PROBING THE HIGH-ENERGY UNIVERSE:

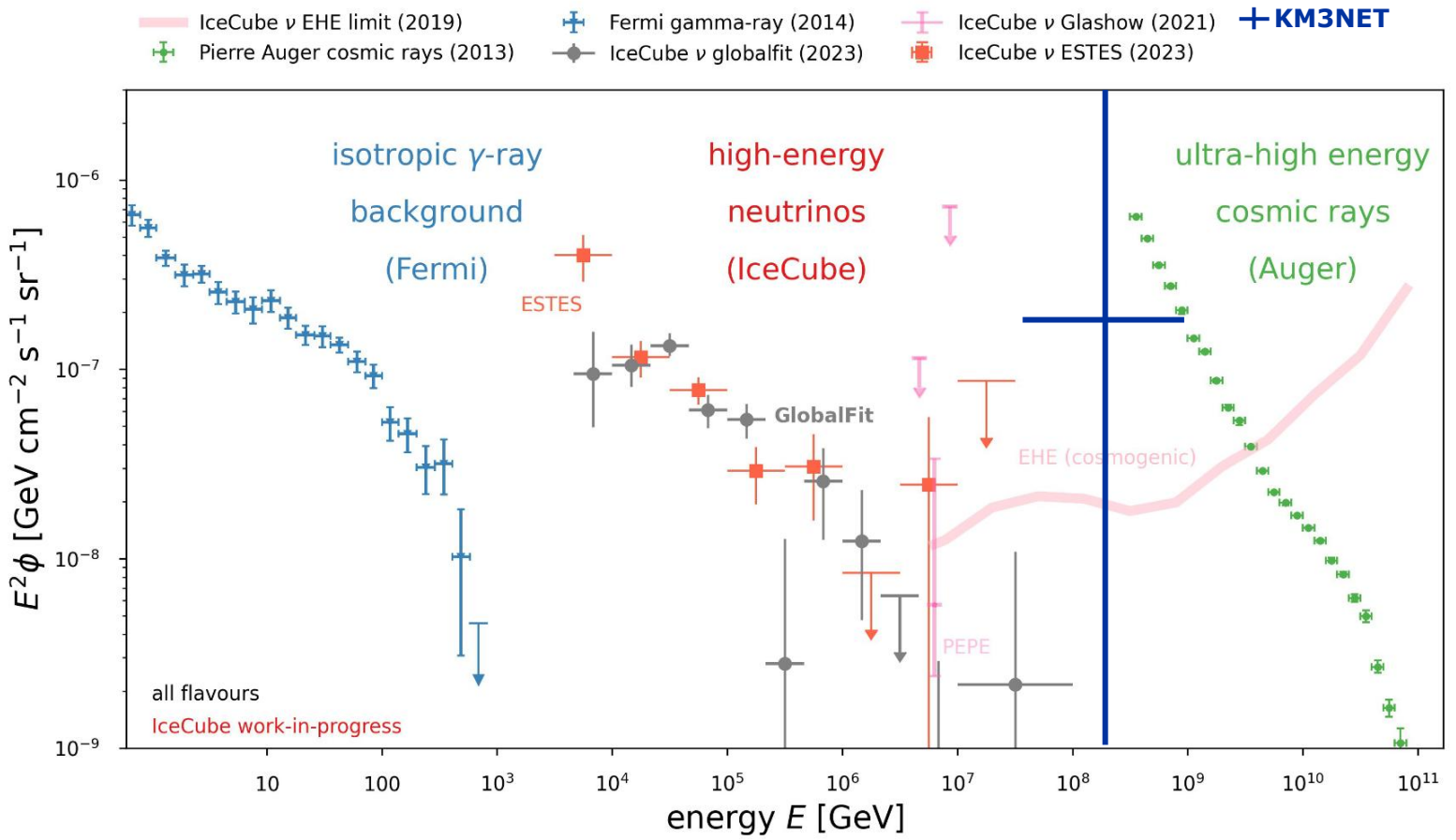
DETECTING THE HIGHEST ENERGY COSMIC MESSENGERS – BELGIAN CONTRIBUTIONS

KRIJN D DE VRIES

VRIJE UNIVERSITEIT BRUSSEL
INTERUNIVERSITY INSTITUTE FOR HIGH ENERGIES

HIGH-ENERGY COSMIC MESSENGERS

GAMMA-RAYS, NEUTRINOS AND COSMIC RAYS



C. Haack, IceCube Collaboration, The 43rd International Symposium on Physics in Collision PIC 2024.

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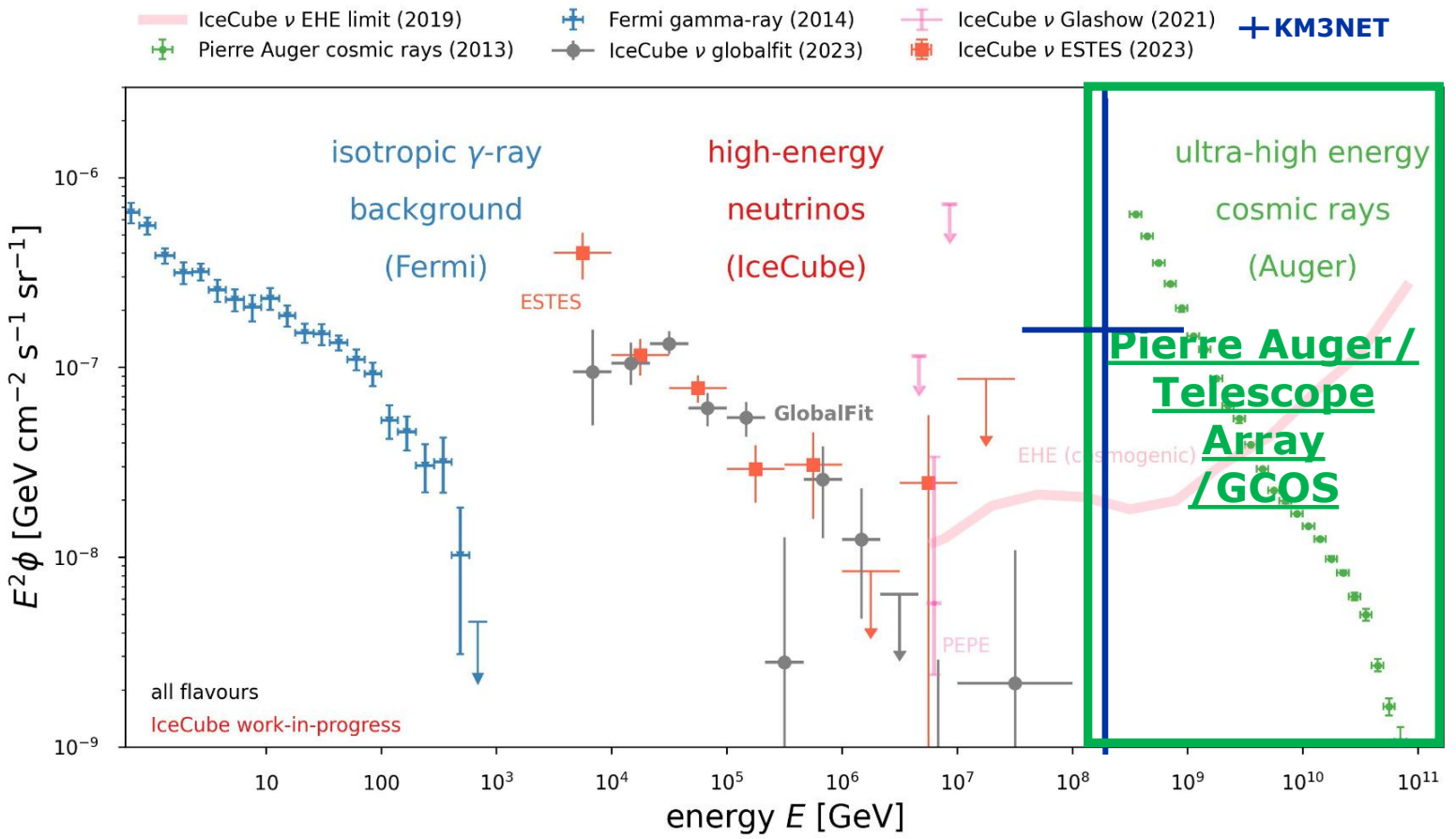

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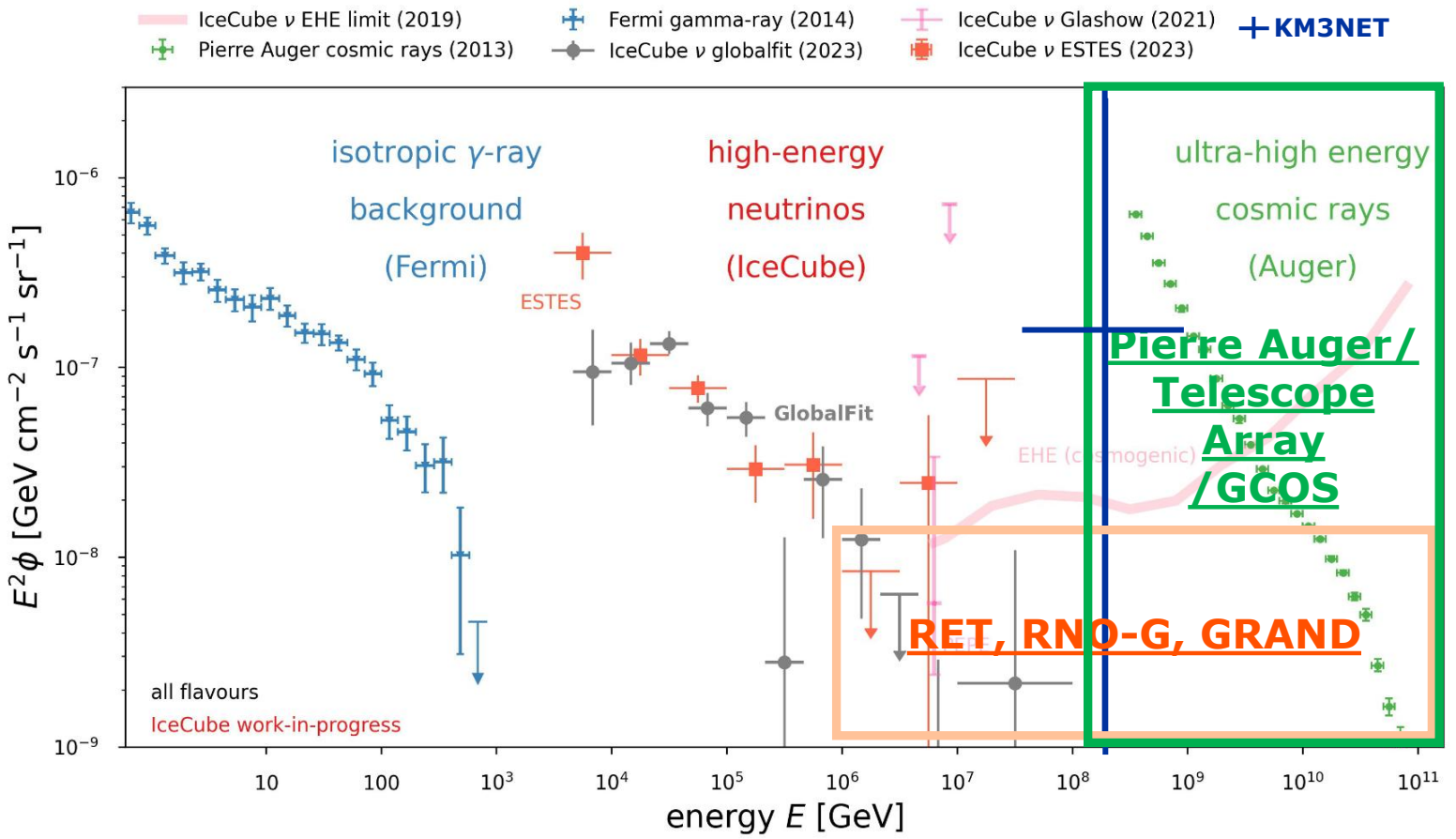
HIGH-ENERGY COSMIC MESSENGERS

GAMMA-RAYS, NEUTRINOS AND COSMIC RAYS



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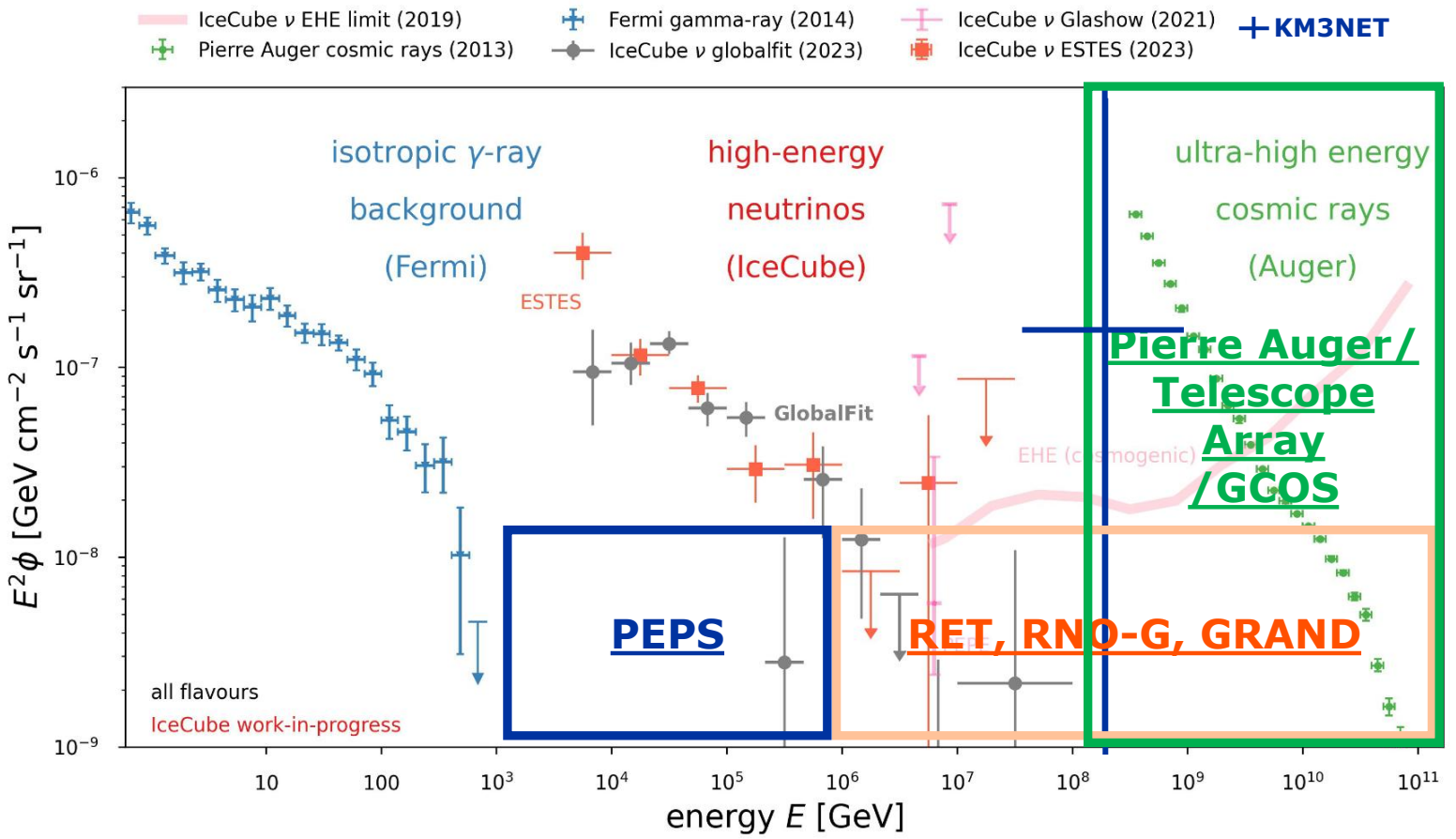

