The Square Kilometre Array: a unique high-precision cosmic-ray observatory

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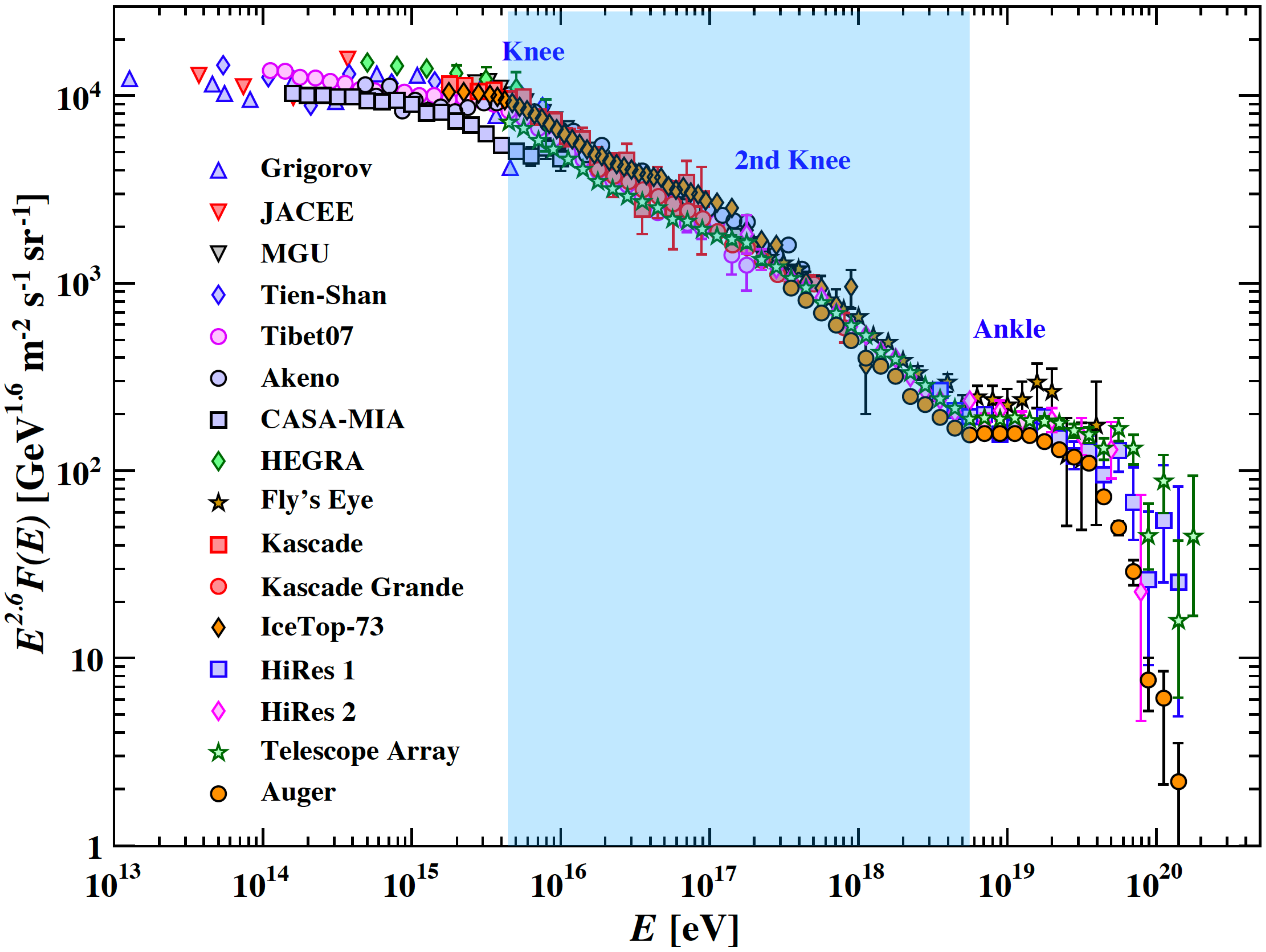
TevPA 2023, Napoli, 13 sept 2023

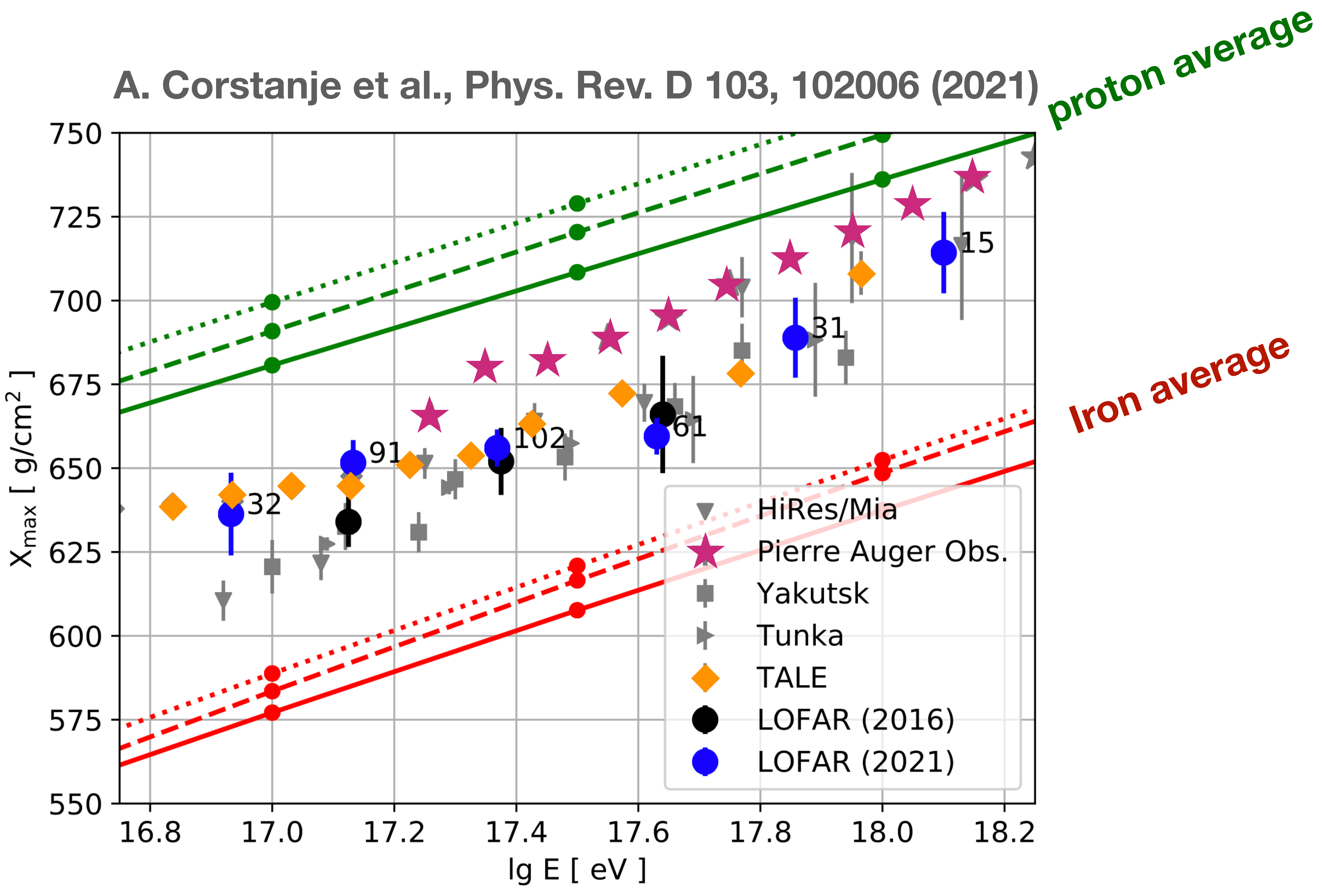
Cosmic rays between knee & ankle



- Where is the Galactic to extragalactic transition?
- What are the most powerful Galactic accelerators?
- Is there a secondary Galactic component between 2nd knee and ankle?
- **Needed:** accurate mass composition!
- **Warning:** some models show very subtle transition.
  E.g. Helium-rich Wolf-Rayet supernova expanding into magnetised wind
  Gal/XGal transition = He to proton !

