

Cosmic rays with LOFAR 2.0 - what's next?

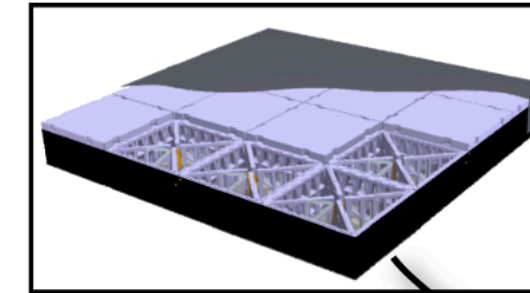
Katie Mulrey for the LOFAR CR-KSP

R. Bekaert, S. Bouma, S. Buitink, A. Corstanje, M. Desmet, H. Falcke, B. Hare, V. de Henau, J. Hörandel, T. Huege, V.B. Jhansi, N. Karastathis, G. Krampah, P. Laub, P. Mitra, K. Mulrey, A. Nelles, H. Pandya, S. Saha, O.Scholten, K. Terveer, S. Thoudam, G. Trinh, P. Turekovam, S. ter Veen, K. Watanabe, T. Wybouw, L. van Zuijlen

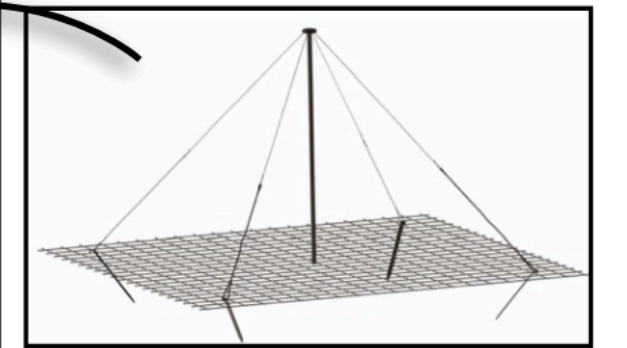
What is LOFAR 2.0?

- LOFAR is getting an upgrade, primarily to serve astronomical observations - but is also highly beneficial for cosmic rays!

High-Band Antenna (HBA)



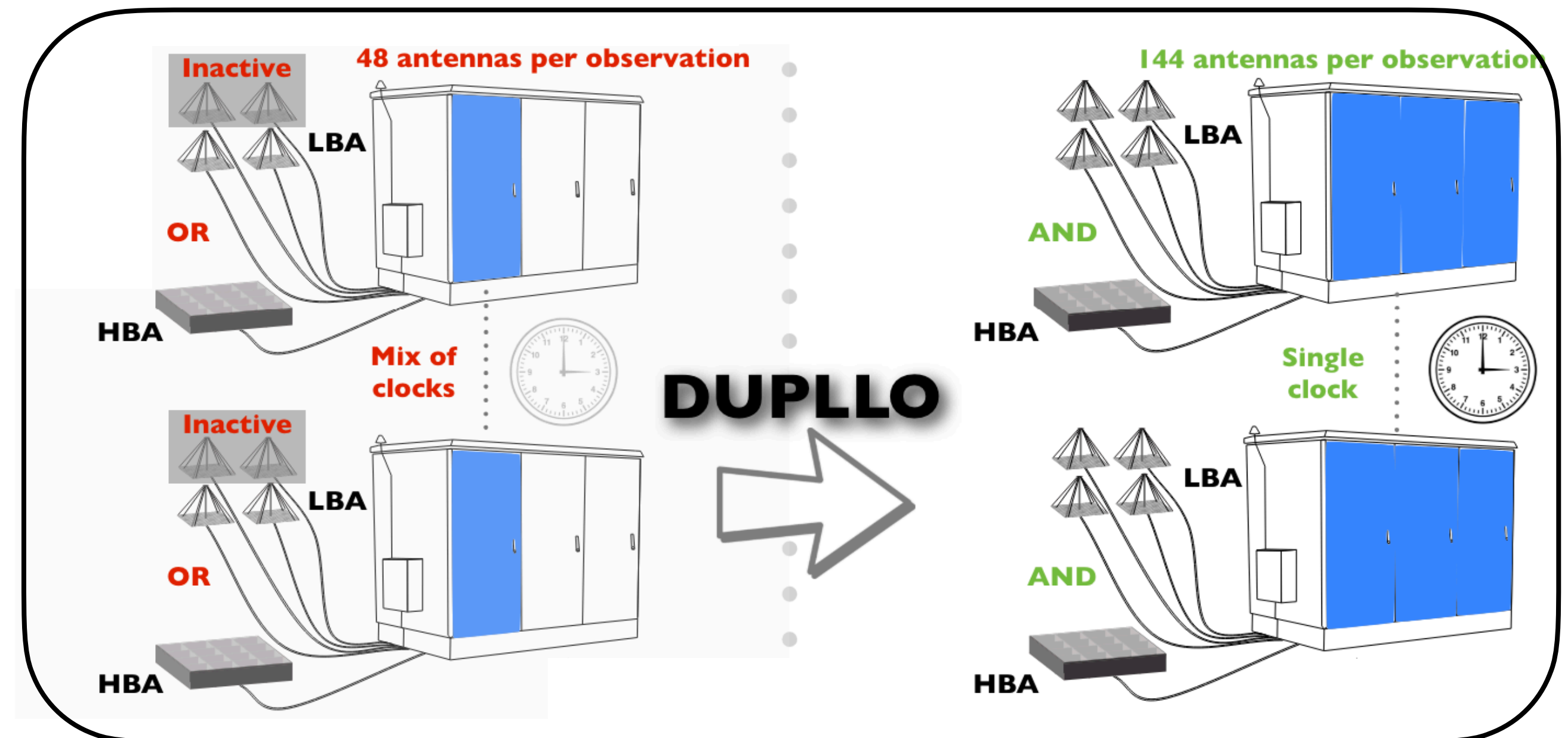
Low-Band Antenna (LBA)



Digital Upgrade for Premier LOFAR Low-band Observing: DUPLLO

- Key improvements:

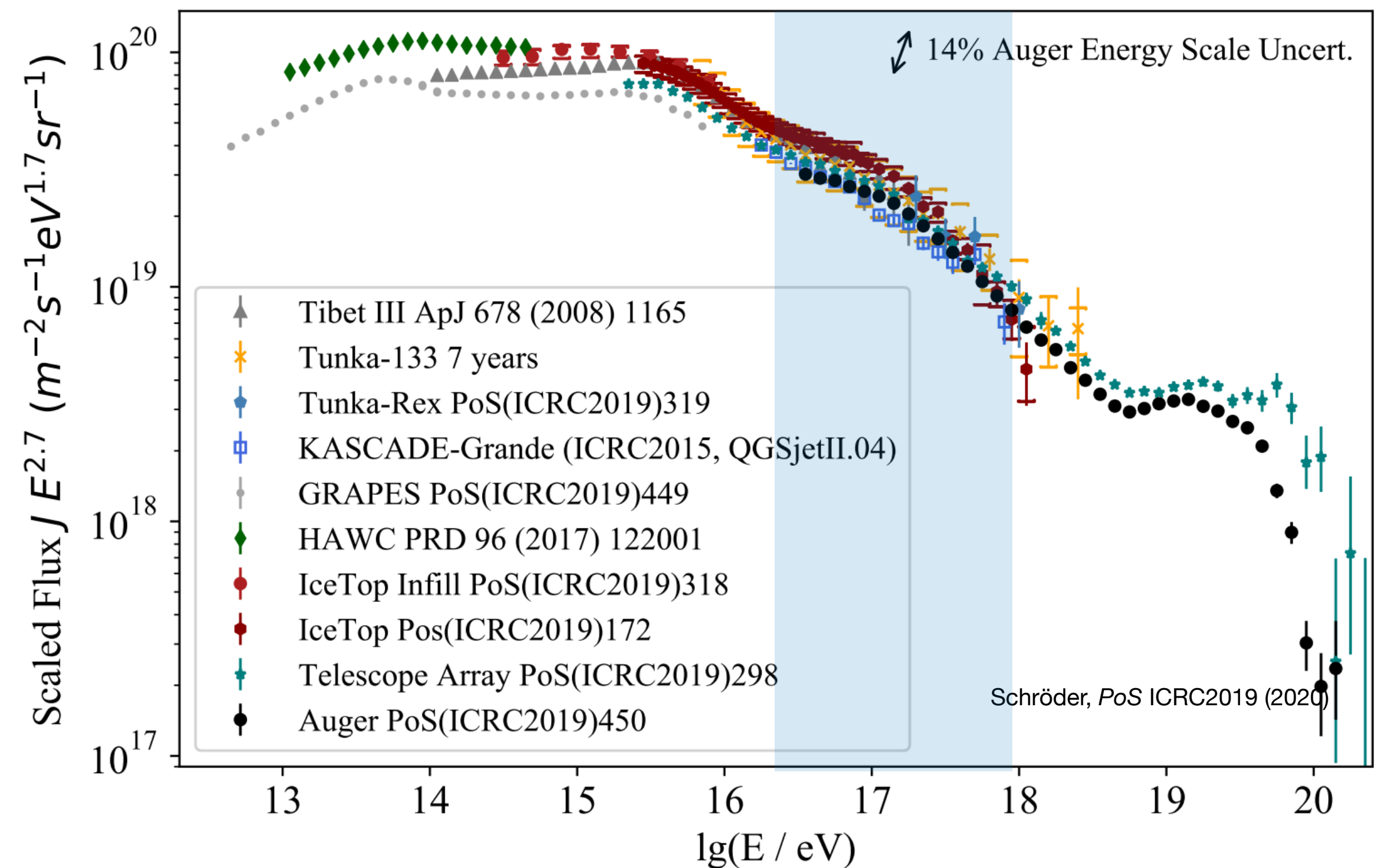
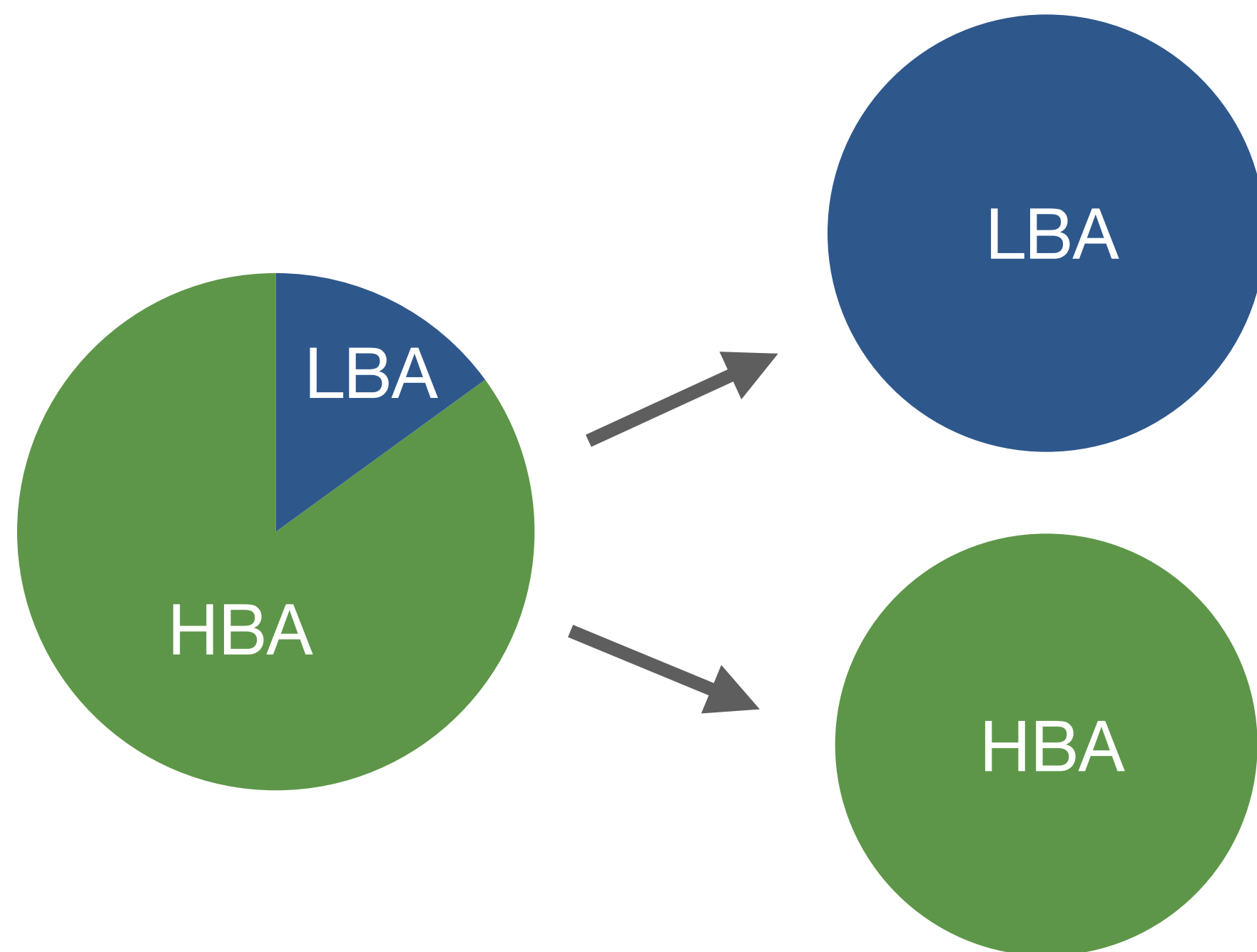
- continuous observations for all antenna sets
- un-beamformed HBA antennas
- increased network speed



What does LOFAR 2.0 mean for cosmic rays?

