Measurements of Cosmic Rays with LOFAR

ARENA - Acoustic and Radio EeV Neutrino Detection Activities
12-15 June 2018 Catania, Italy

Stijn Buitink for the LOFAR Cosmic Ray KSP

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European Research Council

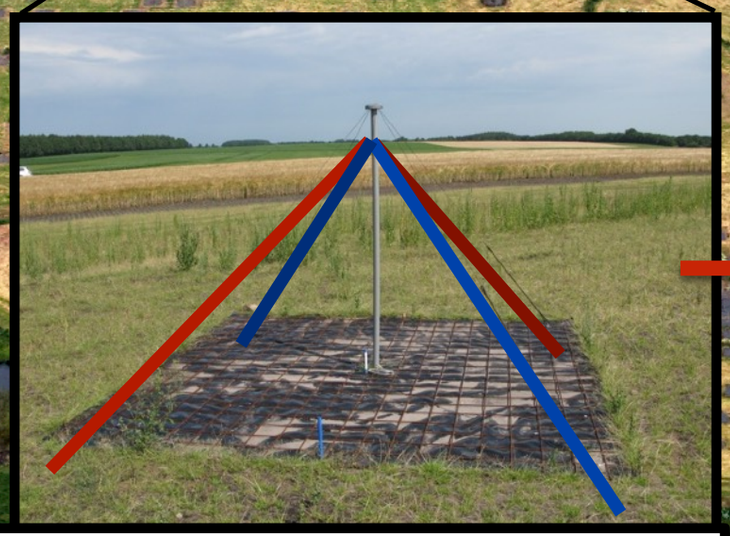
LORA
LOFAR Radboud Array
scintillator detectors

Superterp:
* diameter ~ 300 m
* 20 LORA detectors
* 6 LBA stations
  (= 6 x 48 antennas)

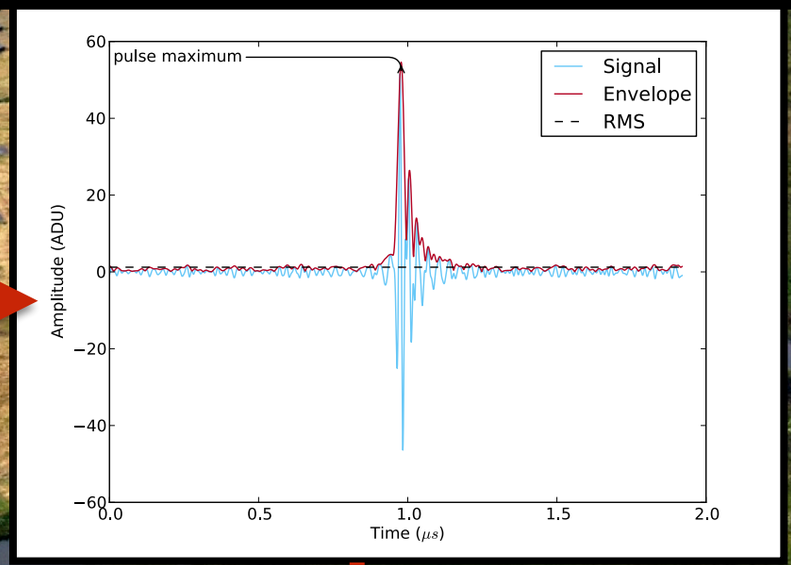
* more LBA stations around superterp

trigger: 13 of 20 detectors

offline analysis
P. Schellart et al., A&A 560, 98 (2013)