See Thoudam et al, A&A 595, A33 (2016)

Xmax measurements below the ankle

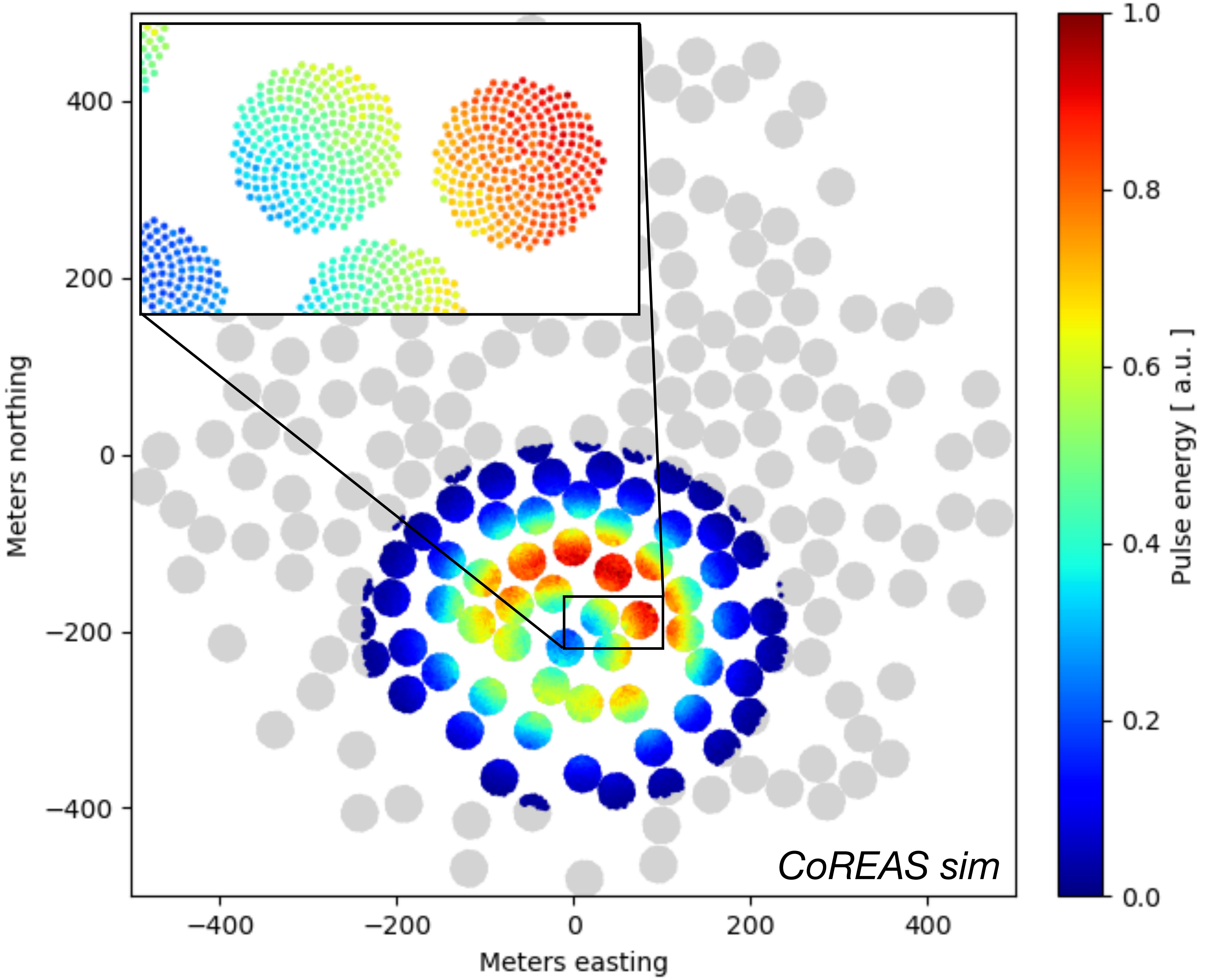


- Light particles interact deeper in atmosphere on average
  Xmax = atmospheric depth of shower maximum
- Tension between observations of Auger fluorescence + radio vs. LOFAR and Telescope Array
- Not much data below 10^{17} eV (TA down to $10^{15.3}$ eV)
- **Our goal for the SKA: Provide high-resolution Xmax measurements in 10^{16} - 10^{18} eV range (and maybe lower…)**

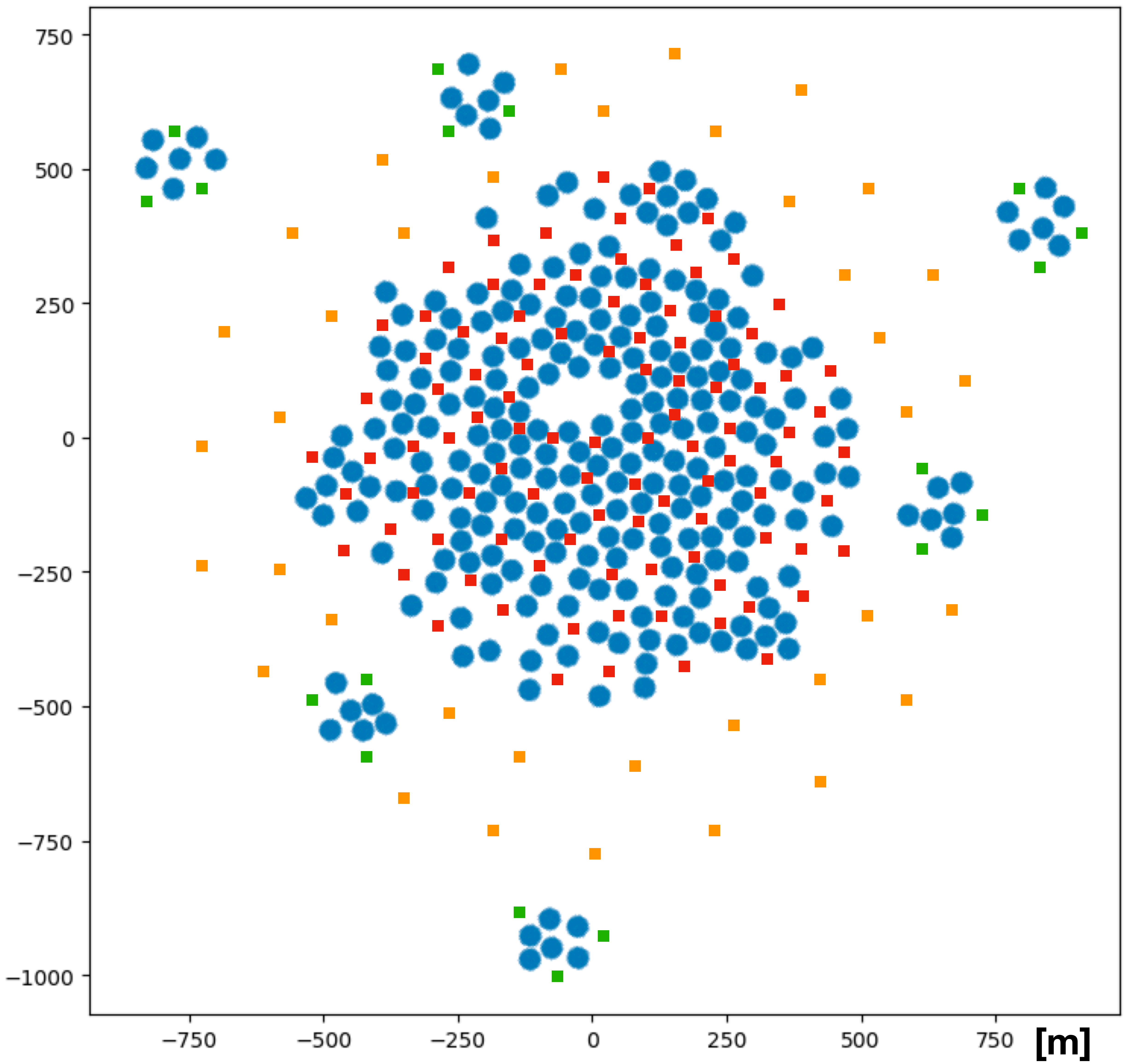
The radio high-density frontier

- SKA-low (Australian site) will consist of **57,344 log-periodic antennas** within an area of **~1 km^2**
- Frequency bandwidth **50-350 MHz**
- Construction phase started. **Raw voltage buffers** on all antennas.
- With **particle detector array** for triggering, SKA can observe CRs
- **Extremely high resolution radio CR observations at 10^{15} eV - 10^{18} eV**

256 dual-polarised antennas per field



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)
- Particle detectors remote (~18 units)

Scintillators from KASCADE-Grande coll.

