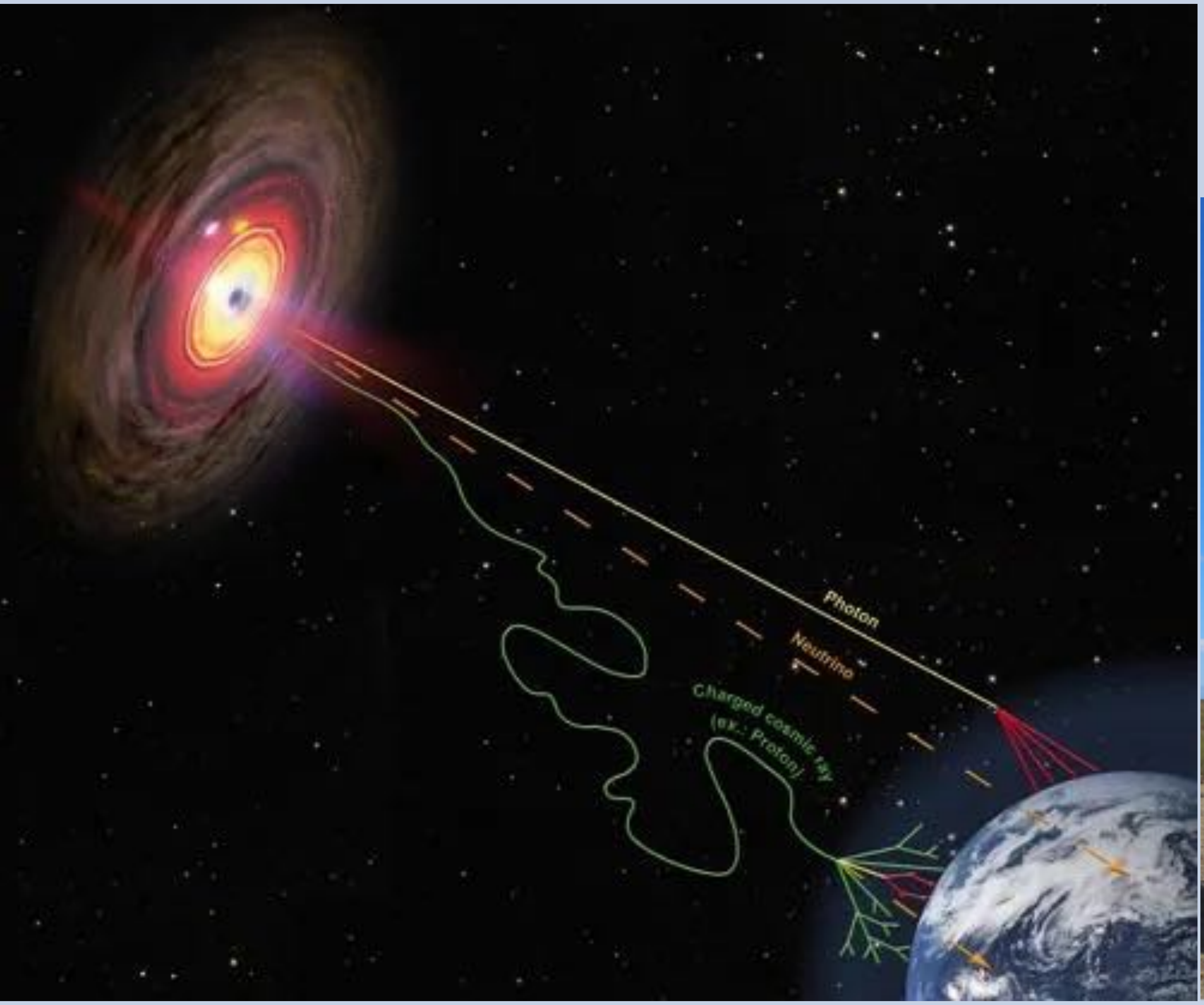
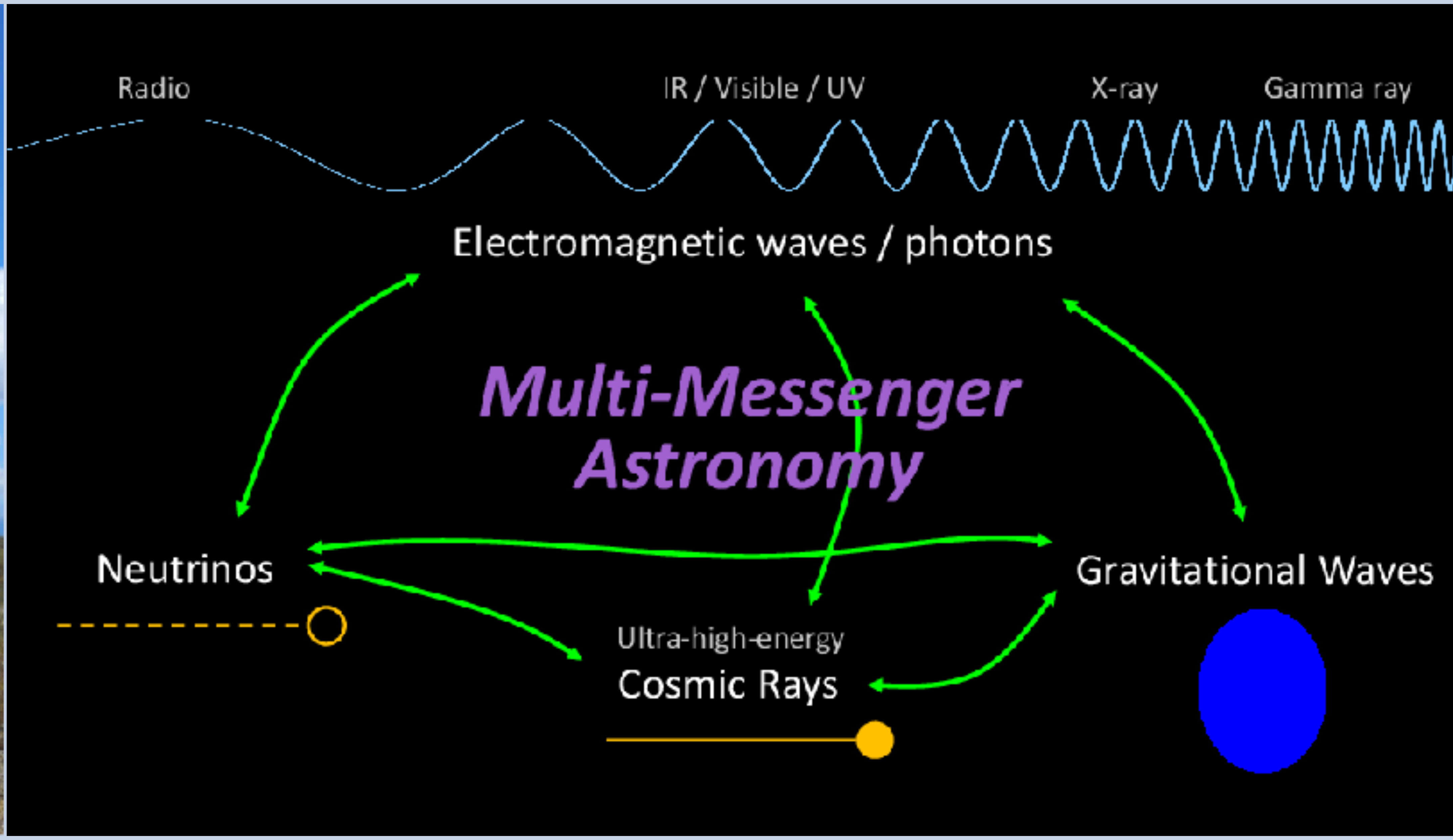
ARENA 2024

CHICAGO 2024

11.–14. Juni 2024
University of Chicago

The Radio Detector of the Pierre Auger Observatory





P.S. Shawhan, PoS(ICHEP2018)695

Jörg R. Hörandel

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

A lagre radio array at the Pierre Auger Observatory

Precision measurements of the properties of cosmic rays at the highest energies

ARENA 2018

Laboratori Nazionali del Sud

Catania, 12th -15th June 2018

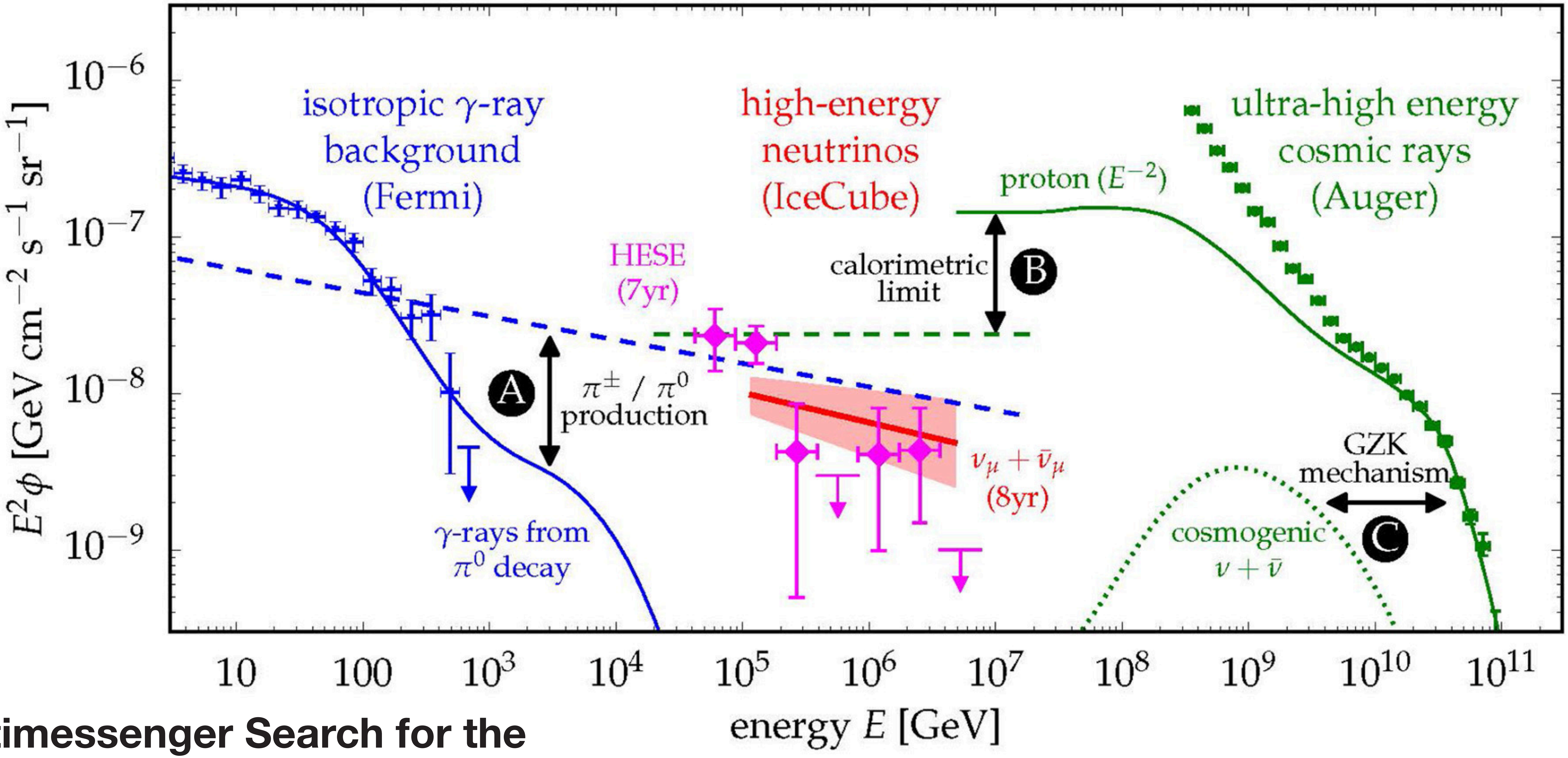
taskleader radio at Pierre Auger Observatory, for the Pierre Auger collaboration

Jörg R. Hörandel

Radboud University Nijmegen, Nikhef

http://particle.astro.ru.nl

Observing the ultra-high-energy Universe



Multimessenger Search for the Sources of Cosmic Rays Using Cosmic Neutrinos

Frontiers in Astronomy and Space Sciences | www.frontiersin.org 1 May 2019 | Volume 6 | Article 32

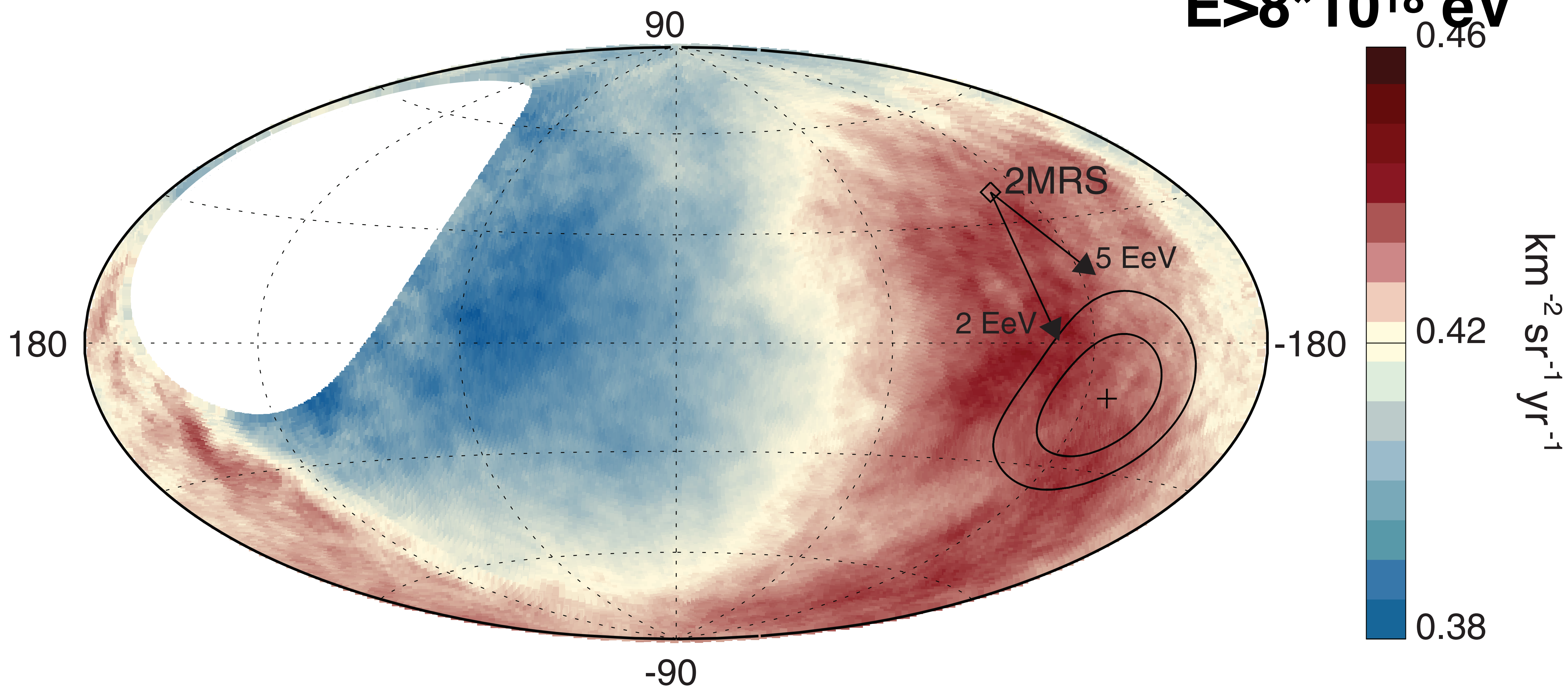
Francis Halzen and Ali Kheirandish**

Observing the ultra-high-energy Universe

sky map of cosmic rays

Anisotropy detected at >5.2 sigma
dipole amplitude 6.5%

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



Longitude l = 233°, Latitude b = -13°

matter from other galaxies

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

The existence of such particles imposes immediate, yet to be answered questions:

- What are the physics processes involved to produce these particles?
- Are they decay or annihilation products of Dark Matter?

If they are accelerated in violent astrophysical environments:

- How is Nature being able to accelerate particles to such energies?
- What are the sources of the particles? Do we understand the physics of the sources?
- Is the origin of those particles connected to the recently observed mergers of compact objects – the gravitational wave sources?

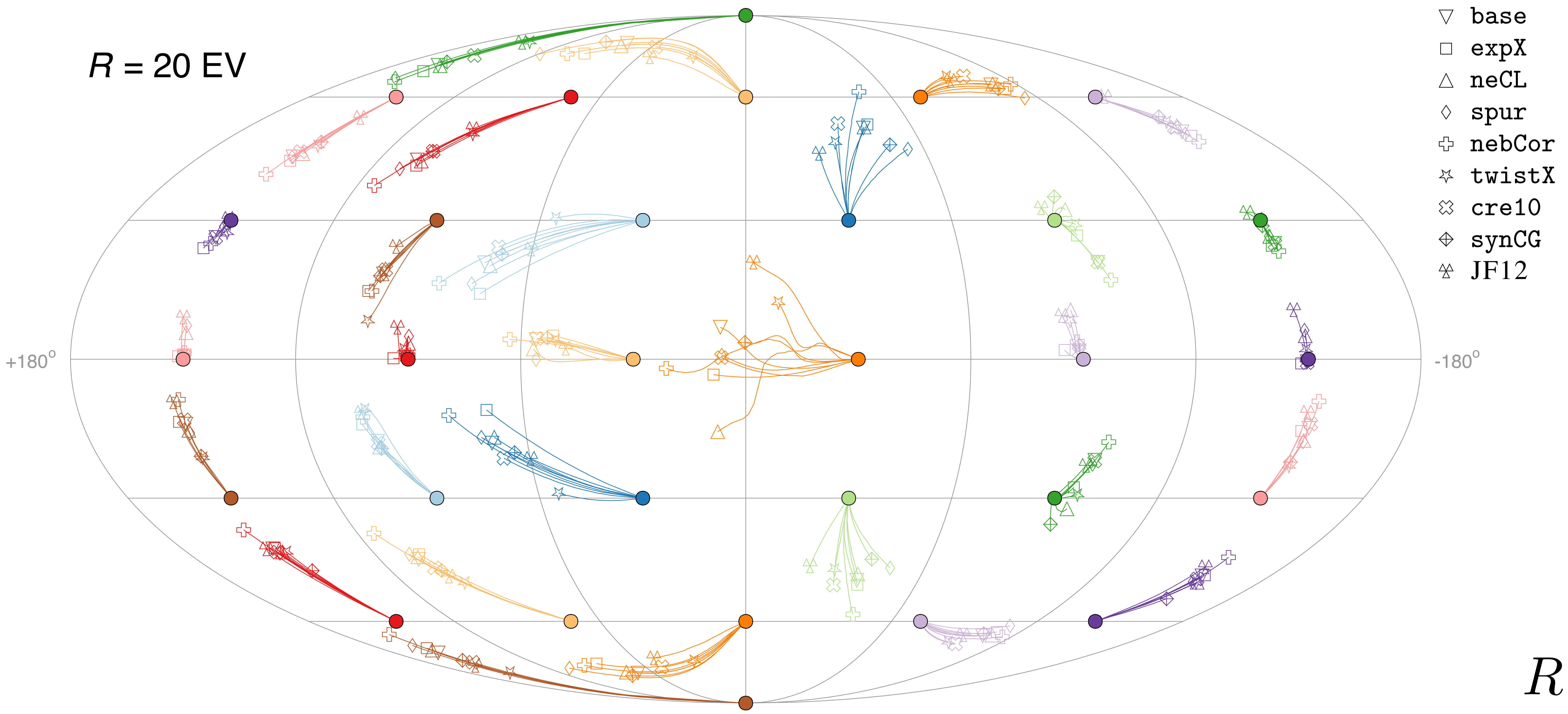
The highly-relativistic particles also provide the unique possibility to study (particle) physics at it extremes:

- Is Lorentz invariance (still) valid under such conditions? How do these particles interact?
- Are their interactions described by the Standard Model of particle physics?

When the energetic particles interact with the atmosphere of the Earth, hadronic interactions can be studied:

- What is the proton interaction cross section at such energies?

