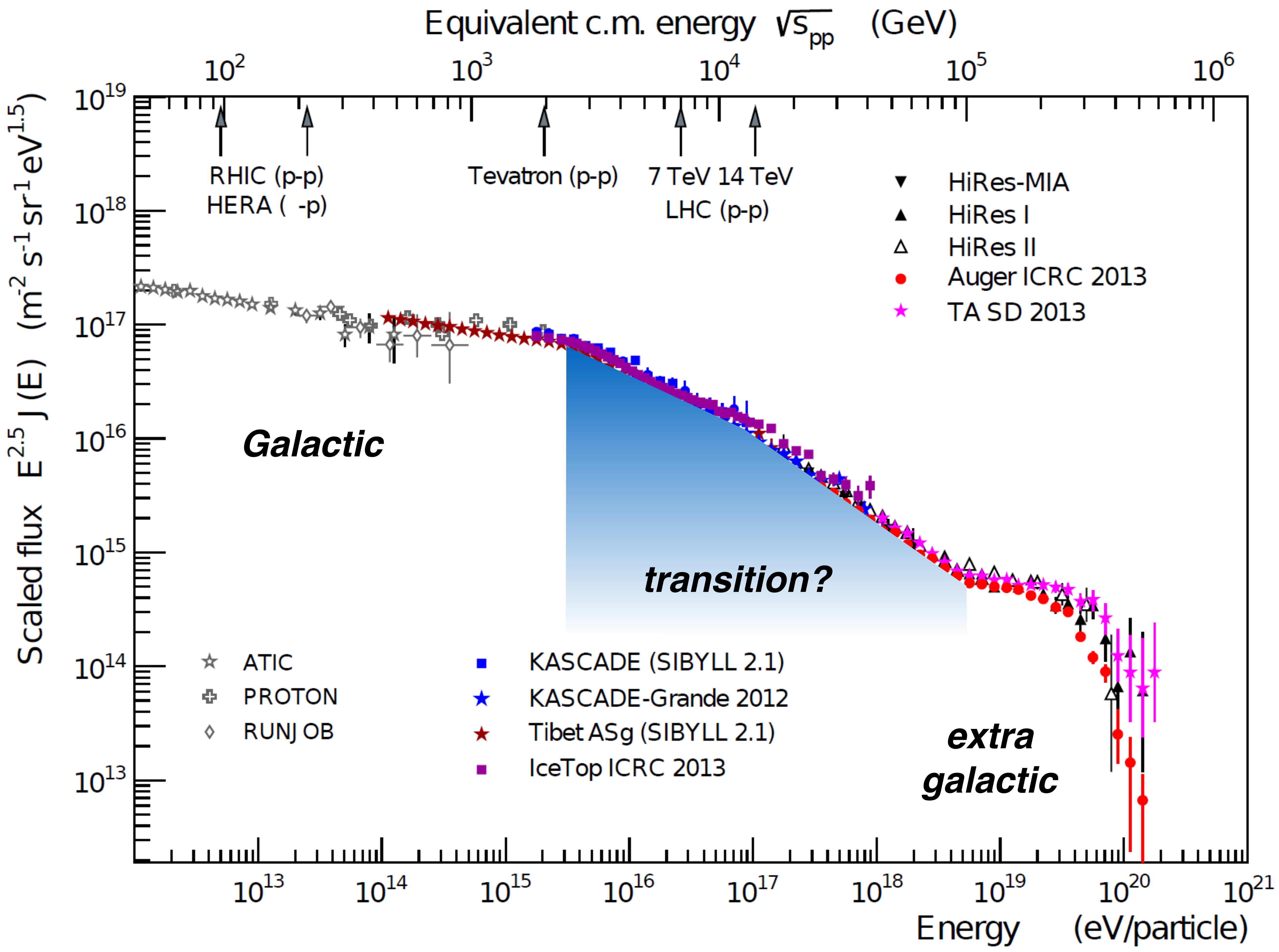
Cosmic Ray detection with LOFAR

Stijn Buitink (Vrije Universiteit Brussel)

Arthur Corstanje
Mitja Desmet
Heino Falcke
Brian Hare
Jörg Hörandel
Tim Huege
Godwin Krampah
Pragati Mitra
Katie Mulrey
Anna Nelles
Hershal Pandya
Olaf Scholten
Satyendra Thoudam

COSPA meeting 21-4-2022 UCLouvain

Origin of cosmic rays



- Likely diffusive shock acceleration in Supernova remnants below $\sim 10^{15}$ eV
- Extragalactic above $\sim 10^{19}$ eV Active Galactic Nuclei ?
- Transition region ? Supernova Remnants of Wolf-Rayet stars ?
- Measure mass composition!

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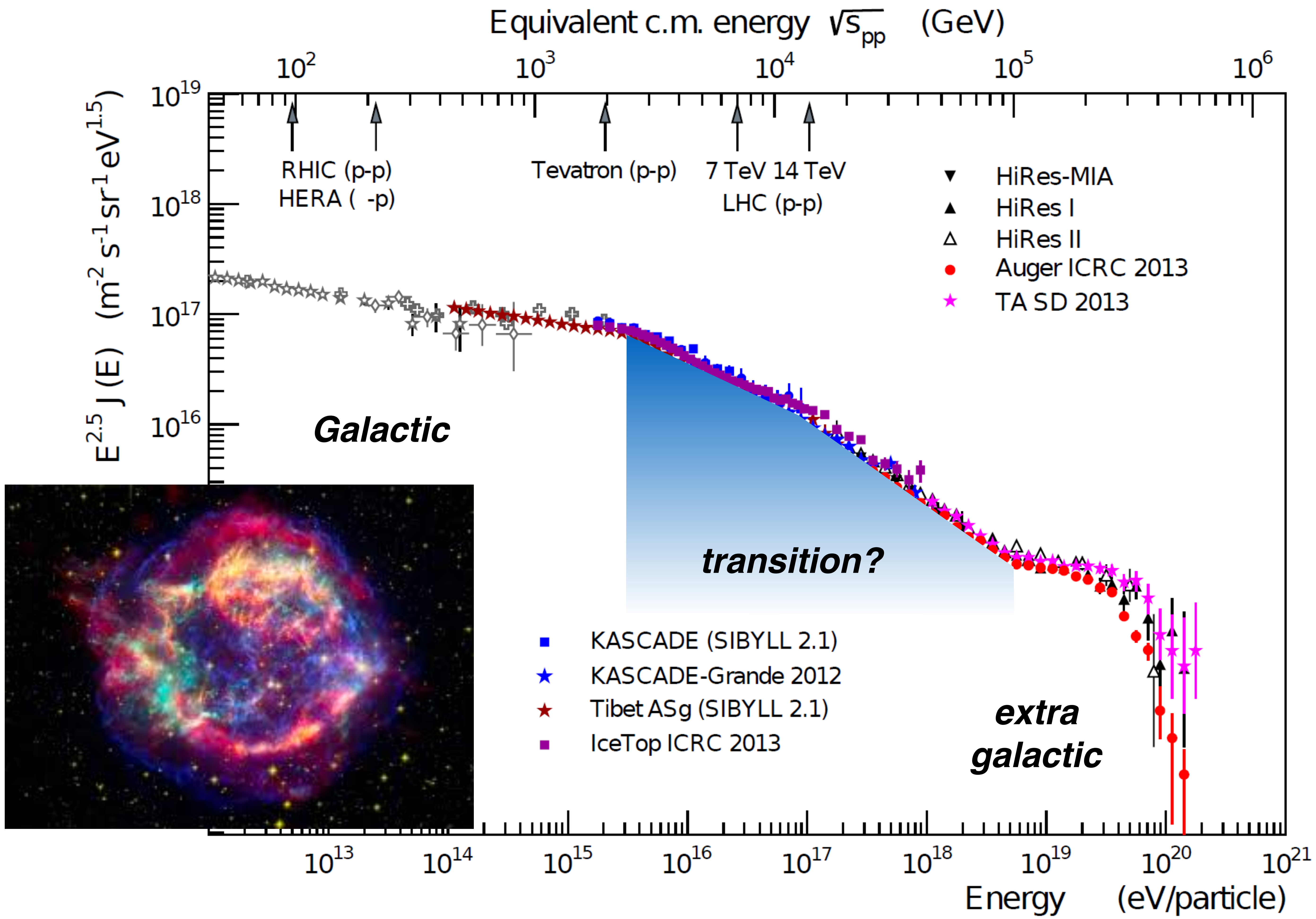

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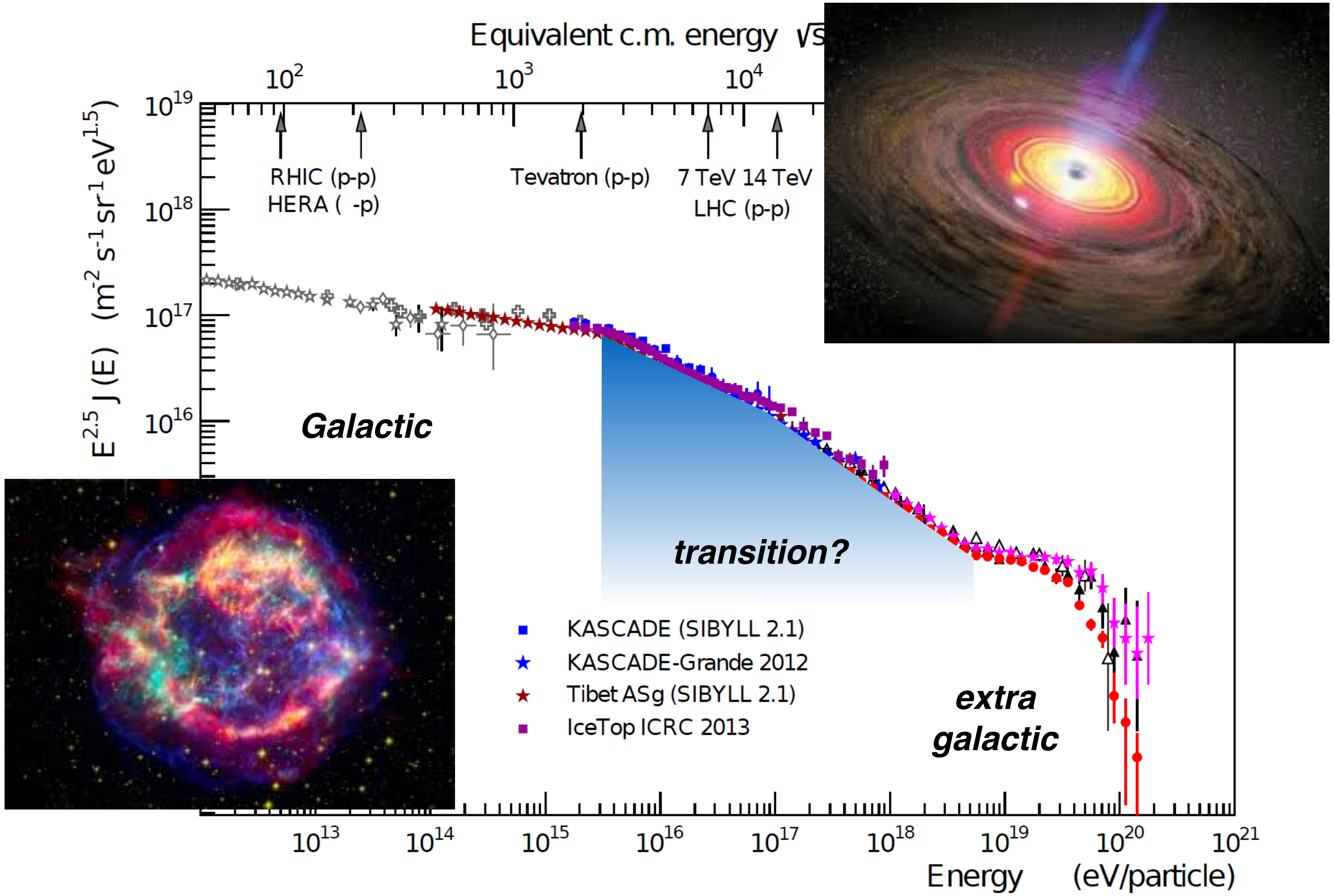

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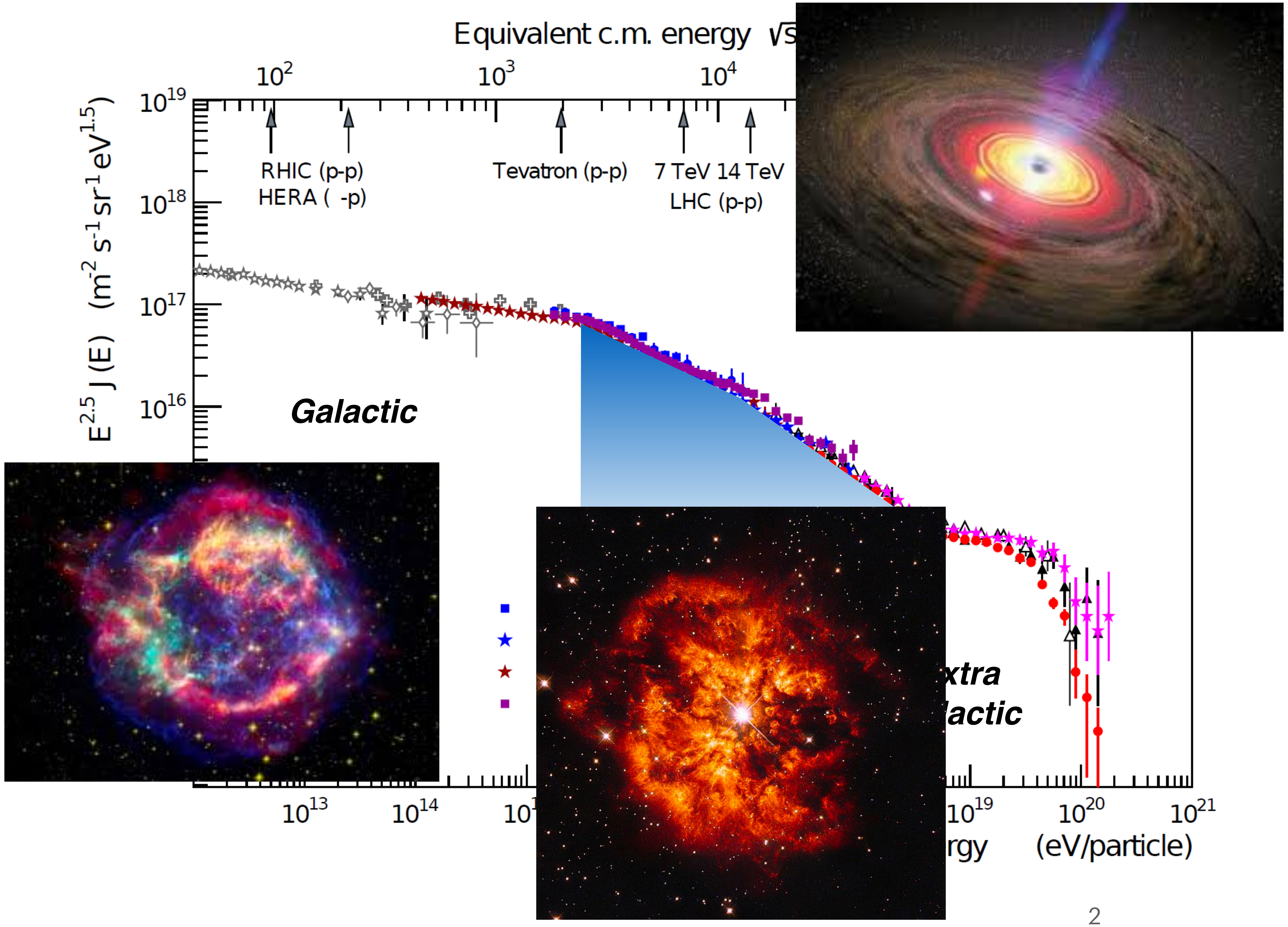

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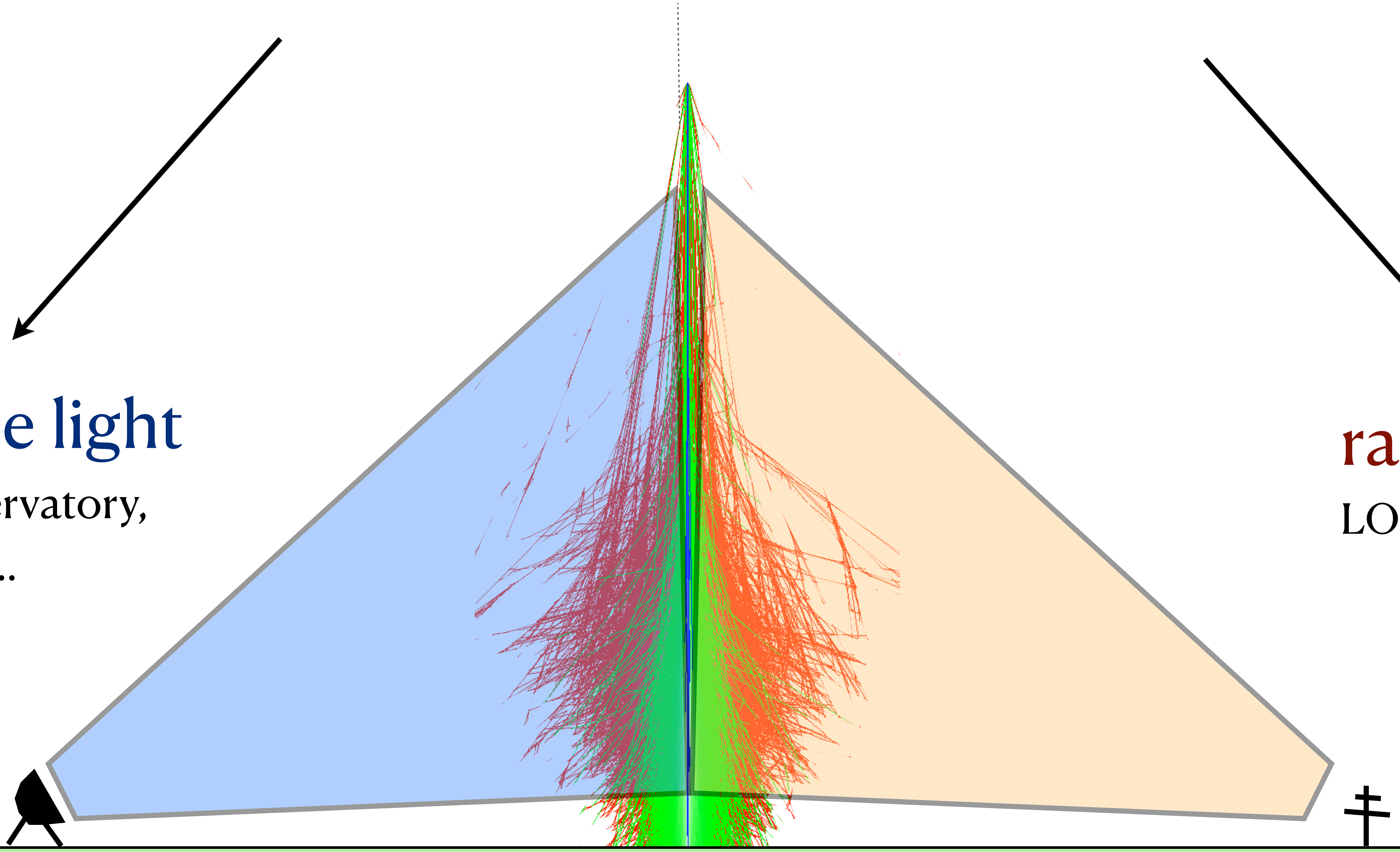
How to measure the mass?

