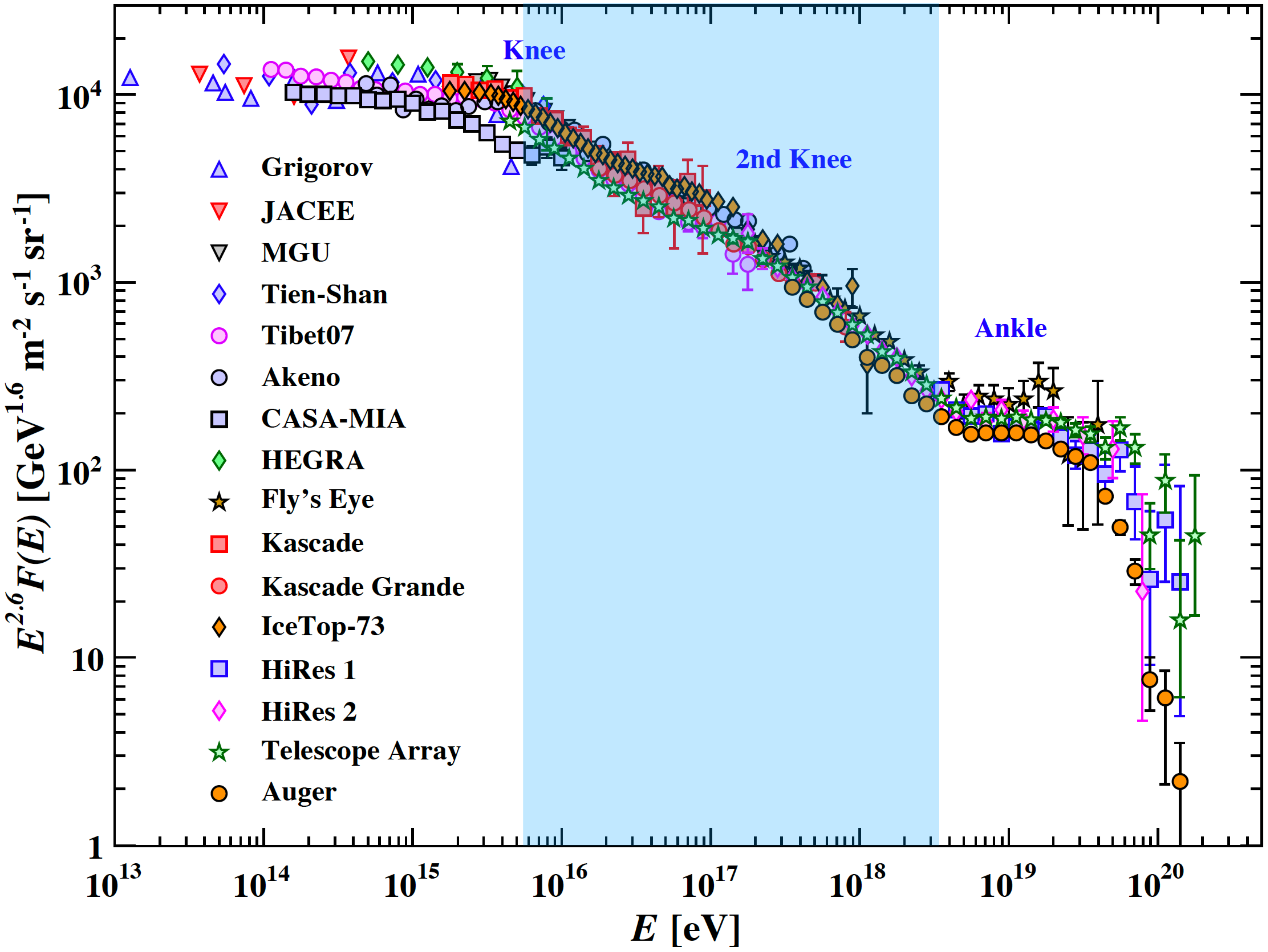
Observing cosmic rays with SKA and LOFAR

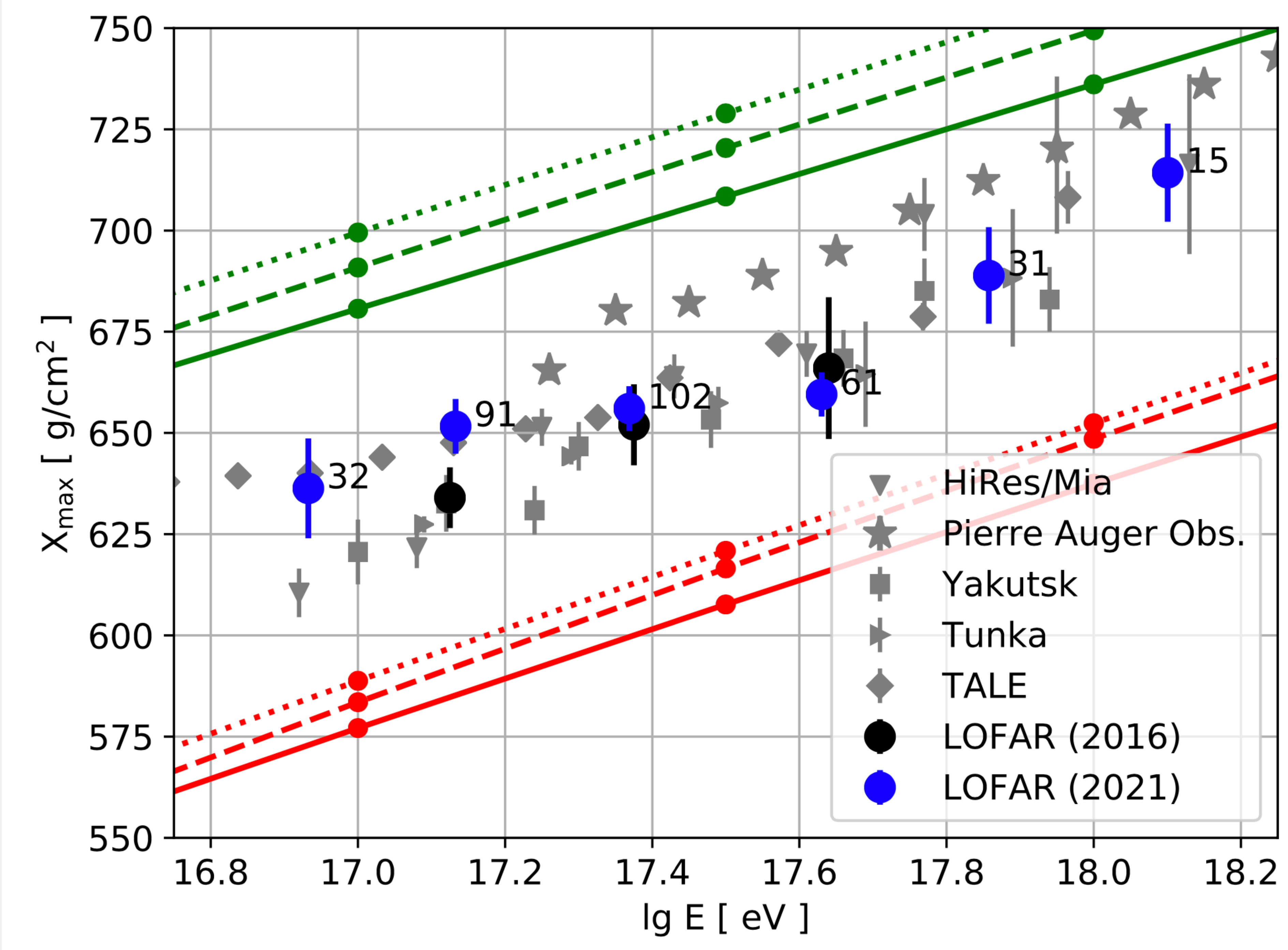
LOFAR cosmic ray Key Science Project
SKA High Energy Cosmic Particles Science Working Group
VUB members: Stijn Buitink, Arthur Corstanje, Vital De Henau, Mitja Desmet, Tim Huege

28 November 2024, IIHE Annual meeting, Brussels

Air shower observations with SKA & LOFAR



- Where is the Galactic to extragalactic transition?
- What are the most powerful Galactic accelerators?
- What is the mass composition of cosmic rays?
- Can radio be used to study shower physics?



A. Corstanje et al., Phys. Rev. D 103, 102006 (2021)

LOFAR 1.0 finished

- Understanding emission mechanism
- Full Stokes polarization, frequency dependence, wavefront shape, atmospheric effects, thunderstorm influence, etc.
- Mass composition measurements based on Xmax.
- Calibration of absolute energy scale based on Galactic background emission.

Transition period

LOFAR 1.0

LOFAR 2.0

- Fully commensal data taking + expanded particle detector array
  more statistics (roughly one order of magnitude)

- simultaneous Low Band (30-80 MHz) and High Band (110-180)
  higher precision

- radio trigger / hybrid trigger
  reach lower energies (~10^{17} eV → $10^{16.5}$ eV)

Transition period

LOFAR 1.0

LOFAR 2.0

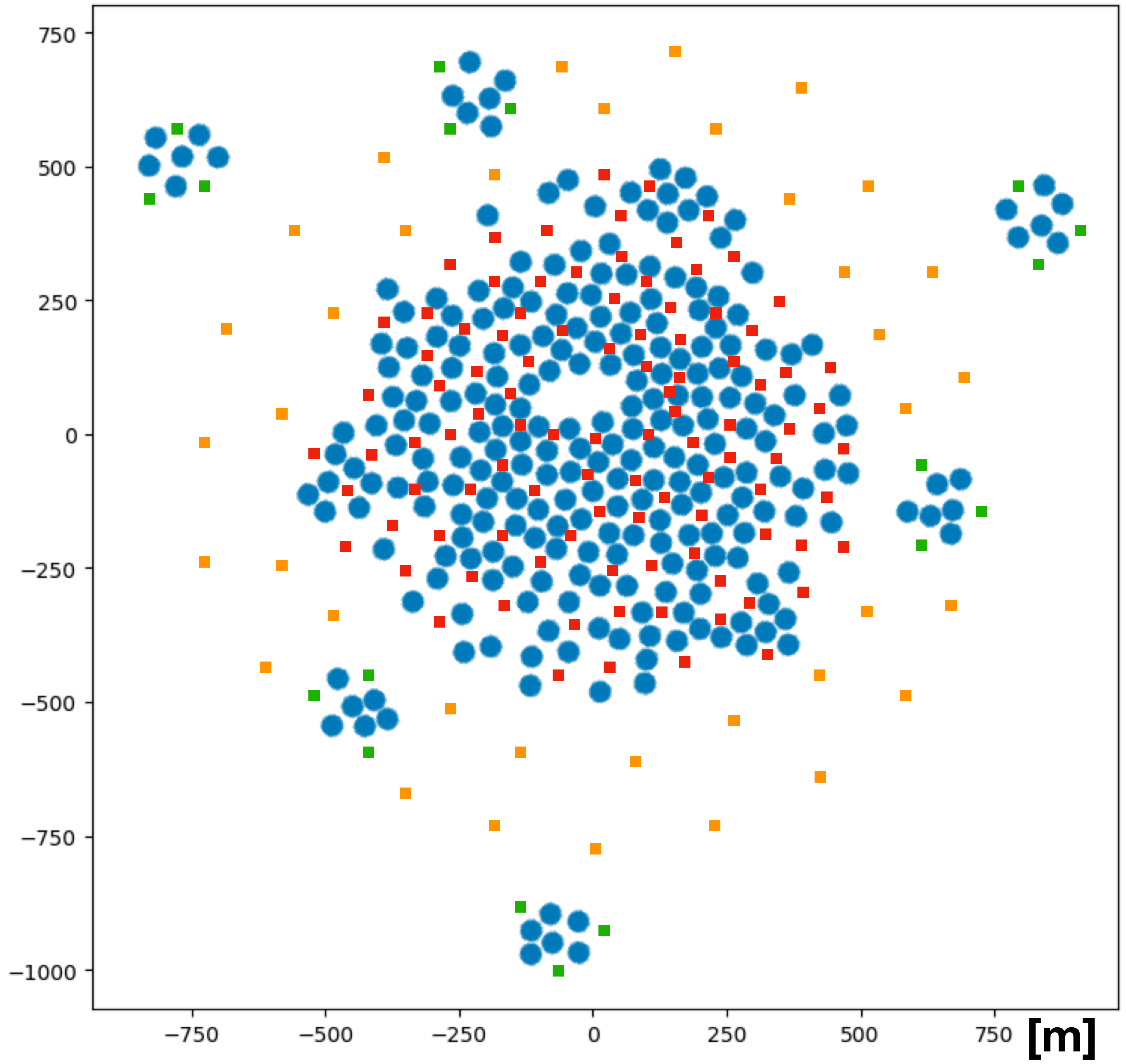
Square Kilometer Array (SKA)

The Square Kilometre Array

- SKA will have mid-freq array in South-Africa and low-freq in Australia. Construction has started.
- SKA-low will consist of 57,344 log-periodic antennas within an area of ~1 km^2
- Frequency bandwidth 50-350 MHz
- Extremely high-density & homogeneous coverage: very precise radio observations of air showers
- Energy range: 10^{16} eV - 10^{18} eV. Further extension down to knee energy possible with interferometric techniques. Schoorlemmer & Carvalho arXiv:2006.10348 (2021), Schlüter & Huege, JINST arXiv:2102.13577 (2021)

Prototype @MRO (256 antennas)

The SKA Particle detector array



Layout of particle detector array at SKA-low

- **Antenna field**
- **Particle detectors dense array (~100 units)**
- **Particle detectors ring (~50 units, optional)**
- **Particle detectors remote (~18 units, optional)**

Scintillators from KIT (KASCADE-Grande coll.)

Prototype station
@ Murchison Widefield Array

Low noise system:
SiPMs & RFoF comm.

