

ASTROPARTICLE PHYSICS

COSMIC RAYS

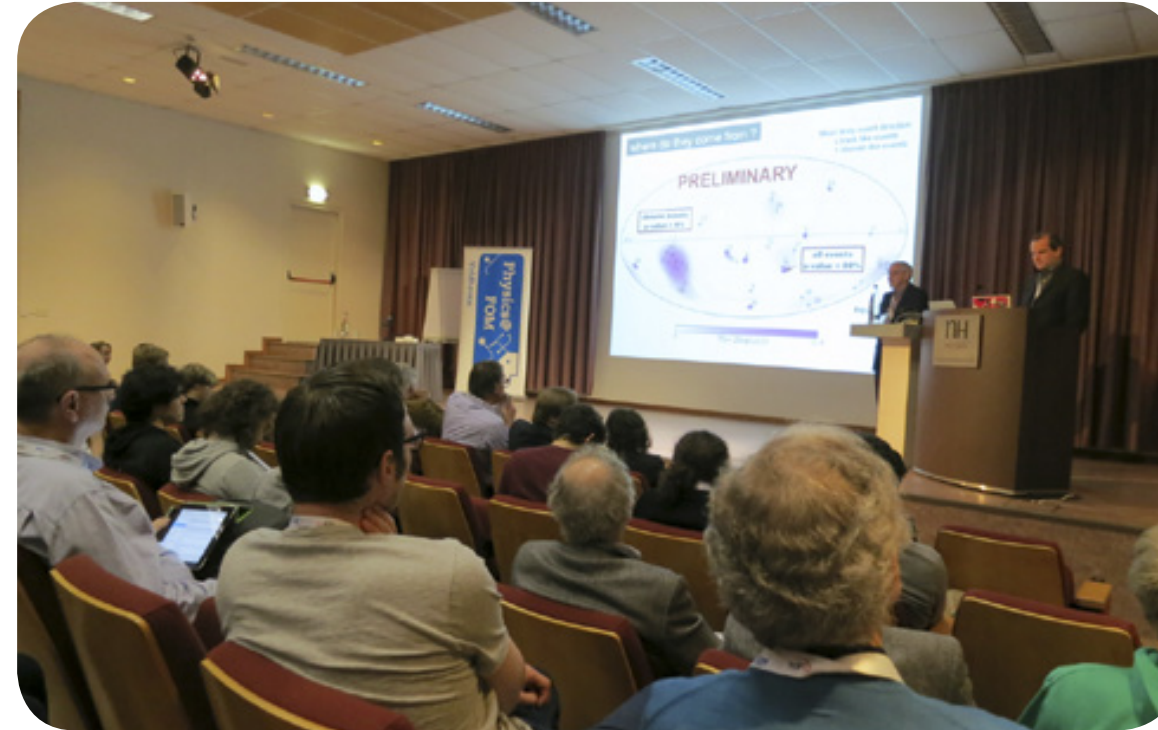
Jörg R. Hörandel
Radboud Universiteit Nijmegen
Nikhef, Vrije Universiteit Brussel

RECFA 2018

Committee for Astroparticle Physics in the Netherlands (CAN)

Objectives:

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



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)

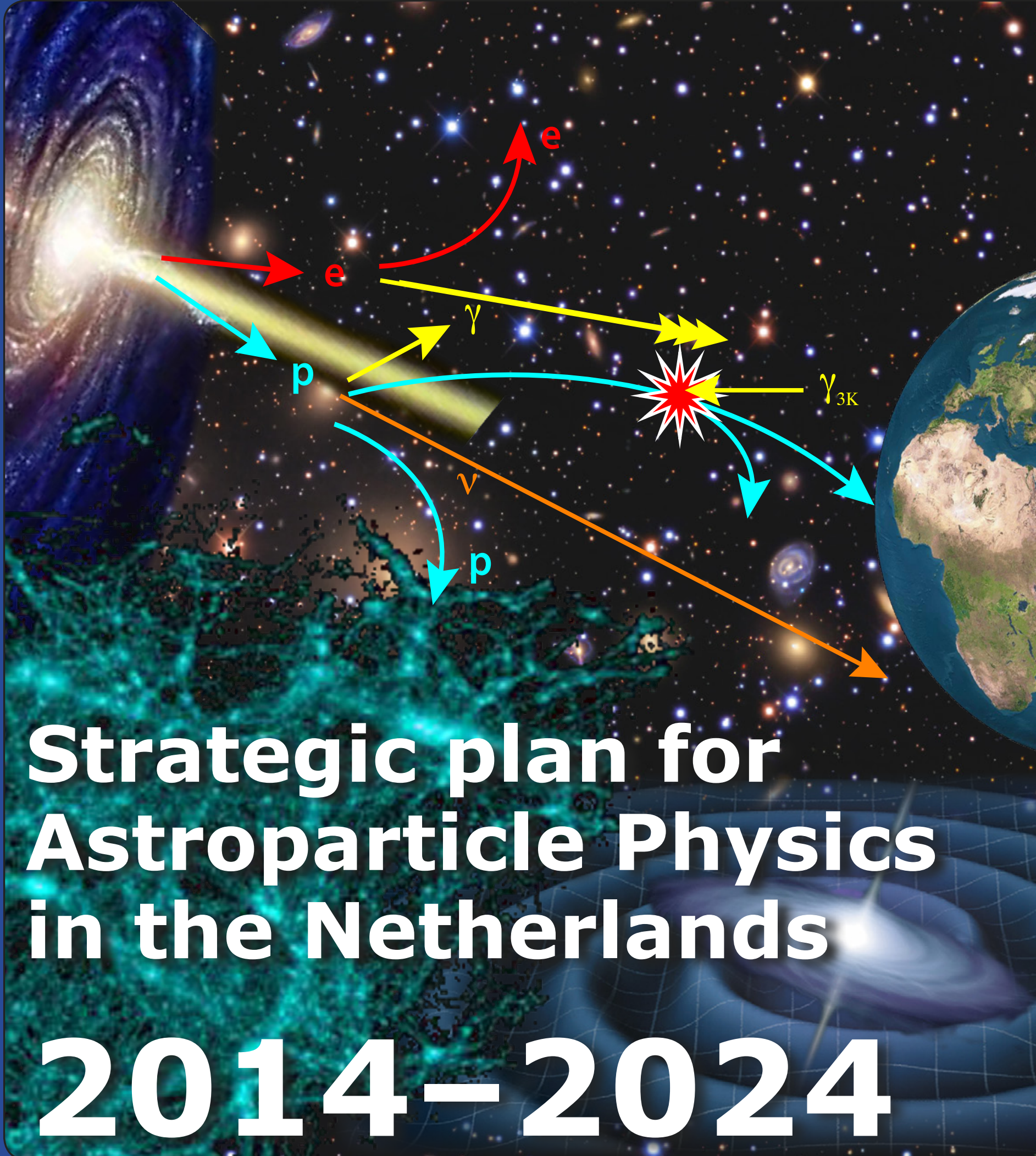
C. Timmermans (Nijmegen, Nikhef)

C. Van Den Broeck (Nikhef) [co chair]

J. Vink (Amsterdam)

R. van den Weygaert (Groningen)

Theory
Cosmic rays
Gamma rays
Neutrinos
Dark matter
Gravitational waves



Strategic plan for Astroparticle Physics in the Netherlands 2014-2024

Contents

Executive Summary	3
1 Introduction.....	5
2 Science questions for the next decade.....	6
2.1 What is the origin of the highest energy particles in the Universe?.....	6
2.2 What is the nature of spacetime?.....	8
2.3 What is the nature of Dark Matter?.....	9
2.4 What is the origin of the large-scale structure of the Universe?.....	10
2.5 What is the structure of the physics beyond the Standard Model?.....	11
3 Achievements since 2005 —Astroparticle Physics: a strongly increasing field in the Netherlands.....	12
3.1 Measurement of cosmic rays	12
3.2 Neutrino astronomy.....	12
3.3 Gamma ray astronomy.....	13
3.4 Gravitational wave detection	13
3.5 Dark matter detection.....	14
4 Dutch priorities 2014-2024	14
4.0 Theoretical research.....	14
4.1 Measurement of cosmic rays — Pierre Auger Observatory.....	15
4.2 Neutrino astronomy — KM3NeT.....	16
4.3 Gamma ray astronomy — CTA.....	17
4.3 Detection of gravitational waves — Virgo, Einstein Telescope.....	17
4.5 Direct detection of dark matter — XENON	18
4.6 Complementary Activities	18
5 Financial roadmap.....	19
6 Education and Outreach.....	20
7 Concluding remarks	21
Appendix: Staff/faculty members and institutes	22

NW

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**

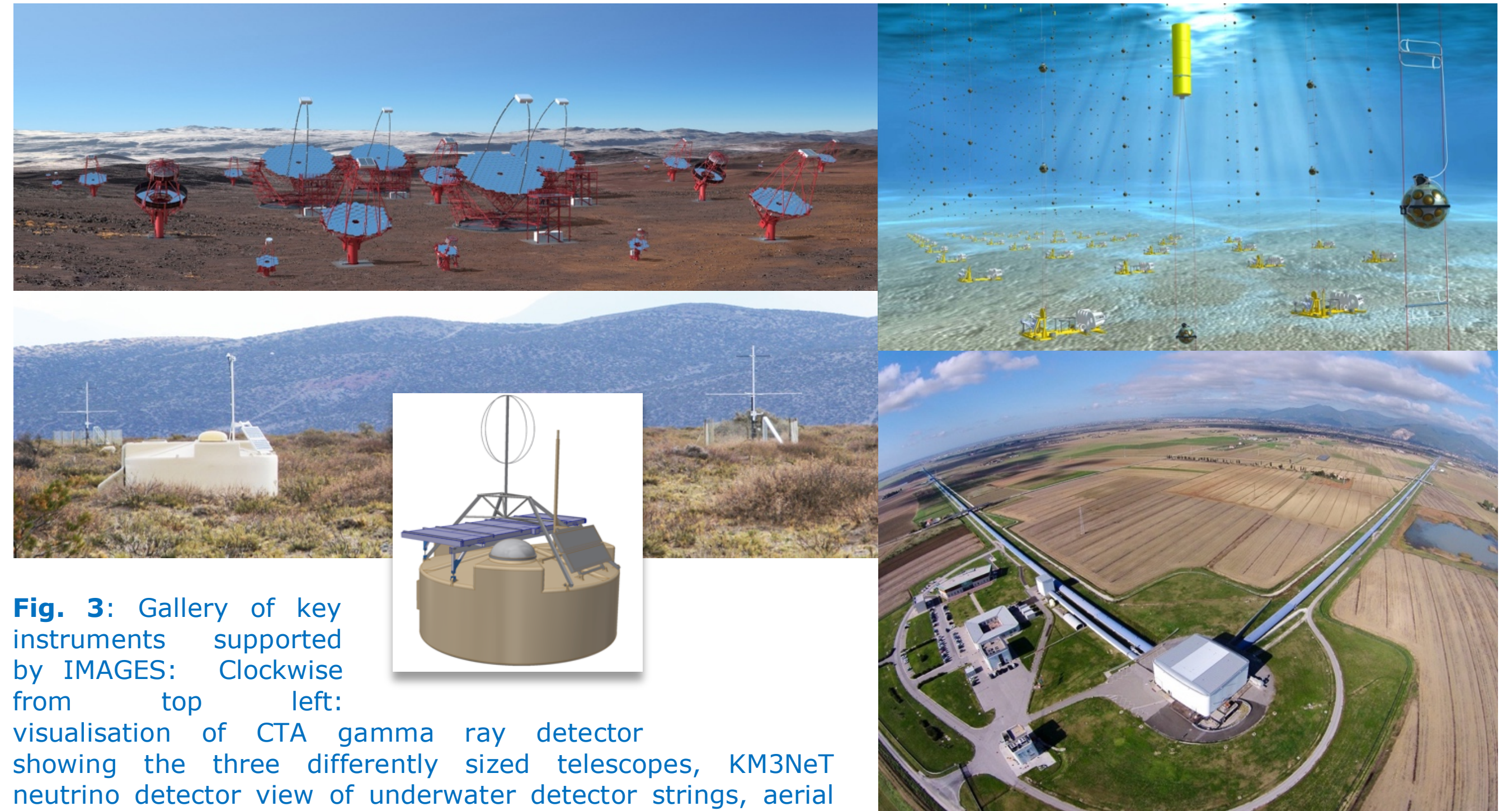
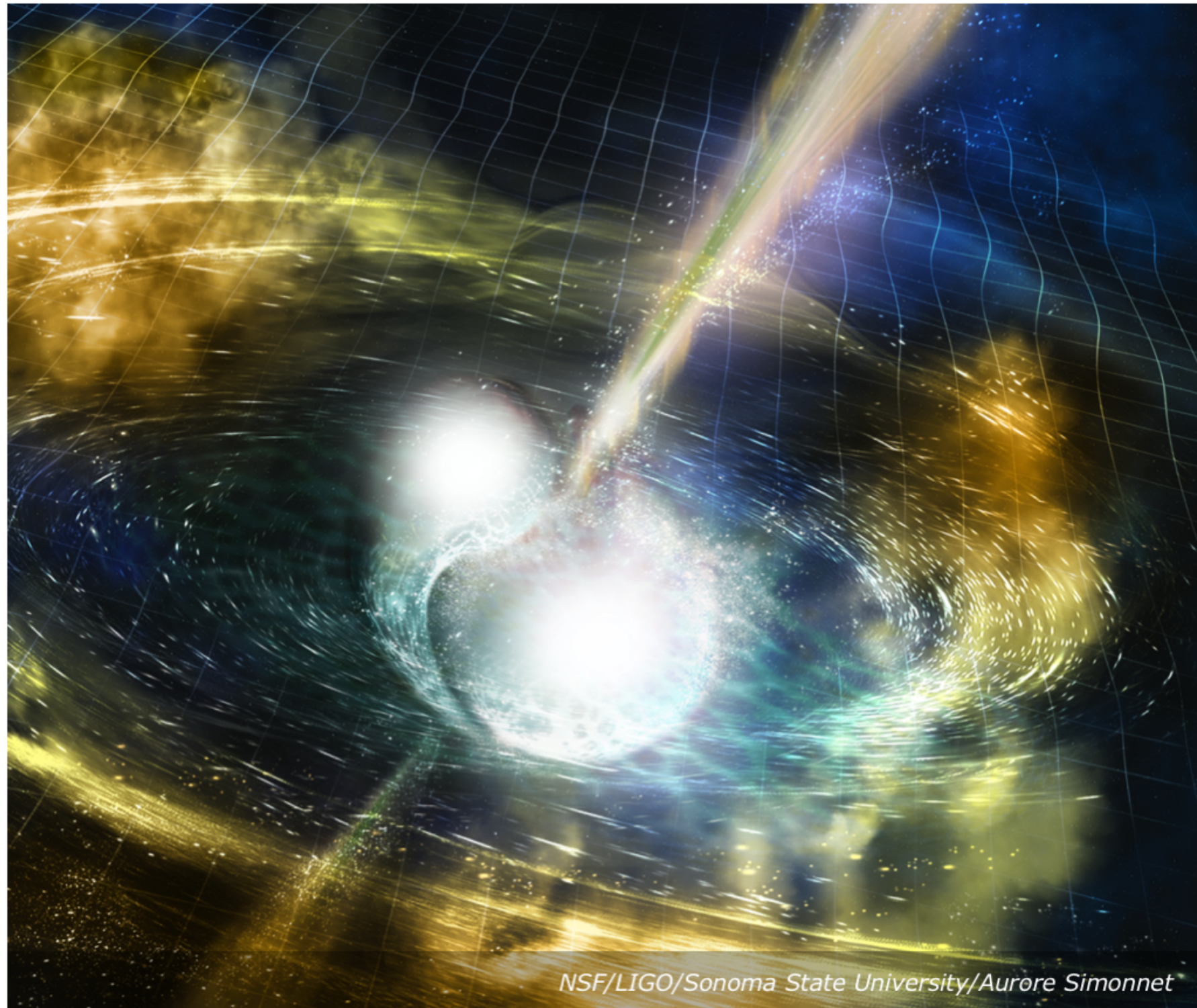
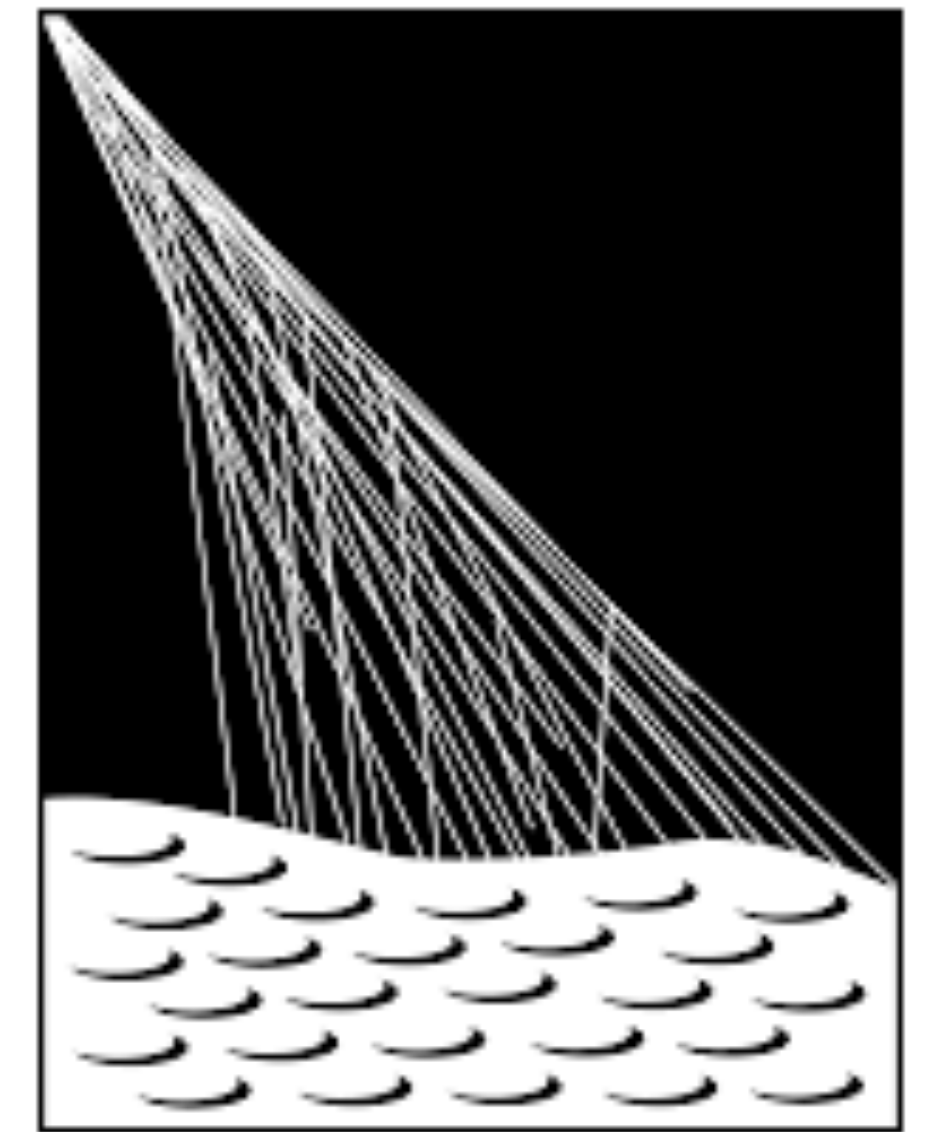


Fig. 3: Gallery of key instruments supported by IMAGES: Clockwise from top left: visualisation of CTA gamma ray detector showing the three differently sized telescopes, KM3NeT neutrino detector view of underwater detector strings, aerial view of Virgo GW detector and photograph of CR detector PAO showing 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)



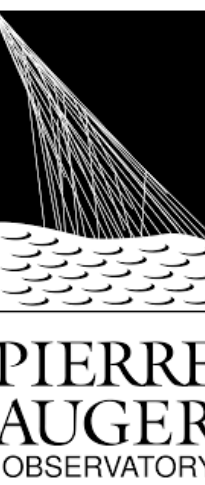
Radboud Universiteit Nijmegen



rijksuniversiteit
groningen



UNIVERSITEIT VAN AMSTERDAM



PIERRE
AUGER
OBSERVATORY

FUNDING (SINCE 2013)

hardware investment:

3.5 M € ERC Advanced 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

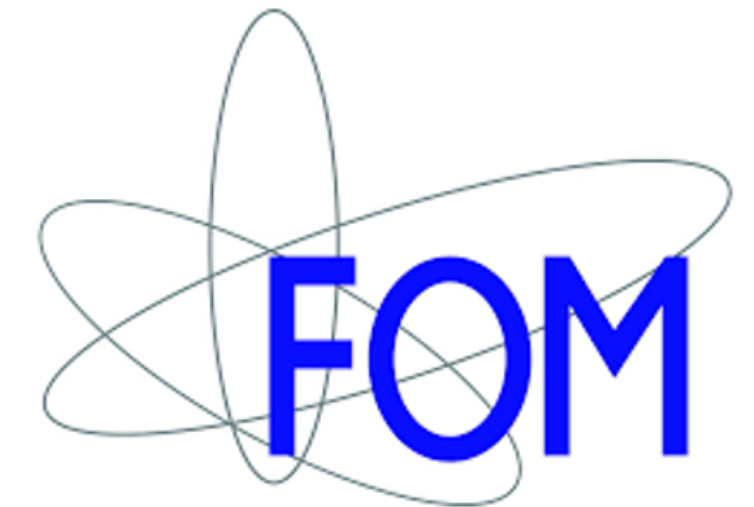
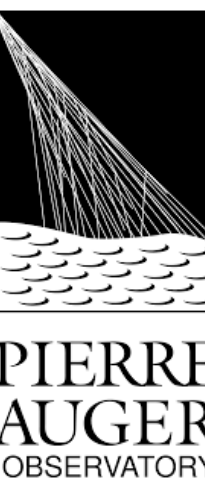
1 PD NWO WARP

continuing into reporting period:

6 PhD projects FOM

1 PhD project NOVA

1 PhD project NWO



SUCCESSFULLY FINISHED PHD'S (SINCE 2013)



Radboud Universiteit Nijmegen



- **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)**



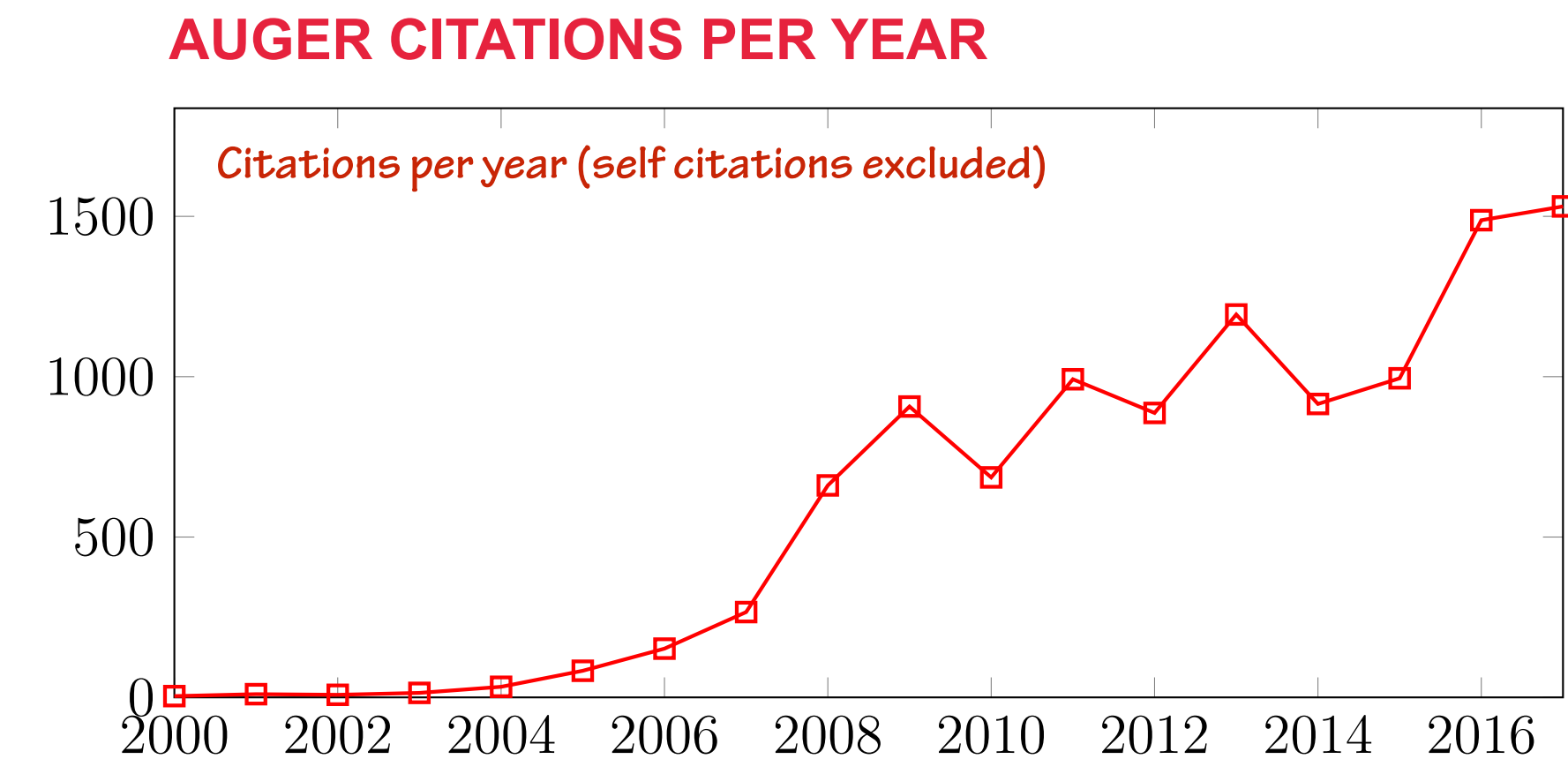
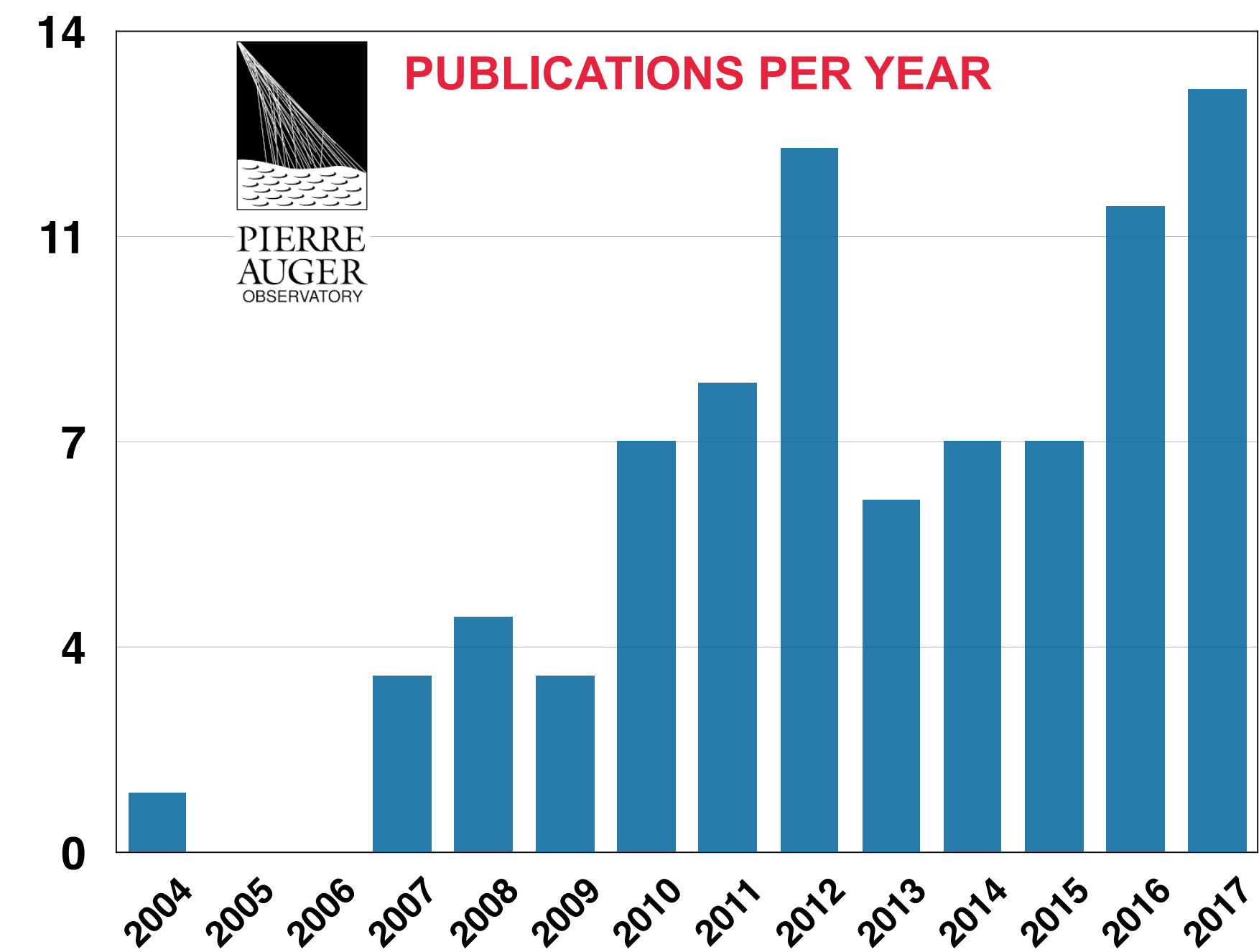
PUBLICATIONS (2013 -)

2013-now: total 44 articles

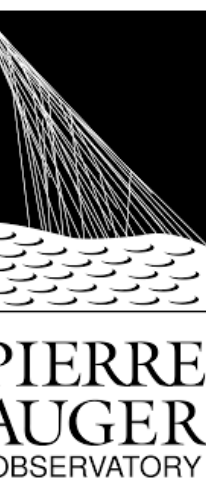
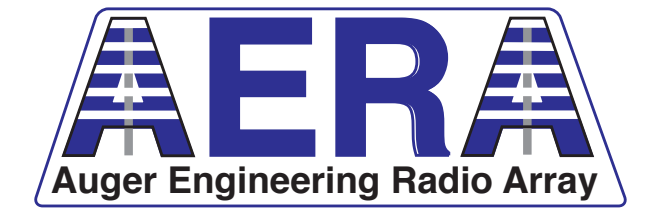
(mass composition, energy spectrum, arrival direction, photons, neutrinos, hadronic interactions, ...)

Auger general (selection)

- Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above $8 \cdot 10^{18}$ 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



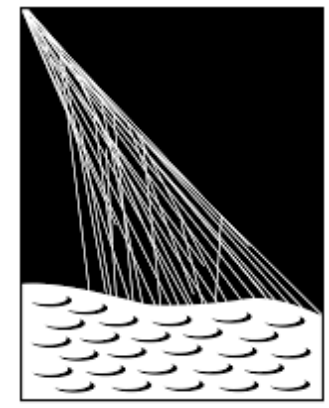
PUBLICATIONS (2013 -)



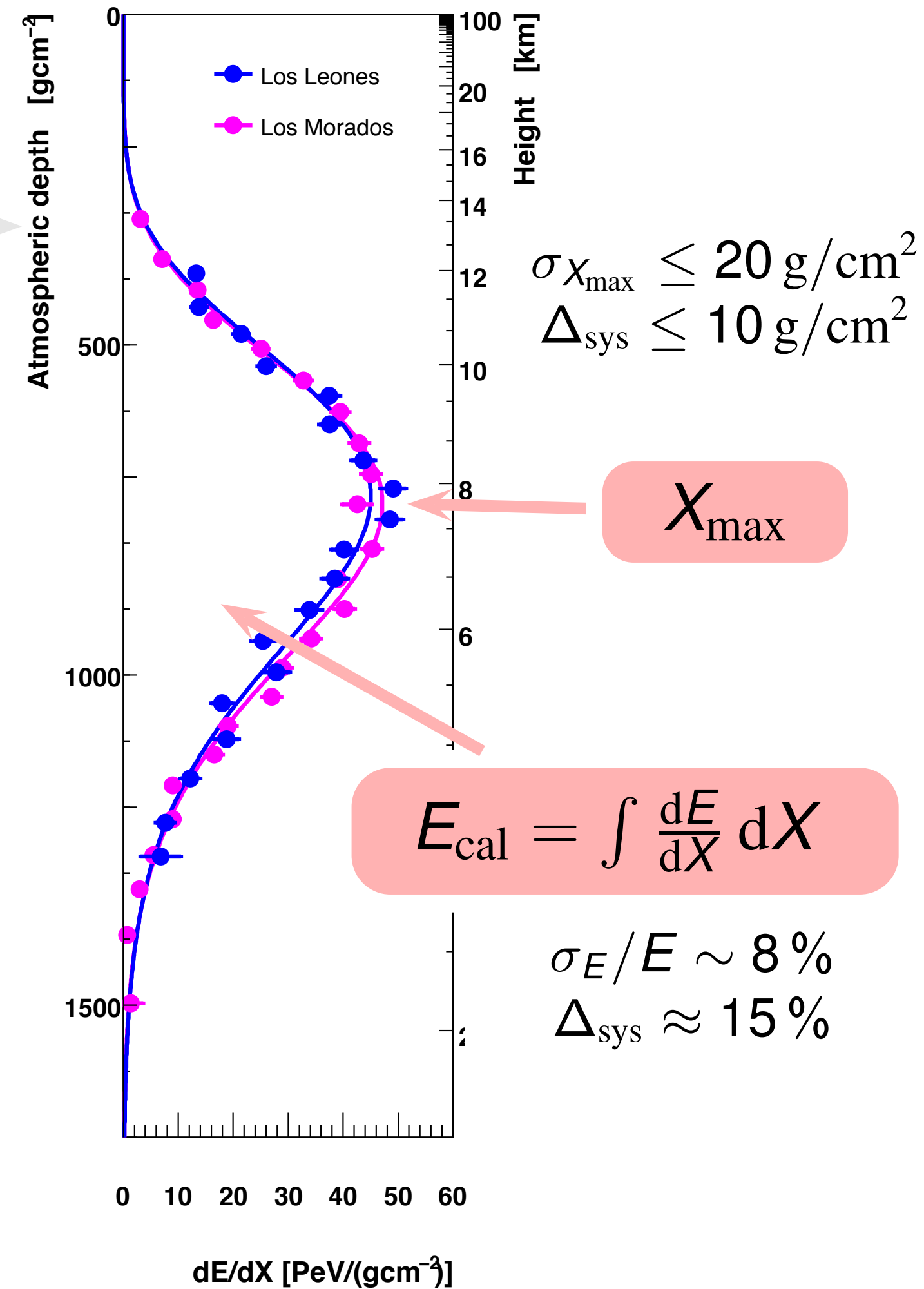
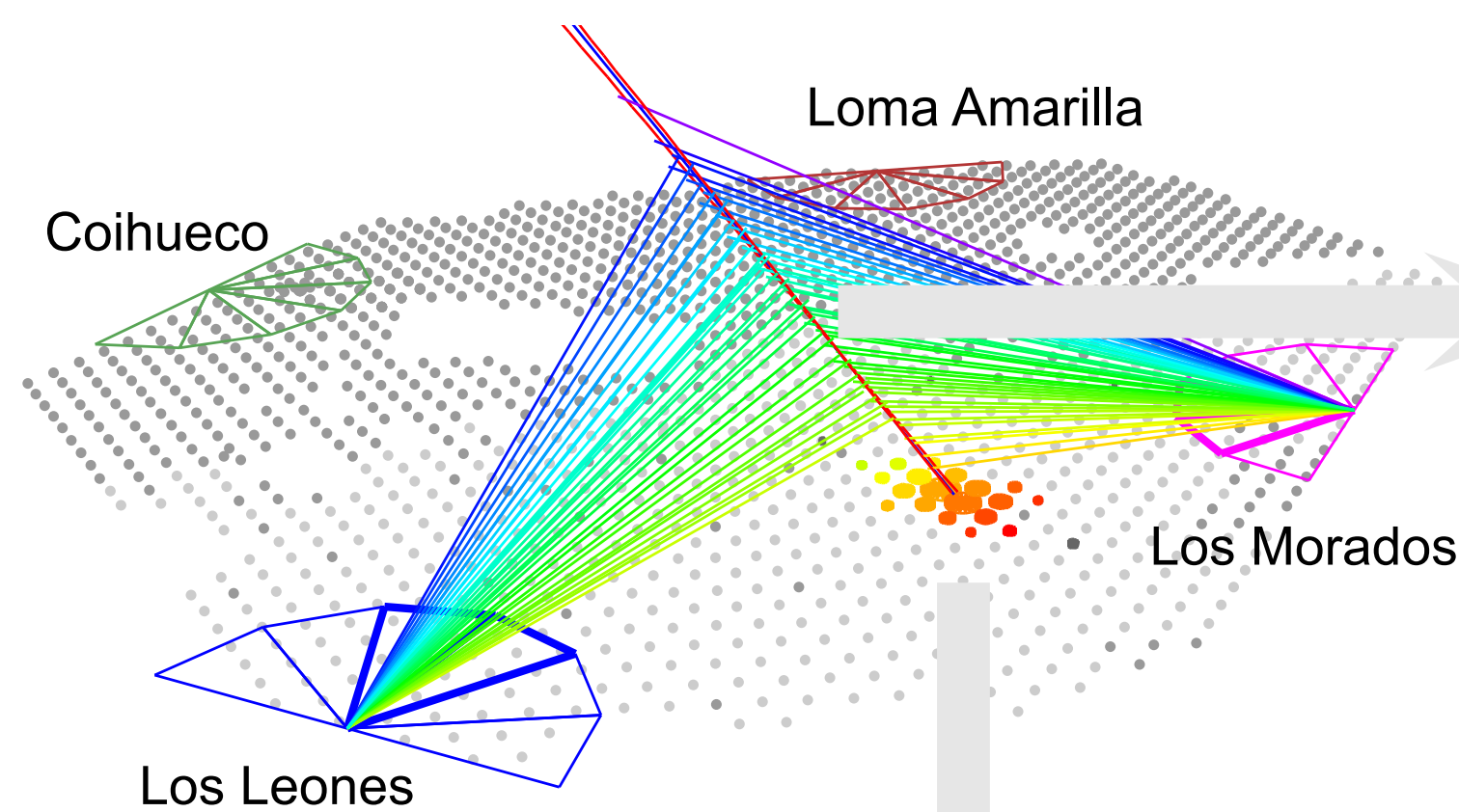
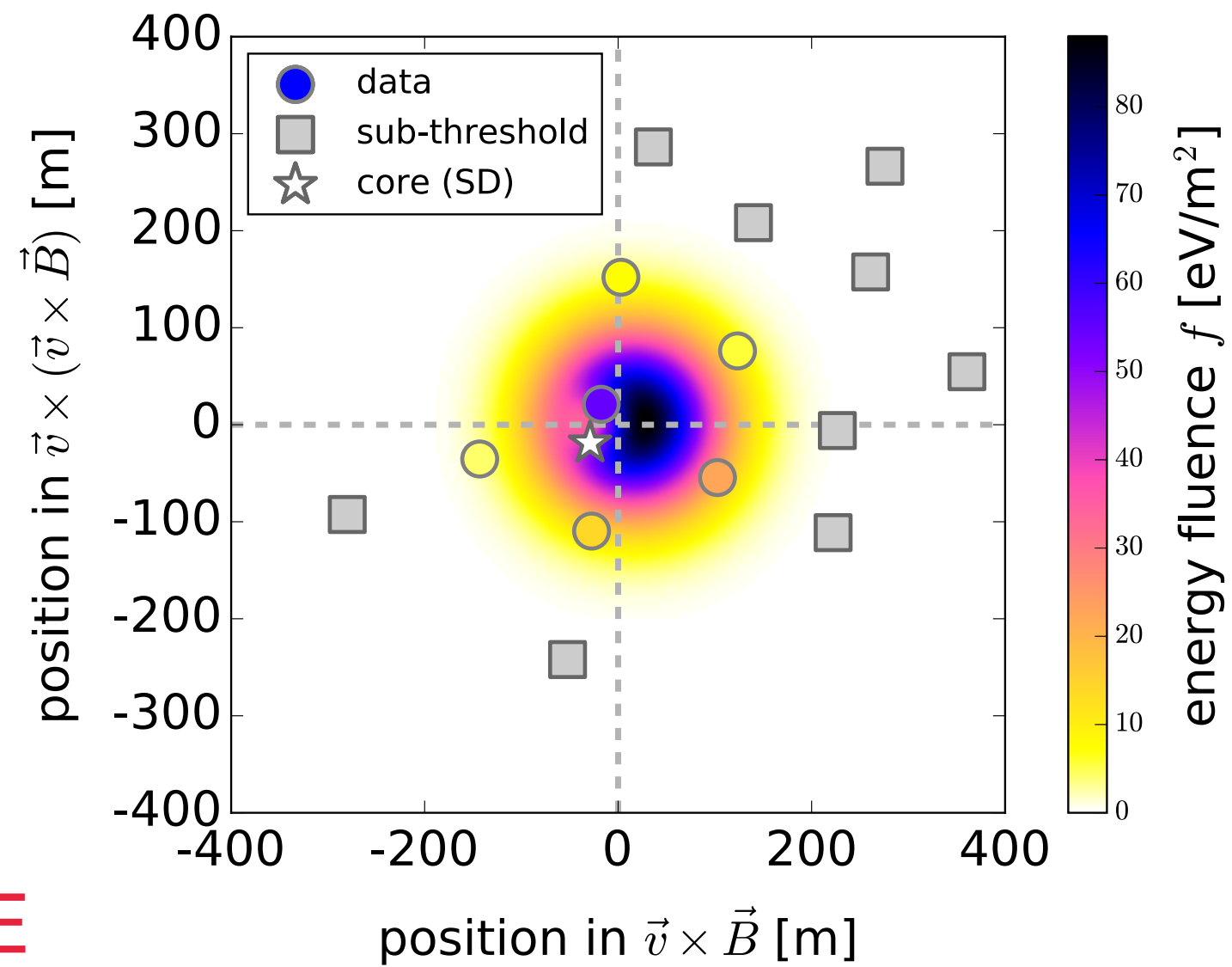
radio group

