Nikhef Jaarvergadering 2015
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The highest energy cosmic rays:
status and future perspectives

Jörg R. Hörandel Radboud University Nijmegen/Nikhef http://particle.astro.ru.nl

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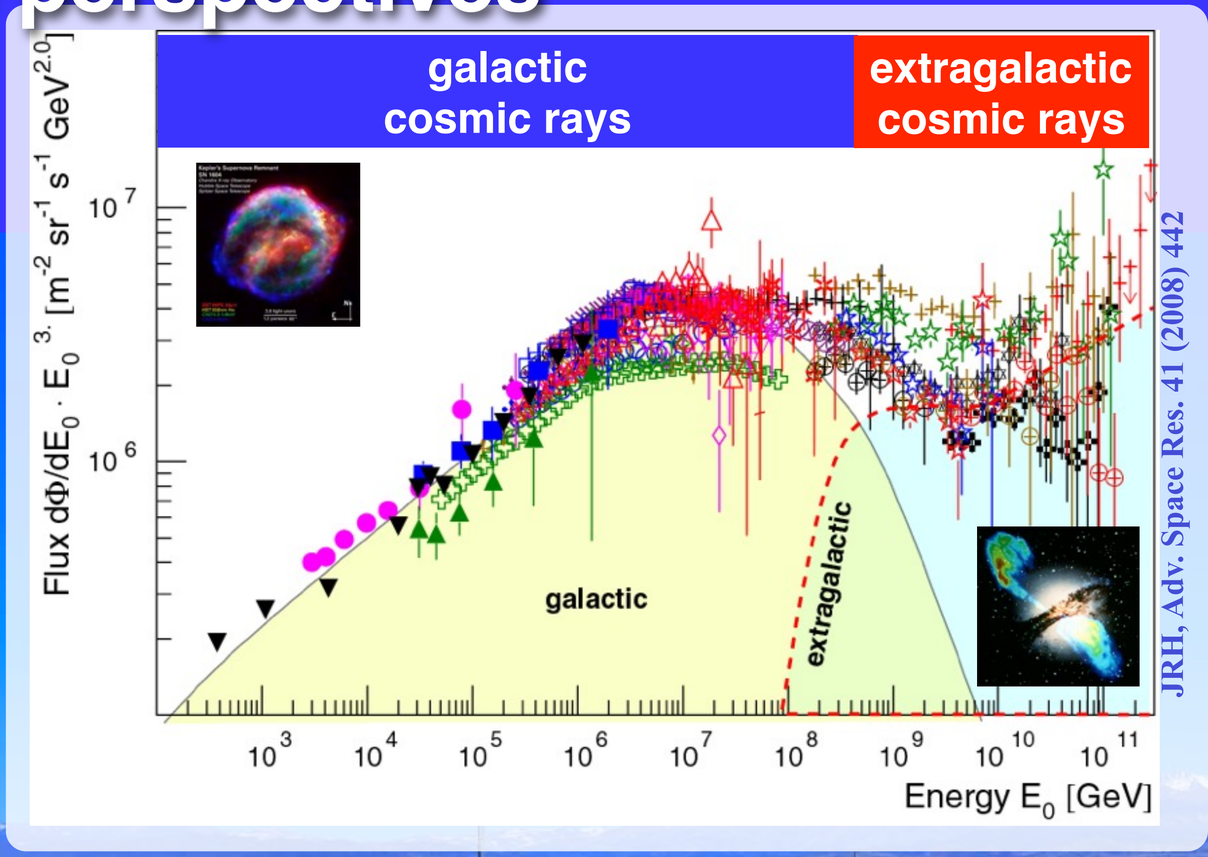
status and future perspectives



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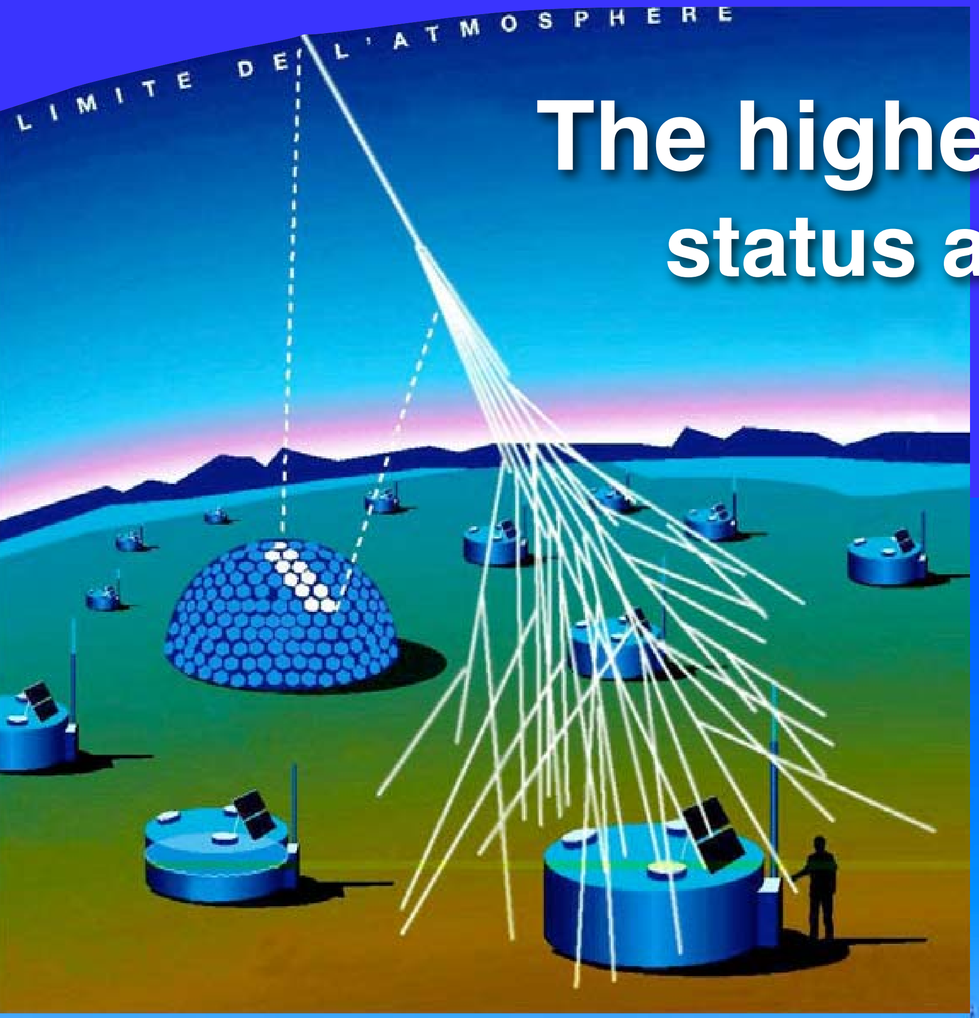
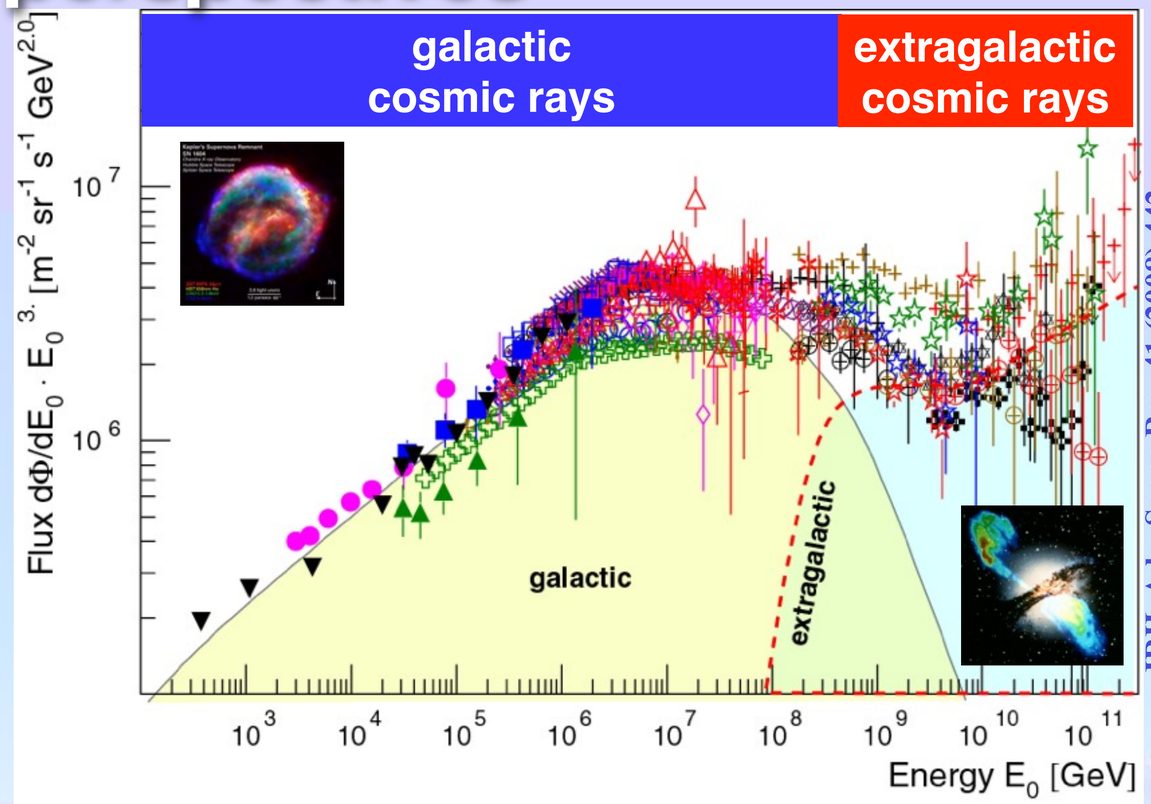


PIERRE AUGER OBSERVATORY



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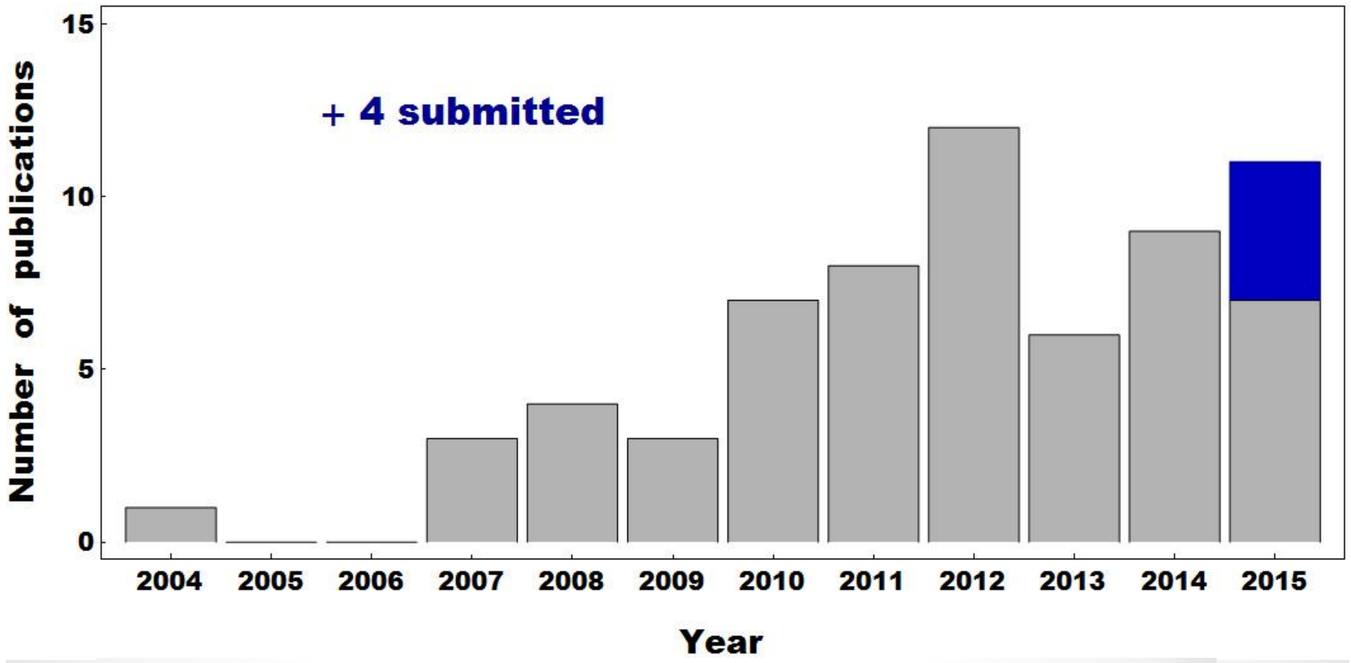
Auger full-author list papers:
60 published (7 papers in 2015 *two of them: PRD, editor suggestion: Highlight*)



Paper	Journal
submitted	
The prototype muon module for the AMIGA project of the Pierre Auger Observatory	JINST
The energy in the radio signal of extensive air showers	PRL
Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory	PRD
Nanosecond-level time synchronization of autonomous radio detector stations using a reference beacon and commercial airplanes	JINST

twins

AERA

Auger Top 10 by citations (INSPIRE)

Auger Top 10 (by citations, INSPIRE)

paper	# citations	rank in Journal	
NIM 2004 (Engineering Array)	602	2 (after D0)	#1 after exclusion of self citations
Science 2007 (VCV)	549	2 (after CDMS II)	
PRL 2008 (spectrum)	481	22	
PRL 2010 (X_{max})	425	17	*82 citations last 12 months*
APP 2008 (VCV)	362	1	*61 citations last 12 months*
PLB 2010 (spectrum)	318	9	*58 citations last 12 months* (only Higgs & SUSY got more)
APP 2010 (VCV update)	261	1	
NIM 2010 (Flouresc. Det.)	178	3 (after ALICE, T2K)	
APP 2008 (photons)	165	3 (after Auger, Fermi-LAT)	
PRL 2008 (tau neutrinos)	148	199	

Total number of citations of Auger papers ~7400
average of 83 citations per paper

last year: 1500 citations

Compilation: K.-H. Kampert

Search for correlations between the arrival directions of IceCube neutrino events and ultrahigh-energy cosmic rays detected by the Pierre Auger Observatory and the Telescope Array

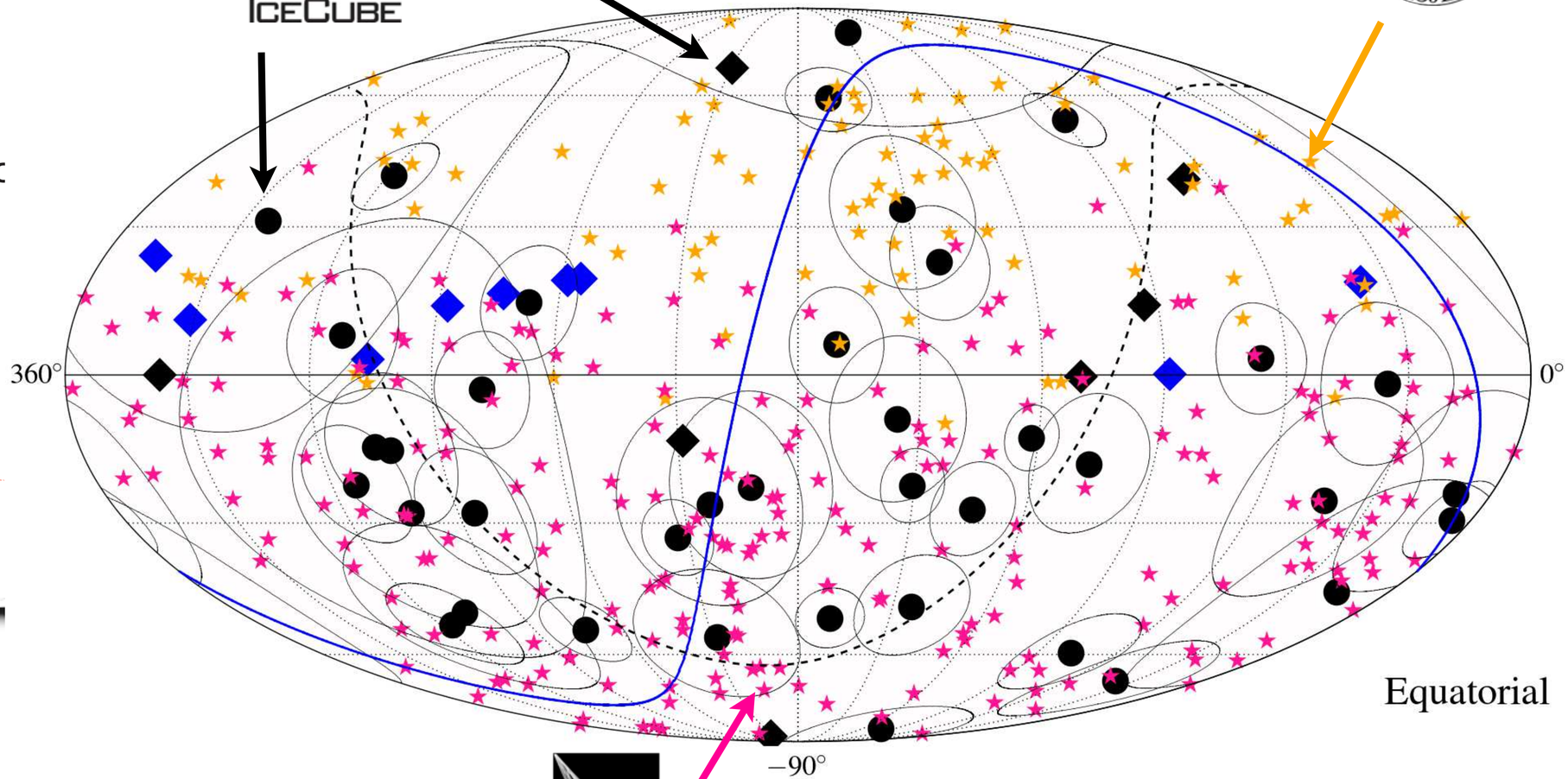
The IceCube, Pierre Auger and Telescope Array C

Abstract. This paper presents the results of different searches for correlations between very high-energy neutrino candidates detected by IceCube and the highest-energy cosmic rays measured by the Pierre Auger Observatory and the Telescope Array. We first consider samples of cascade neutrino events and of high-energy neutrino-induced muon tracks, which provided evidence for a neutrino flux of astrophysical origin, and study their cross-correlation with the ultrahigh-energy cosmic ray (UHECR) samples as a function of angular separation. We also study their possible directional correlations using a likelihood method stacking the neutrino arrival directions and adopting different assumptions on the size of the UHECR magnetic deflections. Finally, we perform another likelihood analysis stacking the UHECR directions and using a sample of through-going muon tracks optimized for neutrino point-source searches with sub-degree angular resolution. No indications of correlations at discovery level are obtained for any of the searches performed. The smallest of the p-values comes from the search for correlation between UHECRs with IceCube high-energy cascades, a result that should continue to be monitored.