J. Bray et al., NIMPA 973, id. 164168 (2020)

This year:
Deployment of 8-station array at MWA

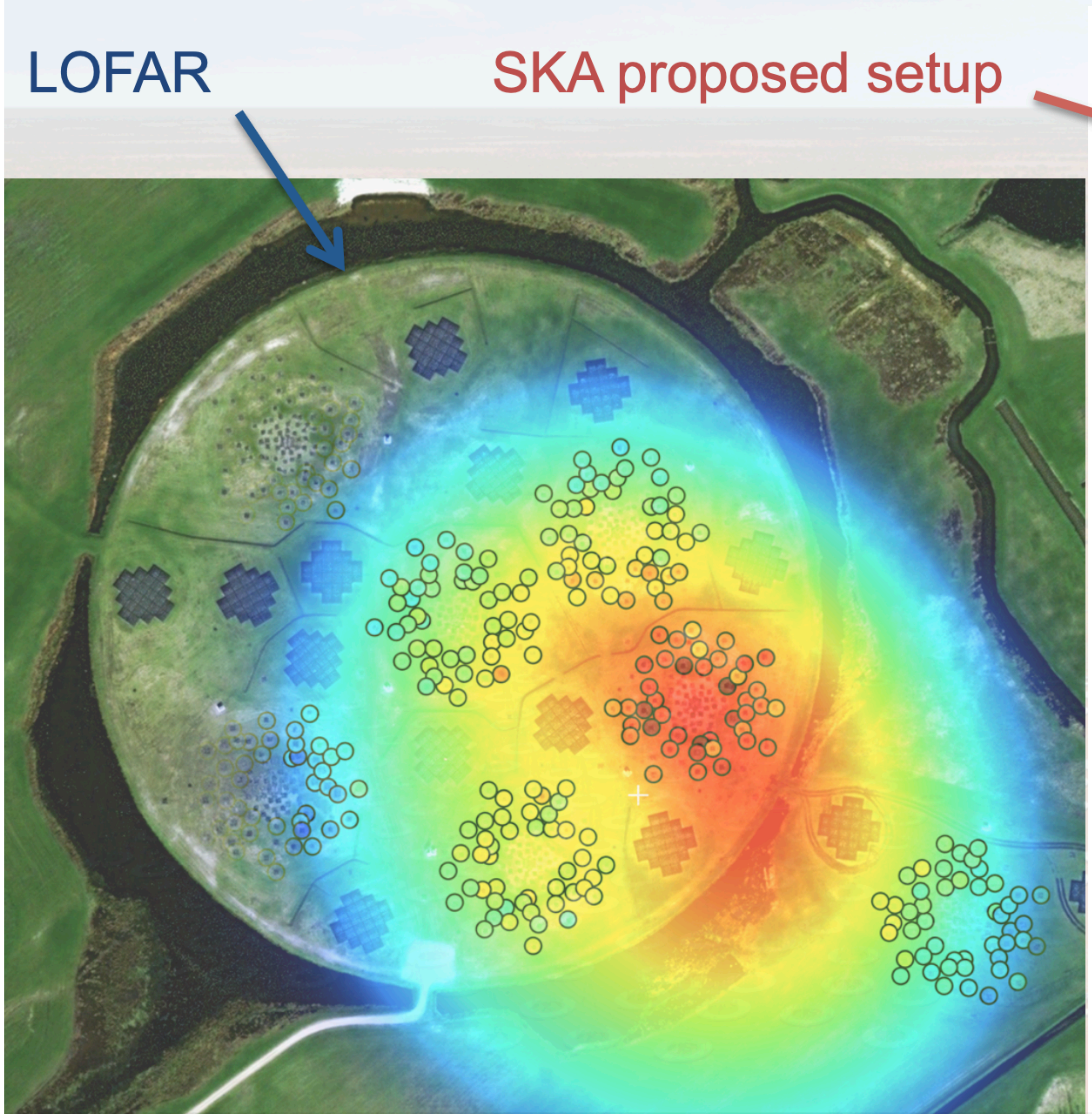
Design: Univ. of Manchester (J. Bray, R. Spencer)
Deployment: Curtin Univ. (C.W . James)
DAQ: CSIRO

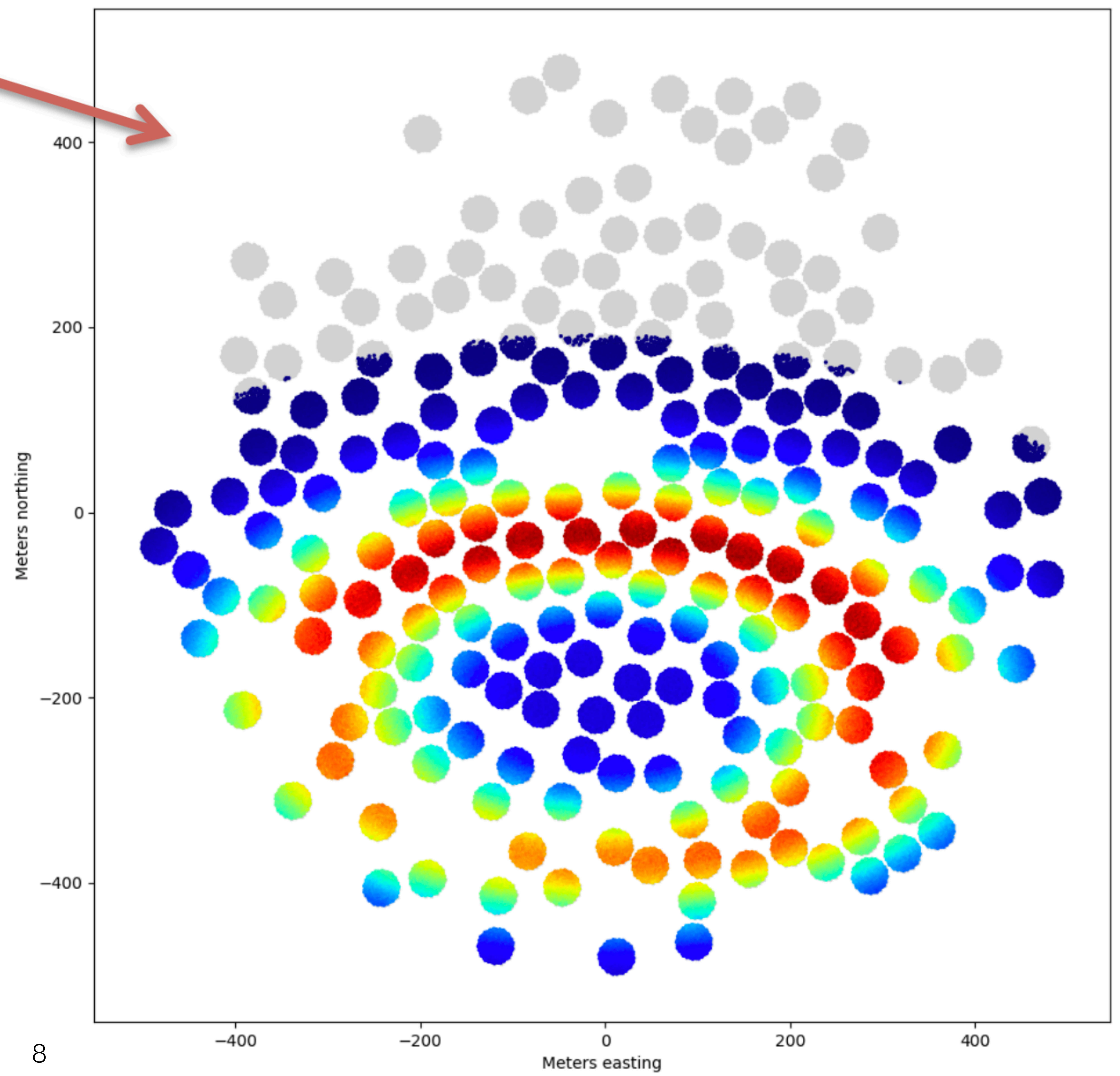
Upcoming:

Redesign to 3rd generation in Karlsruhe (KIT)

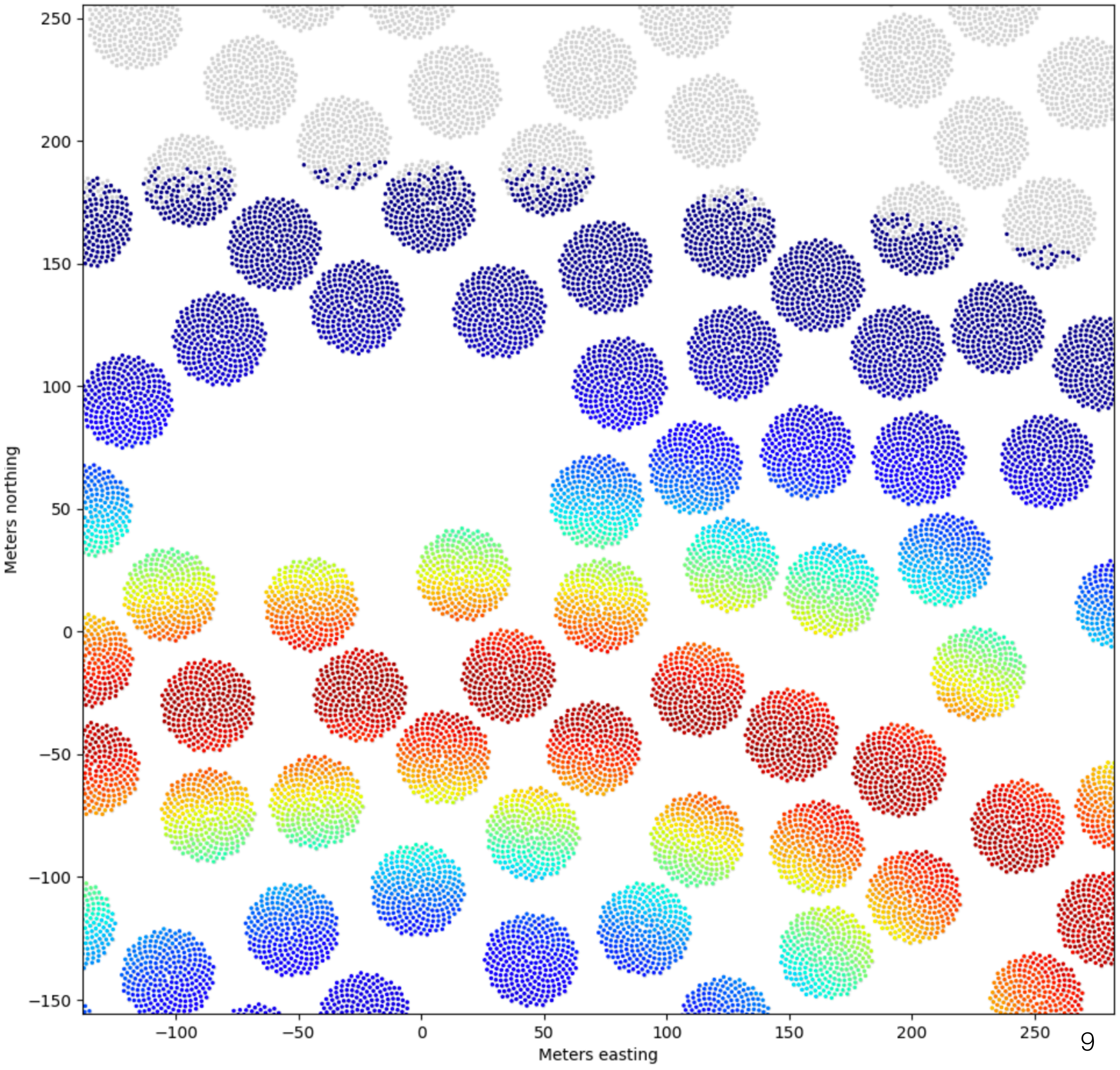
740 kEuro funding from FWO (medium scale infrastructure)

