Review on extragalactic cosmic rays detection

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LPNHE PARIS

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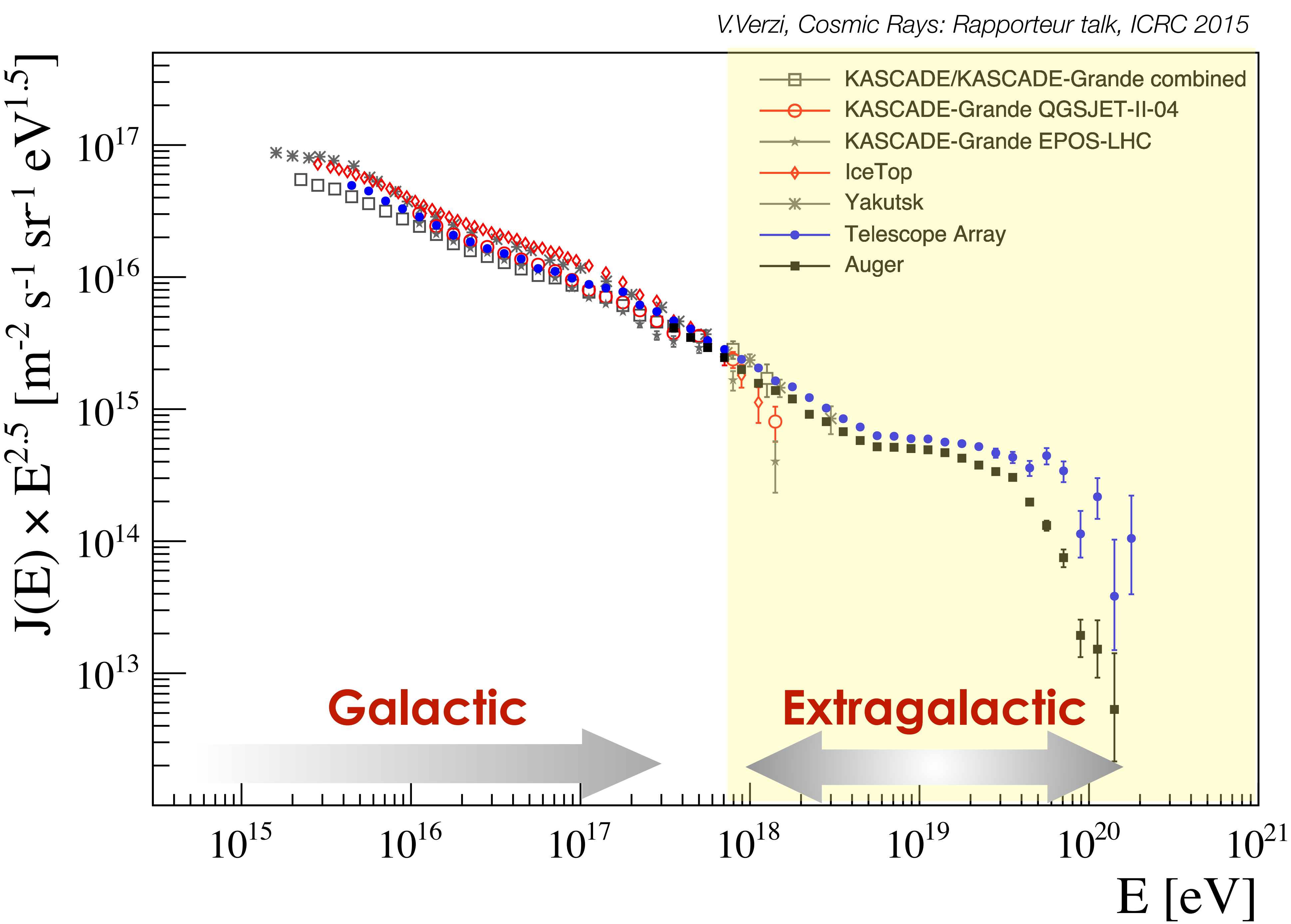
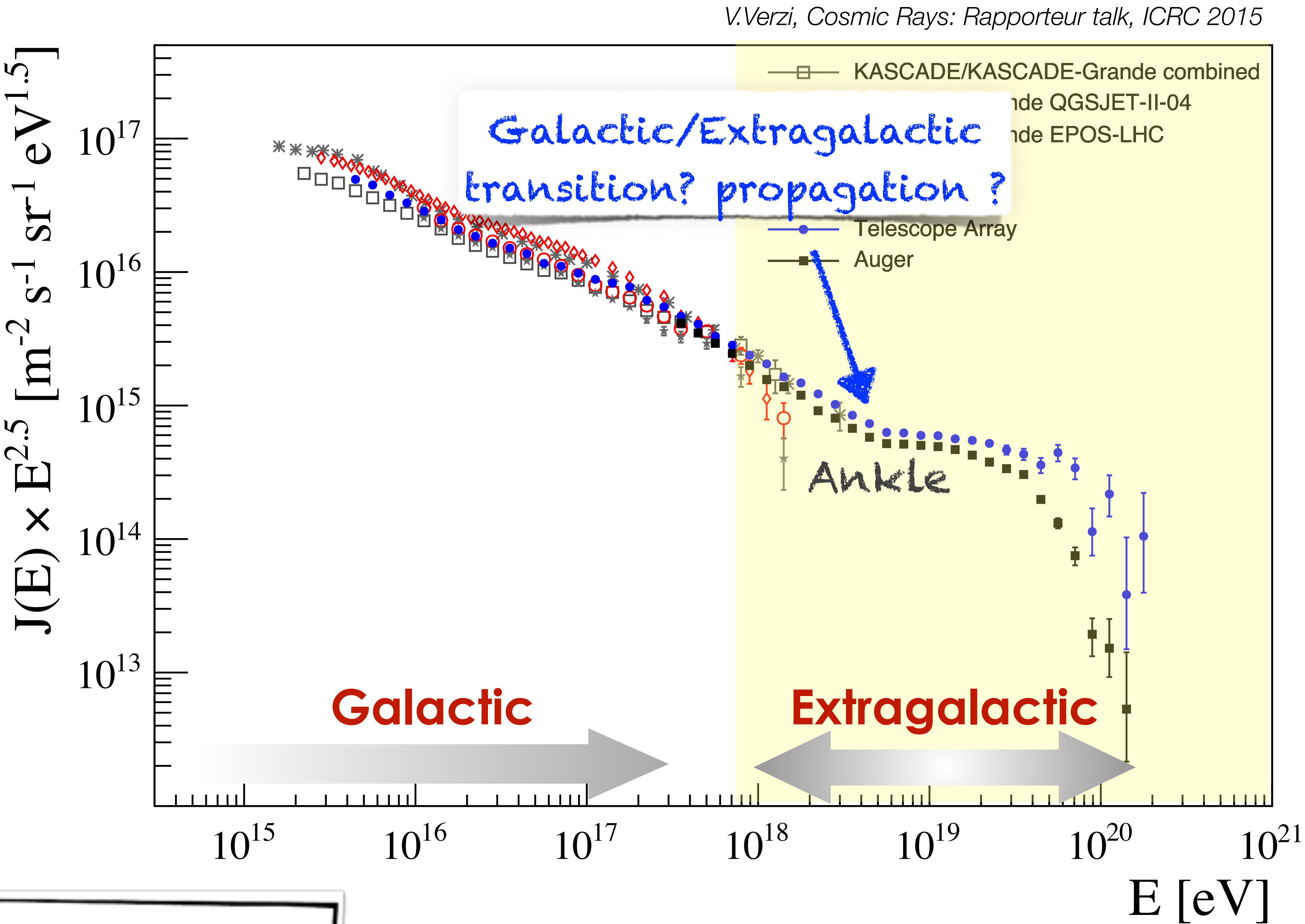
ECRS 2016

The ultra-high-energy regime



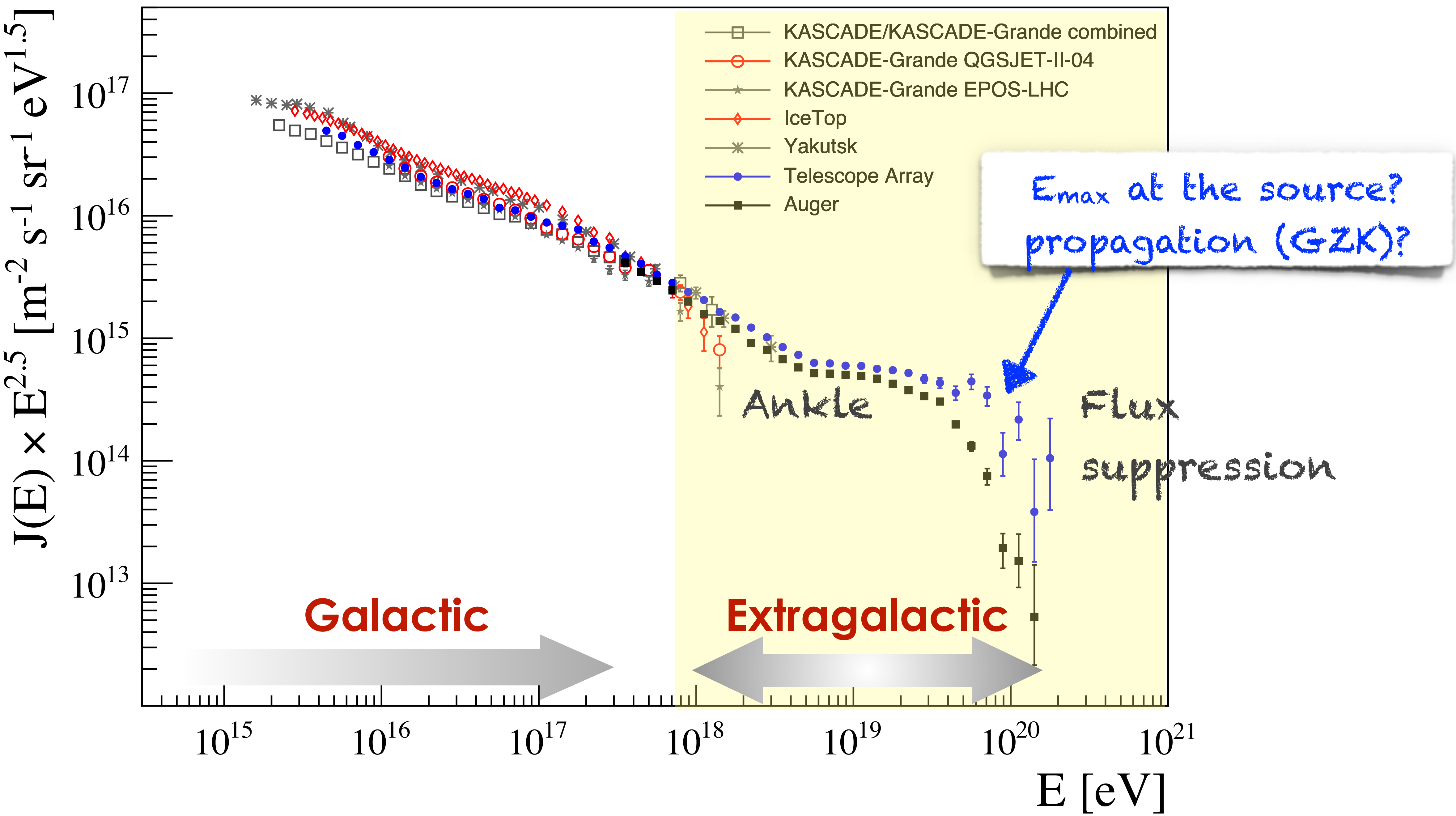
The ultra-high-energy regime



See A. Taylor's talk

The ultra-high-energy regime

V.Verzi, Cosmic Rays: Rapporteur talk, ICRC 2015



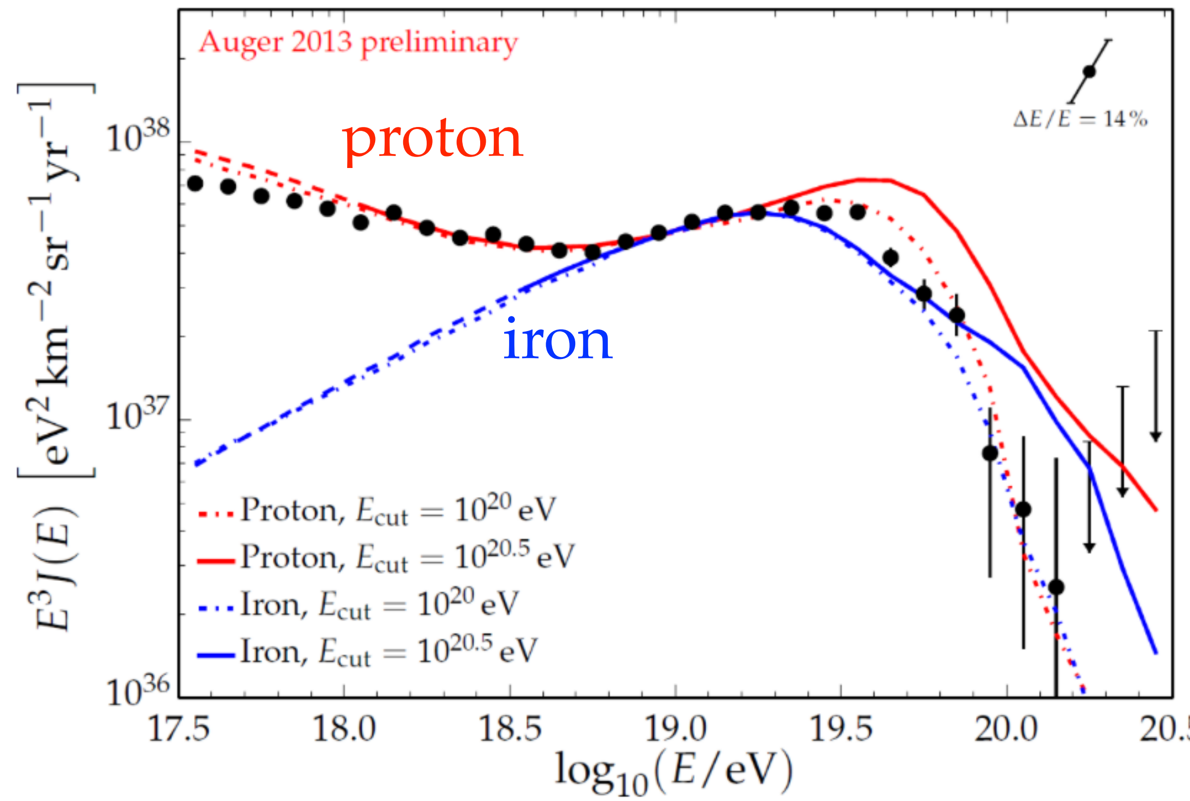
Propagation effect or source exhaustion?

1. Propagation scenario (GZK / photo-disintegration)

$p + \gamma_{CMB} \rightarrow n + \pi^+$ → cosmogenic neutrinos

$\rightarrow p + \pi^0$ → cosmogenic photons

E ≳ $10^{19.5}$ eV, "horizon" ~ 100 Mpc



Auger 2015,
best-fit mixed comp.

Propagation effect or source exhaustion?

1. Propagation scenario (GZK / photo-disintegration)

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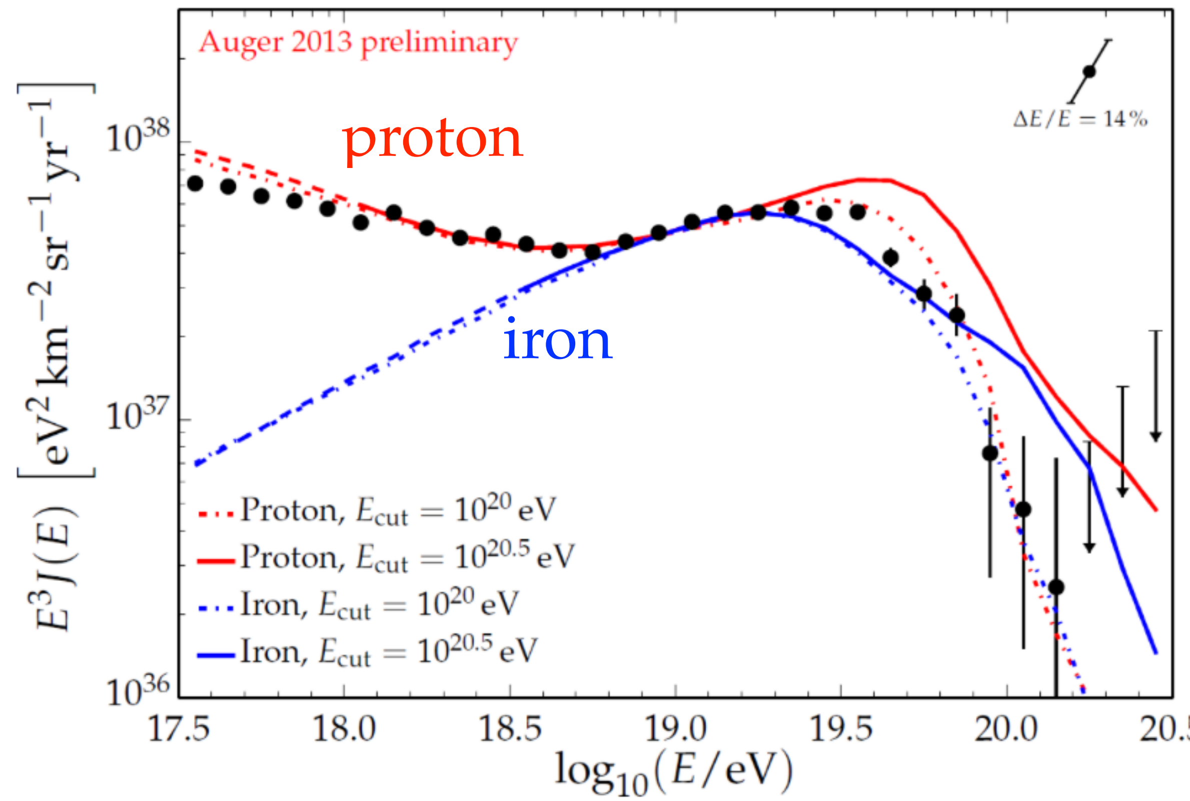
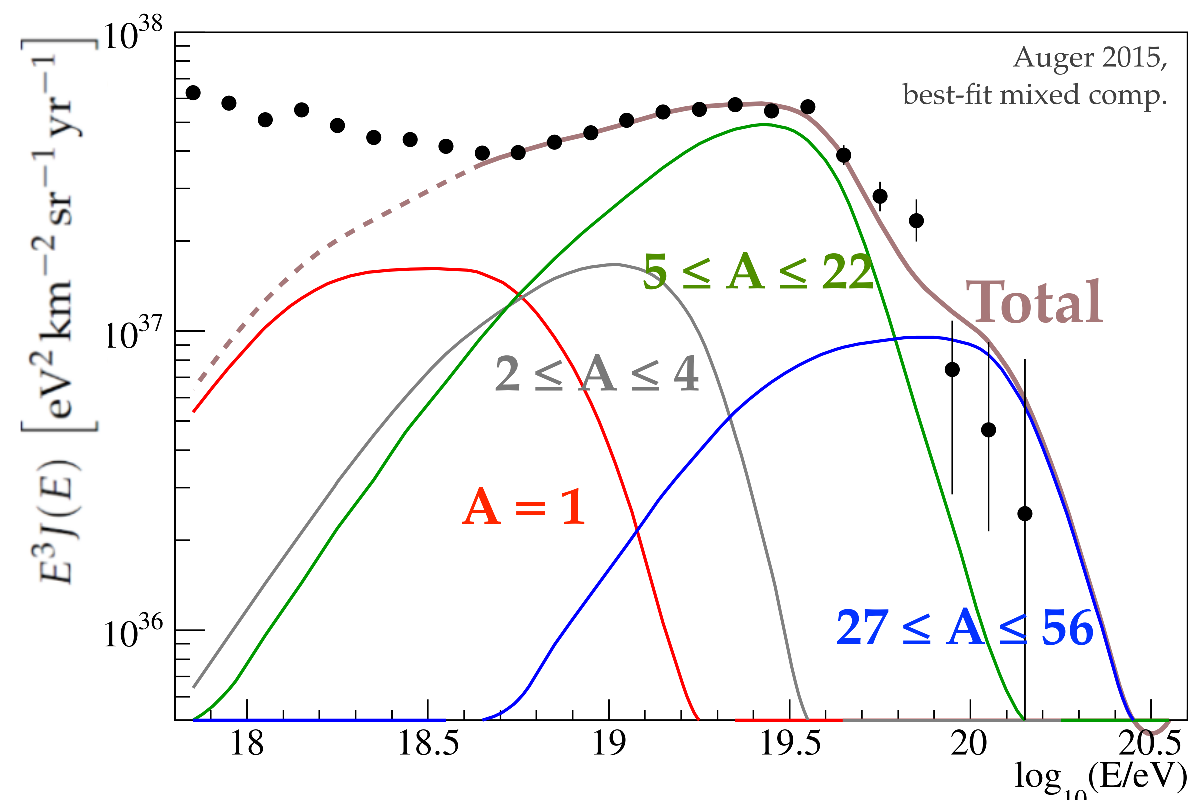


2. Limitation of the maximal energy at the source

mixed composition

$$E_Z^{max} \propto Z \times E_p^{max}$$



How to discriminate the two scenarios?

- **Energy Spectrum features**
  increase statistics, pile-up for the GZK scenario

- **Mass composition** (in the GZK region)

- **Observation of cosmogenic photons/neutrinos**
  specific signature of GZK process (or new physics)

- **Anisotropy**
  small scale in case of a light composition (see next talk)

OUTLINE
Detection techniques,
experiments in operation and some recent results

How do we observe ultra-high-energy cosmic rays?

Extensive-Air-Showers and Ground-based detectors

Extensive Air Showers: observables

Using the atmosphere as a calorimeter

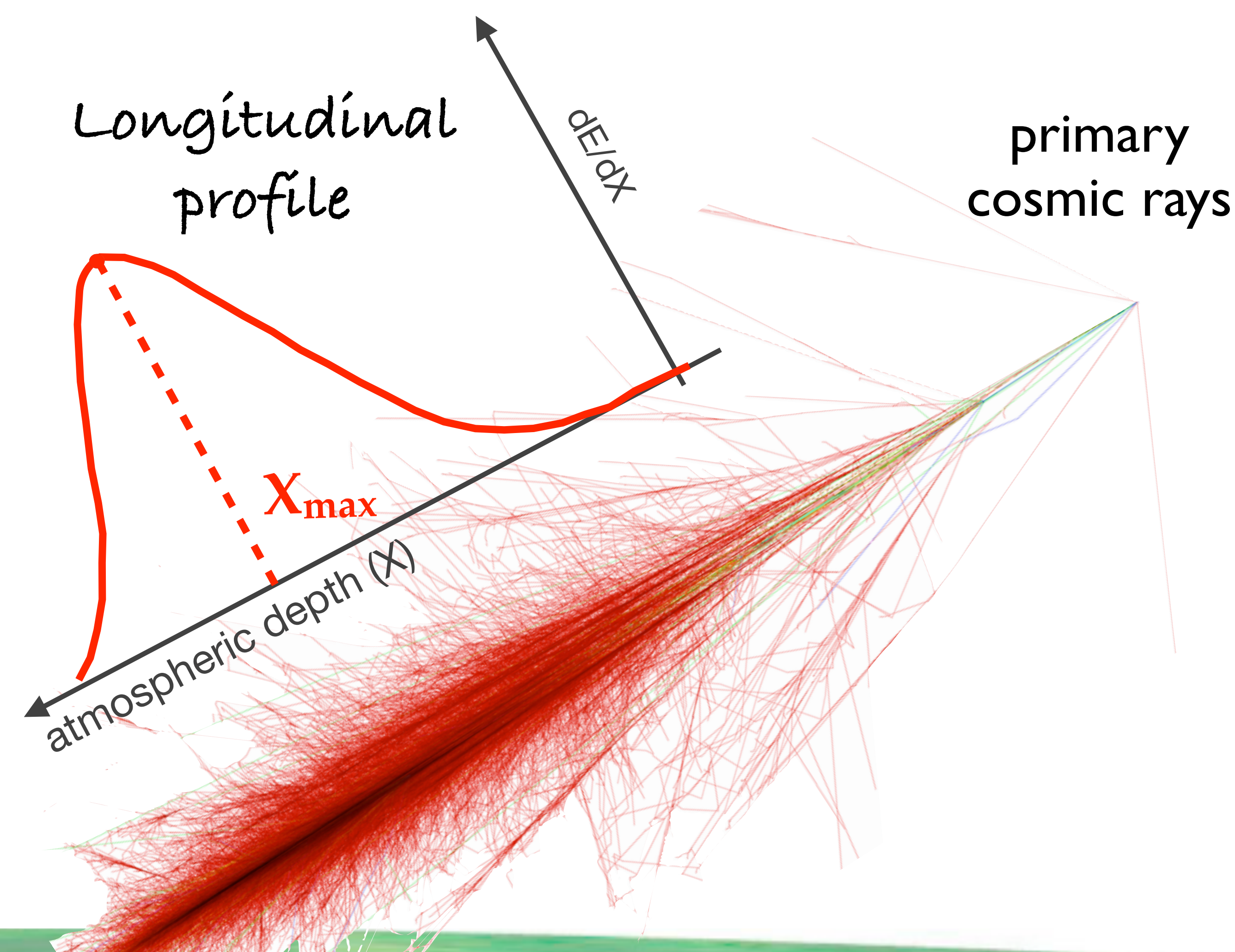
- Evolution of the EM cascade

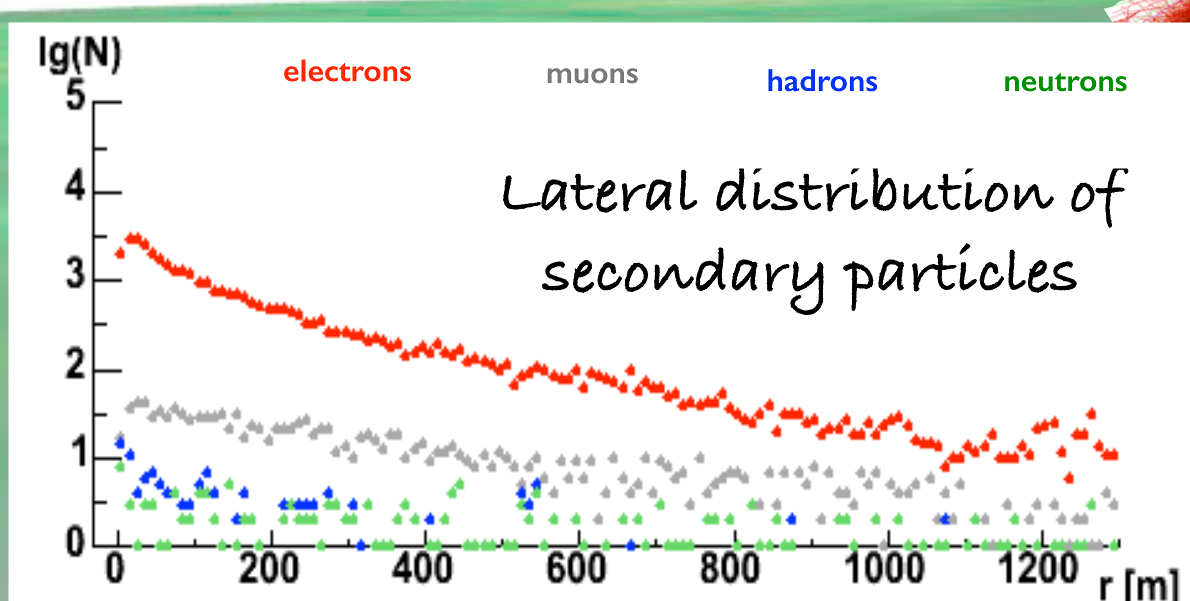
  Calorimetric Energy

$$E \propto \int \frac{dE}{dX} dX$$

- Maximum of the EAS (X_{max})