Continuous observations for all antenna sets

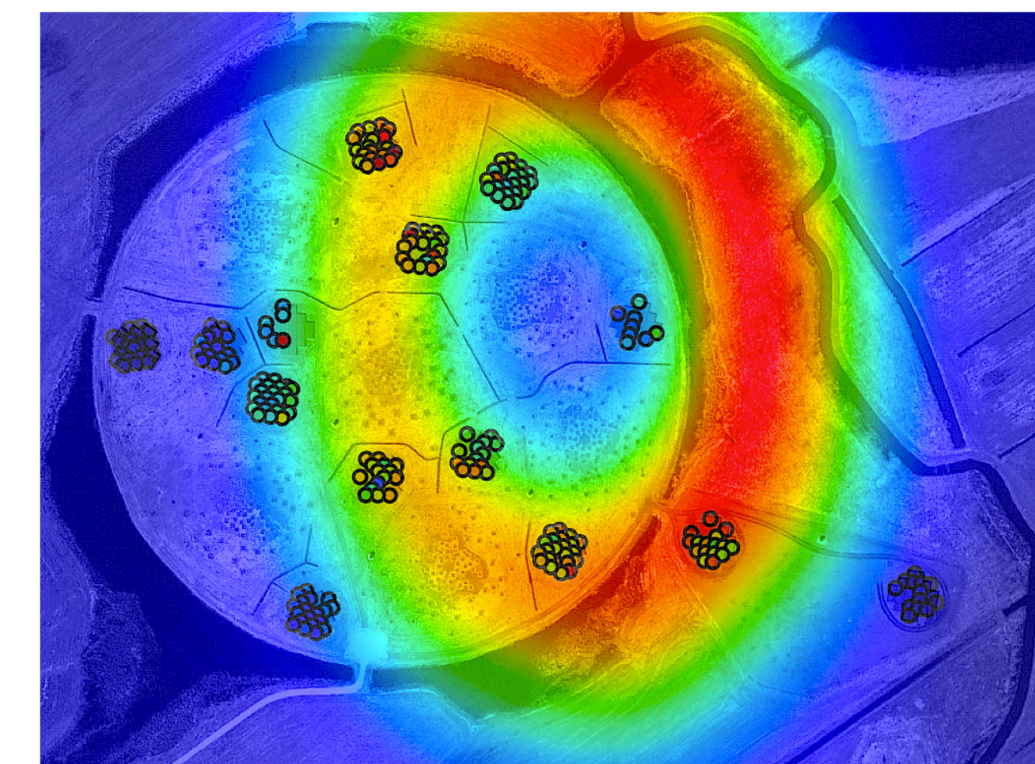
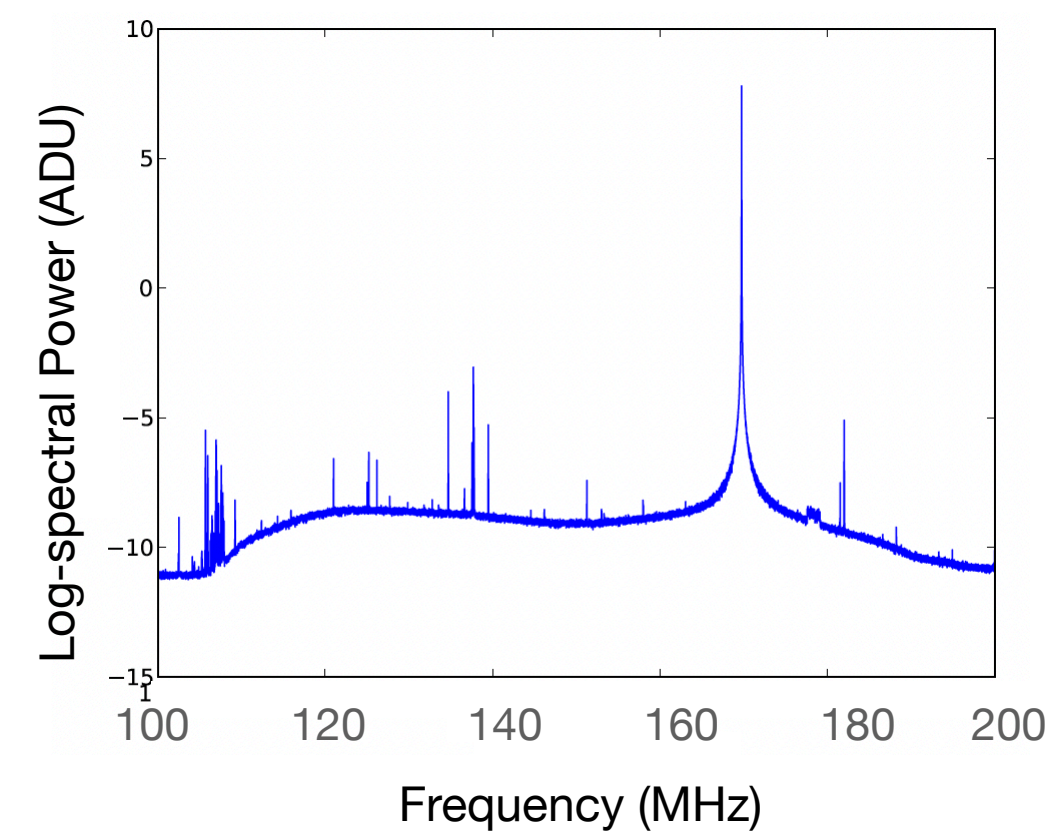
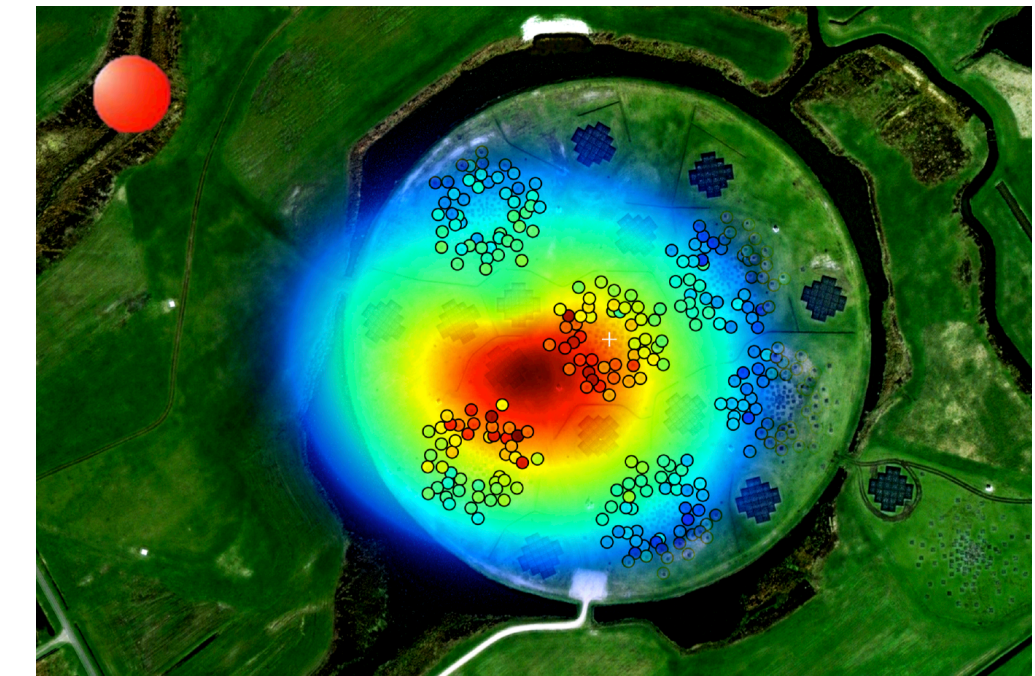
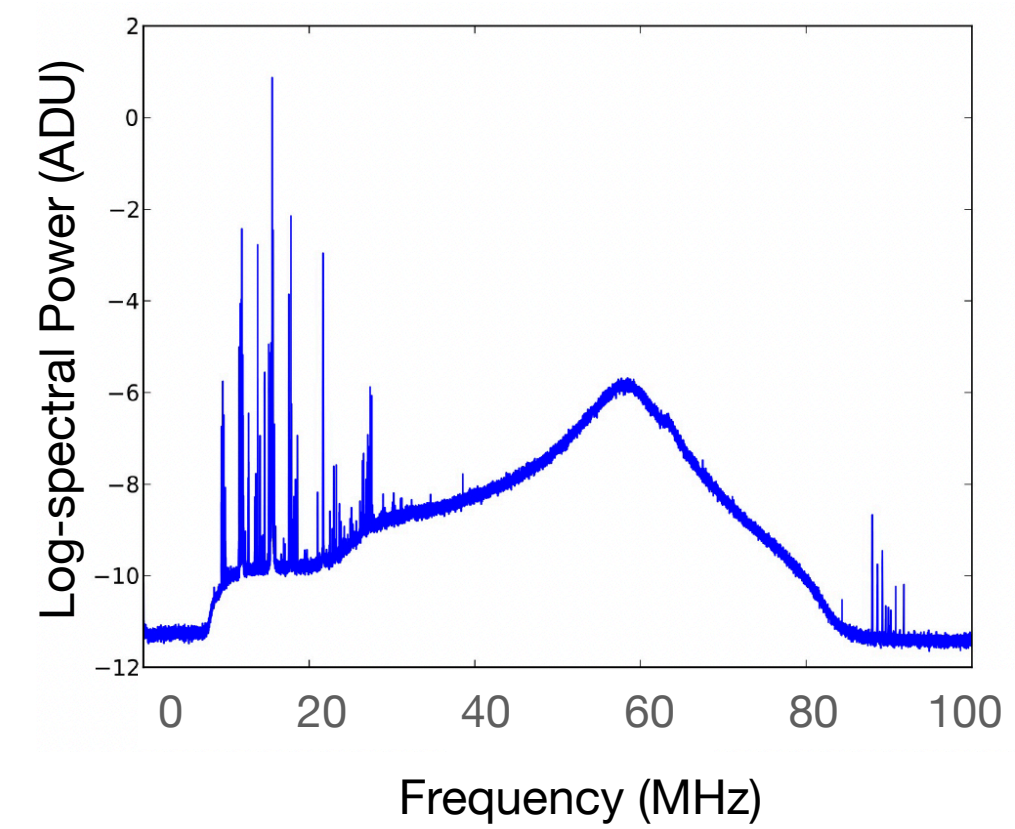
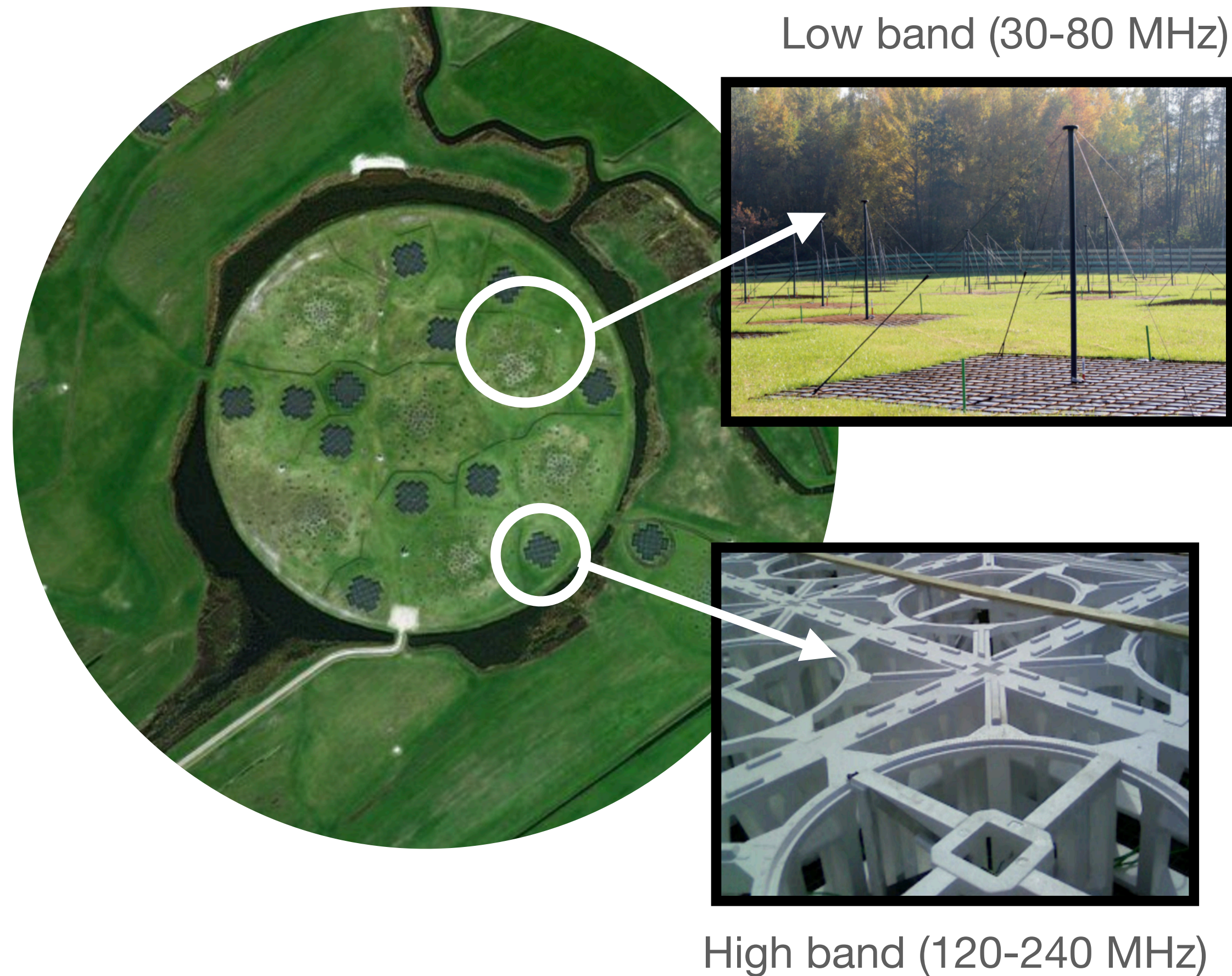
- Overall higher event rate (LBA currently ~ 15% observation) - 10x increase in usable events
- Consistent, predictable observation



What does LOFAR 2.0 mean for cosmic rays?

Un-beamformed HBA antennas

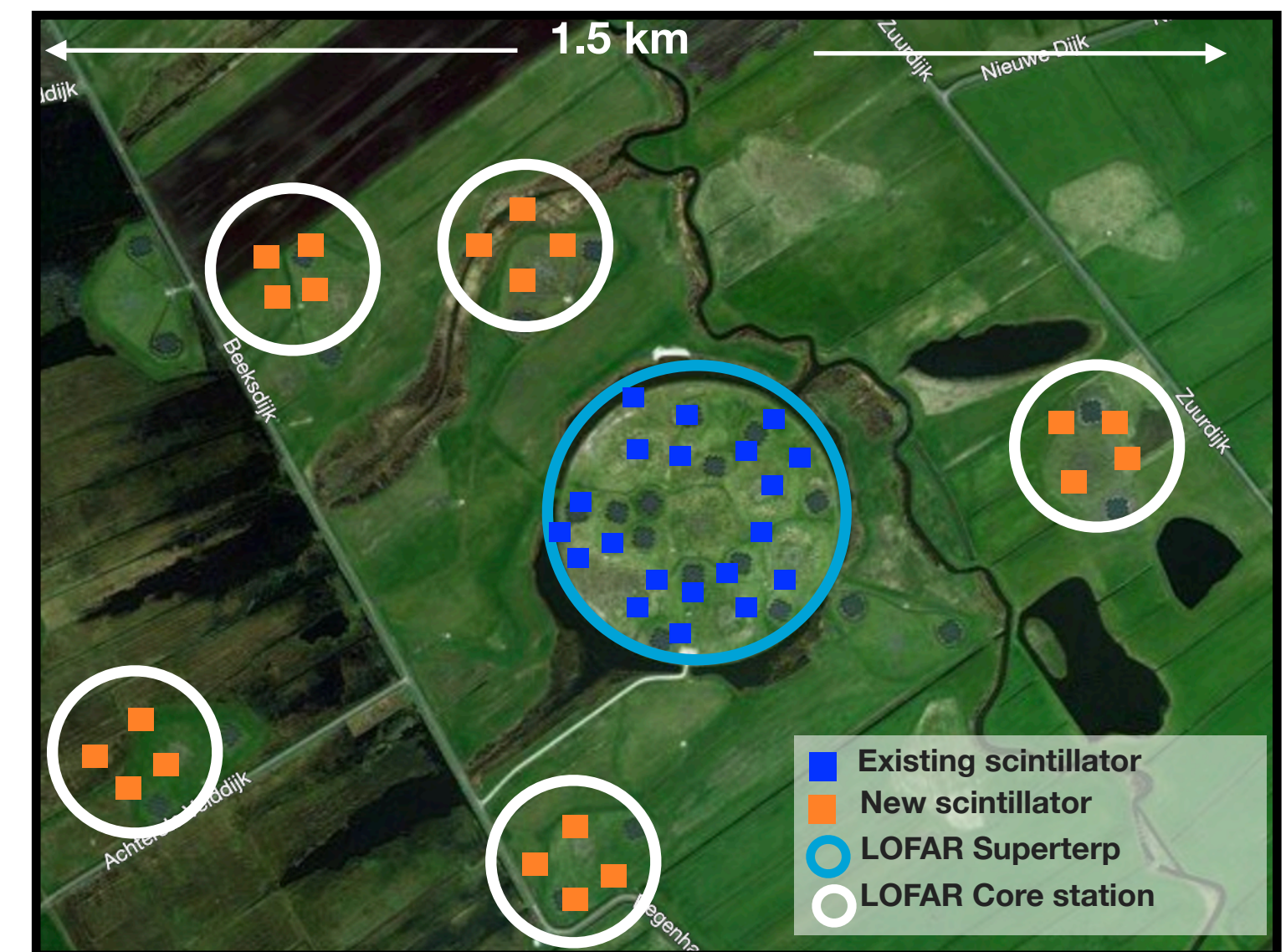
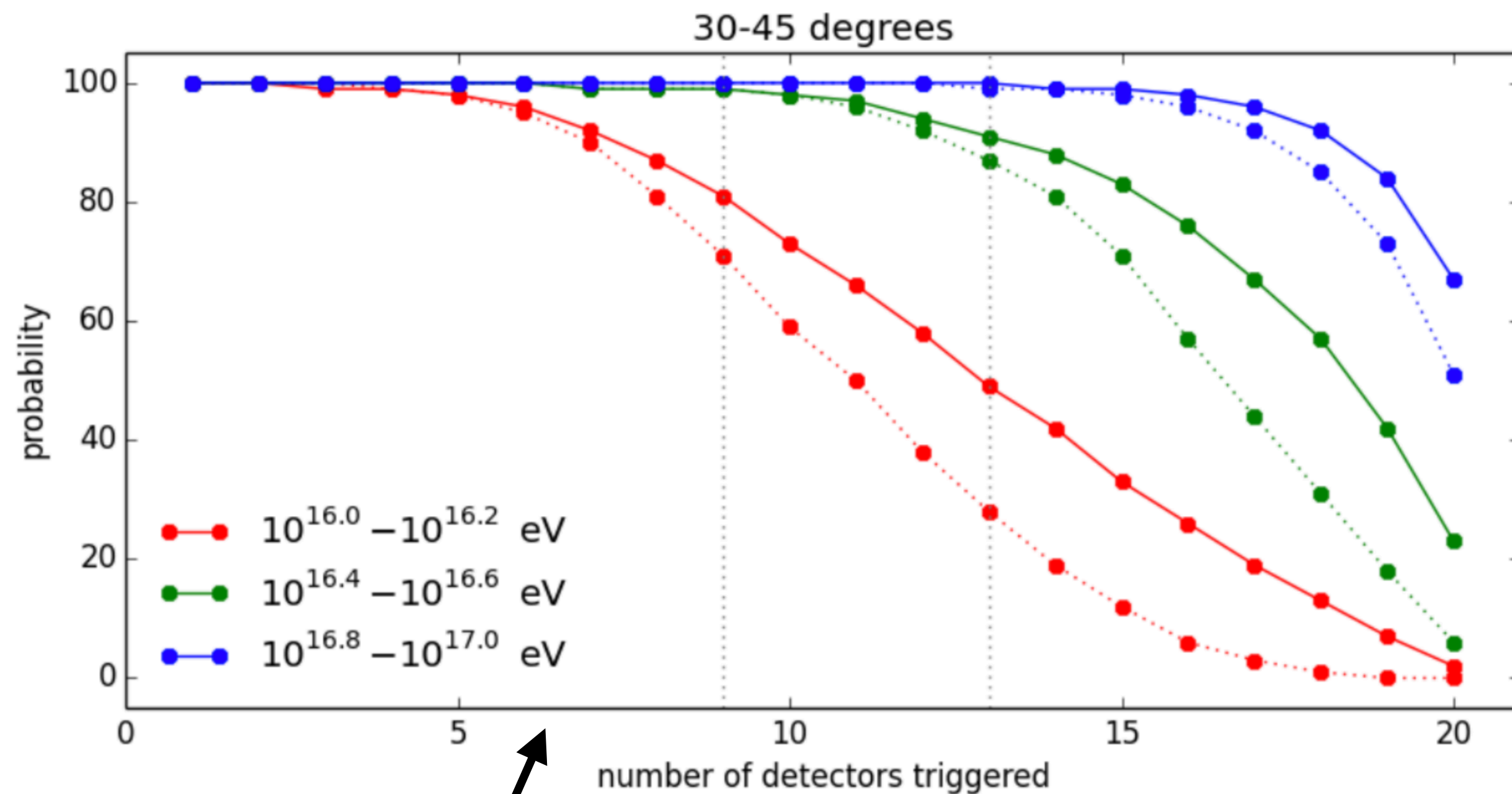
- Simultaneous observation with LBA (30-80 MHz) + un-beamformed HBA (120-240 MHz)



What does LOFAR 2.0 mean for cosmic rays?