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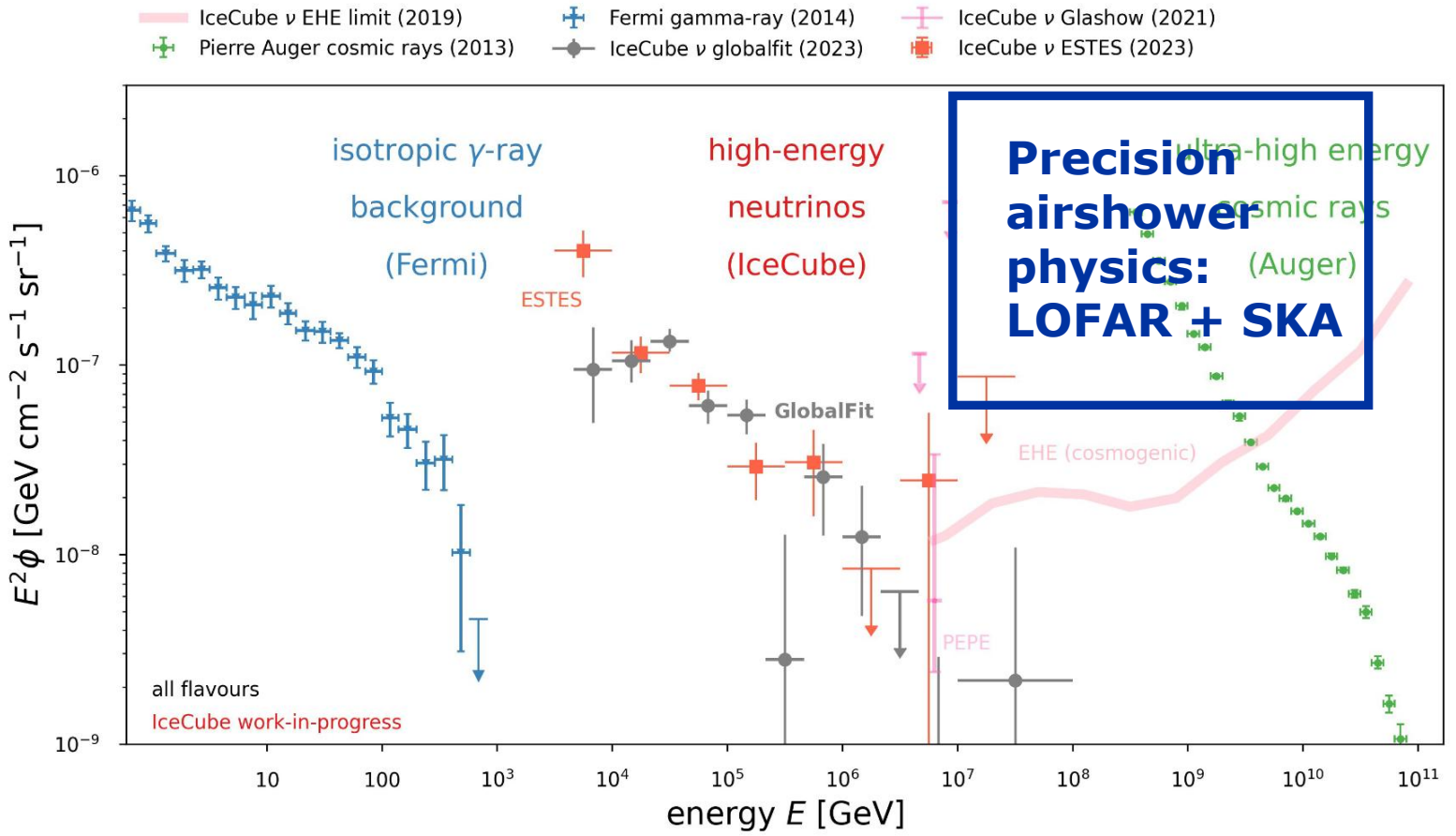

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HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – THE PIERRE AUGER /TELESCOPE ARRAY OBSERVATORIES ULB/VUB

Ultra-High-Energy Cosmic Rays

- Particles (p, nuclei) with $E>10^{18}$ eV
- Pierre Auger and TA have a large accumulated exposure with >20 years of operation
- Fluorescence and water Cherenkov (PA) /scintillator particle detectors (TA).
- Recently added at Auger:
  Radio and scintillator components -> AugerPrime.
- Auger MOU assures **operation till at least 2035**

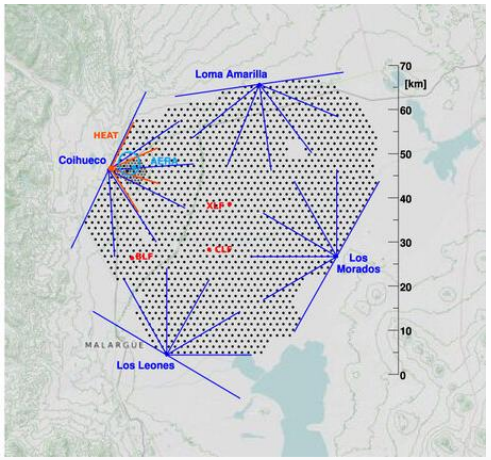


Figure credits: Pierre Auger Collaboration / Telescope Array collaboration

Belgian groups:

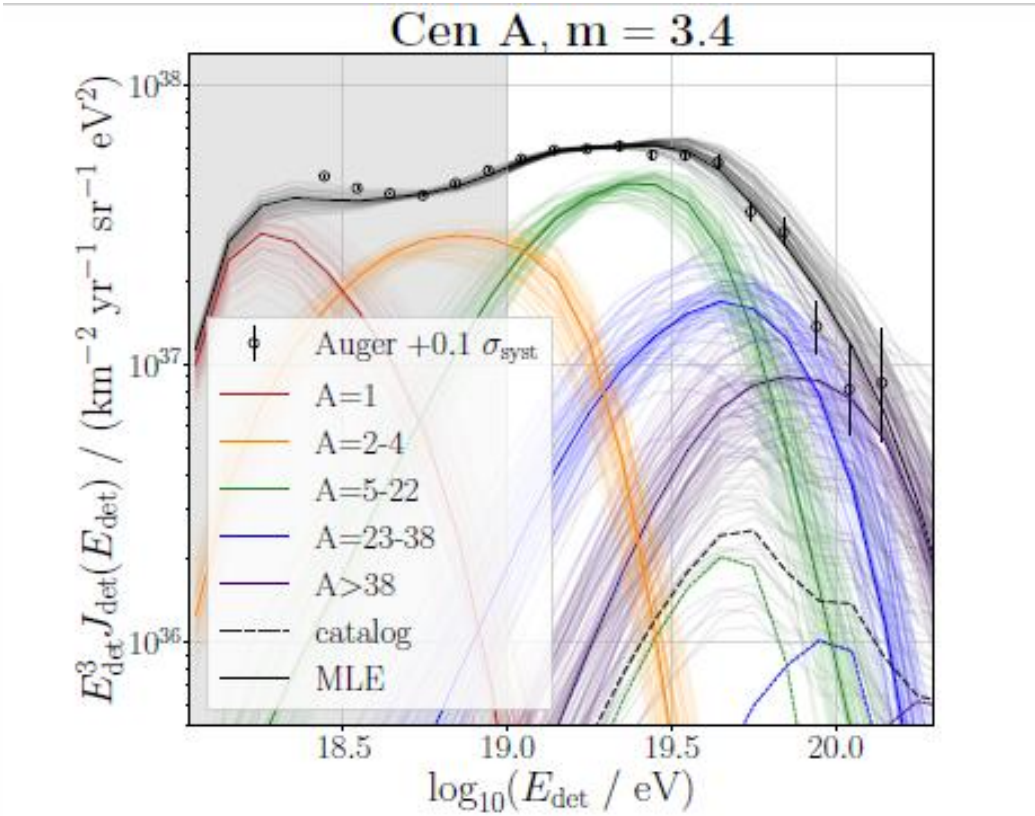
- **Auger: I. Maris (ULB), S. Buitink (VUB)**
- **TA: P. Tinyakov (ULB)**

HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – THE PIERRE AUGER OBSERVATORY ULB/VUB-IIHE

Ultra-High-Energy Cosmic Rays

- Precise measurement of the spectral features with discovery of a new feature above 10^{19} eV.
- Establishment of the presence of intermediate-mass nuclei at the highest energies.
- Test of hadronic interaction models at $\sqrt{s} > 14$ TeV and measurement of the p-air cross-section



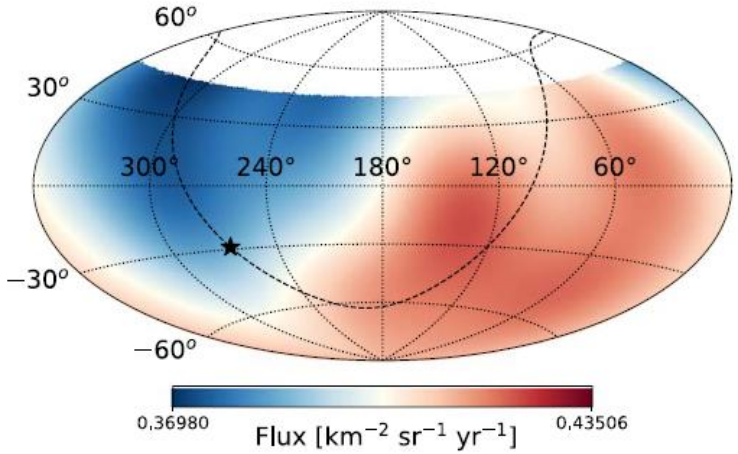
HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

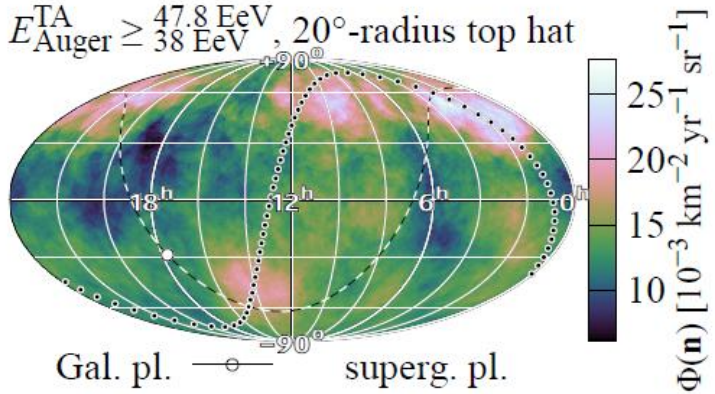
COSMIC RAYS – THE PIERRE AUGER OBSERVATORY ULB/VUB-IIHE

The UHECR sky is anisotropic

- The dipole structure (>7σ above 10^{18} eV) gives evidence of an **extra-galactic origin**

- Hints (>3σ) for intermediate scales: Centaurus A, Starburst Galaxies, Perseus Pieces Cluster, TA hotspot





HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

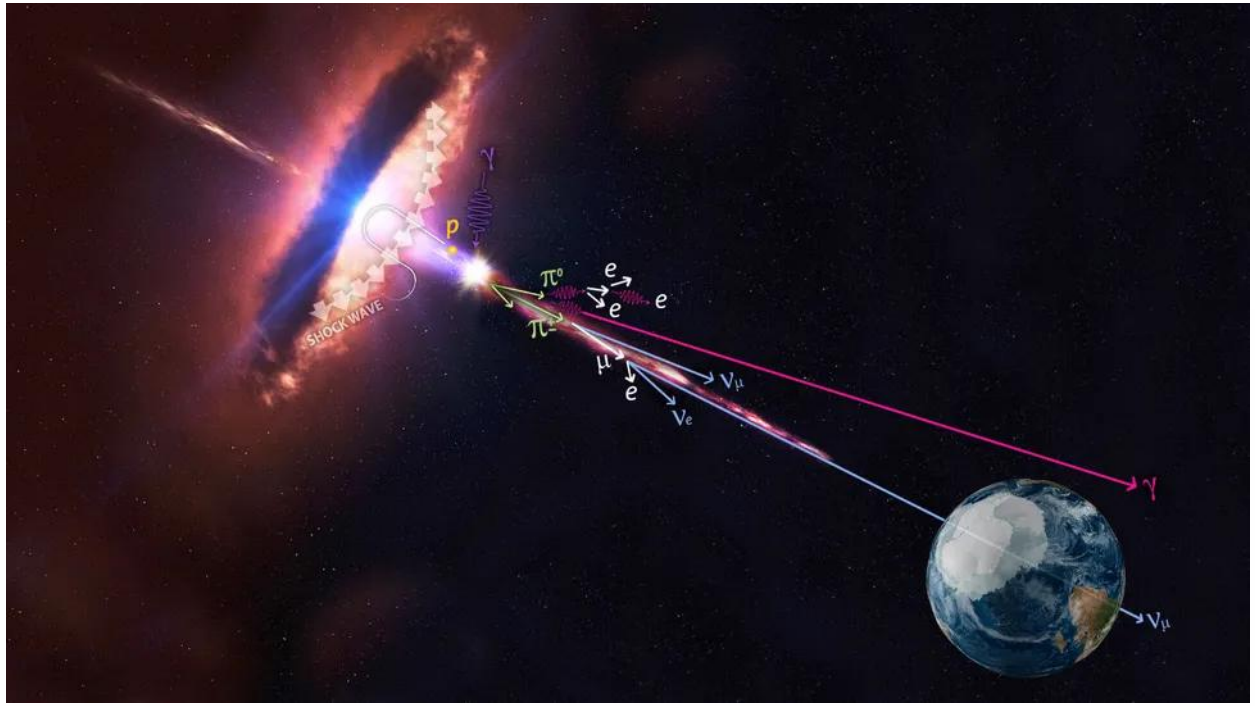
COSMIC RAYS – THE PIERRE AUGER OBSERVATORY – ULB/VUB-IIHE

Multimessenger astrophysics

- Continuous search for **ultra-high energy neutrinos and photons** with limits excluding several theoretical models