  Mass composition





http://www-ik.fzk.de/corsika/

Particle density at ground

Energy

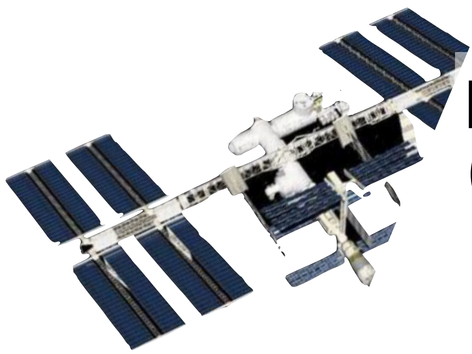
Number or muons

Hadronic component, Mass

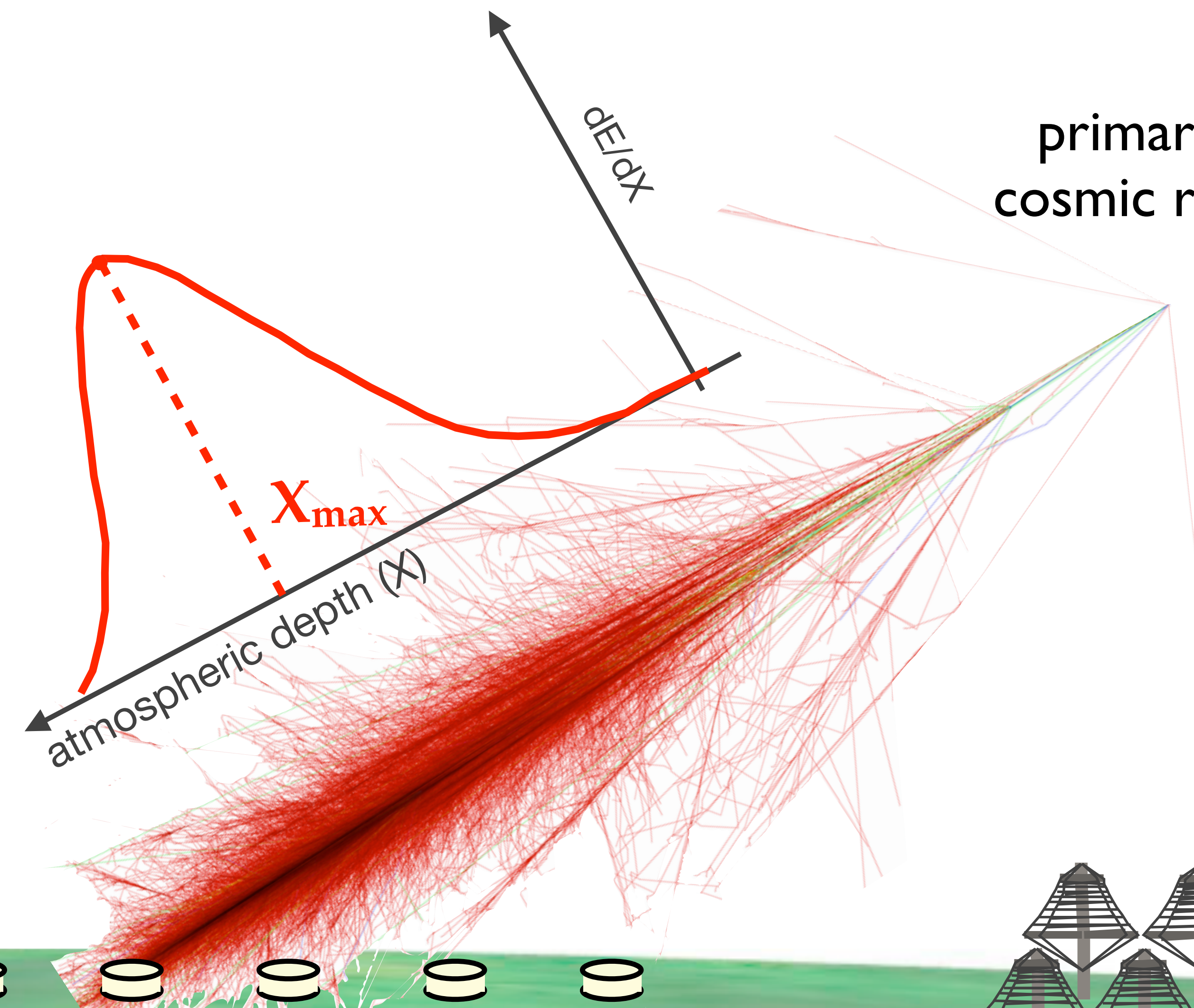
Dependence on EAS simulations

Detection techniques

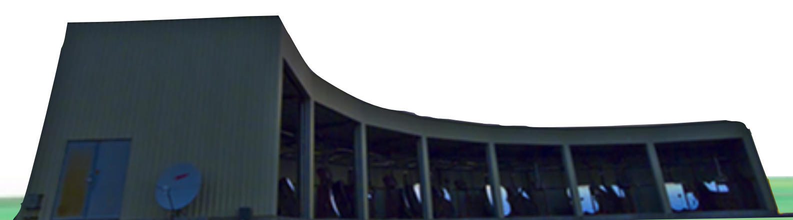
Using the atmosphere as a calorimeter

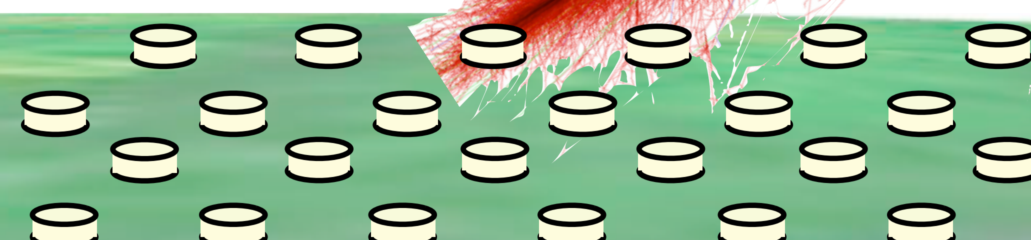


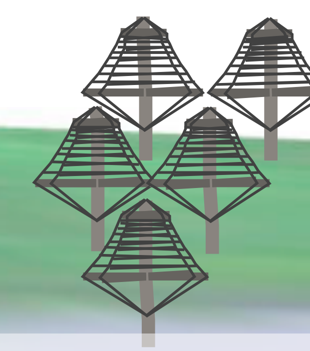
New techniques (II)
(See parallel session)



Fluorescence Telescopes
longitudinal shower development
calorimetric energy
10-15% duty cycle
atmospheric monitoring







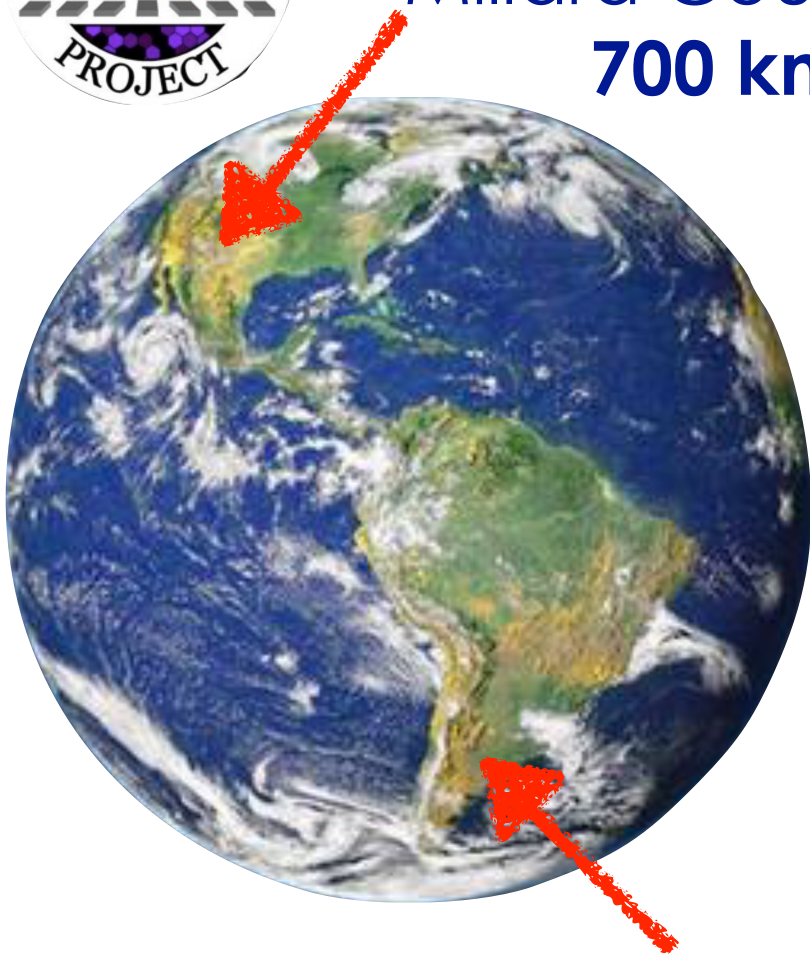
Surface array detector
Particle density at ground
100% duty cycle
dependence on EAS models

New techniques
(See Tuesday session)

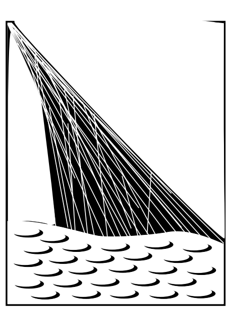
Two observatories for UHECRs

Telescope Array

Millard County, Utah, USA,
700 km², 1400 m a.s.l.
since 2008

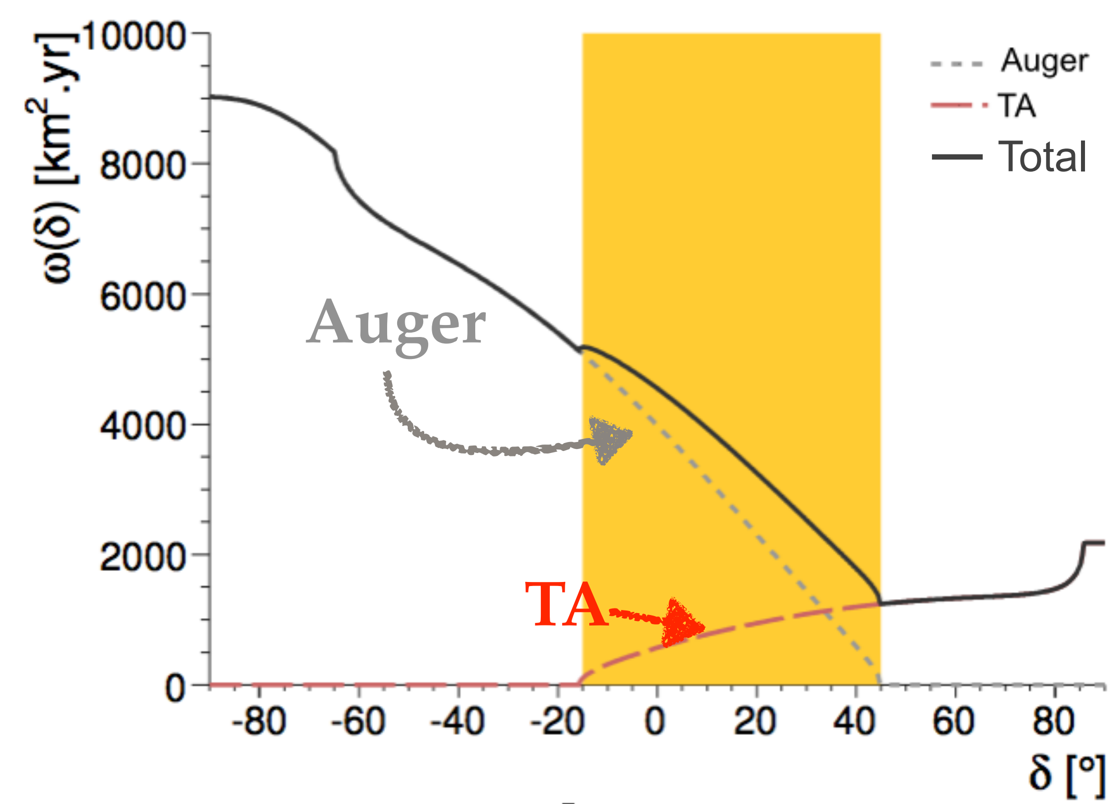


Pierre Auger Observatory



Malargue, Argentina,
3000 km², 1400 m a.s.l.
since 2004

One in each hemisphere:
different skies observed!

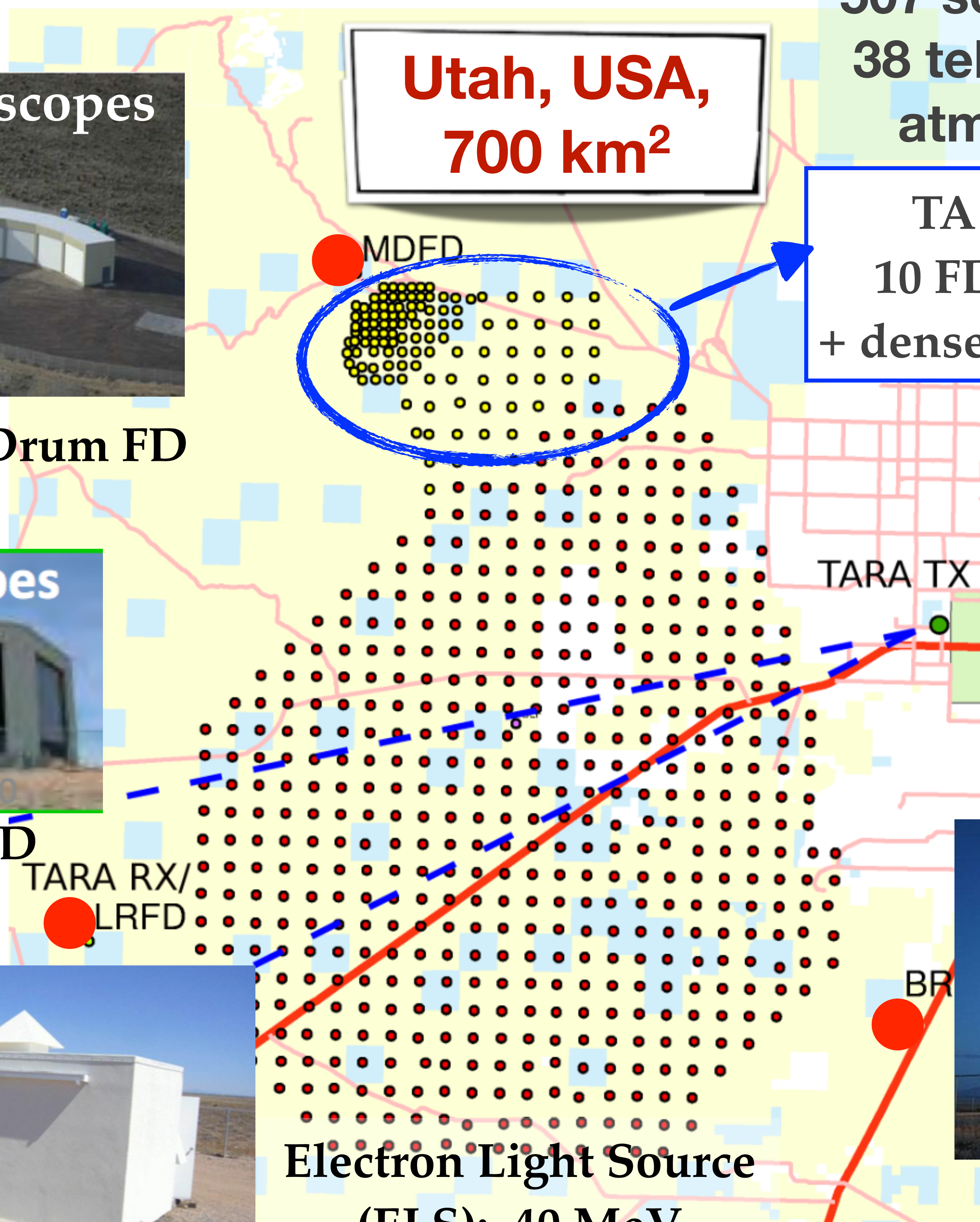


Auger exposure:
50000 km² sr yr
~ 10 times larger than TA

Telescope Array Project

507 scintillators (1.2 km grid)
38 telescopes in 3 buildings
atmospheric monitoring

Middle Drum FD



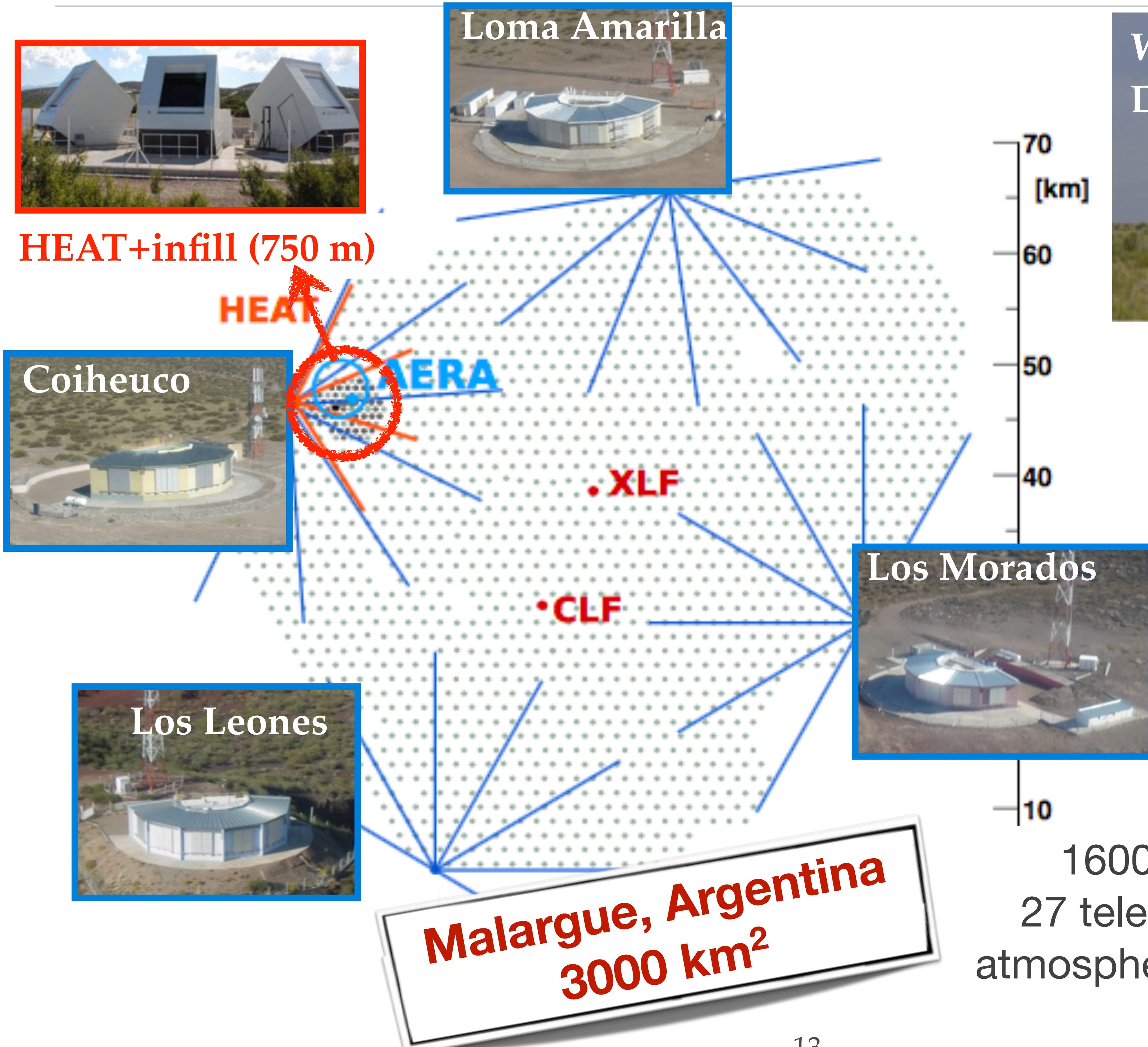
TA Low Energy (TALE):
10 FD (field of view 31-59°)
+ dense array of 103 scintillators

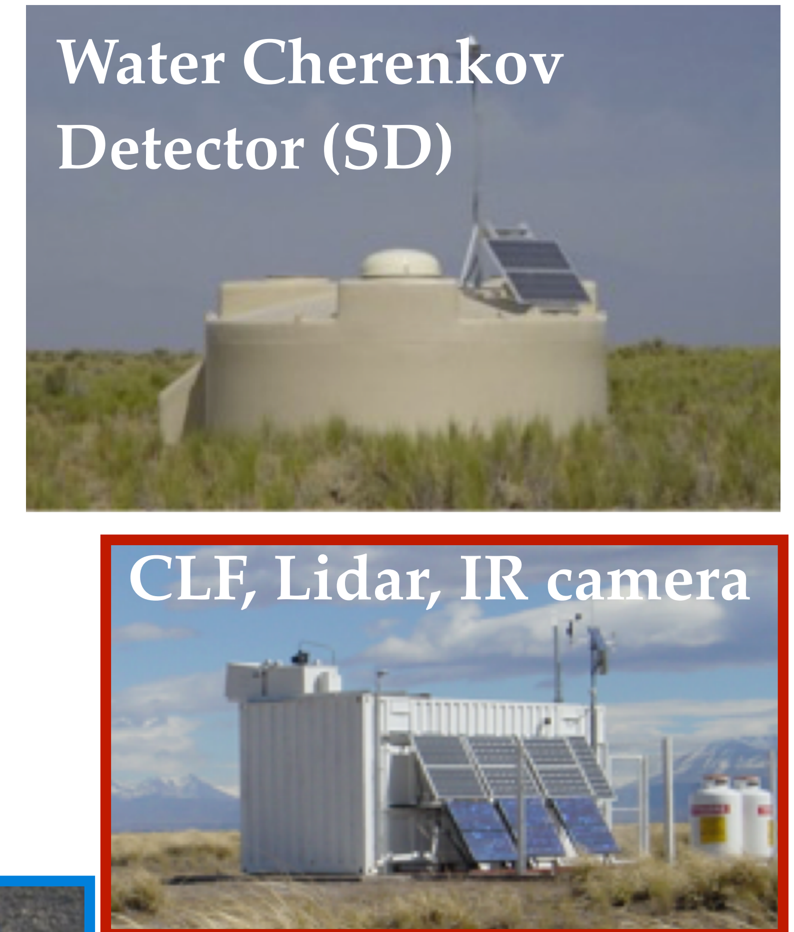
Long Ridge FD

Black Rock FD

Electron Light Source
(ELS): 40 MeV

The Pierre Auger Observatory

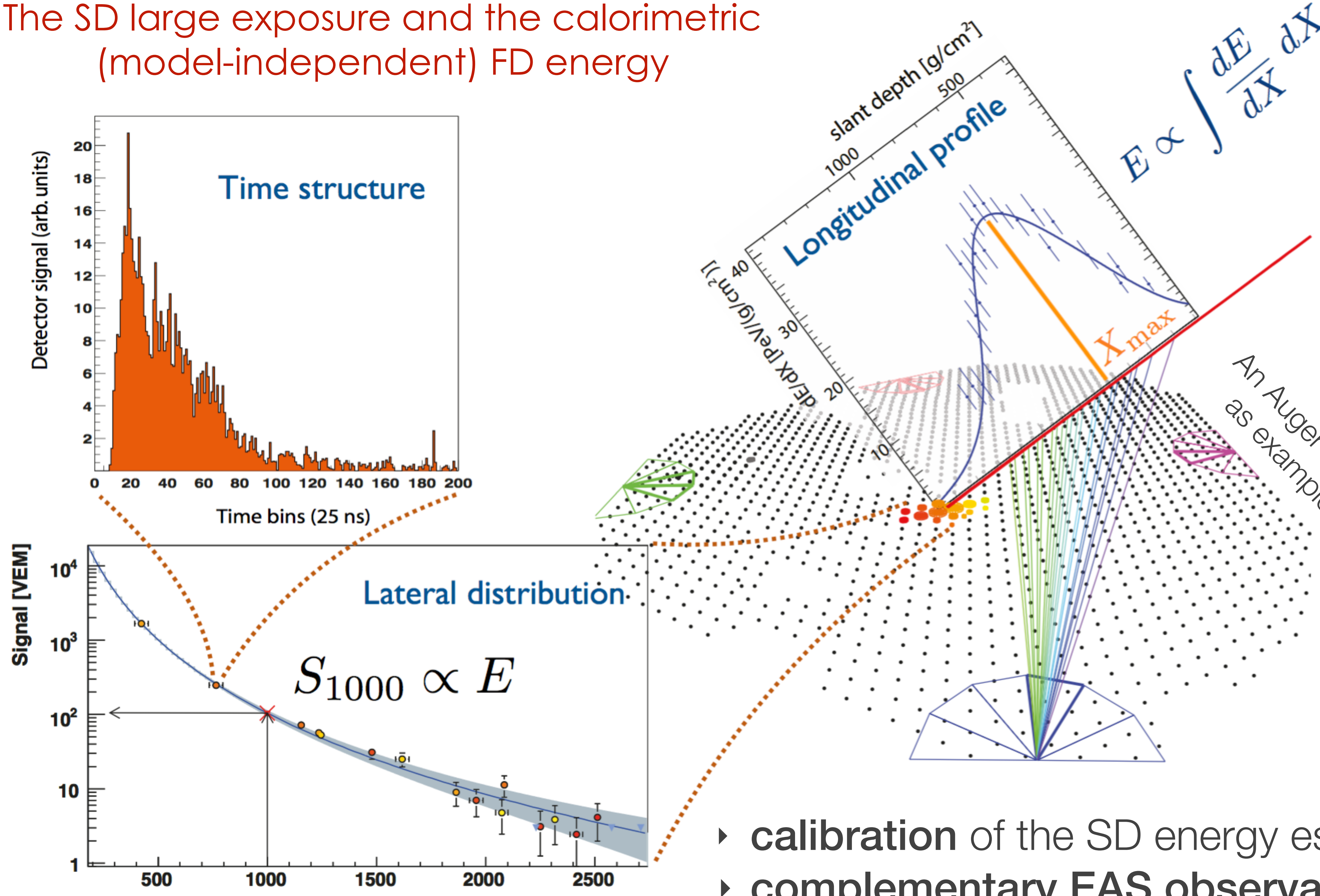




1600 SD on 1.5 km grid
27 telescopes in 5 buildings
atmospheric monitoring systems

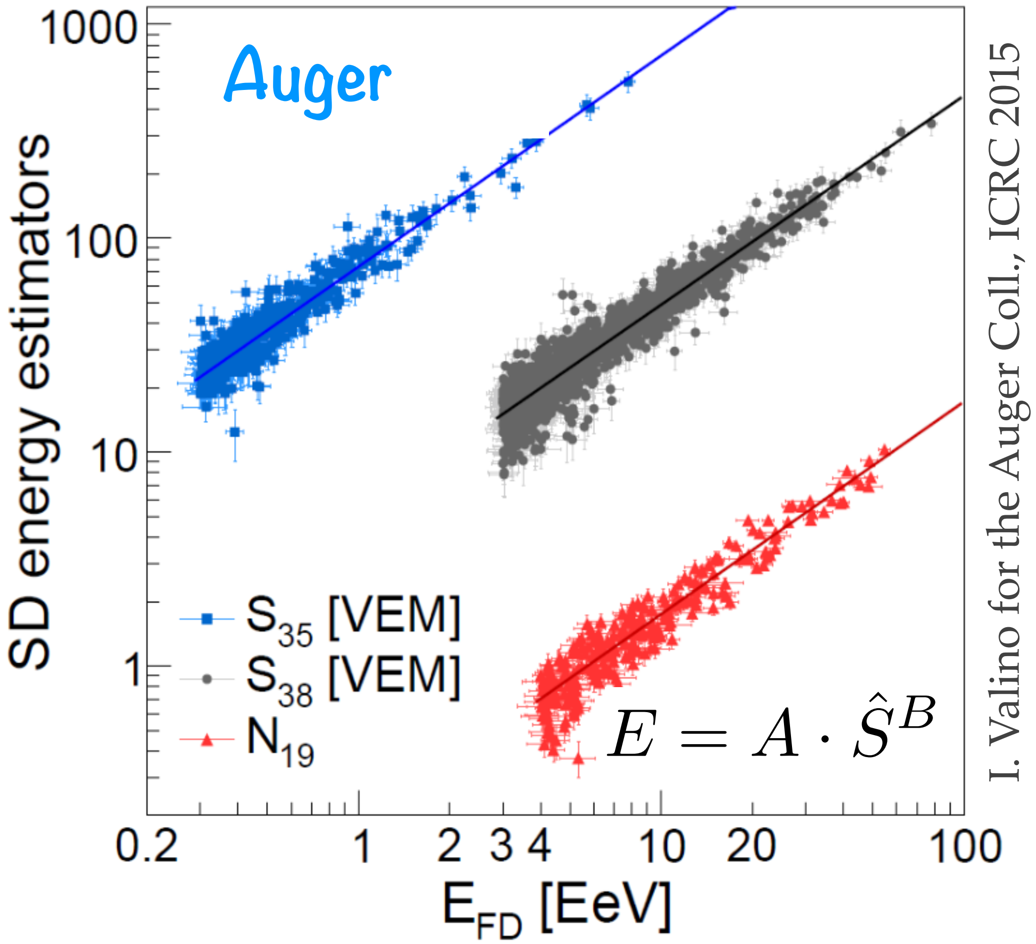
The hybrid concept

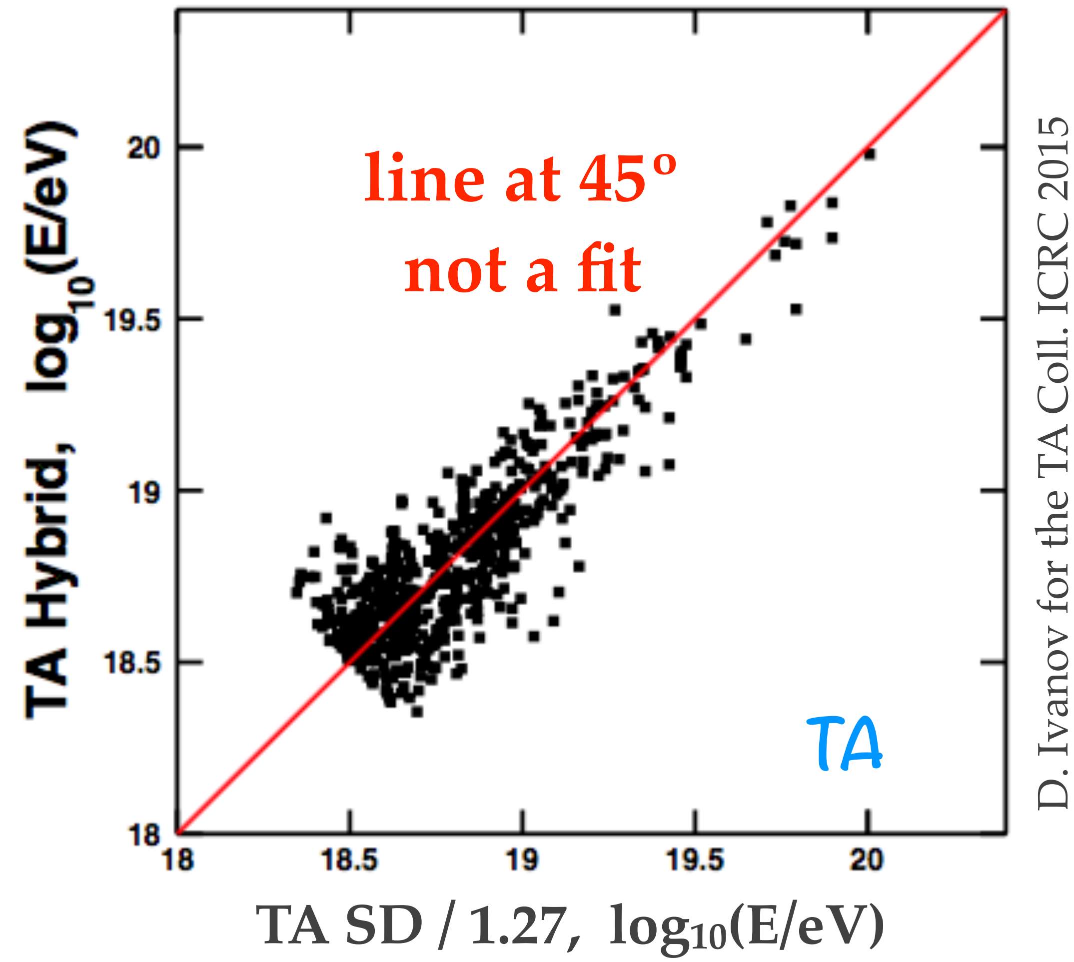
The SD large exposure and the calorimetric (model-independent) FD energy



