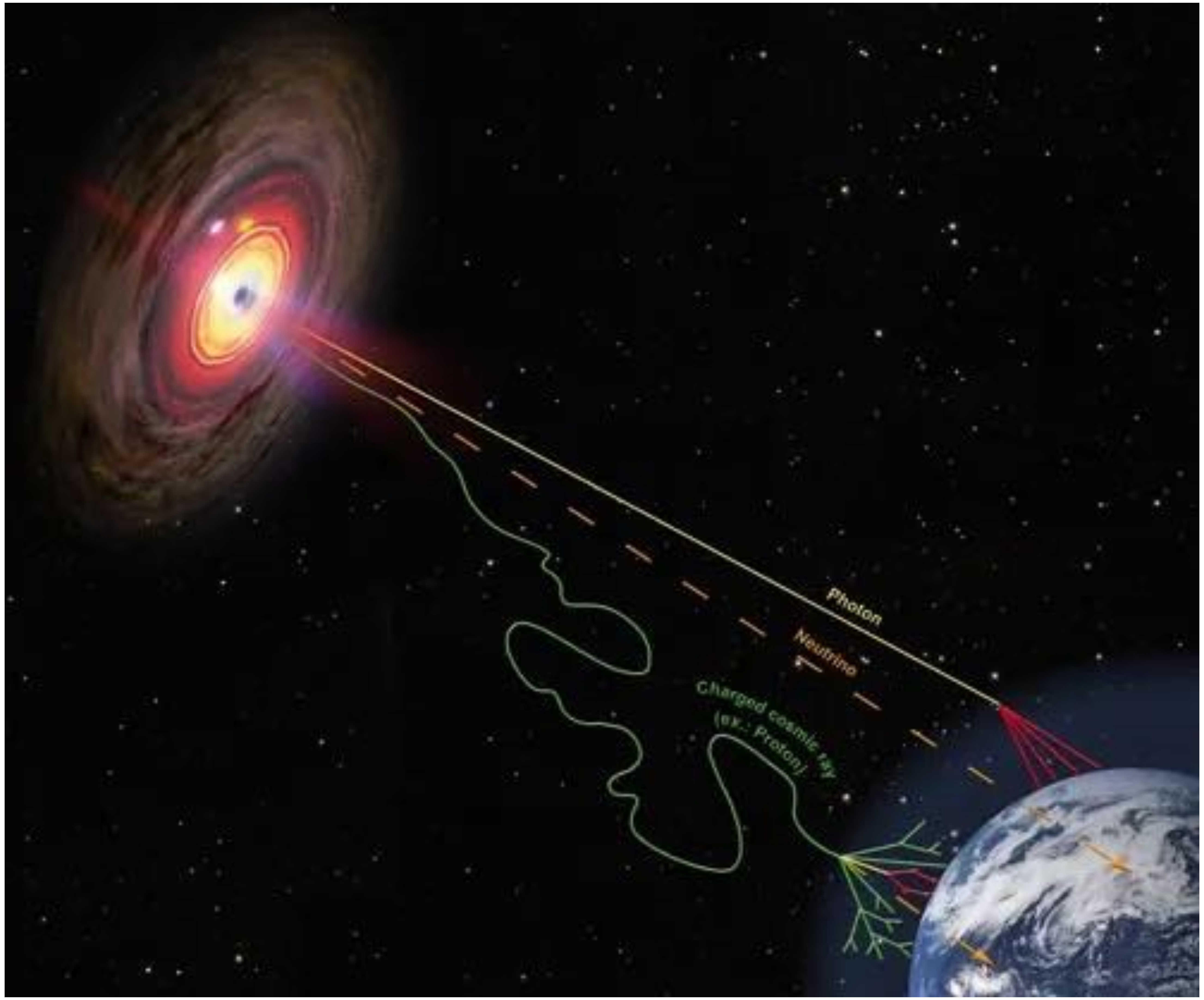
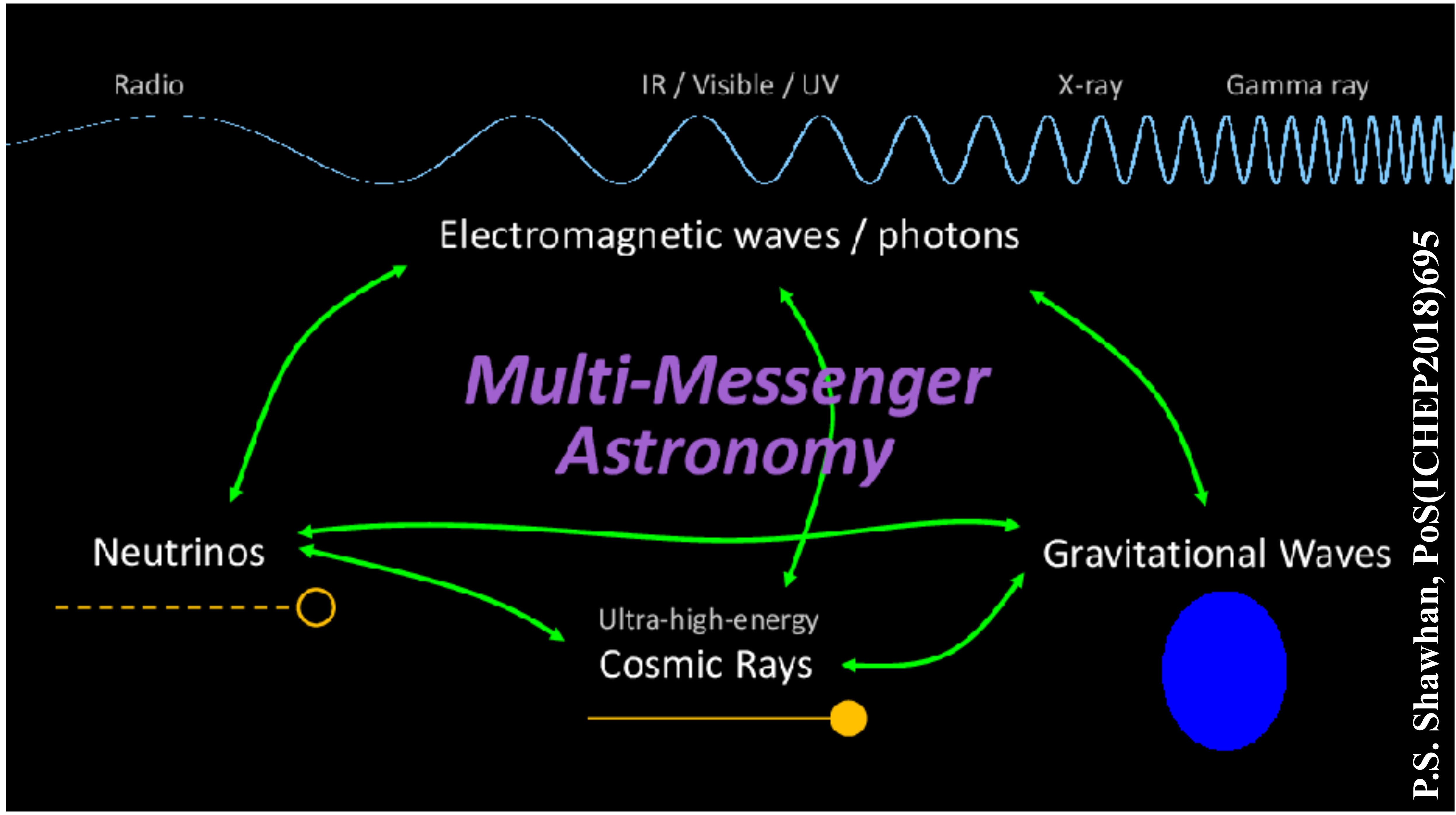
Cosmic Rays

28th Symposium on Astroparticle Physics in the Netherlands
Soesterberg, July 2024



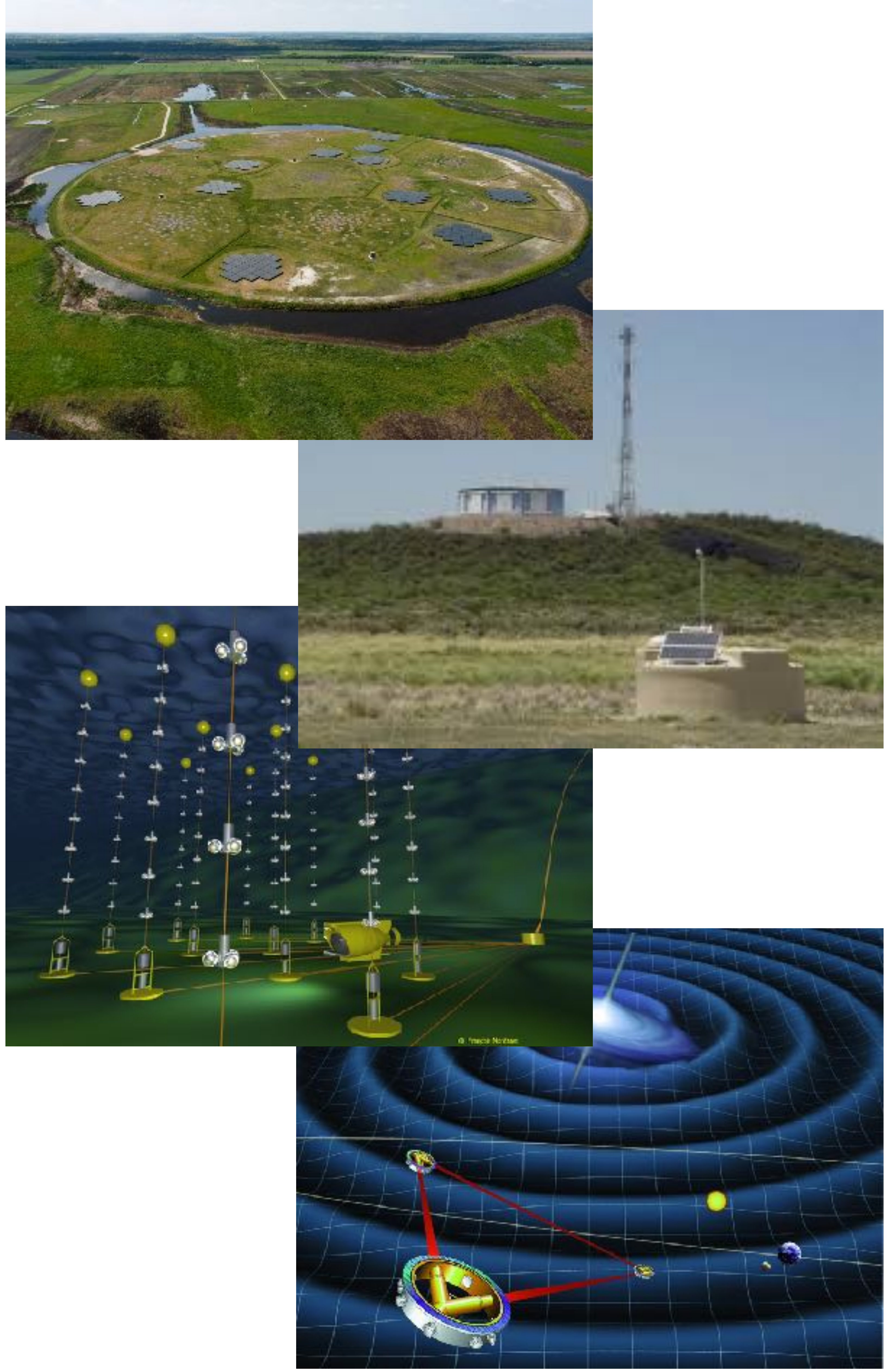
Understand the origin and physics of the highest-energy particles in the Universe



P.S. Shawhan, PoS(ICHEP2018)695

Jörg R. Hörandel
Radboud University, Nijmegen - Vrije Universiteit Brussel - http://particle.astro.ru.nl

Cosmic Rays



Strategic plan 2005

Strategic Plan for
Astroparticle Physics
in the Netherlands

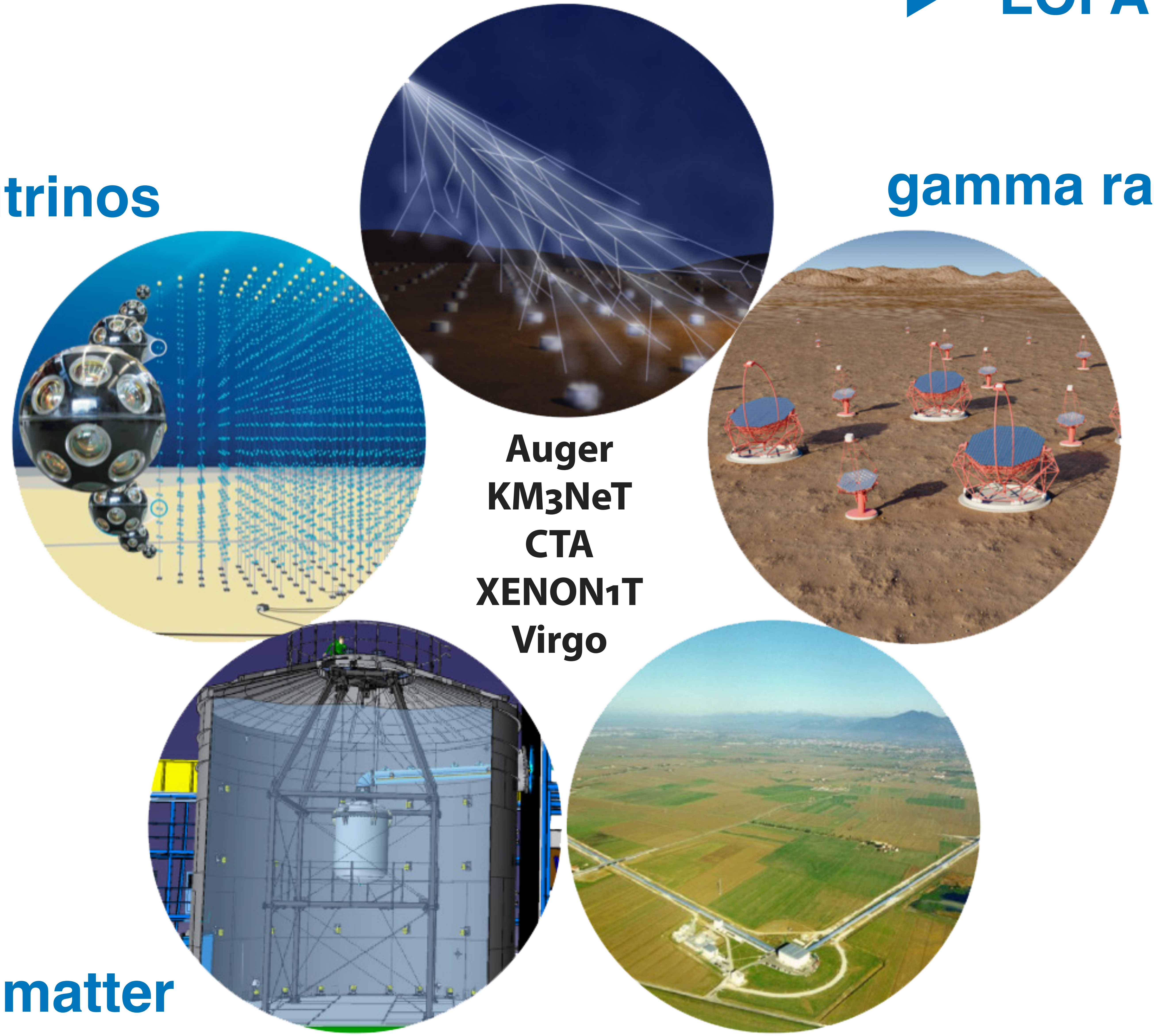
Commissie voor de
Astrodeeltjesfysica
in Nederland (CAN)

Table 1. Foreseen involvement (in 2006) of tenured senior scientists in the selected observational and/or experimental projects that are part of the present strategic plan.

Research Area	Institute	Scientific Staff	Research Interests
Radio Detection of Cosmic Rays	UvA - Amsterdam	RAMJ Wijers S. Markoff	LOFAR; compact objects (GRB, AGN)
	ASTRON - Dwingelo	H Falcke (& RU)	LOFAR, Auger
	KVI - Groningen	JCS Bacelar AM van den Berg MN Harakeh J Messchendorp HJ Wörtche	LOFAR, Auger, Westerbork, extended air showers
	RU - Nijmegen	P Groot SJ de Jong J Kuijpers Ch Timmermans (new UD astron.)	Expertise centre for LOFAR/cosmic rays Auger
Deep-sea neutrino detection	NIKHEF - Amsterdam	M de Jong P Kooijman G vd Steenhoven E de Wolf	ANTARES, KM3NeT
	UvA - Amsterdam	RAMJ Wijers	ν-astronomy; GRBs
	KVI - Groningen	MN Harakeh N Kalantar H Löhner	ANTARES, KM3NeT
	UU/SRON – Utrecht	A Achterberg N v Eijndhoven J Heise	ν-astronomy; GRBs AMANDA/IceCube analysis; KM3NeT
Gravitational wave detection	NIKHEF - Amsterdam	H vd Graaf FL Linde	LISA electronics and analysis
	VU - Amsterdam	JFJ vd Brand Tj Ketel	LISA simulation and analysis
	LU - Leiden	G Frossati	MiniGRAIL
	RU - Nijmegen	J Kuijpers	GW-astronomy
	SRON - Utrecht	A Selig M Smit	ISTM for LISA Pathfinder, LISA
Outreach	VU - Amsterdam	HJ Bulten	HiSparc
	NIKHEF - Amsterdam	B van Eijk JW van Holten	HiSparc
	KVI - Groningen	J Messchendorp	HiSparc
	LU - Leiden	P van Baal	HiSparc
	RU - Nijmegen	Ch Timmermans	HiSparc LOFAR@School
	UU – Utrecht	J Kortland GJL Nooren	HiSparc