Keywords: Neutrino, UHECR, cosmic ray sources, magnetic deflection.

ICECUBE

TELESCOPE ARRAY PROJECT

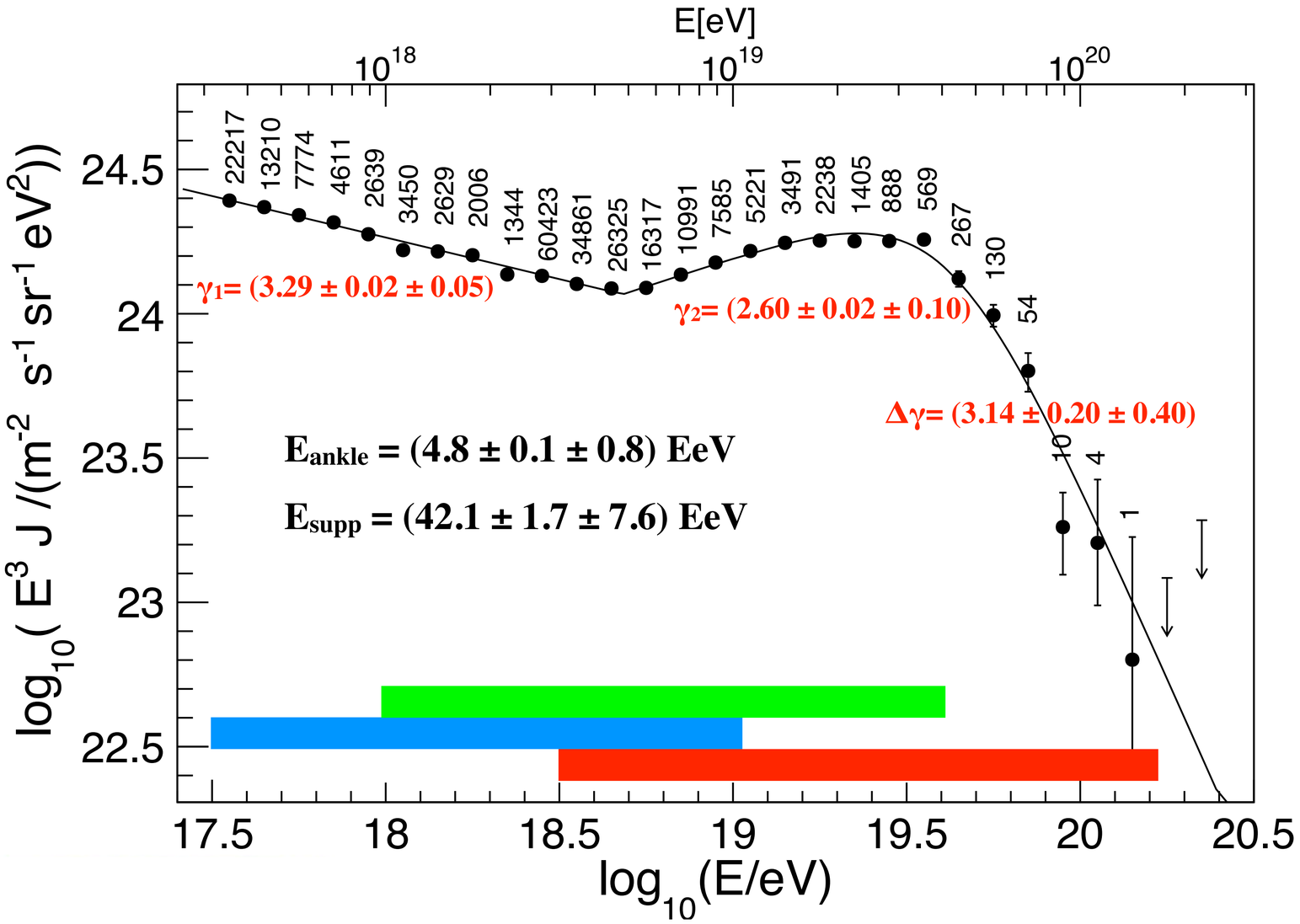


PIERRE AUGER OBSERVATORY

Figure 7. Maps in Equatorial and Galactic coordinates showing the arrival directions of the IceCube cascades (black dots) and tracks (diamonds), as well as those of the UHECRs detected by the Pierre Auger Observatory (magenta stars) and Telescope Array (orange stars). The circles around the showers indicate angular errors. The black diamonds are the HESE tracks while the blue diamonds stand for the tracks from the through-going muon sample. The blue curve indicates the Super-Galactic plane.

arXiv:1511.09408

Precise measurementof the all-particle energy spectrum over 3 decades in energy



4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0°-60°), SD 1500 m (60°-80°)

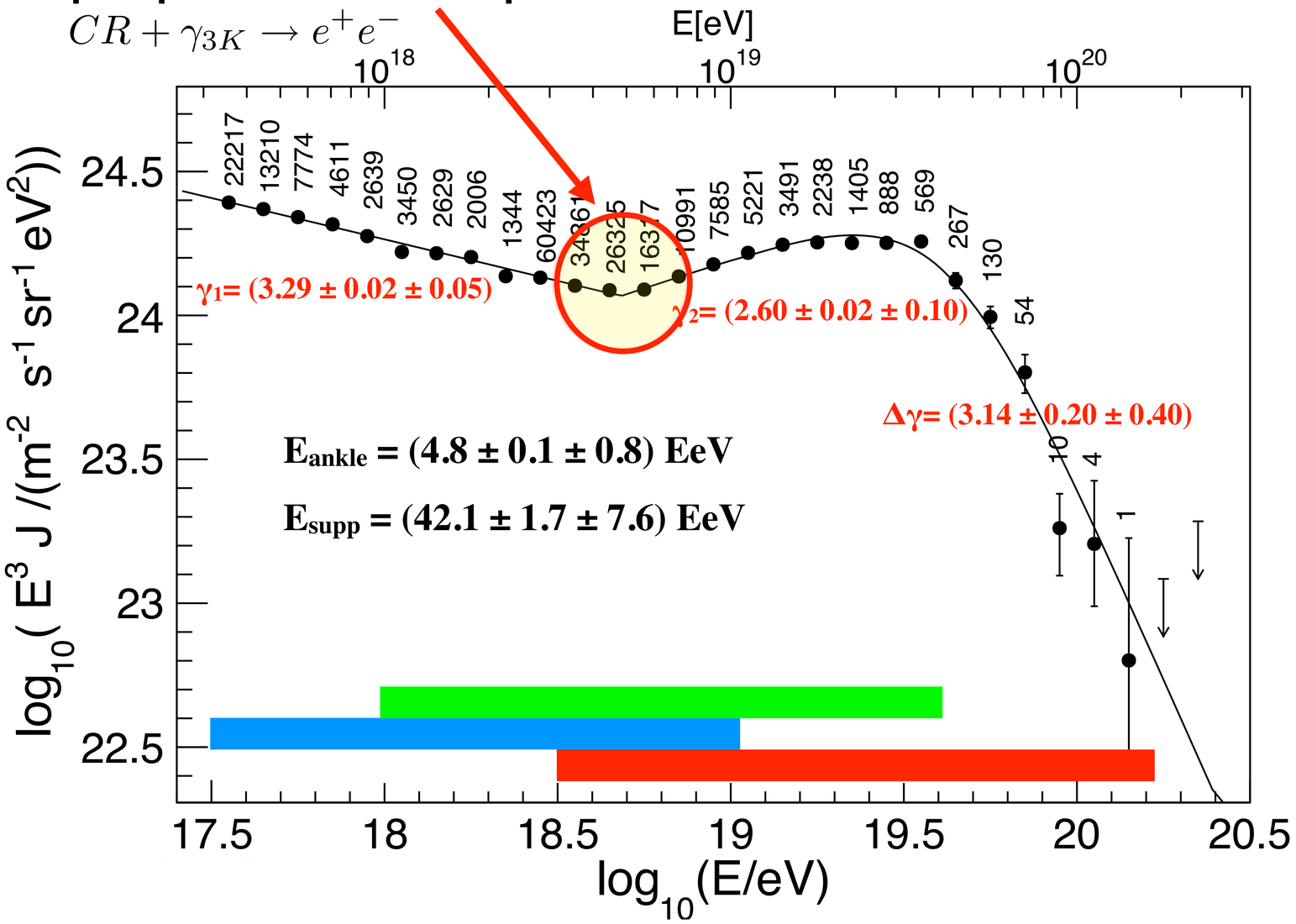
~200000 showers, ~50000 km2 sr yr exposure, FOV -90° < d < 25°

Precise measurementof the all-particle energy spectrum over 3 decades in energy

ankle E=4 10^{18} eV

pair production at 3-K photons

$CR + \gamma_{3K} \rightarrow e^+e^-$



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Precise measurementof the all-particle energy spectrum over 3 decades in energy

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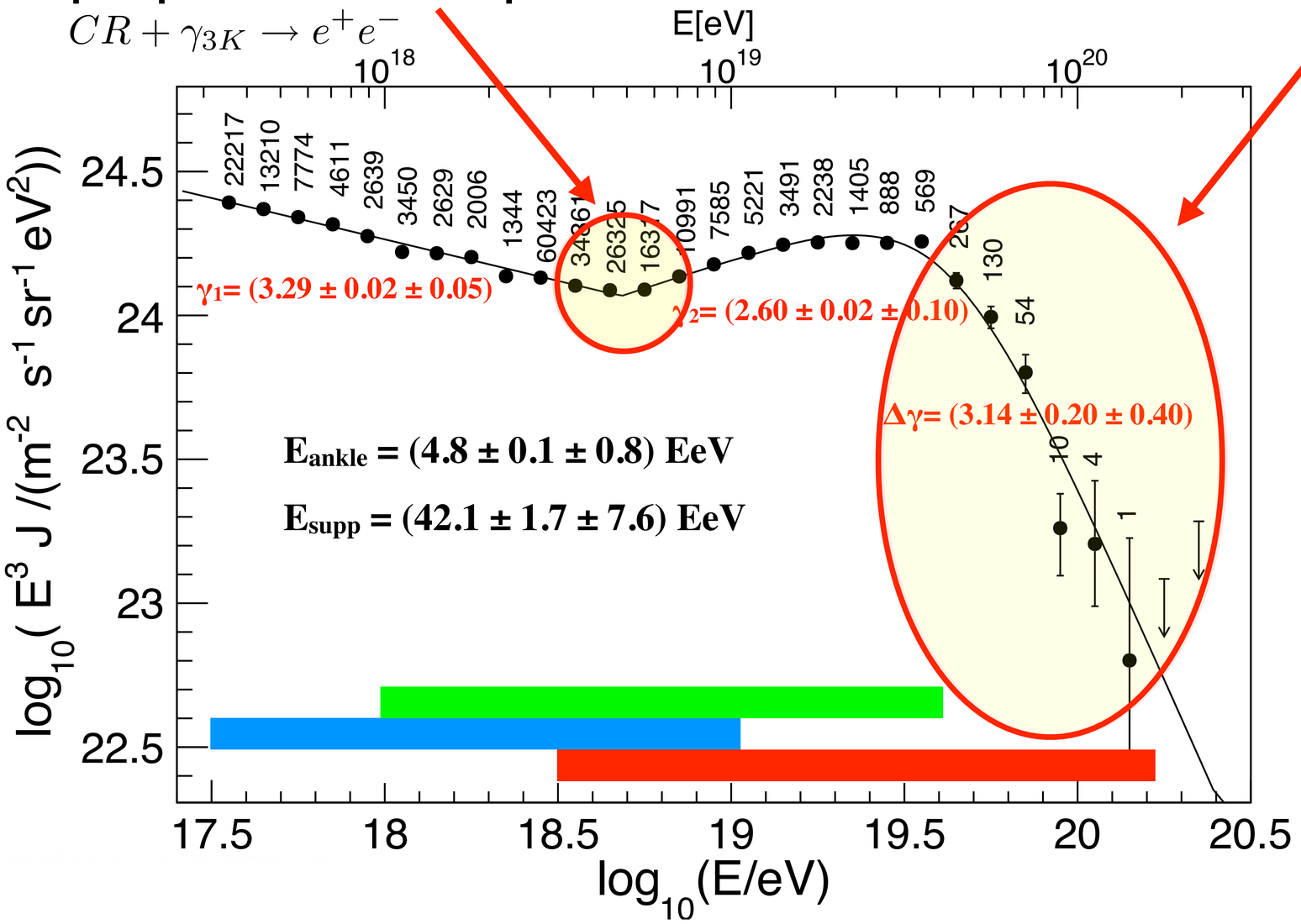
pair production at 3-K photons

$CR + \gamma_{3K} \rightarrow e^+e^-$

depression E>4 10^{19} eV



- **photo pion production at 3-K photons, GZK effect**

$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0; n + \pi^+$

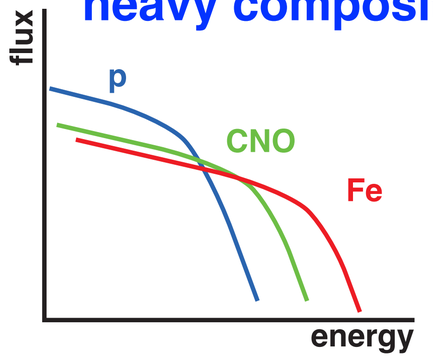
light composition

- **maximum energy of accelerators**

$E_{max} \propto Z \cdot B \cdot L$

(Hillas condition)

heavy composition



4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0°-60°), SD 1500 m (60°-80°)

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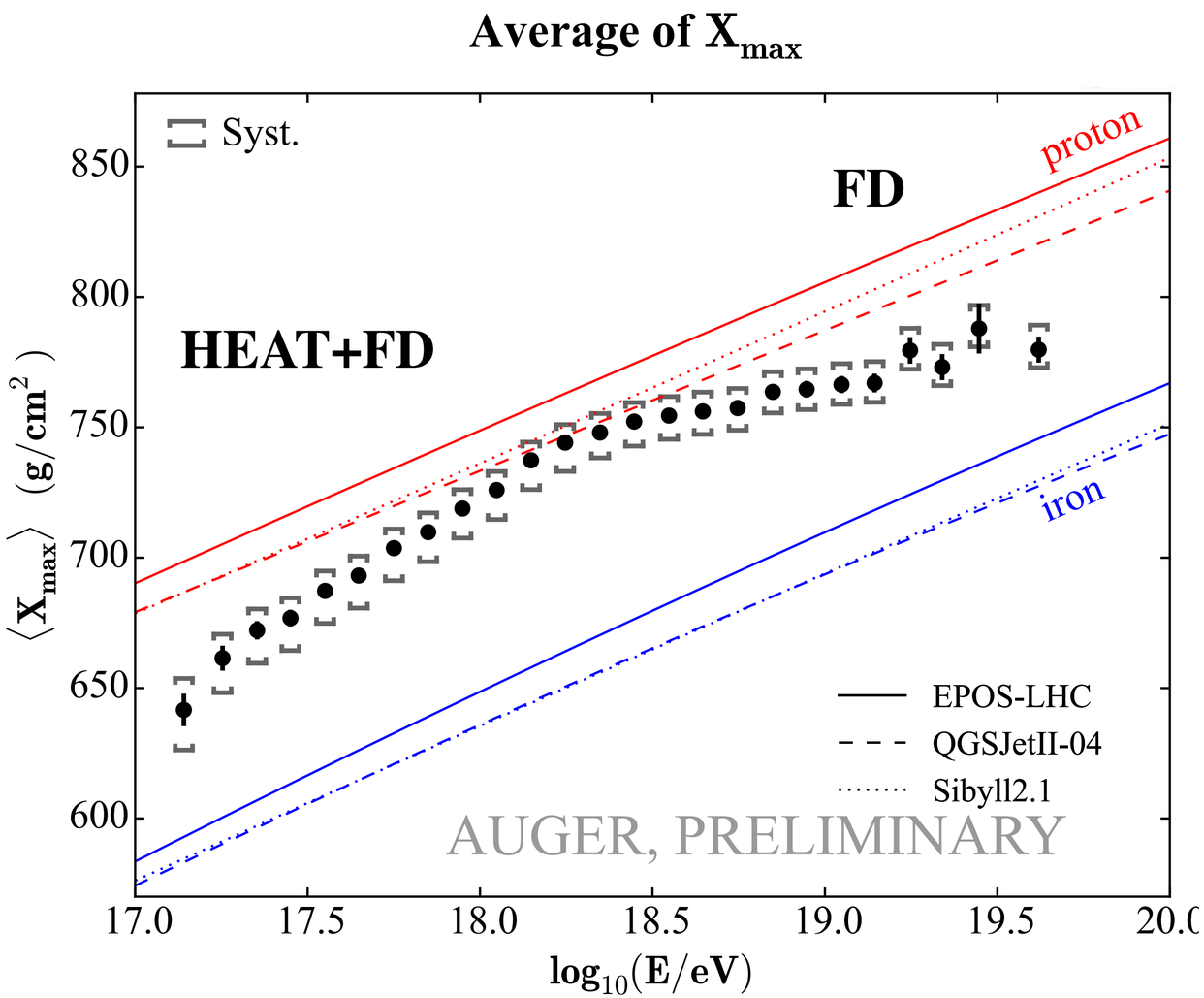
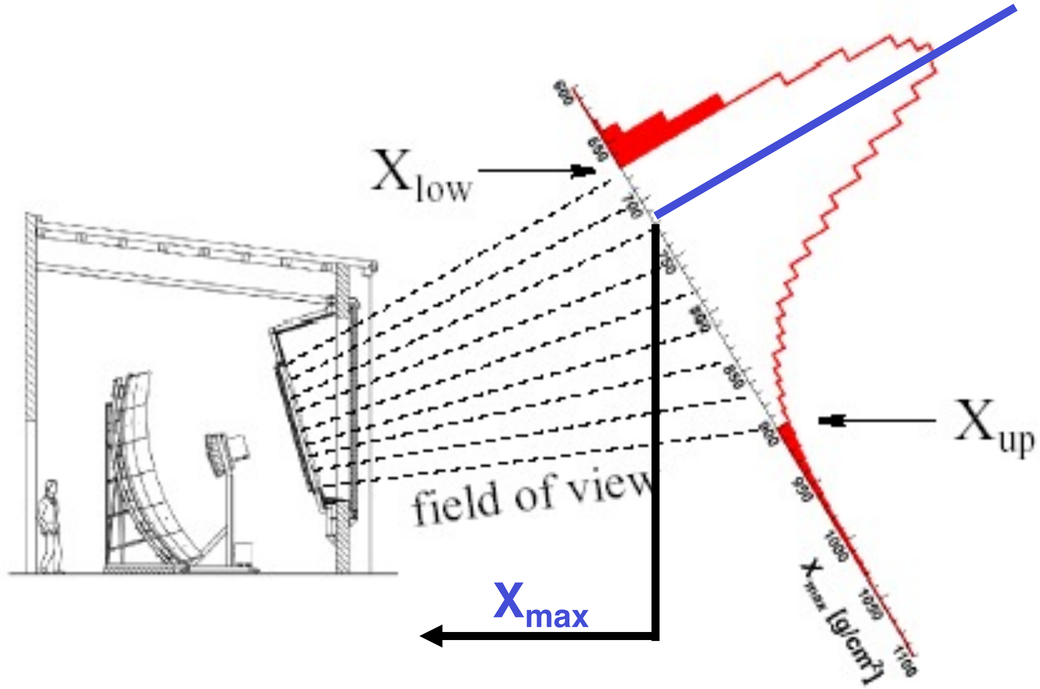
First measurement of the depth of shower maximum over 3 decades in energy

Depth of shower maximum is premiere observable for mass composition studies .
HEAT data extend the FOV of the fluorescence detector up to 60°.
Extension of the depth of shower maximum measurements down to 10^{17} eV.





