Instituto Galego de Física de Altas Enerxías

Radio detection of air showers at Auger

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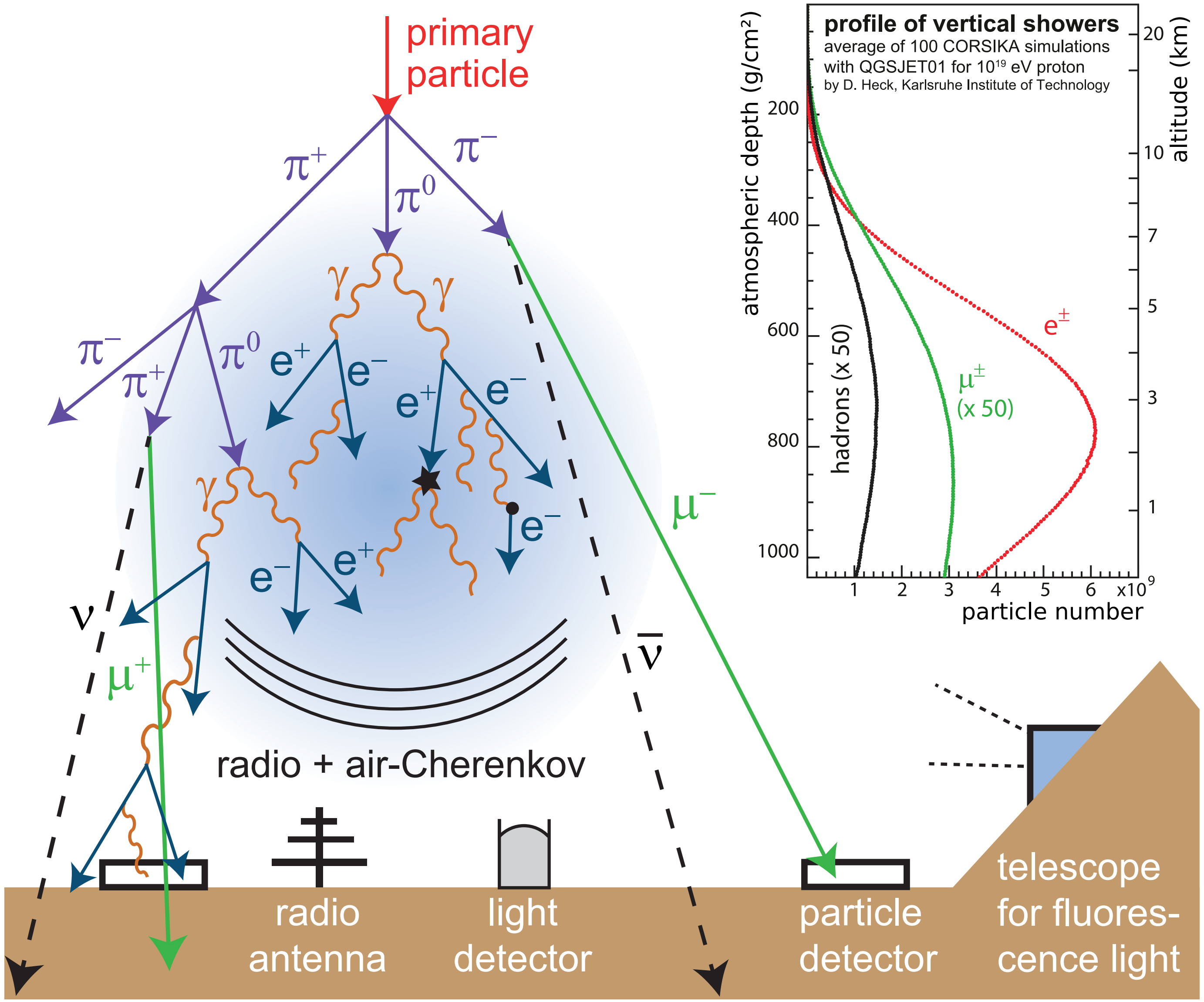
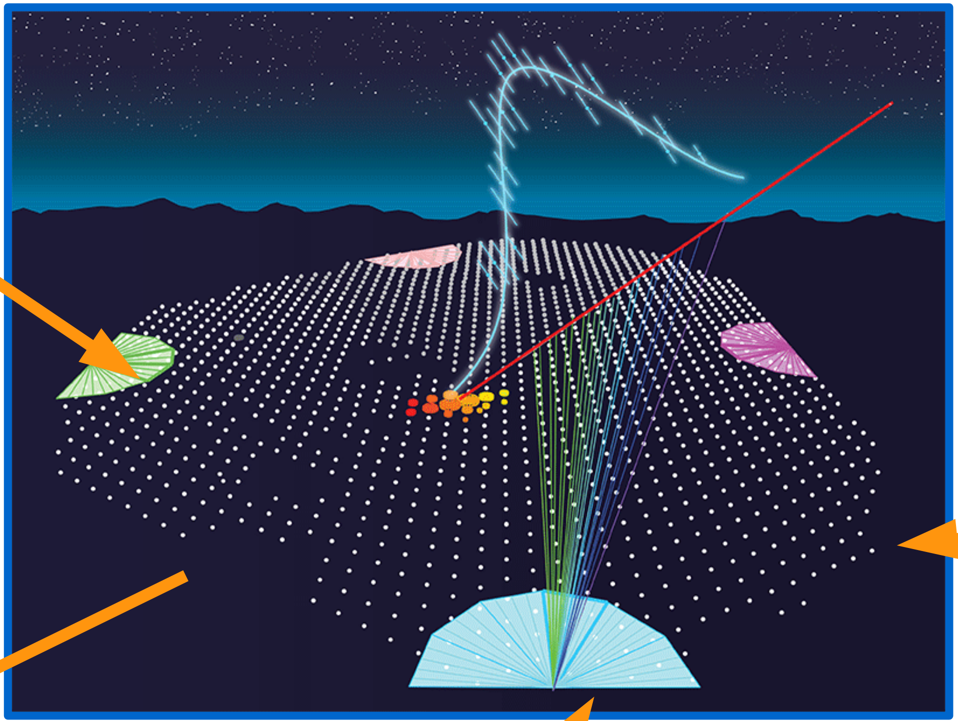
Extensive air shower (EAS)



- Interaction of incoming cosmic ray with atomic nucleus generates highly energetic secondary particles
- Further interactions or decay of secondary particles
- Cascade of secondary particles ~10^{11} particles for a 10^{20} eV primary
- Maximal number of secondary particles at an atmospheric depth X_{max}

The Pierre Auger Observatory

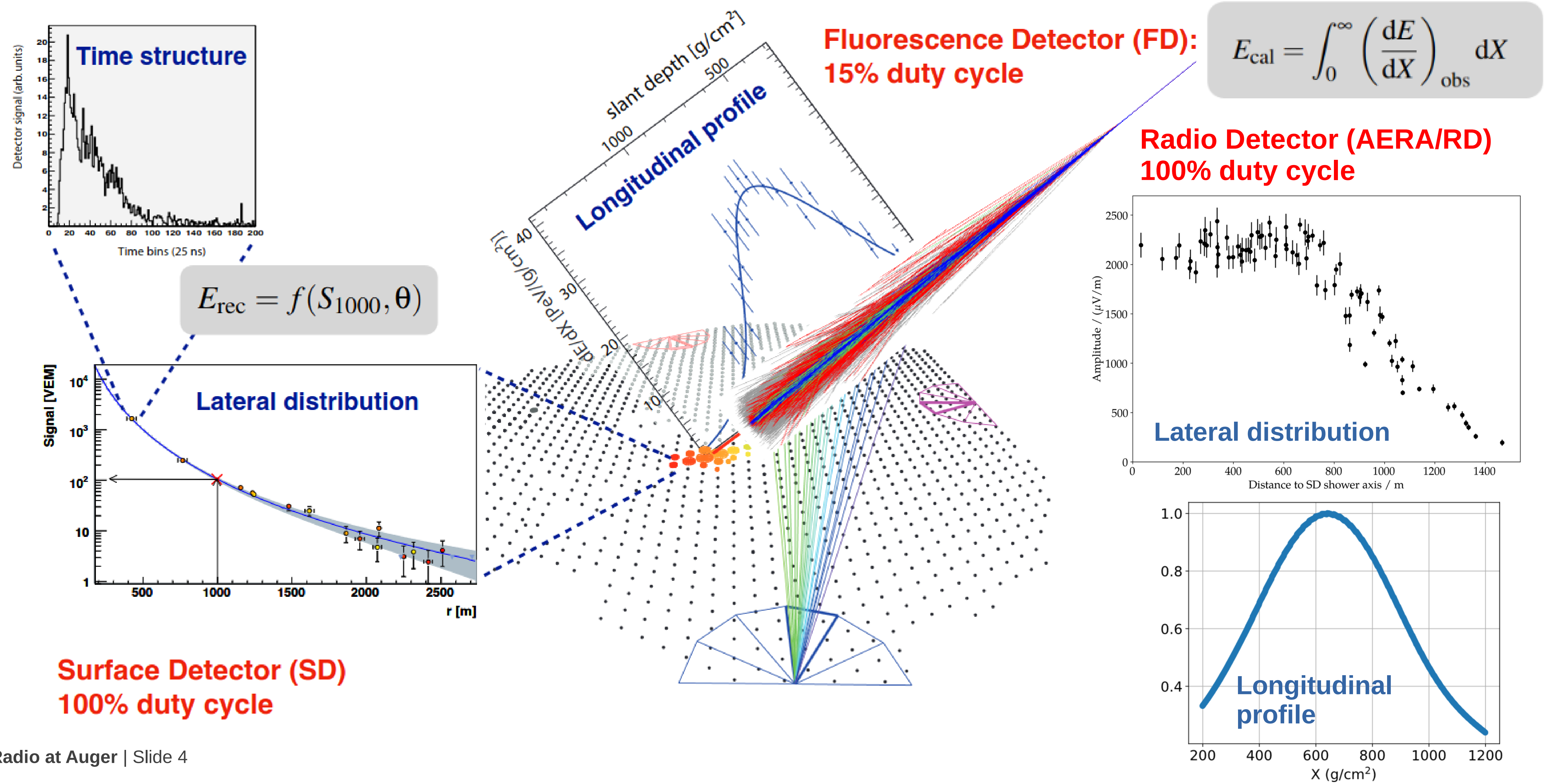
Auger Engineering Radio Array (AERA)
153 autonomous radio stations, total area: 17 km^2