Atmospheric depth of shower maximum Xmax



fluorescence light

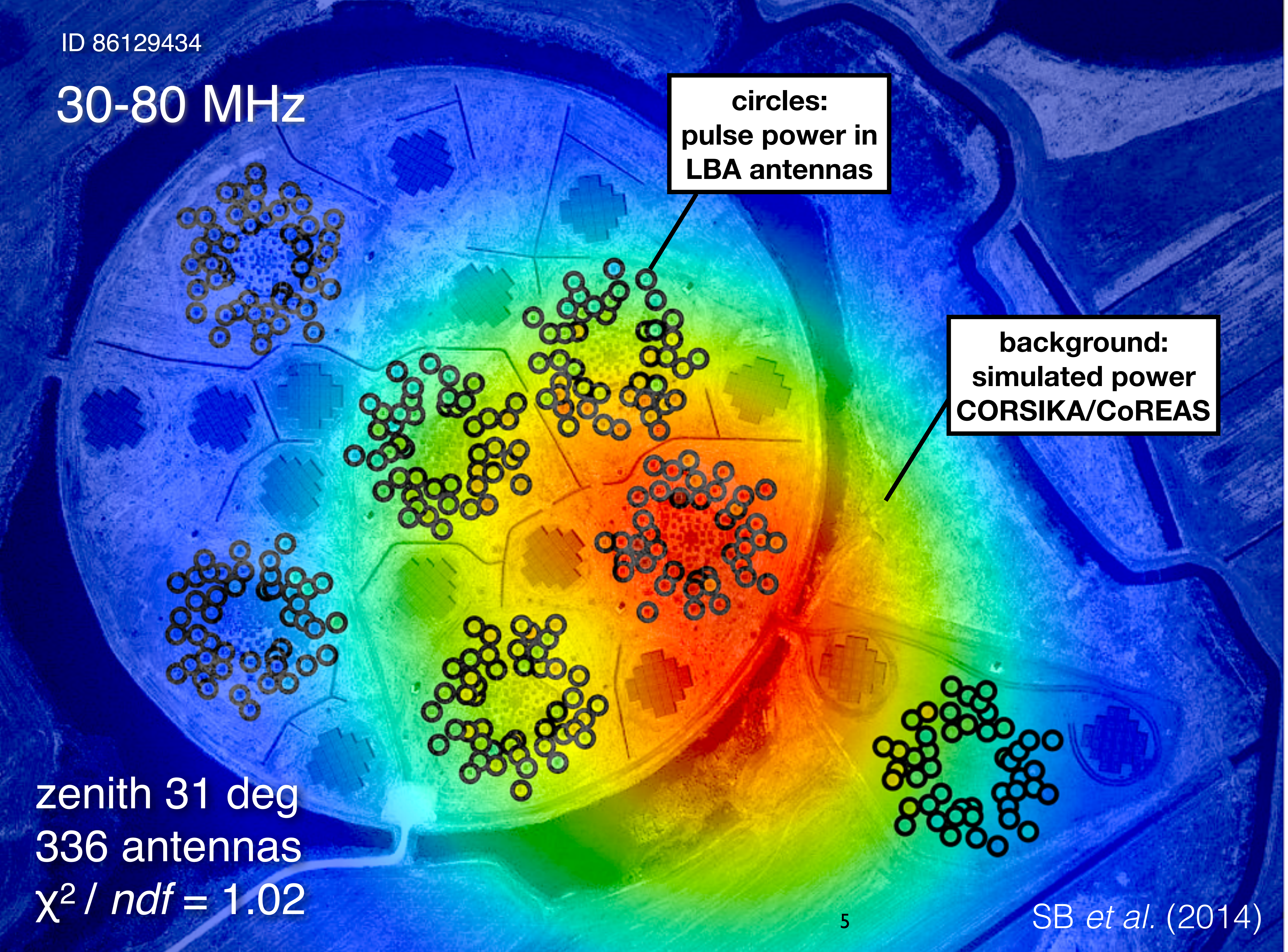
Pierre Auger Observatory,
Telescope Array, ...

radio detection

LOFAR, AERA, Tunka-rex, ...

Two independent techniques with very different systematic uncertainties

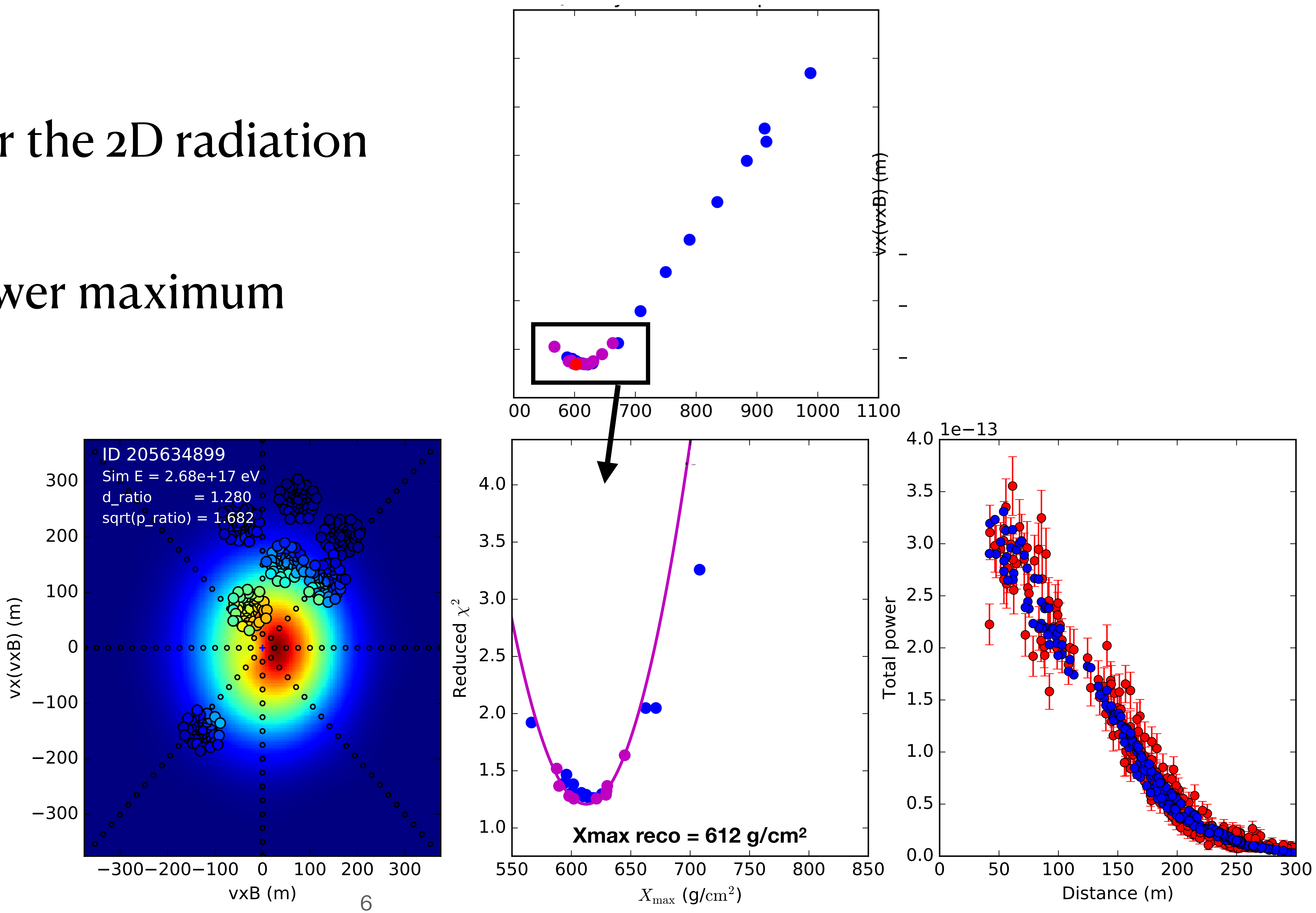

LORA
LOFAR Radboud Array
scintillator detectors
Superterp:
* diameter ~ 300 m
* 20 LORA detectors
* 6 LBA stations
(= 6 x 48 antennas)
Around superterp:
* more LBA stations
* NEW: +20 LORA detectors
trigger
buffer: 2ms readout
pulse maximum
Signal
Envelope
RMS
60
40
20
0
−20
−40
−60
0.0
0.5
1.0
1.5
2.0
Amplitude (ADU)
Time (μs)
Low Band Antennas (LBA)
30 - 80 MHz



- Radio patterns not rotationally symmetric!
- Interference between geomagnetic and charge excess radiation.
- Excellent agreement data & simulation for intensity, polarization, and frequency spectrum

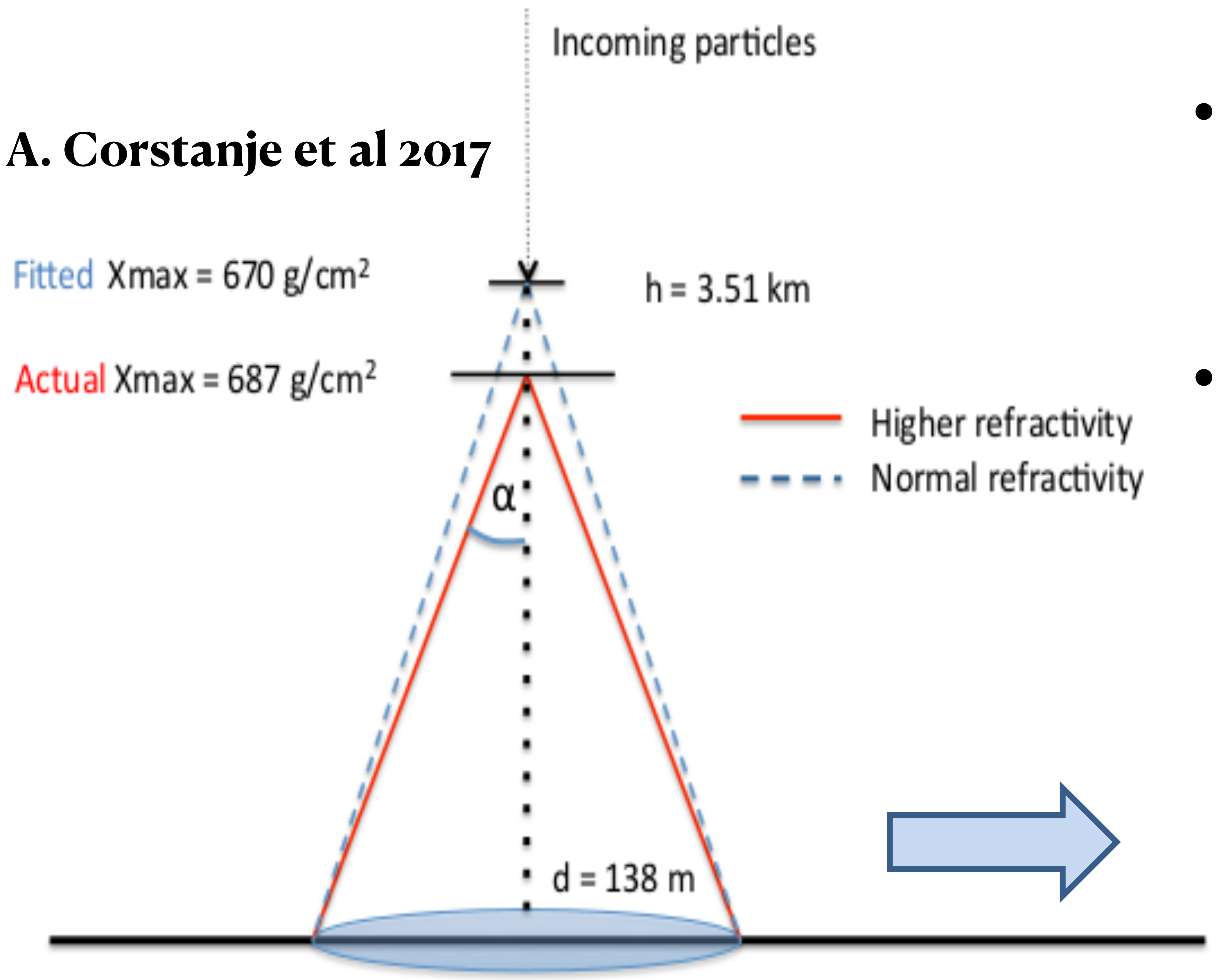
Cosmic Ray Mass Composition

- For each simulated shower the 2D radiation pattern is fitted to data
- Reconstruct depth of shower maximum Xmax
- Same Monte Carlo sets are used to remove bias towards deep (Iron-like) or shallow (=proton-like) showers.

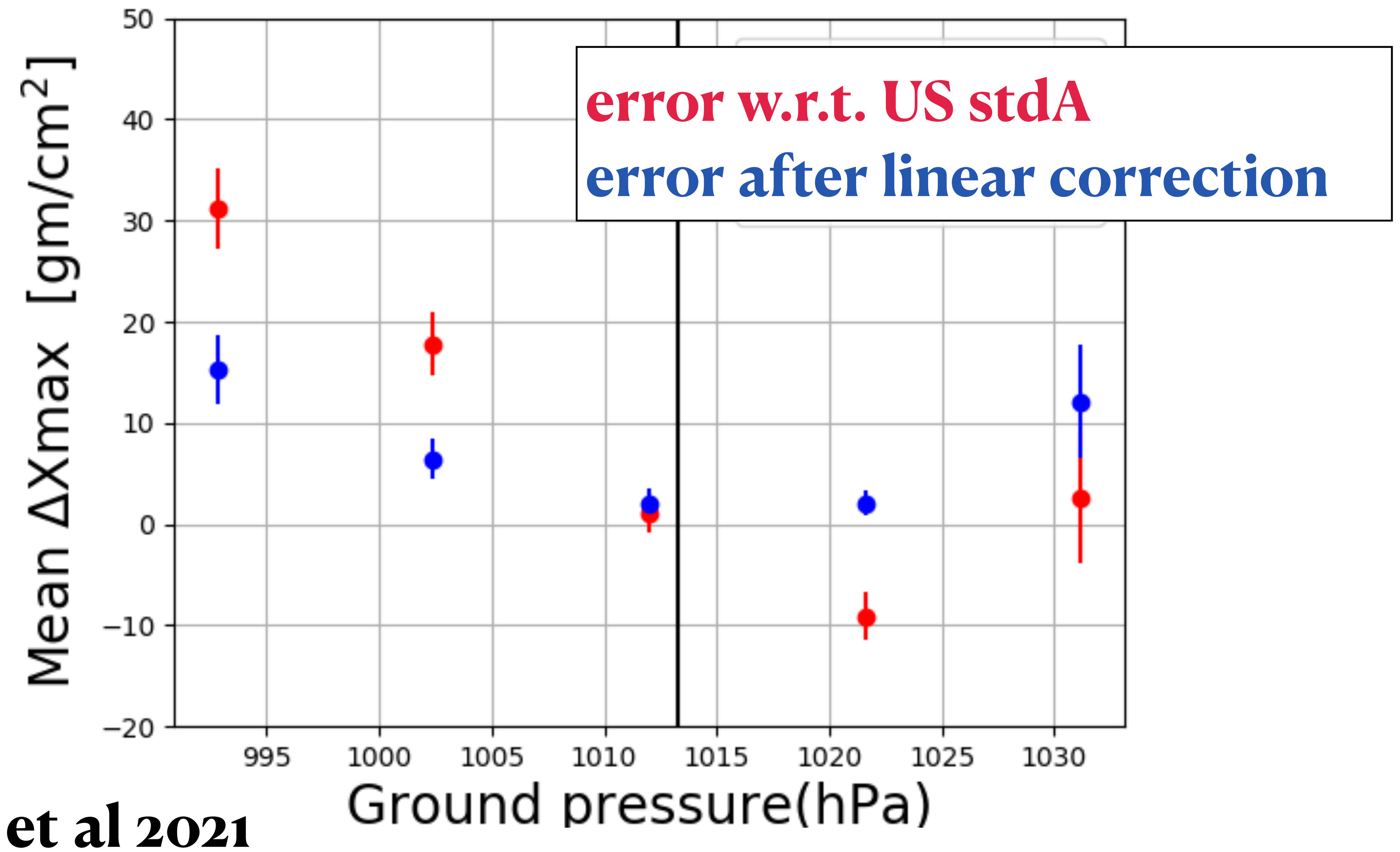


Event-specific atmospheres

A. Corstanje et al 2017



- Refractive index of air depends on weather ➜ effect on Xmax reconstruction
- GDAStools reads online weather database ➜ builds air density & refractive index profiles for CORSIKA
  now bundled in CORSIKA download, also used for gamma-ray telescopes
- Each LOFAR shower is simulated with unique atmosphere



P. Mitra et al 2021

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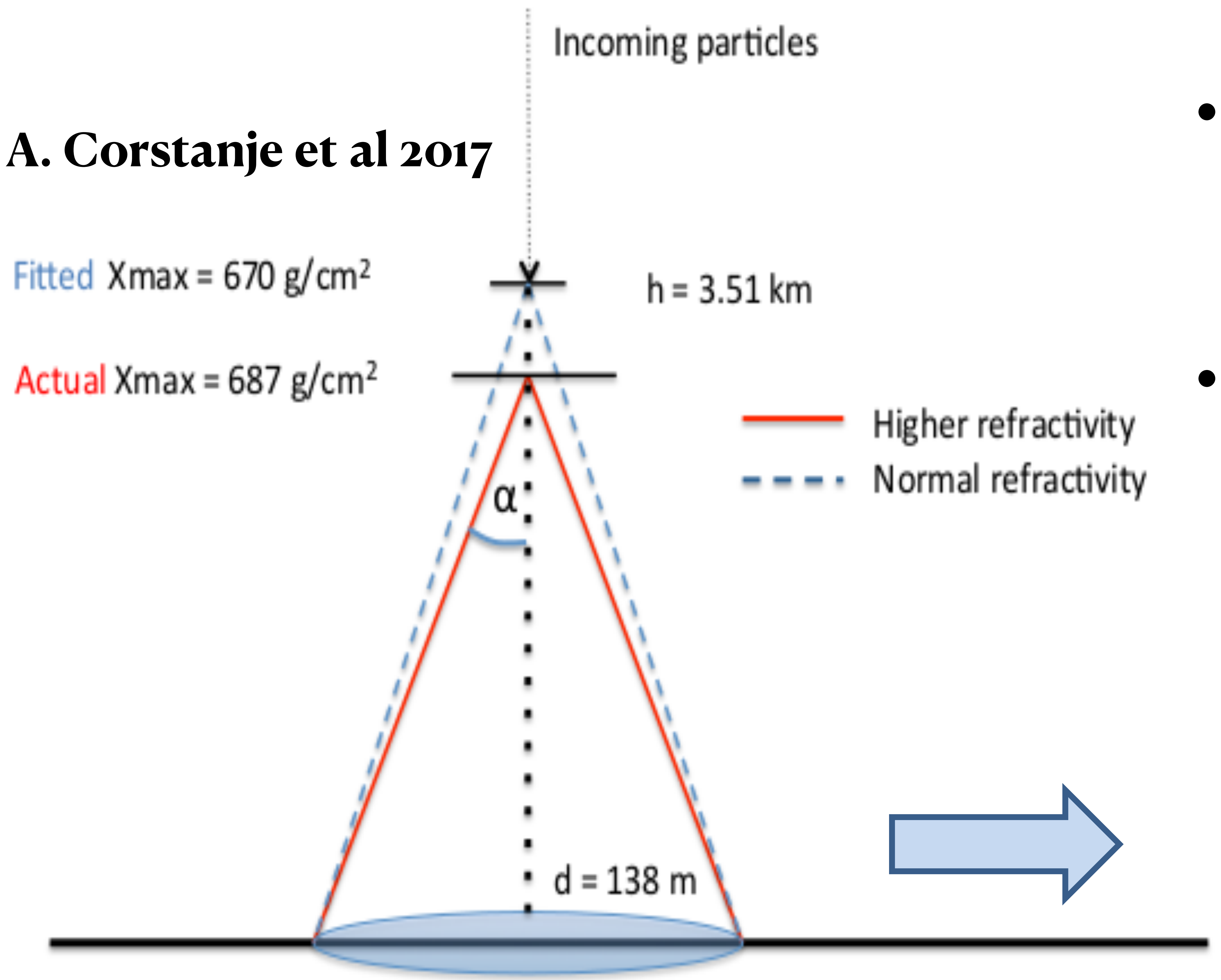

