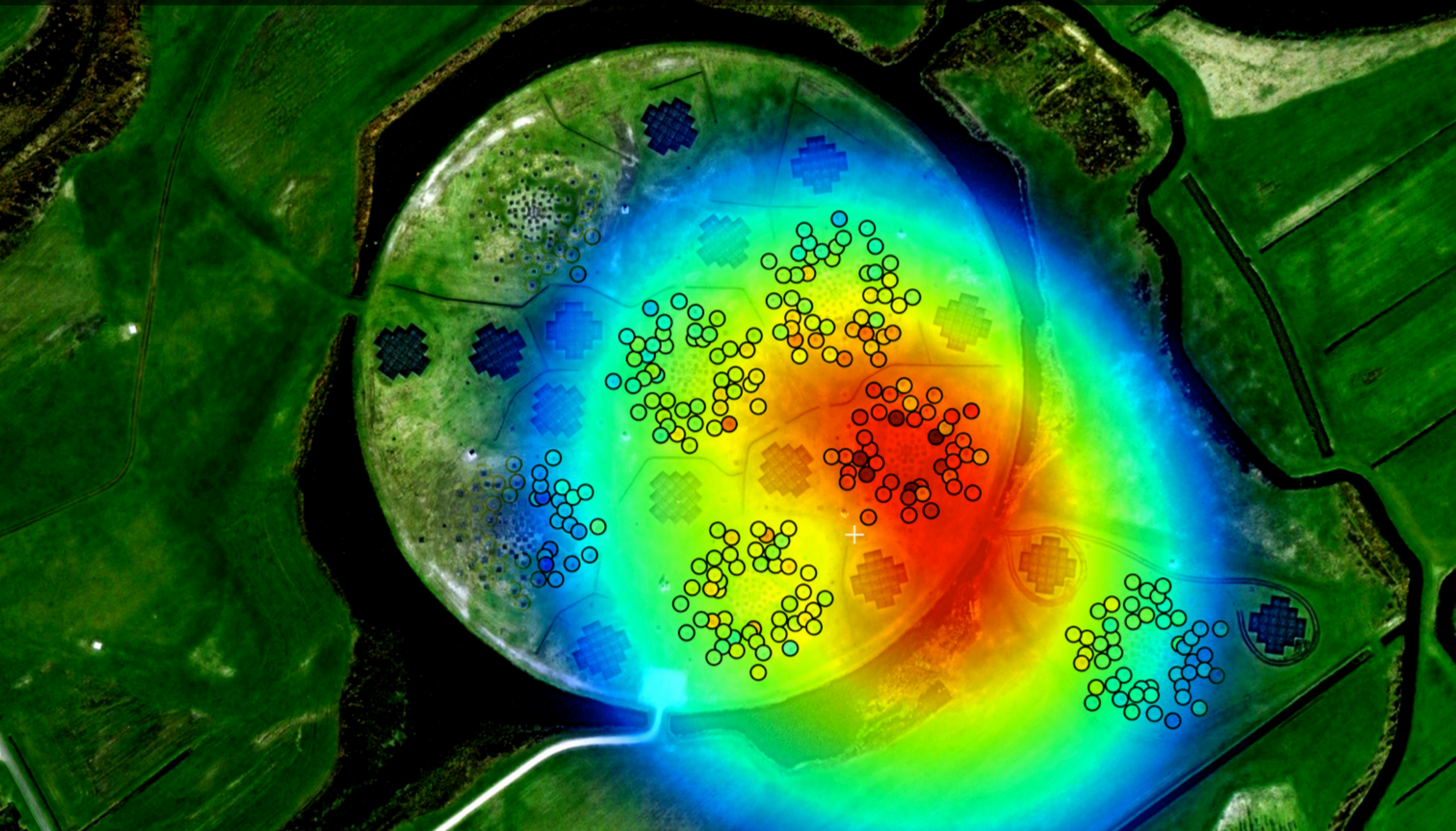
Cosmic ray composition measurements with LOFAR

