Something about SKA simulations



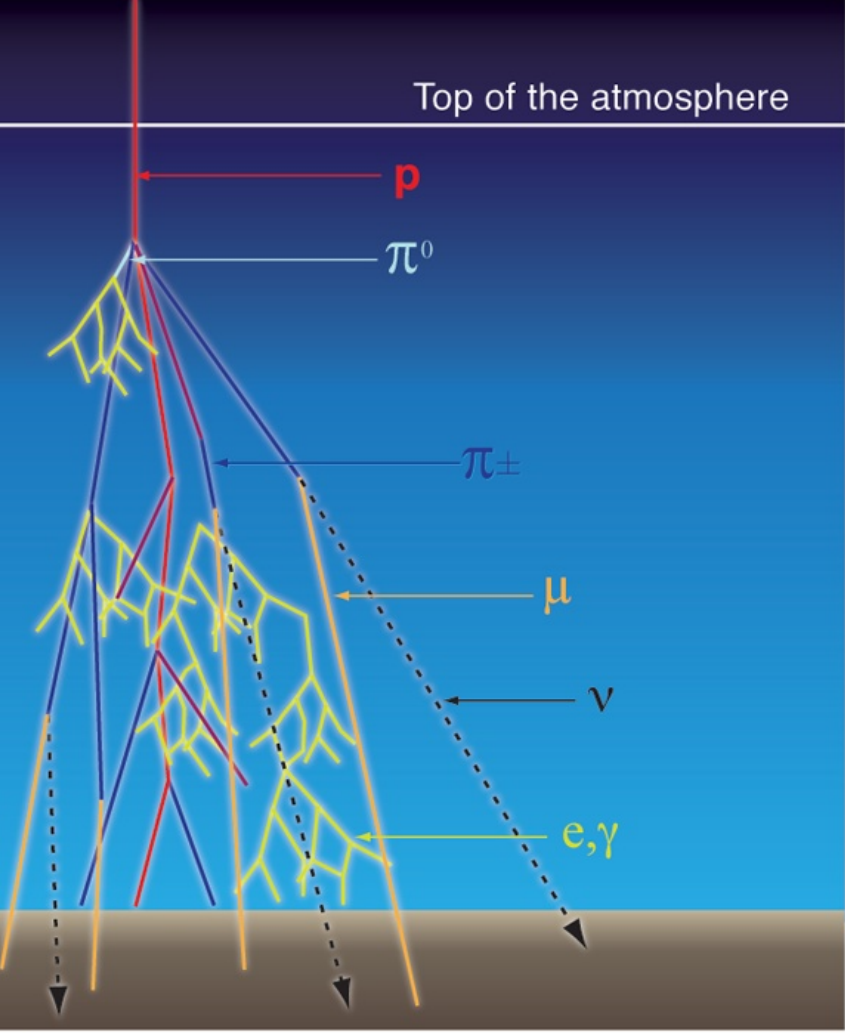
Arthur Corstanje
Vrije Universiteit Brussel

LOFAR-CR meeting Nijmegen,
April 8-10, 2024

VUB VRIJE UNIVERSITEIT BRUSSEL

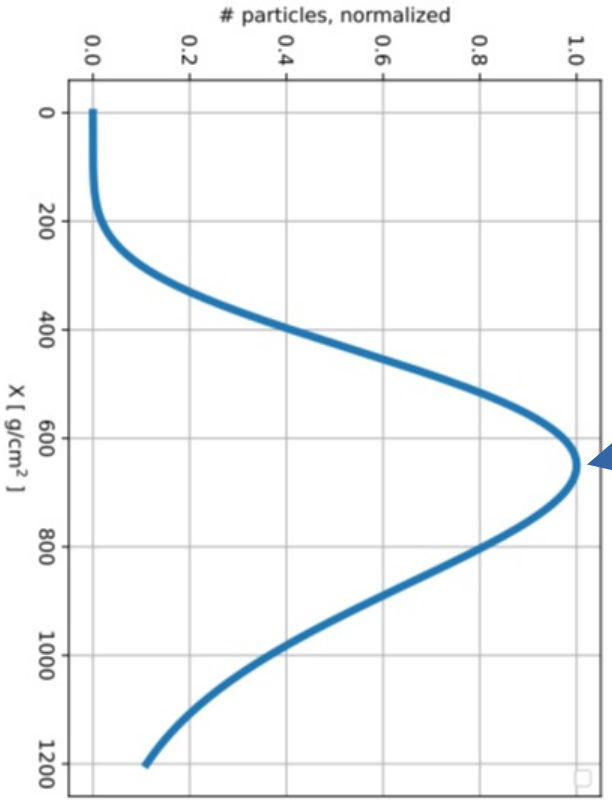
SKAO

Radboud Universiteit



Extensive air showers

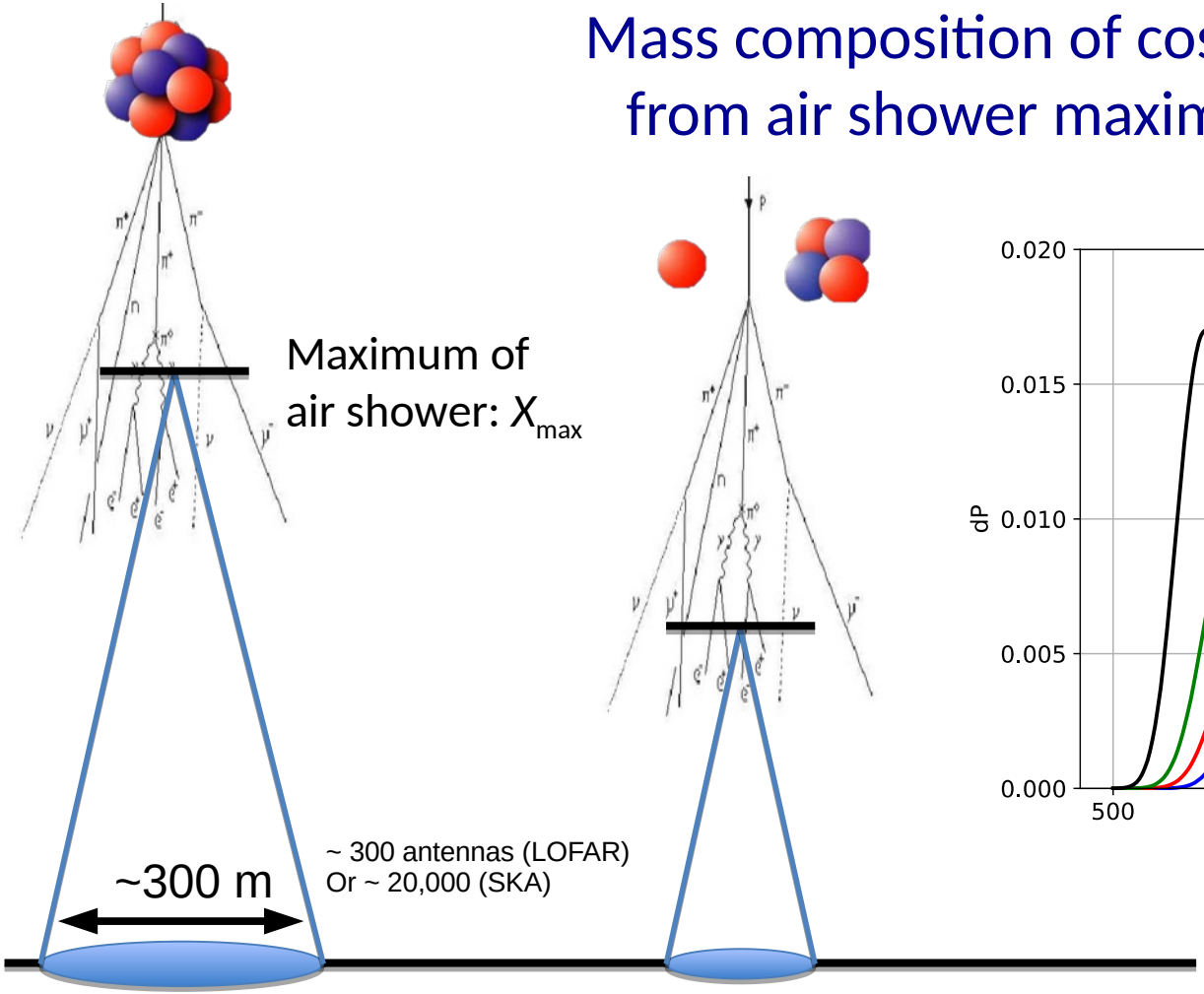
Longitudinal profile of number of particles

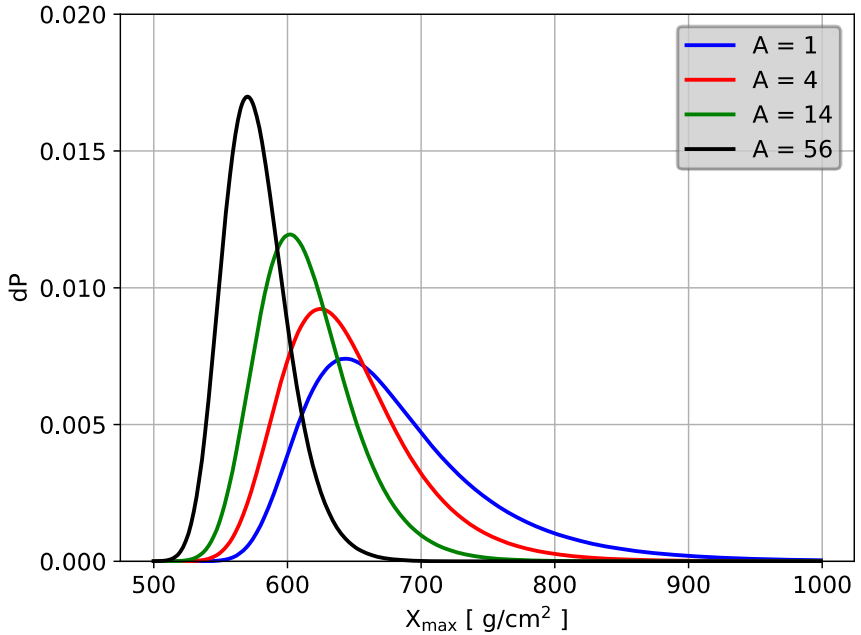


Shower maximum X_{max} varies with primary particle mass
- on average
- in distribution

X_{max}

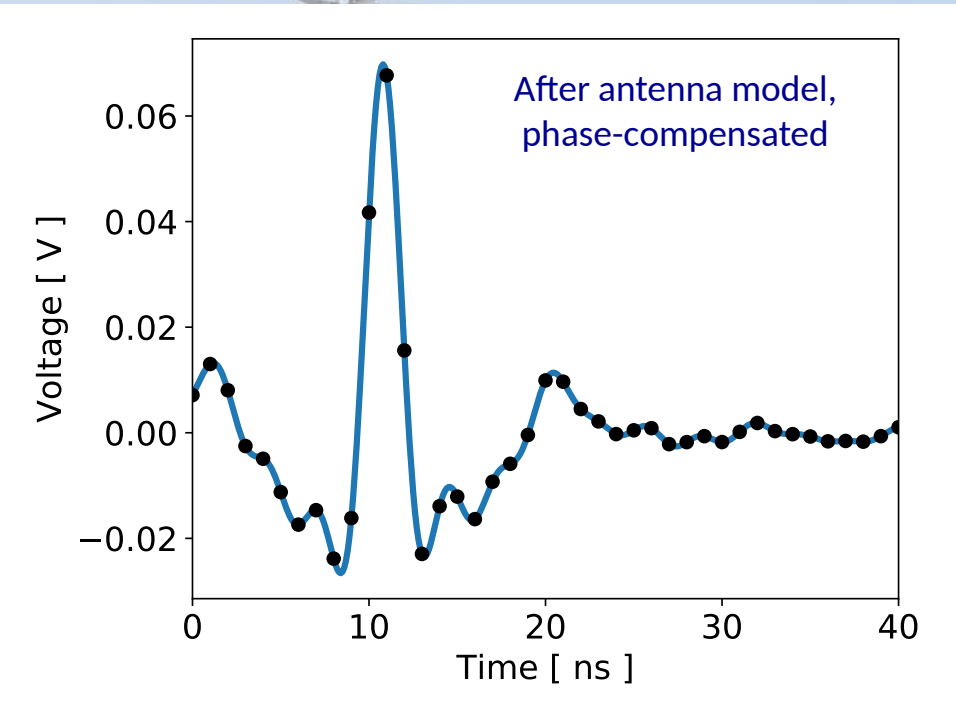
Mass composition of cosmic rays, from air shower maximum X_{max}