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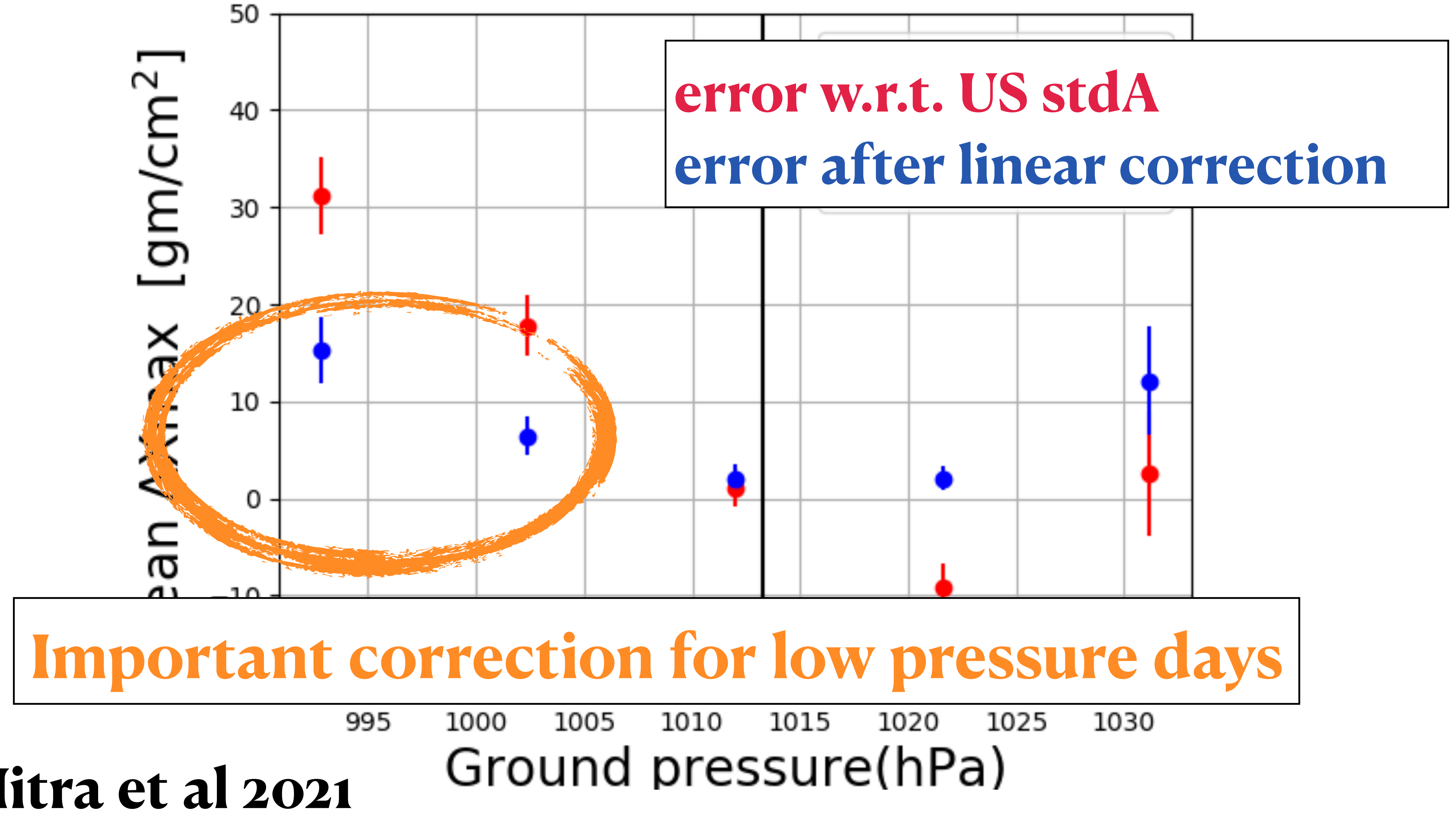
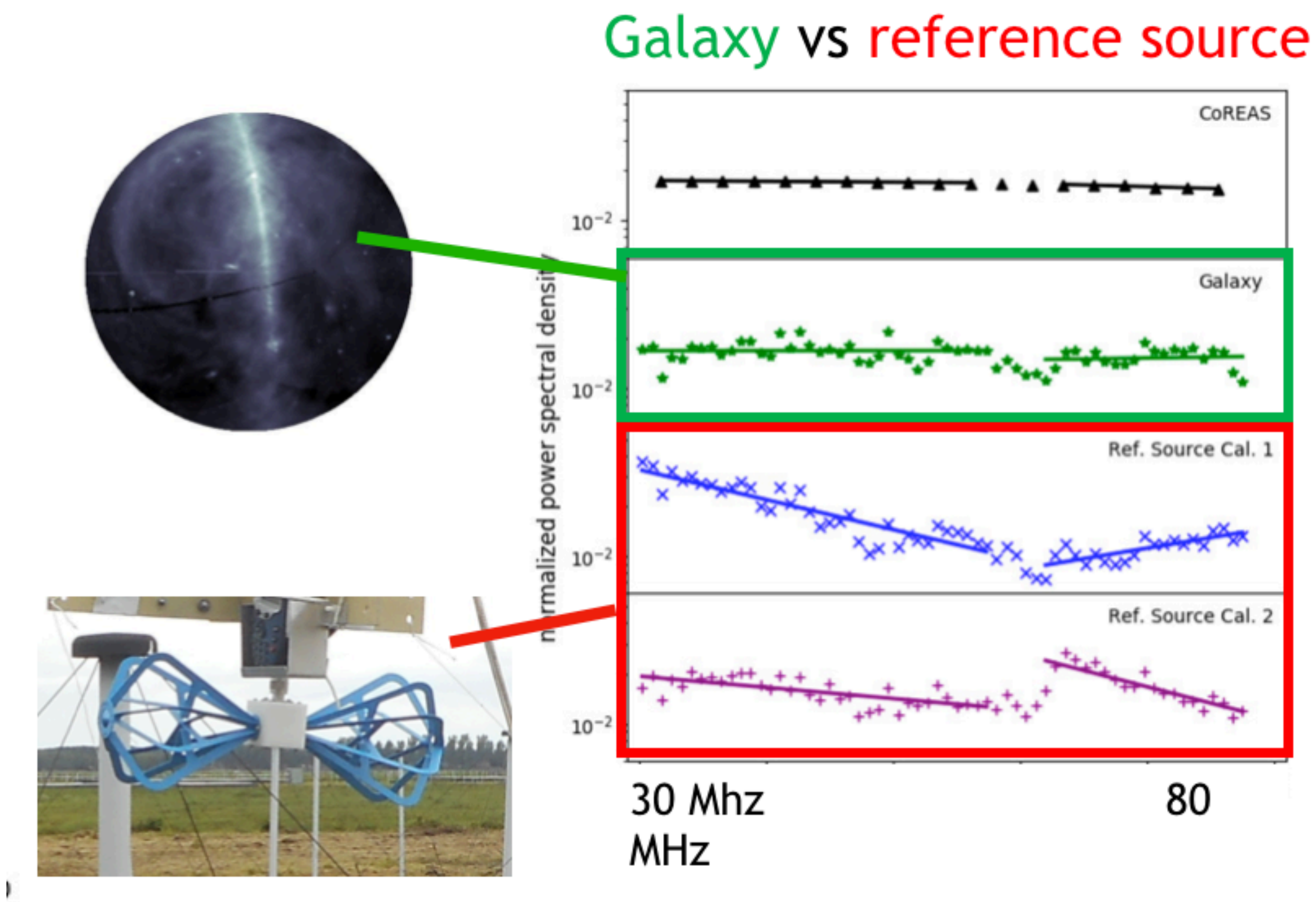


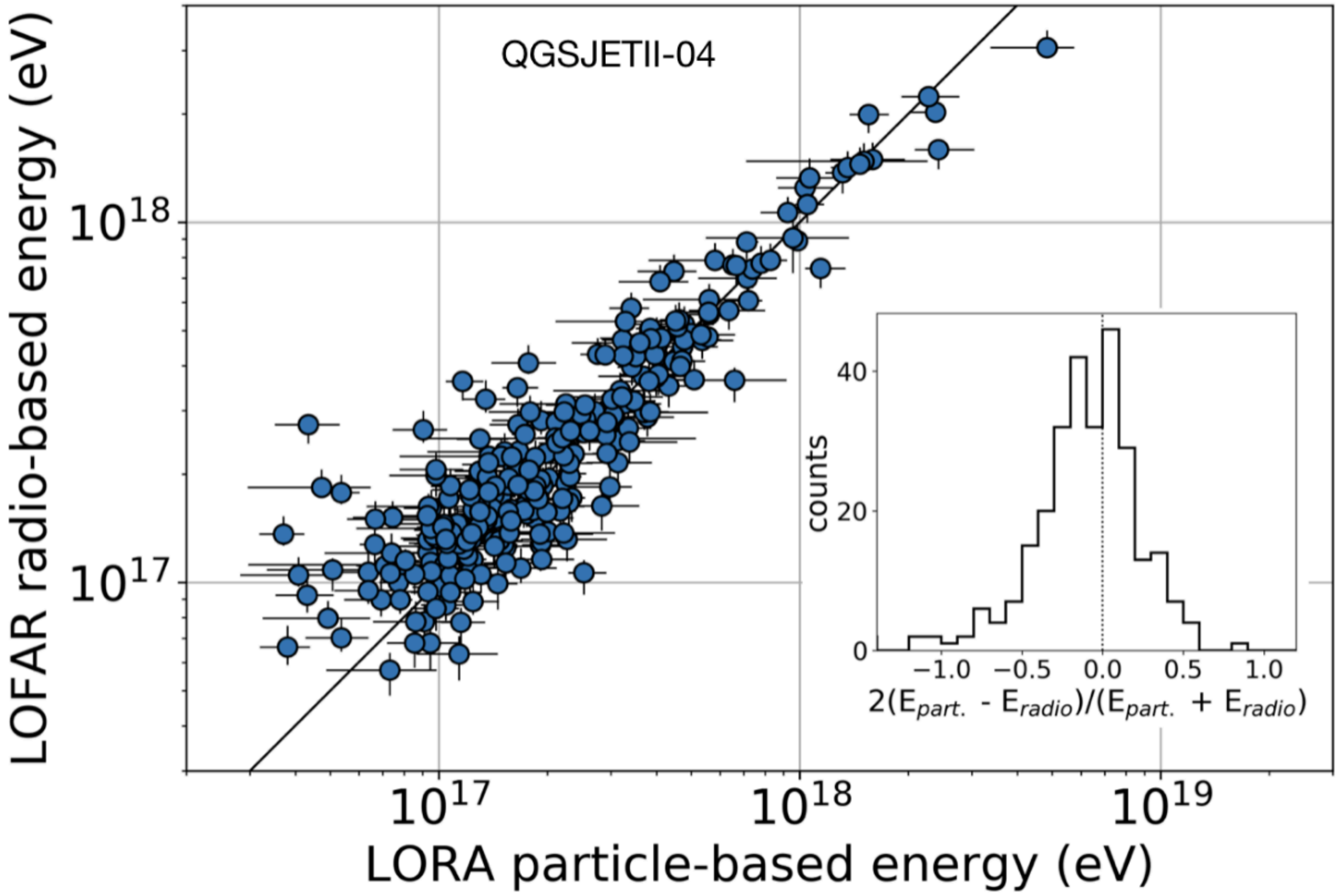
P. Mitra et al 2021

Energy calibration

- Calibration on Galactic background radiation; syst. uncertainty ~14% below 77 MHz
  In development: portable radio array for energy-scale calibrations between experiments (K. Mulrey)
- Agreement between independent energy scales **radio ↔ particle**

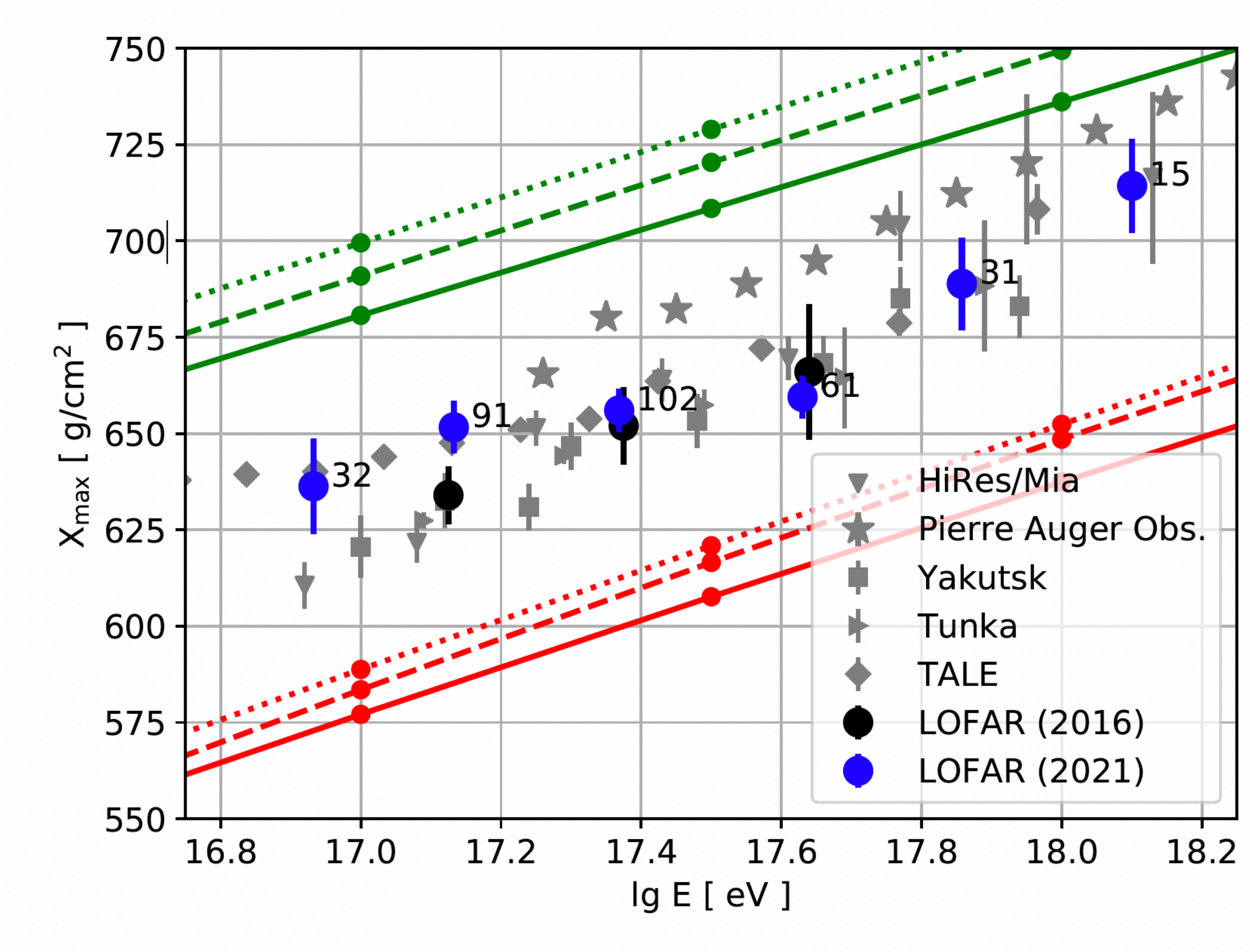


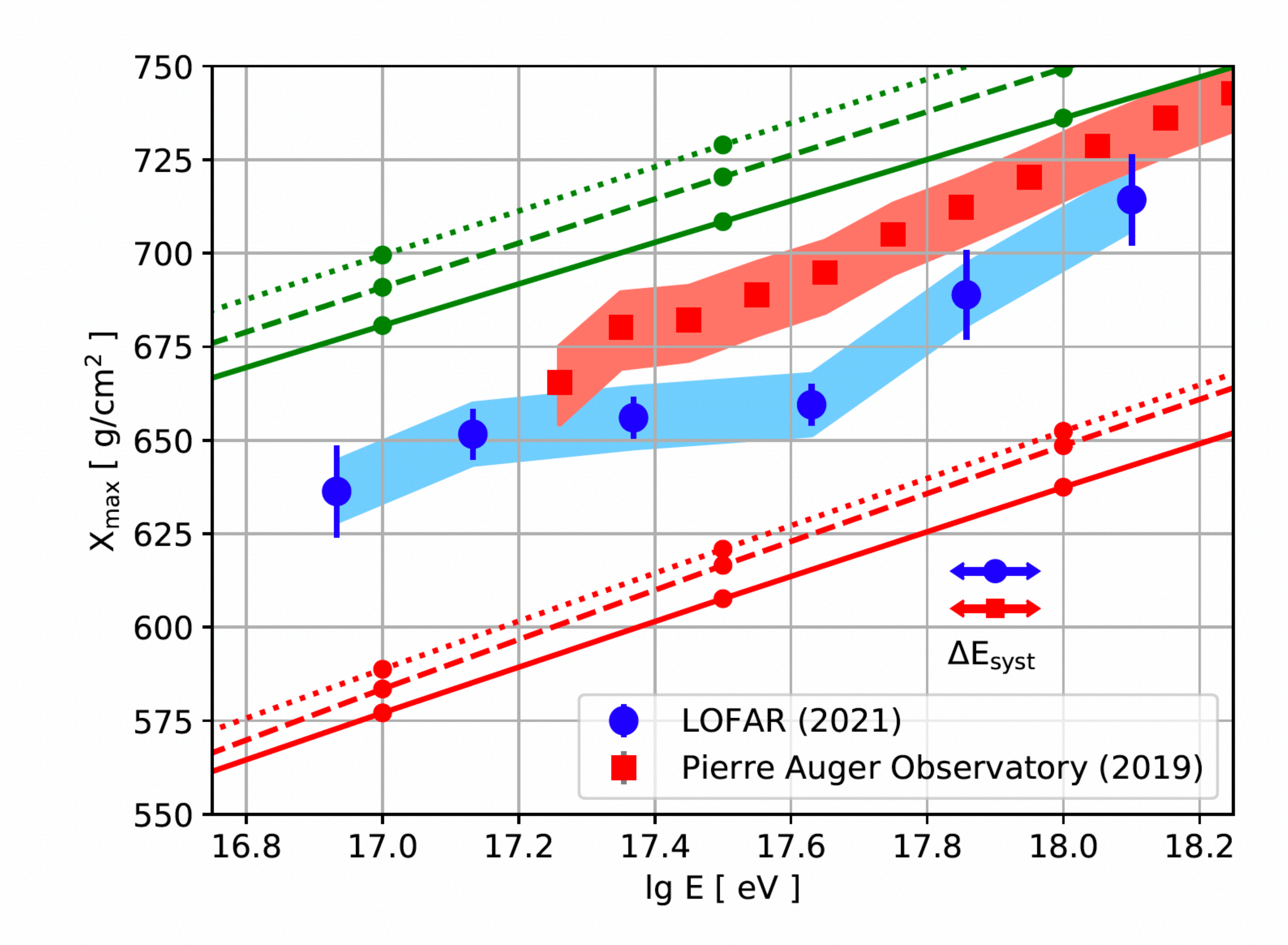
K. Mulrey et al 2019



K. Mulrey et al 2020

Mass composition 2021





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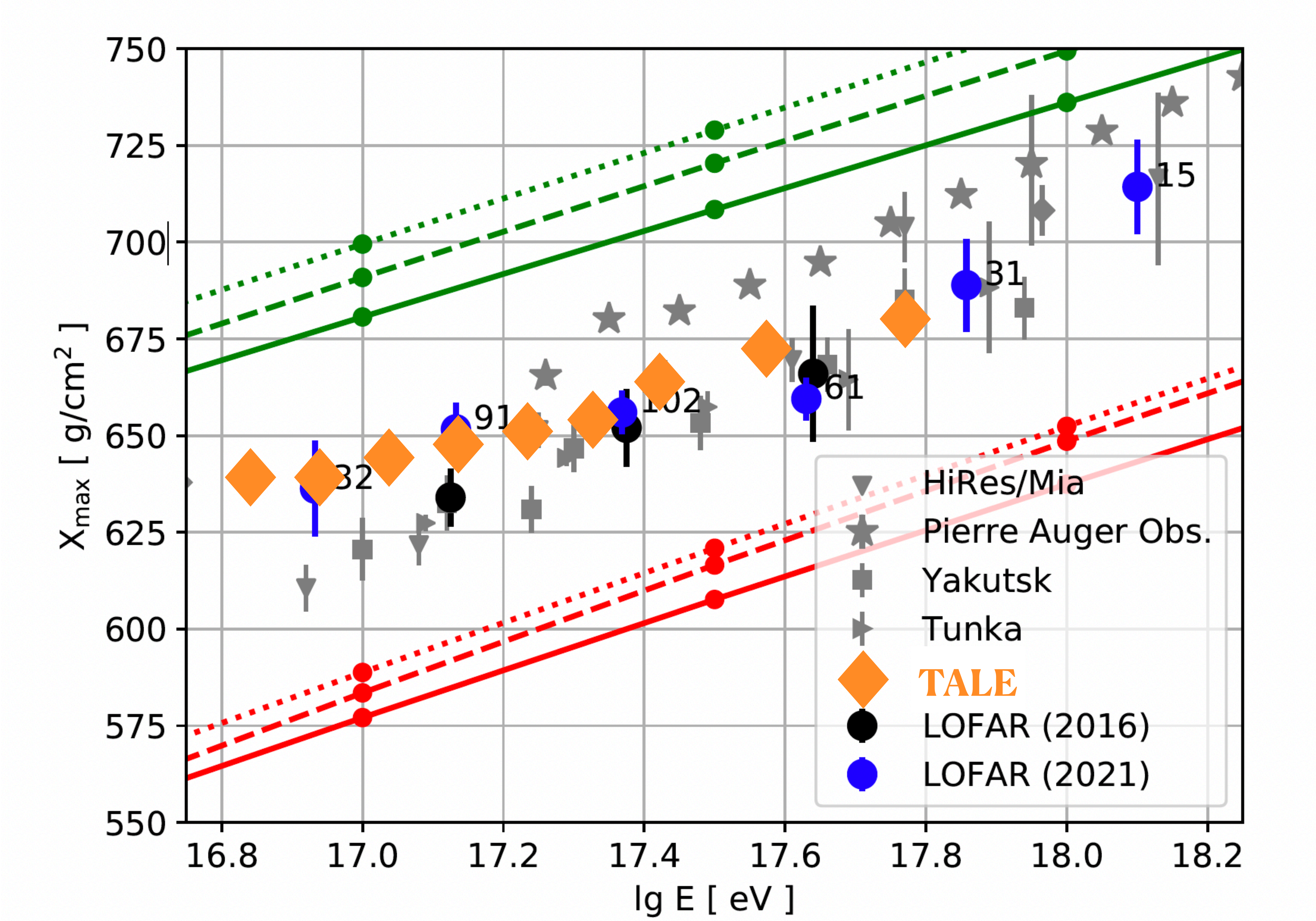
Cosmic Ray Mass Composition



