Update on GRAND simulations

Olivier and Anne

GRAND White Paper workshop
Aug 22-24 2018

OUTLINE

Summary of what was presented in the last calls since February and partly new things

- Updates on the sensitivity study
- Radio morphing vs Zhaires
- Frequency band
- Machine learning

What's new in the sensitivity study

- Energy correction if pion is primary in radio morphing (minor)

- Extended star shape pattern since for heigh-energetic events also antennas outside the Cherenkov cone see a detectable signal,
  now fits to cone selection cut

- Bug fix in treatment of refraction index in the propagation fixed by Matias (done recently):
  → Added planes at larger distances (max. 99km from Xmax) added
  → has to be still checked in detail,
  results for sensitivity in good agreement with former ones

- Calculation of the mountain slope used in the application of the antenna response

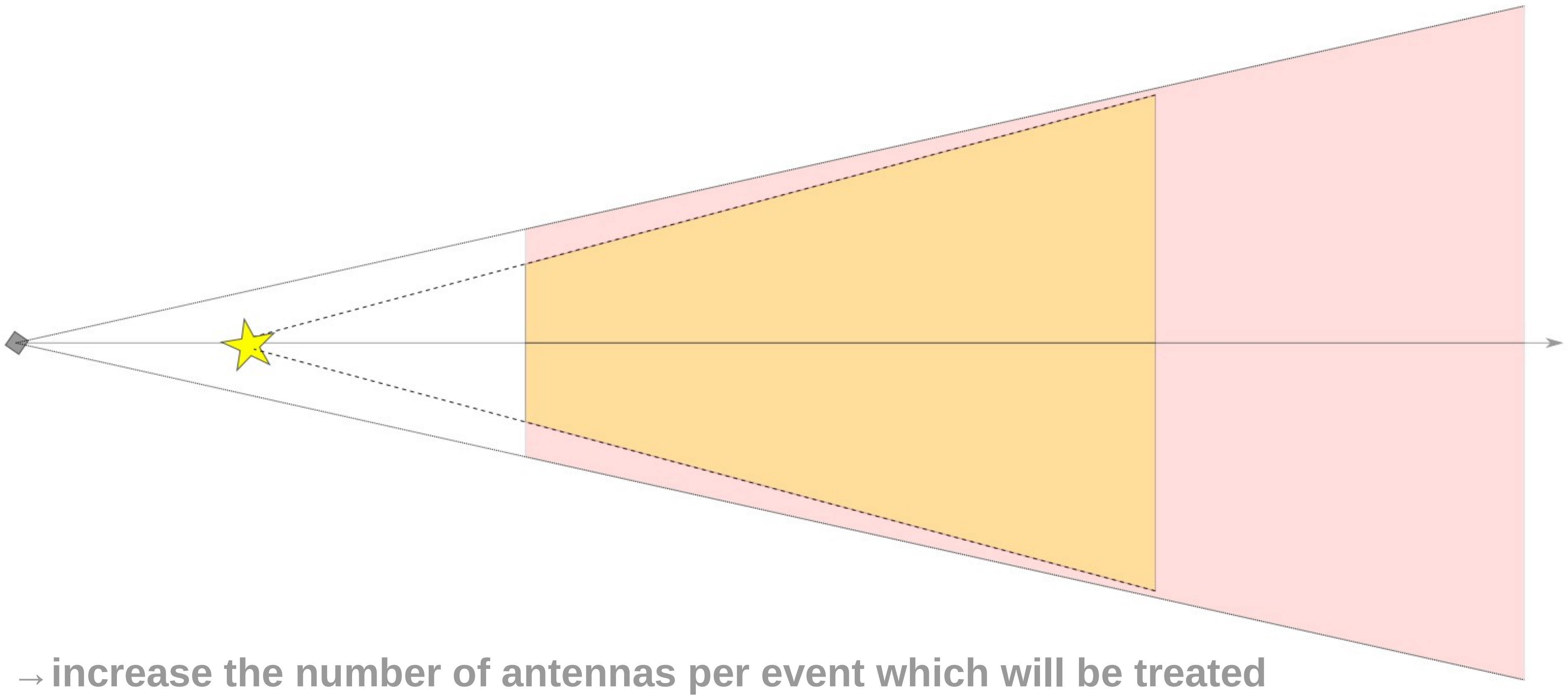
- Antenna response cross-check with free-space propagation

- Clustering in new analysis:
  new: trigger for 4 neighbouring antennas out of 8 surrounding antennas, arranged in a SQUARED box, for test antenna
  initial:4 out of 8, but arranged in ANY shape, as long as the 8 antennas were separated less than 3 steps

Enlargement of the reference shower

- For the planes closer to Xmax: adopt to the cone selection,
  → antenna cone does not start any more at Xmax, now at the tau decay
  → we observed that also antennas outside the Cherenkov cone see a detectable signal

- Recent fix in Zhaires' treatment of the refractive index:
  → planes in far distanst to Xmax (up to 99km instead of 79km from Xmax) included



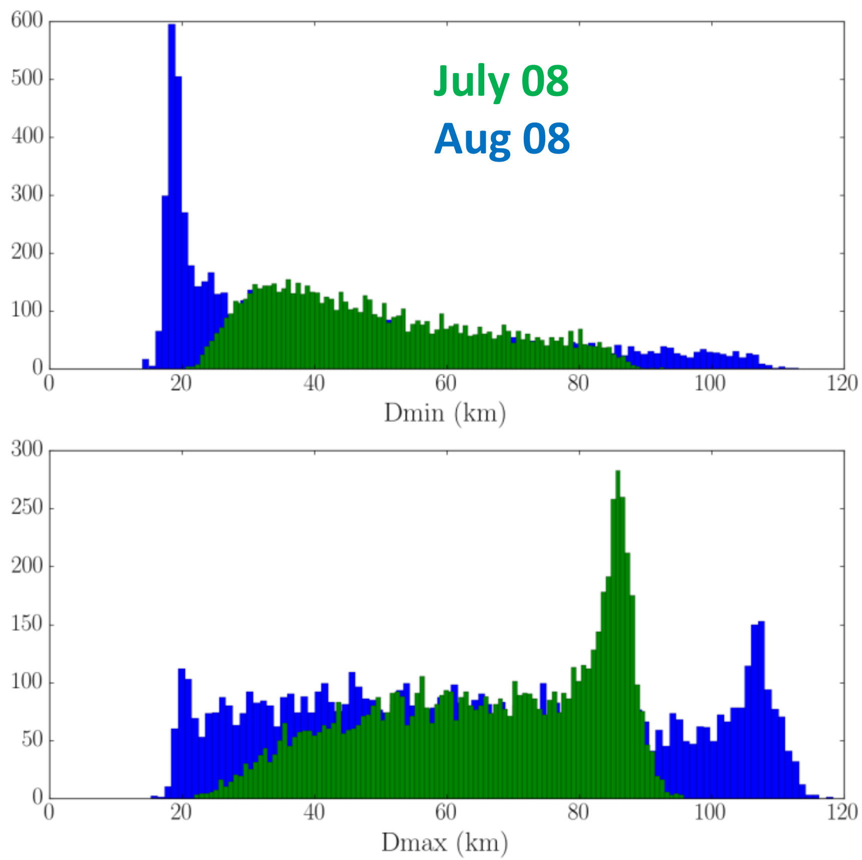
→increase the number of antennas per event which will be treated
→expected to increase also the number of detected events ...

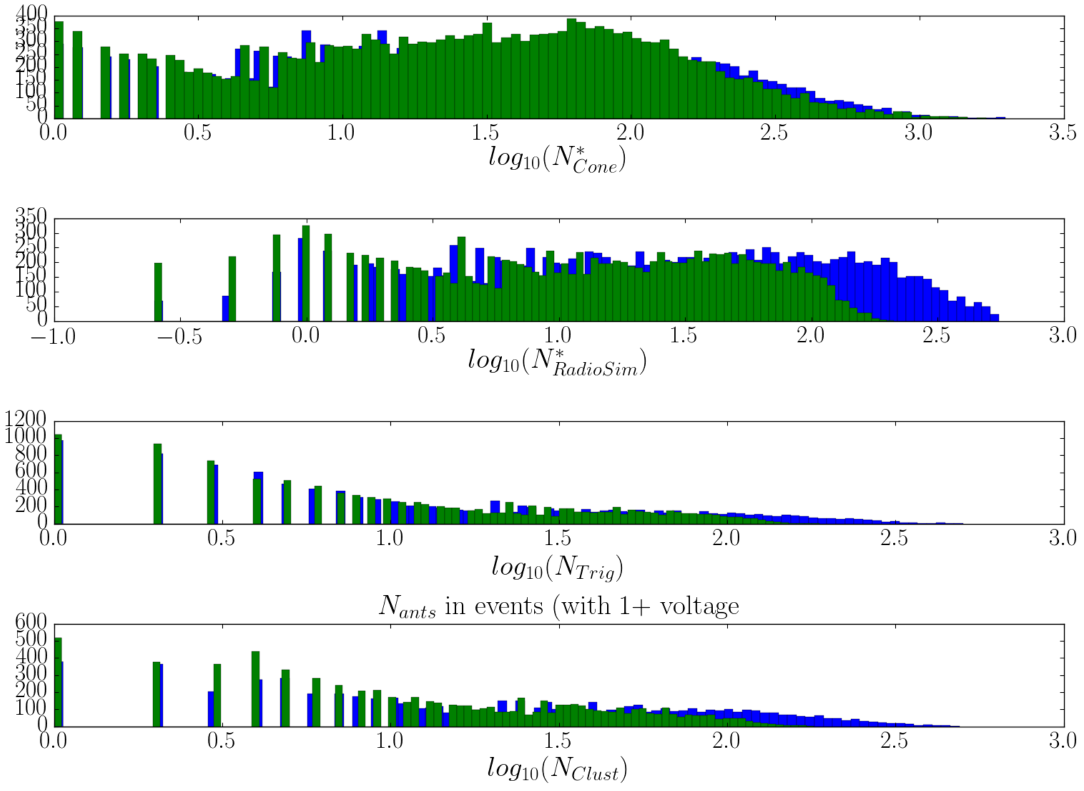
Checks done

- RadioMorphing
  - Larger reference shower ⬄ larger volume with Efield computation
    - Wider cone opening
    - More distant planes after Zhaires bug fixed
    - Slides to be added
- **Small effect on sensitivity in the end (<10%)** but much more antennas in events.

July:
Cones: 19948
Radio sim: 13211
Trigged events: 8721
Clustered events: 6208 (<Nants>=30)

August:
Cones: 17853
RadioSim: 14489
Trigged events (5+ ants): 9068
Clustered events: 6215 (<Nants>=115)



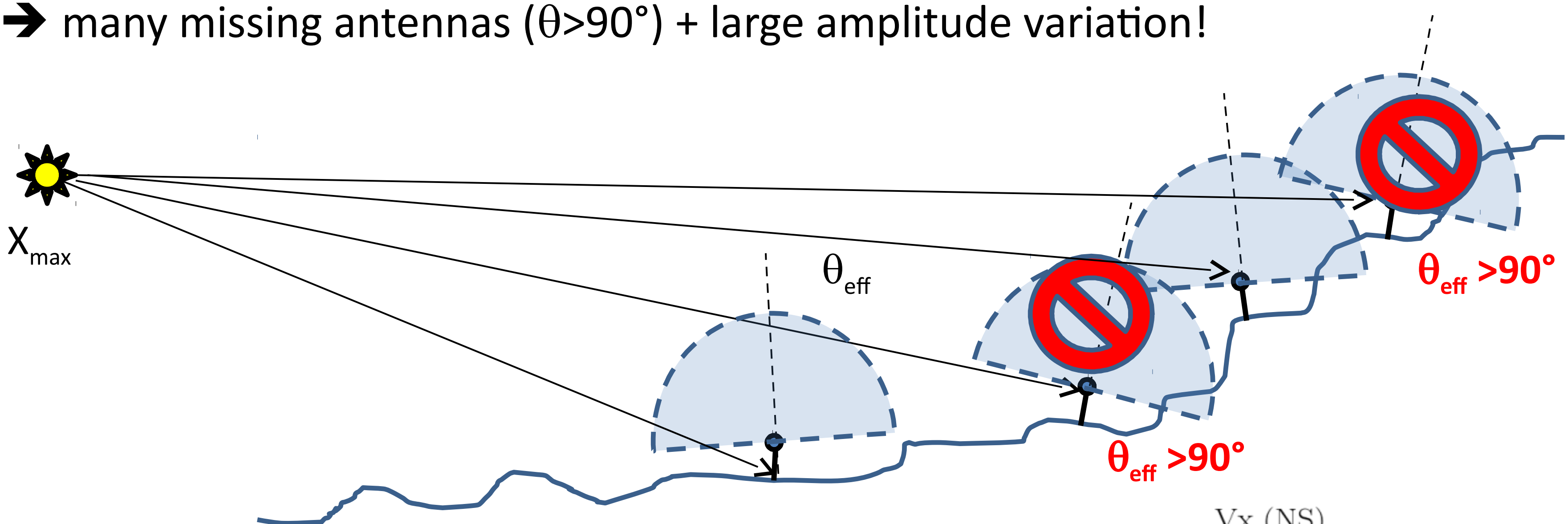


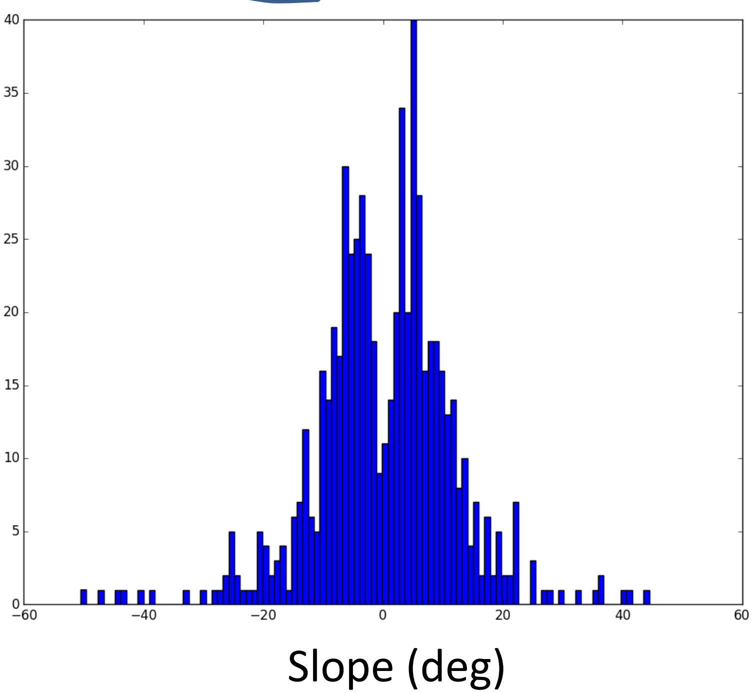
Effect of mountain slope @antenna

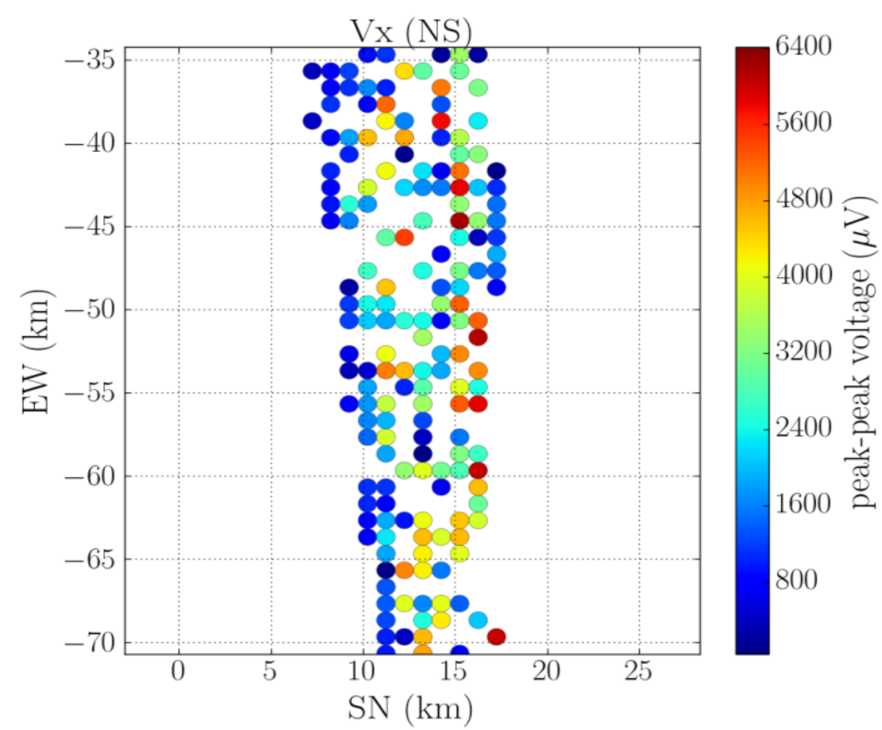
http://www.iap.fr/grand/wikigrand/index.php?title=File:GRANDsimstatus_May2018.pptx

