Radio Telescopes and Ultra-High Energy Cosmic Rays

With many thanks to LOFAR CRKSP and SKA SWG members for figures and graphics

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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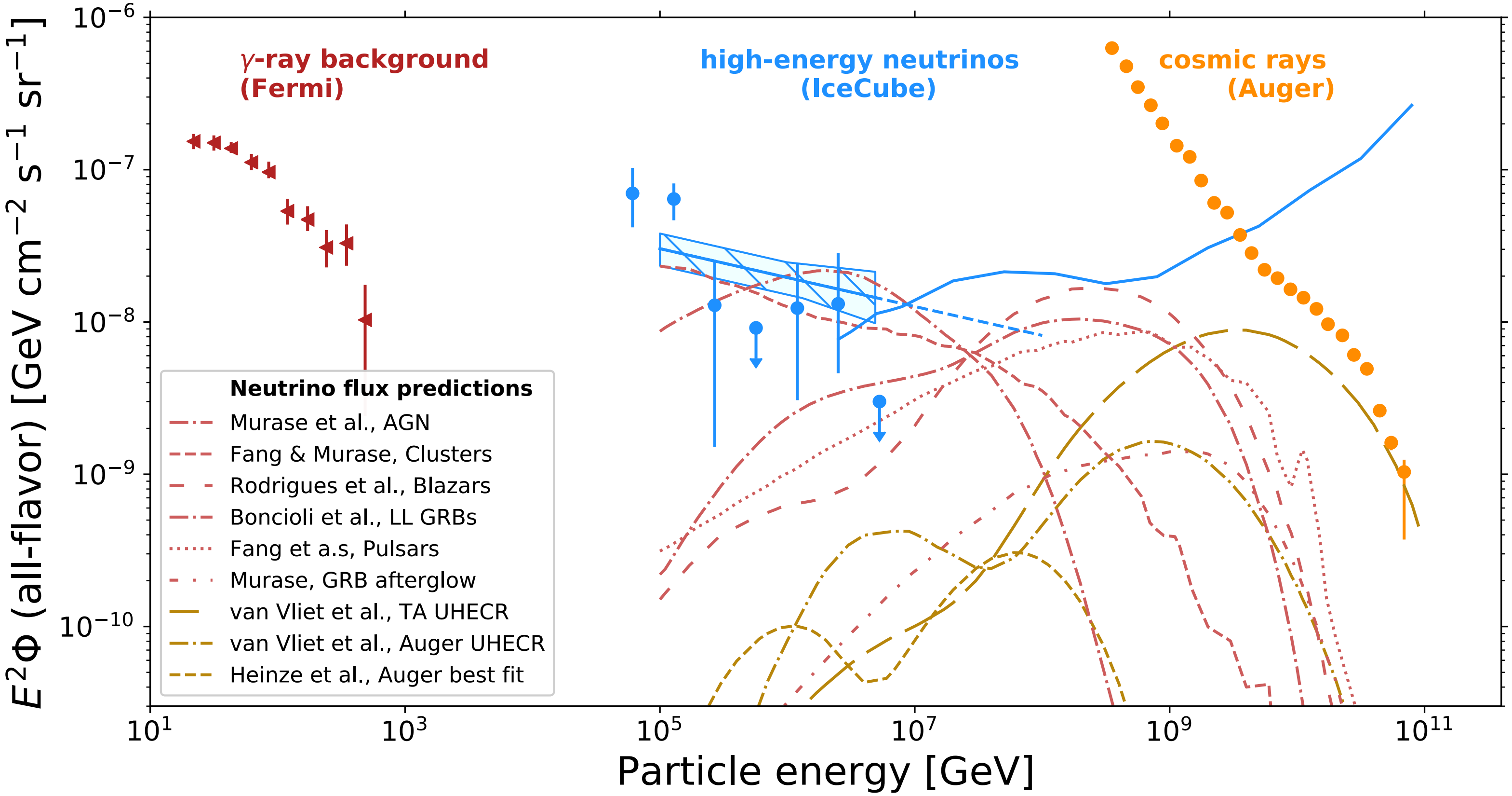
ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

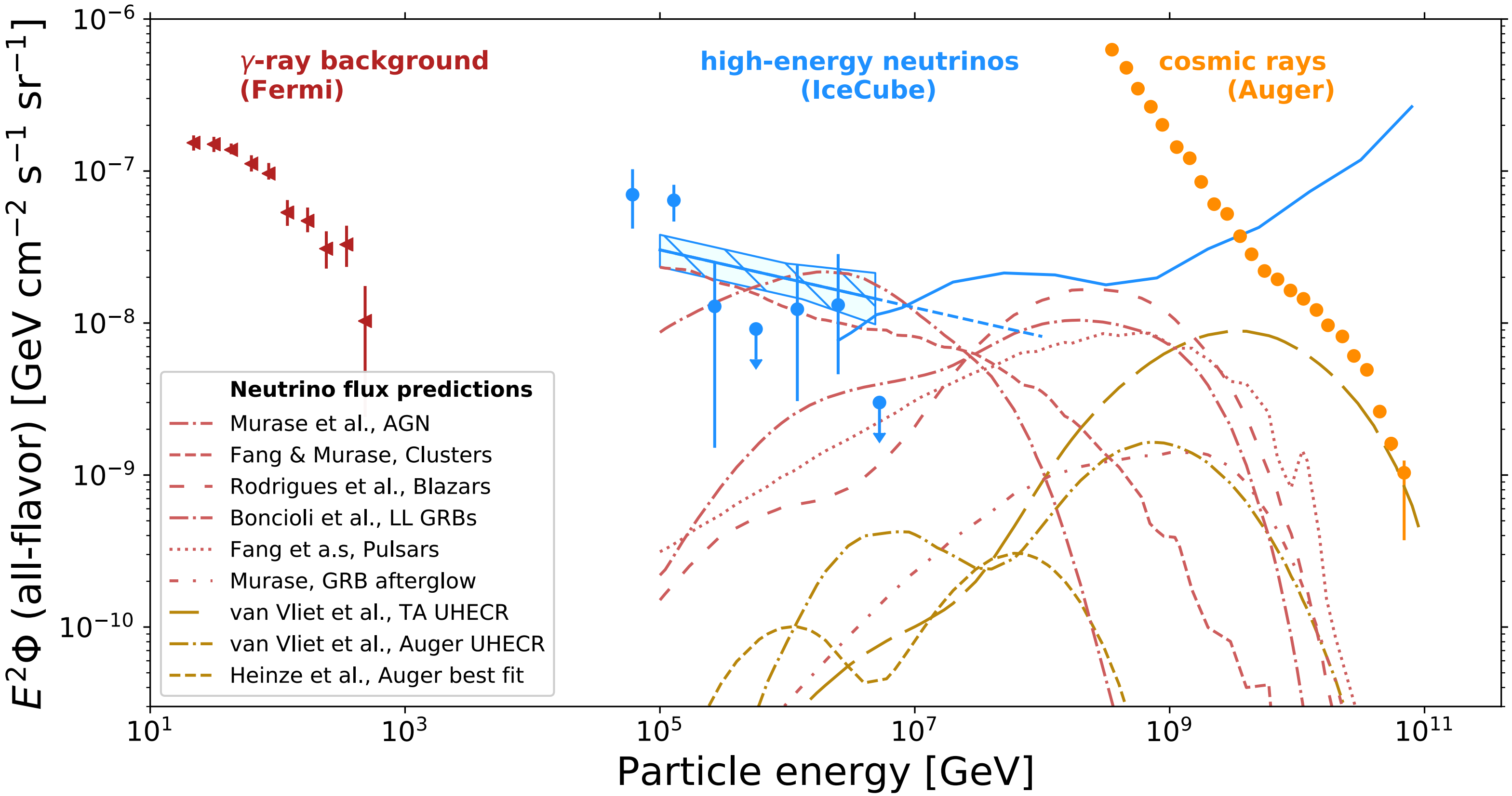
DESY.

Scientific motivation

Where are ultra-high energy cosmic rays from?



How to address this?



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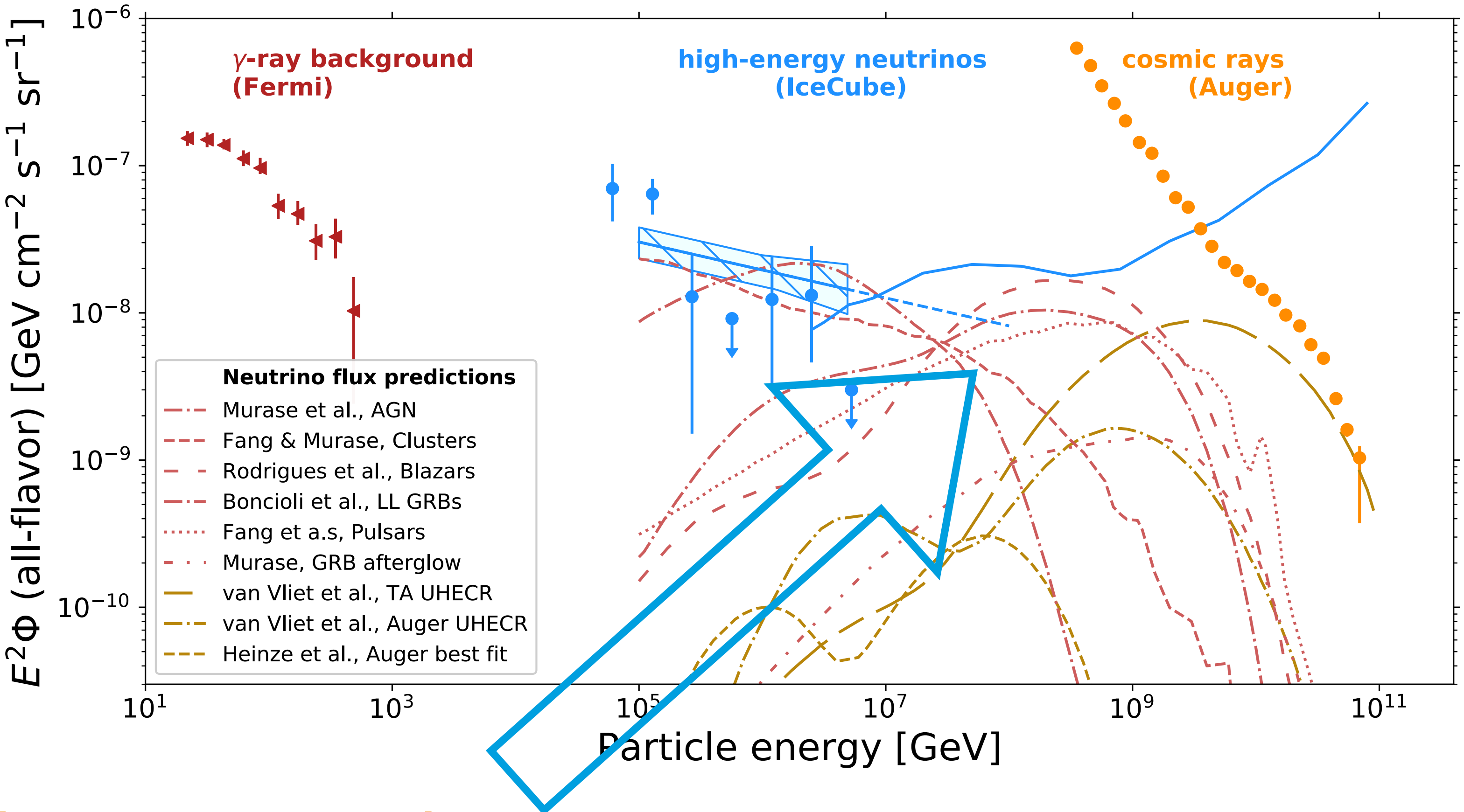
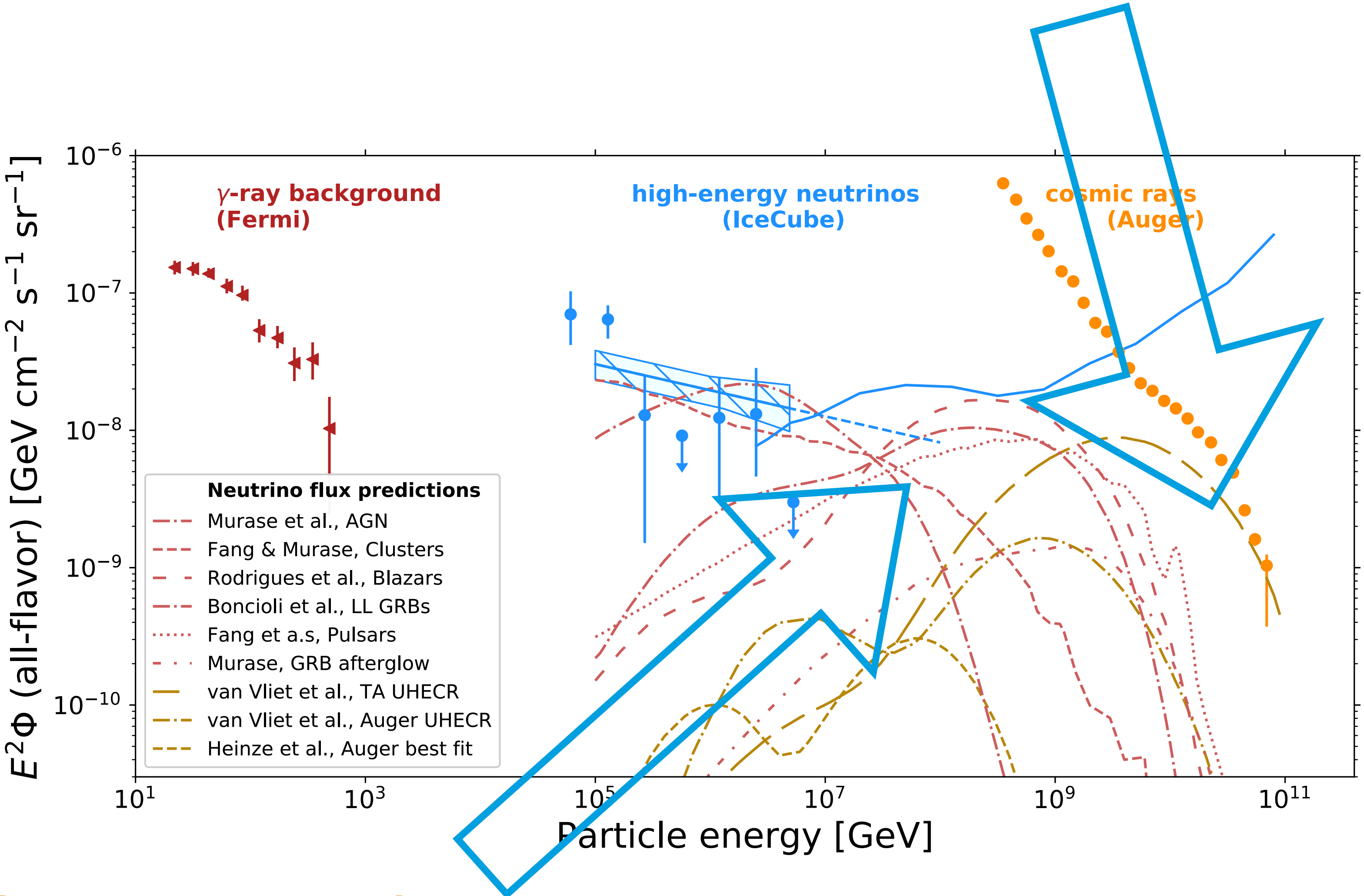