Cosmic Rays

cosmic rays → **Auger**
LOFAR



neutrinos

gamma rays

Auger
KM3NeT
CTA
XENON1T
Virgo

dark matter

gravitational waves

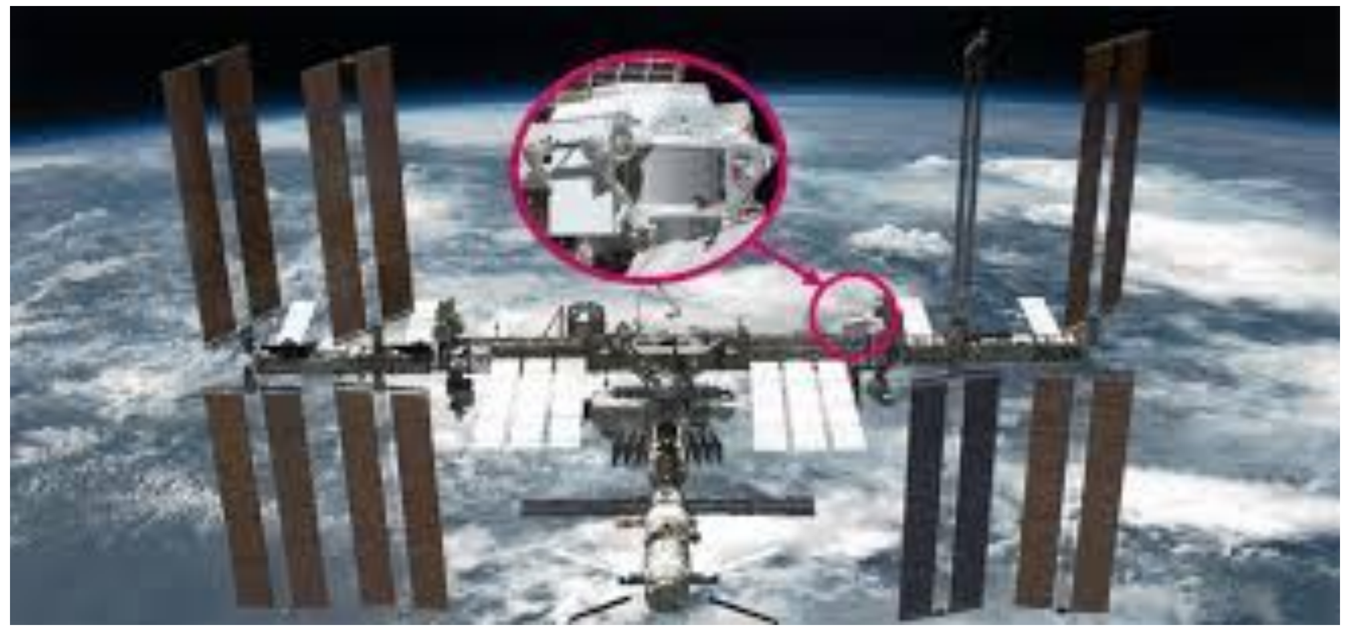
Strategic plan 2014

CAN
Committee for
Astroparticle
Physics in
the Netherlands

March 2014

Strategic plan for
Astroparticle Physics
in the Netherlands
2014–2024

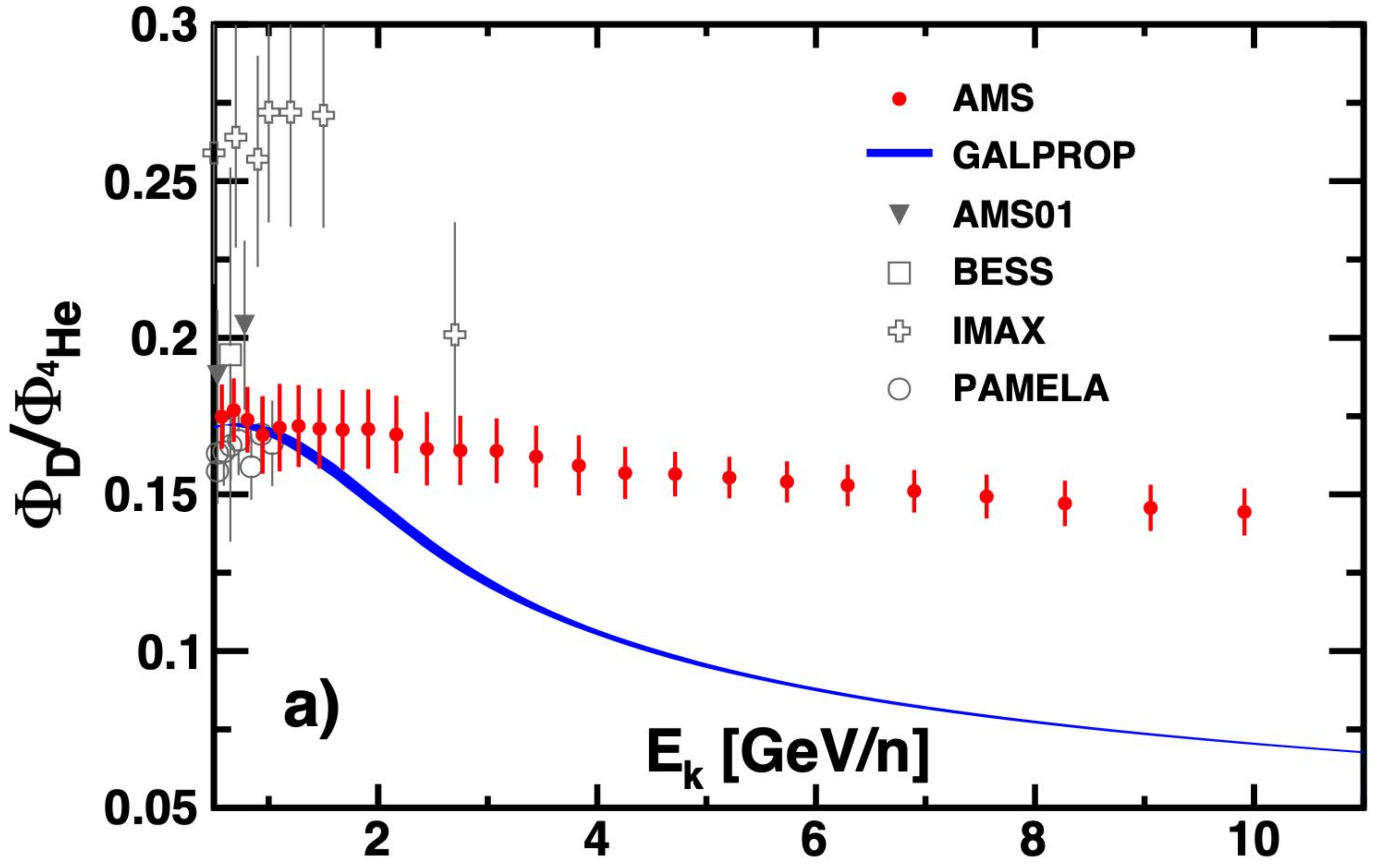
The Alpha Magnetic Spectrometer (AMS-02)



- Particle physics experiment in space detecting GeV to TeV cosmic rays on the International Space Station since 2011.
- AMS-02 detected so far more than 200 billion cosmic-ray events.

Activities in the Netherlands (Groningen):

- CR isotopes identification methods
- Deuteron flux measurement (accepted PRL)
- Antideuteron searches
- interpretation of AMS data

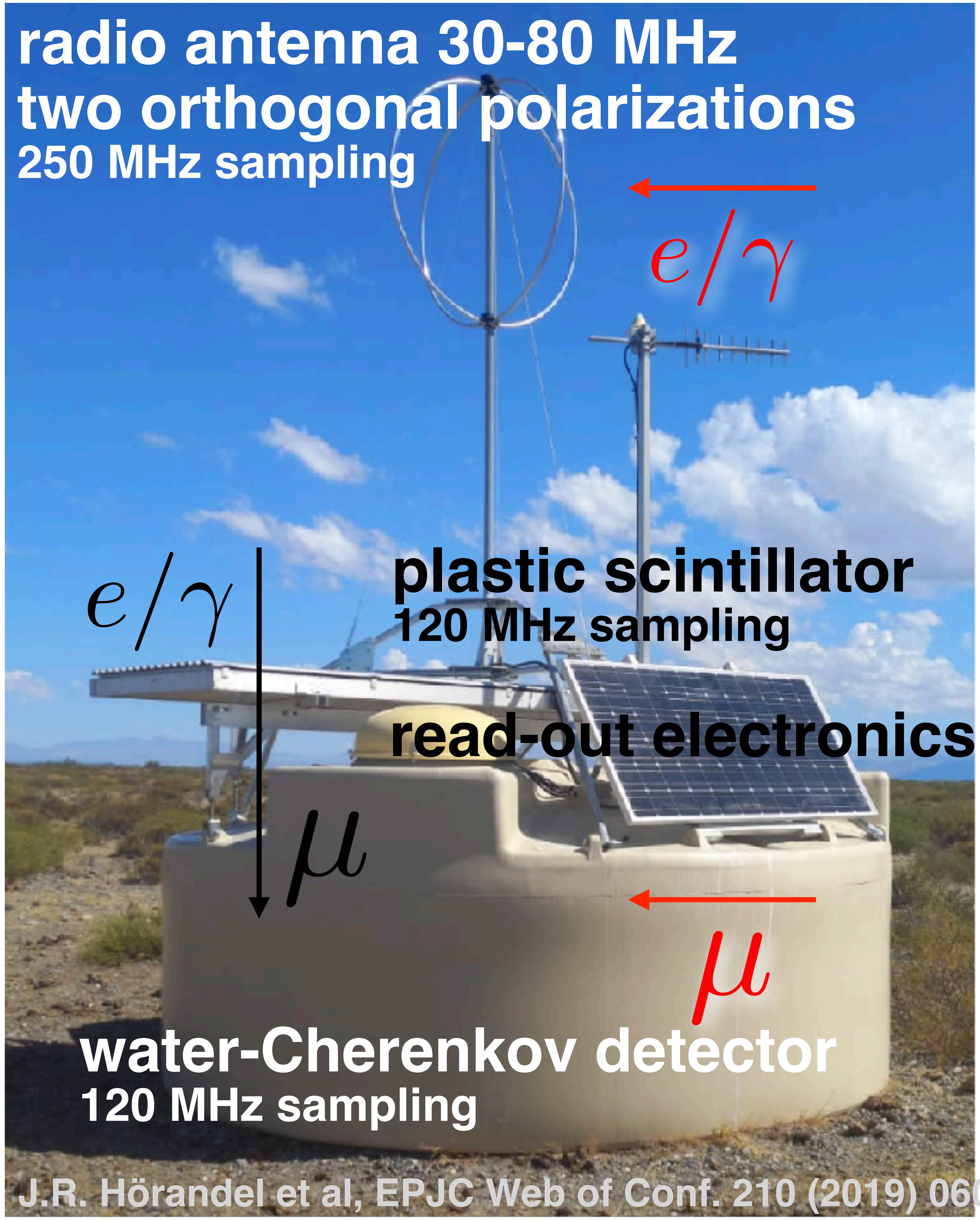


See Marta's talk tomorrow

Our team: Manuela Vecchi, Marta Borchiellini

M. Vecchi

Upgraded Surface Detector of Auger Observatory



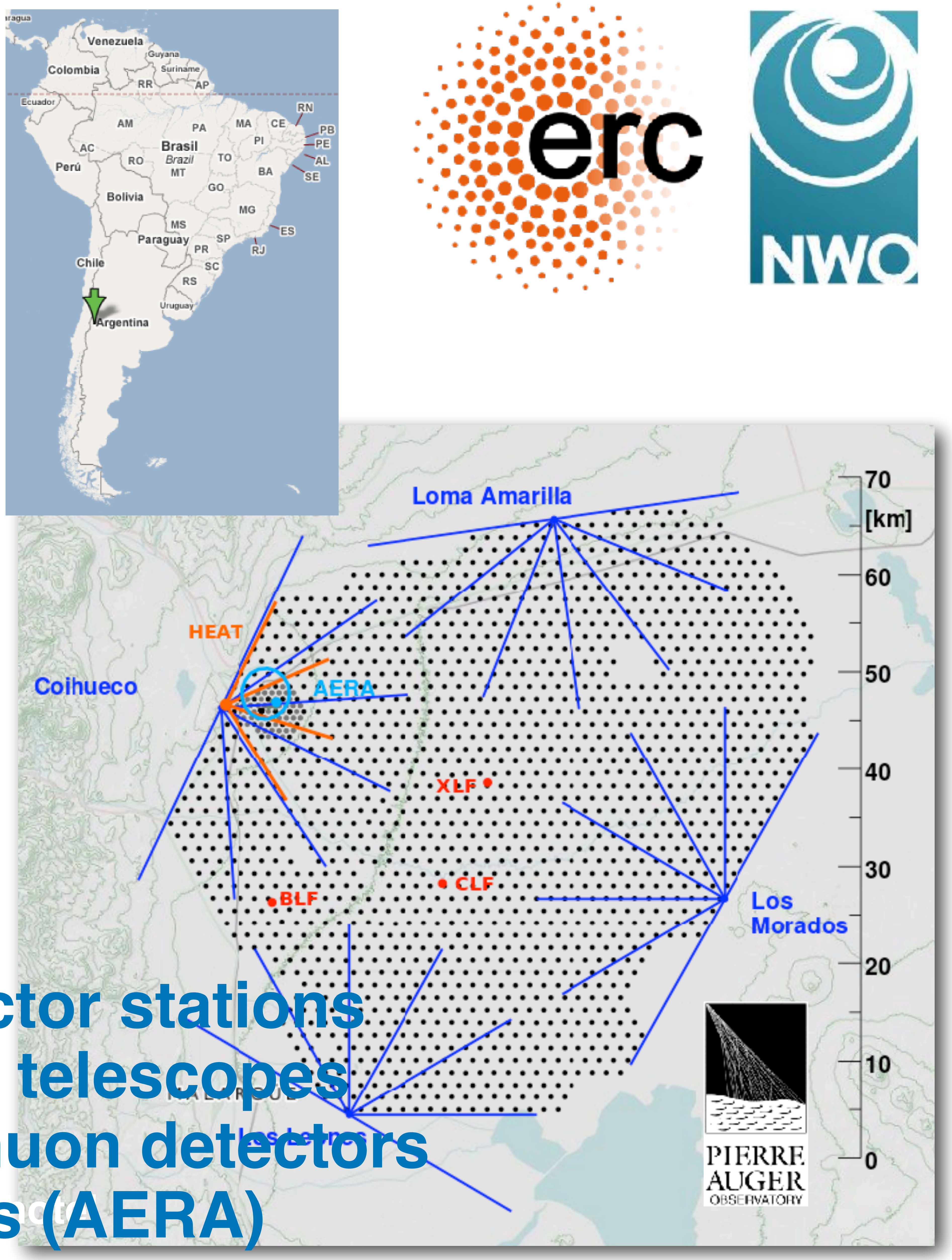
radio antenna 30-80 MHz
two orthogonal polarizations
250 MHz sampling

plastic scintillator
120 MHz sampling

read-out electronics

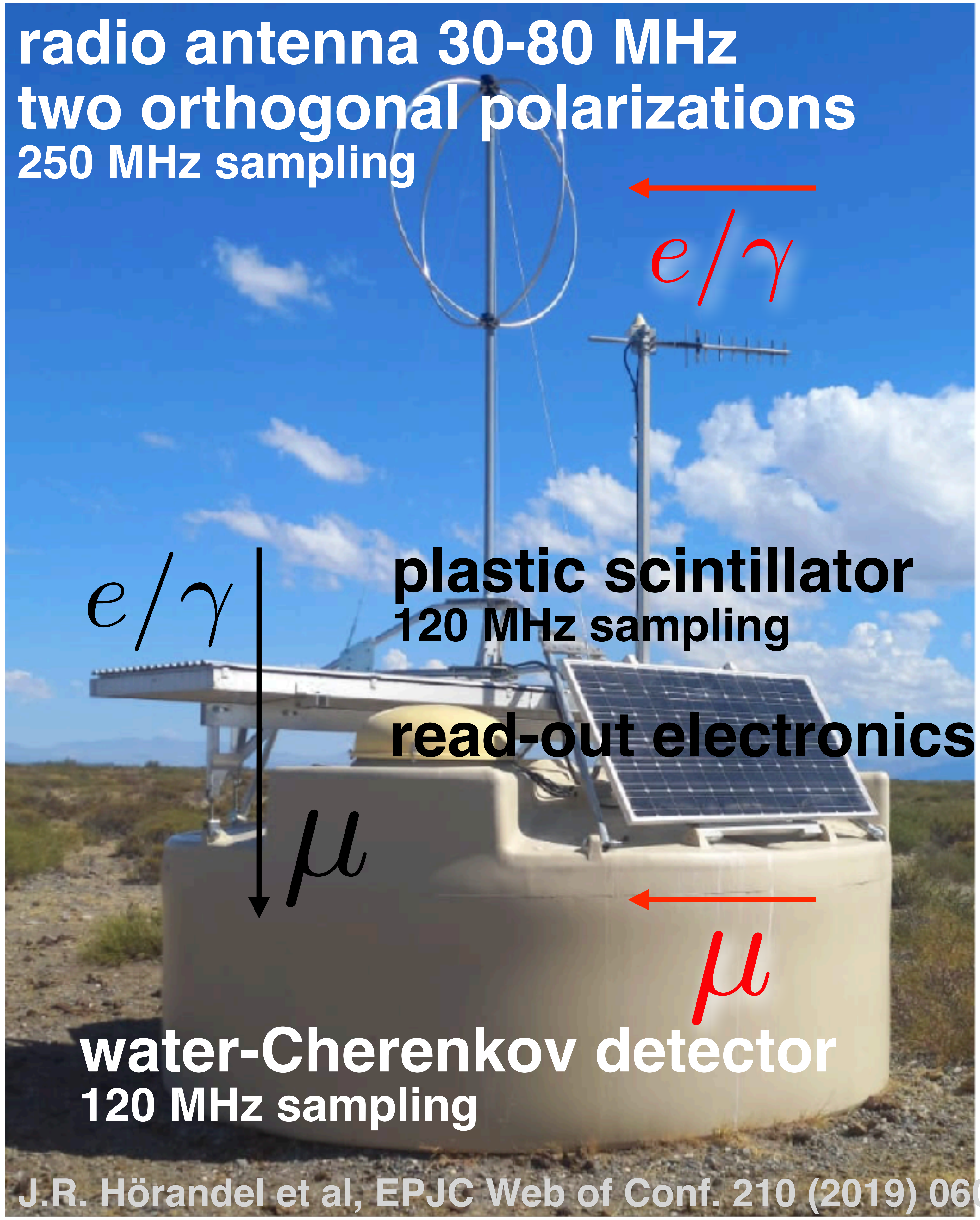
water-Cherenkov detector
120 MHz sampling

J.R. Hörandel et al, EPJC Web of Conf. 210 (2019) 06005



3000 km²
1660 surface detector stations
24+3 fluorescence telescopes
61 underground muon detectors
150 radio antennas (AERA)

