Cosmic ray observations with the Square Kilometre Array

Stijn Buitink

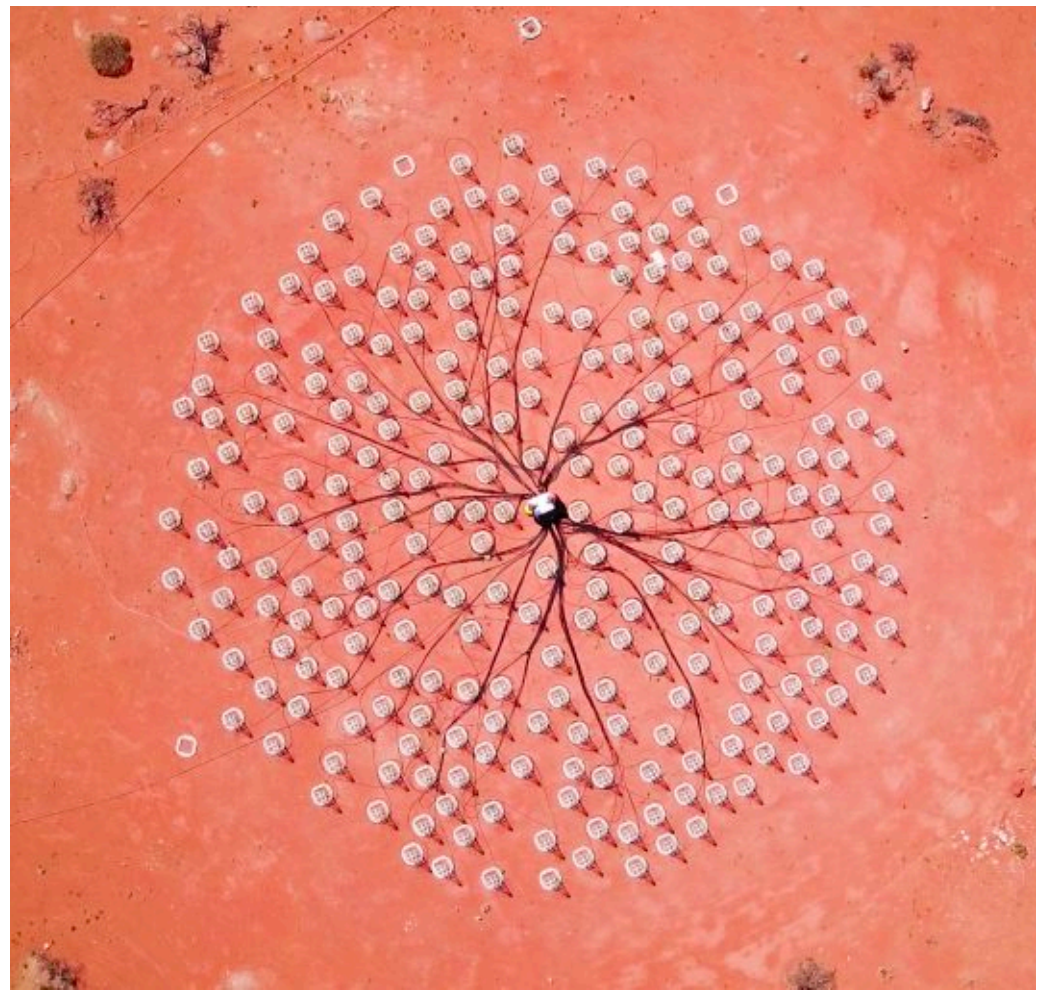
VRIJE UNIVERSITEIT BRUSSEL

J. Bray, A. Corstanje, M. Desmet, H. Falcke, K. Gayley, B.M. Hare, J.R. Hörandel, T. Huege, C.W. James, V.B. Jhansi, N. Karastathis, G.K. Krampah, P. Mitra, K. Mulrey, B. Neijzen, A. Nelles, H. Pandya, O. Scholten, F. Schröder, R. Spencer, K. Terveer, S. Thoudam, G. Trinh, S. ter Veen, and M. Waterson

12 June 2024, ARENA Chicago

Cosmic Ray observations with the SKA

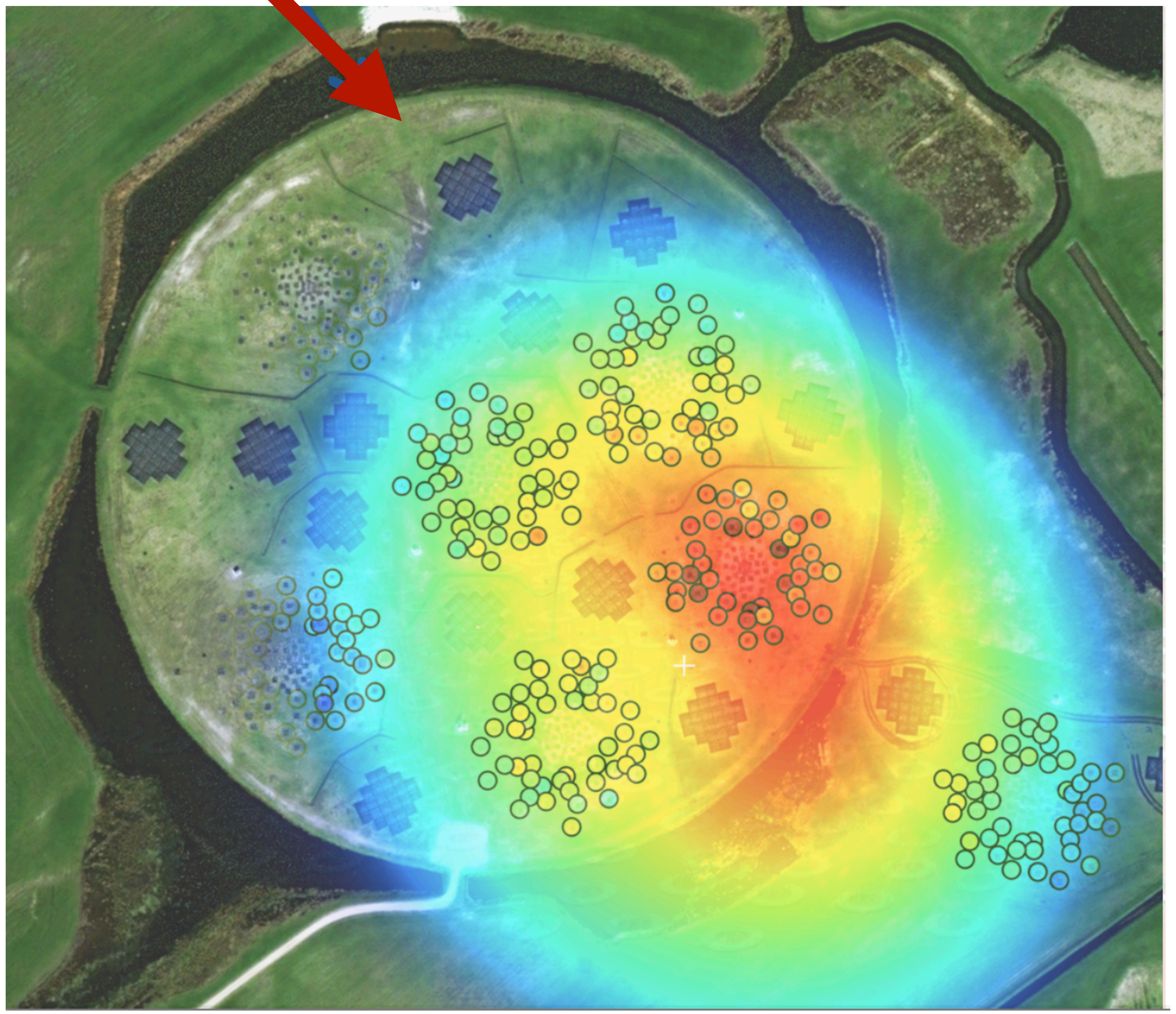
- SKA will have mid-freq array in South-Africa and low-freq in Australia. Construction has started.
- SKA-low will consist of 57,344 log-periodic antennas within an area of ~1 km^2
- Frequency bandwidth 50-350 MHz
- Extremely high-density & homogeneous coverage: very precise radio observations of air 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)



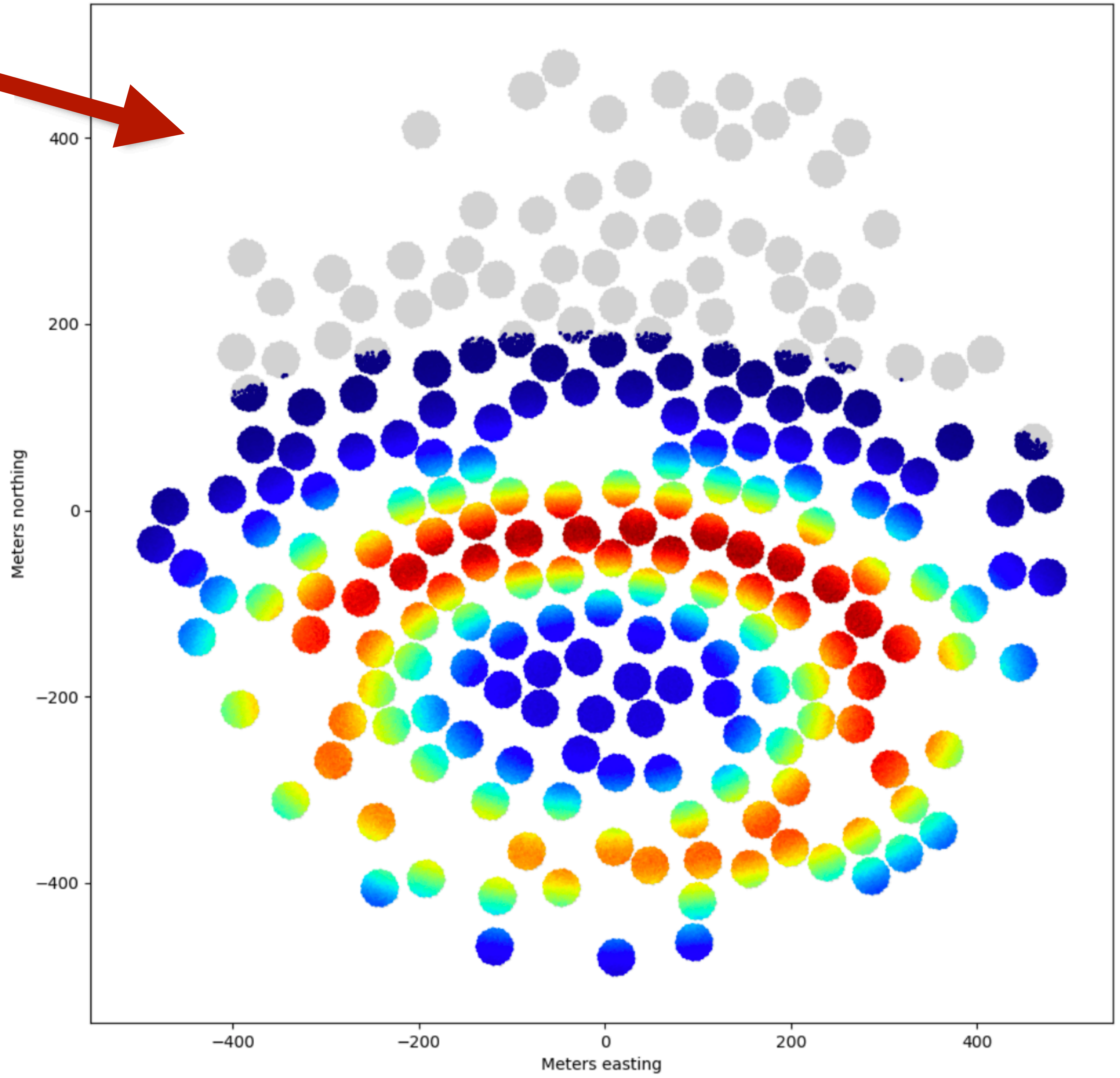
Prototype @MRO (256 antennas)