Prototype station @ Murchison Widefield Array

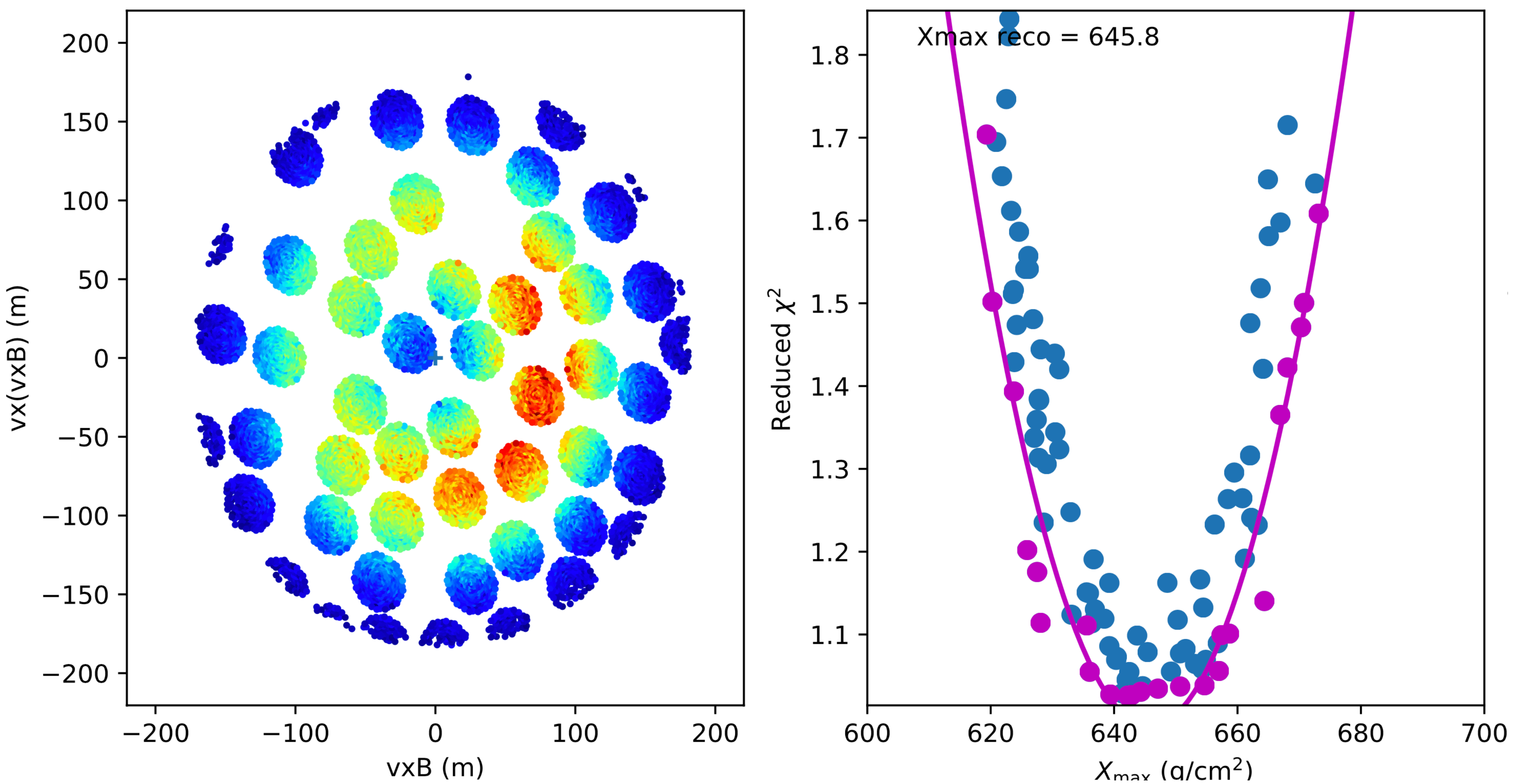
Low noise system: SiPMs & RFoF comm.