Increased network speed

- Higher trigger rate = less bias, more low energy events, more events total

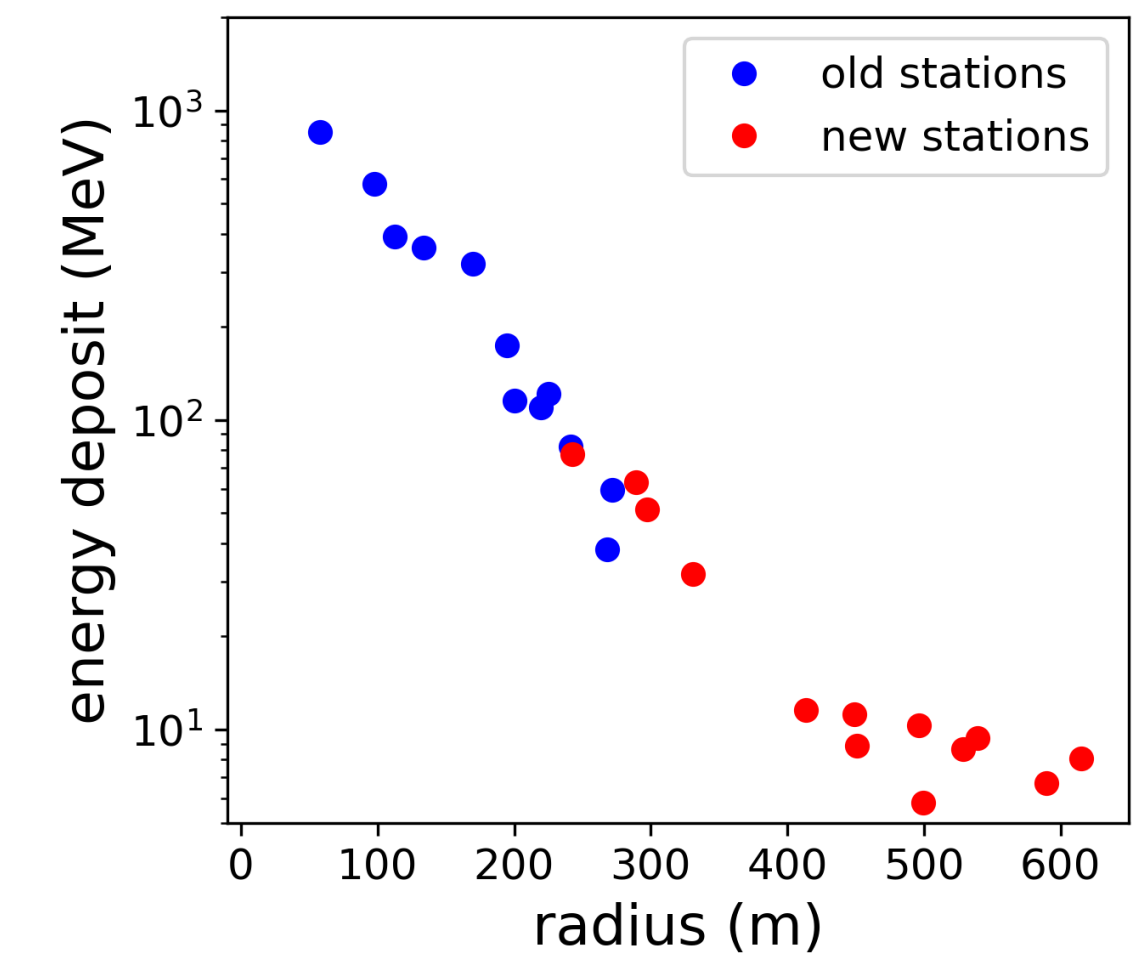
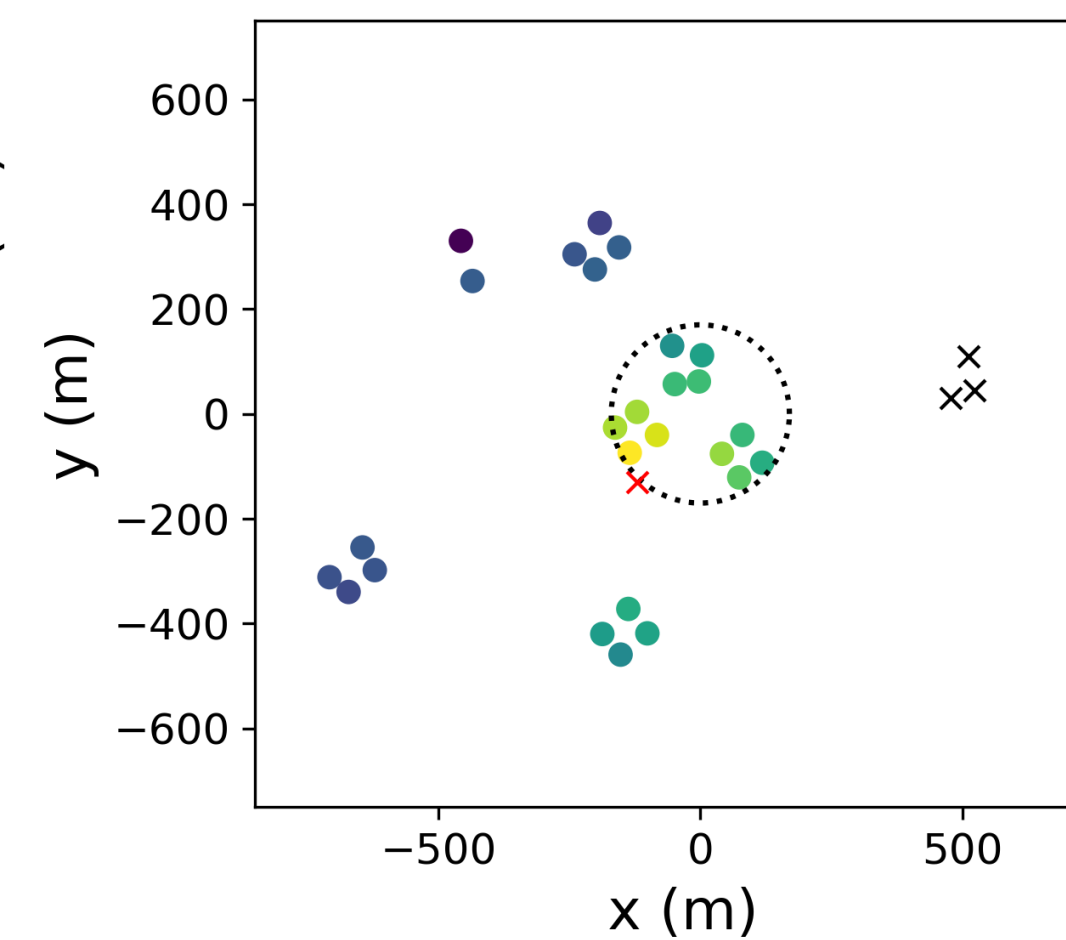
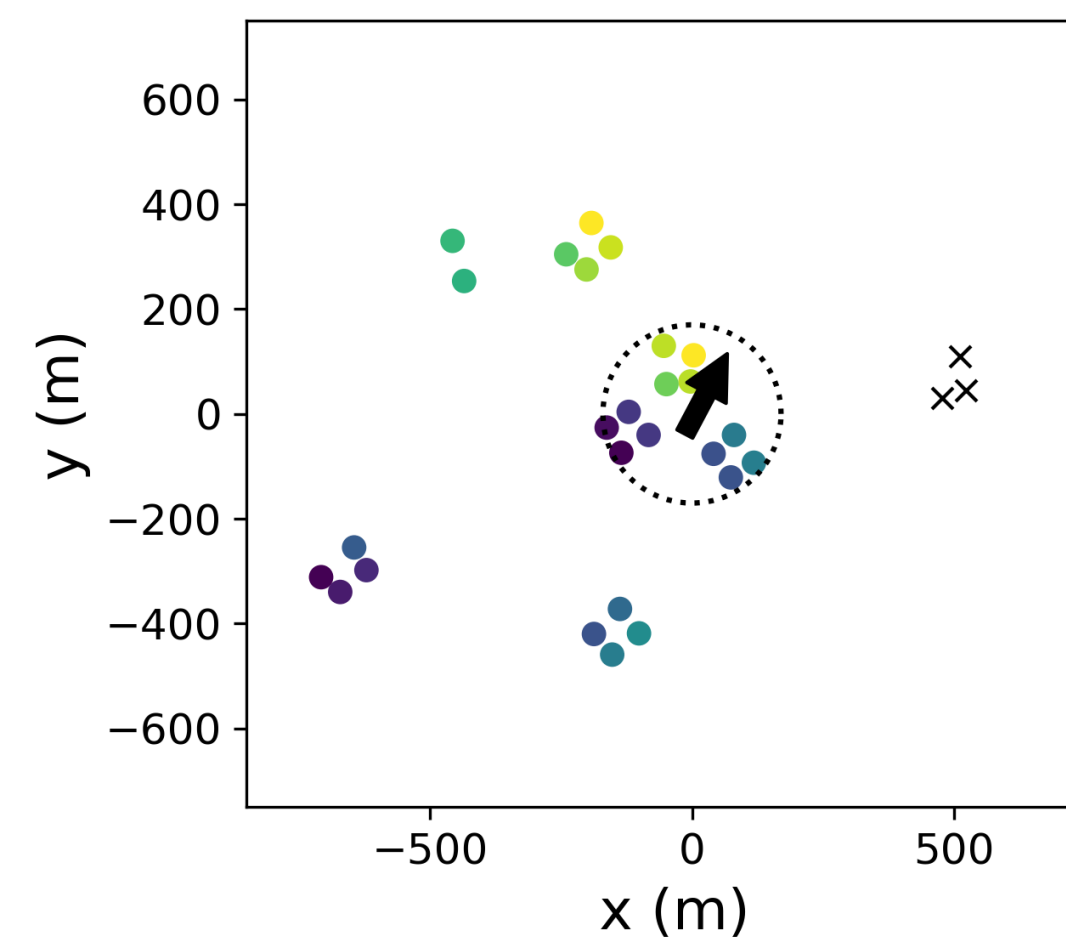
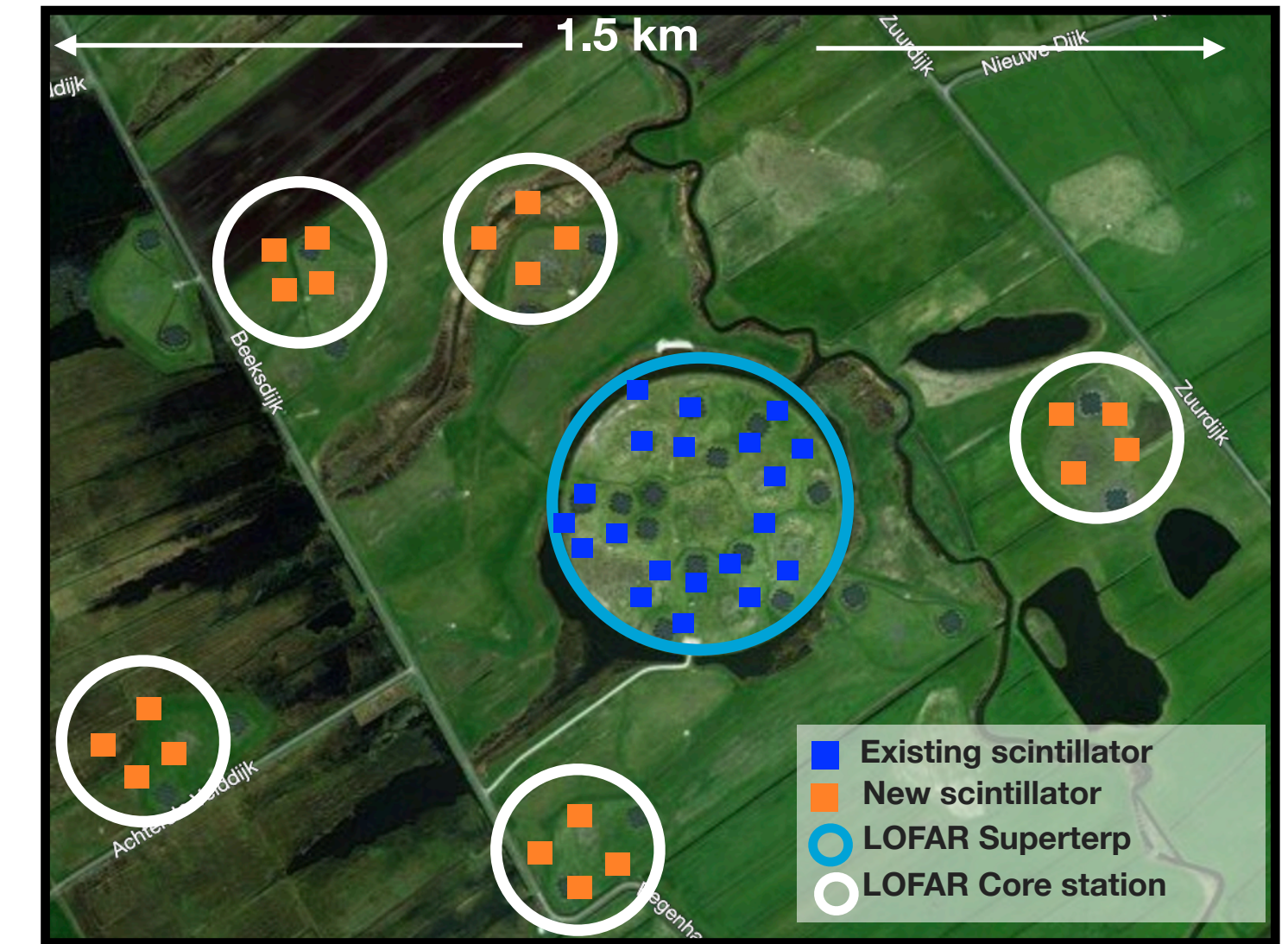
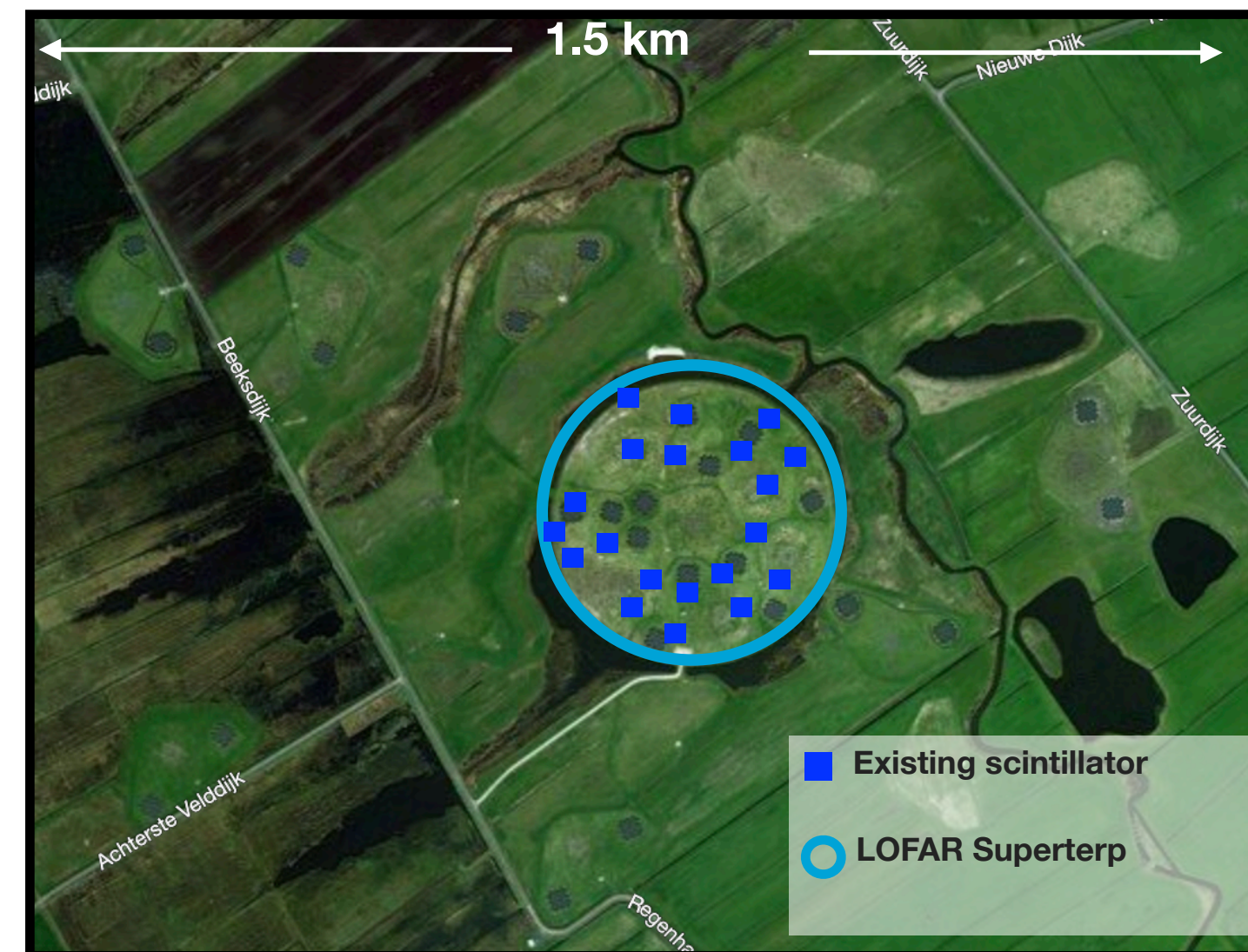


