Detecting Cosmic Rays with LOFAR

Stijn Buitink for the Cosmic Ray Key Science Project
LOFAR Family Meeting 2024 Leiden

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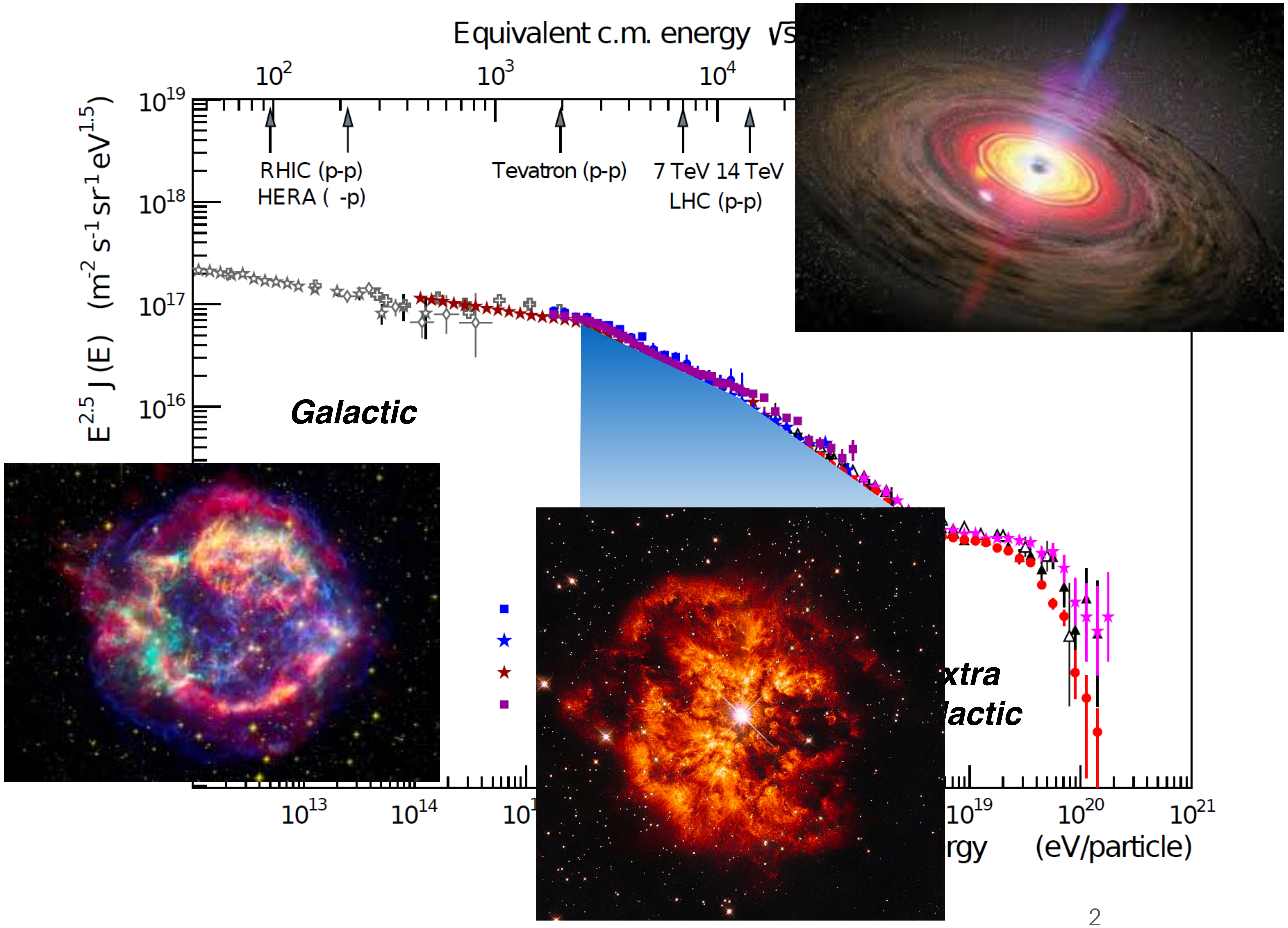
K. Terveer, S. Thoudam, G. Trinh, and S. ter Veen

Origin of cosmic rays



- Likely diffusive shock acceleration in Galactic sources below $\sim 10^{15}$ eV
- Extragalactic above $\sim 10^{18}$ eV
  Active Galactic Nuclei? Starburst galaxies?
- Transition region?
  Supernova Remnants of Wolf-Rayet stars ?
- Radio detection of cosmic-rays with LOFAR & SKA: best resolution in transition region.

Part I
LOFAR 1.0 results

LORA
LOFAR Radboud Array
scintillator detectors

Superterp:
- diameter ~ 300 m
- 20 LORA detectors
- 6 LBA stations
  (= 6 x 48 antennas)

Around superterp:
- more LBA stations
- +20 LORA detectors

trigger

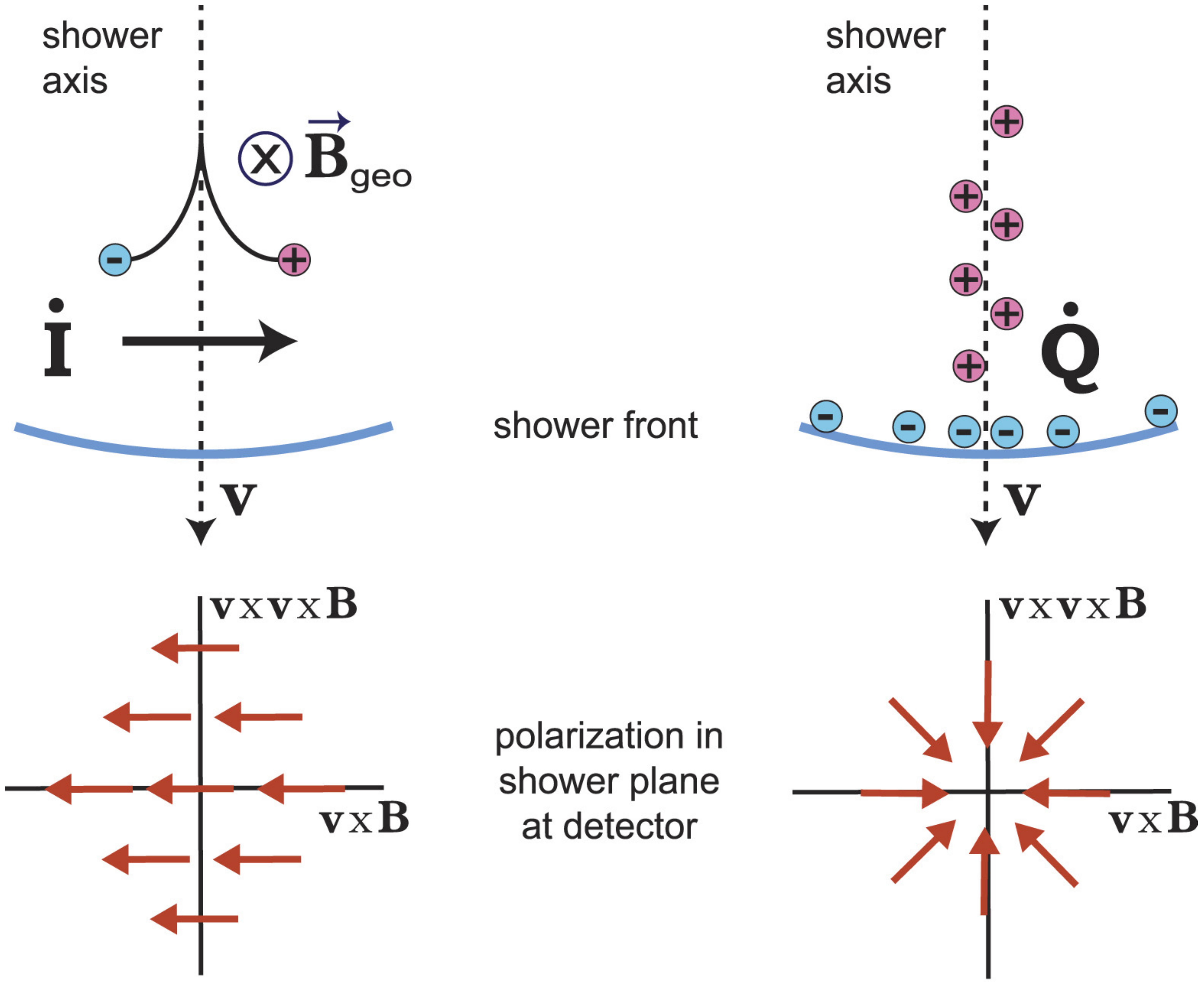
buffer: 2ms readout

Low Band Antennas (LBA)
30 - 80 MHz

The radiation mechanism

- When LOFAR observed first air showers, **radiation mechanism** was not yet understood.
- LOFAR was unique amongst cosmic-ray radio observatories with its **high antenna density**: perfect to test theory.
- Now understood as combination of **geomagnetic & charge excess radiation**.
- All radio pulse properties well explained by models: **power, polarization, spectrum, and timing**

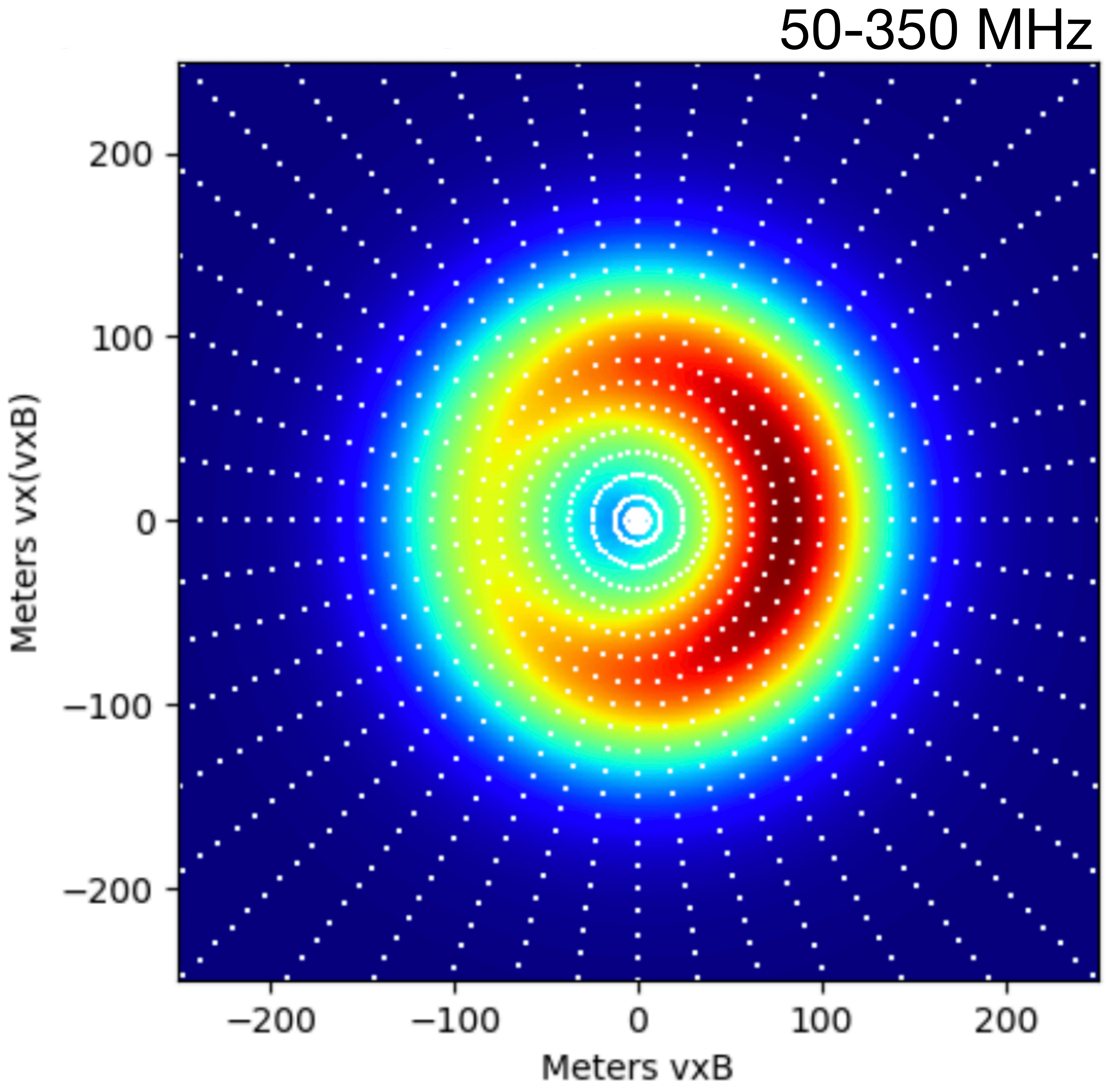
The radiation mechanism



Geomagnetic emission

Askaryan emission

Picture: F. Schröder



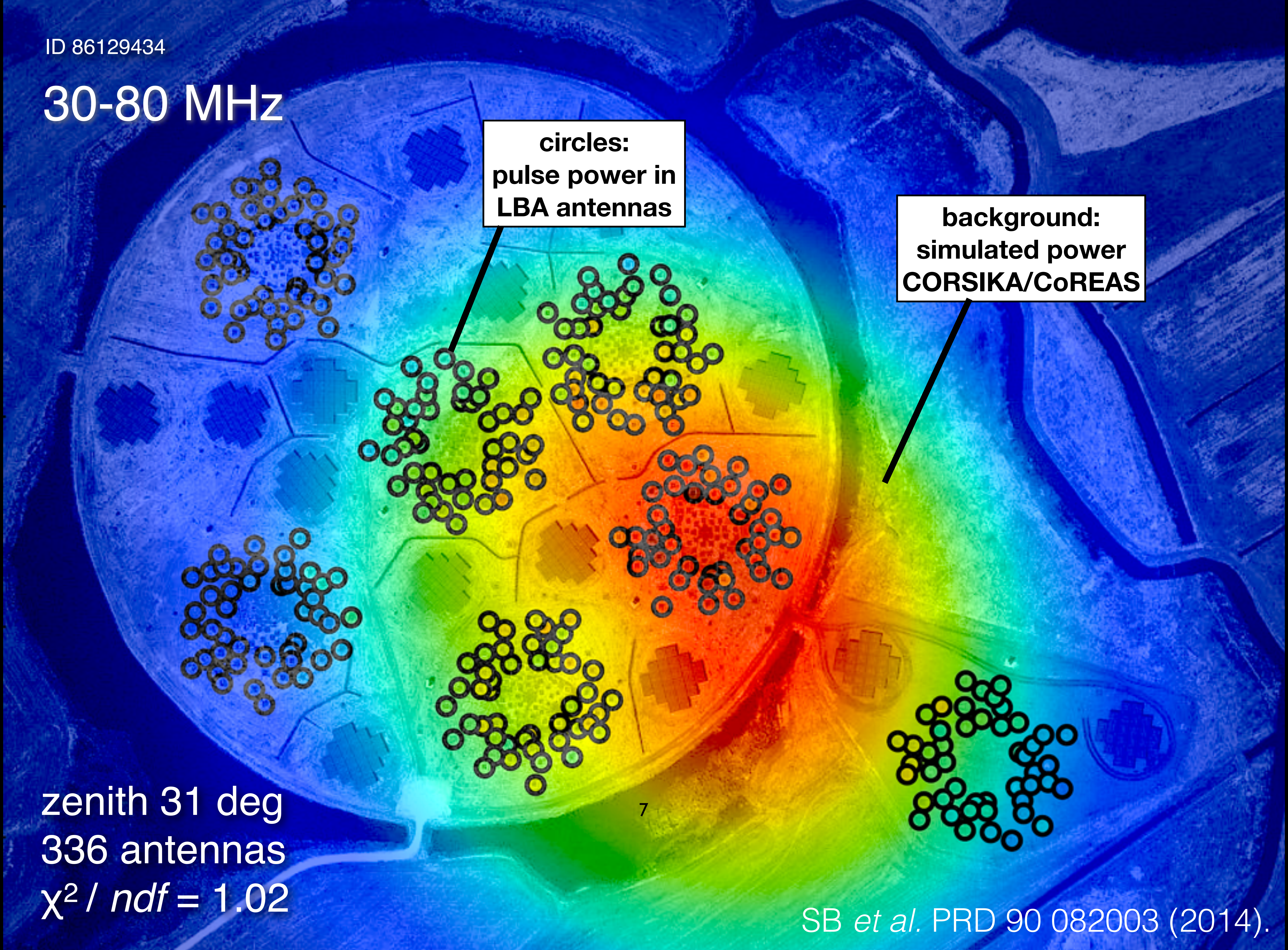
Coherency: radiation around Cherenkov angle