Bumpy ground inducing a large variation of slopes because slope is computed on the very local area surrounding the antenna (~30m radius)

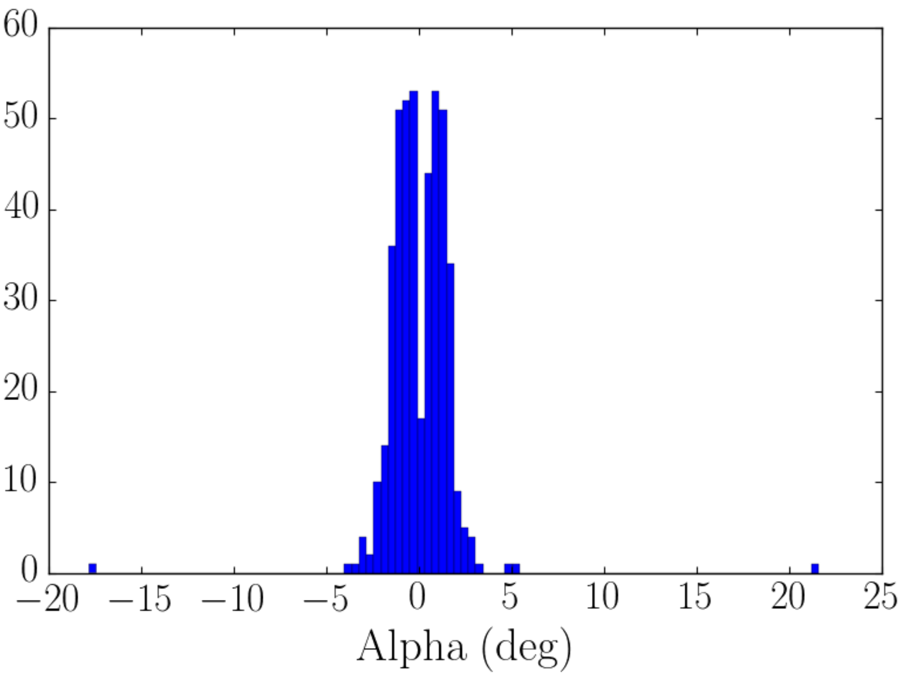
➔ many missing antennas (θ>90°) + large amplitude variation!







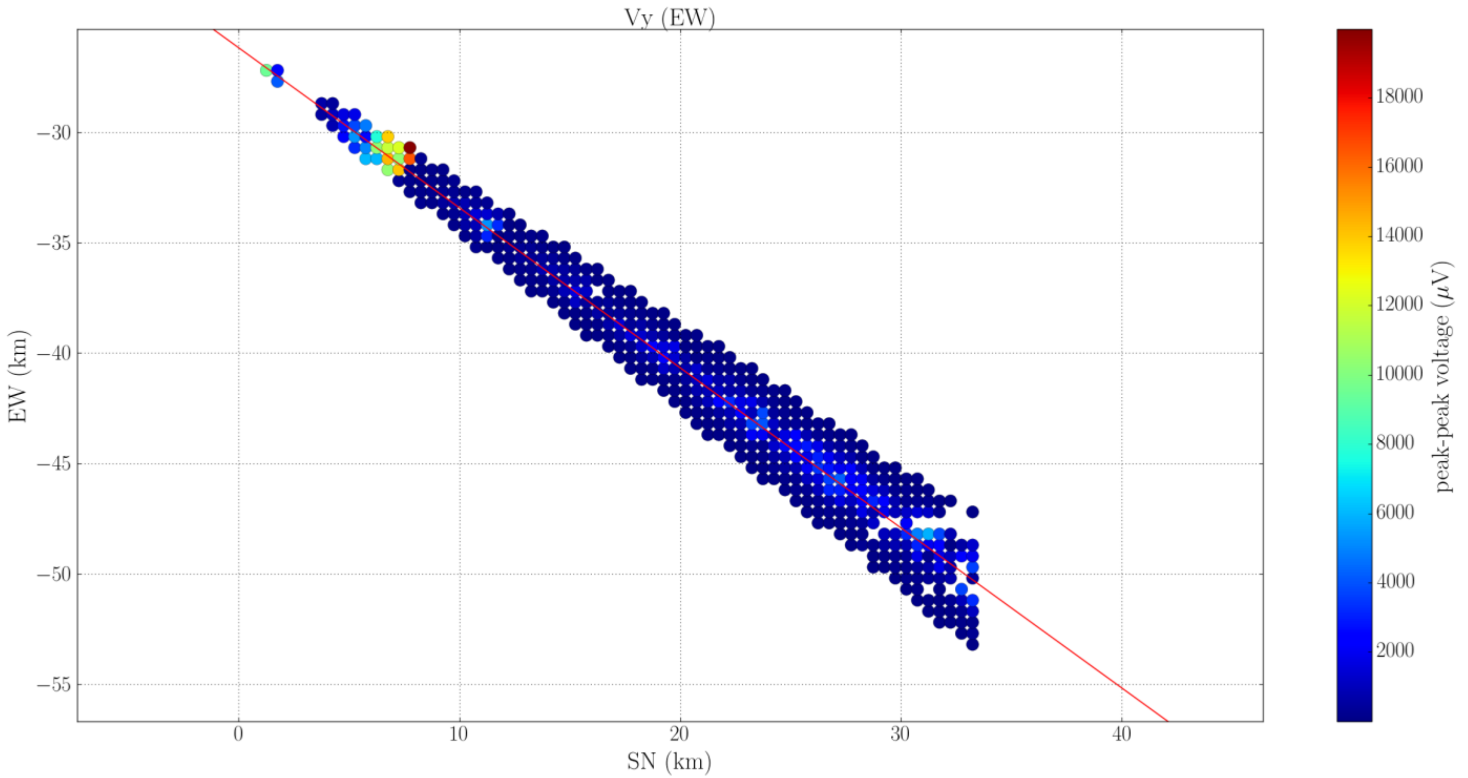
Effect of mountain slope @antenna



- Ground simulation: **now slope computed on 200m radius.** Slope values closer to 0.

➔ Less holes!

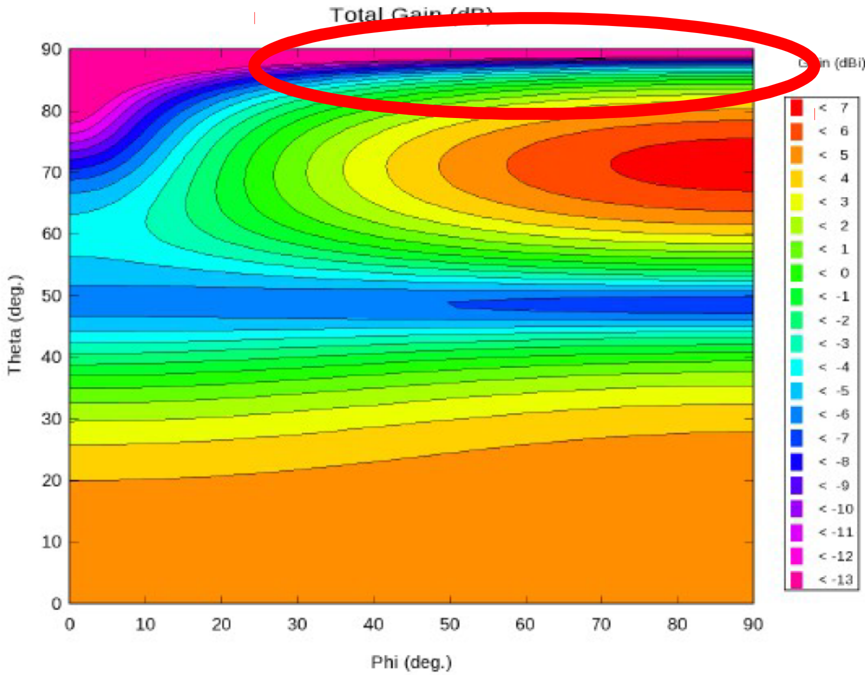
Ex:
E.2e19_Z.89_A.324_La.42_Lo.87_H.1477_D.3582049546

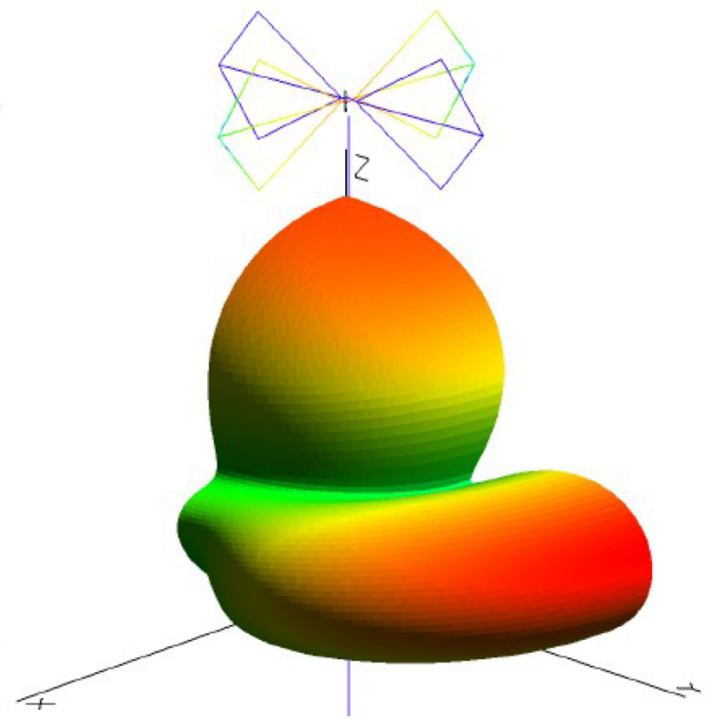


Effect of the antenna response

http://www.iap.fr/grand/wikigrand/index.php?title=File:GRANDsimstatus_May2018.pptx

Antenna gain pattern





Symmetrical pattern for $\varphi > 90°$

G(θ,φ): unloaded butterfly antenna X-arm response to θ,φ wave @ 50 MHz
NEC4 simulation wih infinite ground ("sandy dry") hypothesis
→ G = 0 @ θ >= 90°, huge gradiant (<-18dB between 80 & 90°), effect of infinite ground simulation

Sandra presentation @ Nijmegen meeting

'blind' at 90°

http://www.iap.fr/grand/wikigrand/index.php?title=File:GRANDsimstatus_May2018.pptx

Effect of the antenna response

- For details see: wiki - GRANDSimStatus_May2018
- 2 alternative approaches:
  - ground effect included in antenna response (only if signal coming from above antenna horizon ➔ conservative)

  - Alternative antenna response computation

    Free space simulation + analytical computation for ground effect (complex topograhies discarded ➔ conservative)

    1) Compute attenuation during propagation analytically
    2) Use free-space antenna model to compute response

       - Free propagation if Fresnel ellipsoid above ground.
       - Analytical formulas for diffraction computation otherwise
       - Several topographies considered in the doc, only spherical Earth implemented so far for GRAND.
       - compute (frequency-dependant) attenuation for these events, assuming «flat-Earth-like» topography within Fresnel range