- **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

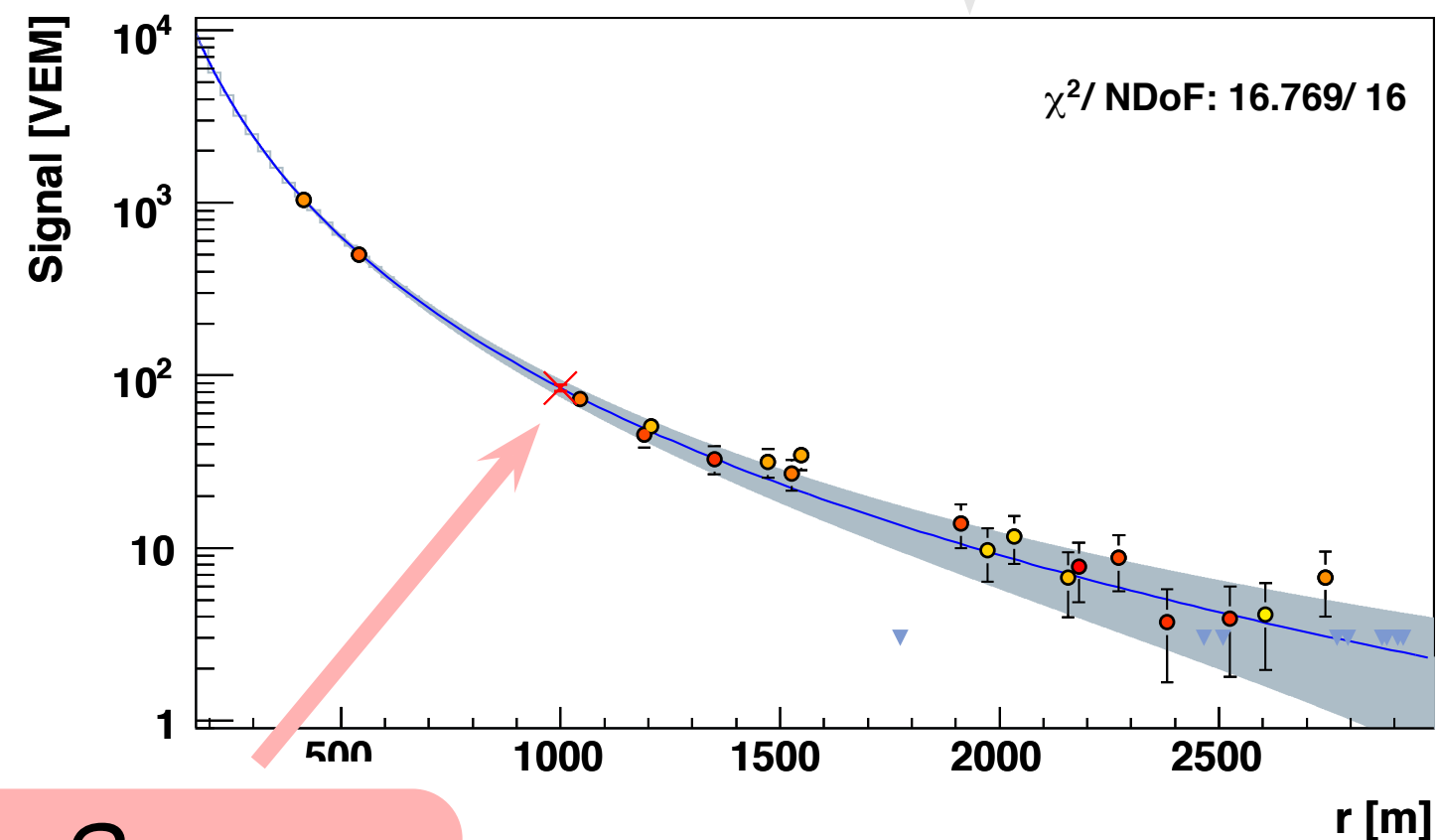
MEASURING AIR SHOWERS WITH MULTIPLE TECHNIQUES



PIERRE AUGER OBSERVATORY



SURFACE DETECTOR



S_{1000}

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

EXPOSURE

Auger $9.0 \cdot 10^4 \text{ km}^2 \text{ sr yr}$

TA $0.8 \cdot 10^4 \text{ km}^2 \text{ sr yr}$

RADIO DETECTOR

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

FLUORESCENCE DETECTOR

2017 HIGHLIGHT

RESEARCH

COSMIC RAYS

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

The Pierre Auger Collaboration*†

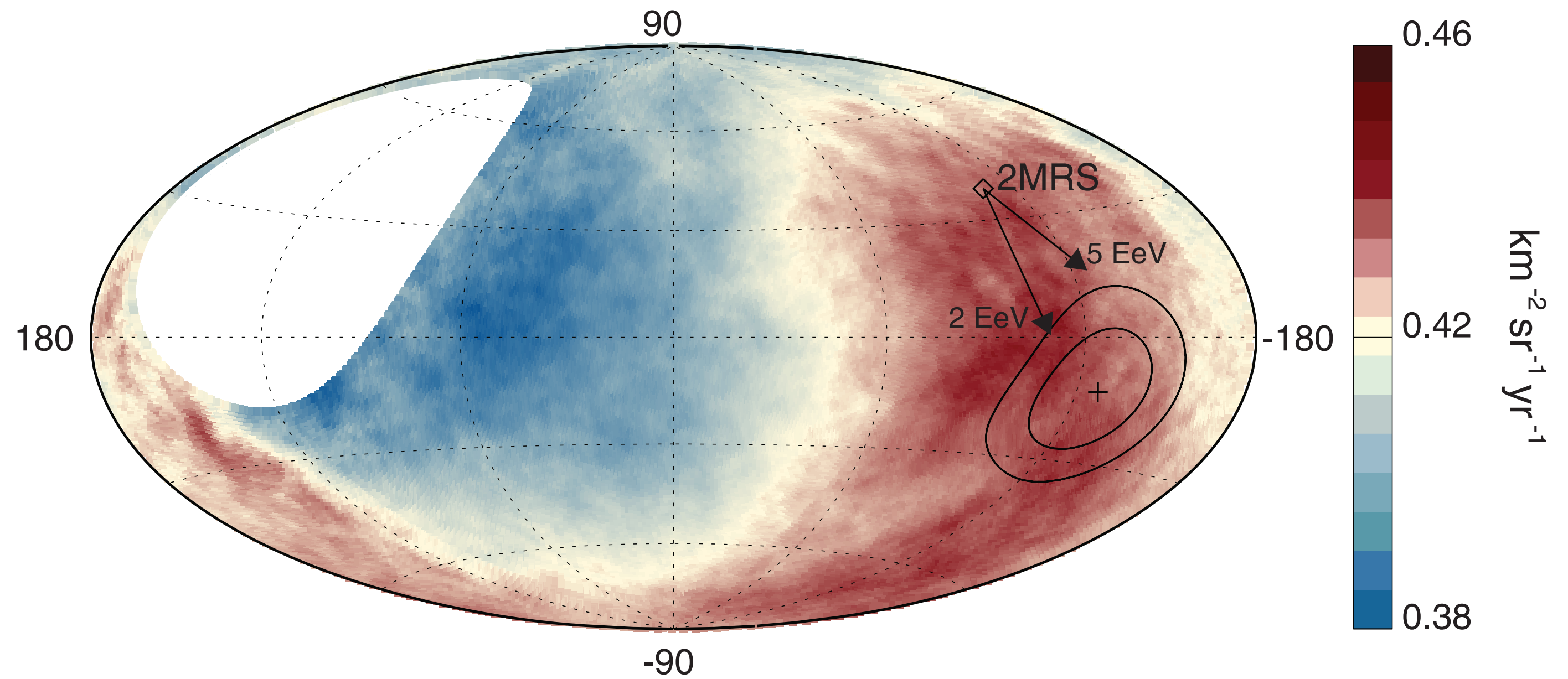


Fig. 3. Map showing the fluxes of particles in galactic coordinates. Sky map in galactic coordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45° top-hat function. The galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% 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.

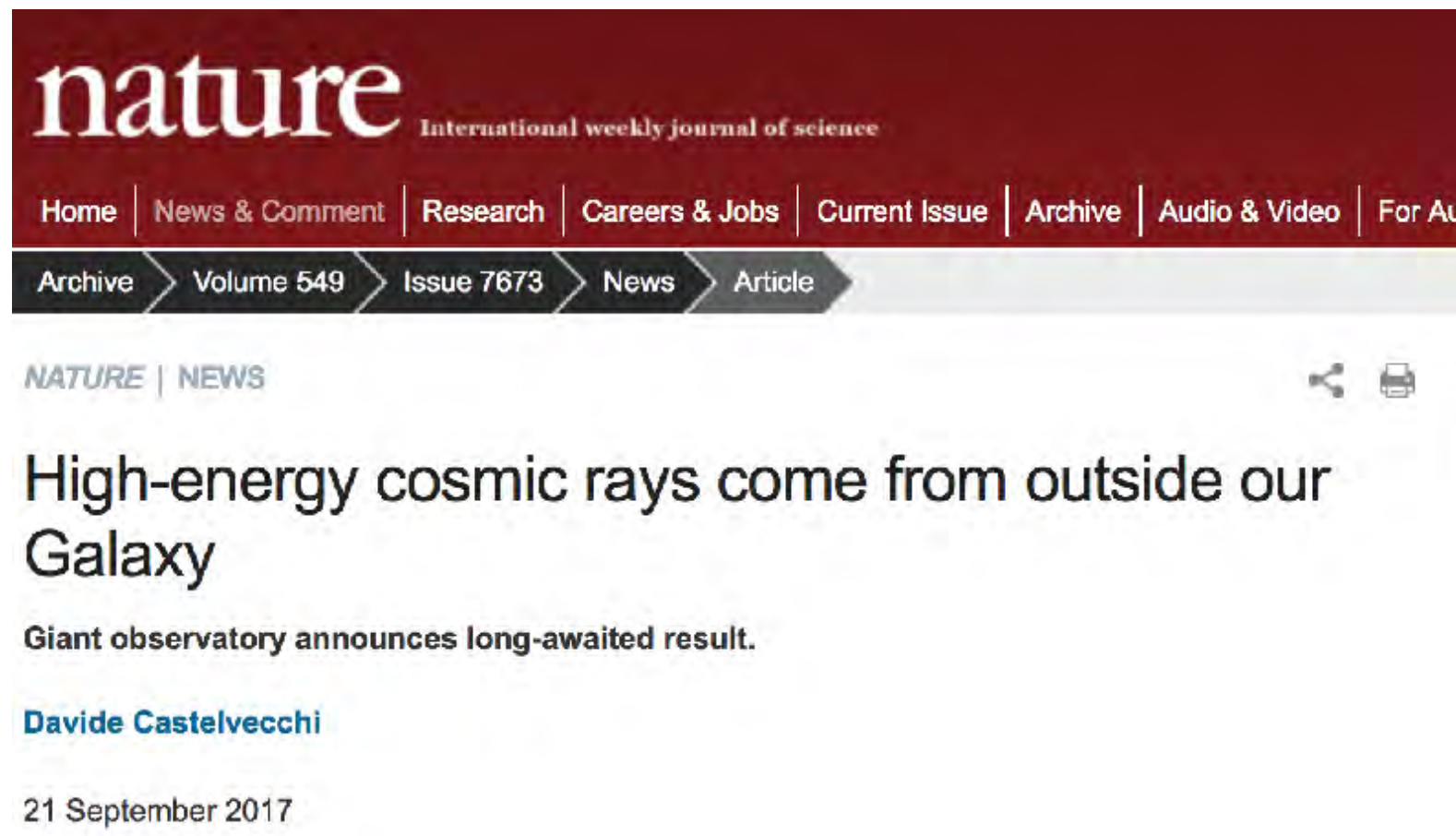
Anisotropy detected at >5.2 sigma
dipole amplitude 6.5%

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

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

BIG MEDIA ATTENTION

~200 press reports
from all over the world



nature International weekly journal of science
Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For Authors
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NATURE | NEWS

High-energy cosmic rays come from outside our Galaxy

Giant observatory announces long-awaited result.

Daide Castelvechi

21 September 2017



New Scientist
DAILY NEWS 21 September 2017

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

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

LE FIGARO

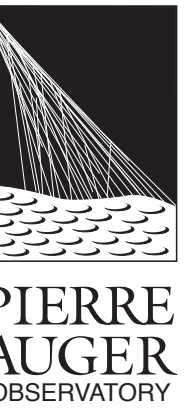
Des rayons cosmiques venus d'ailleurs

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



Le Monde

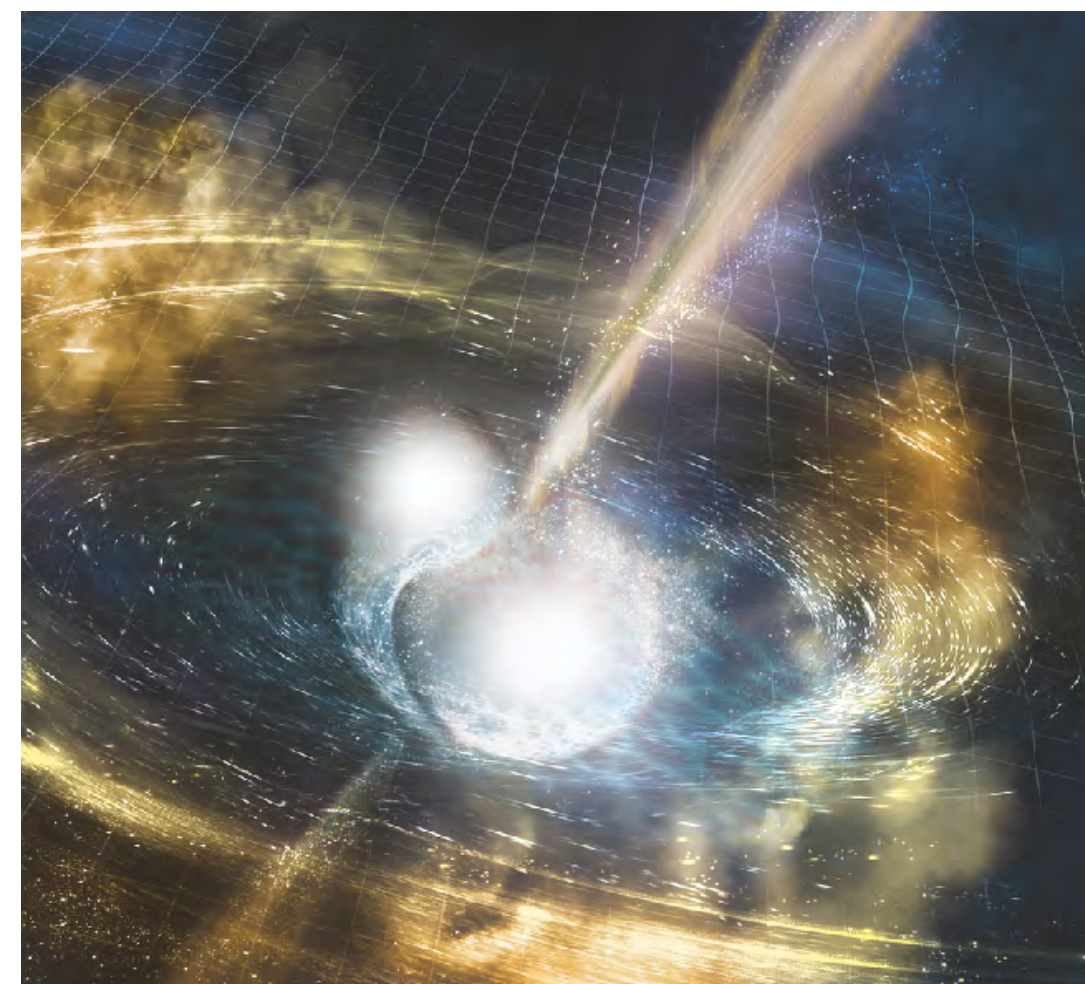
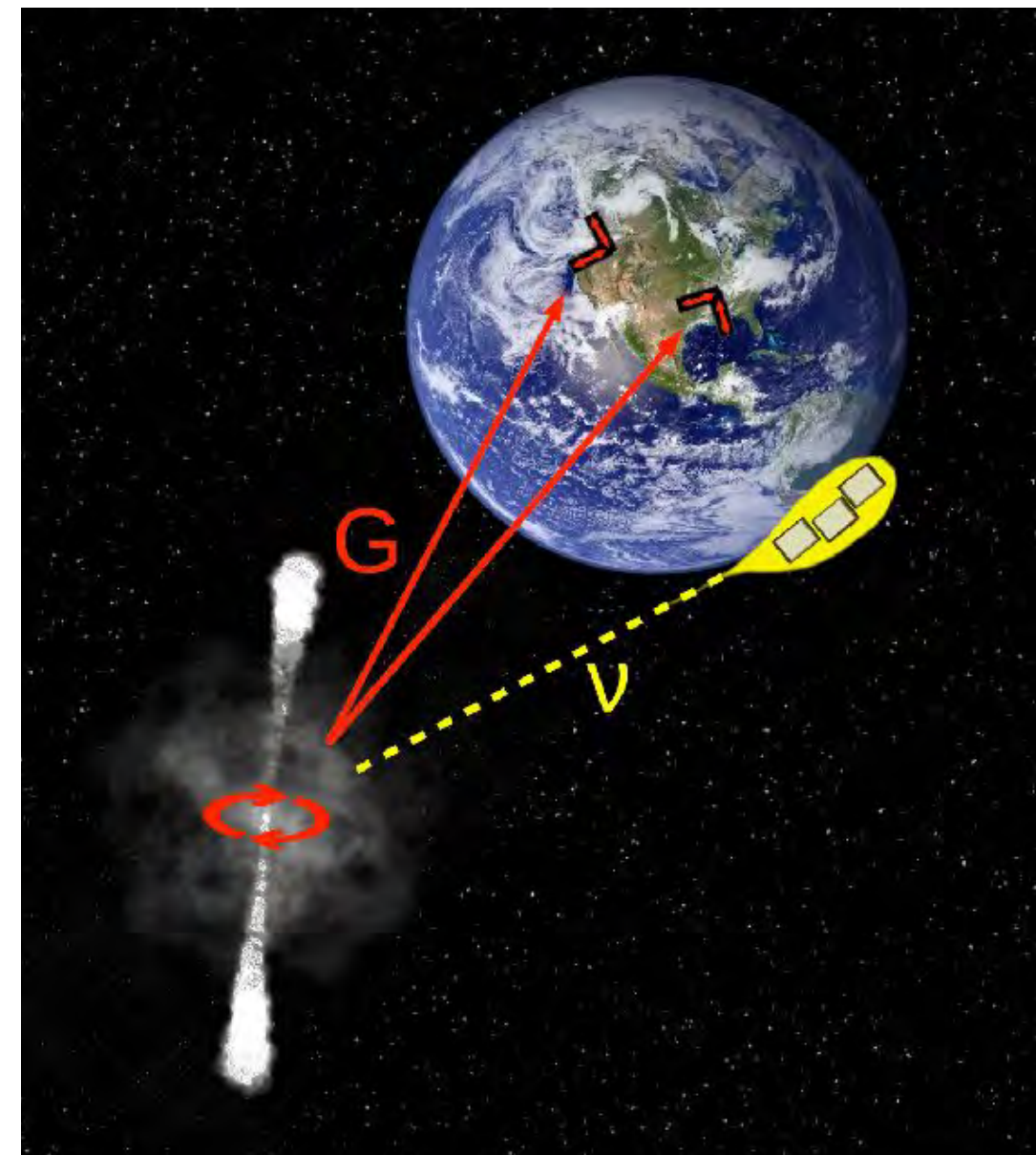
Sciences

