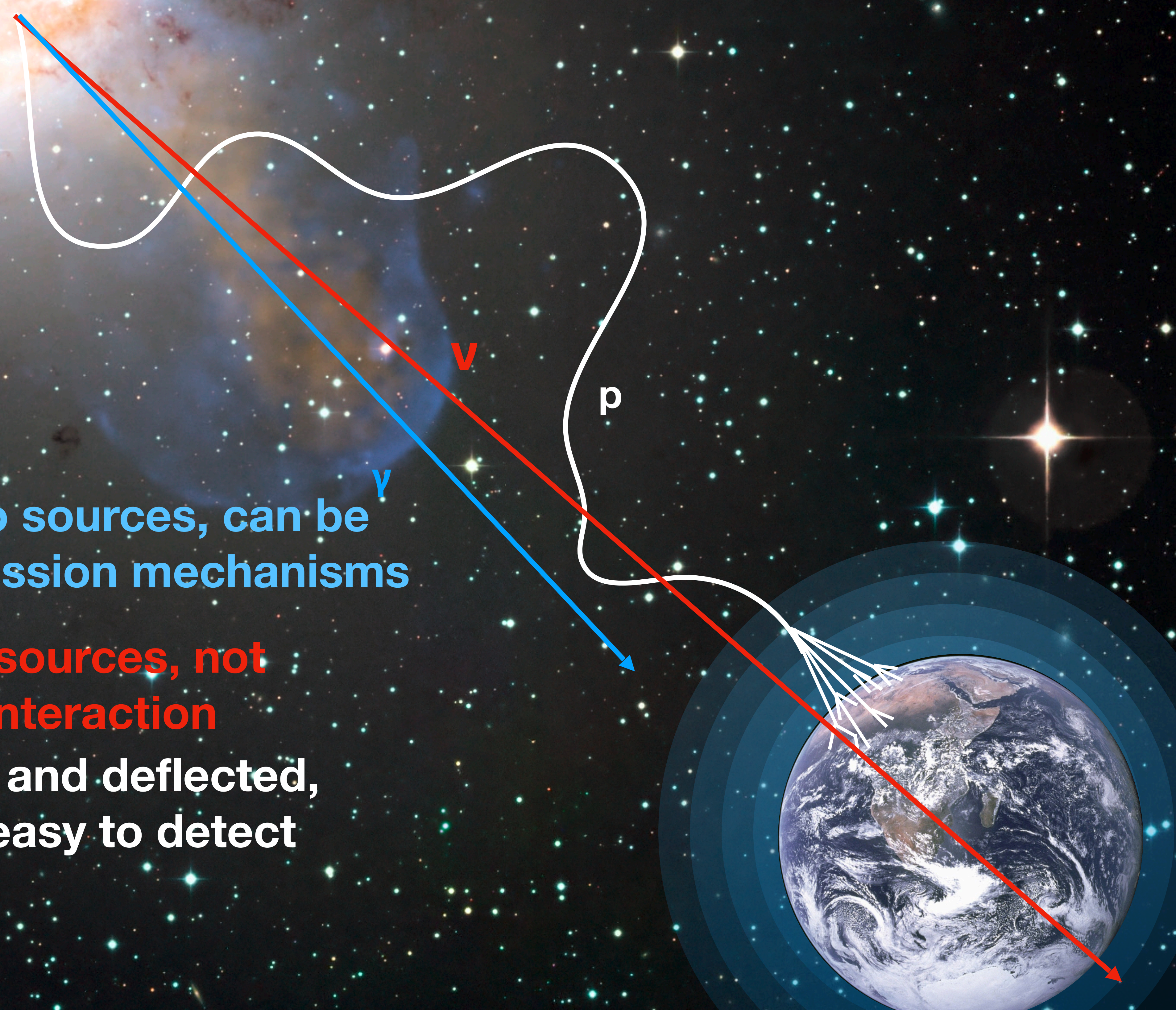
Detecting Cosmic Rays with LOFAR

2019 IIHE Annual Meeting

K. Mulrey for the LOFAR CR Group

KIT erc European Research Council VUB VRIJE UNIVERSITEIT BRUSSEL LOFAR KVI university of groningen Radboud Universiteit Nijmegen ASTRON HUMBOLDT-UNIVERSITÄT ZU BERLIN

Cosmic Rays and Multi-Messenger Astronomy

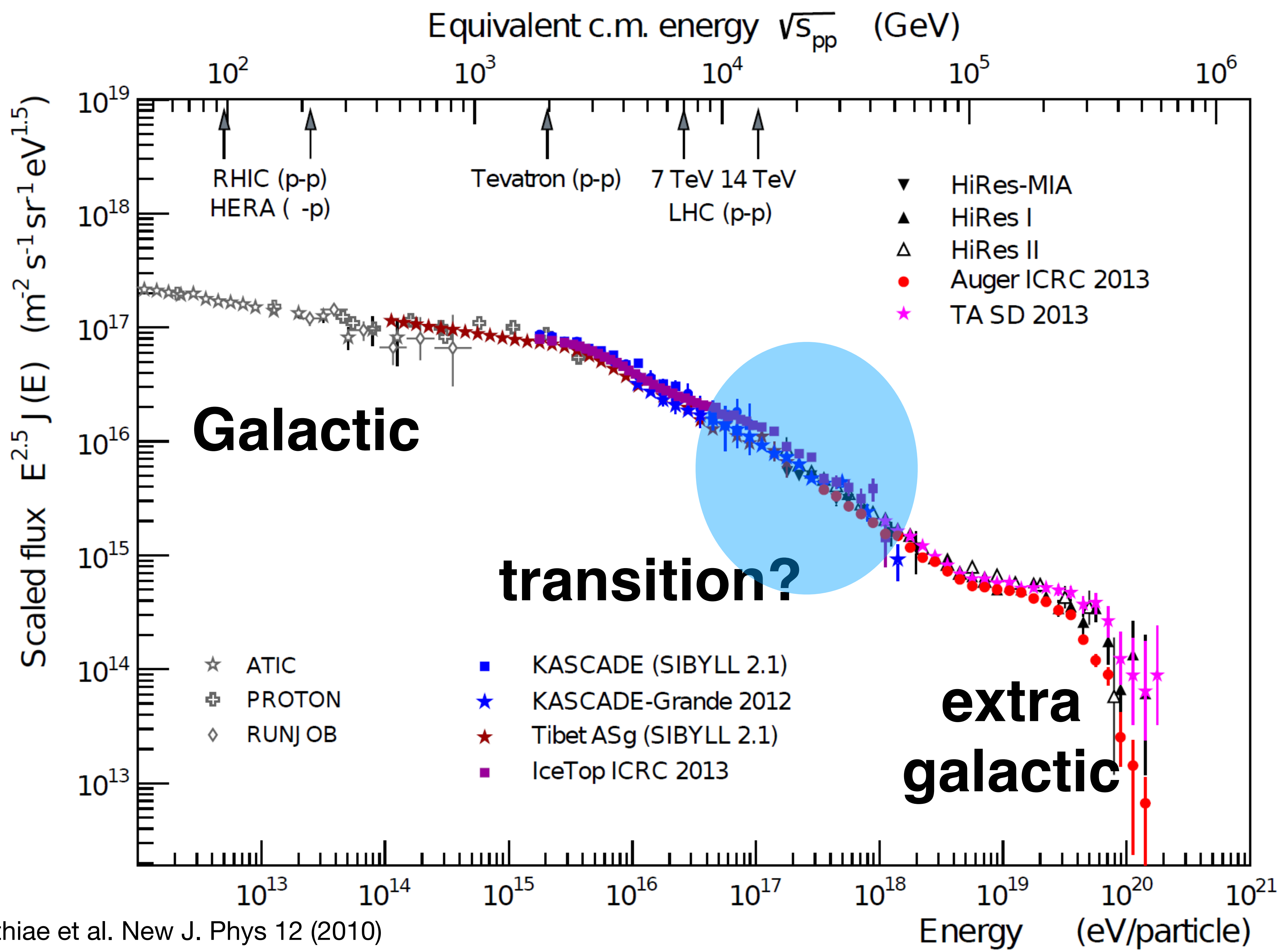


Gamma rays: point to sources, can be absorbed, multiple emission mechanisms

Neutrinos: point to sources, not absorbed, weak interaction

Cosmic rays: charged and deflected, info in composition, easy to detect

Cosmic Ray All-particle Spectrum

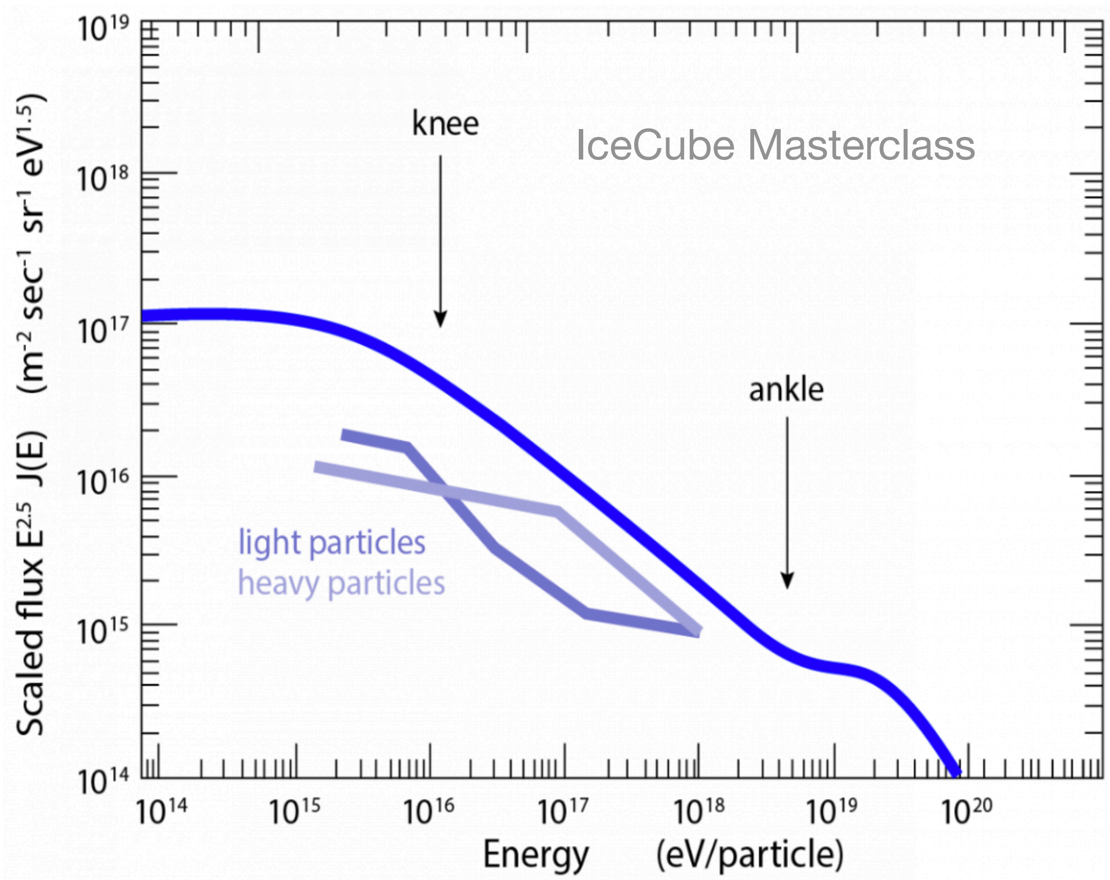


G. Matthiae et al. New J. Phys 12 (2010)

Cosmic-ray Energy & Composition

Galactic: SNR ??