Measure more neutrinos

How to address this?

Measure cosmic rays with better precision

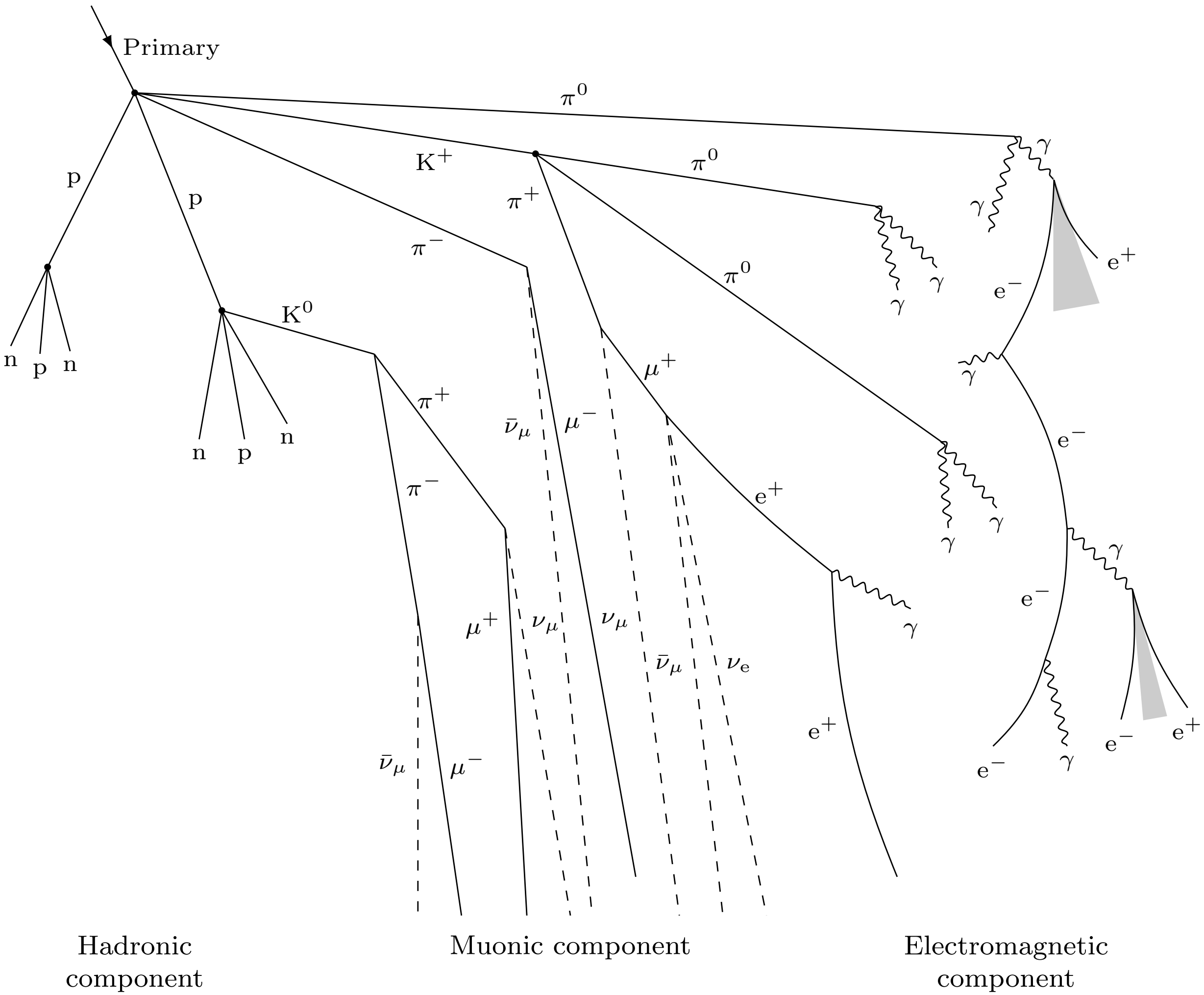


Measure more neutrinos

Radio signals

A theoretical introduction

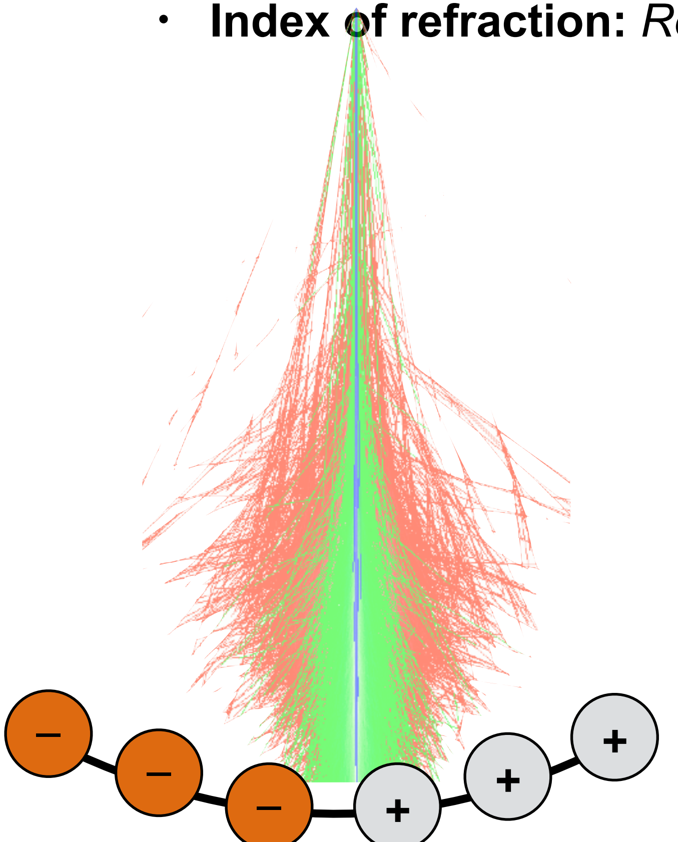
- Highly energetic particles interact with medium and create shower of secondary particles
- Generally one distinguishes hadronic and electromagnetic showers
- Hadronic showers always have a electromagnetic component



Radio emission of showers

The story of the two effects and the refractive index

- Radio emission of showers can be explained from first principles and three aspects
  - **Magnetic field:** *Geomagnetic field, Lorentz-force*
  - **Charge imbalance:** *Particle Physics processes*
  - **Index of refraction:** *Relativistic compression*



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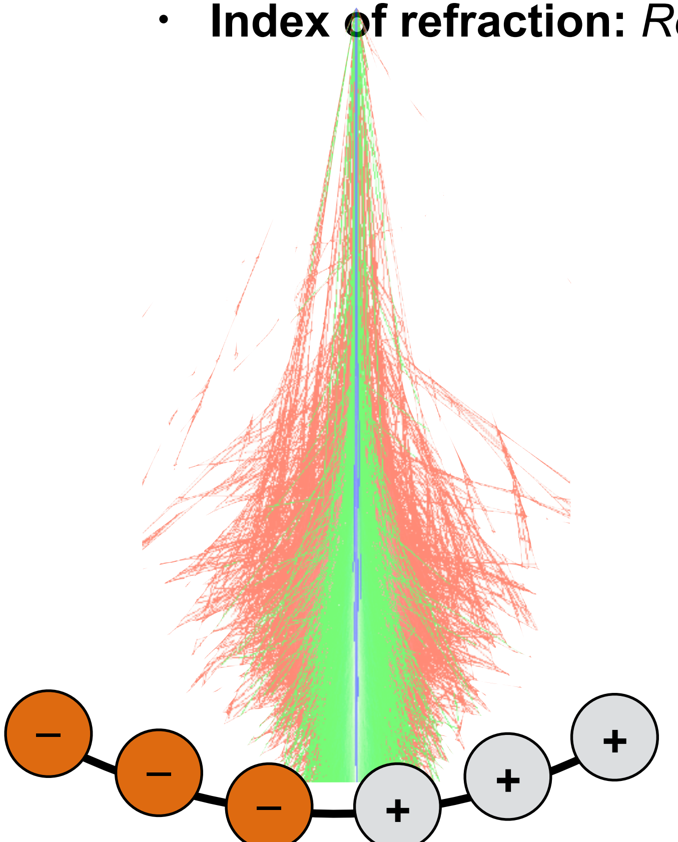