- Constrains on the **lifetime and mass of super-heavy dark matter**

- Providing infrastructure and a **test environment for: FAST, IceCube-Gen2, GCOS, GRAND, SWGO, PEPS**



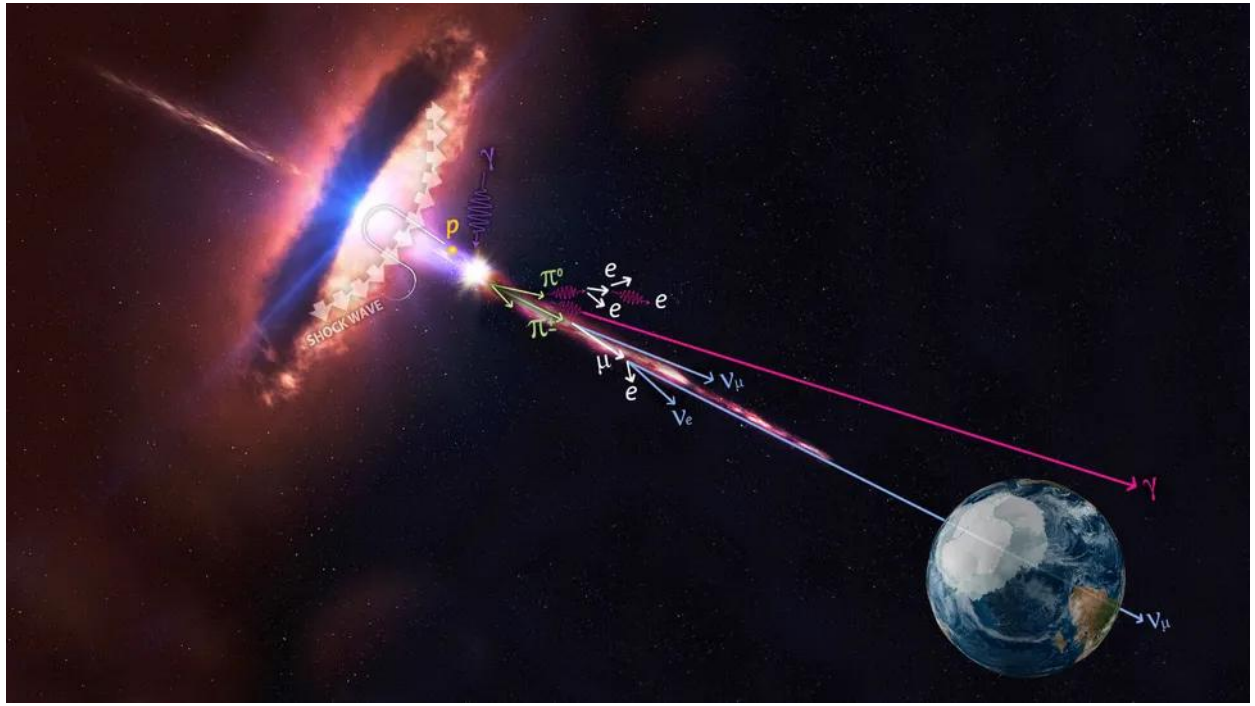
HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – THE PIERRE AUGER OBSERVATORY – ULB/VUB-IIHE

Belgian leadership/responsibilities:

Ioana Maris (ULB):

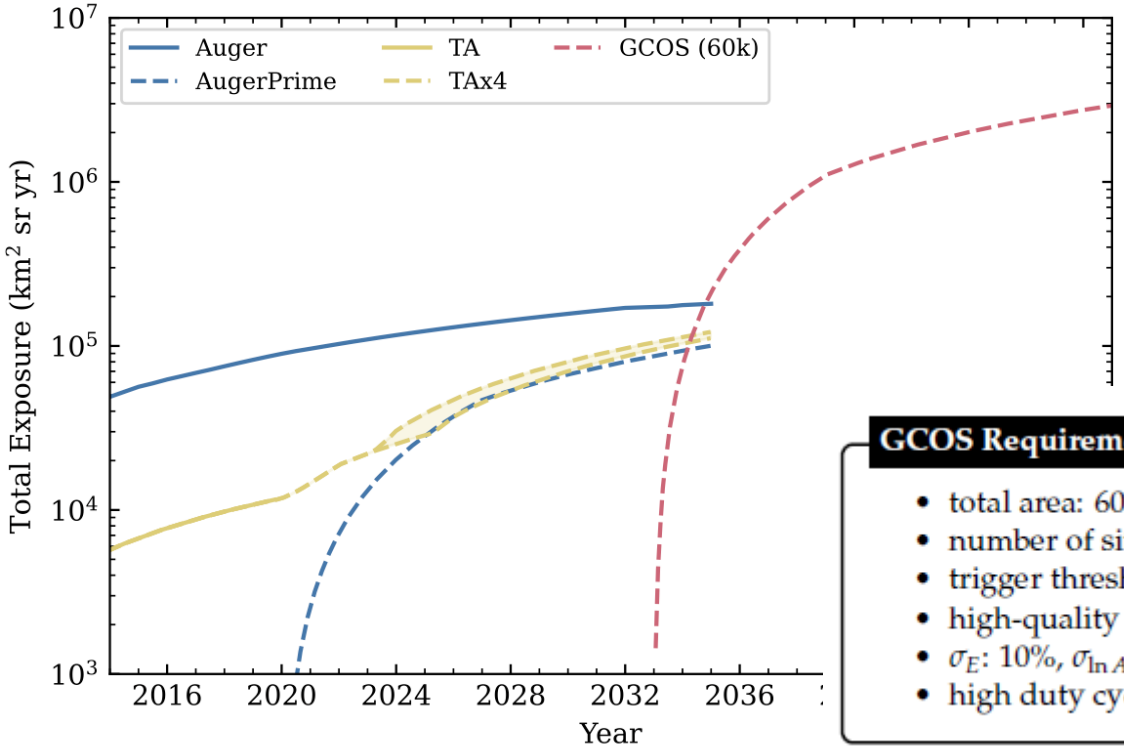
- **Publication Committee Chair Pierre Auger collaboration.**
- **Task leader: Auger as test environment.**



HIGH-ENERGY COSMIC MESSENGERS – FUTURE PROJECTS

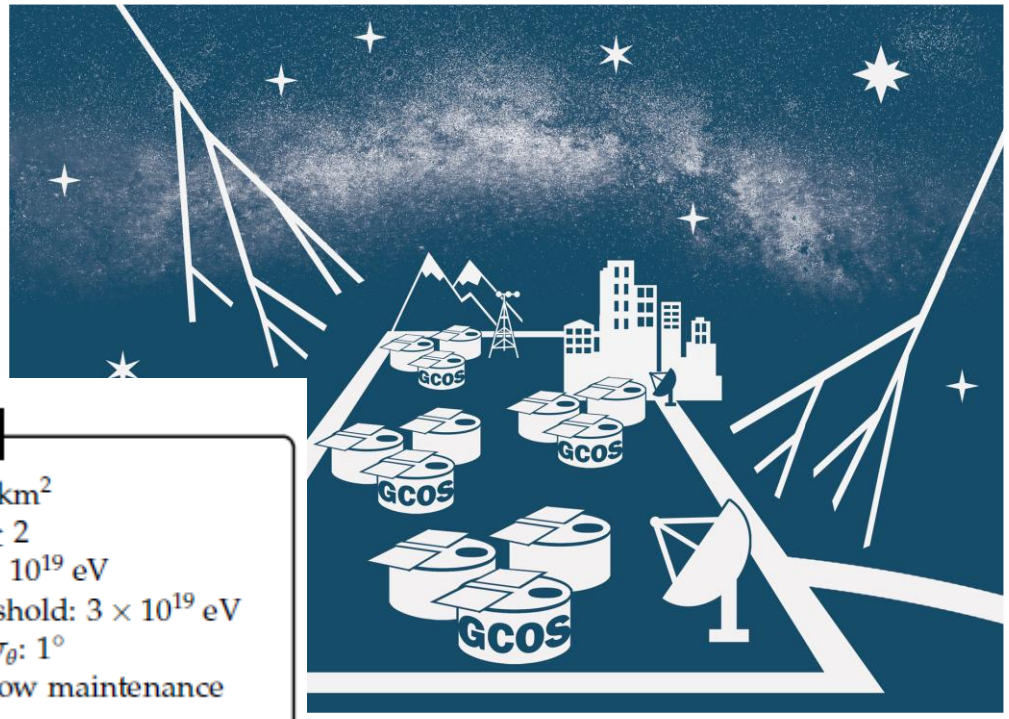
COSMIC RAYS – GCOS – ULB-IIHE

Figures from and more information at: https://arxiv.org/abs/2502.05657
(GCOS white paper)



GCOS Requirements

- total area: 60 000 km^2
- number of sites ≥ 2
- trigger threshold: 10^{19} eV
- high-quality threshold: 3×10^{19} eV
- σ_E: 10%, $\sigma_{\ln A}$: 1, σ_θ: 1°
- high duty cycle, low maintenance



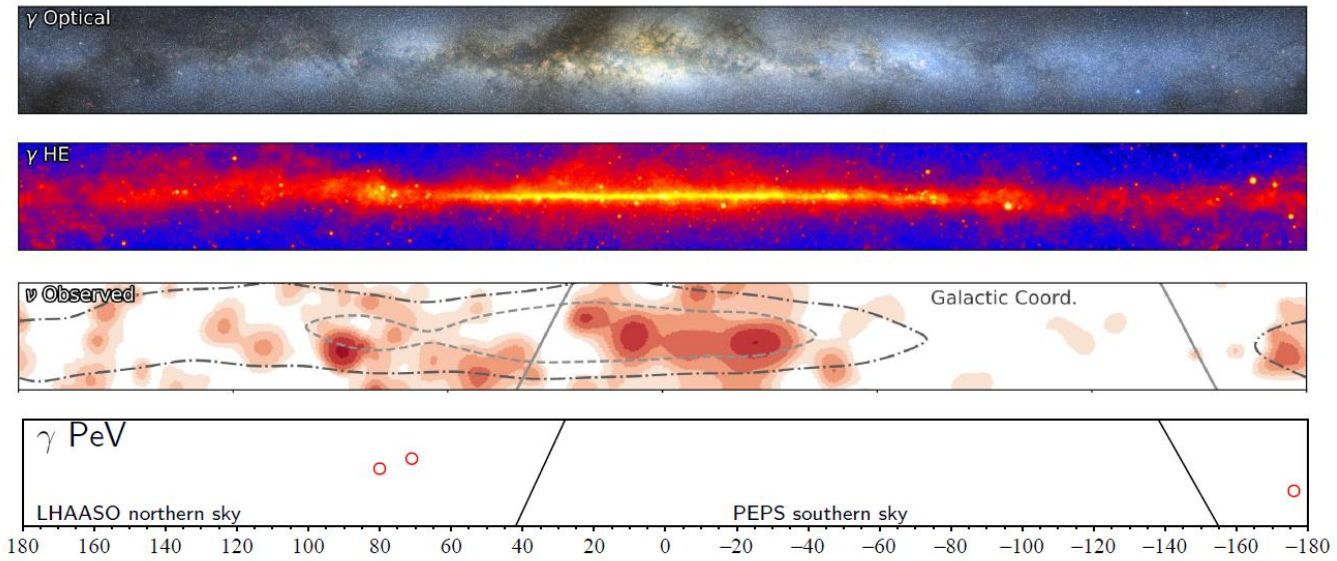
Belgian contributions and responsibilities:
Ioana Maris member of the GCOS core group.

HIGH-ENERGY COSMIC MESSENGERS – FUTURE PROJECTS

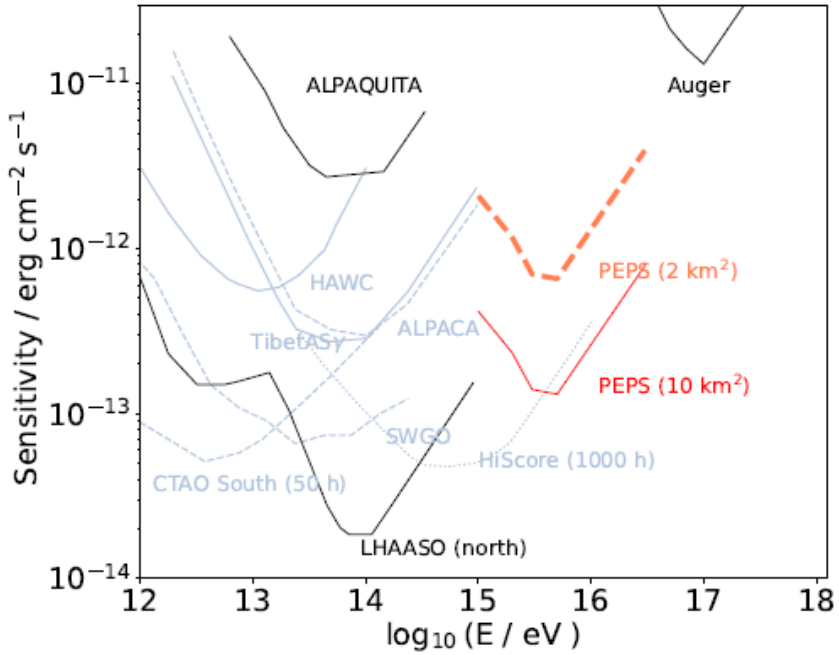
GAMMA-RAYS – PEPS – ULB-IIHE

Probing Extreme PeVatron Sources (PEPS) ; Project PI: Ioana Maris (ULB-IIHE)

$10\,\mathrm{km}^2$ detector to measure gamma-rays between 1 PeV and 50 PeV



Discovery potential in the new energy range with
a unique view of the Galactic Center and southern galactic sky!



HIGH-ENERGY COSMIC MESSENGERS – FUTURE PROJECTS

GAMMA-RAYS – PEPS – ULB-IIHE

Probing Extreme PeVatron Sources (PEPS)

Prototype stations:
- **Components build and tested in Brussels.**
- **First 2 prototype layered Water Cherenkov Detectors installed at Auger, 3 under construction.**

Envisioned array: 55 stations/km².

- **Phase 1: 110 stations**
- **Phase 2: 550 stations**

Timeline since funding – 2-2.5 yr. Completion phase 1 aimed at for 2027-2028.

