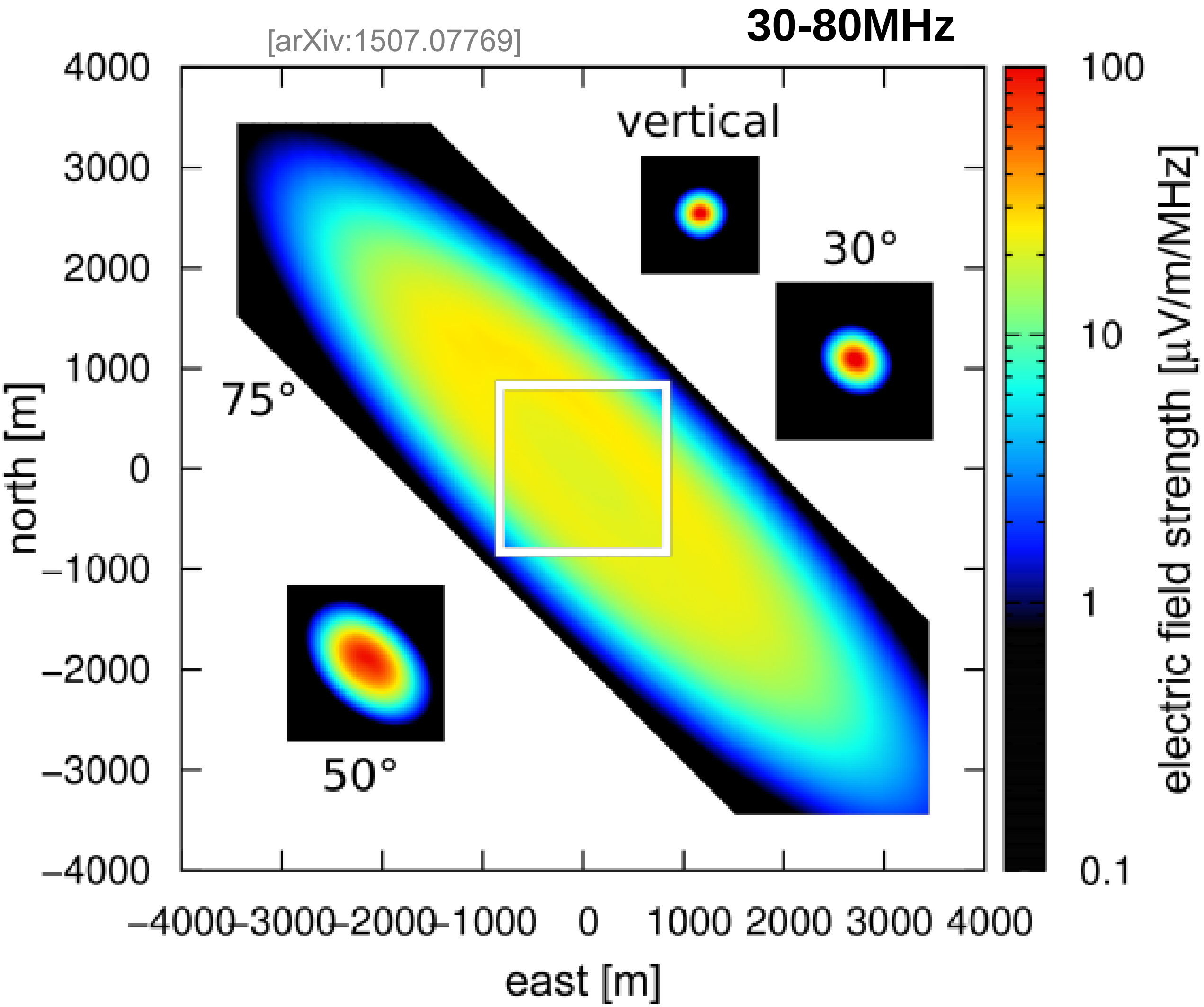
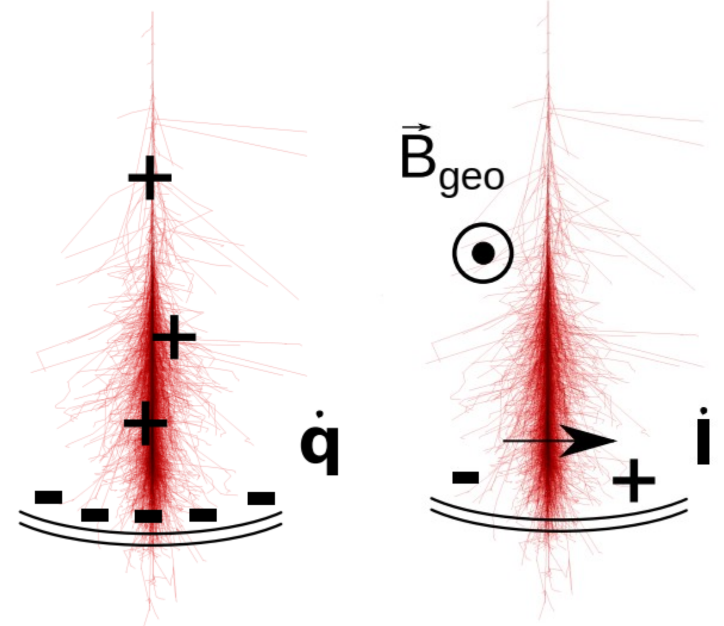
Standard methods of shower reconstruction with radio data and *personal thoughts* on how they could be adapted to GRAND/GRANDproto300

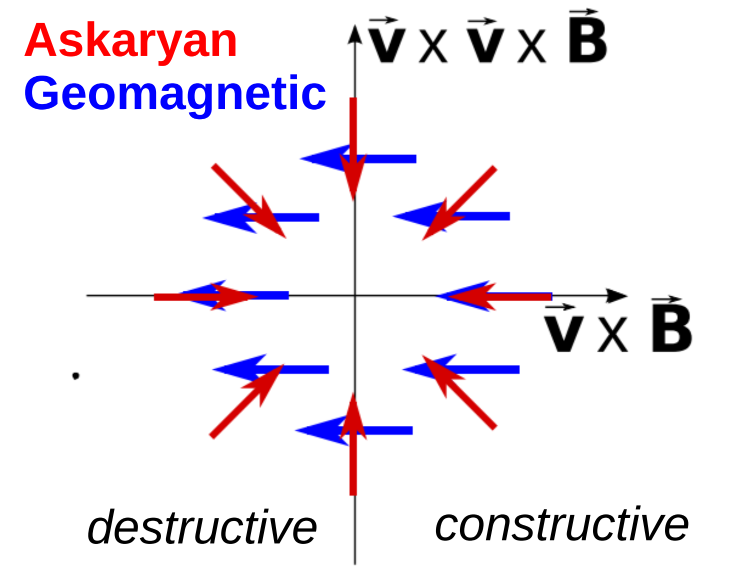
By Anne (zilles@iap.fr)

I will not give the citations always properly. There is also no chance to discuss all methods used in all radio arrays (It‘s is just a small personal selection – biased!). It is far from being complete or detailed.
For still recent reviews on radio detection, please see:
F.G. Schroeder, arXiv:1607.08781
T. Huege, arXiv:1601.07426