- **calibration** of the SD energy estimator
- **complementary EAS observables**

Energy calibration with hybrids





	Auger [%]	TA [%]
Atmosphere	3.4-6.2	11
Detector calib.	9	10
Reconstruction	6.5 - 5.6	9
Stability of E scale	5	-
Invisible energy	3 - 1.5	5
Fluorescence Yield	3.6	11
Total	***14***	***21***

SD energy calibrated using a sub-set of hybrid events having SD and FD independent reconstructions

Energy spectrum

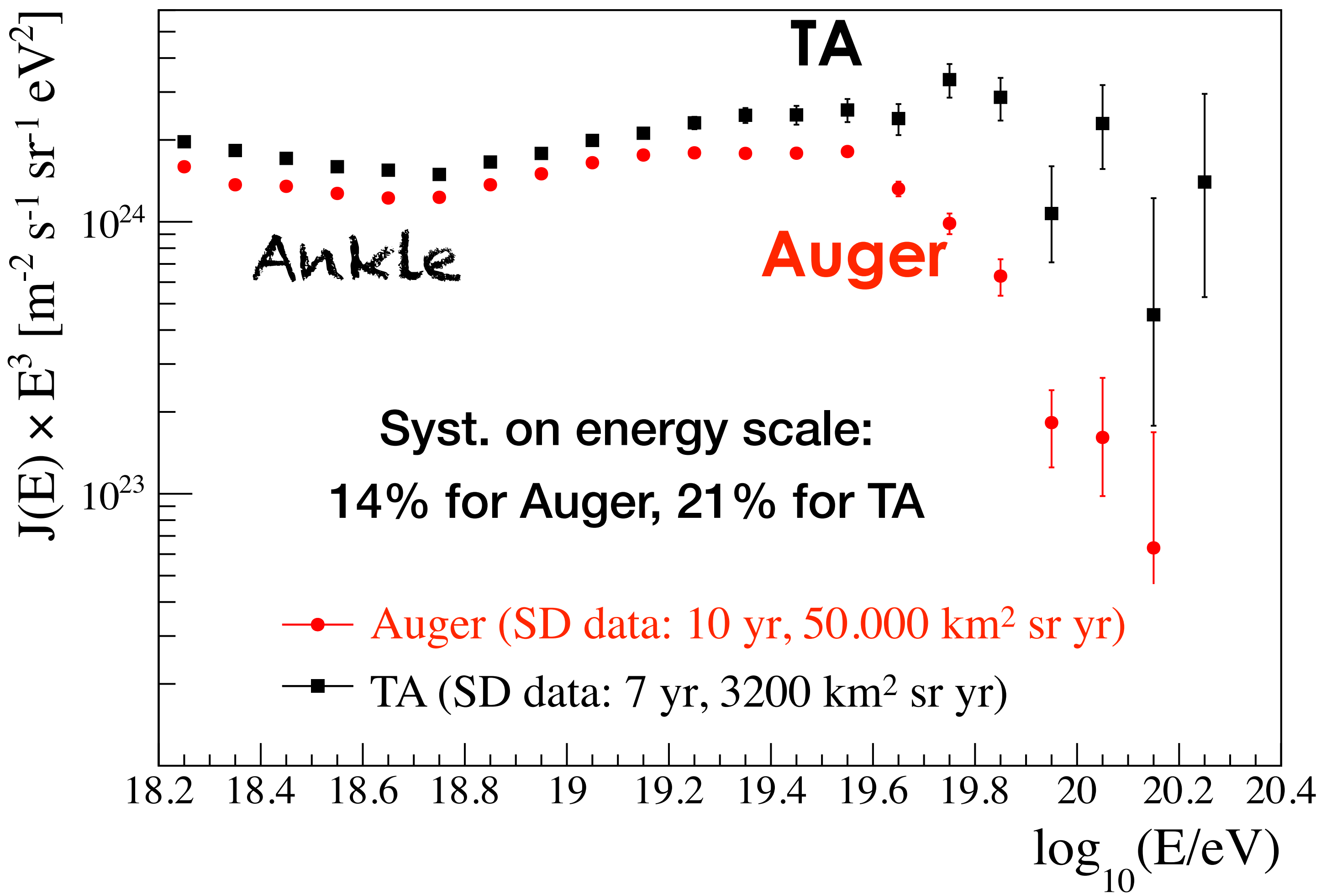
Mass Composition

Hadronic physics

Cosmogenic photons and neutrinos

Anisotropy (see next talk)

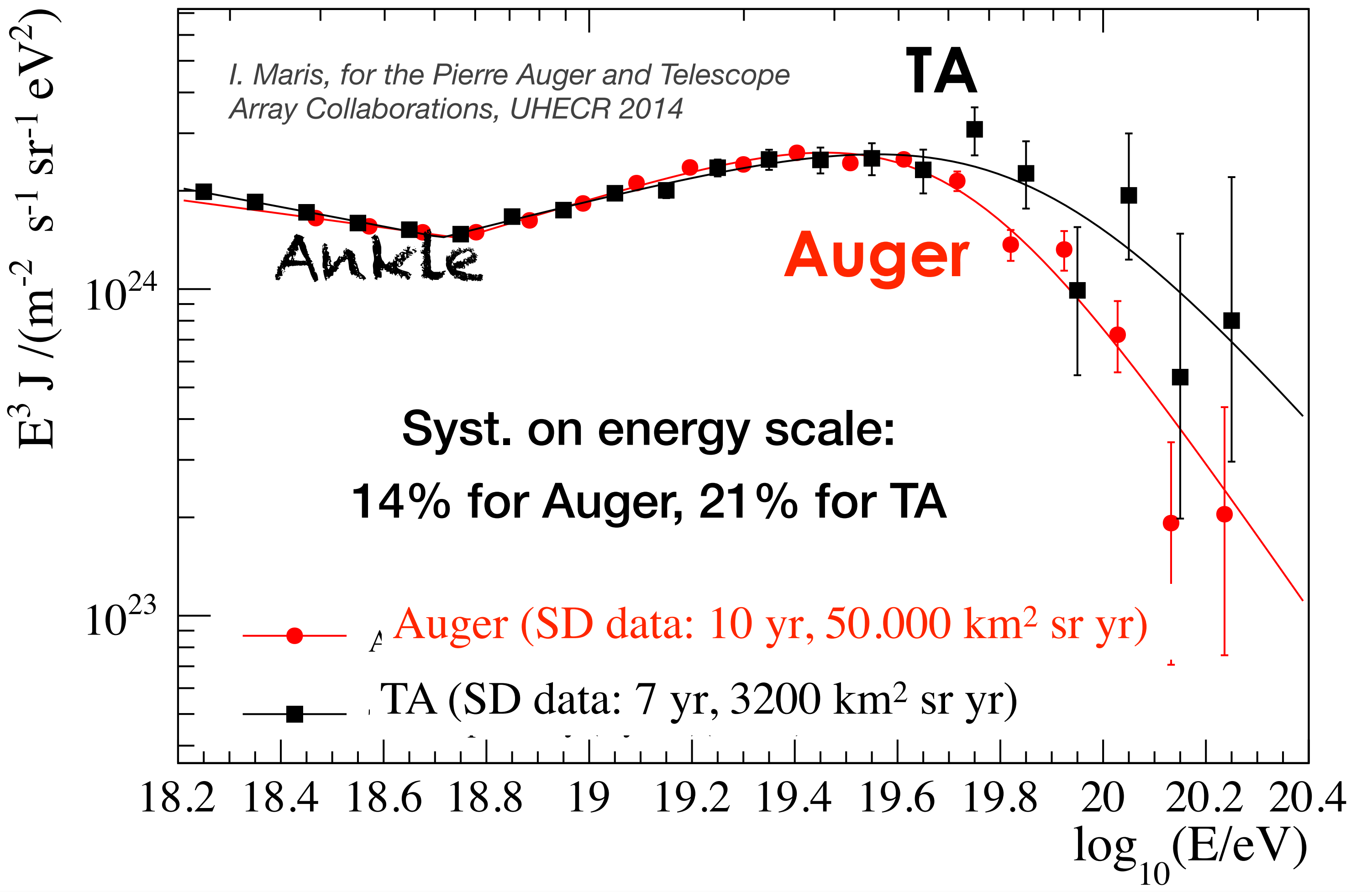
Energy spectrum above 10^{18} eV



	Auger	Telescope Array
E_{ankle} [EeV]	4.82 ± 0.07 ± 0.8	5.2 ± 0.2
$E_{1/2}$ [EeV]	42.1 ± 1.7 ± 7.6	60 ± 7
γ_1 ($E < E_{ankle}$)	3.29 ± 0.02 ± 0.05	3.226 ± 0.007
γ_2 ($E > E_{ankle}$)	2.60 ± 0.02 ± 0.1	2.66 ± 0.02

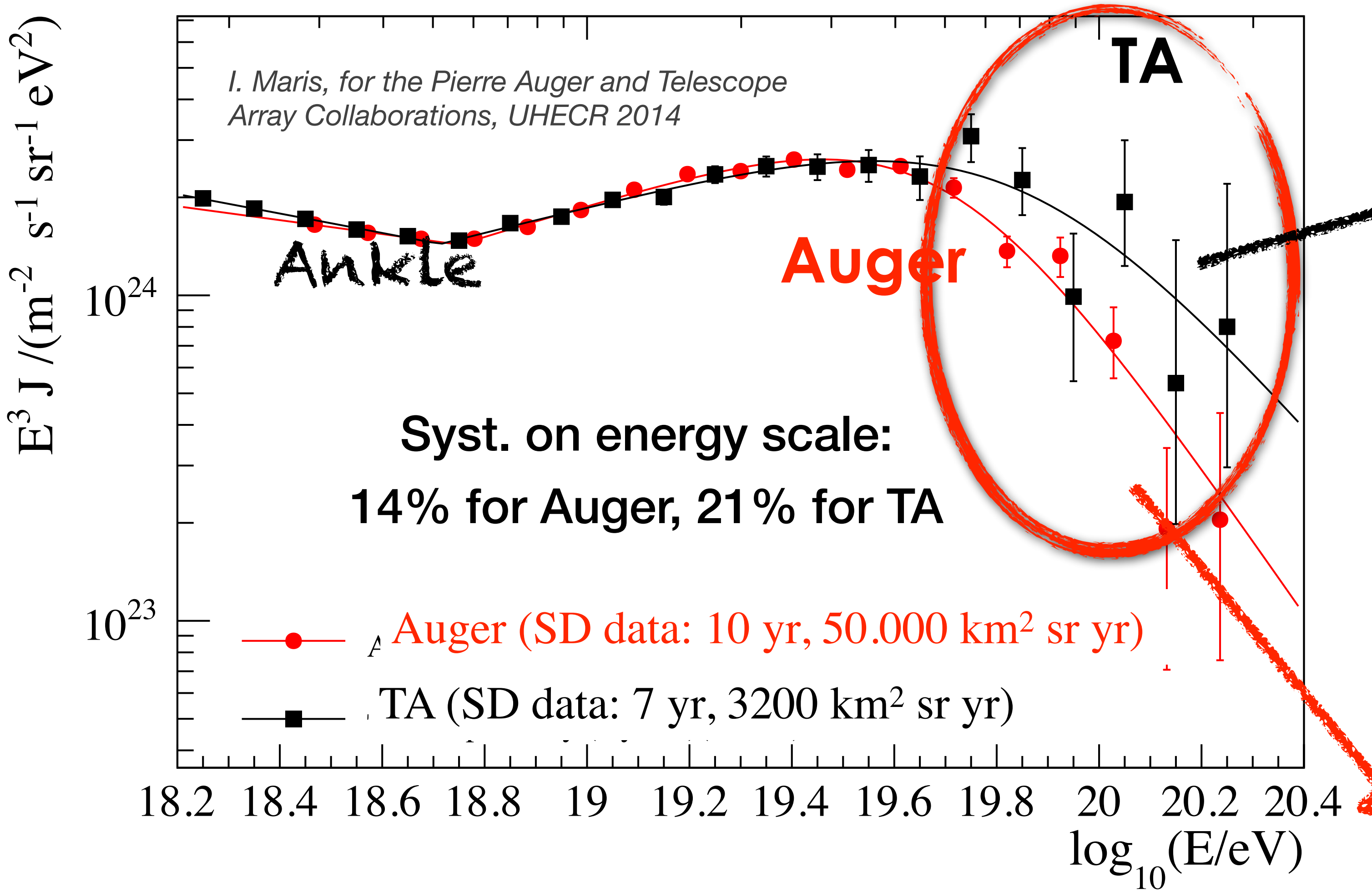
based on ICRC 2015

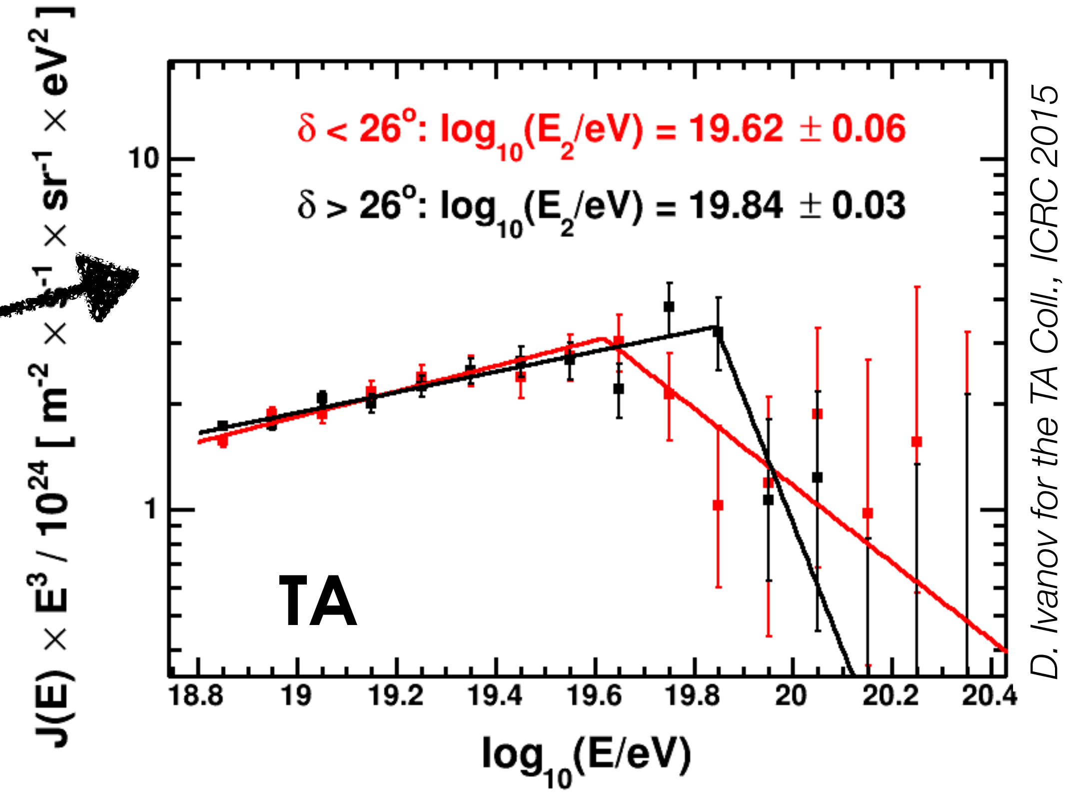
Energy spectrum: a comparison

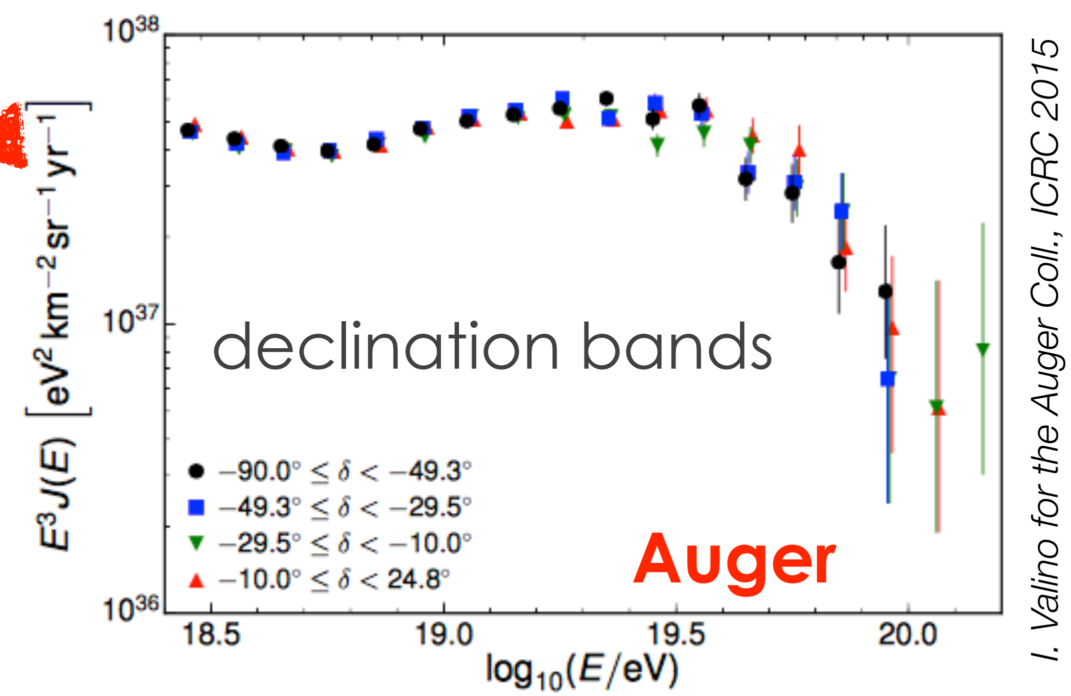


- **Ankle** position in good agreement
- **Flux suppression** at different energies **(different skies?)**

Are Northern and Southern skies different?







- **Ankle** position in good agreement
- **Flux suppression** at different energies **(different skies?)**

Energy spectrum

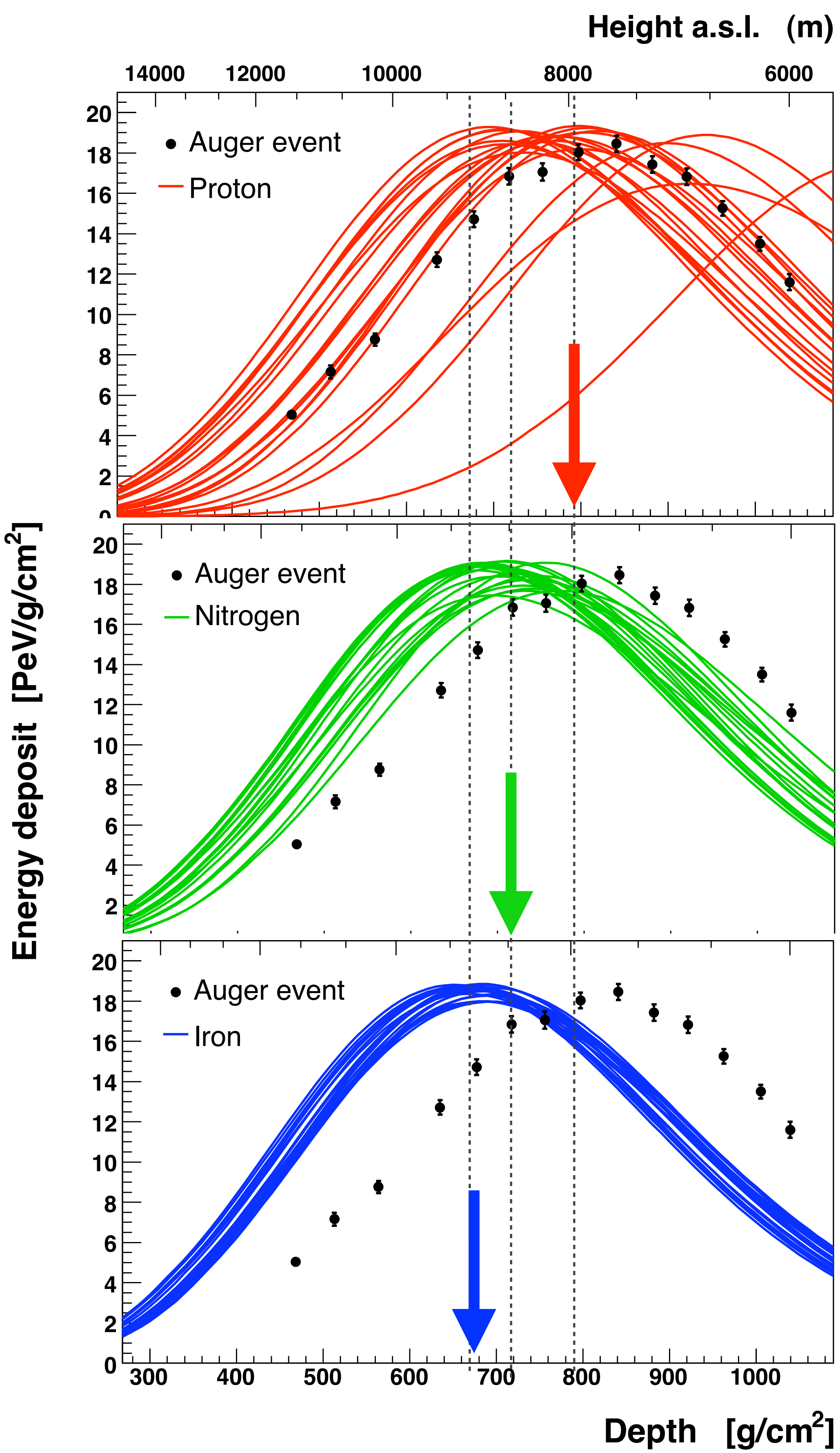
Mass Composition

Hadronic physics

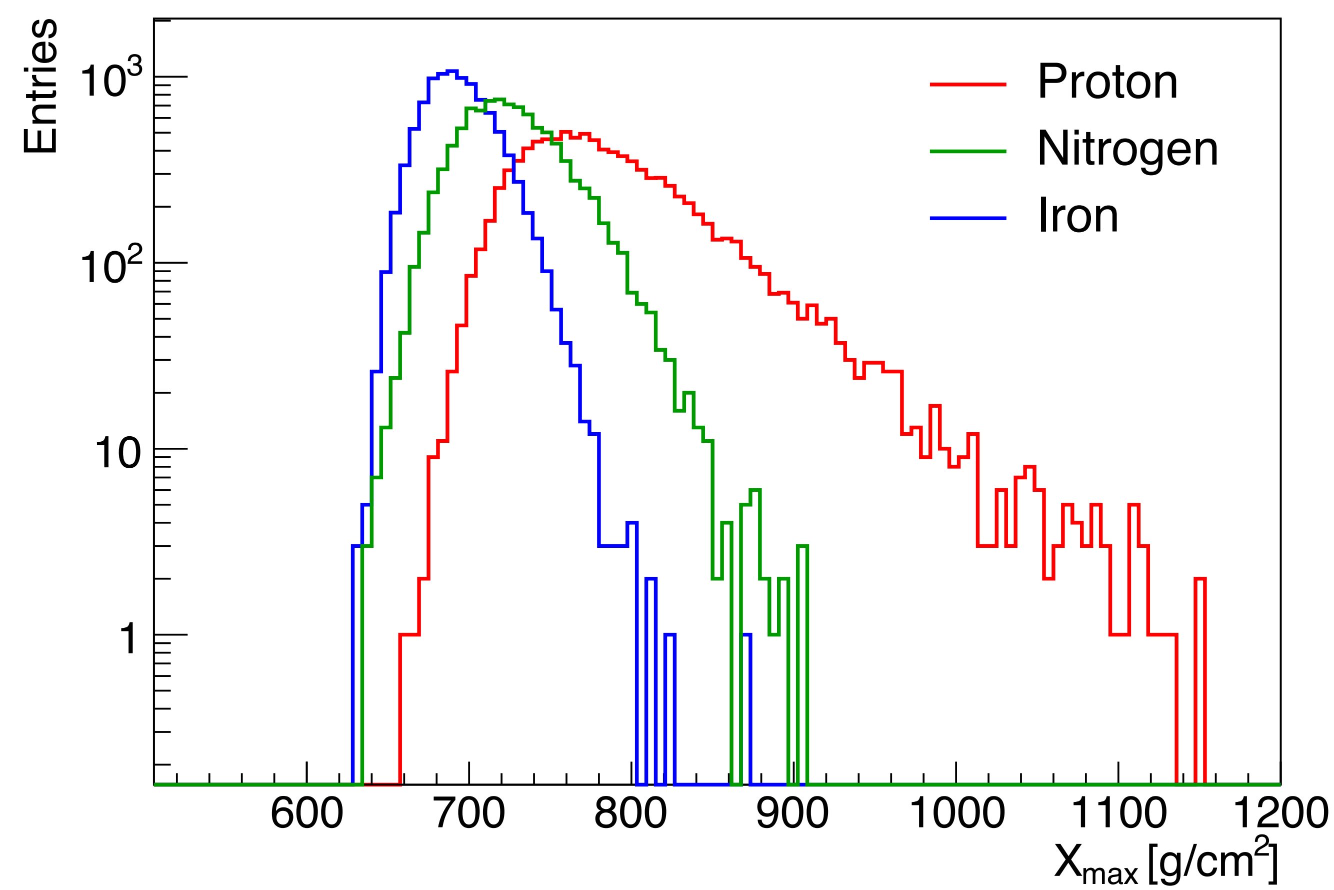
Cosmogenic photons and neutrinos

Anisotropy

Longitudinal Shower Profile

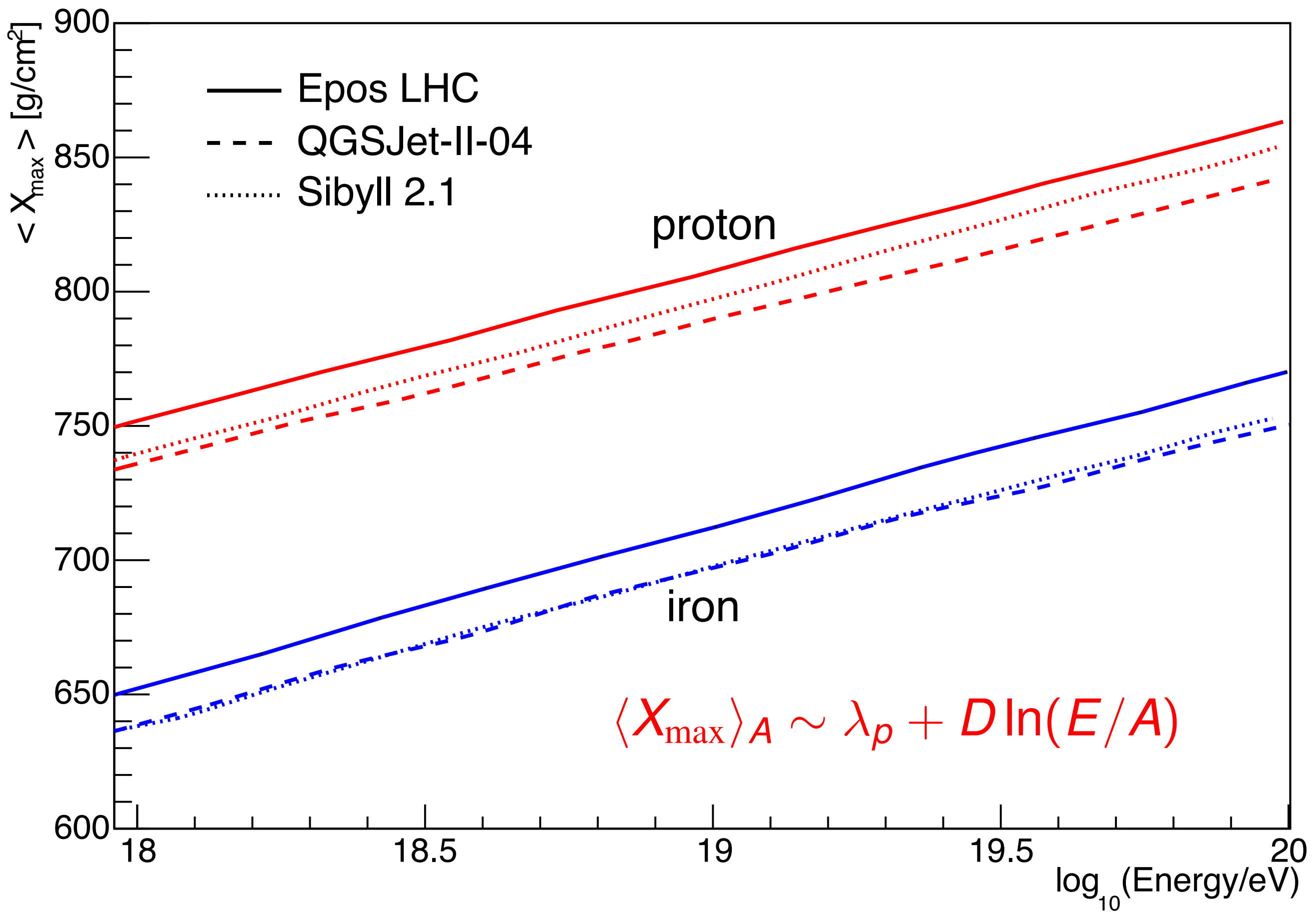


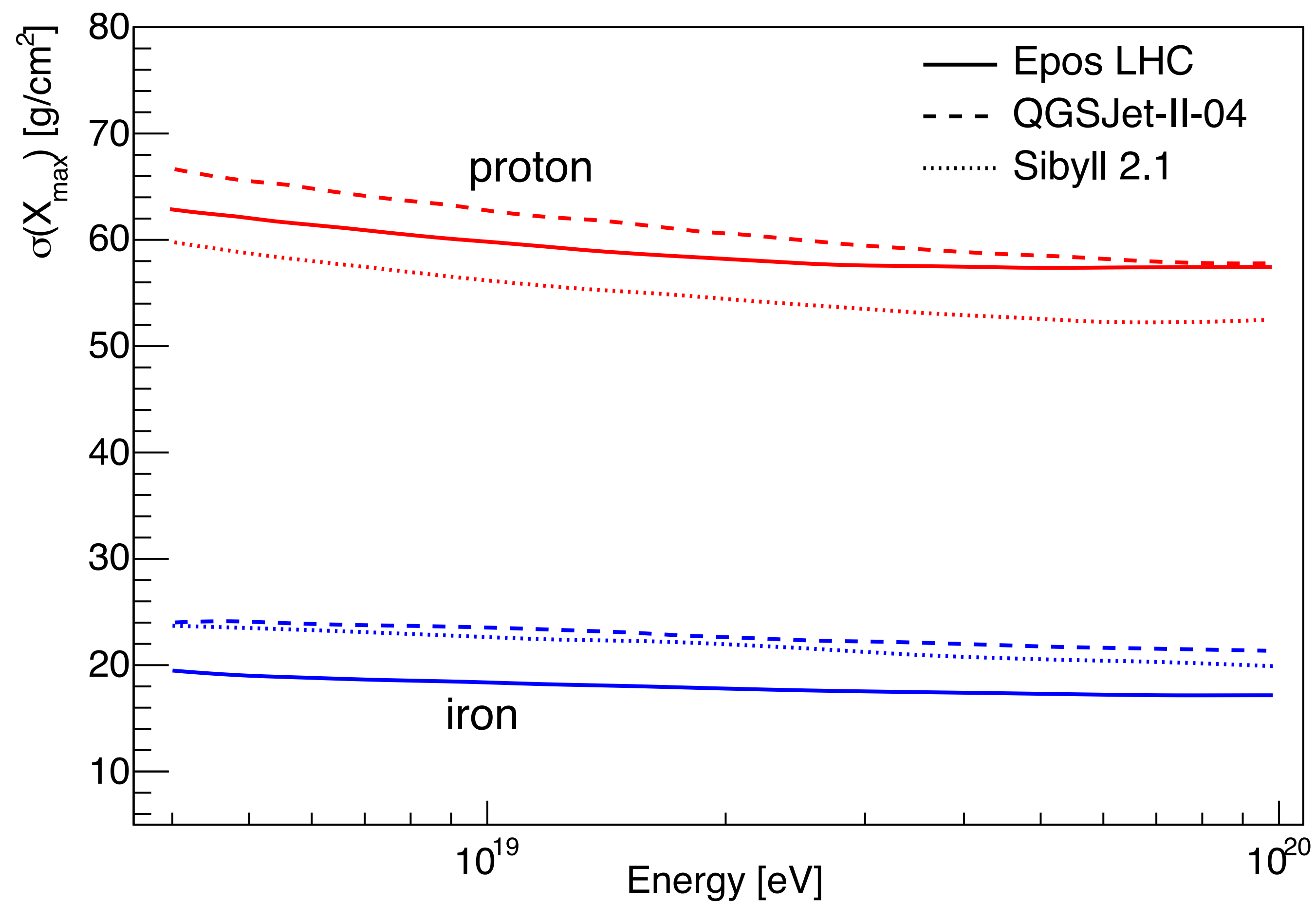
Shower profiles for varying primaries (or hadronic models) differs in **$<X_{max}>$ and its dispersion**



