Astrofizyka cząstek

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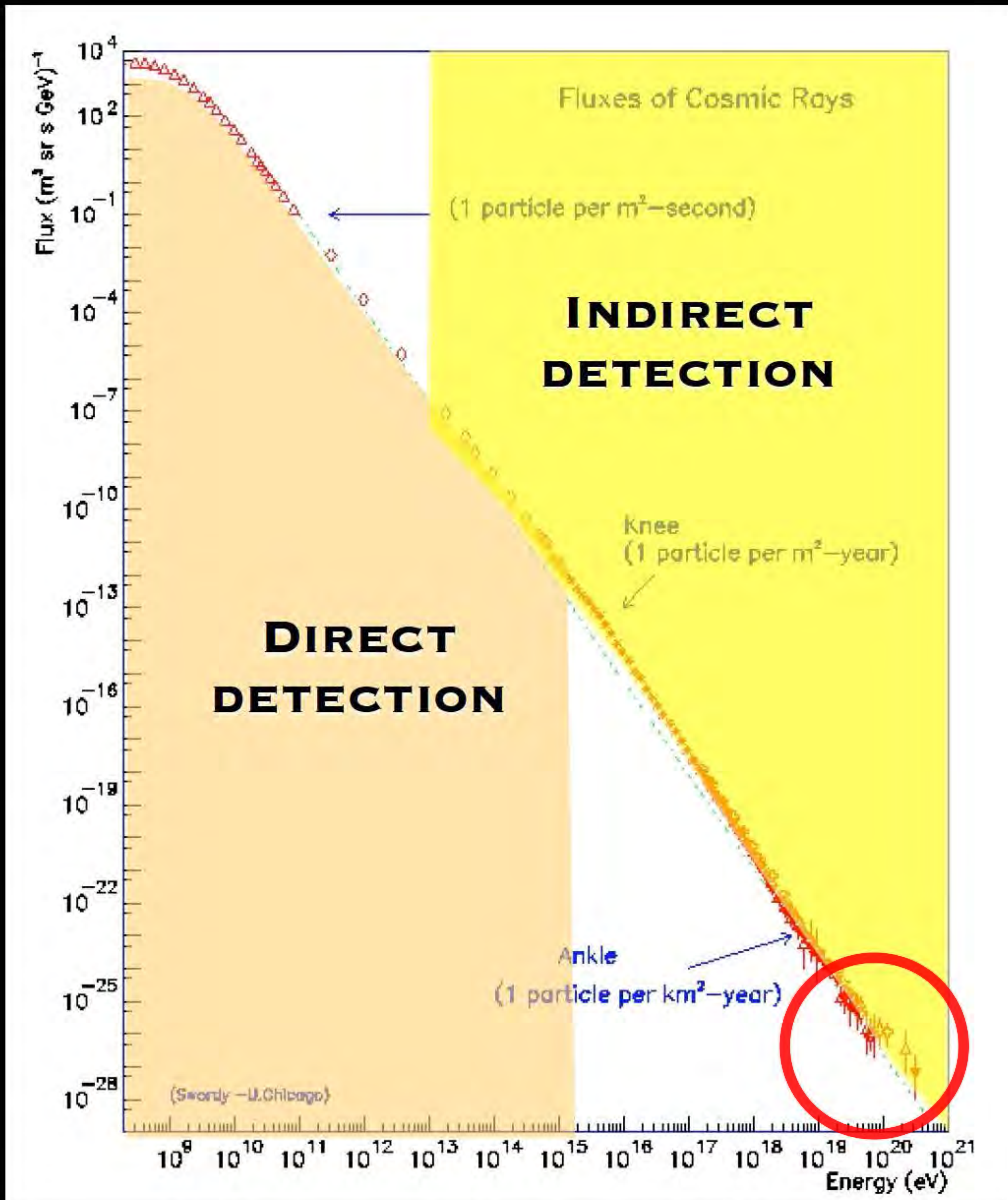
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład IX

- anizotropia UHECR
- projekt JEM-EUSO
- radiodetekcja pęków atmosferycznych

...WHOSE LOCATION IS DICTATED BY THE CR FLUX



Low-energy CRs: rather high flux (1/ m^2 s) but absorbed in the upper atmosphere.
Direct detection (top of the atmosphere or in space)

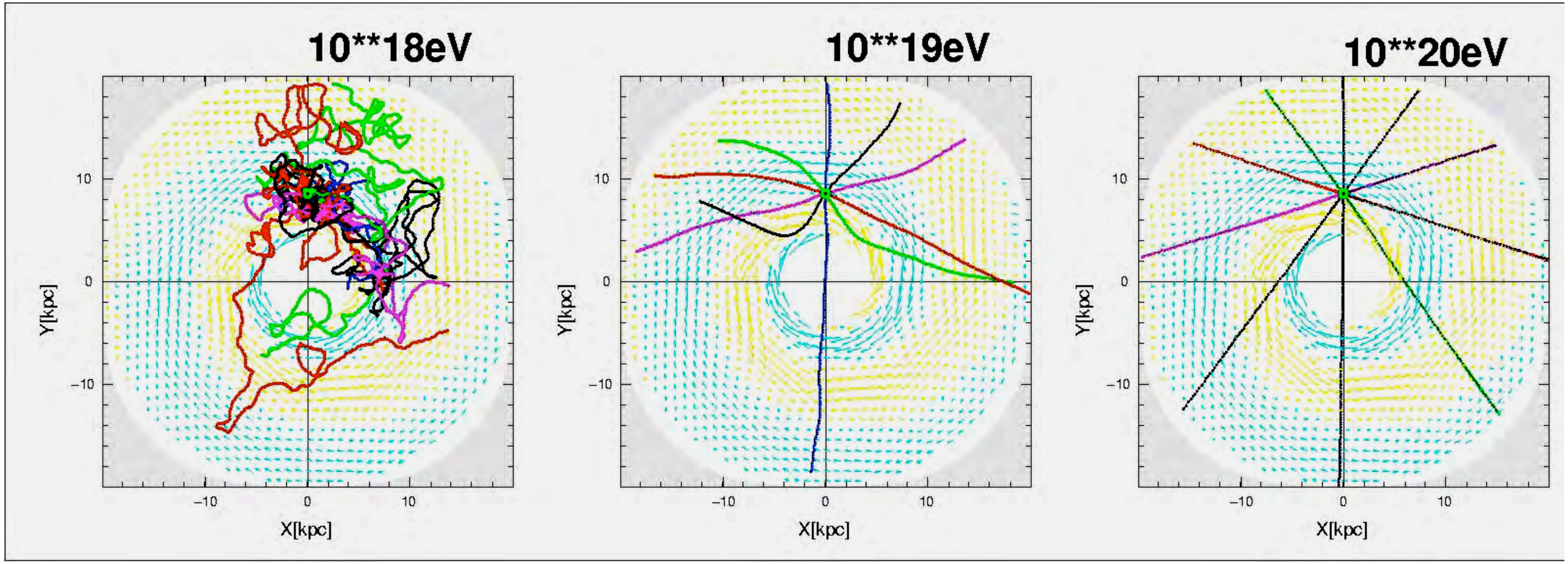
Balloons
Rockets
Satellites

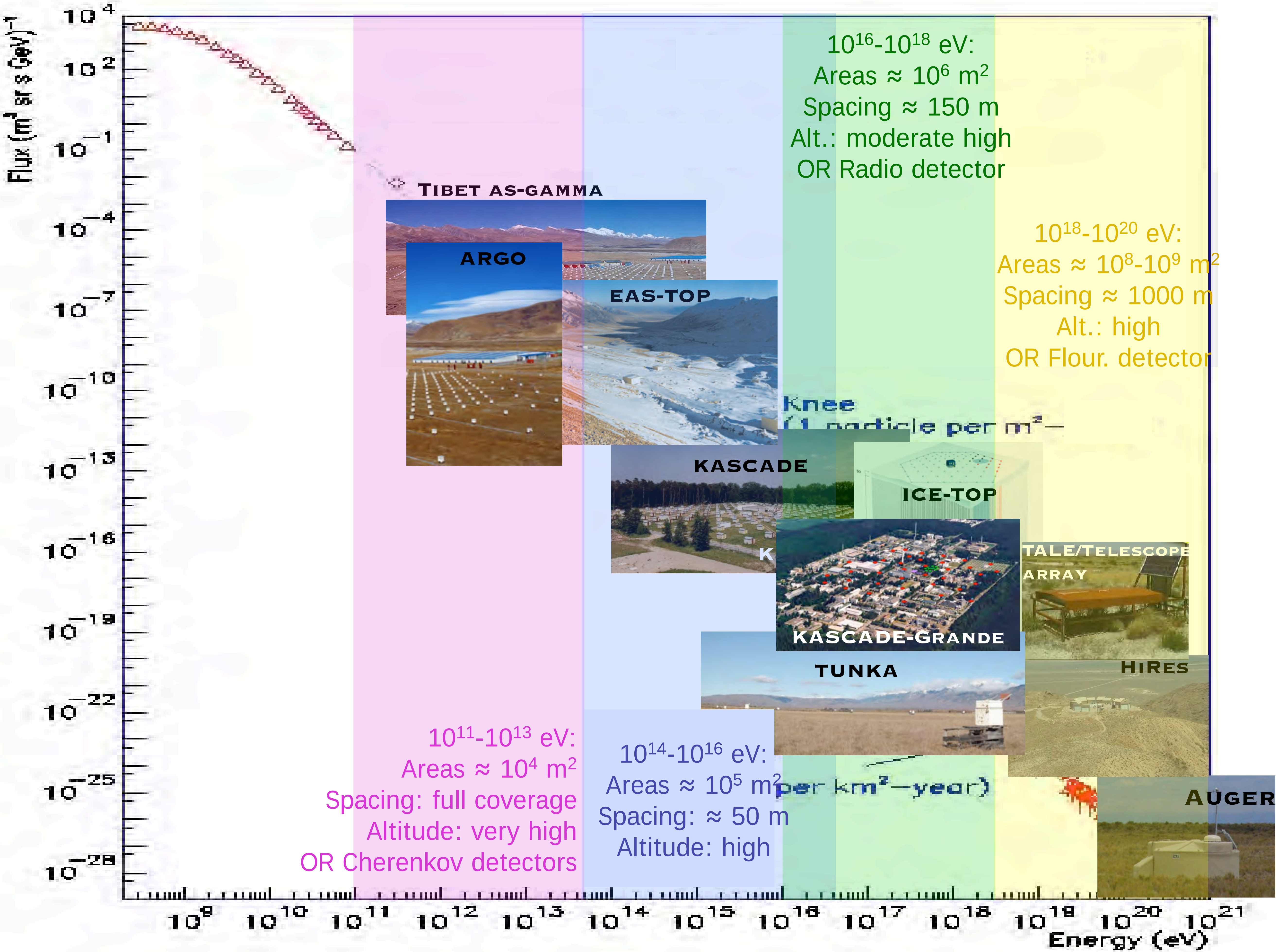
High energy cosmic rays: very rare (1/km^2 y), but "penetrating" up to ground (atmospheric air-showers).
Indirect detection: long-lived large arrays (ground level)

Large telescopes
Extensive Air showers arrays

UHECR propagation in Milky Way

- Deflection angle ~ 1-2 degrees at 10^{20}eV for protons
  - Astronomy by hadronic particles?



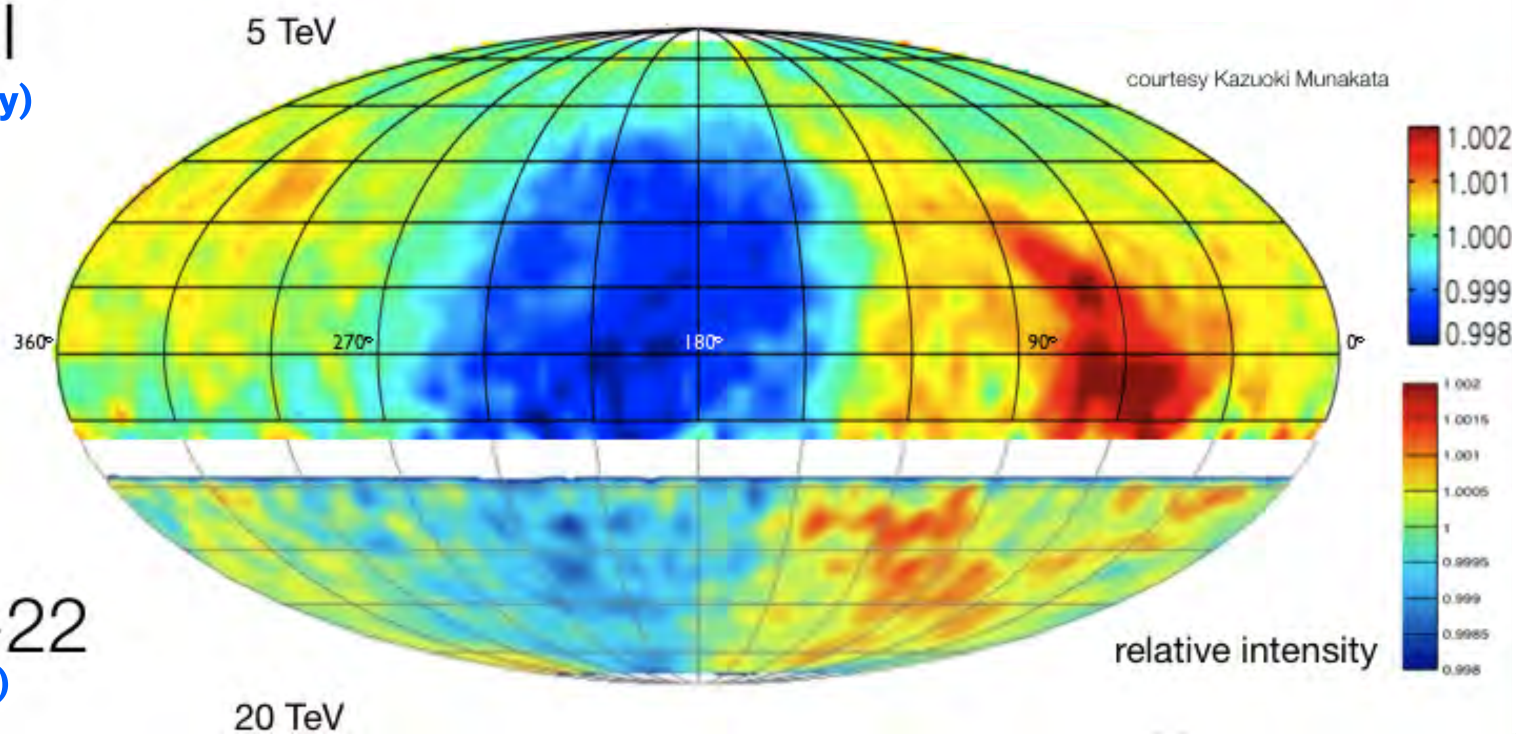


Flux (m² sr s GeV)⁻¹
Energy (eV)
Tibet AS-gamma
ARGO
EAS-TOP
Knee
(1 particle per m²–
per km²–year)
KASCADE
ICE-TOP
KASCADE-Grande
TALE/Telescope array
TUNKA
HiRes
Auger
10^16-10^18 eV:
Areas ≈ 10^6 m^2
Spacing ≈ 150 m
Alt.: moderate high
OR Radio detector
10^18-10^20 eV:
Areas ≈ 10^8-10^9 m^2
Spacing ≈ 1000 m
Alt.: high
OR Flour. detector
10^11-10^13 eV:
Areas ≈ 10^4 m^2
Spacing: full coverage
Altitude: very high
OR Cherenkov detectors
10^14-10^16 eV:
Areas ≈ 10^5 m^2
Spacing: ≈ 50 m
Altitude: high

Relative intensity skymap in equatorial coordinates

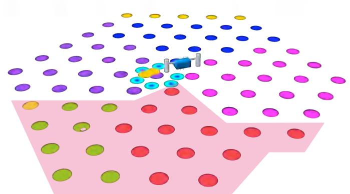
Tibet-III

(Northern sky)



IceCube-22

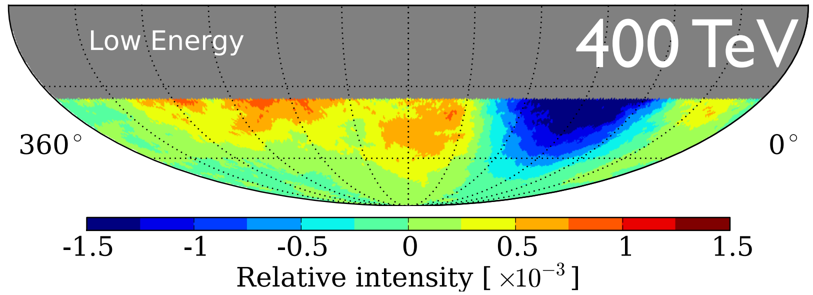
(Southern sky)

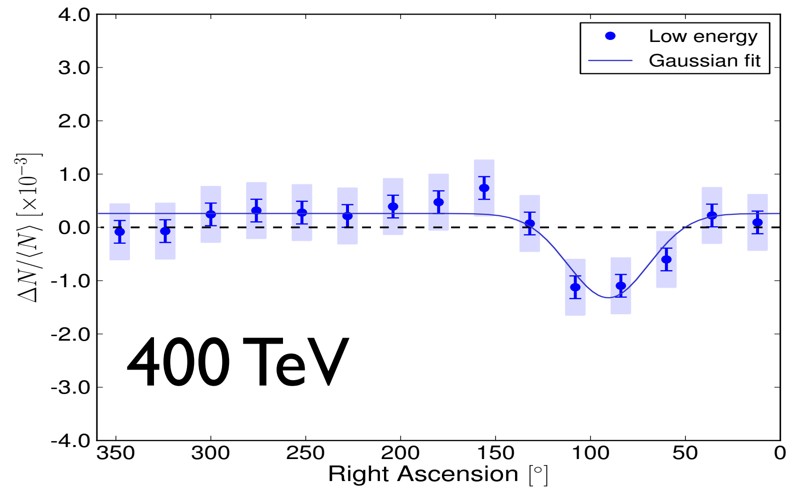


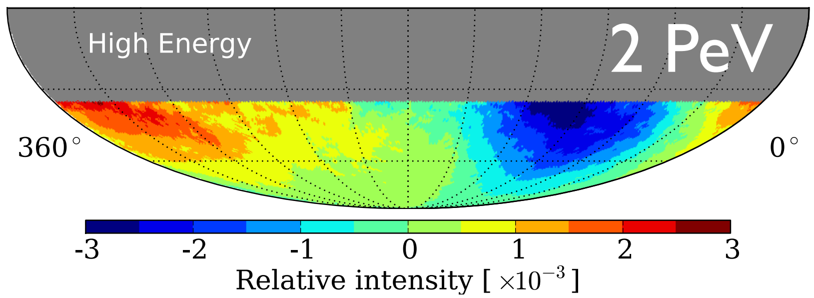
Abbasi et al., ApJ, 718, L194, 2010
arxiv/1005.2960

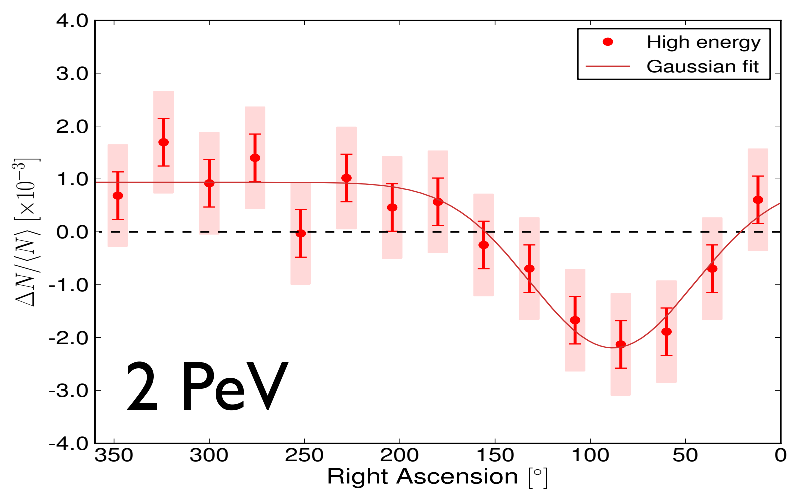
from Marcos Santander ICRC 2013

Higher Energies: IceTop



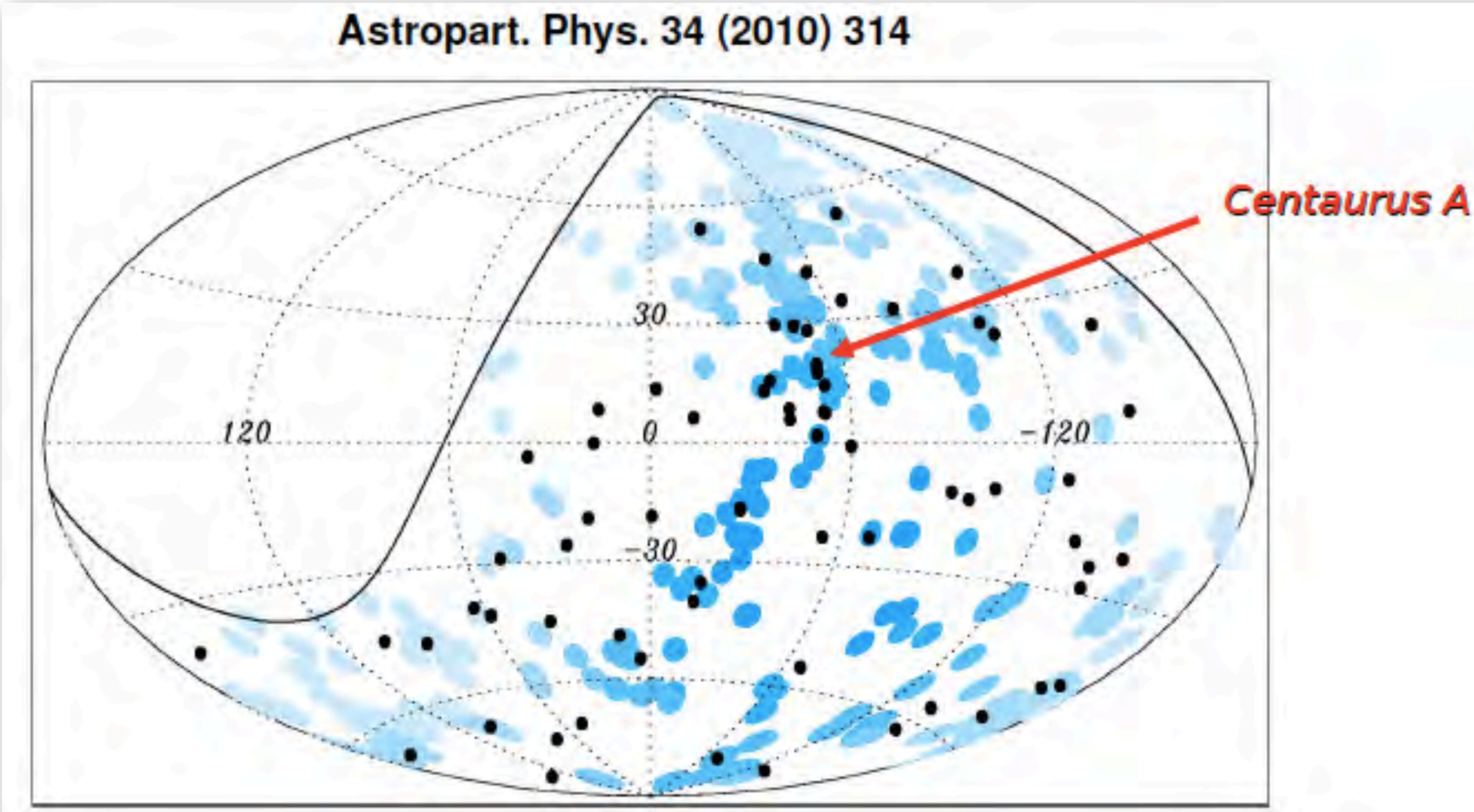






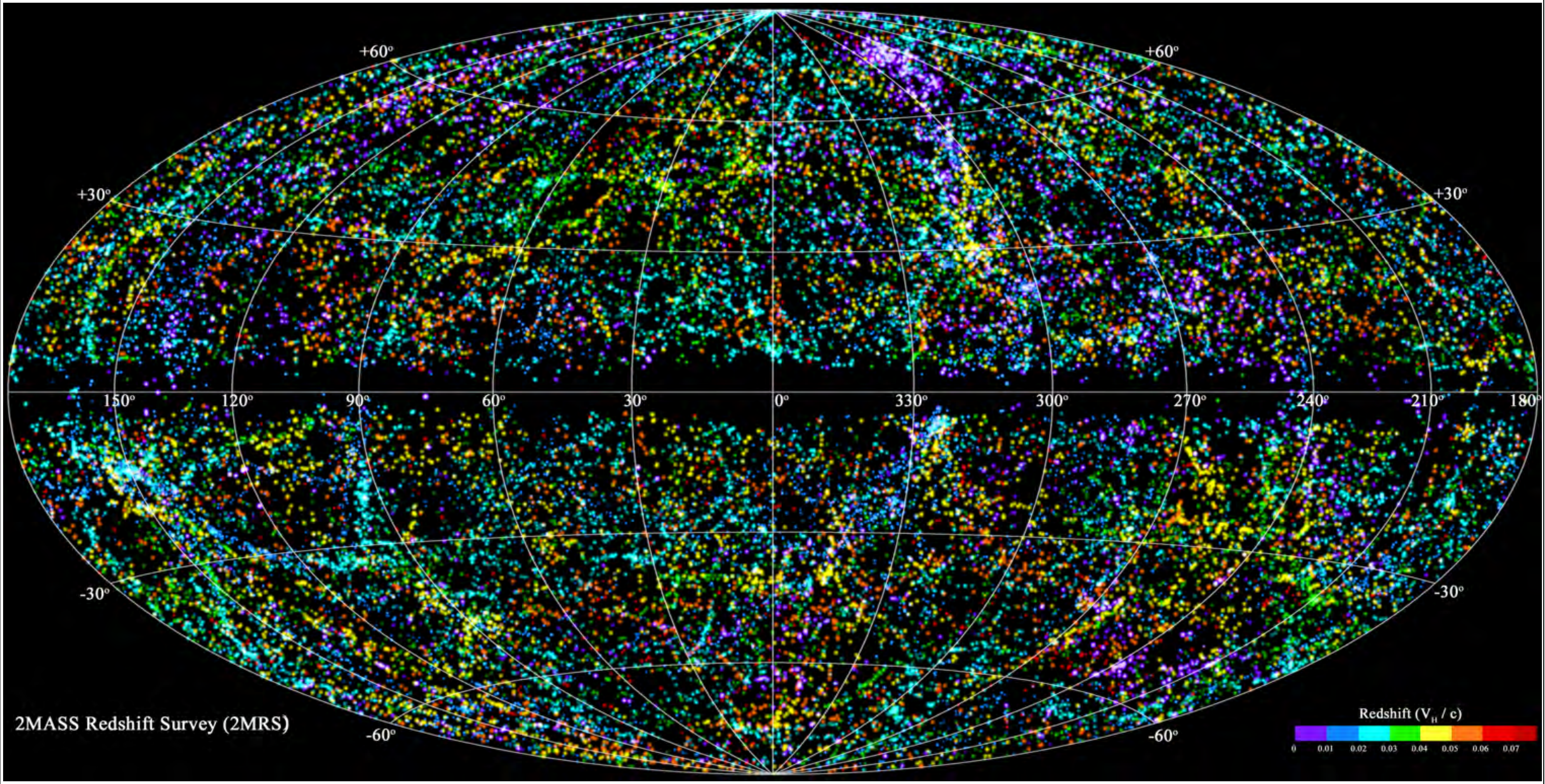
- At 400 TeV consistent with IceCube
- Amplitude increases with energy

UHECR: Correlations with AGN



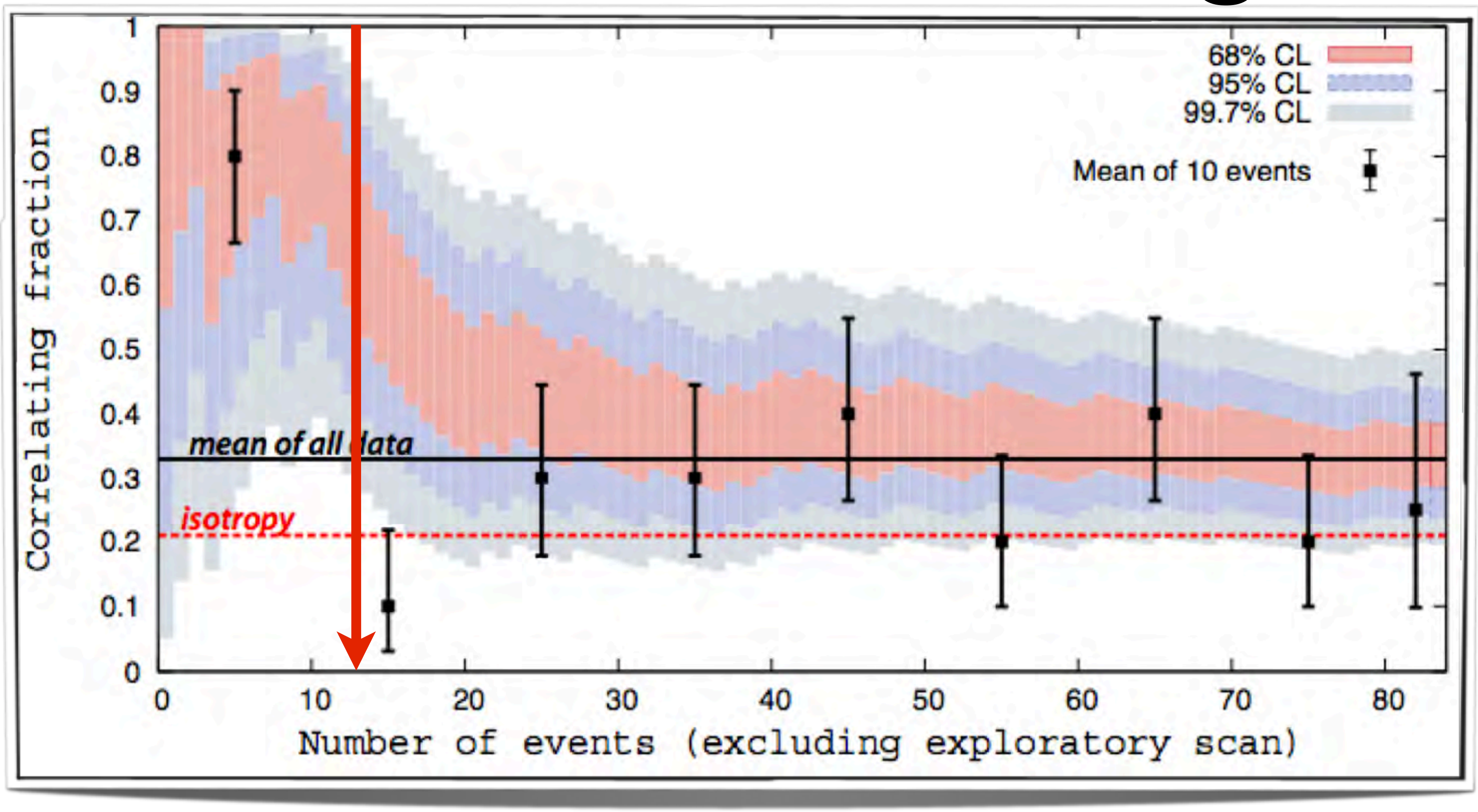
- Clear prescription established by Auger
  - Energy > 55 EeV
  - Veron-Cetty & Veron Catalog (2006) of AGN < 75 Mpc
  - 3.1° radius circle

2MASS Galaxy Redshift Survey



Auger VCV Events

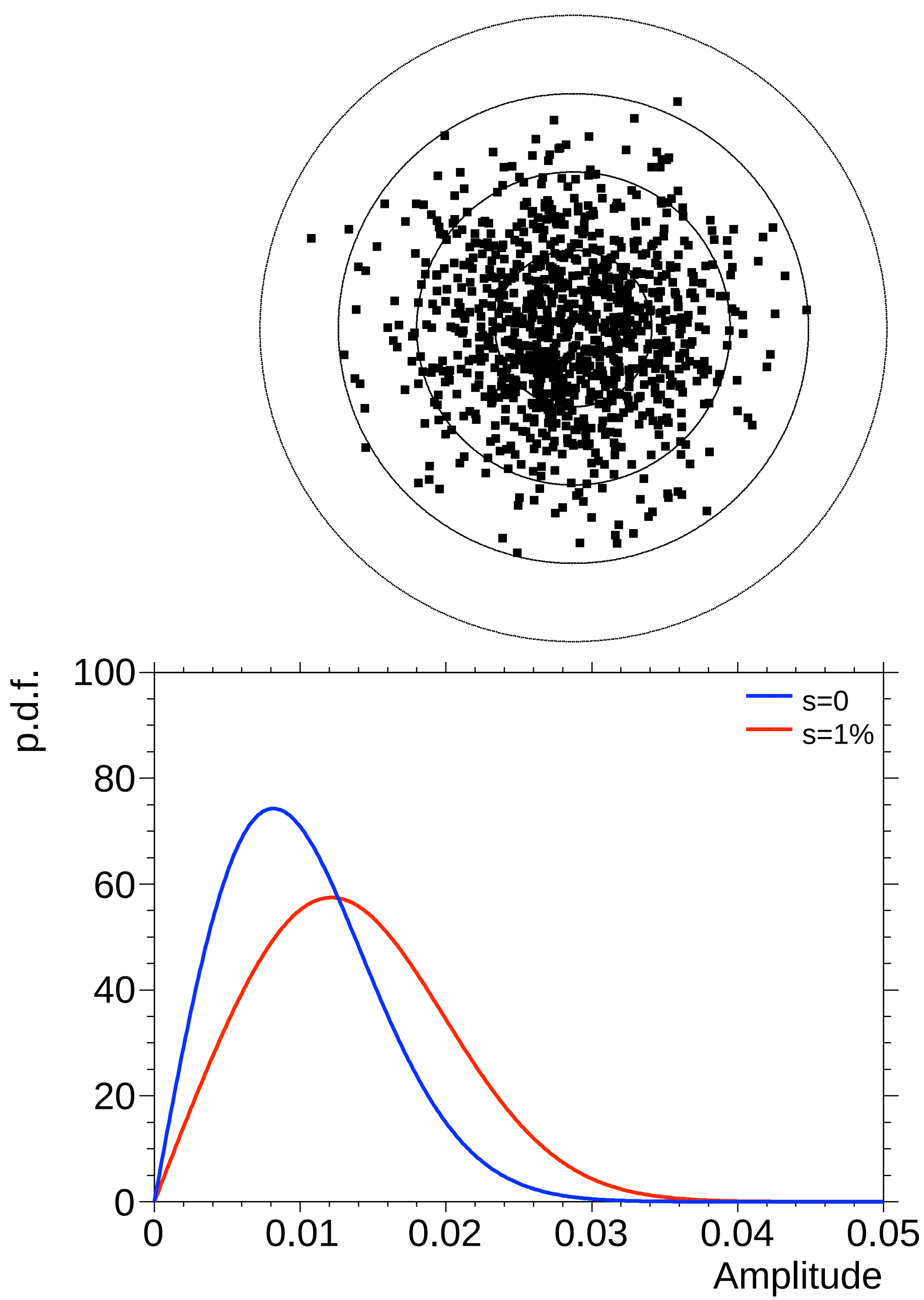
Current Status: Auger



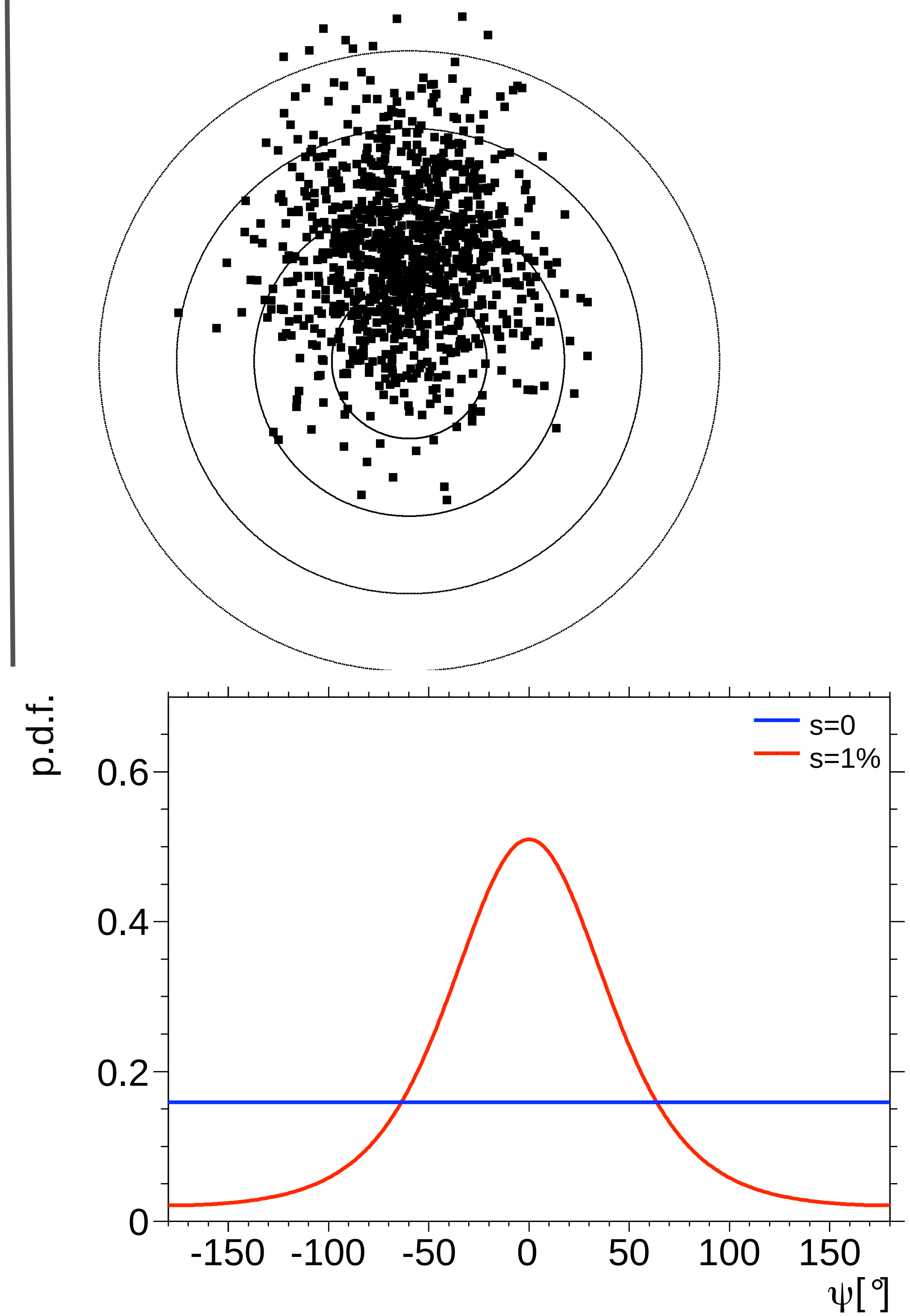
- From 2011 ICRC
- Current situation ~unchanged (now have 110 events)
  - Correlating fraction now at 32% (21% is isotropy) and still ~2.8 σ

Phase vs Amplitude

Pure isotropy



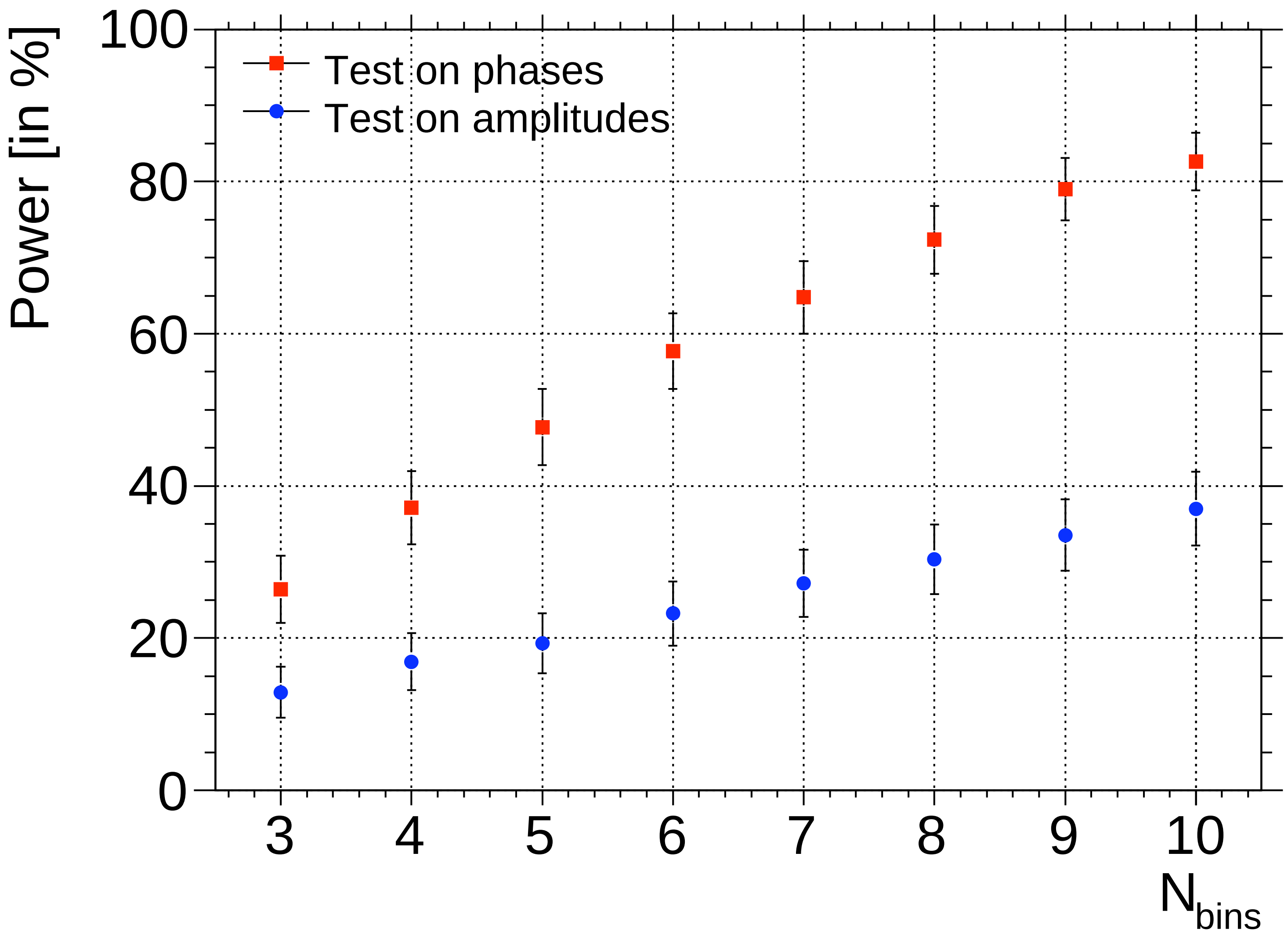
Almost isotropy
(signal size = mean noise)



Phase vs Amplitude : Detection Power

Test on the phase for N_b bins

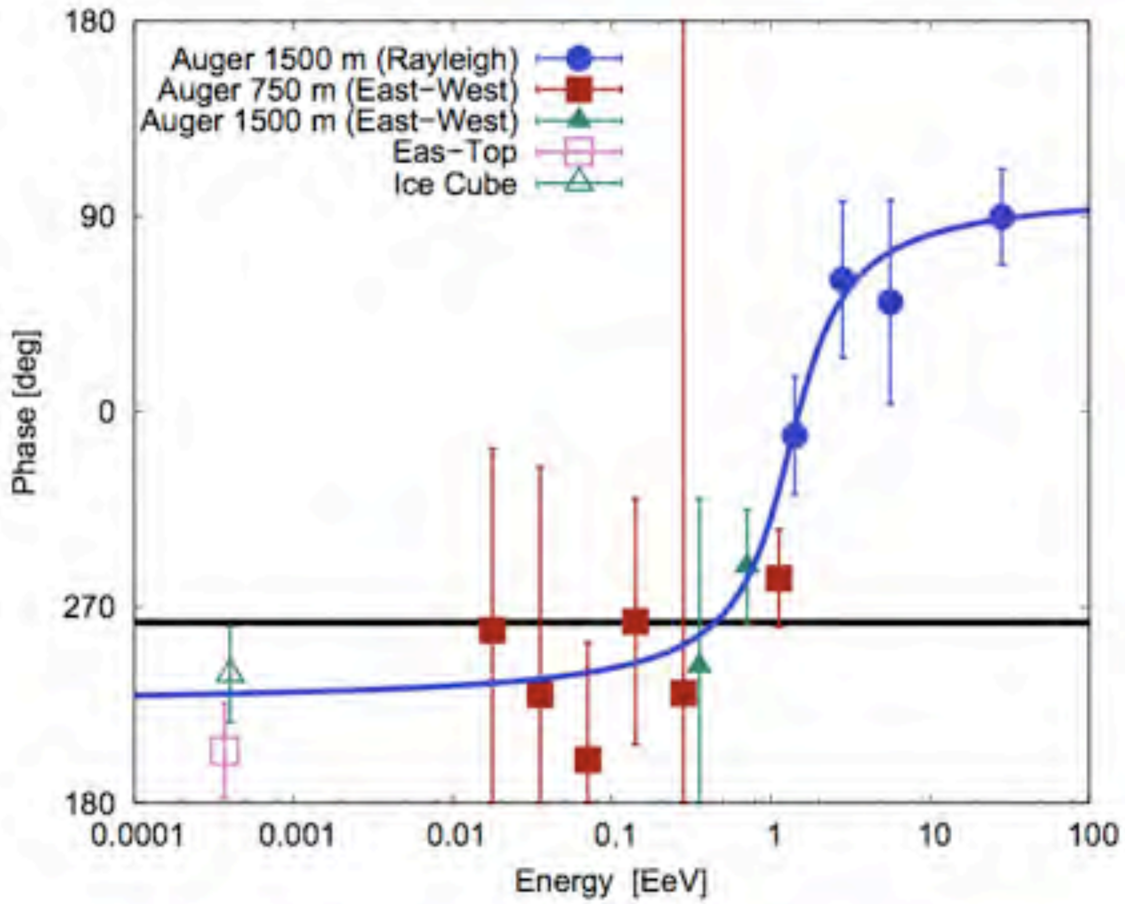
- LL ratio method: $L_0 = \prod_{i=1}^{i=N_b} p_{\mathrm{iso}}(\phi_i), \qquad L_1 = \prod_{i=1}^{i=N_b} p_{\Phi}(\phi_i) \rightarrow \lambda = \frac{L_0}{L_1}$
- $-2\ln(\lambda)$ pdf have to be computed
- $p = \int_{-2\ln(\lambda)_{\mathrm{MC}}}^{\infty} \mathrm{pdf}(-2\ln\lambda)$



➡ Phase test ≈2.5 times more efficient

➡ A consistency of the phase measurement in adjacent energy intervals is thus expected with lower statistics than that required for the amplitude to significantly stand out from the background noise

Phase of the First Harmonic

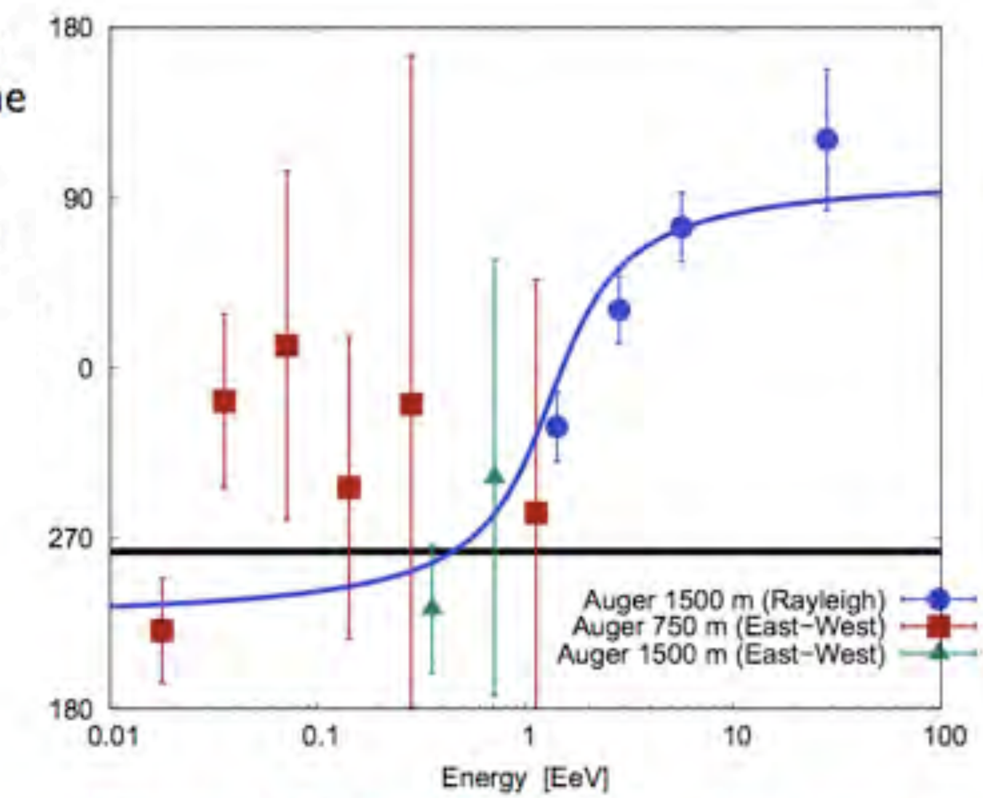


Eas-Top: M. Aglietta *et al.* 2009 ApJ **692** L130
IceCube: R. Abbasi *et al.* 2012 ApJ **746** 33

Infill data until April 2011
E = 0.01-2 EeV
Constant line fit
$\alpha \simeq 263^\circ \pm 19^\circ$

Prescription to check with new data at 99% CL:

- Started on the 25 of June 2011
- Constancy of phase at E<1 EeV with the Infill data
- Transition in phase at high energies



Phase of the first harmonic with events from 25 June 2011 to 31 December 2012.