Arthur Corstanje for the Cosmic Rays KSP

LOFAR Science Week, May 22, 2019

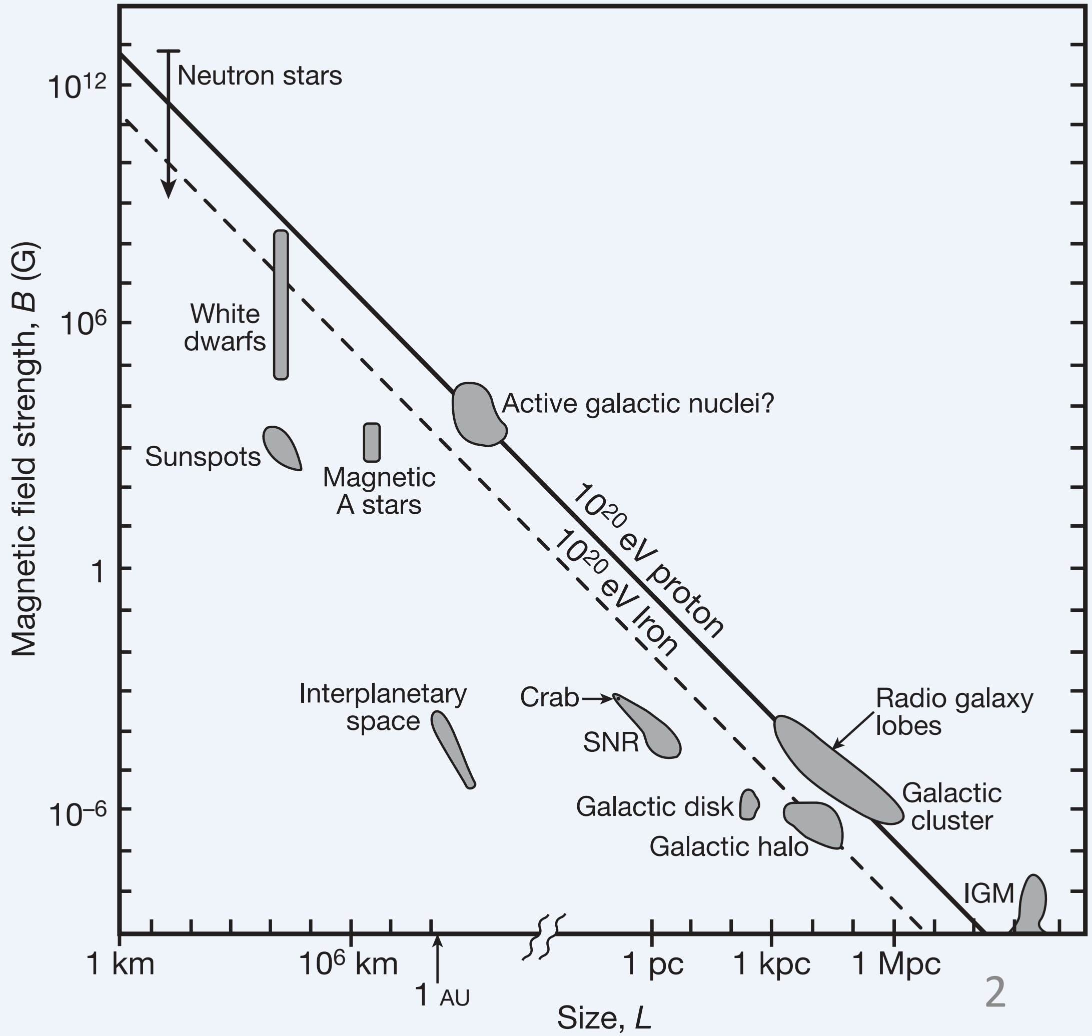


Origin and composition of cosmic rays

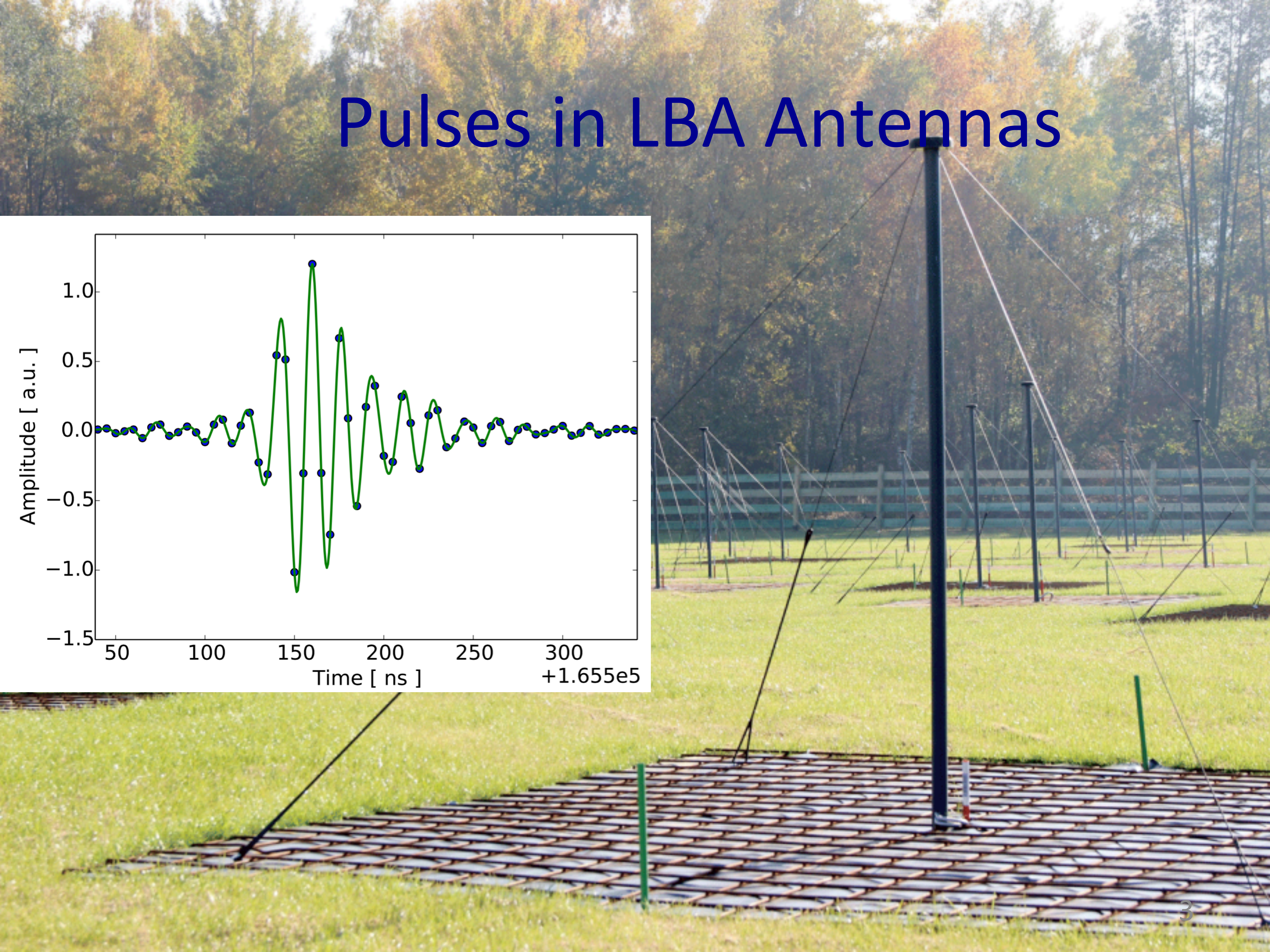
Cannot trace back CRs to sources due to magnetic fields

Hillas criterion for maximum energy of particles produced by a given source (proportional to charge *Z*)

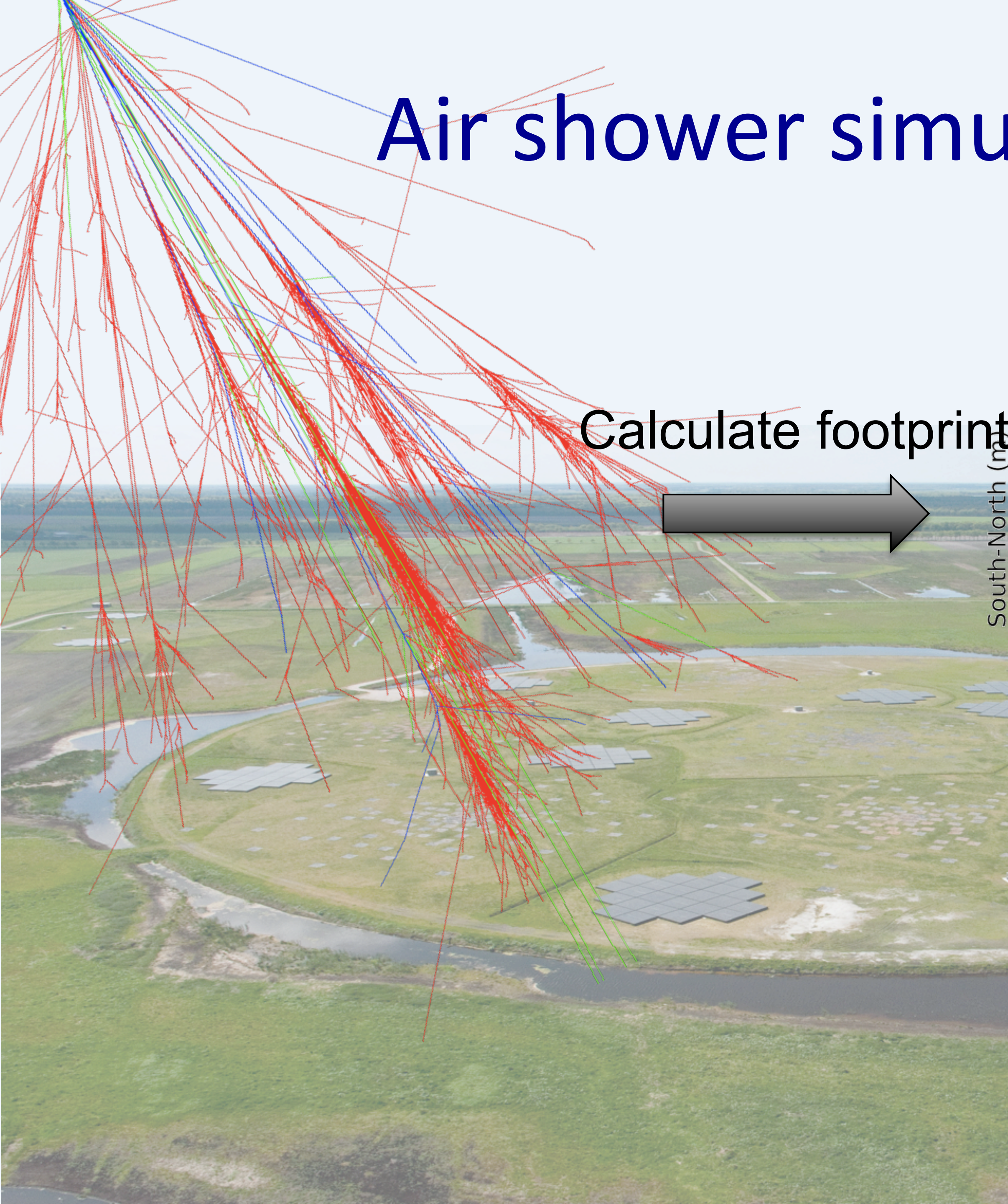
Transition galactic – extragalactic origin expected between ~ 10^{17} and 10^{18} eV (in range of LOFAR!)
First for protons, heavier nuclei can reach higher energies