high freq = sharp ring

Low freq = large blob

ID 86129434

30-80 MHz



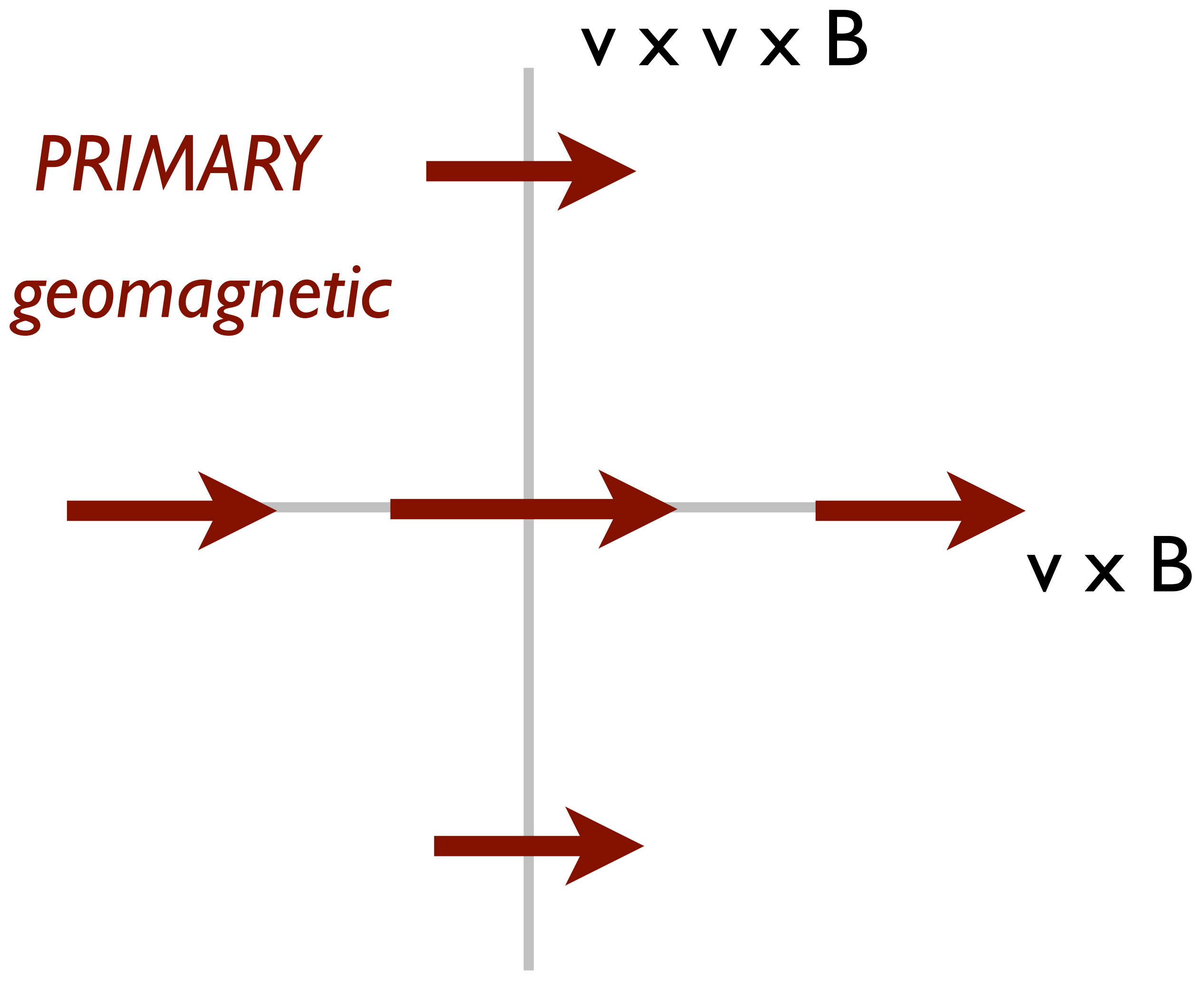
circles:
pulse power in
LBA antennas

background:
simulated power
CORSIKA/CoREAS

zenith 31 deg
336 antennas
$\chi^2 / ndf = 1.02$

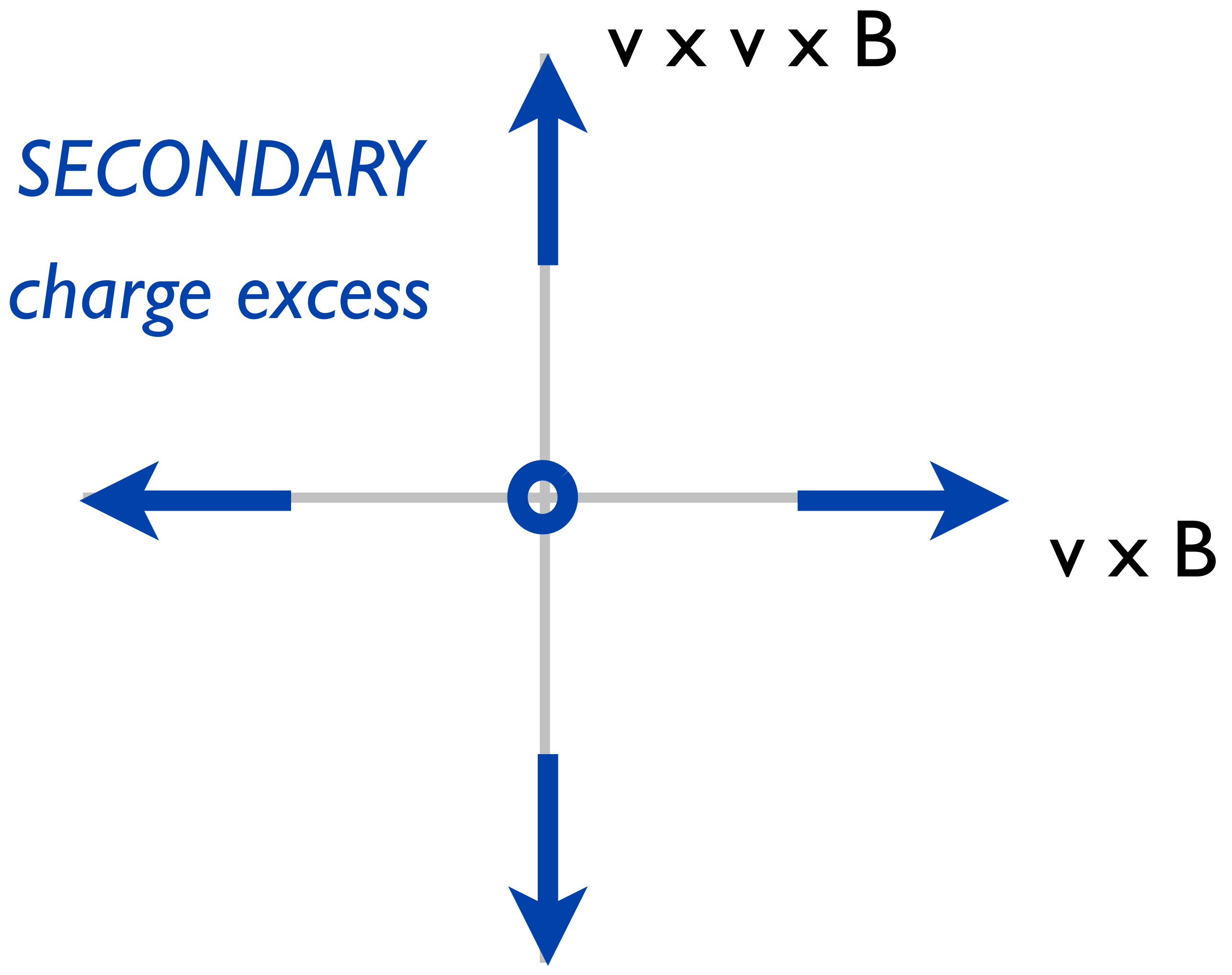
SB *et al.* PRD 90 082003 (2014).

Understanding the radio emission



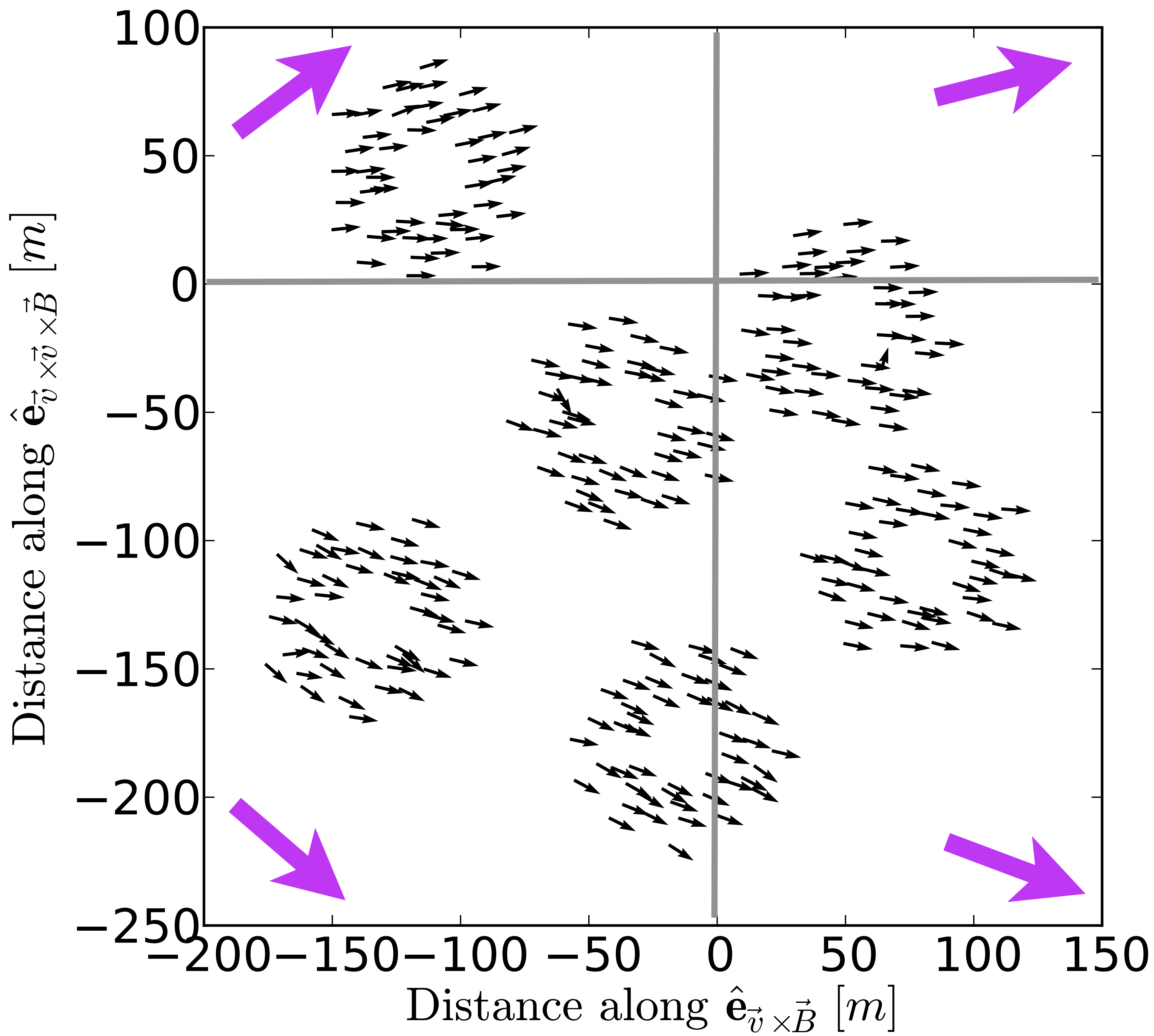
PRIMARY

geomagnetic



SECONDARY

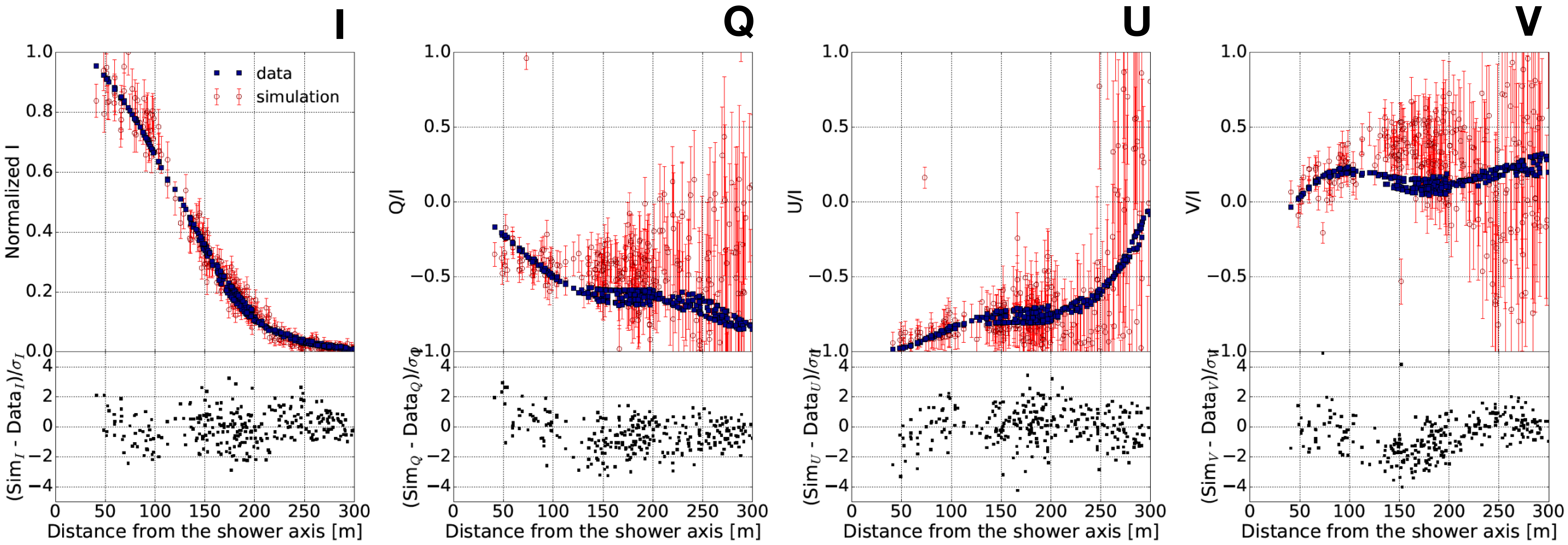
charge excess



Interference: emission pattern = asymmetric

Pim Schellart et al., *JCAP* **10** 14 (2014)

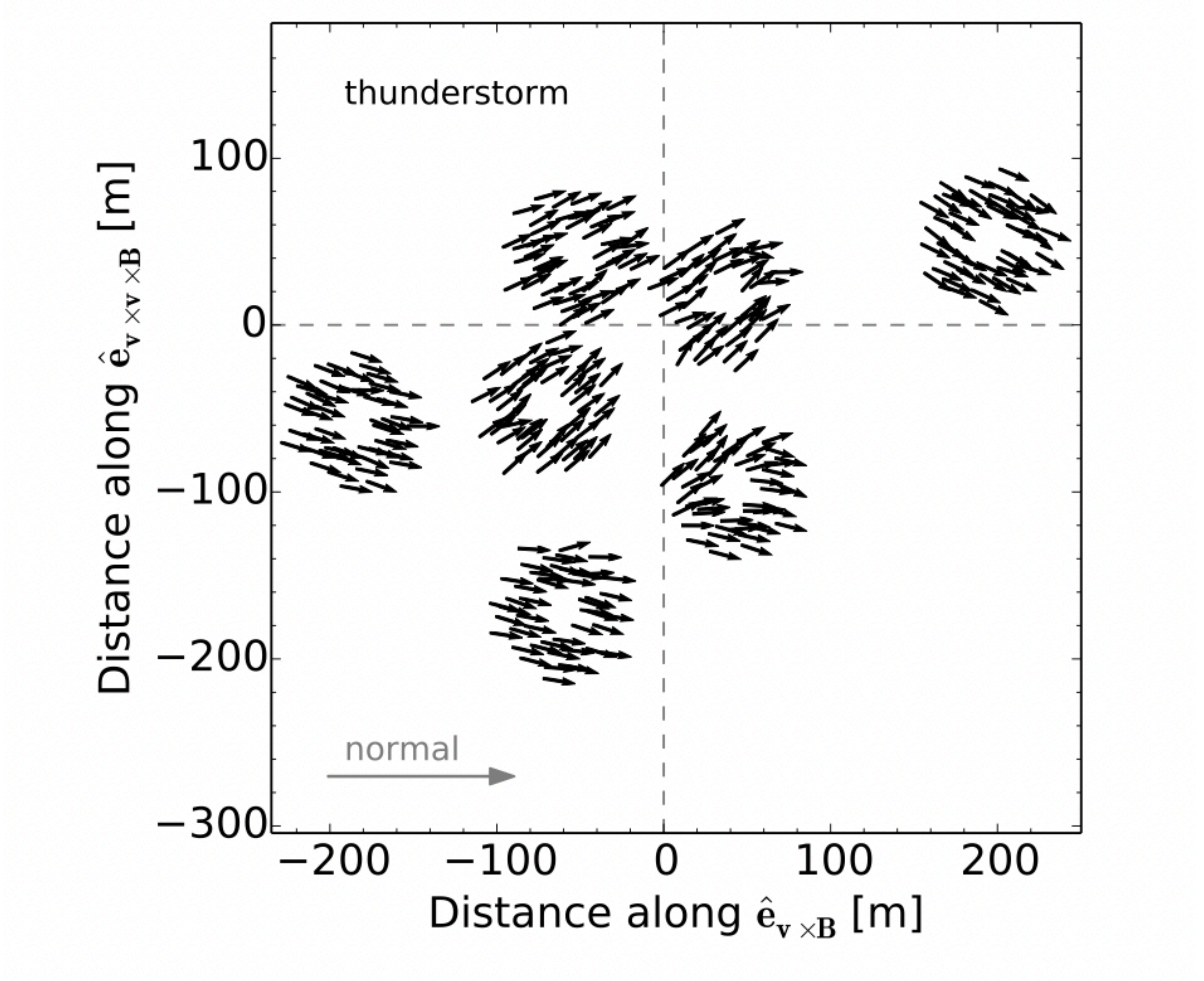
Full Stokes polarisation

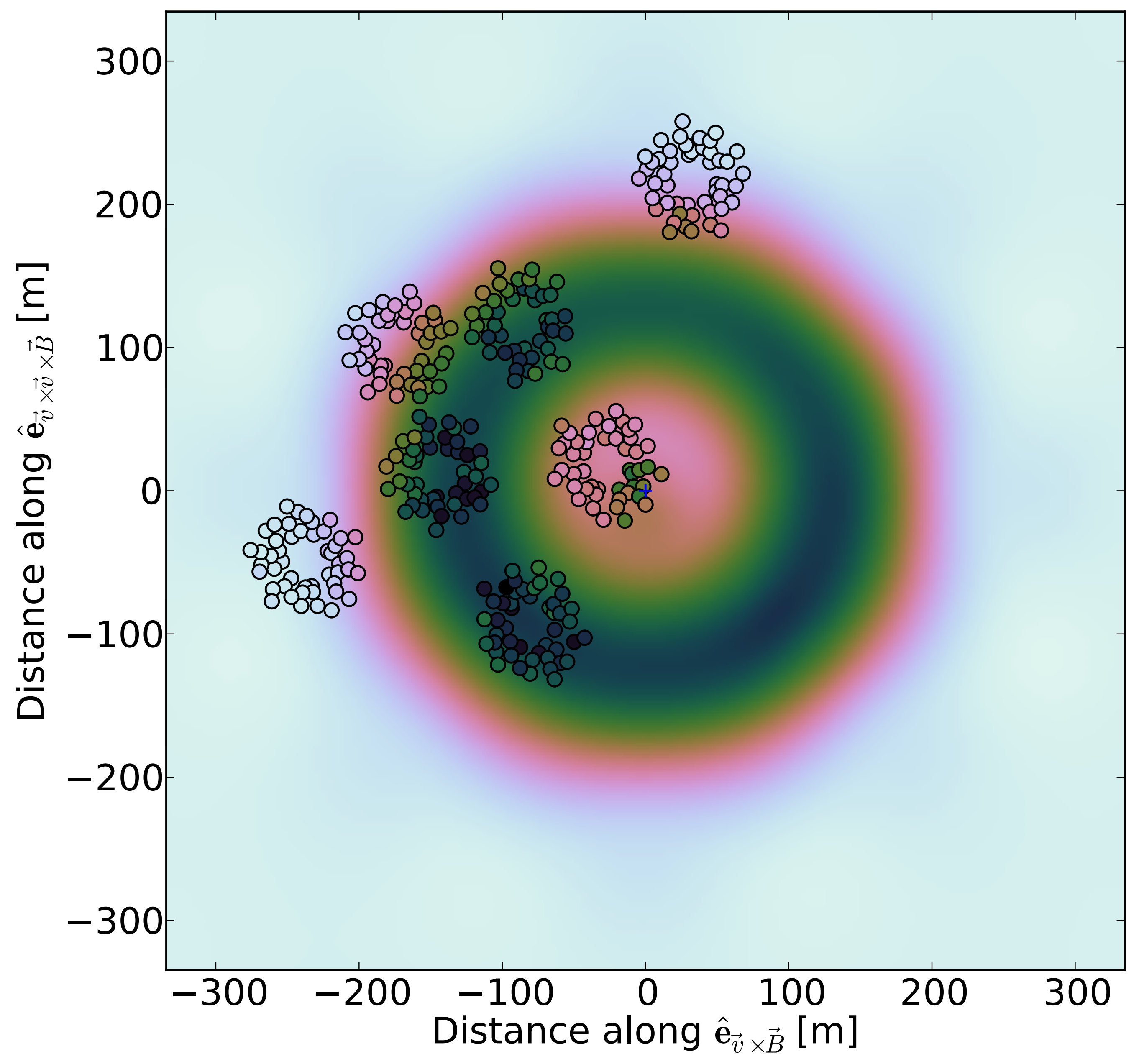


- Fair weather: small amount of circular polarisation confirmed by data
  O. Scholten et al., PRD **94** 1030101 (2016)

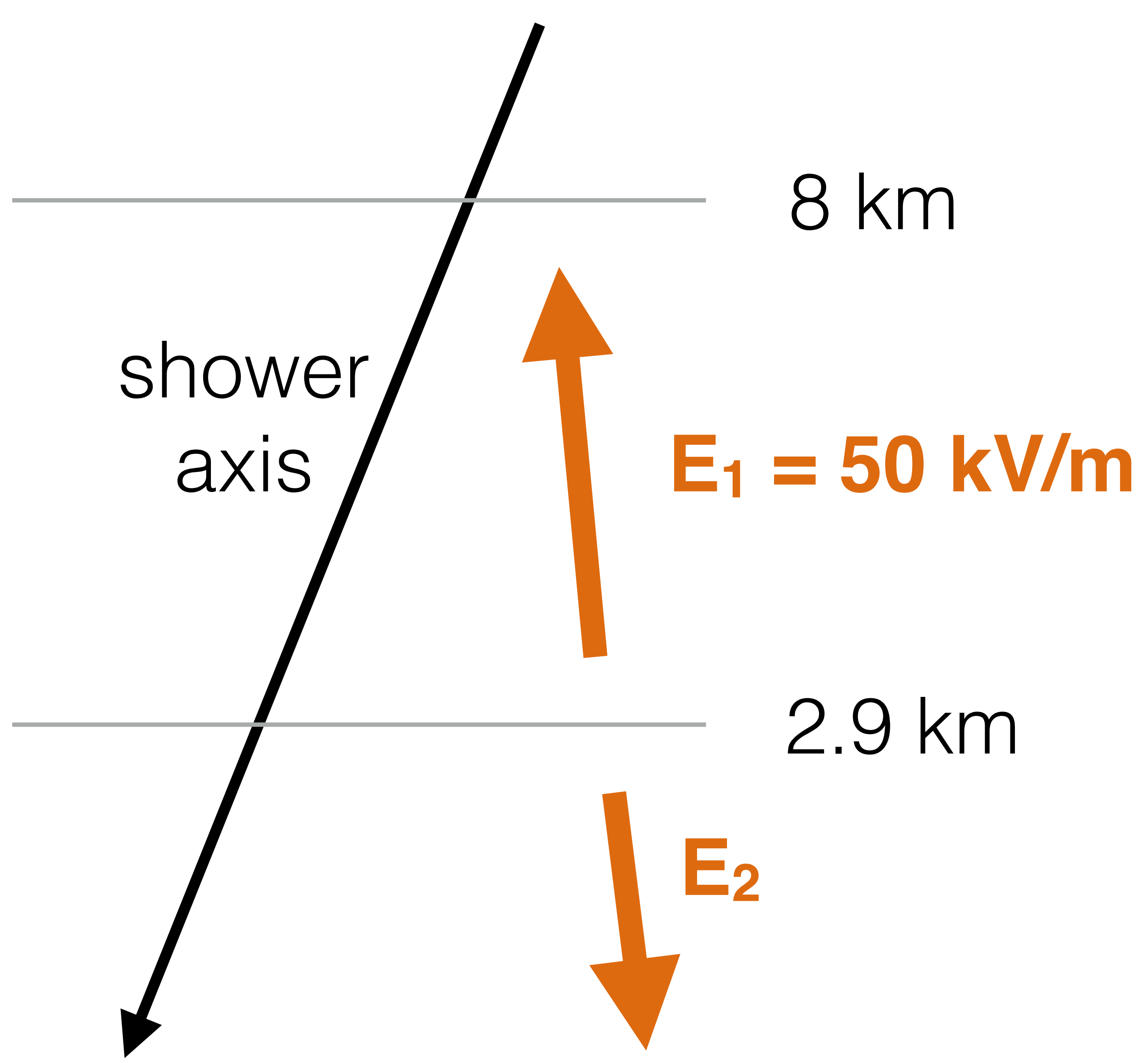
- Thunderstorms: strong signal in all Stokes parameters used to reconstruct atmospheric electric fields
  G. Trinh et al., PRD **95** 083004 (2017)