Cosmic Ray observations with the SKA

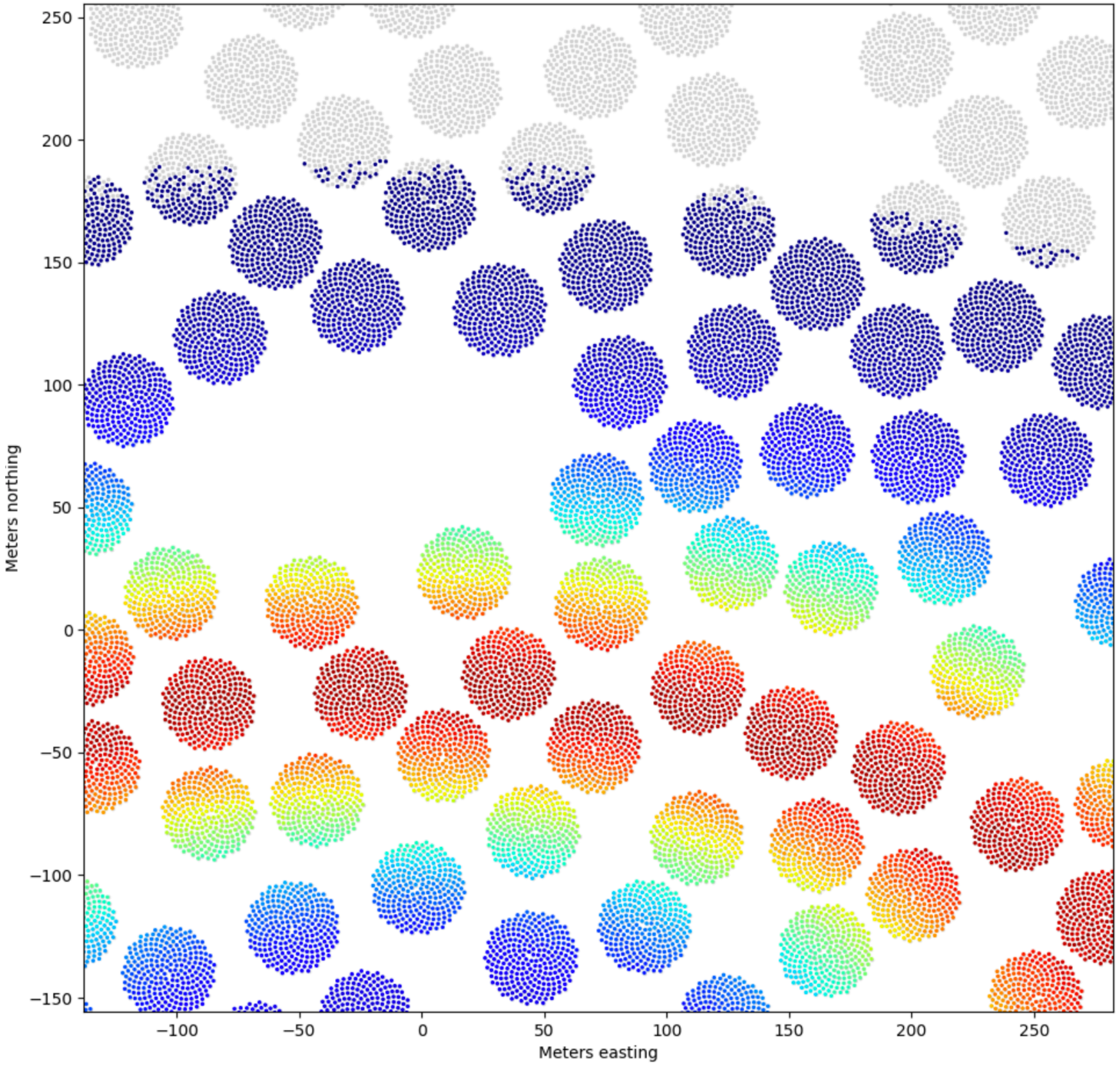
LOFAR

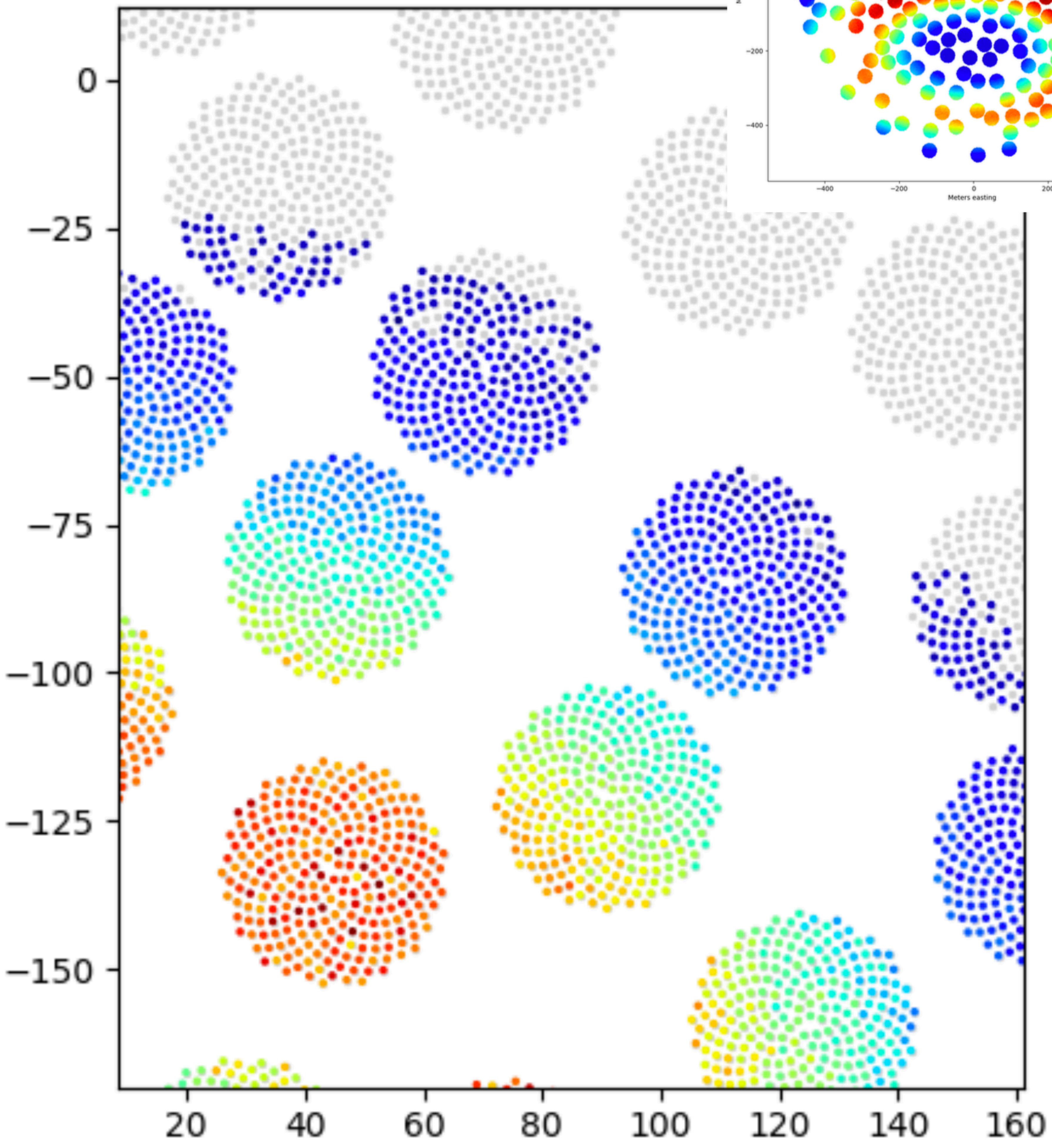


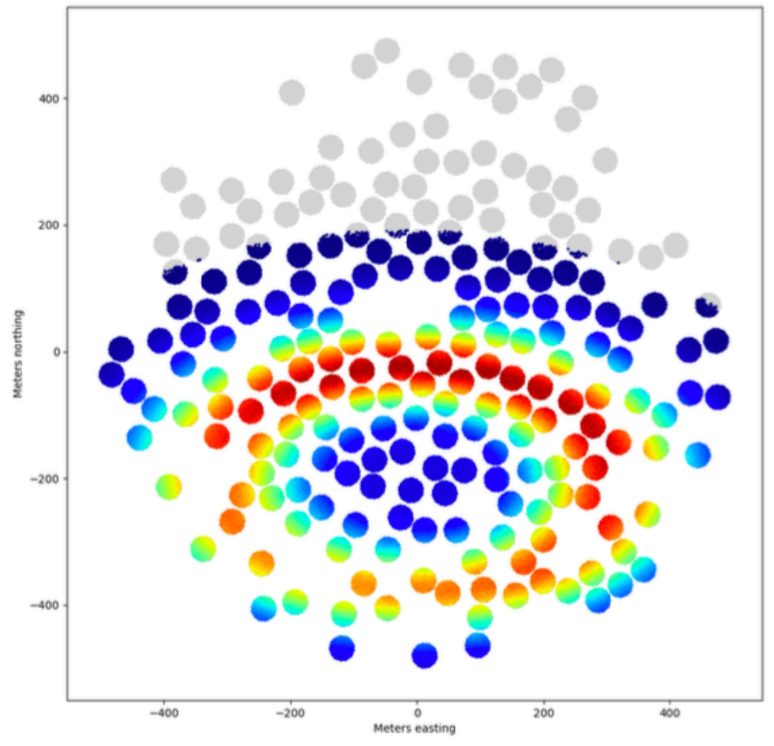
SKA



SKA-low: a really dense array!

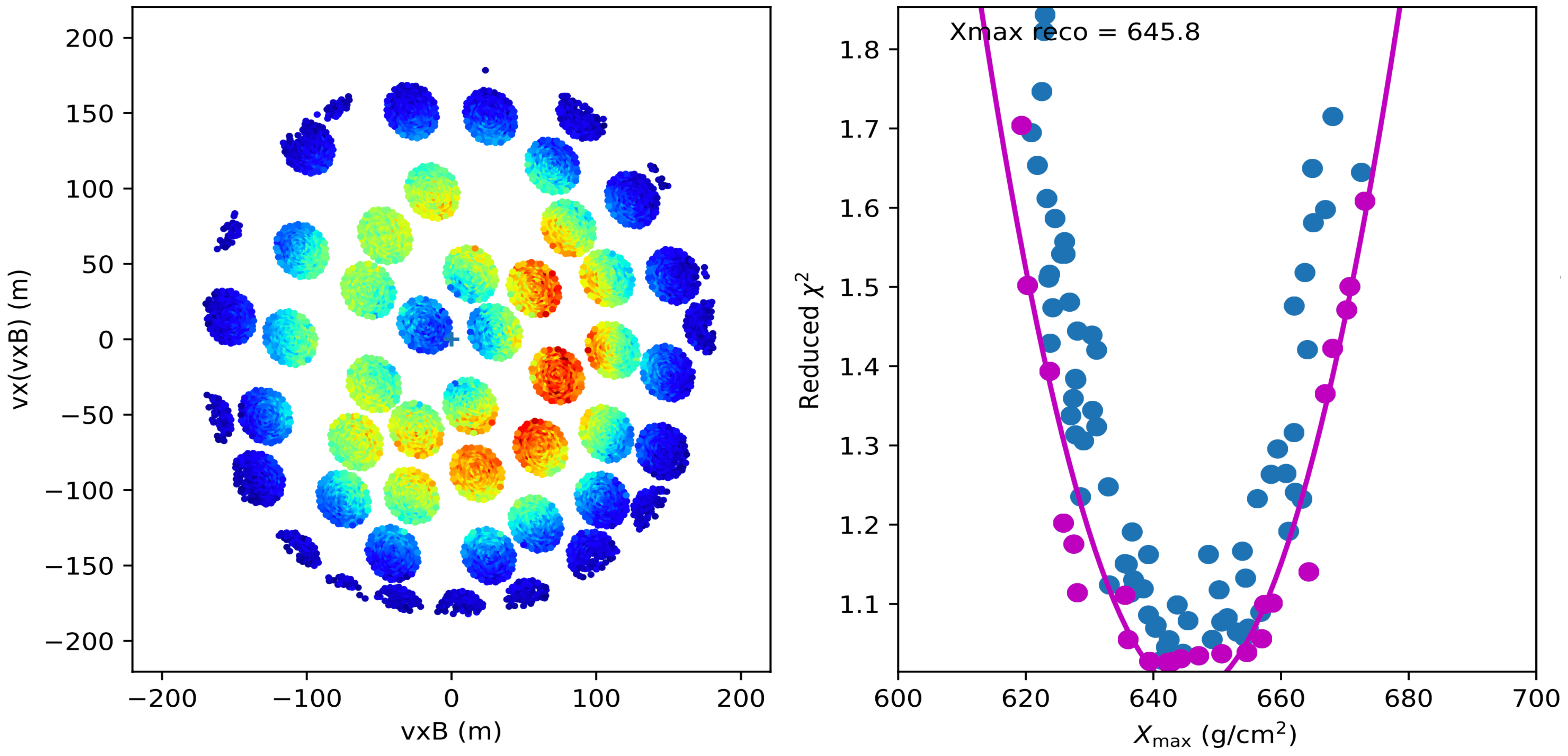






57,344 SKALAs total

Simulations: X_{max} with SKA



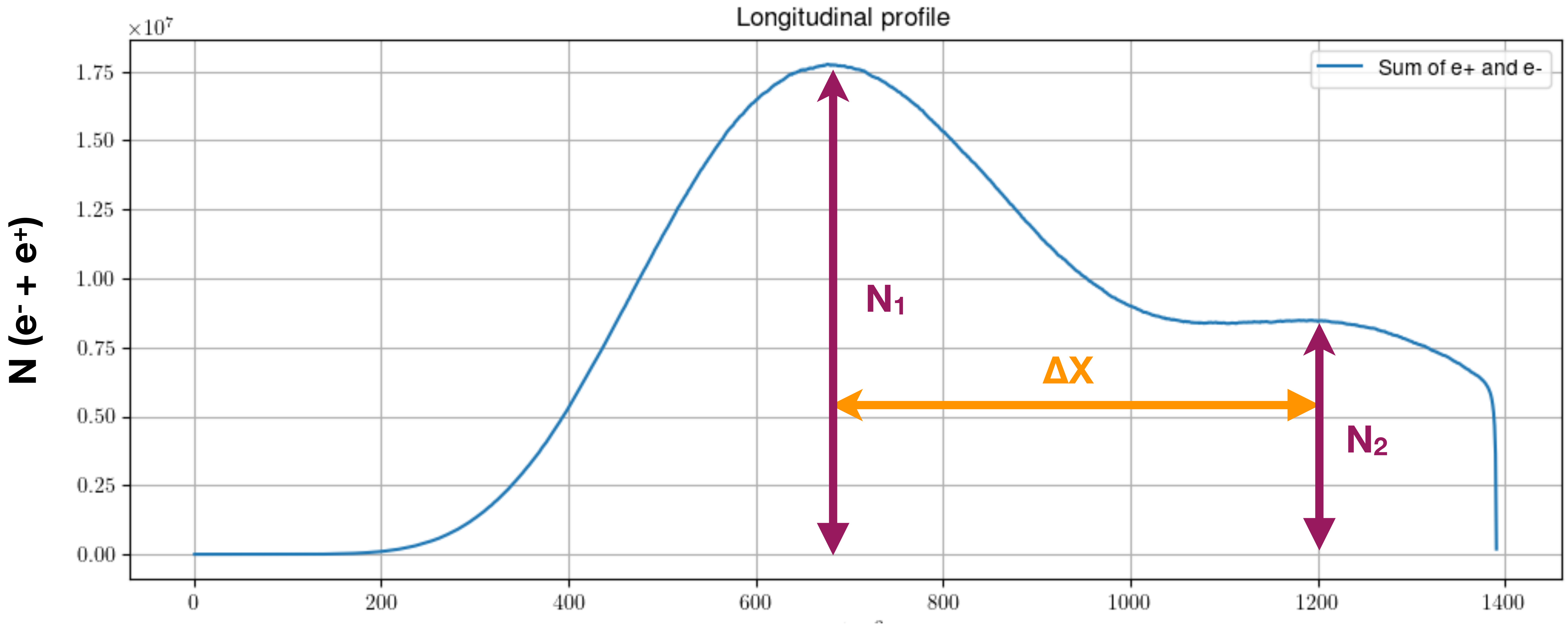
	SKA (simulated)	LOFAR
X_{max} resolution	: **6 - 8 g/cm²**	20 g/cm²
Energy resolution	: **3 %**	9 %
Core resolution	: **50 cm**	3 – 10 m

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

- Reconstruction using LOFAR method (no SKA optimization)
- Using Gaussian noise based on:
  Galactic background
  (dominant < 200 MHz)
  system noise (dominant > 200 MHz)
- X_{max} reco for dedicated sets of SKA simulations.
- Resolution limited by number of simulated showers in sample.

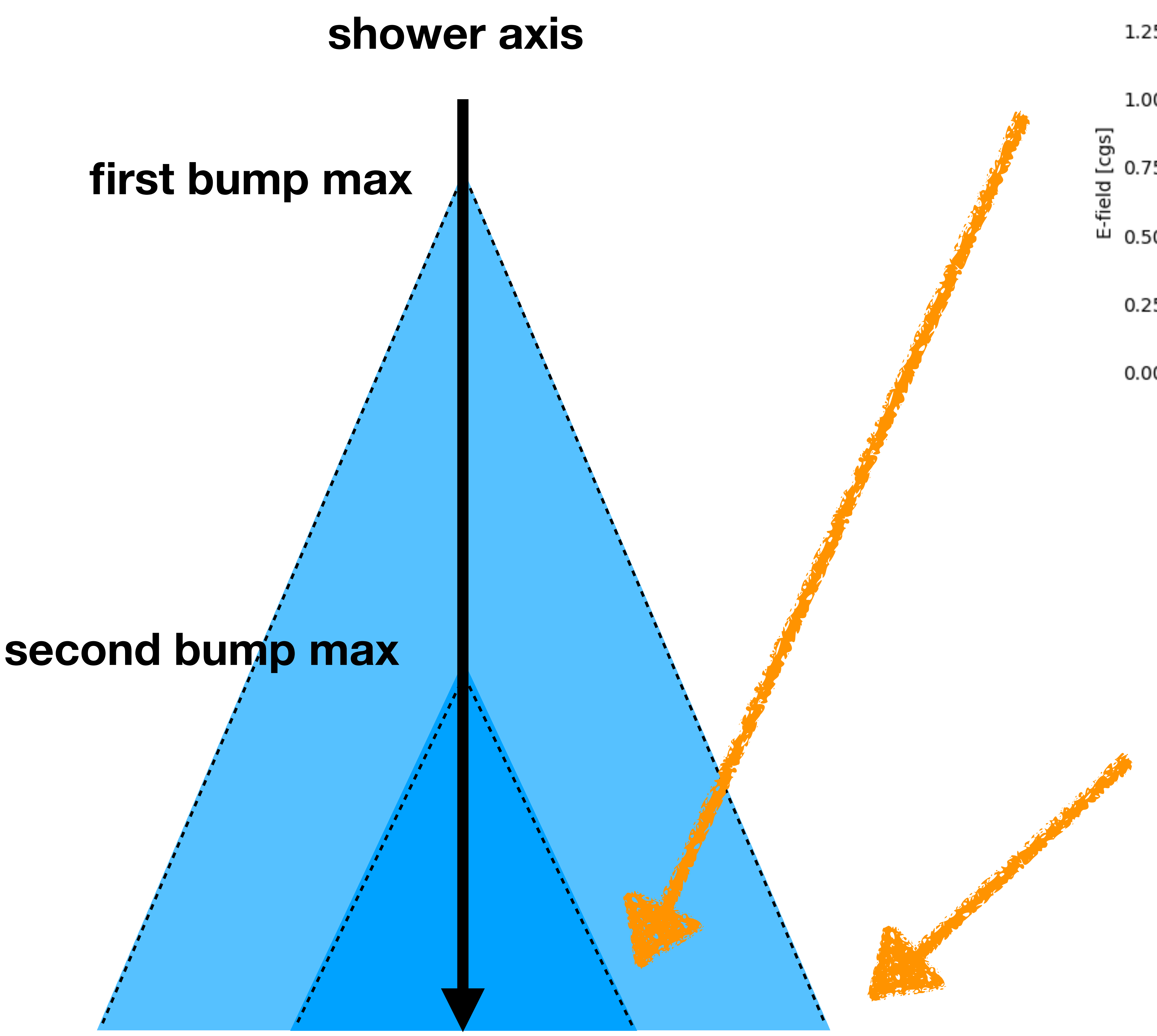
Final resolution will depend on uncertainties in:
- Antenna model
- Atmosphere
- Galactic background (via calibration)
- MC simulations