SCIENCES Vidéos Archéologie Supplément partenaire : Les Prix EDF Pulse Affaire de

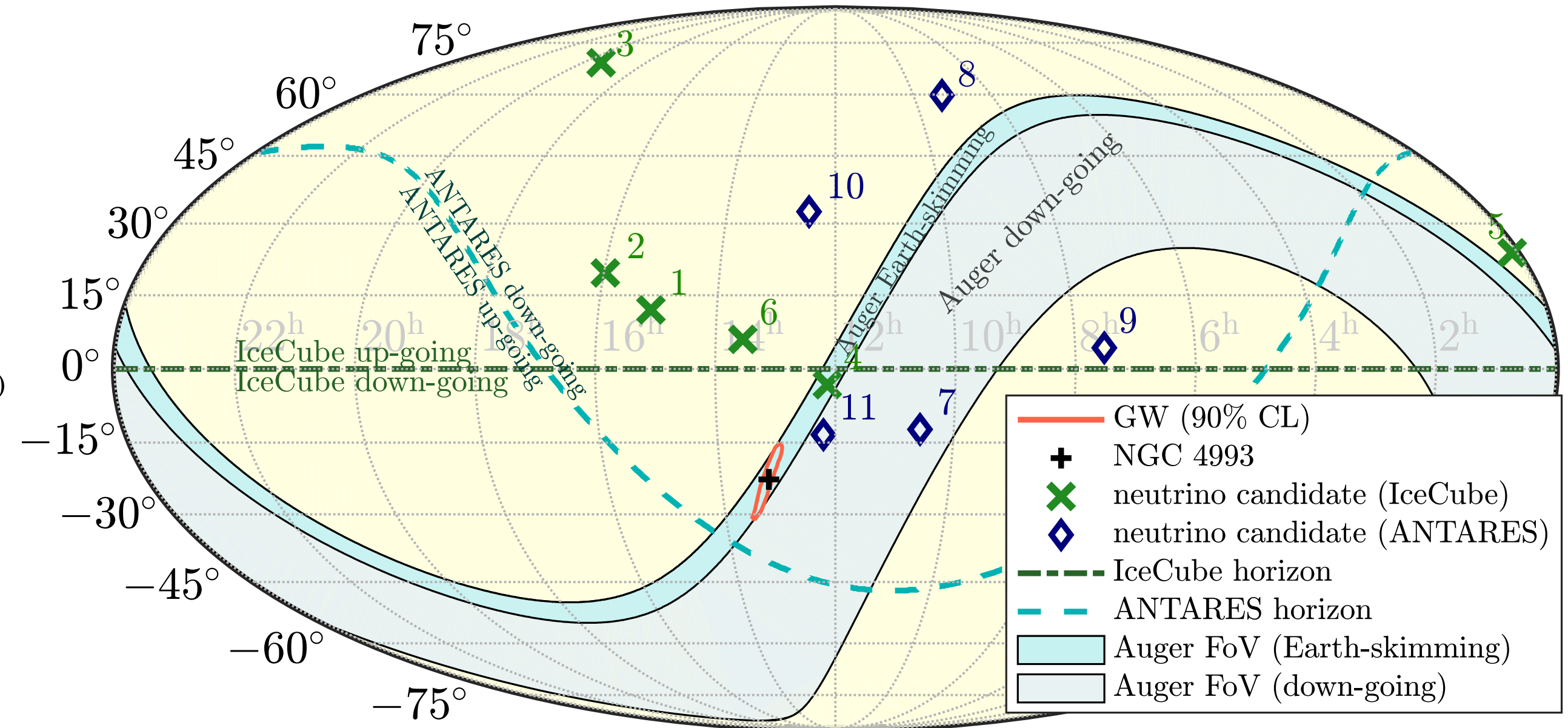
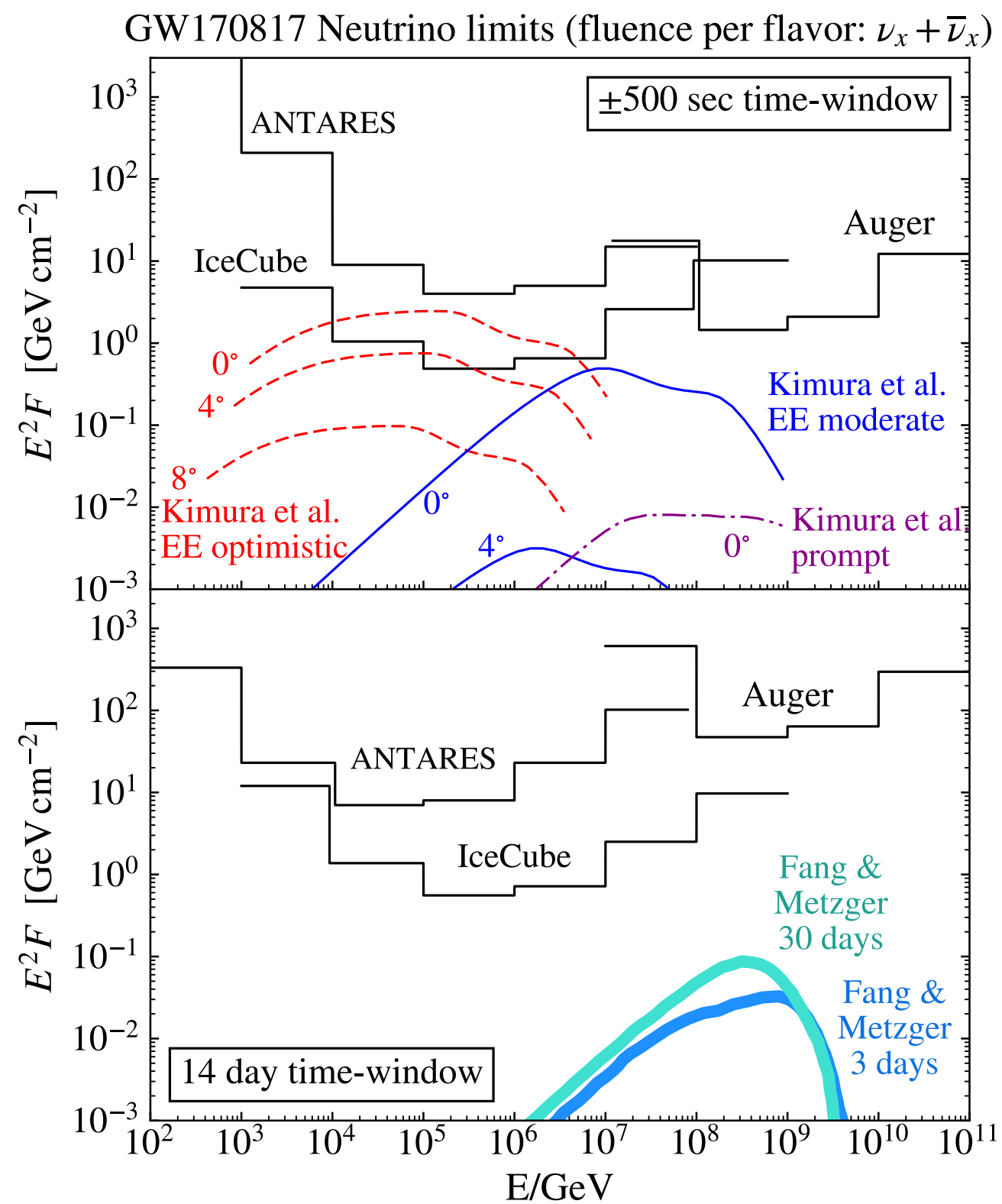
On sait désormais d'où viennent les rayons cosmiques

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
© 2017. The American Astronomical Society. All rights reserved.

<https://doi.org/10.3847/2041-8213/aa91c9>

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.)

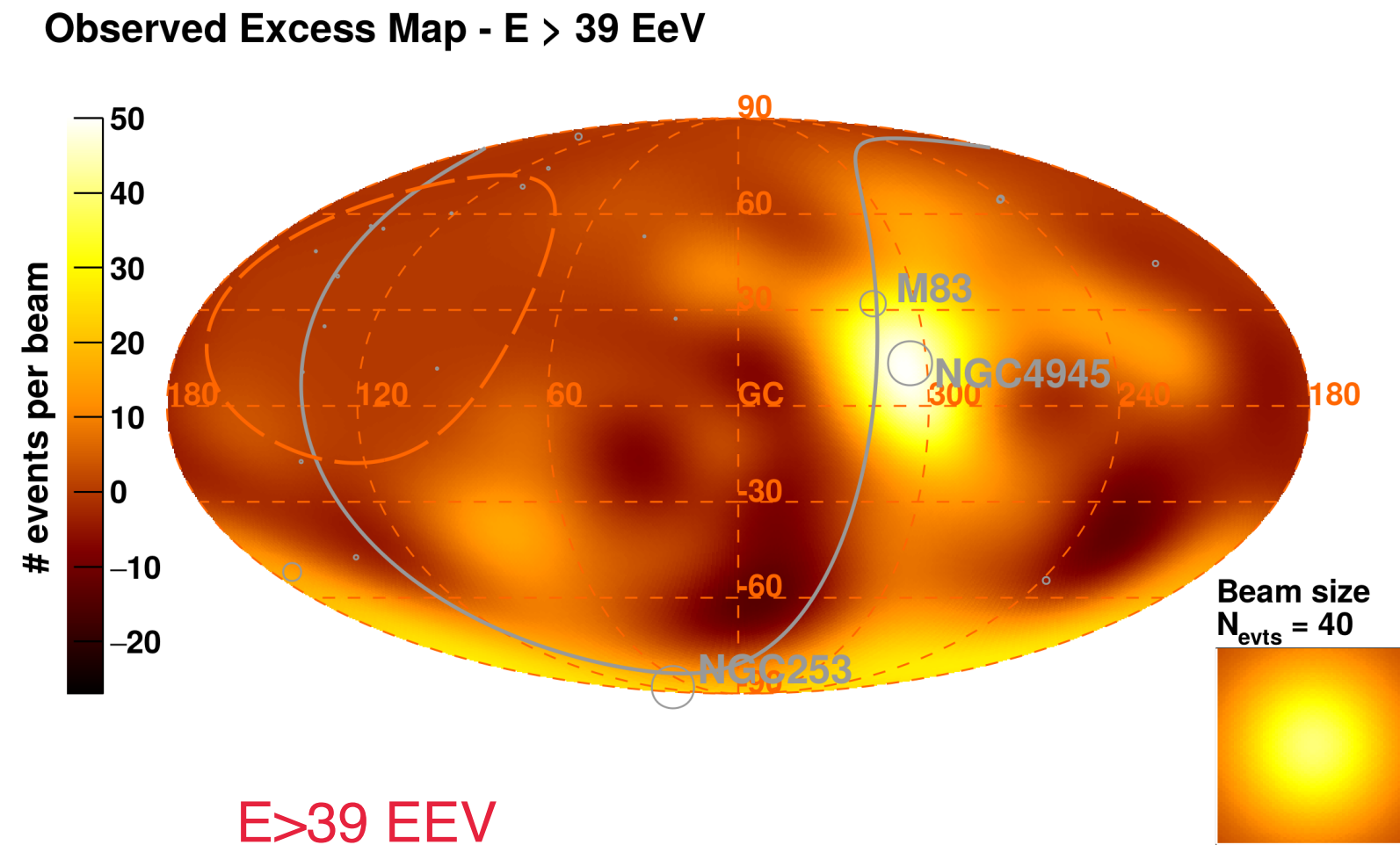
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Malaria: Nr

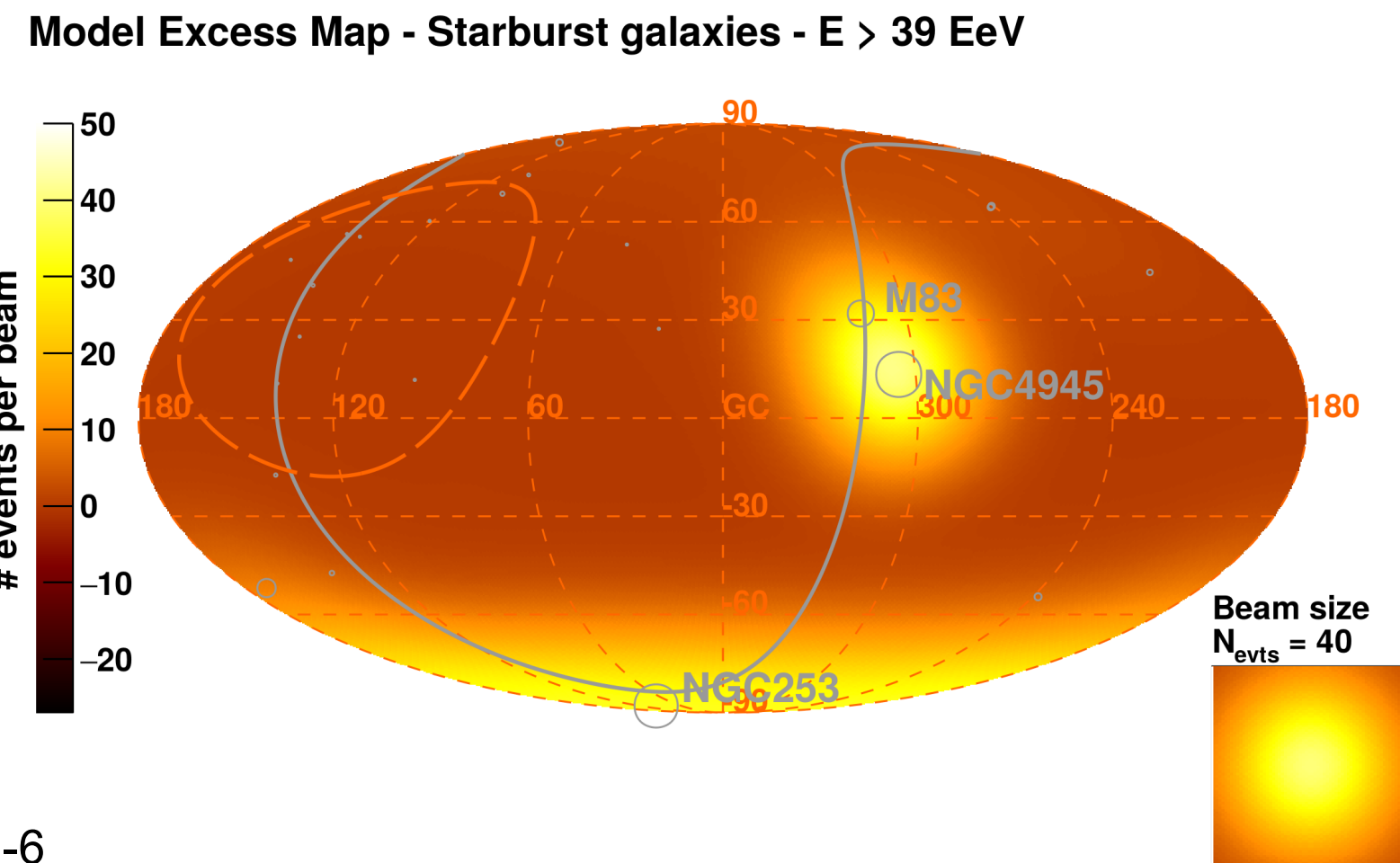


SEARCH FOR INTERMEDIATE-SCALE UHECR ANISOTROPIES

STARBURST

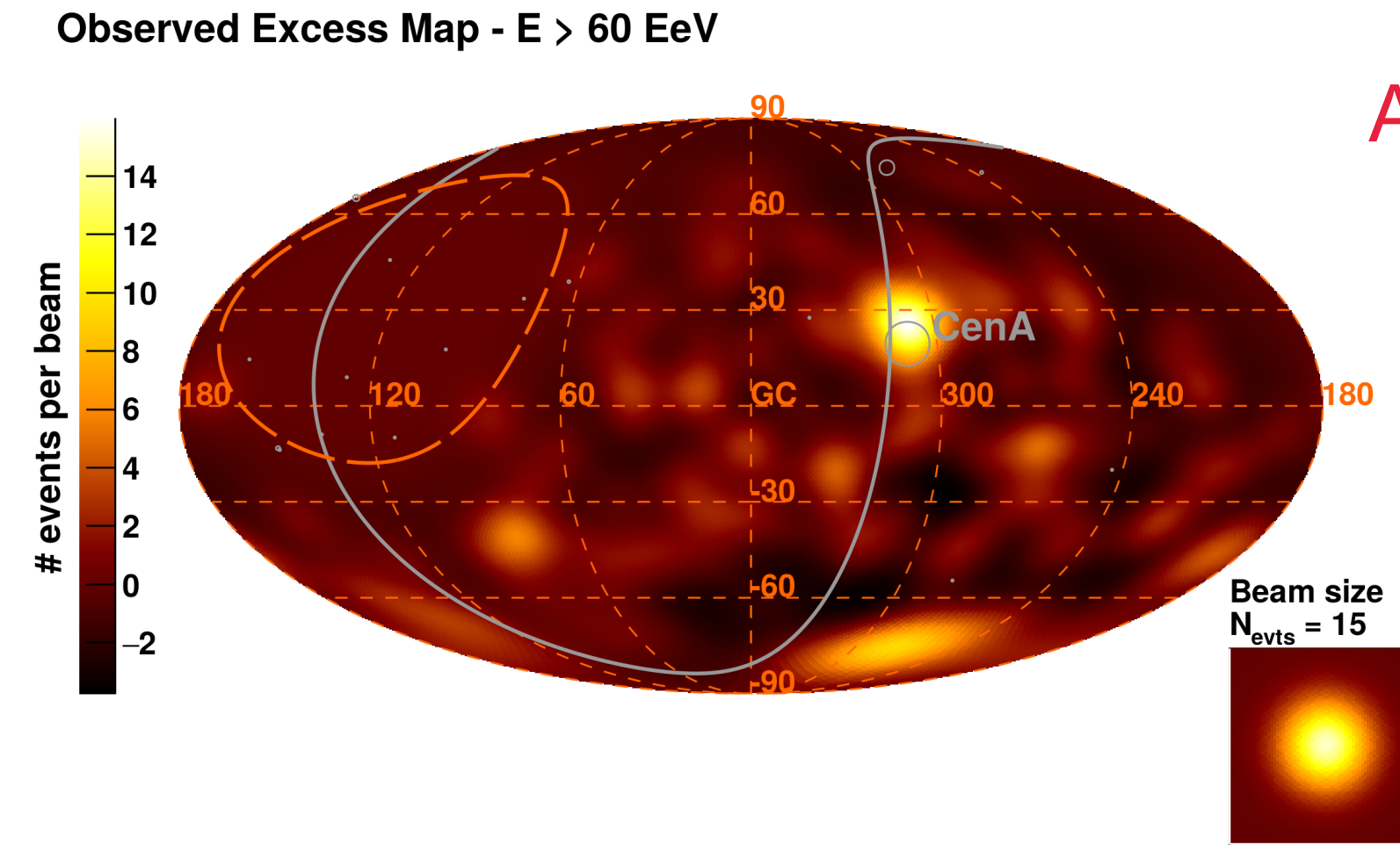


$E > 39$ EeV

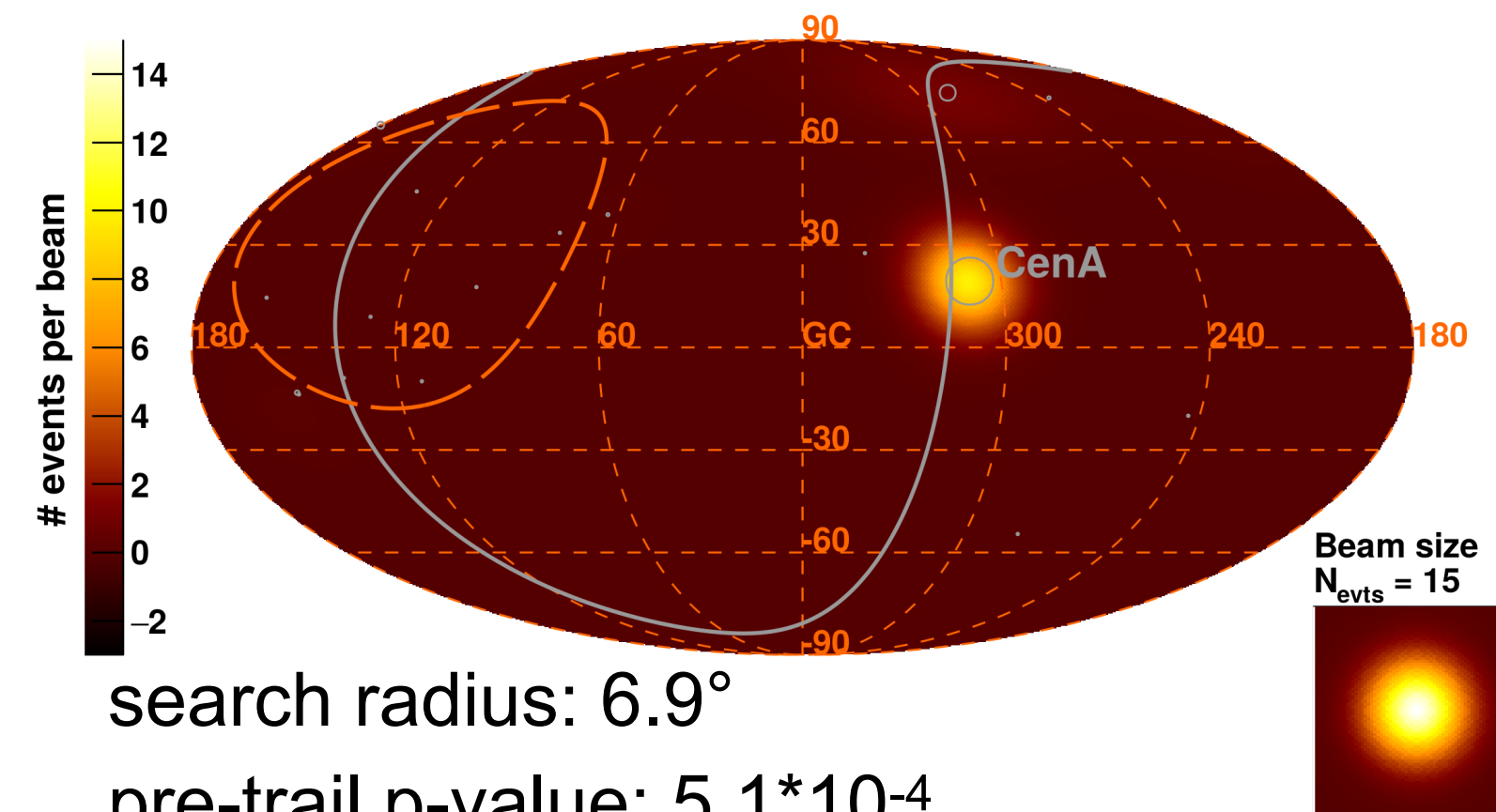


SBG fraction: 9.7%
 search radius: 12.9°
 pre-trail p-value: $3.8 \cdot 10^{-6}$
 post-trial p-value: $3.6 \cdot 10^{-5}$
 post-trial significance: 4.0 sigma

