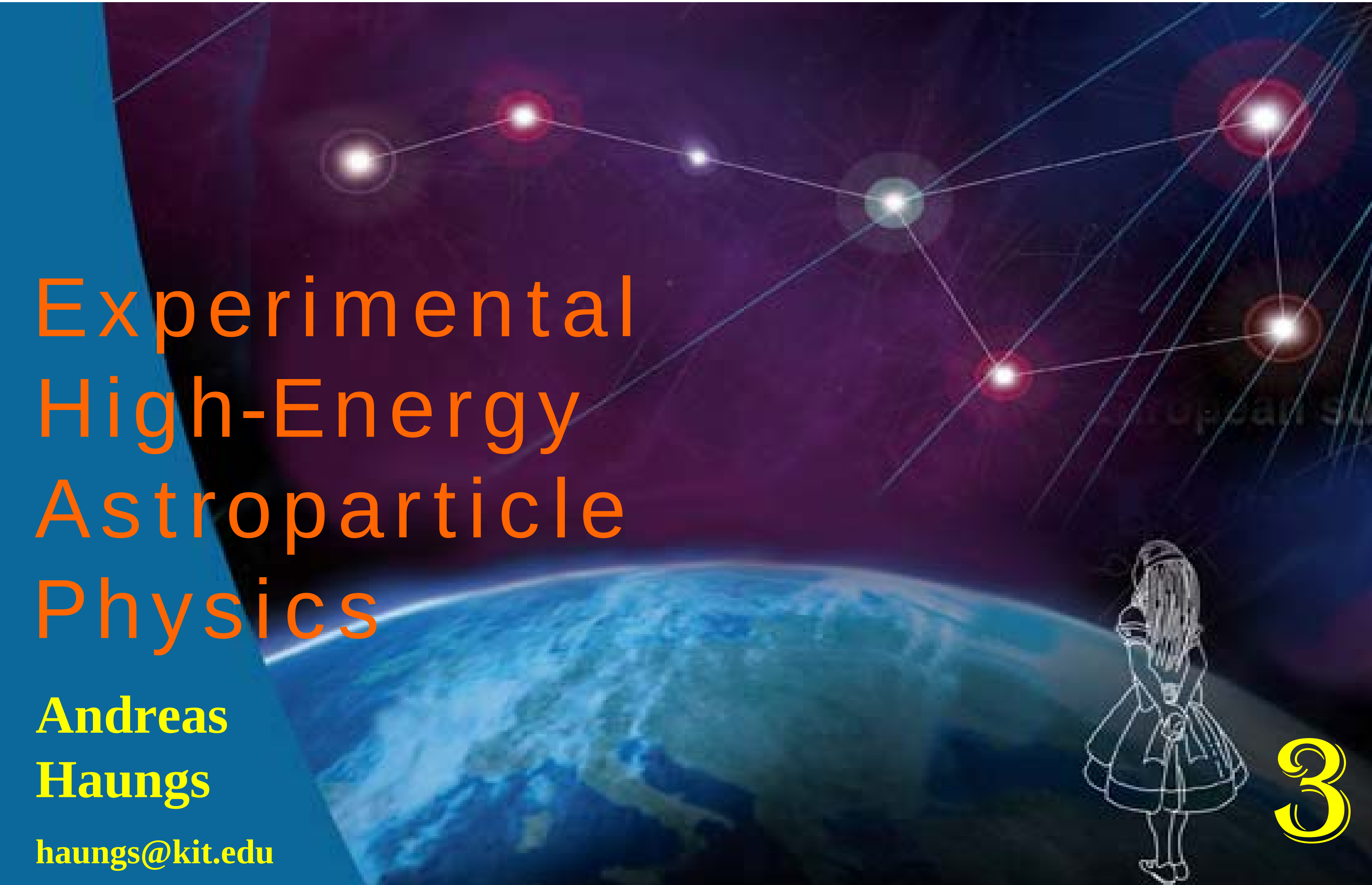


Experimental High-Energy Astroparticle Physics

Andreas Haungs

haungs@kit.edu

3

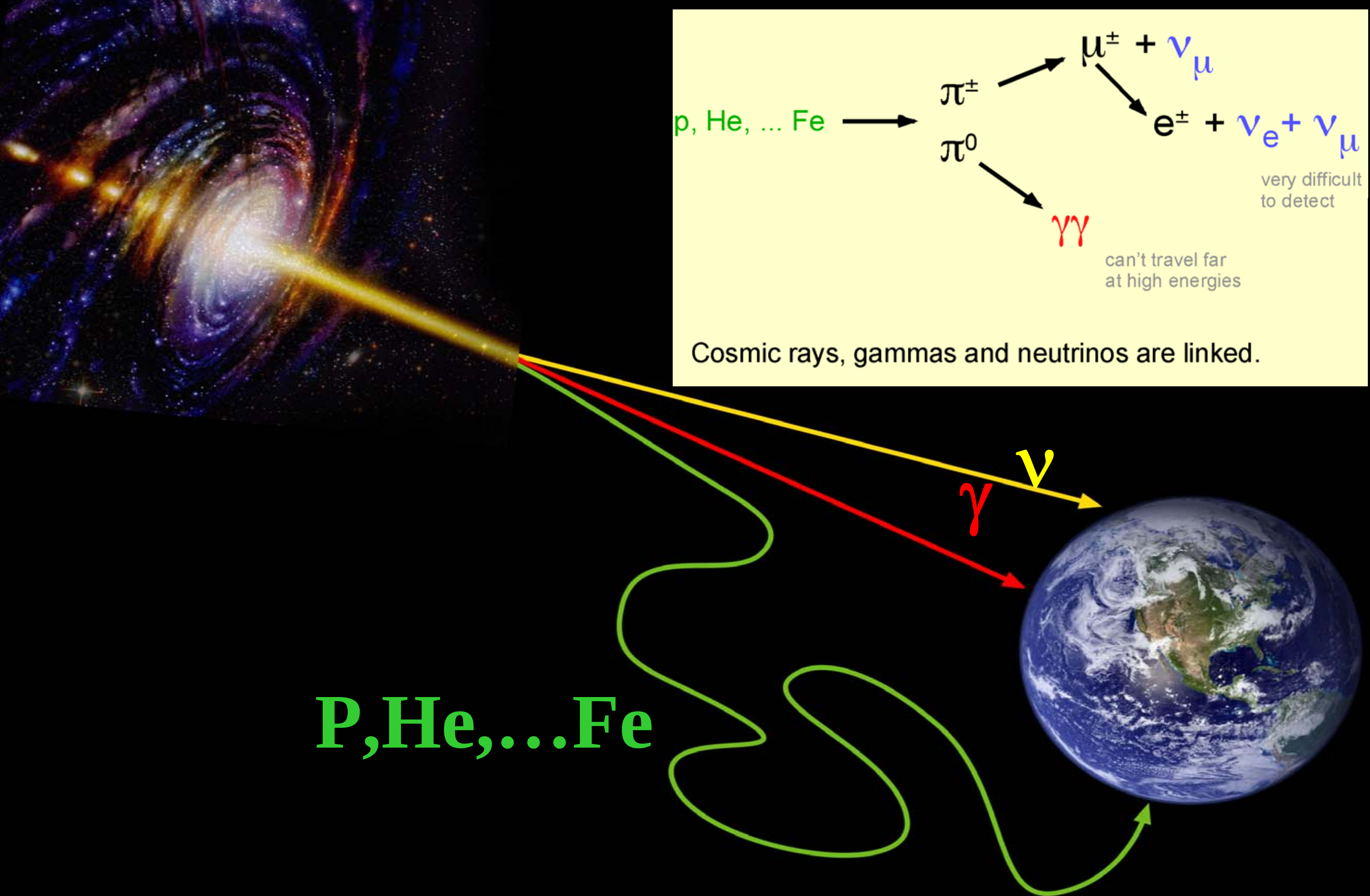
Content:

1. **Introduction in HEAP**
   - **source-acceleration-transport**
   - **short history of cosmic ray research**
   - **extensive air showers**
2. **High-Energy Cosmic Rays**
   - **KASCADE, KASCADE-Grande and LOPES**
3. **Extreme Energy Cosmic Rays**
   - **Pierre Auger Observatory, JEM-EUSO**
4. **TeV-Gamma-rays & High-energy Neutrinos**
   - **TeV gamma rays**

     H.E.S.S., MAGIC, CTA
   - **high-energy neutrinos**

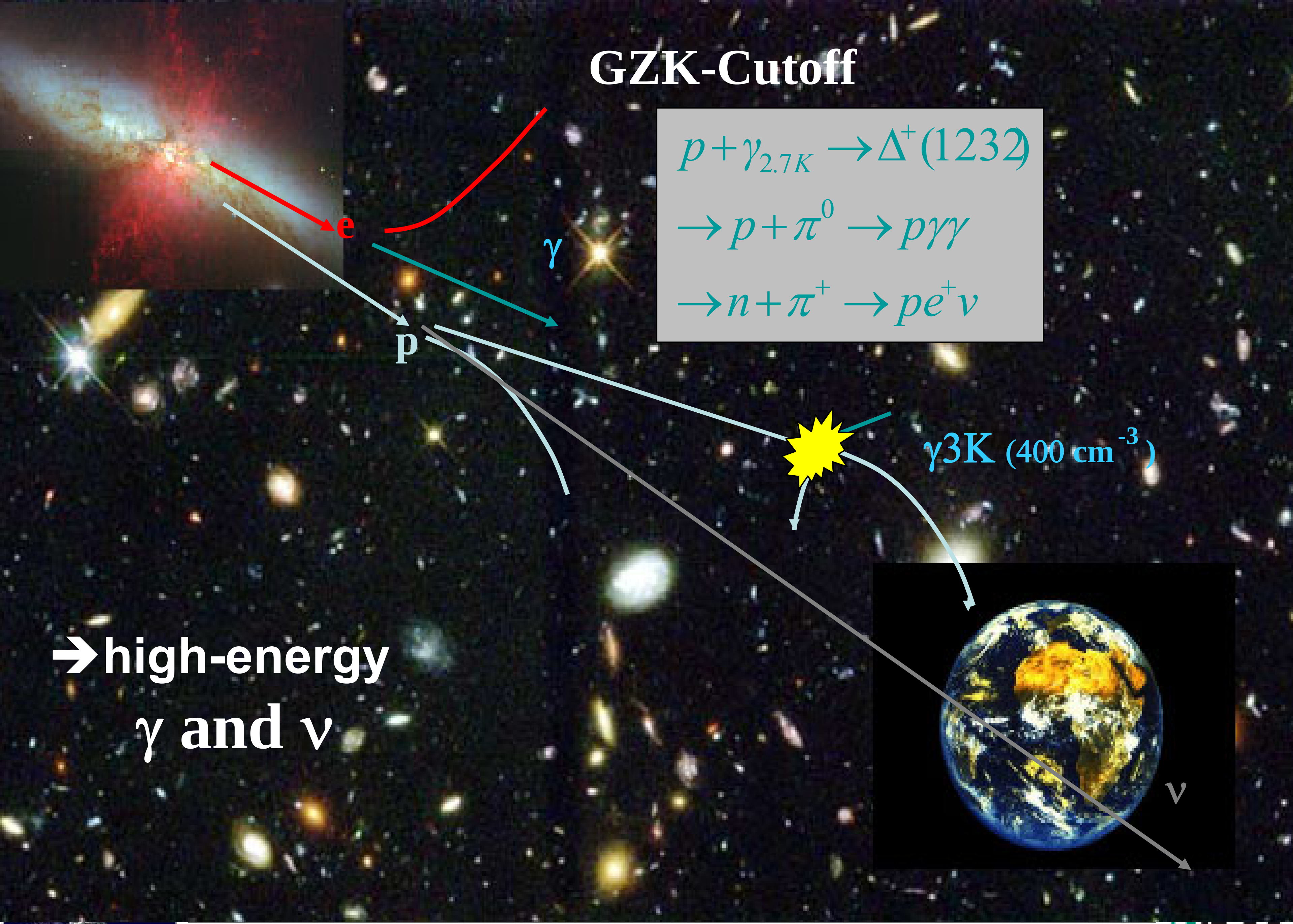
     IceCube and KM3Net

Multi-messenger Approach in Astroparticle Physics



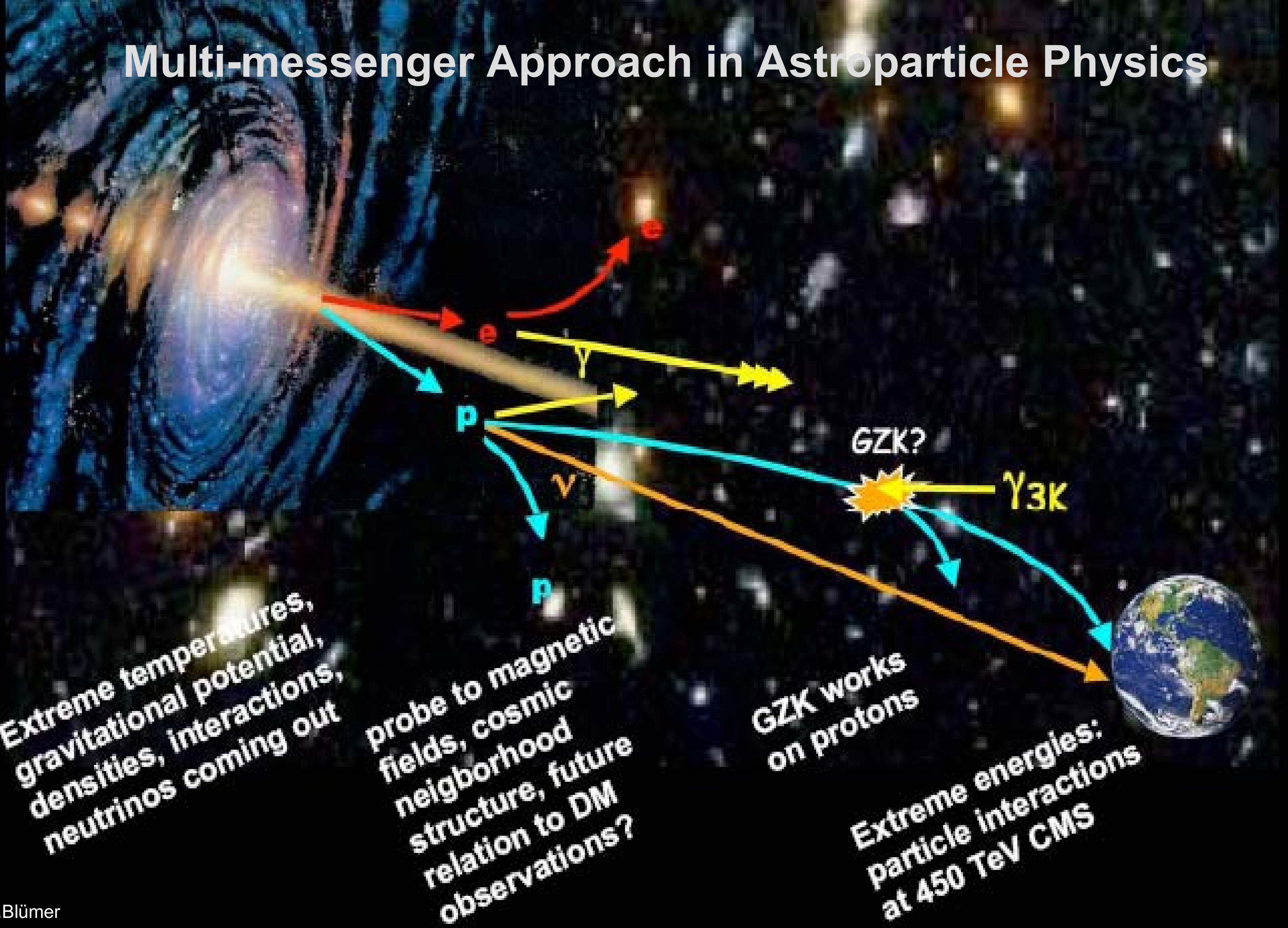
GZK-Cutoff

$$p+\gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n+\pi^{+} \rightarrow pe^{+}\nu$$



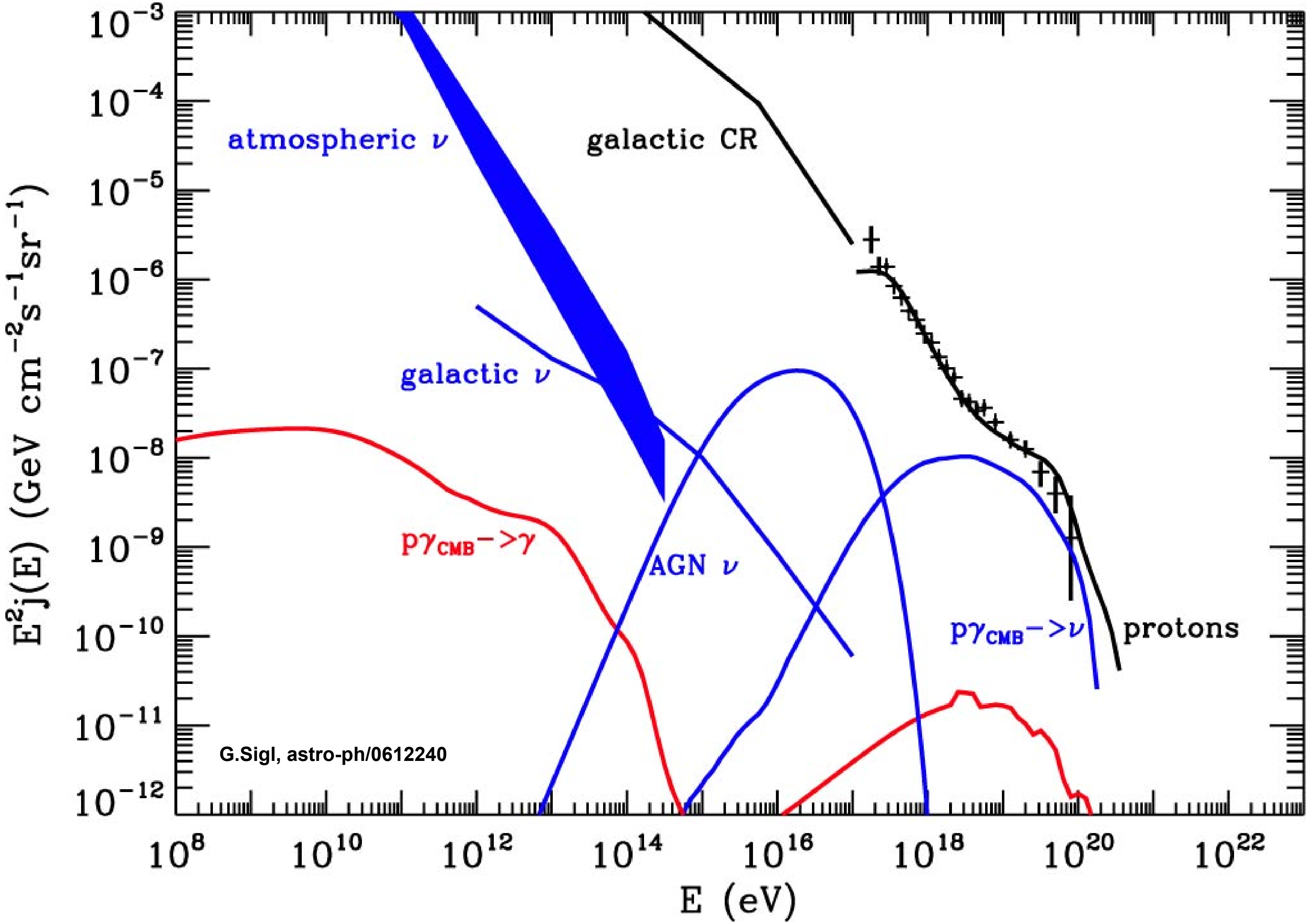
➔high-energy
γ and ν

Multi-messenger Approach in Astroparticle Physics

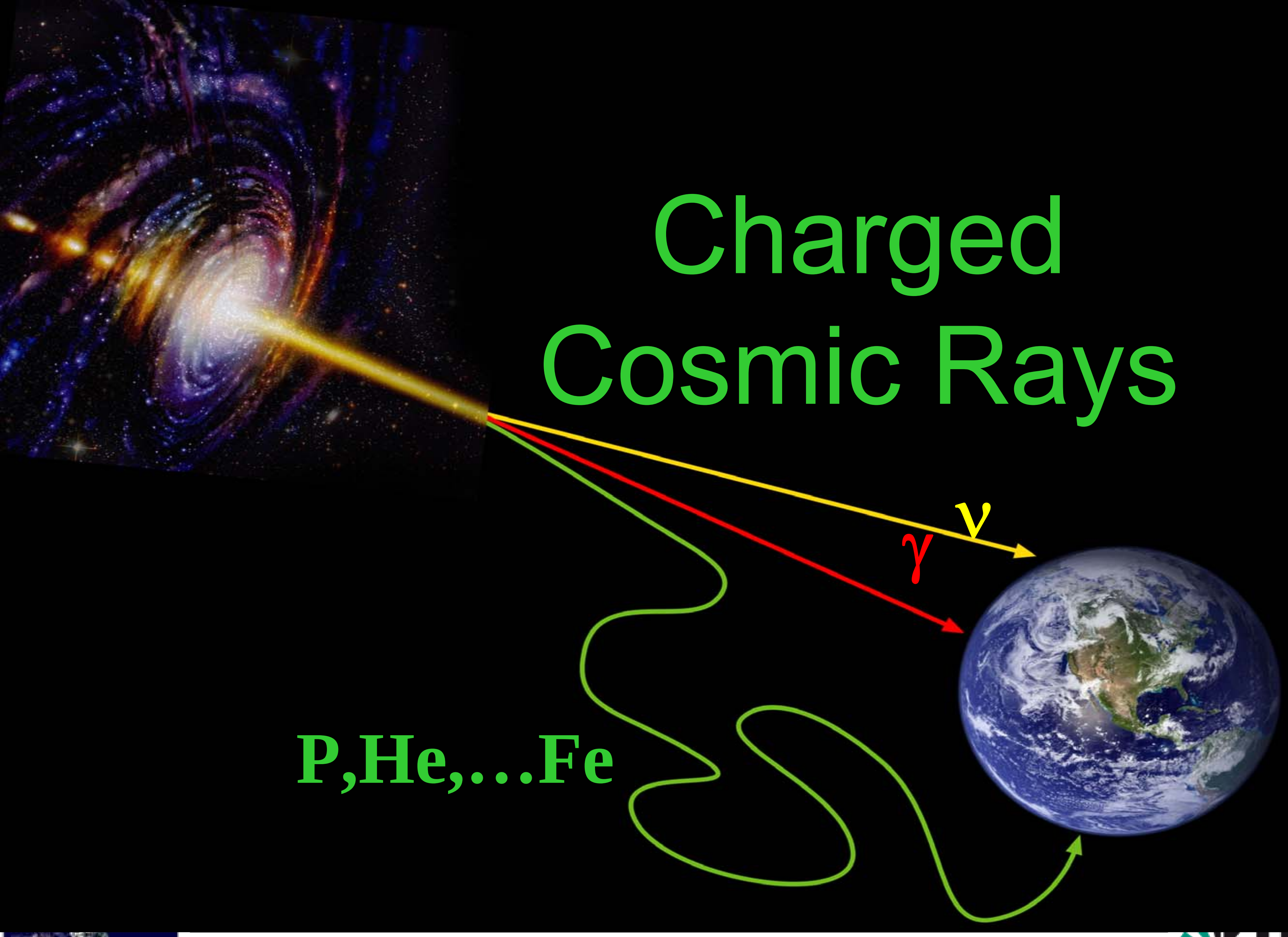


J.Blümer

High Energy Universe: nuclei, γ's, and ν's



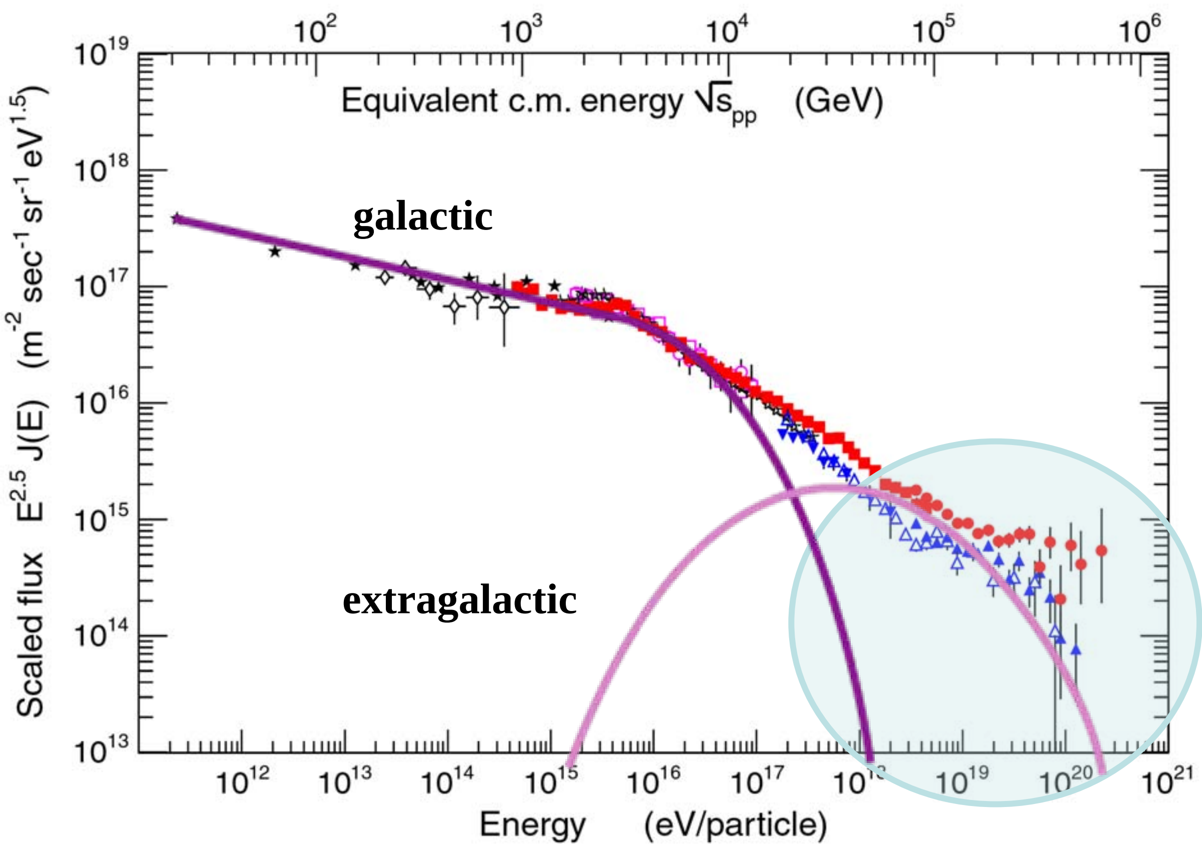
Charged Cosmic Rays



Cosmic Rays at highest energies

Source, acceleration, and mass of the particles unknown – but they exist !

