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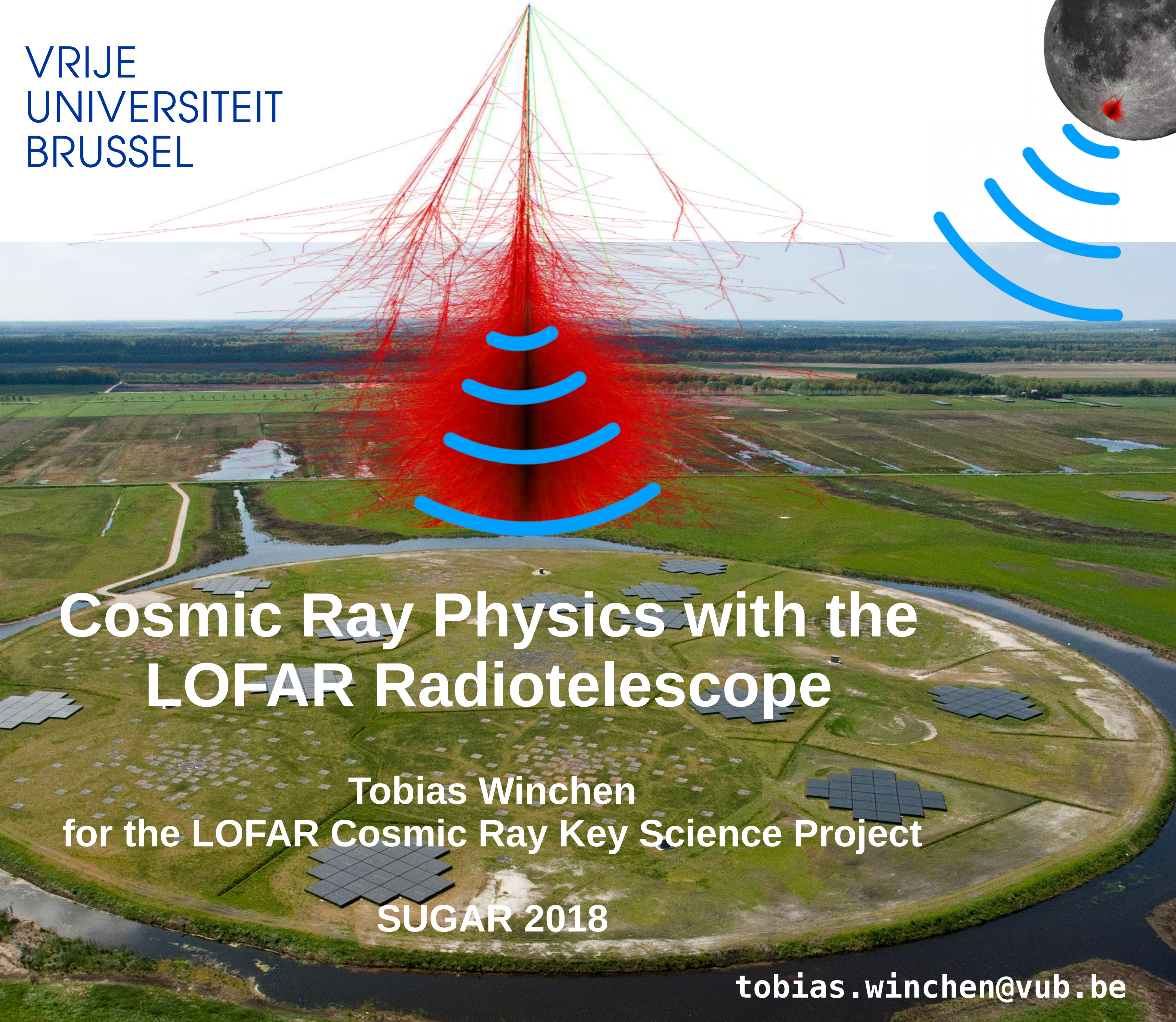

Cosmic Ray Physics with the LOFAR Radiotelescope

Tobias Winchen
for the LOFAR Cosmic Ray Key Science Project

SUGAR 2018

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The LOw Frequency ARray

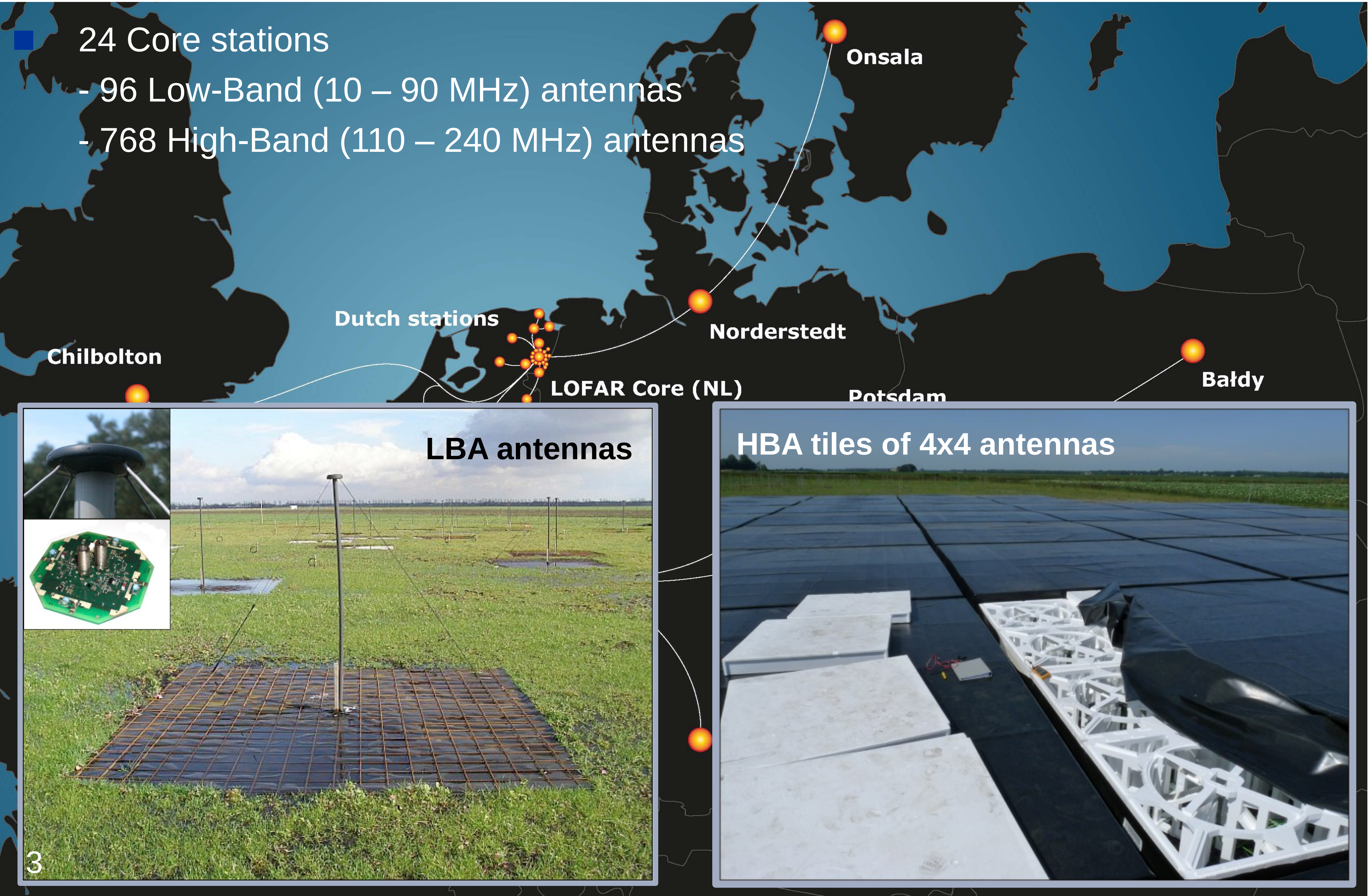
- Fully digital radio telescope
- 50+ Stations throughout Europe
- Dense core of 24 stations in the Netherlands

LOFAR

ASTRON

The LOw Frequency ARray

- 24 Core stations
  - 96 Low-Band (10 – 90 MHz) antennas
  - 768 High-Band (110 – 240 MHz) antennas



A Fully Digital Radio Telescope

Conventional radio telescope:

Mechanically point (few) directional antennas into observing direction + combine signals

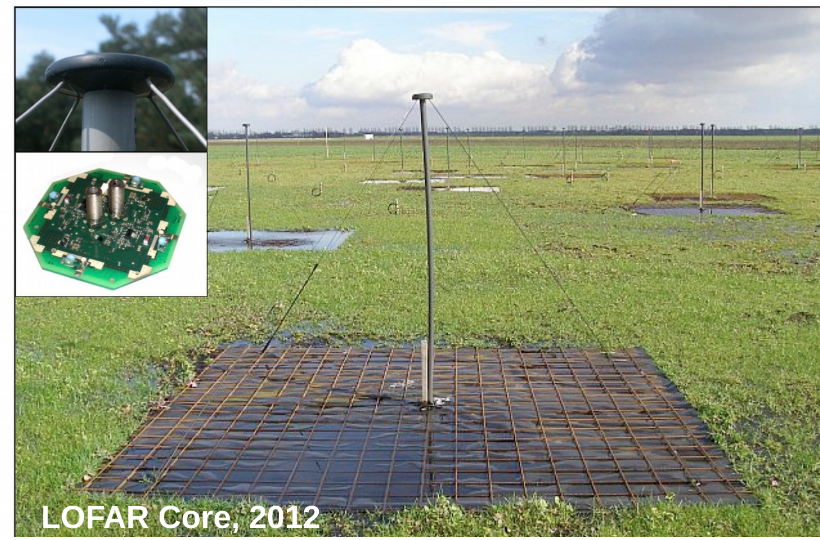
Observe only one direction at a time

Digital radio telescope:

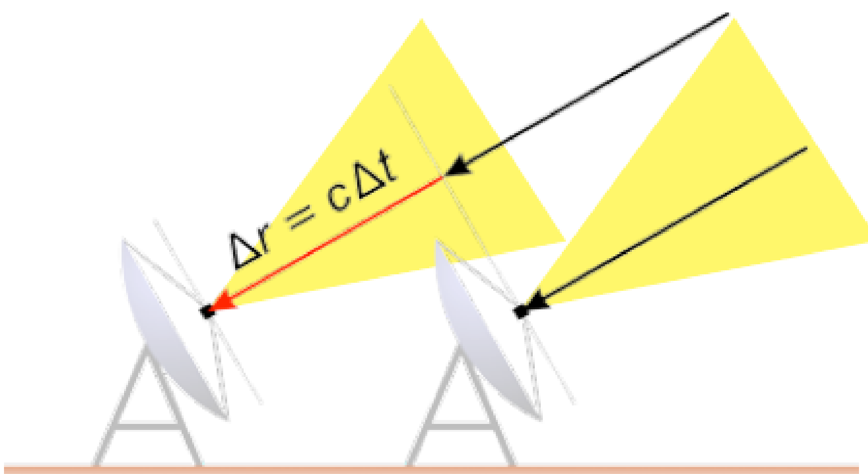
Many omni-directional antennas digitally combine signals according to direction

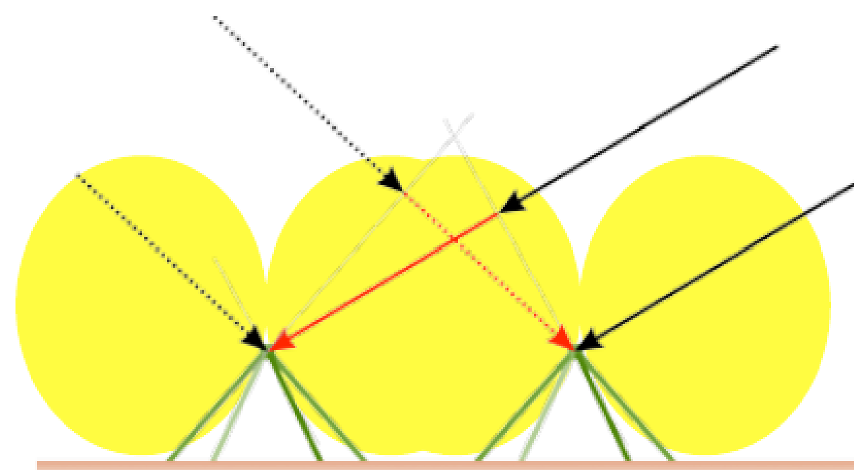
Observe multiple directions simultaneously