AGN



Model Excess Map - Active galactic nuclei - $E > 60$ EeV



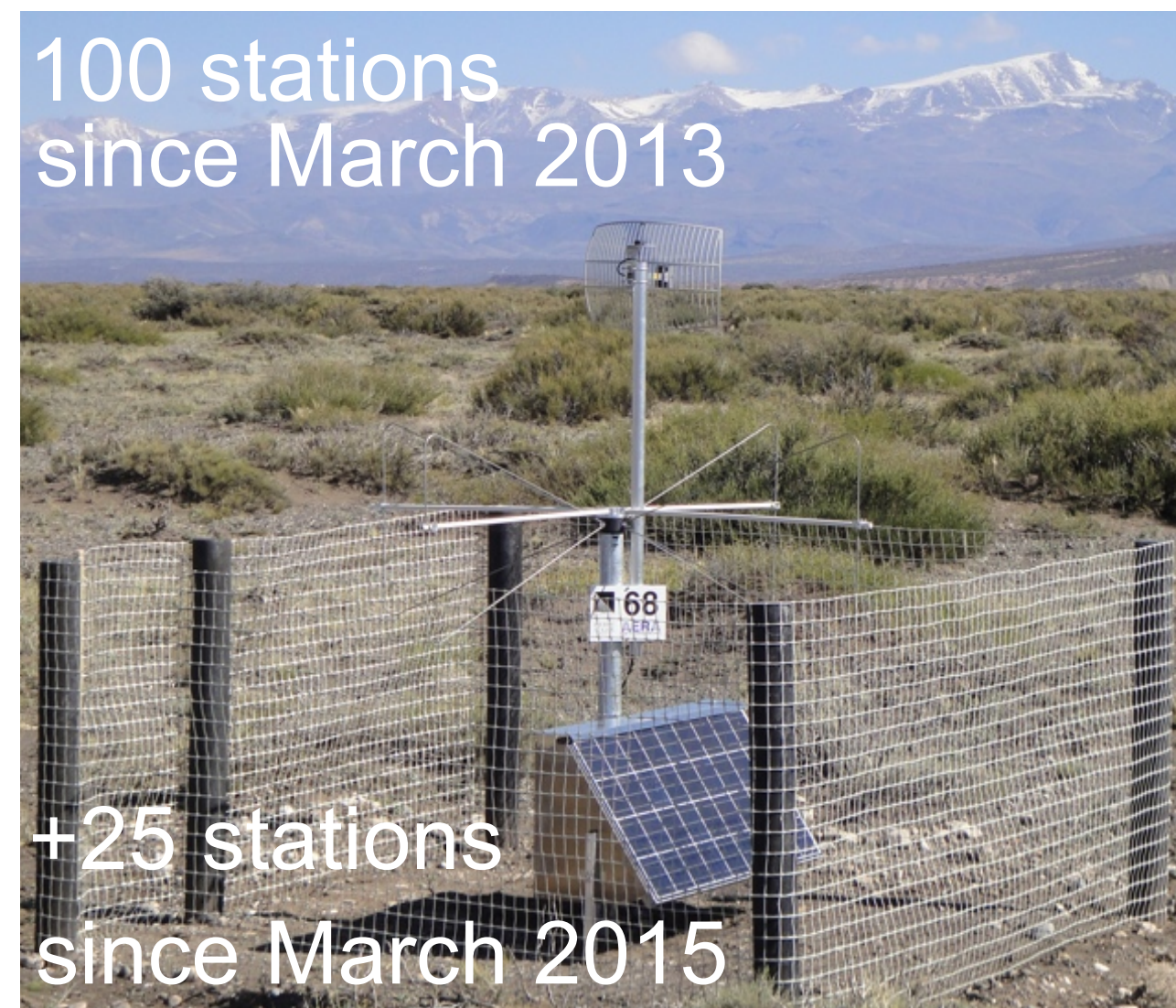
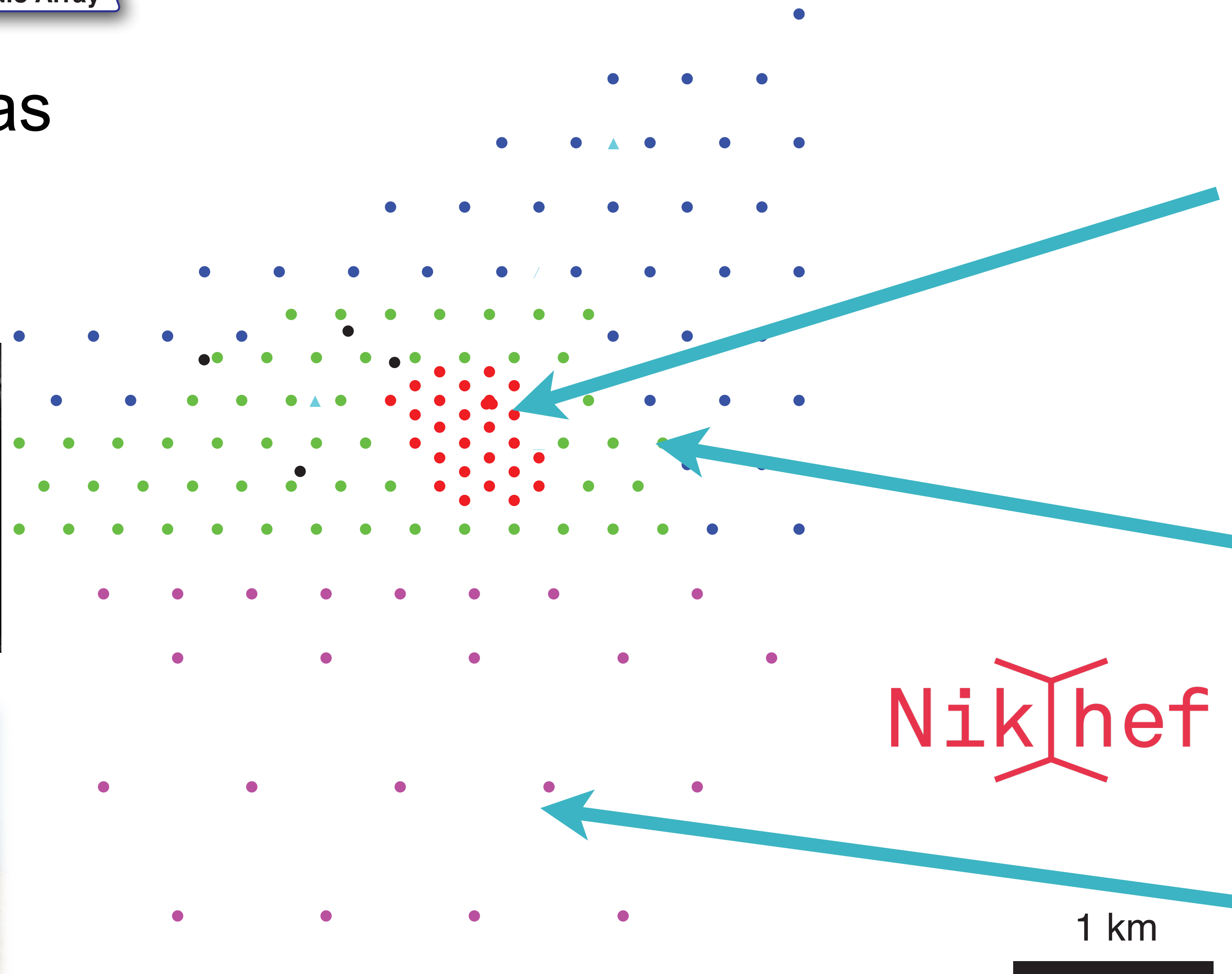
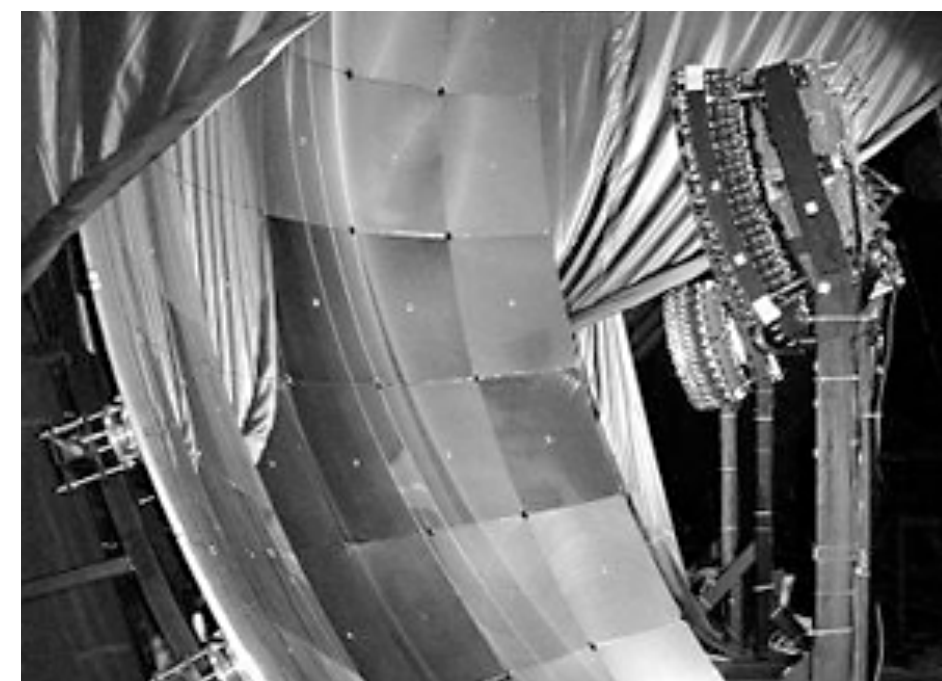
search radius: 6.9°
 pre-trail p-value: $5.1 \cdot 10^{-4}$
 post-trial p-value: $3.1 \cdot 10^{-3}$
 post-trial significance: 2.7 sigma

