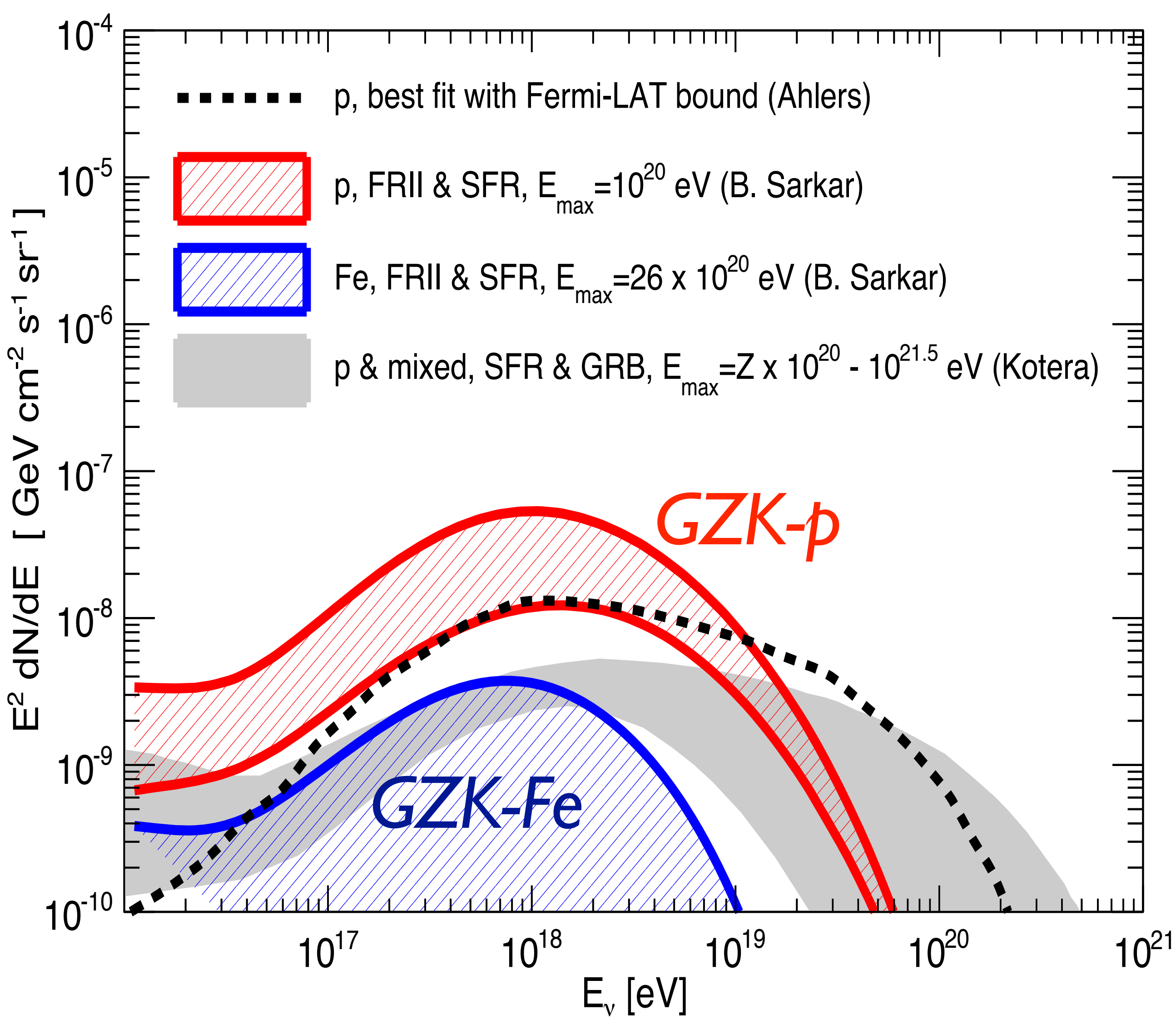
UHECRs come from within GZK sphere
⇛ limited number of sources
sky needs to become anisotropic

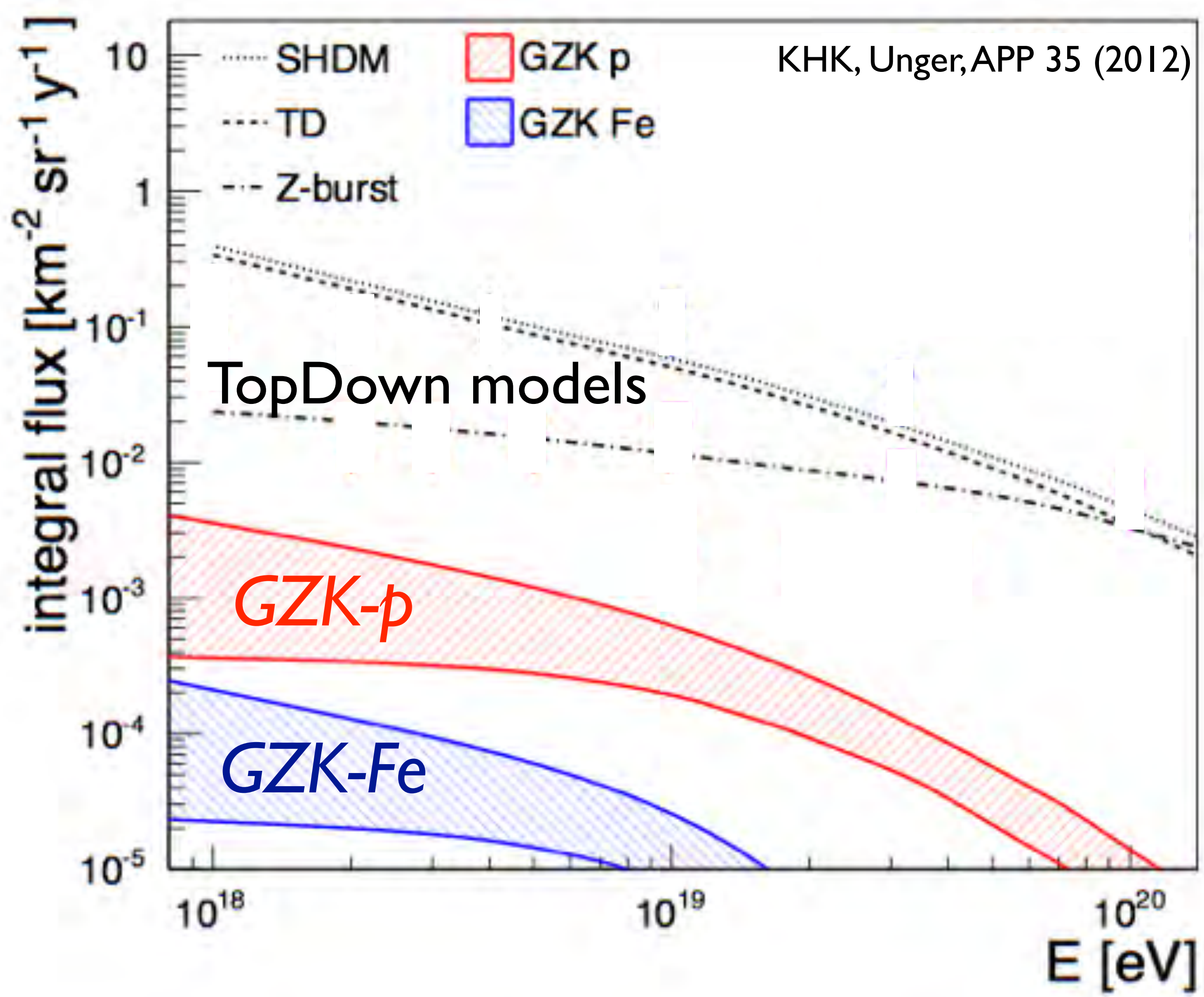
Density & Luminosity compare well to UHECRs !

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

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

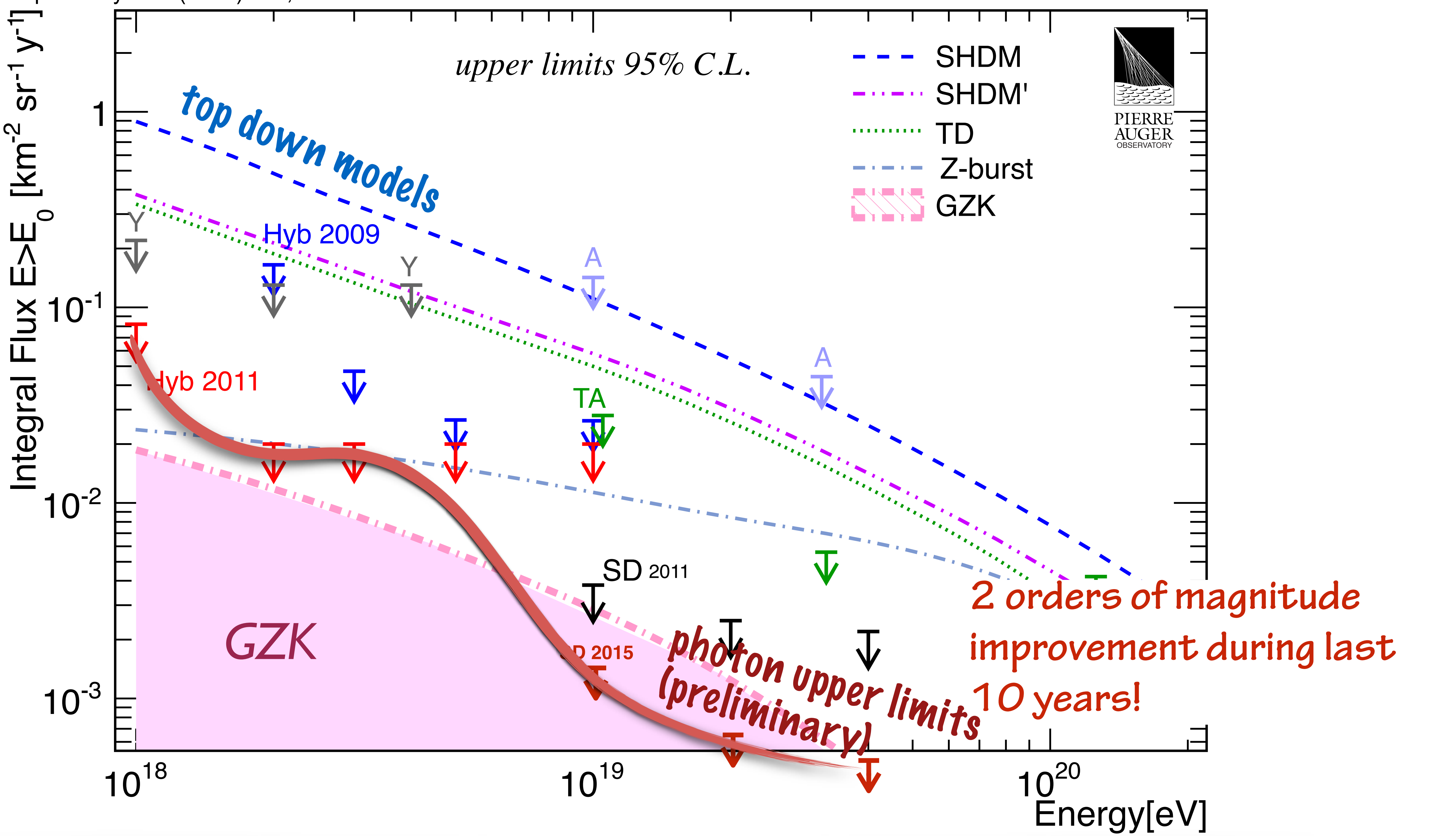
$$\to n + \pi^+ \to \nu_{\text{EeV}} \qquad \to p + \pi^0 \to \gamma_{\text{EeV}}$$