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

<u>This year:</u>
Deployment of 8-station array at MWA

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

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

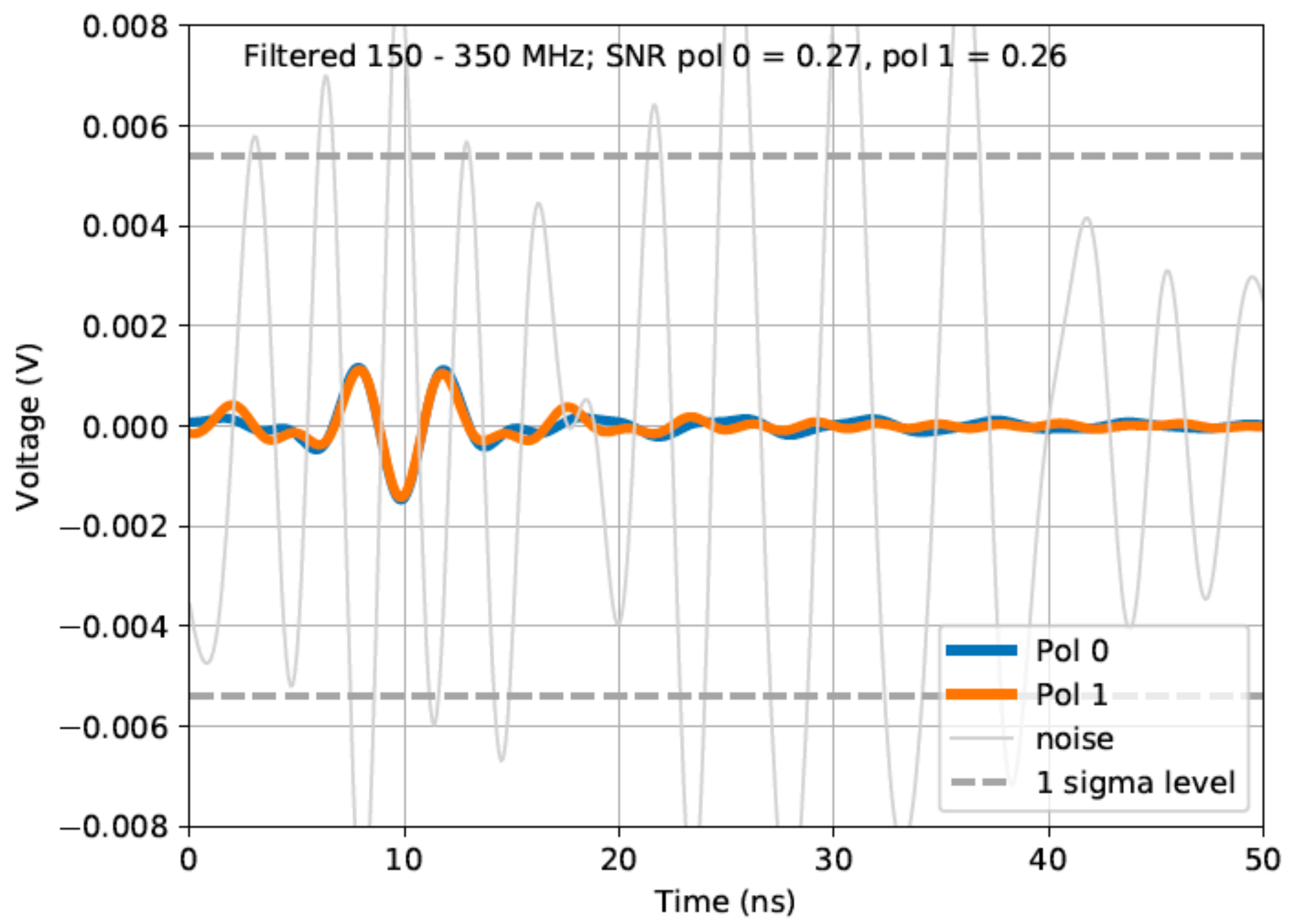
A. Corstanje et al., PoS(ARENA2022)024

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

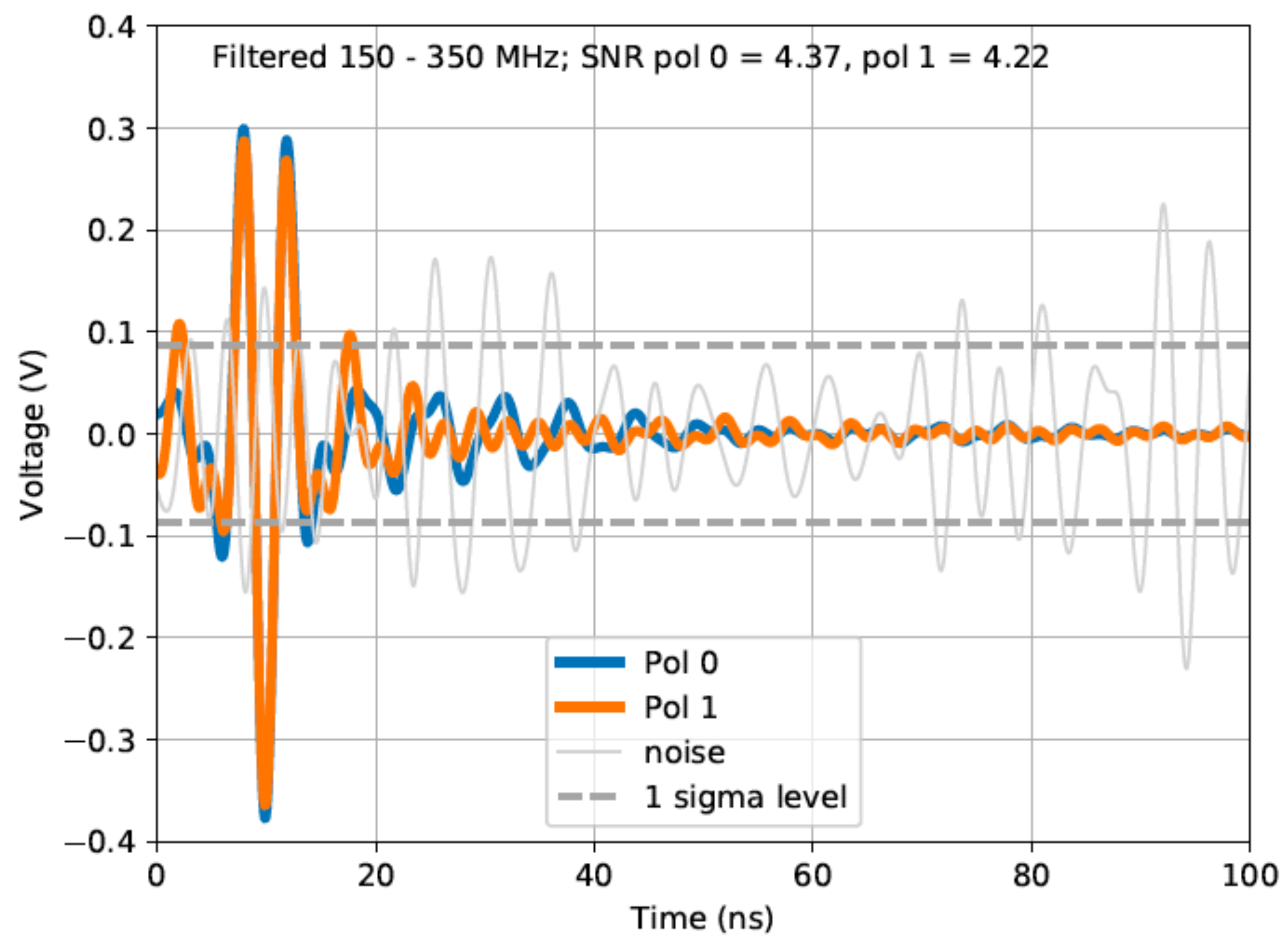
Towards lower energies

CR radio pulse energy ∝ E^2
hard to detect below 10^{16} eV

Beamforming with antenna fields improves SNR by 16
CR mass composition at lower energies!

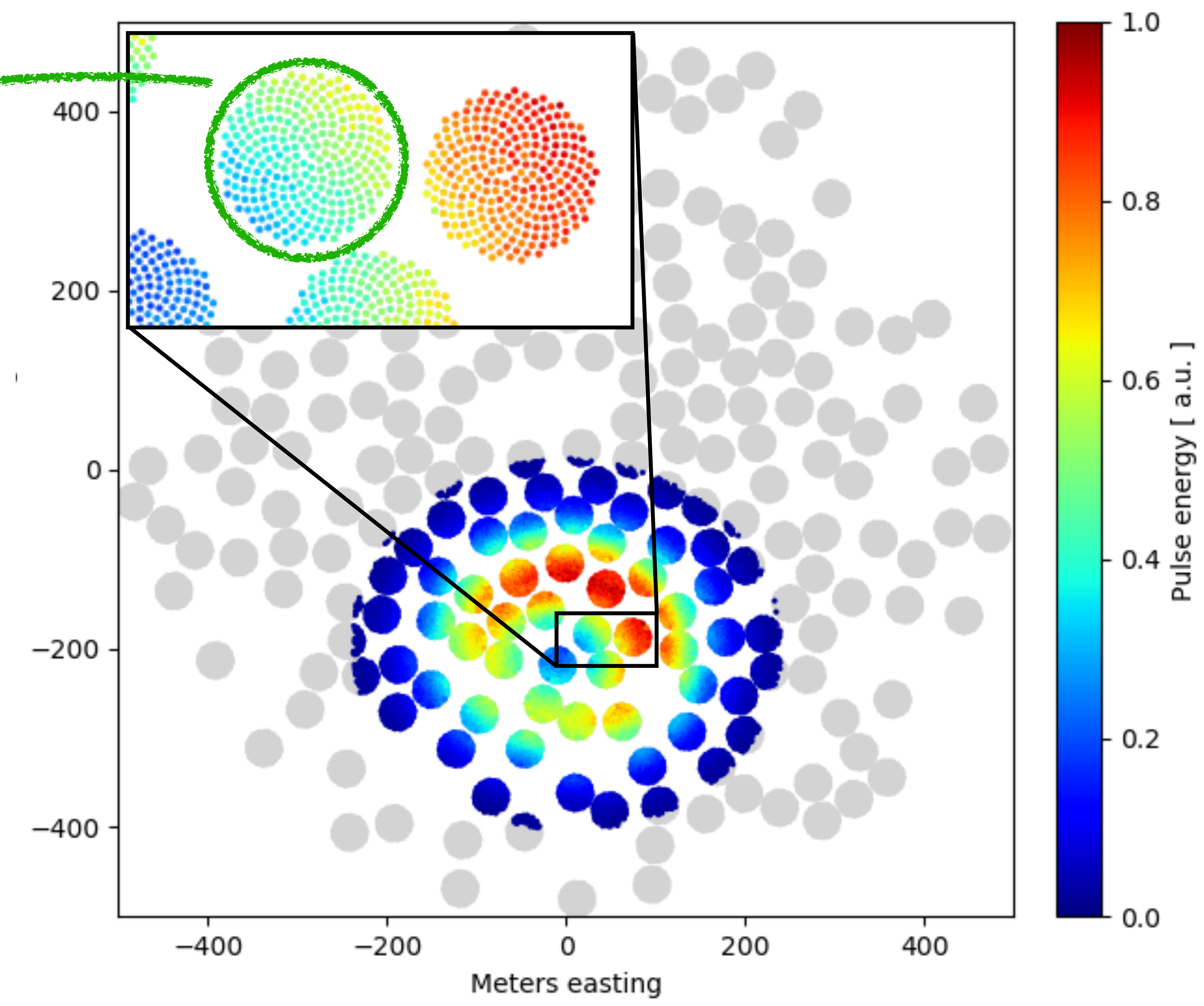


Radio pulse of PeV shower
filtered 150-350 MHz
SNR = 0.27



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

256 dual-polarised antennas per field



PeV gamma rays are detectable but triggering and hadron separation still huge challenge…