Deligny (679),
Sidelnik (739),
de Almeida (768),
Salesa Greus (1125),
Revenu (1206)

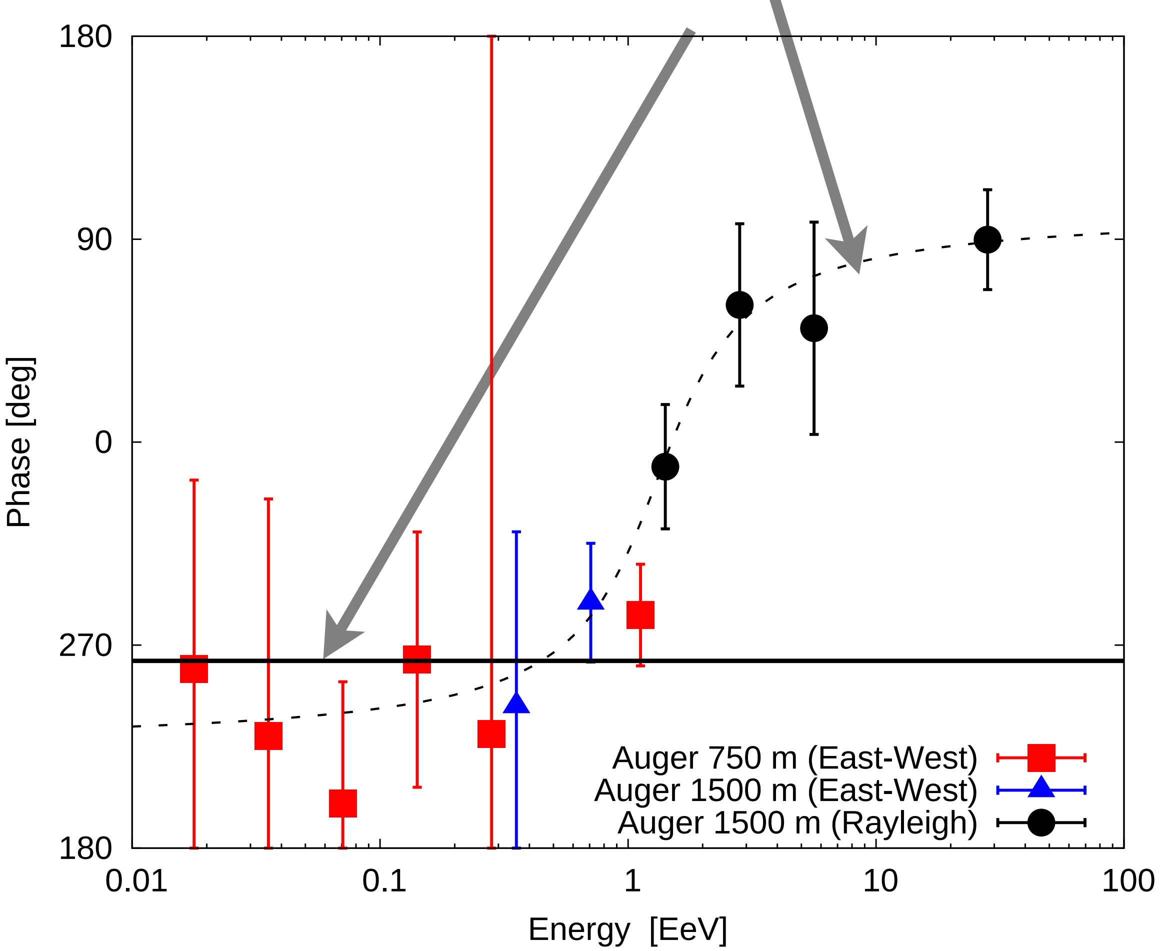
ANISOTROPY I

Large scale first harmonic analyses

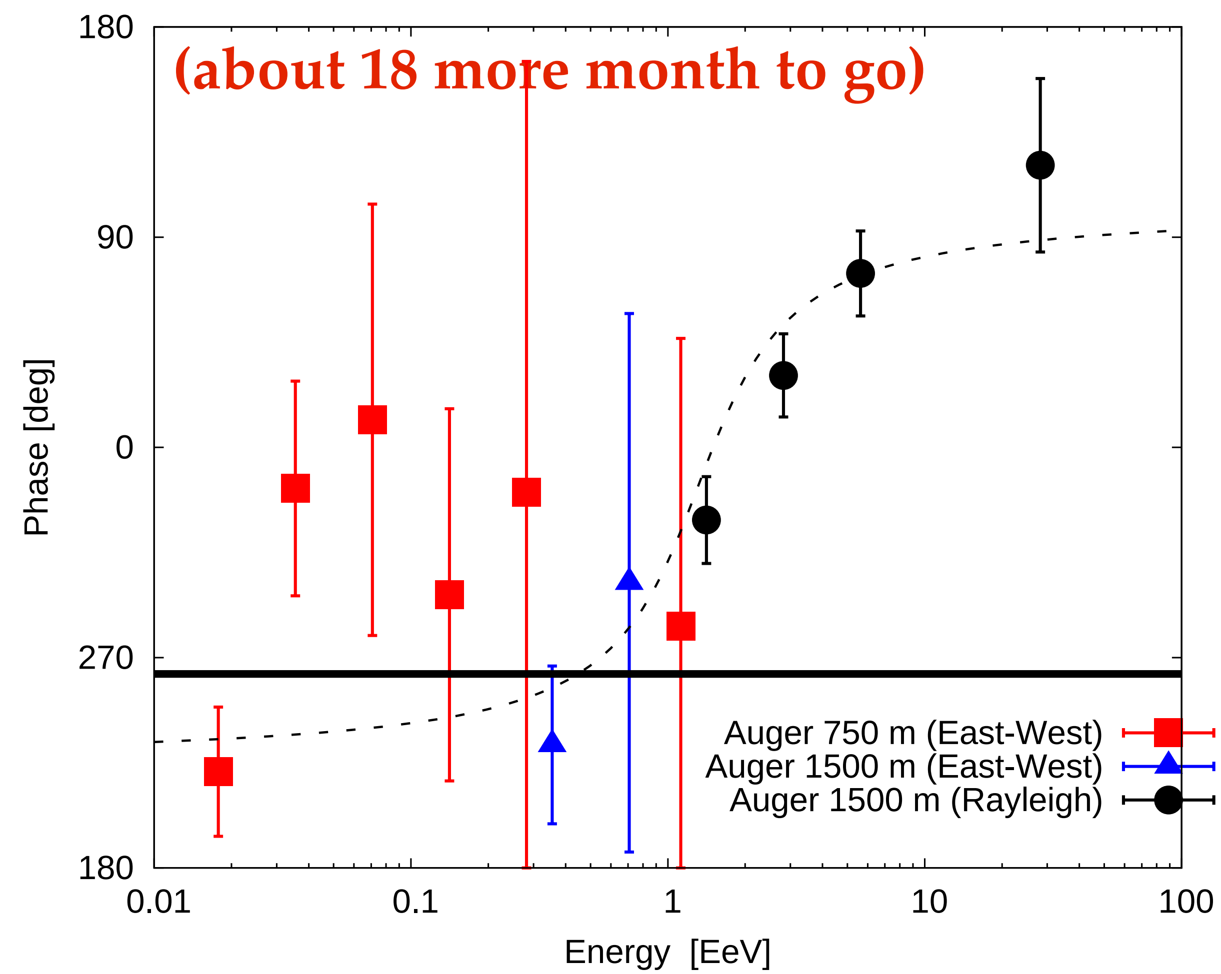
PIERRE AUGER OBSERVATORY

Data up to December 2010

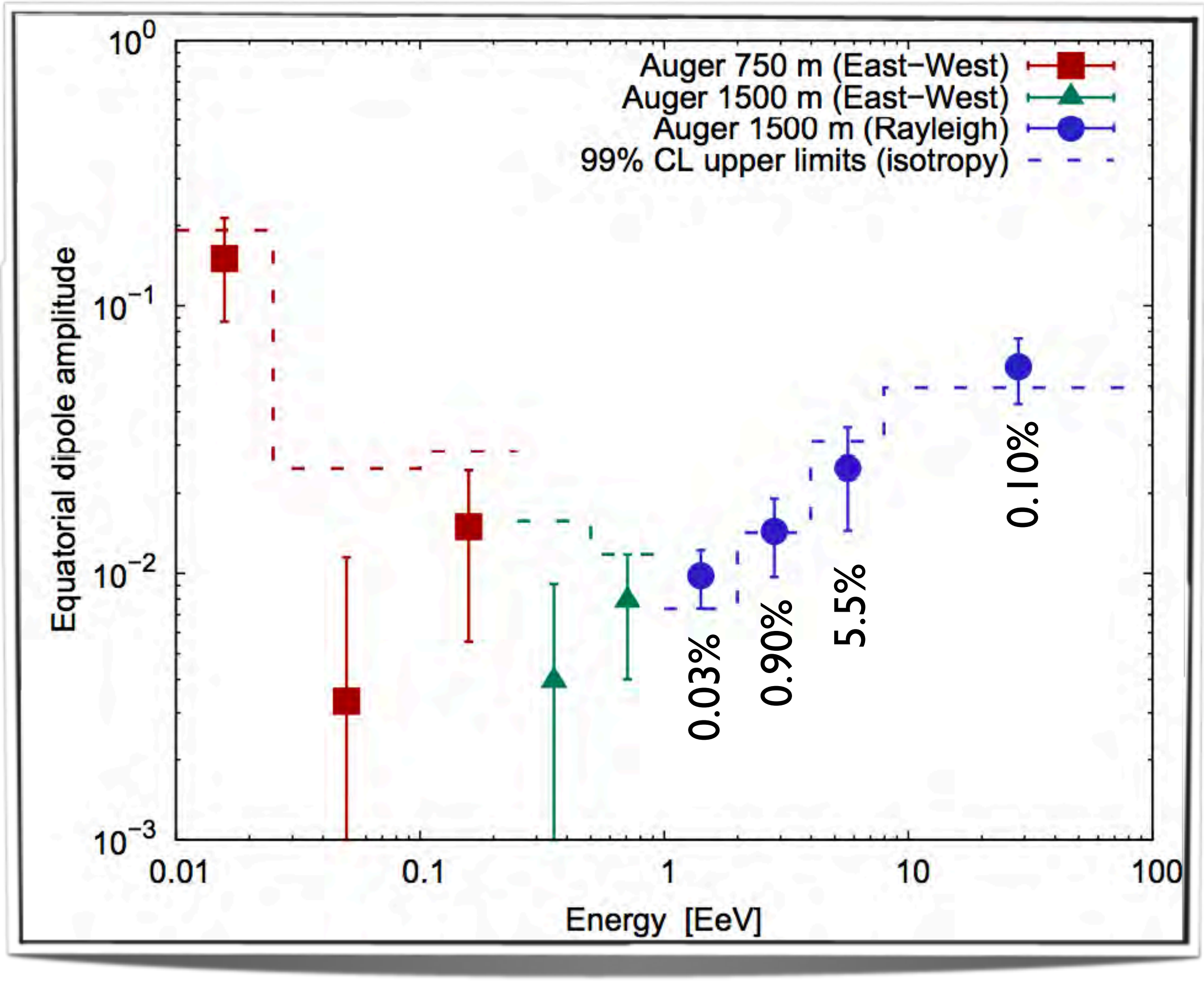
(April 2011) Prescription set



New data Prescription status



Auger Phase results



Deligny (679),
Sidelnik (739),
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Salesa Greus (1125),
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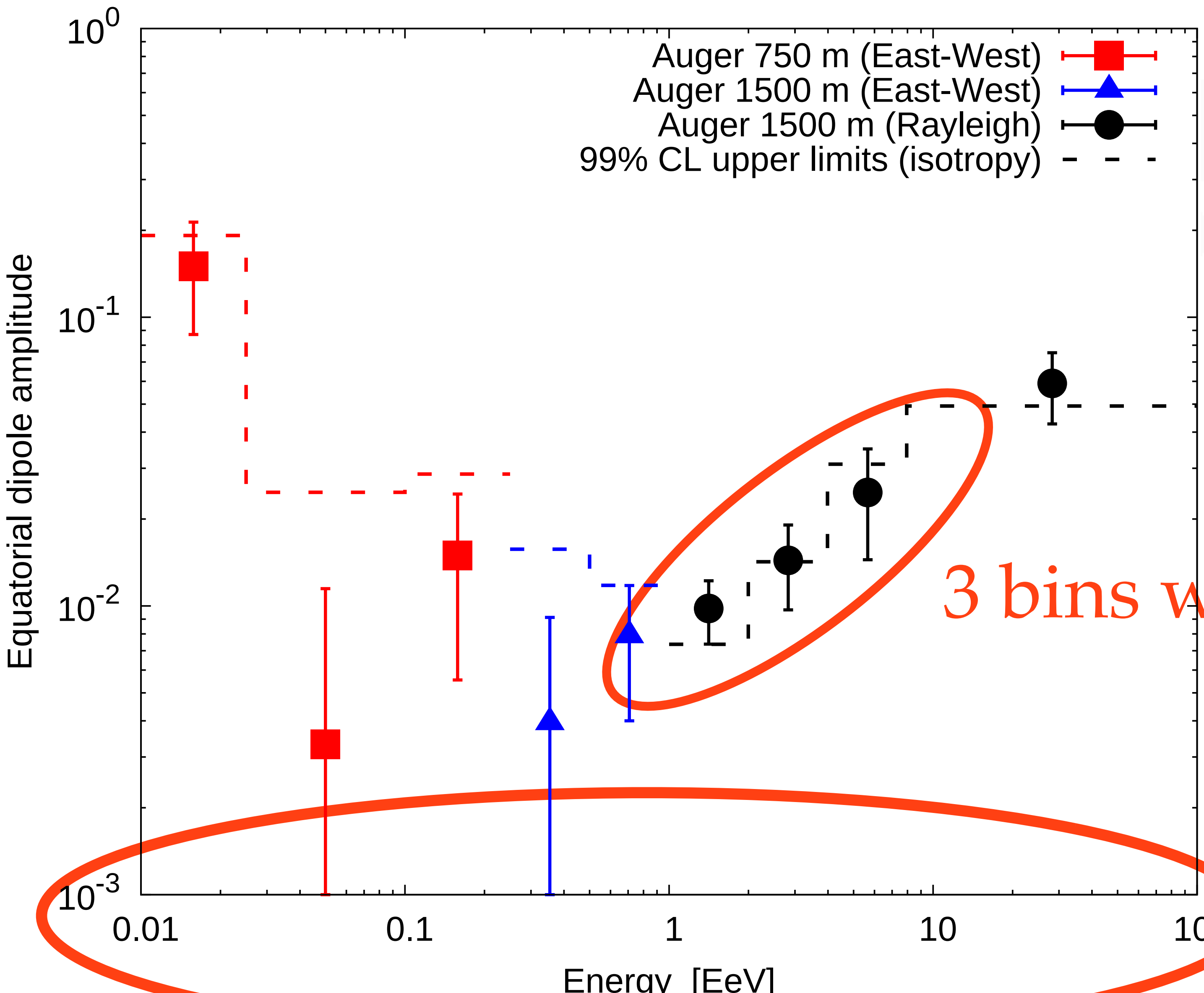
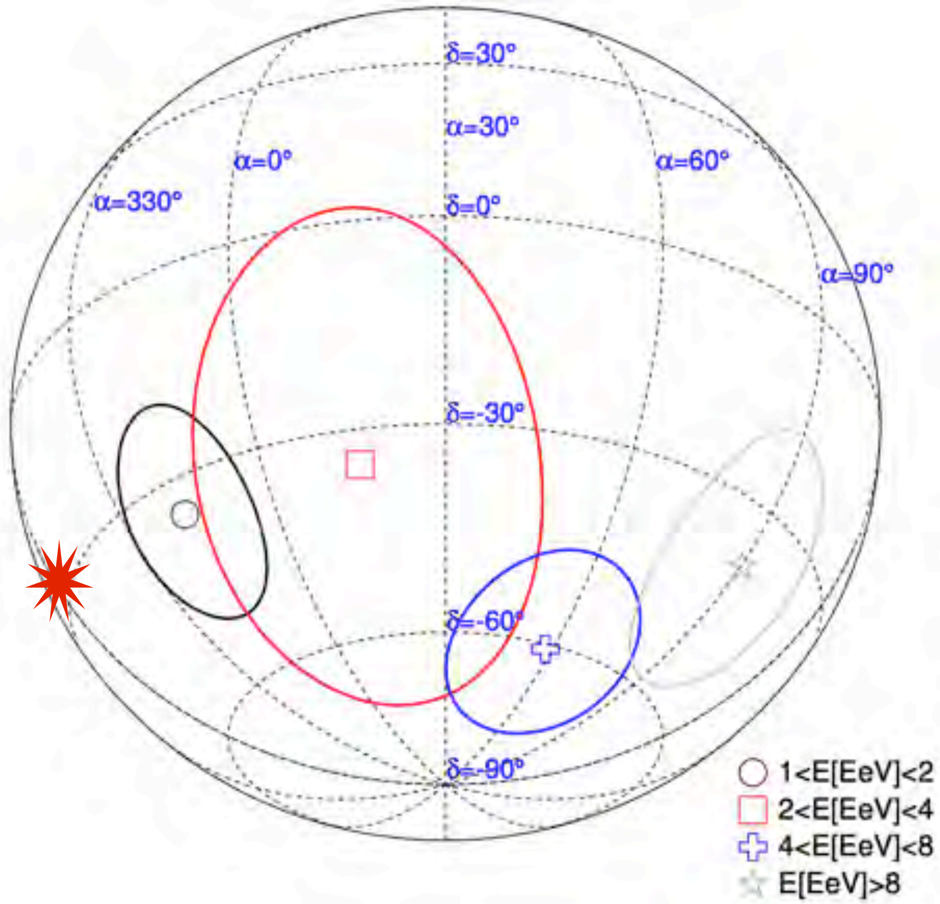
ANISOTROPY II

Large scale first harmonic analyses

Data up to December 31st 2012



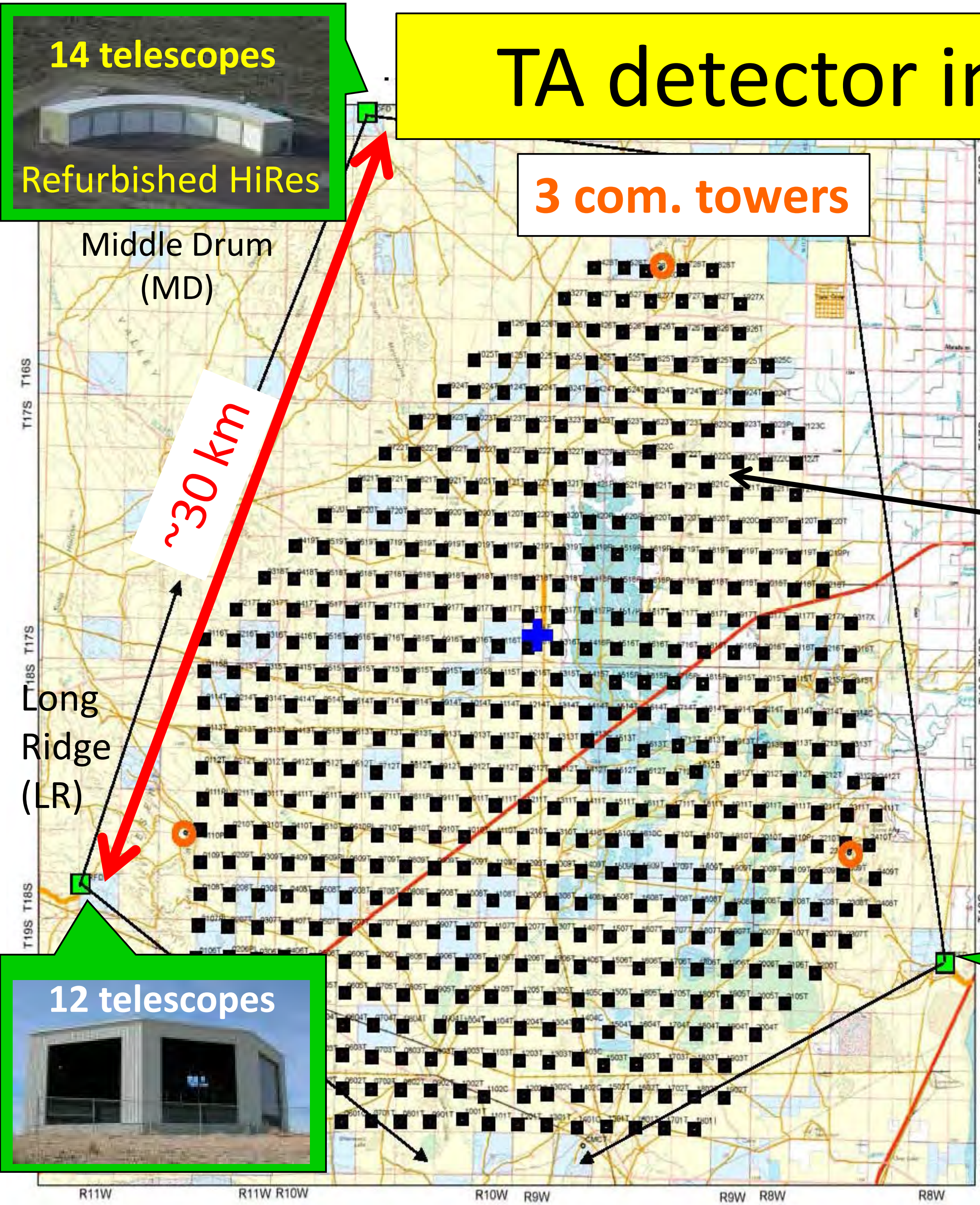


3 bins with chance probability < 1%

Extended energy range

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



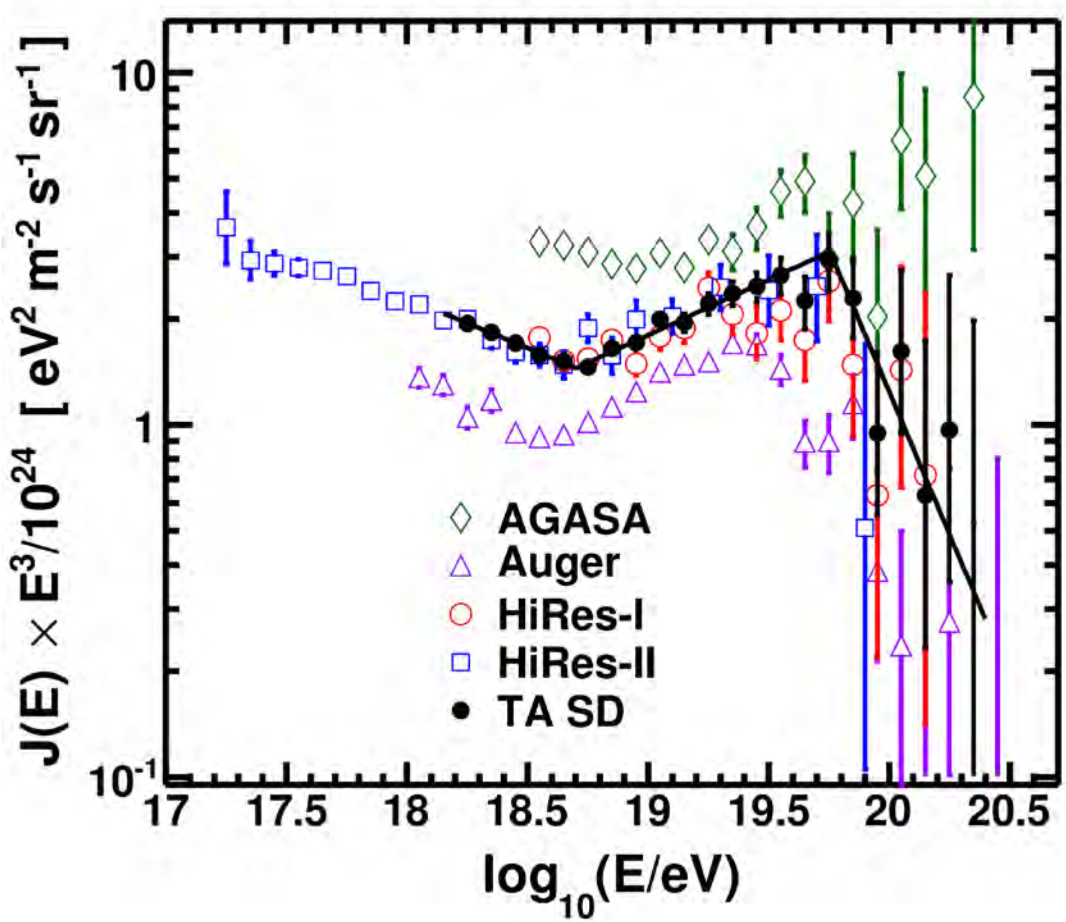
Surface Detector (SD)

507 plastic scintillator SDs
1.2 km spacing
700 km²

Fluorescence Detector(FD)

3 stations
38 telescopes

5 year TA SD spectrum



TA data
May, 2008 – May, 20013
Zenith angle < 45^o
14787 ev. (E > $10^{18.2}$ eV)
Exposure 4500 km^2 sr yr

Broken power law fit

$\gamma_1 = -3.283 \pm 0.032$

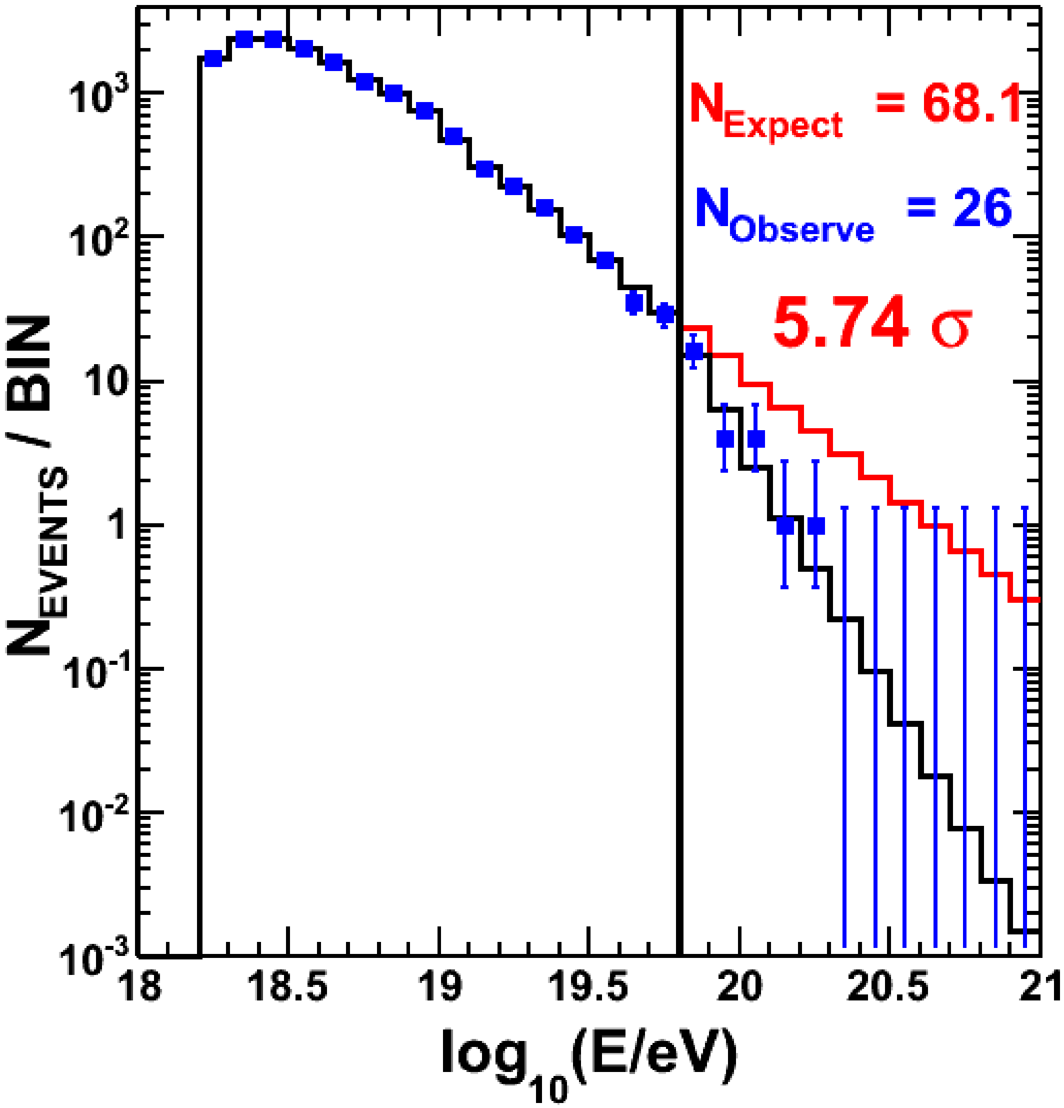
$E_{ankle} = (5.04 \pm 0.27) \times 10^{18}$ eV

$\gamma_2 = -2.685 \pm 0.030$

$E_{GZK} = (5.68 \pm 1.05) \times 10^{19}$ eV

$\gamma_3 = -4.62 \pm 0.74$

Significance of suppression



Comparison with isotropic distribution by KS test

KS p-values:

- 2130 events with $E > 10$ EeV

Coords	right ascension	declination
Equatorial:	0.23	0.84
Supergalactic:	0.41	0.63

- 132 events with $E > 40$ EeV

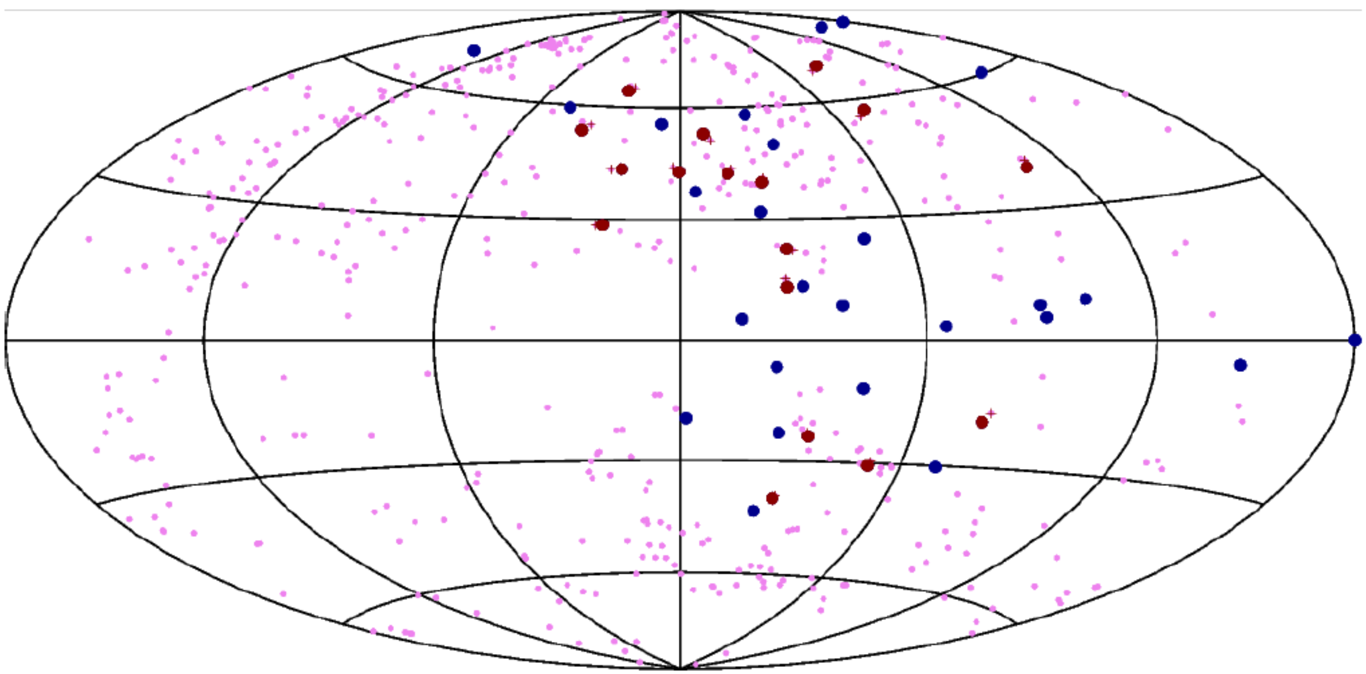
Coords	right ascension	declination
Equatorial:	0.11	0.27
Supergalactic:	0.08	0.18

- 52 events with $E > 57$ EeV

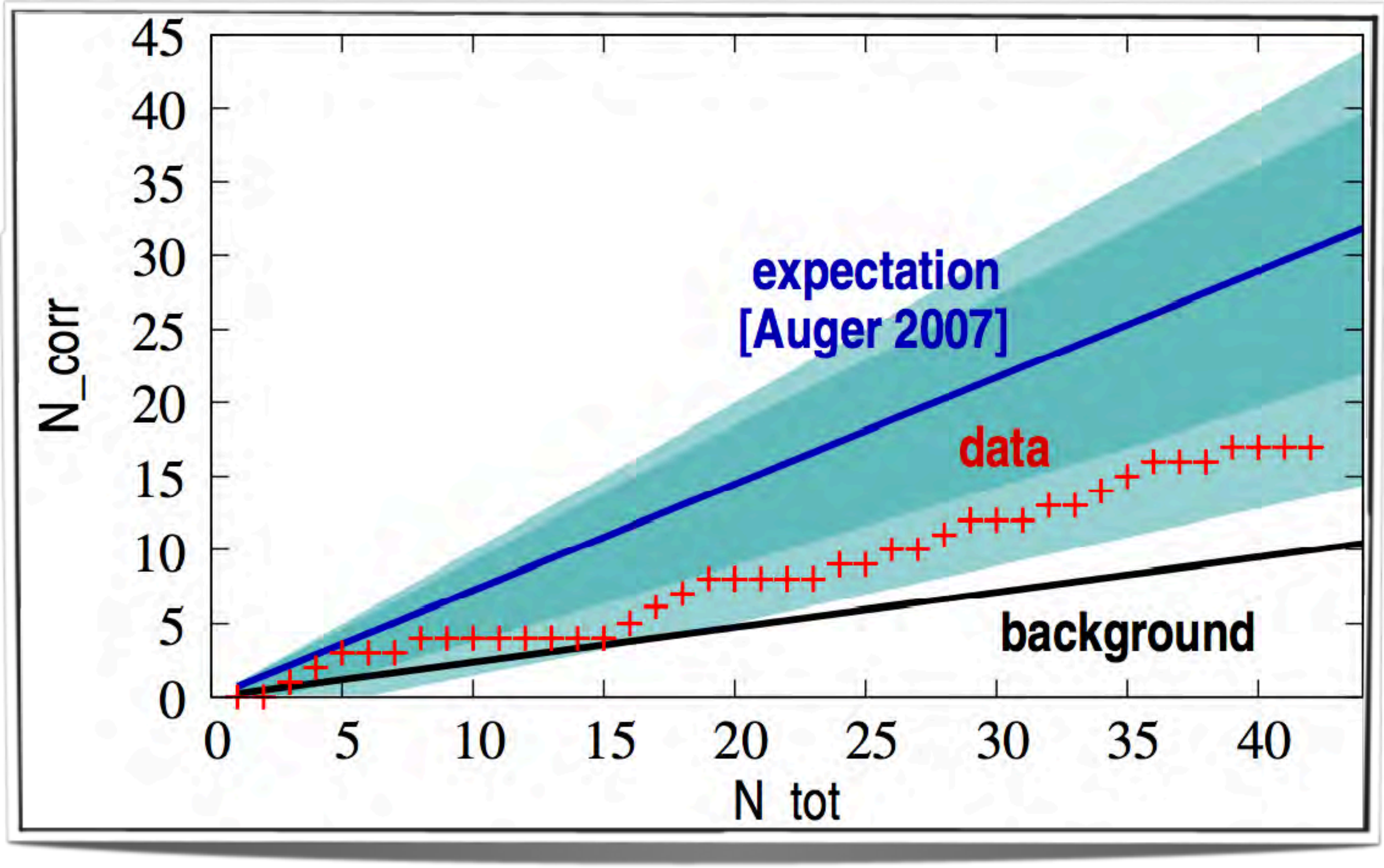
Coords	right ascension	declination
Equatorial:	0.015	0.15
Supergalactic:	0.06	0.003

Correlations with AGN

- 472 AGN from 2006 Veron catalog with z < 0.018
- E > 57 EeV, zenith angle < 45°, N = 42 (5 yr)
- Separation angle = 3.1°



AGN Correlation: TA

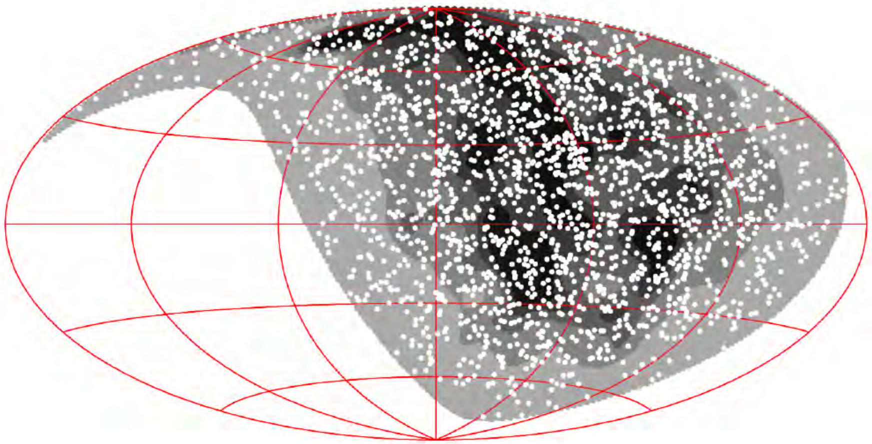


- Applied Auger criteria
- Different sample of AGN (northern hemisphere)
- 17 of 42 events correlate
- Probability 1.4%

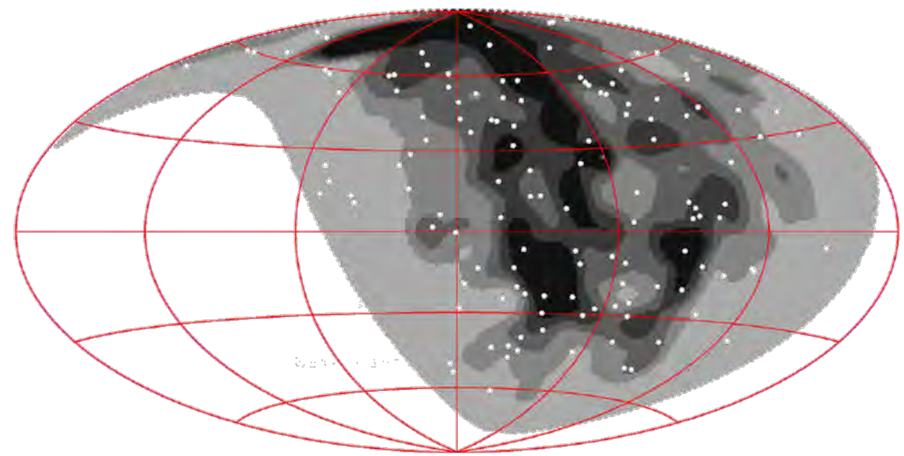
P. Tinyakov, oral, 1033

Correlations with LSS

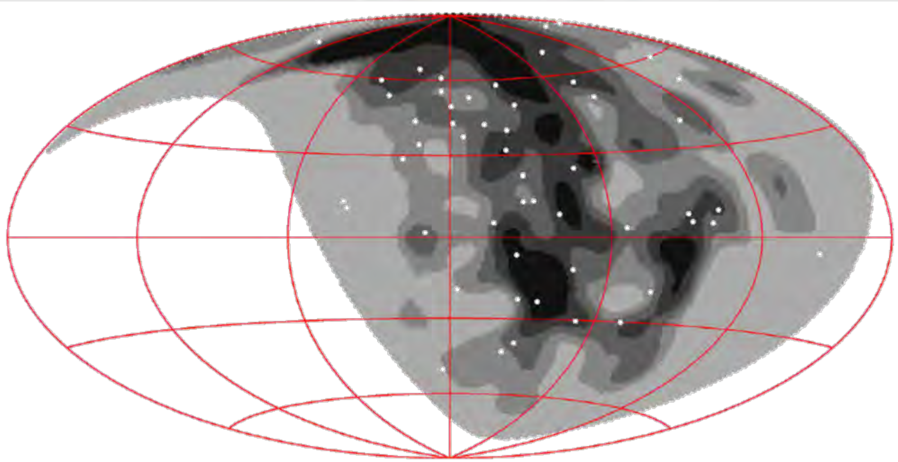
E > 10 EeV: 2130 ev.



E > 40 EeV: 132 ev.



E > 57 EeV: 52 ev.