Compared to prediction for protons and iron nuclei according to the hadronic interaction models EPOS-LHC, QGSJETII-04, Sybill2.1

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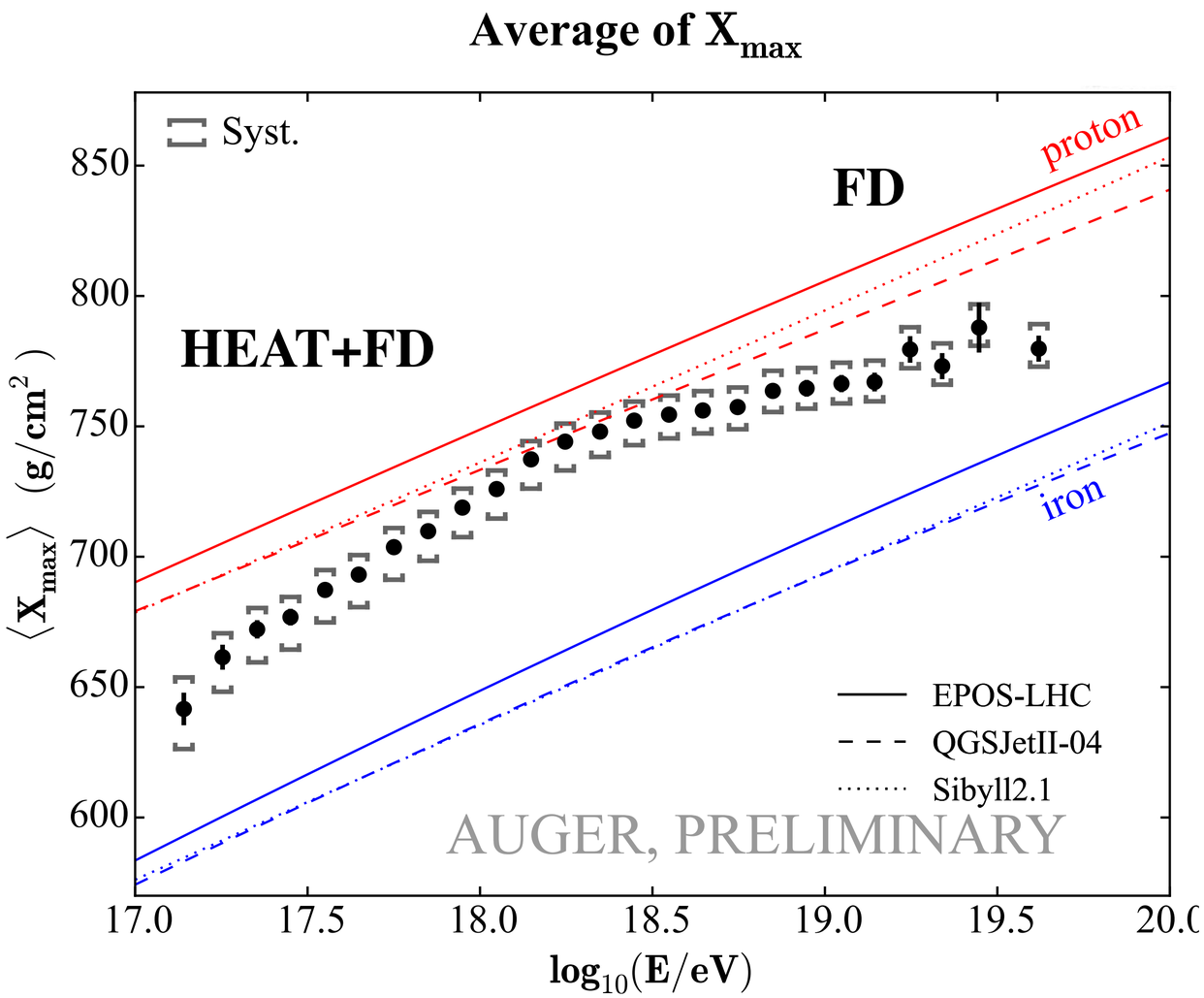

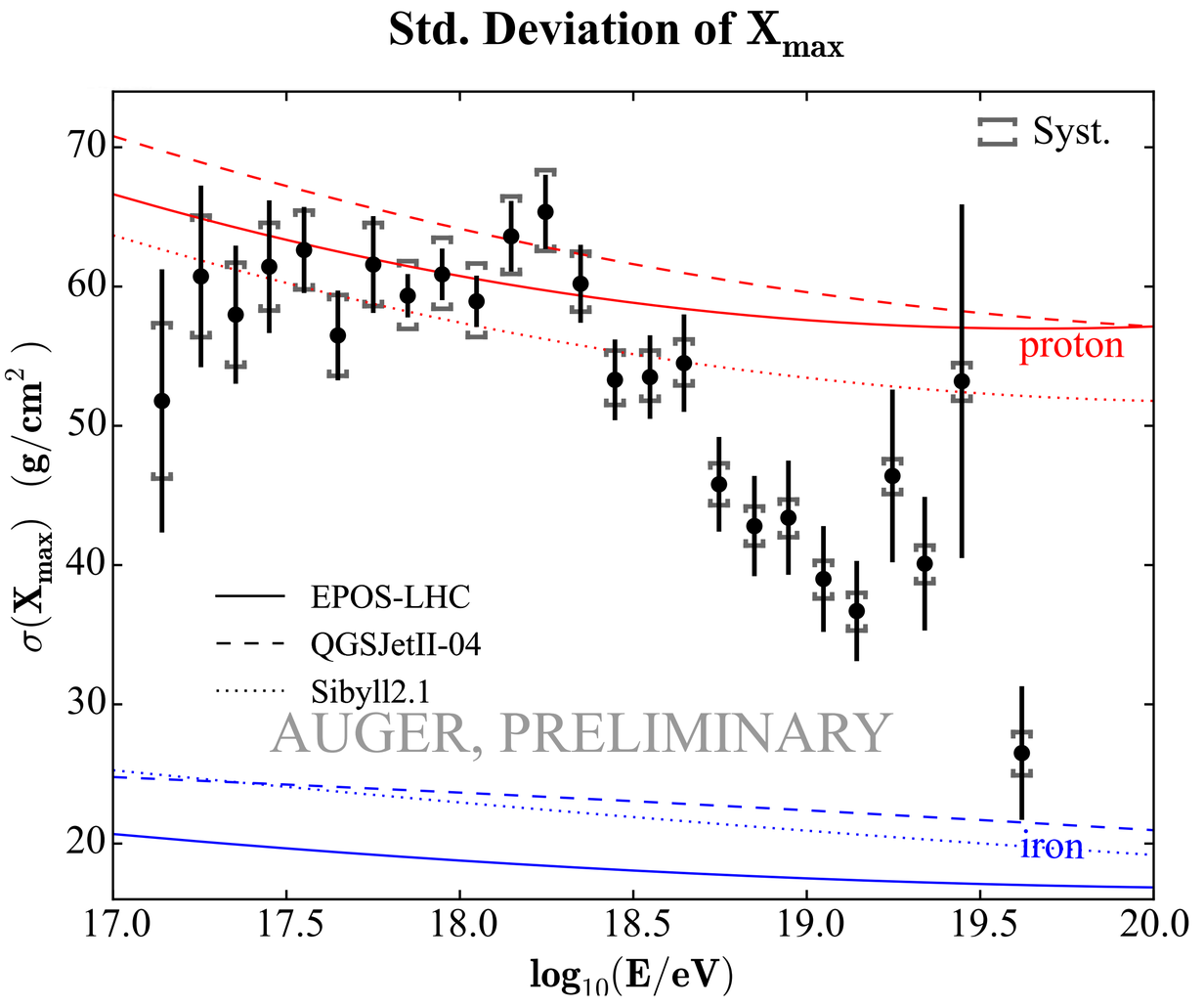

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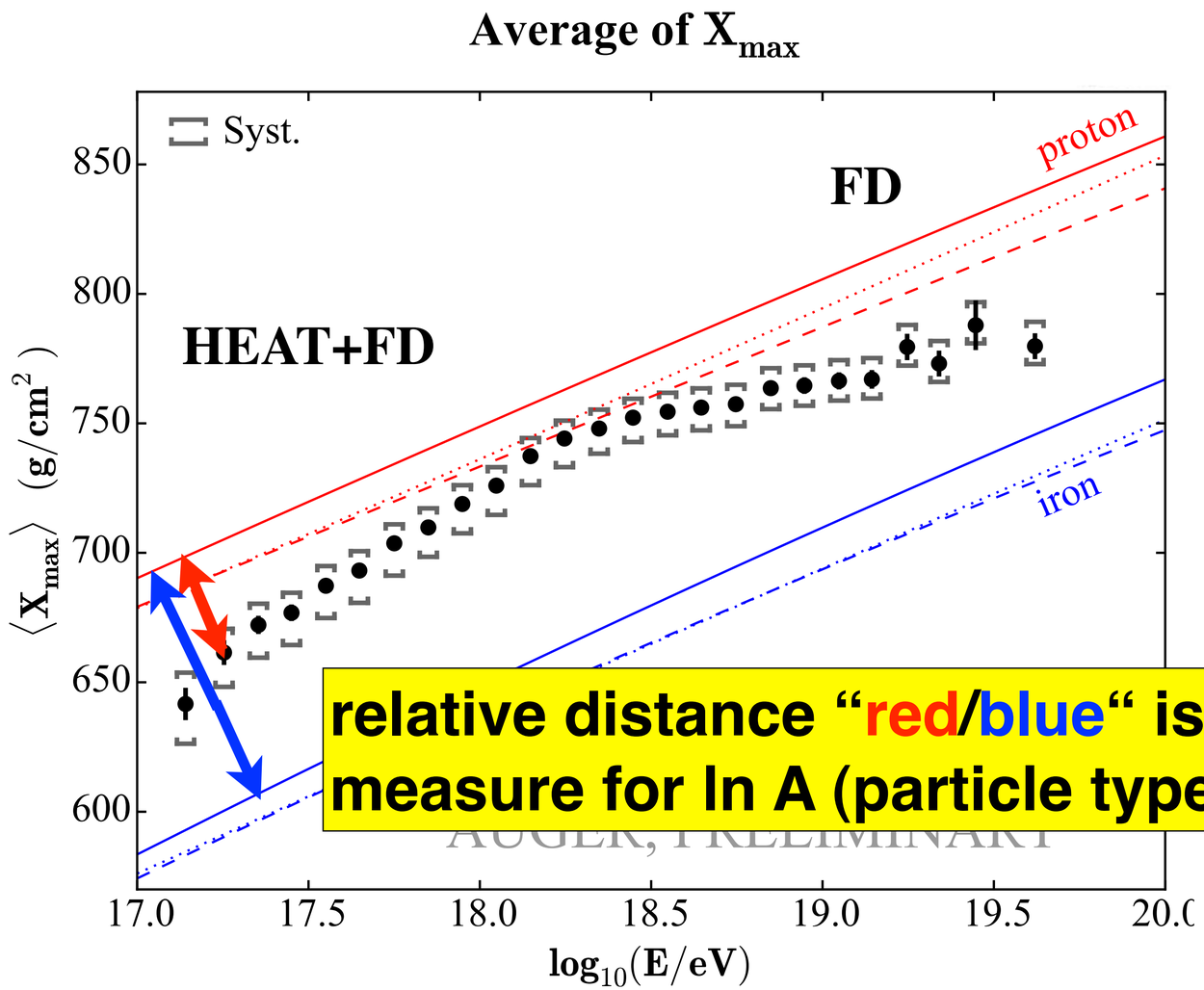
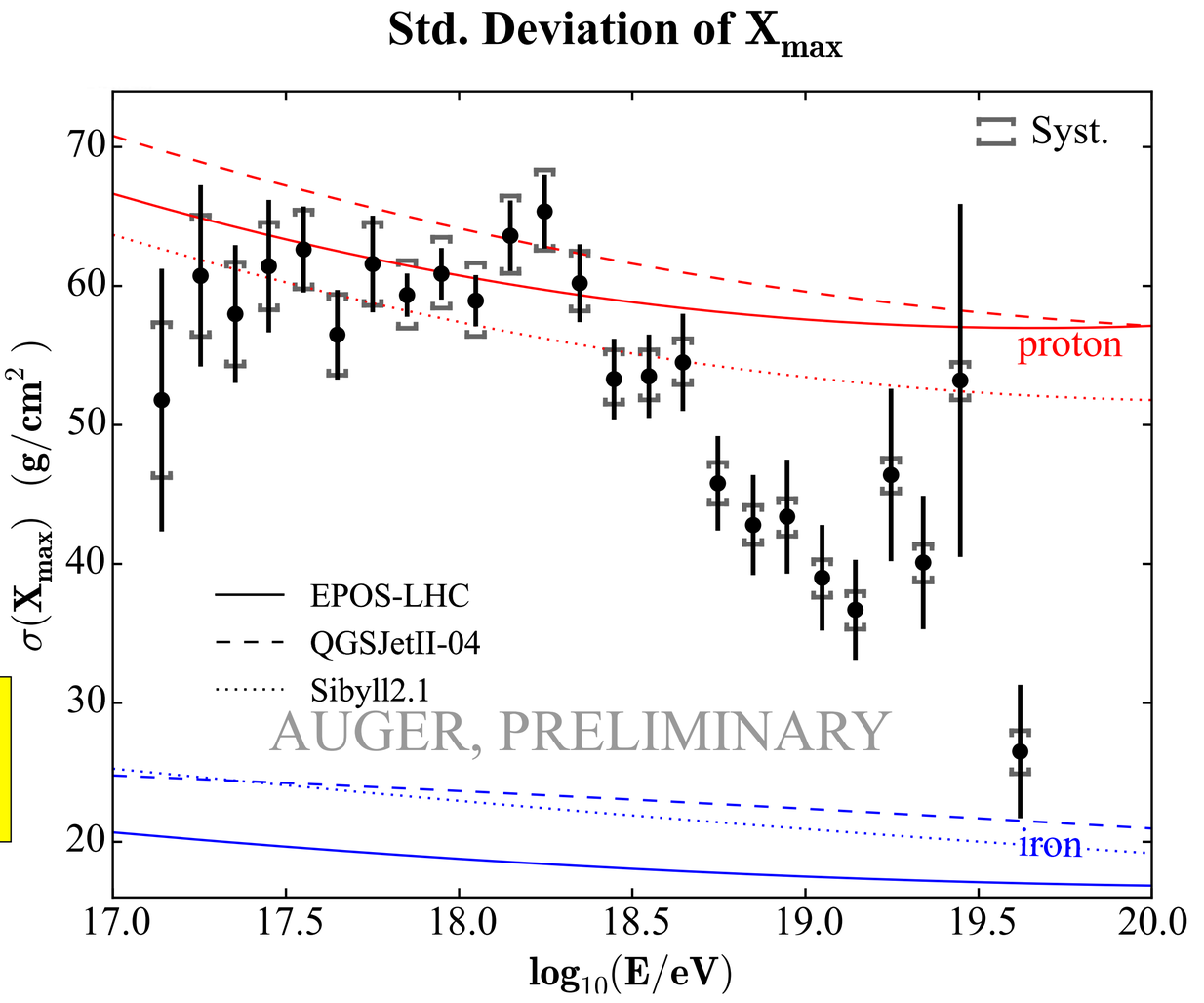
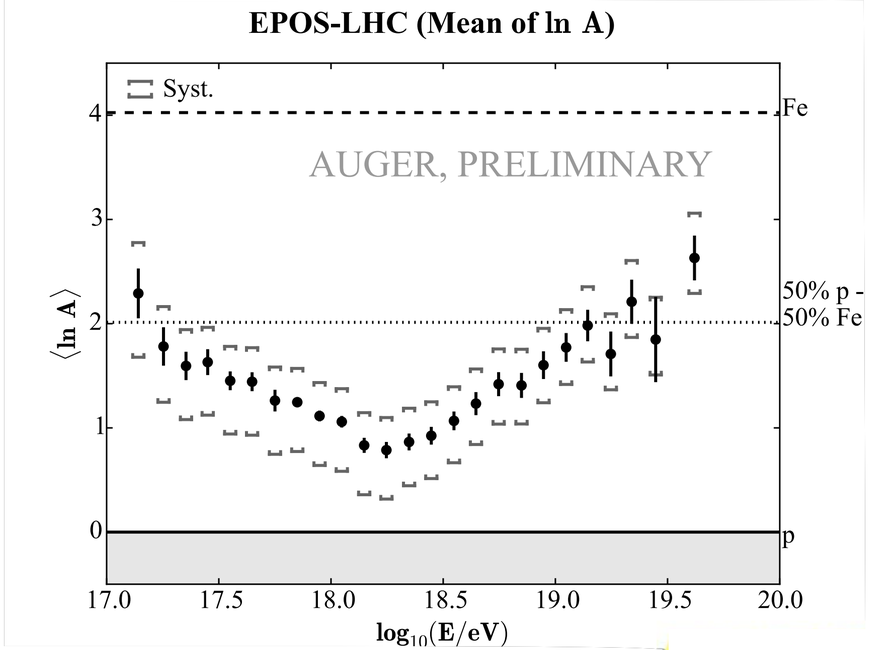