Measurements by large particle detector arrays (AGASA ➔ no cutoff)
or fluorescence telescopes (HiRes ➔ cutoff)



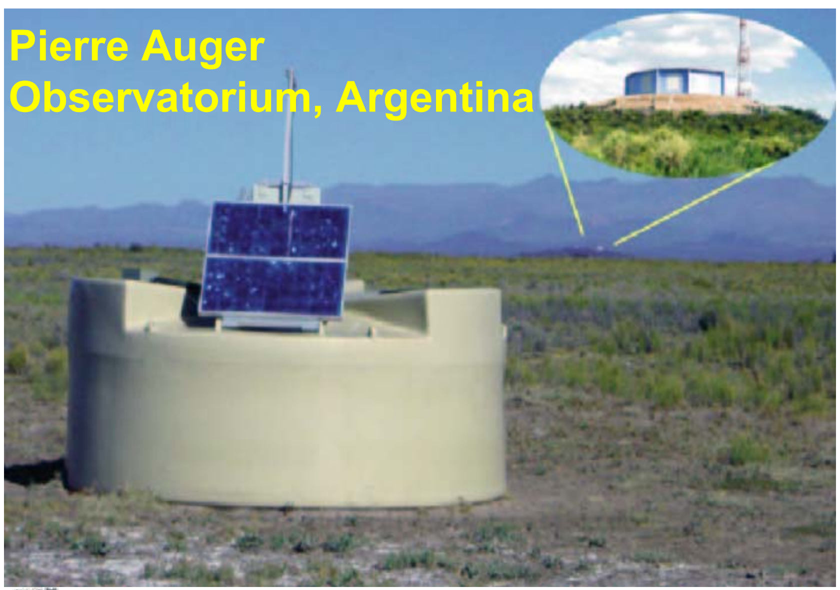
GZK cutoff E>5•10^{19}eV expected

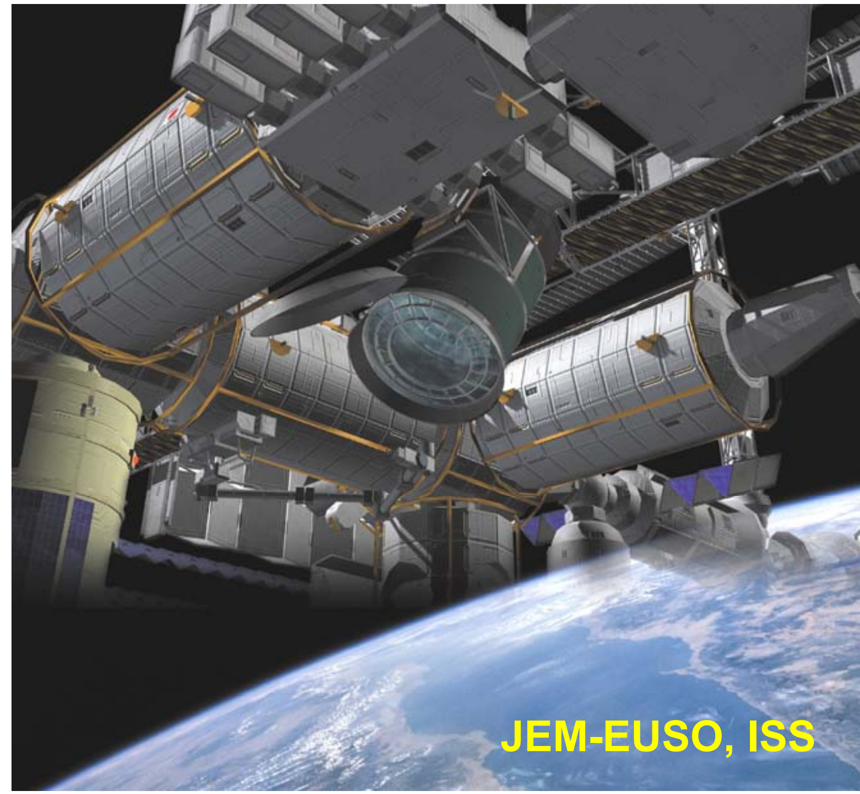
$$p+\gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n+\pi^{+} \rightarrow pe^{+}\nu$$

- **If no GZK:**
  - Nearby sources:
    GUT fossils (TD, DM, ...)
  - Propagation effects:
    violation of Lorentz invariance
    Z-Bursts, …

- **Near sources should be identified by point source astronomy**
  High magnetic rigidity of the primaries (charged particle astronomy)

Cosmic Ray Experiments





Ultra High Energy Cosmic Ray Investigations with the
Pierre Auger Observatory

Pierre Auger Observatory: Science Objectives

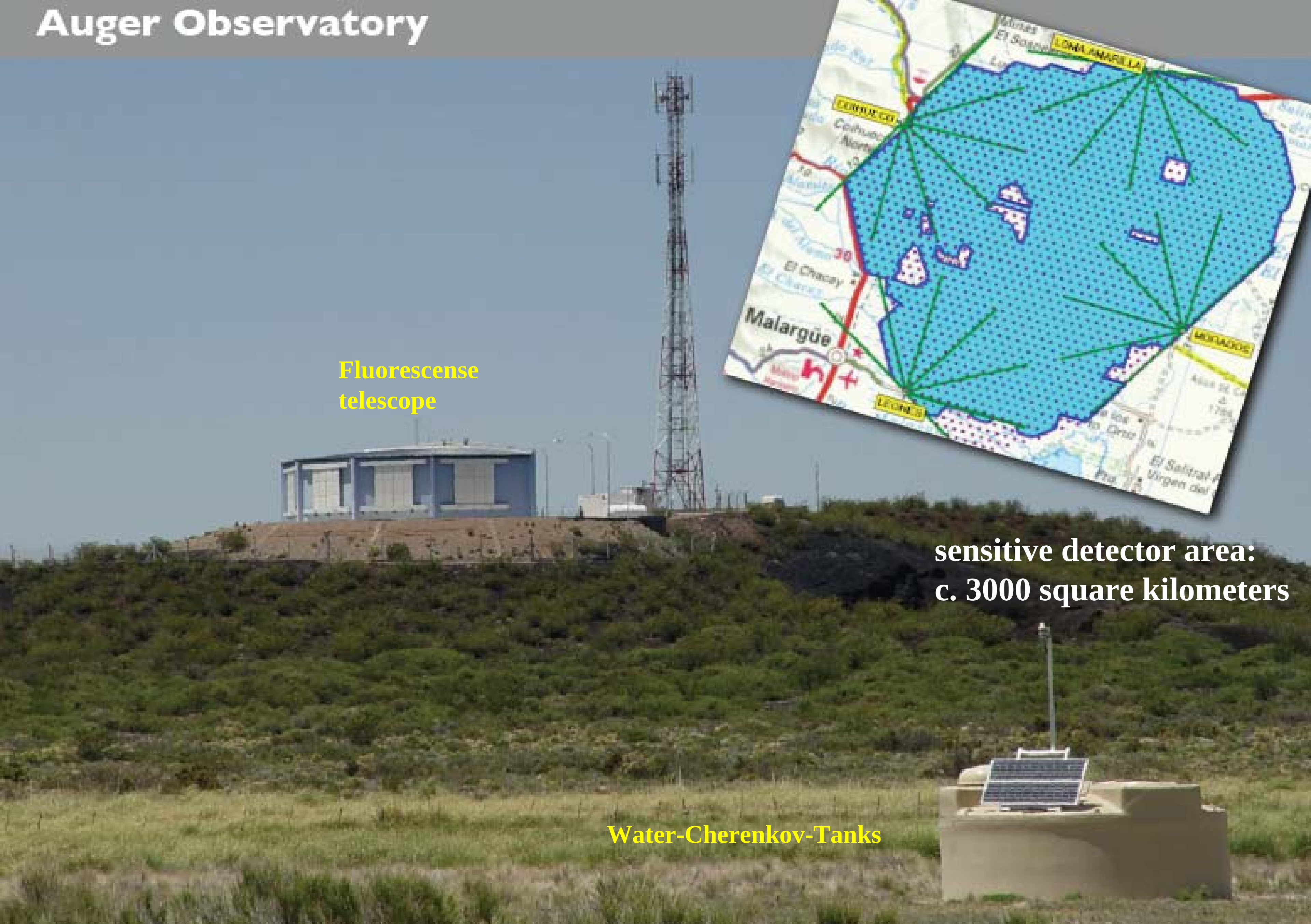
- **understand the nature, origin and propagation of UHECR**
  - point sources?
  - An-/Isotropy of arrival directions?
  - GZK cut-off or continuing spectrum or other structures?
  - primary particle mass, type?
  - acceleration or decay of exotics?
- **measure cosmic rays with high statistics and quality**
  - aperture > 7 000 $km^2 sr$ @10^{19}eV
  - ~ degree angular resolution, zenith angle θ°... 90°
  - primary particle discrimination (light, heavy, γ, ν)
  - calorimetric energy calibration

➔ **hybrid design:**

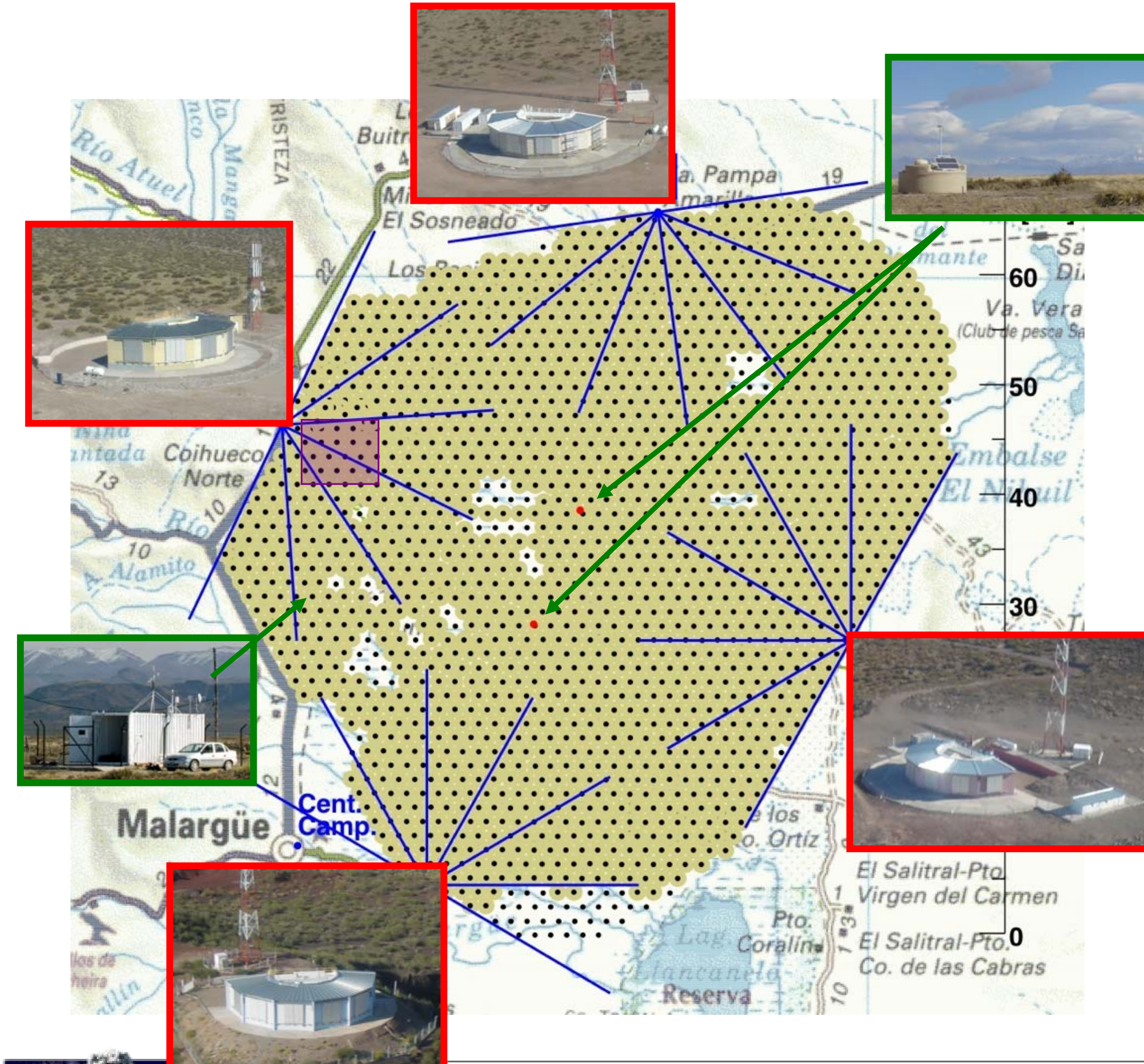
surface detectors and fluorescence telescopes

- measurement of direction, energy and composition of primaries

Auger Observatory



The Pierre Auger Observatory: completed July 2008



1600 surface detector stations: water-Cherenkov tanks (triangular grid of 1.5 km)

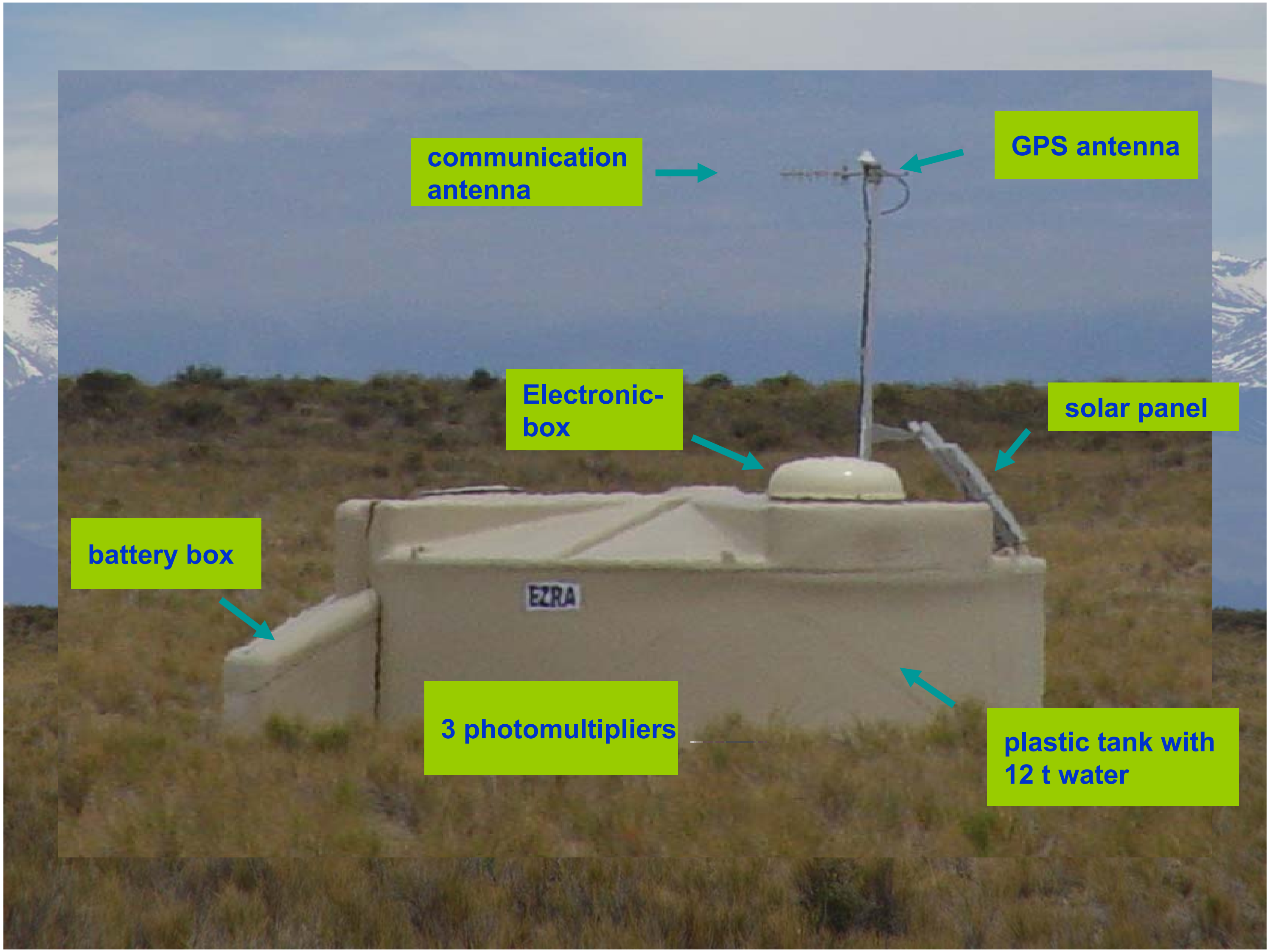
4 fluorescence detectors (24 telescopes in total)

2 laser stations
balloon station

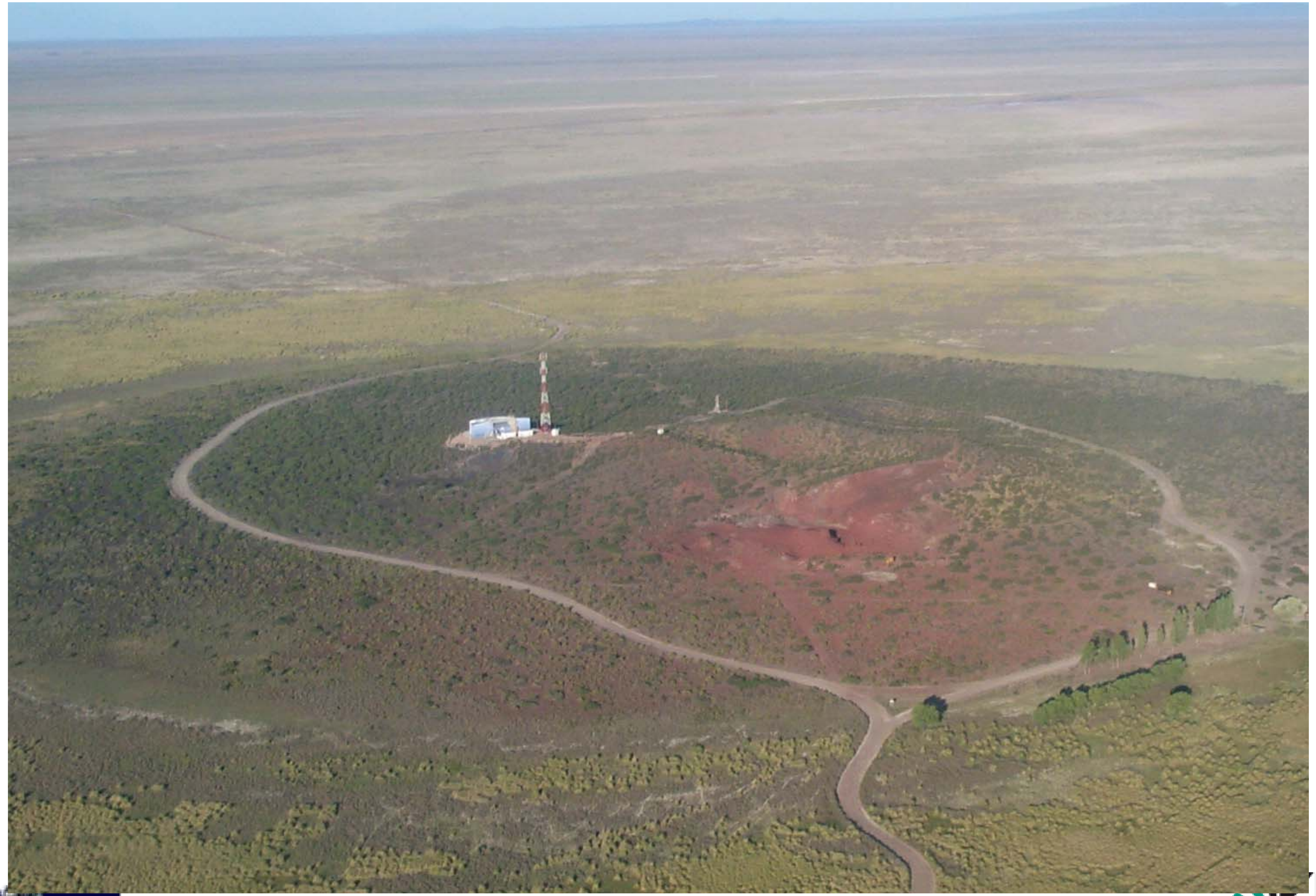
~25km² infill area
HEAT, AMIGA, AERA

Surface array in the Argentinean Pampa

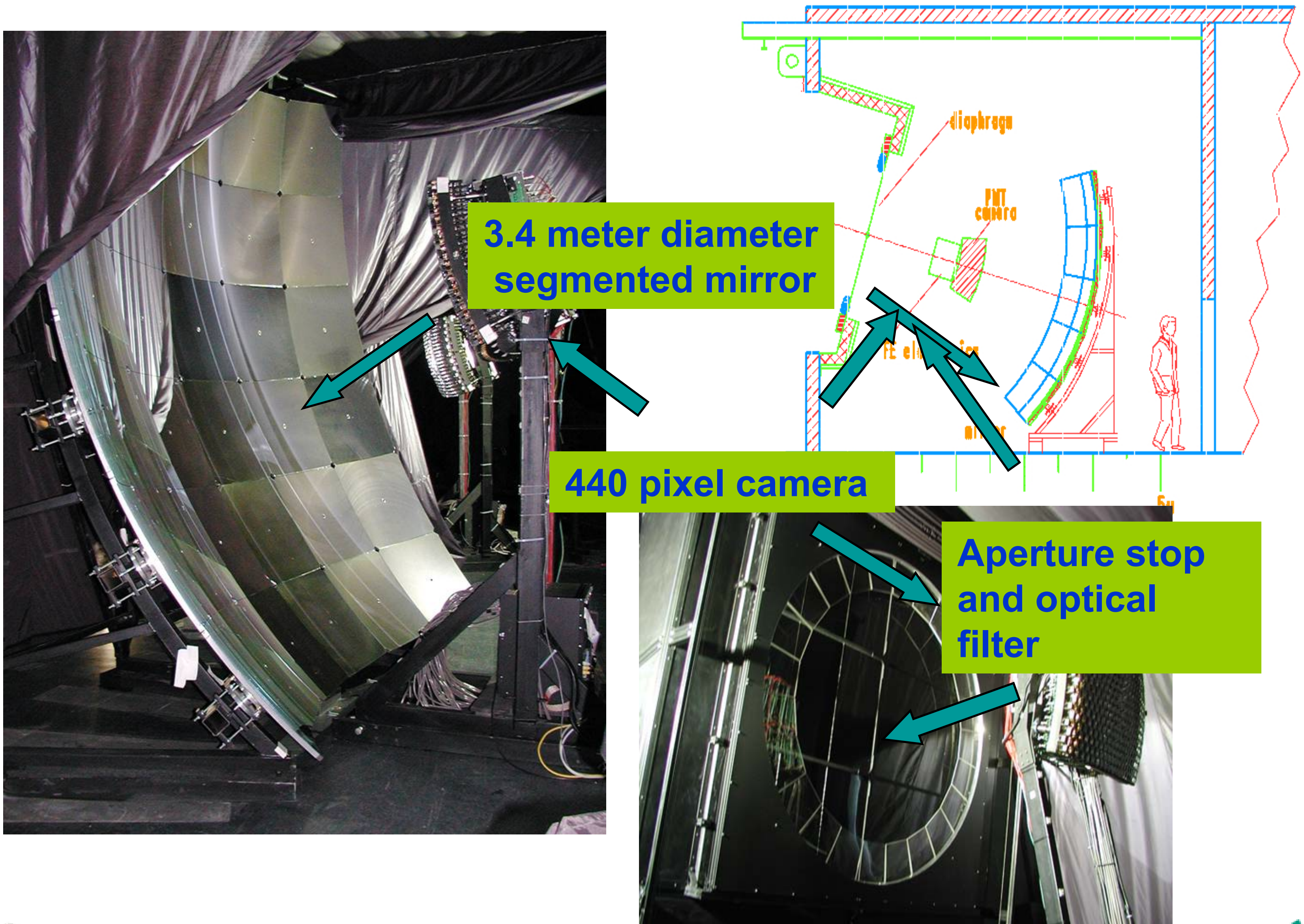
Water Cherenkov Detector



Fluorescence Telescopes



The Fluorescence Detector



Atmospheric Monitoring and Calibration

Atmospheric Monitoring

Central Laser Facility

Lidar at each fluorescence eye

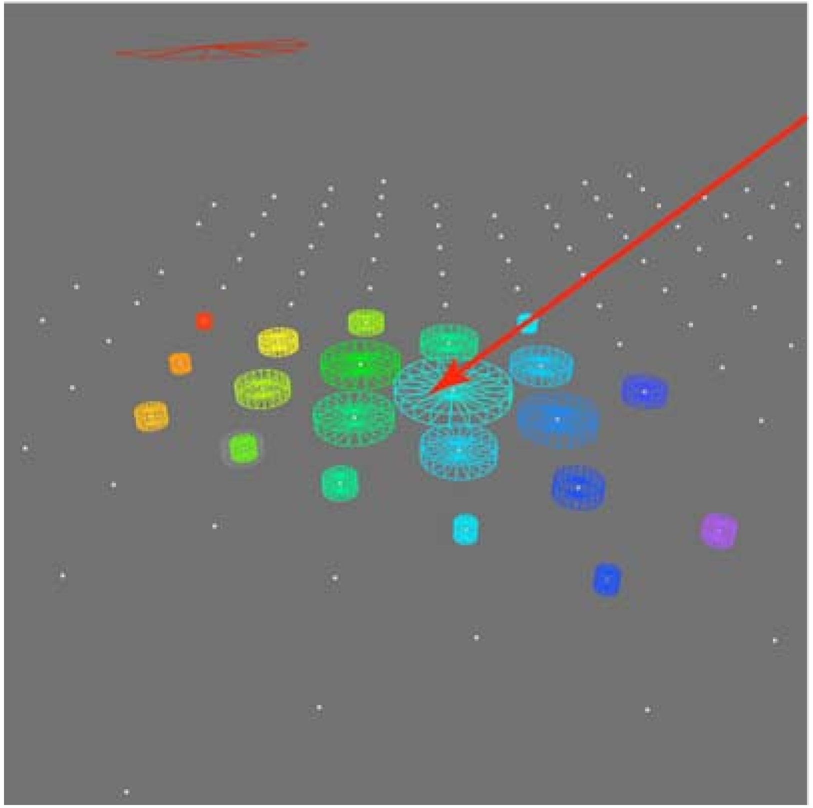
Atmospheric radio sounding measurements

Absolute Calibration

Drum for uniform camera illumination:

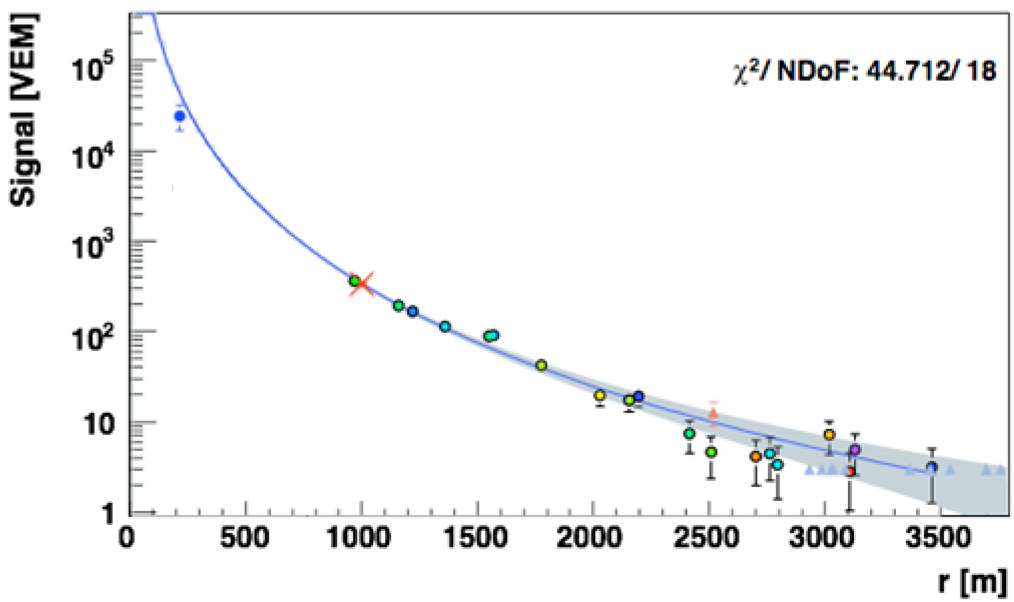
end to end calibration

Surface detector events



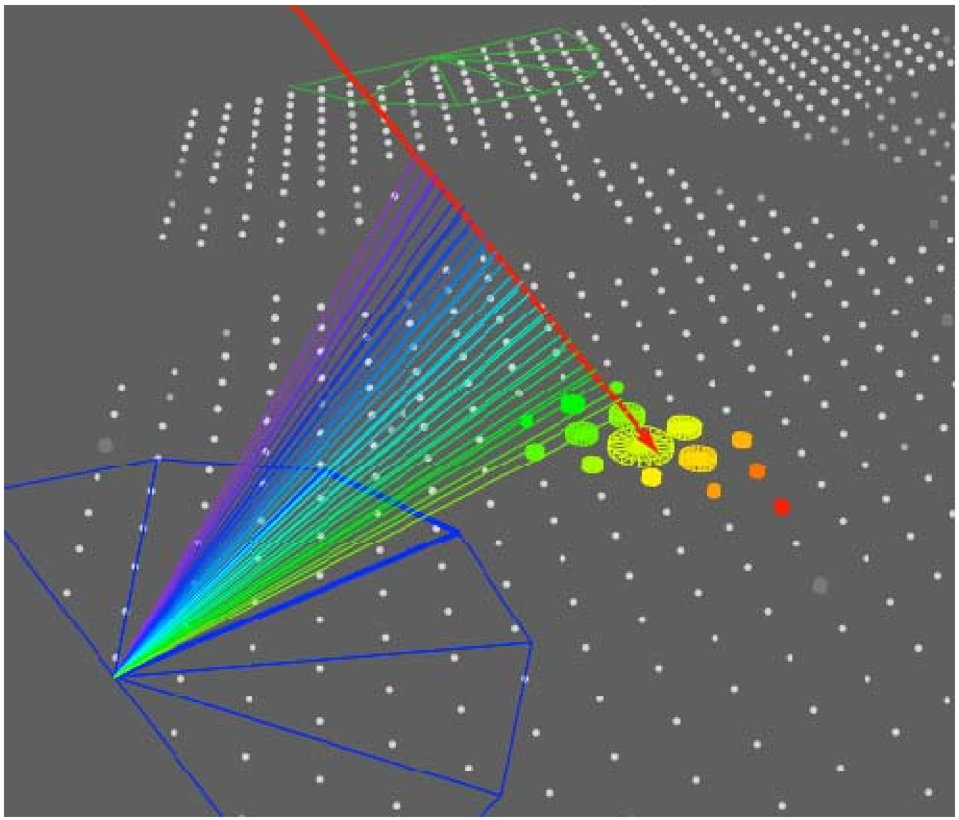
More than 2,000,000 events

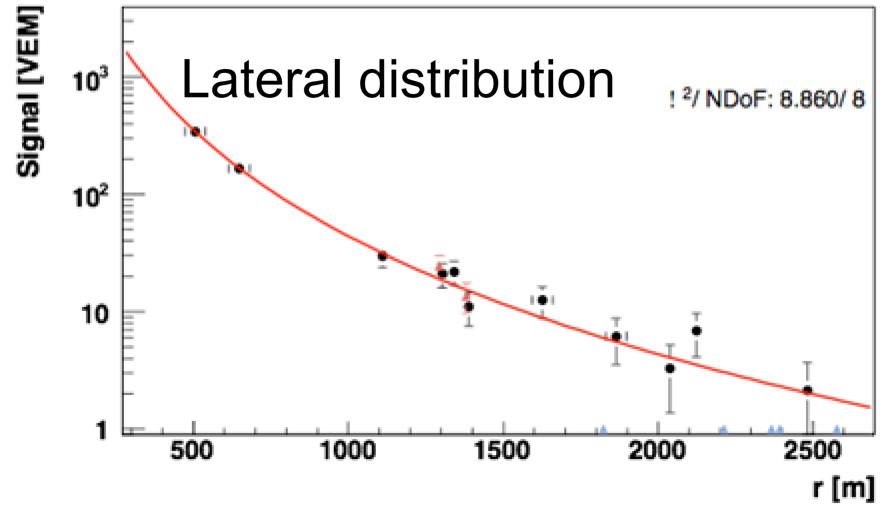
Example: E > 10^{20} eV, θ ≈ 45°

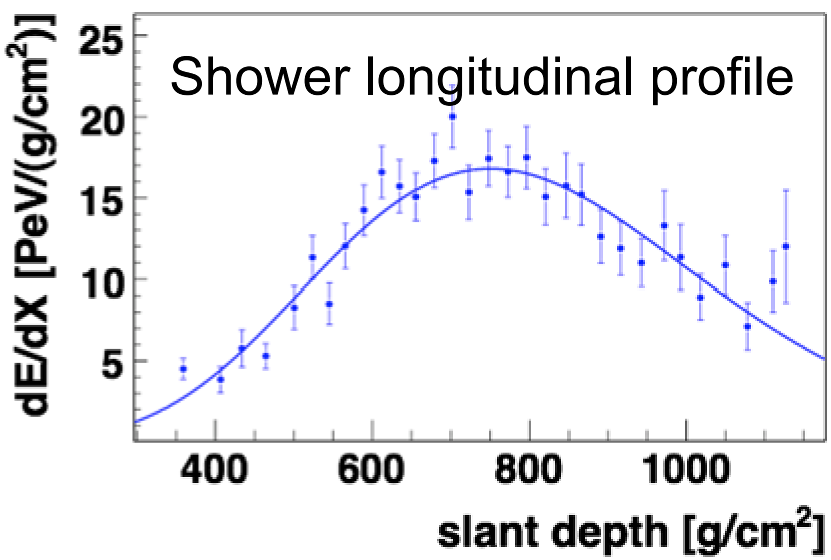


Tank signal in units
of the signal of
a vertical muon

Golden hybrid events

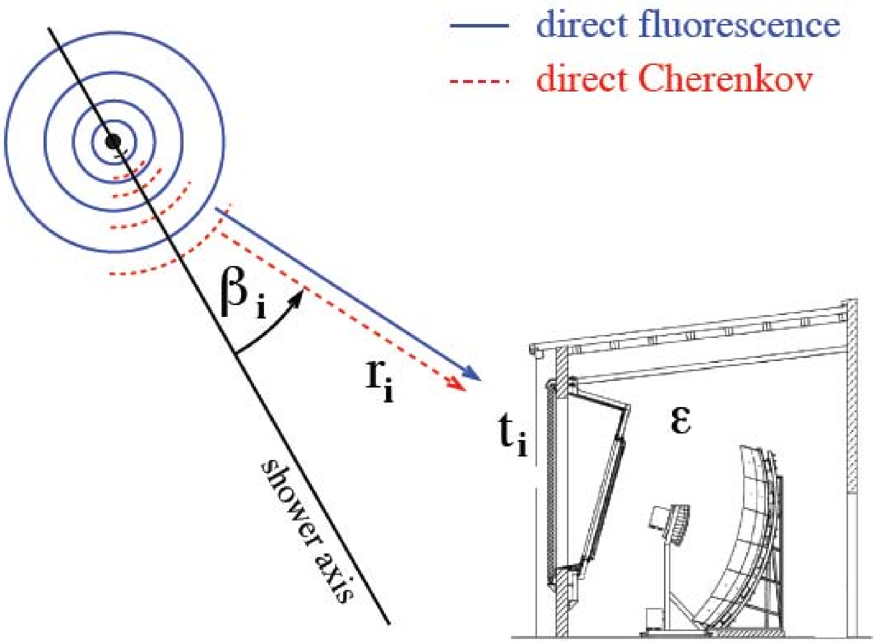


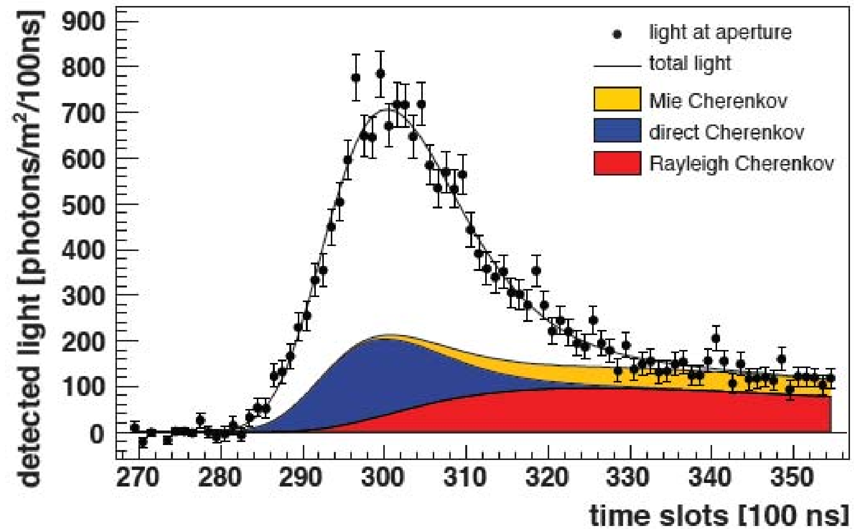


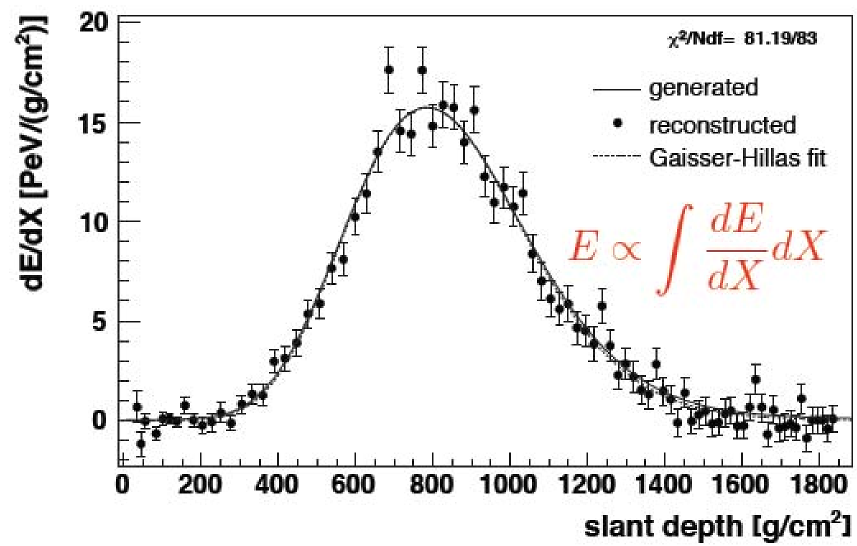


Hybrid events ~120,000
Golden hybrid events ~ 15,000

FD: energy reconstruction

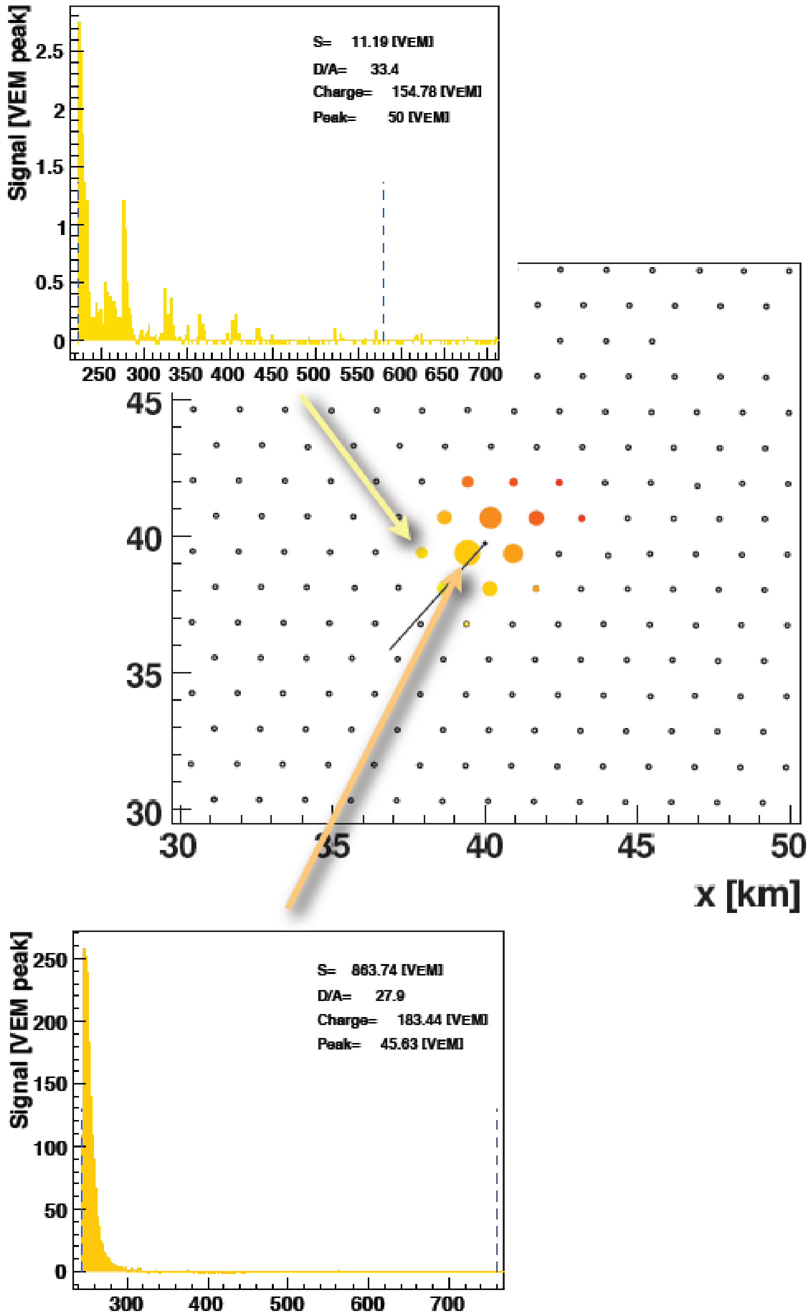


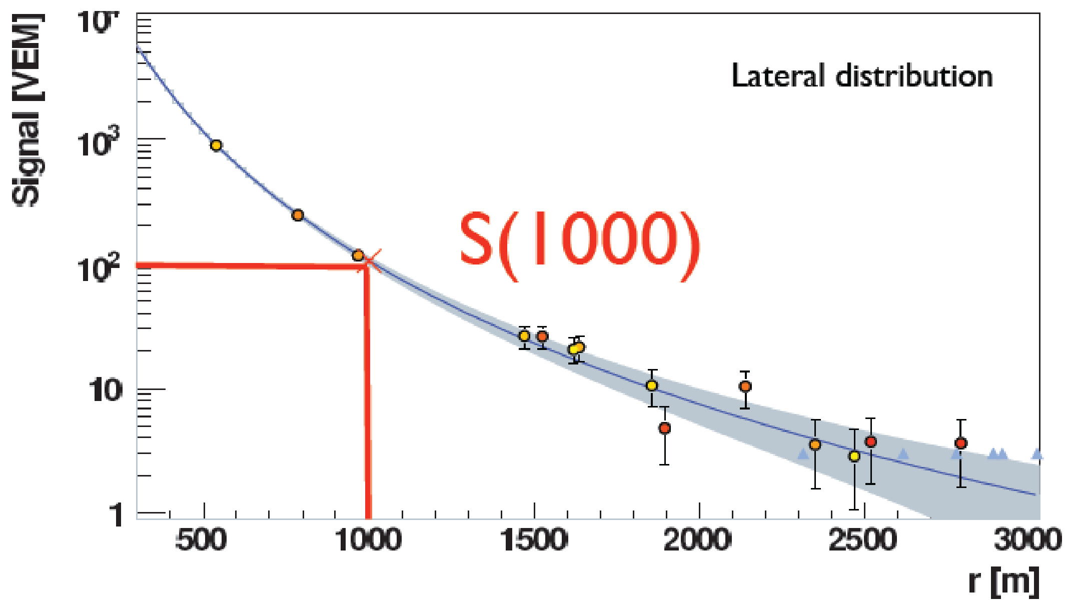




M. Unger et al.
NIM A: 588, 2008, p. 433

SD: S(1000) reconstruction



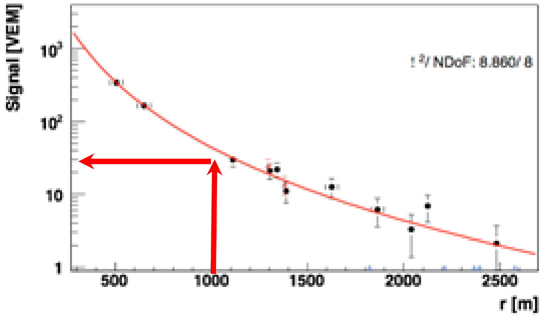


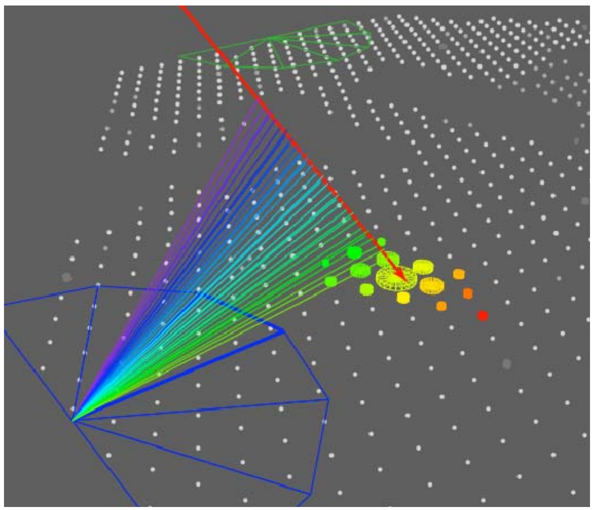
Detector signal at 1000 m from shower core

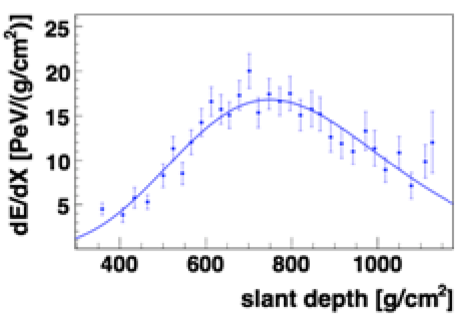
- S(1000)
- determined for each surface detector event

S(1000) ~ E

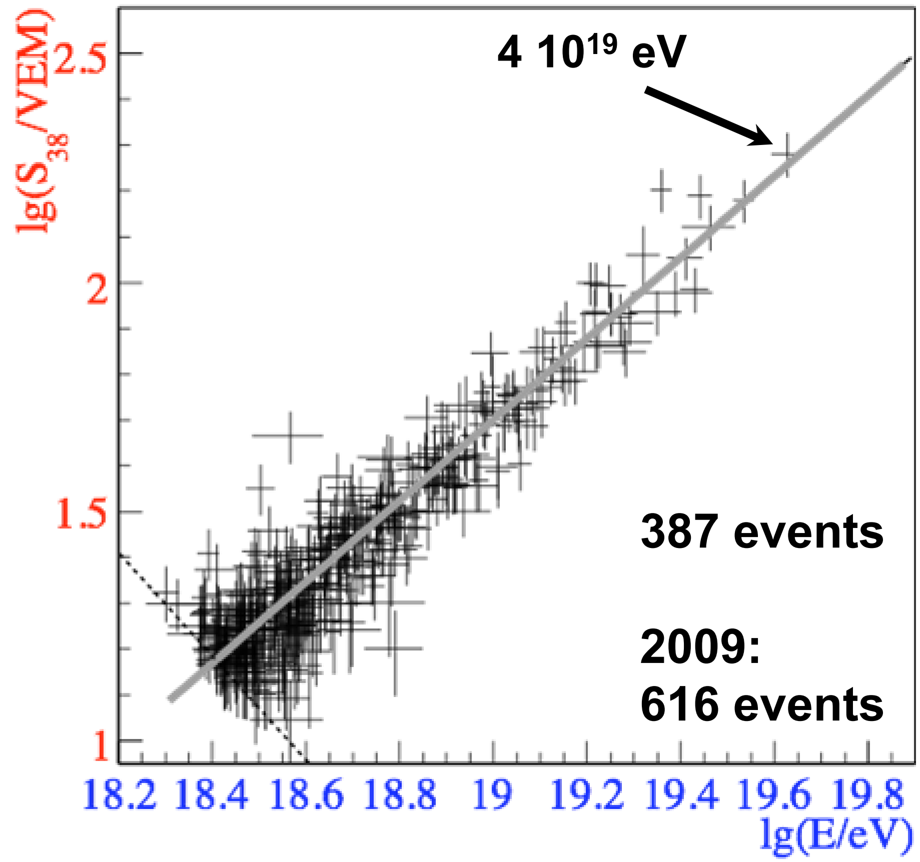
Energy calibration of surface detector by Hybrid events







Shower size at 1000m and θ=38°

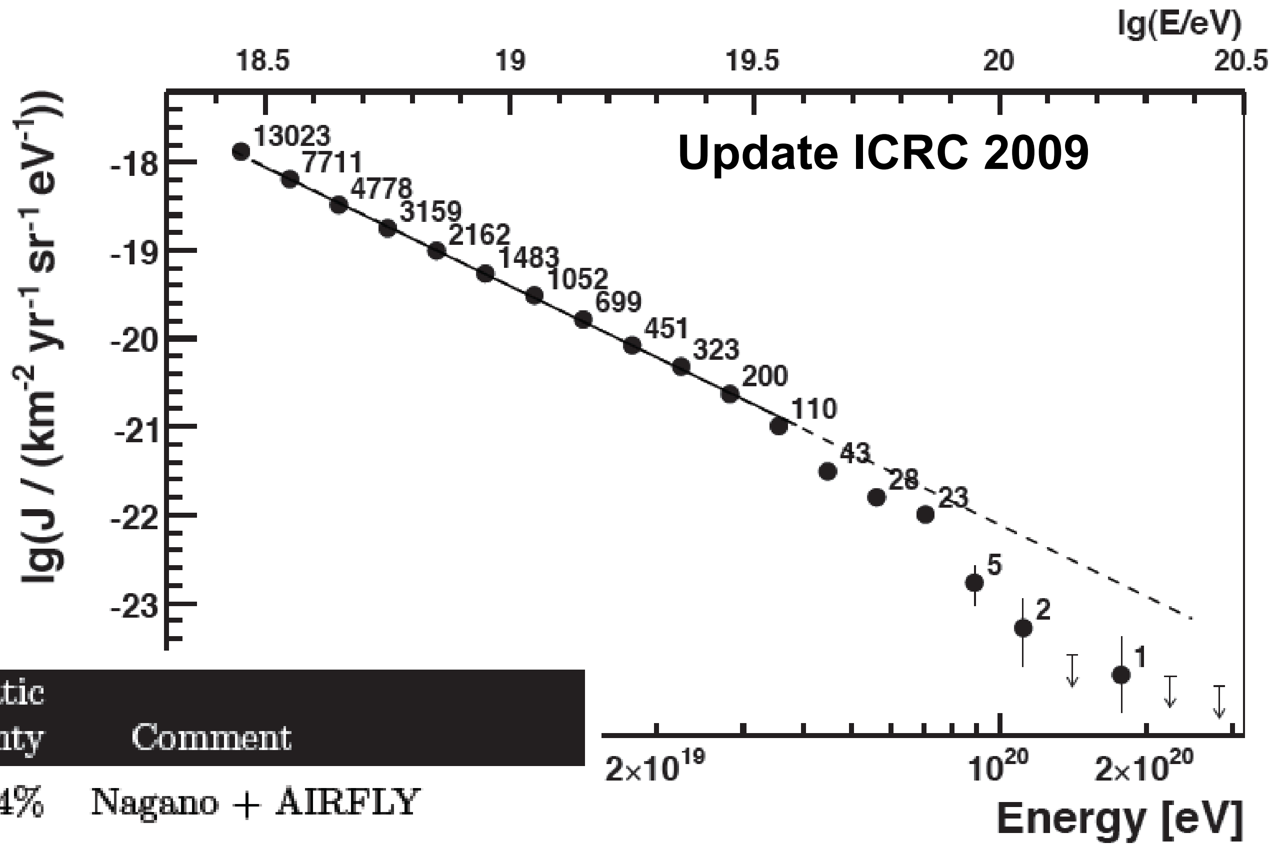


Fluorescence detector energy

$$E_{\mathrm{prim}} = f_{\mathrm{corr}} \cdot \int \frac{dE_{\mathrm{ion}}}{dX}\, dX$$

Energy spectrum

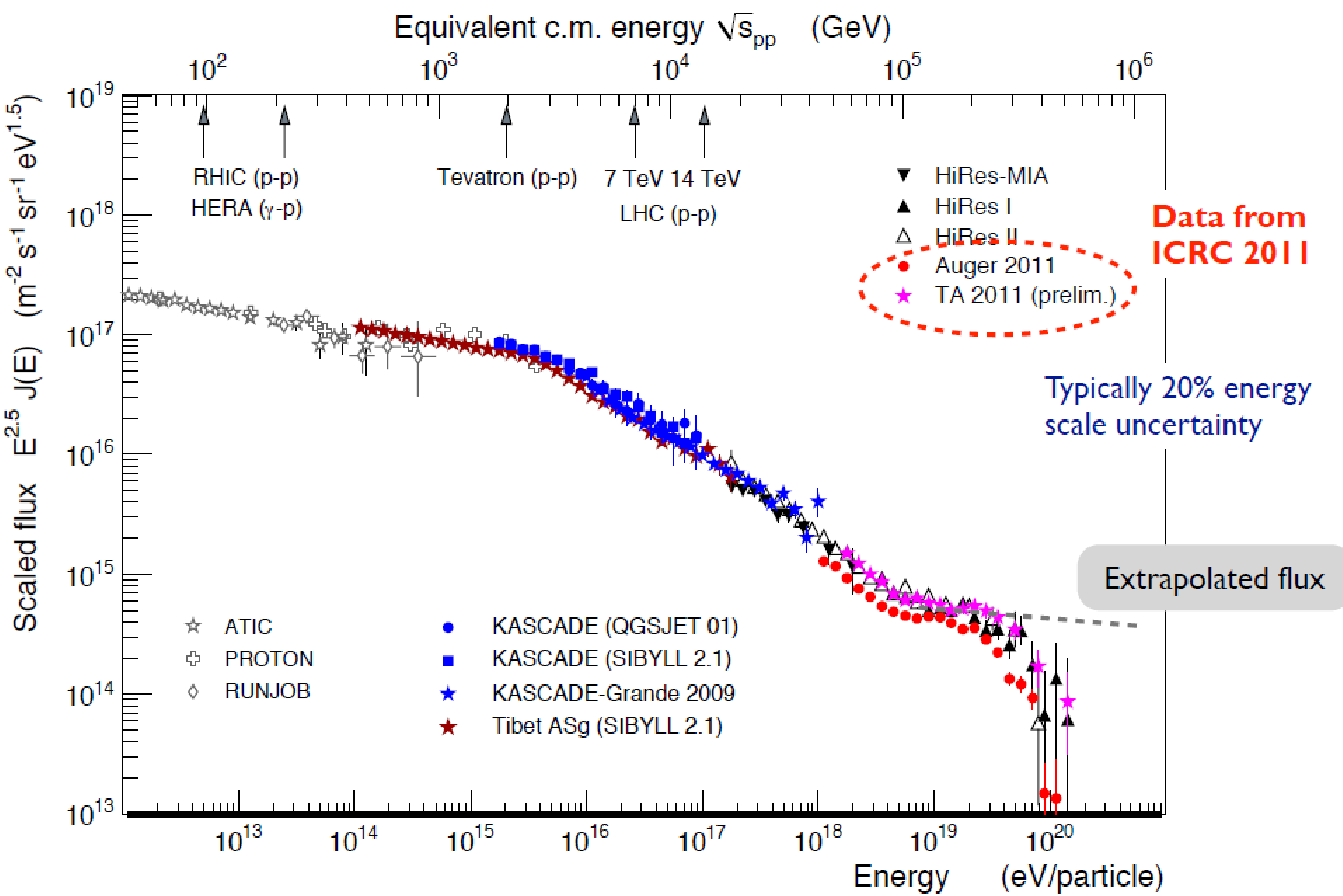
Corrected for energy resolution by a forward folding procedure
- **energy dependent**
- **less than 20% over the full range**



Source	Systematic uncertainty	Comment
Fluorescence yield	14%	Nagano + AIRFLY
P,T and humidity effects on yield	7%	
Calibration	9.5%	Calib. source, laser
Atmosphere	4%	
Reconstruction	10%	Optical spot, Lat. Ch. dist.
Invisible energy	4%	Model dependence
Total	22%	

➔ Suppression is there!

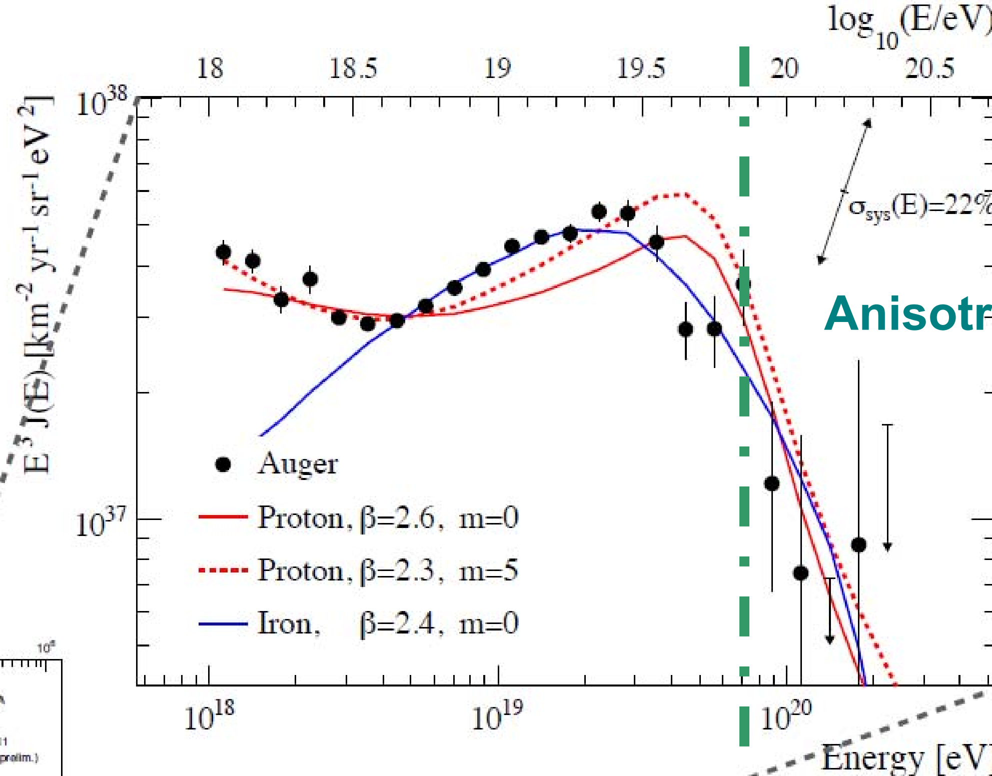
Energy spectrum

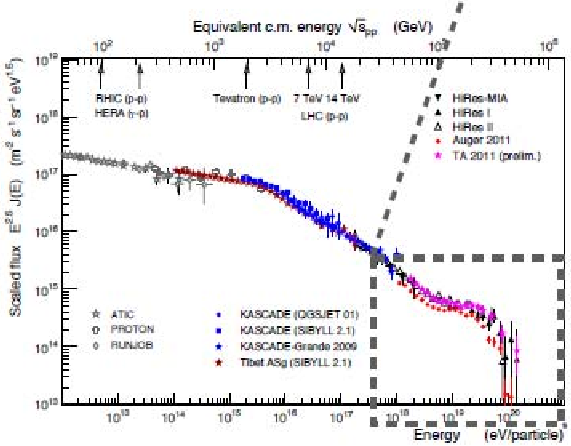


Energy spectrum

Proton dominated flux
Ankle: e^+e^- pair production
Suppression: delta resonance

(Dip model of Berezinsky et al.)