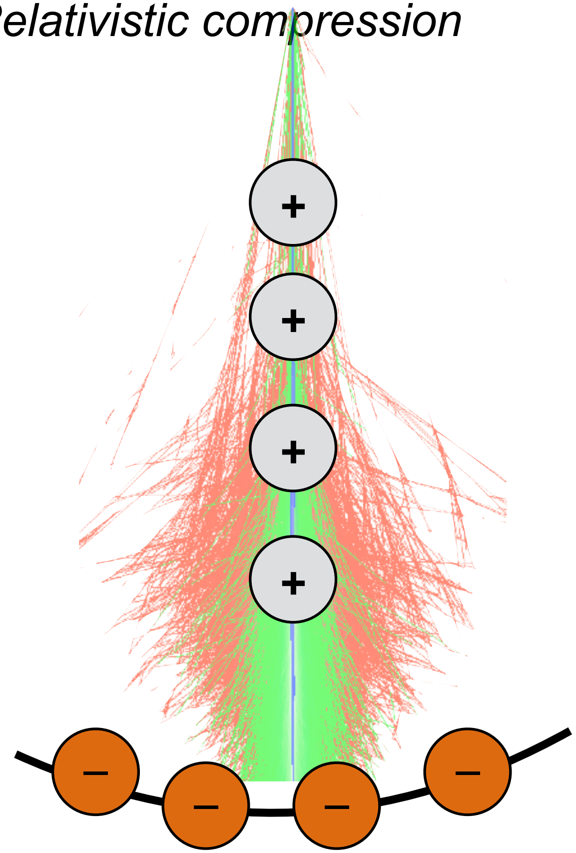

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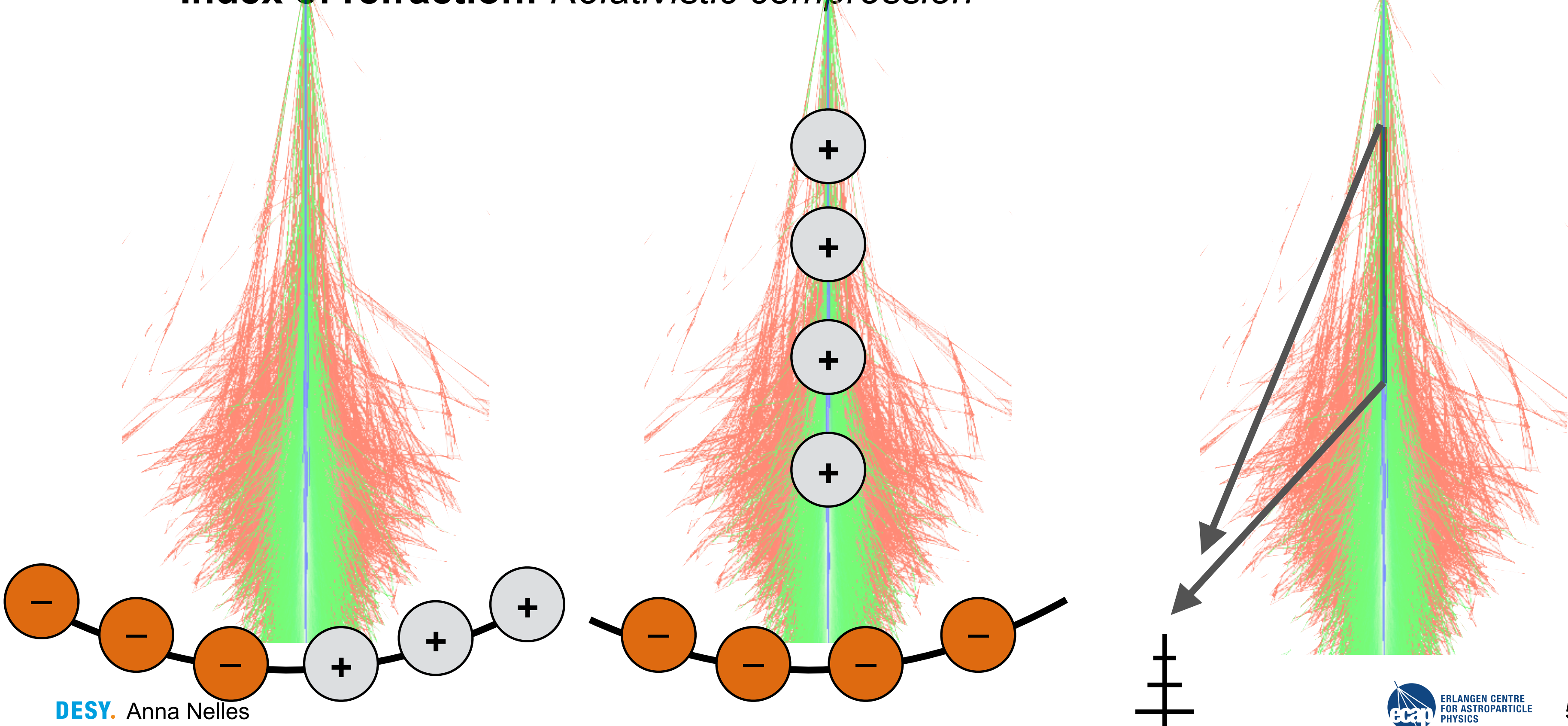
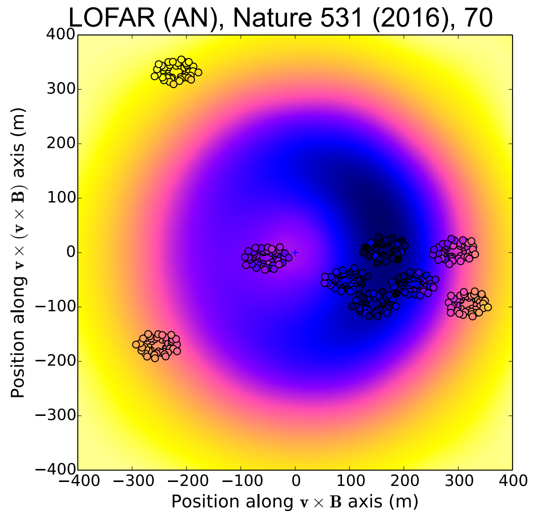


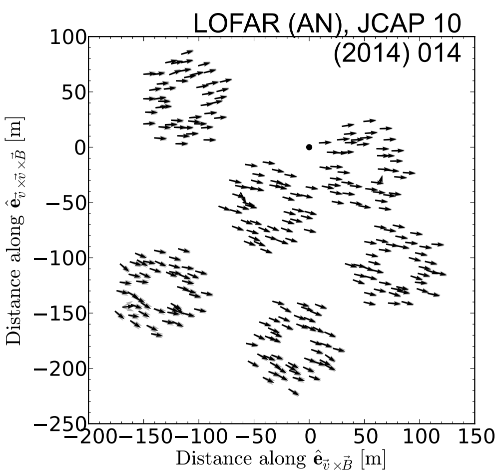
Are we really sure that we have understood this?

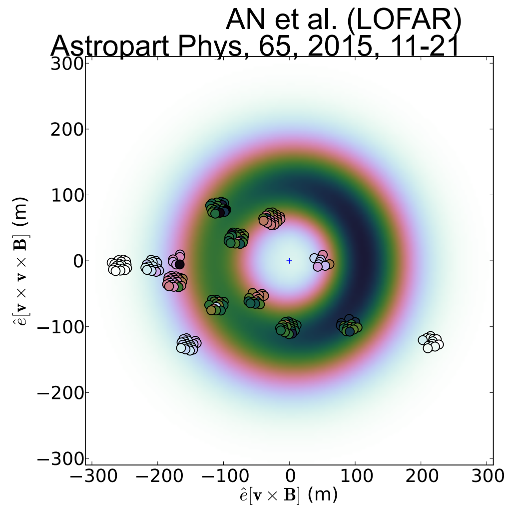
Quite a lot of experimental evidence:

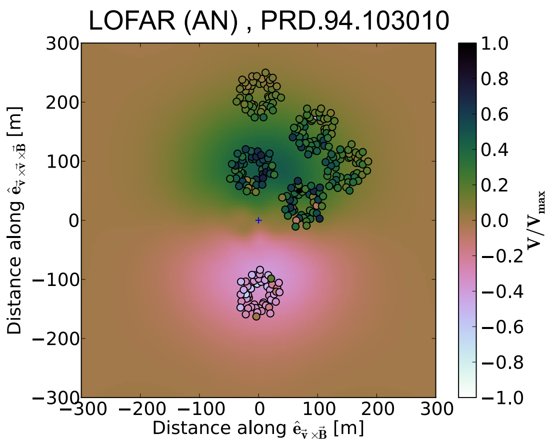
LOFAR has been THE instrument for this

- Signal distribution ✅
- Signal amplitude ✅
- Signal polarization ✅
- Signal frequency spectrum ✅
- Dependence on magnetic field ✅





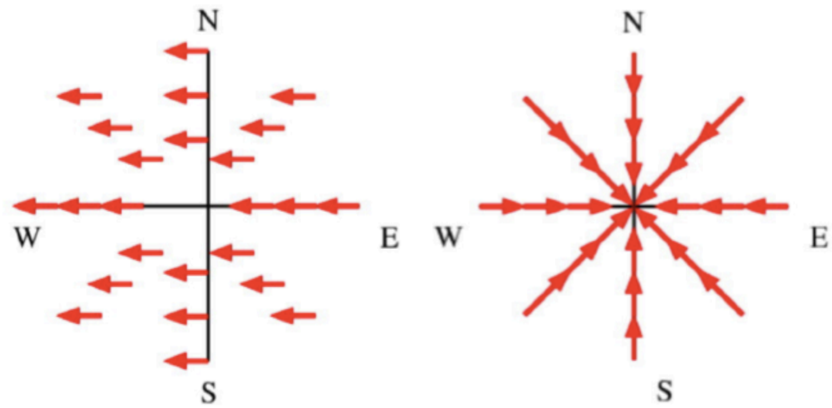




Radio emission of showers

How do we know this?

- The key evidence: **Polarization**
  - **Geomagnetic effect:** *Lorentz-force, polarization orthogonal to shower axis and magnetic field*
  - **Askaryan effect:** *Polarization points towards shower axis*



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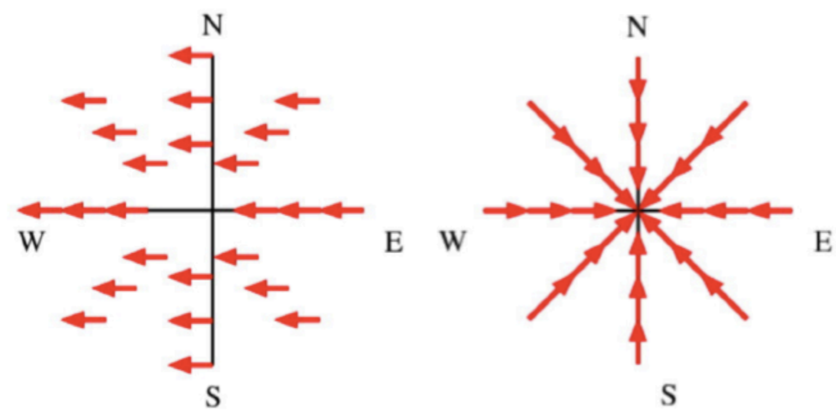
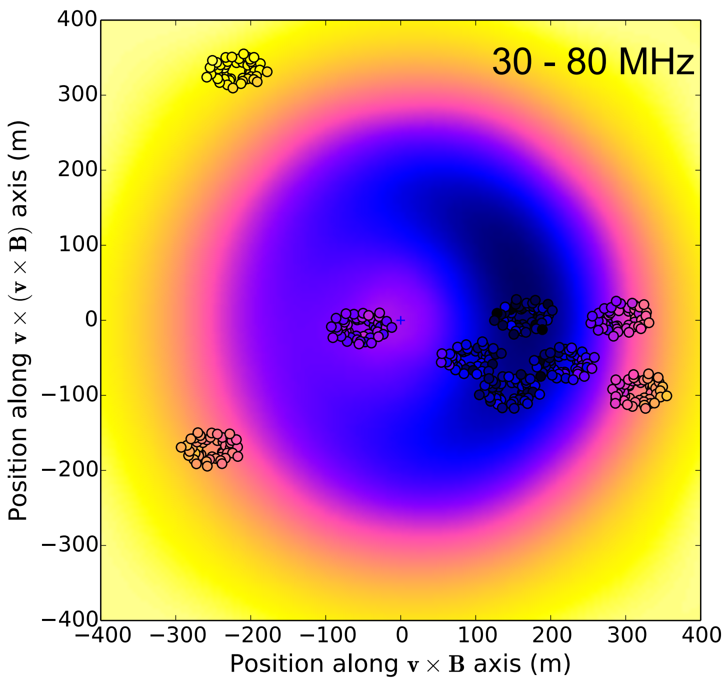
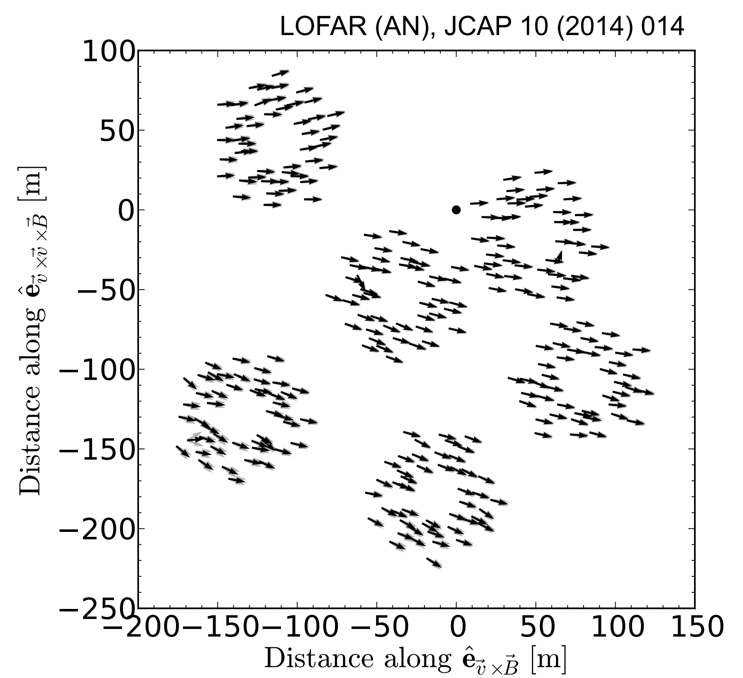




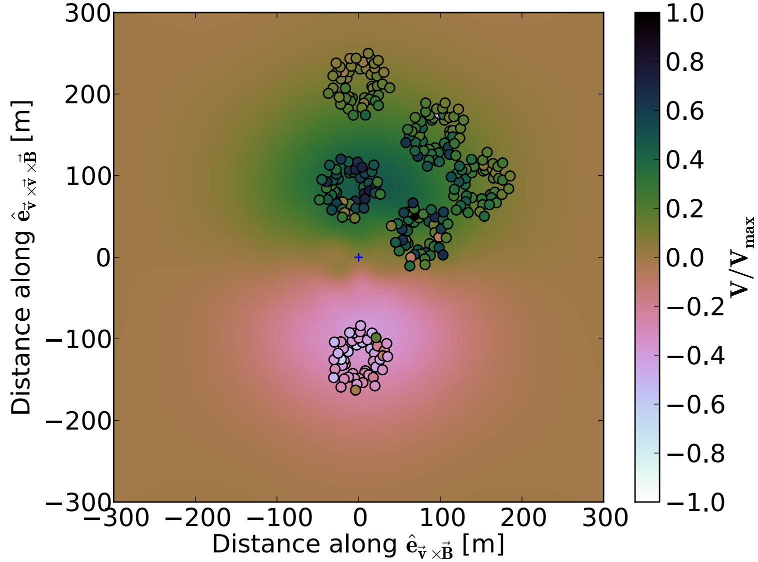


Radio emission of showers

How do we know this?

