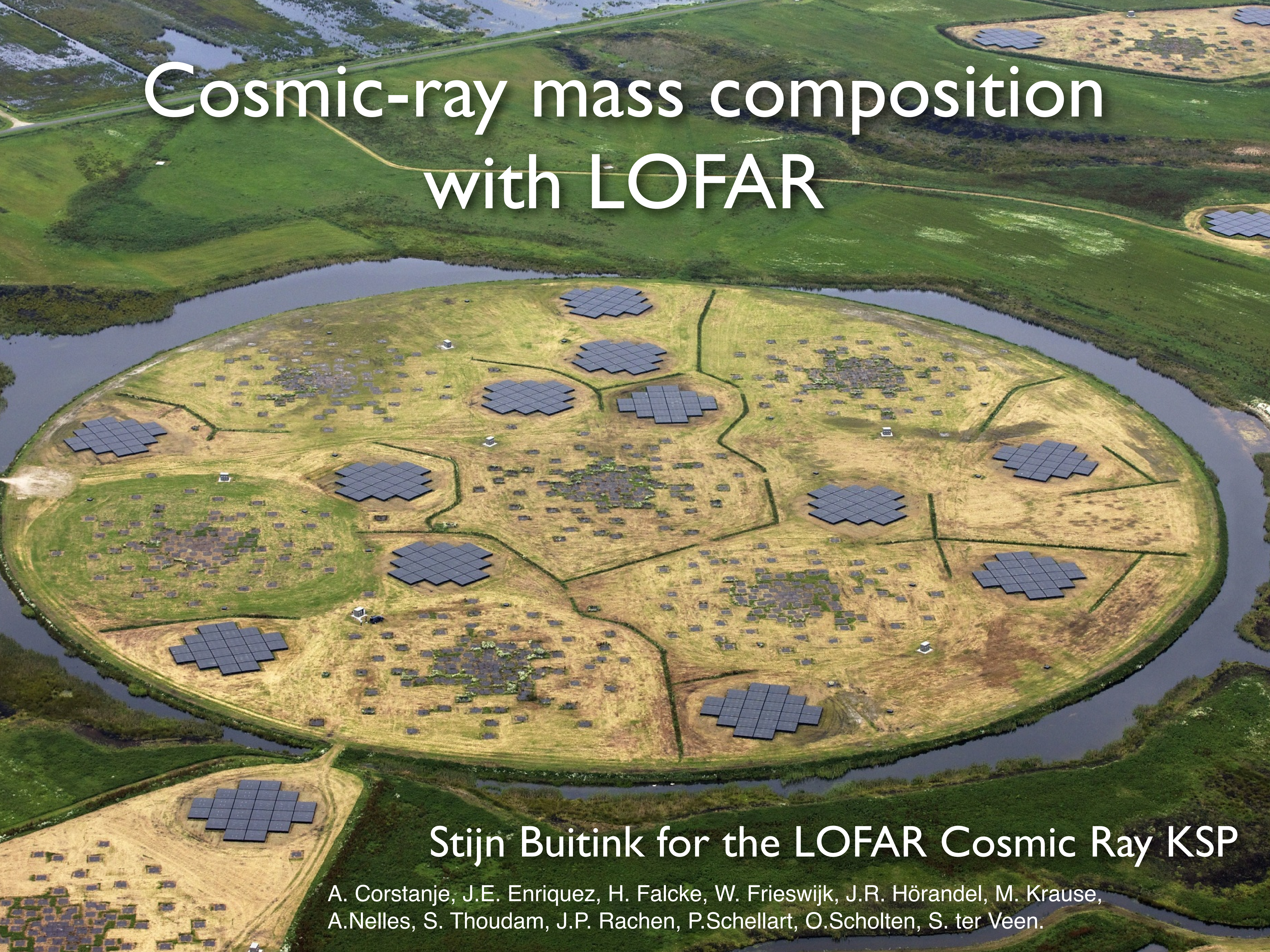
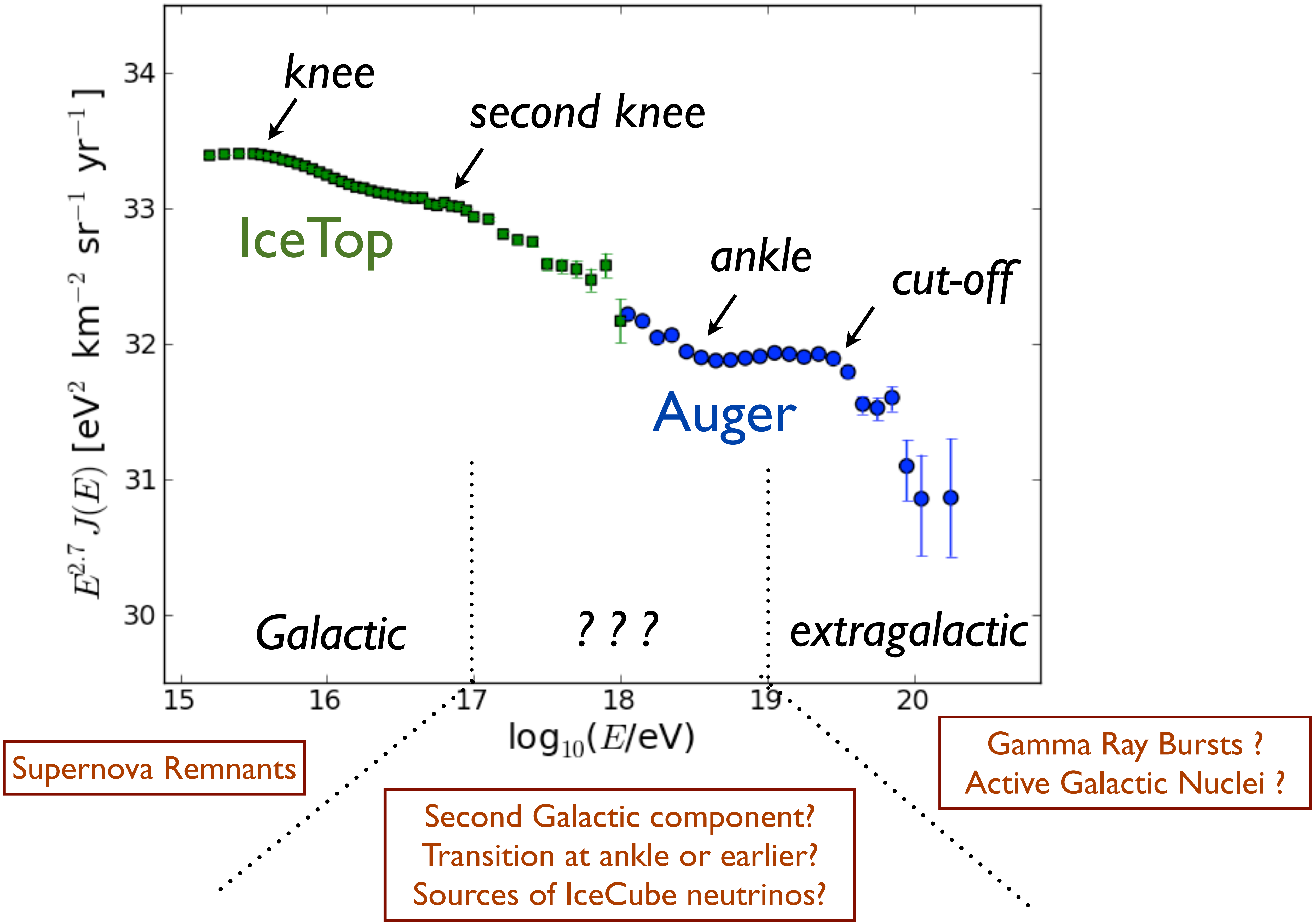


