The Square Kilometer Array: ultra-high precision observations of cosmic rays in the PeV-EeV range.

VRIJE UNIVERSITEIT BRUSSEL

Stijn Buitink

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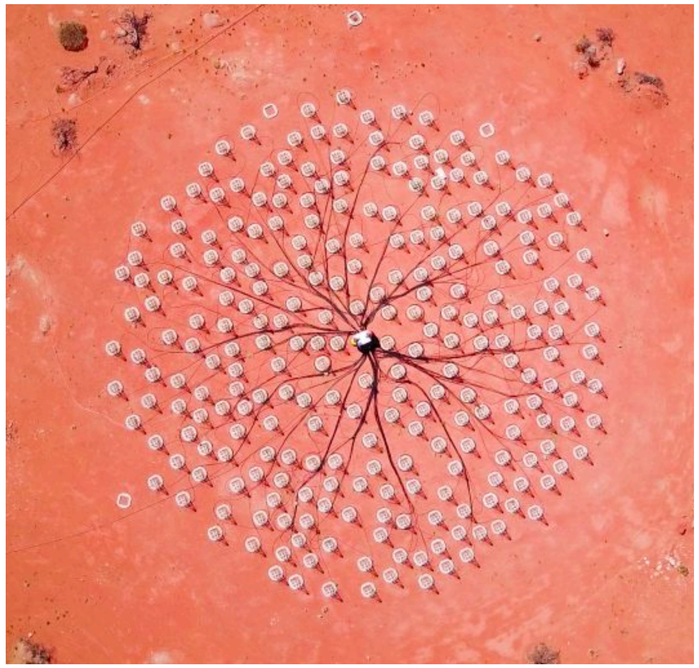
13th CosPa meeting, Ghent University, 19 June 2023

Cosmic Ray observations with the SKA

- 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)

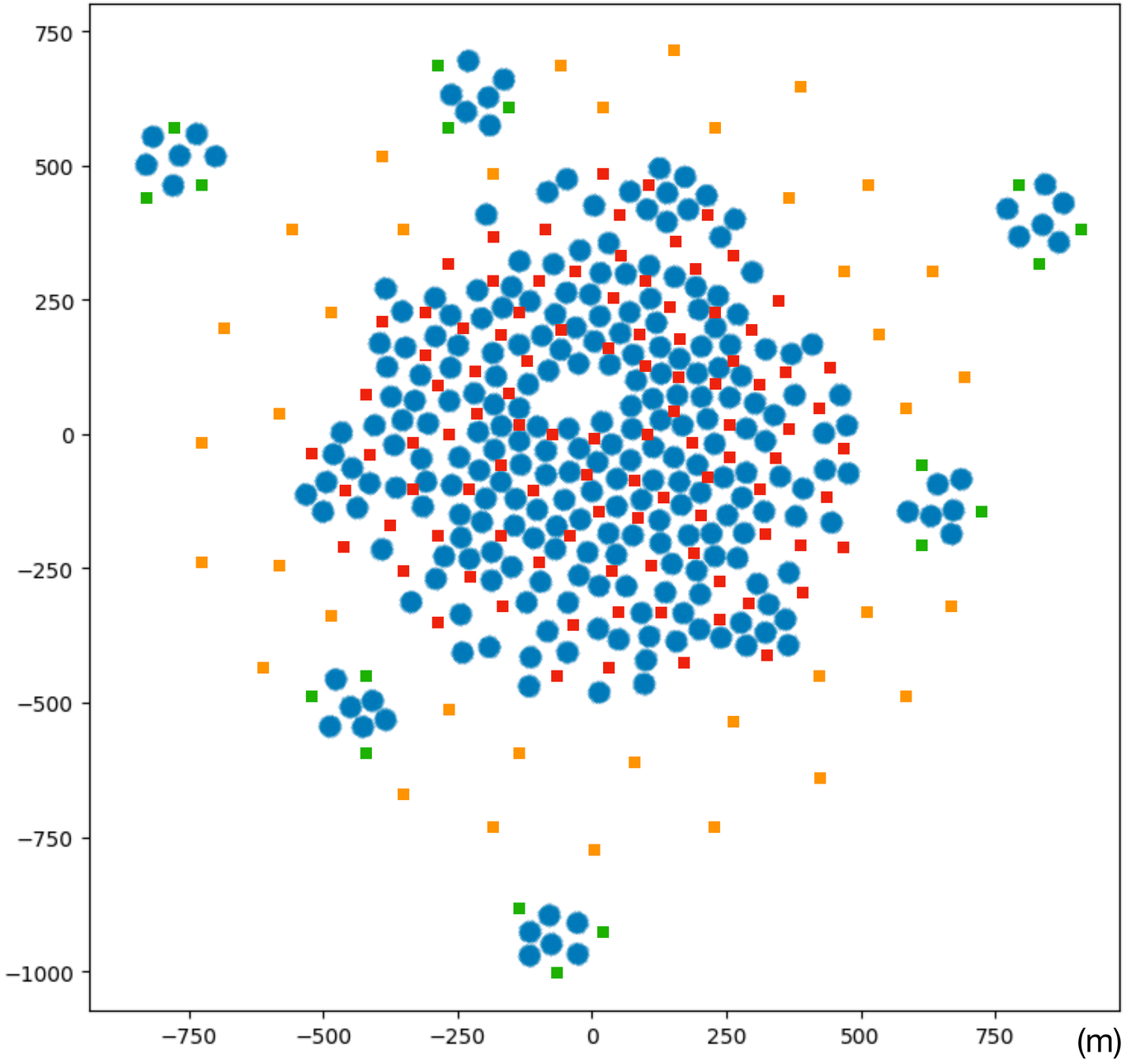


Prototype @MRO (256 antennas)

Scintillator array

- Scintillator array for triggering and support in reconstruction.
- ~100 detectors to cover SKA-low area
- Prototype station with KASCADE scintillator + SiPMs running at MRO.
- Eight additional stations will be deployed with ~half year.
- In due time, array can be moved to SKA-low

Prototype scintillator station deployed at Murchison Radio-astronomy Observatory
Bray et al., NIMPA 973, 164168 (2020)



Example layout of particle detector array at SKA-low

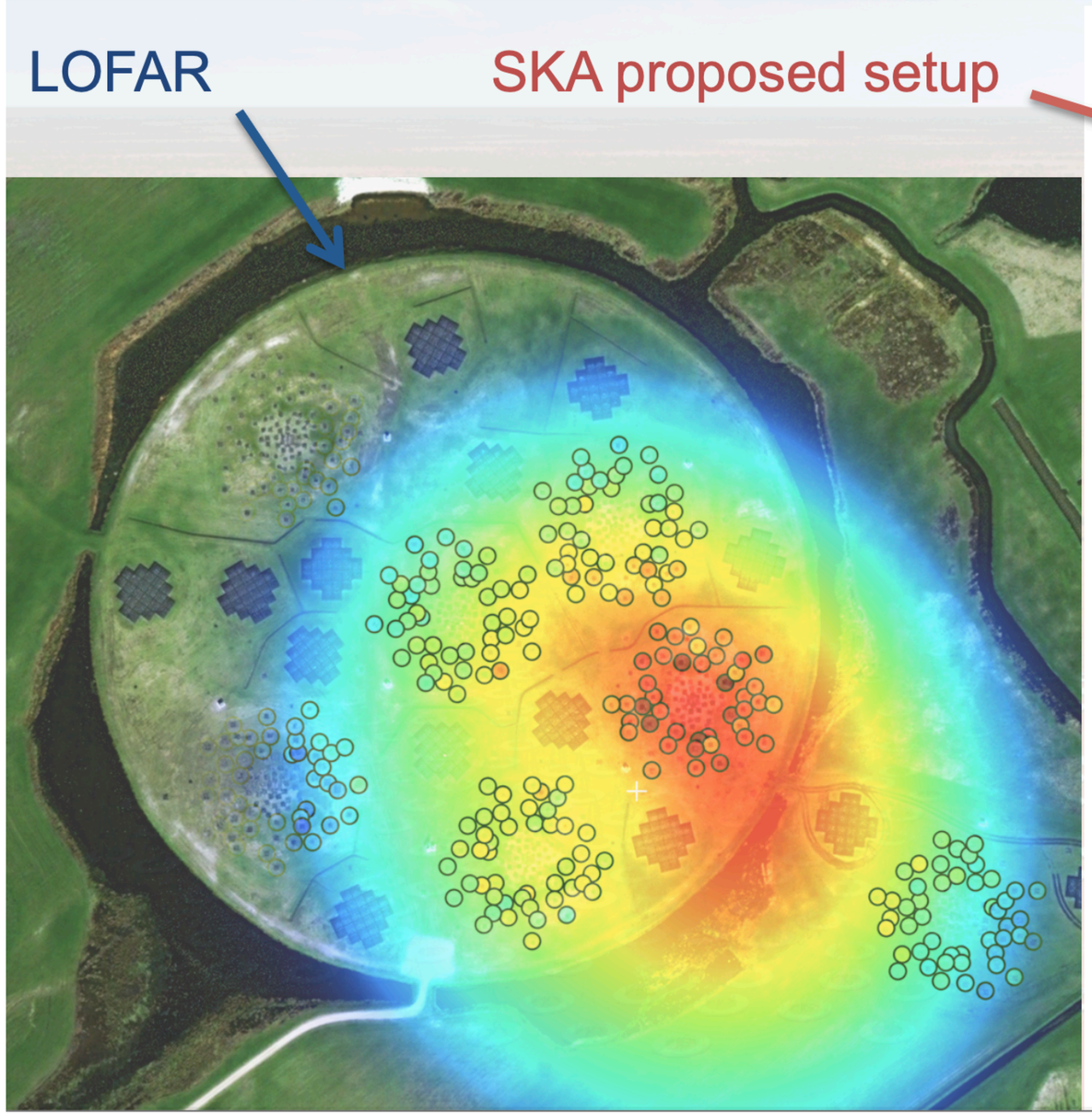
- **Antenna field**
- **Particle detectors dense array (~100 units)**
- **Particle detectors ring (~50 units)**
- **Particle detectors remote (~18 units)**

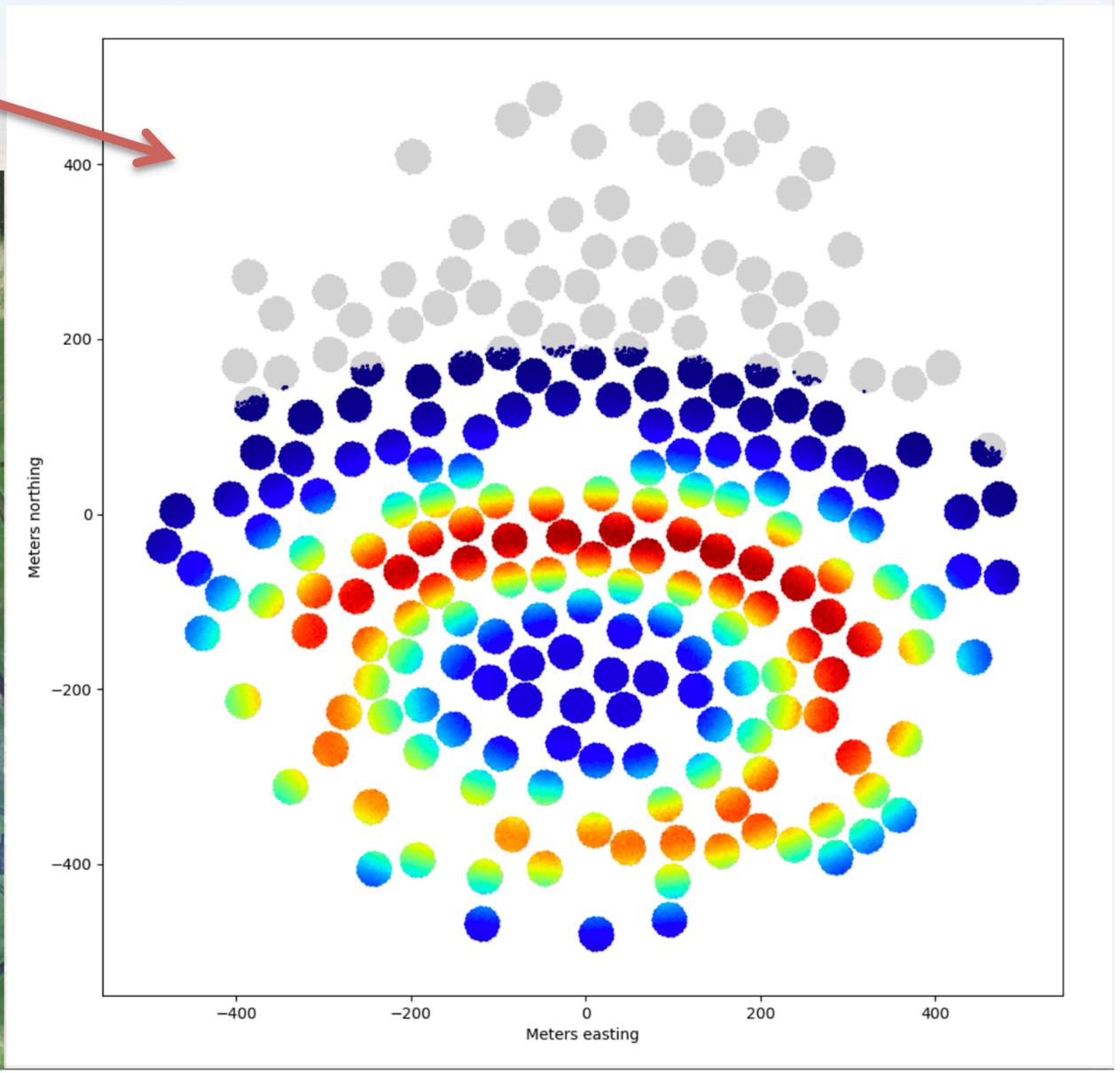
Particle detectors are ~m² size
(= *smaller than drawn here*)