GZK photons get constrained as well

Update from: Astropart. Phys. 31 (2009) 399; ICRC2015

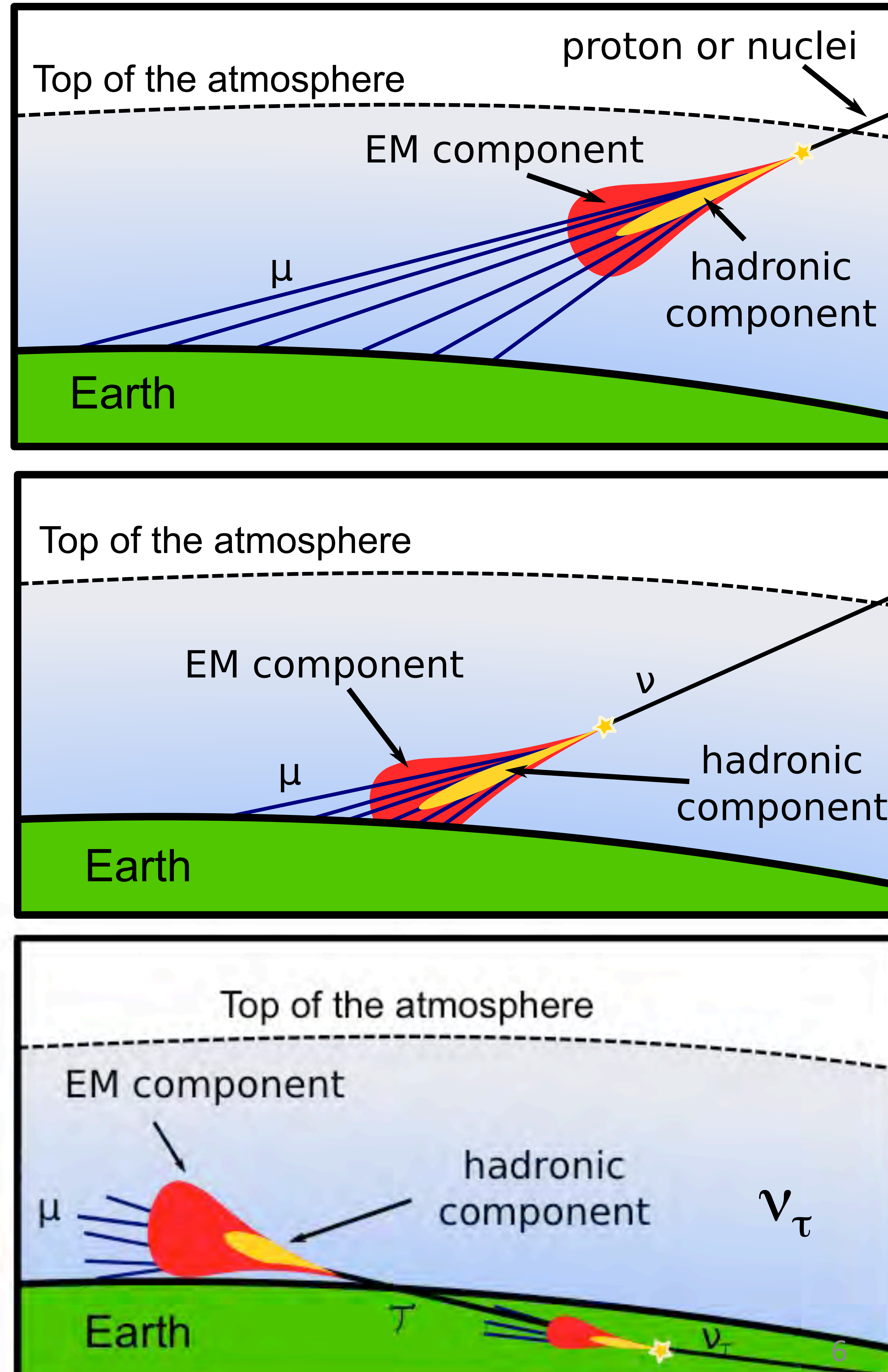


Photon upper limits rule out Top-Down Models and start to constrain GZK-expectations

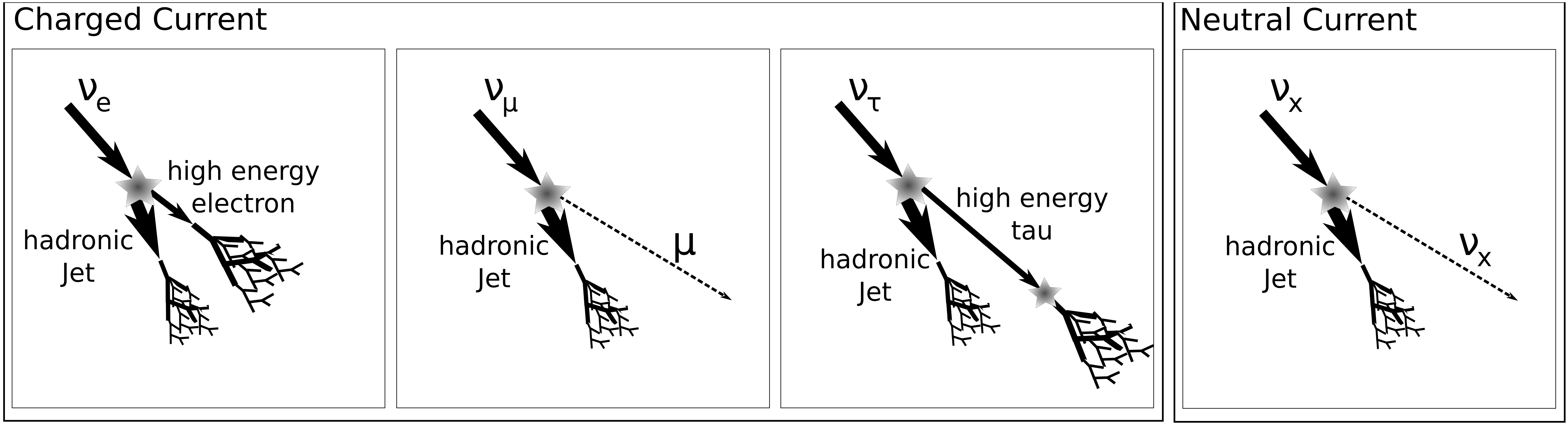
Search for EeV Neutrinos in inclined showers

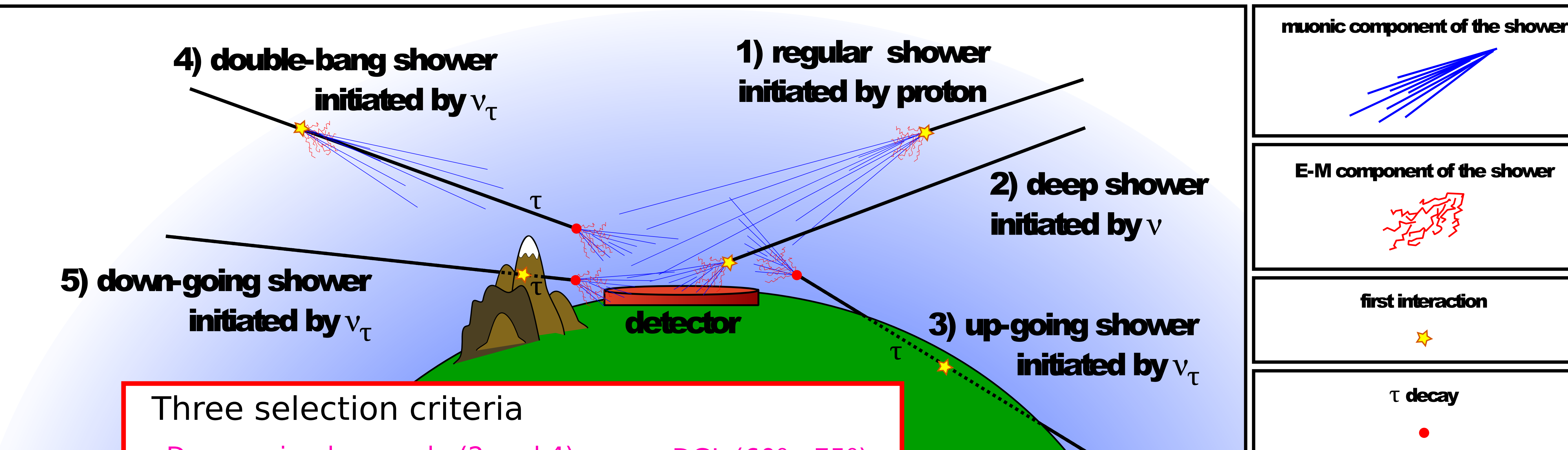
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component



Sensitivity to all ν flavors and channels





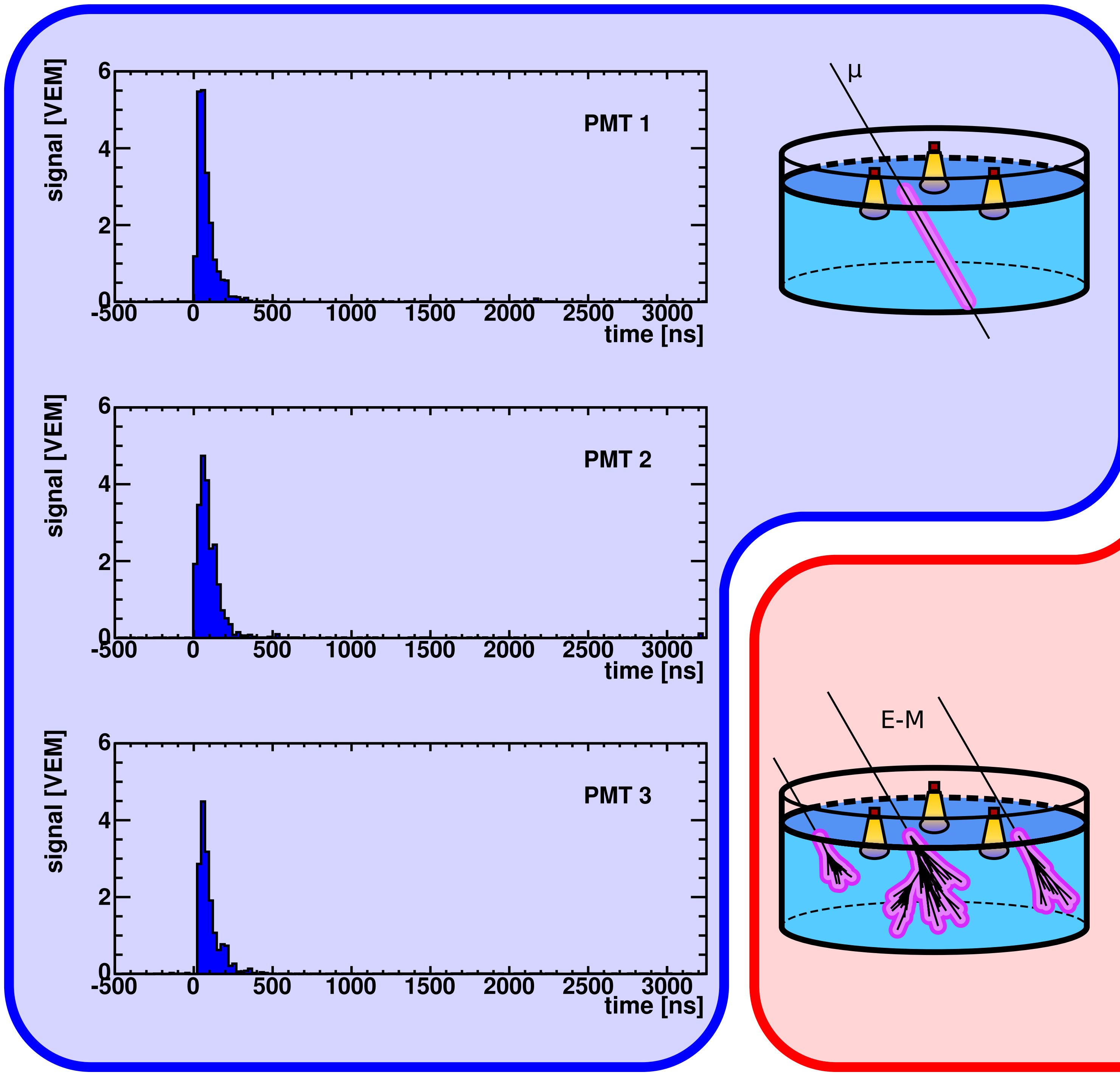
Three selection criteria

- 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)