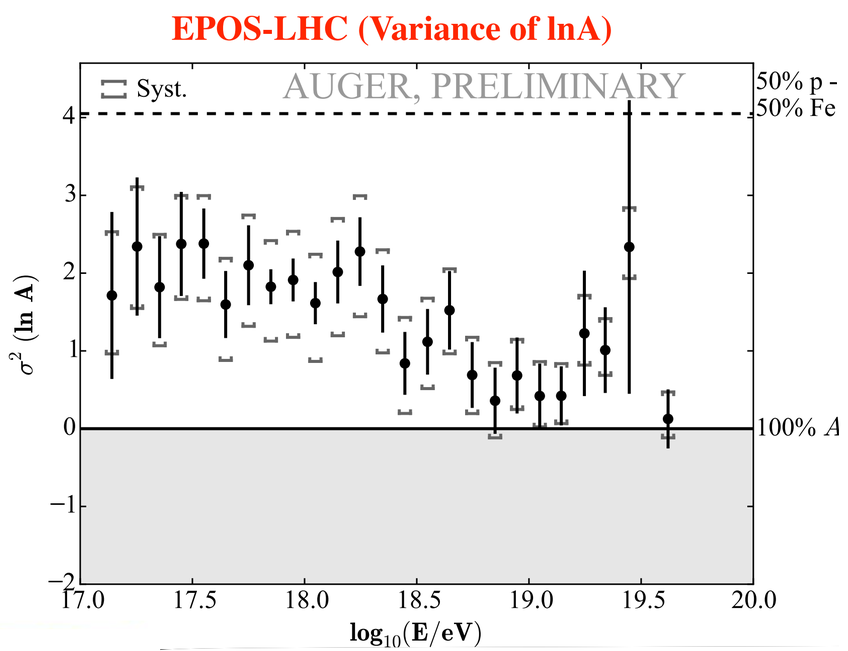


Compared to prediction for protons and iron nuclei according to the hadronic interaction models EPOS-LHC, QGSJETII-04, Sybill2.1

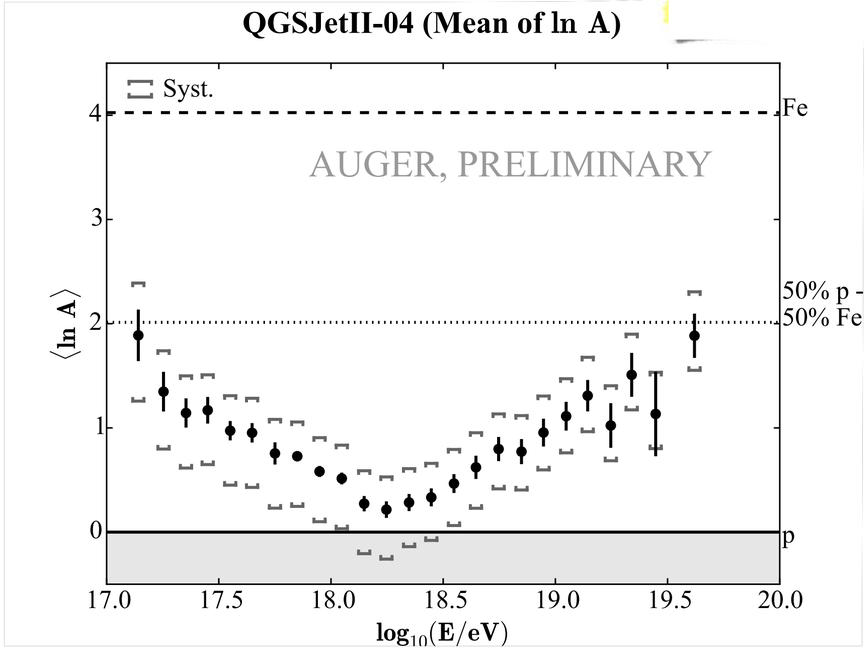
From the depth of the shower maximum to the type of cosmic ray/mass (ln A)

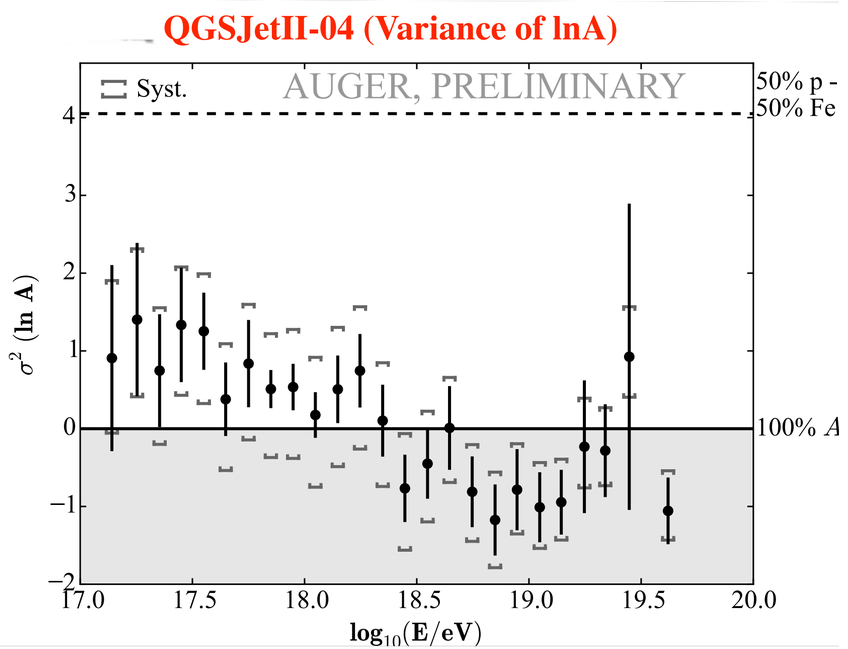
Epos-LHC





QGSJetII-04

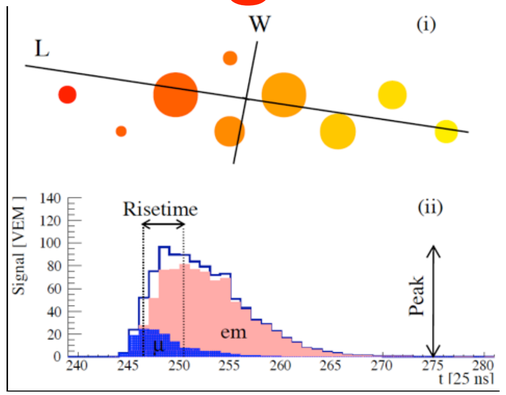




Similar trend for both models:
heavier composition at low energies (largest mass dispersion),
lightest ln A at ≈ 2x10^{18} eV, getting heavier again towards higher energies (smaller mass dispersion)
[N.B: very few data above ≈ 40 EeV)

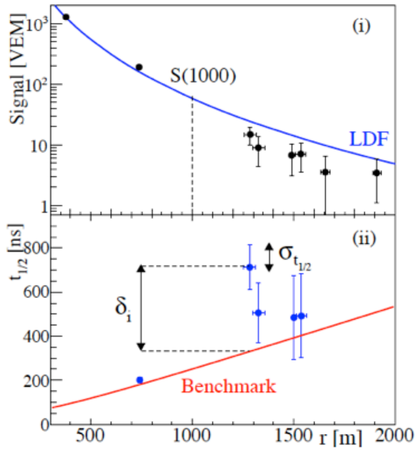
Mass measurement and test of hadronic interaction models.
The conversion to σ^2(lnA) using QGSJETII-04 yields unphysical results.

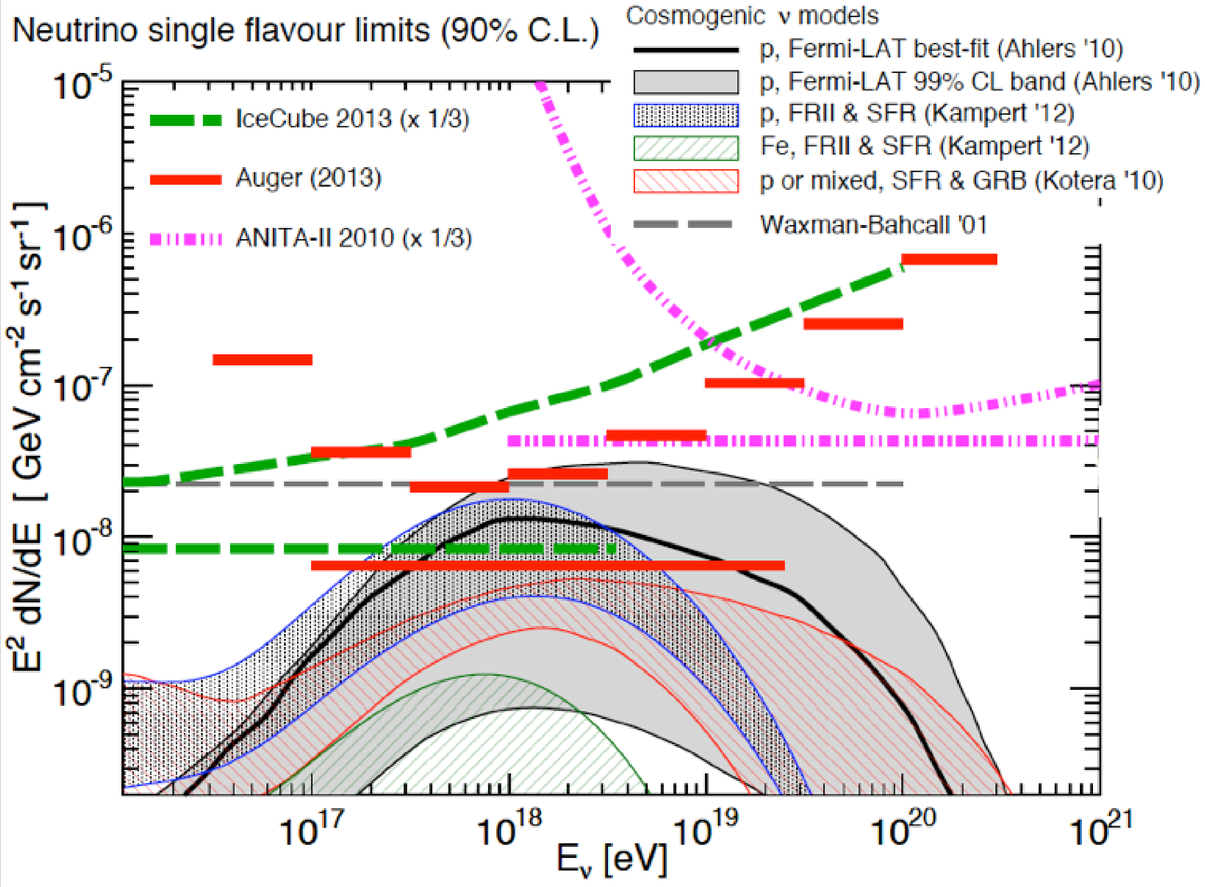
Stringent neutrino- and photon-flux limits at EeV energies

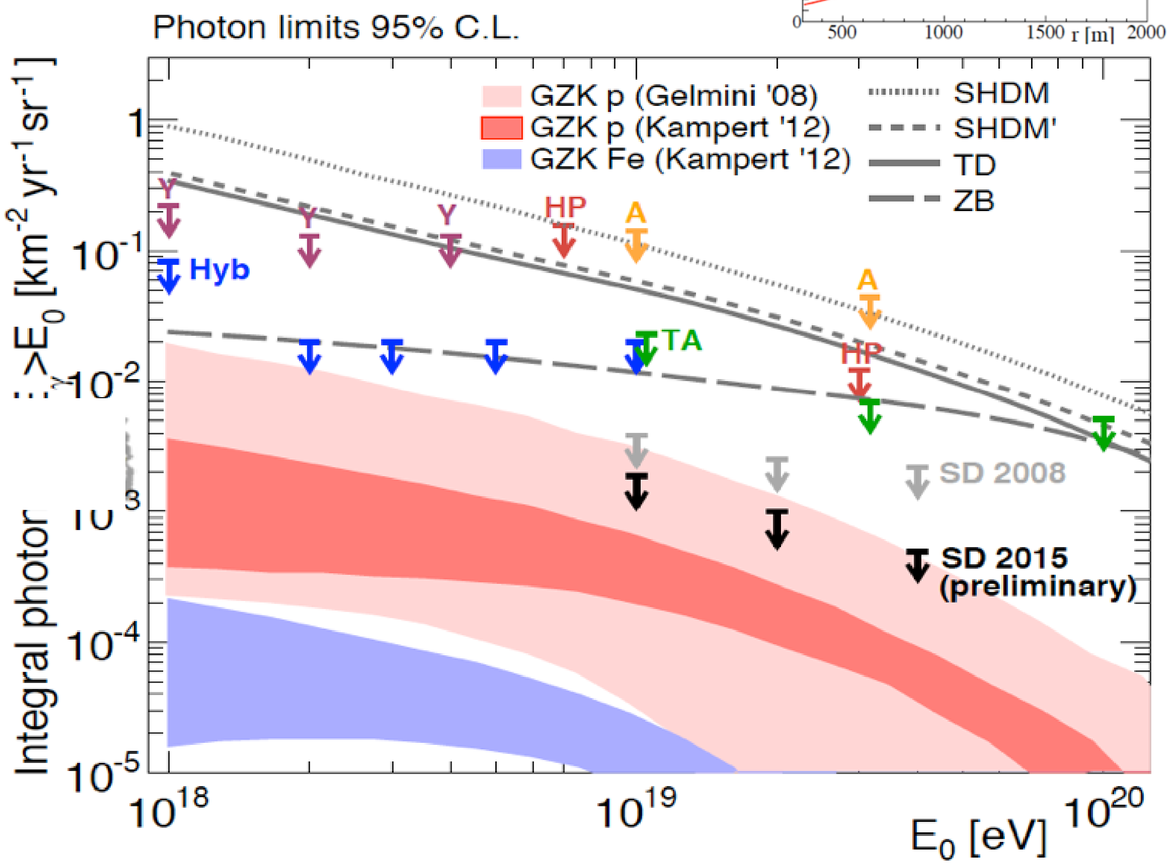


Observables to select neutrinos: shape of the footprint and time structure of signals in very inclined showers (θ>60°)

EAS observables to select photons: shape of the LDF and time structure of signals in showers with 30<θ<60







First limit from an EAS array below WB bound

Top-down models strongly disfavored

a complementary path to the future:

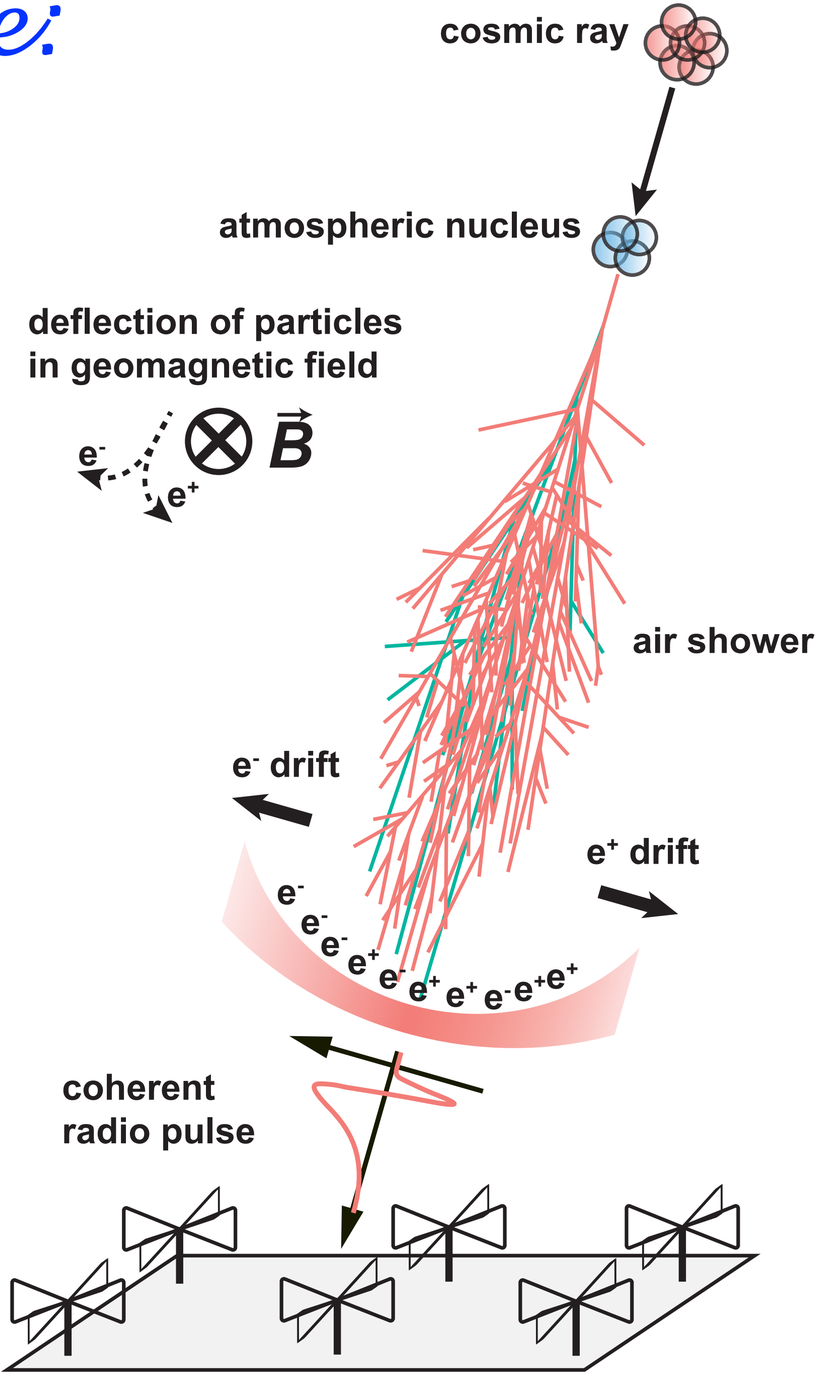
Radio Emission in Air Showers

- **Mainly: Charge separation in geomagnetic field**

$$\vec{E} \propto \vec{v} \times \vec{B}$$

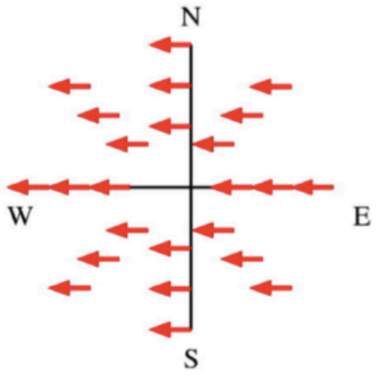
Theory predicts additional mechanisms:

- **excess of electrons in shower: charge excess**
- **superposition of emission due to Cherenkov effects in atmosphere**