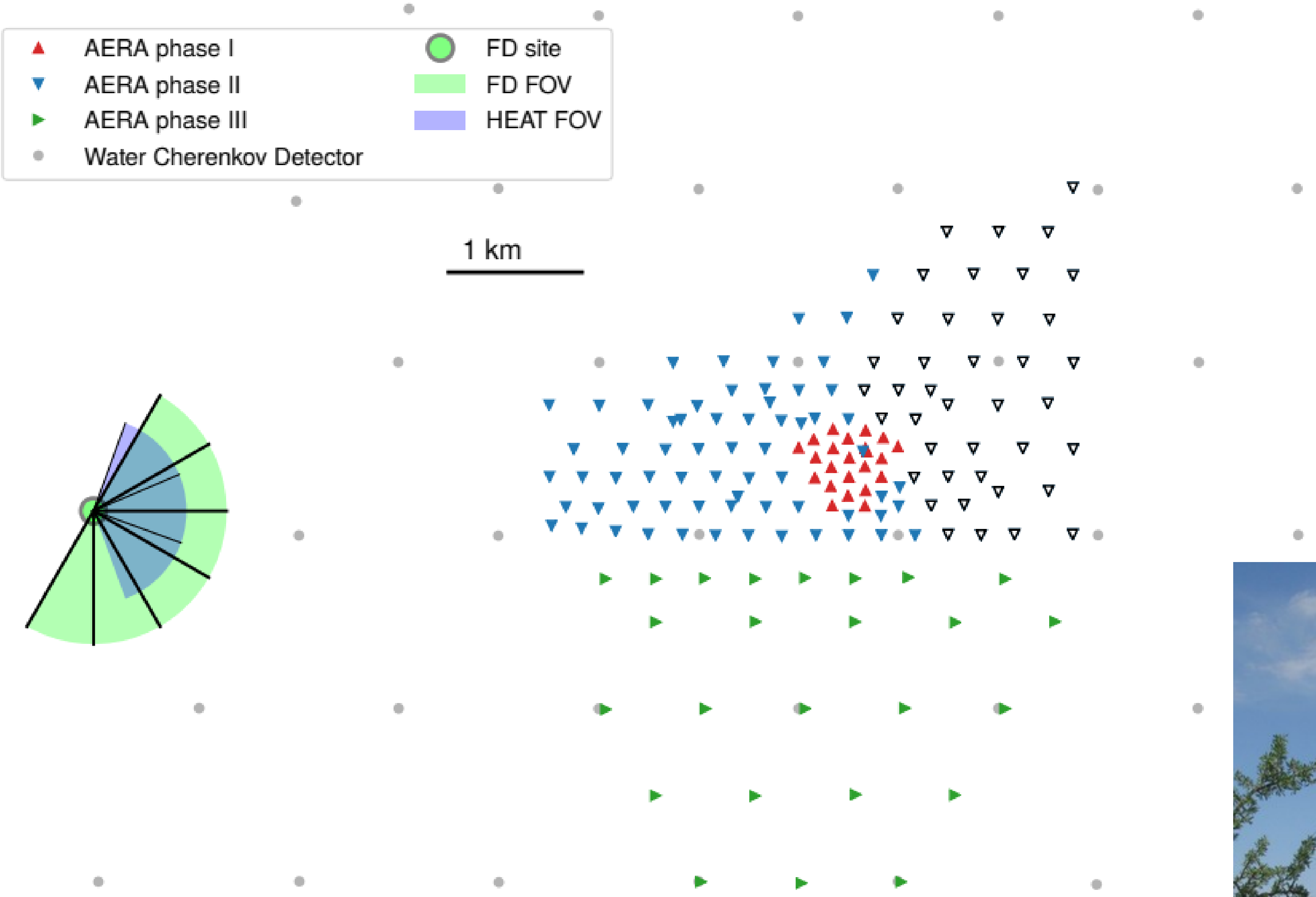
Water Cherenkov Detector (WCD)
1660 stations with 1.5 km spacing
total area: 3000 km^2

Fluorescence Detector (FD)

Hybrid Observation



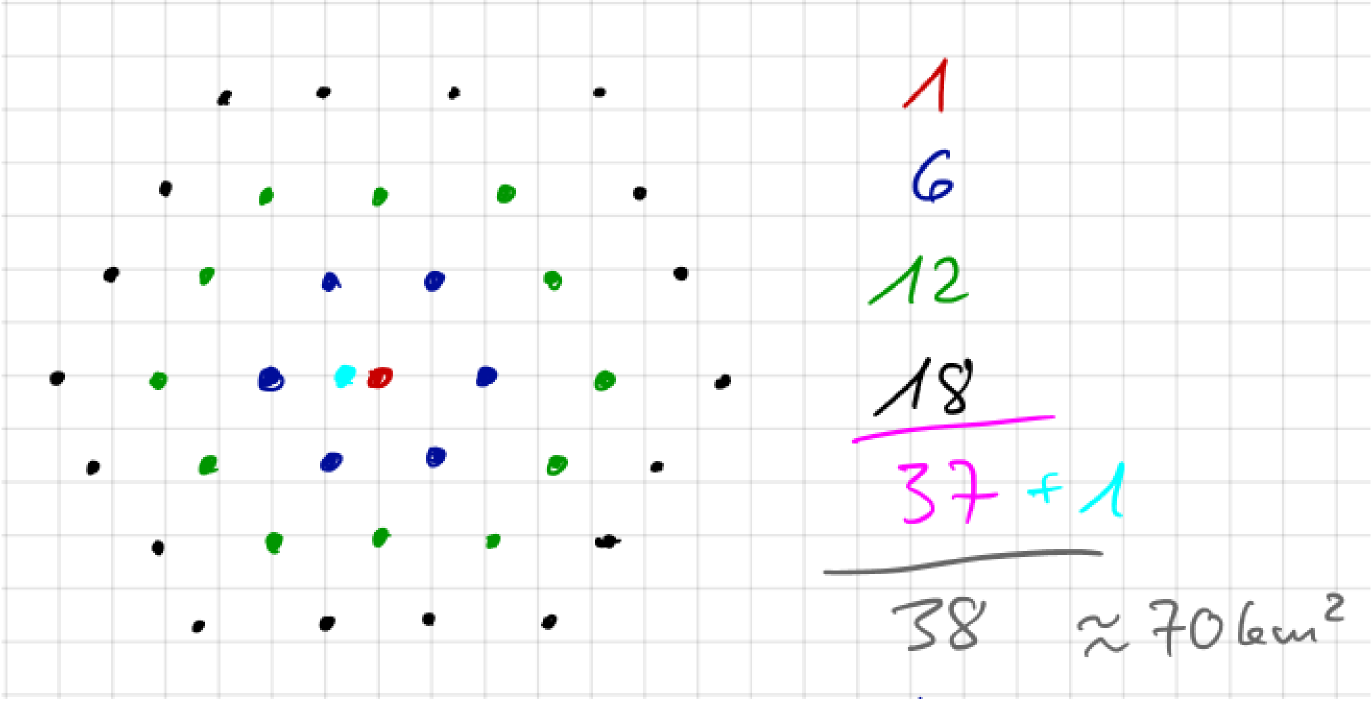
Auger Engineering Radio Array (AERA)