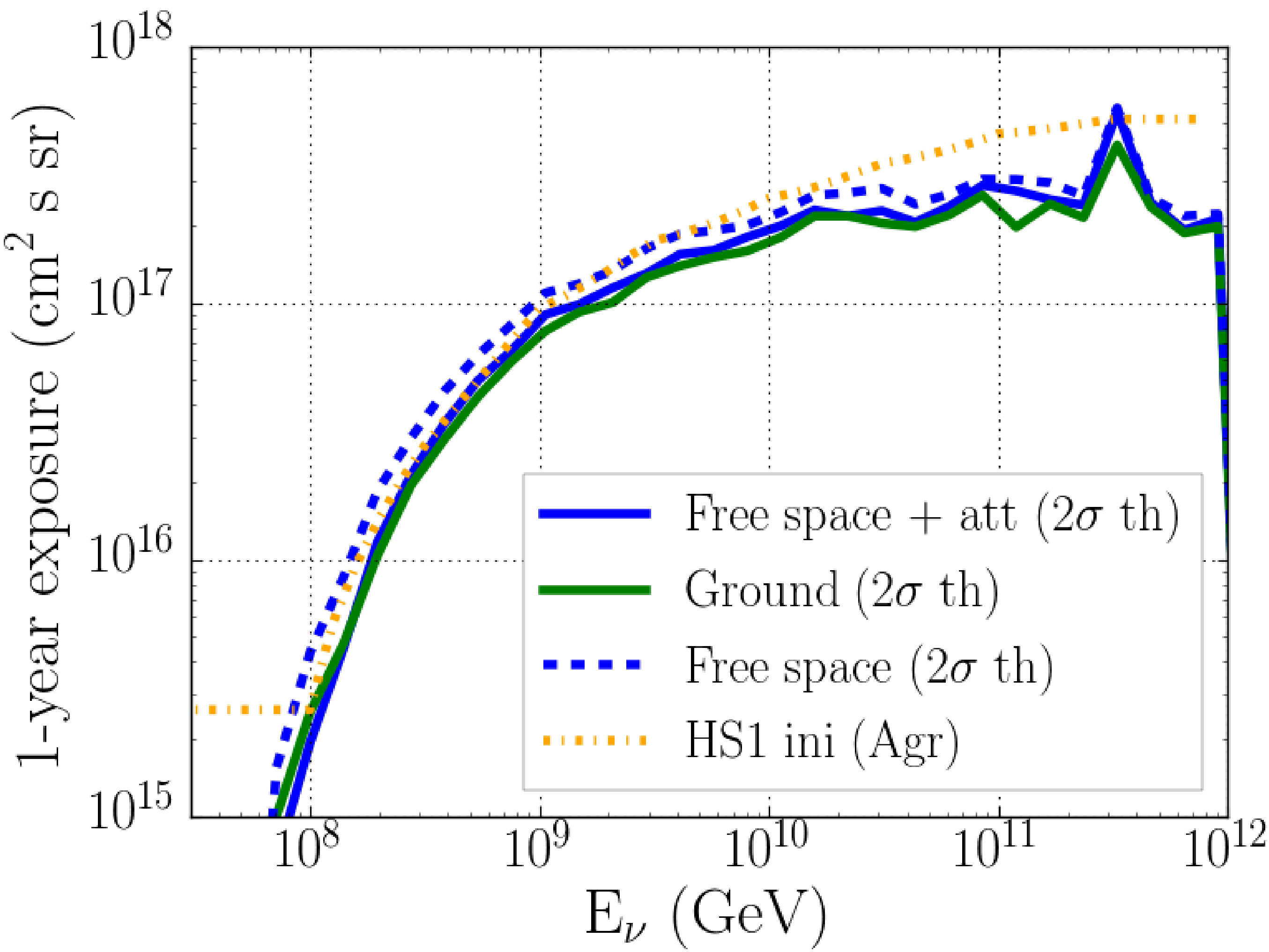
Results: ground vs free space

→ Checking «agressive» scenario (2s threshold)

- **Very similar results between ground & free space (<+10%)**
- But significantly more antennas in FreeSpace events (<N>: 47 vs 30)

➔ **A lot of work for a very similar result ☹ but gives a nice « robustness check » of our exposure computation ☺.**

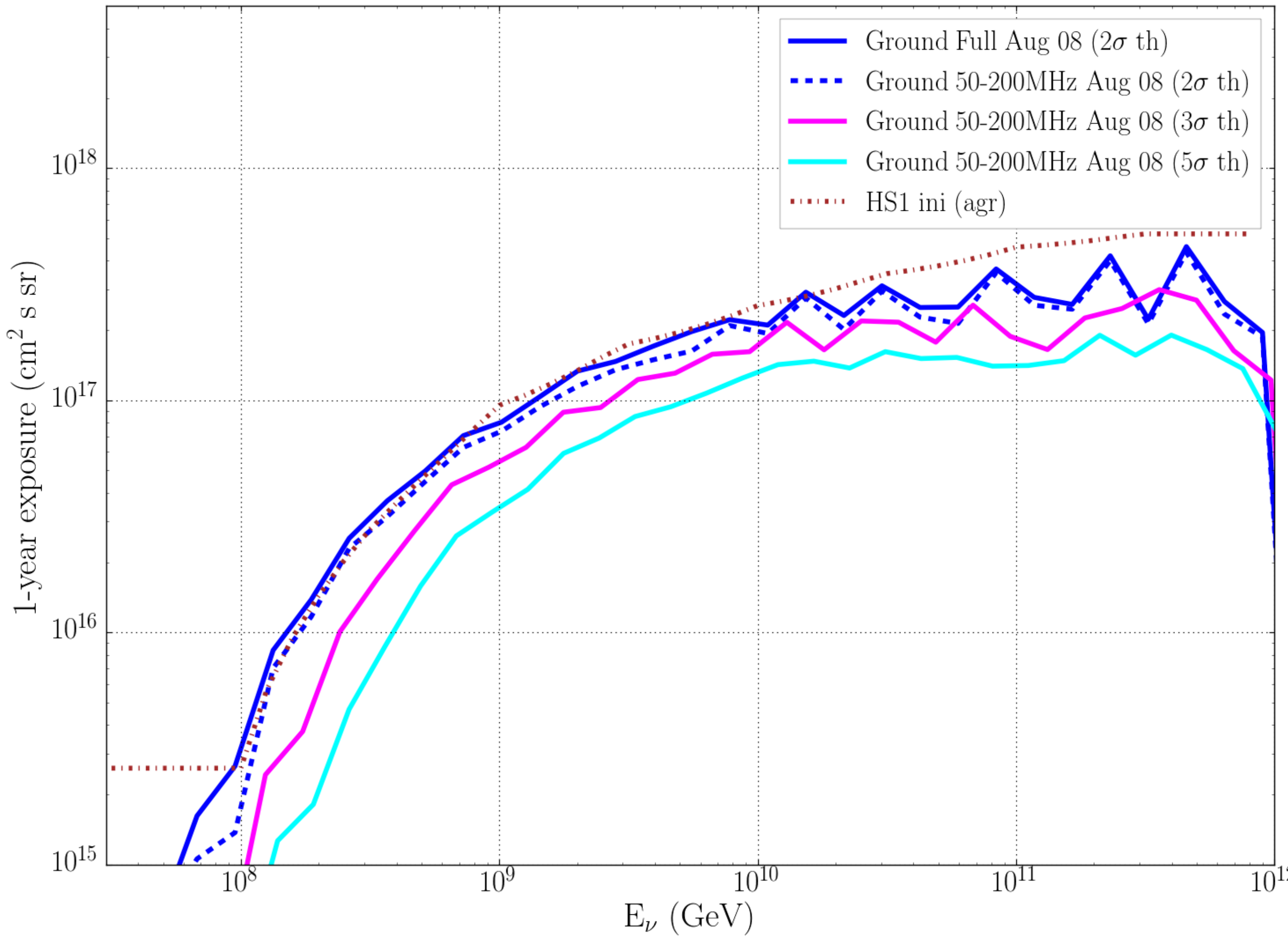
➔ A 3rd way being explored in Argentina (thx to Matias): point source simulation + ground



HS1 limit

- <u>Final</u> result for a 3-years all-flavor exposure on HS1 (10000km²+1km step) in 50-200MHz, with 5+ antenna cluster above 2sigma threshold
- **Flux limit = 7.9 10^{-9} GeV/cm²/s/sr**

~4 10^{-10} GeV/cm²/s/sr when extrapolated to GRAND200k



- Initial limit:
  for HS1: 7.2 10^{-9} GeV/cm²/s/sr (7500km²+800m step)
  For GRAND200k 2.2 10^{-10} GeV/cm²/s/sr (200'000km²+800m step)

=> Limits presented so far (Nijmegen) seems to be robust!

Sensitivity study - summary

- All elements of sensitivity computation chain now tested.
  → recent fix in Zhaires: test still ongoing
  → next step: error on trigger rate for radio morphing with statistics
- New limit now seems robust & reliable
- Aggressive limit is ~2x worst than initial, mostly because of clustering strategy + different array/step size.

Outlook

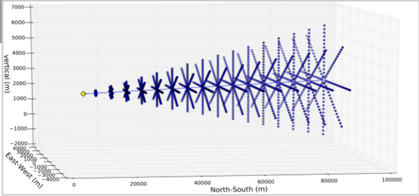
- Look for other hotspots (Tian-Shan cosmic ray station (Kazakhstan)
  → contact to D. Kostunin – KIT)
- Include 'athmosphere' events
- Impact of frequency optimisation
- Layout optimisation (step size, real grid != square)

The Radio Morphing recipe

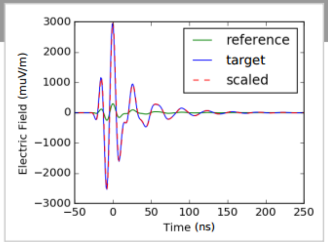
Not GRAND specific!
→ universal method

1

Preparing the reference shower: simulated electric field traces for antennas positions arranged in star-shape patterns in fixed distances to X_{max}



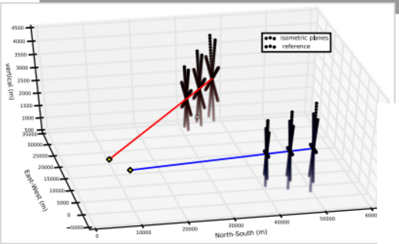
Scaling of the electric field amplitude according target shower parameters:
$E_A(t) = k_{AB} \, E_B(t)$



Desired shower parameters

2

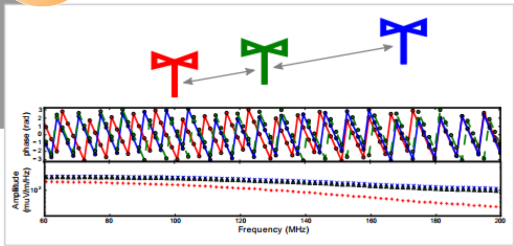
Isometry of reference positions: translation and rotation according target shower direction



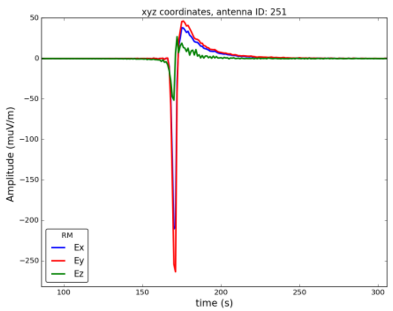
Desired antenna positions

3

Interpolation of pulse shape at desired antenna position:
$E_A(x_i,t) \longrightarrow E_A(x_j,t)$



4

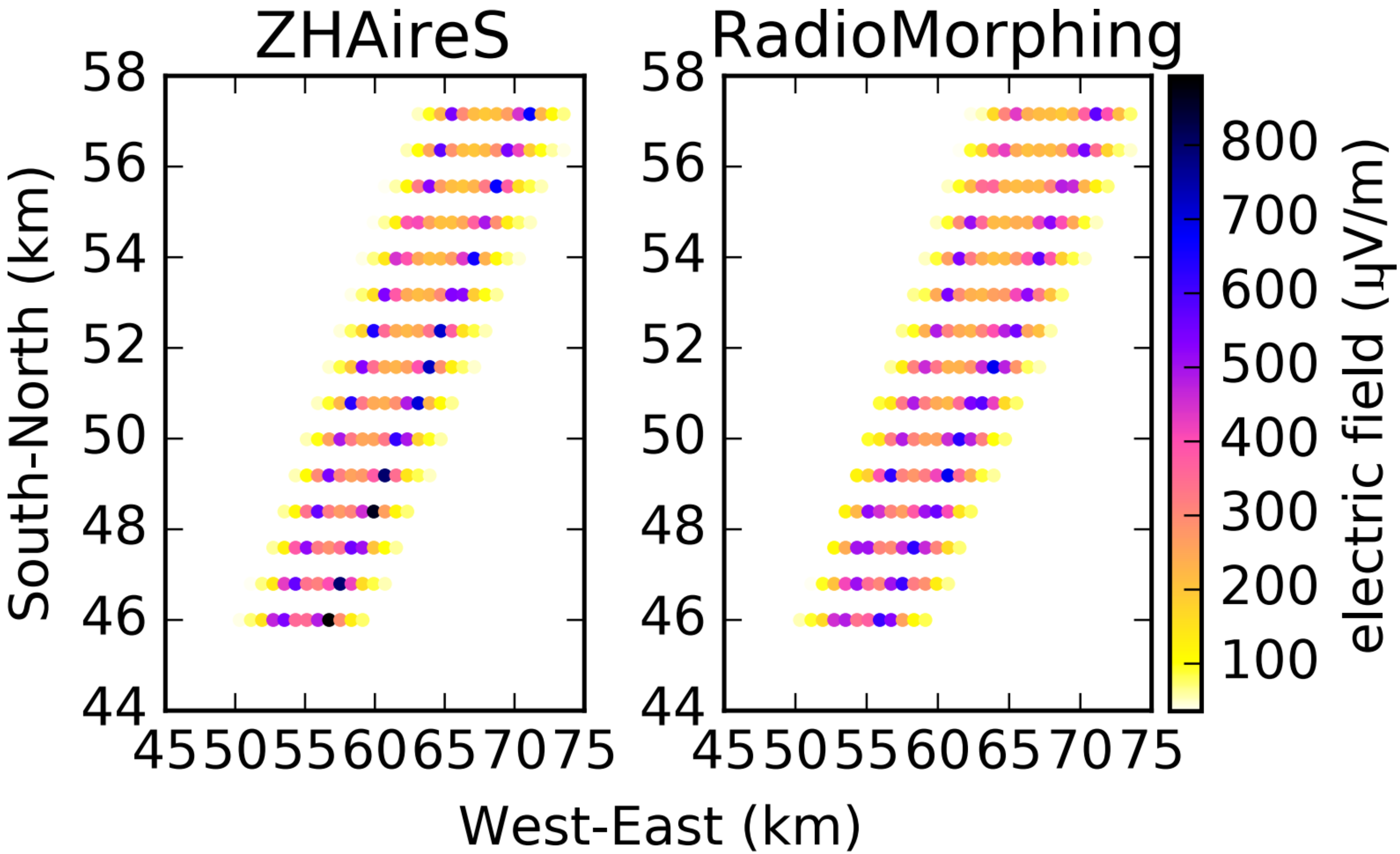


Electric field traces at desired antenna positions

AZ et al., in prep.