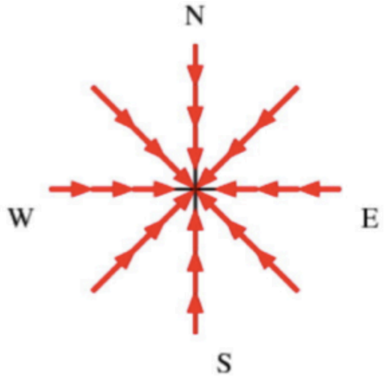


polarization of radio signal

geomagnetic



Askaryan



Radio emission pattern on ground is sensitive to

energy

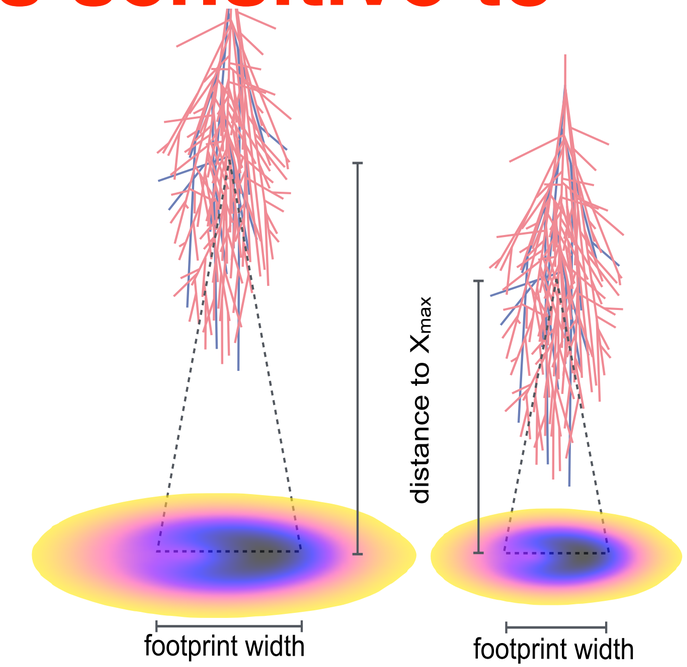
total energy (integral) is sensitive to shower energy

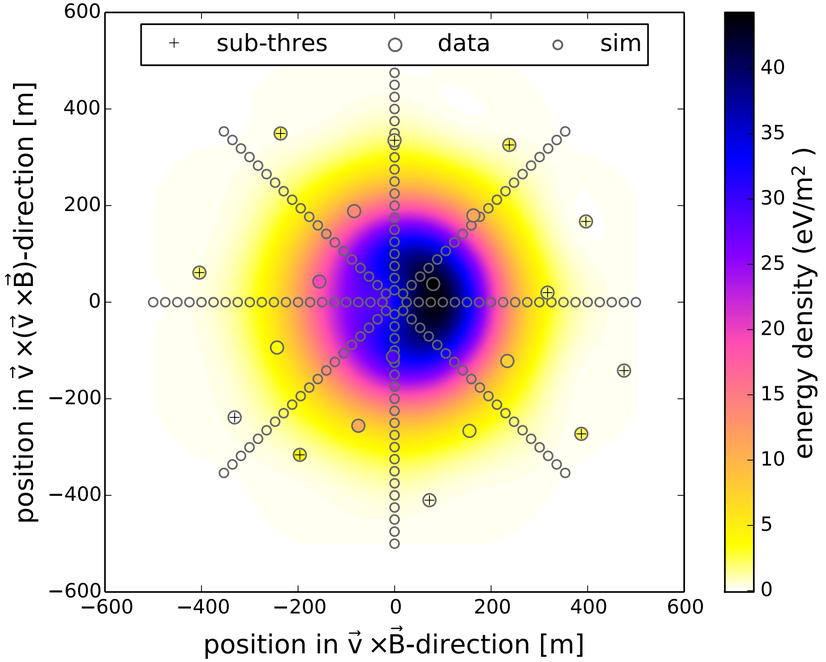
see e.g.
- **Auger PRL/PRD**
- **LOFAR, Nelles et al., JCAP 05 (2015) 018**

particle type/Xmax

width of footprint sensitive to distance to Xmax

see e.g.
- **LOFAR, Buitink et al., PRD 90 (2014) 082003**





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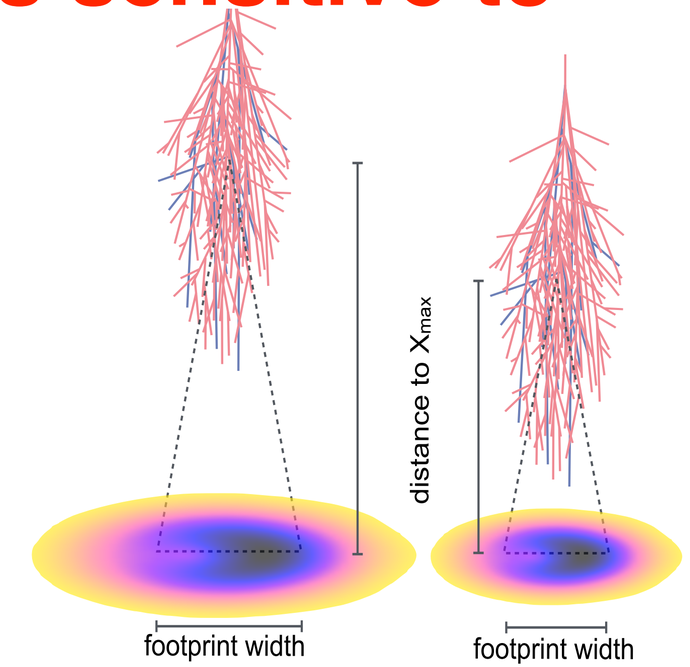
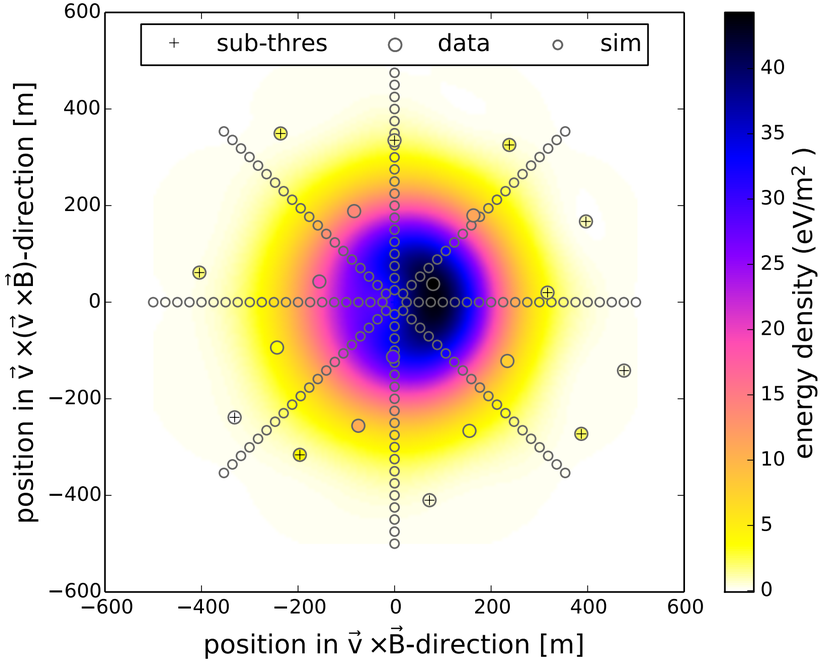


example:

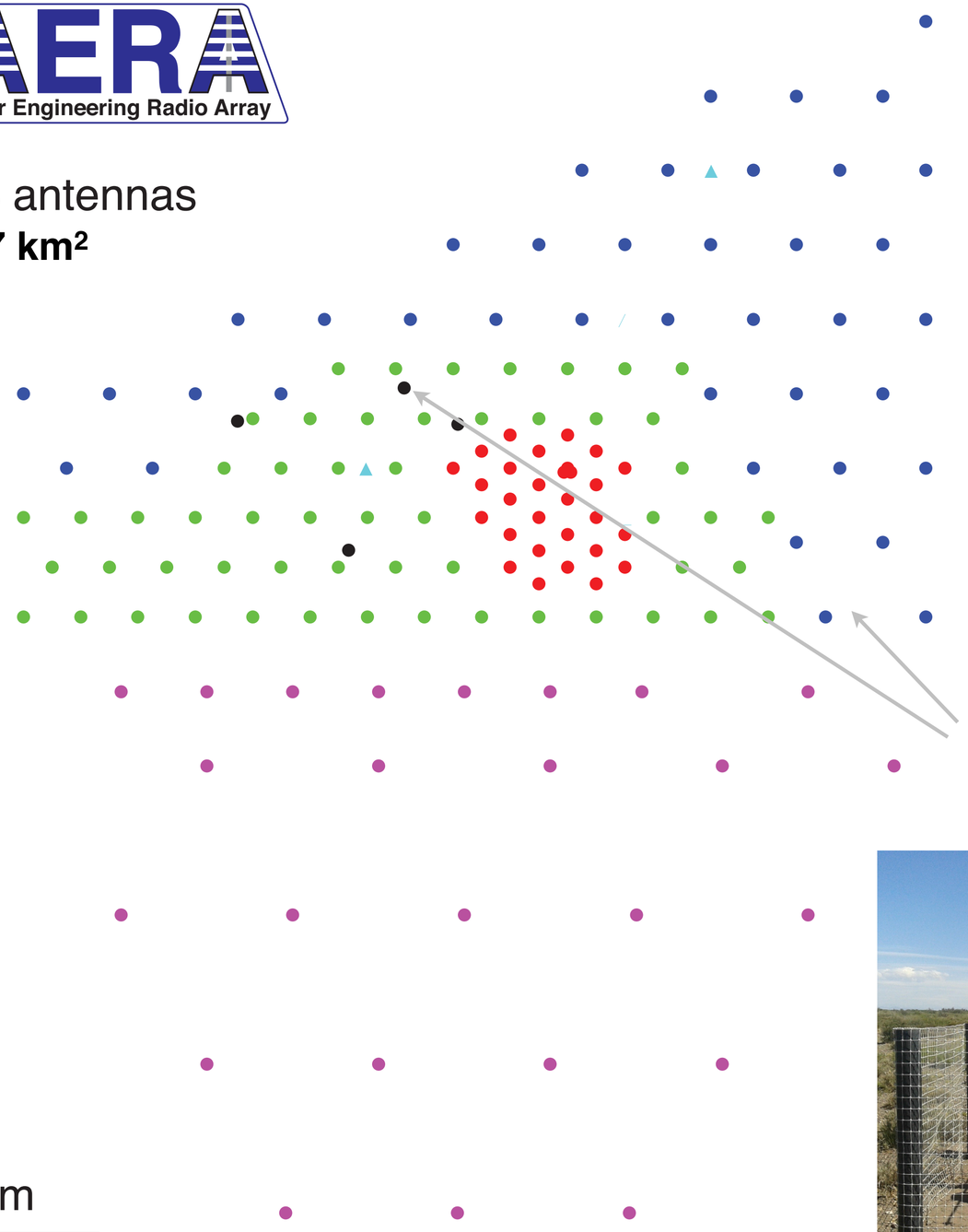
$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

A. Nelles et al., Astroparticle Physics 60 (2015) 13

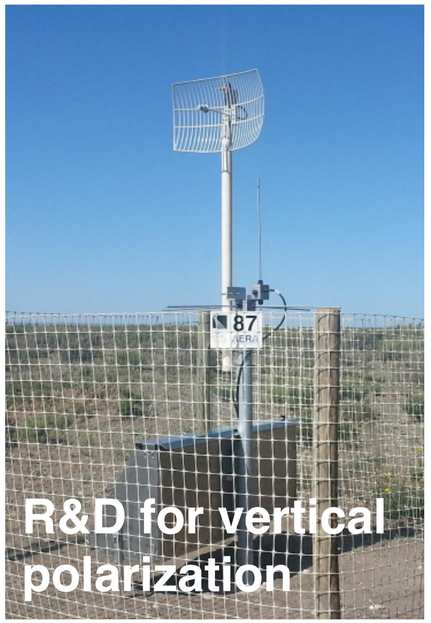


AERA
Auger Engineering Radio Array

153 antennas
~17 km²



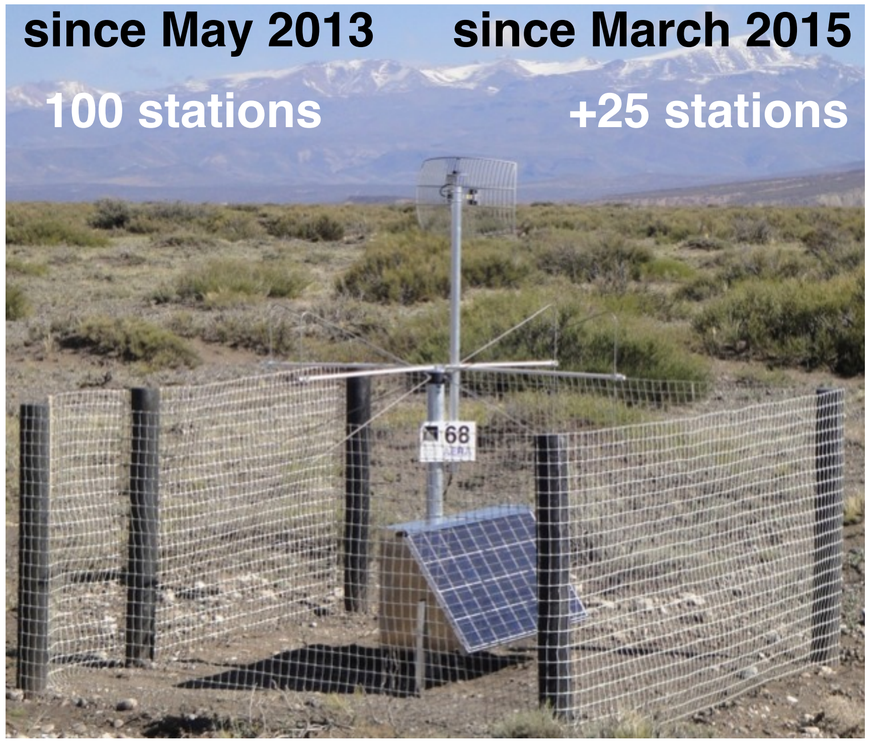
1 km

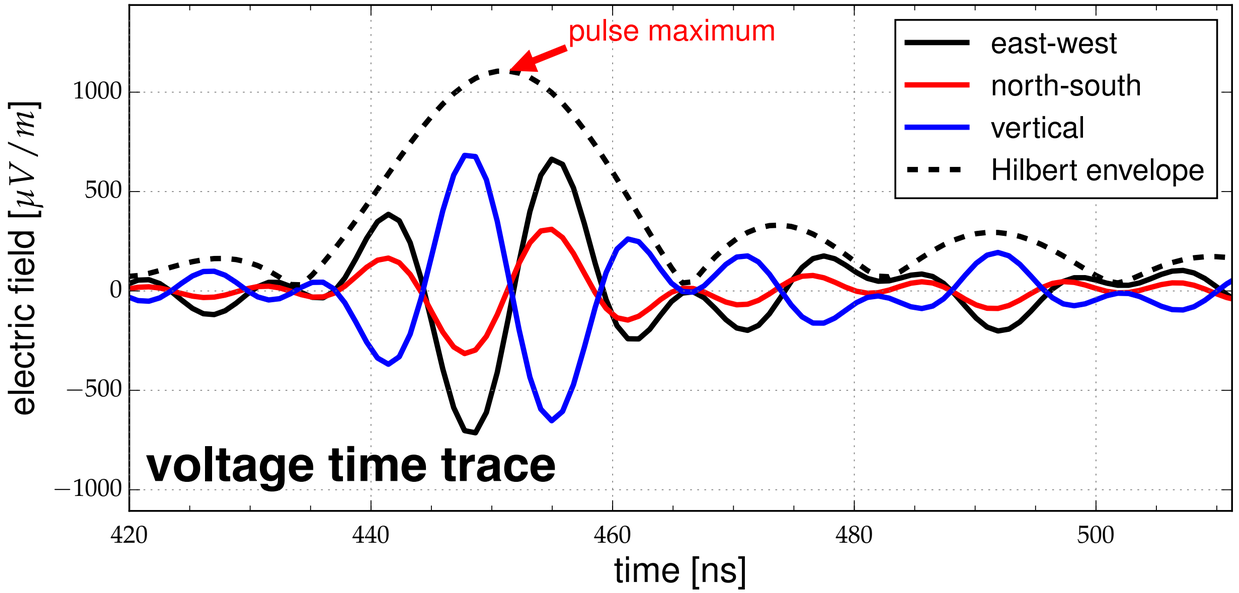


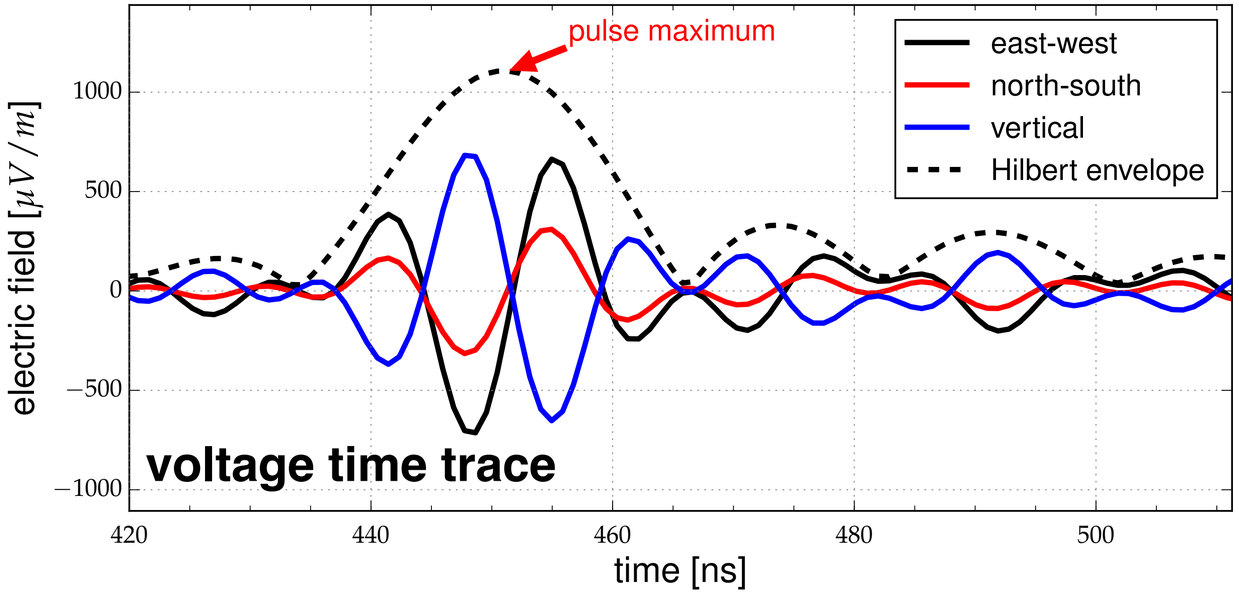
since August 2010
24 stations

since May 2013
100 stations

since March 2015
+25 stations




pulse maximum
east-west
north-south
vertical
Hilbert envelope
voltage time trace
electric field [$\mu V/m$]
time [ns]
1000
500
0
−500
−1000
420
440
460
480
500