Extragalactic: AGN ??



Hillas criterion:

$$E_{max} \propto Z\ e\ B\ r$$

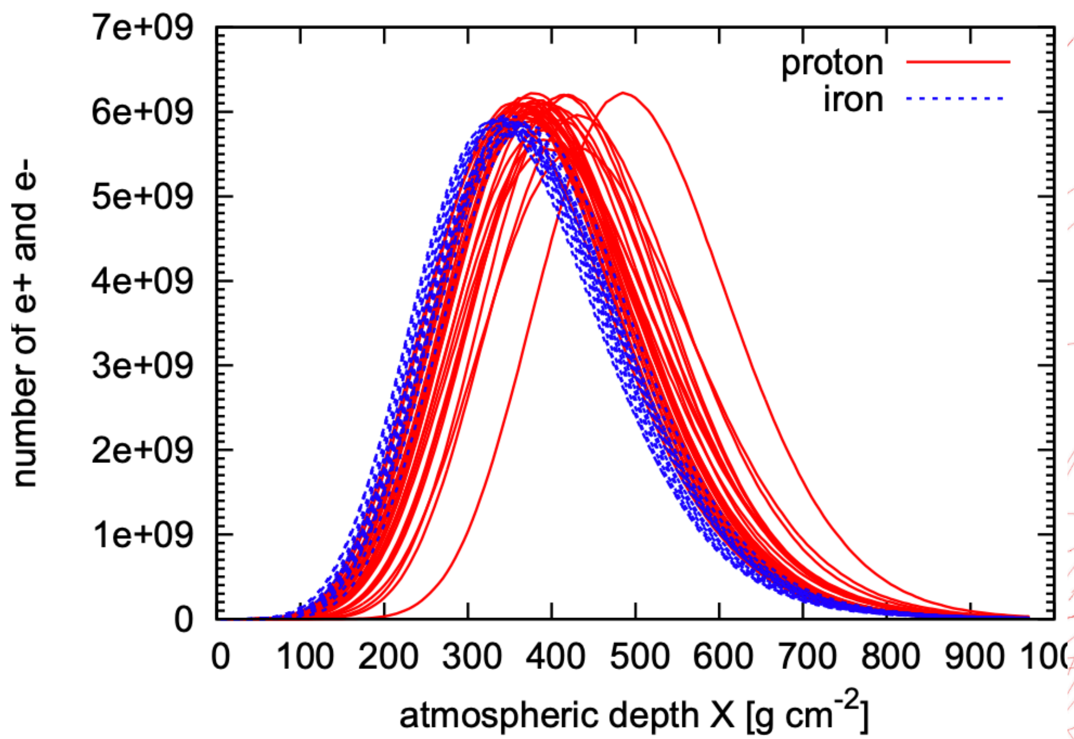
Max Energy

$$E_{Fe,\ max} = 26 \times E_{p,max}$$

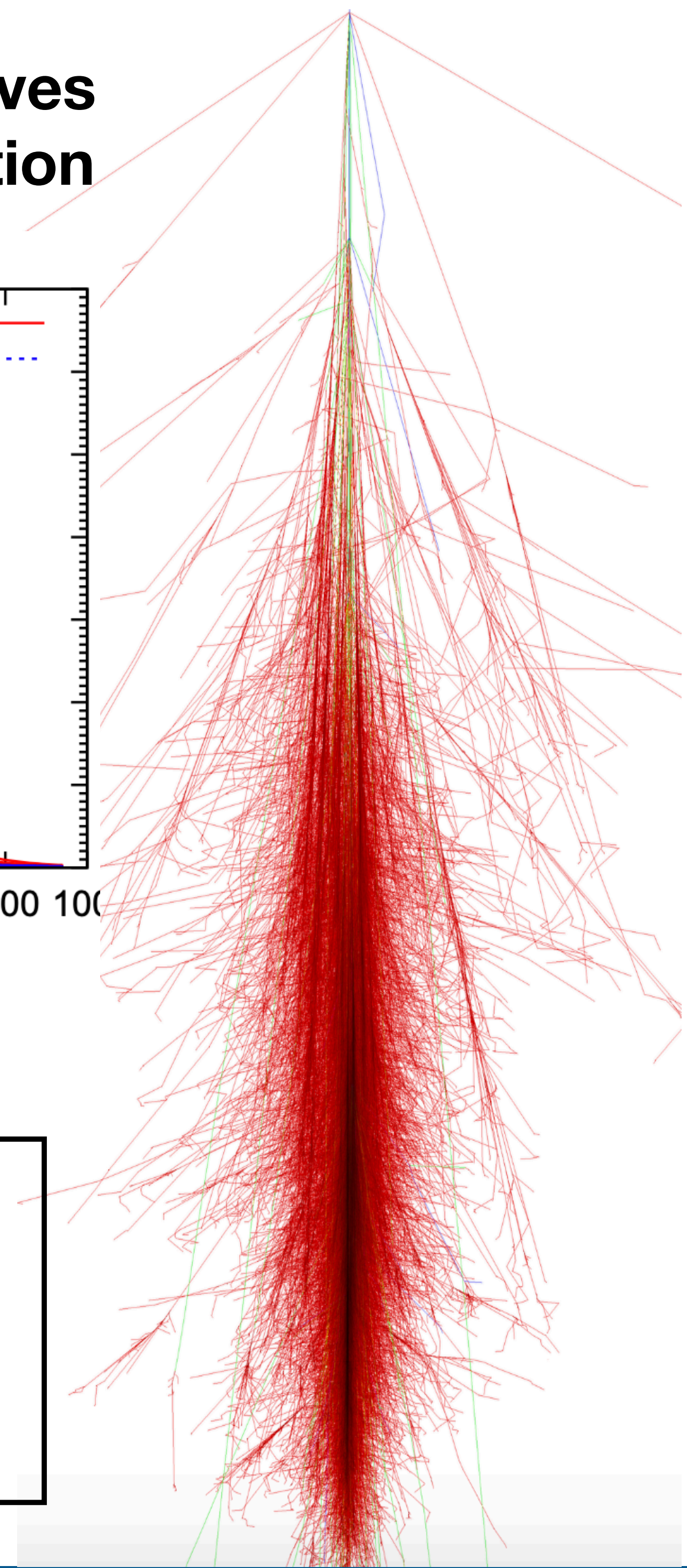
- Below 10^{19} eV, can't point directly to sources
- Use composition to understand origin
- **Transition to heavier composition indicates the maximum source energy is reached**

Composition: Measuring X_{max}

X_{max} is an observable that gives information about composition



T. Huege. Physics Reports, 620:1-52,2016

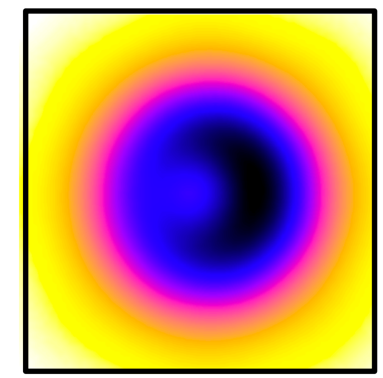


electron/muon ratio

particles on ground (snapshot)
Hadronic interaction models
Kascade Grande

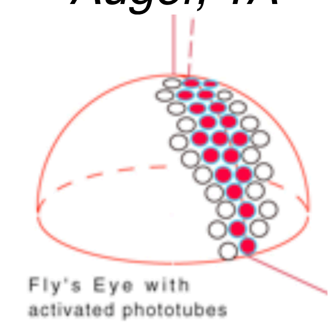
radio detection

nearly 100% duty cycle
good resolution
calorimetric energy measure
LOFAR, AERA, Tunka