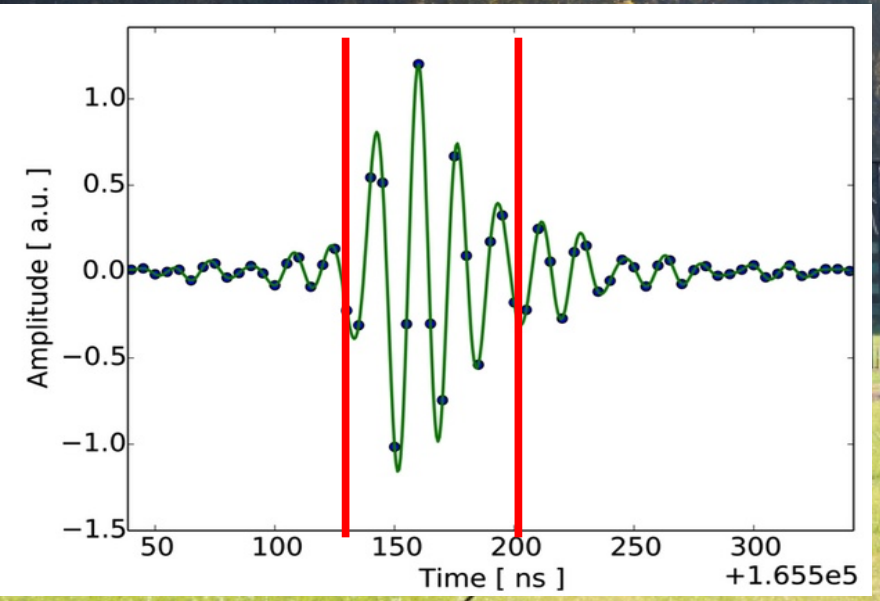


Pulses in SKA-Low antennas

Use raw voltage signals per antenna



Measuring energy fluence



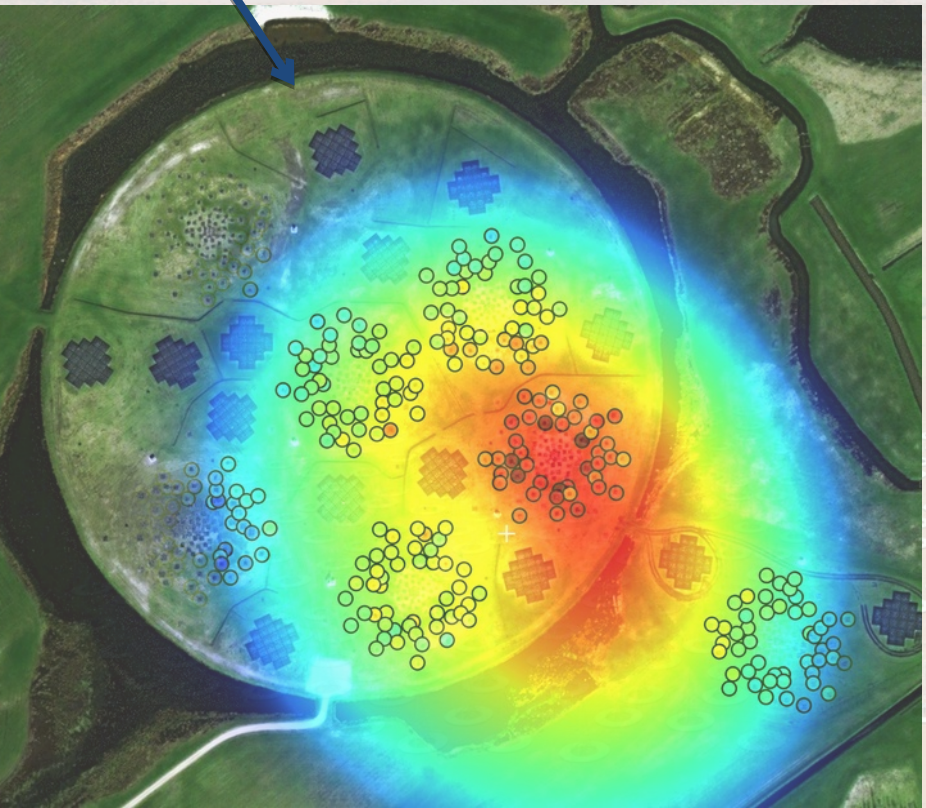
Integrate ‘power’ in a time window

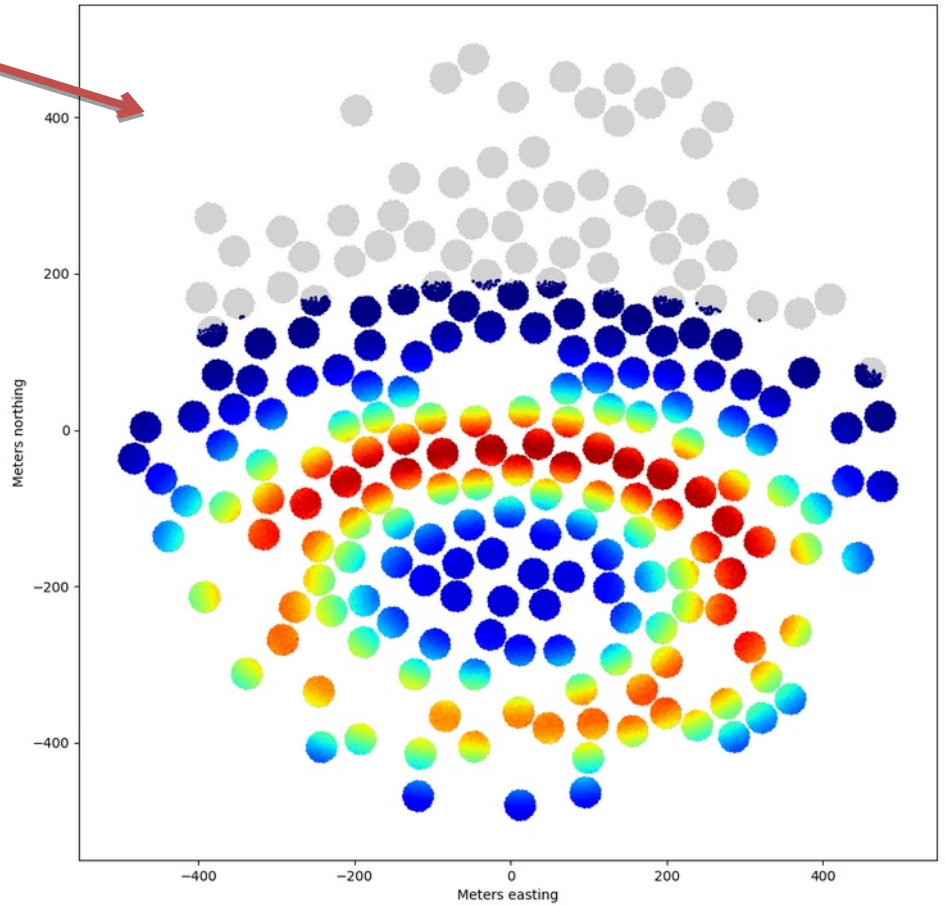
- Width of time window not too large (noise)

SKA-Low, a really dense array

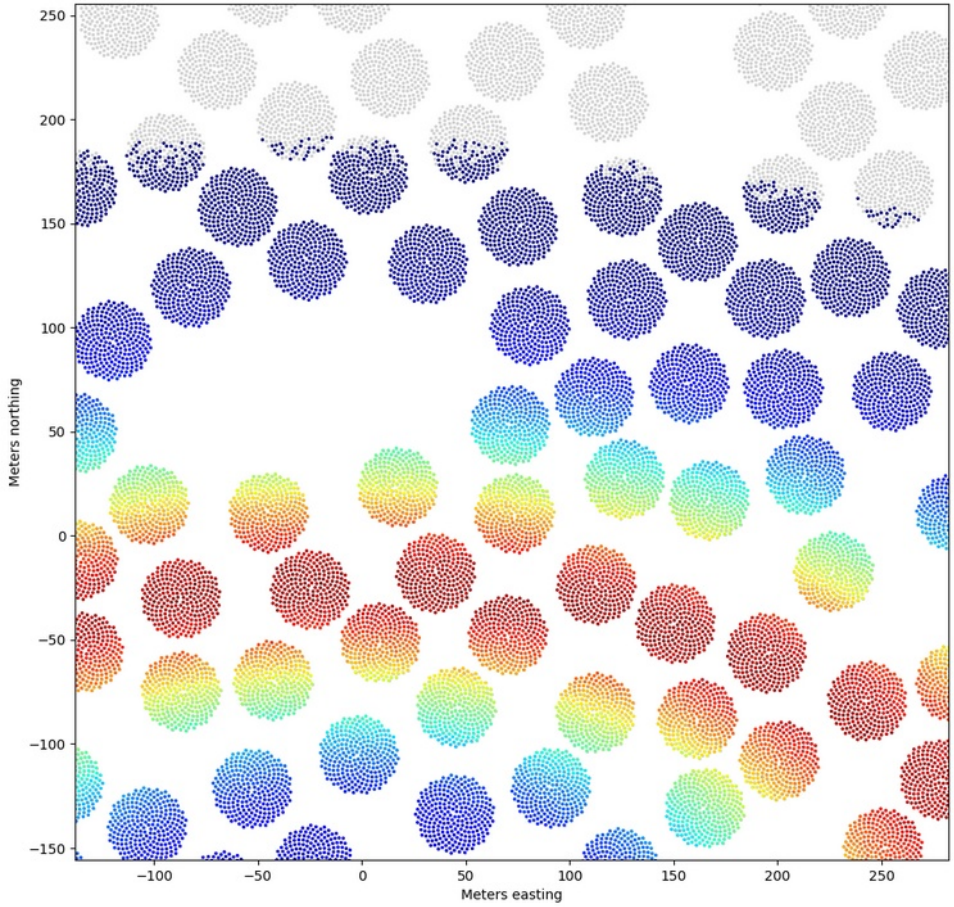
LOFAR

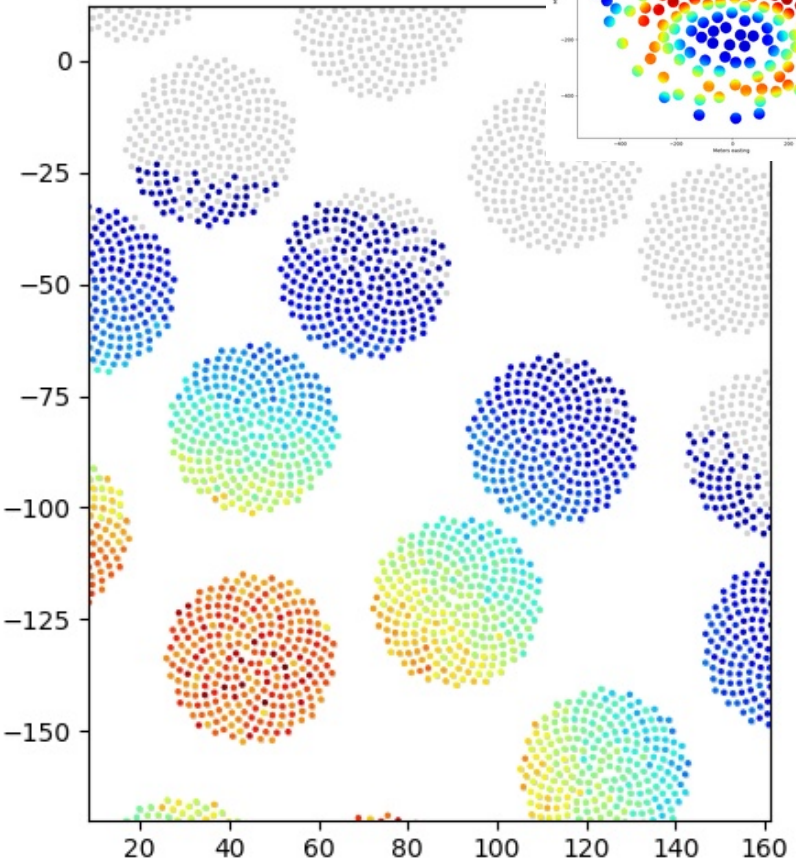
SKA antenna layout

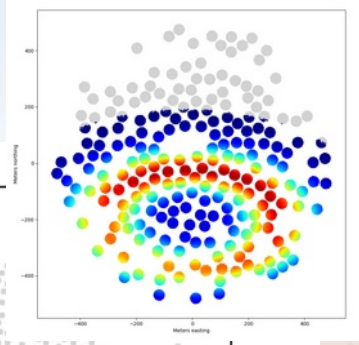




SKA-Low, a really dense array!





