

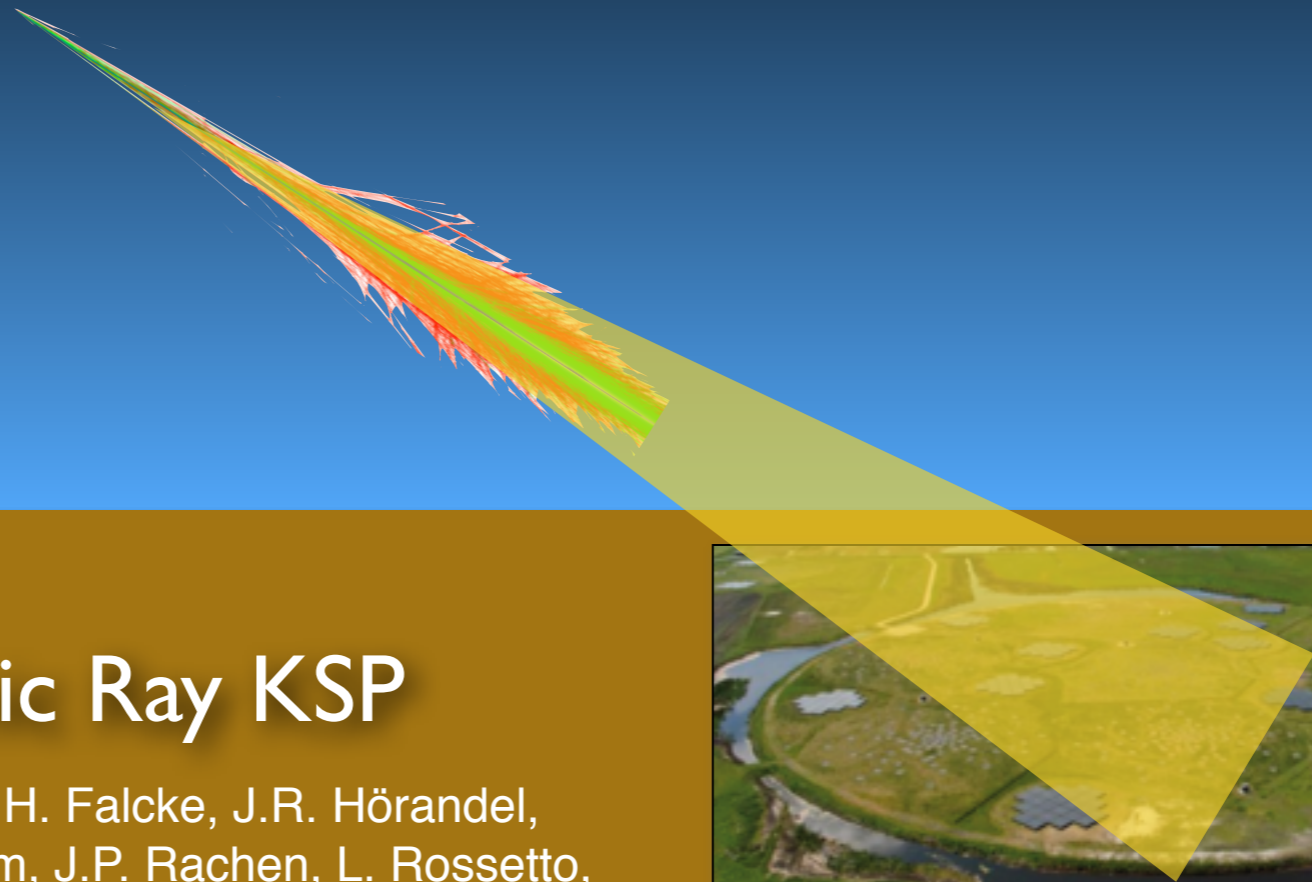
Cosmic-ray mass composition

LOFAR Science 2016
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Stijn Buitink - Vrije Universiteit Brussel



European Research Council



for the LOFAR Cosmic Ray KSP

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source?



source!