- The key evidence: Polarization
  - The **two processes** stem from slightly different heights
  - Time difference = phase offset between two emission components
  - Leads to **circular polarization**

LOFAR (AN) , Phys. Rev. D.94.103010



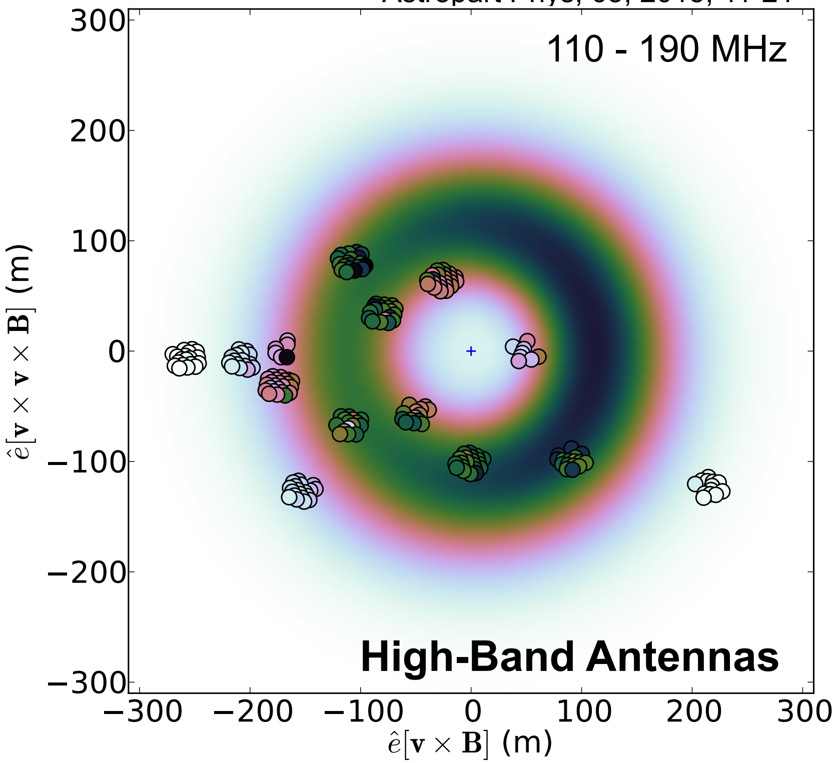
- Emission is due to **both geomagnetic emission** (dominant in air) and **Askaryan emission**
- Geosynchrotron radiation is a correction of < 1% to these effects

Radio emission of showers

There is also a Cherenkov ring but not Cherenkov emission

- The emission is only strong if it arrives coherently (at the same time for all frequencies, high frequencies more pronounced effect)
- At the Cherenkov angle, an enhancement is seen, in air this is very close to the shower axis
- Same effect for showers in ice, but here Cherekov angle ~ 52 degrees, so it looks much more like “Cherenkov radiation”, but it is not
- If one had the same shower development in vacuum, it would still radiate

A.Nelles et al. (LOFAR)
Astropart Phys, 65, 2015, 11-21



We know all this from air showers

Are air showers still interesting?

- Air shower measurements were used to:
  - Provide the proof-of-principle for radio detection of particle showers
  - Confirm the emission mechanisms down to subtle features, agreement with Monte Carlo simulations astonishingly good
  - Develop methods of how to reconstruct data, remove the contribution of noise, understand antenna theory for impulsive events, …
- But a technique is only useful, if it can also contribute to advancing the astroparticle science case

Cosmic-ray energy spectrum

Air shower physics

Particle Physics

Acceleration

Sources of UHECR

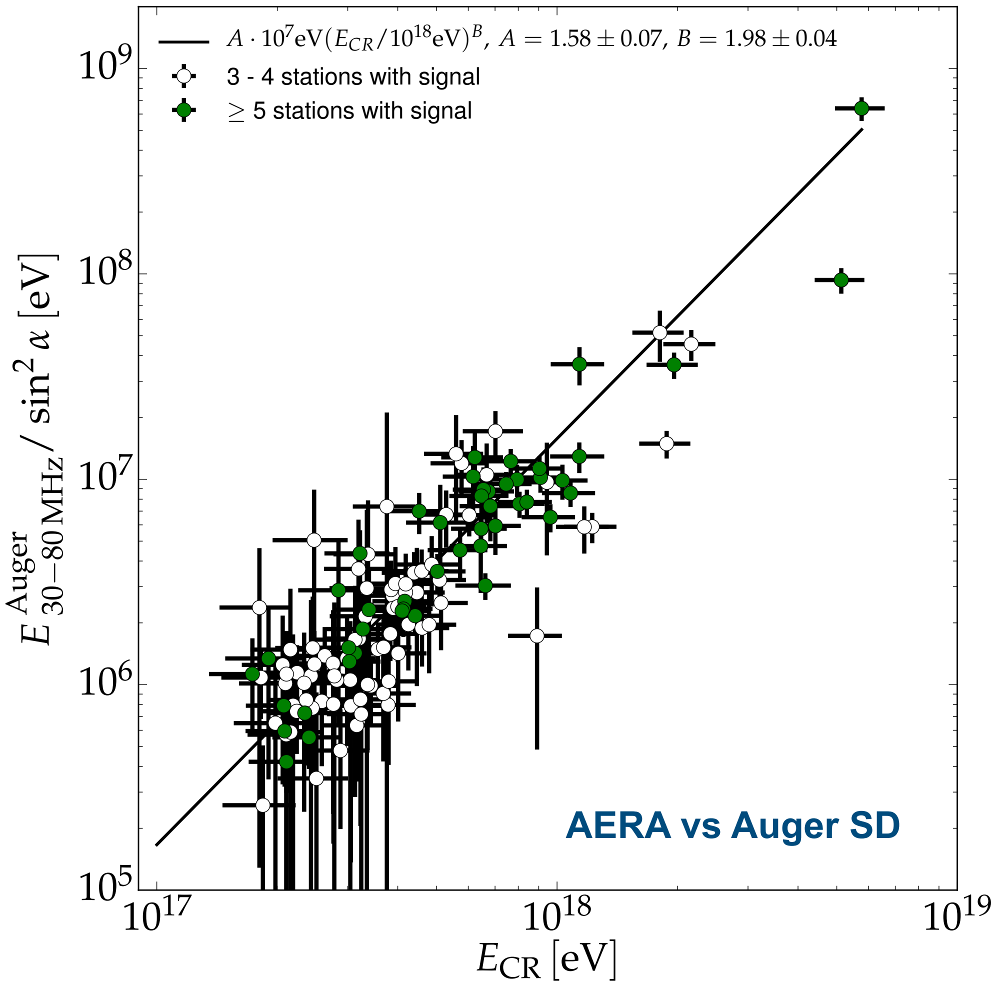
Cosmic-ray composition

Propagation

Detecting radio emission of air showers

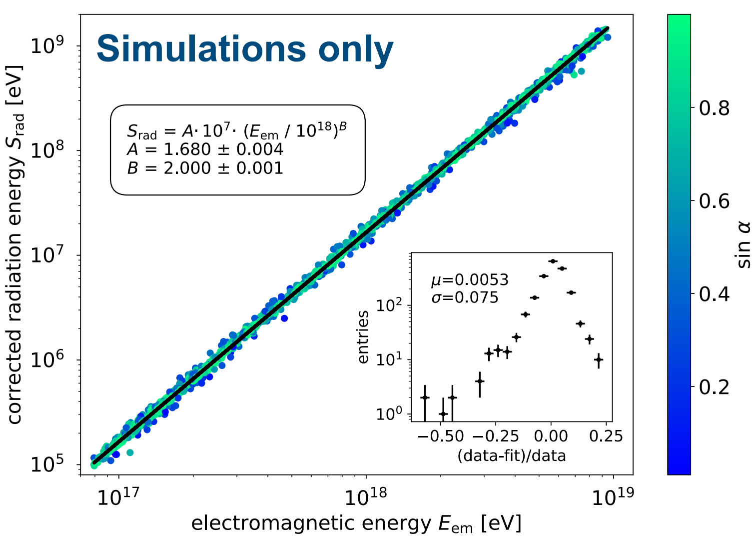
Energy estimation of cosmic rays

A. Aab et al. (AN), PRL 116 (2016) 24, 241101



- Radio detection provides and excellent **energy estimator**
- Calculation from first principles
- Very little systematic uncertainties (< 5%) in method

M. Gottowik et al. Astropart. Phys. 103 (2018) 87



Detecting radio emission of air showers

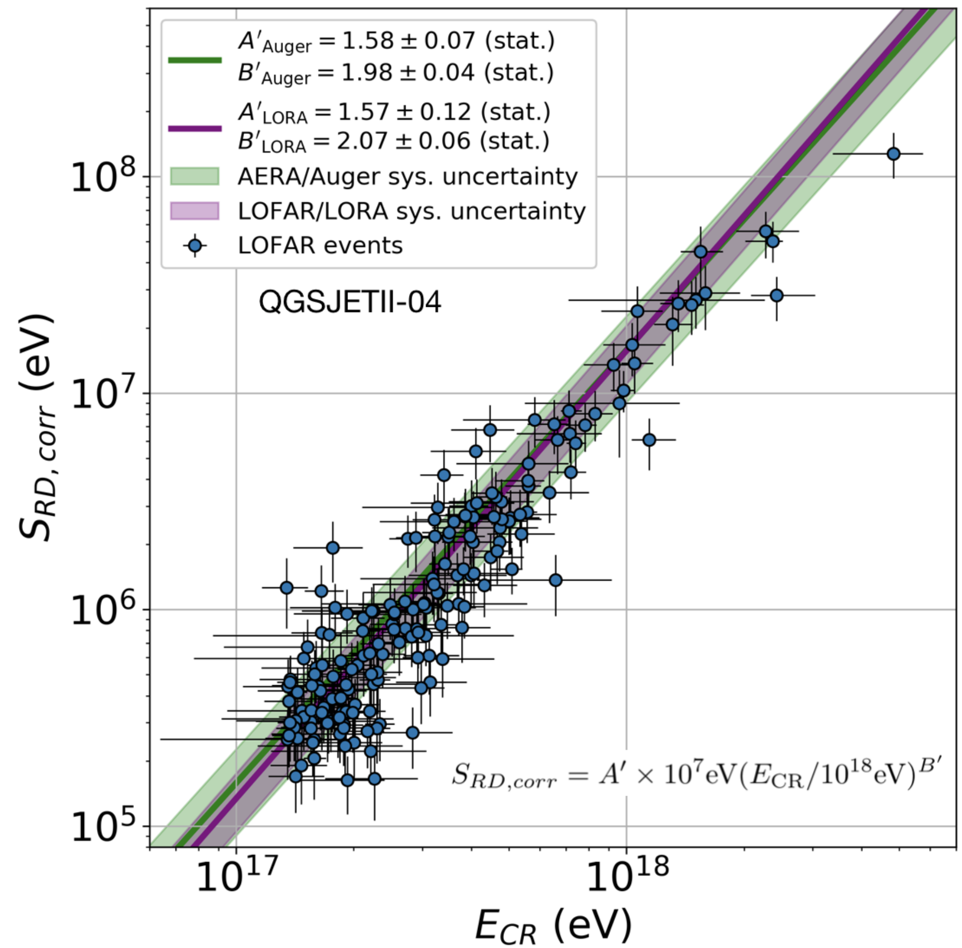
Energy estimation of cosmic rays

- **A radio energy estimate could reduce systematic uncertainties between observatories**