Cosmic-ray mass composition with LOFAR

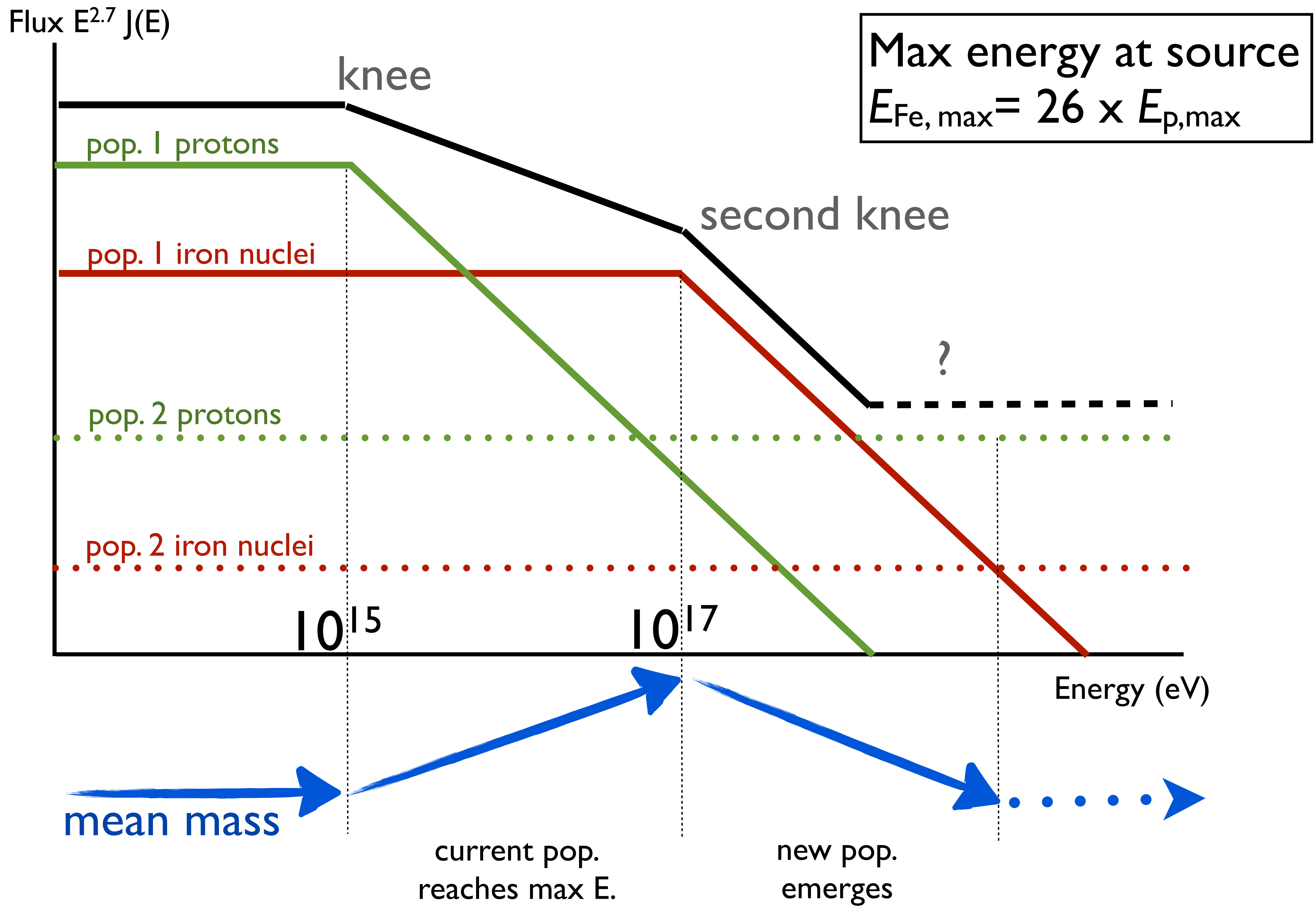
Stijn Buitink for the LOFAR Cosmic Ray KSP

A. Corstanje, J.E. Enriquez, H. Falcke, W. Frieswijk, J.R. Hörandel, M. Krause,
A.Nelles, S. Thoudam, J.P. Rachen, P.Schellart, O.Scholten, S. ter Veen.