Nancay Radioheliograph, 2009



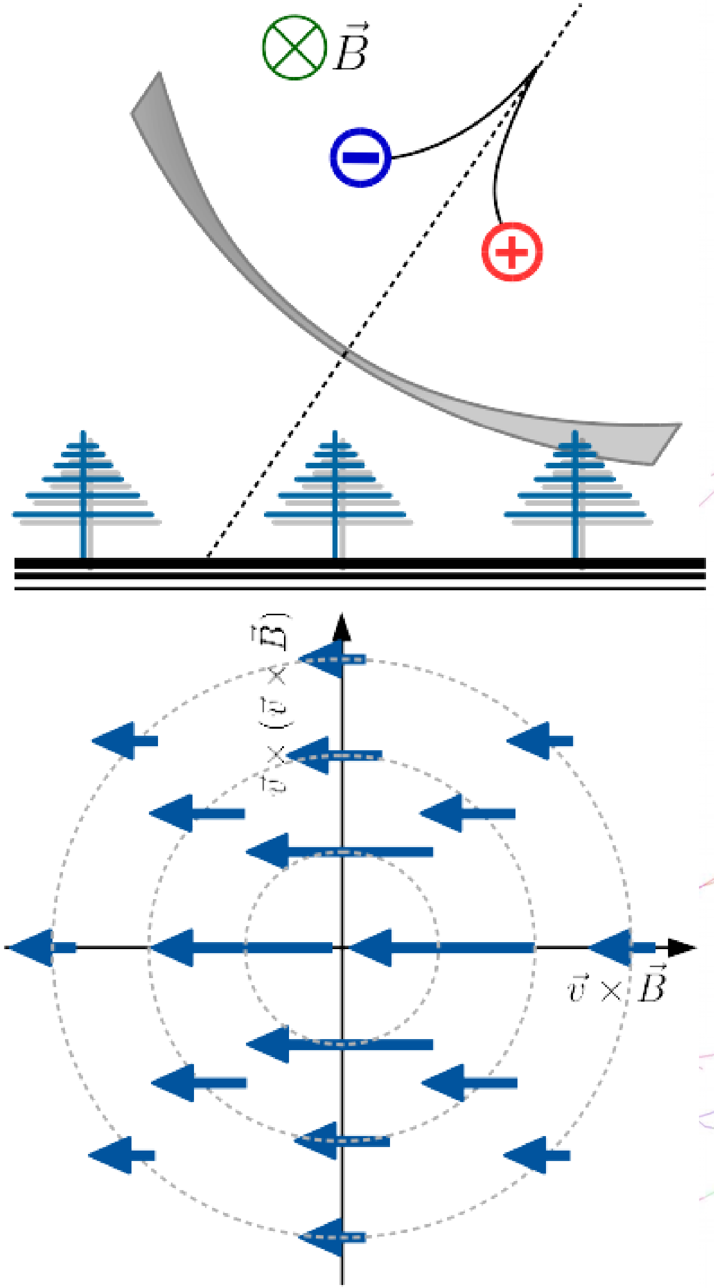
LOFAR Core, 2012

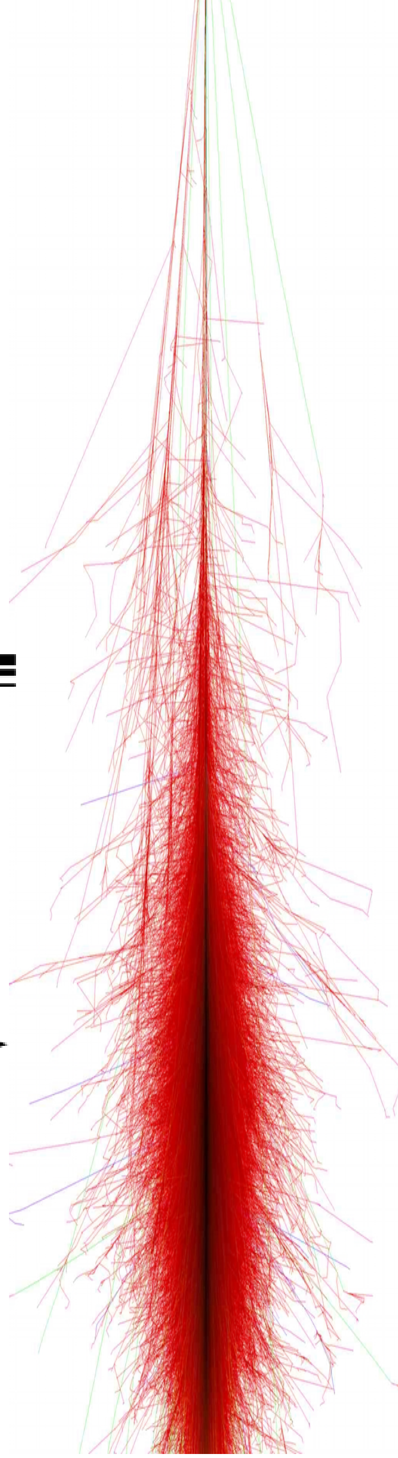




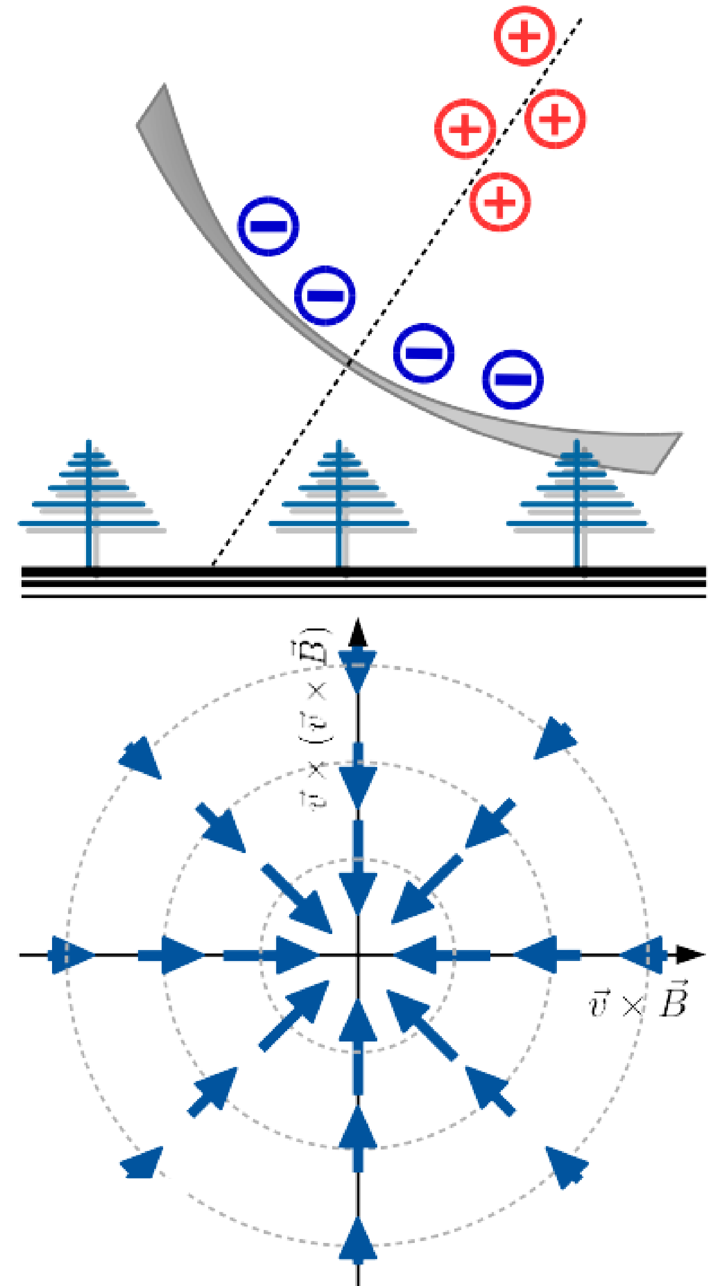
Radio Emission From Air Showers

Geomagnetic Emission