Upgraded Surface Detector of Auger Observatory



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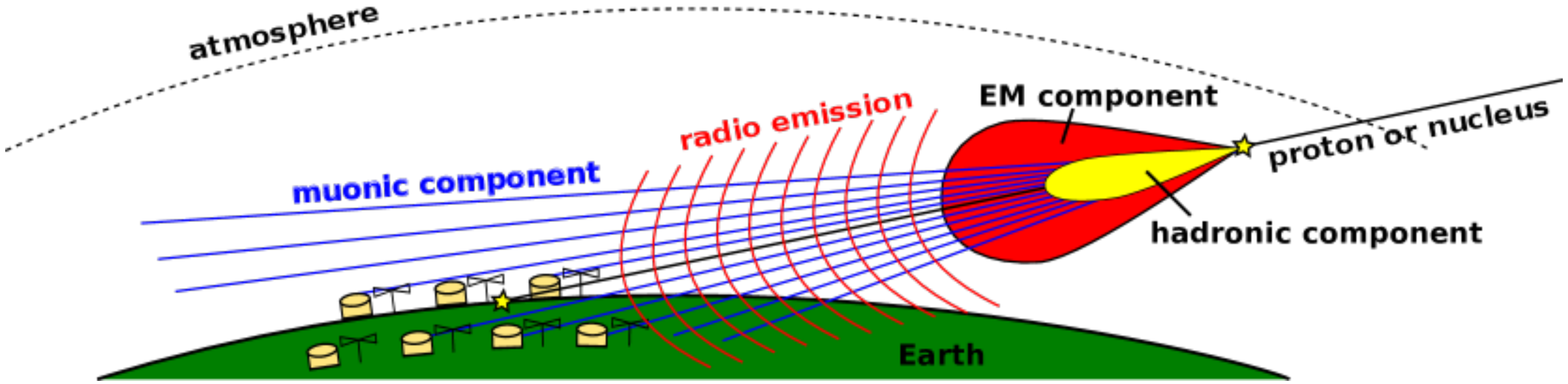
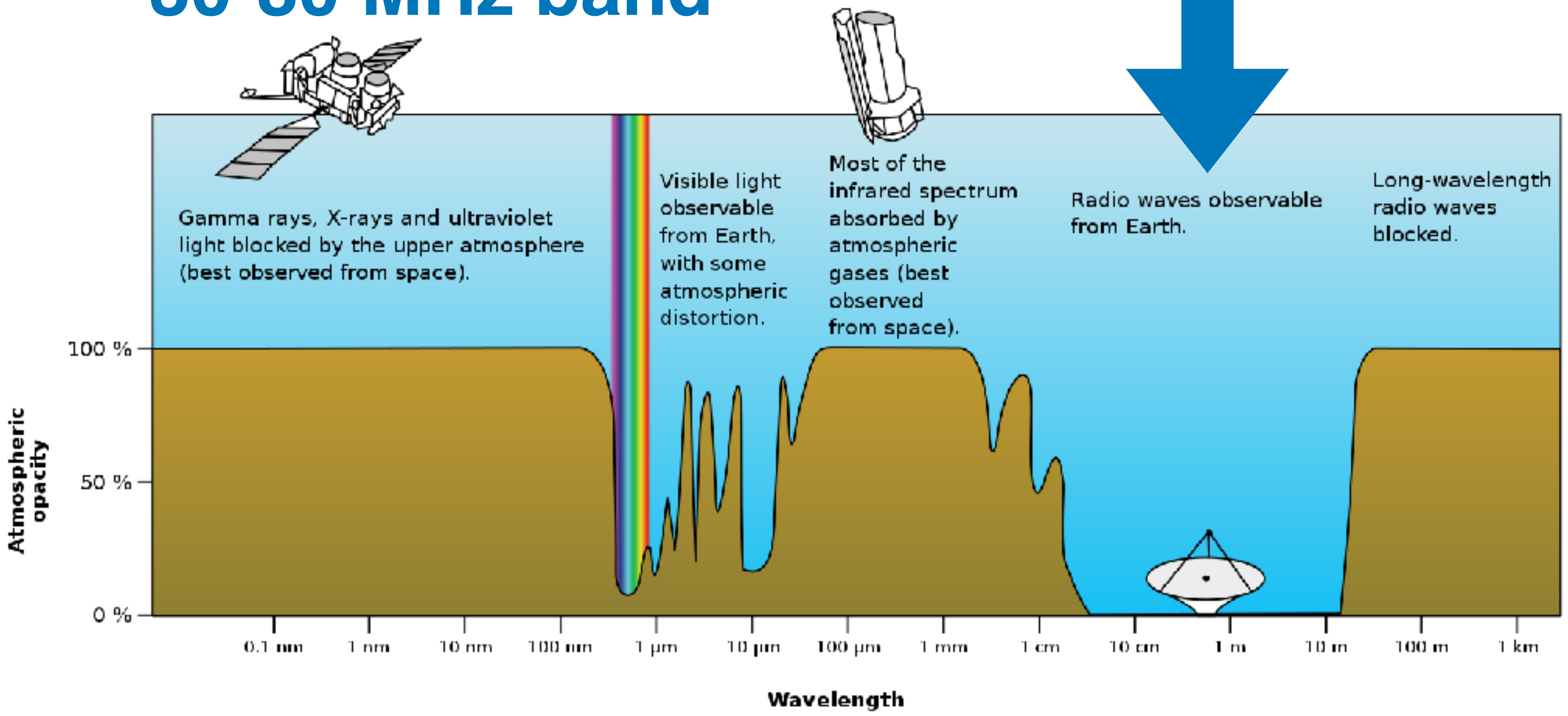
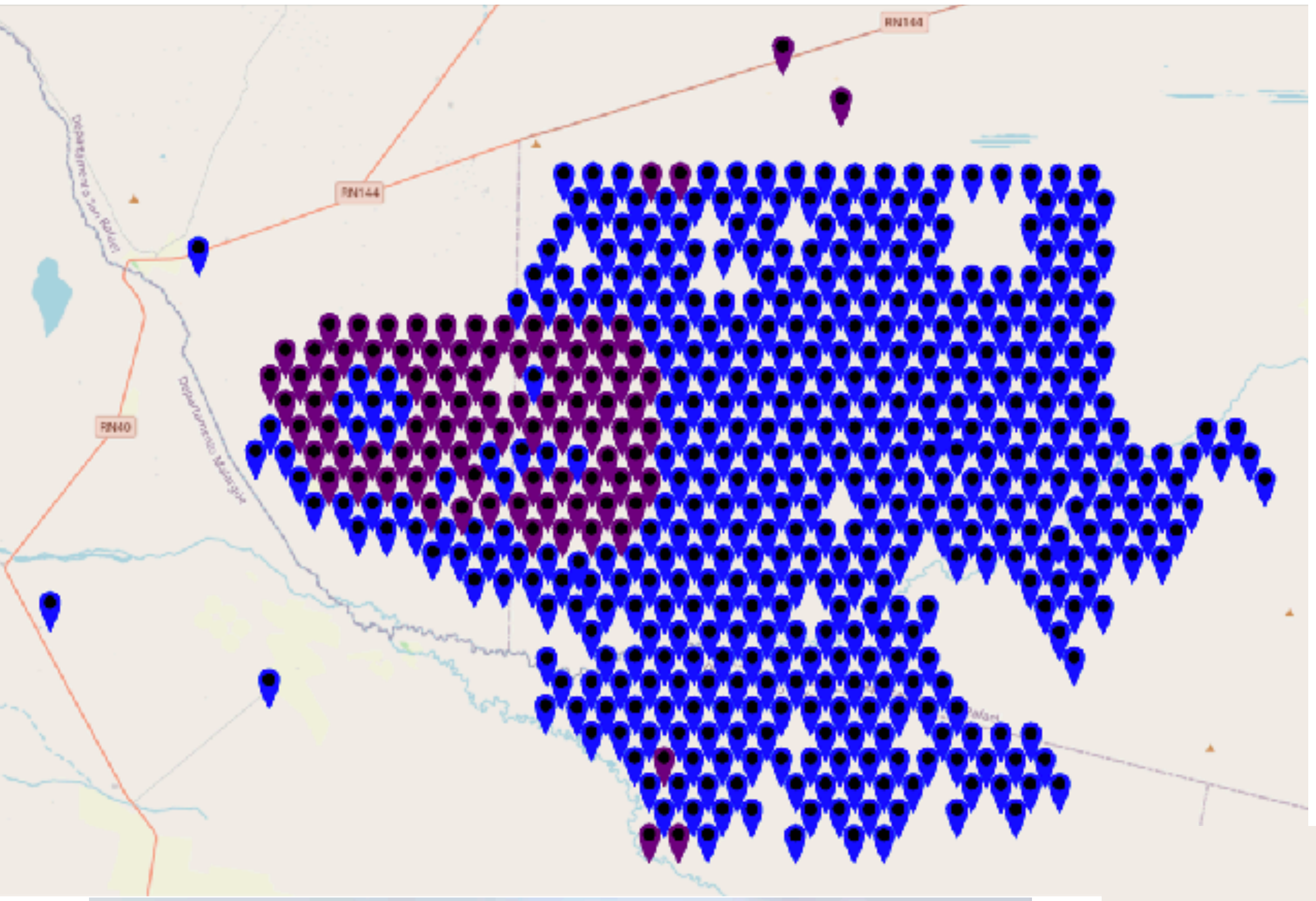


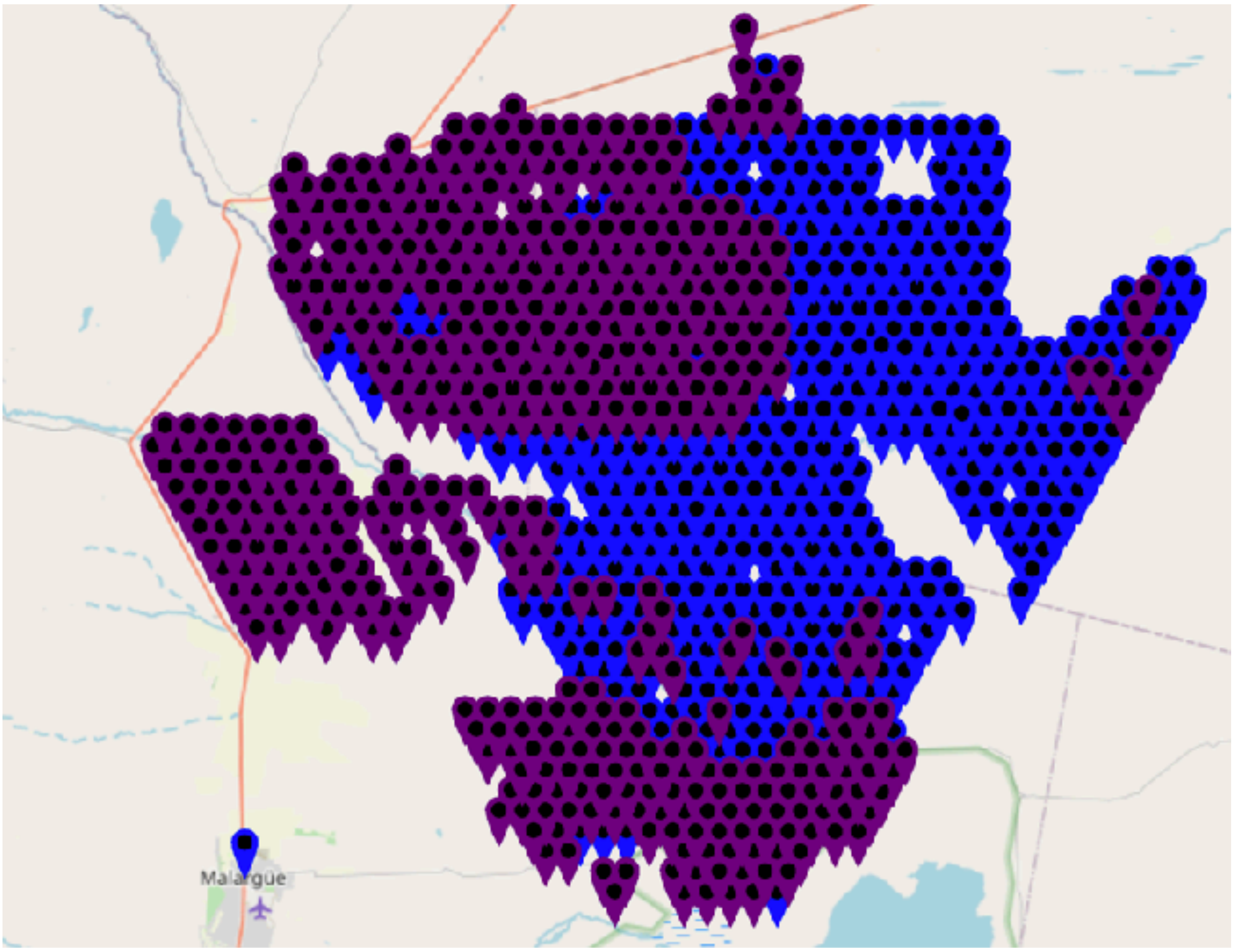
atmosphere of Earth is transparent in 30-80 MHz band

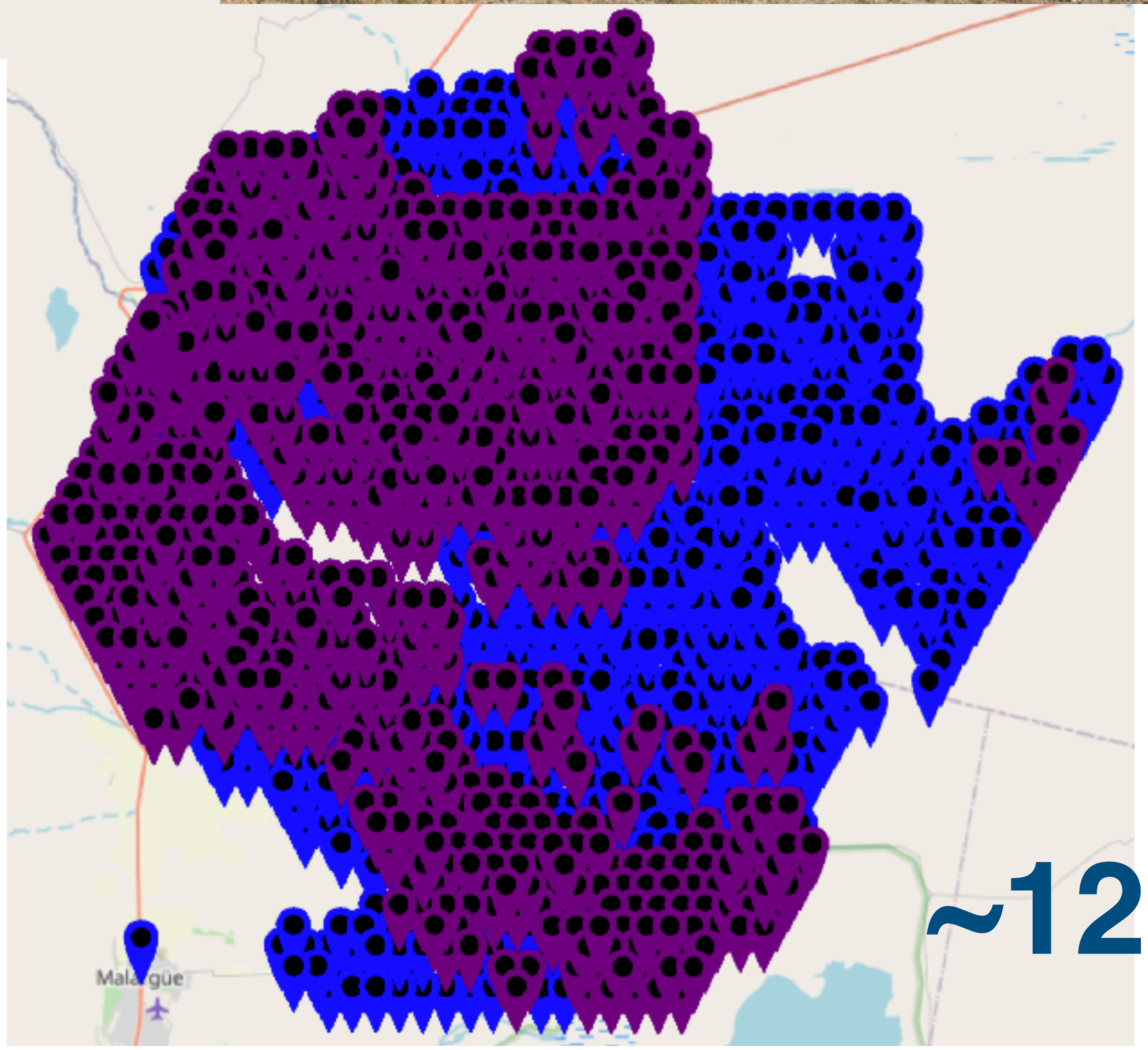


~500 stations Nov 2023



~1000 stations Mar 2024

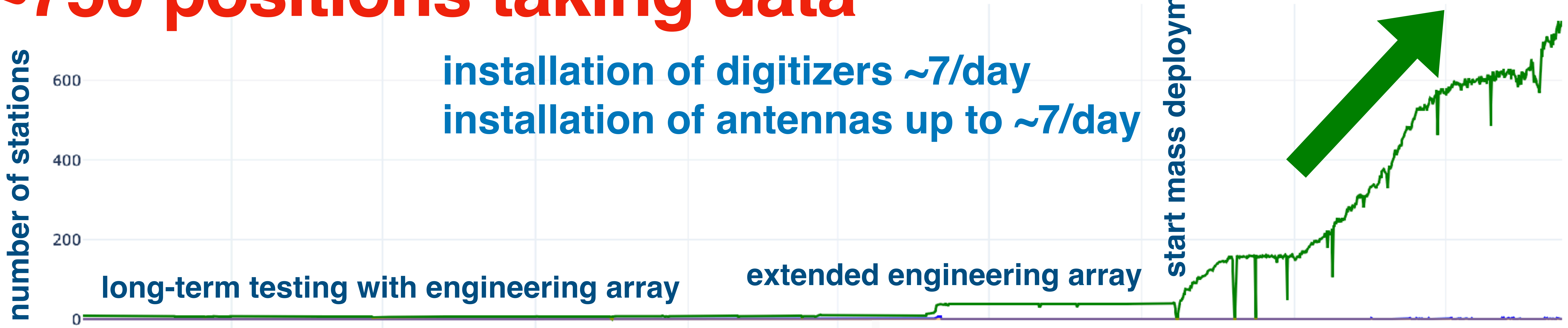




~1200 stations June 2024

PIERRE
AUGER
OBSERVATORY

~750 positions taking data



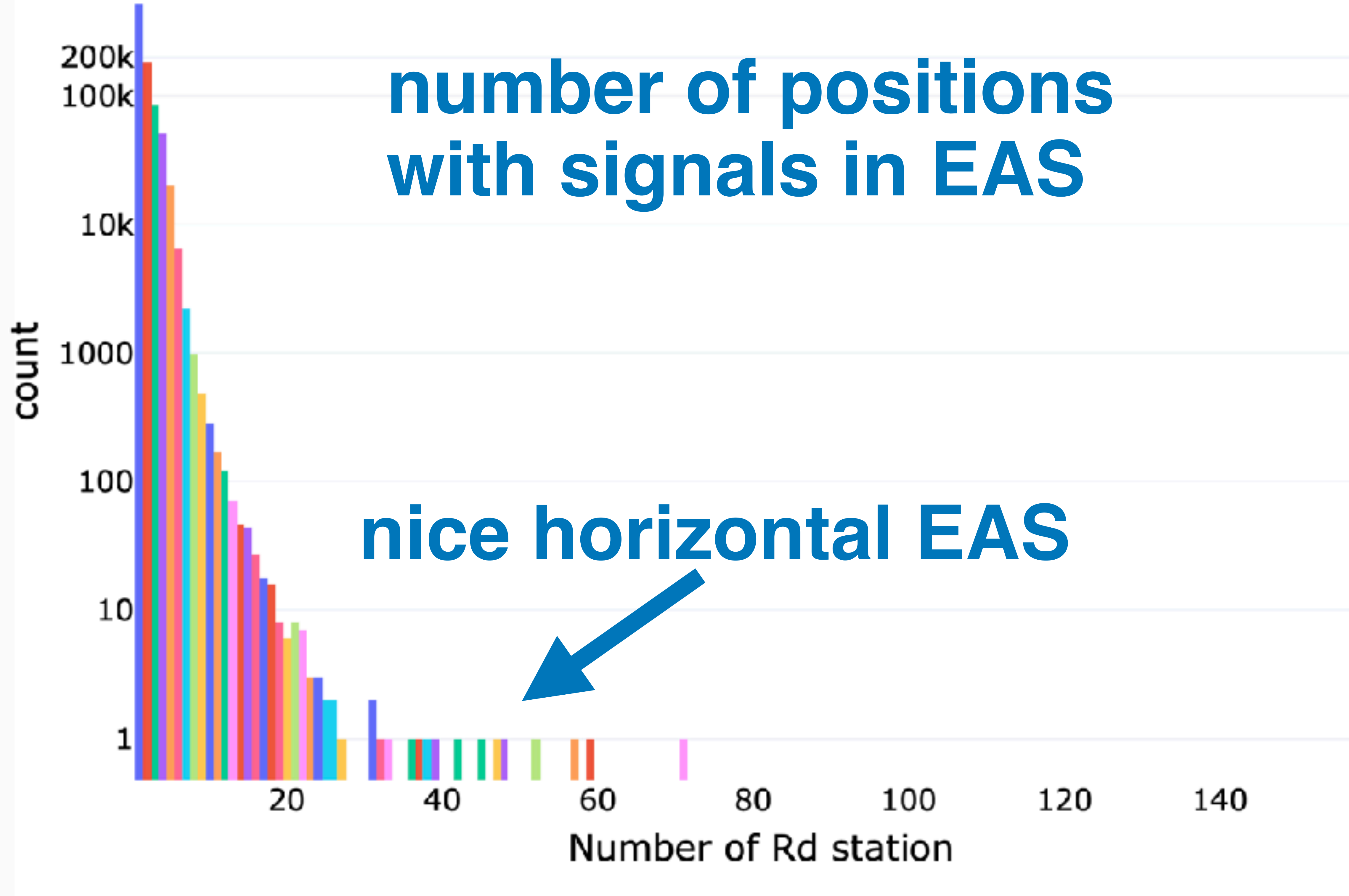
installation of digitizers ~7/day
installation of antennas up to ~7/day