$$E_{\max} \propto Z B R$$

cosmic ray

air shower

radio pulse

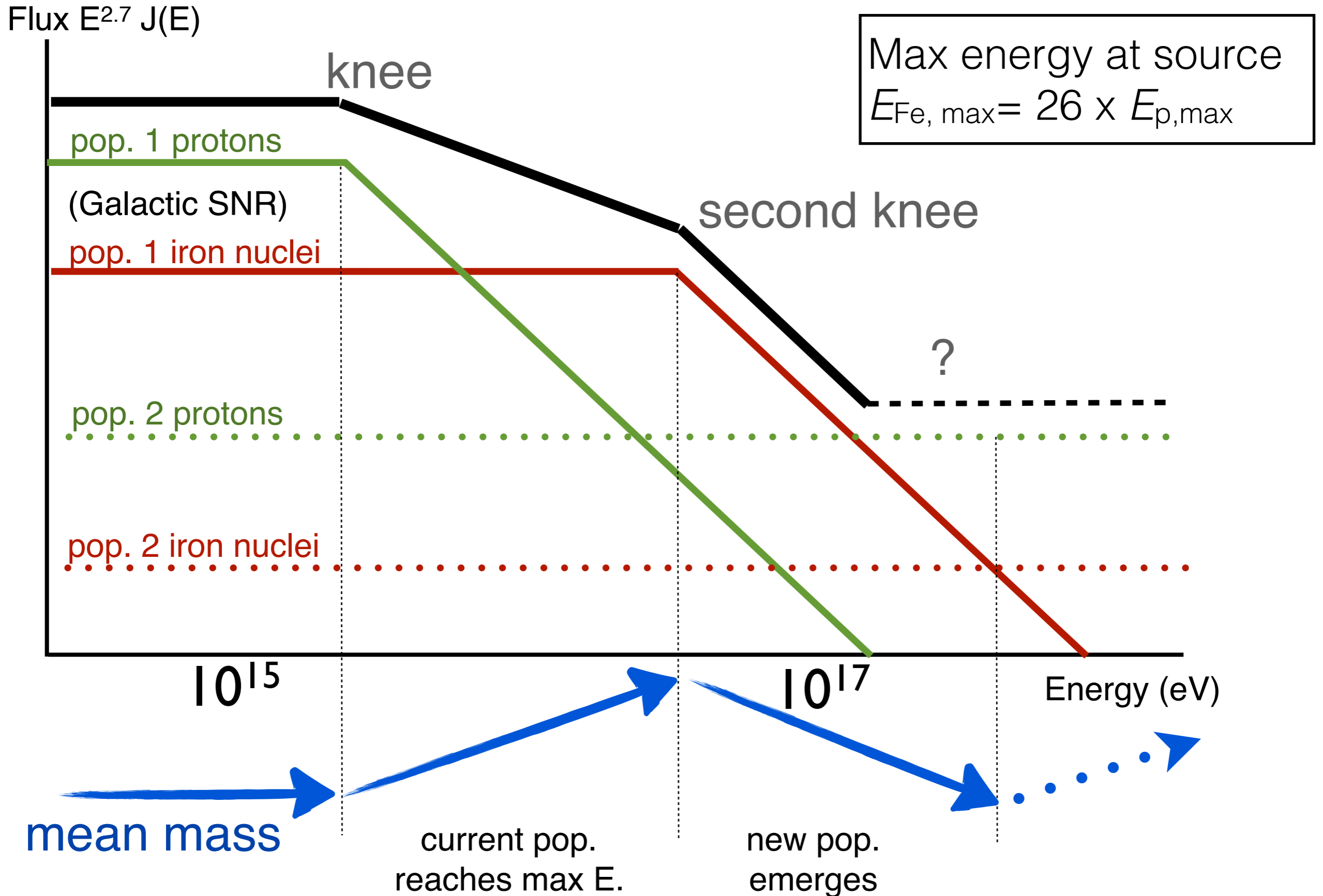
LOFAR superterp

to identify sources: measure CR mass!

**lighter nuclei penetrate
deeper in atmosphere**



What Cosmic-Ray Masses tell us...



How to measure the mass?

Atmospheric depth of shower maximum X_{\max}

fluorescence light

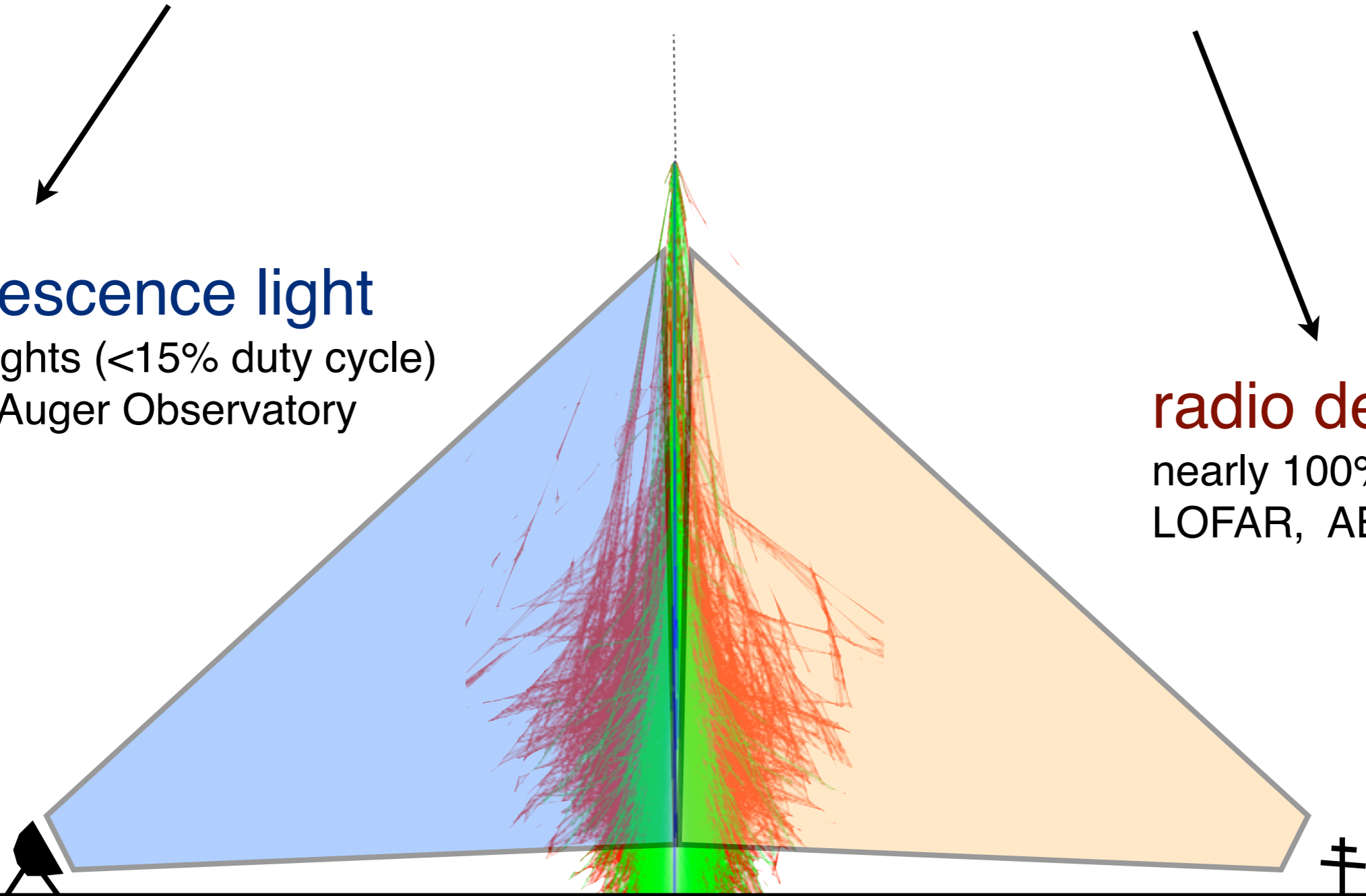
dark nights (<15% duty cycle)
Pierre Auger Observatory

radio detection

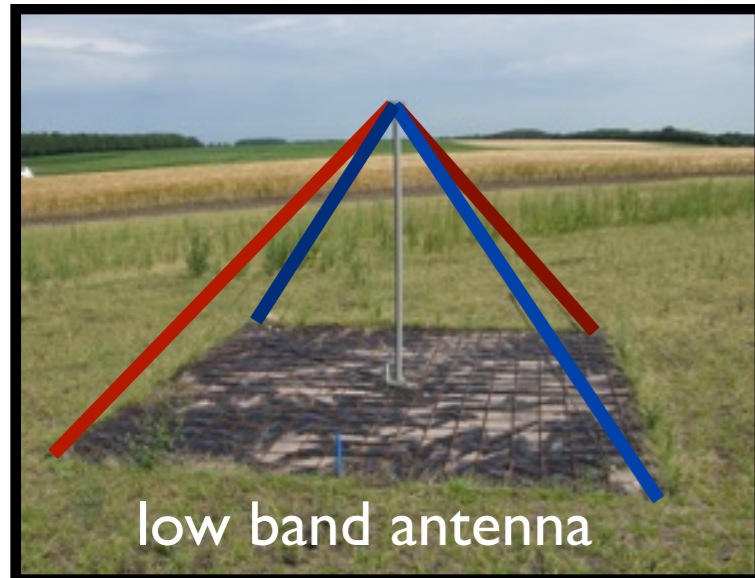
nearly 100% duty cycle
LOFAR, AERA, Tunka