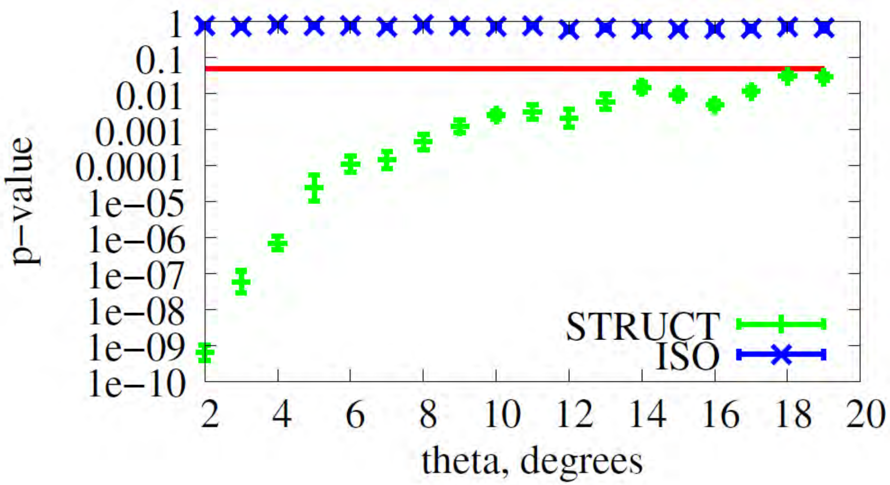


White dots: TA data with zenith angle < 55^o

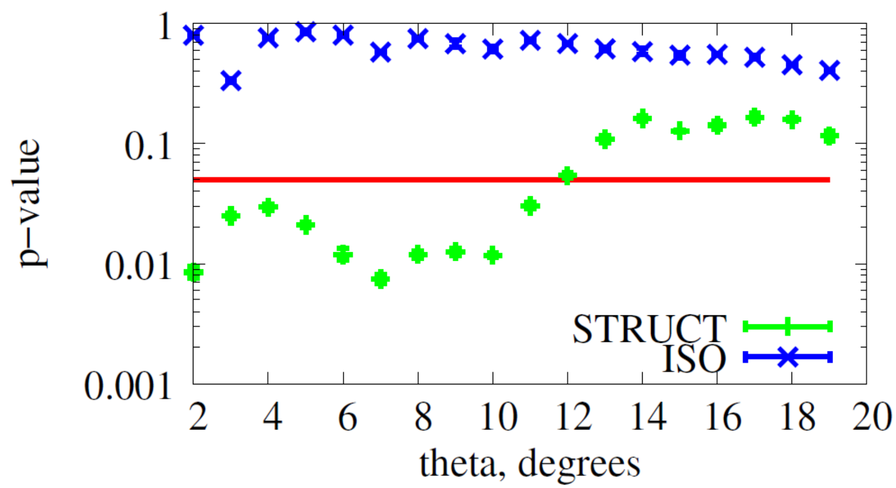
Gray patterns:
expected flux density from proton LSS
2MASS Galaxy Redshift catalog (XSCz)

Correlations with LSS

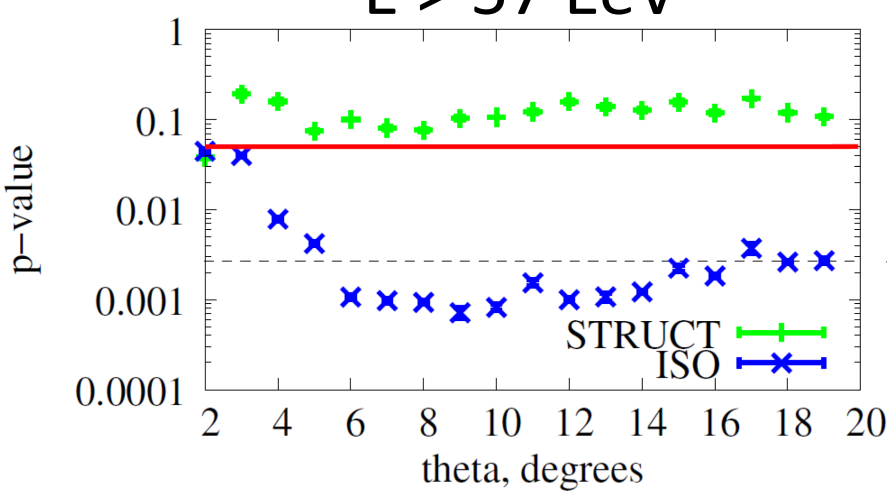
E > 10 EeV



E > 40 EeV



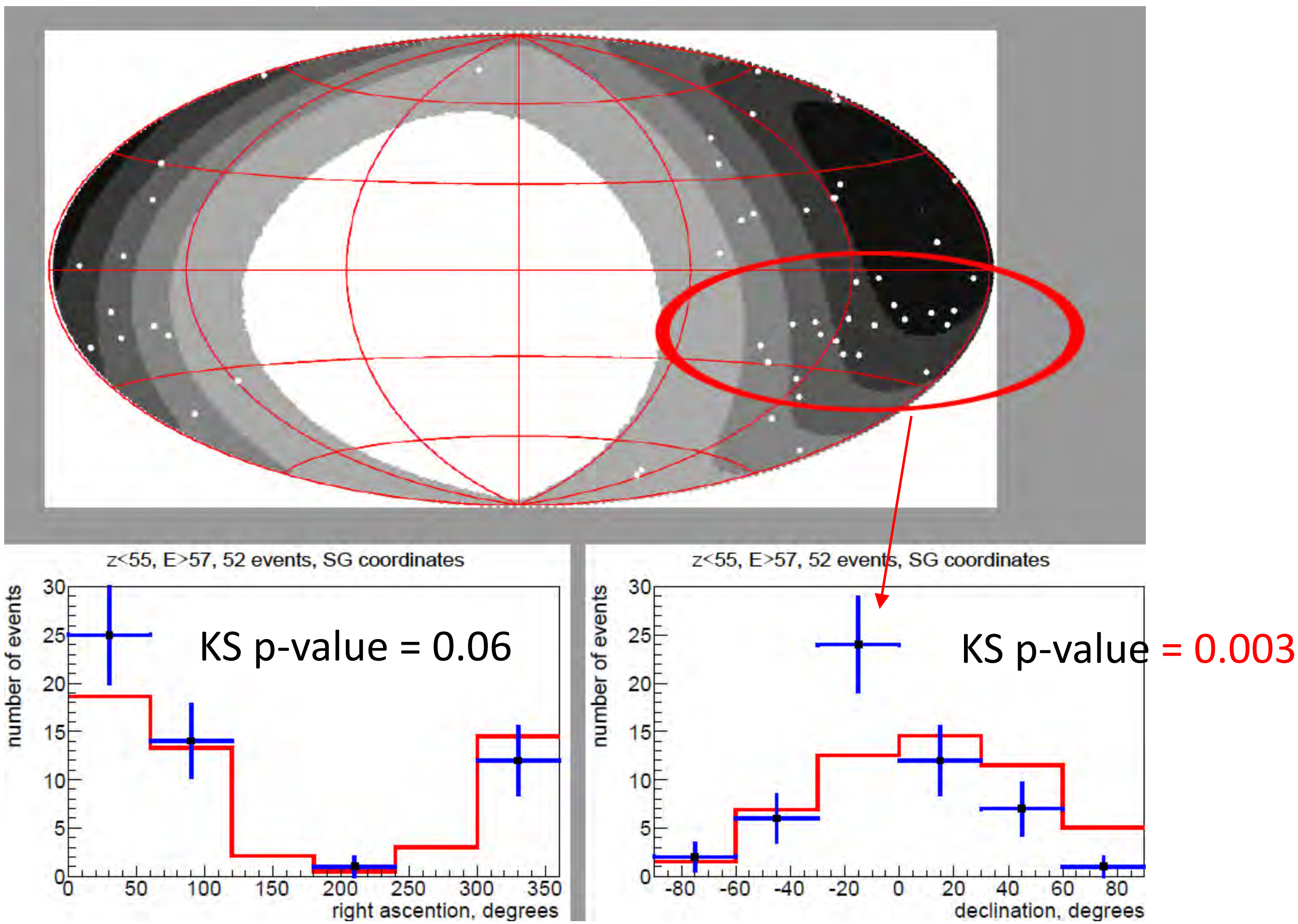
E > 57 EeV



Theta: deflection angle

~3σ (pre-trial)

Super galactic coordinates



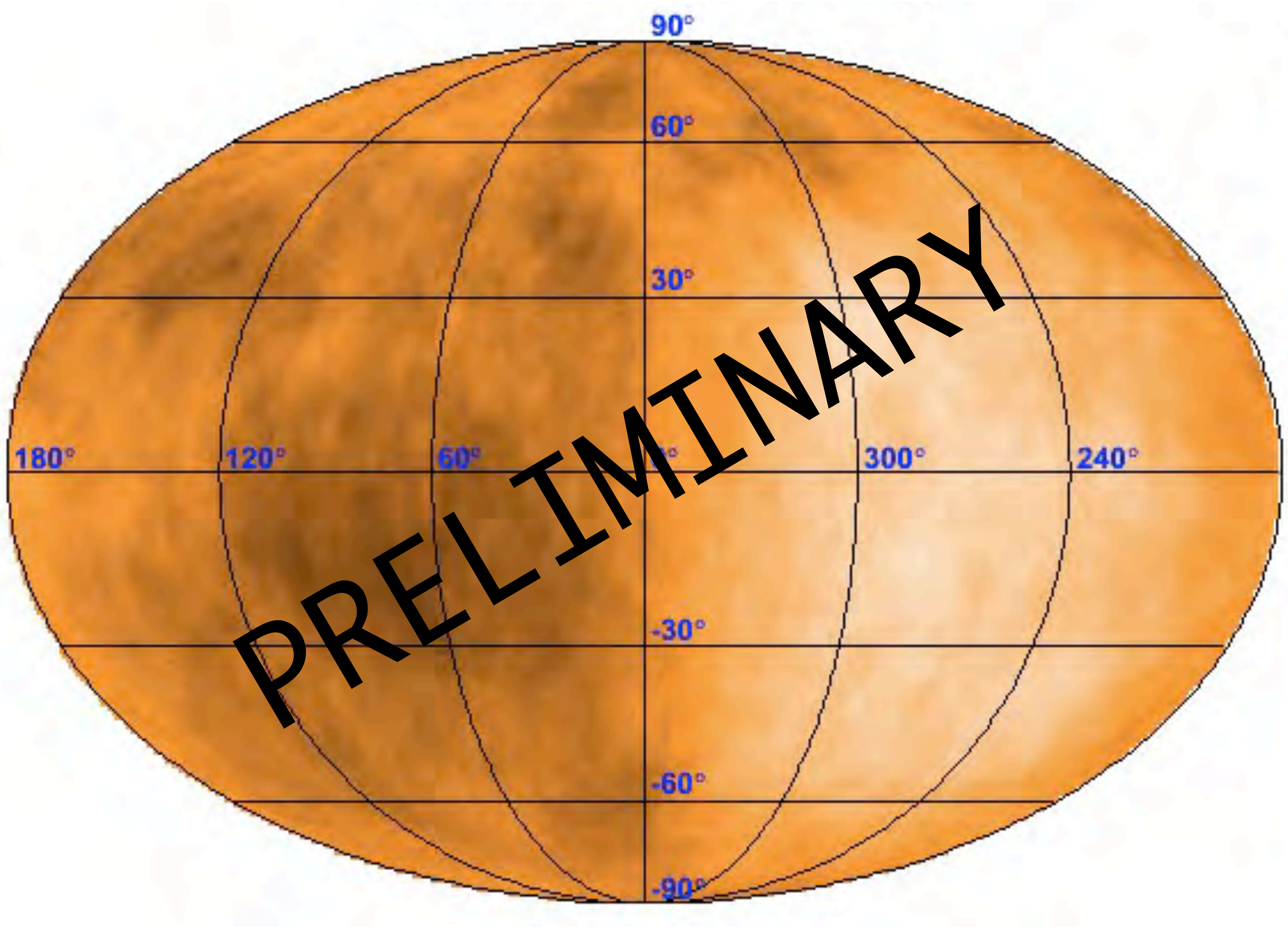
Full-Sky Map >10 EeV (60° smoothing)

N_{TA}~1800

(~5200 km^2 sr yr)

N_{Auger}~10900

(~32000 km^2 sr yr)



In the overlap :

N_{TA}~650

N_{Auger}~3400

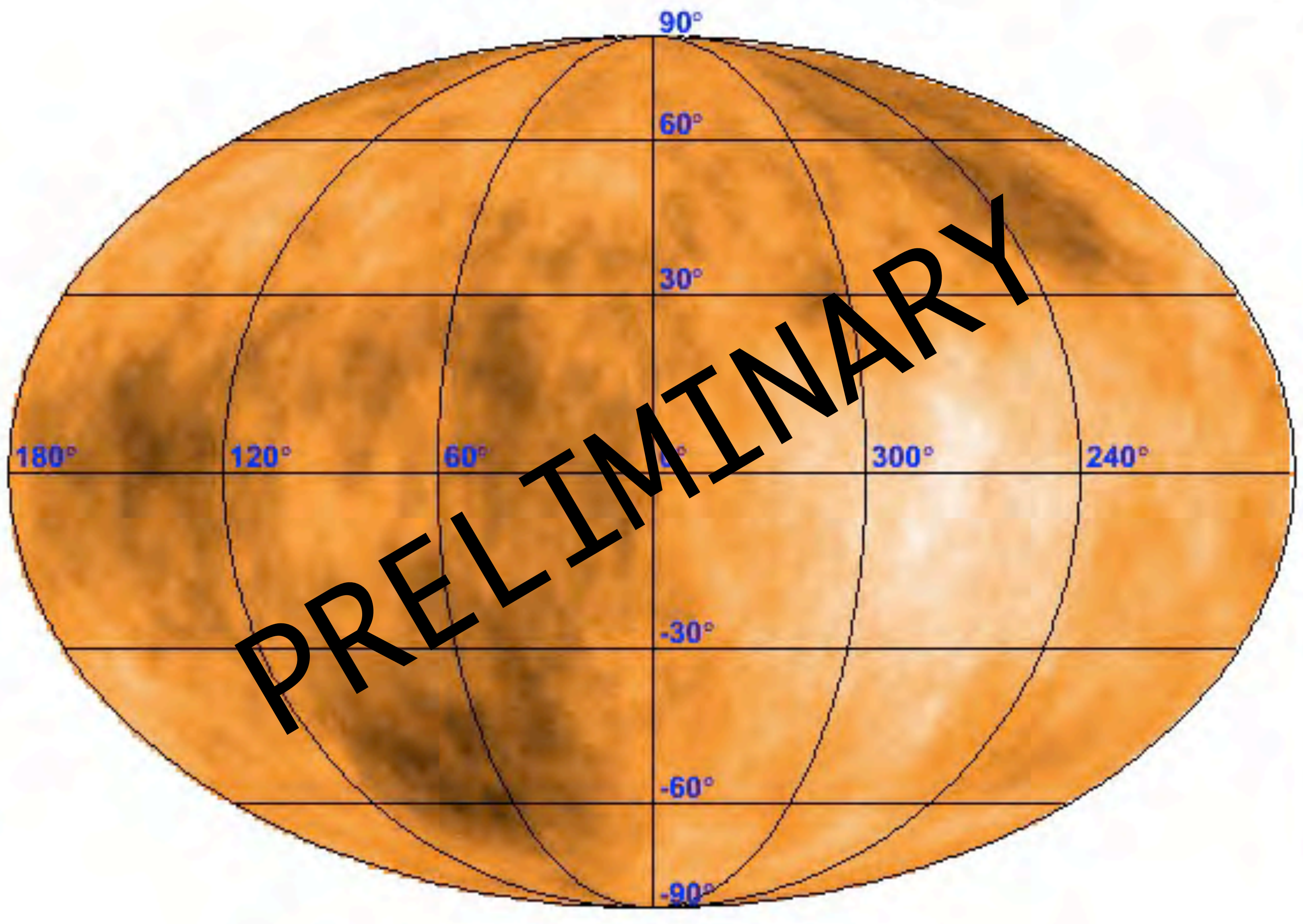
Full-Sky Map >10 EeV (30° smoothing)

N_{TA}~1800

(~5200 km^2 sr yr)

N_{Auger}~10900

(~32000 km^2 sr yr)



In the overlap :

N_{TA}~650

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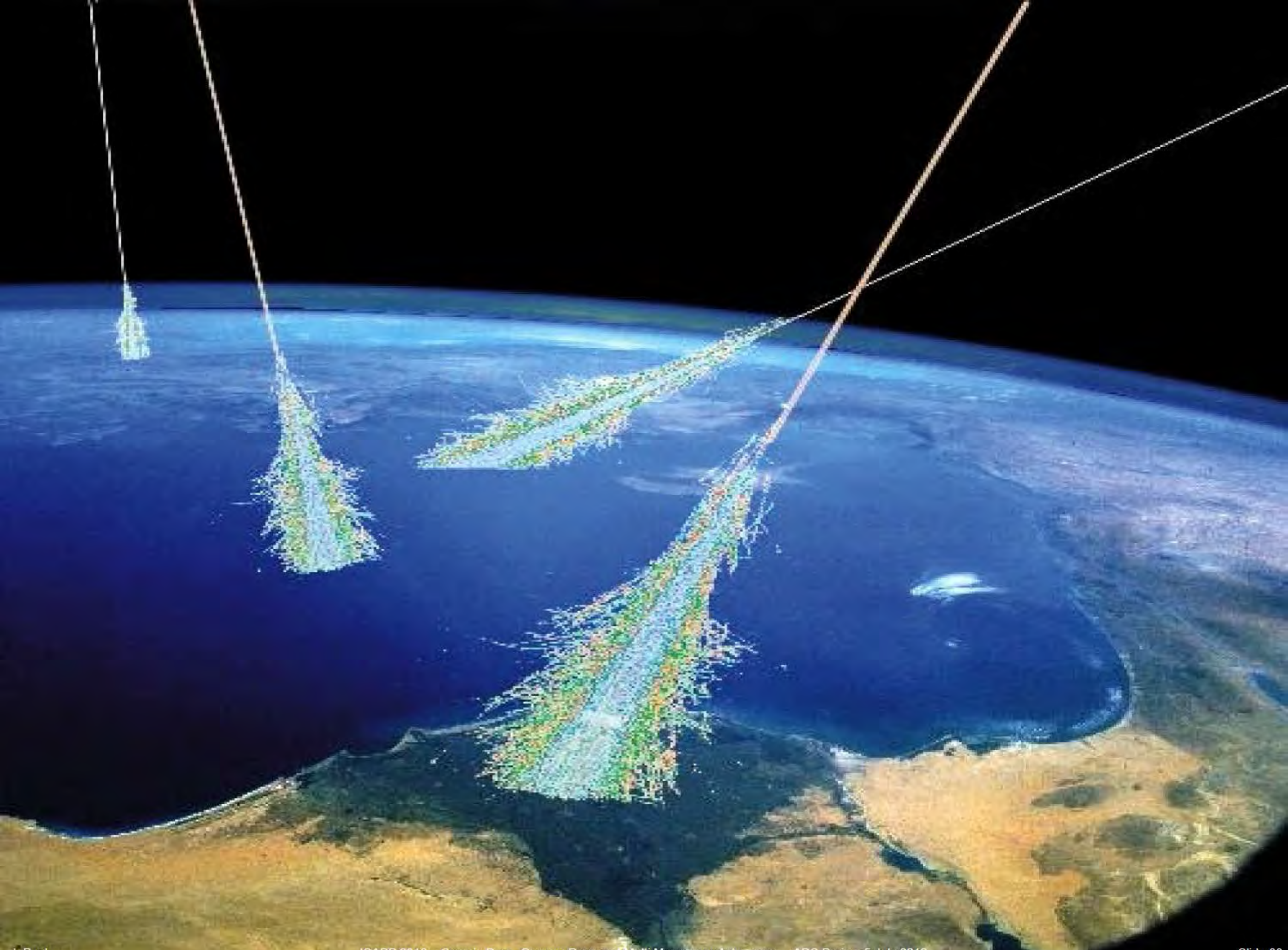
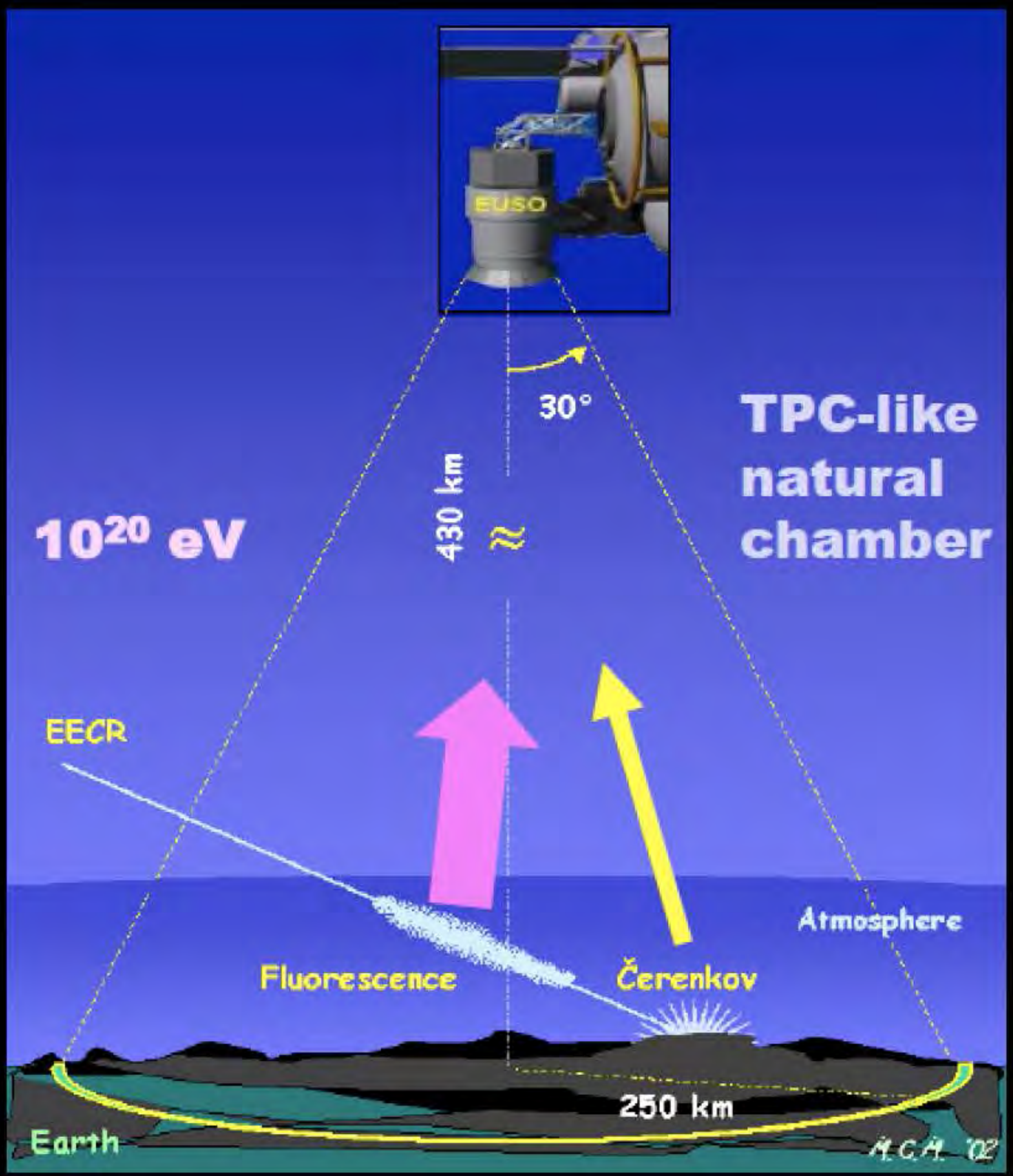
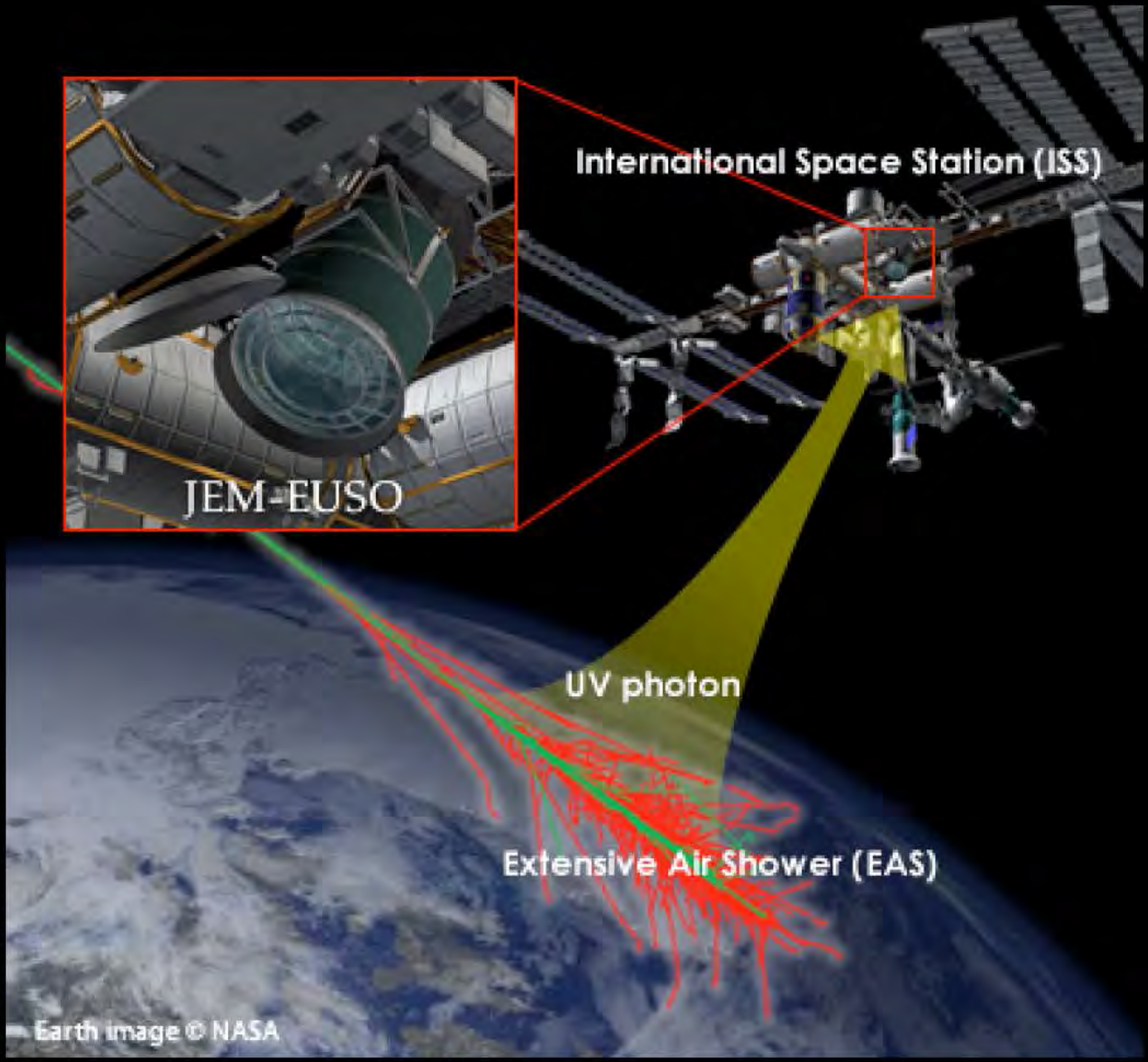


TO MEASURE COSMIC RAYS AT > 10^{20}: JEM-EUSO





In space: to be installed on ISS (altitude ≈ 400 km)
Fluorescence detector
6000 PMTs for a 2.25 m focal surface
Fresnel lenses
Aperture: 10^5-10^6 km2 sr; Energy range: >10^{20} eV

UHECRs: current status

- $\exists$ steepening above ~60 EeV (probably GZK $\otimes$ E_{max})

  Compatible with standard astrophysical expectations

  $\Rightarrow$ very low fluxes, but also good news! (much fewer sources at UHE)

- Very limited statistics at ~100 EeV !

- Low level of anisotropy ⇒ Interesting hints, but without clear status

  ⇒ Does not generate info about sources…

  ⇒ General agreement in the community: current experiments have shown that there is something to see at UHE, but much larger statistics will be needed to actually see it!

- CR composition probably becomes heavier at UHE (or showers not understood)

  ⇒ Important information!

  ⇒ Does not help the observation of clear, meaningful anisotropies!

  But does not prevent it either! ⇒ further speaks for larger exposures

Specific focus of JEM-EUSO

- Part of a global effort to understand the UHE universe
  - Complementary to ground-based UHECR observatories
  - Complementary to gamma-ray, neutrino and non-thermal astronomy
  - In coordination with the global study of cosmic rays, particle acceleration in astrophysical environments and the modeling of high-energy sources

- Main focus of JEM-EUSO: the extreme energies!
  - ⇒ Gather as much information as possible about EECRs
  - ⇒ Establish the first consistent, high-sensitivity, 4π-steradian map of the UHECR sky
  - ⇒ Discover and study the first sources of UHECRs
  - ⇒ Explore the UHE universe with unprecedented power

- New, innovative answer to the problem of very low fluxes
  - instead of building larger arrays, with more and more detectors, go to space and look down to cover a huge area with a single instrument

"5 orders of magnitude to go!"

- Current area covered $< 10^{-5} \times$ Earth's surface

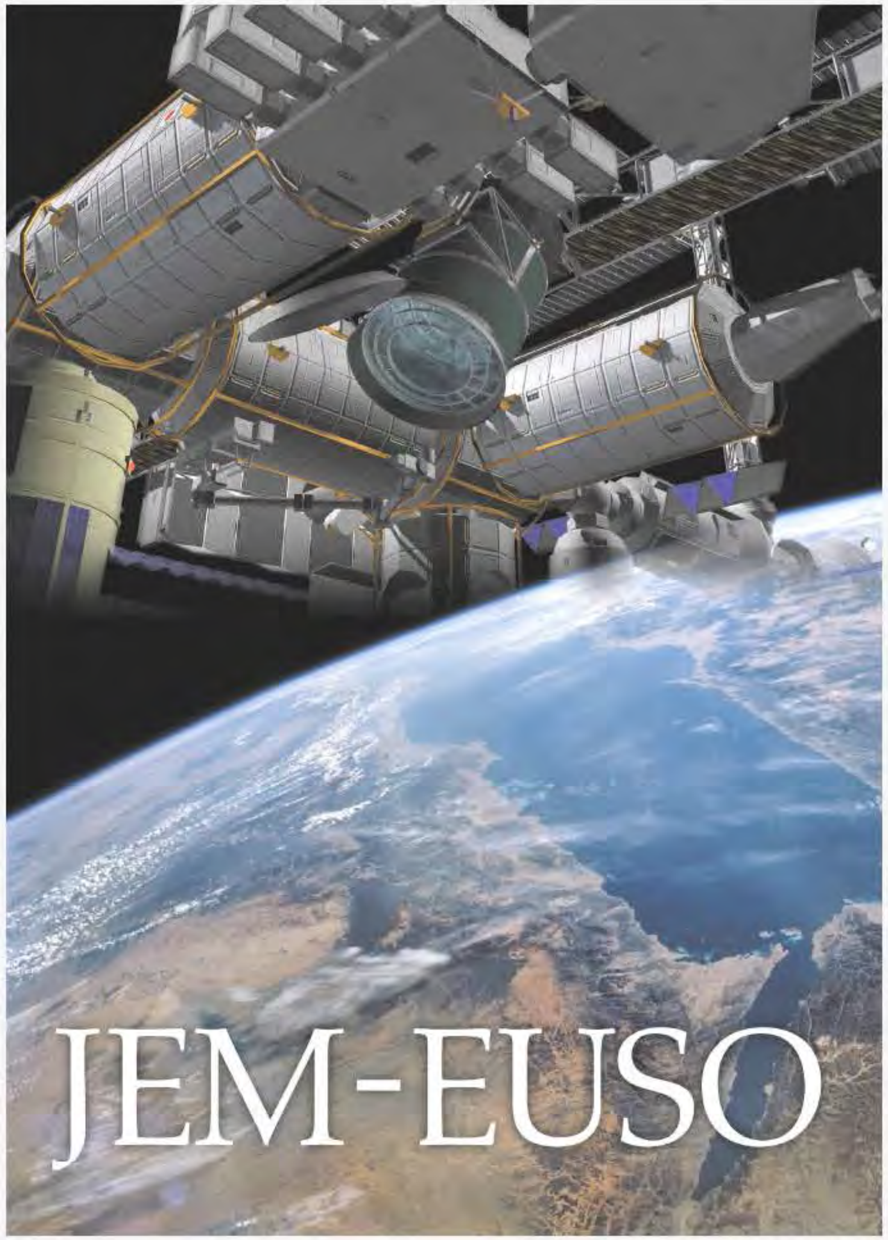
- JEM-EUSO will pioneer UHECR studies from space

- JEM-EUSO will instantly monitor $> 10^6$ km^3 of atmosphere

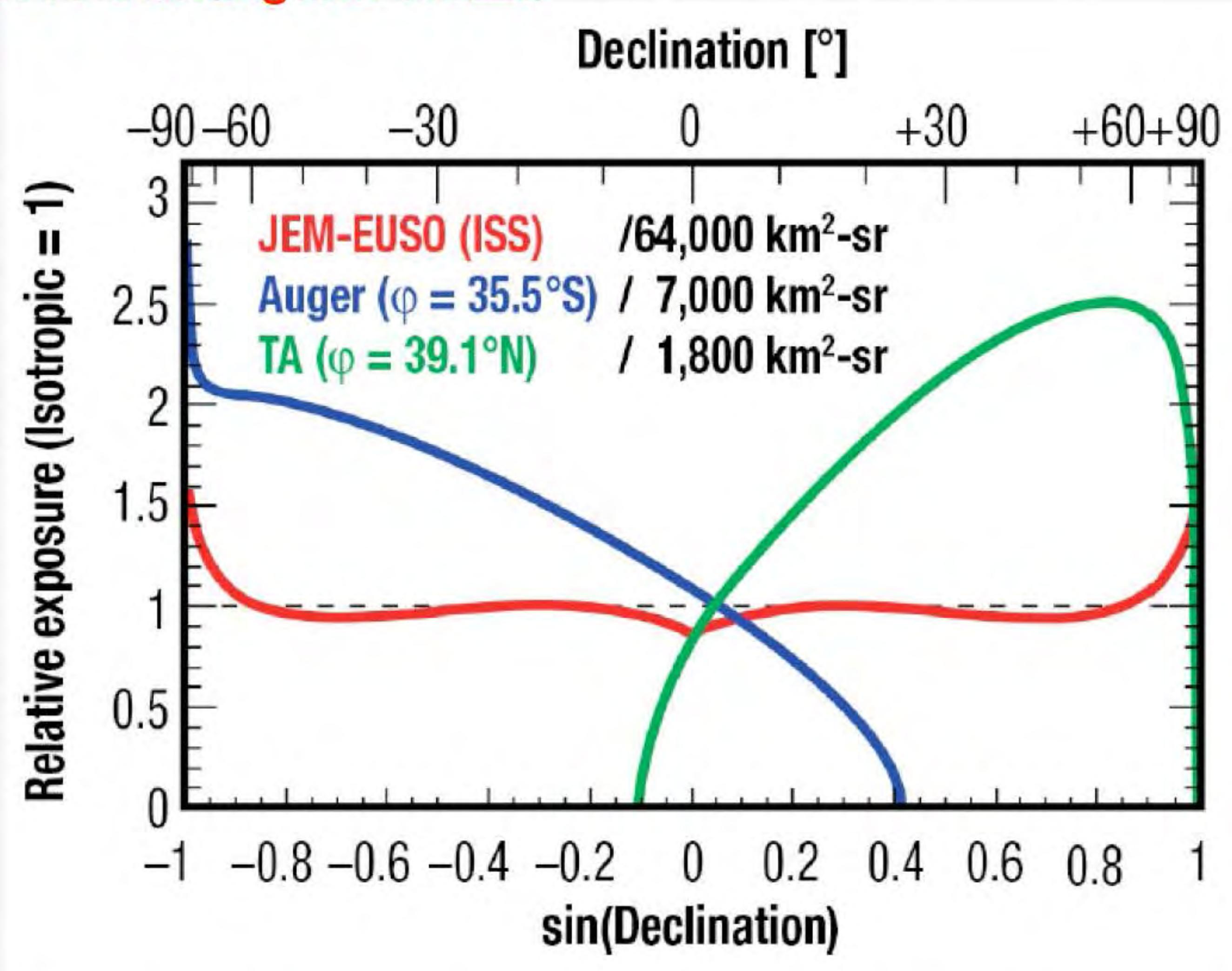
- Achieving an annual exposure in Nadir mode of 60 000 km^2 sr yr

(i.e. Auger × 9)

JEM-EUSO



0738 Santangelo/Picozza

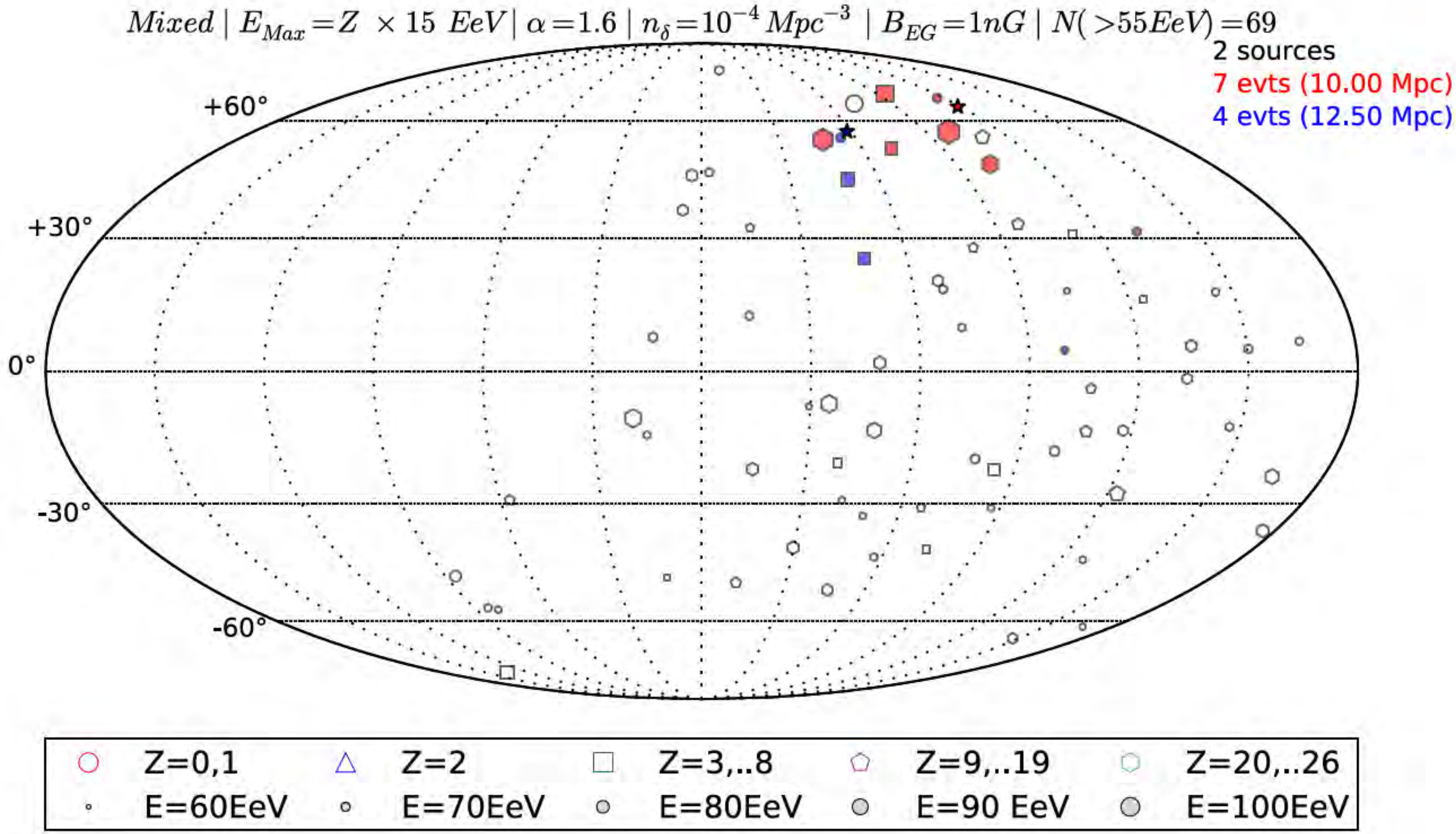


- Huge exposure ---> Significant anisotropy expected! (0984 Parizot)
- 31 CR-contributions
- R&D successful
- Pathfinders: TA-EUSO, EUSO-Baloon
- Launch: 2017

Simulated sky maps

Example for $E_{max}(p) = 15$ EeV and $n_s = 10^{-4}$ Mpc^{-3}

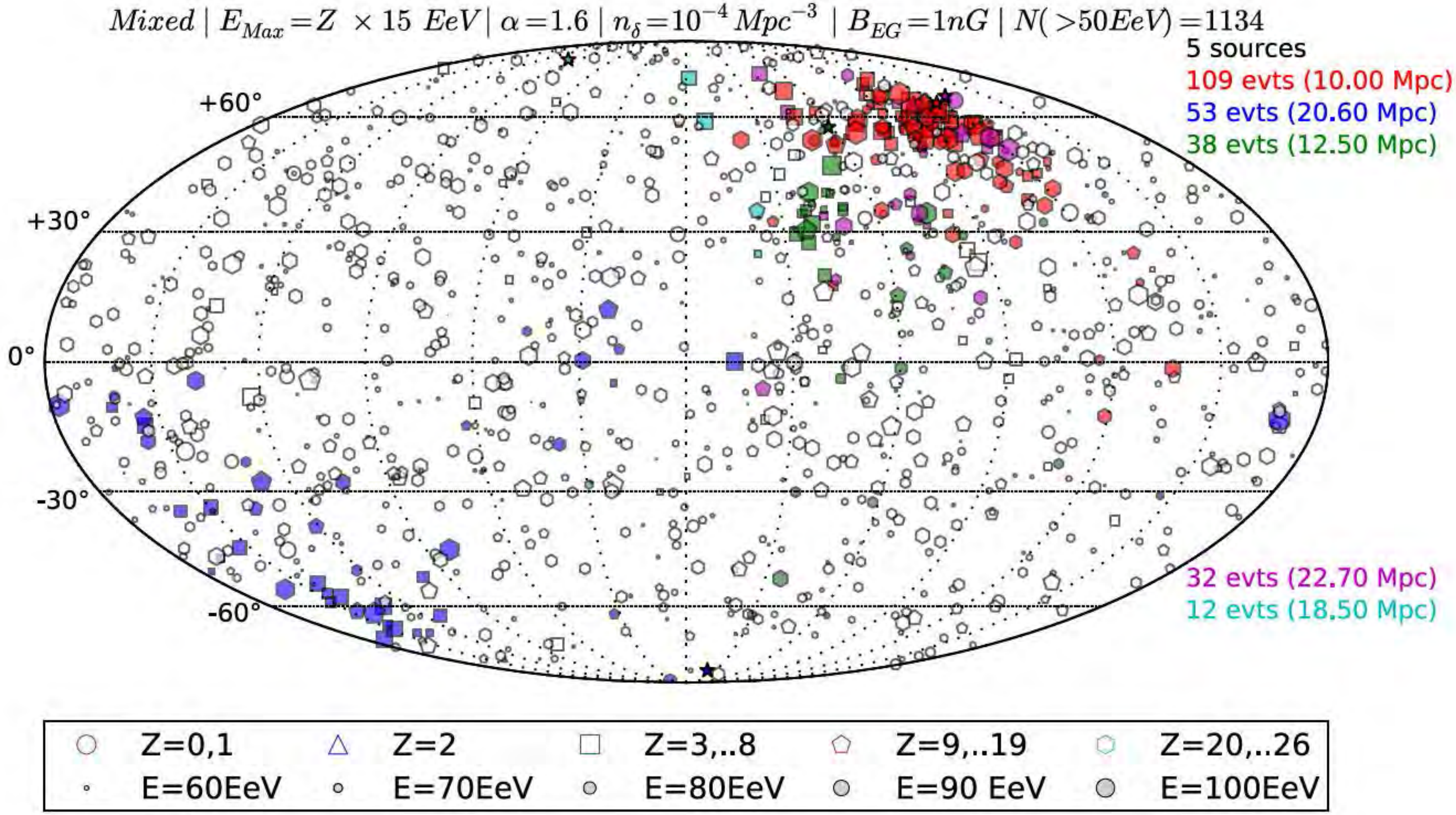
"Auger statistics": 69 events above 55 EeV



Simulated sky maps

Example for $E_{max}(p) = 15$ EeV and $n_s = 10^{-4}$ Mpc^{-3}

"JEM-EUSO statistics": 1100 events above 50 EeV (Auger energy scale)



Specific focus of JEM-EUSO

- Part of a global effort to understand the UHE universe

  - Complementary to ground-based UHECR observatories
  - Complementary to gamma-ray, neutrino and non-thermal astronomy
  - In coordination with the global study of cosmic rays, particle acceleration in astrophysical environments and the modeling of high-energy sources

- Main focus of JEM-EUSO: the extreme energies!

  ⇒ Gather as much information as possible about EECRs

  ⇒ Establish the first consistent, high-sensitivity, 4π-steradian map of the UHECR sky

  ⇒ Discover and study the first sources of UHECRs

  ⇒ Explore the UHE universe with unprecedented power

- New, innovative answer to the problem of very low fluxes

  - instead of building larger arrays, with more and more detectors, go to space and look down to cover a huge area with a single instrument

Main science objectives

- Begin the new field of particle astronomy & astrophysics by identifying the first sources of UHECRs

→ Reach an exposure of 300 000 km^2 sr yr in a 5-years mission

+ each additional year will add the equivalent of 9 years of operation of a ground detector as large as Auger at the highest energies

- Unprecedented anisotropy studies

⇒ Establish the first consistent 4π-sr map of the UHECR sky

⇒ Search for the first UHECR sources

⇒ Study large scale anisotropies (dipole and quadrupole) (~uniform full-sky coverage!)

⇒ Study signatures of the cosmic variance / constrain source density

⇒ Constrain source density / deflections / magnetic fields

⇒ Constrain UHECR composition through anisotropy measurements

- study of extended multiplets (energy/deflection) - close multiplets => protons !

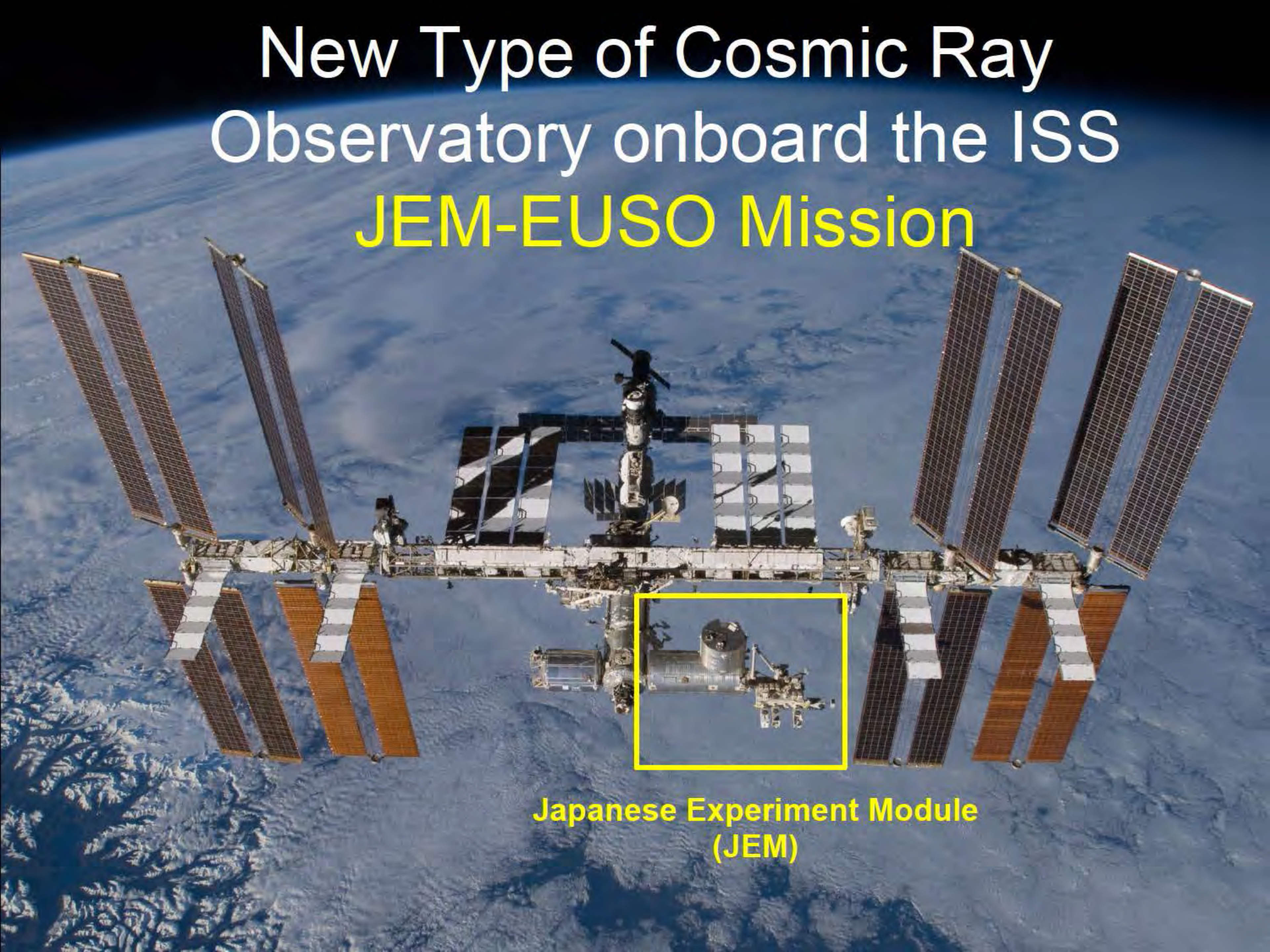
JEM-EUSO on ISS explores the origin of the highest energy particles in the Universe

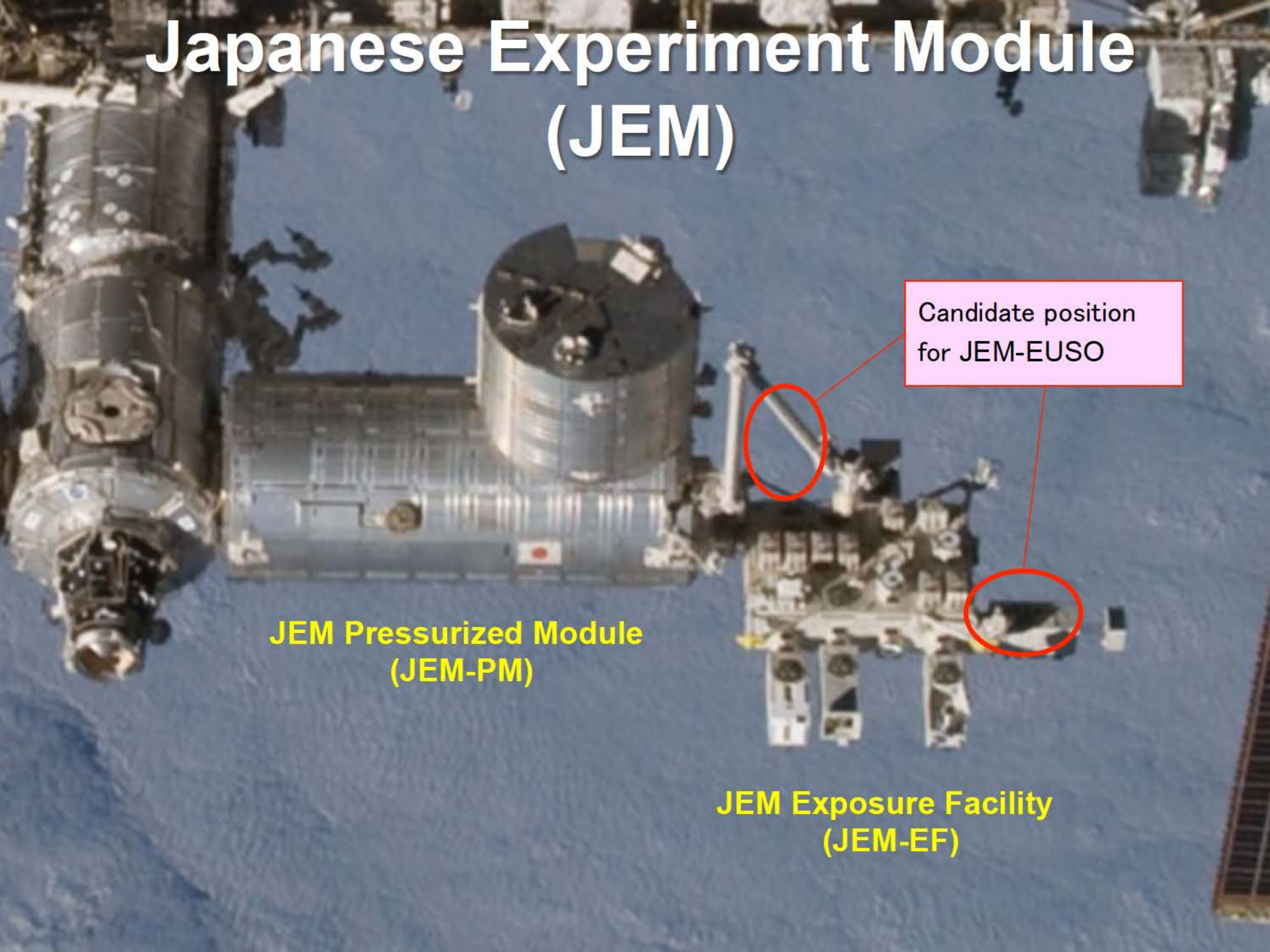
JEM-EUSO Collaboration

- **13 (+1) countries, 80 institutions, > 285 researchers**

  - **Japan** : *RIKEN, Konan Univ., Fukui Inst. Tech., Aoyama Gakuin Univ., Saitama Univ., NIRS, Univ. Tokyo, Hokkaido Univ., ICRR/Univ. Tokyo, Nagoya Univ., KEK, Chiba Univ., NAOJ, ISAS/JAXA, Kanazawa Univ., STEL/Nagoya Univ., YITP/Kyoto Univ., Kyoto Univ., Kobe Univ., Kinki Univ., Hiroshima Univ., Osaka Univ., Osaka City Univ., Tokyo Inst. Tech. , Kavli IPMU/Univ. Tokyo, Nihon Univ.*
  - **USA** : *Univ. Alabama, Univ. Chicago, NASA/MSFC, Univ. Wisc. Milwaukee, Color. Sch. Mines, UC Berkeley, Vanderbilt Univ.*
  - **France** : *APC-Paris 7, LAL/IN2P3-CNRS, CESR*
  - **Germany**: *MPI Munich, Univ. Tuebingen, MPI Bonn, Univ. Wuerzburg, Univ. Erlangen, LMU & MPQ, Univ. Hamburg, KIT*
  - **Italy** : *INFN & Univ.Bari, INFN & Univ.Catania, CNR-INO Firenze, CNR-IFAC Firenze, INFN-LNF, INFN-Naples, Univ. "Federico II" di Napoli, IASF-PA/INAF, INFN & Univ. Rome "Tor Vergata", INAF-IFSI Torino, INFN & Univ. Torino, Univ. Torino / ARPA Piemonte, INAF-OATO*
  - **Mexico** : *ICN-UNAM, UNAM-II, BUAP, UMSNH*
  - **Republic of Korea** : *Ehwa W. Univ., Yonsei Univ., KASI, Pusan National Univ., Sungkunkwan Univ., Hanyang Univ., Chungam National Univ., KAIST*
  - **Russia** : *SINP MSU, Dubna JINR*
  - **Switzerland** : *CSEM, ETHZ, ISDC*
  - **Spain** : *Univ. Alcala, INTA, Univ. Carlos III, IACT*
  - **Poland** : *IPJ, Podlasie Univ., Kielce Univ., Jagiellonian Univ.*
  - **Slovakia** : *Inst. Experimental Phys./ KOSICE*
  - **Bulgaria** : *Univ. of Sofia*