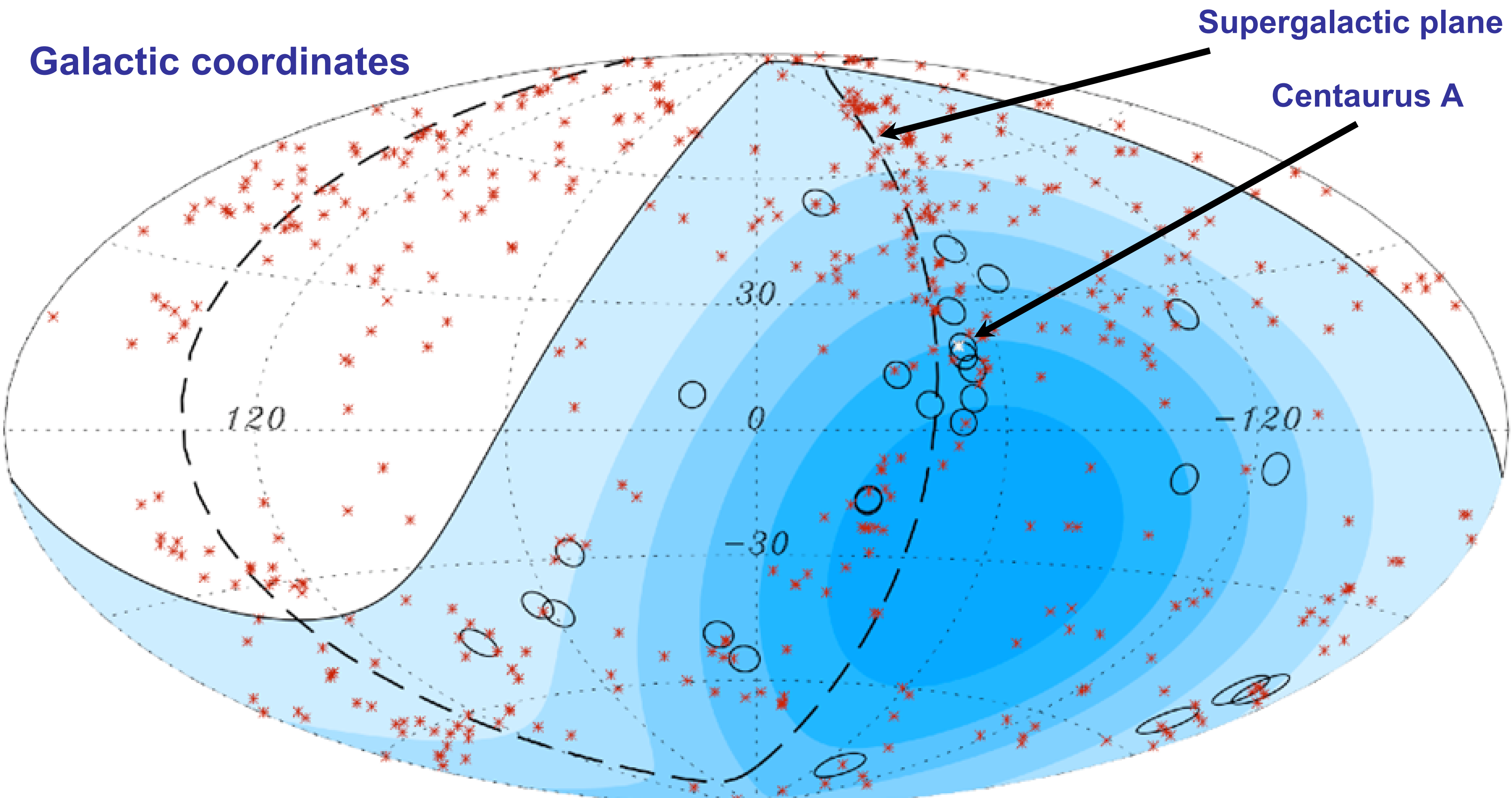


Iron dominated flux
Ankle: transition to galactic sources
Suppression: giant dipole resonance

? Observed flux suppression is due entirely to GZK effect
? Observed flux suppression is signature of maximum acceleration energy
? Observed flux suppression is due to both source cutoff and GZK effect

Anisotropy of ultra-high energy cosmic rays

Galactic coordinates



Veron-Cetty: 472 AGN (z< 0.018, ~75 Mpc)
318 in field of view of Auger

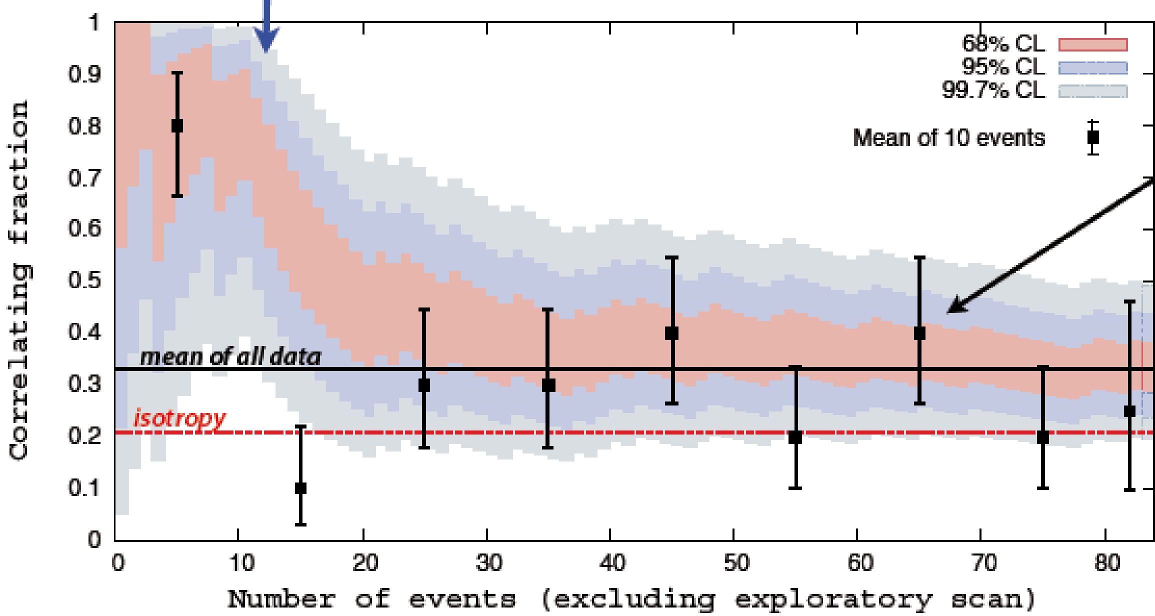
Auger: 27 events above 5.7 10^{19} eV,
20 correlated within 3.1°,
5.7 expected

The Pierre Auger Collaboration (9 November 2007) *Science* 318 (5852), 938

Current status of correlation with AGNs

Auger Observatory (2011)

Science publication: 9/13 events ~69% correlated, expectation for isotropy 21%

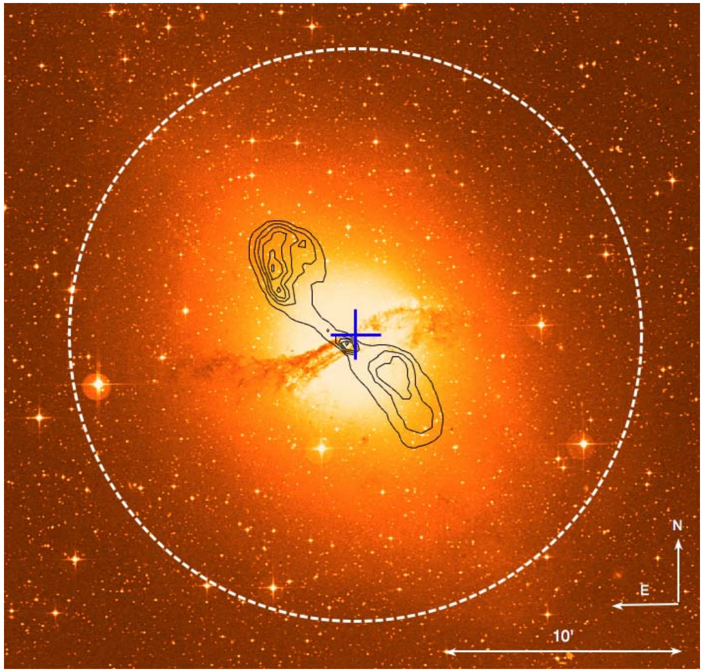


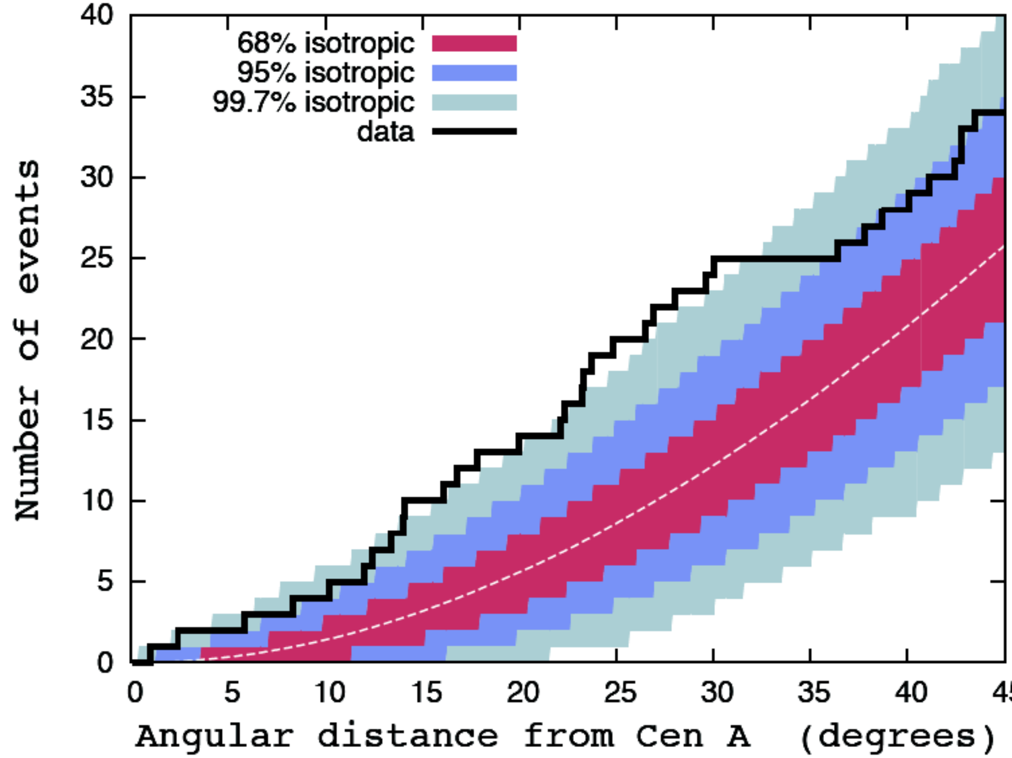
Differential estimate every 10 events

June 2011: 28 out of 84 correlated estimate now 33 ± 5% (P = 0.006)

Indications for weak anisotropy

Special case: Centaurus A





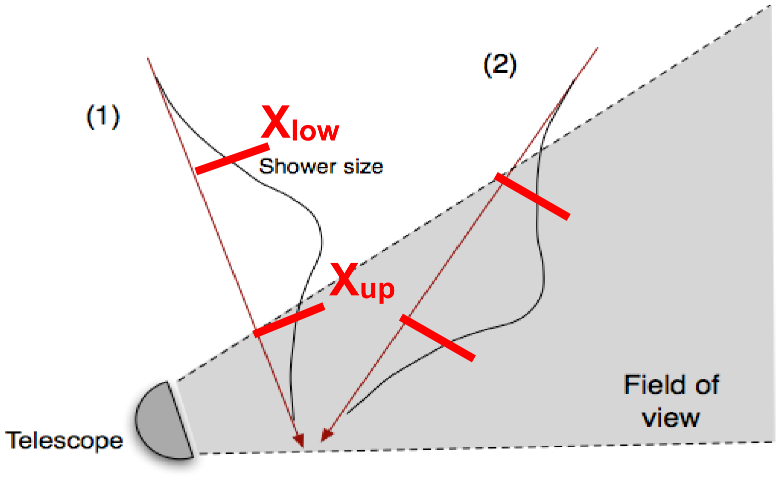
CEN A:
optical image plus radio contours (VLA), Arxiv 0903.1582v1

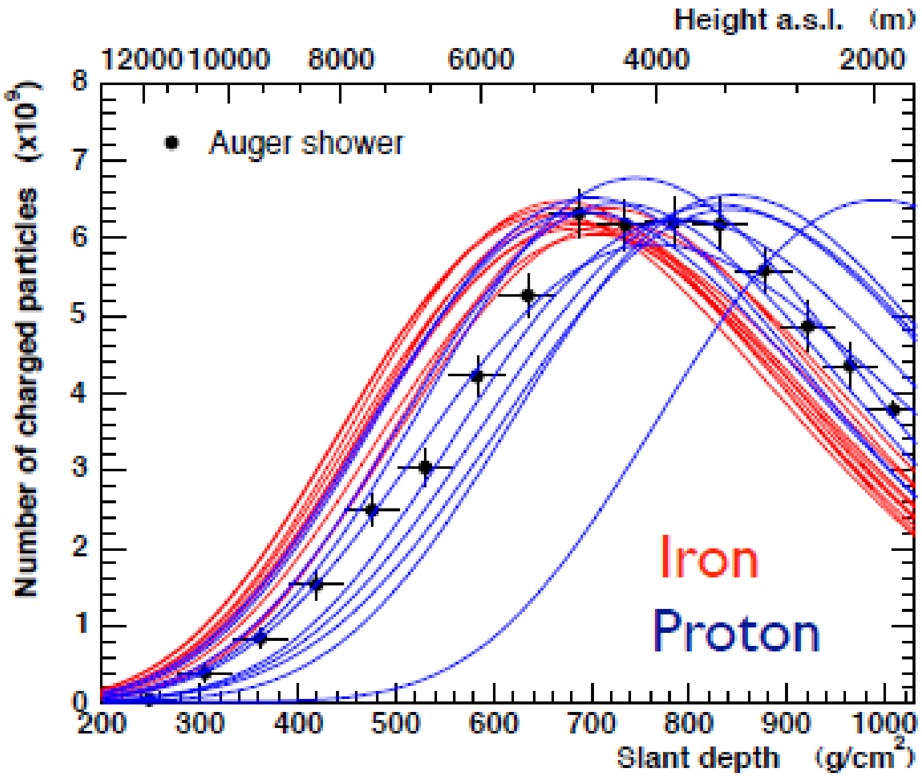
Cumulative number of events with energy E>=55 EeV as a function of angular distance from the direction of Cen A.

Maximum deviation from isotropy at 24°!
19 observed vs 7.6 expected ➔ LiMa 3.3 sigma

Astropart. Phys. 34 (2010) 314

Composition: measurement of longitudinal profile





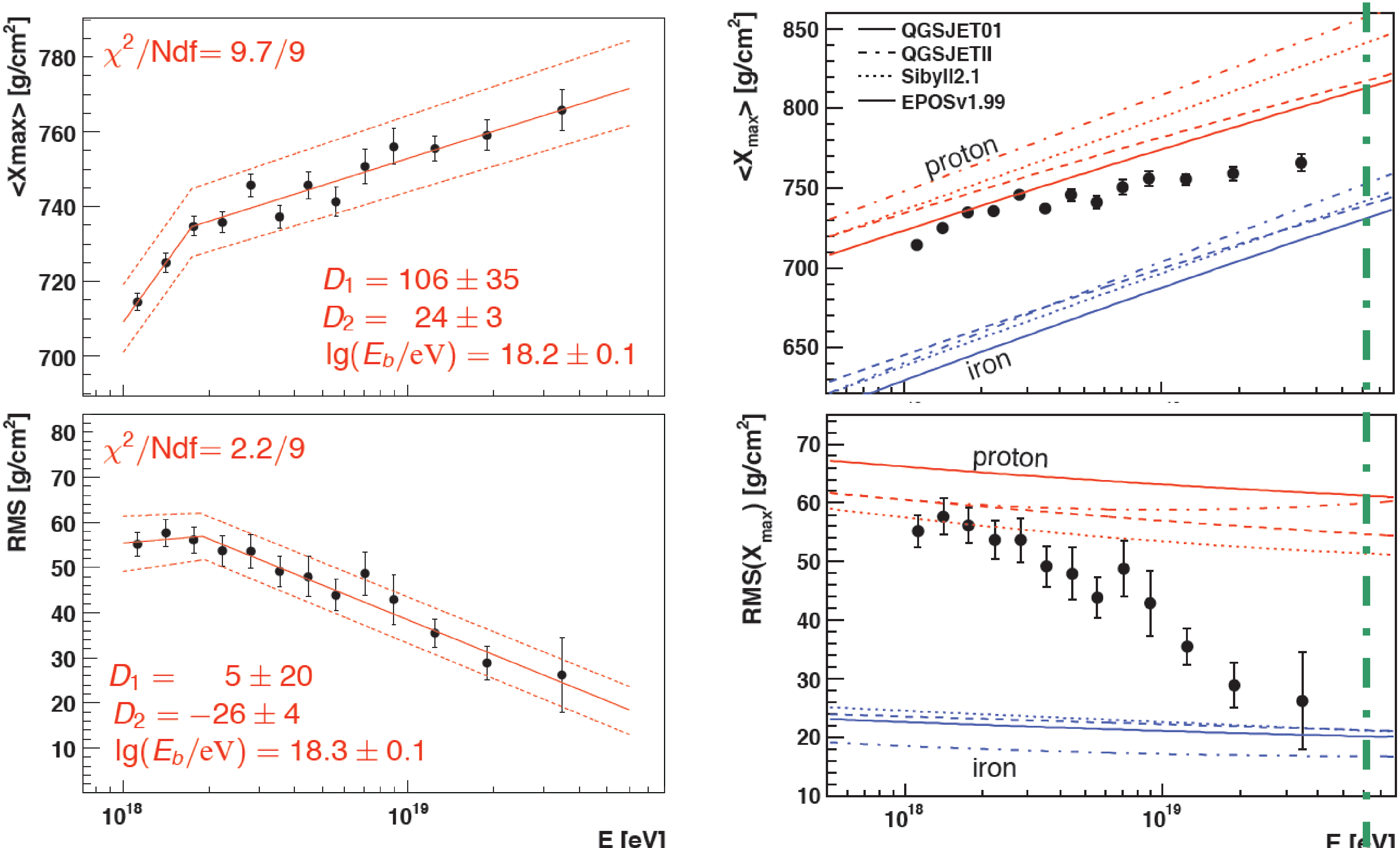
Field of view bias needs to be accounted for

X_{low}, X_{up} are determined from data, no simulation needed

Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

(Unger et al., ICRC 2007)

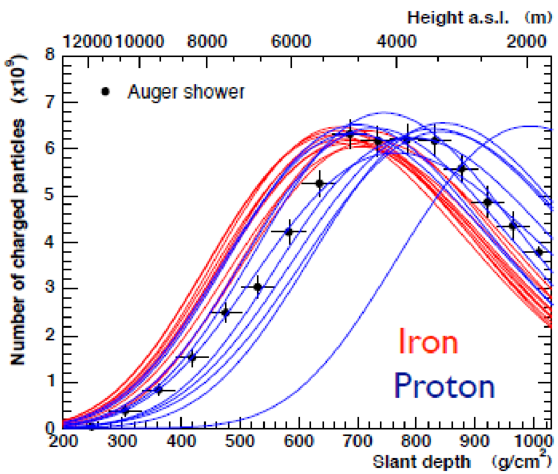
Composition: mean depth and rms of shower maximum

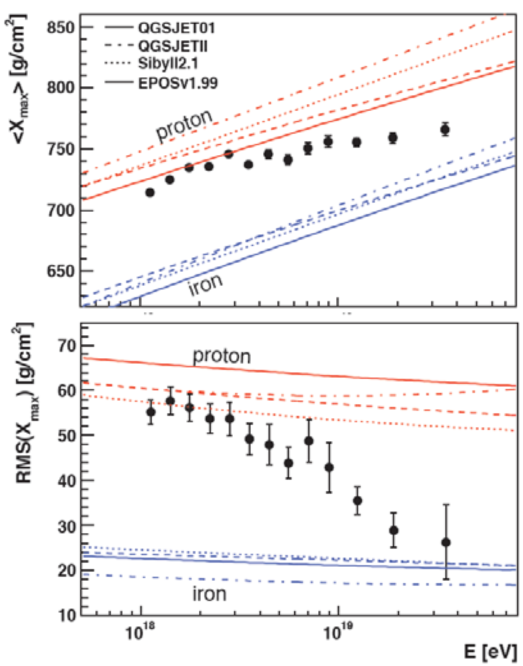


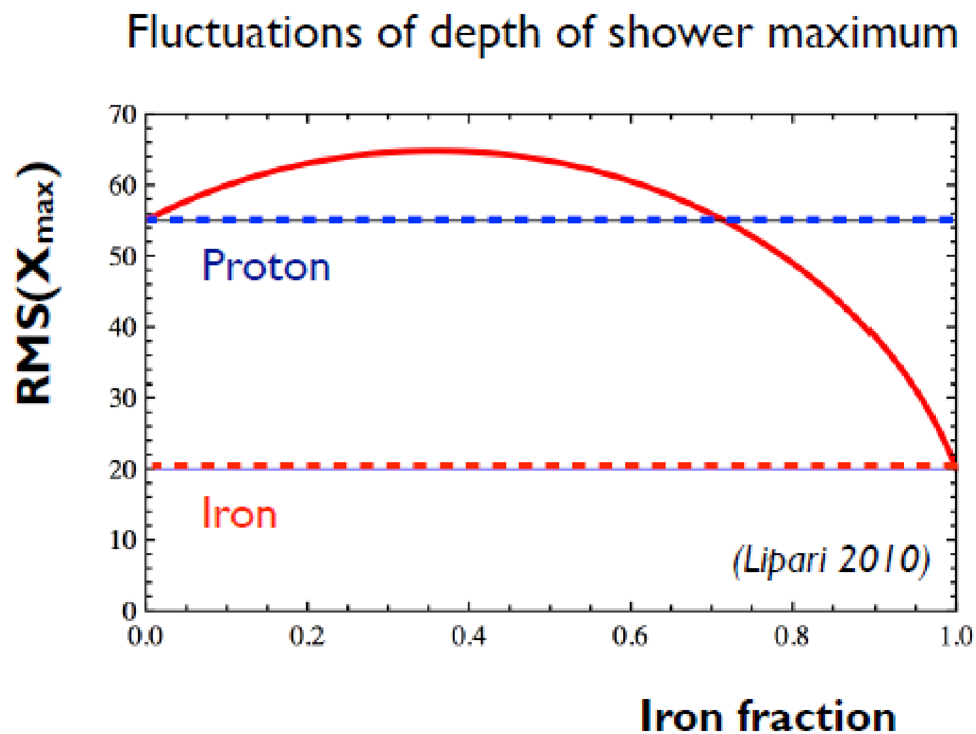
J.Bellido-Auger Collaboration, ICRC09

Anisotropy

Composition: be careful with RMS





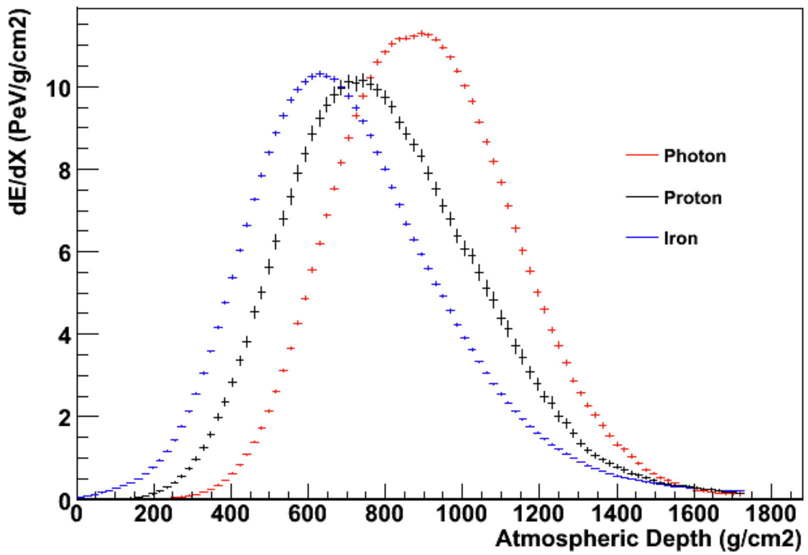


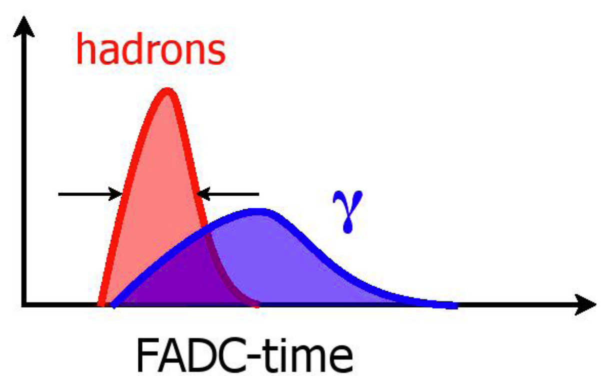
RMS value is not linearly composition dependent!

Photon search: muon poor EAS

Photon inititated showers penetrate deeper in the atmosphere
➔higher X_{max} (FD)

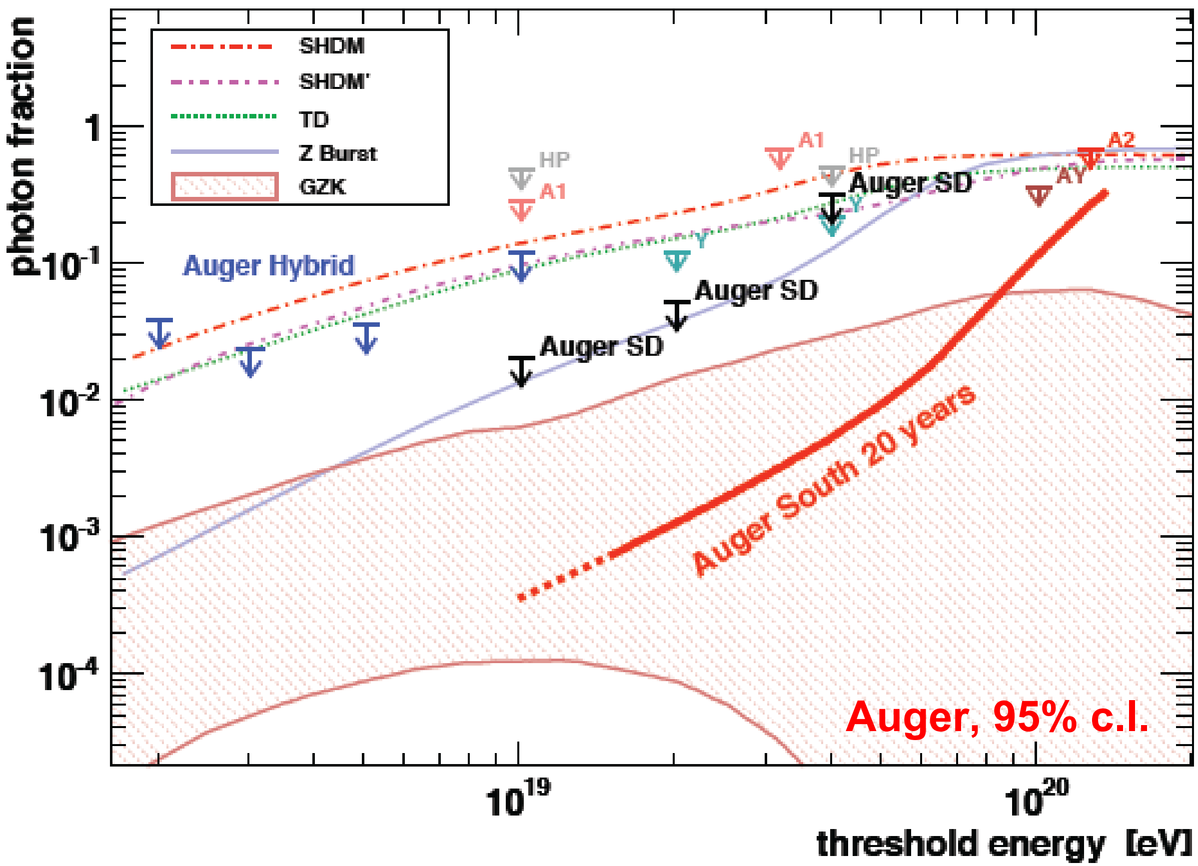
Photon inititated showers are pure electromagnetic EAS
➔ less muons, different signal shape in particle detector (SD)





Limit on fraction of photons in UHECR flux

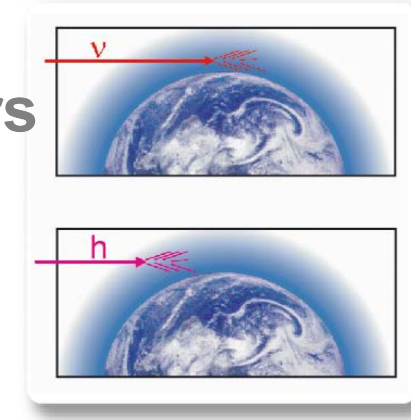
Photons penetrate deeper in Atmospheres and have less muons



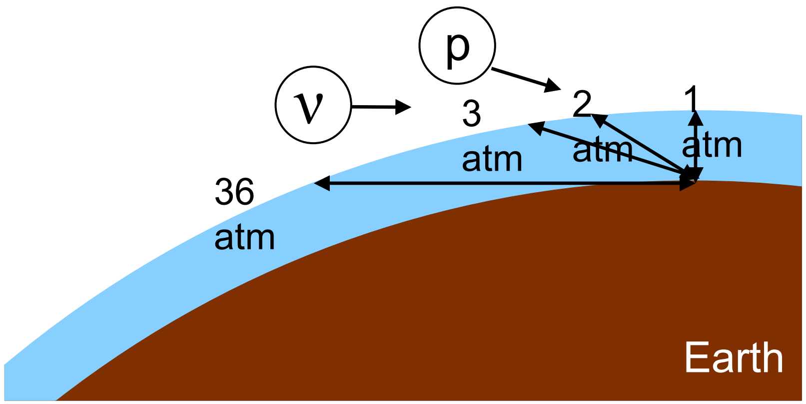
Astropart. Phys. 29 (2008) 243
Astropart. Phys. (2009), arxiv 0903-1127