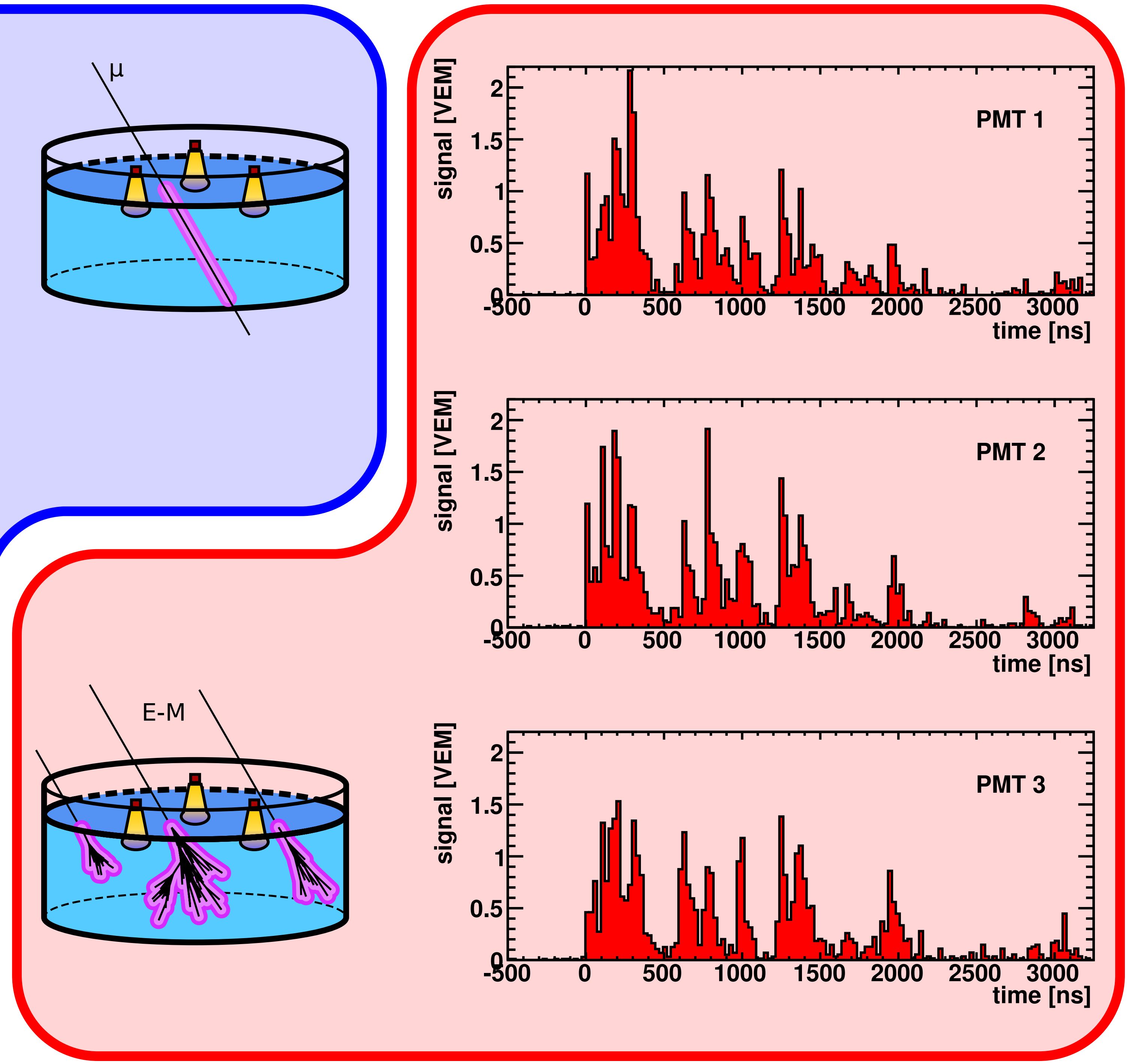
Identifying νs in surface detector data

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

Muonic shower front: narrow signals



EM shower front: broad signals



Identifying νs in surface detector data

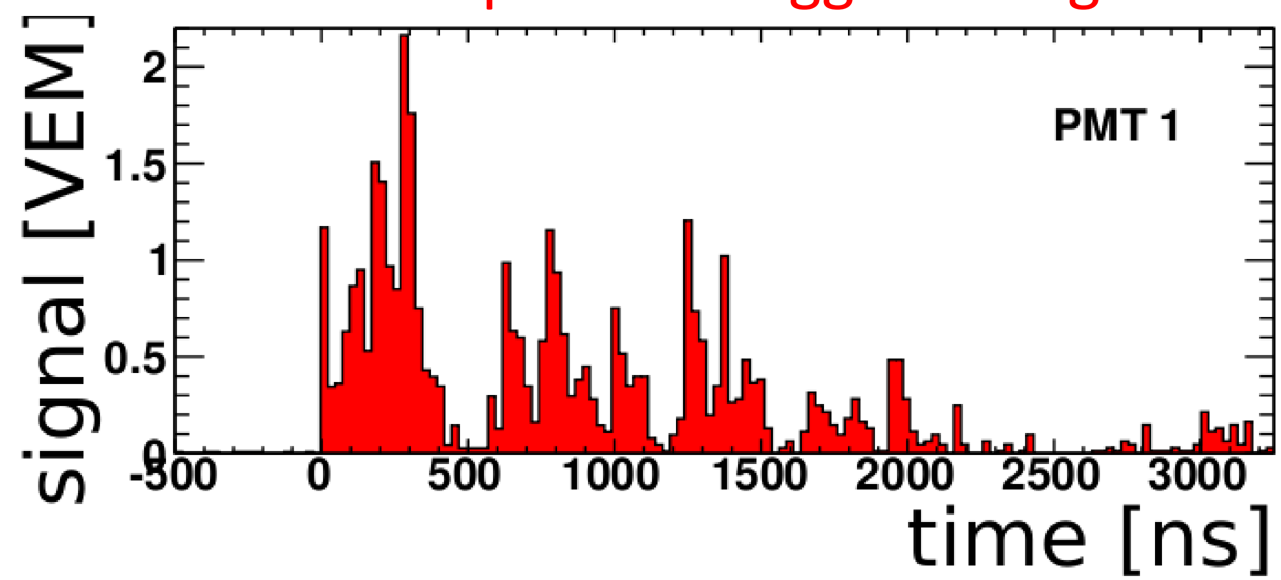
From the observational point of view, signals extended in time:

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

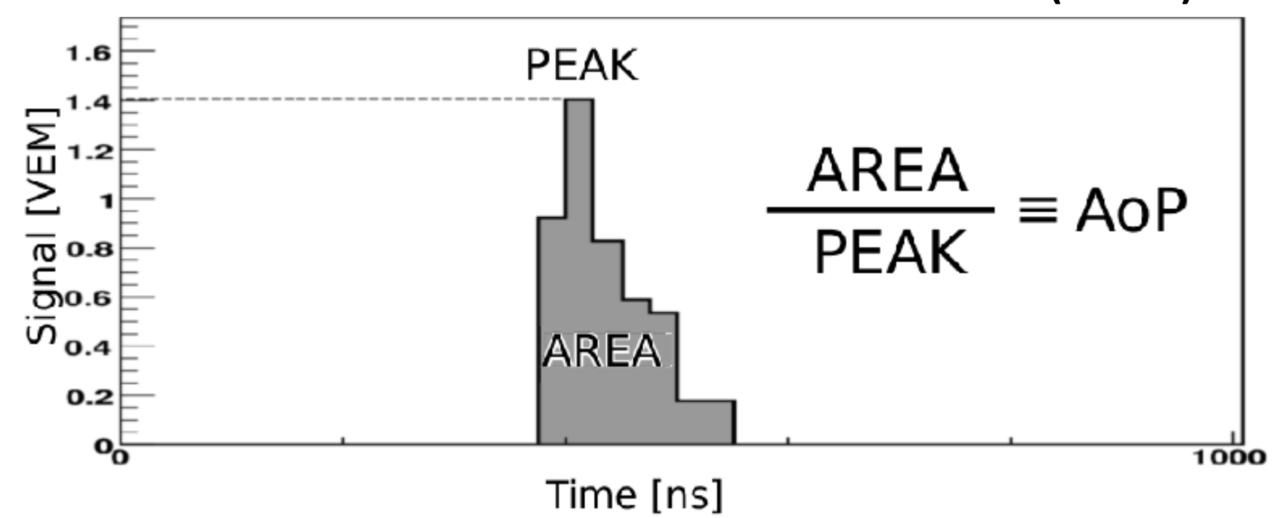
and/or

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

Trace example: ToT trigger & large AoP



Definition of Area-over-Peak (AoP)