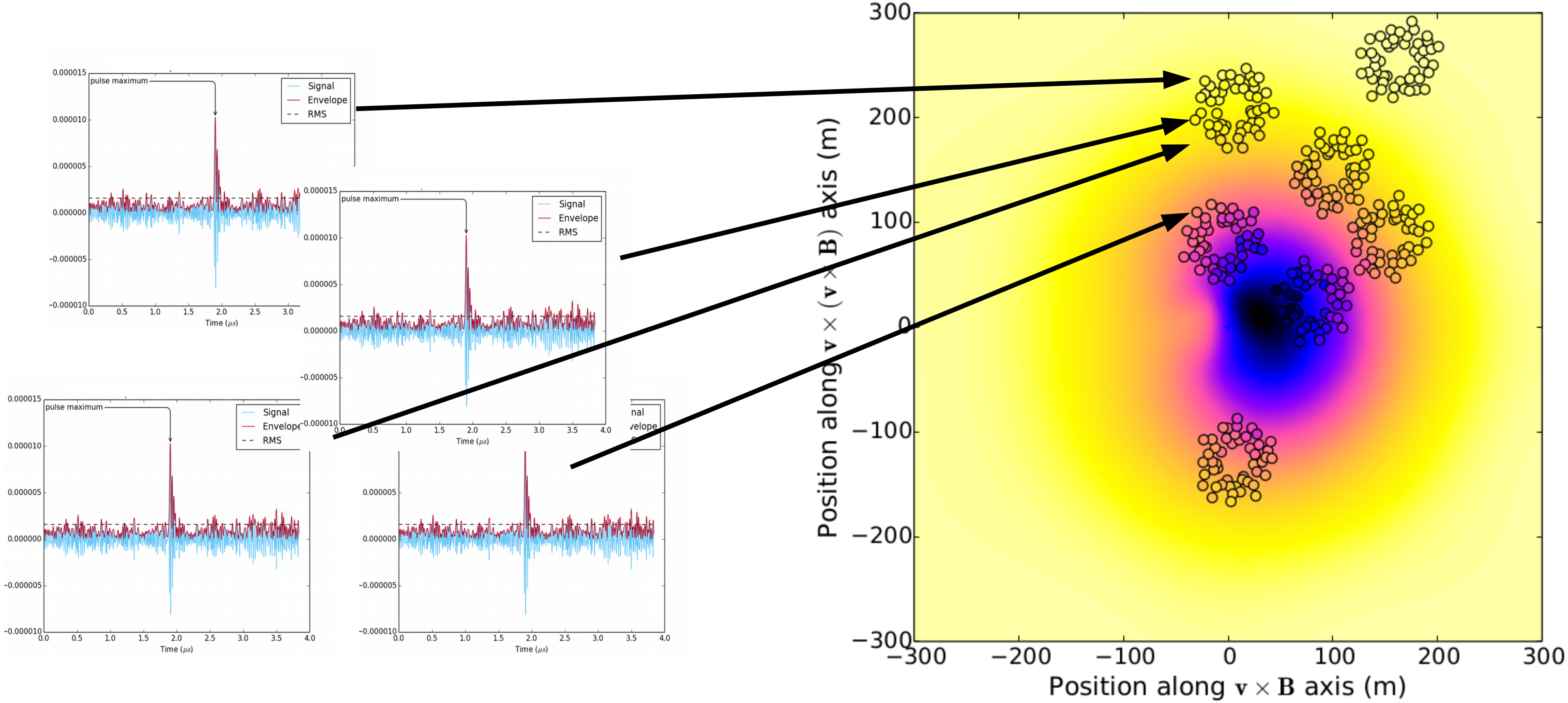
Charge Excess



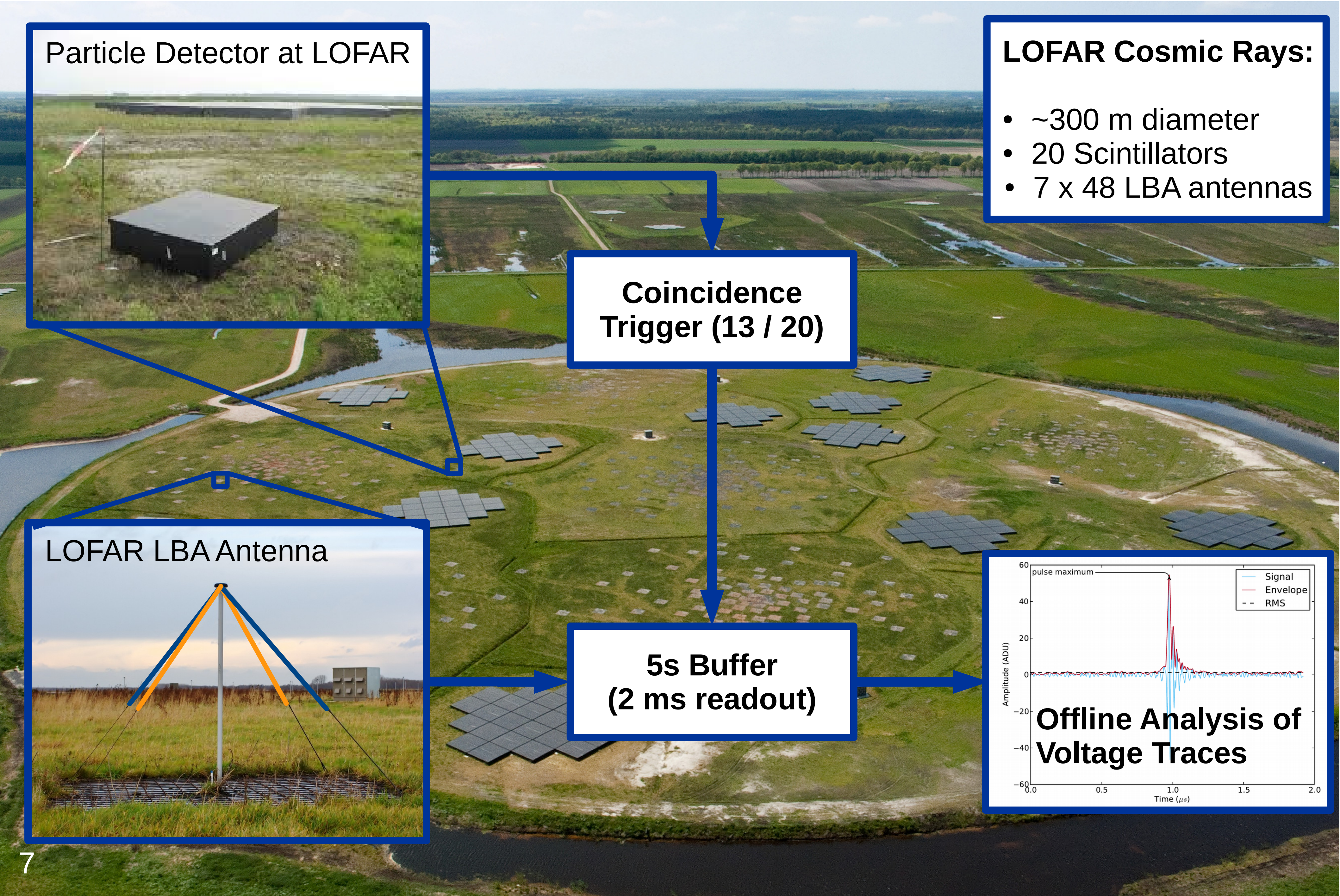
Sketch by C. Glaser

Cosmic Ray Air Shower with LOFAR

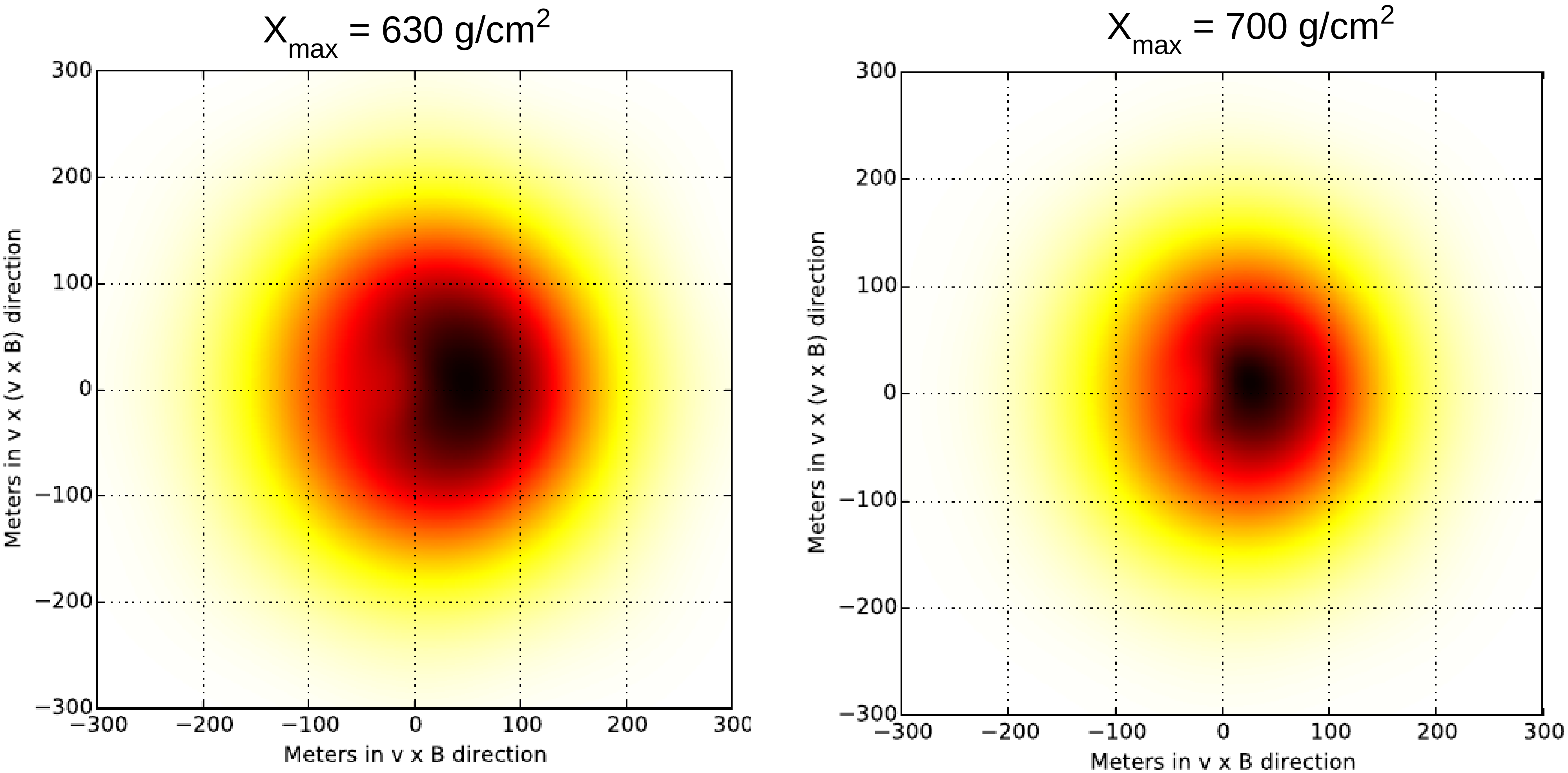
Intensity in every Antenna → Intensity Distribution on Ground