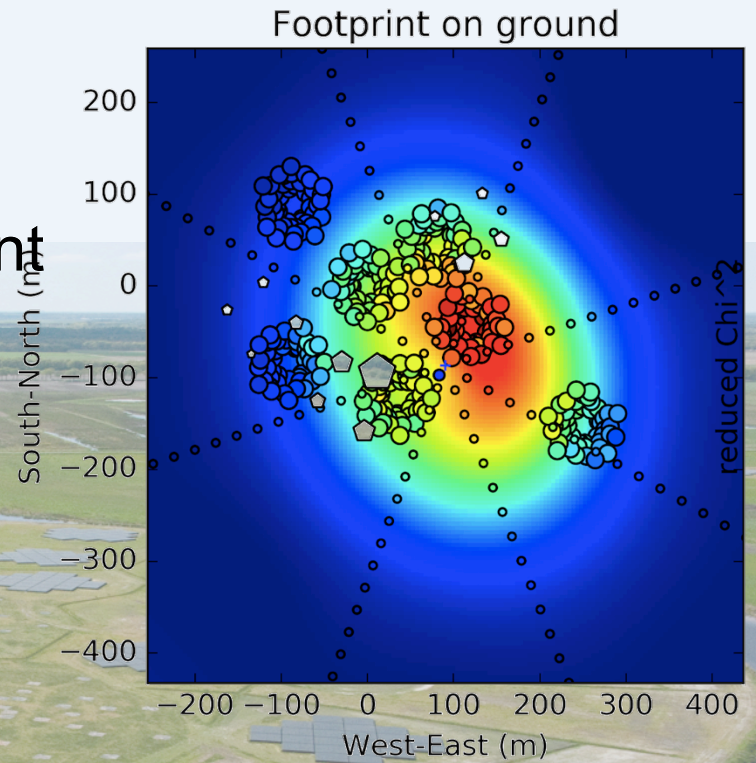


Pulses in LBA Antennas

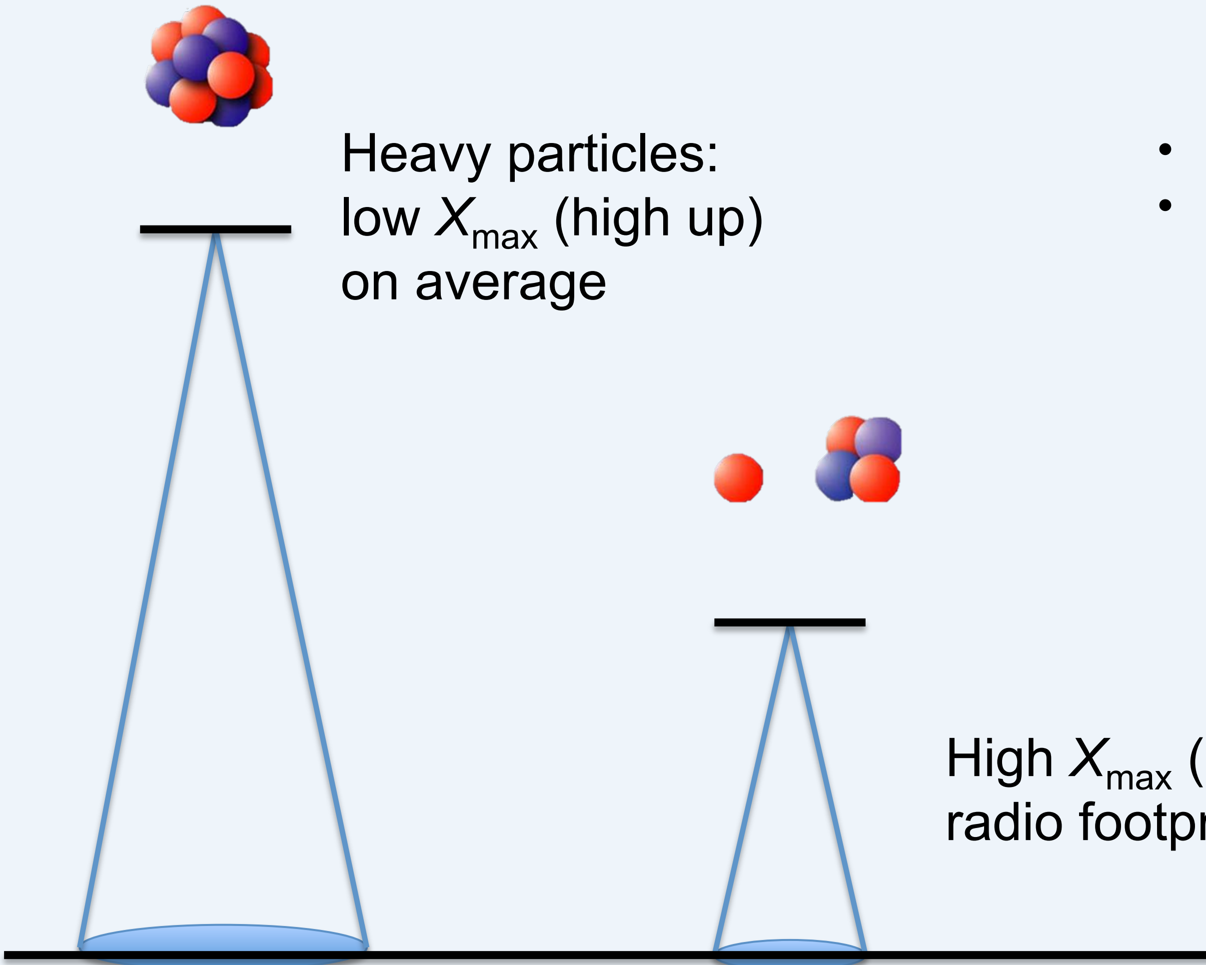


Air shower simulations





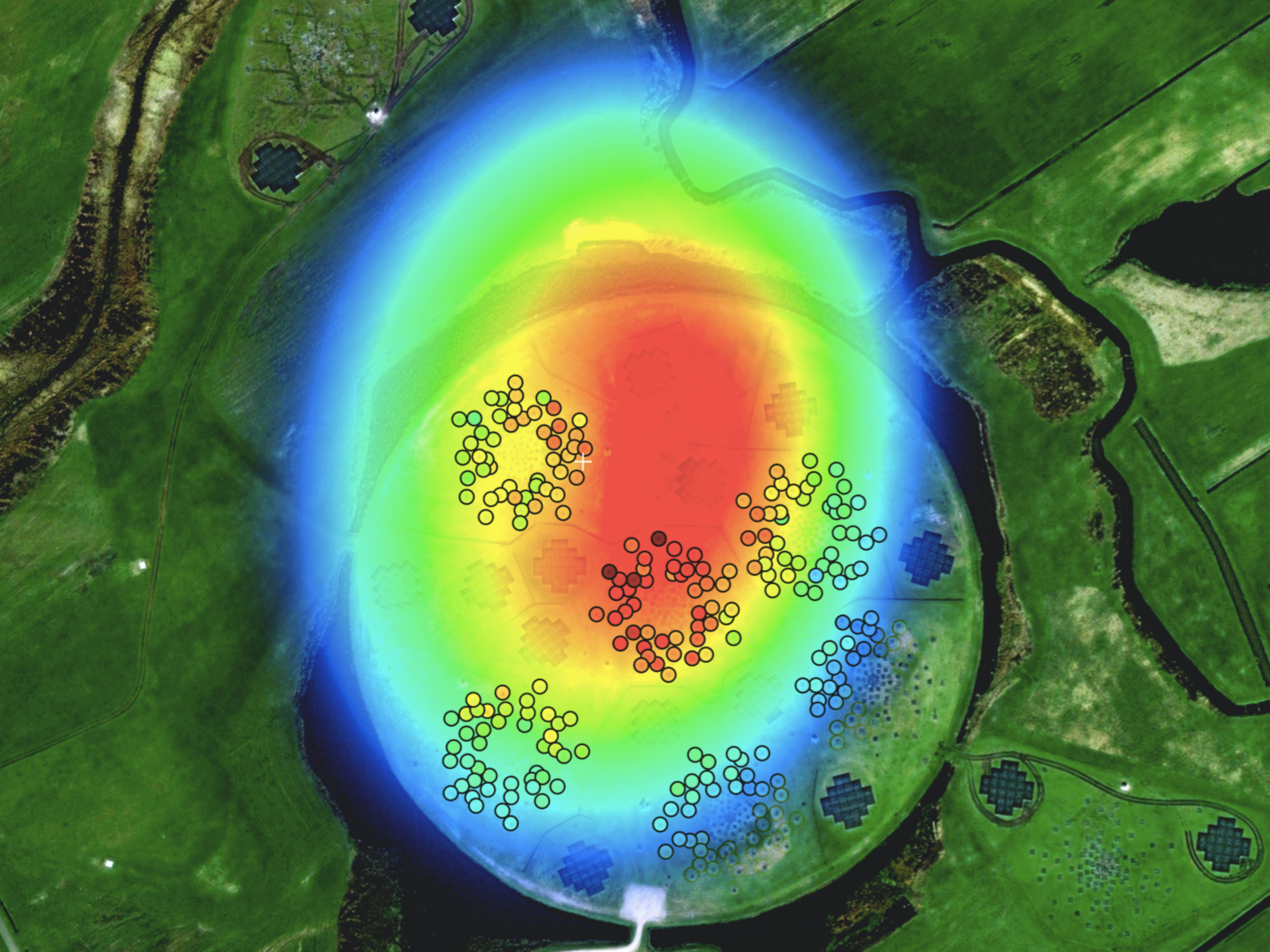
Air shower maximum X_{max}

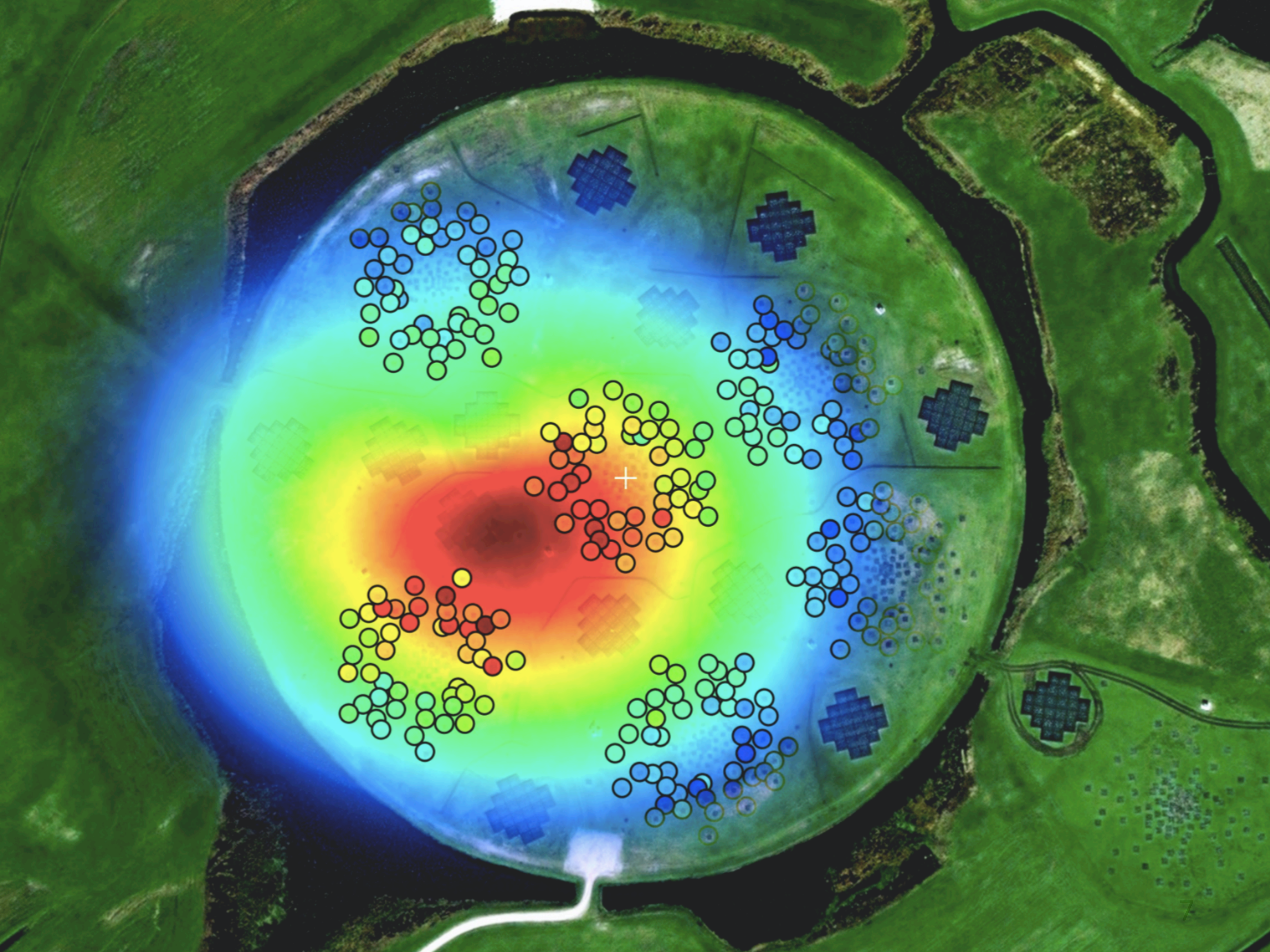


Heavy particles:
low X_{max} (high up)
on average