Cross-check radio morphing

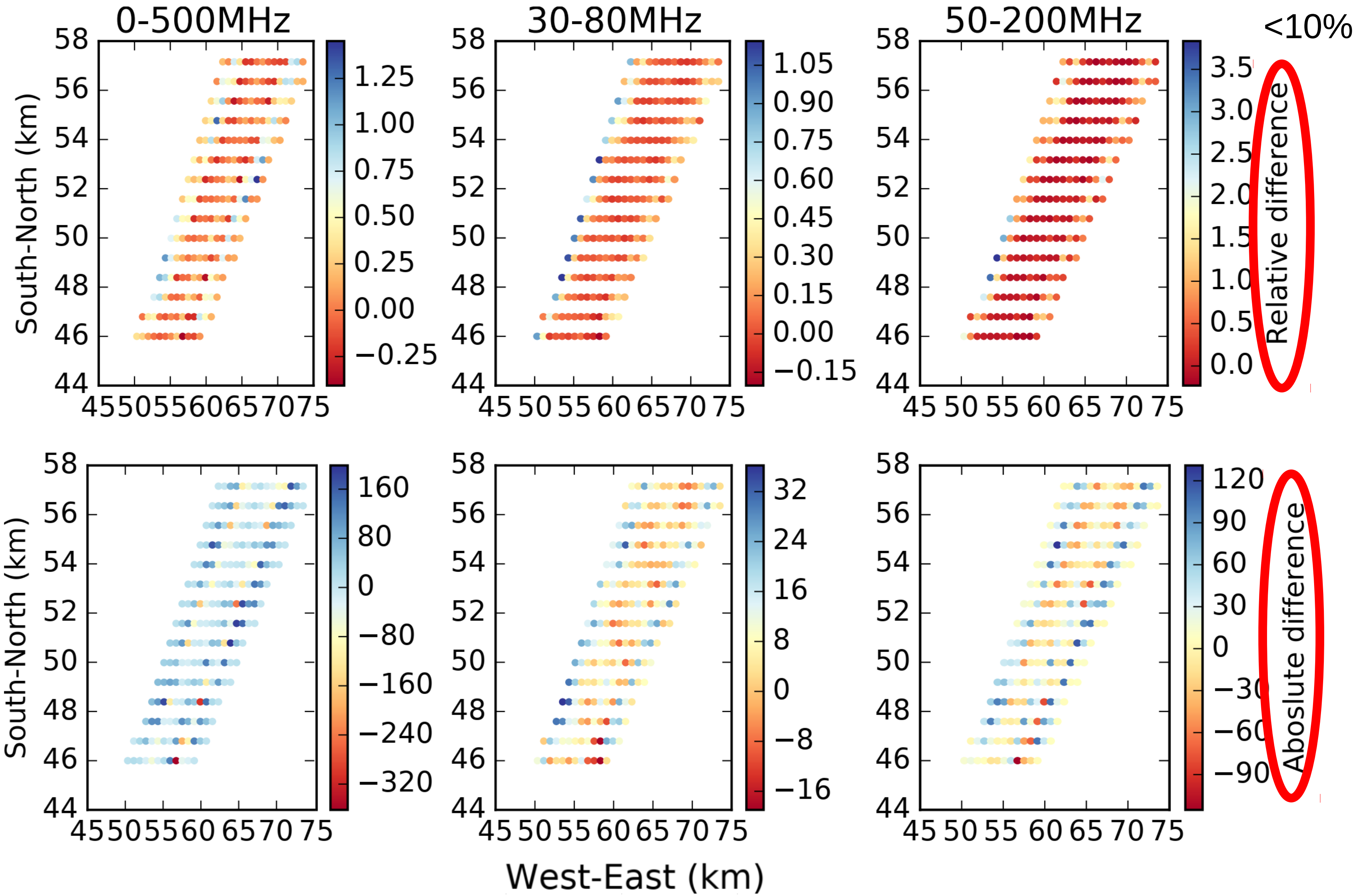
Example shower: electron, 1.05 EeV, zen=89.5°, az=50° (GRAND conv), h=2200m
Toymodel array, slope of 5deg
Reference shower: electron, 0.1 EeV, zen=88.5°, az=220° (GRAND conv), h=1700m



EW component,
1ns sampling,
not filtered

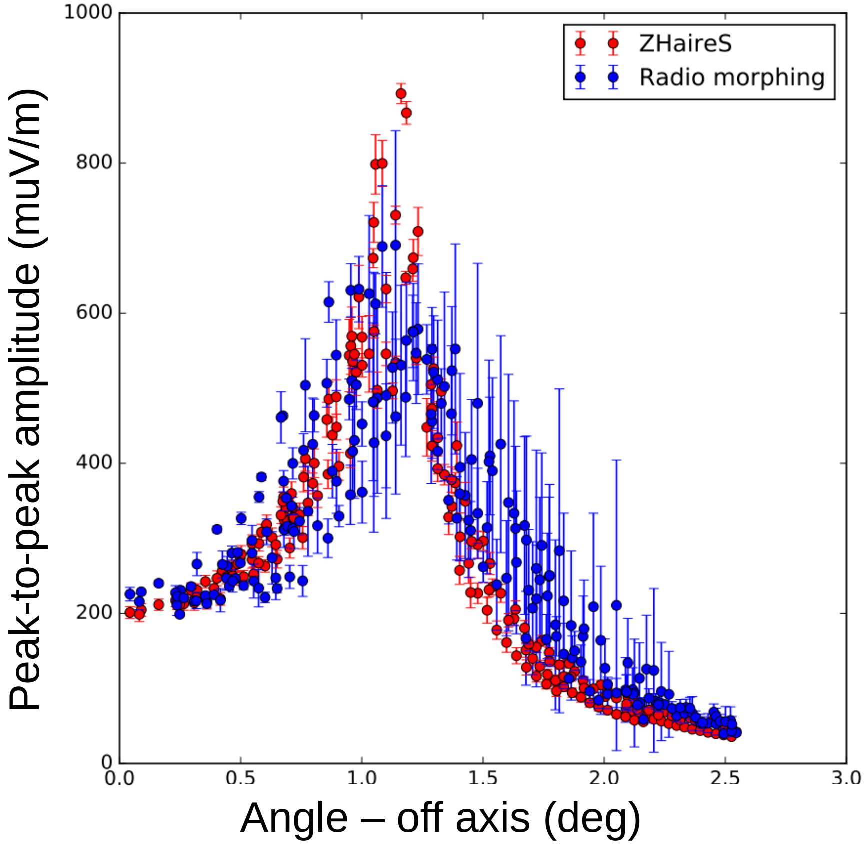
→ **Radio morphing can nicely reproduce features as the Cherenkov ring and strength of signal**

Cross-check radio morphing



Highest differences at the edges of the Cherenkov cone
→ signal drops exponentially, sensitive to the smallest offset in the positions of the ring

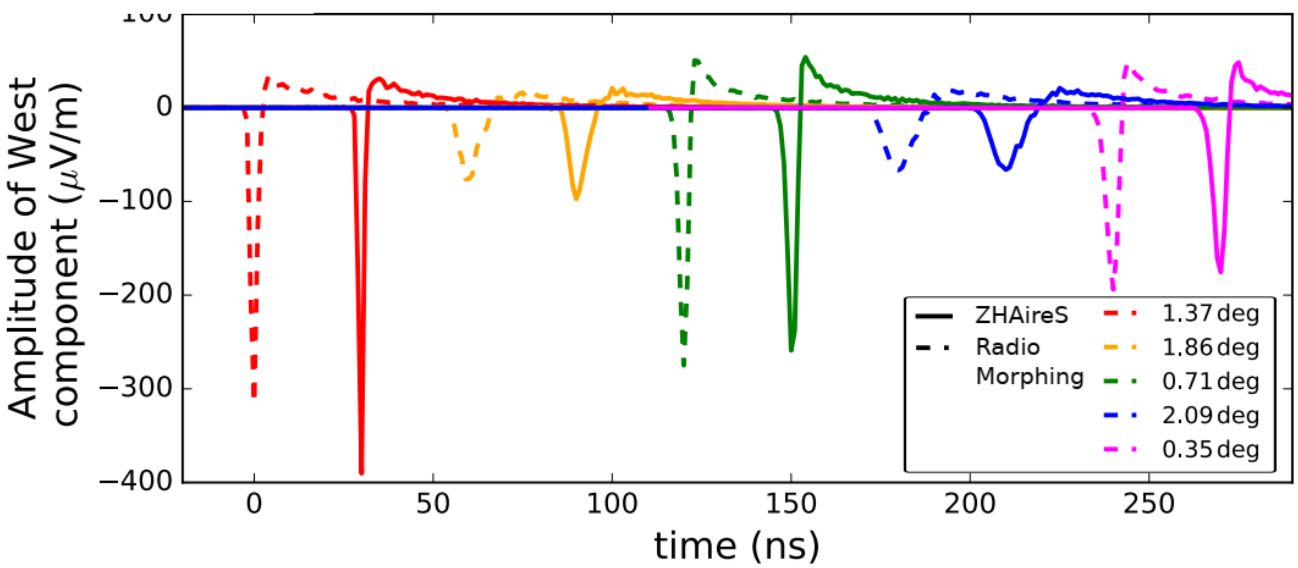
Cross-check radio morphing



‘LDF’ of EW component
10 Zhaires simulations vs radio morphing run with 10 different reference shower

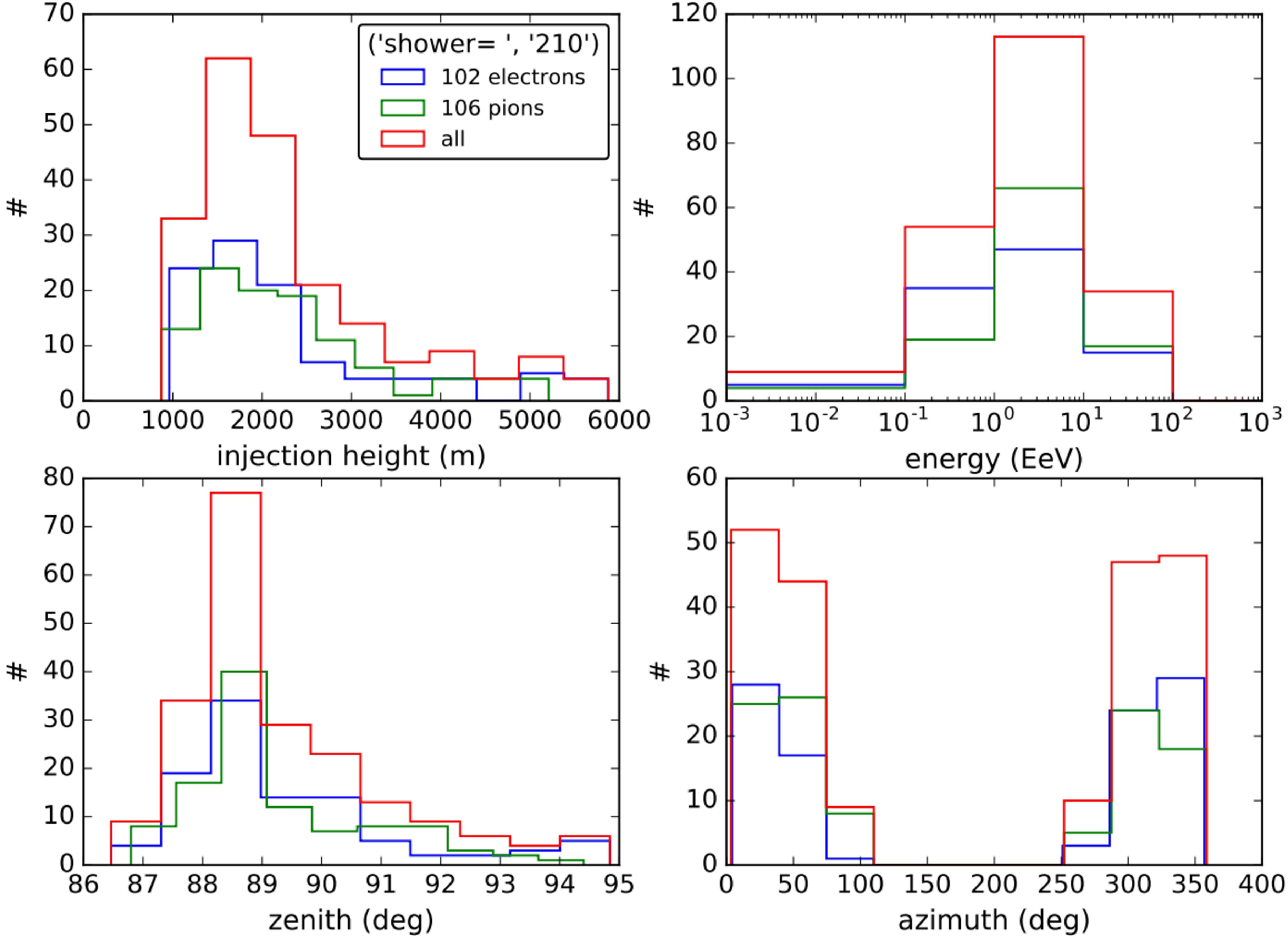
→ reference showers had energy of 0.1EeV
→ “flatter LDF gets scaled up”
=> better for low-energetic shower (don’t get missed)
=> for high-energetic shower: more antennas trigger, but for events which should nevertheless be detected)