- Long standing issue in interpreting cosmic-ray data between observatories:

  Remove ad-hoc scaling, which has been impacting theory

K.Mulrey et al. (AN) *JCAP* **2020** 017

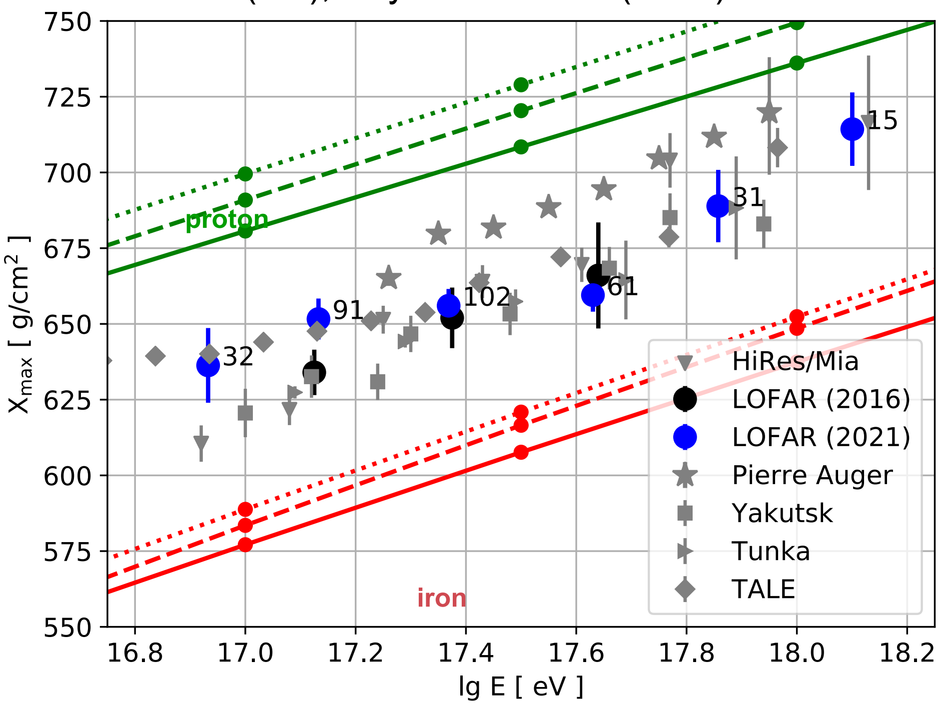


Detecting radio emission of air showers

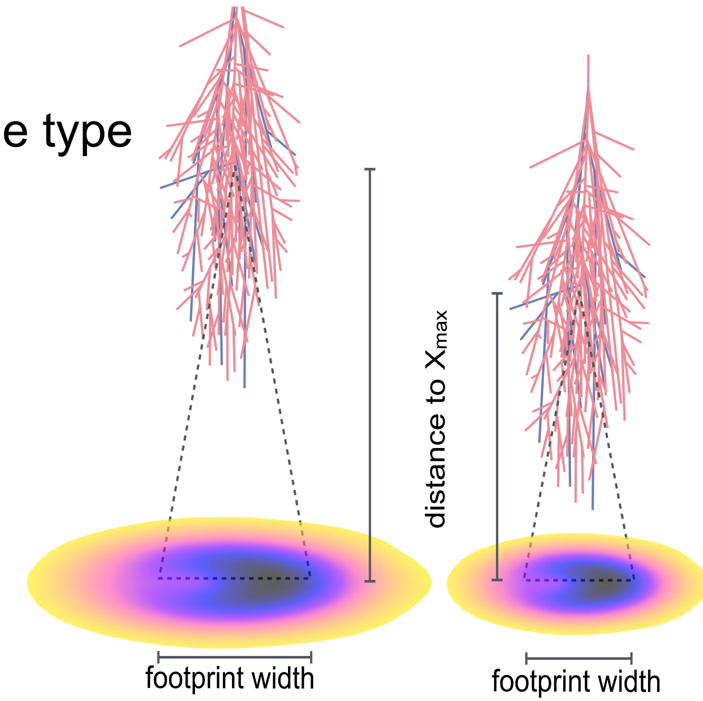
What is in it for the science?

- Radio pattern is very sensitive to X_{max} = particle type

LOFAR (AN), Phys.Rev.D 103 (2021) 10

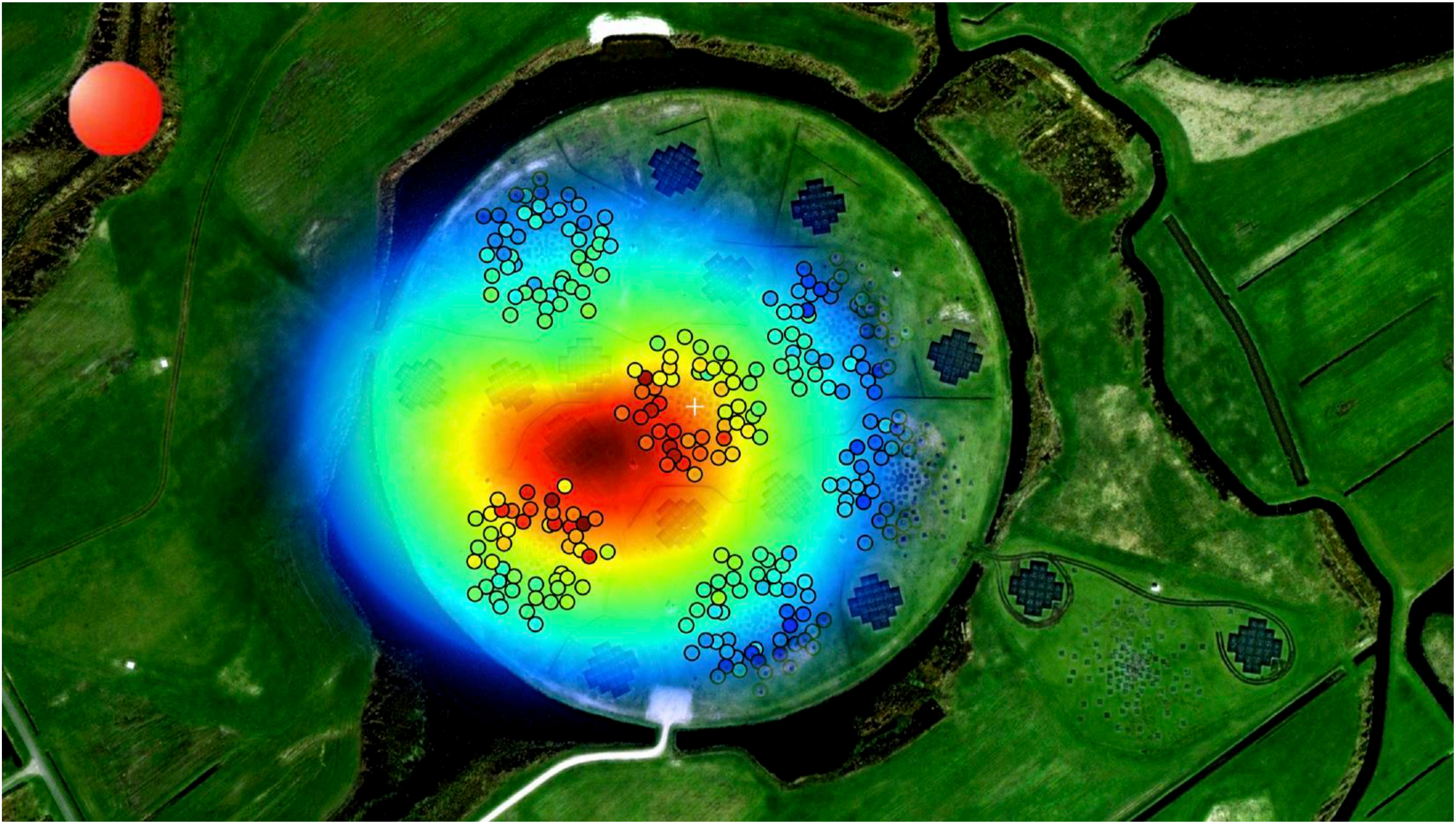


Most recent high-light publication



- Tension to Auger measurements, but agreement with Northern hemisphere experiments
- **Potential for radio measurement on Southern hemisphere**

Estimator of the mass composition



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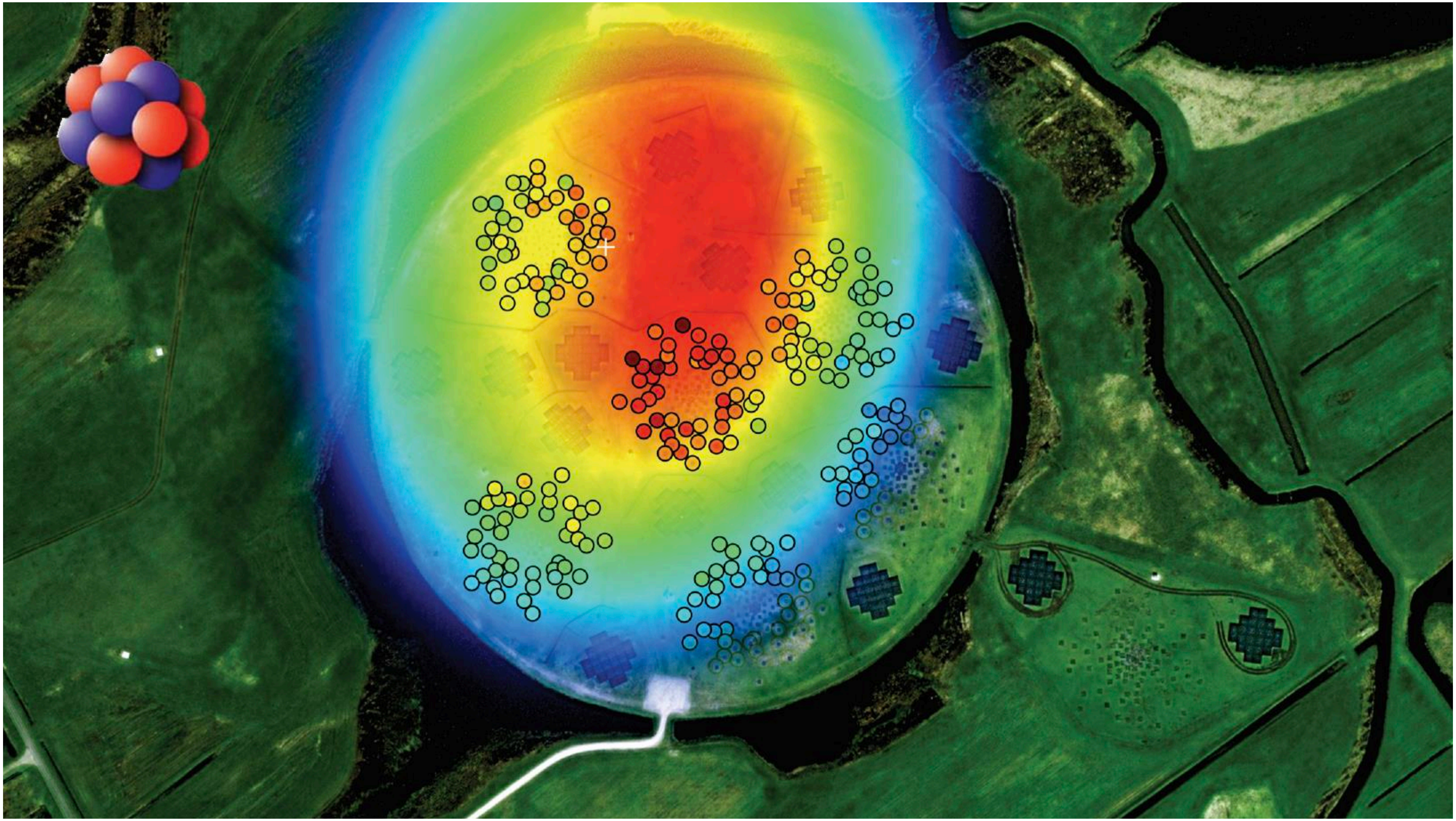
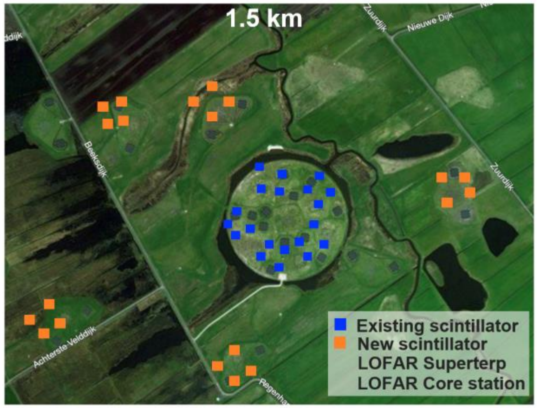


Will this image remain like this?