Thunderstorm reconstruction





Two layer model


8 km

shower axis

E_1 = 50 kV/m

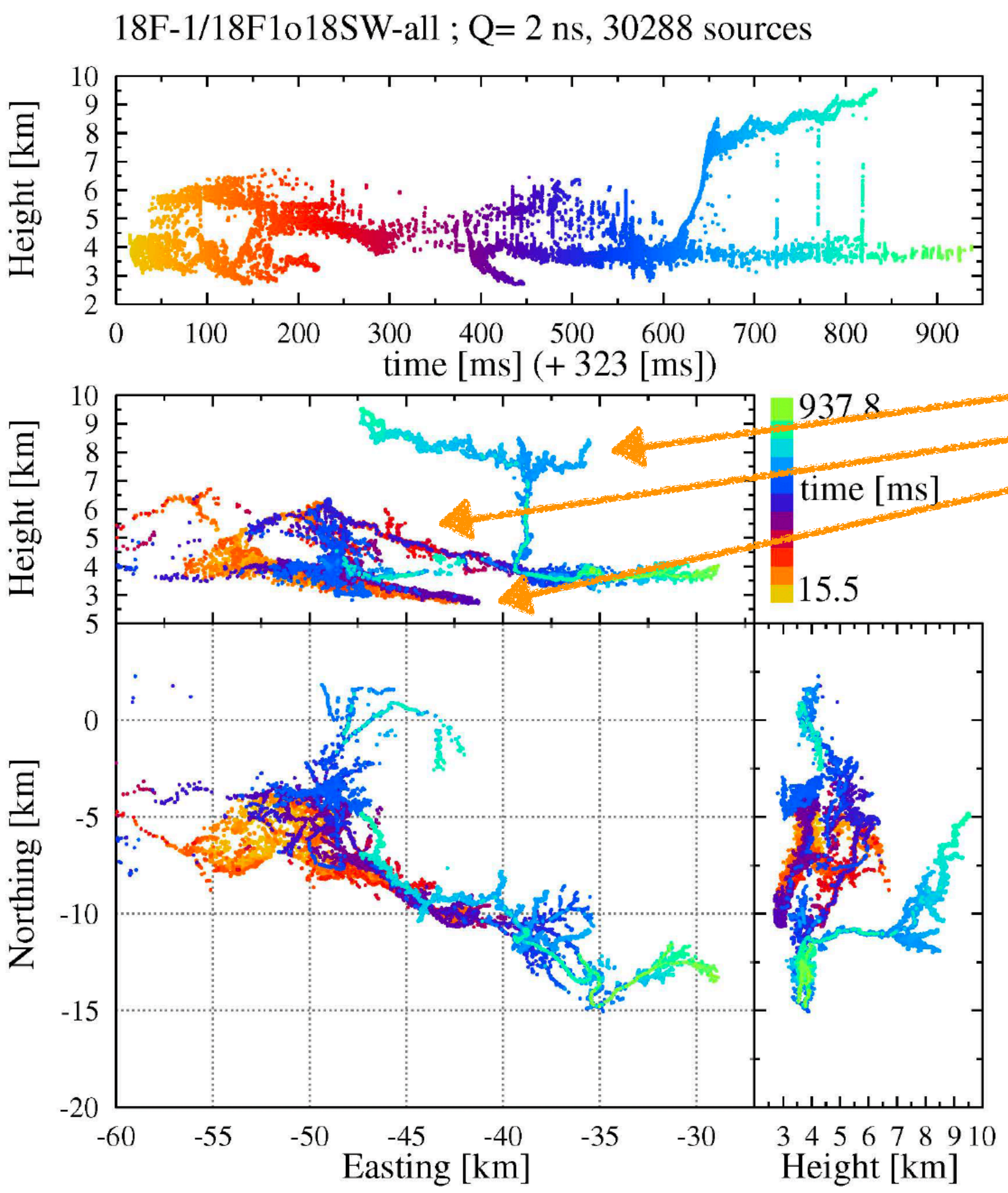
2.9 km

E_2

- Thunderstorm event have very particular polarization maps
- Fit two-layer model to full Stokes parameters

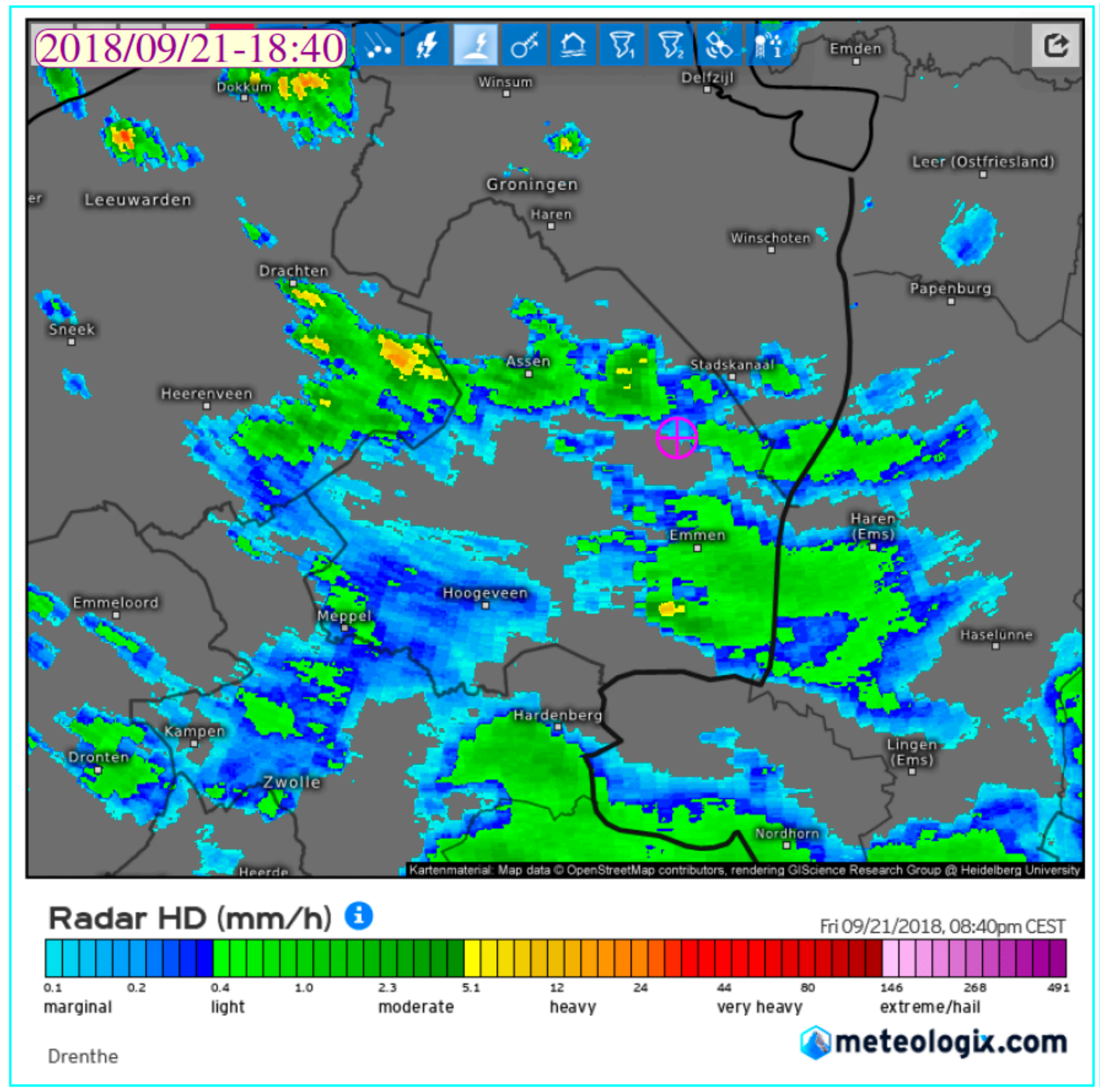
Pim Schellart et al., *PRL* **114** 165001 (2015)

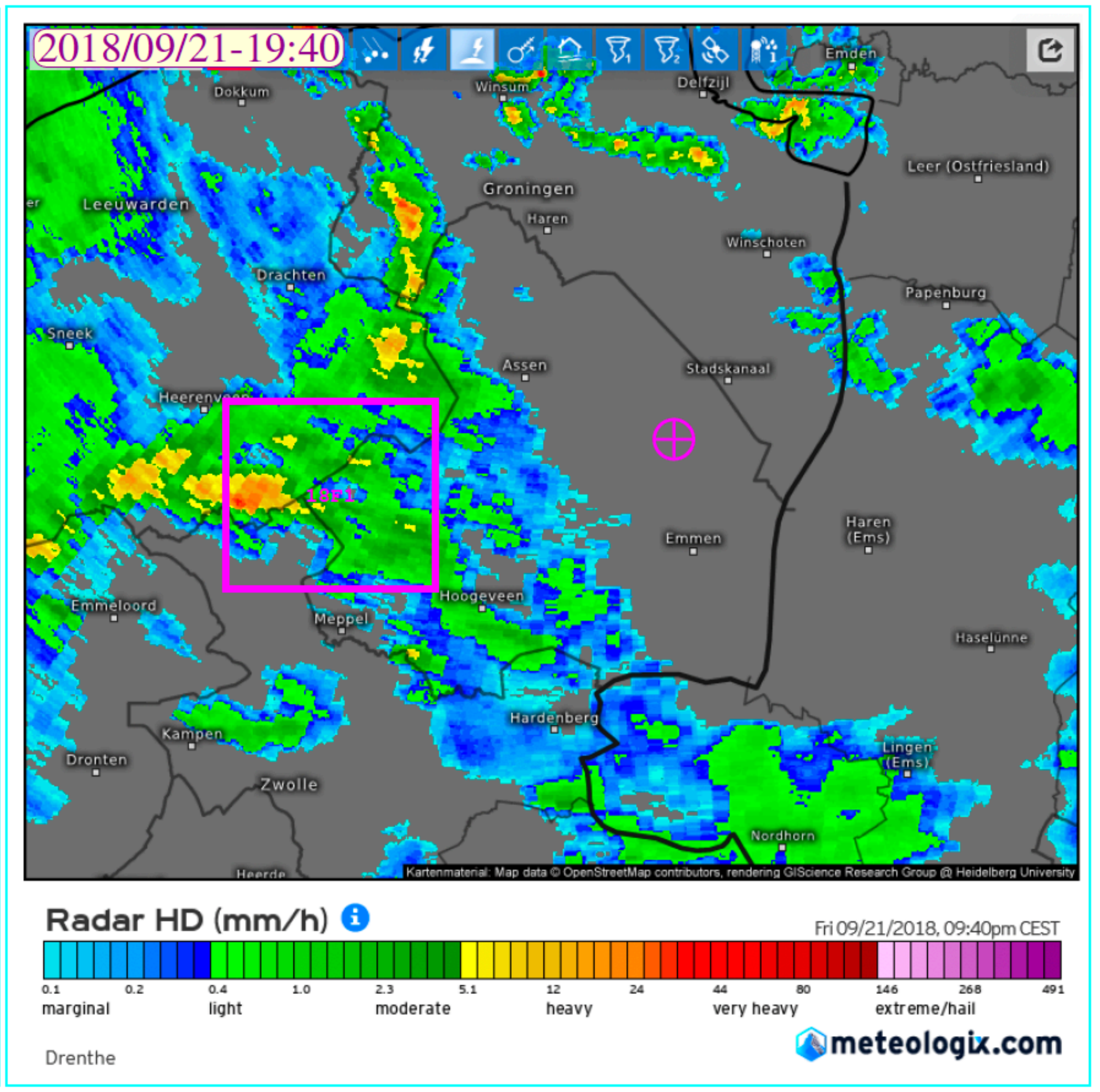
Combining with lightning imaging



- Reconstruction of air shower in thunderstorm with 3-layer model
- Compare to lightning imaged one hour later

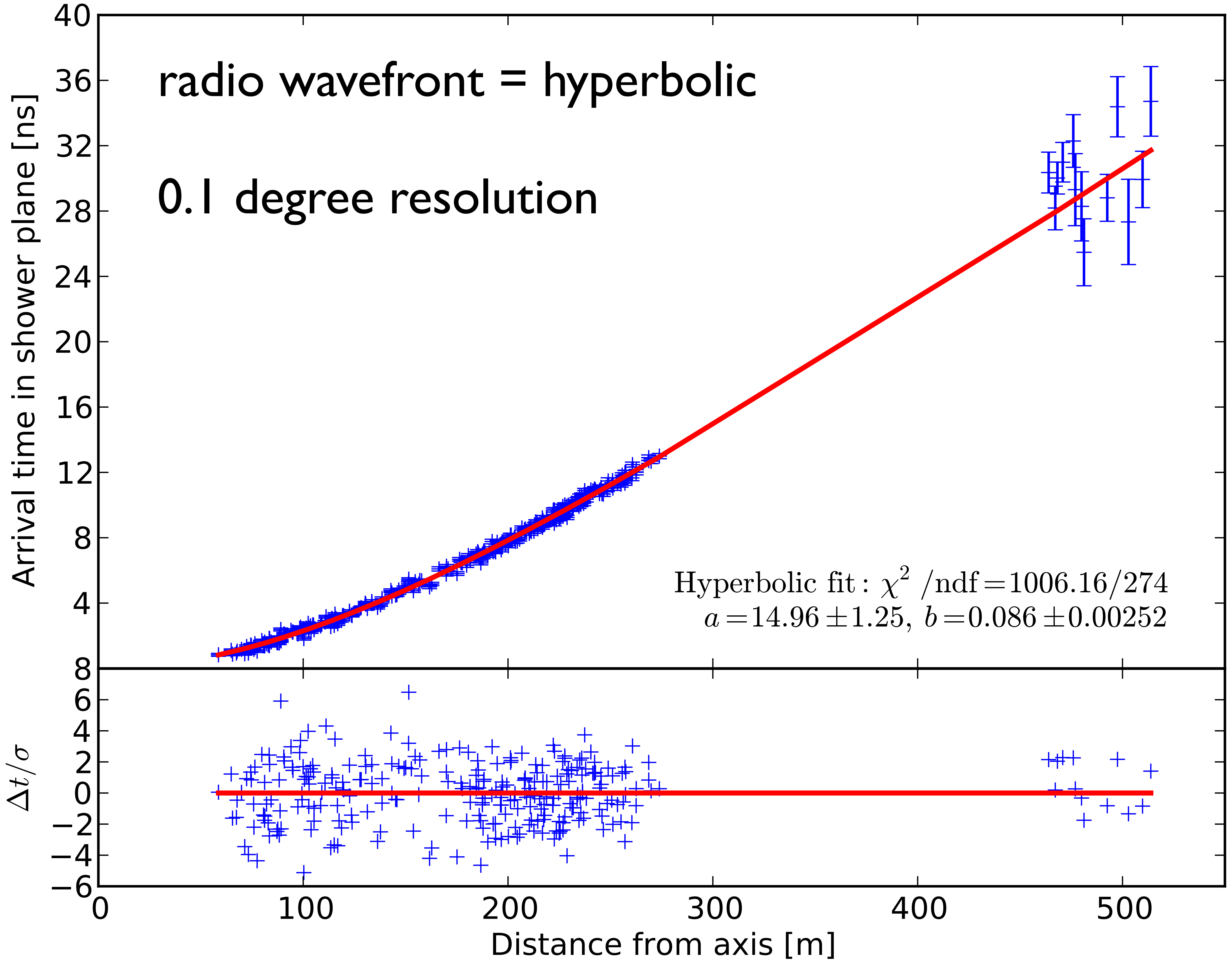
Layer	h [km]	E [kV/m]	E_{vxz} [kV/m]	$E_{vx[vxz]}$ [kV/m]	E_z^m [kV/m]	E_z^0[kV/m]
1	8.1	45	41	18	-30	-11
2	6.1	58	-12	-57	93	35
3	4.9	52	-47	-23	38	14

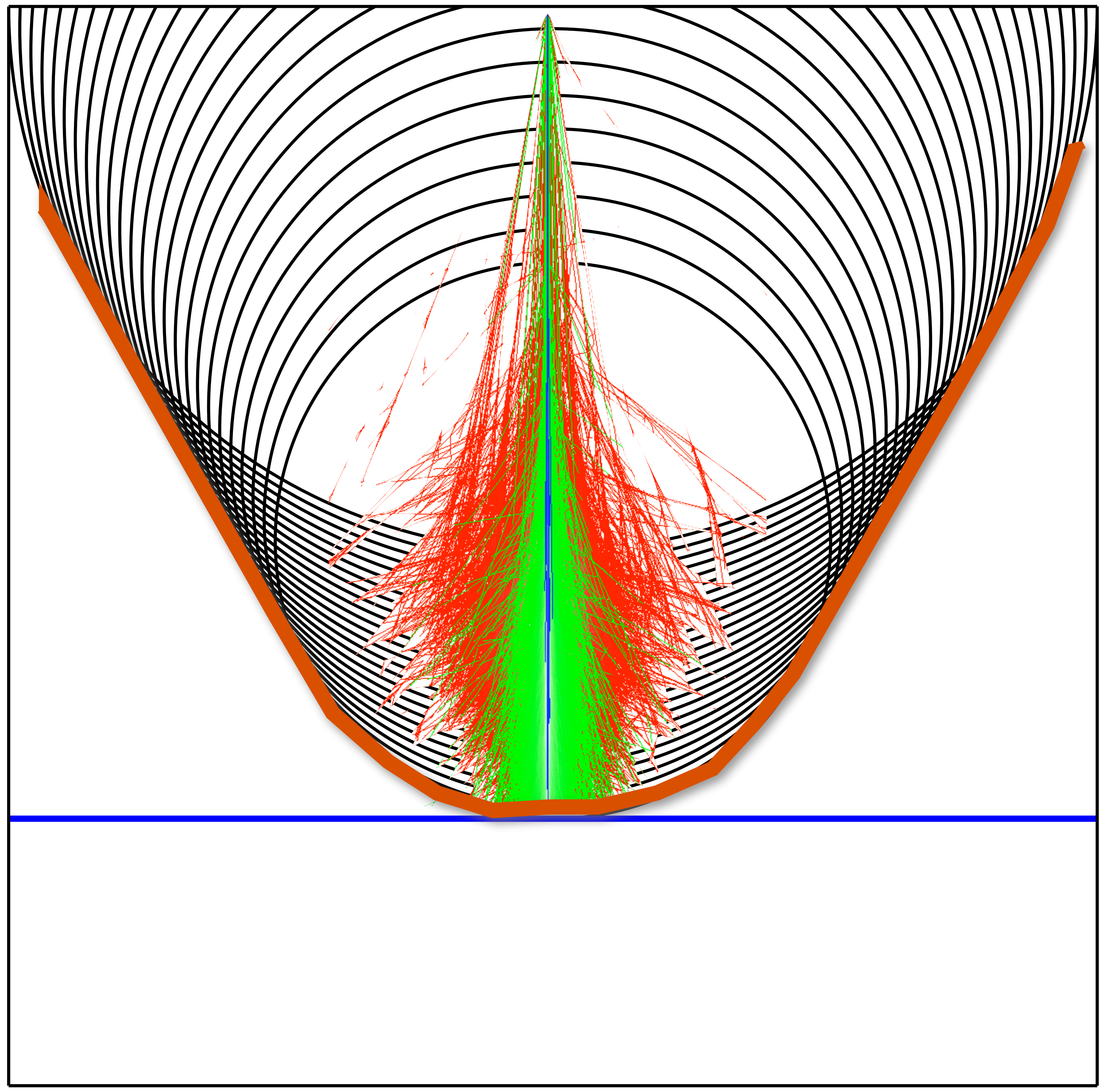




T.N.G. Trinh et al., in prep (2024)