Mass composition from the first two momenta of X_{max} distribution

Mass composition from Xmax distribution



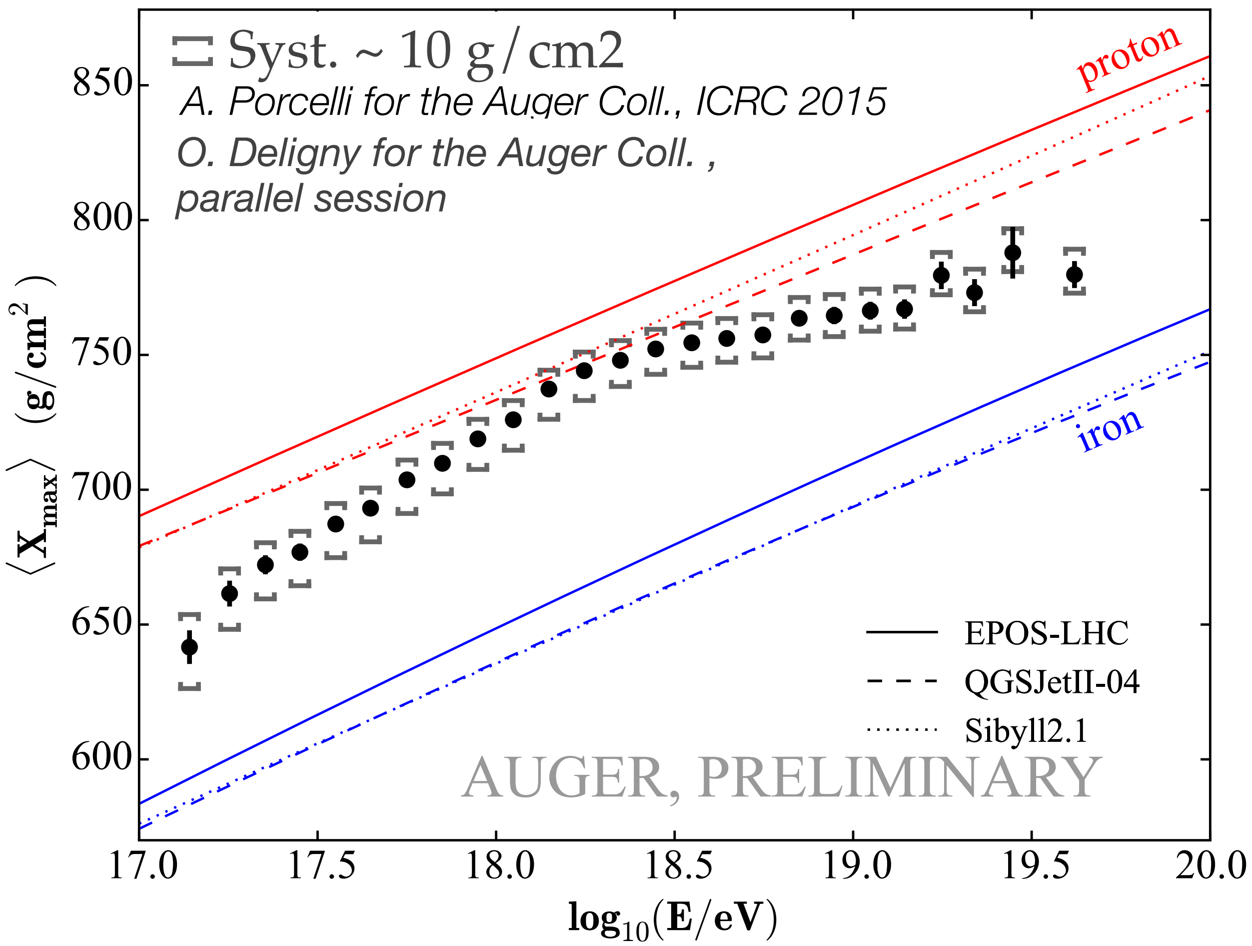


Elongation rate:
D ~ 60 g/cm^2/energy decade

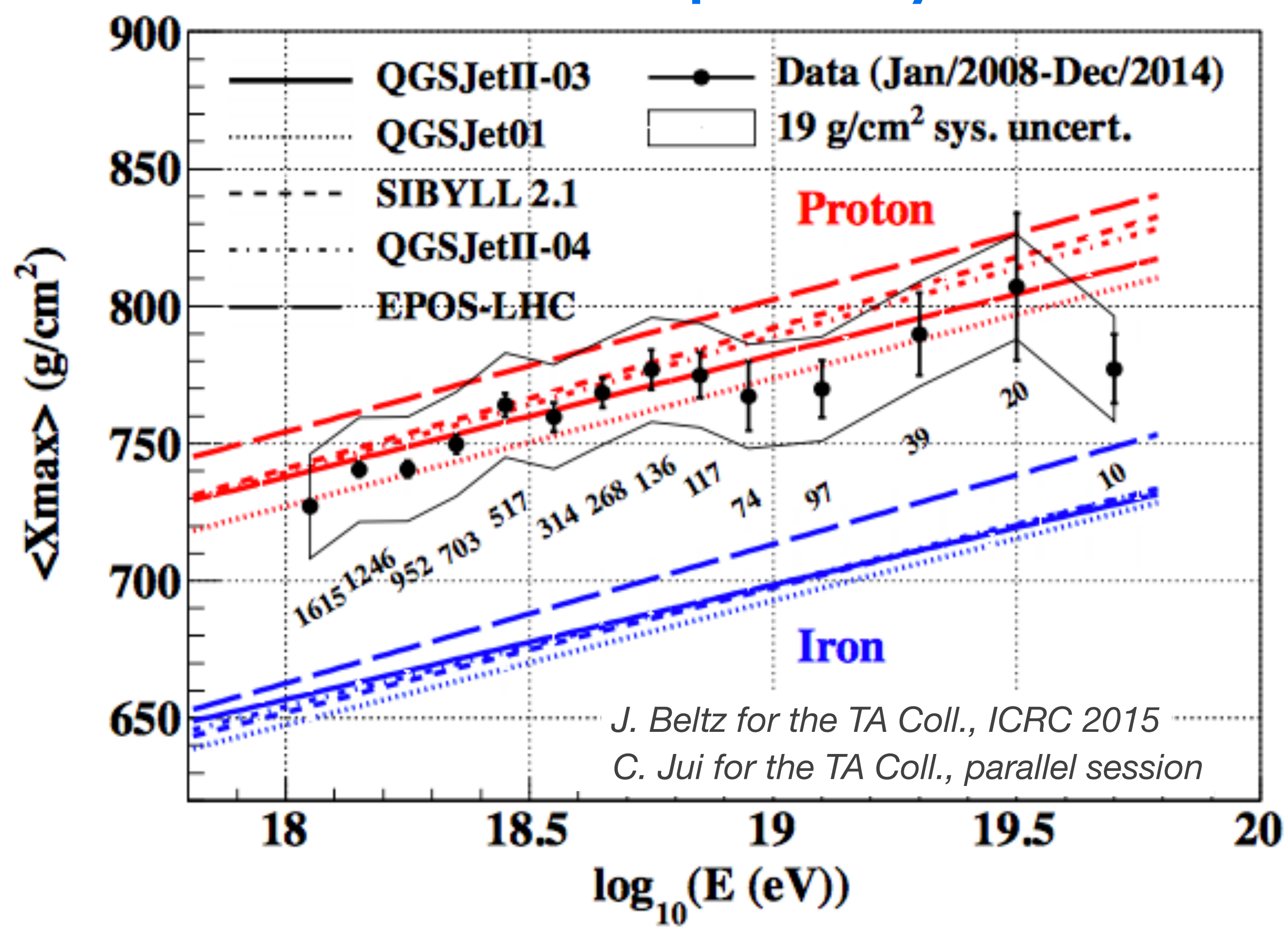
Data: Longitudinal profile fit by a Gaisser-Hillas function
Uncertainties on Xmax measurements < 20 g/cm^2 (depending on the energy and specific FD performance)

Mass composition from Xmax

Pierre Auger Observatory



Telescope Array



Change in composition and break point at E ~$10^{18.3}$ eV

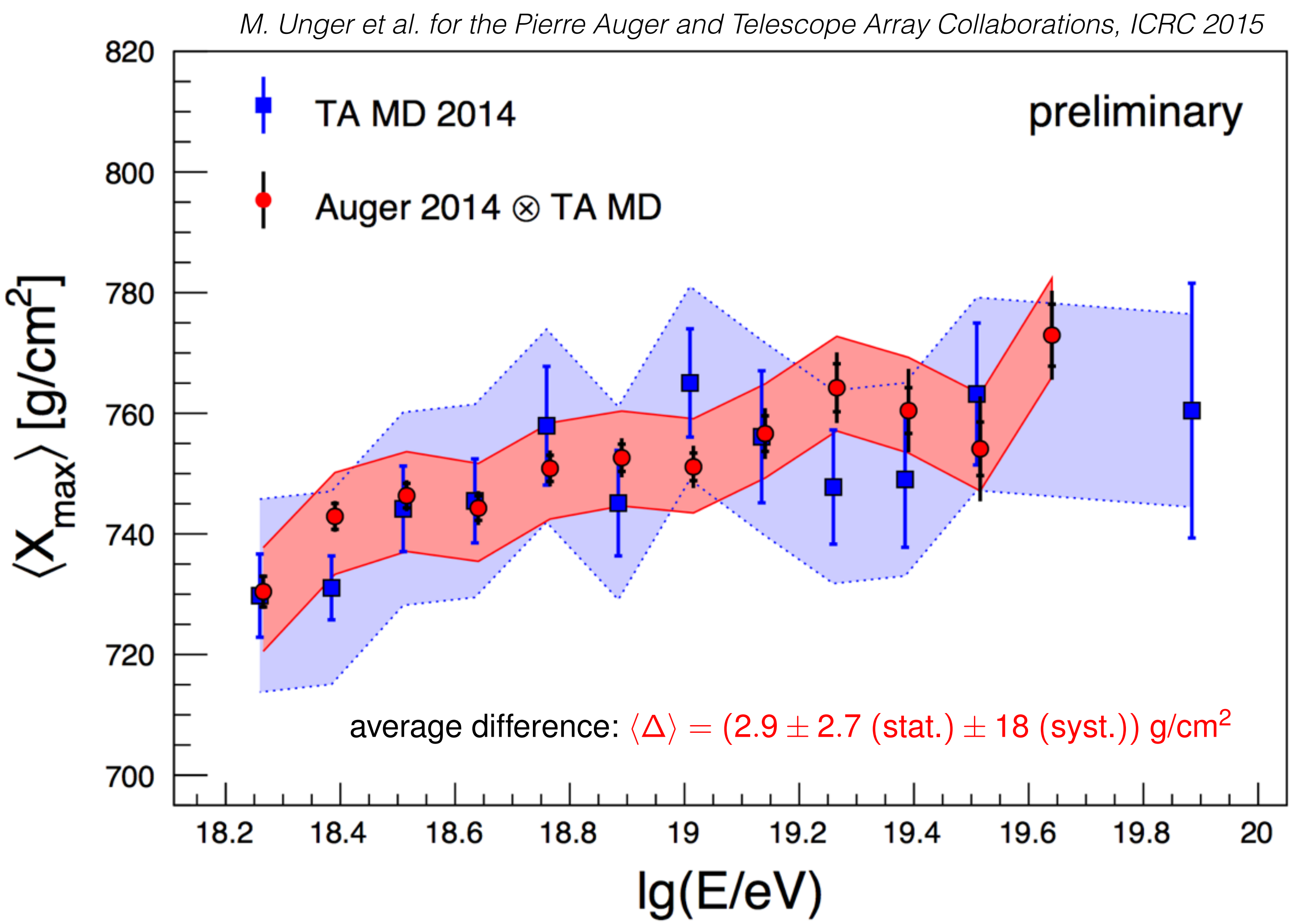
Proton dominant composition

Similar conclusions from $\langle X_{max} \rangle$ and $\sigma(X_{max})$
Flux suppression region not covered by FD measurements

Are Auger and TA results in tension?

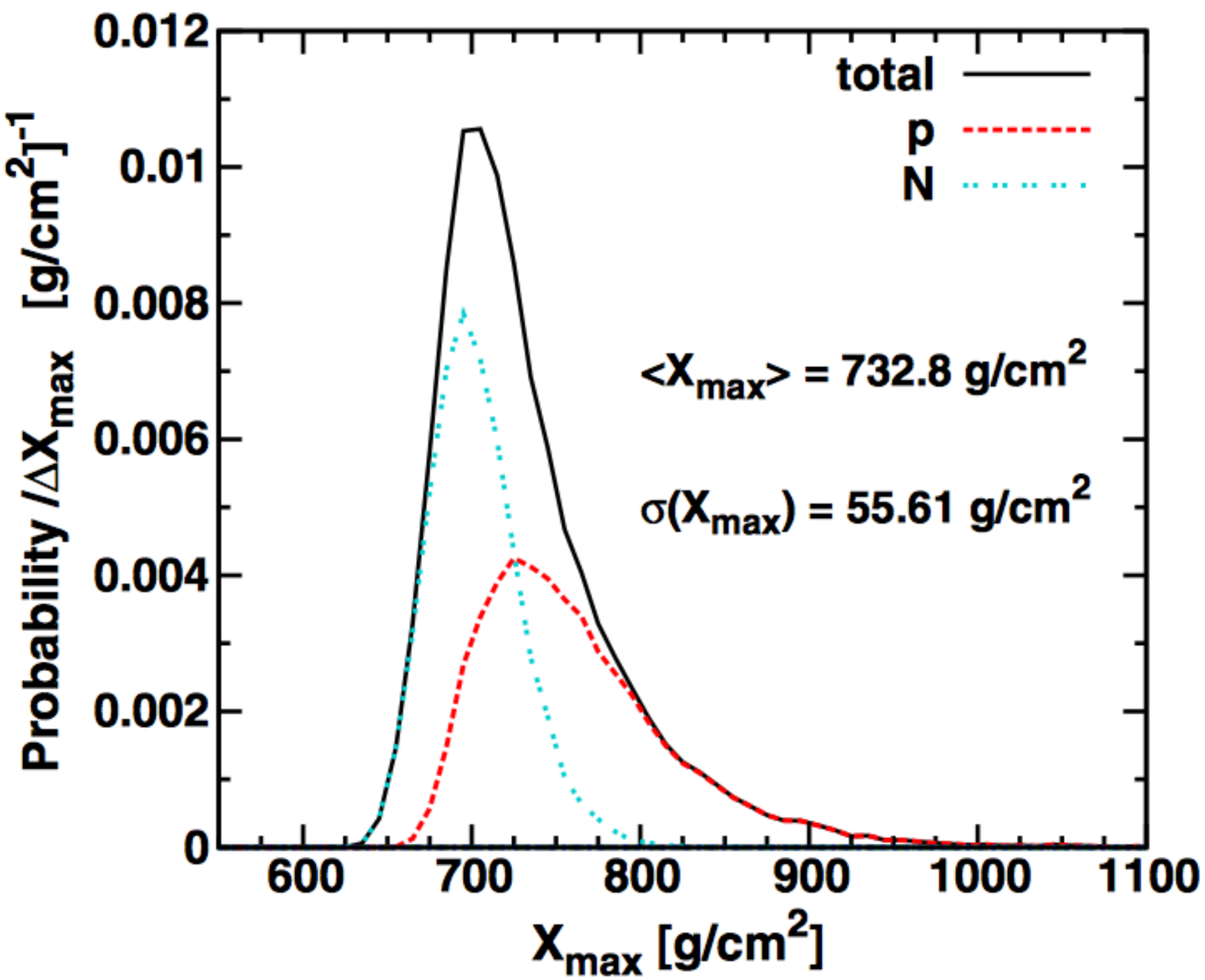
Auger & TA joint work

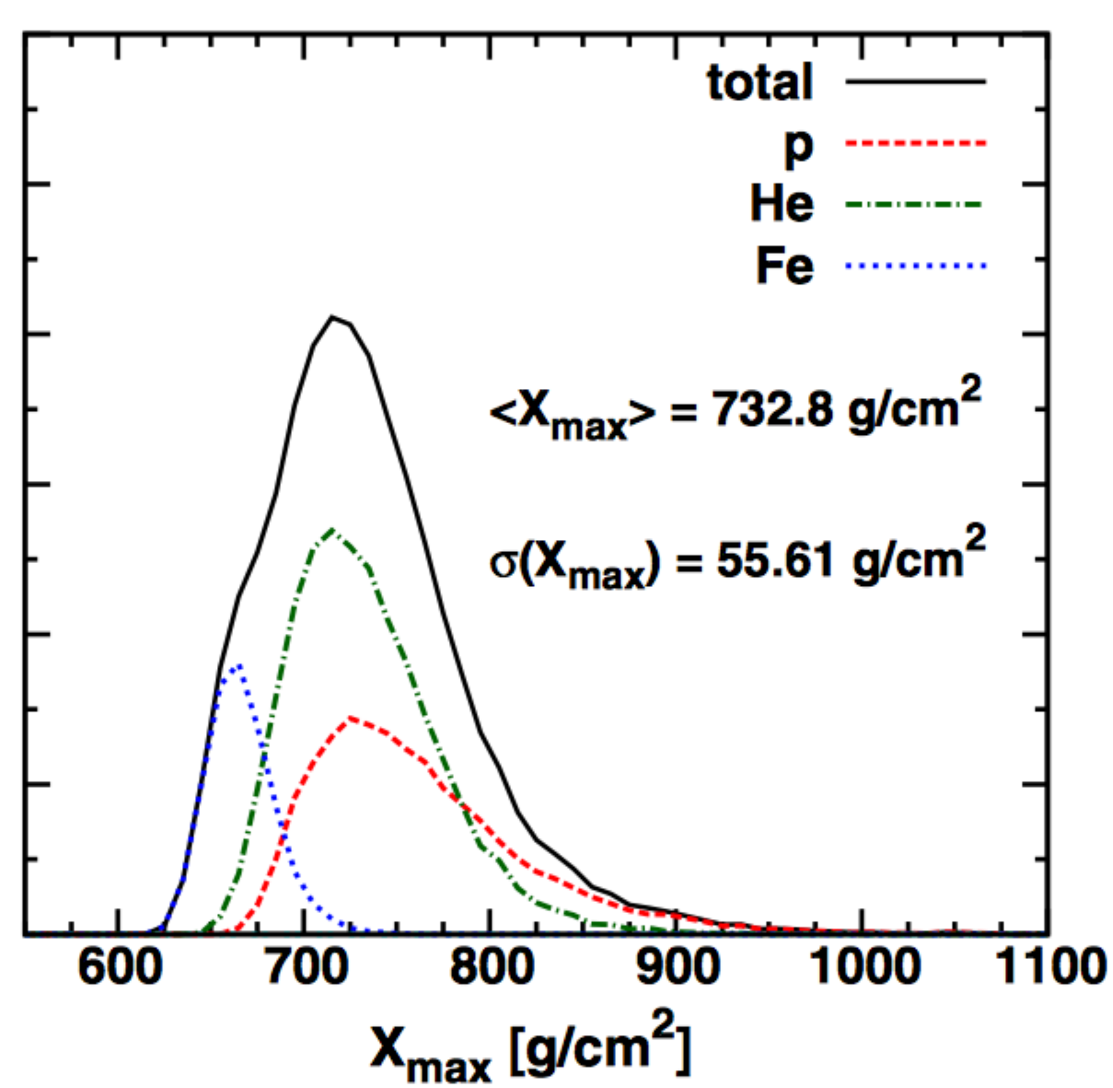
1) Construct a model of X_{max} distribution describing the Auger data
2) Simulate and reconstruct the "Auger-mix" with TA analysis chain



TA uncertainties too large to distinguish between Auger-mix and light composition

Are the moments of the X_{max} distribution enough?



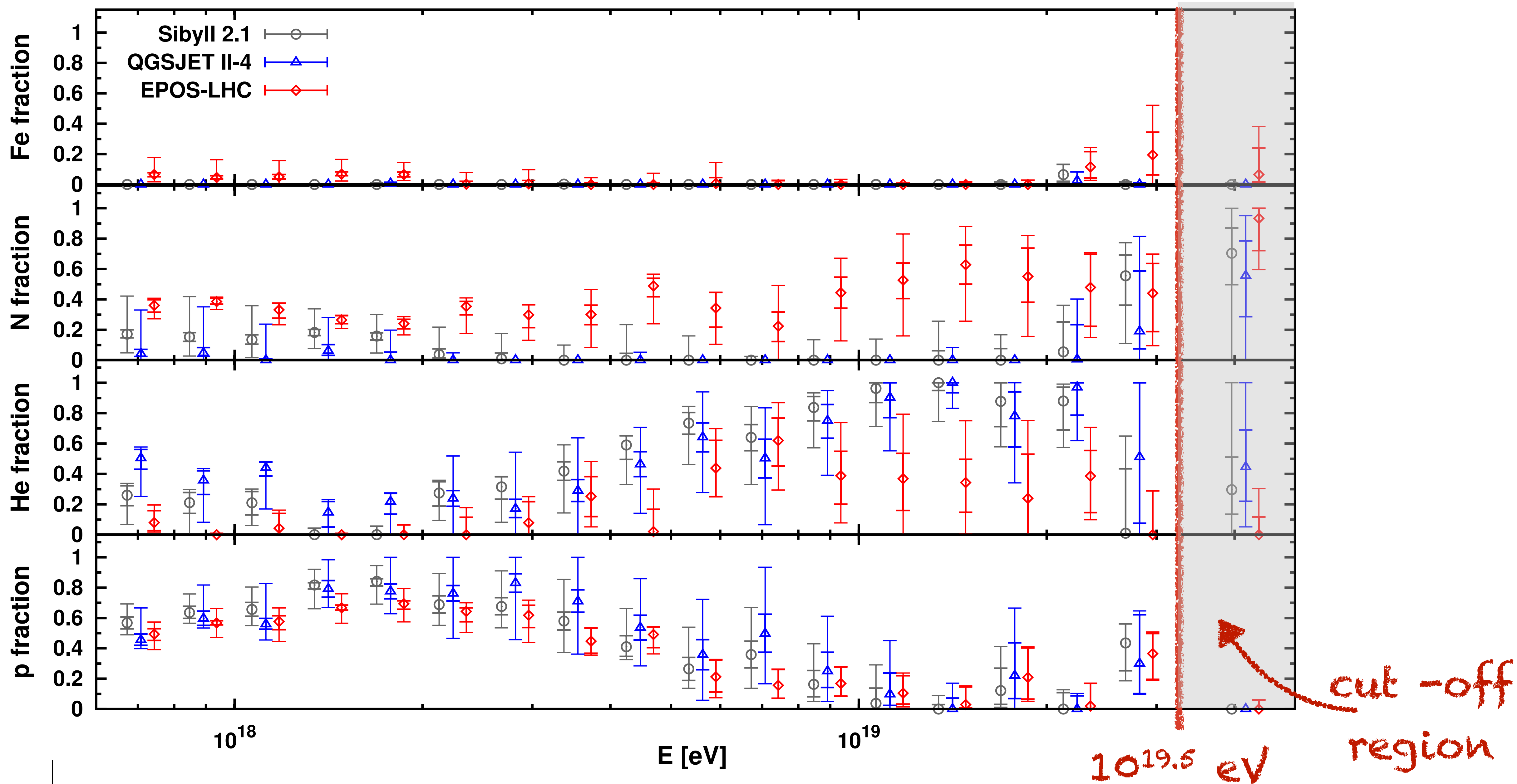


Same X_{max} and $\sigma(X_{max})$ but different mixtures

fit the X_{max} distribution with a ***N-components model***

Inferring the fraction of chemical components

Fit of the X_{max} distribution with simulation templates (N-components)



The Pierre Auger Coll., Phys. Rev. D 90, 122006 (2014)