Recap







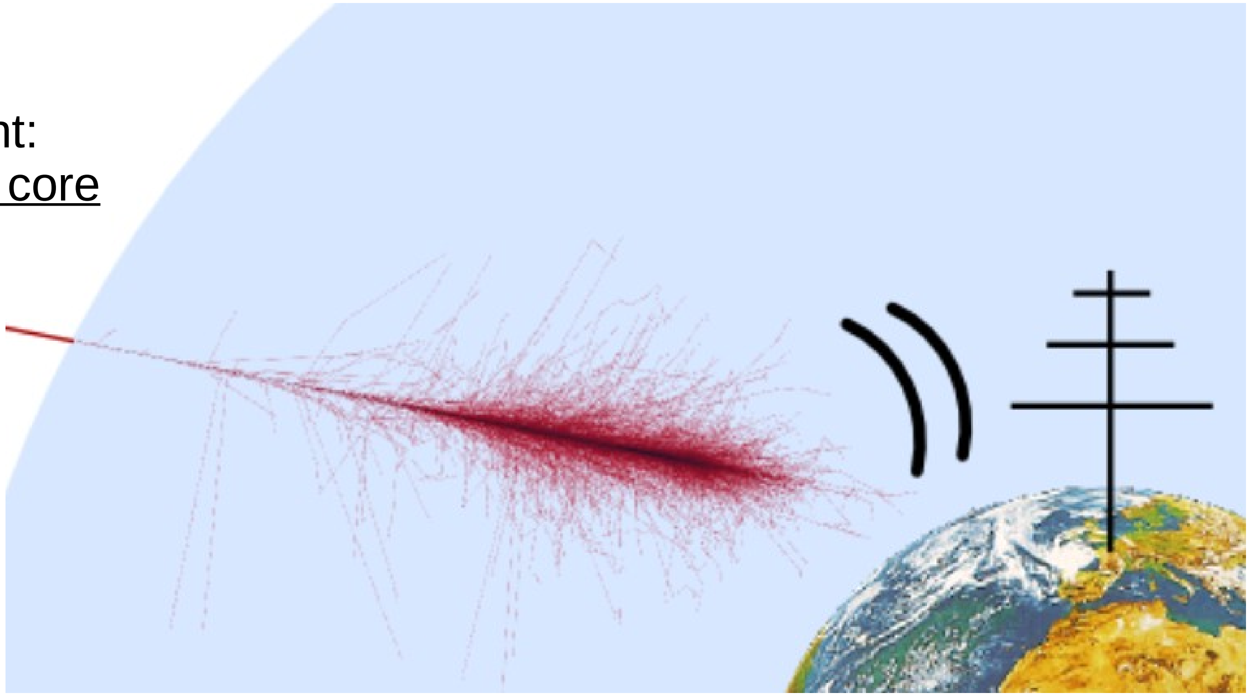
- Huge footprint for horizontal showers
- Asymmetric footpint due to emission mechanisms

Event information

What to reconstruct:

- Geometry of the air-shower event:
  arrival direction and shower core
- Primary's energy
- Mass of primary

→ What is needed as input?
→ What resolution is achievable?

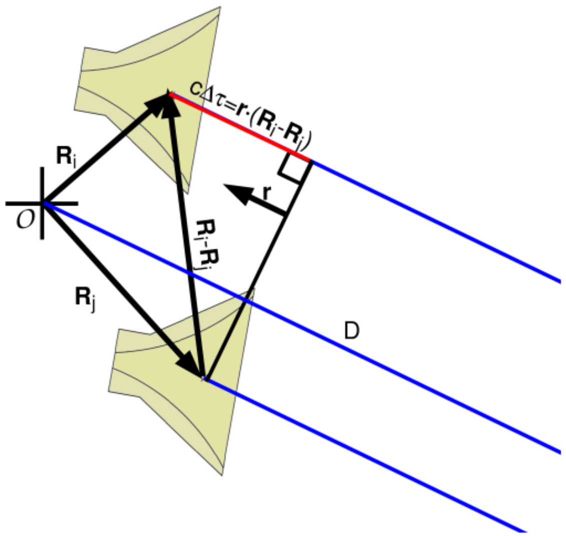


Most of the methods:
- are developed for ground-based air-shower radio arrays triggered by particle detectors (besides ANITA in these slides)
  → need input from the PD.
- are developped for the 30-80MHz frequency range
- are developped for vertical/down-going showers

→ **GP300: develop and test now the methods for GRAND**

Arrival direction

<u>Arrival direction</u>: physical parameters
== arrival direction of particle

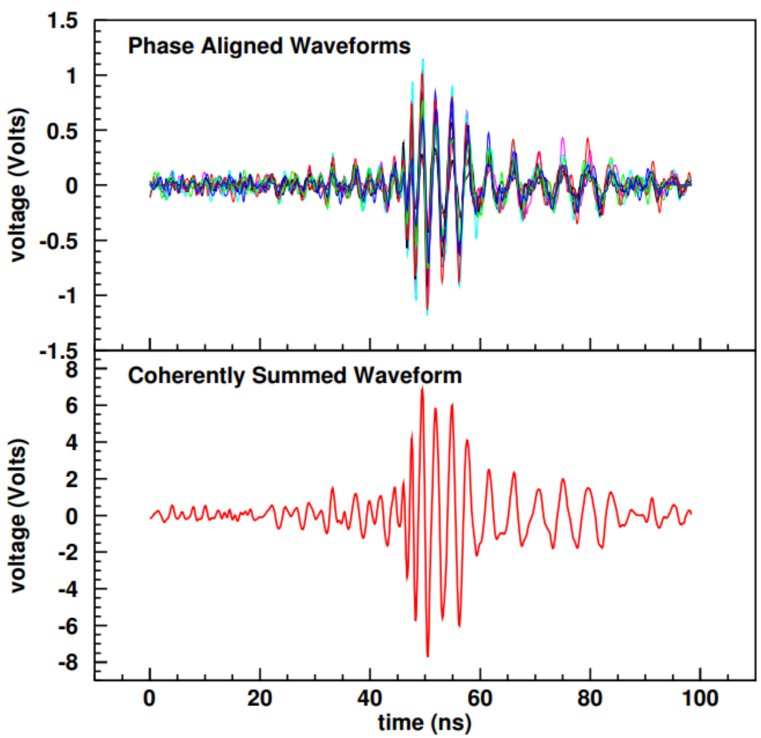


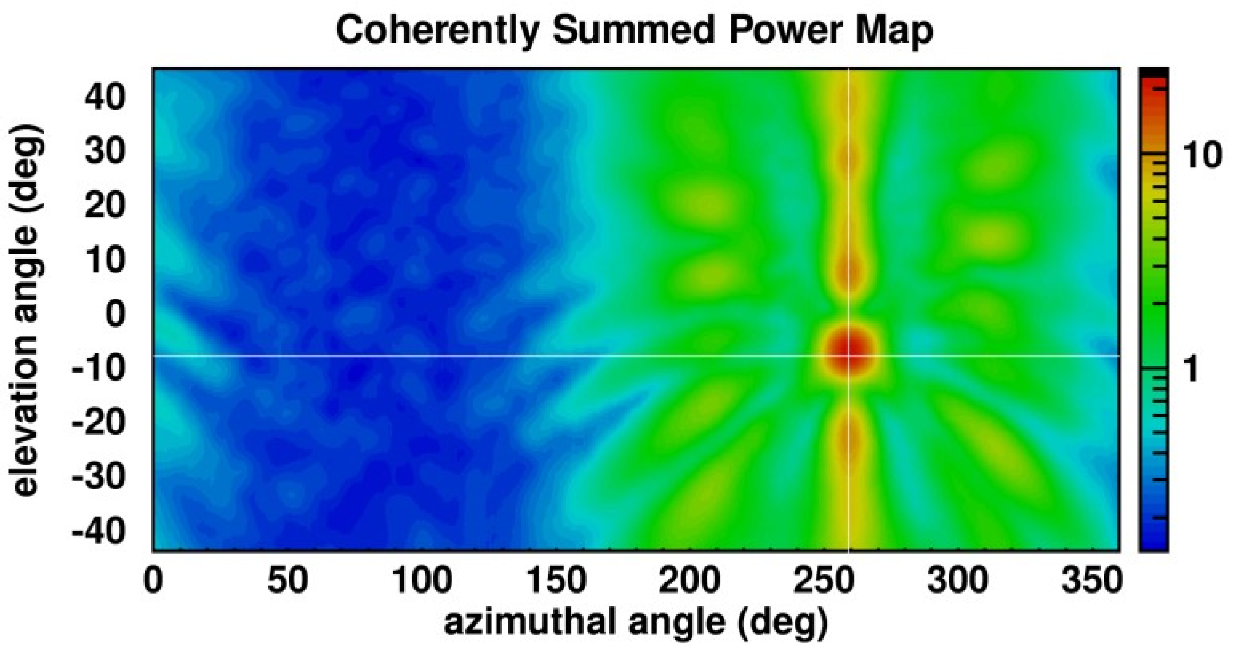
Interferometry (similar to detecting FRBs)

- Geometrical delay for a pair of antennas
  → delayed combination of waveforms
- For ANITA: elevation and azimuth errors: 0.26° and 0.56°