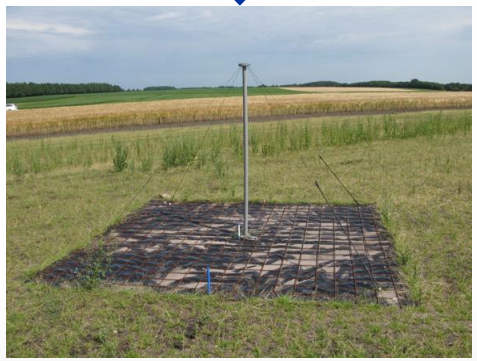
Total hardware cost < 10 M€

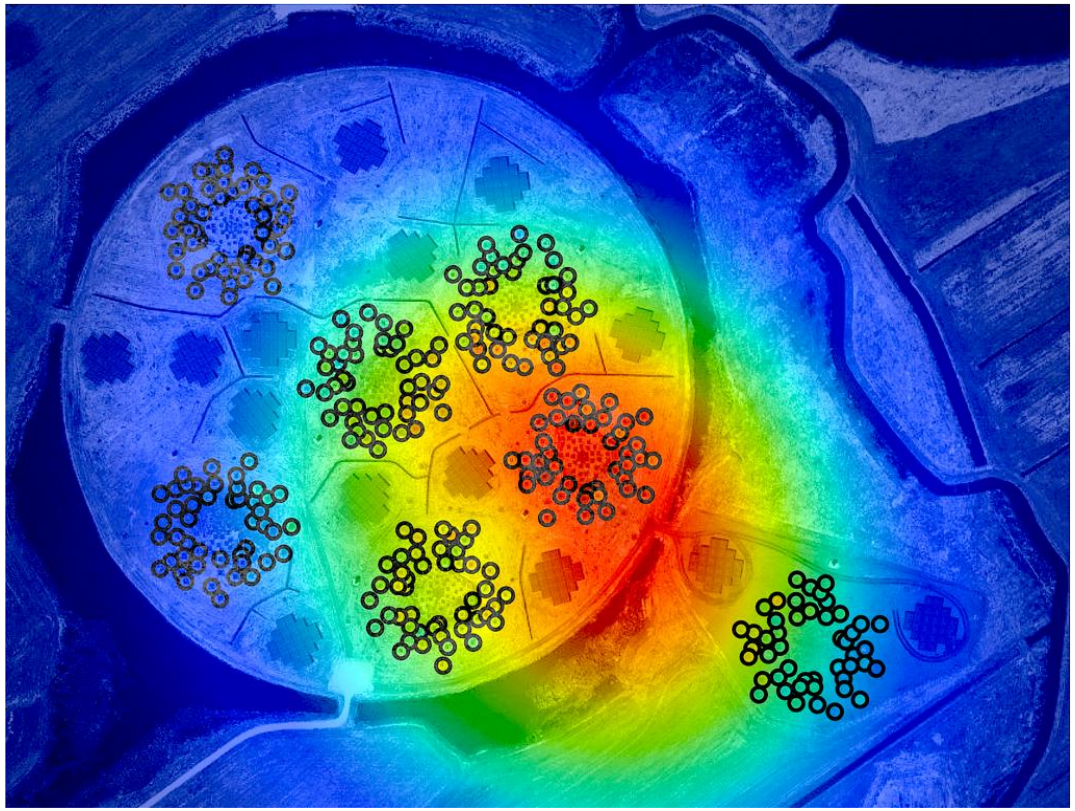
(2024)

HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – PRECISION PHYSICS USING RADIO: LOFAR AND SKA – VUB-IIHE

Cosmic-ray trigger from particle detectors (LORA)

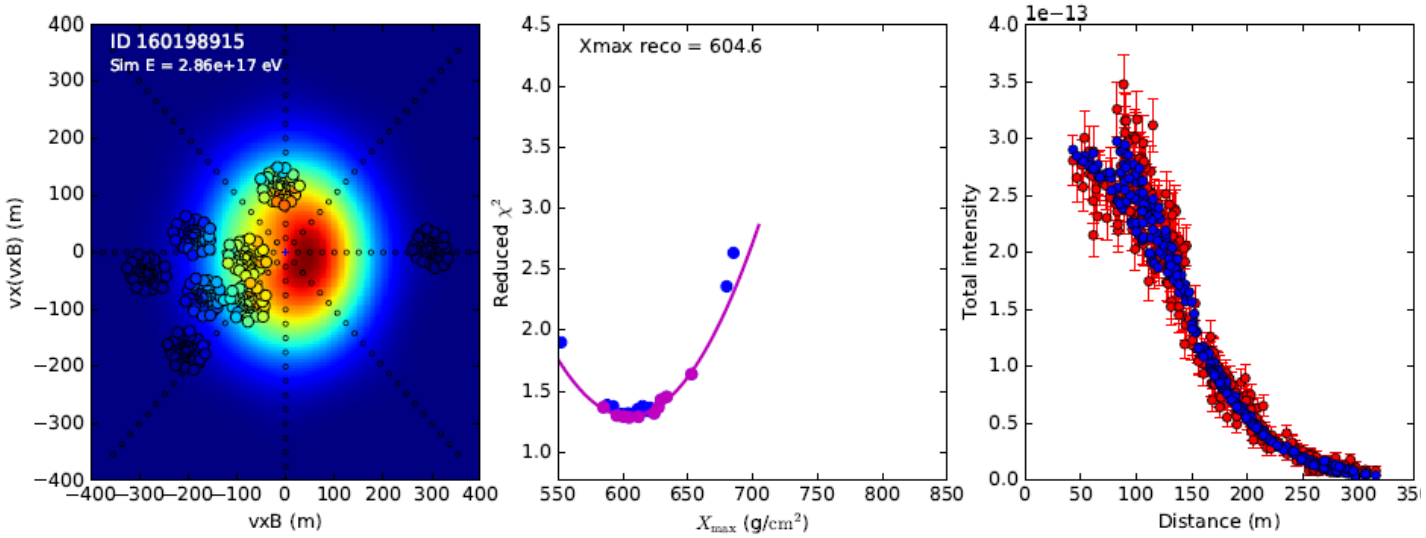


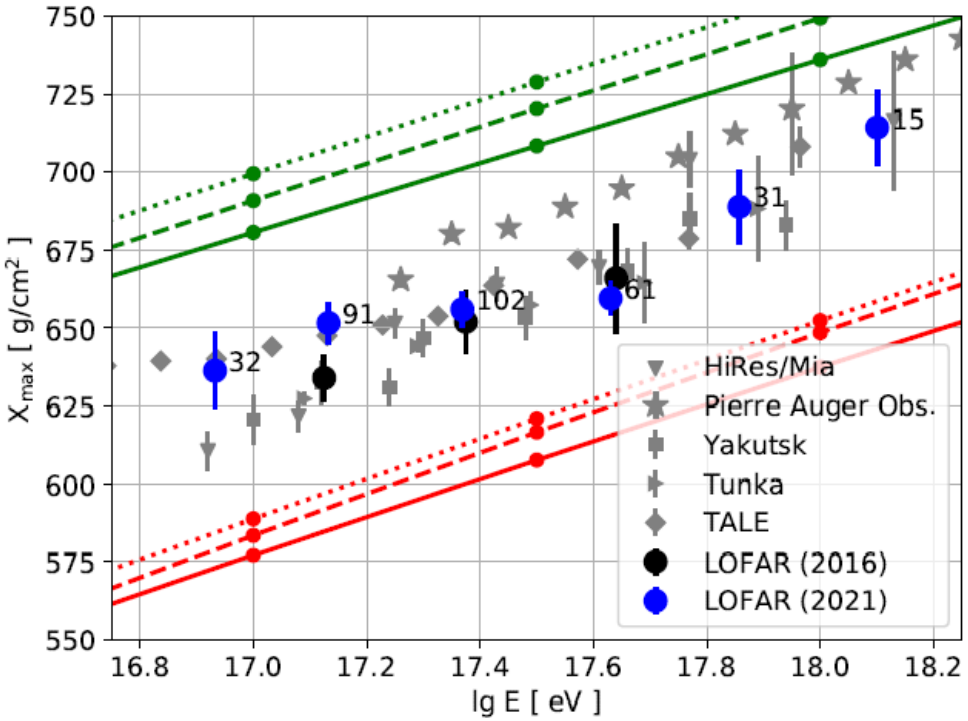


LOFAR CR detection project PI: Stijn Buitink (VUB-IIHE)

HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – PRECISION PHYSICS USING RADIO: LOFAR AND SKA – VUB-IIHE



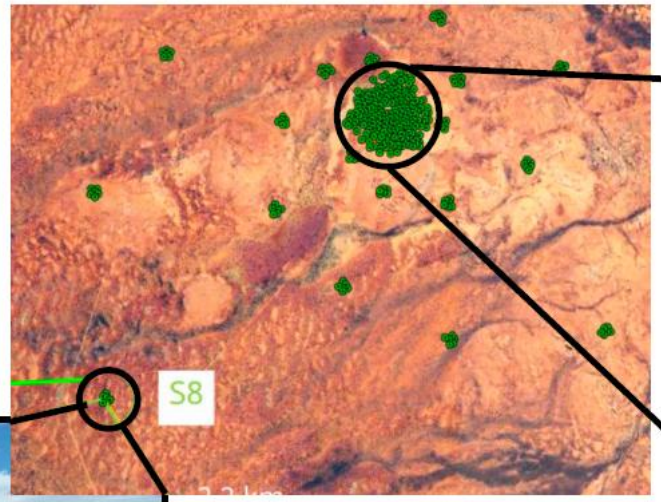


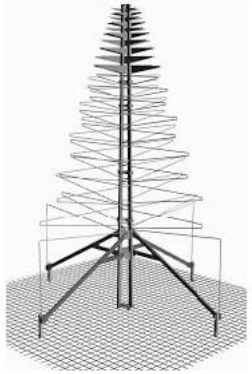
Phys. Rev. D 103, 102006 (2021)

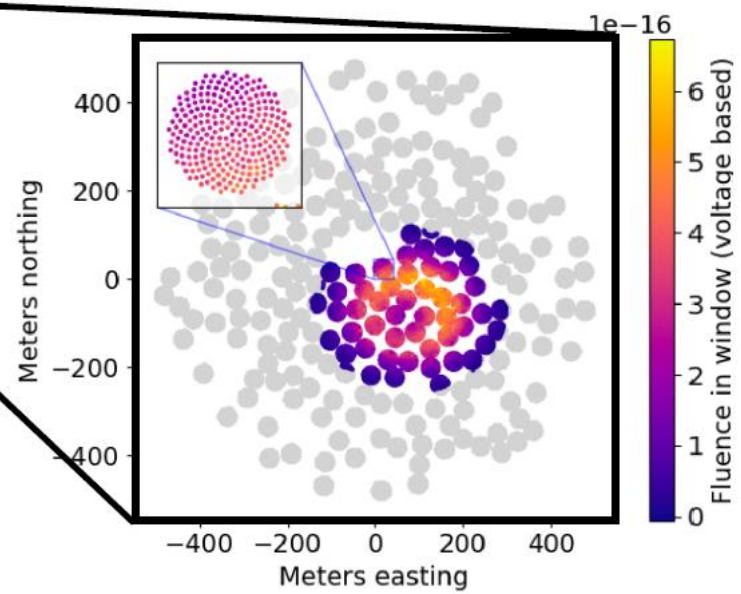
HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – RADIO: SKA-LOW CORE CONSTRUCTION STARTED – VUB-IIHE

Western Australia
700 km north of Perth







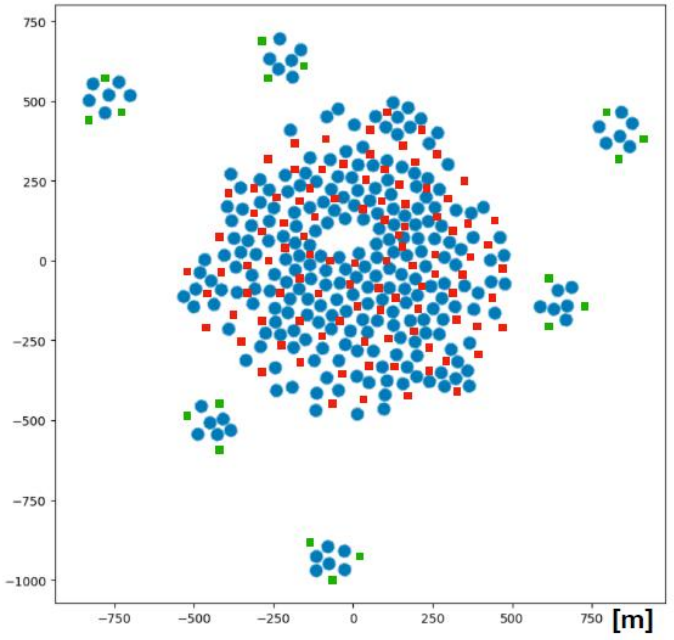
core region: ~60.000 antennas within 1 km²
clustered in stations of 256 antennas
SKALA4 LPDA antennas 50-350 MHz

2

Stijn Buitink ICRC2025 Geneva

COSMIC RAYS – RADIO: SKA-LOW CORE CONSTRUCTION STARTED – VUB-IIHE

The SKA Particle detector array



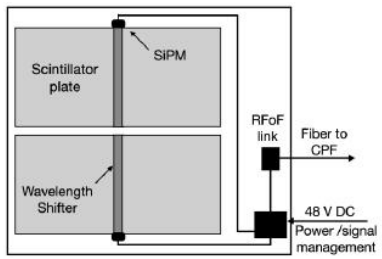
- Antenna station
- Particle detectors dense array (~100 units)
- Particle detectors satellite (~18 units, optional)

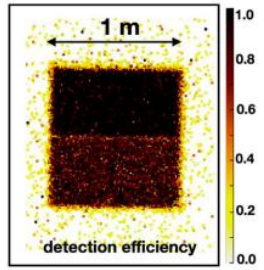
8-station prototype array installed at Murchison Widefield Array

Design: **Univ. of Manchester**
Deployment: **Curtin Univ.**
DAQ: **CSIRO**
J. Bray et al., NIMPA 973, id. 164168 (2020)

Construction of scintillator array now fully funded:

FWO Belgium, **NOVA** Netherlands + in-kind contributions **KIT** (Karlsruhe, Germany)
3rd generation design developed at **KIT** and **Radboud Nijmegen**