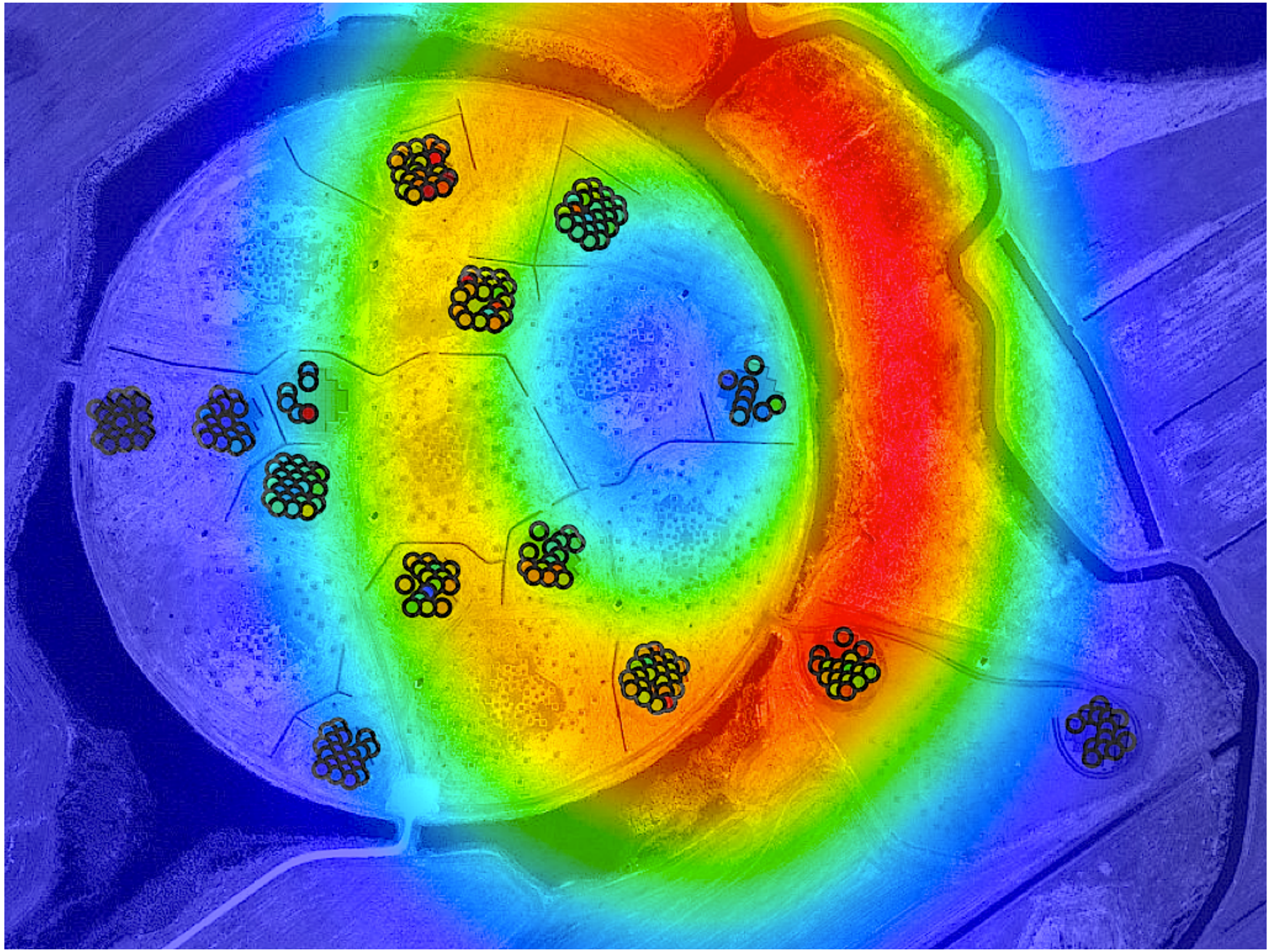
Timing: the wavefront shape





Arthur Corstanje et al., *Astropart. Phys.* **61** 22 (2015)

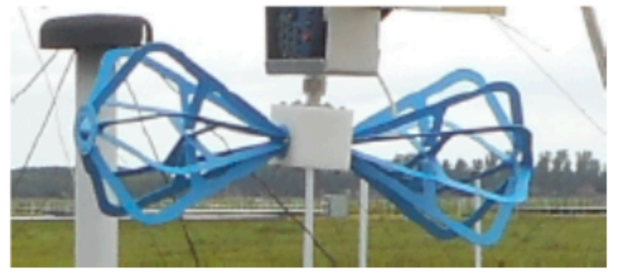
Spectrum: including HBAs

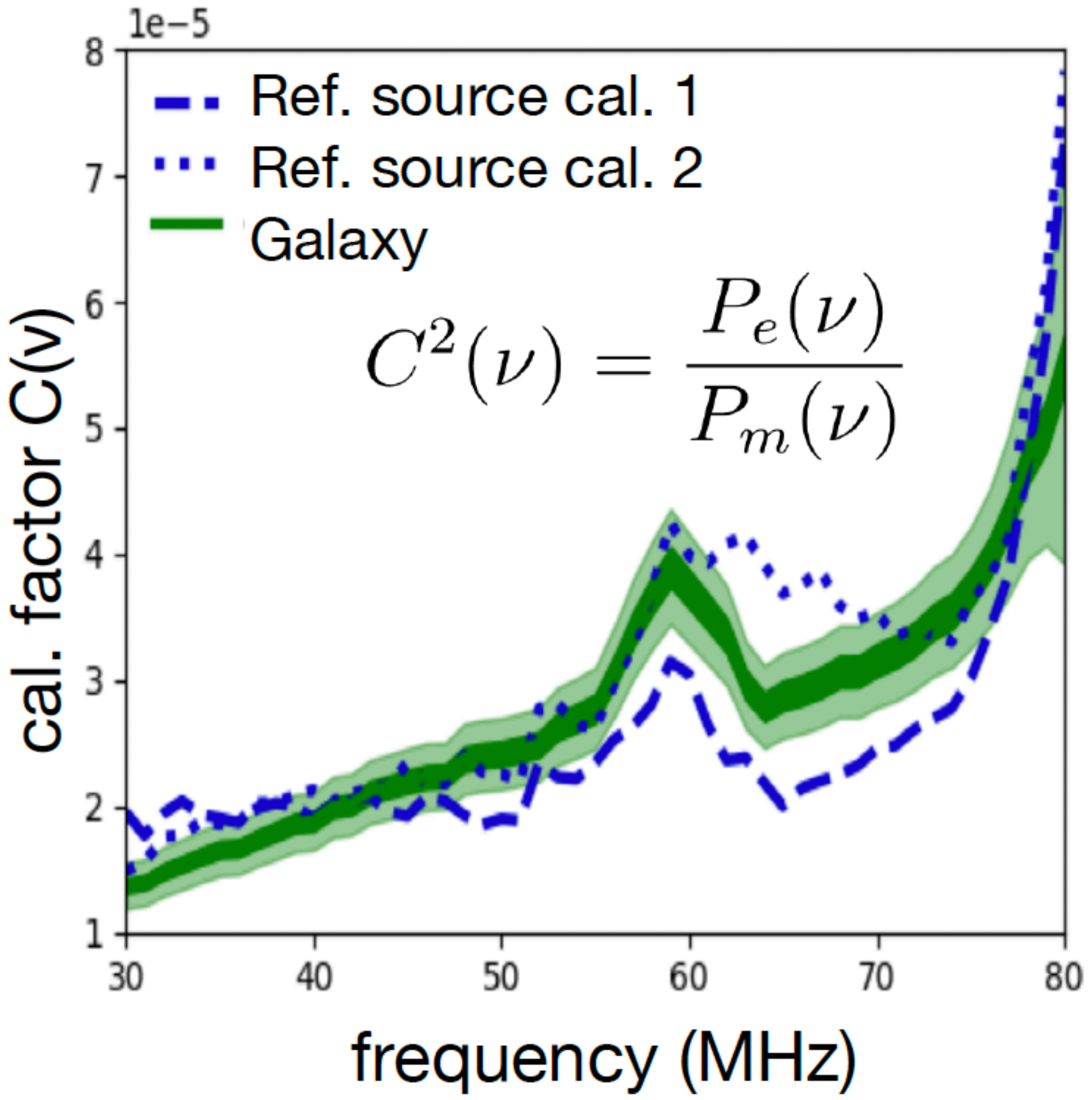


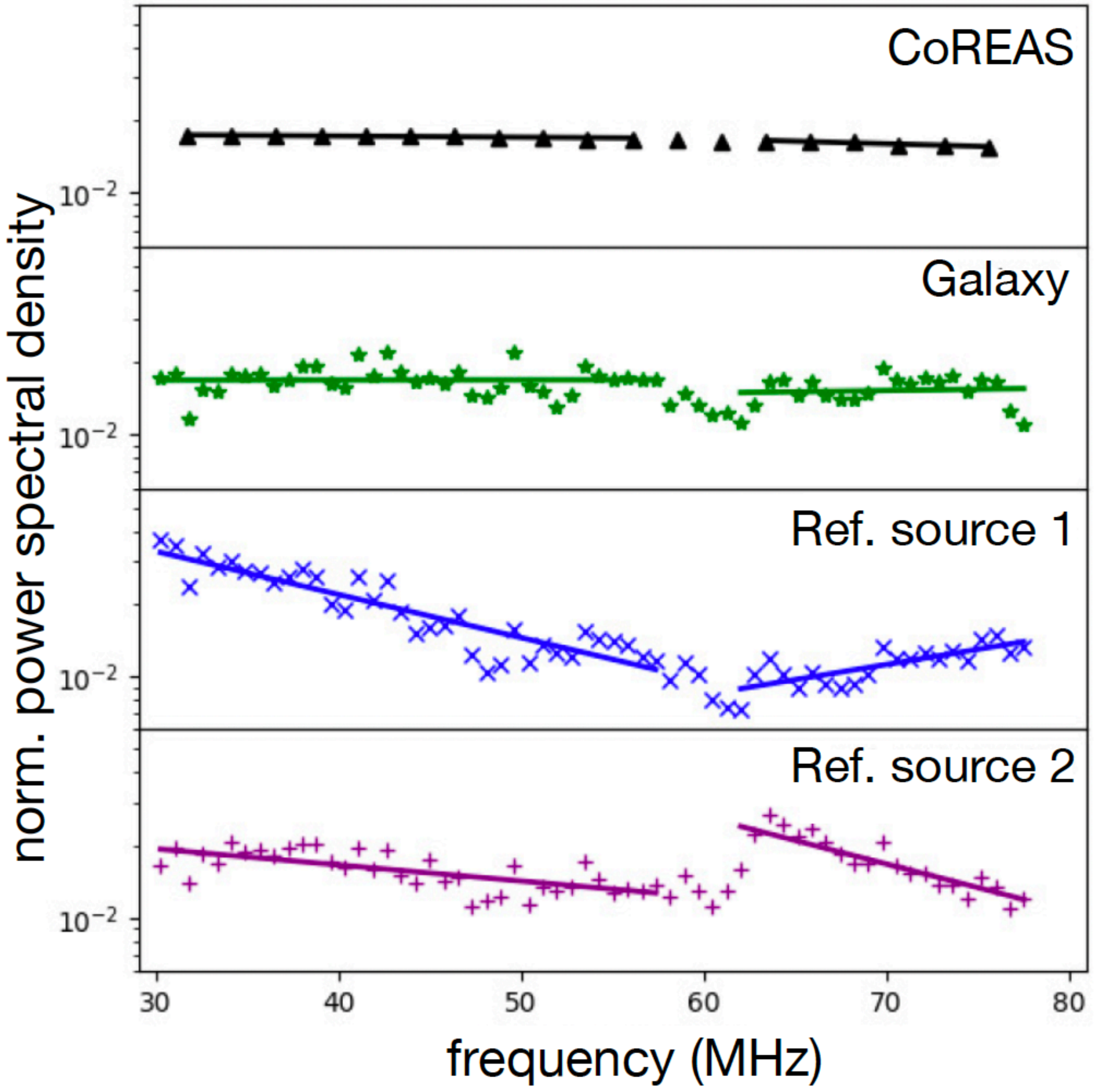
- At high frequencies coherency condition only met near Cherenkov angle
- LOFAR 1.0: HBA data hard to interpret because of tile beam forming
- LOFAR 2.0: LBA + single element HBA, spectral information + resolution
- SKA-low (50-350 MHz) will also see ring structures

Anna Nelles et al., *Astropart. Phys.* **65** 11 (2015)

Energy calibration

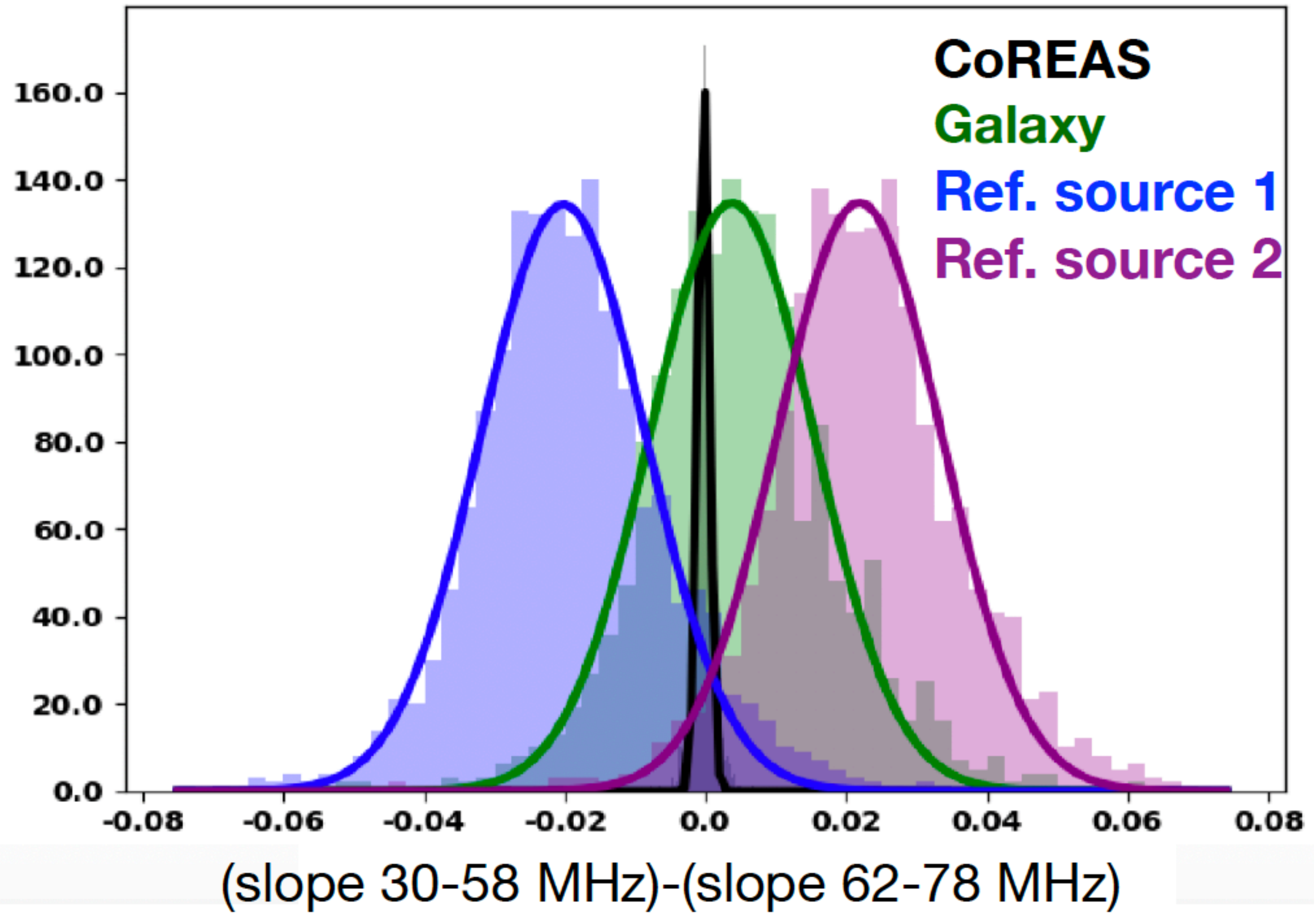






K. Mulrey et al. Astropart.Phys 111 (2019)

Systematic Uncertainty	Percentage
antenna model	2.5
sky model	11
electronic noise < 77 MHz	6.5
electronic noise > 77 MHz	20
total < 77 MHz	**13**

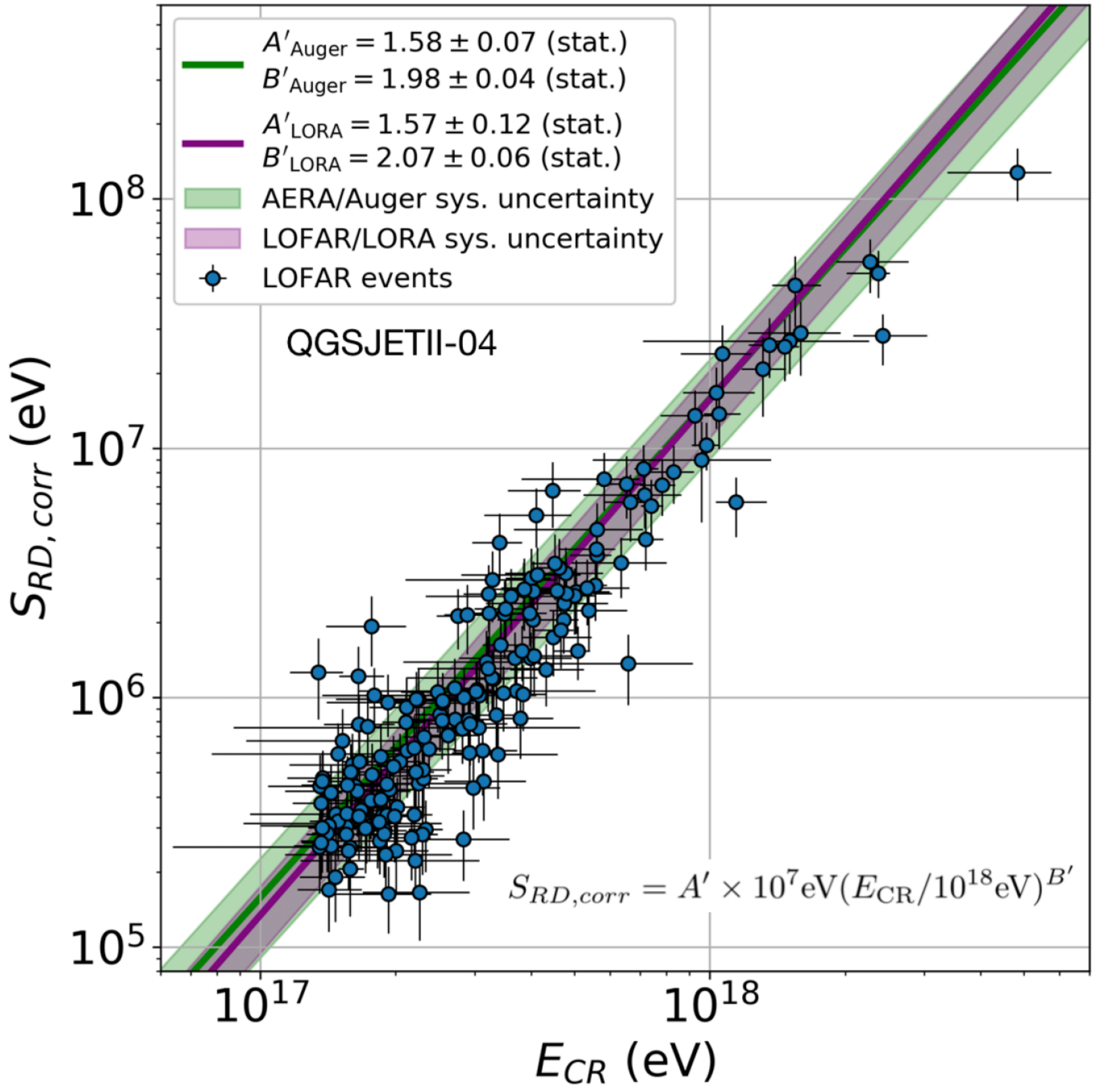


Cosmic ray energy scale

- Coherent emission: radiation energy scales quadratically with shower energy

$$S_{RD,corr} = A'_{\mathrm{LORA}} \times 10^{7}\mathrm{eV}(E_{\mathrm{CR}^{\mathrm{LORA}}}/10^{18}\mathrm{eV})^{B'_{\mathrm{LORA}}}$$

- Radiation energy scale can be compared to other observatories after correcting for local magnetic field.