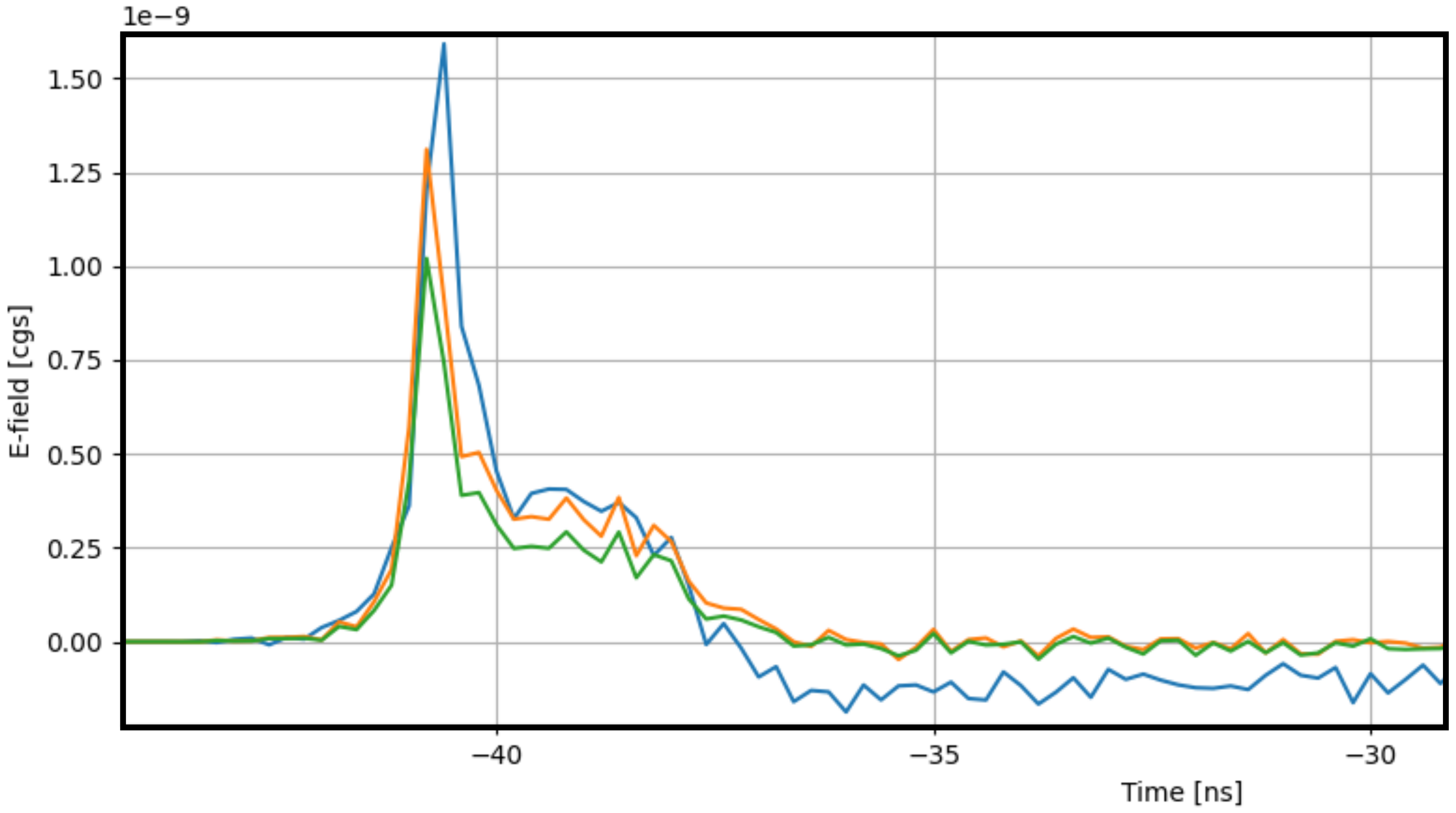
Double-bump showers

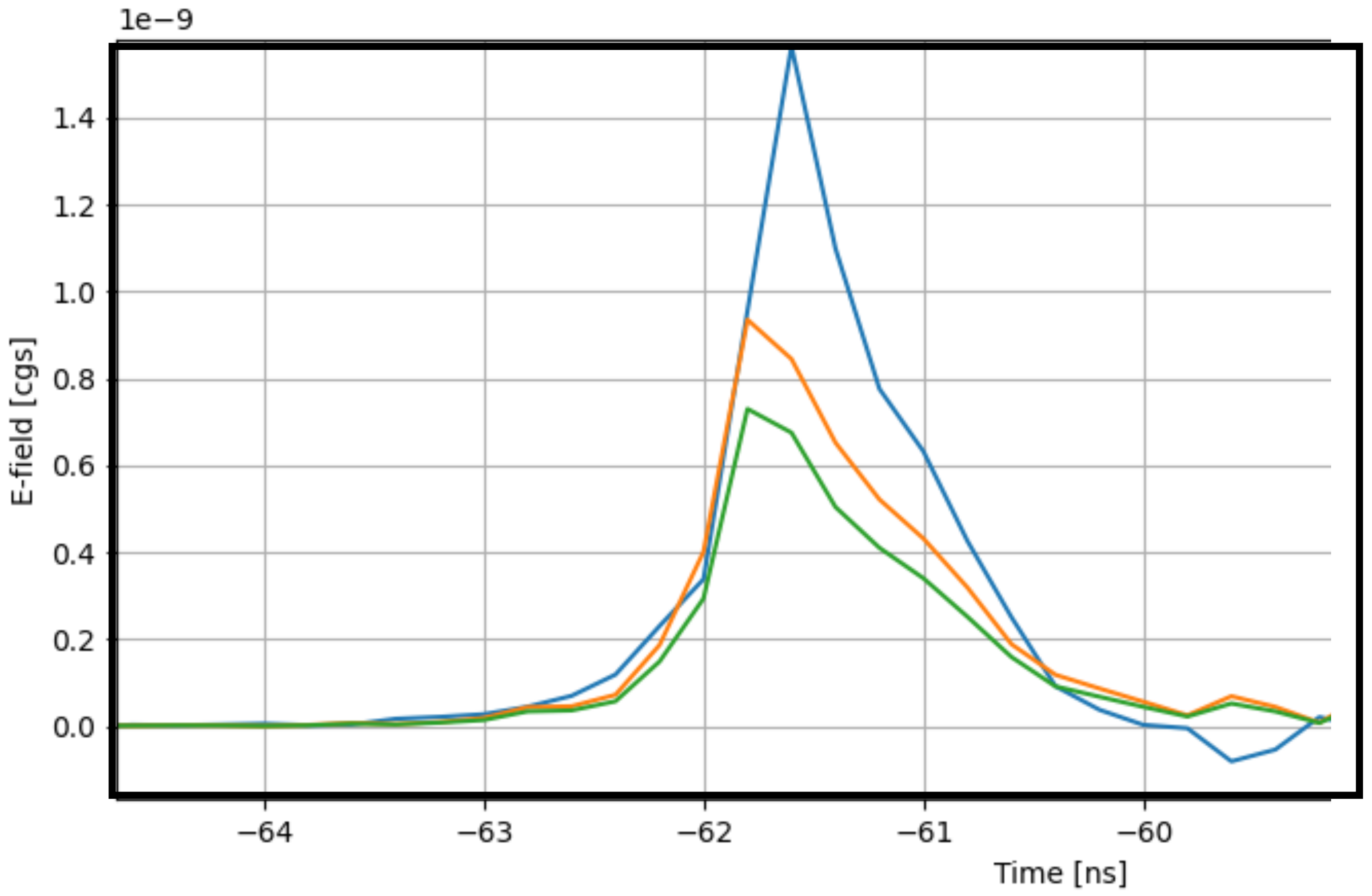


- **A high-energy hadron** (or other fragment) from first interaction can **interact late** causing a **second bump**
- Double-bump showers are rare, more frequent at **lower energies**
- Study hadronic cross section by measuring ΔX and N_1/N_2
- **Most frequent for Helium**: additional constraints on mass composition