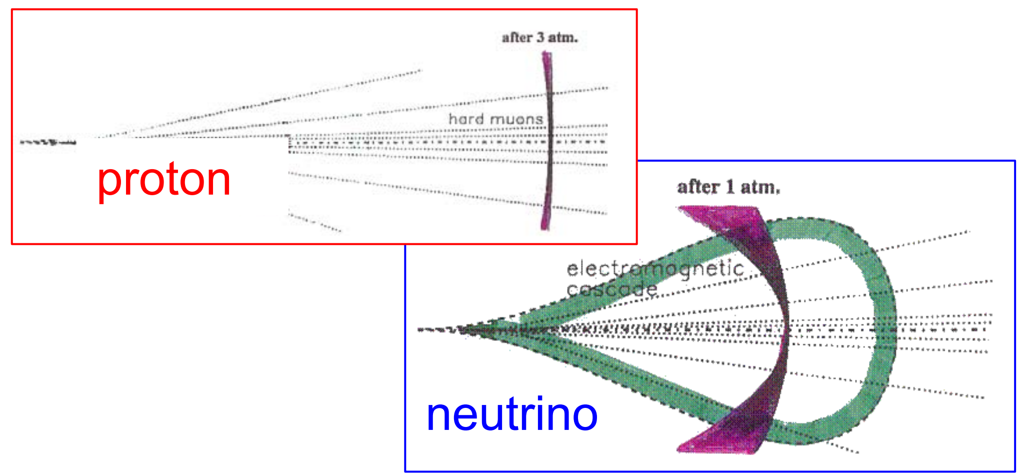
Many exotic source scenarios excluded

Neutrino search: horizontal air showers

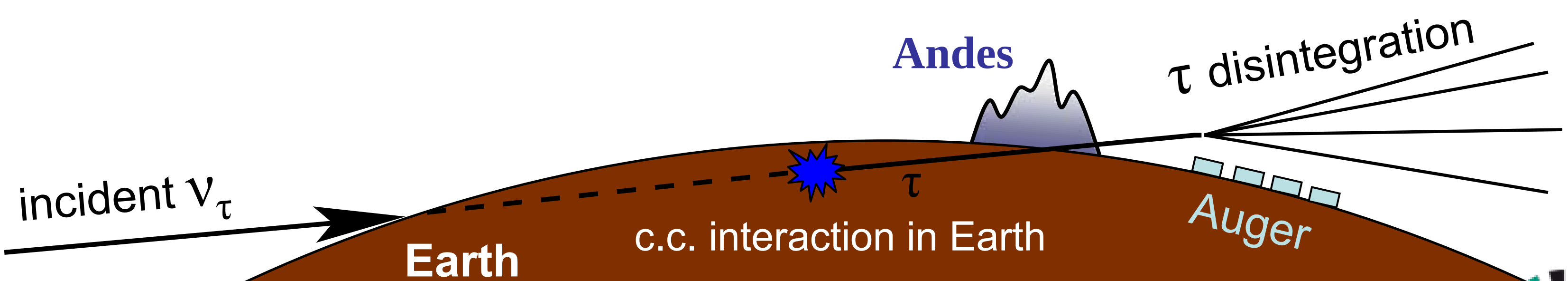


nearly horizontal air showers from extremely high energy ν_e or ν_μ neutrinos



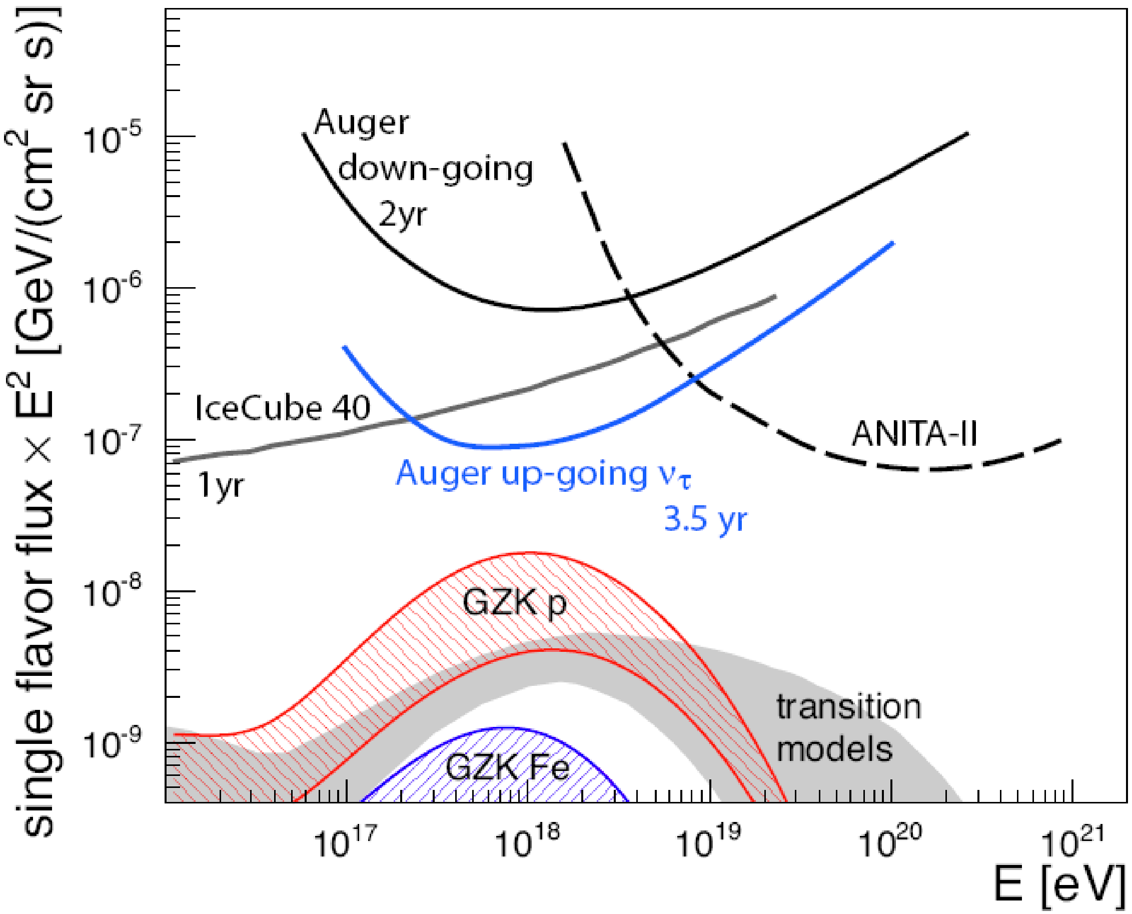


air showers from skimming ν_τ neutrinos



Limit on flux of neutrinos in UHECR flux

Horizontal or Earth skimming EAS with electromagnetic component



PRL 100 (2008) 211101
ApJ (2012) accepted

No Neutrinos detected

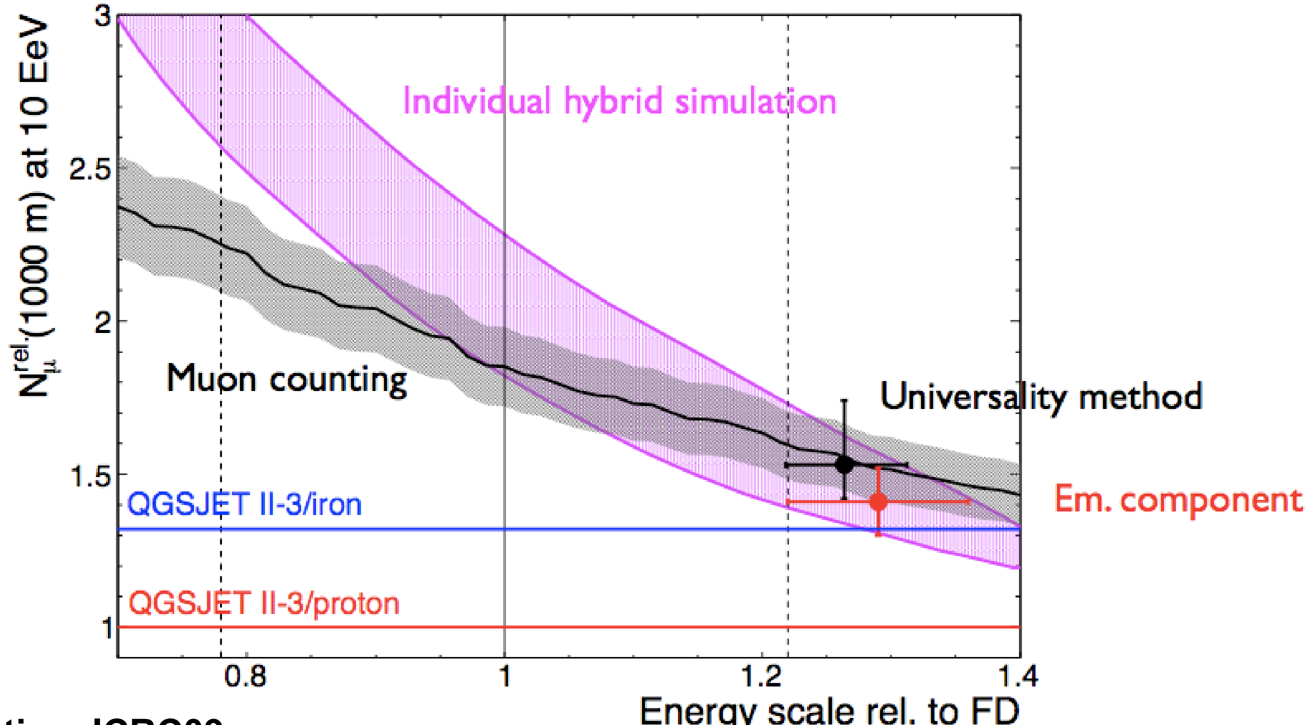
Validity of hadronic interaction models

A self consistent description of the Auger data is obtained only with a number of muons 1.3 to 1.7 times higher

than that predicted by QGSJET-II for protons at an energy 25-30% higher than that from FD calibration

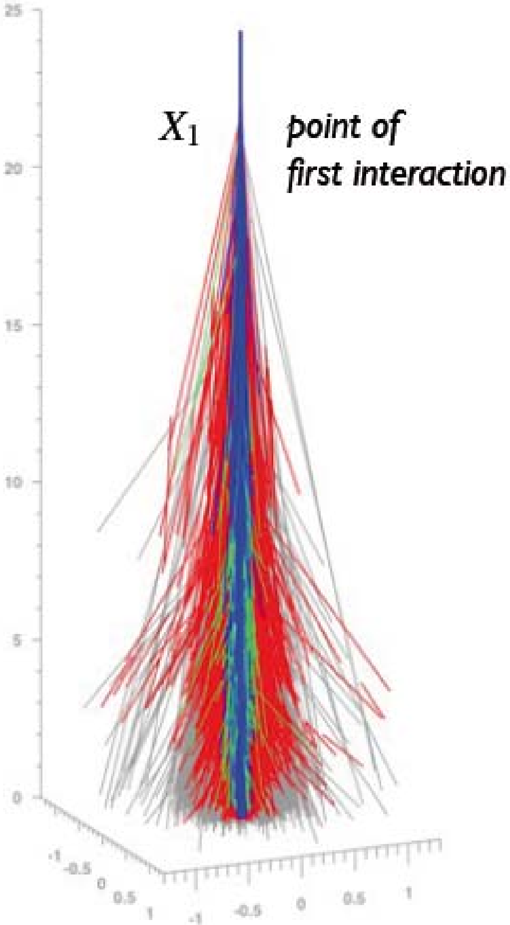
The results are marginally compatible with the predictions of QGSJET-II for Iron primaries

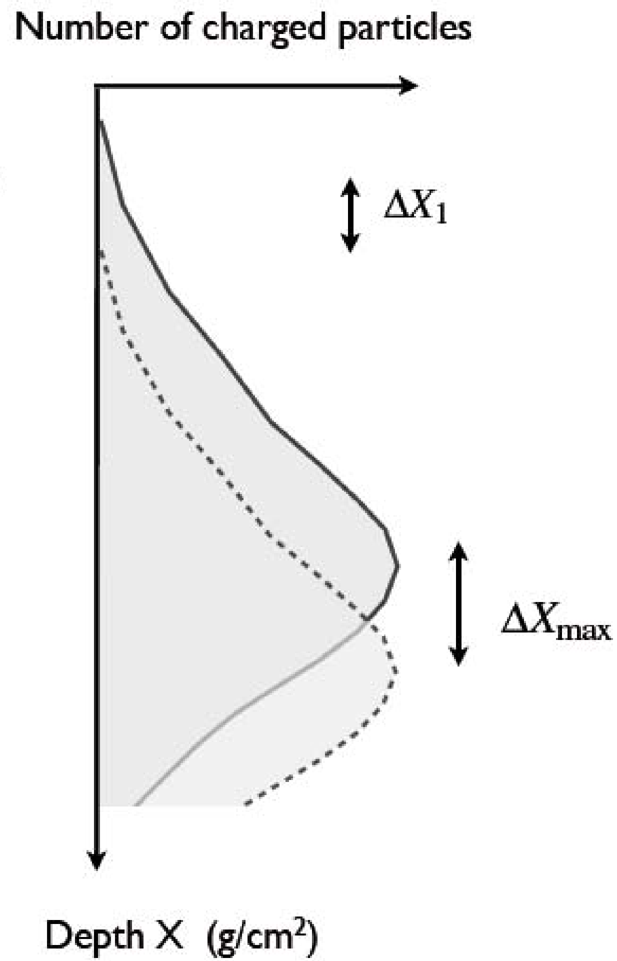
Discrepancy: shower profile and muons at ground



A.Castellina-Auger Collaboration, ICRC09

Particle Physics: Cross section





$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

$$\mathrm{RMS}(X_1) = \lambda_{\mathrm{int}}$$

$$\sigma_{\mathrm{p-air}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

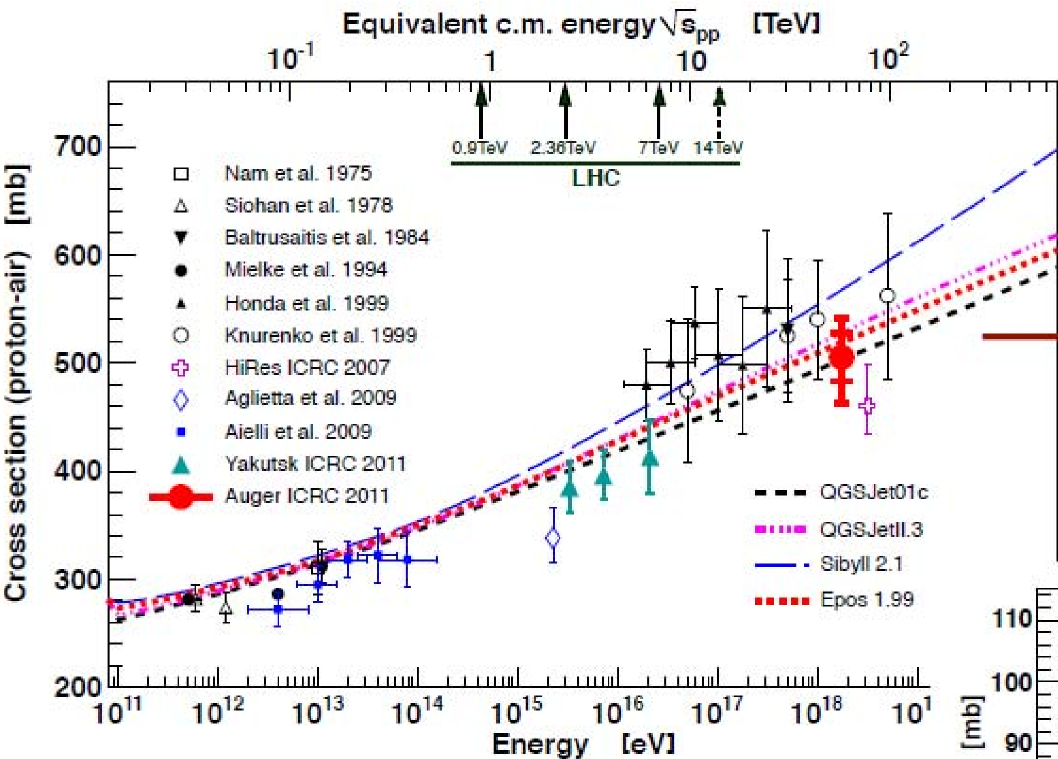
Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)

  $\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{\mathrm{max}} - X_1)$
- experimental resolution ~20 g/cm^2

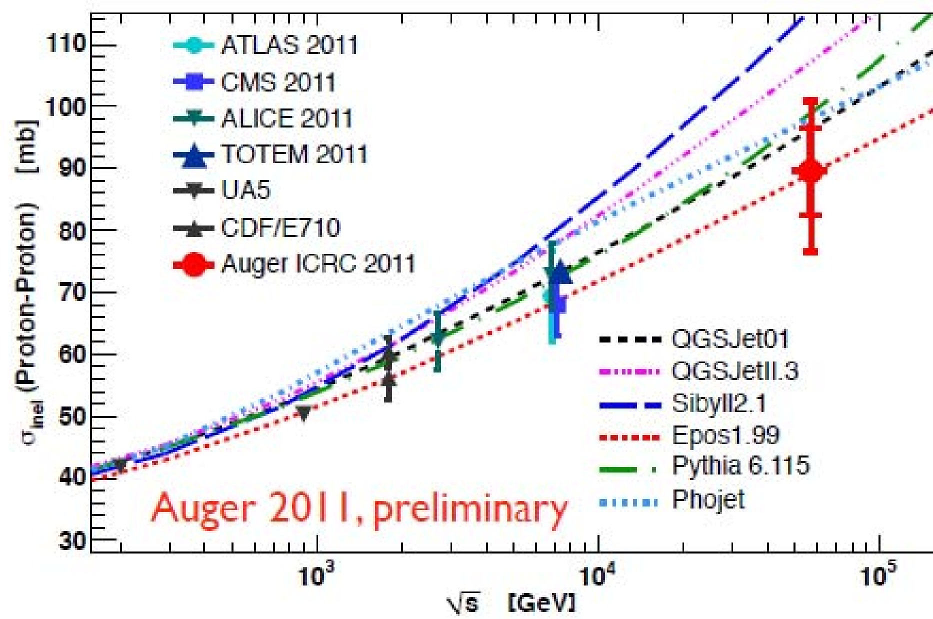
R. Ulrich et al. NJP 11 (2009) 065018

Cross section



Conversion from p-air to p-p cross section always model-dependent

Glauber model



Cross section independent of LHC data, very good agreement with extrapolated data

Physical Review Letters, in press, 2012

(Pierre Auger Collab. 1107.4804)


OBSERVATORIO
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AUGER
Entrada


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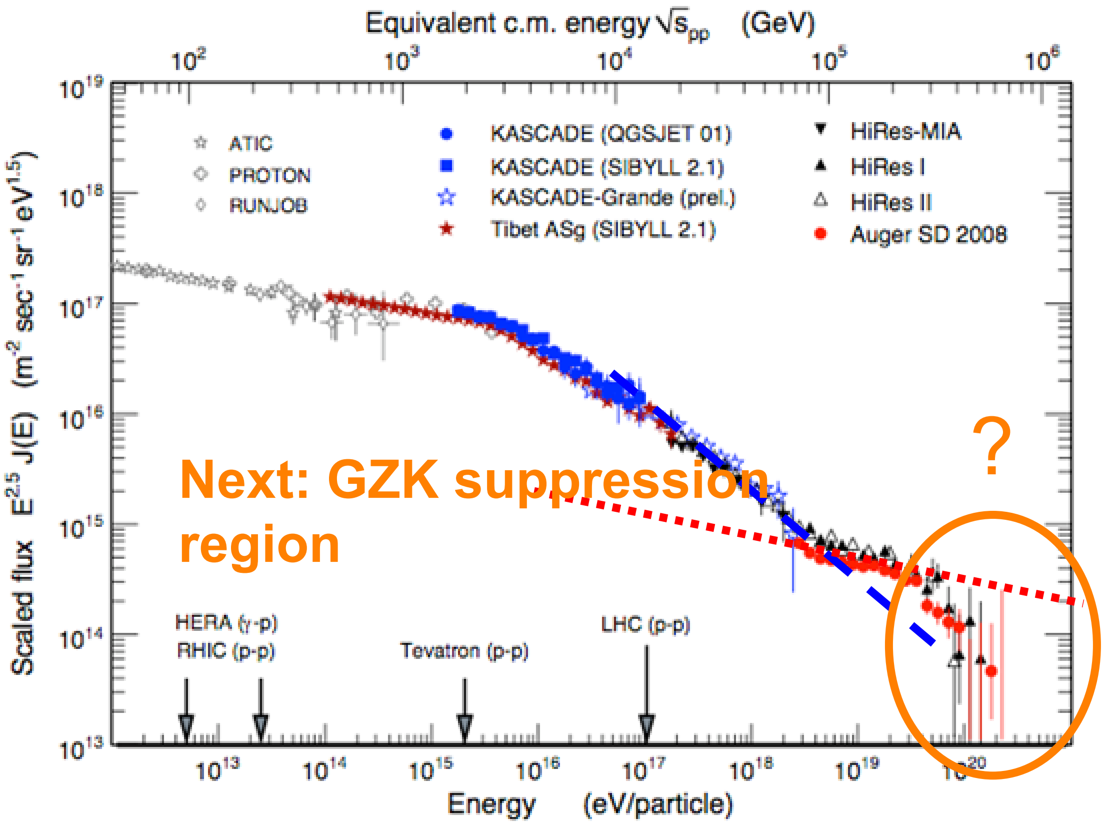
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam
Portugal
Croatia

The future: Go for highest energies



Auger Enhancements

Auger + TA

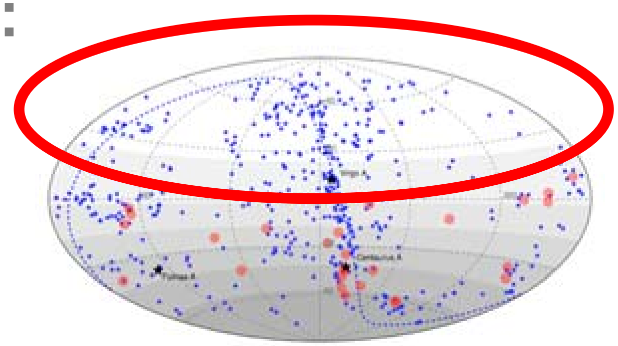
Next generation + JEM-EUSO

Auger + TA results:

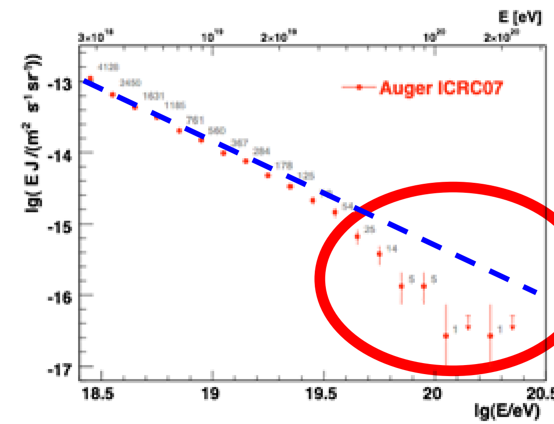
- Suppression of flux (like GZK effect)
- Anisotropy E > $6x10^{19}$ eV (?)
- Mixed cosmic ray comp. at lower energy
- Trend to heavy composition >10^{19}eV (?)
- Problems with hadronic interaction models
- Photon fraction small
- Neutrino flux low

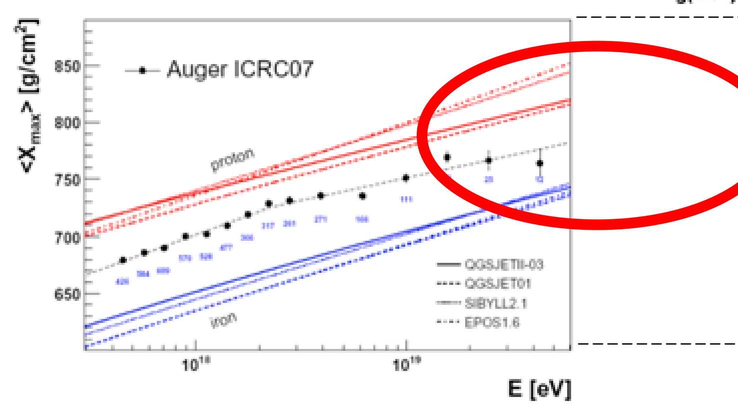
Karlsruhe Institute of Technology

Future generation Cosmic Ray Array: Motivation and aims



- **The sources of UHECR**
  - Anisotropy ⇉ correlations ⇉ source classes
  - Study individual sources with spectra and composition on the whole sky
- **The acceleration mechanism**
  - Composition evolves from source to here
  - Proton beam !? calibration !
  - E>>10^{20} eV still difficult; E_{max} ?
- **Propagation and cosmic structure**
  - Map galactic B-field
  - Matter within 100 Mpc
  - Extragalactic B-field small ?
- **Particle physics at 350 TeV**
  - Mass and X_{max}
  - Had. interactions, cross sections ?
  - New physics, Lorentz invariance
- **Multi-messenger astrophysics**
  - Combine the data from photons, neutrinos and charged particles !
  - Sources within field of view of IceCube



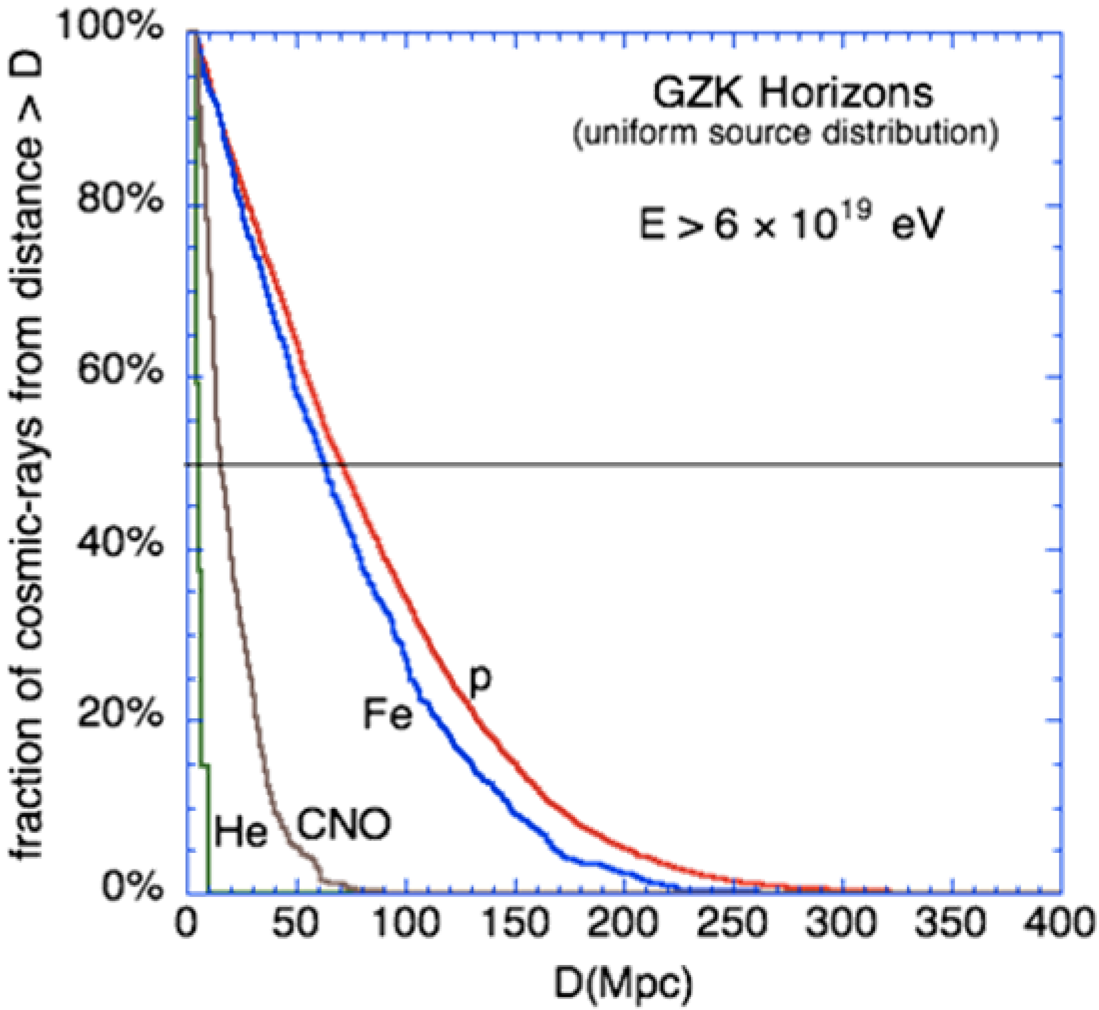


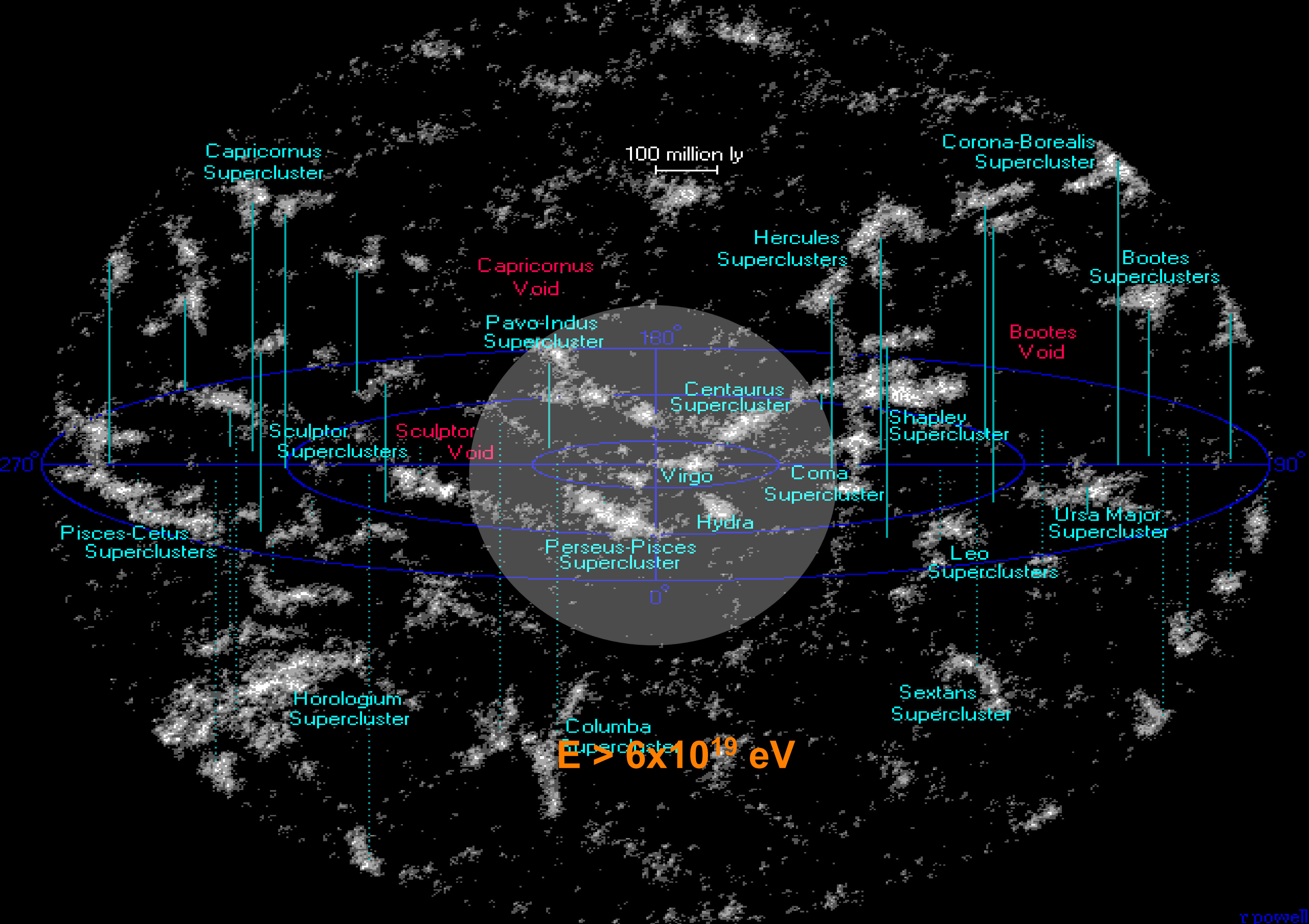
Highest energies: Trans GZK composition is simpler