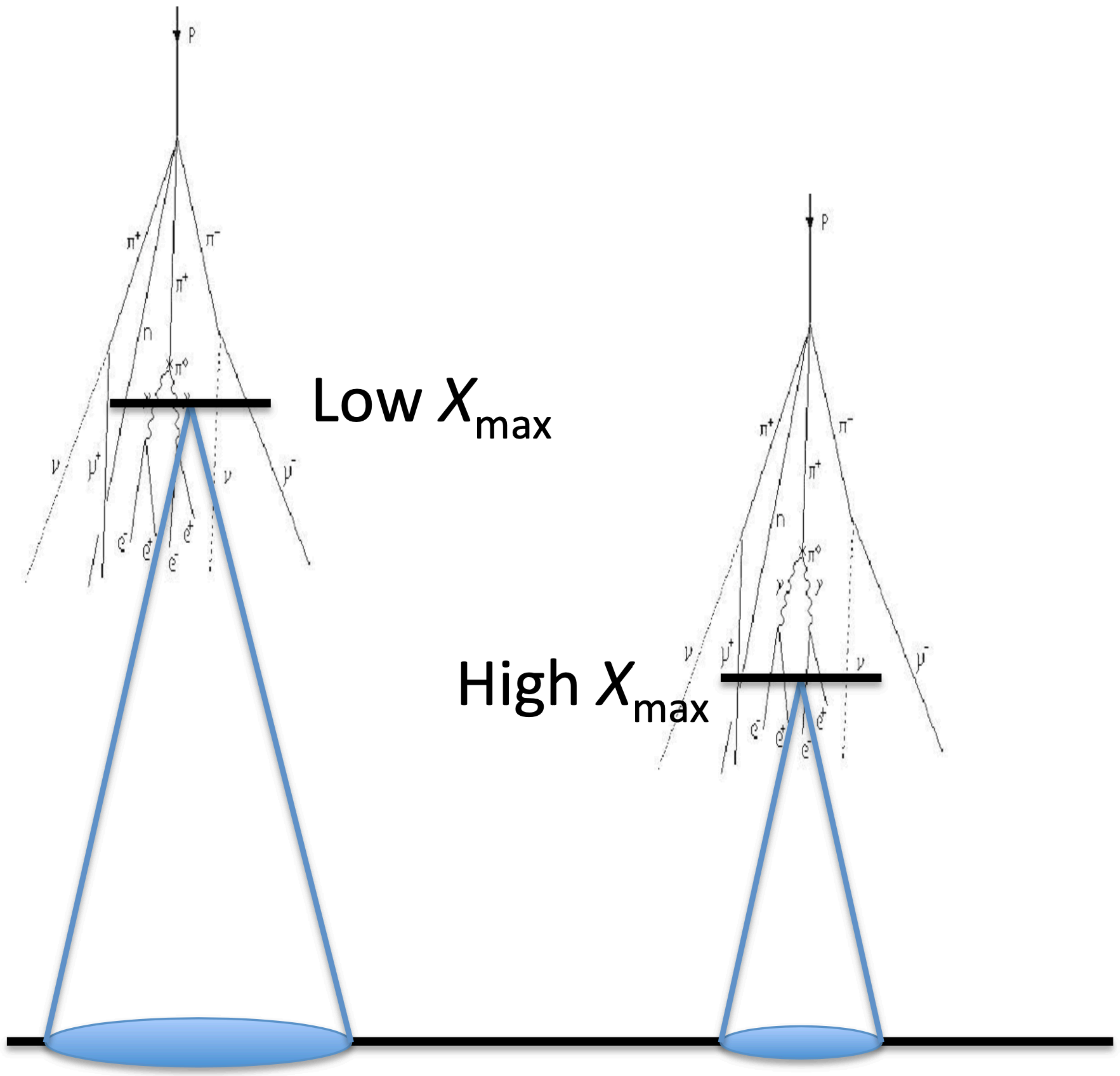


K. Mulrey et al., JCAP 11 17 (2020)

Reconstruction of Xmax

Toy model

(radiation actually comes from whole shower)

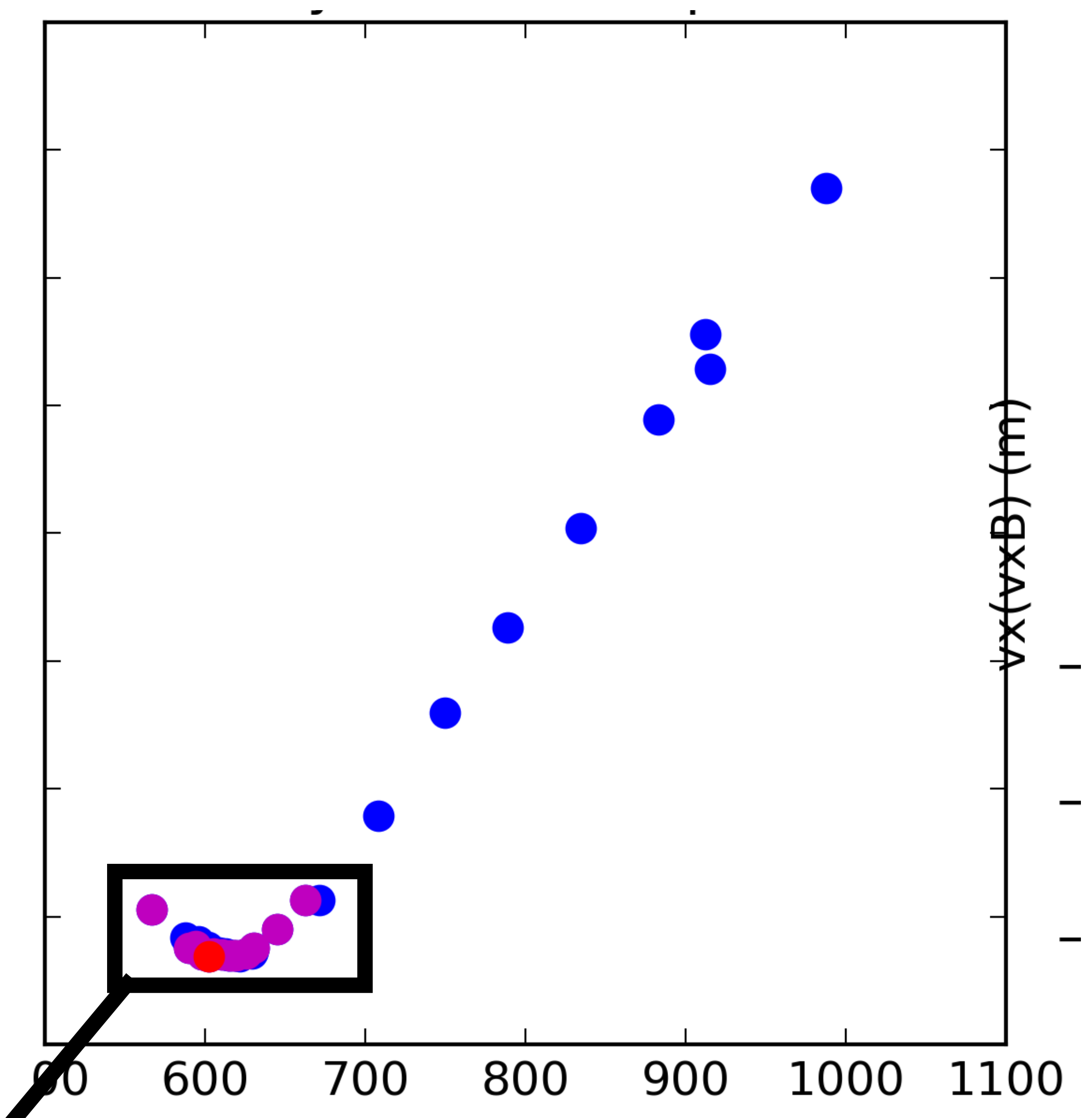


Size of radio footprint scales with Cherenkov angle at Xmax.

General geometry gives rough reconstruction of Xmax.

More precise Xmax by matching simulated 2D radio footprint with data.

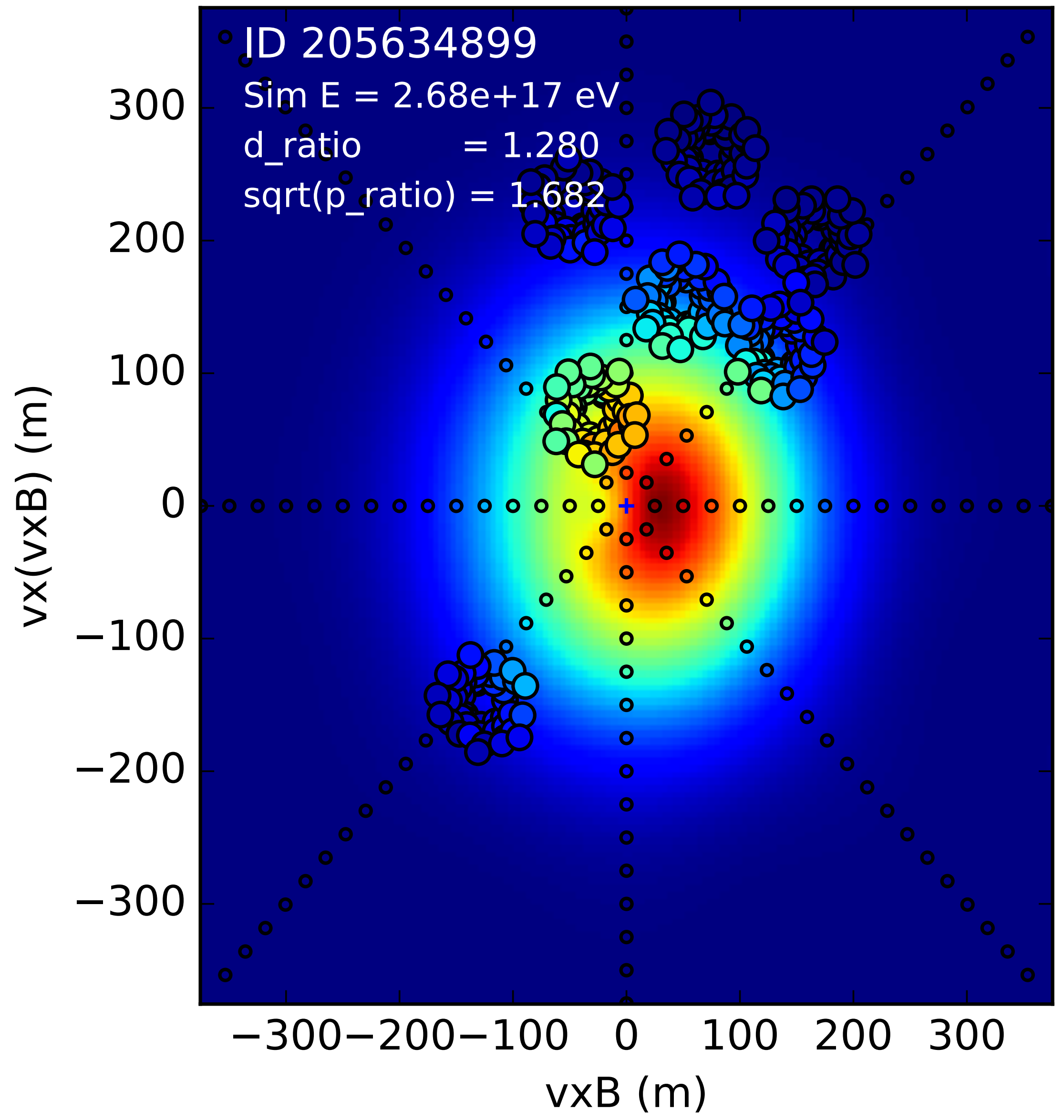
Reconstruction of Xmax

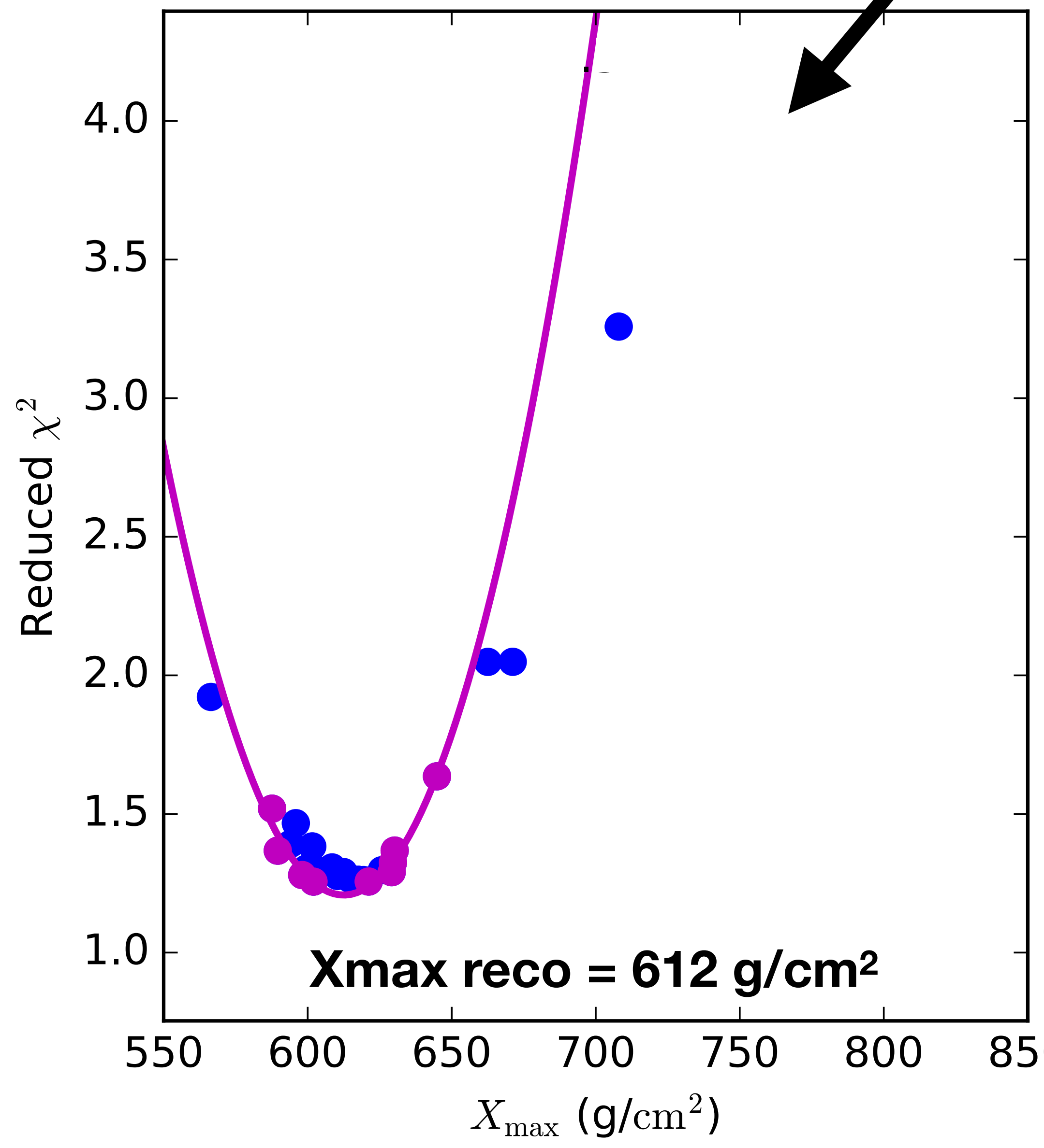


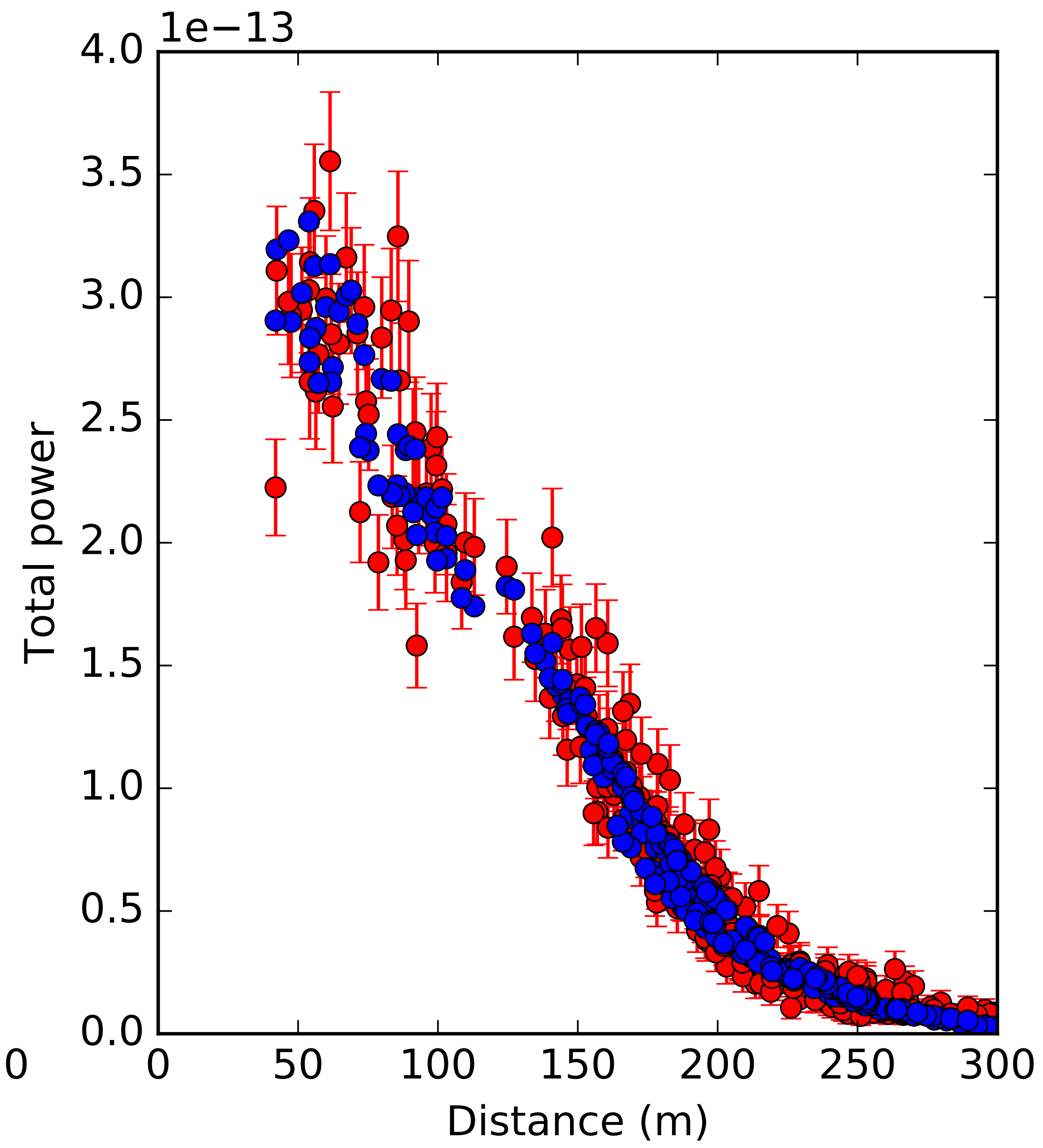
Xmax estimate from fast fit = 613 g/cm²

CONEX: **dense coverage** around Xmax estimate

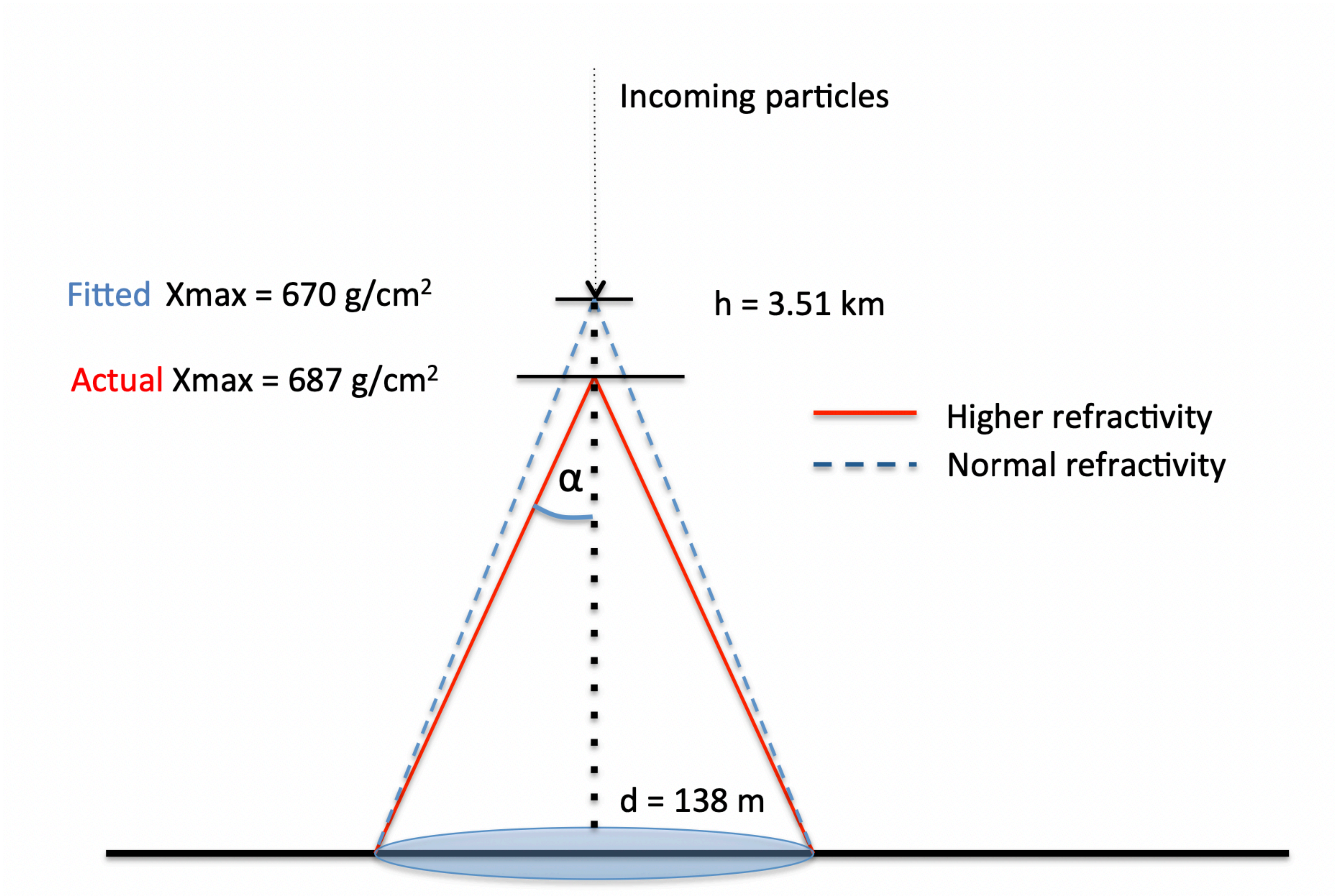
sparse coverage of whole range needed for bias evaluation: all showers in sample must pass trigger & cuts