Radio from double-bumps

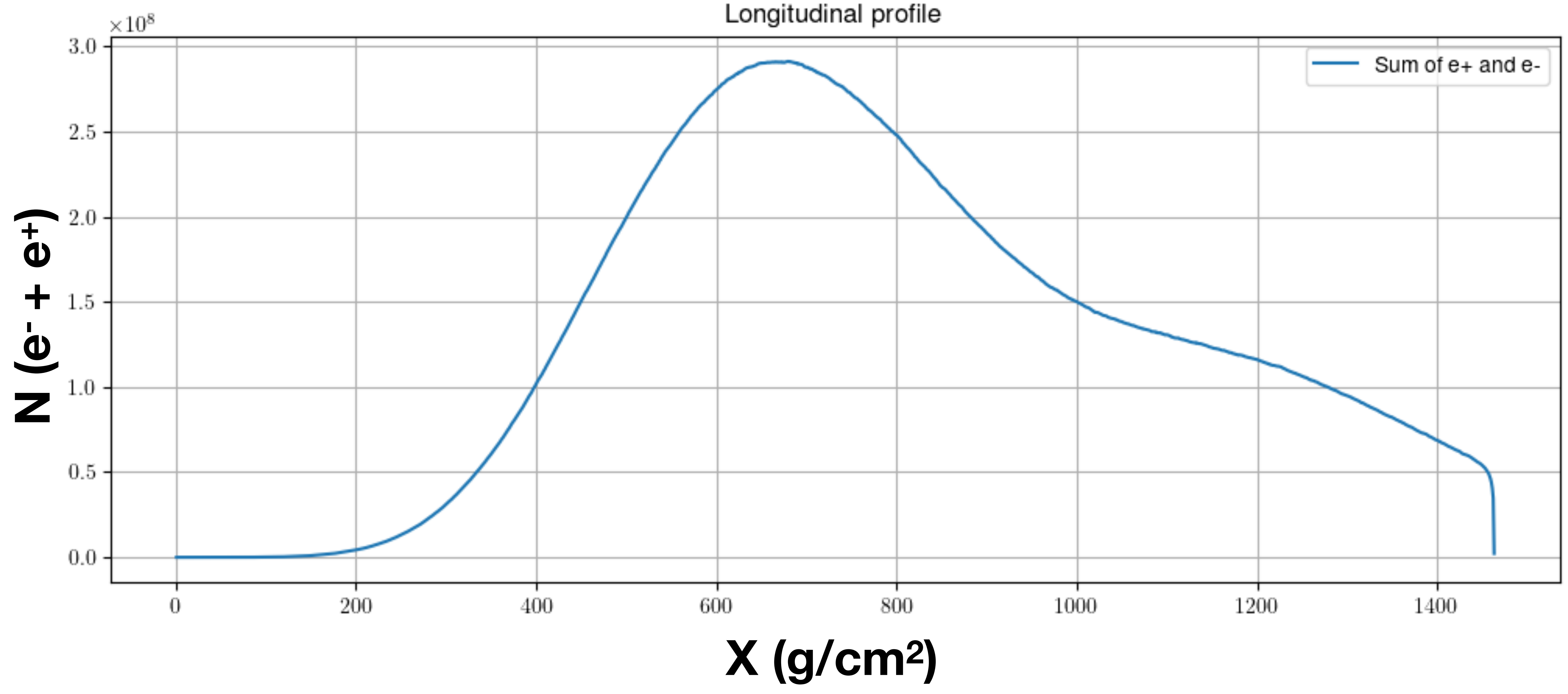


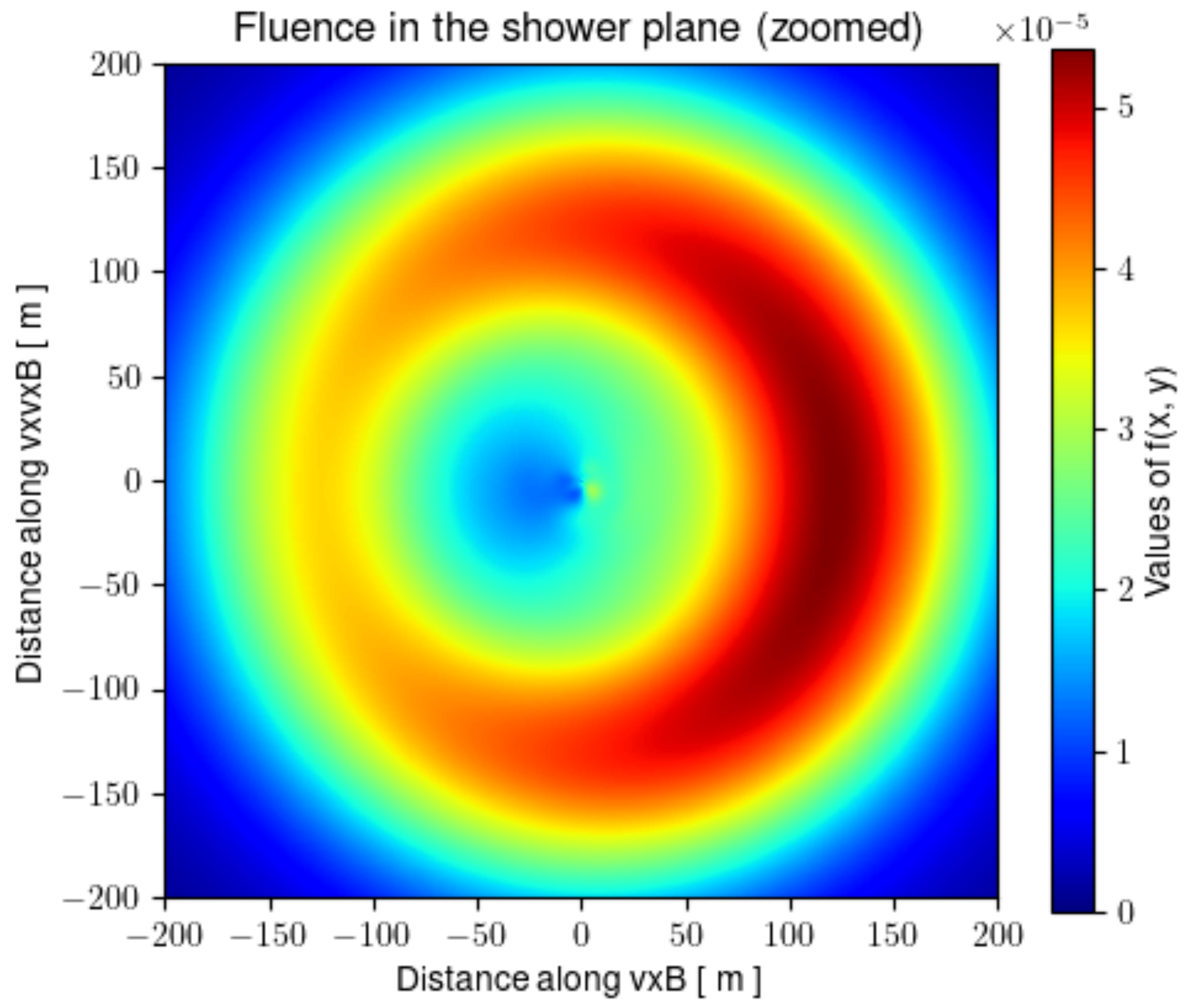




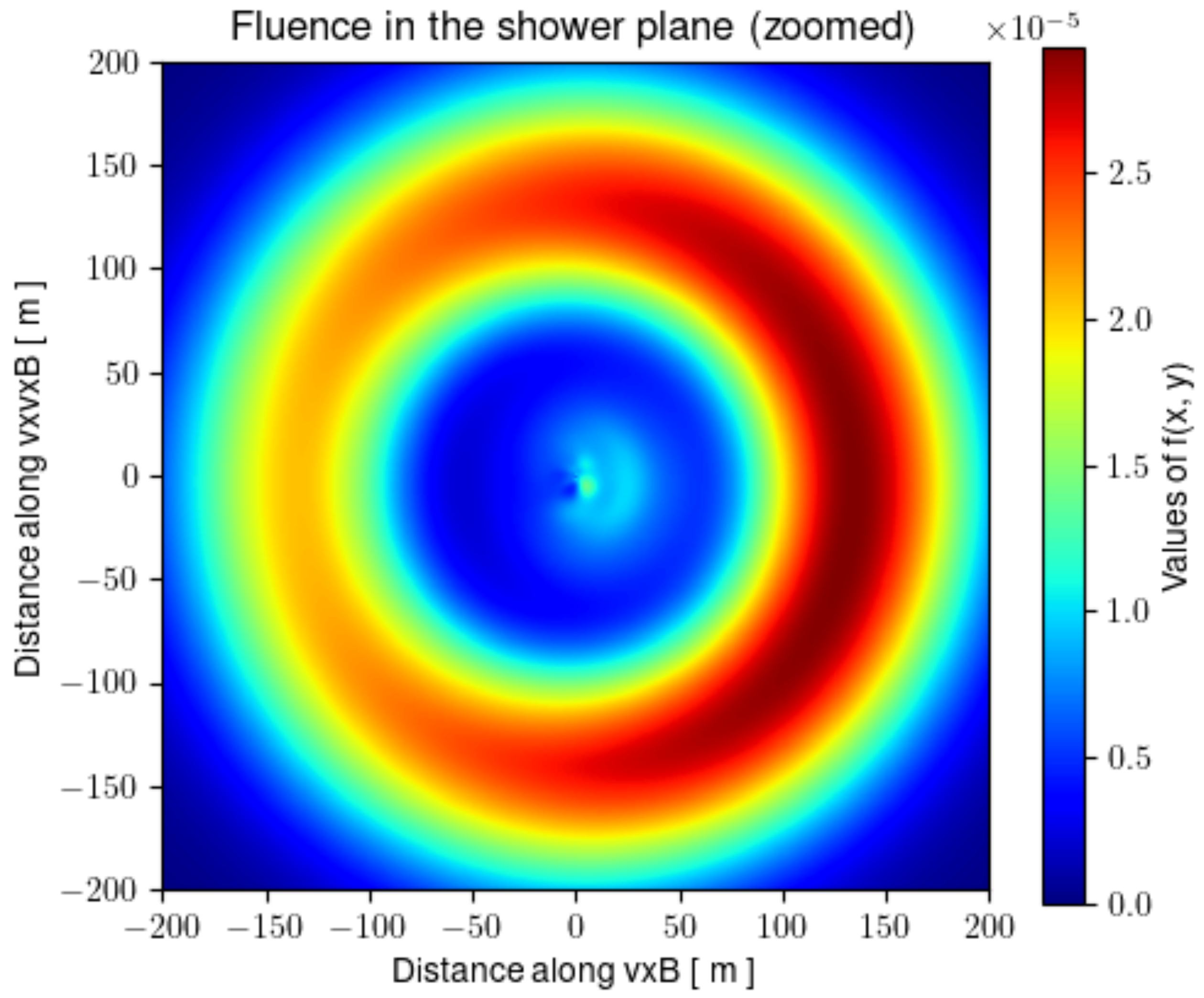
Radio from double-bumps

Helium 5.6 x 10^{17} eV





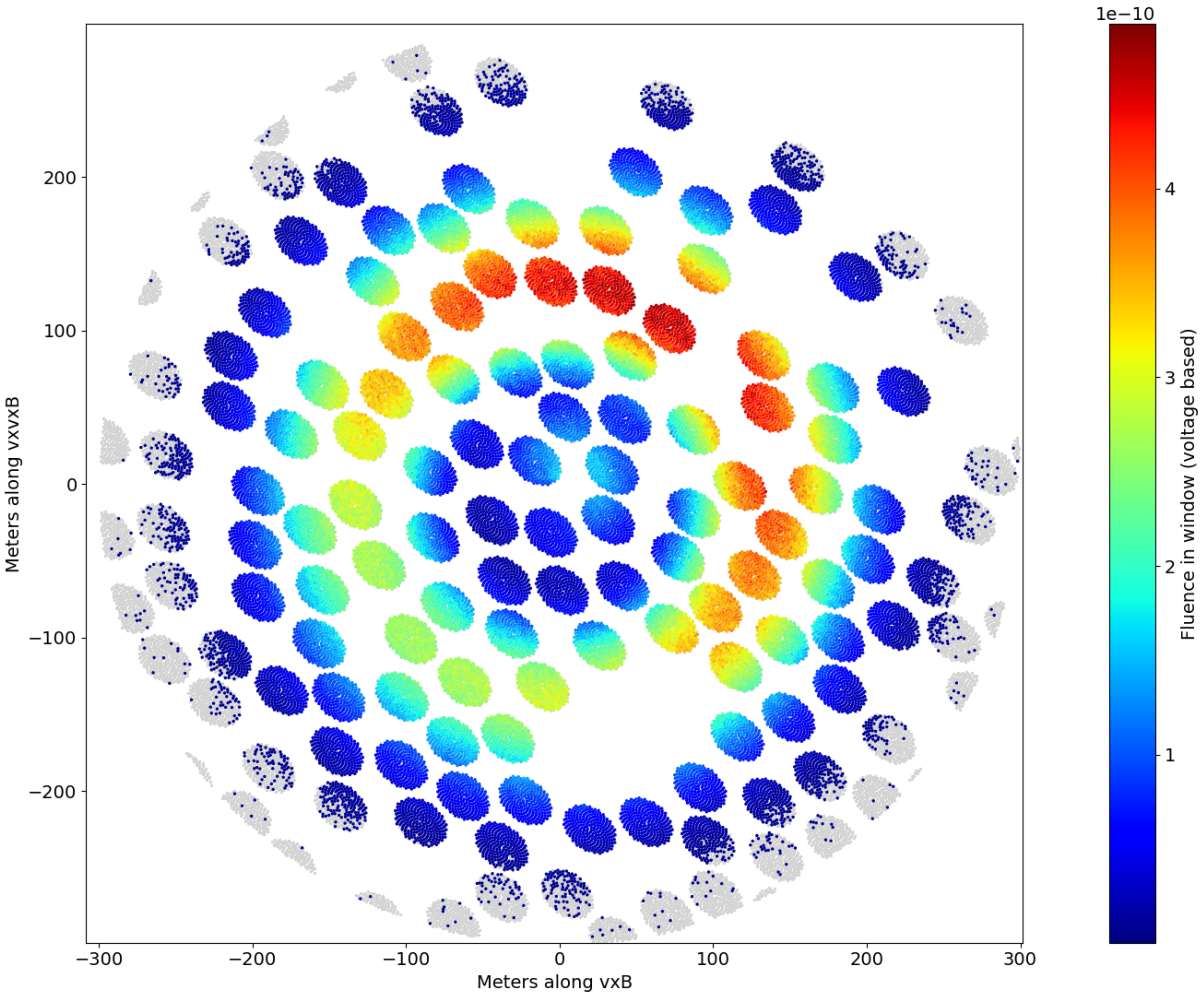
CORSIKA simulated E-field (50-350 MHZ)



High band: 150-350 MHz

filter out low frequencies to separate rings visually

Radio from double-bumps

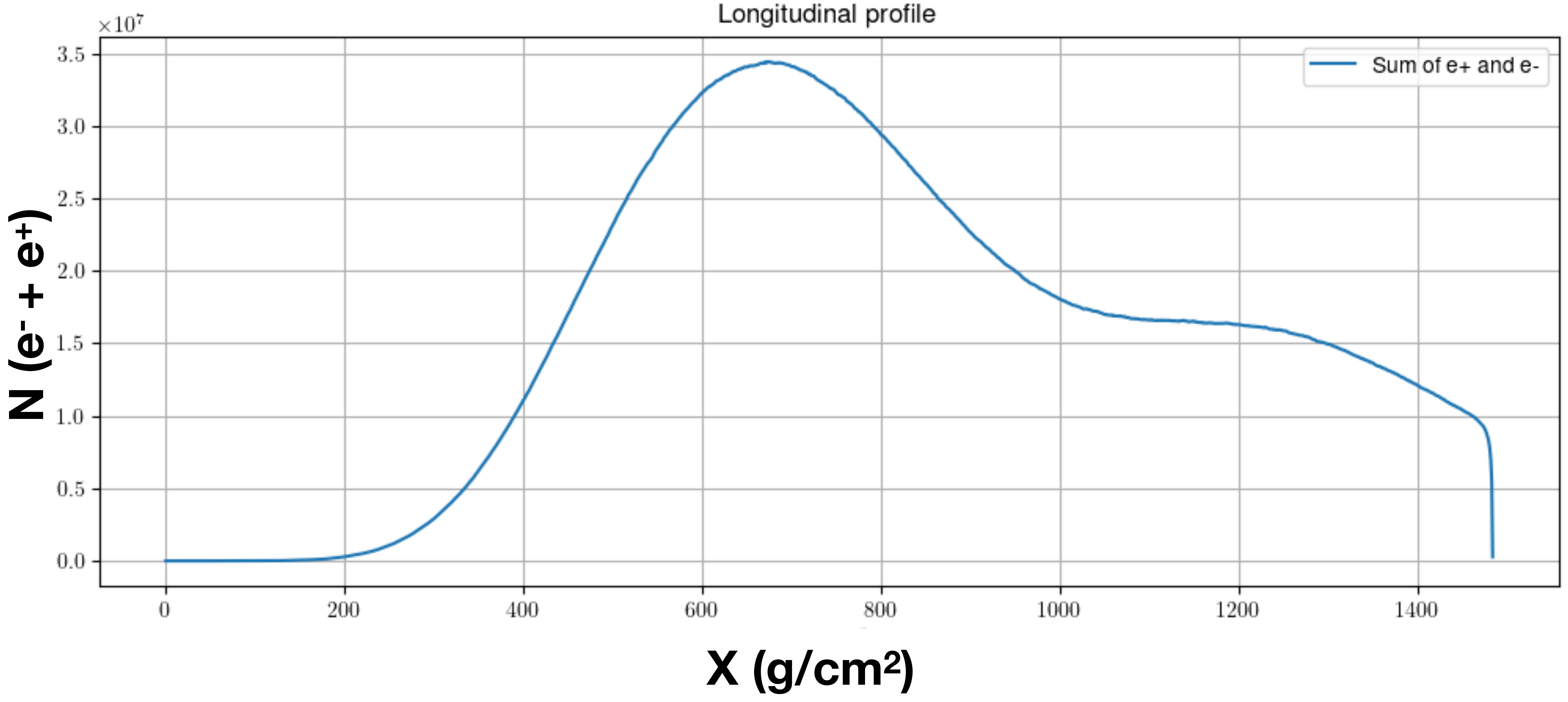


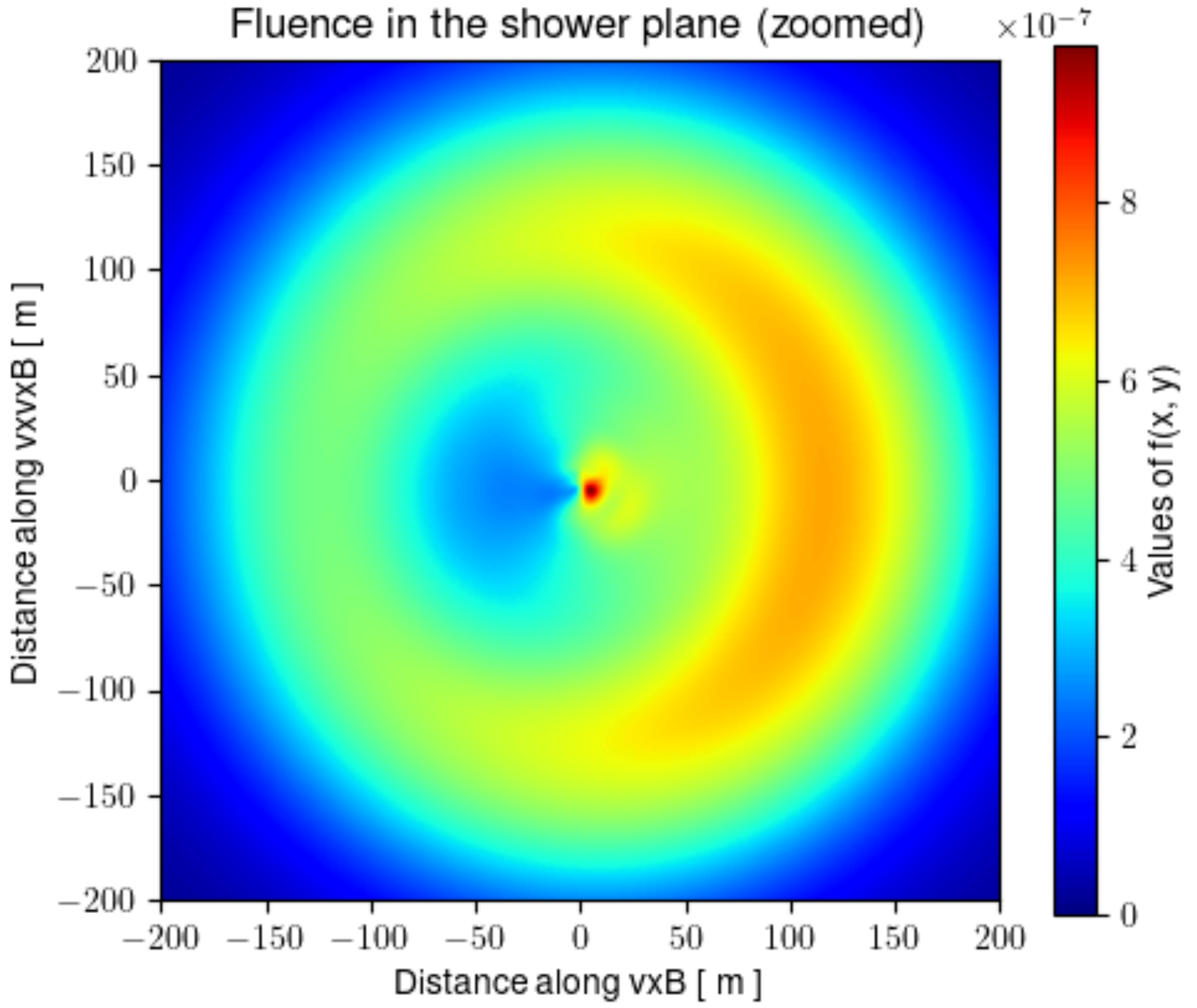
Full simulation including:
Antenna response
Galactic + instrumental noise