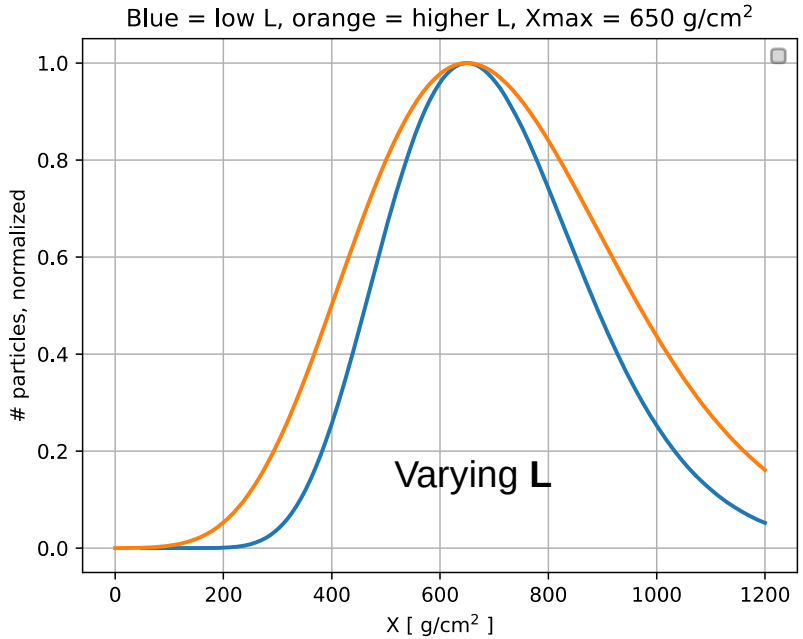


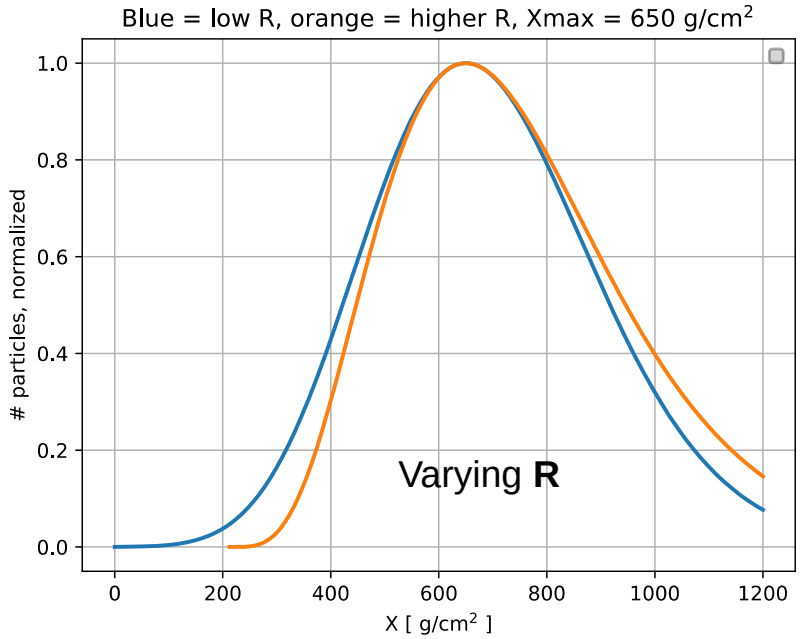
Beyond Xmax: Longitudinal distribution of particles

$$N(X) = \exp\left(-\frac{X - X_{\max}}{RL}\right)\left(1 - \frac{R}{L}(X - X_{\max})\right)^{\frac{1}{R^2}}$$

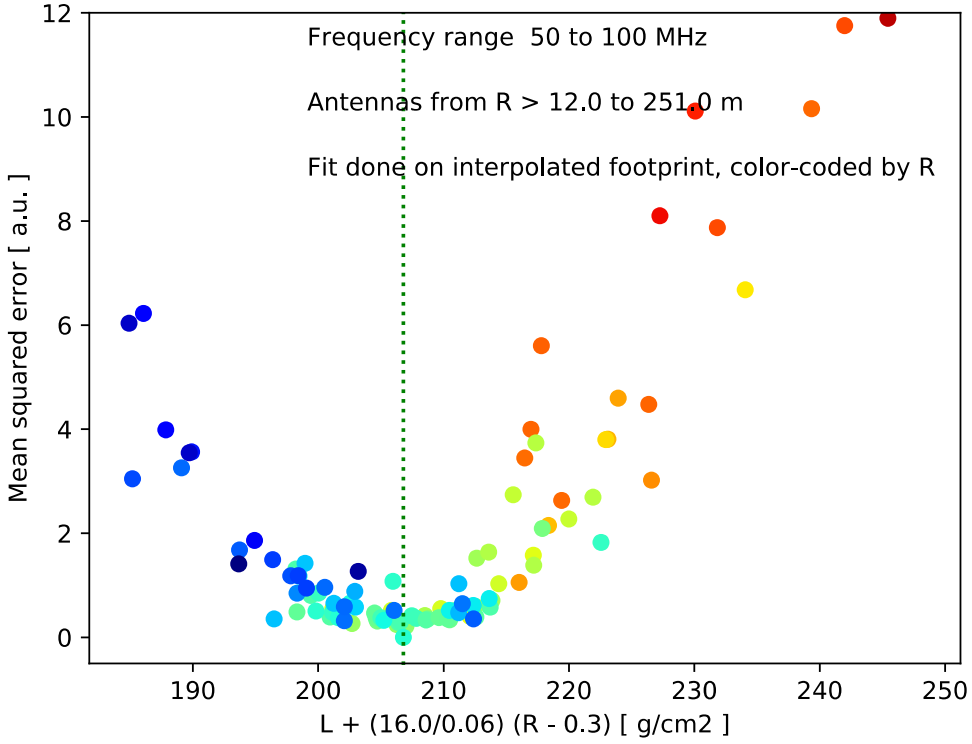
Parameter **L**: width (variance)

Parameter **R**: asymmetry (skewness)





Footprint sensitive to combination of **L** and **R**



- This has a clear optimum!
- Sensitive parameter is:
  L + **16 g/cm²** (**R** – 0.3) / 0.06
  - "**L + R**" in ~ equal proportions
- Range of R is ~ 0.30 +/- 0.06, hence those numbers
- **16 g/cm²** tuned by hand for now
- Sensitive to **frequency range**

So, sensitivity is on **L** and **R** combined!

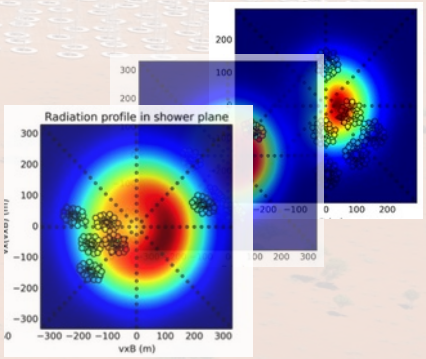
Monte Carlo setup for SKA reconstruction

- Mimic LOFAR-style measurement & Xmax reconstruction

- Use CoREAS simulated showers
- Full signal interpolation to all ~ 30,000 SKA antennas within ~ 300 m
- SKA Antenna model (currently SKALA2, **to be updated!**)
- Add sky noise (**to be updated!**)
- Trigger threshold **4** sigma, to be tuned further

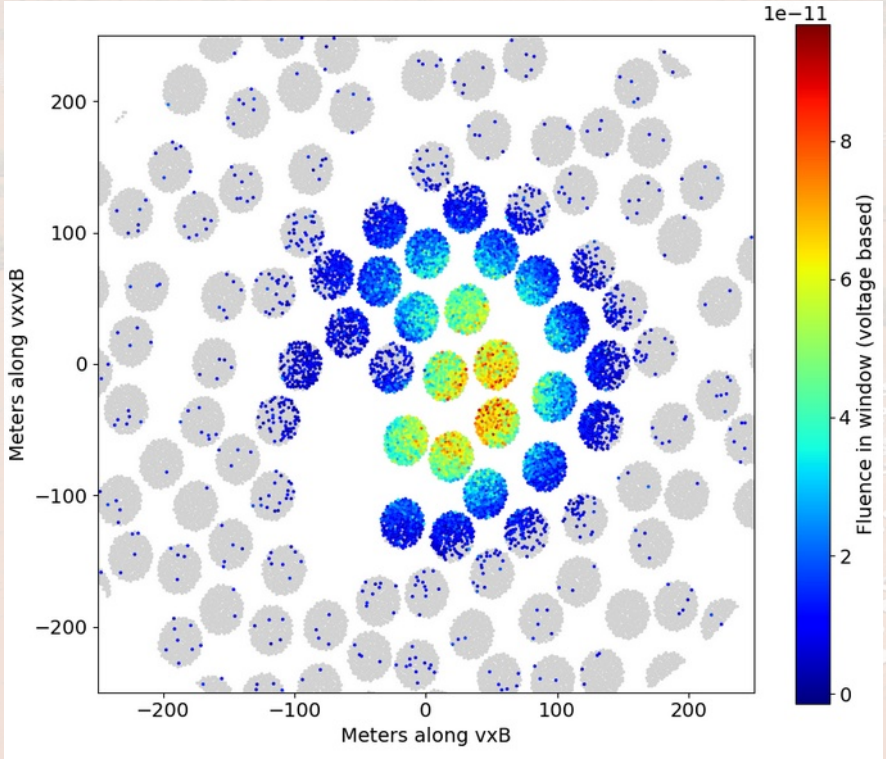
- For each SKA antenna, determine pulse energy fluence
- Use MC-derived formula for **fluence uncertainty** vs fluence
- Store ‘measurements’ + uncertainties

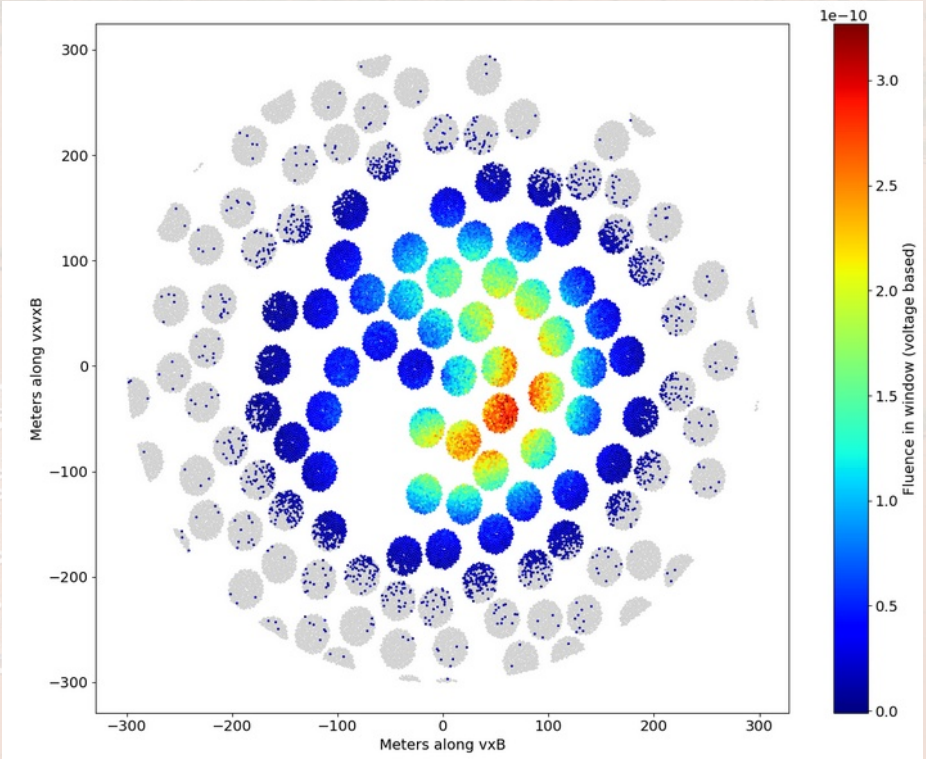
- Simulated ensemble of **140** showers, use each in turn as ‘data’
- Run reconstruction pipeline



Measured footprint

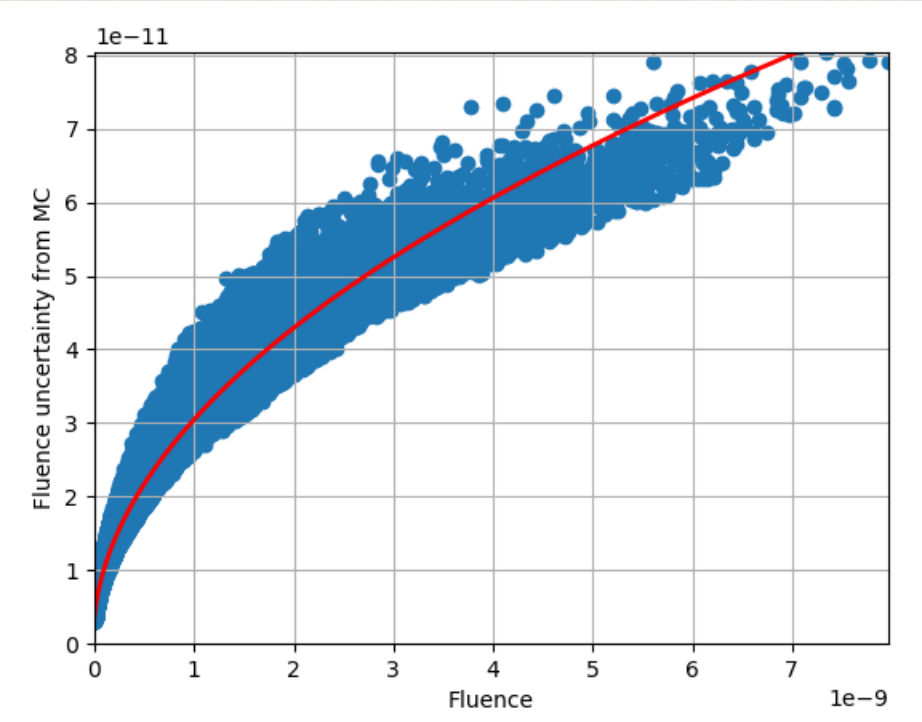
- Scatter and false positives using **4** sigma
  - Tune threshold, or just include all non-detections? (see later)





