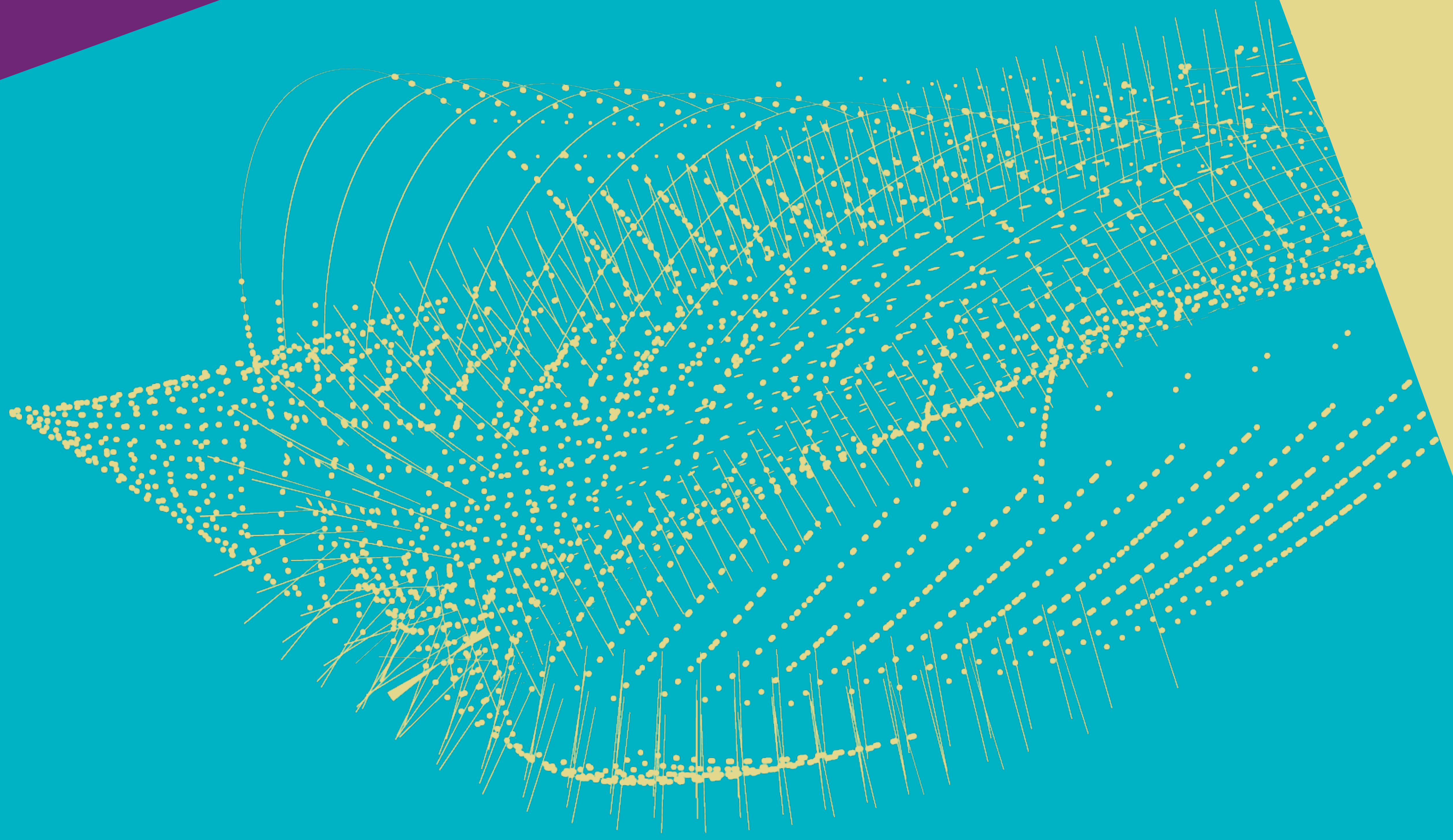


# ASTROPARTICLE PHYSICS
# COSMIC RAYS

**Jörg R. Hörandel**
Radboud Universiteit Nijmegen
Nikhef, Vrije Universiteit Brussel

RECFA 2018


# Committee for Astroparticle Physics in the Netherlands (CAN)

**Objectives:**

- **community forming**
  **23 annual symposia since 2004**
- **policy making, strategic planning**


**Theory**
**Cosmic rays**
**Gamma rays**
**Neutrinos**
**Dark matter**
**Gravitational waves**

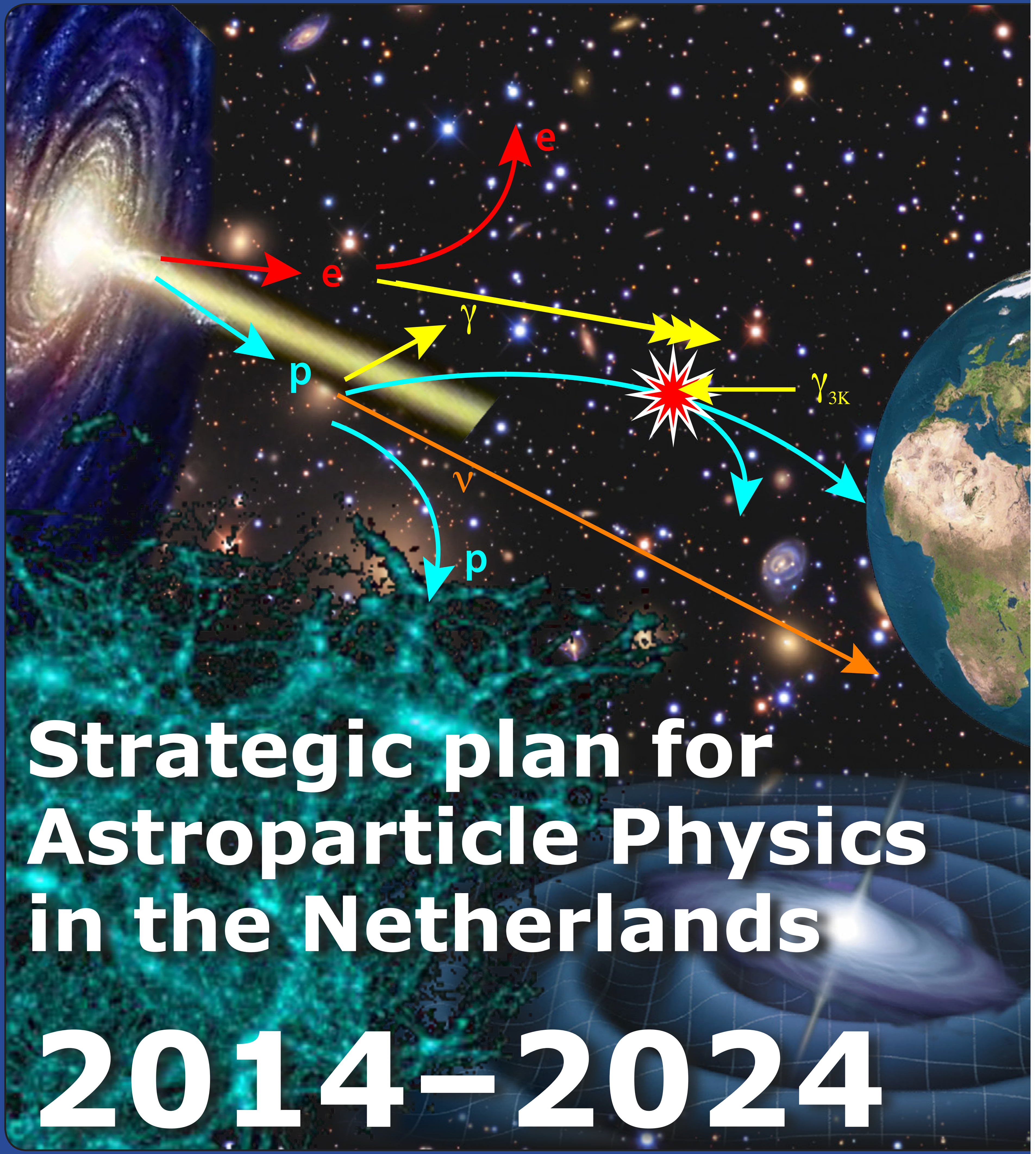
**Committee for Astroparticle Physics in the Netherlands (CAN)**

A.M. van den Berg (Groningen)
G. Bertone (Amsterdam)
J. van den Brand (Amsterdam)
A. Boyarsky (Leiden)
M. P. Decowski (Amsterdam, Nikhef)
J. Hessels (ASTRON)
J.R. Hörandel (Nijmegen, Nikhef) [chair]
P. Jonker (SRON)
S. Markoff (Amsterdam)
E.M. Rossi (Leiden)
D. Samtleben (Leiden, Nikhef)
C. Timmermans (Nijmegen, Nikhef)
C. Van Den Broeck (Nikhef) [co chair]
J. Vink (Amsterdam)
R. van den Weygaert (Groningen)

**WWW.ASTROPARTICLEPHYSICS.NL**

**CAN**
**Committee for Astroparticle Physics in the Netherlands**

**March 2014**




# Contents

Application form

Gravitation Programme
2018 – 2019

# nation-wide proposal for multi-messenger astroparticle physics

***IMAGES: Institute for Multi-messenger Astroparticle physics of Gravity and Extreme Sources***

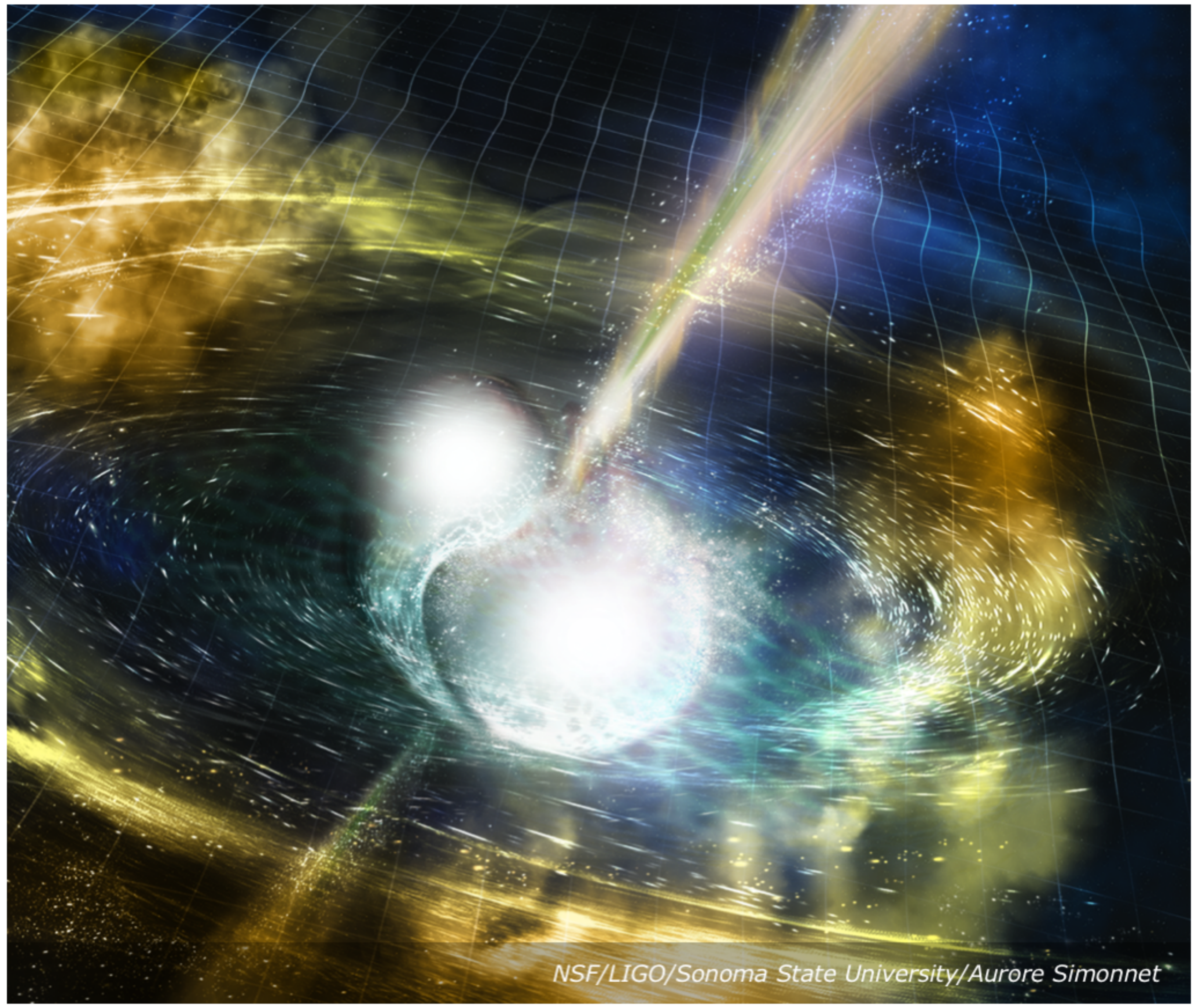



**Fig. 3**: Gallery of key instruments supported by IMAGES: Clockwise from top left: visualisation of CTA gamma ray detector showing the three differently sized telescopes, KM3NeT neutrino detector view of underwater detector strings, aerial view of Virgo GW detector and photograph of CR detector PAO showing a water Cherenkov detector, a radio detector and inset a schematic of upgraded water Cherenkov detector with scintillators and radio antenna.

# COSMIC RAYS - PIERRE AUGER OBSERVATORY


PIERRE AUGER OBSERVATORY

# GROUP (2017)

**6 (7) staff: S. de Jong, H. Falcke, J. Hörandel, O. Scholten, C. Timmermans,**
**A. van den Berg, J. Vink (since 2018)**
**1 PD: A. van Vliet**
**4 PhD: A. Aab, F. Canfora, G. de Mauro, B. Pont**

## Leadership positions in Pierre Auger collaboration:

**S. Bentvelsen member financial board (S. de Jong until 2016)**
**J. Hörandel collaboration board member**
**A. van den Berg (now S. de Jong) collaboration board member**
**J.R. Hörandel radio task leader (A. van den Berg until 2014)**
**C. Timmermans outreach co-taskleader**

## Universities involved:

**Nijmegen, Groningen, UvA (since 2018)**

Radboud Universiteit Nijmegen

rijksuniversiteit groningen

Universiteit van Amsterdam

# FUNDING (SINCE 2013)

## hardware investment:

3.5 M € ERCAdvanced Grant Hörandel, Auger radio upgrade, 2018
2.5 M € NWO-Groot, Auger radio upgrade, 2018
450 k € Nikhef mission, Auger scintillator upgrade (SSD)

## personnel:

### new since 2013:

1 technician (SSD upgrade) Nikhef
2 PhD projects Nikhef
1 PhD project RU Nijmegen
1 PhD project NWO Top Grant
1 PD NWO WARP

### continuing into reporting period:

6 PhD projects FOM
1 PhD project NOVA
1 PhD project NWO

# SUCCESSFULLY FINISHED PHD'S (SINCE 2013)

- **Guus van Aar, On the nature and origin of ultra-high-energy cosmic rays, 2016 (RU Nijmegen)**
- **Stefano Messina, Extension to lower energies of the cosmic-ray energy window at the Pierre Auger Observatory, 2016 (Groningen)**
- **Stefan Jansen, Radio for the masses - Cosmic ray mass composition measurements in the radio frequency domain, 2016 (RU Nijmegen)**
- **Johannes Schulz, Cosmic Radiation - Reconstruction of cosmic-ray properties from radio emission of extensive air showers, 2015 (RU Nijmegen)**
- **Wendy Docters, Unraveling the mysteries of high-energy cosmic rays using radio detection, 2015 (Groningen)**
- **Anna Nelles, Radio emission of air showers. The perspective of LOFAR and AERA, 2014 (RU Nijmegen)**
- **Erik Daniel Fraenkel, From radio pulse to elusive particle, 2014 (Groningen)**
- **Stefan Grebe, Finger on the pulse of cosmic rays, 2013 (RU Nijmegen)**
- **Krijn de Vries, Macroscopic modelling of radio emission from ultra-high-energy-cosmic-ray-induced air showers, 2013 (Groningen)**