Same power cables & RFoF links as antennas
Very strict regulations on radio quietness
On-board SiPM voltage control to correct for temperature fluctuations

first light at KIT muon tower

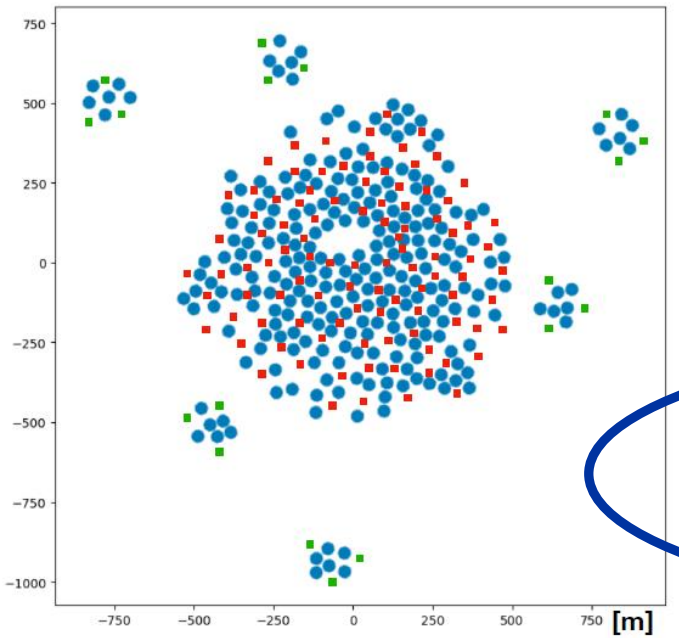
4

Stijn Buitink ICRC2025 Geneva

HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

COSMIC RAYS – RADIO: SKA-LOW CORE CONSTRUCTION STARTED – VUB-IIHE

The SKA Particle detector array



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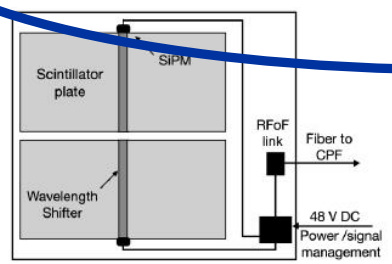

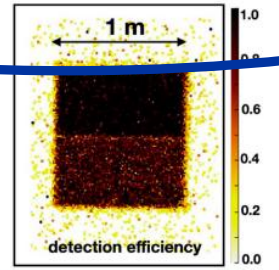

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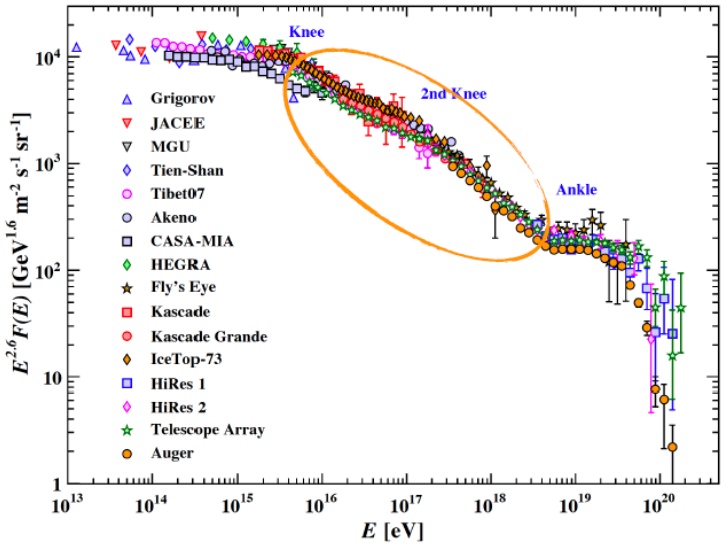
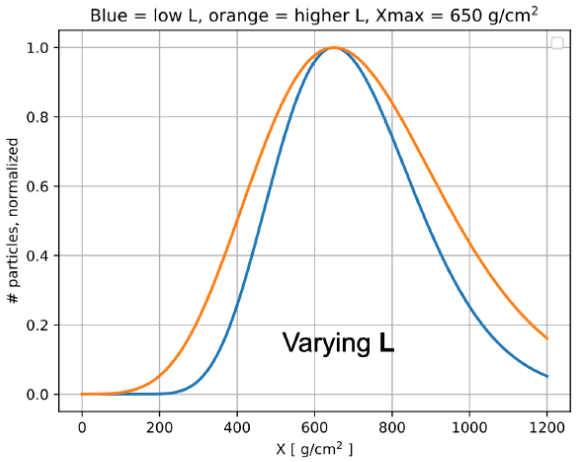
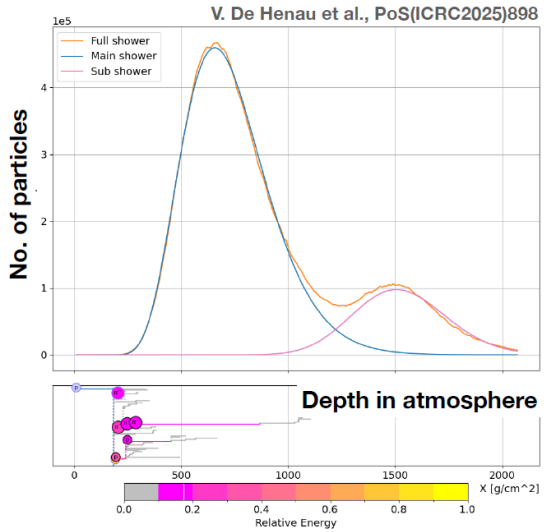
HIGH-ENERGY COSMIC MESSENGERS – CURRENT PROJECTS

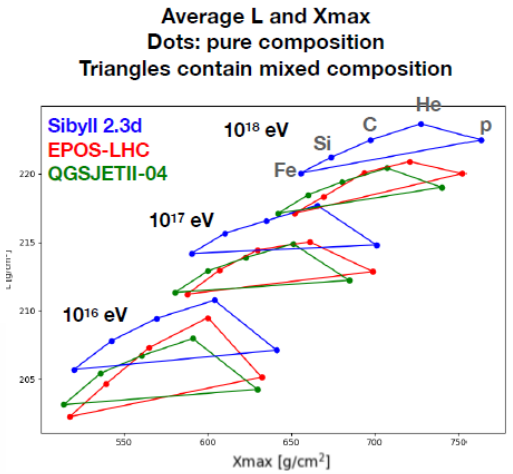
COSMIC RAYS – RADIO: SKA-LOW CORE CONSTRUCTION STARTED – VUB-IIHE





A. Corstanje et al., PoS(ARENA2022)024





- **Extremely detailed mass-composition studies in the galactic-extragalacitic transition region.**
- **Precision tests of hadronic interaction models.**

HIGH-ENERGY COSMIC MESSENGERS

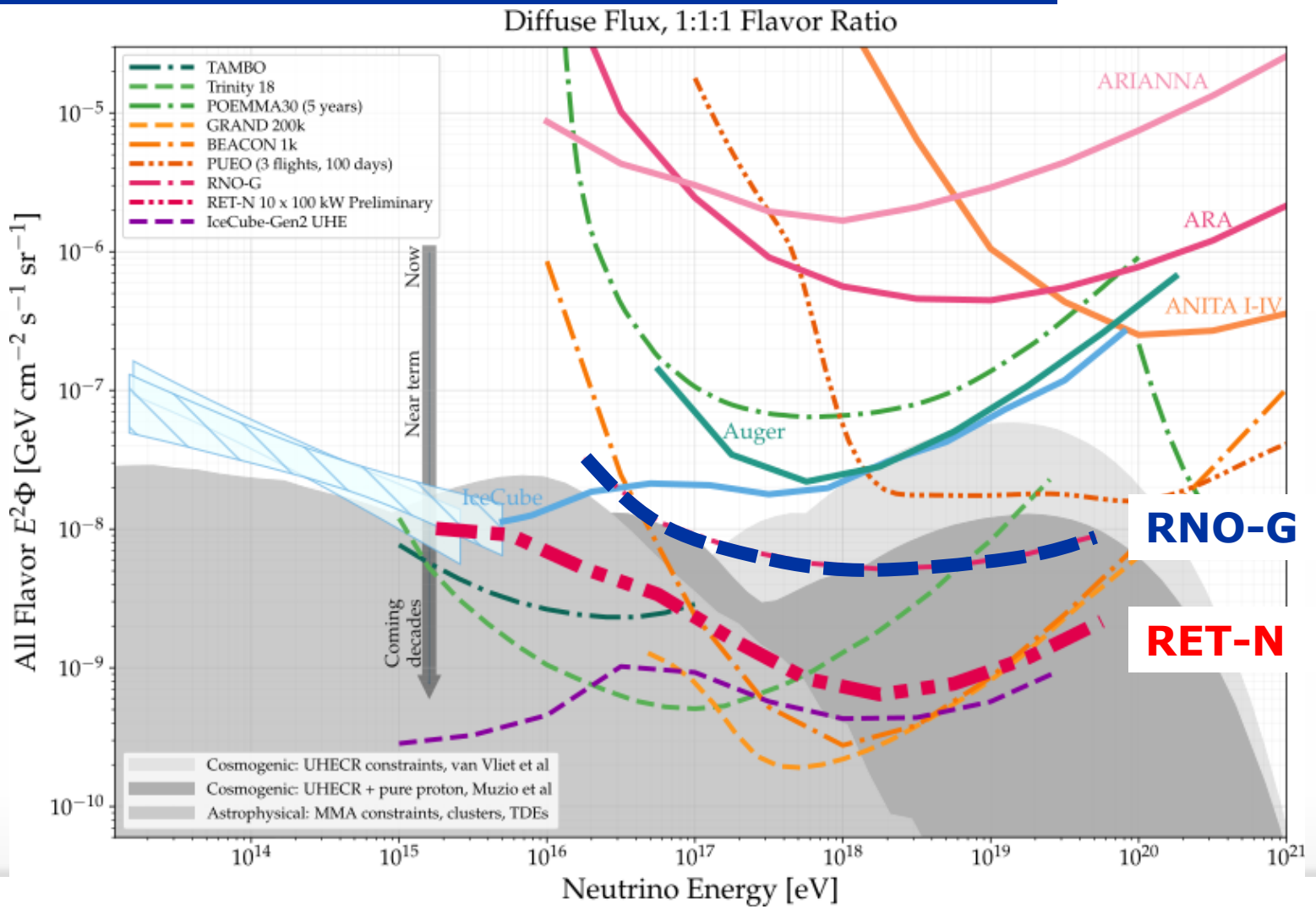
NEUTRINOS – RNO-G (VUB/ULB-IIHE - UGENT) AND RET (VUB/ULB-IIHE)

RNO-G
Radio Neutrino Observatory - Greenland

- **Currently under construction: 8/35 stations taking data**
- **Completion in coming 2-3 years**

RADAR ECHO TELESCOPE

- **RET-CR pathfinder operated in 2023-2024**
- **RET-N first station installation foreseen ~2028**
- **Completion 2030-2035**



HIGH-ENERGY COSMIC MESSENGERS

NEUTRINOS – RNO-G AND RET VUB/ULB-IIHE - UGENT

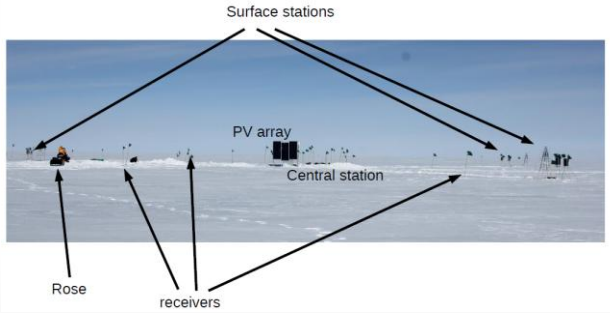
RNO-G
Radio Neutrino Observatory - Greenland

Belgian groups RNO-G:

VUB-IIHE:
N. van Eijndhoven – project PI
K.D. de Vries
ULB-IIHE: S. Toscano, J.A. Aguilar
Ugent: J. Stachurska

https://geo-summit.org/summit-station

RADAR ECHO TELESCOPE

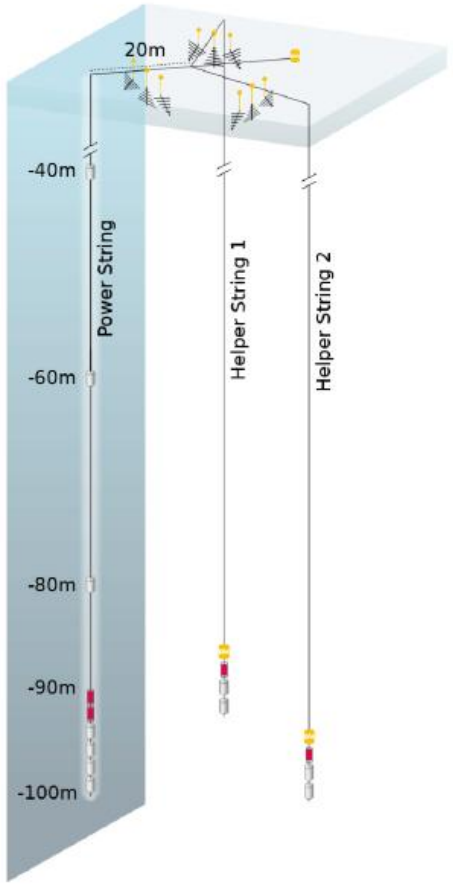


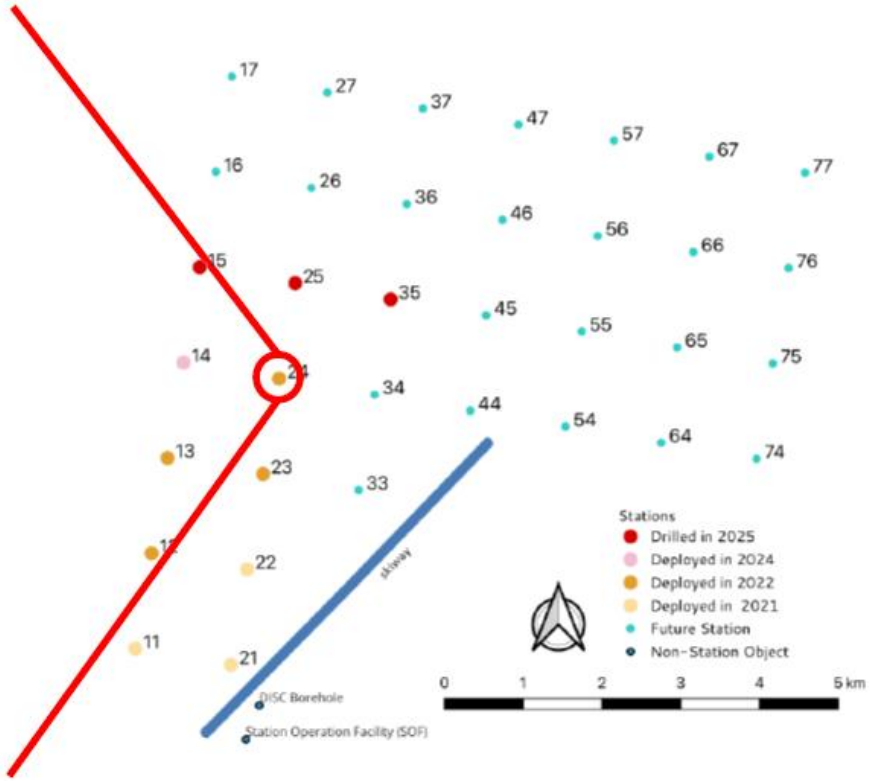
Belgian groups RET:

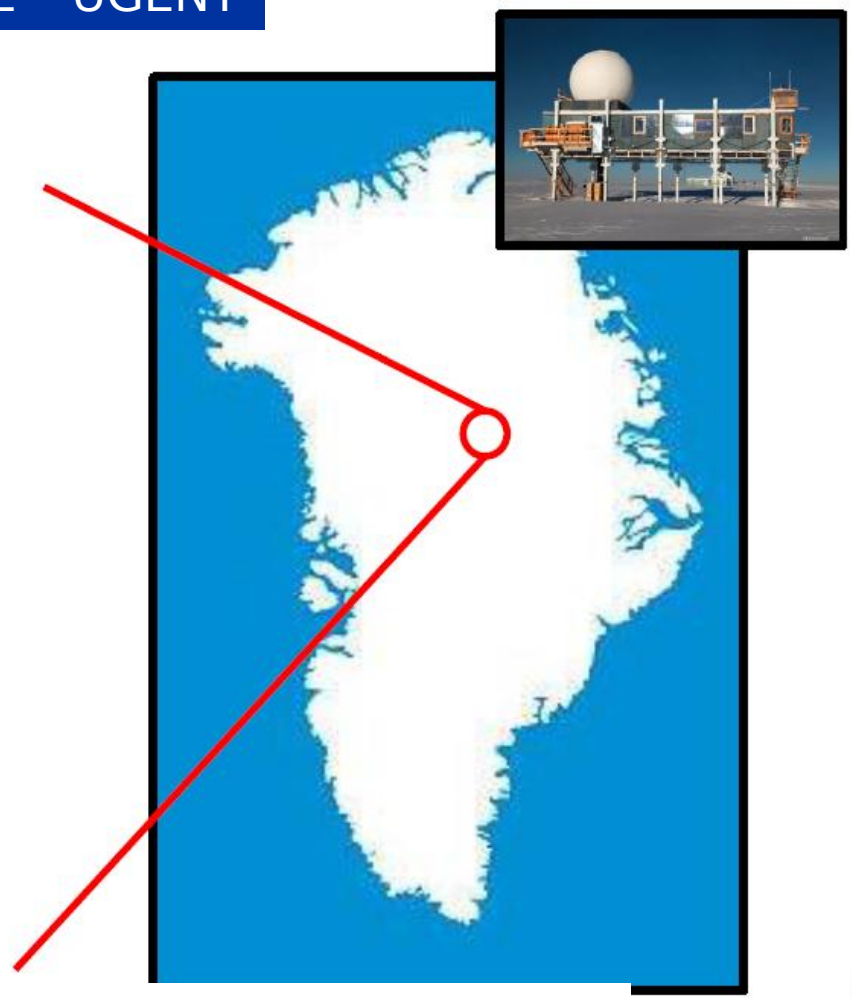
VUB-IIHE:
K.D. de Vries – project PI
N. Van Eijndhoven
ULB-IIHE: S. Toscano

HIGH-ENERGY COSMIC MESSENGERS

NEUTRINOS – RNO-G VUB/ULB-IIHE - UGENT







J. Stoffels (VUB-IIHE), TAUP 2025

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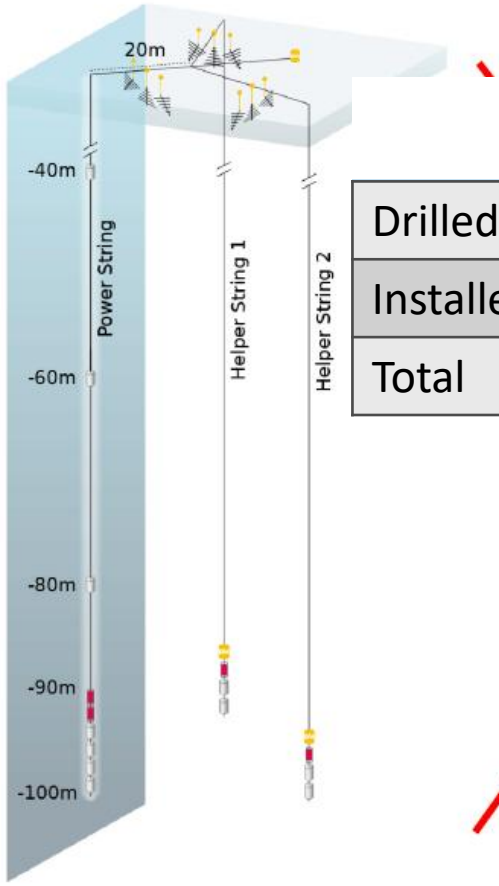
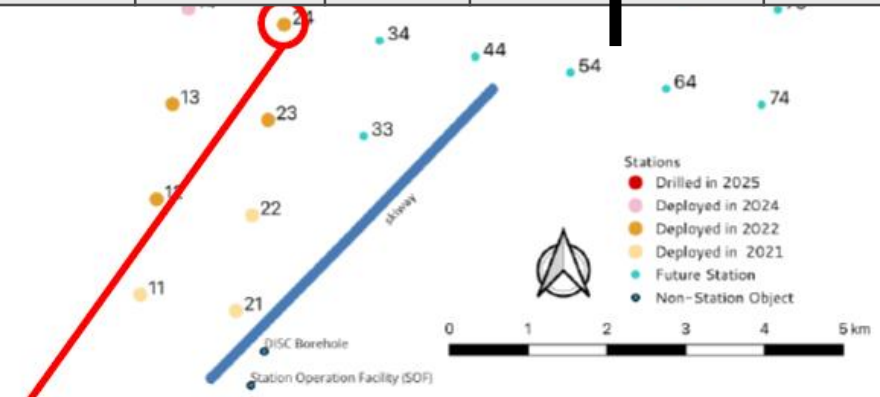
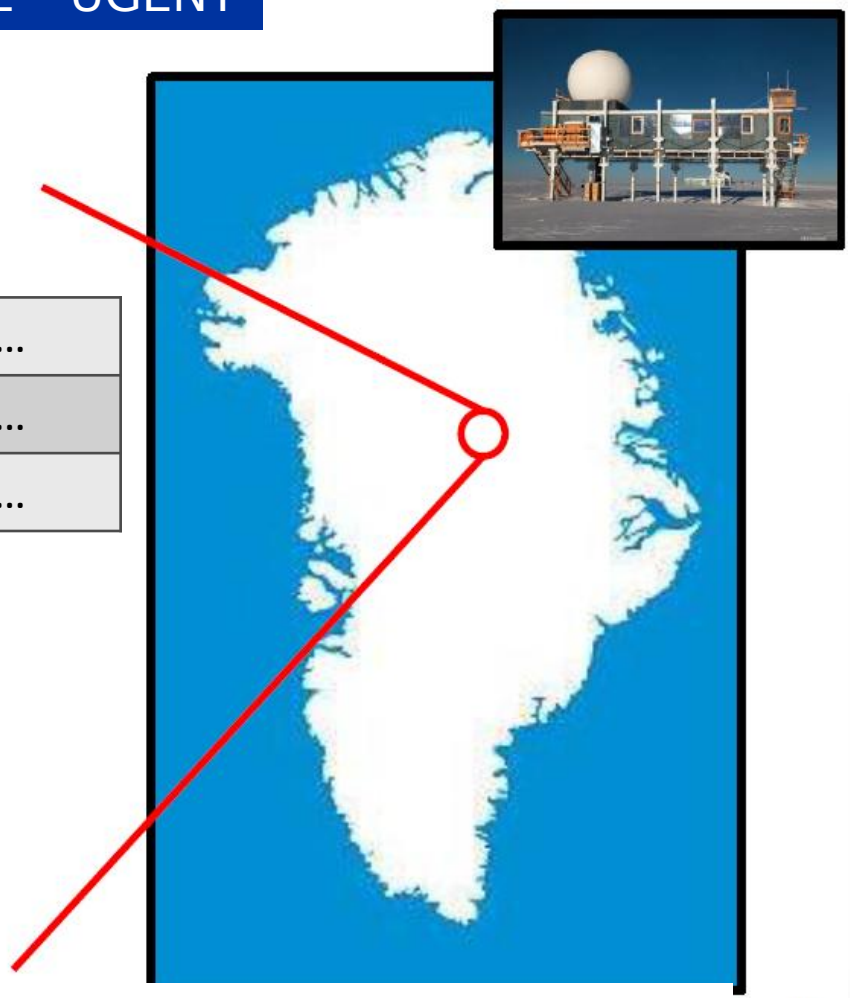
HIGH-ENERGY COSMIC MESSENGERS

NEUTRINOS – RNO-G VUB/ULB-IIHE - UGENT



	≤ 2023	2024	2025	2026	2027	
Drilled	7	1	4	>4	>6	…
Installed	7	1	0	>8	>6	…
Total	7	8	8	>16	>22	…





J. Stoffels (VUB-IIHE), TAUP 2025

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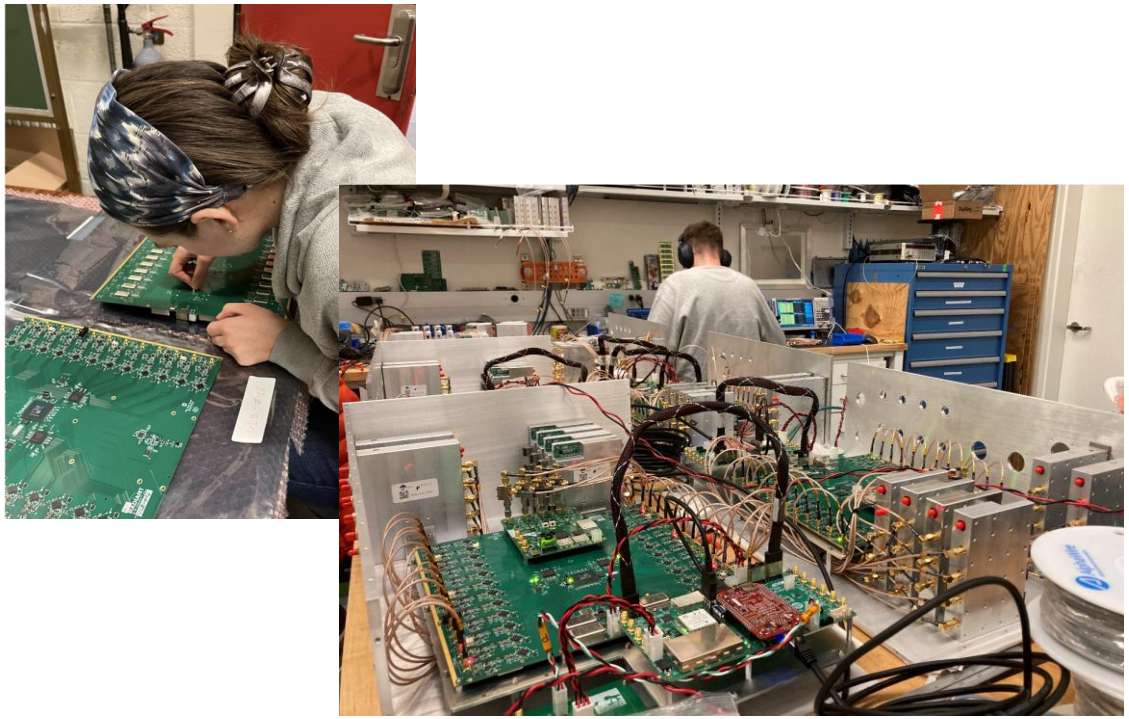
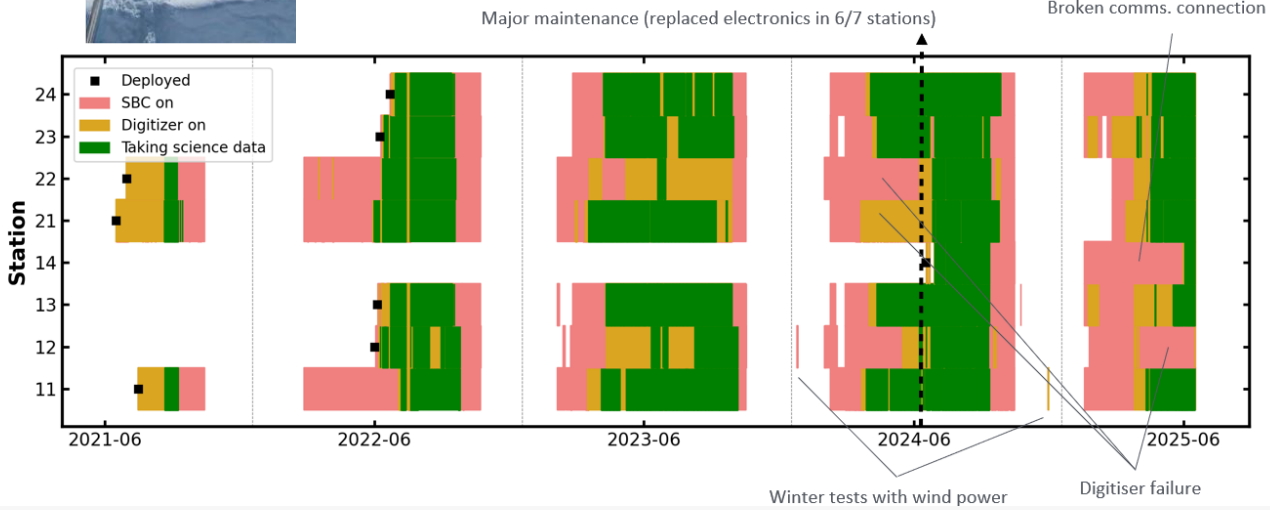
HIGH-ENERGY COSMIC MESSENGERS

NEUTRINOS – RNO-G – BELGIAN INVOLVEMENT

Hardware efforts at the IIHE (ULB-VUB): Radiant board testing and development



Commisioning and deployment (ULB-VUB):