buffer
2 ms read-out

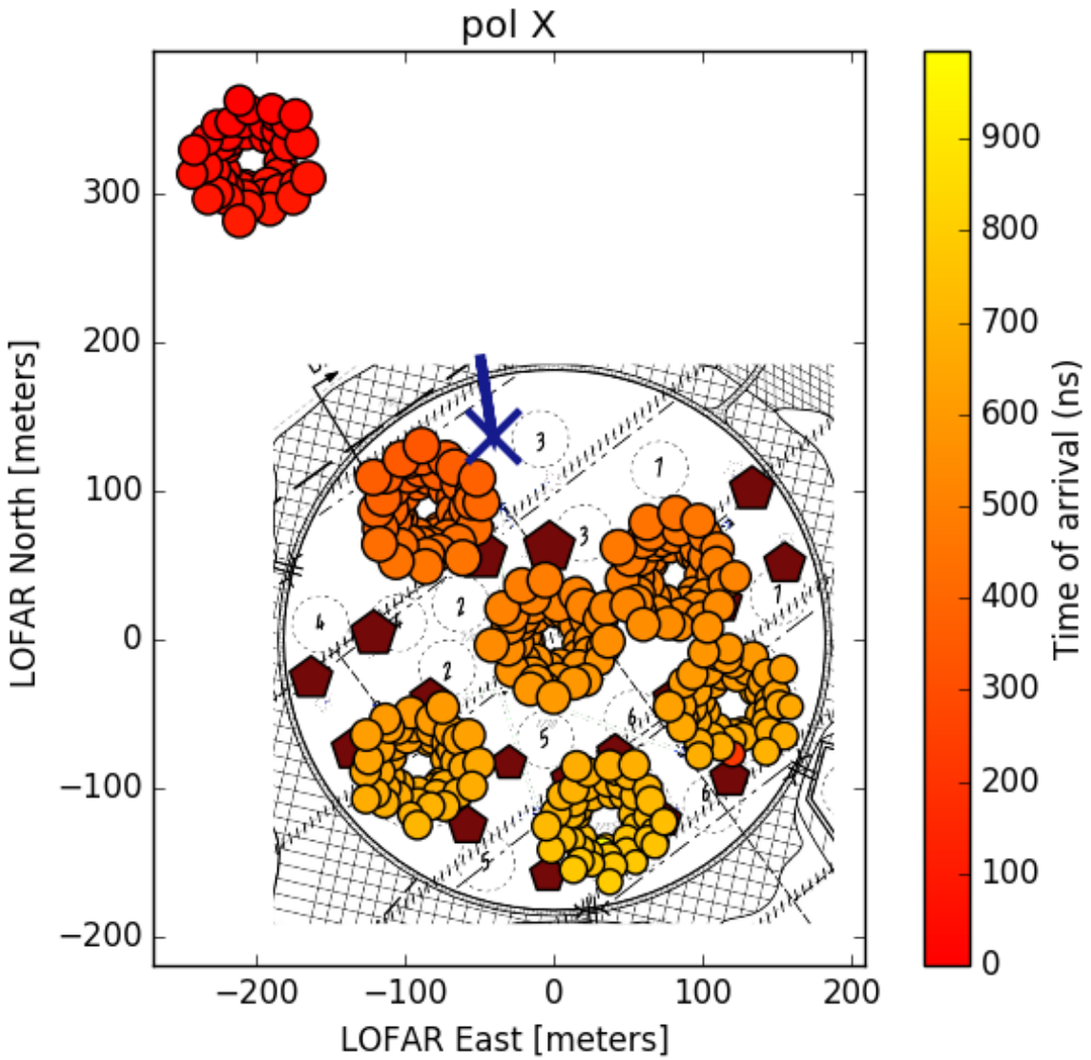


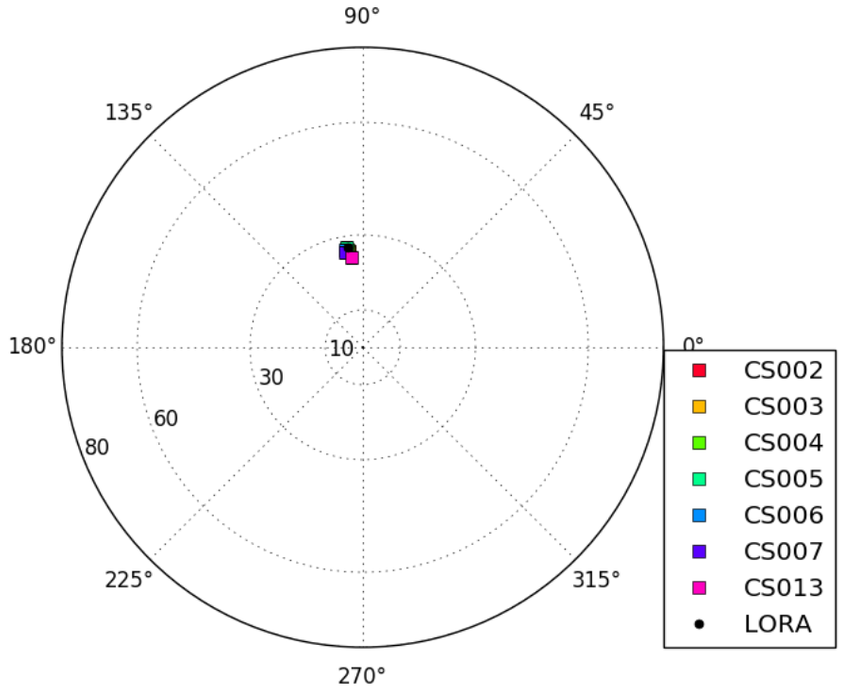
Low Band Antennas (LBA)
30 - 80 MHz

Selection this analysis:
4+ LBA stations

Event selection pipeline

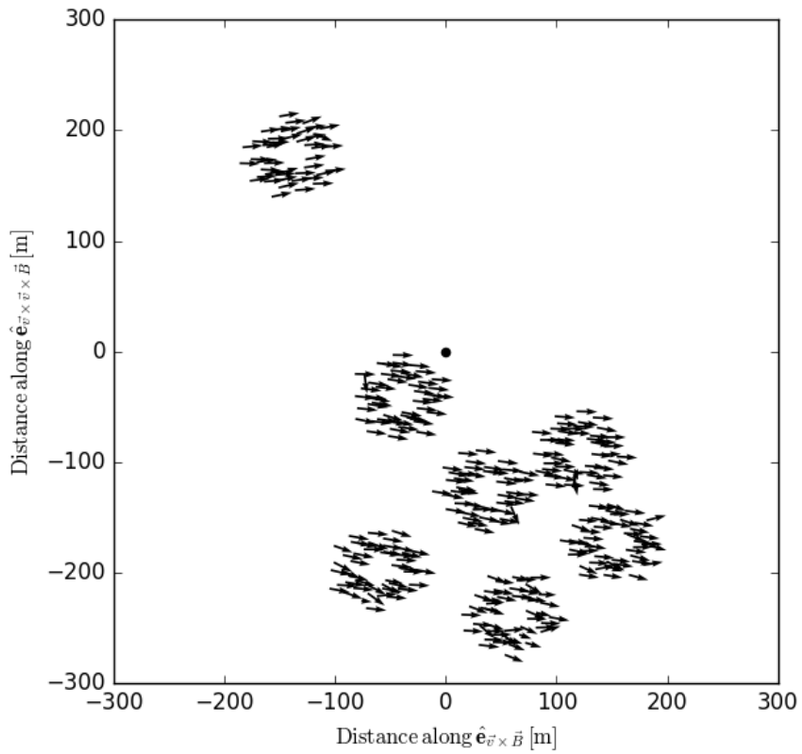
Event ID 205634899 2016-06-12 18:06:42





Same direction all stations & LORA

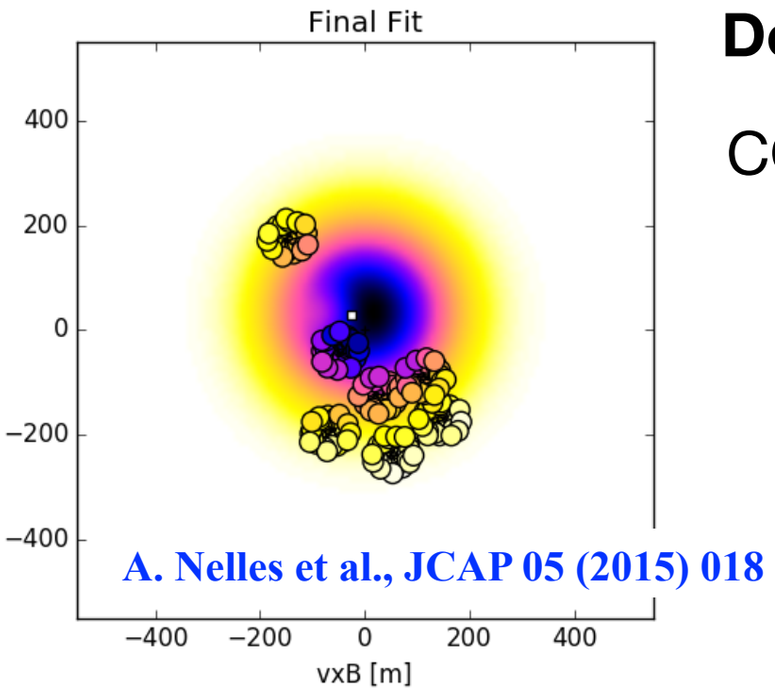
Showers detected with 3+ LBA stations



Polarization features correct

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

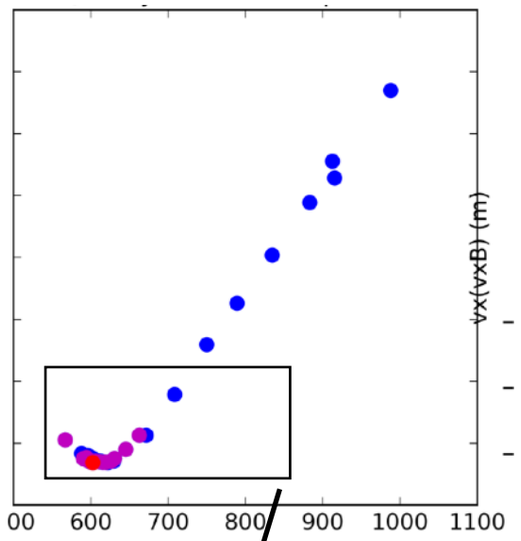
Simulation pipeline



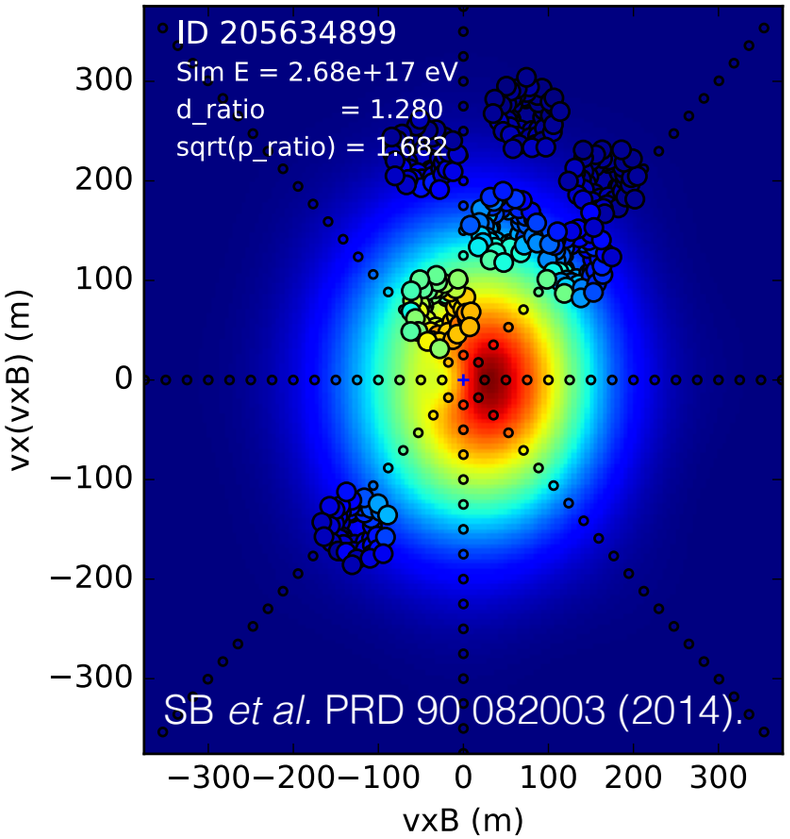
A. Nelles et al., JCAP 05 (2015) 018

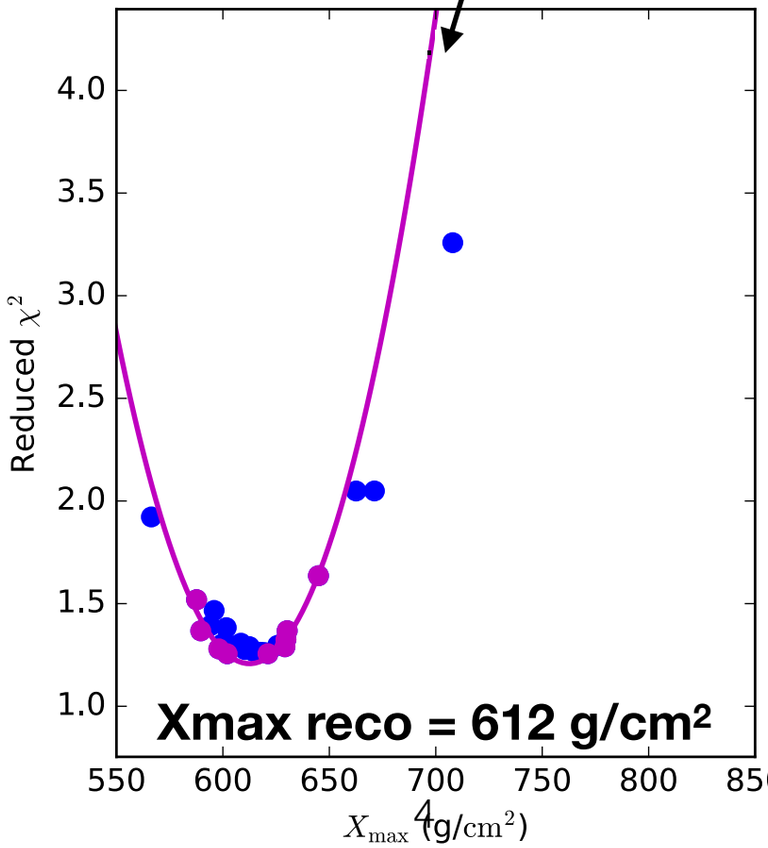
Double Gaussian fit Xmax = 613 g/cm²

CONEX: **dense coverage** around Xmax estimate

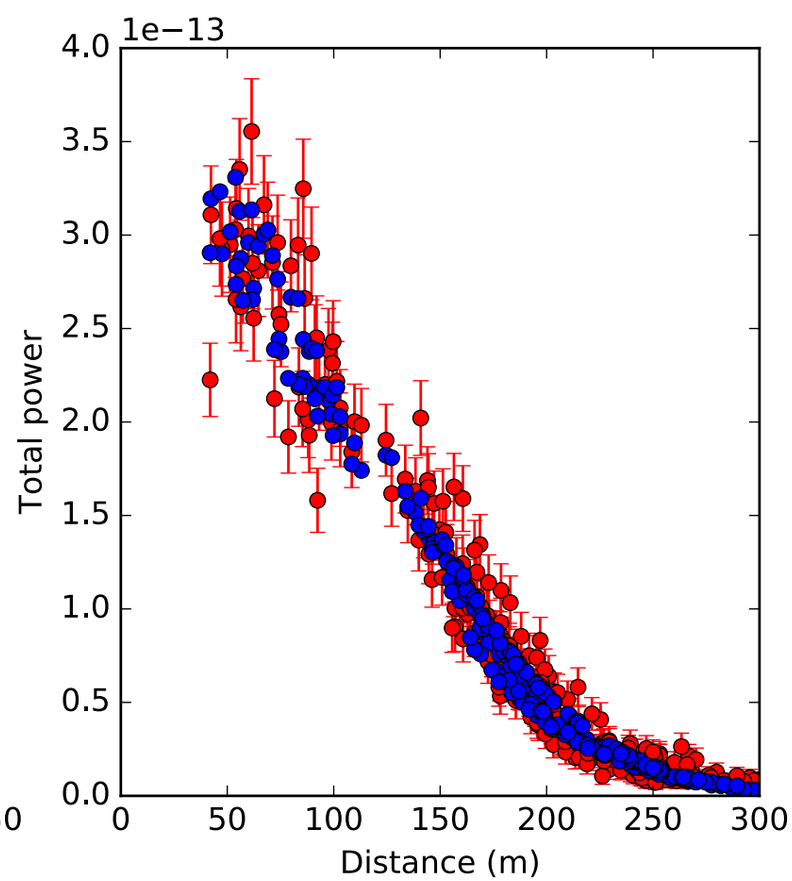


sparse coverage of whole range
(needed for bias evaluation)