Energy spectrum

Mass Composition

Hadronic physics

Cosmogenic photons and neutrinos

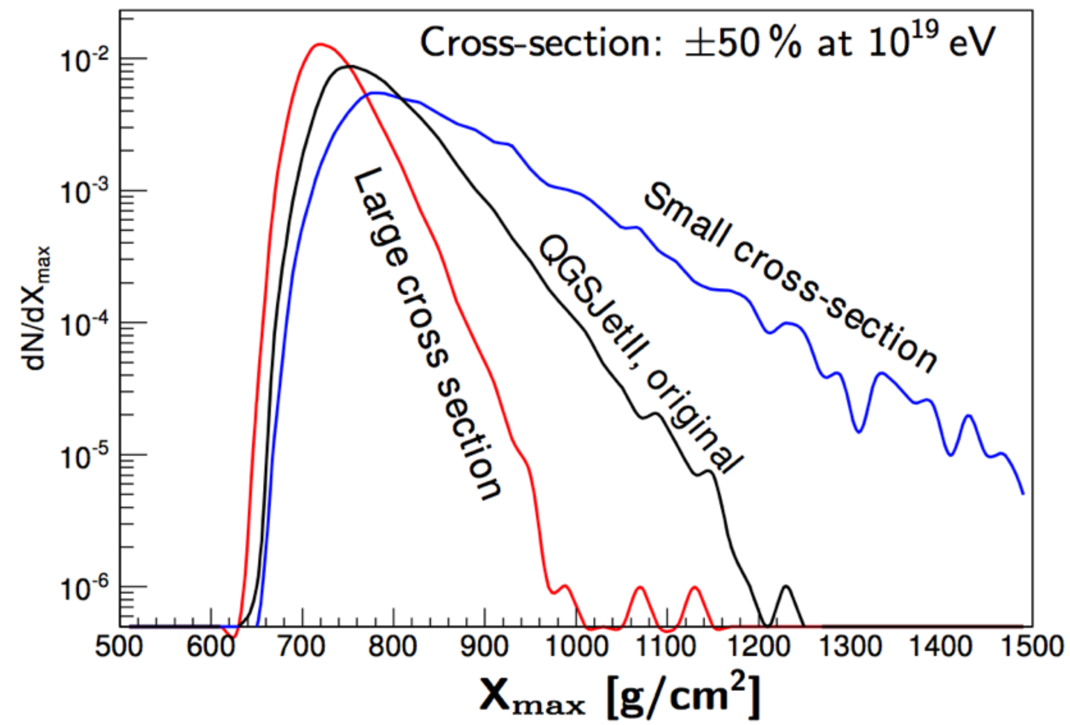
Anisotropy

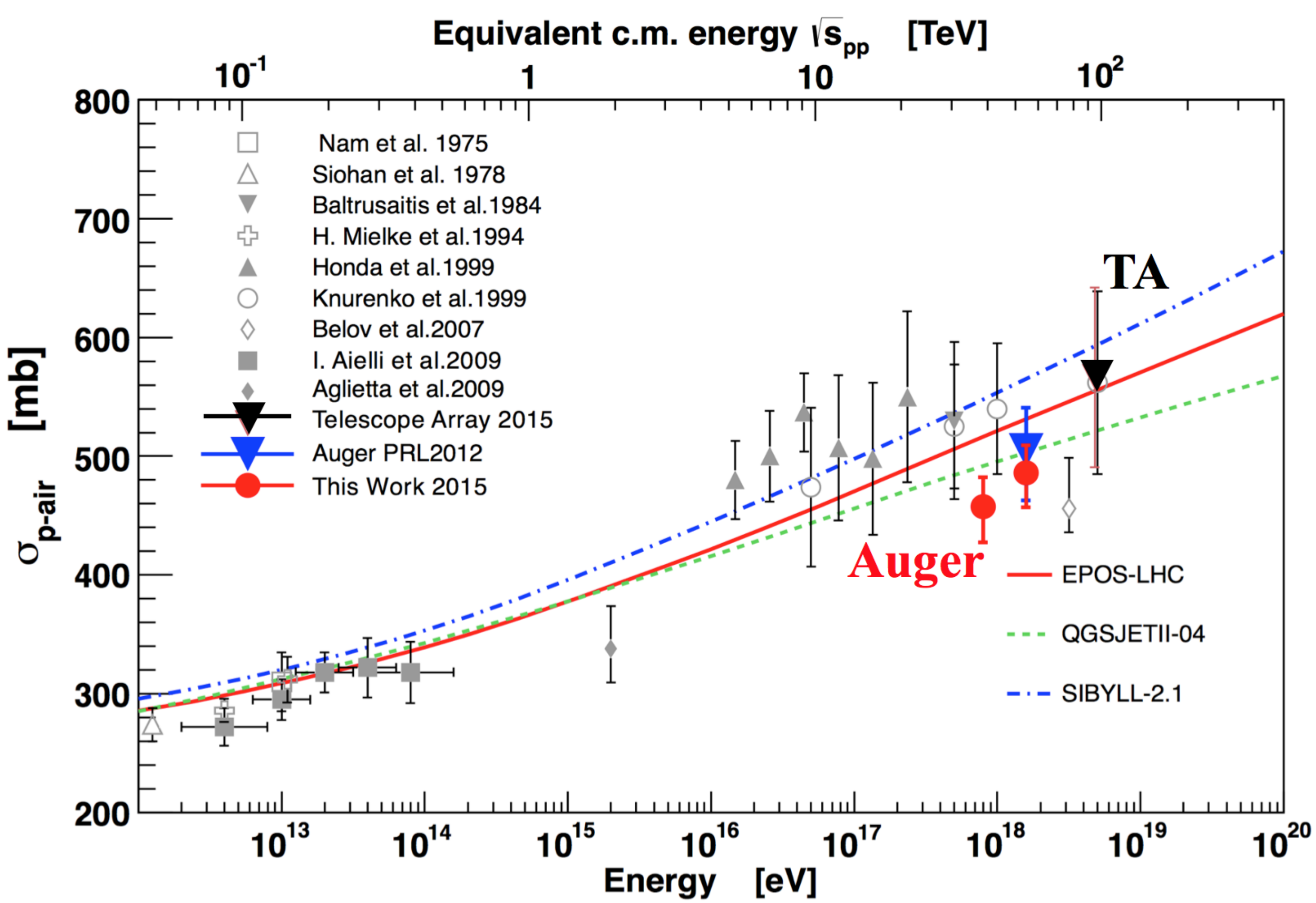
Proton-air cross-section

- Select proton-like events
- Fit the tail of the X_{max} distribution

$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

- Convert Λ_η to $\sigma_{p\text{-}air}$ using MC simulations





$$\sigma^{\text{Auger}}_{\text{p-air}}(E = 10^{17.9}\,eV) = 457.5 \pm 17.8\,(\text{Stat})\,^{+19}_{-25}\,(\text{Syst})\,[\text{mb}]$$

$$\sigma^{\text{Auger}}_{\text{p-air}}(E = 10^{18.2}\,eV) = 485.8 \pm 15.8\,(\text{Stat})\,^{+19}_{-25}\,(\text{Syst})\,[\text{mb}]$$

$$\sigma^{\text{TA}}_{\text{p-air}}(E = 10^{18.68}\,eV) = 567.0 \pm 70.5\,(\text{Stat})\,^{+29}_{-25}\,(\text{Syst})\,[\text{mb}]$$

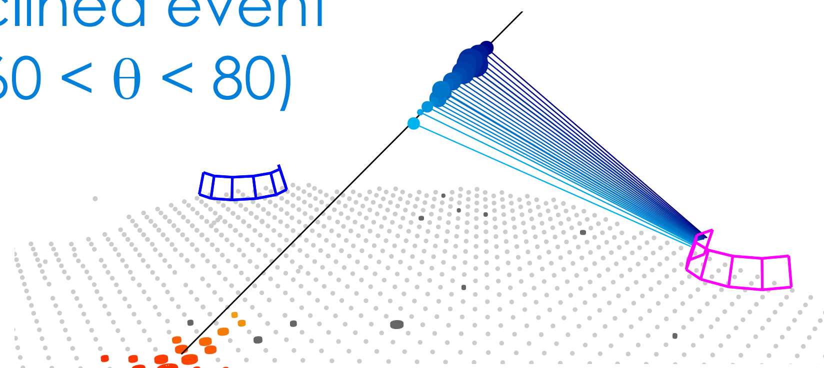
Main systematics source:

- helium contamination

R. Abassi for the Telescope Array Collab., ICRC 2015
R. Ulrich, for the Pierre Auger Collab., ICRC 2015

Test of air-shower models at UHE

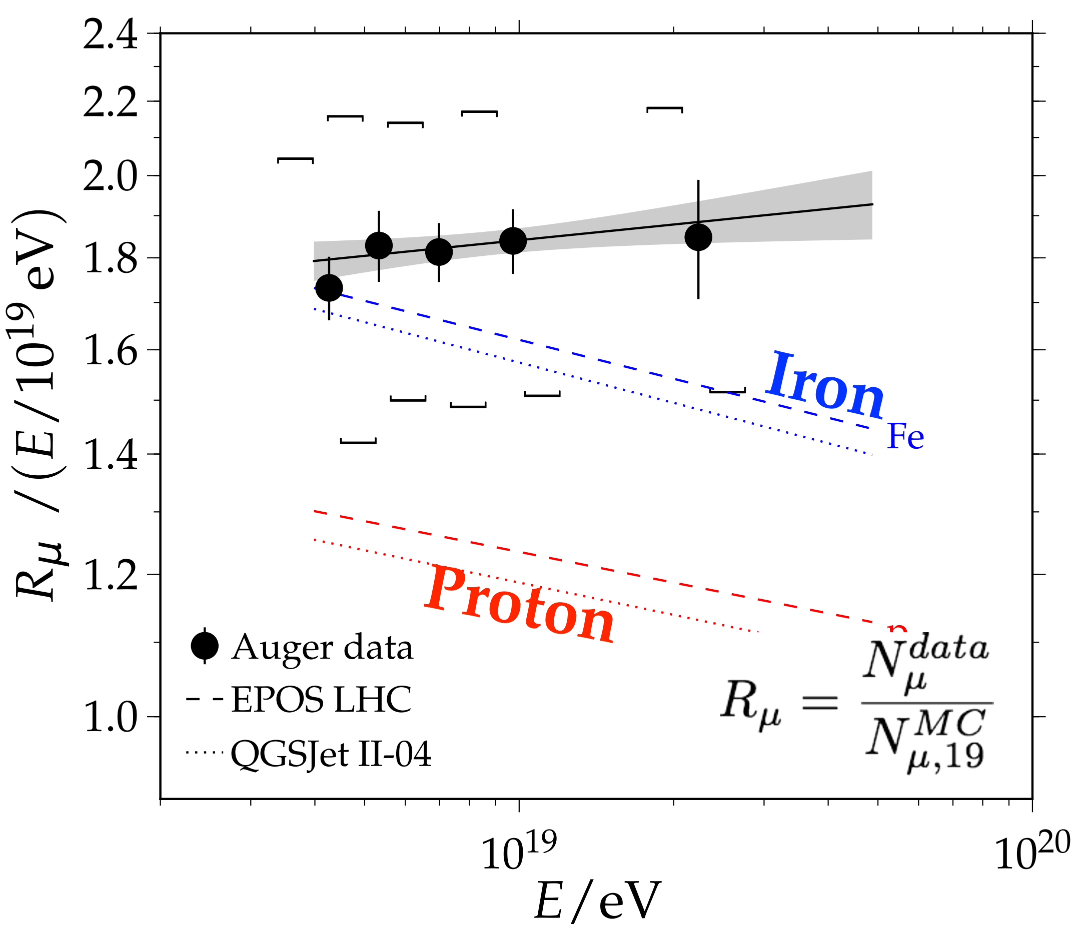
Inclined event (60 < θ < 80)

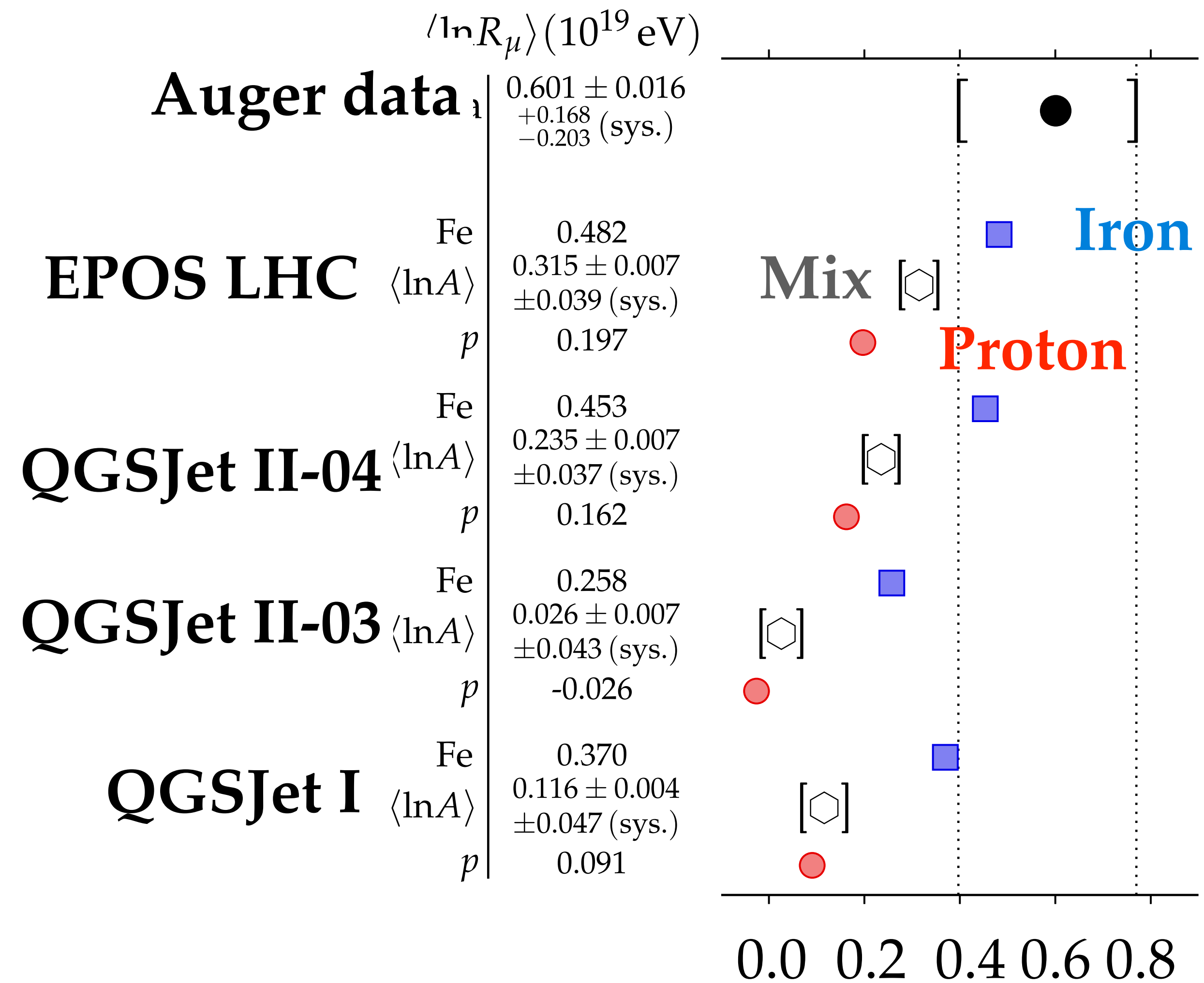


The Pierre Auger Collaboration, Phys. Rev. D 91, 032003 (2015)

Using the signal in the Auger SD

Confirmed with an independent analysis (θ < 60°)





The Pierre Auger Collab., Phys. Rev. D 91, 032003 (2015)
L.Collica for the Auger Collab.,ICRC 2015

Muon deficit in simulations from 30% to 80% at 10^{19} eV

Energy spectrum

Mass Composition

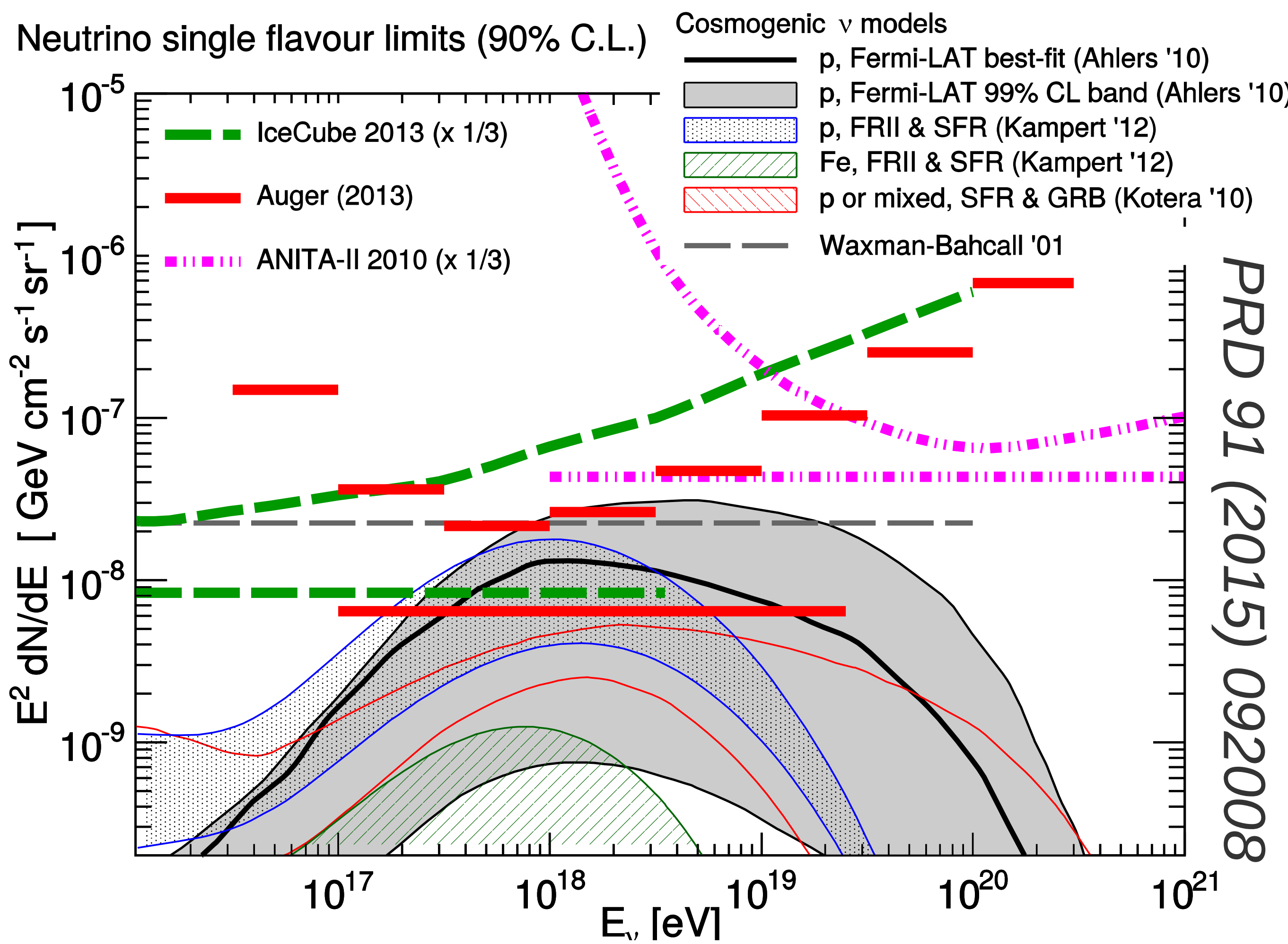
Hadronic physics

Cosmogenic photons and neutrinos

Anisotropy

Cosmogenic neutrinos...

The Pierre Auger Collaboration, PRD 91 (2015)

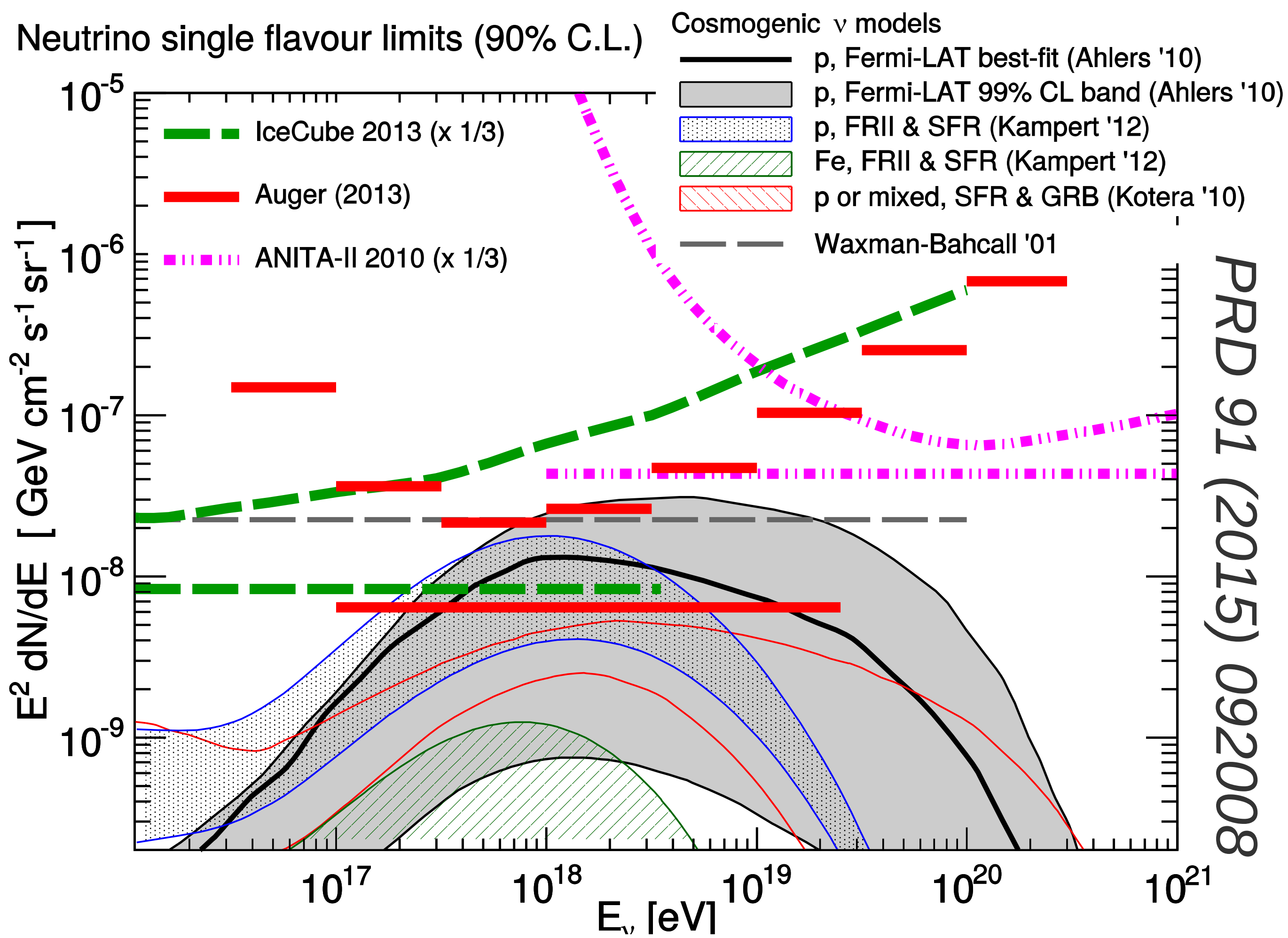


✓ **Waxman-Bahcall landmark reached**

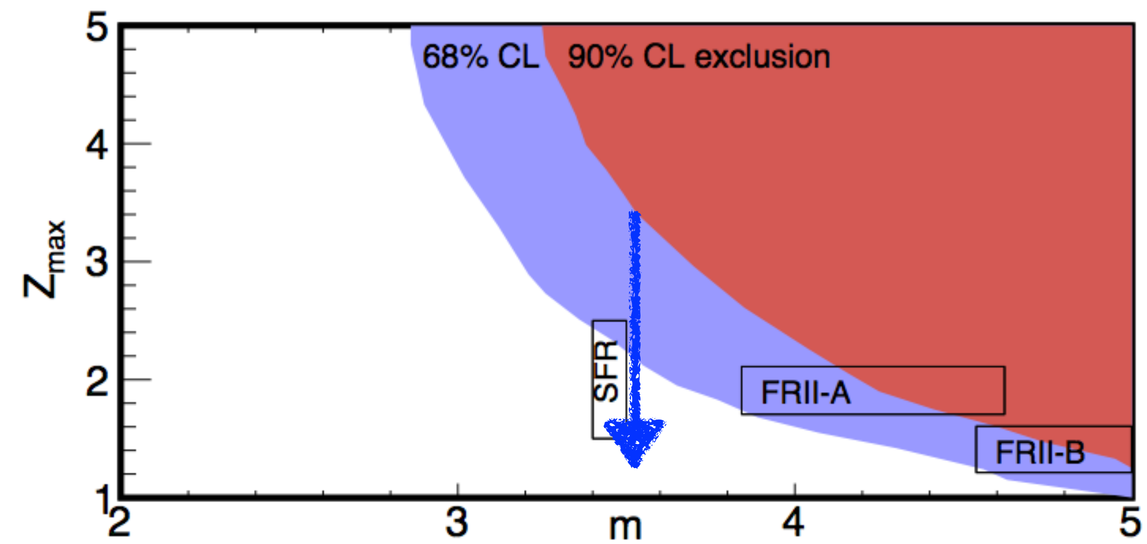
✓**cosmogenic model with pure p composition at the source and strong evolution disfavored**

Cosmogenic neutrinos...

The Pierre Auger Collaboration, PRD 91 (2015)



The IceCube Collaboration, arXiv:1607.05886



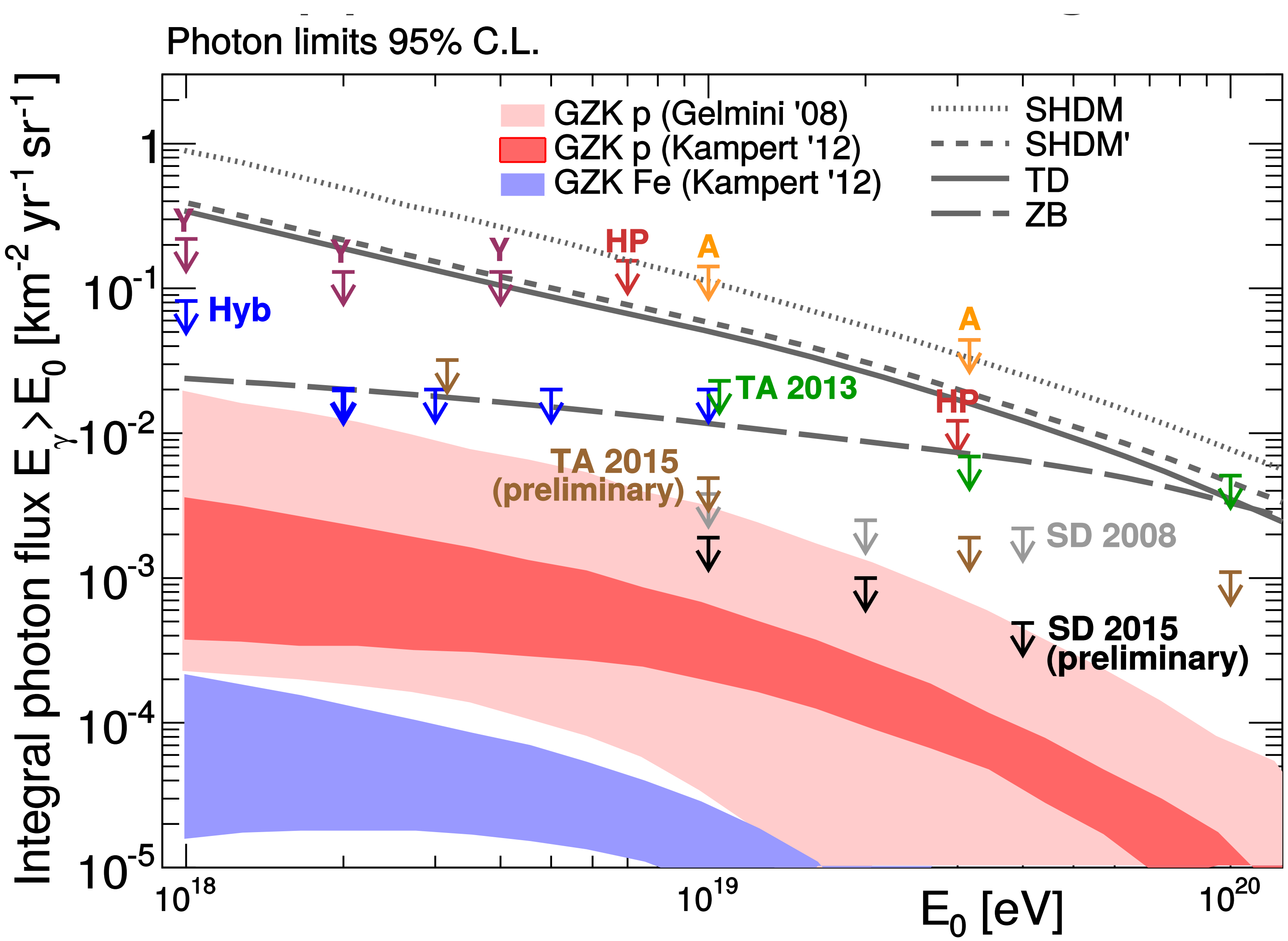
✓ **Waxman-Bahcall landmark reached**

✓ **cosmogenic model with pure p composition at the source and strong evolution disfavored**

A proton dominant composition scenario is disfavored if sources of UHECRs have an evolution stronger than SFR (for zmax = 2)

... and photons

UHE photons observed from EAS development (deep Xmax, shower particles content)



- ✓ **top-down models disfavored**
- ✓ **GZK flux region within reach**

Energy spectrum

Mass Composition

Hadronic physics

Cosmogenic photons and neutrinos

Anisotropy (see next talk)

Anisotropy at UHE (E ≳ 55 EeV)

No significant deviation from isotropy at small angular scale.
Maximum significance at intermediate angular scales.