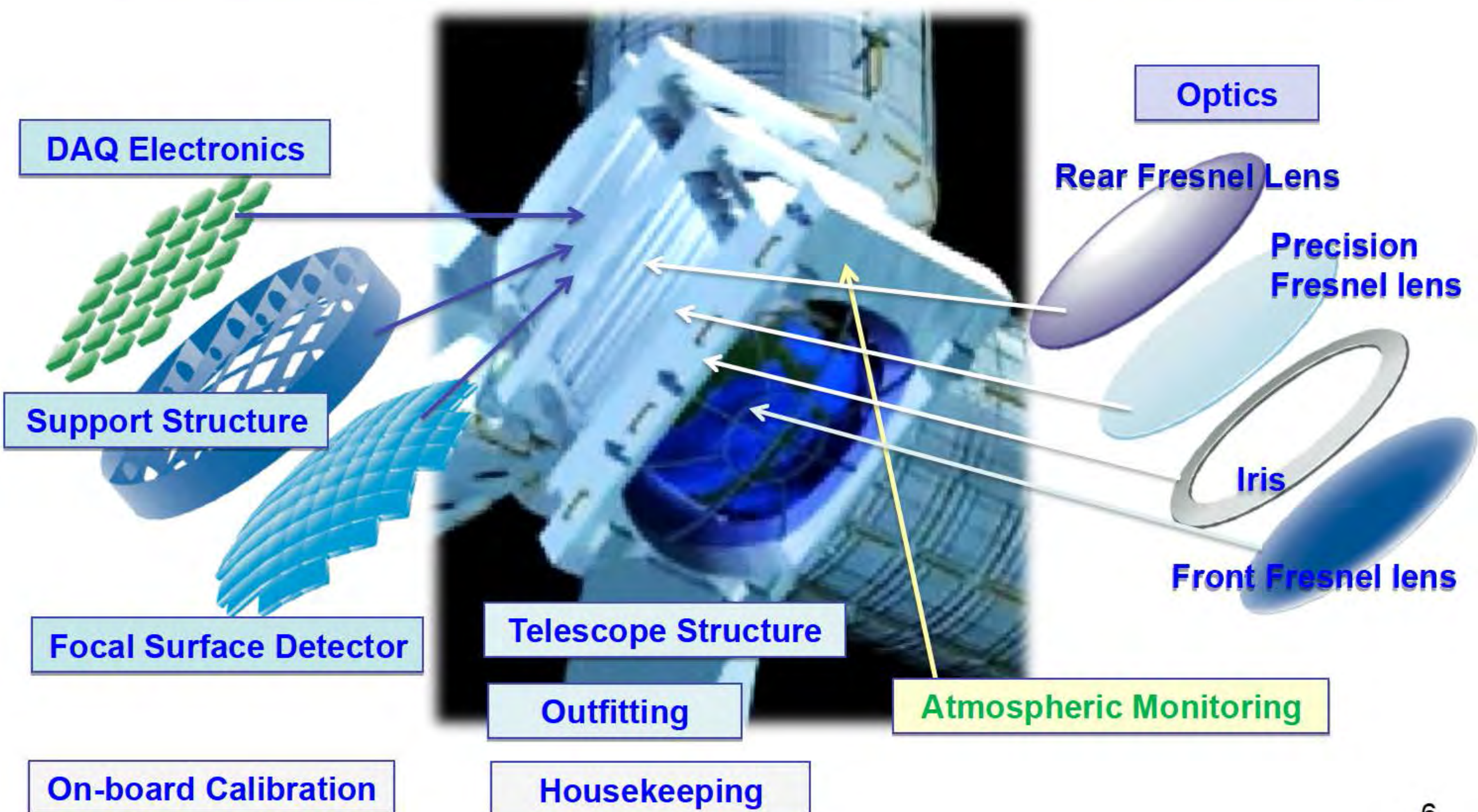
New Type of Cosmic Ray Observatory onboard the ISS
JEM-EUSO Mission




Japanese Experiment Module
(JEM)
Candidate position
for JEM-EUSO
JEM Pressurized Module
(JEM-PM)
JEM Exposure Facility
(JEM-EF)

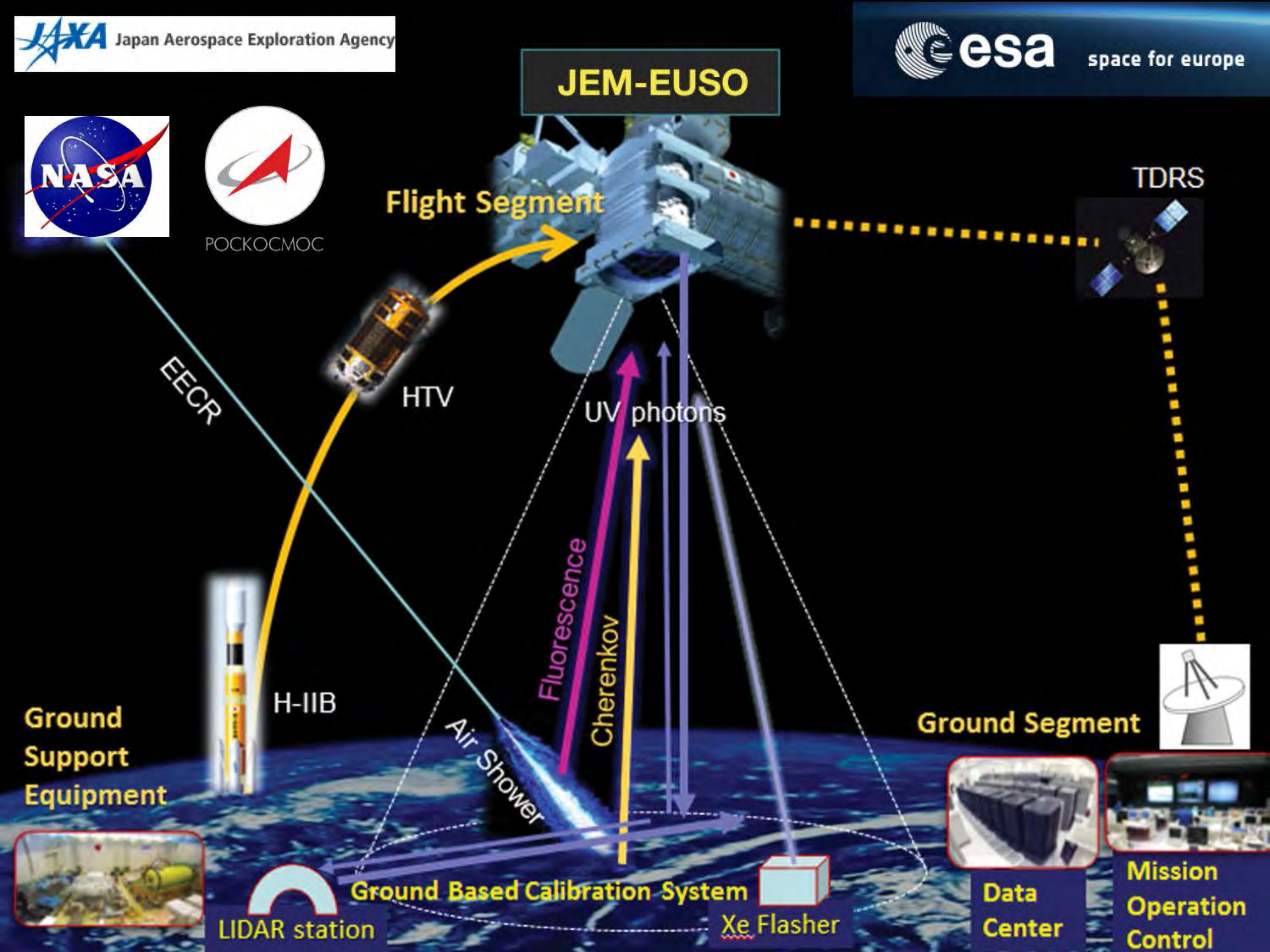
Science Instrument

UV Telescope + Atmospheric Monitoring

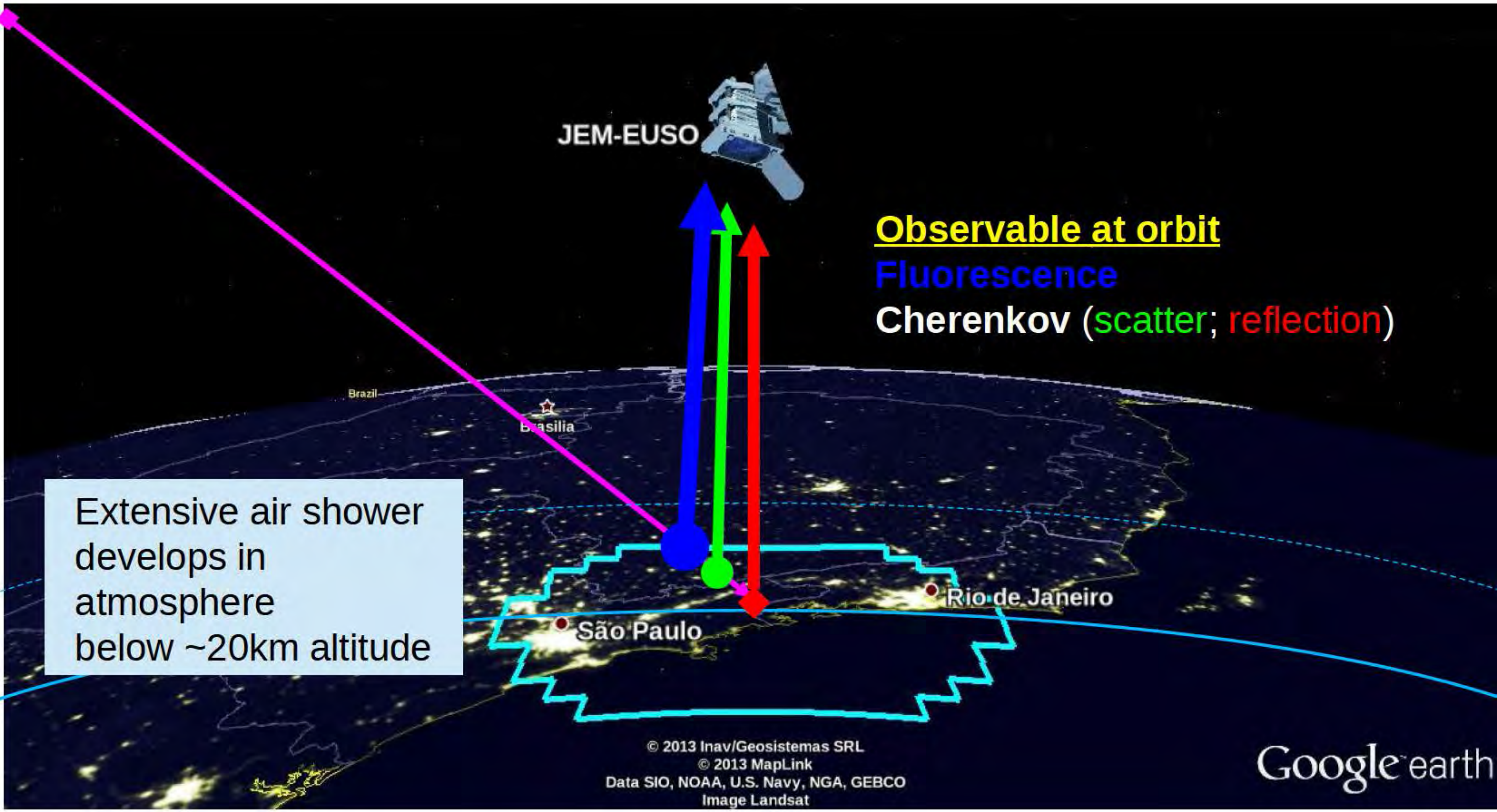


The UV Telescope Parameters

Parameter	Value
Field of View	±30°
Monitored Area	$>1.4\times10^5 km^2$
Telescope aperture	≥2.5 m
Operational wavelength	300-430 nm
Resolution in angle	0.075°
Focal Plane Area	$4.5\ m^2$
Pixel Size	<3 mm
Number of Pixels	$\approx3\times10^5$
Pixel size on ground	≈560 m
Time Resolution	2.5 μs
Dead Time	<3%
Photo-detector Efficiency	≥20%


Japan Aerospace Exploration Agency
esa space for europe
JEM-EUSO
NASA
РОСКОСМОС
Flight Segment
TDRS
HTV
EECR
UV photons
Fluorescence
Cherenkov
H-IIB
Air Shower
Ground Support Equipment
Ground Segment
Ground Based Calibration System
LIDAR station
Xe Flasher
Data Center
Mission Operation Control

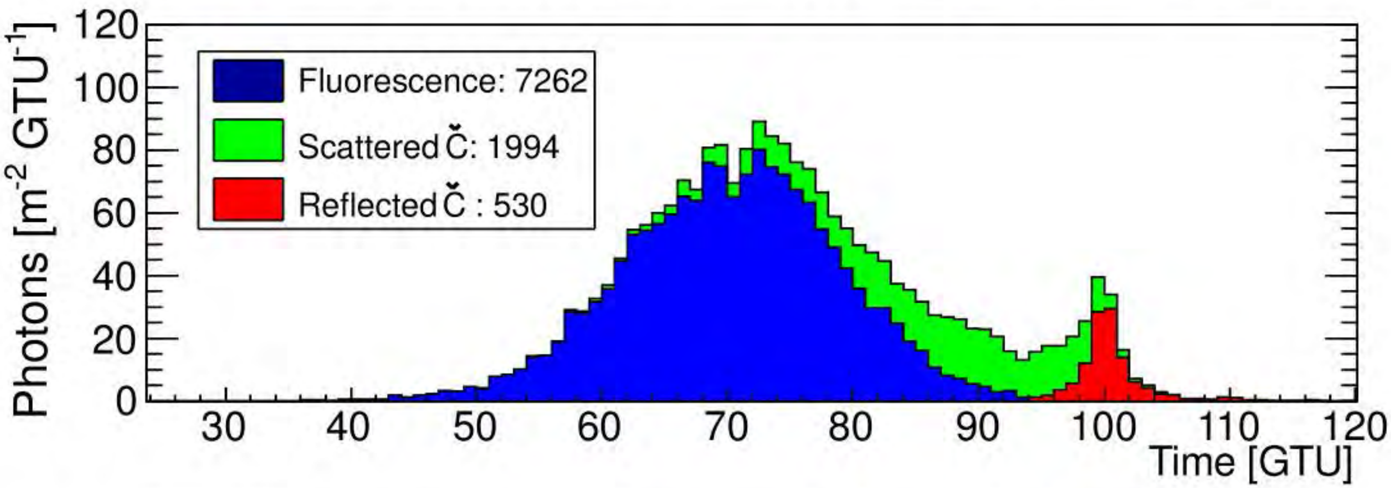
Observation principle

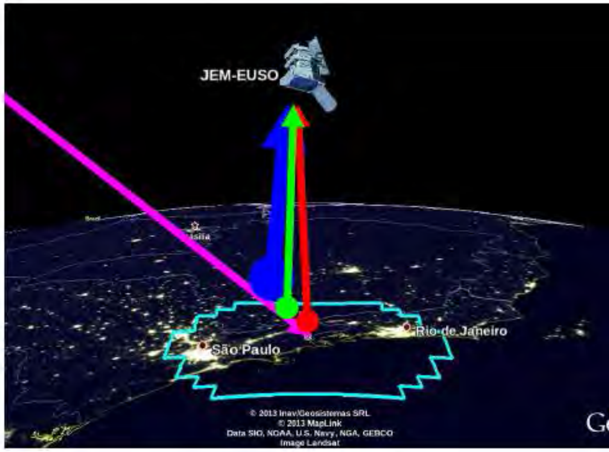


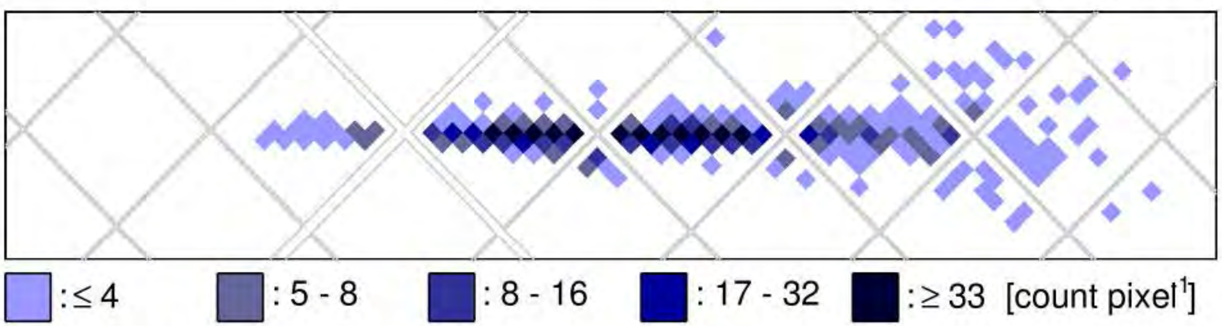
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Observation principle

E = 10^{20} eV from Θ=60° → 10,000 photons to pupil







Observable at orbit
Fluorescence
Cherenkov (scatter; reflection)

Temporal-spatio-profile: arrival direction determination

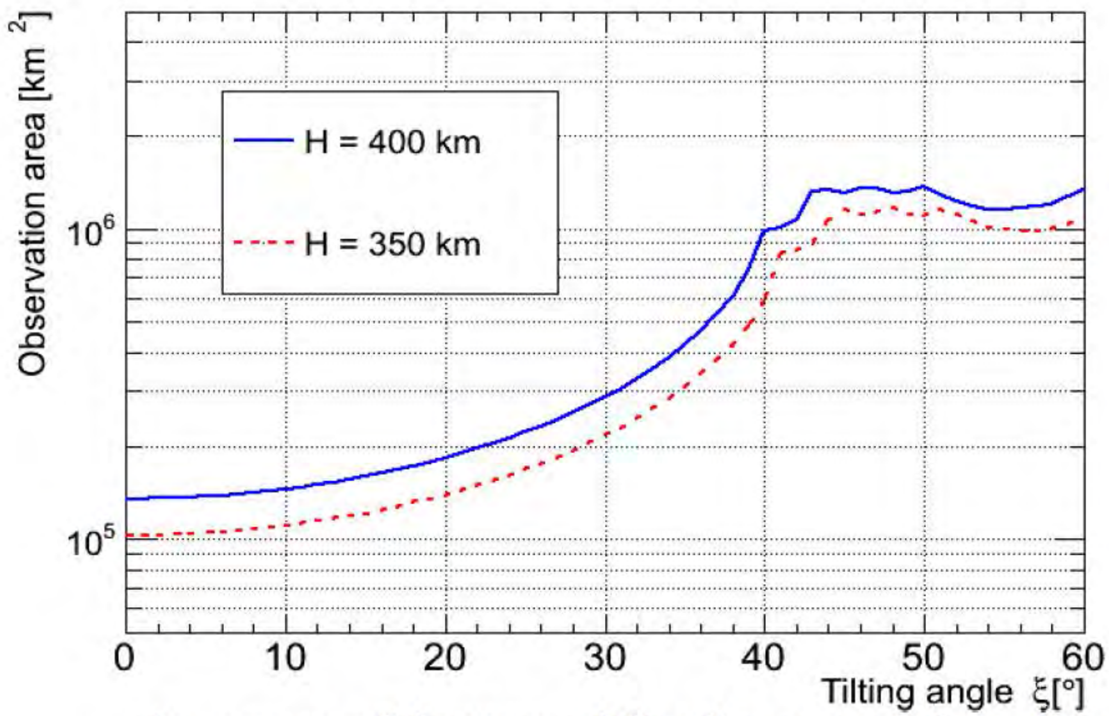
Reflected Cherenkov signals: Impact position determination

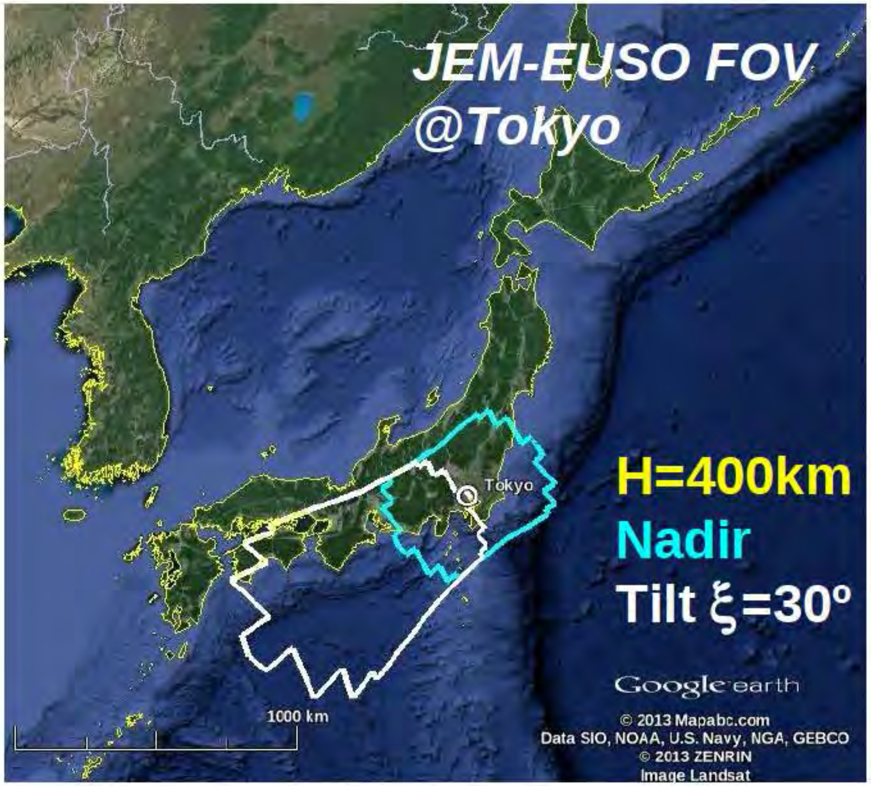
Fluorescence signals: energy & Xmax estimation

Observation areas in tilt mode

At small tilting angle

(Area scaling) ~ $(\cos \xi)^{-3}$

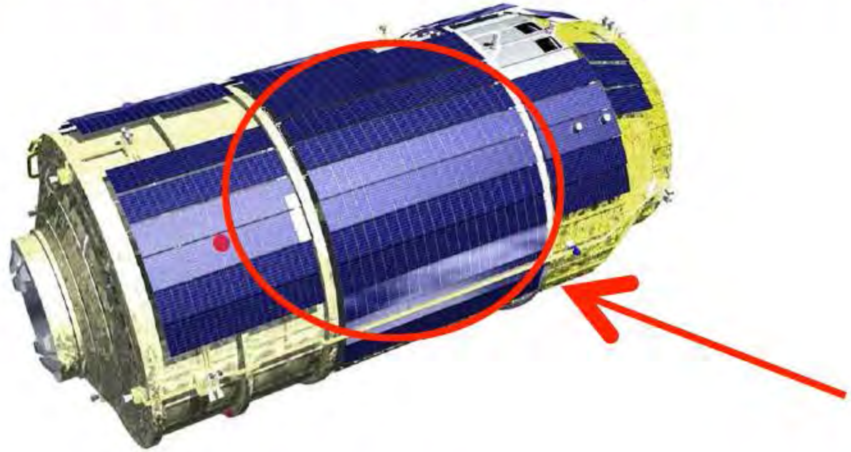




- **In case of lower altitude operation (eg. 350km), titling ~25º (quasi-nadir mode) allows recovery in reduced observation area**
- **Large tilting angle ~30º and higher enhances observation area up to ~6 times to explore extreme energies**

Science Instrument on HTV

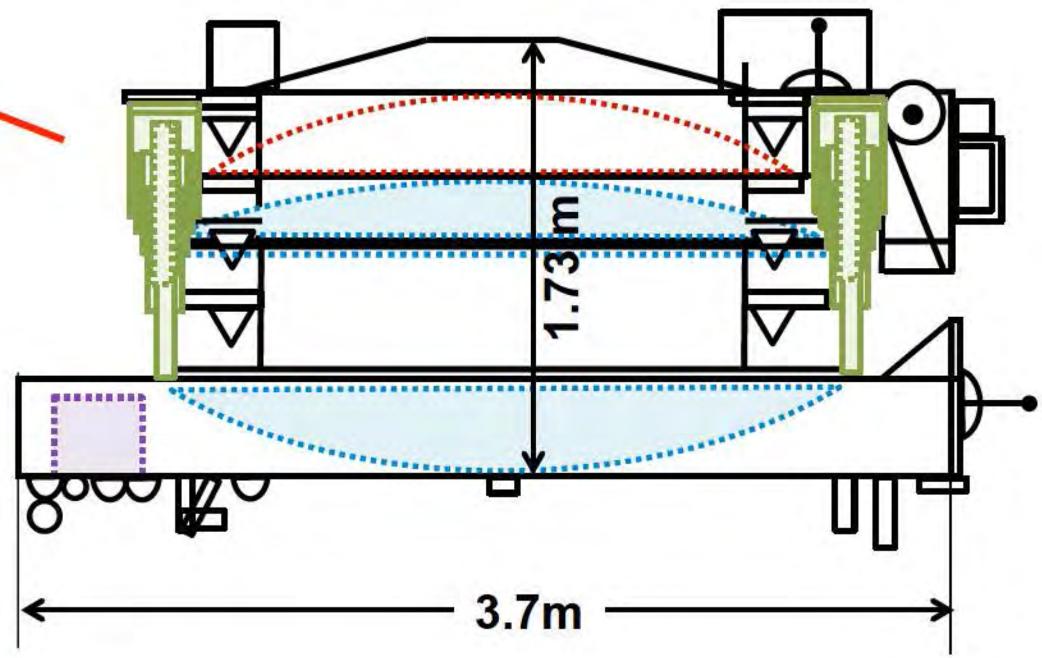
H2B Transfer Vehicle (HTV)



H2B Rocket

Stowing configuration
to carry by HTV

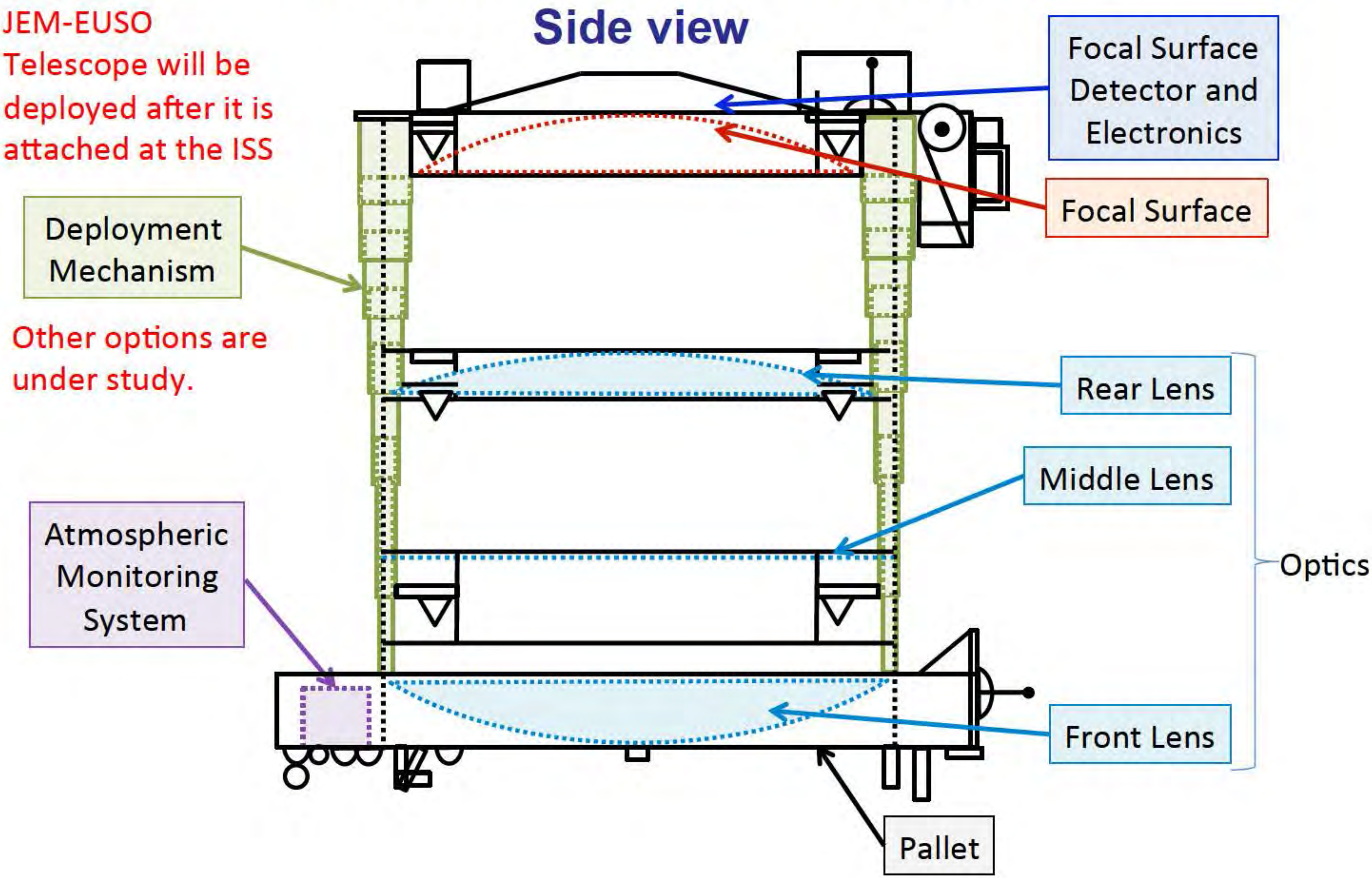
Side view



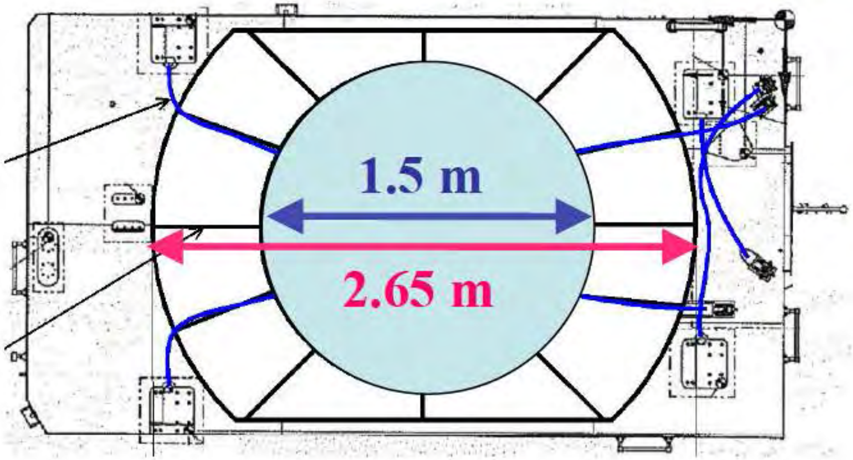
Science Instrument

JEM-EUSO Telescope will be deployed after it is attached at the ISS

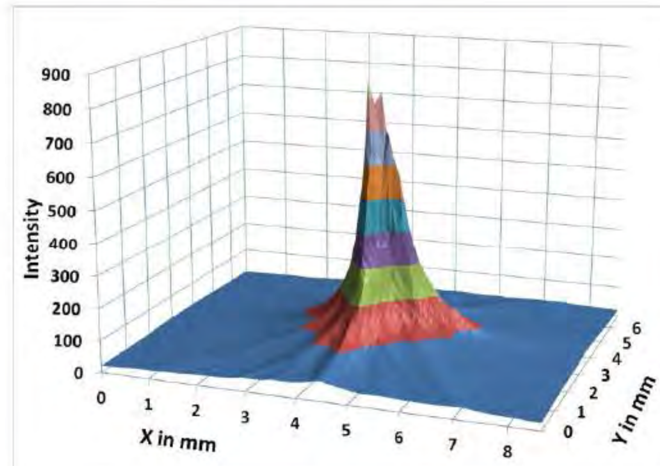
Other options are under study.

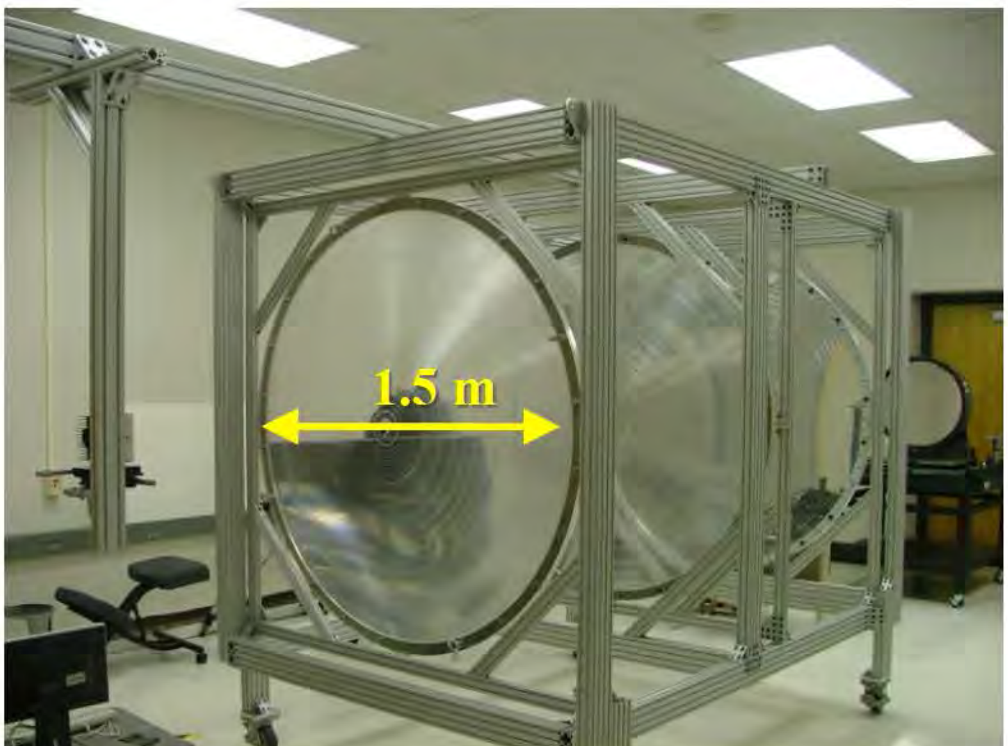


Breadboard Model Lenses



3 Breadboard Model (BBM) Fresnel lenses (1.5m ϕ) are manufactured and tested.





Tested performances meet the requirements.

Result: ~3mm RMS

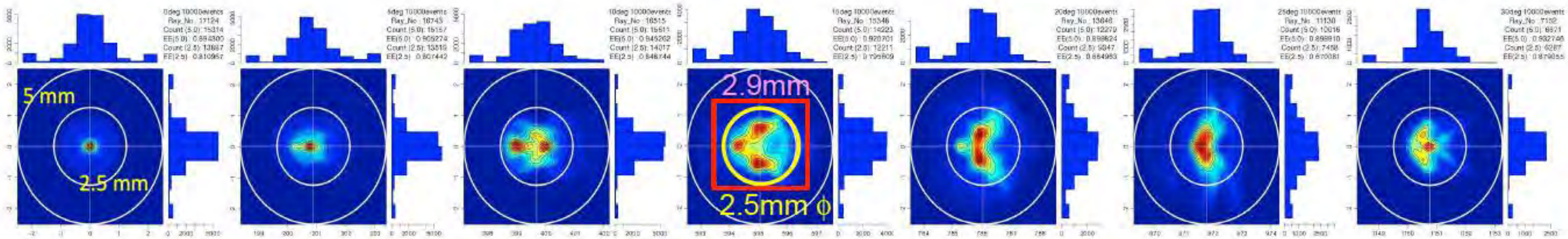
Req. : 4.6mm RMS

Spot size at the Focal Surface

Simulation

Field angle (deg)

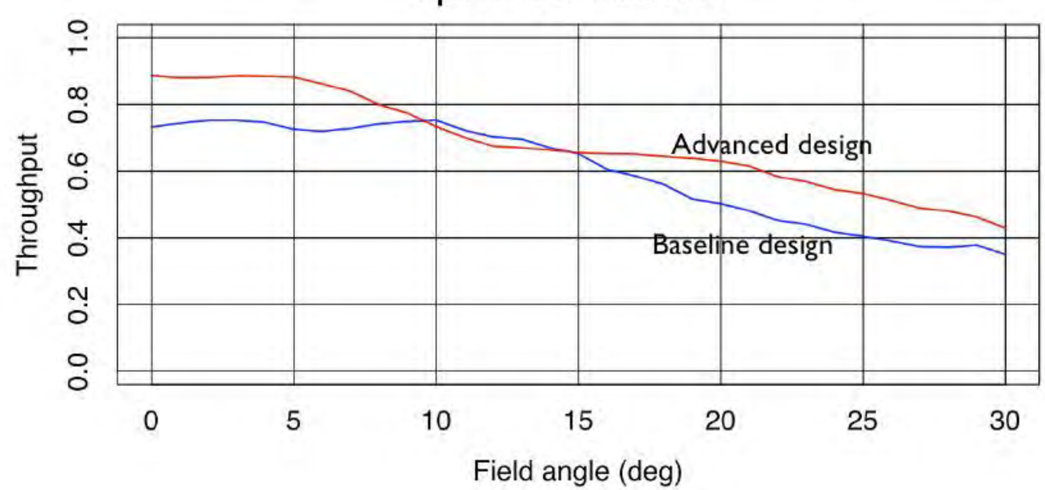
0° 5° 10° 15° 20° 25° 30°



Simulated spot size is < 2.5 mm in diameter.

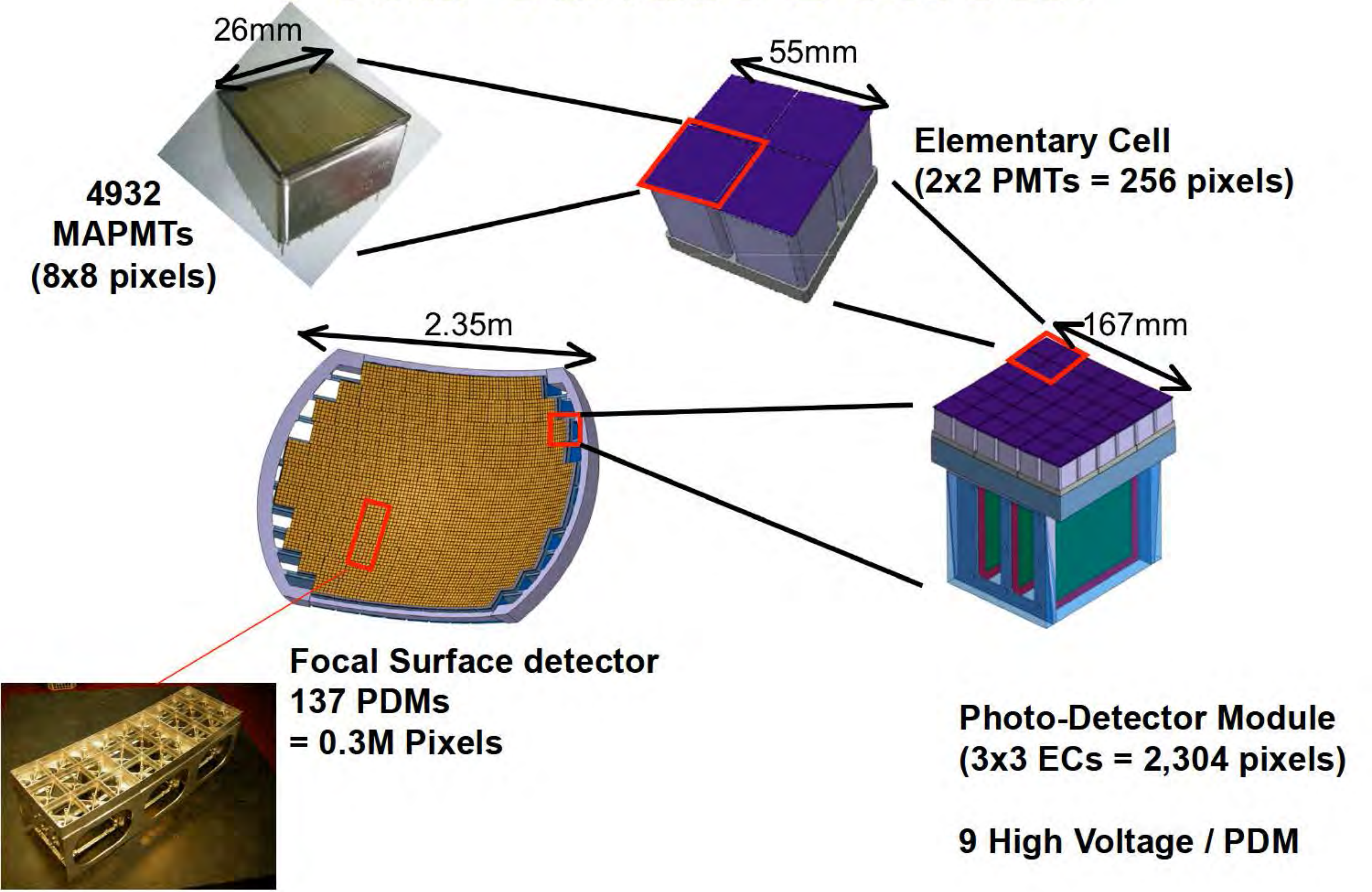
spot size < pixel size of photo-detector (2.9mm)

Baseline design vs Advanced design
Spot Size 2.5mm

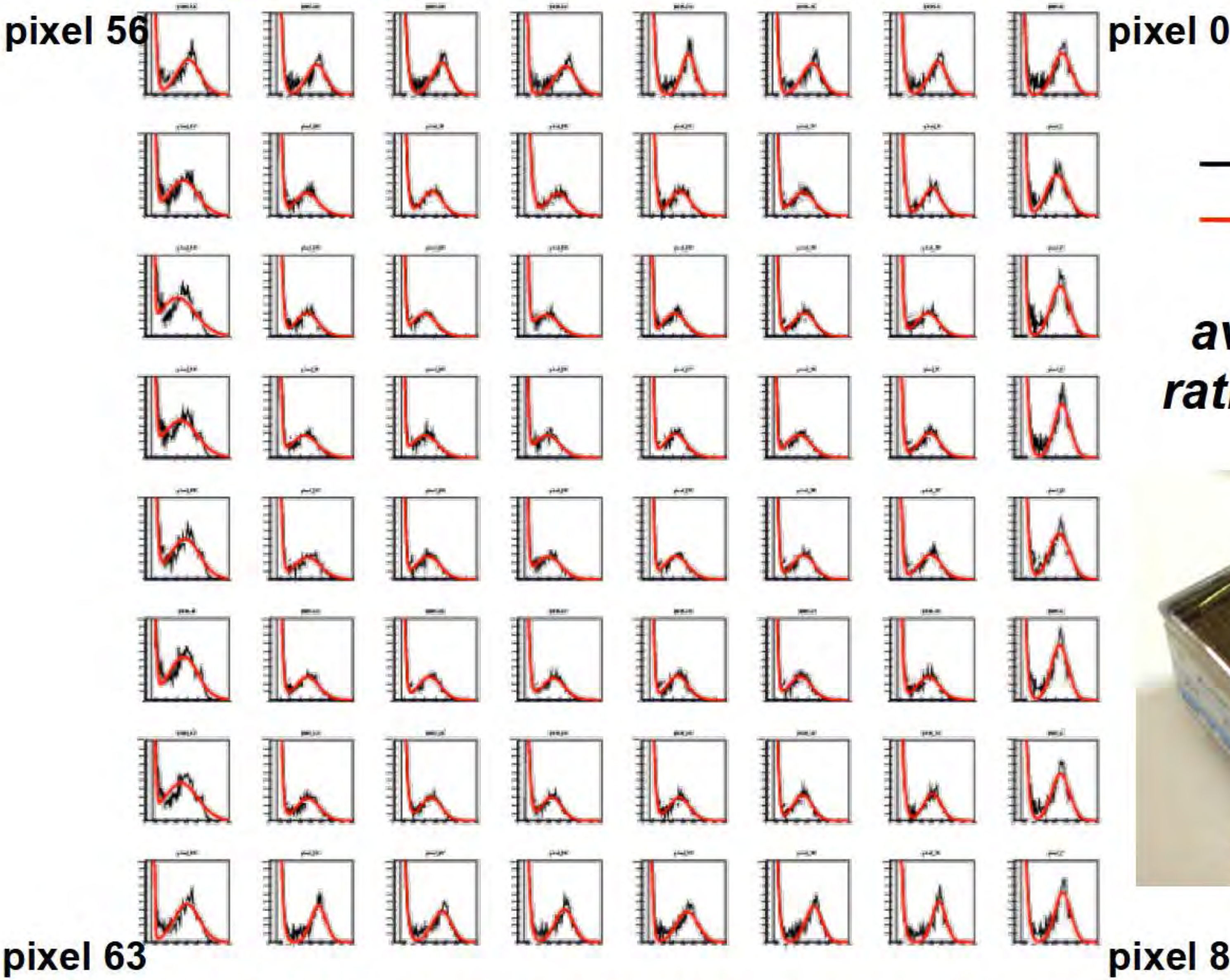


Throughput is the ratio between the number of photons in the spot area and those passing through the Aperture Stop.

Focal Surface Detector



Single photoelectron distribution

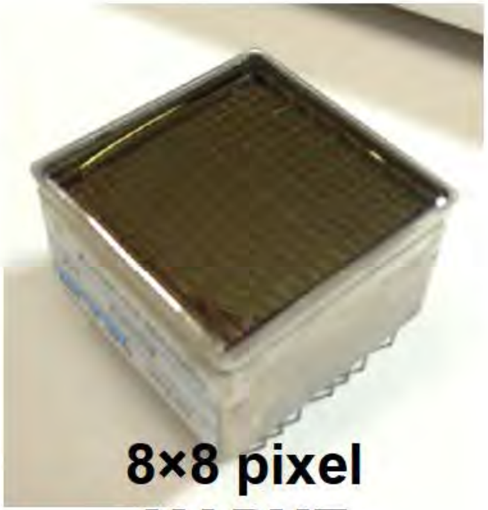


MAPMT + SPACIROC1

— *data*

— *fitting curve*

average S/N ratio = 35.8 dB

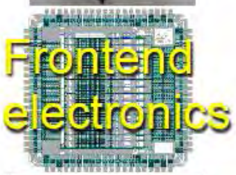


8×8 pixel MAPMT

SPACIROC can measure 1 p.e. for every MAPMT ch

Data Acquisition and Trigger System

137 GB/s (FS) 10^{-4} compression 10^{-3} compression 297 kbps 3 Gbyte/day



J. Bayer et al. ID 1256

FEE ASIC +FPGA	9EC	PDM Control Board FPGA Track Trigger	8PDM PhotoDetector Modules	Cluster Control Board DSP Fine Trigger	20CCB	FS Control Board MPU Operation Control
Count 316kch 1,233 EC		137 Boards		18 Boards		2 Boards

LVDS with SpaceWire (ECSS-E-50-12A)

Integrated test is progressing by TA-EUSO and EUSO-Balloon.