- Largest radio detector for cosmic rays (so far), running since 2011
- Energy range: 10^{17} – 10^{19} eV
- Built in phases with different antenna types and spacings 144 m to 750 m
- 2 polarizations (NS, EW), bandwidth 30 – 80 MHz
- Precursor of the AugerPrime Radio Detector

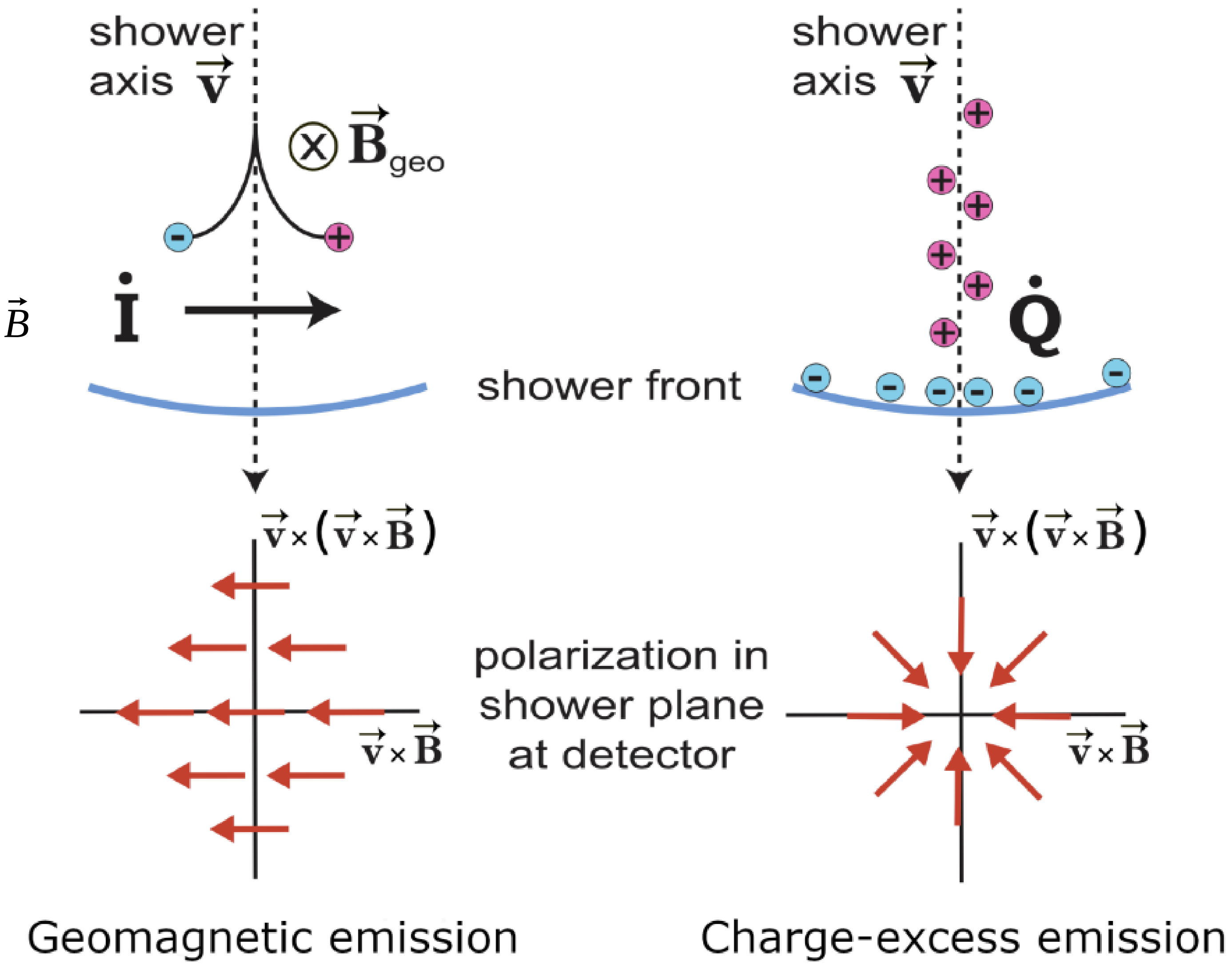
AugerPrime Radio Detector

- Externally triggered by WCD, developing an independent radio trigger for air showers with small particle footprint
- Full hexagon (7 stations) deployed since in November 2019 in the field. Now extending to 38 stations, ~70 km
  → This will be the largest radio detector for cosmic rays



Radio emission

- **1st order: geomagnetic radiation**
  - Electrons/Positrons deflected in Earth's magnetic field
  - Scales with magnetic-field strength and angle between shower axis and $\vec{B}$
  - Polarized into direction of Lorentz force $\vec{v} \times \vec{B}$
- **2nd order: charge excess / Askaryan effect**
  - Time varying net charge excess due to ionization of ambient medium
  - Radially polarized towards shower core
- Superposition of both emissions and Cherenkov-like compression of signal on a ring around shower axis
  → asymmetric (bean-like) radio footprint