start mass deployment

long-term testing with engineering array

extended engineering array

positions in DAQ

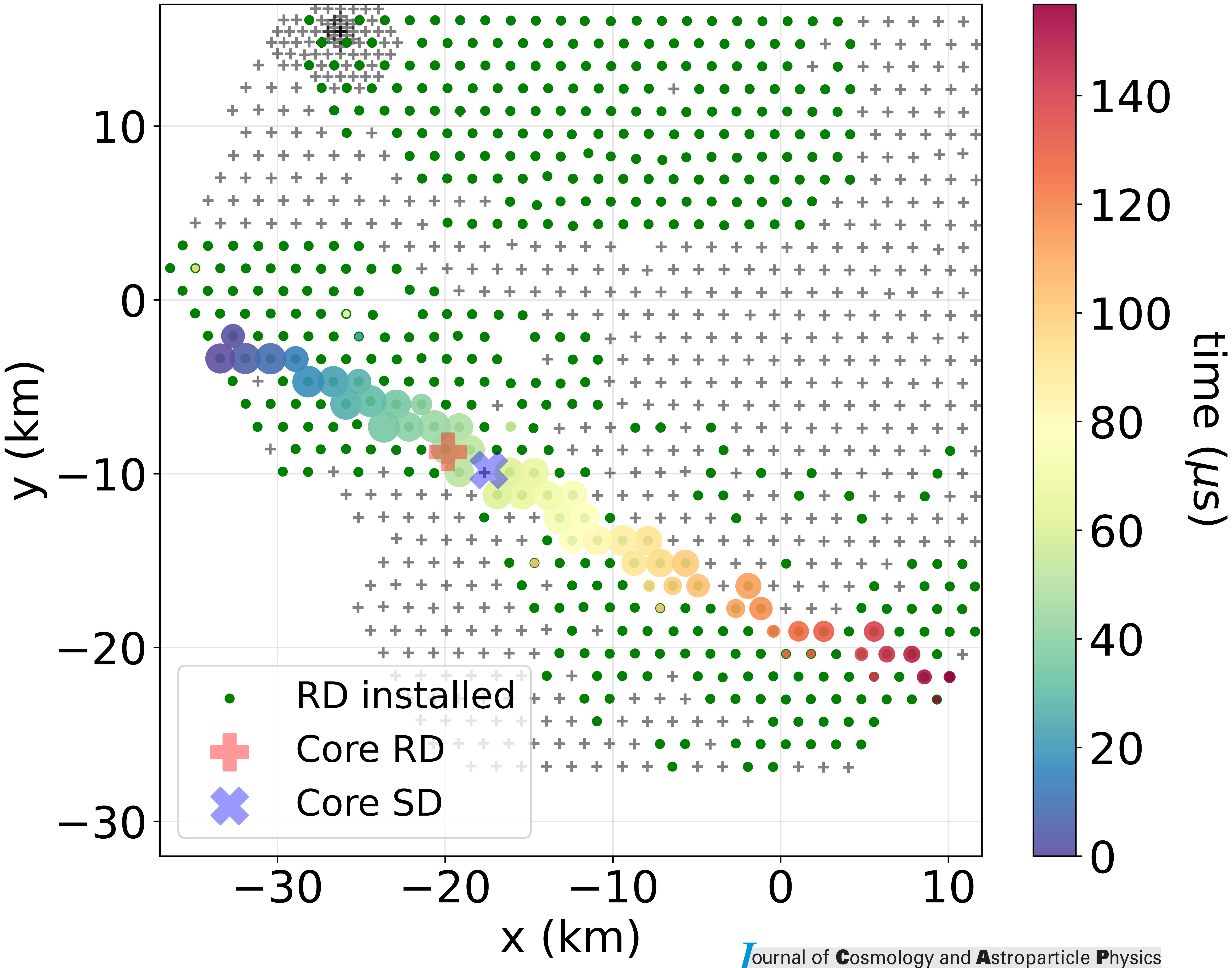


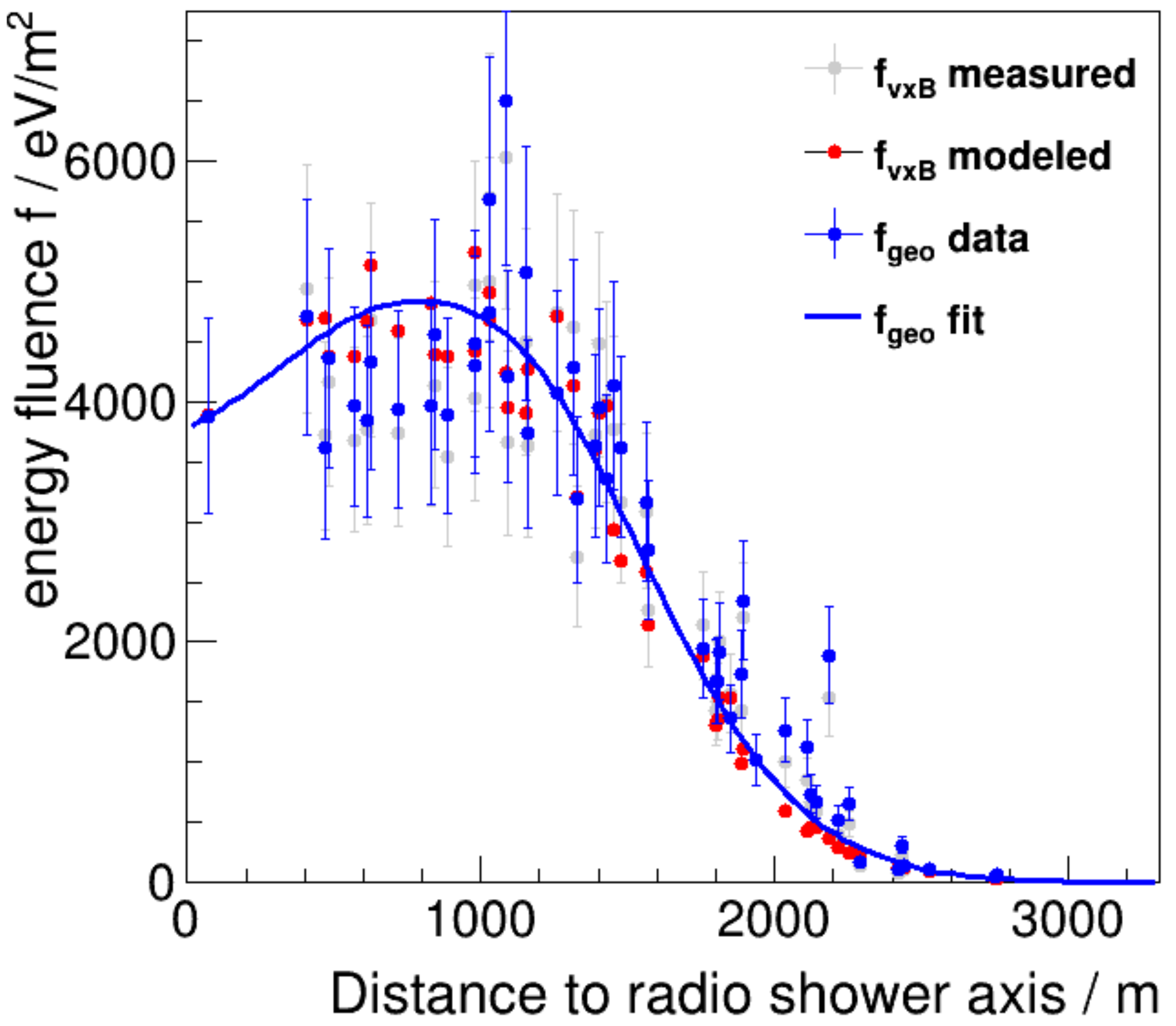
number of positions with signals in EAS

nice horizontal EAS

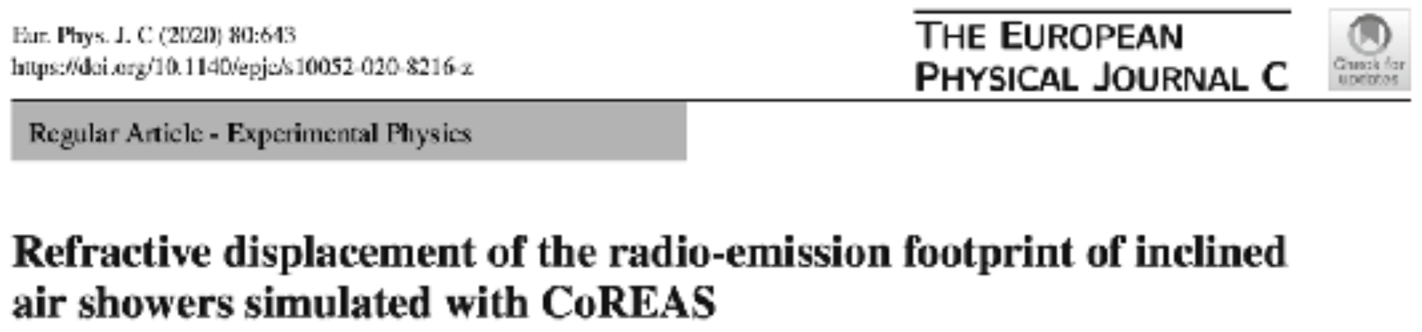
PIERRE AUGER OBSERVATORY

A measured cosmic ray





	RD	SD
Azimuth (deg)	156.99±0.01	157±0.1
Zenith (deg)	84.7±0.01	84.7±0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40±0.88
Core Y (km)	-8.73	-9.78±0.45


Eur. Phys. J. C (2020) 80:643
https://doi.org/10.1140/epjc/s10052-020-8216-z

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

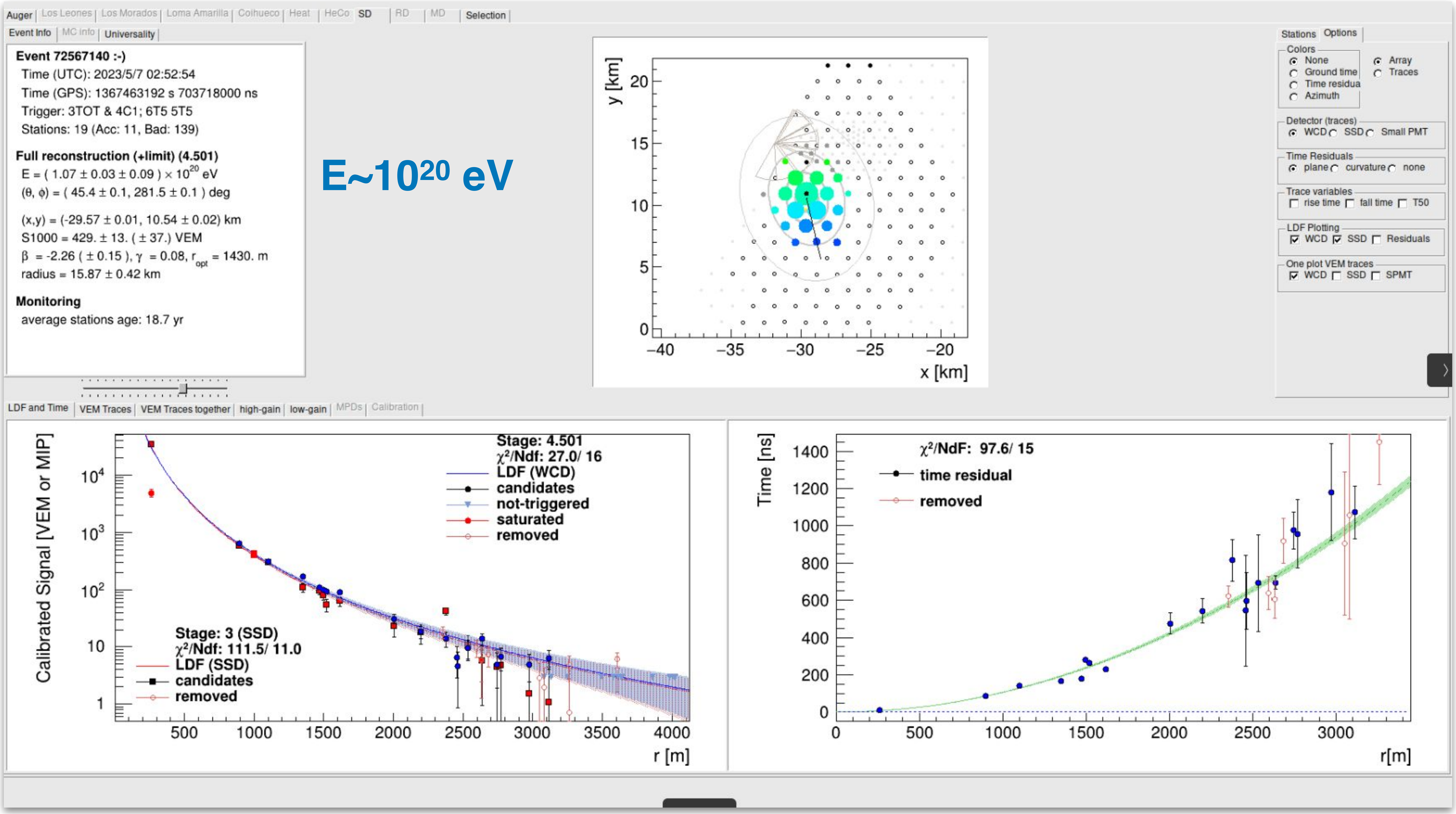
Refractive displacement of the radio-emission footprint of inclined air showers simulated with CoREAS


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Signal model and event reconstruction for the radio detection of inclined air showers

F. Schlüter[a,b,*] and T. Huege[a,c] JCAP01(2023)008

Pierre Auger Observatory - SSD



Event 72567140 :-)

Time (UTC): 2023/5/7 02:52:54

Time (GPS): 1367463192 s 703718000 ns

Trigger: 3TOT & 4C1; 6T5 5T5

Stations: 19 (Acc: 11, Bad: 139)

Full reconstruction (+limit) (4.501)

$E = (1.07 \pm 0.03 \pm 0.09) \times 10^{20}$ eV

$(\theta, \phi) = (45.4 \pm 0.1, 281.5 \pm 0.1)$ deg

$(x,y) = (-29.57 \pm 0.01, 10.54 \pm 0.02)$ km

$S1000 = 429. \pm 13. (\pm 37.)$ VEM

$\beta = -2.26 (\pm 0.15), \gamma = 0.08, r_{opt} = 1430.$ m

radius = 15.87 ± 0.42 km

Monitoring

average stations age: 18.7 yr

E~10^{20} eV

Stations | Options

Colors: ● None ○ Ground time ○ Time residua ○ Azimuth

● Array ○ Traces

Detector (traces): ● WCD ○ SSD ○ Small PMT

Time Residuals: ● plane ○ curvature ○ none

Trace variables: ☐ rise time ☐ fall time ☐ T50

LDF Plotting: ☑ WCD ☑ SSD ☐ Residuals

One plot VEM traces: ☑ WCD ☐ SSD ☐ SPMT

Stage: 4.501

χ^2/Ndf: 27.0/ 16

LDF (WCD)

candidates

not-triggered

saturated

removed

Stage: 3 (SSD)