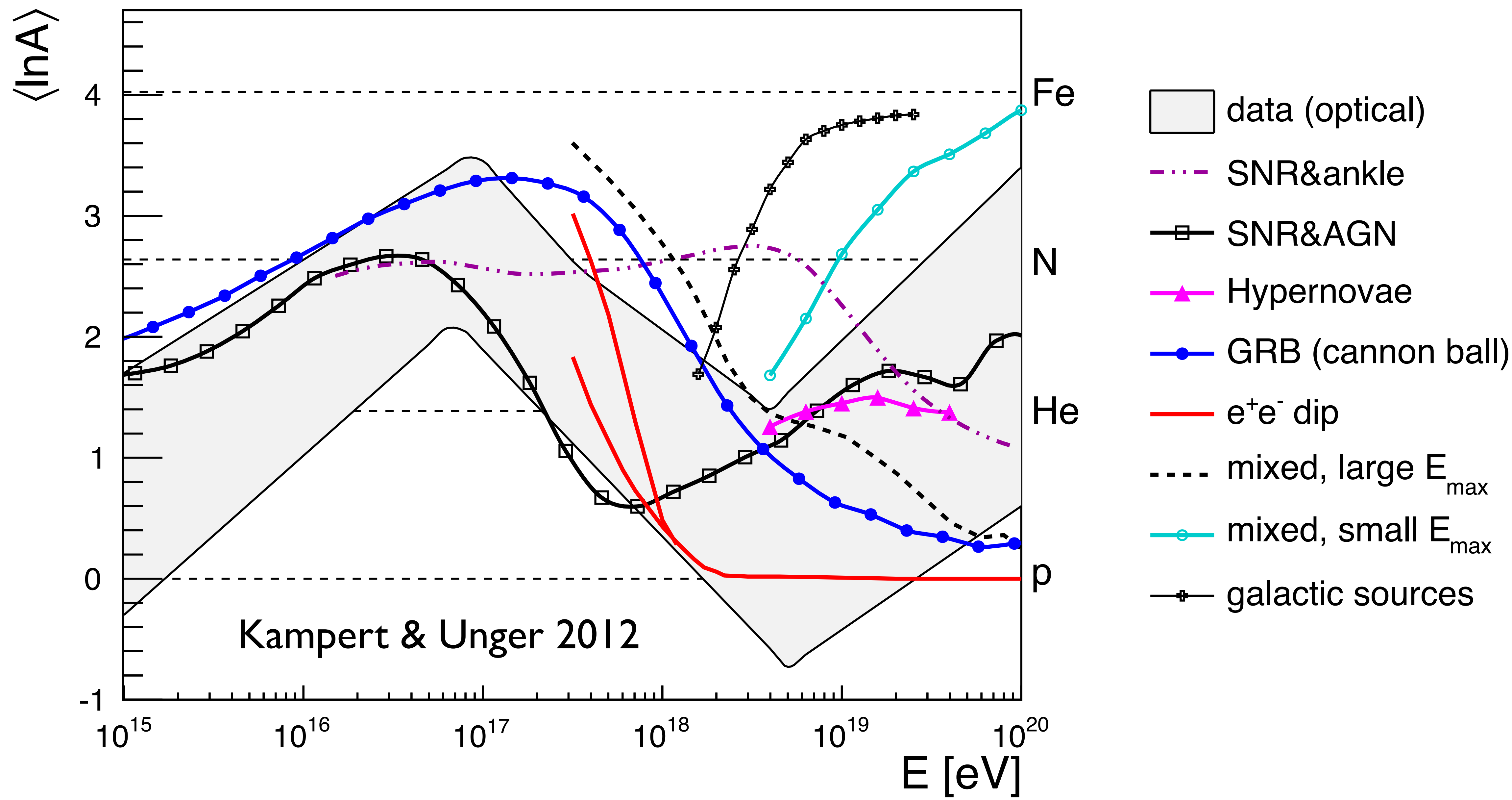
The all-particle cosmic ray spectrum



What Cosmic-Ray Masses tell us...



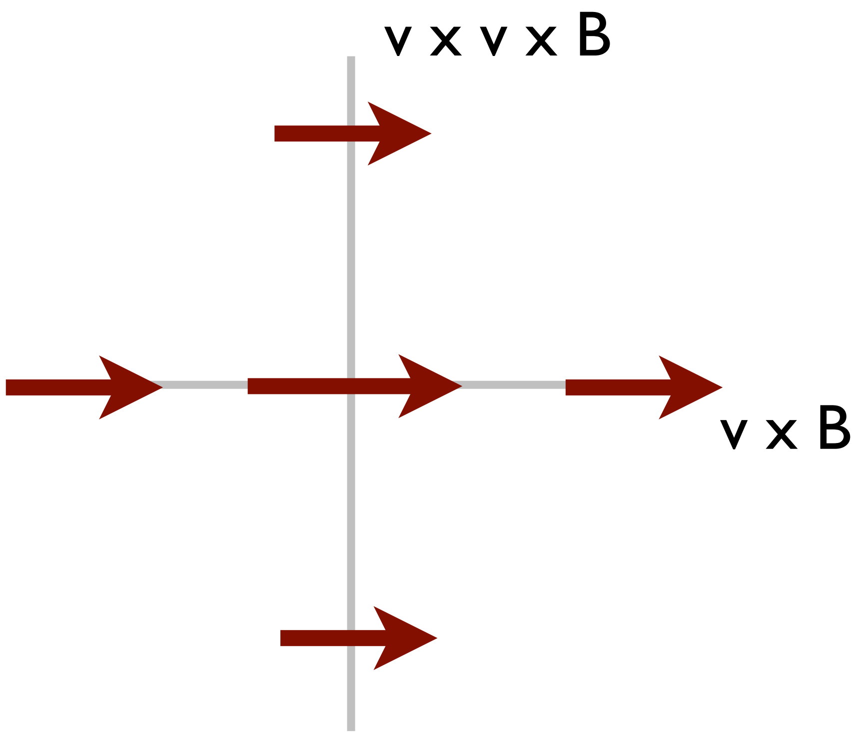
Galactic/extragalactic transition models