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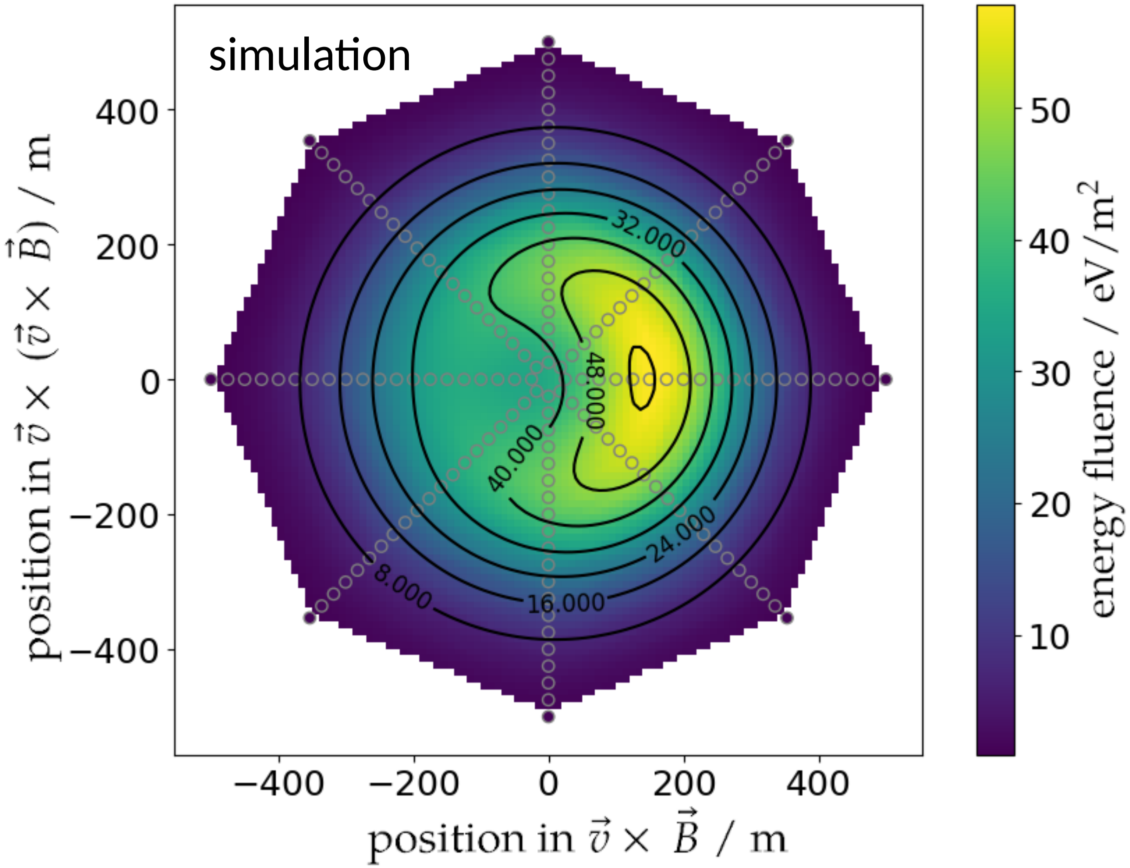
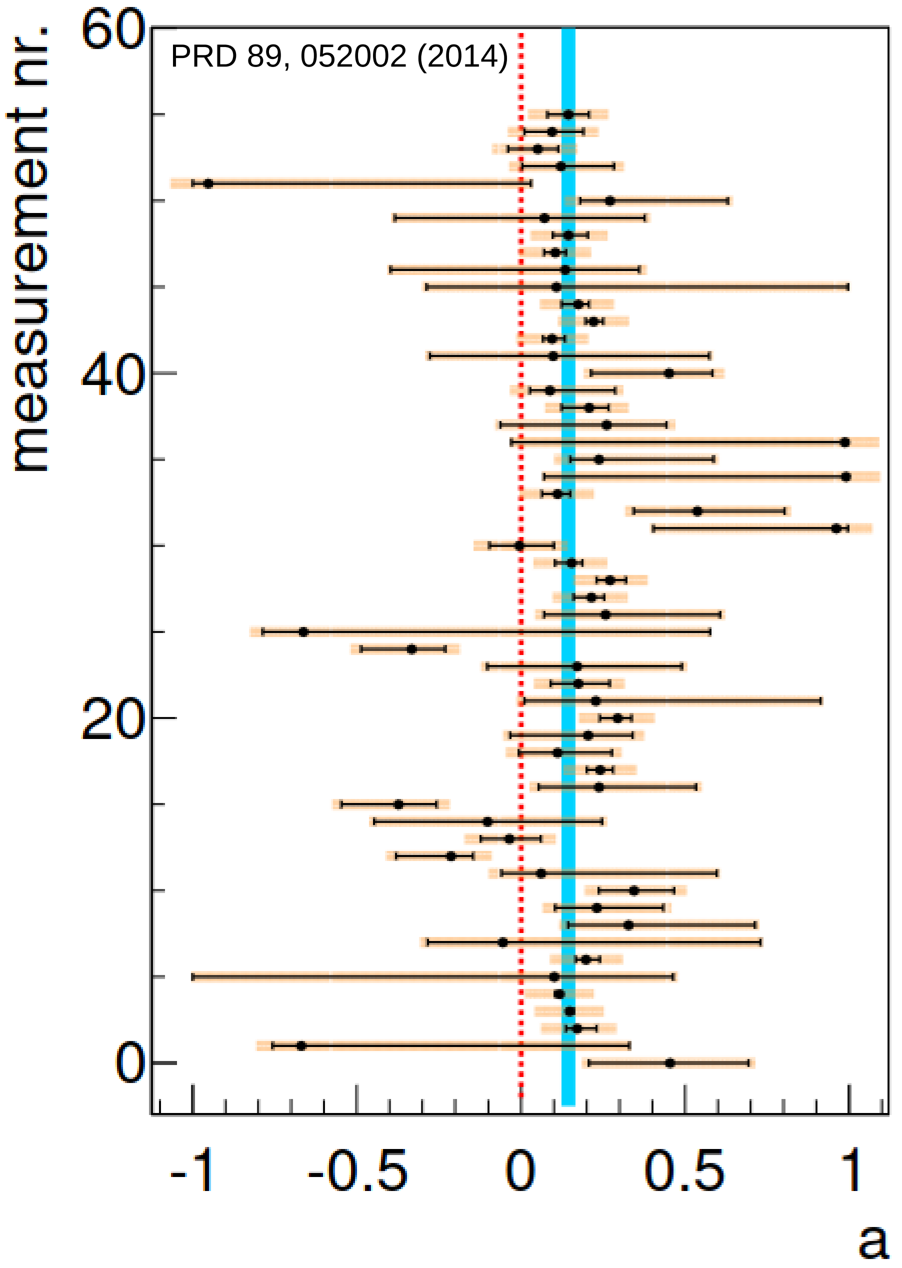


Charge excess fraction

- Derive relative strength of the electric fields induced by both processes, a, from measured polarization
- AERA: $\bar{a}$ = 0.14 ± 0.02 for 56 stations in 17 events
  - There is a charge excess component
  - Geomagnetic mechanism is dominant in air



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- LOFAR: increase of the charge-excess fraction with
  - Increasing radial distance from the shower axis r'
  - Decreasing zenith angle θ
- We have much more data by now.
  No inclined air showers with θ > 60° analysed
- MA student in Wuppertal repeating analysis to obtain full description of
  a(zenith angle, position in the showerplane)

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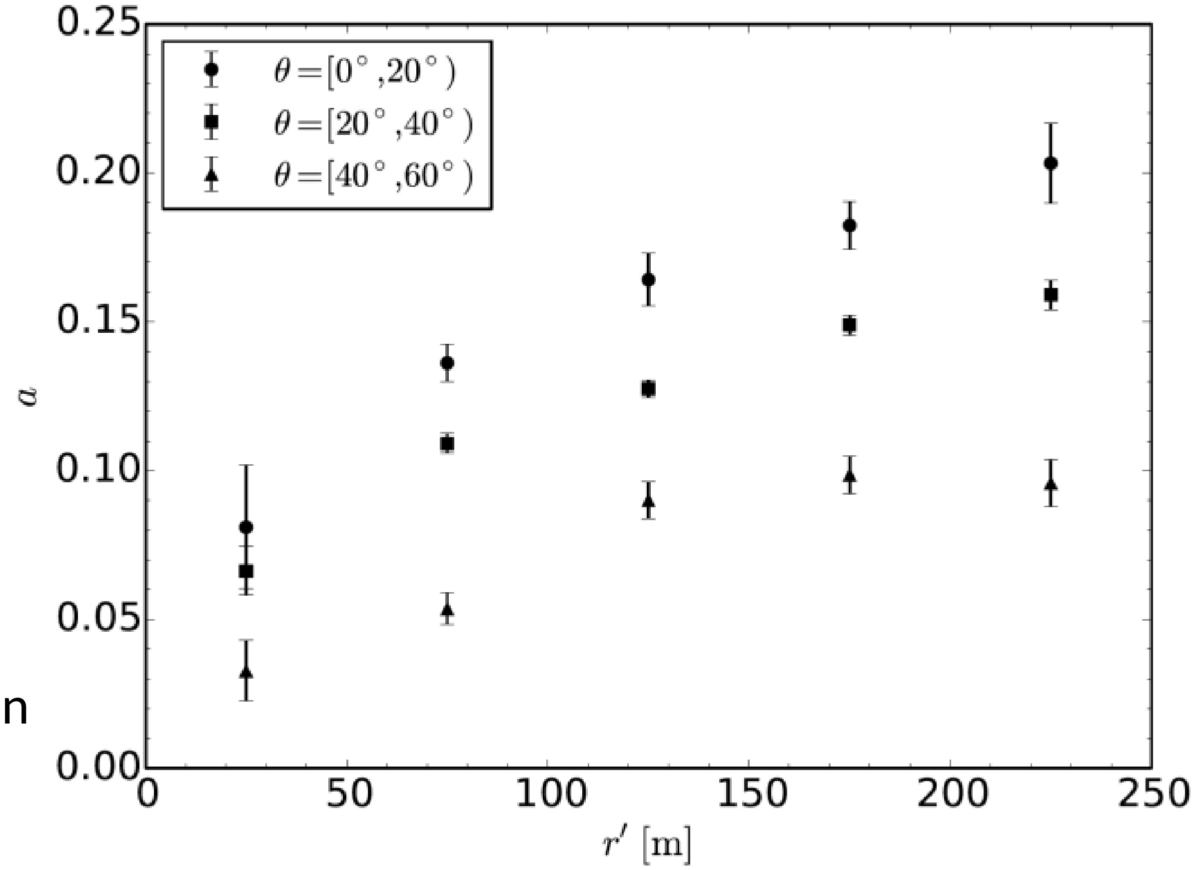
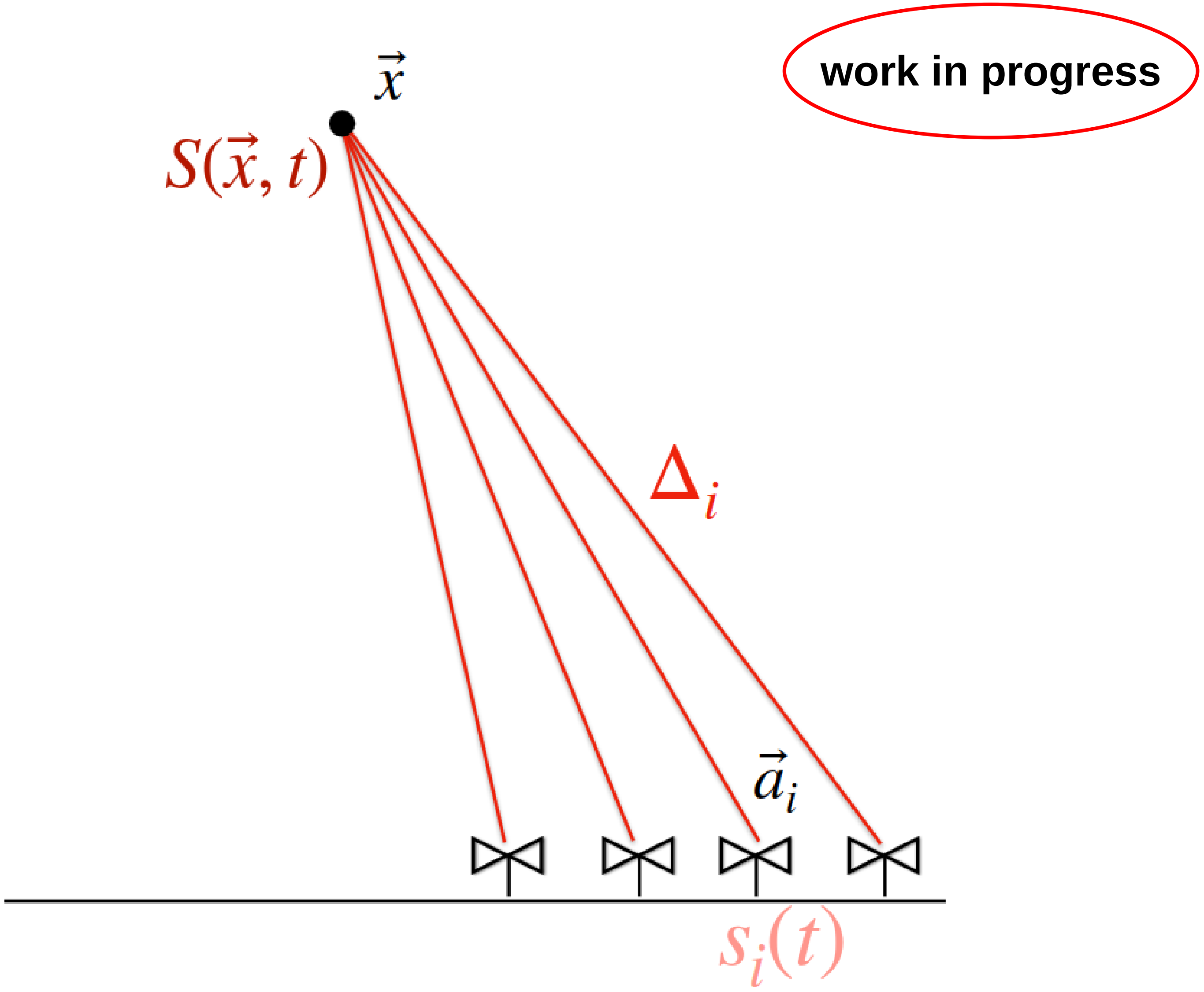