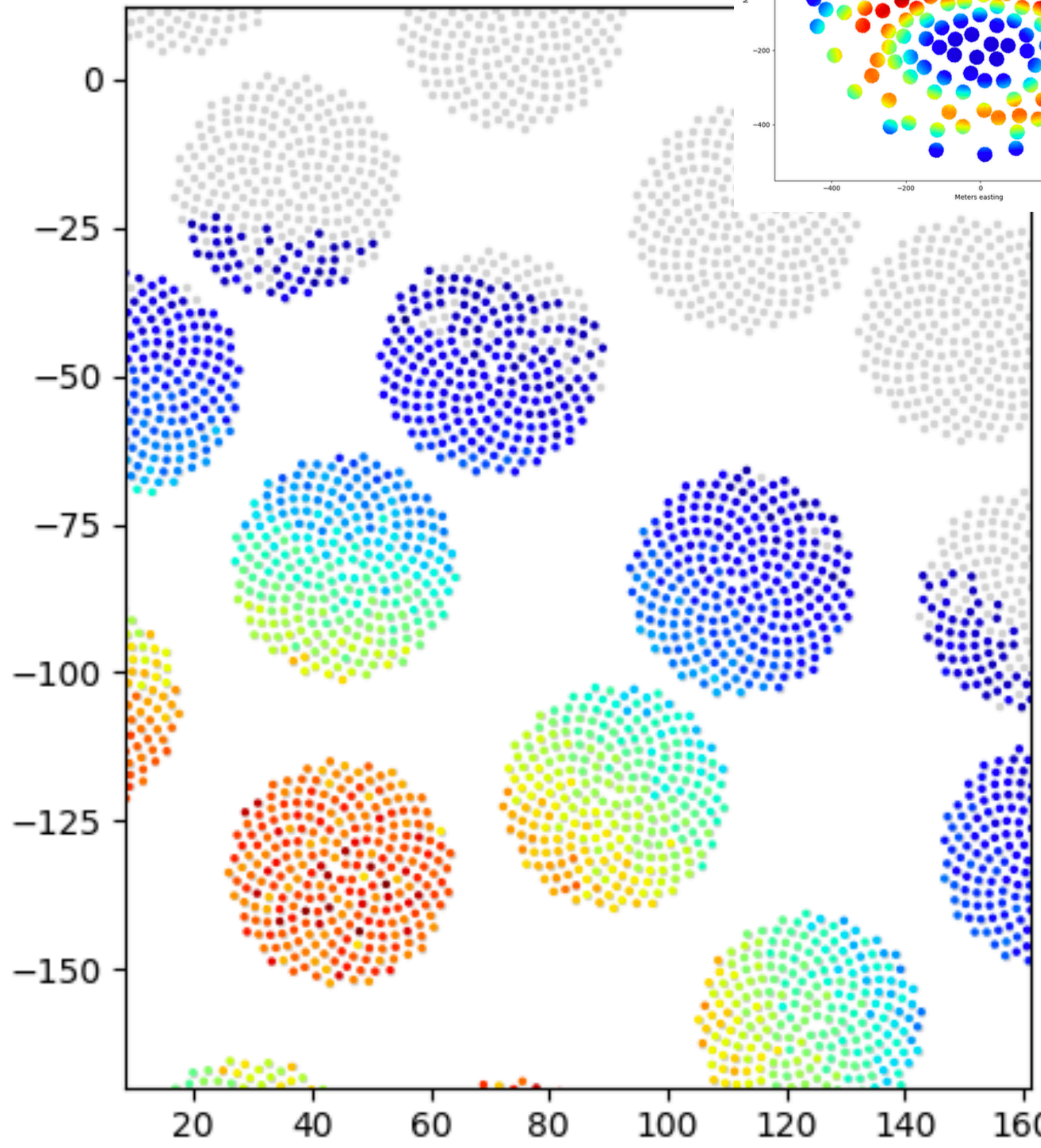
SKA simulations

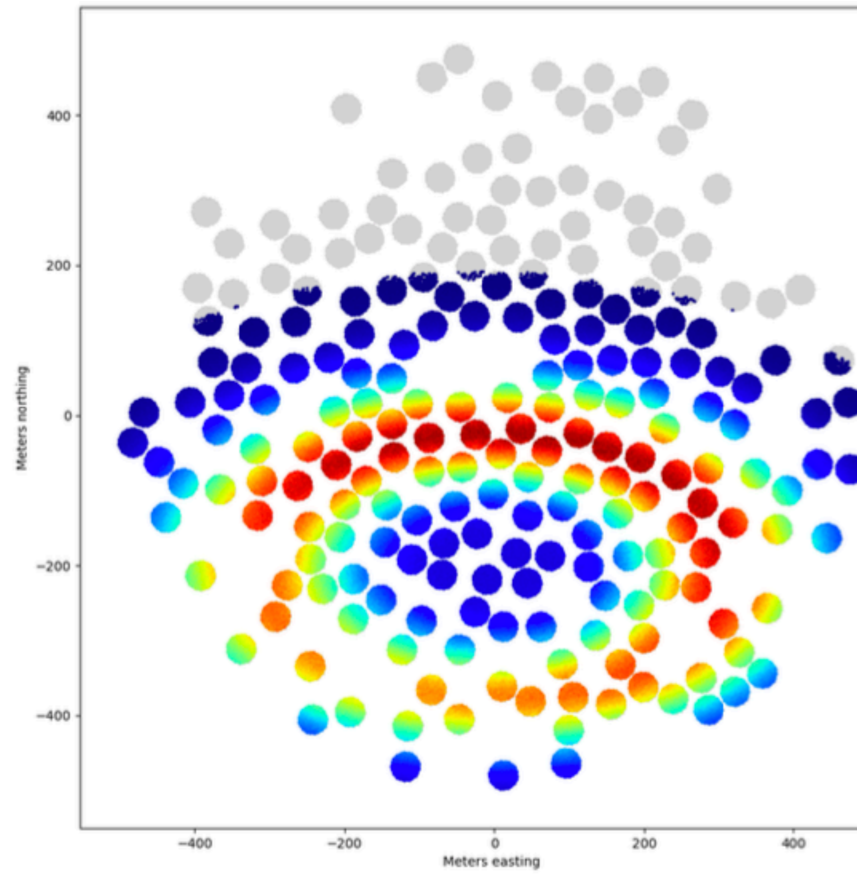




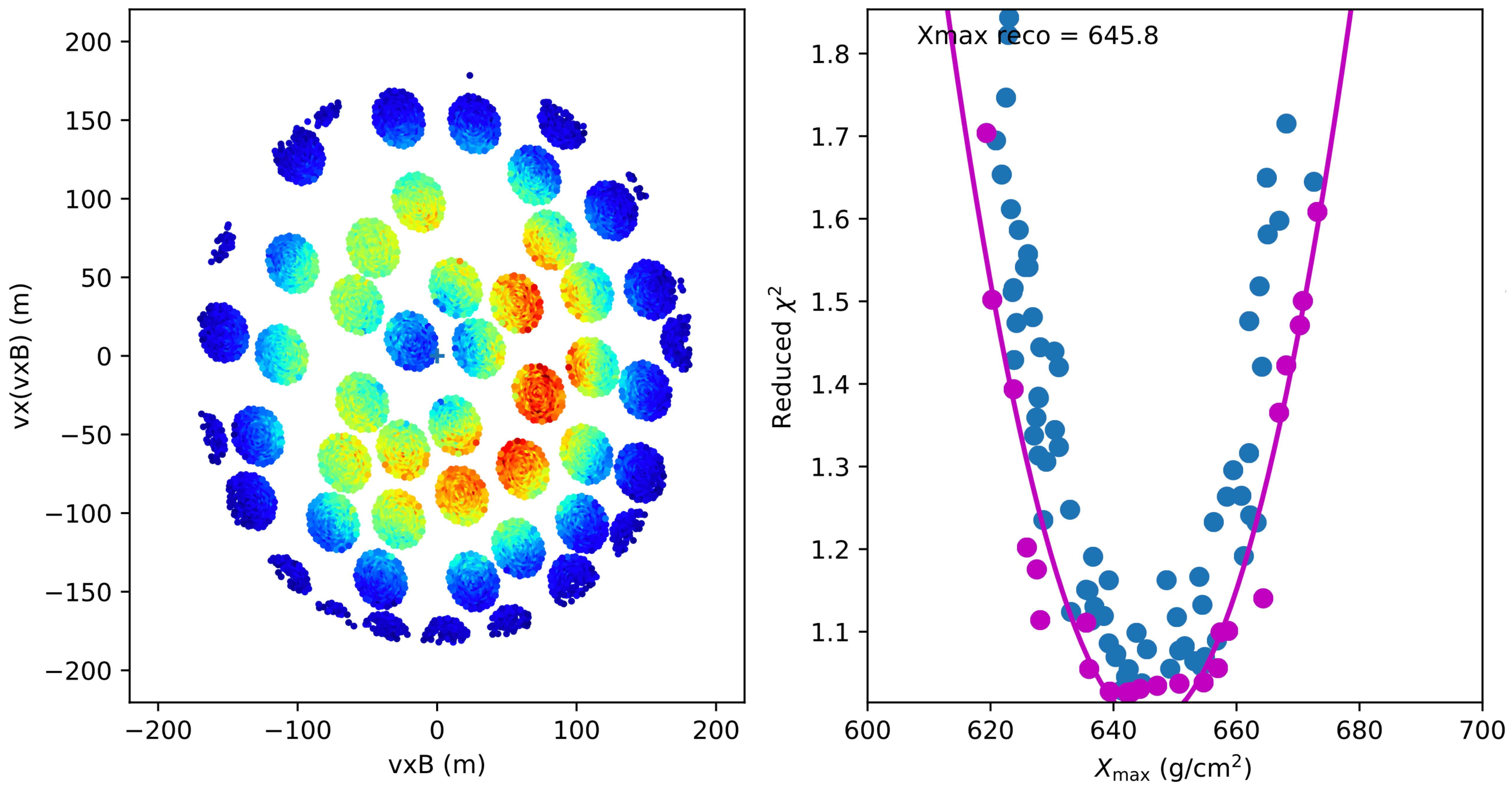
SKA-Low, a really dense array!







Simulations: Xmax with SKA



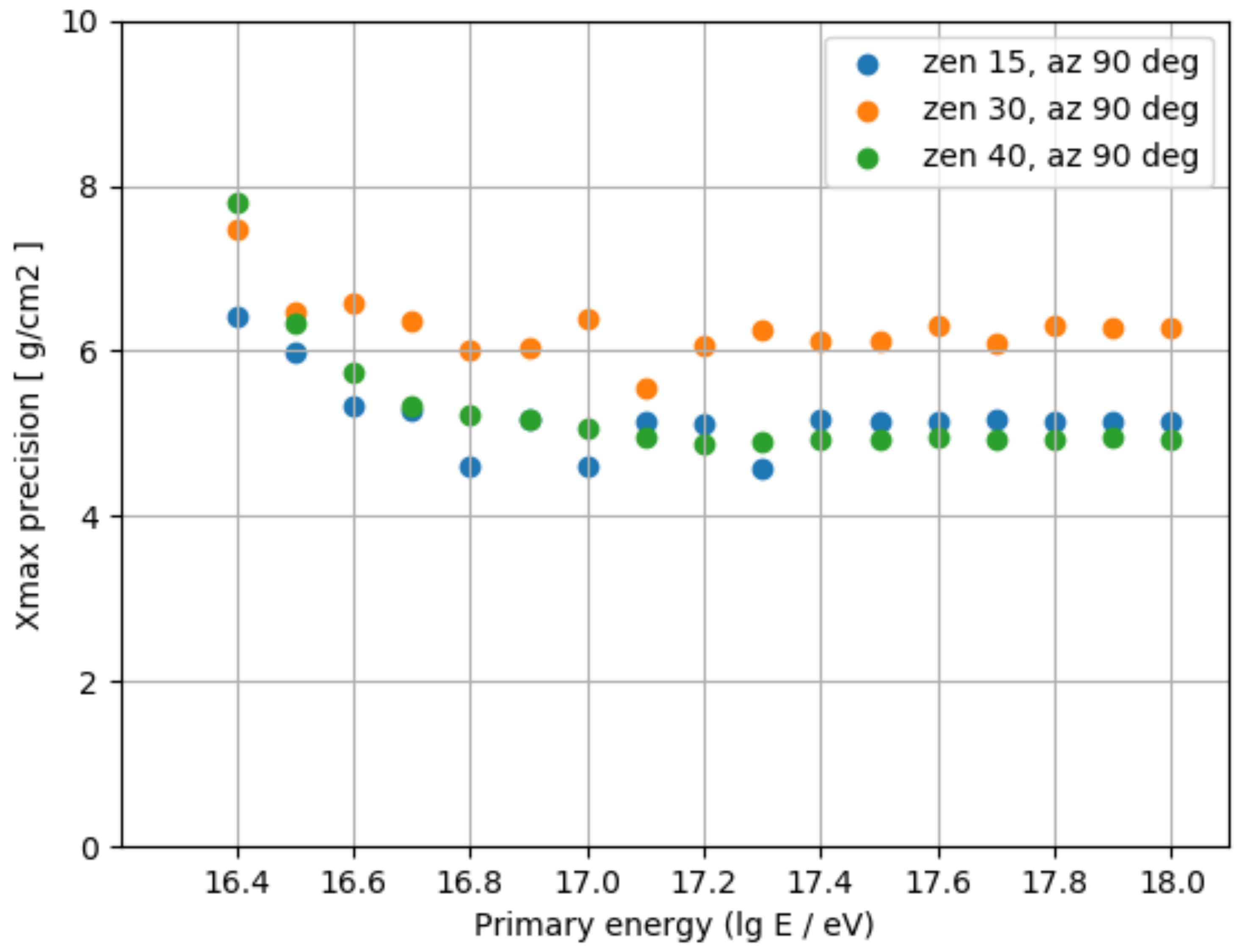
- Using Gaussian noise based on:
  Galactic background
  (dominant < 200 MHz)
  system noise (dominant > 200 MHz)
- Xmax reco for dedicated sets of SKA simulations.
- Resolution limited by number of simulated showers in sample.

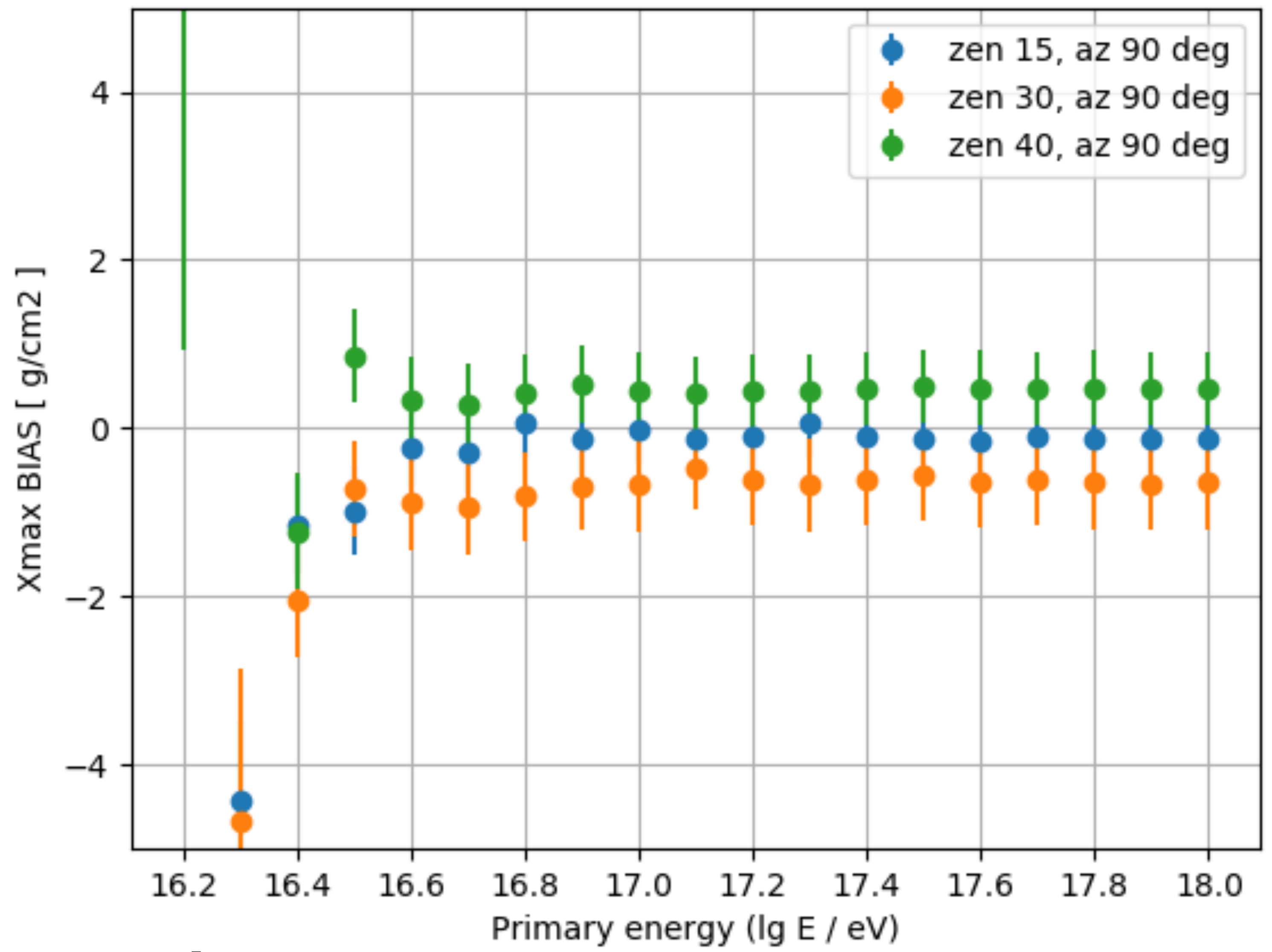
	SKA (simulated)	**LOFAR**
X_{max} resolution	: **6 - 8 g/cm²**	20 g/cm²
Energy resolution	: **3 %**	9 %
Core resolution	: **50 cm**	3 – 10 m

Final resolution will depend on uncertainties in:
- Antenna model
- Atmosphere
- Galactic background (via calibration)
- MC simulations