Deflection of cosmic rays in magnetic fields



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

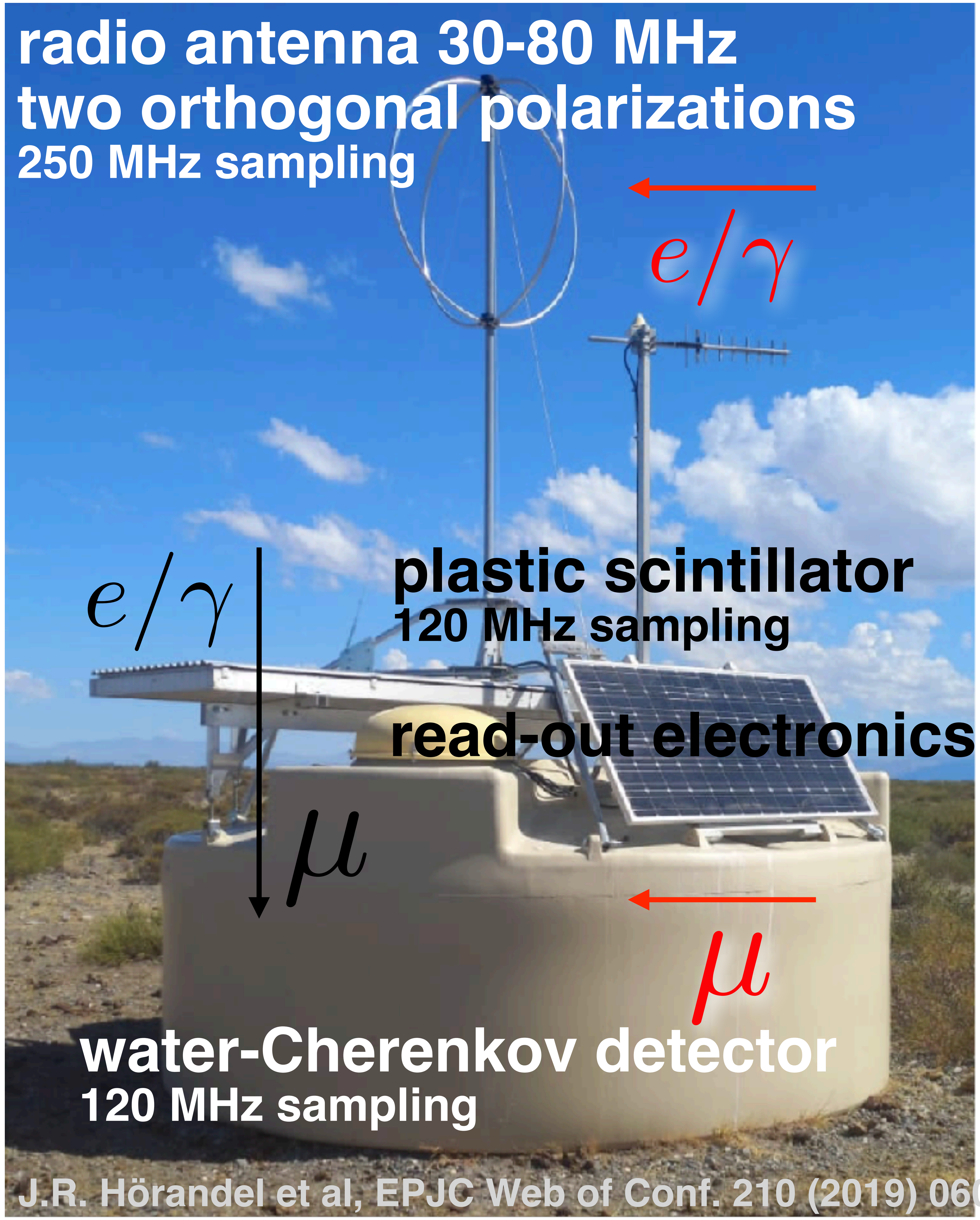
Figure 19. Angular deflections of ultrahigh-energy cosmic rays in the eight model variations derived in this paper and JF12. The cosmic-ray rigidity is 20 EV (2×10^{19} V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

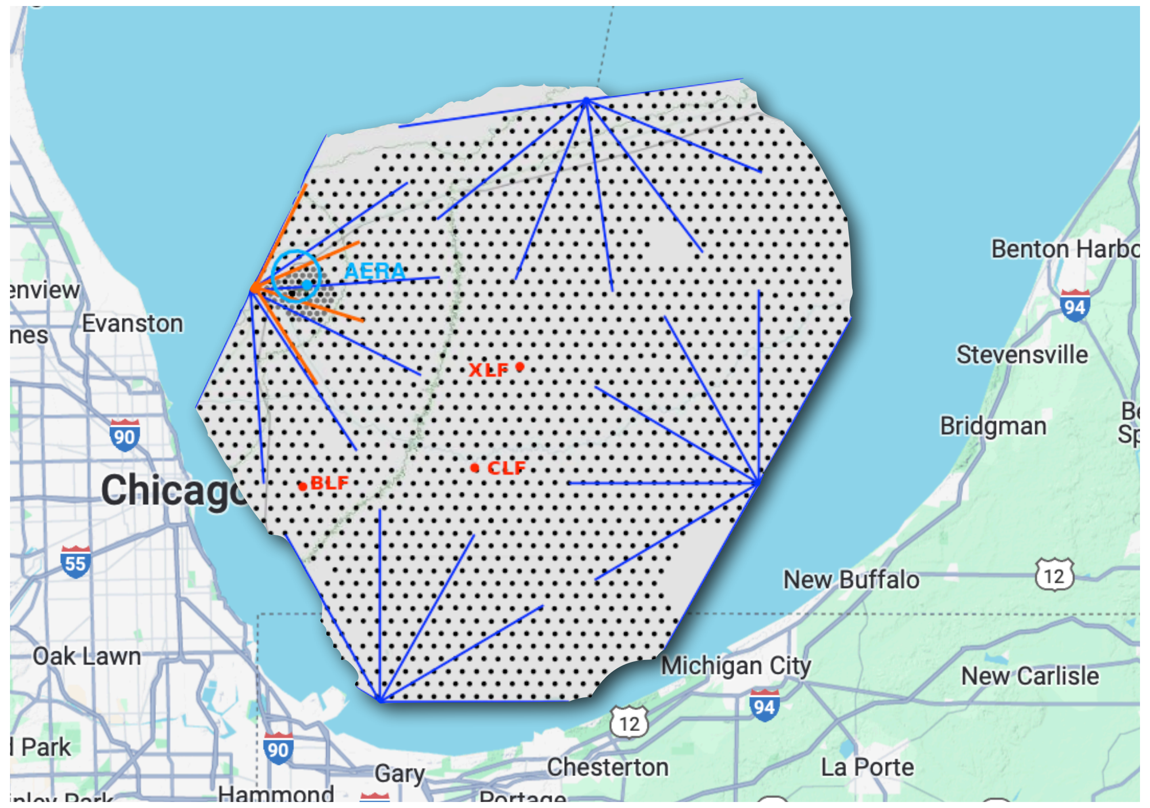
The Coherent Magnetic Field of the Milky Way

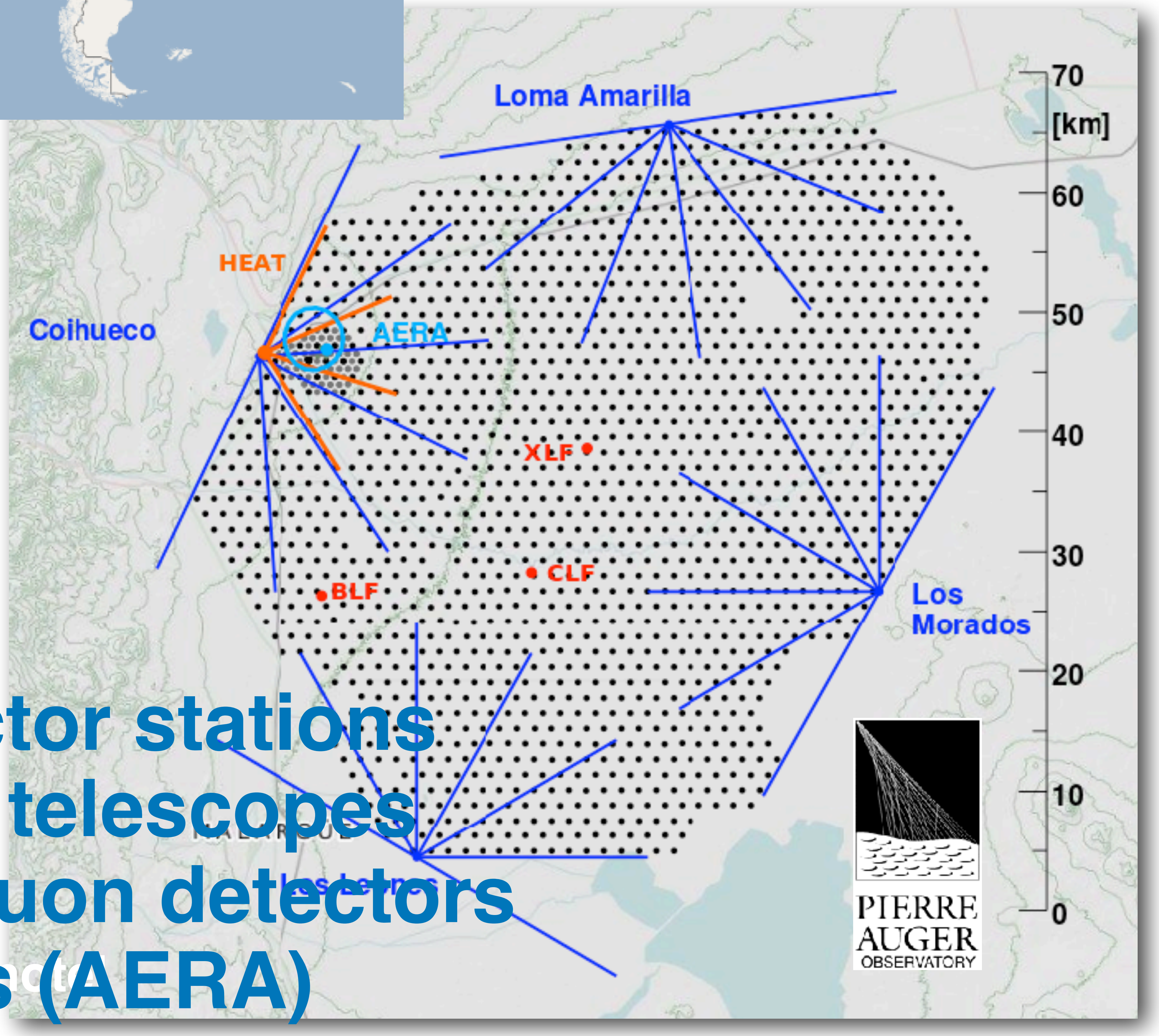
Michael Unger [1,2] and Glennys R. Farrar [3]

need to know rigidity (mass) of incoming cosmic rays

Upgraded Surface Detector of Auger Observatory



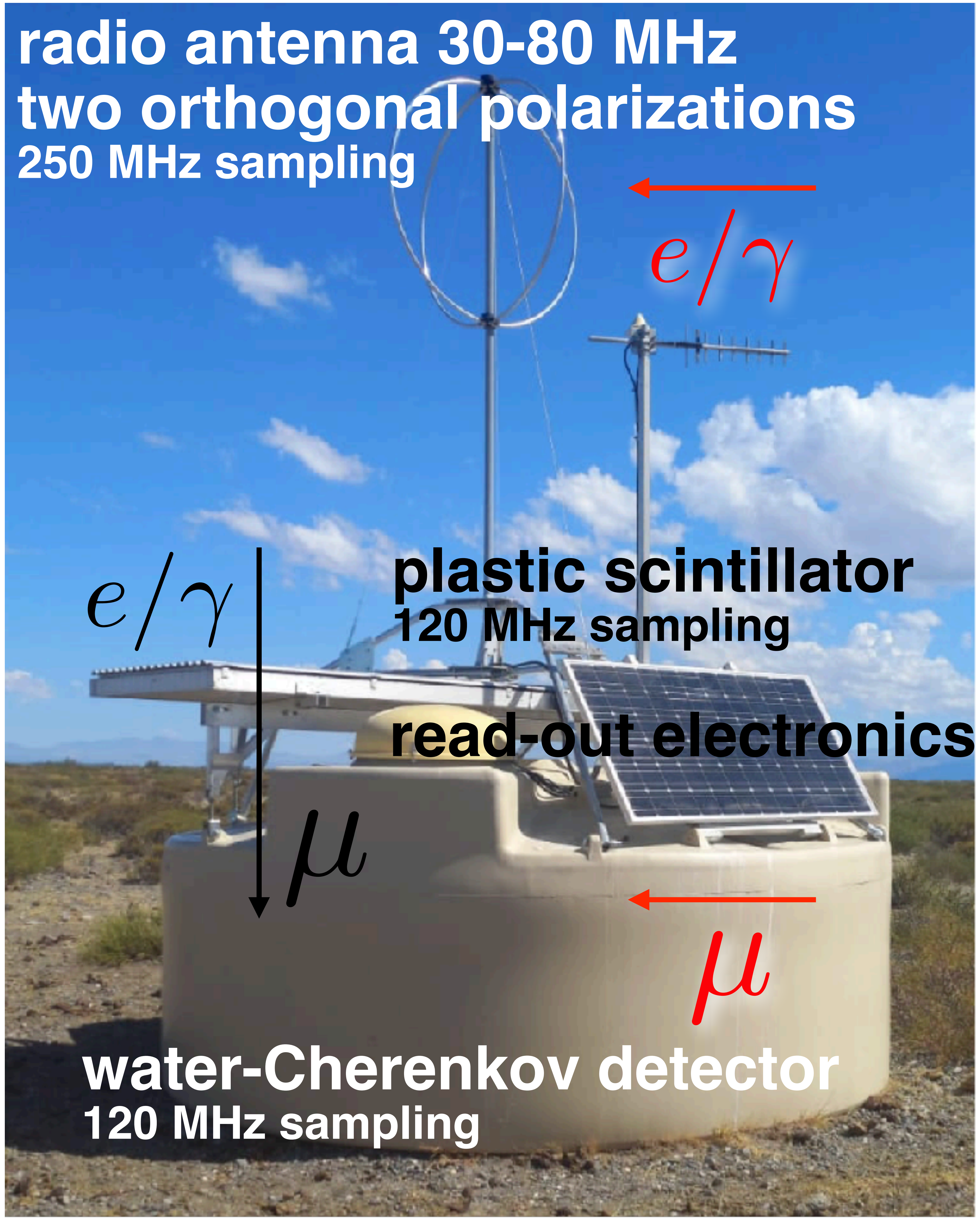


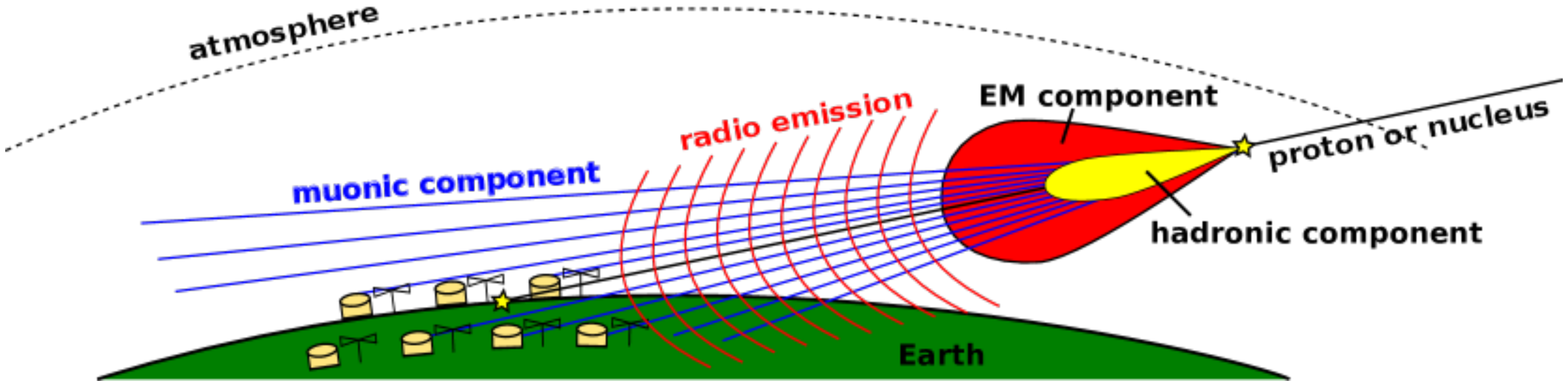


3000 km²
1660 surface detector stations
24+3 fluorescence telescopes
61 underground muon detectors
150 radio antennas (AERA)

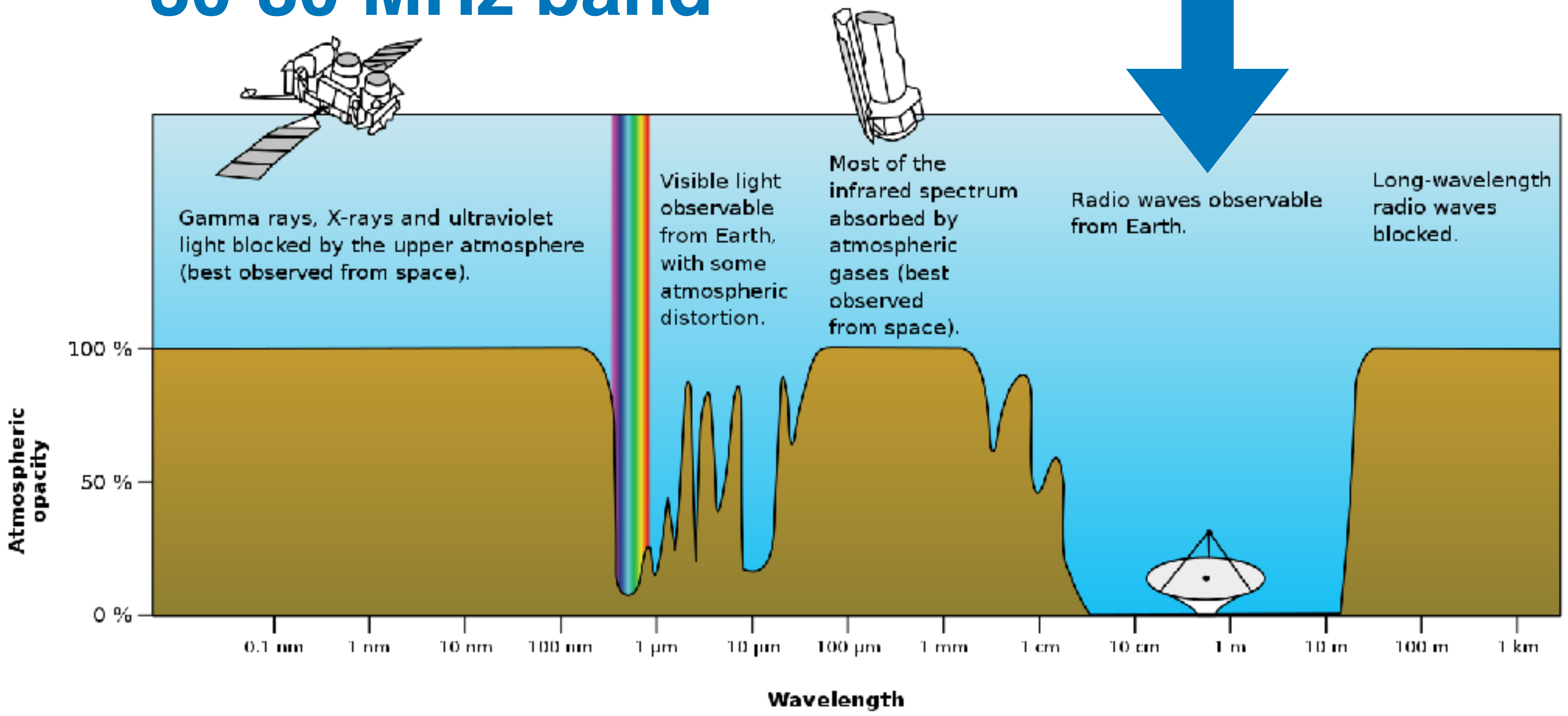
J.R. Hörandel et al, EPJC Web of Conf. 210 (2019) 06005

Upgraded Surface Detector of Auger Observatory





atmosphere of Earth is transparent in 30-80 MHz band



Radio Detector of the Pierre Auger Observatory

extend mass sensitivity to inclined showers $\theta > 60^\circ$

- increasing measurements of e/m and μ components for inclined showers by an order of magnitude
- close to ideal p-Fe separation
- increase sky coverage and overlap with TA
- RD/WCD has different systematic effects as compared to SSD/WCD
- clean measurement of e/m shower component —> independent energy scale

European Research Council
Established by the European Commission

NWO

PIERRE AUGER OBSERVATORY

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

Radio Detector of the Pierre Auger Observatory

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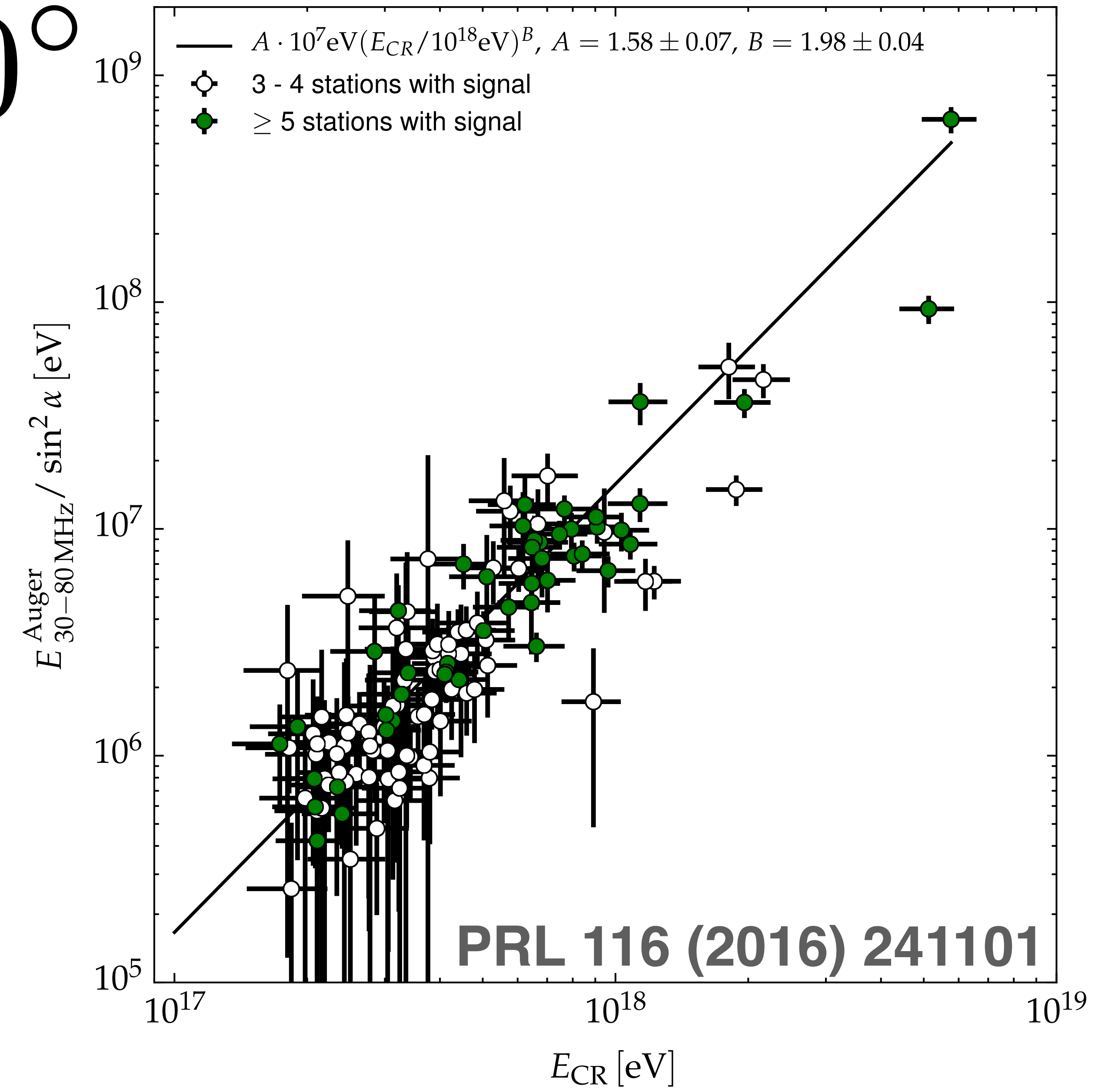
- RD/WCD has different systematic effects as compared to SSD/WCD
- clean measurement of e/m shower component —> independent energy scale
- based on 15 years of experience with AERA