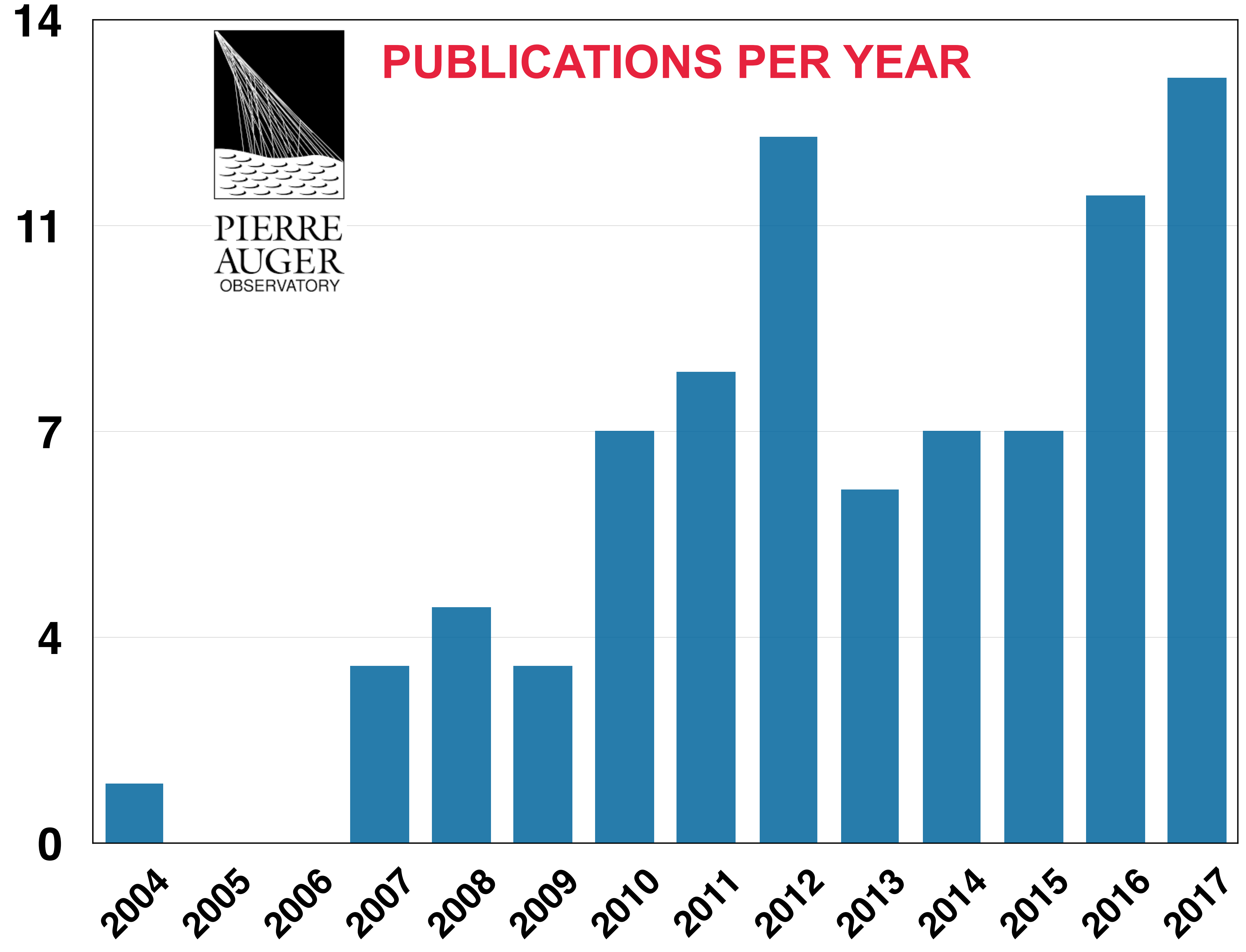
Radboud Universiteit Nijmegen

rijksuniversiteit groningen

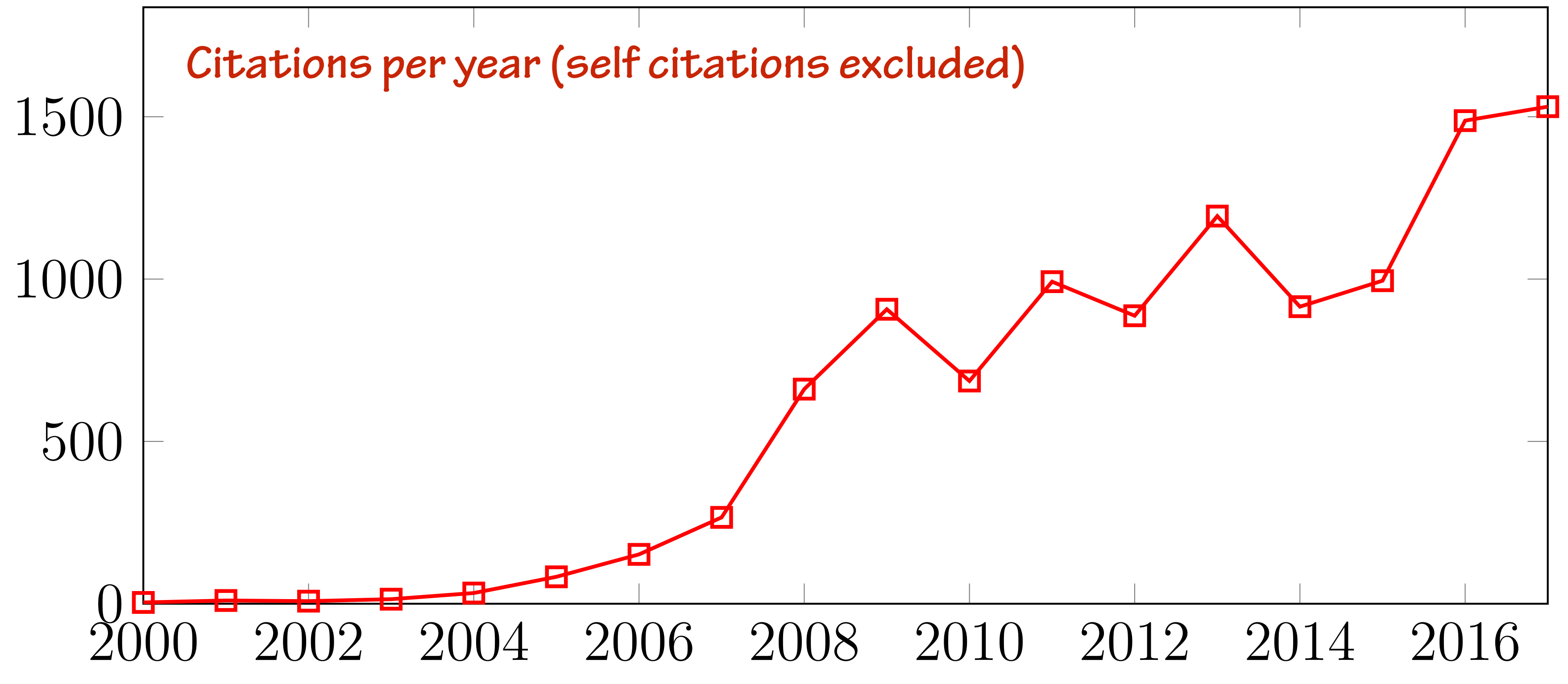
PIERRE AUGER OBSERVATORY

# PUBLICATIONS (2013 -)

**2013-now: total 44 articles**
**(mass composition, energy spectrum, arrival direction, photons, neutrinos, hadronic interactions, …)**




AUGER CITATIONS PER YEAR




## Auger general (selection)

- **Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above $8*10^{18}$ eV**
  **A. Aab et al. (Pierre Auger Collaboration)**
  **Science 357 (2017) 1266**

- **An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources**
  **A. Aab et al. (Pierre Auger Collaboration)**
  **Astrophysical Journal 835 (2018) L29**

- **Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory**
  **A. Albert et al., ANTARES, IceCube, Pierre Auger, LIGO, VIRGO collaborations**
  **Astrophysical Journal 850 (2017) L35**

- **Multi-messenger Observations of a Binary Neutron Star Merger**
  **B.P. Abbott et al.**
  **Astrophysical Journal 848 (2017) L12**

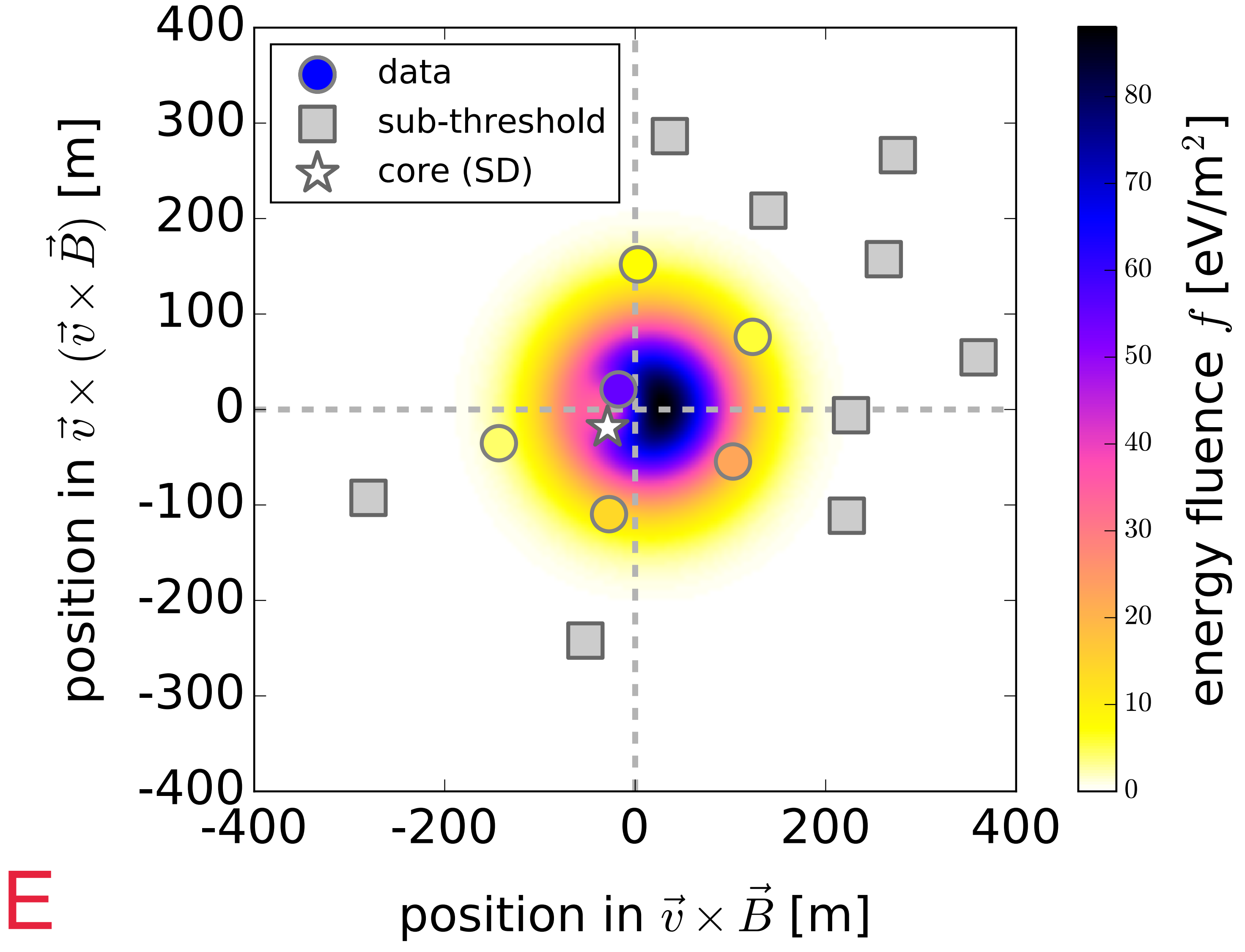
# PUBLICATIONS (2013 -)

## radio group

- Probing the radio emission from air showers with polarization measurements
  A. Aab et al. (Pierre Auger Collaboration)
  Physical Review D 89 (2014) 052002
- Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory
  A. Aab et al. (Pierre Auger Collaboration)
  Physical Review D 93 (2016) 122005
- Measurement of the radiation energy in the radio signal of extensive air showers as a universal estimator of cosmic-ray energy
  A. Aab et al. (Pierre Auger Collaboration)
  Physical Review Letters 116 (2016) 241101
- Simulation of radiation energy release in air showers
  C. Glaser, M. Erdmann, J.R. Hörandel, T. Huege, J. Schulz
  Journal of Cosmology and Astroparticle Physics 1609 (2016) 024
- Nanosecond-level time synchronization of autonomous radio detector stations for extensive air showers
  A. Aab et al. (Pierre Auger Collaboration)
  JINST 11 (2016) 01018
- Calibration of the Logarithmic-Periodic Dipole Antenna (LPDA) Radio Stations at the Pierre Auger Observatory using an Octocopter
  A. Aab et al. (Pierre Auger Collaboration)
  JINST 12 (2017) T10005
- Observation of inclined EeV air showers with the radio detector of the Pierre Auger Observatory
  A. Aab et al (Pierre Auger Collaboration)
  JCAP 10 (2018) 026

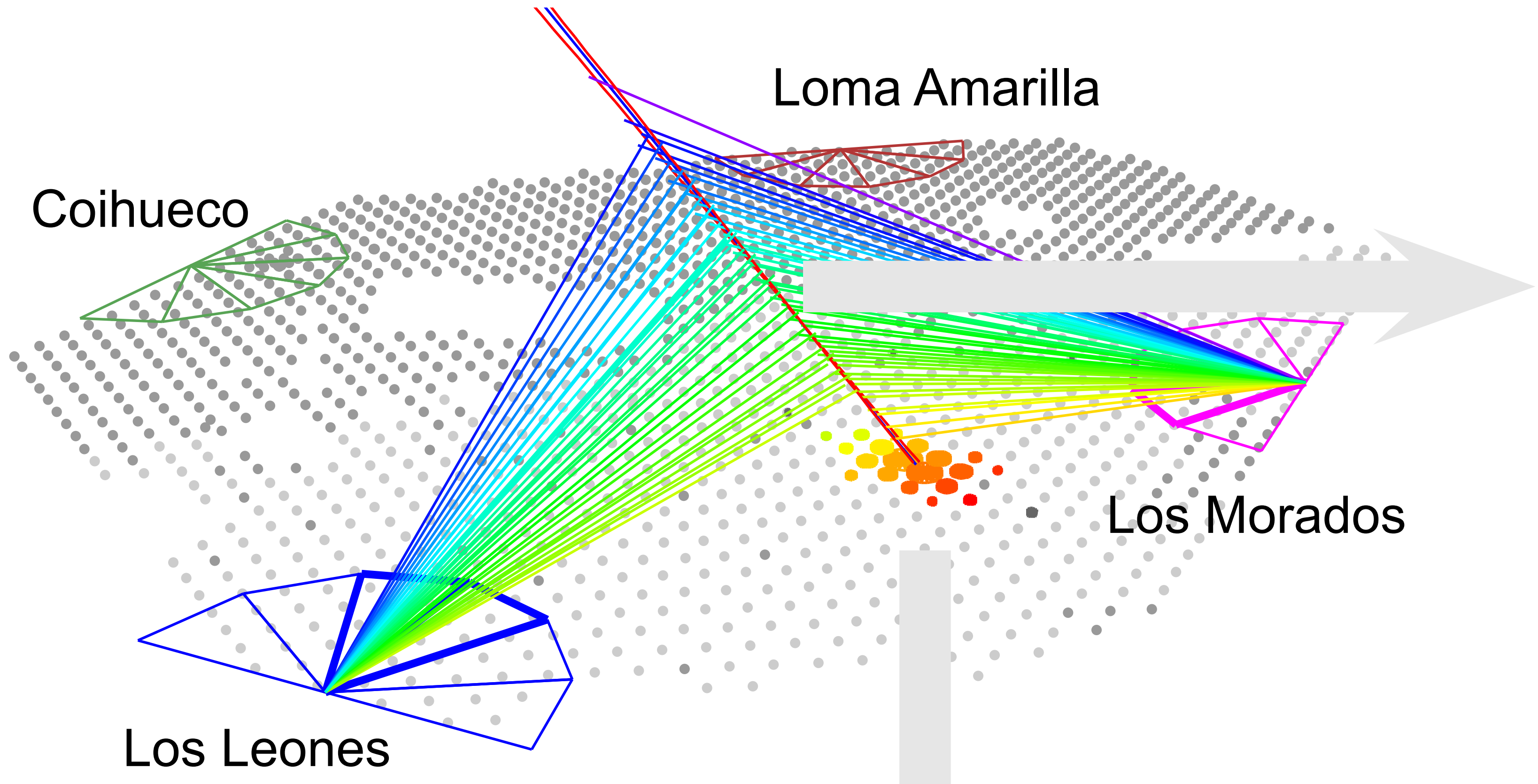
# MEASURING AIR SHOWERS WITH MULTIPLE TECHNIQUES

PIERRE AUGER OBSERVATORY

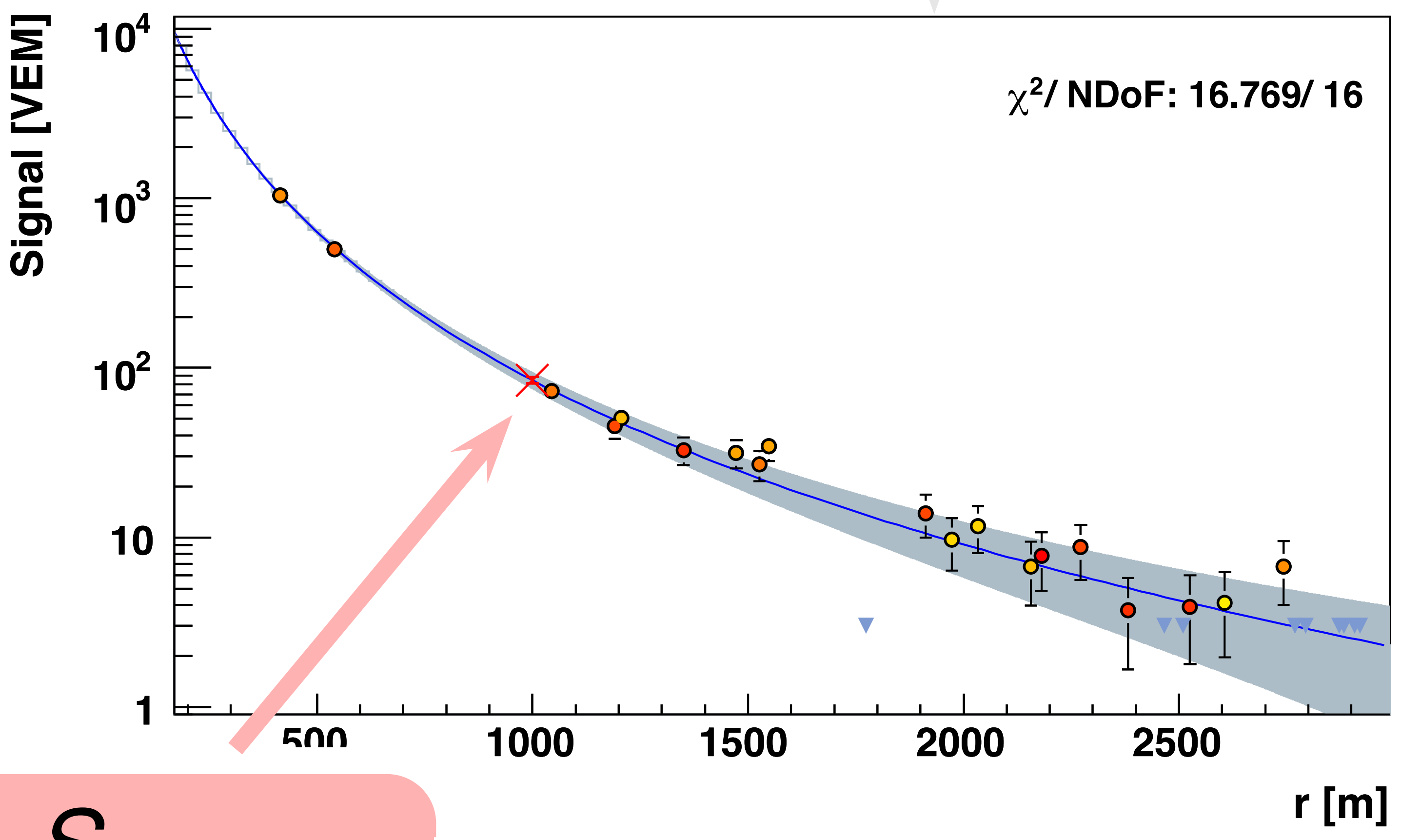



## RADIO DETECTOR

$X_{max}$, $E_{cal}$

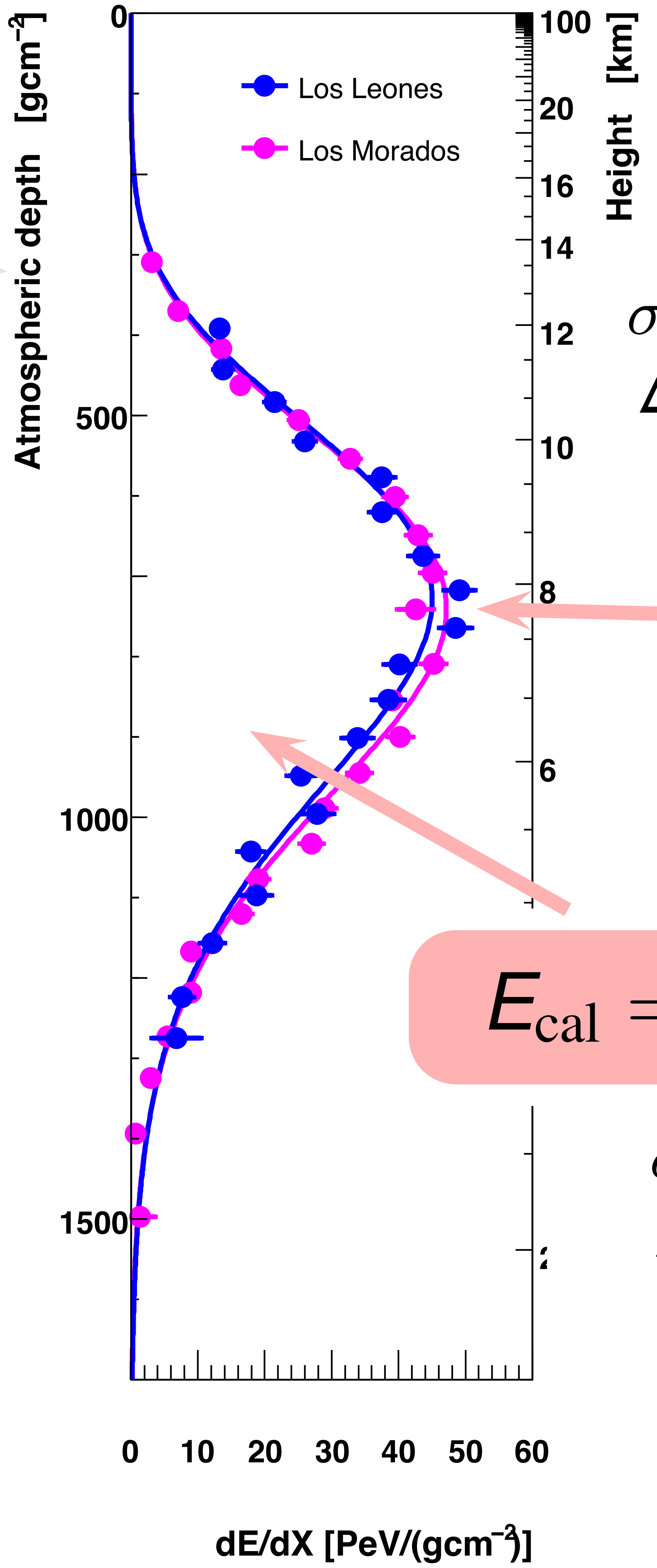



## SURFACE DETECTOR




$S_{1000}$

$E_{surface} = f(S_{1000}, \theta)$




$X_{max}$

$\sigma_{X_{max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{sys} \leq 10\,\mathrm{g/cm^2}$