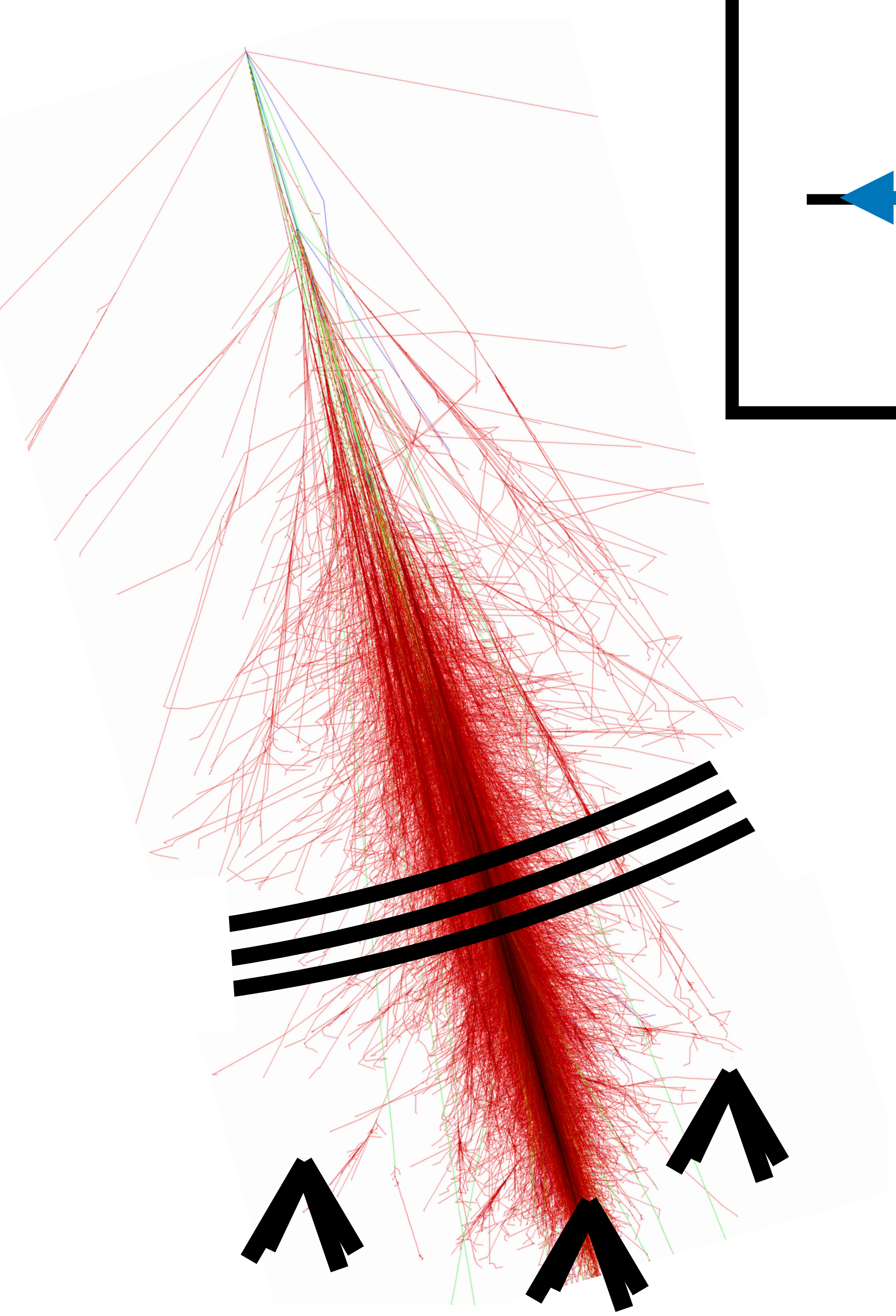


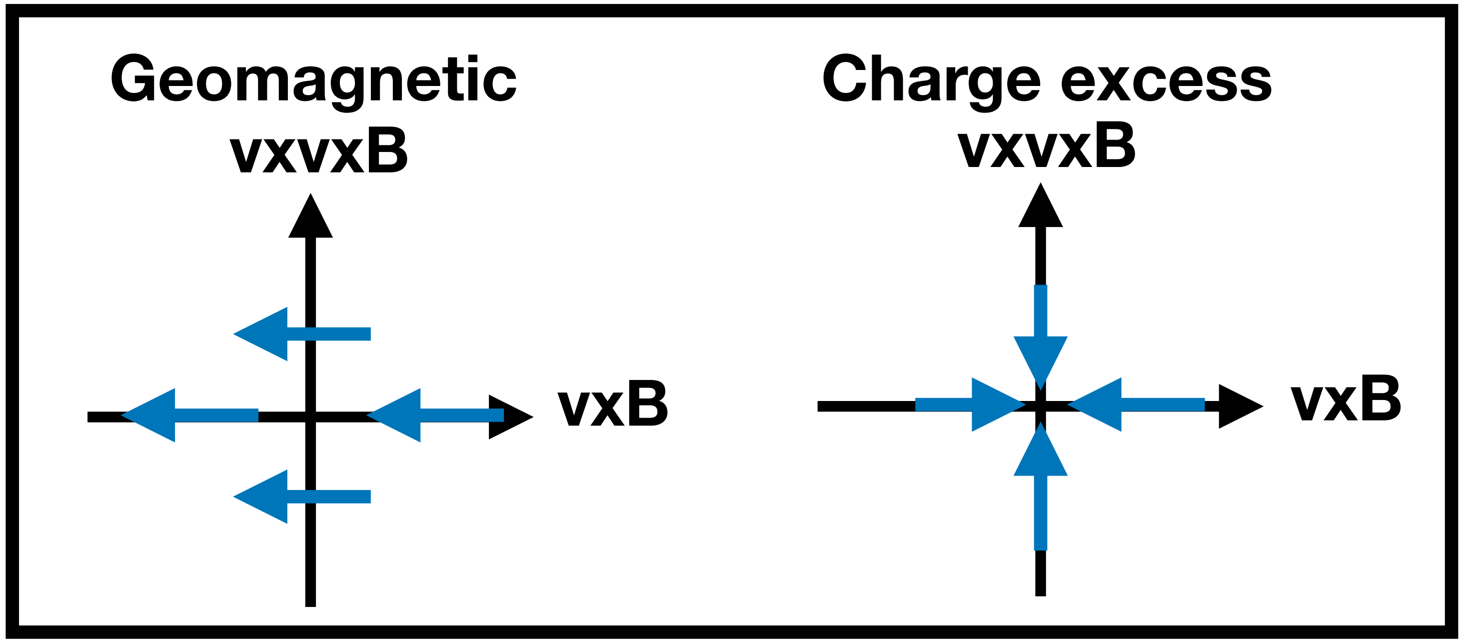
fluorescence light

dark nights (<15% duty cycle)
good resolution
calorimetric energy measure
Auger, TA



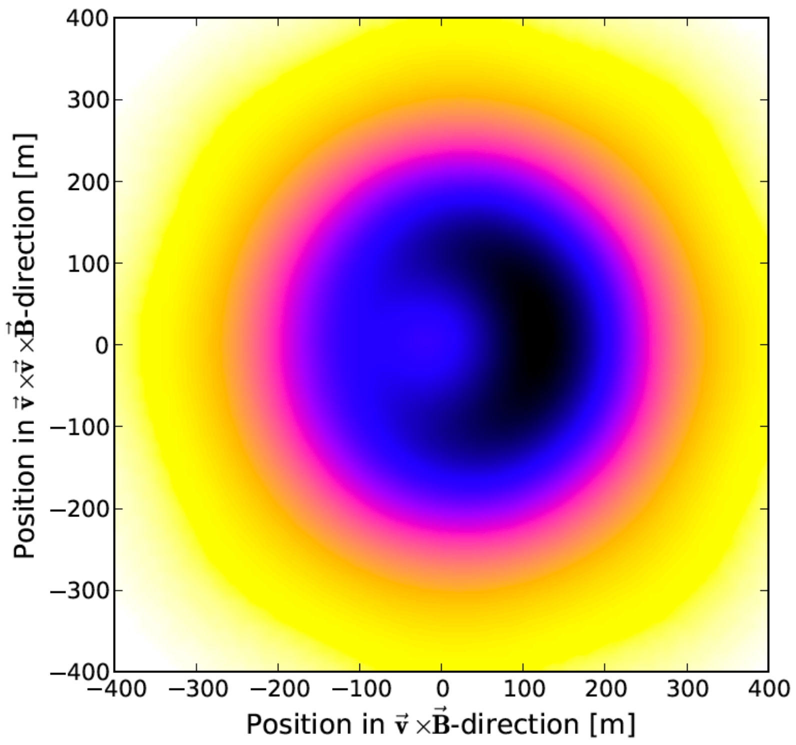
Radio Emission





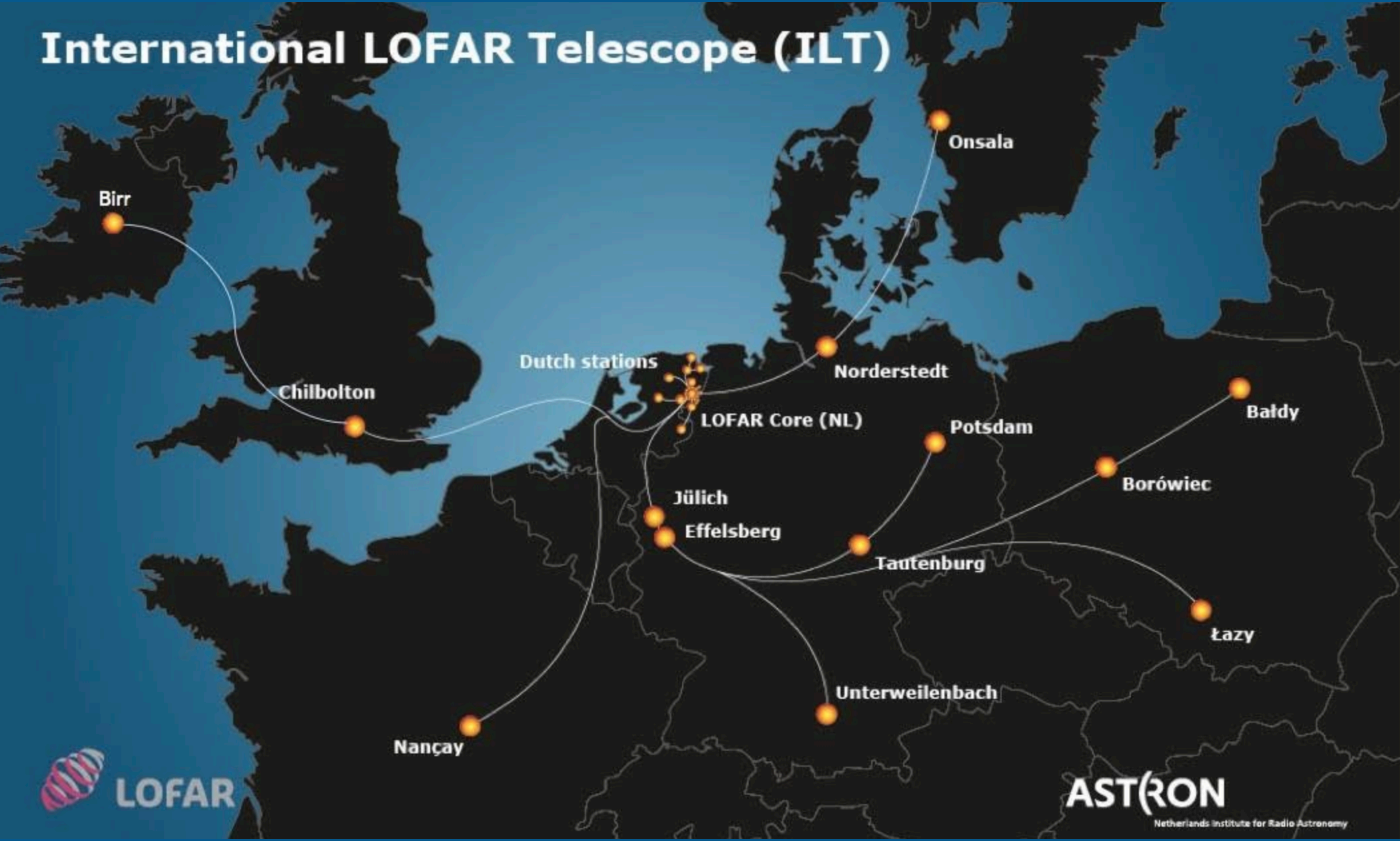
Radiation Pattern:

- Direction
- Magnetic Field
- Energy
- X_{max}
- Atmosphere

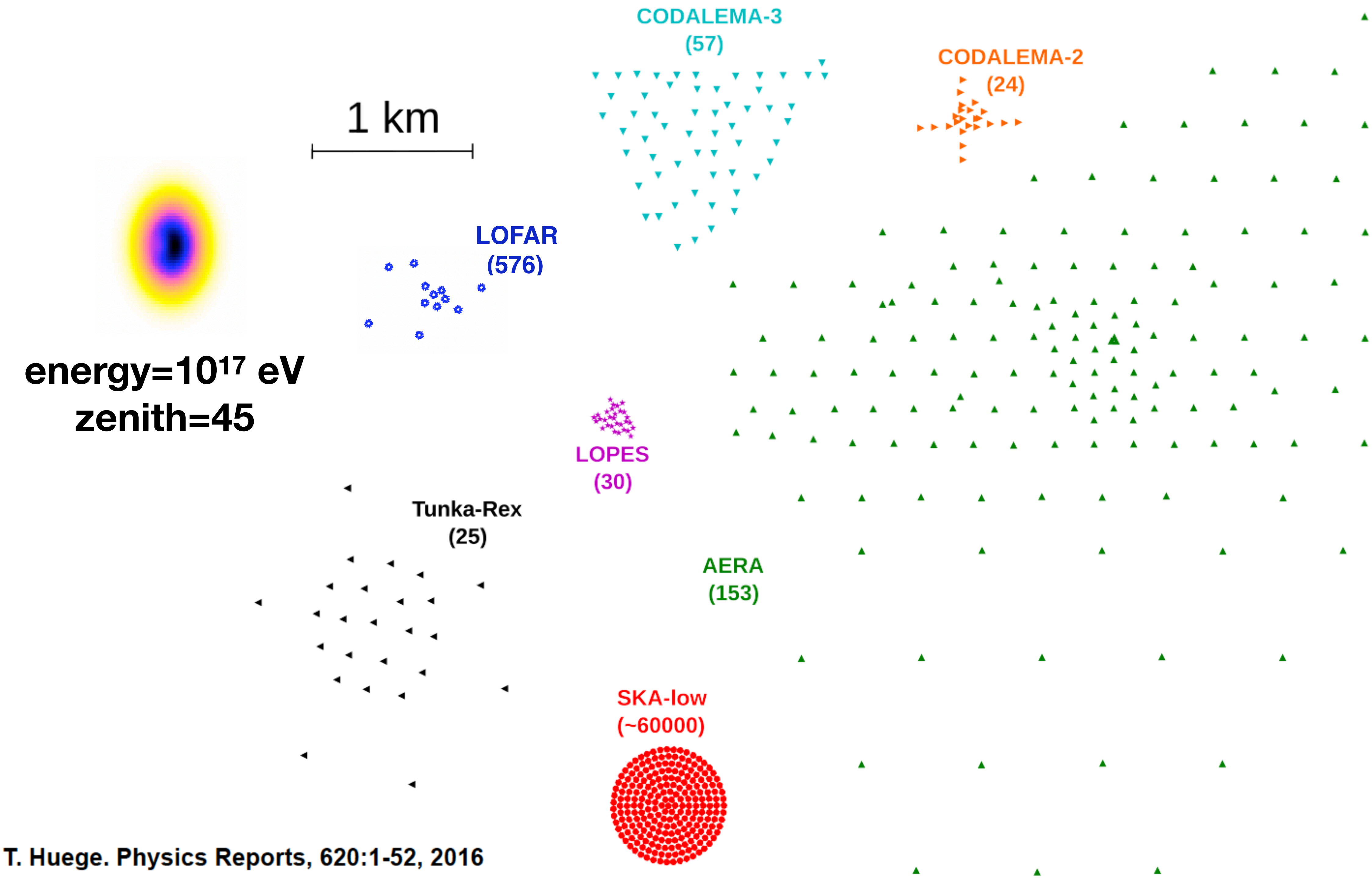


A. Nelles et al., Astropart. Phys. 60, 13 (2015).

LOFAR Observatory



Radio Detection Experiments



T. Huege. Physics Reports, 620:1-52, 2016

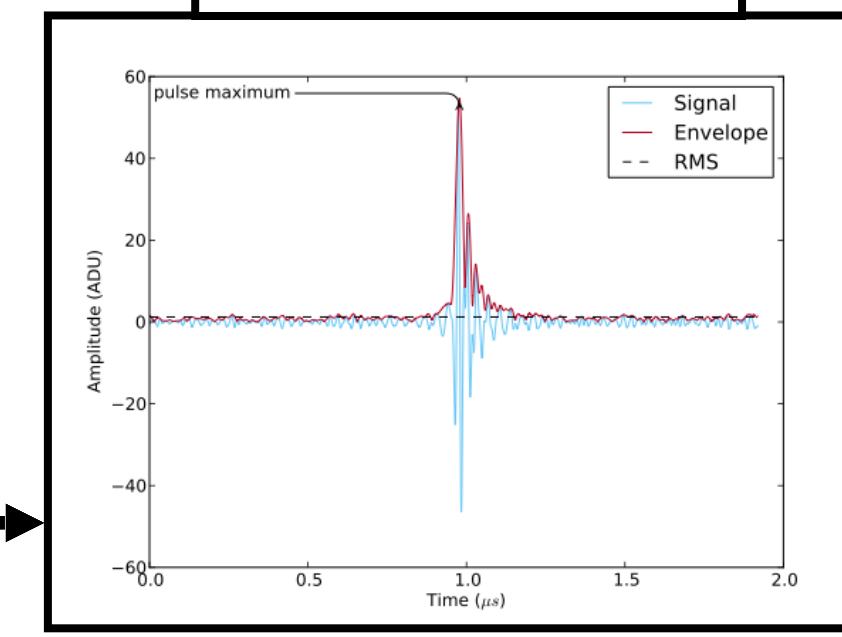
Cosmic Ray Detection at LOFAR

300 m

- LOFAR Radboud Array
- scintillator detectors
- provides trigger for antenna readout

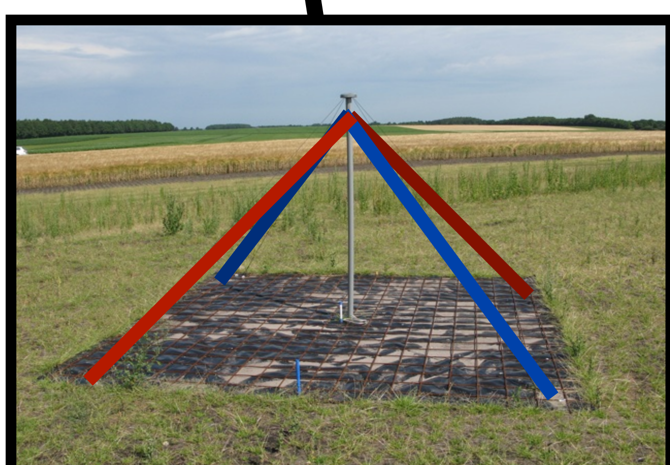
trigger

offline analysis



buffer

2 ms read-out

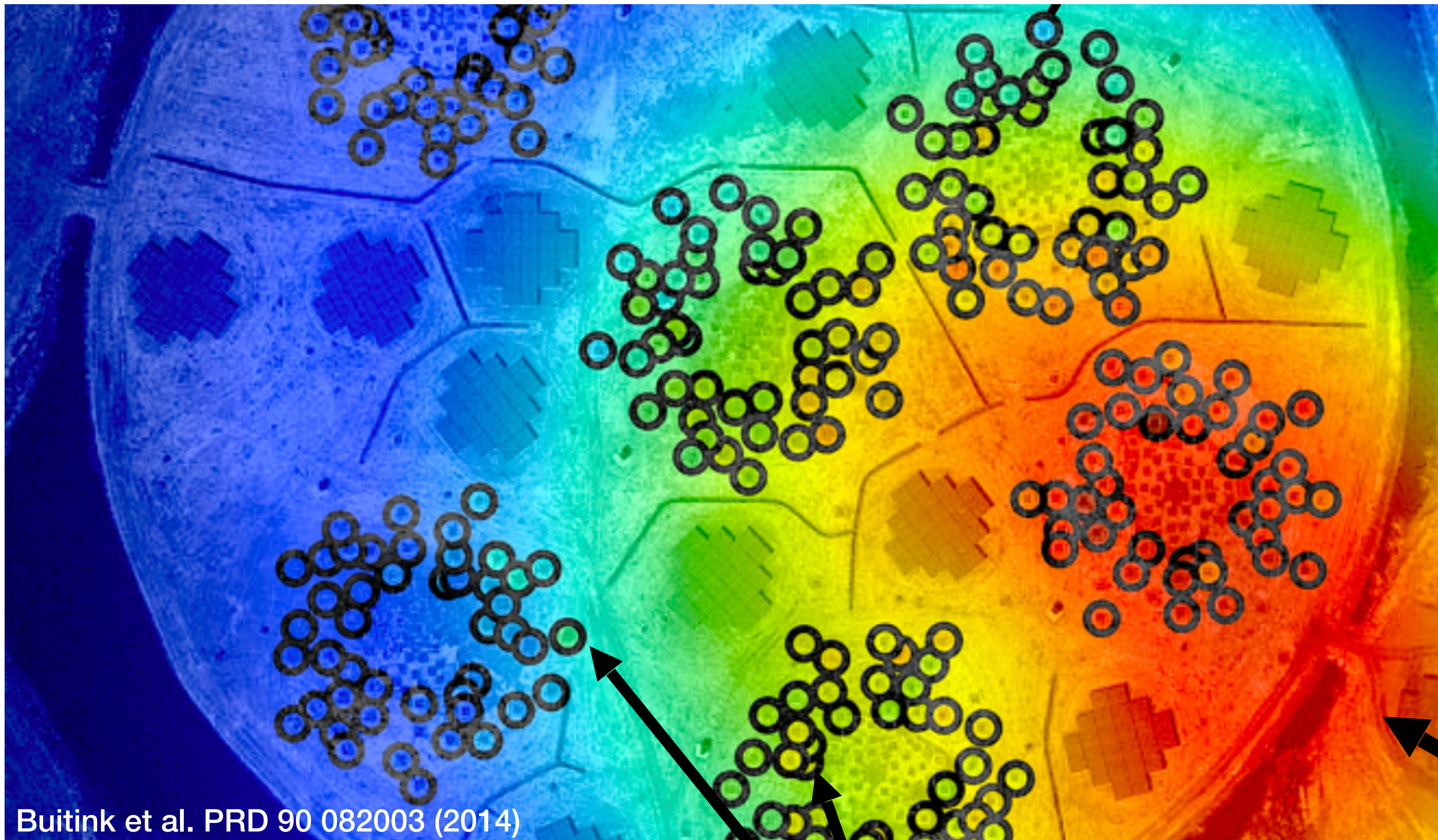


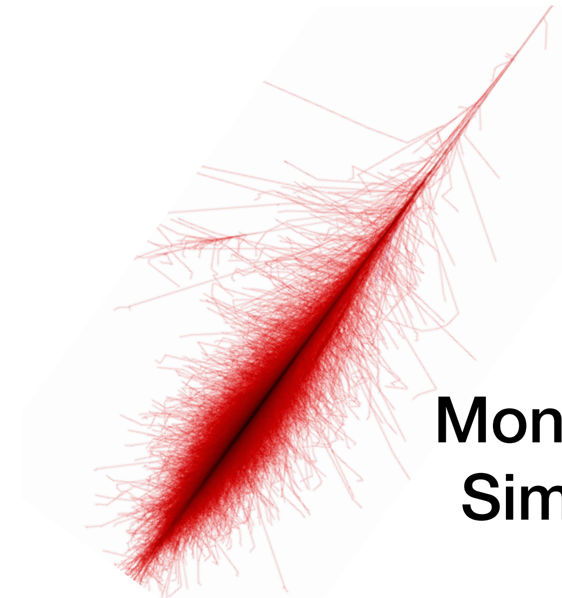
6 LBA stations (6 x 48 antennas)
+ stations outside Superterp