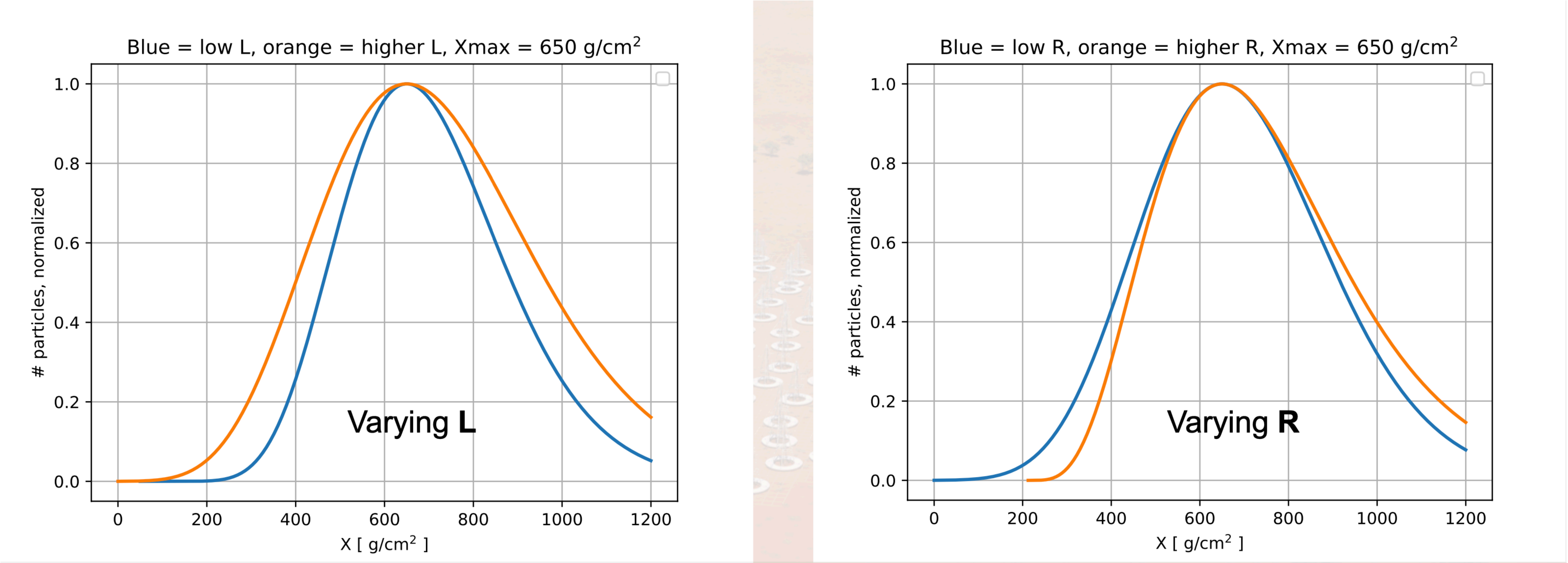
New analysis techniques

- Thousands of antennas per air showers = more than needed for standard techniques.
  What new stuff can we do?
- Reconstruction of shape parameters: $N(X) = \exp\left(-\frac{X - X_{max}}{RL}\right)\left(1 - \frac{R}{L}(X - X_{max})\right)^{\frac{1}{R^2}}$

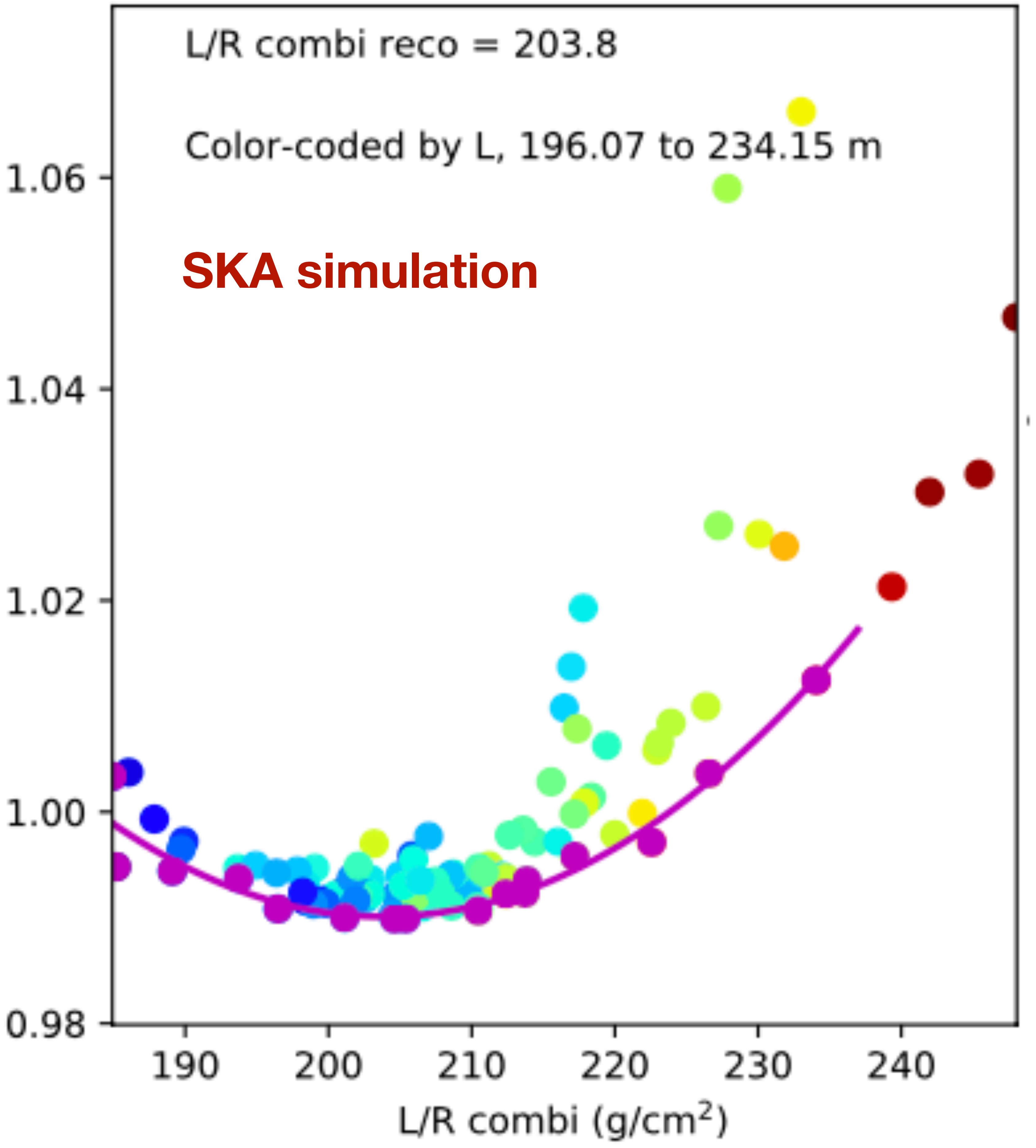
radio signal is coherent below some frequency f_{coh}