European Research Council
Established by the European Commission

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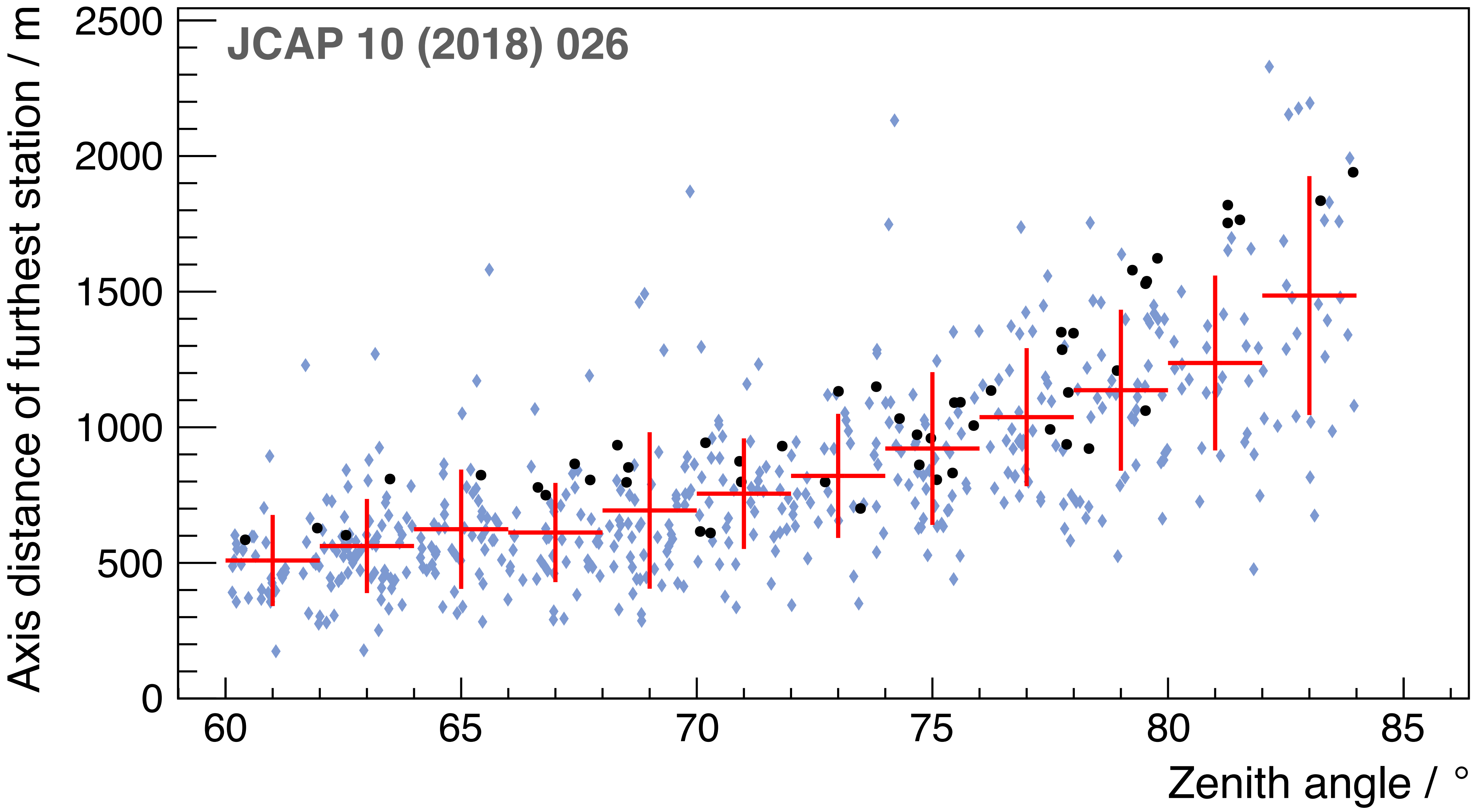
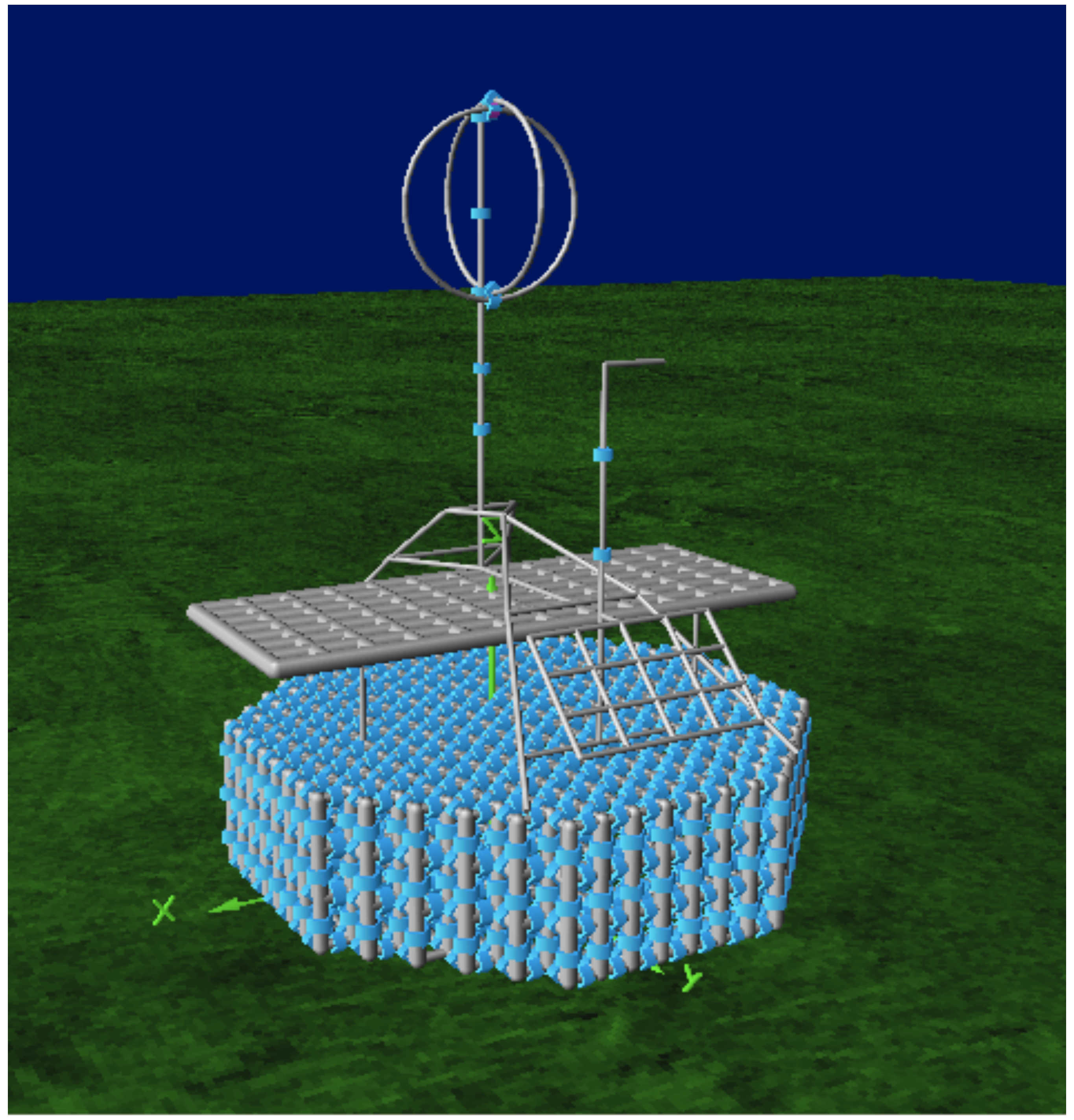
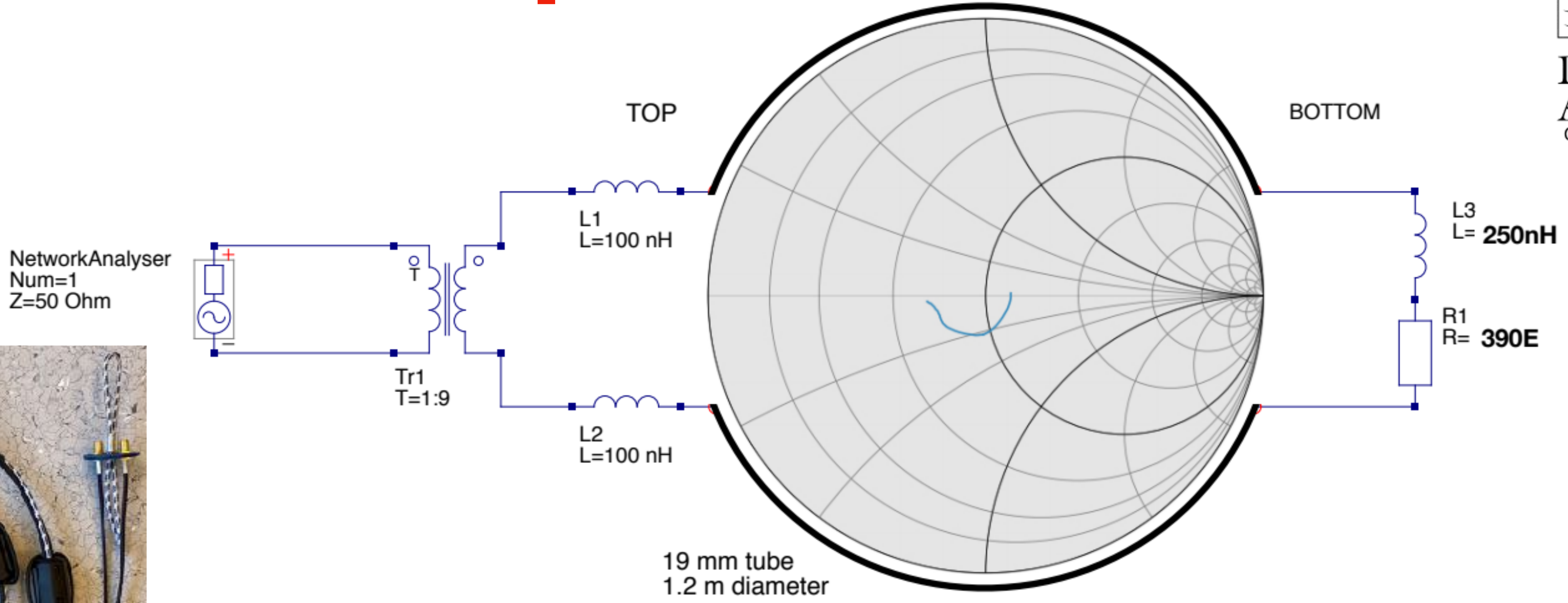


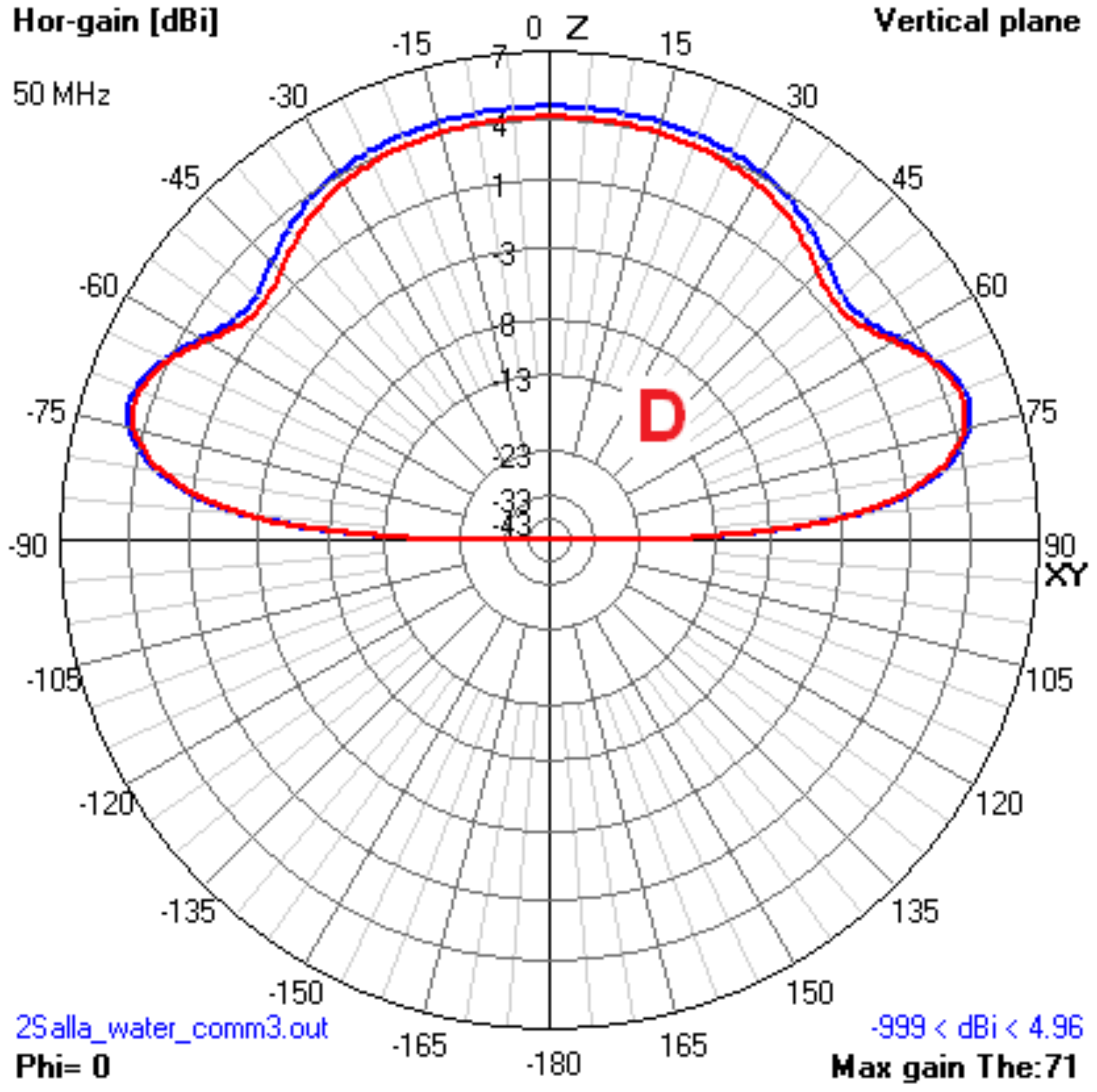
J.R. Hörandel et al, EPJC Web of Conf. 210 (2019) 06005

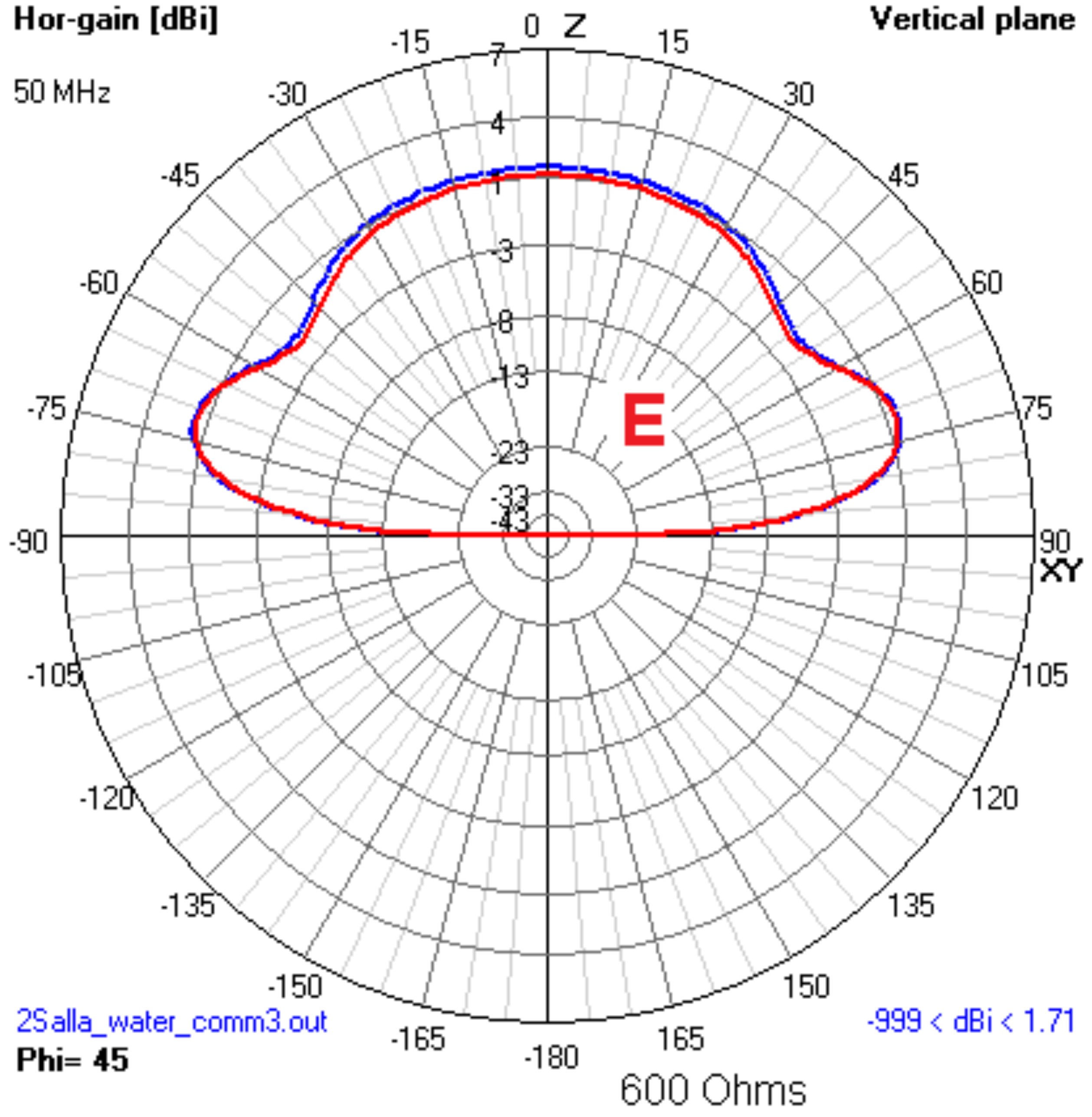
Short Aperiodic Loaded Loop Antenna

- bottom load to reduce influence of structures below antenna
- ferrites to reduce influence of cables on antenna pattern



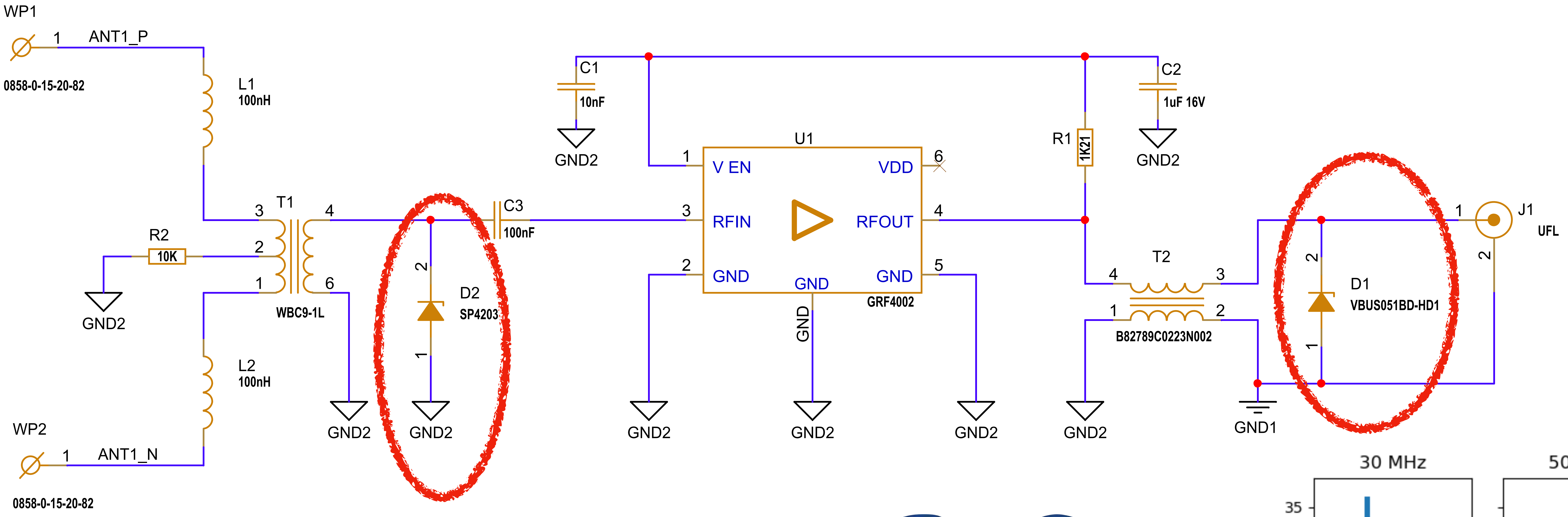




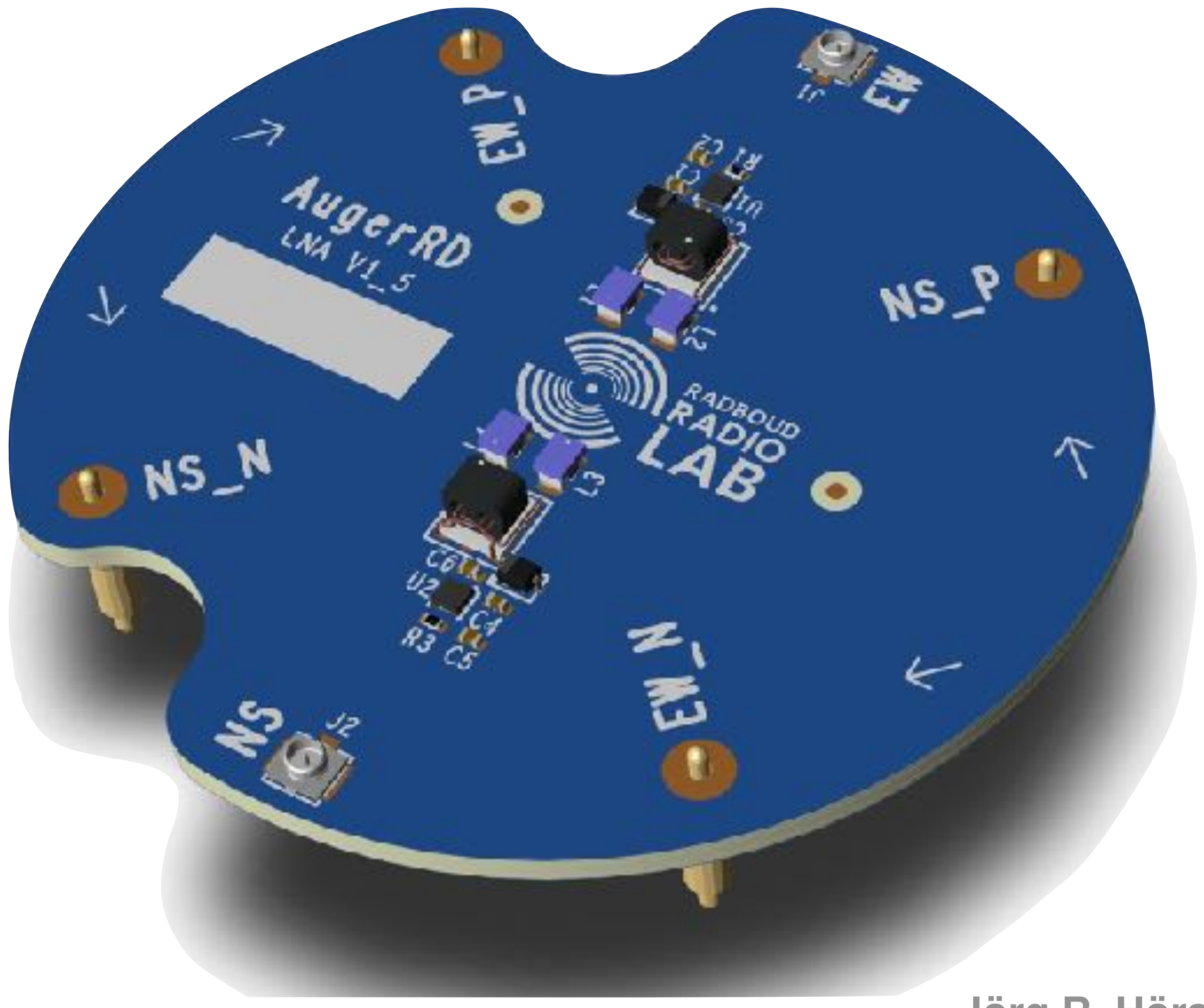


Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory 2012 JINST 7 P10011

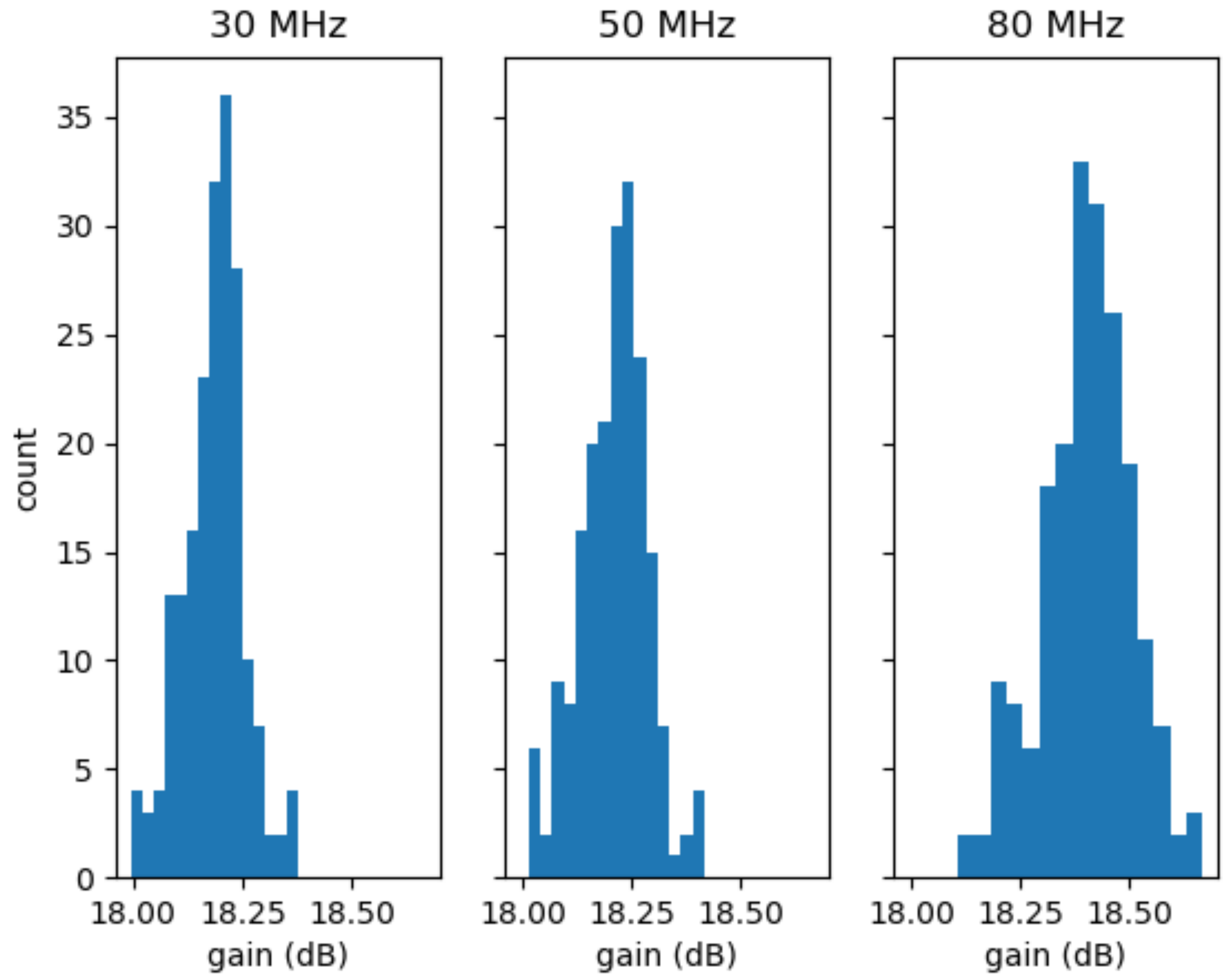
Low Noise Amplifier



antenna is highest point of assembly
—> attractive for lightning
—> protection diodes
& design to allow easy maintenance