$E_{cal} = \int \frac{dE}{dX}\, dX$

$\sigma_E / E \sim 8\,\%$
$\Delta_{sys} \approx 15\,\%$

## FLUORESCENCE DETECTOR

## EXPOSURE

**Auger 9.0*10$^4$ km$^2$ sr yr**

**TA 0.8*10$^4$ km$^2$ sr yr**

# 2017 HIGHLIGHT

***RESEARCH***

**COSMIC RAYS**

## Observation of a large-scale anisotropy in the arrival directions of cosmic rays above $8 \times 10^{18}$ eV

The Pierre Auger Collaboration*†

physicsworld TOP 10 BREAKTHROUGH 2017

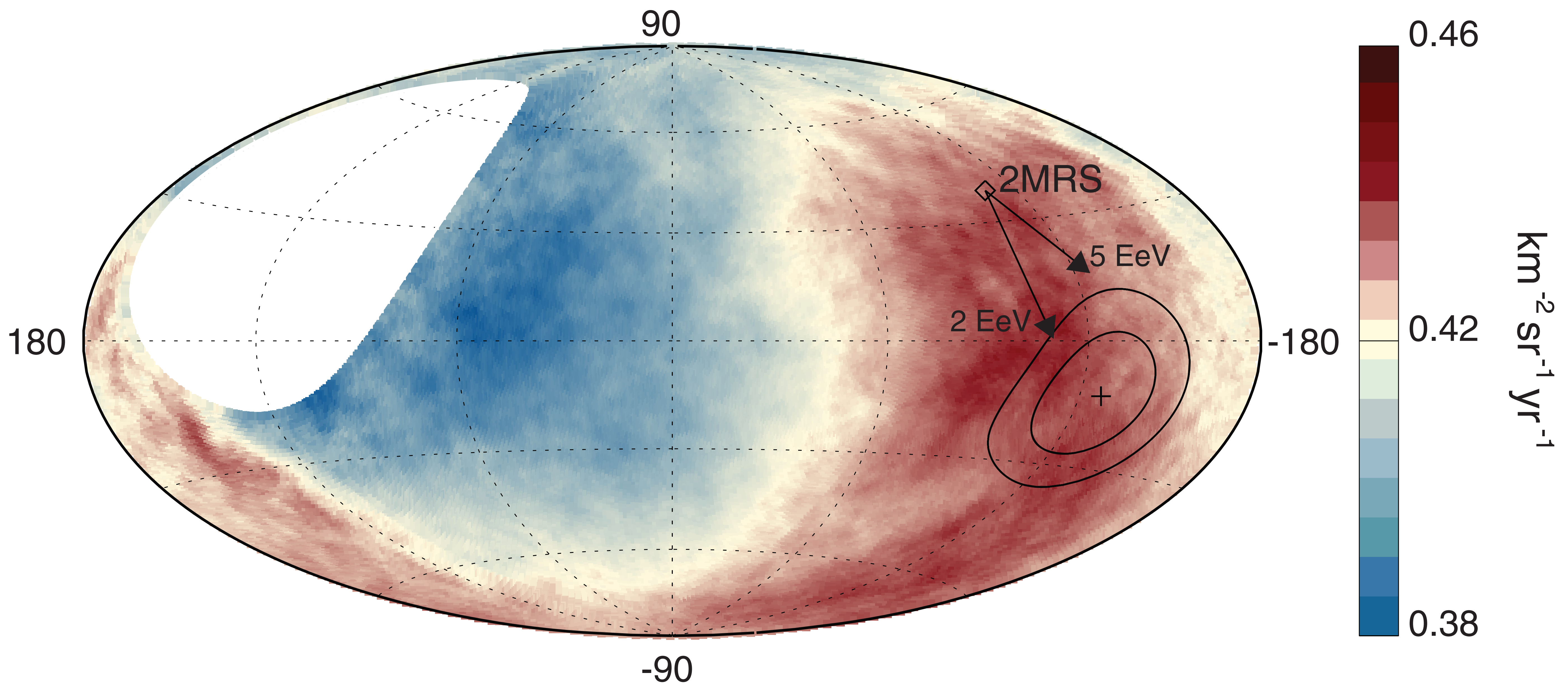



**Fig. 3. Map showing the fluxes of particles in galactic coordinates.** Sky map in galactic coordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45° top-hat function. The galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for a particular model of the galactic magnetic field (*8*) on particles with $E/Z$ = 5 or 2 EeV.

Anisotropy detected at >5.2 sigma

dipole amplitude 6.5%

$E>8*10^{18}$ eV  $3*10^{4}$ cosmic rays

A. Aab et al., Science 357 (2017) 1266

# BIG MEDIA ATTENTION

## ~200 press reports
## from all over the world

**XINHUANET** — www.news.cn 新华网 — Sunday, Nov

**Ultra-high-energy cosmic rays come from galaxies far away: study**

Source: Xinhua | 2017-09-22 03:21:45 | Editor: Mu Xuequan

**LA NACION** Ciencia

**Develan un misterio: el origen de los rayos cósmicos**

Llegan desde fuera de la Vía Láctea; aporte argentino

**nature** International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For Aut

Archive > Volume 549 > Issue 7673 > News > Article

NATURE | NEWS

**High-energy cosmic rays come from outside our Galaxy**

Giant observatory announces long-awaited result.

Davide Castelvecchi

21 September 2017

**LE FIGARO**

**Des rayons cosmiques venus d'ailleurs**

**Le Monde** — Sciences

SCIENCES | Vidéos | Archéologie | Supplément partenaire : Les Prix EDF Pulse | Affaire d

**On sait désormais d'où viennent les rayons cosmiques**

PIERRE AUGER OBSERVATORY

**New Scientist**

DAILY NEWS 21 September 2017

**Far-off galaxies are firing rare high-energy cosmic rays at us**

**LA CROIX**

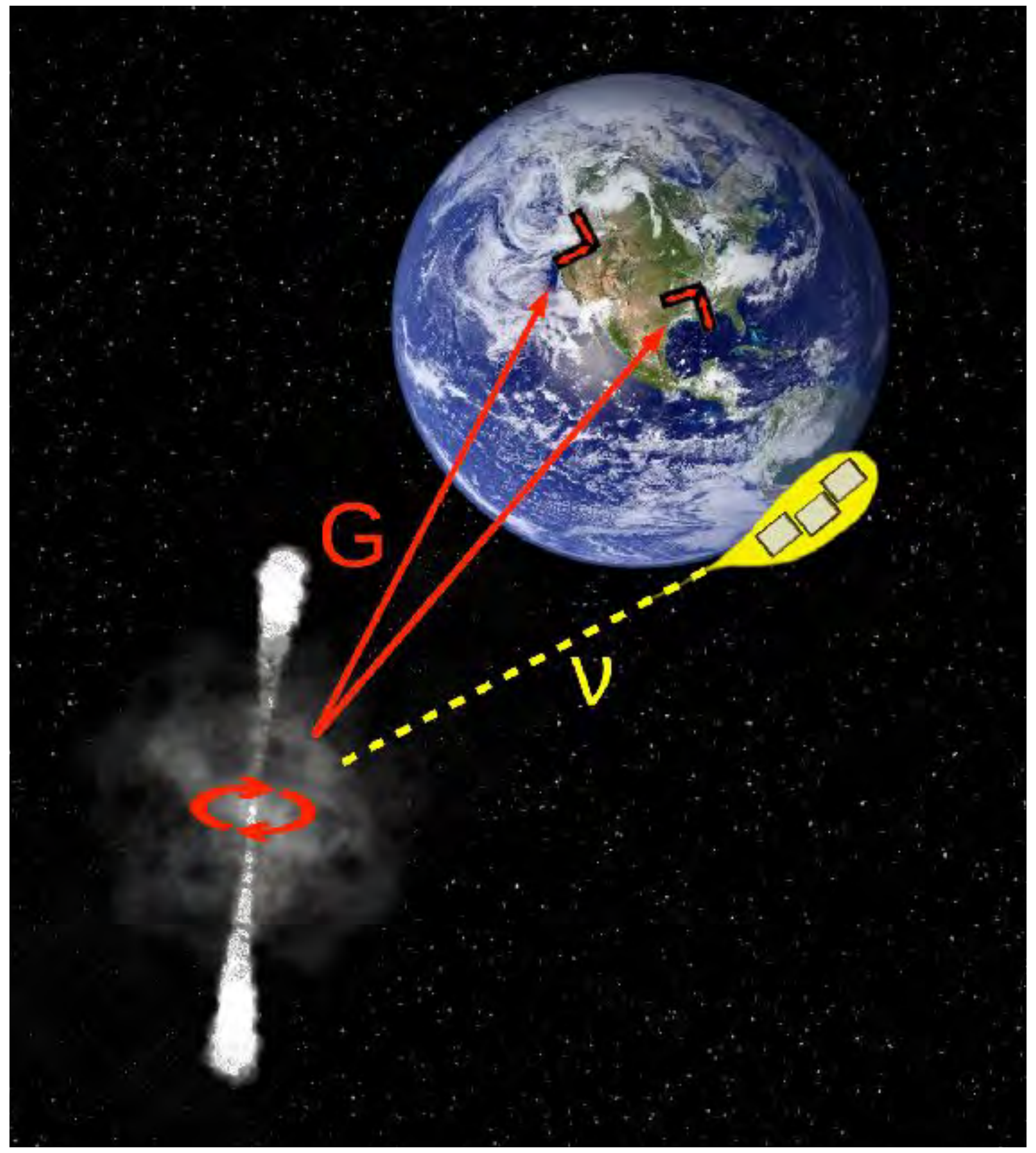
**On a trouvé d'où viennent les rayons cosmiques qui nous bombardent**

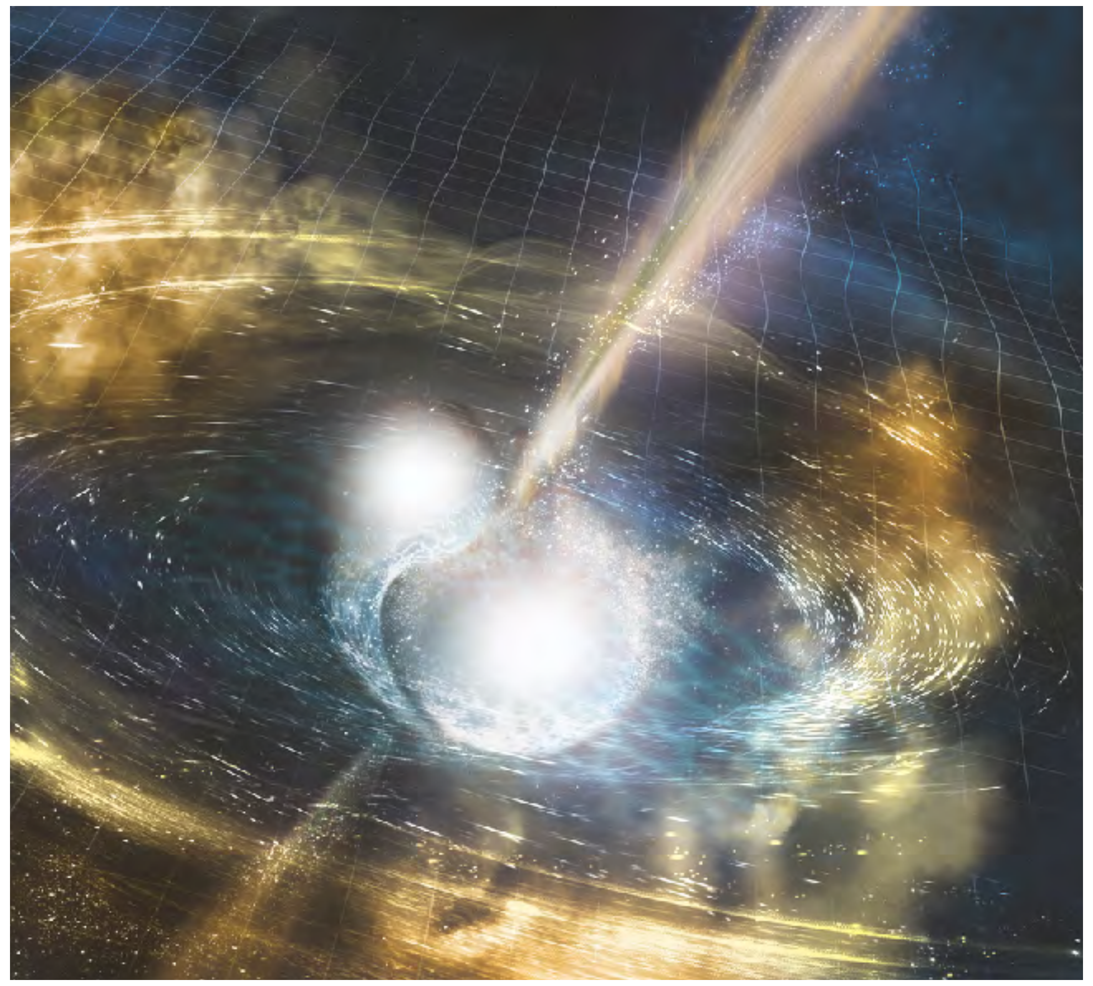
**de Volkskrant**

**Aarde ligt onder vuur: krachtpatserdeeltjes worden vanuit 'deep space' op ons afgeschoten**

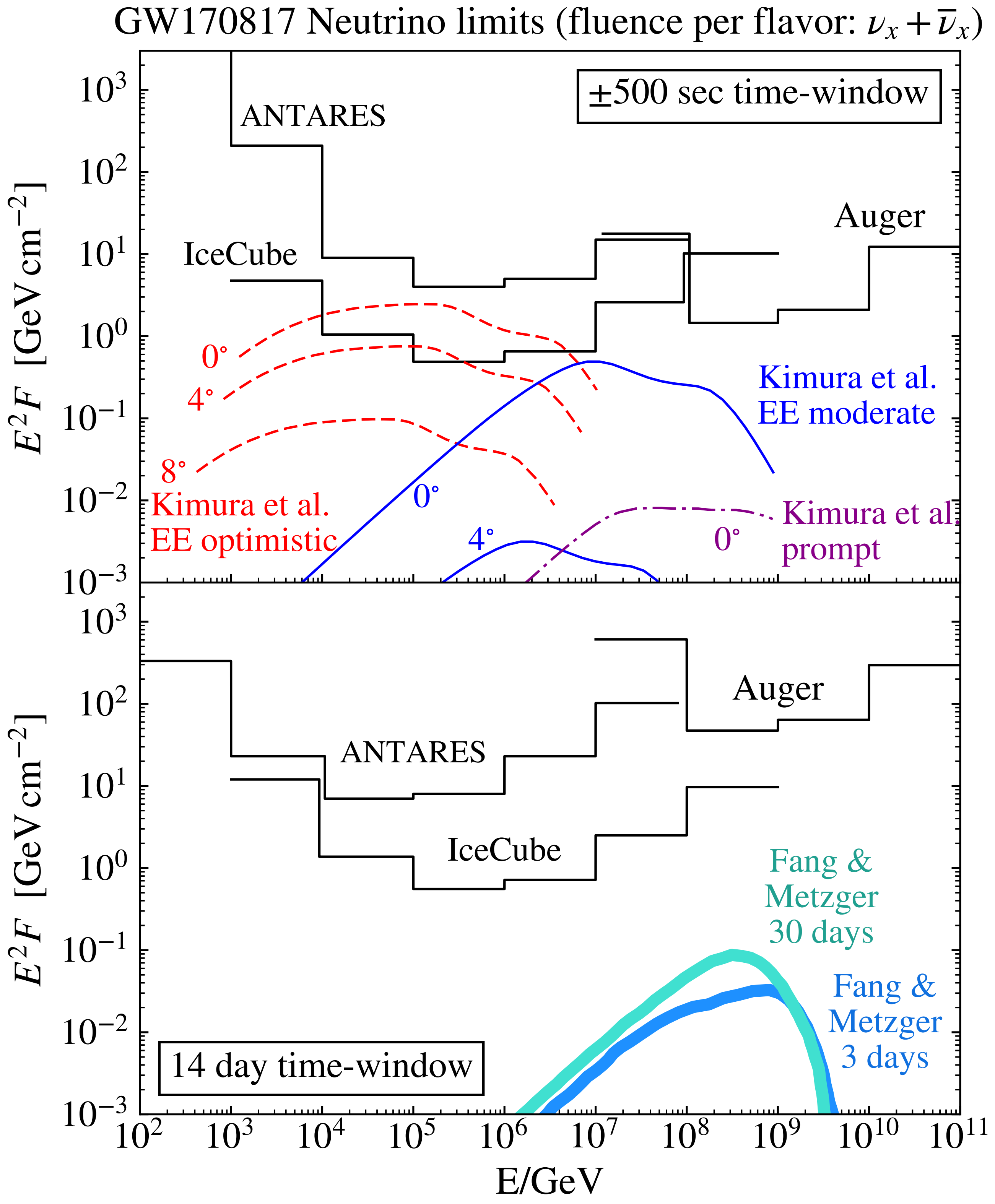
Malargüe, November 2017

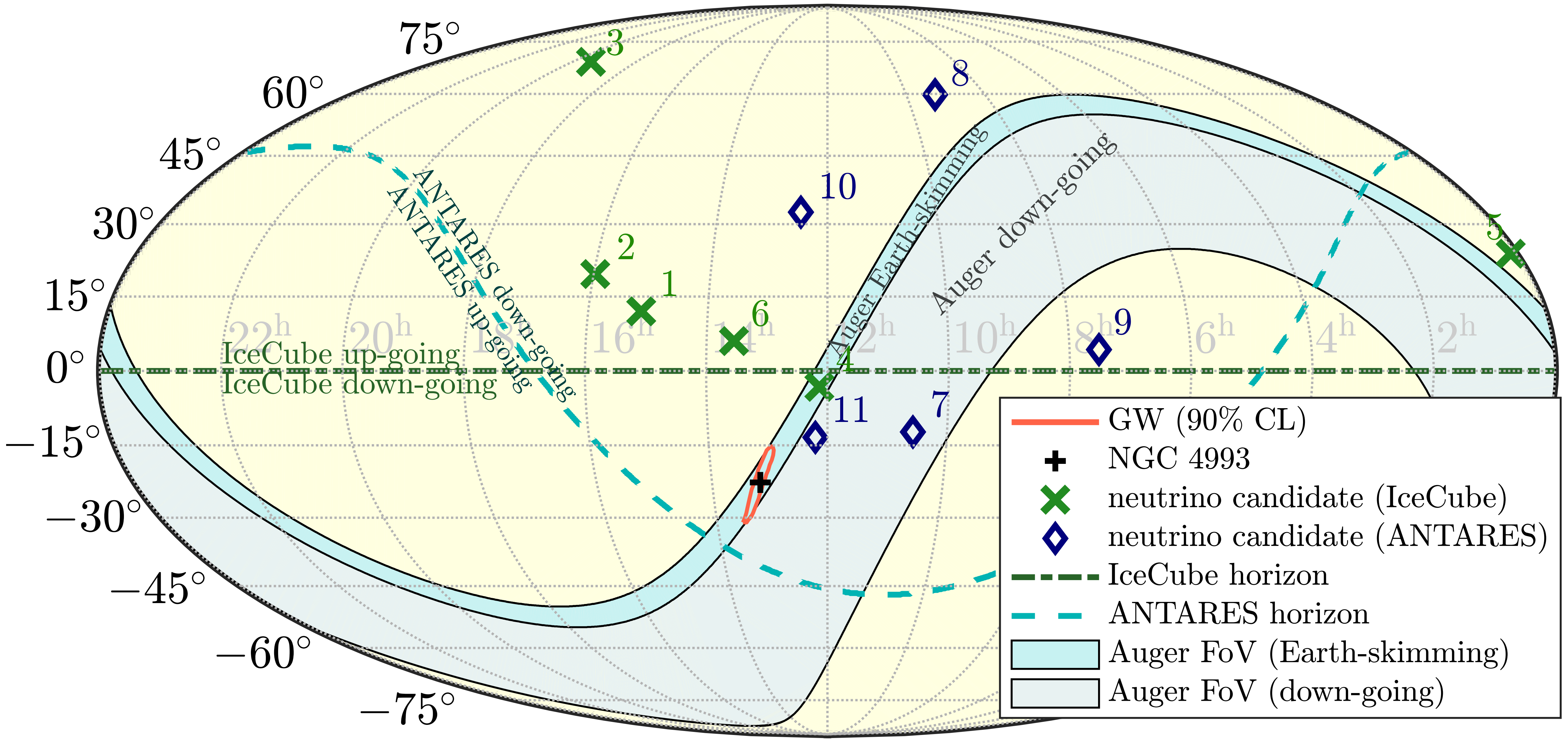
# FOLLOW-UP OF GW170817 WITH POA (NEUTRINOS)