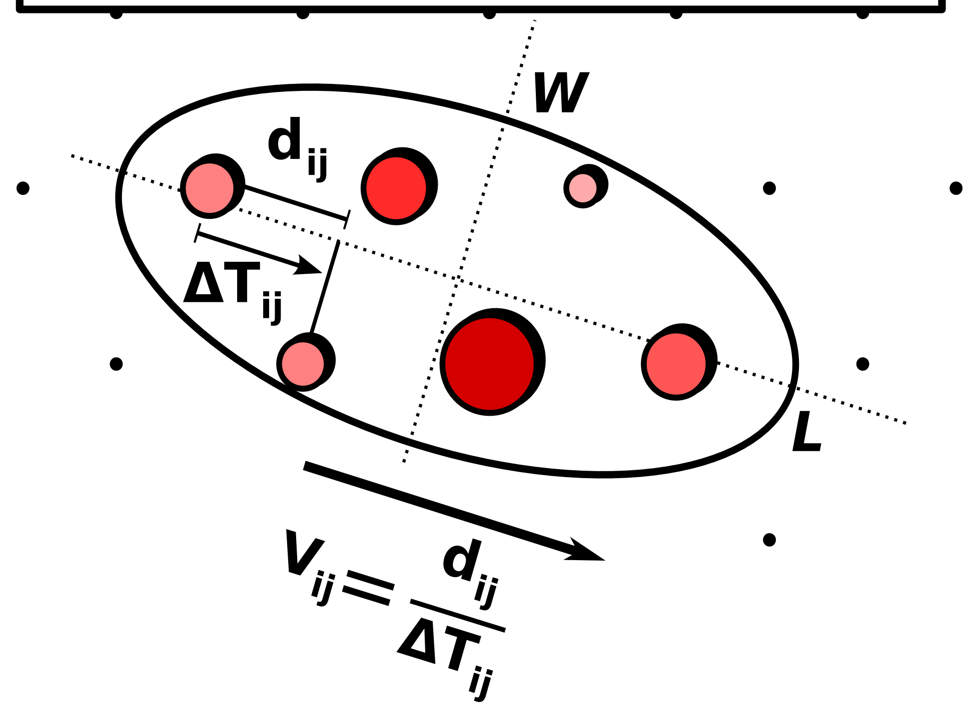


$$\frac{\text{AREA}}{\text{PEAK}} \equiv \text{AoP}$$

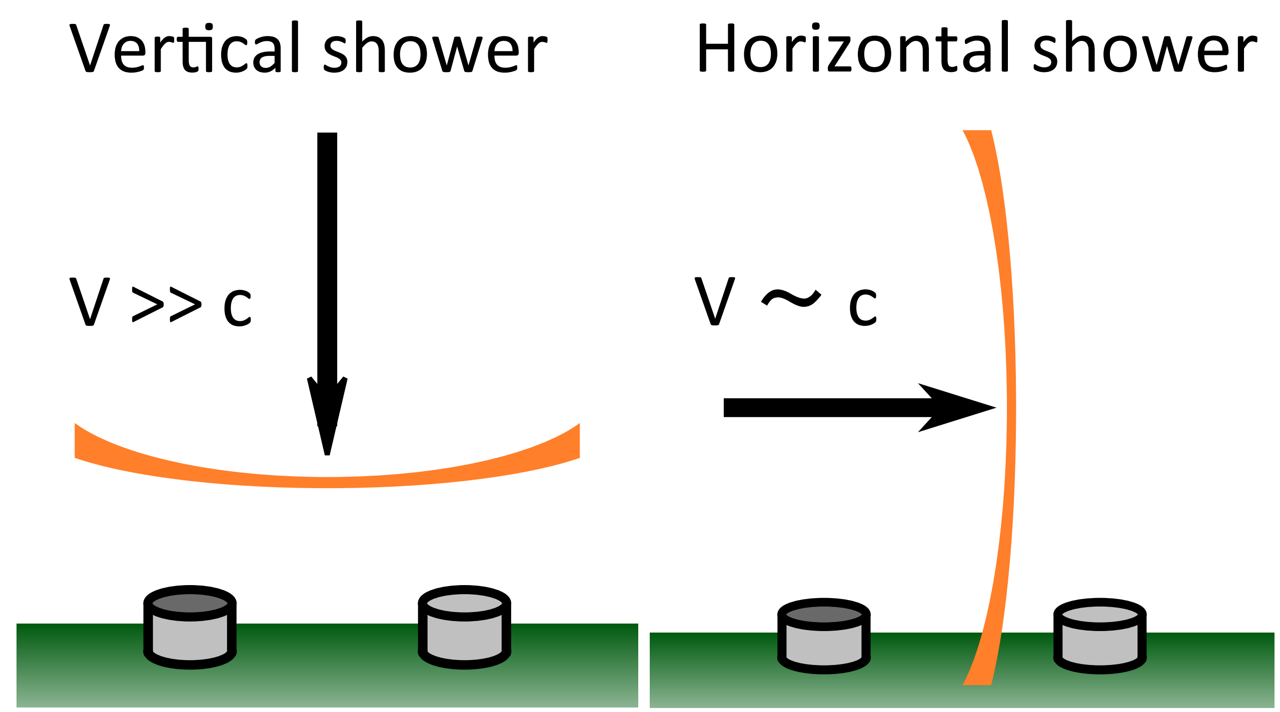
Searching for neutrinos ⇒
Searching for inclined showers with stations with ToT triggers and/or large AoP

Selection of inclined showers:

(1) Elongated footprint



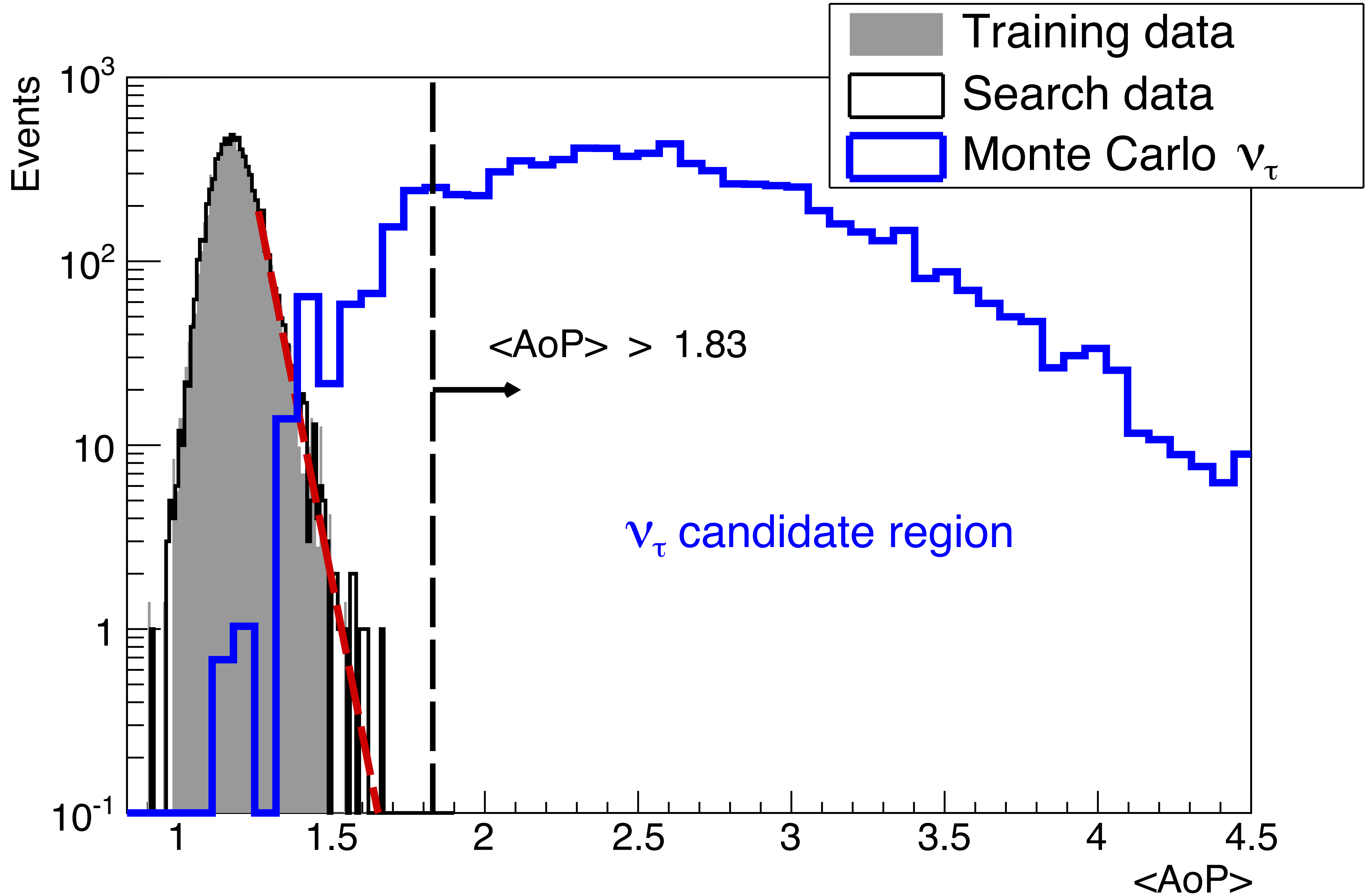
(2) Apparent velocity V of propagation of shower front at ground along major axis L



(3) Reconstructed θ

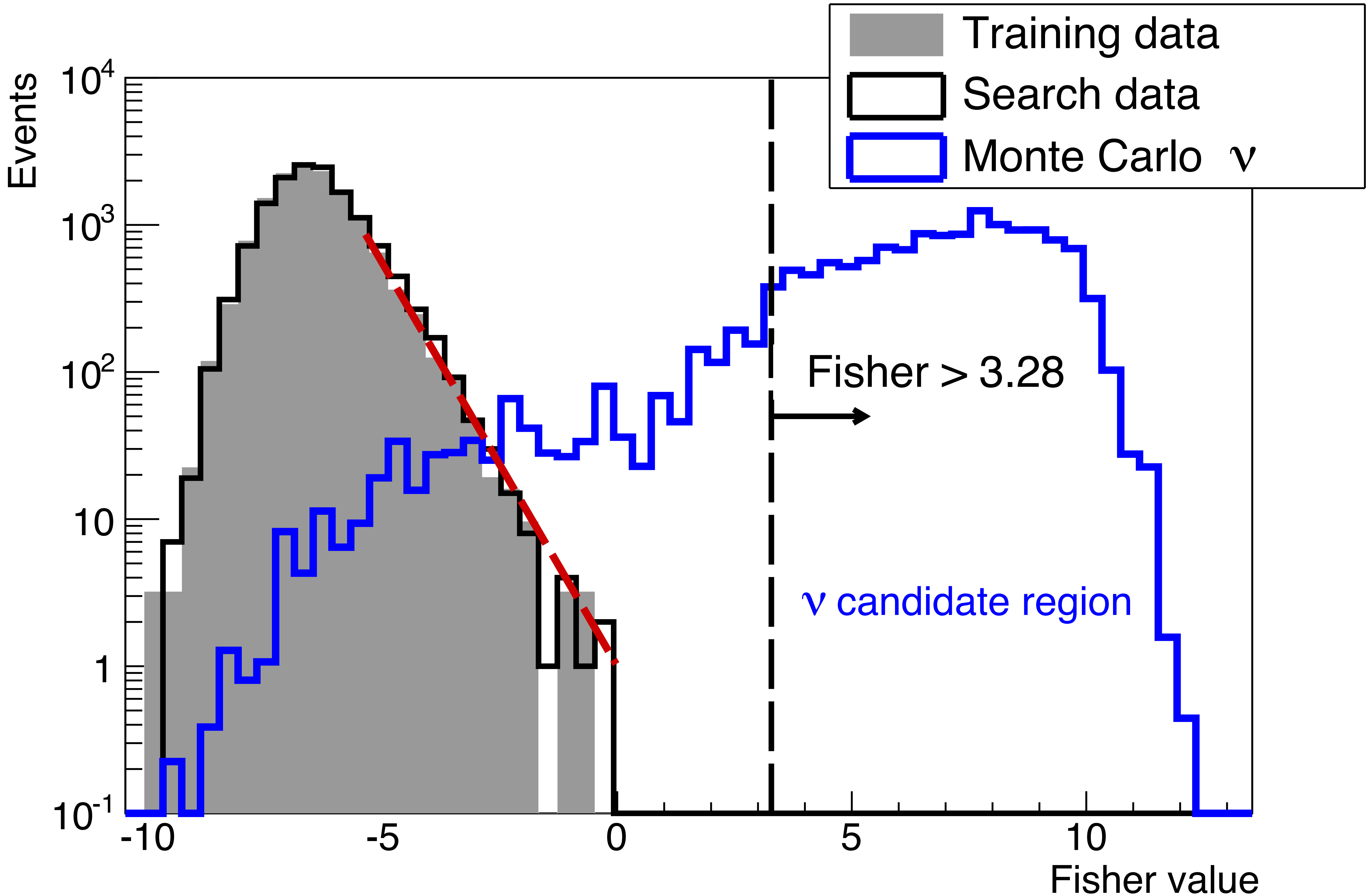
Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
$L/W > 5$	$L/W > 3$	–
$\langle V \rangle \in (0.29,\ 0.31)\ \mathrm{m\ ns^{-1}}$	$\langle V \rangle < 0.313\ \mathrm{m\ ns^{-1}}$	–
$\mathrm{RMS}(V) < 0.08\ \mathrm{m\ ns^{-1}}$	$\mathrm{RMS}(V)/\langle V \rangle < 0.08$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