Fluence uncertainty vs fluence

- From Monte Carlo
  - Several showers x several primary energies
  - 1000 noise trials each



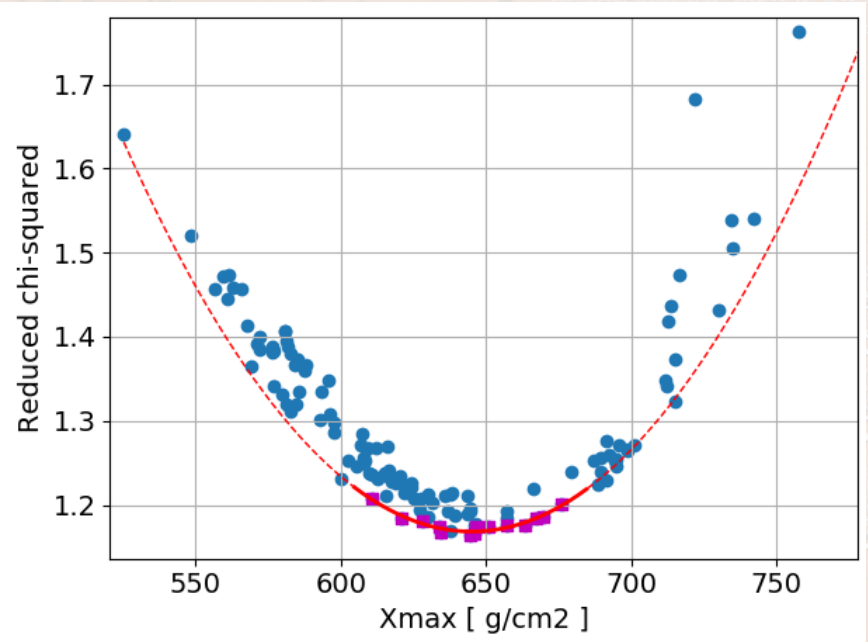
Reconstruction result for X_{max}

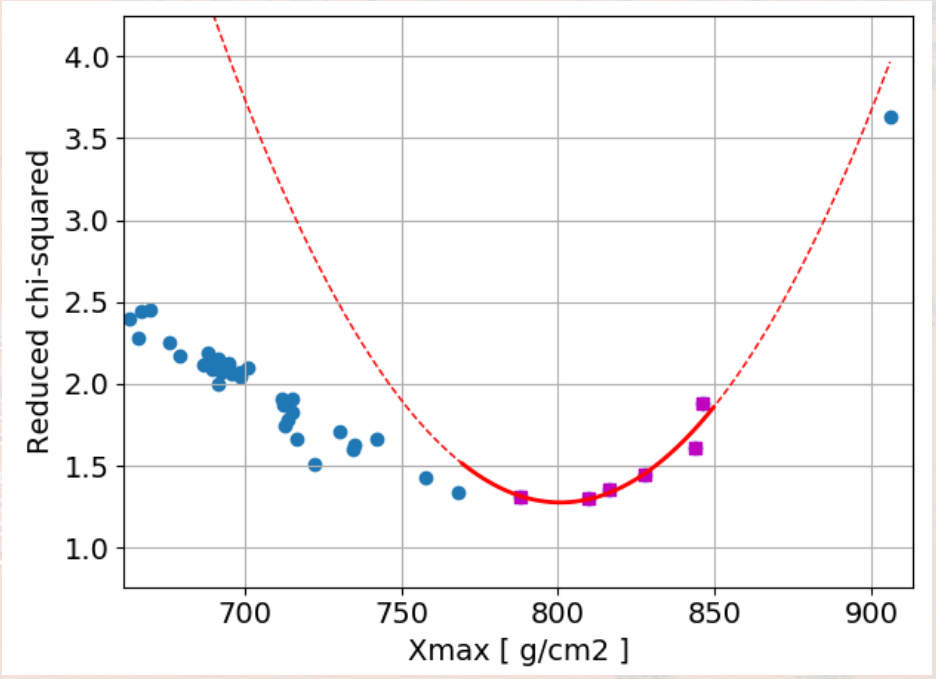
50 – 350 MHz

Primary energy 2 x 10^{17} eV

~ 8000 antennas triggered

Lower-envelope prescription as before, range +/- 40 g/cm2

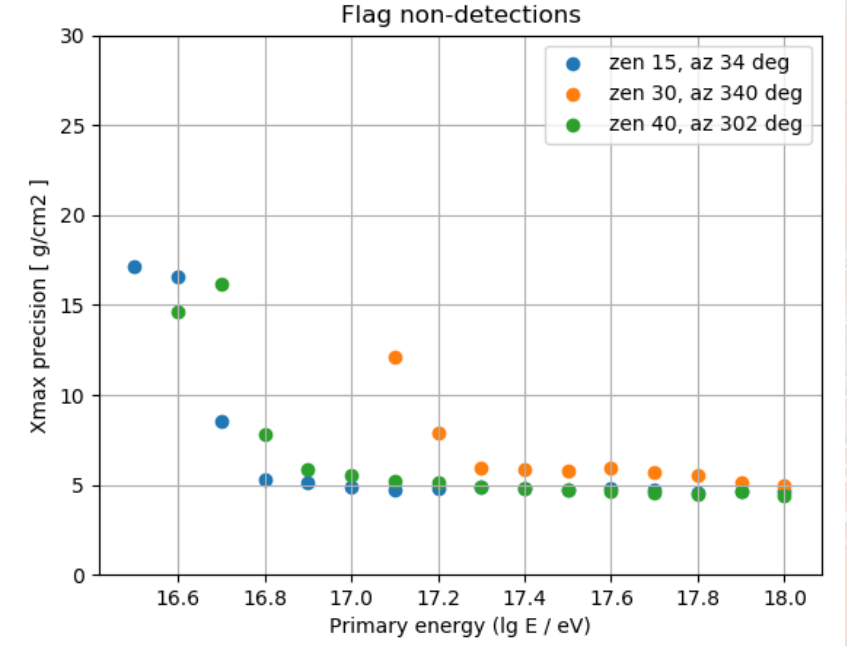




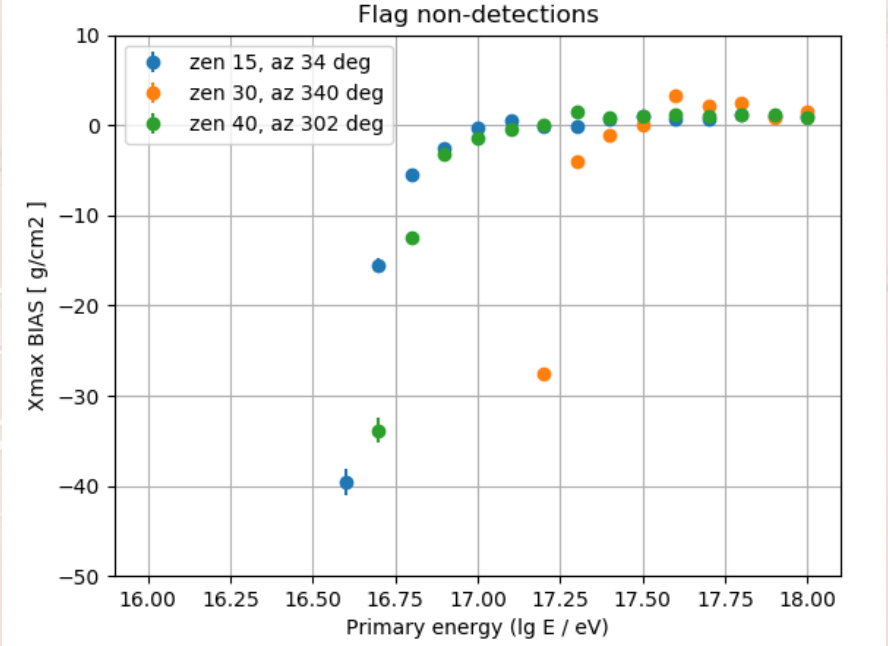
Xmax precision versus energy

- Low-energy cutoff is visible, varies with geometry
- Some bias is there around the low-energy cutoff

Xmax precision (stddev only)



Xmax bias

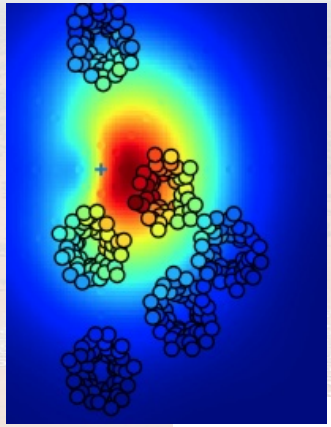


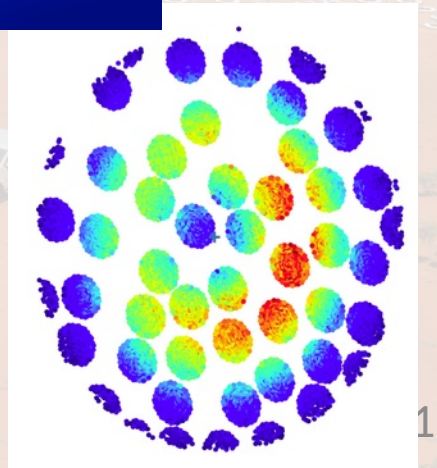
X_{max} reconstruction precision

	SKA	LOFAR
X_{max} resolution	: **6 - 8 g/cm²**	20 g/cm²
Energy resolution	: **3 %**	9 %
Core resolution	: **50 cm**	3 – 10 m

- The Xmax result from an earlier analysis still holds in the latest, more explicit analysis using full pulse interpolation

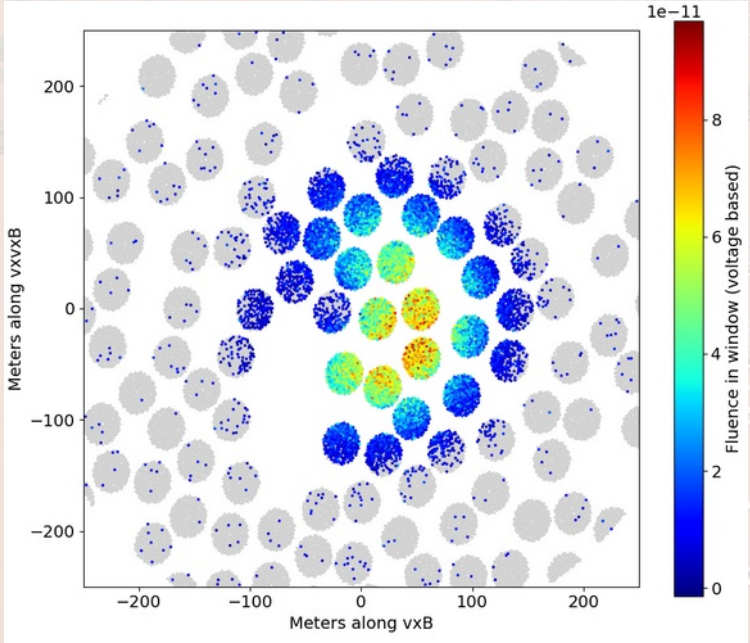
- Energy and core resolution to be checked

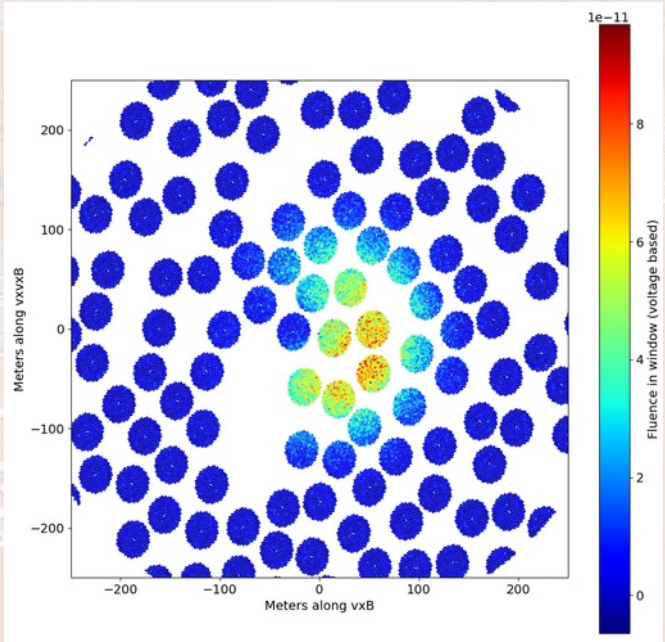




Including non-detections in the fit ??