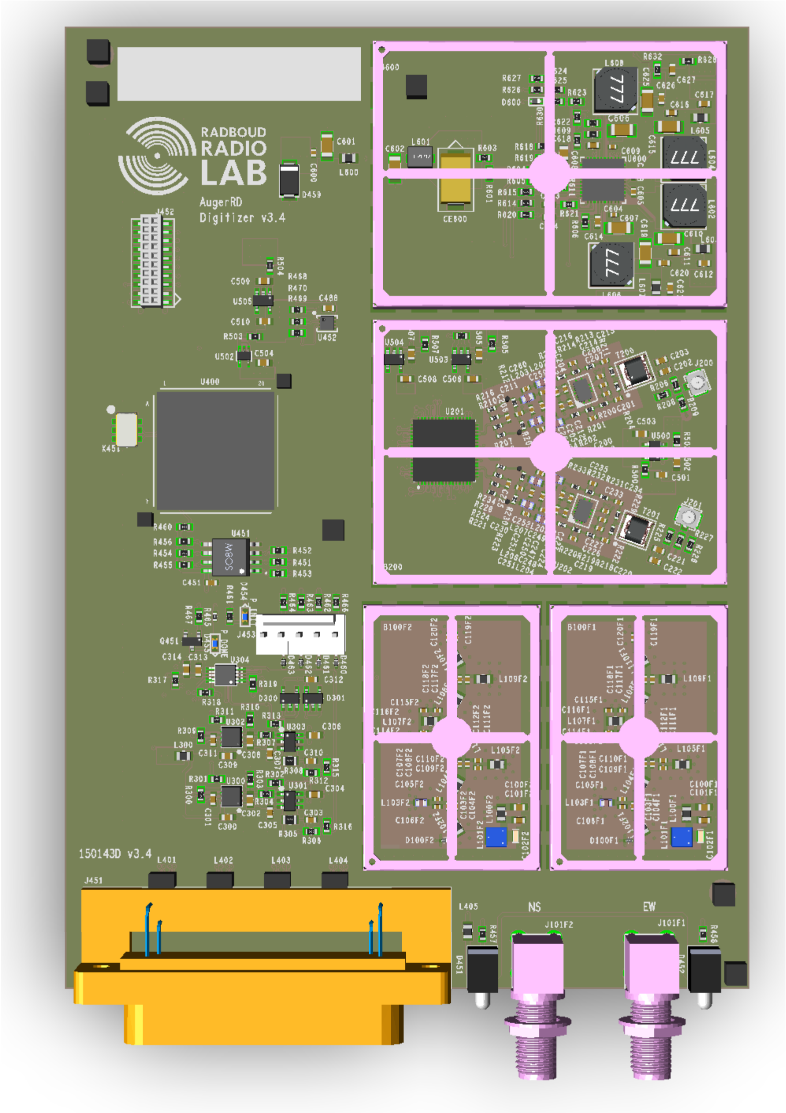


~1% in voltage

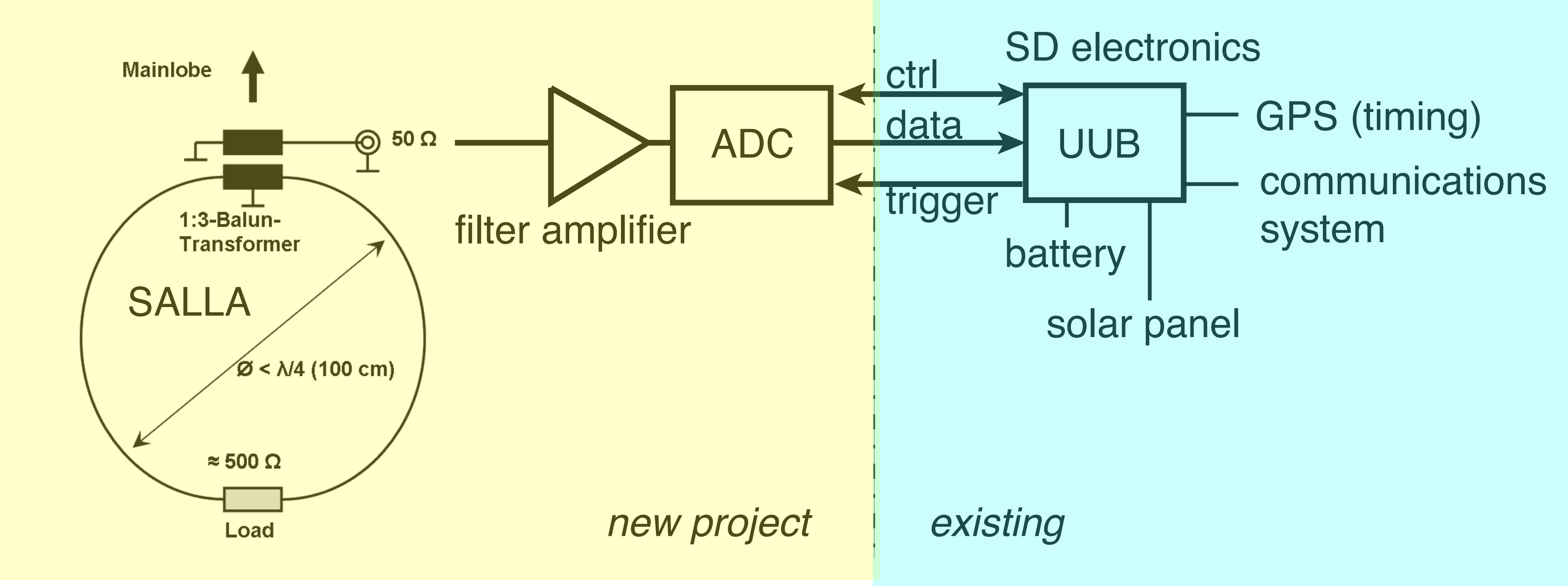


power consumption: 0,2 W

RD Digitizer



power consumption: 2,4 W



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Characteristics of digitizers (filter)

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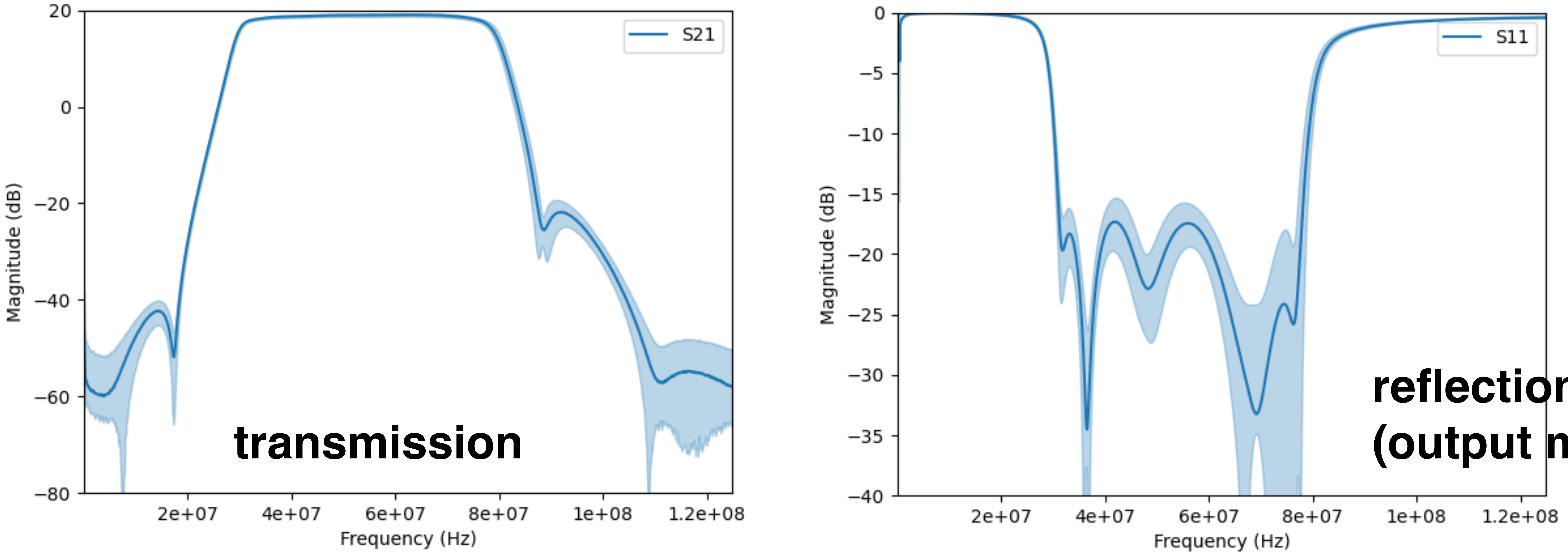


transmission

reflection at input (output matched)

Figure 12: The filter amplifier characteristics with their uncertainty bounds. Shown after calibration of the first 989 front-end boards of the Radio Detector.