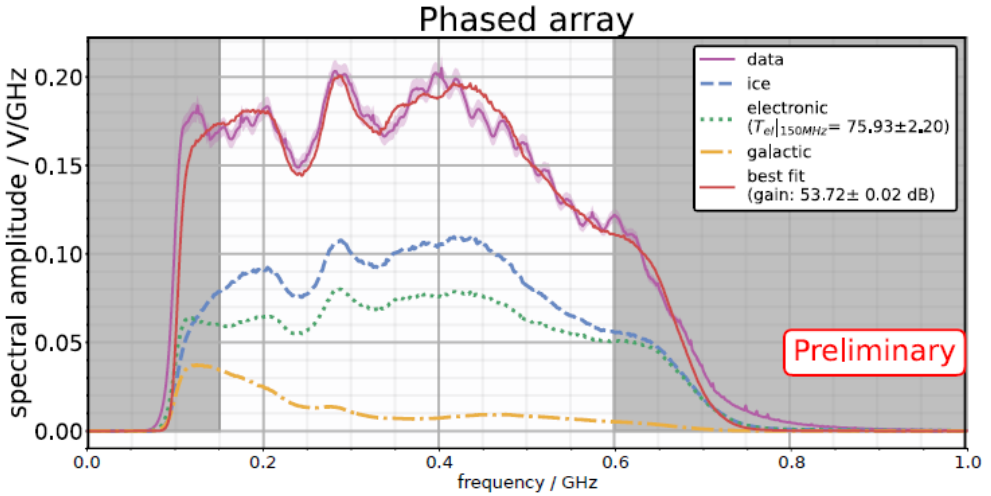


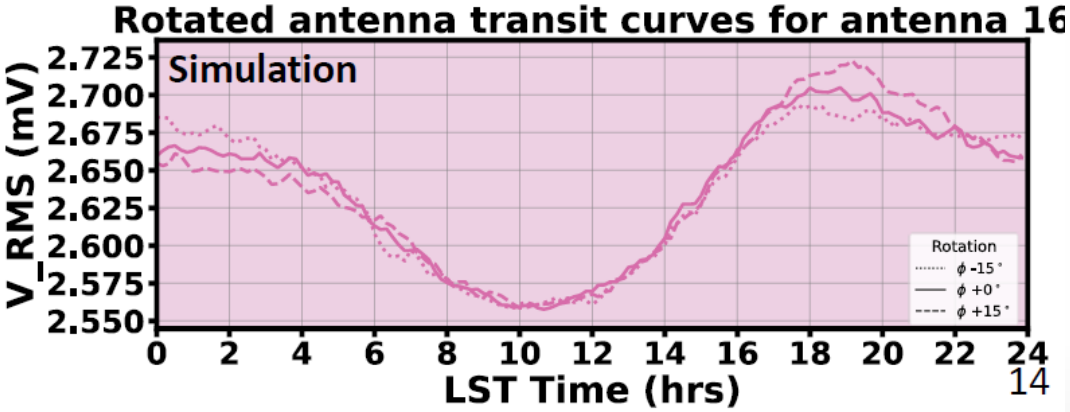
Detector calibration (VUB/ULB-IIHE)

- Absolute calibration of signal amplitude using thermal noise

- Investigating surface antenna orientation using Galactic noise

Thermal and Galactic noise

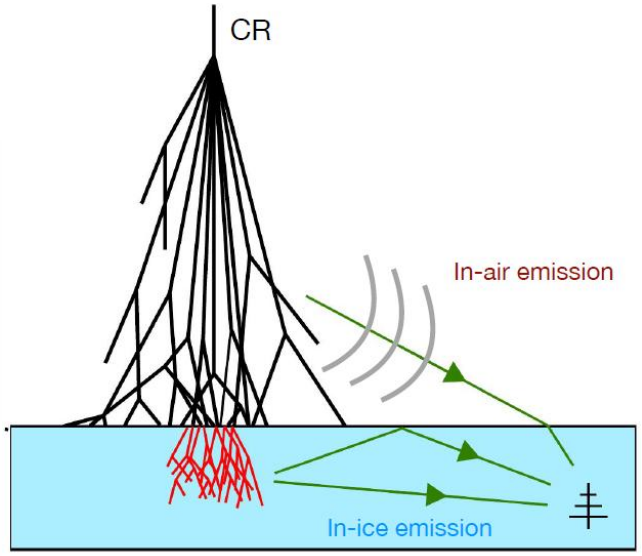




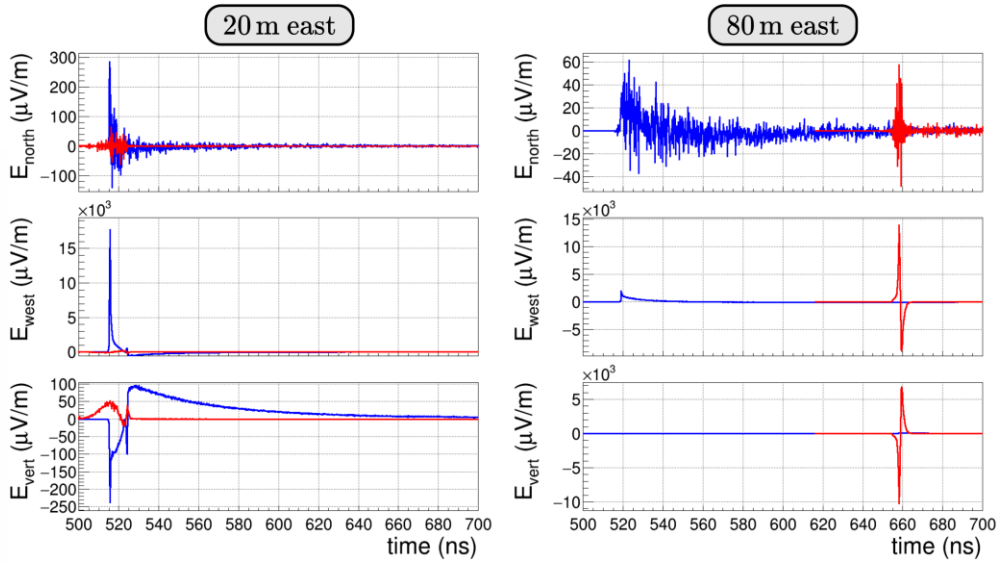
HIGH-ENERGY COSMIC MESSENGERS

NEUTRINOS – RNO-G – BELGIAN INVOLVEMENT

Cosmic-Ray analysis and simulations: Focus on Cosmic-ray in-ice signals
FAERIE simulation framework developed at VUB-IIHE
RNO-G In-ice Cosmic-Ray analysis working group lead by S. Toscano (ULB-IIHE)



credits:
Simon de Kockere



Data analysis ongoing: first signals expected soon

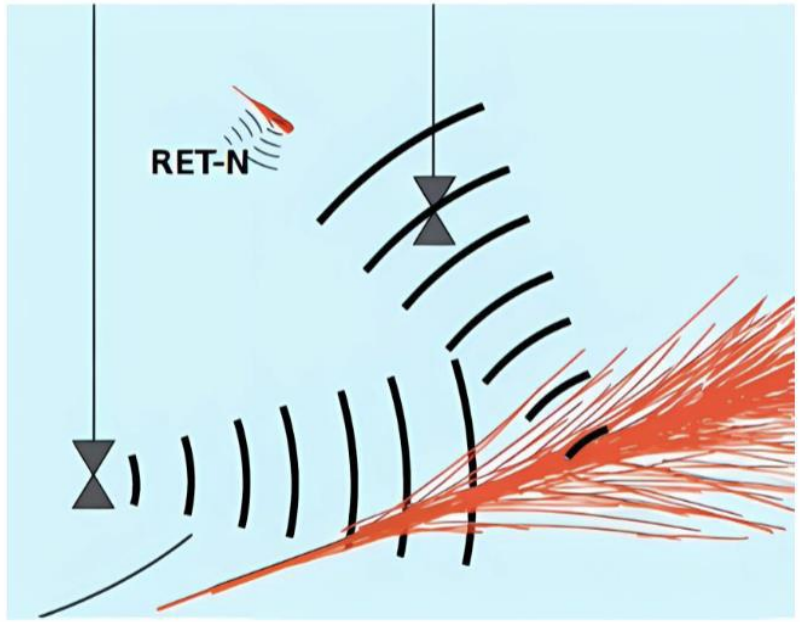
→

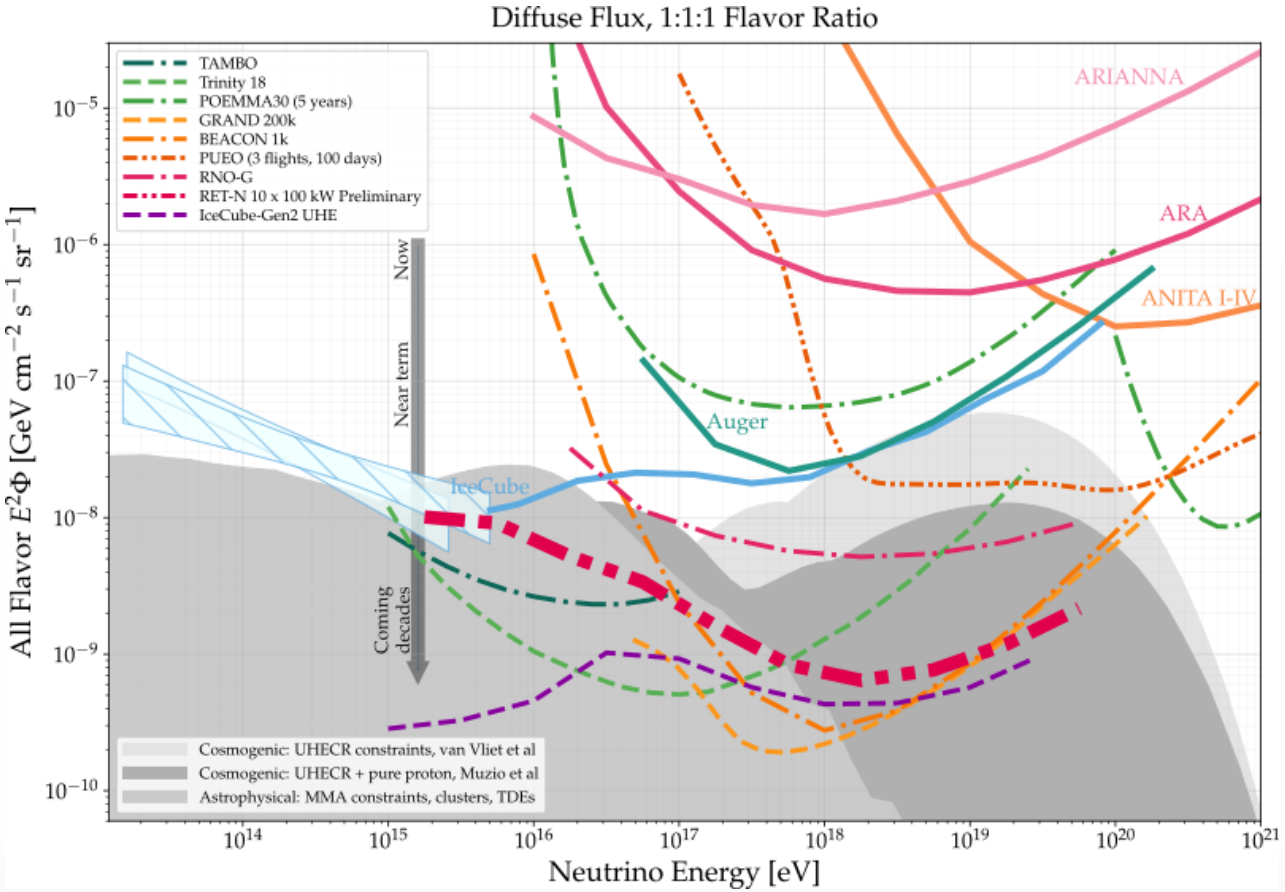
Proof of concept of the detector and method!!

HIGH-ENERGY COSMIC MESSENGERS – PATHFINDERS

NEUTRINOS – THE RADAR ECHO TELESCOPE (RET) – VUB/ULB-IIHE

RADAR ECHO TELESCOPE

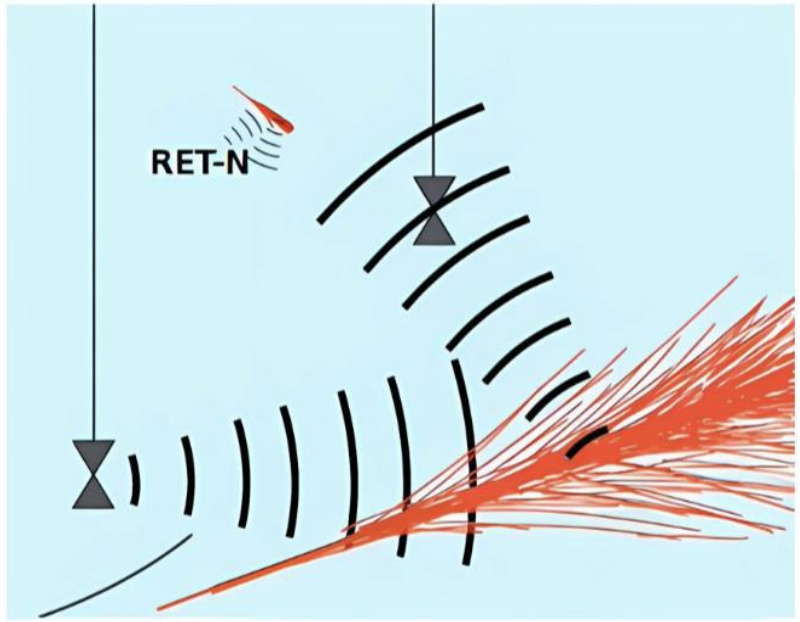


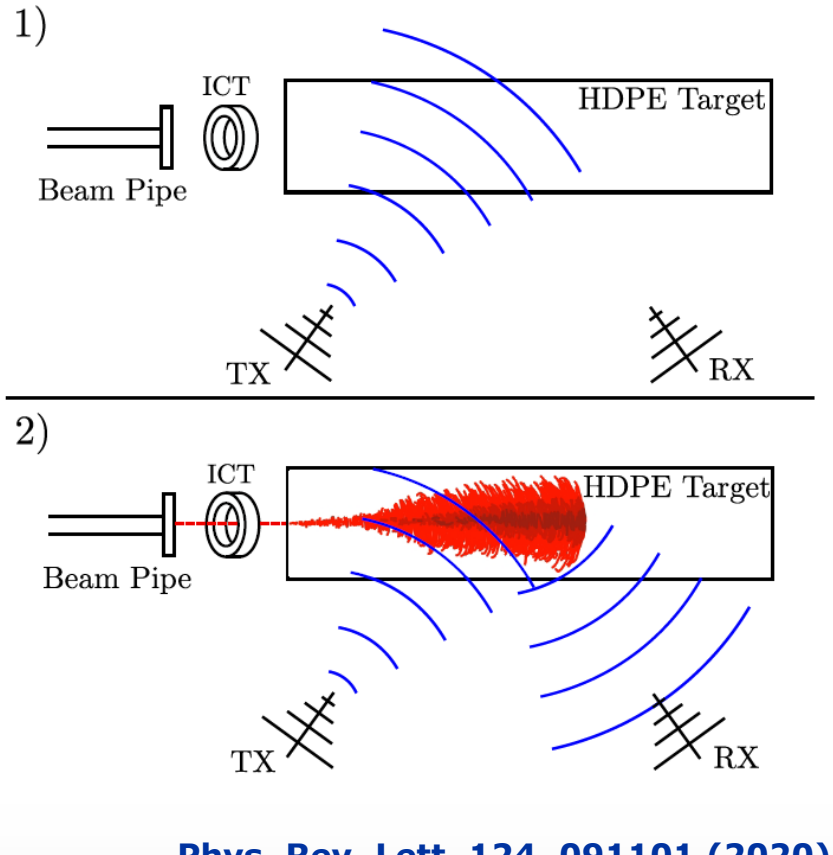


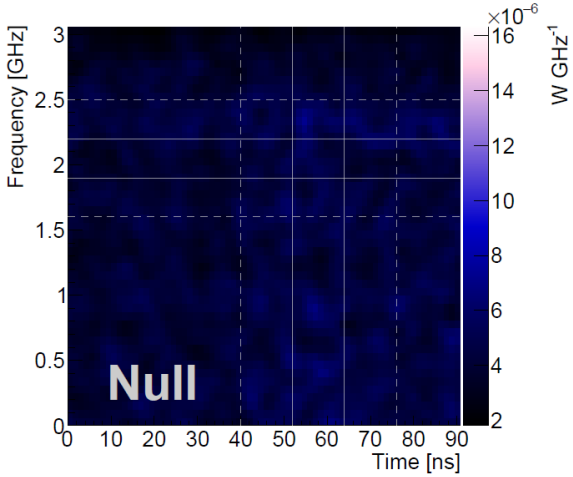
HIGH-ENERGY COSMIC MESSENGERS – PATHFINDERS