Telescope Array

Max significance: 5.1σ (pre-trial)
post-trial: 3.4 σ
E_{thr} > 57 EeV, ψ = 20°

(N_{obs} = 24, N_{bg}=6.88)

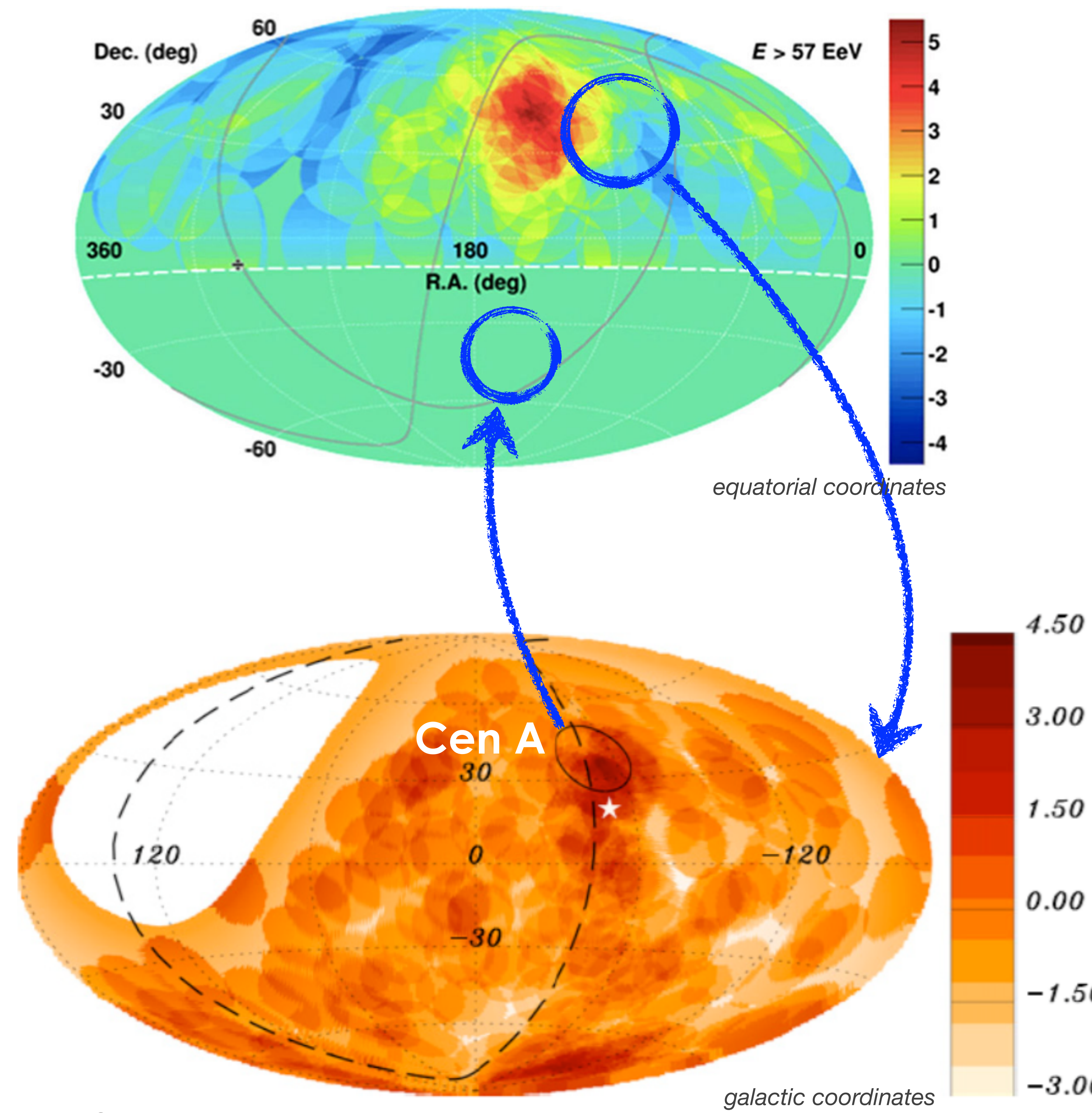
K.Kawata for the Telescope Array Collab., ICRC 2015

Pierre Auger Observatory

Largest excess: pre-trial 4.3 σ,
69% post-trial probability)

E_{thr} > 54 EeV, ψ = 12°,
N_{obs} = 14 / N_{bg} = 3.23

The Pierre Auger Collaboration, ApJ, 804 , 15, (2015)
J. Aublin for the Auger Coll., ICRC 2015

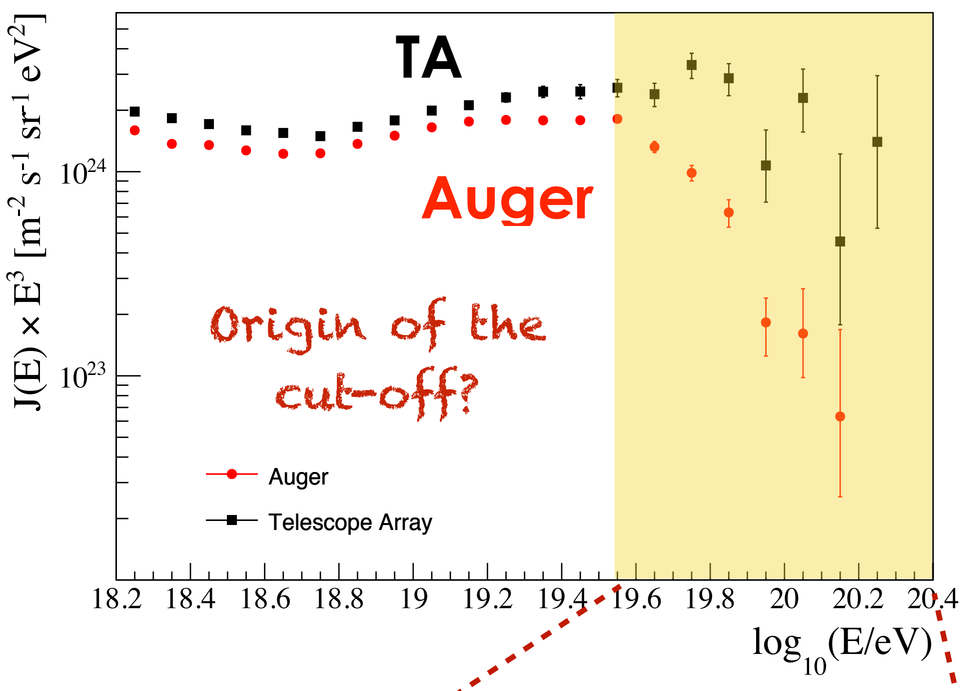


equatorial coordinates

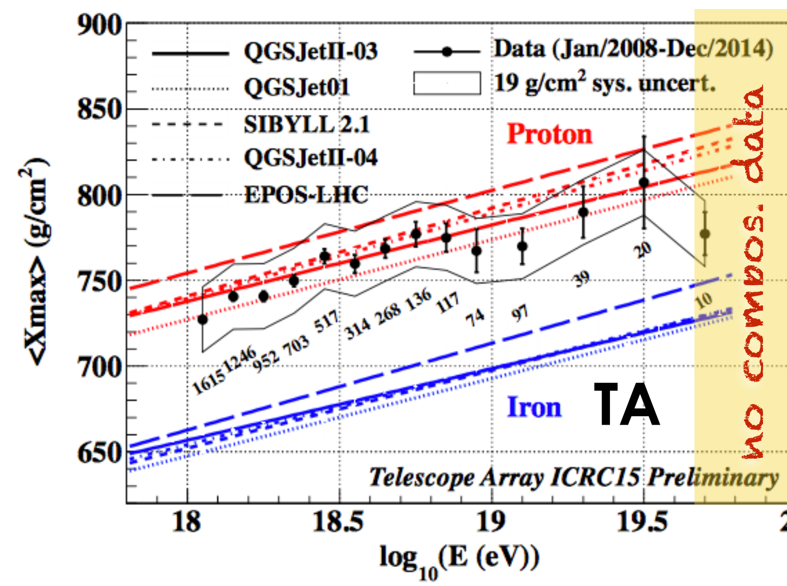
galactic coordinates

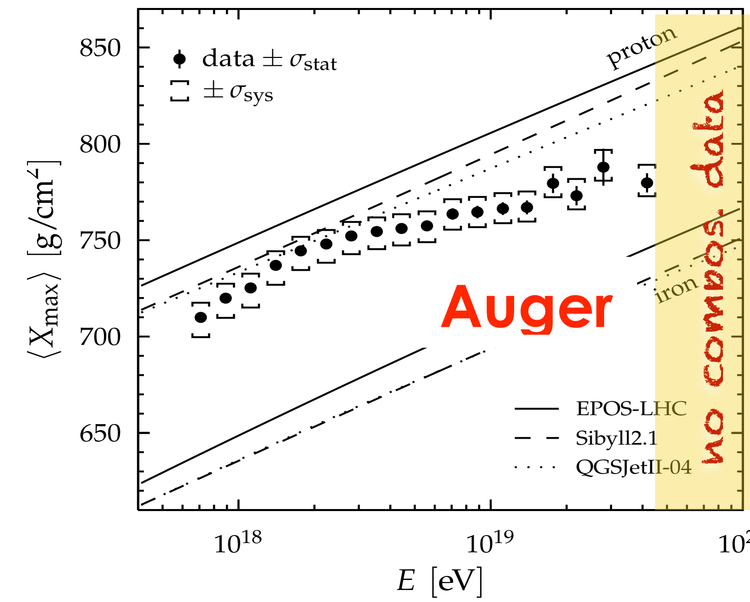
Major results obtained and new questions opened

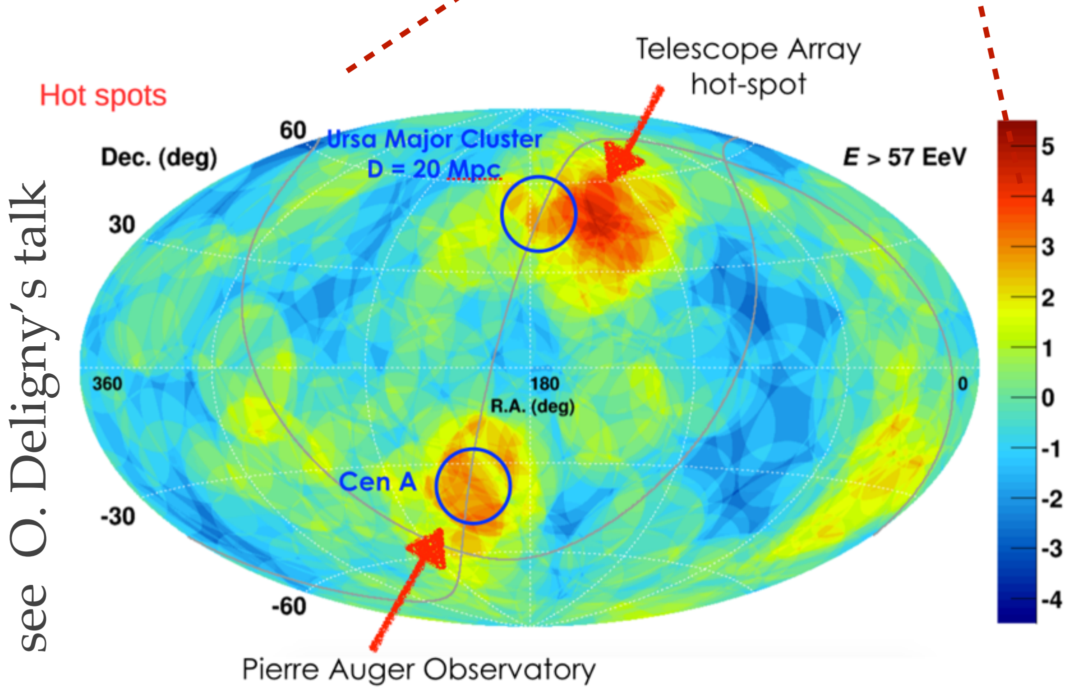
What have we learnt?

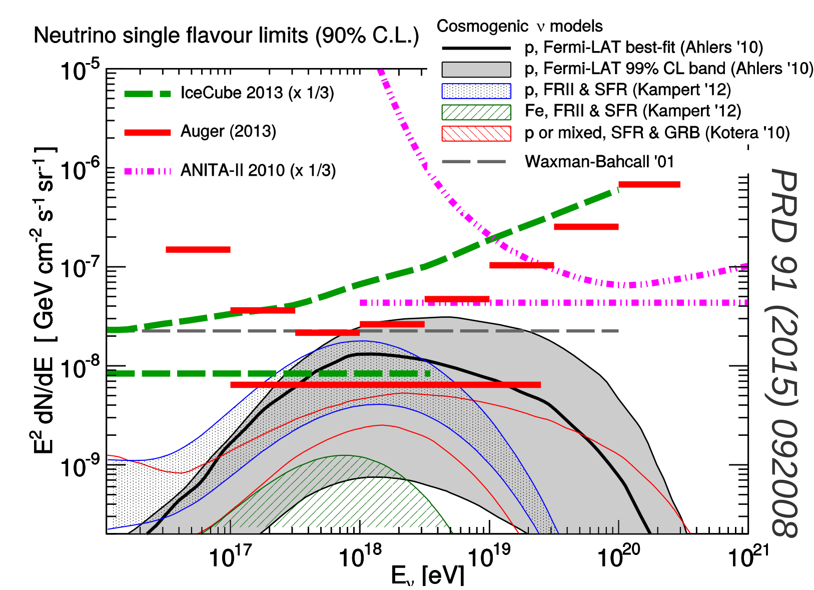


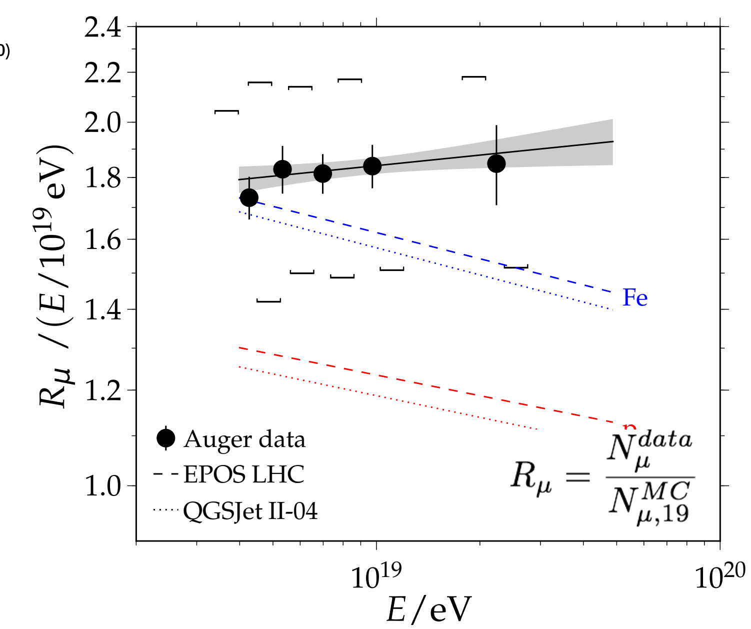
mass composition: light or mixed?











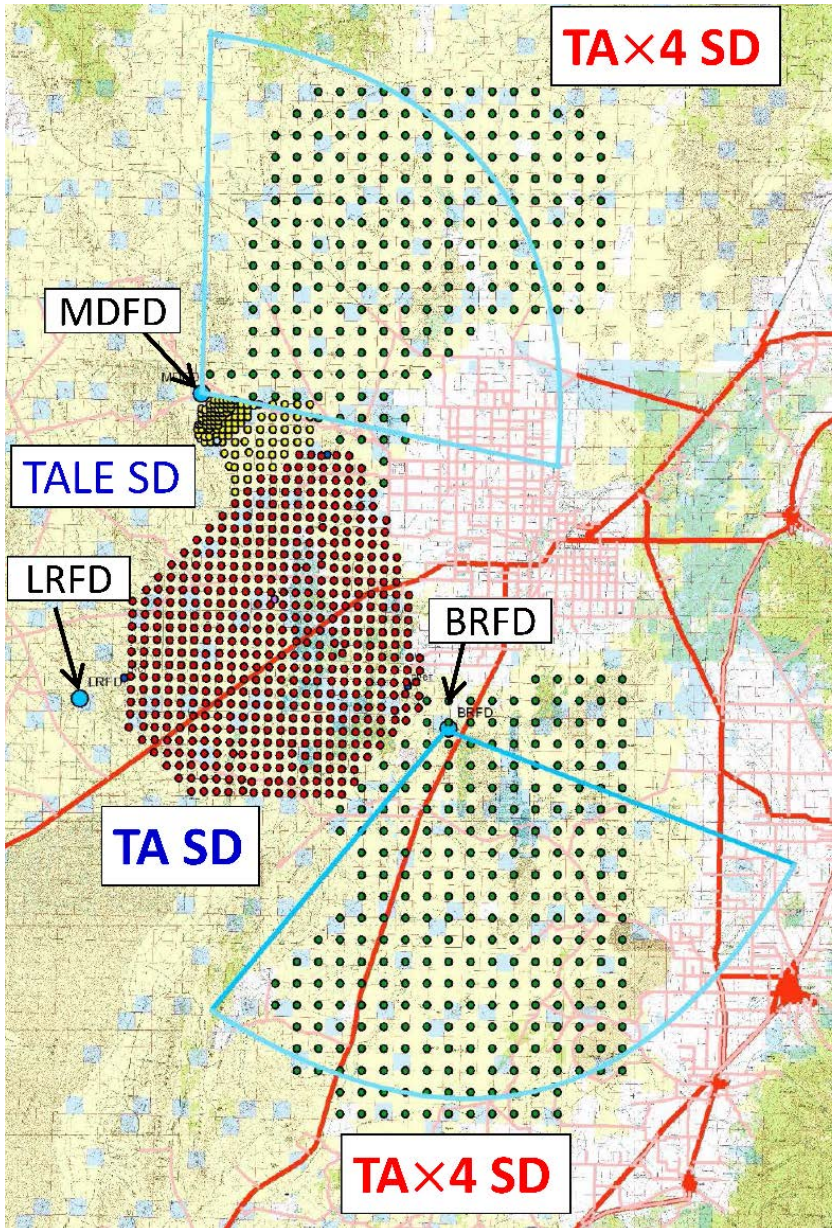
No anisotropy at small angular scale.
weak signal at ~ 20° angular scale

neutrino and photon limits constrain source properties

muon deficit in simulation

More answers in the short term?

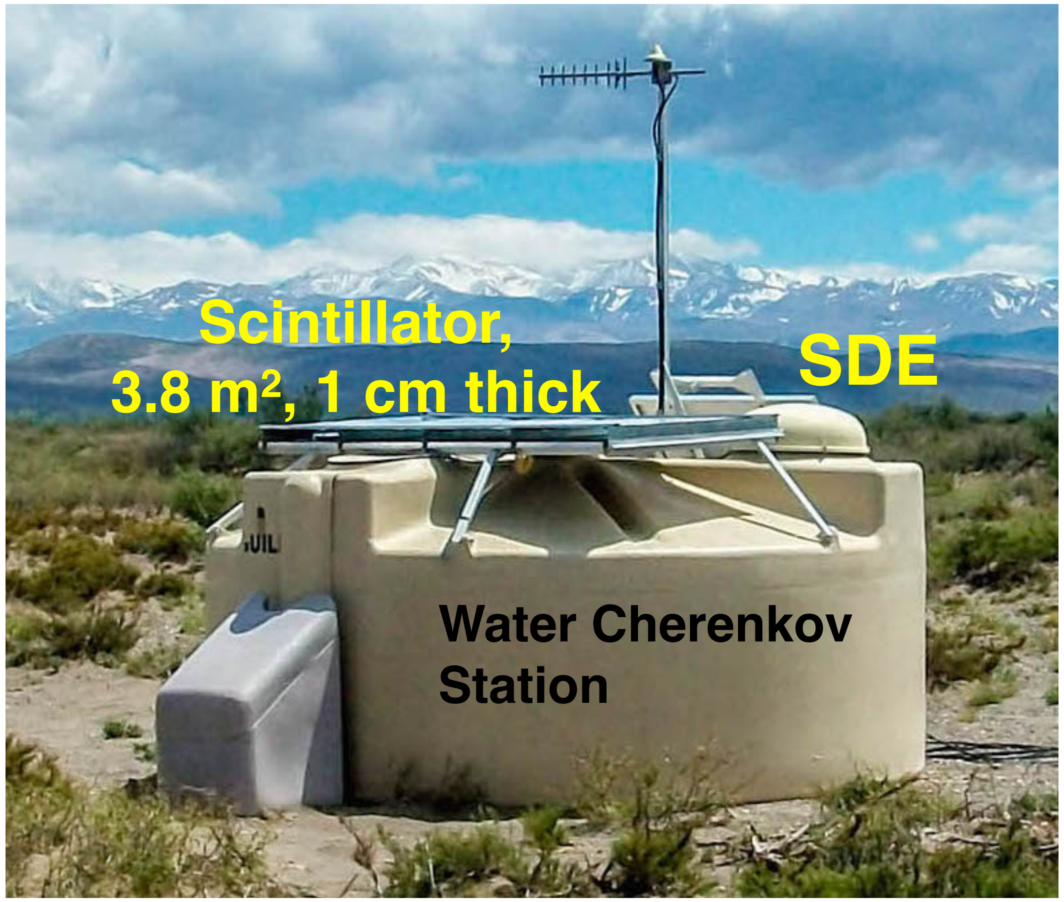
TA extension to ~ 3000 km^2



- **Hot-spot** at > 5 σ
- Statistics for **mass composition** and **energy spectrum** at highest energies

AugerPrime

- **Muon content and mass composition**
- Origin of the **flux suppression**
- Search **proton flux**
  (test **astronomy** for future detectors)
- **Hadronic models** and EAS physics

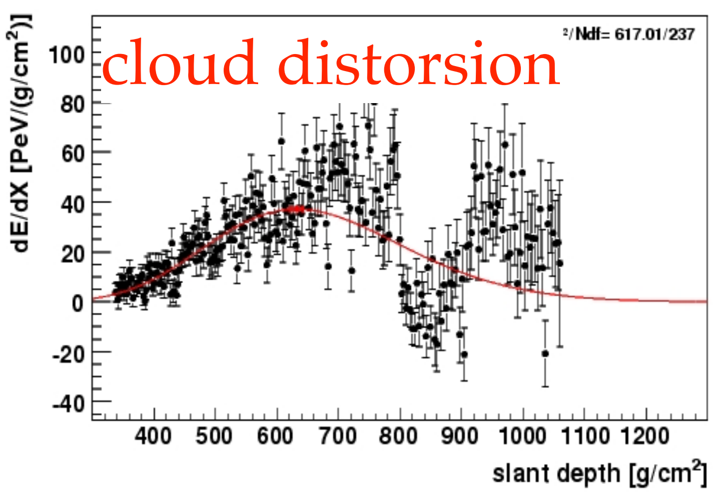


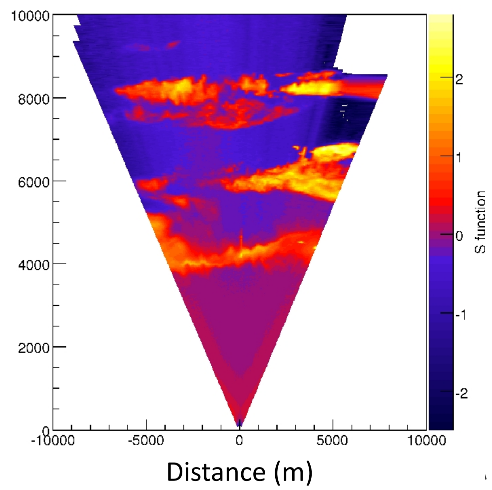
Summary and Outlook

- Current detectors have lead to **high-quality observations**
  - **Unexpected results and new questions** in astrophysics and particle physics
- Lack of statistics, air-shower dependence the major challenges for extragalactic cosmic rays
  - **Upgrades of the current experiments** decisive in the next few years
- **Multi-messenger approach** needed for a coherent picture
- **New techniques and ambitious projects to follow in the future**

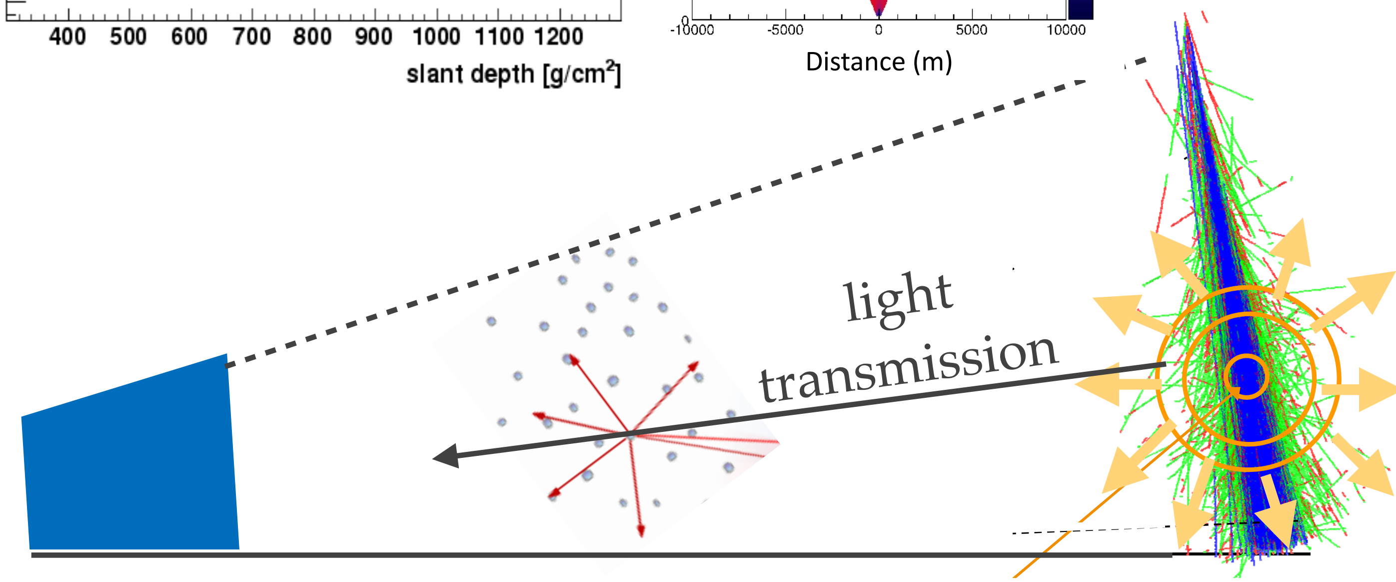
Backup

Monitoring of the atmosphere

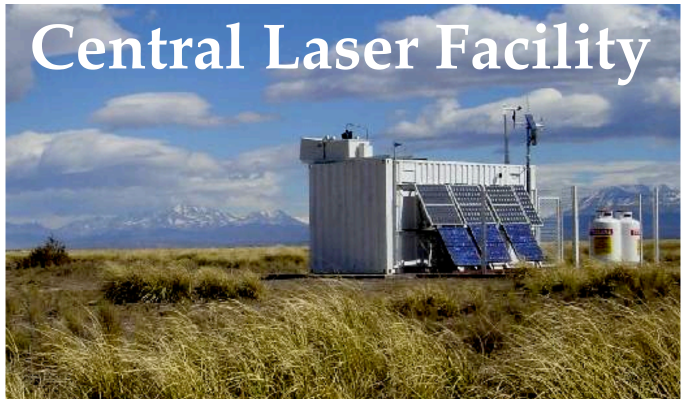


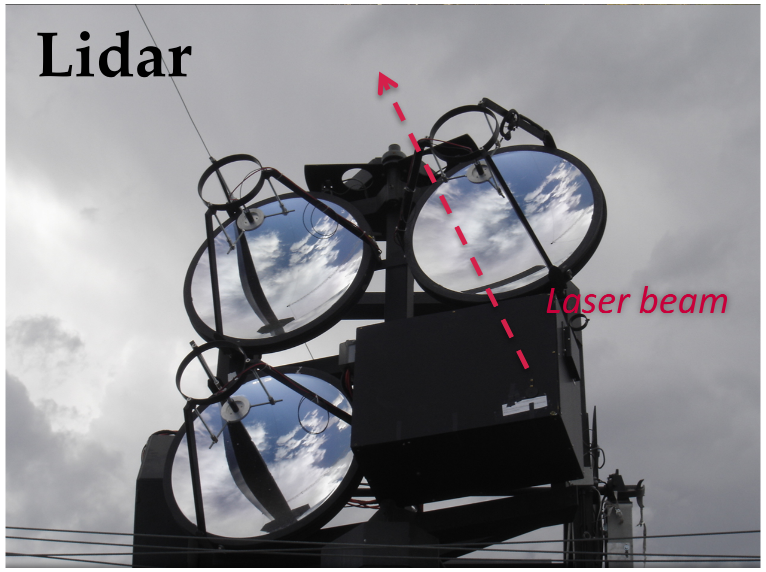


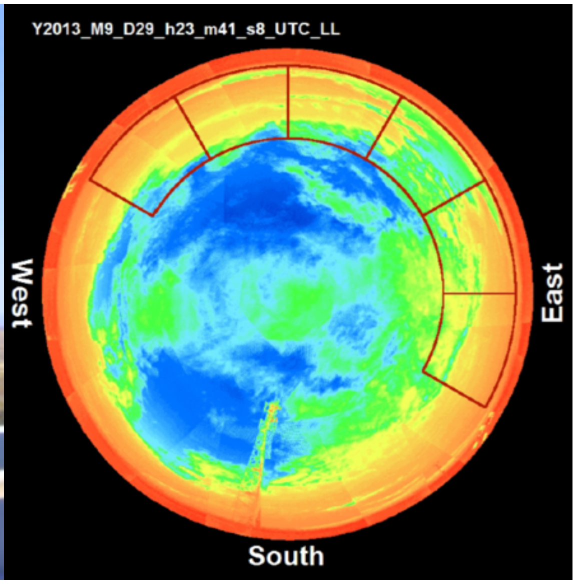
FD relies on the propagation, absorption and scattering of the light in atmosphere