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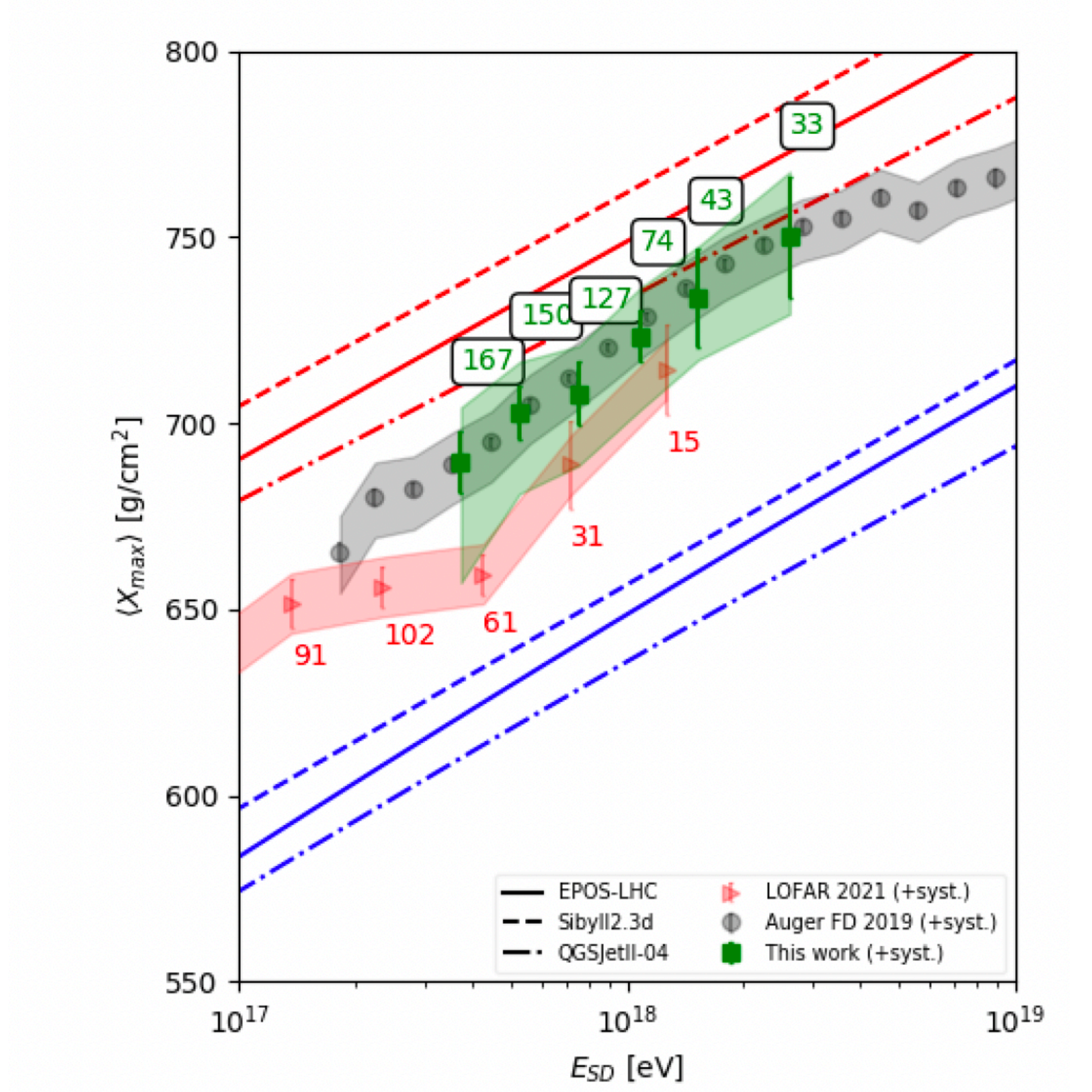
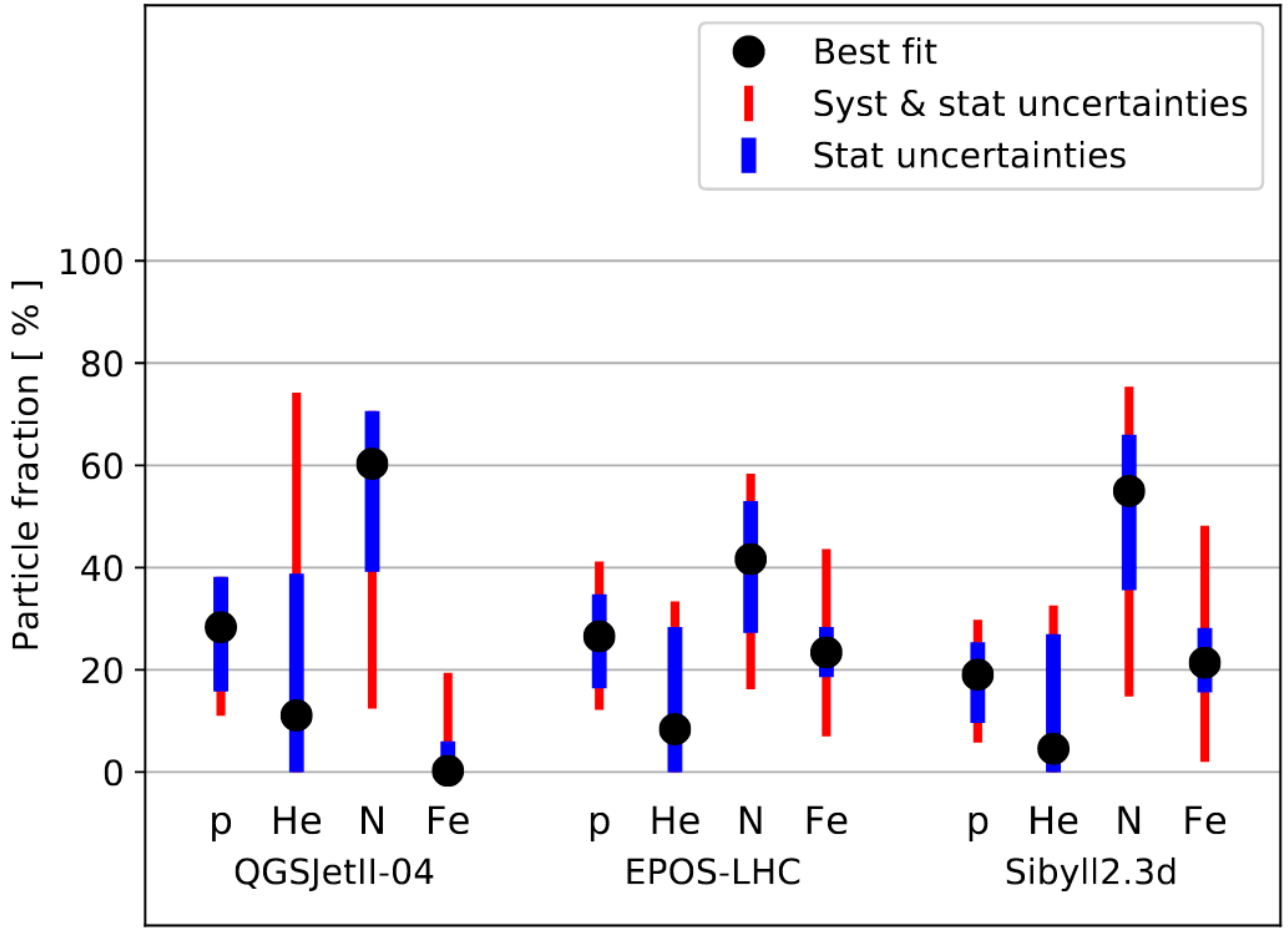


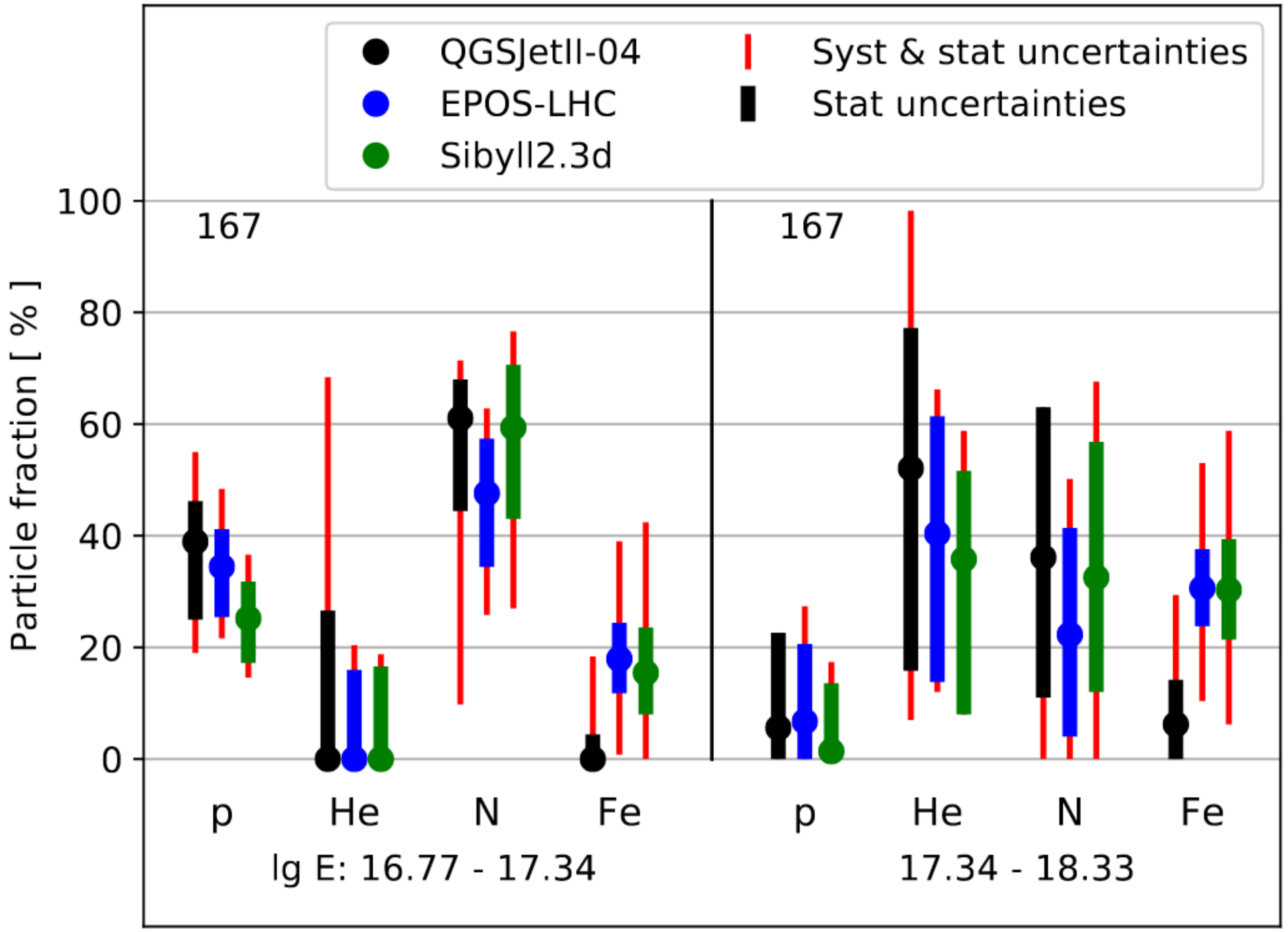
Pierre Auger Observatory ICRC 2021

Agreement between LOFAR and TALE
(= Low energy extension of the Telescope Array)

Agreement between Auger fluorescence detectors
and radio array (AERA)