Time averaged power for the summed waveforms

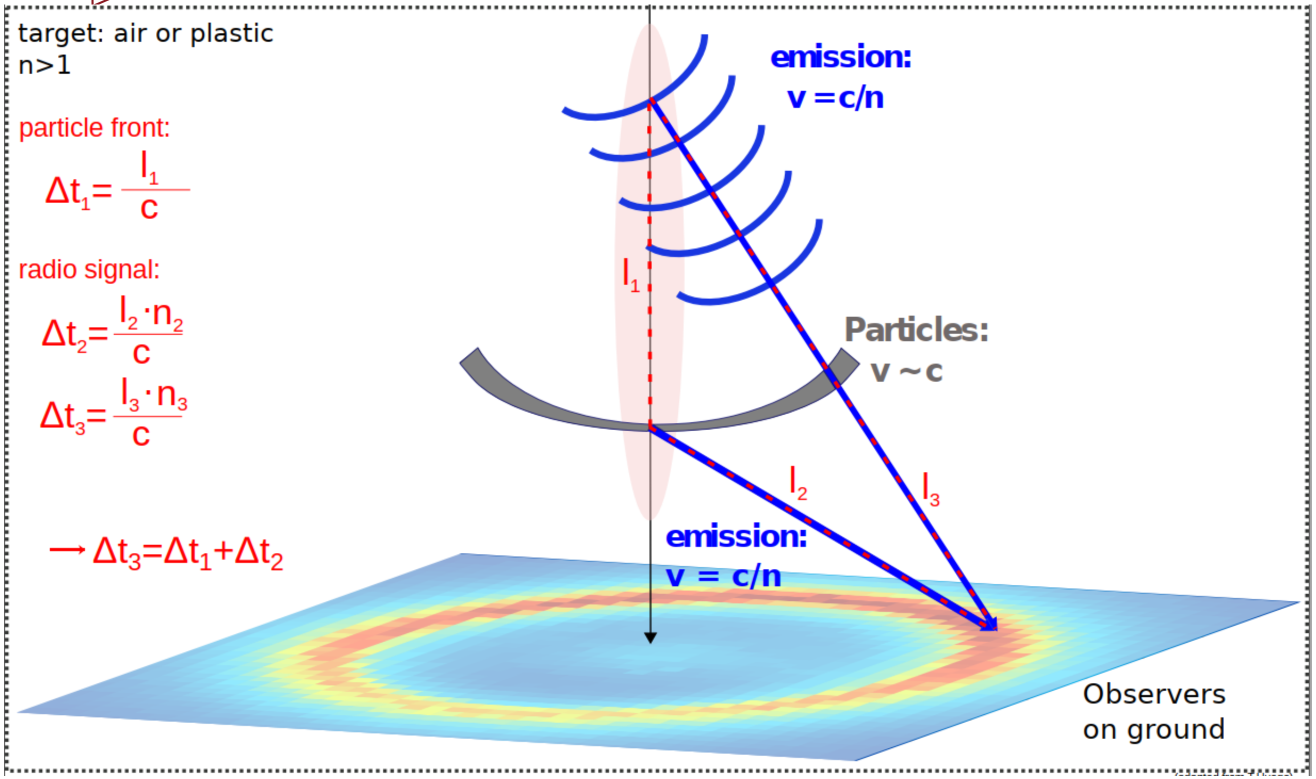
$$P_\Sigma(\hat{\mathbf{r}}) = \frac{1}{Z_L}\frac{1}{T}\int_0^T dt\, V_\Sigma^2(t,\hat{\mathbf{r}})$$

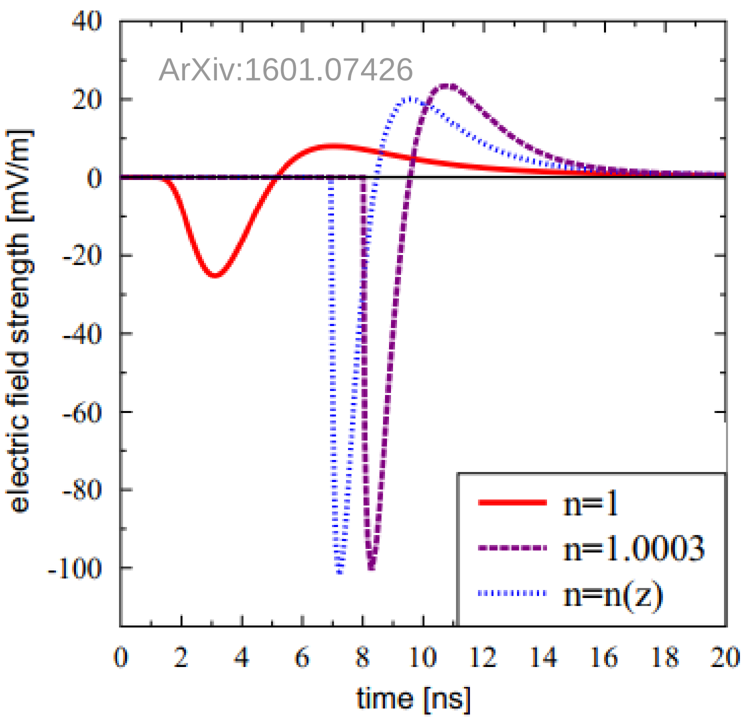




Input: only radio traces, only <u>few</u> needed

Can we use the Cherenkov ring?





- coherence is frequency-dependent
  → more pronounced at low frequencies

- But n!=1: signal arrives simultaneously at specific positons → signal becomes becomes short → leads to coherence up to GHz → **Cherenkov ring** appears for frequencies above ~100MHz