- RFI cleaning
- direction reconstruction
- antenna pattern unfolding
- calibration

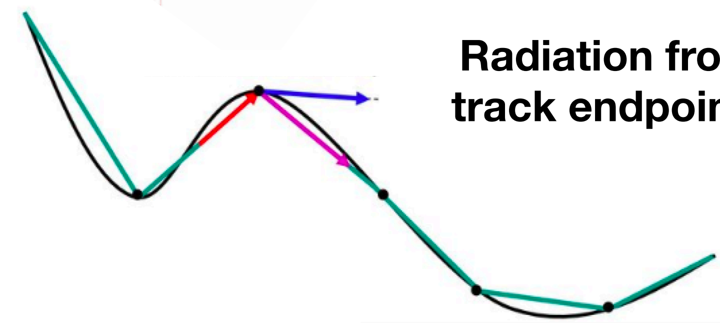
P. Schellart et al., A&A 560, 98 (2013)

Event Analysis





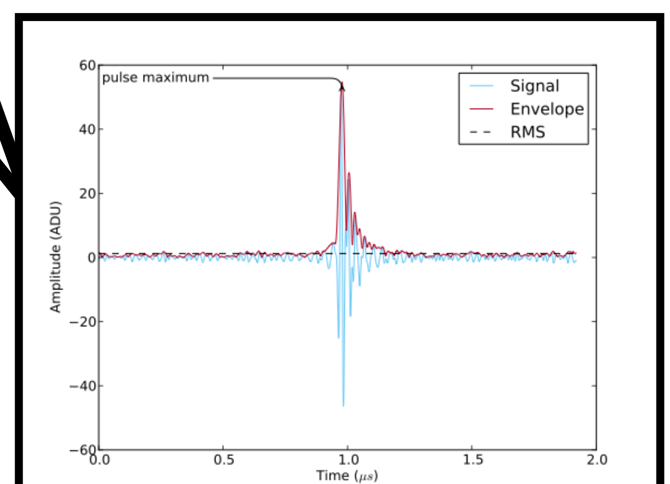
Monte Carlo Simulation



Radiation from track endpoints

LOFAR data

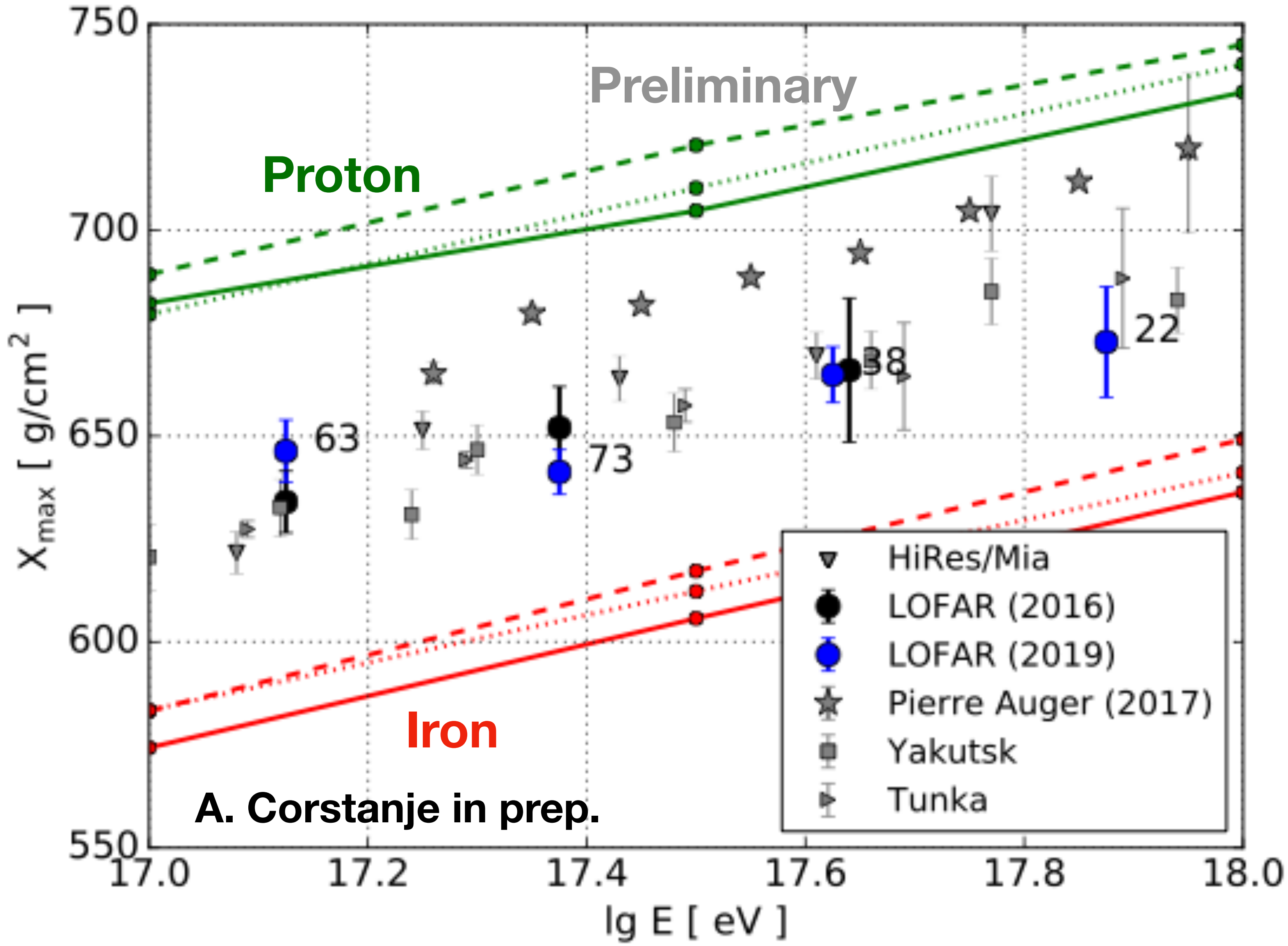
- **200-450 antennas / event**
- **Total power within 55 ns of peak emission**



CoREAS simulation

- **no assumptions about emission**
- **independent of hadronic models**
- **effort to develop analytical code**