Prototype station Murchison

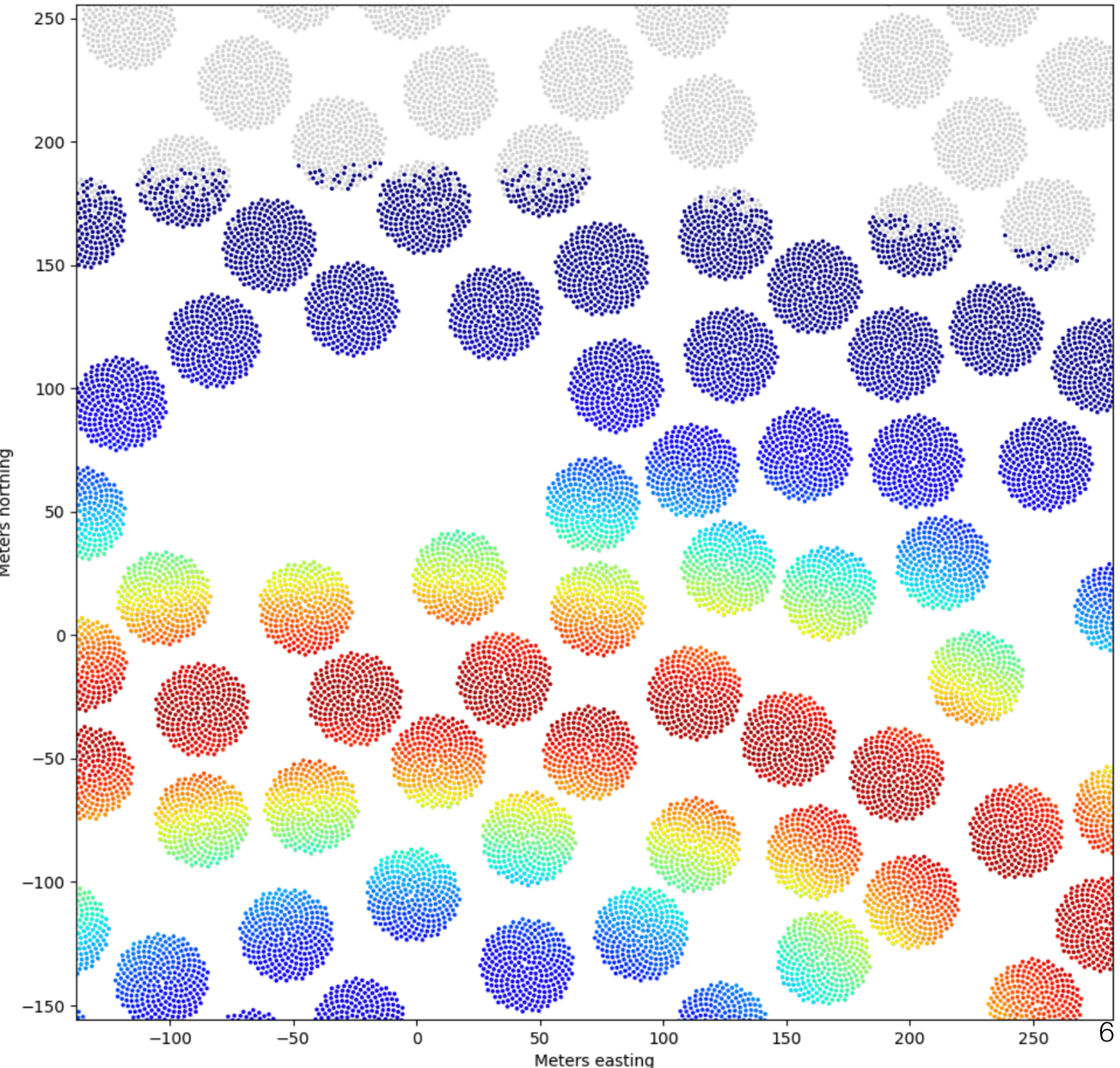
Array consists of ~170 detectors

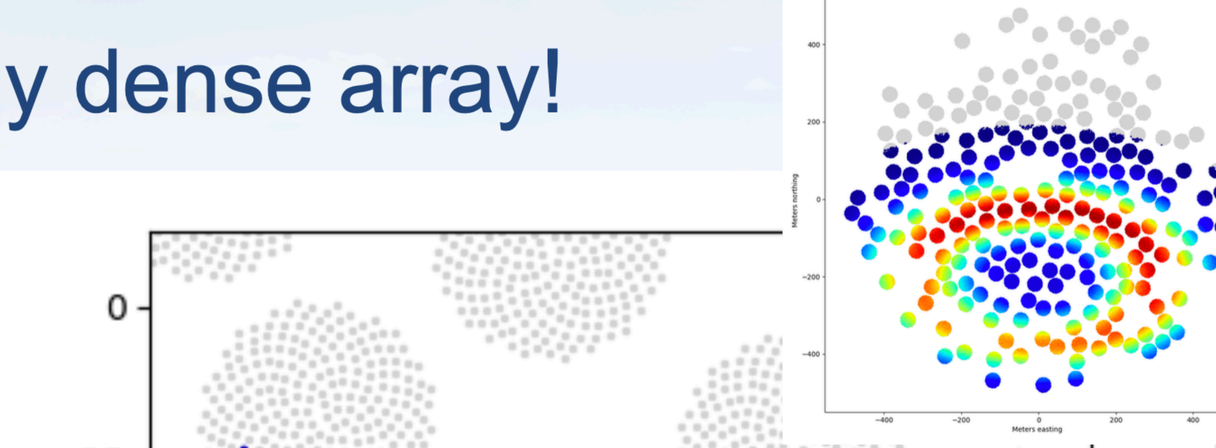
<u>Placement consideration:</u>
Exact locations are flexible
Distance between detectors ~50 - 100m (dense part)

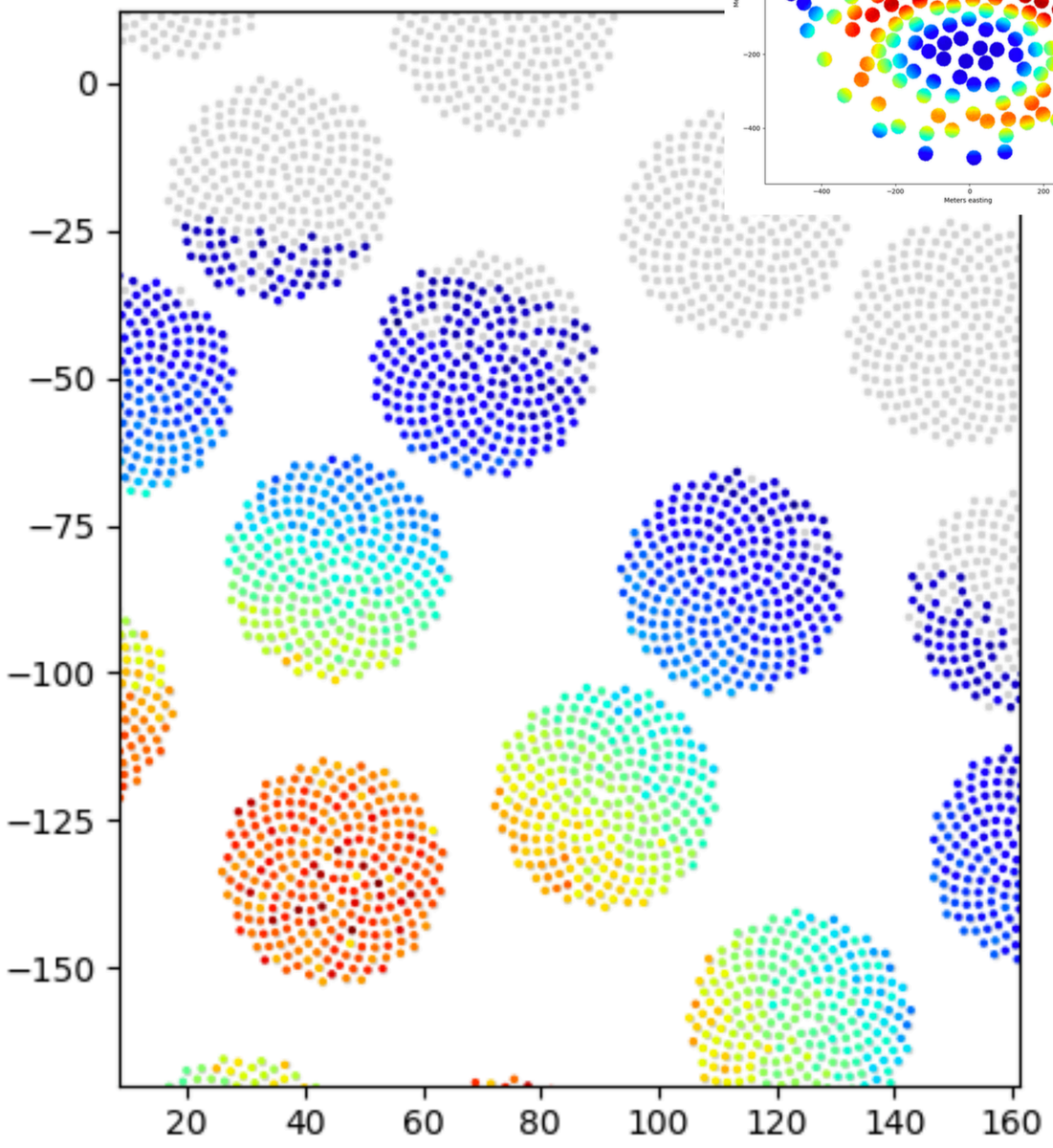

LOFAR
SKA proposed setup


400
200
0
−200
−400
Meters northing
−400
−200
0
200
400
Meters easting

SKA-Low, a really dense array!







Science case

- **Origin of cosmic rays in the galactic-extragalactic transition region**
  High energy threshold: ~10^{18} eV
  Low energy threshold: ~10^{16} eV (broad frequency range, beam forming)

- **Search for PeV gamma-rays**
  Beamforming with 256 antennas = 16x SNR
  Matched filtering of antenna pattern / NN denoising = 3-5x SNR
  Challenge: trigger strategy

- **Most precise test to MC radio simulation codes (CoREAS, ZHAireS, …)**

- **High-precision air shower physics**
  Validation of hadronic interaction models
  Advanced reconstruction techniques (interferometry, shower tomography, …)

Science case

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  High energy threshold: ~10^{18} eV
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focus of this talk

- **Search for PeV gamma-rays**
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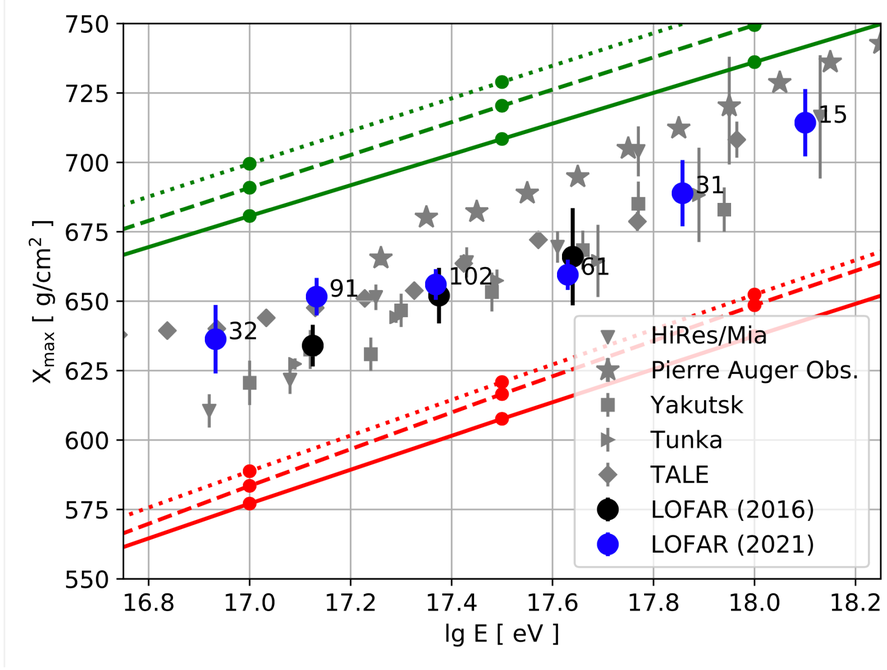
Composition studies