f_{coh} depends on projected length scales of shower

broad bandwidth + many viewing angles = sensitivity to shape



Reconstructing shape parameters



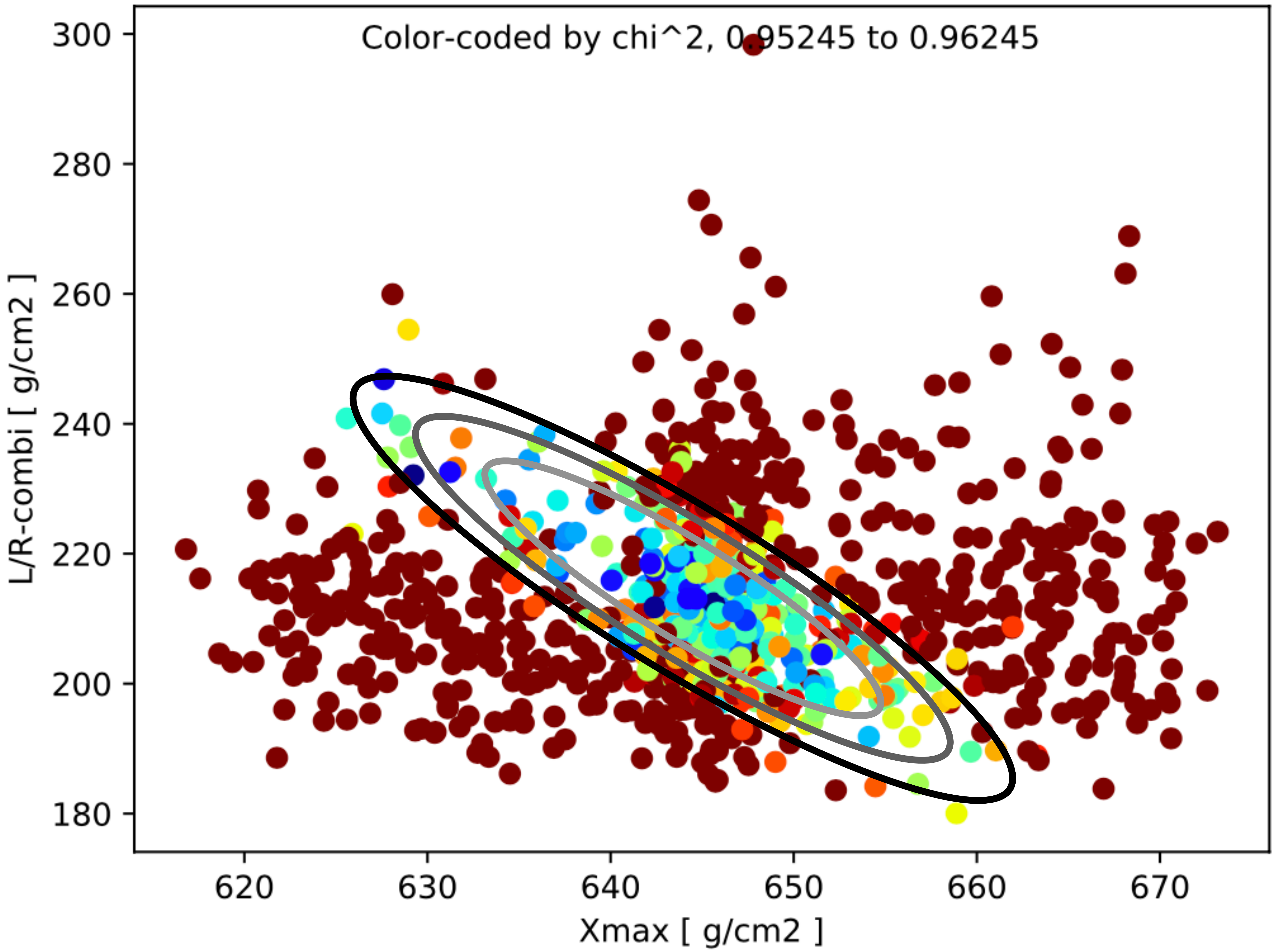
A. Corstanje et al., PoS(ARENA2022)024

- 100 showers of same Xmax,
- Interpolated footprint
- Free core fit.
- MC truth: S = 204.6 g/cm^2
  reco: S = 203.8 g/cm^2

SKA can reconstruct a linear combination of L and R:

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

The radio simulation frontier

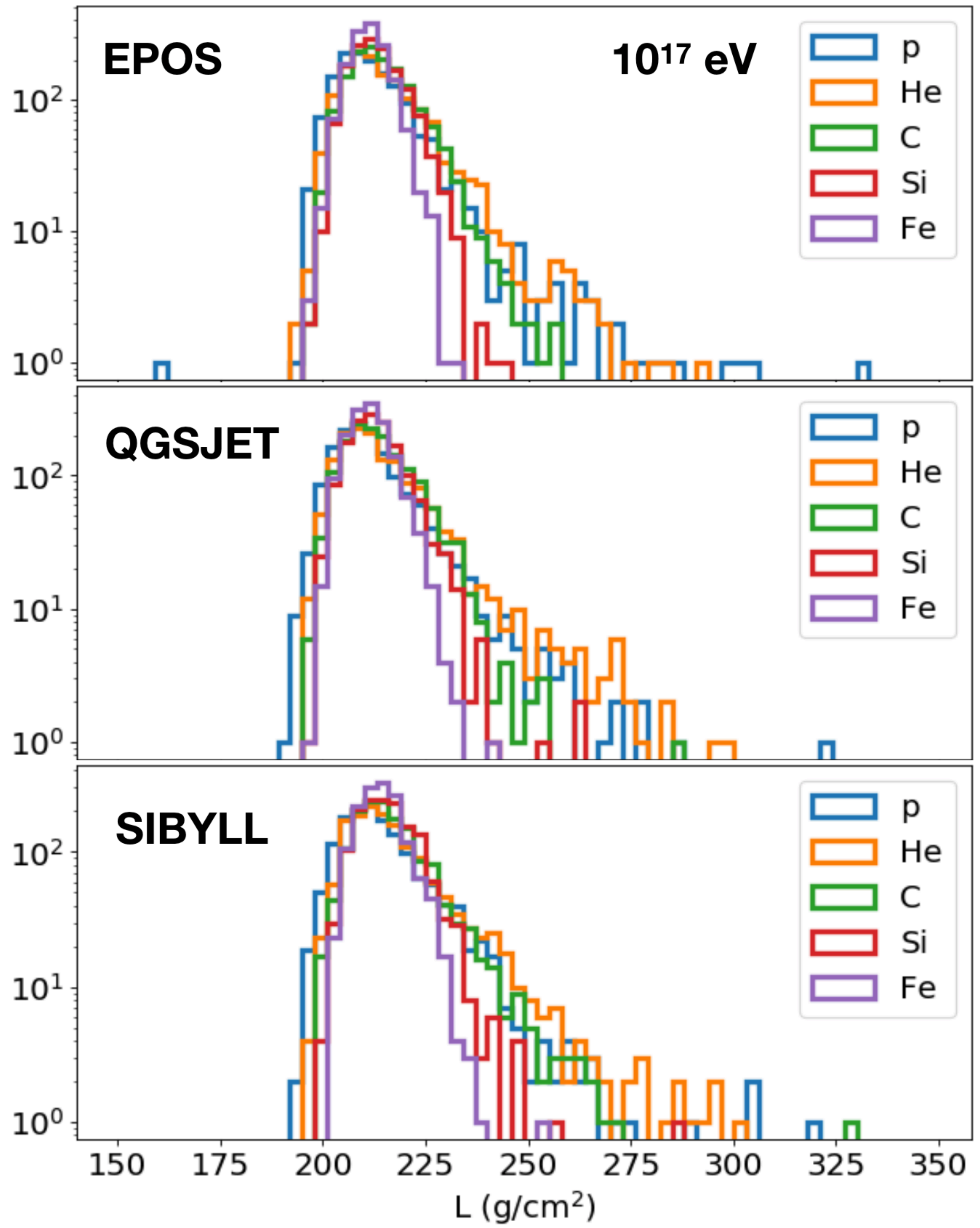


A. Corstanje et al., PoS(ARENA2022)024

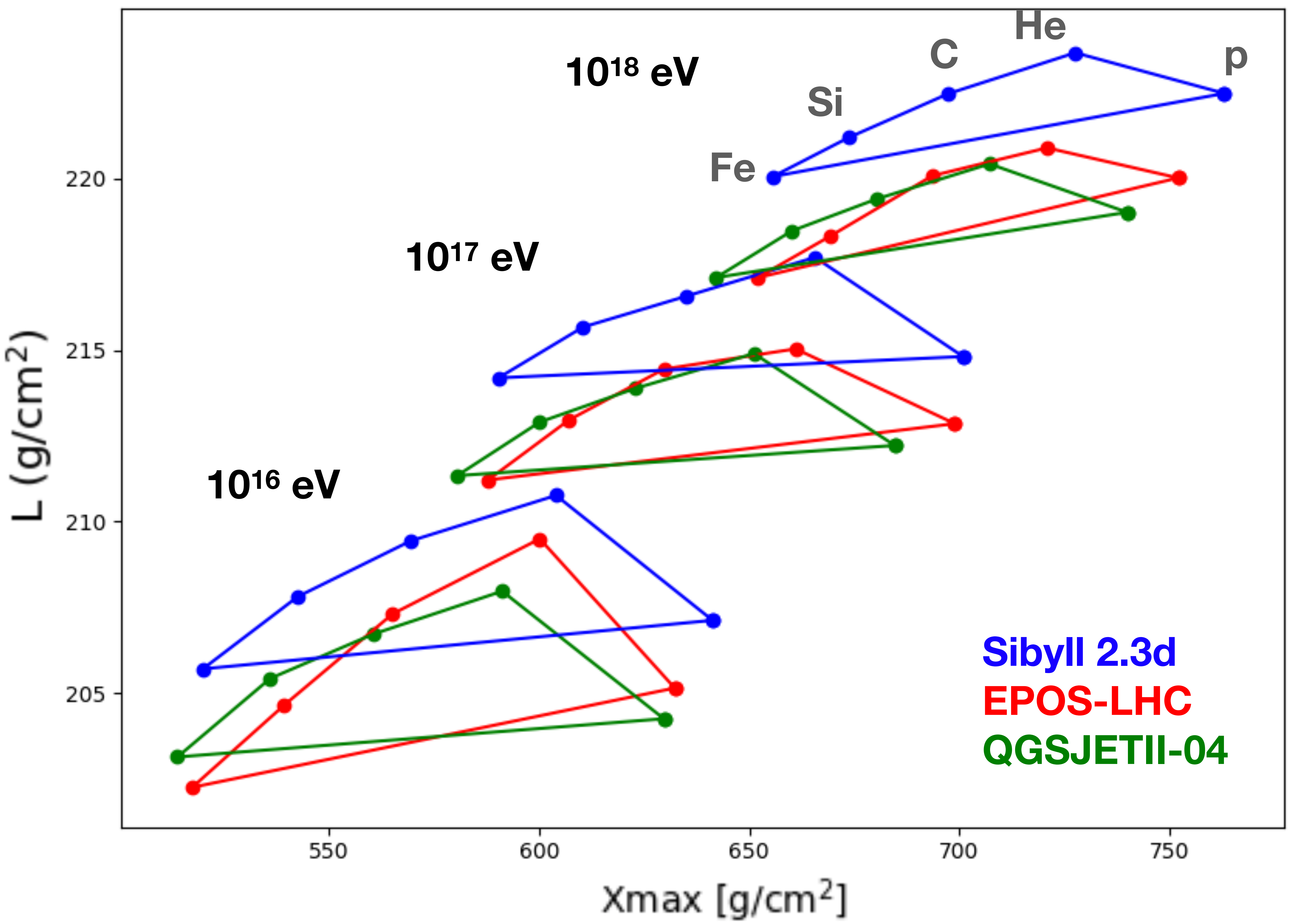
- In a real analysis Xmax and L/R have to be fitted simultaneously.
- This currently requires too much computational resources to analyse all shower.
- New approaches are in development to produce fast & accurate simulations.