Antenna positions for one shower at several angles to the shower axis

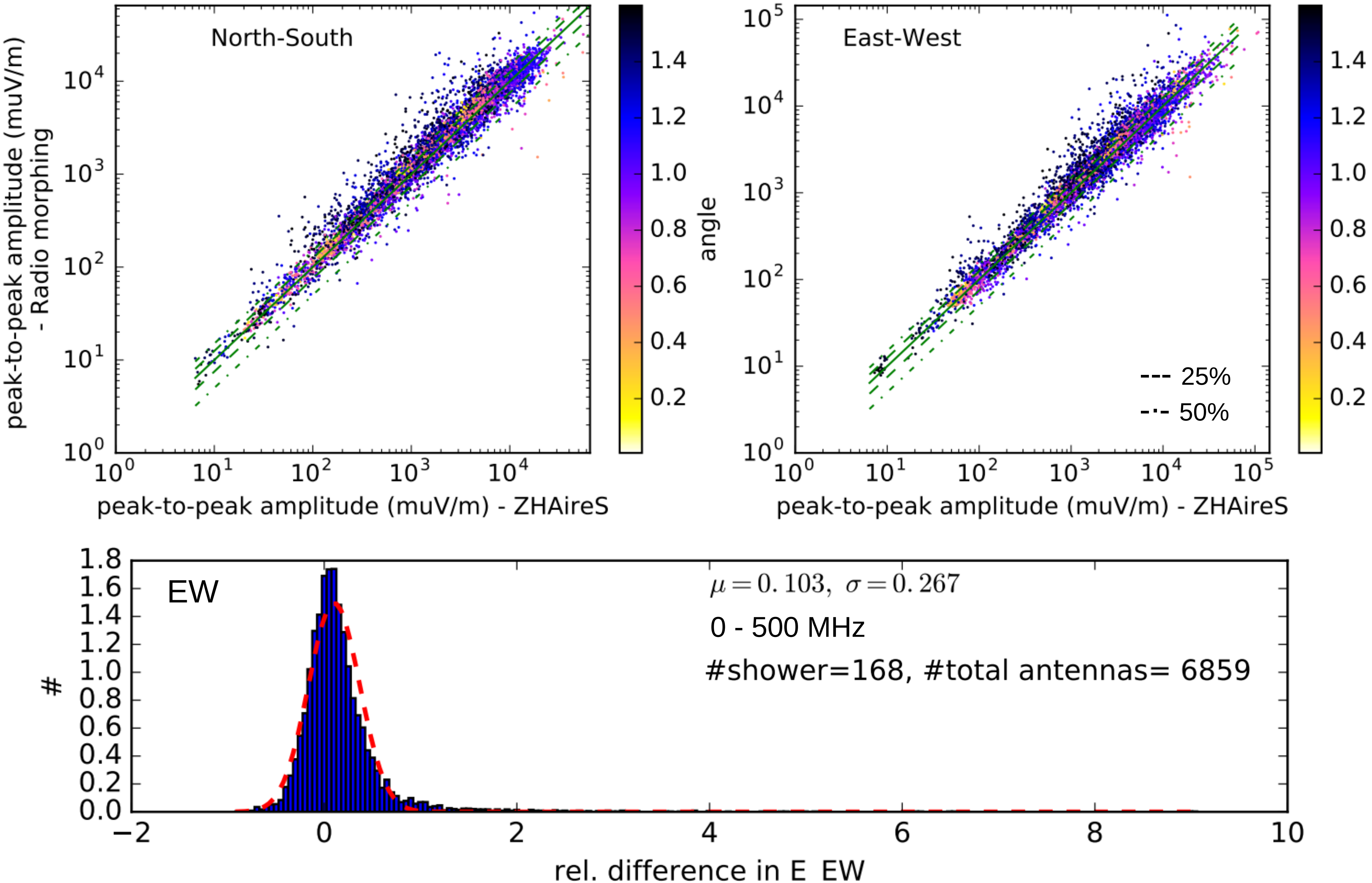


Radio morphing – comparison to a set of showers

Example events from HS1 neutrino set



Radio morphing – comparison to a set of showers

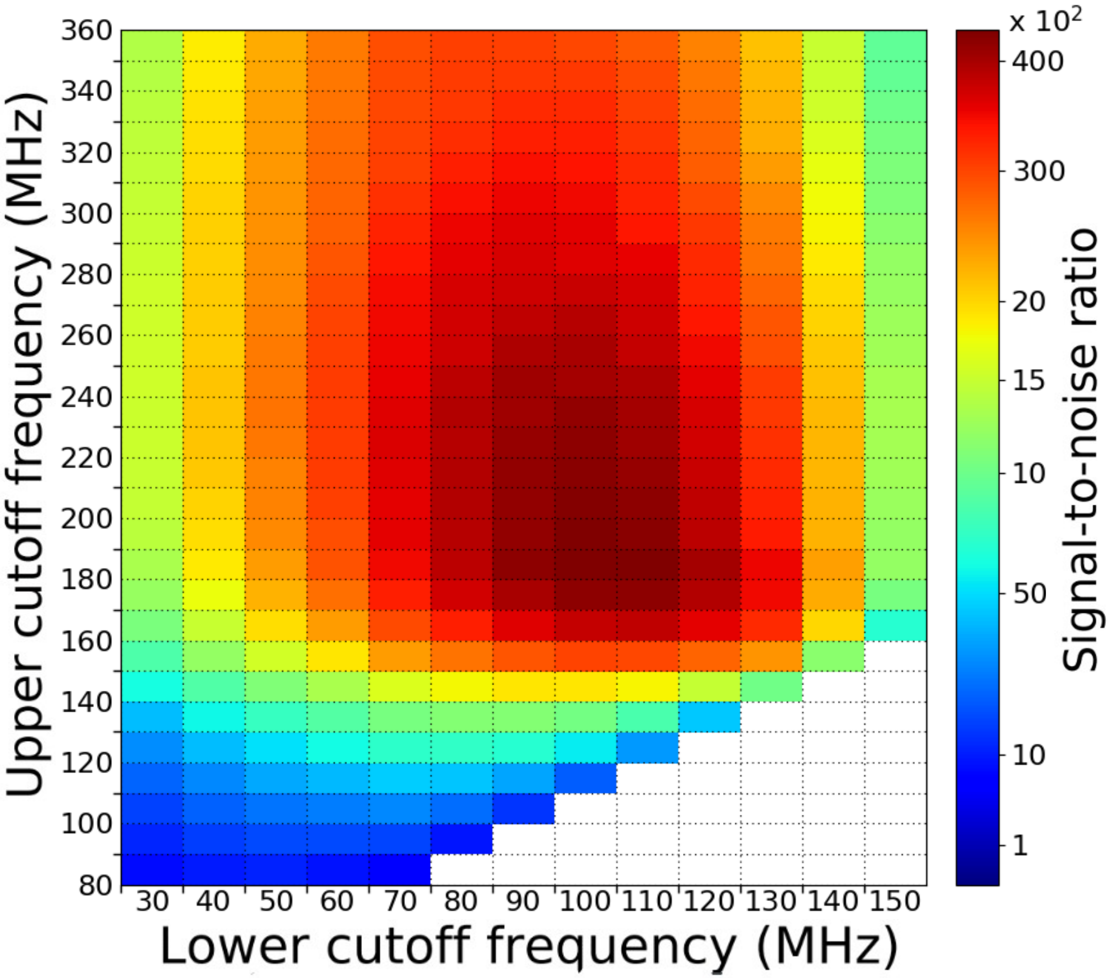


As expected: electric field from radio morphing tends to be slightly to higher due to the choice of the reference shower (difference decreasing slightly after filtering)

Cross-check frequency range (by Aswathi Balagopal - KIT)

- Same study as performed for IceTop (arXiv:1712.09042)
- Antenna response of a dipole antenna used
- ZHAireS simulation with 1ns binning, Crs and neutrinos

Bug in sampling rate while applying antenna response led first to 70-150MHz band



antenna@cone
neutrino
5 10^17 eV, zen=87° (GRAND conv)
h=2800m

Best SNR for 100-180MHz band
(same as for IceTop, AERA, TRex)

Aswathi wrote a paragraph for the White Paper
→ include Aswathi Balagopal (and Andreas Haungs?) to WP author list

Triggering and reconstruction of air shower using neural networks

(by Florian Führer and Tom Charnock – IAP)

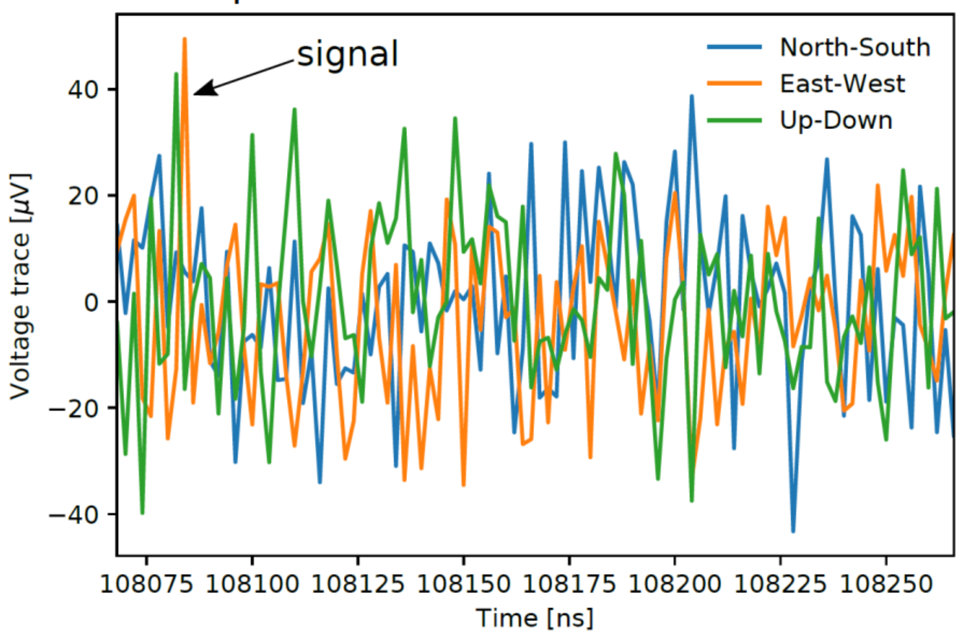
Training set

Supervised training with simulated data (ZHAireS)

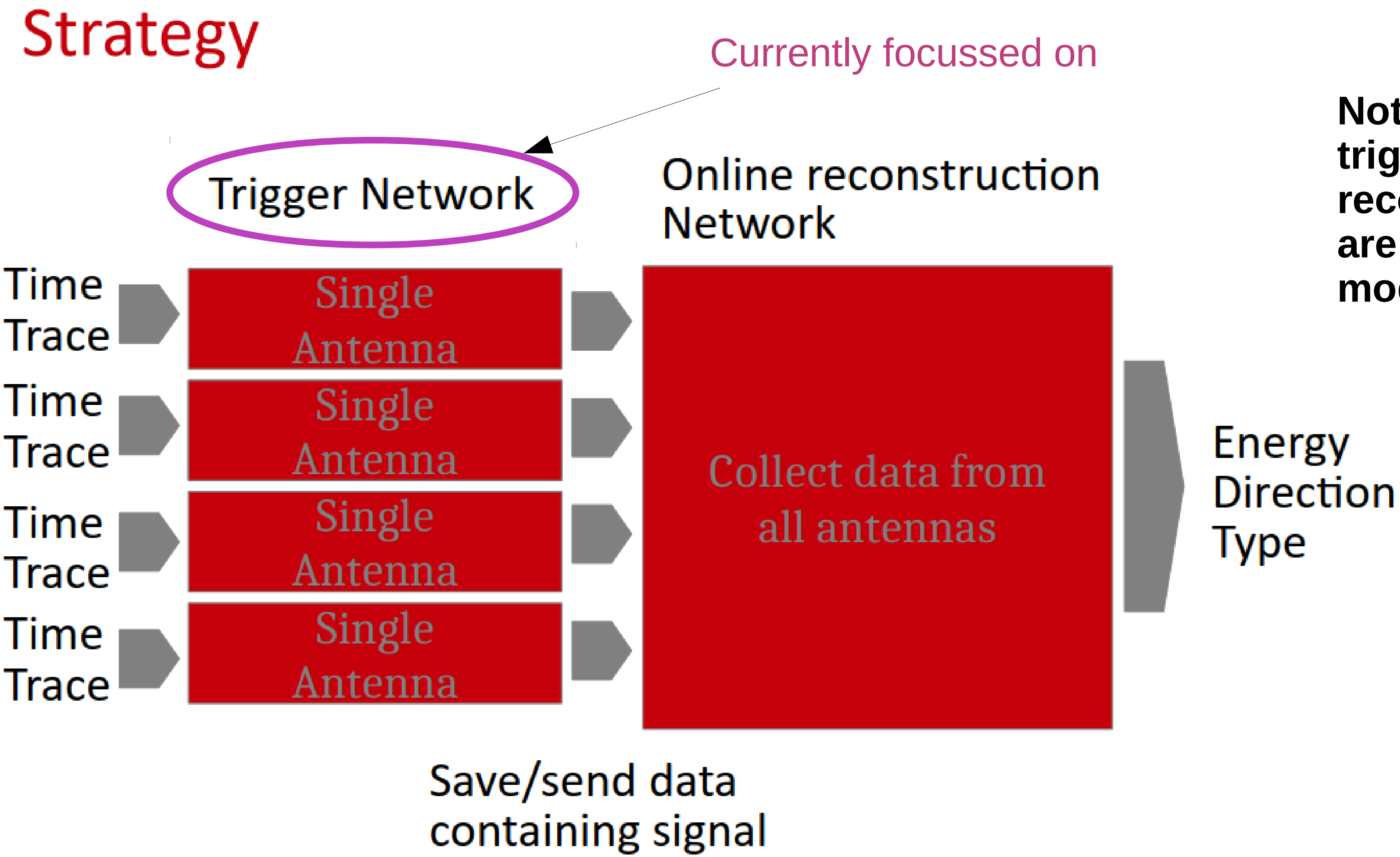
>150k samples, 50% with signal and 50% only with noise

- Toy model antenna array:
  - rectangular array of 35 x 35 antennas
  - slope of 5°
- Cosmic rays (p): E=1-100EeV, zenith=65-85deg
- Expected neutrino distribution in energy and arrival direction for GRAND
- Simulations include:
  - antenna response
  - white noise V_{rms} =15μV
  - filtered to 50-200MHz

Example simulation



Triggering and reconstruction of air shower using neural networks



Note:
trigger and reconstruction are two separate modules!

Preliminary results

Comparison of the NN-based trigger to a conventional one
Total accuracy increases form 0.69 to 0.72

Accurancy = number of correctly classified time traces

	Simulation		
		Signal	Noise
Network Threshold 60 µV	Signal	0.43 0.42	<2E-3 0.04
	Noise	0.57 0.58	~1 0.96

Reduces data stream from 100kHz to < 5kHz

Note: Tested on 50% Signal and 50% Noise
Threshold applied to all 3 Voltage components separately
Value of 60µV chosen to maximize the classification accuracy

OUTLOOK:

- Open questions:
  - Improvement from coincidence
  - Computational performance/energy consumption → How to put on antenna?
- Currently we are producing more data, needed to
  - Evaluate whether SN or data limited
  - Do statistics on full events, i.e. how well are events recovered
  - Train reconstruction network

Summary

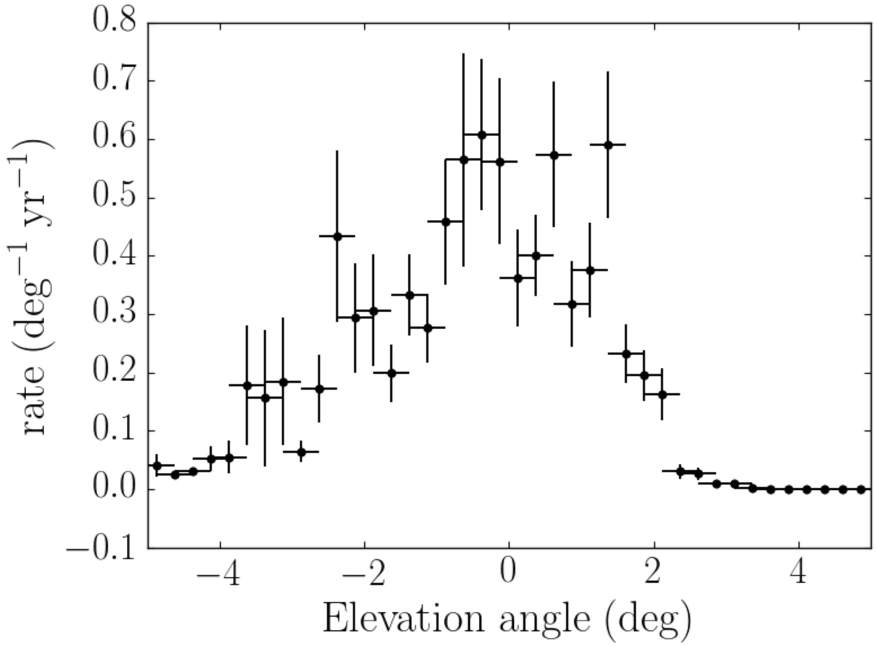
- Radio morphing – ready for publication
  - calculation of the arrival time still to be fixed (but not urgent)