Composition Results

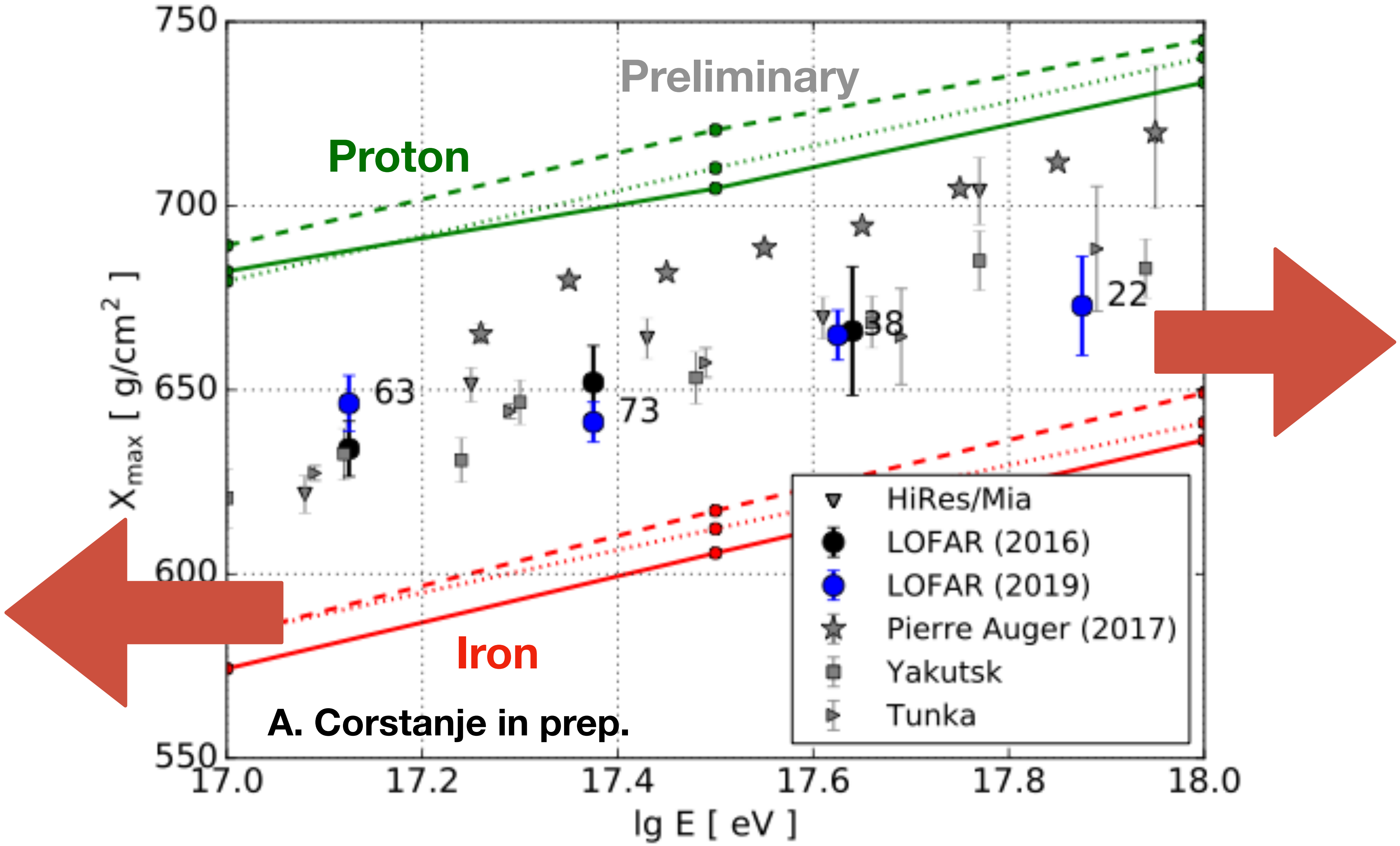


- **Resolution < 20 g/cm²**

A. Corstanje et al, in prep.
S.Buitink. et al, *Nature* **531**, 70 (2016)

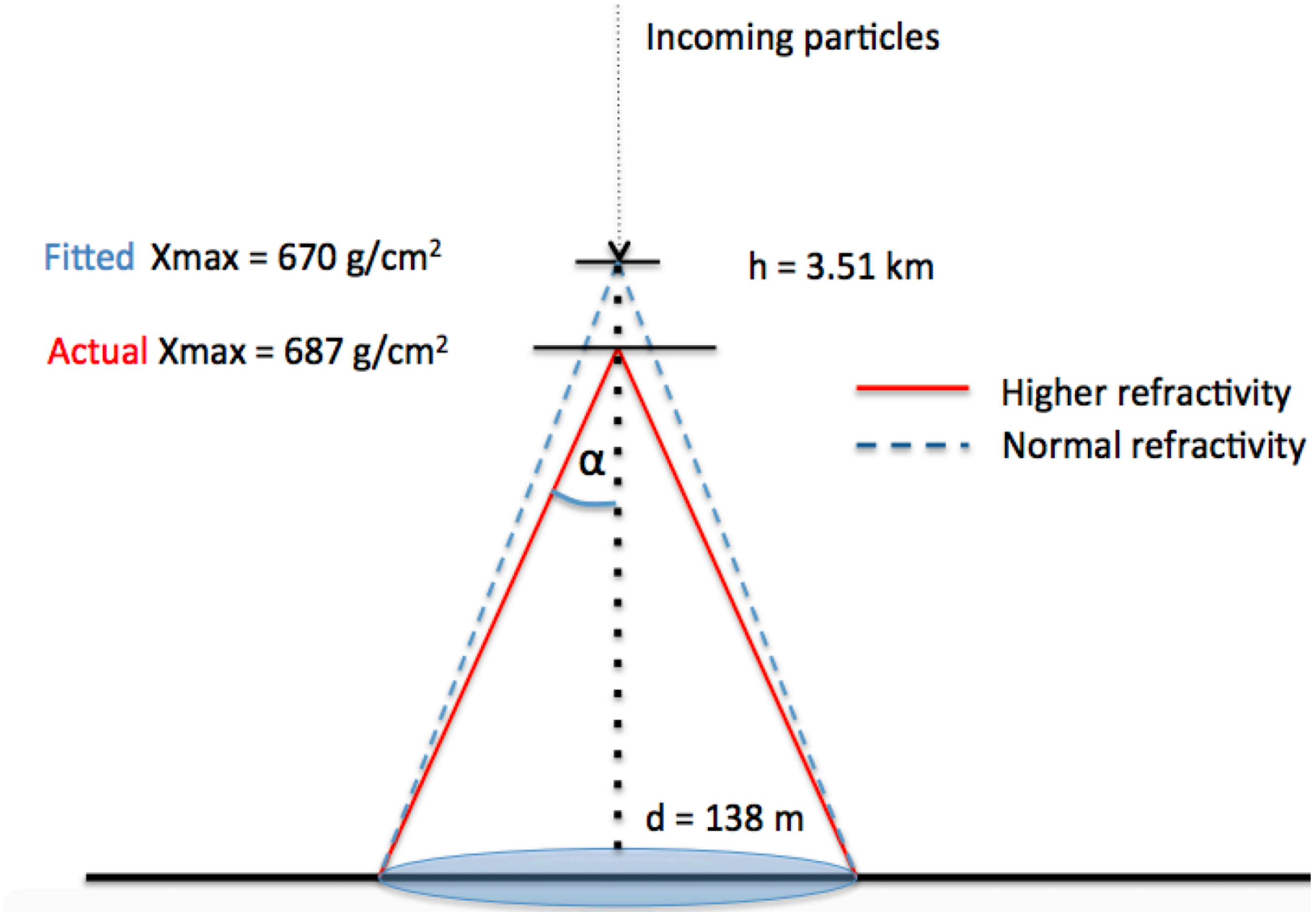
- **Best fit (2016): 80% light particles (p+He) at 10^{17} -$10^{17.5}$ eV**

Composition Results



- Expand energy range for X_{max} measurements
- Reduce systematics on energy and X_{max}

Atmospheric Corrections

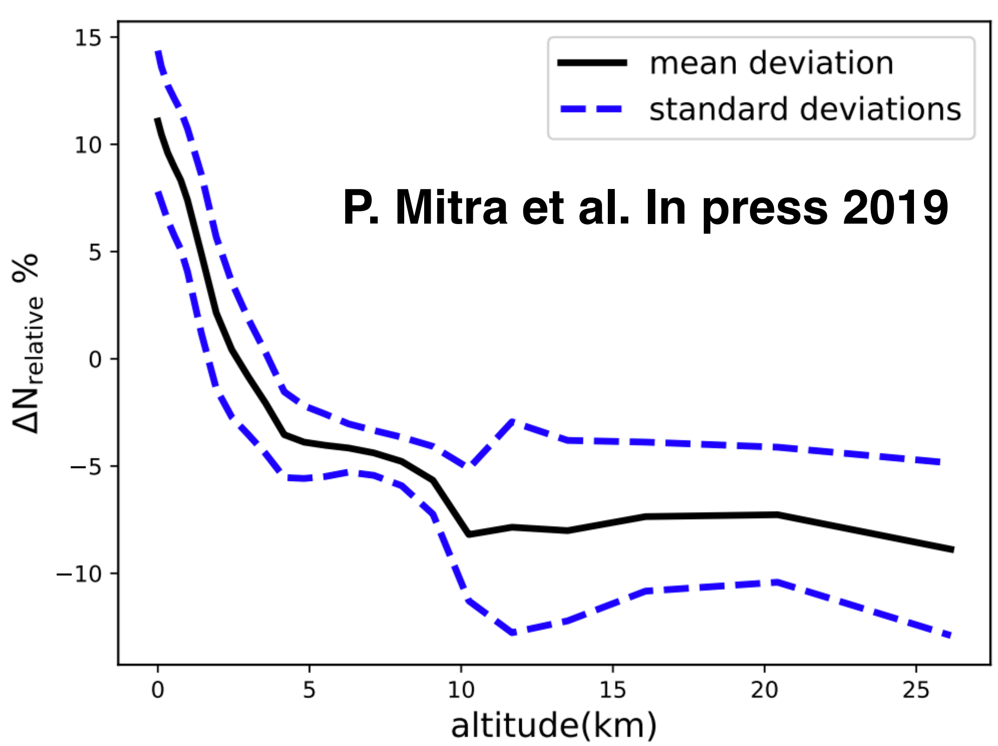


A. Corstanje Astropart.Phys. 89 (2017)

- Reduce systematic uncertainties on atmospheric conditions
- Previous: use density profile to do linear correction on Xmax

→ ***Move to realistic GDAS atm.***

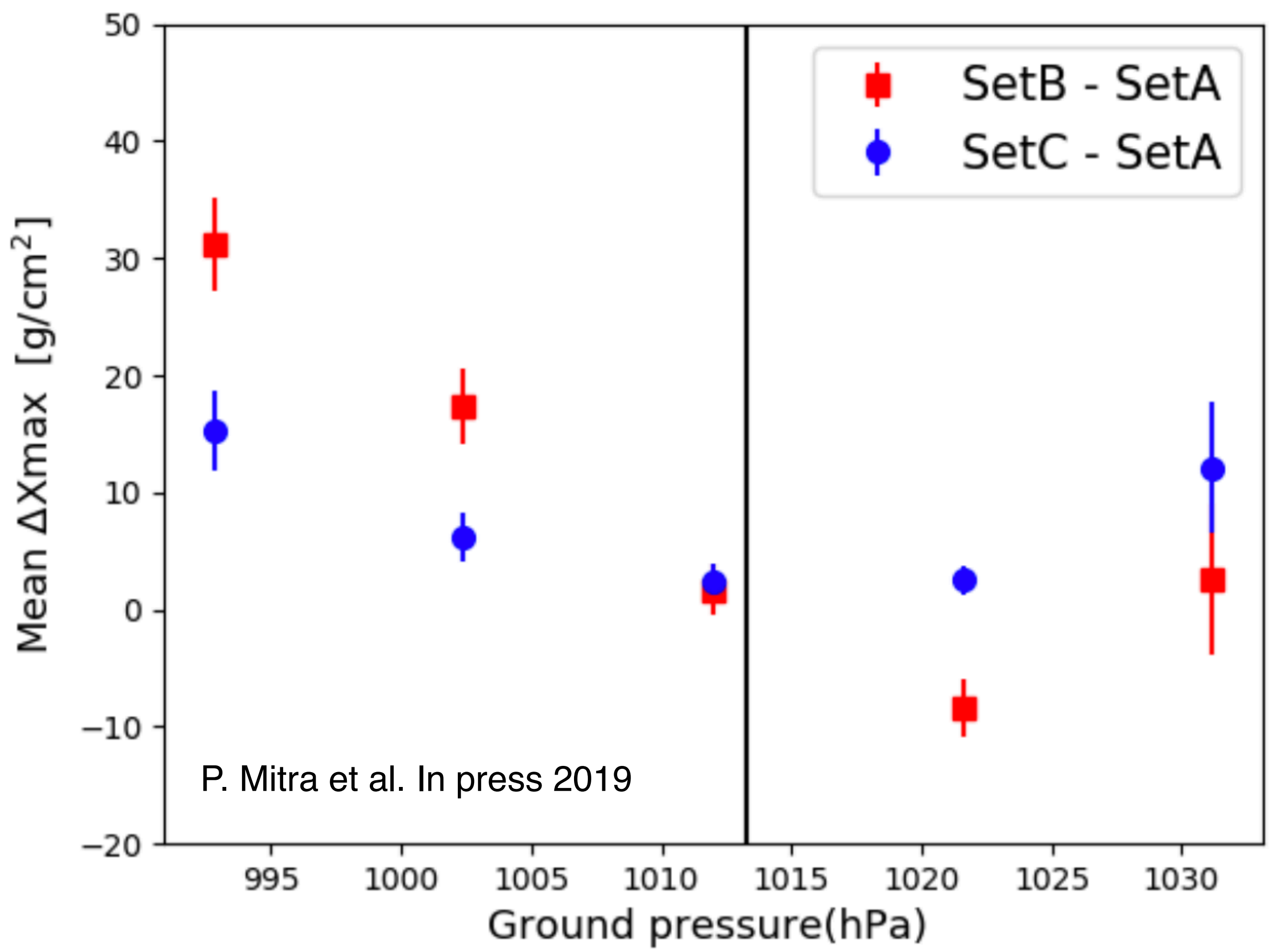
"Global Data Assimilation System"