Helium double-bump 5.6 x 10^{17} eV

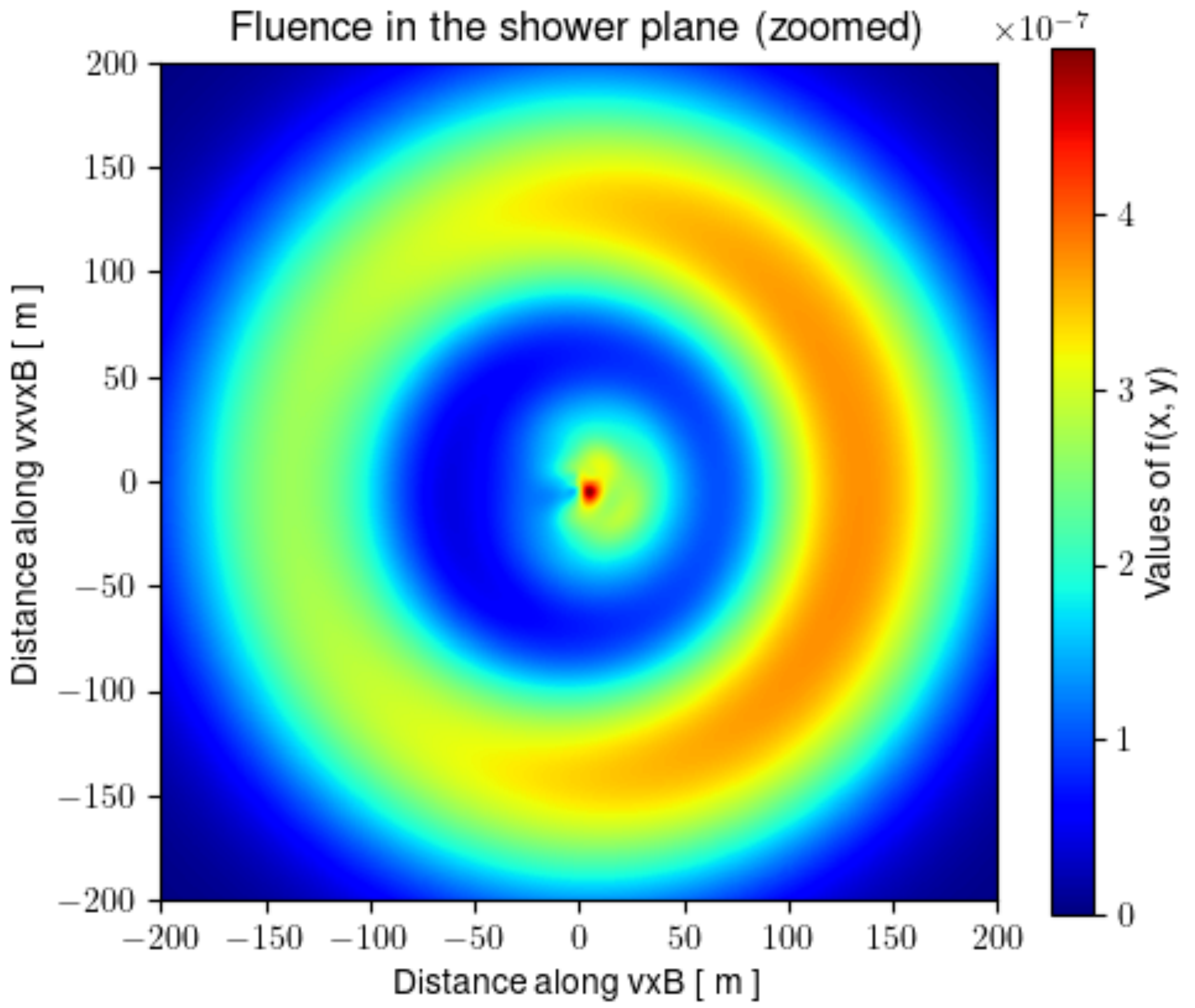
Radio from double-bumps

Helium 7.4 x 10^{16} eV





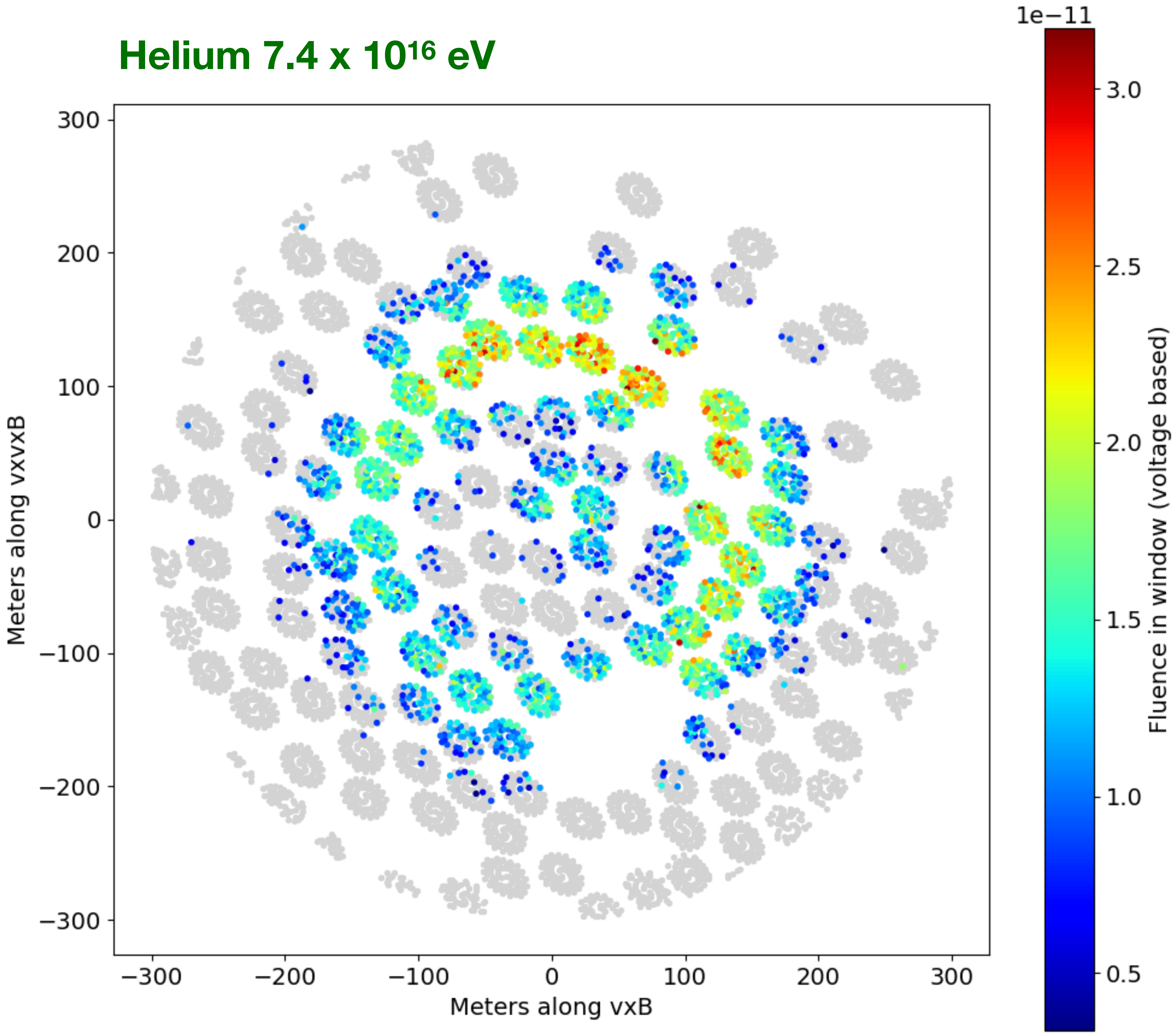
CORSIKA simulated E-field (50-350 MHZ)



High band: 150-350 MHz

Radio from double-bumps

Helium 7.4 x 10^{16} eV



Antenna decimation factor 4
SNR increase 2

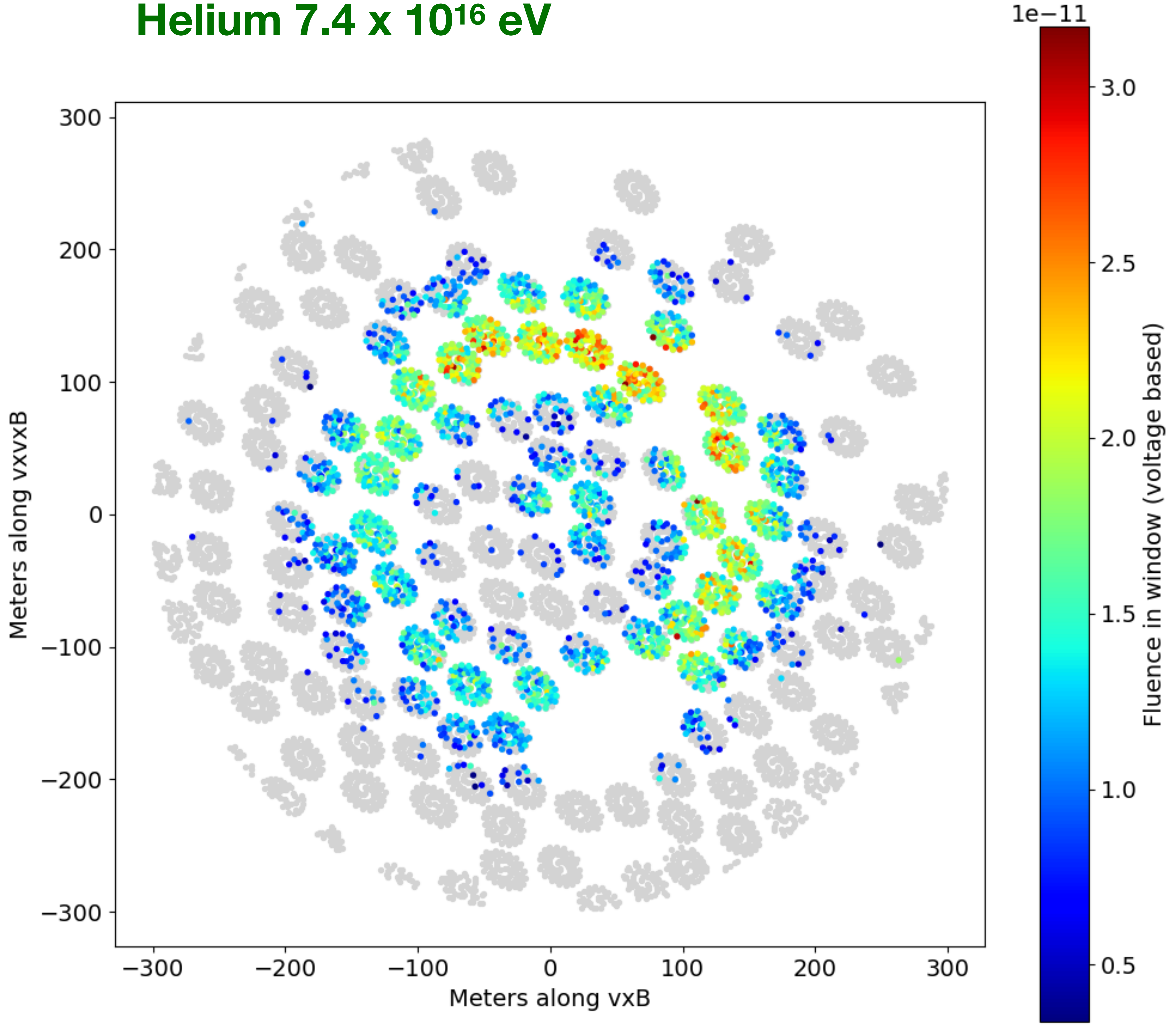
Full simulation including:
Antenna response
Galactic + instrumental noise

Beamforming:

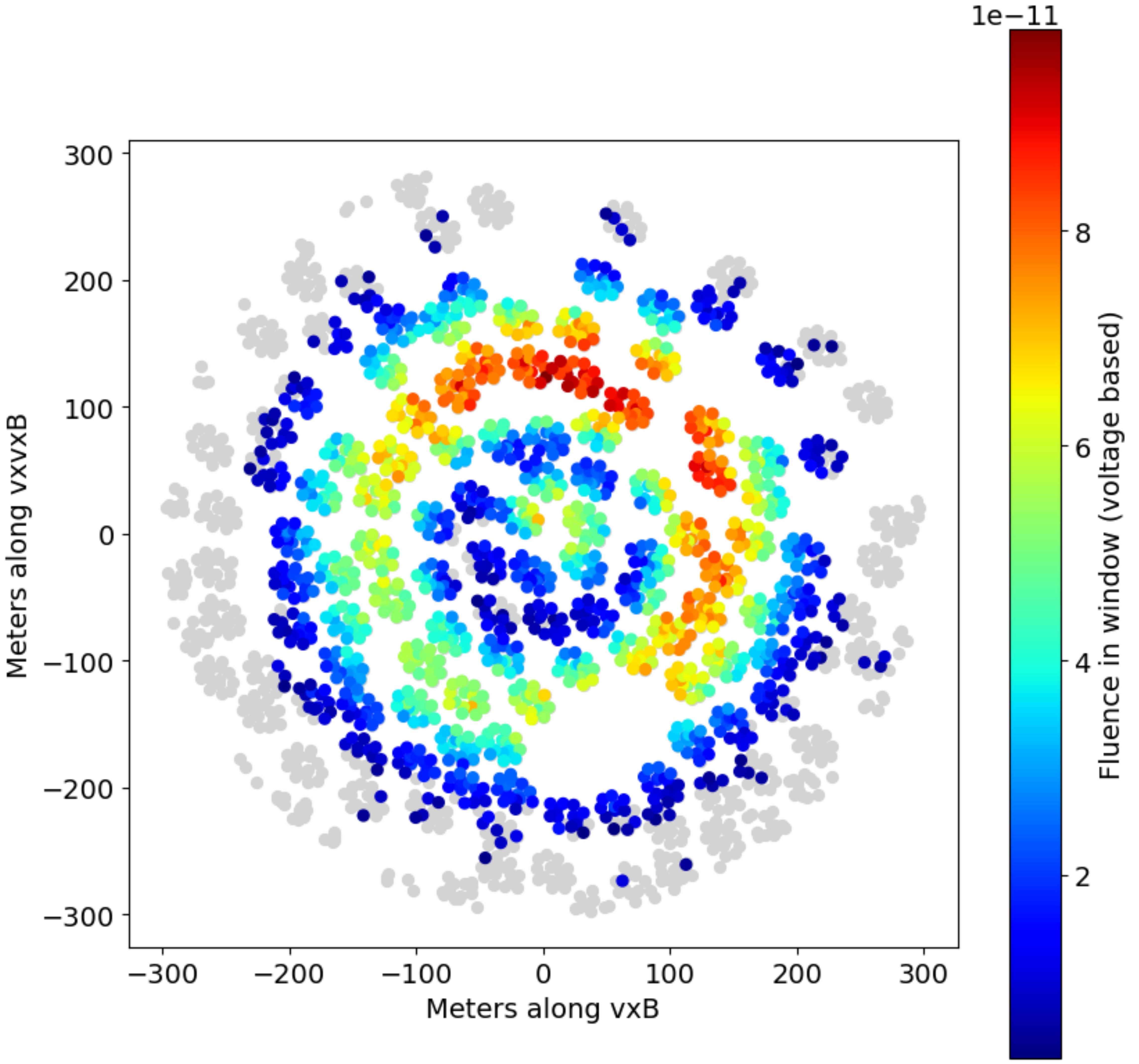
- add waveforms from *N* antennas
- signal add coherently ~*N*
- background add incoherently ~srqt(*N*)
- Dot size - # of beam formed antennas

Radio from double-bumps

Helium 7.4 x 10^{16} eV



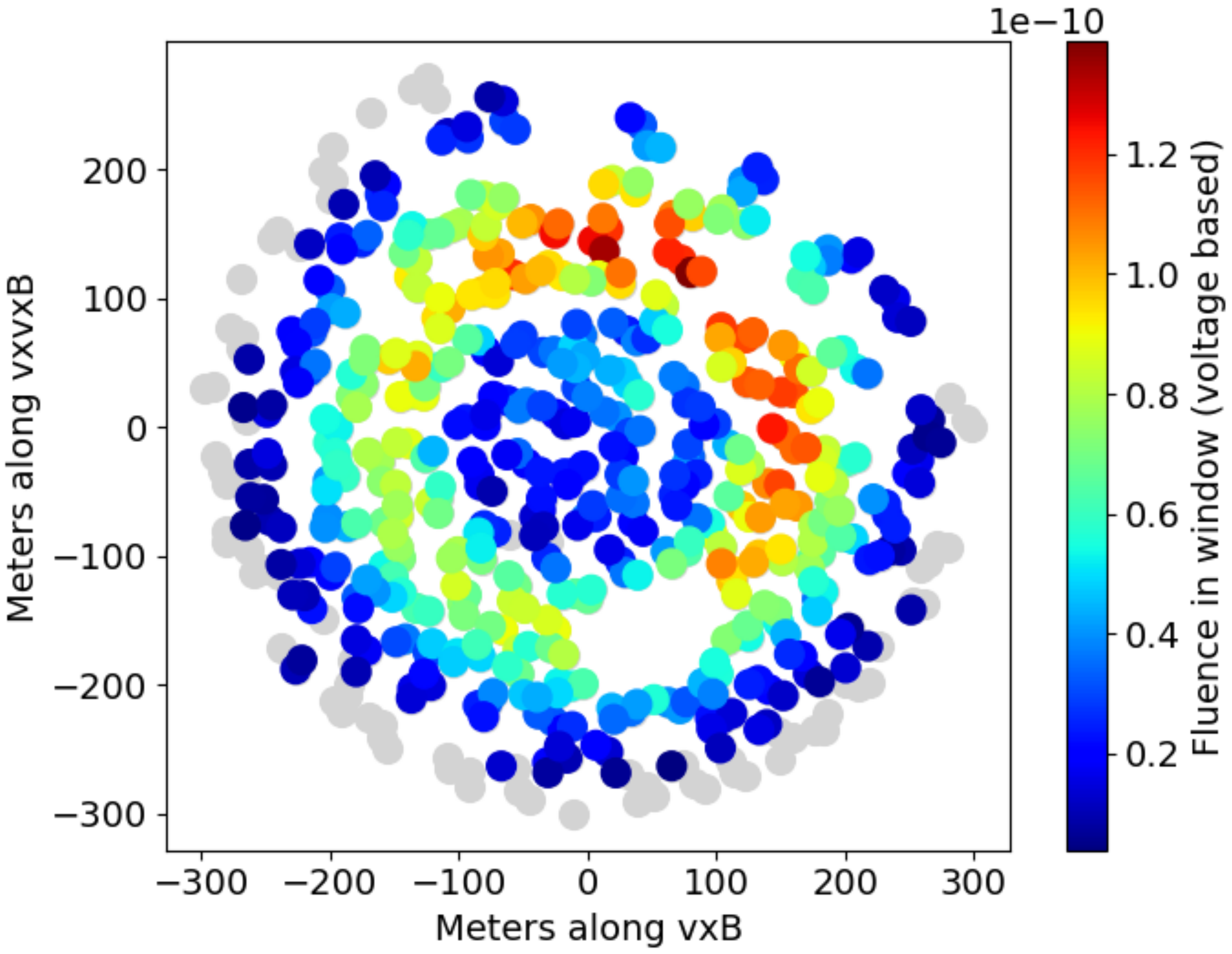
Antenna decimation factor 4
SNR increase 2