A. Corstanje et al., PoS(ARENA2022)024

Towards low energies

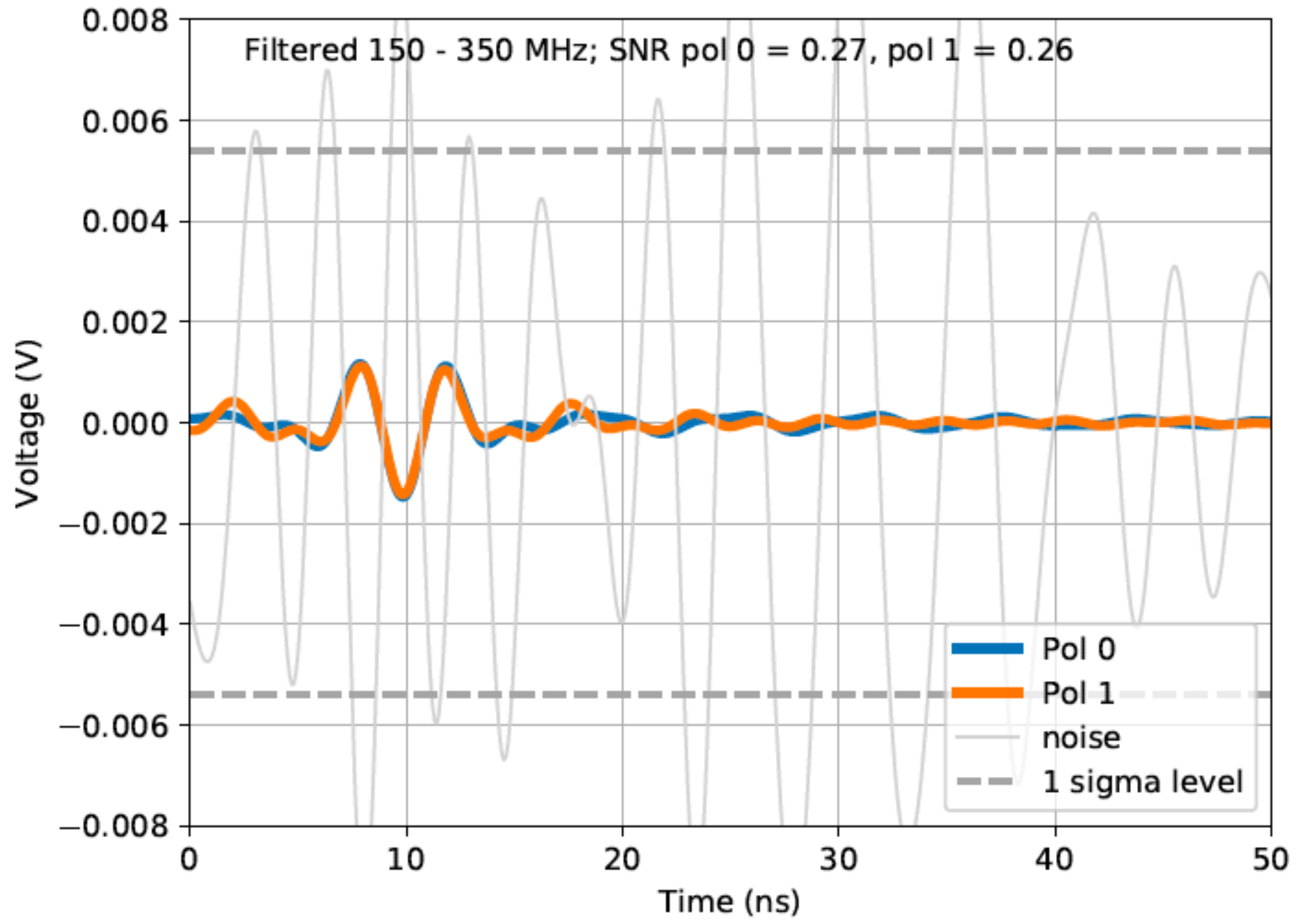


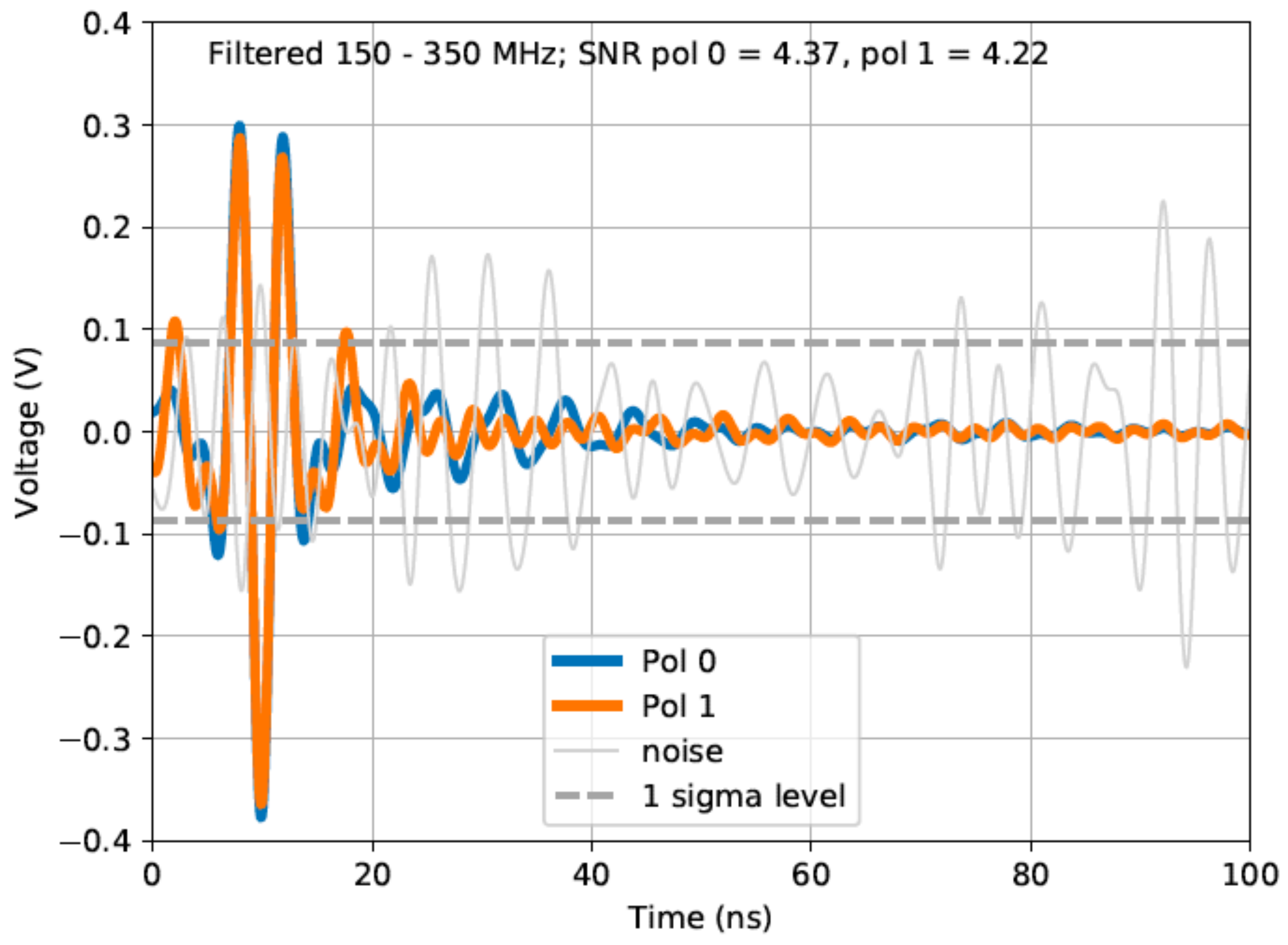


Traditional reco:

High precision, small bias down to $10^{16.4}$ eV

Arthur Corstanje



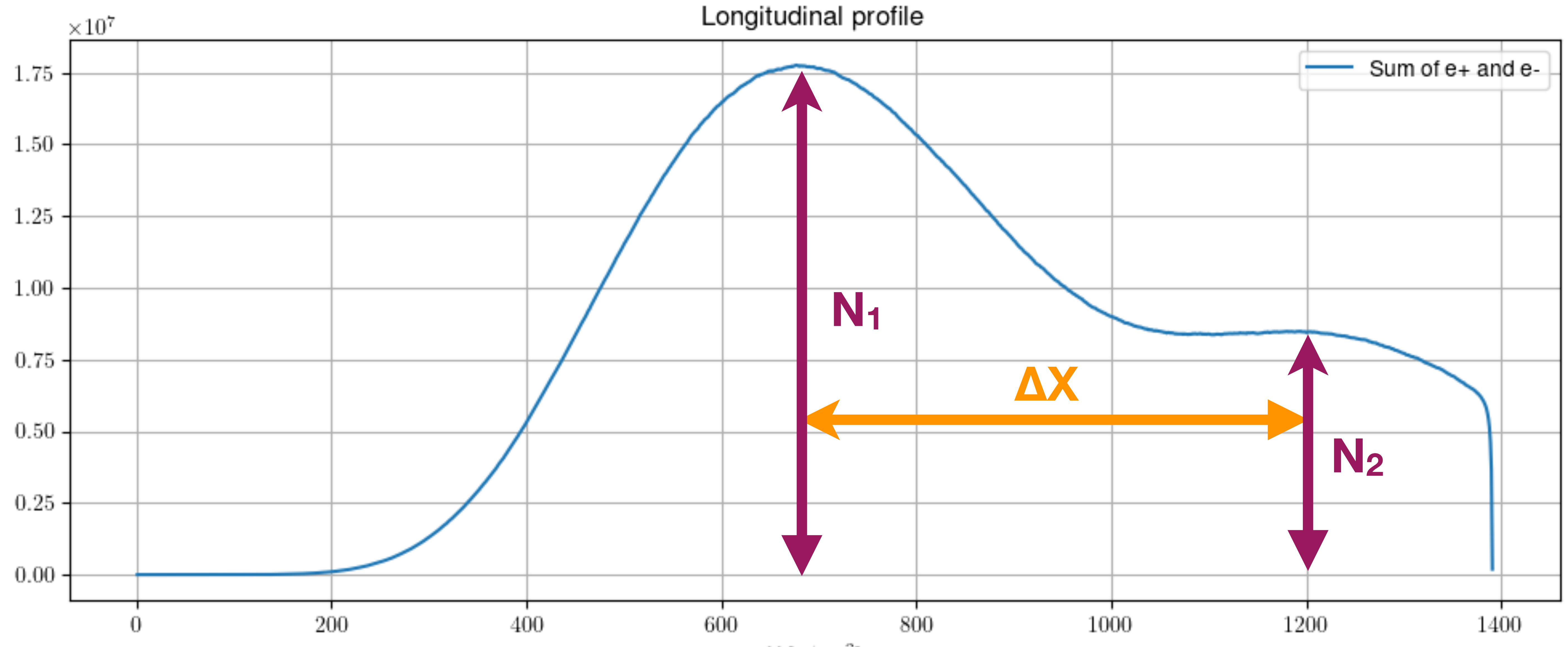


Beamforming:

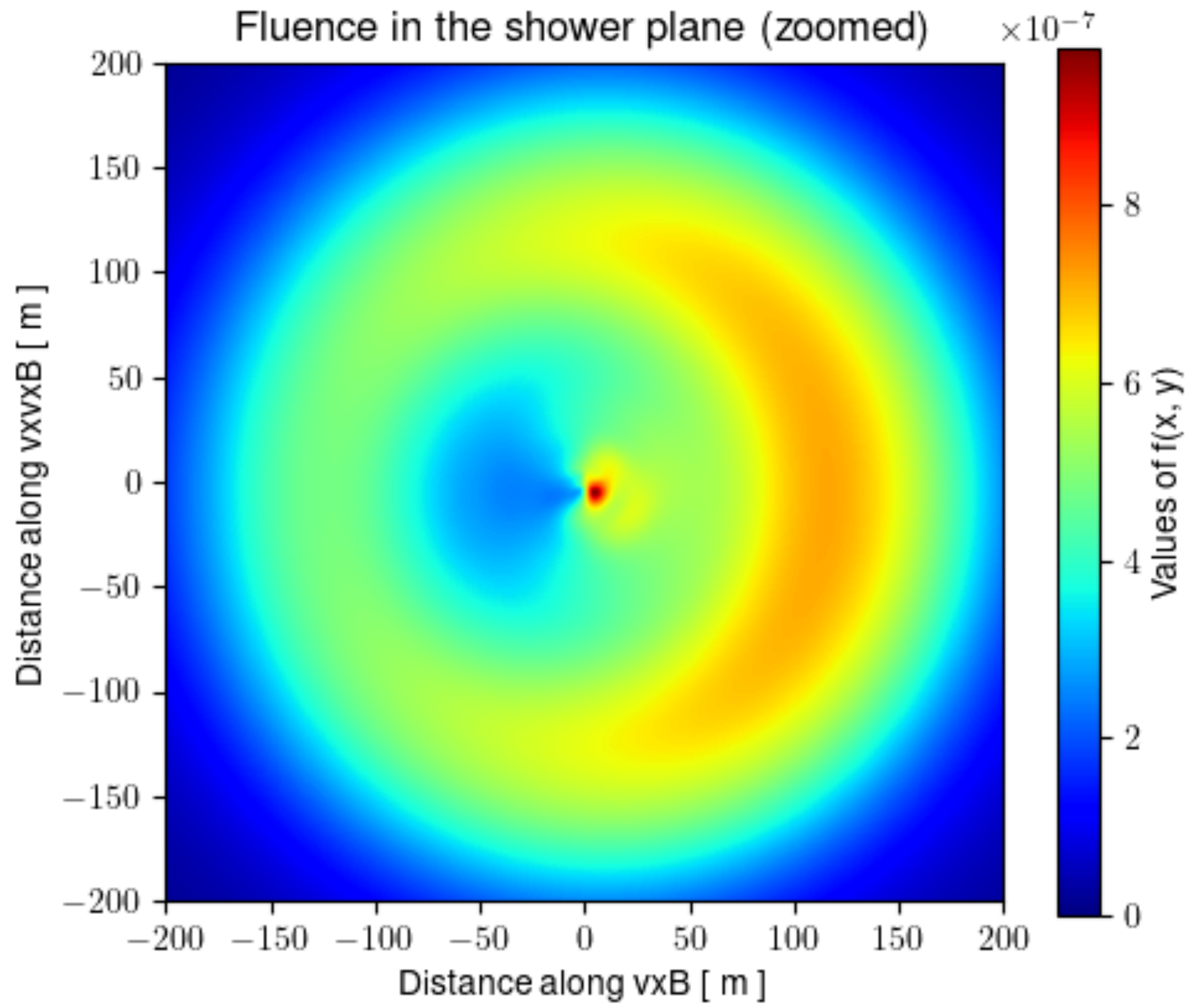
Mass composition down to 10^{16} eV

Signal down to 10^{15} eV
Galactic gamma-rays?