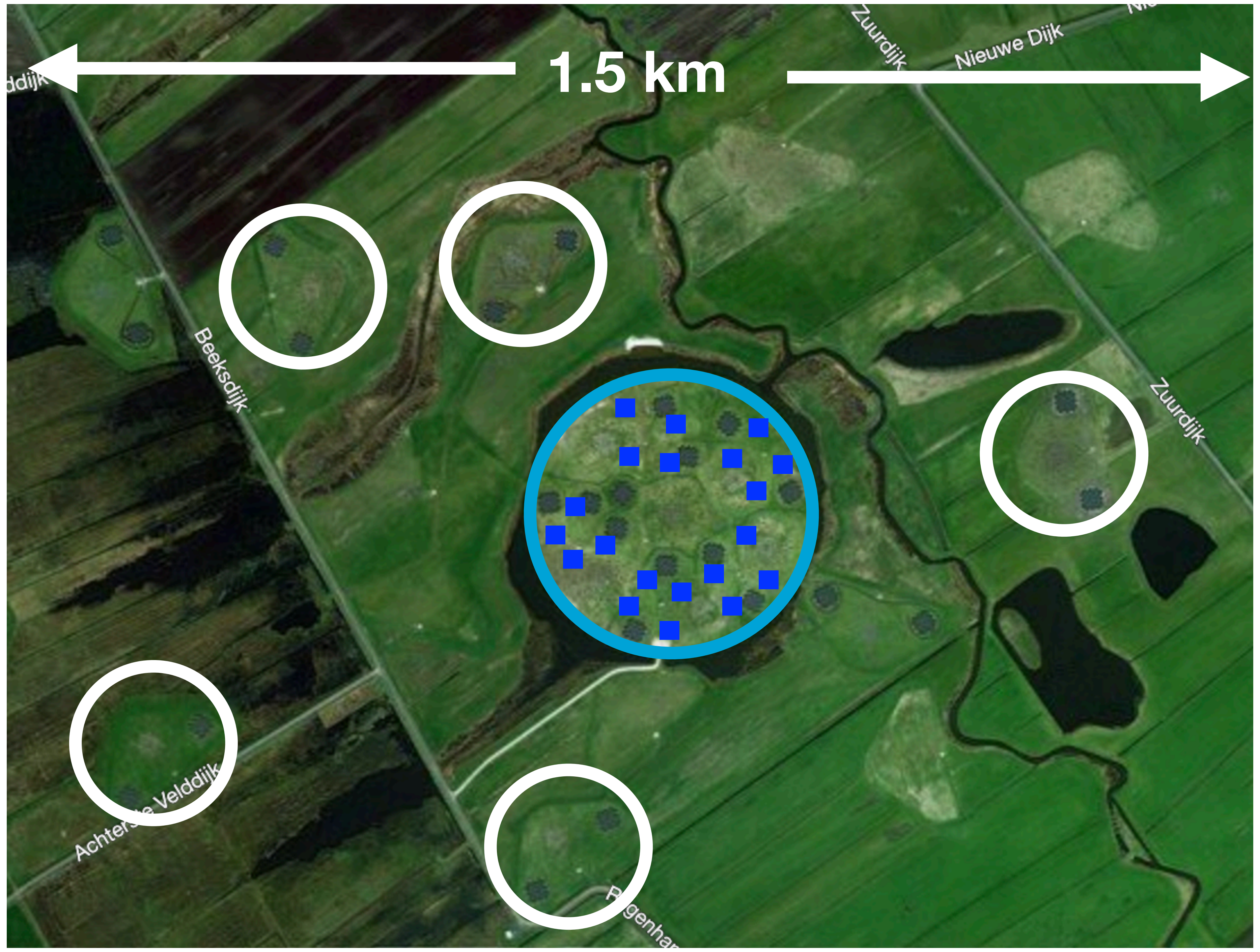
LOFAR mass composition



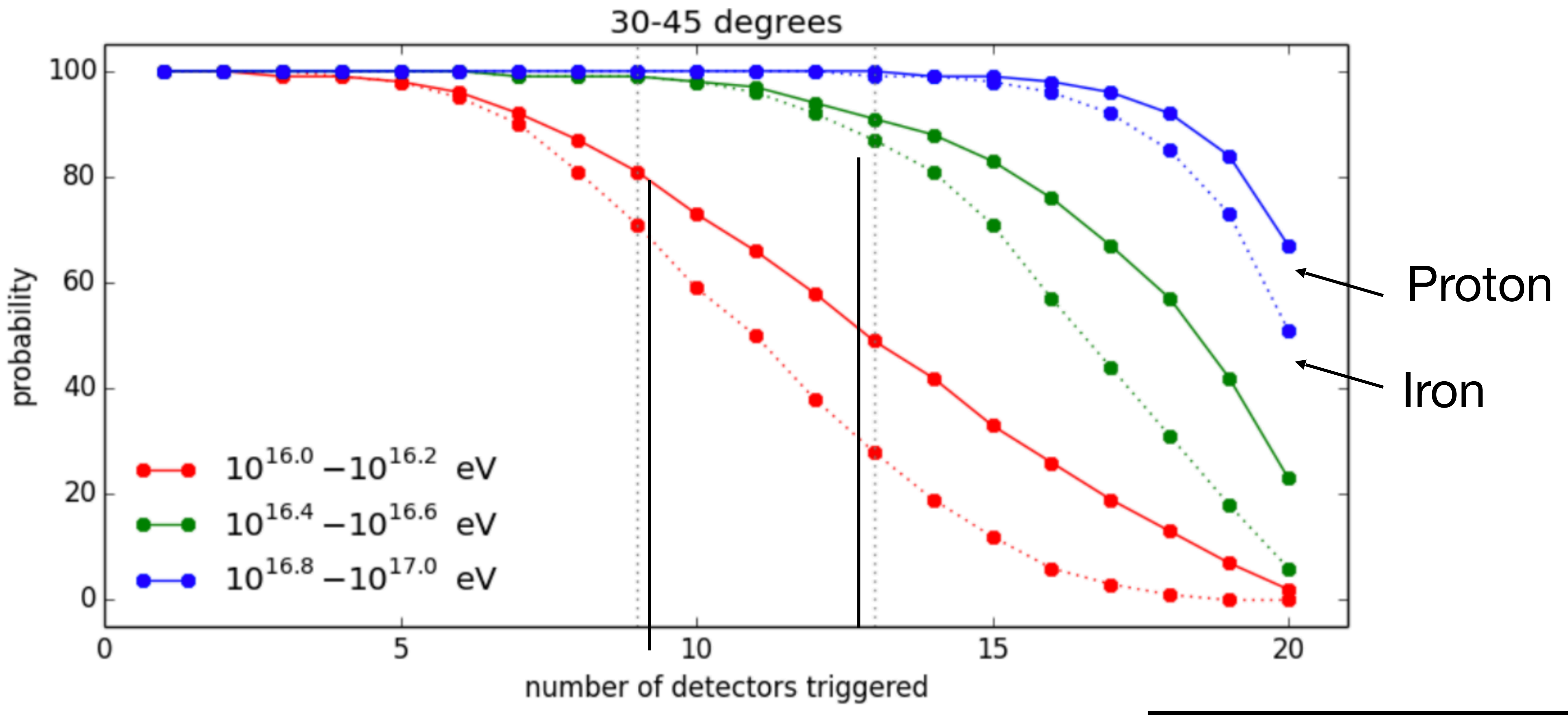


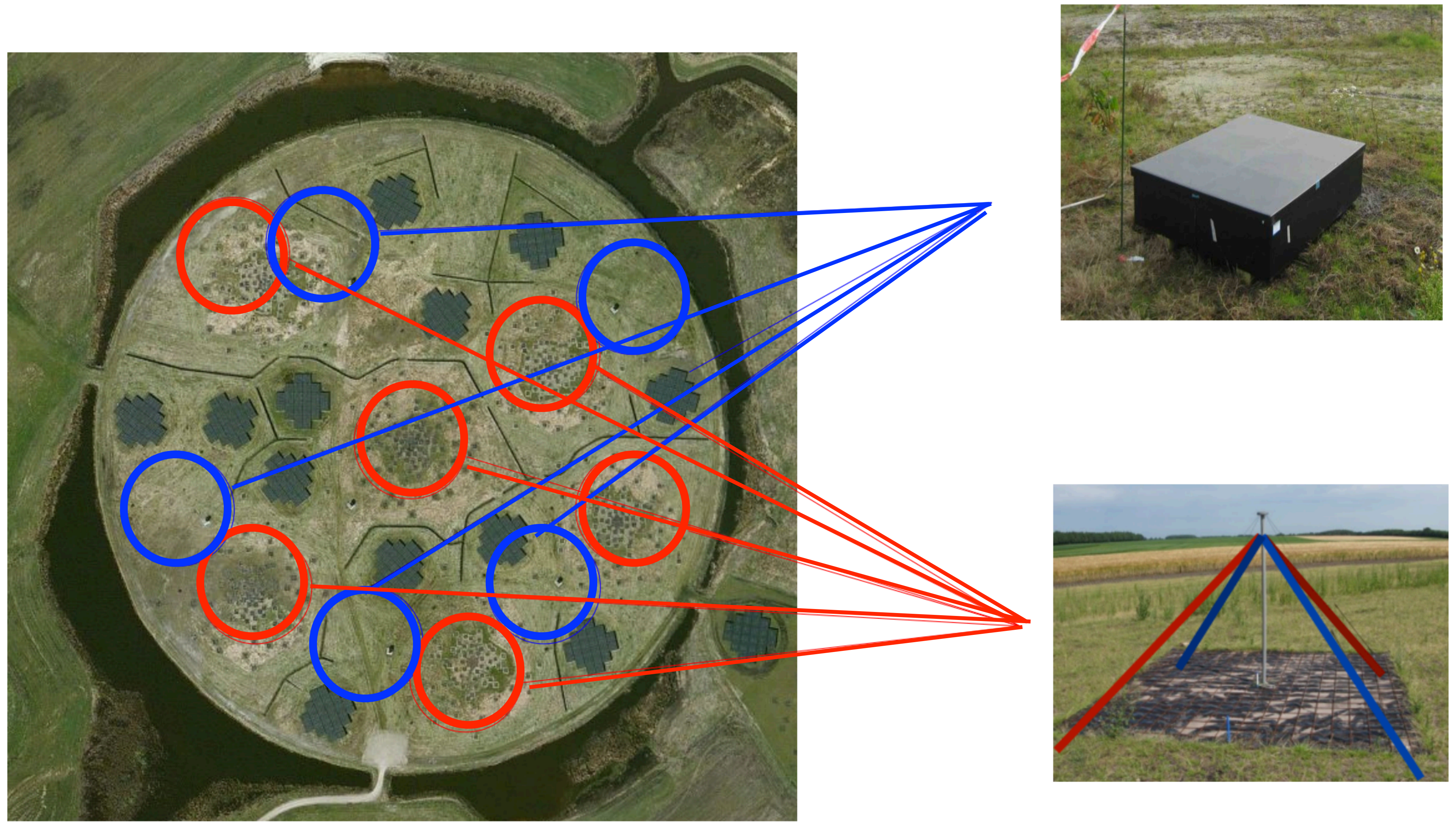
Upgrade, upgrade, upgrade!

- LOFAR 2.0: possibility to run cosmic ray observations with low+high band **continuously**
  increased observation time
- Expansion of the LORA trigger array
  increased observation area
- Development of hybrid trigger (radio + particle)
  increased data purity



Hybrid trigger system





Preferred trigger

Current trigger

Particle trigger

- **High rate with low trigger threshold**
- **Composition bias at low energies**

\+ **Guaranteed cosmic ray**

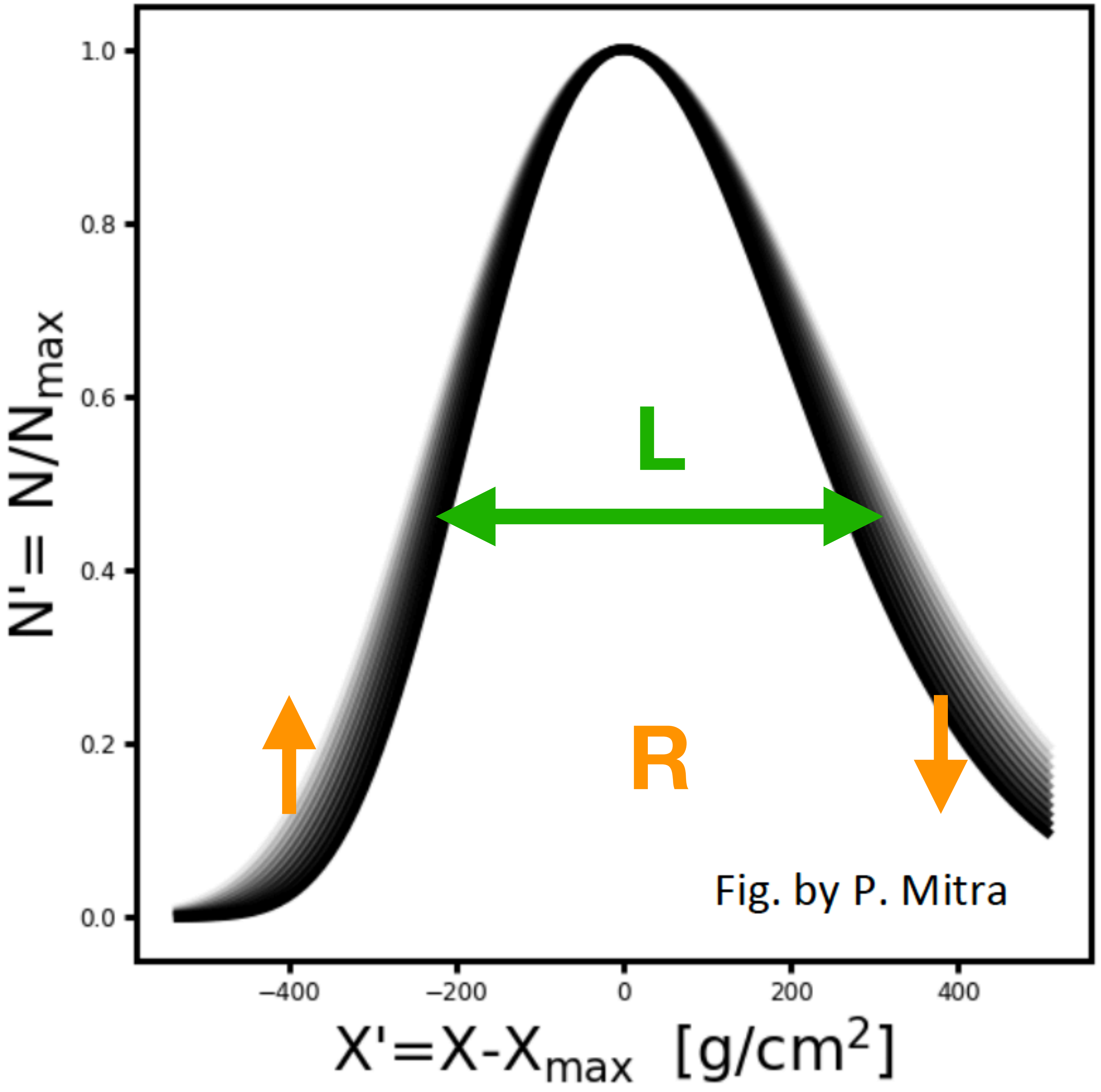
Radio trigger

- **Flooded with RFI**

\+ **Ensures a usable CR signal**

Cosmic ray
+
good radio signal
+
RFI rejection
+
Reduced trigger threshold

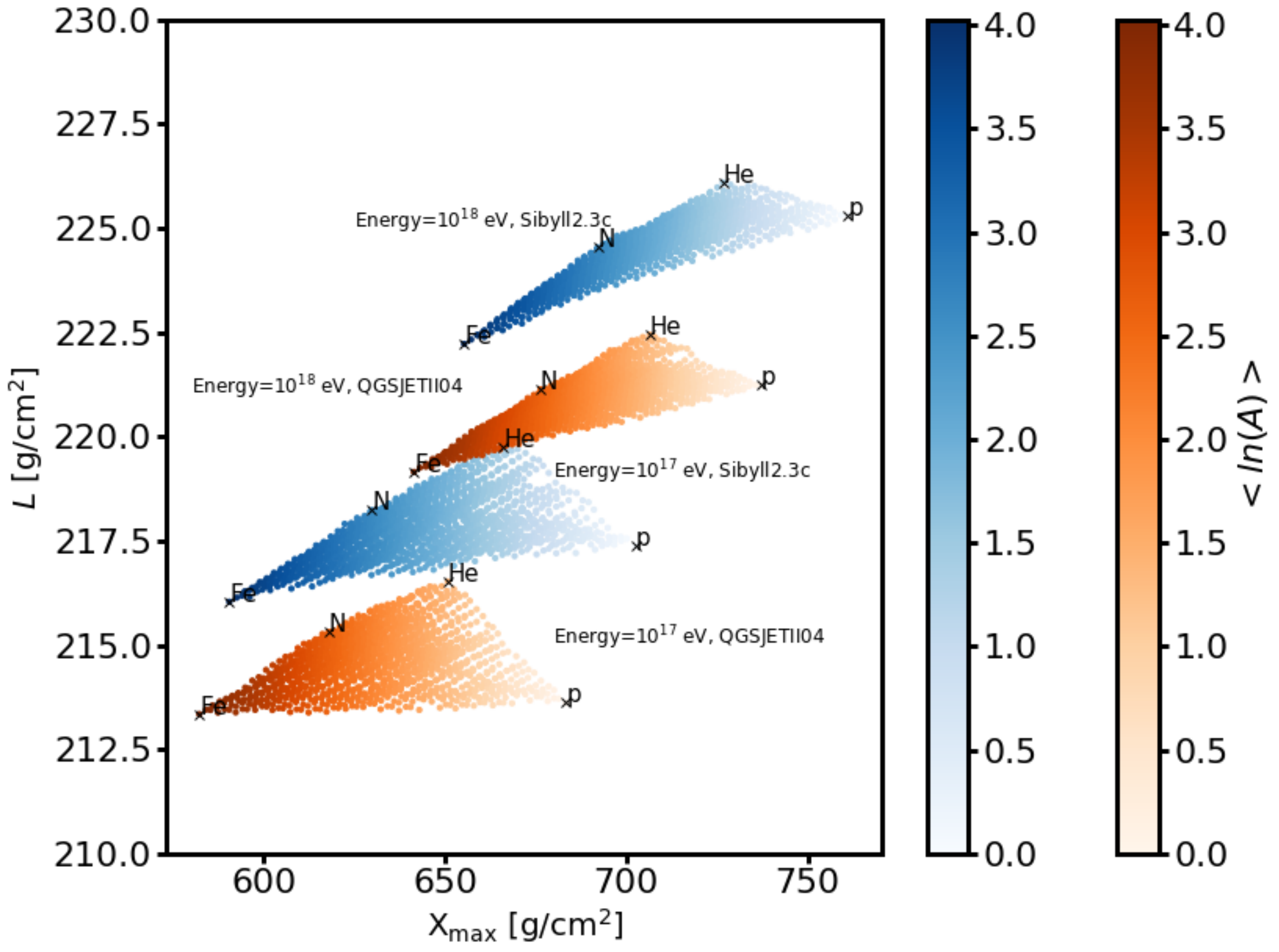
Shape of longitudinal evolution



$$N' = \left(1 + \frac{RX'}{L}\right)^{R^{-2}} \exp\left(\frac{-X'}{LR}\right)$$

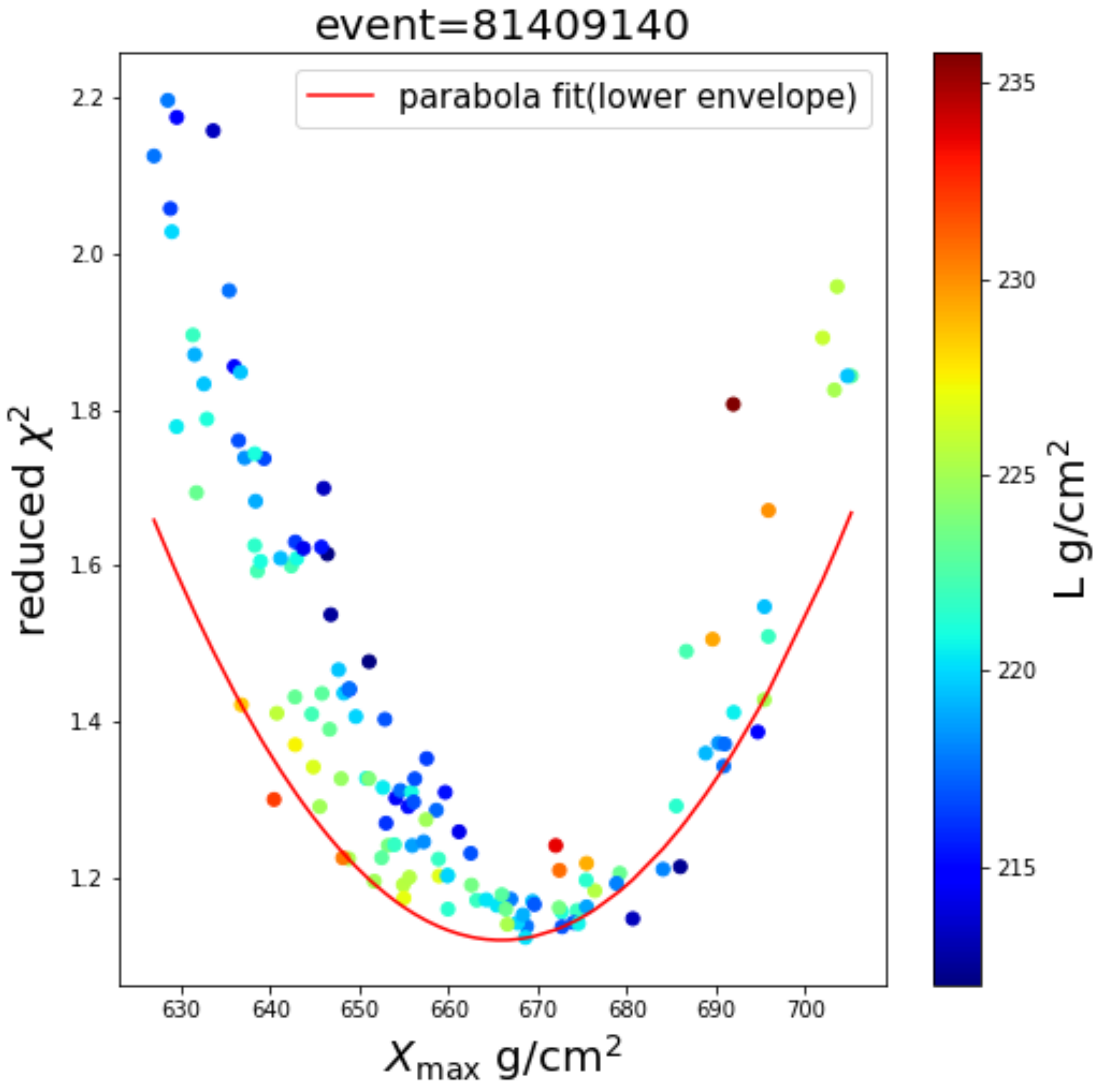
- LOFAR reconstructs Xmax with precision < 20 g/cm²
- Longitudinal development can be parametrised with R/L parameters
- Radio signal is sensitive to L
  (P. Mitra, thesis)

Why measure L?



- Shower length L depends on:
  - mass composition
  - hadronic interaction model
- Disentangle astrophysics and hadronic physics!

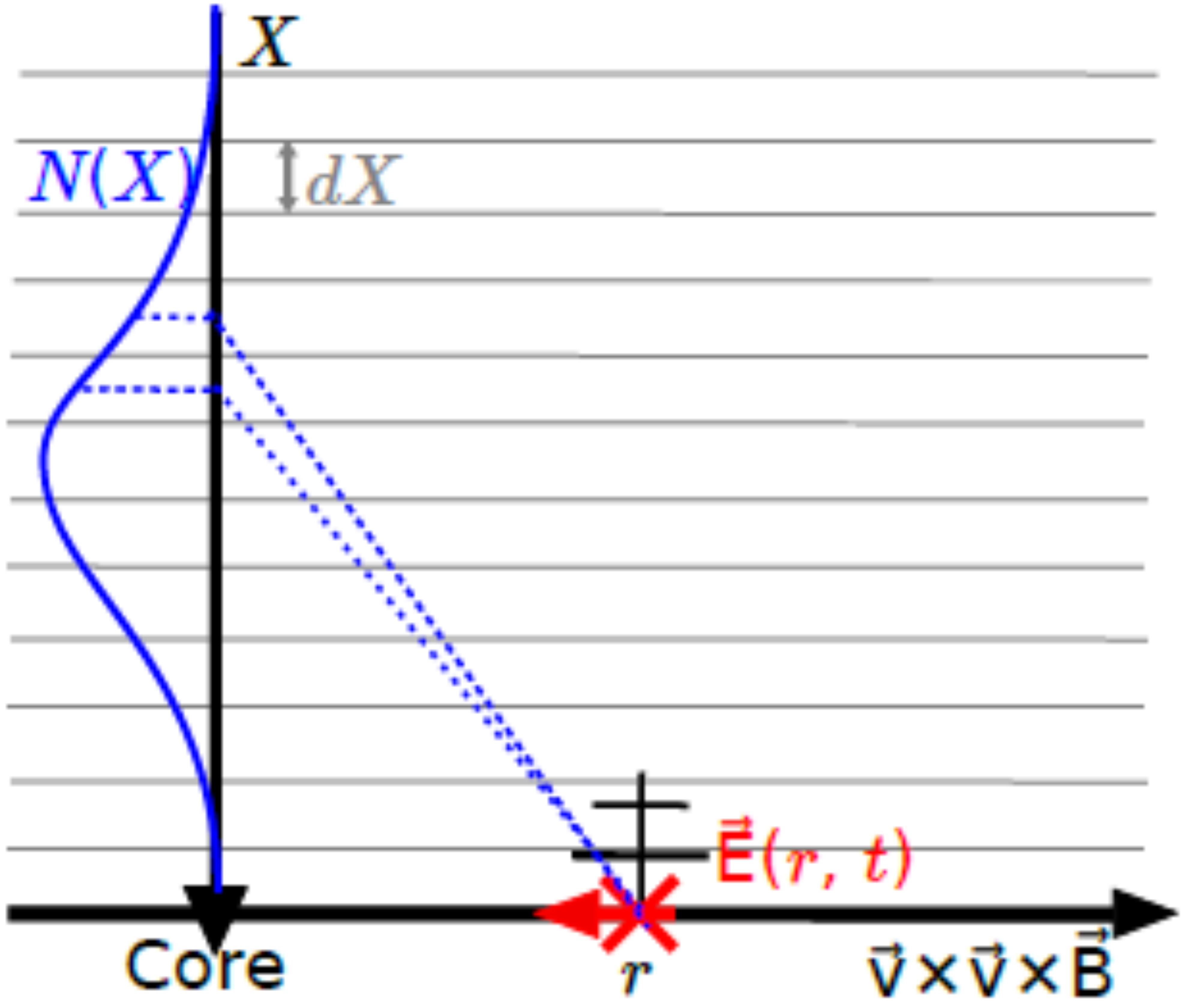
Can LOFAR measure L?