1st ~1000 units calibrated

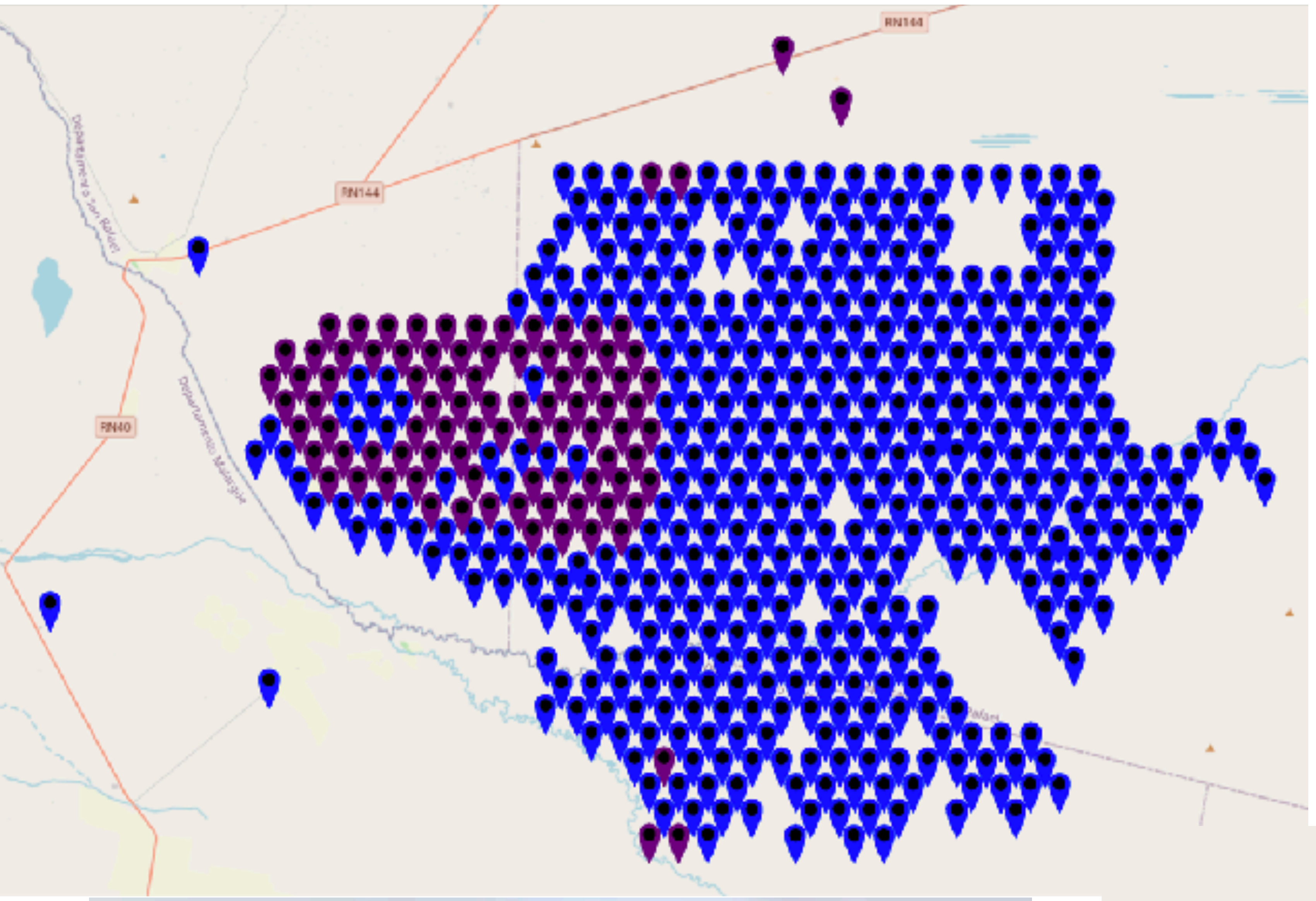
very homogeneous performance

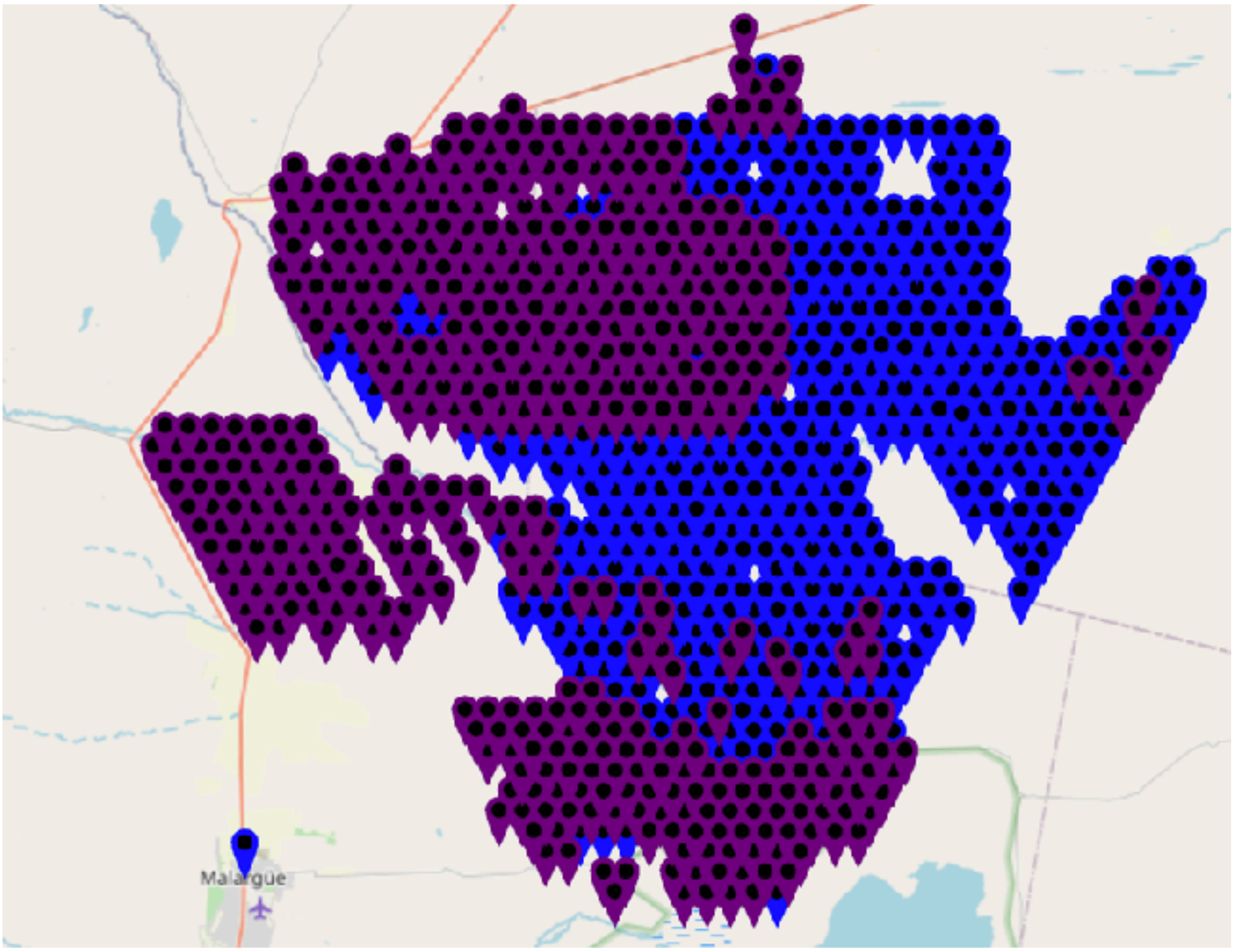
Roel Jordans

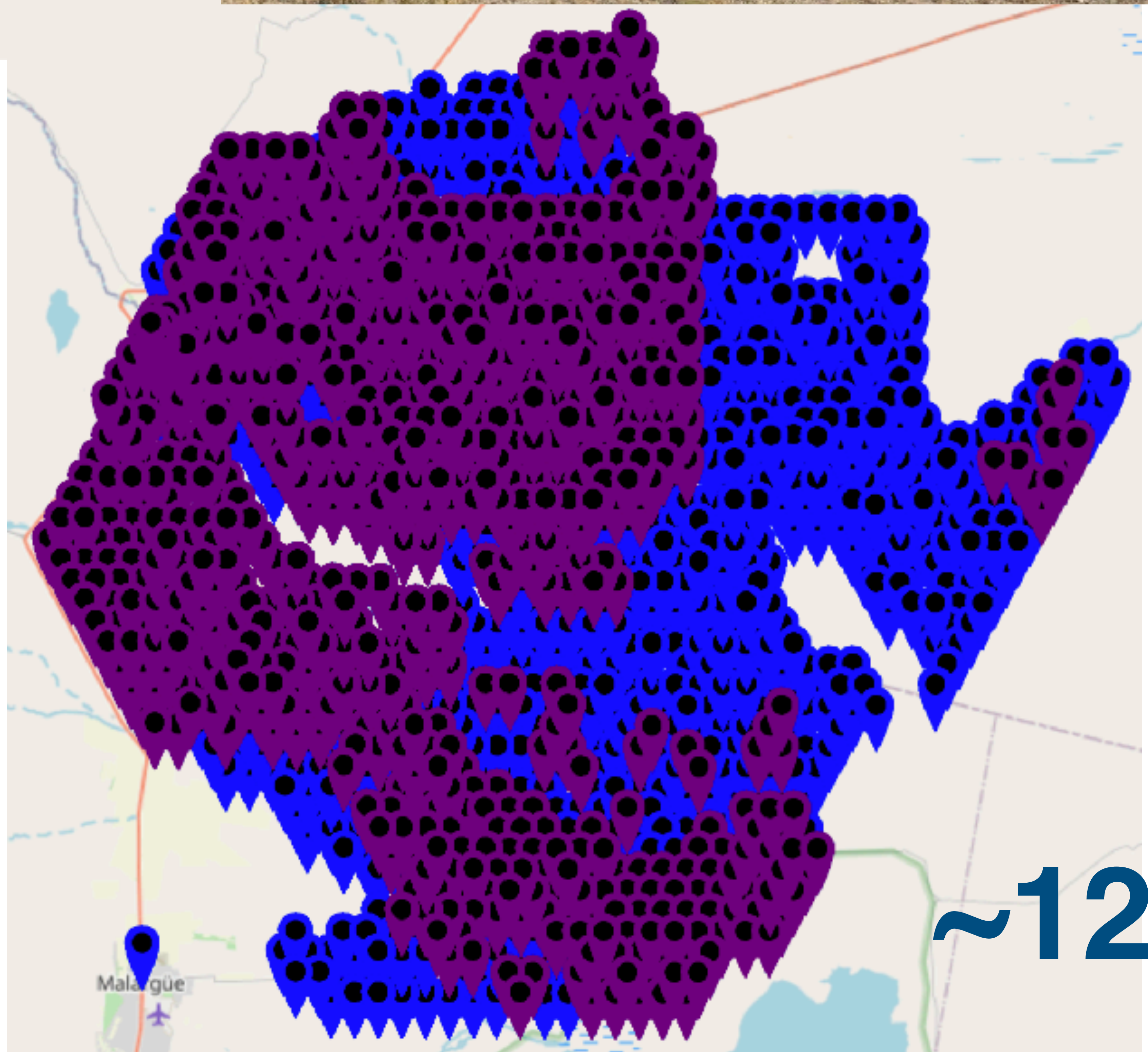
Antenna assembly in field

~500 stations Nov 2023

~1000 stations Mar 2024

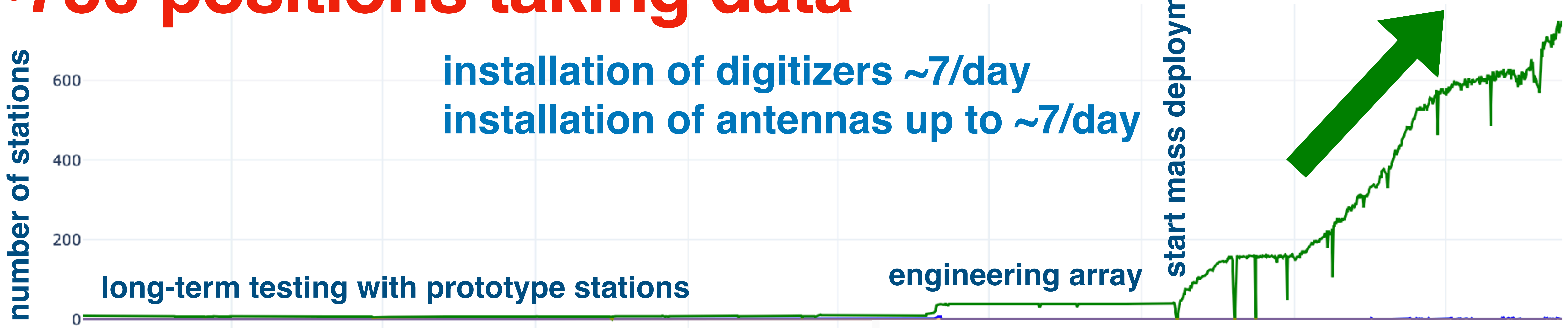




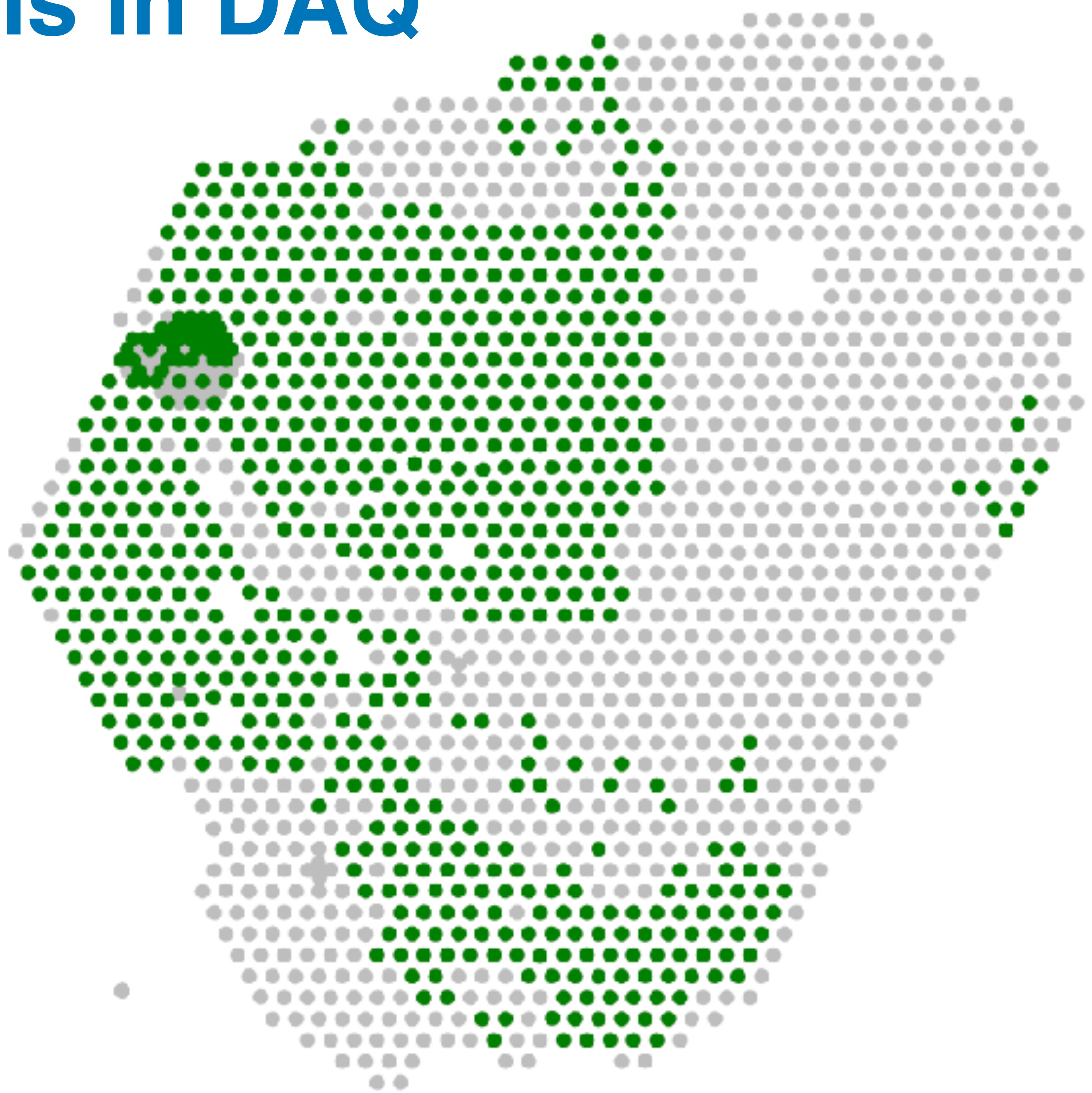


~1200 stations June 2024

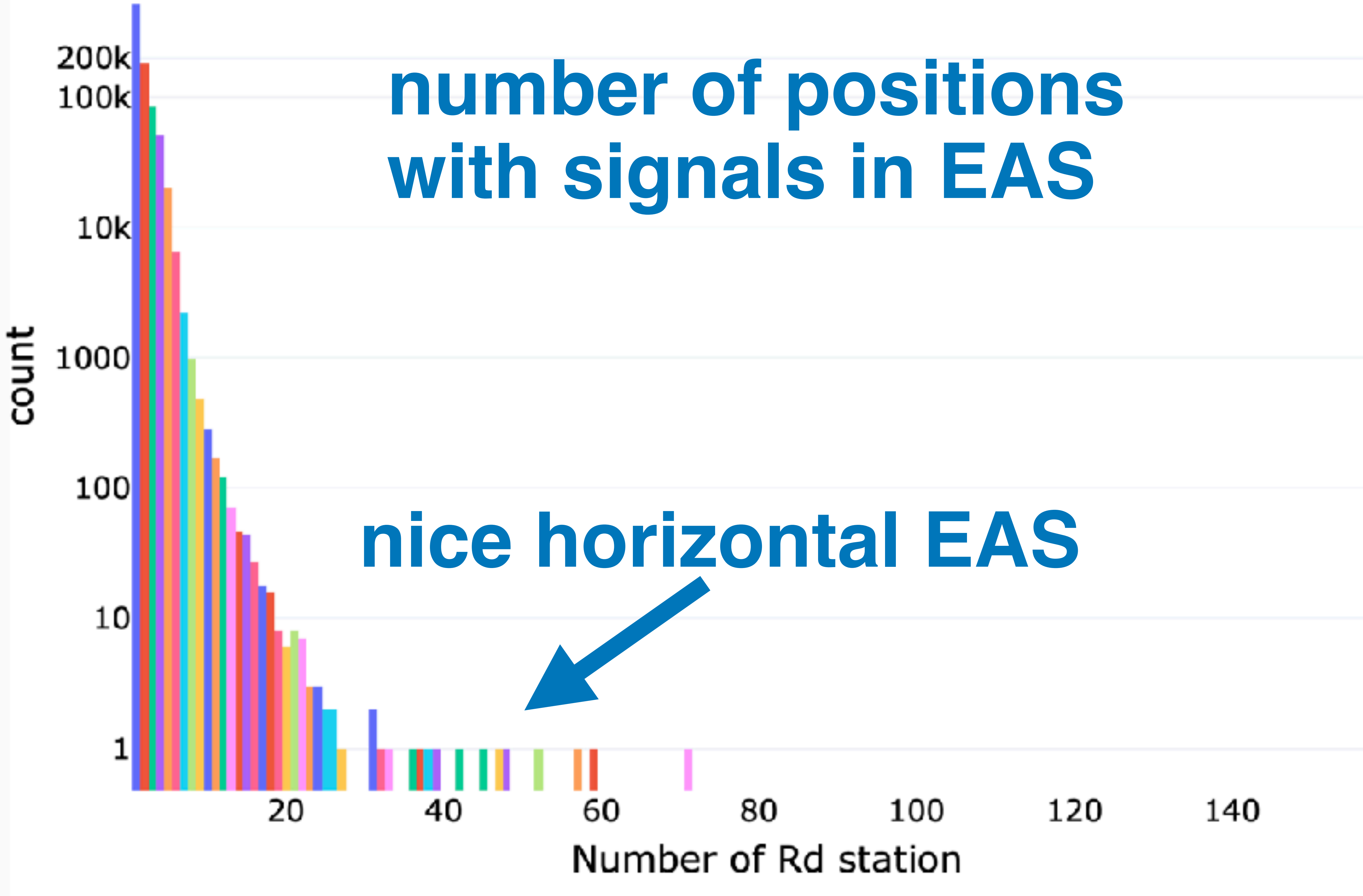
~750 positions taking data



positions in DAQ



number of positions with signals in EAS



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How to find alignment with a known source

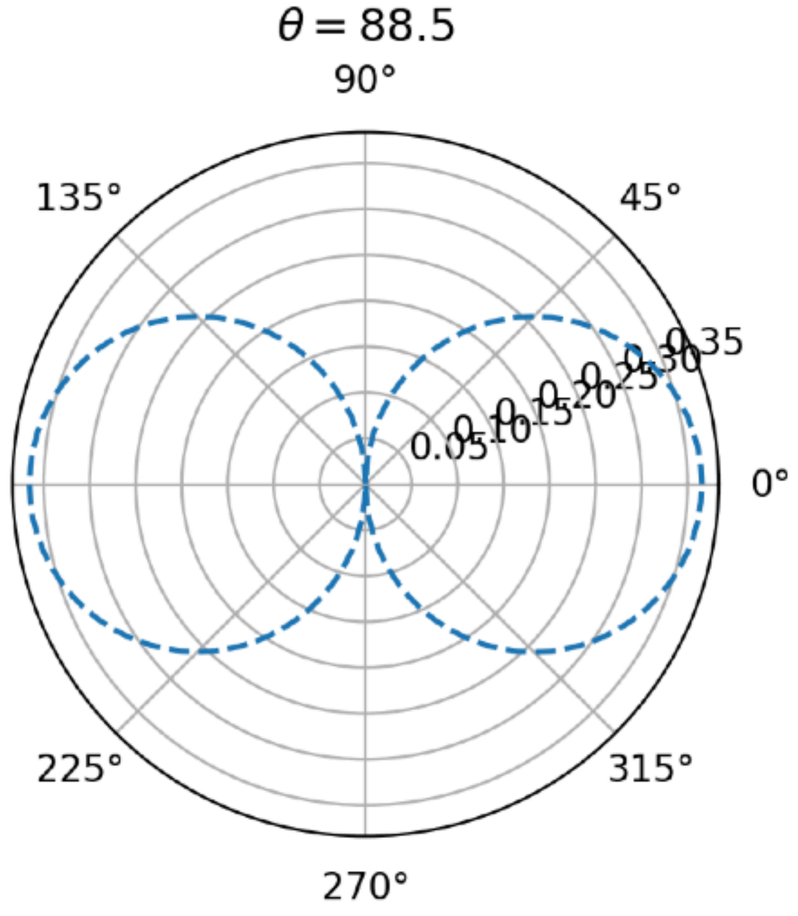
Ch0 and ch1 amplitudes —> channel ratio

antenna pattern & source location —> channel ratio

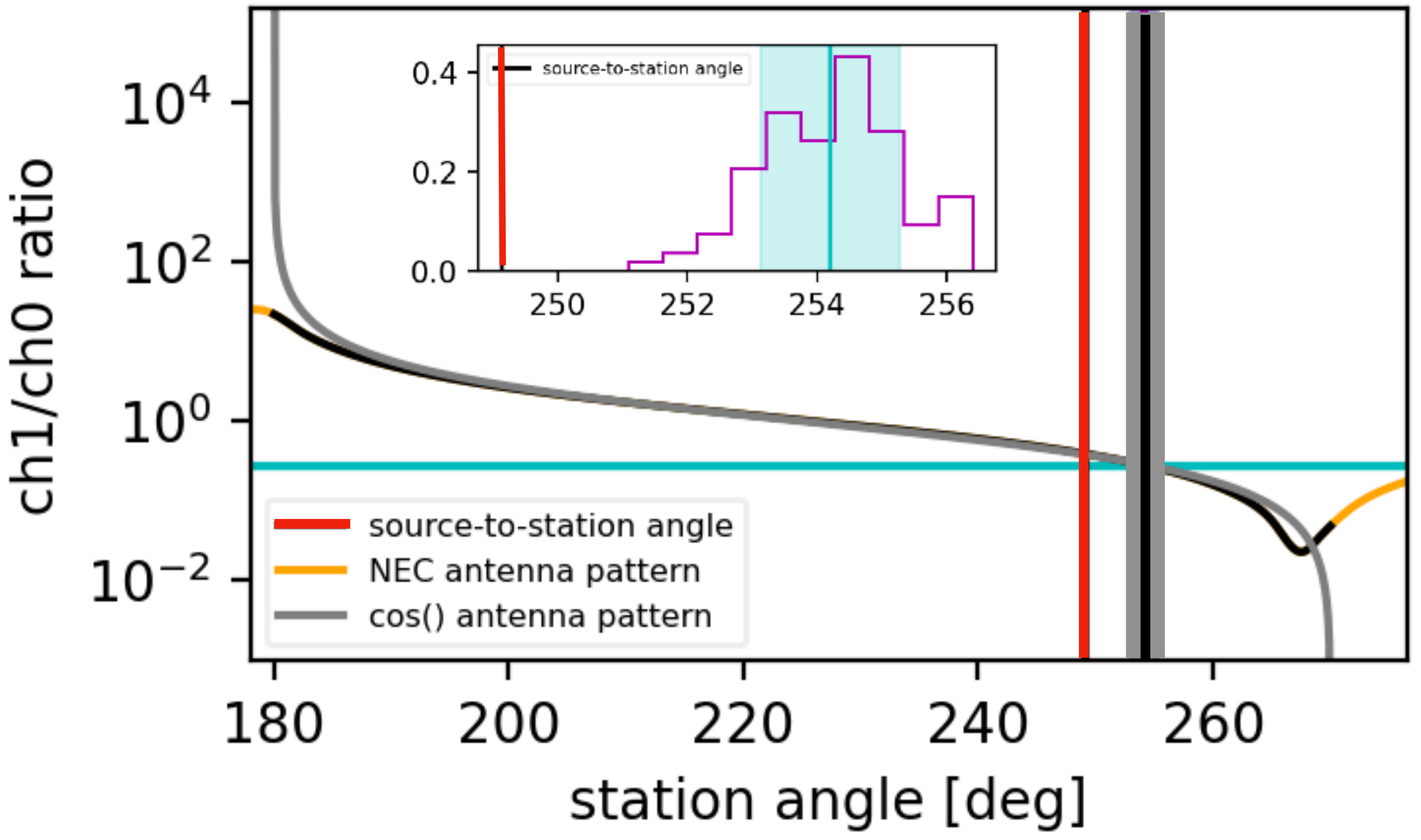
—> offset to source location = antenna rotation

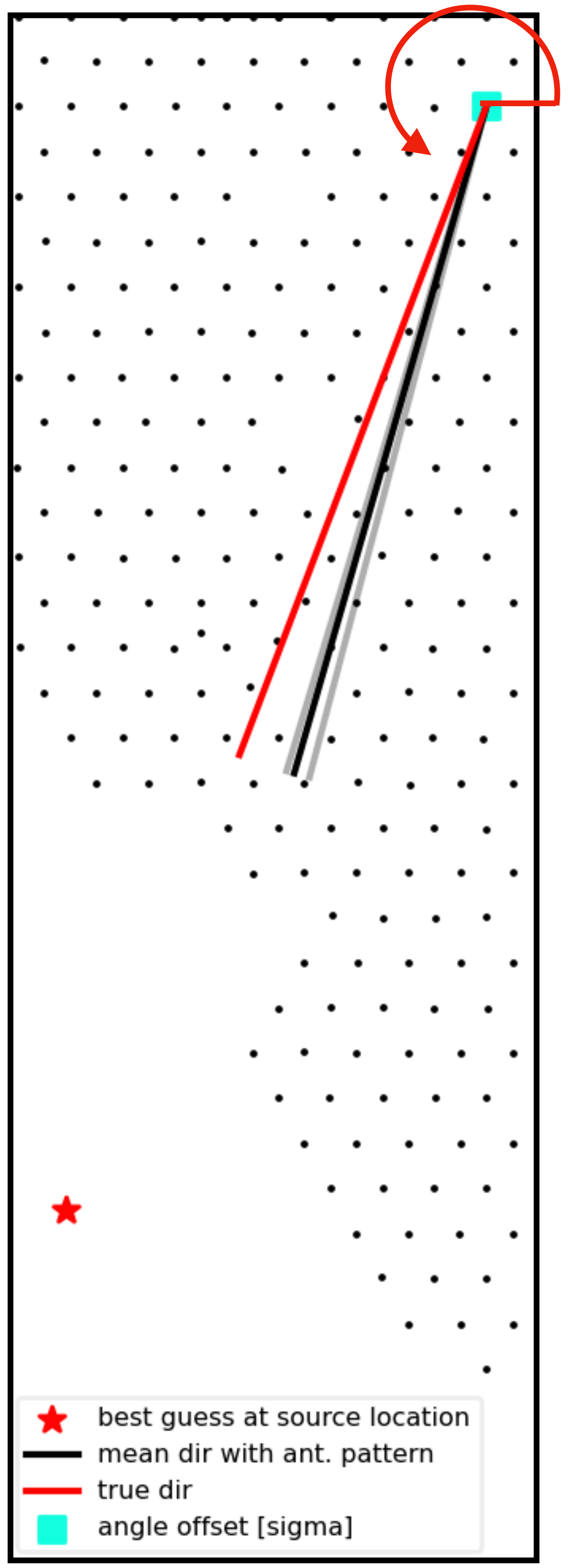
- Get misalignment:
  - Ratios vs angles from NEC antenna pattern (depends on Frequency and zenith!)
  - + ratio from data —> angle of station
  - **Offset =** angle of station - expected angle
    (for this station: -5.0+-1.1 degrees, using 7d of data)

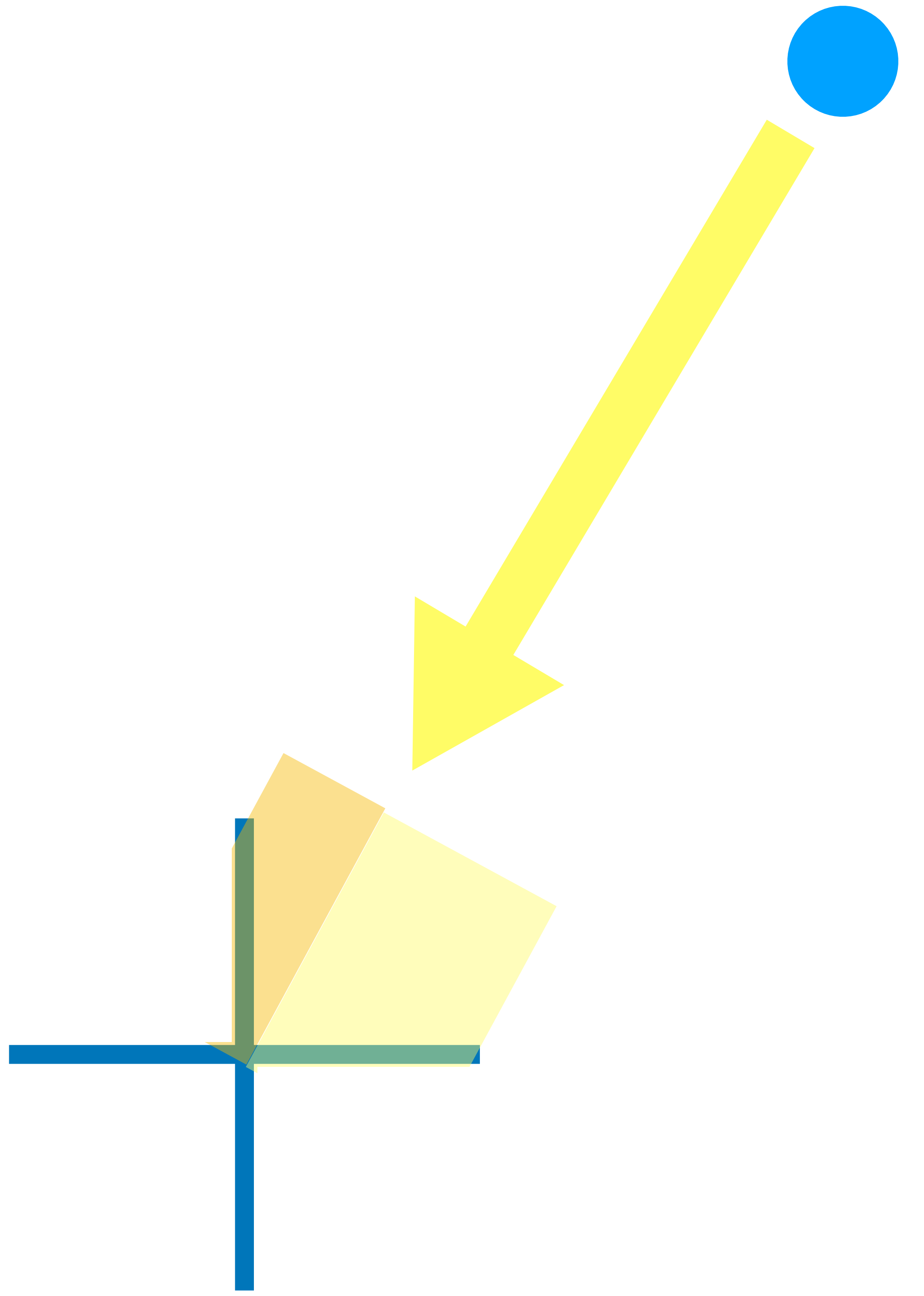
NEC antenna pattern



Matching ratios



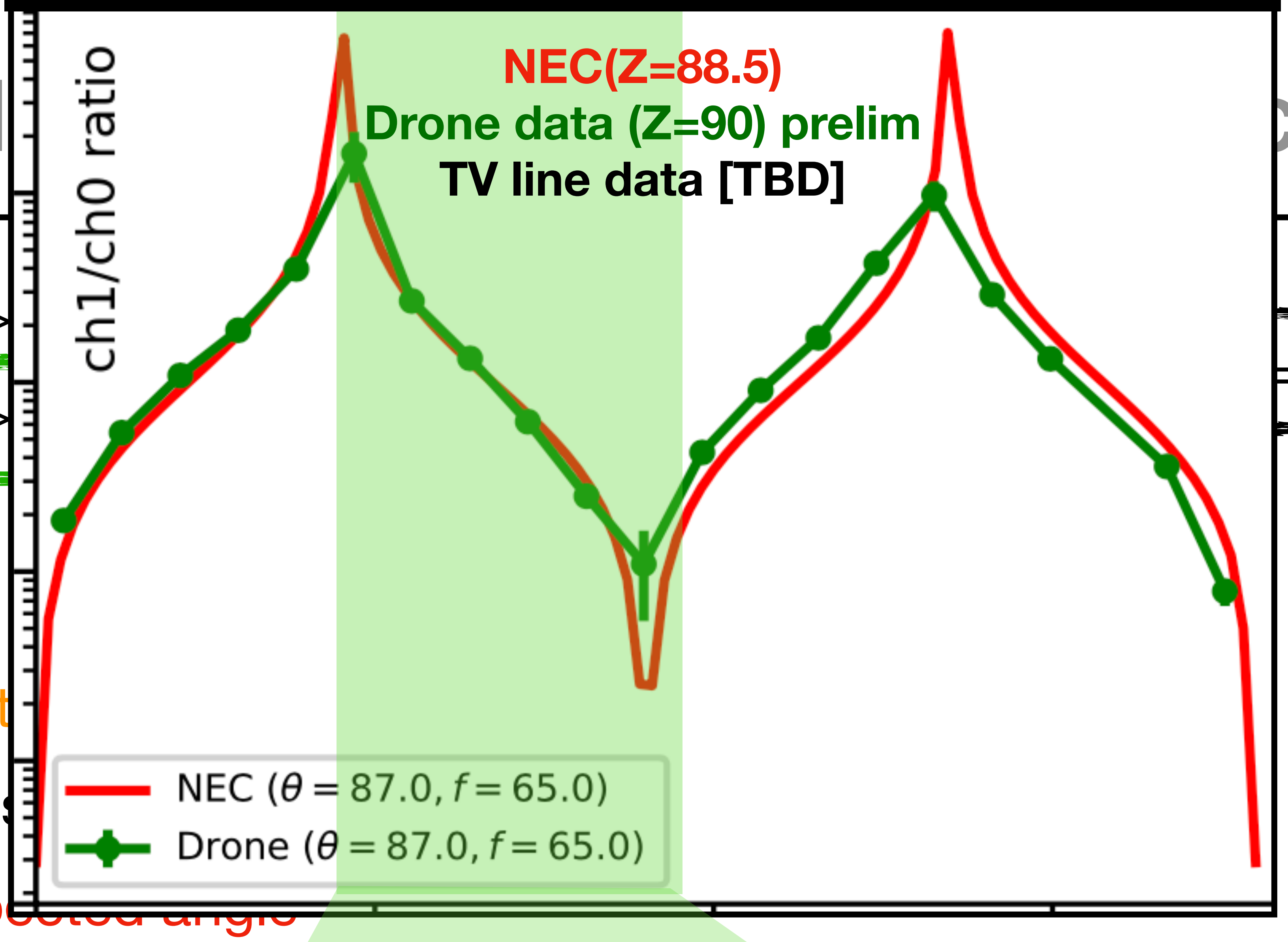




see Bjarni @10:05

How to find al ce

Drone data will probably help here…[TBC]