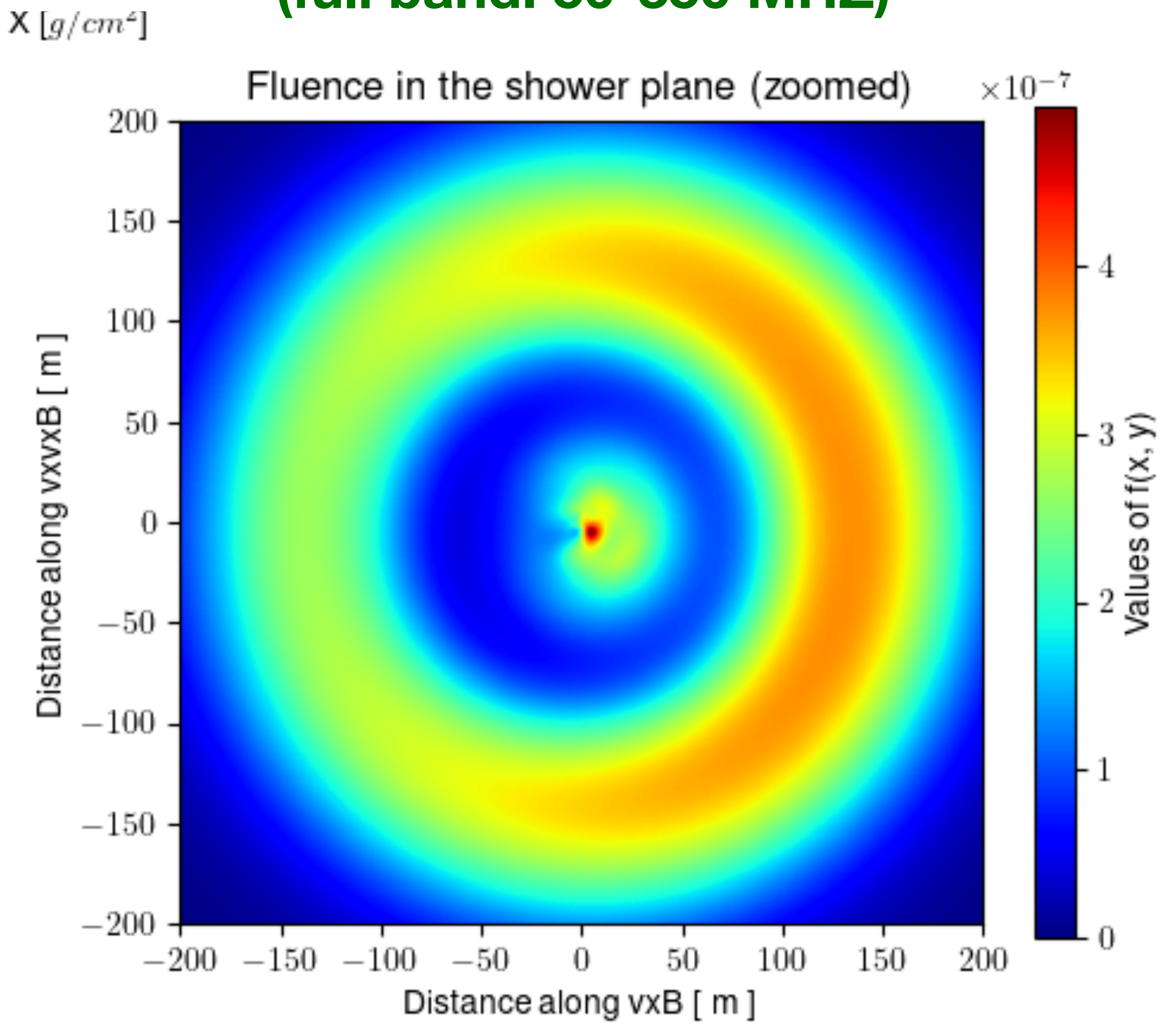
Double-bump showers



- **A high-energy hadron** (or other fragment) from first interaction can **interact late** causing a **second bump**
- Double-bump showers are rare, more frequent at **lower energies**
- Study hadronic cross section by measuring *ΔX* and *N1/N2*
- **Most frequent for Helium**: additional constraints on mass composition

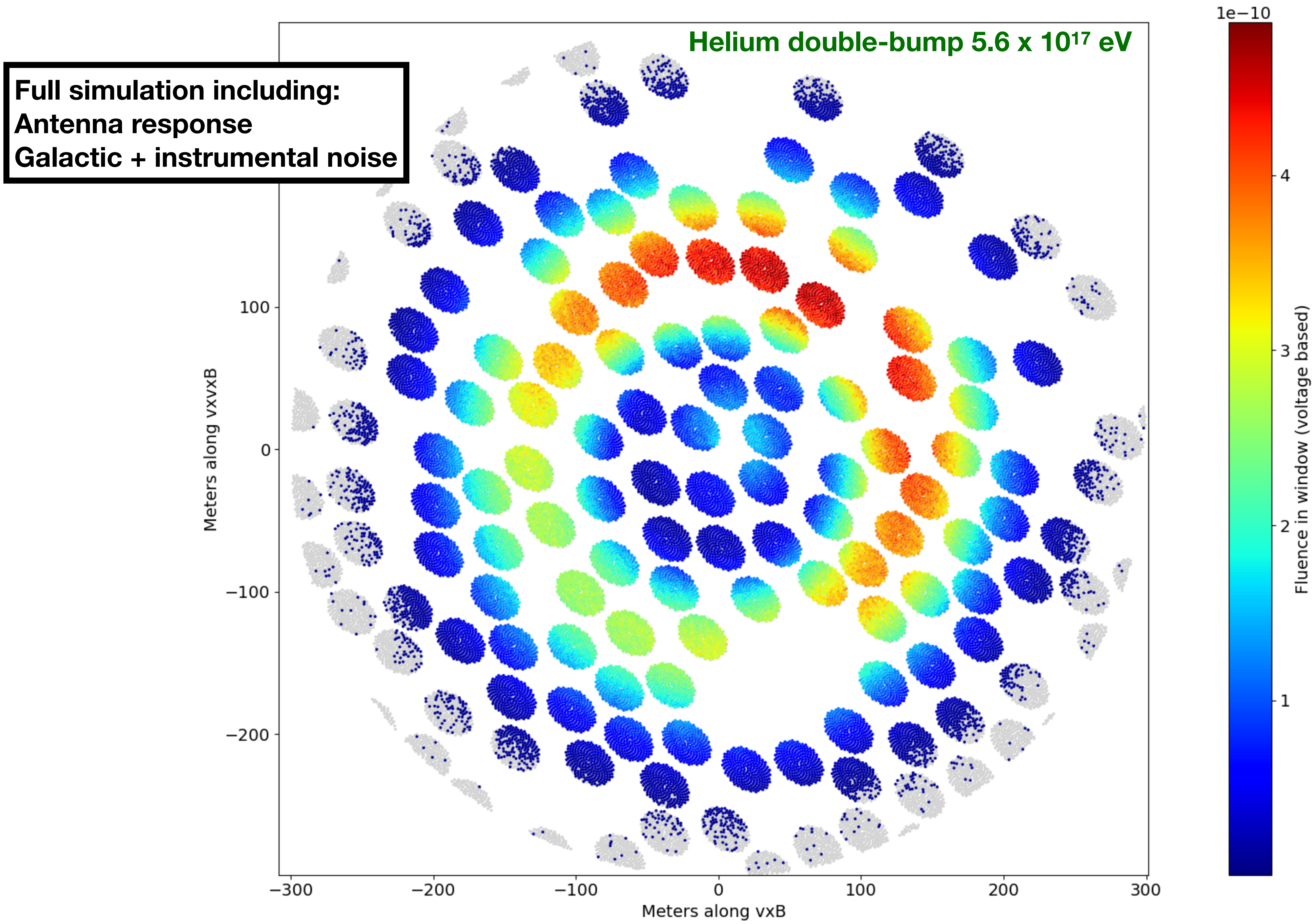


CORSIKA simulated E-field (full band: 50-350 MHZ)