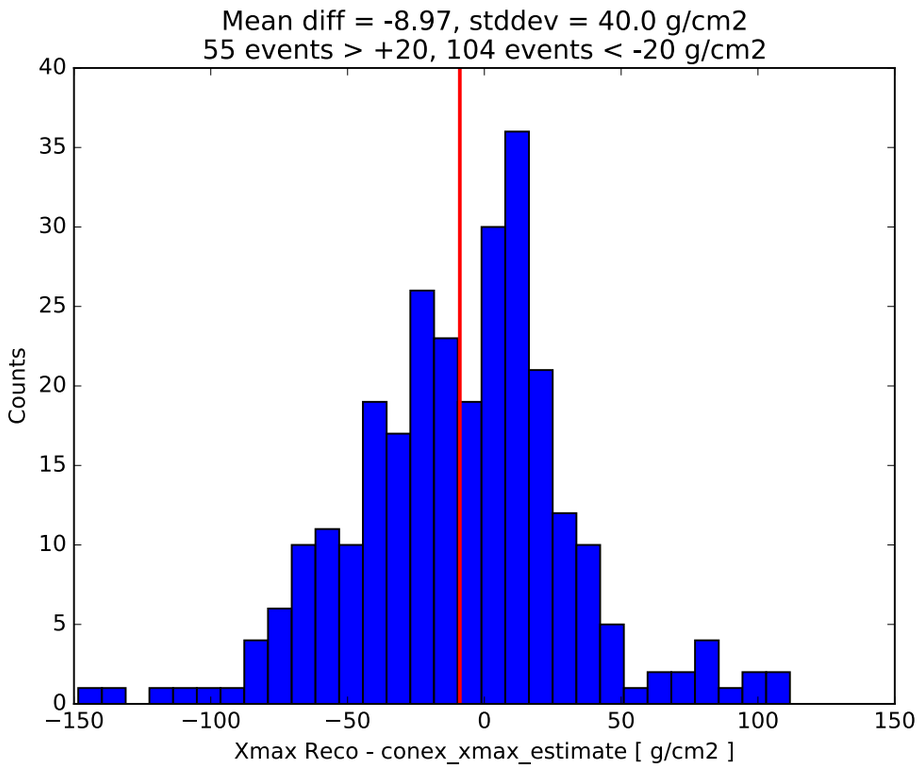


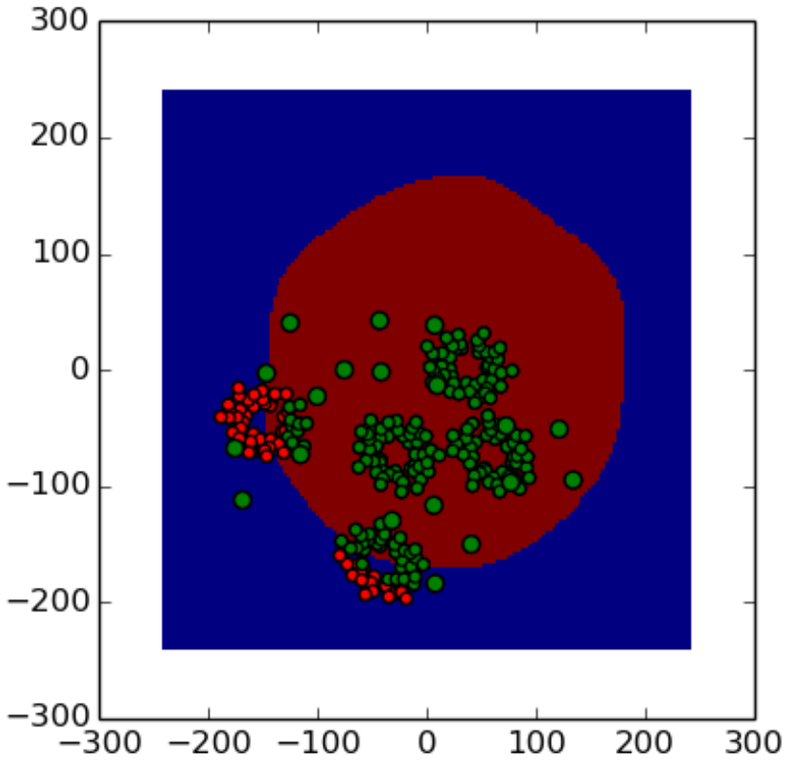


analysis: Arthur Corstanje



Towards new composition results



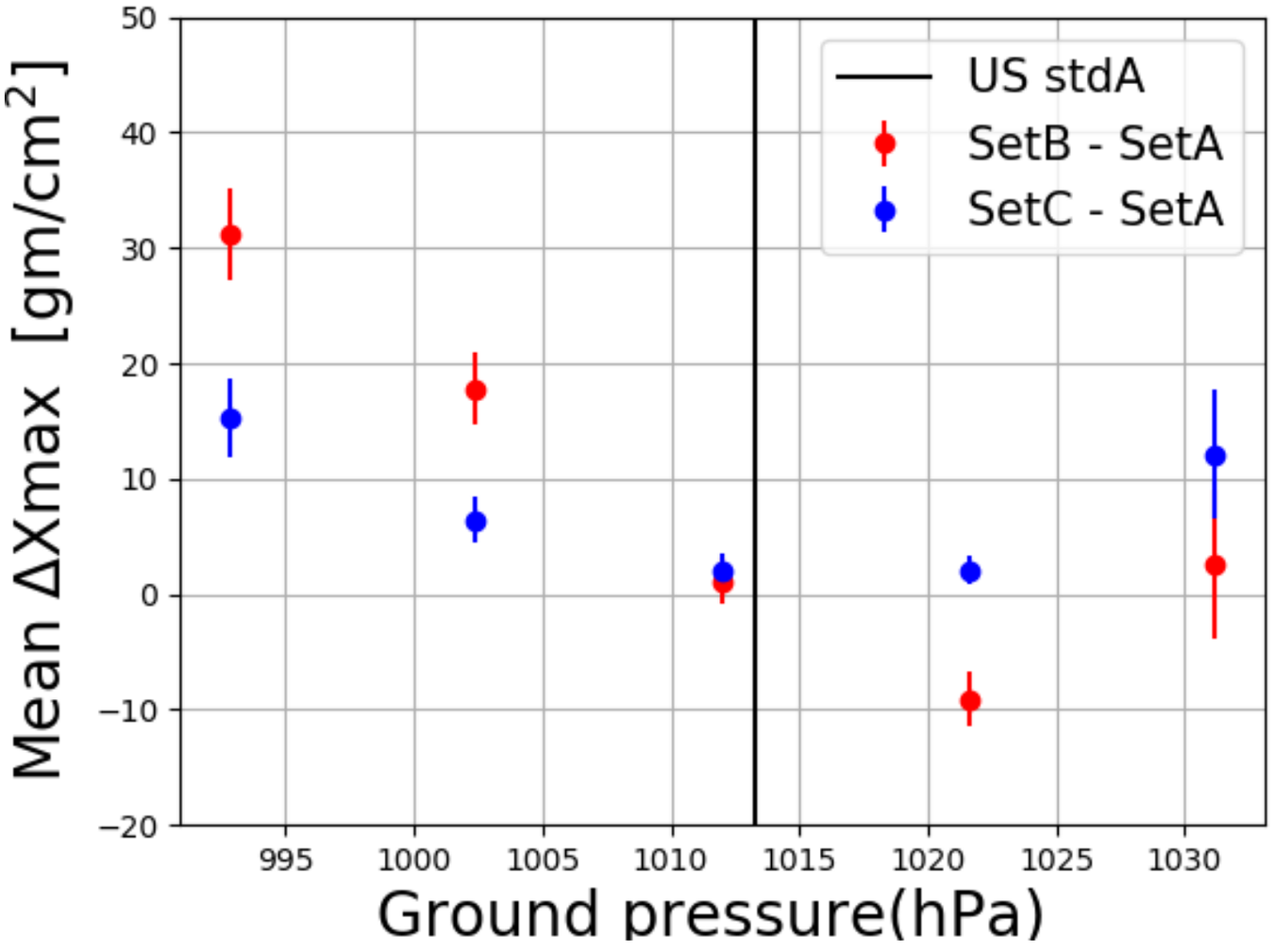


- Xmax with realistic GDAS atmospheres
- Absolute radio calibration
- Iterate simulations until:
  - Ereco in agreement with Esim (within resolution)
  - Xmax reco within dense simulation range
- Update anti-bias criteria
  (all simulations for shower should pass trigger & cuts)

analysis: Arthur Corstanje

GDAS atmospheres

- GDAS provides specific profiles for density and refractivity per event
- Previous: use density profile to do linear correction for Xmax
- New: implement density and refractivity profile directly into CORSIKA/CoREAS sims



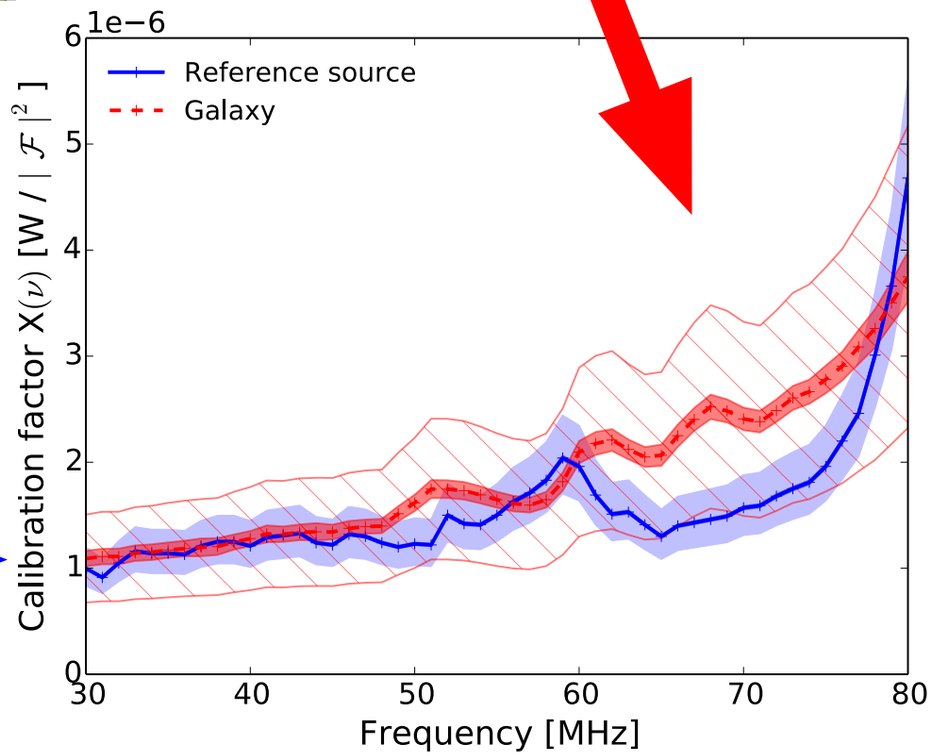
Linear correction too small for very low pressures!