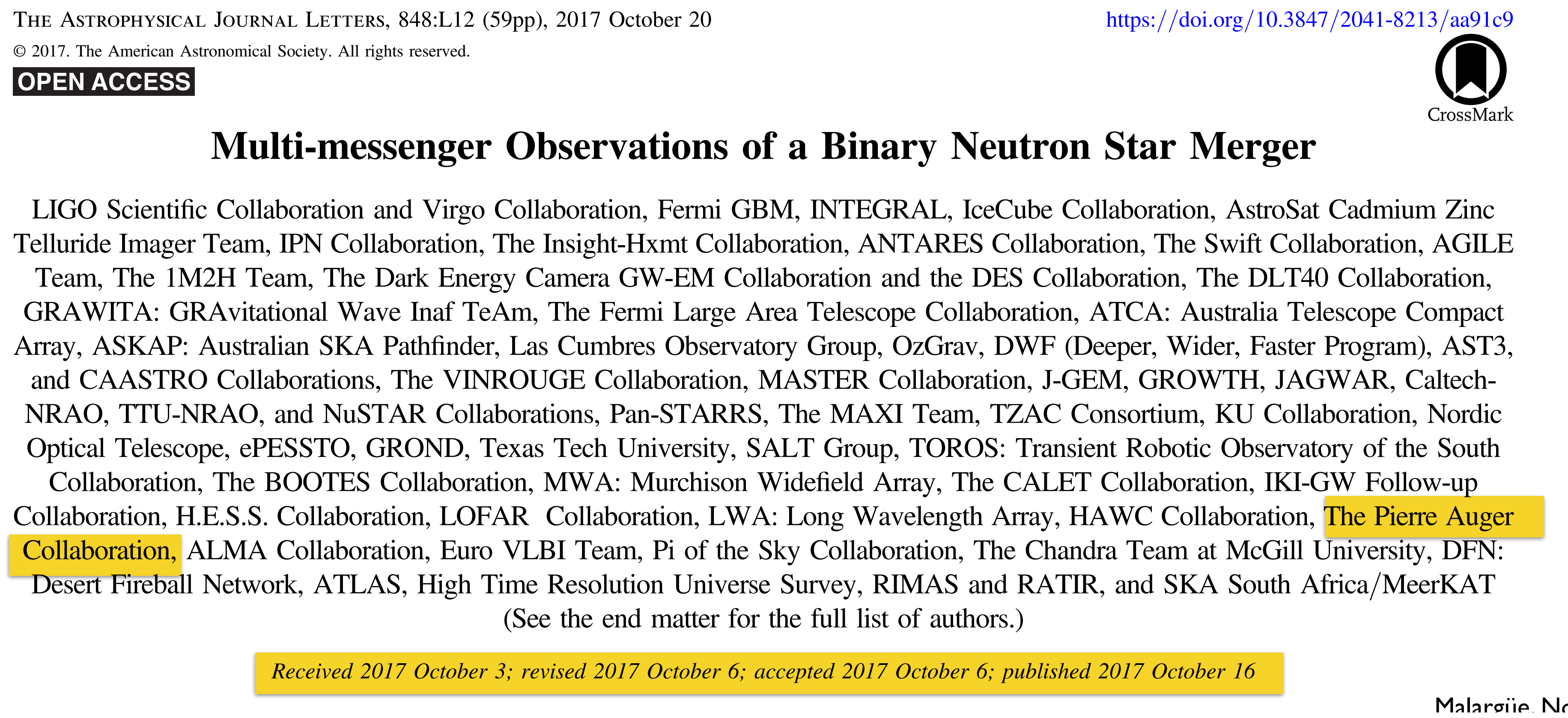



PAO in pre-defined +/- 500 s window as sensitive as IceCube







The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

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OPEN ACCESS

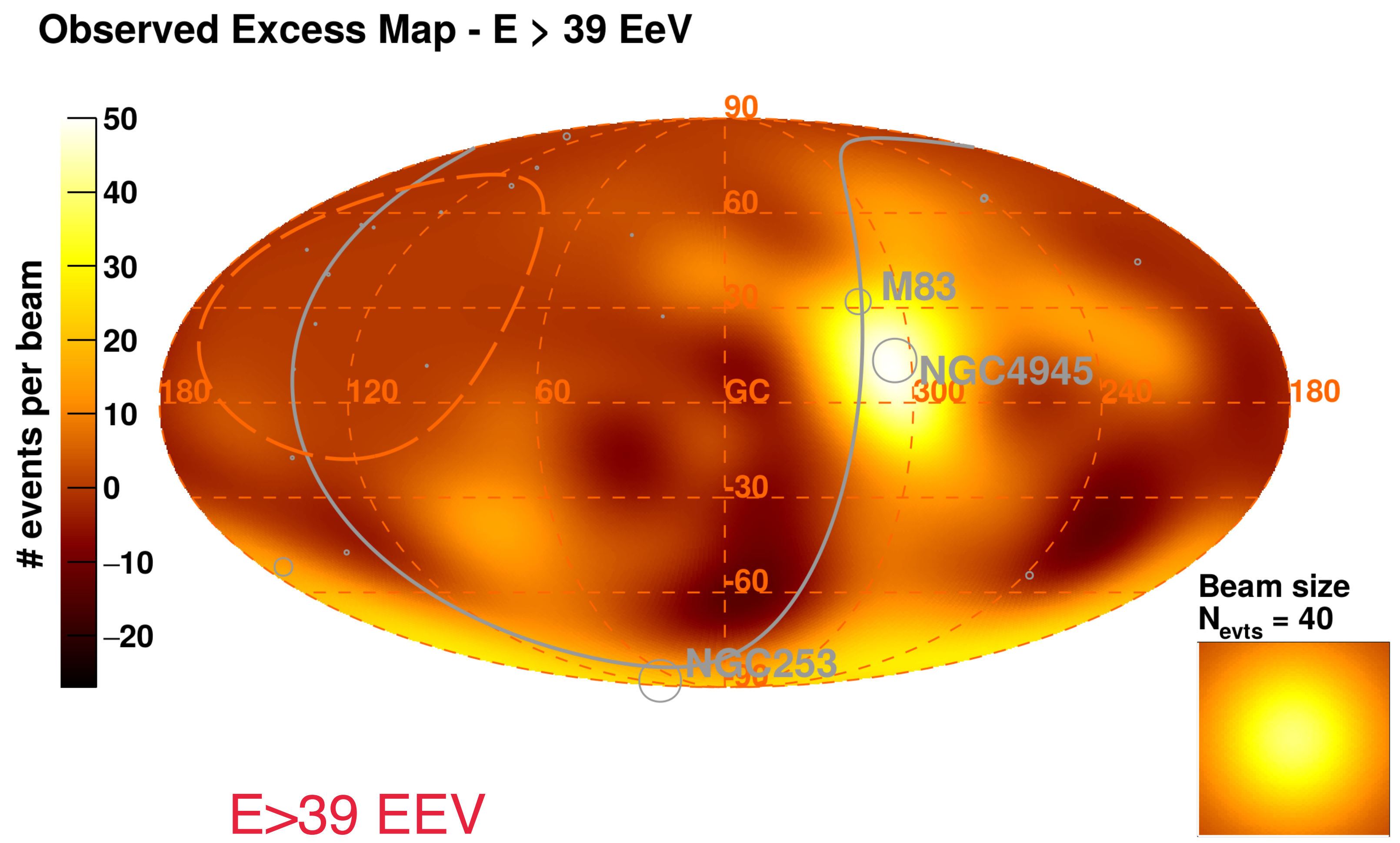
**Multi-messenger Observations of a Binary Neutron Star Merger**

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

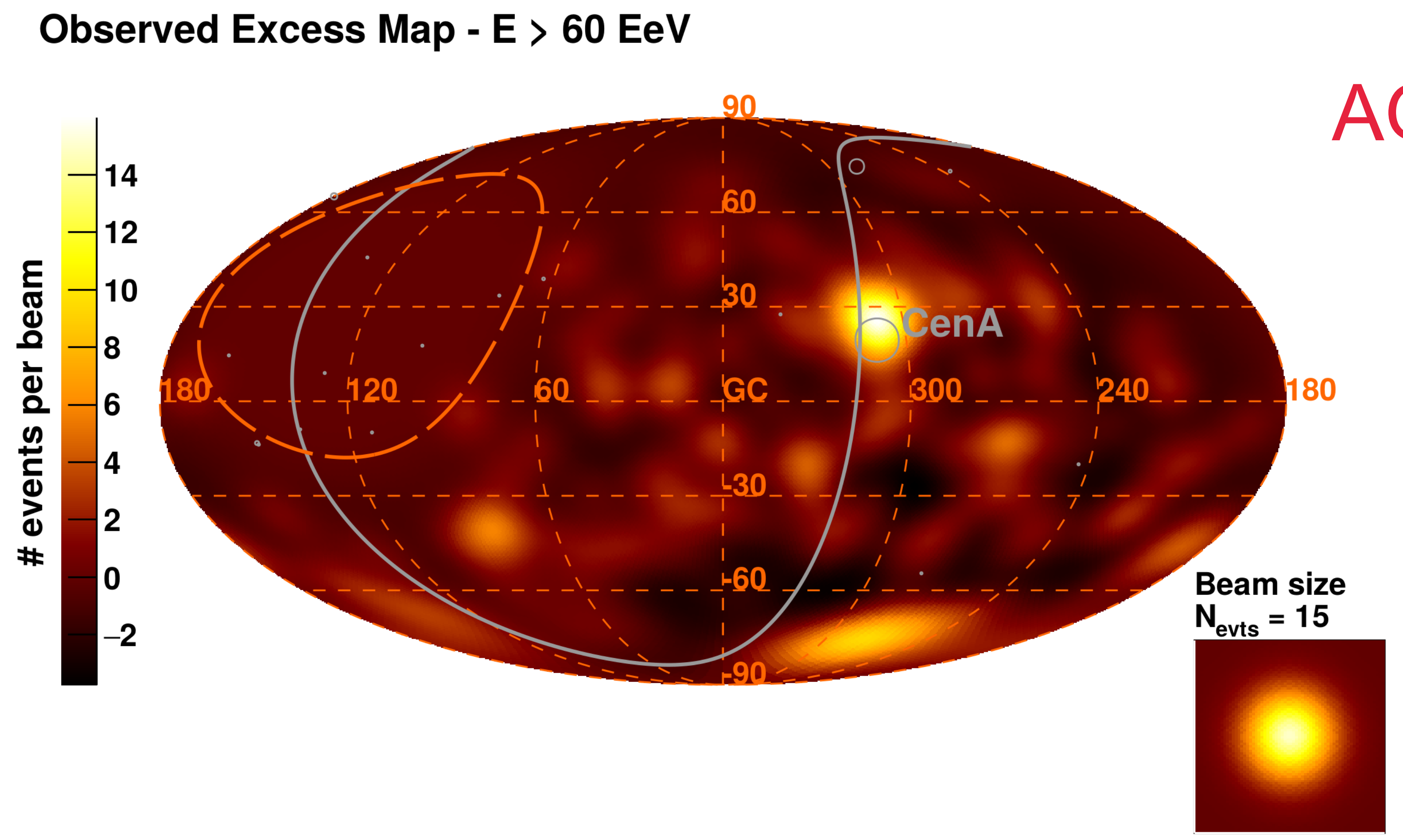
*Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16*

# SEARCH FOR INTERMEDIATE-SCALE UHECR ANISOTROPIES

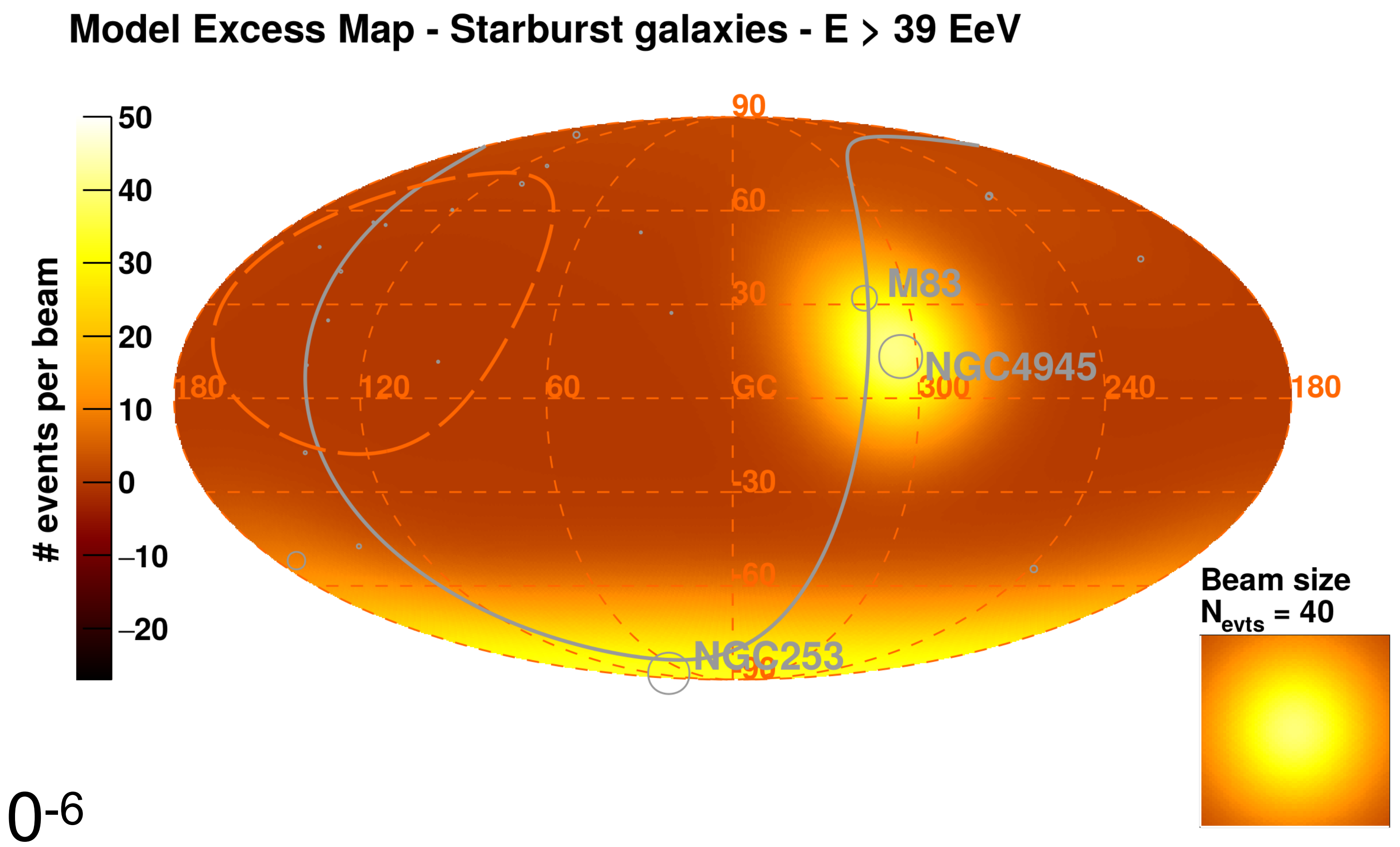
STARBURST

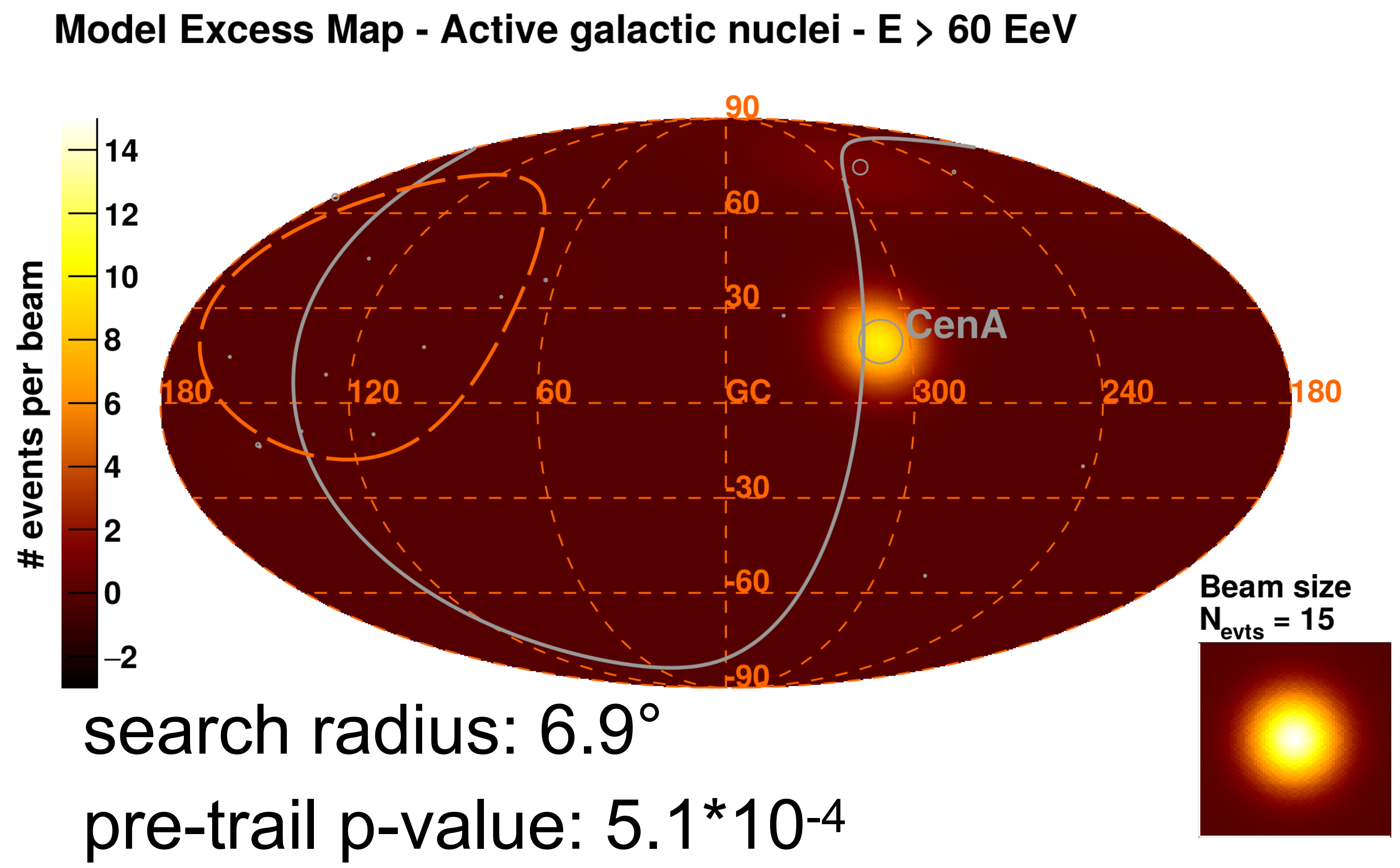



AGN




E>39 EEV




SBG fraction: 9.7%
search radius: 12.9°
pre-trail p-value: $3.8*10^{-6}$
post-trial p-value: $3.6*10^{-5}$
post-trial significance: 4.0 sigma

search radius: 6.9°
pre-trail p-value: $5.1*10^{-4}$
post-trial p-value: $3.1*10^{-3}$
post-trial significance: 2.7 sigma