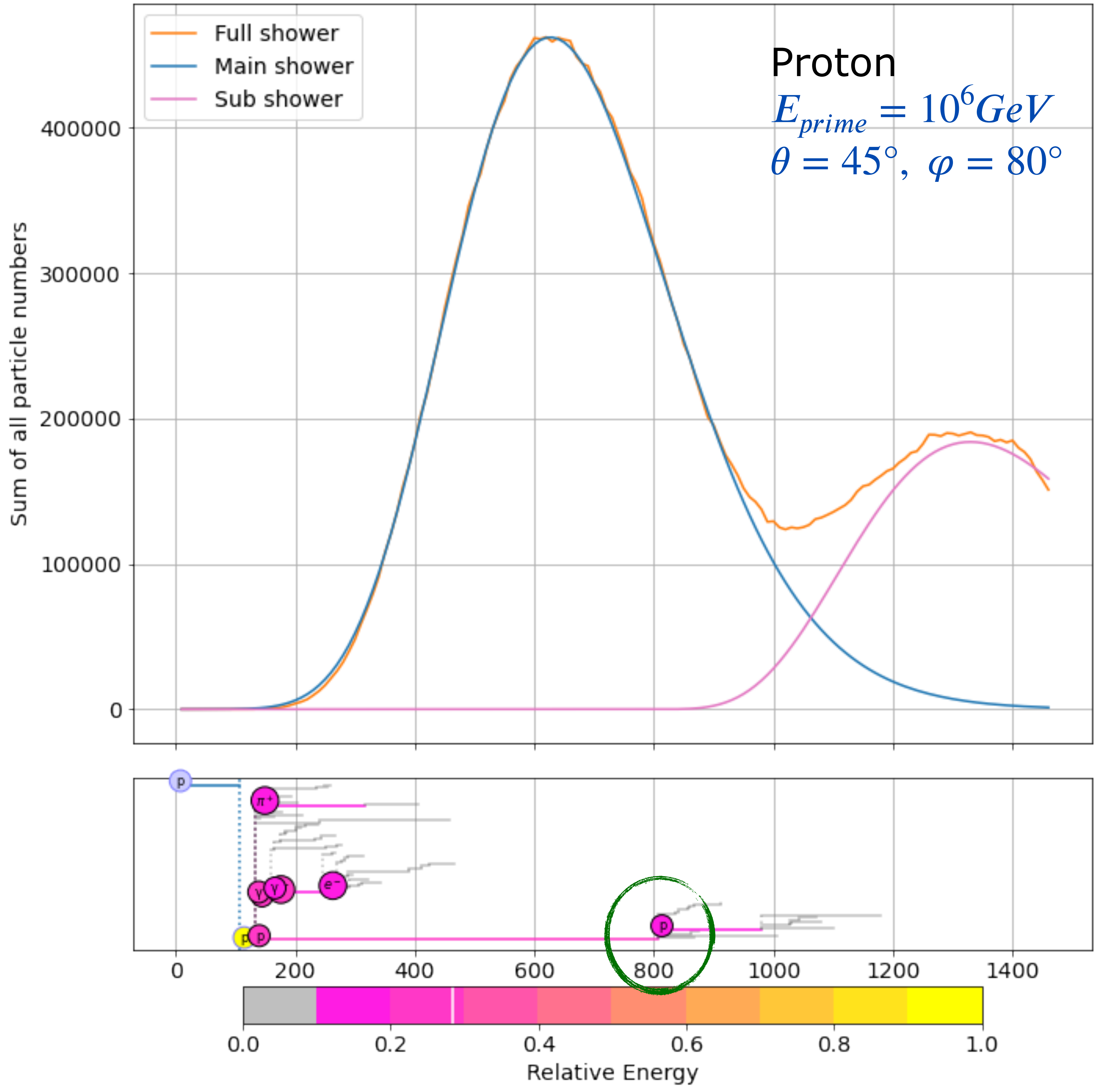
High band: 150-350 MHz

Arthur Corstanje, Mitja Desmet

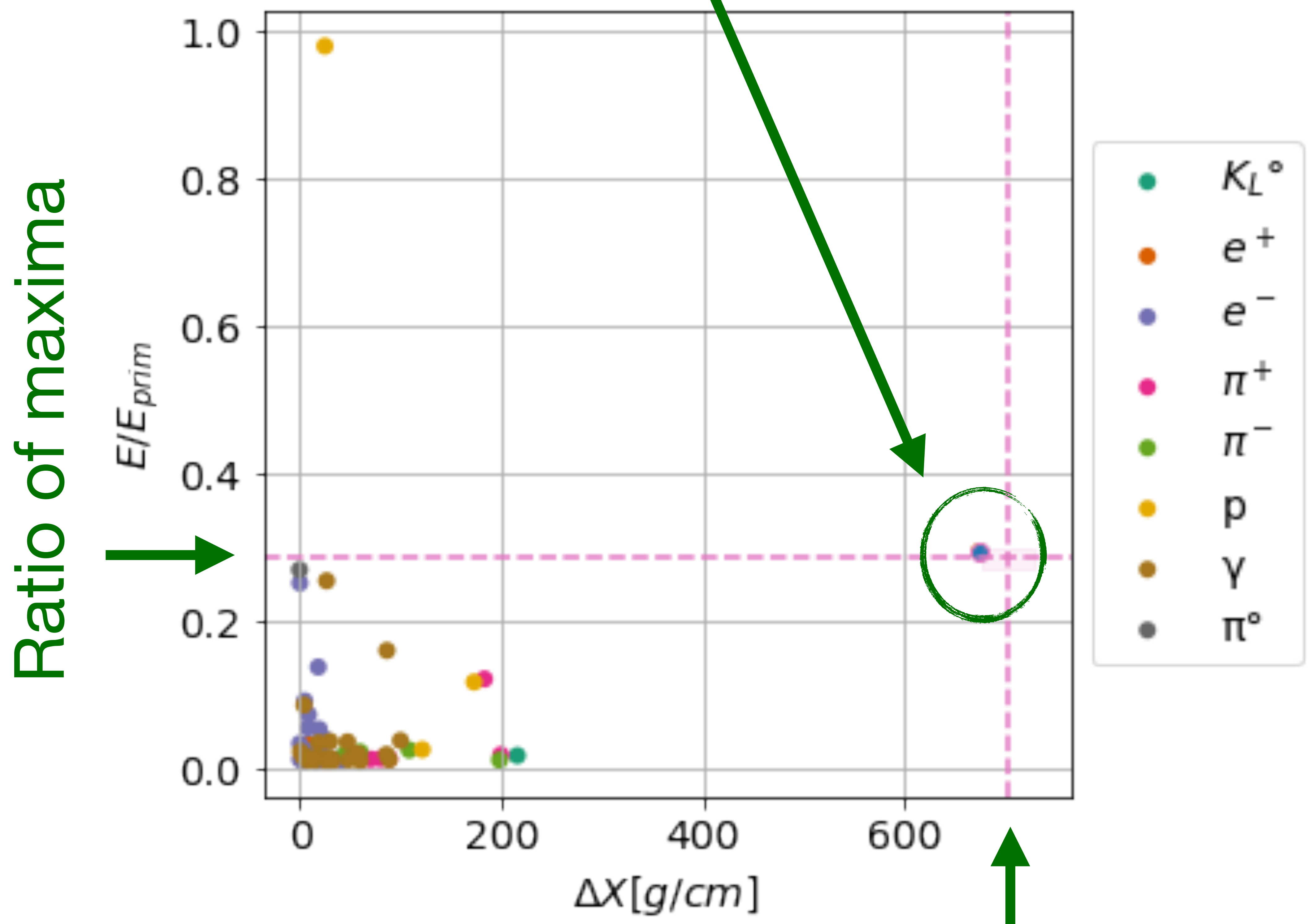


Arthur Corstanje,
Mitja Desmet

Tracking the particles



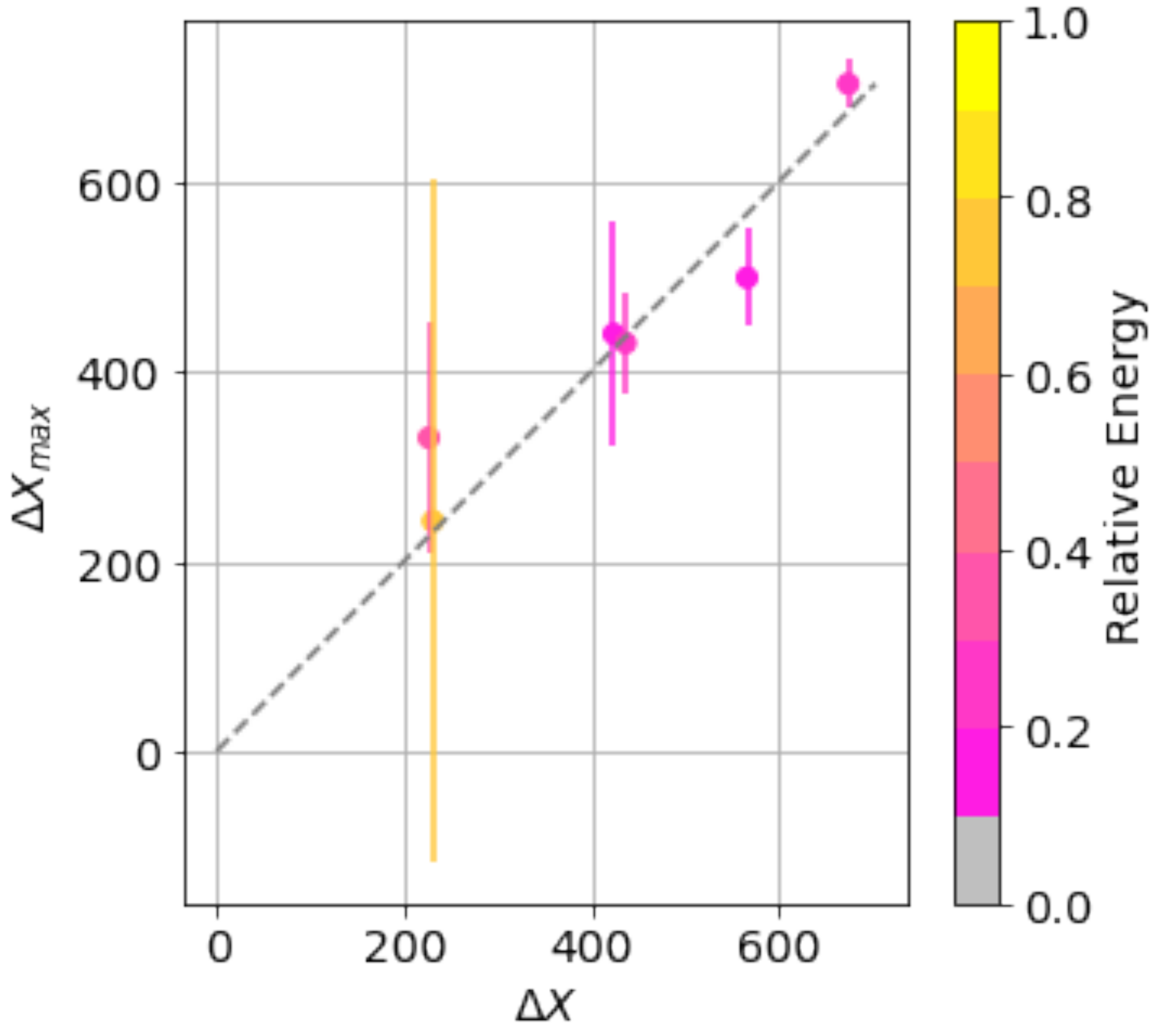
Distance travelled and energy of proton making 2nd bump

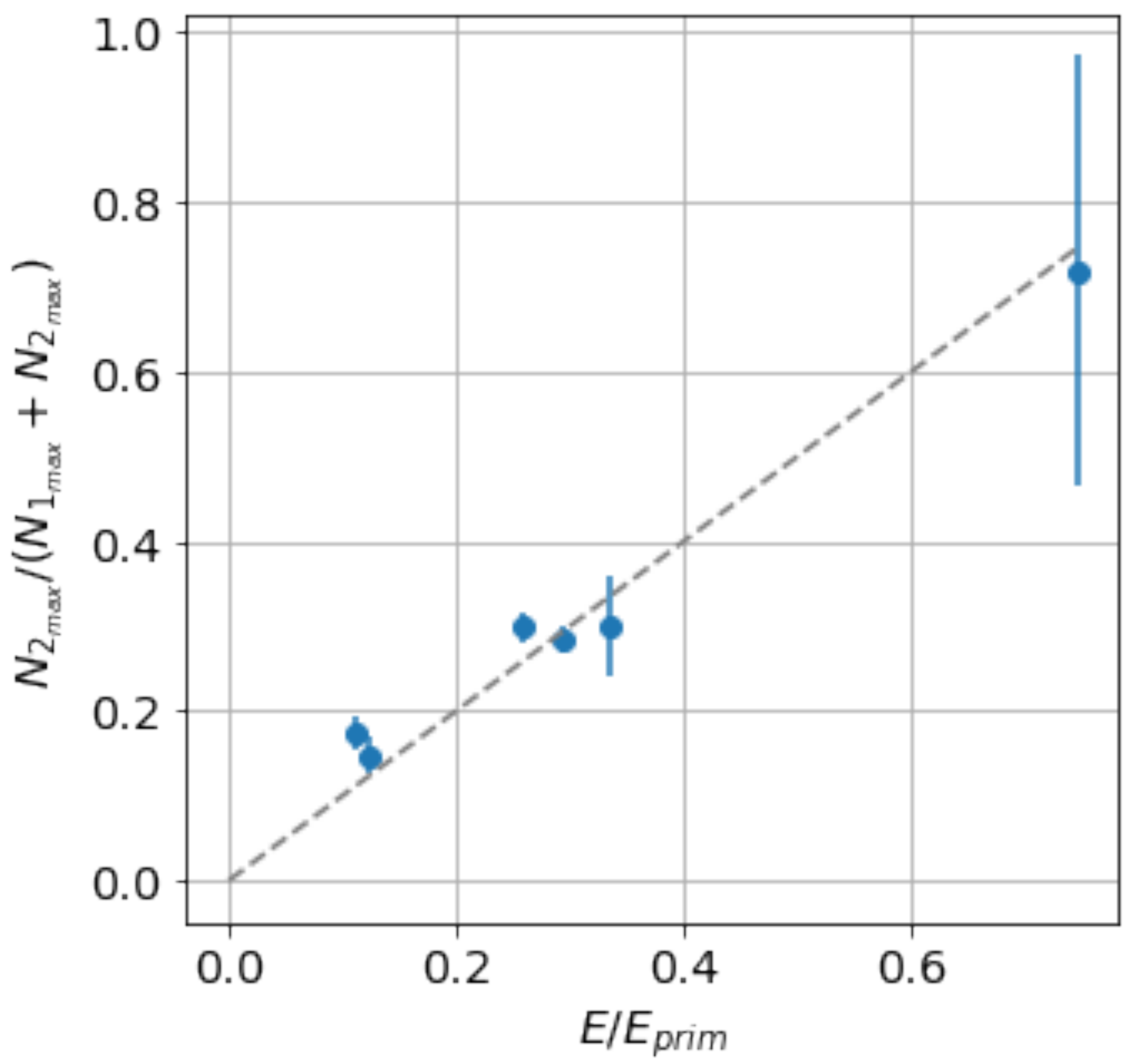


Distance between maxima

Vital De Dehau

Results for first 6 proton sims

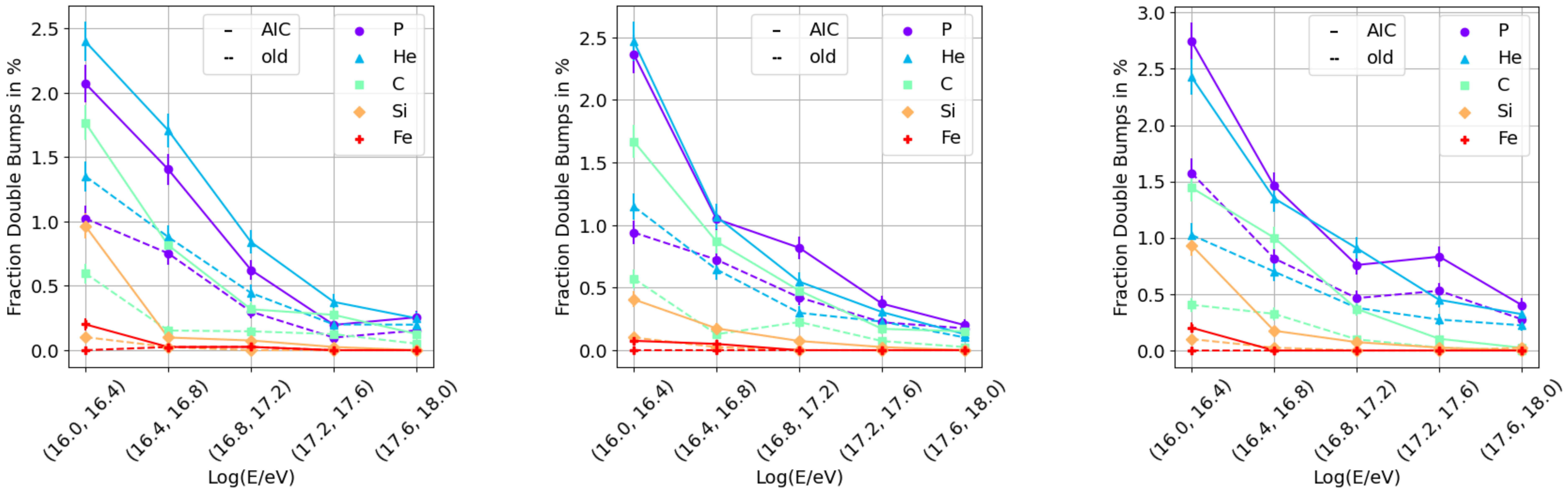




Vital De Dehau

Applications

QGSJET-II EPOS SIBYLL

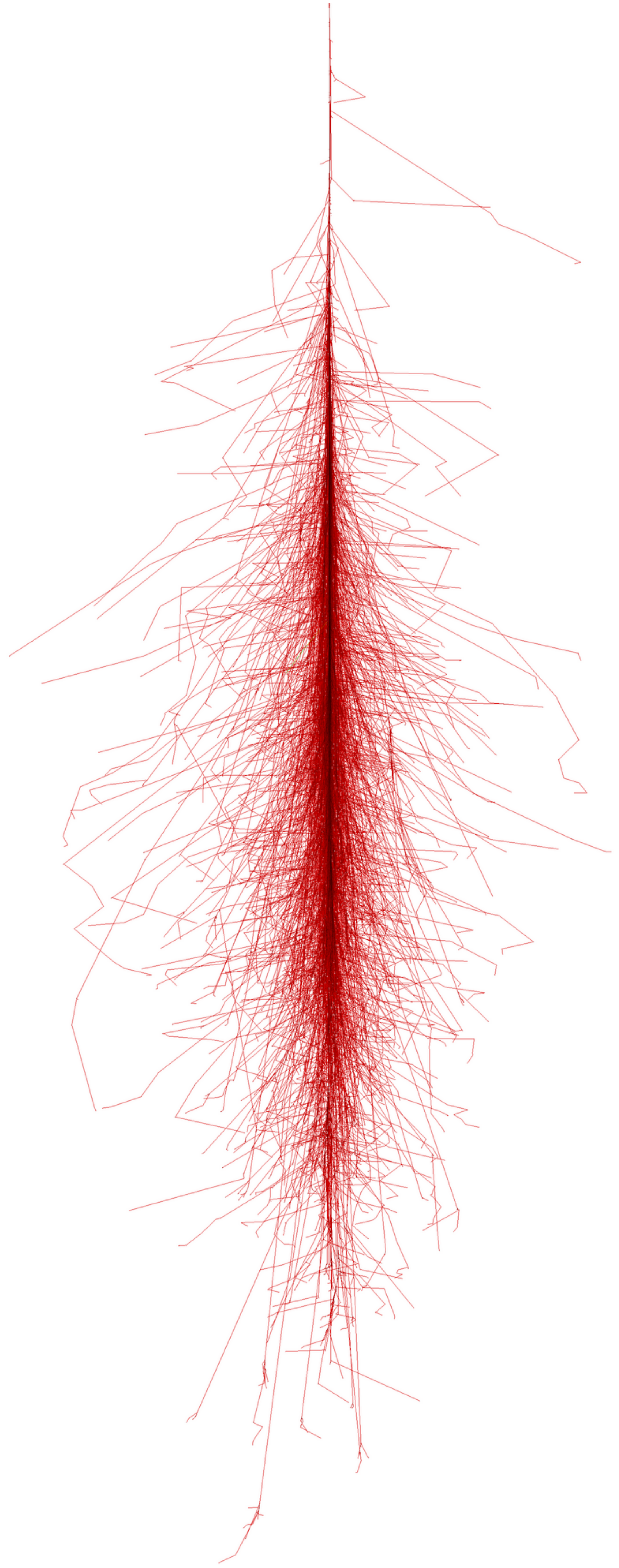


Vital De Dehau

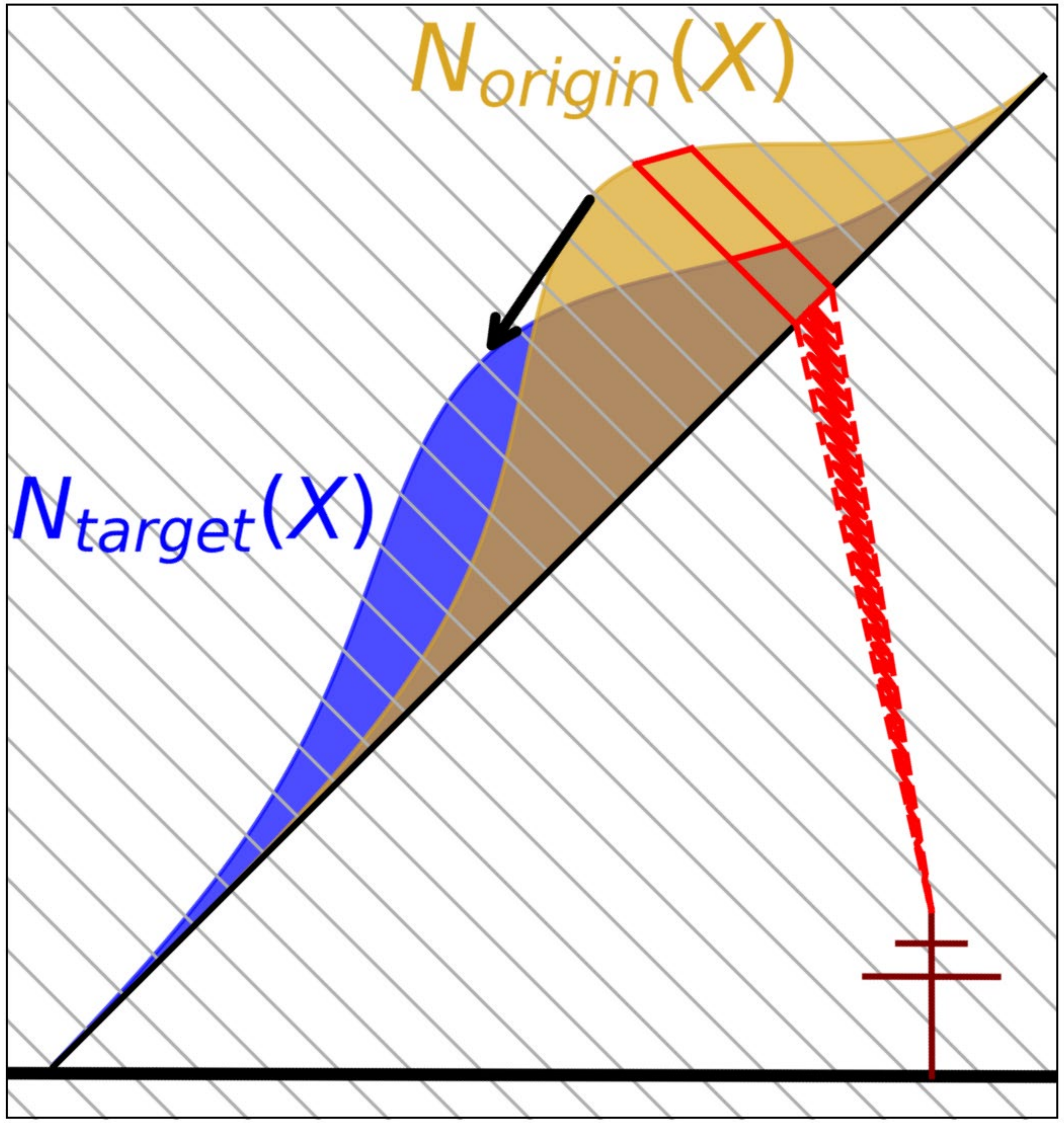
- Frequency of double bump depend on hadronic physics model and mass composition
- Additional opportunities for proton/Helium separation: early bumps, bump ratios
- Small separation: stretched showers (much more common)

Simulation challenge

- Current generation CR-radio (LOFAR, Auger) uses dedication sets of ~25 simulations for each observed shower.
- CORSIKA/CoREAS full radio sim take days on a single node.
- SKA: higher statistics, more antennas, multivariate fitting
  simulations need to be faster by orders of magnitude!