electron/muon ratio

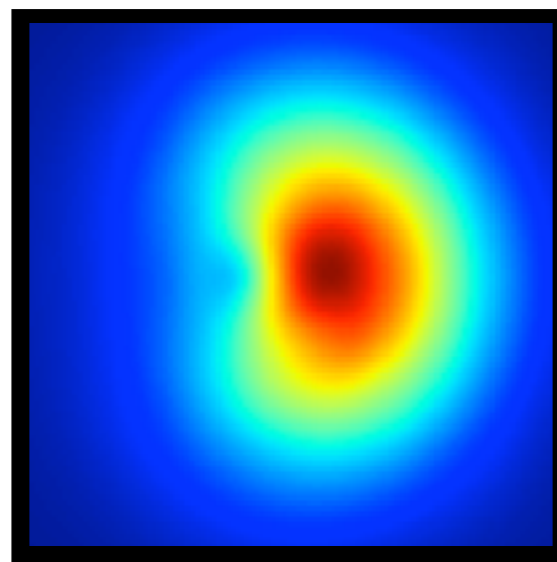
particles on ground,
sensitive to shower-to-shower fluctuations
Kascade Grande, IceTop



For each LOFAR shower:



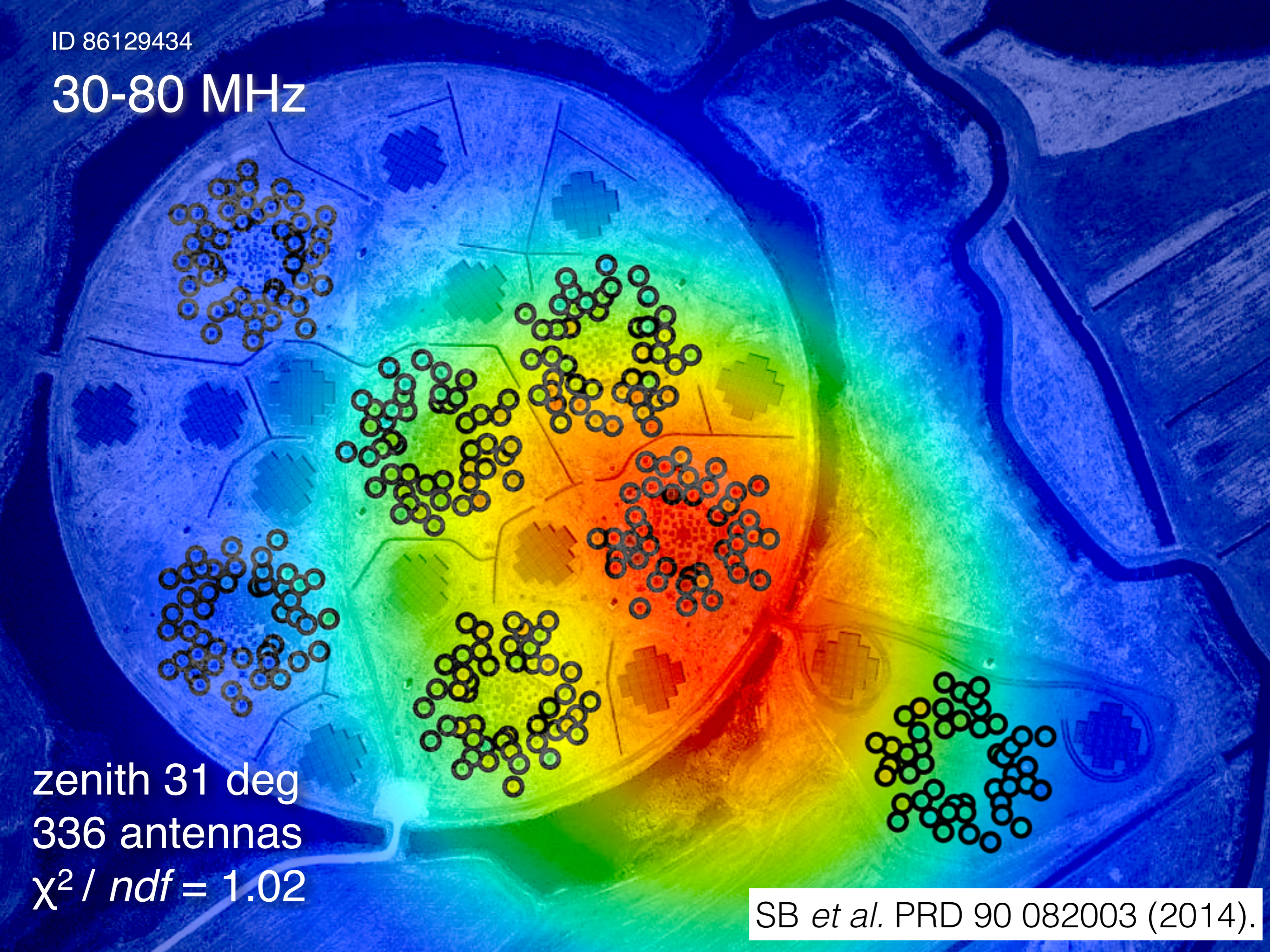
- Reconstruct **direction** from antennas (plane wave) + **energy** estimate from particle array (LORA)
- Produce **50 p + 25 Fe** showers
CoREAS
CORSIKA 7.4 (QGSJETII.04, Fluka, thinning 10^{-6})
- Calculate **total power** in 55 ns around peak emission
- GEANT4 LORA simulation: total **deposited energy**