High network speed, bias-free
low energy detections

Strict trigger requirements to achieve 1 event / hour,
limited by network bandwidth

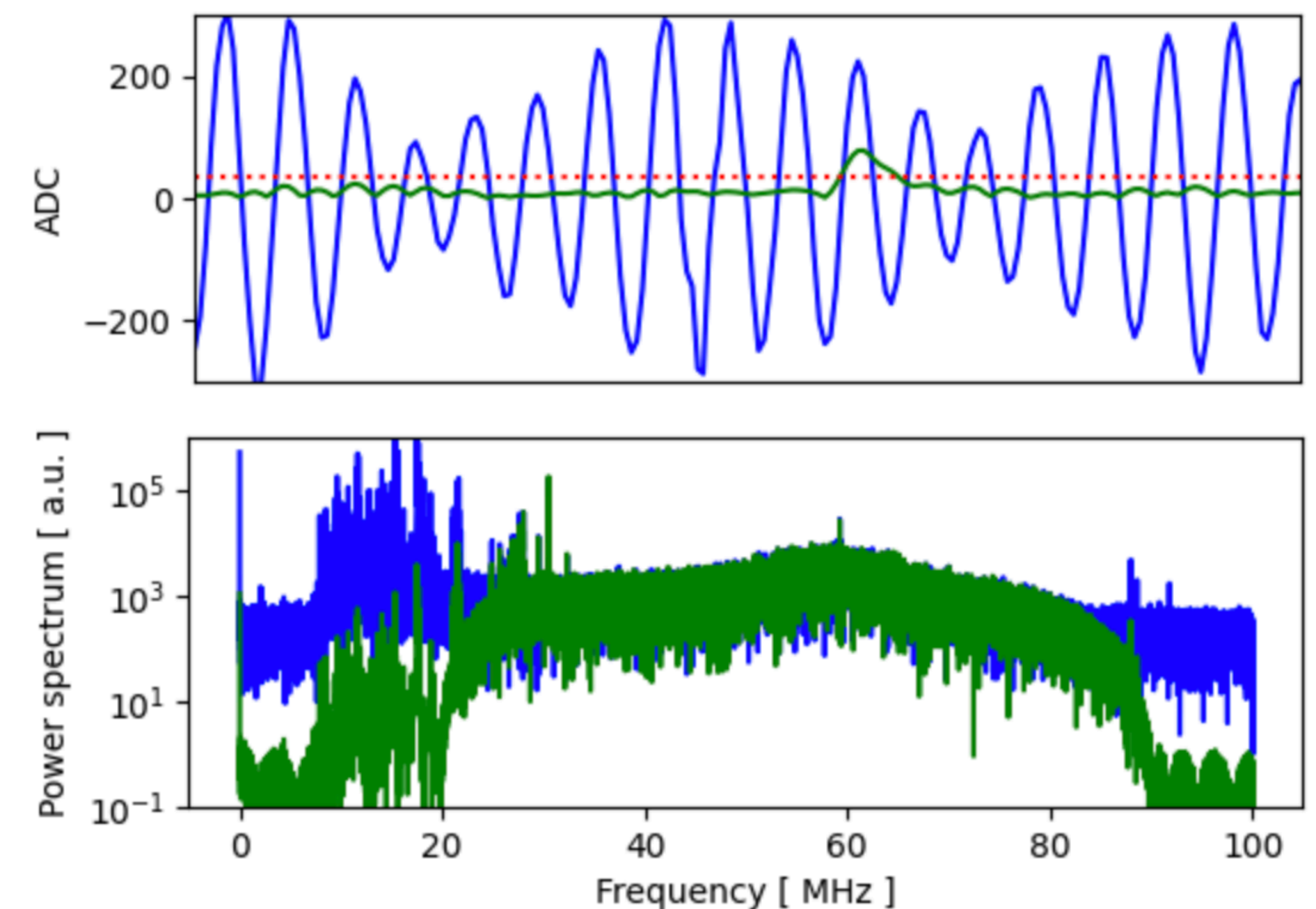
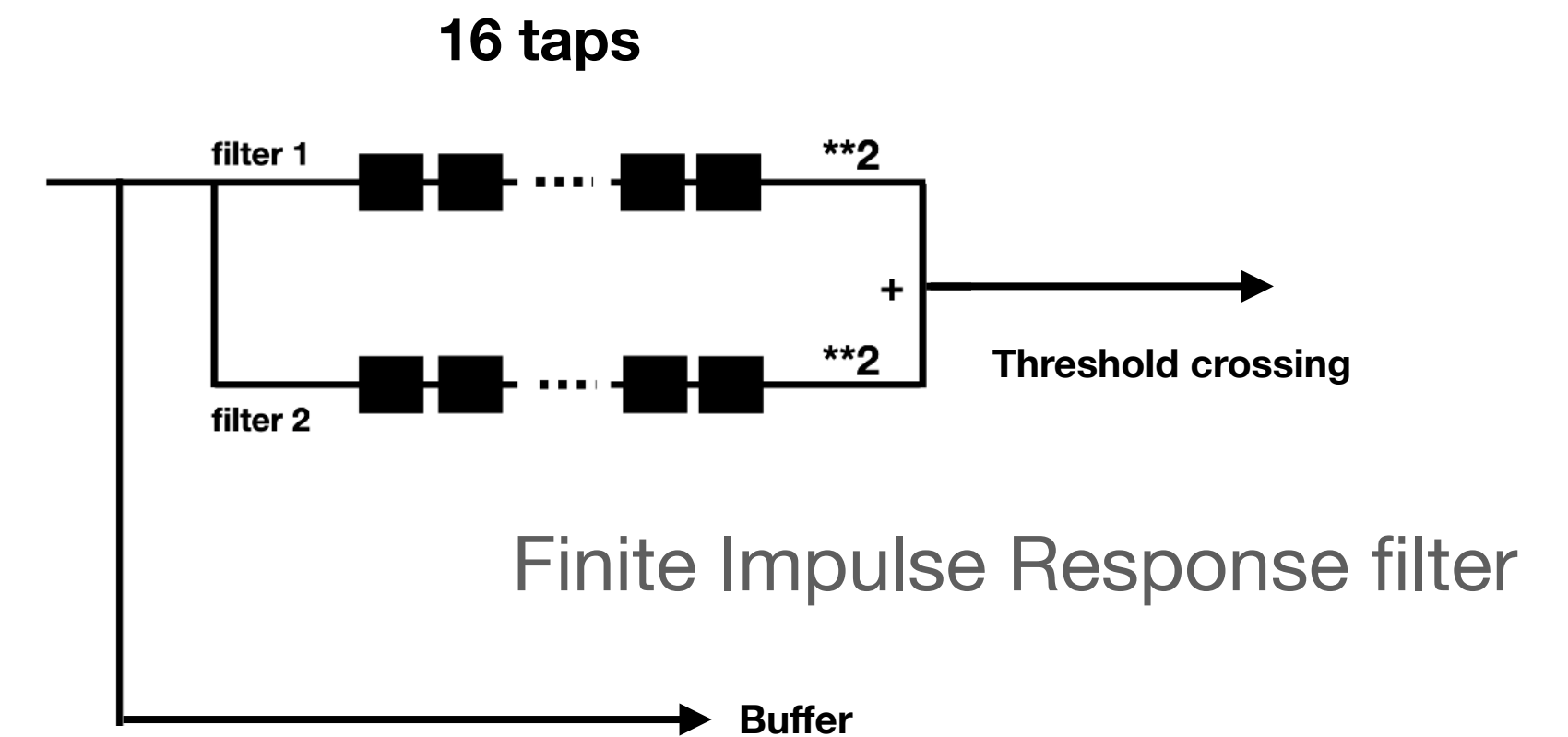
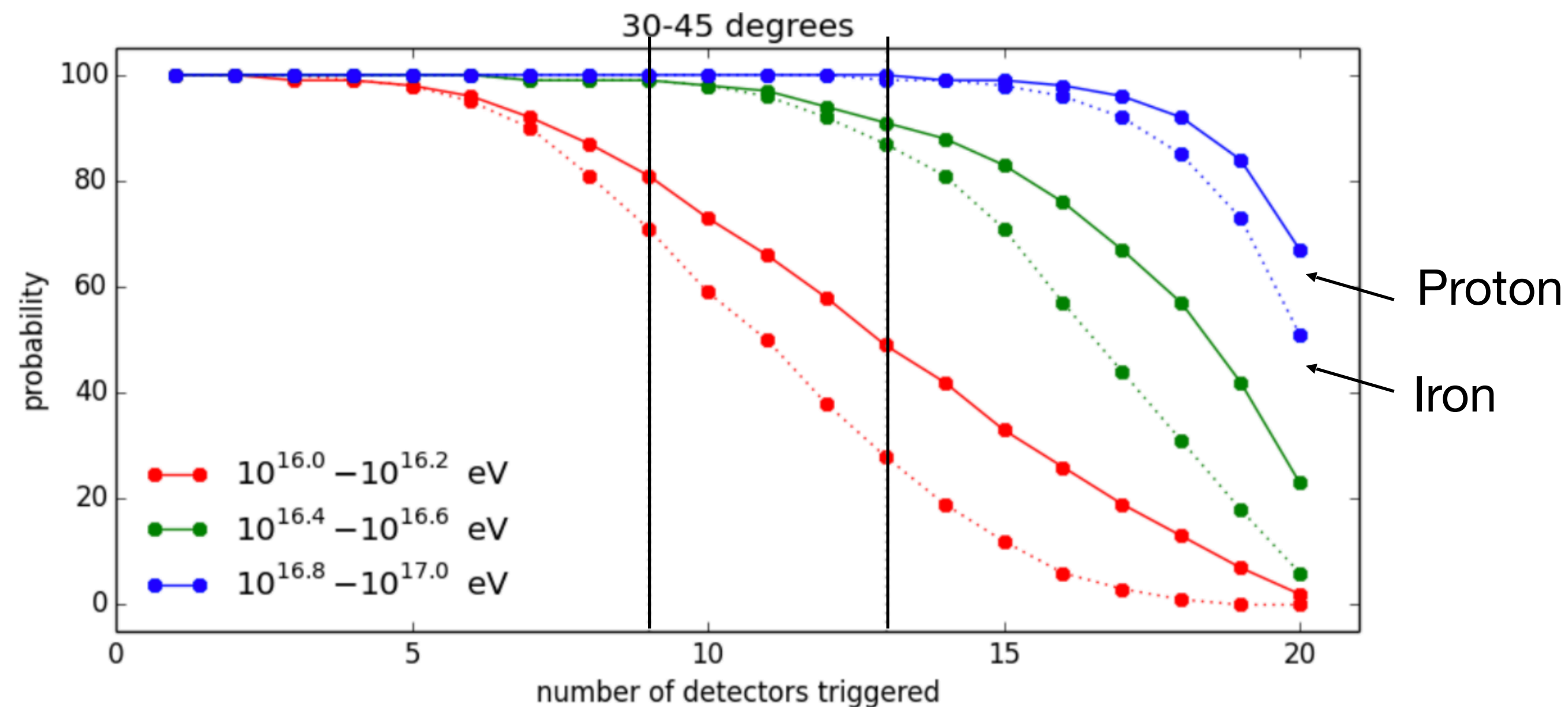
Efforts to maximize benefits of LOFAR 2.0

- Expanded triggering array



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- Hybrid radio - particle trigger



Efforts to maximize benefits of LOFAR 2.0

- Expanded triggering array
- Hybrid radio - particle trigger
- NuRadioReco pipeline & analysis

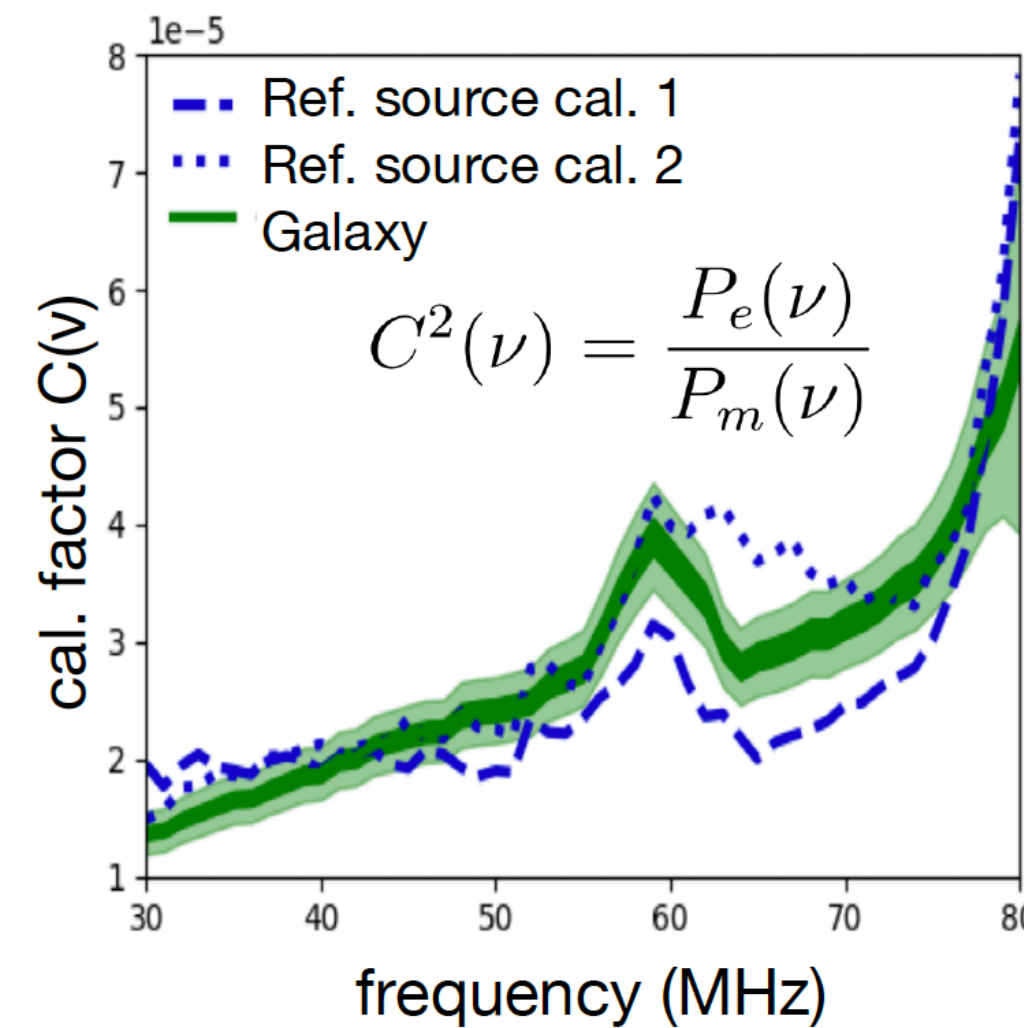


```
from NuRadioReco.detector import detector

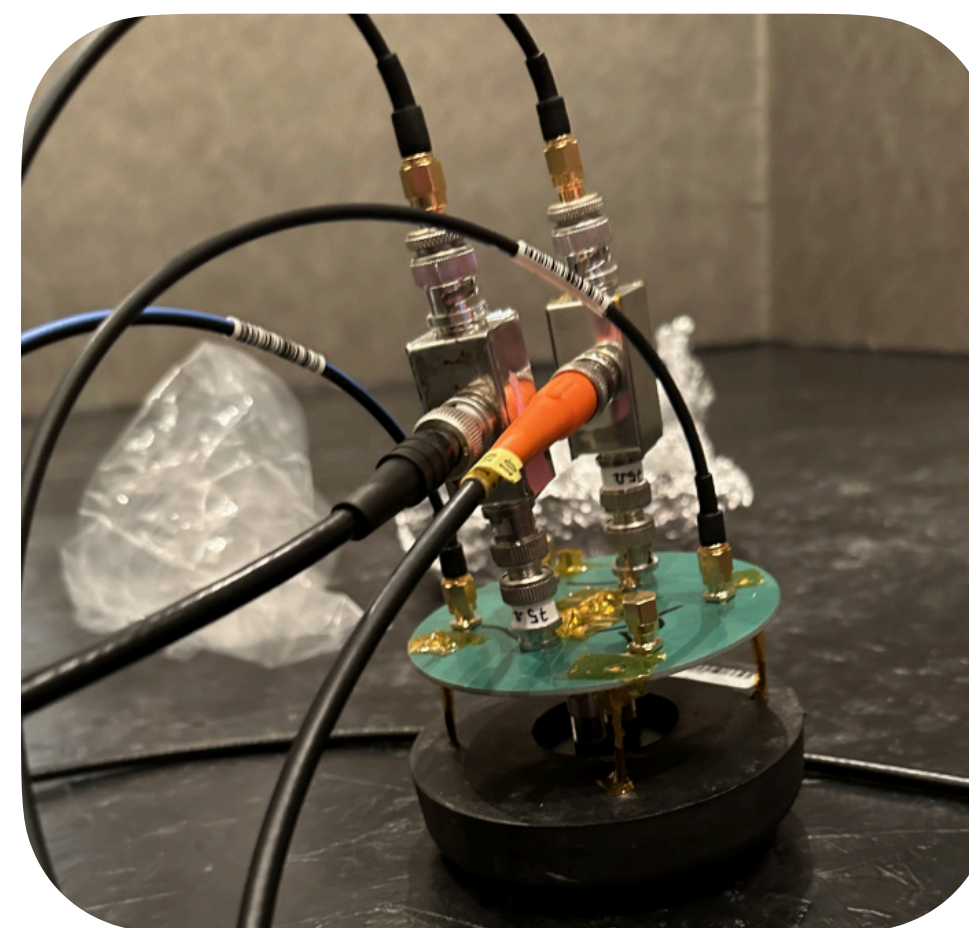
# Load Detector description
det = detector.Detector(
    'LOFAR/LOFAR.json',
    source='json',
    antenna_by_depth=False
)
```