- LOFAR: fit quality depend on L
- Not yet possible to simultaneously reconstruct Xmax and L
- Needed (1): faster, smarter simulation code
- Needed (2): more homogeneous array with extended bandwidth

Template Synthesis

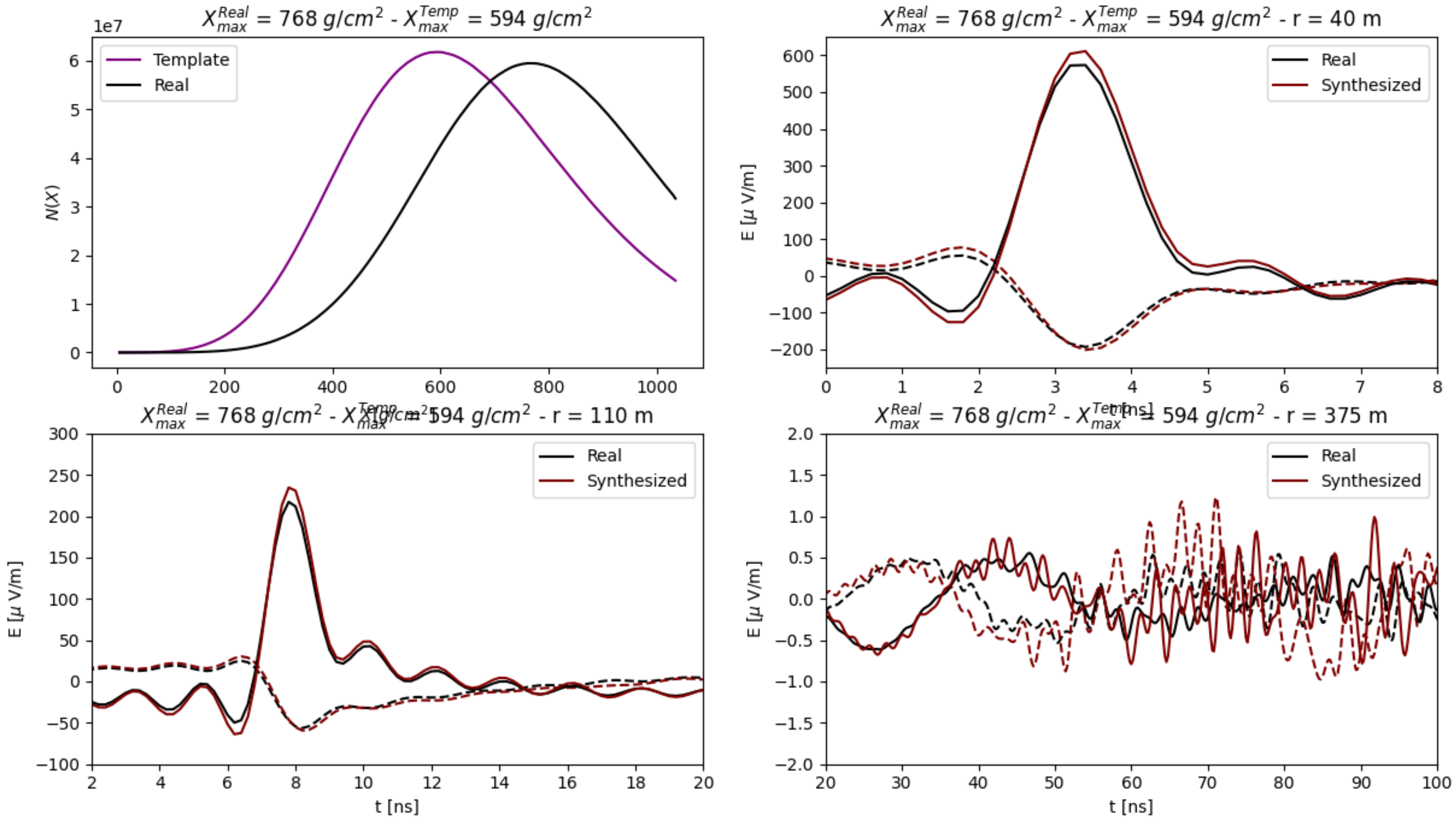
- Template shower = full simulation (CORSIKA/ CoREAS)
- Atmosphere divided in slices of 5 g/cm²
- Calculate radio signal per slice
- Target shower = created by rescaling slices
- Scaling relations depend on shower parameters & geometry
- Now works for vertical showers



Slicing of the atmosphere. Figure taken from: *Butler, D. (2020) "The Radio Signal of Cosmic Ray Air Showers and its Synthesis through Templates" [Unpublished PhD thesis]. Karlsruhe Institute of Technology (KIT).*

Rescaling in action

20-500 MHz



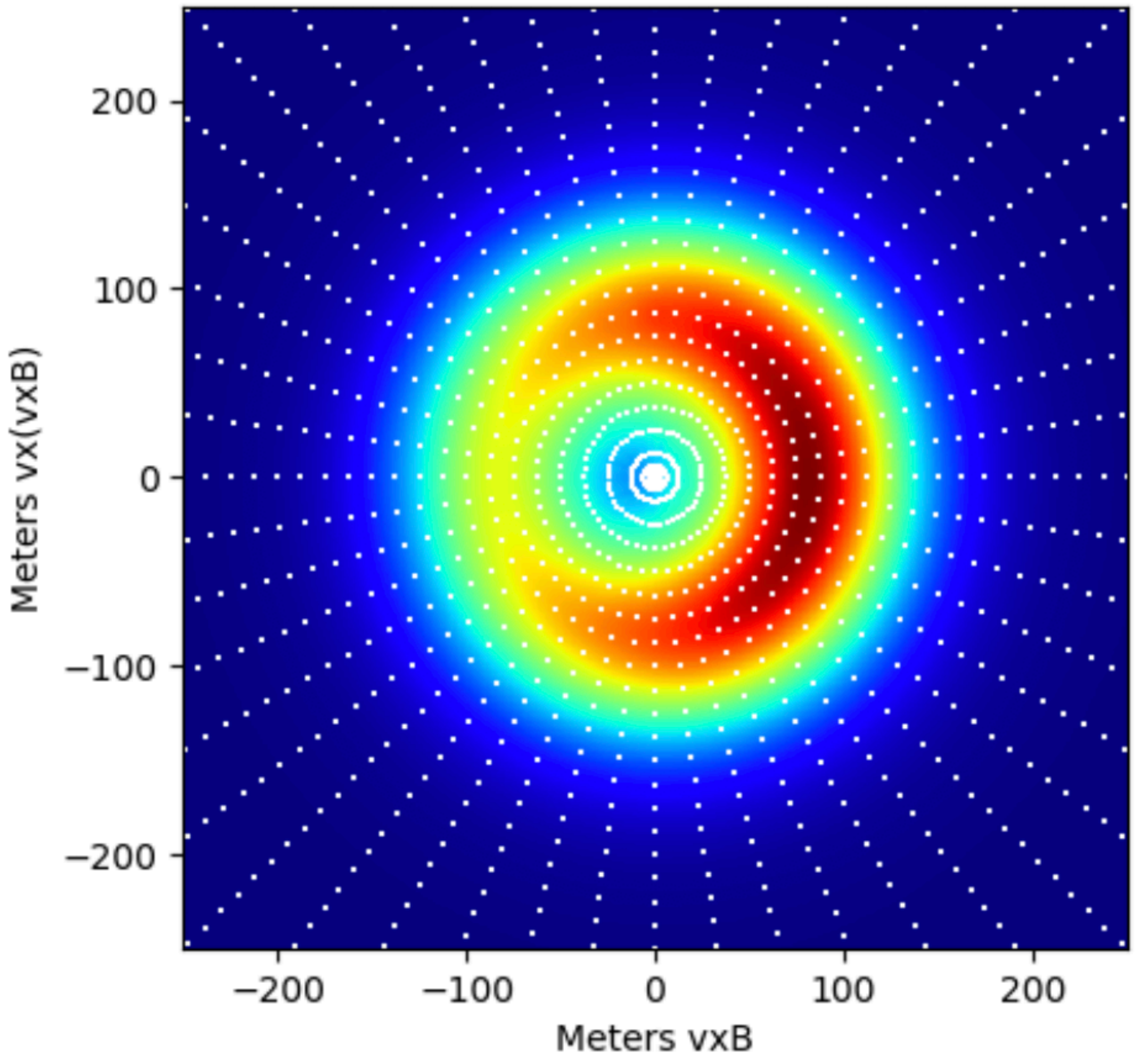
M. Desmet et al (in prep)

The Square Kilometer Array

Prototype @MRO (256 antennas)

- SKA-low is the 50-350 MHz part in Australia
- Almost 60,000 antennas (LPDA)
- Extremely high density & homogeneous coverage
  most precise radio observations of air showers ever

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



CoREAS simulation for SKA footprint

Corstanje et al (in prep)

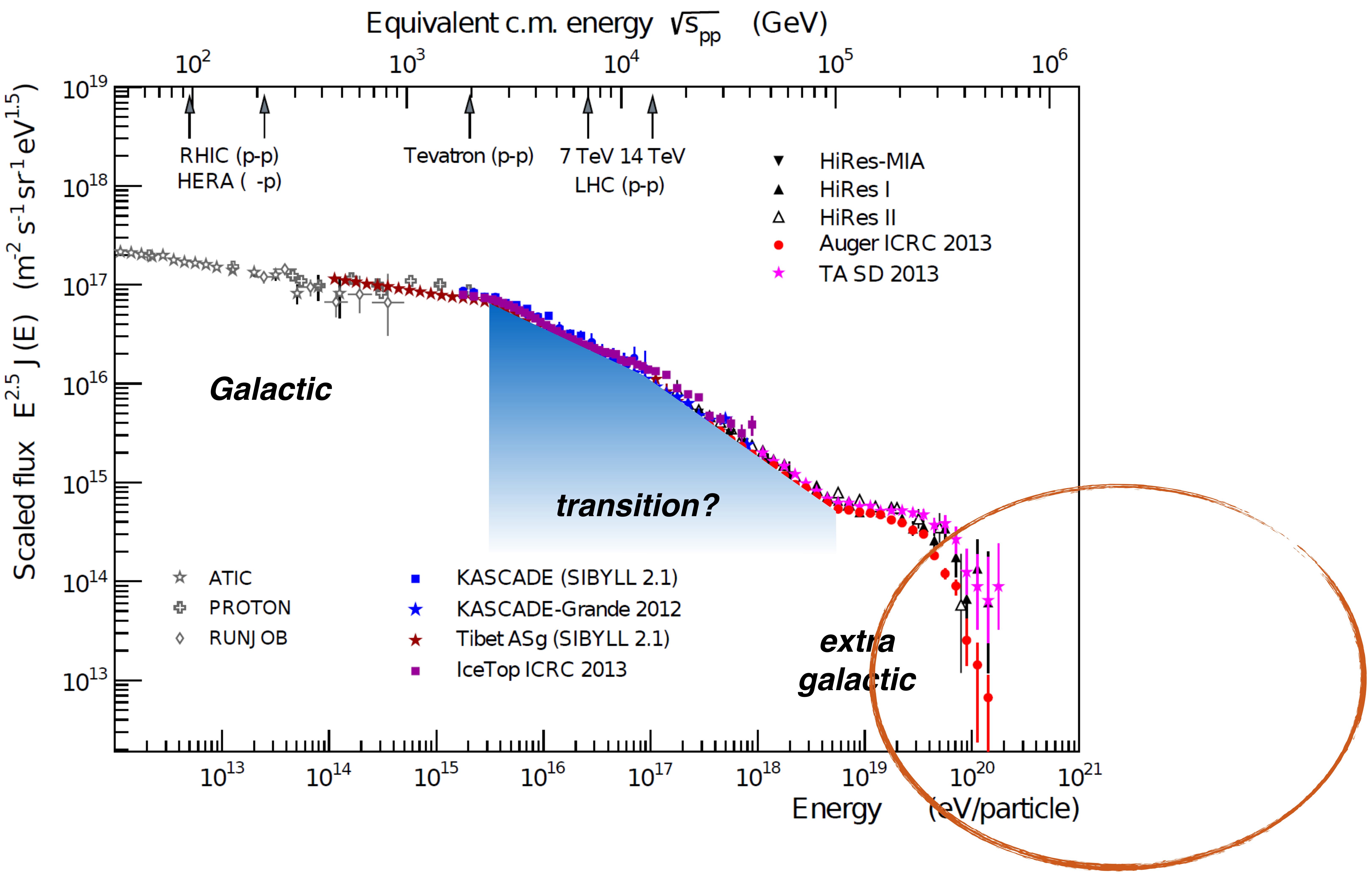
LOFAR

LOFAR

SKA

SKA

The LOFAR NuMoon project

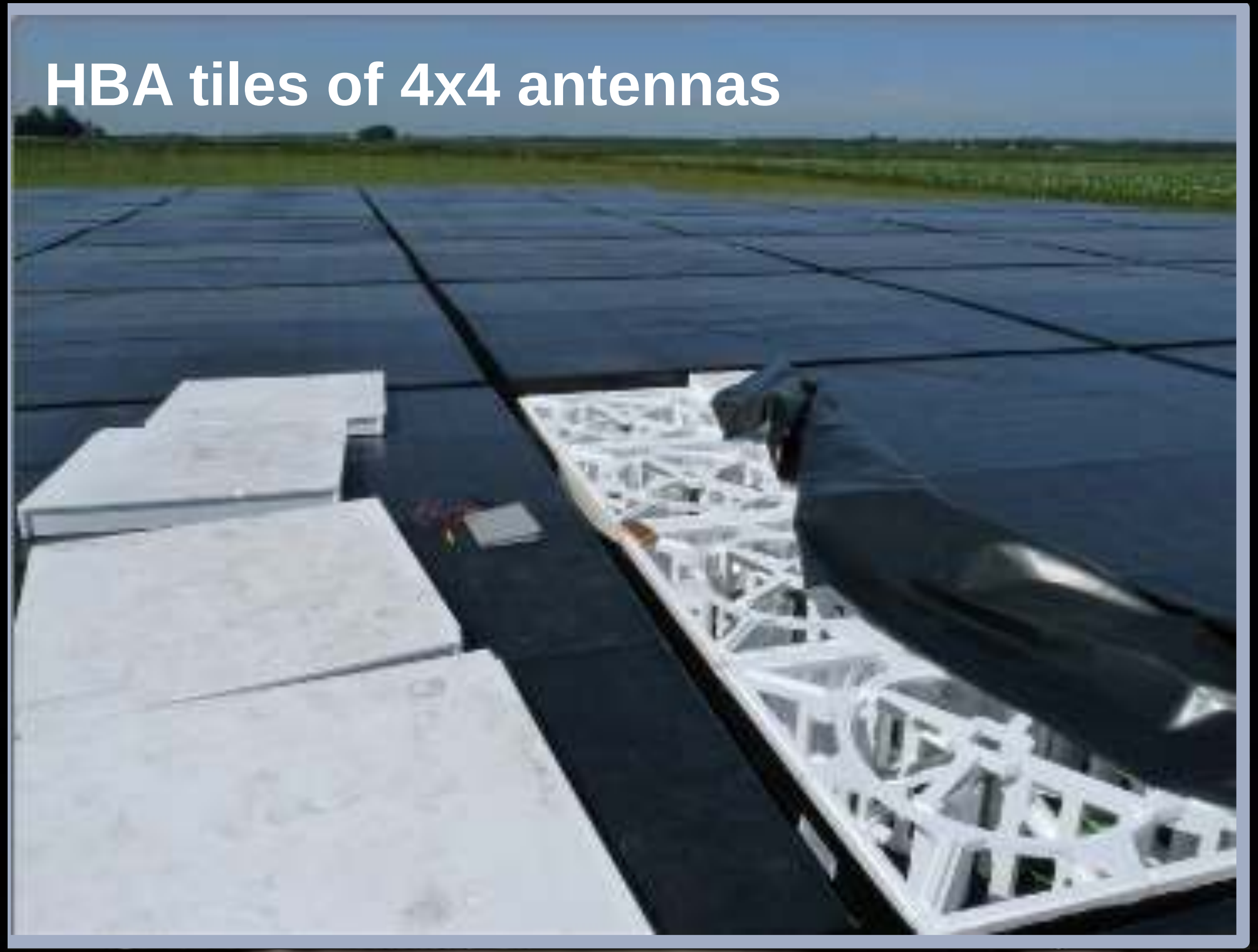


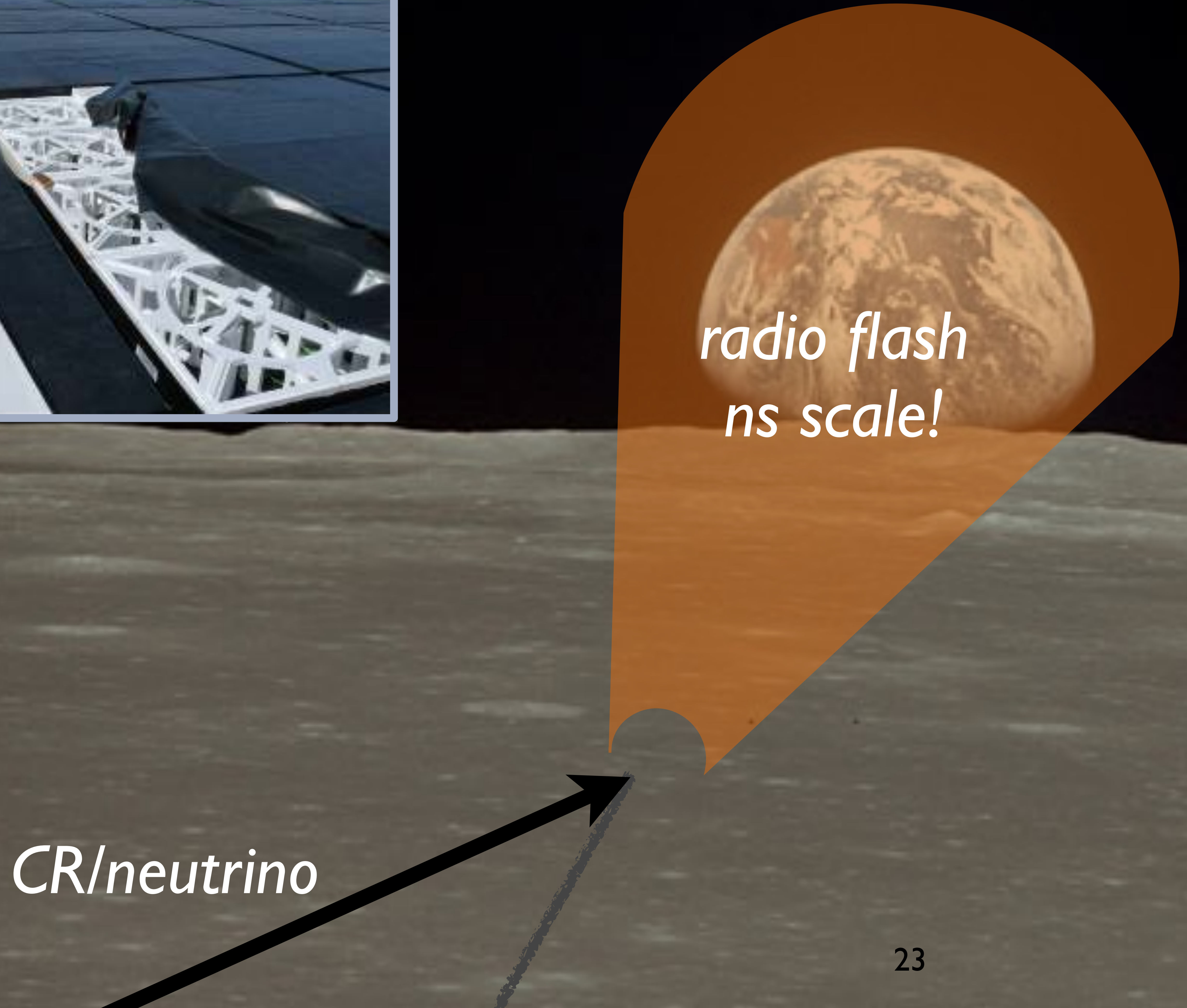
Is there anything here?