See talk Pragati Mitra

Energy calibration

- Crane calibration with reference source VSQ 1000
- Calibration on galactic background LFmap

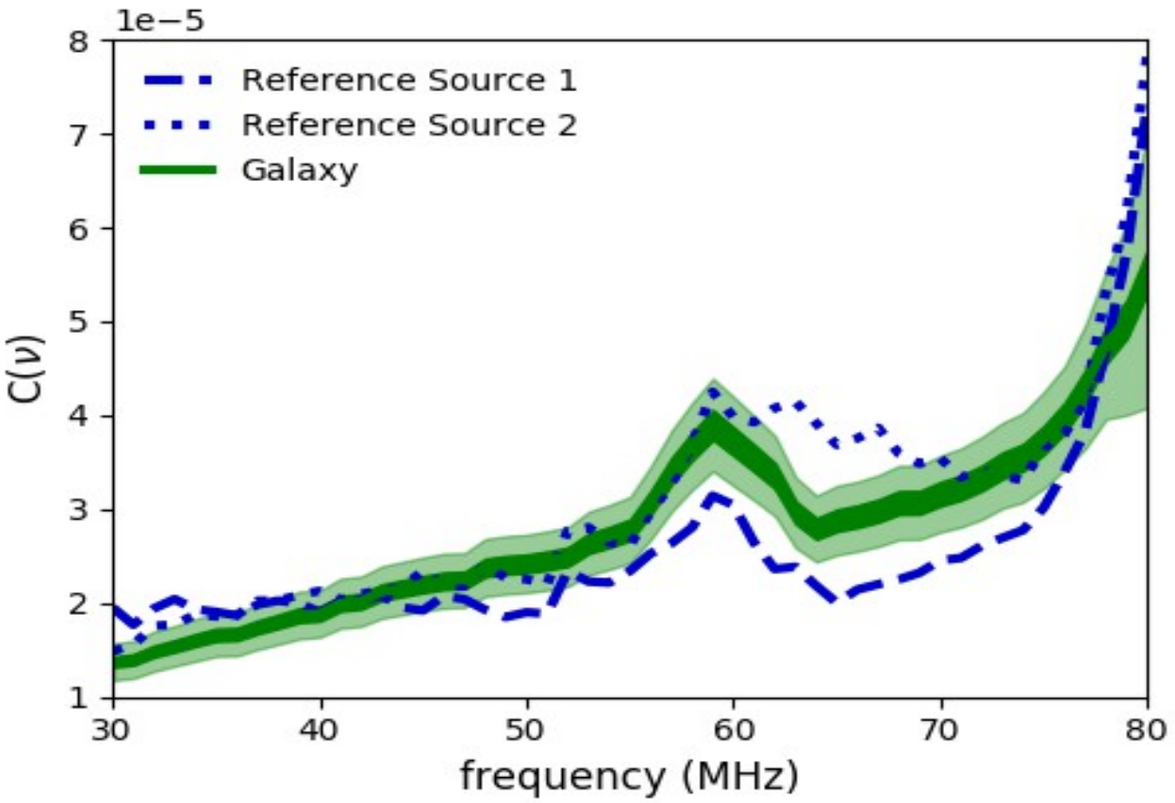
Nelles, A. et al. 2015,Journal of Instrumentation, 10, P11005



60-80 MHz …

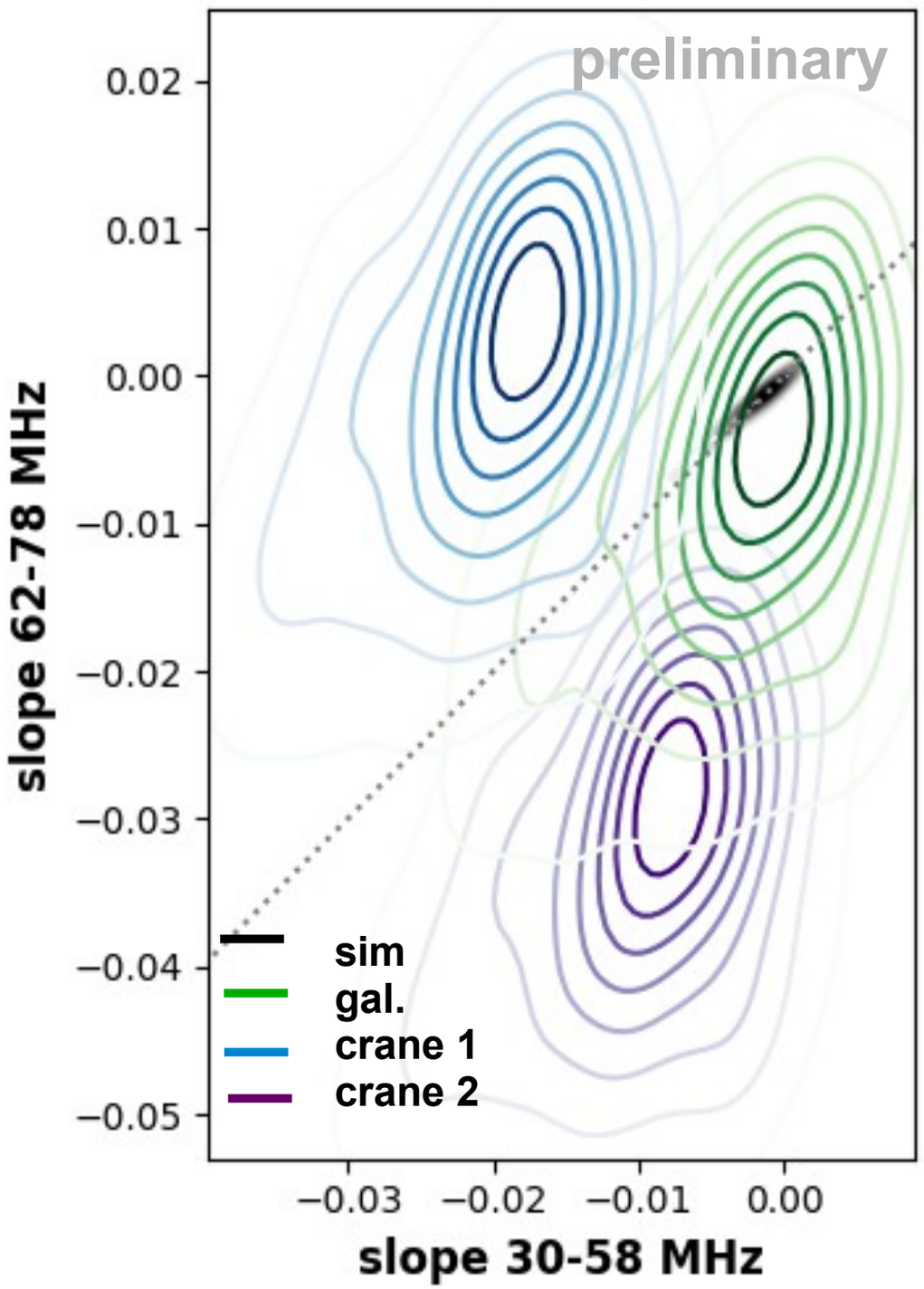
- system noise ?
- ref source specs ?

Improved calibration



- Complete signal chain calibration
- Systematic uncertainty of Galactic calibration ~14% (below 77 MHz)
- Spectral slope in agreement with CoREAS sim