AoP in Earth Skimming Sample



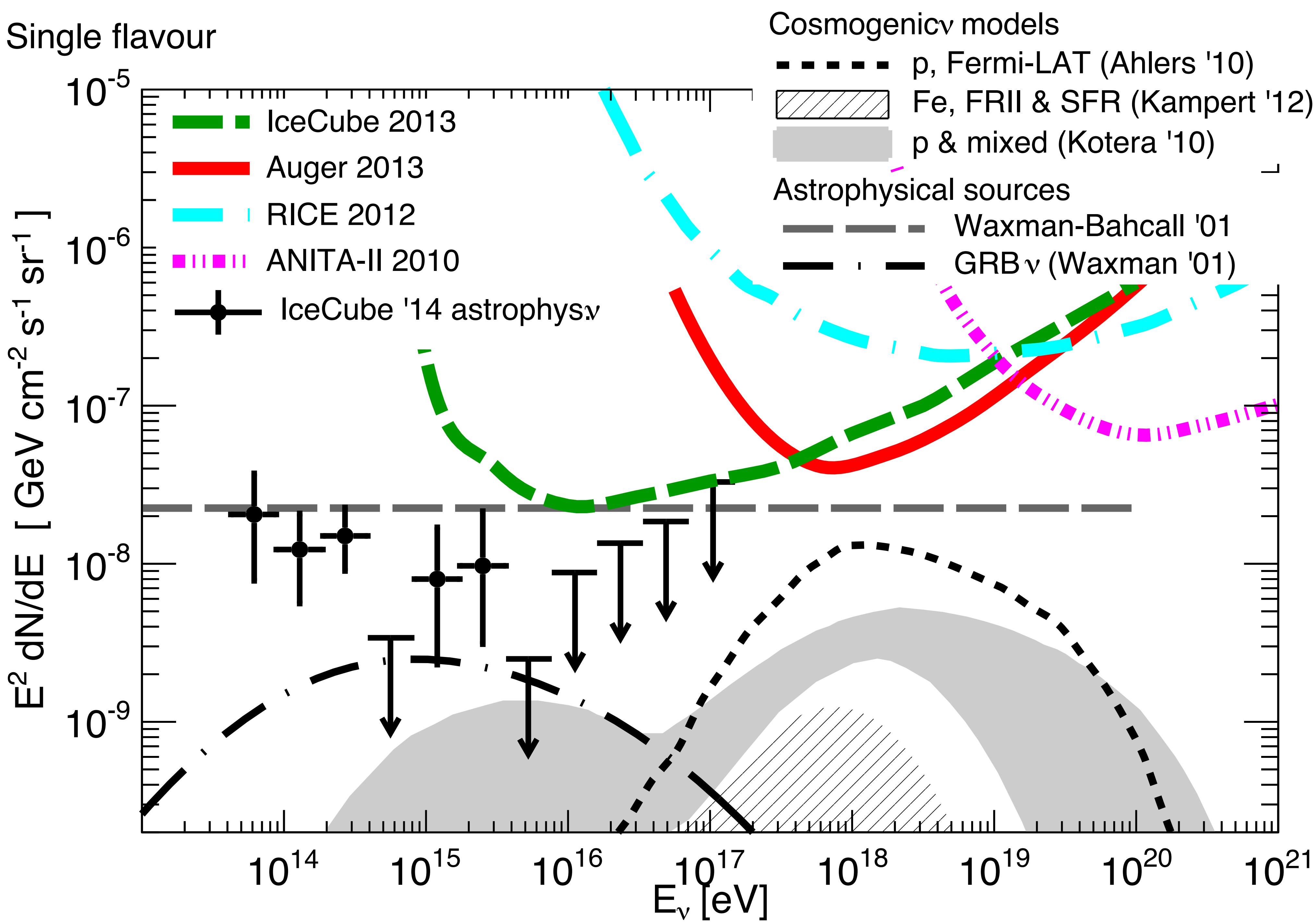
AoP: Area over peak

Combined Fisher Discriminant

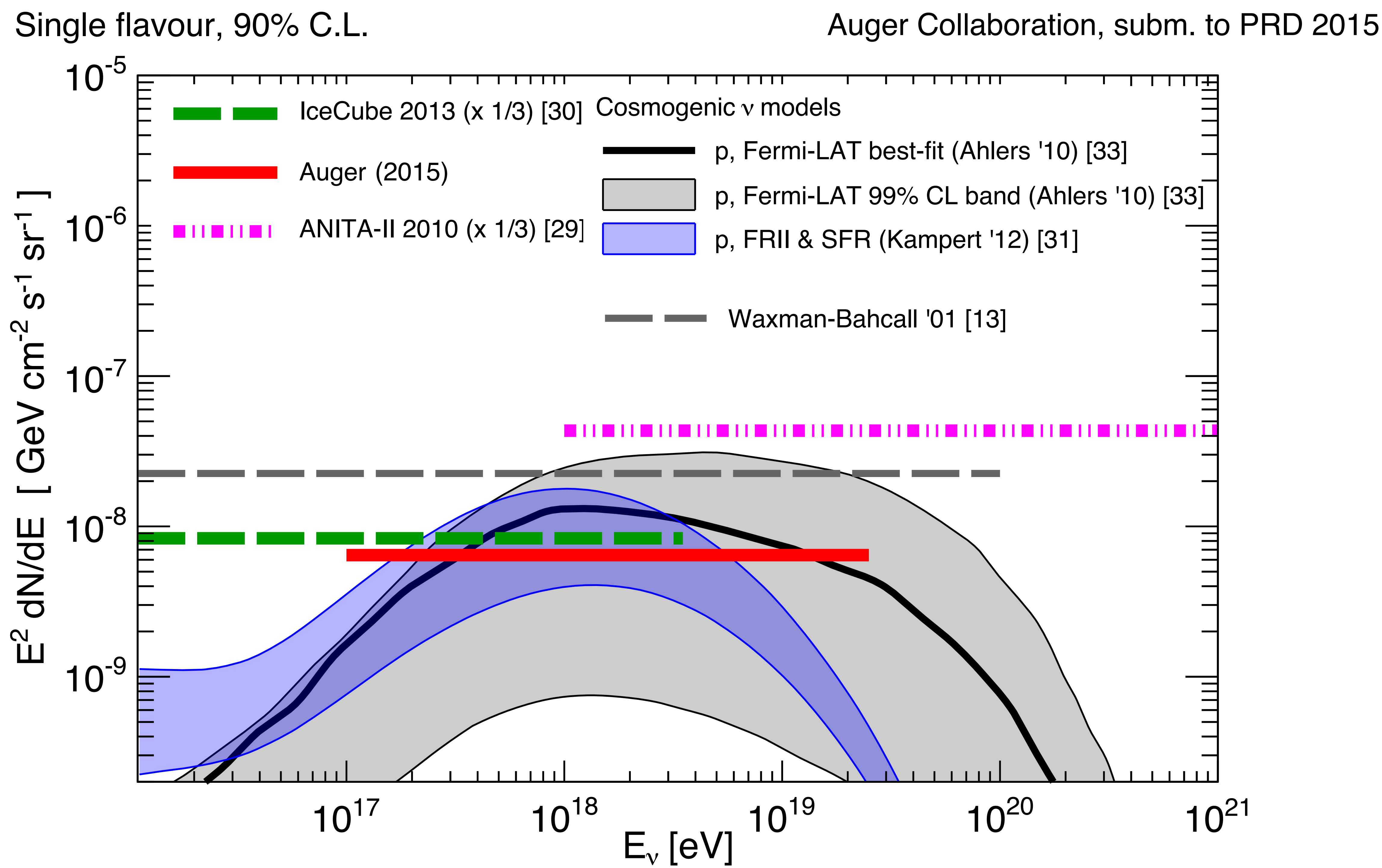


PeV ν-fluxes and EeV ν-limits

Timo Karg for IceCube, Auger, TA Collaborations; UHECR2014

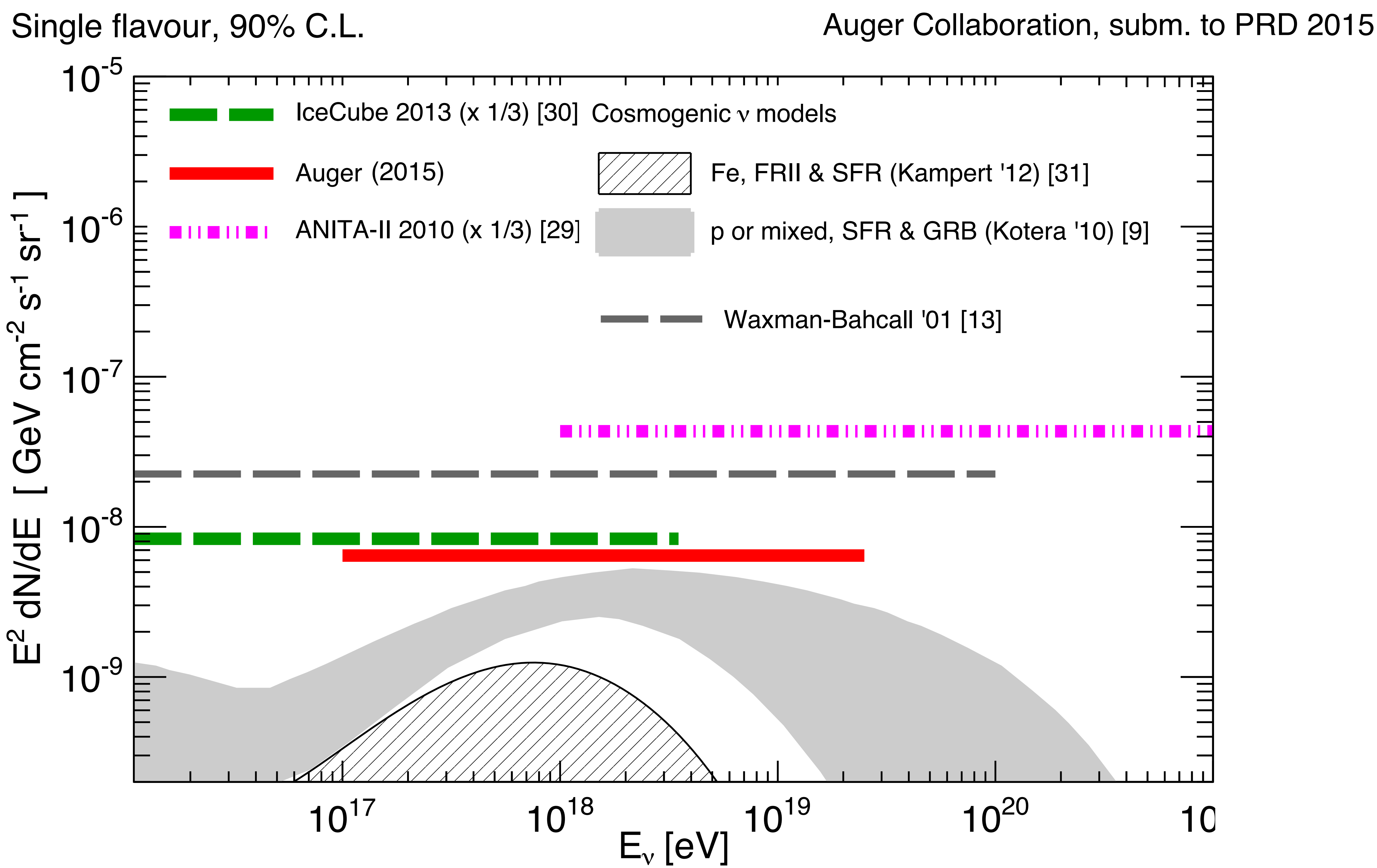


Upper Limits on Neutrinos



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

Upper Limits on Neutrinos



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

Major Achievements in the first 7 years of operation

- Clear observation of flux suppression
- Strongest existing bounds on EeV ν and γ
- Strongest existing bounds on 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 (elfes, solar physics, aerosols...)