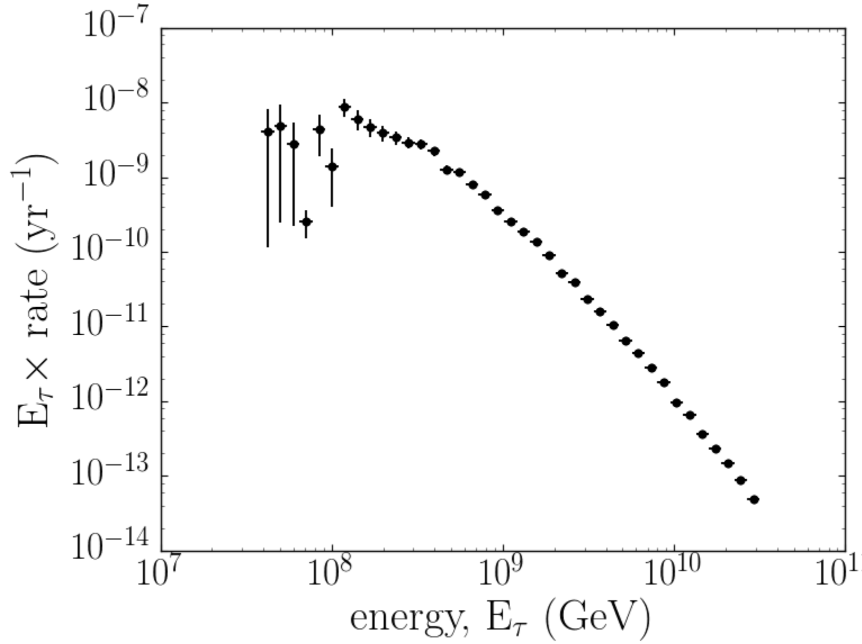
- Frequency band study – done
  - best best 100-180 MHz for neutrinos and Crs

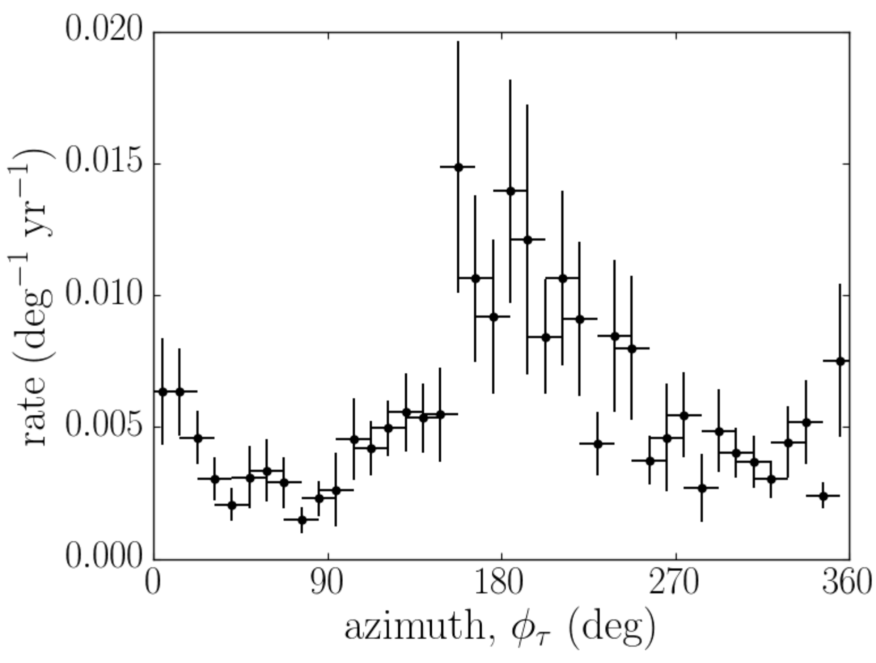
- Machine Learning – ongoing
  - production of simulation for training data ongoing, run now with fixed version of Zhaires
  - current effort focussed on trigger network
    → at the moment slightly better than threshold trigger