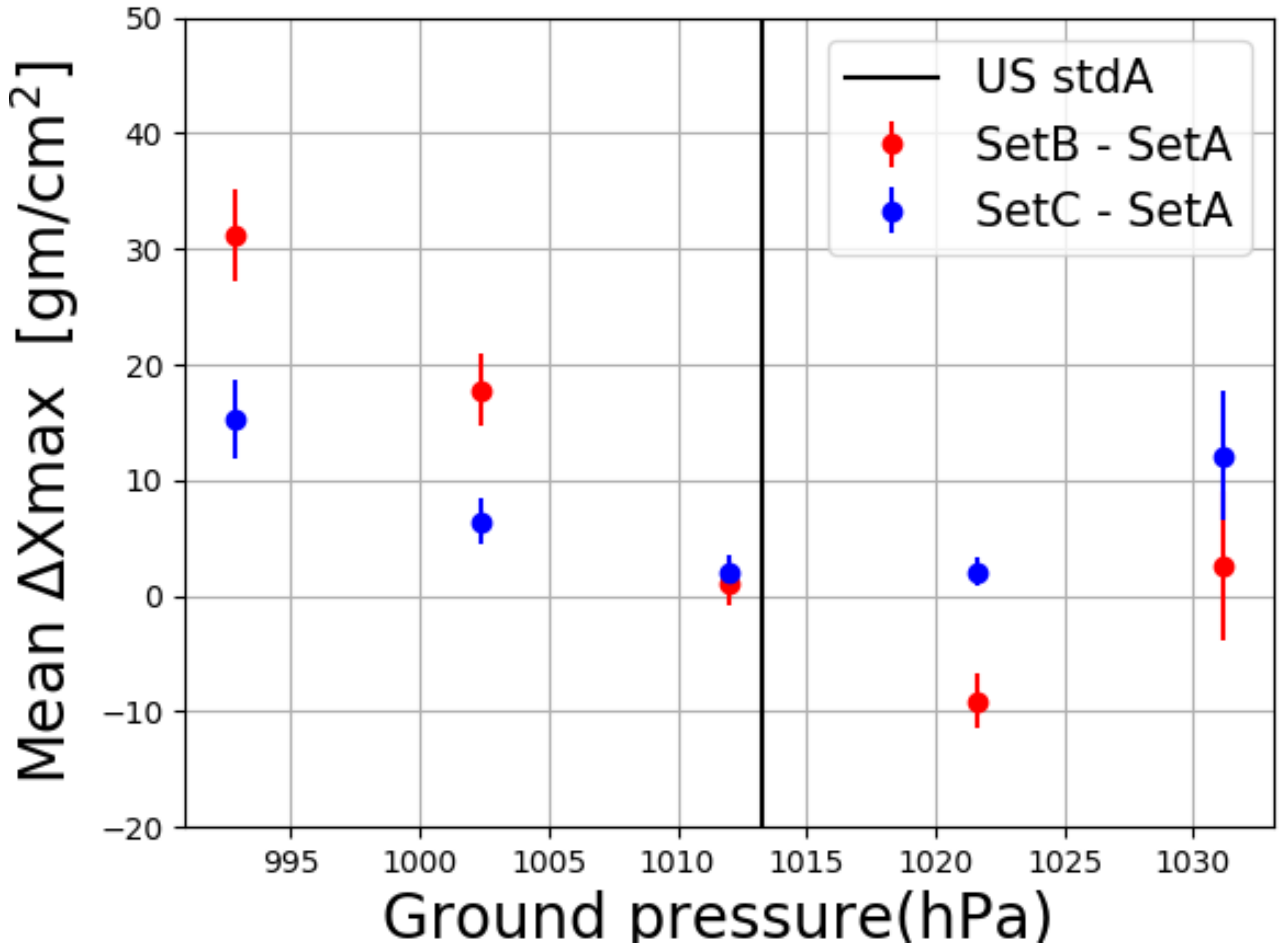




Atmospheric corrections



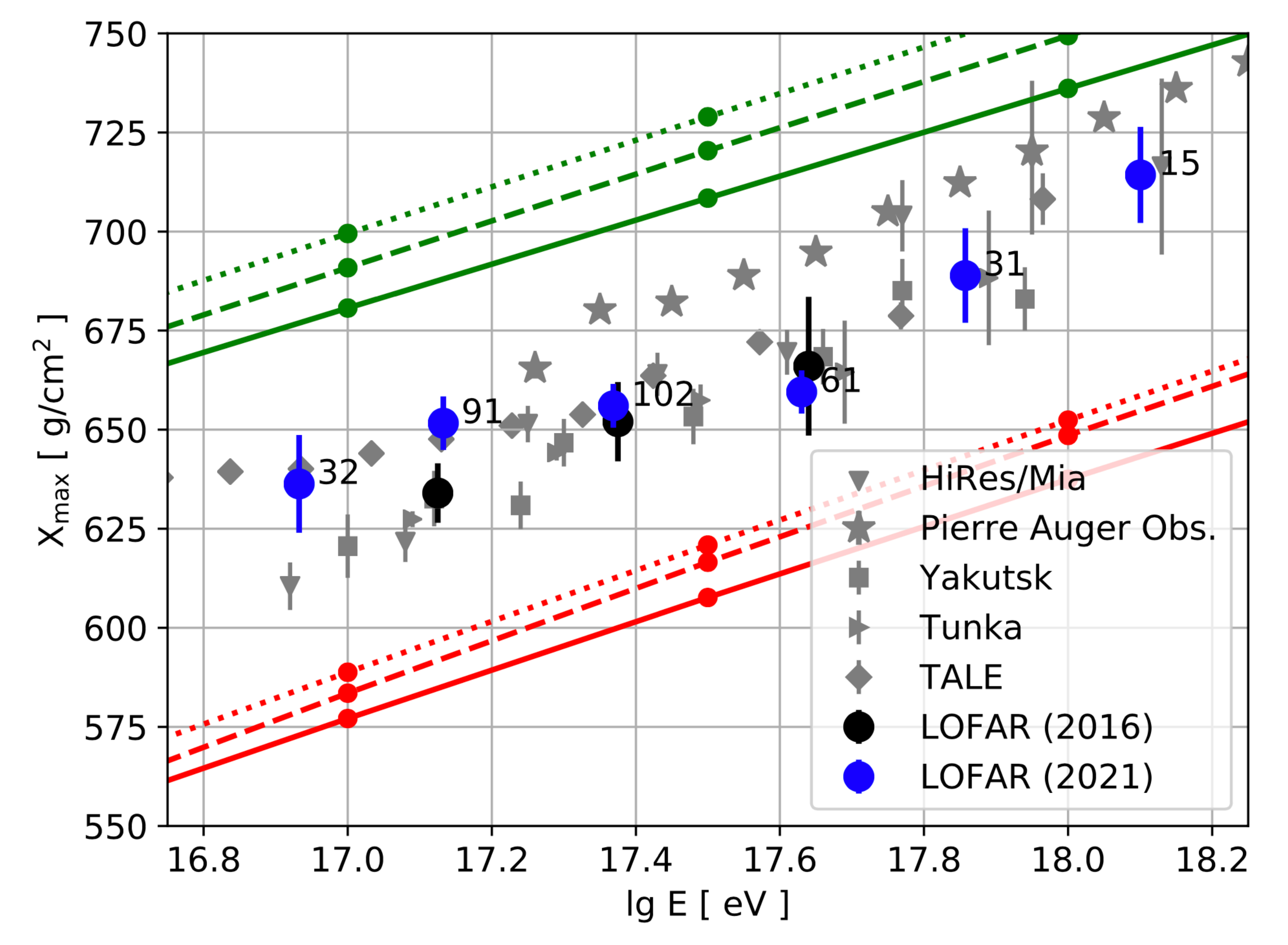
Arthur Corstanje et al., *Astropart. Phys.* **89** 23 (2017)

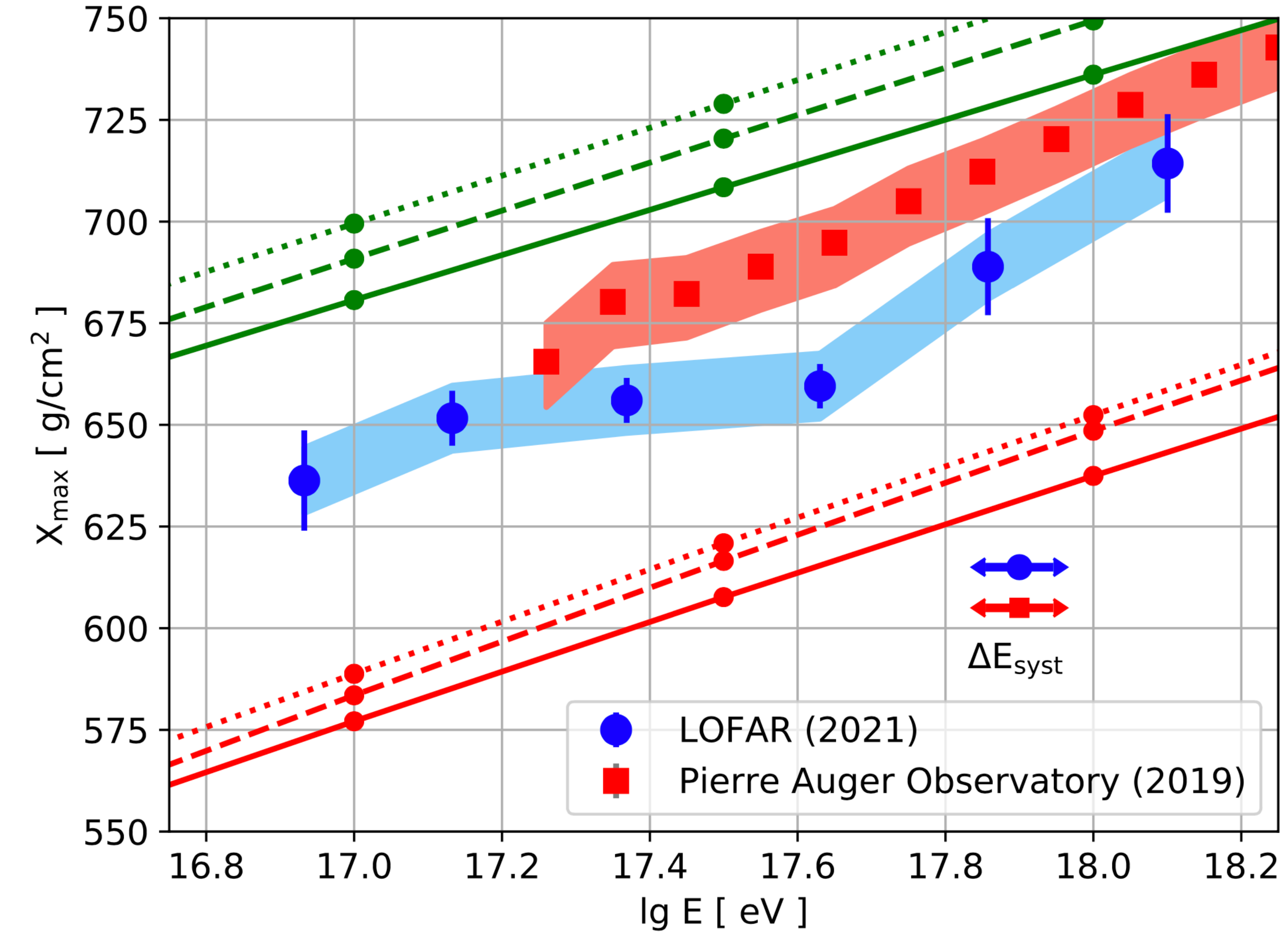


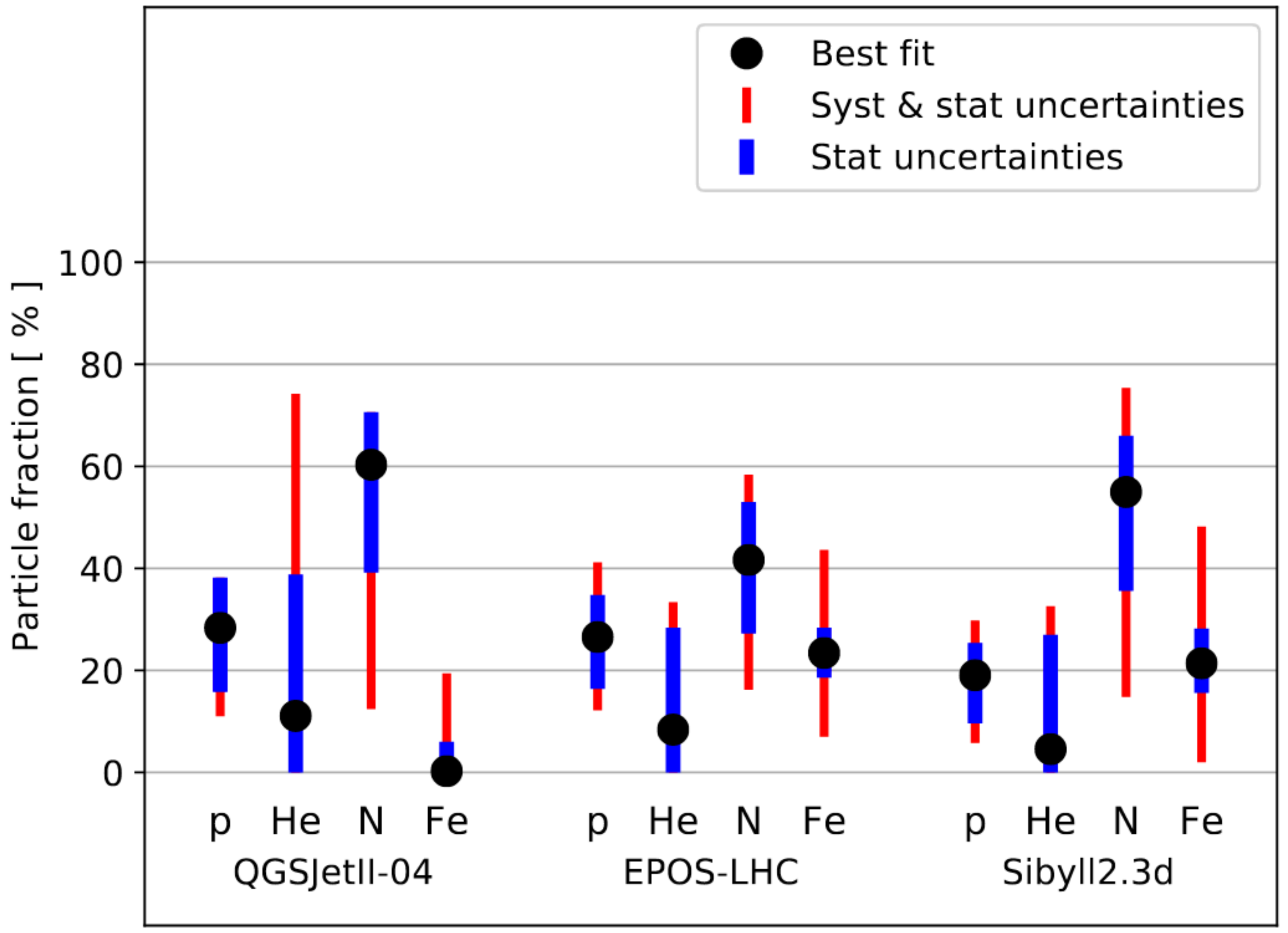
- Full atmospheric profile extracted from GDAS database for each observed shower
- Dedicated simulations with true atmosphere, GDAStool plug-in for CORSIKA simulations

Pragati Mitra et al., *Astropart. Phys.* **123** (2020)

Mass composition







General trend in agreement with world data. Mixed composition around 10^{17} eV with light component

Some tension with Auger? Dense vs. sparse array? Unknown systematic effects? North vs. South?

What's next for LOFAR 2.0 & SKA?

SB, Nature 531, 70 (2016)
A. Corstanje et al., Phys. Rev. D 103, 102006 (2021)

Part II
Towards LOFAR 2.0 & SKA

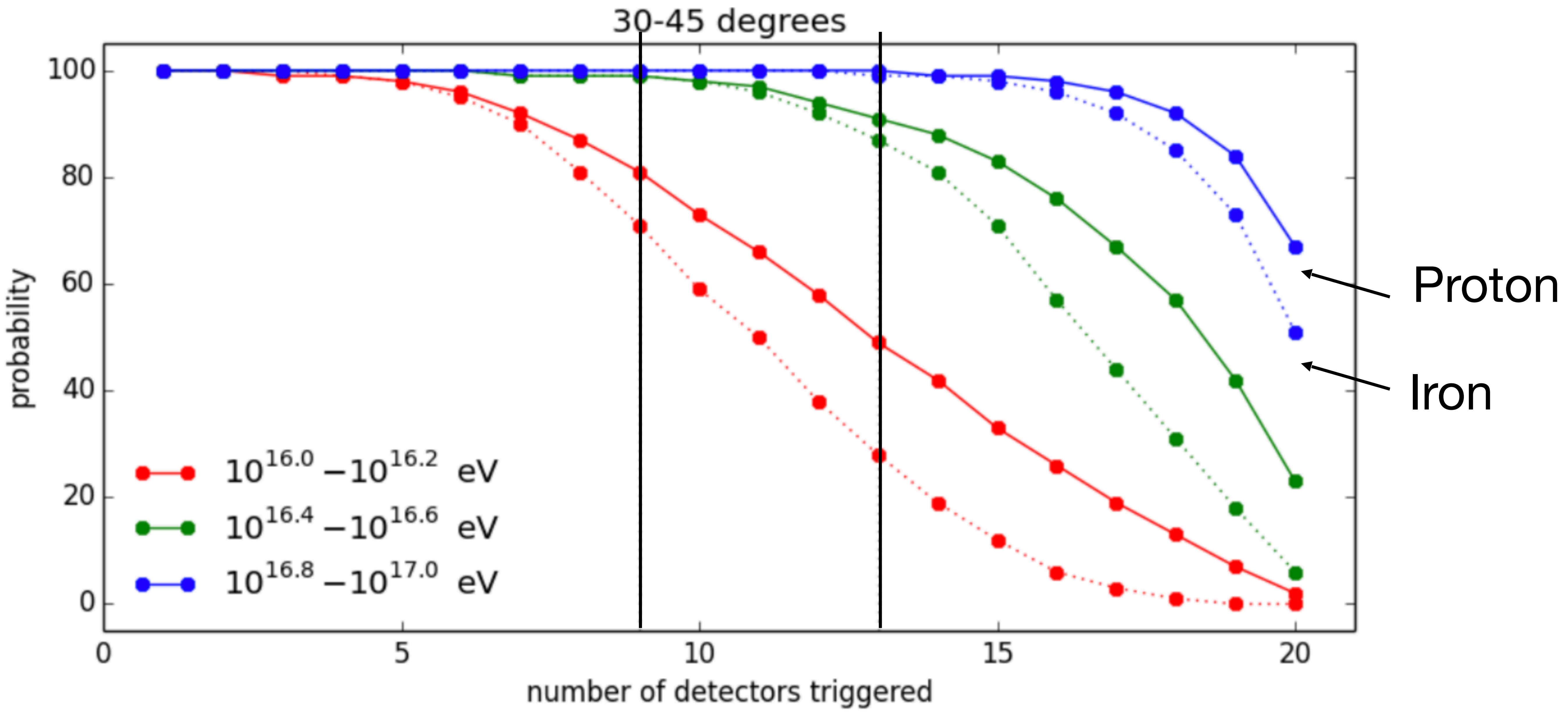
What’s next?