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

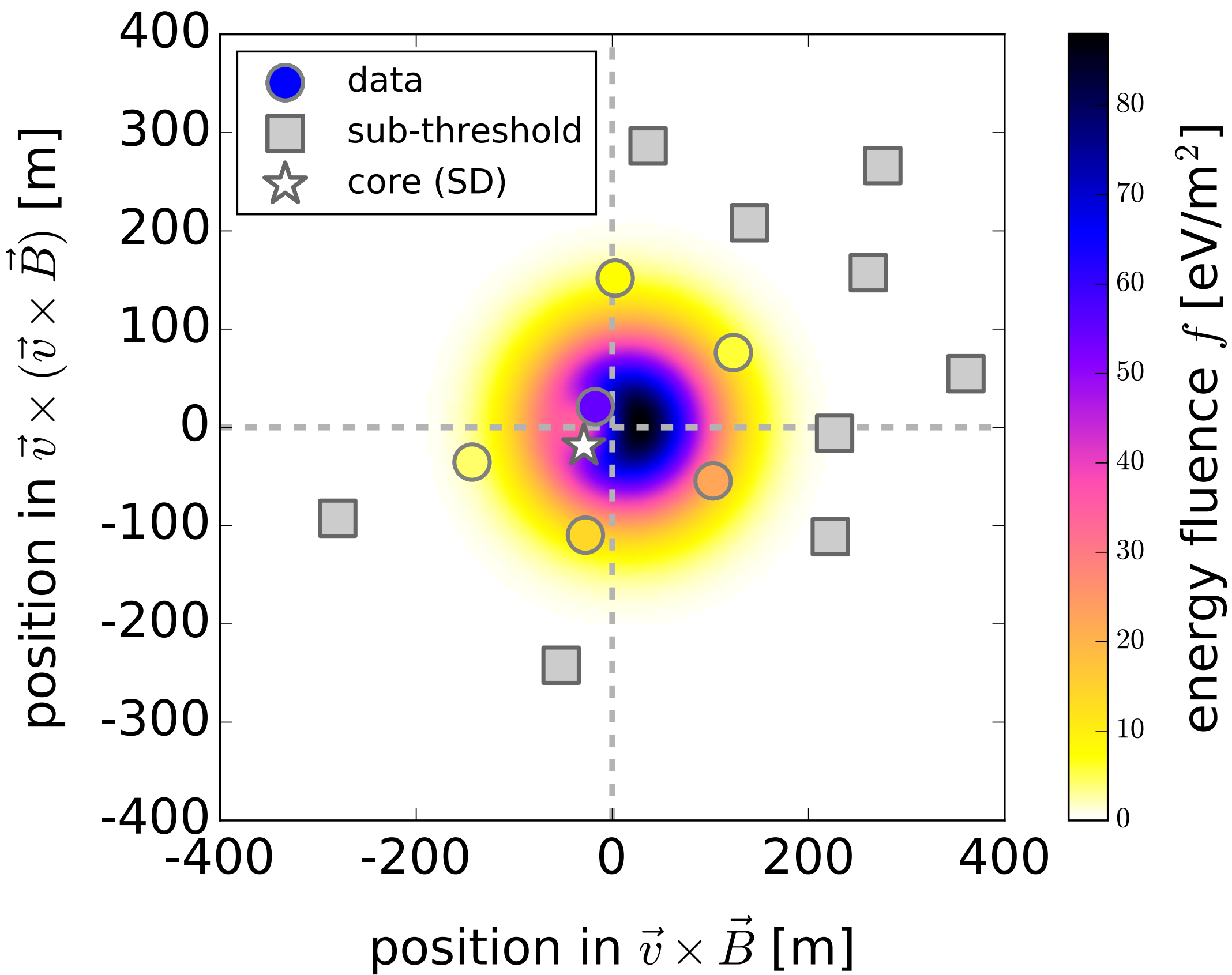
~150 antennas

~17 km²

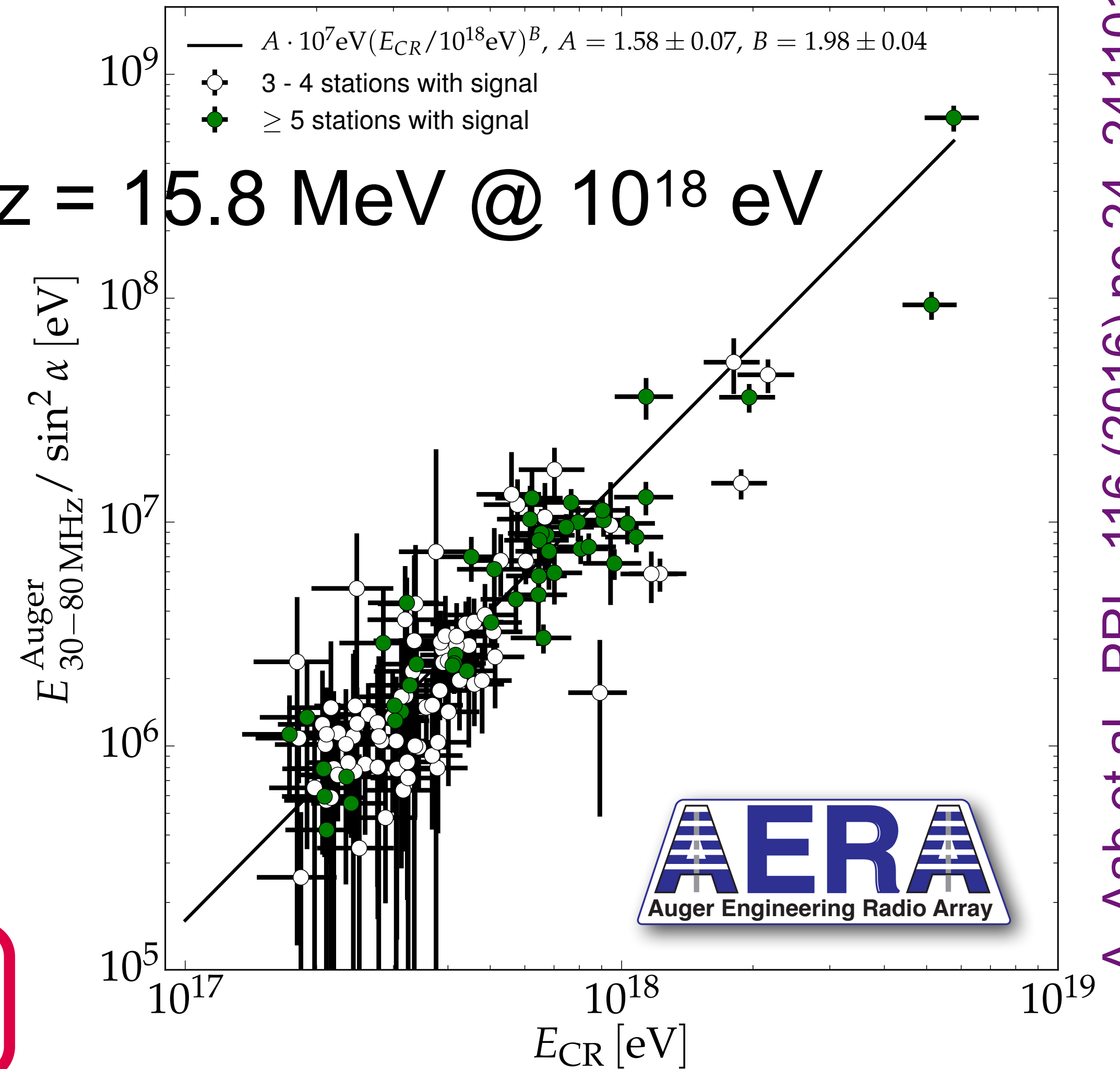
30-80 MHz



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



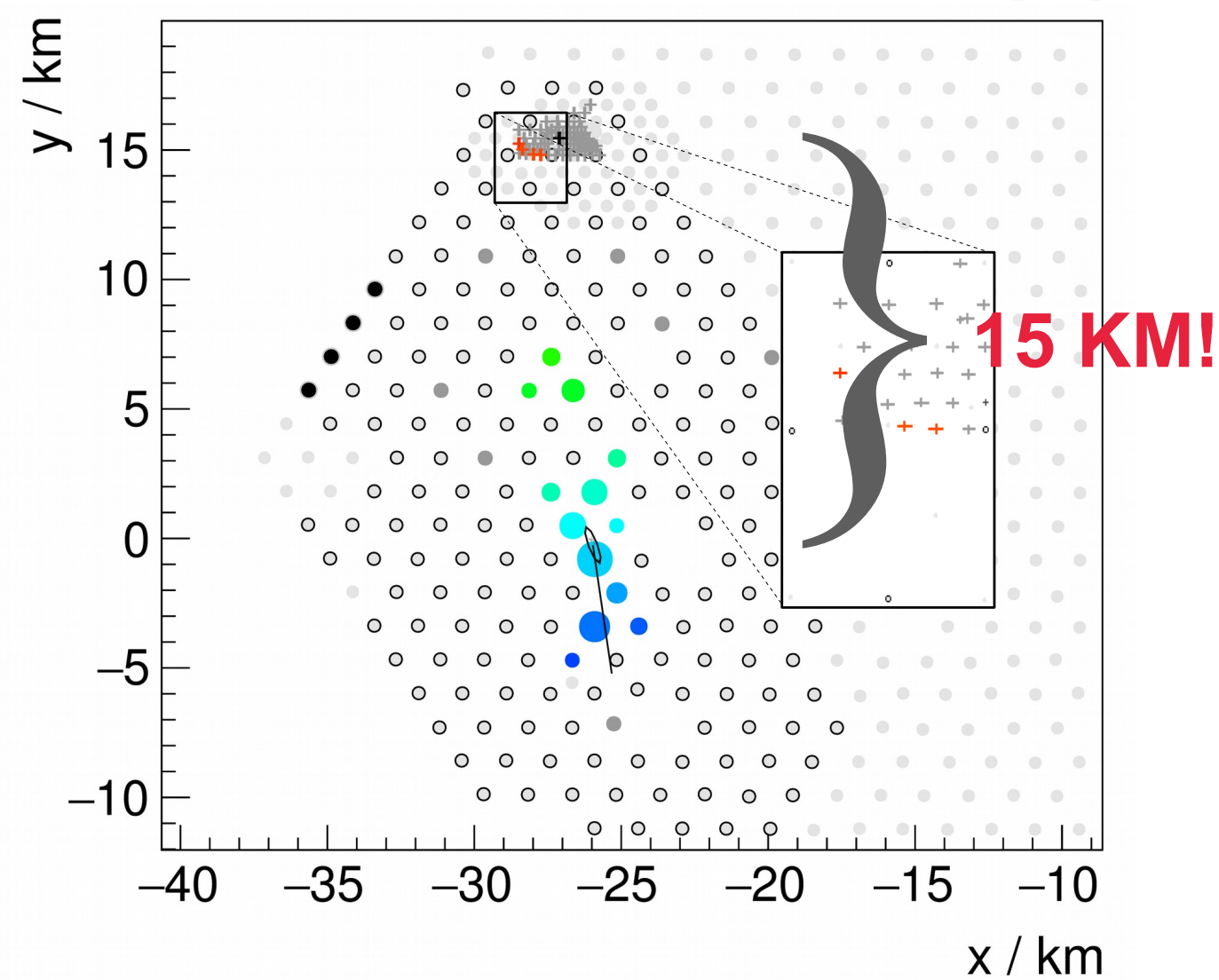
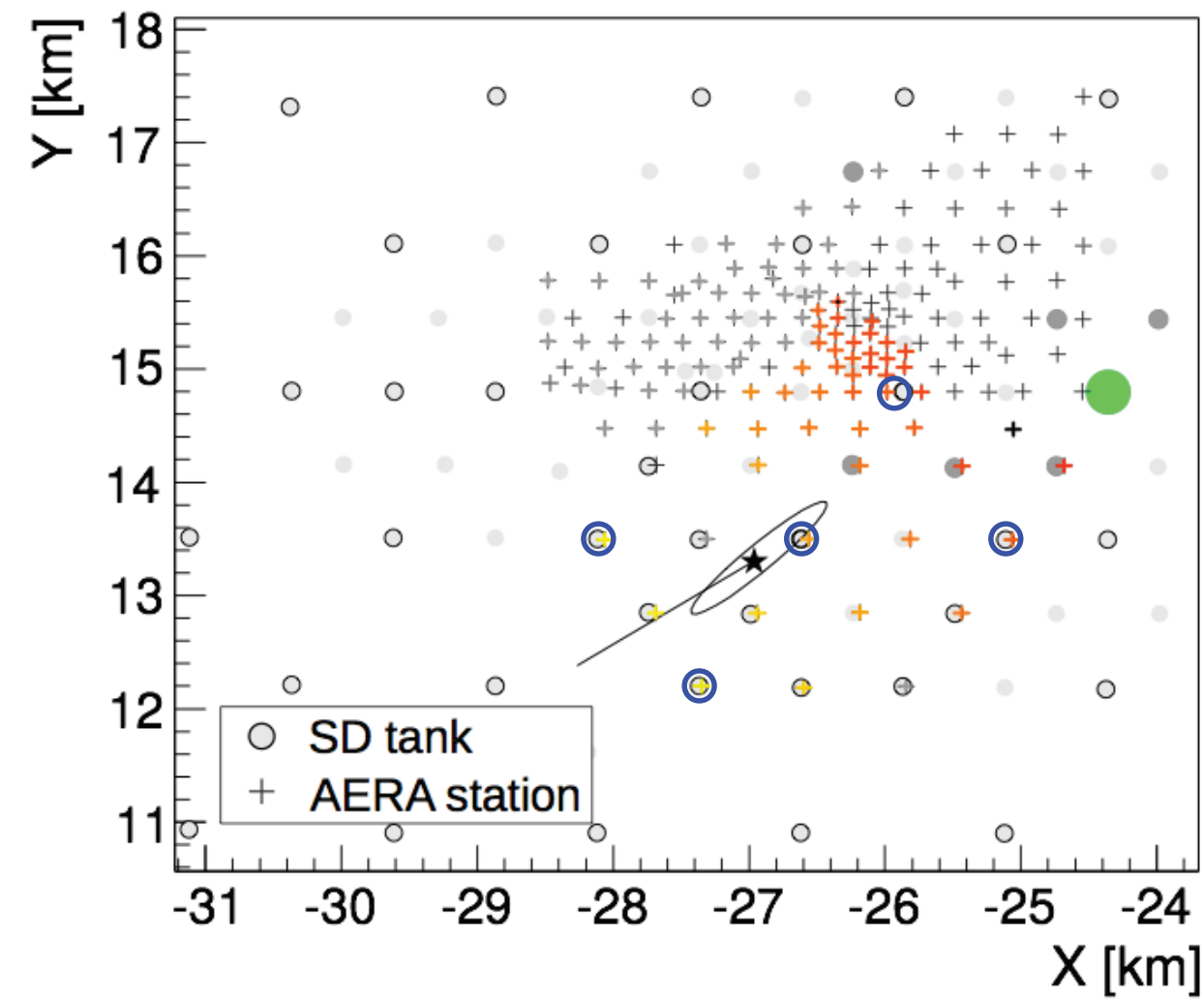
$E_{30-80 \text{ MHz}} = 15.8 \text{ MeV} @ 10^{18} \text{ eV}$



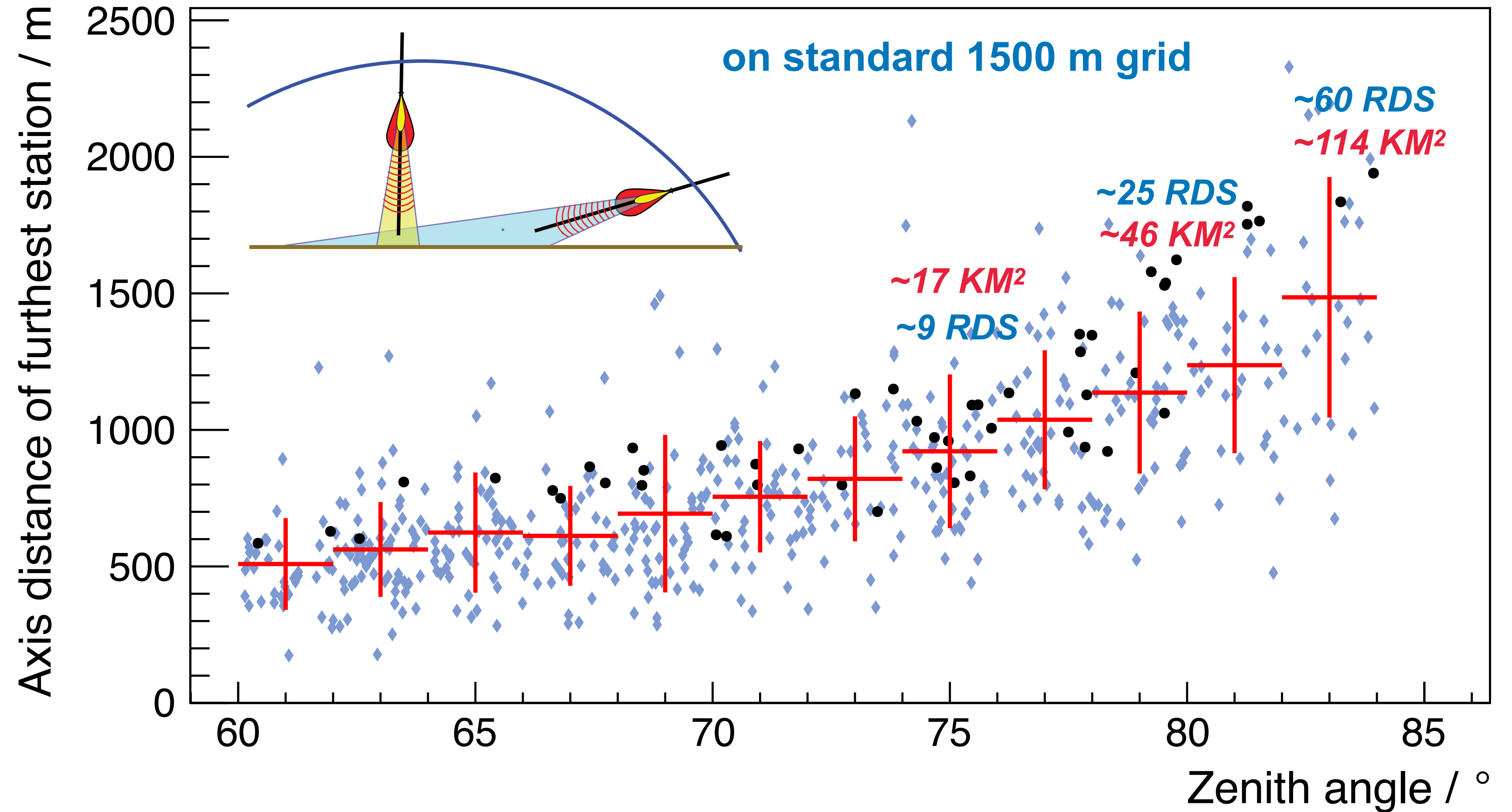
$$E_{30-80 \text{ MHz}} = (15.8 \pm 0.7(\text{stat}) \pm 6.7(\text{syst}) \text{ MeV}) \times \left(\sin \alpha \frac{E_{CR}}{10^{18} \text{ eV}} \frac{B_{Earth}}{0.24 \text{ G}} \right)^2$$

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

HORIZONTAL AIR SHOWERS MEASUREED WITH AERA



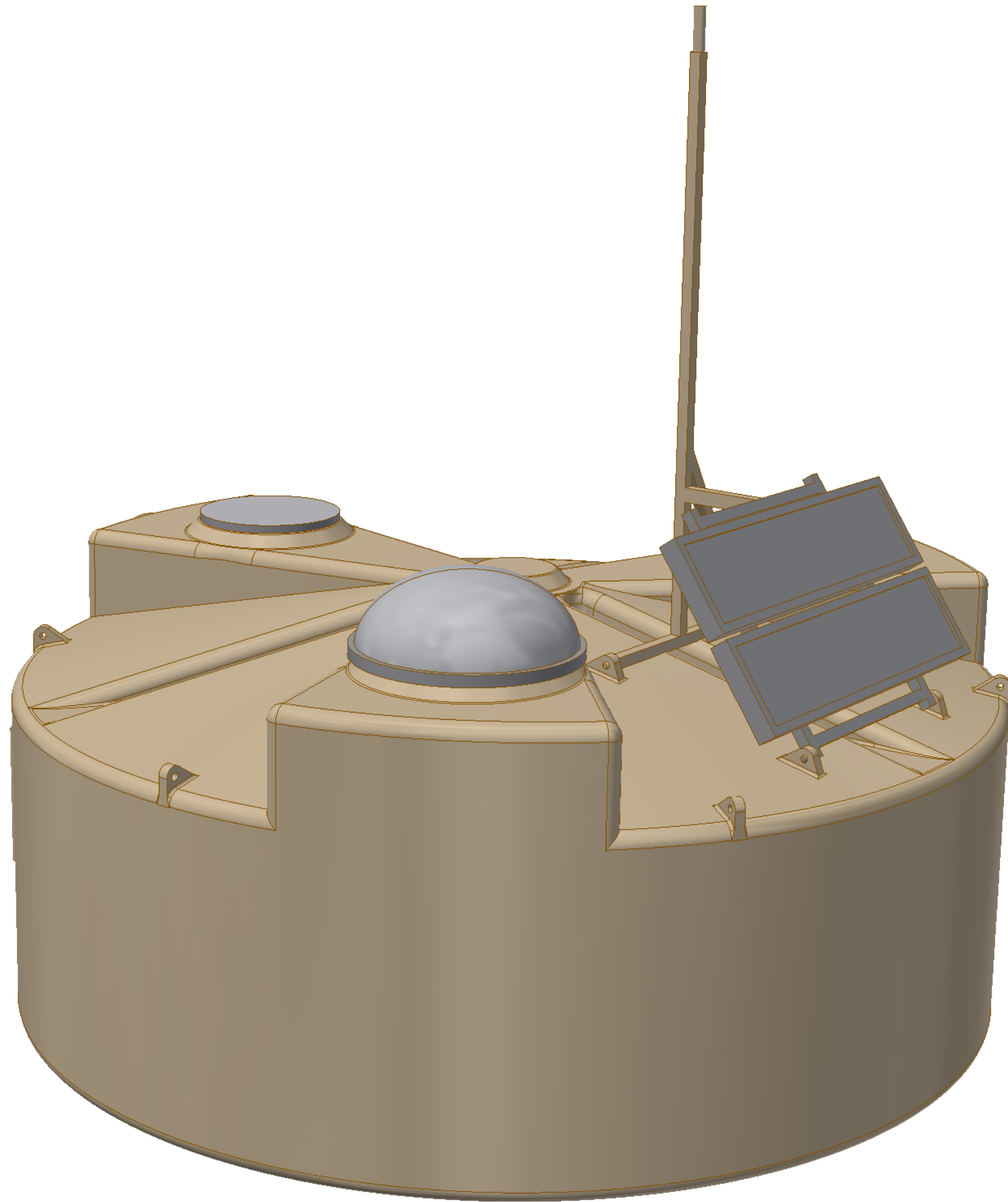
large footprints -> measure showers on 1500 m grid



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

UPGRADE OF THE PIERRE AUGER OBSERVATORY

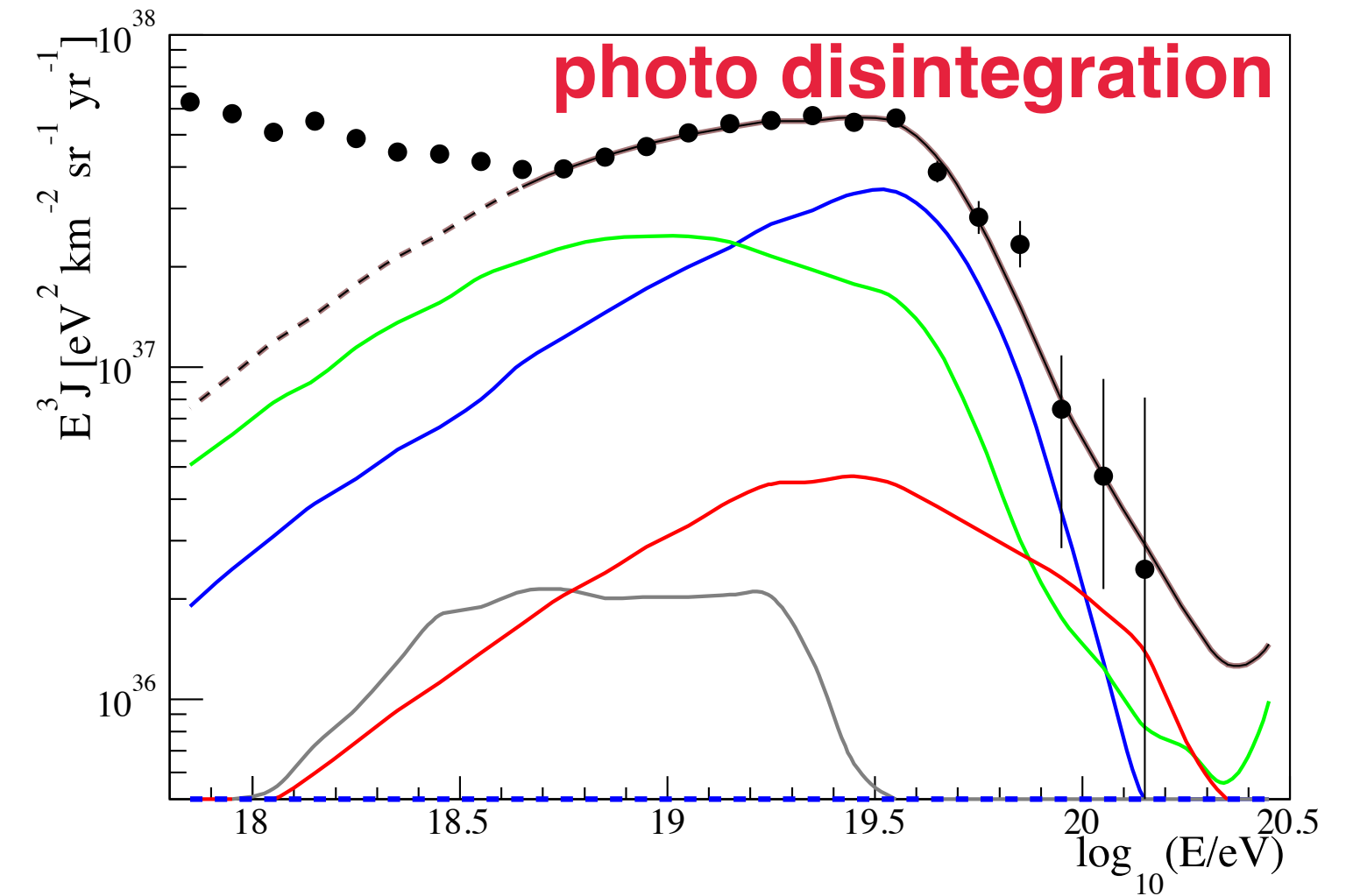
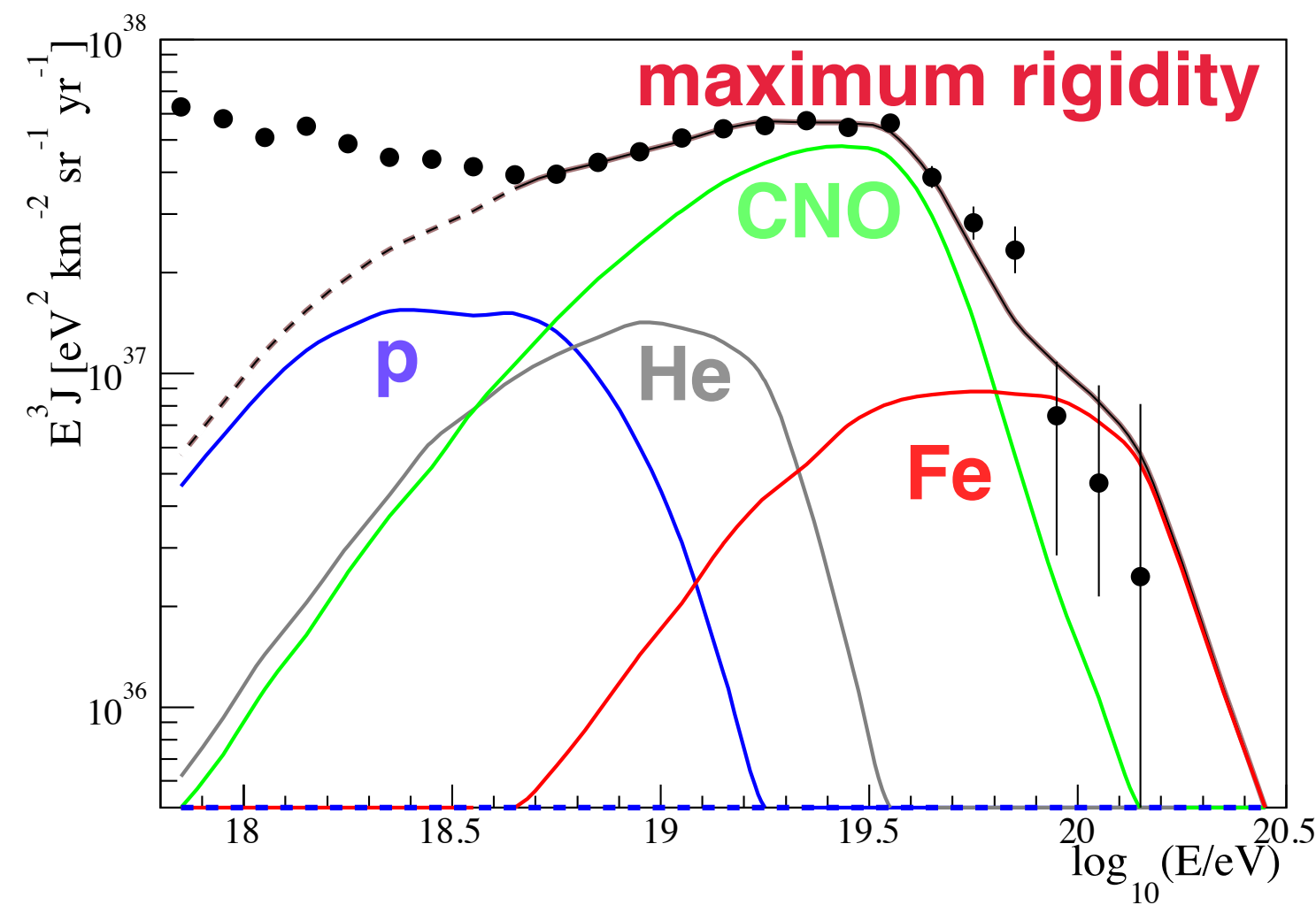
- electronics
- scintillator



Nikhef

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?