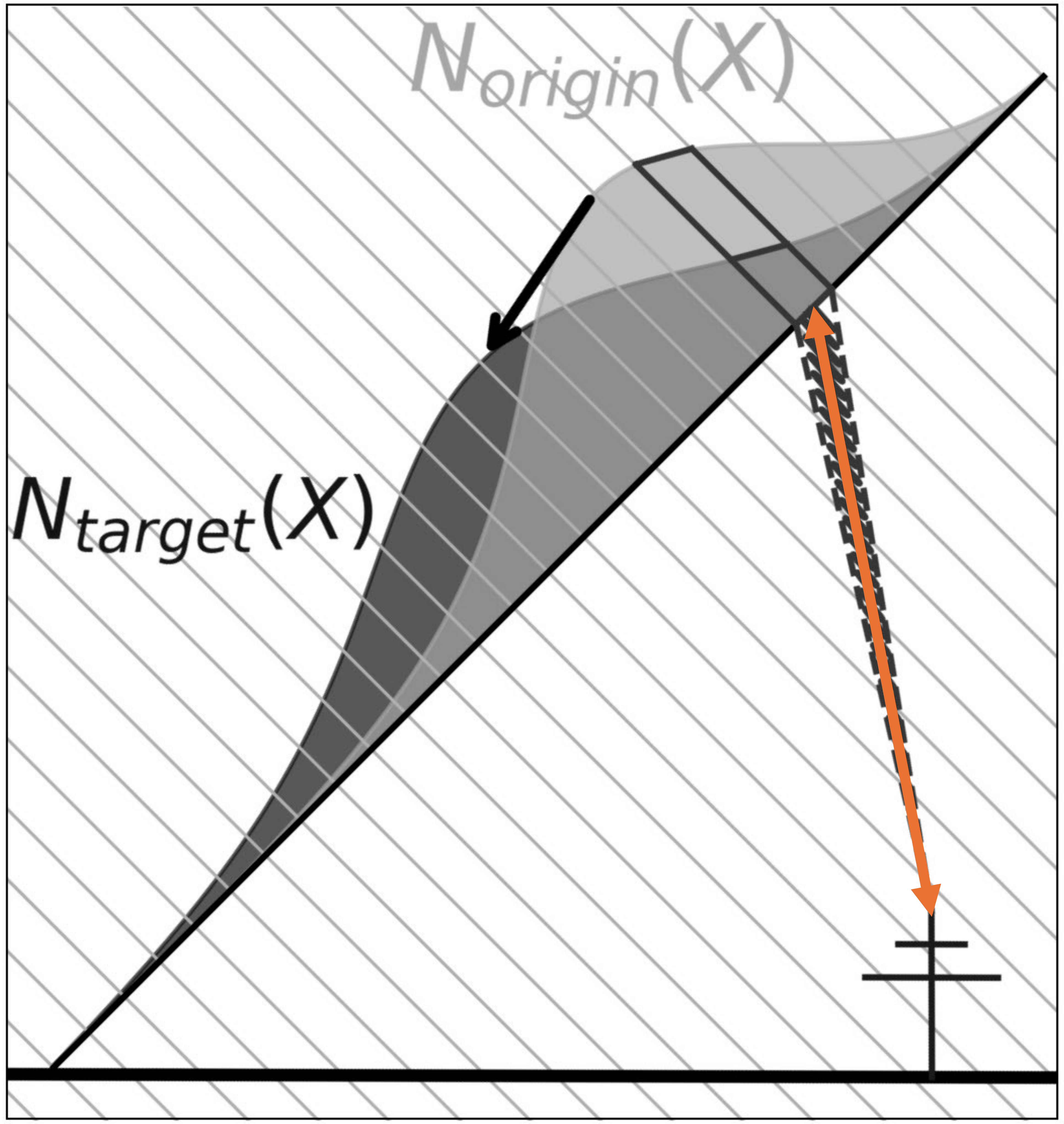
Template synthesis simulates the radio emission from air showers using a hybrid approach



- We take a Monte-Carlo based simulation as input and apply parametrisations to synthesise the emission from a target with different properties.

Mitja Desmet

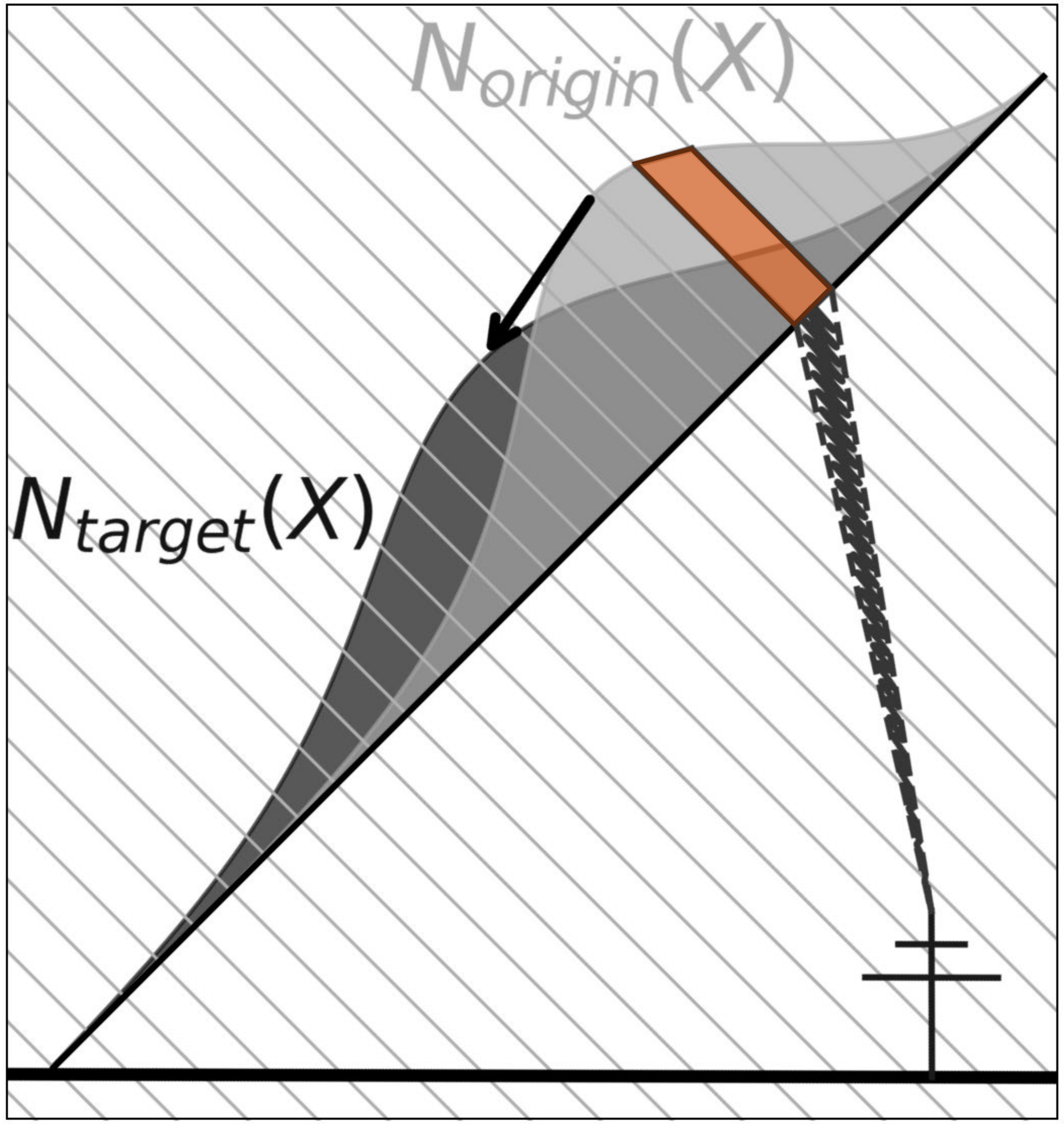
Template synthesis simulates the radio emission from air showers using a hybrid approach



- We rescale the emission coming from each atmospheric slice separately, accounting for the shower properties:
    - Distance from slice to antenna

Mitja Desmet

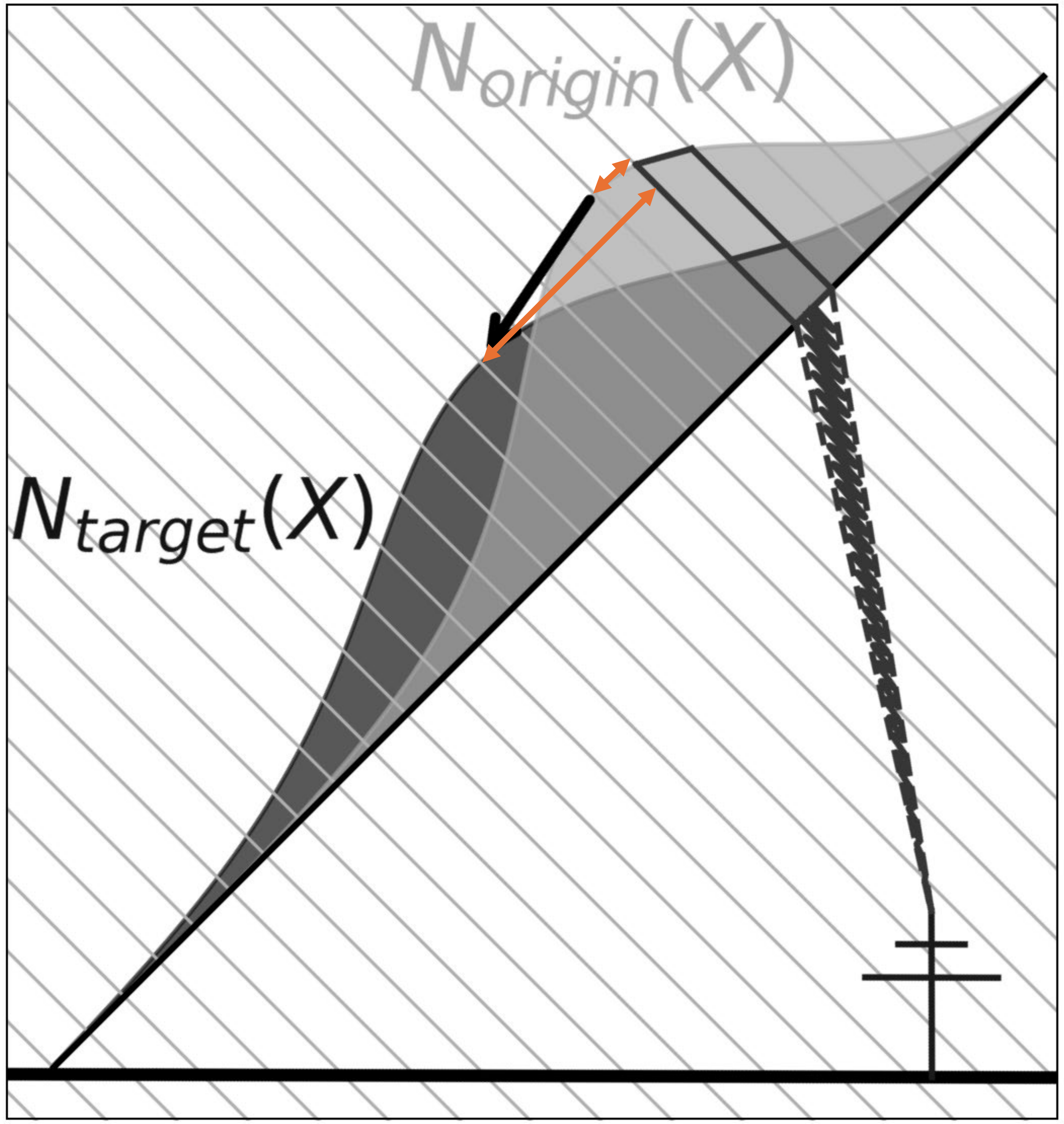
Template synthesis simulates the radio emission from air showers using a hybrid approach



- We rescale the emission coming from each atmospheric slice separately, accounting for the shower properties:
  - Distance from slice to antenna
  - Number of particles, the density and refractive index in the slice