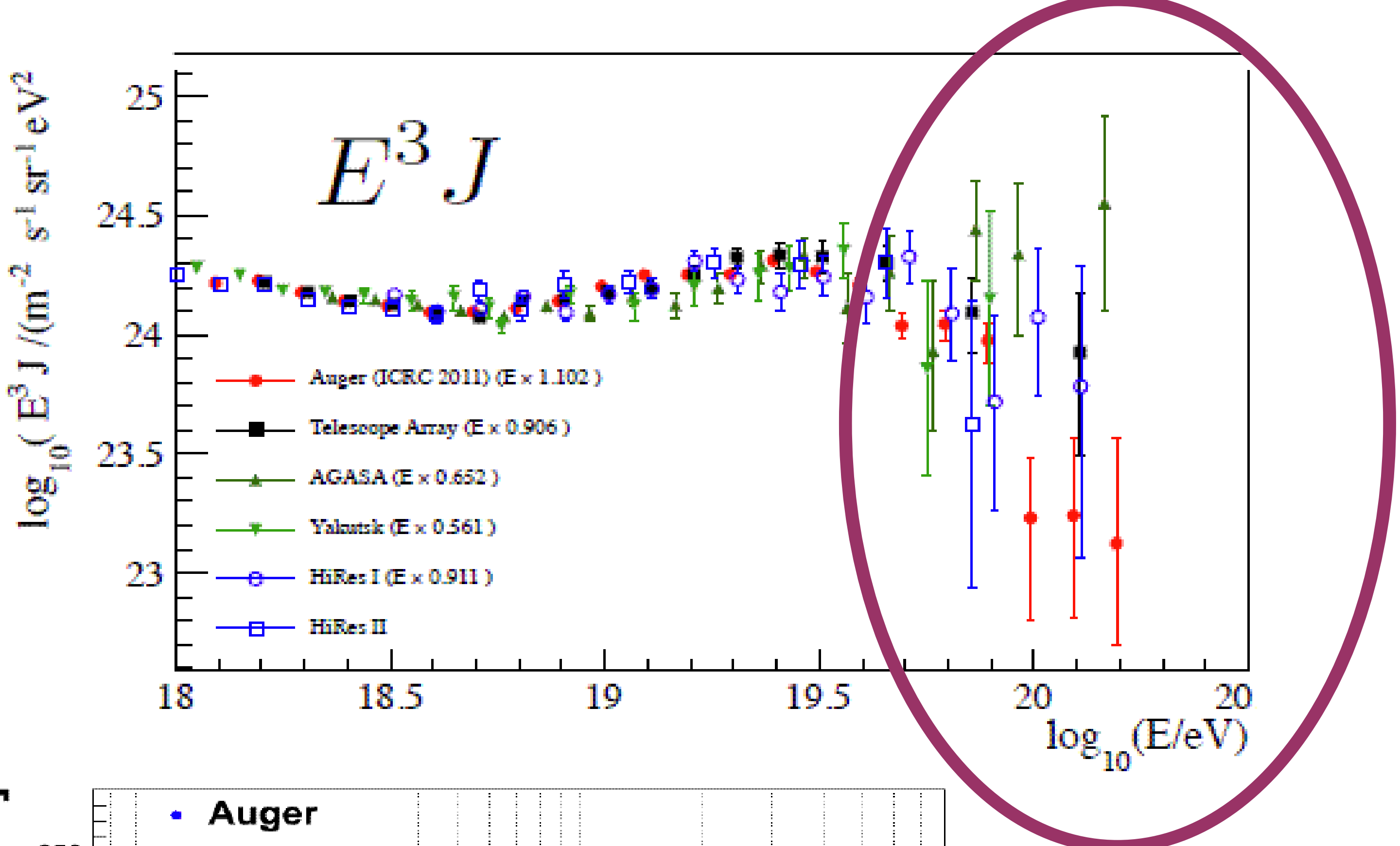
Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.

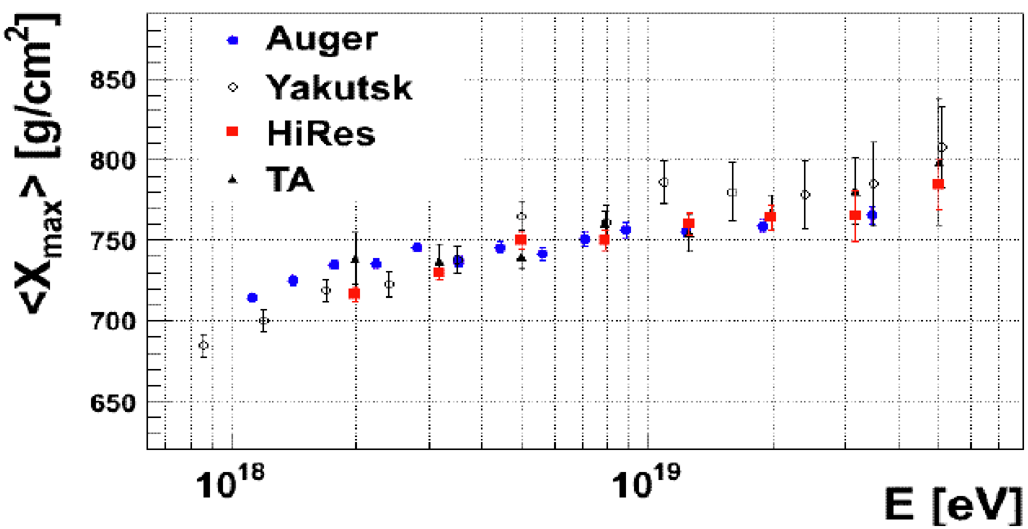



Capricornus Supercluster
100 million ly
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
Virgo
Coma Supercluster
90°
Ursa Major Supercluster
Hydra
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Sextans Supercluster
Horologium Supercluster
Columba Supercluster
E > 6x10^19 eV
r powell



➔Energy range of particle Astronomy

(if these are at least partly protons)



Need for the future

➔more statistics at highest energies

M.Fukushima: CERN Symp, Feb2012

go for future

Results from Auger + Telescope Array have shown

- *that the spectrum has a characteristic break-off at c. 50 EeV;*
- *that (at least a part) of events with highest energy arrive anisotropic;*
- *that CR at highest energies are most probably not build up by Hydrogen only.*

➔requirements for the future:

- **observatories need to be considerably increased in exposure;**
- **observatories need a good sensitivity to composition;**
- **observatories should cover the full sky.**

Steps to the future:

- **Auger + Telescopes upgrade…**
- **R&D studies for next generation ground based array**
- **Validate measurements from space**

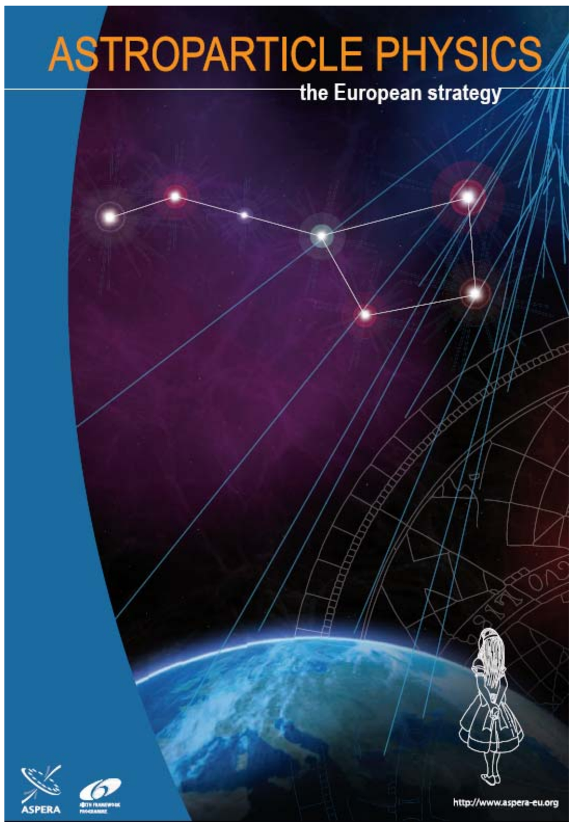
AugerNext

JEM-EUSO

ASPERA

www.aspera-eu.org

AStroParticle ERAnet ASPERA is a network of national government agencies responsible for Astroparticle Physics



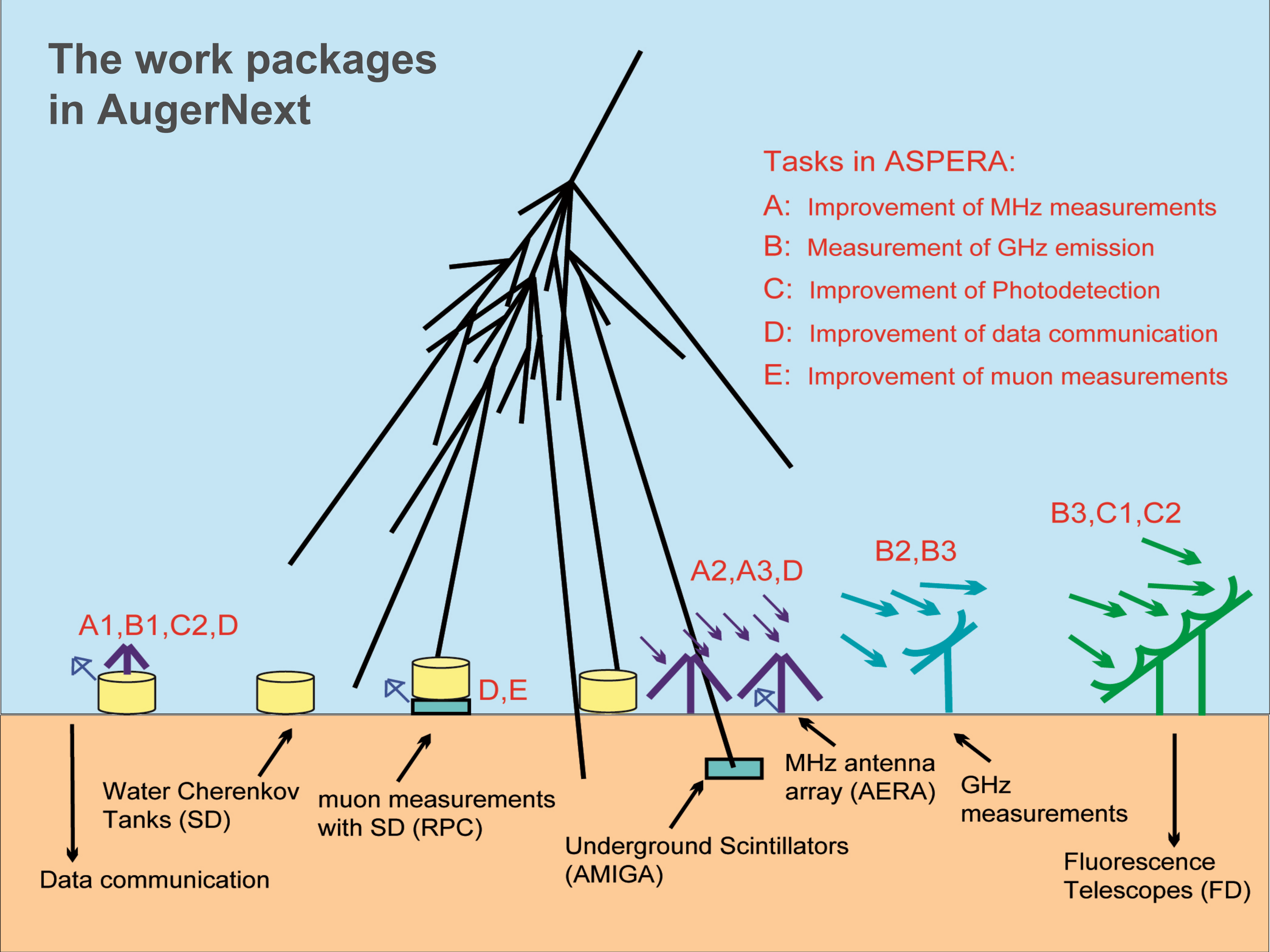
The ASPERA calls:

-Targeted R&D and design studies in view of the realization of future Astroparticle infrastructures

➔ AugerNext

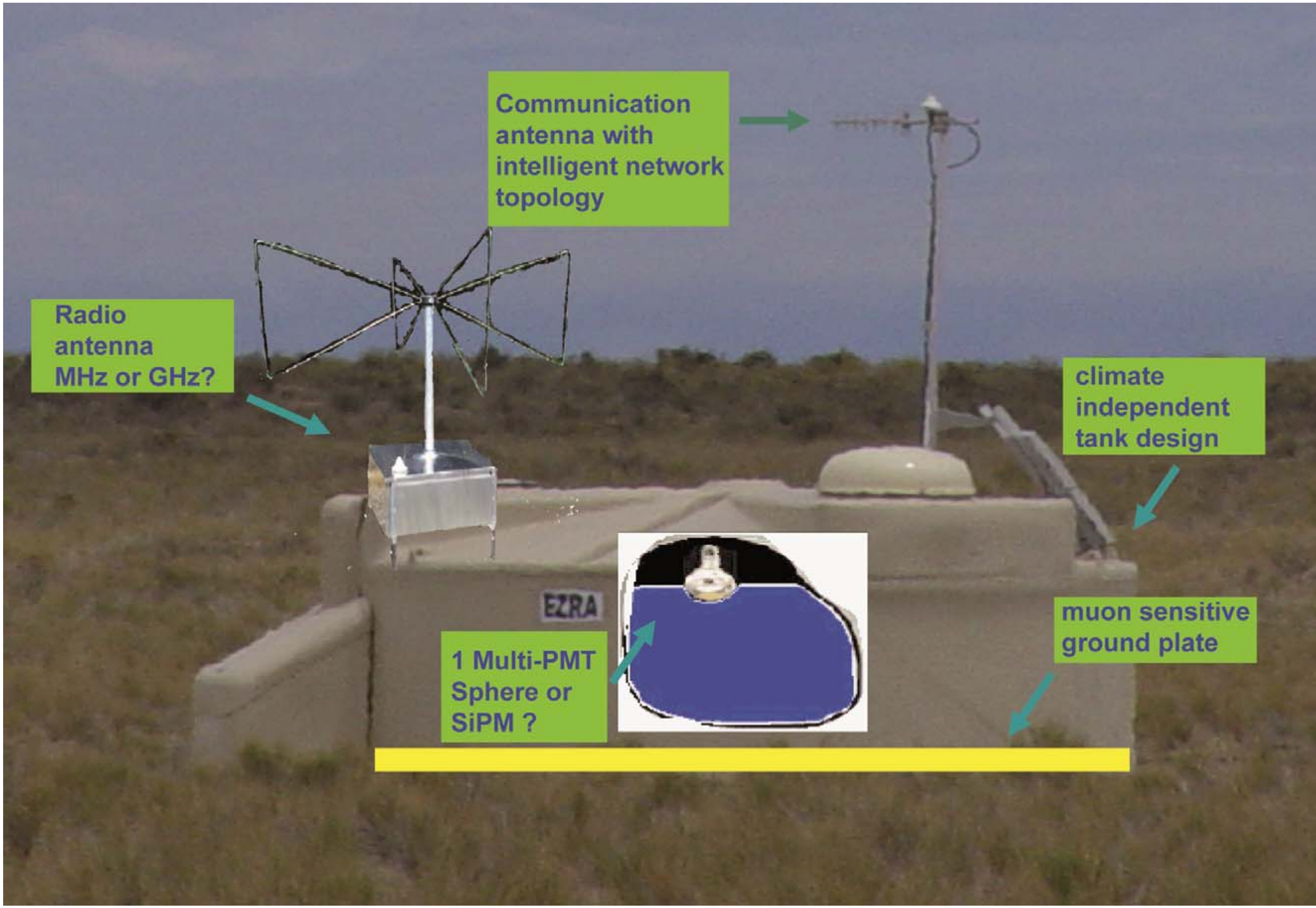
Innovative Research Studies for the Next Generation Ground-Based Ultra-High Energy Cosmic-Ray Experiment

Roadmap from scientists for Funding Agencies!



The work packages
in AugerNext
Tasks in ASPERA:
A: Improvement of MHz measurements
B: Measurement of GHz emission
C: Improvement of Photodetection
D: Improvement of data communication
E: Improvement of muon measurements
A1,B1,C2,D
D,E
A2,A3,D
B2,B3
B3,C1,C2
Data communication
Water Cherenkov
Tanks (SD)
muon measurements
with SD (RPC)
Underground Scintillators
(AMIGA)
MHz antenna
array (AERA)
GHz
measurements
Fluorescence
Telescopes (FD)

Future (next generation) surface detector:



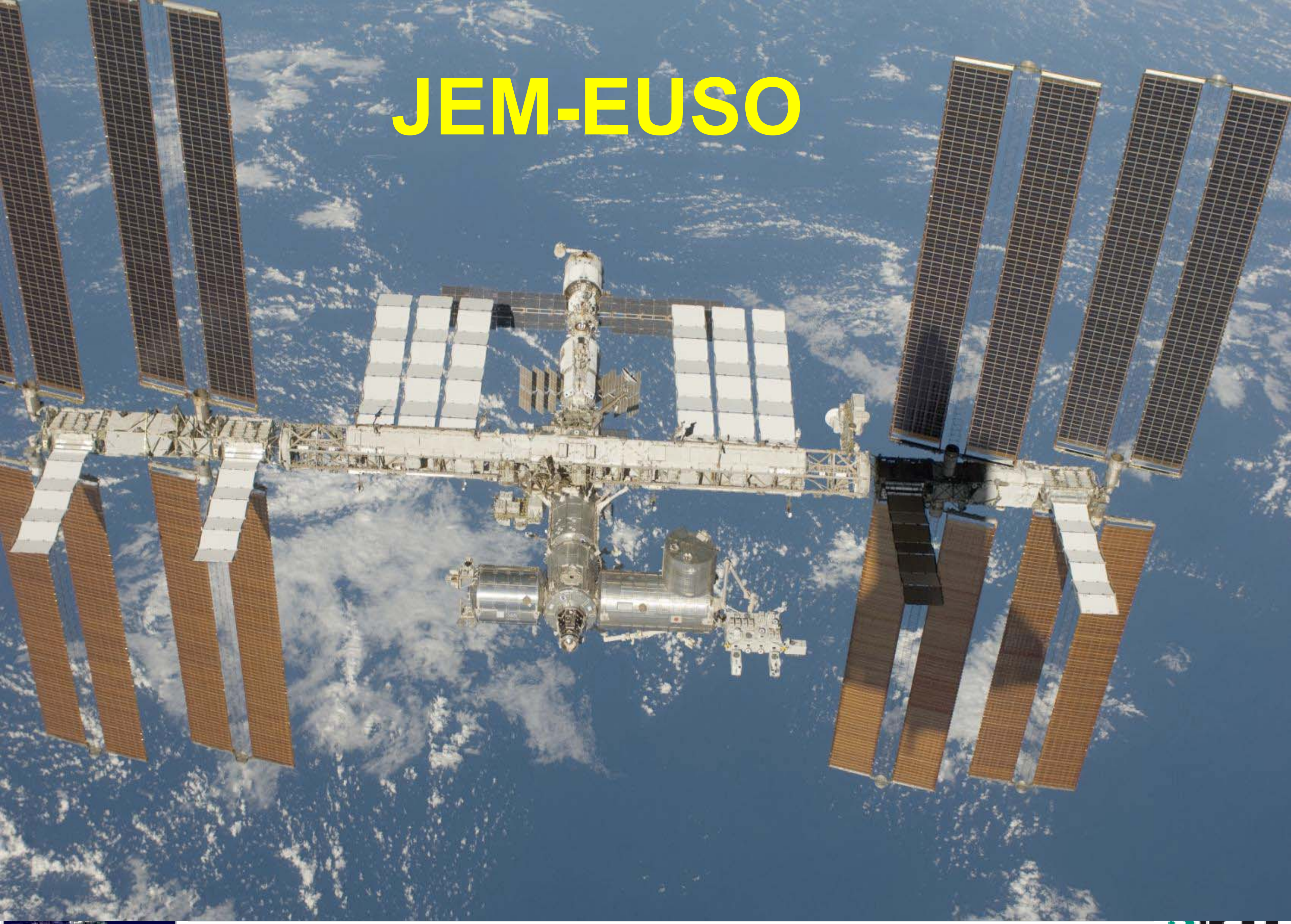
AugerNext

Innovative Research Studies for the Next Generation Ground-Based Ultra-High Energy Cosmic-Ray Experiment

➔

rich R&D program and on-site activities at the Pierre Auger Observatory for the next 5 years.

JEM-EUSO



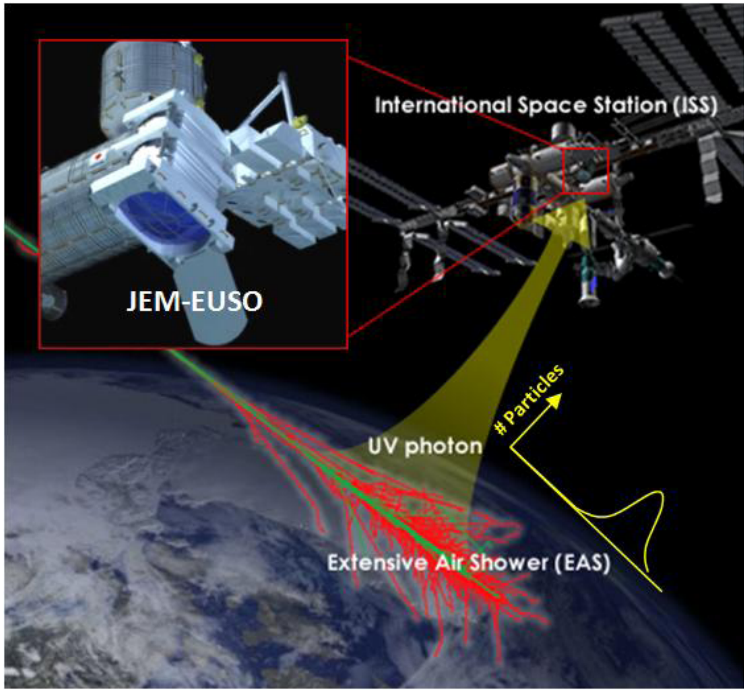
JEM-EUSO main features

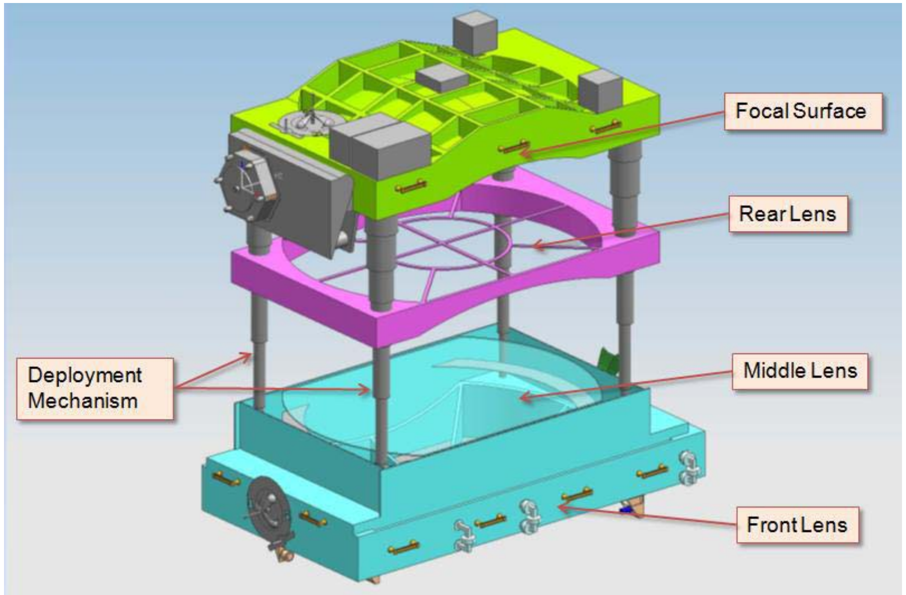
Method: fluorescence (full calorimetric)

Large field of view: ± 30° thanks to double sided spherical Fresnel lenses

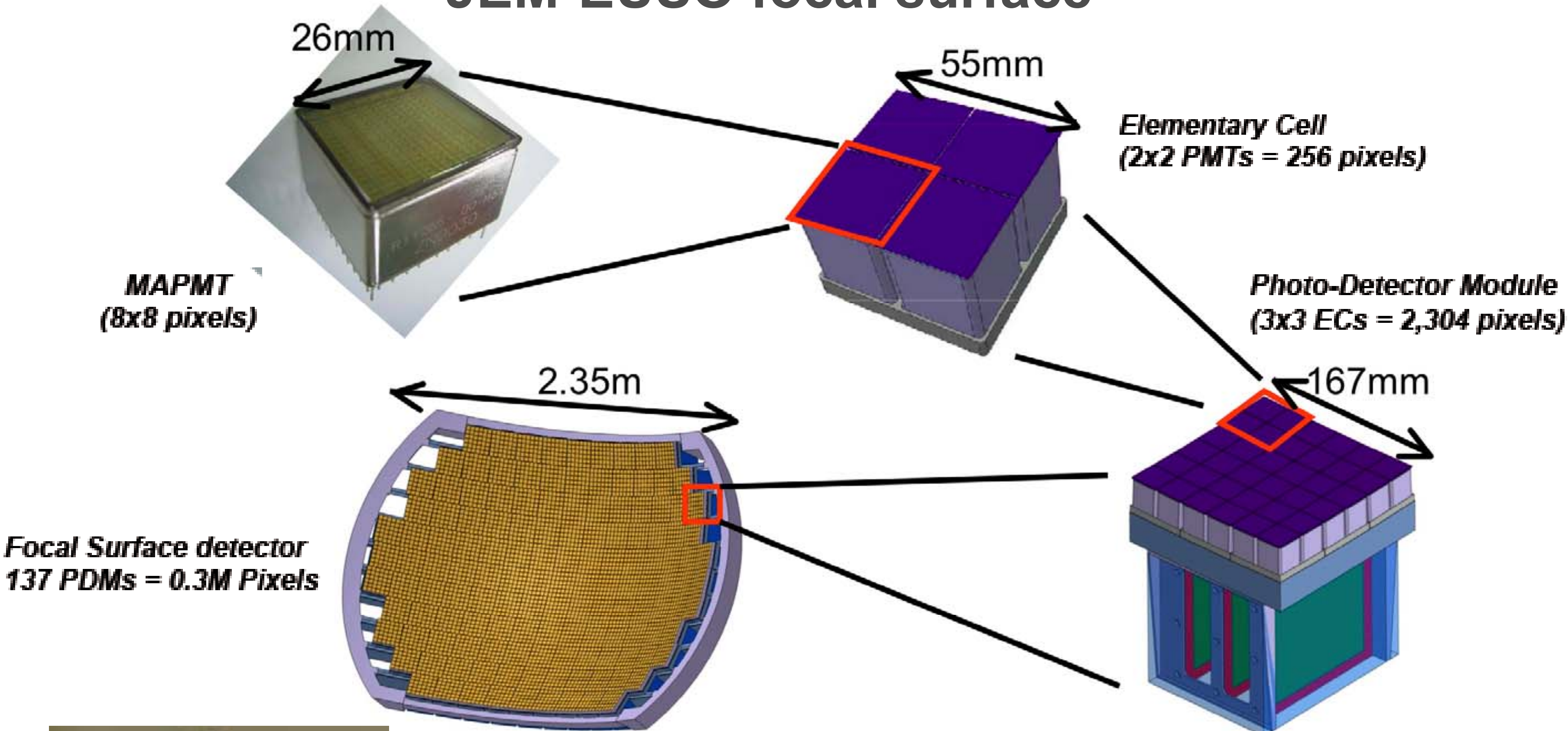
At 400 km (ISS): 2 10^5 km^2 (nadir mode) up to 10^6 km^2 (tilted mode)

No need for stereo: 400 km >> shower length (TPC with a drift velocity = c)