χ^2/Ndf: 111.5/ 11.0

LDF (SSD)

candidates

removed

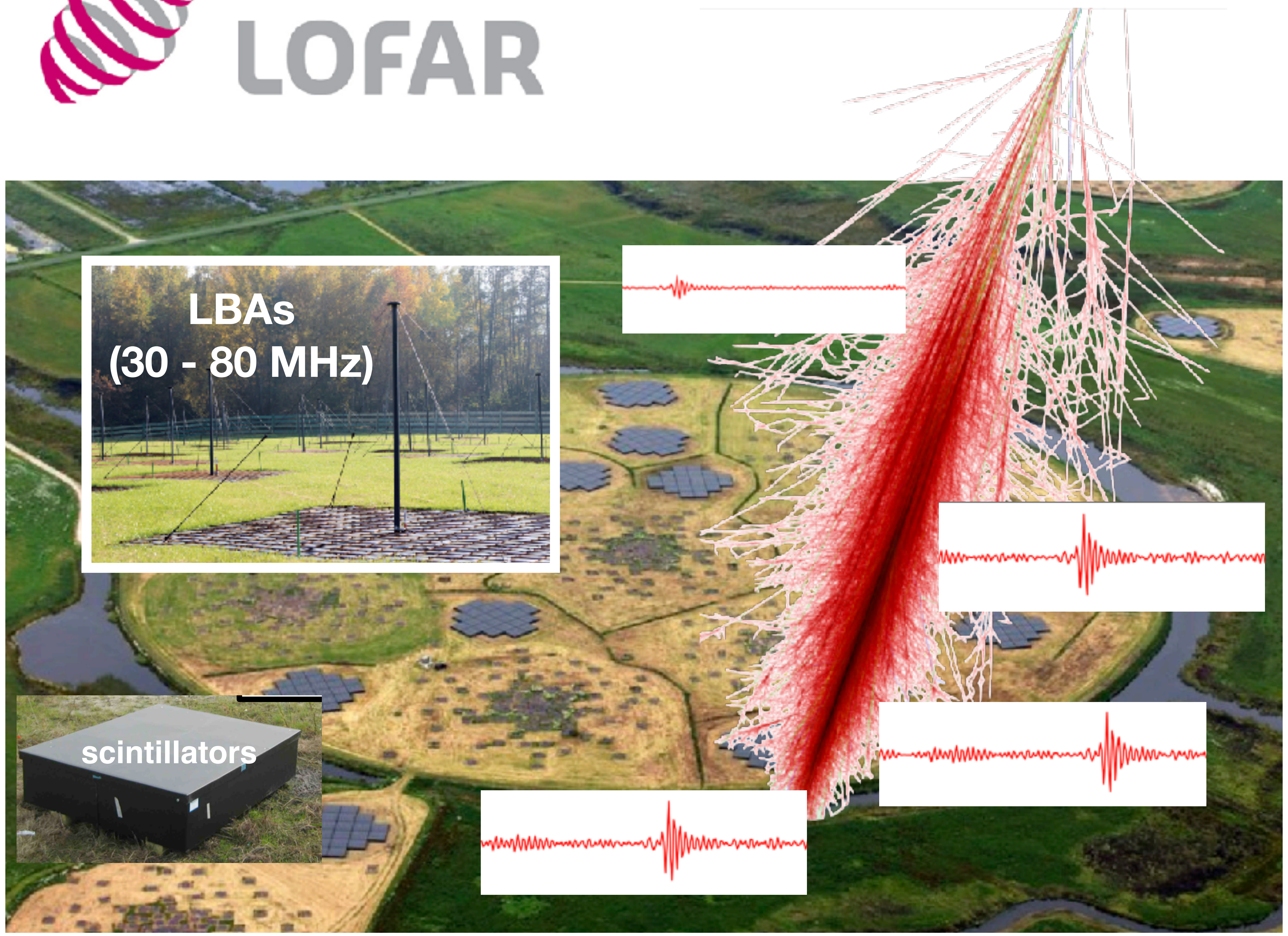
χ^2/NdF: 97.6/ 15

time residual

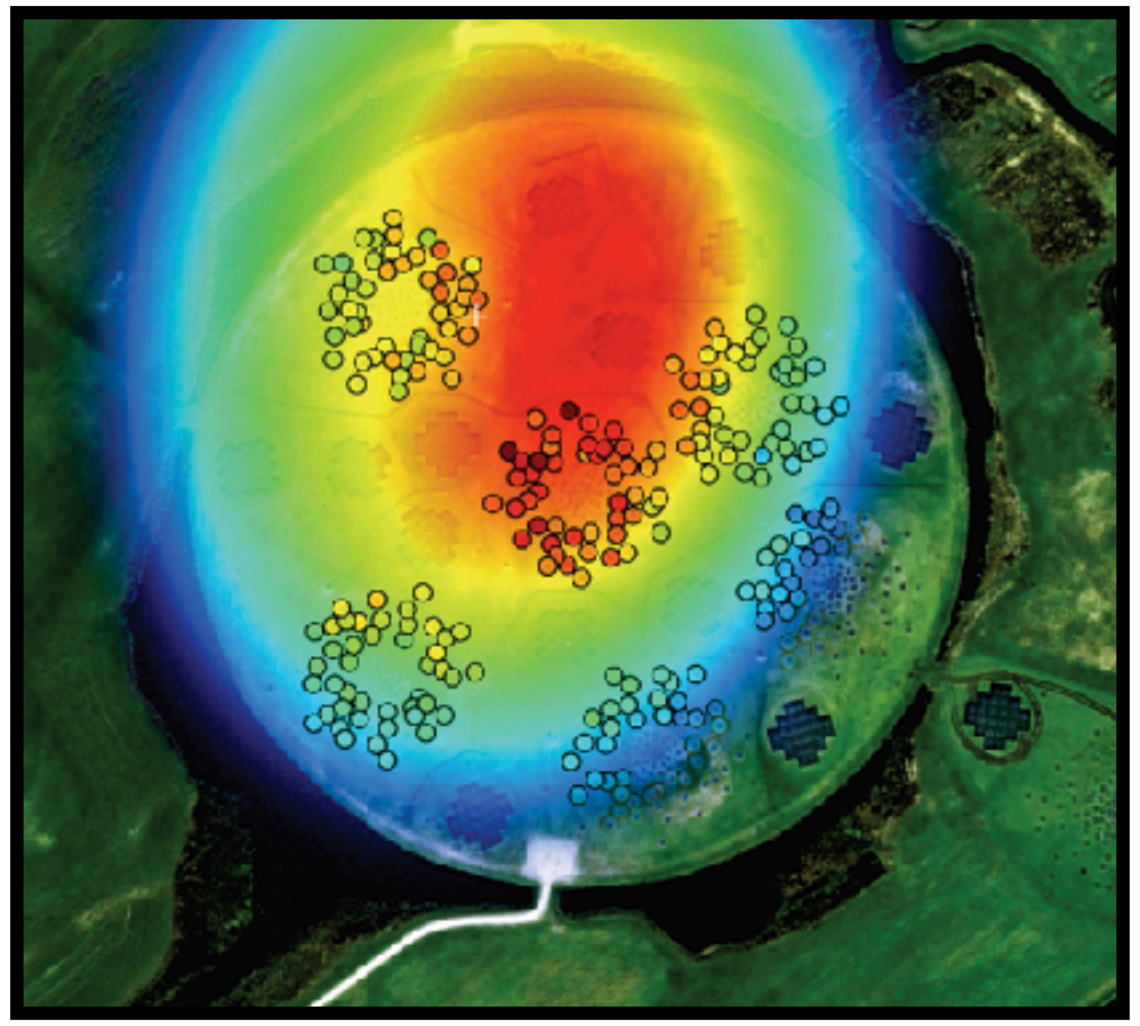
removed

K. Almeida Cheminant

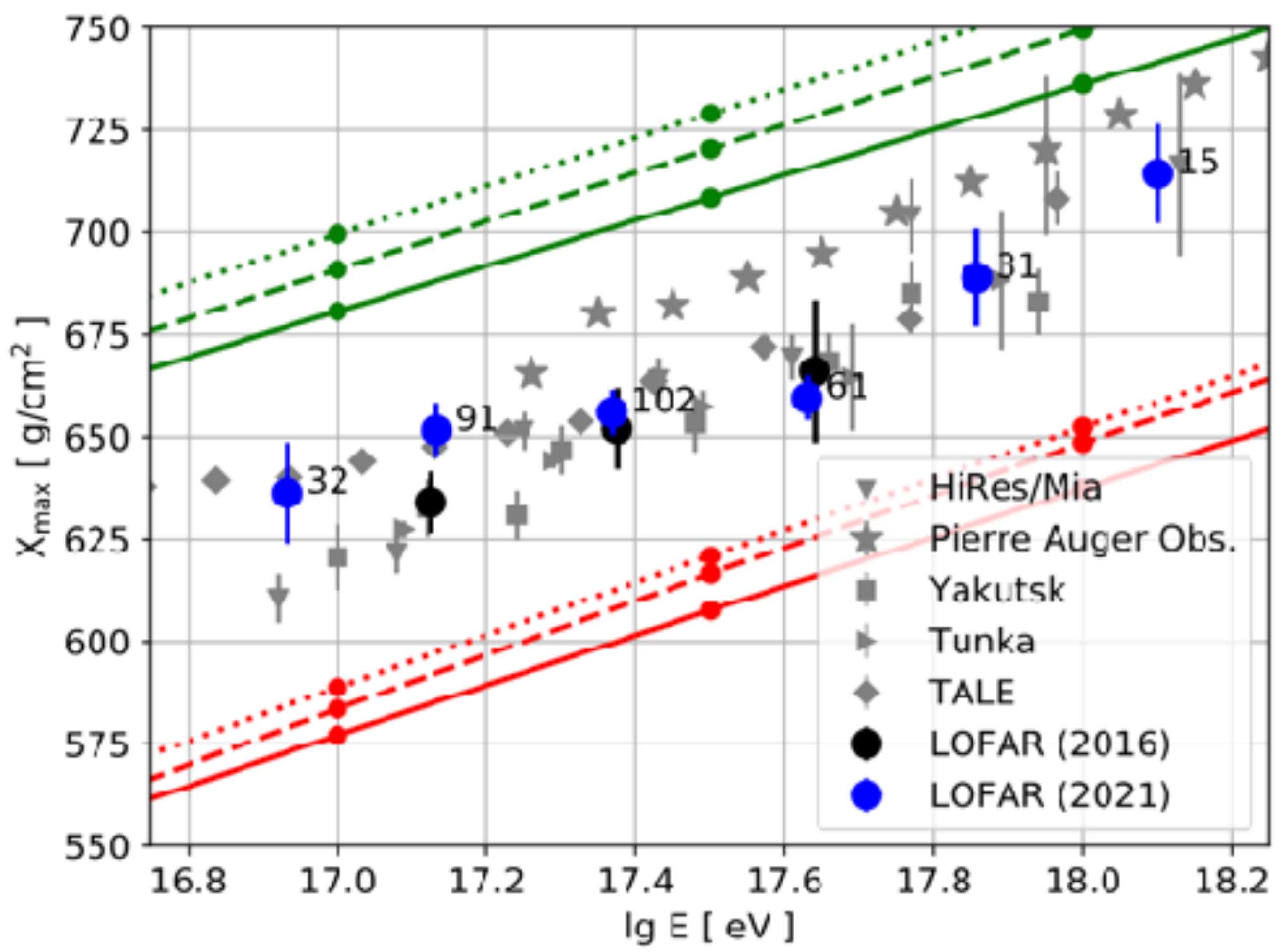
LOFAR Radio cosmic-ray detection with dense arrays



- 10+ years of CR detection at LOFAR
- Confirmation of radio emission mechanisms and signal polarization, important step forward in the field
- Detailed reconstruction of radio footprint - energy and X_{max}



A. Corstanje et al. Phys Rev D 2021



Next up - major upgrade to LOFAR 2.0!

- 10x increase in event rate
- 100% duty cycle
- Increased measurement bandwidth
- Wider energy range

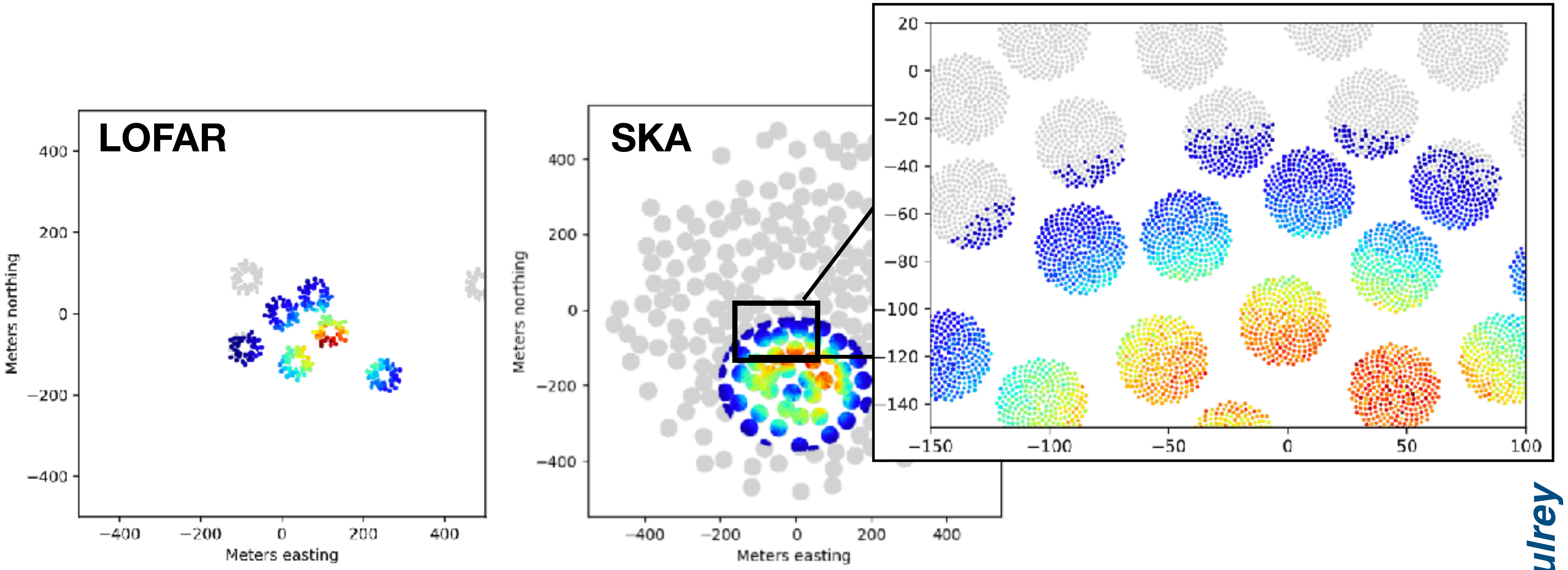
K. Mulrey

SKA

Radio cosmic-ray detection with dense arrays

- The next generation radio telescope is the Square Kilometer Array (SKA), with the 50-350 MHz component being built in the Australian Outback
- We will be able to measure the CR radio footprint between 10^{16} - 10^{18} eV with 10,000+ antennas!
- Deploying now! First data in the next 2 years

- Unprecedented X_{max} reconstruction (6-8 g/cm^2)
- Probe high energy hadronic physics
- Proton / Helium primary separation
- Beamforming - access to very low energies
- Can we detect gamma rays?



K. Mulrey

GRAND concept

200'000 radio antennas over 200'000 km^2
in several sub-arrays at favorable sites worldwide

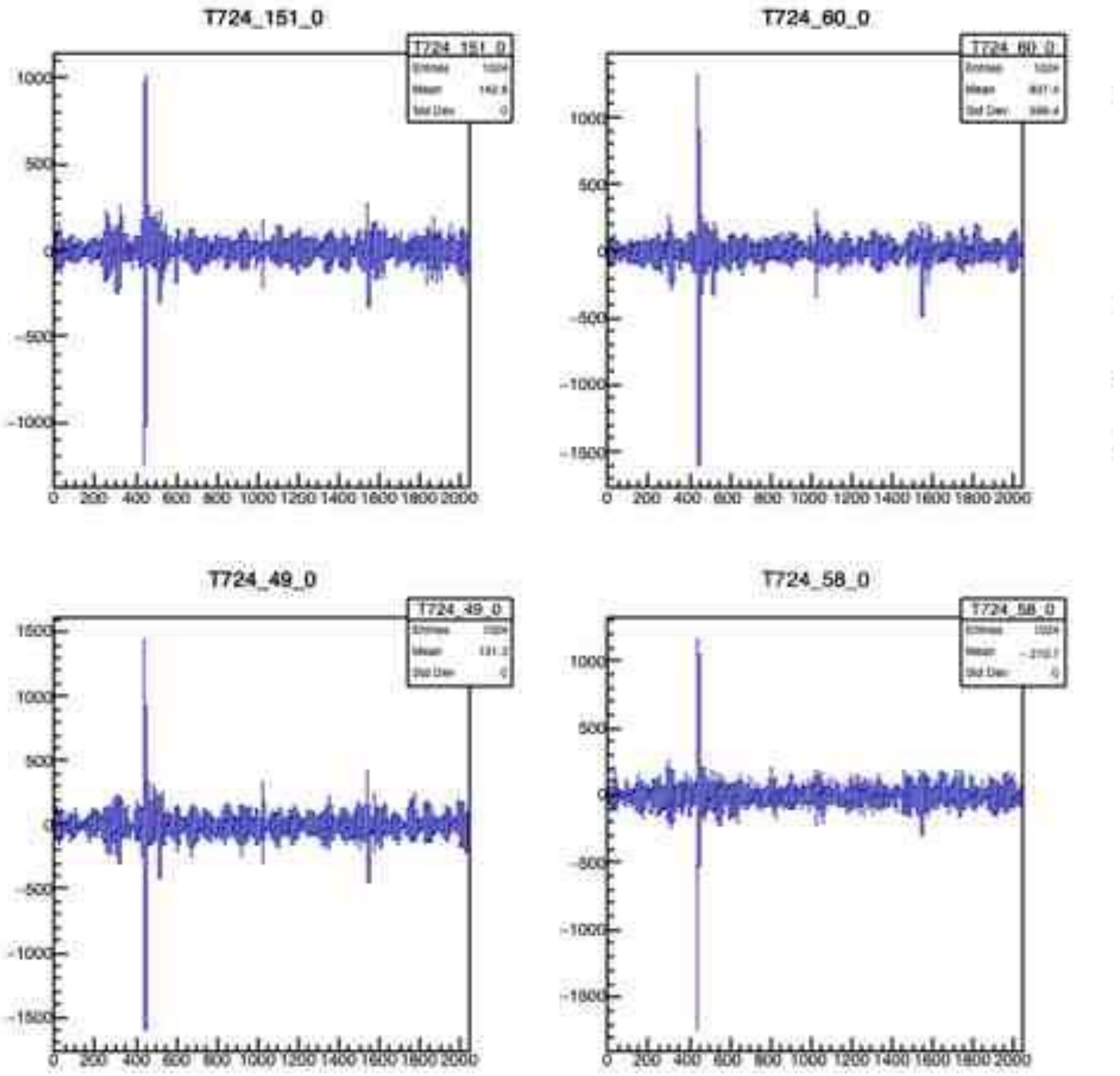
scalable, cheap, robust radio antennas
ideal for **giant** arrays

3 Prototypes	GRAND10k	GRAND200k
2023	2028	203X
cosmic rays $10^{16.5-18}$ eV **autonomous** radio detection of **very inclined** air-showers	**discovery of EeV neutrinos** for optimistic fluxes 2 detectors of 5-10k antennas: GRAND-North (China) GRAND-South (Argentina?)	**1st EeV neutrino detection and/or neutrino astronomy!**