Coreas simulation

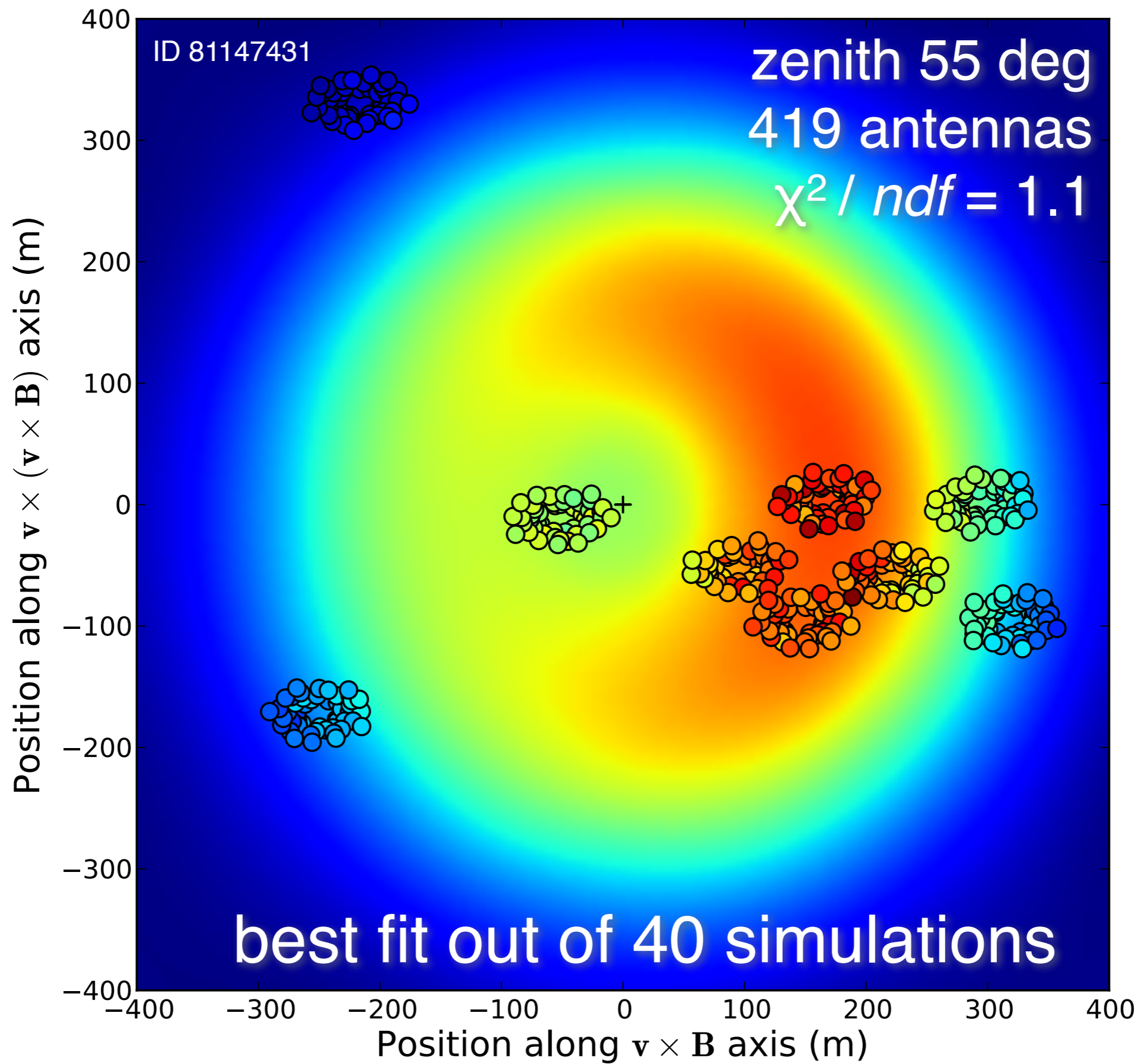
ID 86129434

30-80 MHz

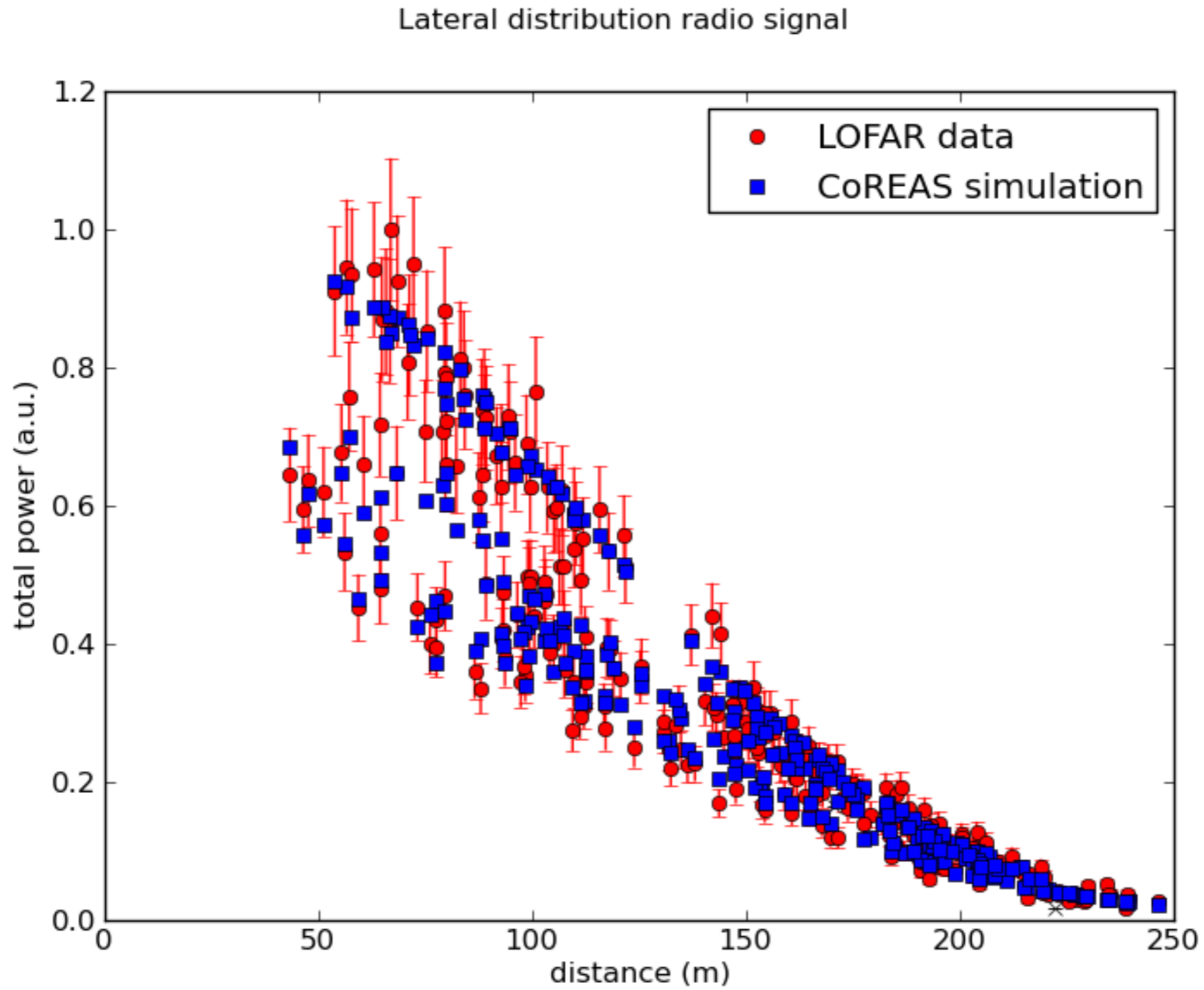


zenith 31 deg
336 antennas