High X_{max} (close to ground):
radio footprint is smaller

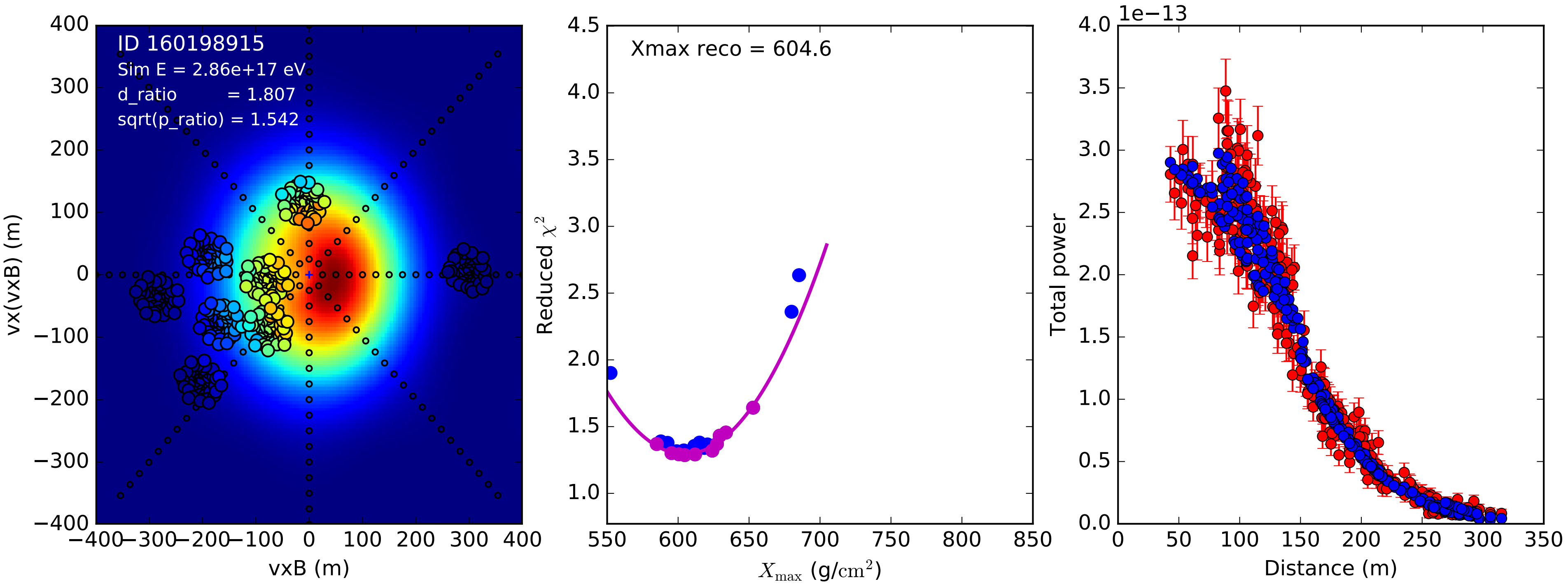
- Over-simplified
- not only size, also the exact footprint shape and strength varies – and can be measured to constrain X_{max}





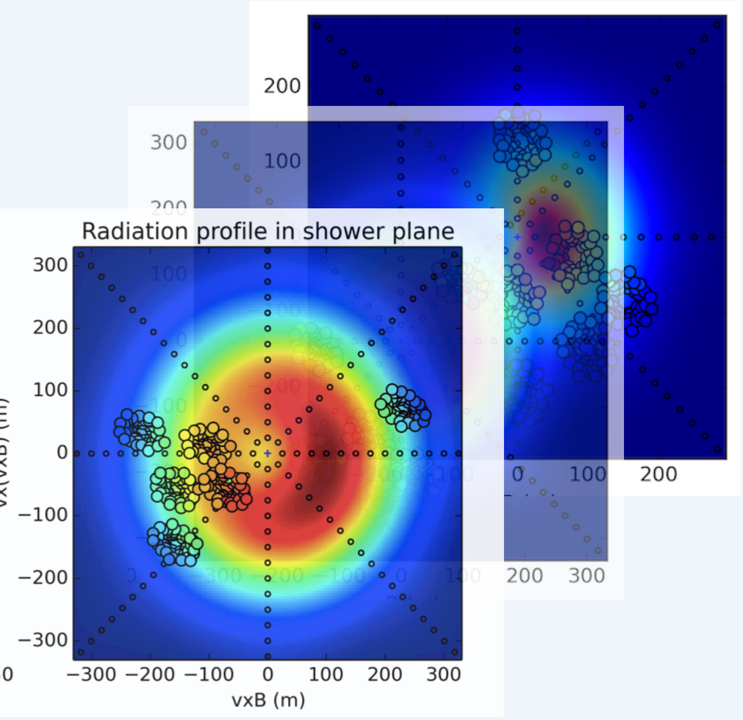
Matching simulated footprints to LOFAR data