Several devices for cloud and aerosol content





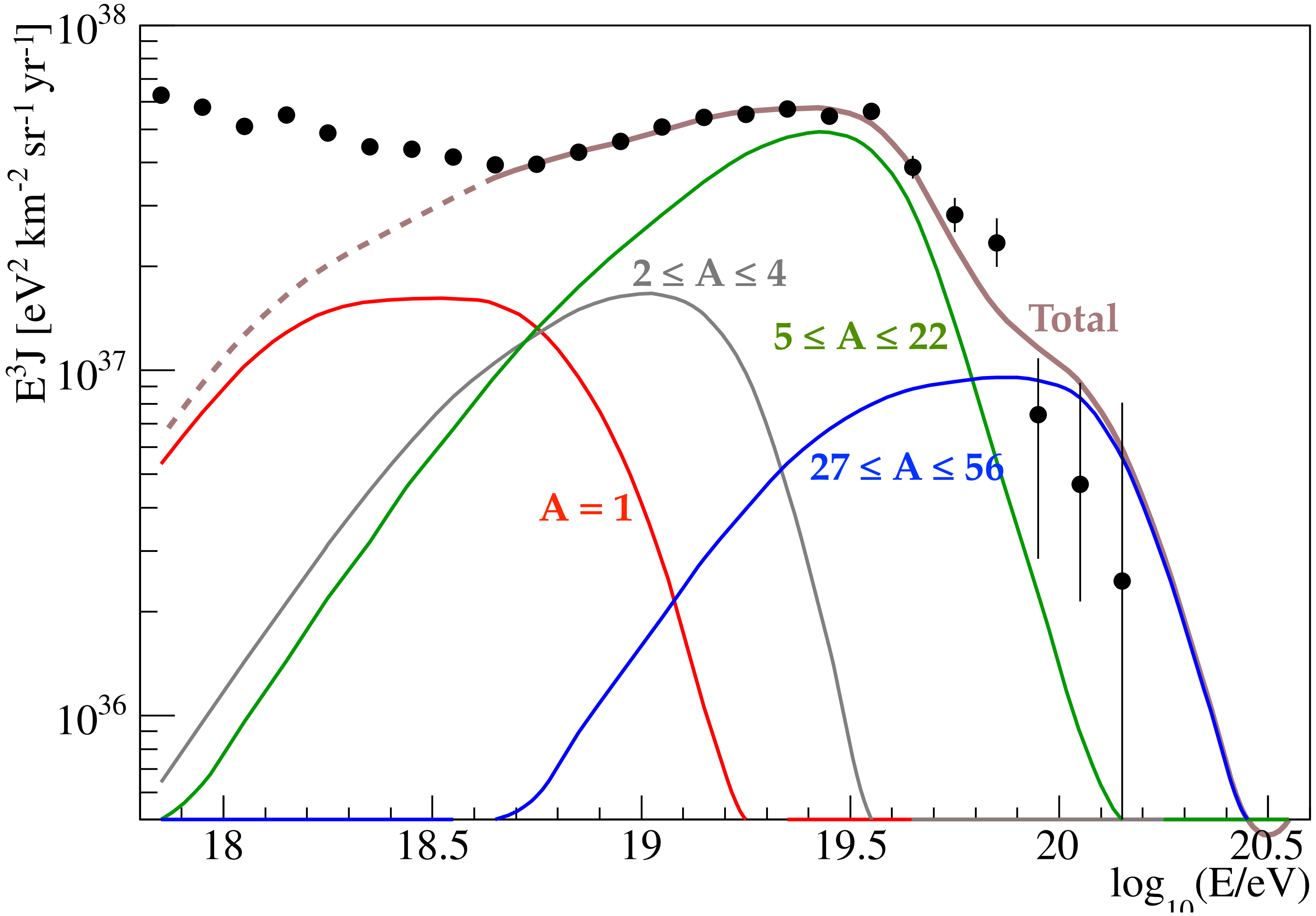


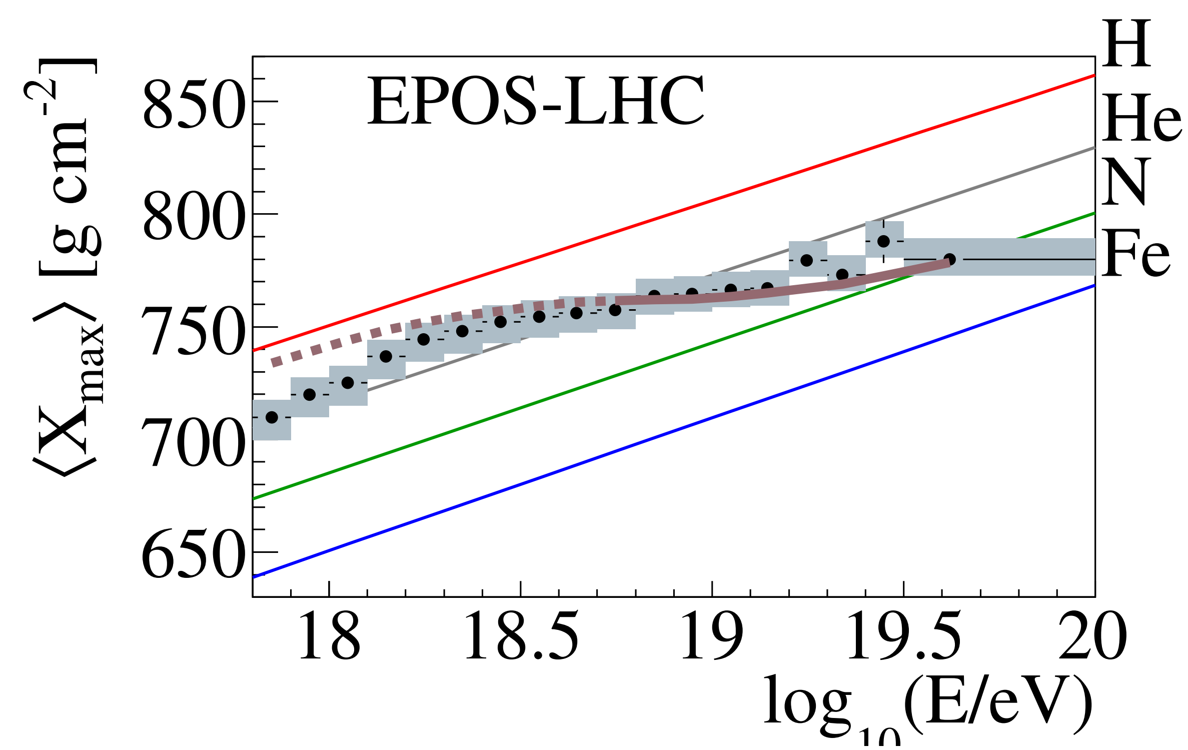
Examples for Auger, similar systems for Telescope Array

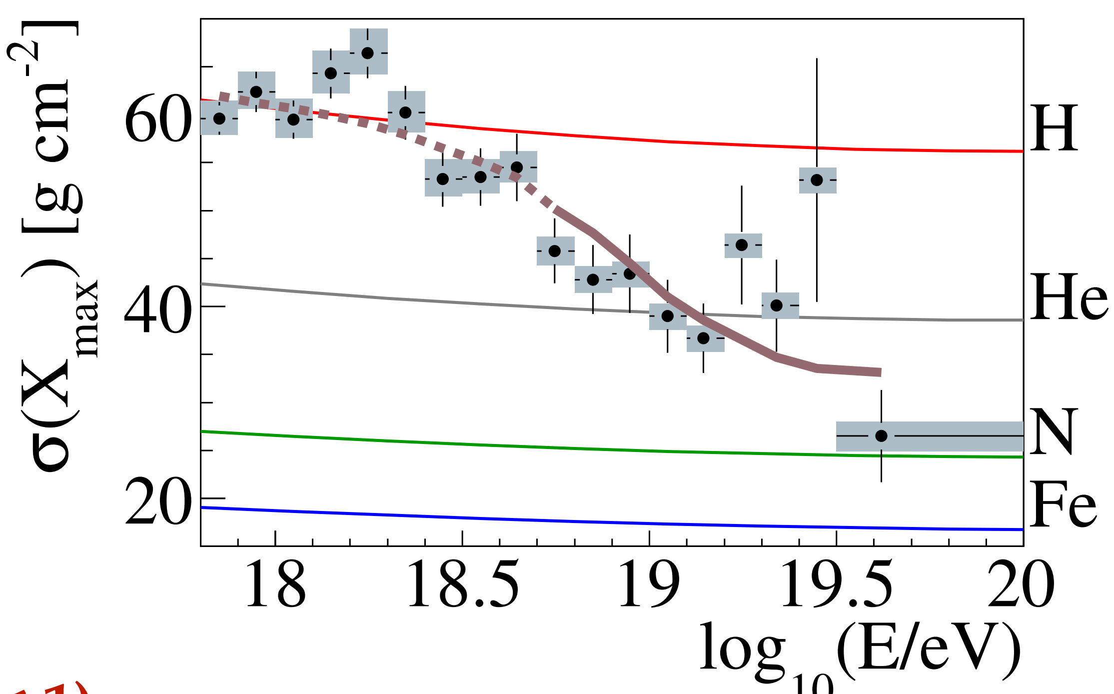
Combined fit: spectrum and mass composition

Model: identical sources (uniformly distributed) accelerating p, He, N, Fe

fit parameters: injection flux, spectral index, energy cut off, mass fractions



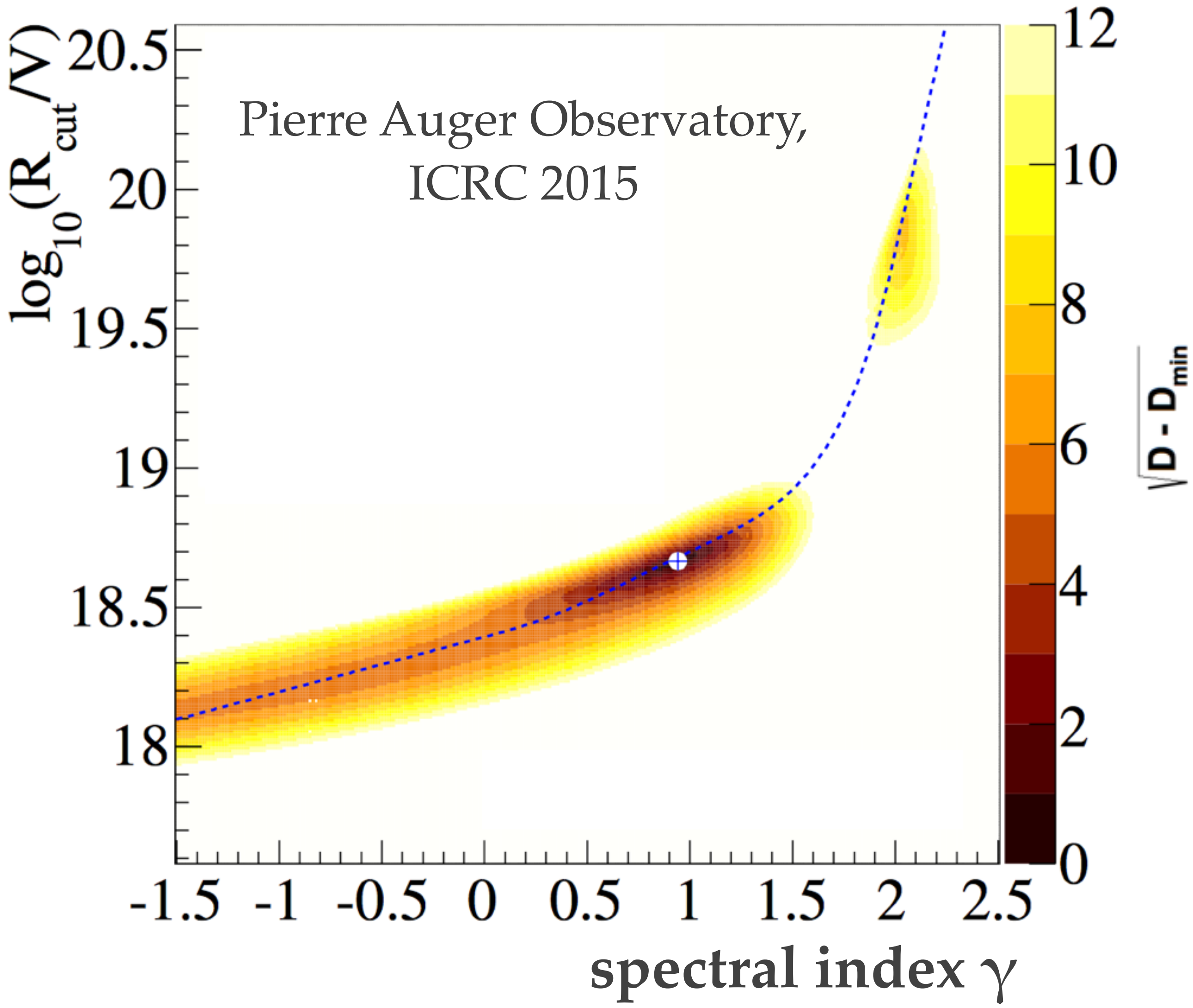




Best fit with very hard spectra (γ ≤ 1)
Prevailing intermediate mass at the source

Astrophysical interpretation of the results

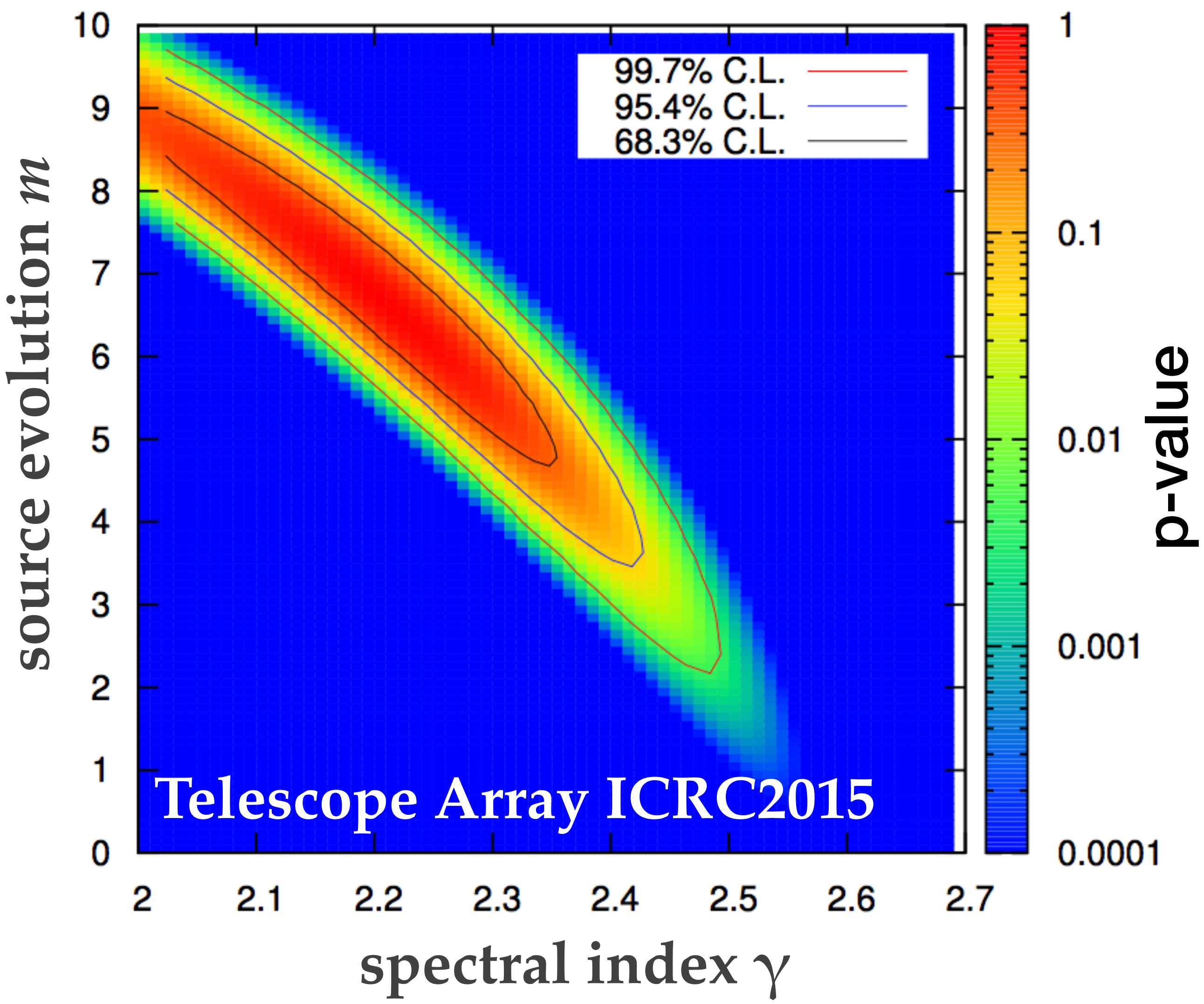
Combined fit of spectrum and mass composition



best fit:

γ	R_{cut}
$0.94^{+0.09}_{-0.10}$	$10^{18.67 \pm 0.03}$

Fit of the mass assuming pure proton at source

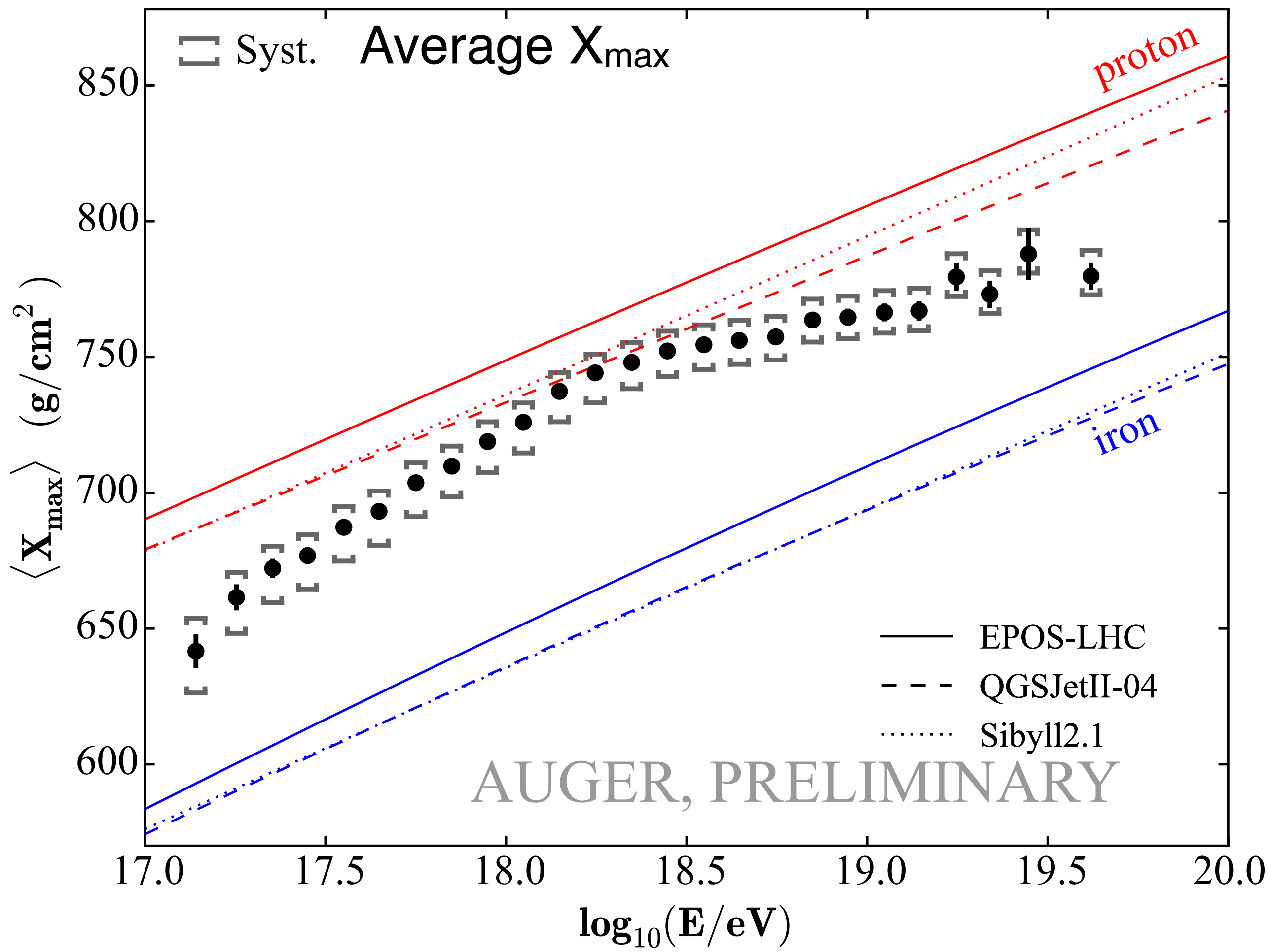


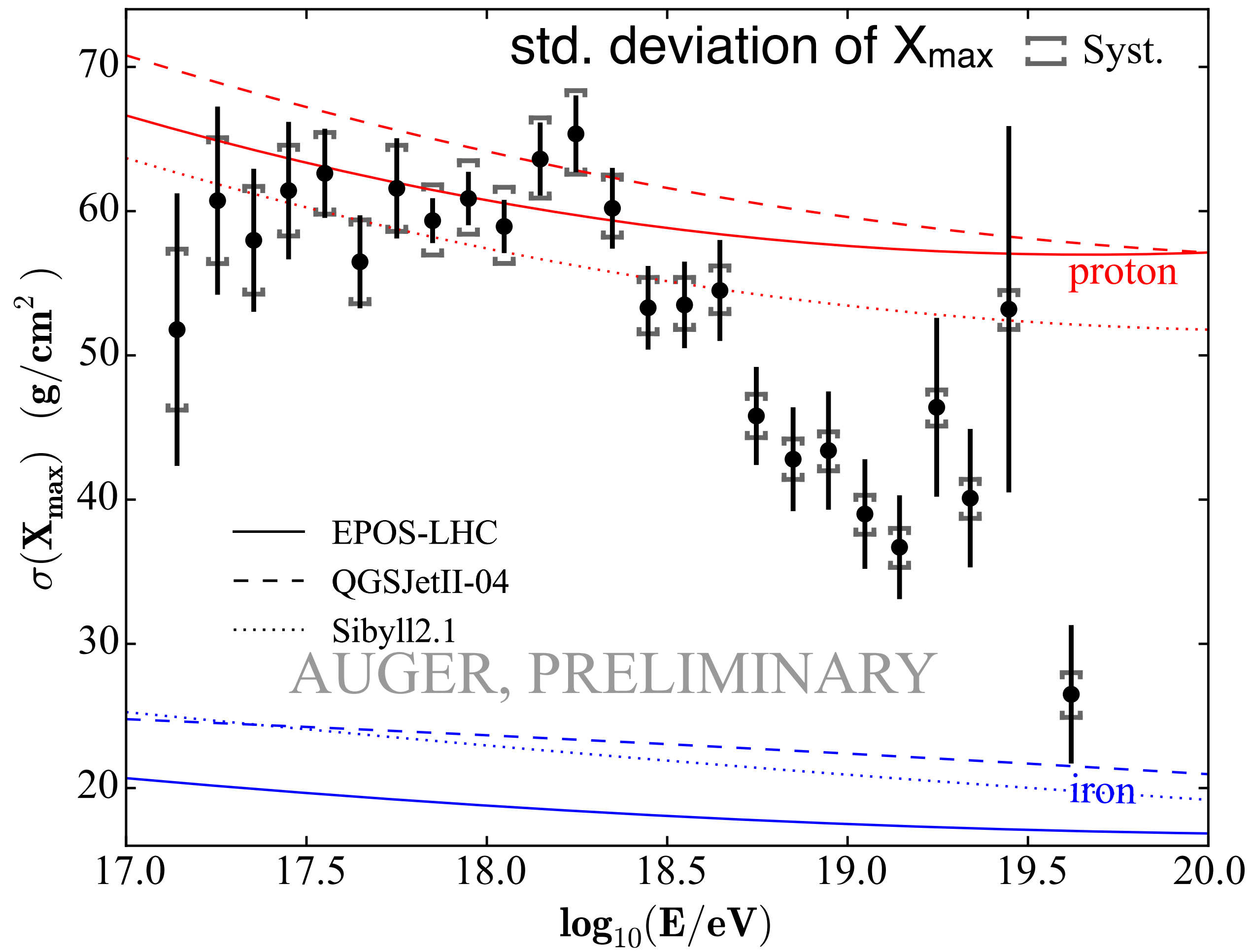
best fit: $\gamma = 2.21^{+0.10}_{-0.15}$ $m = 6.7^{+1.7}_{-1.4}$

Mass composition measurements (Auger)

Depth of shower maximum (Xmax) proportional to the lnA.

Mass inferred from the first two moments of the Xmax distribution





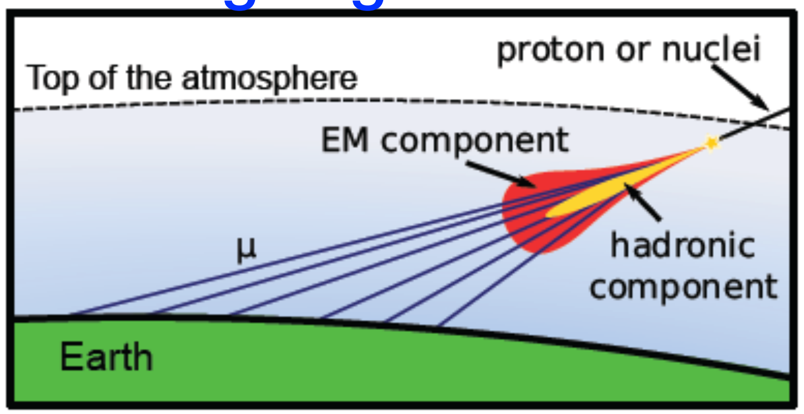
Break-point @ E ~$10^{18.3}$ eV: Mass composition **from intermediate to light primaries at low energy** and **to intermediate/heavy at high energy**

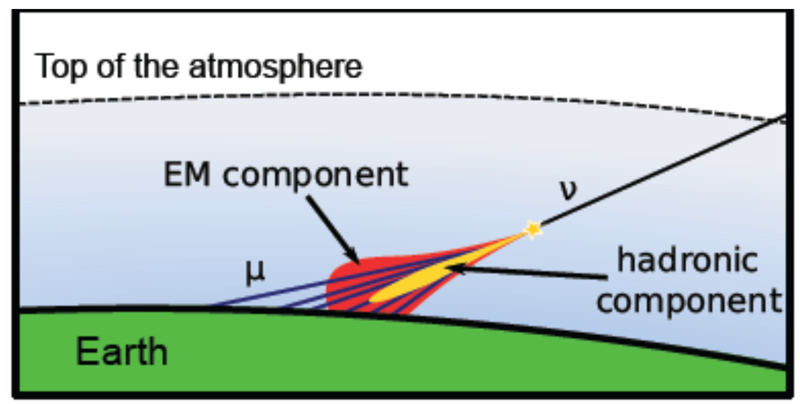
The Pierre Auger Coll., Phys. Rev. D 90, 122005 (2014)
A. Porcelli for the Pierre Auger Coll., ICRC 2015

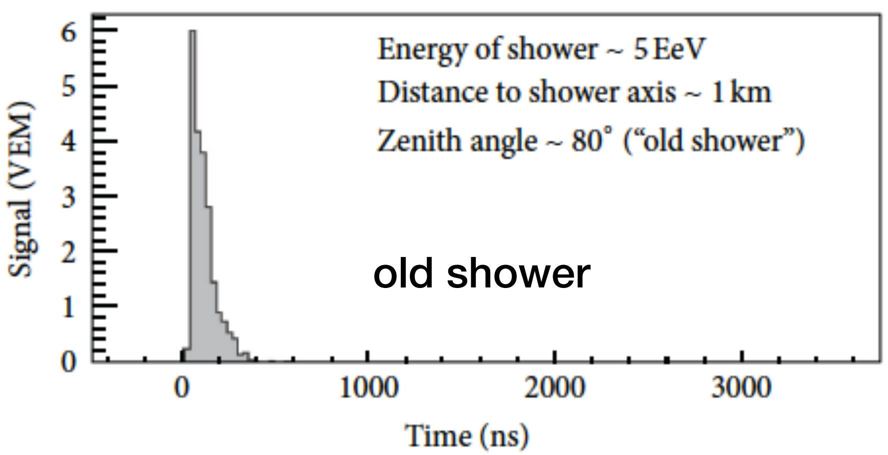
Detection of UHE neutrino

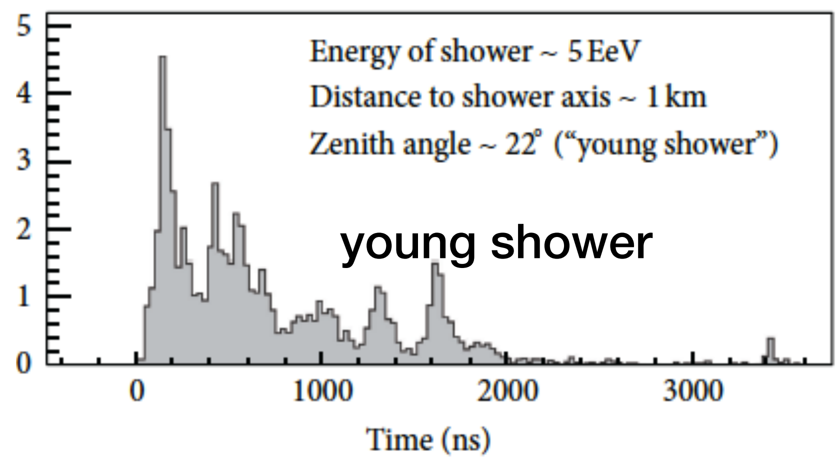
ν selected as inclined showers with large em component (time spread of SD signals)

- down-going





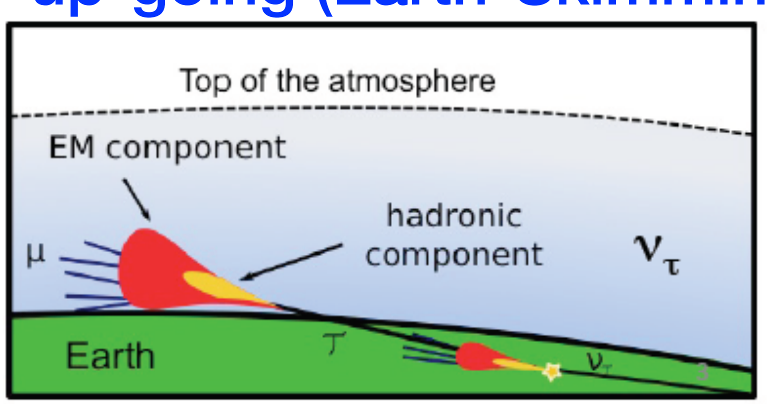




all ν flavor

Low zenith (65º,75º)
contrib. to total evt rate: **23%**
High zenith (75º,90º):
contrib. to total evt rate: **4%**

- up-going (Earth-Skimming)



ν_τ flavor
Earth-Skimming (90º, 95º)
contrib. to total evt rate **73%**

ν identification applied "blindly" to data: 01/2004 - 12/2012

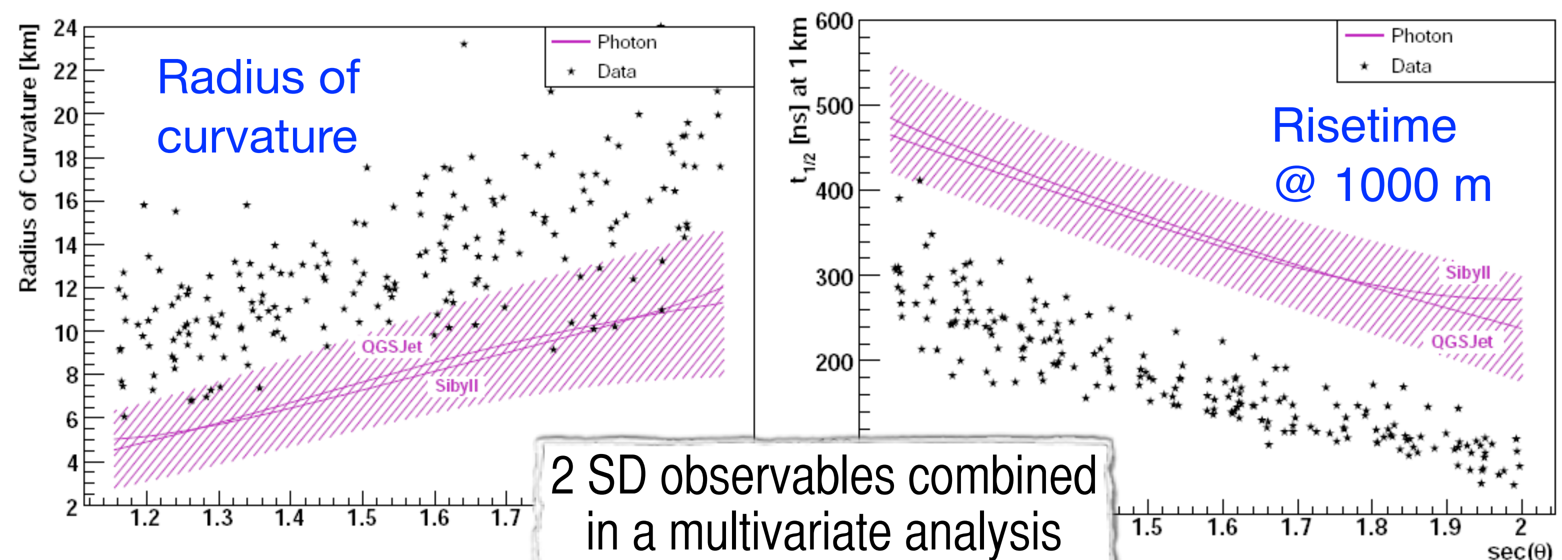
No candidates found!