Efforts to maximize benefits of LOFAR 2.0

- Expanded triggering array
- Hybrid radio - particle trigger
- NuRadioReco pipeline & analysis
- Revisit calibration (phase info)



Galactic calibration corrects amplitude

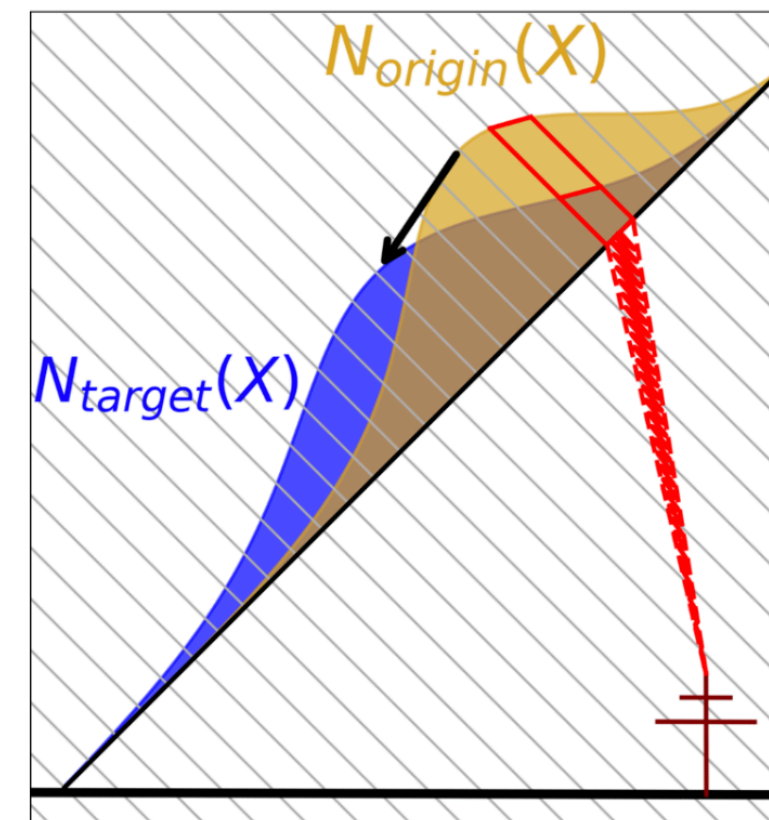


LBA LNA measurements at ASTRON to understand phase response (B. Hare et al)

Efforts to maximize benefits of LOFAR 2.0

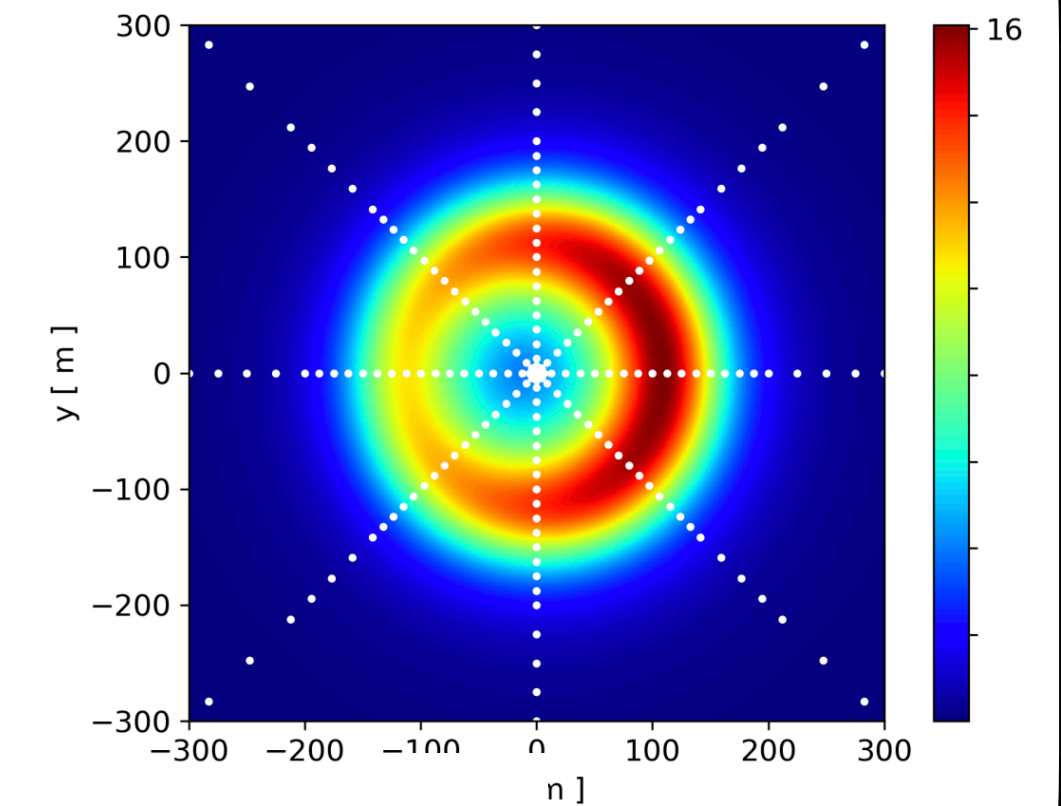
- Expanded triggering array
- Hybrid radio - particle trigger
- NuRadioReco pipeline & analysis
- Revisit calibration (phase info)
- Flexible simulation techniques

Template synthesis



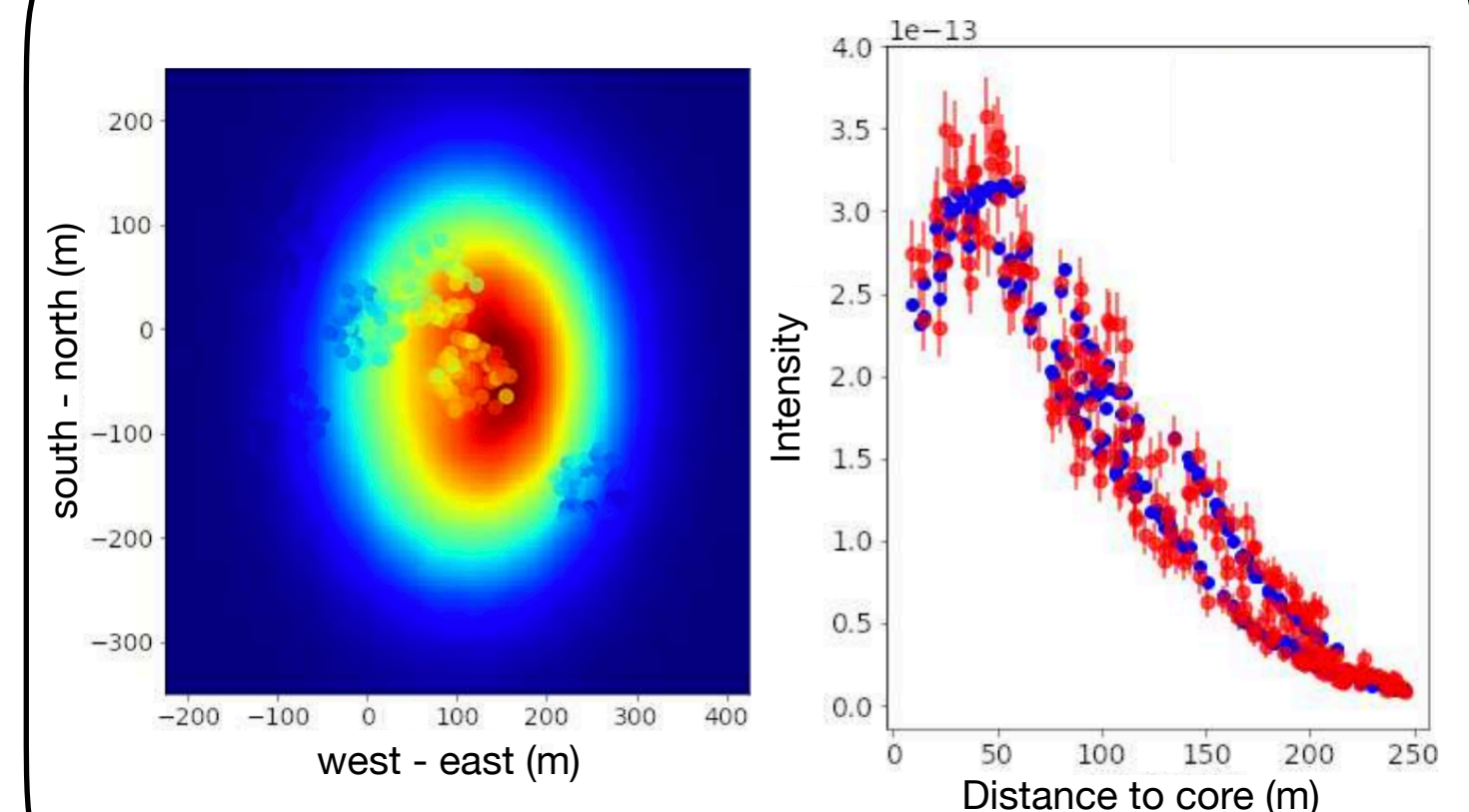
Mitja Desmet et al.
arxiv.org/2307.02939

Pulse interpolation



Arthur Corstanje et al.
[arXiv:2306.13514](https://arxiv.org/2306.13514)

MGMR3D

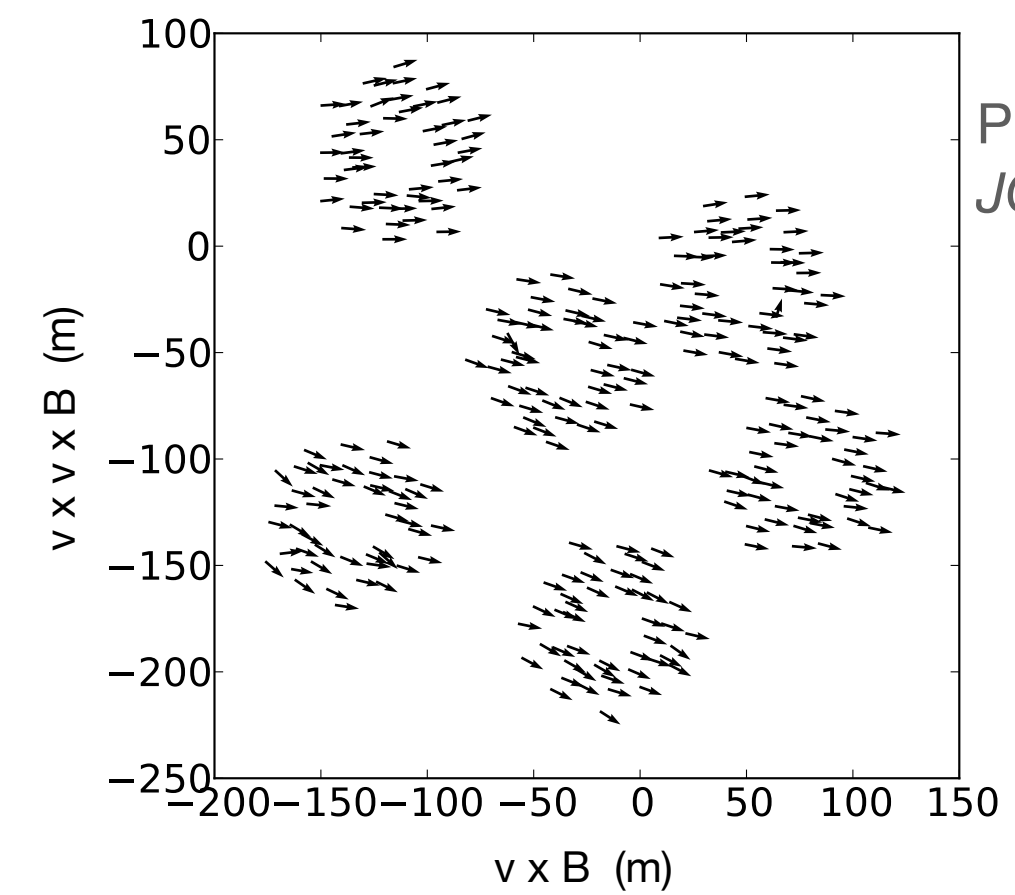
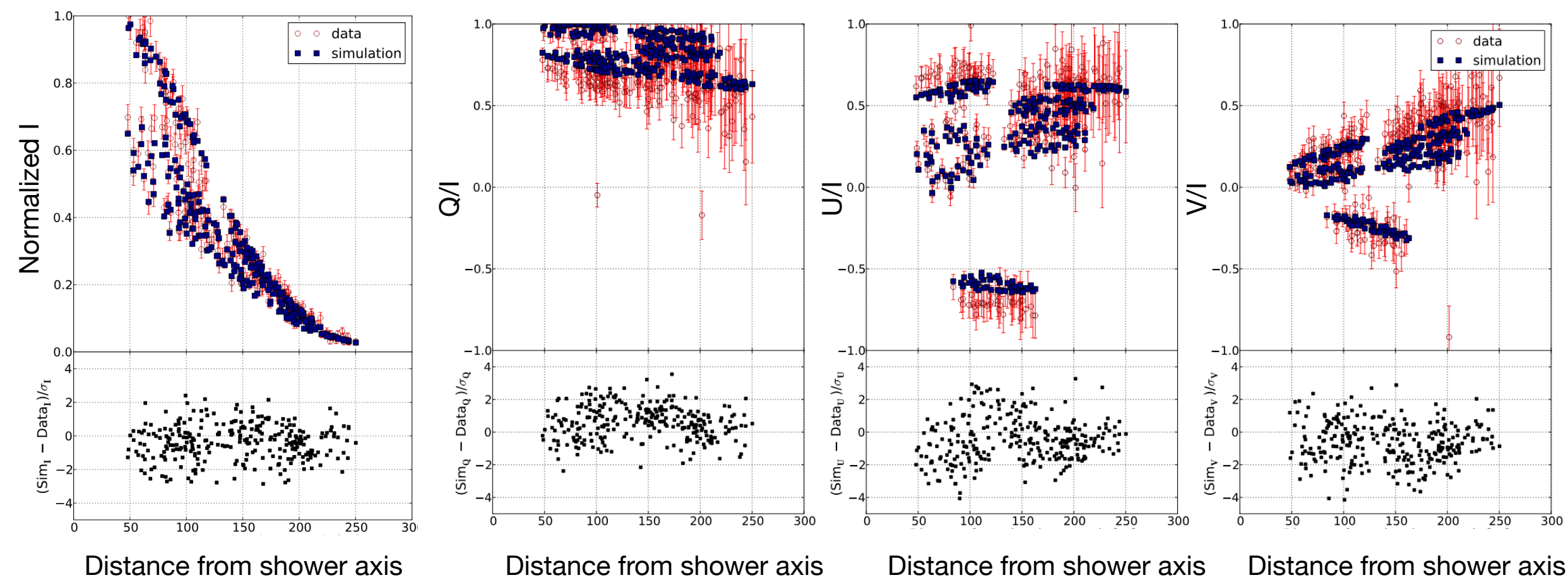


Olaf Scholten et al.