A. Aab et al. ApJ 835 (2018) L29

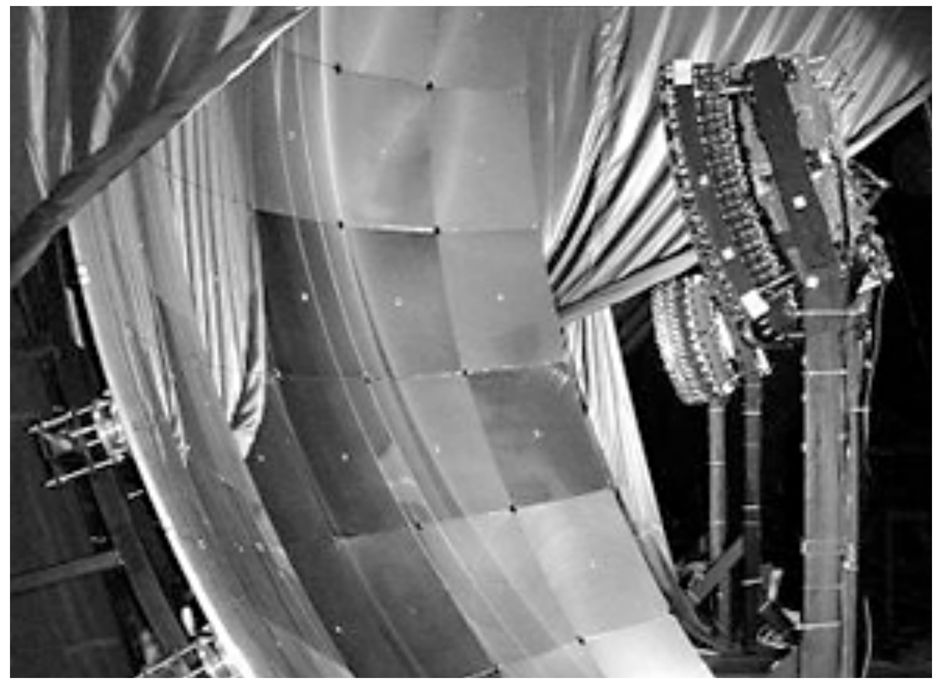
# AERA
Auger Engineering Radio Array

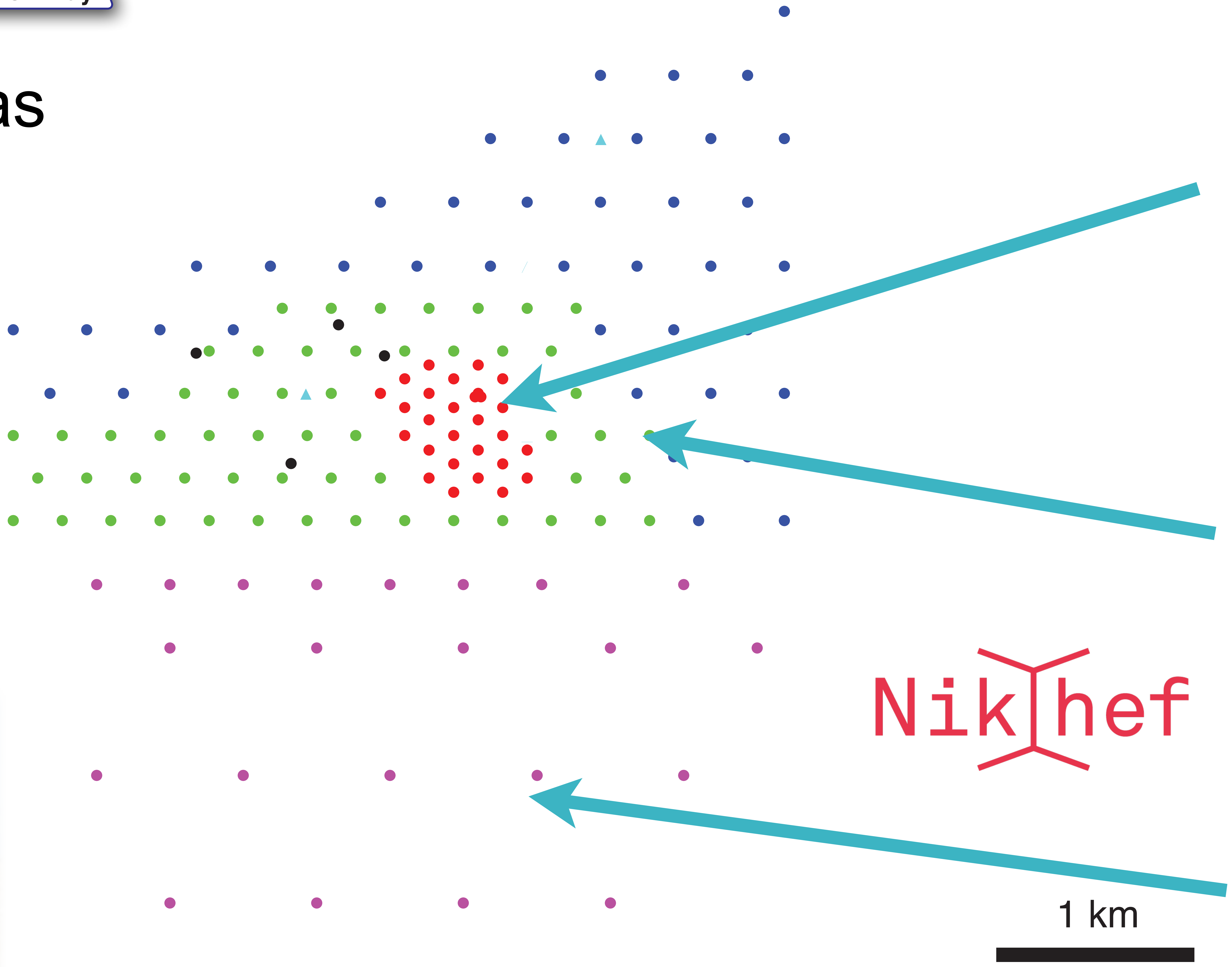
PIERRE AUGER OBSERVATORY

~150 antennas

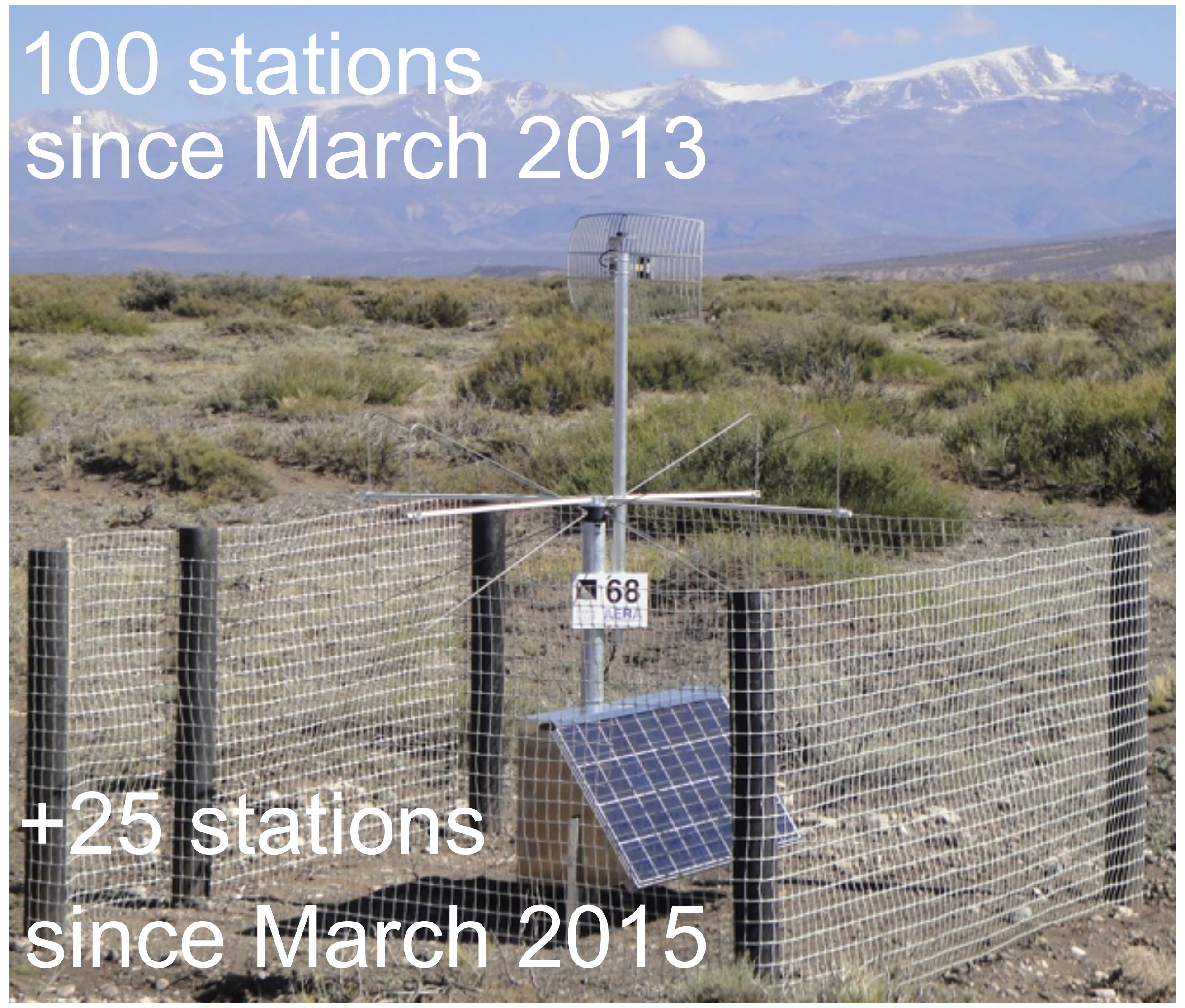
~17 $km^2$

30-80 MHz

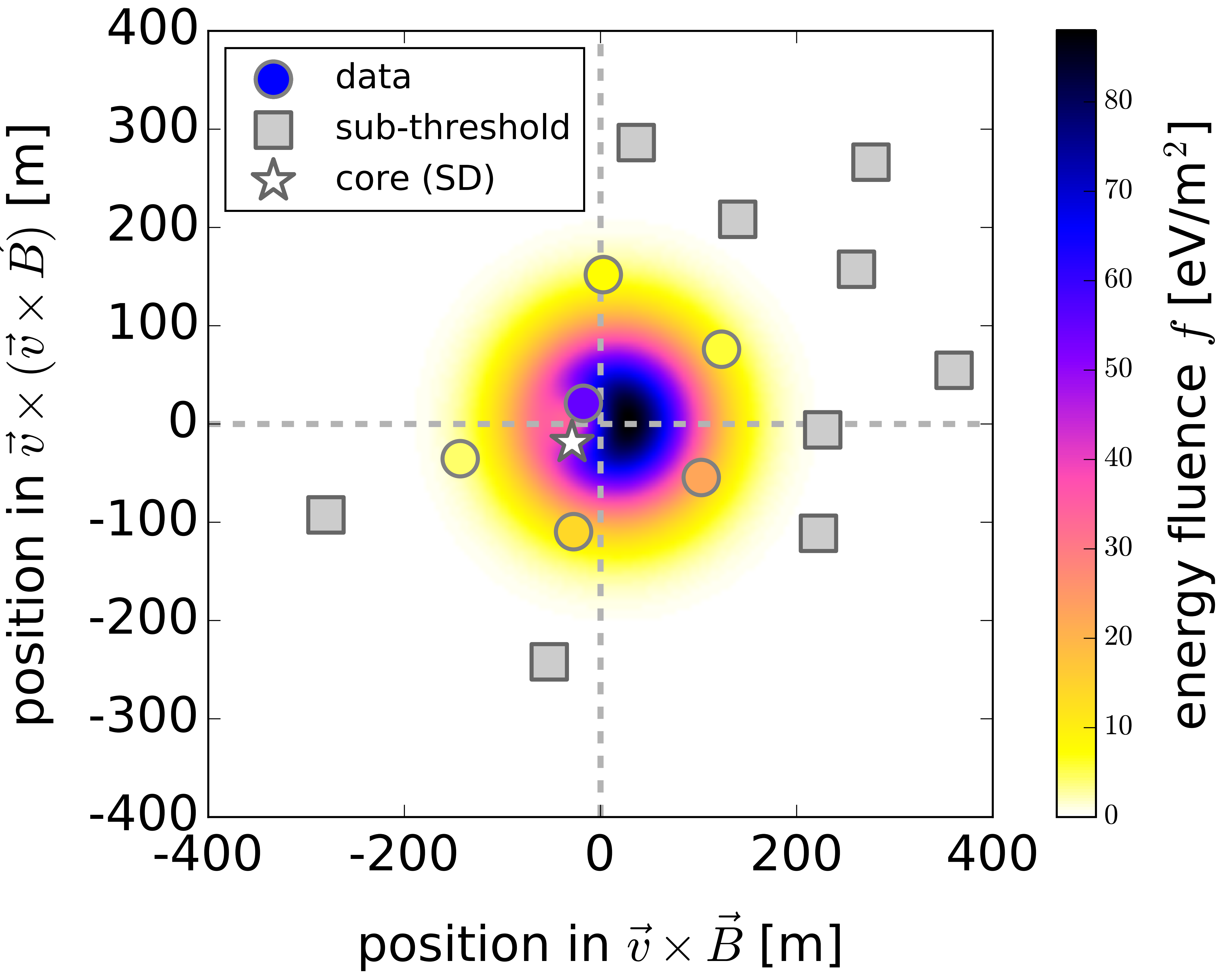




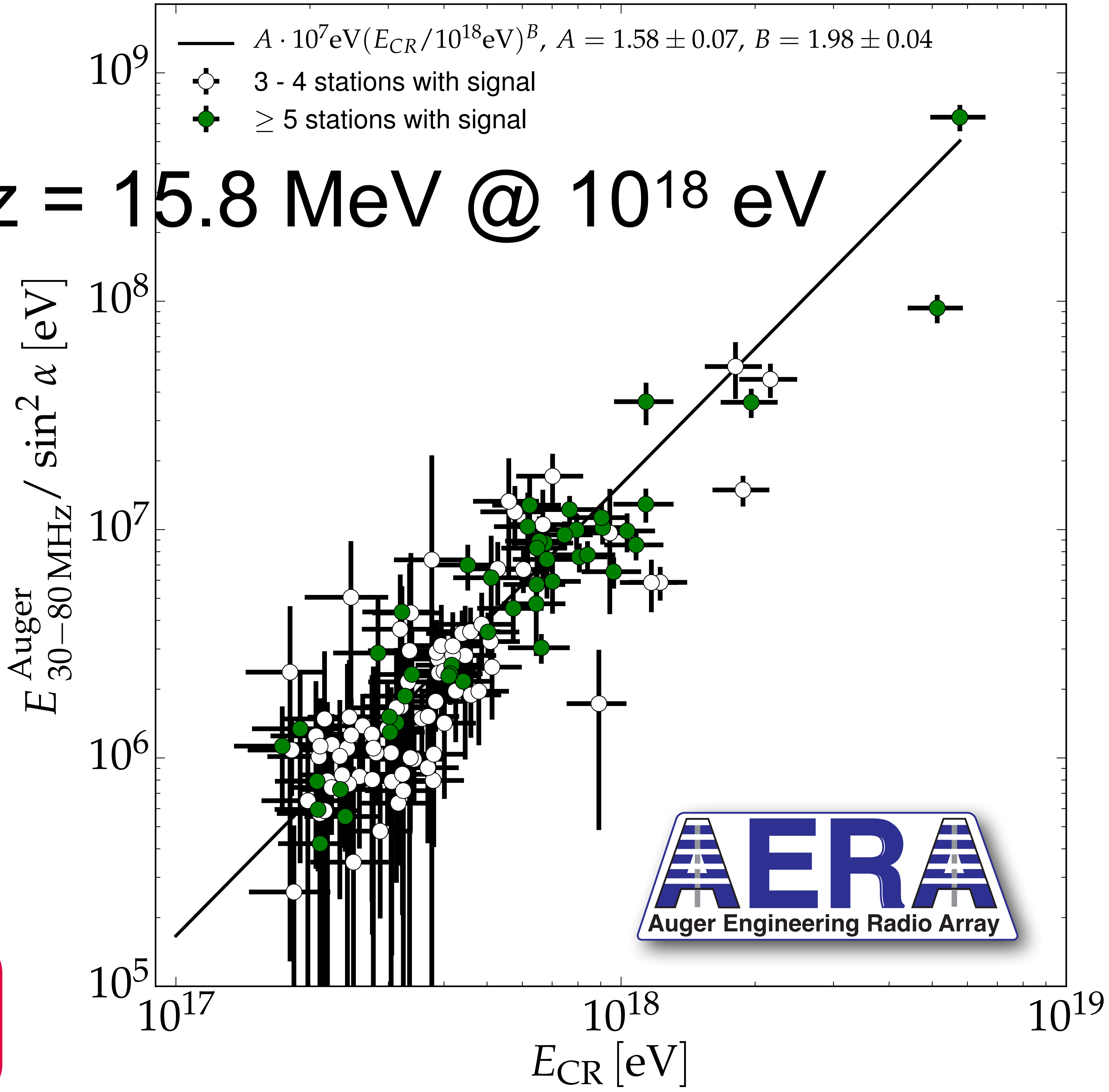




# MEASUREMENT OF THE RADIATION ENERGY IN THE RADIO SIGNAL OF EXTENSIVE AIR SHOWERS AS A UNIVERSAL ESTIMATOR OF COSMIC-RAY ENERGY