- Flag antennas without 4-sigma signal, or include them?
  - Using all antennas is most inclusive
  - But subtleties in fluence measurement:
    looks for peak in a search window, **then** sums in a 12-48 ns window
  - May not have expected chi^2 distribution...

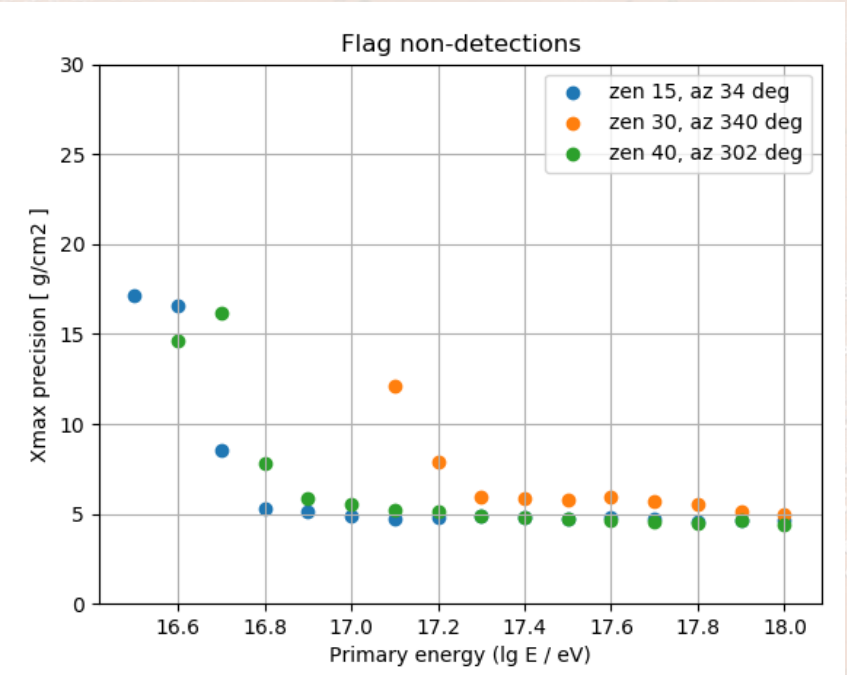




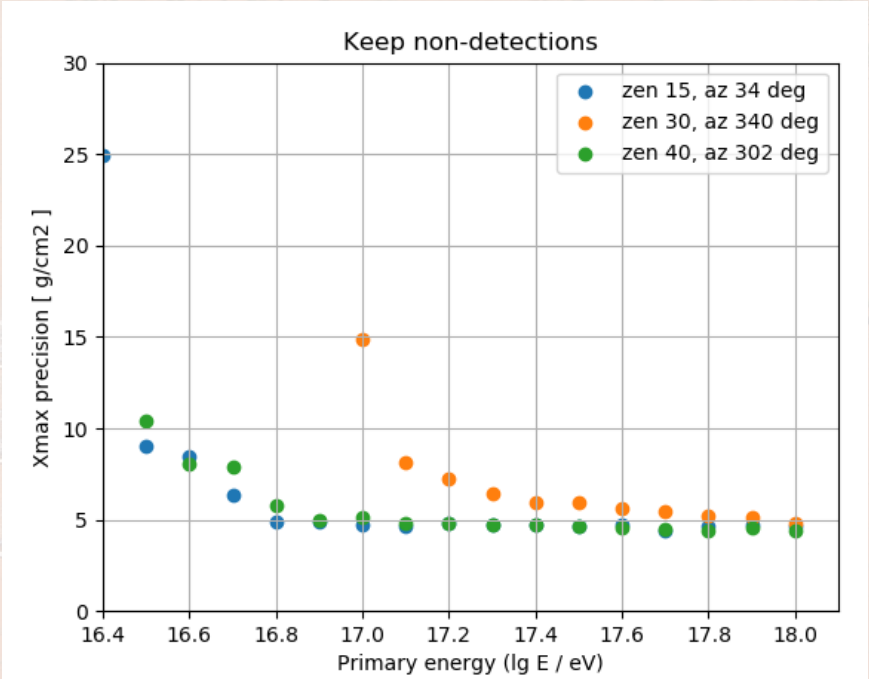
Xmax precision versus energy

- Some effect at low energies
- This is precision, also look at bias (next slide)

Flag non-detections

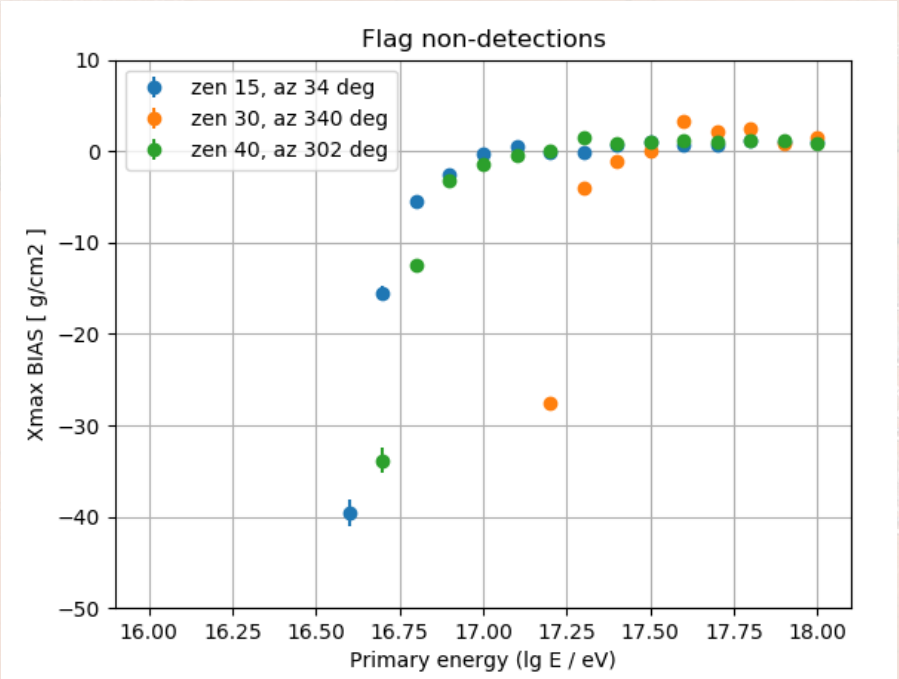


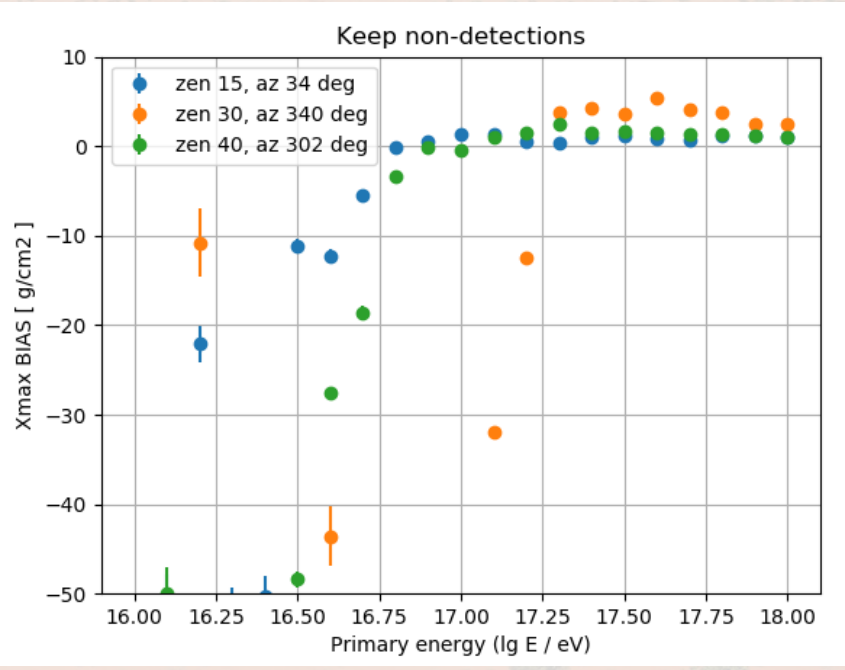
Keep non-detections



Xmax **bias** versus energy

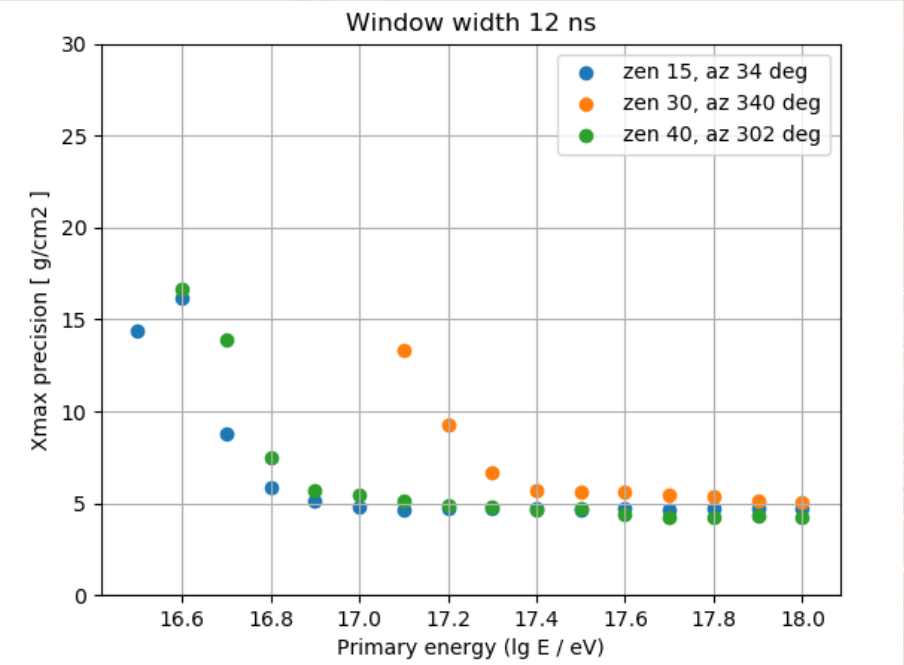
- Bias a bit more favorable near low-energy limit
  - A bit higher at high energies?
- Small effect though, but can push a bit lower