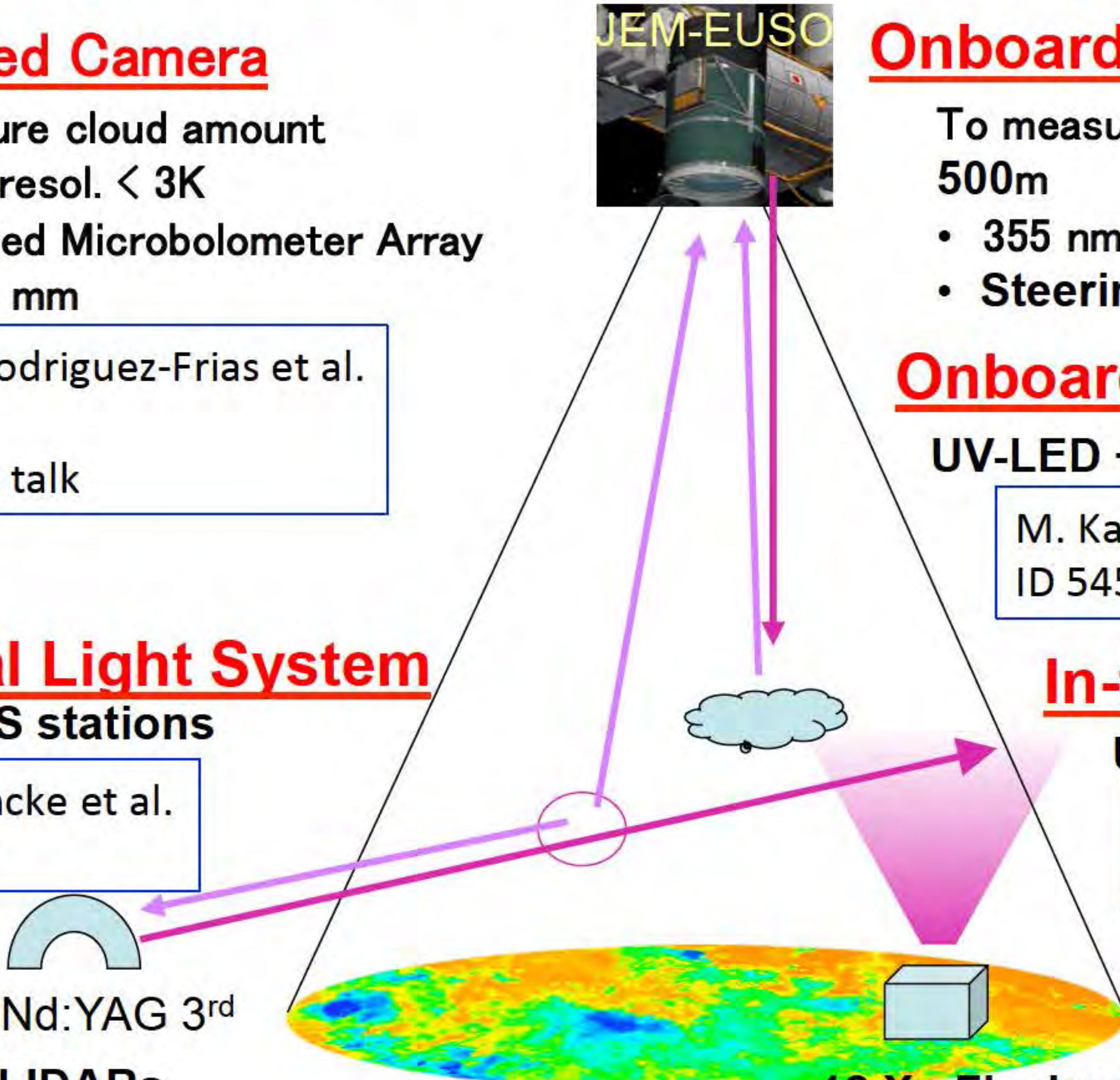
Calibration and Monitor by Onboard LIDAR, Infrared Camera and Global Light System

Infrared Camera

To measure cloud amount

- Temp. resol. < 3K
- Uncooled Microbolometer Array
- 10 –13 mm

M. D. Rodriguez-Frias et al.
ID 900
Today's talk



Onboard LIDAR

To measure cloud top altitude < 500m

- 355 nm, > 1Hz, 20 mJ/pulse
- Steering angle ±30°

Onboard calibration

UV-LED + integ. spheres

M. Karus, N. Sakaki et al.
ID 545

Global Light System

12 GLS stations

L. Wiencke et al.
ID 818

50mJ Nd:YAG 3rd

6 LIDARs

In-flight calibration

Use of moonlight

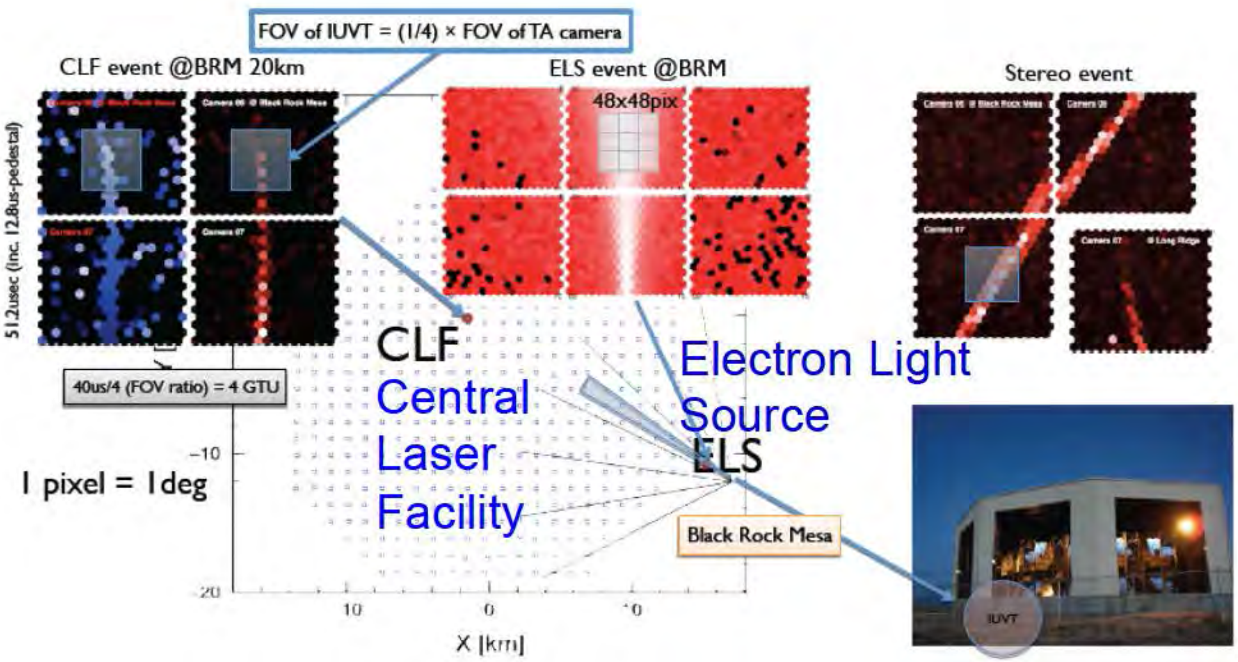
N. Sakaki et al.
ID 546

12 Xe Flashers

TA-EUSO

M. Casolino et al.
ID 1213
Today's talk

The first integrated test using various elements developed for the JEM-EUSO UV telescope at the Telescope Array site in Utah.

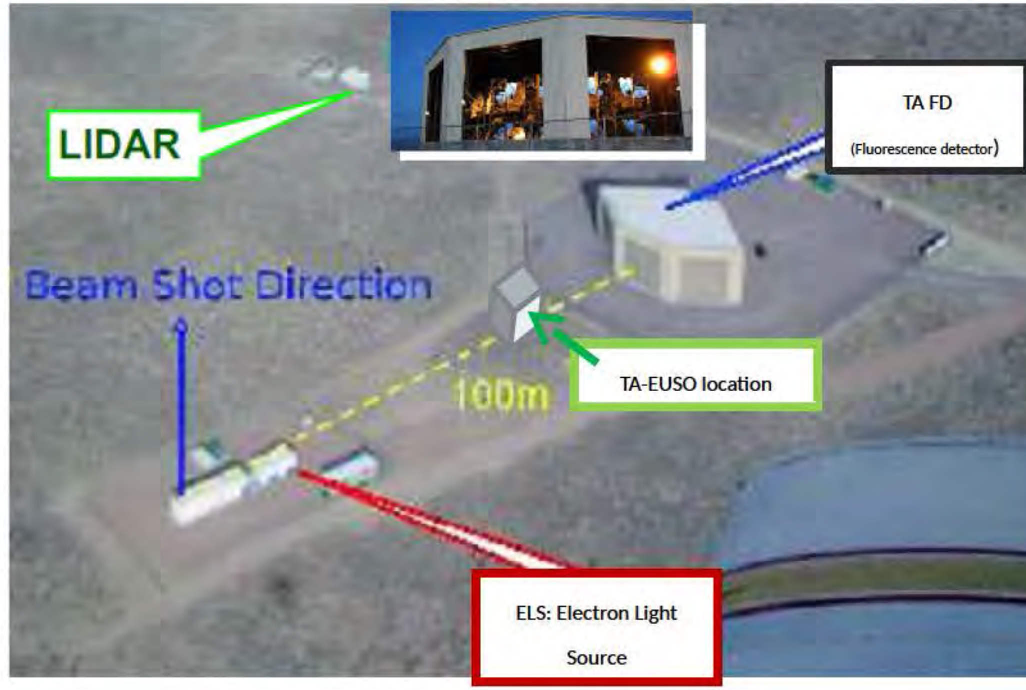


Light from Electron Light Source (ELS) and LIDAR of TA can be observed besides cosmic ray events.

Pathfinders: EUSO-TA

EUSO-TA: *Cross-Calibration tests at the Telescope Array site* in Utah in collaboration with the ICRR in Tokyo and the TA collaboration *Integration of the PDM in RIKEN completed; Campaign sommer 2013*

TA site, UTAH, Black Mesa



located at Black Rock Mesa FD Station

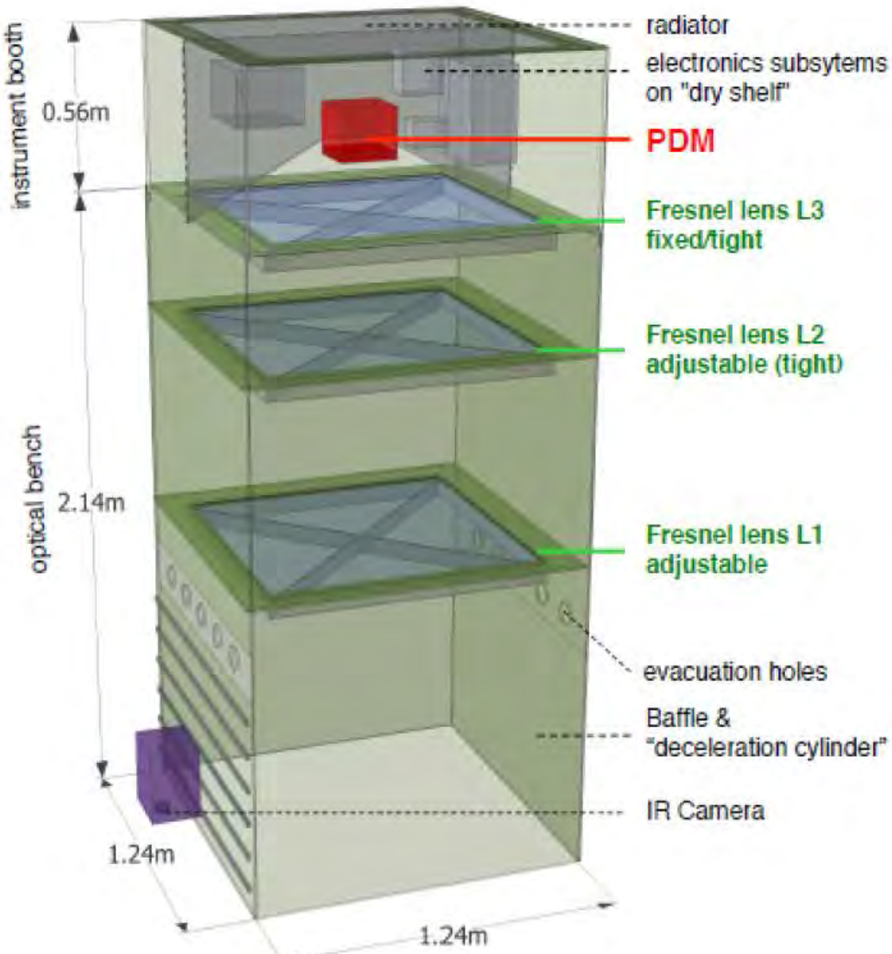
- *Electron Light Source at 100m*
- *Most nearby SD is at ~3.5 km*
- *Central Laser Facility ~21km*

EUSO-TA (2)

Lens have been installed, Focal Surface integration completed

EUSO-Balloon

P. von Ballmoos et al.
ID 1171



The first integrated test using various elements developed for the JEM-EUSO UV telescope from a high altitude of ~40km.

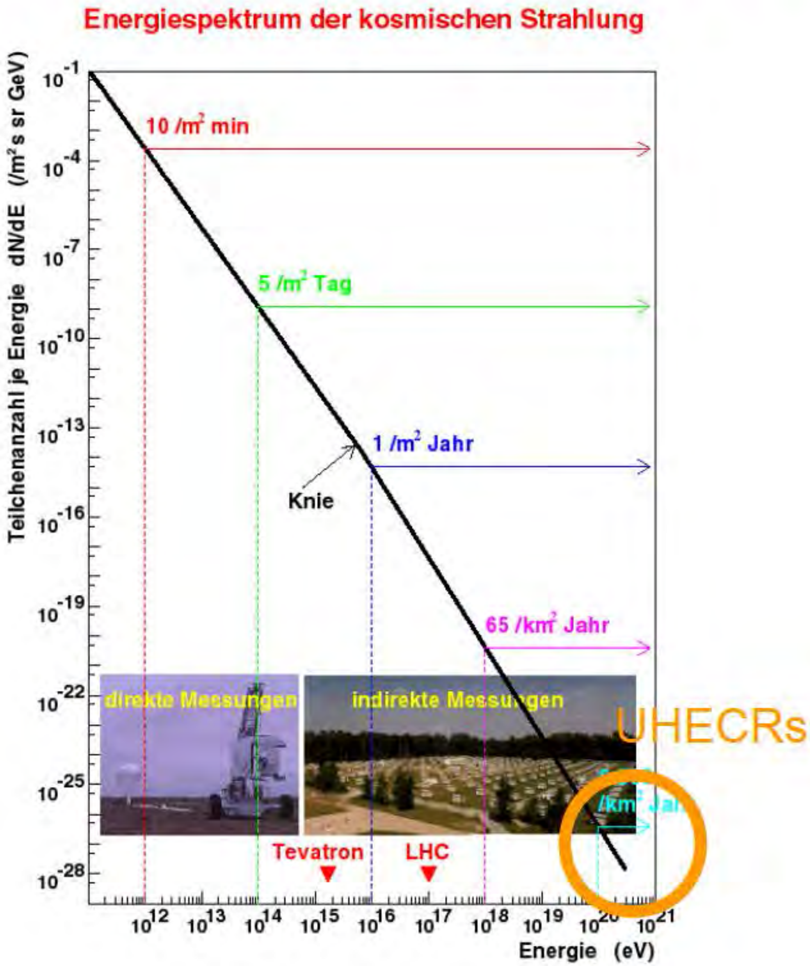
IR camera is also used.

0.2-0.3 CR events/10hr
$E \geq 2 \times 10^{18}$ eV

Launch : 2014

Cosmic Ray Energy Spectrum

- The differential Cosmic Ray spectrum is described by a steep power law with a $E^{-2.75}$ decline.
- Low-energy cosmic rays can be directly measured.
- High-energy cosmic rays are measured through their air showers.



To understand the sources of cosmic rays …

- we need to know their
  - arrival direction
  - energy
  - and mass
- we need large statistics
  - large effective areas and high duty cycles

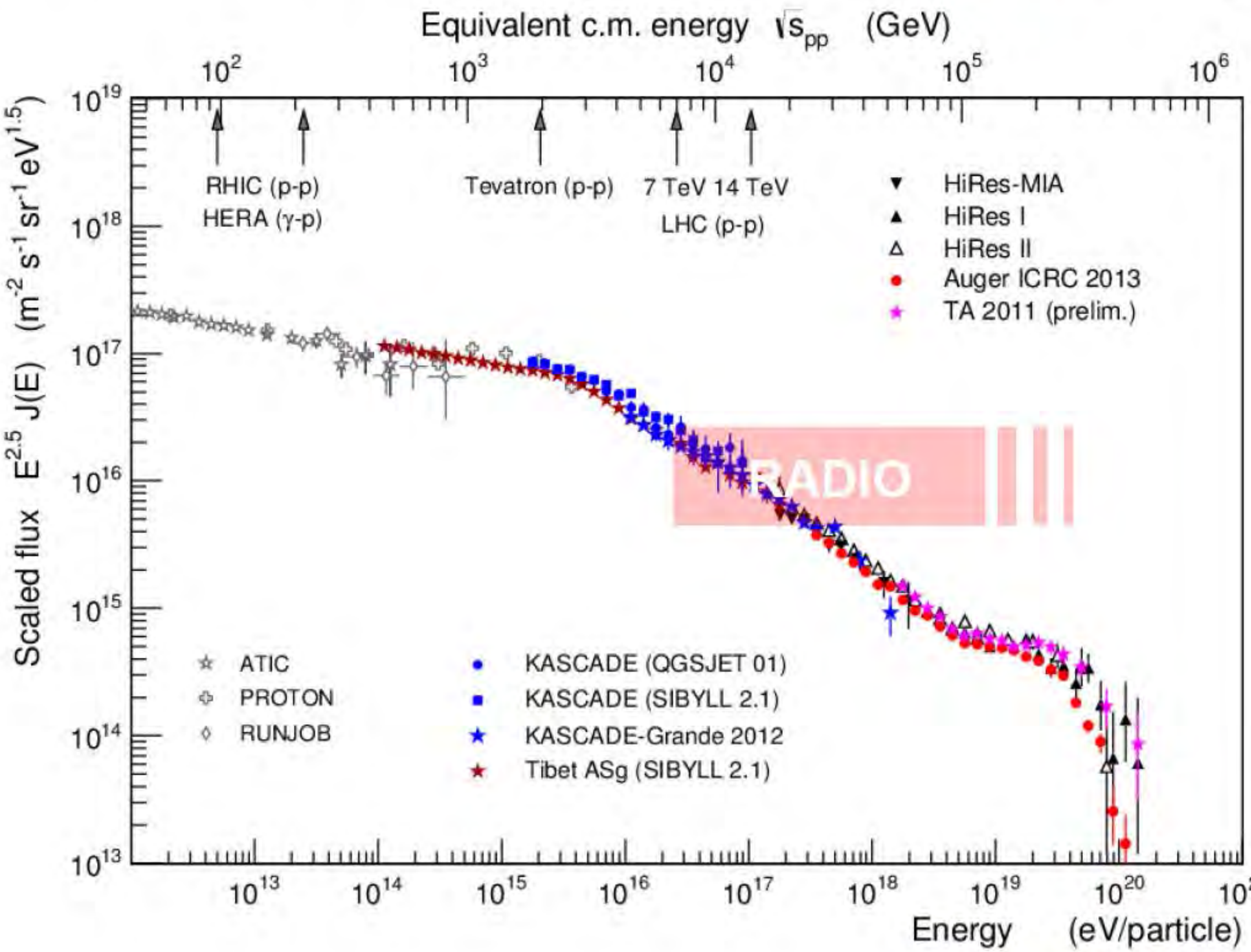
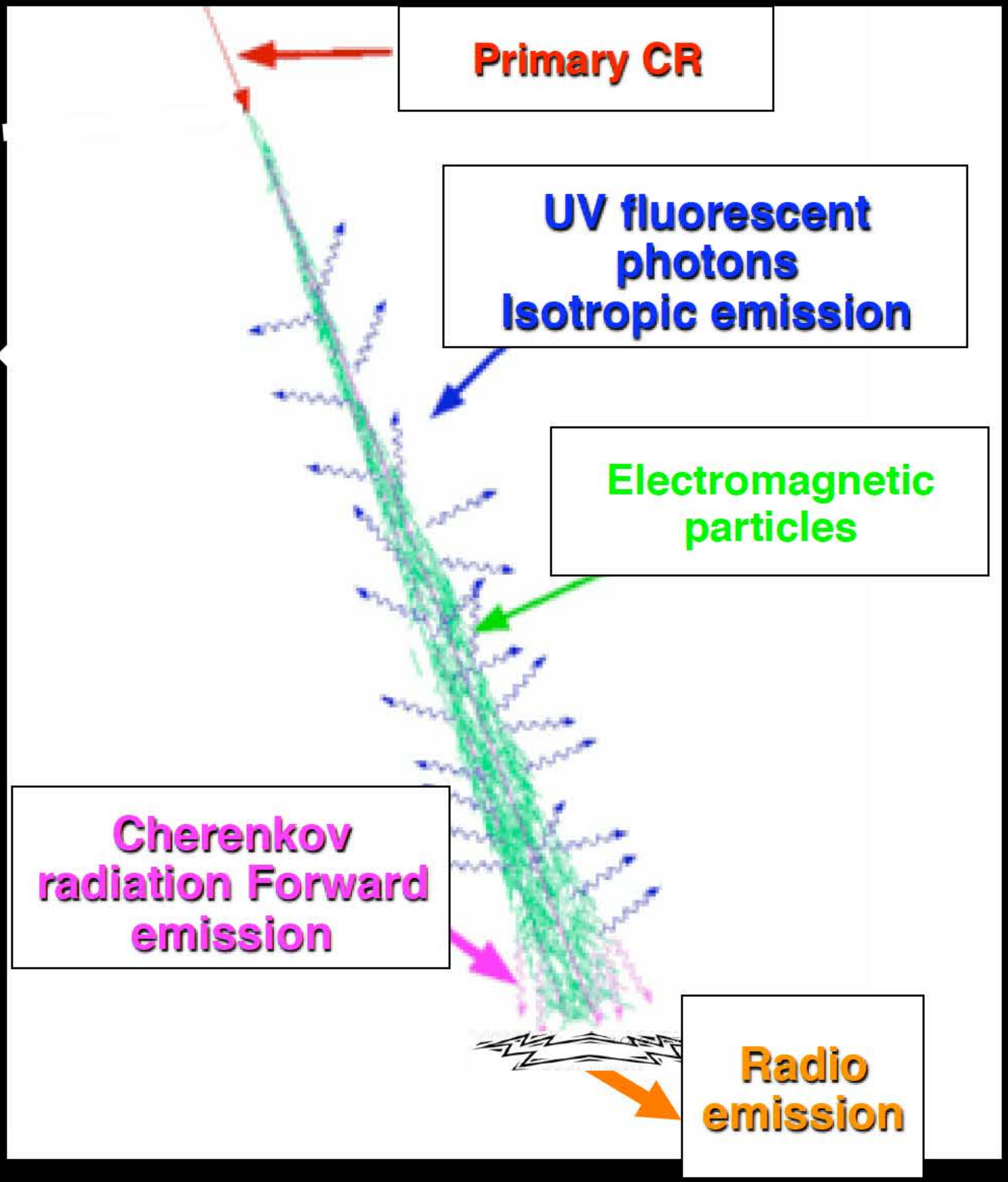


diagram by R. Engel

RADIATION FROM SHOWER DEVELOPMENT



Cherenkov radiation: Electrons and positrons in the shower travel faster than the speed of light in air and emit Cherenkov radiation, mostly in the forward direction

Fluorescence radiation: The passage of air shower e.m. particles in atmosphere results in the excitation of the gas molecules (mostly nitrogen). Some of this excitation energy is emitted in the form of isotropic visible and UV radiation.

Radio emission: Air shower electrons and positrons are deflected in the Earth's magnetic field. Because of their relativistic velocities, they emit synchrotron radiation, beamed very sharply downwards, at radio frequencies below 100 MHz. Many sparkles together produce a bright radio flash

Limitations of current detection techniques

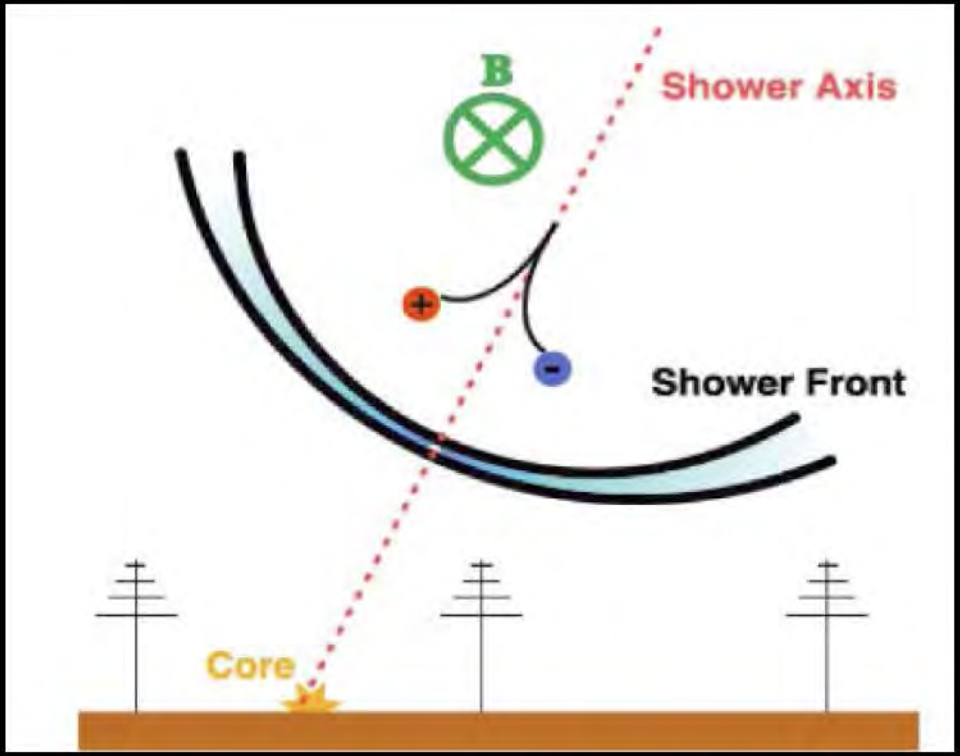
- particle detectors
  - sample showers only at a particular atmospheric depth
  - suffer from uncertainties in hadronic interaction models (muons)
- fluorescence detectors
  - allow calorimetric energy measurement
  - directly yield mass-sensitive depth of shower maximum (Xmax)
  - but have only ~10% duty cycle

The promises of radio detection

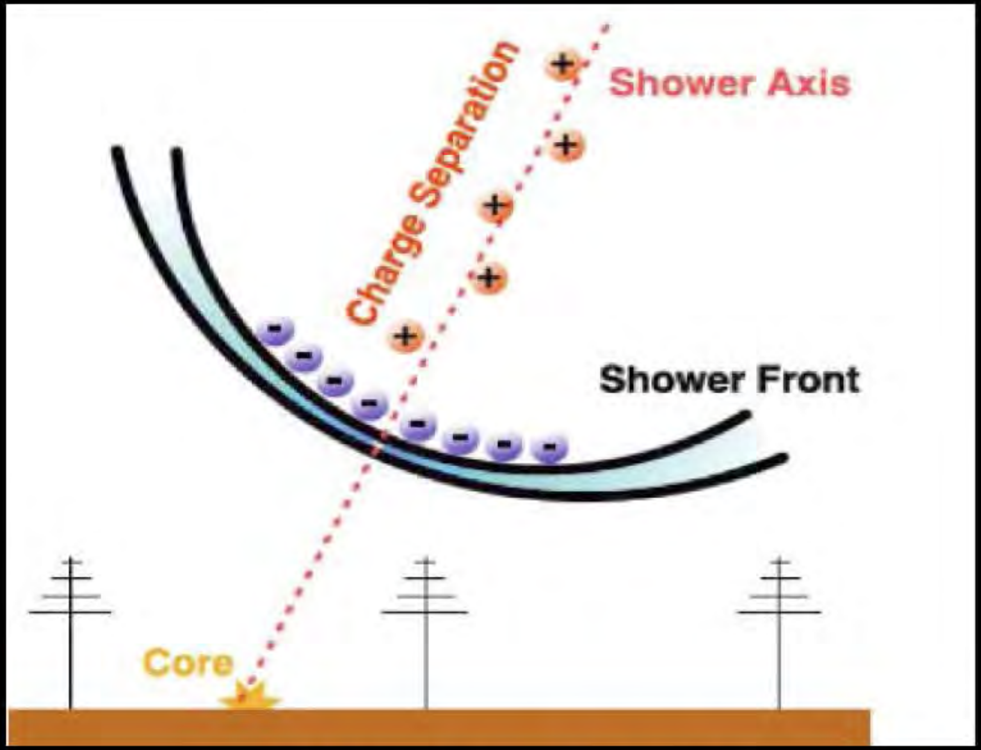
- information complementary to surface particle detectors
  - pure electromagnetic component
- calorimetric energy measurement
- near 100% duty cycle (cf. 10% of optical fluorescence detectors)
- Xmax sensitivity
- high angular resolution (< 0.5°)
- simple (potentially cheap) detectors
- *how well does it all work in practice and on large scales?*

Tim Huege <tim.huege@kit.edu>

RADIO EMISSION FROM EAS

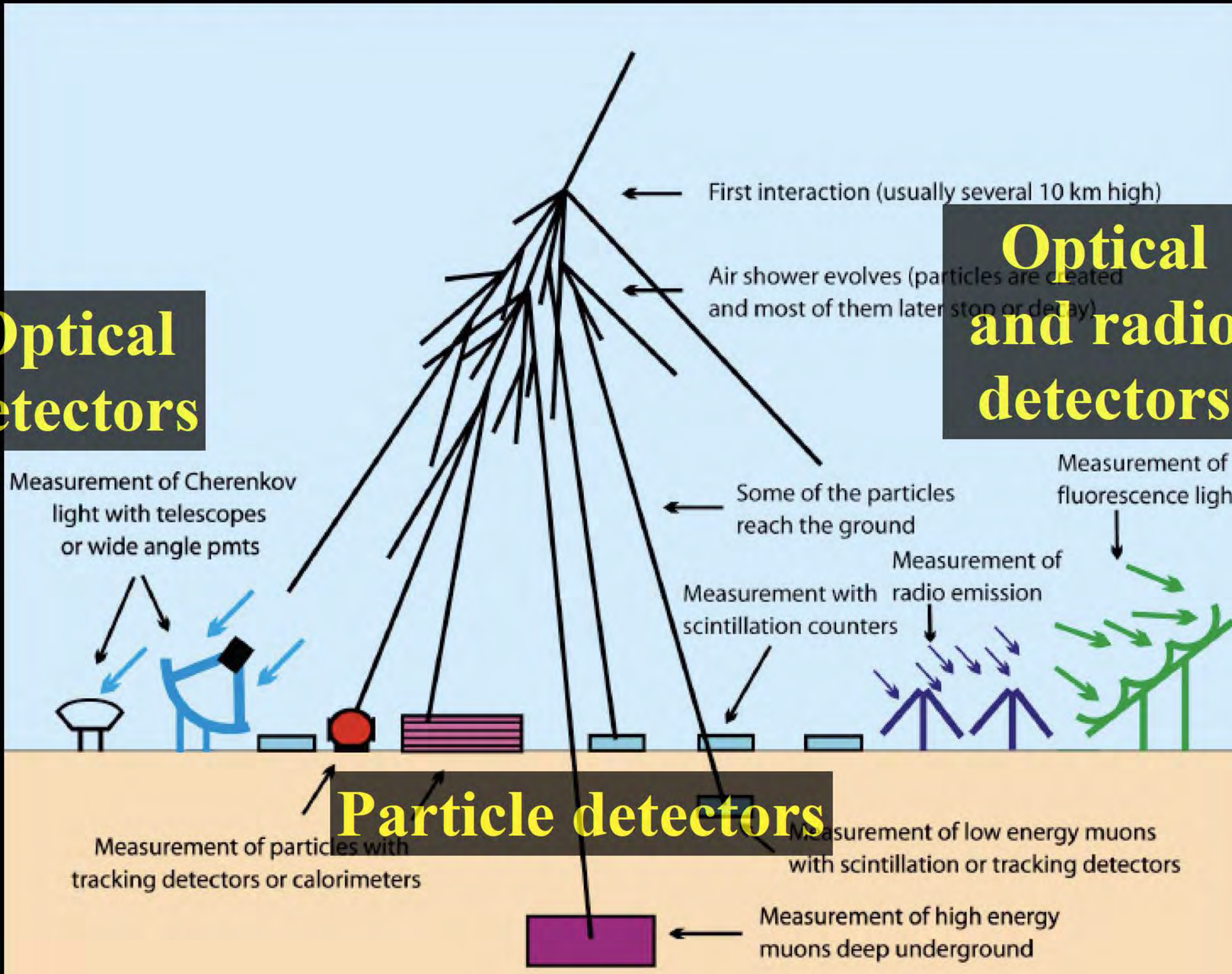


Geomagnetic effect:
deflection of charged particles in Earth's magnetic field (B). Electric current develops when the plasma moves through B. Radiation emitted by time varying electric current



Askarian effect:
radio emission in the form of Cherenkov radiation. Due to the annihilation of positrons an excess of negative charge is created, producing Cherenkov radiation as it moves through the medium (air)

DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

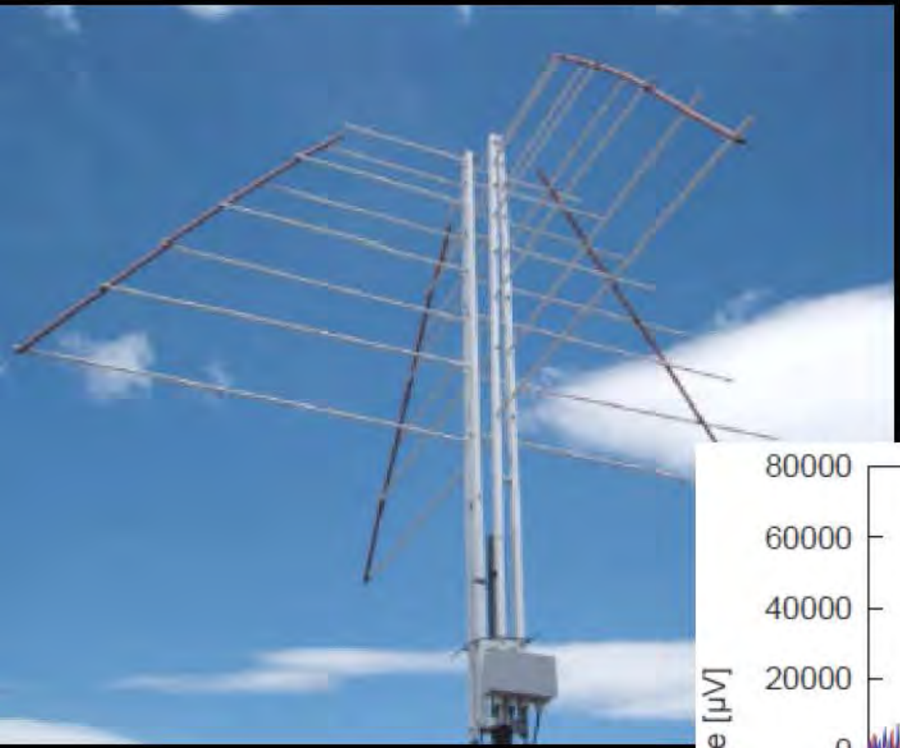


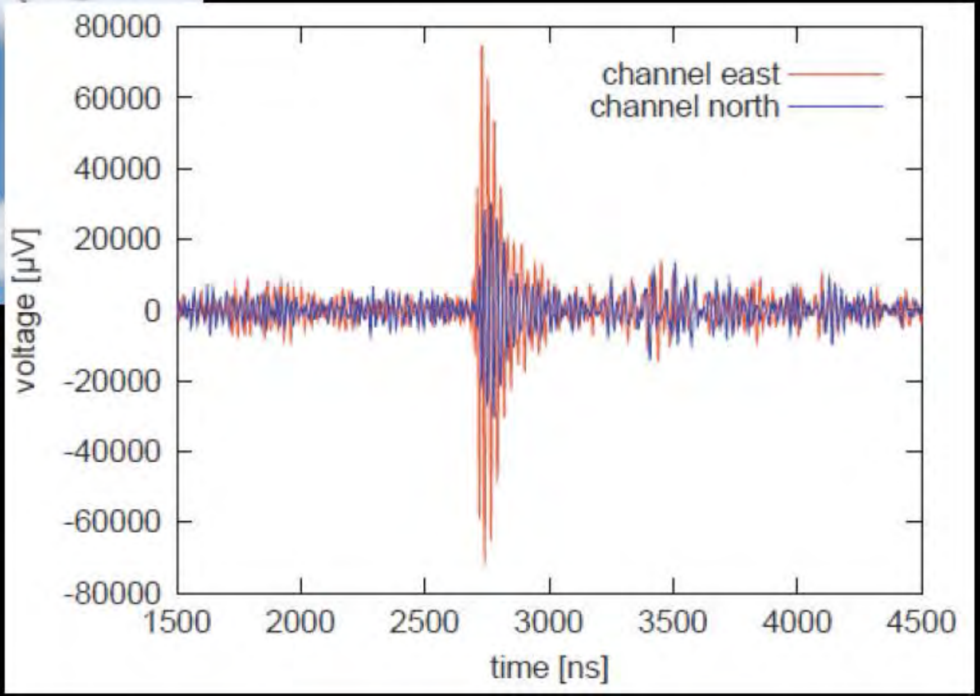
DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

Radio detectors (100% duty cycle)

The measurement of the radio signal requires a detection device, i.e, a radio antenna. Typically, one detector station consists of two antennas that are aligned perpendicular to each other, to allow for a measurement of the signal in two polarisations (EW-NS). Antennas can be triggered by traditional EAS arrays, or self-trigger

ANTENNA TRIGGERED BY PARTICLE DETECTORS

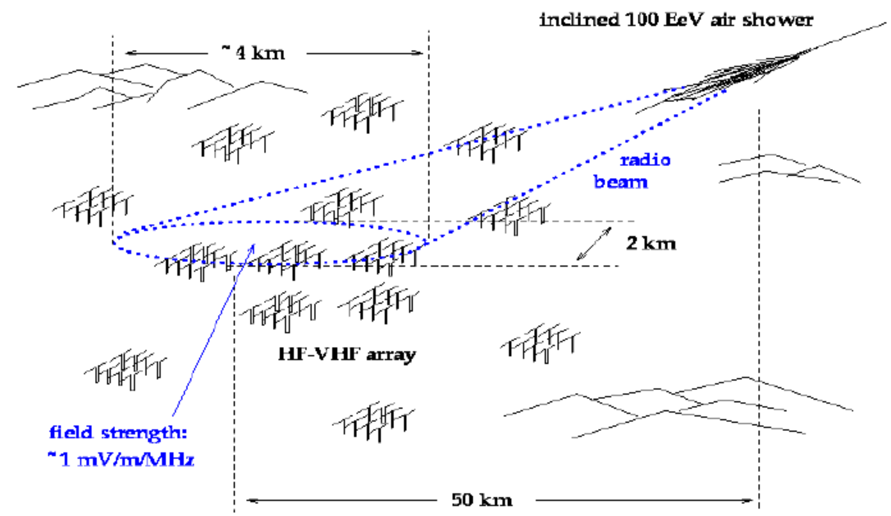




SELF-TRIGGERED ANTENNAS

Advantages of Radio Air Showers

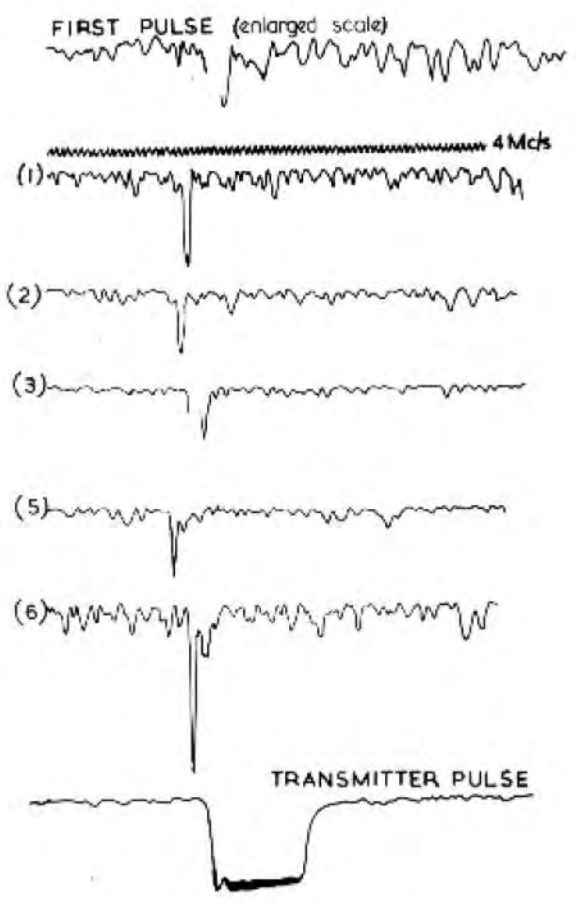
- Particle detectors on ground only measure a small fraction of electrons produced
- Height of cosmic ray interaction depends on energy
- Energy calibration is greatly improved by additional information (e.g., Cerenkov)
- Radio could
  - Observe 24hrs/day
  - See shower maximum and possibly evolution of shower
  - Coherent emission reveals shape



Radio measurements are usually triggered by particle detectors

Radio Emission from Cosmic Ray Air Showers: History

- First discovery: Jelley et al. (1965), Jodrell Bank at 44 MHz.
- Theory papers by Kahn & Lerche (1968) and Colgate (1967)
- Firework of activities around the world in the late 60ies & early 70ies.
- In the late 70ies radio astronomy moved to higher frequencies and also CR work ceased.

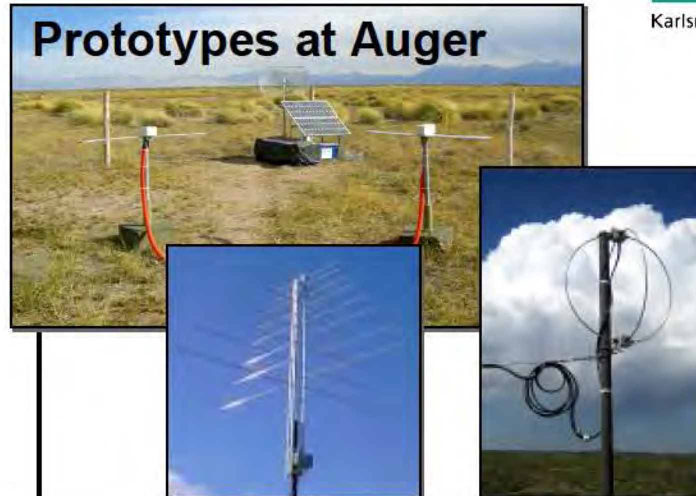


Jelley et al. (1965)

First-Generation modern MHz experiments

LOPES

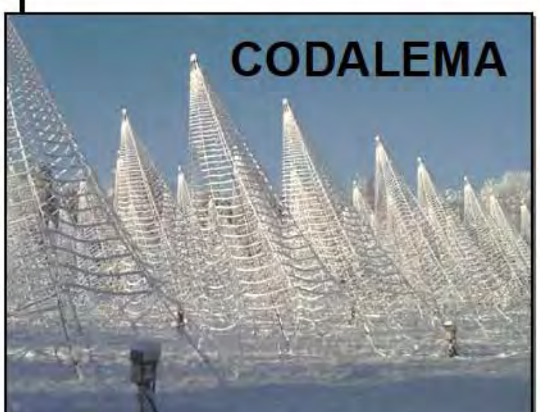
Prototypes at Auger



2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	...	...