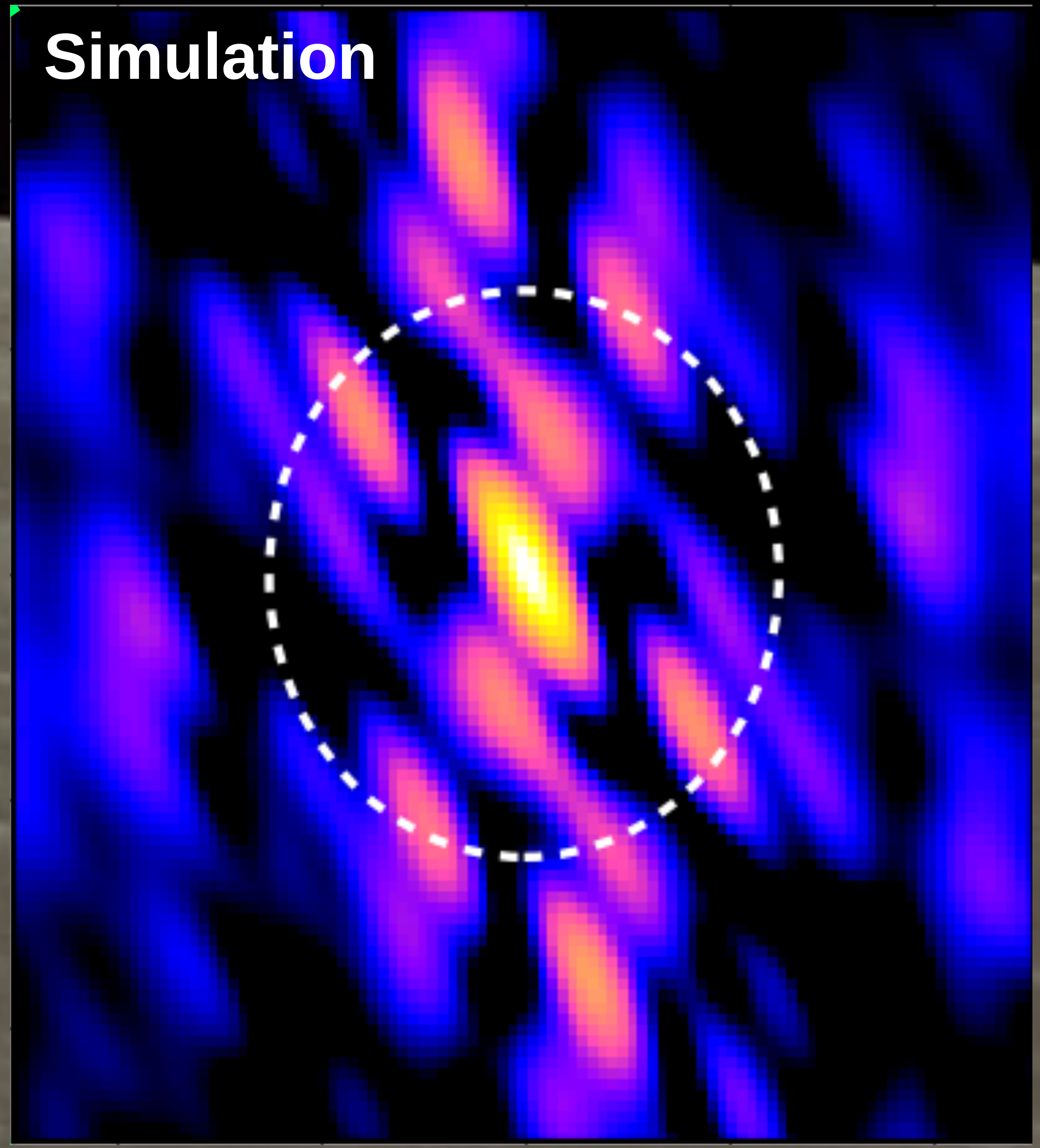
10^{20} - $10^{??}$ eV: Moon = 10^7 km^2 detector area

Observations with GPU cluster

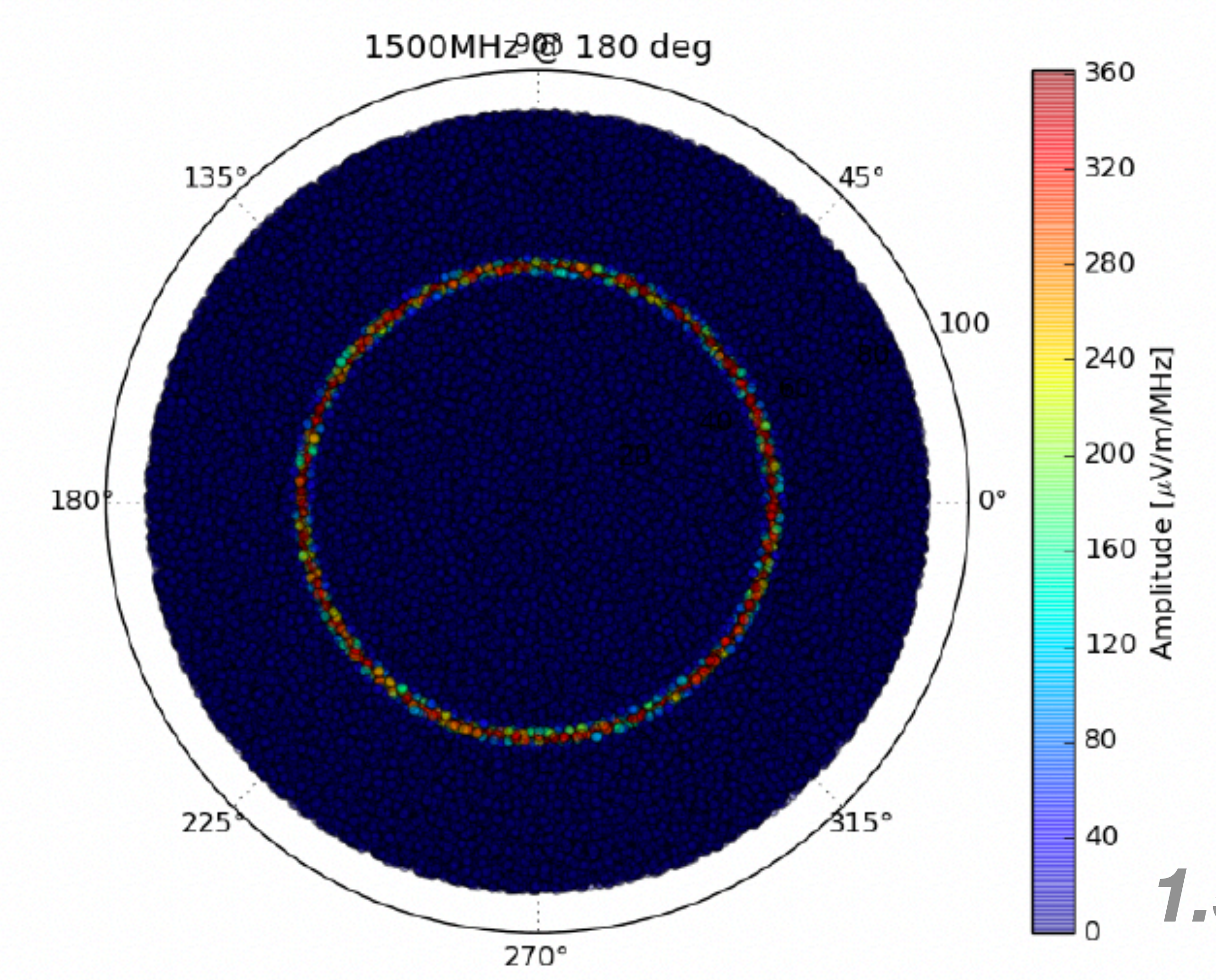
- **HBA antennas (110-240 MHz)**
- **Beamforming: add antenna signals with phase shifts to gain sensativity to spot on Moon**
- **trigger on pulses from that spot**



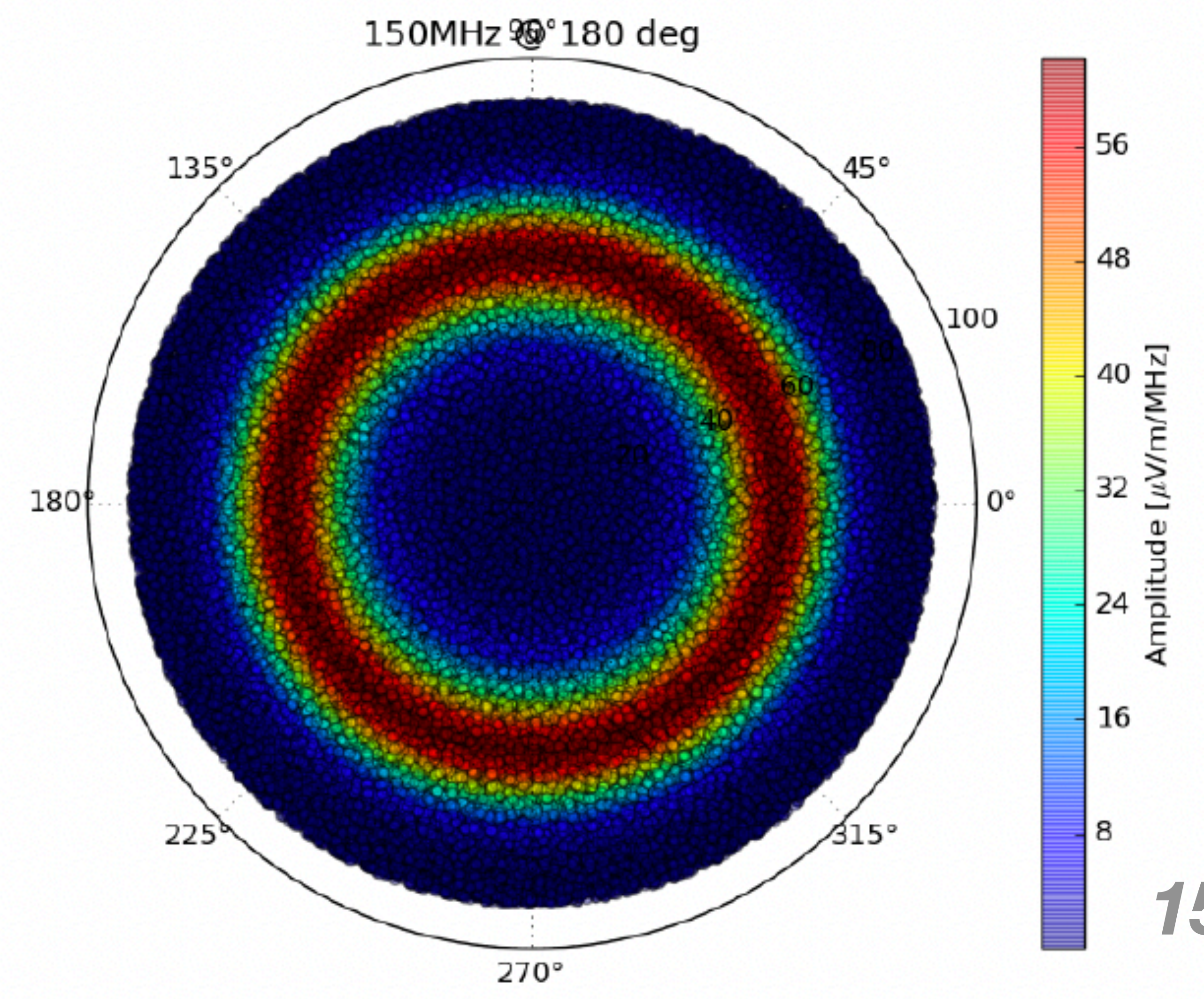




Emission patterns



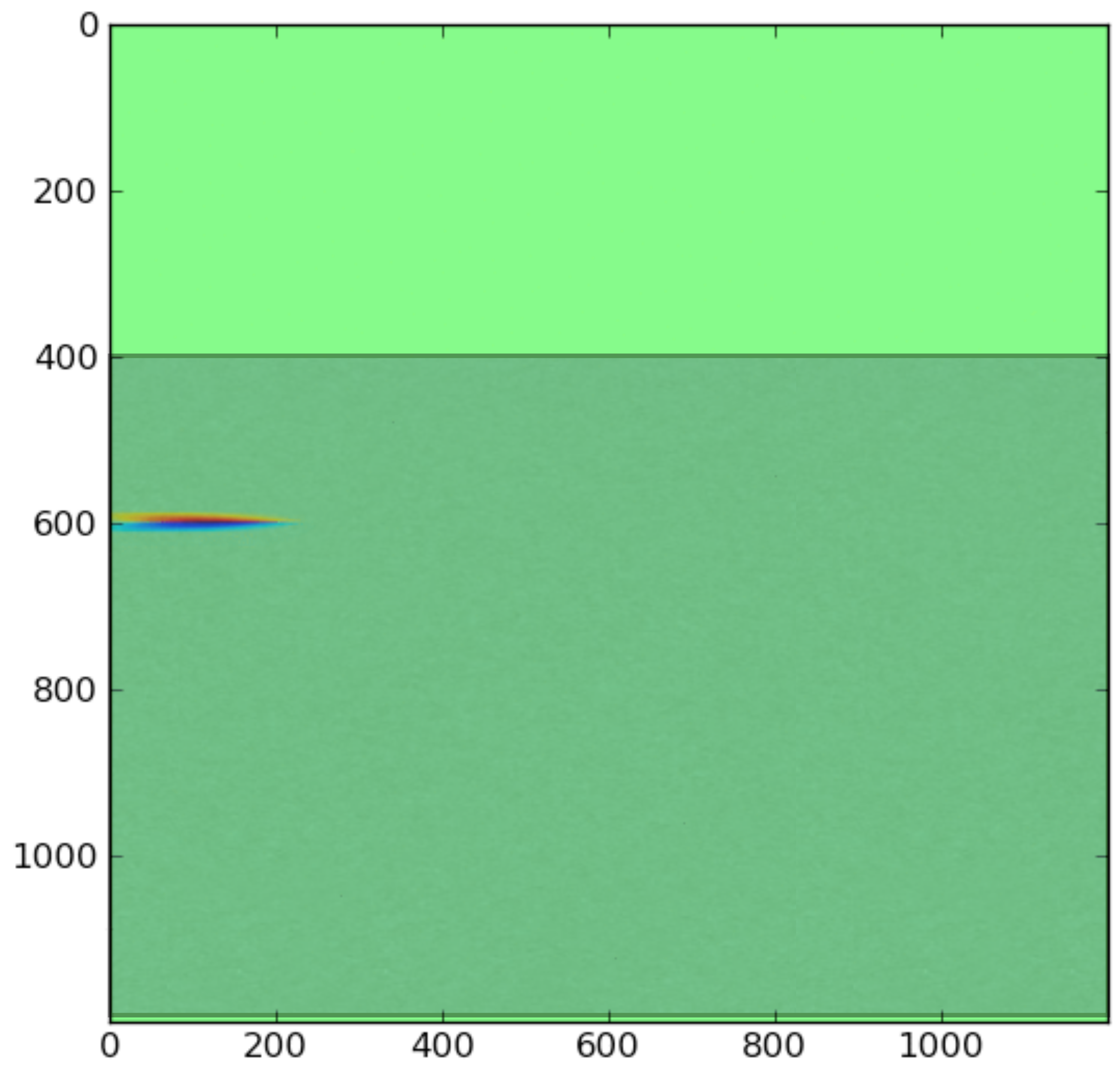
1.5 GHz

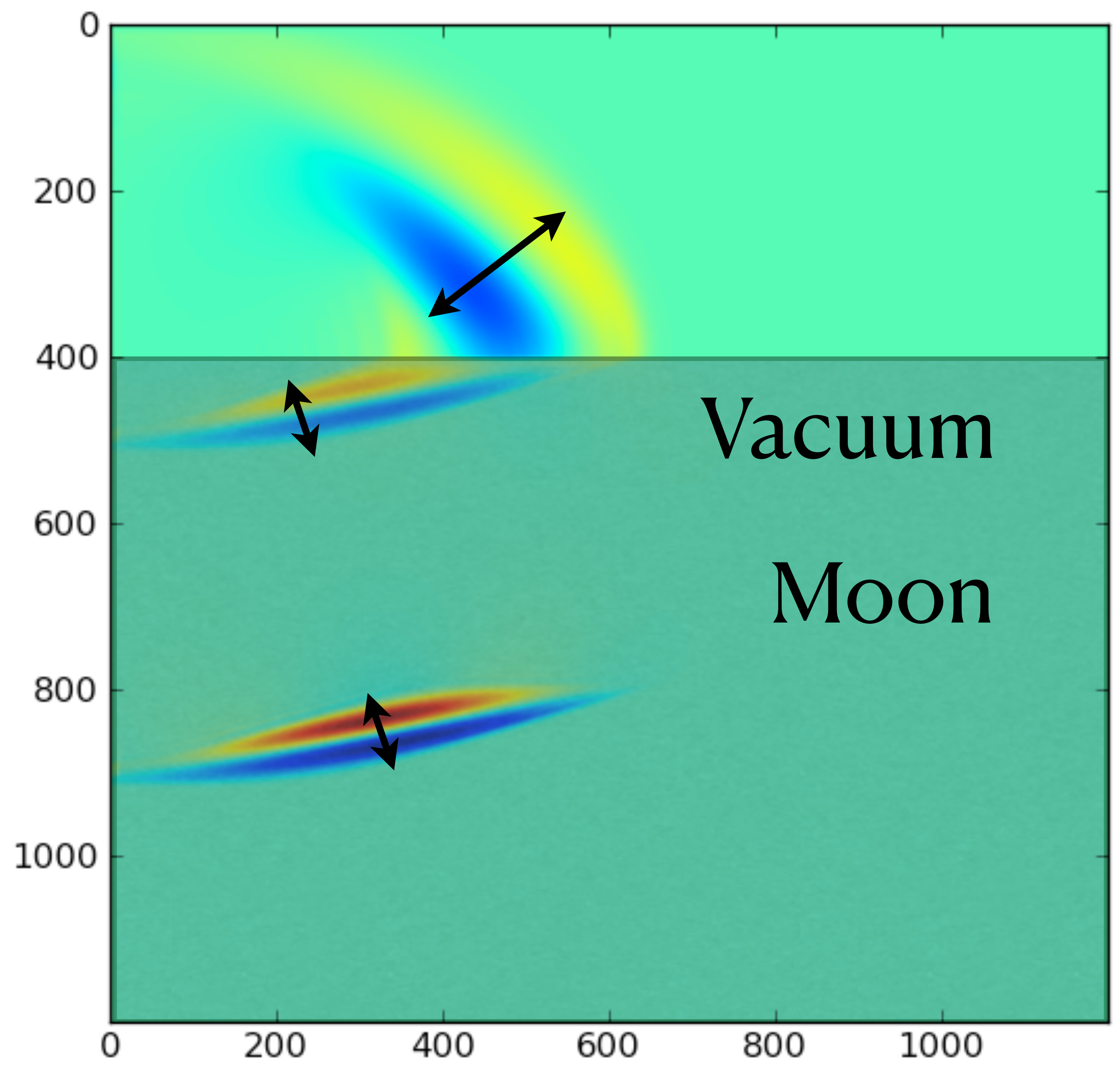


150 GHz

Observing at low frequencies

- At low frequencies (~ 100-200 MHz) the spread of emission around Cherenkov angle is larger
- Better chance for radiation to escape the Moon





Godwin Krampah

Observing at low frequencies

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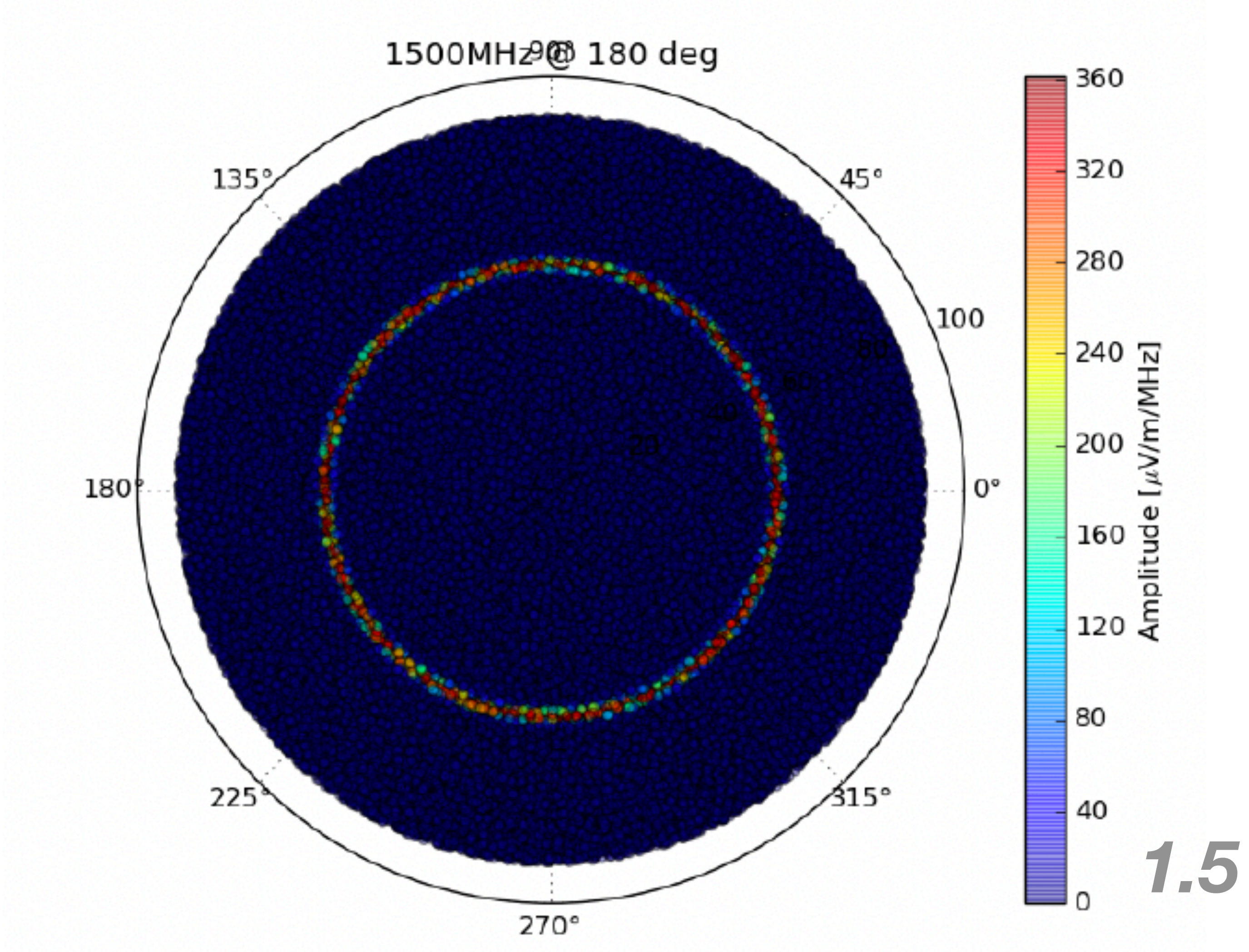