Science Goals of Auger Upgrade

1. **Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario**
   - fundamental constraints on UHECR sources
   - galactic vs extragalactic origin
   - reliable prediction of GZK ν- and -γ fluxes

2. **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%**
   - proton astronomy up to highest energies
   - prospects of future UHECR experiments

3. **Study of extensive air showers and hadronic multiparticle production above $\sqrt{s}$=70 TeV**
   - particle physics beyond man-made accelerators
   - derivation of constraints on new physics phenomena

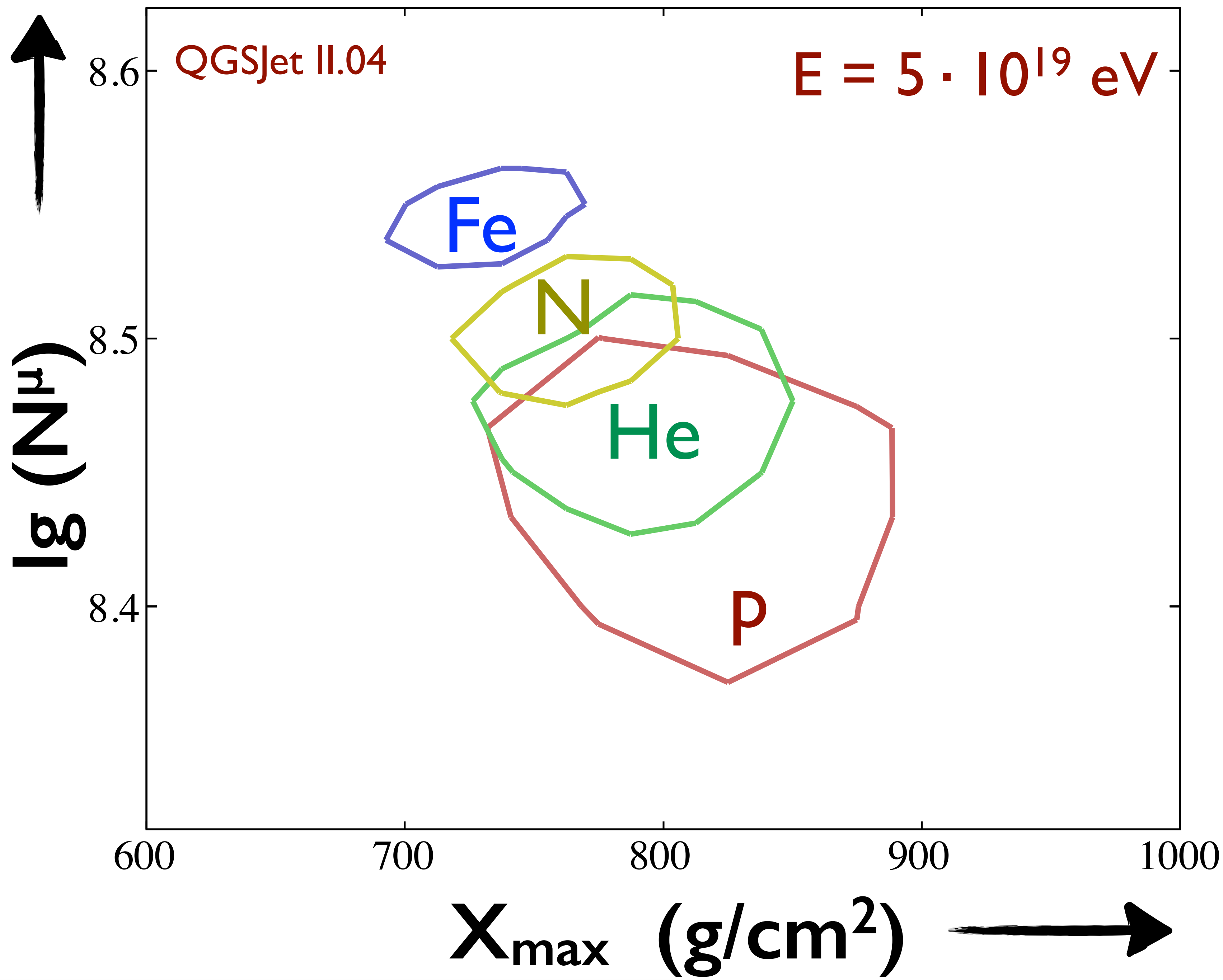
Answering the science questions requires composition sensitivity event-by-event into the flux suppression region

Up to know, composition based solely on Fluorescence Telescopes, duty cycle ~10-15%
(different operation modus planned to yield factor ~2)

➙ most effectively achieved by upgrade of surface detectors (duty cycle 100%)
➙ immediate boost in statistics by a factor of ~10 !

classical approach:
enhance electromagnetic/muonic separation of stations
(and time resolution)

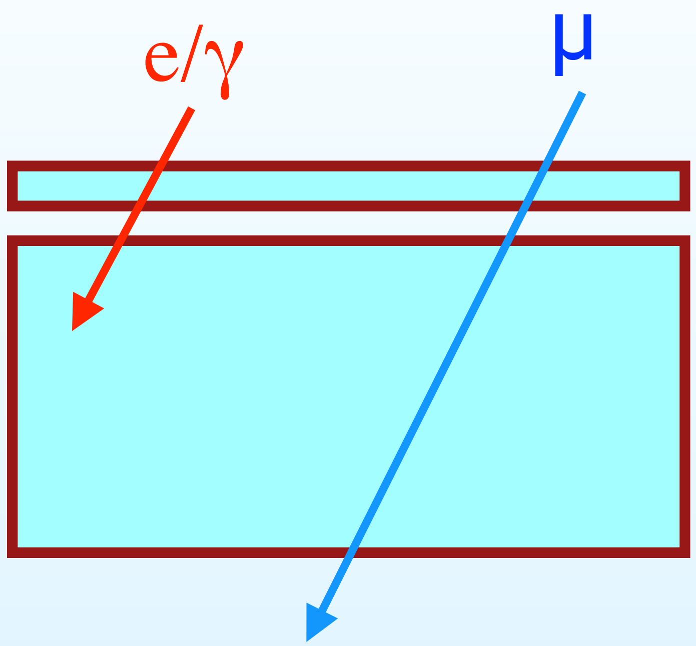
N^{μ}_{max} vs X_{max}



Muons may even outperform X_{max} at highest energies !

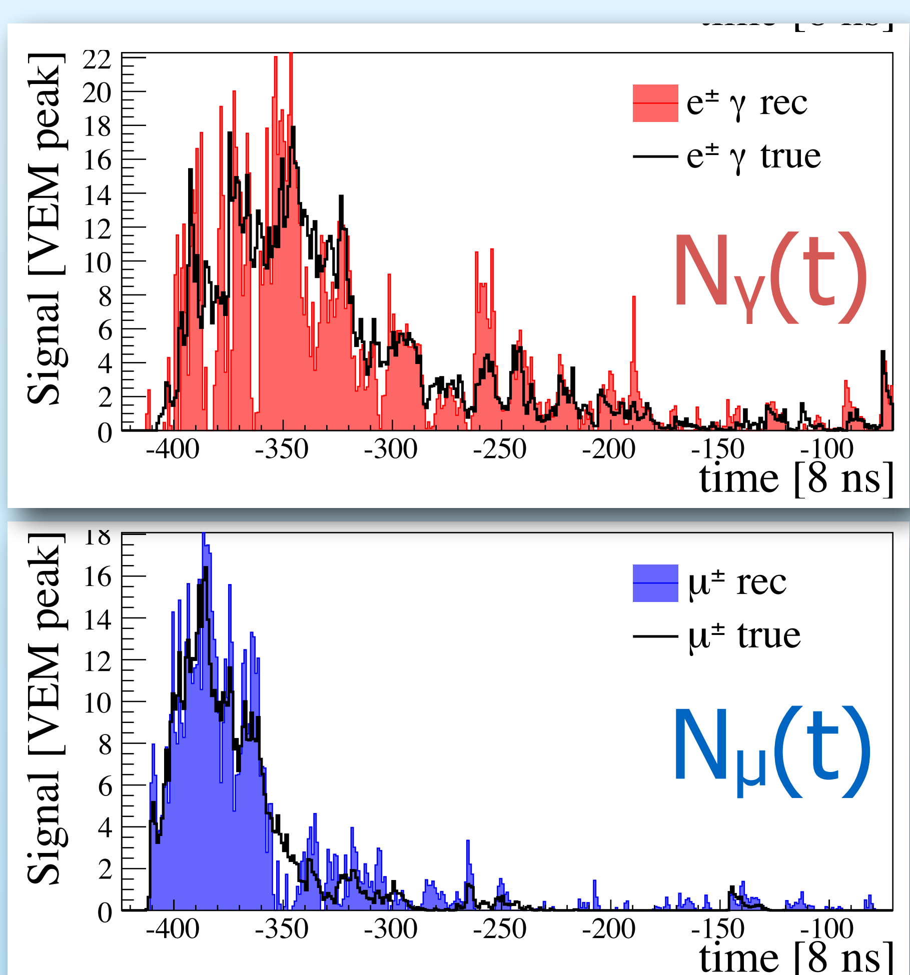
How to Improve e/μ discrimination?

Letessier-Selvon et al., NIM A767 (2014) 41



$$S_{\mathrm{top}} = a_{\mathrm{top},\gamma} \cdot N_\gamma + a_{\mathrm{top},\mu} \cdot N_\mu$$

$$S_{\mathrm{bot}} = a_{\mathrm{bot},\gamma} \cdot N_\gamma + a_{\mathrm{bot},\mu} \cdot N_\mu$$



Linear system of equations:

$$\Rightarrow \begin{pmatrix} S_{\mathrm{top}} \\ S_{\mathrm{bot}} \end{pmatrix} = \begin{pmatrix} a_{\mathrm{top},\gamma} & a_{\mathrm{top},\mu} \\ a_{\mathrm{bot},\gamma} & a_{\mathrm{top},\mu} \end{pmatrix} \begin{pmatrix} N_\gamma \\ N_\mu \end{pmatrix}$$

$$\begin{pmatrix} N_\gamma \\ N_\mu \end{pmatrix} = \begin{pmatrix} a_{\mathrm{top},\gamma} & a_{\mathrm{top},\mu} \\ a_{\mathrm{bot},\gamma} & a_{\mathrm{top},\mu} \end{pmatrix}^{-1} \begin{pmatrix} S_{\mathrm{top}} \\ S_{\mathrm{bot}} \end{pmatrix}$$