- CoREAS: Simulate ~ 30 showers per event, spanning X_{max} range
- Fit chi-squared as function of simulated X_{max}: optimum
- State-of-the-art resolution of < 20 g/cm^2
- Fit now works on radio data only



Matching simulated footprints to LOFAR data

- Simulate ~ 30 showers per event, spanning X_{max} range
- Reconstruction uncertainty from Monte Carlo procedure
  - Take simulated showers, add LOFAR noise levels, reconstruct with other showers from ensemble



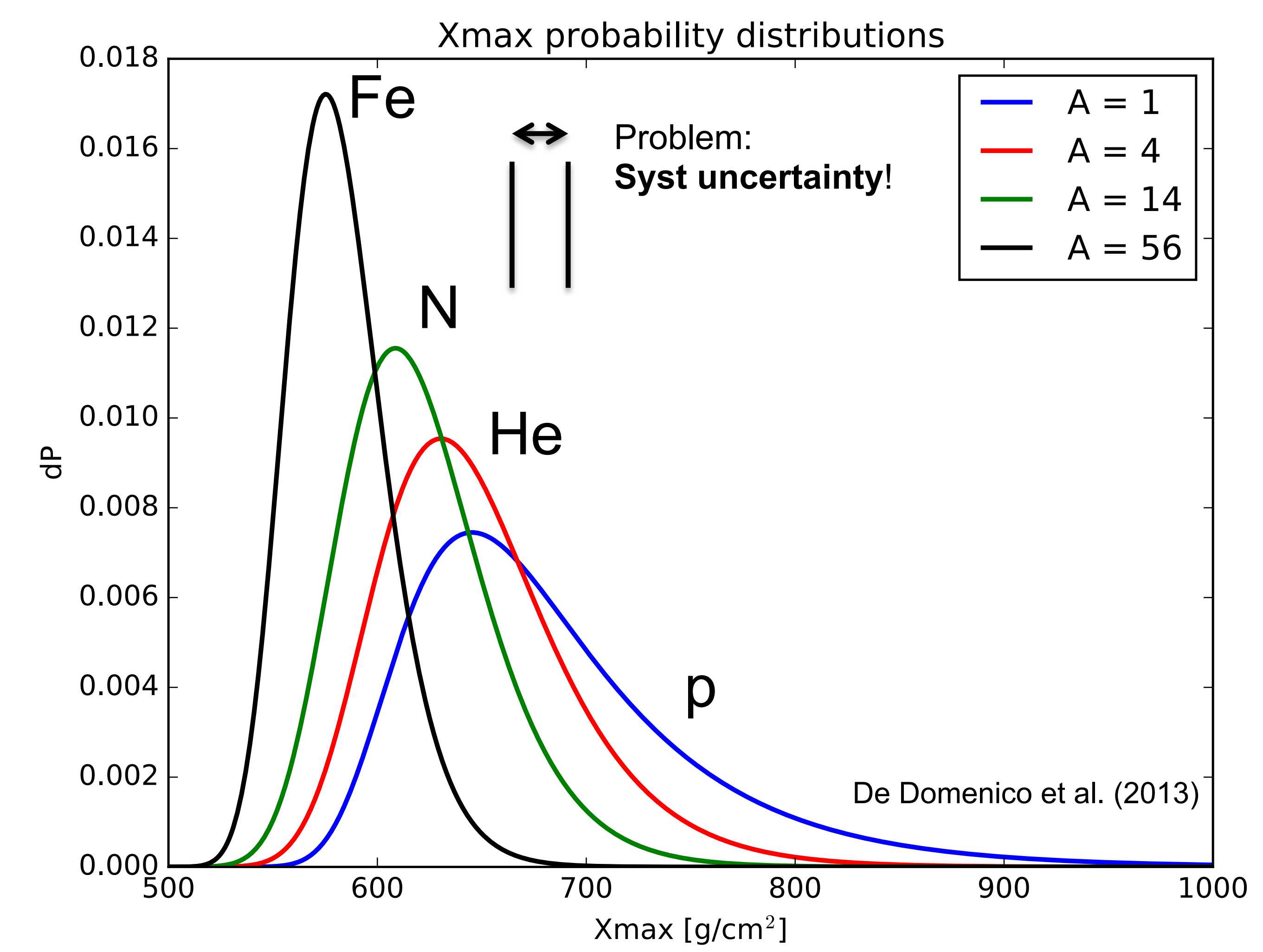
Air shower dataset:

data points

($X_{max} \pm \sigma_X$, log $E \pm \sigma_{\log E}$)

x N ~ 350

X_{max} distributions for the elements



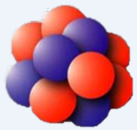
Statistical challenge

Determine which *linear combination* of these curves fits best to the measured X_{max} set

Determine confidence intervals for the element fractions

- Challenging, need to **reduce systematics** wherever possible!

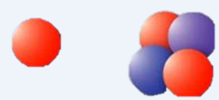
Bias-free sample selection



Low X_{max} (high up)
Few particles reach the ground
(may not trigger LORA)

Criterion:

- Each measured shower must be able to trigger both LORA and LOFAR, would it have any other X_{max} level within natural range
- **196 showers** included



High X_{max} (close to ground):
radio footprint is small
(may not trigger 3 LOFAR stations)

Improving accuracy (reducing systematic uncertainties)

- Add local atmospheric profiles to Corsika / CoREAS, including refractive index
  - Saves a contribution of 4 to 11 g/cm^2 (low to high zenith angle)
- More elaborate fiducial selection criteria
  - Bias now bounded, < 4 g/cm^2
- Attention to curve-fitting for optimal X_{max}
  - Reconstructed X_{max} inside densely simulated region
  - Saves contribution of a few g/cm^2

Systematic uncertainties

	SYST	STAT
On X_{max}:		
• Choice of hadronic interaction model: (for X_{max} reconstruction)	5 g/cm^2	
• Remaining uncertainty, atmosphere	~ 1 g/cm^2	2 g/cm^2
• Atmospheric uncertainty (5-layer Corsika):	2 g/cm^2	4 g/cm^2
• Possible bias, from $<X_{max}>$ vs zenith:	4 g/cm^2	
Total, added in quadrature:	**7** g/cm^2	
For composition analysis:		
• Parametrized X_{max} distributions, Conex:	5 g/cm^2	
Total, added in quadrature:	**9** g/cm^2	**20** g/cm^2
Energy:	**27** %	**10** %

Syst uncertainty from comparison to particle detector energy (standalone later)

Statistical uncertainty: average from radio data (improved! Was 32 %)