- Radius depends on height of emission

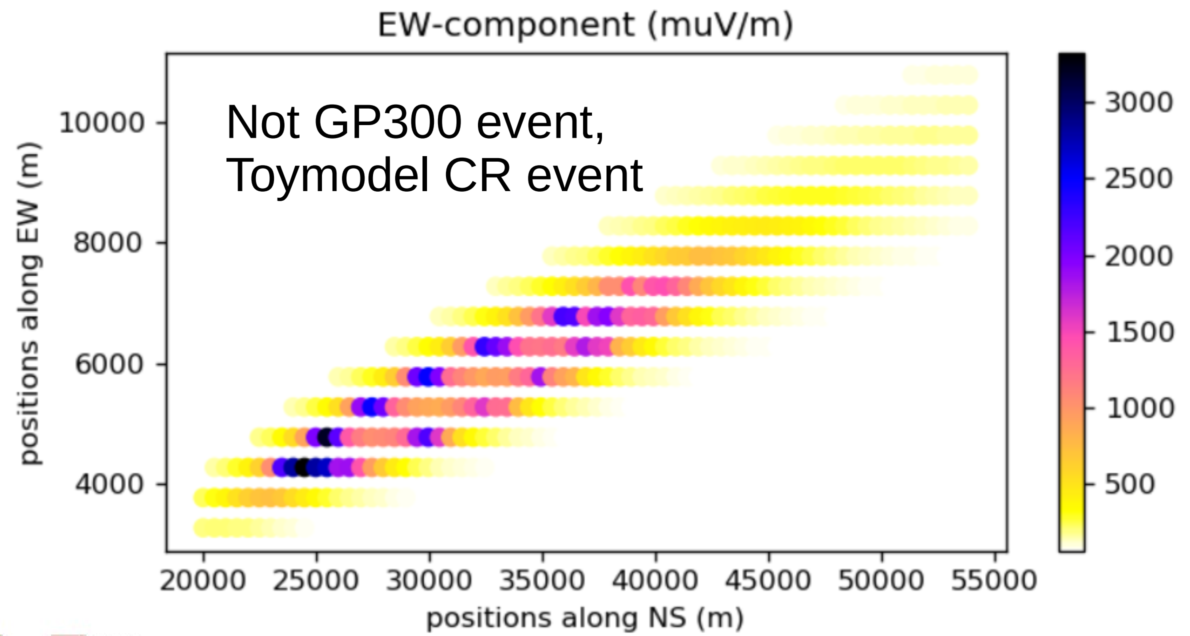
Arrival direction

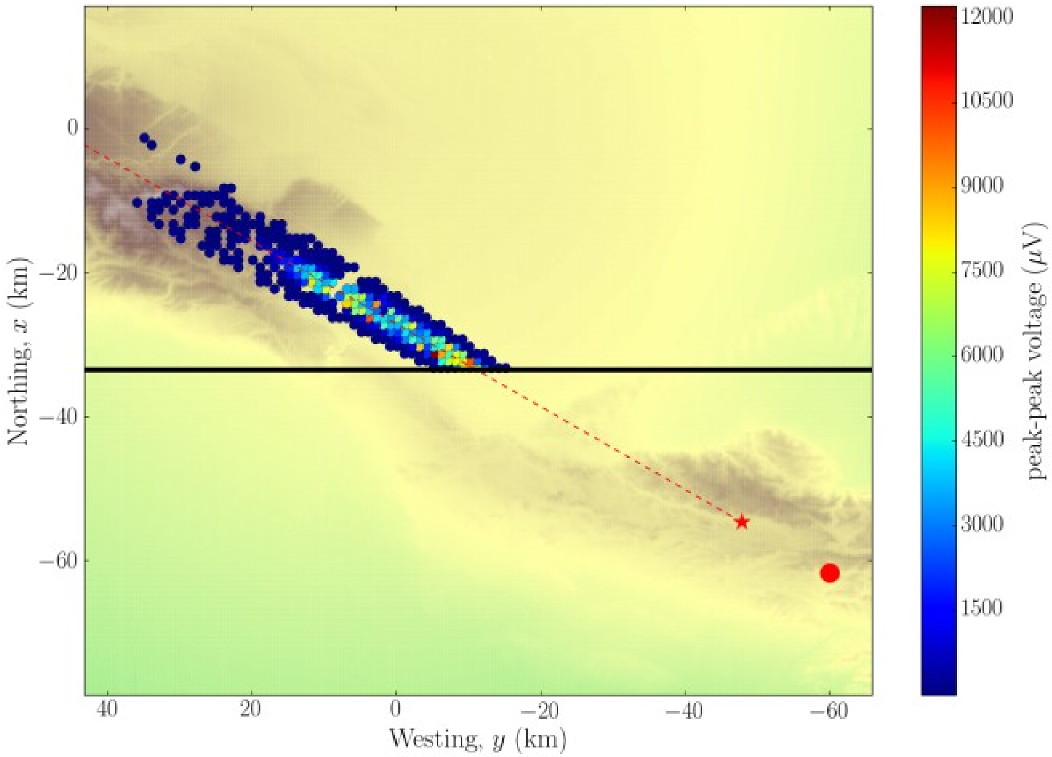
Arrival direction: physical parameters
== arrival direction of particle

Geometry of Cherenkov ring

Use amplitude distribution
→ visible Cherenkov cone
additional info on timining needed to get the right azimuth

→ ring radius should help to determine Xmax by geometry arXiv:1304.1321 (tested on 3 LOFAR events, arXiv:1411.6865)





How well can we sample/identify the position of the ring with a sparse array?

For neutrino events
- Shower passes by the array
  → We will see a conic section in the amplitude distribution
  → will point back to the emission region (cone vertex)

Shower Core – how to construct

Shower core: technical parameters, needed for reco of other parameters

- location where the shower axis hits the ground
- usually input in radio reco from particle detectors
- no publications found on the reconstruction of the shower core
- all properties of the radio signal measured by a detector depend on the distance to the shower axis → plenty of ways to determine it:

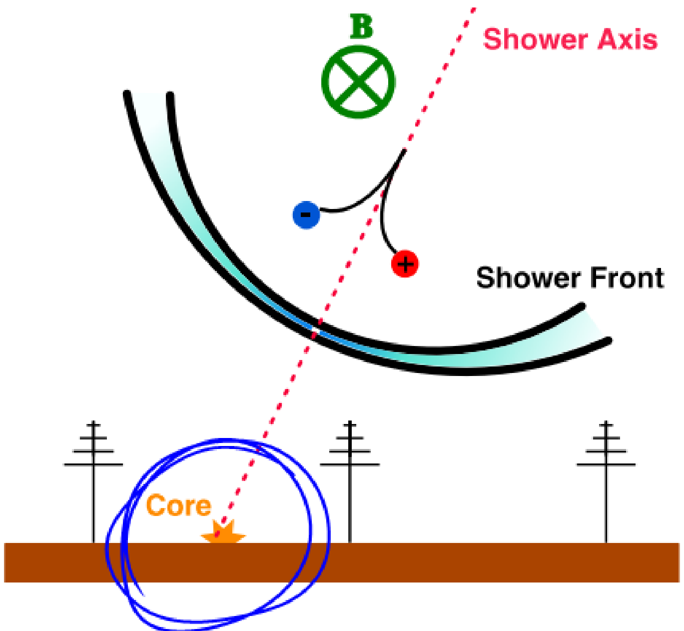
- Wavefront: hyperbolic wavefront points directly to the shower axis,

- Footprint: Cherenkov ring is centered around the shower axis,
  - core position is one of the free parameters when fitting a lateral-distribution function to the measured amplitudes at different positions e.g. in AERA
  - simulated radio footprints can be matched with the measured one to determine thecore position, e.g. in LOFAR.

- Frequency spectrum: slope of the frequency spectrum measured in an individual antenna depends on the distance to the shower axis.

- Polarization: polarization of Askaryan emission points (needs high SNR, not dominanted by background)

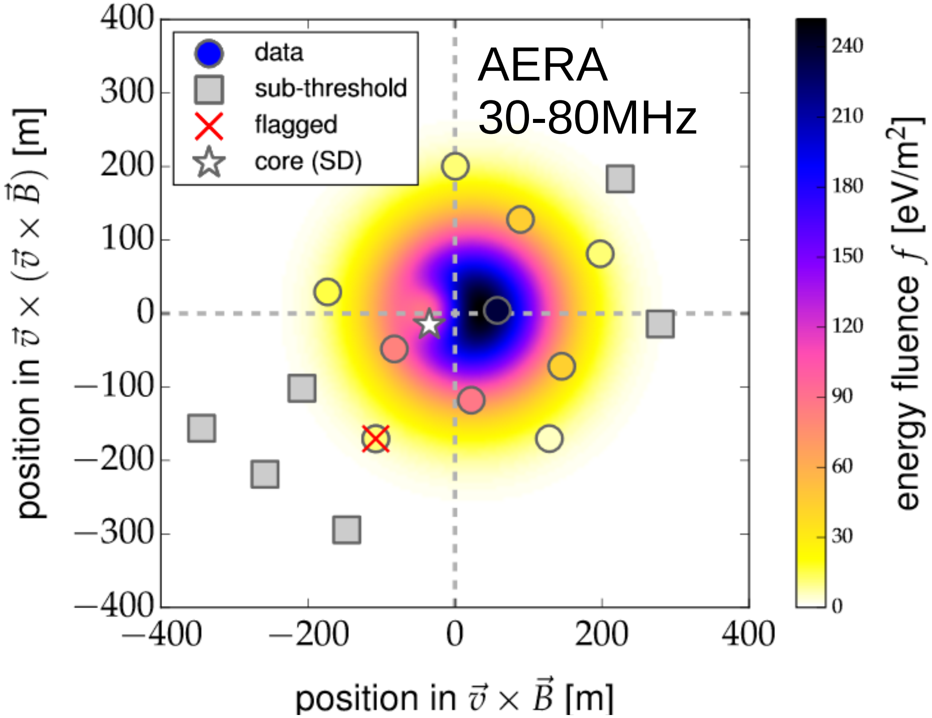
→ methods needs to be investigated! Important input for reconstruction of shower parameters!