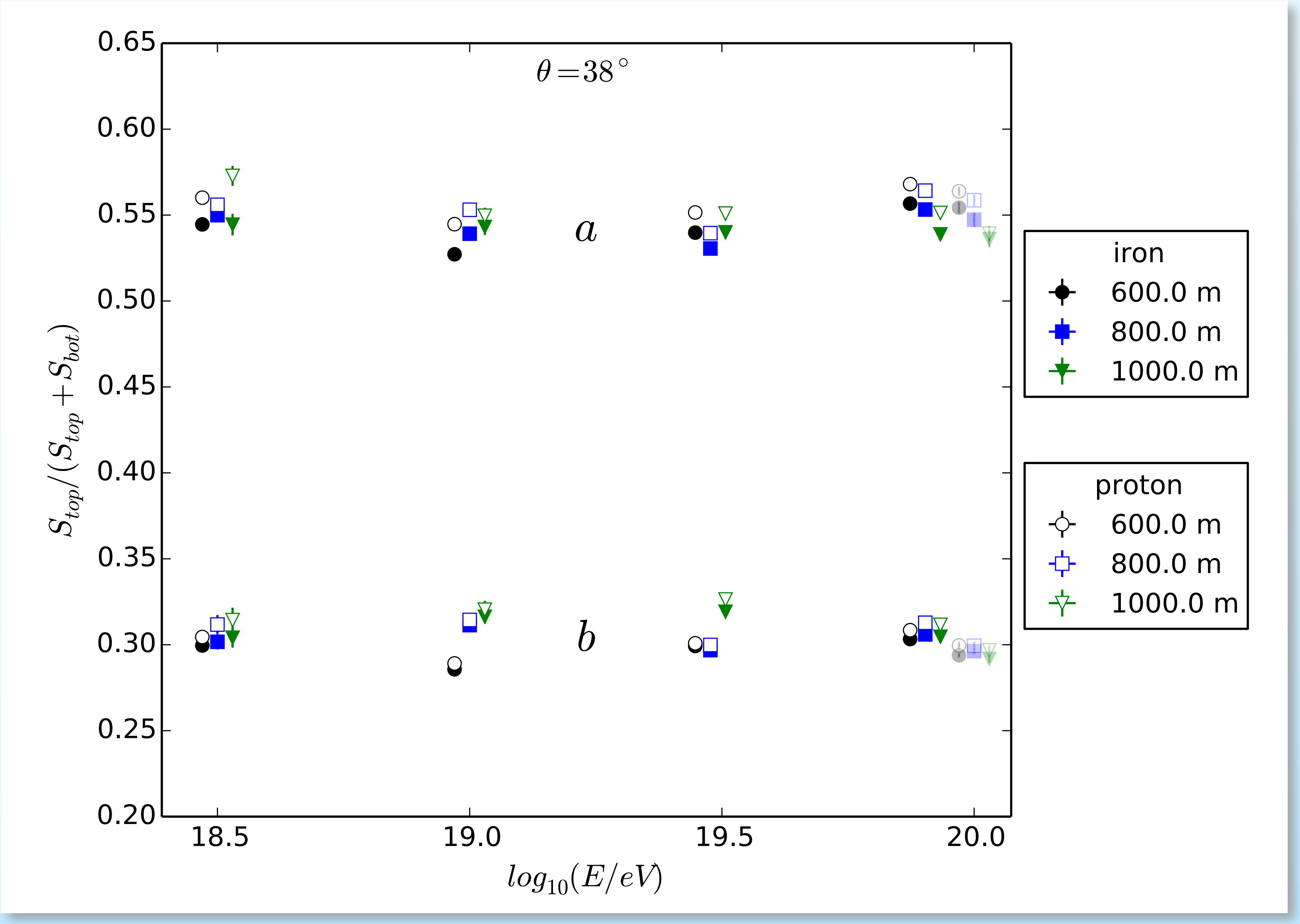
Coefficients determined from detector Monte Carlo (and verified to be constant as a fct of zenith angle, primary energy and mass)

Performance of Scintillator+WCD

May be able to use matrix inversion technique, similar to LSD:

$$\begin{pmatrix} S_{\mathrm{Scin}} \\ S_{\mathrm{WCD}} \end{pmatrix} = \begin{pmatrix} 0.54 & 0.3 \\ 0.46 & 0.7 \end{pmatrix} \begin{pmatrix} S_{\mathrm{em}} \\ S_{\mu} \end{pmatrix}$$

$$b \simeq \frac{A_{\mathrm{Scint}}}{A_{\mathrm{Scint}} + A_{\mathrm{WCD}}} = 4/14 \simeq 0.29$$



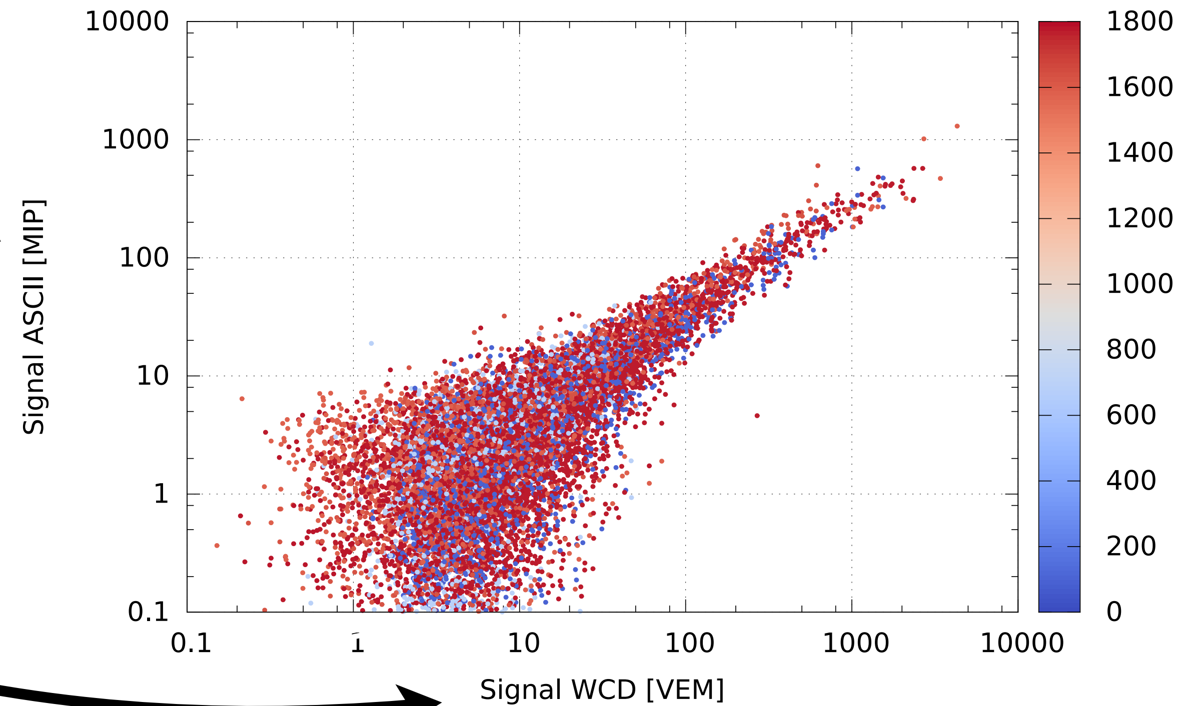
Matrix independent from primary, here:

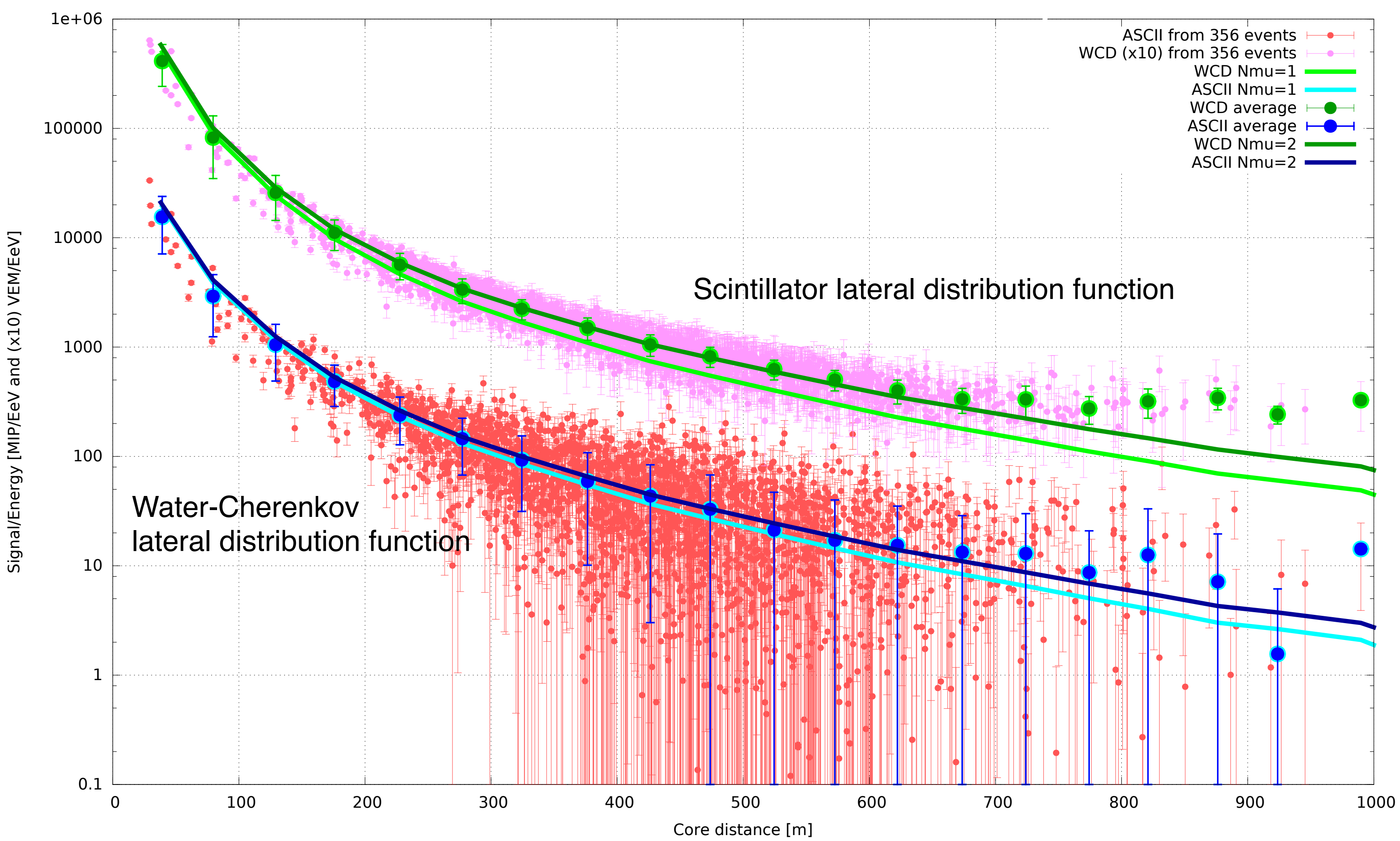
Comparison of proton and iron primaries; ±1%

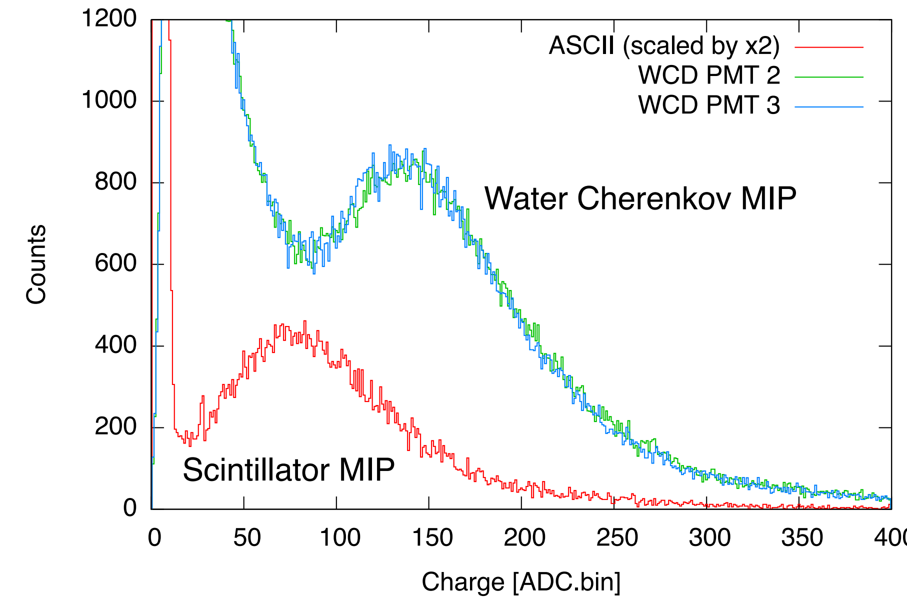
Event-by-Event resolution of μ-ratio ~ 20%