pulse maximum
east-west
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Hilbert envelope
voltage time trace
electric field [$\mu V/m$]
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1000
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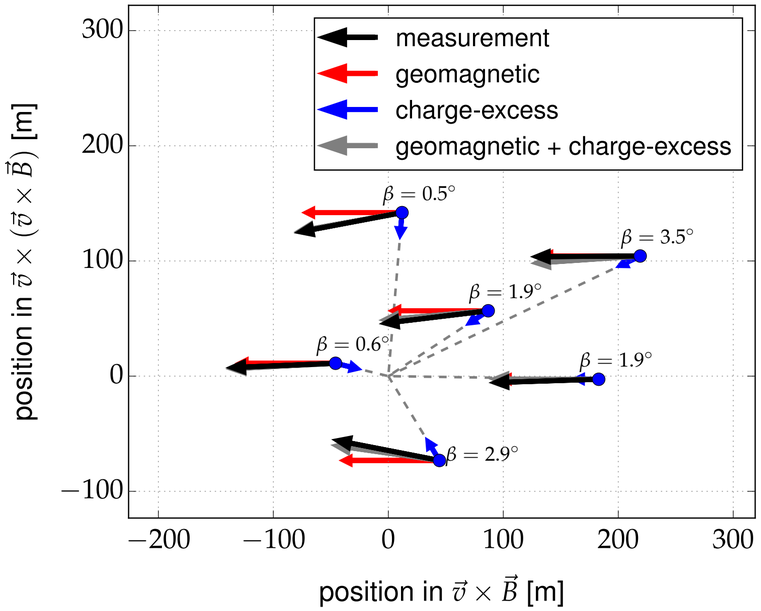
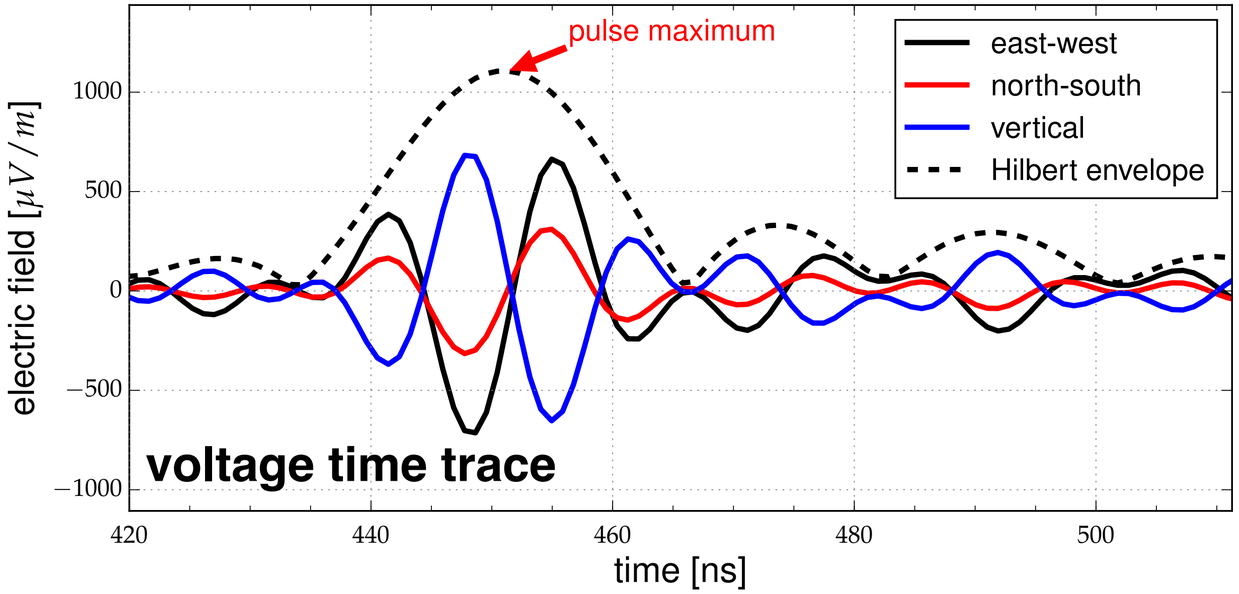
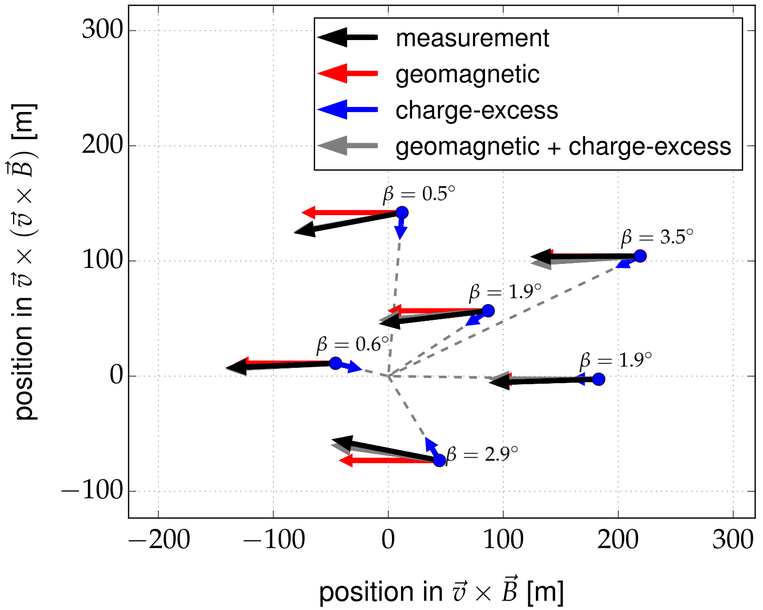
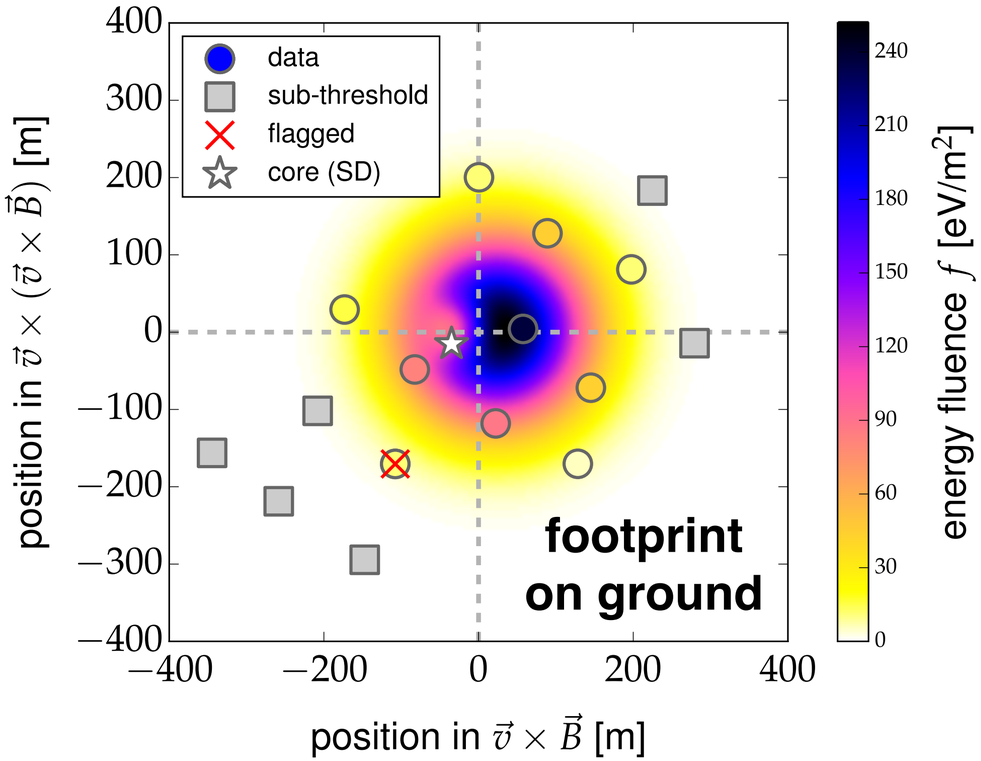
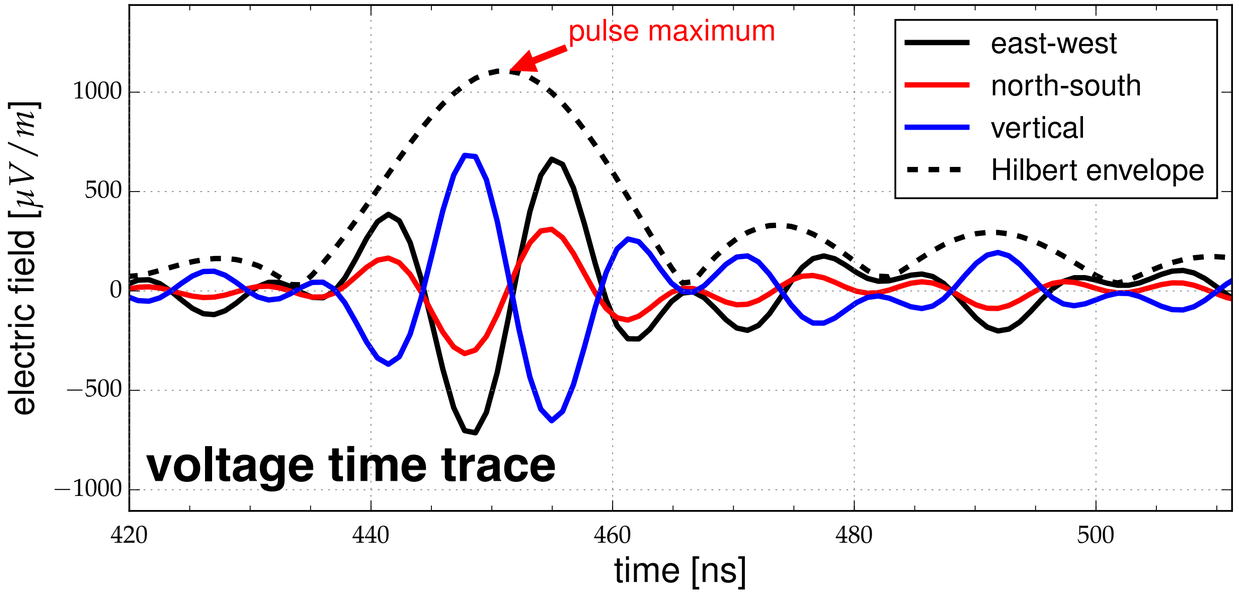
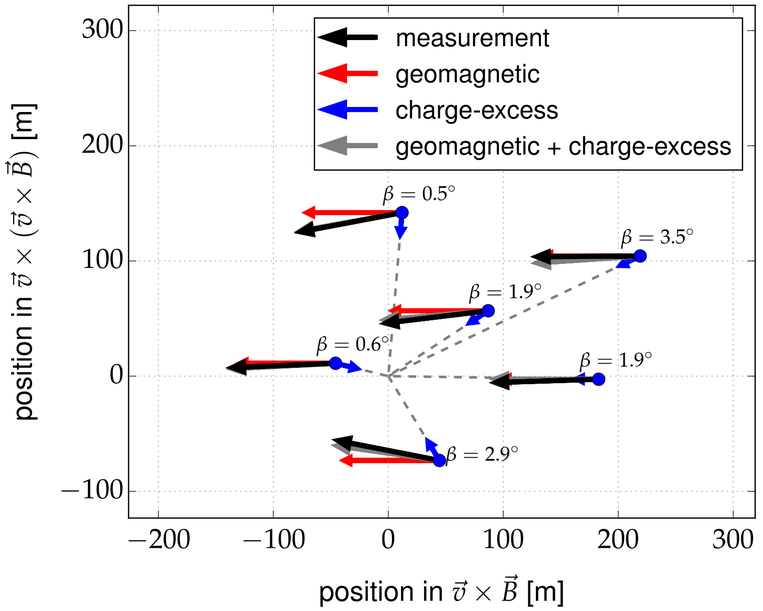

measurement
geomagnetic
charge-excess
geomagnetic + charge-excess
$\beta = 0.5°$
$\beta = 3.5°$
$\beta = 1.9°$
$\beta = 0.6°$
$\beta = 1.9°$
$\beta = 2.9°$
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]
300
200
100
0
−100
−200
−100
0
100
200
300

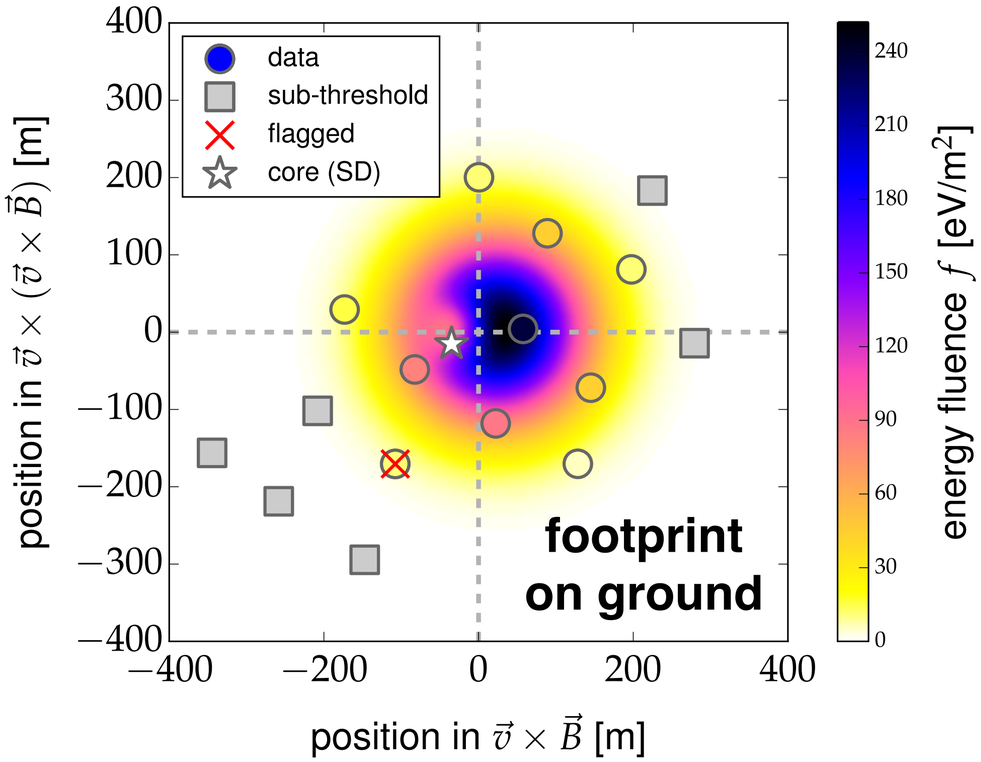

pulse maximum
east-west
north-south
vertical
Hilbert envelope
voltage time trace
electric field [$\mu V/m$]
time [ns]

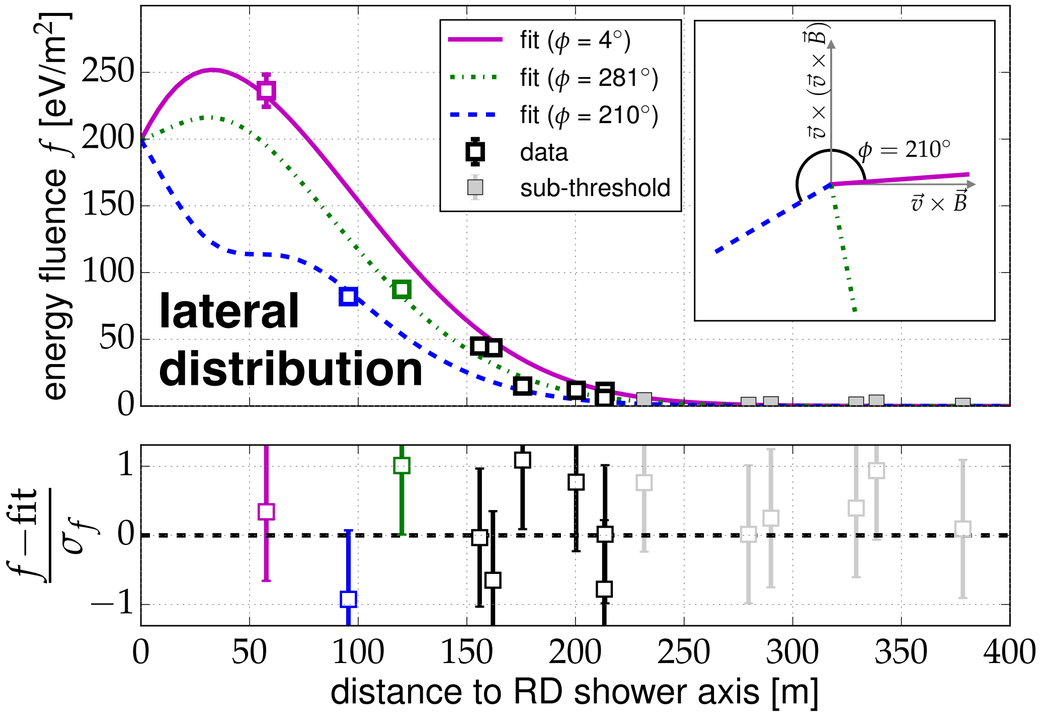

measurement
geomagnetic
charge-excess
geomagnetic + charge-excess
$\beta = 0.5°$
$\beta = 3.5°$
$\beta = 1.9°$
$\beta = 0.6°$
$\beta = 1.9°$
$\beta = 2.9°$
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]