Statistical analysis

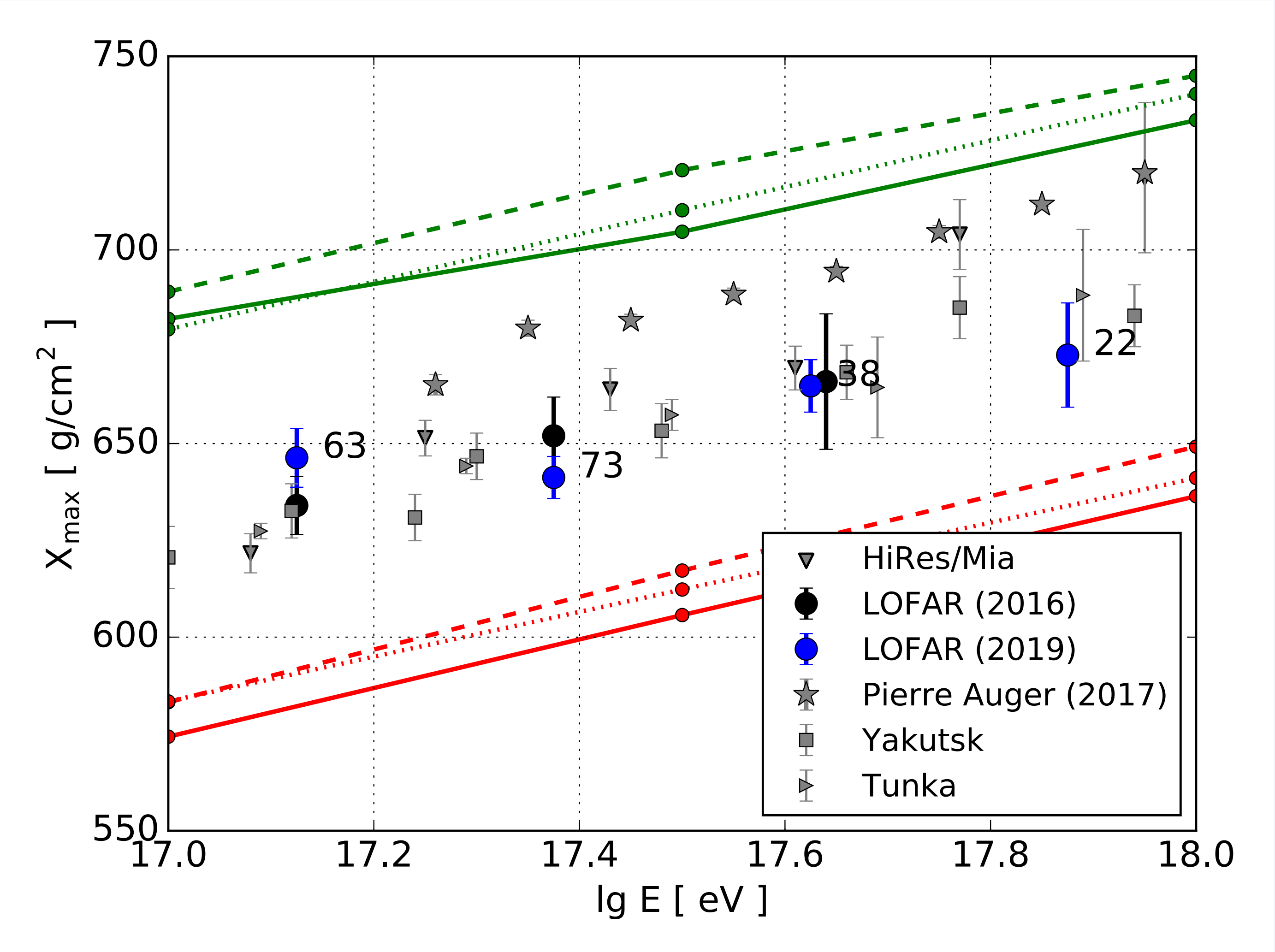
- Measurements take time and effort
- Statistically distinguishing X_{max} distributions is tricky

- Unbinned maximum likelihood analysis for optimal distinguishing power
- Additional goodness-of-fit analysis

  from cumulative distribution (i.e. unique, no binning)
- Likelihood ratio test for confidence intervals

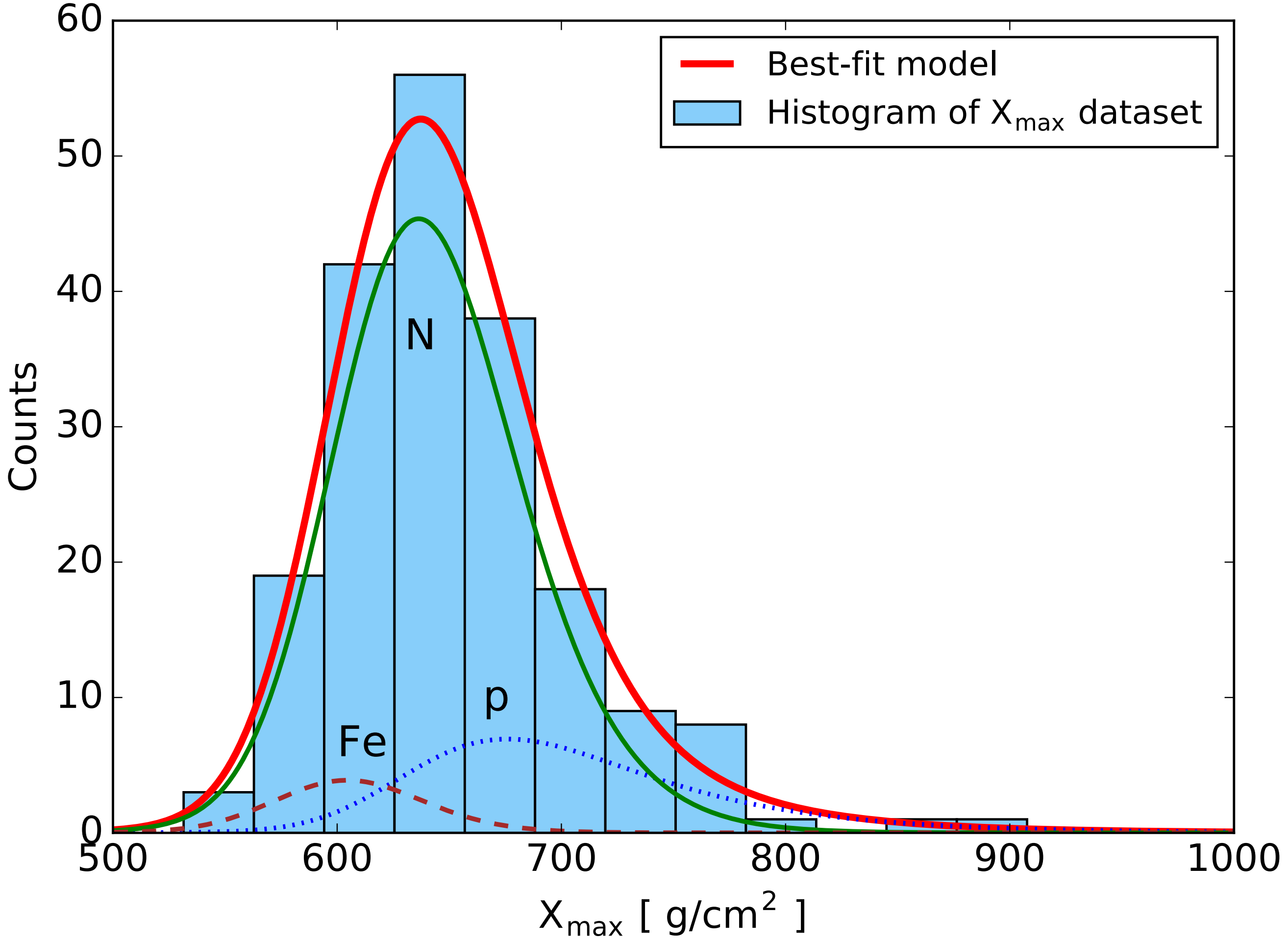
Results: average X_{max}

Figures from A. Corstanje (2019), PhD thesis (to appear this summer)



Average of X_{max} is in line with other experiments, except Auger which finds consistently higher values