Ch0 and ch1 amplitudes —>

antenna pattern & source location —>

= antenna rotation

- Get misalignment:
  - Ratios vs angles from NEC ant
  - + ratio from data —> angle of s
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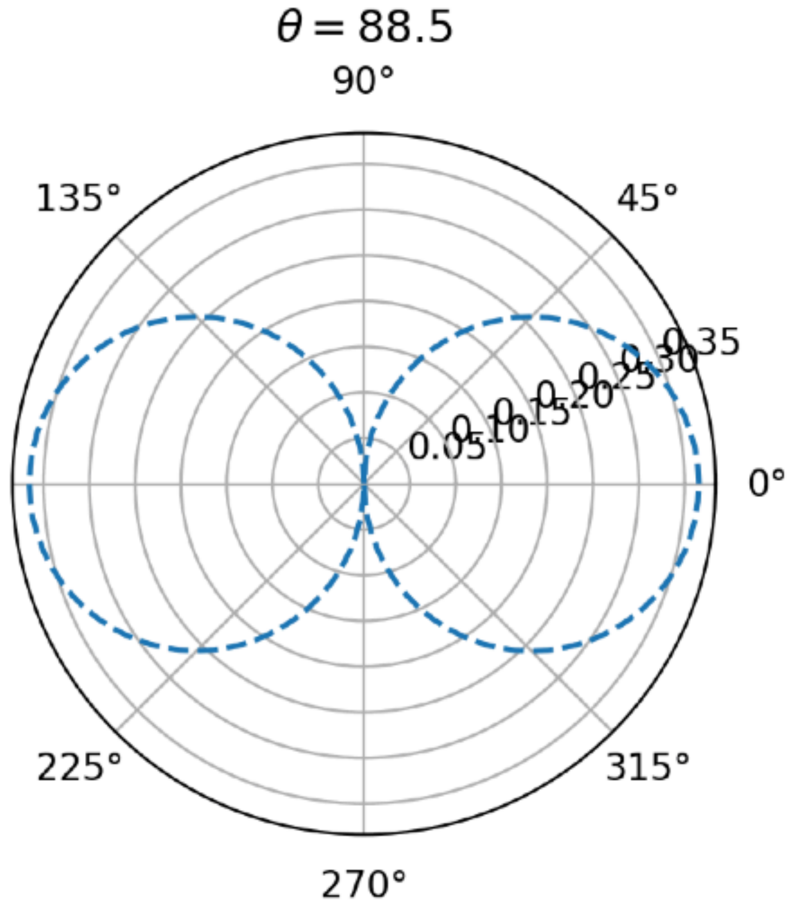
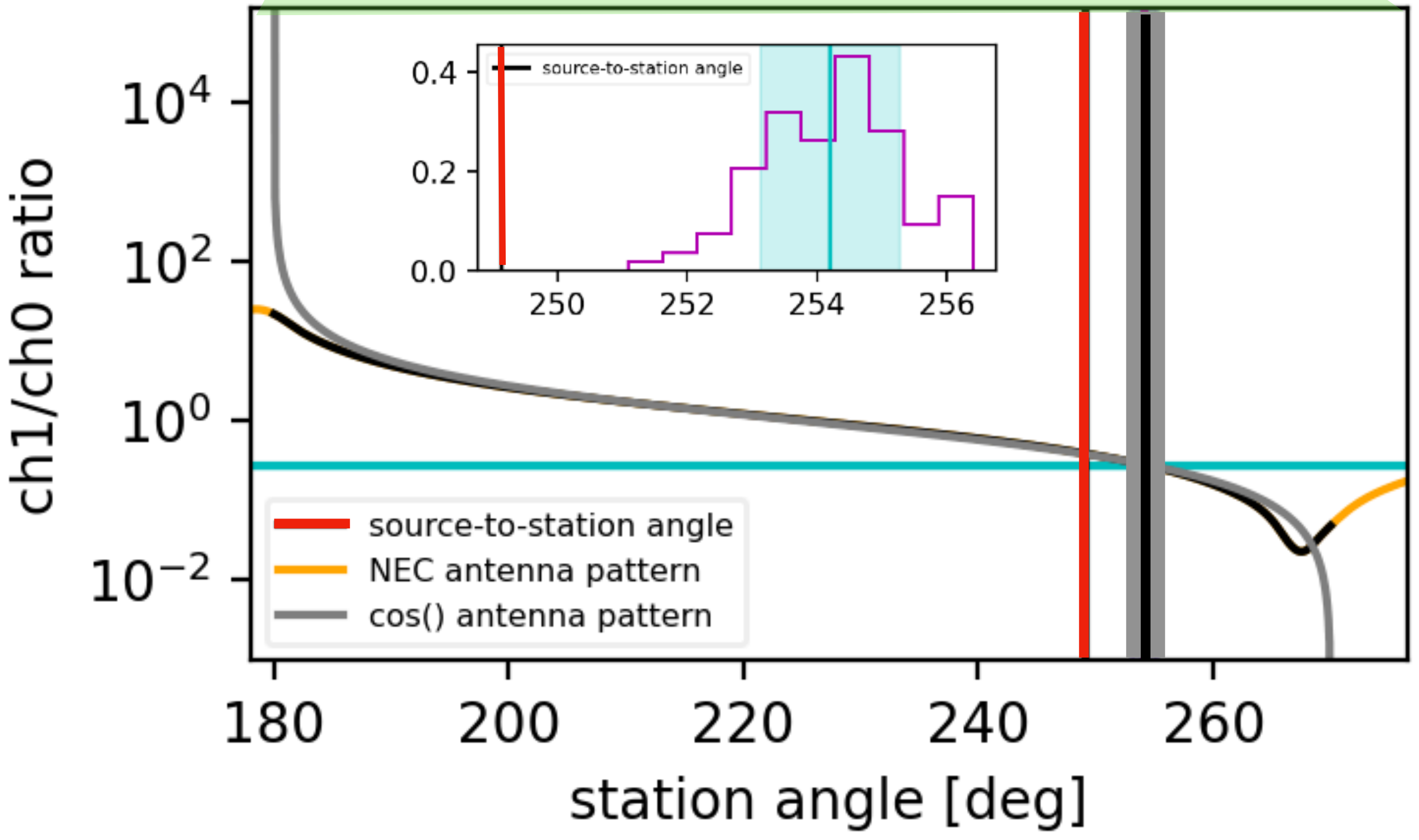
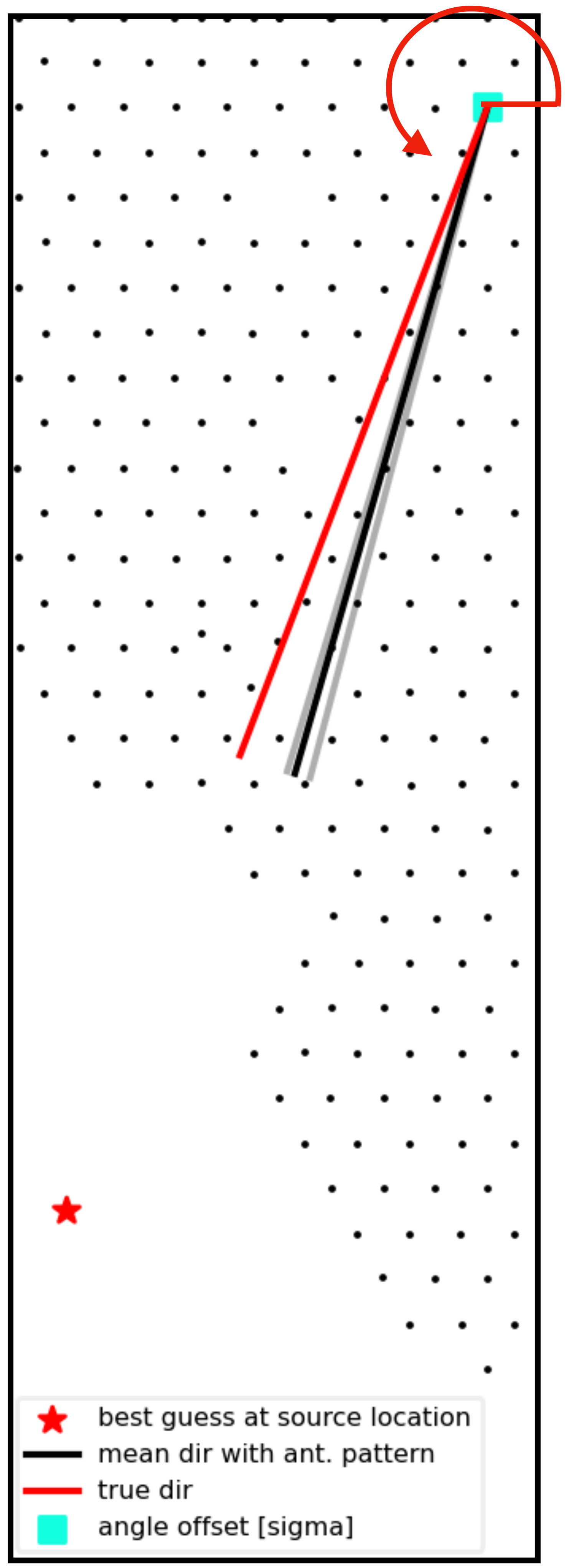
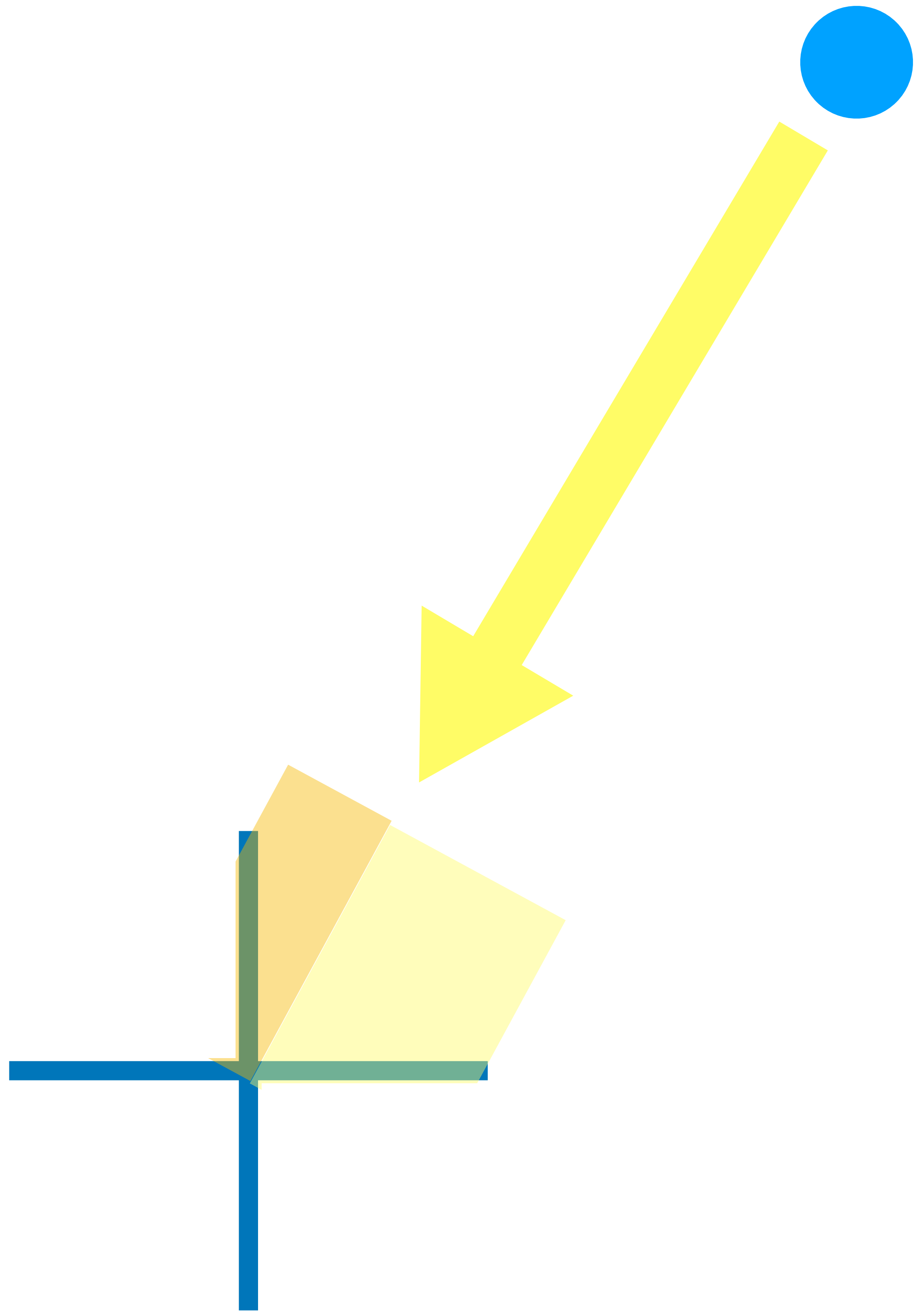
NEC antenna pattern



Matching ratios







see Bjarni @10:05

Detailed commissioning information

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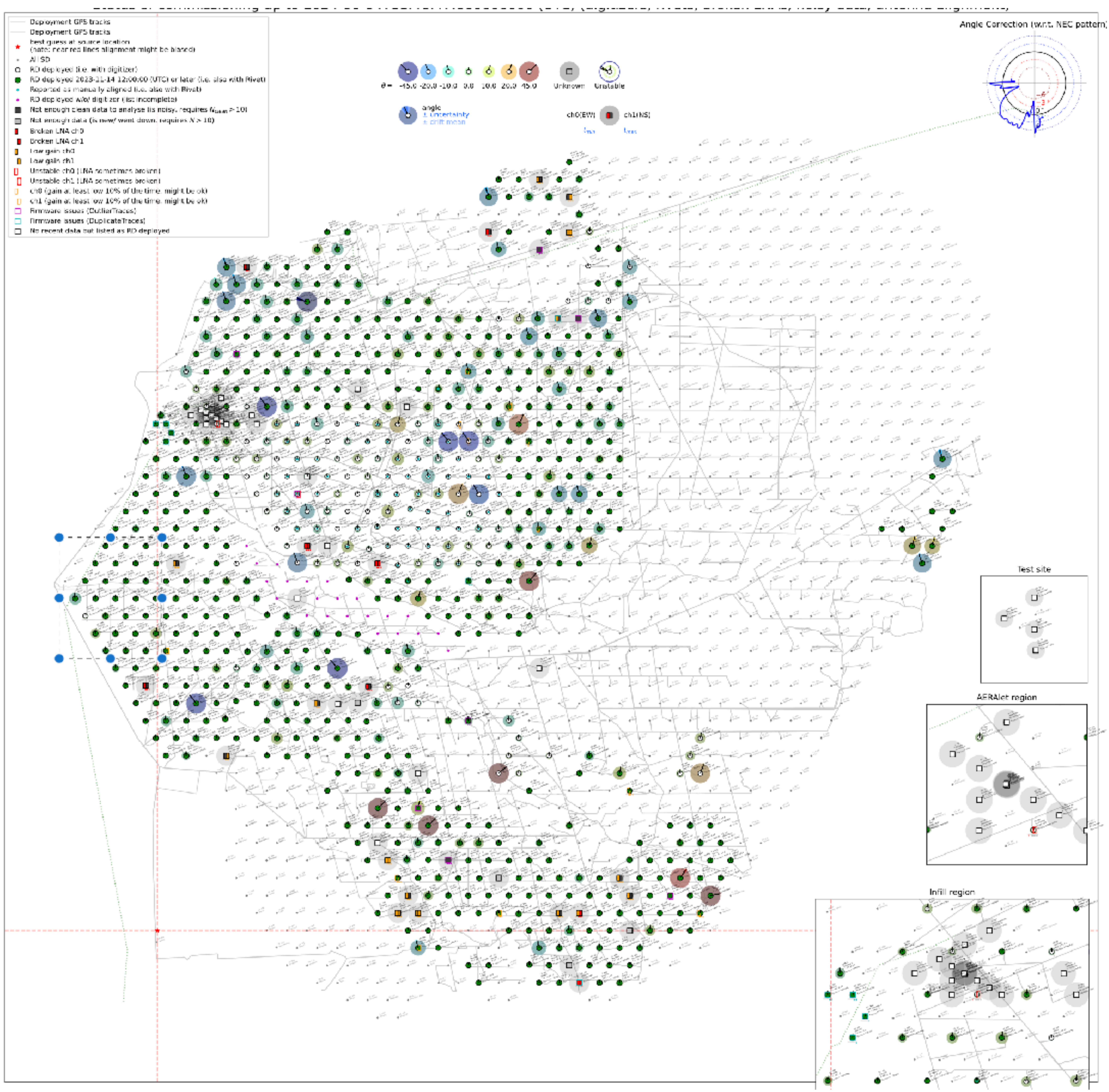
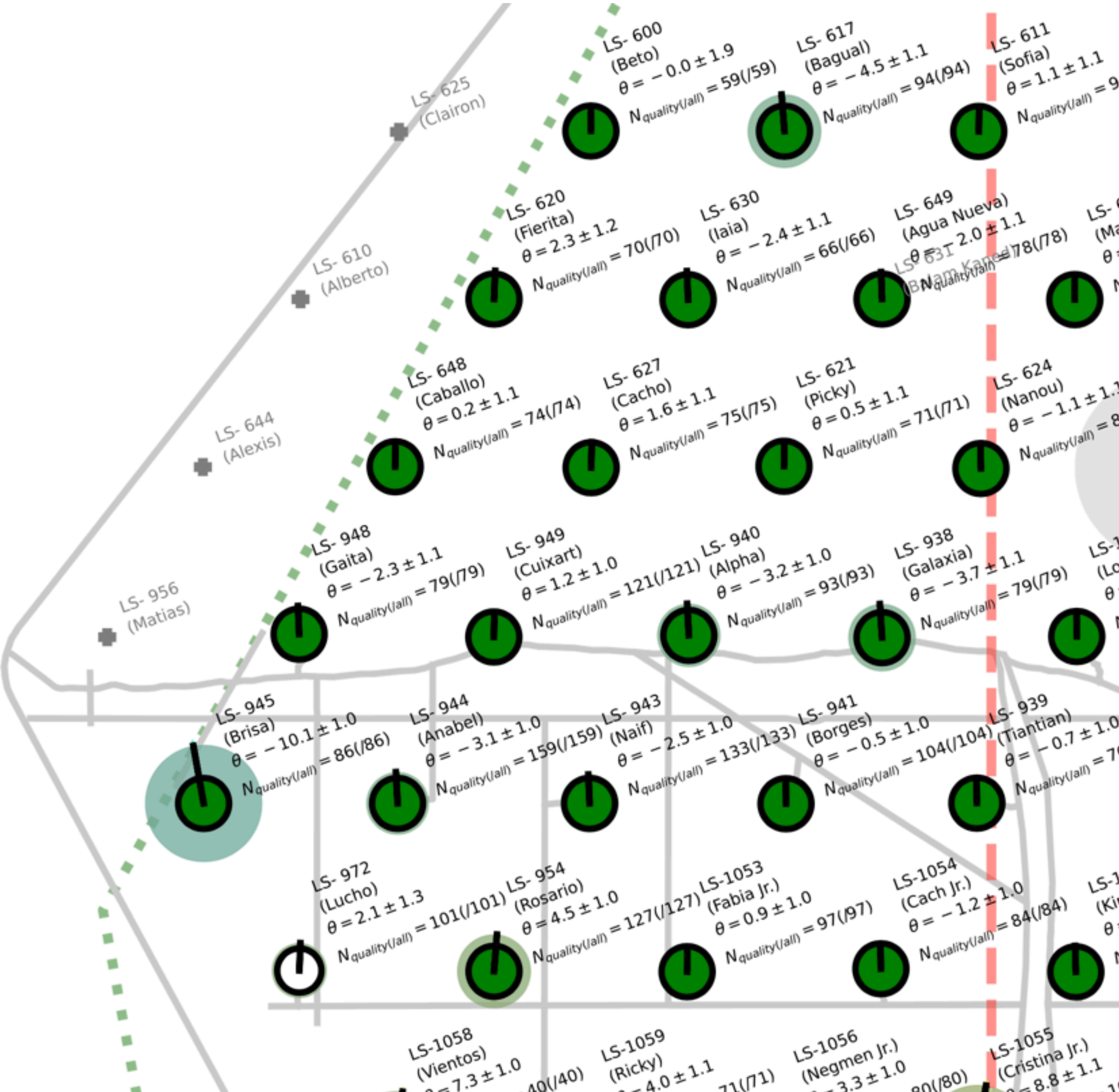
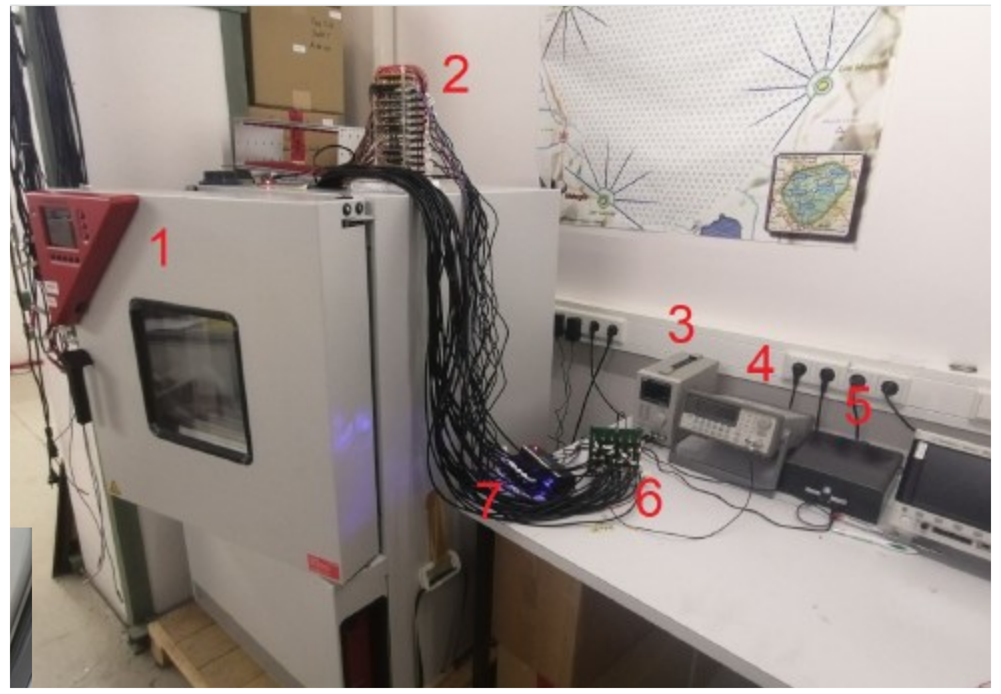