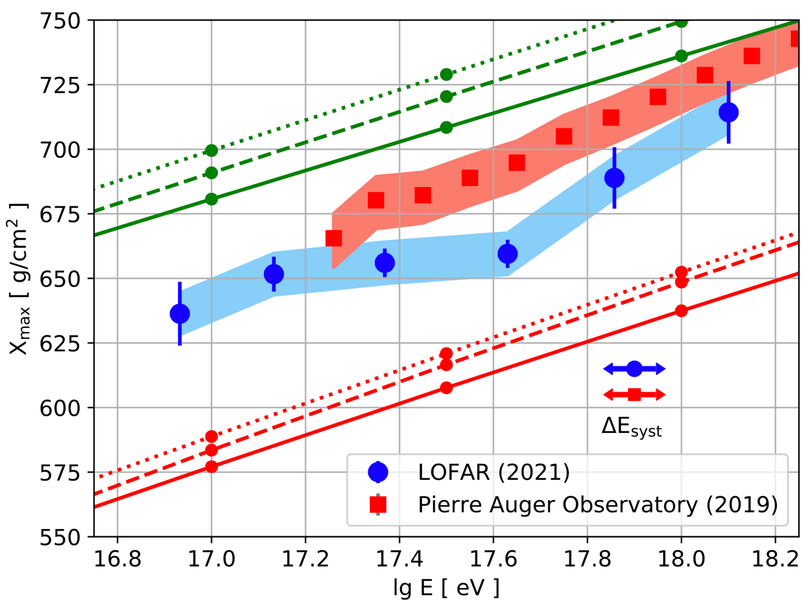
Why is it hard?

- Xmax between observatories & techniques often don’t agree
- Xmax resolution needs to be high
- Difficult to resolve elements with similar masses (e.g. p/He)
- Mass composition depends on hadronic interaction model

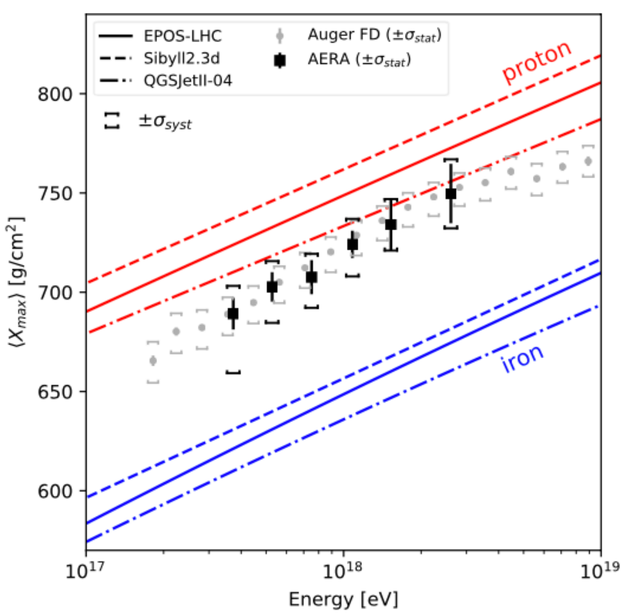
Xmax: LOFAR, AERA, Auger



LOFAR Xmax (blue)



LOFAR (blue) & Auger fluorescence (red)

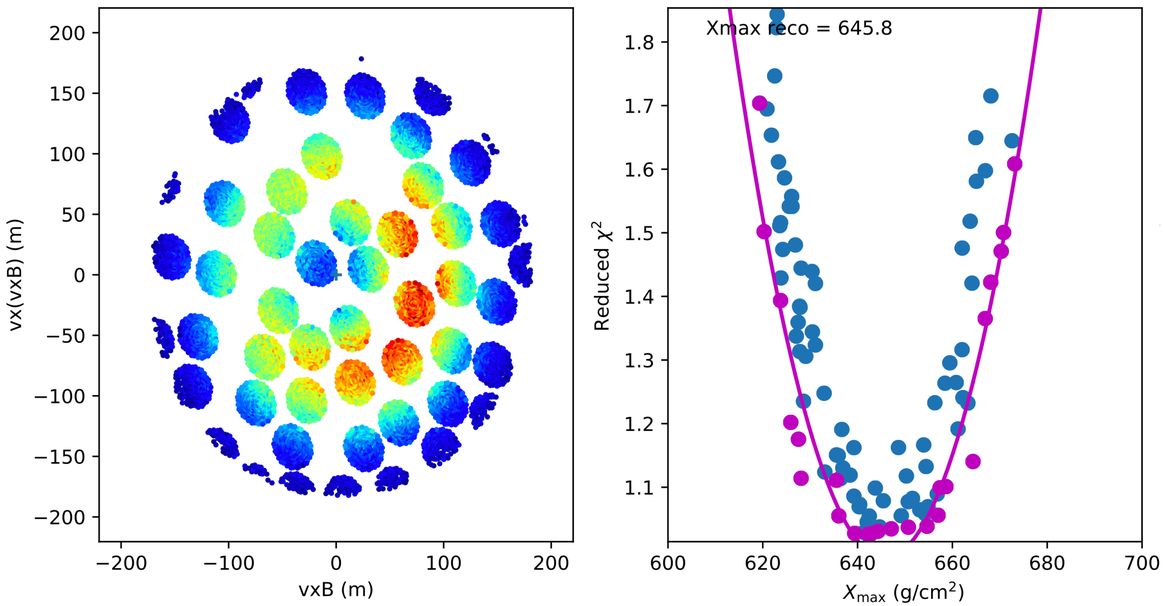


Auger: radio & fluorescence

LOFAR & TA in tension with AERA & Auger fluo
LOFAR/Auger working group: no mistakes/biases/explanations found so far…

What is going on? Dense vs sparse array? North vs. South?
SKA can be "downgraded" to LOFAR or AERA layout & analysis: direct comparison per shower!

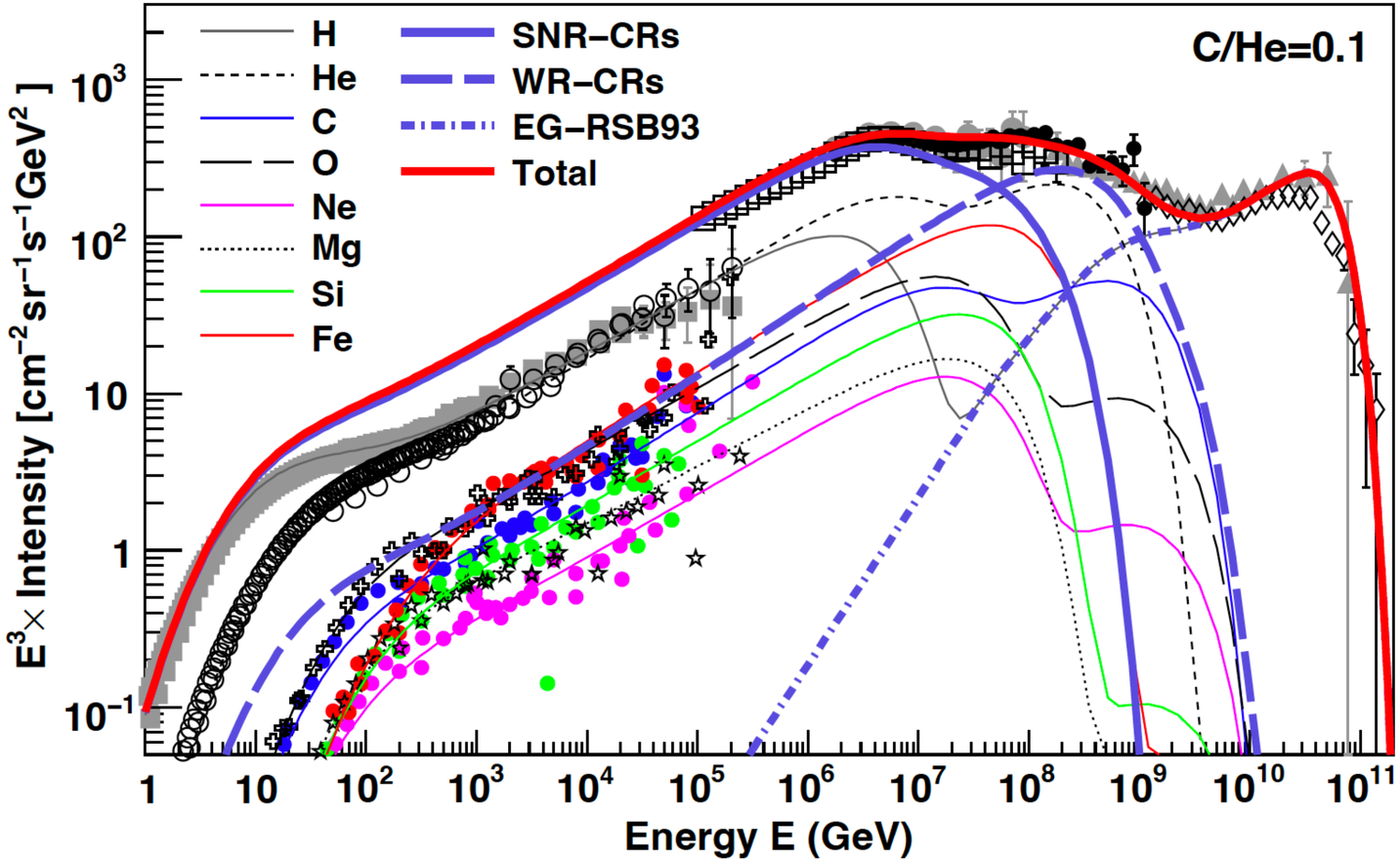
SKA radio simulations



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

- Using Gaussian noise based on: Galactic background
  (dominant < 200 MHz)
  system noise
  (dominant > 200 MHz)
- Resolution limited by number of simulated showers in sample.
- Final resolution will depend on systematic uncertainties on atmosphere and antenna model.

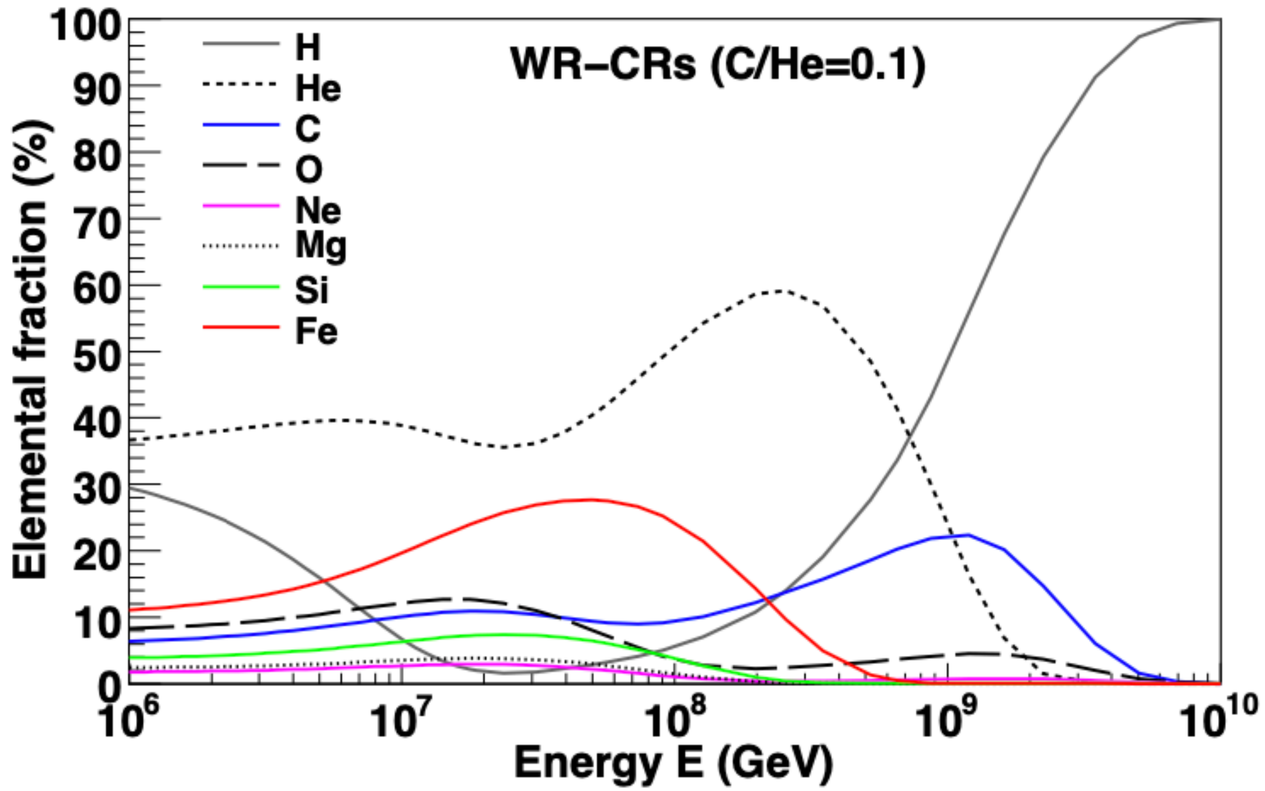
Transition region models



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

- Knee is likely p/He peak of main galactic population
- Extragalactic flux strongly suppressed below EeV.
- How to fill the gap? e.g. Wolf-Rayet stars