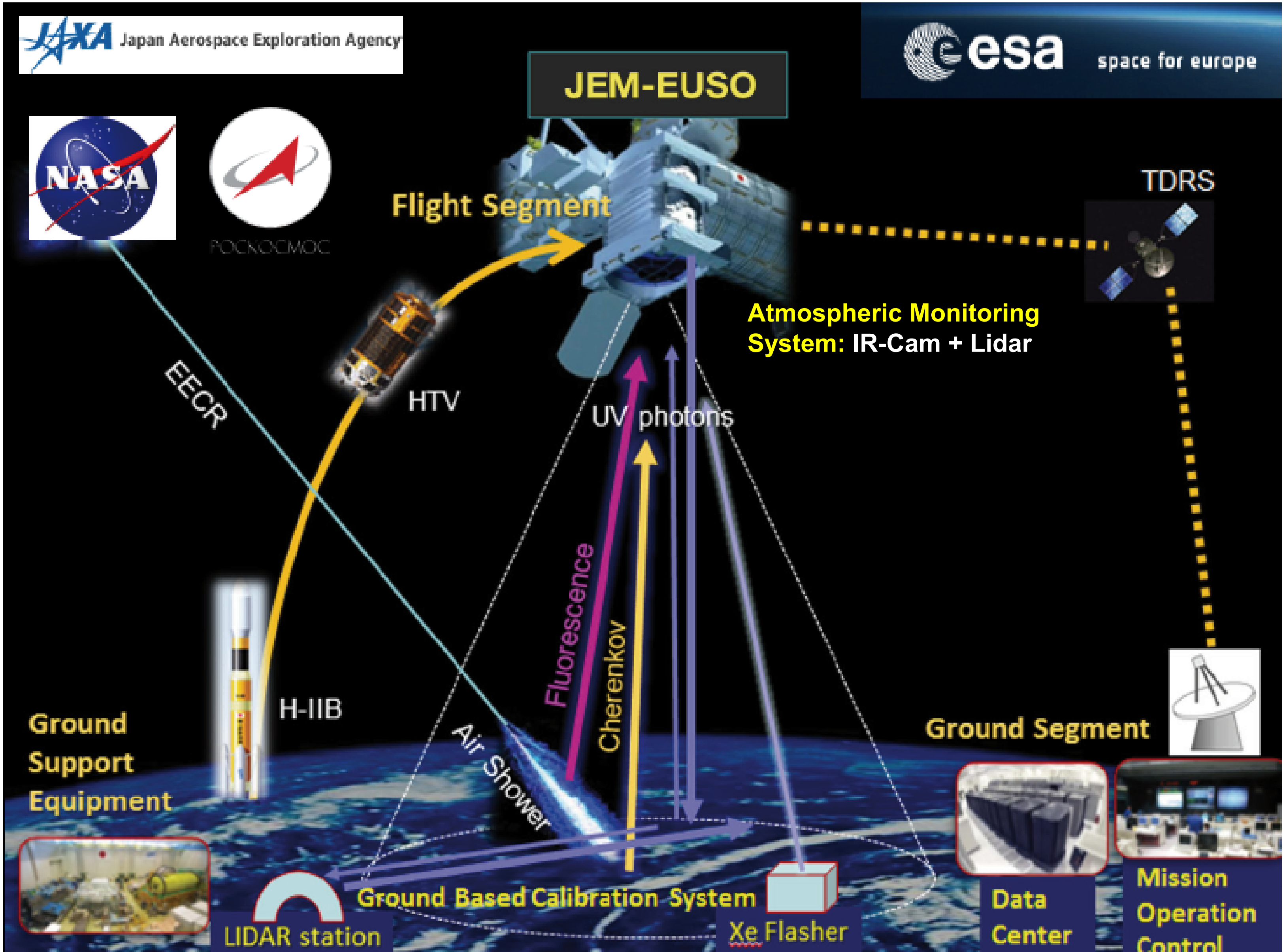
JEM-EUSO focal surface



Focal surface:

- prototypes of PDM in preparation
- FoV of 1 PDM = 27 x 27 km^2

JEM-EUSO: the full machine



Physics Program

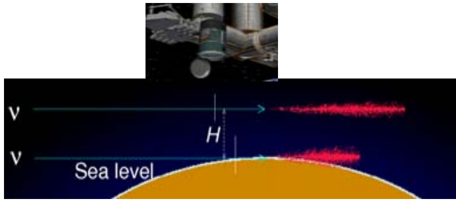
Main scientific objectives

- Measurement of Ultra-high energy Cosmic Rays

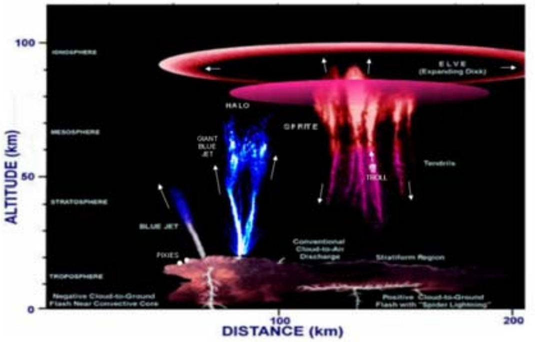
➔ Astronomy and Astrophysics through the particle channel

= Physics and Astrophysics at $E > 5.\times10^{19}$eV

Exploratory scientific objectives



- Exploratory Objectives: new messengers
  - Discovery of UHE neutrinos
    - discrimination and identification via X_0 and X_{max}
  - Discovery of UHE Gammas
    - discrimination of X_{max} due to geomagnetic and LPM effect



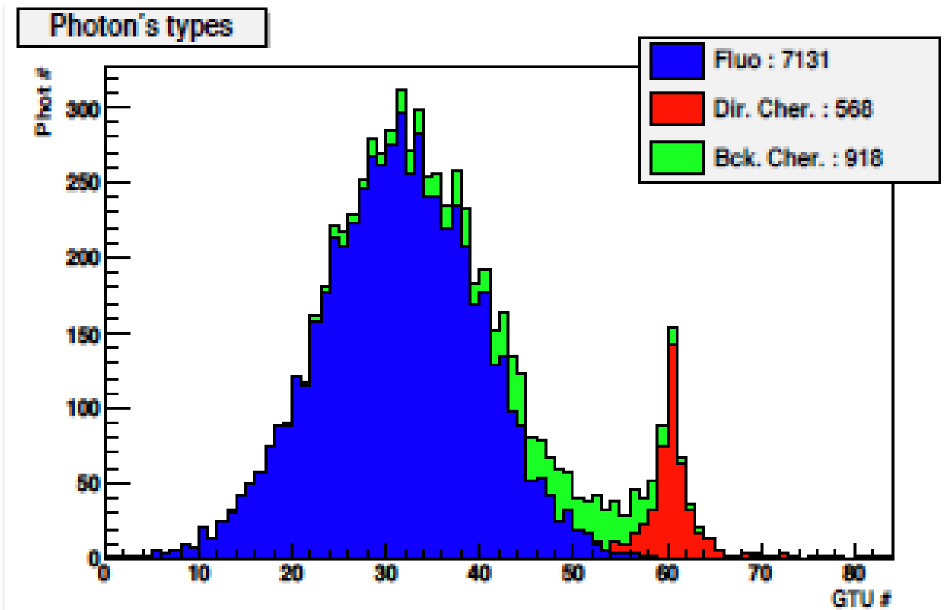
(Elaboration of figure by Lyons et al. 2000)

- Exploratory Objectives: magnetic fields

- Exploratory Objectives: Atmospheric science
  - Nightglow
  - Transient luminous events
  - Space-atmosphere interactions
  - climate change

🡐 with the fast UV monitoring of the Atmosphere

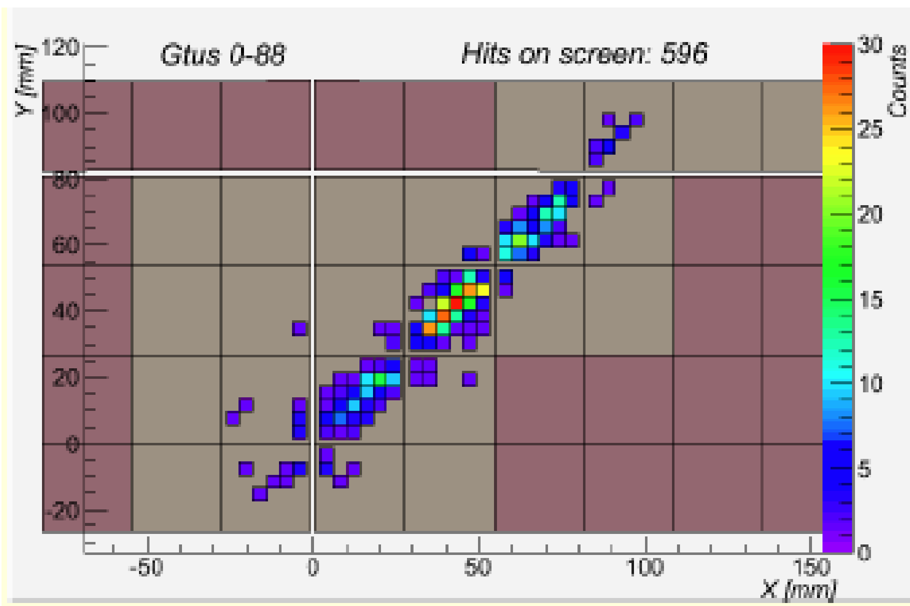
The observation technique



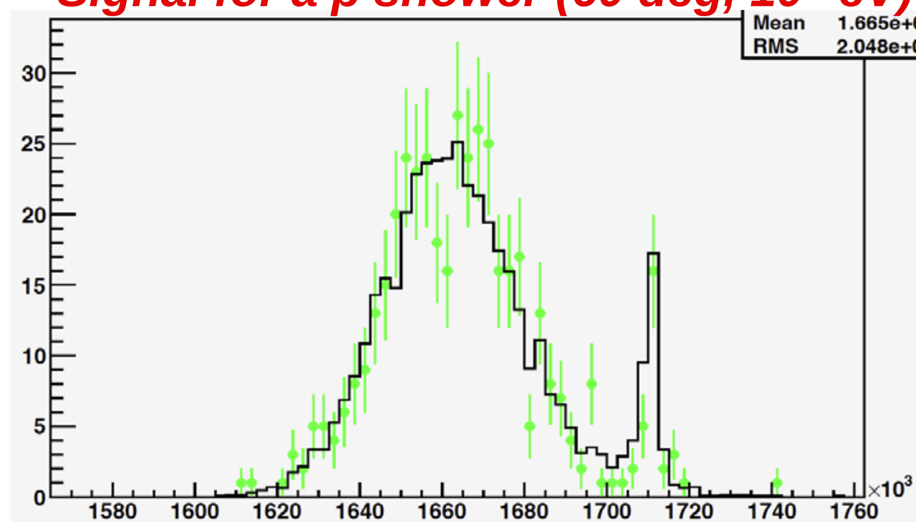
1 GTU = 2.5μs

Background = 500 ph / m^2 sr ns (from Tatiana satellite)

Fast signal: ~50-150μs



Signal for a p shower (60 deg, 10^{20}eV)



ΔE/E < 30% for ~90% of events

JEM-EUSO Performance: Annual Exposure

Depends on zenith angle and energy …

and is determined by four factors:

$$TA \times \eta \times k \times l$$

$TA \rightarrow Trigger\ Aperture$ **Determined by the trigger efficiency**

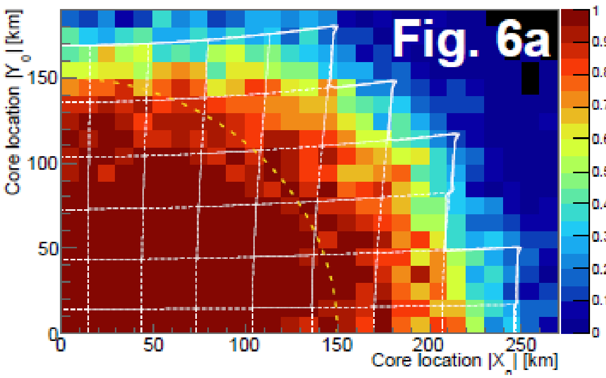
$\eta \rightarrow duty\ cycle$ **Determined by the background (and operation)**

$\kappa \rightarrow cloud\ impact$ **Determined by the cloud coverage**

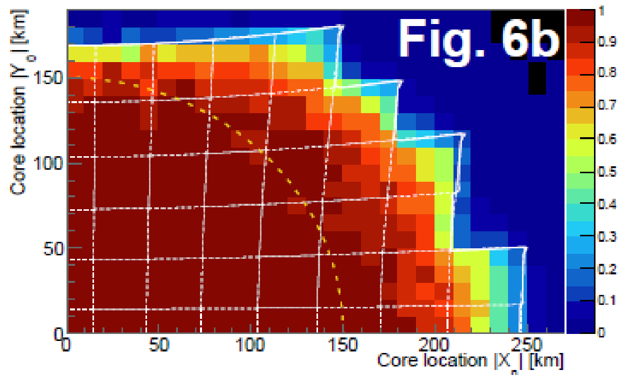
$l \rightarrow citylights\ \&\ lightnings$ **Local effects which limit the aperture**

JEM-EUSO Performance: Efficiency

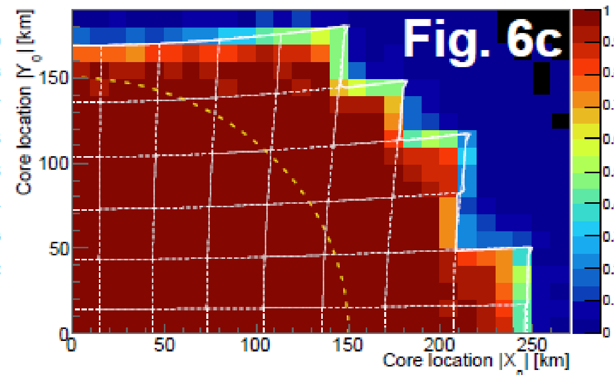
$E > 4 \cdot 10^{19}$eV; $\Theta > 60^o$

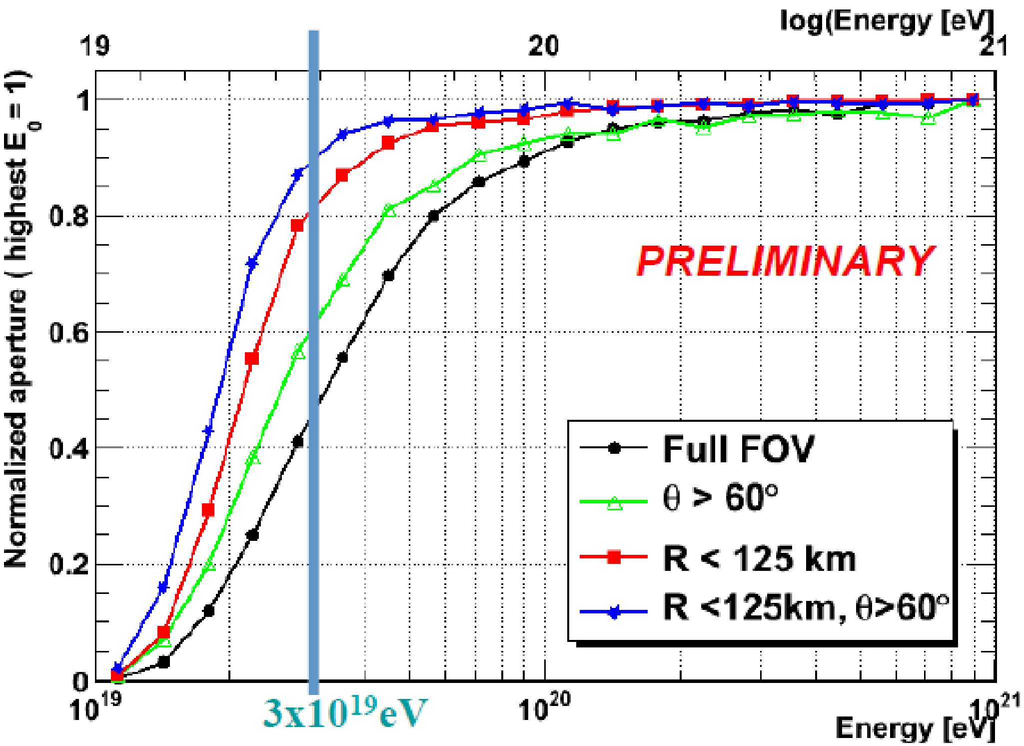


$E > 5.5 \cdot 10^{19}$eV



$E > 10^{20}$eV



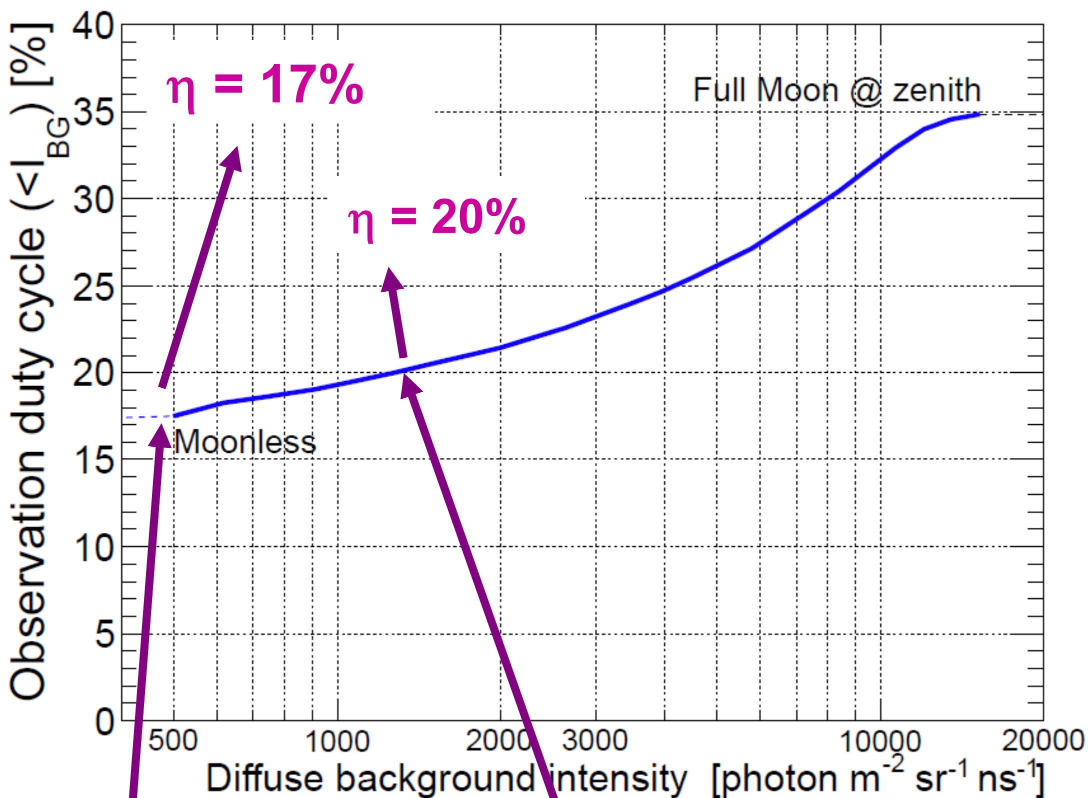


Trigger Efficiency

- 100% at $E = 4 \cdot 10^{19}$eV when $\Theta > 60^o$ and R < 150 m
- 90% at $E = 10^{20}$eV when full FoV

Including bg = 500 ph / m^2 sr ns (Tatiana satellite)

JEM-EUSO Performance: duty cycle



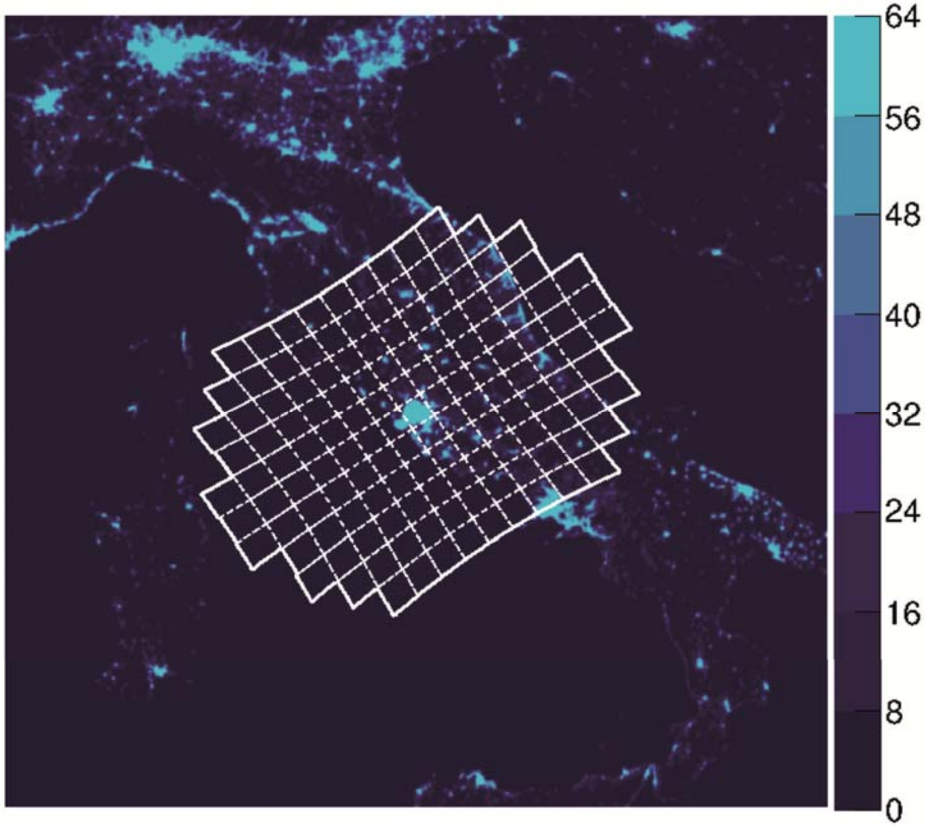
acceptable moon background:
1500 ph / m² sr ns

Night glow background:
500 ph / m² sr ns

Duty Cycle

- **No moon: ~17%**
- **Accepting little moon light: ~20.5%**
  (from analytical calculations)

JEM-EUSO Performance: city lights & lightnings



CITY LIGHTS:

~ 7% (DMSP data)

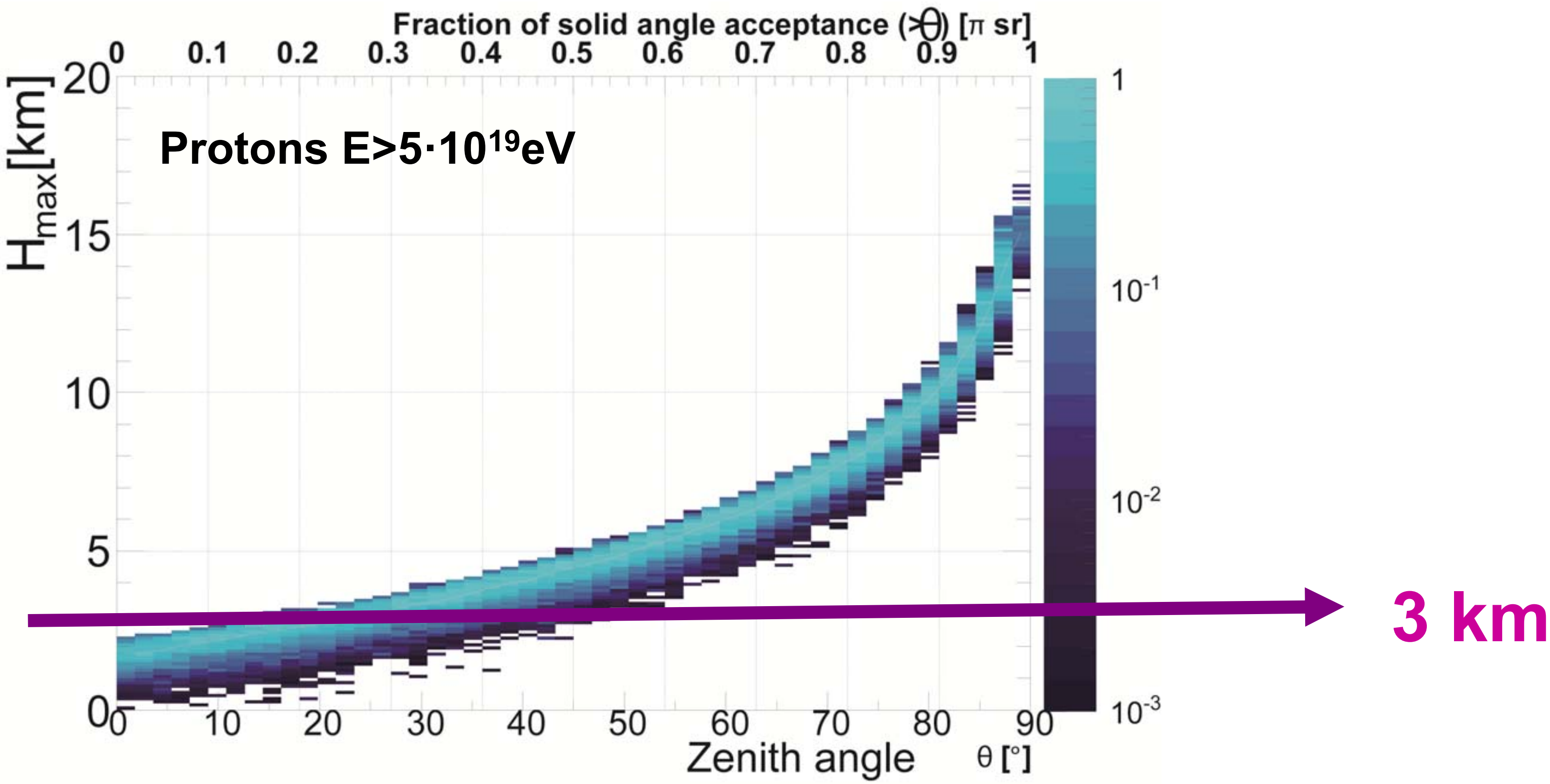
LIGHTNINGS:

~ 2% (Tatiana data)

➔ l = 91%

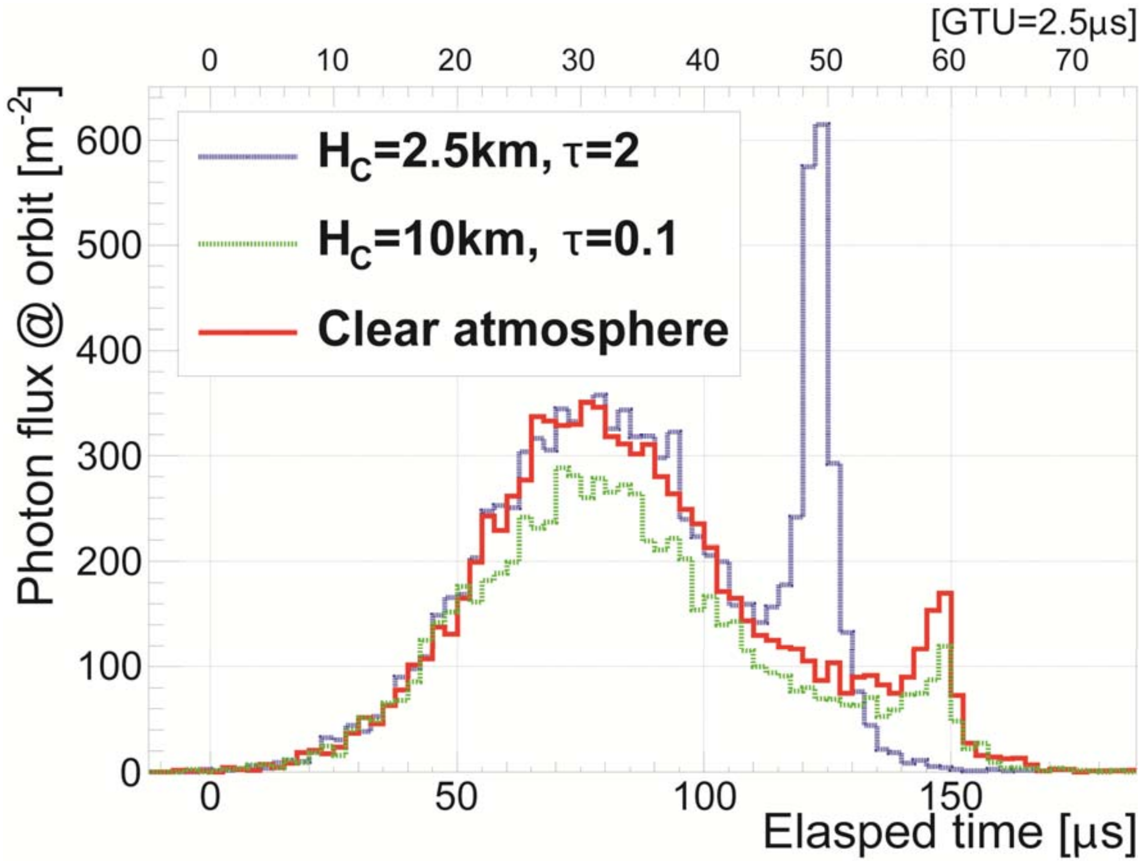
$$l \rightarrow citylights \,\&\, lightnings$$

JEM-EUSO Performance: cloud impact



➔ Most EAS relevant for JEM-EUSO reach maximum above the typical cloud altitudes!