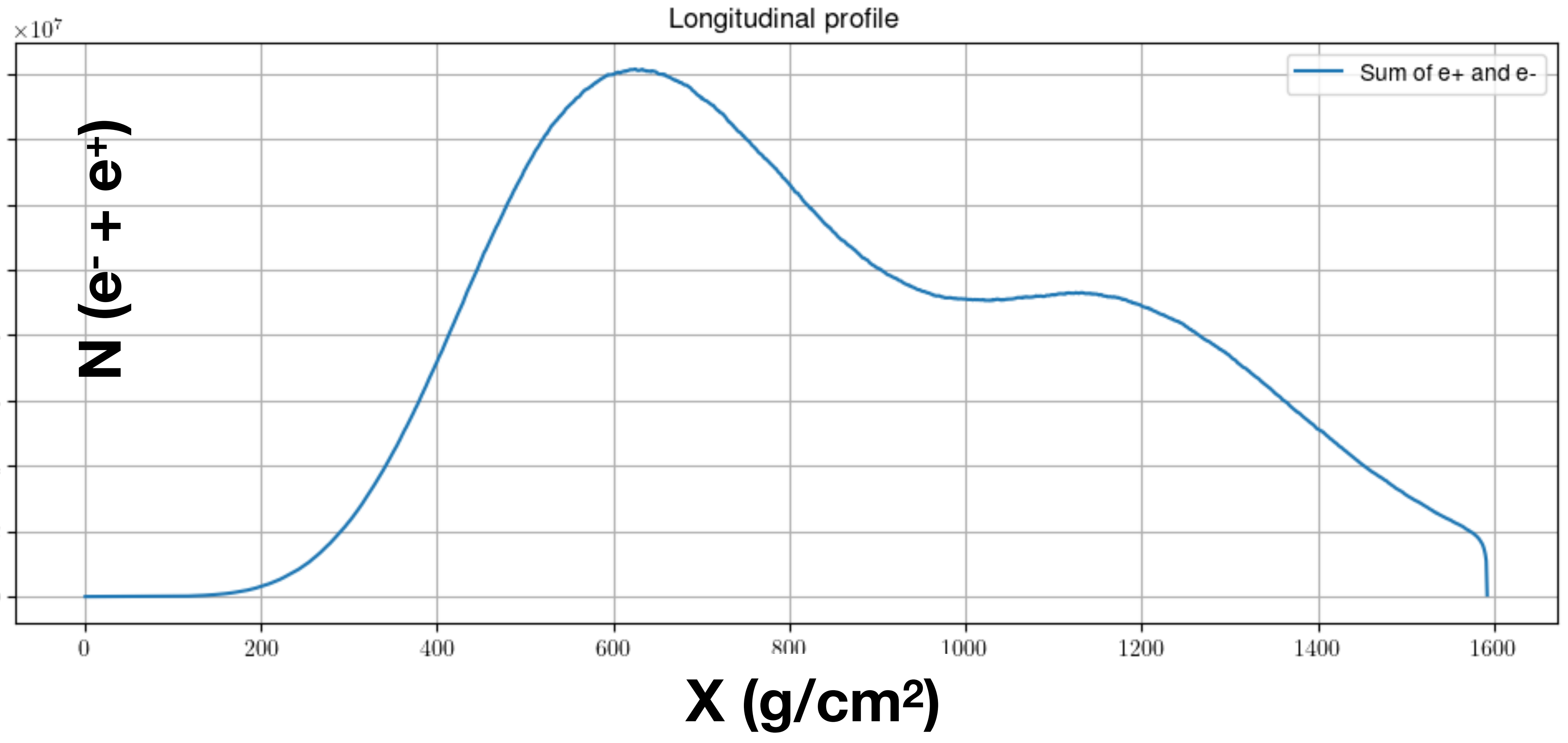


Antenna decimation factor 16
SNR increase 4

Radio from double-bumps

Helium double-bump 3.7 x 10^{16} eV



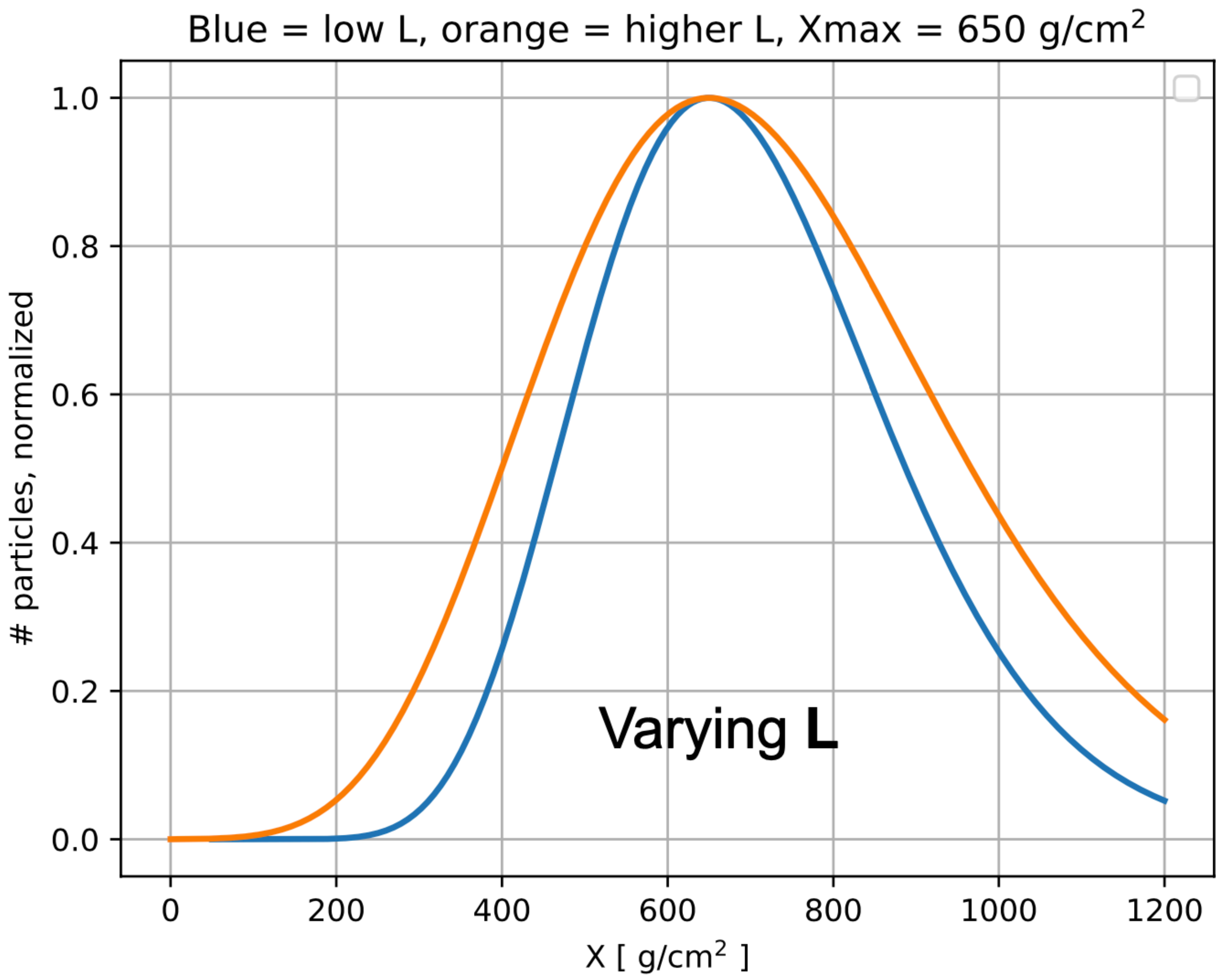


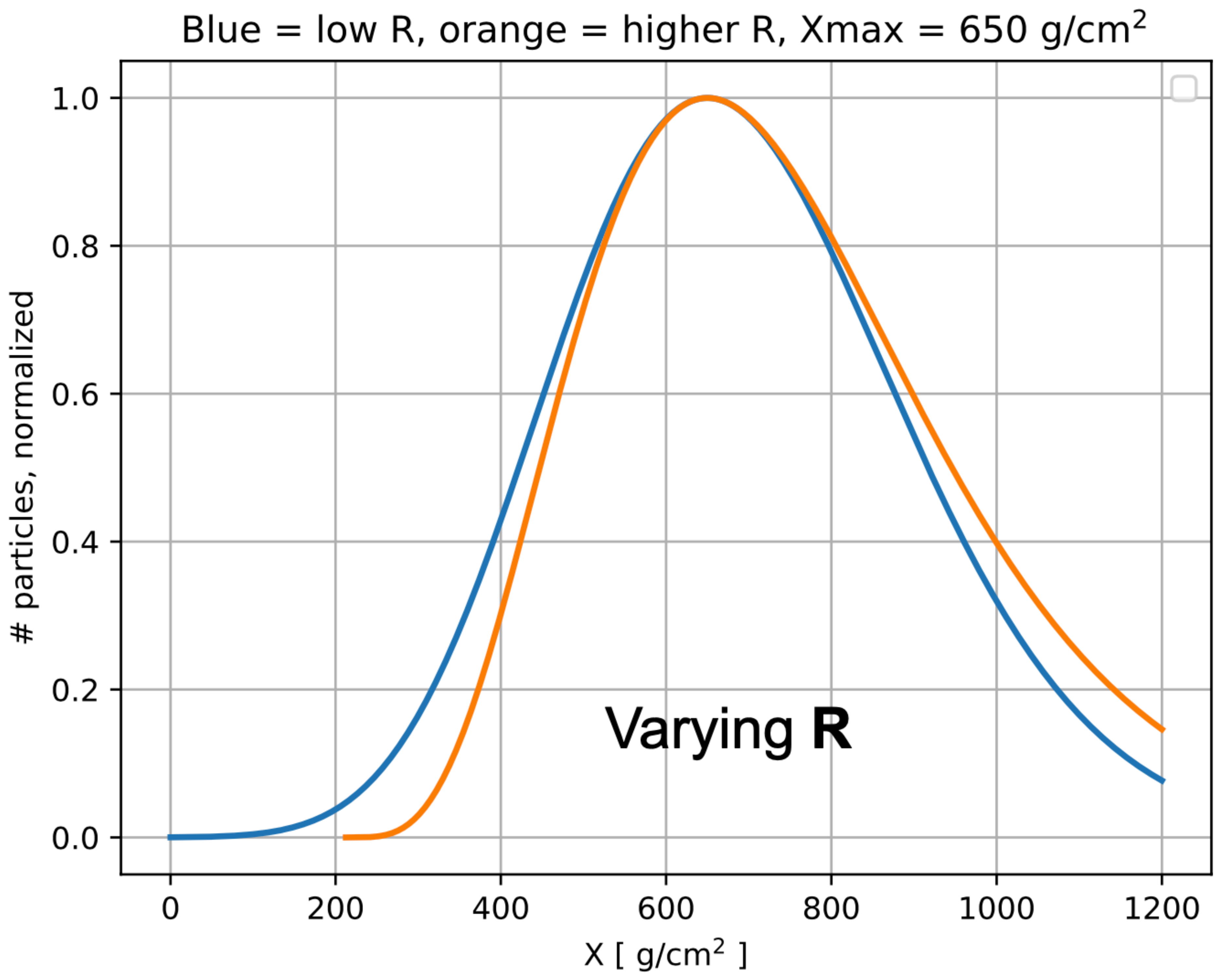
Full simulation including:
Antenna response
Galactic + instrumental noise

Antenna decimation factor 64
SNR increase 8

Small ΔX values → X_{max}, L, R

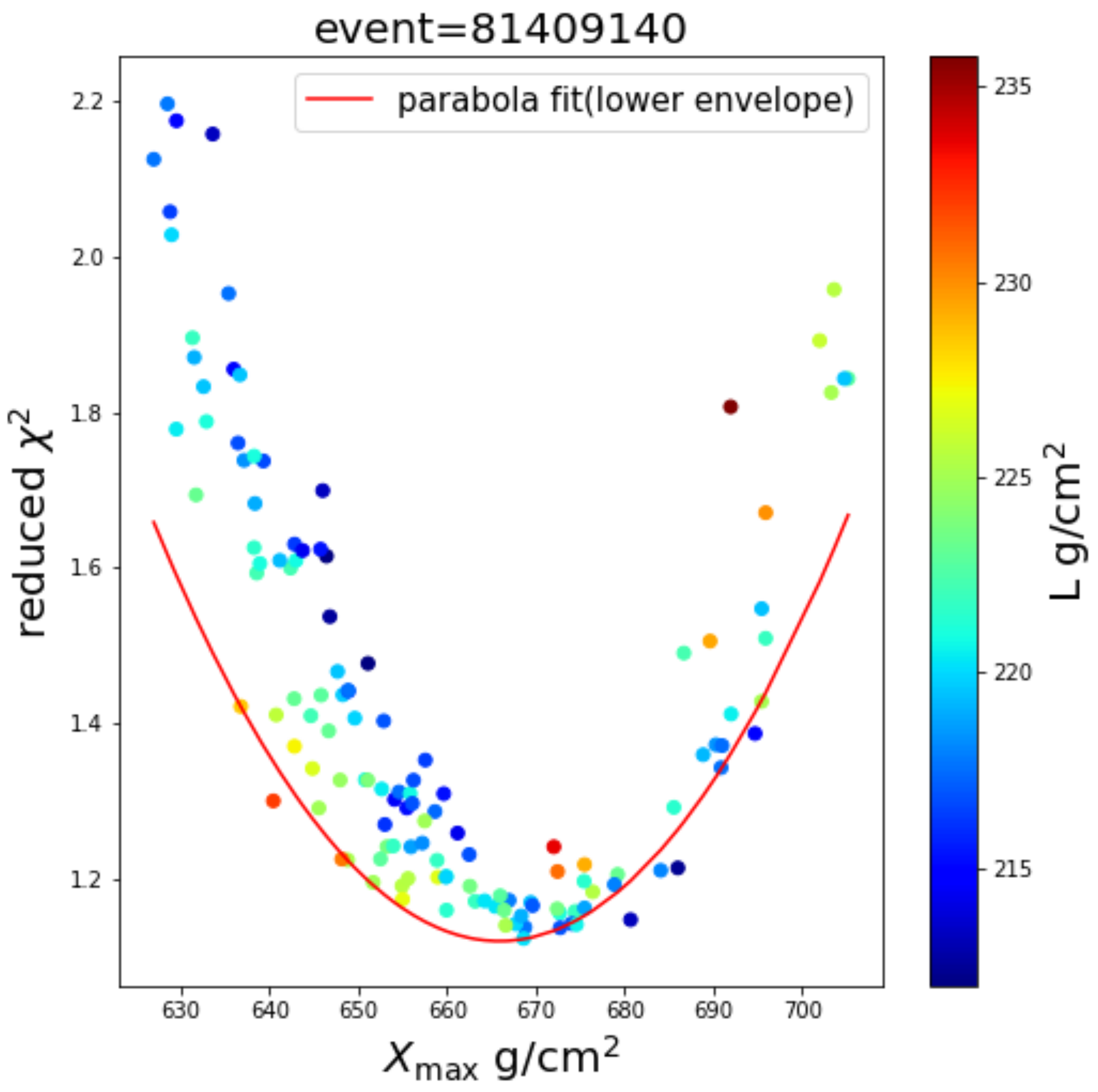
- If ΔX is too small two peaks are not resolved. However, shower can become **elongated** or **strangely shaped**
- Longitudinal evolution can be parametrized as: $N(X) = \exp\left(-\frac{X - X_{\max}}{RL}\right)\left(1 + \frac{R}{L}(X - X_{\max})\right)^{\frac{1}{R^2}}$





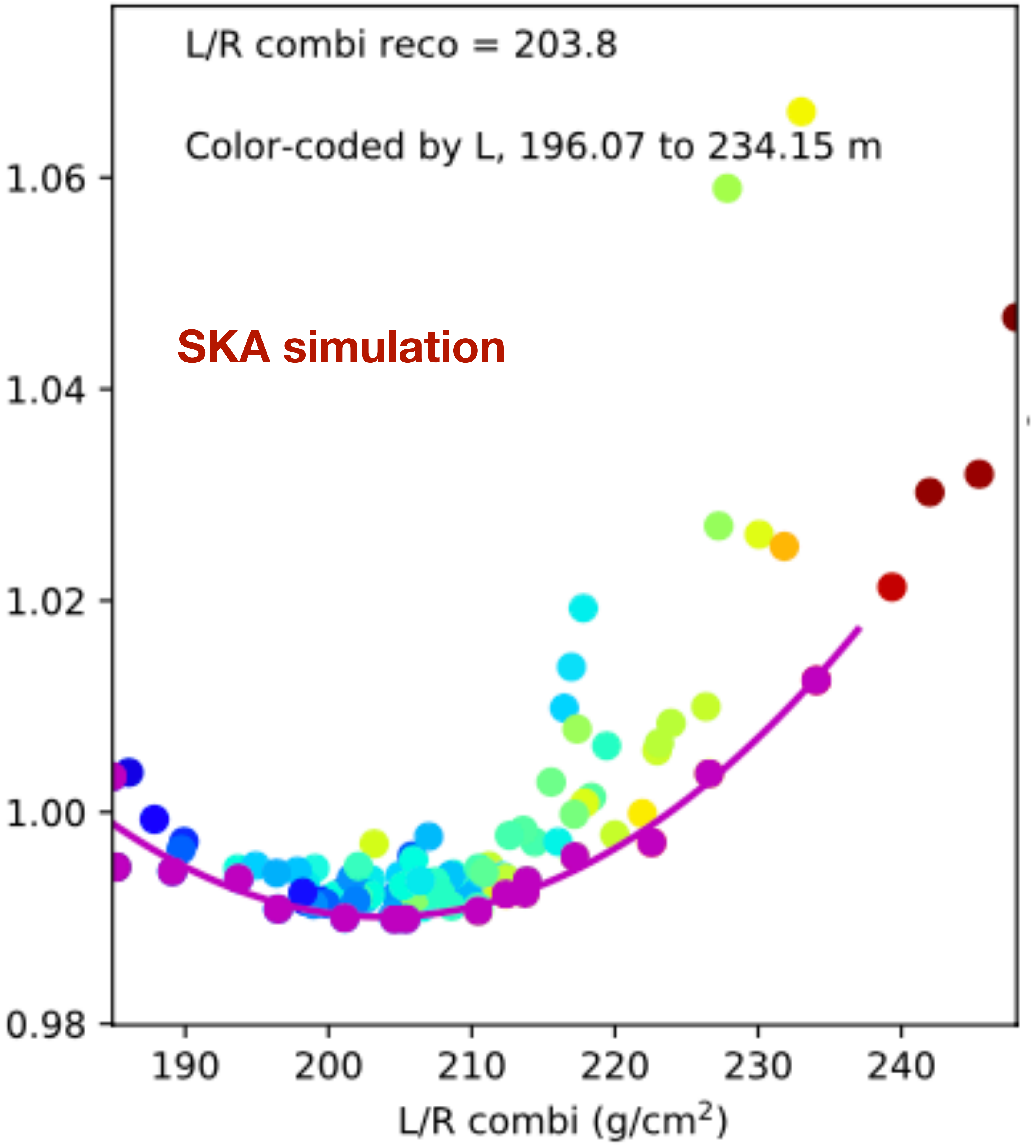
Can SKA reconstruct R or L?