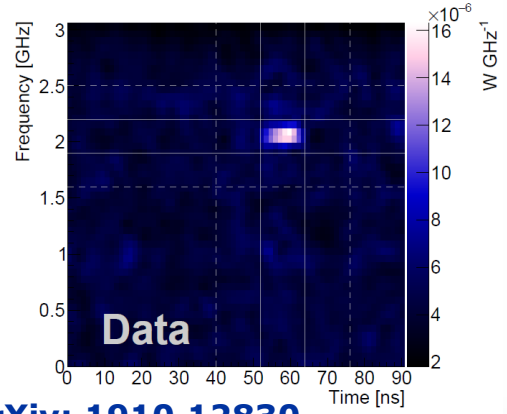
NEUTRINOS – THE RADAR ECHO TELESCOPE (RET) – VUB/ULB-IIHE

RADAR ECHO TELESCOPE





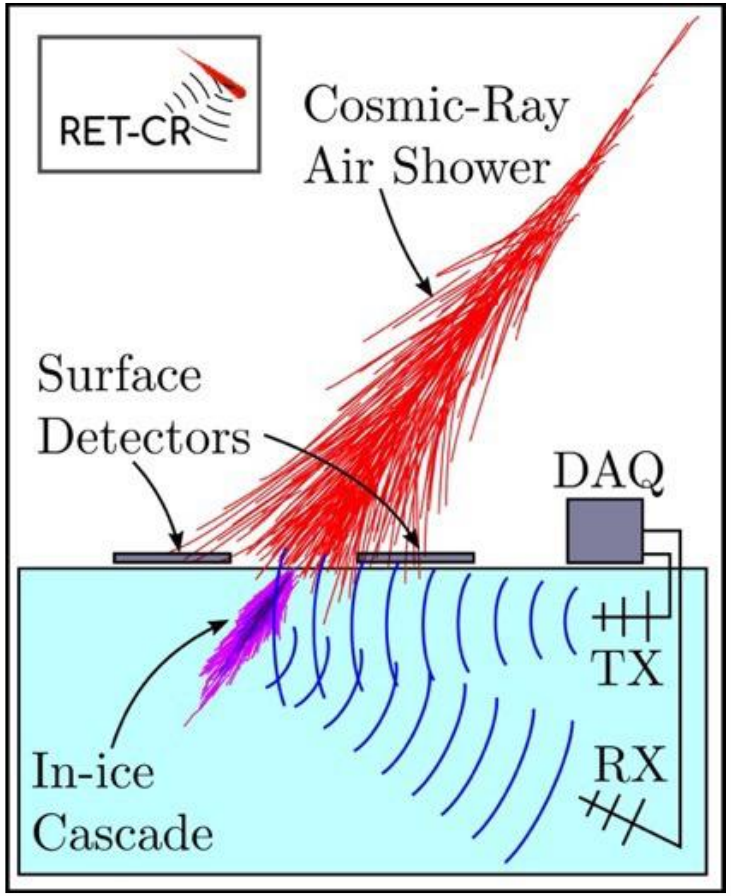


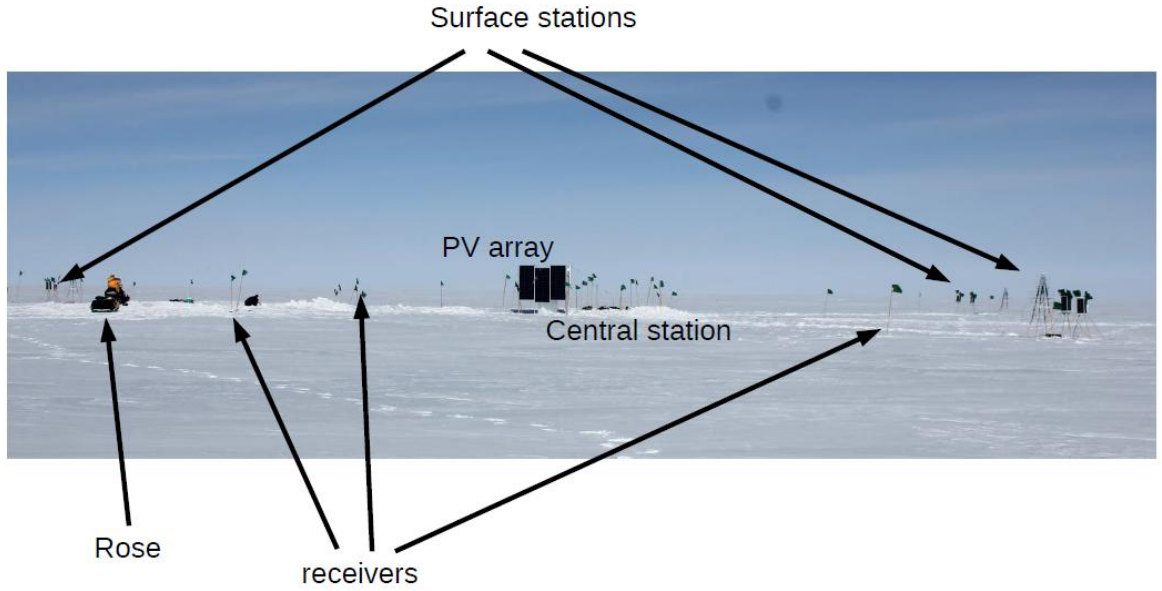


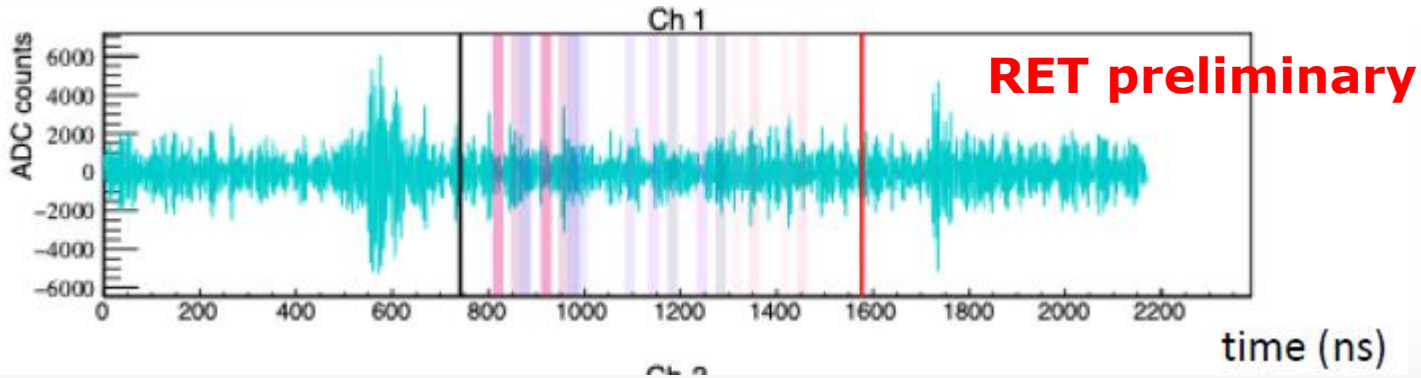
Phys. Rev. Lett. 124, 091101 (2020) ; arXiv: 1910.12830
Details on the method: Phys. Rev. D 100, 072003 (2019) ; arXiv:1810,09914

HIGH-ENERGY COSMIC MESSENGERS – PATHFINDERS

NEUTRINOS – THE RADAR ECHO TELESCOPE (RET) – VUB/ULB-IIHE





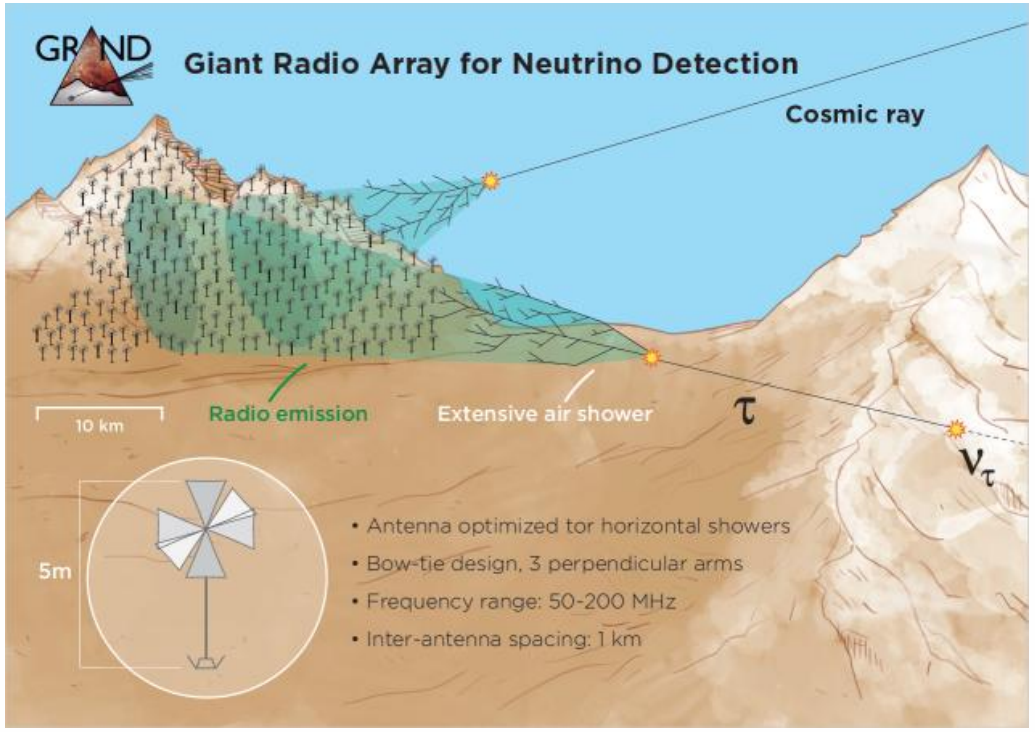


RET preliminary

HIGH-ENERGY COSMIC MESSENGERS – PATHFINDERS

NEUTRINOS – GRAND – VUB-IIHE

Project PI: K. Kotera (10% VUB-IIHE)



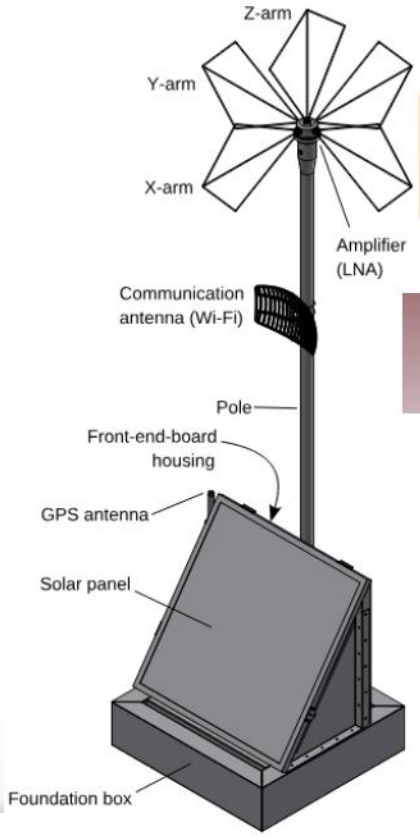
A staged approach with self-standing pathfinders

	GRANDProtos	GRAND10k	GRAND200k
	2023	2028	203x
Goals	**Pure and efficient autonomous radio detection of very inclined air-showers** Cosmic rays $10^{16.5\text{-}18}$ eV • Galactic/extragalactic transition • Muon puzzle • Radio transients	**1st GRAND sub-array** • **discovery of EeV neutrinos for optimistic fluxes** • radio transients (FRBs!)	sensitive all-sky detector **Neutrino astronomy!**
Setup	• **GRANDProto300**: 300 antennas over 200 km² • GRAND@Auger: 10 antennas for cross-calibration • GRAND@Nançay: 4 antennas for trigger testing	• 2 detectors of 5-10k antennas each in each hemisphere: GRAND-North (China) and GRAND-South (Argentina?) *Hybrid design possible (phased/standalone)	• 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • on different continents
Budget	2 M€ 100 antennas produced Funded by China + ANR-DFG NUTRIG (France- Germany) + Radboud University	13 M€ 1500€/unit	300M€ in total 500€/unit to be divided between participating countries

HIGH-ENERGY COSMIC MESSENGERS – PATHFINDERS

NEUTRINOS – GRAND

GRANDProto300 & other prototypes: experimental setup



Deployment of 13 detection units (DUs) in Gansu (China), 65 in 2025 and 289 later

Deployed Feb 2023

Deployment of 10 DUs on the Auger site in Malargüe, Argentina (cross-calibration)

Deployed Aug 2023

Deployment of 4 DUs in Nançay radio observatory (France) for trigger test (LPNHE)

Deployed Oct 2022

50-200MHz analog filtering,
Electronics:
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

HIGH-ENERGY COSMIC MESSENGERS

BELGIAN LEADERSHIP AND RESPONSIBILITIES

Pierre Auger observatory:
- **Publication Committee Chair Pierre Auger collaboration. (Ioana Maris, ULB-IIHE)**
- **Task leader: Auger as test environment. (Ioana Maris, ULB-IIHE)**

GCOS:
- **Core group member (Ioana Maris, ULB-IIHE)**

PEPS:
- **Project PI (Ioana Maris, ULB-IIHE)**

LOFAR/SKA Cosmic-Ray detection:
- **Project PI (S. Buitink, VUB-IIHE)**

RNO-G:
- **Project PI (N. van Eijndhoven, VUB-IIHE)**
- **Deep CR search working group lead (S. Toscano, ULB-IIHE)**

RET:
- **Project PI (K.D. de Vries, VUB-IIHE)**

GRAND:
- **Project PI (K. Kotera, 10% VUB-IIHE)**

APPEC:
- **FWO/FNRS representative (K.D. de Vries, VUB-IIHE / G. Bruno, UCLouvain)**
- **SAC member (I. Maris, VUB-IIHE)**