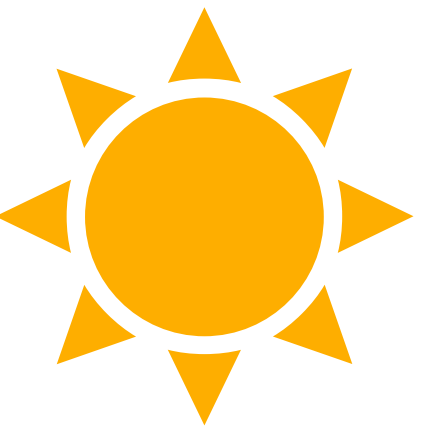
Upcoming LOFAR analyses

Cosmic ray + lightning

Typical cosmic-ray event



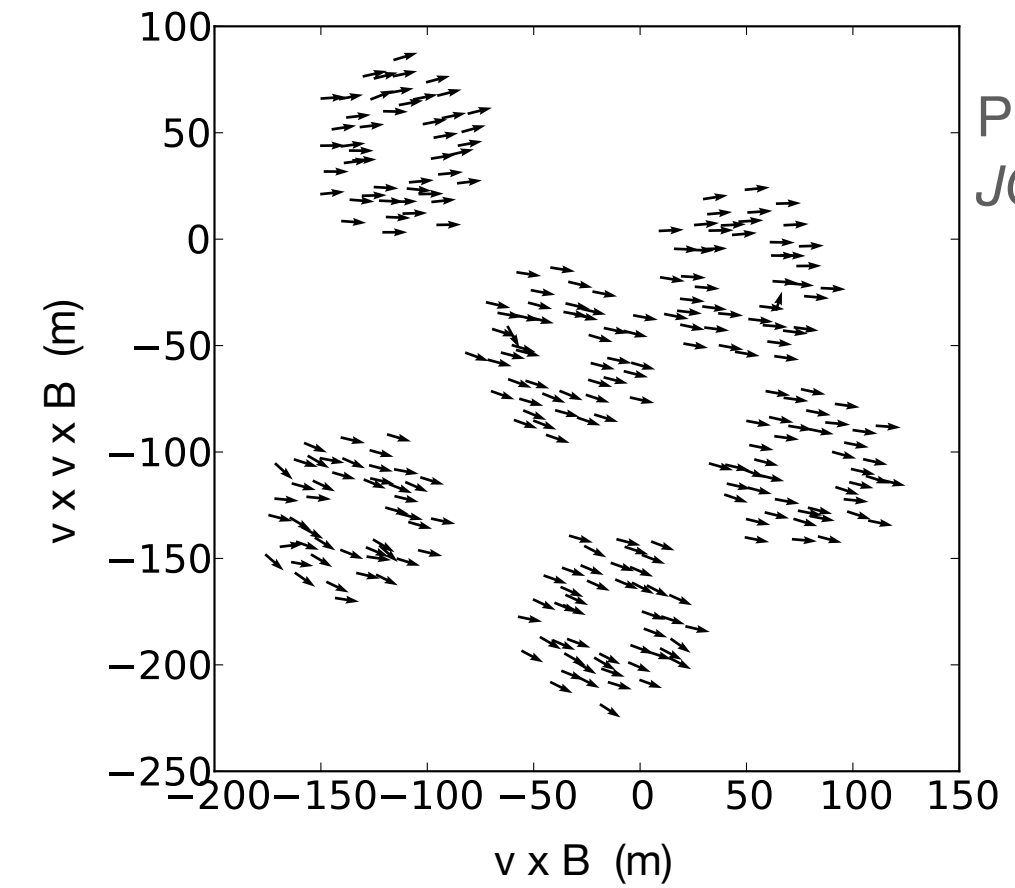
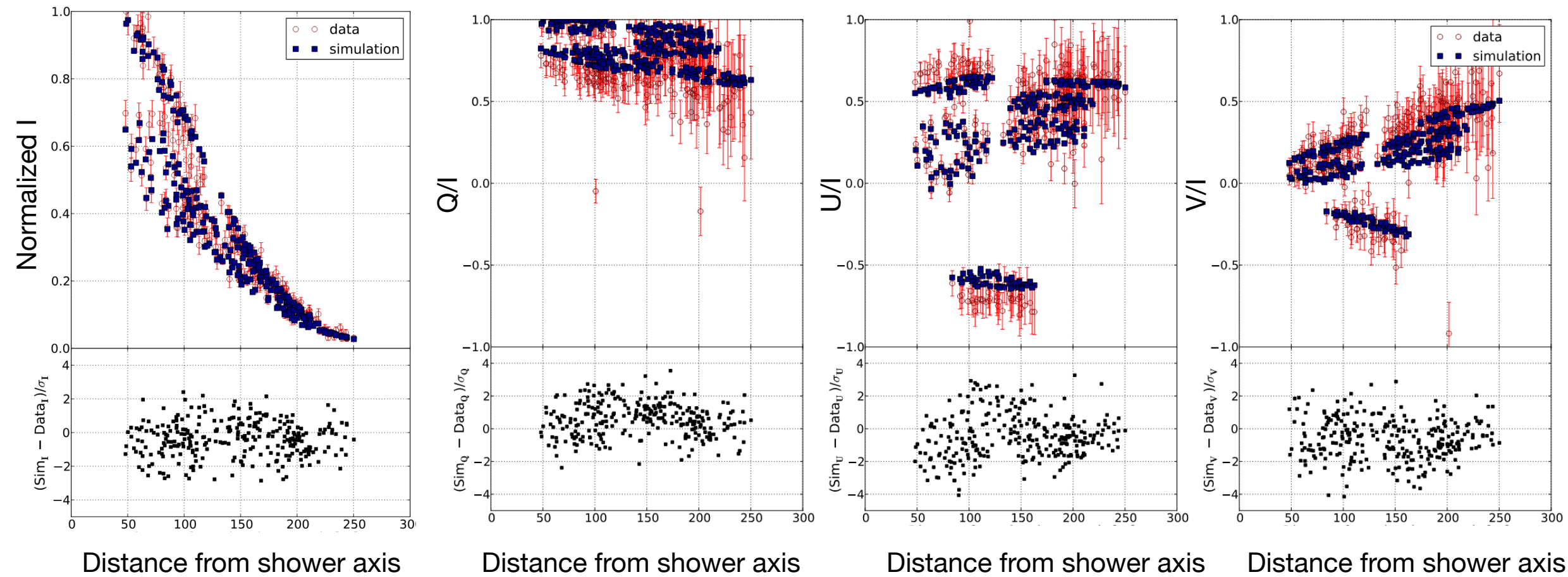
Pim Schellart et al.,
JCAP 10 14 (2014)



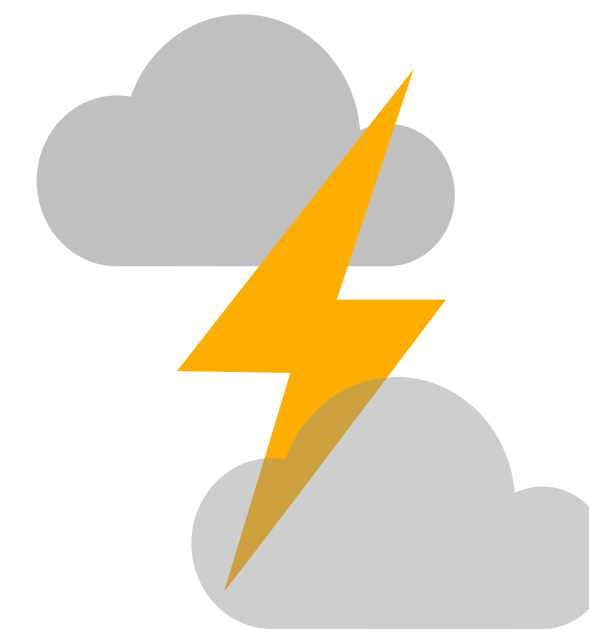
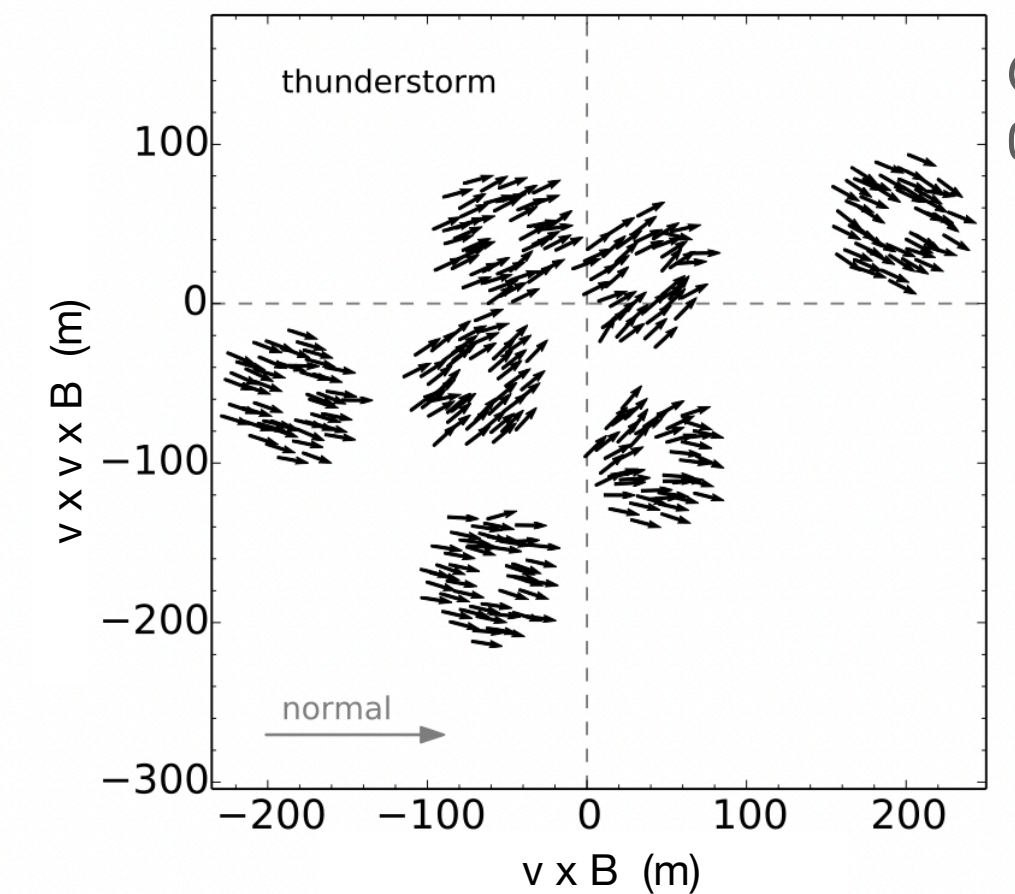
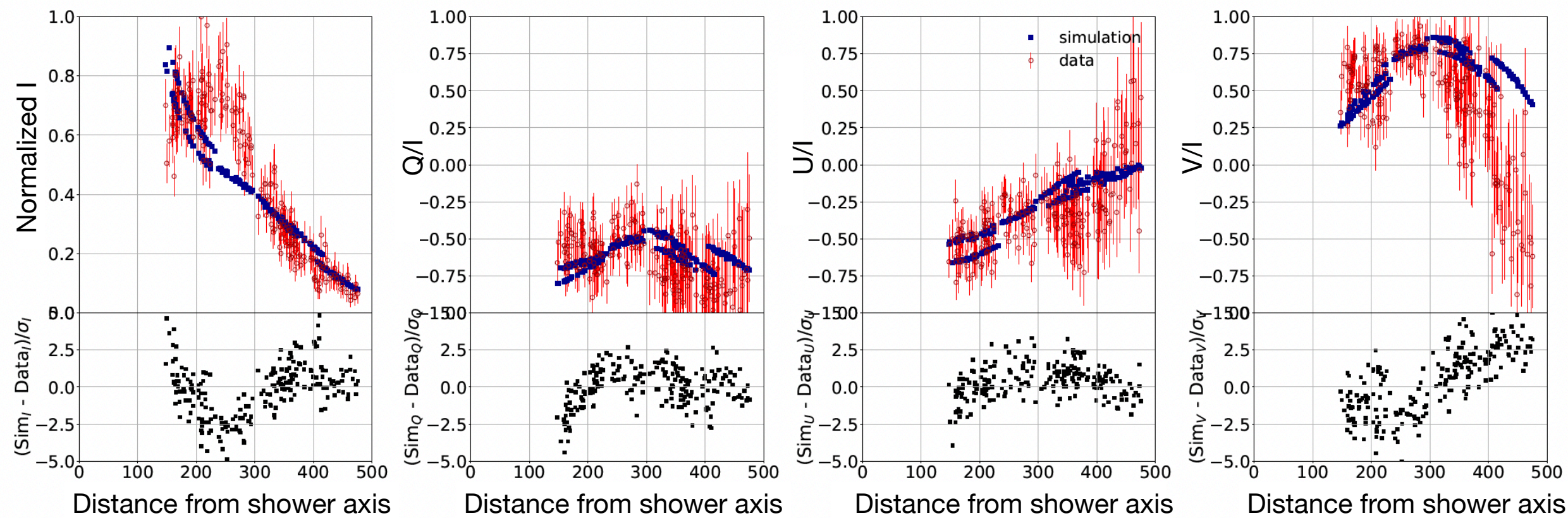
Upcoming LOFAR analyses

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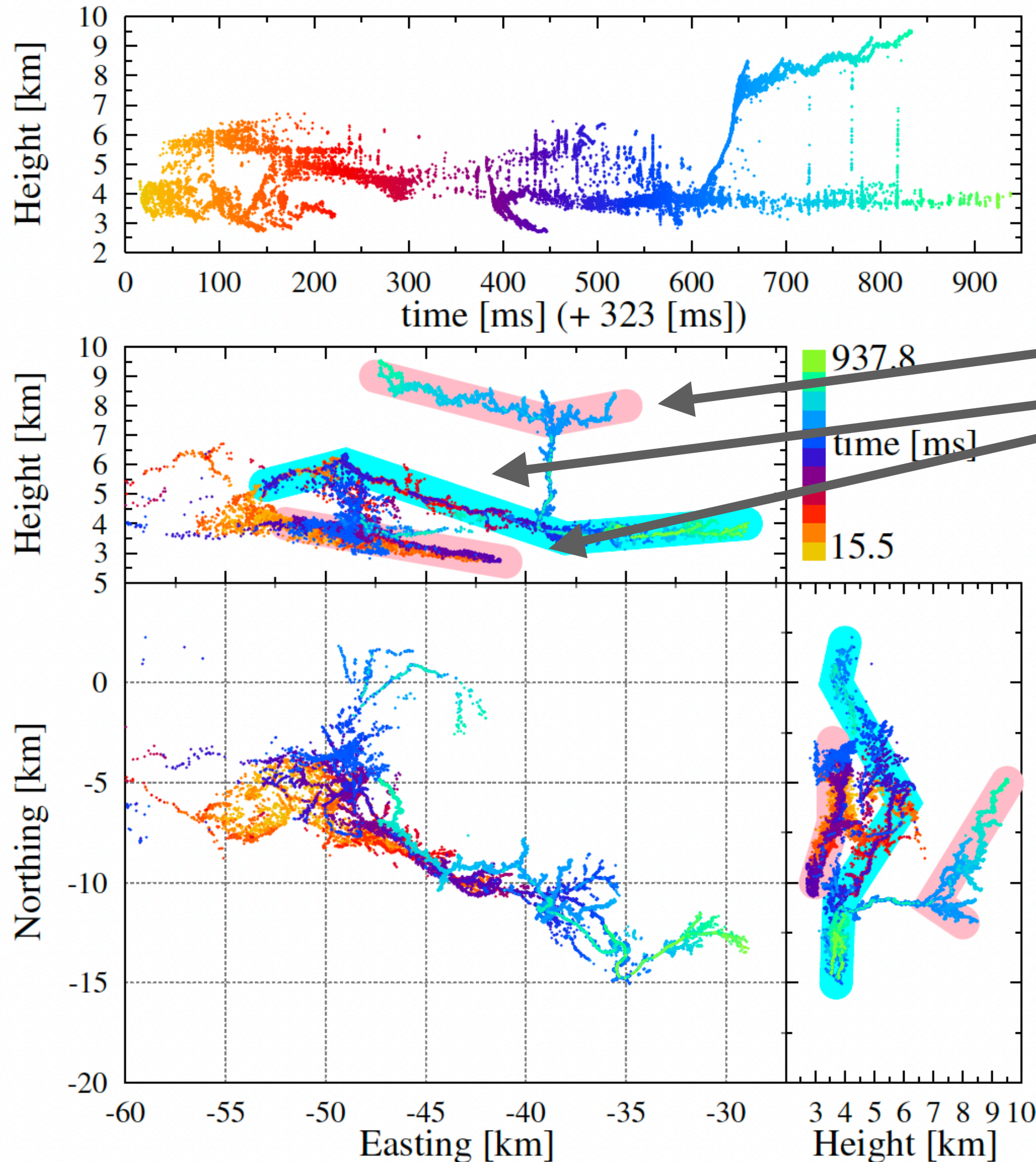
Typical cosmic-ray event