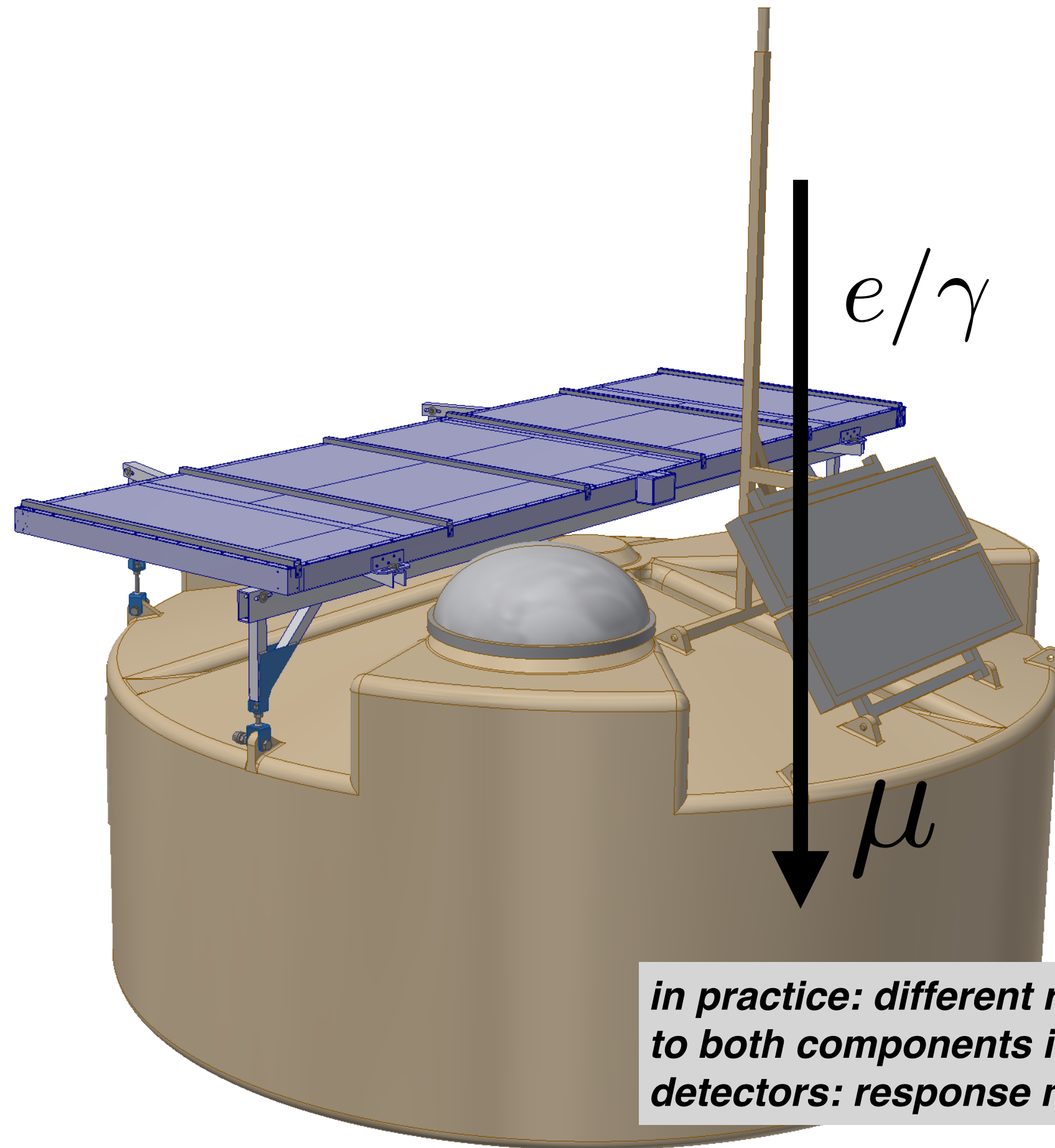


UPGRADE OF THE PIERRE AUGER OBSERVATORY

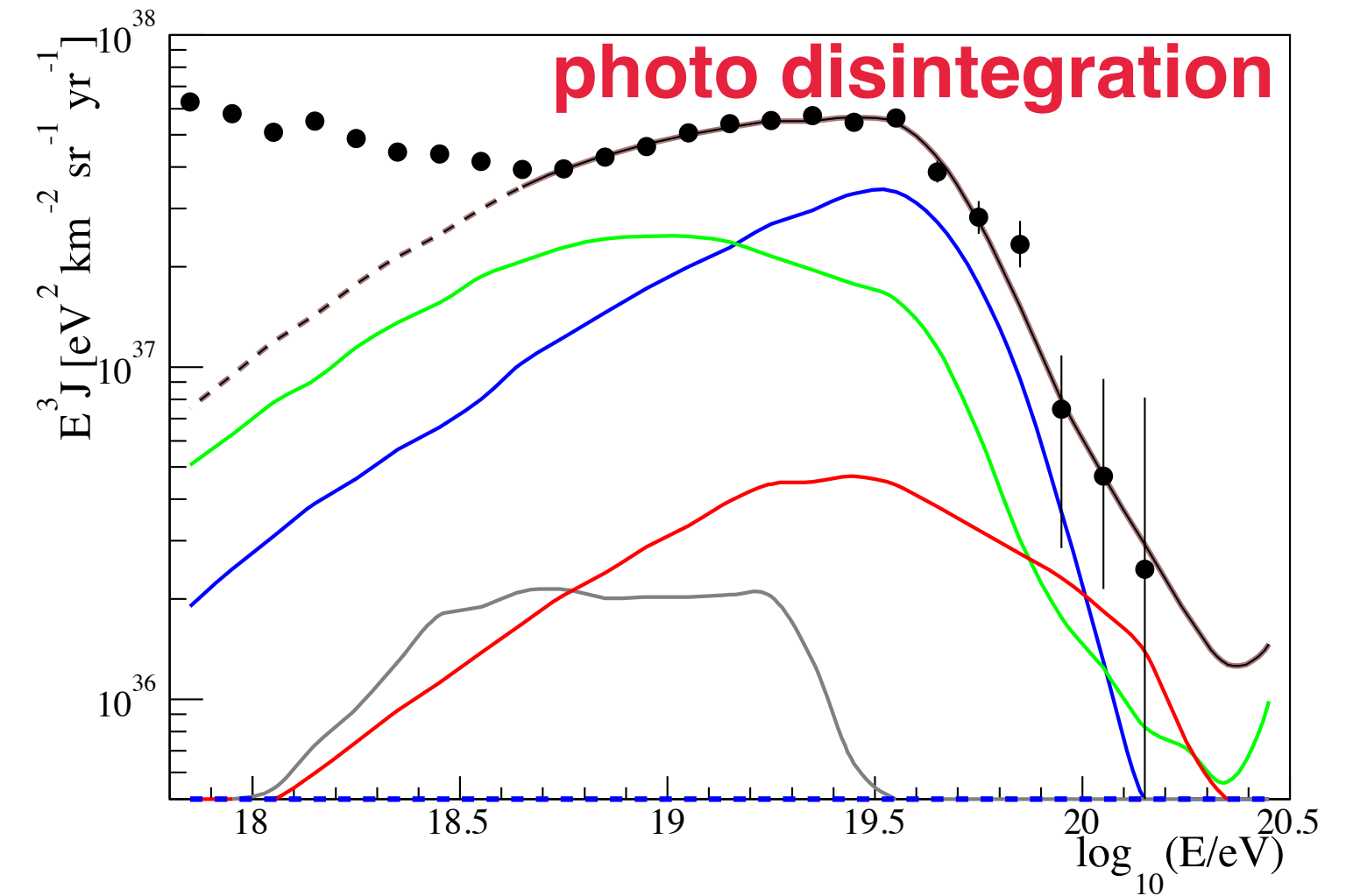
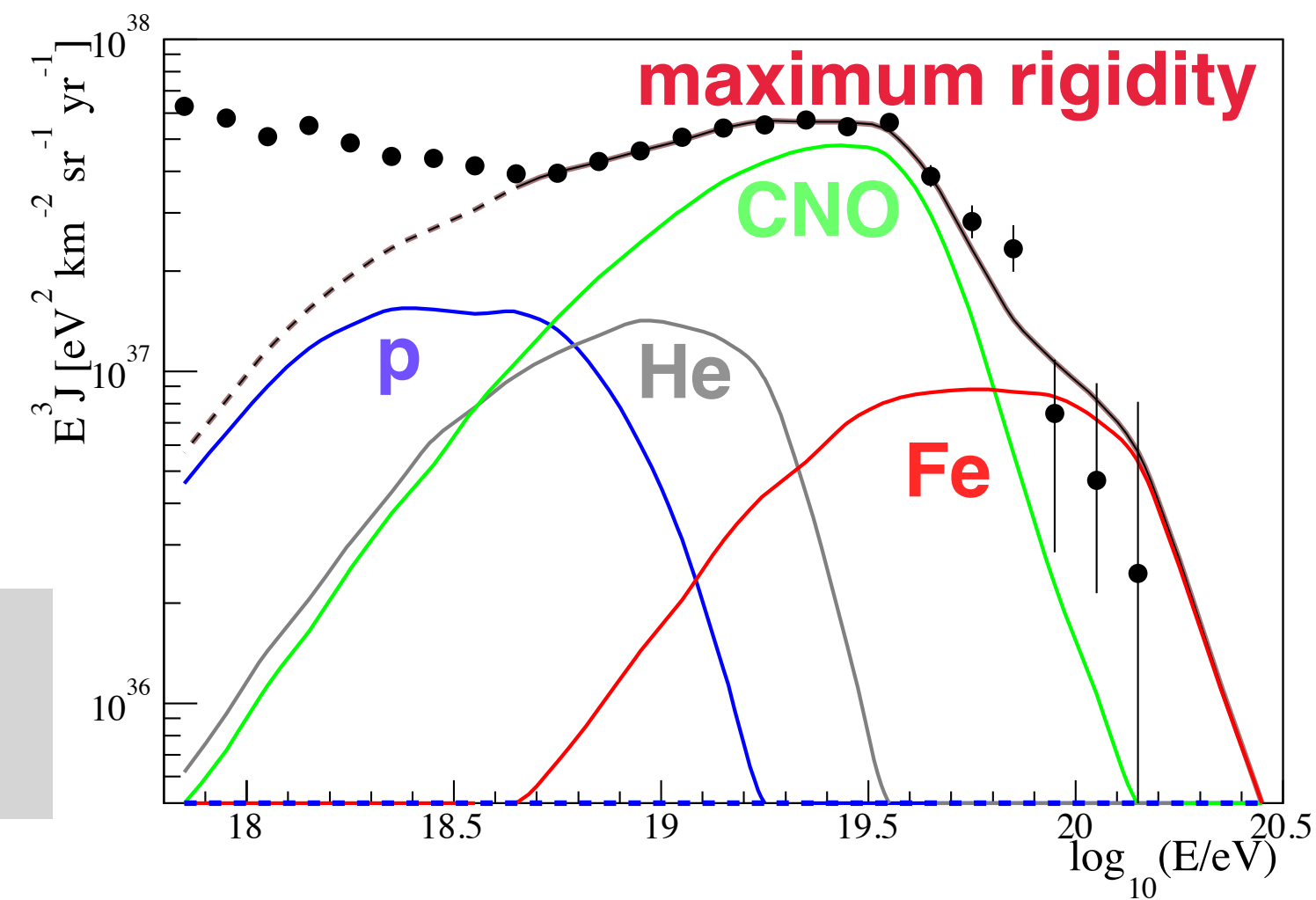
- electronics
- scintillator

Key science questions

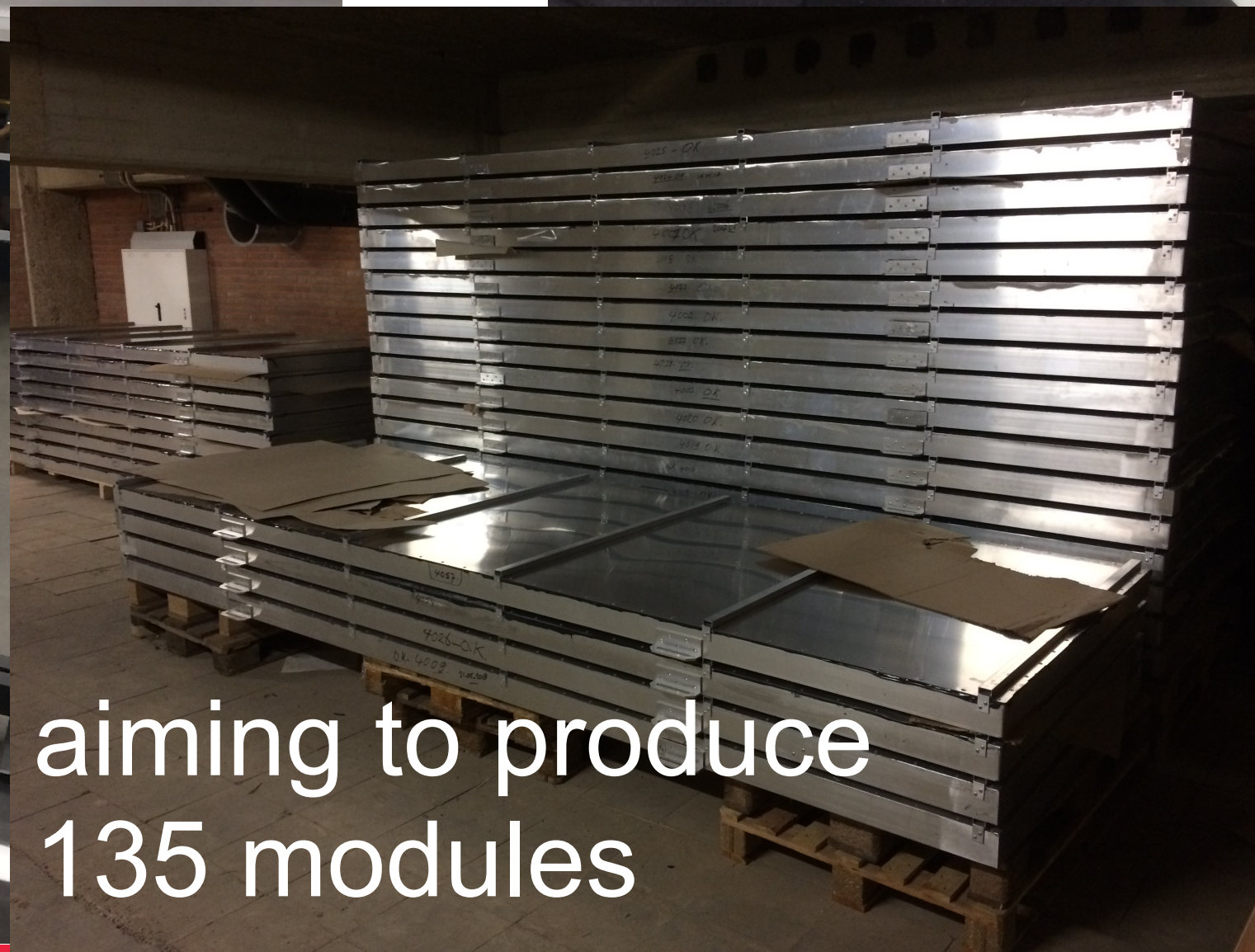
- What are the **sources** and **acceleration** mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand **particle** acceleration and **physics** at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of **protons**, **photons**, and **neutrinos** in cosmic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