Primary's energy

- Independent of observation altitude
- Achieved energy resolution of 17% at ~1EeV

Measure radiation energy by integrating over the footprint



Footprint in shower plane

Parametrisation of LDF for 30-80 MHz and AERA site

$$f(\vec{r}) = A\left[\exp\left(\frac{-(\vec{r}+C_1\,\vec{e}_{\vec{v}\times\vec{B}}-\vec{r}_{\mathrm{core}})^2}{\sigma^2}\right) - C_0\exp\left(\frac{-(\vec{r}+C_2\,\vec{e}_{\vec{v}\times\vec{B}}-\vec{r}_{\mathrm{core}})^2}{(C_3 e^{C_4\,\sigma})^2}\right)\right]$$

$$S_{\mathrm{radio}} = \frac{1}{\sin^2\alpha}\int_{\mathbb{R}^2} f(\vec{r})\,\mathrm{d}^2\vec{r} = \frac{A\pi}{\sin^2\alpha}\left(\sigma^2 - C_0 C_3^2\, e^{2C_4\sigma}\right)$$

$$E_{\mathrm{rad}}(30-80\,\mathrm{MHz}) = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst}))\,\mathrm{MeV}\cdot\left(\sin(\alpha)\frac{E_{\mathrm{shower}}}{\mathrm{EeV}}\frac{B_{\mathrm{geo}}}{24\,\mu\mathrm{T}}\right)^2$$

For inclined showers: correct for ‚early-late' effect (arxiv:1808.00729)

<u>How many antennas</u> would we need to achieve a similar resolution?
Esp. for lower energies

Input: arrival direction, shower core

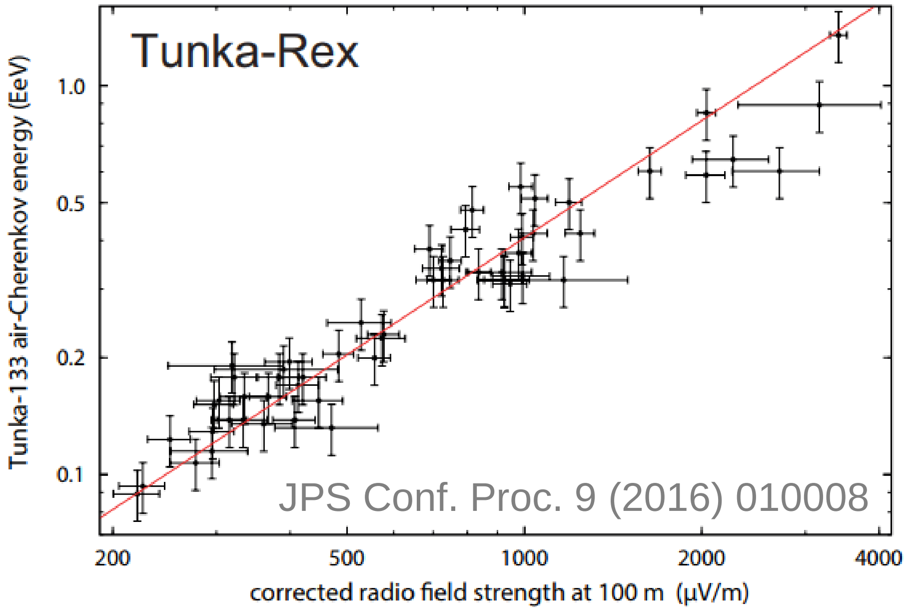
See 1508.04267, 1606.01641, ...

Primary's energy

Amplitude at a reference distance

- Position close to Cherenkov cone: independent to Xmax
- Correct amplitude for geomagnetic angle and asymmetry
- Energy resolution acieved: 15-20%
- Can be also preformed with a single antenna position and help of a average LDF (→ 20% for Trex) – more suitable for hybrid detection

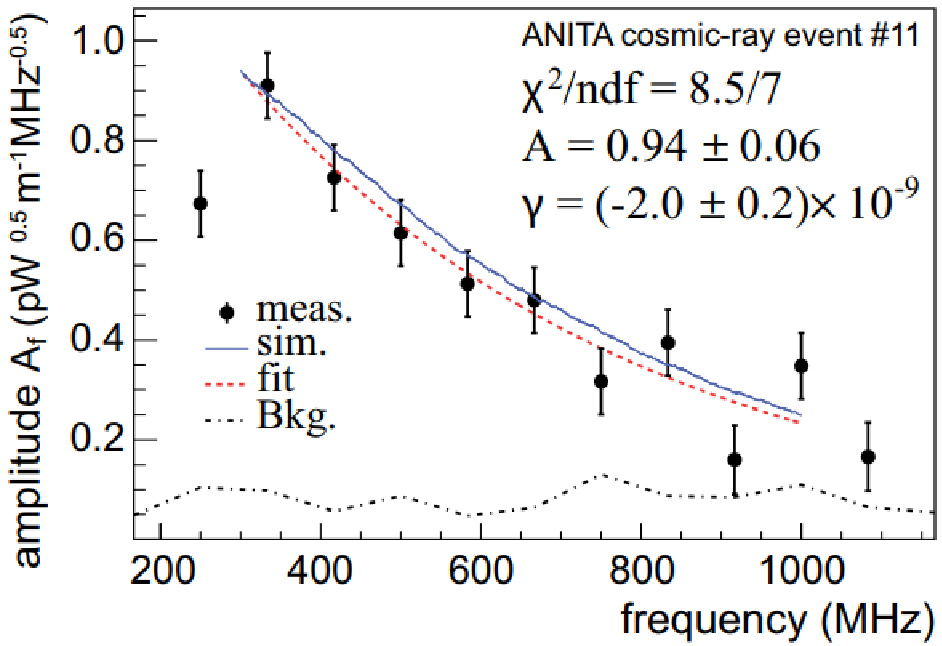
arXiv:1611.09614



Input: Shower core, arrival direction

- ANITA: **<u>single station approach</u>** – detection of signal in several antennas allows reco of shower direction, accurate reco needed!
- spectral slope depends on the distance from the Cherenkov angle → enables an estimation of the amplitude at the Cherenkov angle = amplitude at reference distance
- Achieve energy resolution: ~ 30%

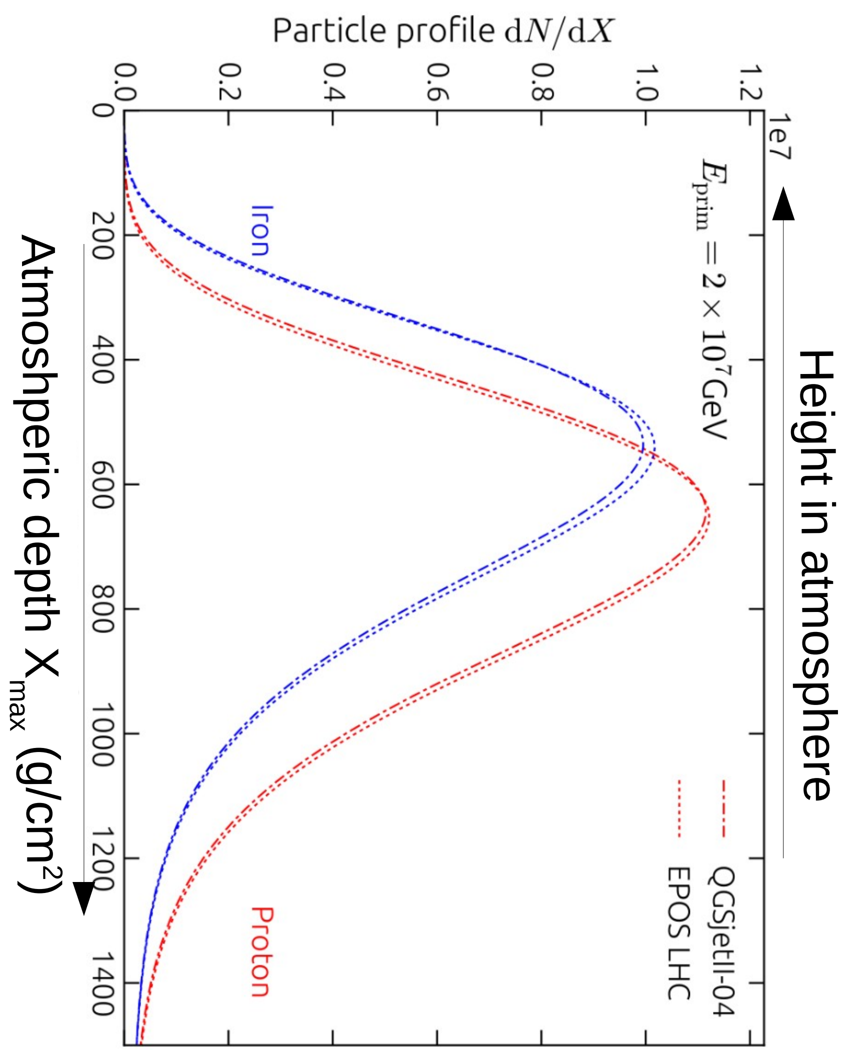
ArXiv:1506.05396



Interesting for GRAND?