L in LOFAR data ?



- LOFAR data:
  for given Xmax, fit quality depends on L
- Not clear yet if simultaneous L-X_{max} fit possible with LOFAR
- Important factors:
  core fit precision
  homogeneous coverage

SKA: Reconstructing shape parameters



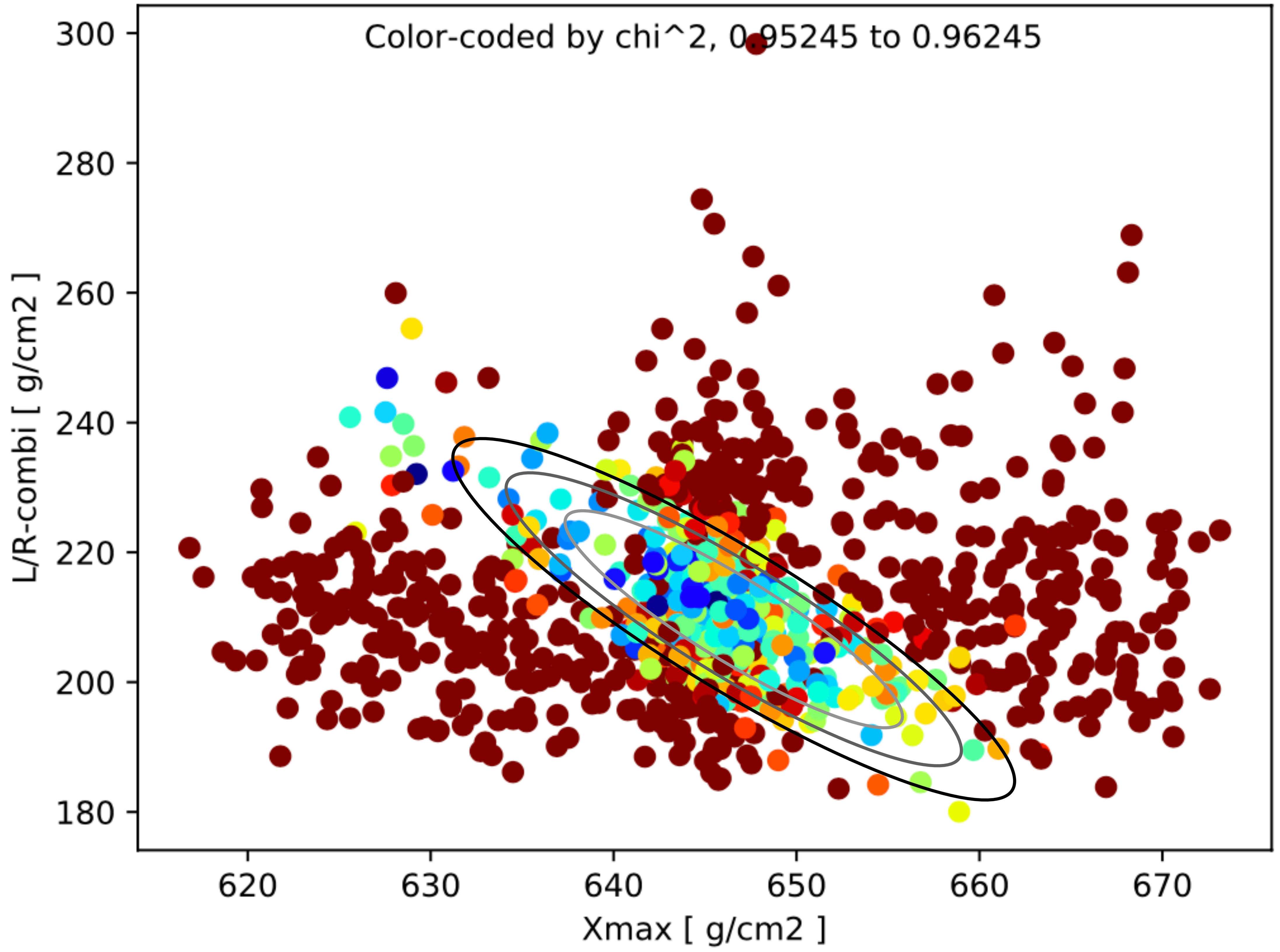
A. Corstanje et al., PoS(ARENA2022)024

- 100 showers of same X_{max}
- Interpolated footprint
- Free core fit
- Noise and antenna response included
- MC truth: $S(L,R) = 204.6$ g/cm^2
  reco: $S(L,R) = 203.8$ g/cm^2

SKA can reconstruct a linear combination of L and R:

$$S(L,R) = L + \frac{16\,\mathrm{g/cm^2}}{0.06}(R - 0.3),$$

A simulation challenge



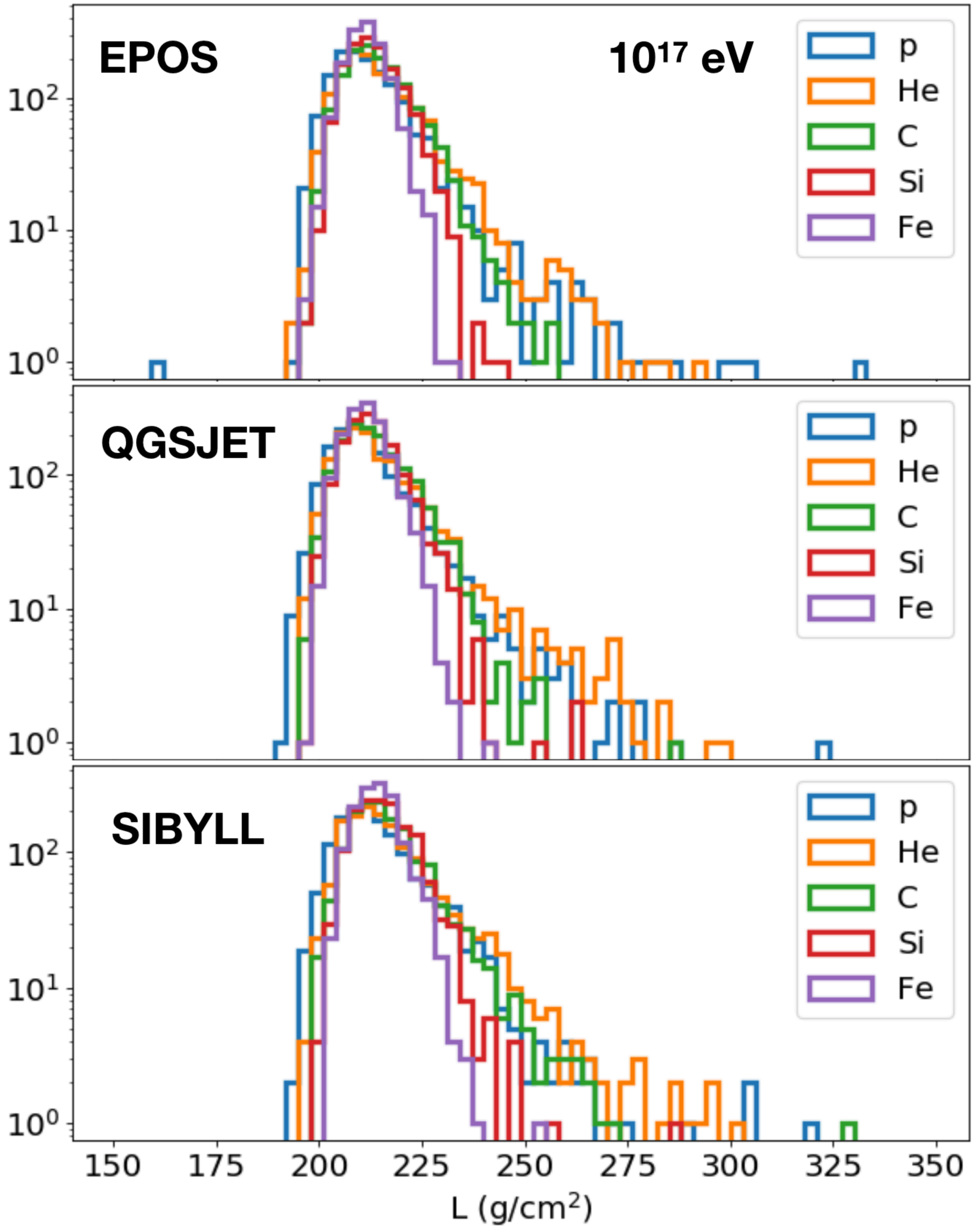
A. Corstanje et al., PoS(ARENA2022)024

- In a real analysis Xmax and L/R have to be fitted simultaneously
- This currently requires too many computational resources to analyse all showers
- New approaches are in development to produce fast & accurate simulations
- **Template synthesis** now achieves 2% accuracy for fast simulation of vertical showers

Mitja Desmet, SB, T. Huege, D. Butler, R. Engel, Astropart.Phys. 157 (2024) 102923

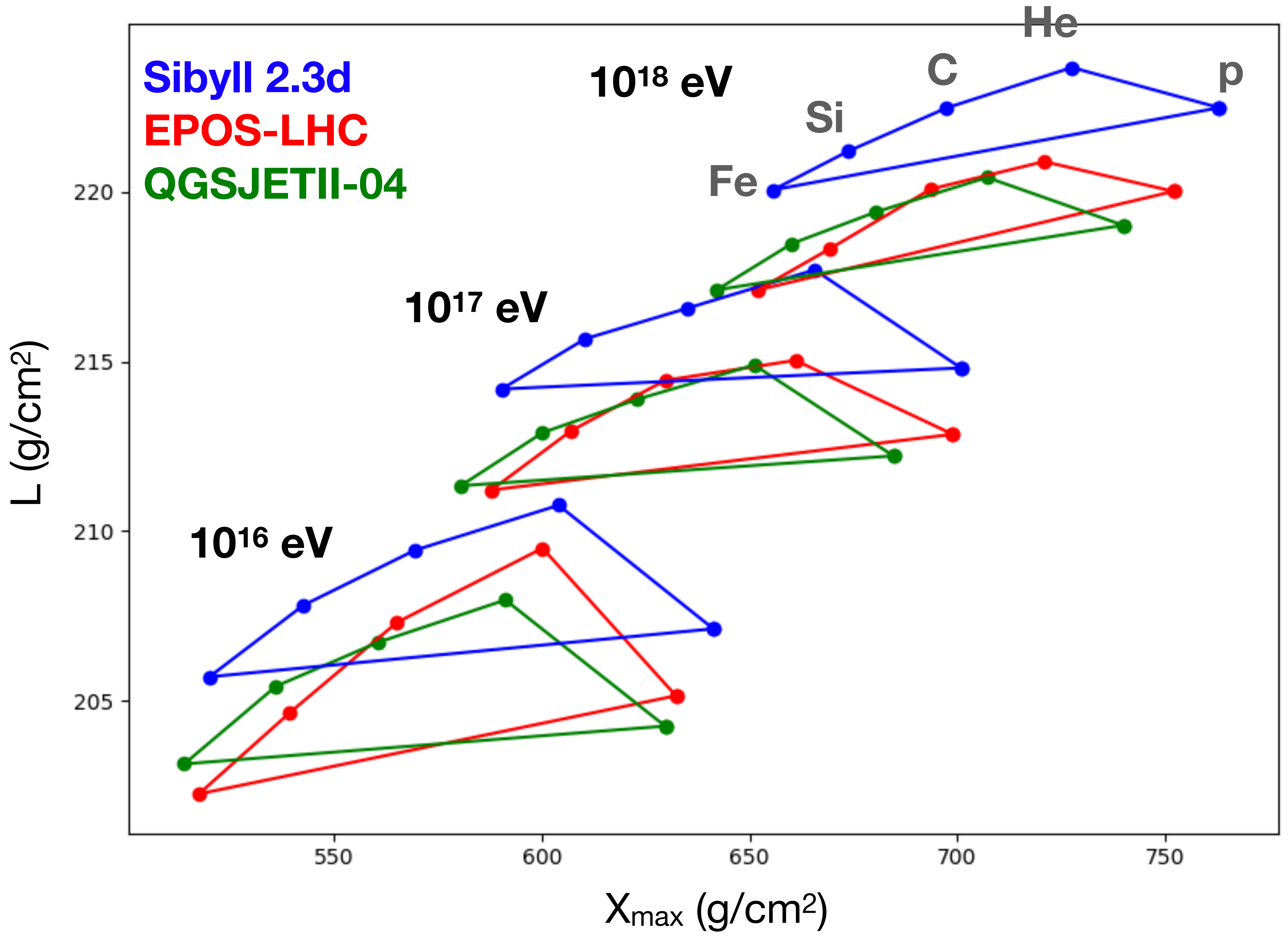
Science with shape parameters

CONEX simulations: *L* distribution



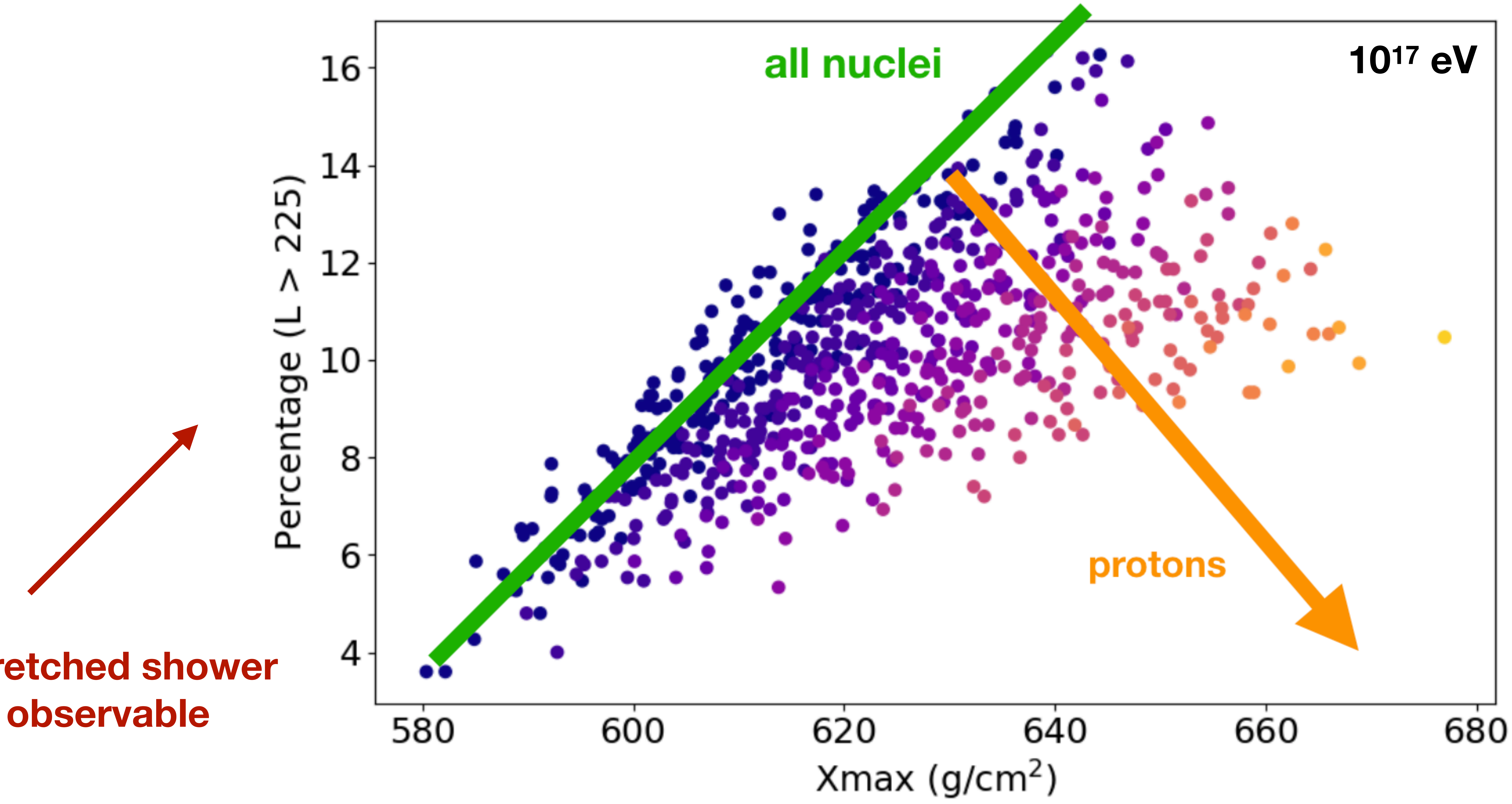
High-L tail largest for Helium

Average *L* and X_{max} for pure compositions
Mixed compositions lie within a triangle