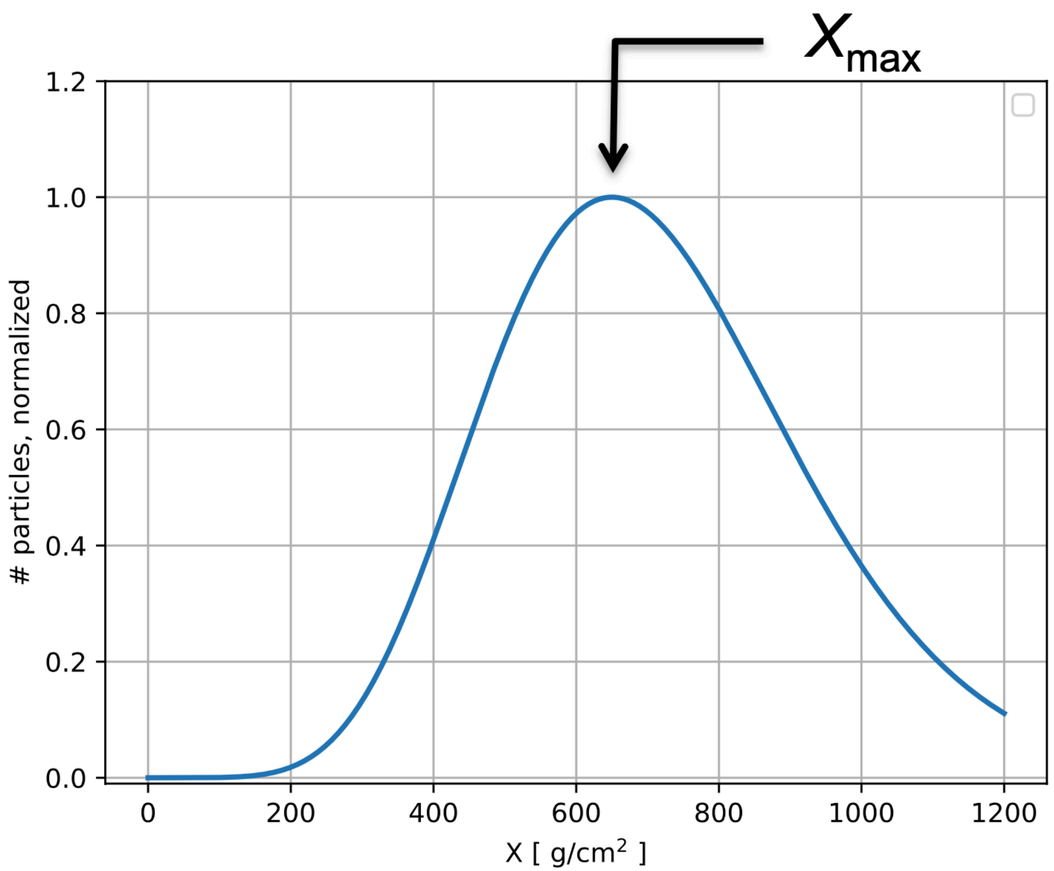
Transition region models



- 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)

Probing the longitudinal evolution



Longitudinal distribution of particles, along the air shower's track

- Xmax
- Width
- Asymmetry (skewness)

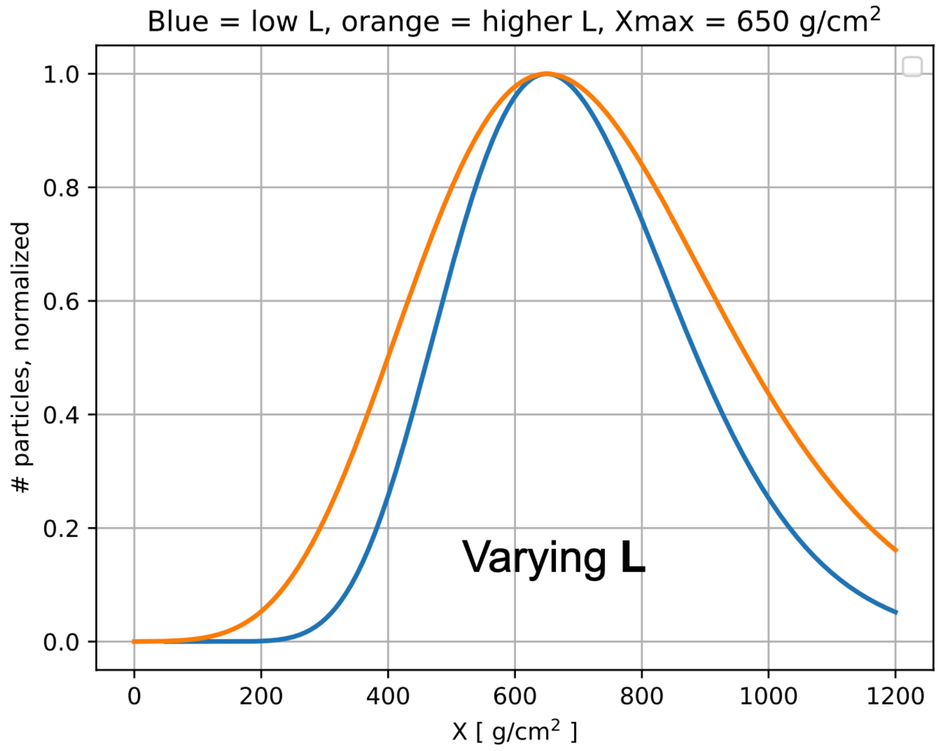
4

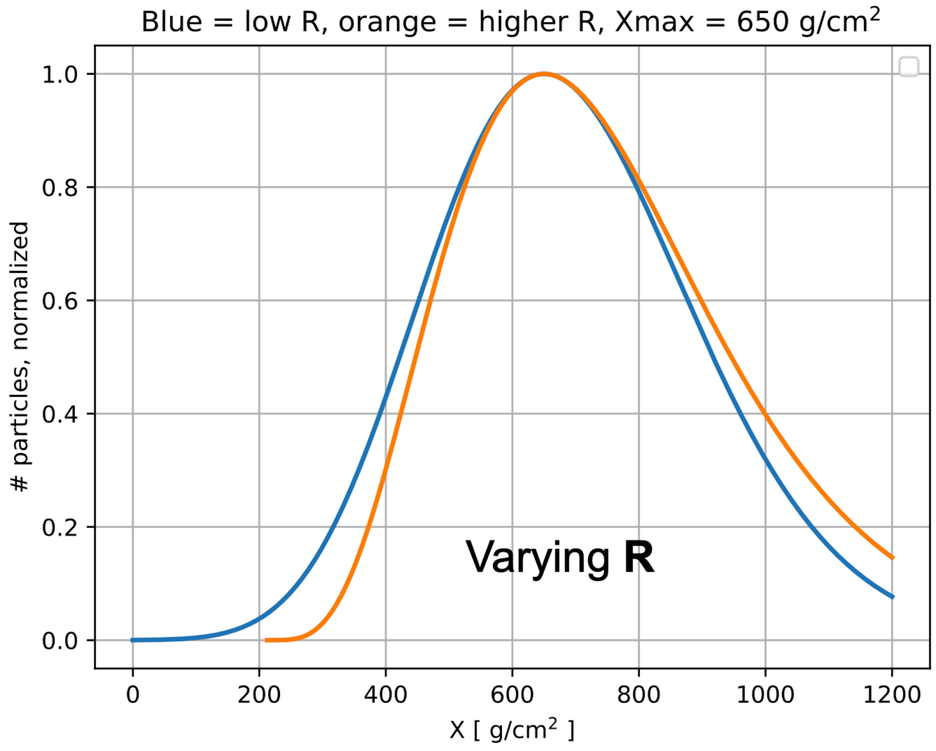
Probing the longitudinal evolution

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

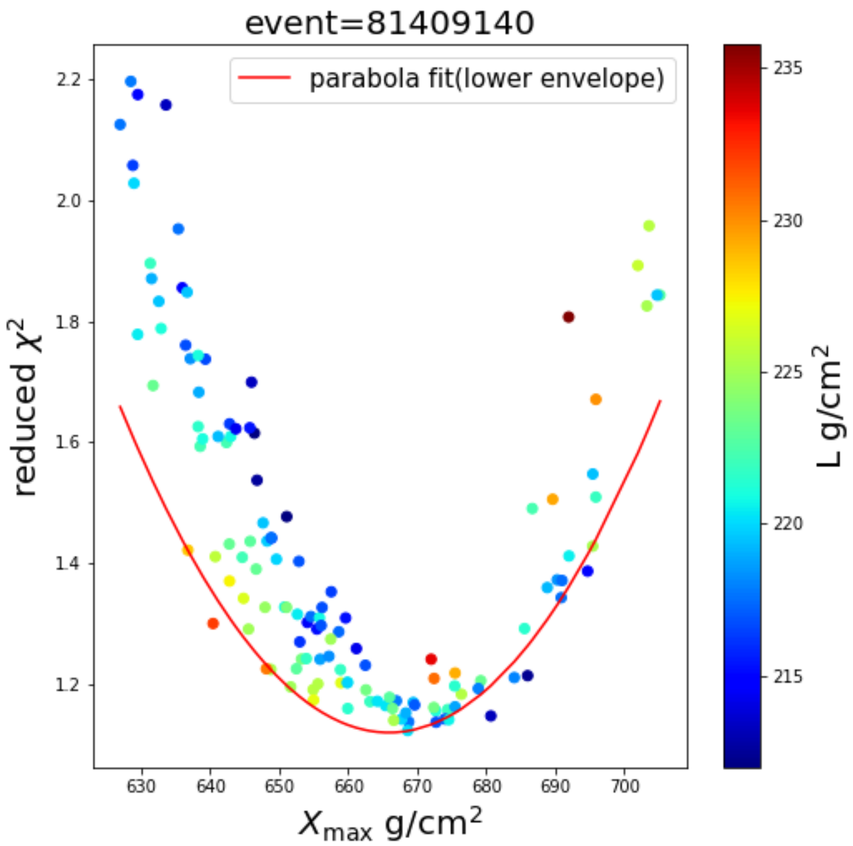
Parameter **L**: width (variance)

Parameter **R**: asymmetry (skewness)





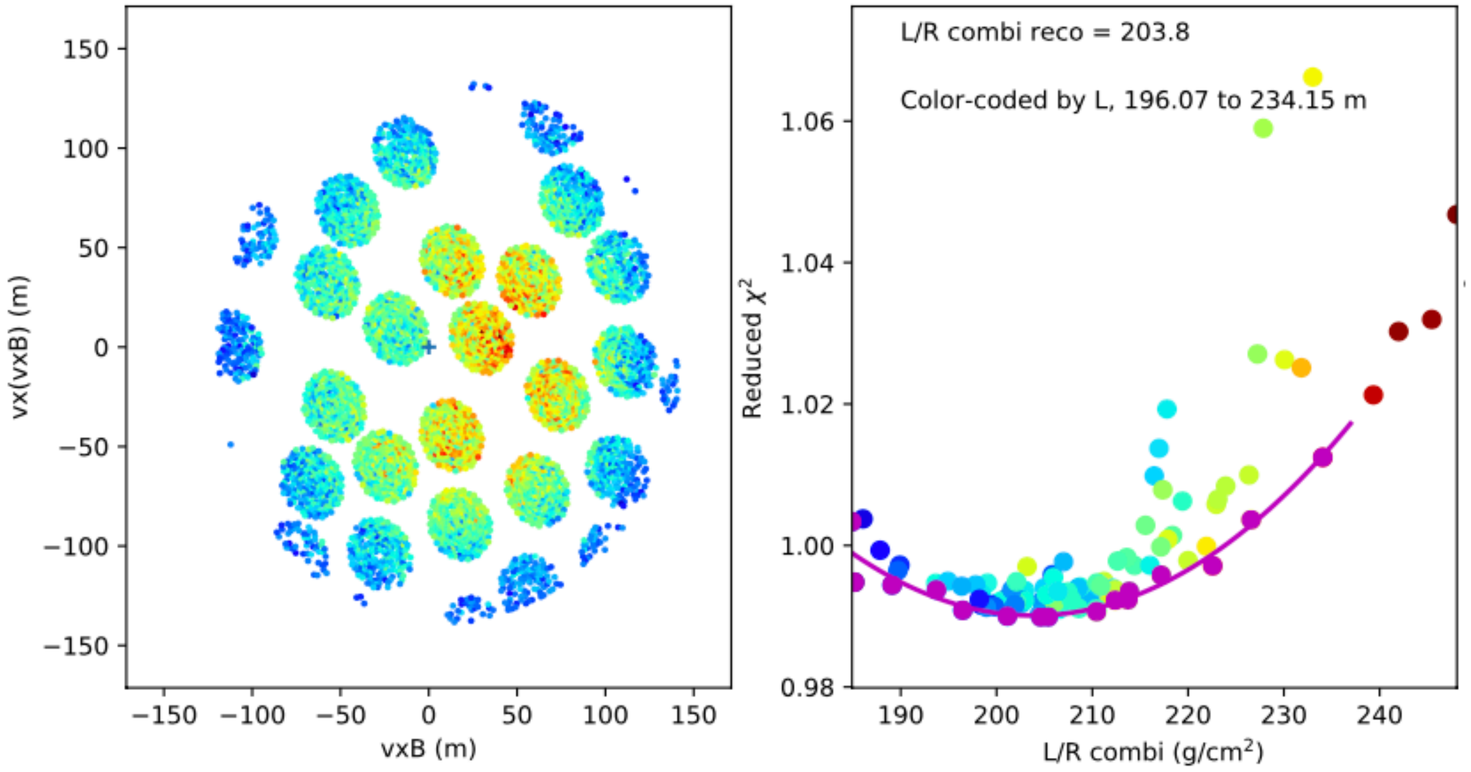
L in LOFAR data



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

SKA reconstruction L/R

- 100 showers of same Xmax,
- Interpolated footprint, free core fit, reference shower: S = 204.6 g/cm^2