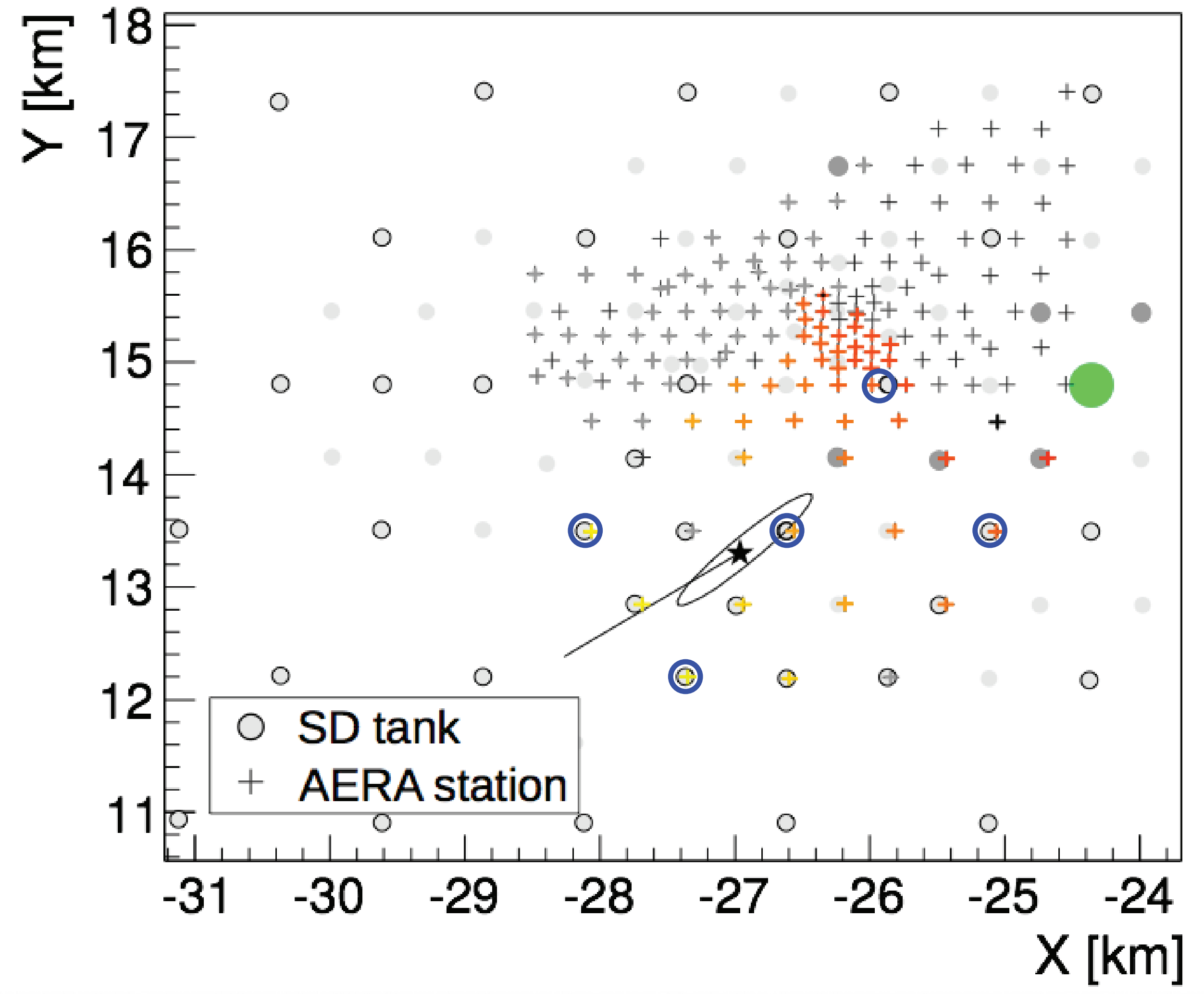

$E_{30\text{-}80}$ MHz = 15.8 MeV @ $10^{18}$ eV

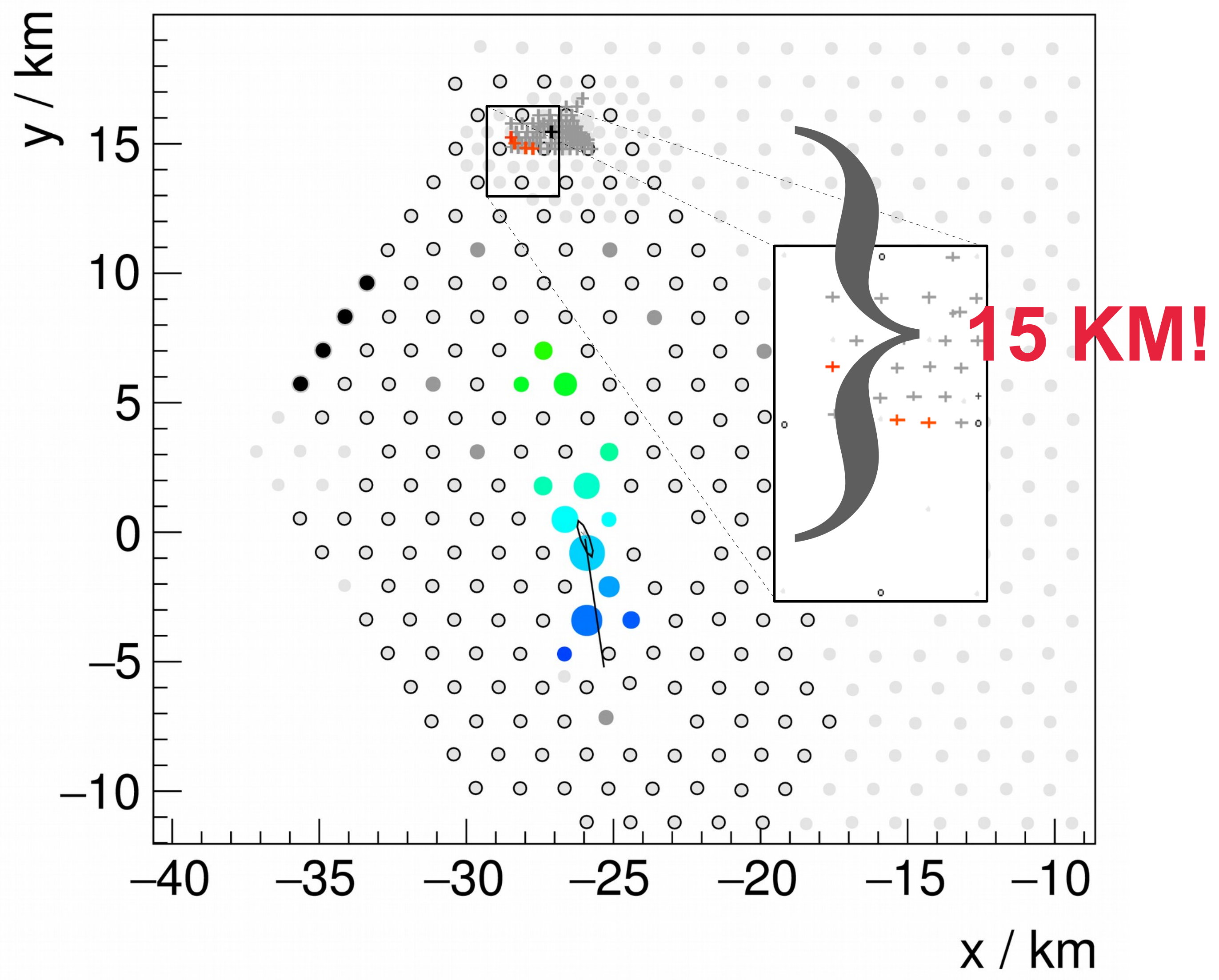



A. Aab et al., PRL 116 (2016) no.24, 241101

$$E_{30\text{-}80\ \mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst})\ \mathrm{MeV}) \times \left(\sin\alpha \frac{E_{CR}}{10^{18}\ \mathrm{eV}} \frac{B_{Earth}}{0.24\ \mathrm{G}}\right)^2$$

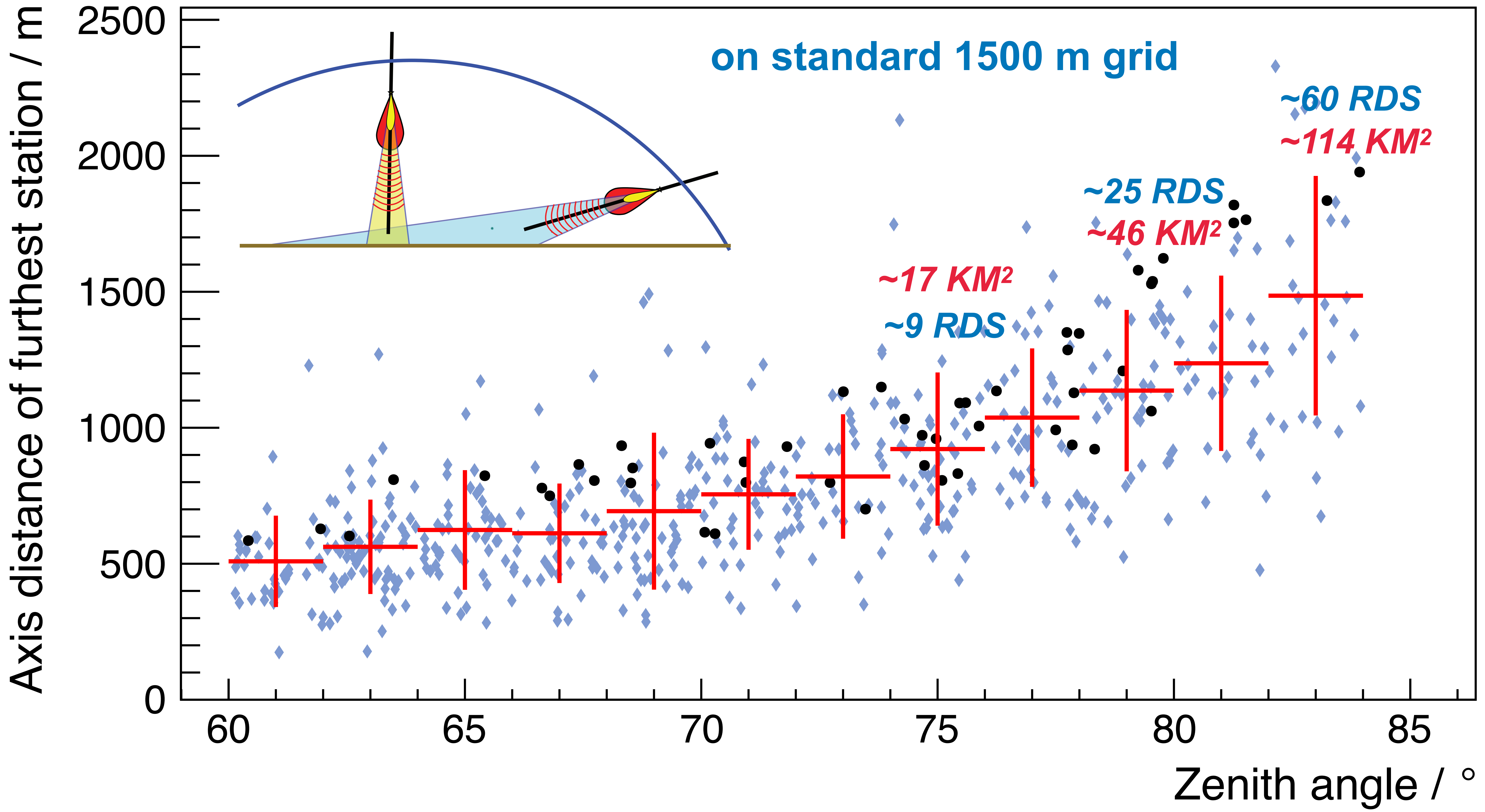
# HORIZONTAL AIR SHOWERS MEASURED WITH AERA



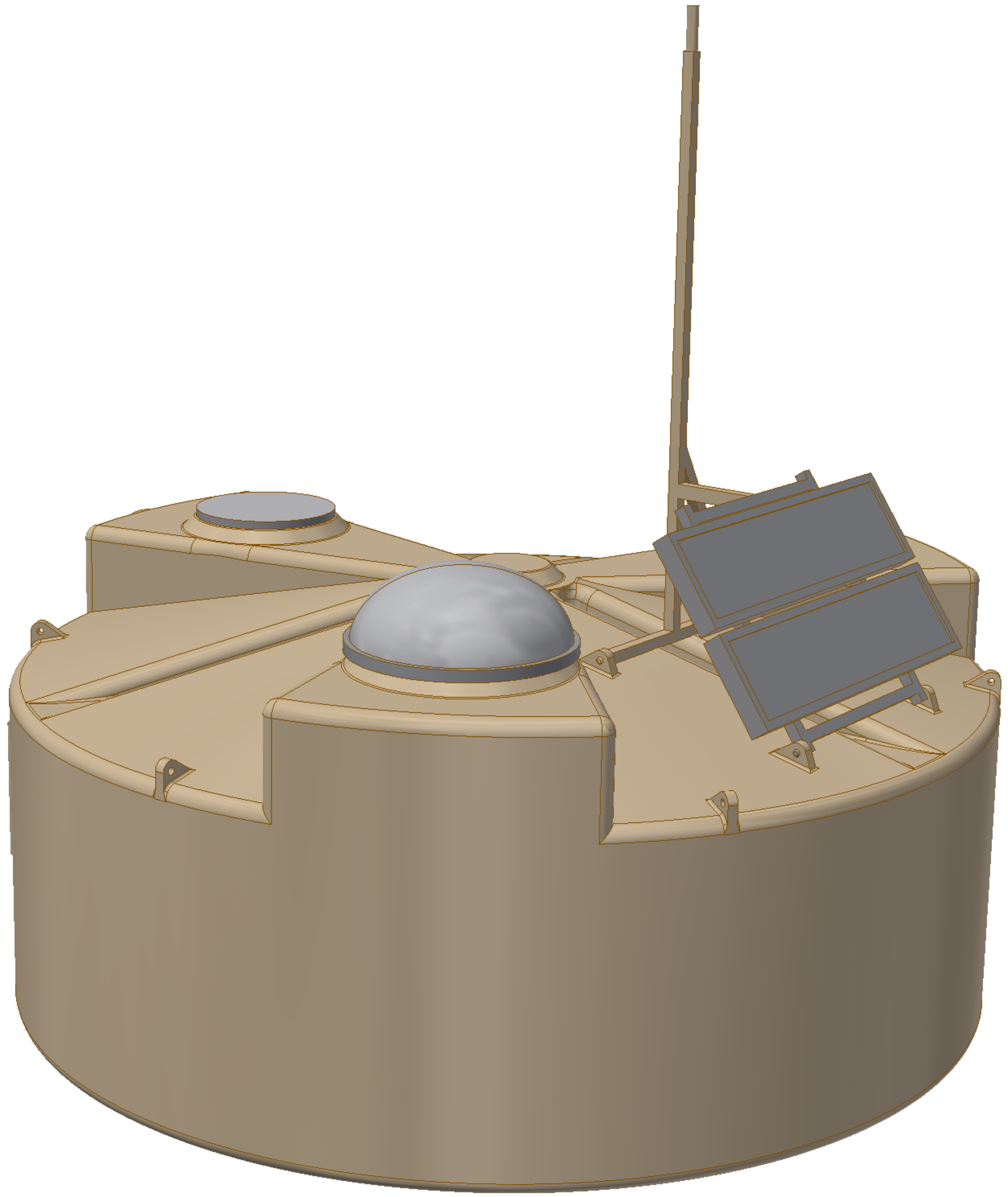

A. Aab et al., JCAP 10 (2018) 026

## large footprints -> measure showers on 1500 m grid



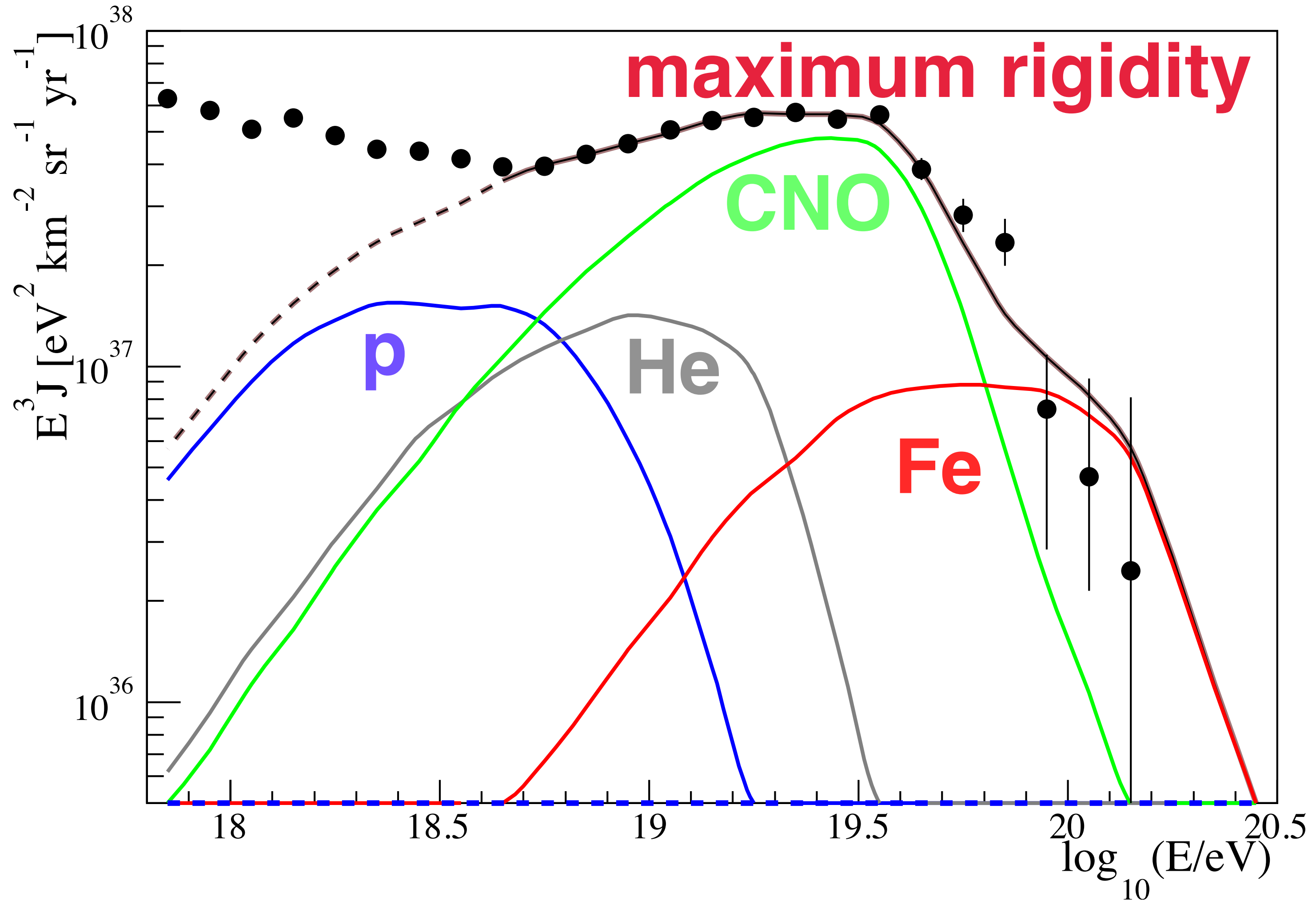
# UPGRADE OF THE PIERRE AUGER OBSERVATORY