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



SSD PRODUCTION IN NIJMEGEN



aiming to produce
135 modules



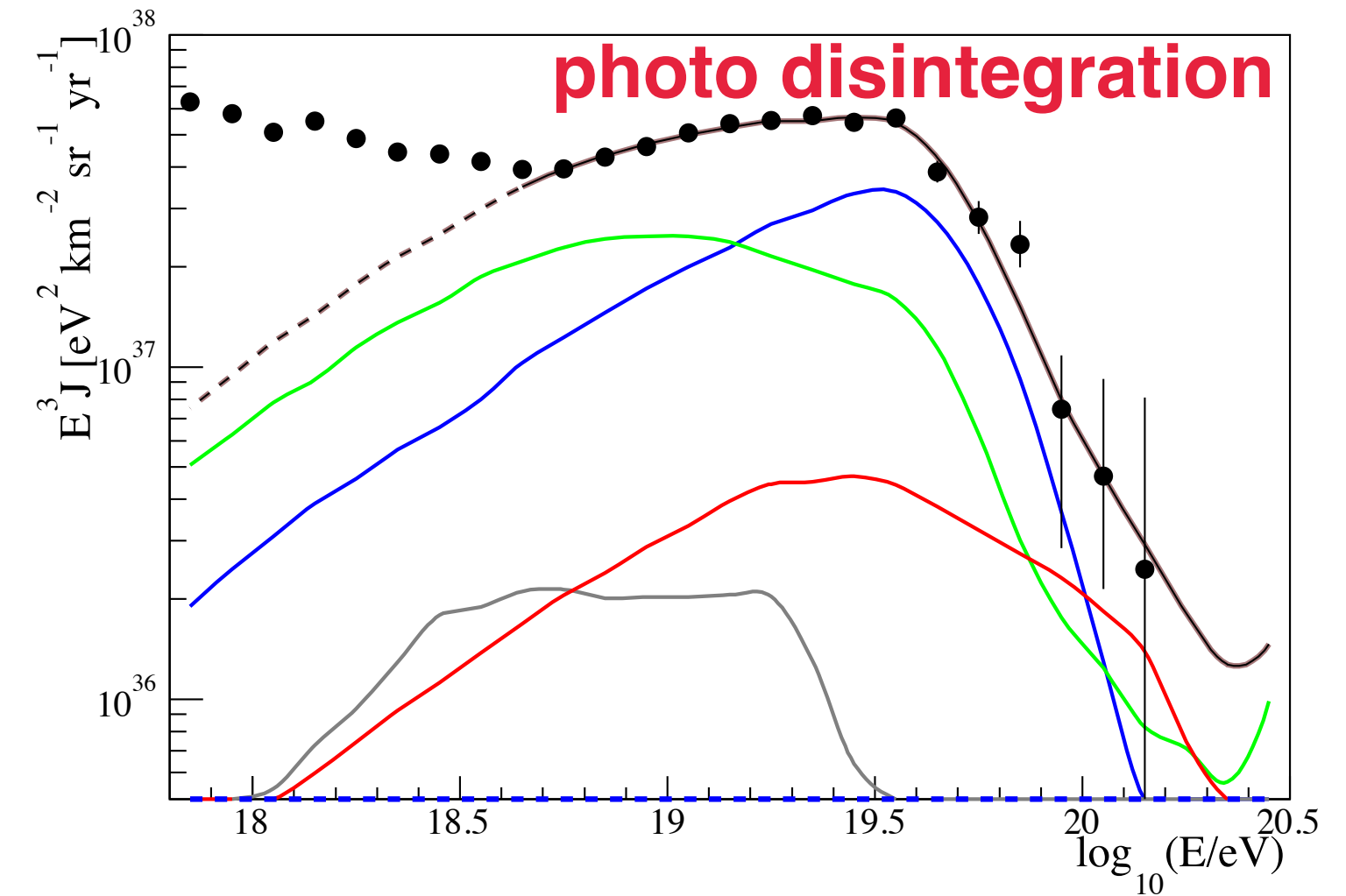
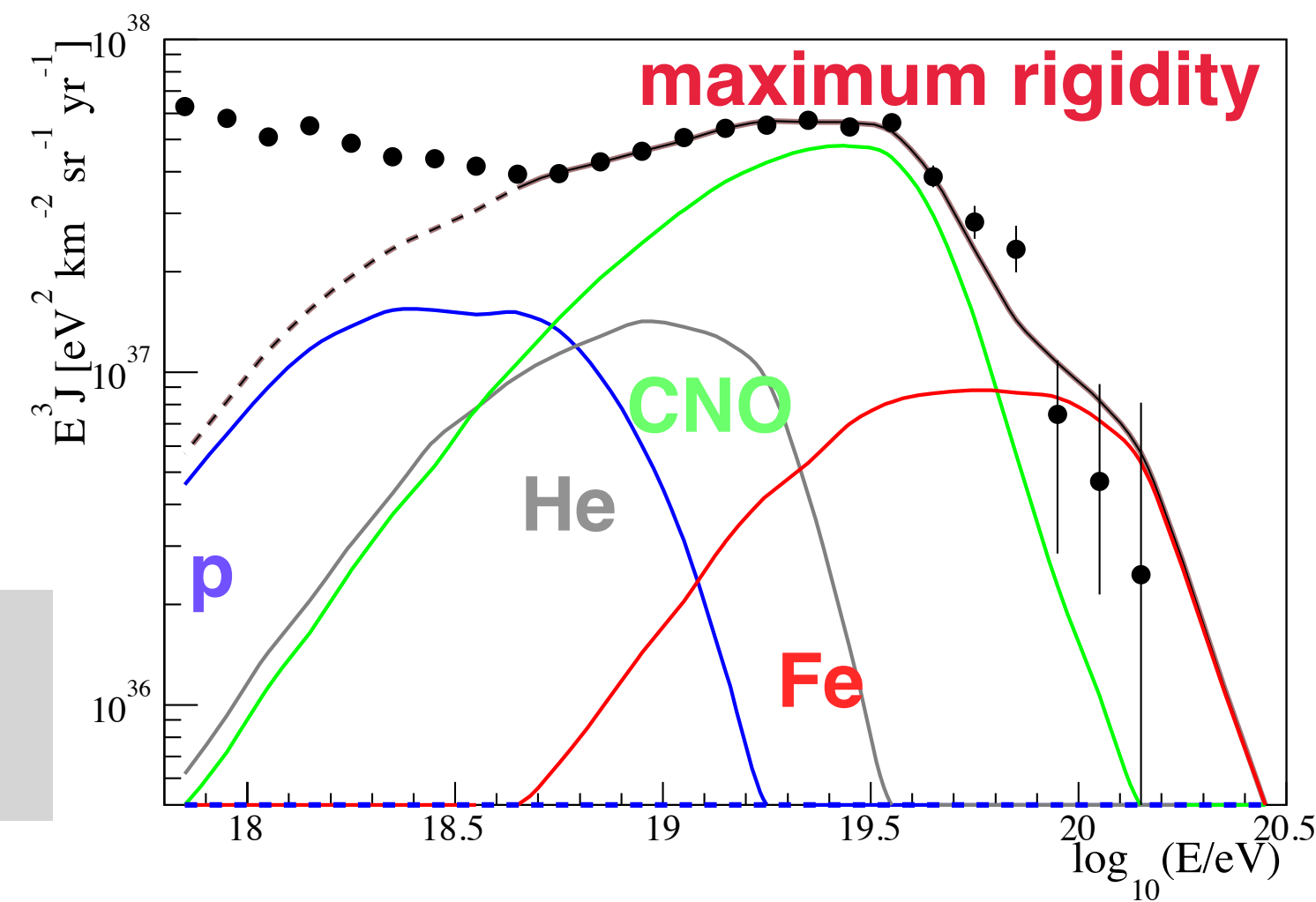
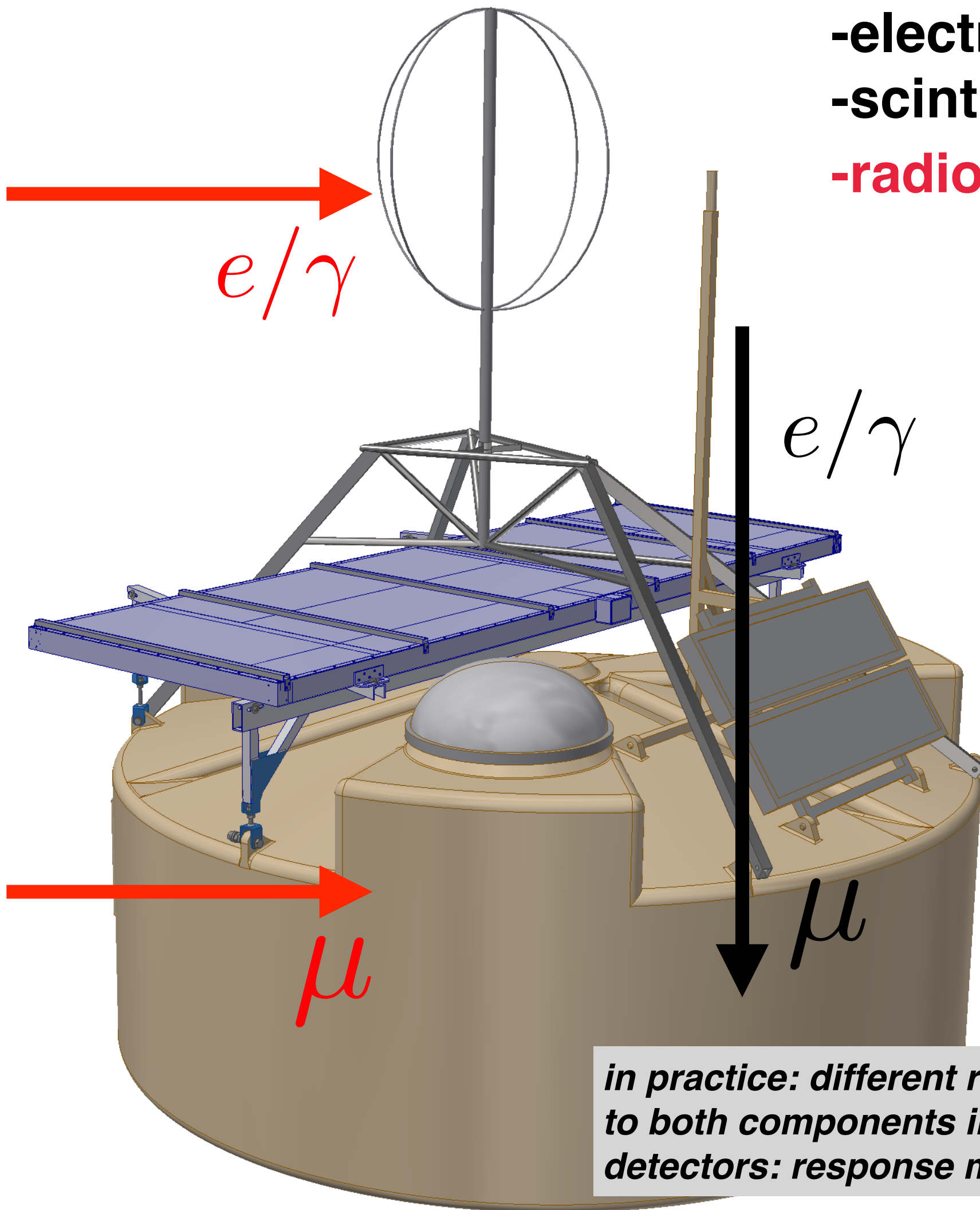
Nikhef

UPGRADE OF THE PIERRE AUGER OBSERVATORY

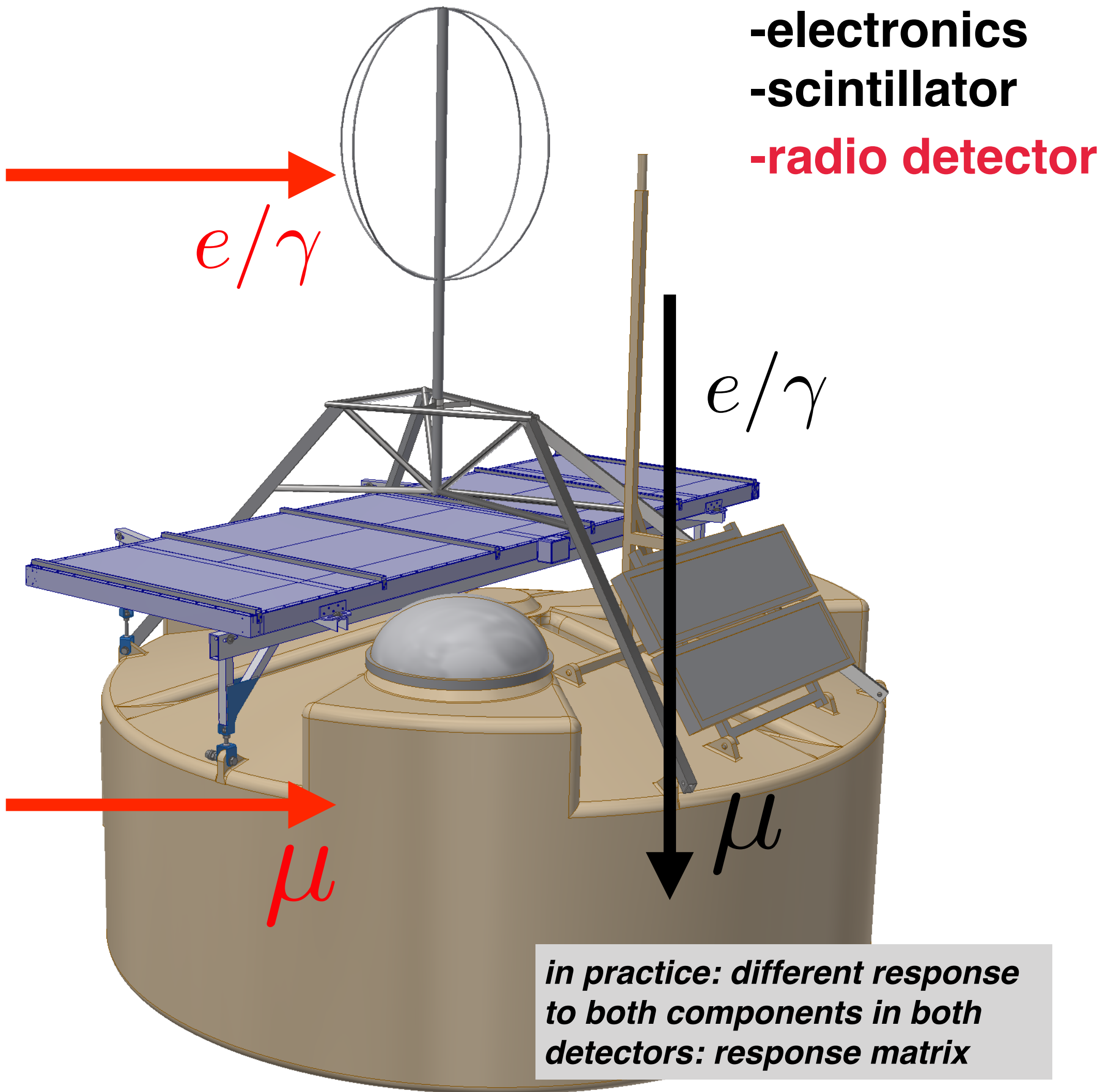
- electronics
- scintillator
- radio detector

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



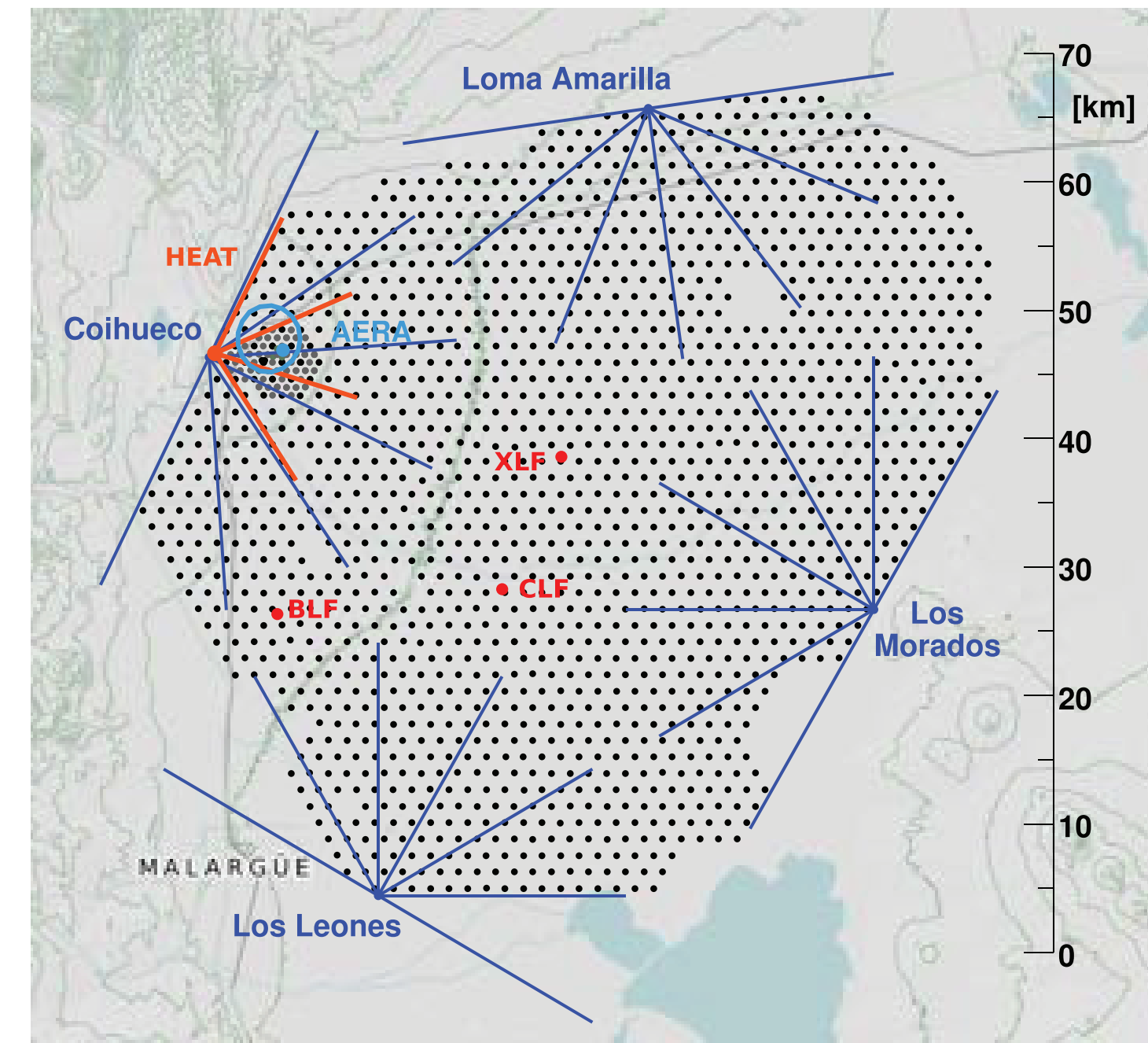
3.5 M€ ERC Advanced Grant Hörandel



2.5 M€ NWO-Groot

1661 detector stations, covering 3000 km²

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

HOOFDSTUK 1. WAT IS KOSMISCHE STRALING?

HOOFDSTUK 2. BETROUWBAAR METEN

0,12. Dit wordt meestal procentueel weergegeven als een meetonzekerheid van 12%. Uit wat we hierboven besproken hebben blijkt dat als we vier keer zo veel metingen doen, de relatieve onzekerheid een factor twee kleiner wordt.

2.9 De meting van muonen op aarde

We willen graag het begrip dat we over metingen en onzekerheid hebben gekregen toepassen op de meting van het aantal muonen met behulp van een detector. Er is wel een verschil met het werpen van dobbelstenen, immers een dobbelsteen geeft in een worp maximaal één "zes", terwijl in een tijdsinterval, hoe klein we dat ook kiezen, er in principe meerdere muonen op aarde kunnen komen. We kunnen de resultaten van de voorgaande secties alleen gebruiken als we de tijdsintervallen oneindig klein maken, oftewel dat we het aantal tijdsintervallen oneindig groot moeten maken. In formule

$$P(k) = \frac{N!}{k!(N-k)!} \left(\frac{\mu}{N}\right)^k \left(1 - \frac{\mu}{N}\right)^{N-k}$$

wil dat zeggen dat N oneindig groot moet zijn. Bovenstaande formule is dan te herschrijven als:

$$P(k) = \frac{\mu^k}{k!} \lim_{N \rightarrow \infty} \frac{N!}{N^k(N-k)!} \left(1 - \frac{\mu}{N}\right)^N$$

en het is vervolgens te bewijzen dat de kansverdeling beschreven wordt door de formule:

$$P(k) = \frac{\mu^k}{k!} e^{-\mu}$$

1.4 Het poollicht verder verklaard

Om het poollicht uit figuur 1.8 te kunnen begrijpen, moeten we ingaan op de samenstelling van de atmosfeer. De atmosfeer bestaat vooral uit moleculen stikstof (N_2) en zuurstof (O_2). Ieder van deze moleculen bestaat uit twee atomen die aan elkaar verbonden zijn. Een atoom bestaat uit een kleine, maar zware, positief geladen kern in een wolk van negatief geladen elektronen. De energie die de elektronen hebben kan niet altijd vrijkomt in een atoom hebben kan niet altijd worden aanneemen, maar bestaat uit verschillende discrete waarden. Onder invloed van bijvoorbeeld een voorbijvliegende betastraling kan een elektron van een atoom een hogere mogelijke energietoestand terecht te komen. Deze energie wordt afgegeven aan een foton, een lichtdeeltje, en de kleur die uitgezonden wordt is karakteristiek voor de Poisson verdeling in de praktijk omgaan.

HOOFDSTUK 5. BRONNEN VAN KOSMISCHE STRALING

waarbij B de grootte van het magnetisch veld is dat de deeltjes vasthoudt, en R de grootte van het versnellingsgebied. Als voorbeeld, de Large Hadron Collider (LHC) is de krachtigste versneller die door mensen is gemaakt. Deze LHC heeft magneten die een veld van 8,4 T produceren, en een straal van ongeveer 4 km (zie figuur 5.3). Dit geeft een maximale energie van 10 TeV voor protonen. Het doel van deze versneller is het veld van de muonen van een energie van 7 TeV. Het doel van deze versneller is het laten stoppen. Dit soort plaatjes wordt dan ook Higgs-plots genoemd, en ze laten zien dat het heel lastig is om in te zien wat de bronnen van de hoogste energie kosmische stralen zijn. Het is immers maar weinig mogelijkheden. Daarbinnen vinden we wel duidelijk dat we die bronnen van de laagste energie kosmische stralen moeten zoeken. Daarbinnen vinden we wel bronnen van meer

3.4 Galactische bronnen: Exploderende sterren

Ongeveer eens in de 50 jaar explodeert er een ster, en ontstaat een supernova. Hierbij wordt het materiaal van de ster met grote snelheid (tot wel 10% van de lichtsnelheid) de ruimte in geslingerd. De schokgolf van het sterremateriaal neemt ook interstellair materie mee, en zo ontstaat er een uitdijende wolk van materie om de positie van de originele ster, dit wordt met een Engelse term een supernova remnant genoemd (SNR). Een voorbeeld hiervan is de Crab-nevel, te zien in figuur 5.4. Na een eeuw of twee is de wolk van materie ongeveer een lichtjaar in doorsnede (de afstand die het licht in één jaar aflegt, ongeveer 10^{16} m), waarna de wolk begint af te koelen en er veel straling uitkomt. De geschatte grootte van het magnetisch veld van een SNR is ongeveer 10^{-8} T en je kunt

Figuur 1.7: Metingen van Clay en Berlage in 1932.

Figuur 1.8: Opname van het poollicht.

Figuur 5.4: Links: Crab nevel. Rechts: Beeld SNR in gammastraling

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.