Trigger from Particle Array LORA

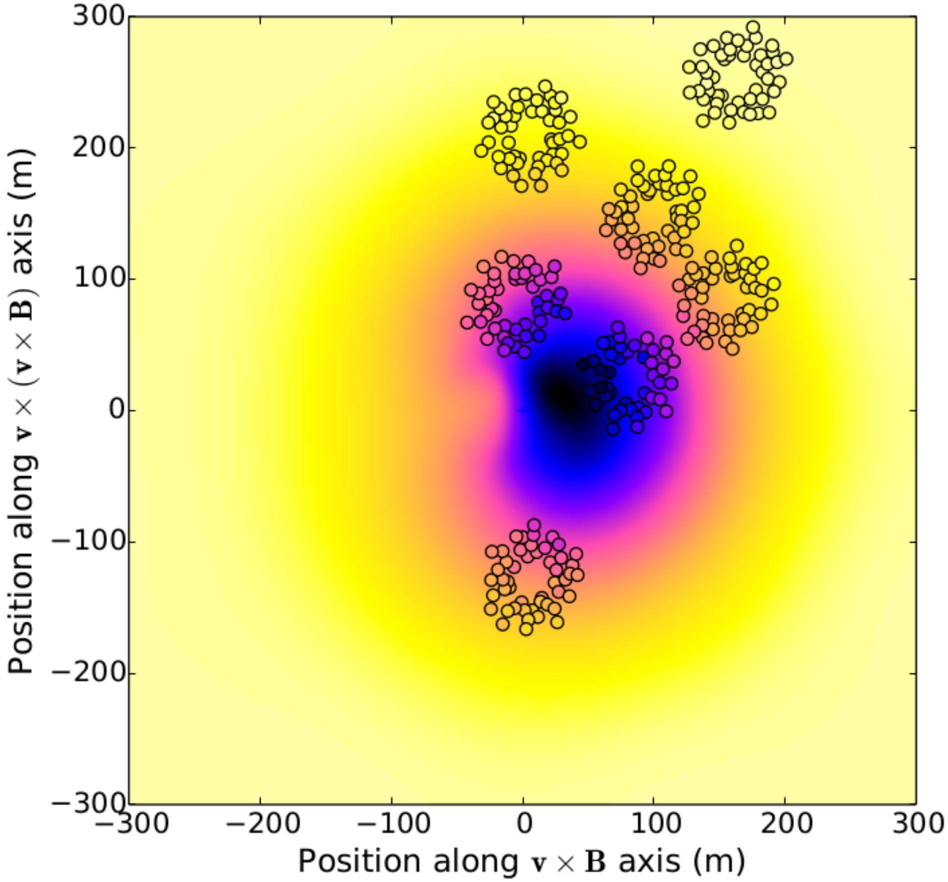


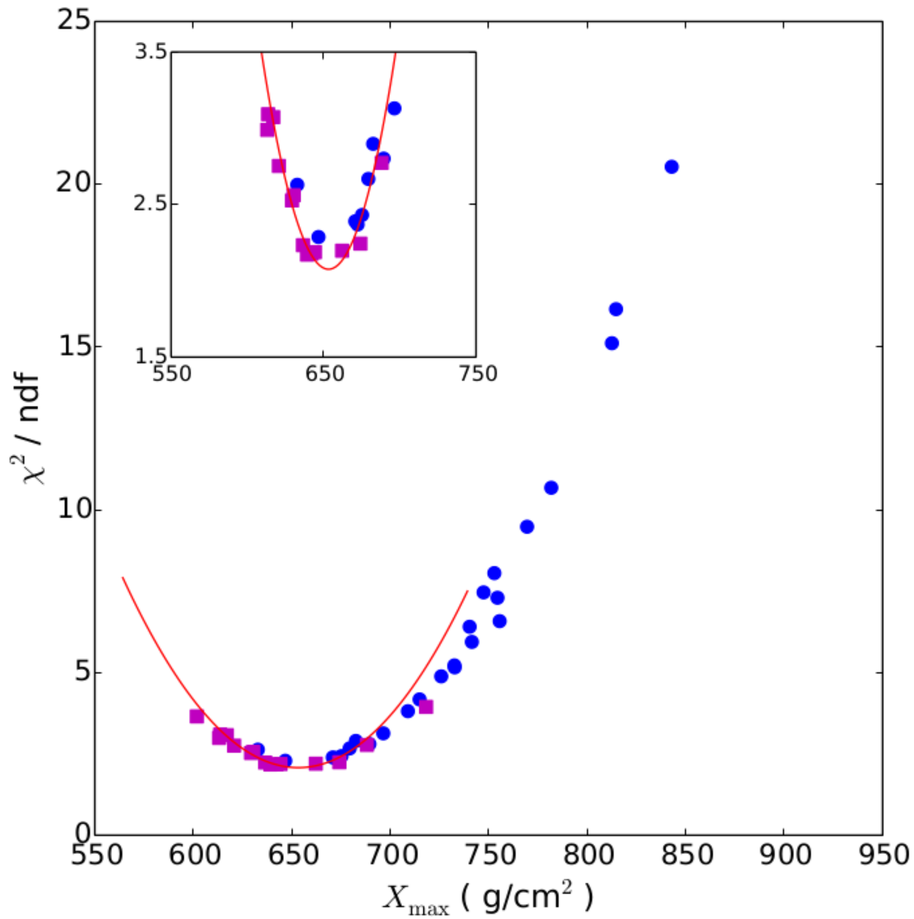
Footprint Size Depends on Xmax



Deeper shower → Smaller footprint

Xmax Reconstruction

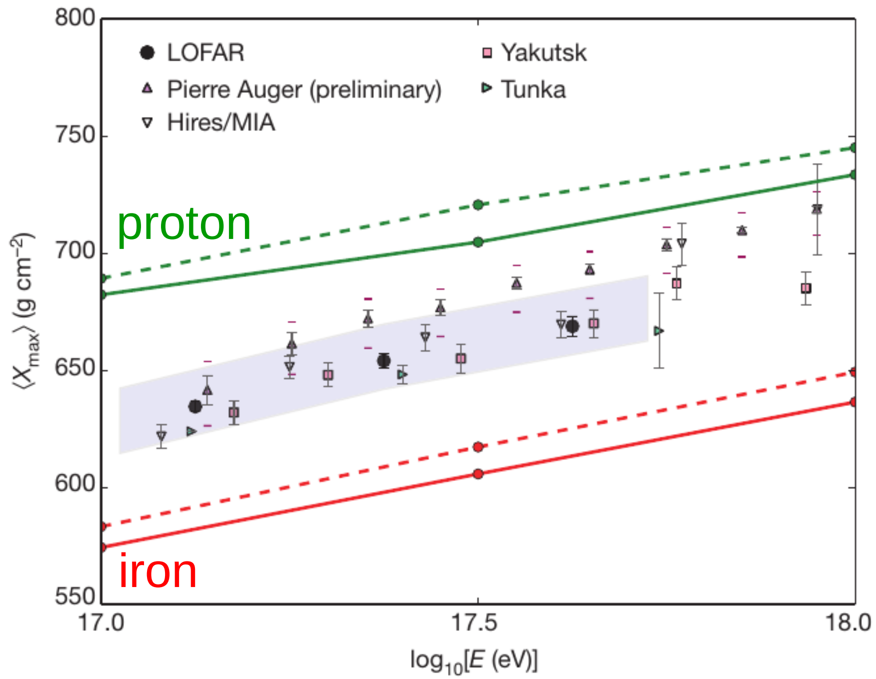


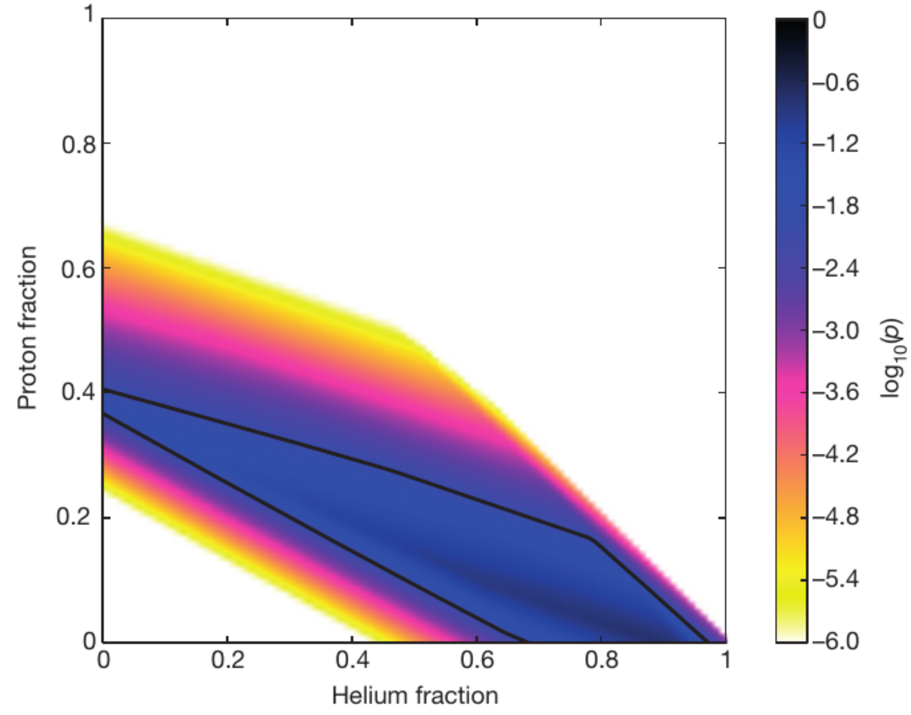


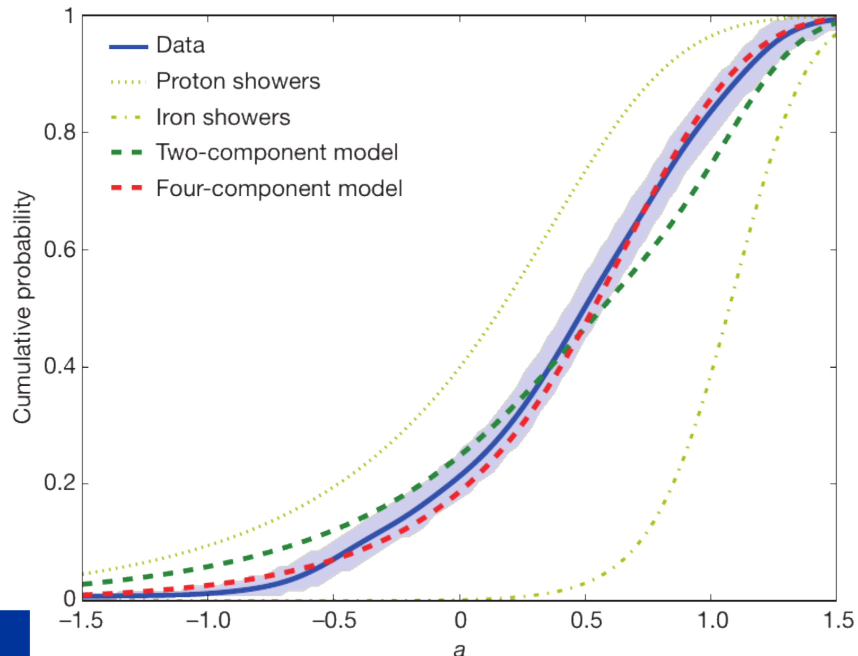
Simulate + reconstruct showers with varying Xmax to fit observation

Systematic uncertainty: -10 / +14 g/cm^2
Mean statistical uncertainty: ±16 g/cm^2

Results Composition Measurement





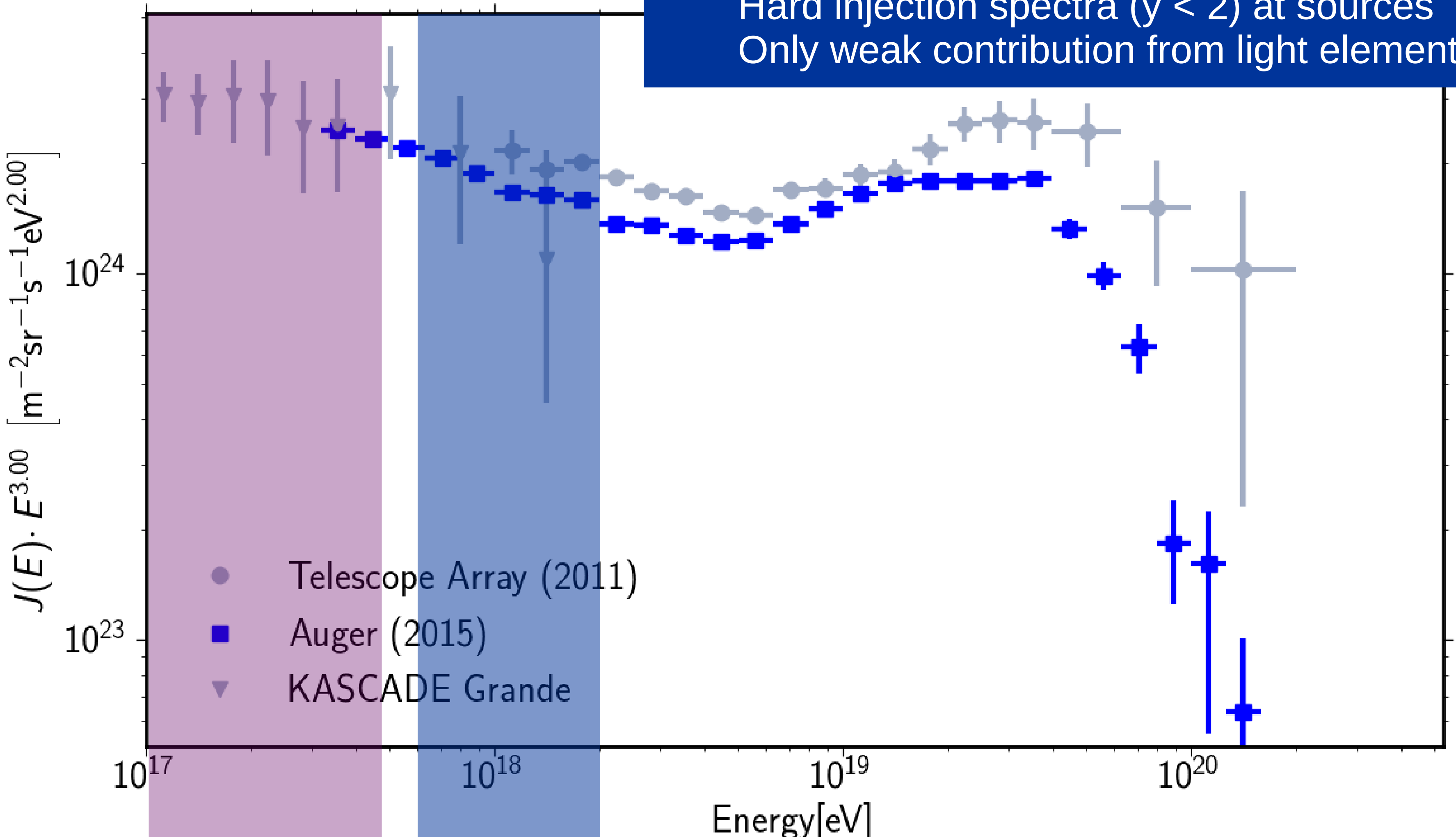


- **2 component models are not sufficient**
- **Strong light component between 0.1 and 0.5 EeV**
- **H + He fraction is larger than 40%**
  (@ 99% confidence)

S. Buitink et al. 2016, Nature 531, 70

Second Light Component

AUGER Combined fit (*JCAP, 2017, 1704, 038)*
Accelerators with rigidity dependent cut off
Surprising result above 5 EeV:
Hard injection spectra (y < 2) at sources
Only weak contribution from light elements



LOFAR
H+He >40%

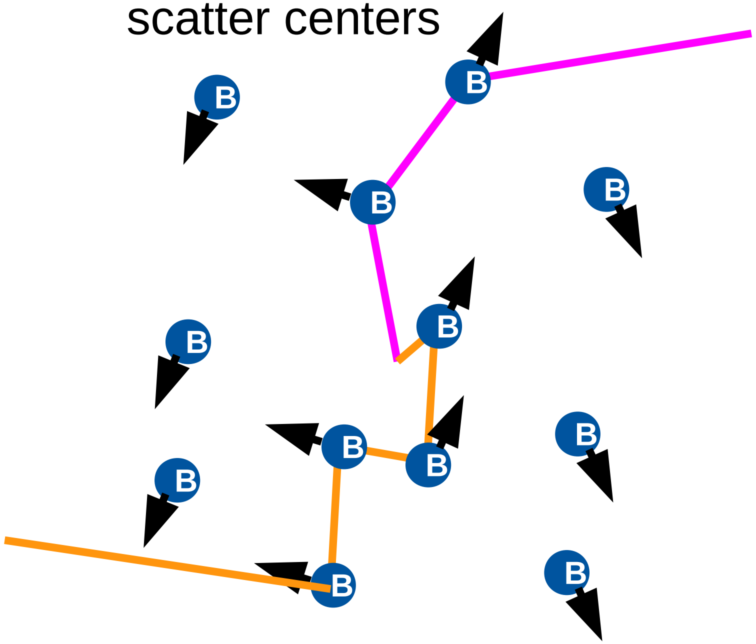
AUGER
Second component dominant below 2 EeV 59% H, 6% He
JCAP, 2017, 1704, 038

Entangle components by modeling acceleration and propagation

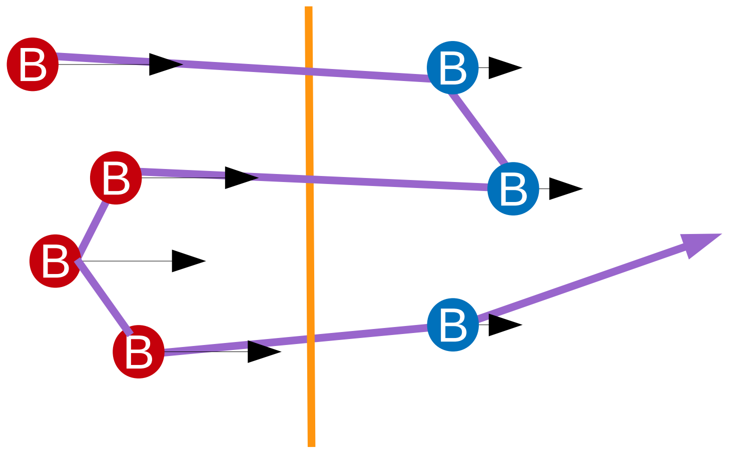
Fermi Acceleration in CRPropa

Scattering on irregularities in magnetic field

Second Order
Random isotropic movement of scatter centers



First Order
Directed movement in two different velocity fields



Step length from quasi linear theory of diffusion in magnetic fields:

- Gyroradius not much larger than coherence length of field
- dB / B not too large

Spectral index of turbulence
(q = 5/3 for Kolmogorov turbulence)

Strength of irregularites

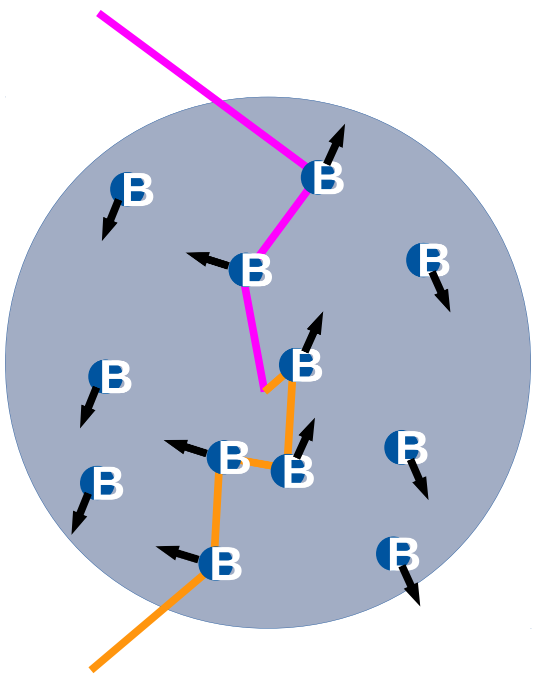
Mean free path: $$\lambda \propto \left(\frac{B}{\delta B}\right)^2 (R_G\, k_{\mathrm{min}})^{1-q}\, R_G \equiv \lambda_0 \left(\frac{E}{1\,\mathrm{EeV}}\,\frac{1}{Z}\right)^{2-q}$$

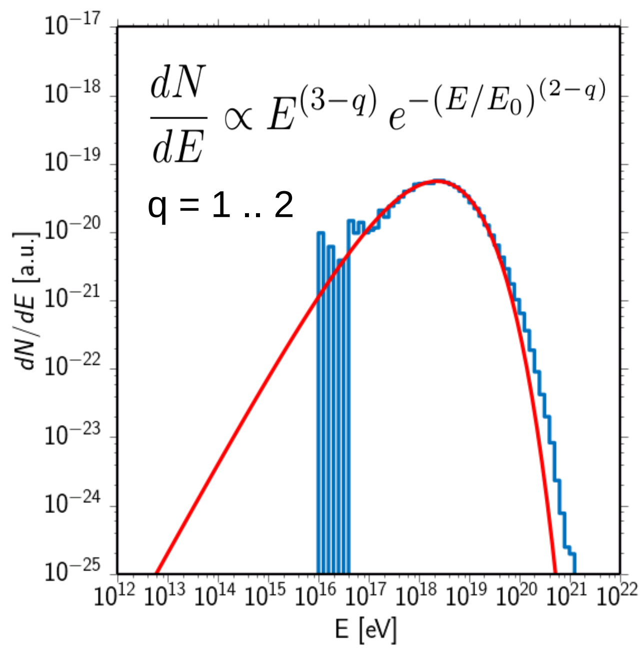
Step – length scaling depends on MHD details

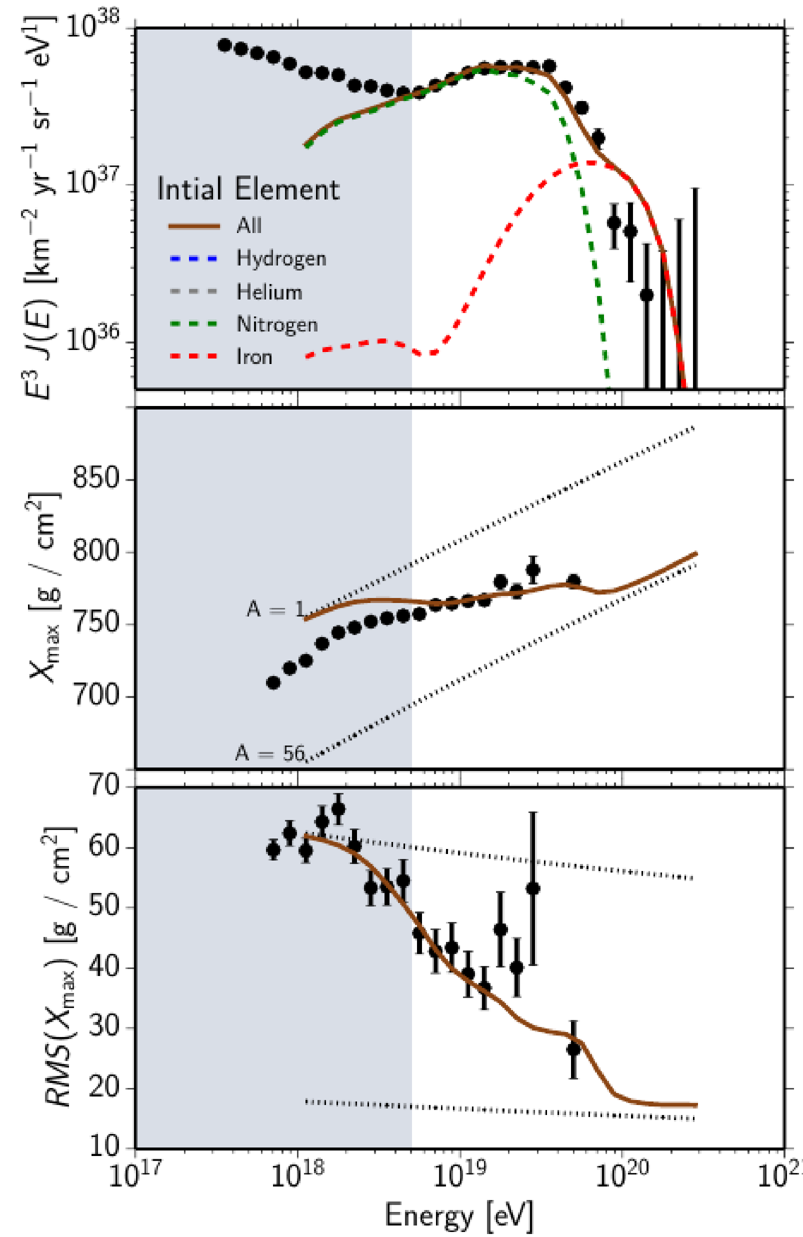
Max. length scale of turbulence

2^{nd} Order Fermi Acceleration
Small Steps between Scatter Events

Simulate acceleration by stochastic scattering







Geometry explains surprising results?

Hard spectra → Peaking source distribution

Light elements at low energies (below ankle)

Consistent with `second' light component?

→ Detailed models

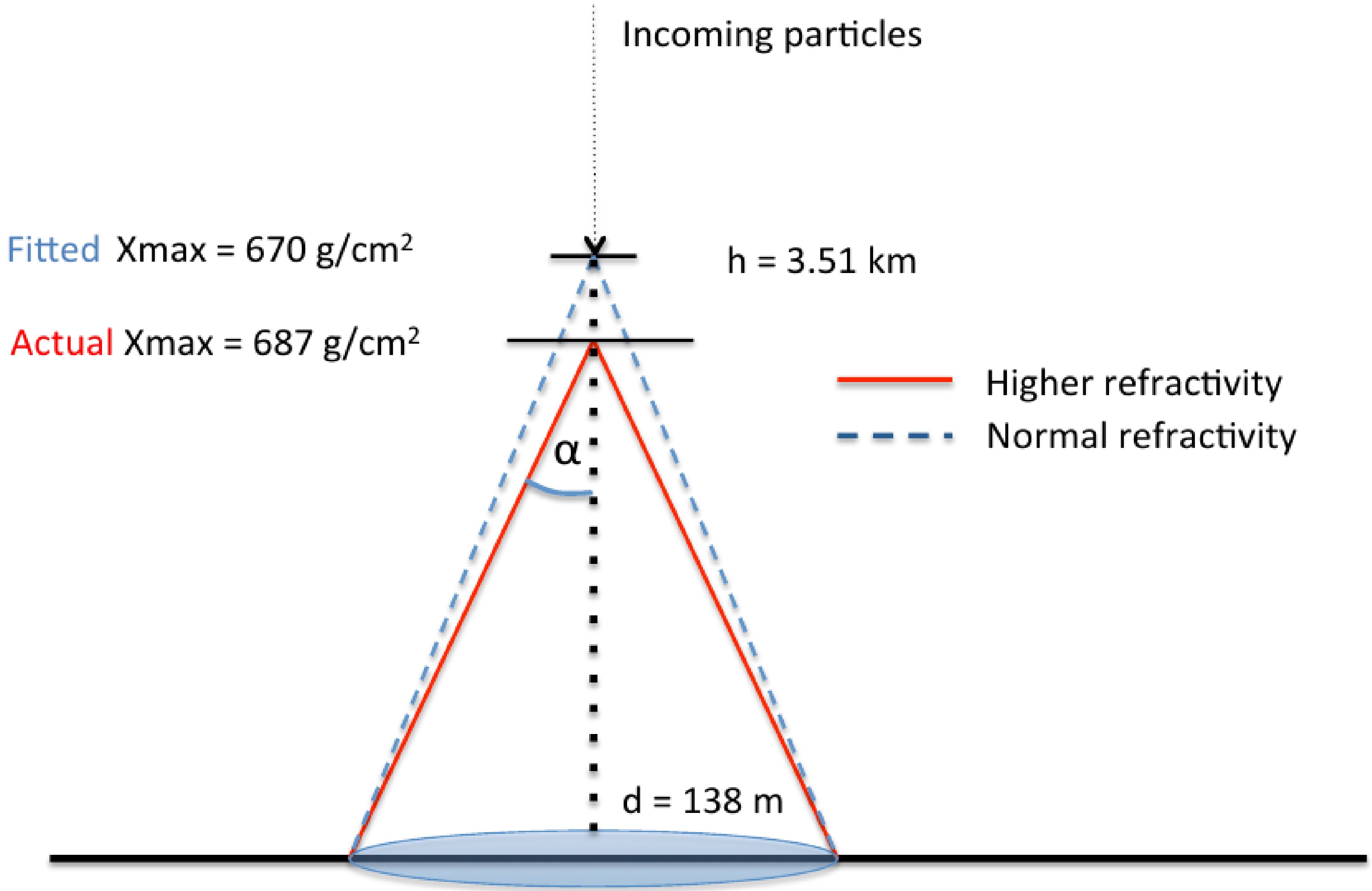
→ More and better data

T. Winchen and S. Buitink 2018,
Under review by Astropart. Phys.

Improved Atmospheric Corrections

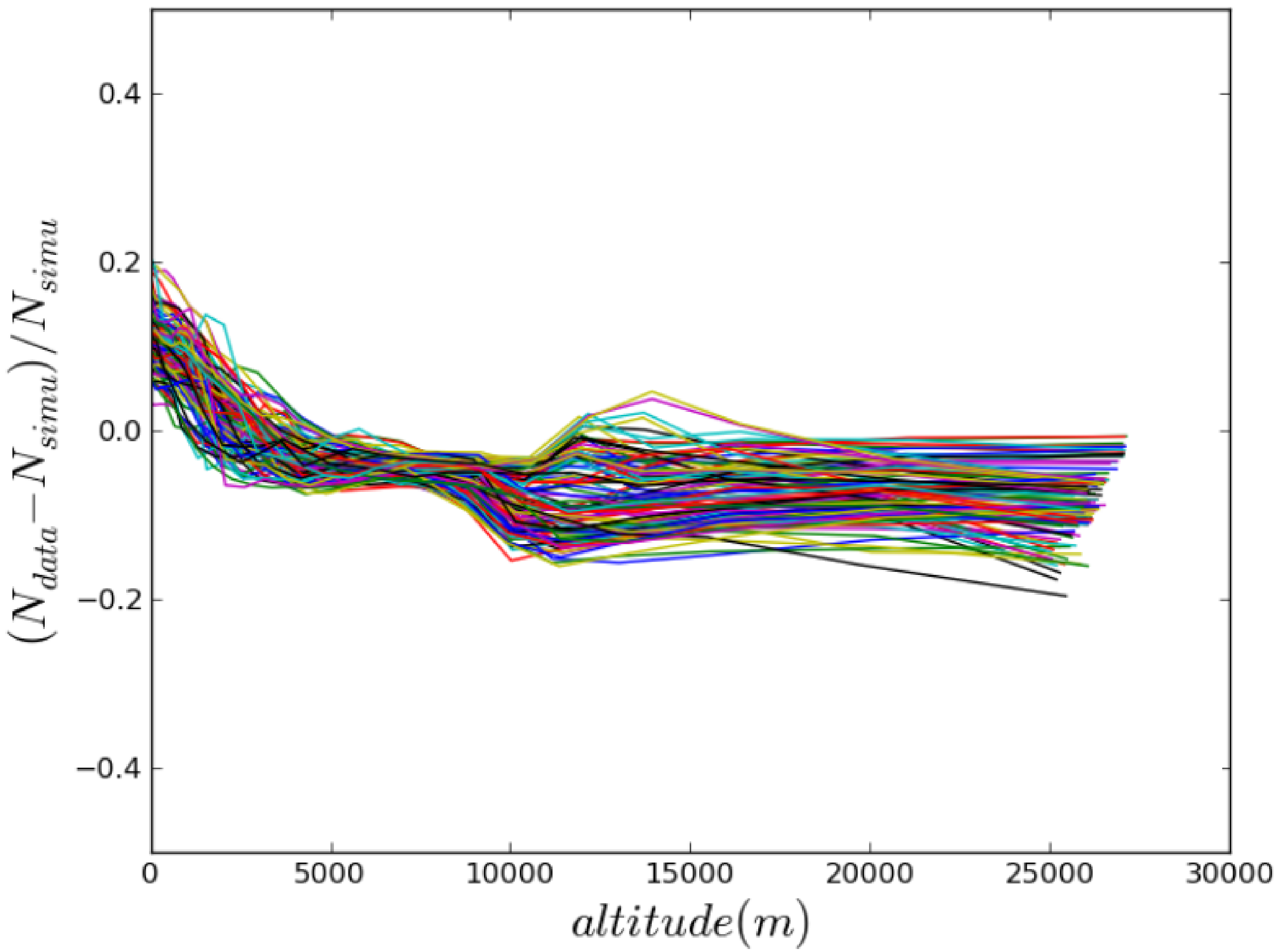
X_{max} measurement depends on index of refraction