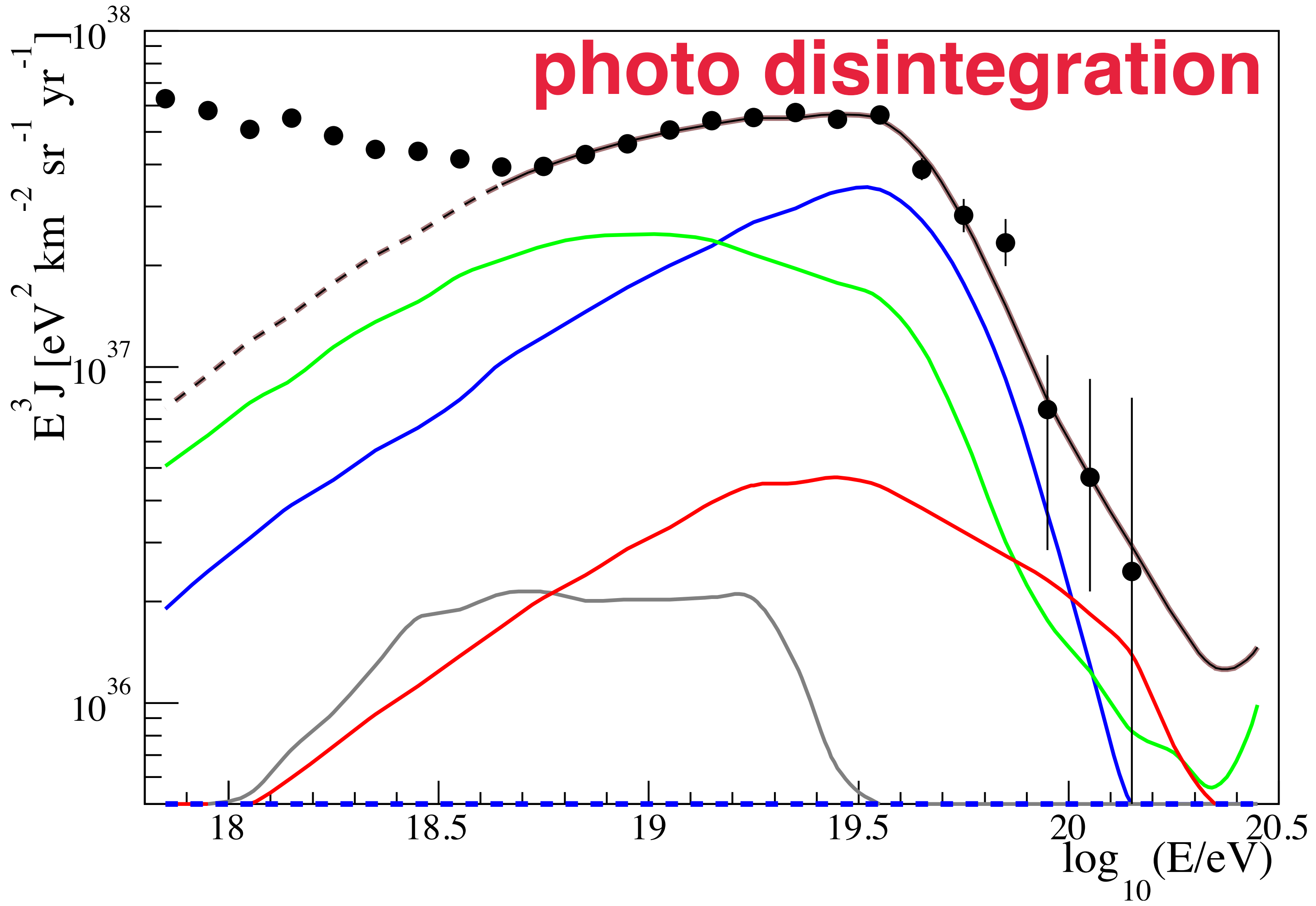
-electronics
-scintillator



## Key science questions

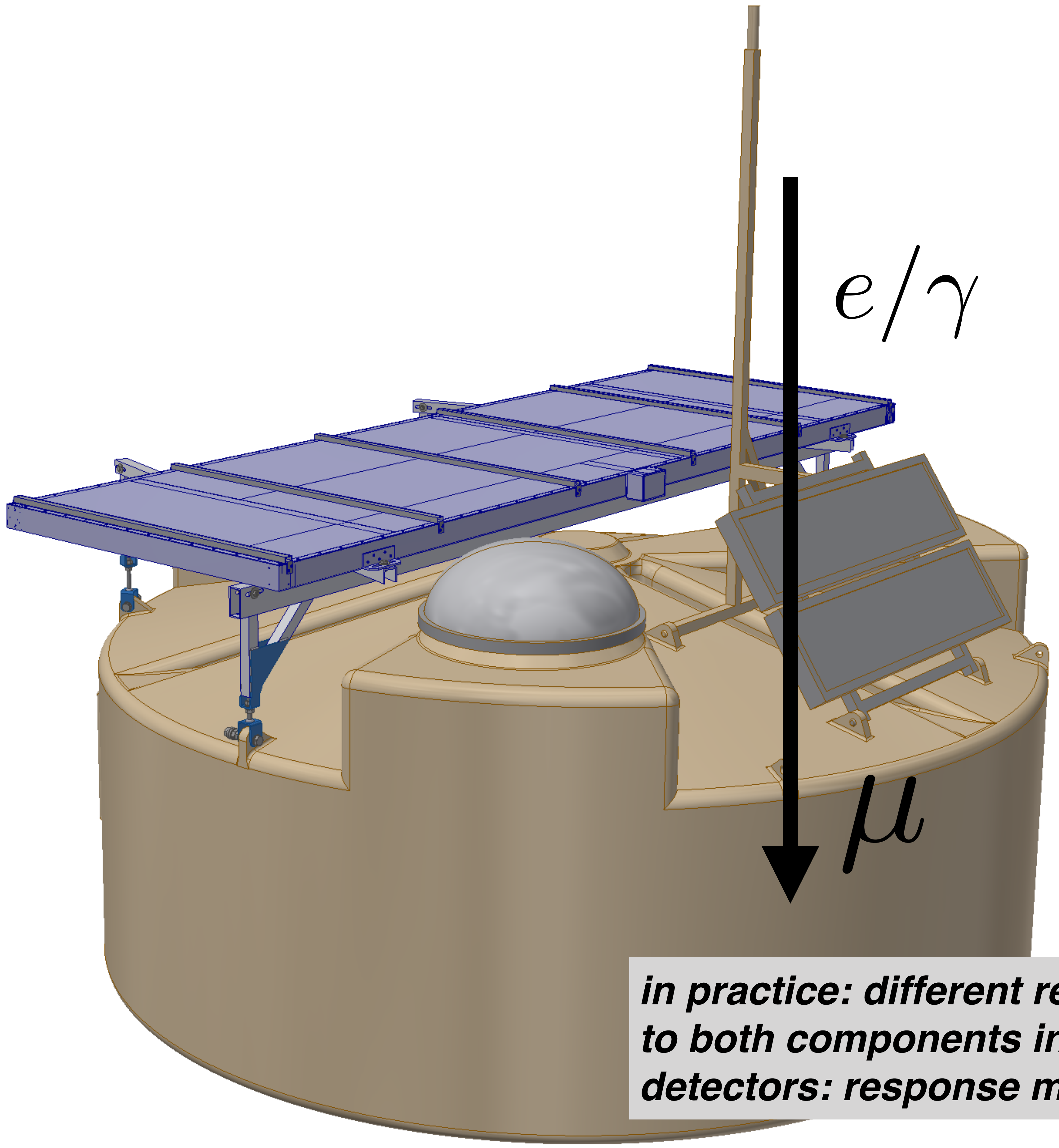
- What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?



# UPGRADE OF THE PIERRE AUGER OBSERVATORY

**-electronics**
**-scintillator**



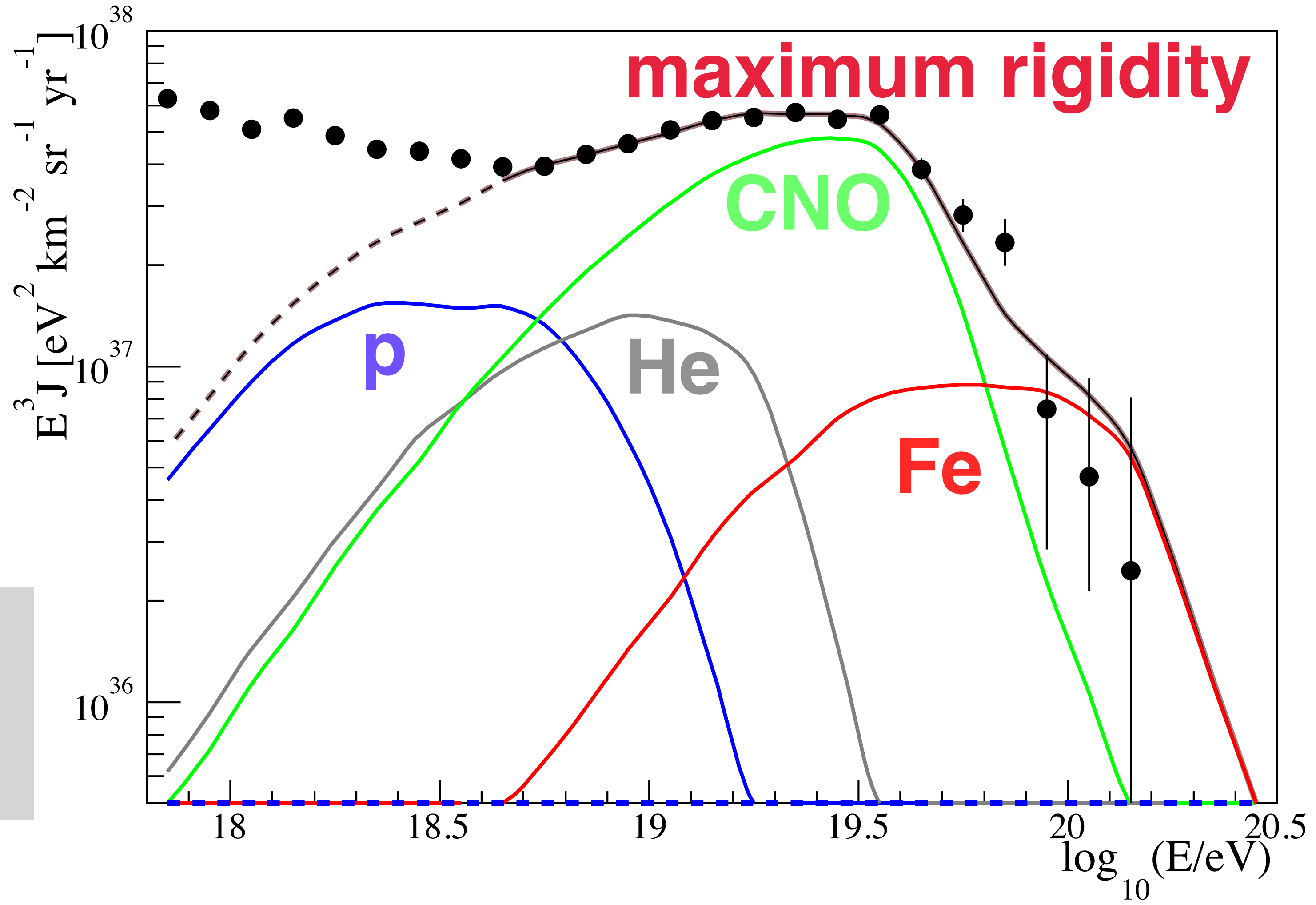

***in practice: different response to both components in both detectors: response matrix***

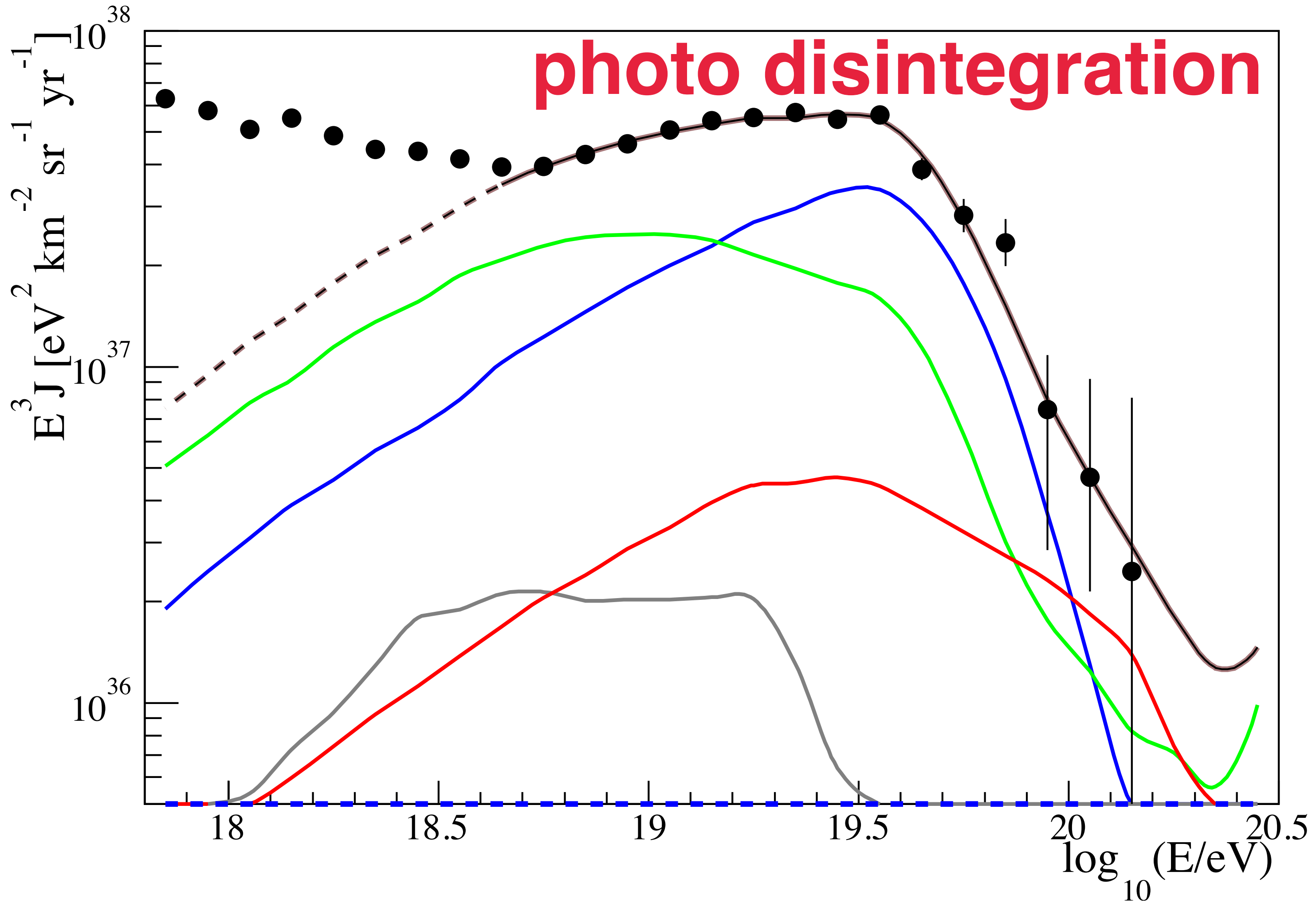
## Key science questions

- **What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?**

- **Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?**

- **What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?**

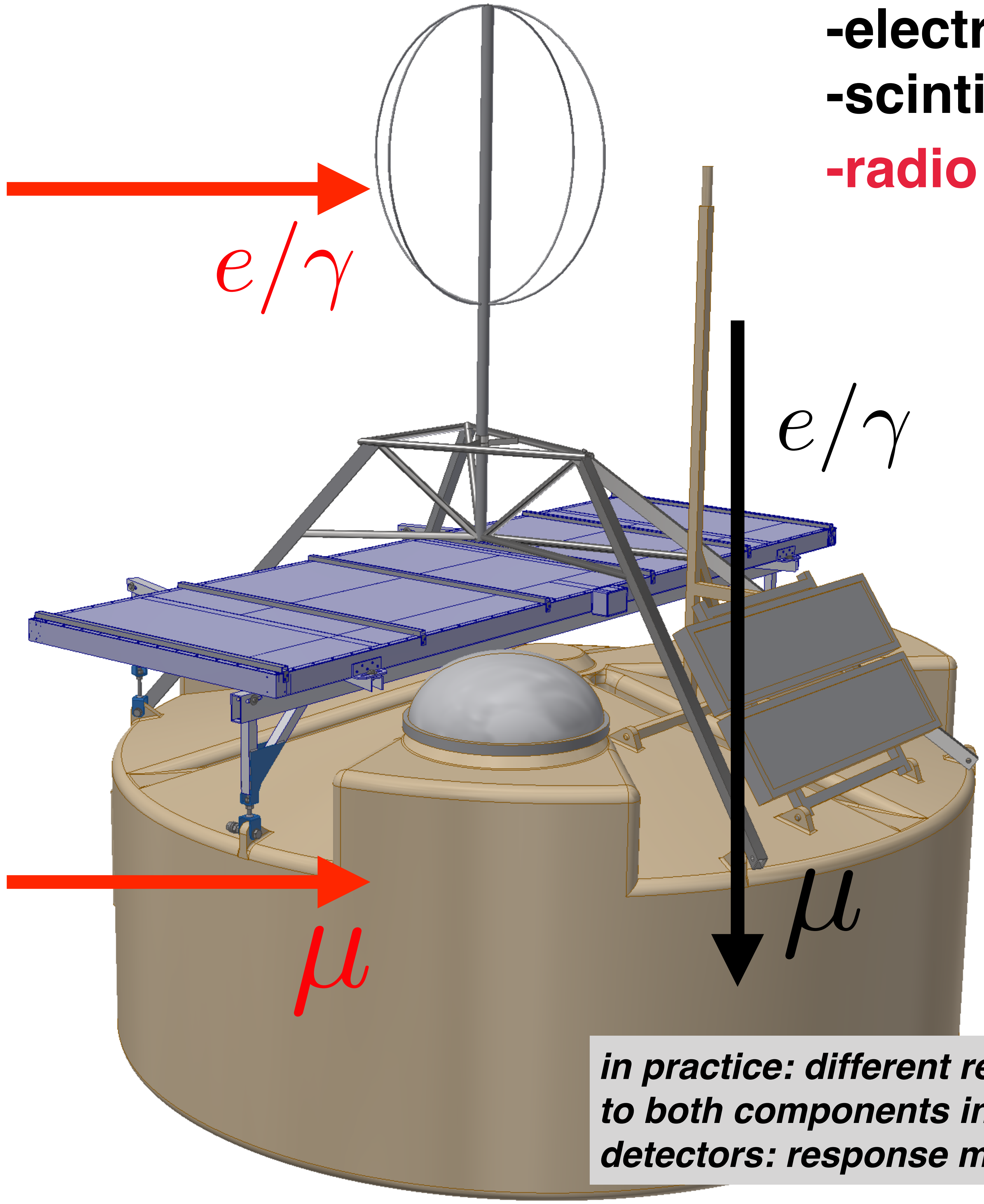


# SSD PRODUCTION IN NIJMEGEN



# UPGRADE OF THE PIERRE AUGER OBSERVATORY




-electronics
-scintillator
-radio detector

*in practice: different response to both components in both detectors: response matrix*