Falcke & Gorham propose „geosyn-chrotron approach"

CODALEMA



TREND

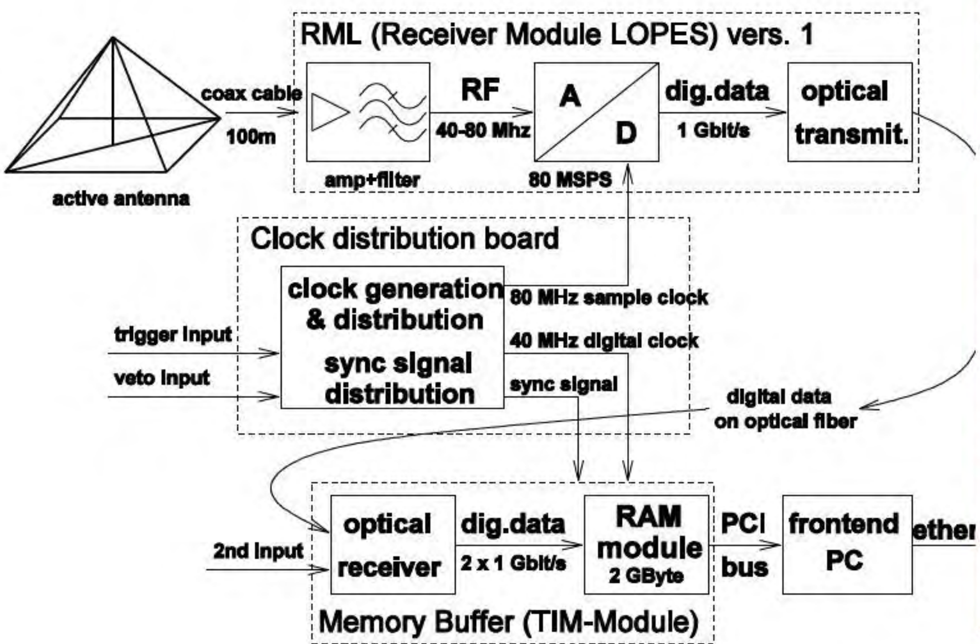
YAKUTSK

LOFAR

- interferometer for the frequency range of 10 - 200 MHz
- array of 100 stations of 100 dipole antennas
- baselines of 10m to 400 km
- fully digital: received waves are digitized and sent to a central computer cluster
- Ideal for observing transient events

Hardware of LOPES10

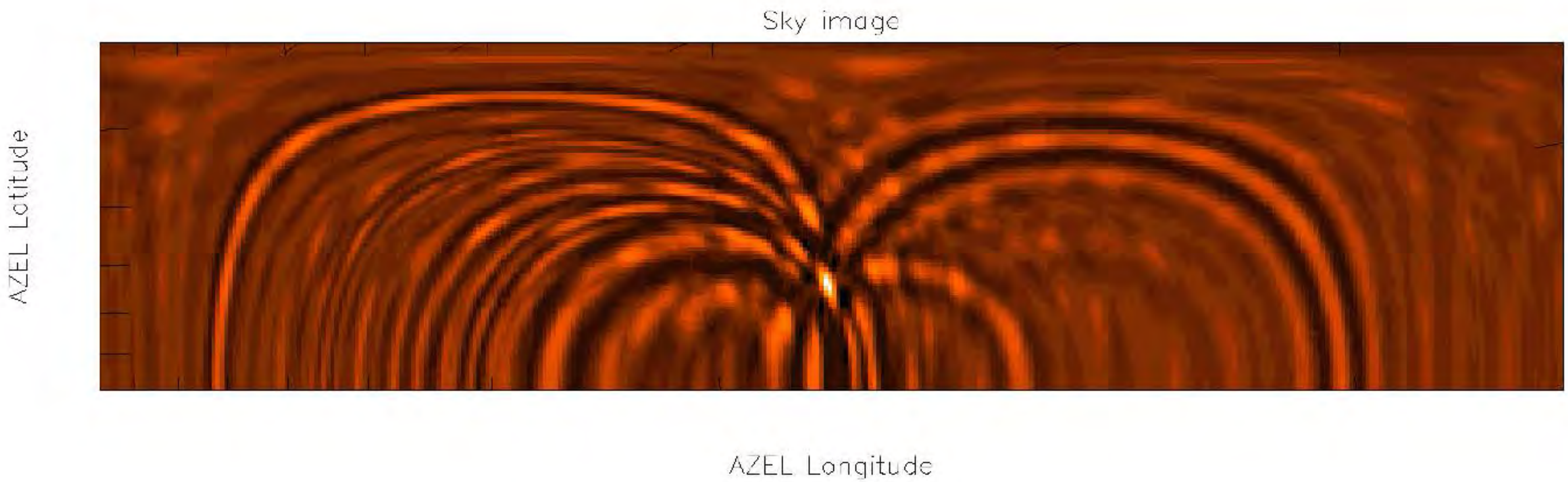
LOPES-Antenna



KASCADE

- The KASCADE experiment is situated on the site of Forschungszentrum Karlsruhe in Germany.
- It measures simultaneously the electromagnetic, muonic and hadronic components of extensive air showers.
- The goal of KASCADE is the determination of the chemical composition of primary particles of cosmic rays around and above the "knee,, (10^{15}-10^{16} eV)

Solar Burst Oct. 28 All-Sky Dirty Map (AzEl)



Solar Burst

Integration: 1 ms

Frequency: 45-75 MHz

Bandwidth: 30 MHz

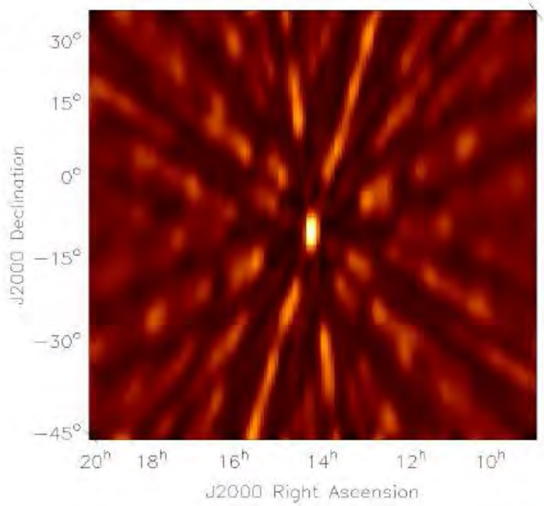
Antennas: 8

Resolution: ~3°

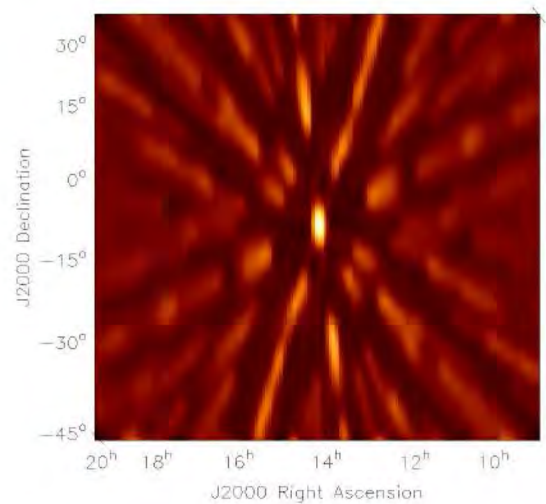
Location: Karlsruhe (research center)

Correlation, Imaging, and Cleaning with aips++

dirty map



simulated map



Solar Burst

Integration: 1 ms

Frequency: 45-75 MHz

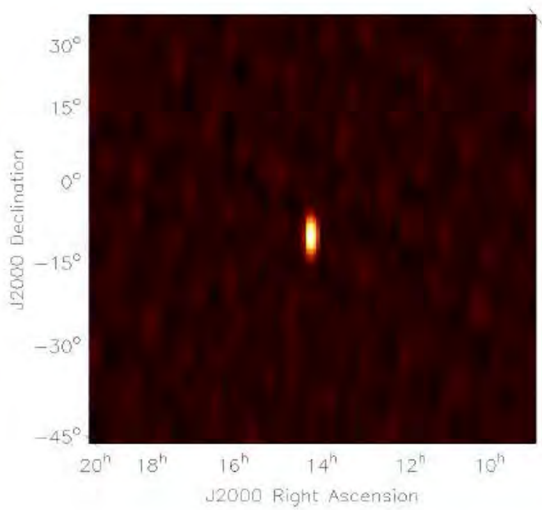
Bandwidth: 30 MHz

Antennas: 8

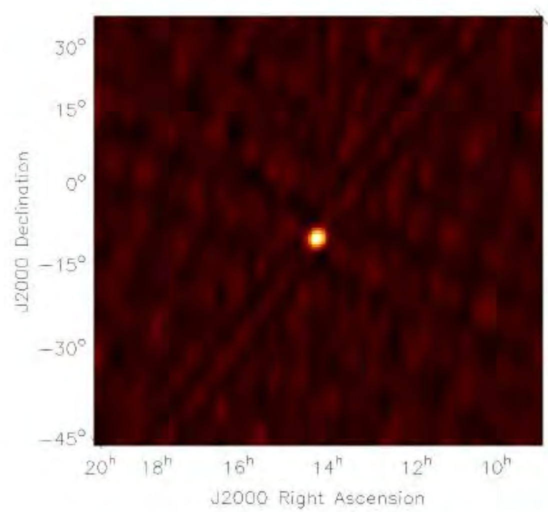
Resolution: ~3°

Location: Karlsruhe (research center)

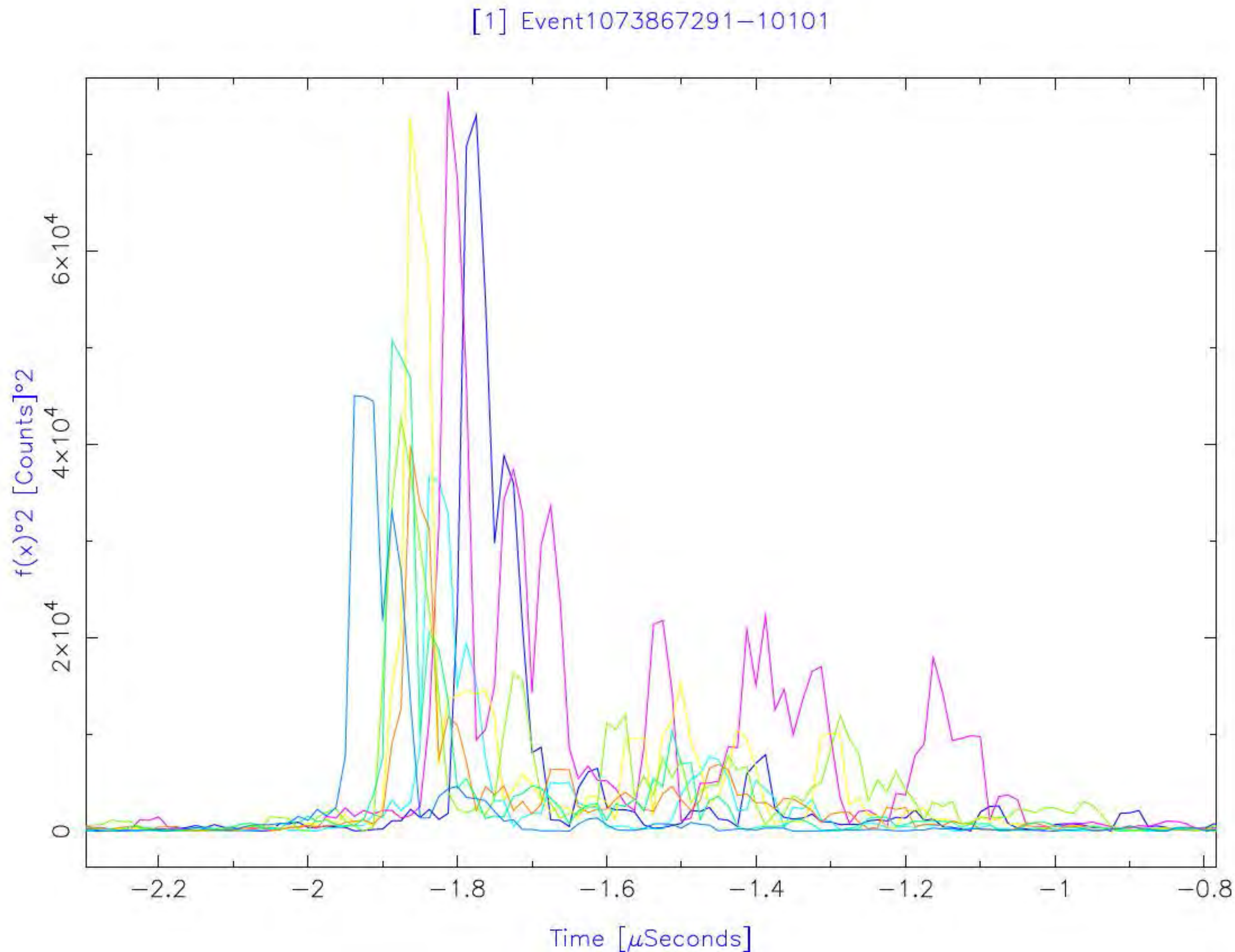
cleaned map



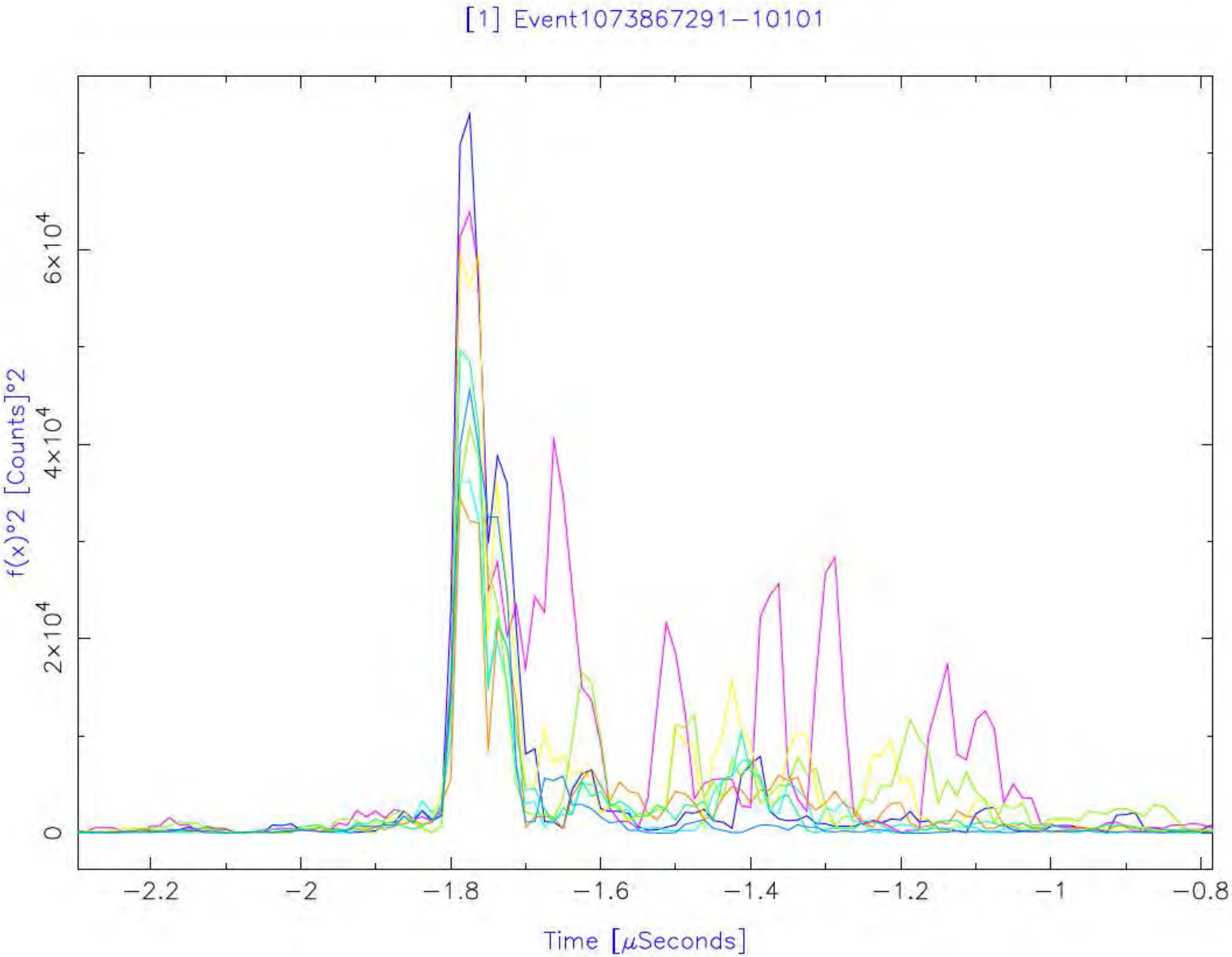
circular beam



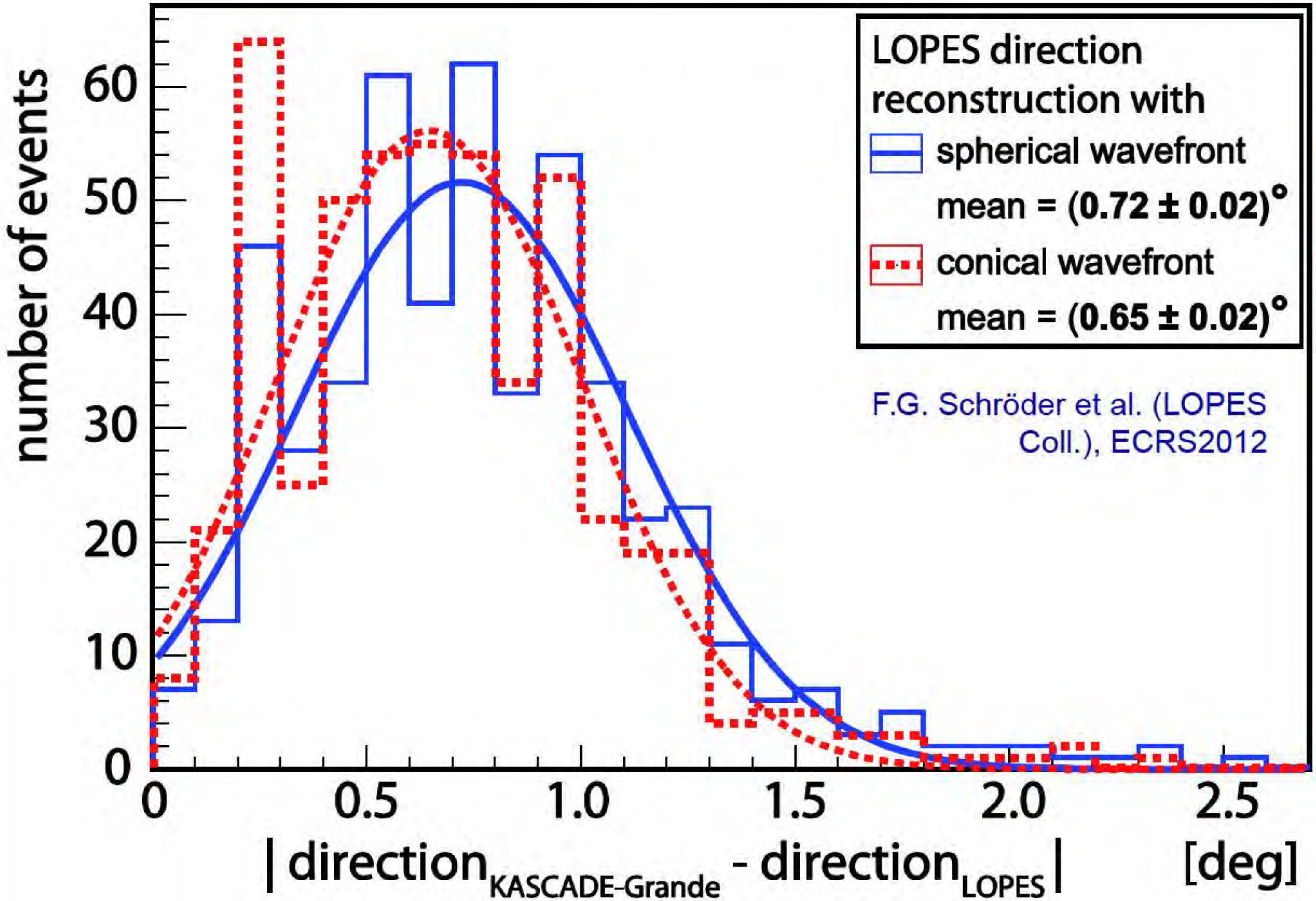
Bright Event Power

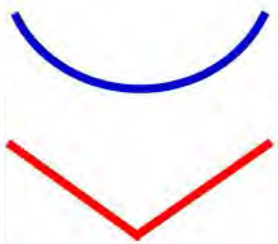


Bright Event
Power after Beamforming



Accuracy of direction reconstruction

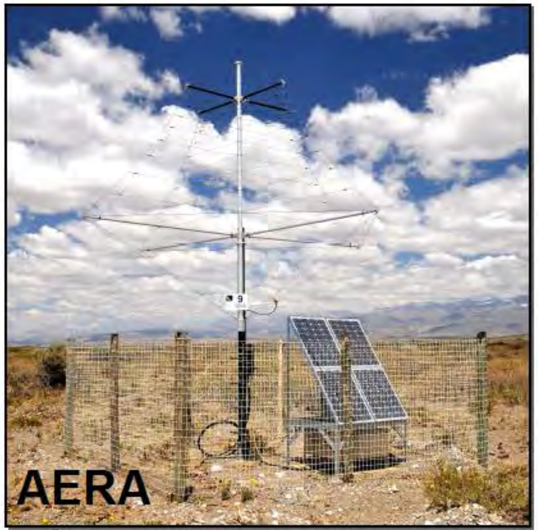




- bigger arrays should do even better

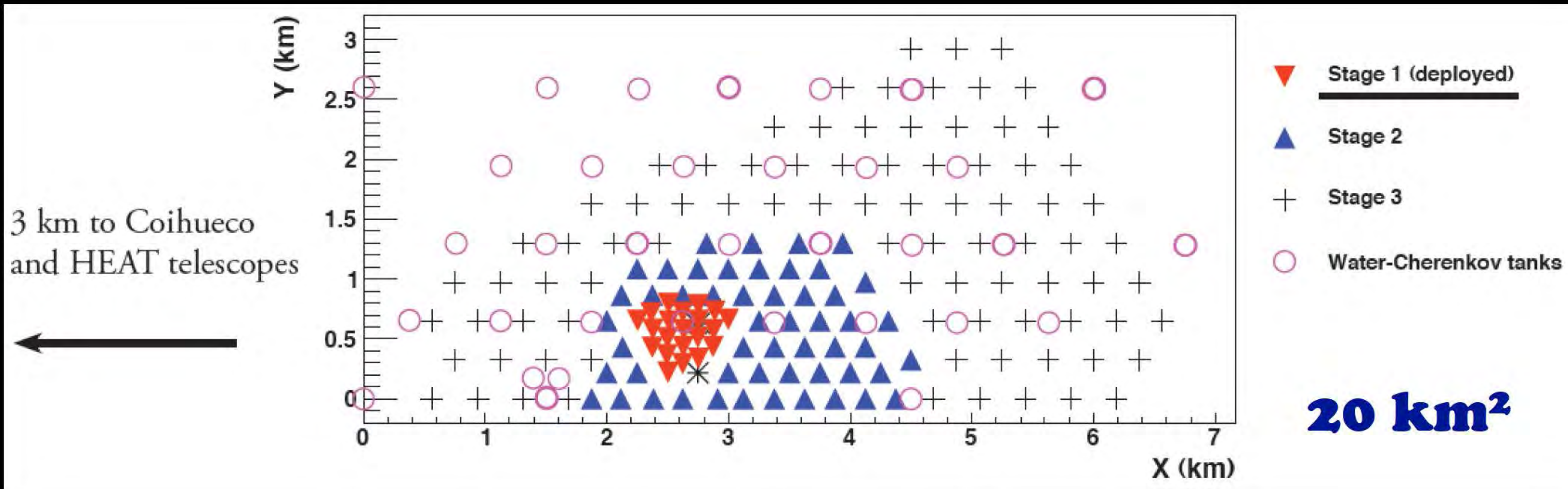
Second-Generation modern MHz experiments

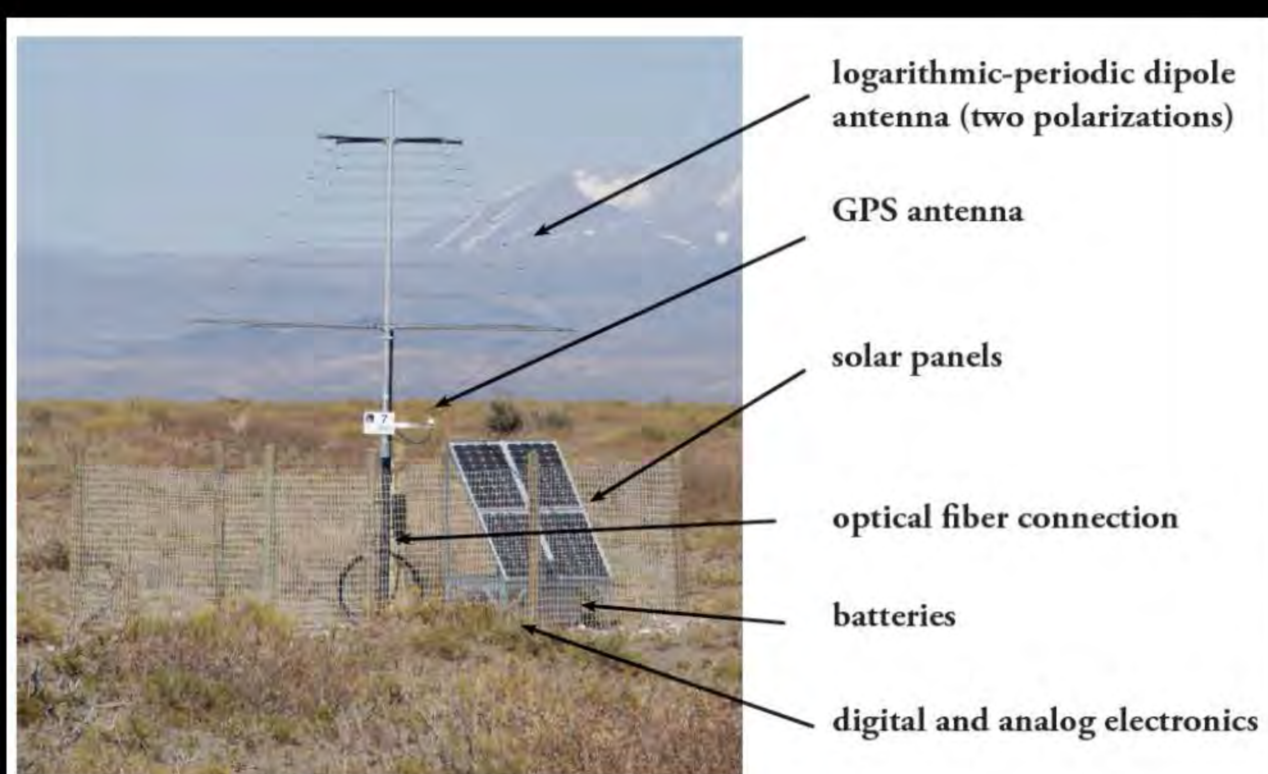
Karlsruhe Institute of Technology



2010	2011	2012	2013

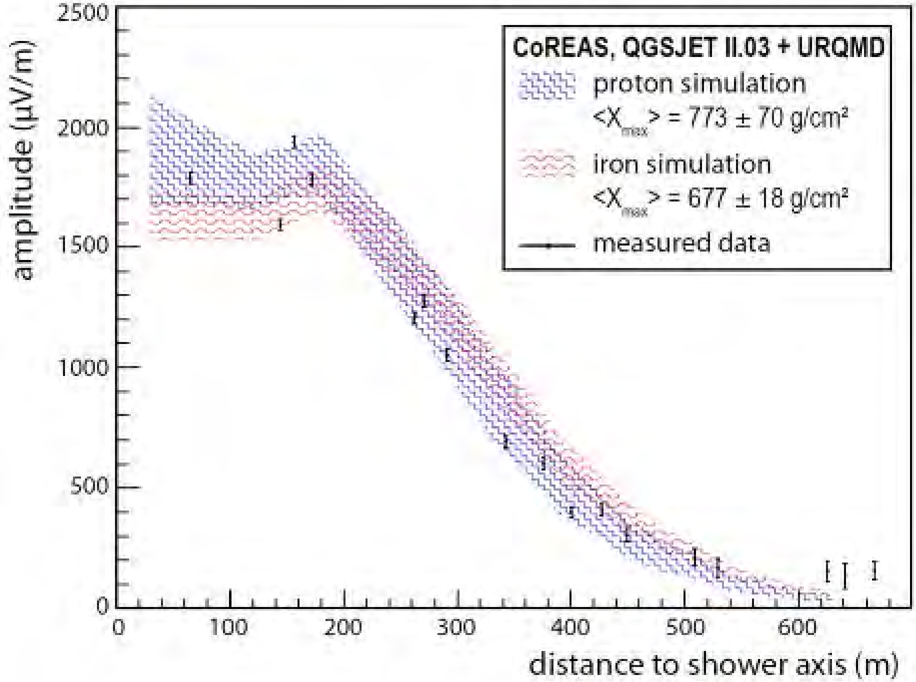
AUGER EXTENSION TO RADIO-TECHNIQUES: AERA

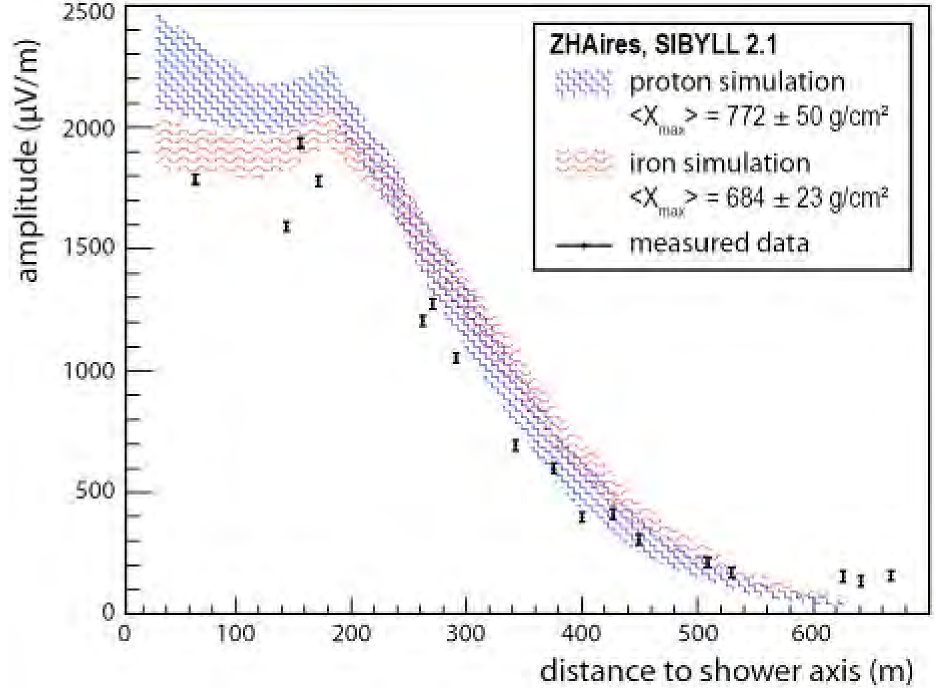




- Foreseen layout: 160 antennas over 20 km2 (spacing 250-350 m)
- Currently: 21 150 m spaced antennas (since Sept 2010)
- Aim: "FD-like" detector (EAS longitudinal development), but with > 90% d.c.
- Energy threshold: $\approx 10^{17}$ eV

Comparison of simulations with AERA data

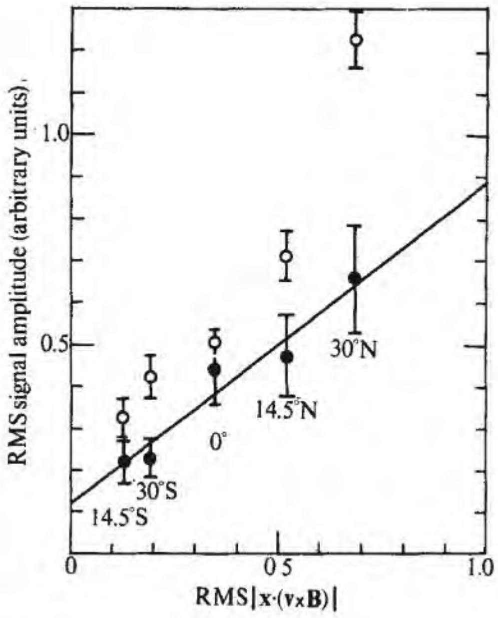


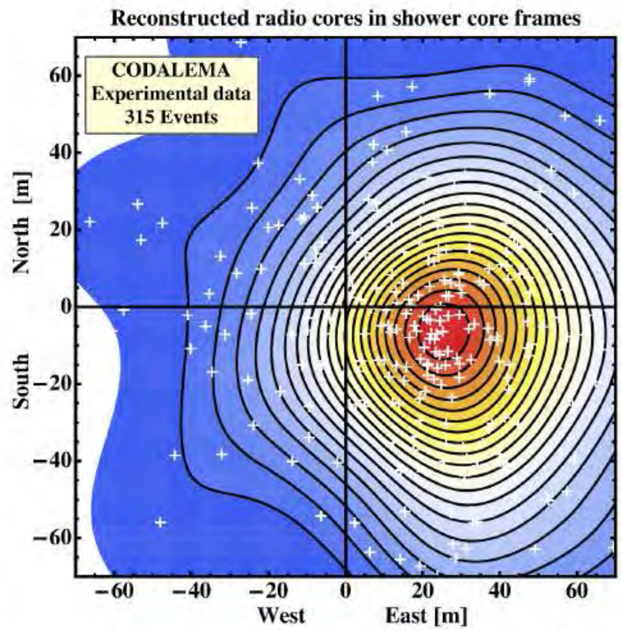


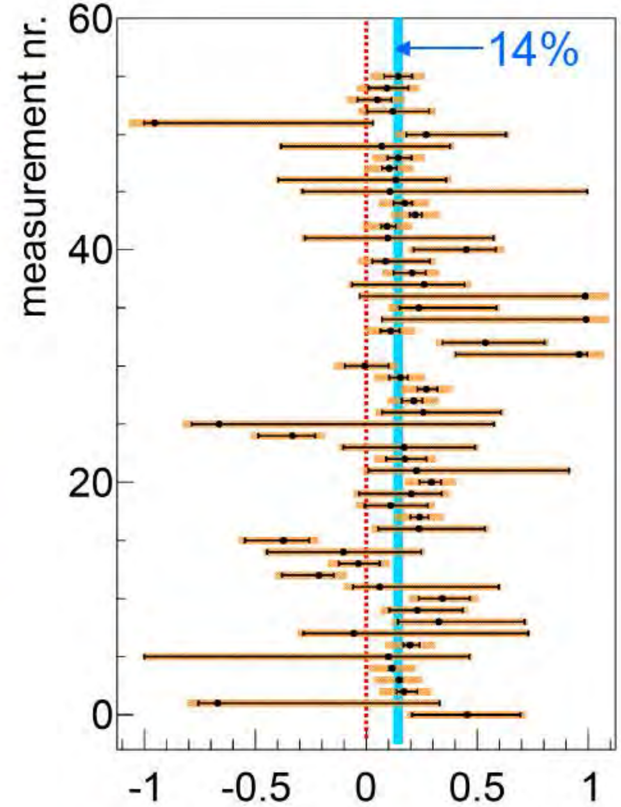
- AERA provides detailed, well-calibrated event data
- simulations can reproduce measurements
  - absolute amplitude
  - complex LDF

Pierre Auger Collaboration, ICRC2013, id #899

Geomagnetic seen by all – but charge excess?







- observation of a non-geomagnetic emission component of 14 ± 6% at 22.5 MHz

Prescott, Hough, Pidcock, Nature (1971)

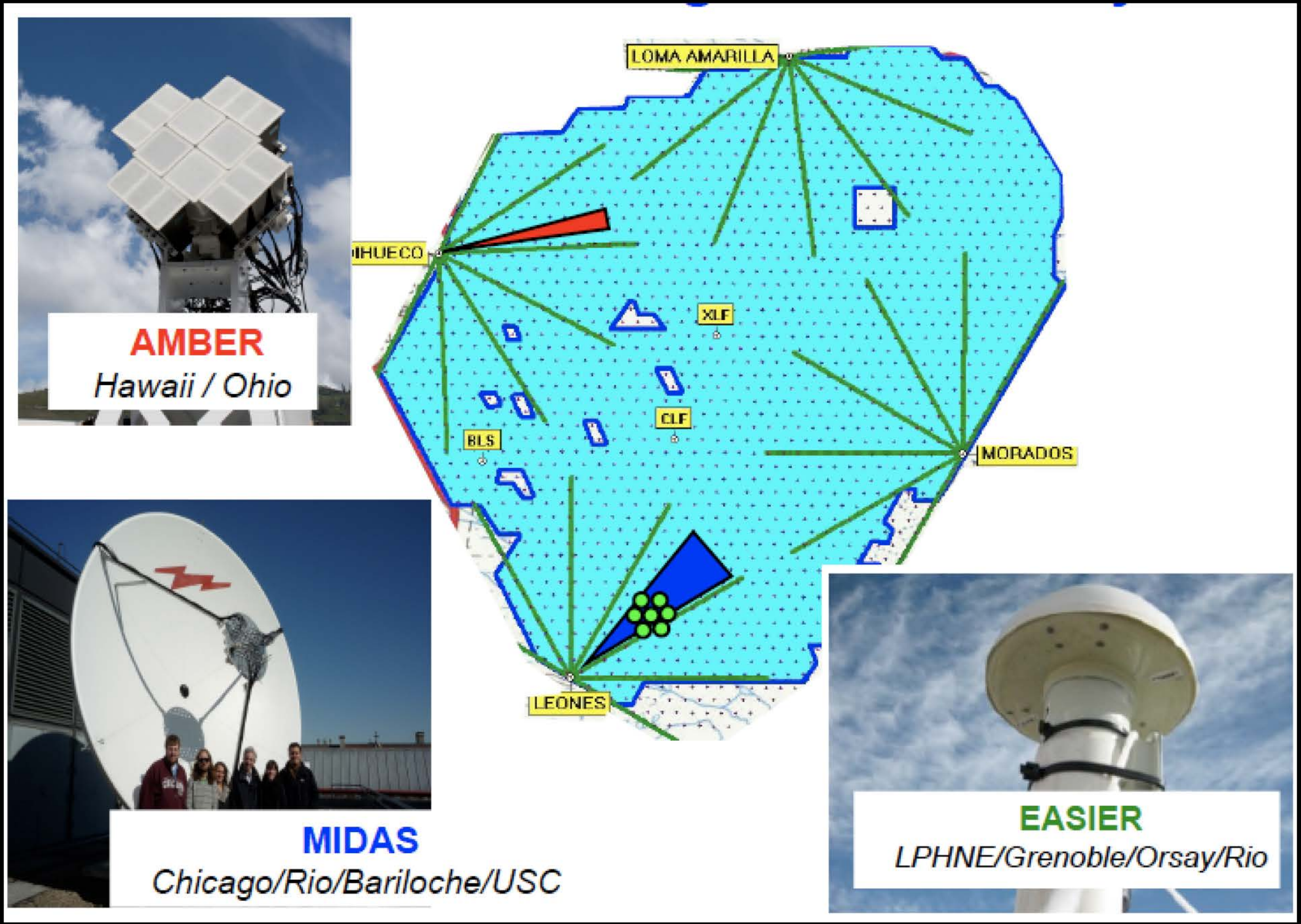
- CODALEMA reports core-shift ↔ east-west asymmetry ↔ charge-excess at ICRC 2011

V. Marin et al. (CODALEMA Coll.), ICRC2011

- AERA quantifies radial component to 14 ± 2%

Pierre Auger Coll., ICRC2013, id #661

GHz R&D AT THE PIERRE AUGER OBSERVATORY



Credit Pedro Facal

ICRC 2013
33rd International Cosmic Ray Conference
2-9 July 2013 – Rio de Janeiro – Brazil
THE ASTROPARTICLE PHYSICS CONFERENCE

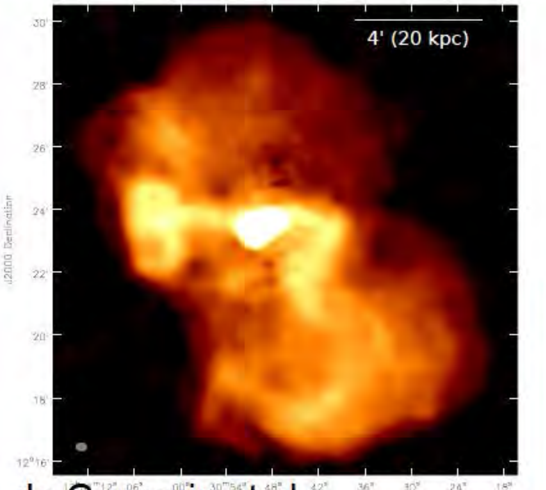
The LOFAR Radio Telescope as Cosmic-Ray Detector

LOFAR key science project Cosmic Rays:

Stijn Buitink, Arthur Corstanje, J. Emilio Enriquez, Heino Falcke, Wilfred Frieswijk, Jörg R. Hörandel, Maria Krause, Anna Nelles, Satyendra Thoudam, Pim Schellart, Olaf Scholten, Sander ter Veen, Martin van den Akker *for the LOFAR Collaboration*

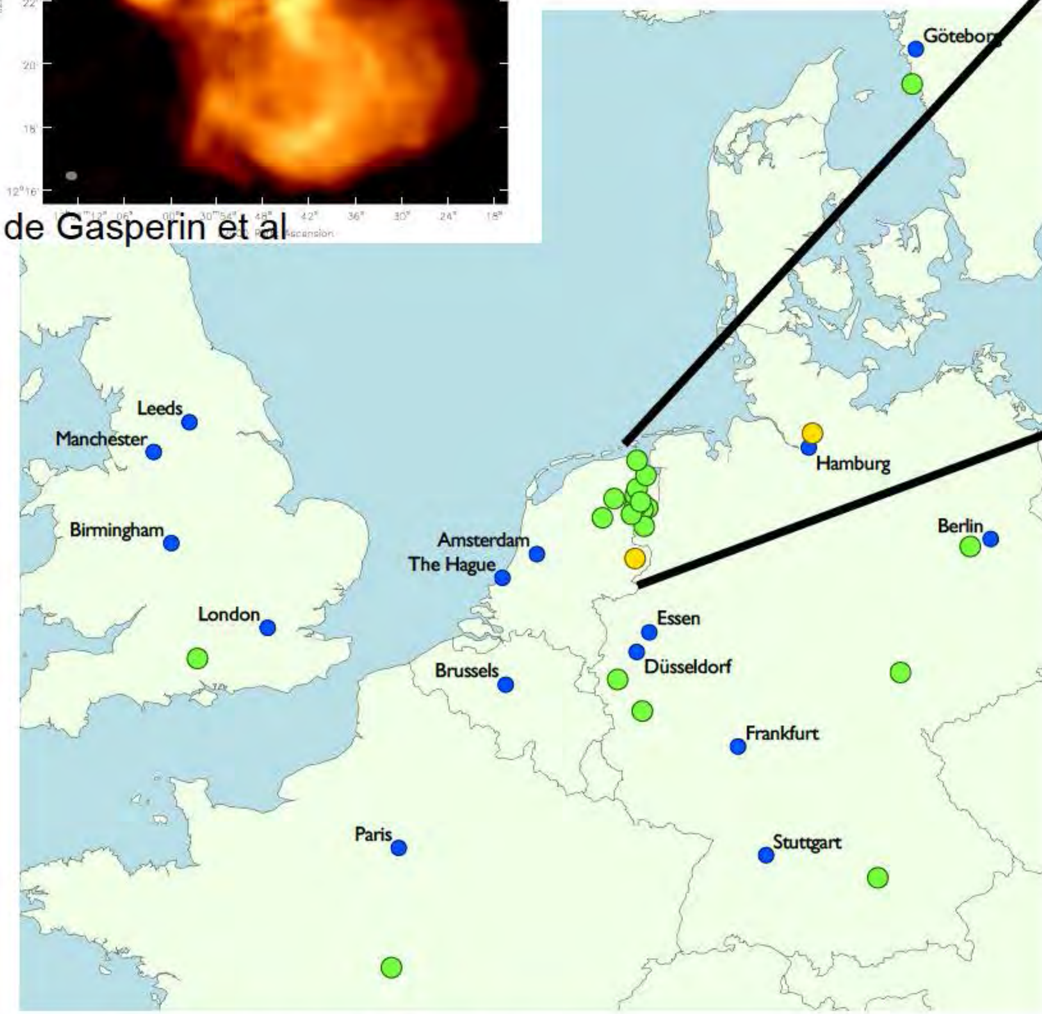
LOFAR

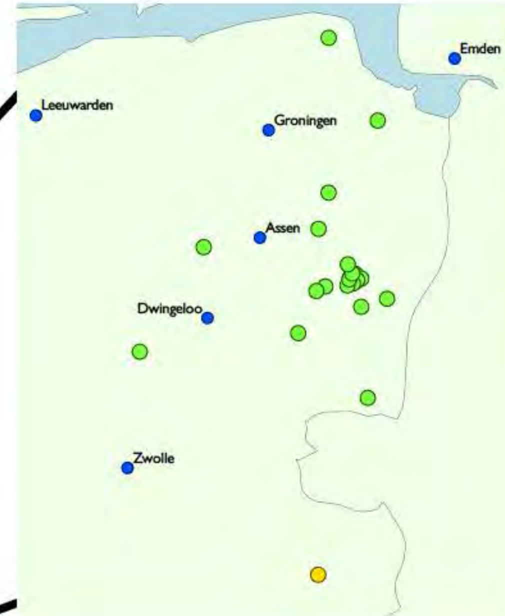
The Low Frequency Array



de Gasperin et al

LOFAR





Stations:

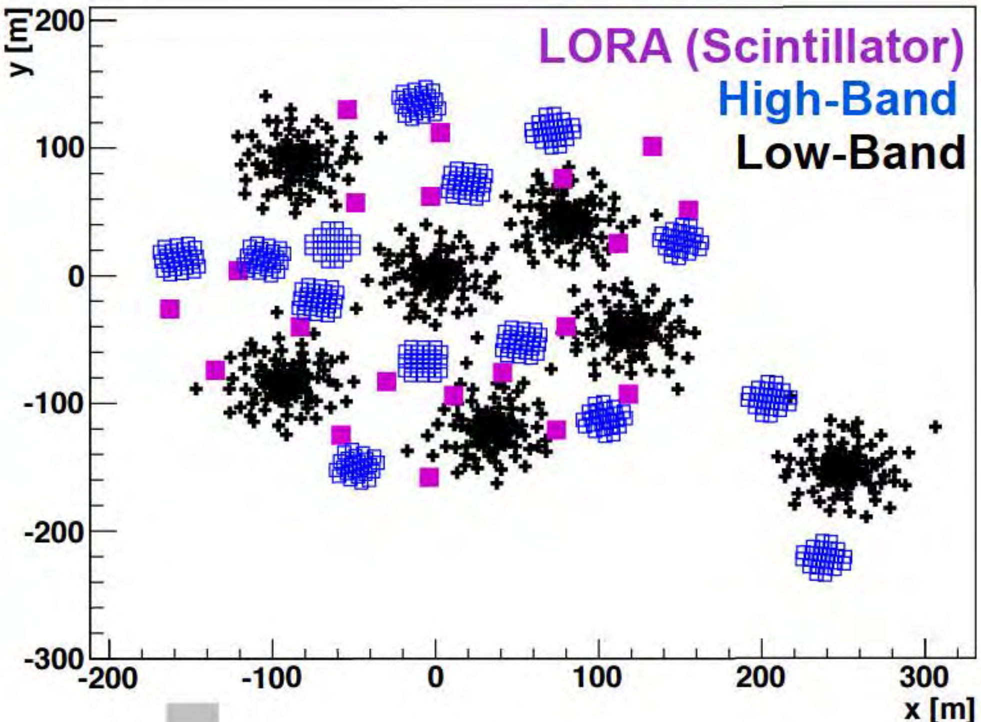
operating

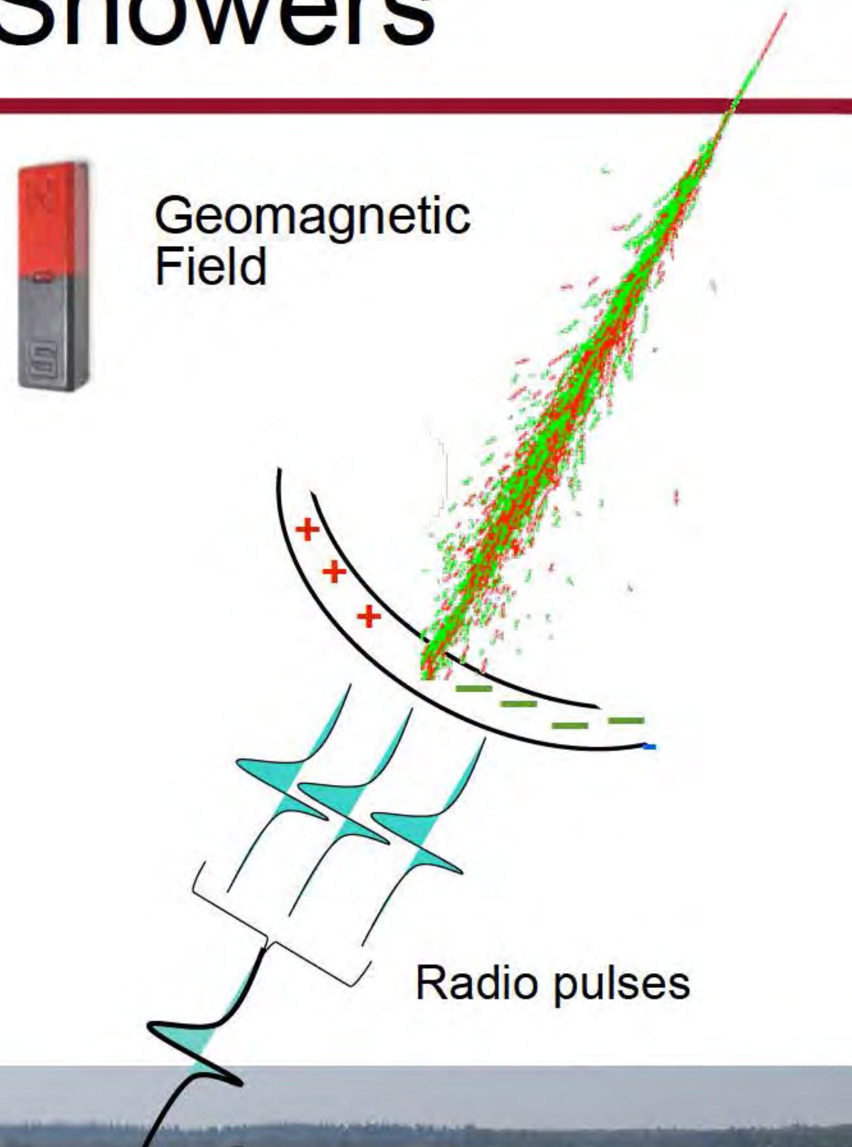
under construction

- large **distributed radio telescope**
- per station/location ~ 200 antennas
- two types of antennas
- sensitivity: **10 - 90 MHz** and **110 - 250 MHz**
- **raw voltage trace buffered** at every antenna parallel to other observations