Recap: Xmax

mass composition can be derived <u>statistically</u> from the Xmax position, shower-to-shower fluctuations and measurement uncertainties too large to reconstruct the particle type for individual events



By Felix Riehn

Development of a heavy ion induced shower starts earlier

→ reaches the maximum number of particles earlier (low atmospheric depth)
+ more muons on ground

than is the case for proton induced showers of the same energy (high atmospheric depth)

Shower depth X_{max} = max. number of particles

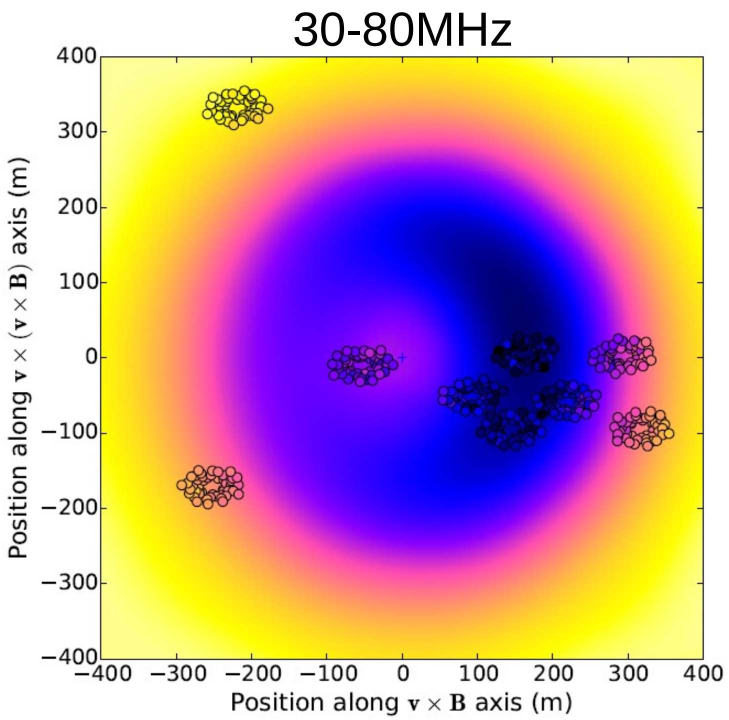
Typically: $(X_{max,p} - X_{max,Fe}) \approx 100$ g/cm^2

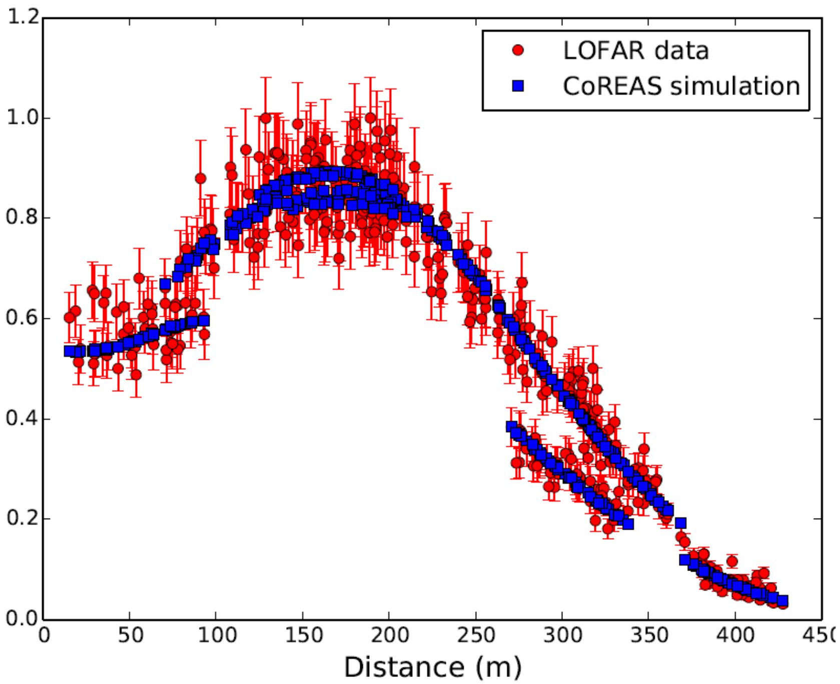
Best reconstruction uncertainty by Fluorescence detection technique: ~ 20 g/cm^2

Top-Down in LOFAR

LOFAR (7x48)

Based on the well-understood emission mechanisms of the radio signal
→ simulations can described accurately the measured radio signal





Radio footprint in the shower plane:
Plane described by the direction of the shower and the Earth's magnetic field

Circles = measurements of LOFAR
Background = simulations

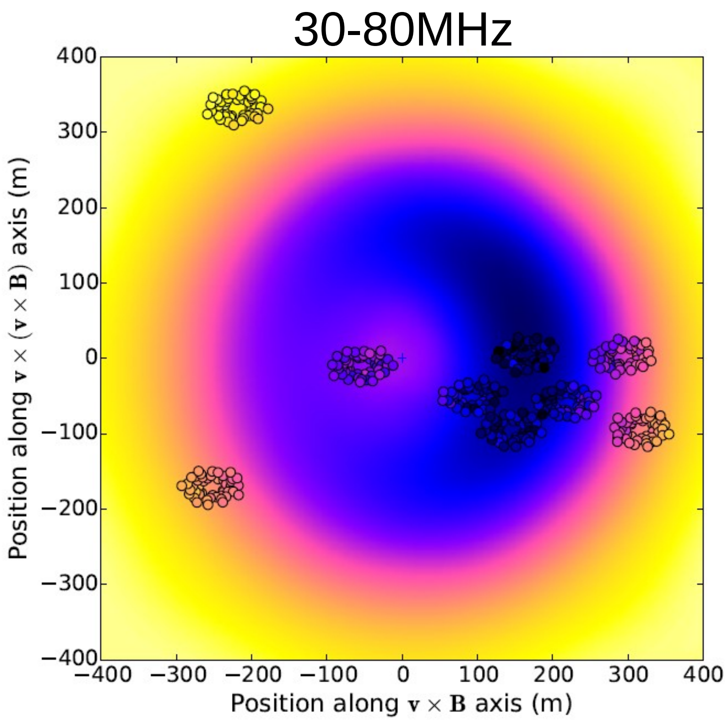
LDF = Lateral distribution function
Measured radio signal depend on the distance to the shower axis

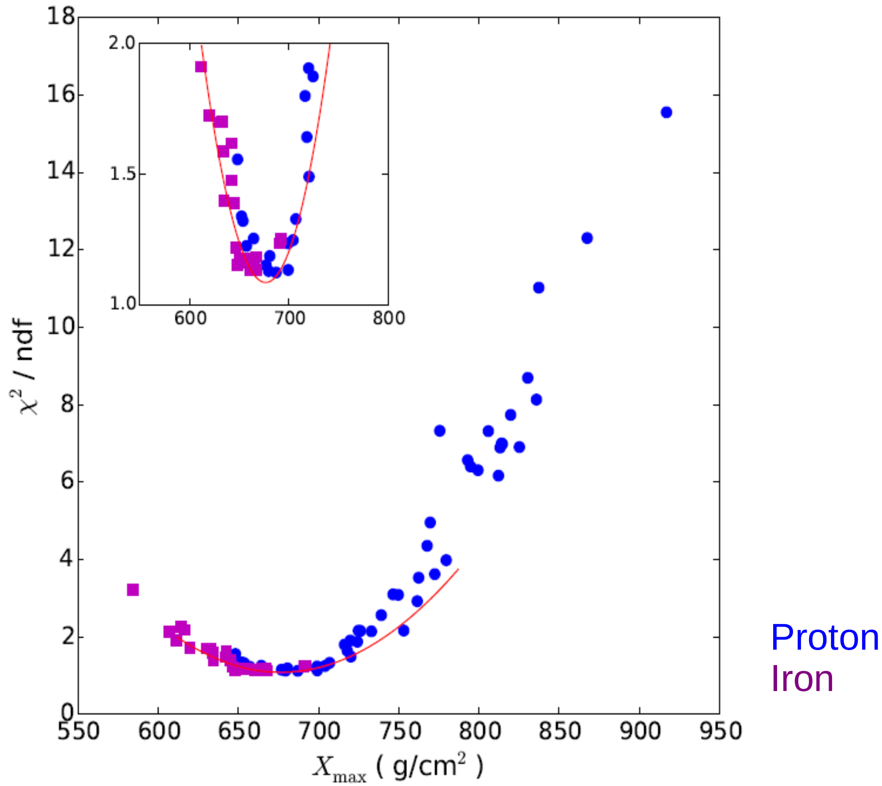
S. Buitink et al., Phys Rev D (2014), arXiv:1408.7001