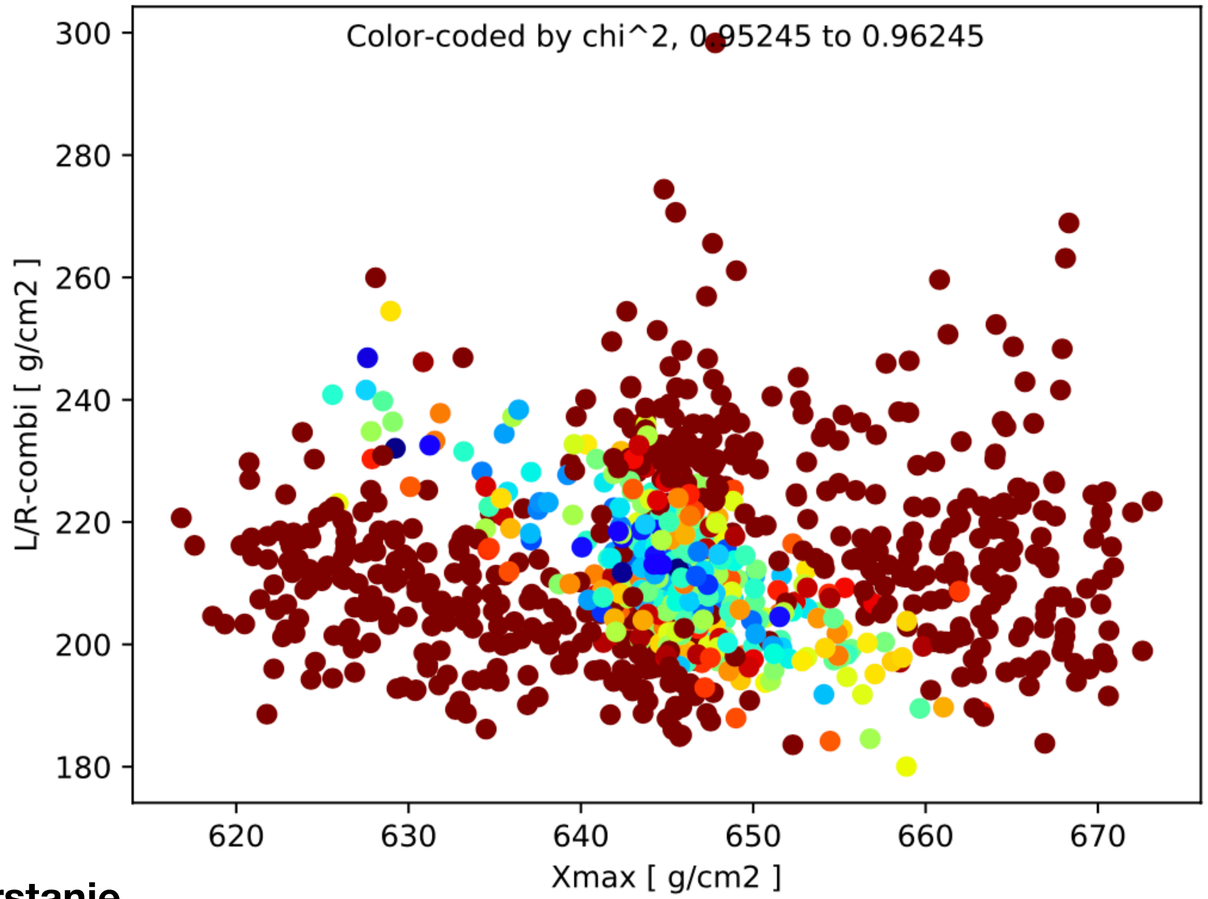


SKA can reconstruct a linear combination of L and R:

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

Full SKA reconstruction strategy

- In a real analysis Xmax and S(L,R) have to be fitted simultaneously. This requires **MANY** full CoREAS simulations!



Plot: Arthur Corstanje

Can simulations become fast enough to use standard minimisation techniques like gradient descent?

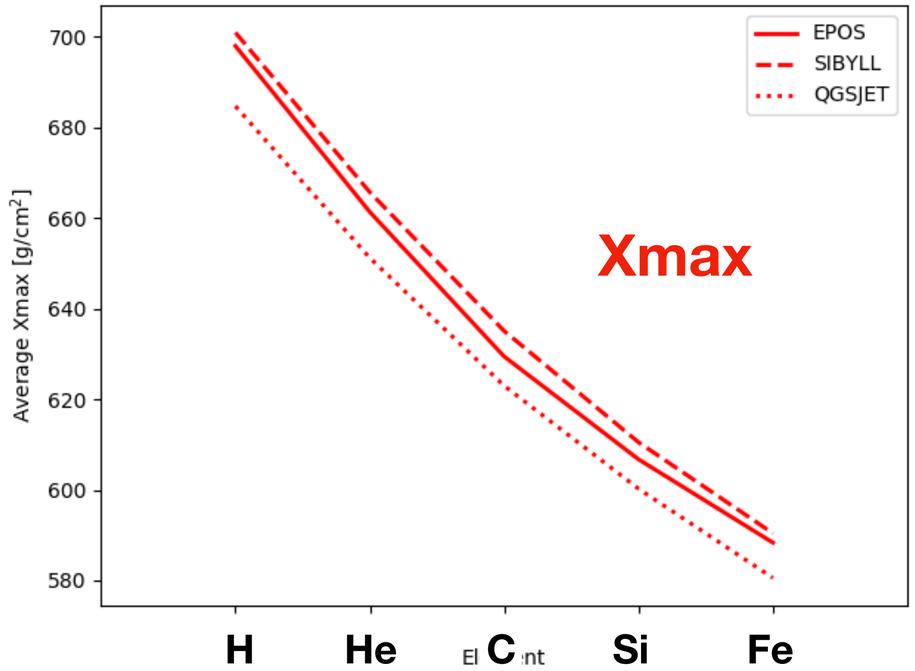
See afternoon talk Mitja Desmet

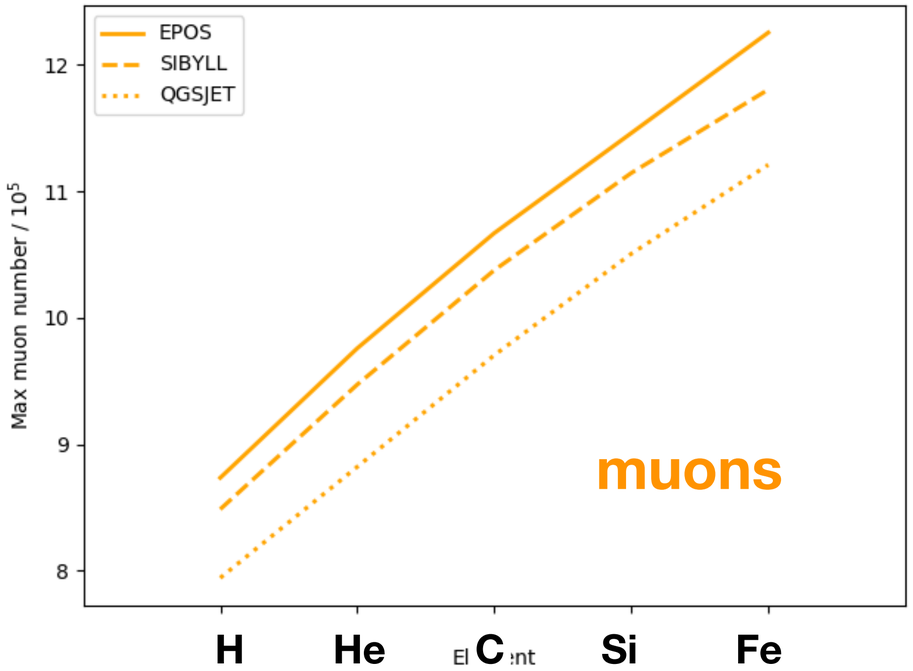
What can we learn from R,L ?

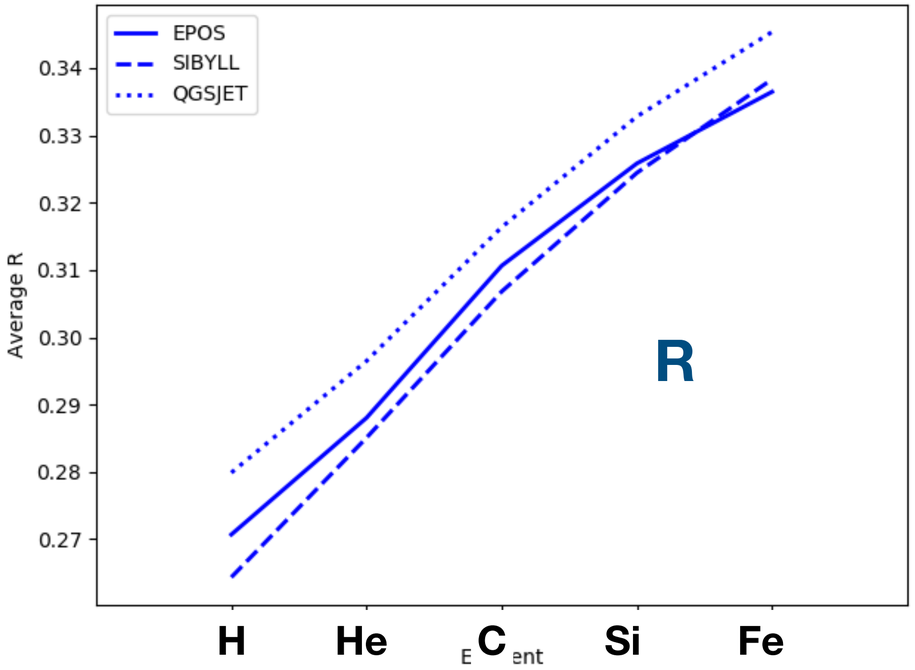
- Conex simulations:
  3 models: EPOS-LHC, QGSJETII-04, SIBYLL 2.3d
  5 elements: p, He, C, Si, Fe
  3 energies: 10^{16} eV, 10^{17} eV, 10^{18} eV

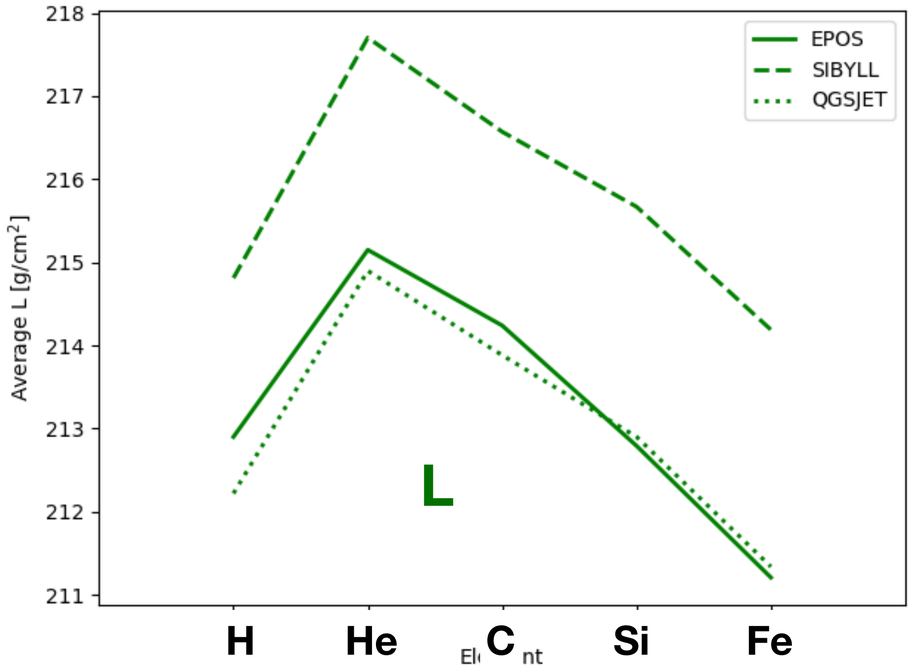
- Longitudinal fit of e^-/e^+ profile
  Xmax, R, L