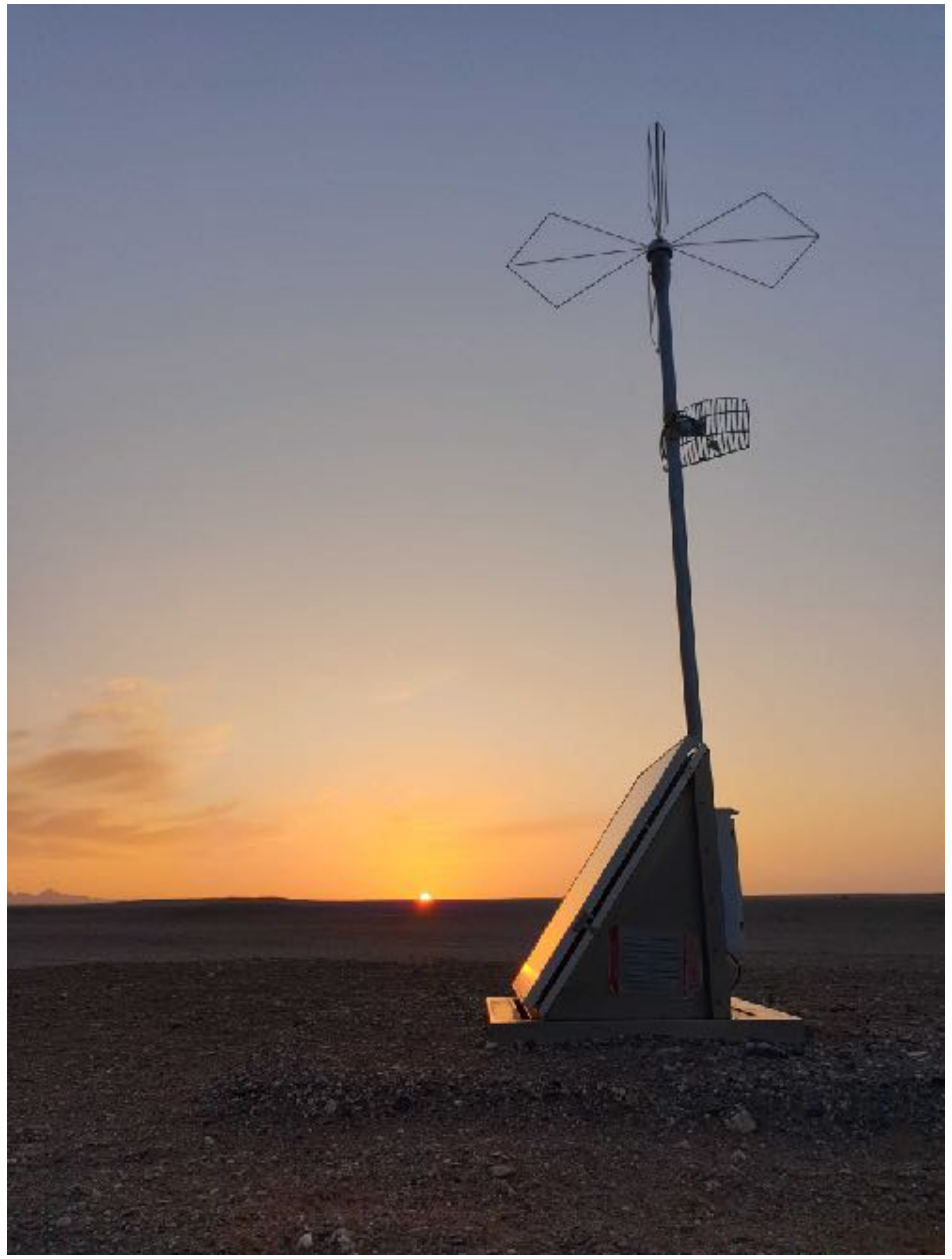
C. Timmermans

Progress in GRAND

prototypes



GRAND@Auger: 10 antennas at the Pierre Auger Observatory



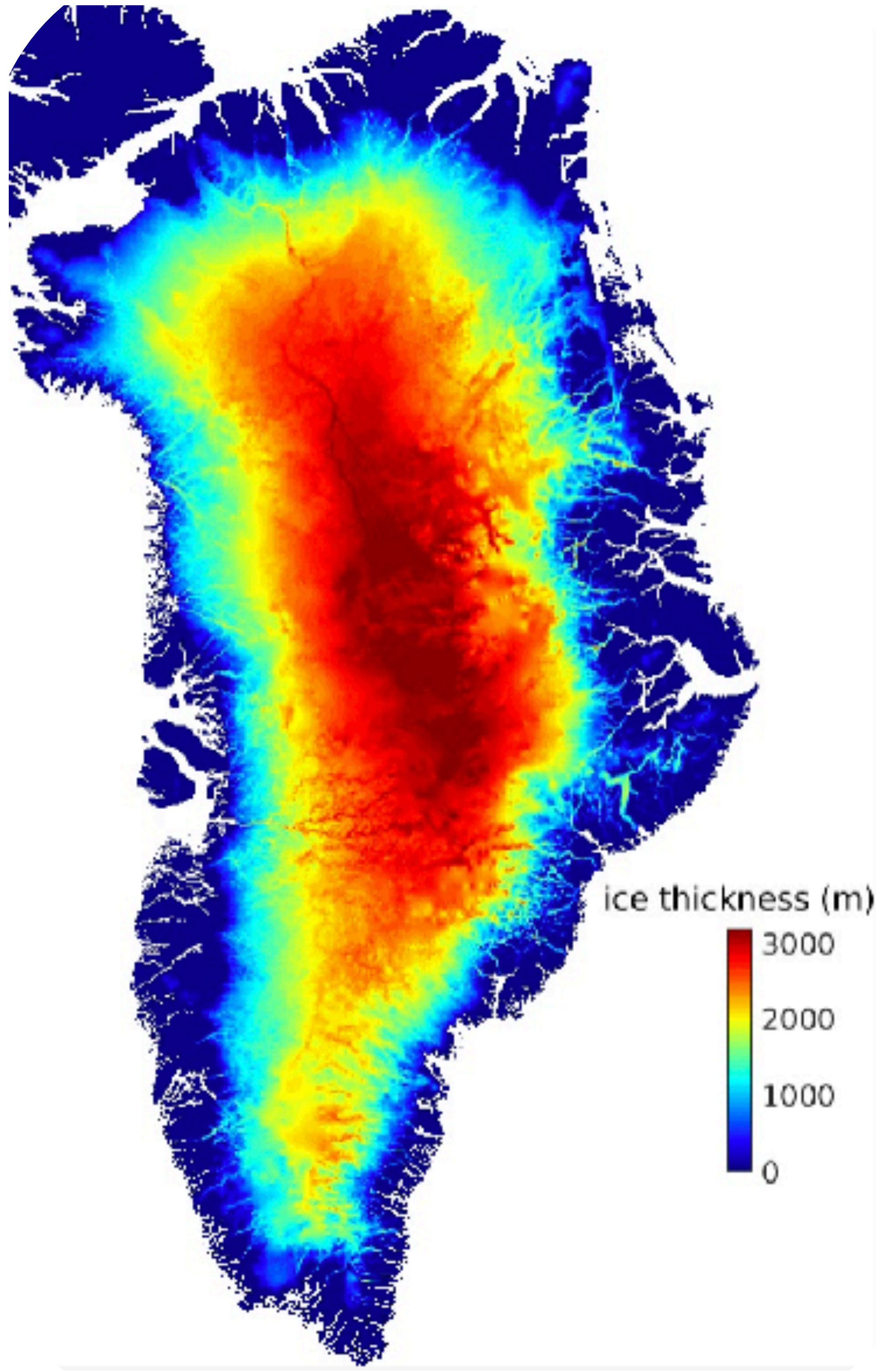
GP13: 13 antennas near DunHuang, China

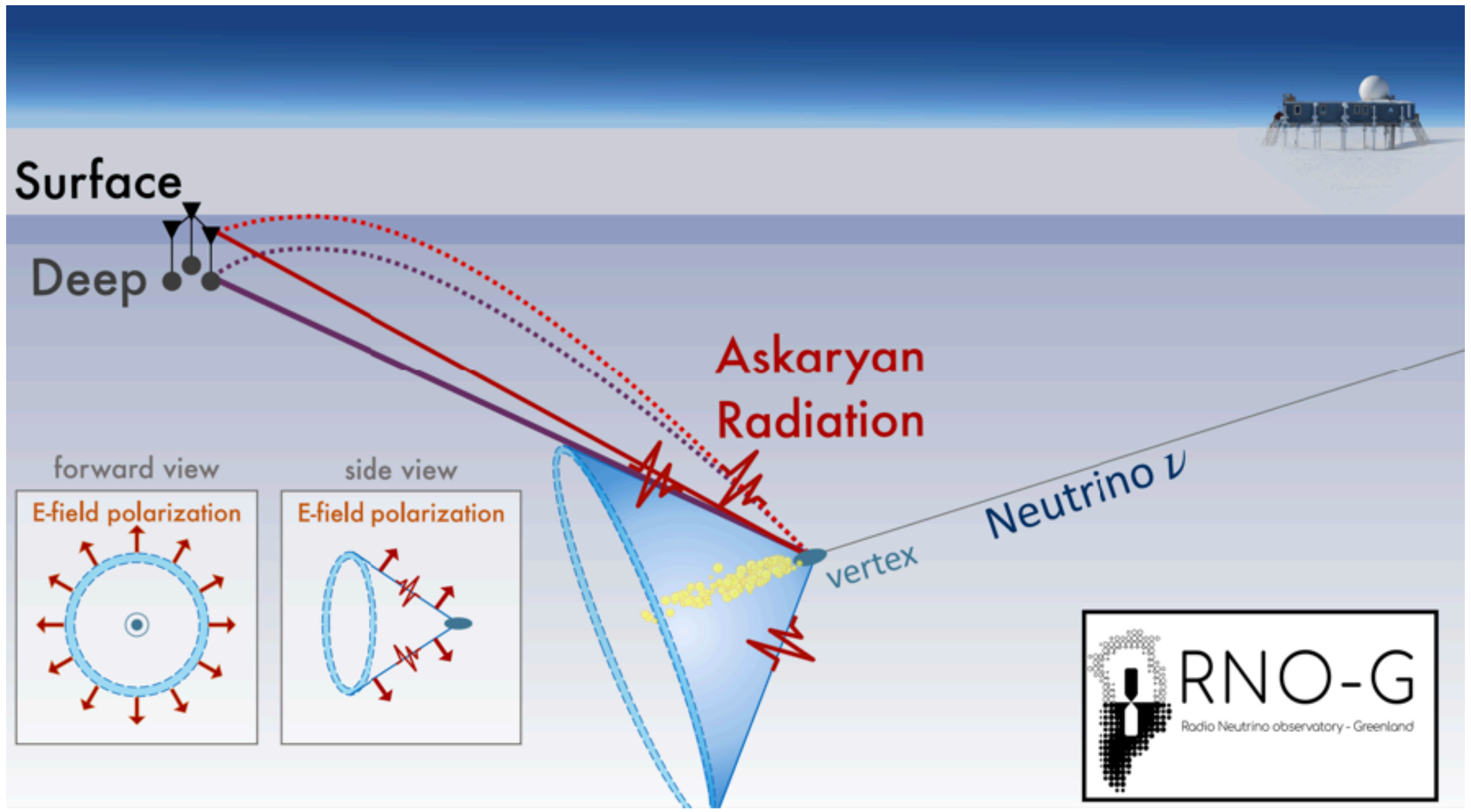
C. Timmermans

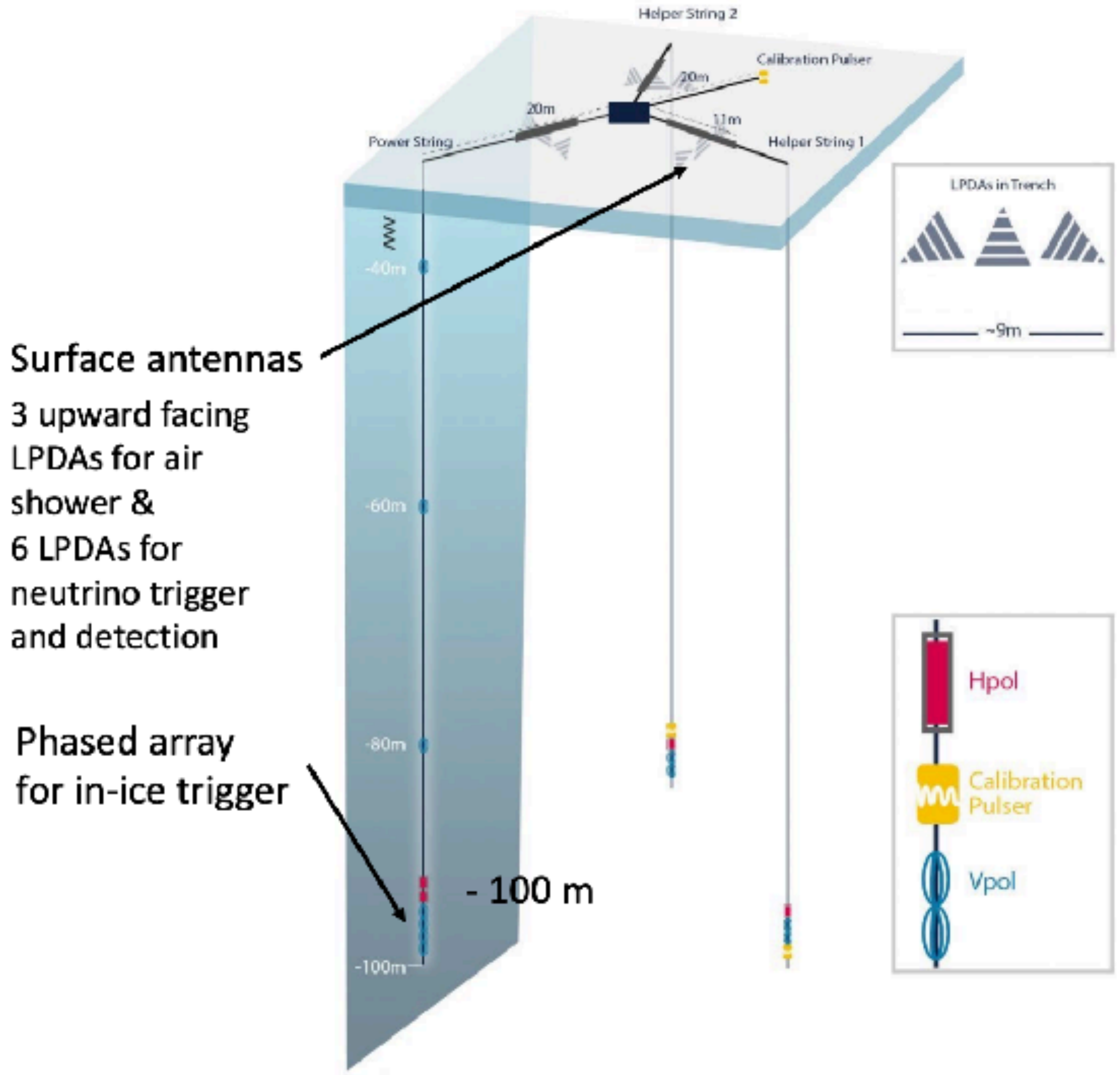
Next steps:
filtering and searching for coincidences with Auger (in GRAND@Auger) or signatures of air showers from direction and polarization (in GP13)

Radio Neutrino Observatory - Greenland

- Polar ice has a radio attenuation length ~ kms (natural target!)
- Very sparse instrumentation can be built to cover large areas
- 35 stations deployed over 5 (+/-) years, makes this a possible detection instrument in the next decade
- First stations deployed in 2021







Surface antennas
3 upward facing LPDAs for air shower &
6 LPDAs for neutrino trigger and detection

Phased array for in-ice trigger

K. Mulrey

RET: Radar Echo Telescope

the RADAR ECHO TELESCOPE for COSMIC RAYS

RET - Neutrinos

- Instrument a large volume of ice with a radar system.
- A radio transmitter (TX) constantly illuminates the ice.
- A neutrino (ν) interacts in the monitored volume, leaving an ionization trail.
- The ionization trail will reflect a radio signal, which is recorded by the receivers (RX).

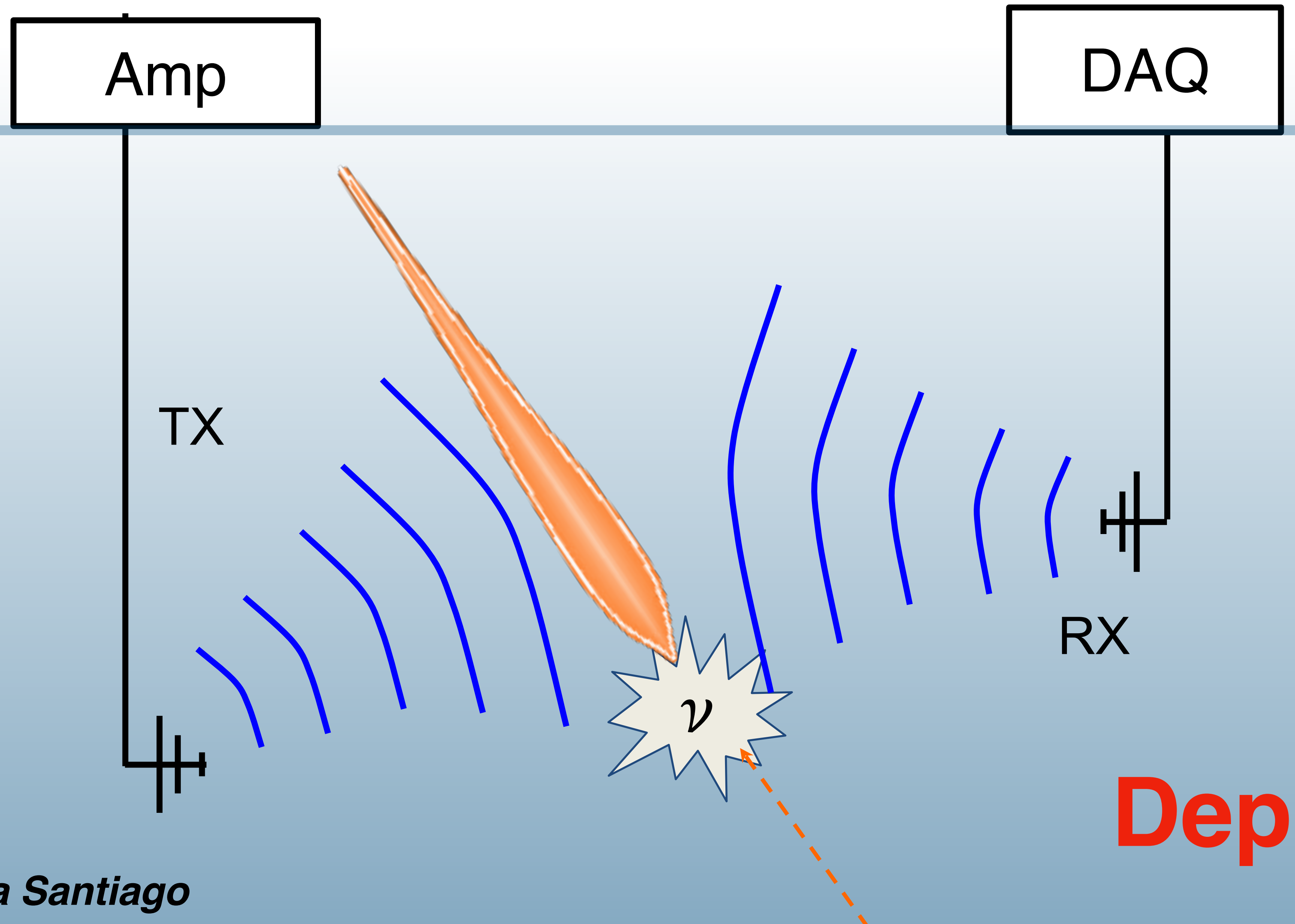
Phys. Rev. D 100, 072003 (2019)
Phys. Rev. Lett. 124, 091101 (2020)