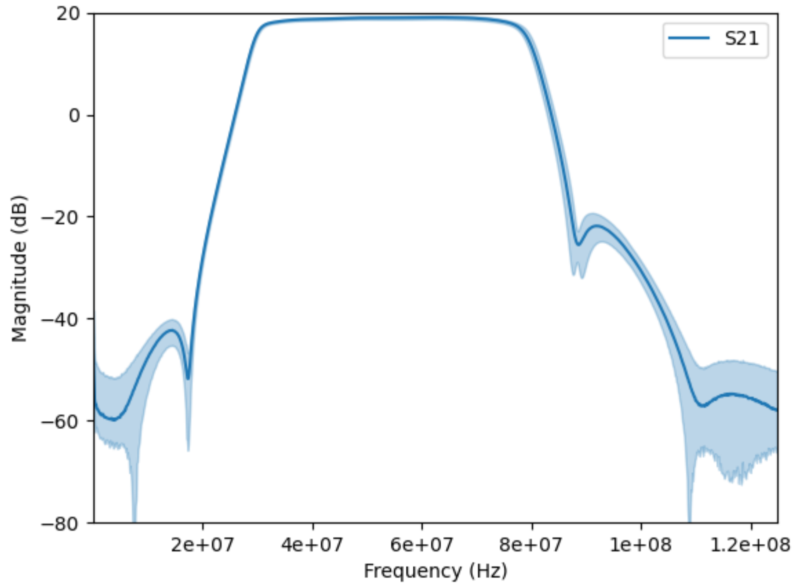


RD calibration concept

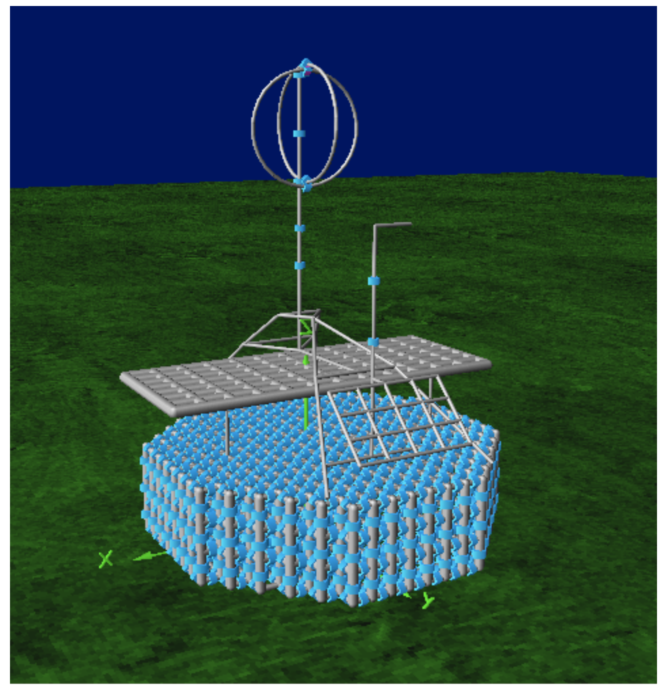
thermal cycling (aging)
LNA & digitizer

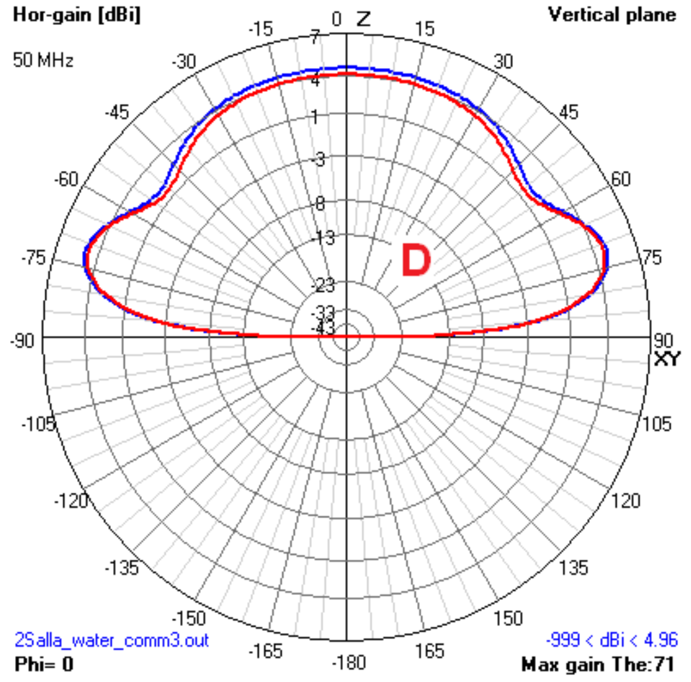


end-to-end calibration in lab
LNA & digitizer



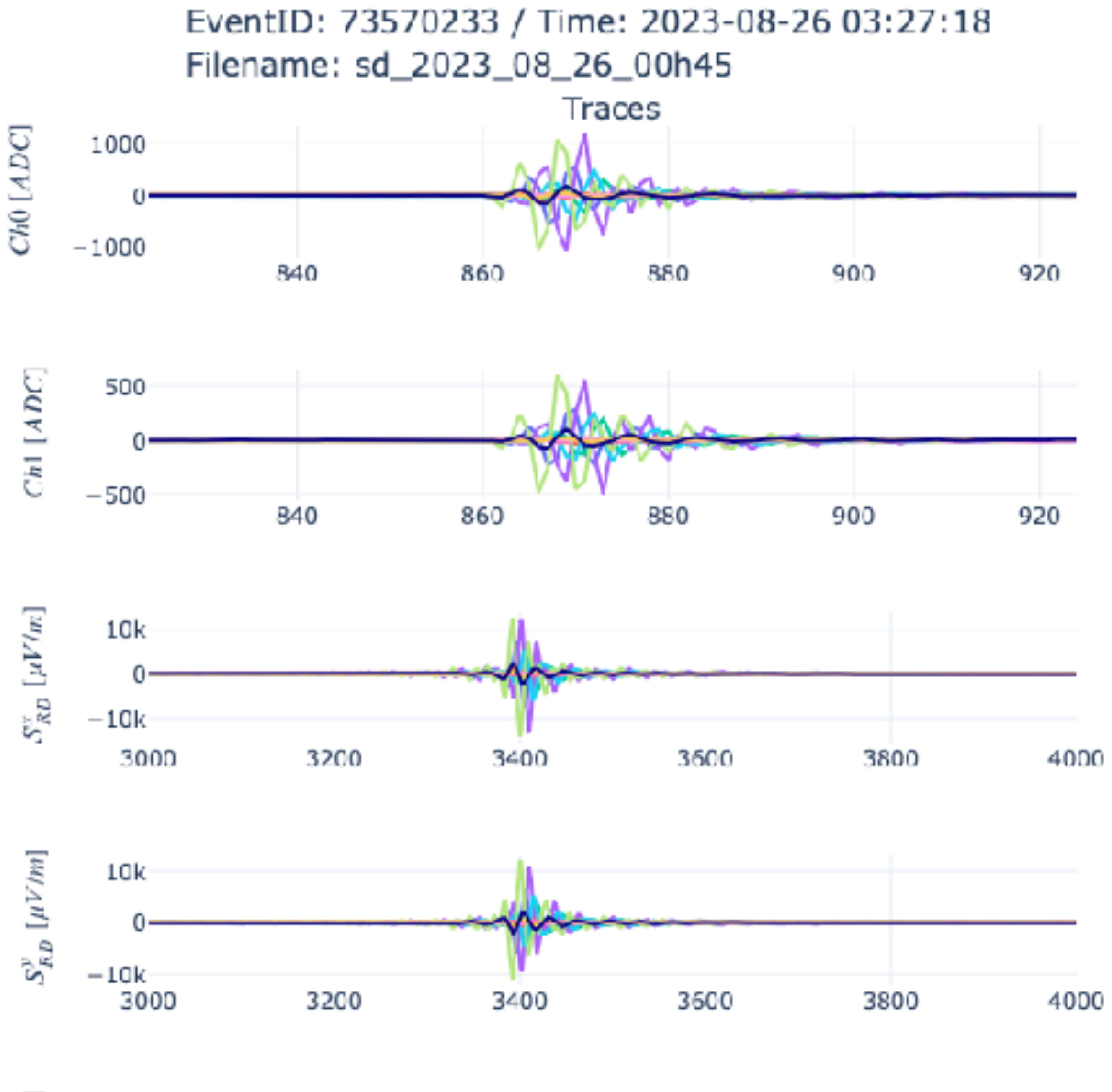
simulation of antenna pattern
NEC



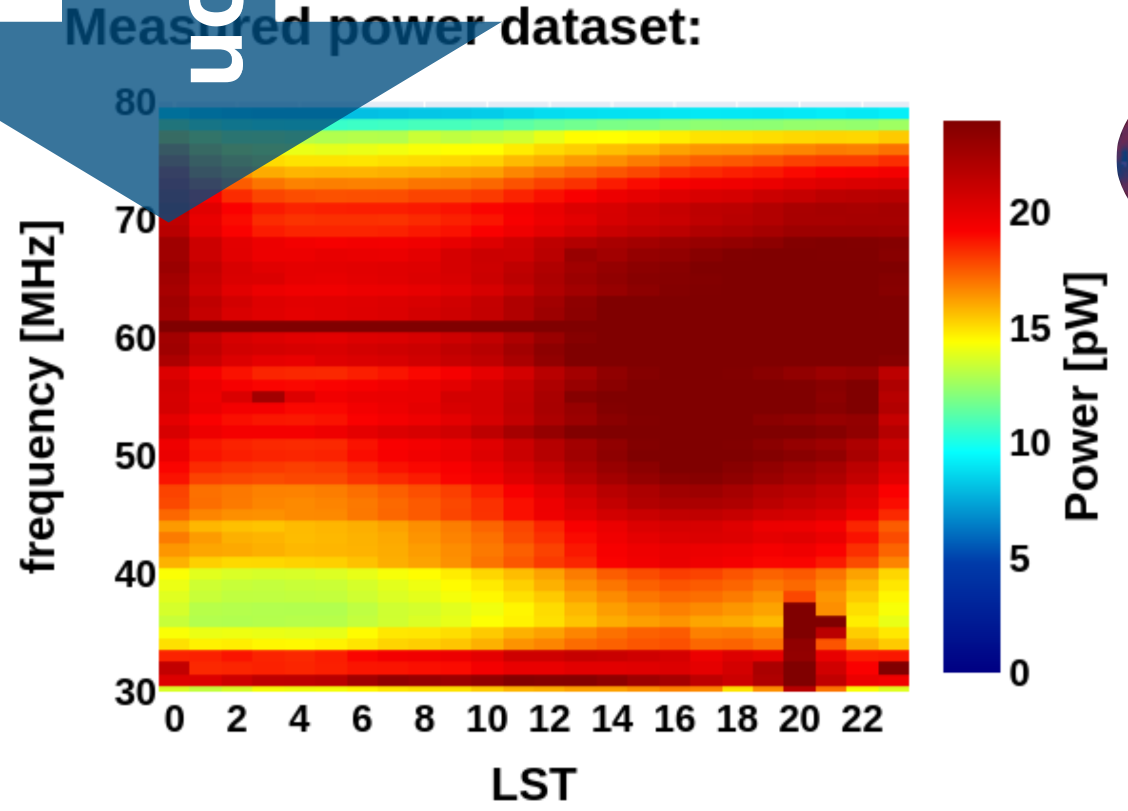


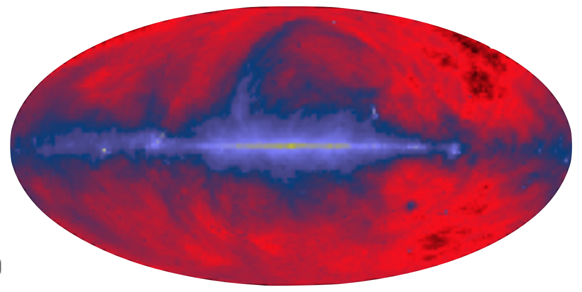
agreement on ~5% level

absolutely calibrated signals



Galactic emission
see Tim @9:50



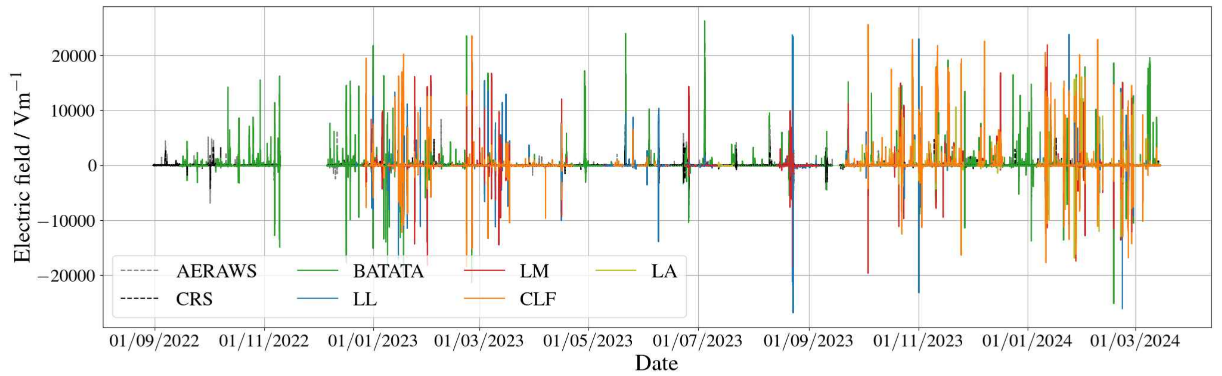


the „muon peak“ for radio

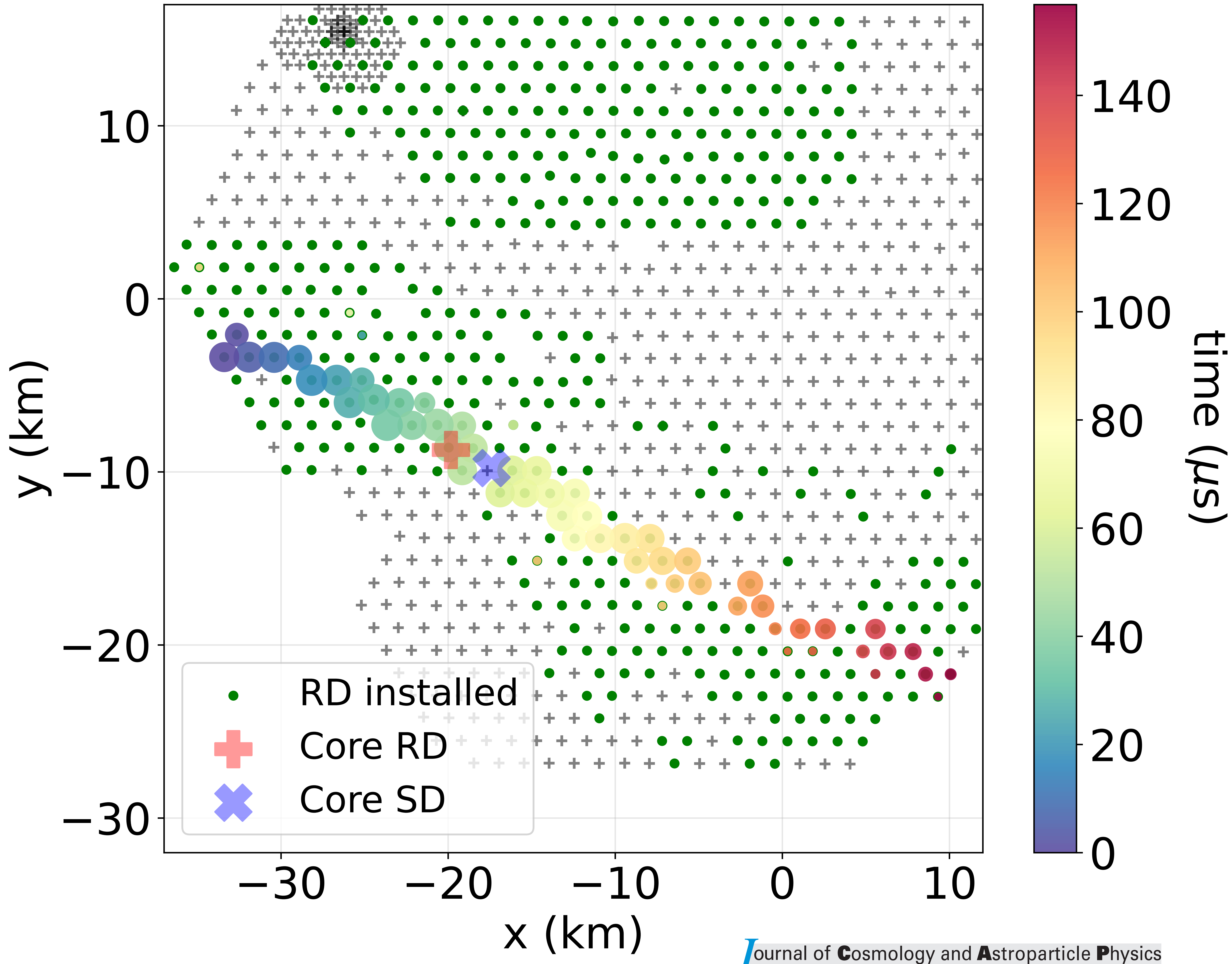
in-situ calibration with reference antenna

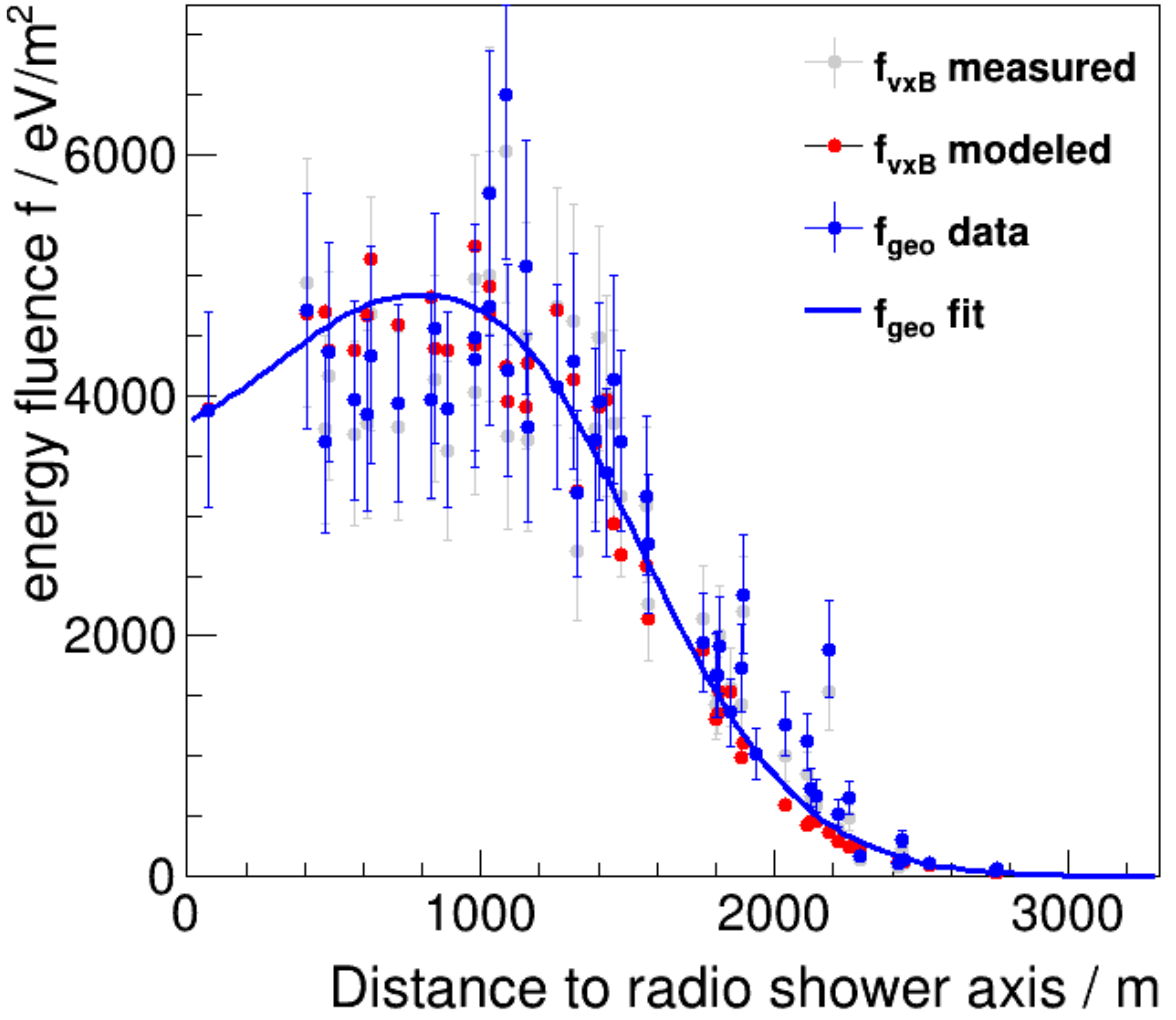
see Alex @9:35

atmospheric electric field



A measured cosmic ray





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	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