Measuring Air Showers

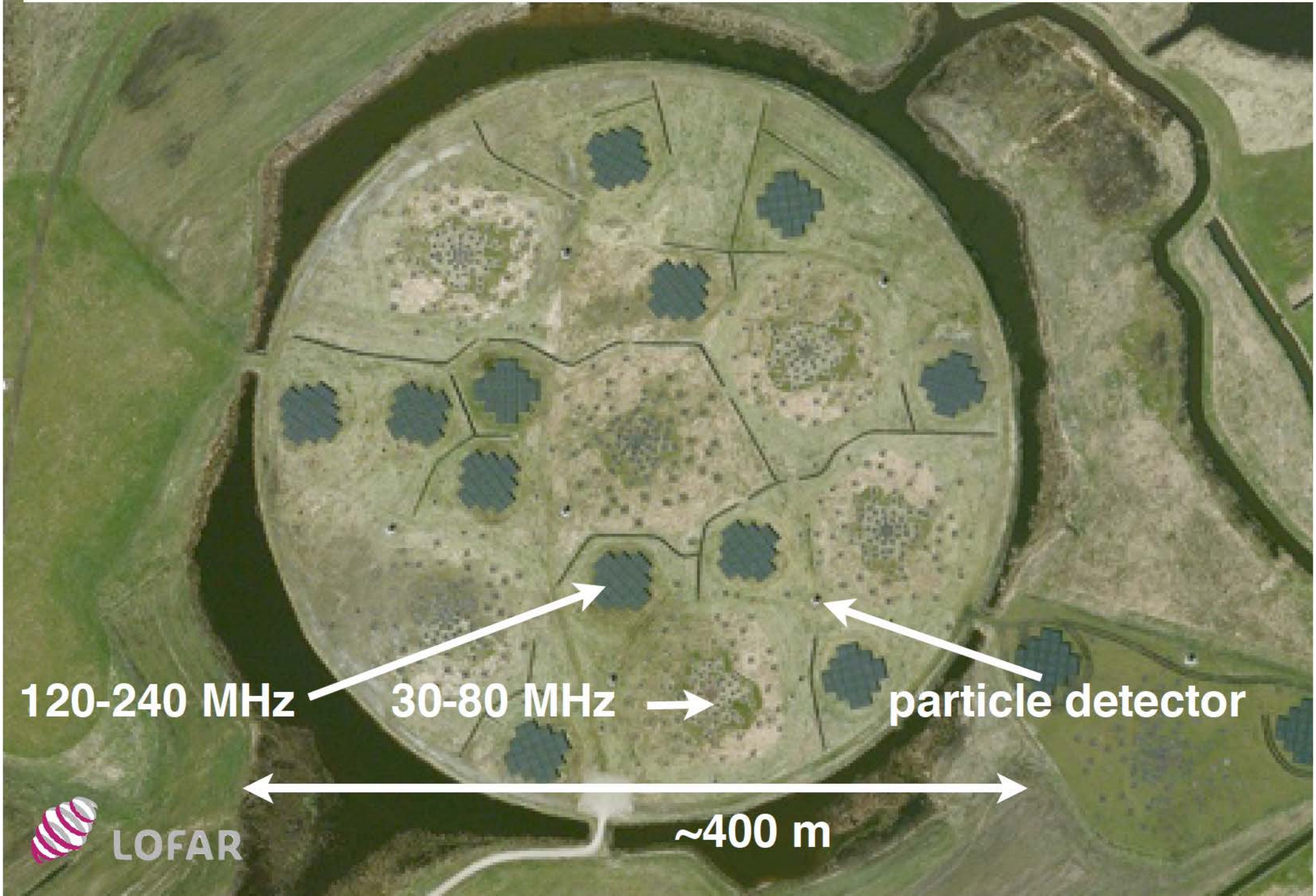
Central Core of LOFAR



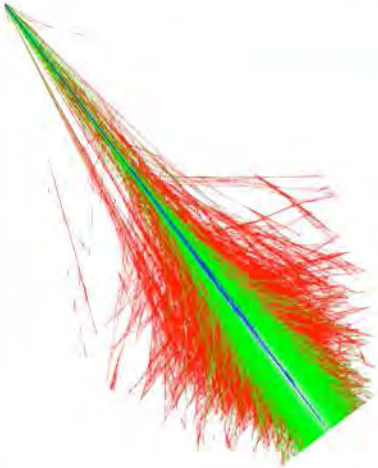


technical details of set-up, J. Hörandel, ICRC 865

LOFAR Radboud Air Shower Array - LORA

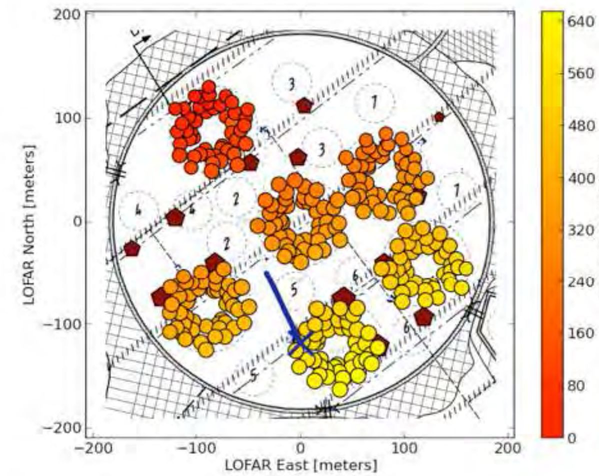


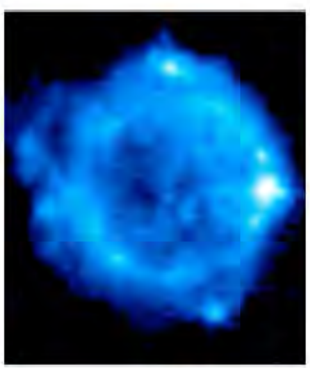
Measuring Air Showers

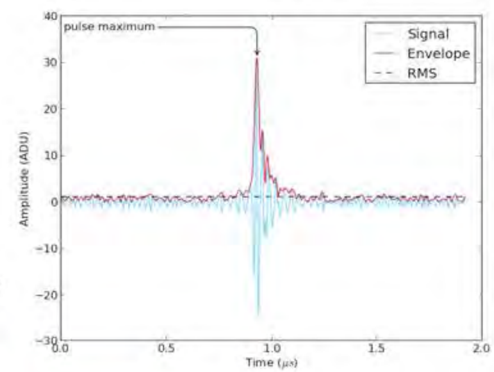


Cosmic-Ray Trigger from
LORA particle detectors

Analysis Pipeline
(P. Schellart
ICRC 556)

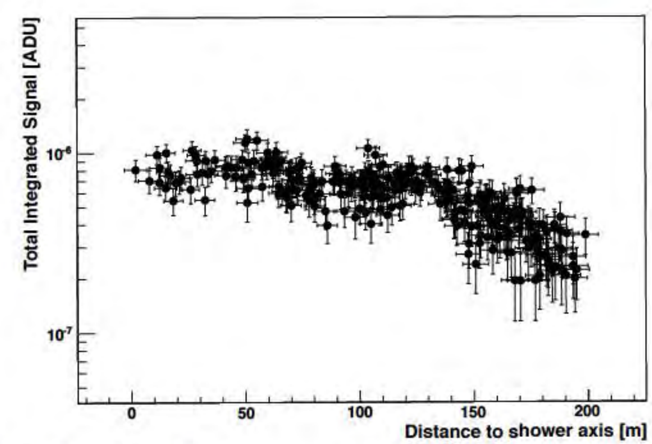






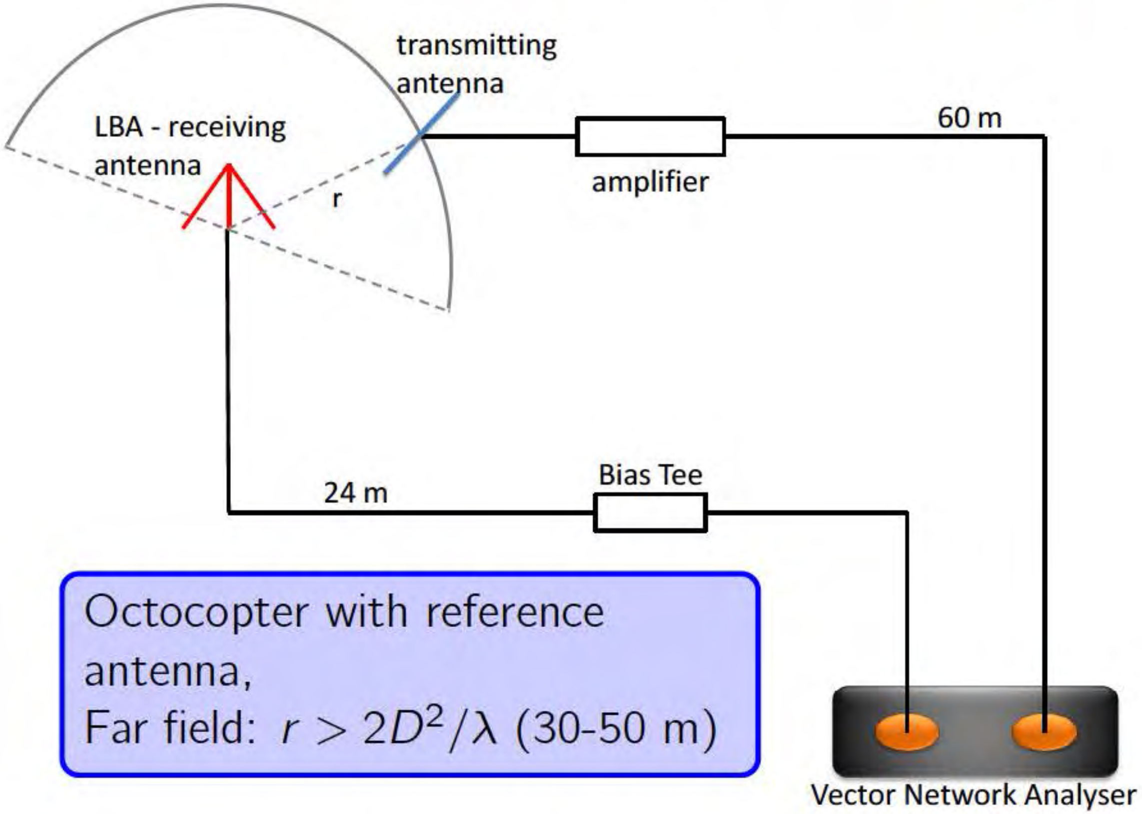
Read-out
Buffers

Ongoing
observation

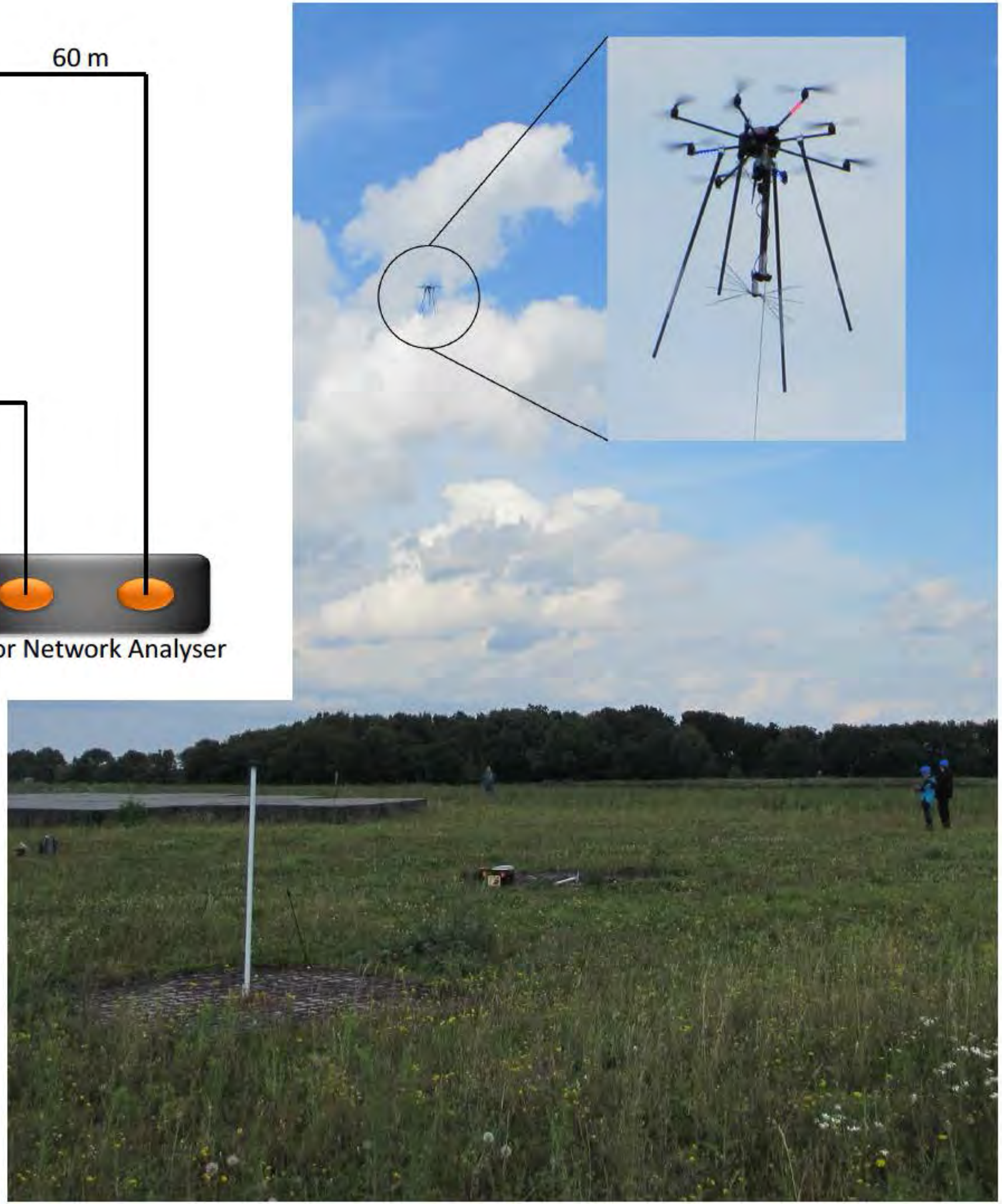


100 - 900 data points per event

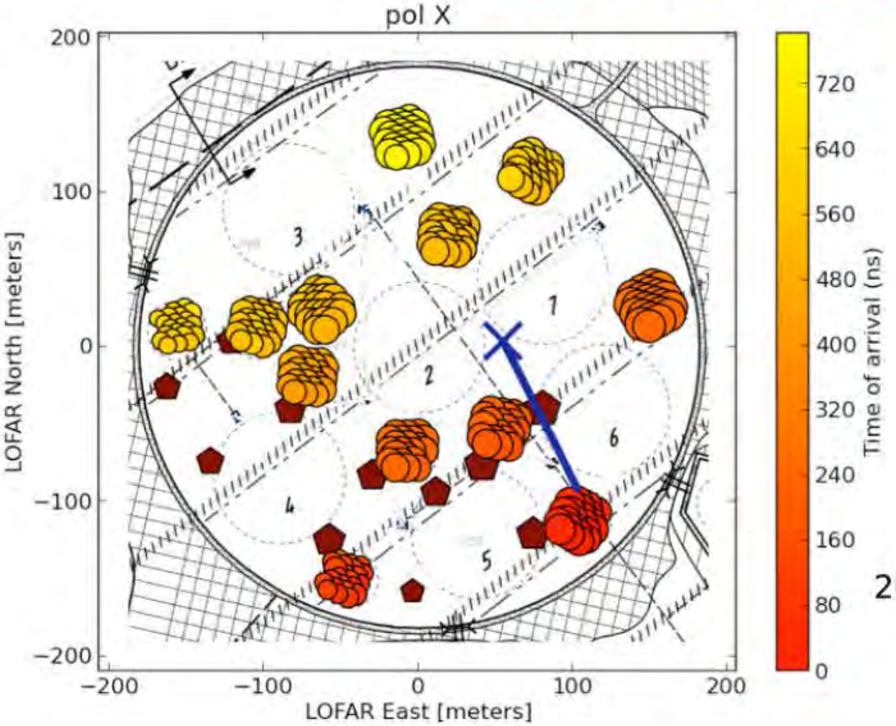
In-situ calibration of the antennas



Octocopter with reference antenna,
Far field: $r > 2D^2/\lambda$ (30-50 m)



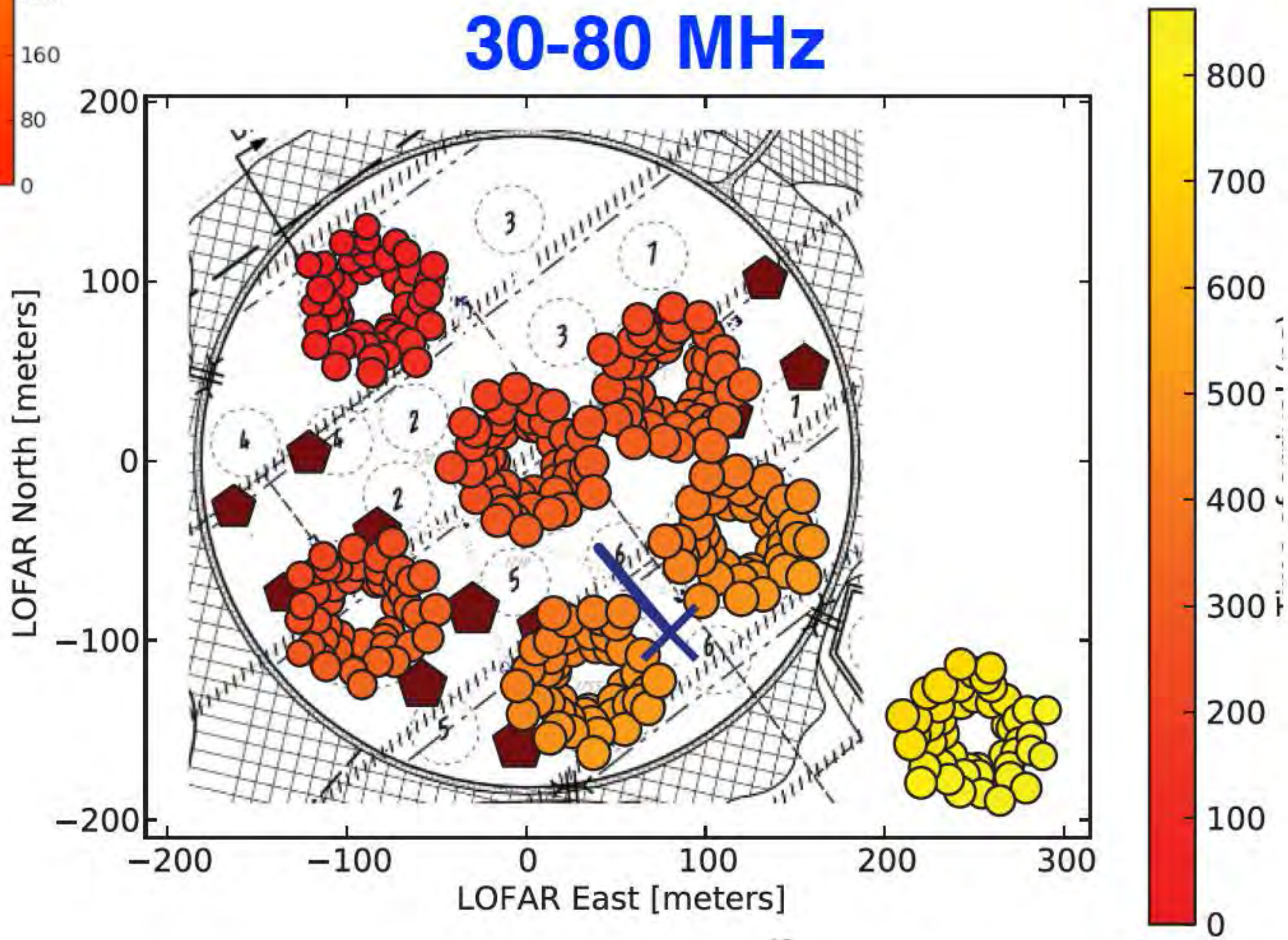
Measured air showers



120-240 MHz

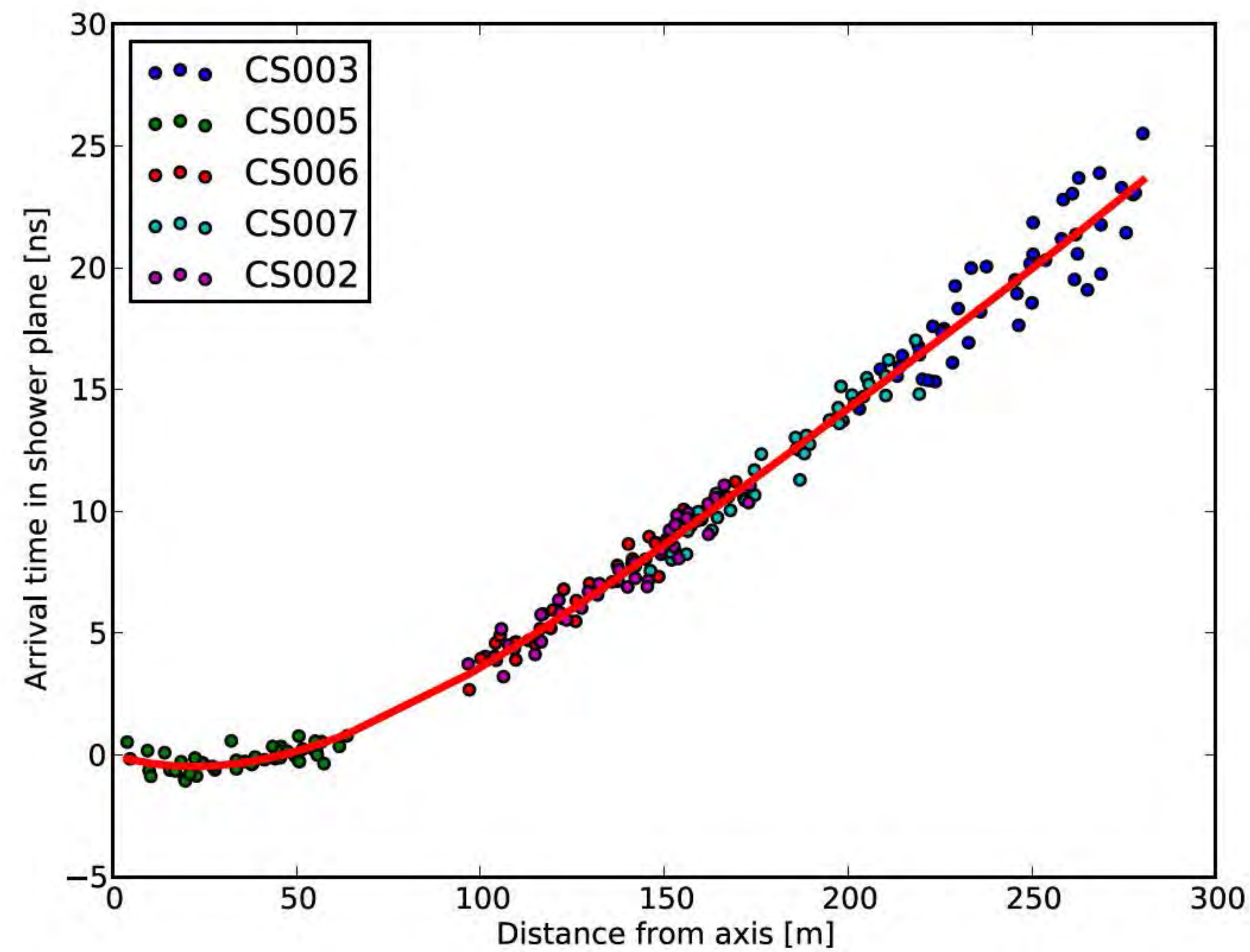
first measurement of radio emission from air showers in the 120-240 MHz regime

30-80 MHz



Wavefront curvature

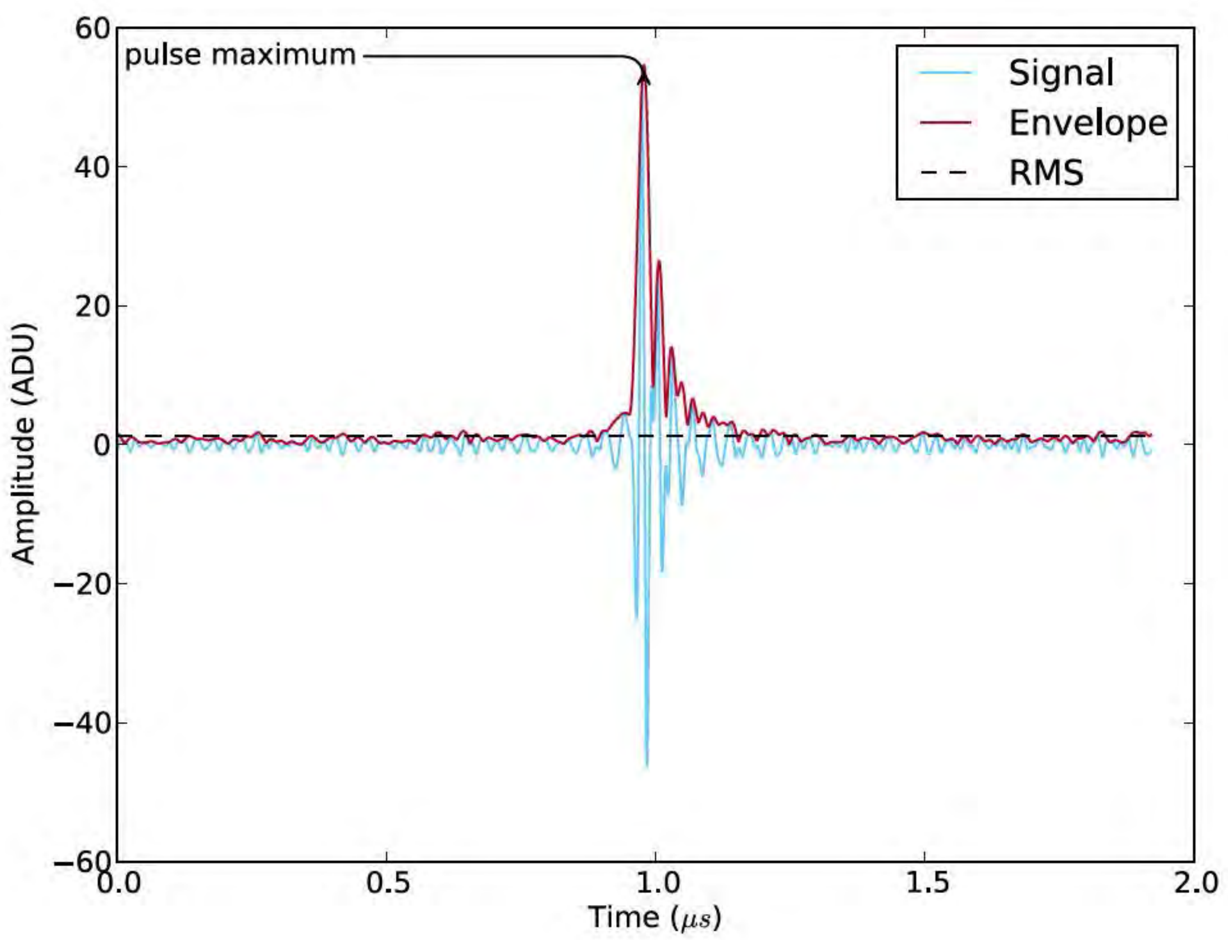
- Subtracting the plane wavefront solution, treating curvature as a perturbation gives ~6 ns delays at edge of the array
- This can be directly measured with LOFAR
- Preliminary results point to mixed spherical / conical wavefront shape
- Wavefront curvature may provide measurement of Xmax independent of pulse power

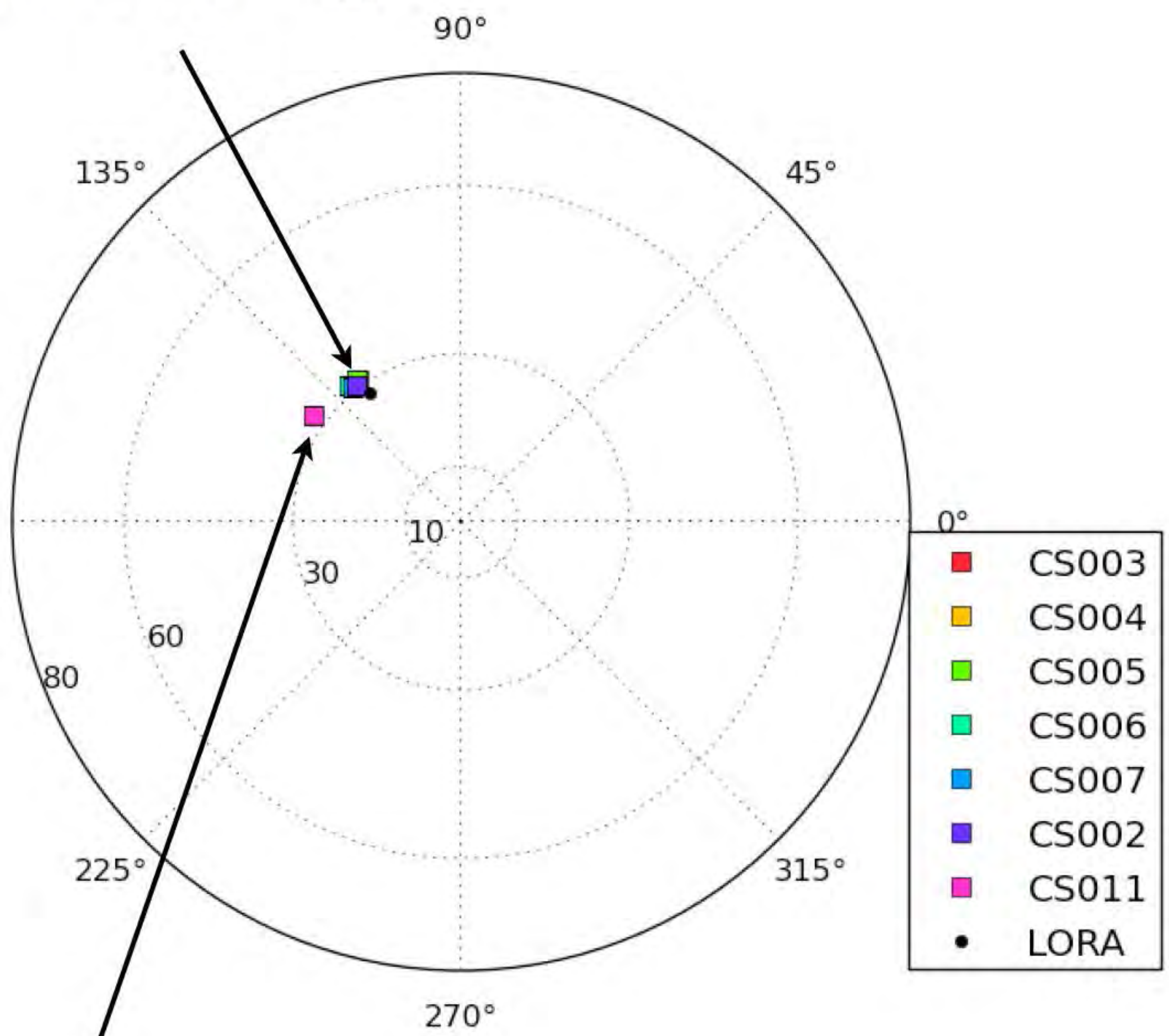


Corstanje et al. (in prep)

Pulse detection and direction fit to arrival times

Particle Detector & Radio Agree



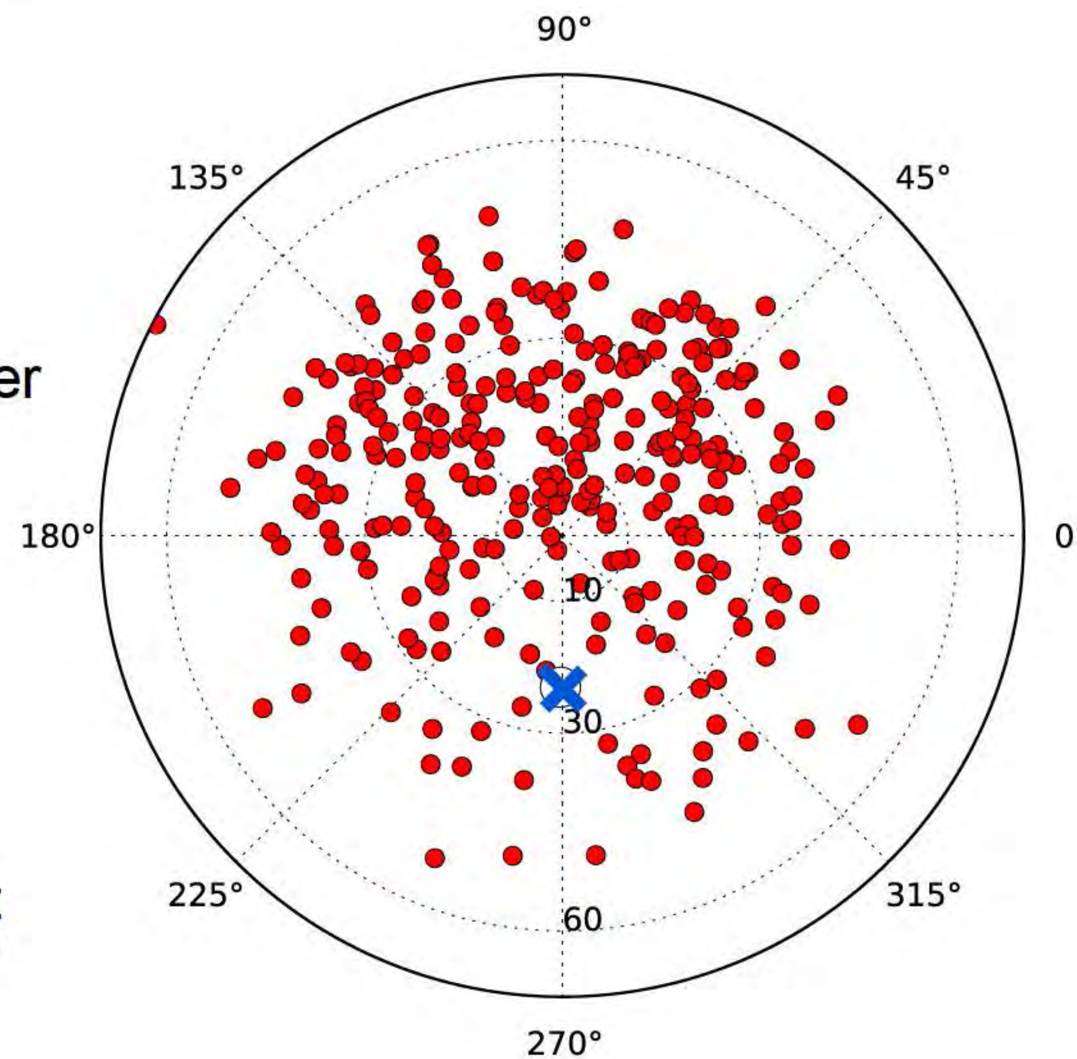


Curvature

Air Showers at 30 - 80 MHz

Measurement with low-band antennas

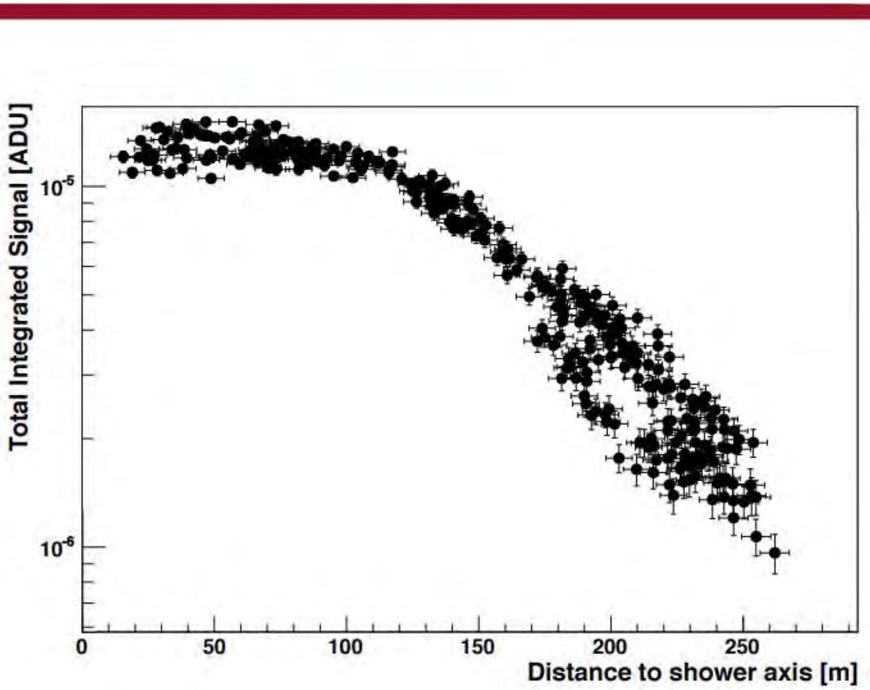
- **scintillator array** used as trigger, **trigger threshold**: 2.4 x 10^{16} eV
- triggers are accepted whenever parallel observation allows
- **375** cosmic ray events detected
- arrival directions: clear **north-south asymmetry**
- probability of a detected event to be from north: 0.69 +/- 0.02

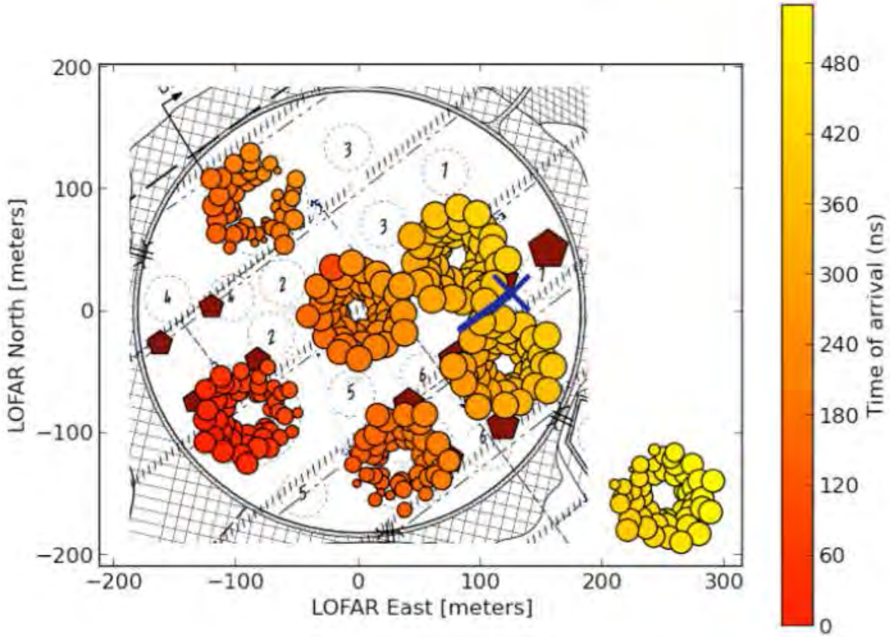


 Anna Nelles, 2013, ICRC 558

Event at 30 - 80 MHz

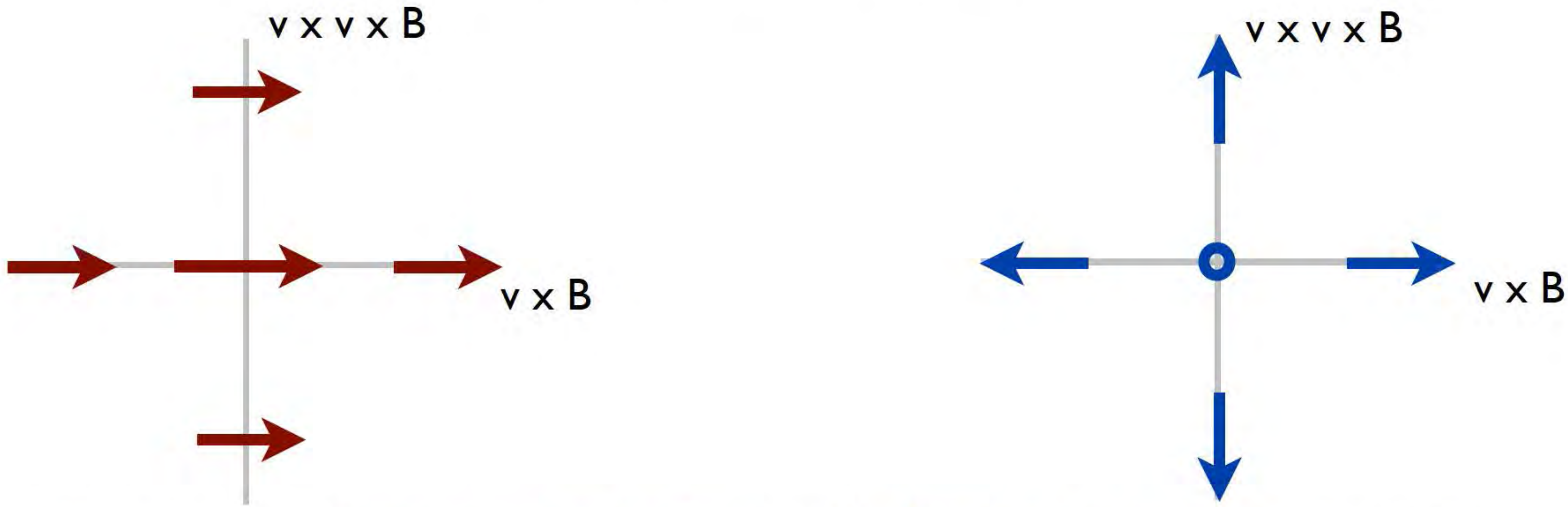
- For **energy calibration**:
- full **reconstruction of lateral profile** needed, including parameters such as shower core, energy, direction, magnetic field, X_{max}
- lateral profile **not radial symmetric** (circular distribution of antennas can be seen)
- too early for full model of lateral distribution
- Can energy calibration be established without exact knowledge of form?





 Anna Nelles, 2013, ICRC 558

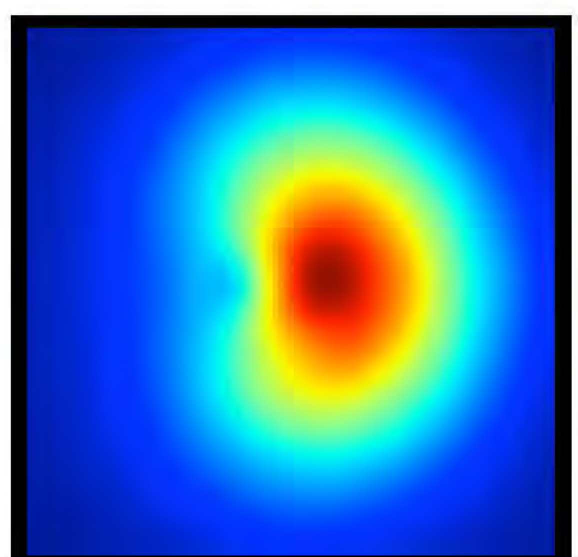
radio pattern



vector sum of geomagnetic and charge excess component

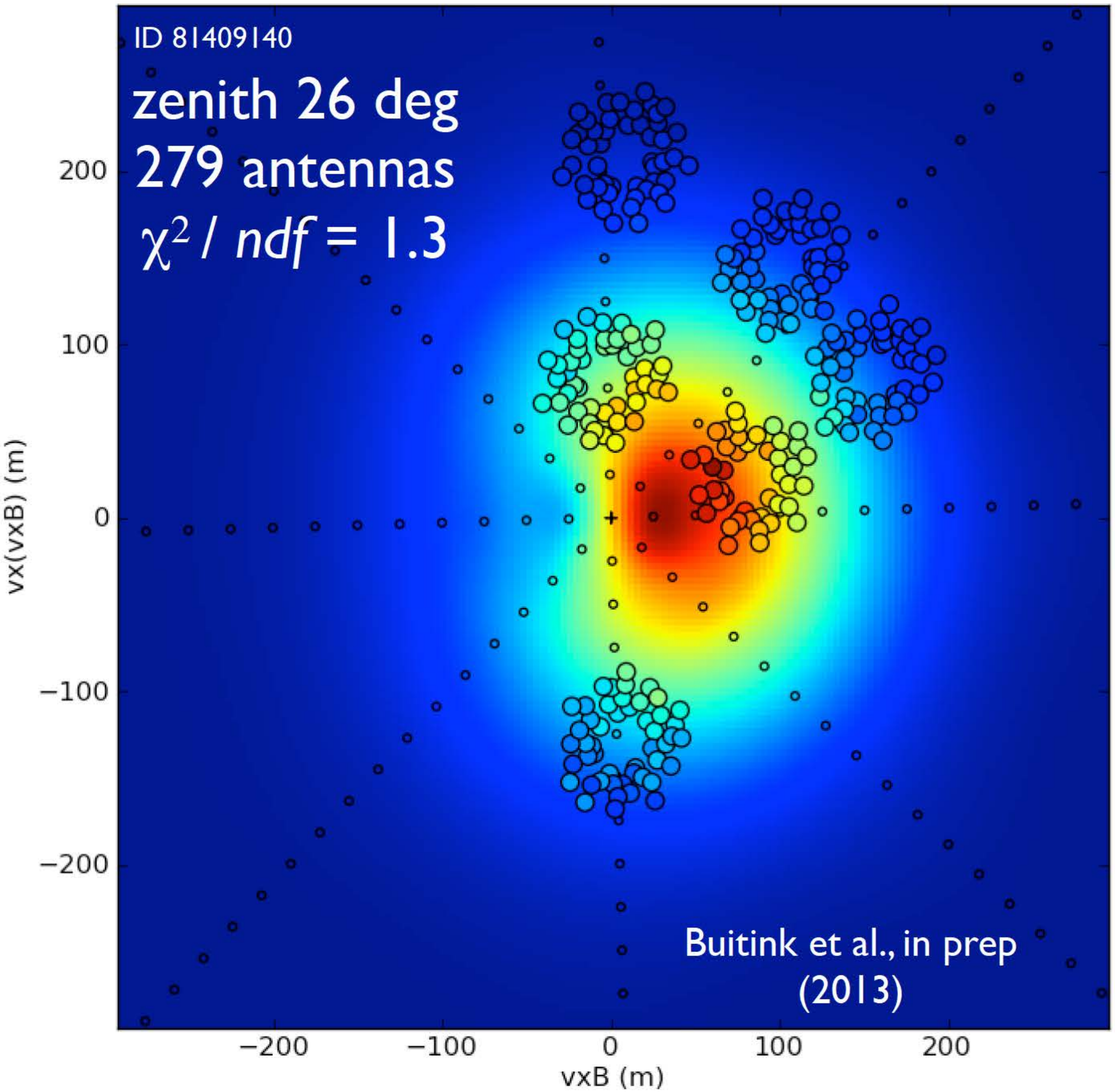
relativistic beaming

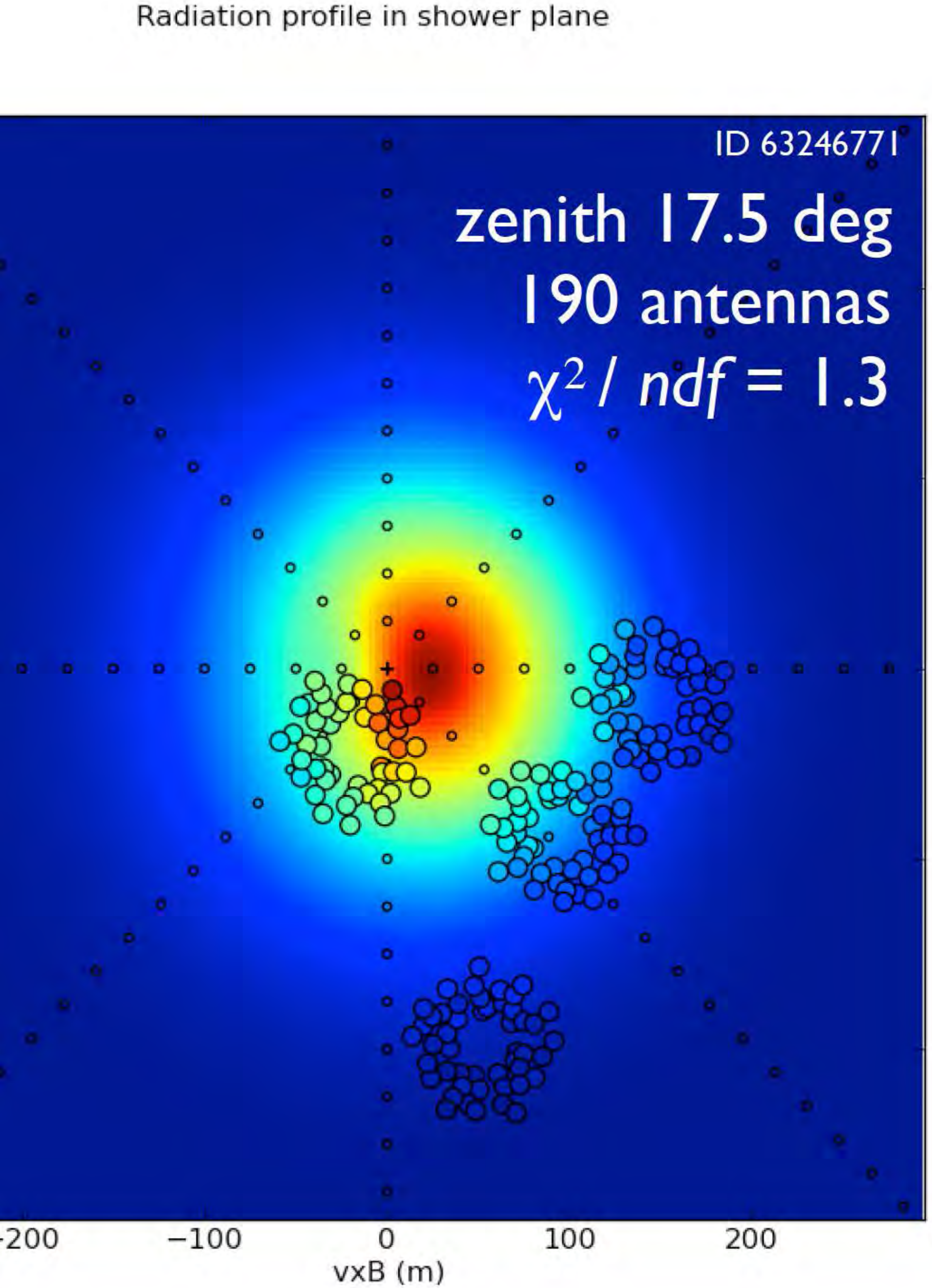
distortion by Cherenkov-like effects ($n \neq 1$)