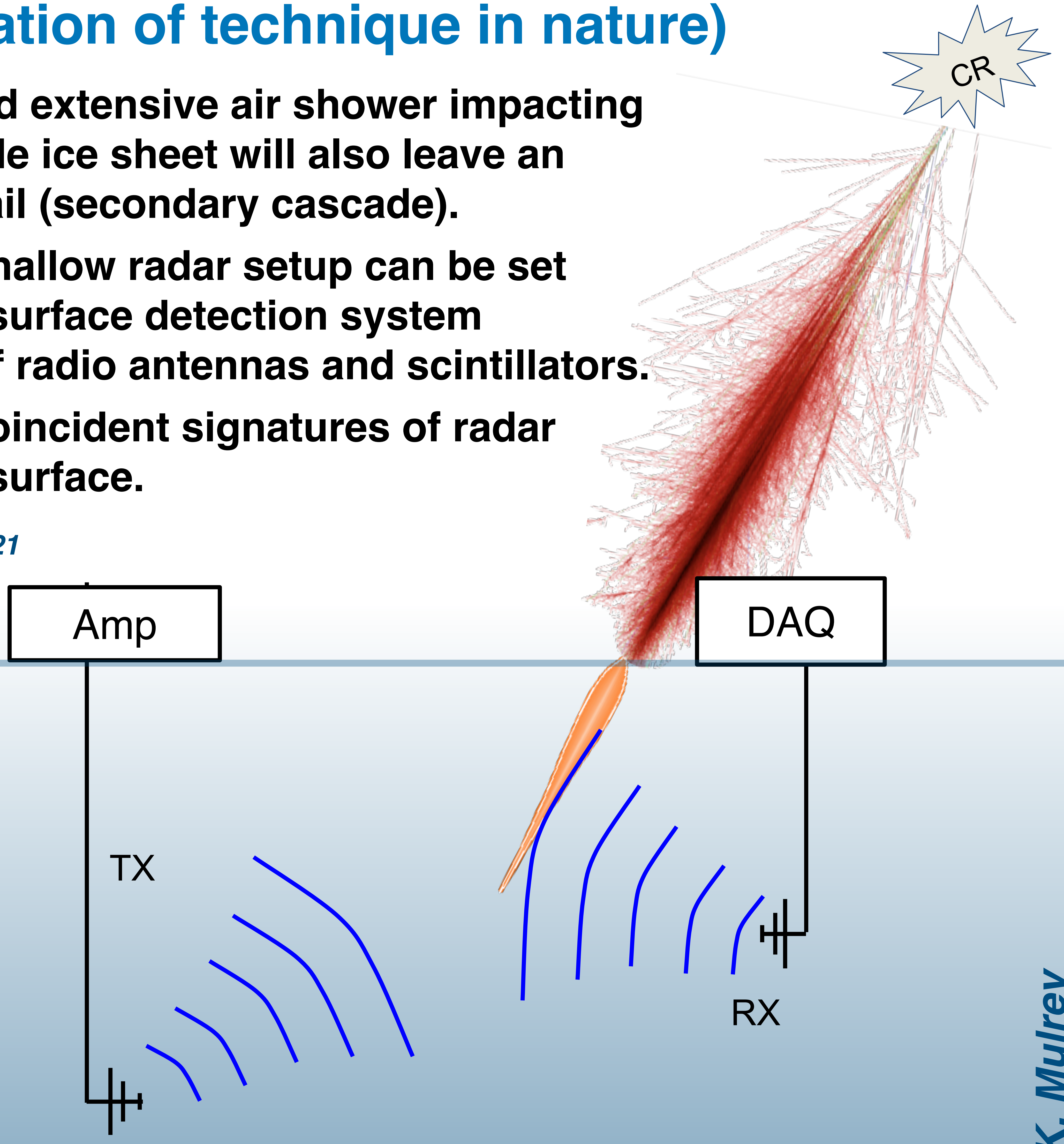
RET - Cosmic Rays

(demonstration of technique in nature)

- A CR-induced extensive air shower impacting a high-altitude ice sheet will also leave an ionization trail (secondary cascade).
- RET-CR: A shallow radar setup can be set alongside a surface detection system composed of radio antennas and scintillators.
- Search for coincident signatures of radar echoes and surface.

Phys. Rev. D 104, 2021



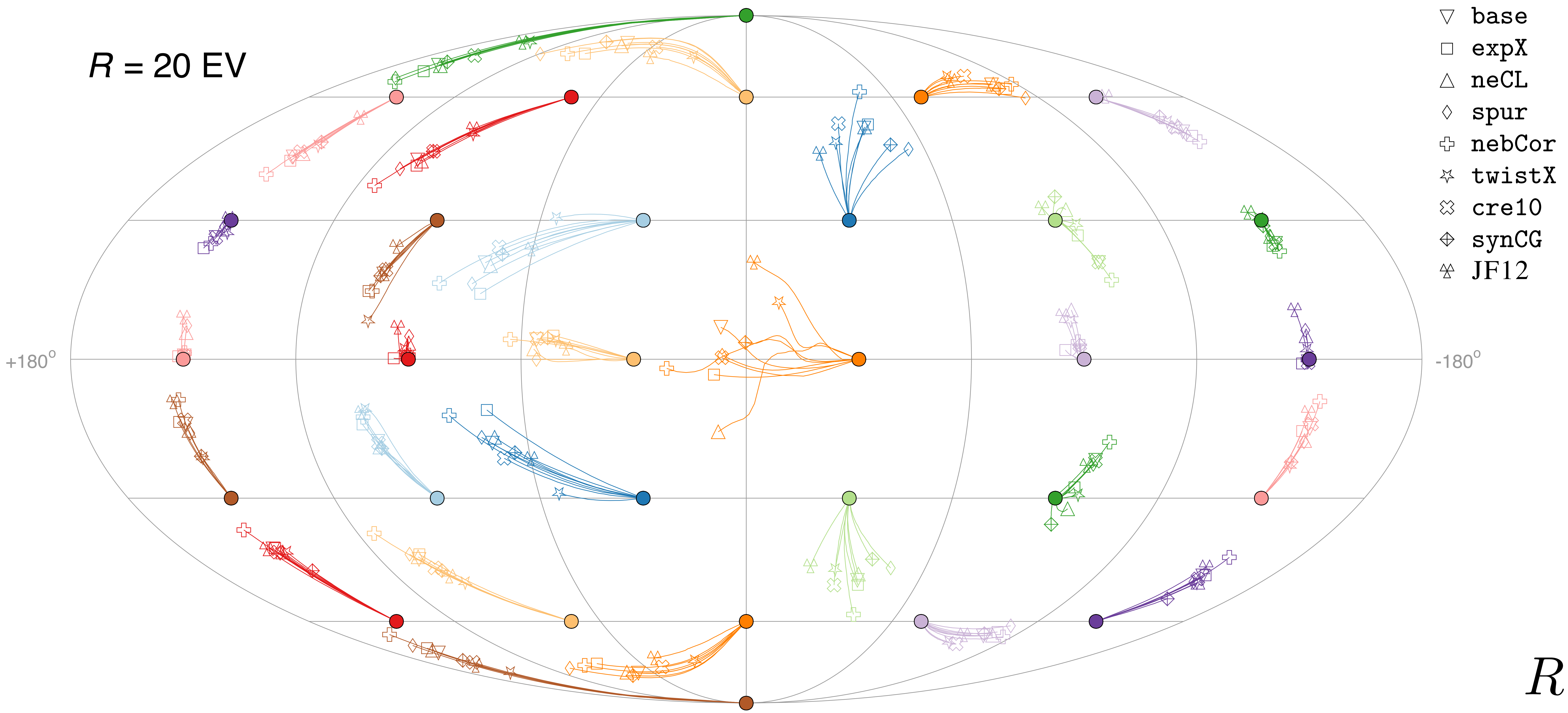


Deployed in 2024!

Slide credit:
Enrique Huesca Santiago

K. Mulrey

Deflection of cosmic rays in magnetic fields



$$R = \frac{E}{Z} \approx \frac{E}{A/2}$$

Figure 19. Angular deflections of ultrahigh-energy cosmic rays in the eight model variations derived in this paper and JF12. The cosmic-ray rigidity is 20 EV (2×10^{19} V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

The Coherent Magnetic Field of the Milky Way

Michael Unger[1,2] and Glennys R. Farrar[3]

➡ **need to know rigidity (mass) of incoming cosmic rays**

GCOS - Global Cosmic Ray Observatory

UHECRs observatory covering more than 60,000 km^2 (40,000 -80,000 km^2)

With $60,000$ km^2 we can reach the integrated Auger 2030-exposure in 1 years
AugerPrime expected exposure in 6 months

Targeting very good quality events for energies $\geq$ 30 EeV (5-fold) and full efficiency at 10 EeV (3-fold events)

Resolutions per event: energy better than 10%, muon resolution better than 10%,
X_{max} better than 30 g/cm^2, and angular resolution better than 1°

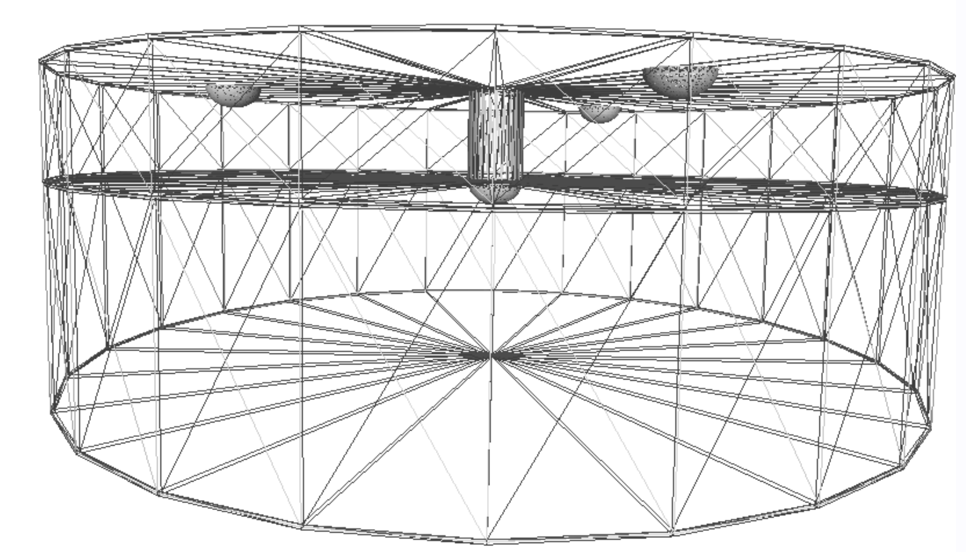
Full sky coverage with sites in both hemispheres and surrounded by mountains

I. Maris et al, UHECR (2022)

GCOS - Global Cosmic Ray Observatory

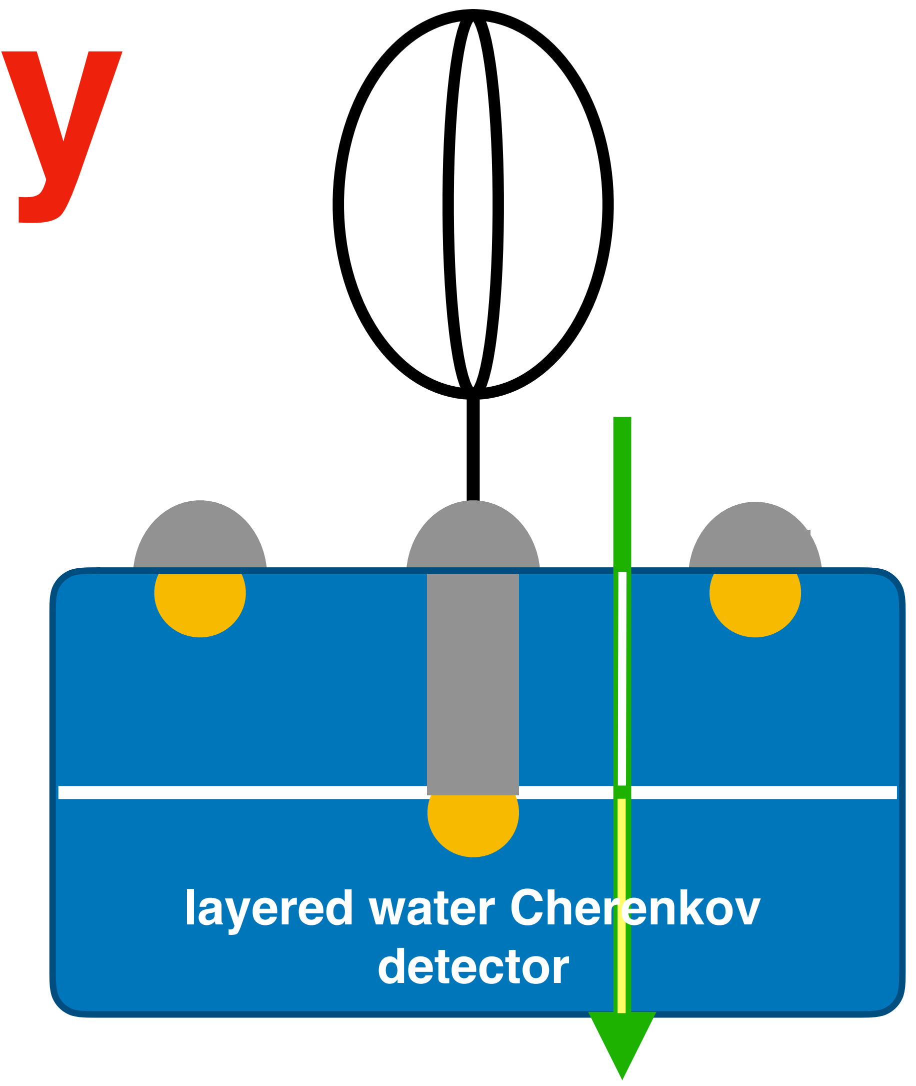
The idea: optical separation of a Water Cherenkov Tank

A water volume responds different to photons, $e^\pm$ and $\mu^\pm$

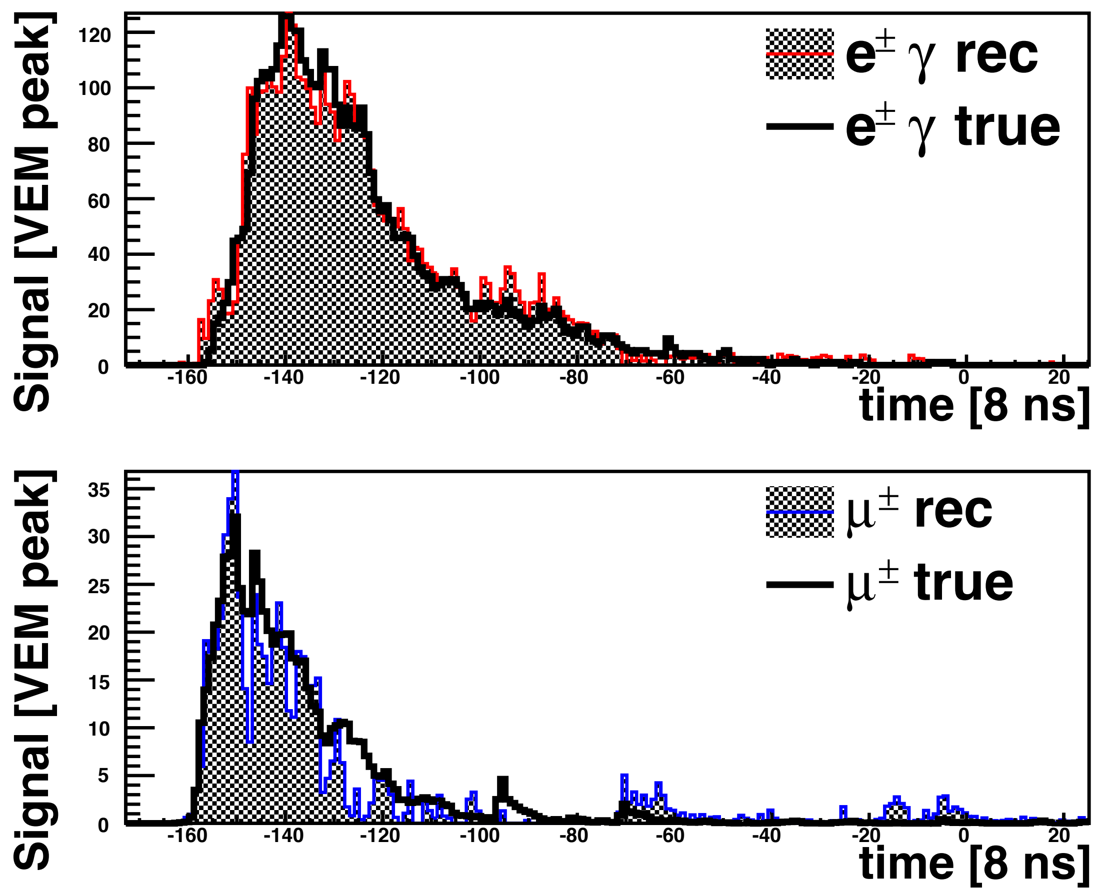


$$\begin{pmatrix} S_{\rm top} \\ S_{\rm bot}\end{pmatrix} = \mathcal{M}\begin{pmatrix} S_{\rm EM}\\ S_\mu\end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b\end{pmatrix}\begin{pmatrix} S_{\rm EM}\\ S_\mu\end{pmatrix}$$

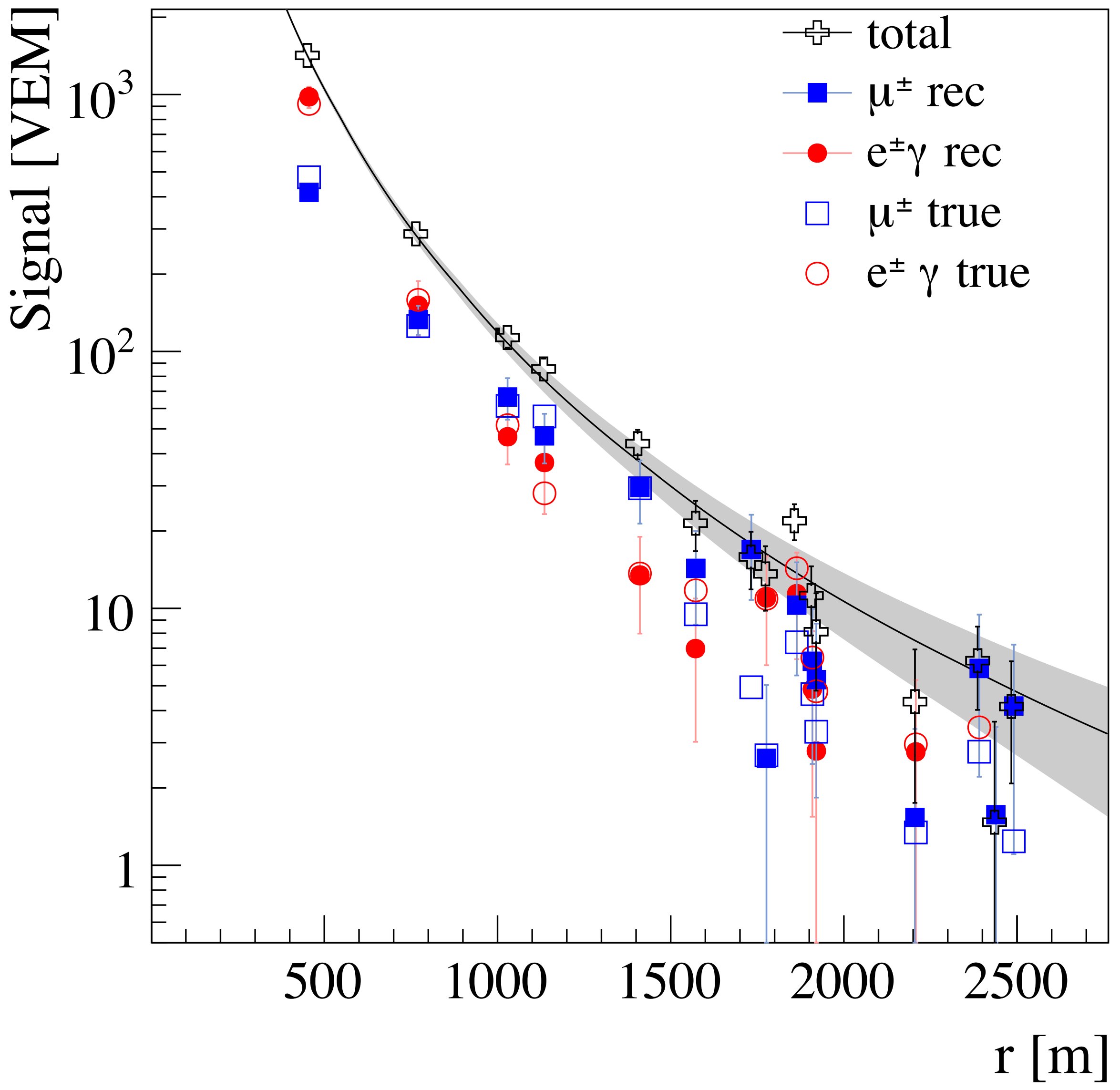
$$\begin{pmatrix} S_{\rm EM}\\ S_\mu\end{pmatrix} = \mathcal{M}^{-1}\begin{pmatrix} S_{\rm top} \\ S_{\rm bot}\end{pmatrix}$$