Top-Down in LOFAR

LOFAR (7x48)

Pick the one of <u>many</u> simulations describing data best





- **2d LDF fit to radio simulations yields mean X_{max} to ~17 g/cm²**

More: S. Buitink et al., Nature 531, 70 (2016)

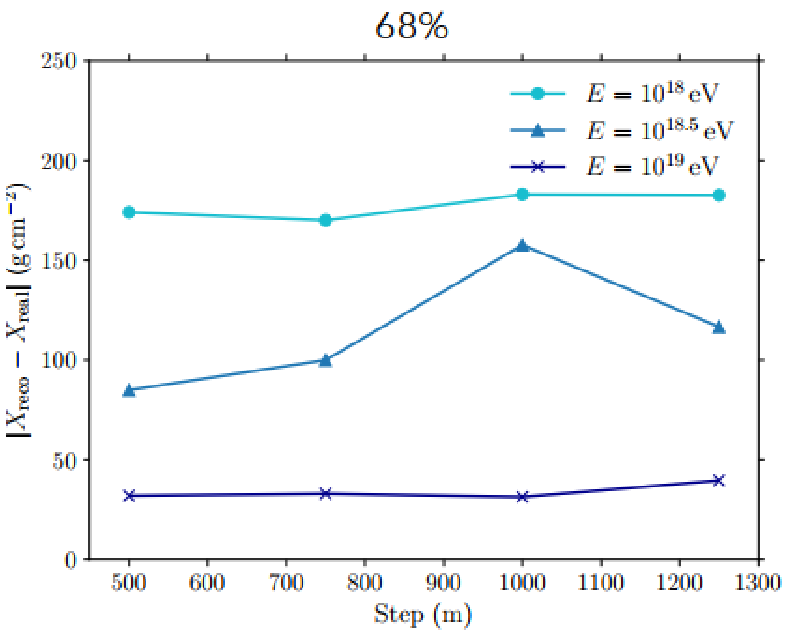
- SKA-Low would even reach below 10g/cm2 → extreme dense array, homogeneously covered footprint, visible Cherenkov ring arXiv:1702.00283
- Tunka-Rex achieves 35g/cm2 with fitting full pulse shape, not just amplitudes arXiv:1803.06862

Input from PD: geometry and energy → produce (many!) simulations accordingly

Top-Down in GRAND (C. Guepin at WP workshop Aug.2018)

Fixed parameters

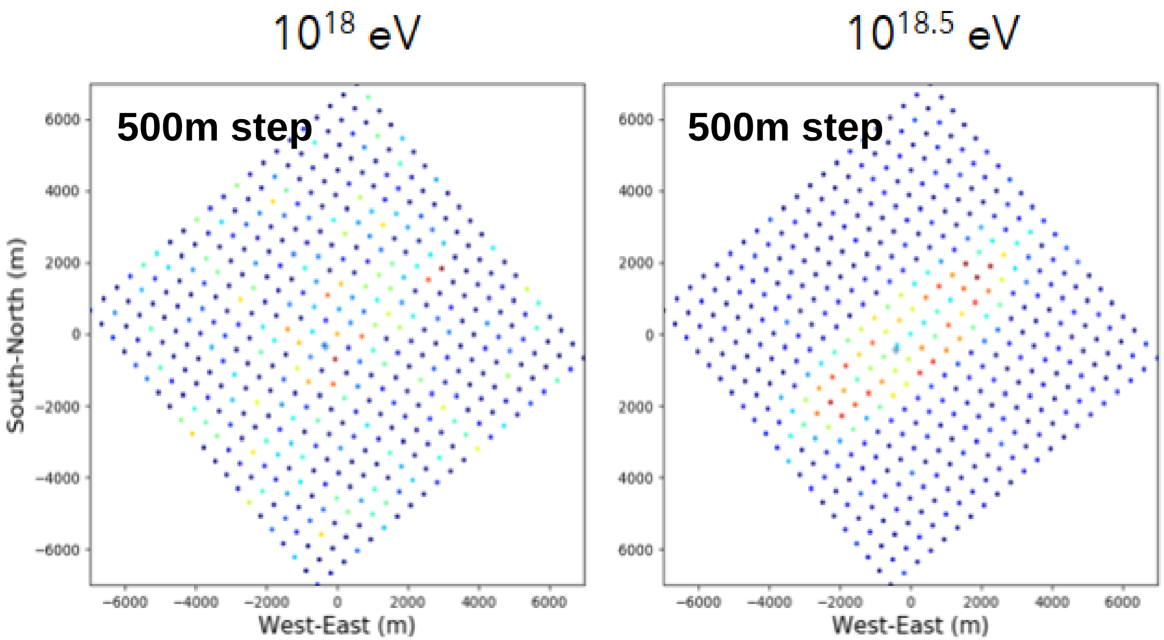
- zenith 83°
- azimuth 40°
- mountain slope 10°



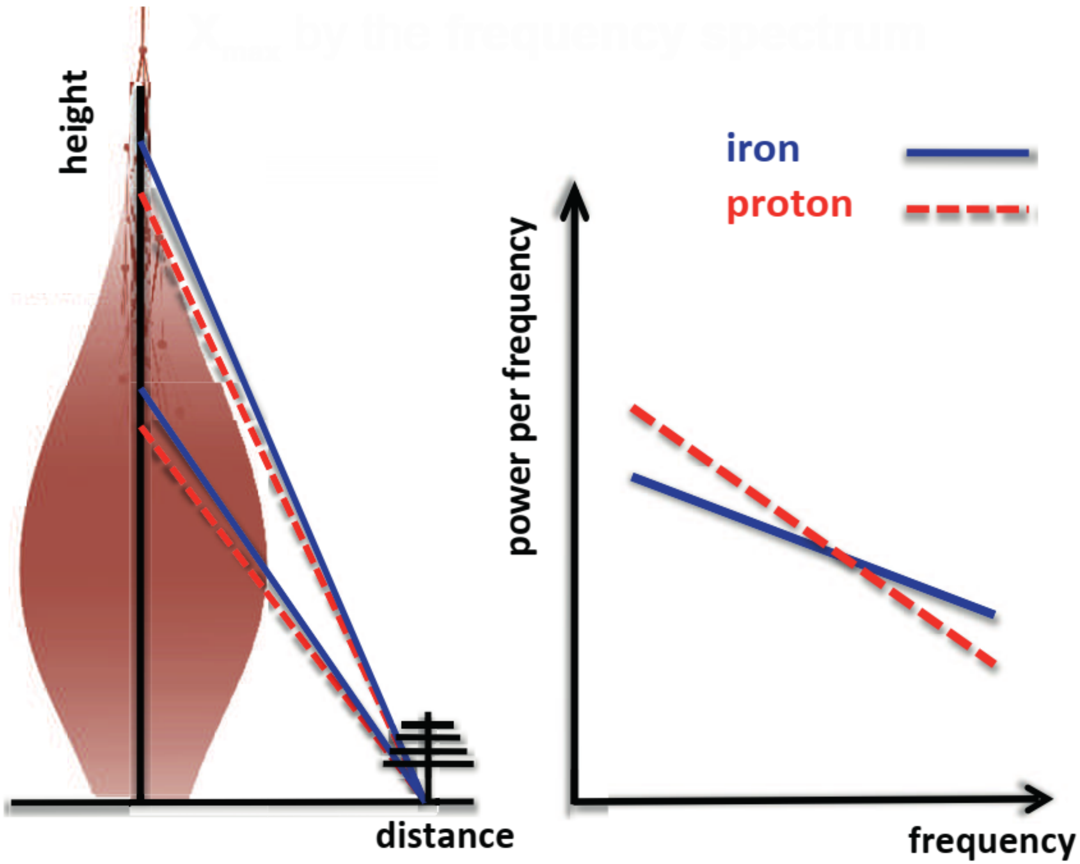
Needed as input:
Shower geometry and energy to minimize the parameter space which has to be covered.

- We should profit from the higher frequencies
  → more structures to fit
- Denser antenna grid should help to lower the reconstrcution uncertainty for lower energies
- we need enough antennas to perform a meaningful comparison to simulated footprints (+ impact of additional uncertainties)
  → a *methof for ‚high-quality events'?* - high number of antennas, well-reconstructed geometry and energy,….