Plans for LOFAR

- Measuring air showers is about statistics
- Enlarge particle array for better trigger
- Use simultaneous observations in low- and high-band (LOFAR 2.0)



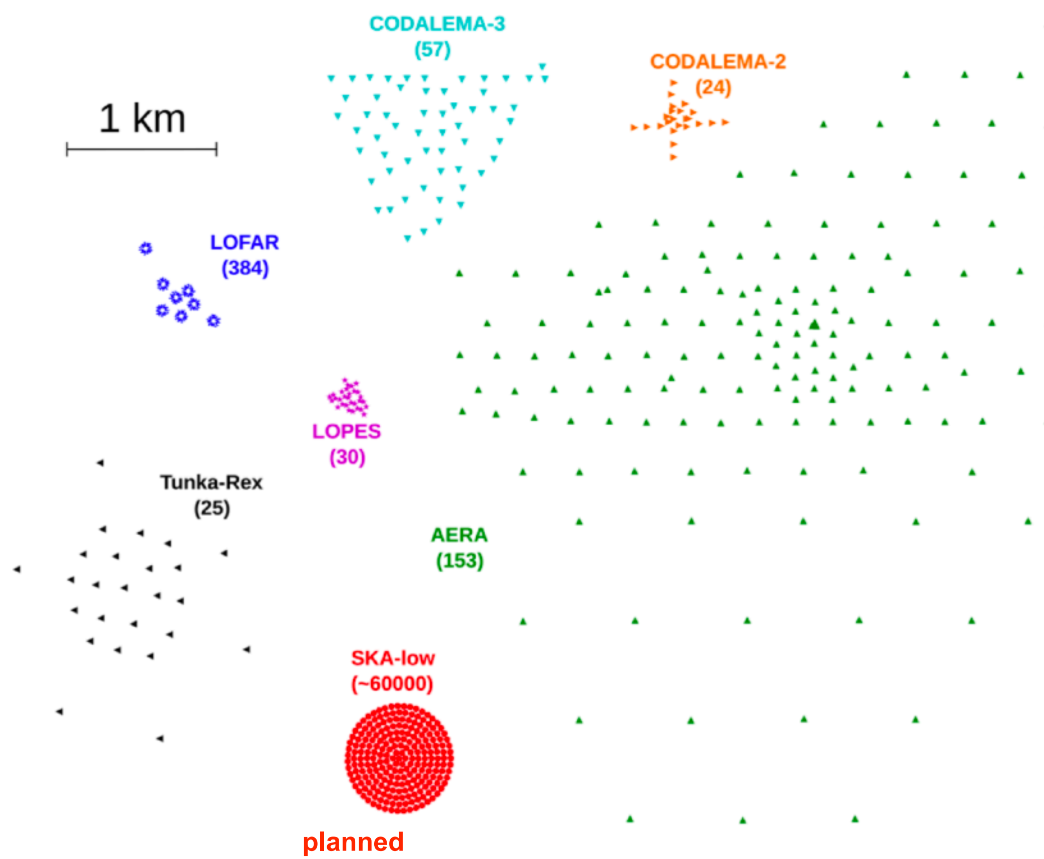
More in Katie's Talk

What is the competition doing?

Experimental neighborhood.

- Multitude of air shower arrays
- Many of them in hybrid configuration, tuned at different purposes
- **LOFAR core still has unrivaled antenna density**
- Square Kilometre Array (SKA) will be direct future competition
    - Although technical feasibility current still under discussion

Figure: Huege 2016

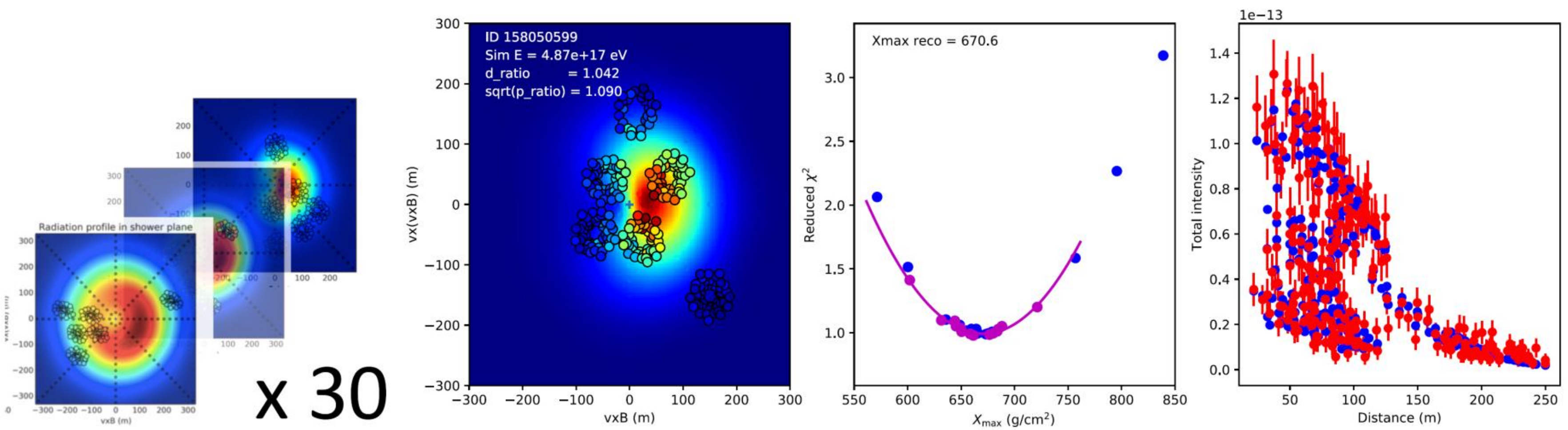


+neutrino detectors in ice ARIANNA, ARA, IceTop, ..
+ANITA balloon

Estimator of the mass composition

How do we do this with LOFAR?

- Make 30 simulations (covering the range of options for shower maximum)
- Fit the simulations to data, including the system response
- Optimize for the best suitable X_{max} which is an estimator for the mass

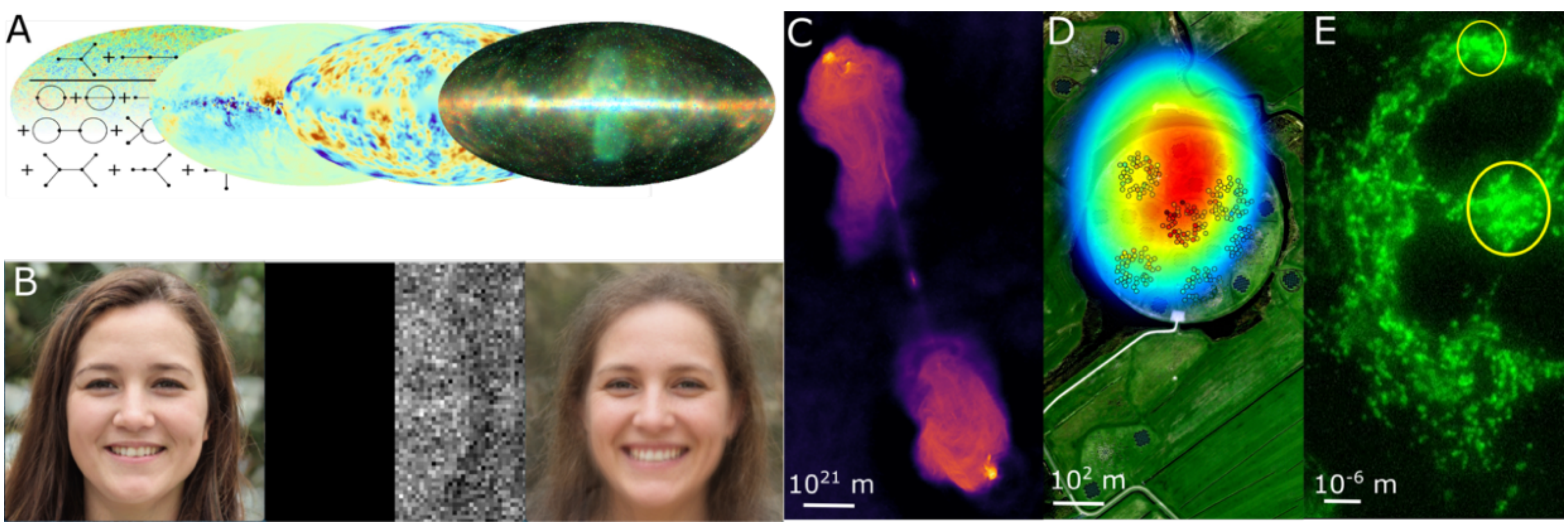


- Very **brute force** and computationally expensive, lots of interpolation
- An array with better antenna coverage would allow more elegant solutions

More elegant solution?

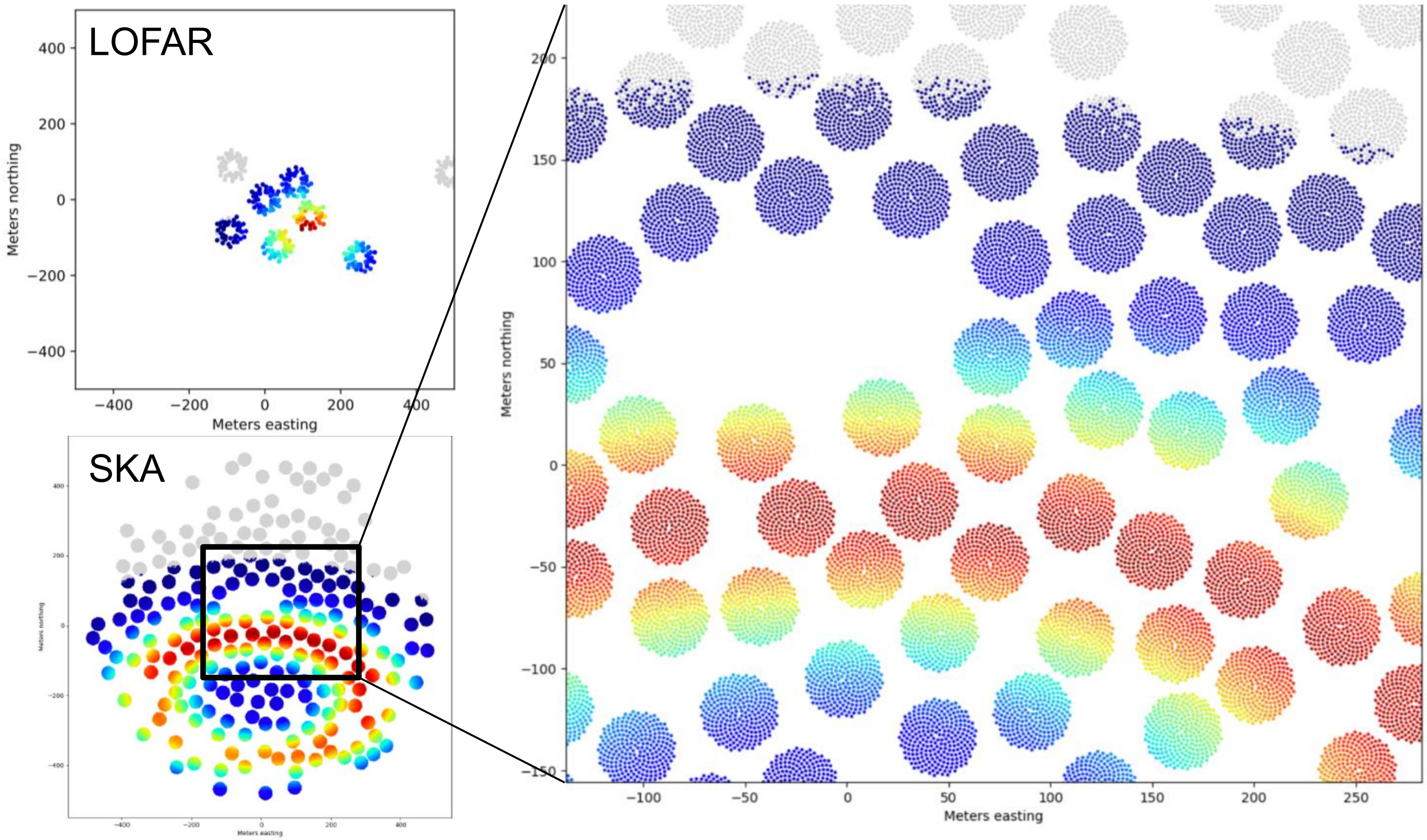
Information Field Theory

- German Federal Ministry recently funded a new consortium: ERUM-IFT
- Torsten Enßlin (MPA), Marcus Brüggen (UHH), Martin Erdmann (RWTH), Ralph Engel (KIT), Jakob Knollmüller (TUM), Anna Nelles (FAU), Judith Reindl (UniBw M), Dominik Schwarz (UBI)
- One project: Novel data analysis for LOFAR cosmic rays
- Goal: Working together on efficient antenna modeling with other LOFAR users