- *How to make progress? Increase statistics, increase energy range, improve resolution, develop more advanced techniques.*

- **LOFAR 2.0**:
  fully commensal data taking + expanded particle detector array
  simultaneous LBA + HBA (single element)
  radio trigger

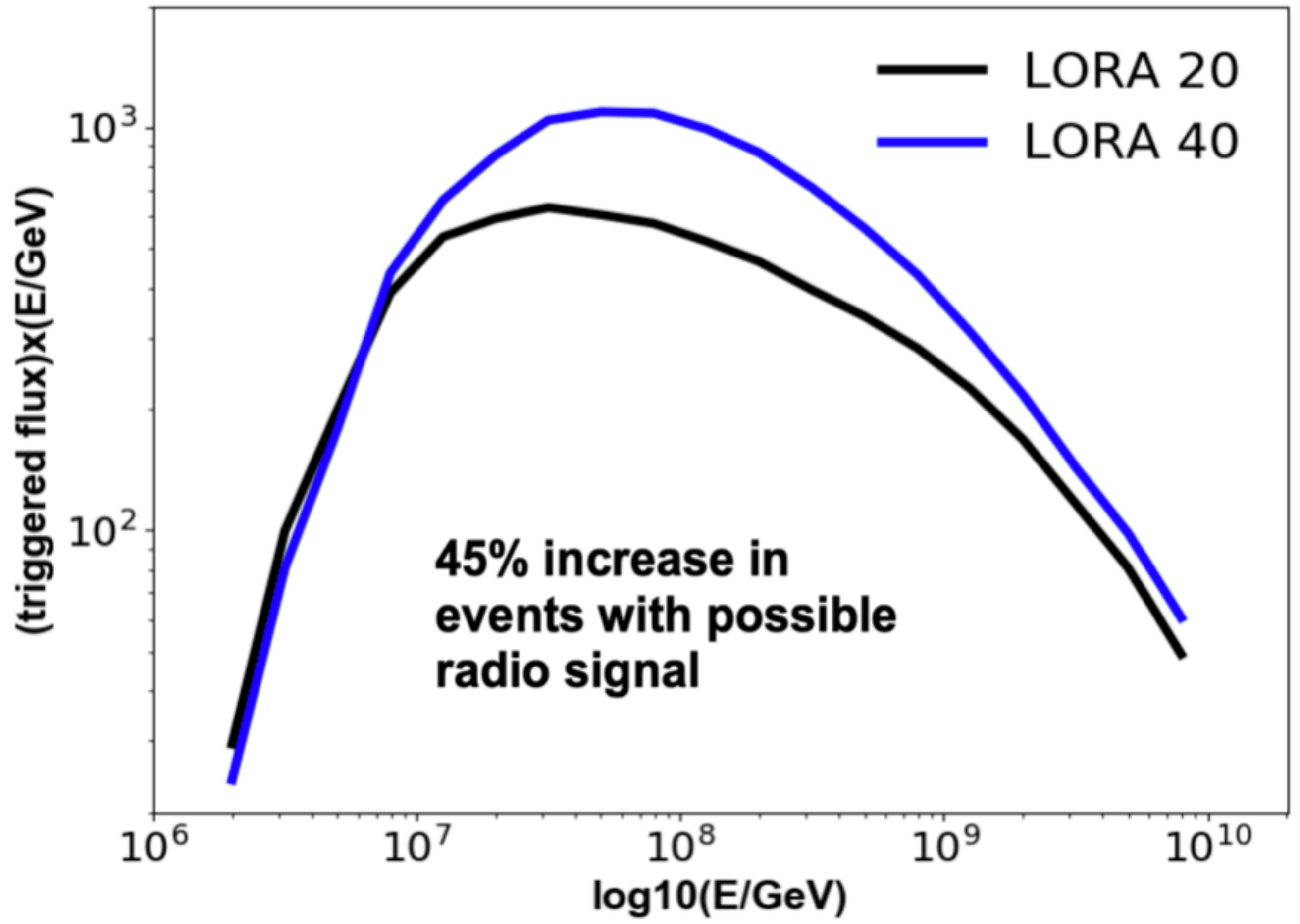
- **SKA** has additional possibilities, including constraining particle physics in shower
  (see next talk Arthur Constanje)

LORA expansion



Preferred trigger
LORA expansion + radio

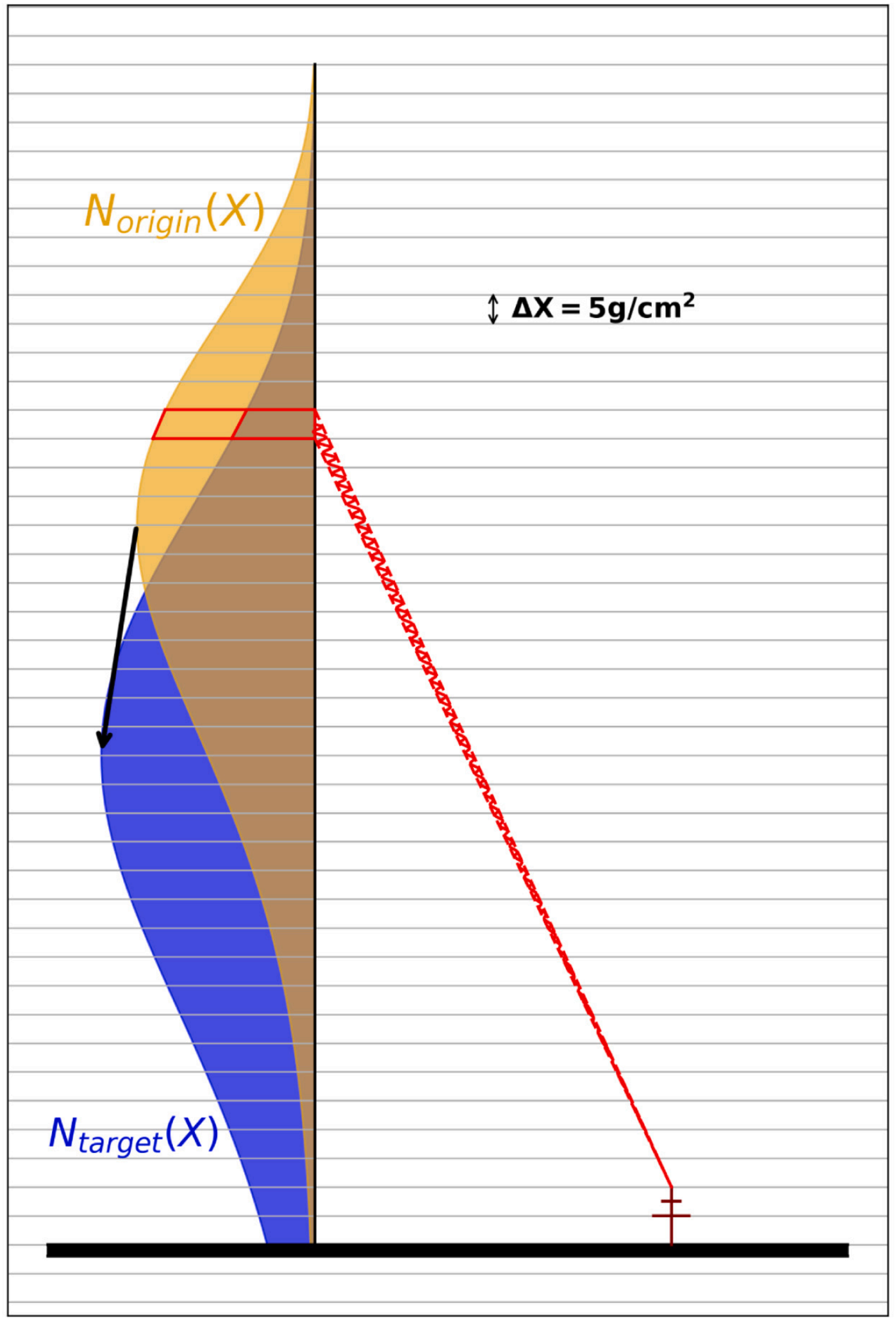
Current trigger



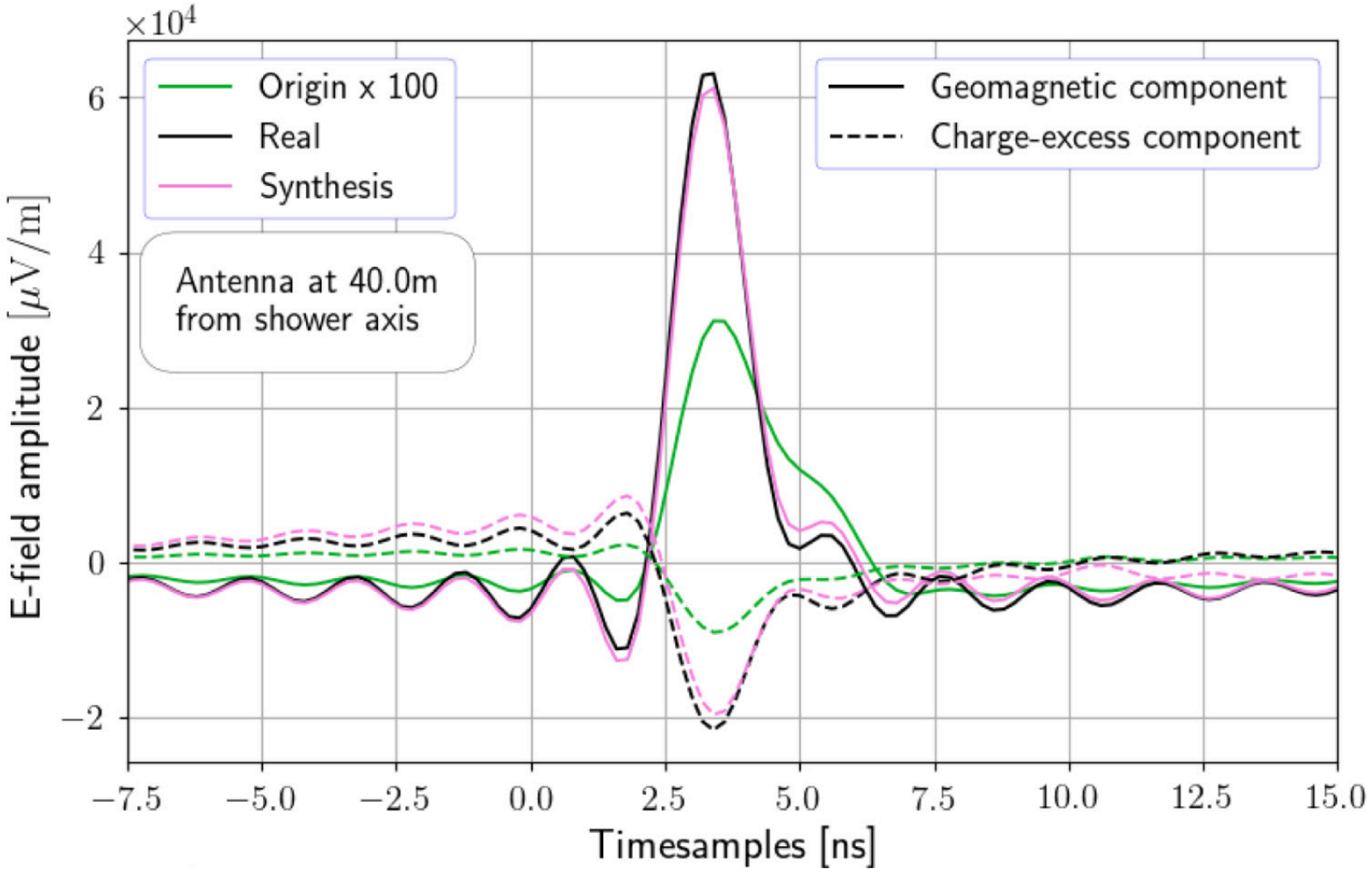
Software development

- LOFAR cosmic-ray calibration & analysis software rewritten.
- Old software had dependencies that are no longer supported
- New software designed to support both LOFAR 2.0 and SKA data modular approach, flexible to data formats and sizes
- Integrated in NuRadioReco framework: modules can be shared with other cosmic-ray and neutrino radio observatories

Template synthesis



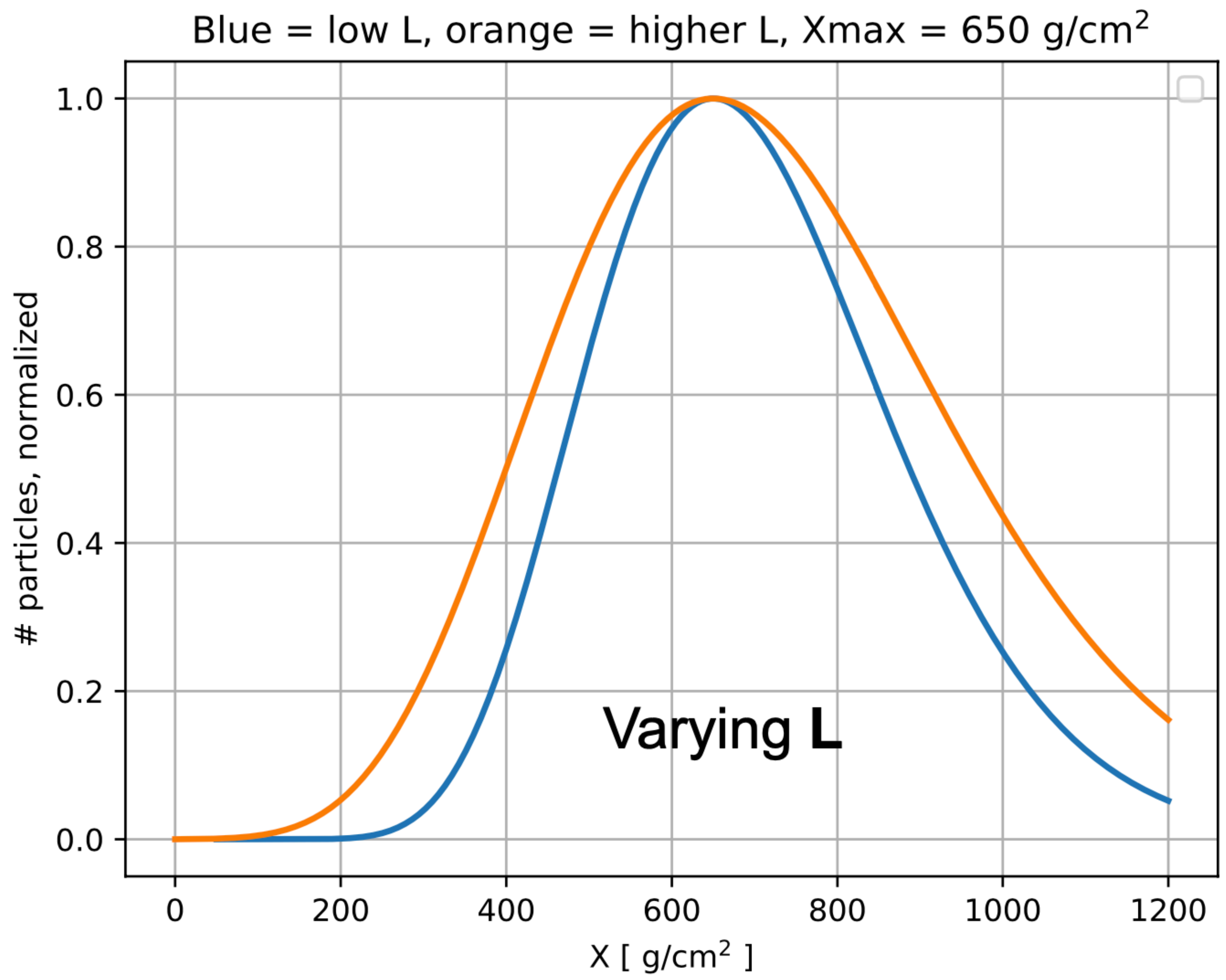
- Faster simulations are essential in LOFAR 2.0/SKA era
- New approach: use scaling relations to synthesize showers from templates
- Error on waveform amplitudes < 2% for vertical showers
- Now extending to all geometries



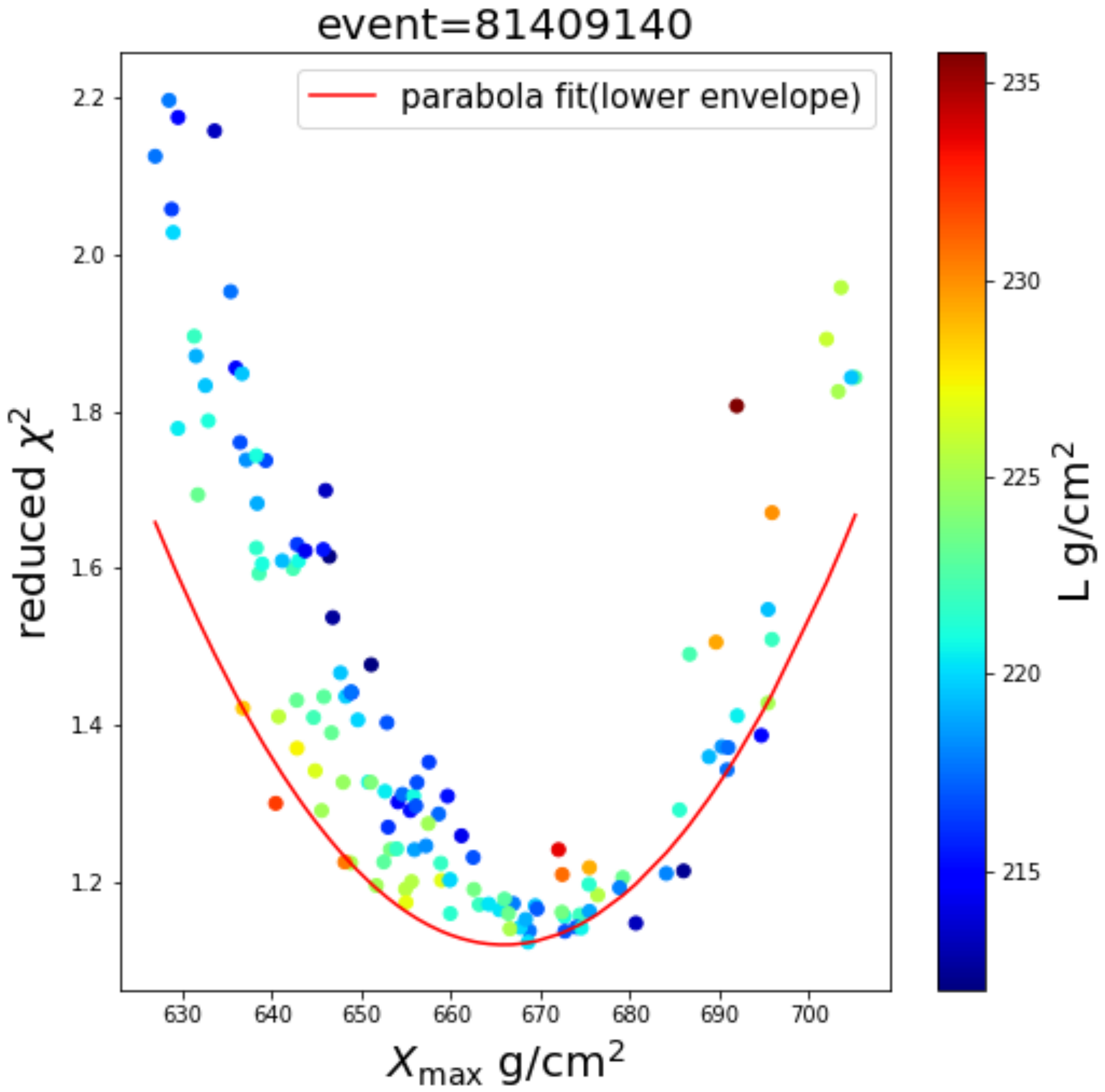
Mitja Desmet et al., *Astropart. Phys.* ***157*** 102923 (2024)

The shape of the shower

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



Blue = low L, orange = higher L, Xmax = 650 g/cm^2



event=81409140

LOFAR sensitive to *L* (shower length)

New parameter to constrain mass composition and hadronic interactions

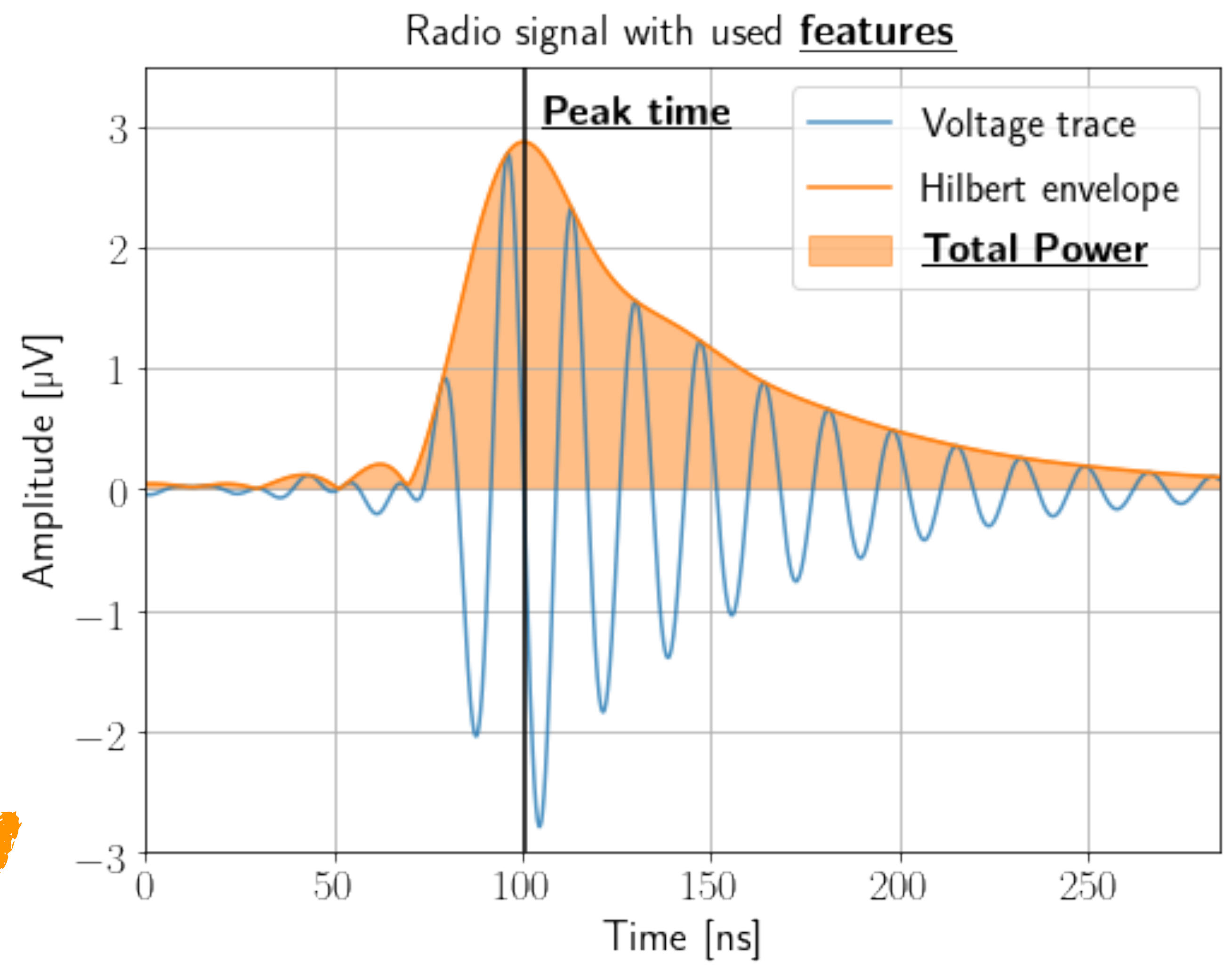
See also next talk on SKA (Arthur Corstanje)