We need to dig deeper into this!



Slope of frequency spectrum



Frequency spectrum measured at an individual antenna positions depends on
- position relative to shower axis
- position of Xmax

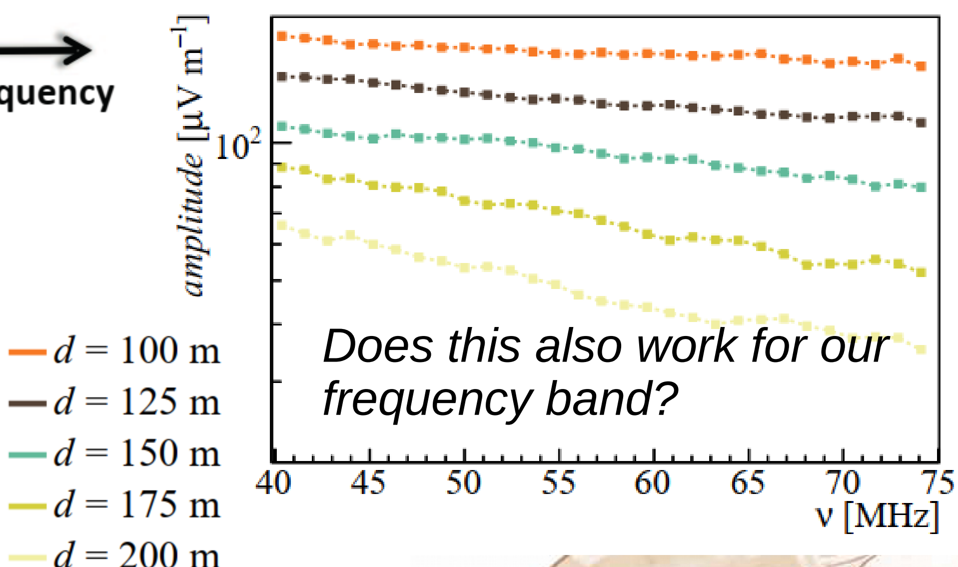
→ **spectrum gets steeper for depper Xmax**

→ on average iron softer than proton, but on 10% level

Advantage: applicable on single antenna (if geometry known)

Input: arrival direction, shower core, antenna position

For AERA:: single antenna: 163g/cm2,
2/3 antennas: 135g/cm2
Theoretical: 60 g/cm2



Does this also work for our frequency band?

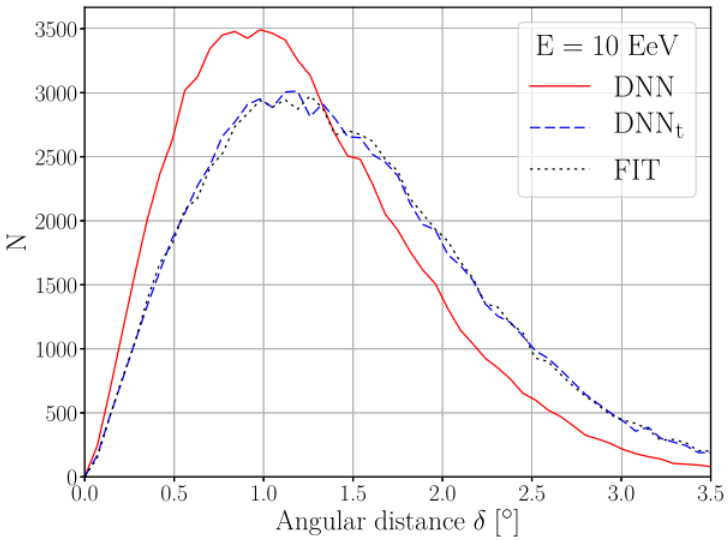
S. Jansen. Radio for the Masses. PhD thesis, University of Nijmegen, 2016.

Deep learning approaches

Not radio!
Auger water tanks!

Input: arrival times, the time-integrated signal amplitudes, and all features extracted from the time traces

Pers. Comment: BigData Workshop Aachen 2019: ML techniques can achieve same resolution, but work better for not fully contained events

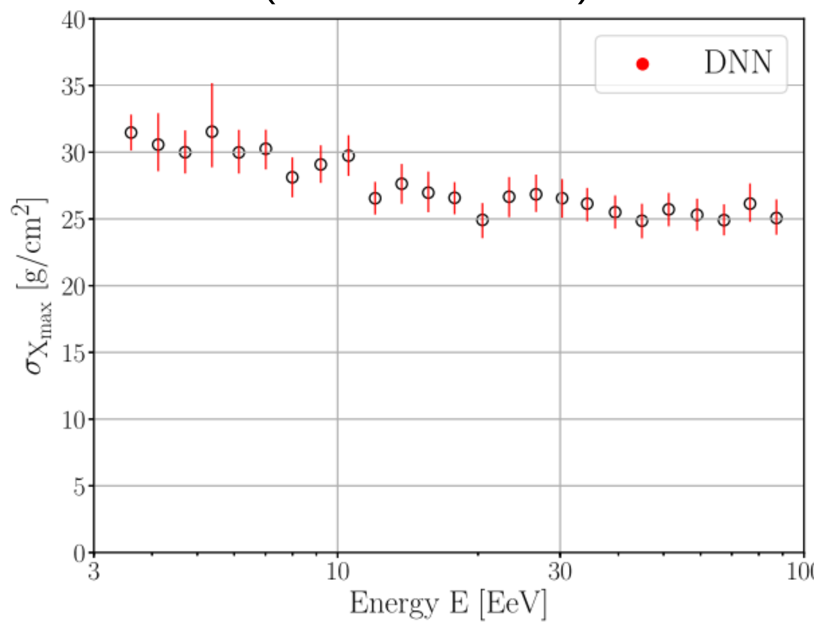


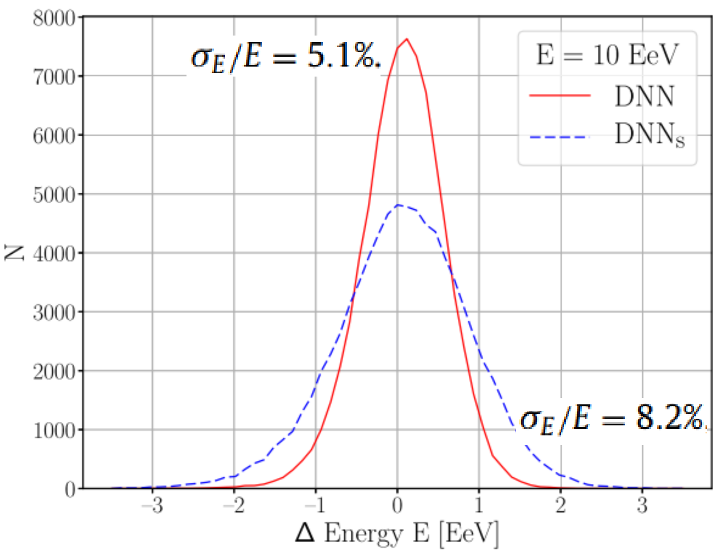
Angular reconstruction

Full info (from time + trace)
Just time
Plane wave fit

Shower max. reconstruction

Full info (from time + trace)





Energy reconstruction

Full info (from time + trace)
Just 2D ampl. Dist.

Could be a good basis to start and see whether similar architectures usable for radio

→ *Classification of type feasible!*

Astroparticle Physics 97 (2018) 46–53

Summary

Giant Radio Array for Neutrino Detection

Study well-understood standard techniques, check whether they are applicable
- to (highly) inclined/ upgoing showers!
- In our frequency band

→ Can we achieve the needed resolution on rado data only (w/o PD input)?

Goals of reconstruction:
Lower the energy threshold as much as possible with achieving the best resolution as possible

Going from GP300 to GRAND10k:
What happens for upward-going shower?

Regarding the ML hype at the moment:
Quote of a HESS guy doing Classification with DN:
„But: Sophisticated „standard“ analysis chains are hard to outperform
→ Don‘t try to beat them on on their home-base, but rather focus on regimes where standard analysis has no chance at all“

You are interested in join the development of reconstruction techniques for GP300 and GRAND?
Pick the method you like the most and check whether it is applicable to our pupose.
If you need a start into the topic, I am happy to point you to some useful papers or try to get you into contact with experts!
Mail to: zilles@iap.fr