Science with shape parameters

CONEX simulations: *L* distribution



High-L tail largest for Helium



L distribution provides new information on mass composition & hadronic interactions

Conclusions

- SKA will produce **highest-resolution radio air shower observations**

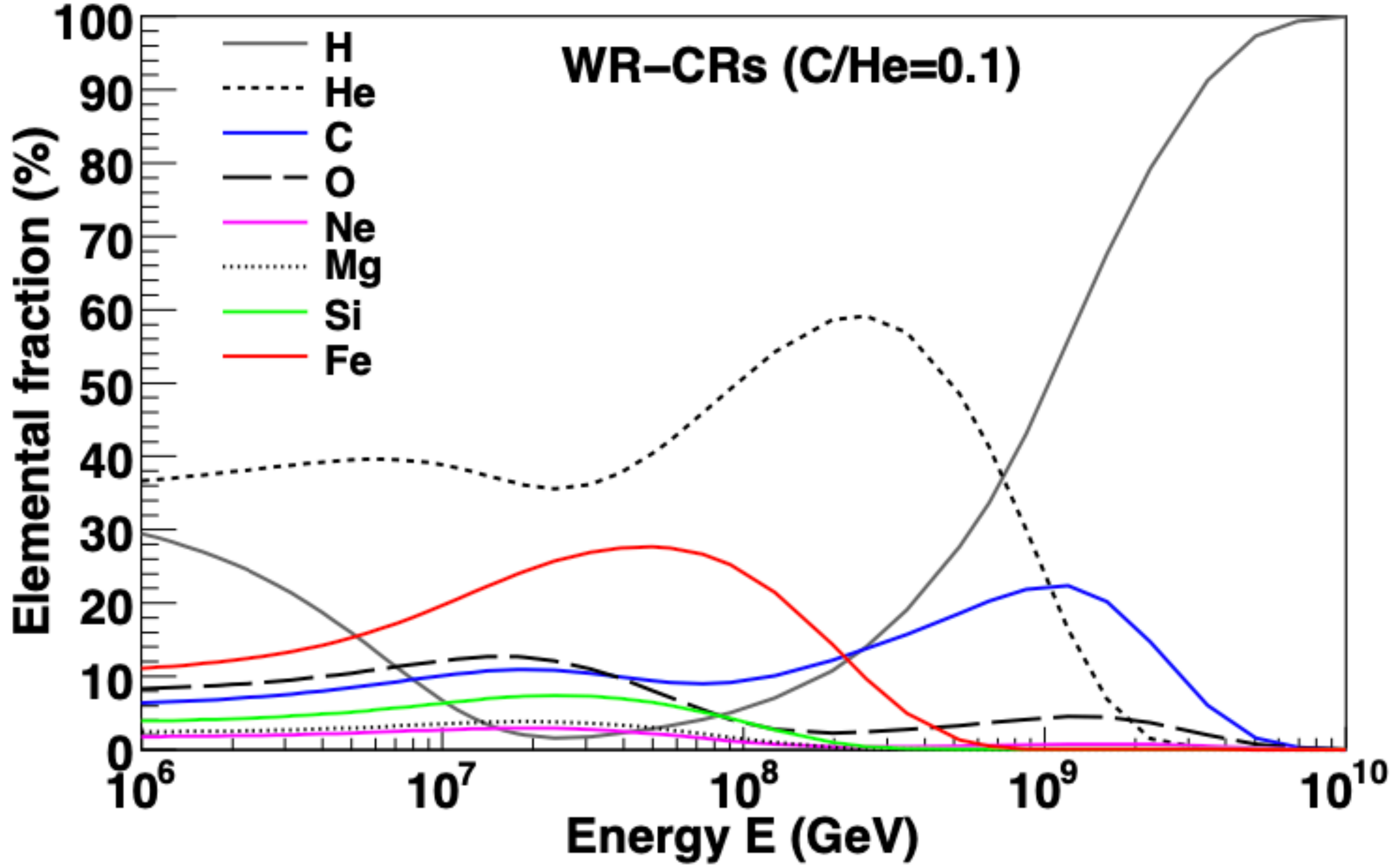
- Unprecedented precision on **Xmax at 10^{16} - 10^{18} eV**

- New reconstruction possibilities
  sensitivity to shape parameters (L/R) demonstrated
  new constraints on CR mass composition & hadronic int. models.

- **Faster simulations needed** to explore possibilities and develop analysis techniques

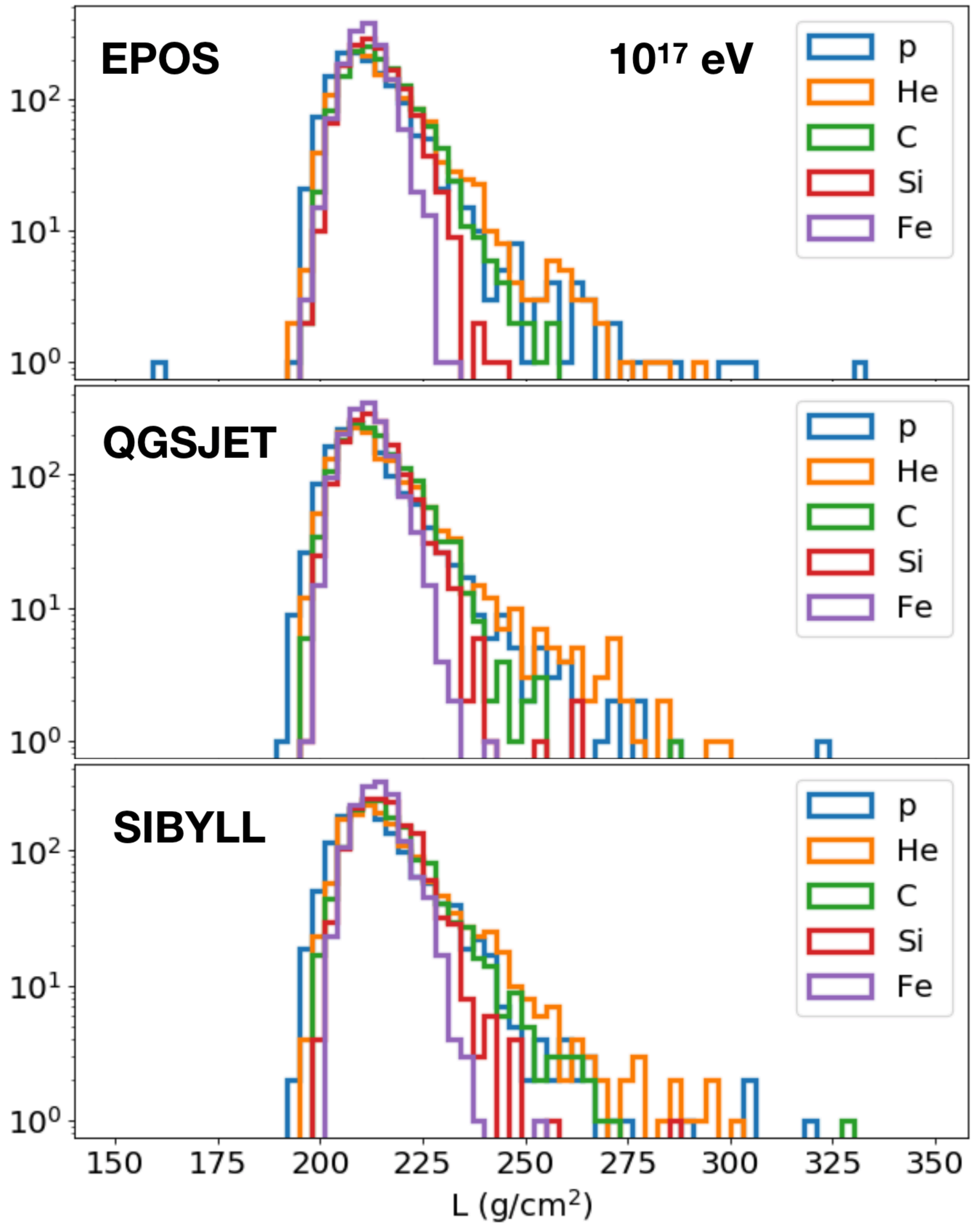
- Beamforming lowers energy threshold:
  CR mass composition down to lower energies
  PeV gamma-rays detectable… but triggering & hadron separation very challenging.