Thunder storm

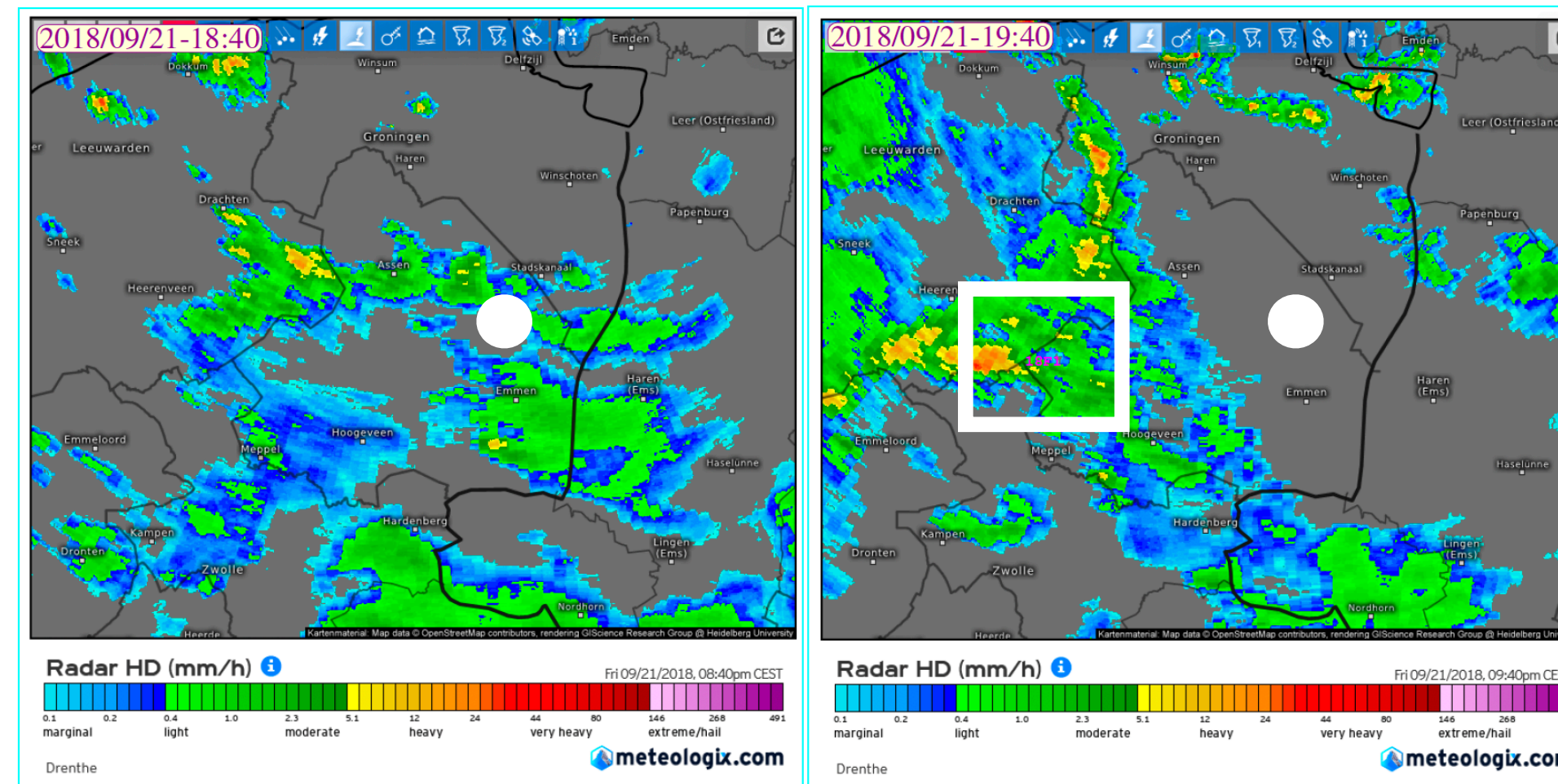
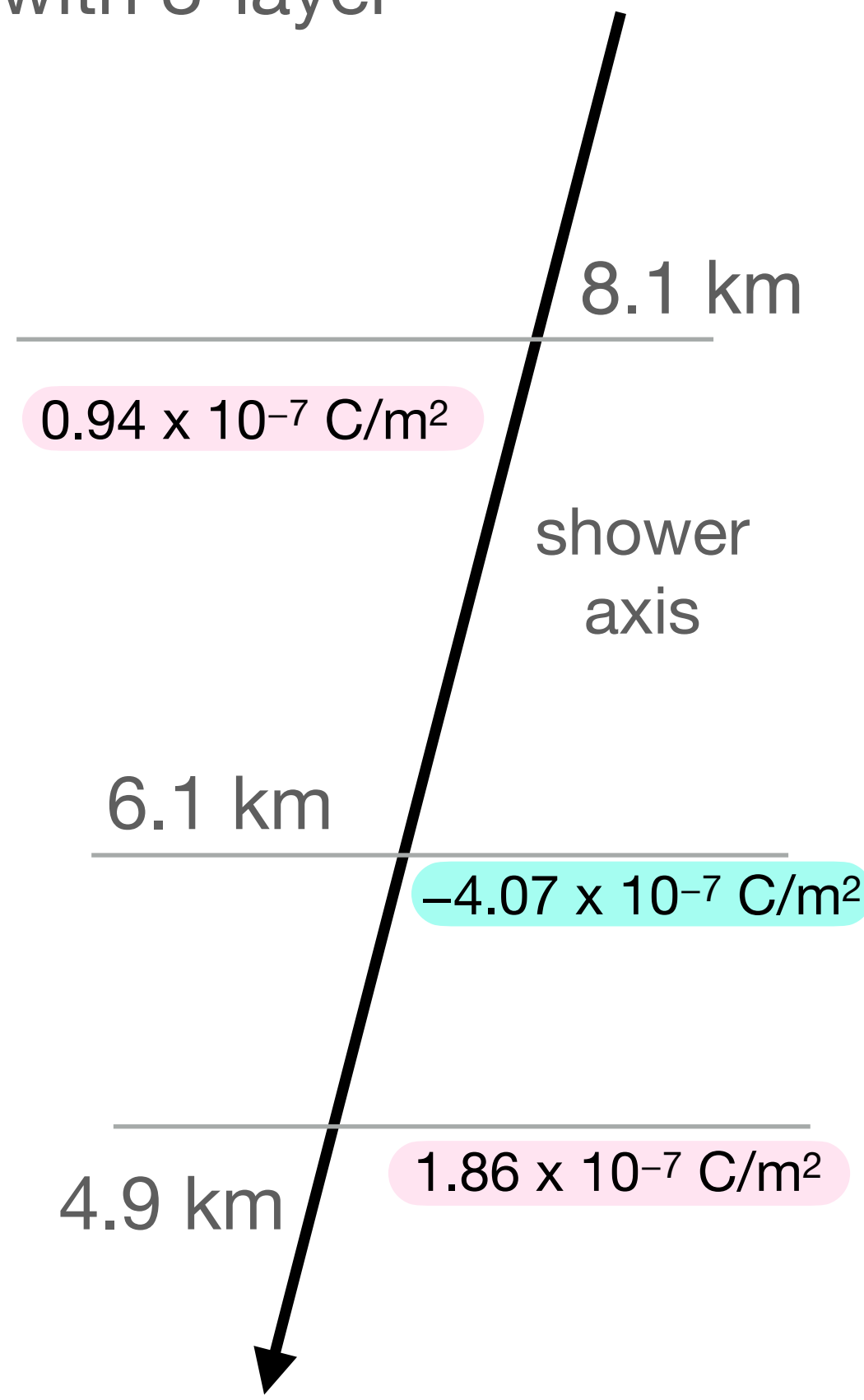


Upcoming LOFAR analyses



- Reconstruction of air shower in thunderstorm with 3-layer model using MGMR3D and CoREAS
- Compare to lightning imaged one hour later

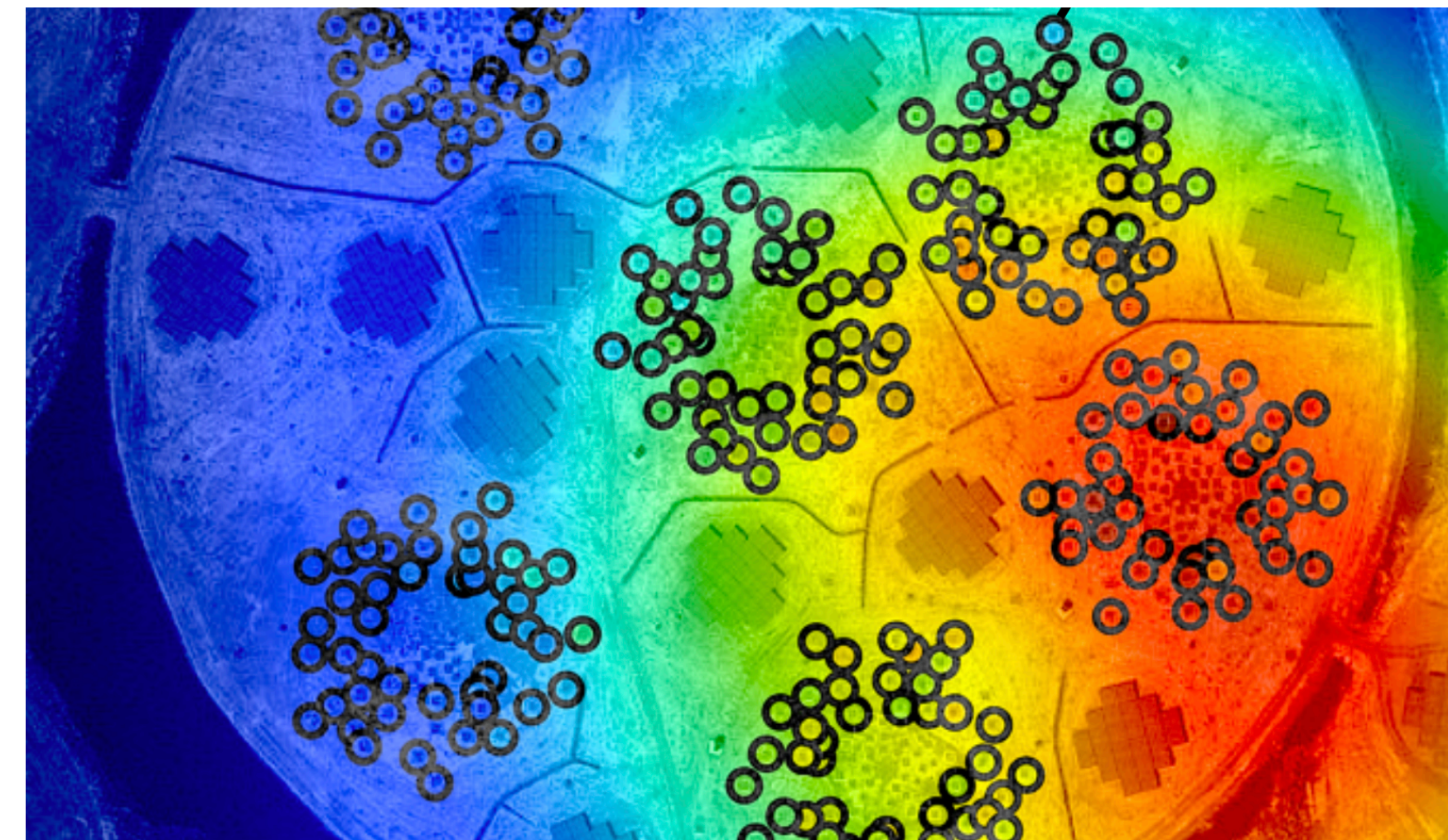
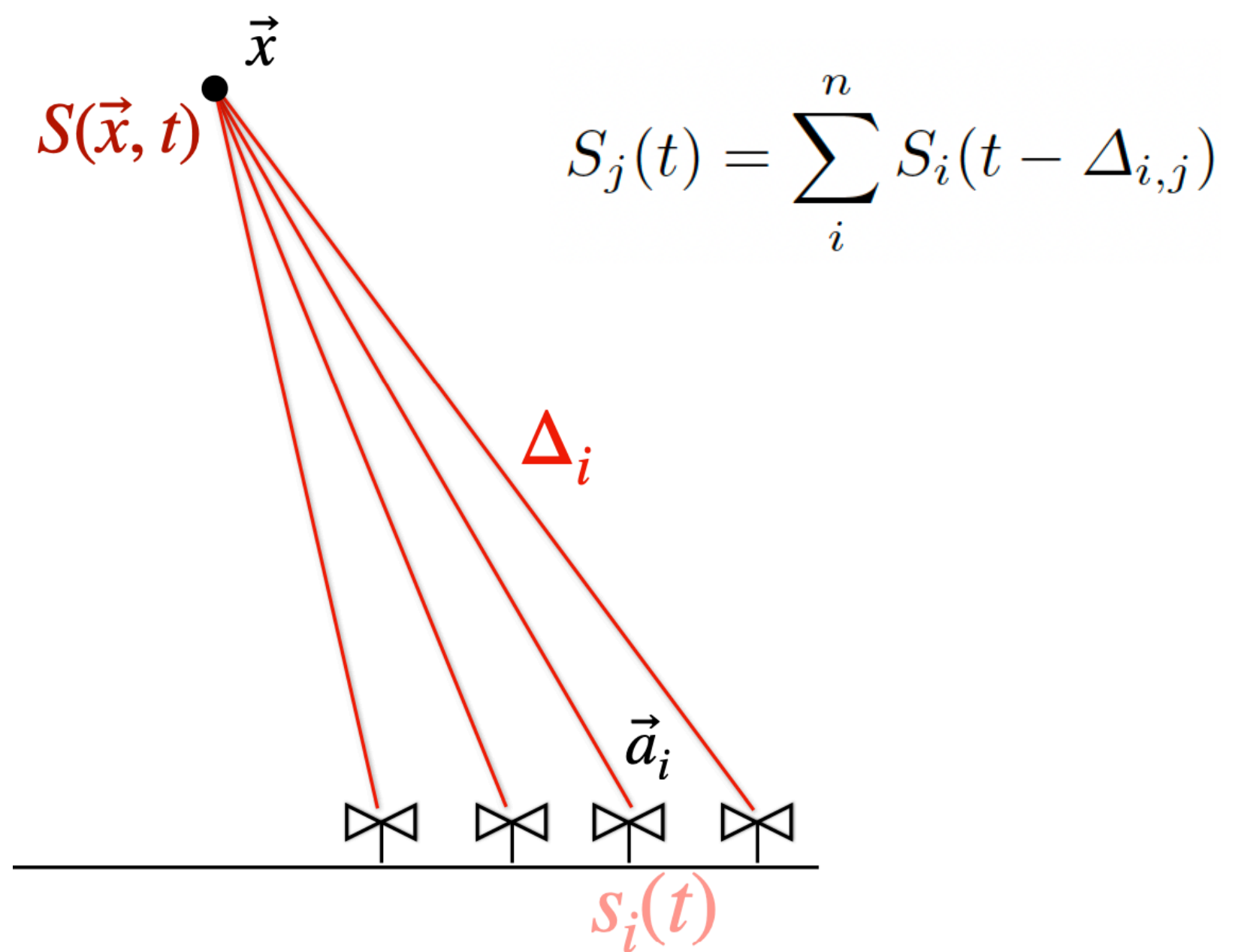
| Layer | h [km] | E [kV/m] | E_{vxz} [kV/m] | $E_{vx[vxz]}$ [kV/m] | E_z^m [kV/m] | E_z^0 [kV/m] |
|-------|--------|----------|------------------|----------------------|----------------|----------------|
| 1 | 8.1 | 45 | 41 | 18 | -30 | -11 |
| 2 | 6.1 | 58 | -12 | -57 | 93 | 35 |
| 3 | 4.9 | 52 | -47 | -23 | 38 | 14 |



T.N.G. Trinh et al., in prep (2024)

Upcoming LOFAR analyses

Interferometry at LOFAR?



Challenge: very irregular antenna spacing

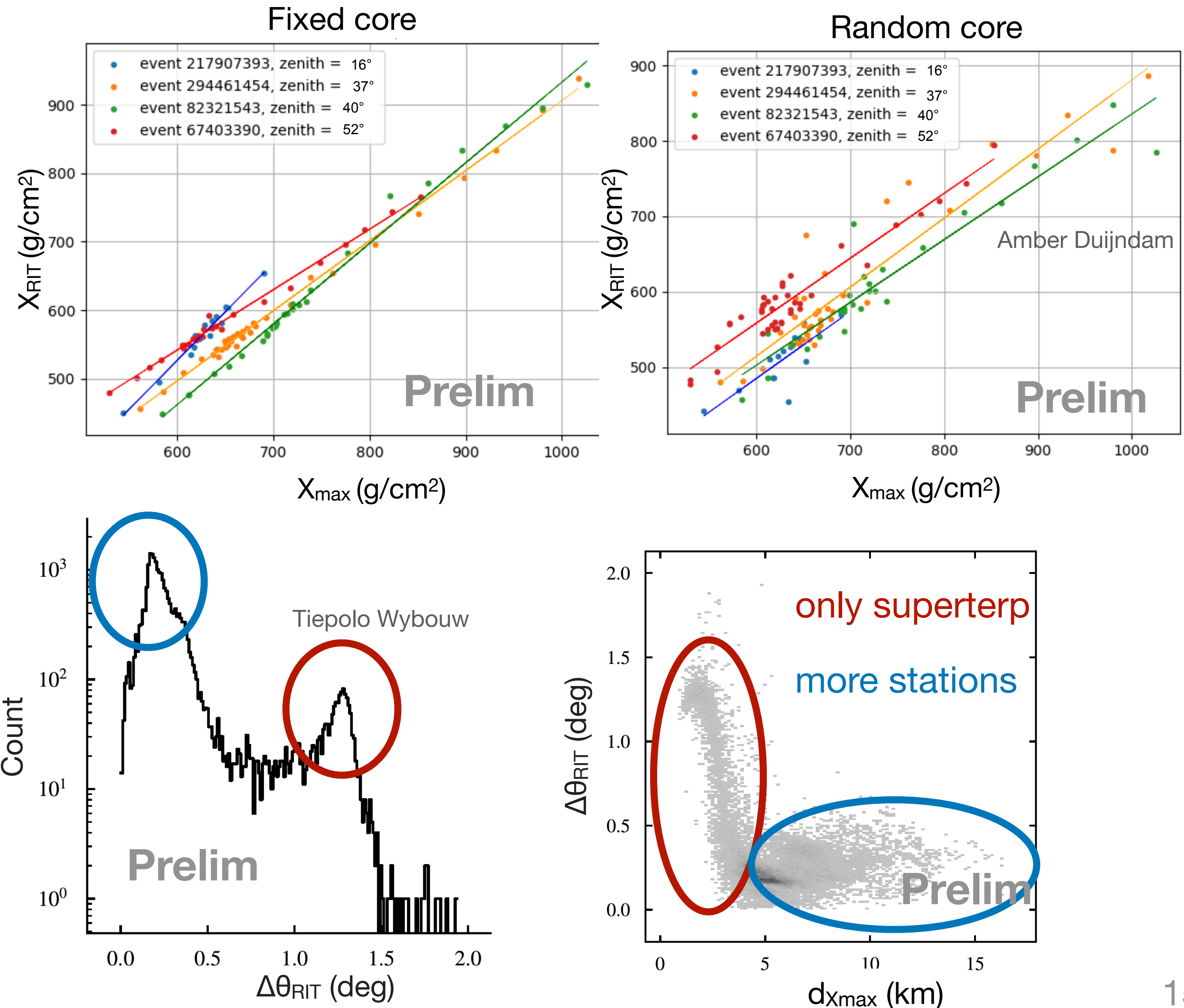
H. Schoorlemmer, W. Carvalho, Eur. Phys. J. C (2021).