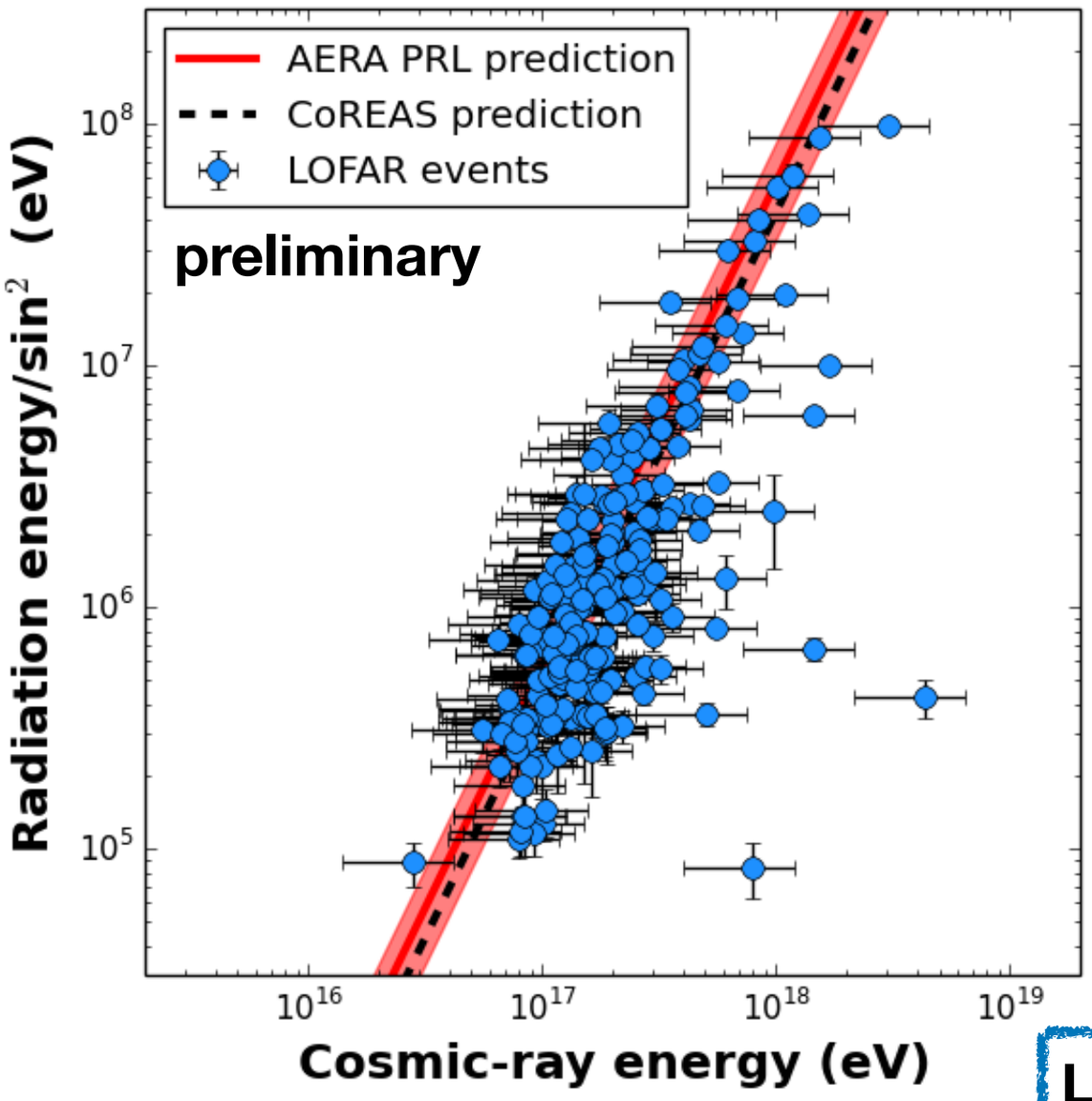
See talk Katie Mulrey



Energy scale

See talk Katie Mulrey

Integrated fluence

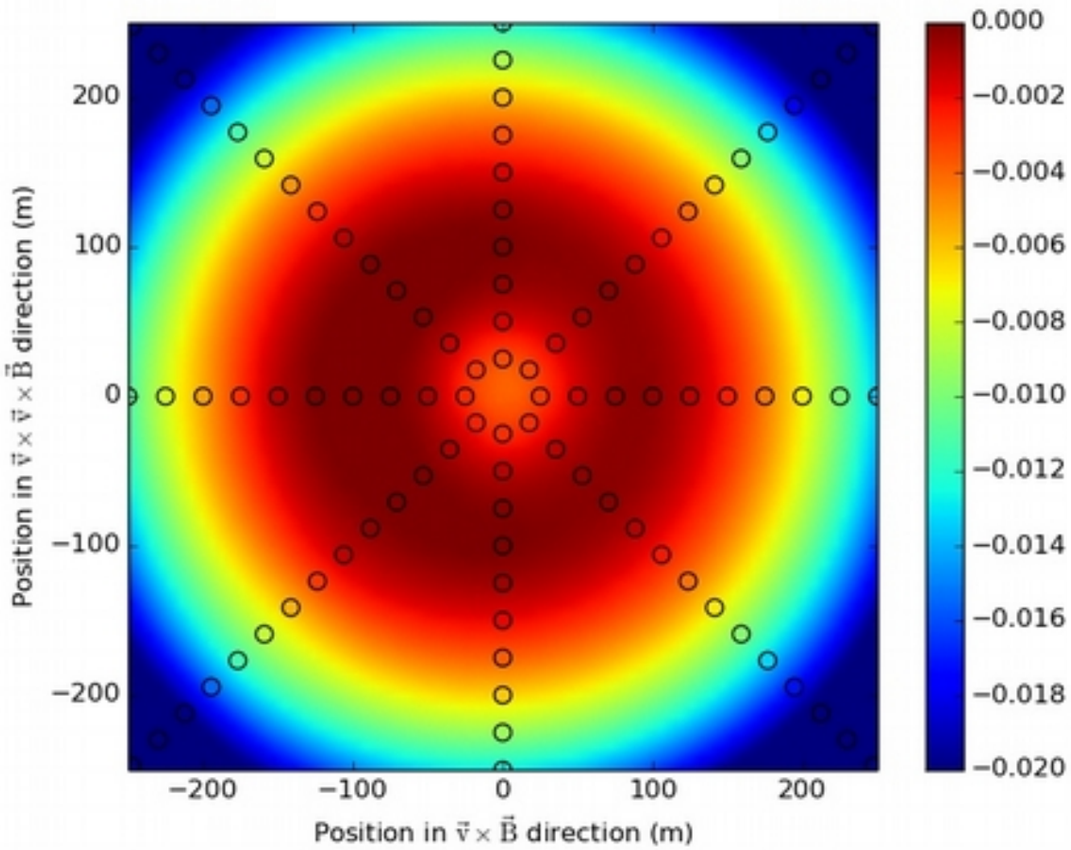


LORA energy

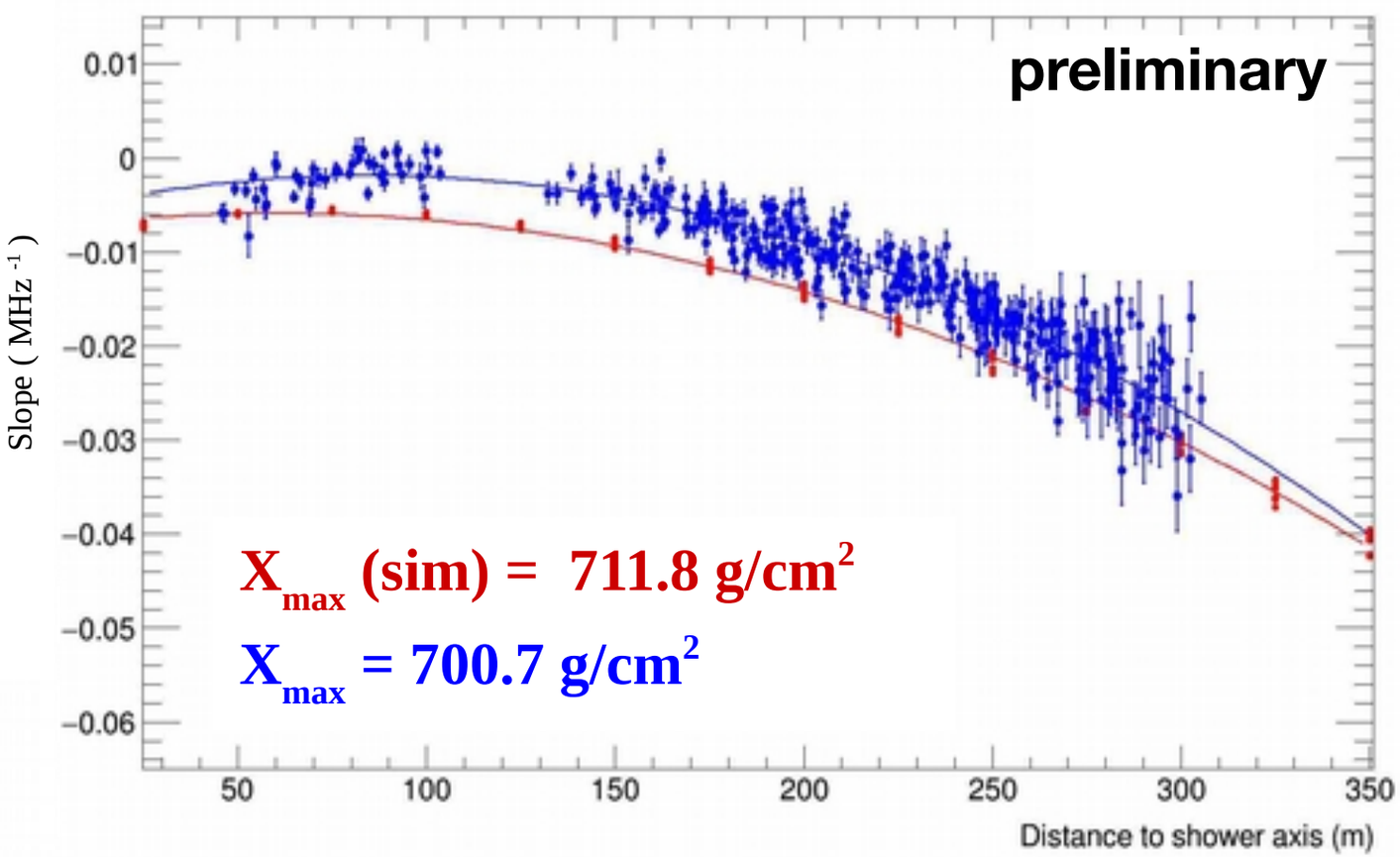
Radio energy scale in agreement with CoREAS & AERA !