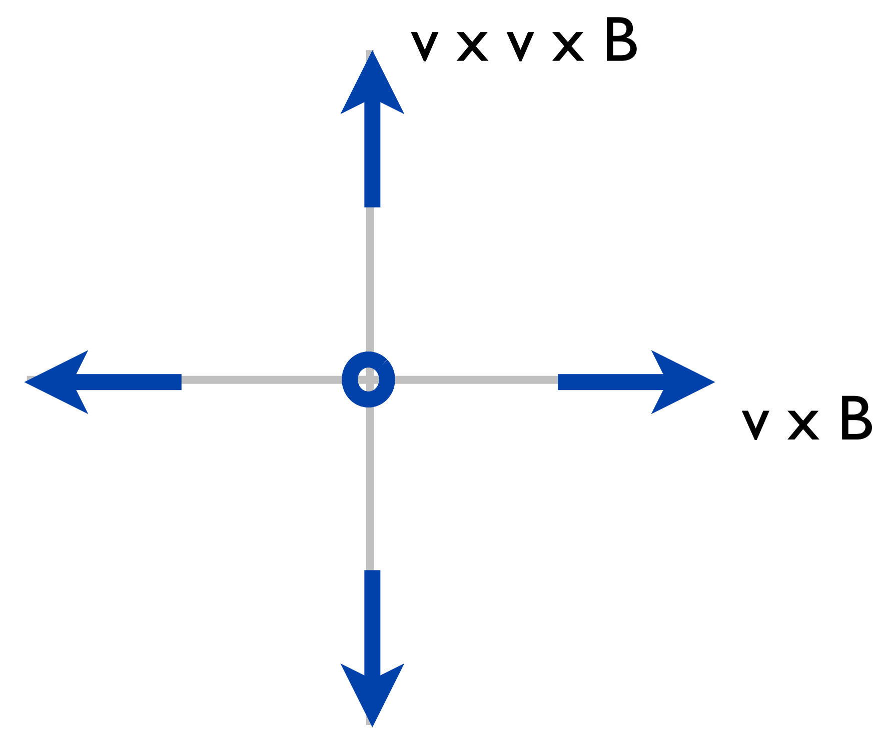


Accurate mass measurements needed!

LOFAR: mass composition at 10^{17} - 10^{18} eV

Understanding the radio pattern

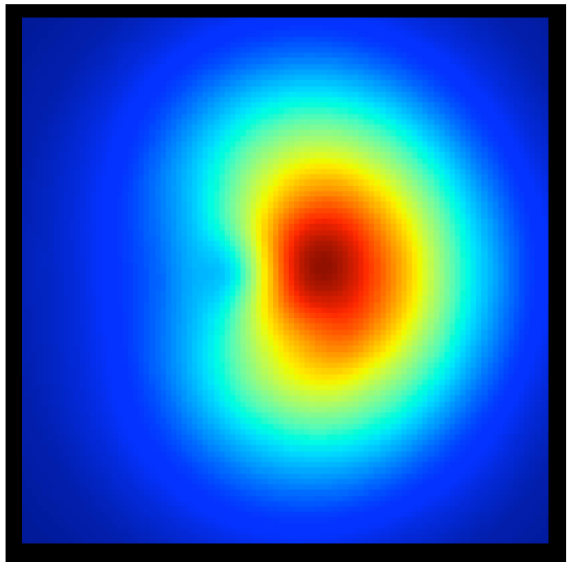




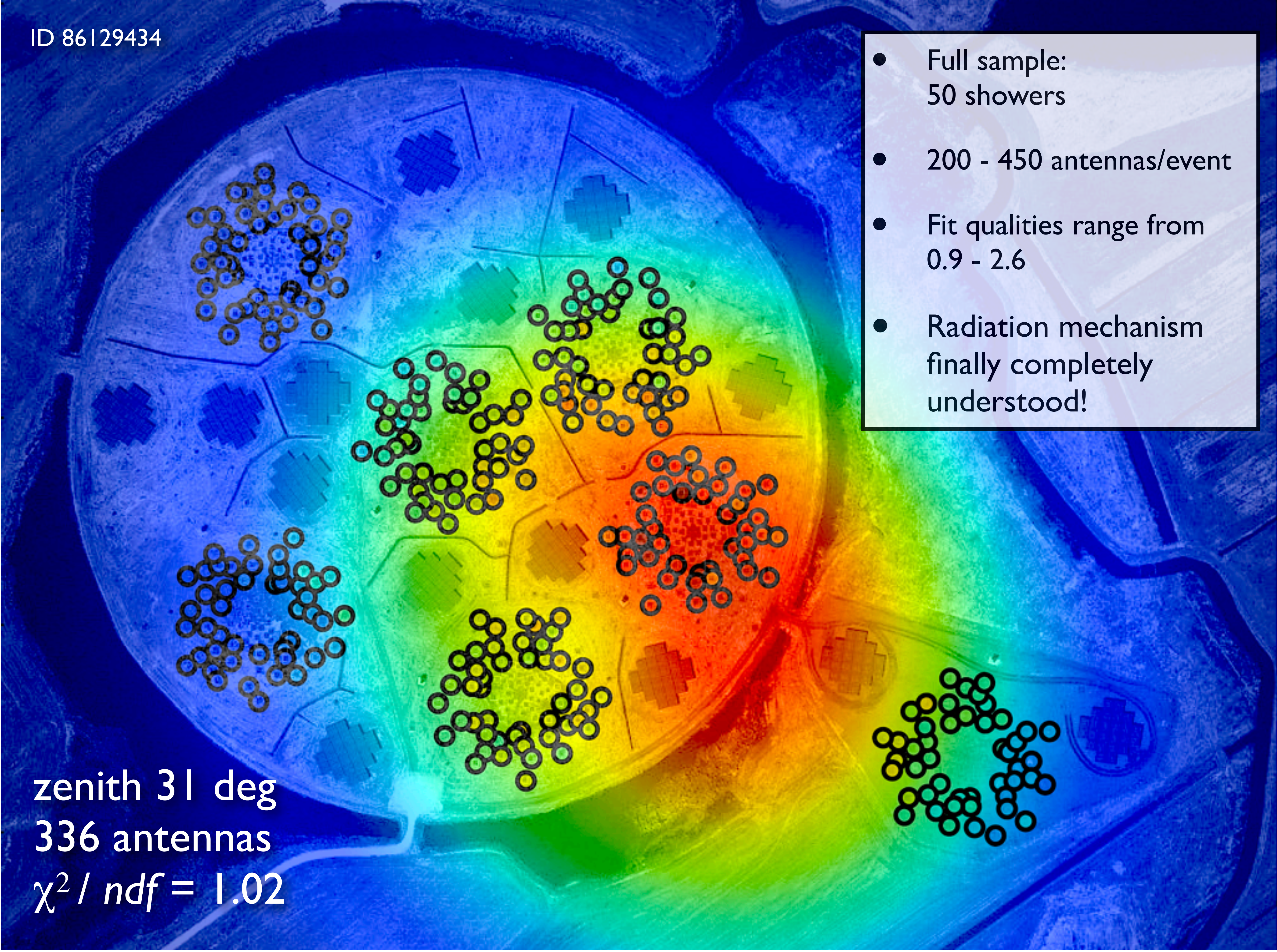
vector sum of geomagnetic and charge excess component

relativistic beaming

distortion by Cherenkov-like effects ($n \neq 1$)