Results: X_{max} histogram

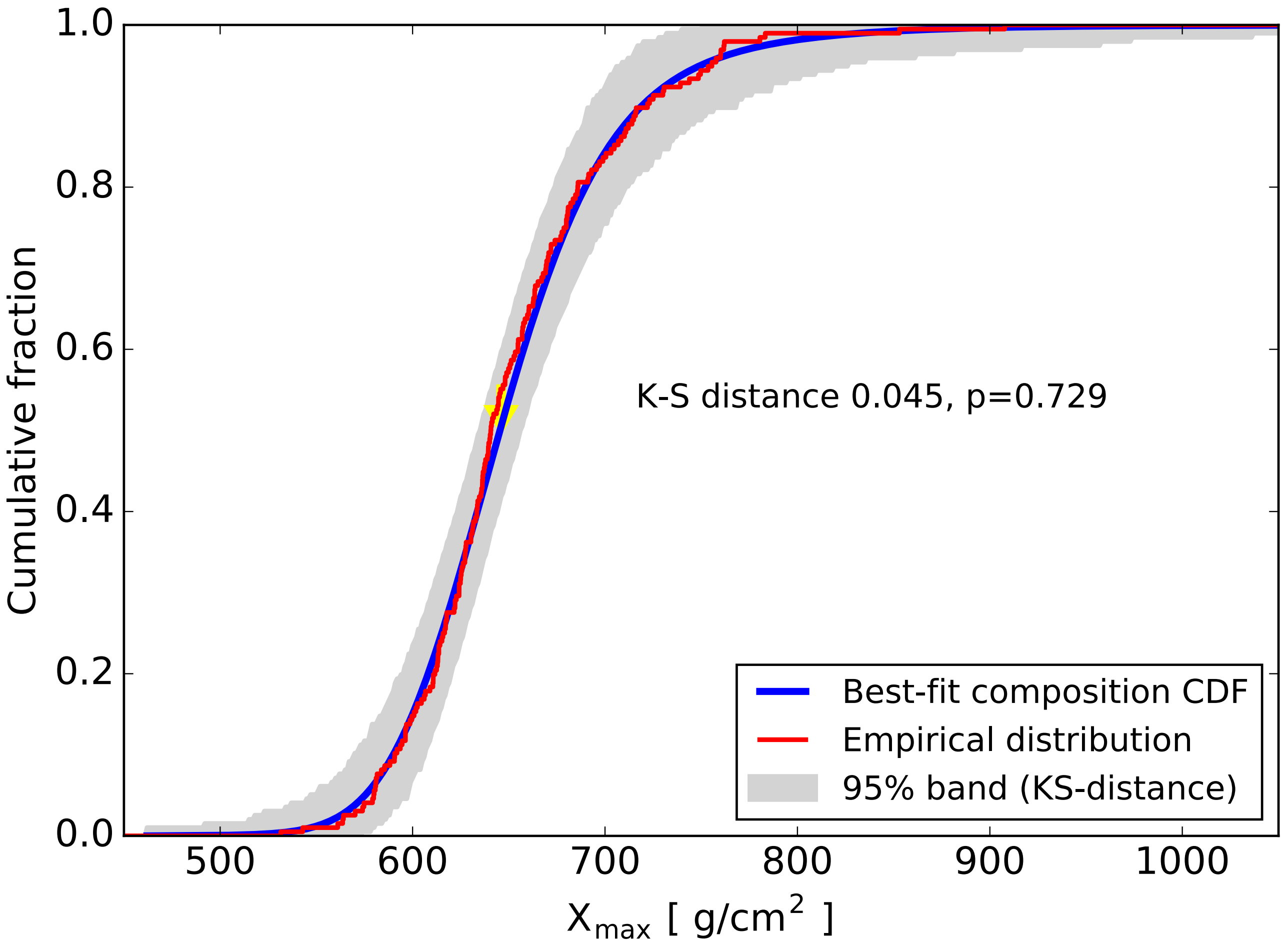


Best fit:
(from unbinned statistical analysis)

17 % p
0 % He
78 % N
5 % Fe

Protons and helium somewhat interchangeable

Results: goodness of fit



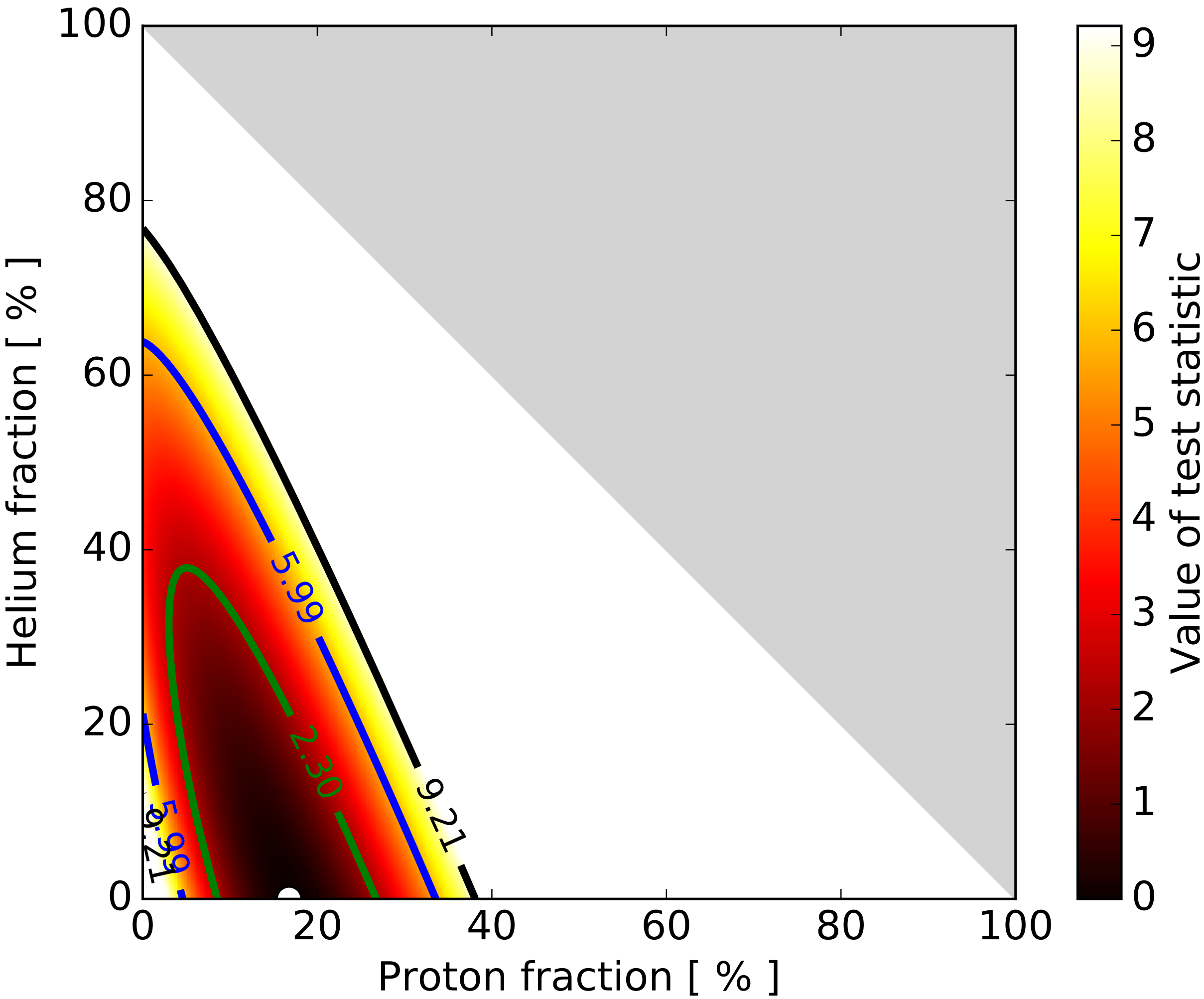
Unbinned analysis gives no goodness of fit estimate

Do separately; Kolmogorov-Smirnov test is a simple method for this.