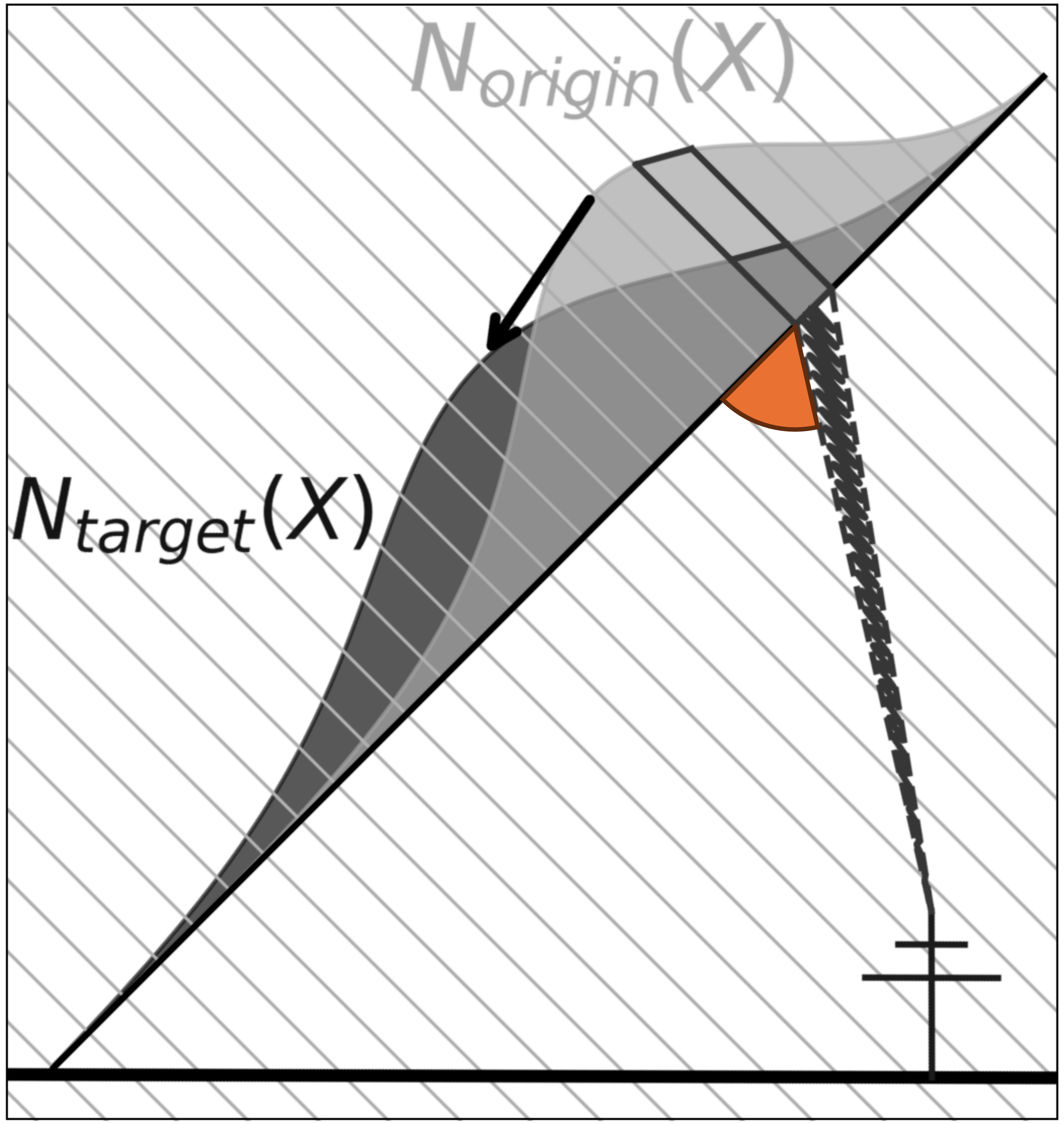
Mitja Desmet

Template synthesis simulates the radio emission from air showers using a hybrid approach



- We rescale the emission coming from each atmospheric slice separately, accounting for the shower properties:
  - Distance from slice to antenna
  - Number of particles, the density and refractive index in the slice
  - The "shower age" in the slice

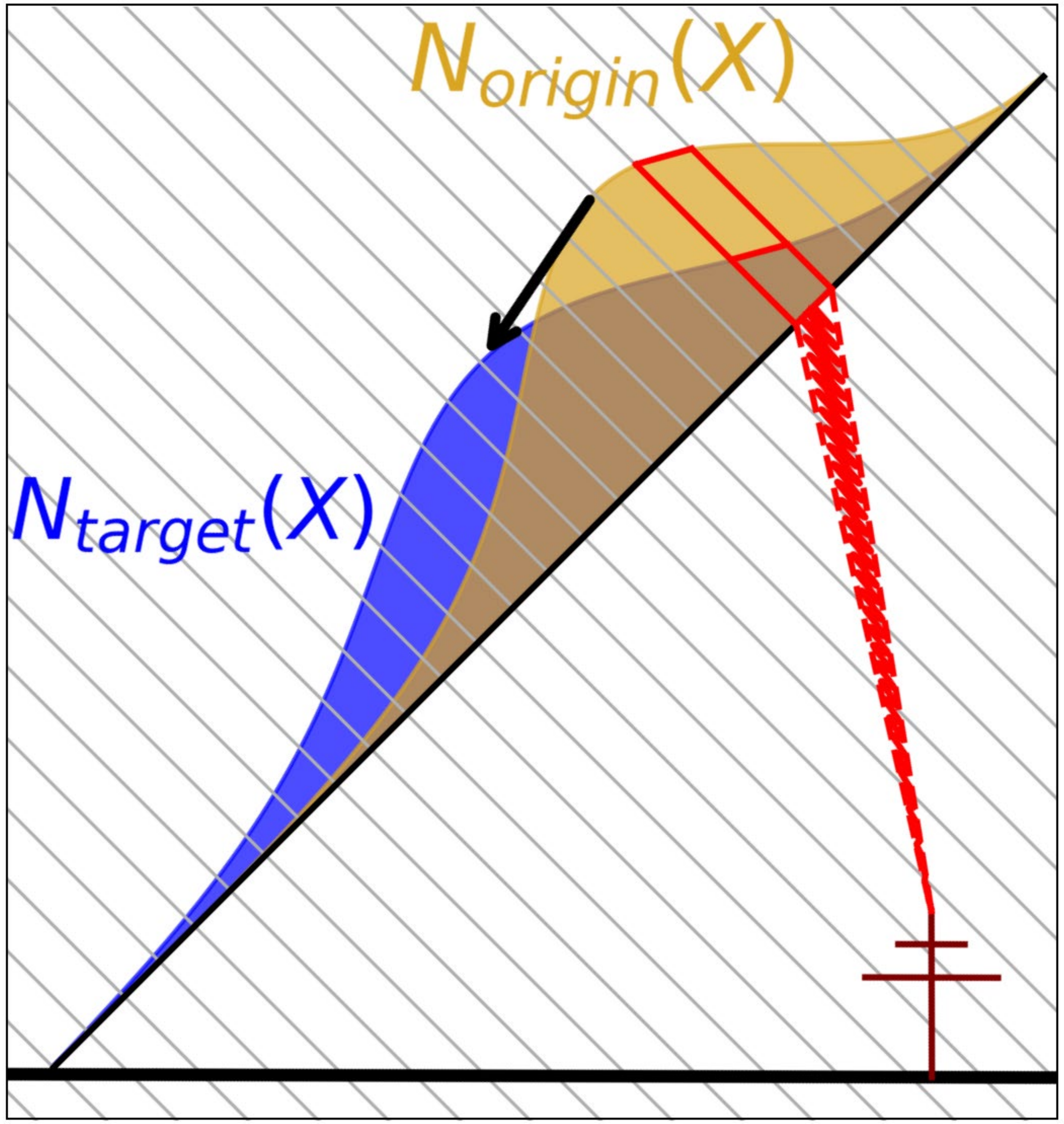
Template synthesis simulates the radio emission from air showers using a hybrid approach



- We rescale the emission coming from each atmospheric slice separately, accounting for the shower properties:
  - Distance from slice to antenna
  - Number of particles, the density and refractive index in the slice
  - The "shower age" in the slice
  - The viewing angle of the antenna, in units of local Cherenkov angle

Mitja Desmet

These scaling relations make template synthesis applicable to all geometries (at least up to 60°)



- We rescale the emission coming from each atmospheric slice separately, accounting for the shower properties:
  - Distance from slice to antenna
  - Number of particles, the density and refractive index in the slice
  - The "shower age" in the slice
  - The viewing angle of the antenna, in units of local Cherenkov angle
- And this in a matter of **seconds**!

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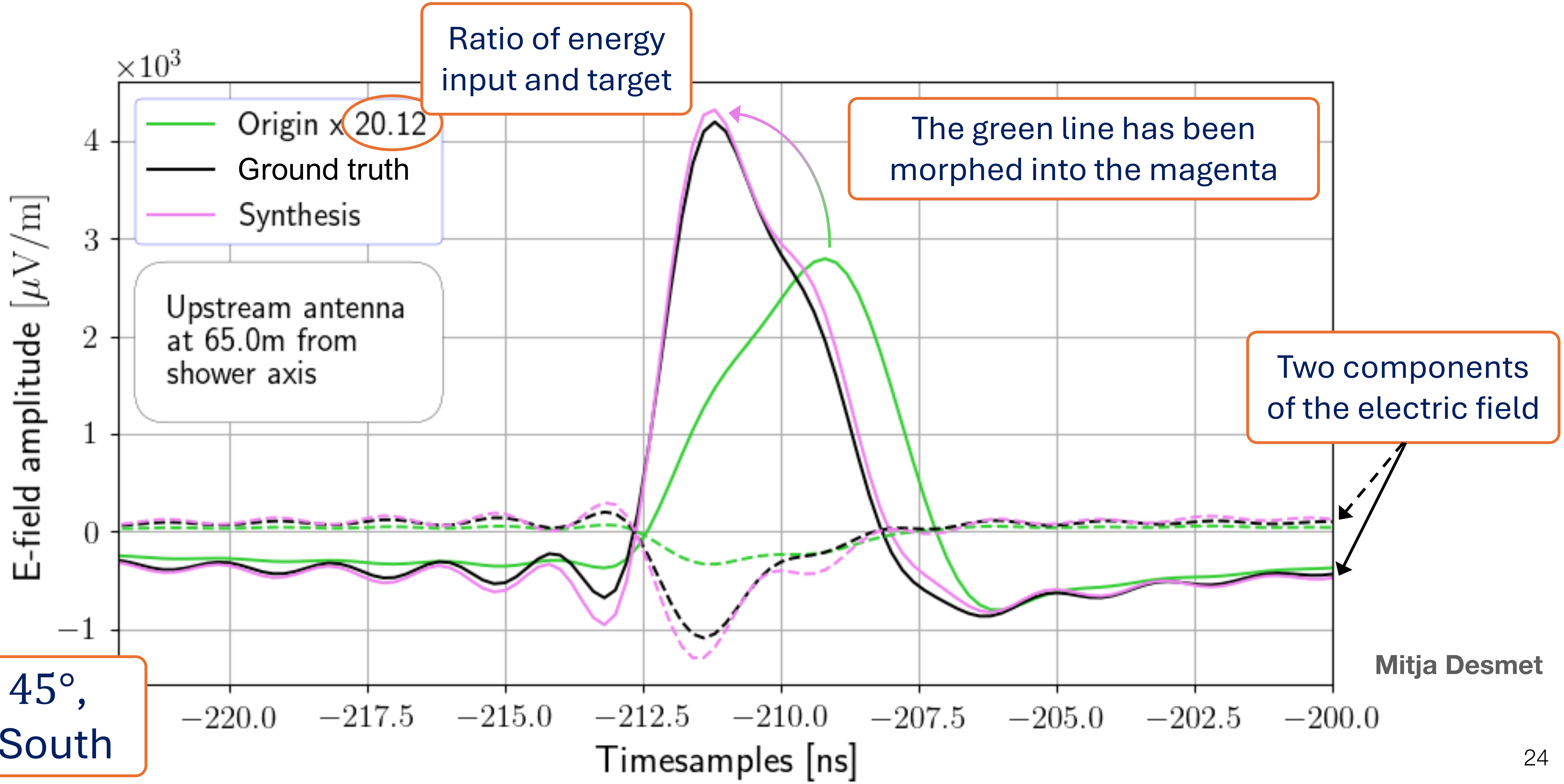
The accuracy of template synthesis is on the same level as the inherent shower fluctuations



$\theta = 45°$,
from South

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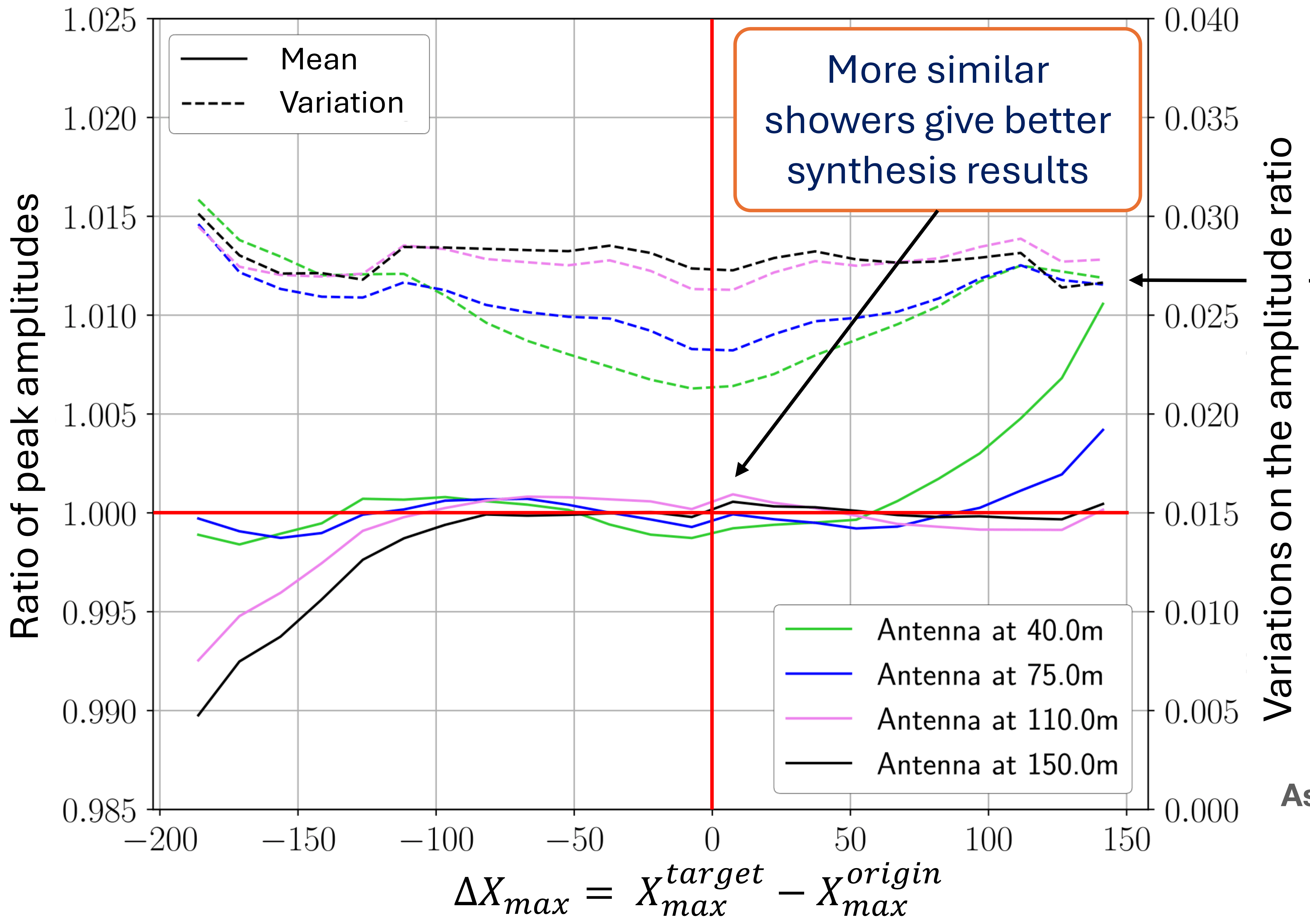
The accuracy of template synthesis is on the same level as the inherent shower fluctuations

We compare the results of synthesis to full MC simulations



The variations are around 3%, which is the level of expected shower fluctuations

Mitja Desmet et al,
Astropart.Phys. 157 (2024) 102923

Conclusions

- LOFAR 1.0 has concluded observations. Next: LOFAR 2.0 and SKA
- SKA will produce highest-resolution radio air shower observations
- Particle detector array of ~100 units, funding by FWO
- Unprecedented precision on Xmax at 10^{16} - 10^{18} eV
  Beamforming for lower energies. PeV gamma-rays?
- New reconstruction possibilities:
  double-bump showers & stretched shower
  hadronic physics & mass composition