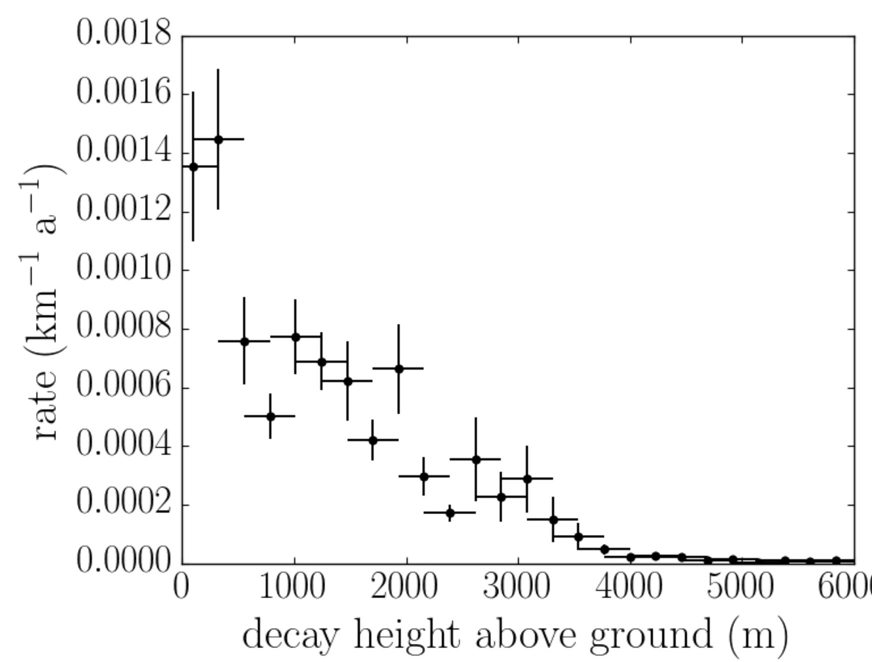
Appendix

Characterisation of HS1



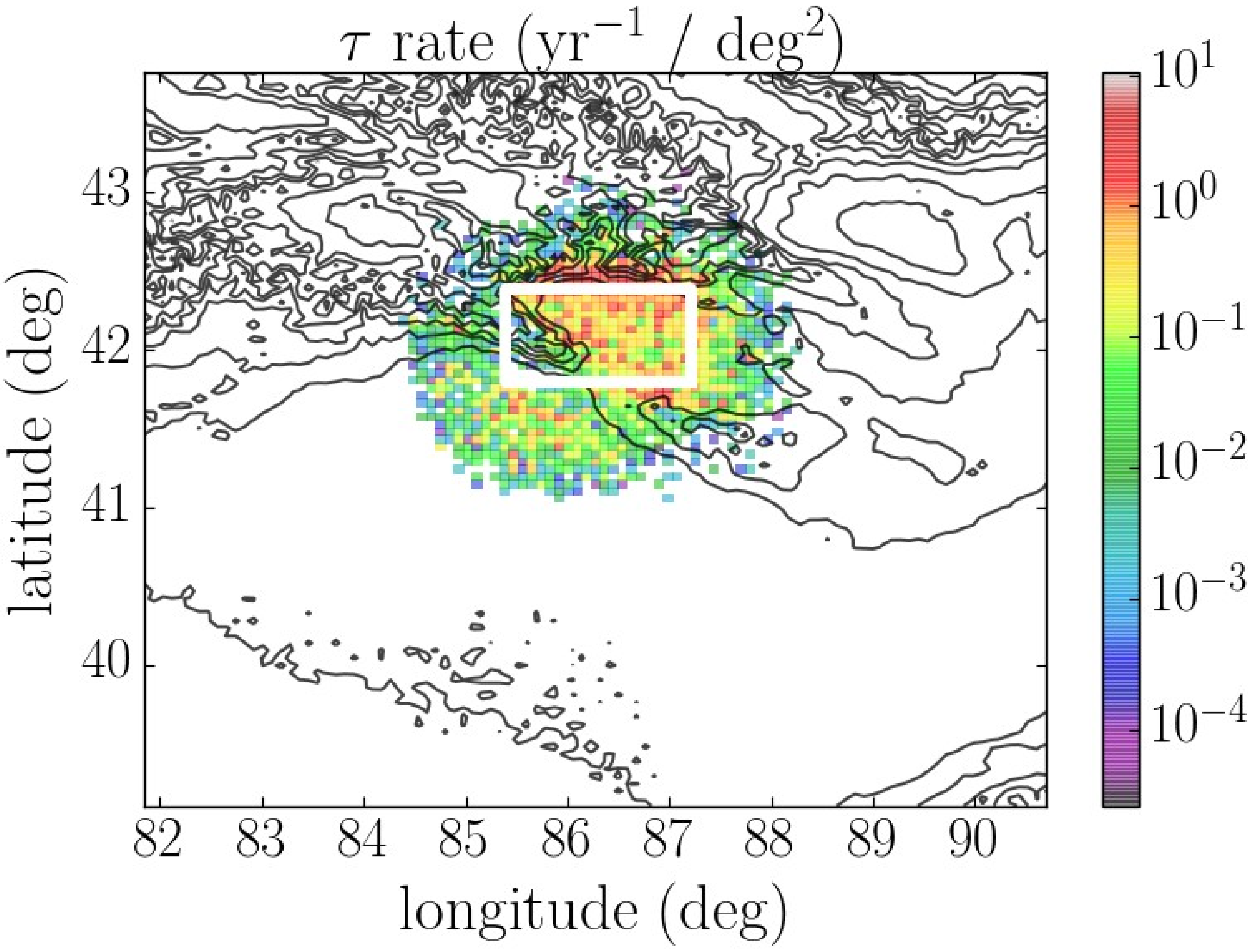


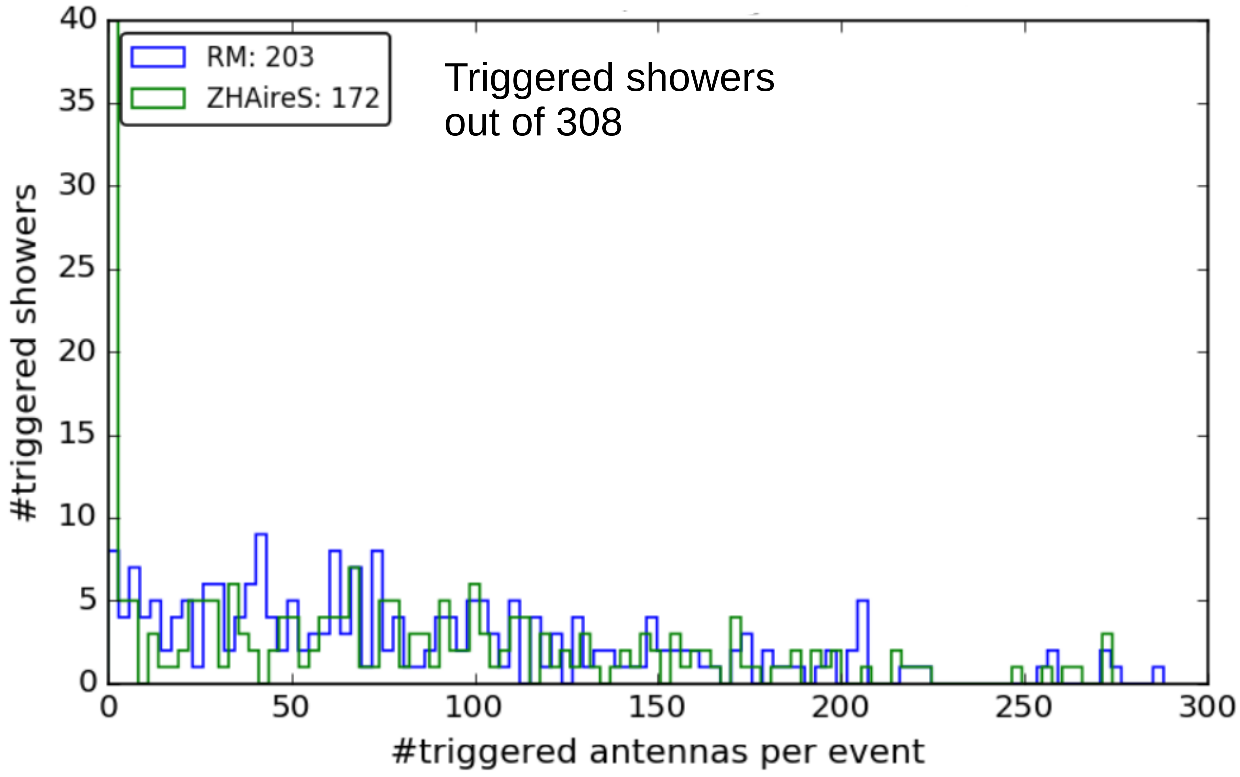


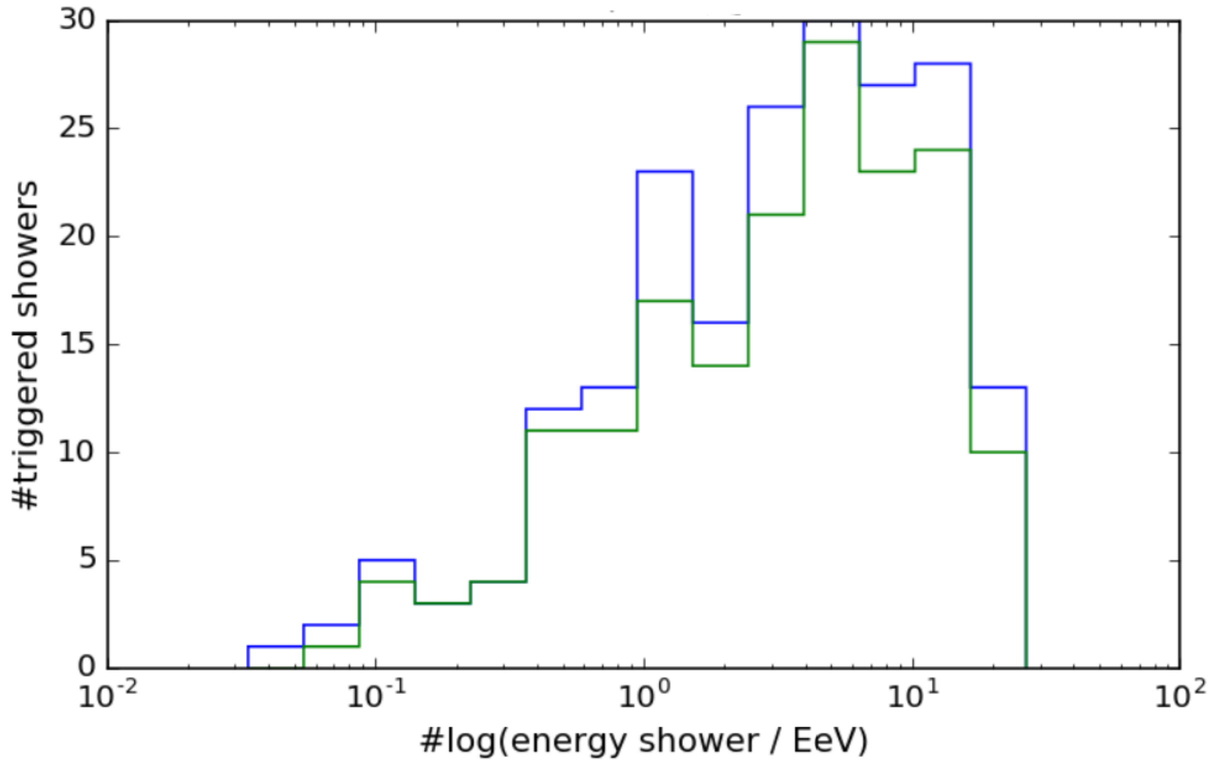


Characterisation of HS1

10 000 km2 area



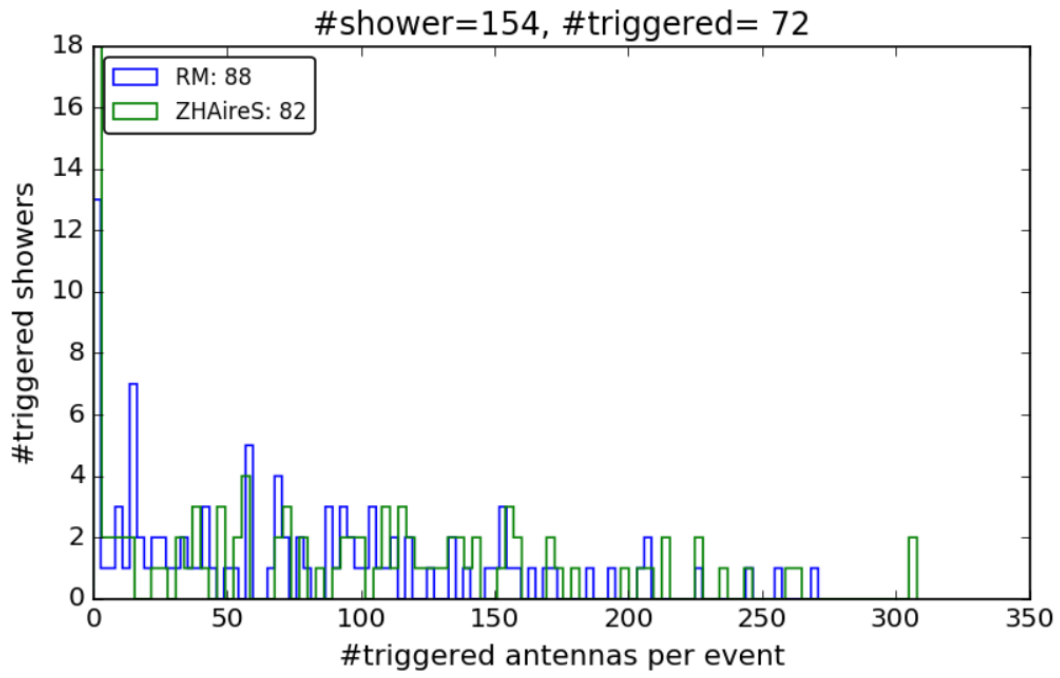


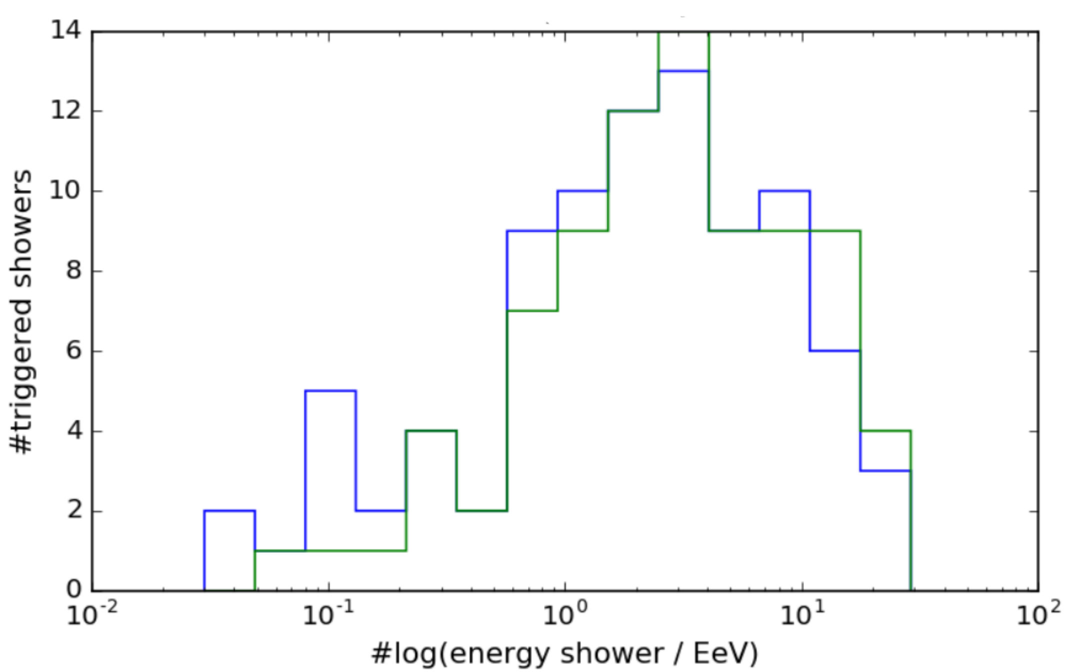


Leading particle study

leading particle gets all the energy
And a toymodel array

→ trigger for radio mophing and zhaires simulations
→ 8 antennas triggered in one component, threshold: 2sigma





<u>Subshower study</u>

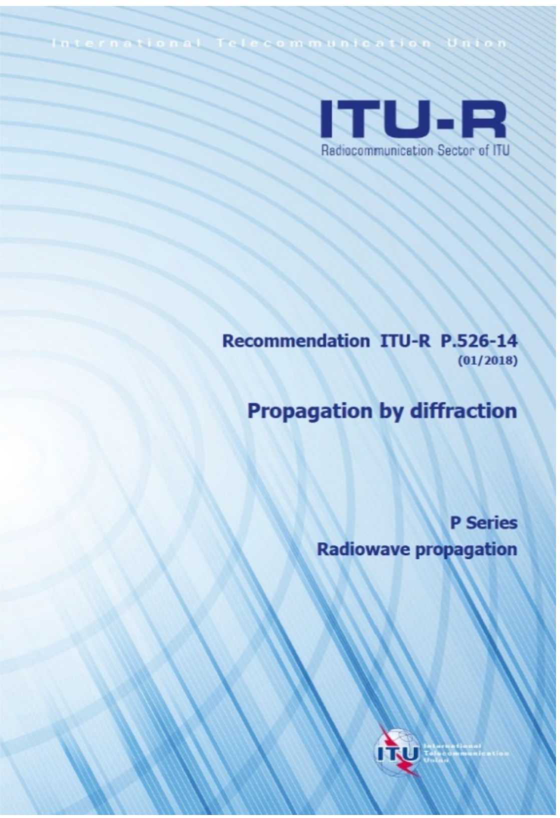
Several possible primaries for Zhaires simulation (but most event have one or one dominant particle)
And a toymodel array

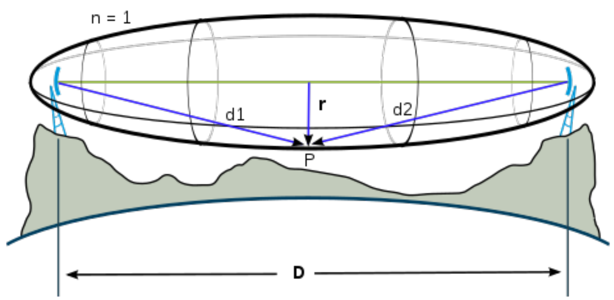
→ trigger for radio moping and zhaires simulations
→ 8 antennas triggered in one component, threshold: 2sigma

Alternative antenna response computation

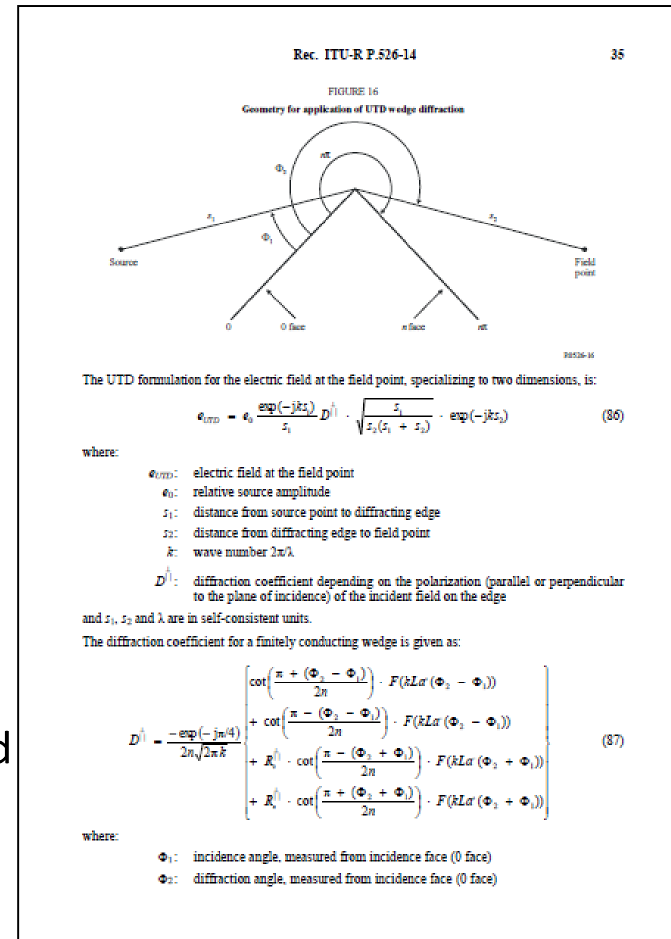
1) Compute attenuation during propagation analytically
2) Use free-space antenna model to compute response

International Telecommunication Union





- Free propagation if Fresnel ellipsoid above ground.
- Analytical formulas for diffraction computation otherwise
- Several topographies considered in the doc, only spherical Earth implemented so far for GRAND.



Rec. ITU-R P.526-14 35

FIGURE 16

Geometry for application of UTD wedge diffraction

Source, Field point, 0, 0 face, n face, nπ, s_1, s_2, Φ_1, Φ_2, nπ

P.0526-16

The UTD formulation for the electric field at the field point, specializing to two dimensions, is:

$$e_{UTD} = e_0 \frac{\exp(-jks_1)}{s_1} D^{\parallel} \cdot \sqrt{\frac{s_1}{s_2(s_1+s_2)}} \cdot \exp(-jks_2) \quad (86)$$

where:

- e_{UTD}: electric field at the field point
- e_0: relative source amplitude
- s_1: distance from source point to diffracting edge
- s_2: distance from diffracting edge to field point
- k: wave number $2\pi/\lambda$
- $D^{\parallel}$: diffraction coefficient depending on the polarization (parallel or perpendicular to the plane of incidence) of the incident field on the edge

and s_1, s_2 and λ are in self-consistent units.

The diffraction coefficient for a finitely conducting wedge is given as:

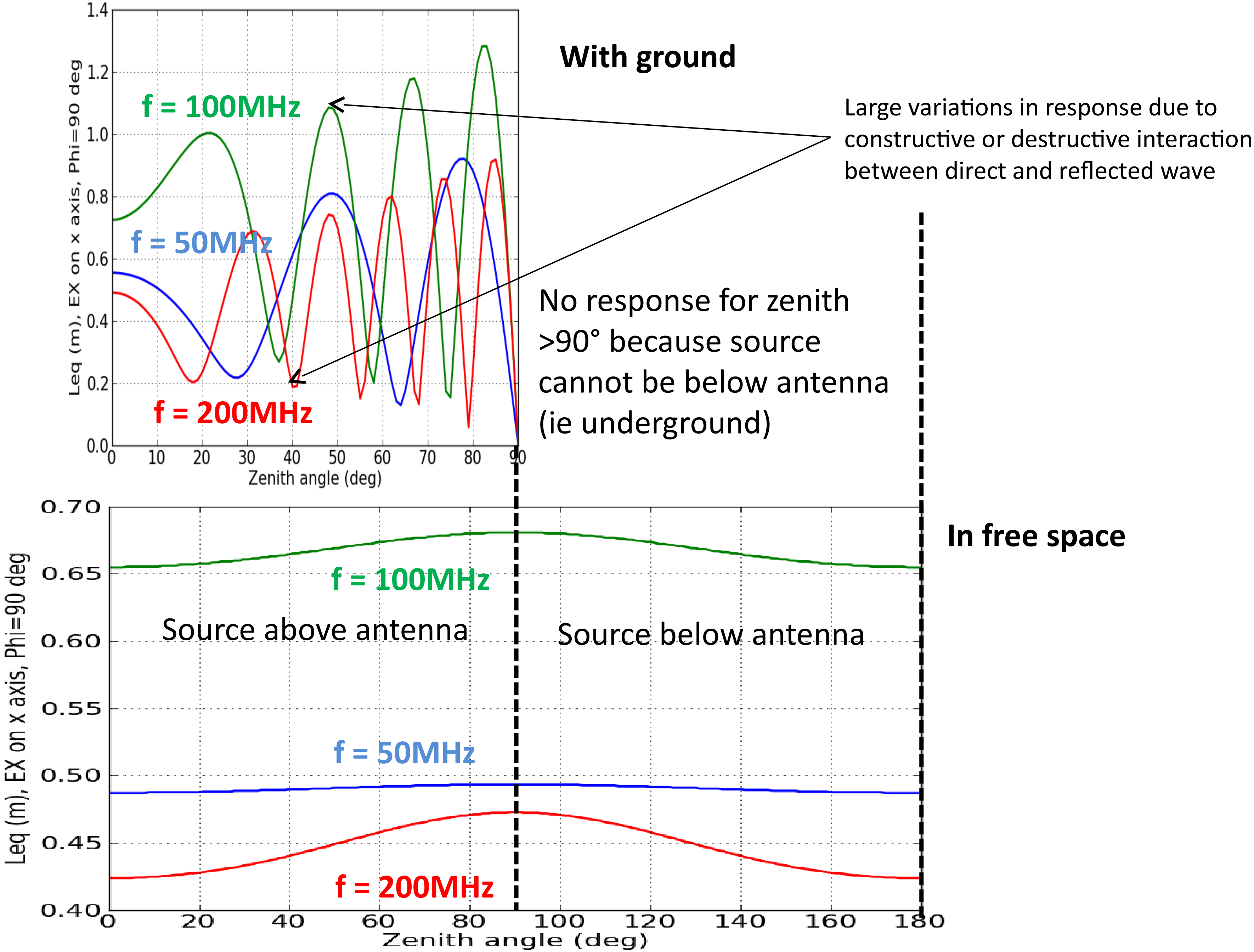
$$D^{\parallel} = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}} \left[\begin{array}{l} \cot\left(\frac{\pi+(\Phi_2-\Phi_1)}{2n}\right) \cdot F(kLa^{+}(\Phi_2-\Phi_1)) \\ + \cot\left(\frac{\pi-(\Phi_2-\Phi_1)}{2n}\right) \cdot F(kLa^{-}(\Phi_2-\Phi_1)) \\ + R_0^{\parallel} \cdot \cot\left(\frac{\pi-(\Phi_2+\Phi_1)}{2n}\right) \cdot F(kLa^{-}(\Phi_2+\Phi_1)) \\ + R_n^{\parallel} \cdot \cot\left(\frac{\pi+(\Phi_2+\Phi_1)}{2n}\right) \cdot F(kLa^{+}(\Phi_2+\Phi_1)) \end{array} \right] \quad (87)$$

where:

- Φ_1: incidence angle, measured from incidence face (0 face)
- Φ_2: diffraction angle, measured from incidence face (0 face)

https://www.itu.int/rec/R-REC-P.526-14-201801-I/fr

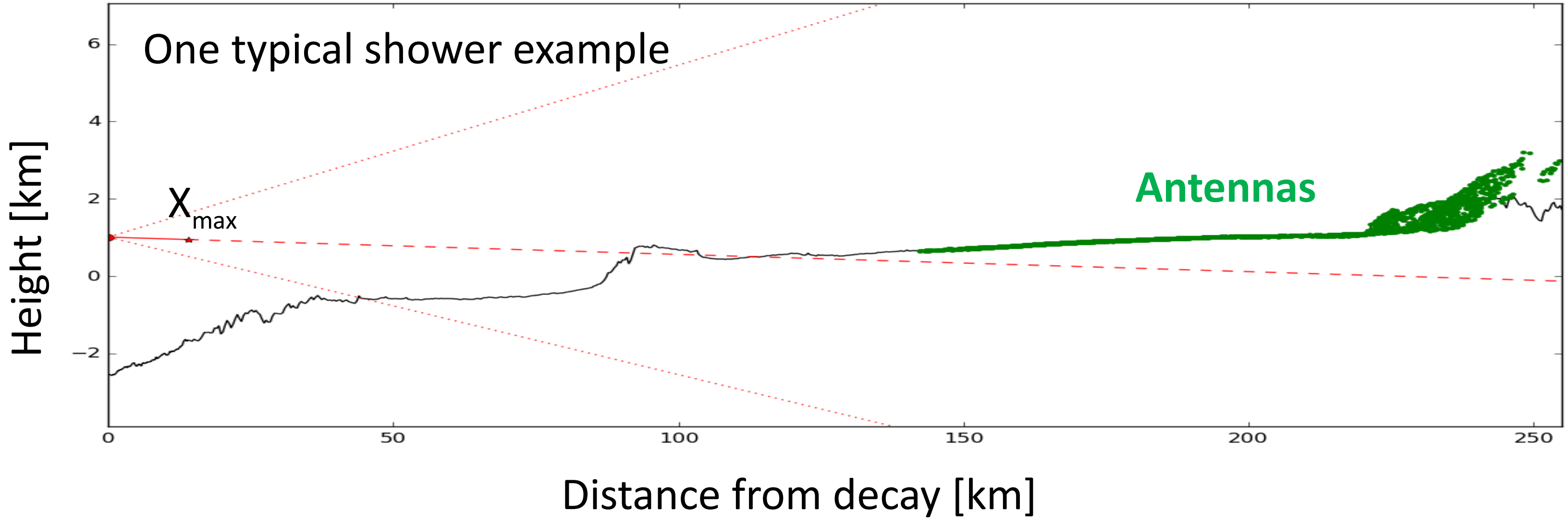
Antenna effective length to incoming wave with polarization // to antenna arm



HS1 topography

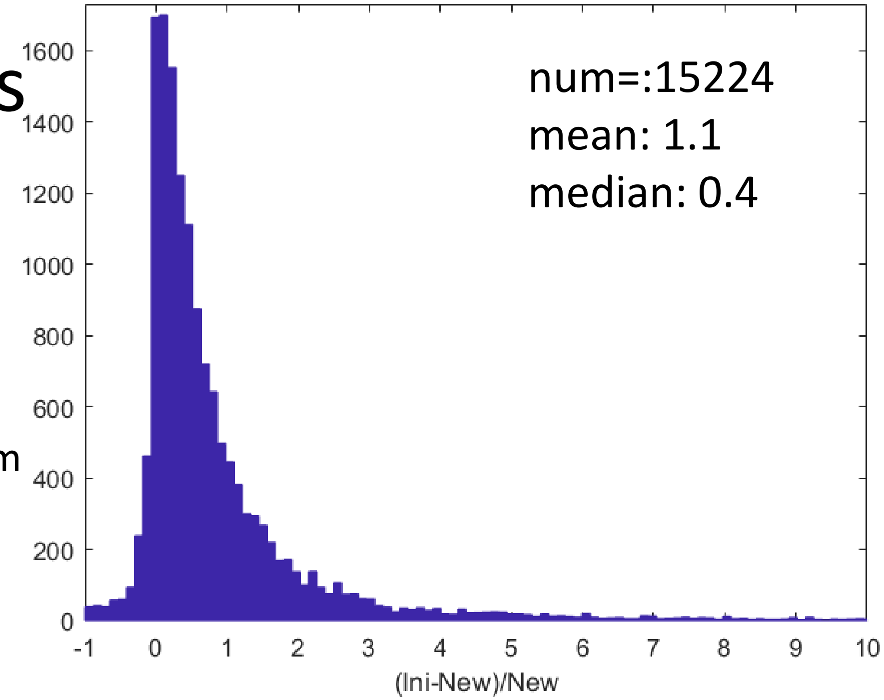
- Large fraction of events (~80%*) with 5+ antennas with short Fresnel range (<5km before antenna) + ~plane ground (σ_{Δ}=1.5m) in this Fresnel range (*: not weigthed)

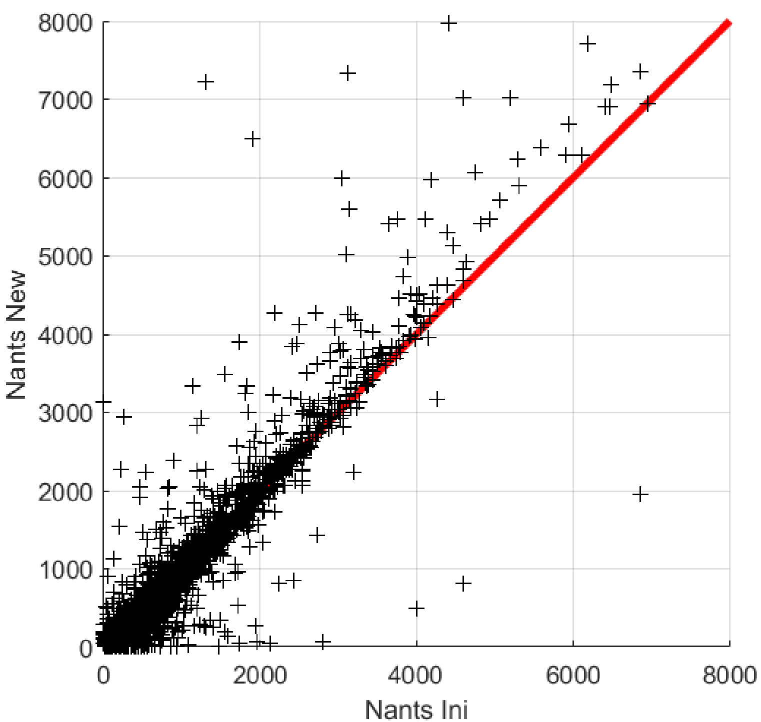
➔ Possible to compute (frequency-dependant) attenuation for these events, assuming «flat-Earth-like» topography within Fresnel range.

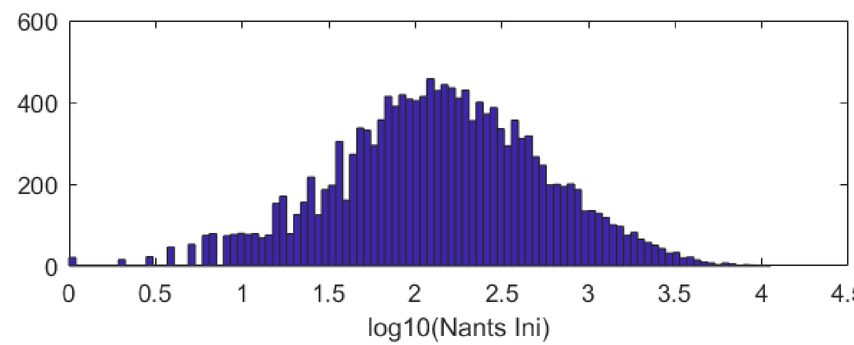


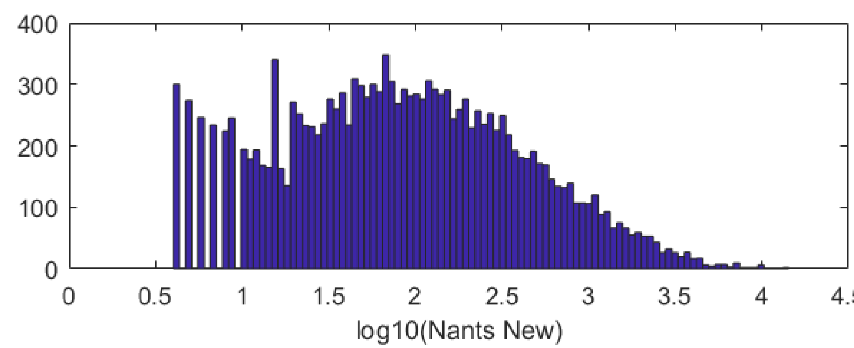
Stat study on 20000 showers from v2

- 15642 showers kept (rest is beyond 200X200km^2 square, no topography for initial study)
  - Initial study: 13980 trigged (20+ antennas @ 400m step) +418 showers discarded. <Nants>=318
  - New study: 12447 trigged. <Nants>=284



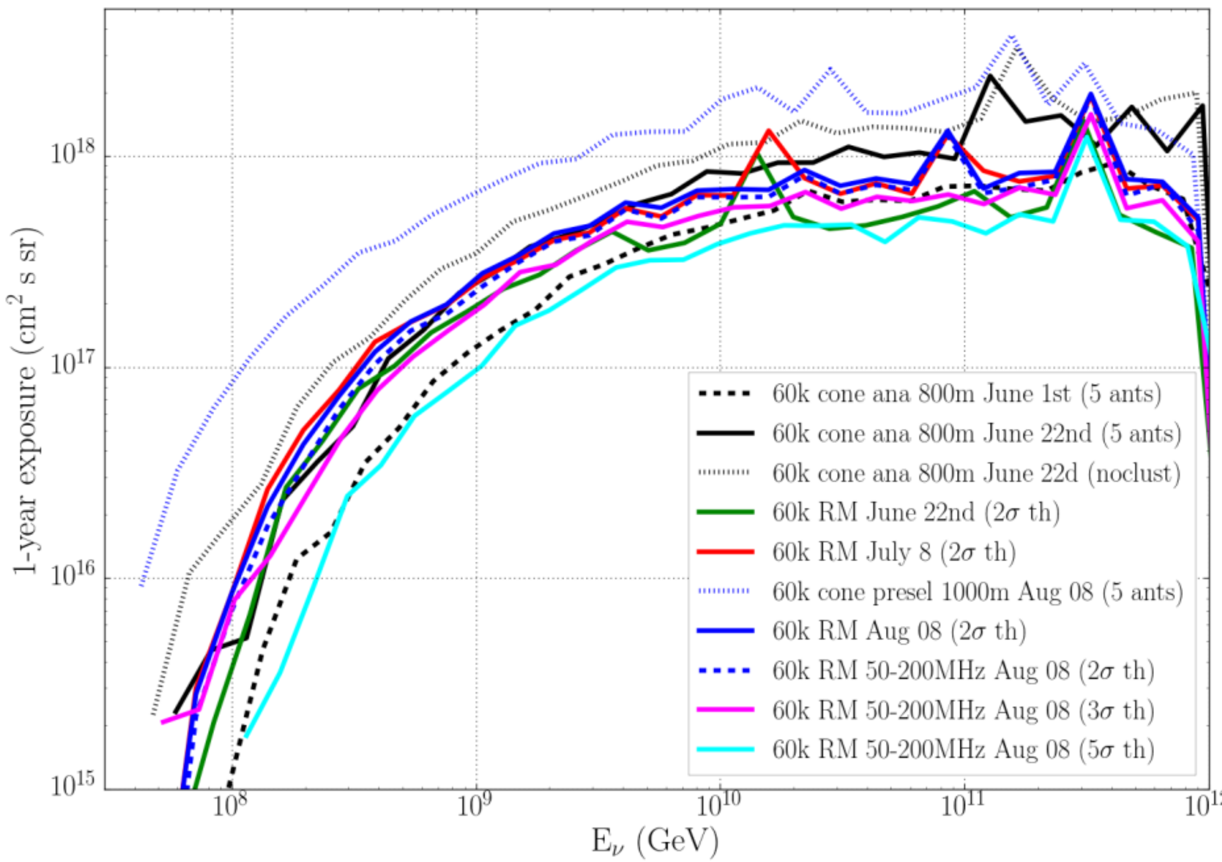






Effect of threshold

- Large effect of antenna trigger threshold on limit.
  - On 60k array:
    - 30µV:
      2.7 10^{-9} GeV/cm²/s/sr
    - 45µV:
      3.3 10^{-9} GeV/cm²/s/sr (x1.2)
    - 75µV:
      6.6 10^{-9} GeV/cm²/s/sr (x2.5)
  - On HS1:
    - 30µV:
      7.9 10^{-9} GeV/cm²/s/sr
    - 45µV:
      1.2 10^{-9} GeV/cm²/s/sr (x1.5)
    - 75µV:
      2.0 10^{-9} GeV/cm²/s/sr (x2.5)



Comparison/changes in initial analysis

Footnote: bug found in initial analysis on cluster selection:
original limit 2 10^{-9} for 60k sim → now 2.2 10^{-9} GeV/cm²/s/sr

- Result: initial analysis slightly more optimistic: 3-years limit to E^{-2} flux:
  - 2.6 10^{-9} GeV/cm²/s/sr (new) vs 2 10^{-9} GeV/cm²/s/sr (initial)
- Possible cause for remaining difference: new clustering selection more selective (4 out 8 closest neighbourgs in new analysis vs 8 antennas chain in initial) : when no cluster, limit = 1.6 10^{-9} in new vs 1.9 10^{-9} in initial
- RadioMorphing (2σ threshold) consistent with cone: 2.7 10^{-9} GeV/cm²/s/sr

Update numbers :)

Preliminary results

Positive = Signal
Negative = No signal

Comparison of the NN-based trigger to a conventional one

	Neural Network	Threshold (60µV)
Classification accuracy	0.72	0.69
True trigger rate	0.43	0.42
False trigger rate	<2E-3	0.04
True negative rate	~1.0	0.96
False negative rate	0.57	0.58

Reduces data stream from 100kHz to < 5kHz

Note: Threshold applied to all 3 Voltage components separately
Value of 60µV chosen to maximize the classification accuracy