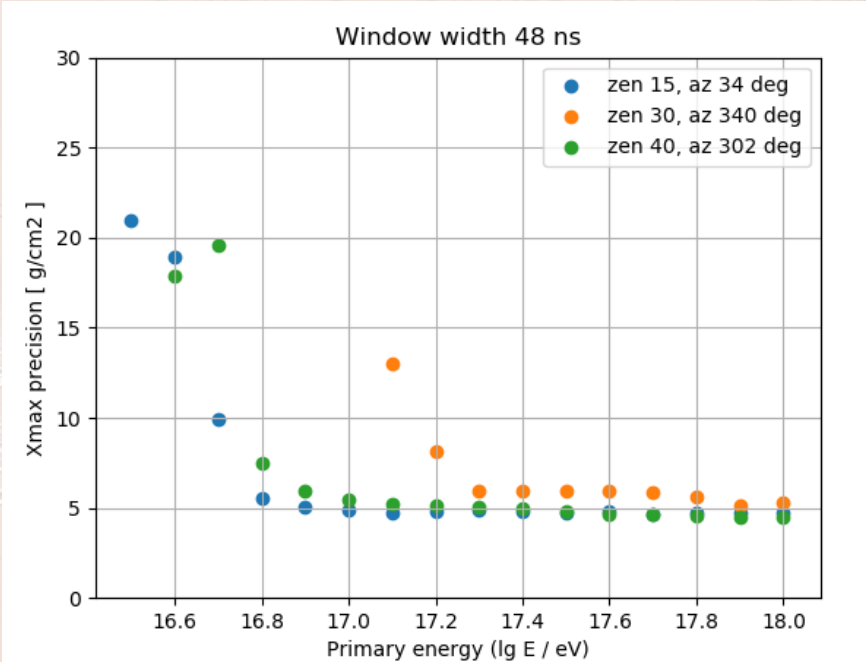




Pulse integration window size: precision

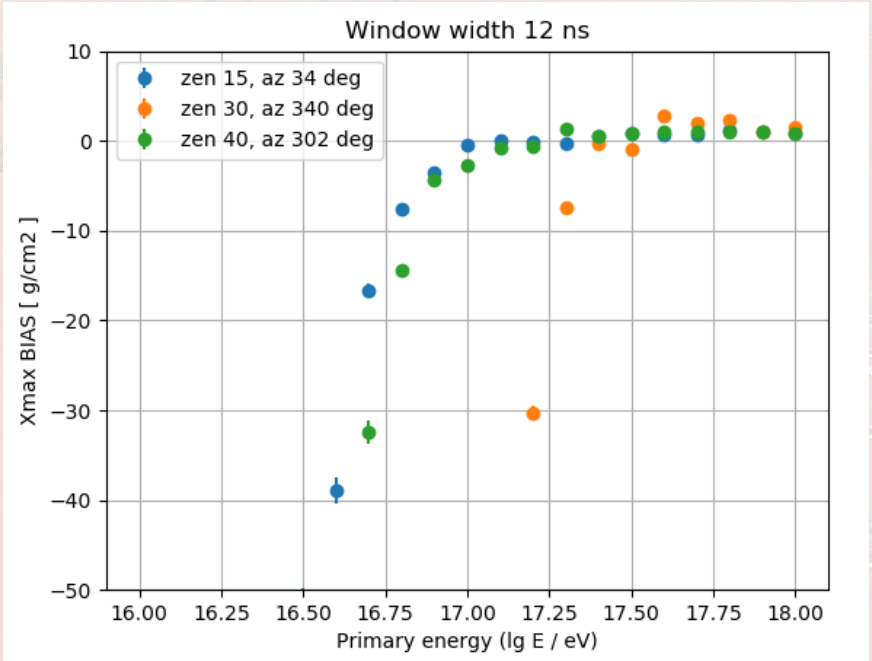
- Differences are negligible

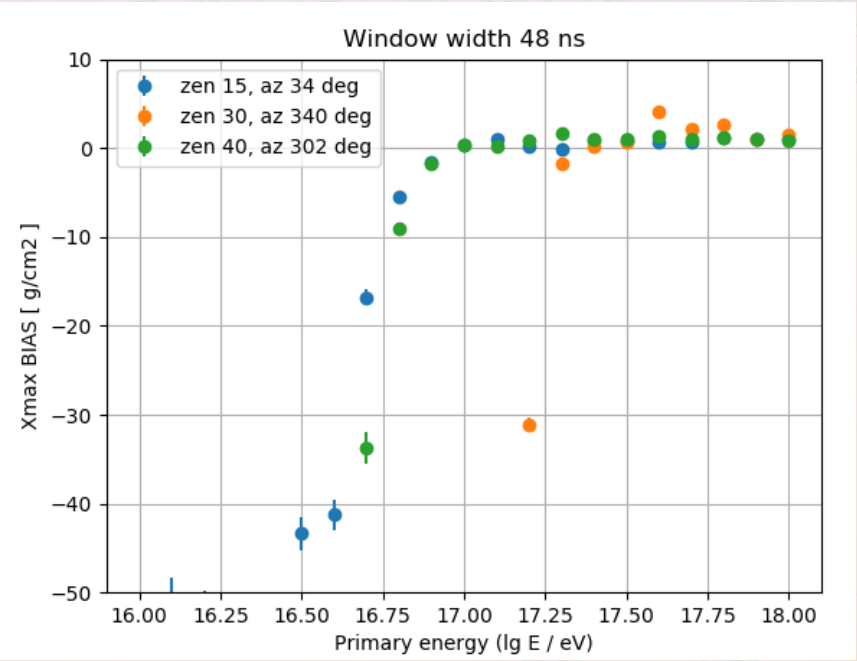




Pulse integration window size: bias

- Differences are small
  - Long window slightly better near energy threshold

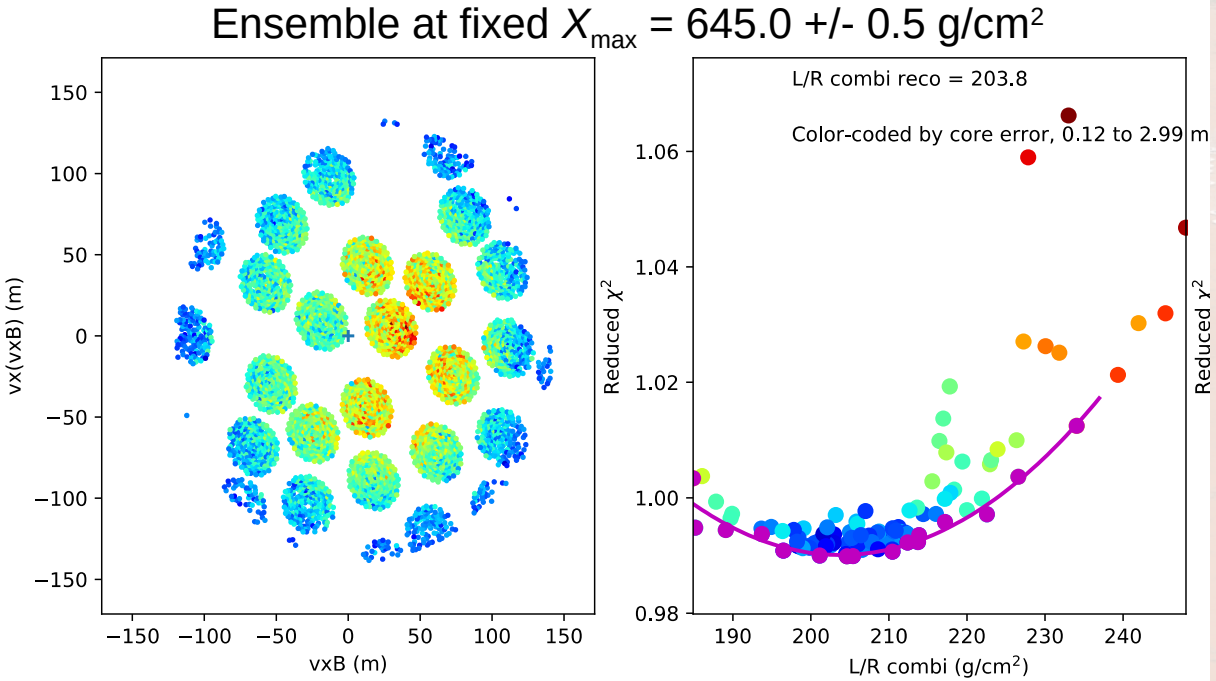




Reconstruction result for L+R combination

50 – 100 MHz

Still **to be reproduced** with new setup, incl statistics!



~ 5000 antennas triggered

Reconstructed “L+R” = 203.8 g/cm^2

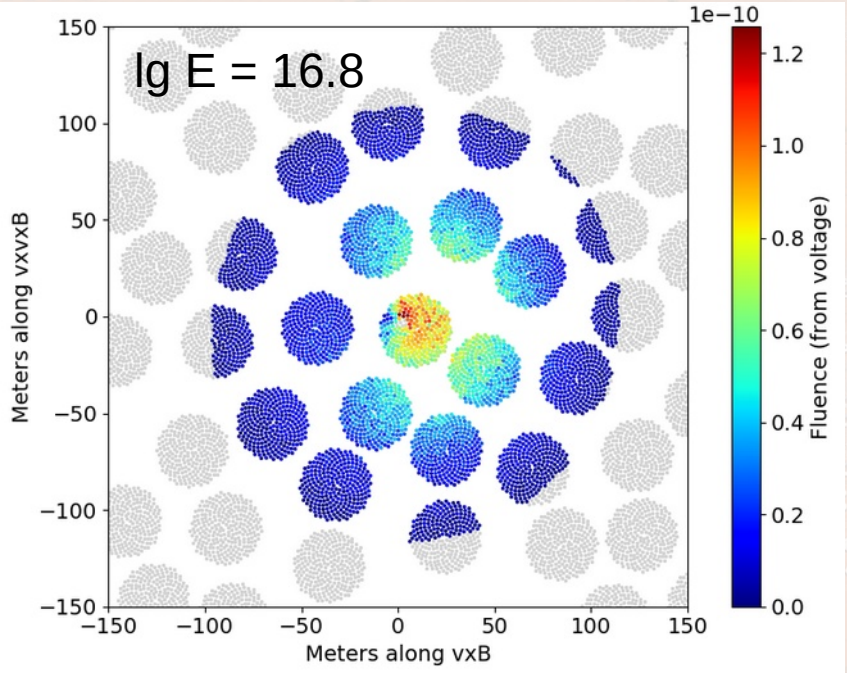
True “L+R” = 204.2 g/cm^2

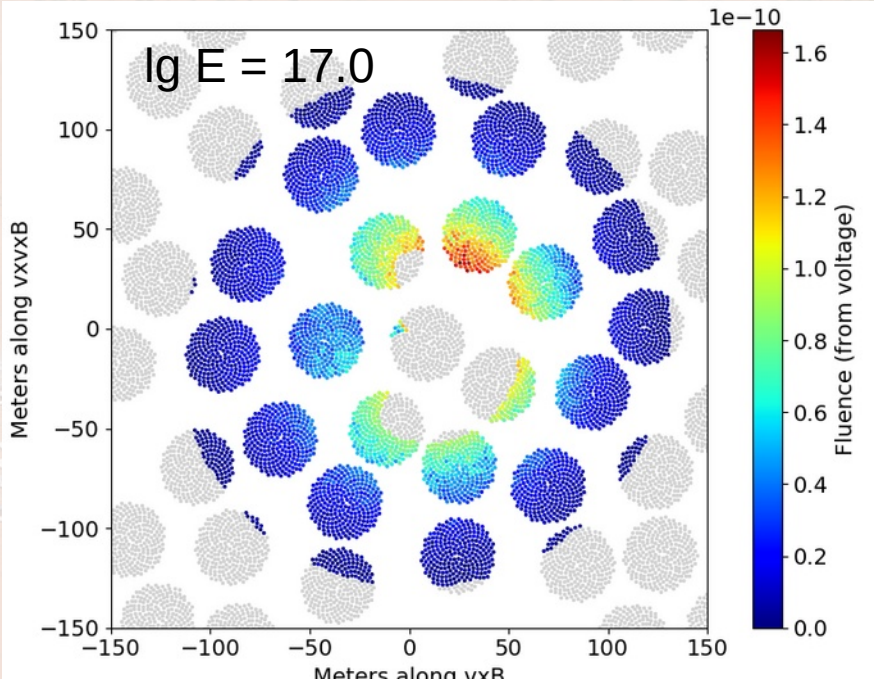
Reconstruction Xmax, and L+R together still to do

Footprints with limited dynamic range

- **To do: disable phase compensation**
- **Will help! Factor 2?**

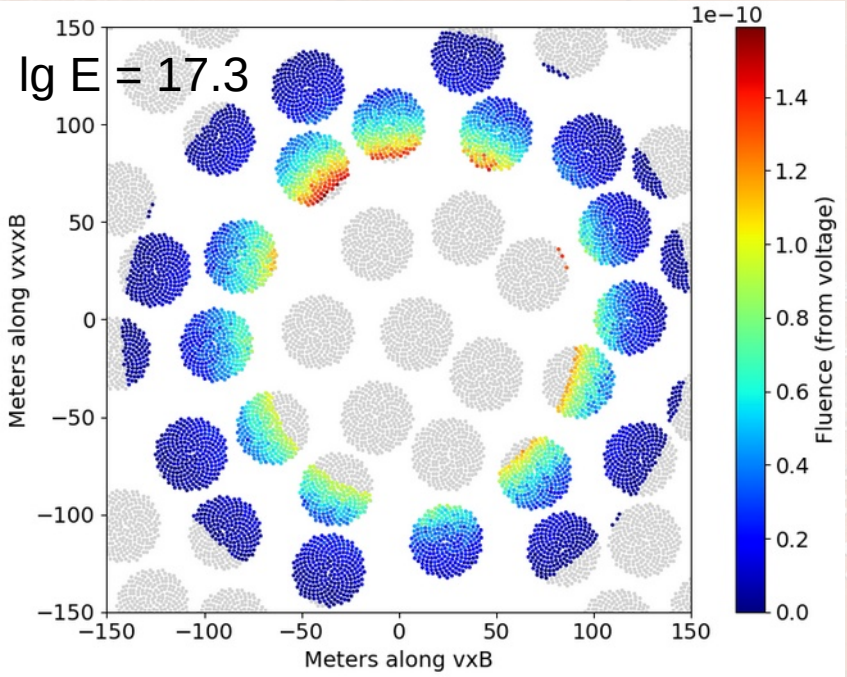
- Dynamic range **16** sigma, i.e. noise level ADC ~ 0000 1111
  - So 4 bits of range for our signals (not a lot)
- Example: zenith angle 15 degrees (clips at lower energies)