Spectral analysis

D_{max} = 5.319 km



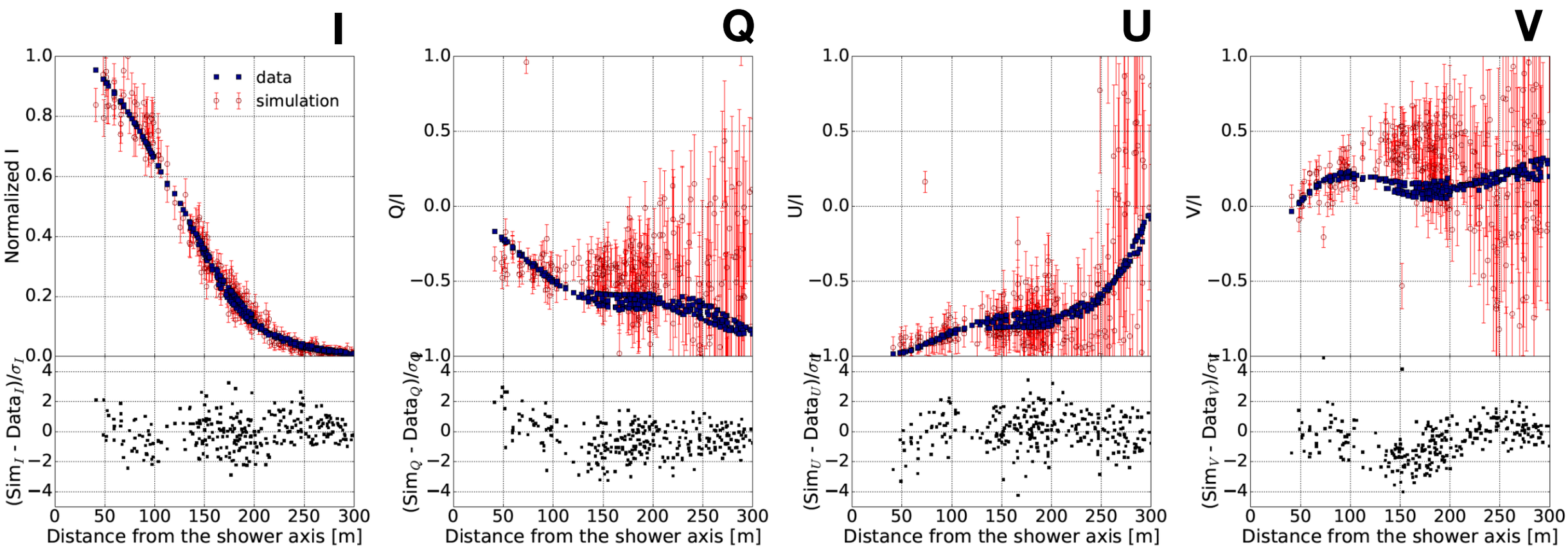
Allows independent fit of shower core & Xmax



Comparison spectral slope
LOFAR data CoREAS sim

See talk Laura Rossetto

Full Stokes polarisation



- Fair weather: small amount of circular polarisation confirmed by data
  O. Scholten et al., PRD **94** 1030101 (2016)

- Thunderstorms: strong signal in all Stokes parameters used to reconstruct atmospheric electric fields
  G. Trinh et al., PRD **95** 083004 (2017)

See talk Olaf Scholten

LORA Extension

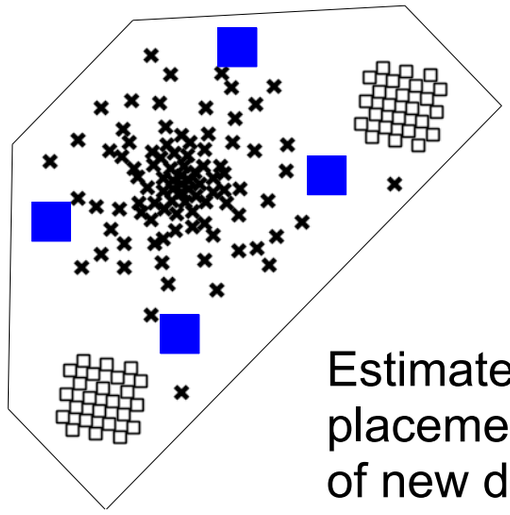
2.5 km

Existing station

New station

Sample New Station

220 m

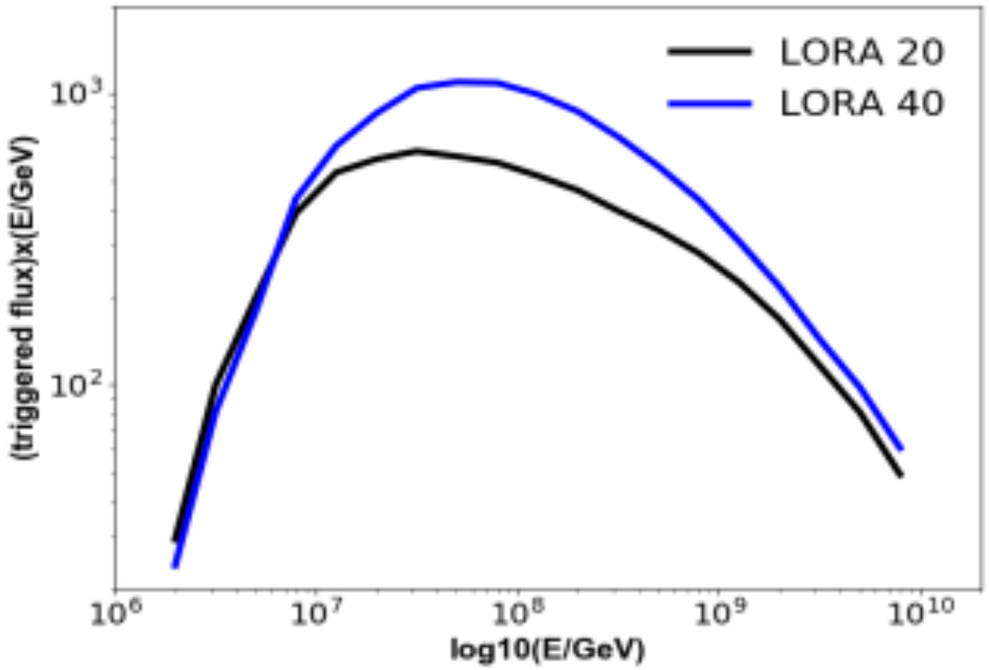


Estimated placement of new detectors

- Increased effective area at higher energies (stronger radio signal)
- Potential for more complicated trigger algorithms
- Potential to probe different parts of the radio footprint
- Reduction of particle bias

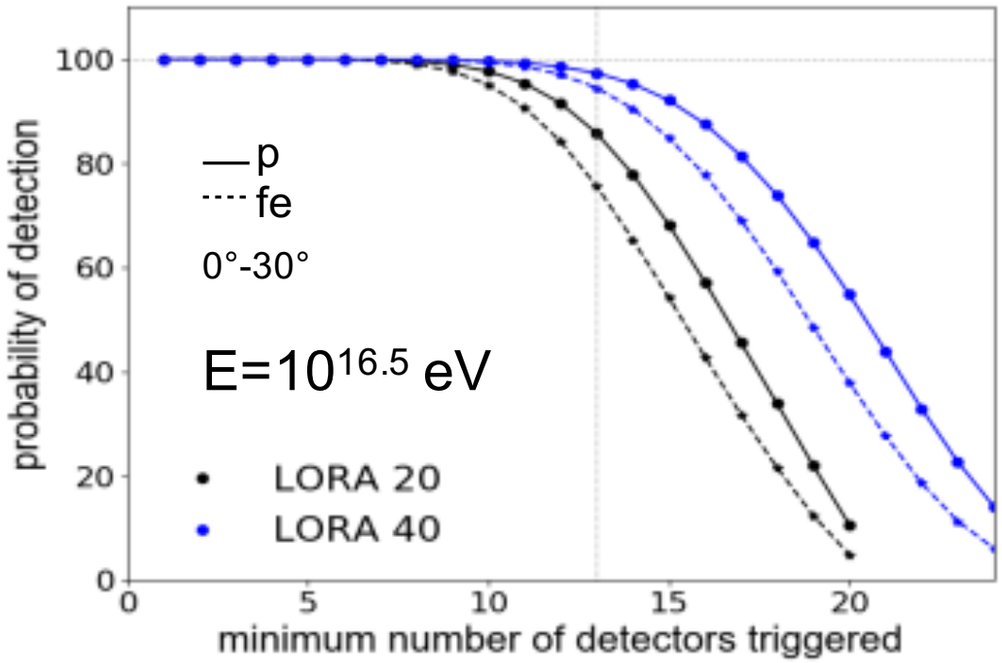
LORA extension

Different configurations were simulated to optimize scintillator placement
(constrained by locations of LOFAR stations)



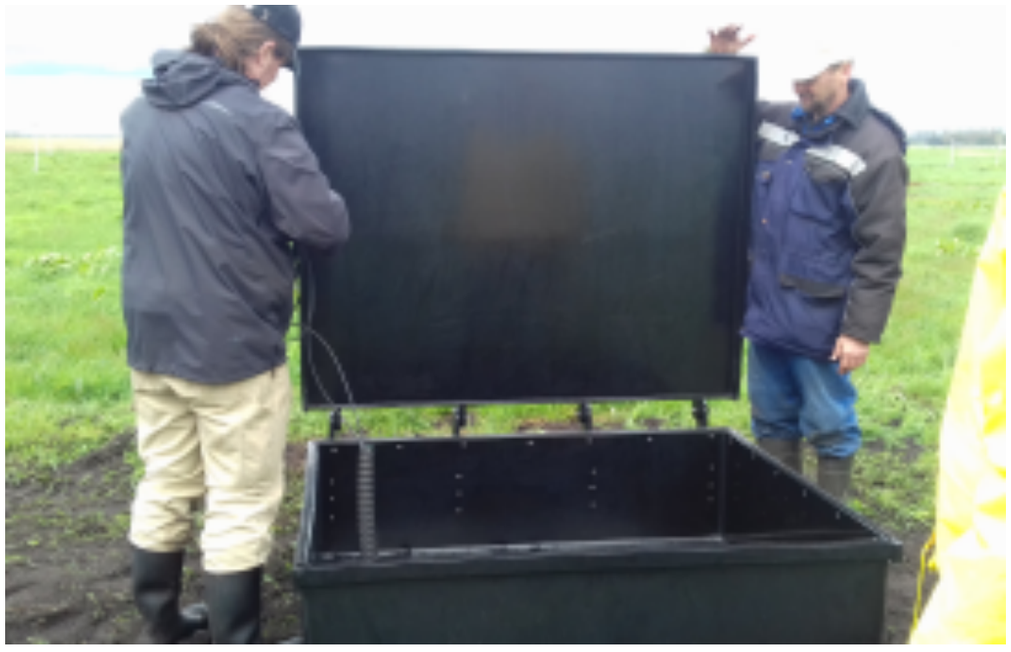
45% increase in events with
possible radio signal

Trigger rate = 1/hour
(13 stations for LORA 20, 14 for LORA 40)