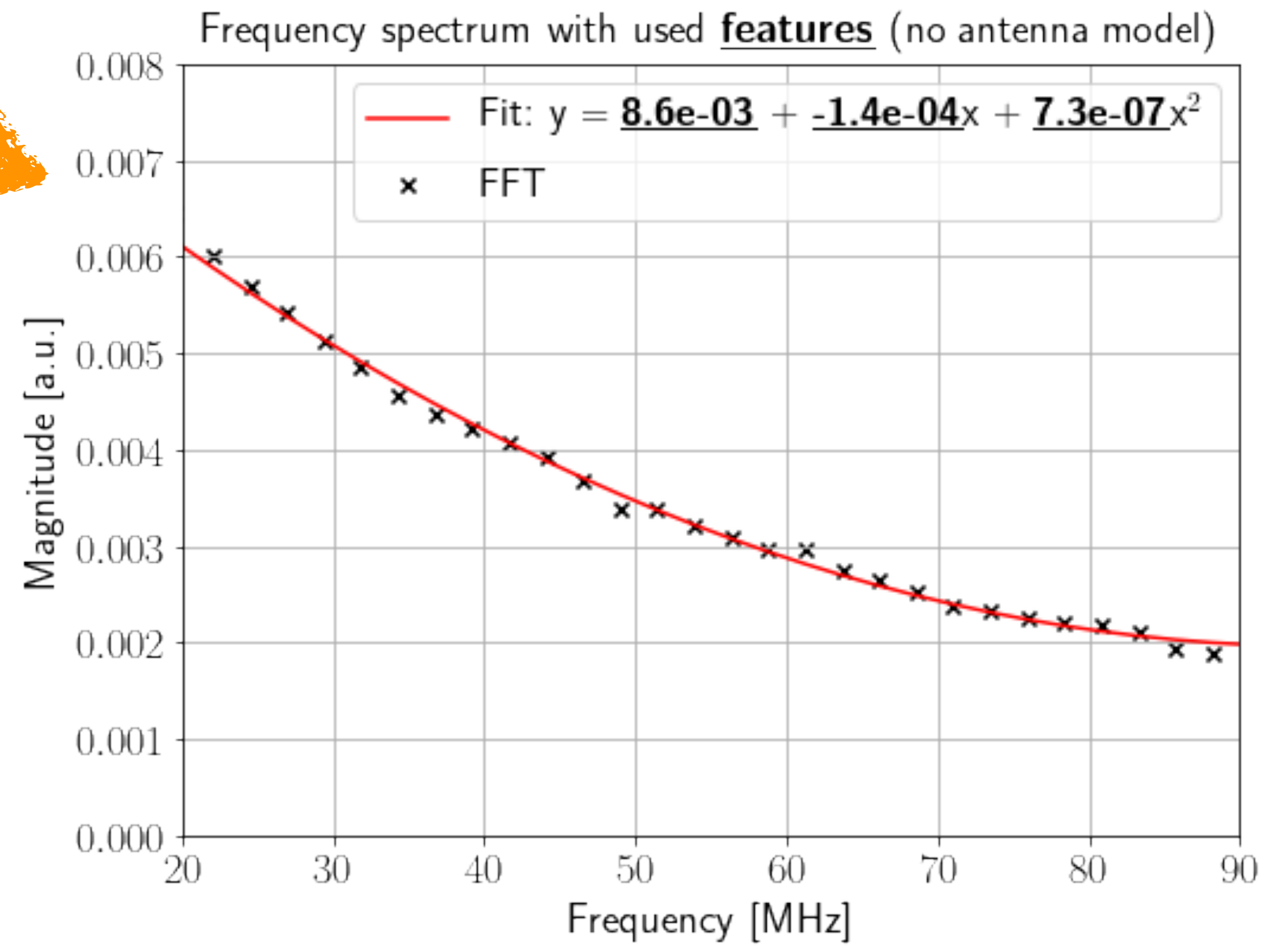
Reconstruction with Neural Networks

300.000 shower simulations with random core location

For each antenna determine:

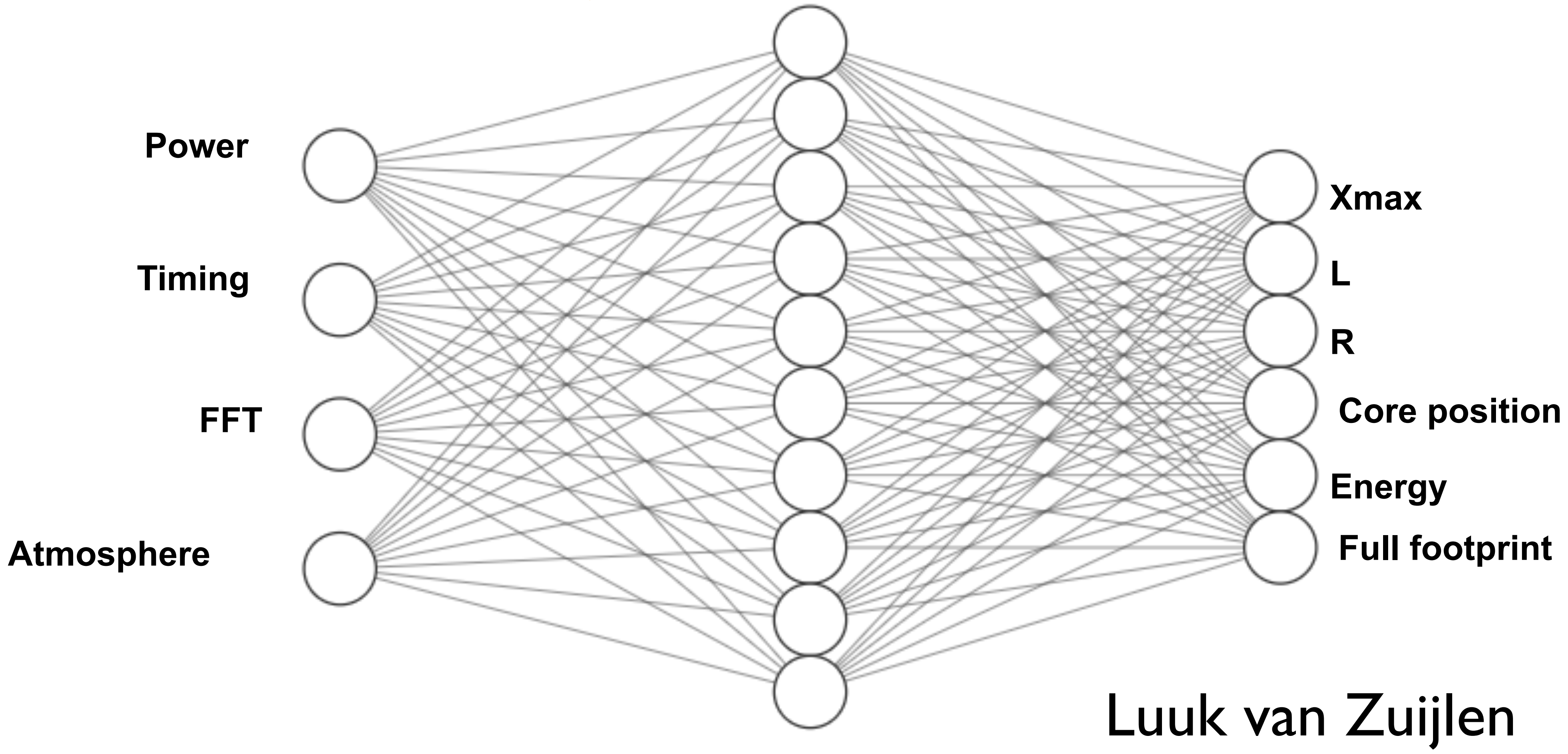
Total Power
Arrival time
Spectral shape





Train model (FCNN) on features to predict **targets:**

- energy
- Xmax
- L, R
- core position
- full footprint

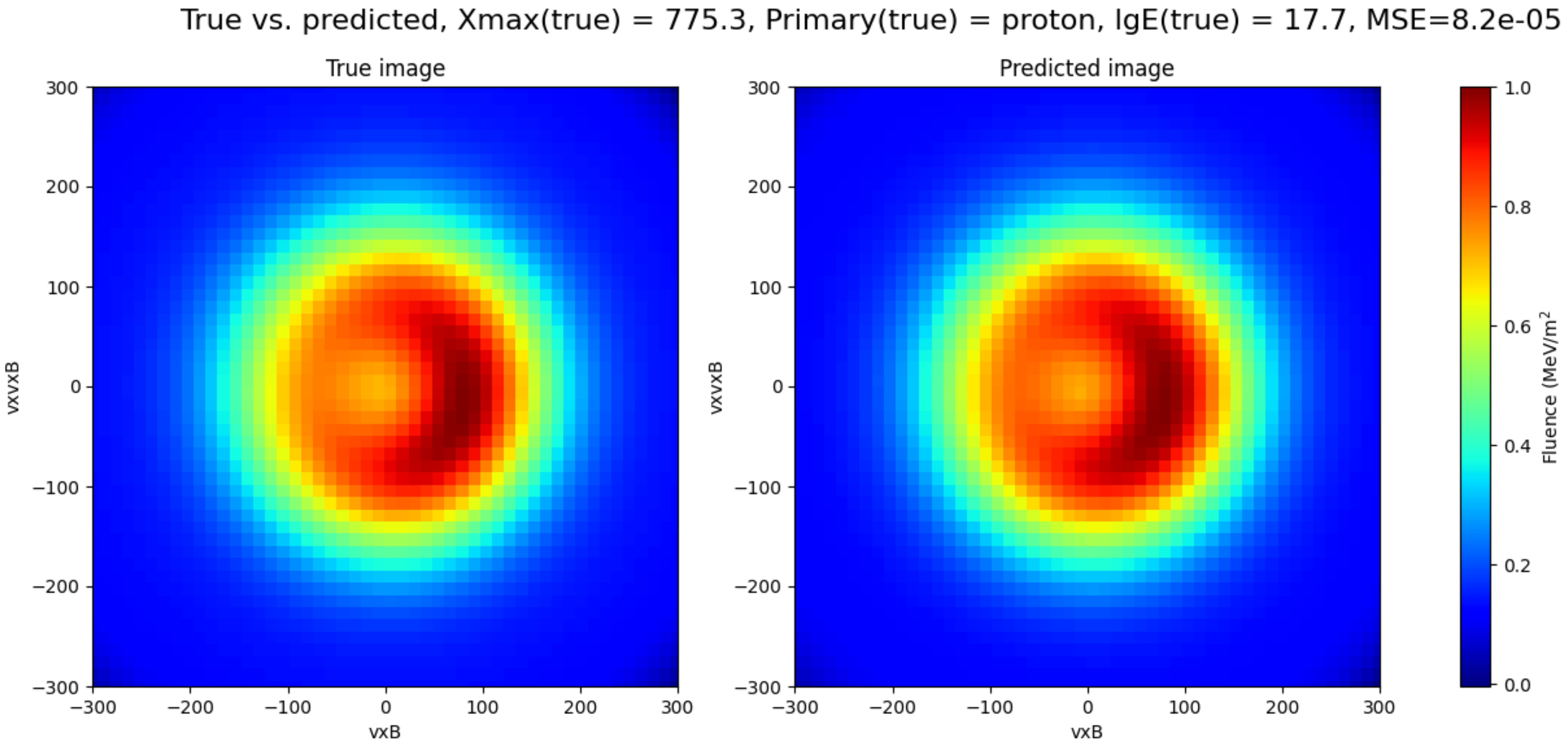


Luuk van Zuijlen

Reconstruction with Neural Networks

Results:

- Xmax MAE = 17 g/cm^2
- L MAE = 6.1 g/cm^2
- R MAE = 0.022
- Log(Energy) MAE = 0.25
- Core resolution = 3.4 m

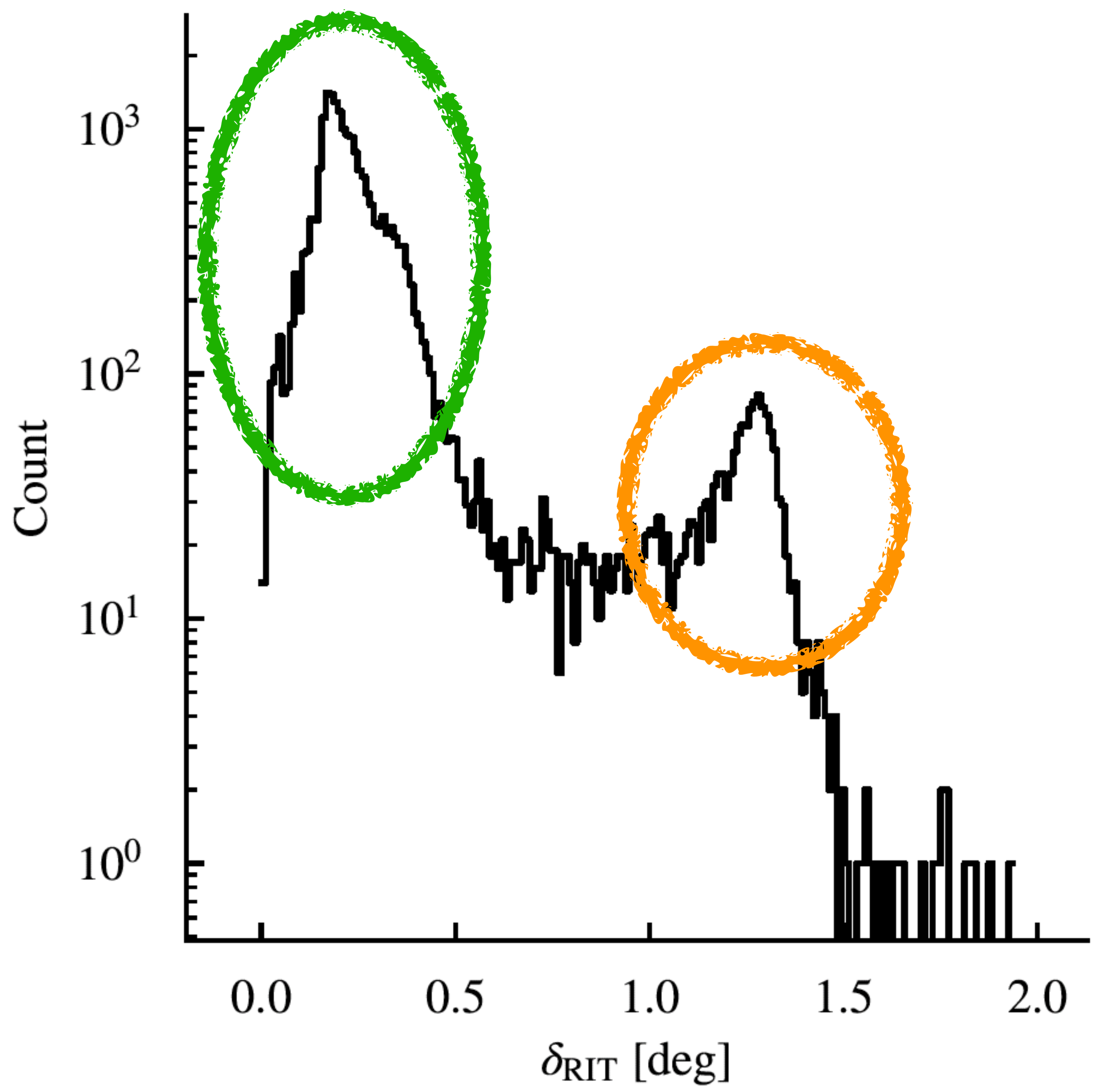


Luuk van Zuijlen

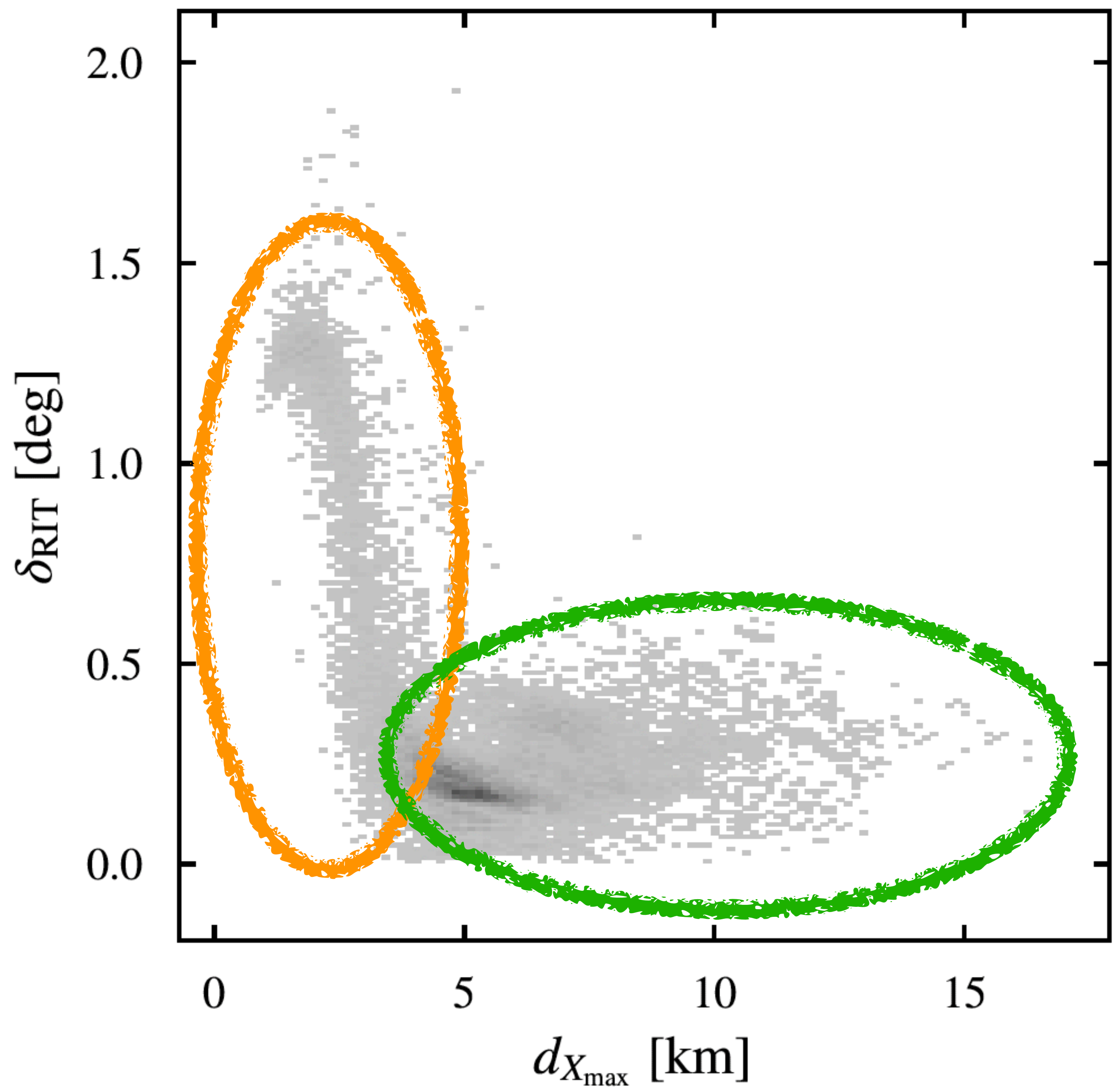
Near-field interferometry

- Shower axis and core position can be reconstructed by beam forming in near-field
- Simulation study achieves 0.1 degree resolution with LOFAR layout

$$\Delta\theta \sim \frac{\lambda}{\max(b)\sin\theta}\,.$$



only superterp
more stations



Tiepolo Wybouw

Conclusions

- **LOFAR 1.0**
  understanding the emission mechanism
  develop calibration & reconstruction techniques
  first high-resolution radio-based mass composition study in transition region

- **LOFAR 2.0**:
  more statistics, larger energy range, LBA + HBA
  new flexible software & faster simulations
  new reconstructions approaches: neural networks, interferometry, …
  shape of the shower evolution: mass composition + hadronic physics