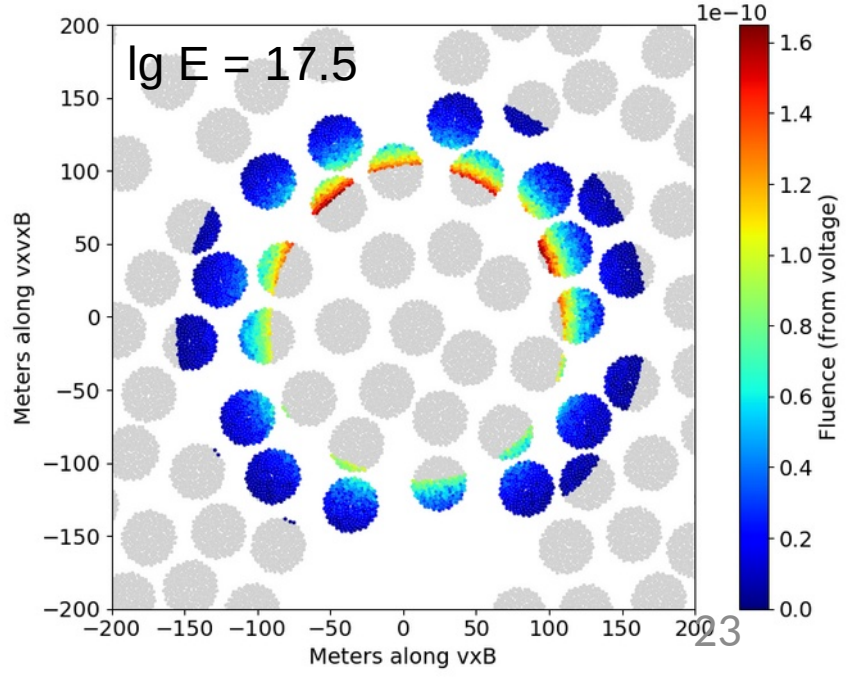


Footprints with limited dynamic range

- Dynamic range 16 sigma, i.e. noise level ADC ~ 0000 1111
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- Example: zenith angle 15 degrees (clips at lower energies)

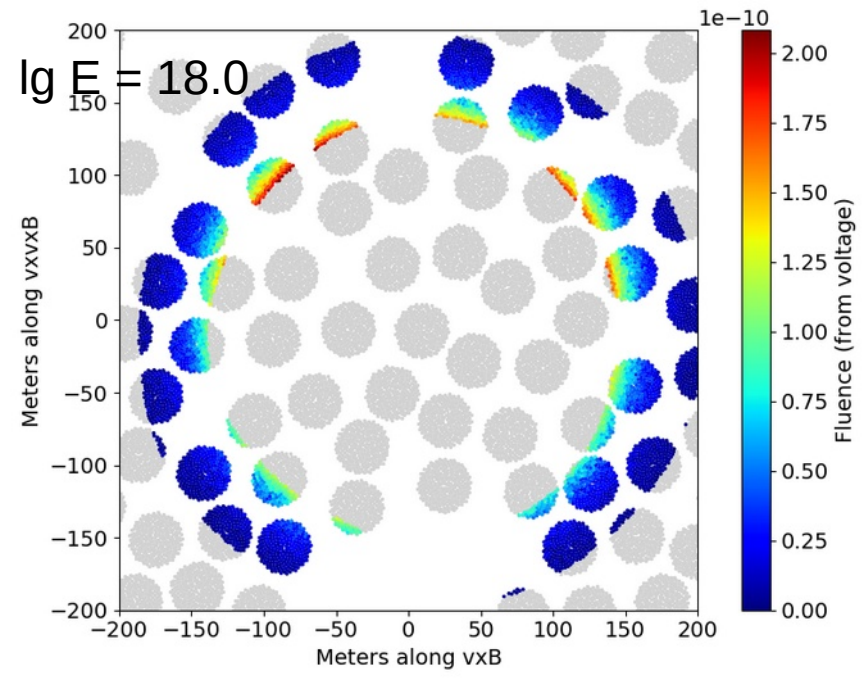


Zoomed out a bit



Footprints with limited dynamic range

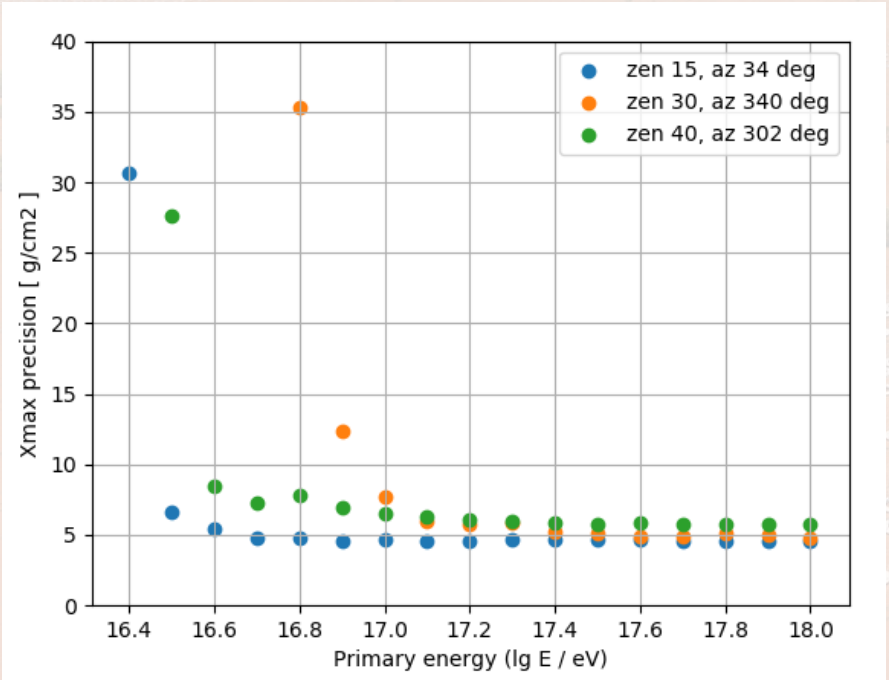
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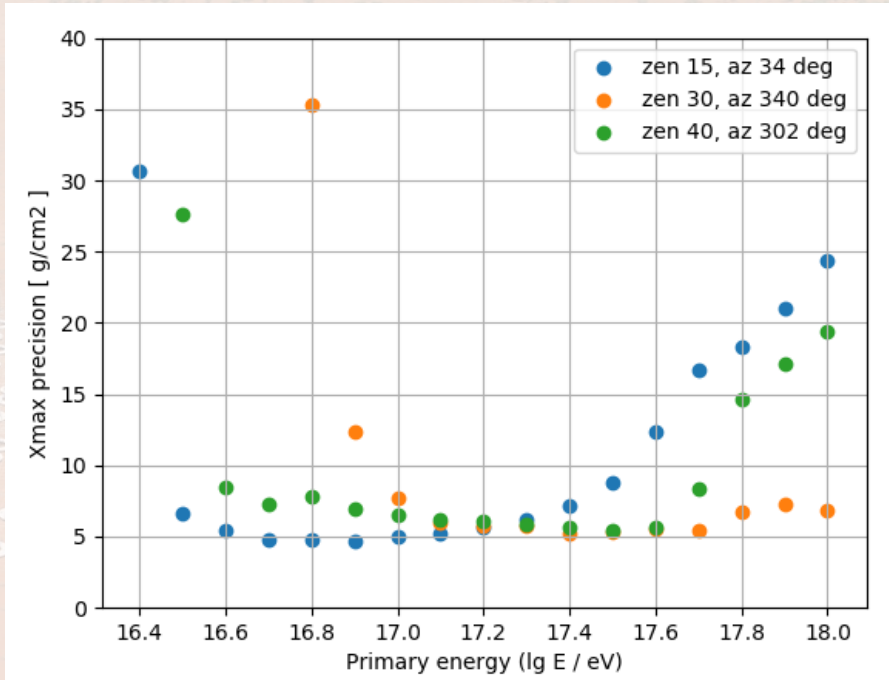
Xmax precision with limited dynamic range

- From **earlier analysis**, to be re-done using full signal interpolation
- Effects of dynamic range 16 sigma
- Effects on higher-order analysis yet unknown...

NO dynamic range restriction



Dynamic range **16 sigma**



Effects of limited dynamic range vs # antennas

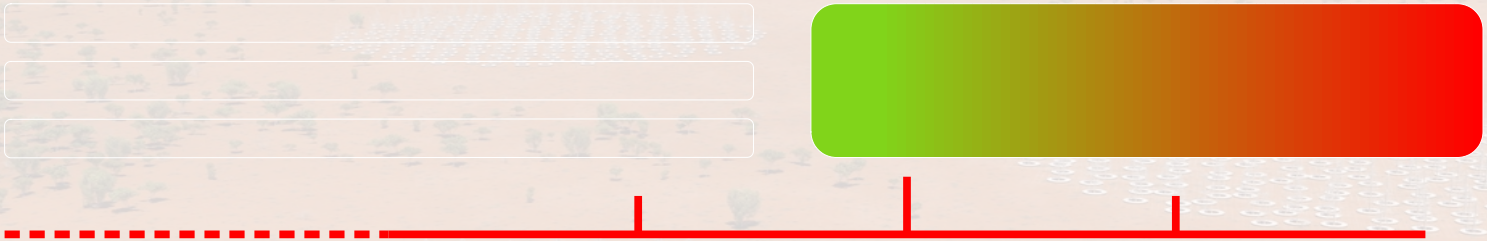
Effect of limited # antennas

Beamforming

Entire array | per station

Dynamic range 16 sigma

Single antenna detections



10^{15} eV 10^{16} 10^{17} 10^{18} eV

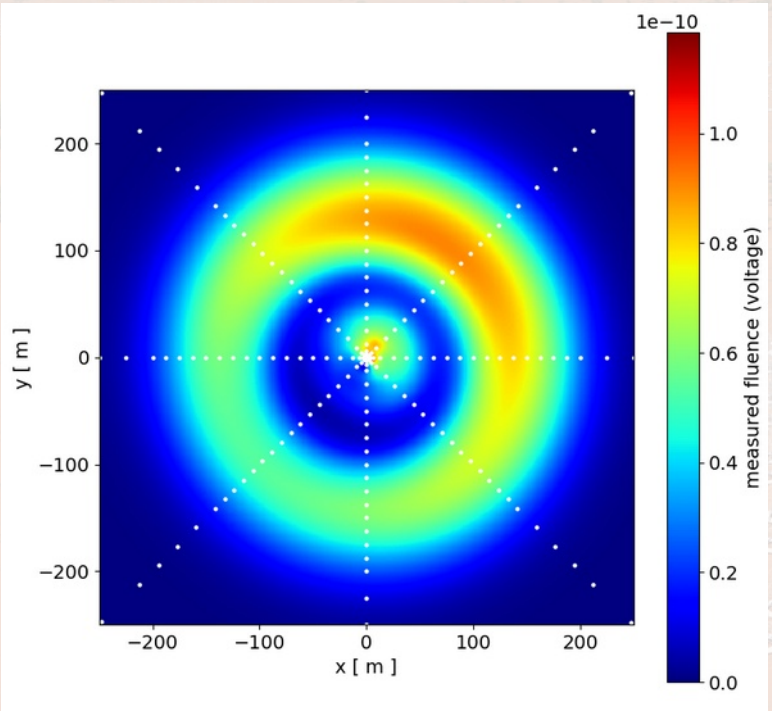
On LOFAR-style Xmax analysis **only**

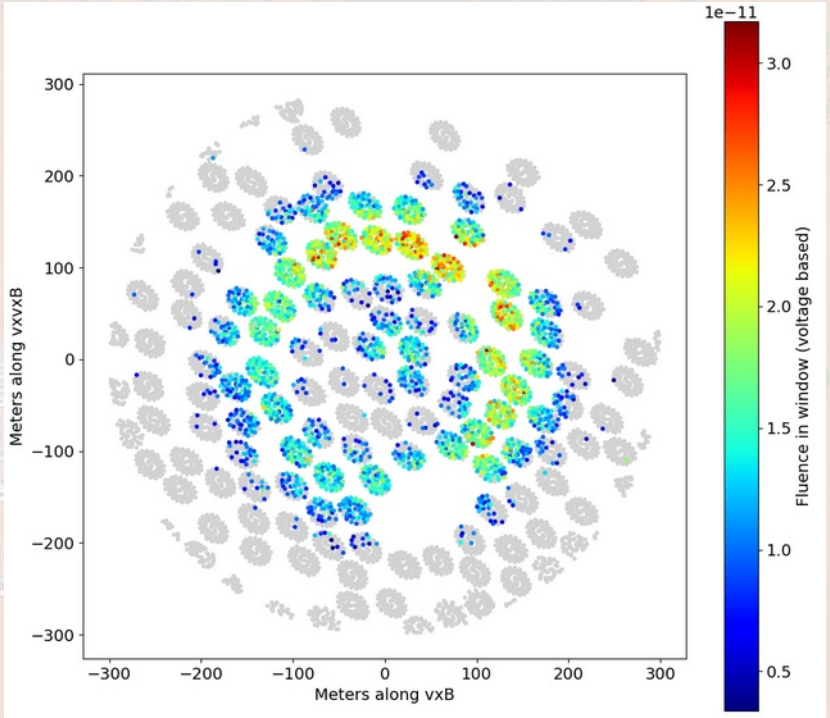
Effect on newer analysis TBD, but expected more severe