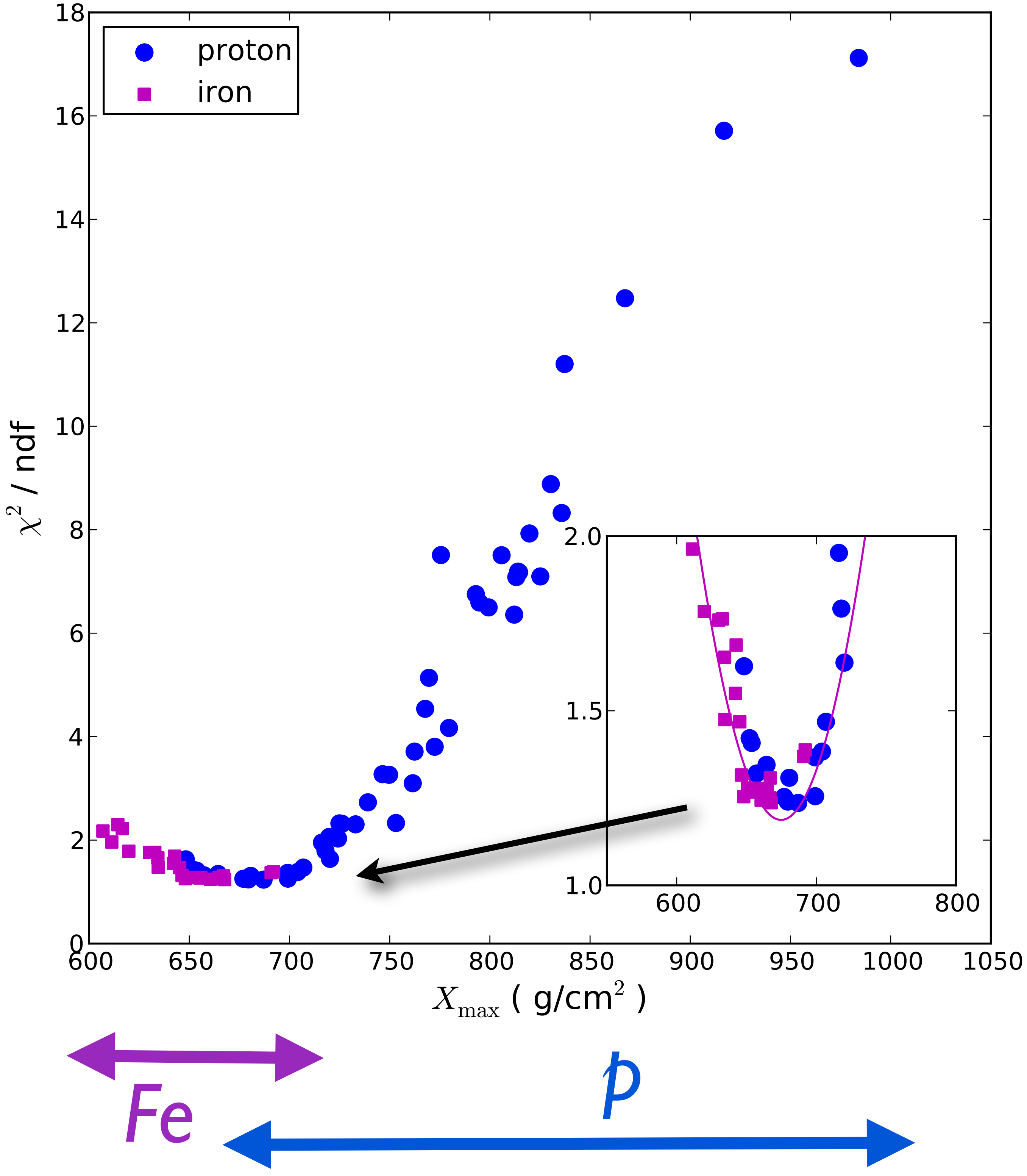


CoREAS simulation


ID 86129434
Full sample: 50 showers
200 - 450 antennas/event
Fit qualities range from 0.9 - 2.6
Radiation mechanism finally completely understood!
zenith 31 deg
336 antennas
χ2 / ndf = 1.02