- GDAS provides specific profiles for temperature, humidity, pressure
- Any location (1°x1°), time (3-hourly)

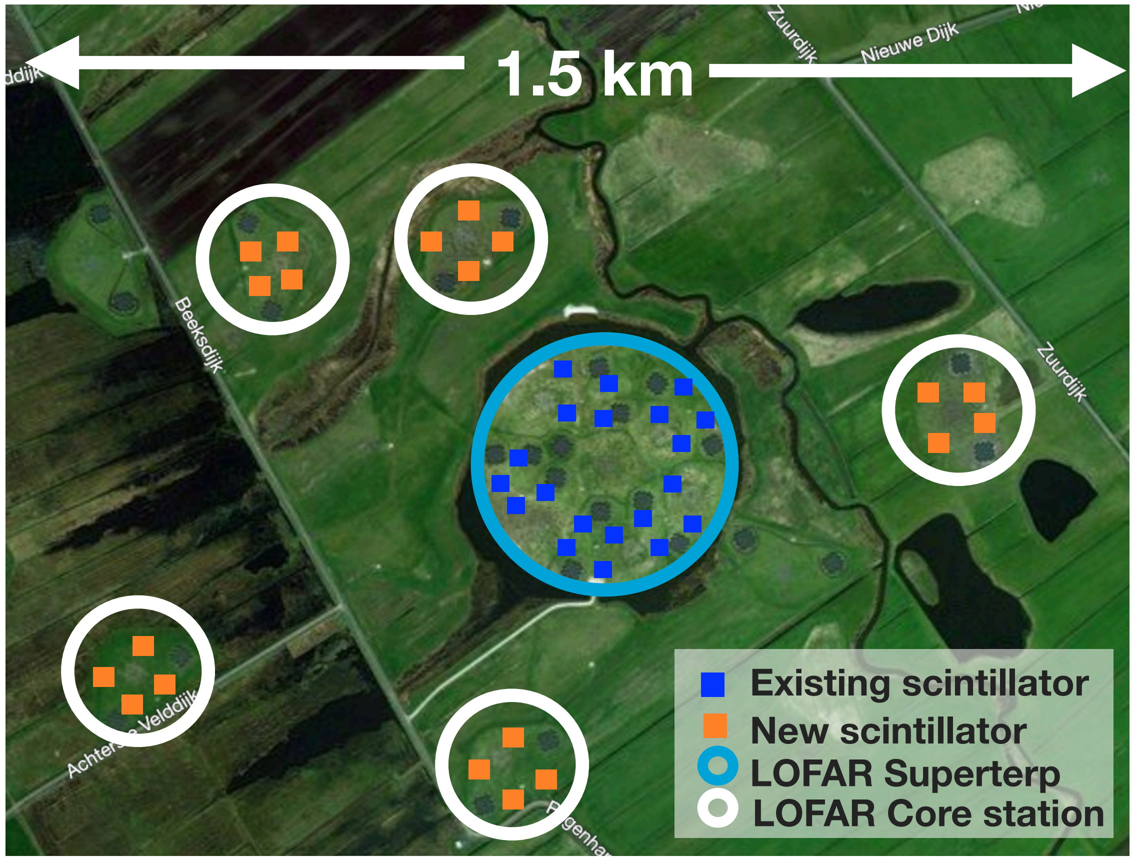
Atmospheric Corrections

- **New: implement density and refractivity directly into CORSIKA/CoREAS simulations**
- **Available as a standard option since CORSIKA 76300**
- **For extreme conditions, can shift X_{max} up to 15 g/cm²**

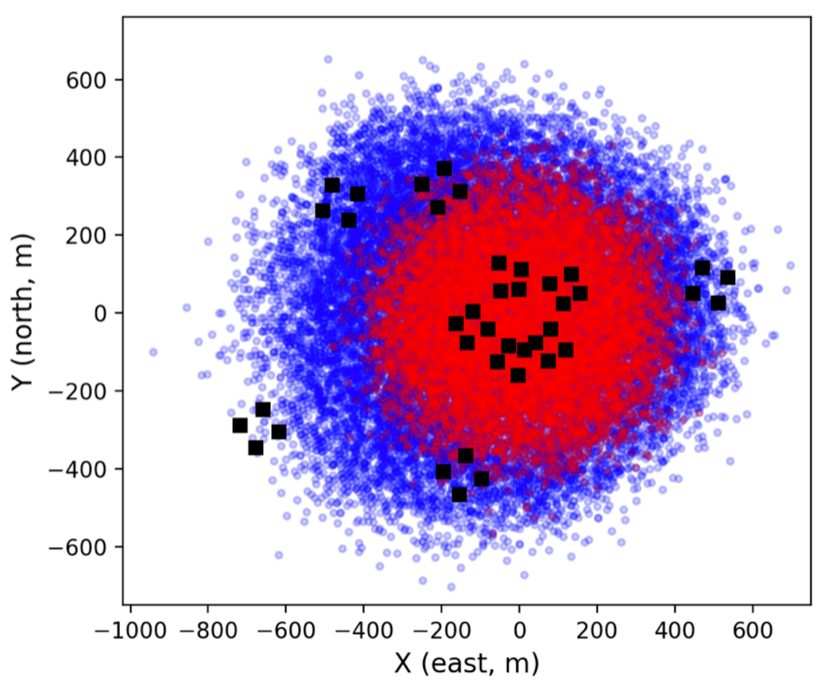


SetA: GDAS atmosphere
SetB: US Standard atmosphere
SetC: SetB + linear correction

Scintillator Array Extension

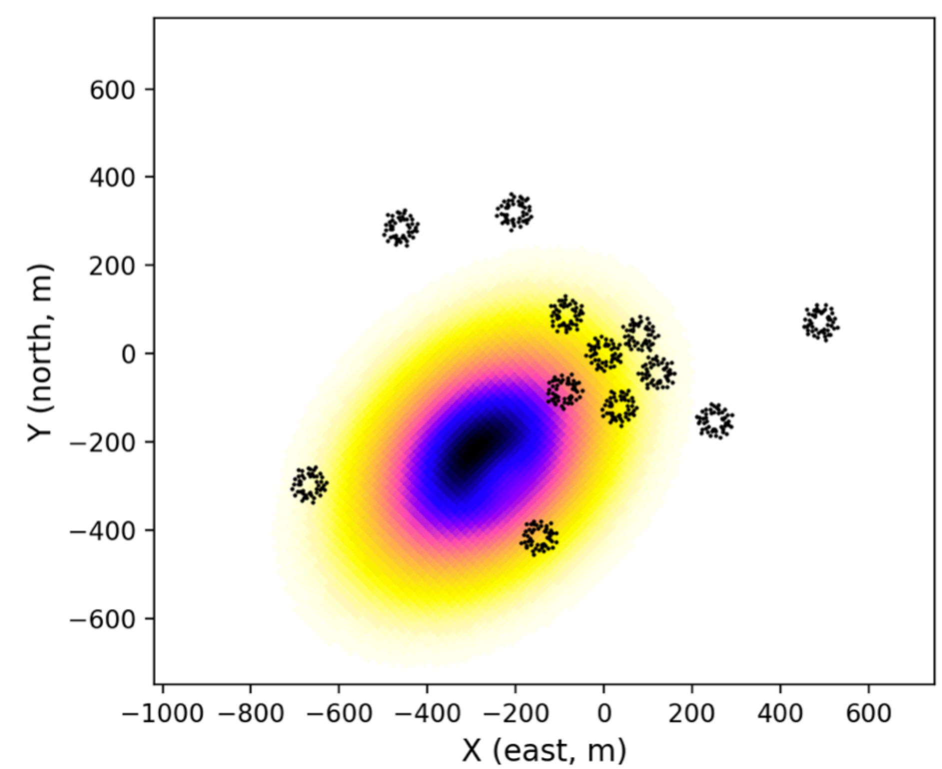


- **Current cosmic-ray trigger is based on 20 scintillators on the superterp**
- **Expand by adding 20 scintillators at neighboring stations**