 $\chi^2 / ndf = 1.02$

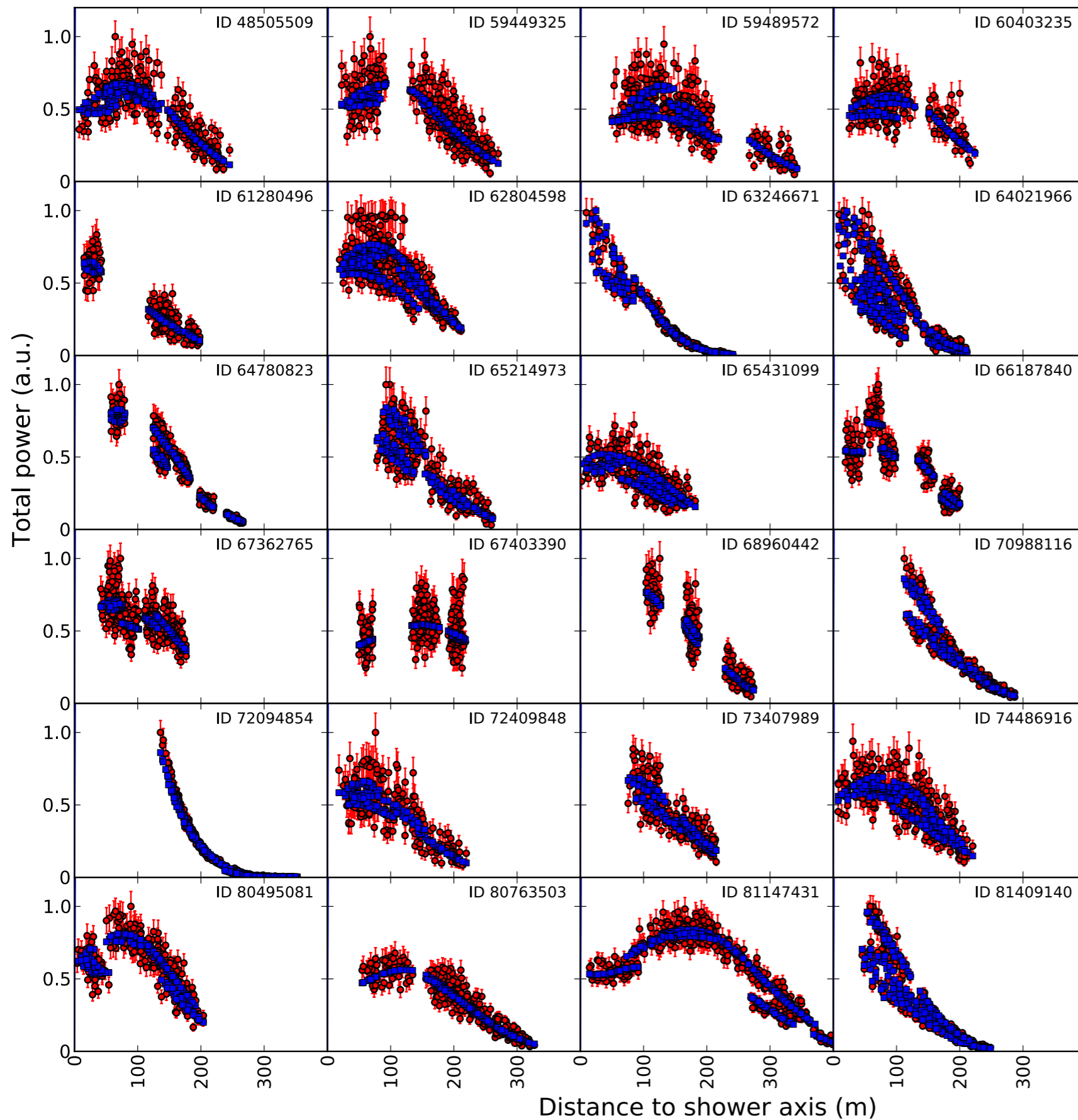
SB *et al.* PRD 90 082003 (2014).



best fit out of 40 simulations



1D LDFs don't fit !