- Number of muons at muon maximum:
  mu

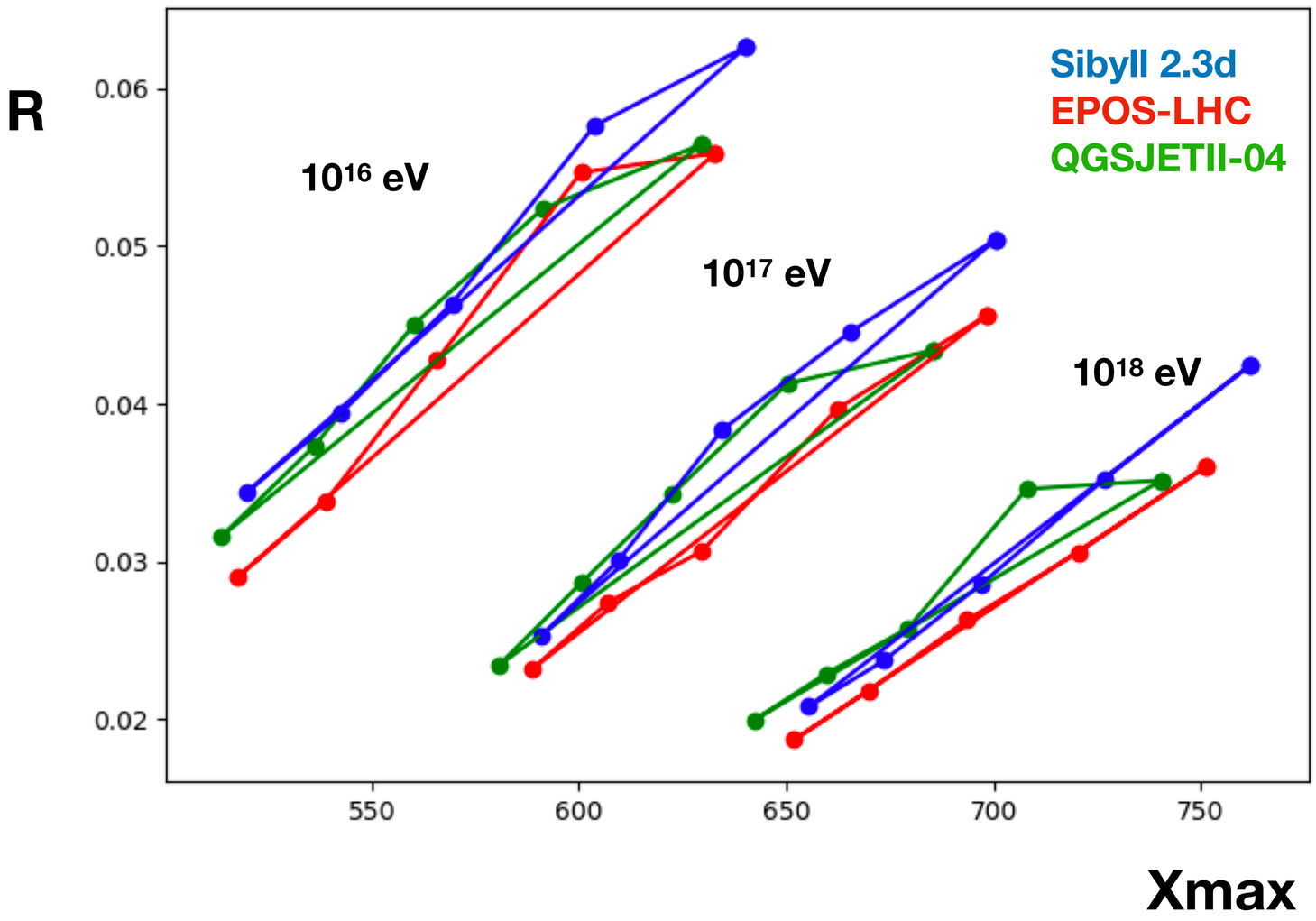

EPOS
SIBYLL
QGSJET
Xmax
Average Xmax [g/cm^2]
700
680
660
640
620
600
580
H
He
C
Si
Fe


EPOS
SIBYLL
QGSJET
muons
Max muon number / 10^5
12
11
10
9
8
H
He
C
Si
Fe

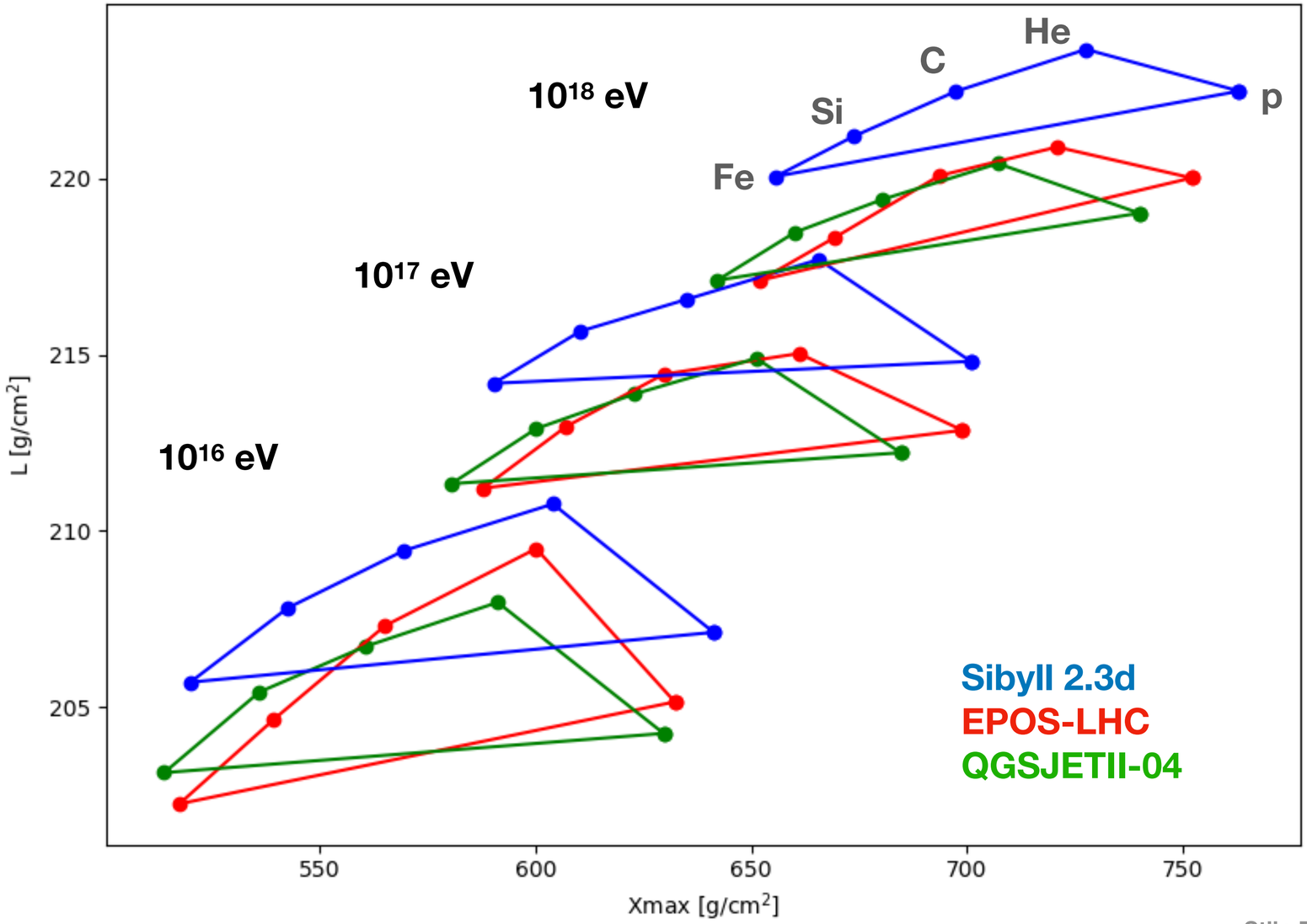

EPOS
SIBYLL
QGSJET
R
Average R
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
H
He
C
Si
Fe


EPOS
SIBYLL
QGSJET
L
Average L [g/cm^2]
218
217
216
215
214
213
212
211
H
He
C
Si
Fe