## Key science questions

- What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?
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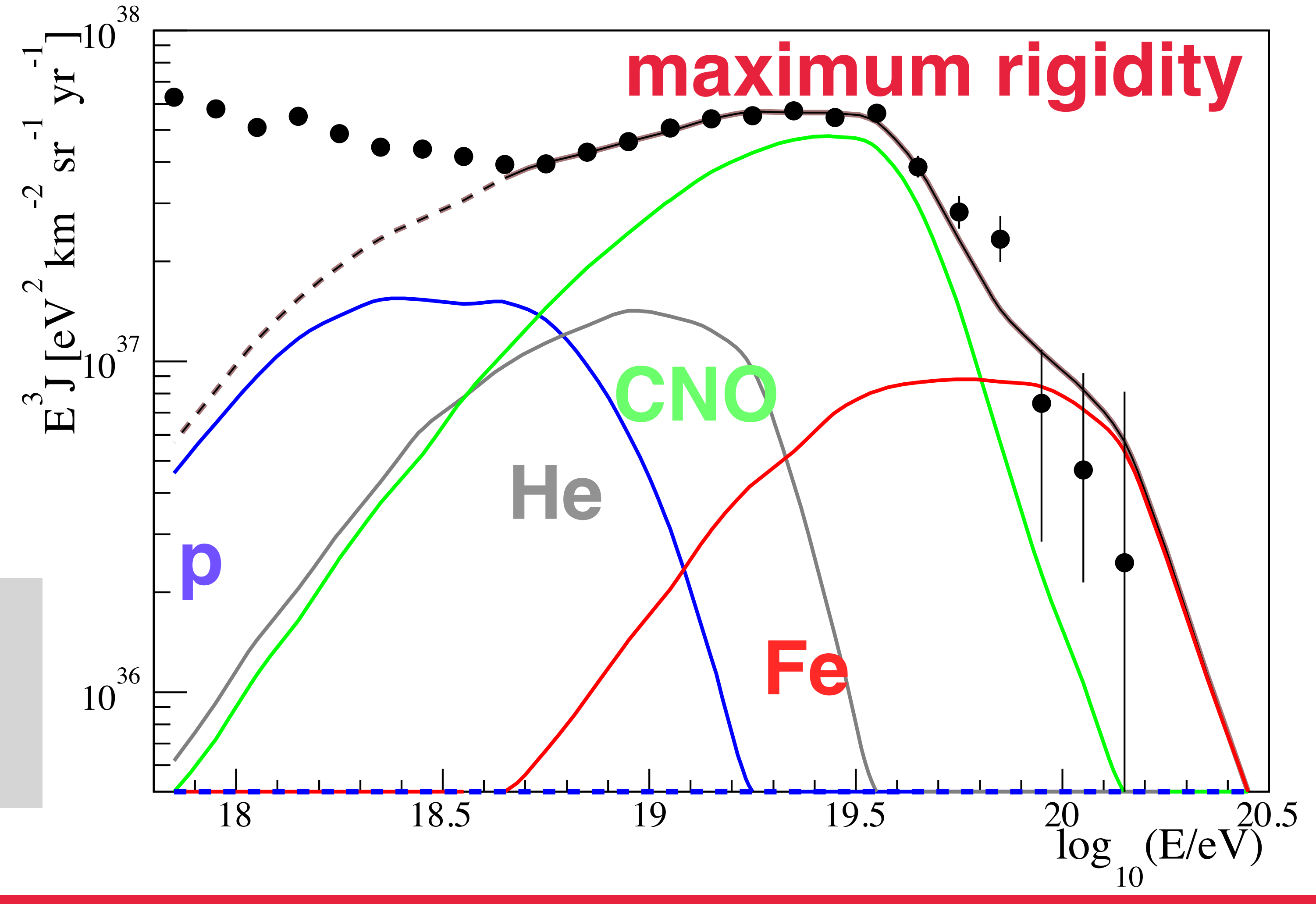
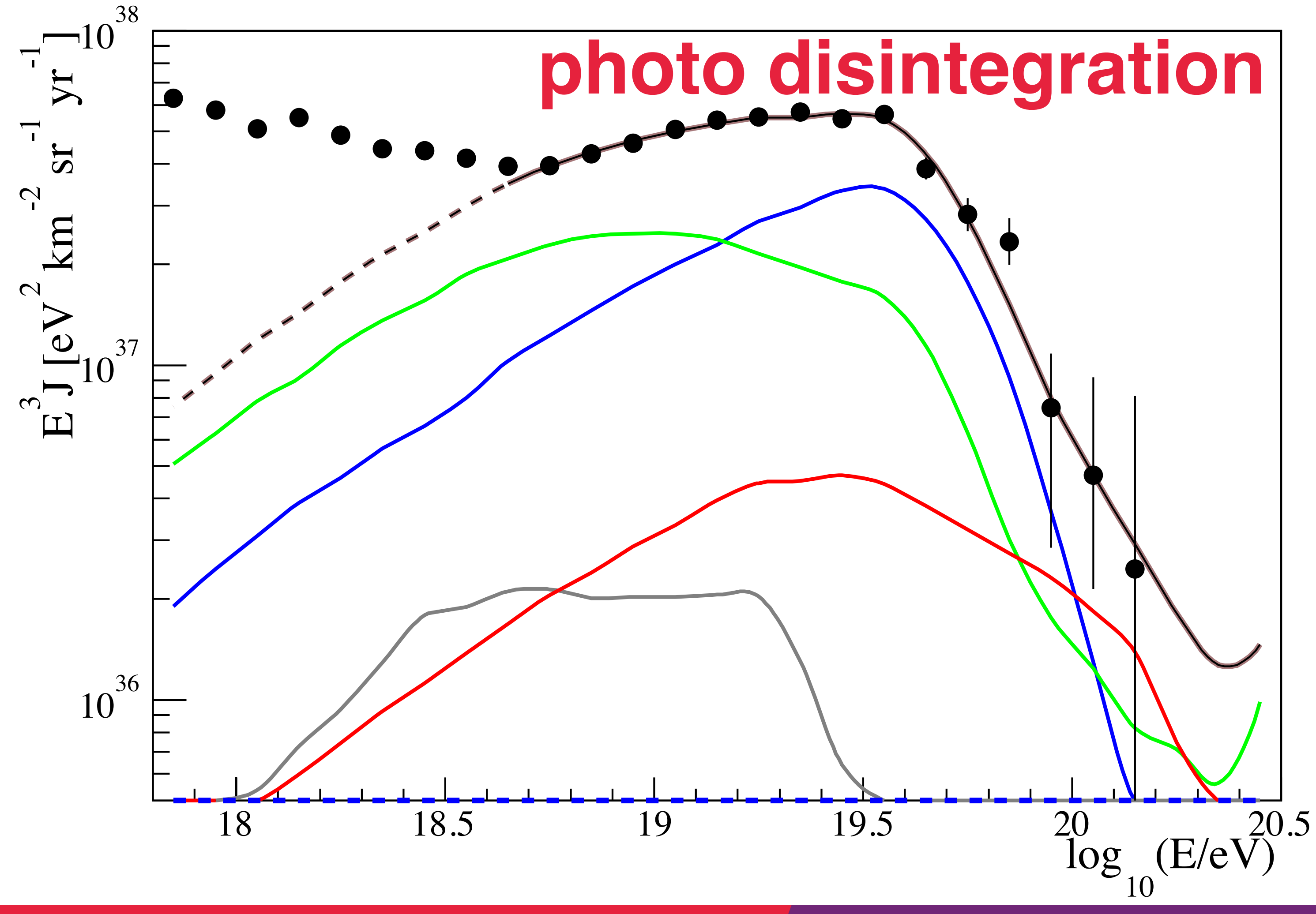
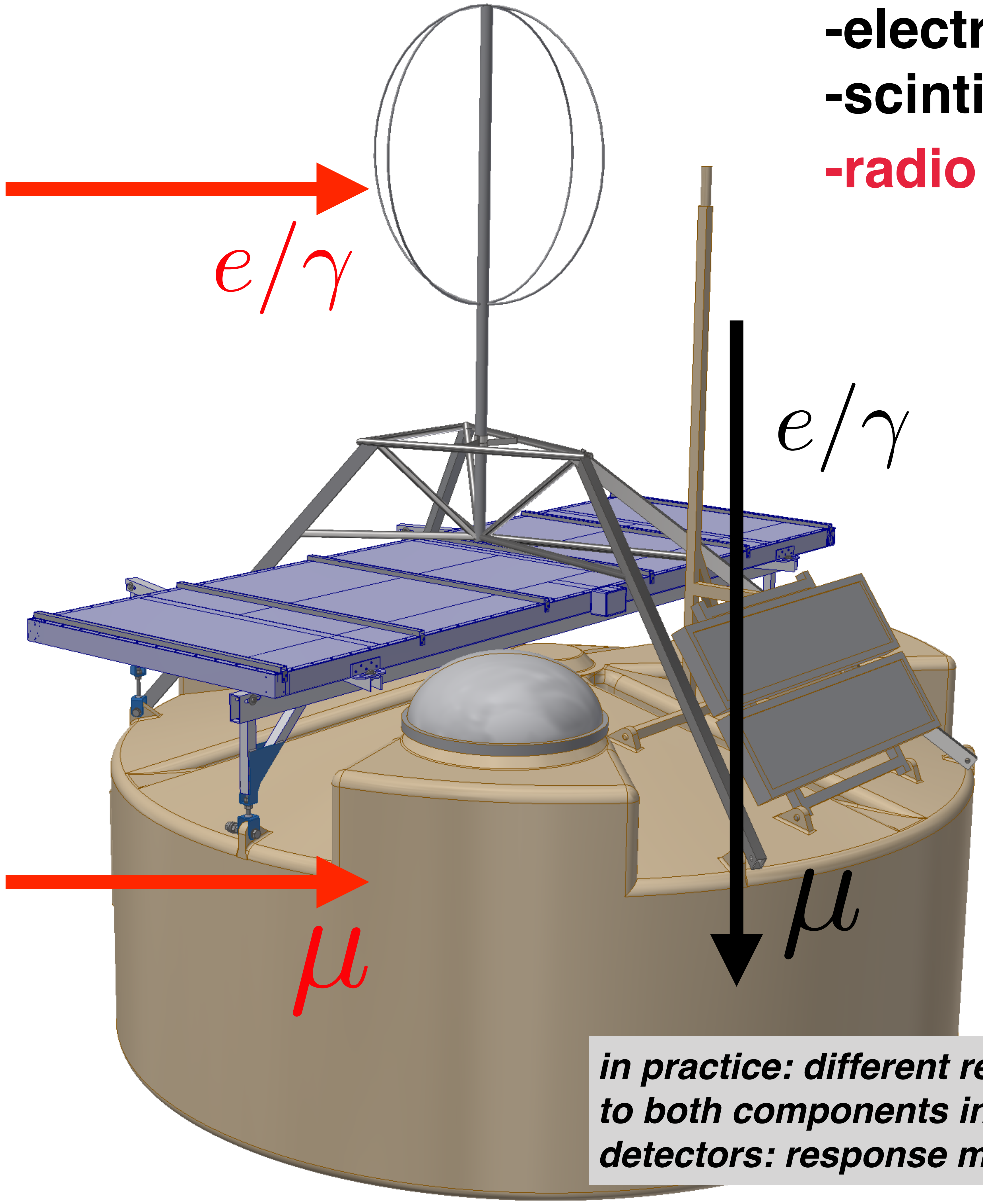


# UPGRADE OF THE PIERRE AUGER OBSERVATORY

-electronics
-scintillator
-radio detector




*in practice: different response to both components in both detectors: response matrix*

erc European Research Council

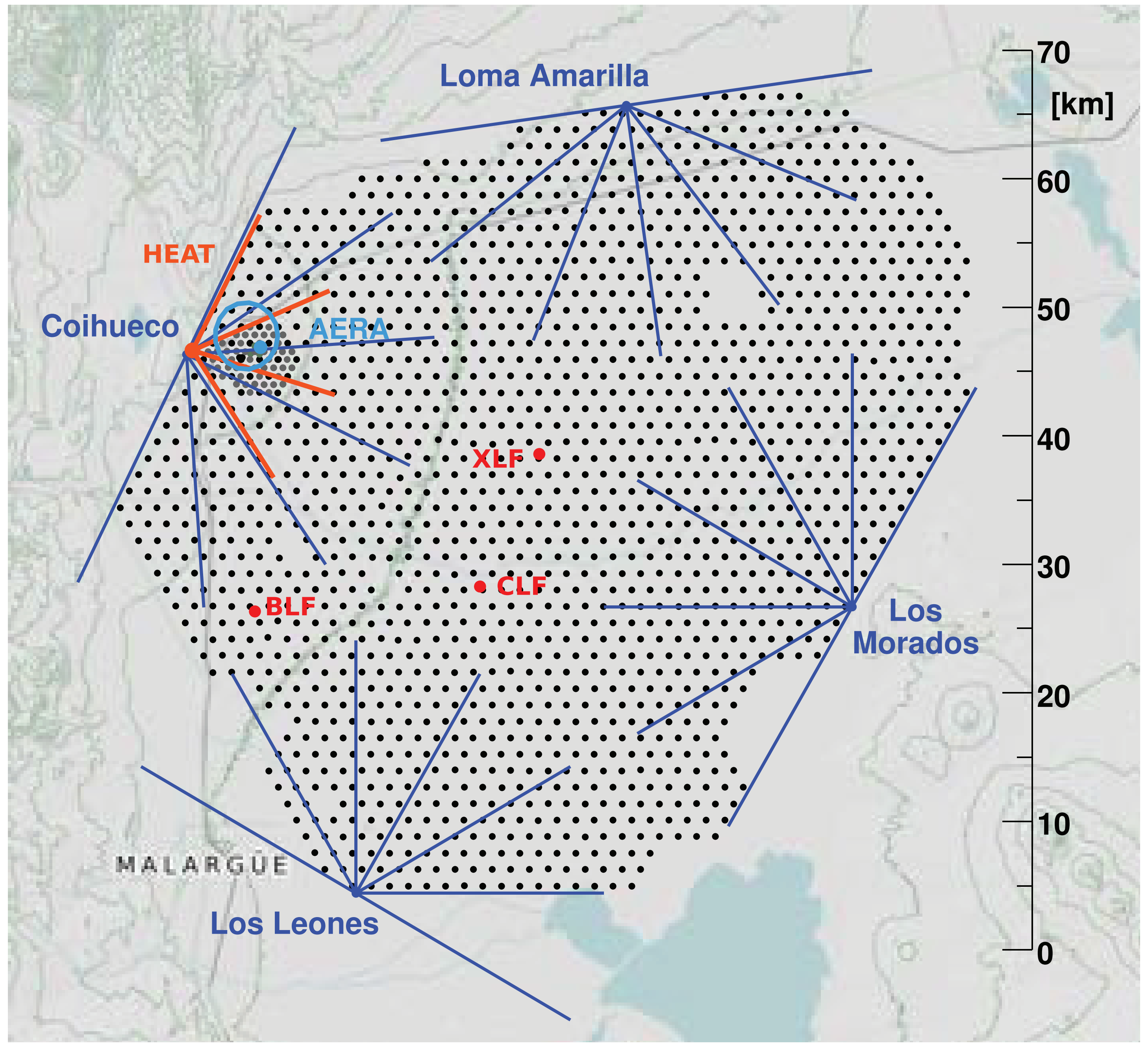
**3.5 M€ ERC Advanced Grant Hörandel**

NWO Netherlands Organisation for Scientific Research

**2.5 M€ NWO-Groot**

1661 detector stations, covering 3000 km$^2$

project implementation in progress

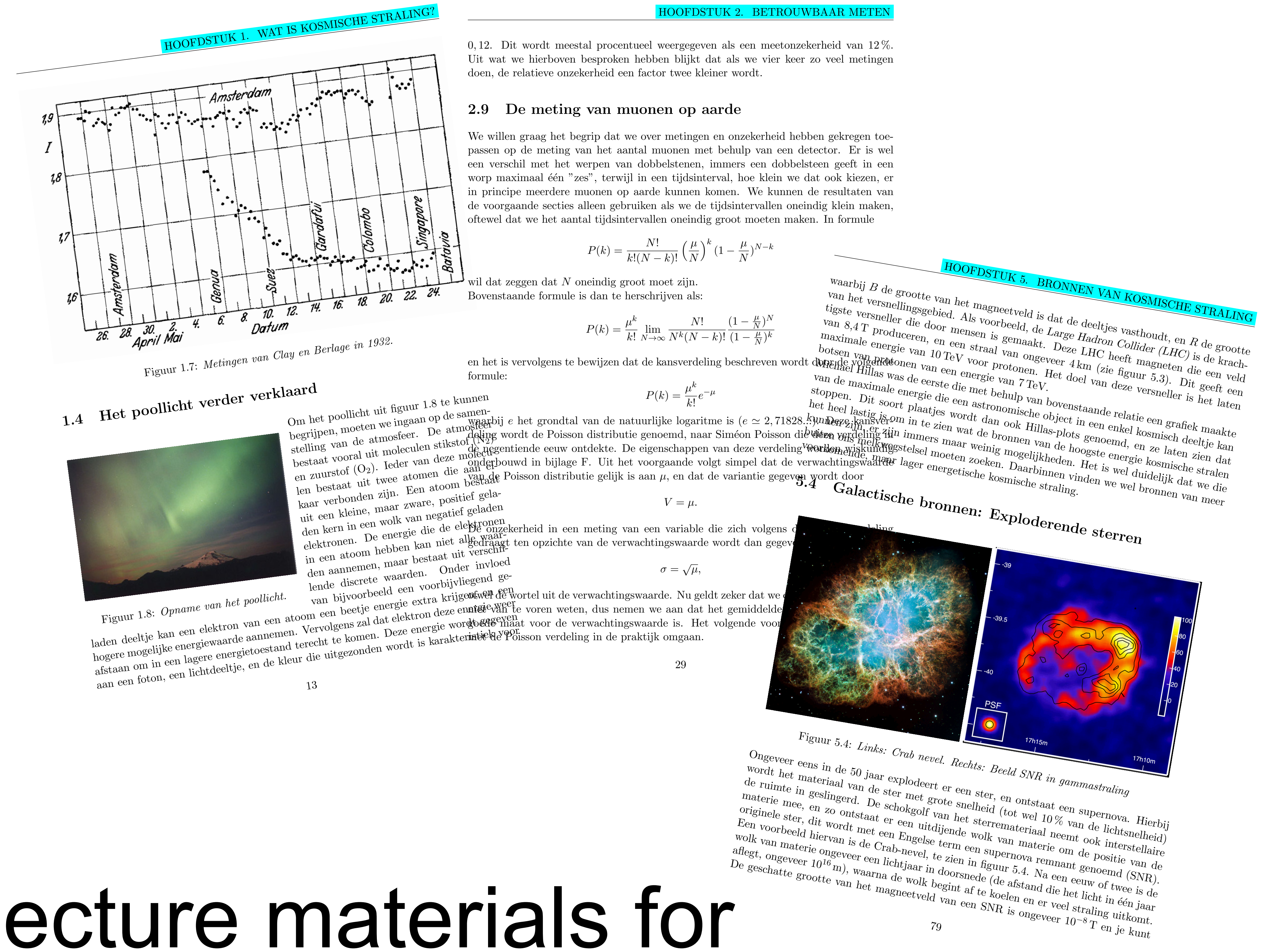


# OUTREACH

Cosmic Rays are the cornerstone of particle physics outreach in the NL

HiSPARC

measuring cosmic rays on the roofs of an array of high schools




lecture materials for NLT, sub-atomic physics in VWO

# SUMMARY

The NL are member in the Pierre Auger collaboration since 2005.
The NL group pioneered the radio detection technique and established the radio detection of air showers as standard tool.

The Radio Upgrade of the observatory with the recent ERC Advanced Grant and the NWO-Groot subsidy is a key contribution to the observatory.
In addition, the NL group contributes to the scintillator upgrade of the observatory.

The NL group has high impact and visibility on international scale.

We need a modest amount of resources (operations costs, PhD students, post docs) to sustain this success for the next decade.