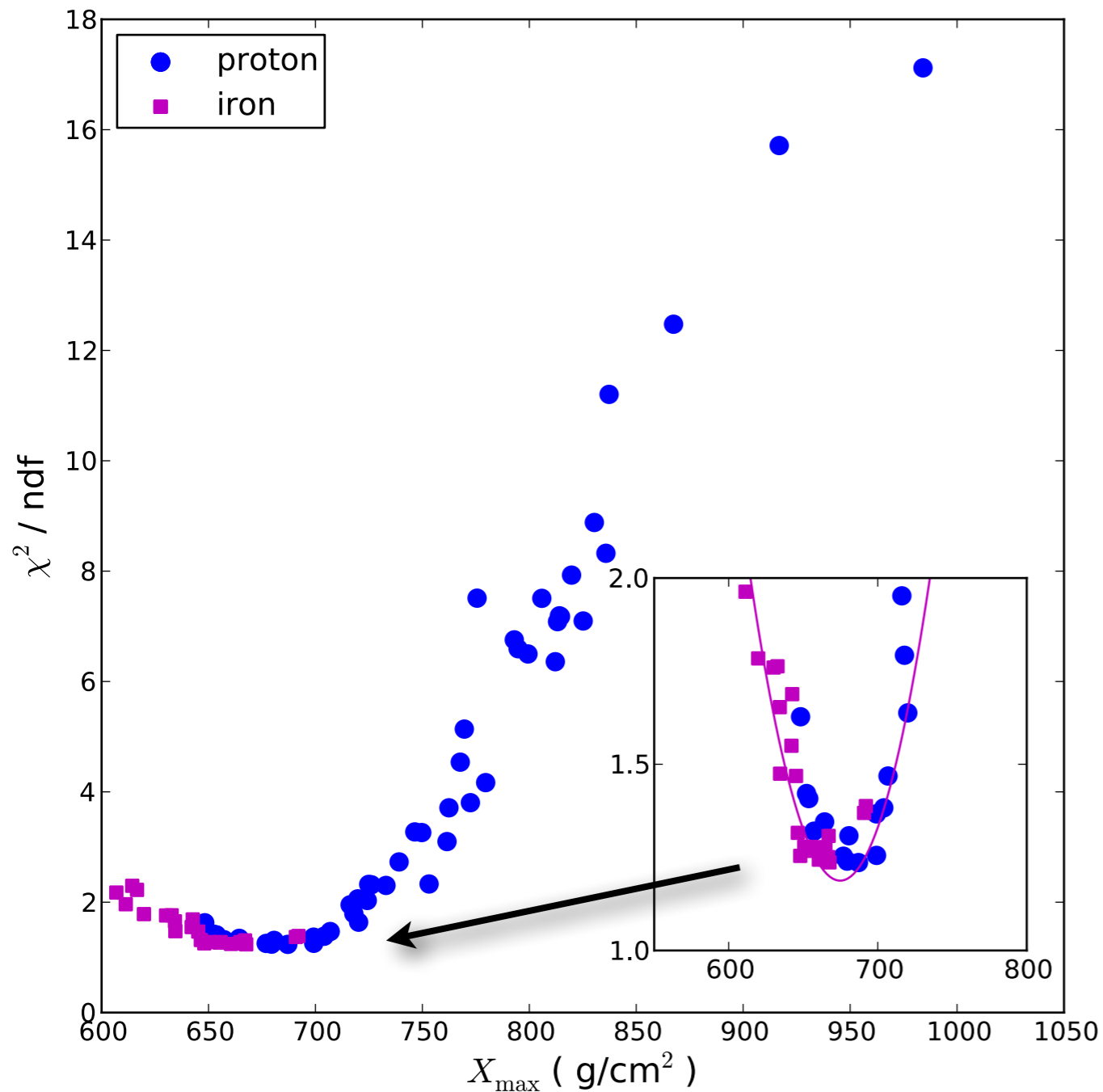


- **First sample:
>100 showers**
- 200 - 450 antennas/
event
- Fit χ^2 /ndf range from
0.9 - 2.6
- Radiation mechanism
finally completely
understood!

LOFAR data CoREAS sim

X_{\max} reconstruction

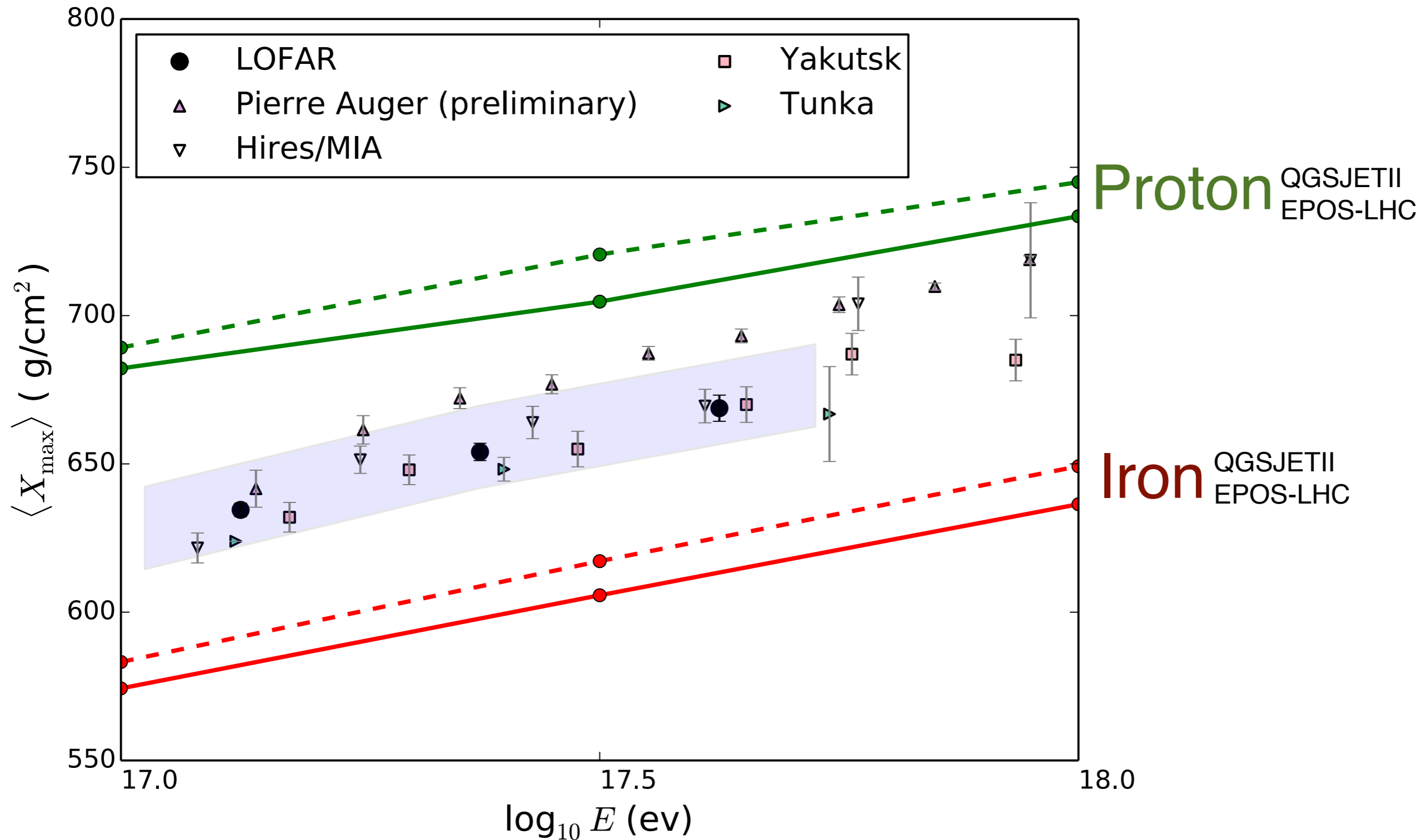
protons penetrate deeper than iron nuclei