Air shower detection with the SKA

And this is also why we need to take a new look at our methods

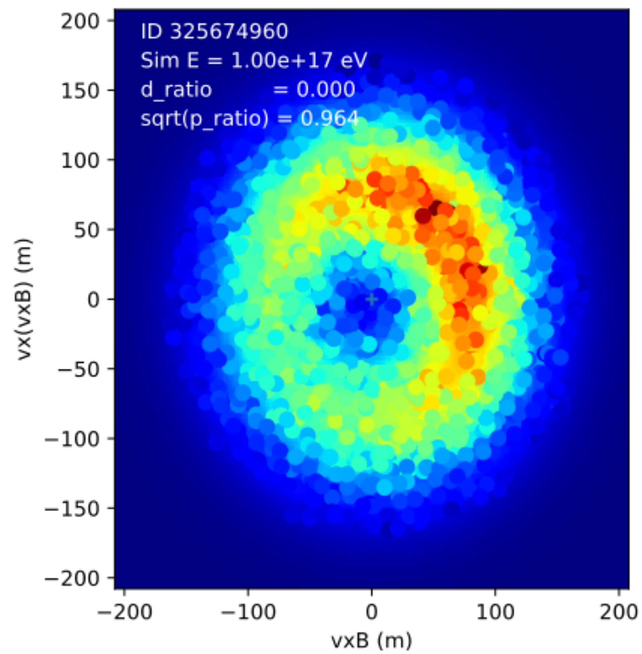


Air shower detection with the SKA

Taking radio emission to the next level of detail

- Next to more antennas, also nicer broad-band frequency coverage 50 - 350 MHz
- SKA has enough antennas to use the raw data directly, no interpolation, no fitting
- Extreme challenge for cutting edge data science
- But: so much more in signal
- May be able to resolve height of first interaction, shape of shower, ‘clumpiness’, etc
- = More precise access to cosmic ray composition, **great for astronomy**
- = Independent handle on hadronic interaction models, **direct implications for particle physics**

Simulations: Arthur Corstanje

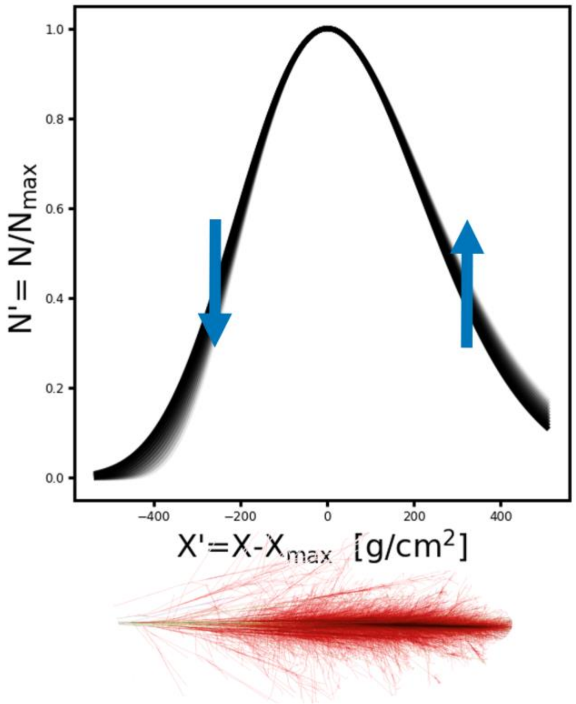


Ideas for the Square Kilometre Array

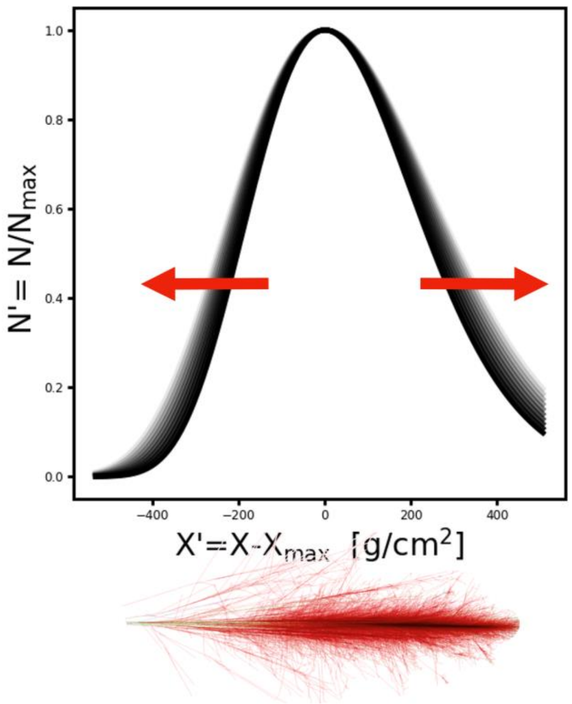
Taking radio emission to the next level of detail

- *Currently all methods work in progress, some ideas a bit speculative, but let's give you an idea*

Changing asymmetry



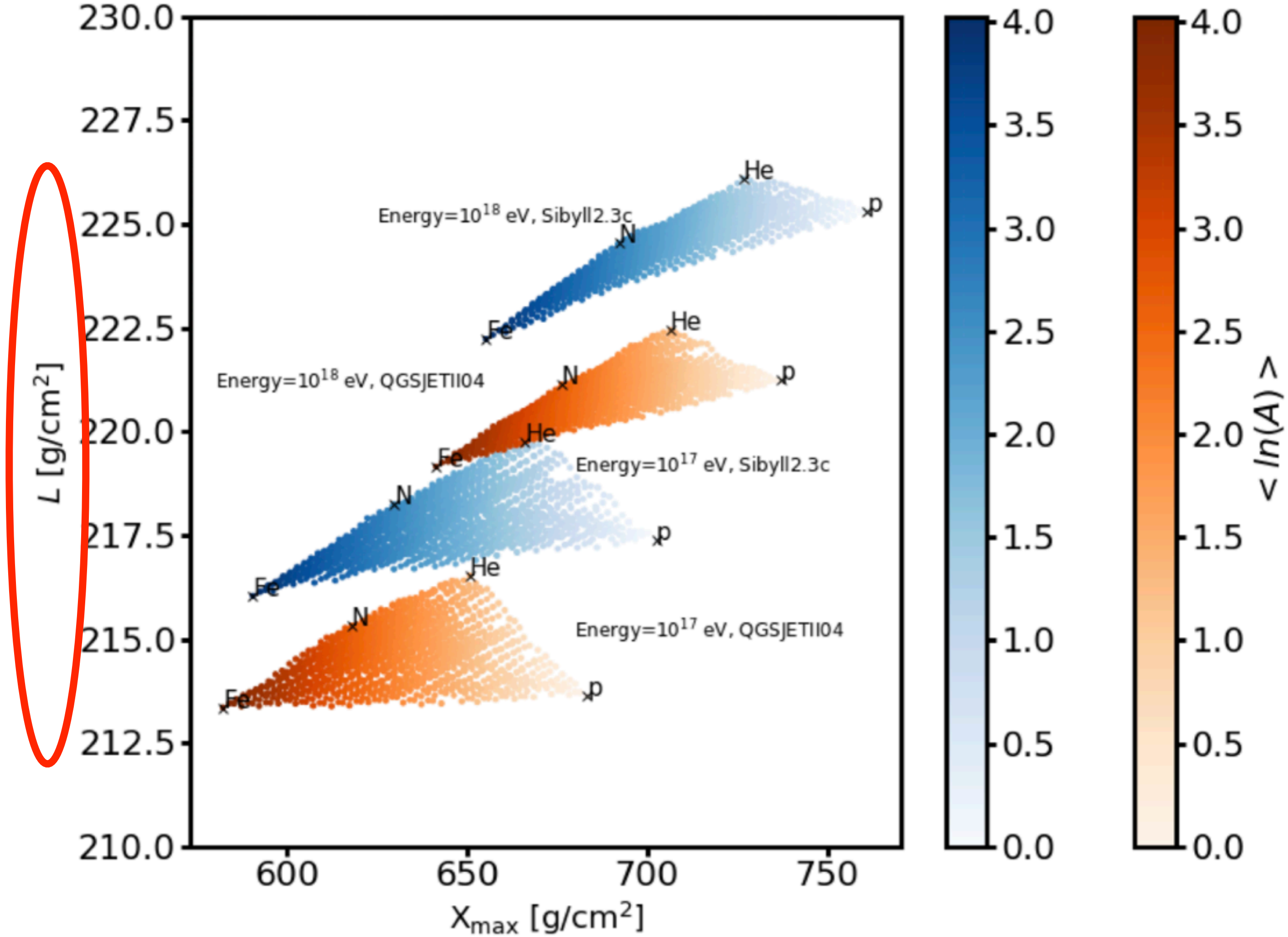
Changing width



- First order: particle type correlated with maximum of distribution
- But hadronic interaction model needed to match them directly

Ideas for the Square Kilometre Array

The problem with hadronic interaction models

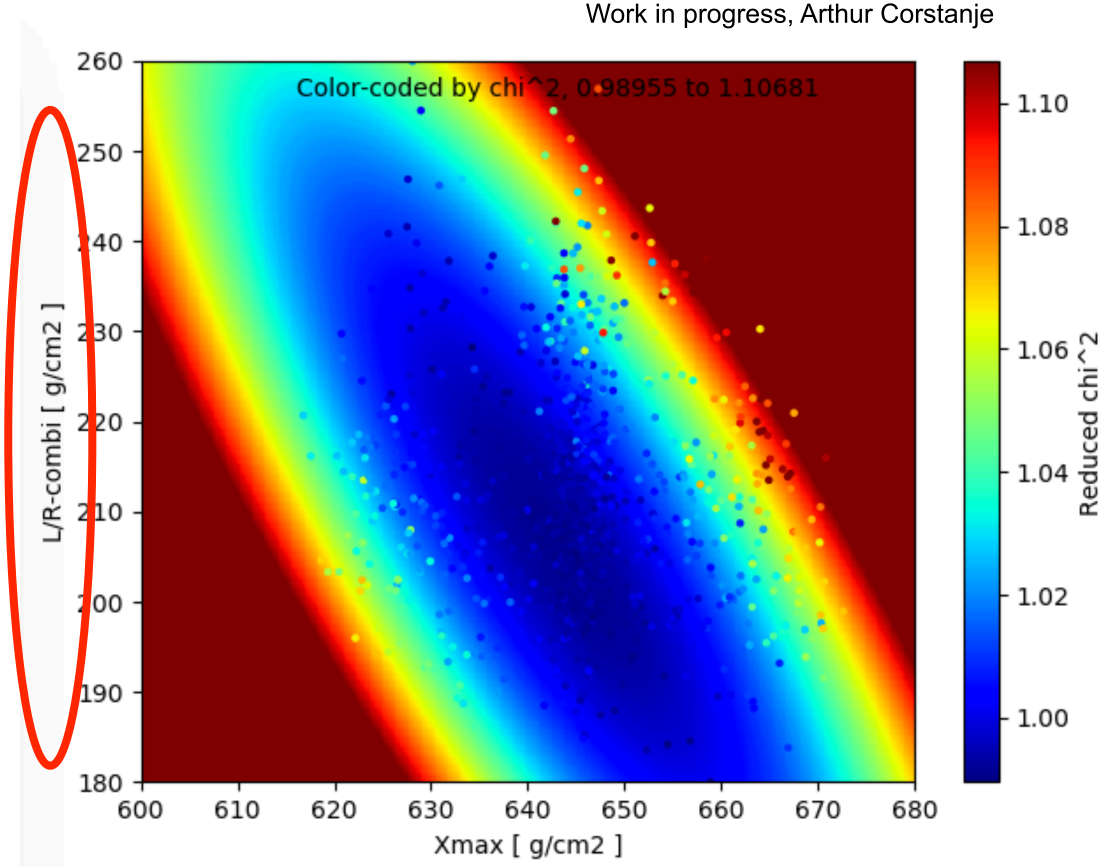


Ideas for the Square Kilometre Array

We have enough free parameters to fit X_{max}, L, R at the same time

- This is using the 'old-style' LOFAR analysis with SKA simulations
- Just to get an idea of what we could do