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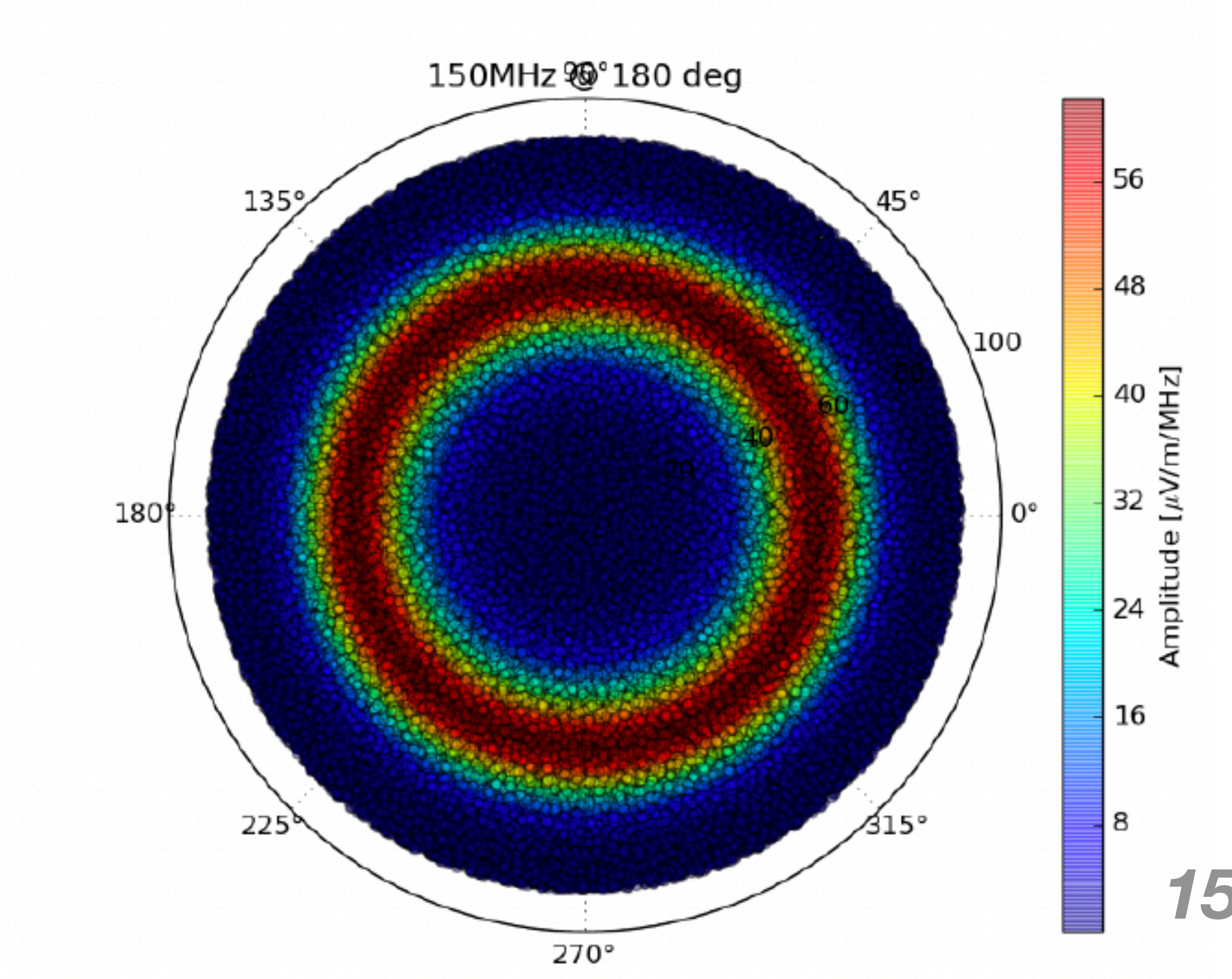

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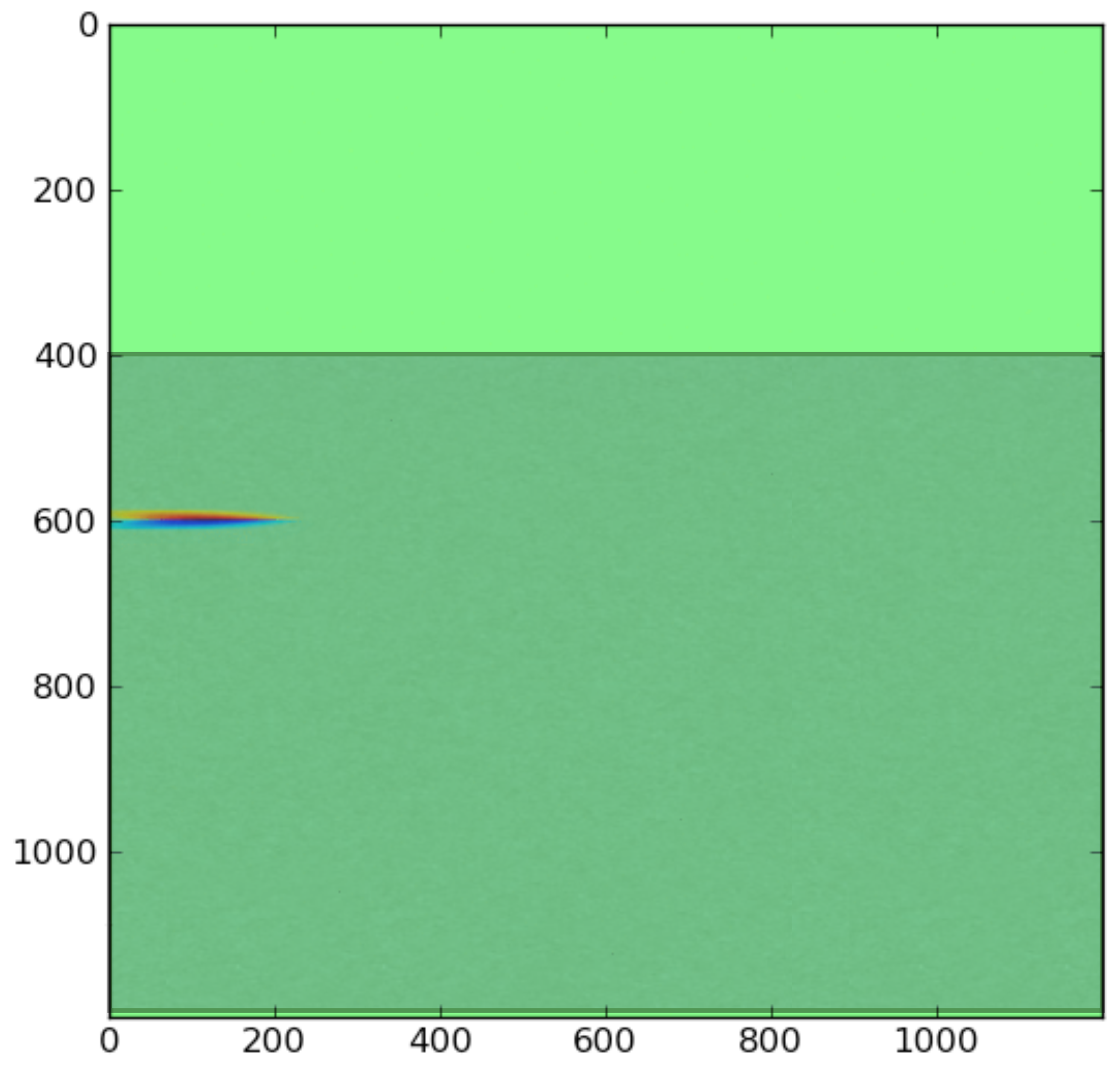
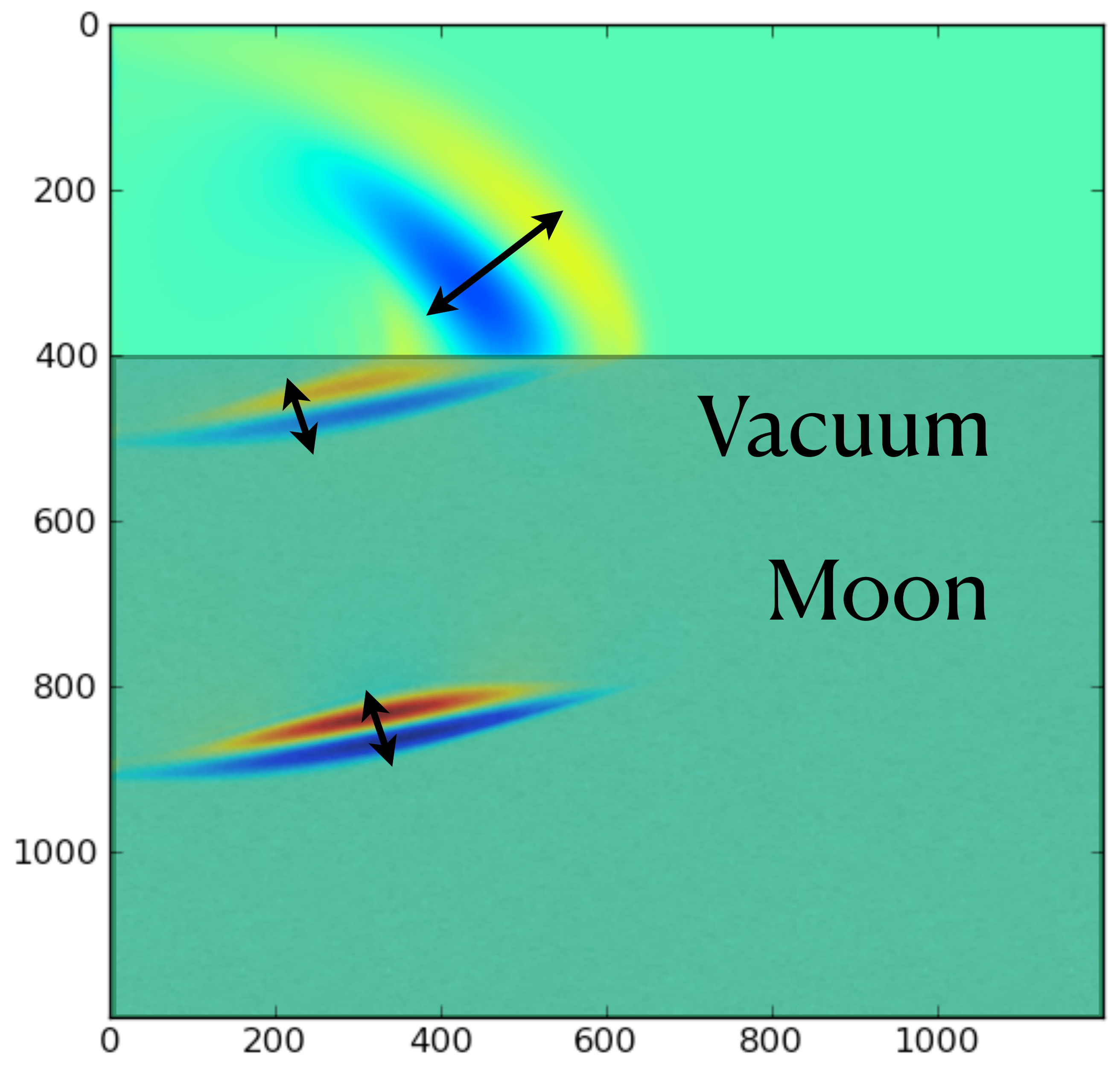
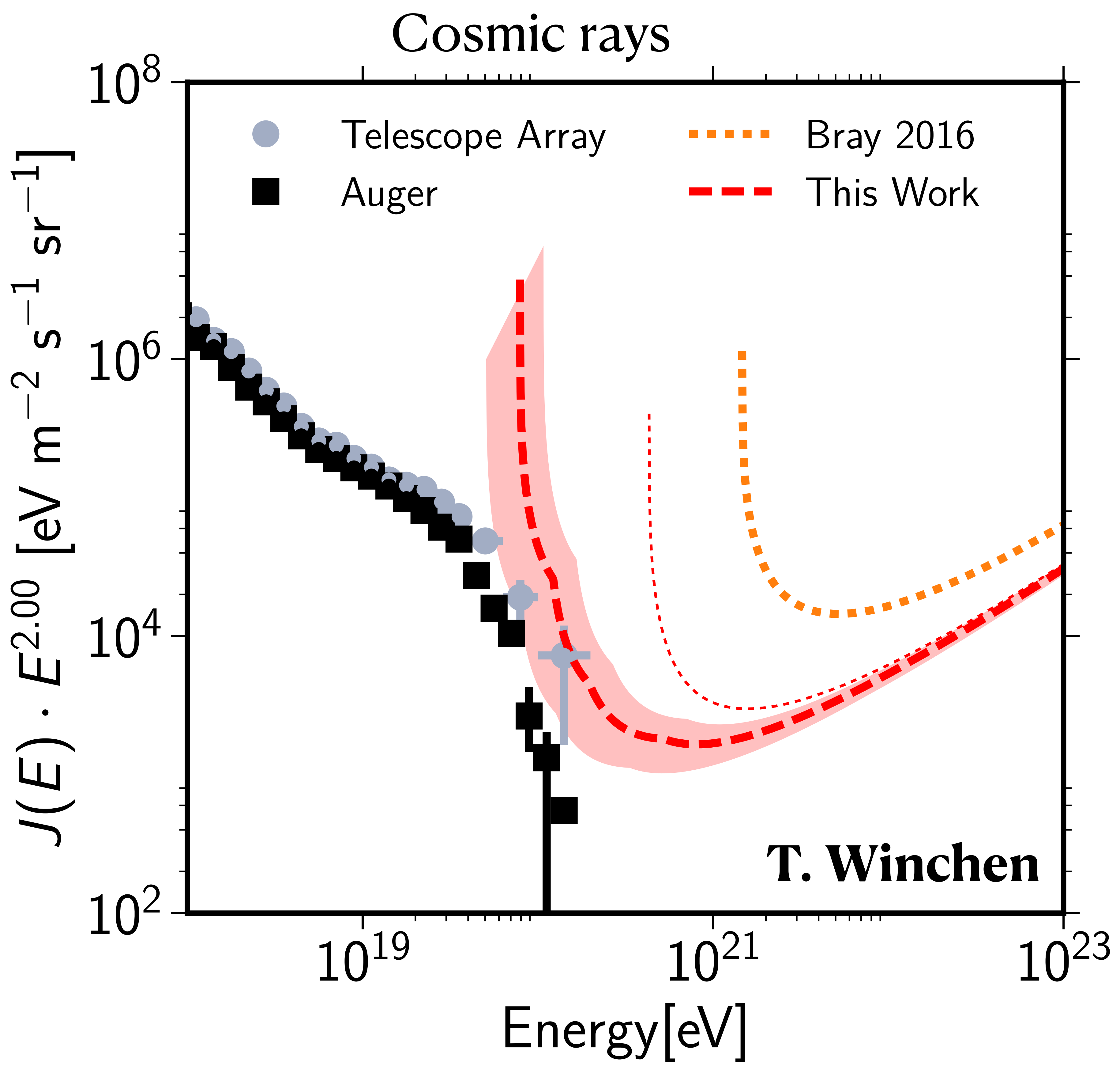
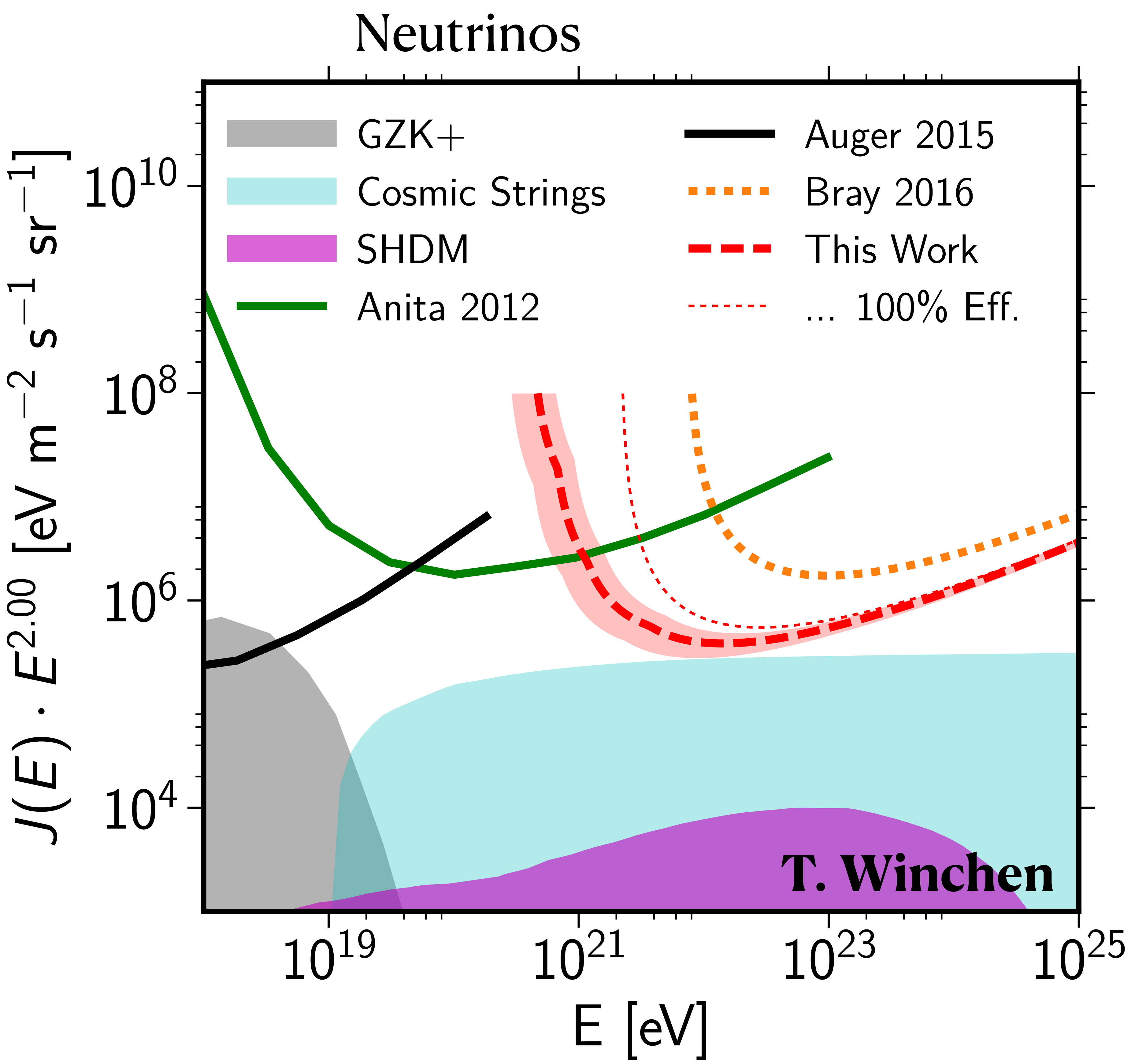




Godwin Krampah

Expected sensitivity (200 hrs)





- Currently testing observation pipeline on first 5-minute observation run (Godwin Krampah)

Future of hyperdense radio arrays

- Potential to disentangle astrophysics & hadronic physics: measure L
- New simulation approaches: fast & accurate
- Mass composition in transition region with LOFAR 2.0 + SKA
- New constraints on hadronic interactions in showers.
- Most sensitive search for CRs and neutrinos > 10^{21} eV with LOFAR 2.0