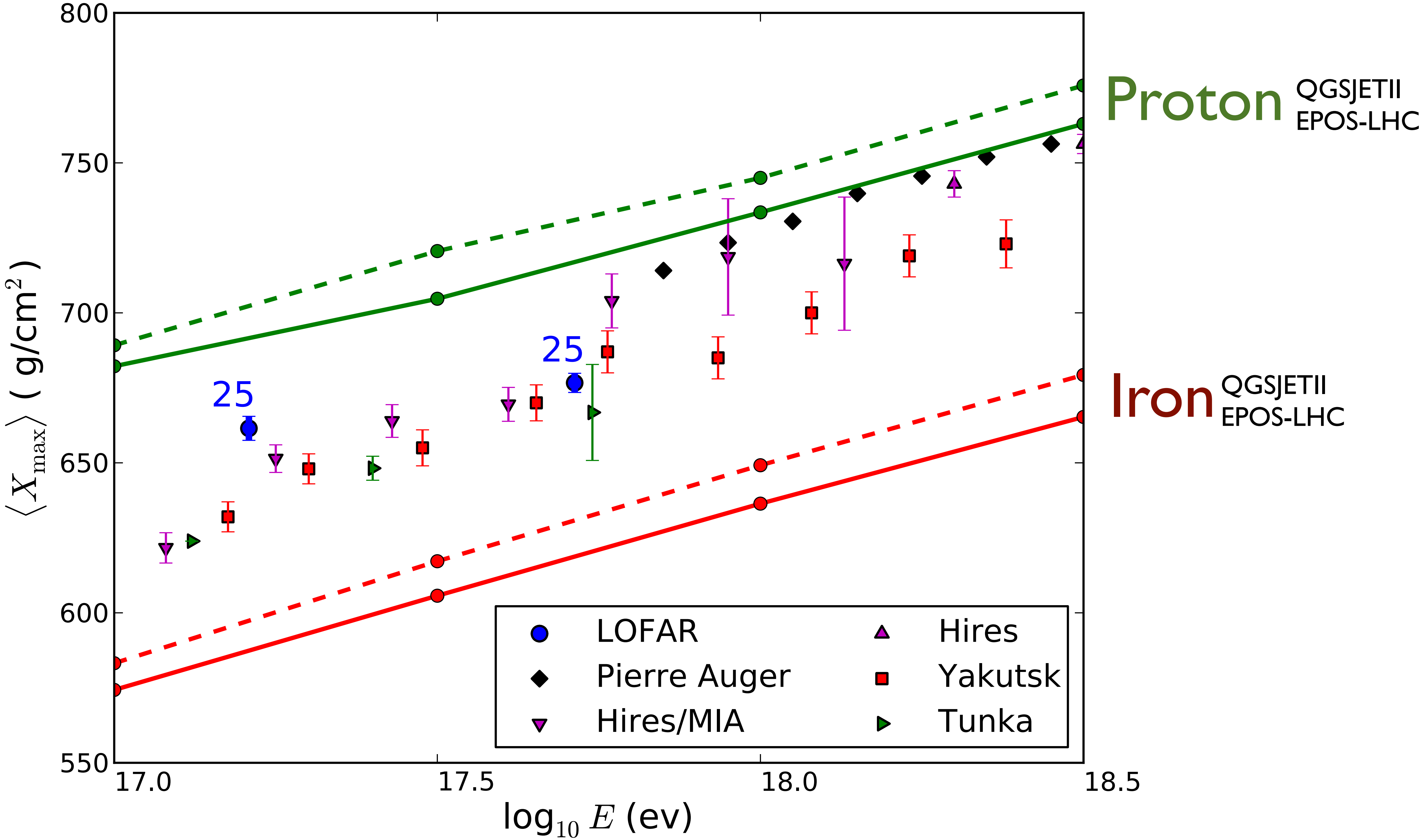
Xmax reconstruction

protons penetrate deeper than iron nuclei

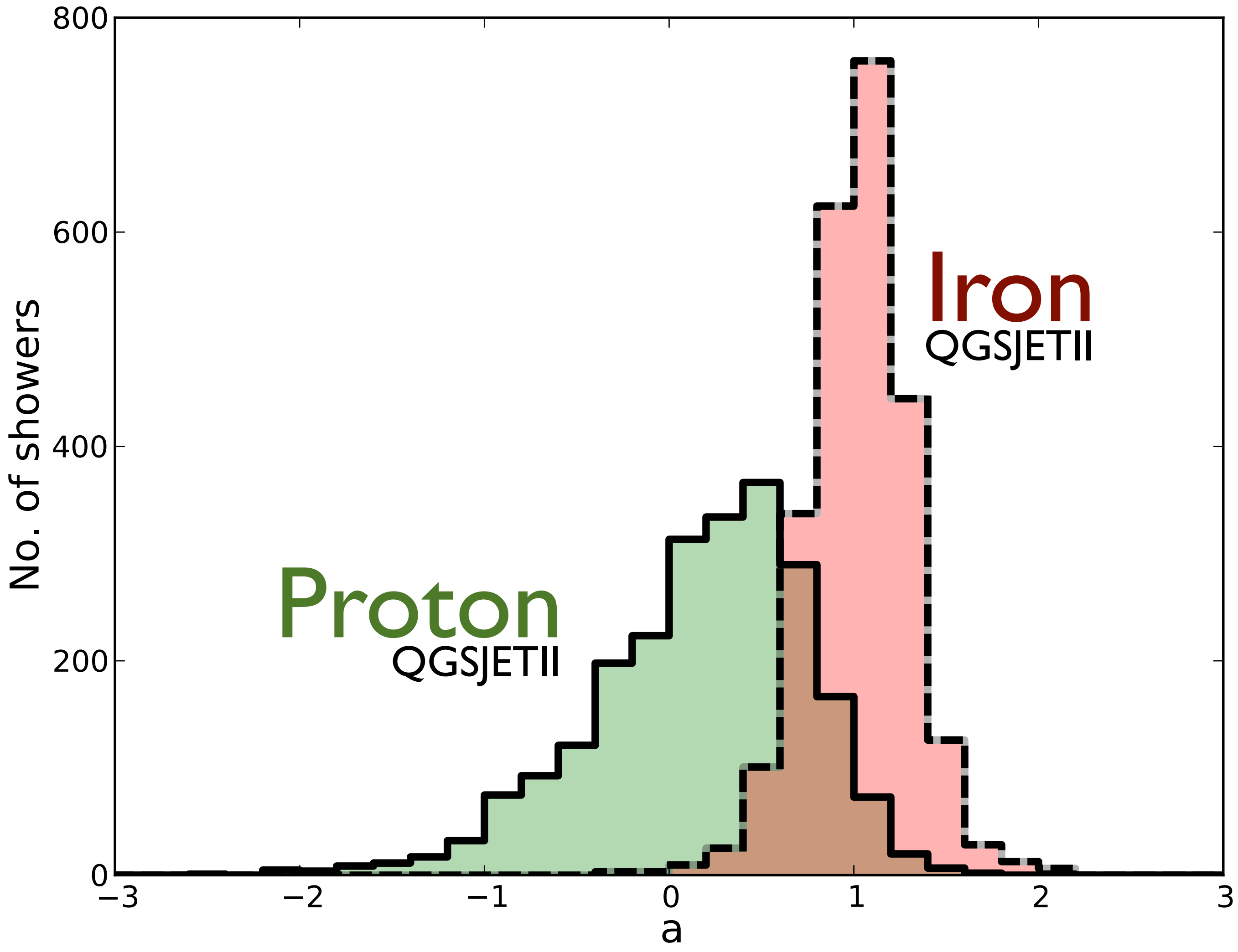


- For each measured shower:
  Simulate many proton and iron showers
- Fit each simulation to the data
  - free parameters:
    - core position
    - energy re-scaling
- Reconstruct depth of shower maximum: Xmax
- Correction for atmospheric variations
- Uncertainty < 20 g/cm^2 !!

Mean Xmax for 50 showers



... we can do better than that!