4 m² ASCII prototype

Some Prototype Results







Prototype experiences accompanied by detailed performance estimates

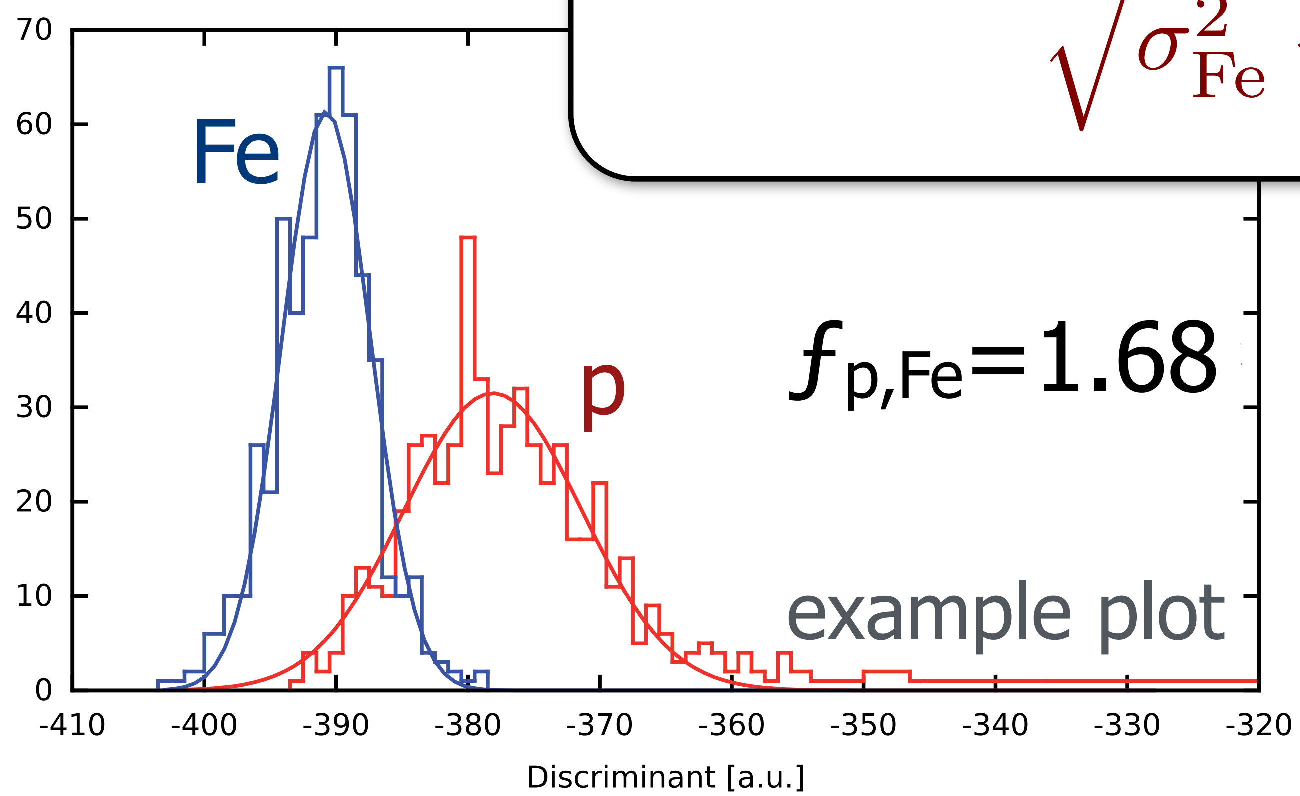
CORSIKA Shower libraries were generated with different
– energies (fixed and continuous)
– primaries
– zenith angles
– interaction models

performance then studied
– per station and
– per event

Note: enhanced SD helps also improving photons and neutrino detection

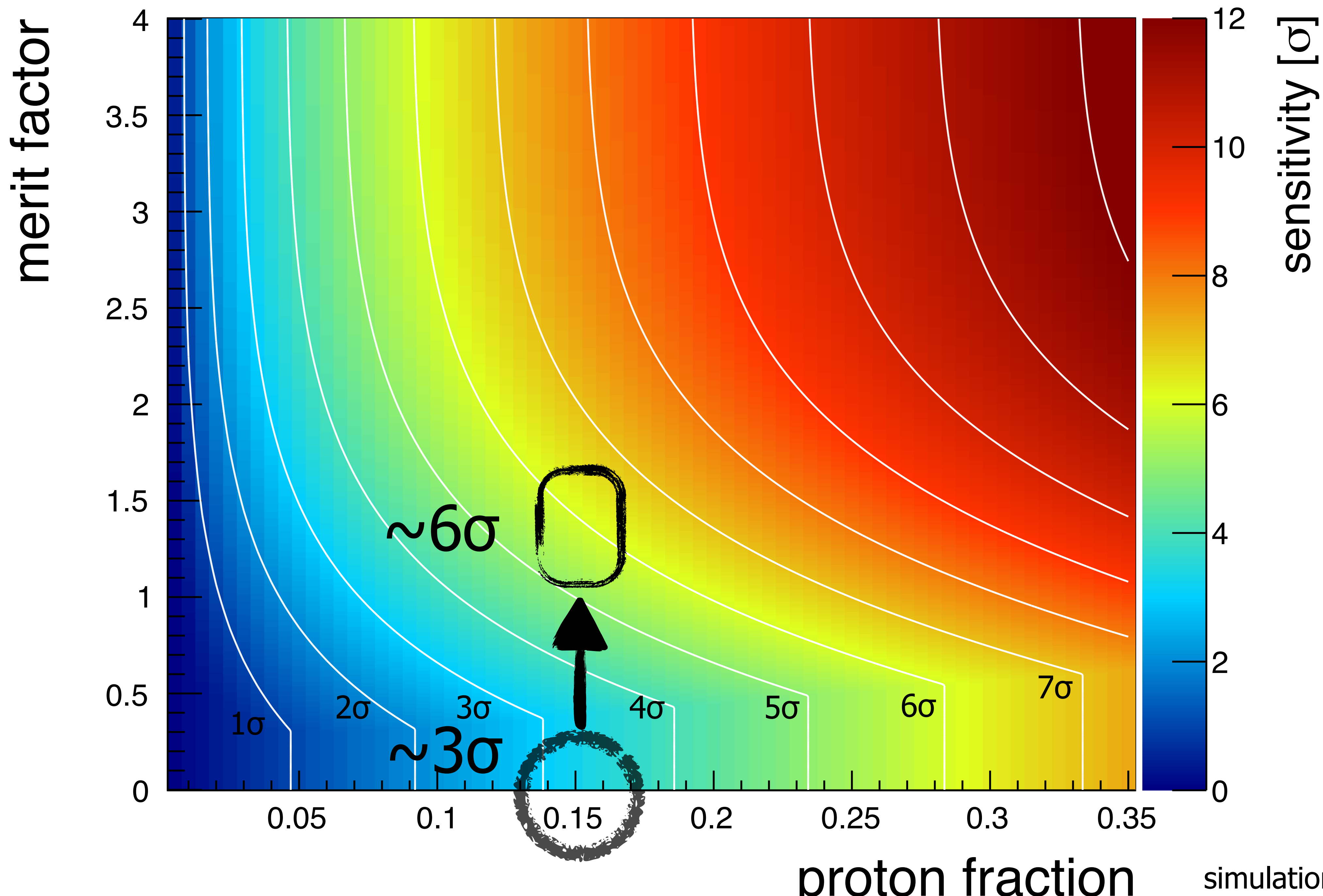
➡ **Merit Factor** (discrimination power):

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



Power of Composition Enhanced Astronomy

assume present statistics: N=146 events (E>57 EeV), P_{iso}=0.21
and study correlation significance when protons correlate, but Fe does not

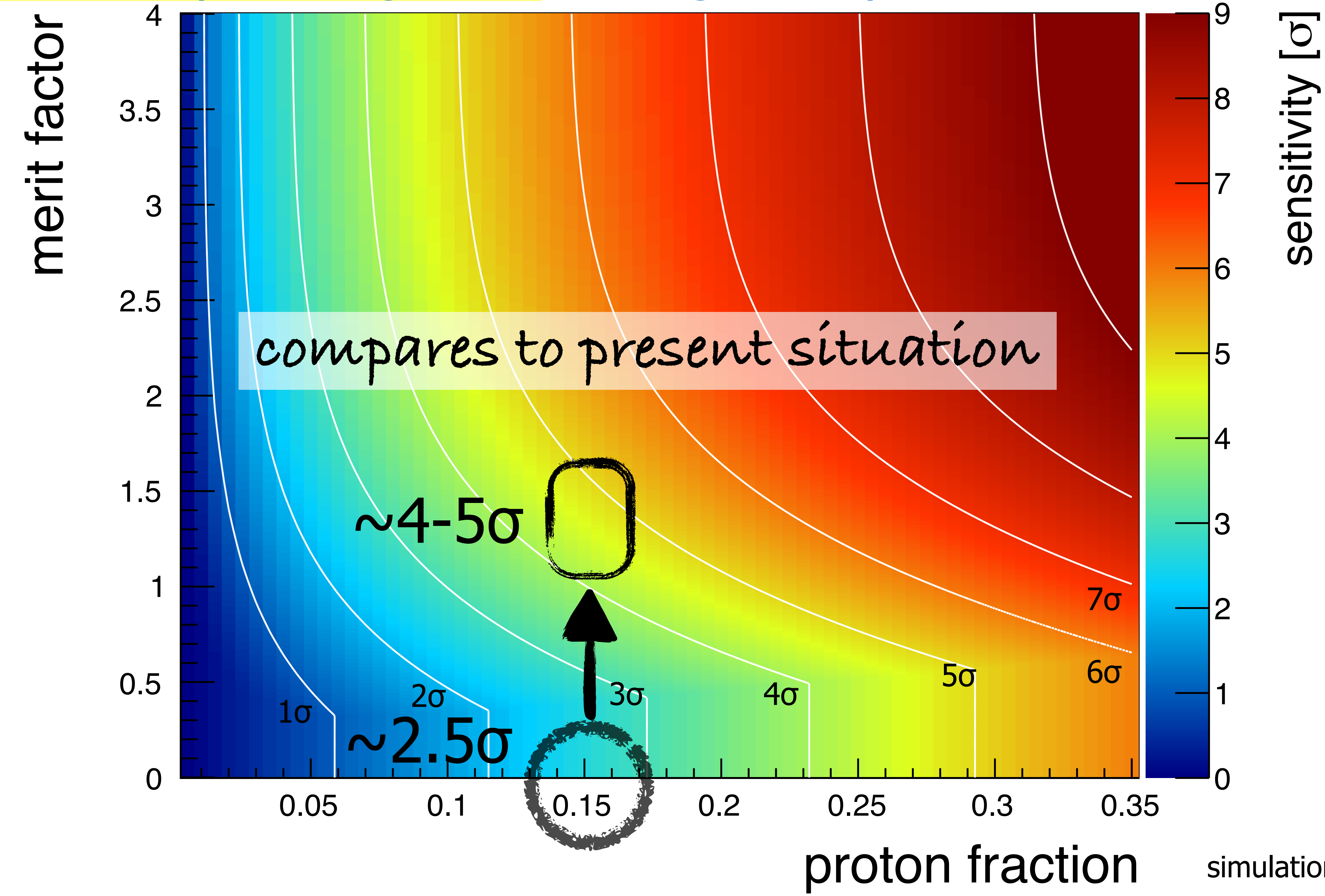


simulations by M. Unger

white lines: contour levels at sigma = 1, 2, 3, ...

Power of Composition Enhanced Astronomy

assume present statistics: N=146 events (E>57 EeV), P_{iso}=0.21
and study correlation significance when protons correlate, but Fe does not
Add <u>20% isotropic</u> background: catalog incompleteness, distant sources, …



simulations by M. Unger

white lines: contour levels at sigma = 1, 2, 3, ...

Conclusions

Enhancing the surface detector array for better em/mu separation will boost the science of Auger

- ➙ factor of ~10 in statistics for composition measurements
- ➙ GZK vs maximum energy
- ➙ allow p-astronomy (composition enhanced anisotropy)
- ➙ learn about global features of hadronic interactions at $\sqrt{s} > 70$ TeV
- ➙ decisive prediction of UHE (cosmogenic) ν-fluxes
- ➙ decisive for next generation UHECR Experiments

Auger is well in place to address these questions for the next decade