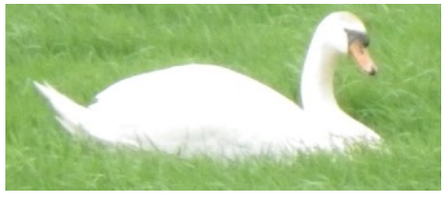
To have an unbiased trigger,
proton and iron showers need
to trigger with same
probability

LORA extension

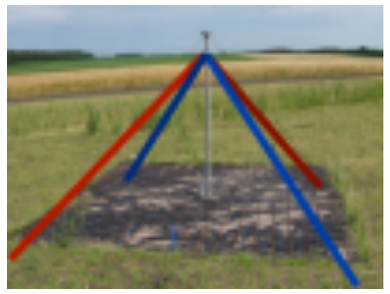


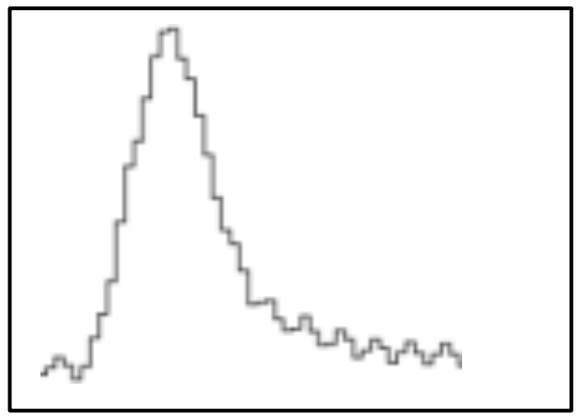
Phase I Scintillator housing, cables, and interface with the electronics cabinets installed April 2018

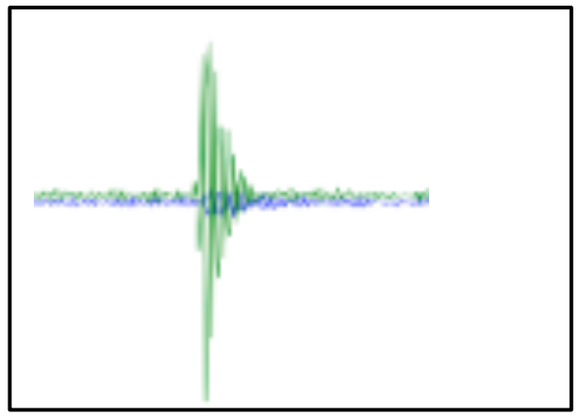
Phase II Digitizing electronics, HV supplies, network interfaces, and scintillators installed (summer 2018)



Hybrid trigger







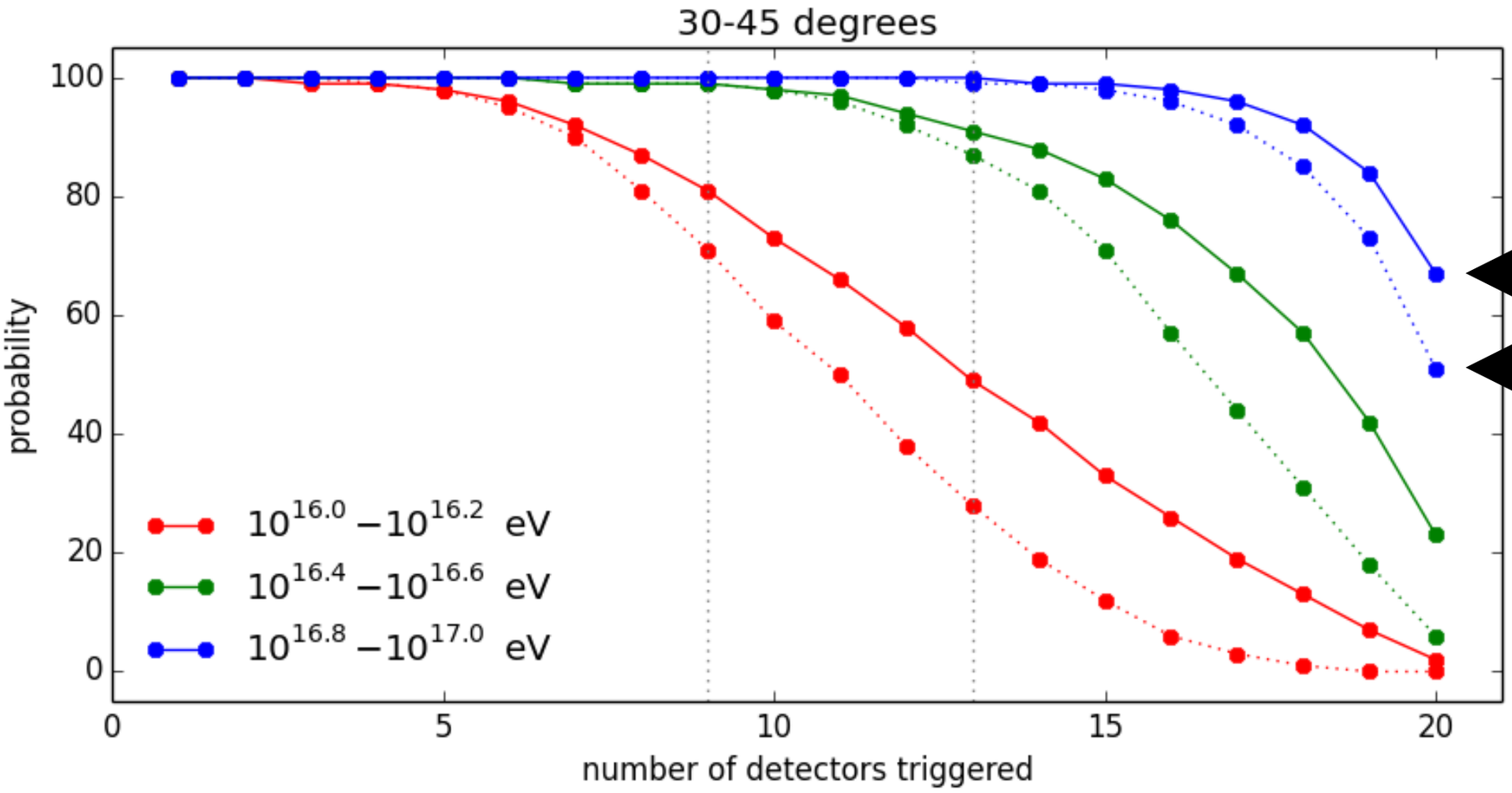
Triggering on particle signal guarantees CR, but is dominated by low energy events

Triggering on radio ensures usable radio signal strength, but is dominated by RFI events

Triggering on both ensures: **CR + good radio signal + RFI rejection**

RFI level is low enough for hybrid triggering ~50% of time

Hybrid trigger



analysis: Katie Mulrey

Particle trigger dominated by low energy events

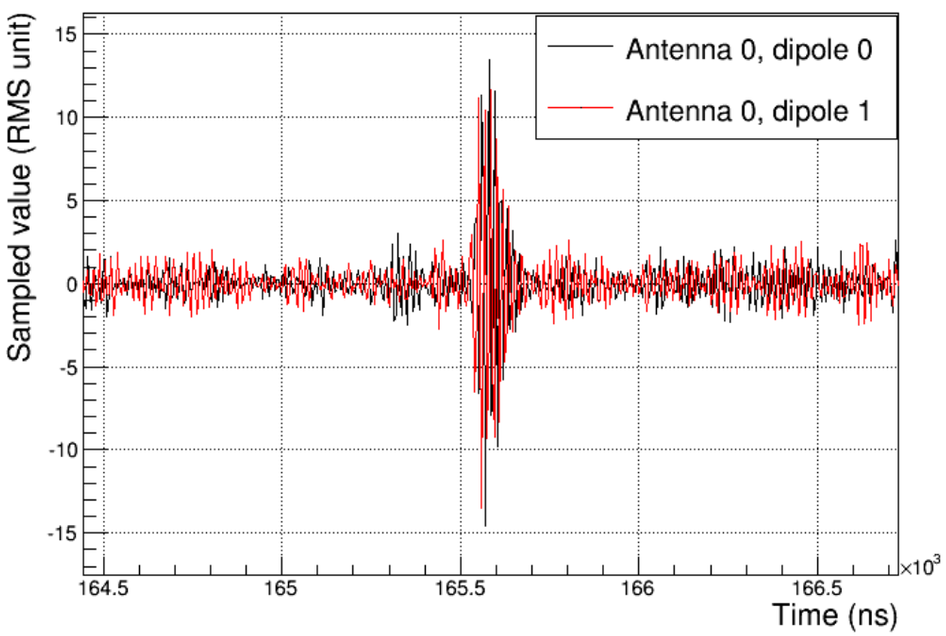
80% does not have detectable radio signal

Hybrid trigger allows trigger on less LORA stations, while removing the low-energy event

Bias-free CR detection down to (at least) $10^{16.5}$ eV (currently ~10^{17} eV)

Radio self-trigger

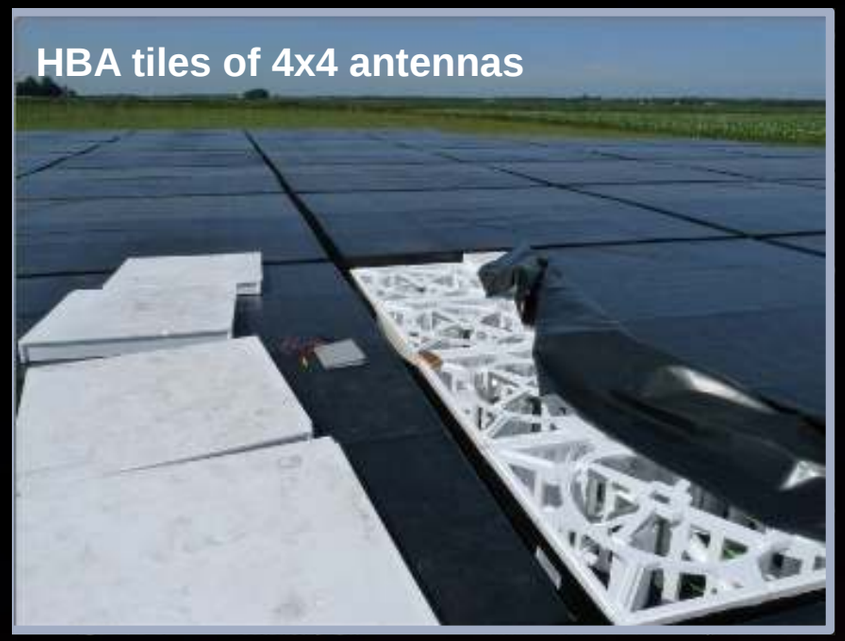
- Self-trigger algorithm for single stations for use at all 50 LOFAR stations
- Trigger based on polarisation, timing & signal strength
- ~20% CR efficiency above 10^{17} eV within 200m
- RFI at 1 event/hour level (based on 24h test run)