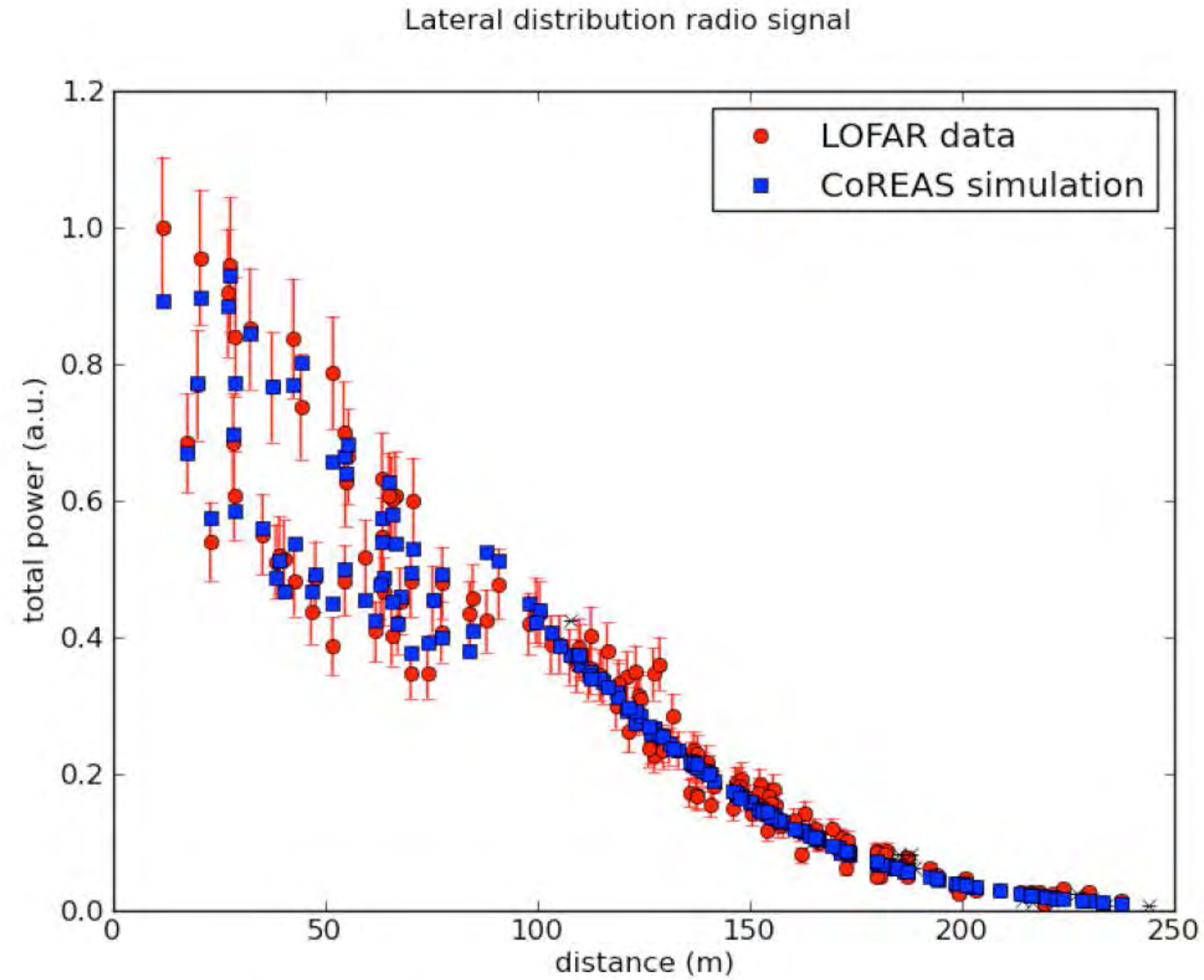


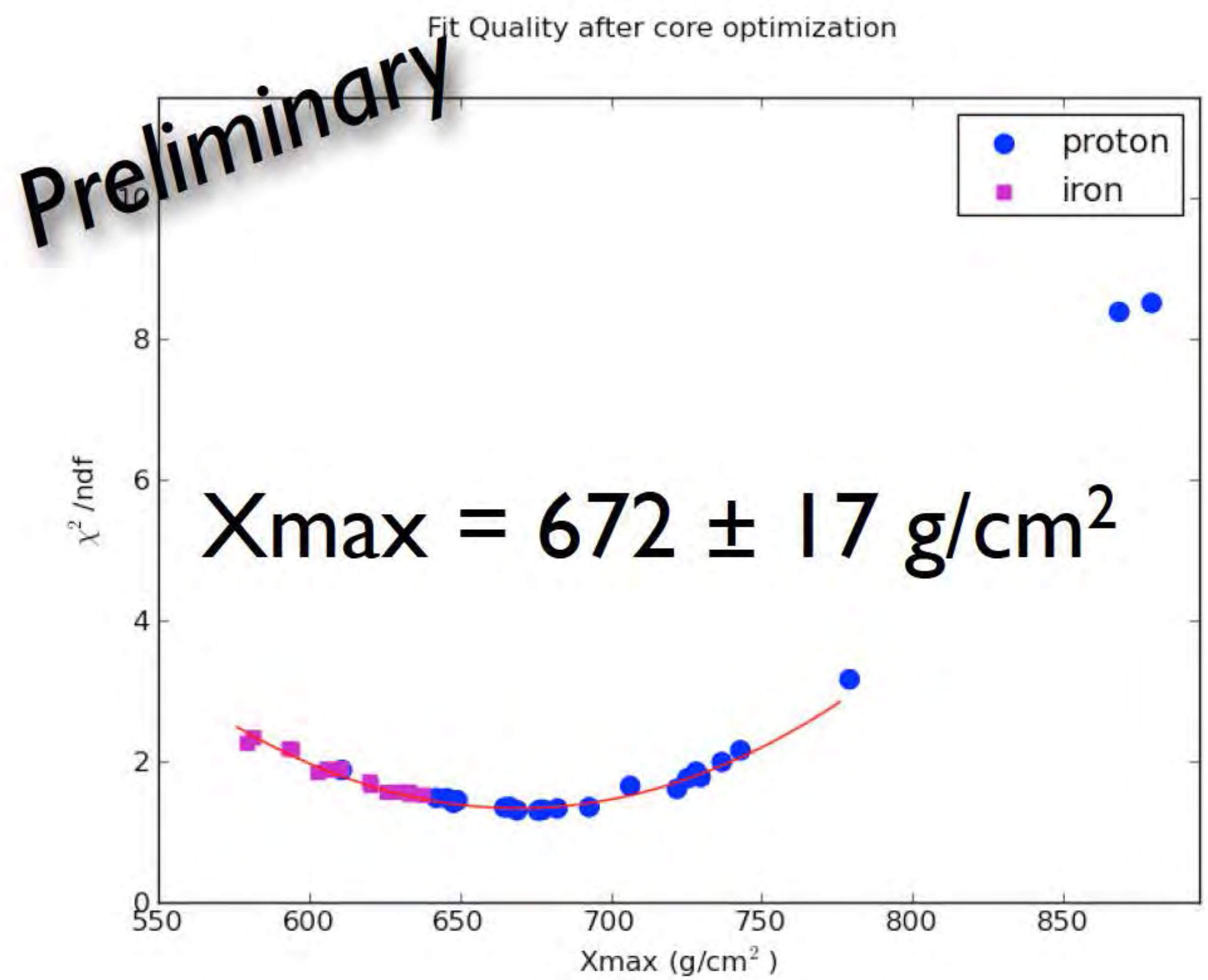
CoREAS simulation

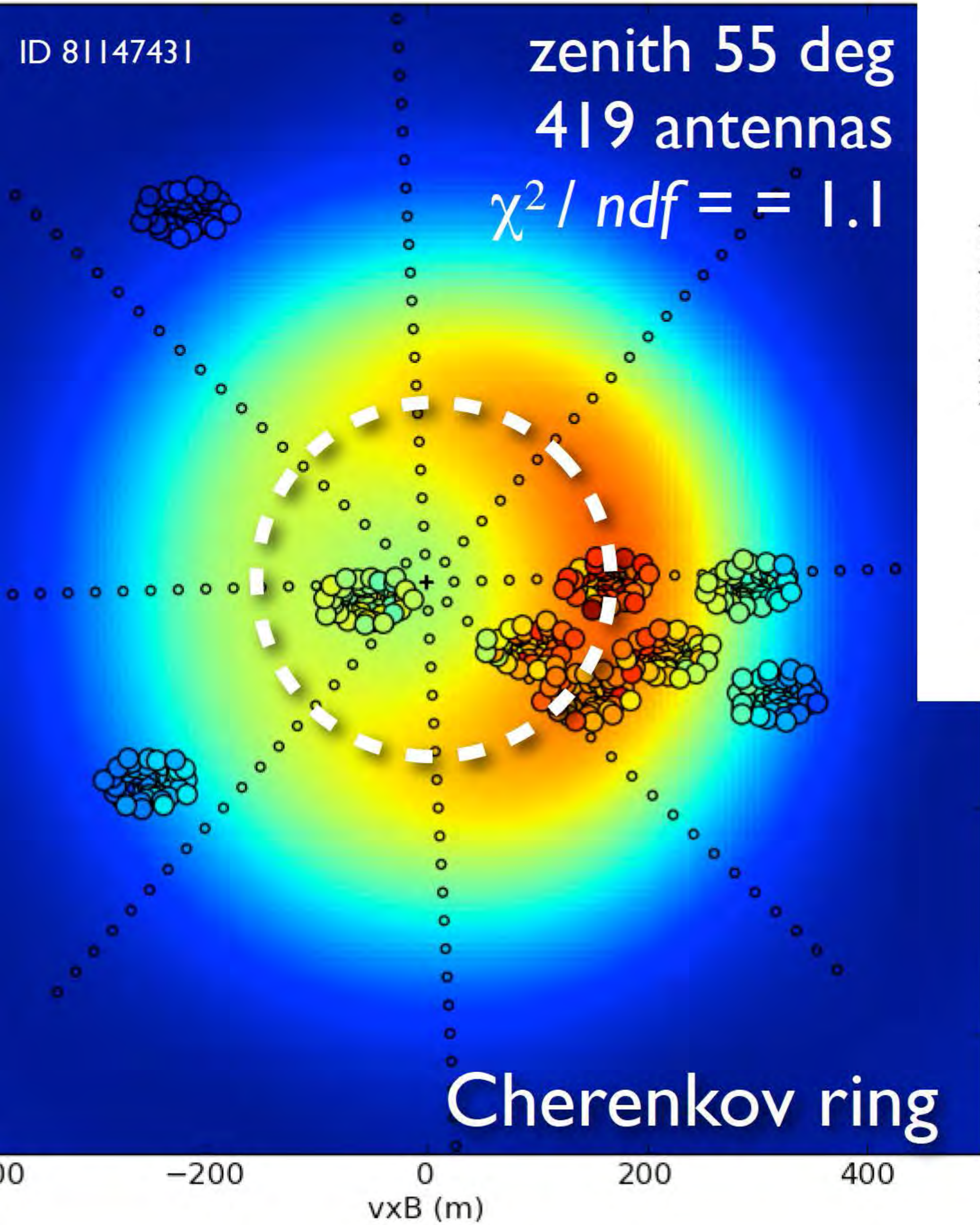
best fit out of 40 simulations

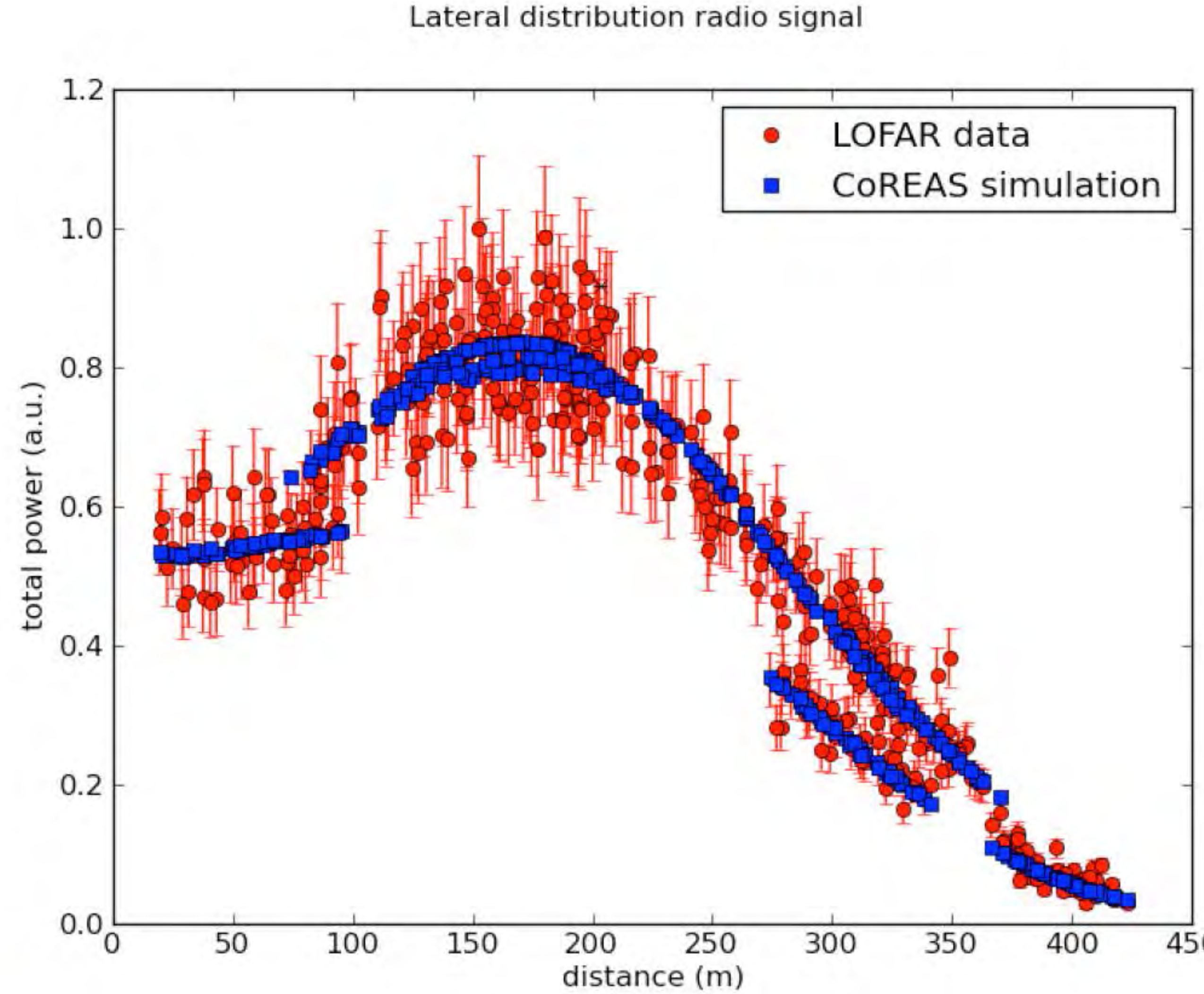


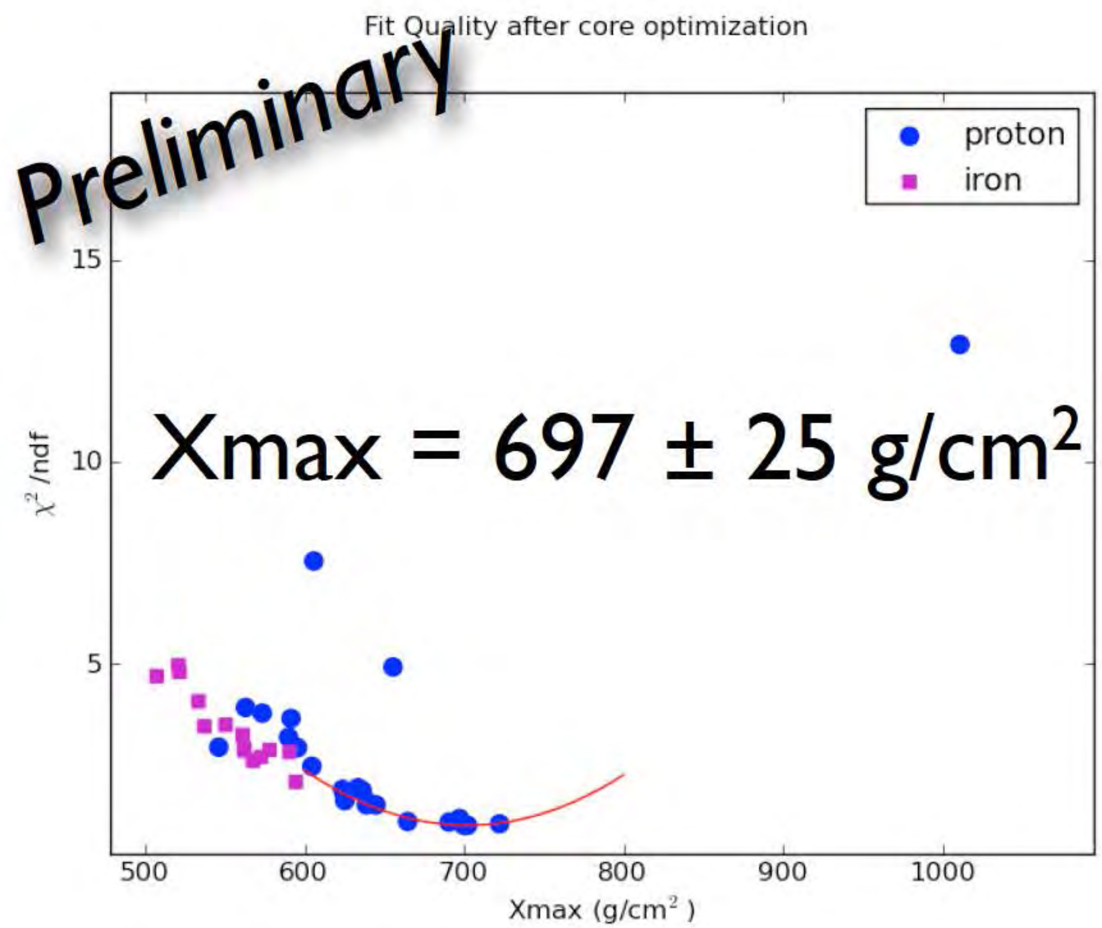

Radiation profile in shower plane
ID 63246771
zenith 17.5 deg
190 antennas
$\chi^2 / ndf = 1.3$
-200
−100
0
100
200
vxB (m)


Lateral distribution radio signal
LOFAR data
CoREAS simulation
total power (a.u.)
distance (m)

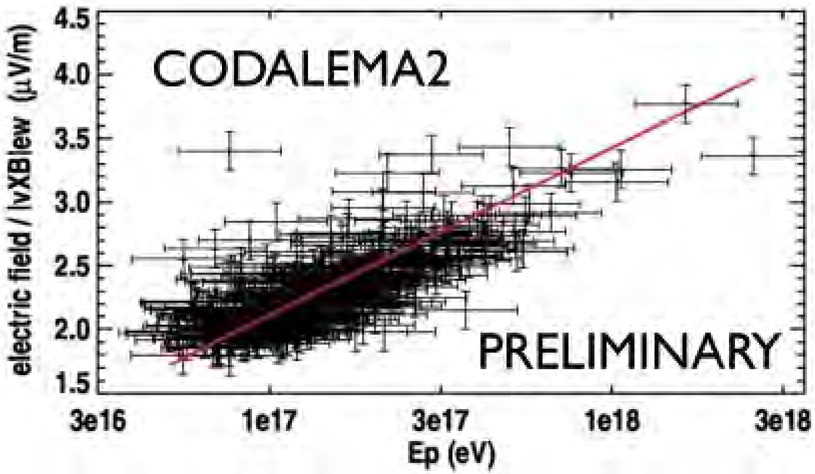

Fit Quality after core optimization
Preliminary
proton
iron
Xmax = 672 ± 17 g/cm^2
χ^2 /ndf
Xmax (g/cm^2)

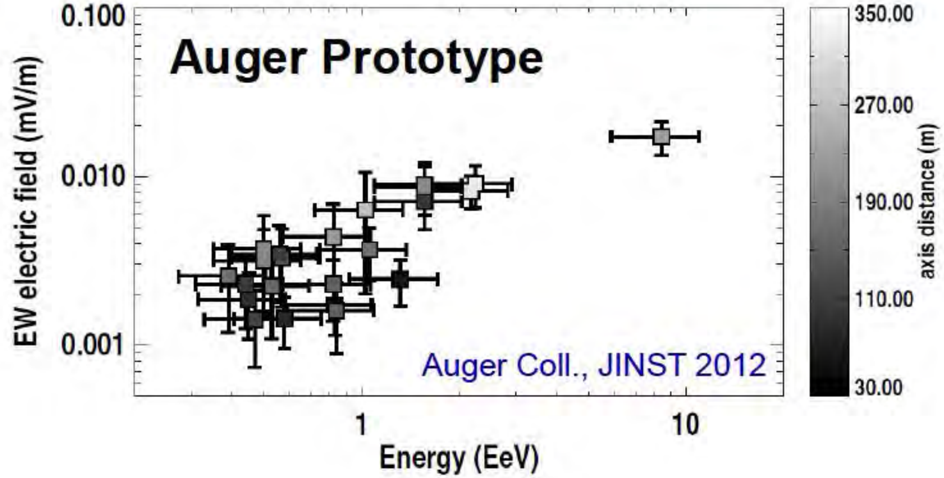

ID 81147431
zenith 55 deg
419 antennas
$\chi^2 / ndf = = 1.1$
Cherenkov ring
−200
0
200
400
vxB (m)

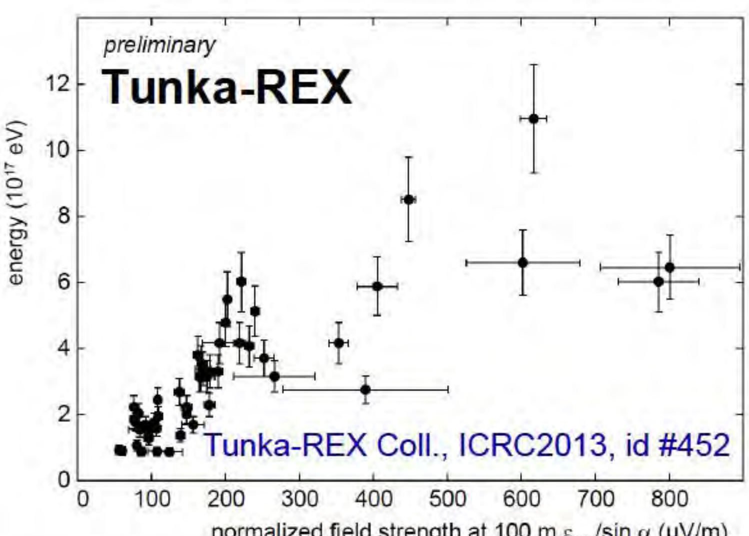

Lateral distribution radio signal
LOFAR data
CoREAS simulation
total power (a.u.)
distance (m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200
250
300
350
400
450

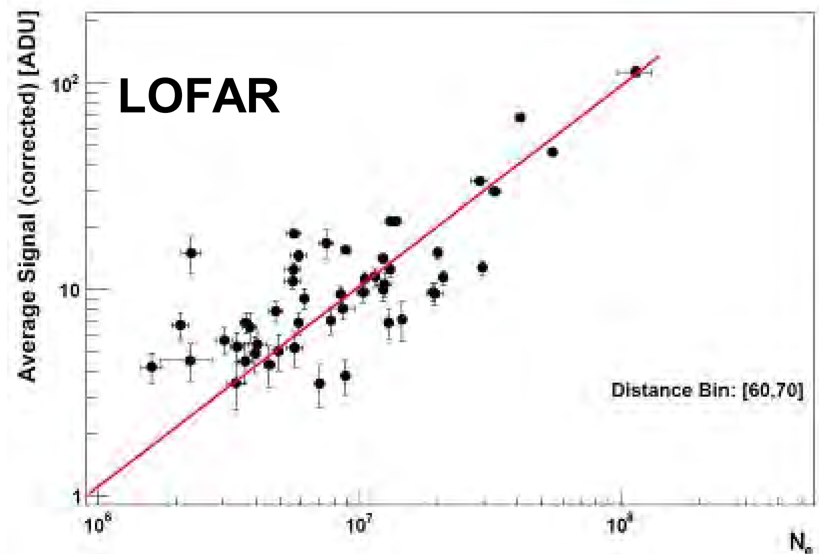

Fit Quality after core optimization
Preliminary
proton
iron
χ^2 /ndf
Xmax = 697 ± 25 g/cm^2
5
10
15
500
600
700
800
900
1000
Xmax (g/cm^2)

Radio amplitude - energy correlation results









Expected energy sensitivity of radio detection

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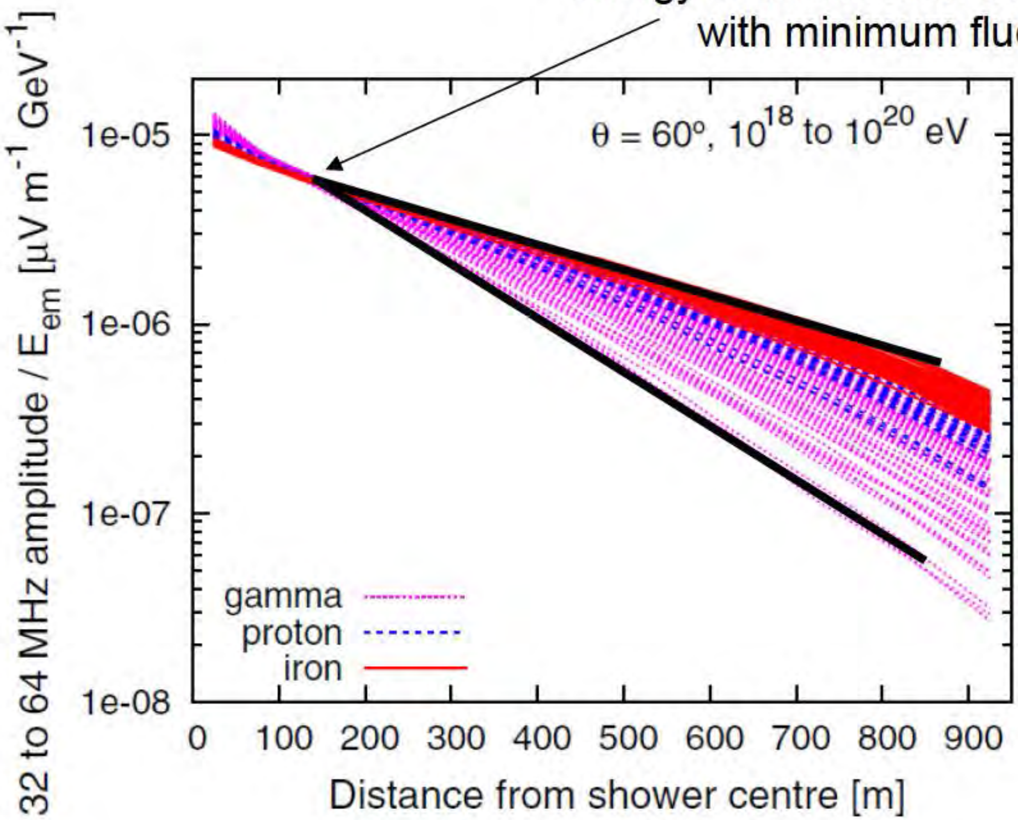
energy determination at distance
with minimum fluctuations



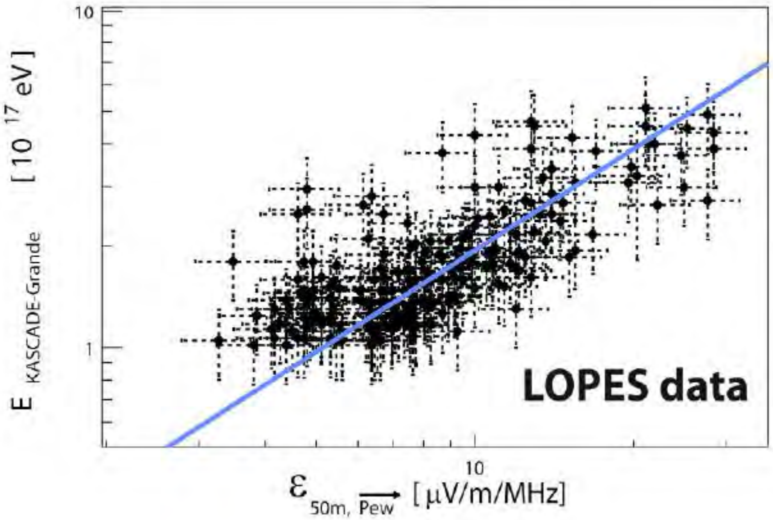
Fe – flat
p – steeper, fluctuating
γ – steepest, fluctuating

TH, Ulrich, Engel
(Astrop. Phys. 2008)

- linear scaling & characteristic distance for best energy estimate

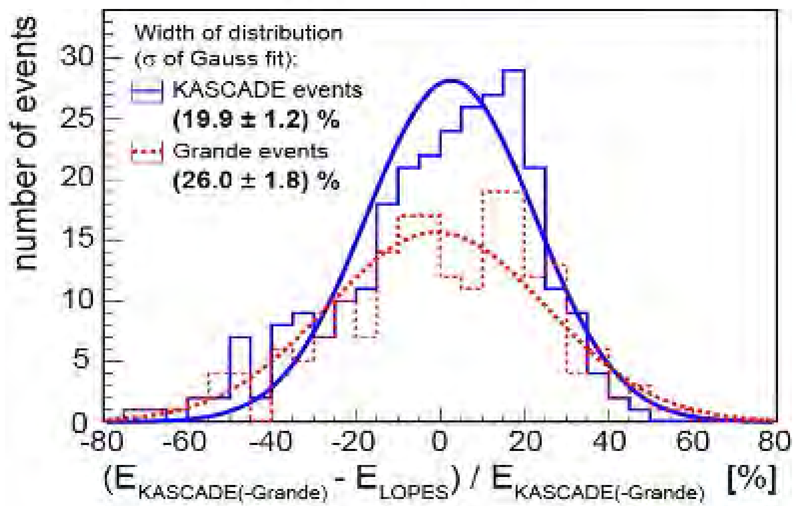
LOPES has made quantitative analyses

Karlsruhe Institute of Technology



- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439



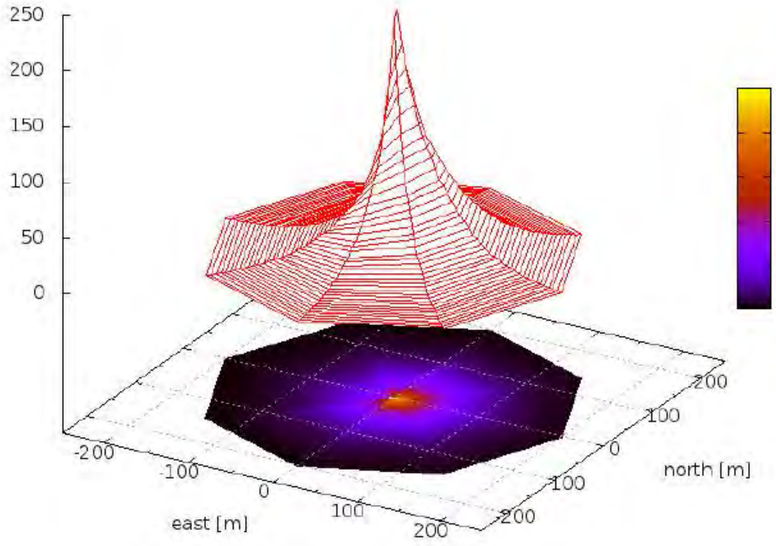
- also works with interferometric analysis, yielding again ~20% uncertainty

F.G. Schröder et al. (LOPES Coll.), ARENA2012

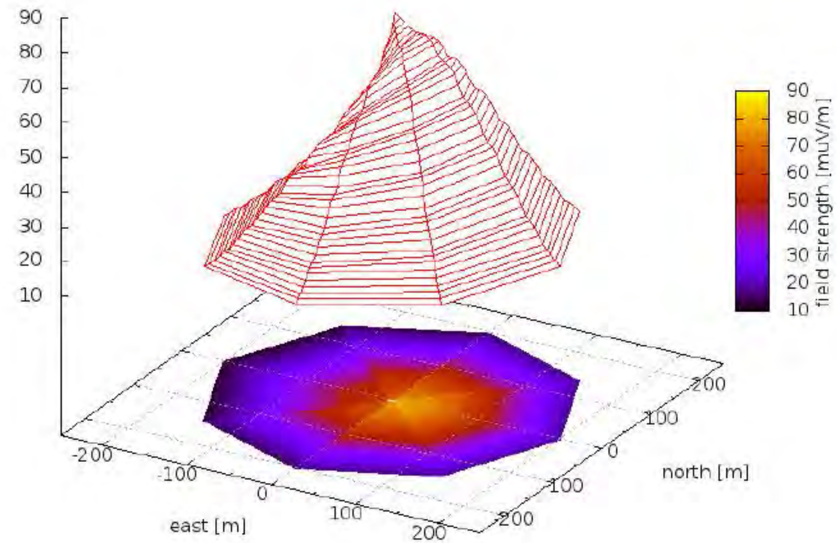
Lateral distribution as probe for composition

- simulations for proton and iron primaries show systematic differences

TH et al., ARENA2012



vertical proton shower
at LOPES frequencies
simulated with CoREAS

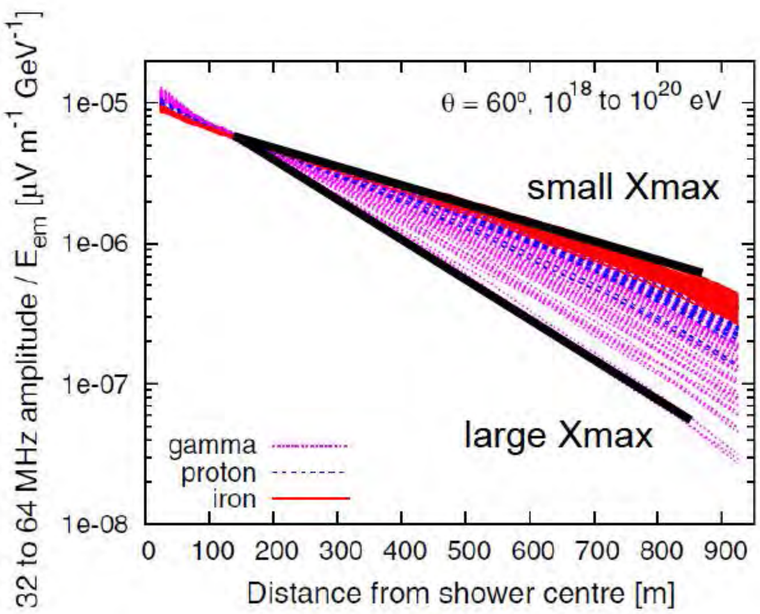


vertical iron shower
at LOPES frequencies
simulated with CoREAS

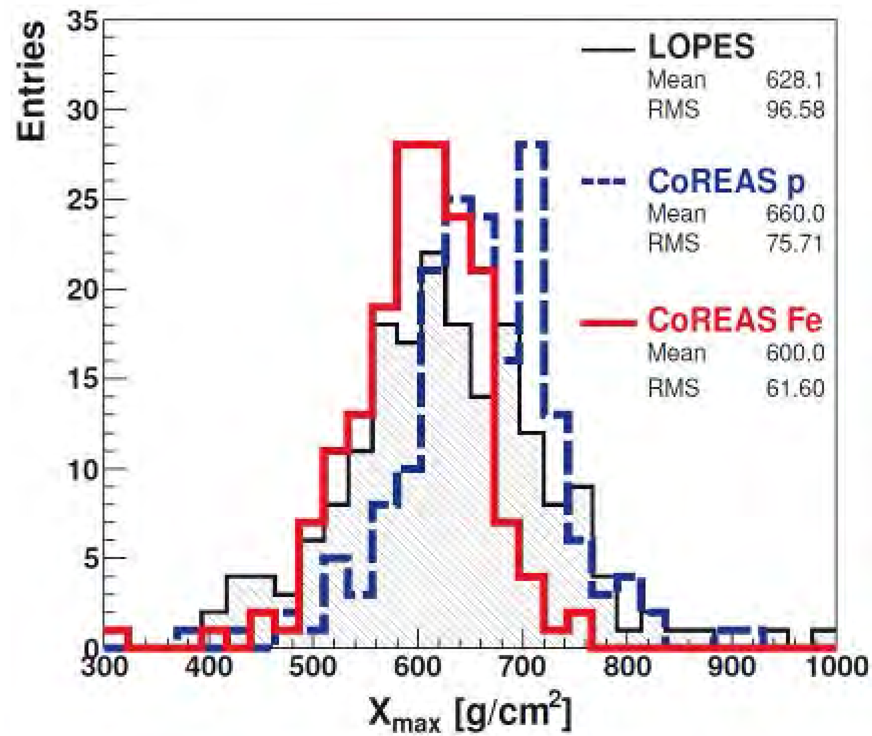
Xmax reconstruction with LOPES

Karlsruhe Institute of Technology

- with simulations, radio LDF slope can be related to Xmax
- using parameterisations derived with CoREAS simulations, Xmax is estimated for each individual LOPES event (method σ_{Xmax} ~ 50 g/cm2)



TH, Ulrich, Engel (Astrop. Phys. 2008)



N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439

External versus self-triggering

Karlsruhe Institute of Technology

- external triggering works well
  - LOPES
  - CODALEMA
  - AERA
  - LOFAR

Is a self-triggering stand-alone radio detector what we really need? Do we not strive to do hybrid measurements anyway?

- self-triggering is very challenging
  - transient noise (RFI)
- it has been done successfully
  - TREND
  - AERA prototype and AERA
  - CODALEMA-III
- but: radio trigger purity is very low
  - need coincidence with other detector for clear identification
  - or need to use many details of radio signal (LDF, polarization) to identify air showers - what is realistic in a low-level trigger?

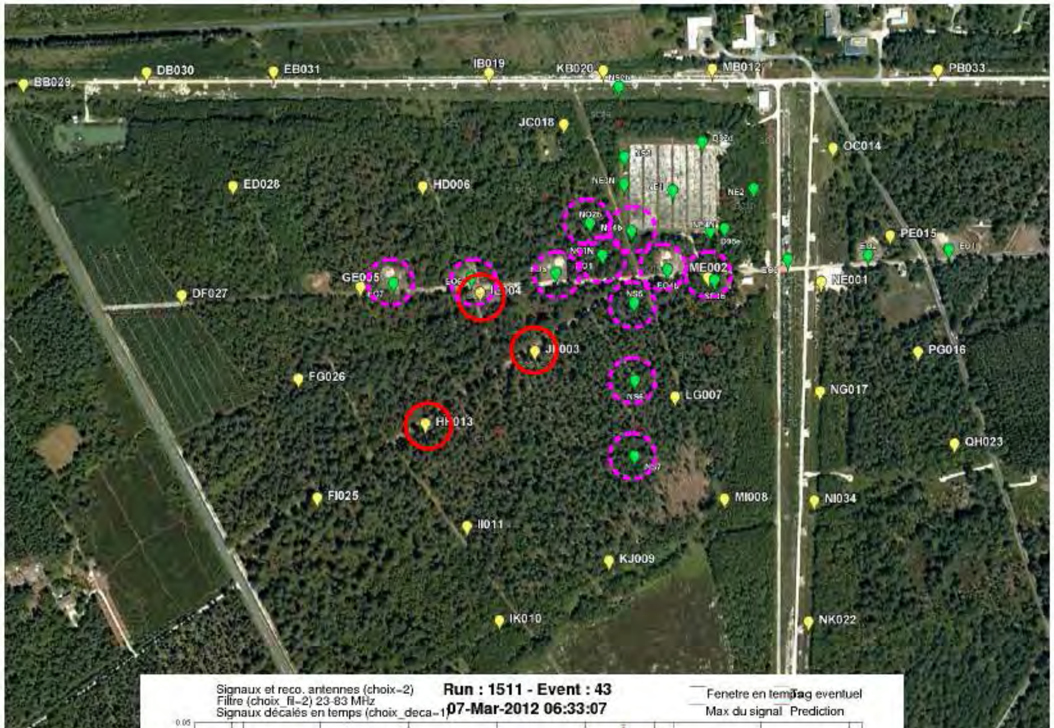
CODALEMA experiment: the antenna array

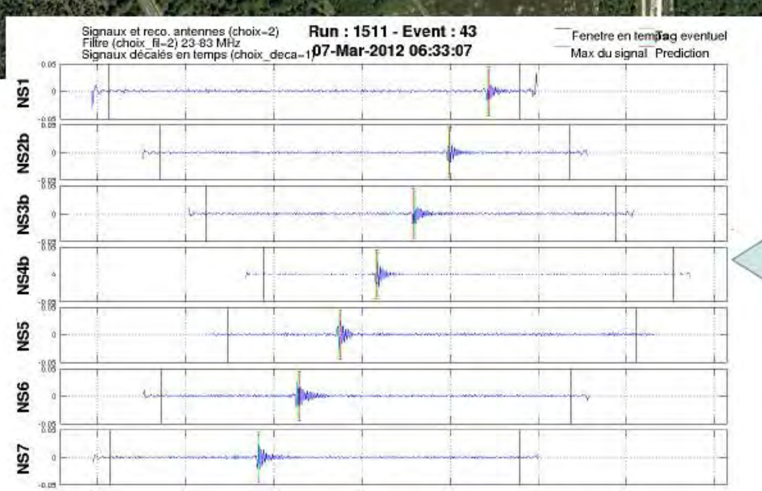
Nançay Observatory

- Area: 0.5km² → more statistics in $10^{16} - 10^{18}$eV energy range
- Better understanding of lateral/longitudinal profiles
- Cosmic rays composition at the 2nd knee
- R&D for future giant & hybrid detectors (AERA, Auger next)

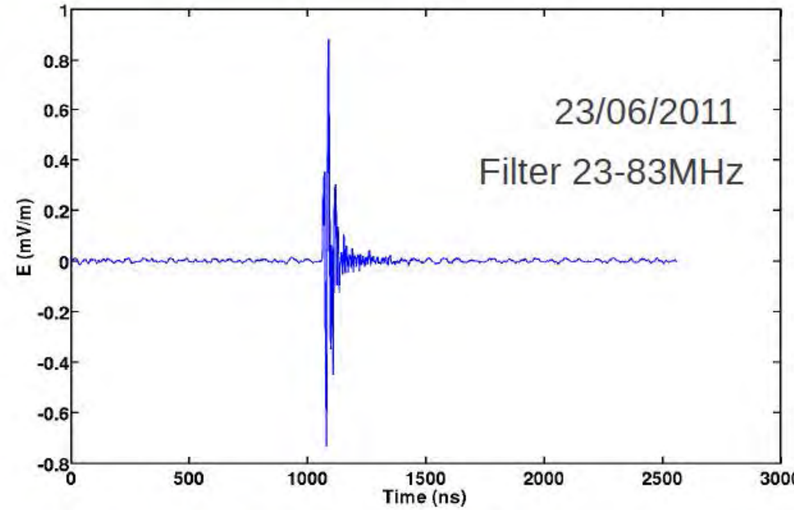
EAS detection & polarization

09/06/2011 20:30:49 TU





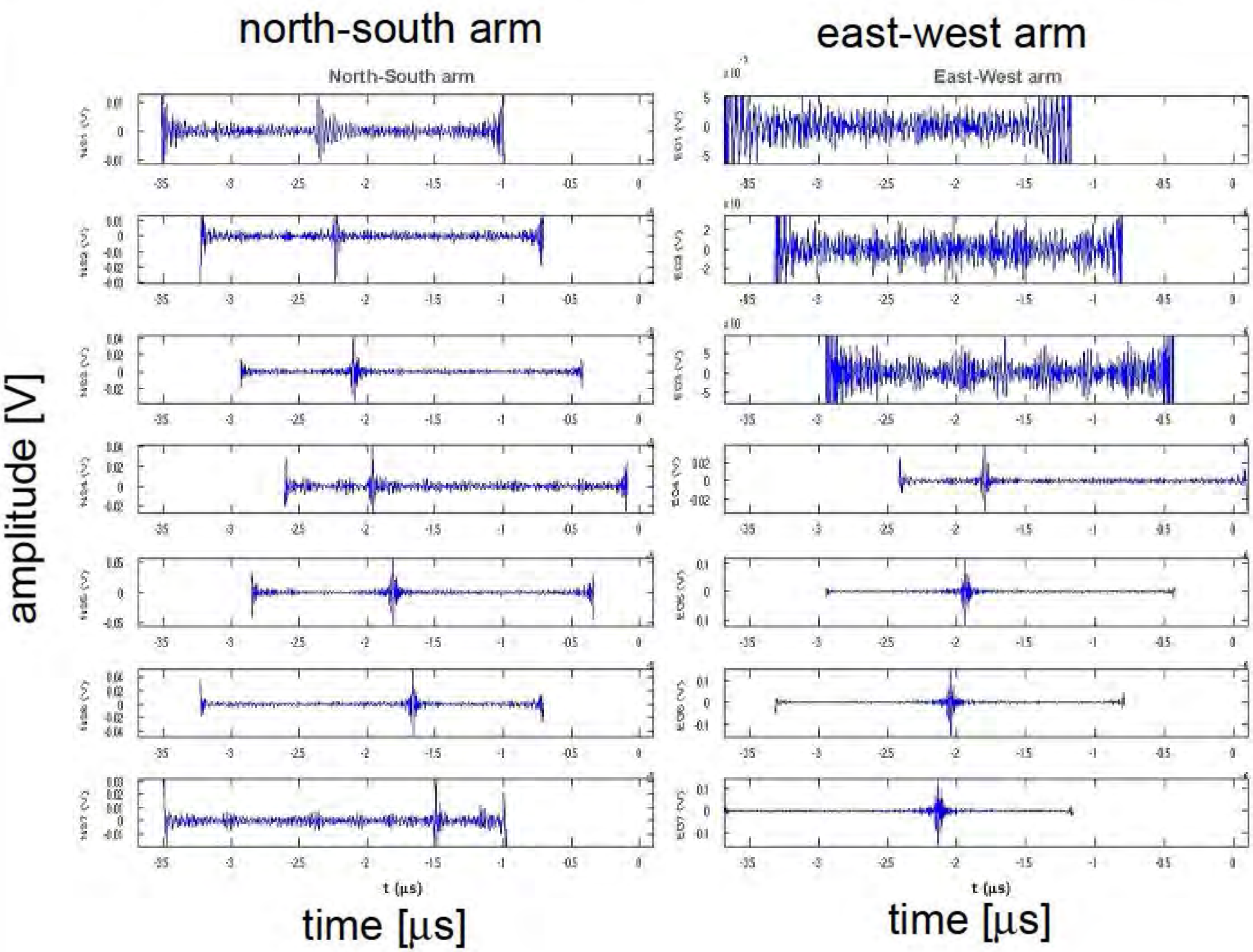
Event observed by all dipole antennas!



07/03/2012 06:33:07 TU – 14 self-triggering antennas in coincidence with scintillators

Wave transit time: 4.3µs

Direction reconstruction with pulse timing



- CODALEMA approach
- analyse channels individually (no inter-ferometry)
- direction from peak timings
- as for particle detectors

P. Lautridou et al (CODALEMA coll.), ARENA 2008

Extensive Air Showers: detection instruments

How to detect it ?

	Observable	Advantages	Drawbacks
Water Cherenkov Detectors Scintillators	Particle density at the ground level ↓ Lateral spread	Duty cycle~100% Direct measure of the particle density	Model-dependent for energy computation
Air Fluorescence Detectors	Nitrogen fluorescence in the atmosphere ↓ Longitudinal spread	3D shower development Detection at several km	Low duty cycle
Radio-Detection	Electric field ↓ Lateral spread of the electric field + Longitudinal spread?	High duty cycle Low cost Angular acceptance	Sensitivity to the Radio Frequency Interferences