Search for photons with Auger

SD events: Radius of Curvature and Rise time of the signal in the SD

- E_{thr}: 10, 20, 40 EeV
- Zenith: 30 - 60°
  (full efficiency range)
- Principal component analysis
- "a-priori" cut at 50% of photon selection efficiency
  - no candidates found

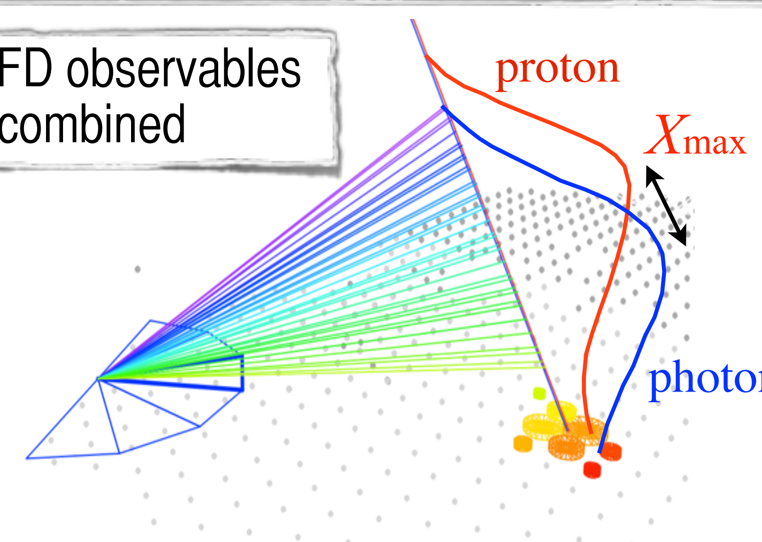
The Pierre Auger Coll., Astrop. Phys. 29 (2008) 243



Hybrid events:

- E_{thr}: 1, 2, 3, 5, 10 EeV
- Zenith: 0 - 60°
- Fisher analysis combining SD and FD information
- a-priori cut at 50% photon efficiency, > 99% bkg rejection(depending on energy)
- FD duty cycle of ~ 10-15%
- 6, 0, 0, 0, 0 candidates (compatible with bkg)

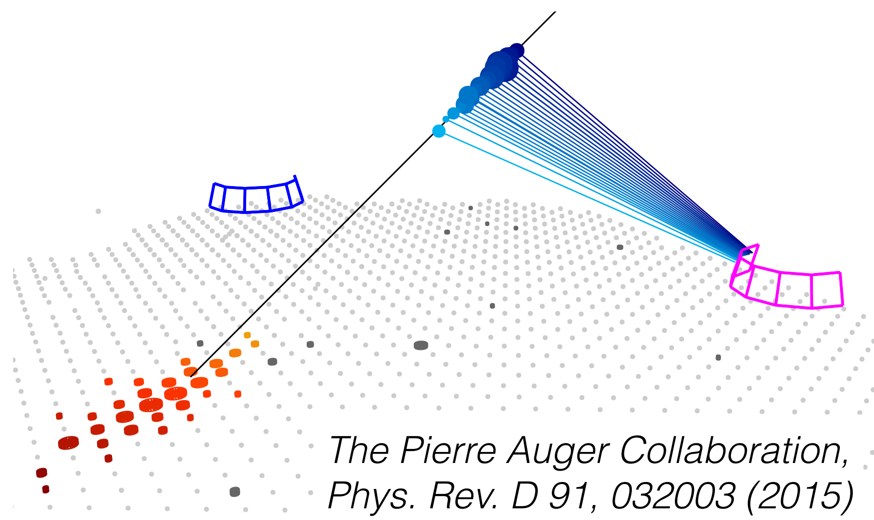
SD & FD observables combined



M.S. for the Pierre Auger Coll, ICRC 2011

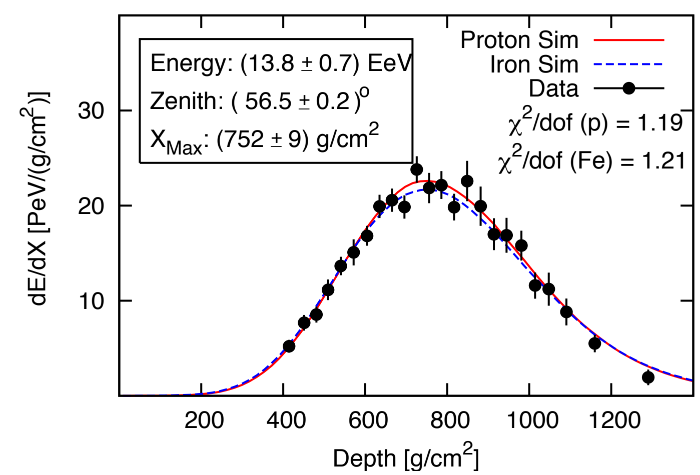
Muon deficit in simulations

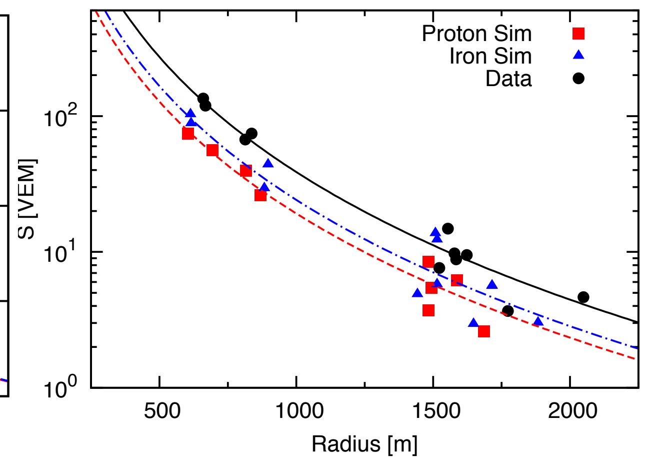
Inclined Events (60 < θ < 80)

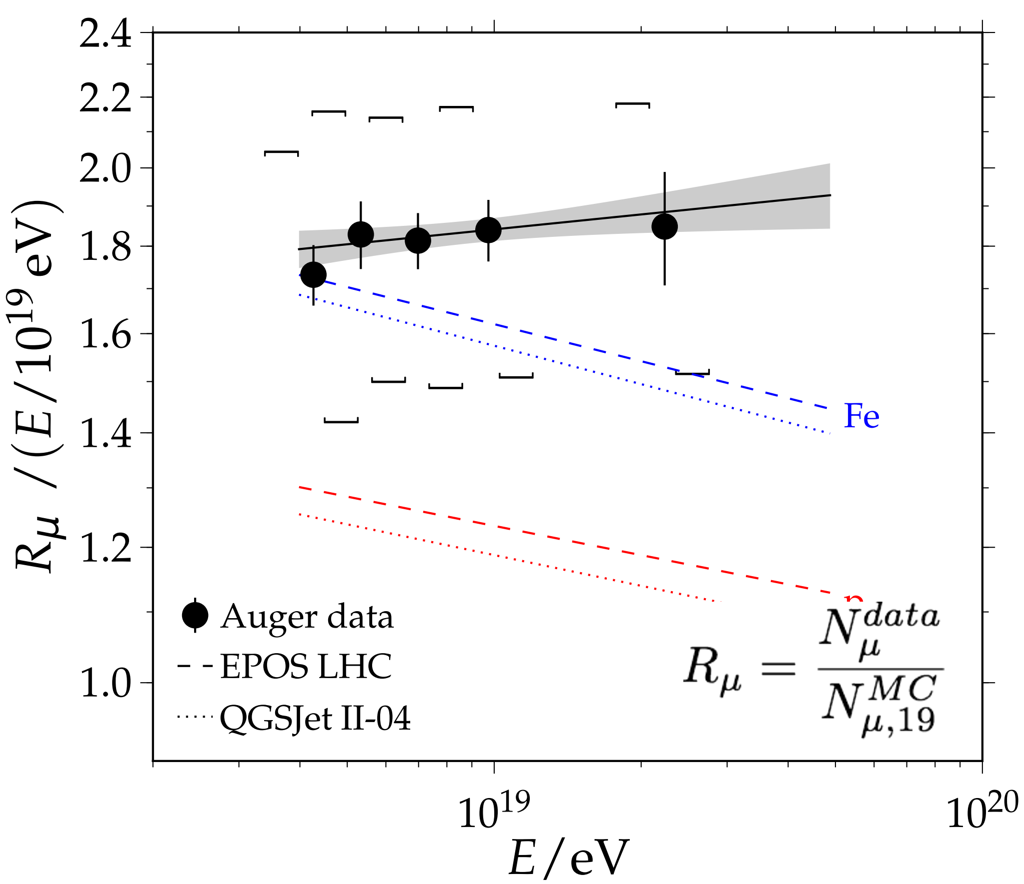


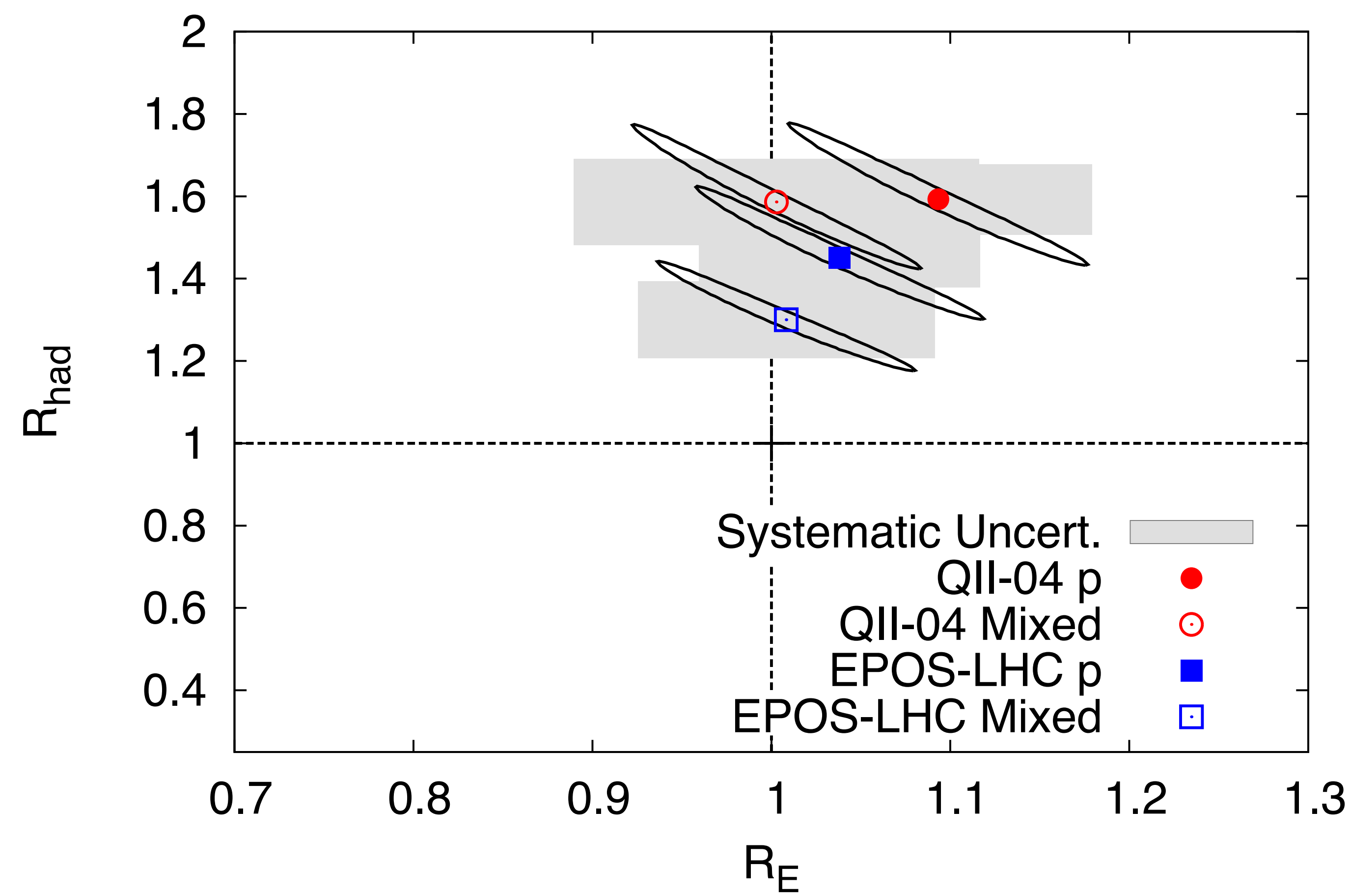
The Pierre Auger Collaboration, Phys. Rev. D 91, 032003 (2015)

Vertical events (θ < 60)







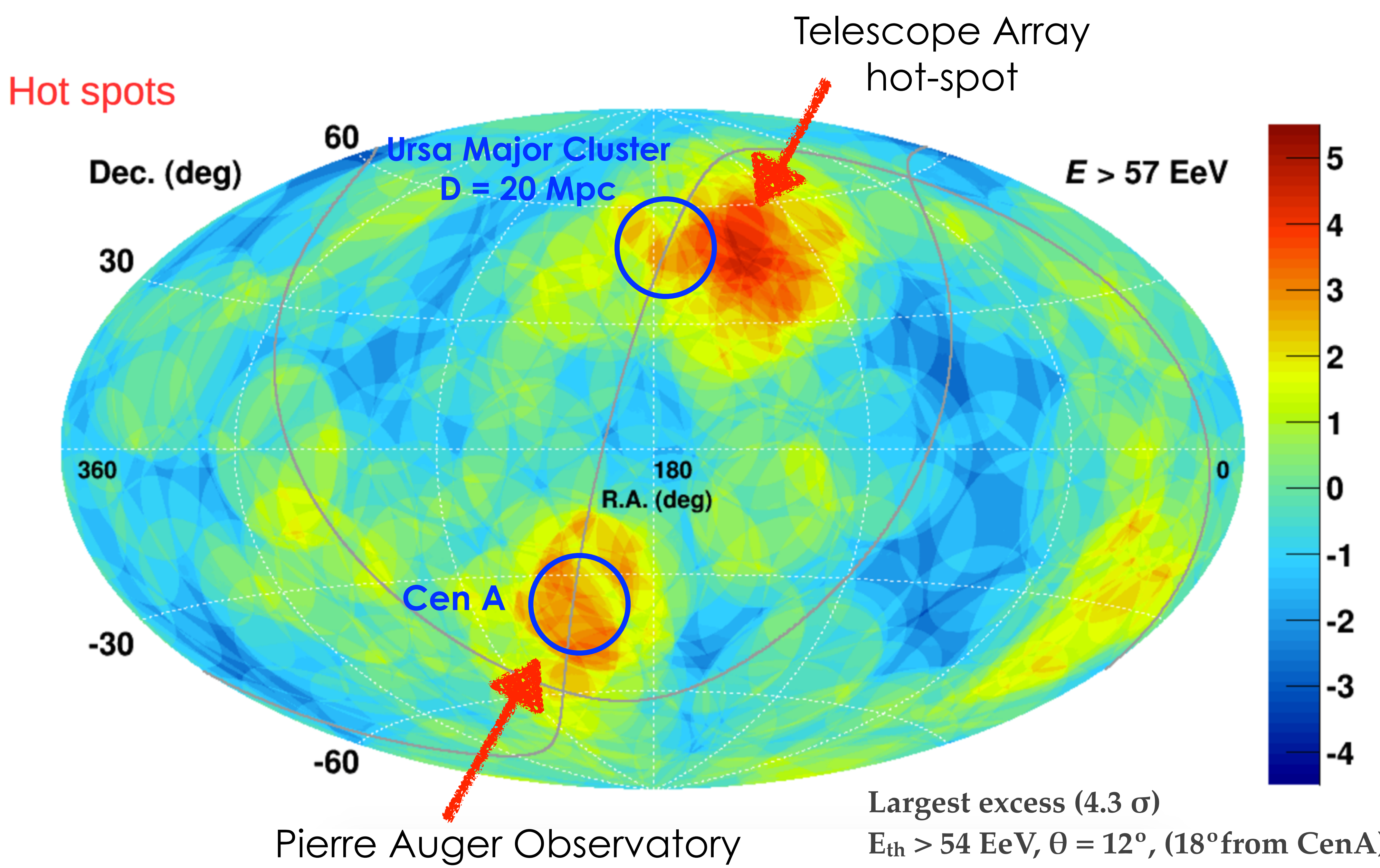


- Muon deficit from 30% to 80% @ 10^{19} eV depending on models

- hadronic models blah blah blah

Anisotropy at UHE (E > 57 EeV)

- T



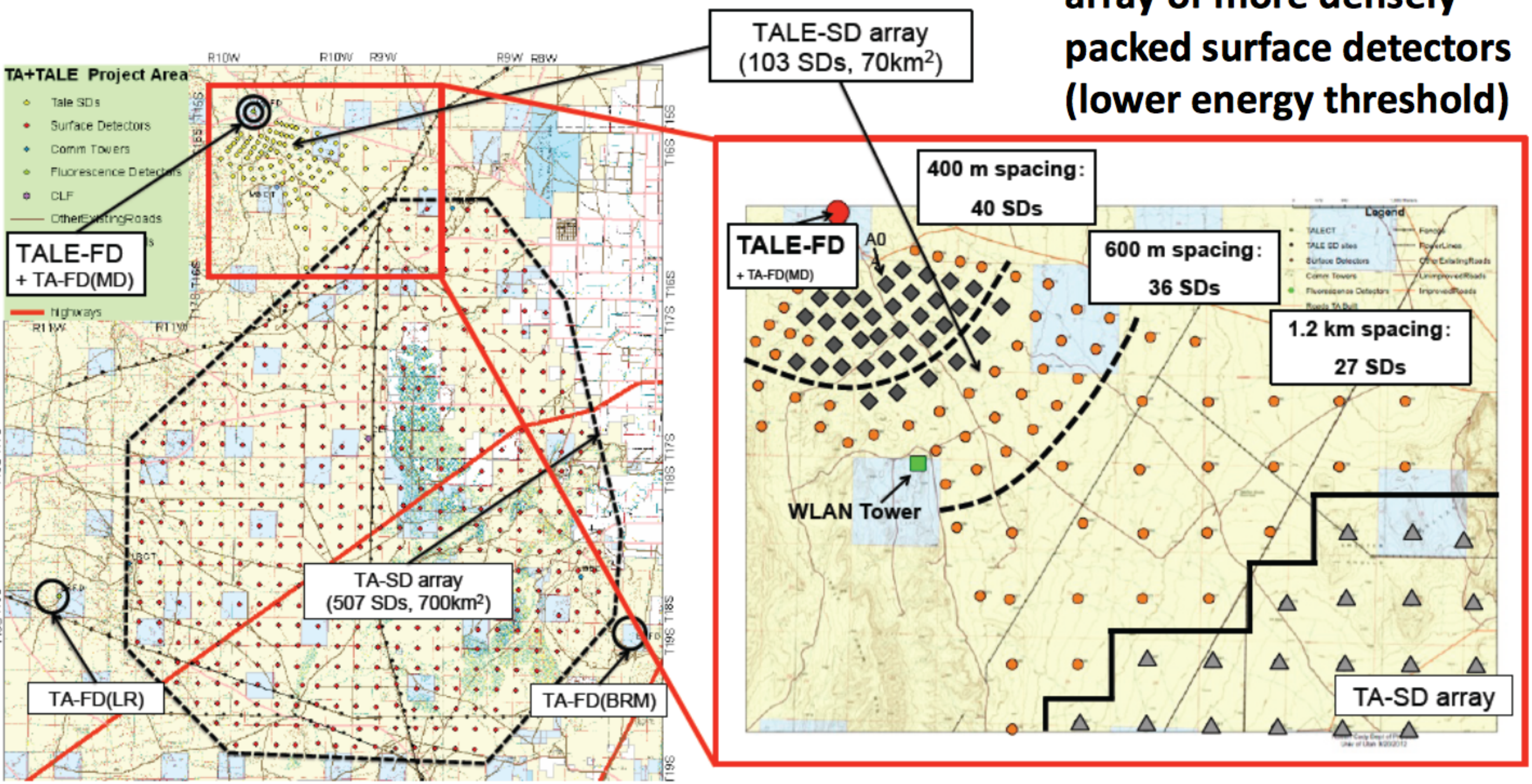
Largest excess (4.3 σ)
E_{th} > 54 EeV, θ = 12°, (18° from CenA)
Post-trial probability: 69%

TA Low Energy Extension (TALE)

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

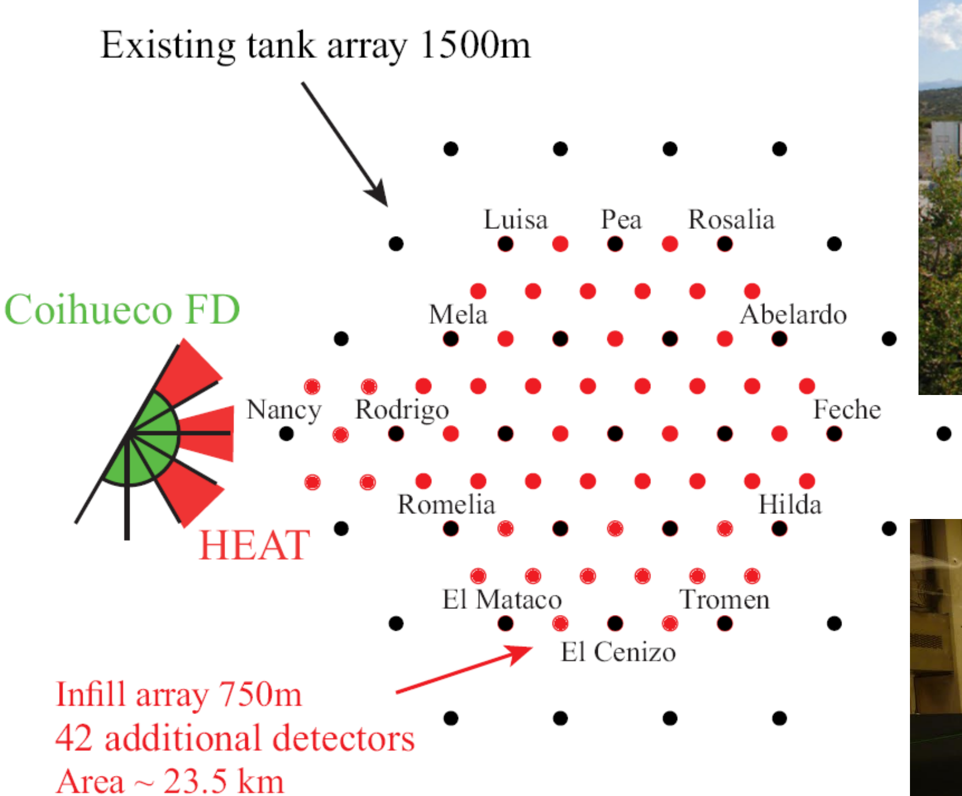
TALE: 10 telescope (field of view 31-59°)
+ dense array of 103 scintillators

Infill surface detector array of more densely packed surface detectors (lower energy threshold)

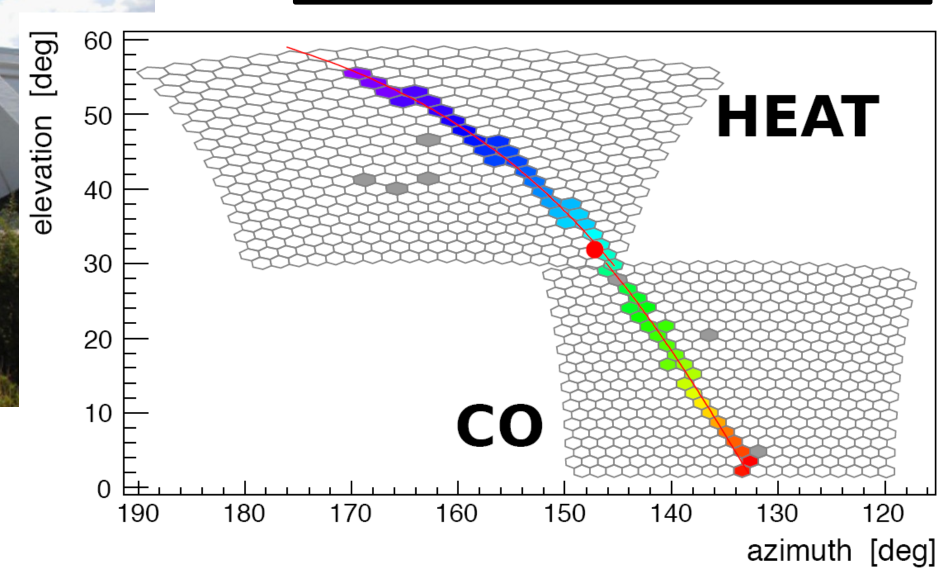


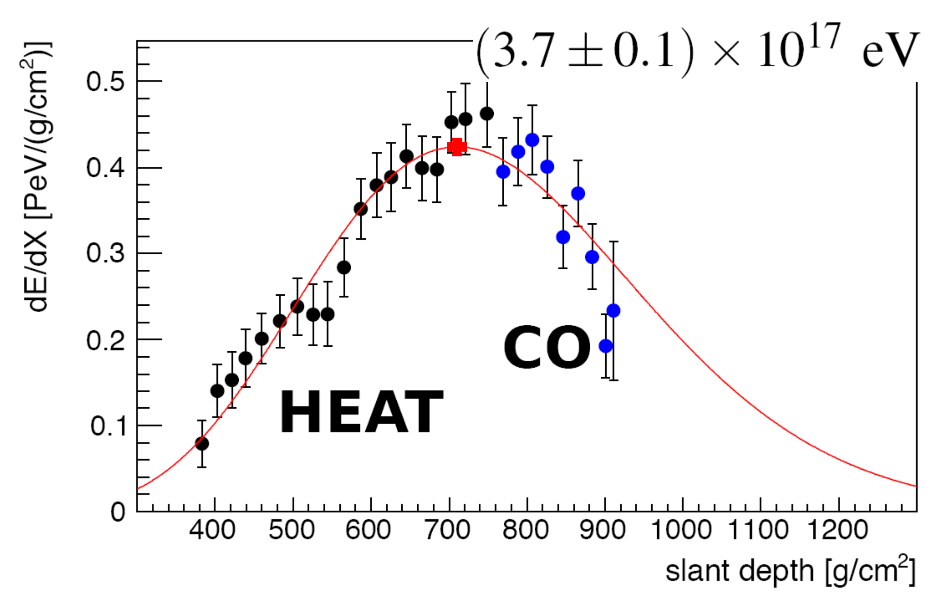
Auger: Extension to low energies

Infill area: 750 m spacing between SD stations



High Elevation Auger Telescopes (HEAT)





AMIGA – muon detectors underground (under construction)