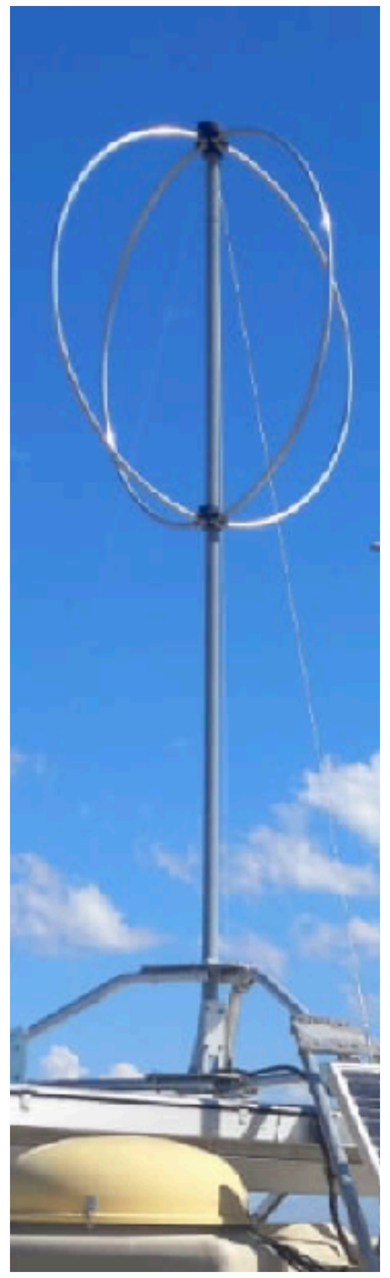
Refractive displacement of the radio-emission footprint of inclined air showers simulated with CoREAS

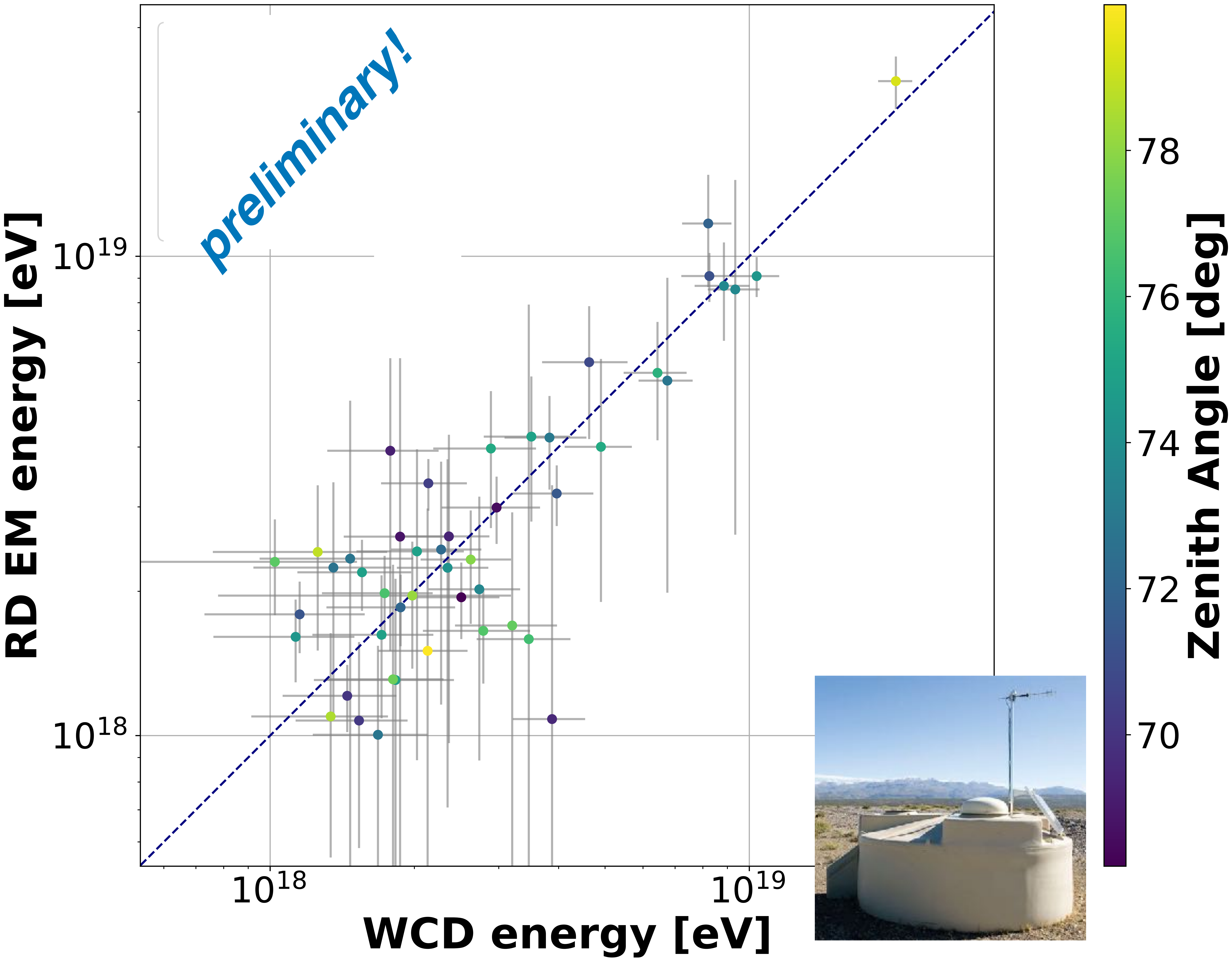
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

Hybrid measurements RD-WCD



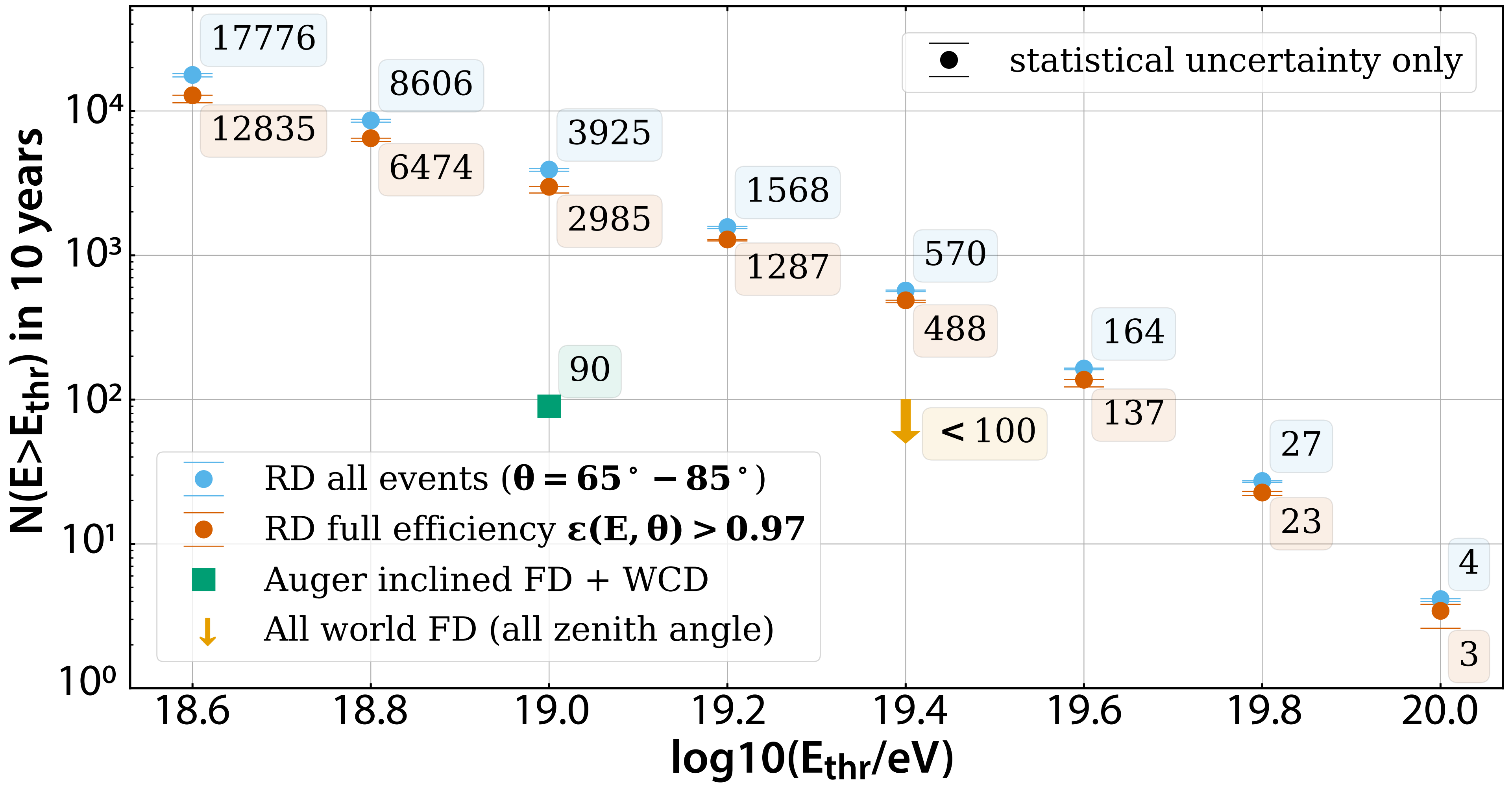


measurement of e/m energy by RD

—> full end-to-end verification of complete chain

RD expected physics contributions

integrated # of cosmic rays



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mass separation

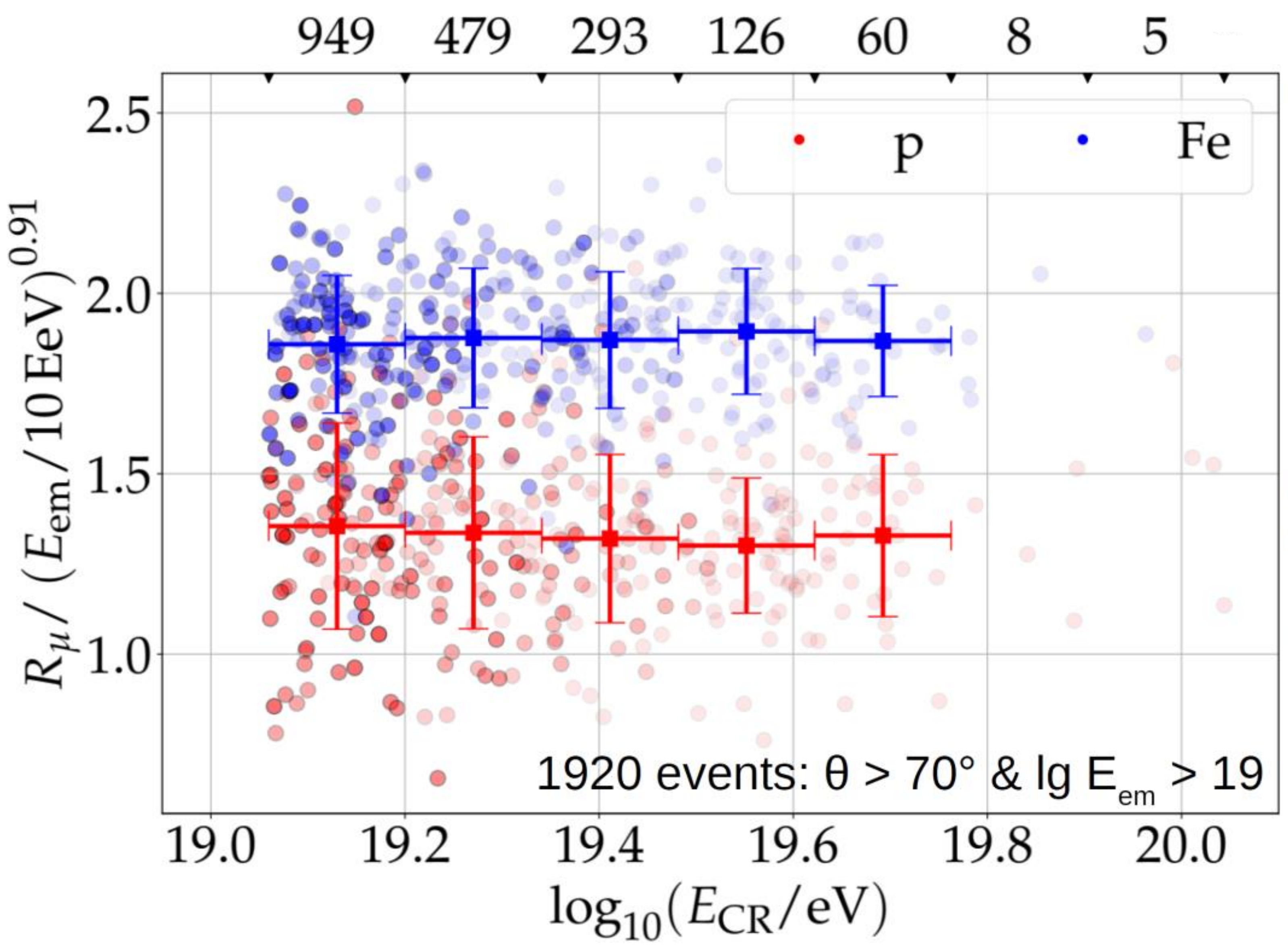


Figure of Merit:

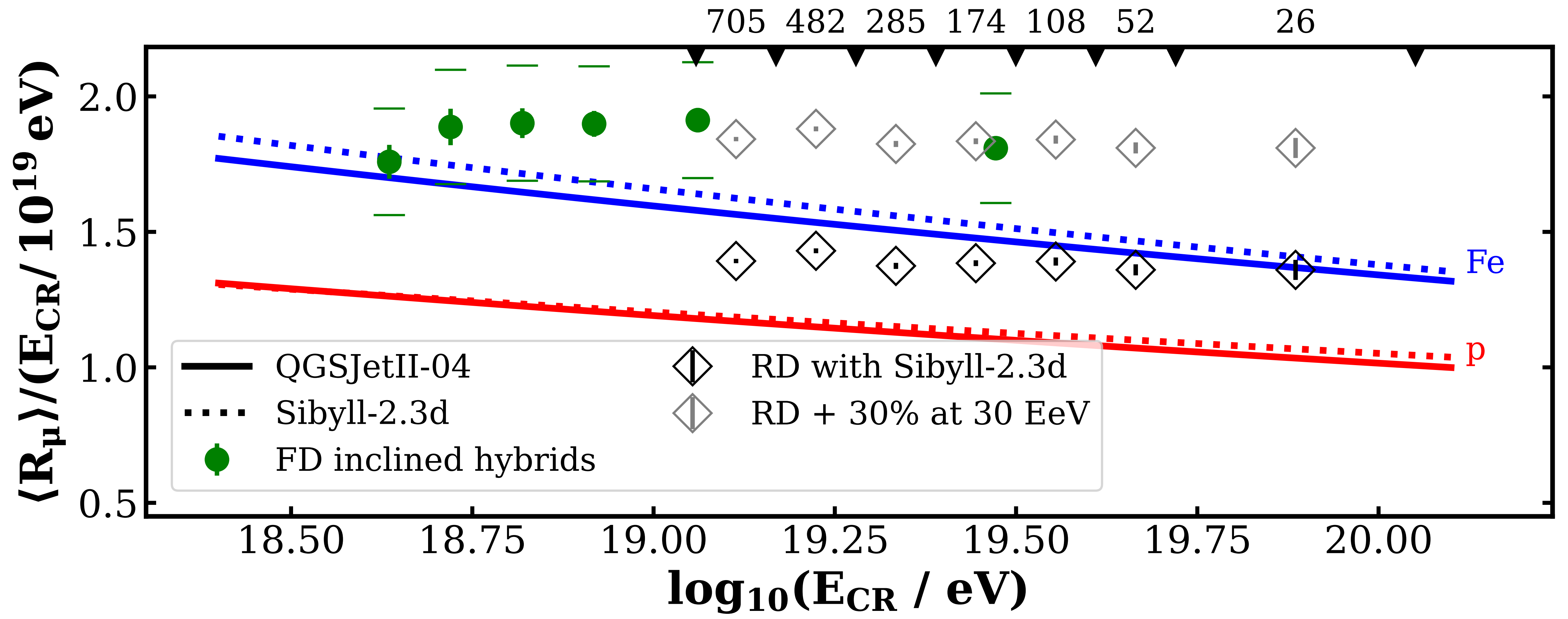
$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma_{r_p}^2 + \sigma_{r_{Fe}}^2}}$$

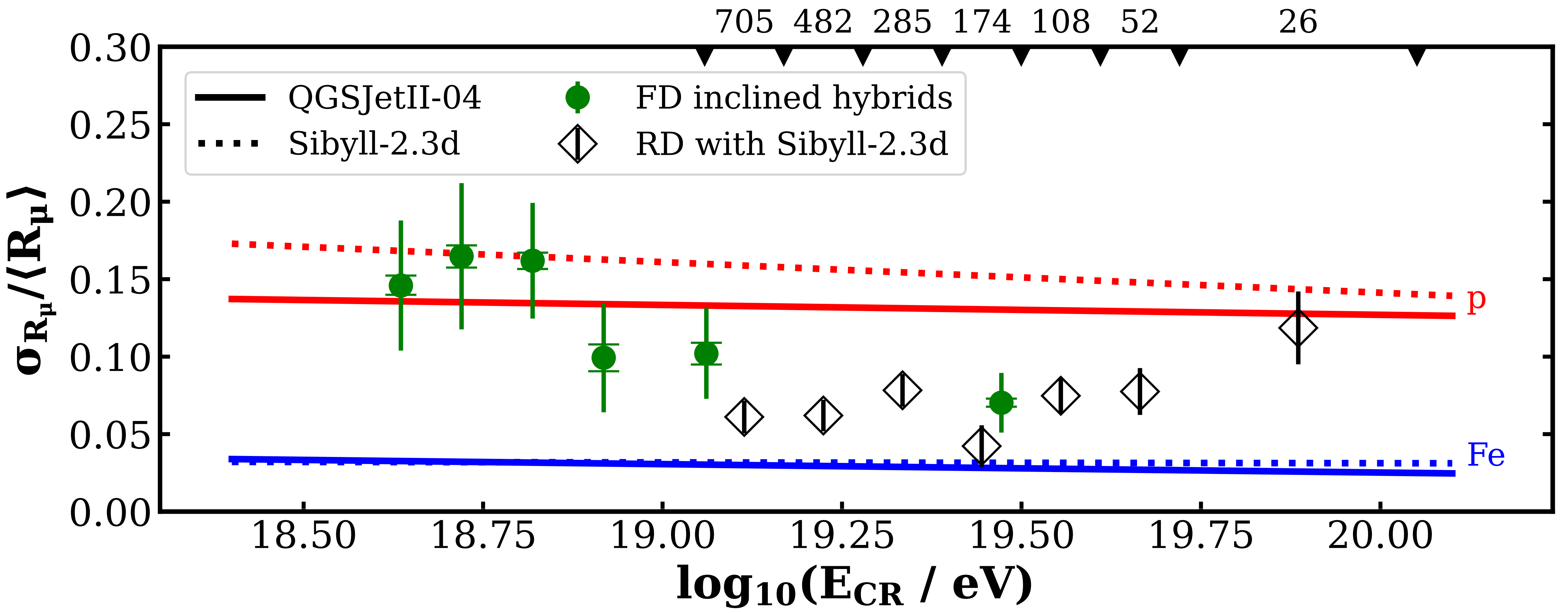
FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5

measurement quality combining RD & WCD





T. Huege et al, EPJ Web of Conf. 283 (2023) 06002

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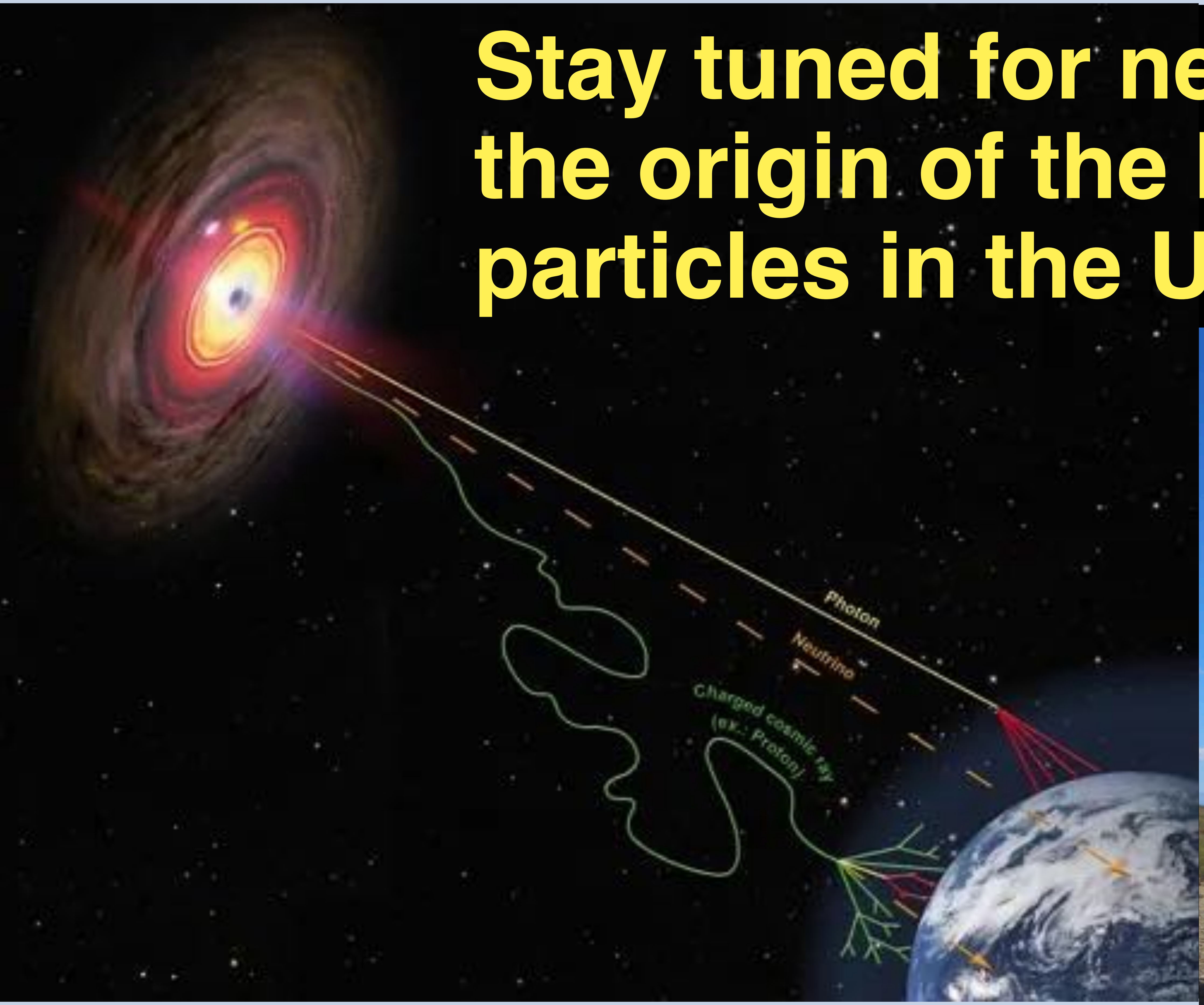

7th International Symposium on Ultra-High-Energy Cosmic Rays

UHECR 2024

Malargüe, Argentina - November 17-21 2024

The symposium is the 7th edition of a series of meetings that bring together the UHECR community. It covers the latest results from UHECR observations, theoretical developments, and future plans in the field. The symposium will focus on the highest energy cosmic rays as well as on cosmic rays with energies above 1 PeV. The agenda includes invited reviews, contributed talks, and reports from inter-collaborative working groups, all in plenary sessions. Poster contributions are also foreseen.

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