Simplified Picture: All radiation from Xmax



A. Corstanje et al. 2017, Astropart. Phys 23-29

Atmosphere Models in Coreas/CORSIKA



- Event – Event variation in refractivity between standard atmosphere and atmospheric data of ~ 3 – 5%
- Systematic uncertainty in Xmax of 10 g/cm^2
- Implemented support for refractivity profiles in Coreas / CORSIKA
- Use data from GDAS in simulations to correct refractivity
- Analysis in progress …

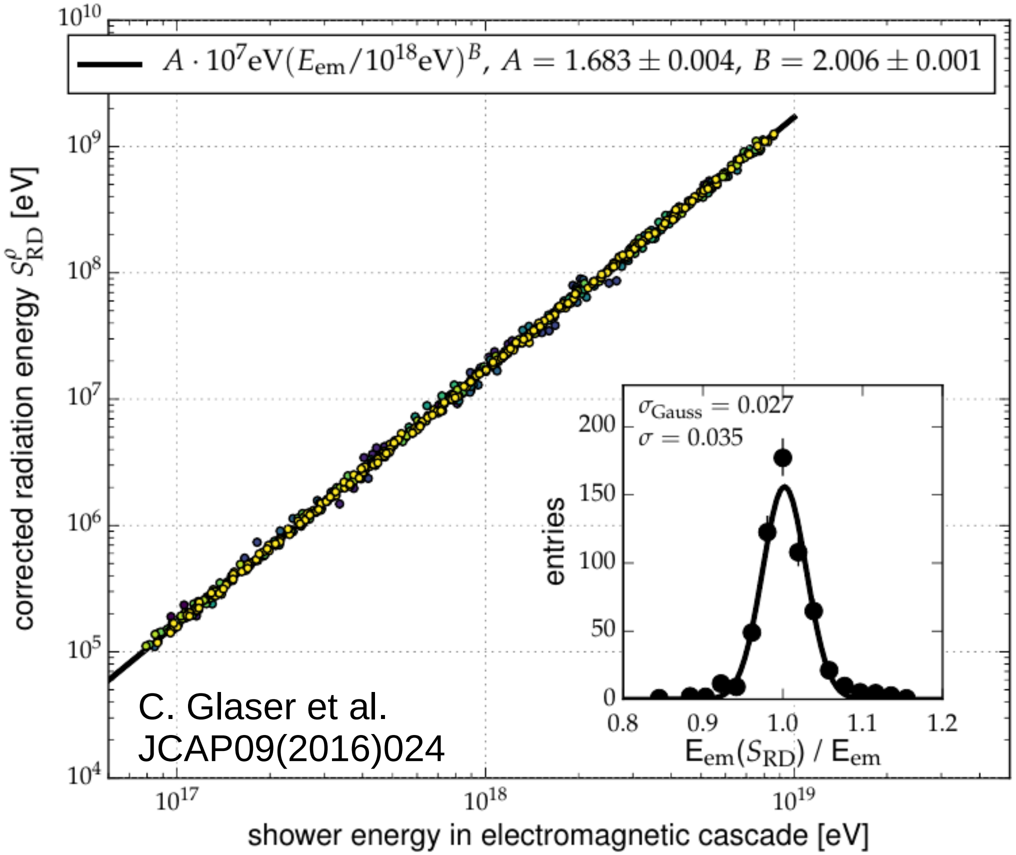
Tool to download GDAS data and create profiles now part of CORSIKA (src/utils/gdastool)

A. Corstanje et al. 2018, In preparation

Radio Only Energy Estimation

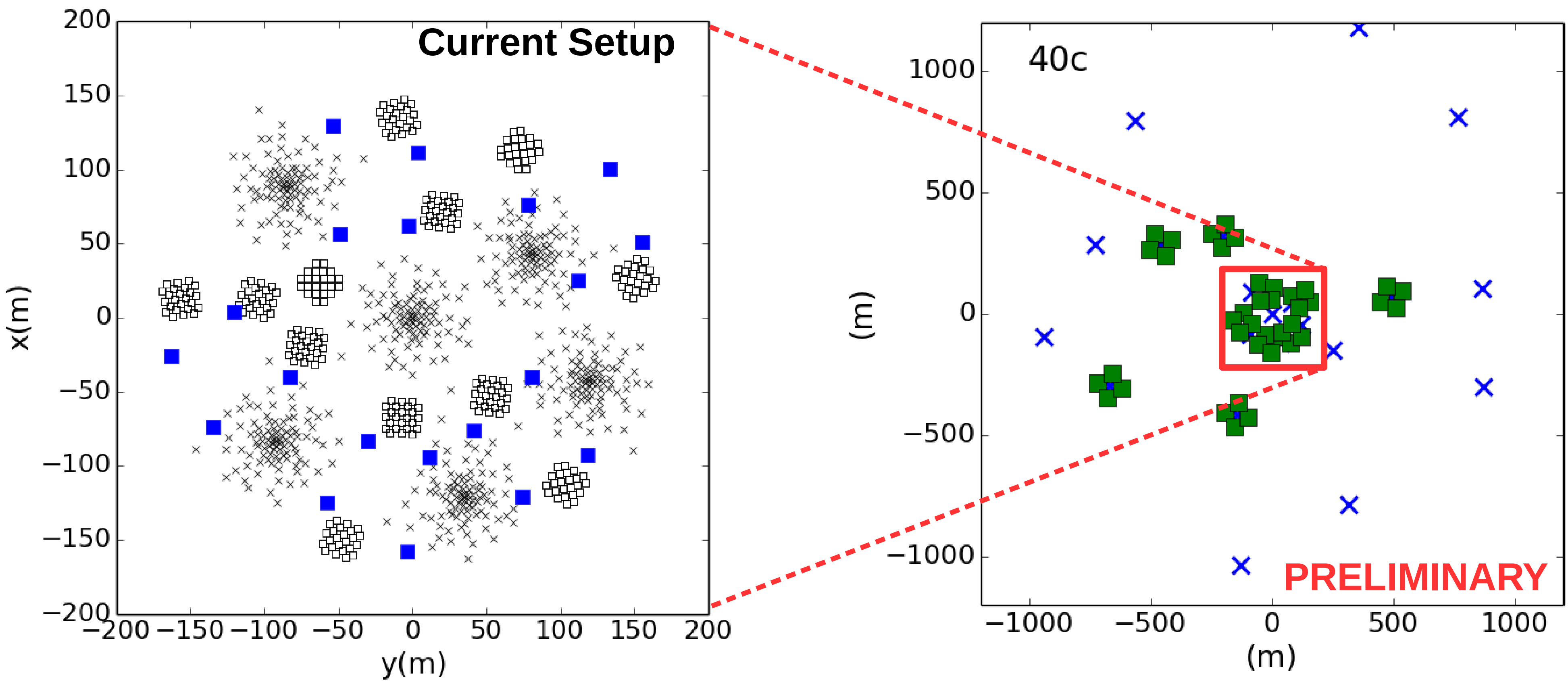
- Particles:
  - 20 Scintillator stations
  - Energy calibration strongly dependent on hadronic interaction models
- Radio:
  - 100 M€ Radio telescope with ~ 50000 Antennas
  - Well understood emission mechanism of radio
  - Direct measurement of energy in electromagnetic cascade

→ **Radio only energy estimation might have lower uncertainties**



P. Mitra et al., in preparation

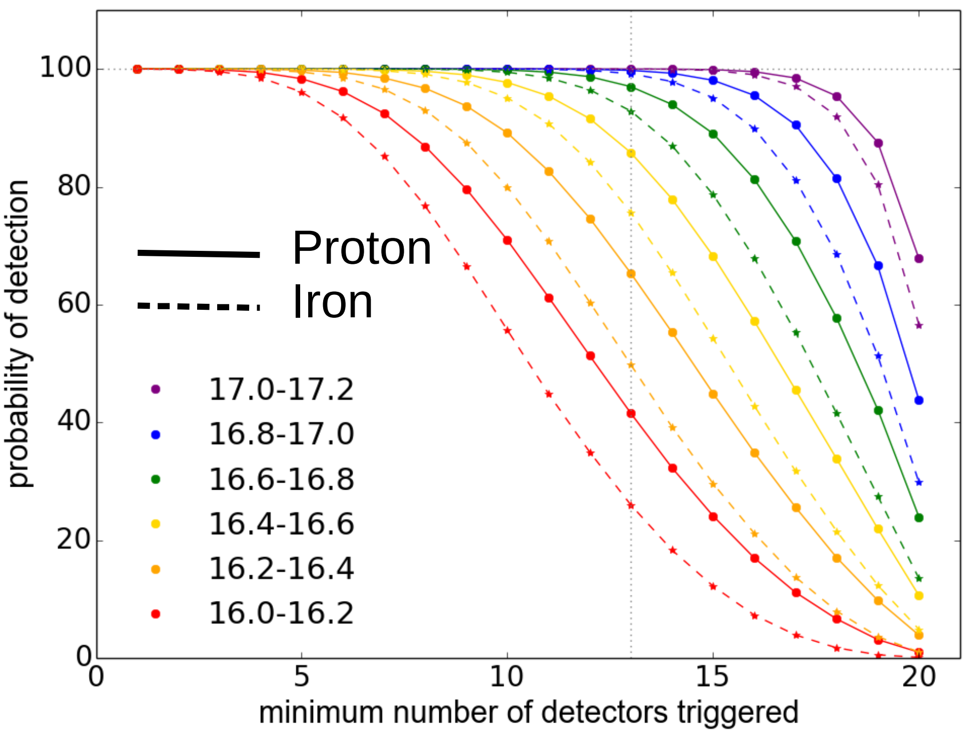
Upgrade LORA Particle Array

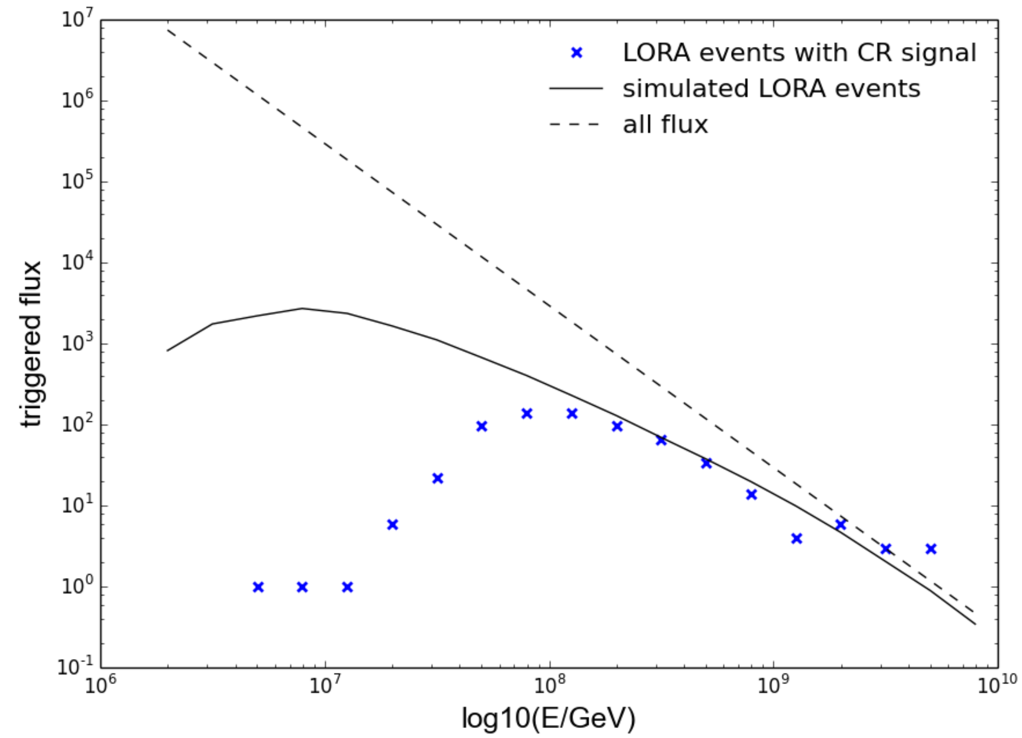


- 20 more Detectors
  - Increase detection rate of high energy events
  - Better showers: contained core, refined trigger, ...