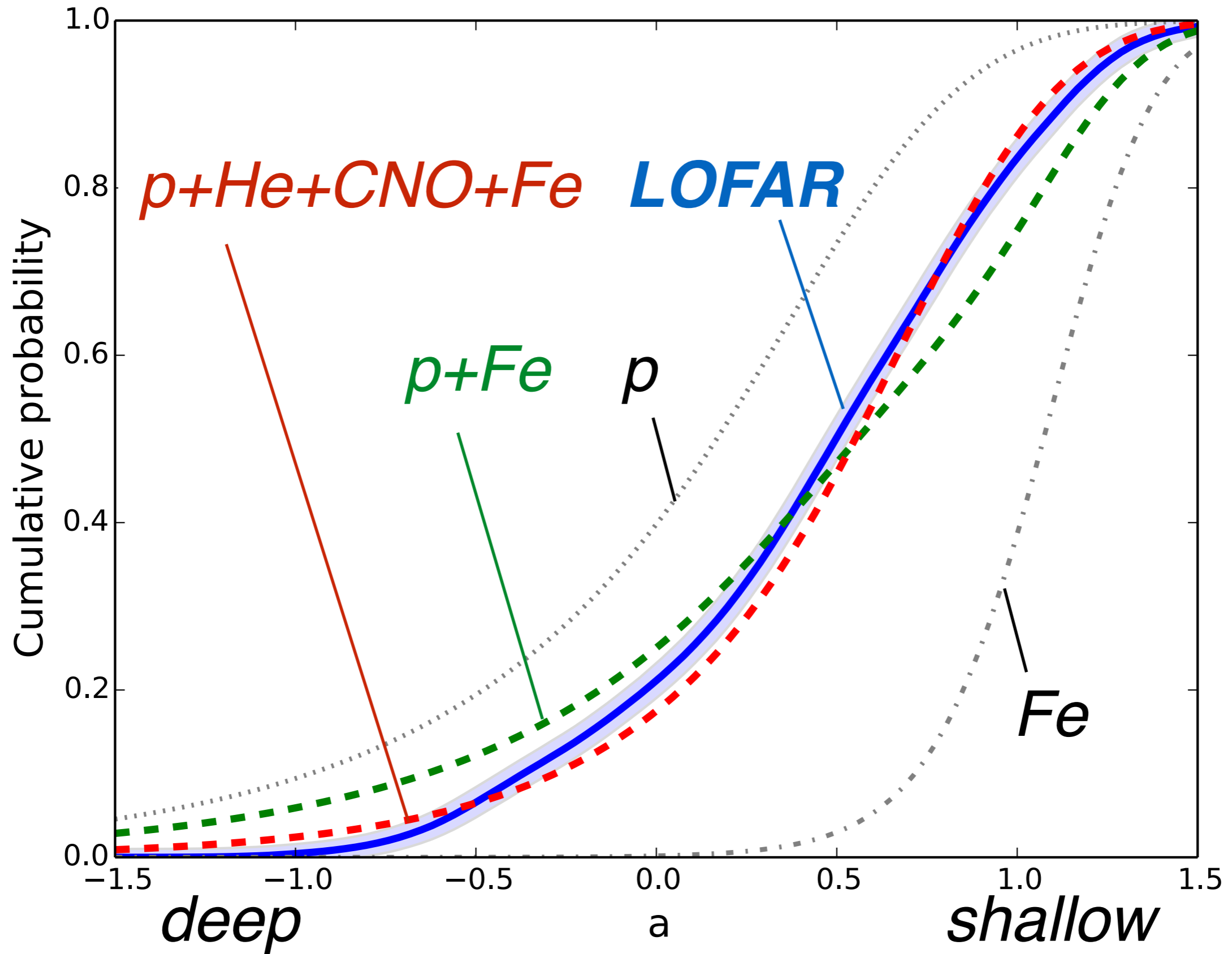


- Reconstruct depth of shower maximum: X_{\max}
- Jitter: other variations in shower development
- Correction for atmospheric variations using GDAS
- Resolution $< 20 \text{ g/cm}^2$!!