Interferometry - Concept



Measure signal $s_i(t)$ at location a_i

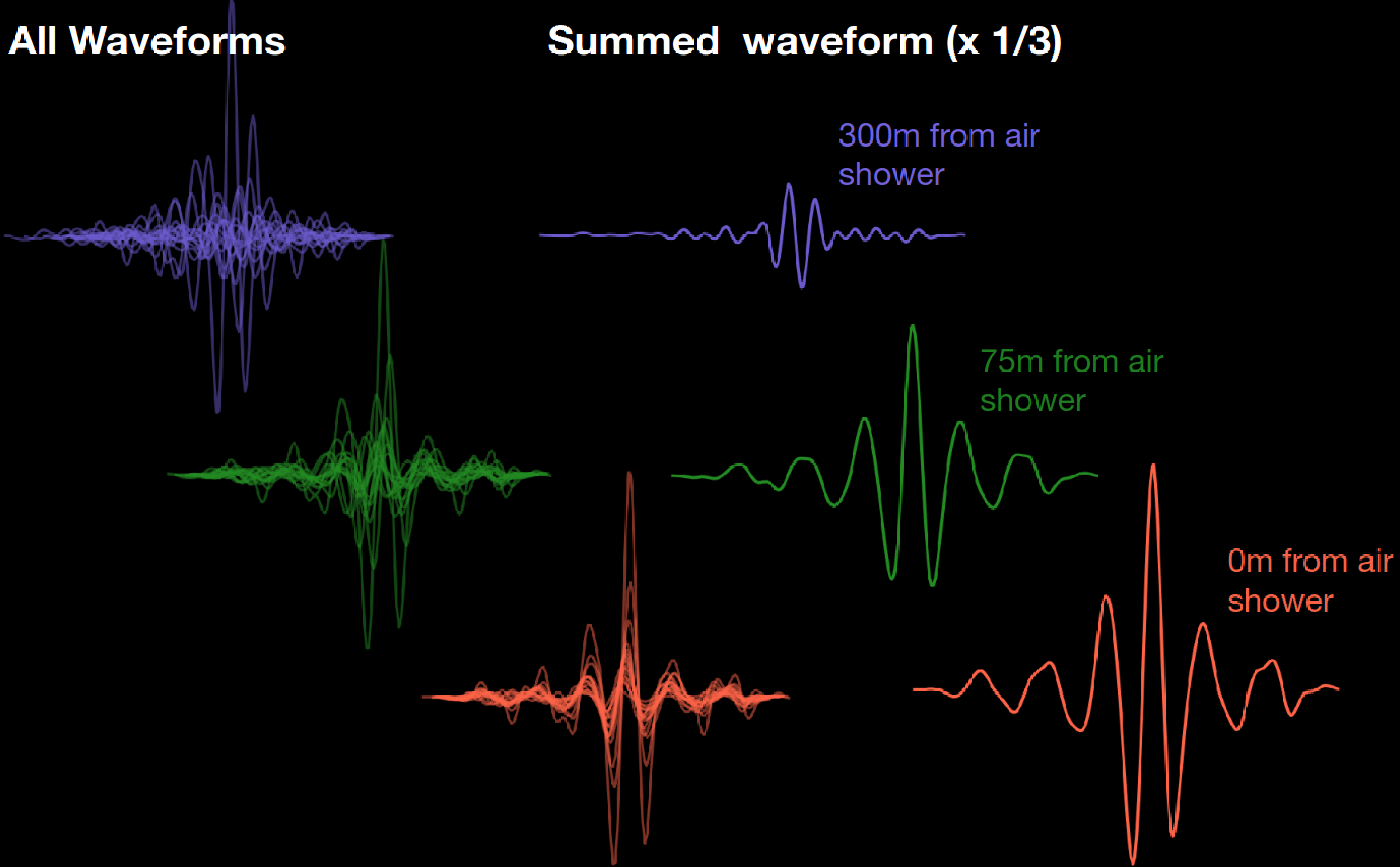
Calculate light travel time from antenna $\vec{a}_i$ to a location in space $\vec{x}$

$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i| n_{eff}}{c}$$

Sum the waveforms from all antennas together with delays $\Delta_i(\vec{x})$ at $\vec{x}$:

$$S(\vec{x}, t) = \sum_i^N s_i(t + \Delta_i(\vec{x}))$$

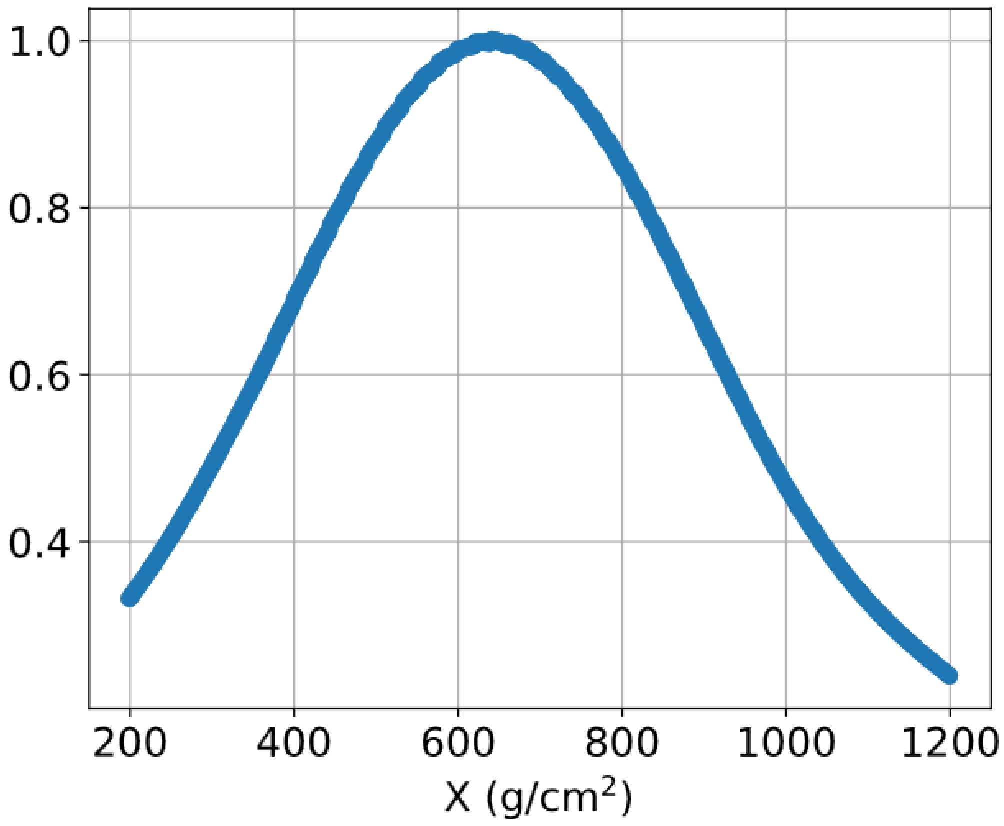
All Waveforms **Summed waveform (x 1/3)**

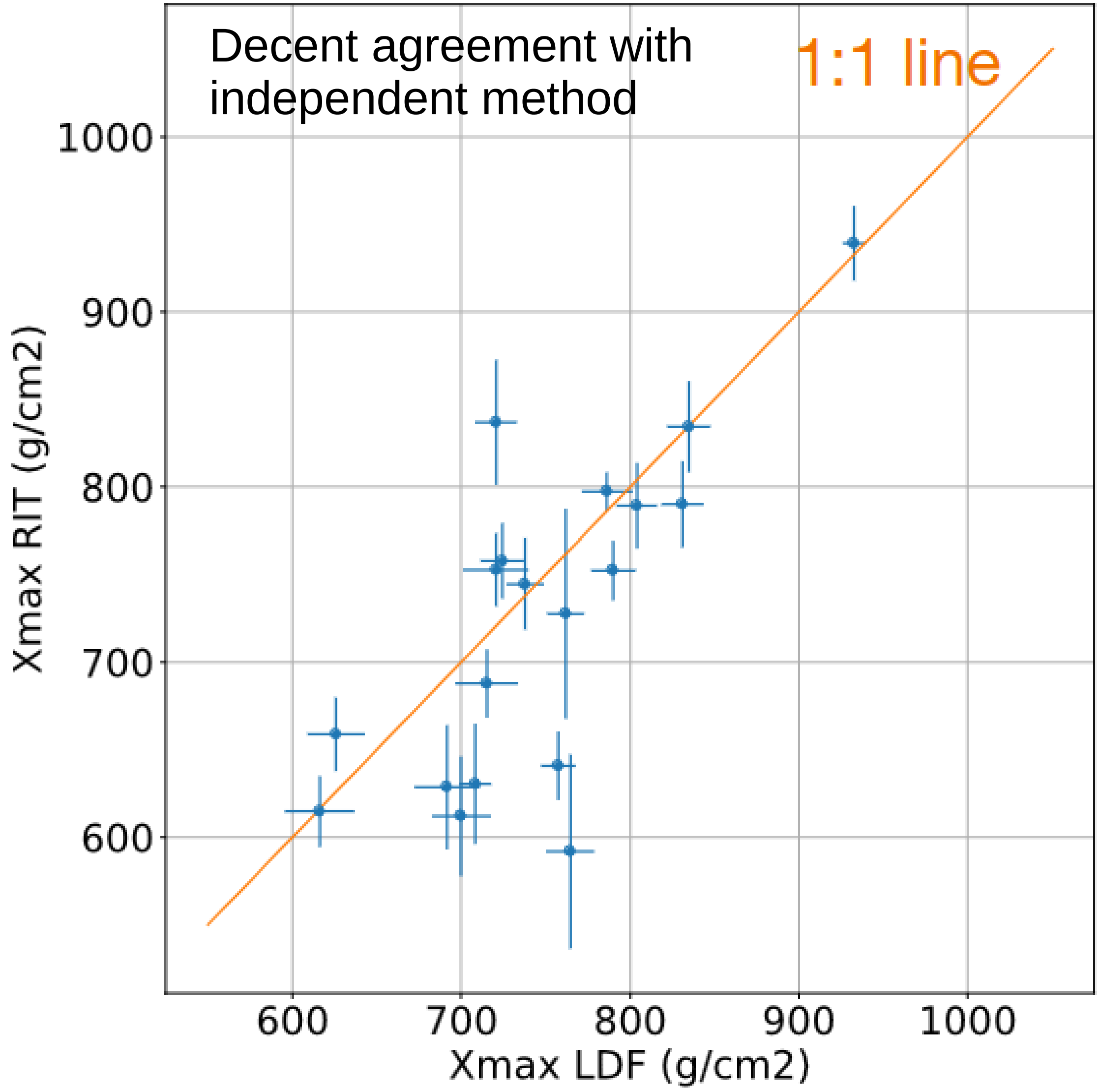


Reconstructed AERA event

- Interested in reconstructing X_{max}
- Very precise timing calibration needed

intensity along axis (normalised)