K. Mulrey et al.,
In preparation

Increase Energy Range



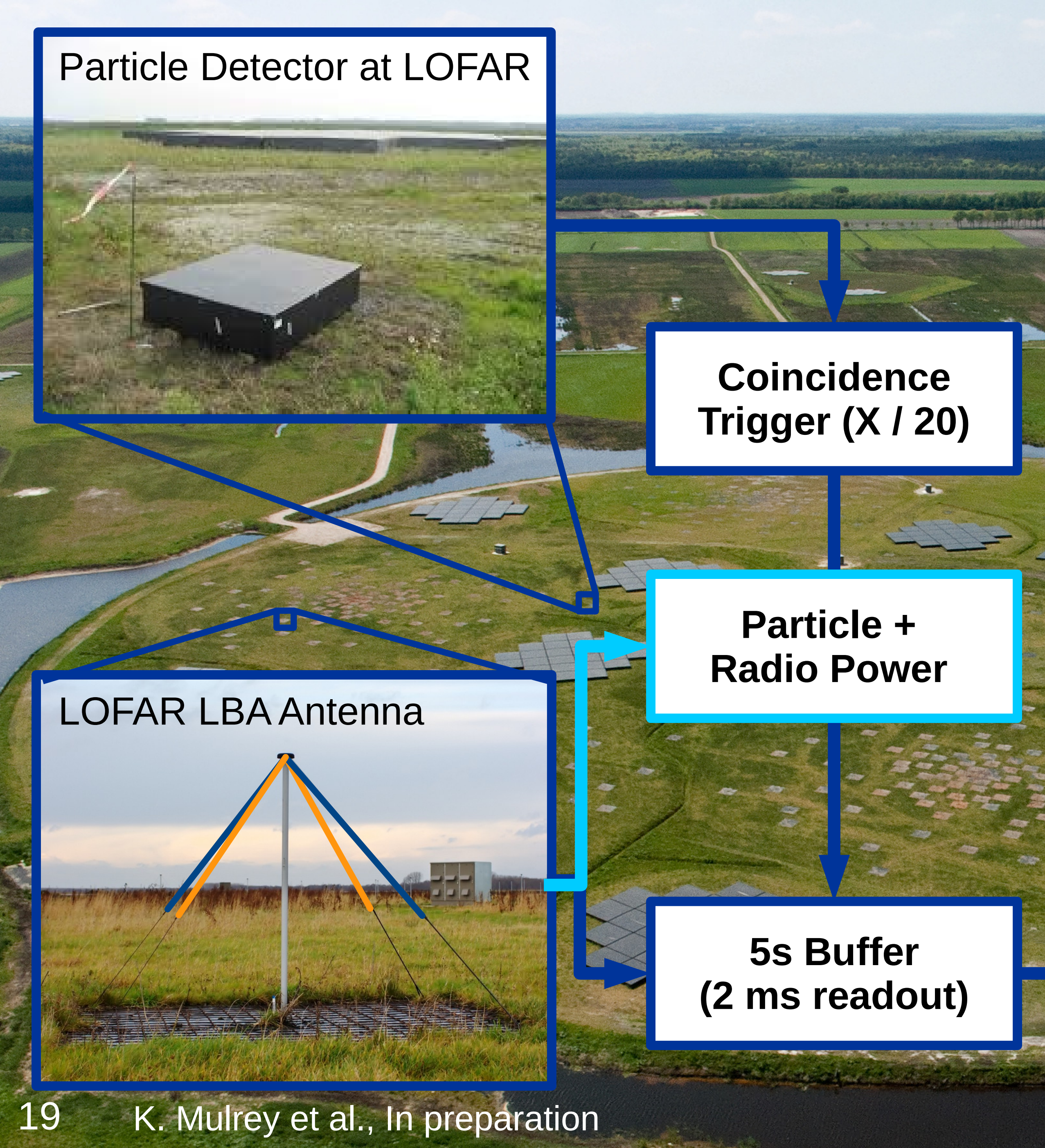


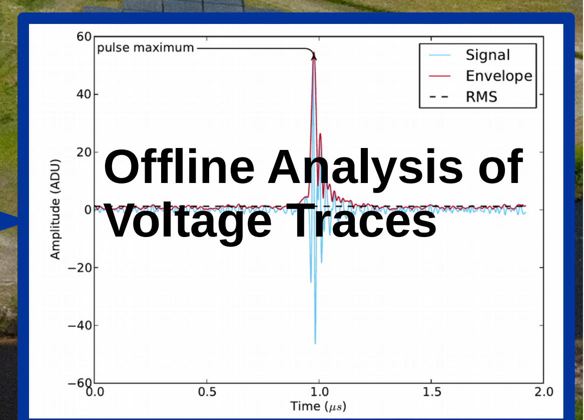
- Trigger rate preferably limited to ~1 per hour to not saturate available bandwidth – Require high number of stations
- Composition bias at low energies
- Low radio signal in low energy showers due to core position / shower direction

K. Mulrey et al., In preparation

Particle + Radio Hybrid Trigger

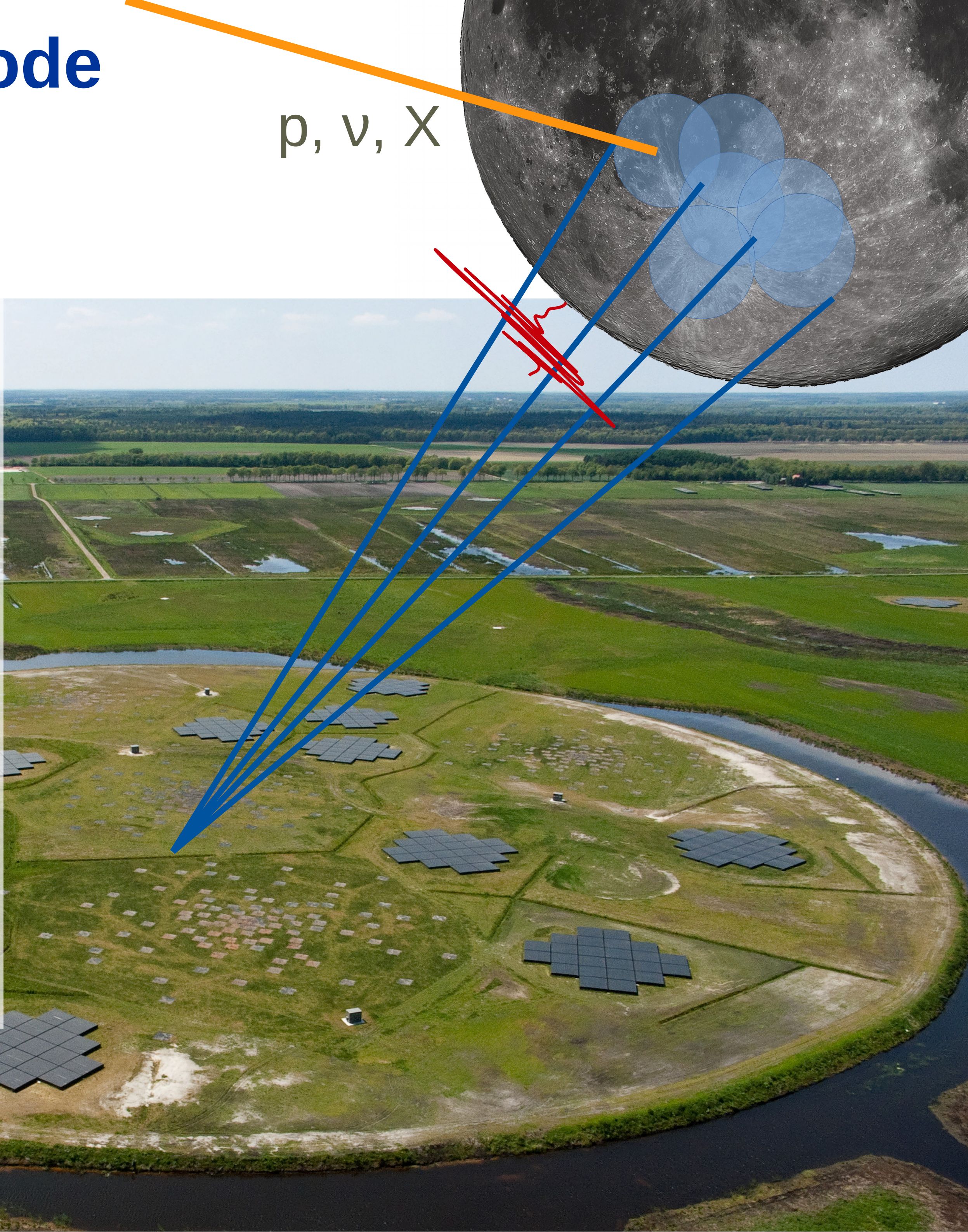
- Many low energy shower with particles but no radio signal
- Hybrid trigger: Only read out if high power in radio
- Use diagnosis channel on Antenna boards that reports integrated power





K. Mulrey et al., In preparation

Lunar Detection Mode

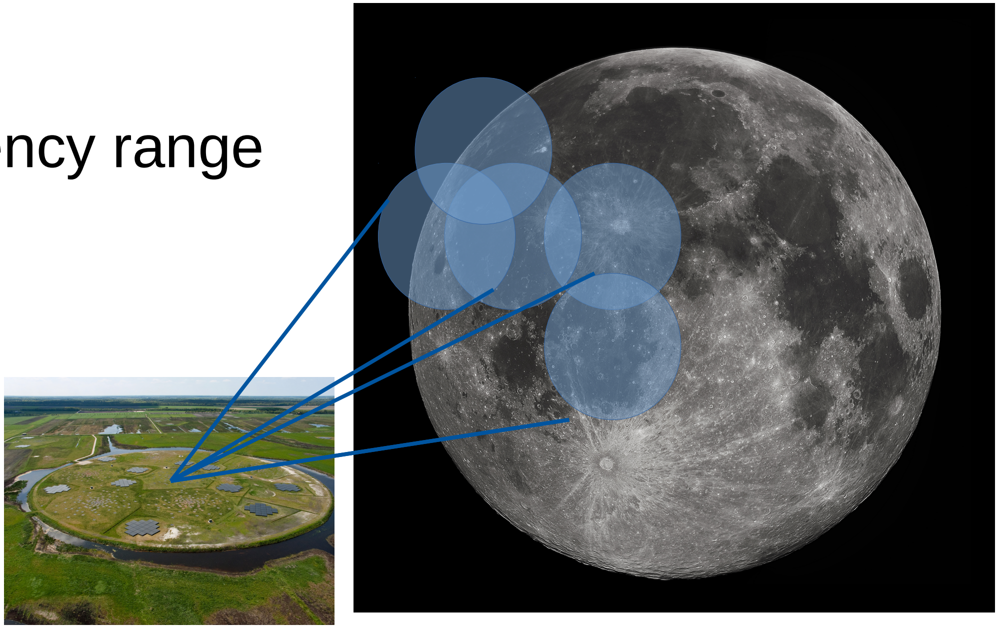


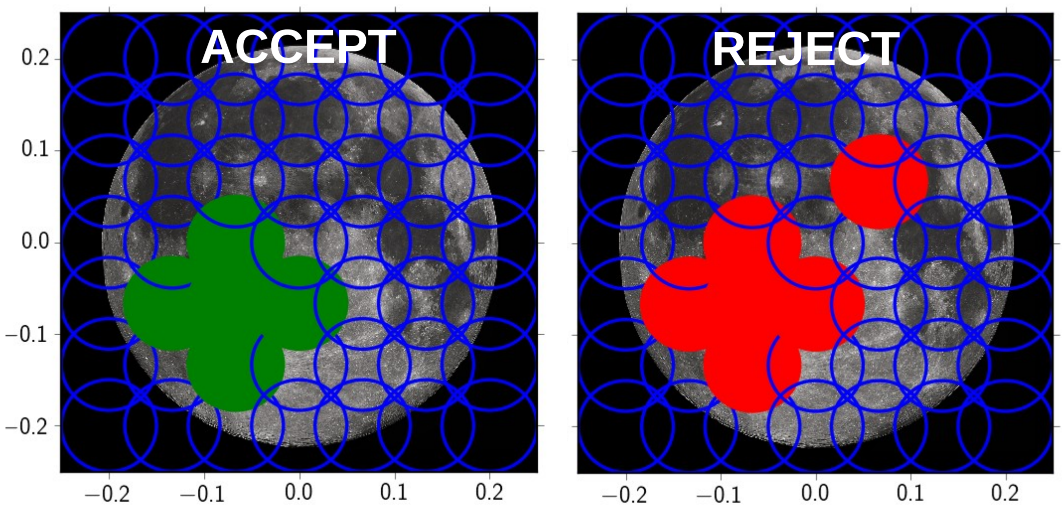
- Using Moon proposed by

  Askaryan 1962
- Several previous searches, e.g.
  - NuMoon, GLUE, RESUN, LUNASKA, ...
- LOFAR potentially most sensitive instrument
  - Frequency Range
  - Collective Area
  - Moon Coverage