***L* distribution provides new information about mass composition & hadronic interactions**

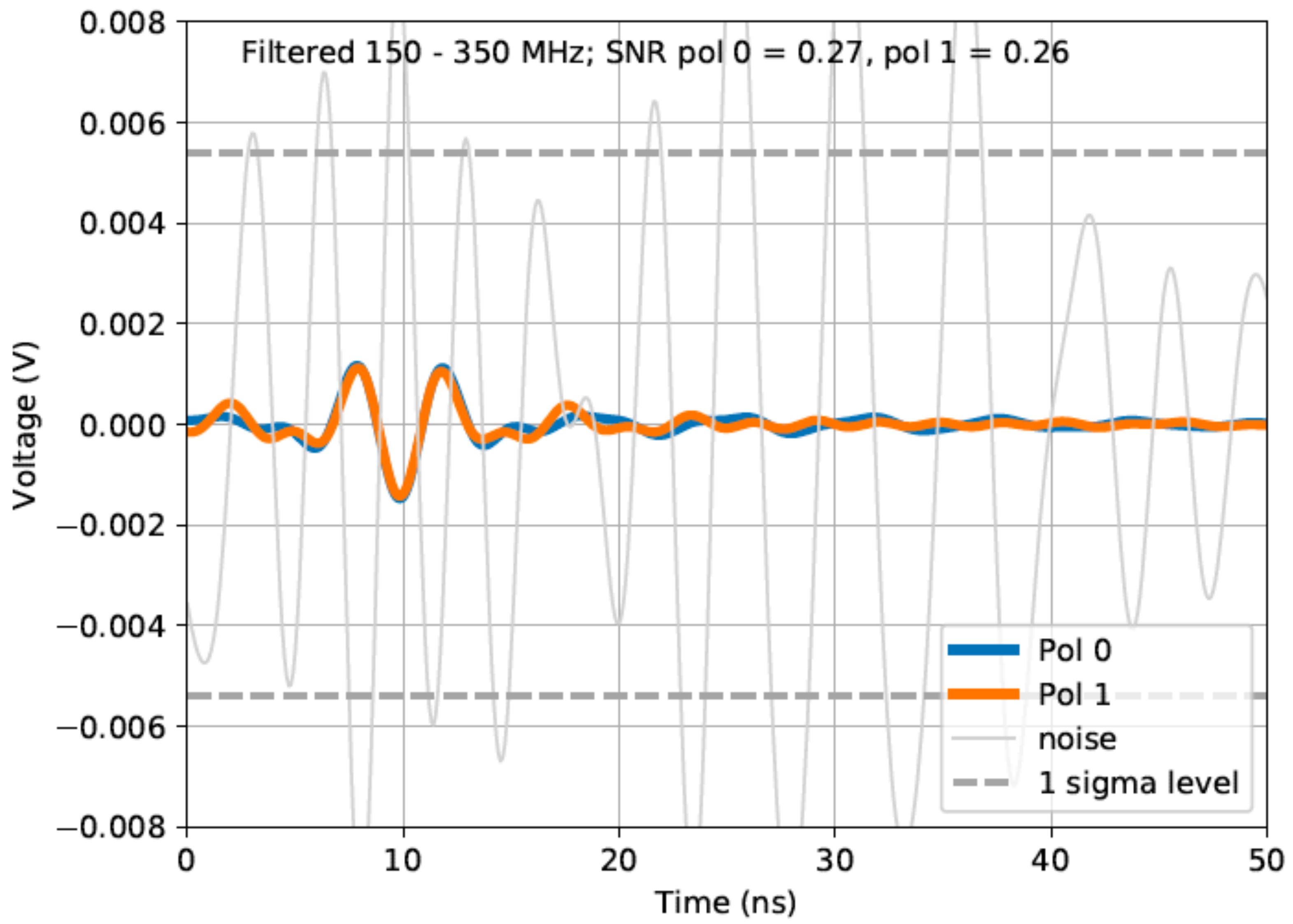
Proton separation



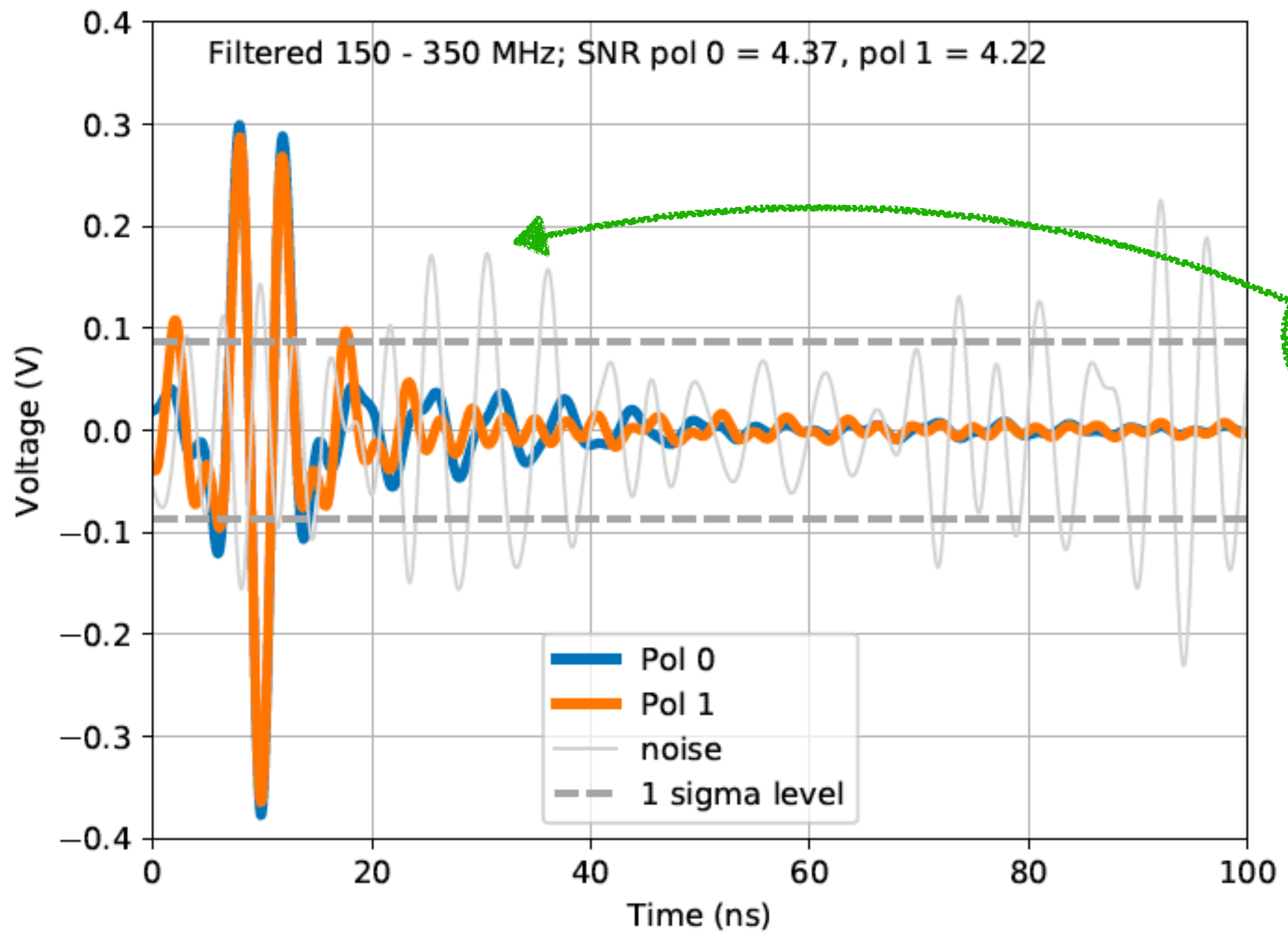
Fraction of stretched shower as robust observable

Each dot = sample of 1000 showers with unique combination of (p, He, C, Si, Fe)
color = proton fraction

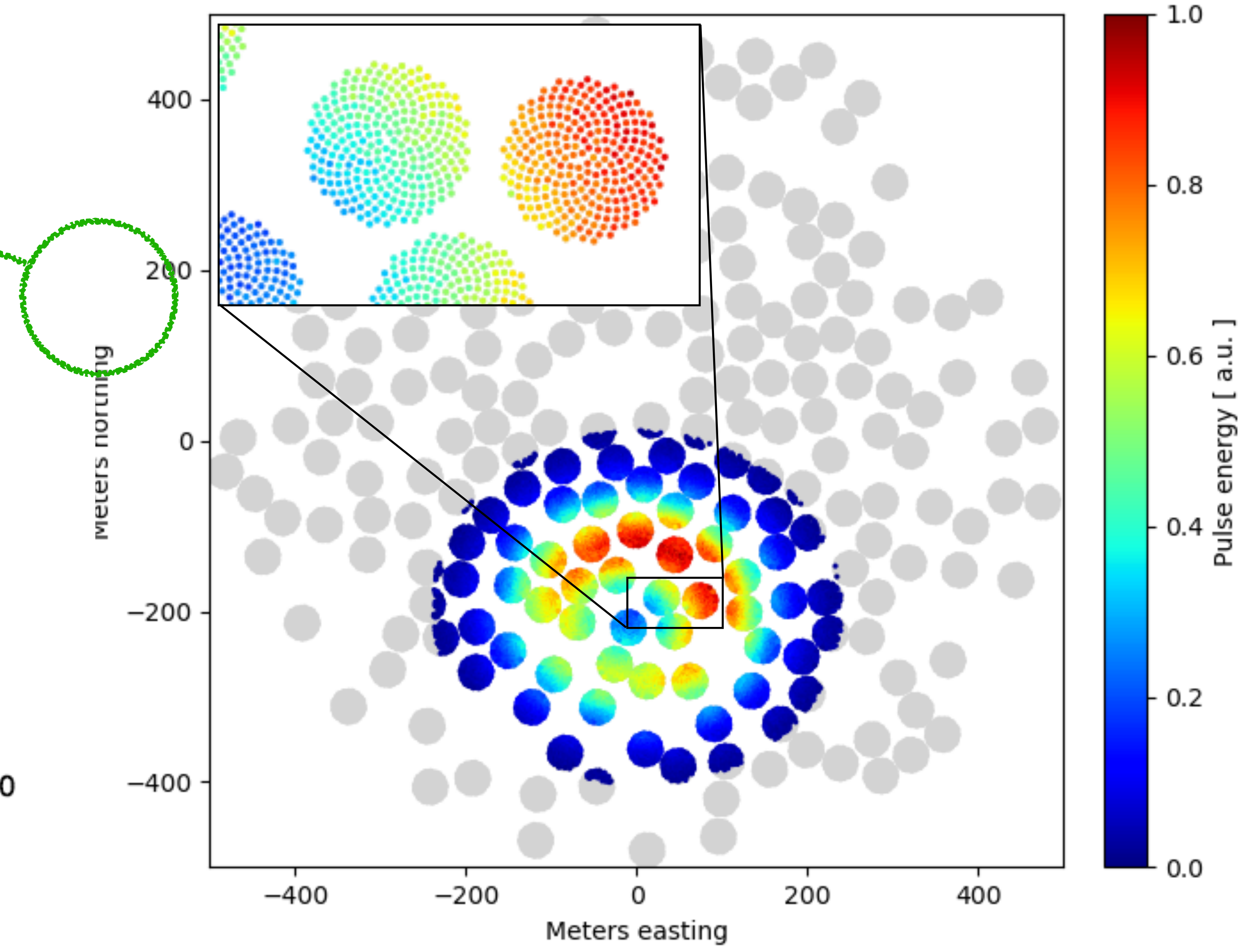
Towards lower energies



Radio pulse of PeV shower
filtered 150-350 MHz
SNR = 0.27



Beamformed with single field
filtered 150-350 MHz
SNR = 4.37

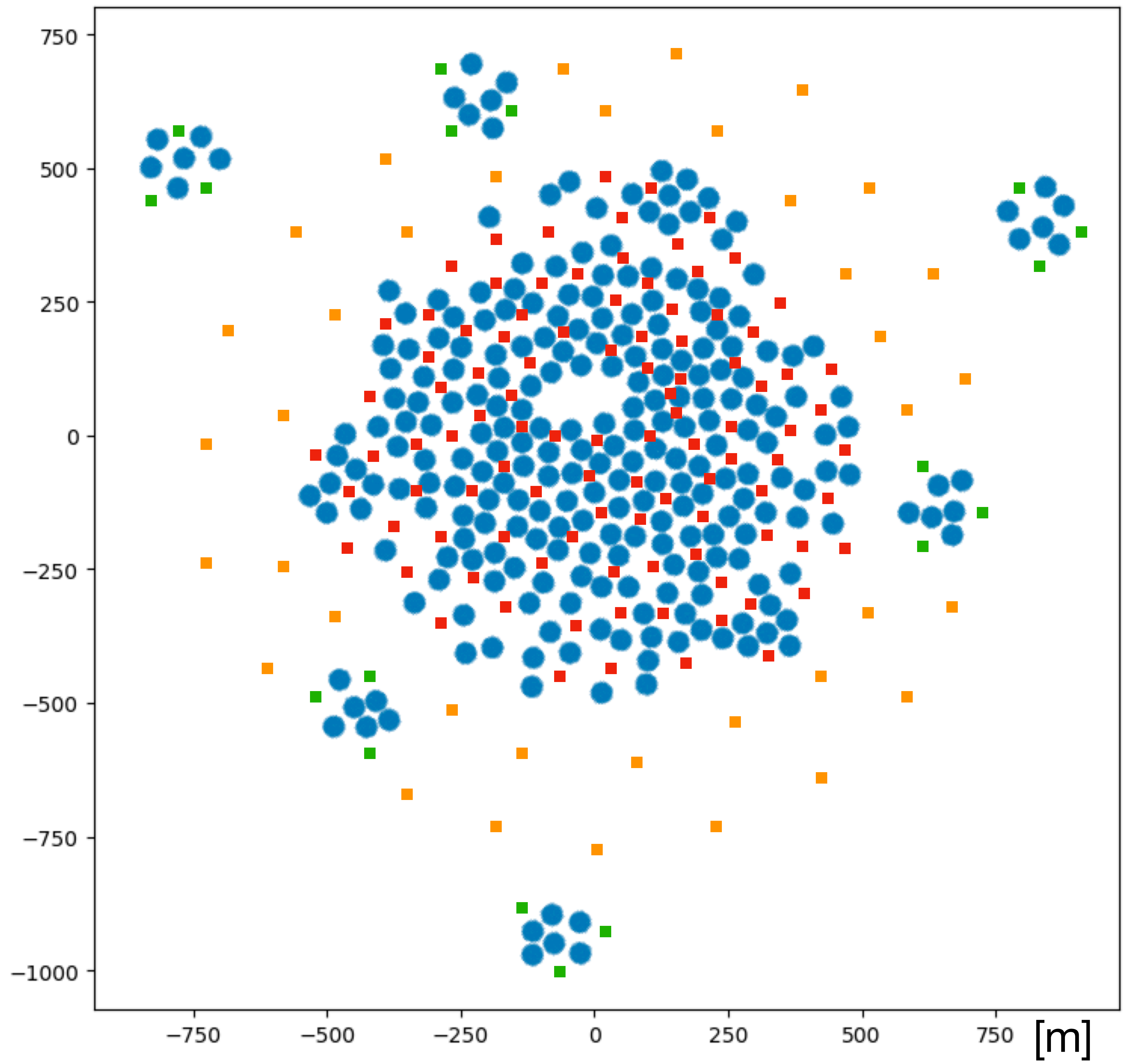


256 dual-polarised antennas per field

Are PeV gamma rays are detectable? Use combination of:

- beamforming (& matched filtering) to improve SNR
- hybrid particle/radio trigger to remove RFI pulses & sub-PeV showers
- small search window around candidate source(s) to reduce CR background
- offline photon/hadron separation from reconstruction?

The SKA Particle detector array



★ FWO (Belgium) contributes 740 kEuro funding for particle detector array

Potential 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

Conclusions

- SKA will produce **highest-resolution radio air shower observations**
- Unprecedented precision on **X_{max} at 10^{16} - 10^{18} eV**
- New reconstruction possibilities:
  double-bump showers & stretched shower (R/L)
  hadronic physics & mass composition
- Beamforming lowers energy threshold:
  CR mass composition down to lower energies
  PeV gamma-rays detectable…
  but triggering & hadron separation very challenging.

Conclusions

- SKA will produce **highest-resolution radio air shower observations**
- Unprecedented precision on **X_{max} at 10^{16} - 10^{18} eV**
- New reconstruction possibilities:
  double-bump showers & stretched shower (R/L)
  hadronic physics & mass composition
- Beamforming lowers energy threshold:
  CR mass composition down to lower energies
  PeV gamma-rays detectable…
  but triggering & hadron separation very challenging.

Particle detector array of ~100 units now funded!

fwo
DFG Deutsche Forschungsgemeinschaft
NOVA