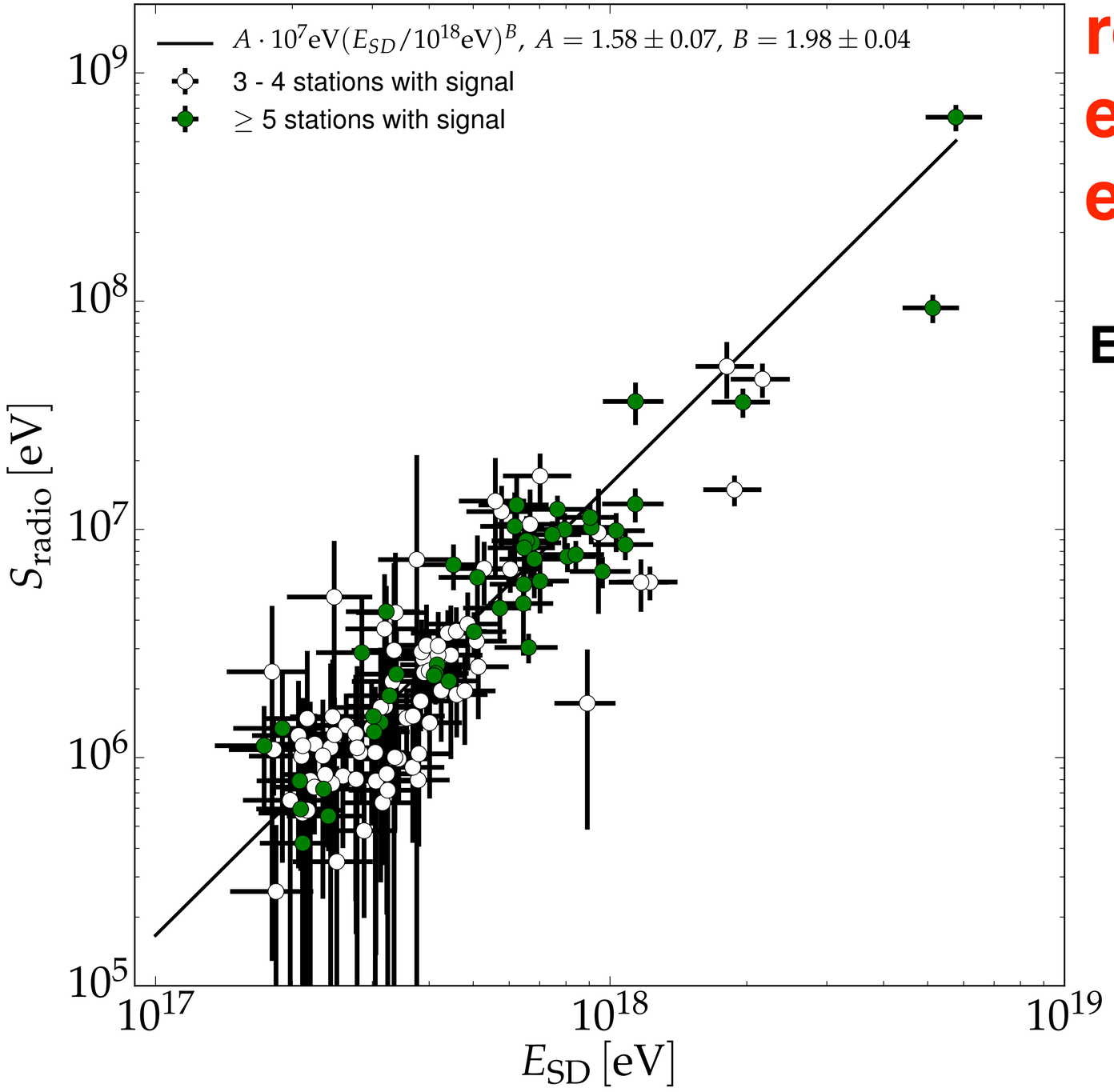

data
sub-threshold
flagged
core (SD)
footprint on ground
energy fluence f [eV/m^2]
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]


pulse maximum
east-west
north-south
vertical
Hilbert envelope
electric field [$\mu V/m$]
time [ns]
voltage time trace


measurement
geomagnetic
charge-excess
geomagnetic + charge-excess
$\beta = 0.5°$
$\beta = 3.5°$
$\beta = 1.9°$
$\beta = 0.6°$
$\beta = 1.9°$
$\beta = 2.9°$
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]


data
sub-threshold
flagged
core (SD)
footprint on ground
energy fluence f [eV/m^2]
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]

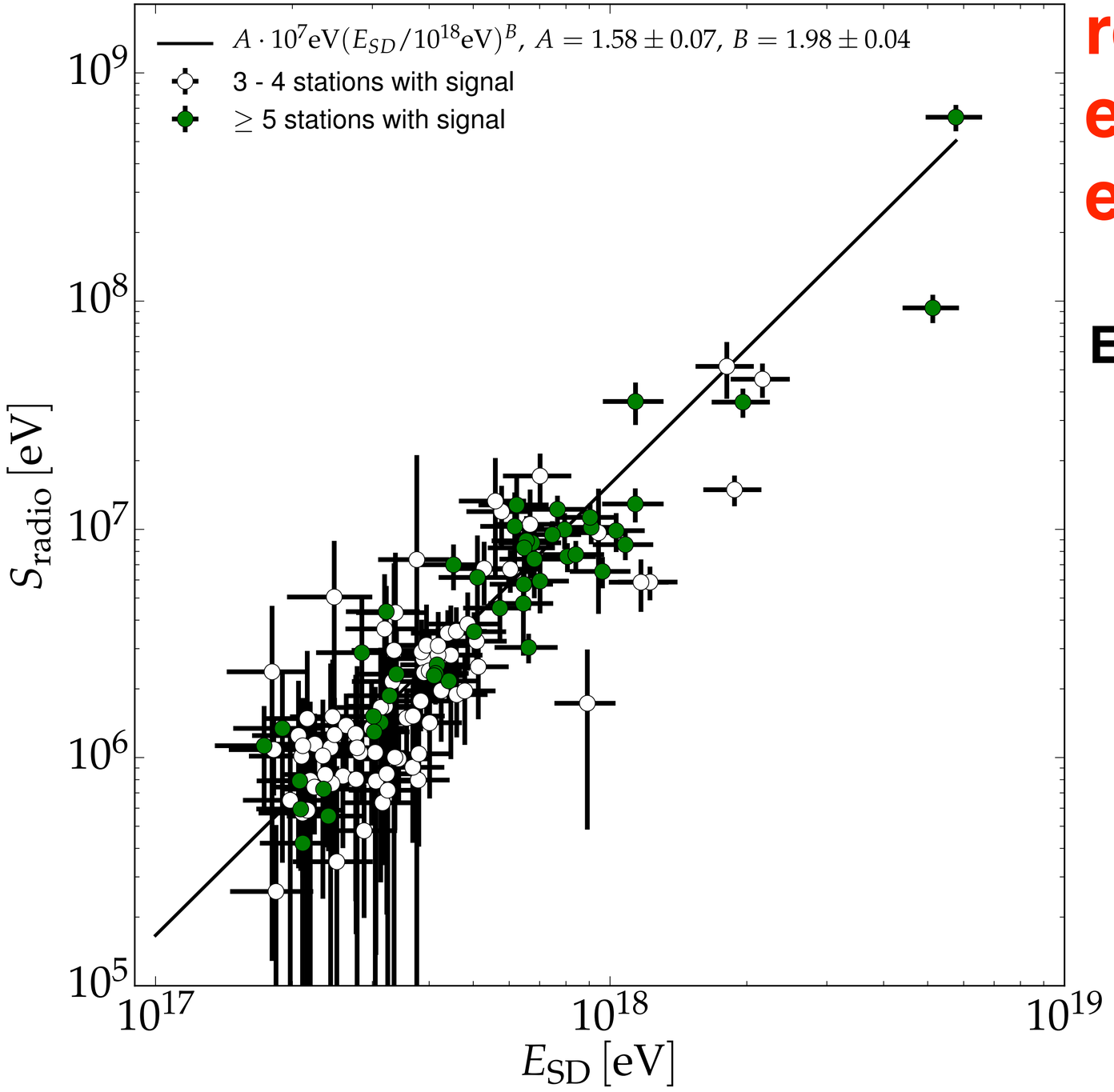

fit (ϕ = 4°)
fit (ϕ = 281°)
fit (ϕ = 210°)
data
sub-threshold
lateral distribution
$\phi = 210°$
$\vec{v} \times (\vec{v} \times \vec{B})$
$\vec{v} \times \vec{B}$
energy fluence f [eV/m^2]
$\frac{f - \text{fit}}{\sigma_f}$
distance to RD shower axis [m]



relation between cosmic-ray energy and energy in radio emission (30 - 80 MHz)

$E_{30\text{-}80\ \text{MHz}}$ = 15.8 MeV @ 10^{18} eV

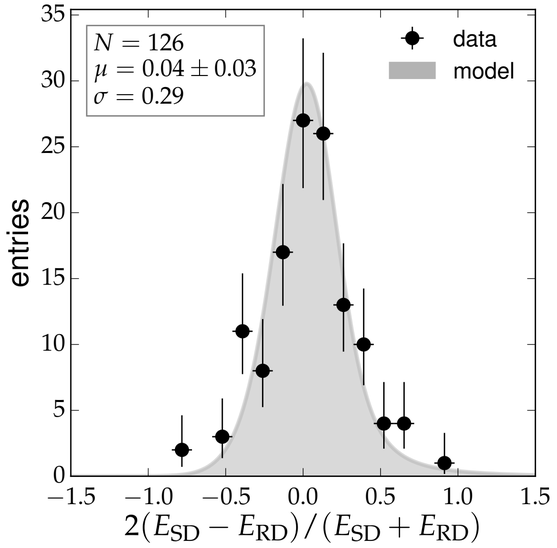
relation between cosmic-ray energy and energy in radio emission (30 - 80 MHz)



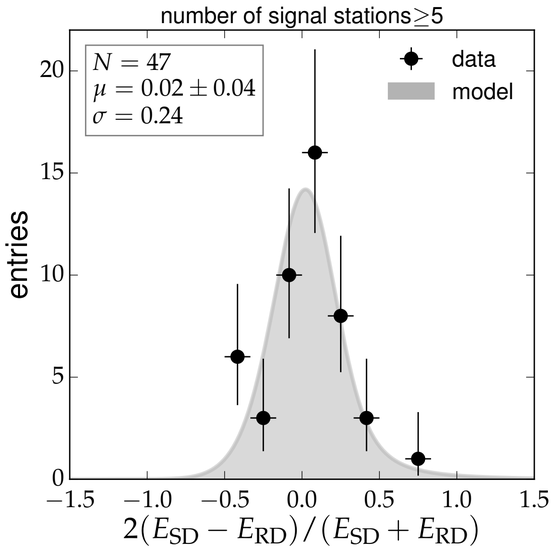
$E_{30\text{-}80\ \text{MHz}}$ = 15.8 MeV @ 10^{18} eV

energy resolution

29% all showers



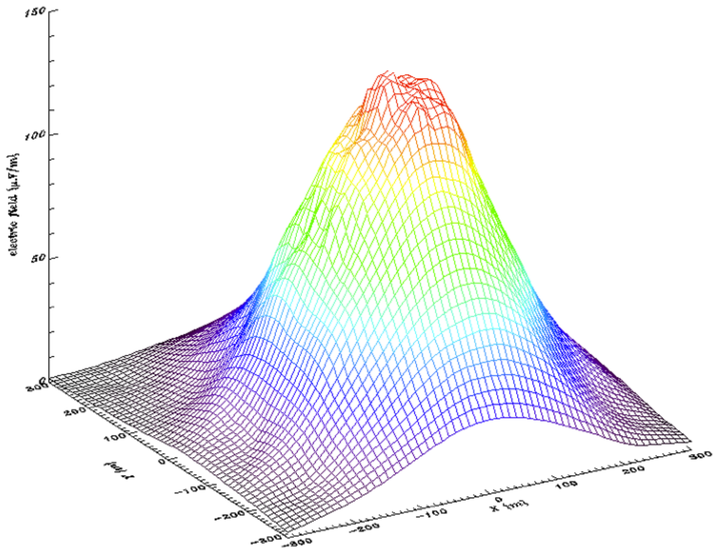
24% high quality



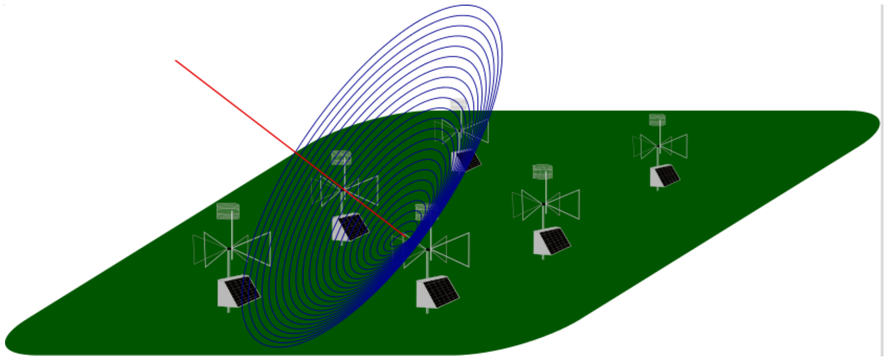
Measurement of the depth of the shower maximum X_{max} with

AERA
Auger Engineering Radio Array

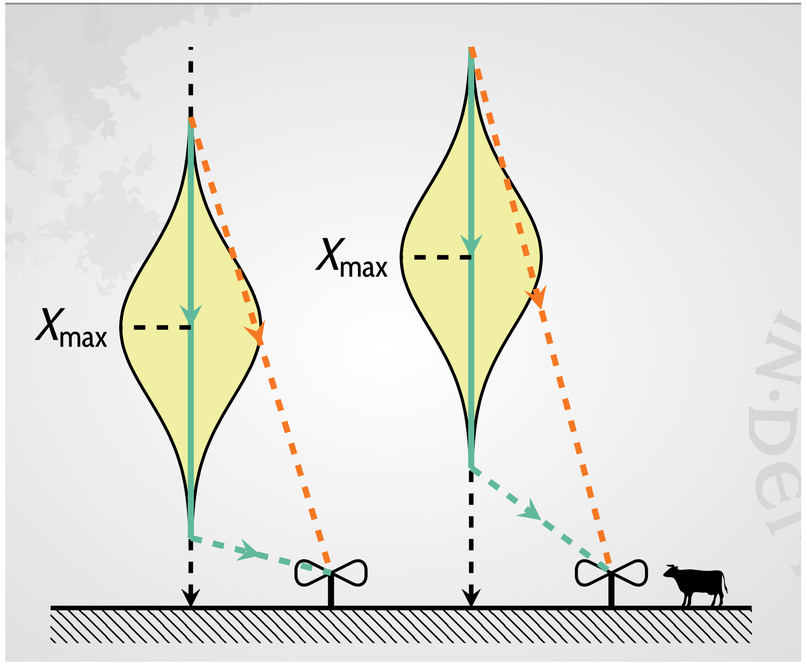
electric field strength



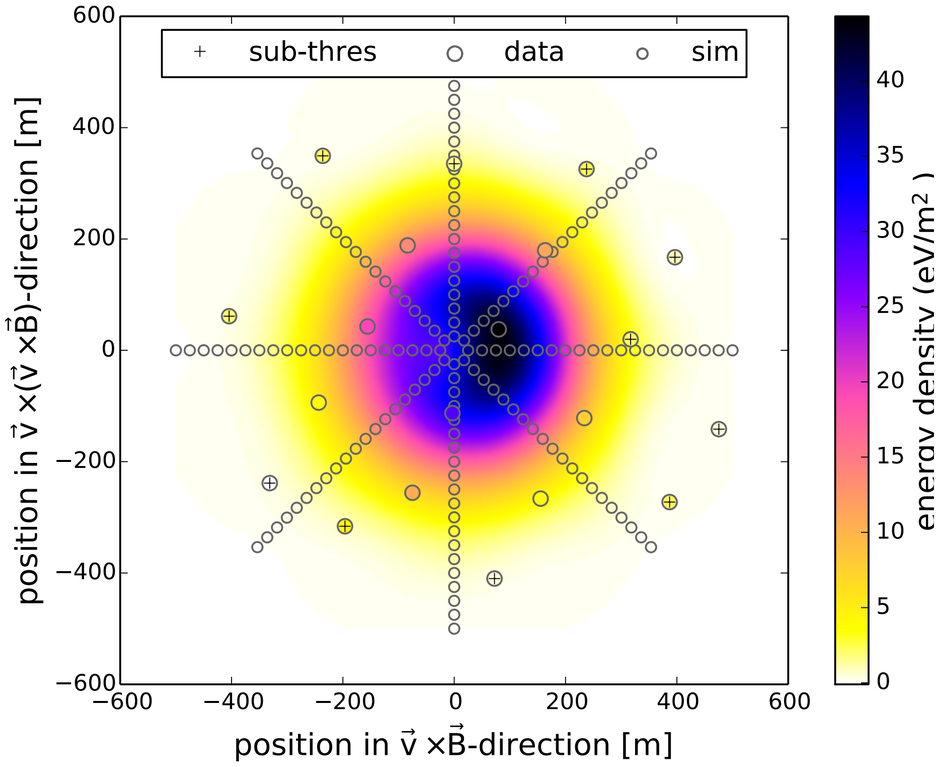
arrrival time
(shape of shower front)

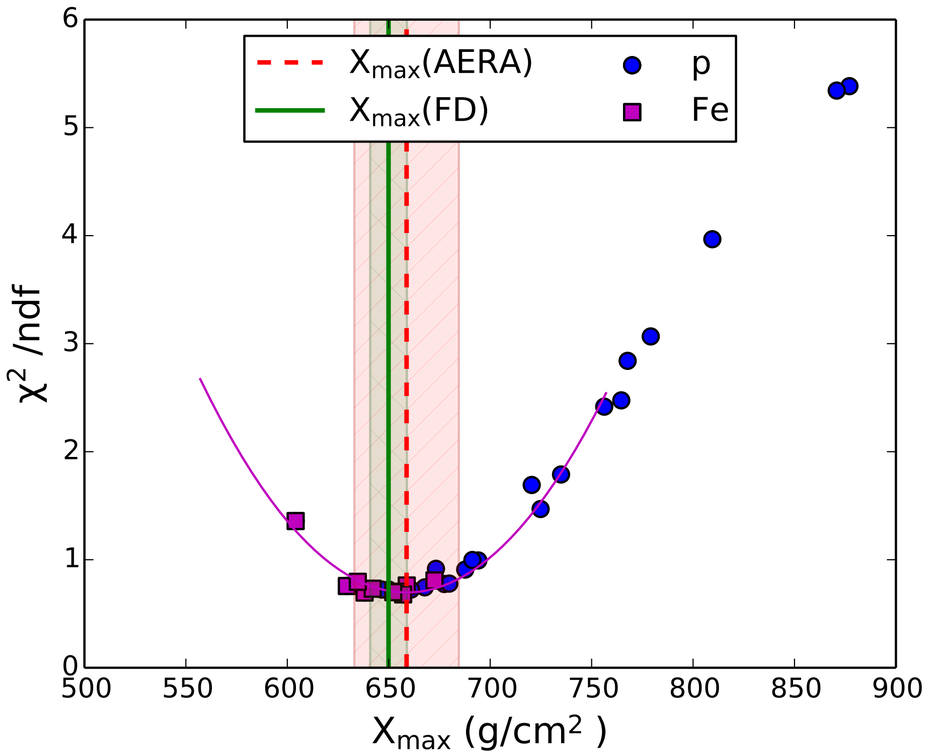


pulse shape
(frequency spectrum)