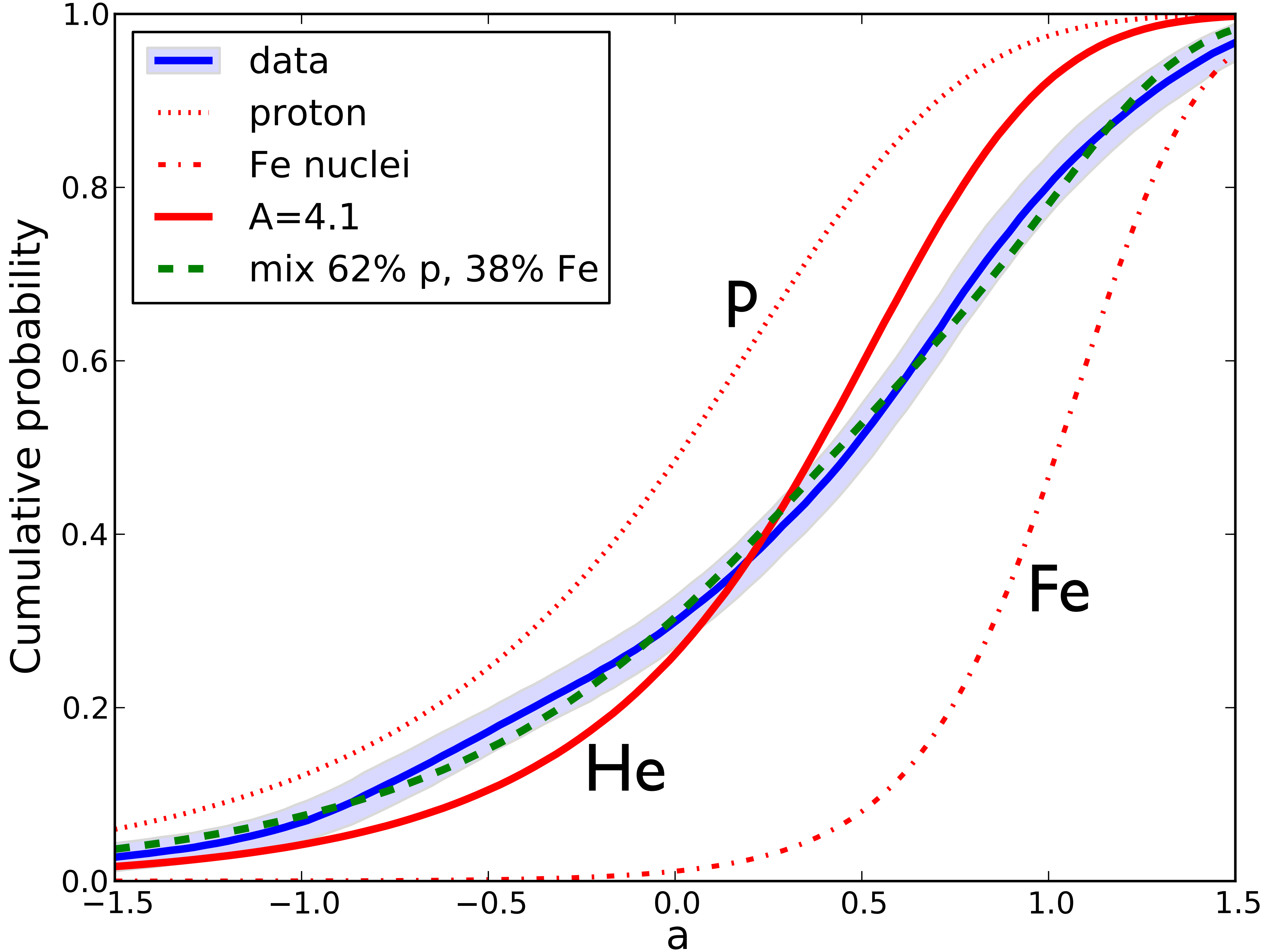


- LOFAR: high precision per event!
- Use **full** distribution of Xmax **not** only mean value
- First calculate mass parameter a

$$a = \frac{\langle X_{\rm proton} \rangle - X_{\rm shower}}{\langle X_{\rm proton} \rangle - \langle X_{\rm iron} \rangle}$$