F. Schluter, T. Huege, J. of Inst. 16(07), P07048 (2021).

Upcoming LOFAR analyses

Interferometry at LOFAR?

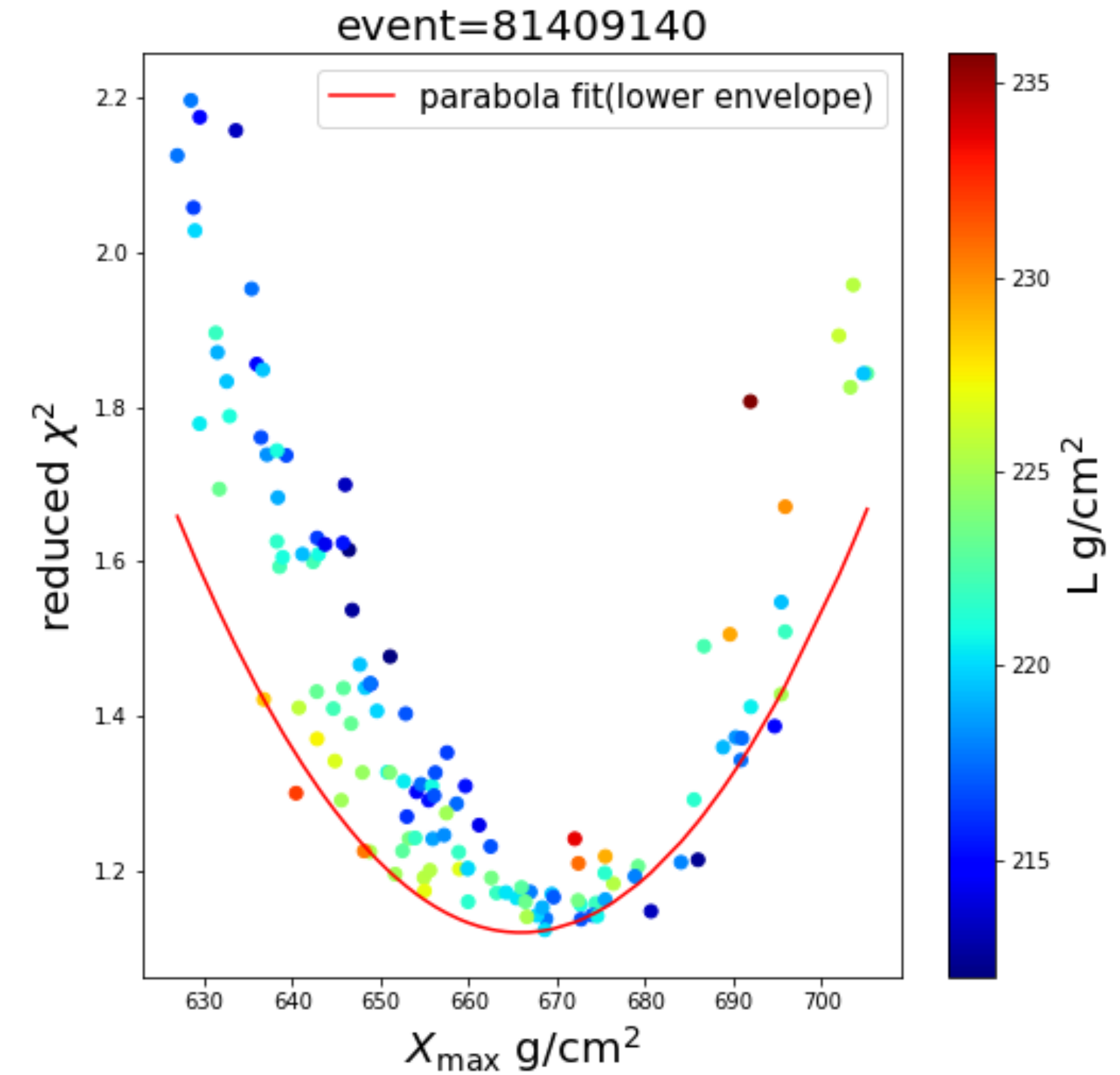
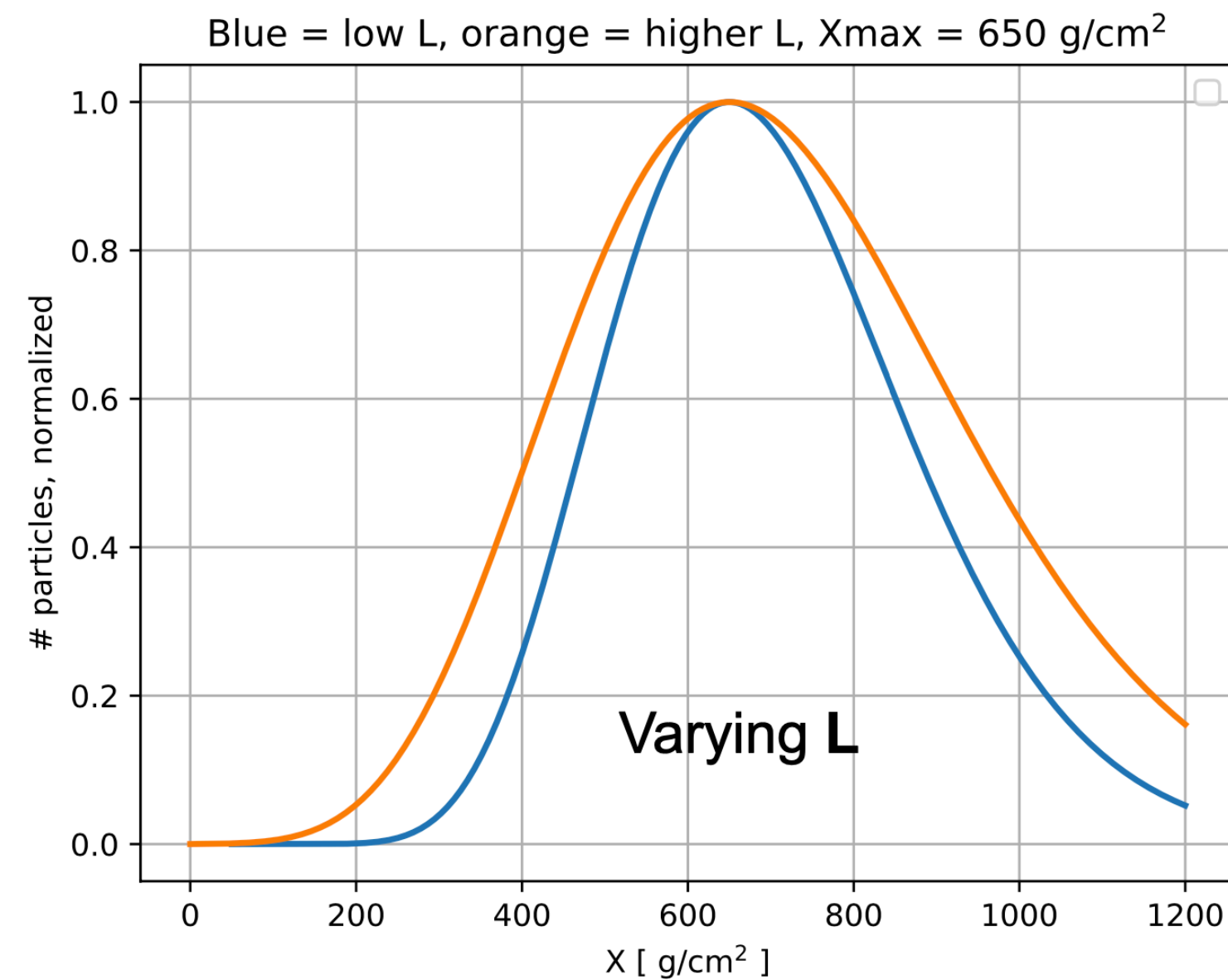
- Preliminary simulation study achieves 0.1 degree resolution with LOFAR layout
- Different core positions introduce scatter into the X_{RIT} X_{max} relation
- *These studies are made simple using NuRadioReco!*



Upcoming LOFAR analyses

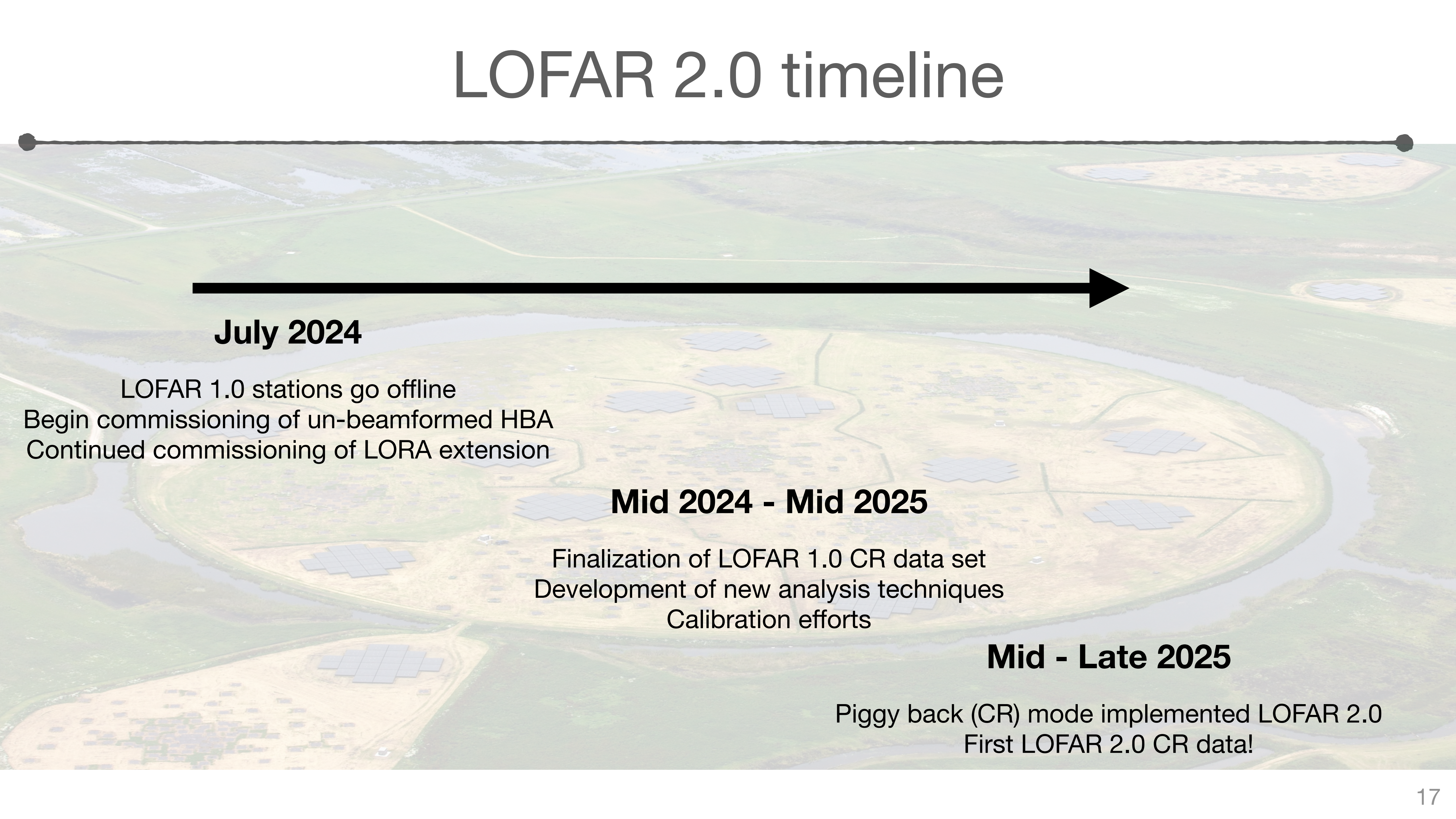
Shower development

- L important to constrain mass composition and hadronic interactions
- L responsible for scatter in parabola fit - indicates that LOFAR is sensitive to L



$$N(X) = \exp\left(-\frac{X - X_{\max}}{RL}\right) \left(1 + \frac{R}{L}(X - X_{\max})\right)^{\frac{1}{R^2}}$$

LOFAR 2.0 timeline



July 2024

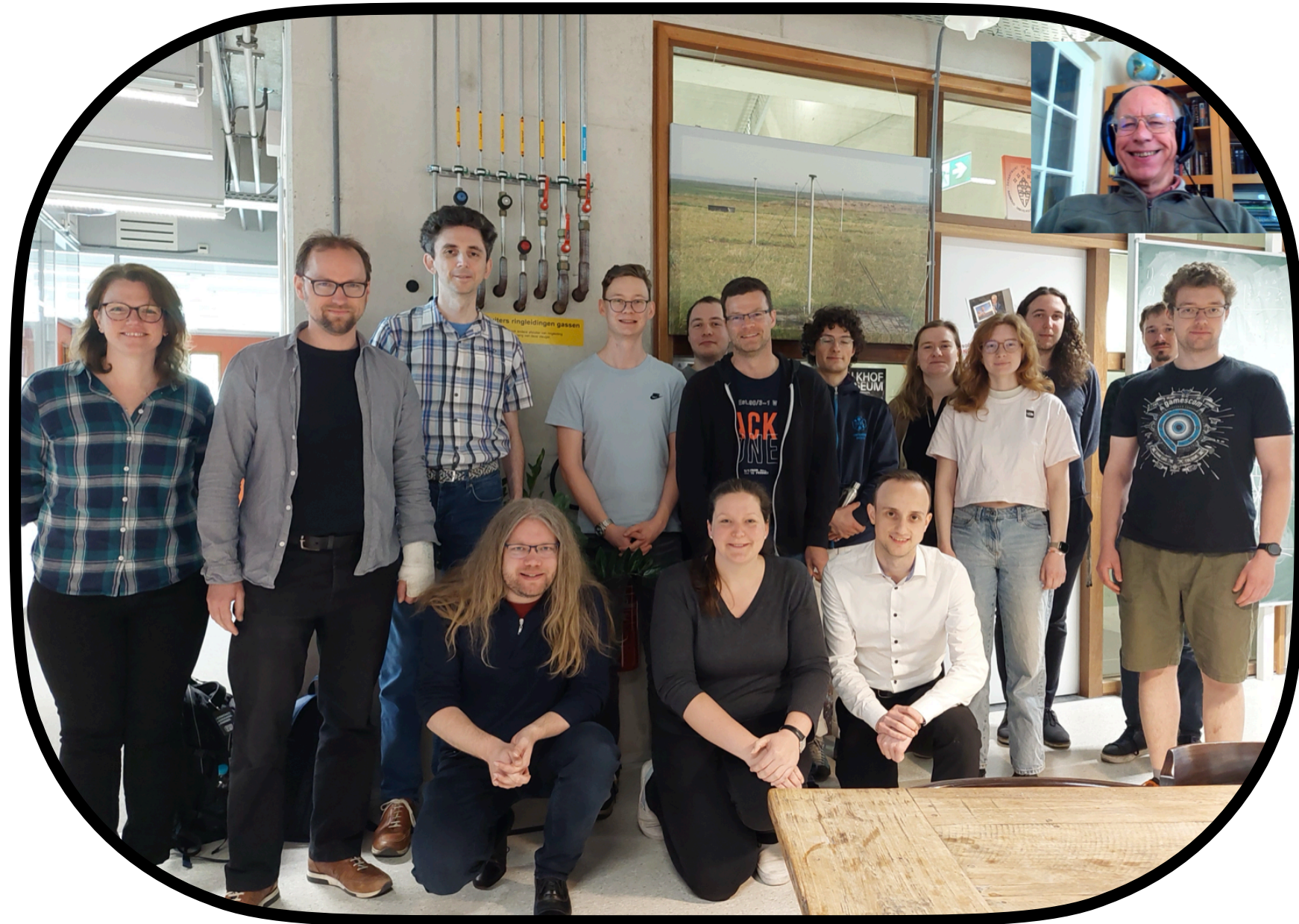
LOFAR 1.0 stations go offline
Begin commissioning of un-beamformed HBA
Continued commissioning of LORA extension

Mid 2024 - Mid 2025

Finalization of LOFAR 1.0 CR data set
Development of new analysis techniques
Calibration efforts

Mid - Late 2025

Piggy back (CR) mode implemented LOFAR 2.0
First LOFAR 2.0 CR data!



Thanks!