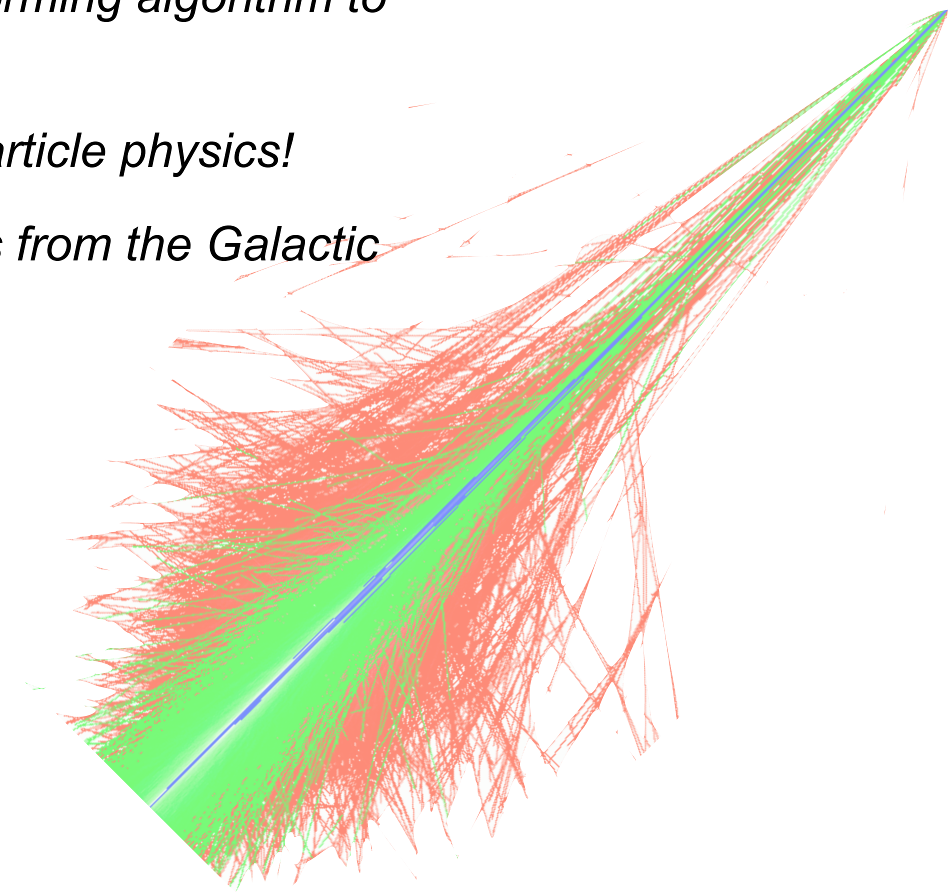
Work in progress, Arthur Corstanje



Ideas for the Square Kilometre Array

What else?

- *Maybe use a 3D beamforming algorithm to reconstruct this directly?*
- *Direct implications for particle physics!*
- *Detect PeV gamma-rays from the Galactic Center?*



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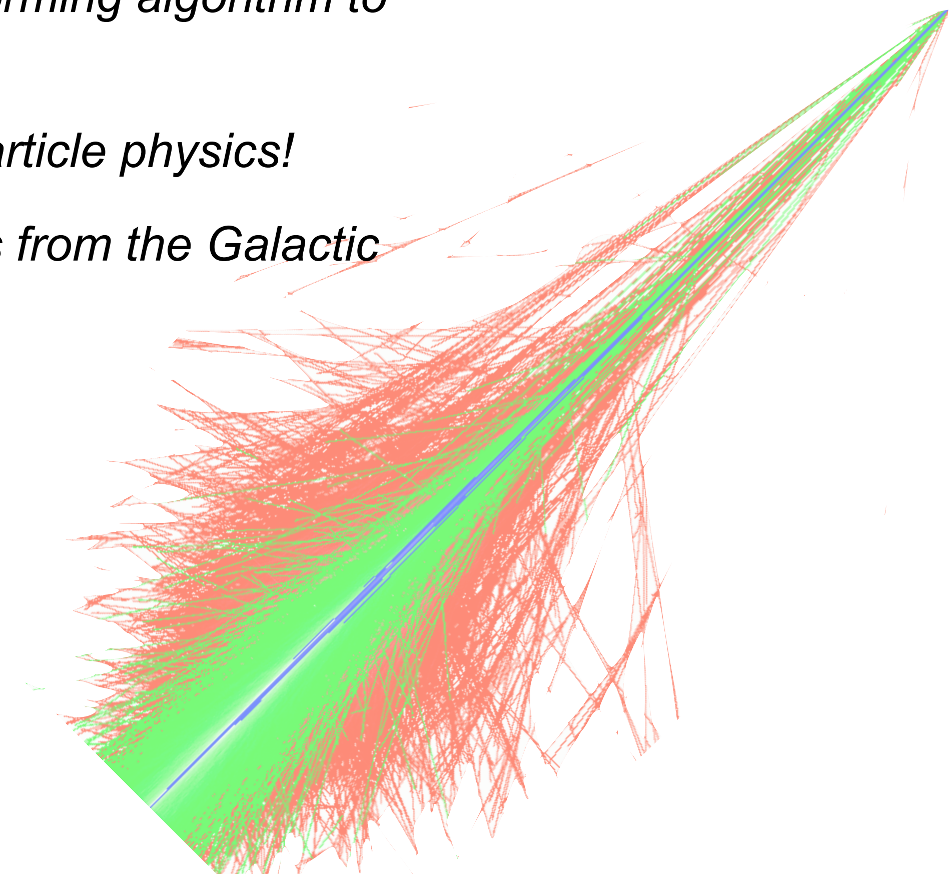


LOFAR will not be able to reach SKA resolution, but is a very important testing and preparation ground!

Lessons learned from LOFAR for SKA

The perspective of the Cosmic Ray Key Science Project

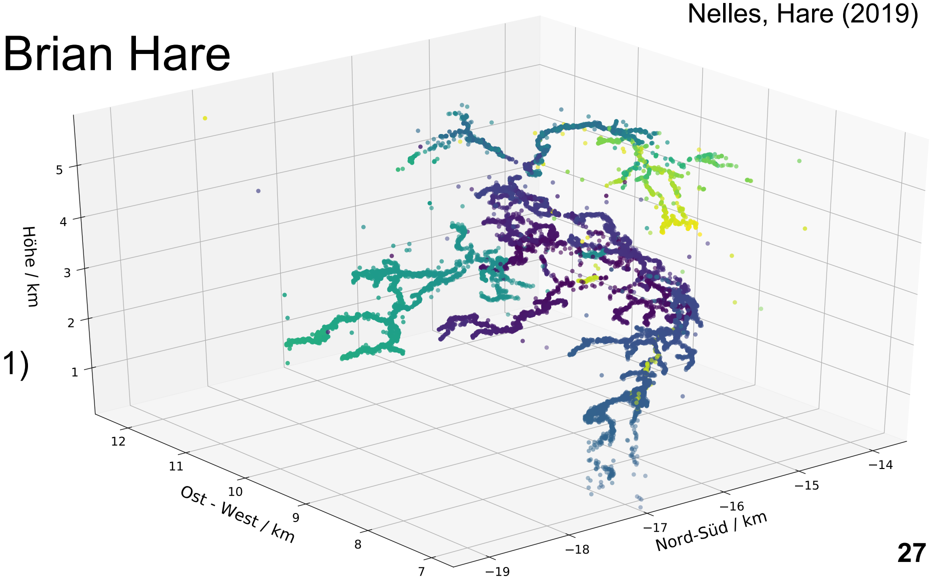
- Get your users involved early in software development, new ground-breaking measurements come through software in distributed telescopes
  You won't know what we need, until we know what we can do!
- It is important to connect the people building the array and the ones doing data-analysis!
- **Don't underestimate the challenge in understanding the antennas**
  - LOFAR started science operation in 2011
  - Model for LBAs still work in progress (as you know!)
- I think we have a responsibility here to spread our knowledge on all levels

Short digression:

Lightning science part of CRKSP

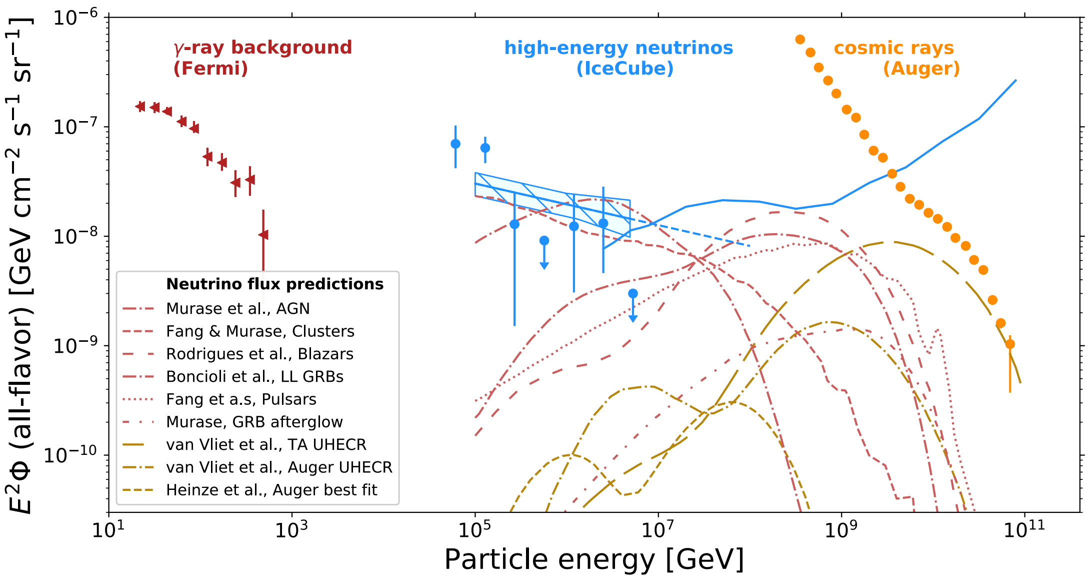
- When working on the air shower detection with LOFAR, we realized:
- Thunderstorms influence air showers and their radio emission
- See e.g. Trinh et al (AN), JGR: Atmospheres 125 (8) 31433, Schellart et al (AN), PRL 114 (16) id.165001
- LOFAR is the world’s most powerful lightning interferometer
- Undoubtedly due to the hard work of Brian Hare (and Olaf Scholten)
- See e.g.: Nature 568 (7752), 360-363
  PRL 124 (10), 105101
  JGR: Atmospheres 123 (5), 2861-2876
  Phys.Rev.D 104 (2021) 6, 063022
  Geophys. Res. Lett., Volume 48, Issue 23, e95511 (2021)
  Scientific Reports volume 11, 16256 (2021)
  Phys. Rev. D 105, 062007 (2022)

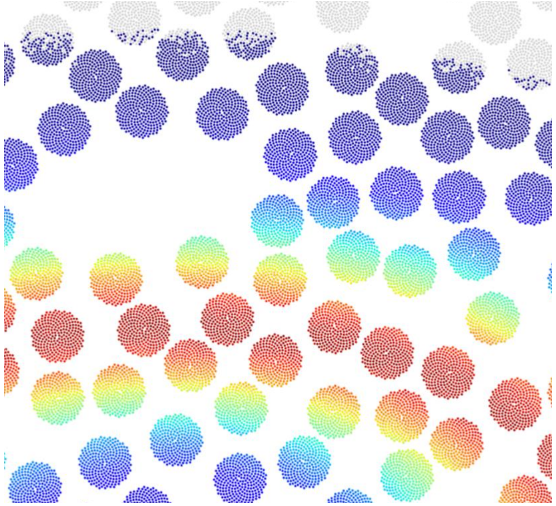
Nelles, Hare (2019)



Conclusions

Cosmic Rays and Radio Telescopes





- **Sources of high energy cosmic rays**
  - Radio detection of air showers already now leading in precision measurement of mass composition
  - LOFAR has been instrumental!
  - SKA: ultimate precision
- **Understanding air showers**
  - Particle physics unknown at highest energies
  - High-accuracy measurements with SKA could deliver particle physics insights