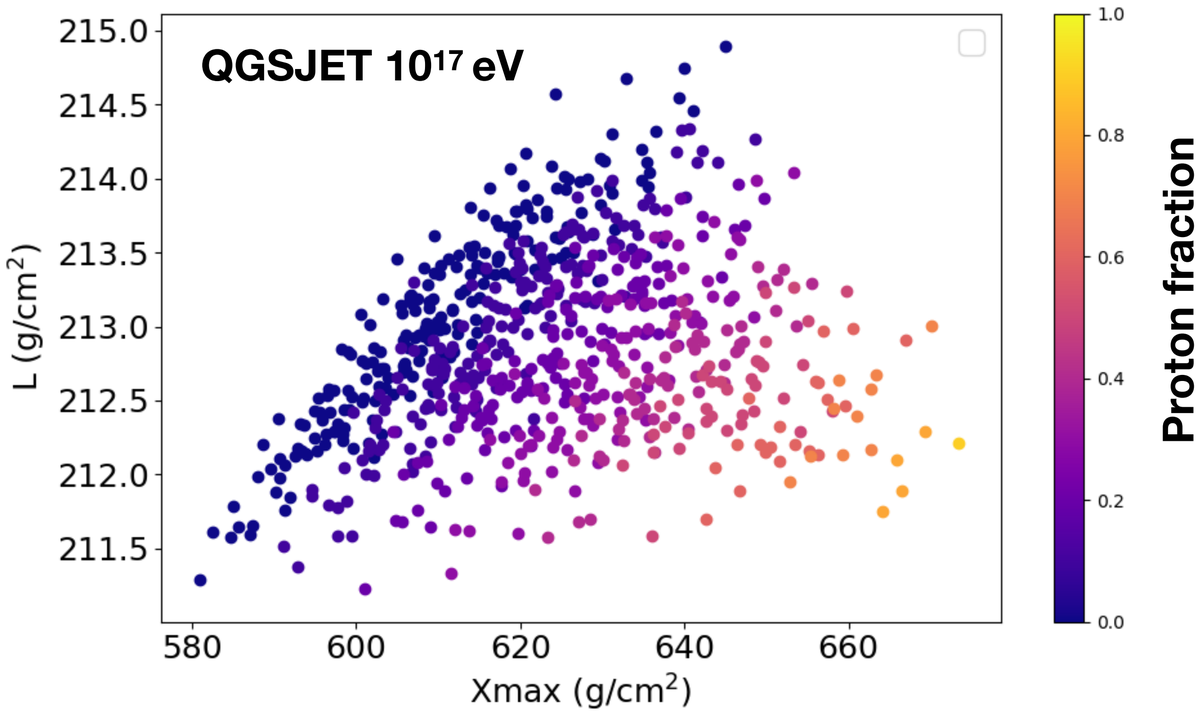
R and Xmax are strongly correlated…



… but L provides new information



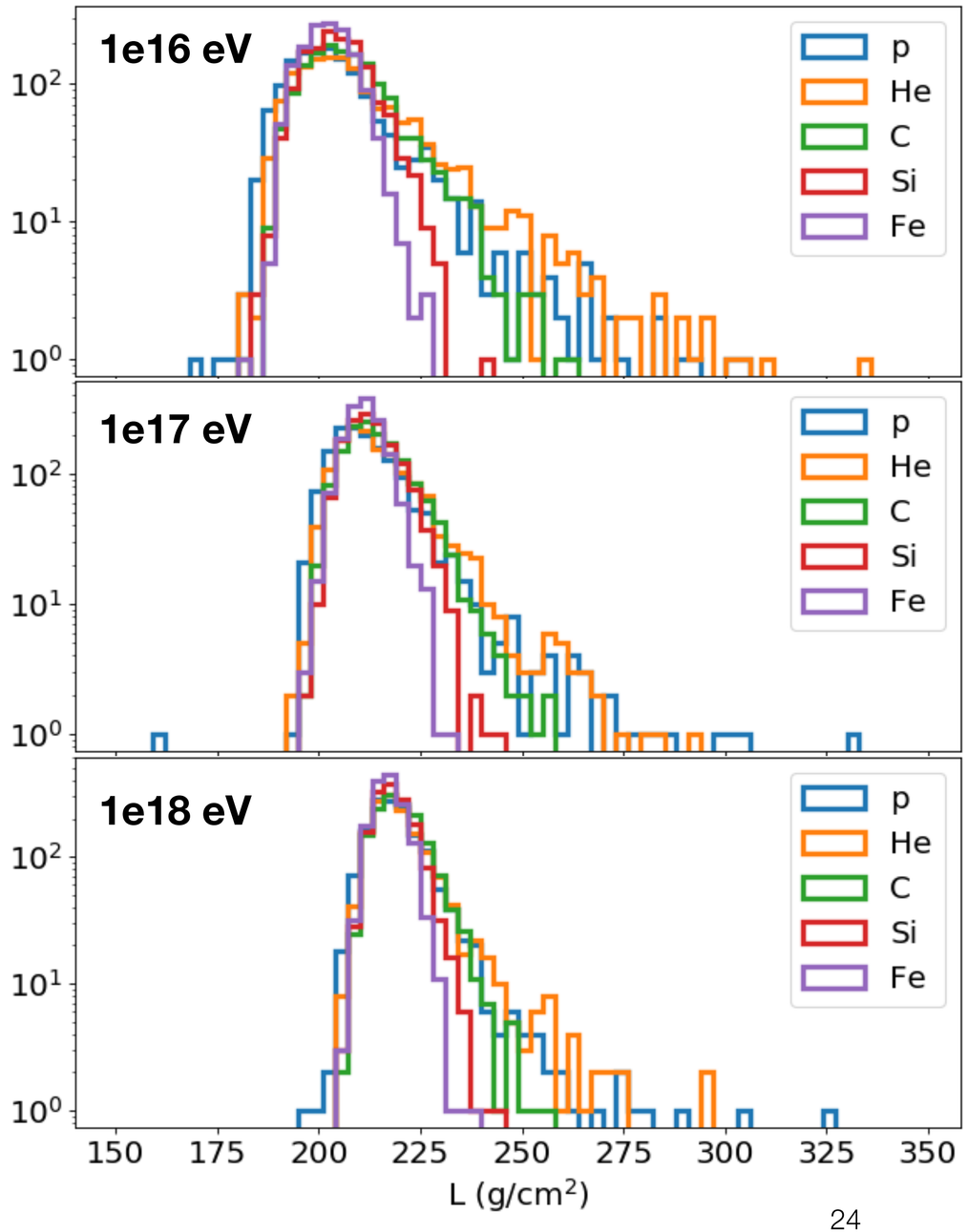
Power of triangles



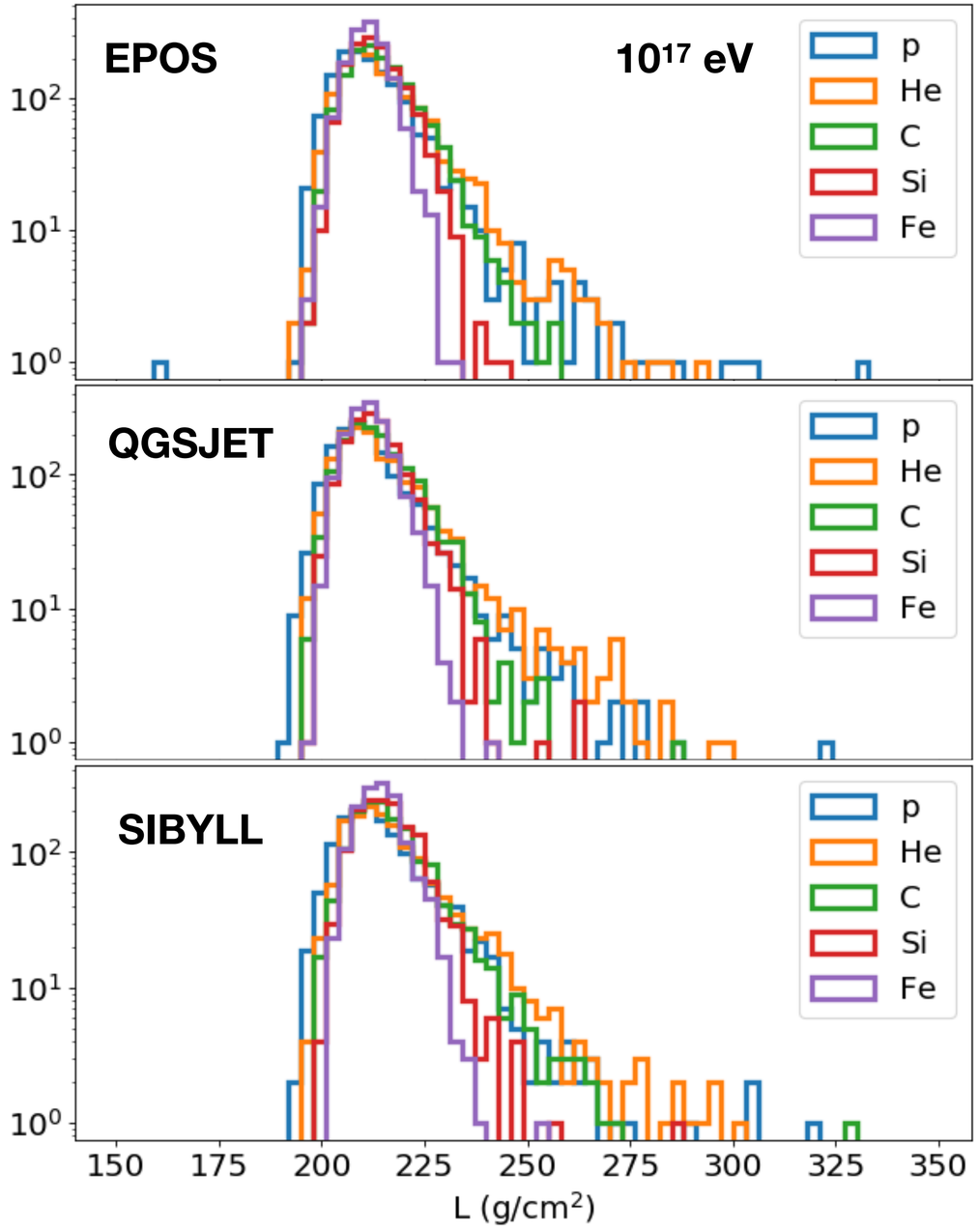
- Each point is average of a set of 1500 observed showers includes uncertainty of 10 g/cm^2 on Xmax and L per shower

- Each point has different ratio of p, He, C, Si & Fe

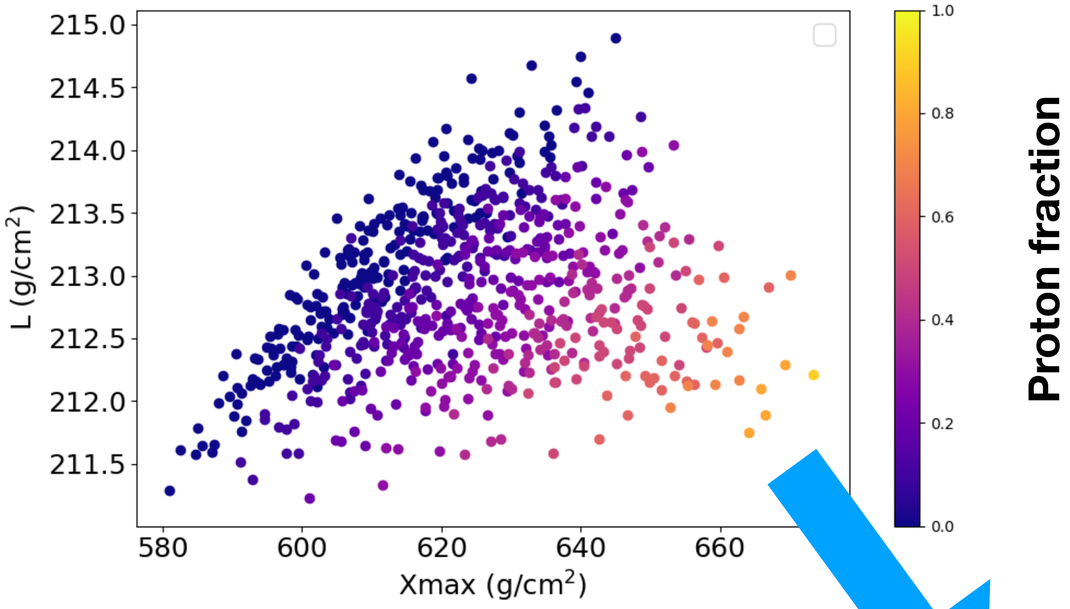
EPOS



- Is average L the best parameter to use?
- Difference between elements small w.r.t. spread
- High-L flank much more sensitive to mass!