Example irreducible RFI background (airplane)

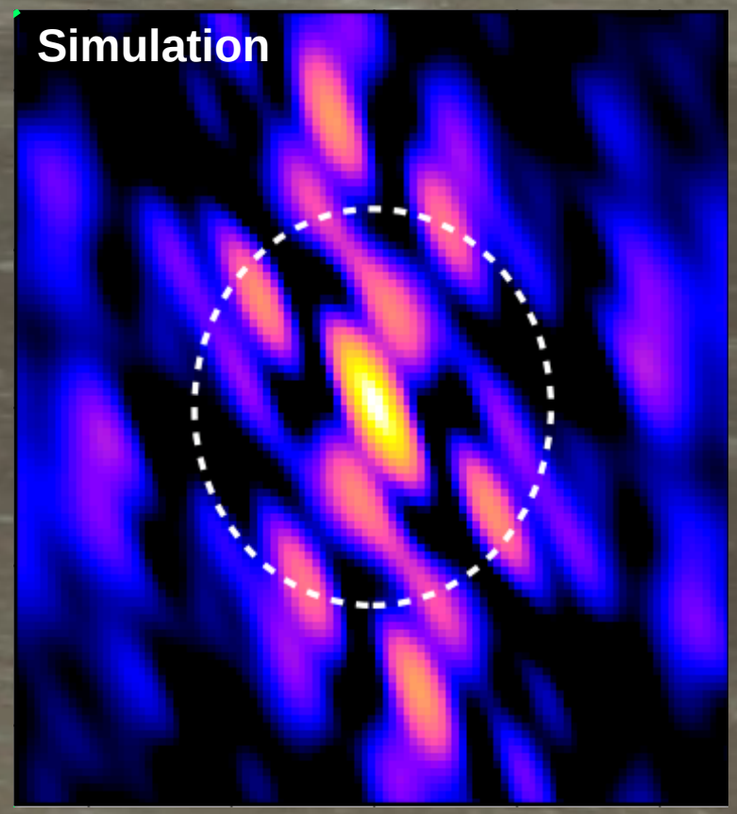
See talk Antonio Bonardi

NuMoon: CRs & neutrino lunar Askaryan

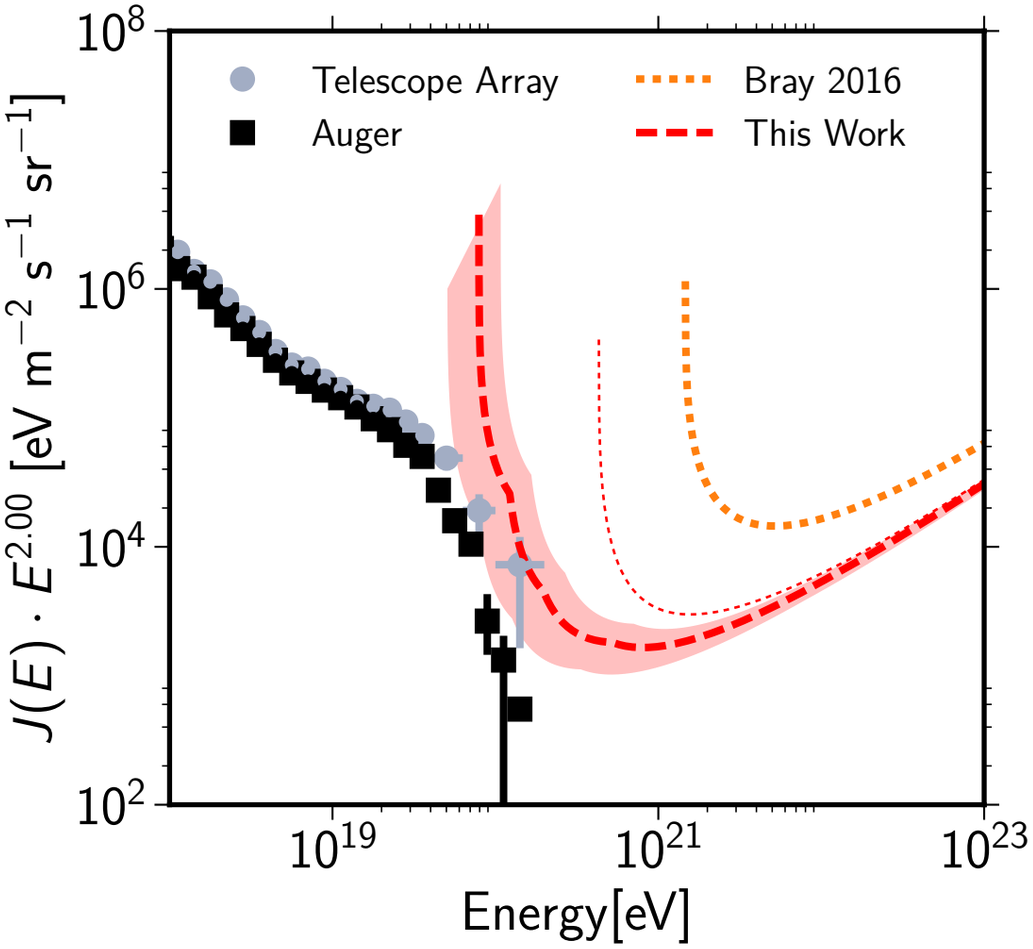


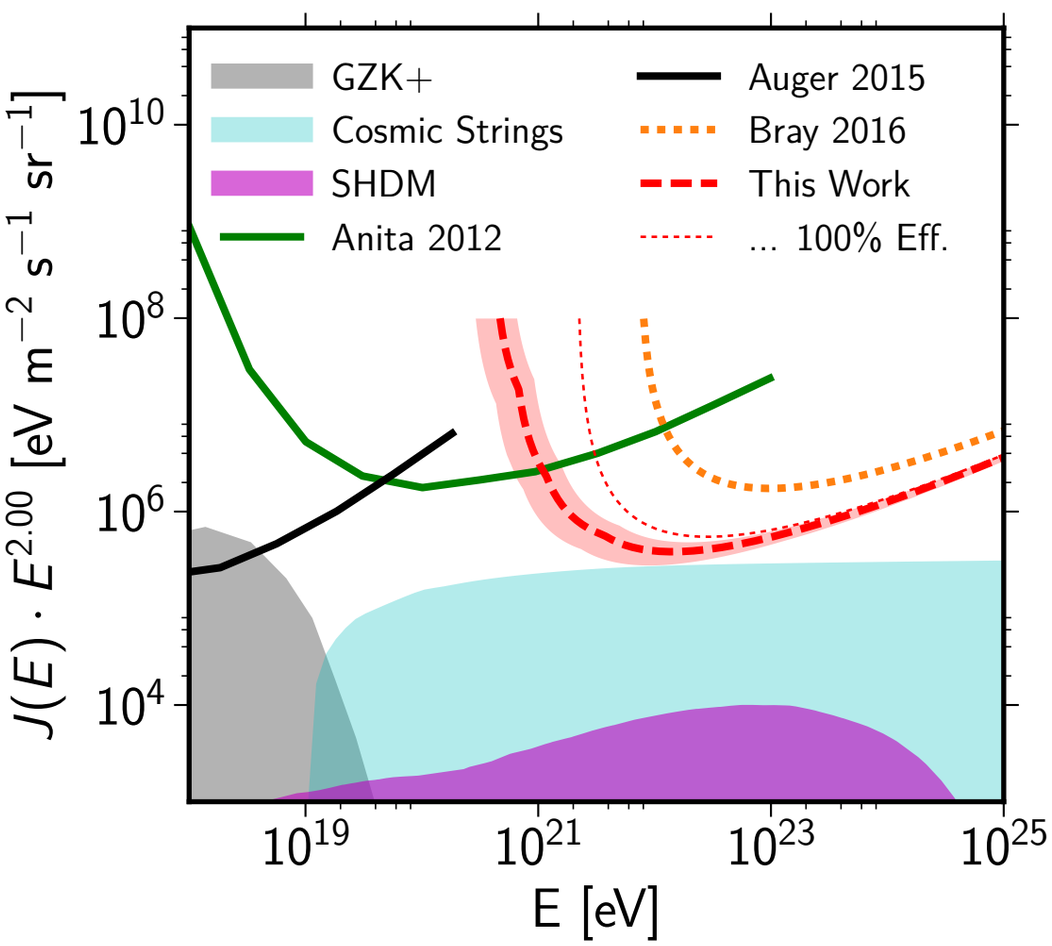
observation pipeline designed for GPU cluster (pulsar KSP)

- **input HBA station beams**
- **polyphase filter inversion**
- **ionospheric dedispersion**
- **beam forming on Moon**
- **triggering**



Expected sensitivity (200 hrs)





Difference to previous values (Bray 2016):

- 5 instead off 24 stations
- Increased bandwidth
- Reduced trigger threshold
- Full detector simulation instead of semi analytical parametrization

See talk Tobias Winchen

LOFAR2.0

- LOFAR Enhanced Generation & Operation (LEGO)
  Leverage of existing investments (hardware/software/brainpower)

- Upgrade to Cobalt central correlator/beamformer funded (NWO)
  Selected for list major scientific infrastructure on ~2025 timescale (KNAW)
  Proposal under review: DUPLLO (Digital Upgrade for Premier LOFAR Low-Band Observing (NWO)

- Triple electronics
  currently 48 LBA antennas active per station
  upgrade: all 96 LBA + 48 HBA per station
  better sampling of shower profile
  broader frequency range

- Continuous feed of Transient Buffer Boards
  currently only piggy-back mode
  upgrade: **nearly 100% duty cycle**