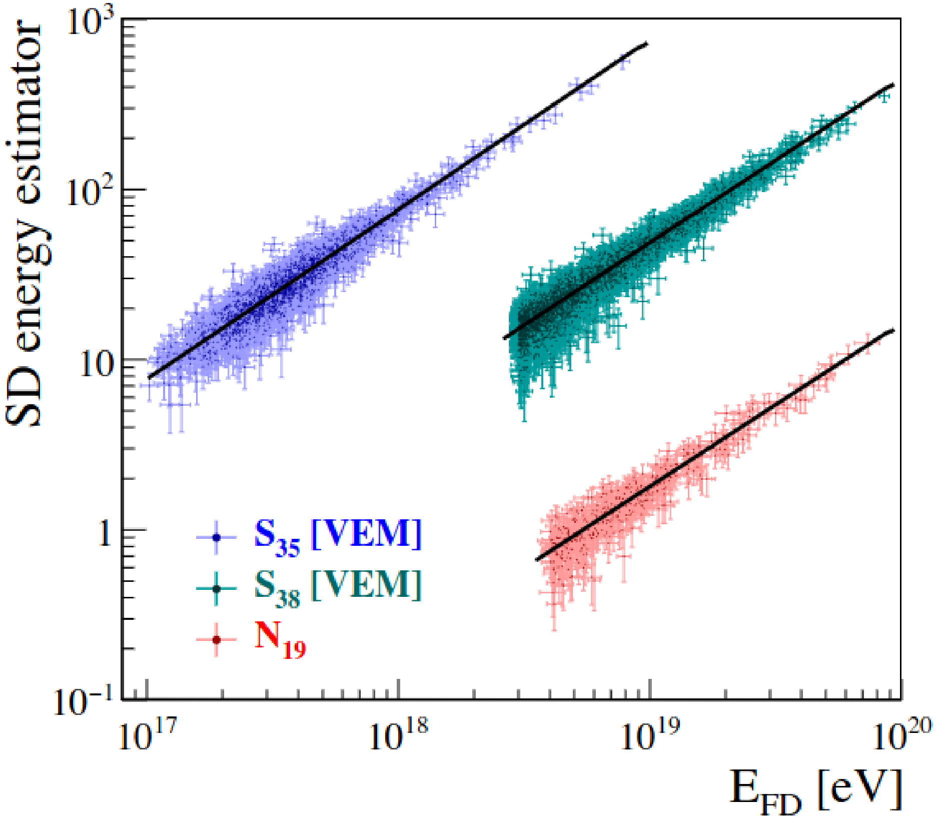


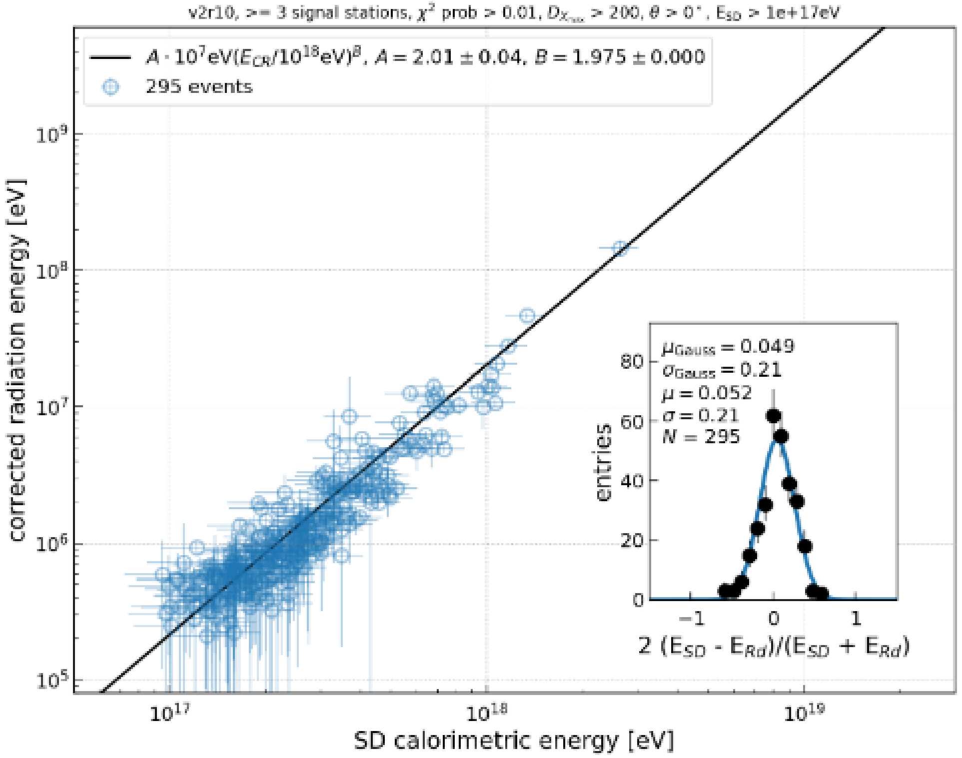


Calibration with FD energy scale

work in progress

- FD sets the only energy scale for Auger!
- Energy estimators of other detectors need to be calibrated with the FD

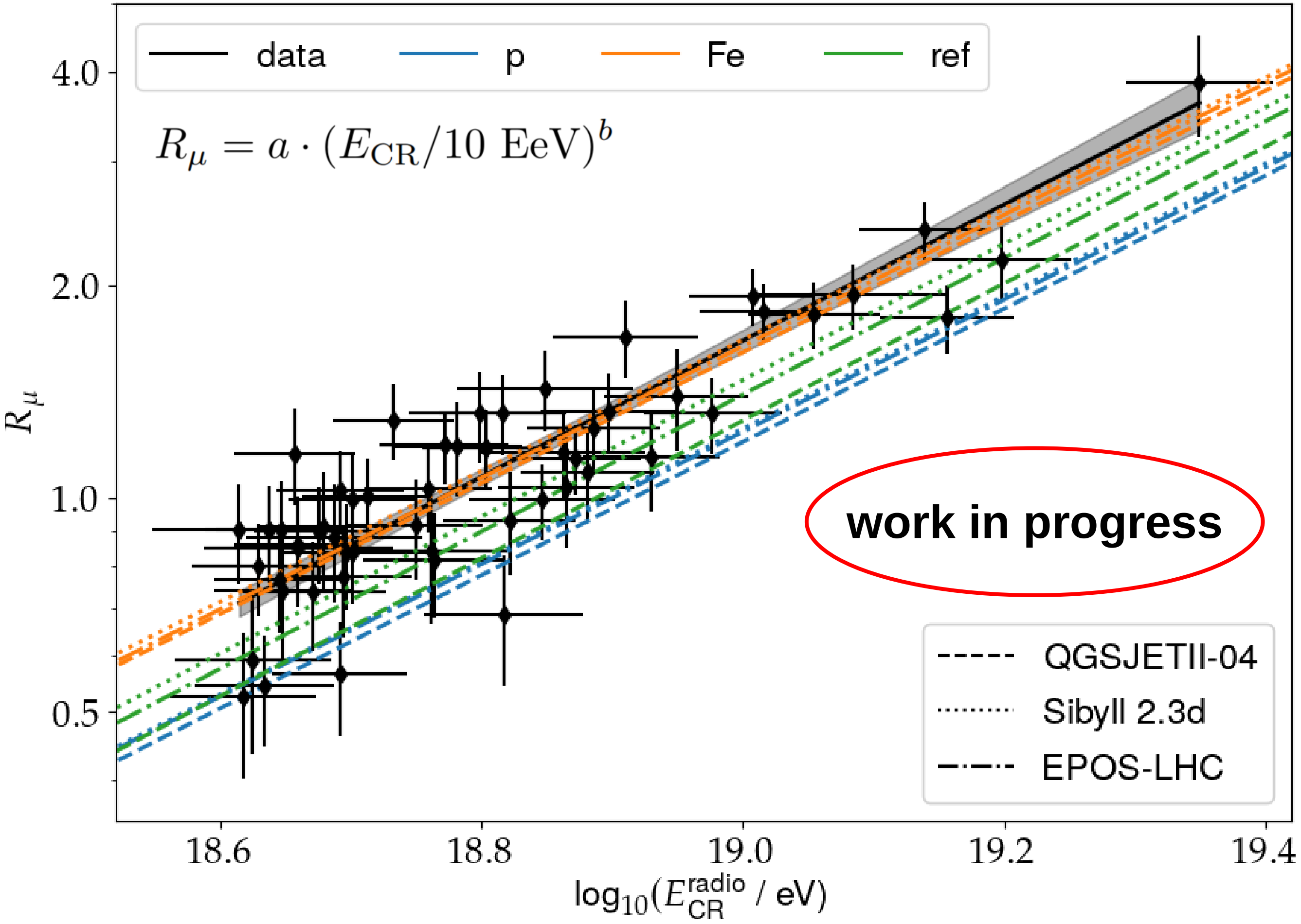


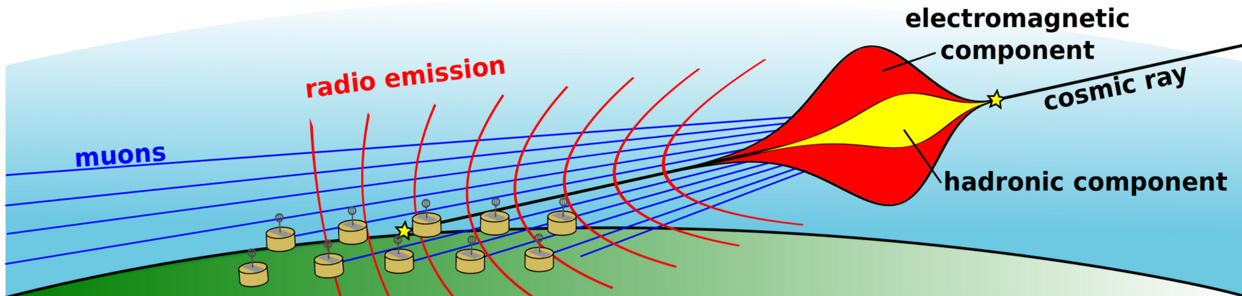


All heil 👑 to King FD

Muon content

- For inclined WCD-AERA hybrid events separation of electromagnetic and muonic component in the atmosphere
  - WCD: muon estimator, R_μ
  - AERA: energy, E
- Hybrid events allow measuring $R_\mu(E)$ and compare result for data and simulations
- AERA data from 26.06.2013 to 16.11.2019 → 59 events after cuts
- Deficit of muons in simulations
- Challenge: low number of events
  - AERA is small → RD is not
  - High energy threshold originating from the WCD 1500m array → develop reconstruction for the 750m sub-array