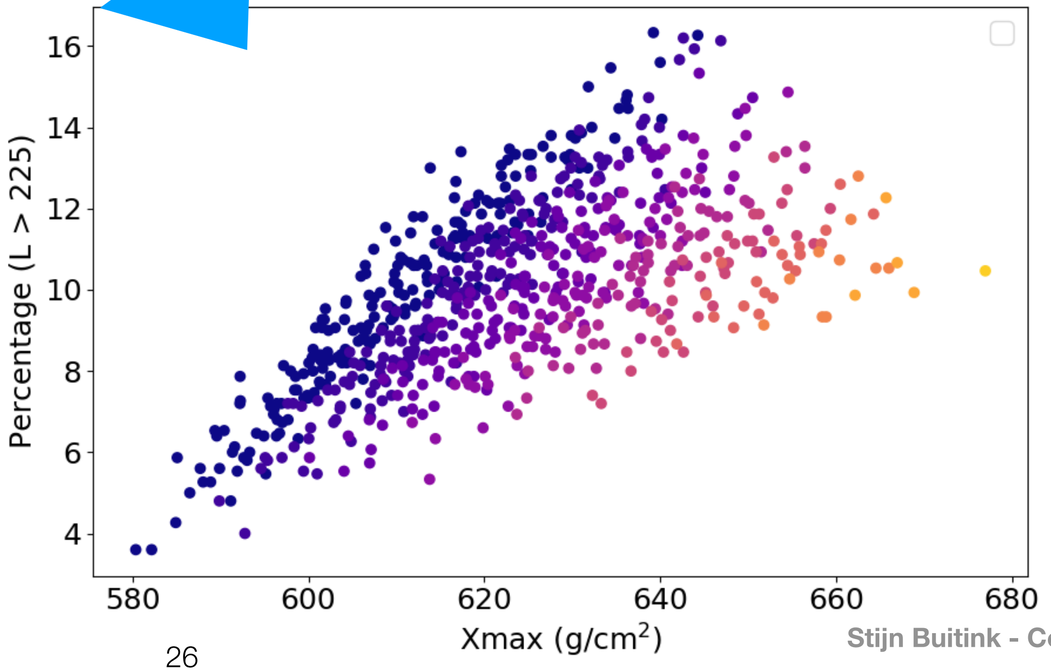


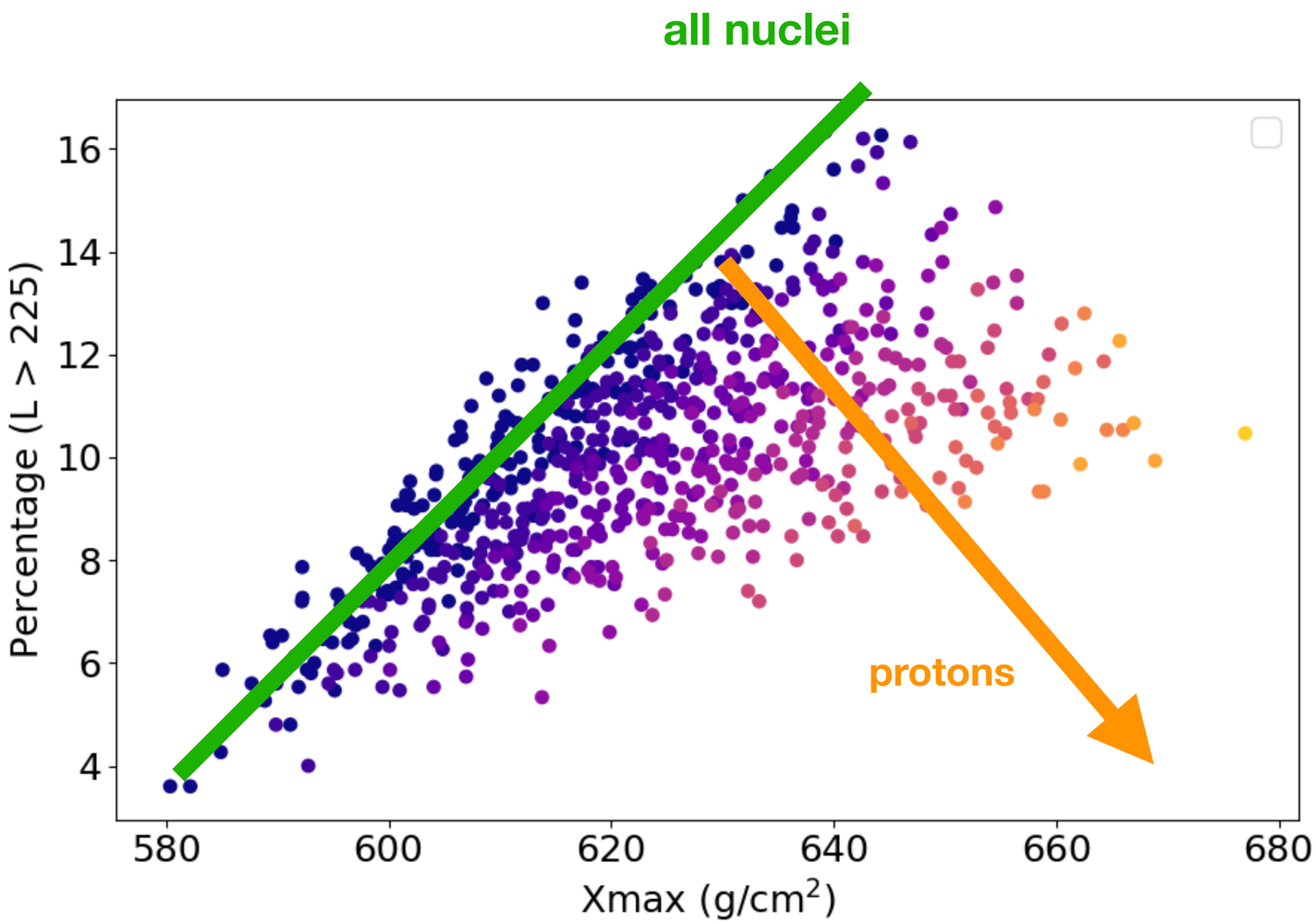
- All hadronic models have similar mass-dependence in flank
- Finetune analysis to minimise dependence on model
- Simple toy analysis: count showers with L > 225 g/cm2



Average L vs. Xmax

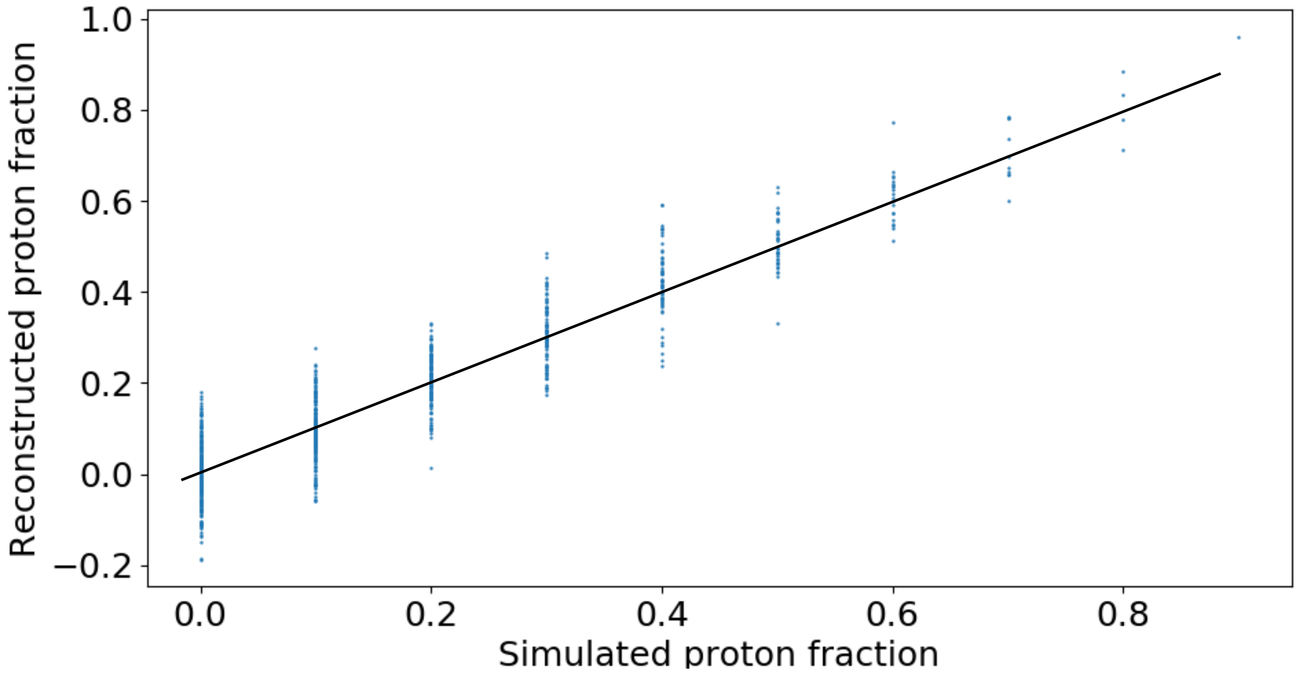
(L > 225) vs. Xmax





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

Reconstructed proton fraction



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

Composition studies with SKA

conclusions

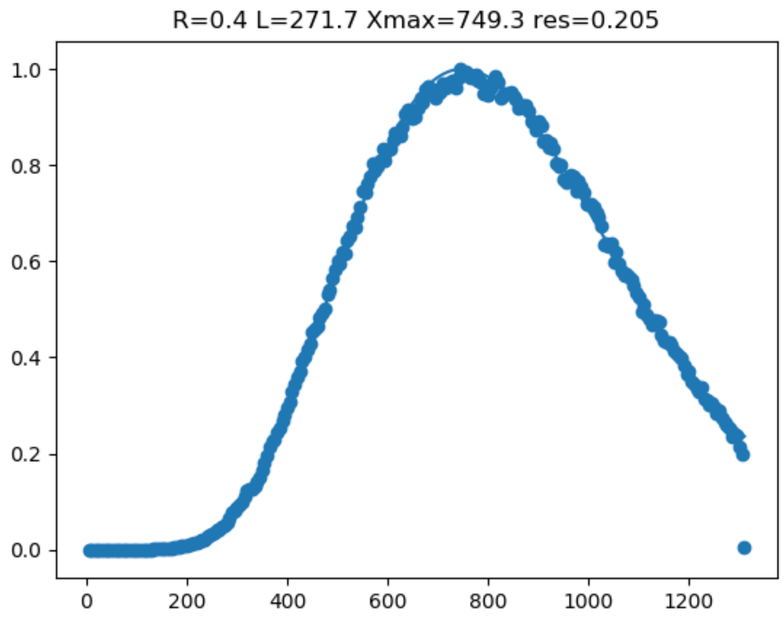
- Xmax between observatories & techniques often don't agree
  SKA can emulate different radio arrays: resolve LOFAR/Auger tension

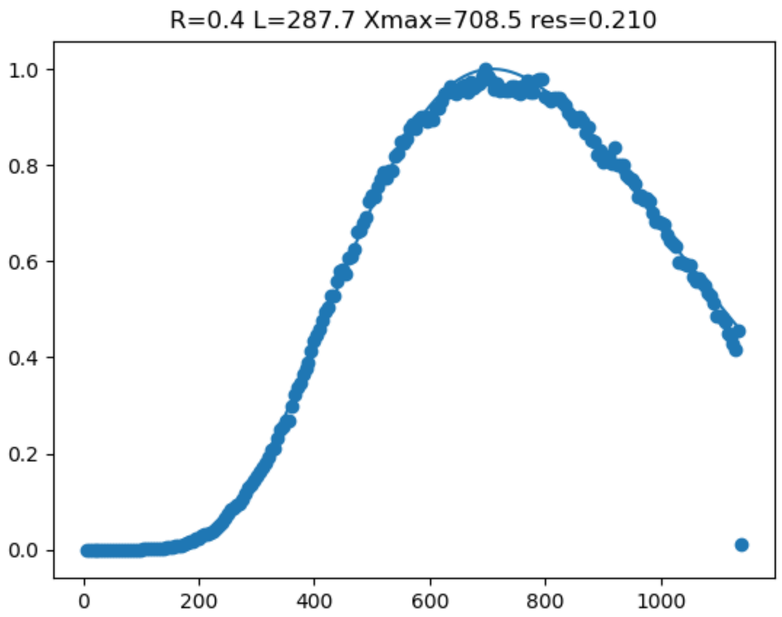
- Xmax resolution needs to be high
  SKA reconstruction resolution < 8 g/cm^2
  uncertainty will be dominated by antenna model & atmosphere

- Difficult to resolve elements with similar masses (e.g. p/He)
  SKA can reconstruct shower length L: isolate proton fraction

- Mass composition depends on hadronic interaction model
  SKA Xmax + L: constrain interaction models & mass composition

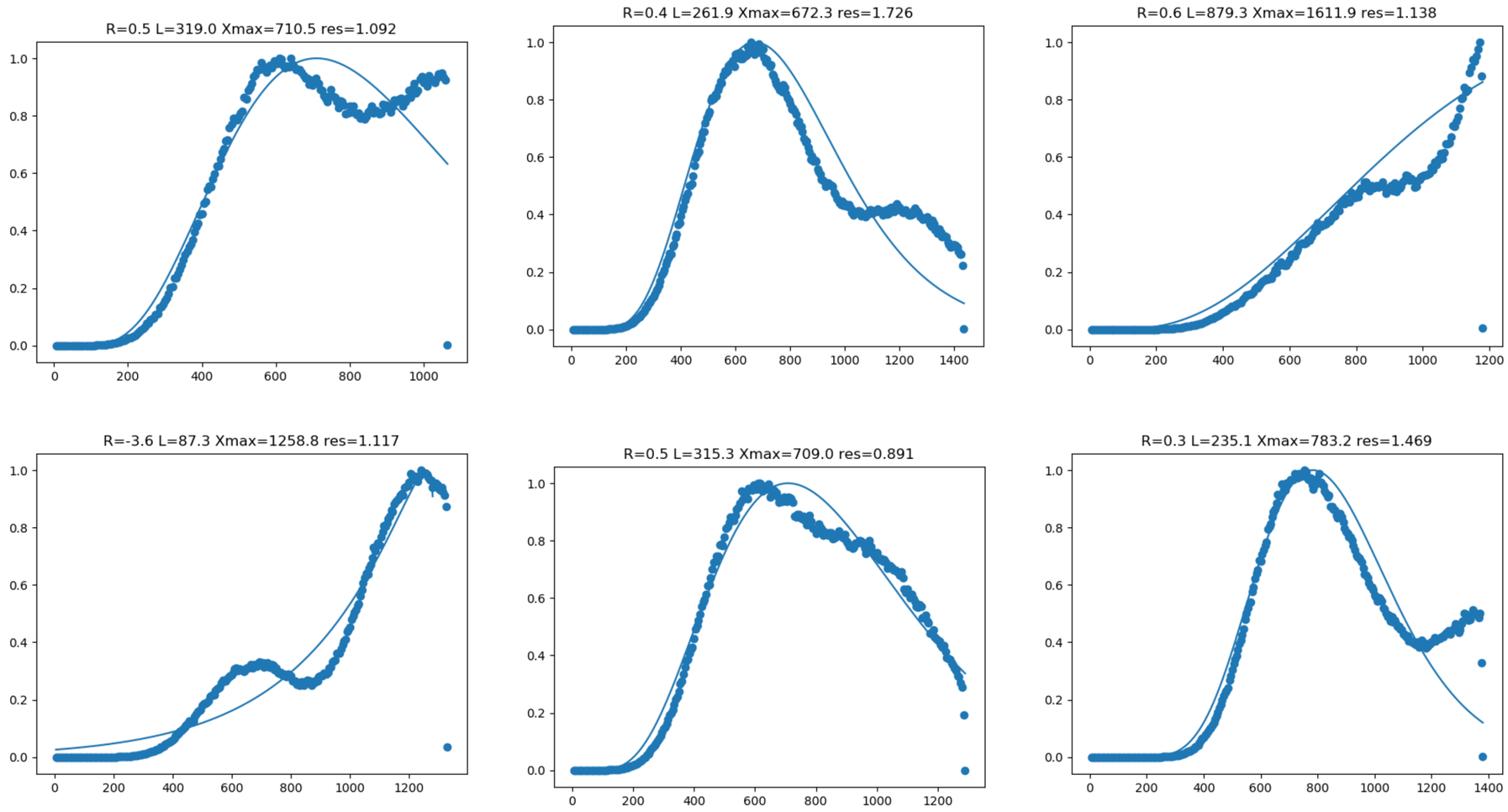
Examples high L





- Almost all high L showers have a well-behaved fit

Camel showers



- No converging fit for 0.2% of showers (complete set)

  10^{16} eV: 2-3% 10^{17} eV: <0.5% 10^{18} eV: <0.1%

  p: ~2% He: ~3% C: <1% Si: <0.1% Fe: 0 found