Observation Strategy

- HBA Antennas have optimal frequency range
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to check lunar origin





Challenge:

Realtime data processing of beamformed data with ns precision:

- DRAGNET: 96 High-End GPUs (J. Hessels et al, pulsar search)
- Use buffered traces for analysis

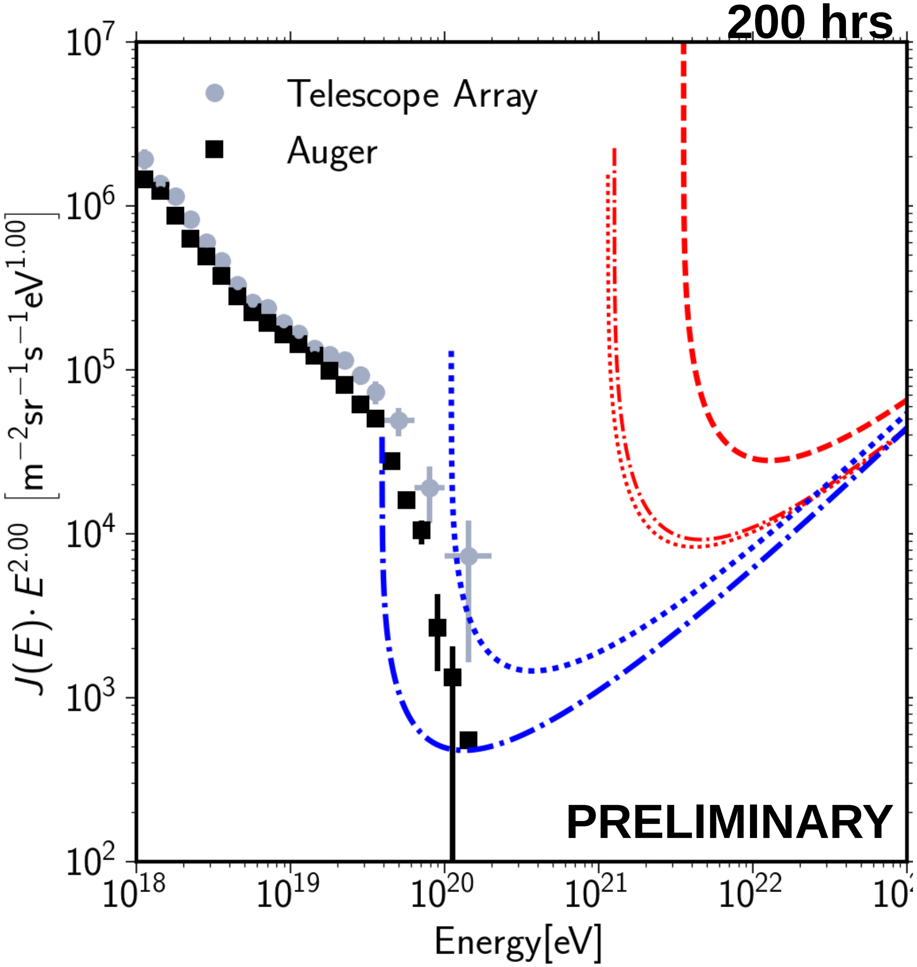
Prototype of online system ready, simulations in progress!

First Data Expected in 2018!

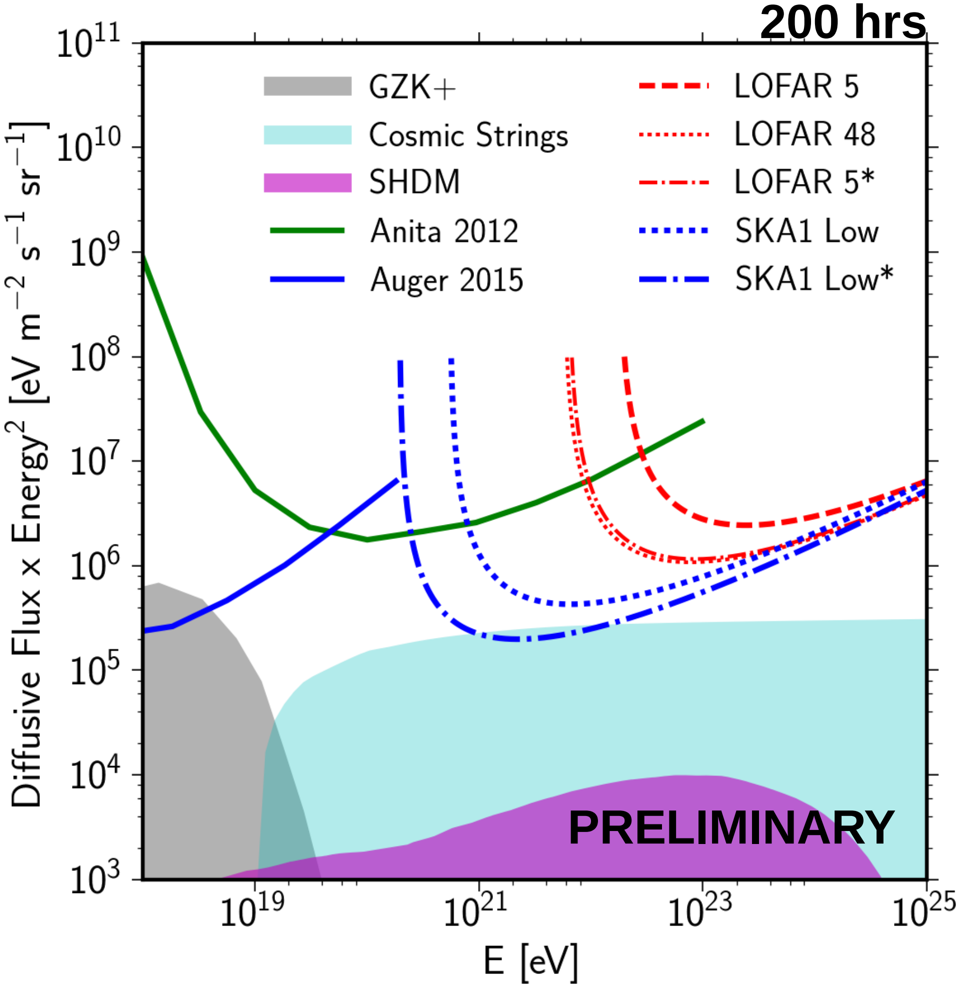
T. Winchen et al. 2018, In preparation

Expected Limits

COSMIC RAYS



NEUTRINOS



Very preliminary
Limits based on semi-analytical calculation optimized for GHz frequencies:

- Underestimates sensitivity at MHz
- Over simplified trigger

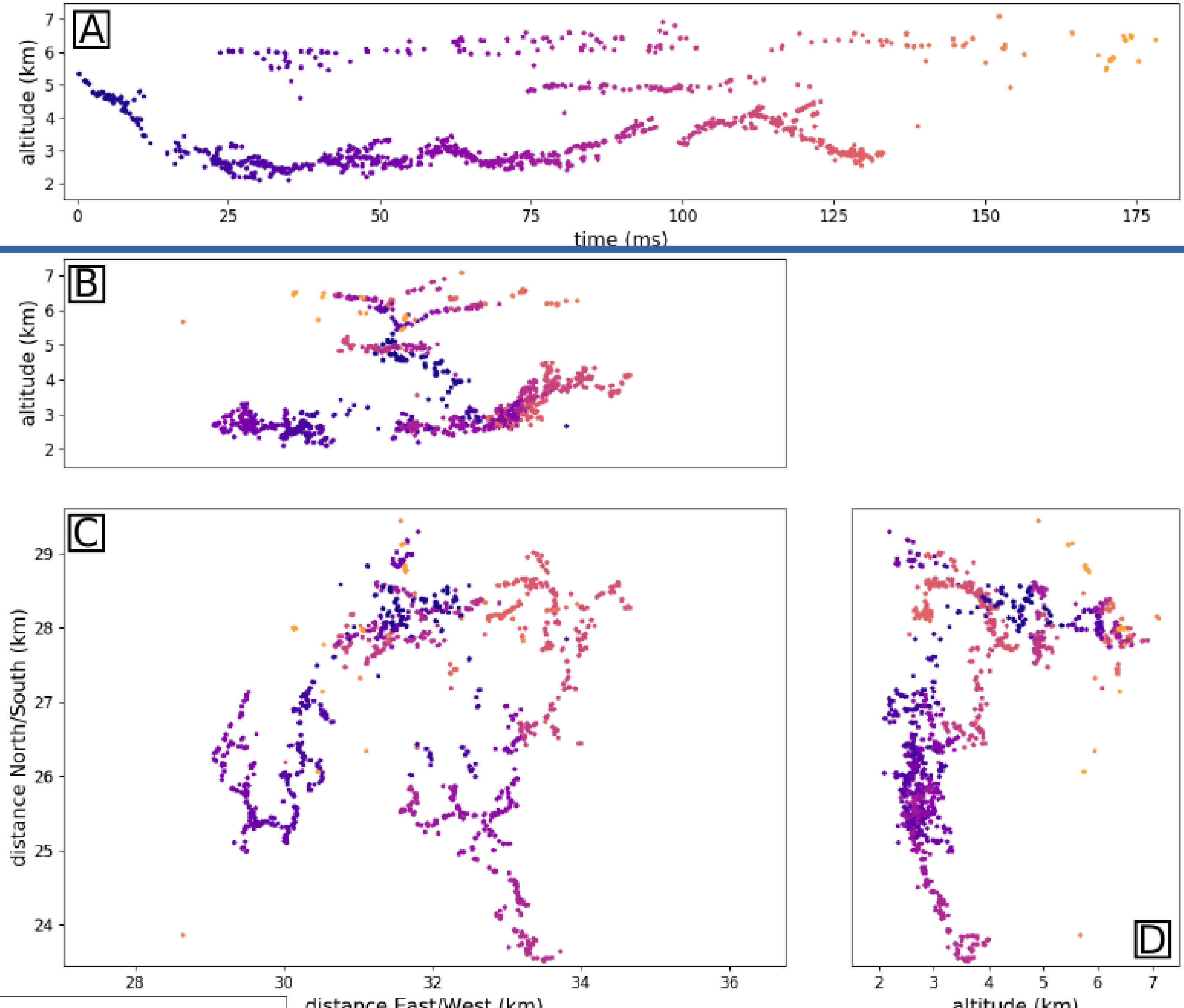
→ **Full simulations in progress**

Cosmic Rays detectable by LUNAR Observations with SKA

Beyond Cosmic Rays: Lightning Physics

Time

Space



LOFAR is most sensitive lightning mapping array!
B. Hare et al. 2018, Under review by Journal of Geophysical Research

LOFAR can measure electric fields in thunderstorm clouds!
T.N.G. Trinh et al.2018, in preparation

Conclusions

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- LOFAR measures composition and energy around 10^{17} eV
  → Ankle and second light component
- Future:
  - Higher Precision
  - More data + increased energy range
  - Lunar observation mode
- Technology developed for Cosmic Rays enables research on lightning

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