JEM-EUSO Performance: reconstruction with clouds



- shower profiles are attenuated for optically thin clouds (eg. cirri).
- optically thick clouds (eg. strati) block photons emitted below cloud
- cloud reflected Cherenkov light improves the reconstruction

JEM-EUSO Performance: cloud coverage

Clear sky ~ 31%
Green band ~ 60%

Cloud top

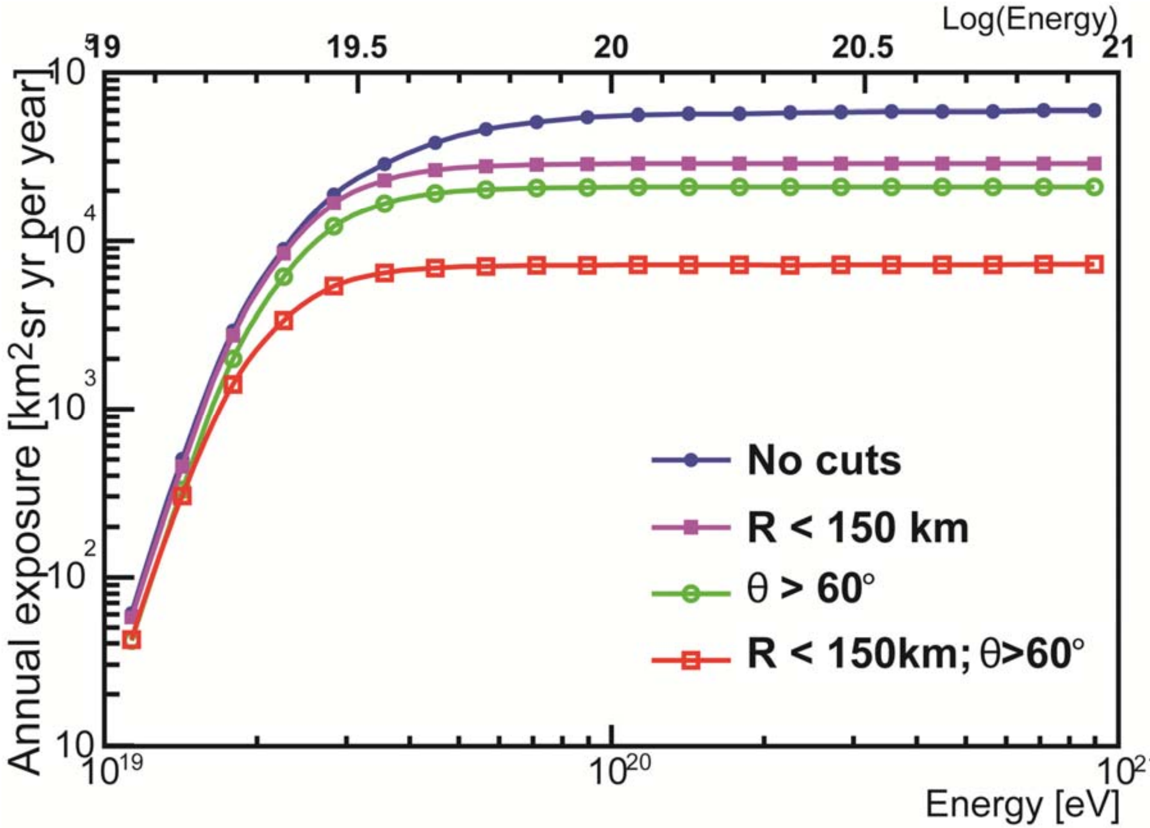
Optical Depth

	<3.2 km	3.2-6.5 km	6.5-10 km	>10 km
OD>2	16	5.9	8.6	5.0
OD:1-2	6.0	3.0	4.2	2.5
OD:0.1-1	6.5	2.0	3.2	5.0
OD<0.1	31	<0.1	<0.1	1.2

- **Occurrence of clouds (in %) between 50° N and 50° S on TOVS database**
  (Confirmed by ISCCP,CACOLO & MERIS database)

➔ In ~72% of the cases the UV track including X_{max} is observable

JEM-EUSO Exposure (…Nadir mode)



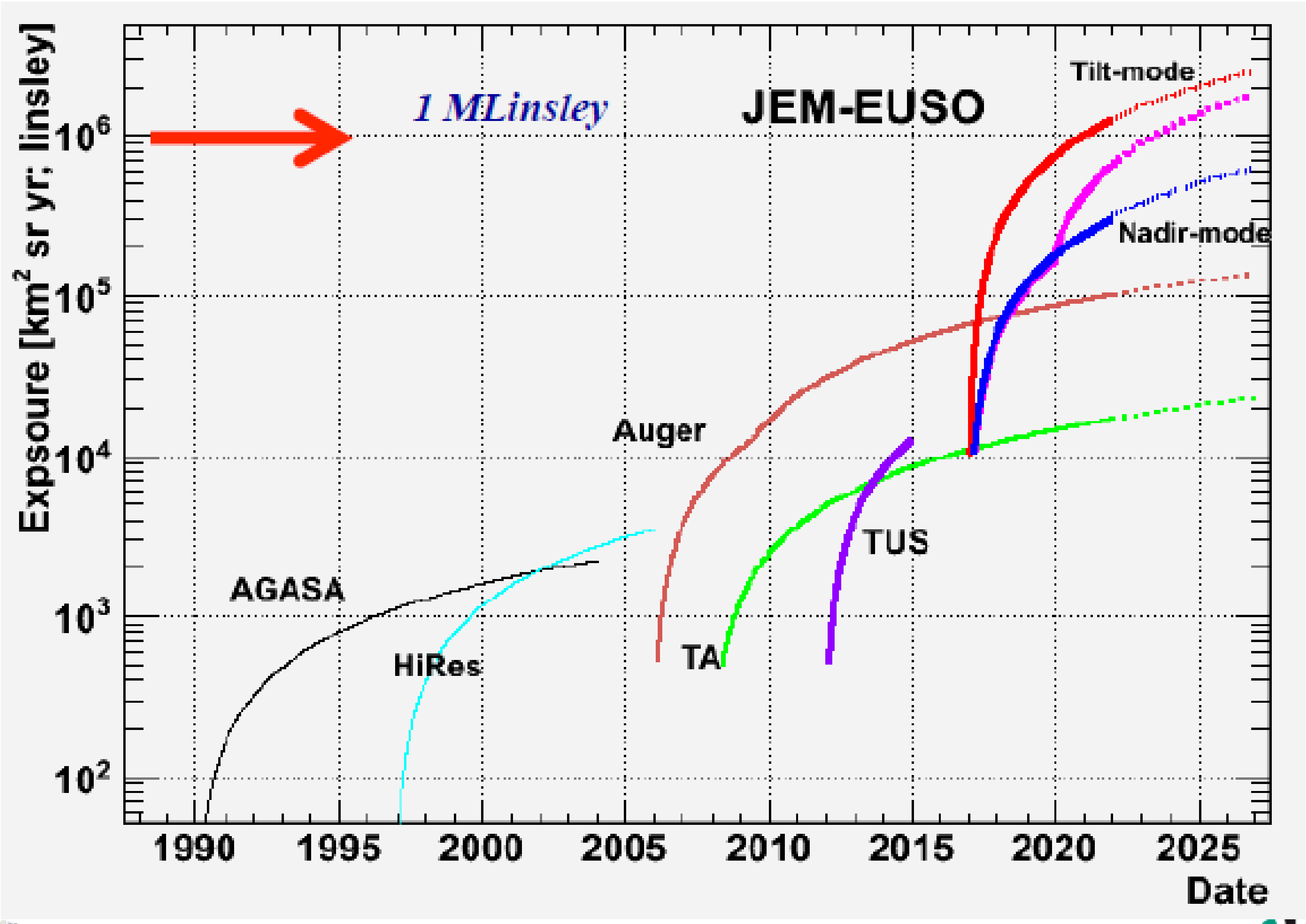
60,000 km^{2}sr yr

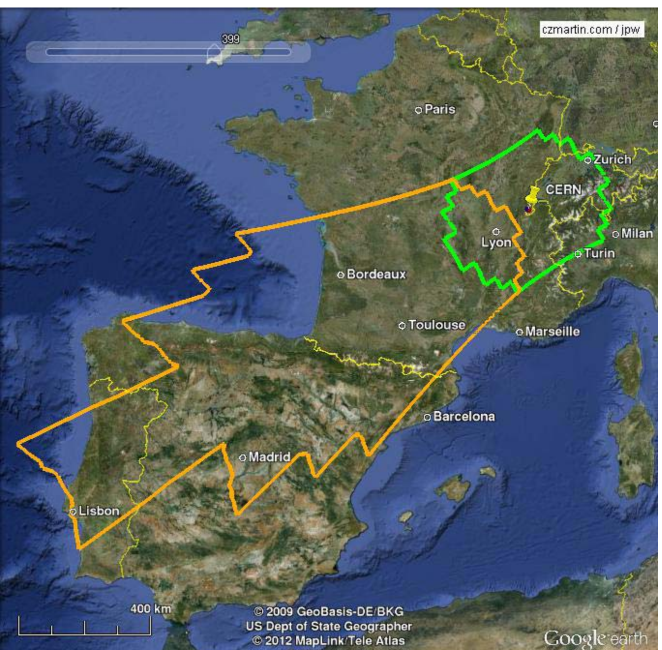
7,000 km^{2}sr yr

$$TA\times\eta\times k\times l$$

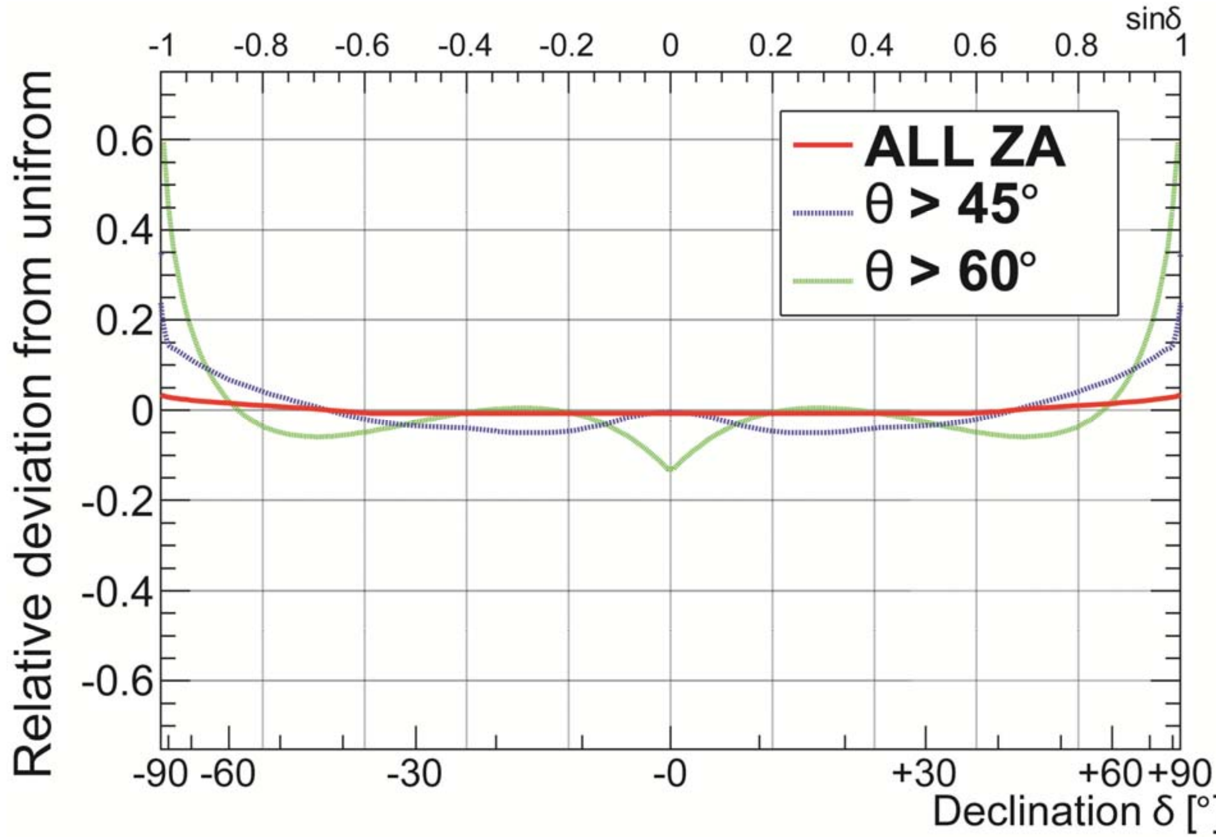
- **With tight geometrical cuts a direct comparison with ground-based observatories possible**
- **full FOV provides about one order higher exposure than Auger at higher energies**
- **When accepting higher BG level improvements possible**

JEM-EUSO Exposure

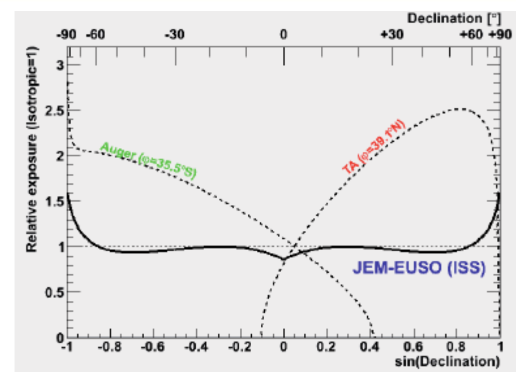




JEM-EUSO: aperture

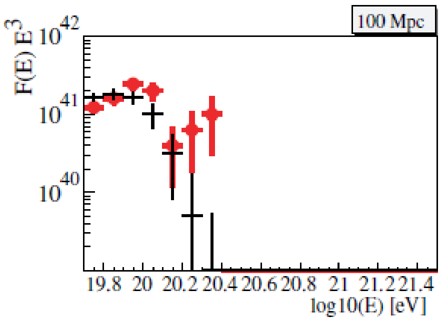


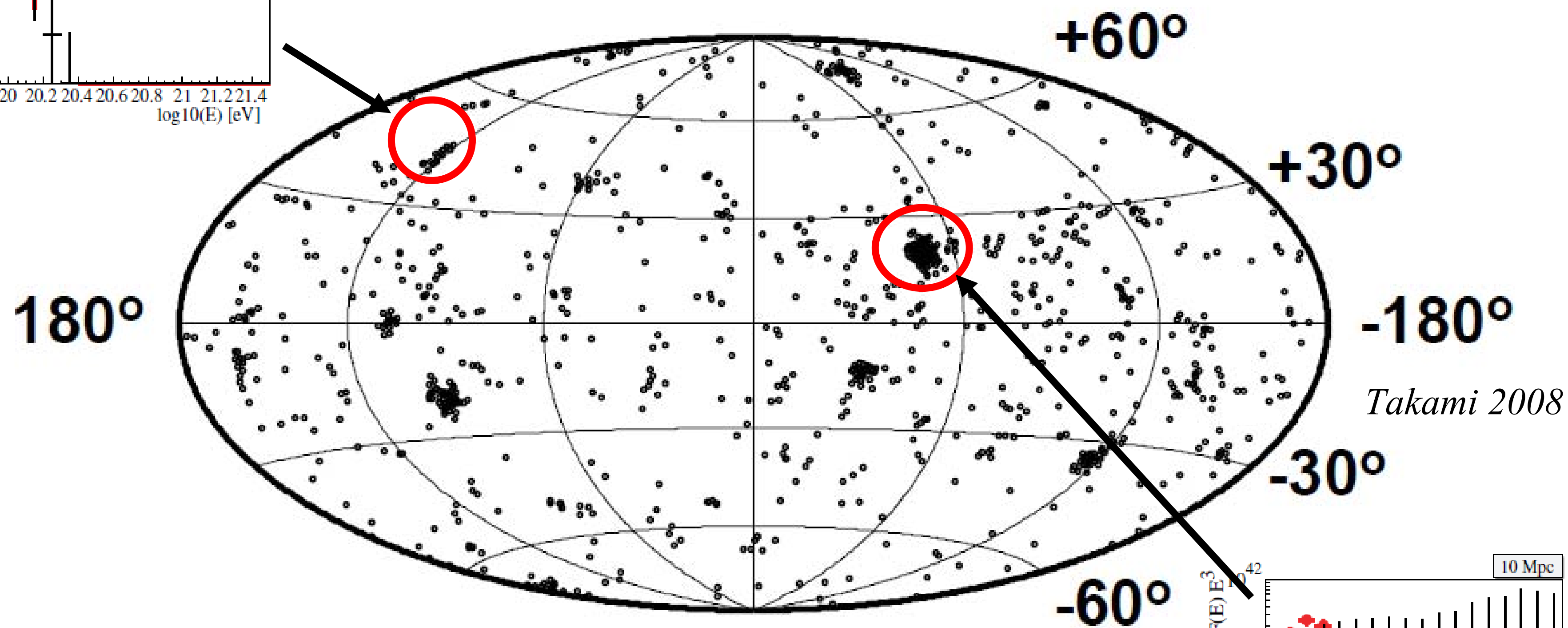
- **Uniform coverage of both hemispheres!**

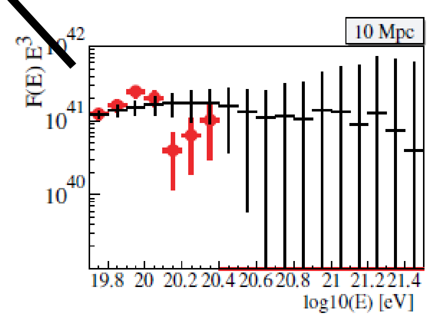


JEM-EUSO sky

Forecast in case of 1,000 events
Brightness of particles ∝ X-ray (AGN)







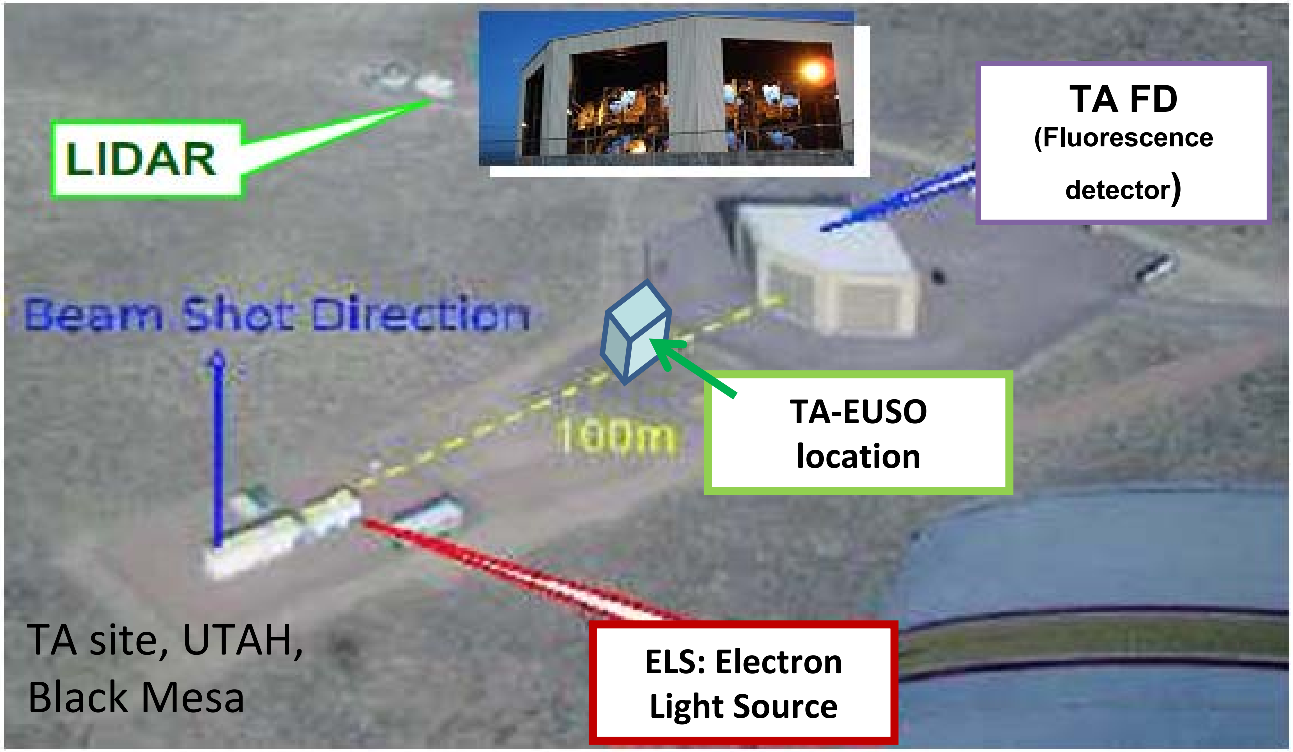
- More than 1,000 events: $E>7\times10^{19}$eV
- We expect to discover several dozens of clusters
- Can observe the whole sky

TA-EUSO
Cross-calibration tests at Telescope Array site, Utah

<u>**Main purpose: calibration using existing FD telescope**</u>

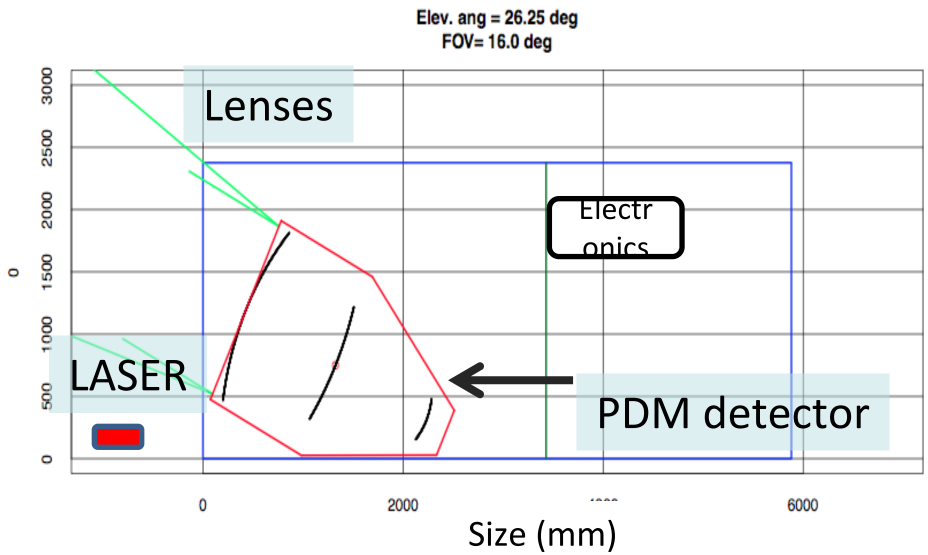
- **Lidar and electron beam → absolute calibration**
- **Few showers in coincidence with TA**
- **Later repeat also at the Pierre Auger Observatory**

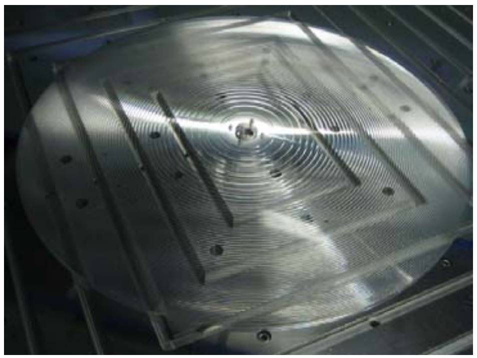
Operation early 2013!

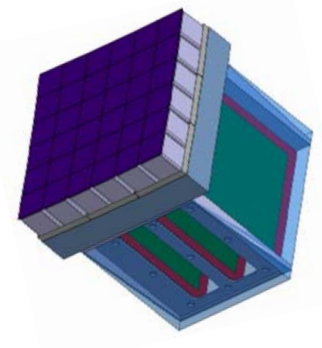


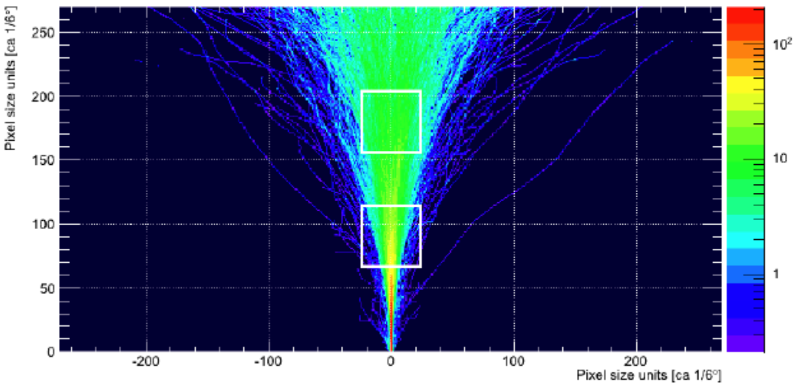
TA-EUSO
Cross-calibration tests at Telescope Array site, Utah

- **2 (squared 1 m^2) Fresnel Lenses → FoV = 8 degree**
- **focal surface: 1 PDM (36 MAPMT, 2304 pixels)**







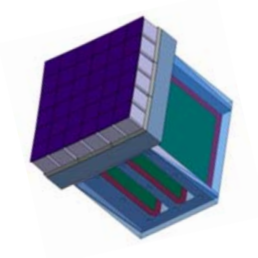


Simulation of UV photons of TA ELS
Squares: FoV of the EUSO-Ground telescope.

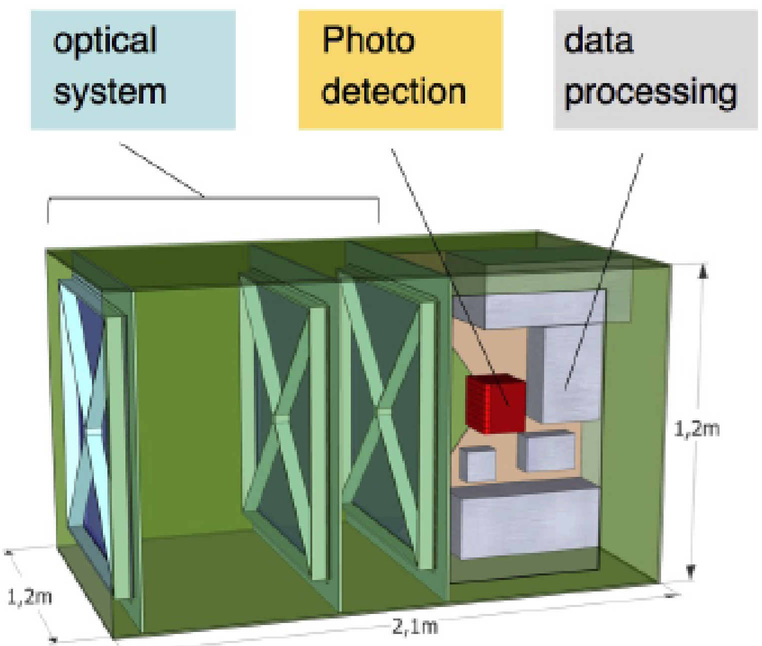
EUSO-Balloon
JEM-EUSO prototype at 40km altitude

Main purpose: Background measurements and engineering tests

- Engineering test
- UV-Background measurement
- Air shower observations from 40 km altitude



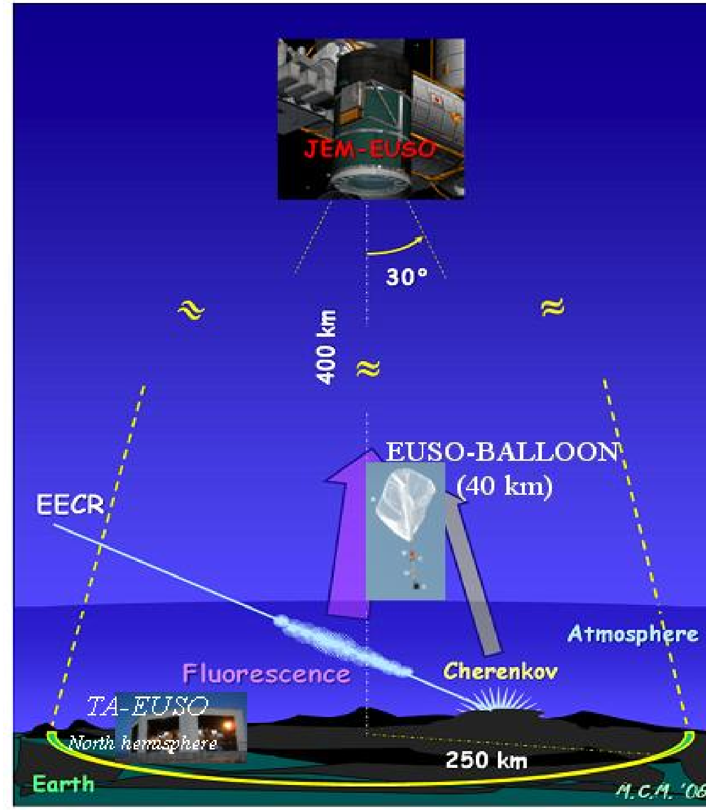
First flight: 2014!

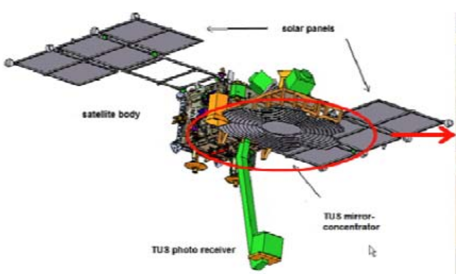


Summary JEM-EUSO

- **Study of EECR from**
  - **Ground (Utah)** ➔ **early 2013**
  - **Balloon (40 km)** ➔ **2014-15**
  - **Space (ISS)** ➔ **launch 2017**

    - TUS/KLYPVE on Lomonosov satellite launch 2012/13
      - technical pathfinder of EUSO
      - survey of UV-background





JEM-EUSO Collaboration

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13 countries

75 institutes

258 members

Discussion / Question / Exercise

- **why neutrino and photon observations are important?**
  - **pointing to the source**
  - **GZK signature**
  - **multi-messenger astronomy**
- **how to distinguish GZK-suppression from max. acceleration?**
  - **anisotropy**
  - **composition**
  - **photon and neutrinos**
- **what JEM-EUSO could be be do better than Auger?**
  - **statistics**
  - **energy spectrum north and south hemisphere**
  - **interdisciplinary physics**