Not only total signal, but also time distributions



Based on Universality or DNN we can get $X_{\rm max}$



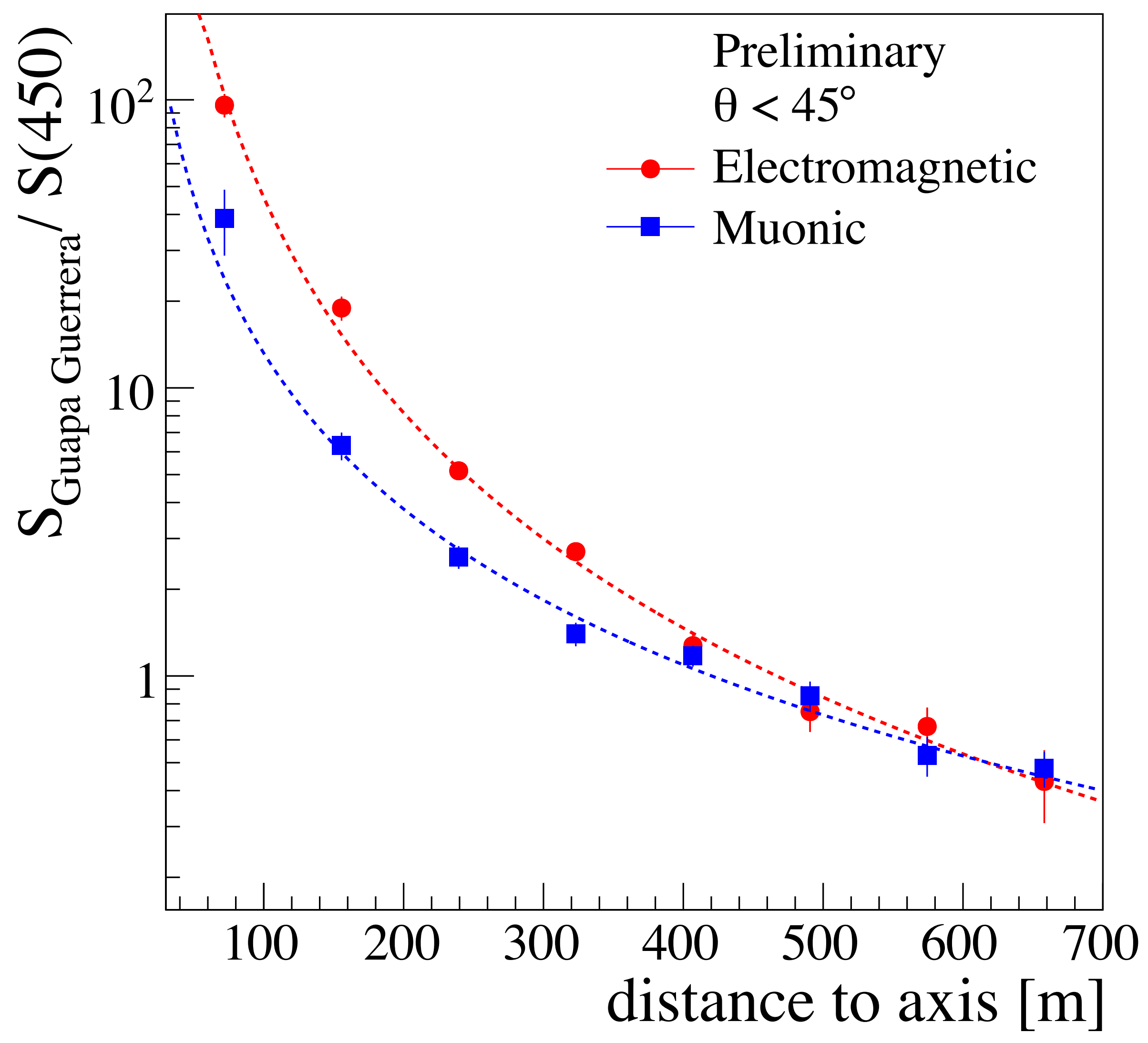
Ioana Maris

Antoine Letessier-Selvon et al., Nucl. Instr. Meth. A 767 (2014) 41–49

prototype measurements at Auger Observatory

Mean LDFs for the electromagnetic and muonic components

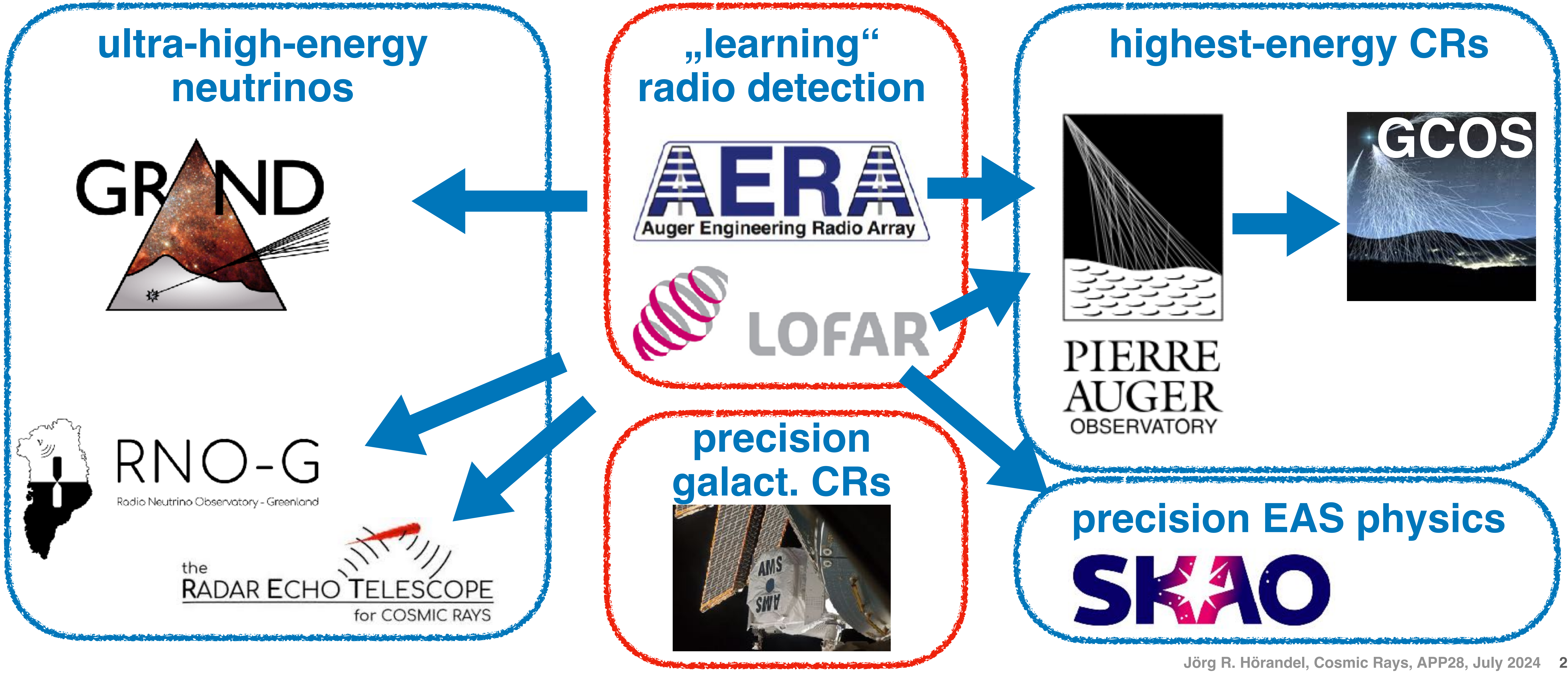
900 events ($E > 0.03\,\mathrm{EeV}$, $\theta < 45^\circ$)



Cosmic Rays 2024-2034

NOVA Nikhef

In NL successful collaboration between high-energy physics and astrophysics



ultra-high-energy neutrinos

GRAND

RNO-G
Radio Neutrino Observatory - Greenland

the RADAR ECHO TELESCOPE for COSMIC RAYS

„learning“ radio detection

AERA
Auger Engineering Radio Array

LOFAR

precision galact. CRs

AMS

highest-energy CRs

PIERRE AUGER OBSERVATORY

GCOS

precision EAS physics

SKAO

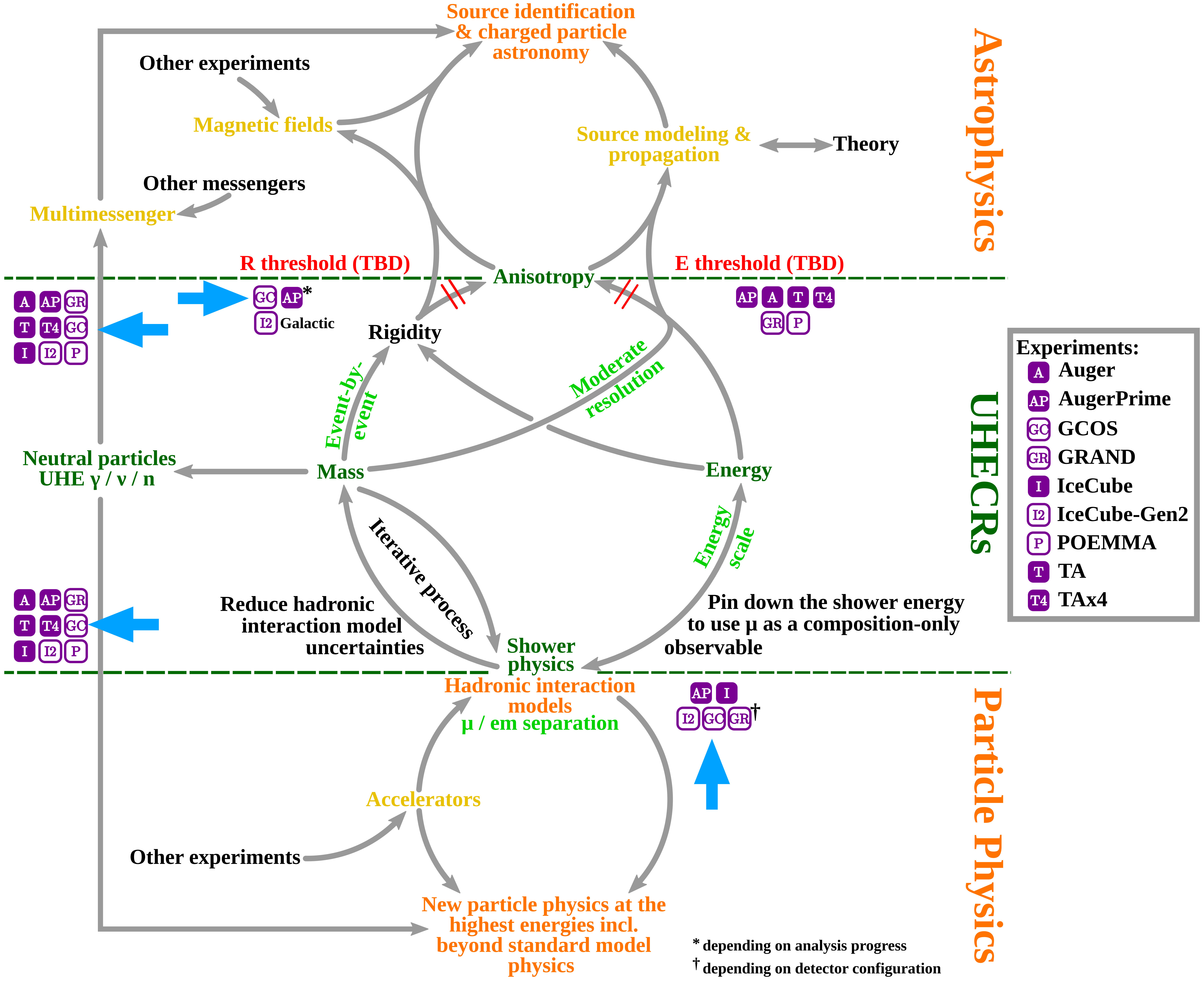
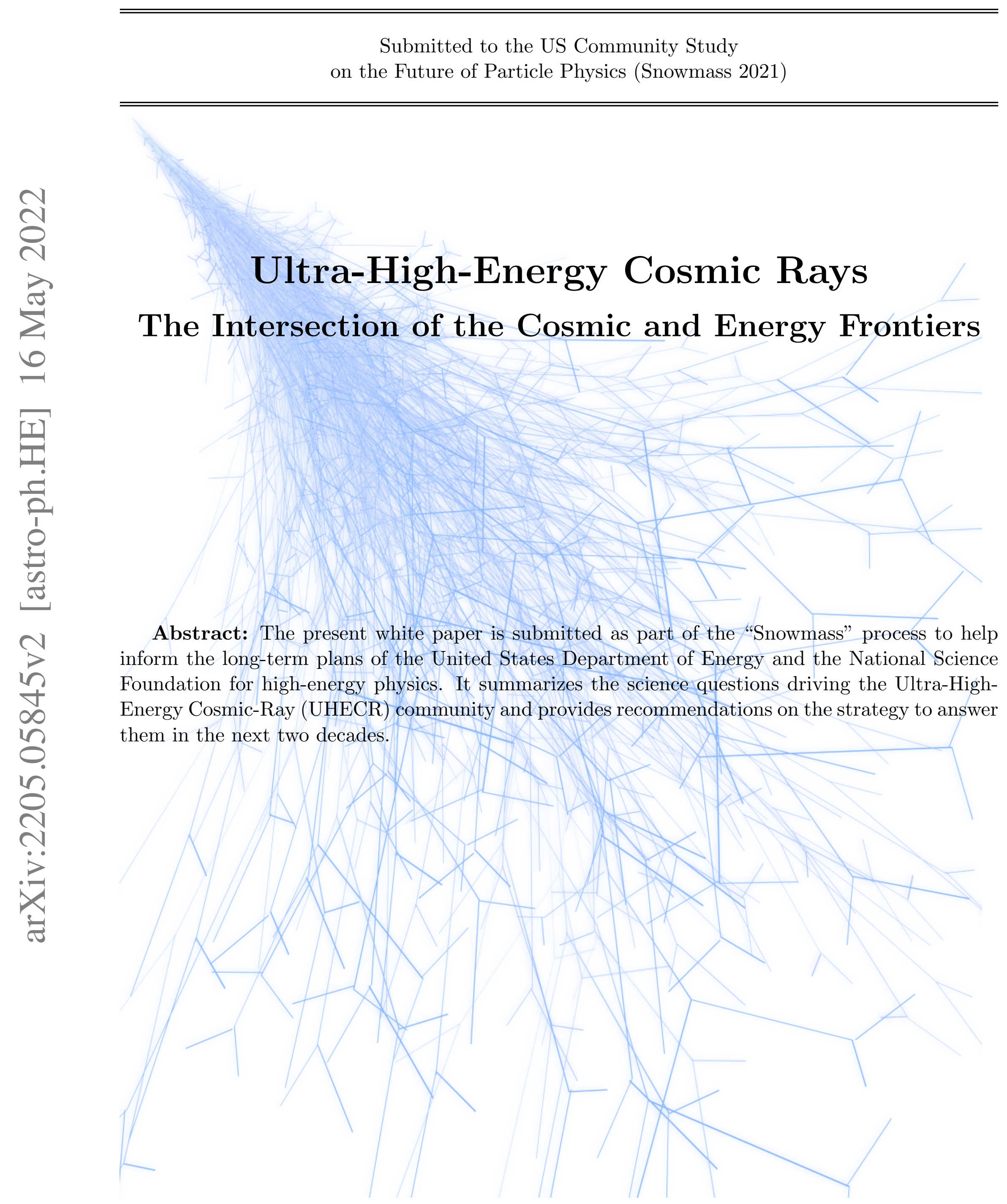


Figure 1: Diagram summarizing the strong connections of UHECRs with particle physics and astrophysics, the fundamental objectives of the field (in orange) for the next two decades, and the complementarity of current and next-generation experiments in addressing them.



arXiv:2205.05845v2 [astro-ph.HE] 16 May 2022

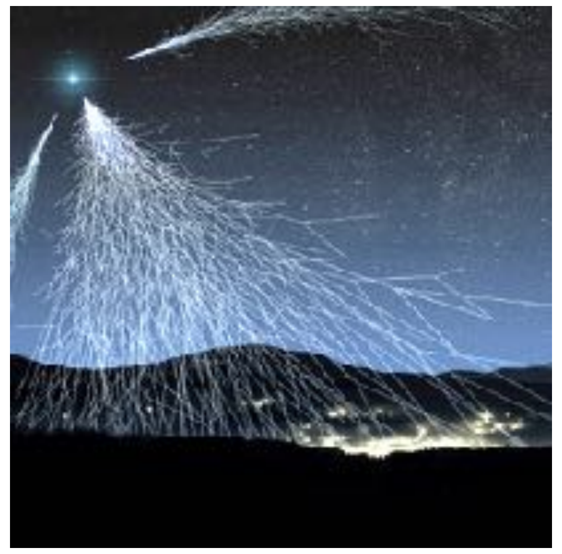
Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Ultra-High-Energy Cosmic Rays

The Intersection of the Cosmic and Energy Frontiers

Abstract: The present white paper is submitted as part of the "Snowmass" process to help inform the long-term plans of the United States Department of Energy and the National Science Foundation for high-energy physics. It summarizes the science questions driving the Ultra-High-Energy Cosmic-Ray (UHECR) community and provides recommendations on the strategy to answer them in the next two decades.

arXiv: 2205.05845



9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities
7-10 June 2022, Santiago de Compostela

GCOS
The Global Cosmic Ray Observatory

Multi-messenger astroparticle physics beyond 2030

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement IceCube-Gen2 deployment IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 GRAND 10k GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	EUSO program POEMMA
GCOS	Hybrid array with $X_{\max} + e/\mu$ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Workshop July 2022, Wuppertal (Germany) https://agenda.astro.ru.nl/event/21

GCOS homepage: http://particle.astro.ru.nl/gcos