- Fit model distribution to measured distribution

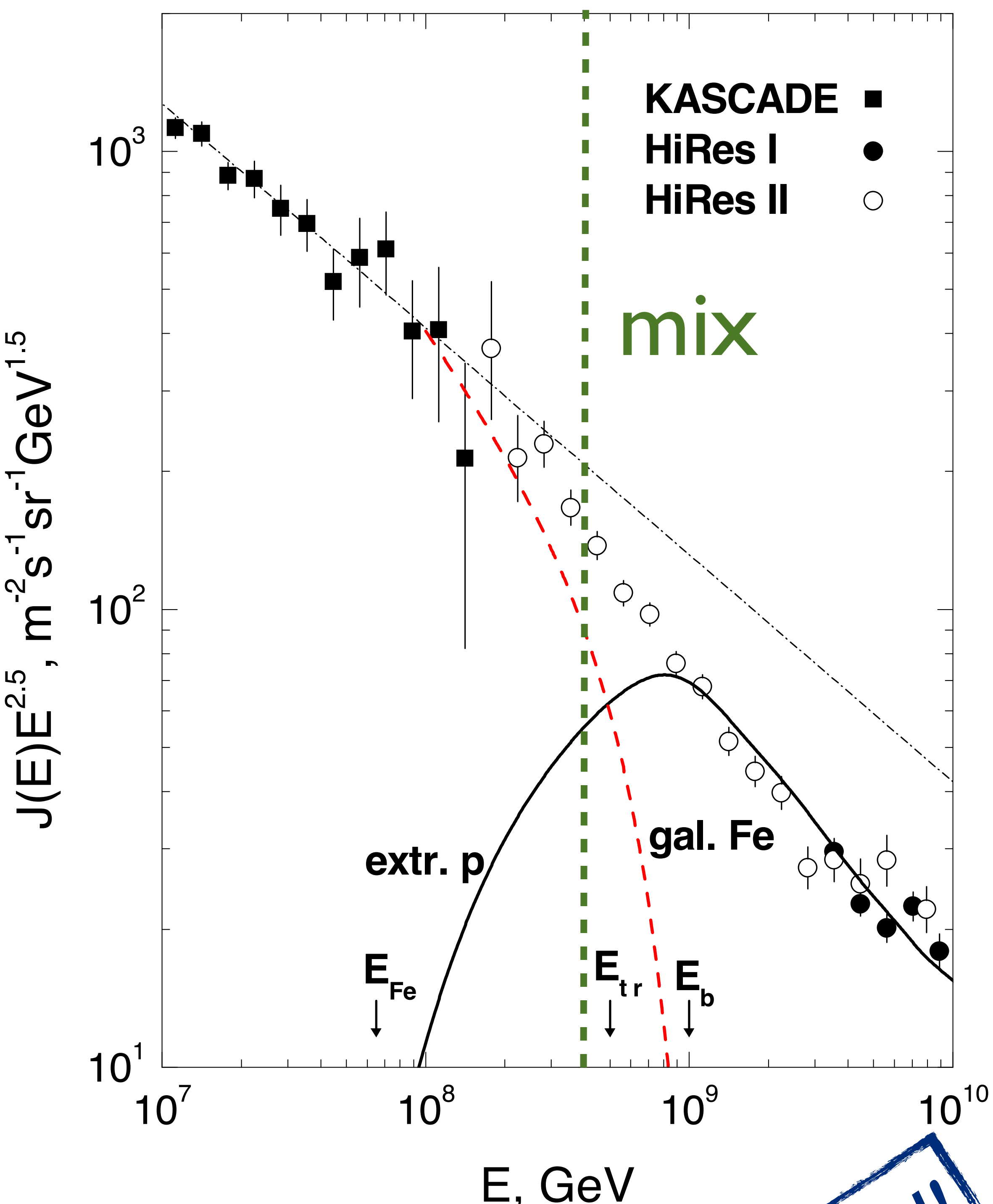
Cumulative distribution: model fits



We can already separate 2 mass components with only 50 showers!

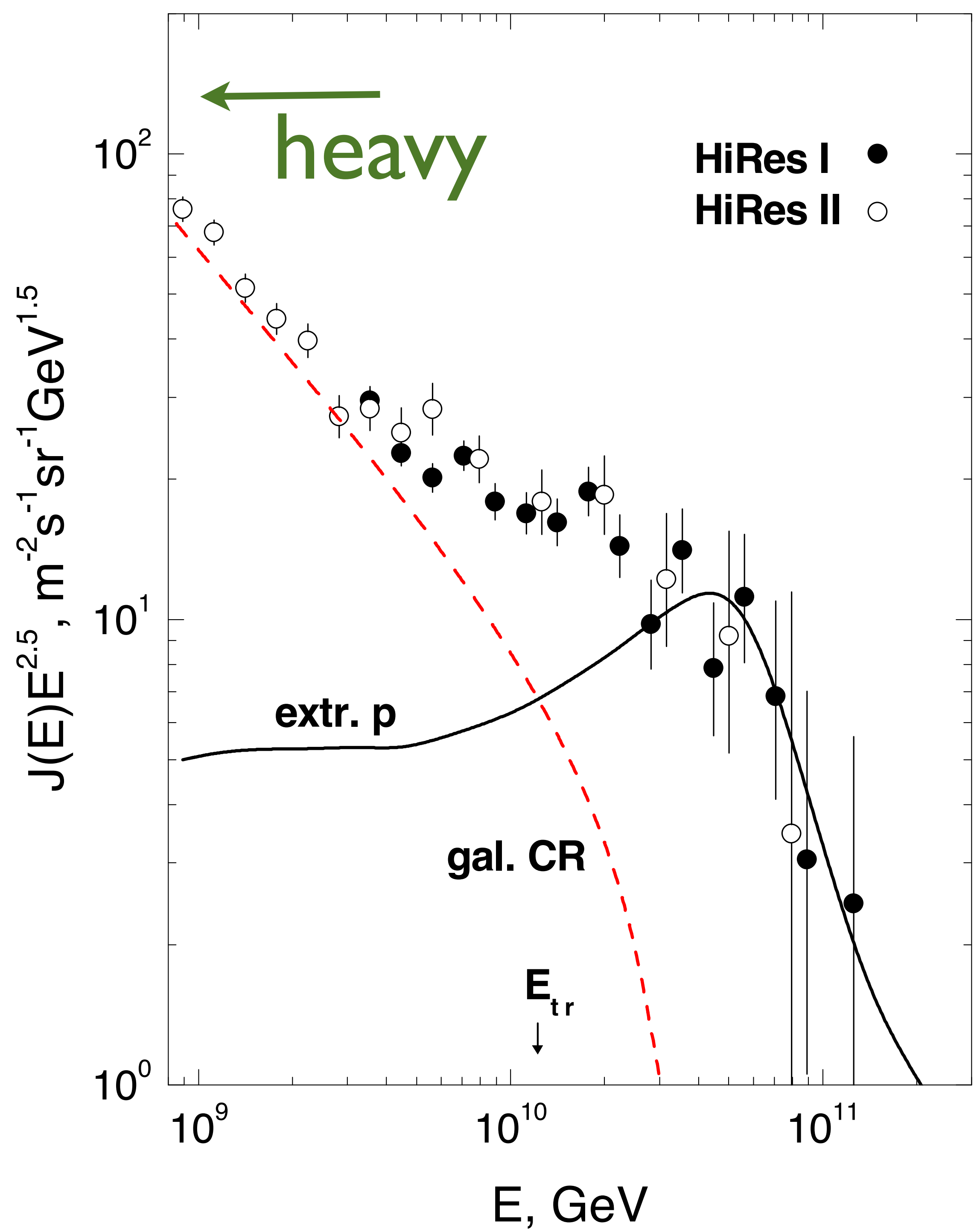
LOFAR: proton fraction = 0.6 ± 0.1 at $E = 4 \times 10^{17}$ eV

Aloisio et al 2007



"dip" model

favoured!



"ankle" model

Conclusions

- LOFAR is first radio telescope that can accurately measure CR mass composition
- Radio emission mechanism finally understood
- Xmax accuracy of < 20 g/cm^2
  similar to fluorescence detection + higher duty cycle
- First 50 events: strong proton fraction below 10^{18} eV
- Result favours early transition to extragalactic component
  also constrains models of (extra-)galactic IceCube neutrinos
- Future:
  - energy dependent mass ratios for 4 mass components
  - more precise reconstruction techniques

Thanks