Uses cumulative distribution and empirical distribution (uniquely defined)

Fit quality is good

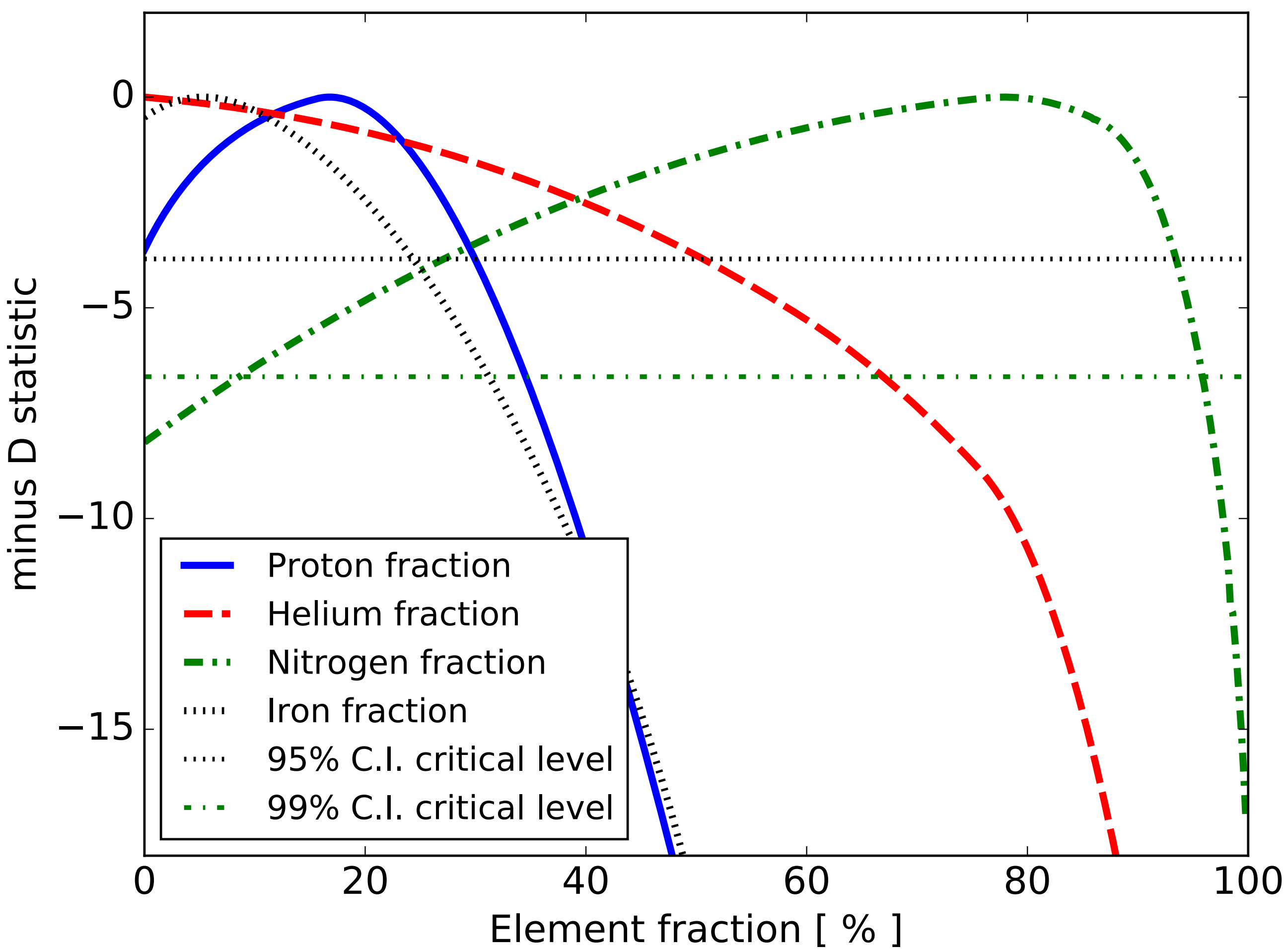
Results: protons vs helium



Within the one-sigma (green) contour, protons and helium can be interchanged, in a ratio near 1:3 for p:He

Contours show one-sigma, 95 and 99% C.L., respectively

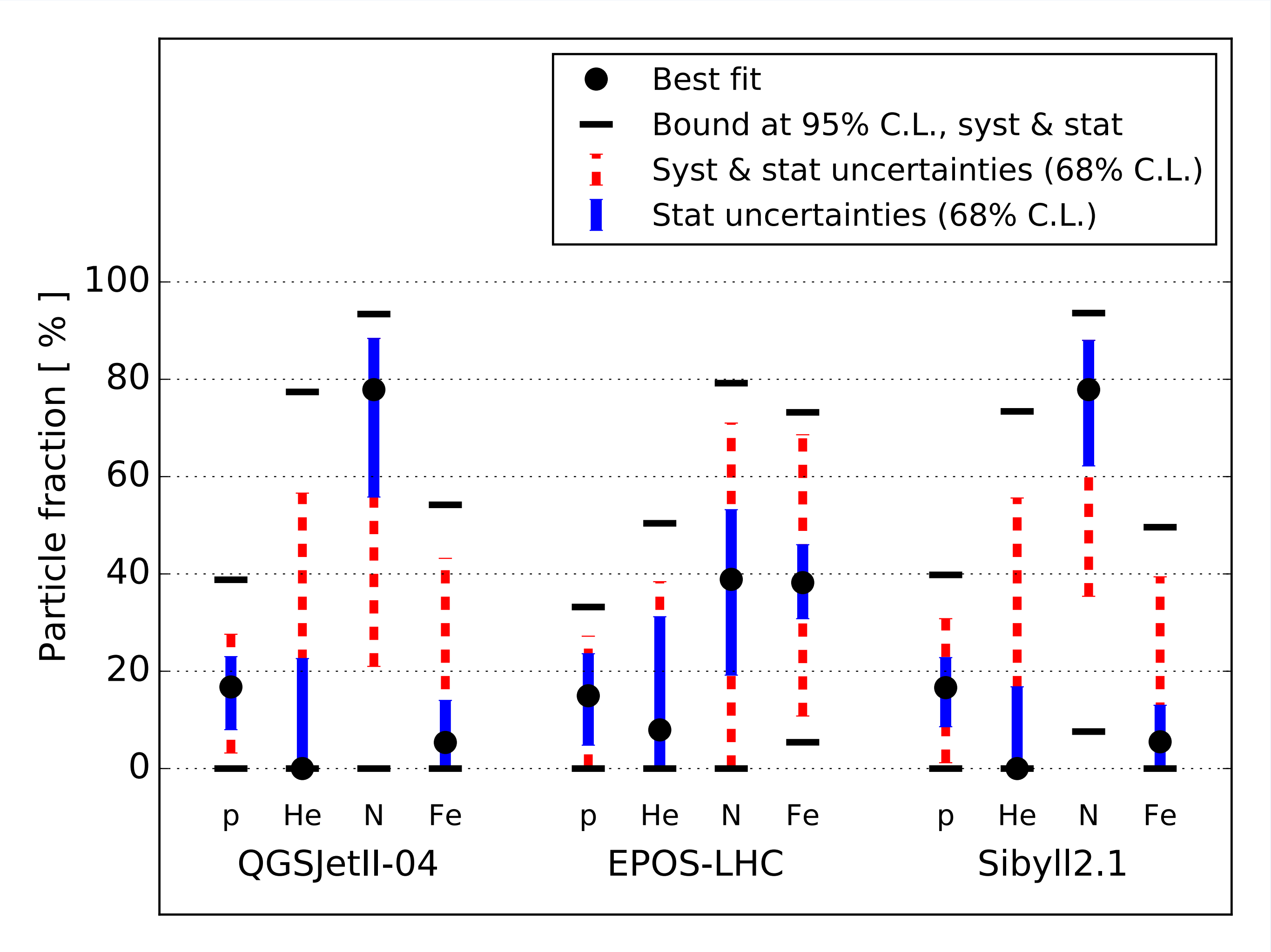
Results: likelihood ratio test



Test statistic for likelihood ratio test

Confidence intervals defined by having the curves above the horizontal line for the desired C.L.

Composition result per element



CRs in our energy range are mostly intermediate-mass nuclei
Some tendency to C/N/O rather than He (syst. limited)

Upper bound on protons of 40 %, at 95 % C.L. and across 3 hadronic interaction models

- Cannot (yet) resolve He and N

Summary

- Composition analysis for our data set
  - Mostly intermediate-mass elements
  - Upper bound on protons and on iron

- Distinguishing power is still limited by statistics, N=196 is a small set compared to e.g. Auger (> 3000 per bin)
  - However, result for iron is already systematics-limited

- Radio X_{max} measurements: stat. uncertainty **< 20 g/cm^2** and syst. uncertainty **~ 9 g/cm^2**
  - Competitive with state-of-the-art experiments!

- Proton component likely from extragalactic origin; heavier nuclei may be (re)accelerated inside the Galaxy e.g. supernova remnants with strong magnetic fields, or termination shocks

Outlook

- Radio X_{max} measurements: stat. uncertainty **< 20 g/cm^2** and syst. uncertainty **~ 9 g/cm^2**
  - Competitive with state-of-the-art experiments!

Improvements:

- LORA expansion, doubles detector count
- Extension to lower energies, not available with e.g. fluorescence detection; capture 'second knee' in CR spectrum: hybrid trigger needed
- 24/7 LBA background mode

All these increase the effective (bias-free) exposure, for the next factor of 3 in statistics.