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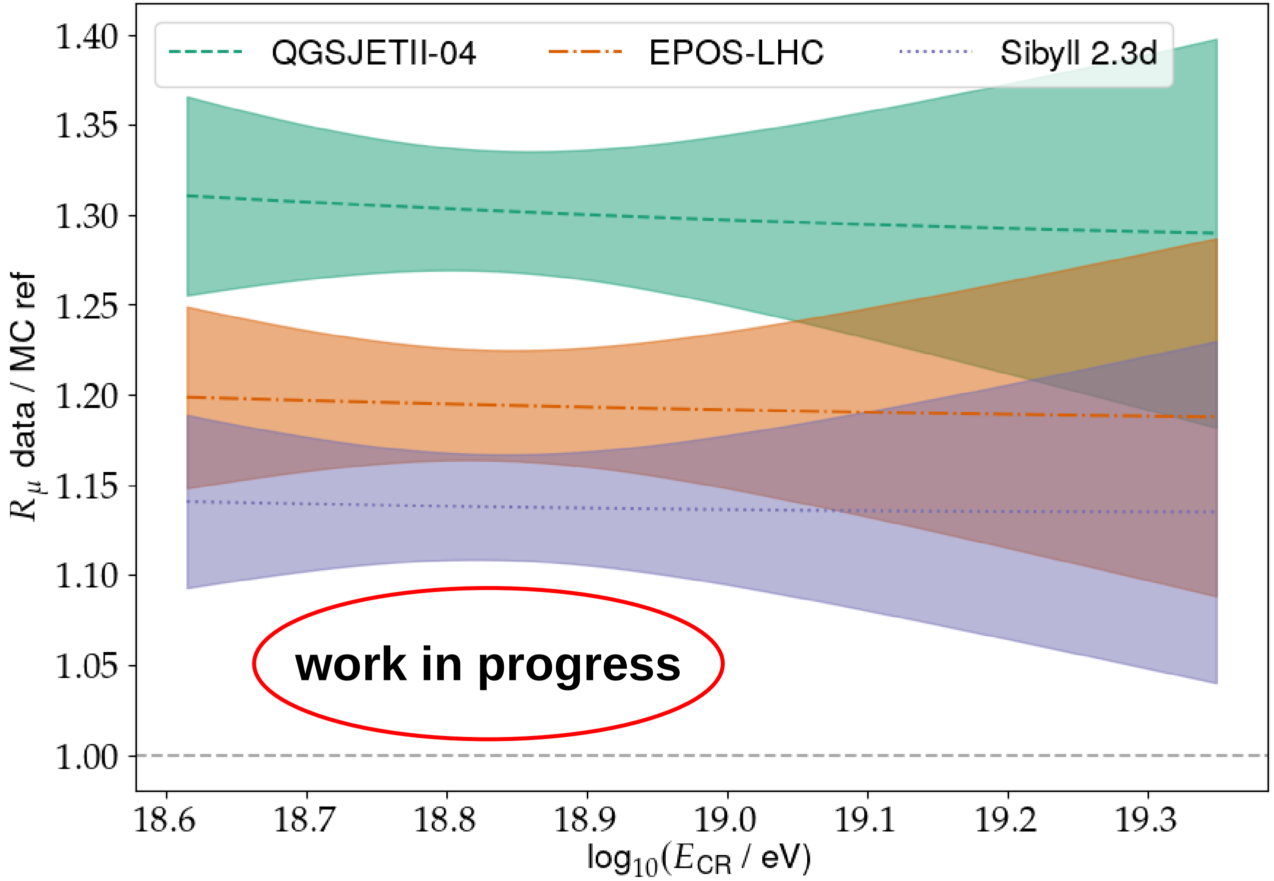
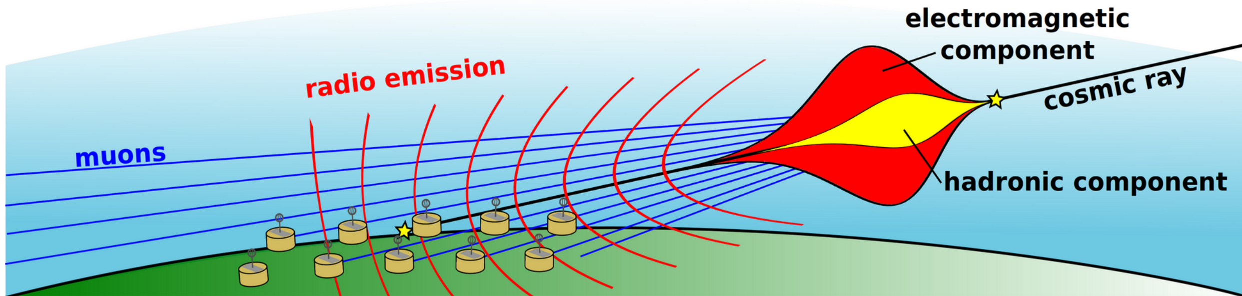
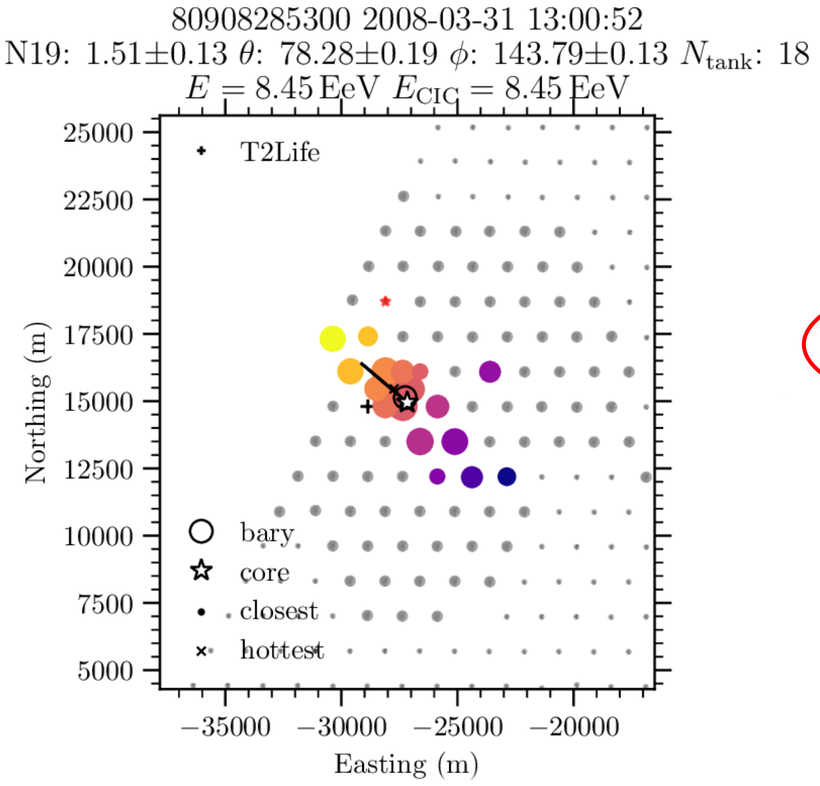




Calibration of the SD HAS infill with AERA

Particles (Felix Riehn)

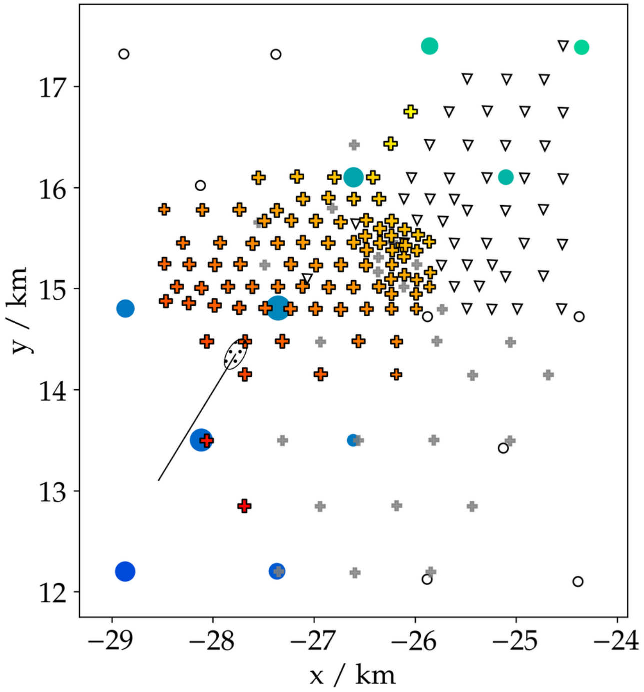
- Use infill and regular array in Efit
- Energy estimator (N19)



Radio (me)

- Standard reconstruction
- Read external geometry from Efit

work in progress



Combine both information

```
event_ID  n19_efit  other ...  radio_enery_offline
     123         1          0         1.000000e+19
```

Summary

- With radio we can reconstruct all important shower observables: arrival direction, energy, X_{max}.
  Sensitive to neutral particles, hard(er) to detect with other detectors
- AERA showed maturity of the radio detection,
  RD will collected CR at the highest energies with large statistics
- Still a lot of interesting physics to explore, esp. with hybrid events
- Event statistics of the RD for 10-year exposure using measured flux at Auger