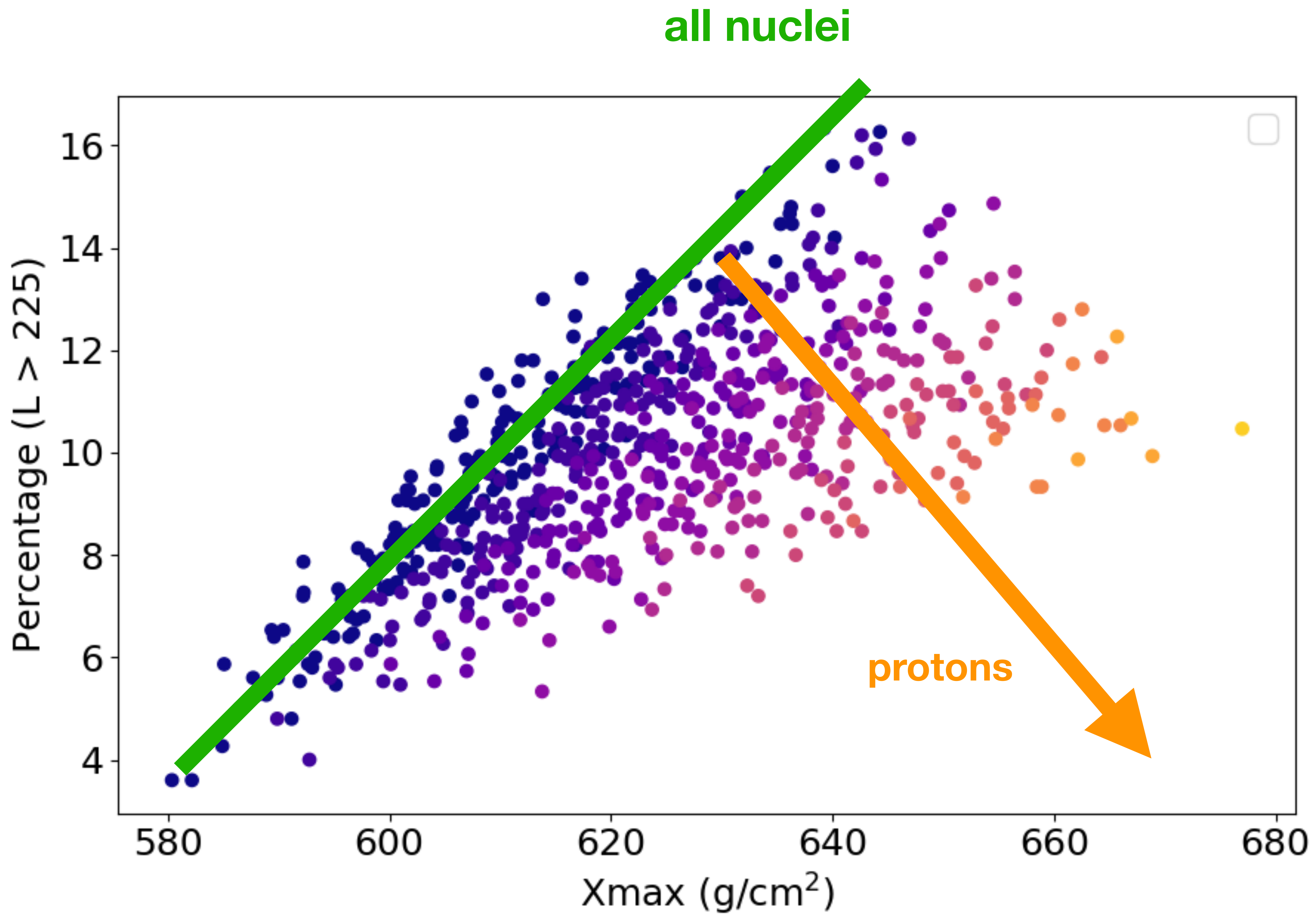
Transition region models



- Composition below ankle? Many different possibilities
- Wolf-Rayet scenario: C/He to p transition
- How to distinguish p from He?

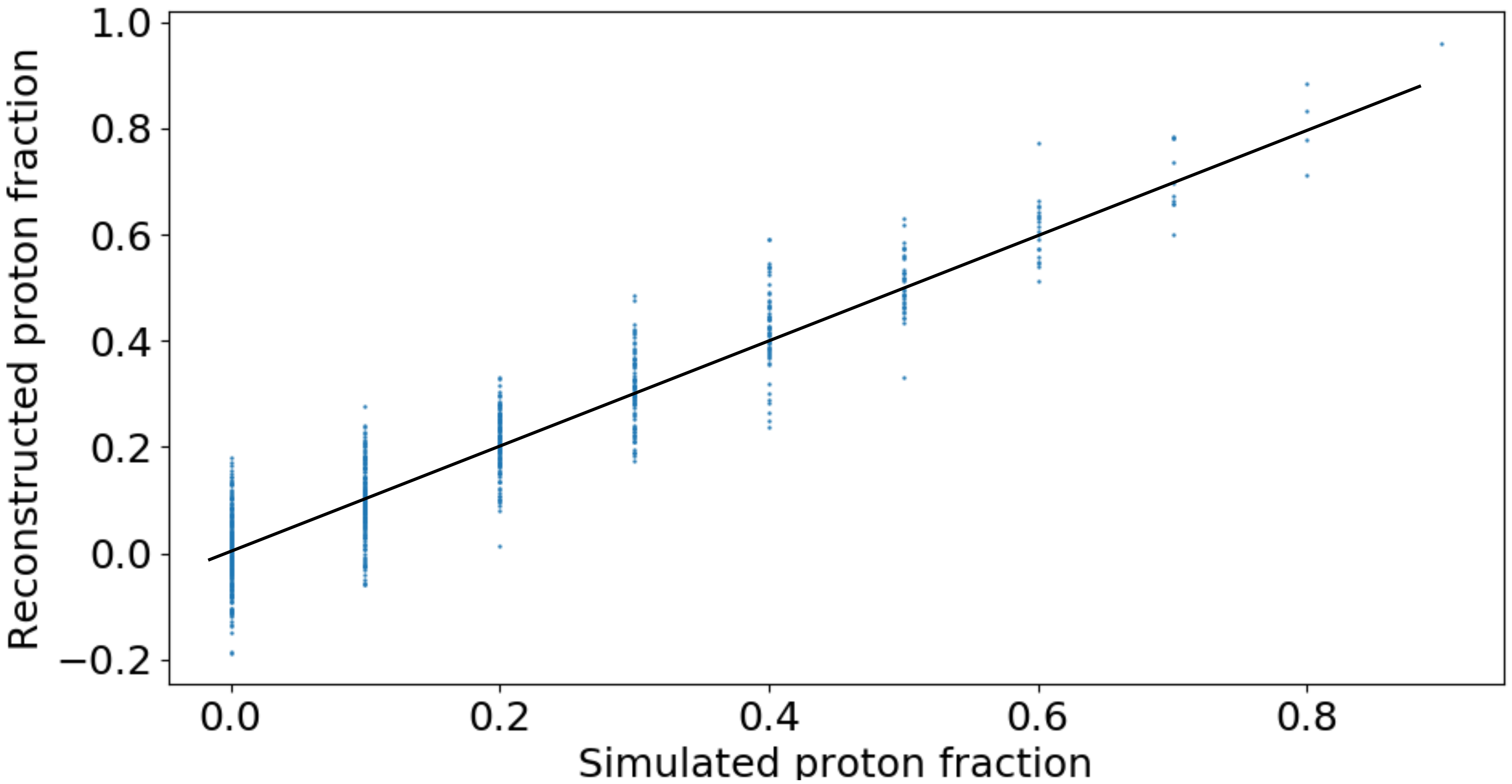
Thoudam et al, A&A 595, A33 (2016)





- All nuclei (except H) are on one side of the triangle
- Distance to line = proton fraction

Reconstructed proton fraction



- Proton fraction found within ~10% with very simple method
- Includes error on Xmax and L of 10 g/cm^2
- Will not get worse when adding more than 5 elements