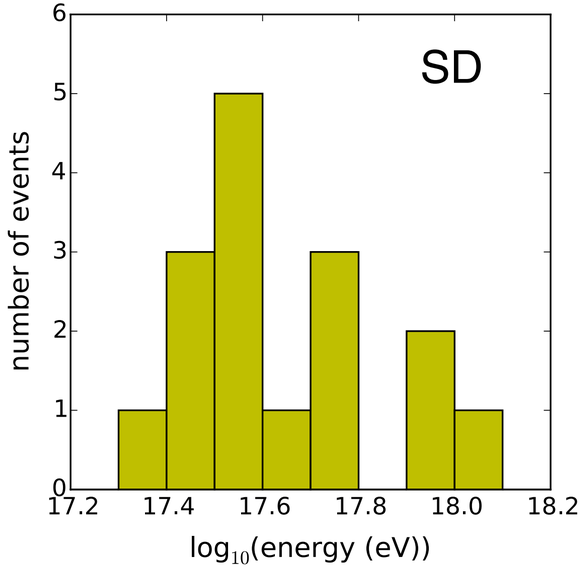


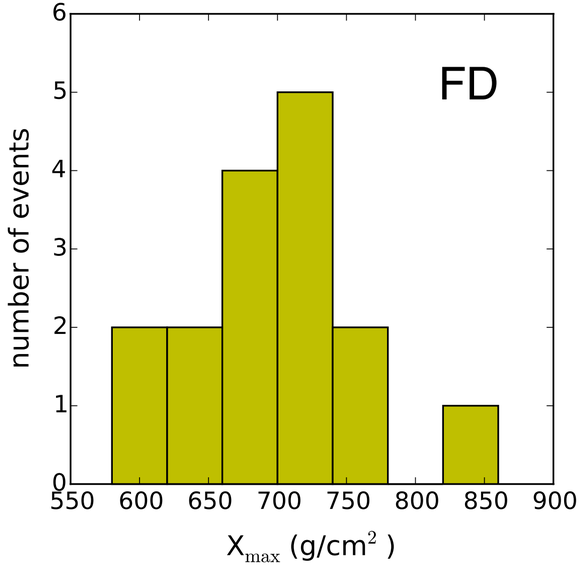
fit of simulations to data



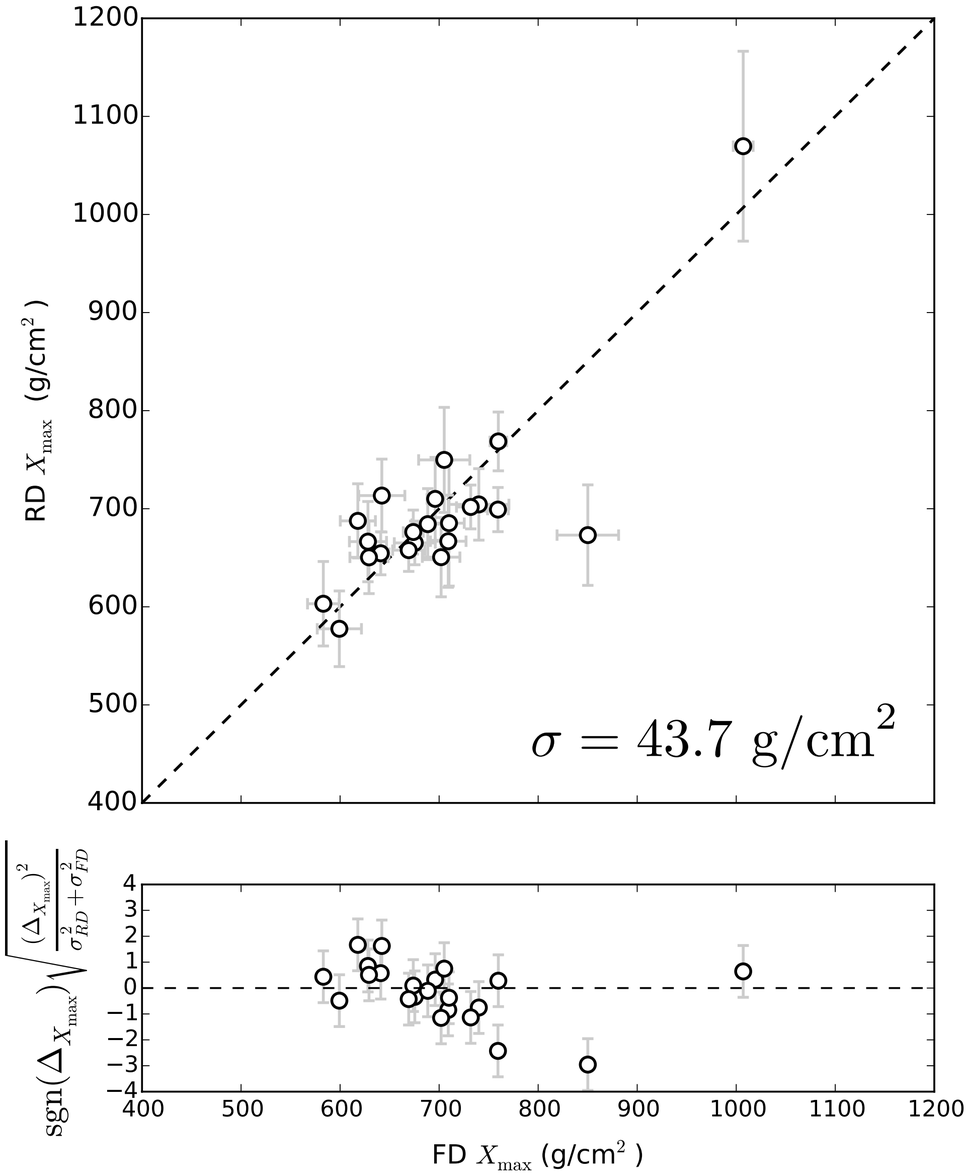


fit of simulations to data

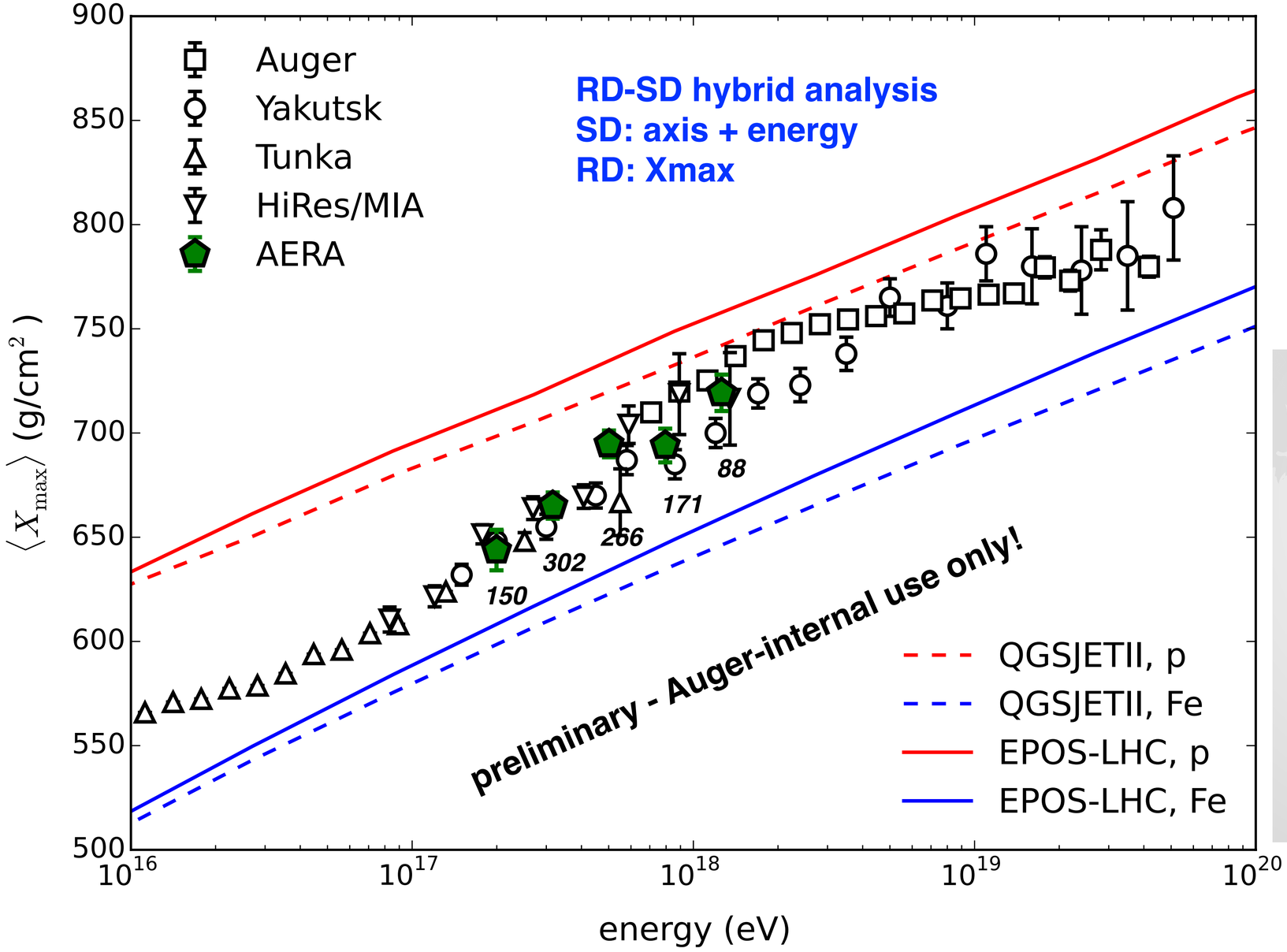




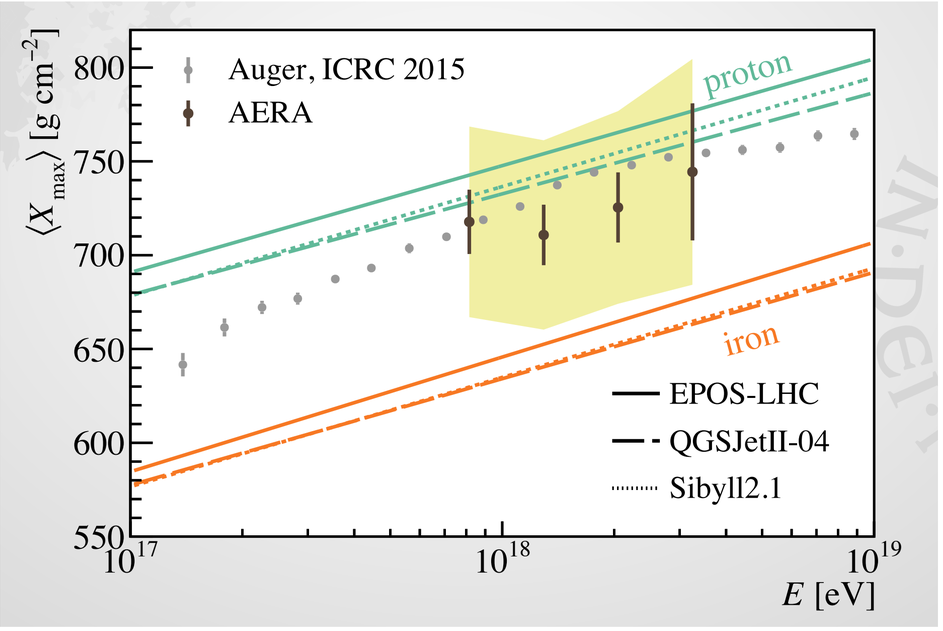
SD-FD energy calibration cuts:



Depth of the shower maximum (particle type)



analysis of spectral shape



whats next?

AERA is producing full-author list Auger papers

- time calibration paper (JINST)
- absolute energy scale of radio emission (PRL/PRD)
- technical description (NIM/JINST paper) in preparation

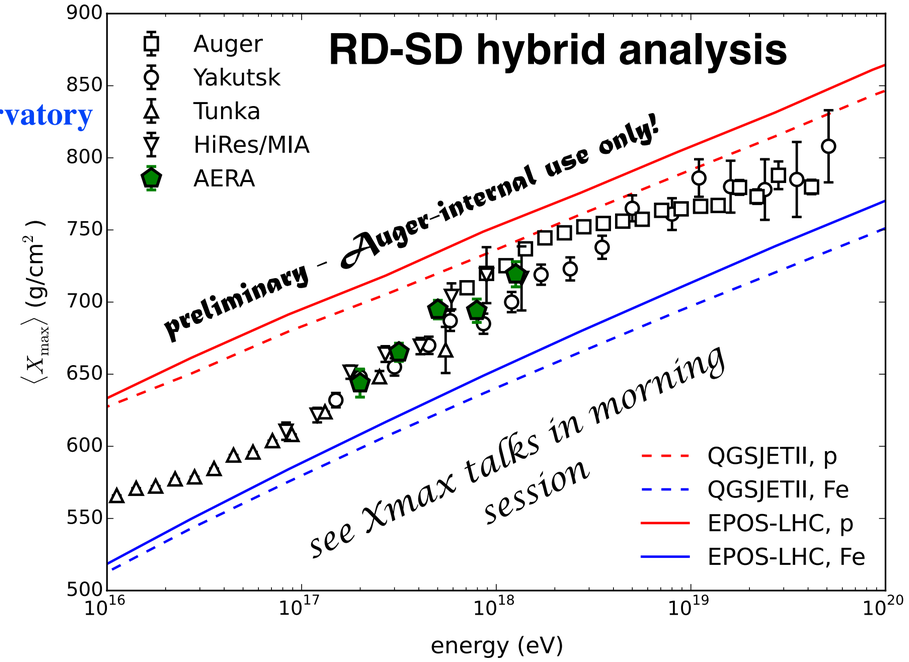
Probing the radio emission from air showers with polarization measurements
A. Aab et al. (Pierre Auger Collaboration)
Physical Review D 89 (2014) 052002 (arXiv:1402.3677)

Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory
P. Abreu et al. (Pierre Auger Collaboration)
JINST 7 (2012) P10011

Advanced functionality for radio analysis in the Offline software framework of the Pierre Auger Observatory
P. Abreu et al. (Pierre Auger Collaboration)
Nuclear Instruments and Methods A 635 (2011) 92 (arXiv:1101.4473)

Results of a self-triggered prototype system for radio-detection of extensive air showers at the Pierre Auger Observatory
S. Acounis et al. (Pierre Auger Collaboration)
JINST 7 (2012) 11023

more to come ...
e.g. promising Xmax analyses



Time to officially integrate AERA to the PAO!
--> ORR during next Collaboration meeting!

Nikhef Jaarvergadering
15 December 2015

The highest energy cosmic rays:
status and future perspectives

Auger Observatory after 10 years of operation:

1. All-particle spectrum: flux suppression above ≈ 40 EeV (GZK-reminiscent)

2. Trend towards a heavier composition at the highest energies. Spectrum and Xmax data together favor a scenario where the suppression is a source effect.

NEED FOR MASS COMPOSITION DATA IN THE SUPPRESSION REGION - ACCESSED BY THE SURFACE DETECTOR

Mass-related shower observables provide tight constraints on hadronic interaction models

NEED FOR MORE MASS-RELATED DATA FROM THE SURFACE DETECTOR

3. Stringent photon limits strongly disfavor exotic sources: astrophysical sources expected. But a high degree of (small-scale) isotropy observed.

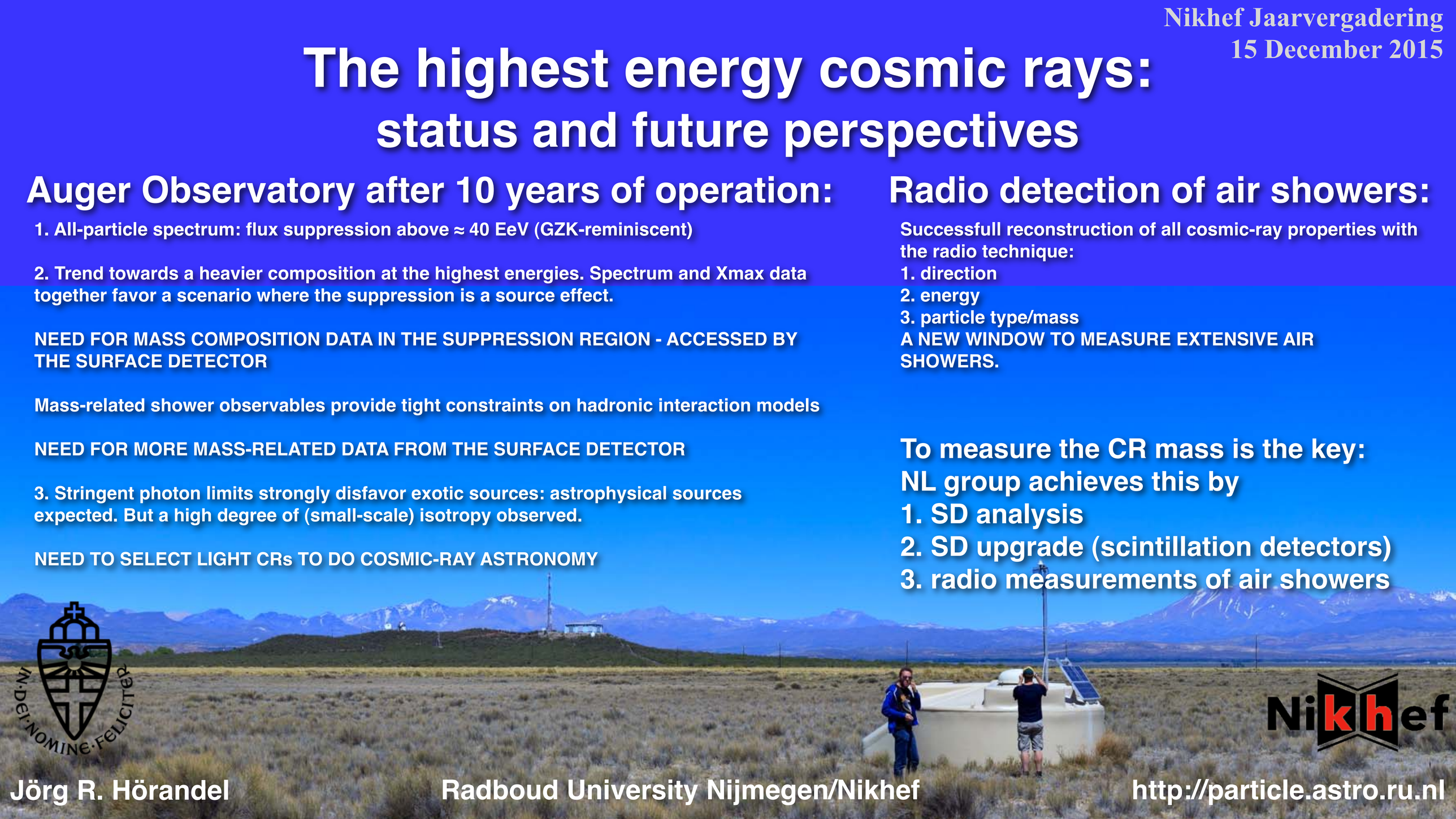
NEED TO SELECT LIGHT CRs TO DO COSMIC-RAY ASTRONOMY

Radio detection of air showers:

Successfull reconstruction of all cosmic-ray properties with the radio technique:
1. direction
2. energy
3. particle type/mass

A NEW WINDOW TO MEASURE EXTENSIVE AIR SHOWERS.

To measure the CR mass is the key:
NL group achieves this by
1. SD analysis
2. SD upgrade (scintillation detectors)
3. radio measurements of air showers



Jörg R. Hörandel Radboud University Nijmegen/Nikhef http://particle.astro.ru.nl