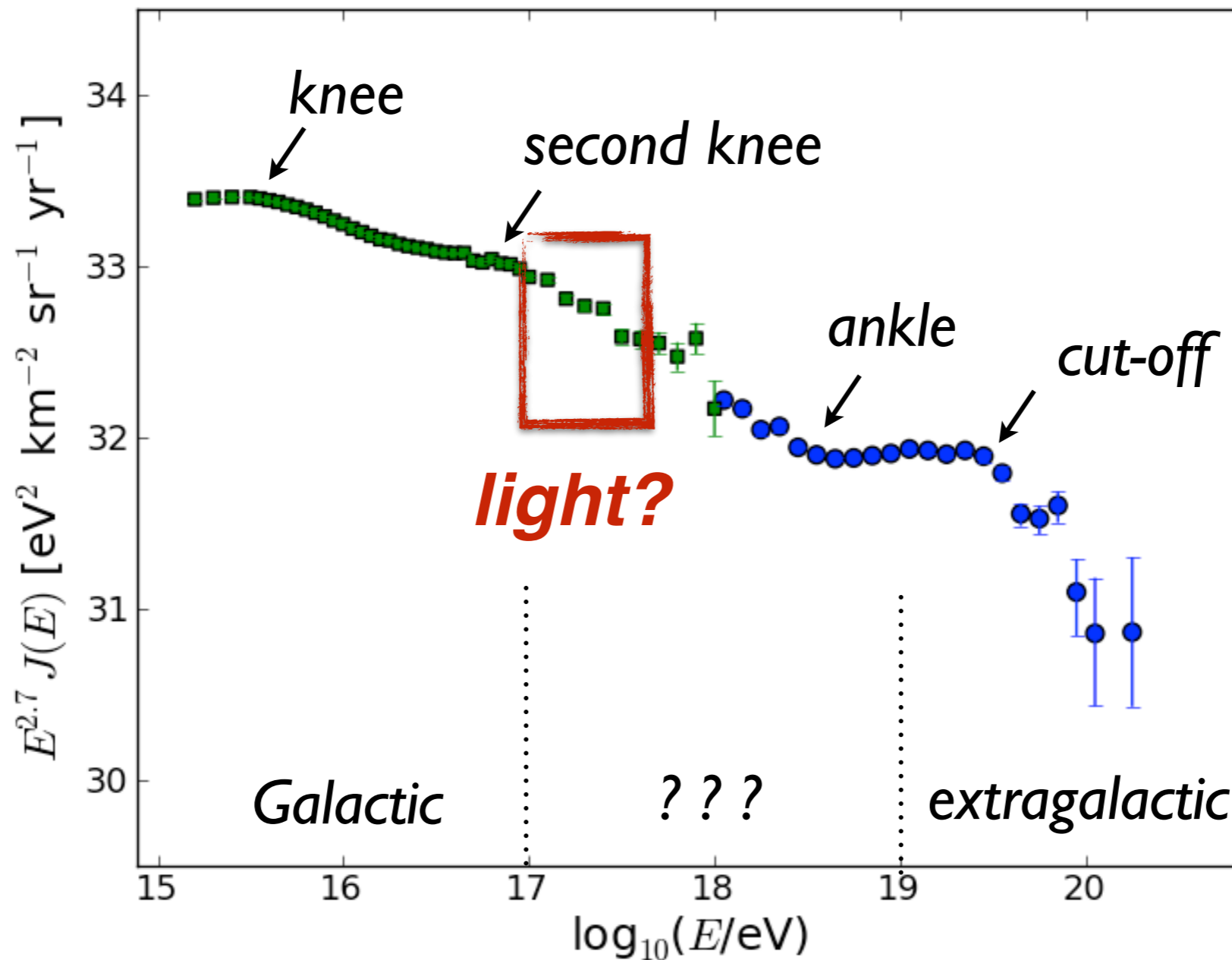
Mean X_{\max} for 114 showers





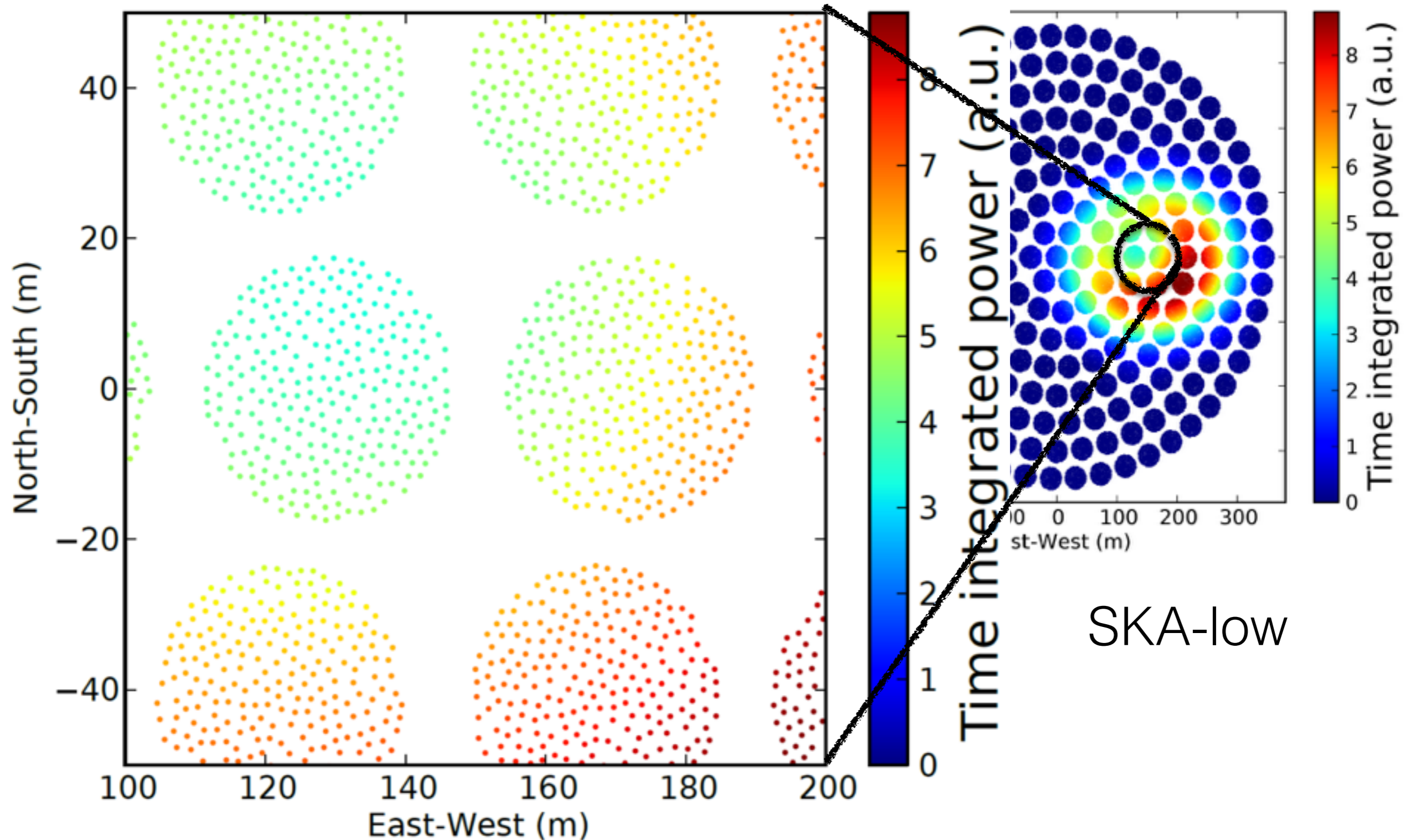
Best fit: 80% light particles ($p+He$) at $10^{17} - 10^{17.5}$ eV

What does it mean?



Galactic or extragalactic?
Wolf-Rayet stars? Reacceleration in halo?
Same sources as IceCube neutrinos?

SKA: ultrahigh precision measurements



Conclusions

- Air shower radio emission mechanism **finally understood!**
- LOFAR can **measure cosmic ray mass composition**
 X_{\max} resolution of **$< 20 \text{ g/cm}^2$**
similar to fluorescence detection + higher duty cycle
- First composition results based on 100+ high-res reconstructions using **full shape of X_{\max} distribution**
light mass component at $10^{17} - 10^{17.5} \text{ eV}$
- Future: ultra-high precision with **SKA**

Thanks