Measuring uncommon showers

- Mitja / Vital's shower 28982
- 150 – 350 MHz, voltage (after antenna model)
- **7.4 x 10^{16}** eV

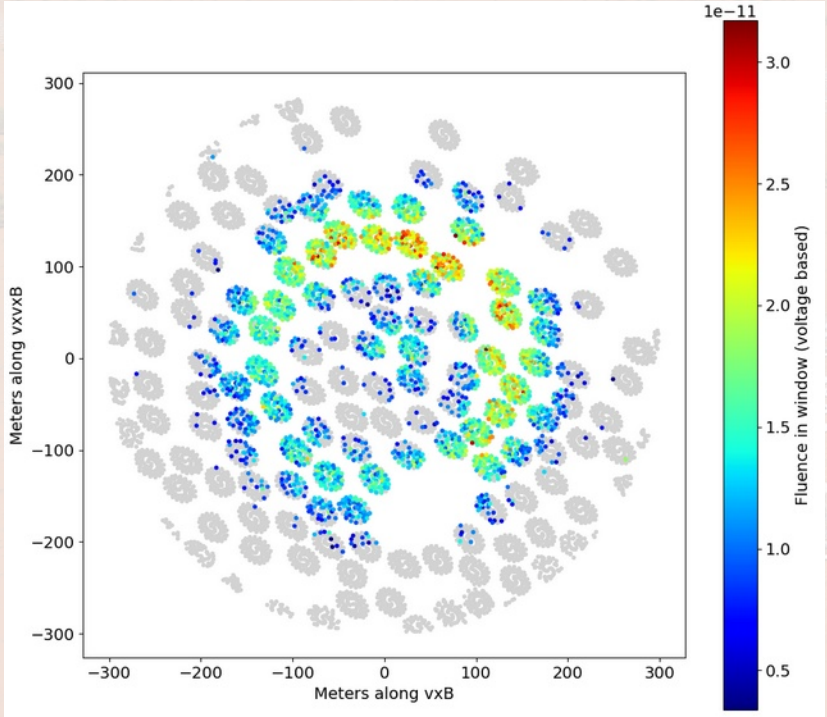
Factor 2 boost, 1 in 4 antennas



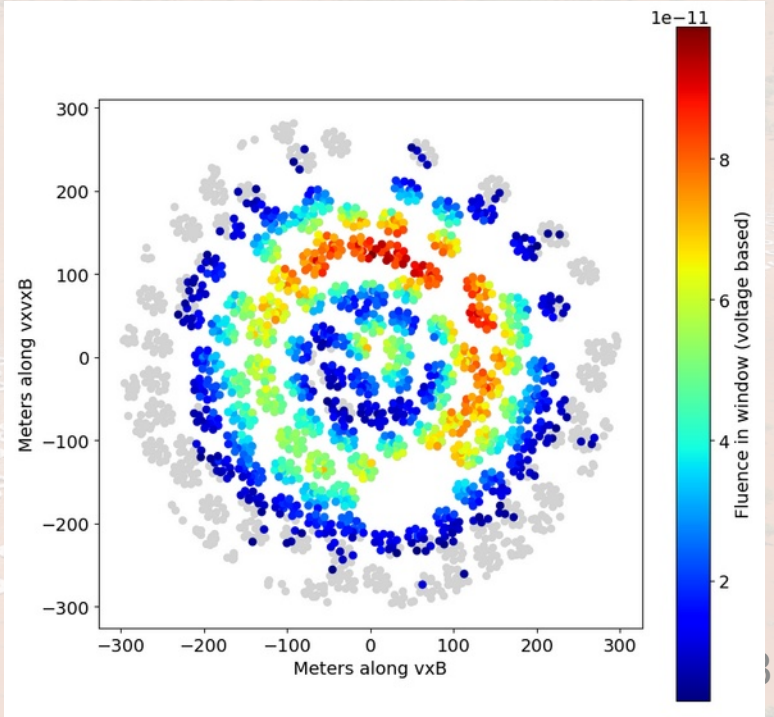


Measuring uncommon showers

Factor **2** boost, **1 in 4** antennas



Factor **4** boost, **1 in 16** antennas

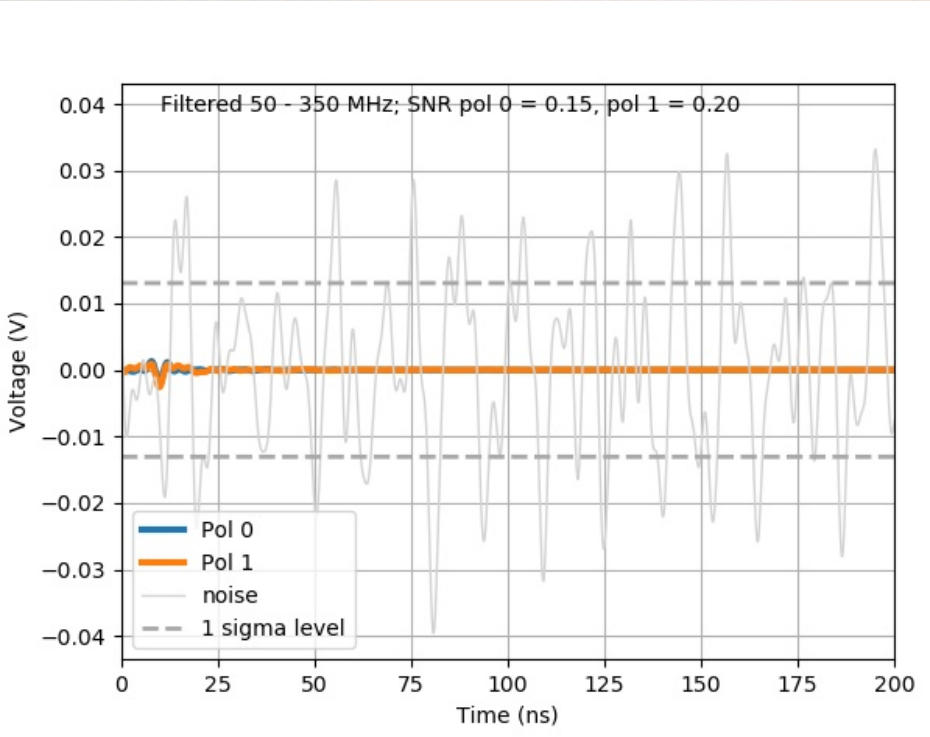


Detecting PeV gamma rays

- Detecting radio signals that are well below the noise in every antenna
  - interferometry/beamforming needed
  - Angular resolution ~ 0.1 degree
  - Other distinguishing features?

- If we had an external trigger, can we “beamform” and see it above the noise?

- Particle trigger: sensitive enough?
  - Distinguish gamma from CRs?
- Sky noise
  - Beware: when pointing at e.g. Galactic center, noise may be higher!



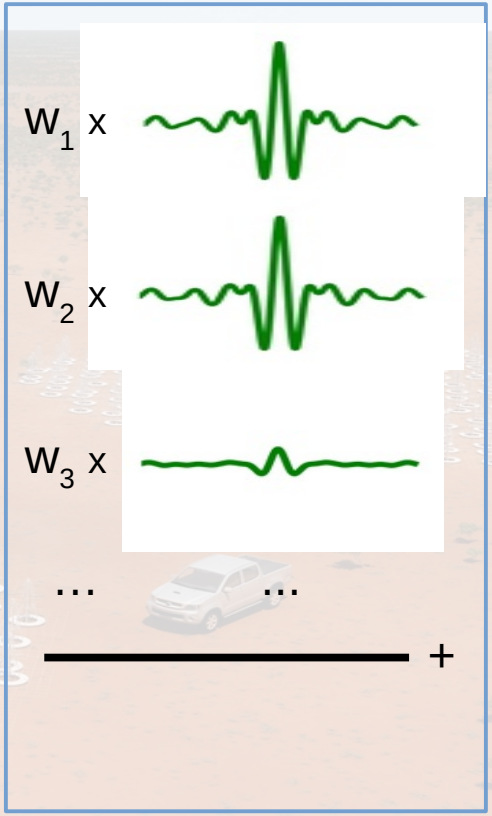
How to get optimal signal-to-noise ratio: **Matched filtering**

- A.k.a. **template matching**, also used in e.g. gravitational wave analysis
- Mathematically optimal for output SNR
  (if antenna model and noise well known)
- Template = set of all traces from simulation
  - Contain arrival times, pulse amplitudes, pulse shapes etc.
  - In well-matching simulations, filtered pulses will align in time and can be added up
    (“hyperbolic beamforming”)

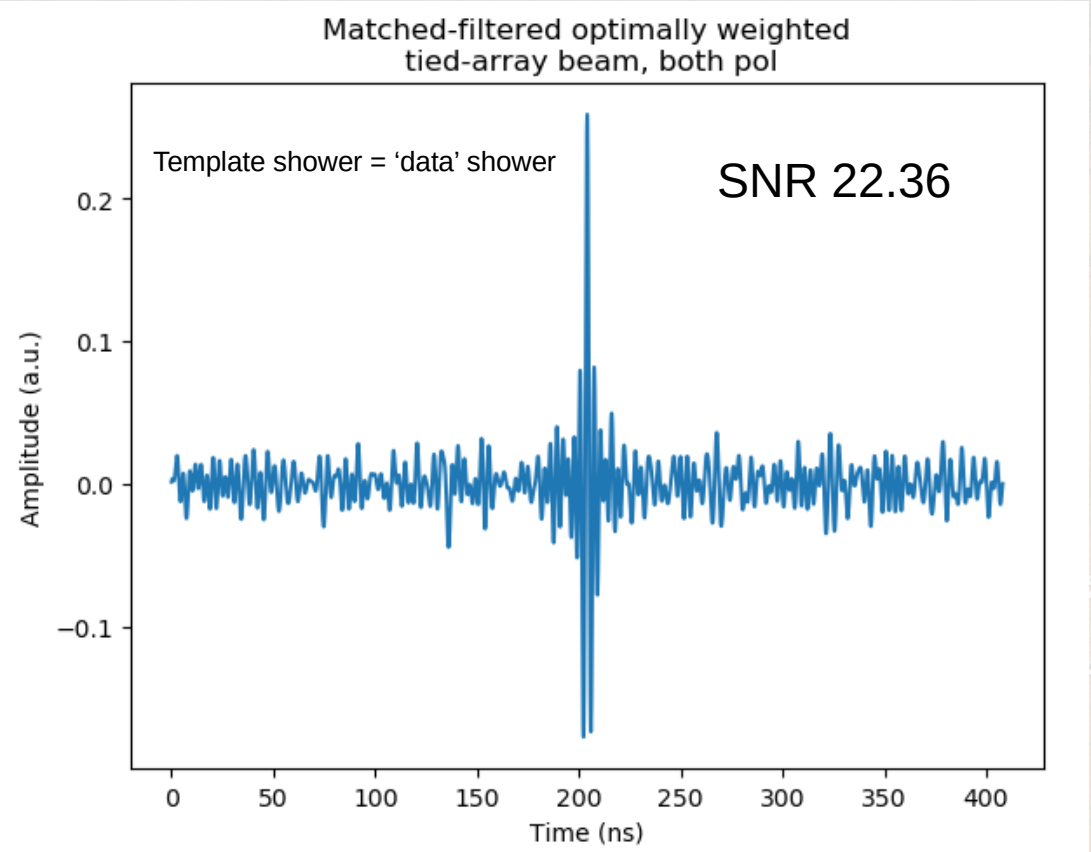


Weighted addition (beamforming) for optimal SNR

- Signals after filtering will have vastly different SNR
- How to proceed?
  - Make use of all antennas
  - Determine weight factors for a weighted sum
  - Give strong signals stronger weight (by amplitude)



Matched-filtered optimally weighted beam



But beware, this is for 'standard' sky noise

Noise in direction of sources, e.g. Galactic center, may be 2 to 3 times higher...

Core position not fitted, exact
Same for incoming direction (known for sources)

Next steps

- Paper on Xmax capabilities
  - To do: **noise model!** (Fodran's code)
  - **SKALA4** antenna model (should not make big difference)
  - More showers (?)
  - Have to agree on the measurement and fit procedure **(!!)**
  - What is the high-level message we want to spread
- Do R/L as well
- Better fit techniques
  - Needed for gamma rays, low-energy CRs
  - Needed to fully unlock beyond-LOFAR capability
- Port to NRR? (at some point)
  - Can it handle processing
    50k antennas x 140 showers x 3 window sizes x 3 other settings?