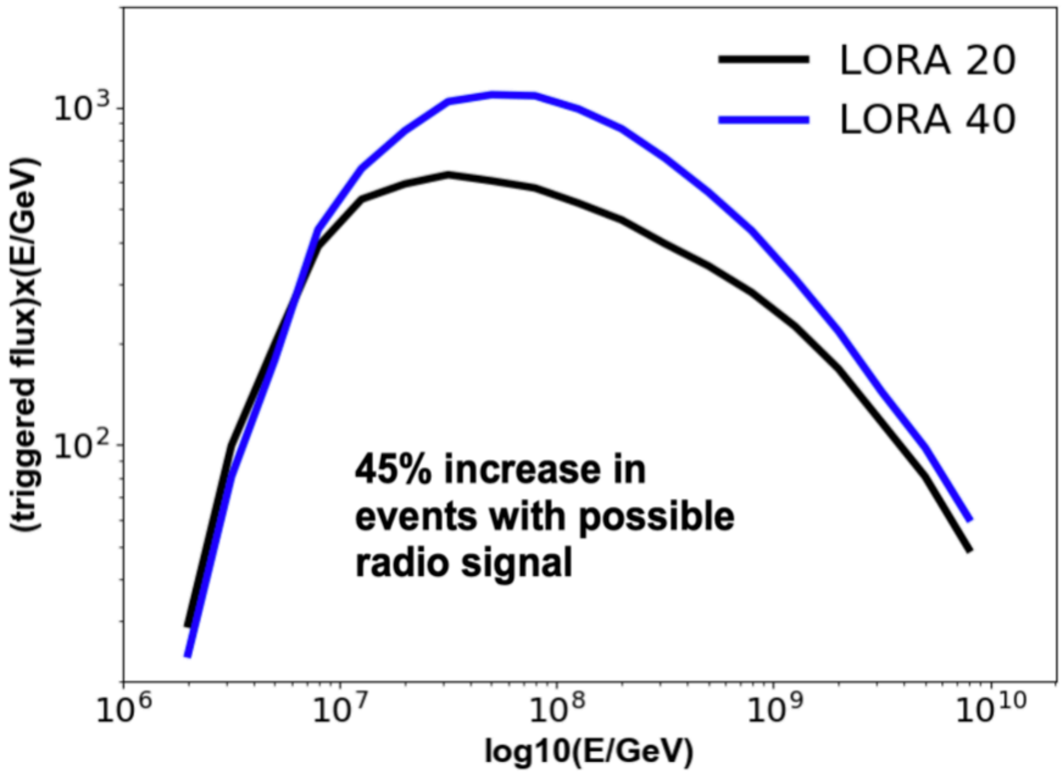
Simulated core positions

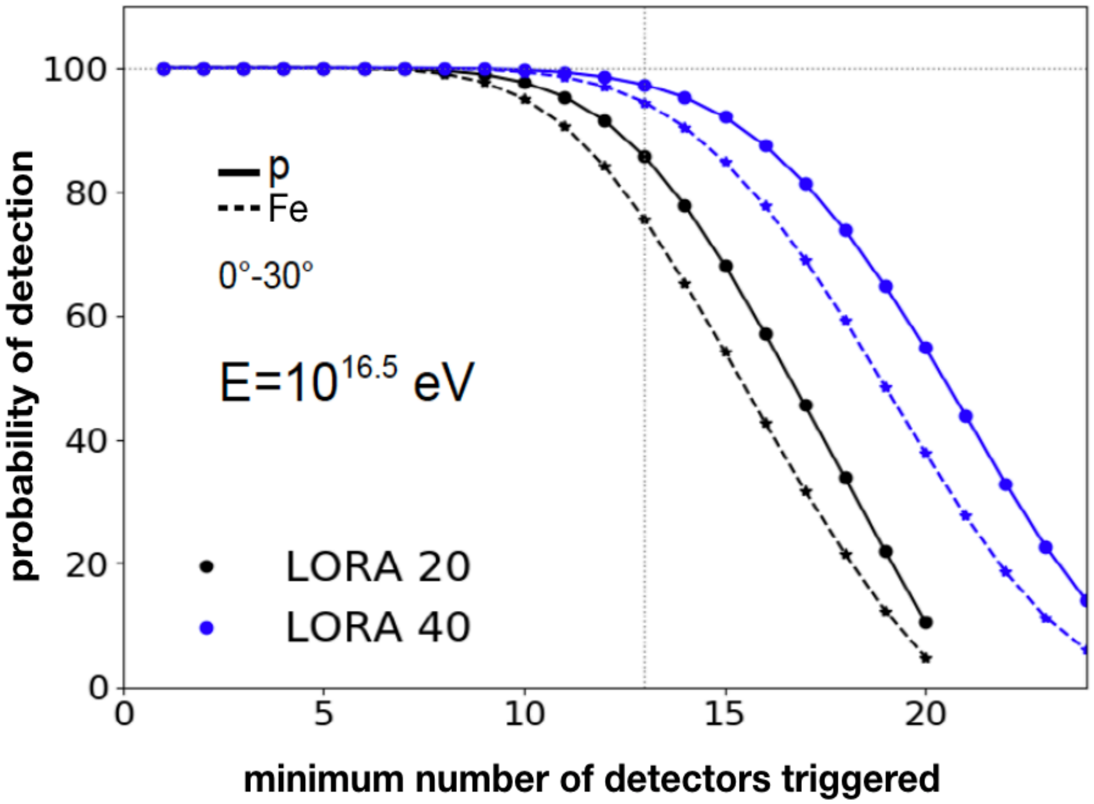
- Existing stations (red)
- Expansion (blue)



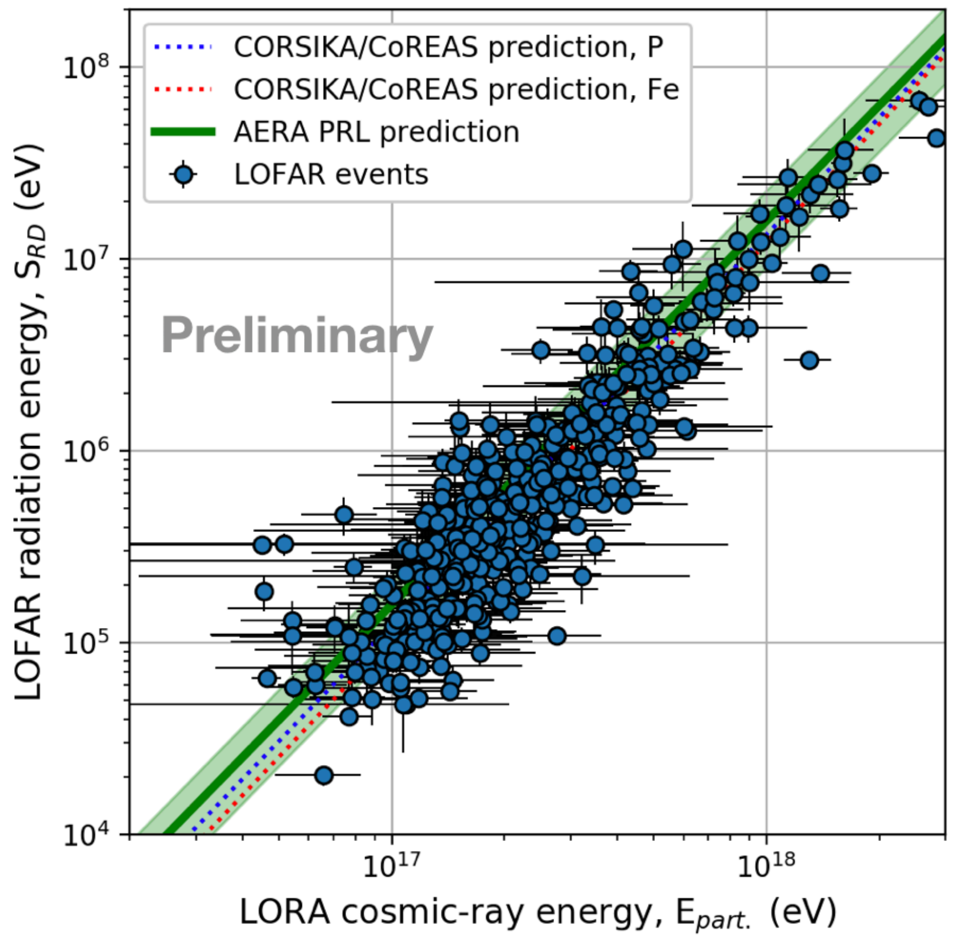
Triggering outside superterp: Explore fringes of footprint

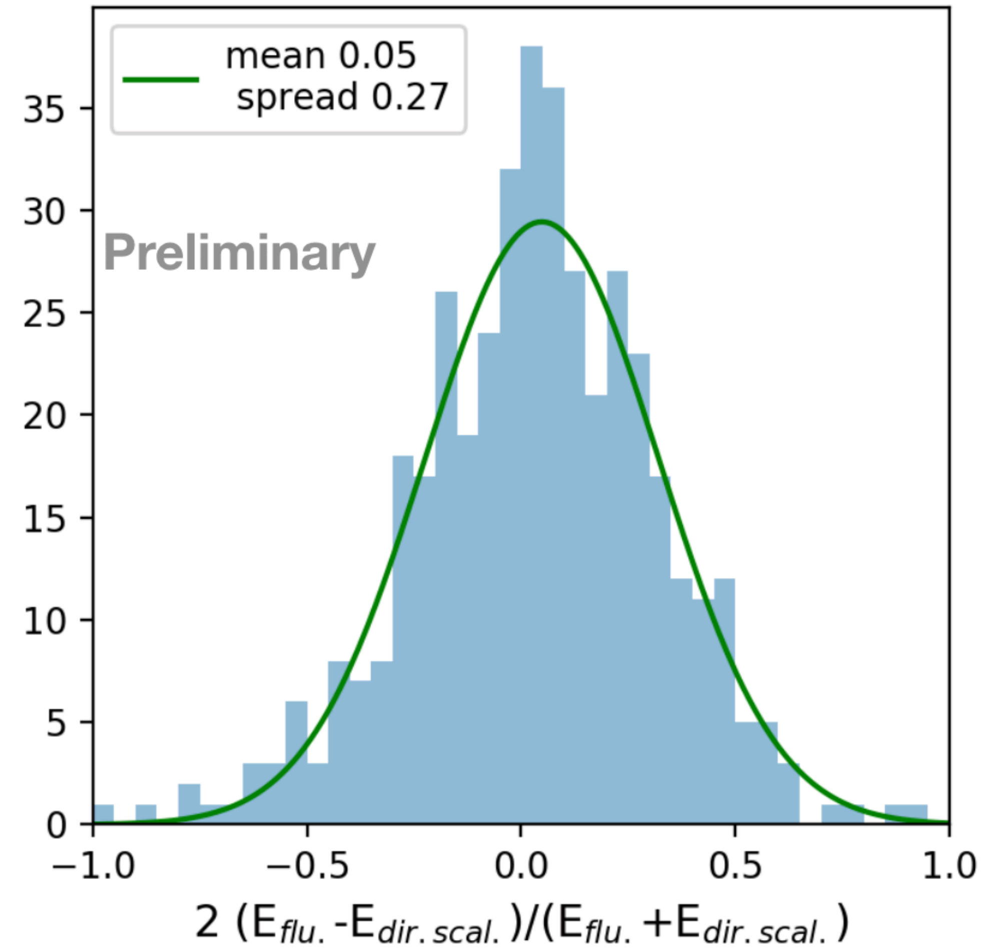
Scintillator Array Extension



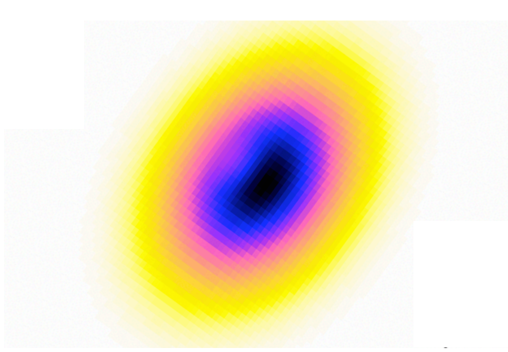


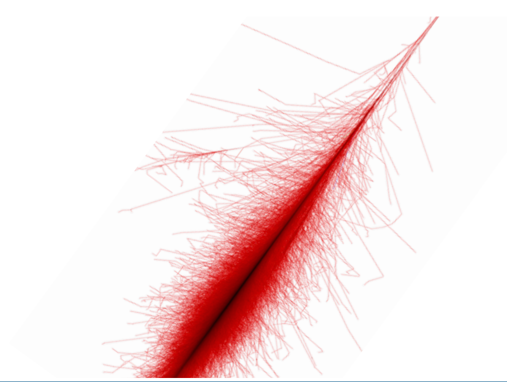
Energy Reconstruction





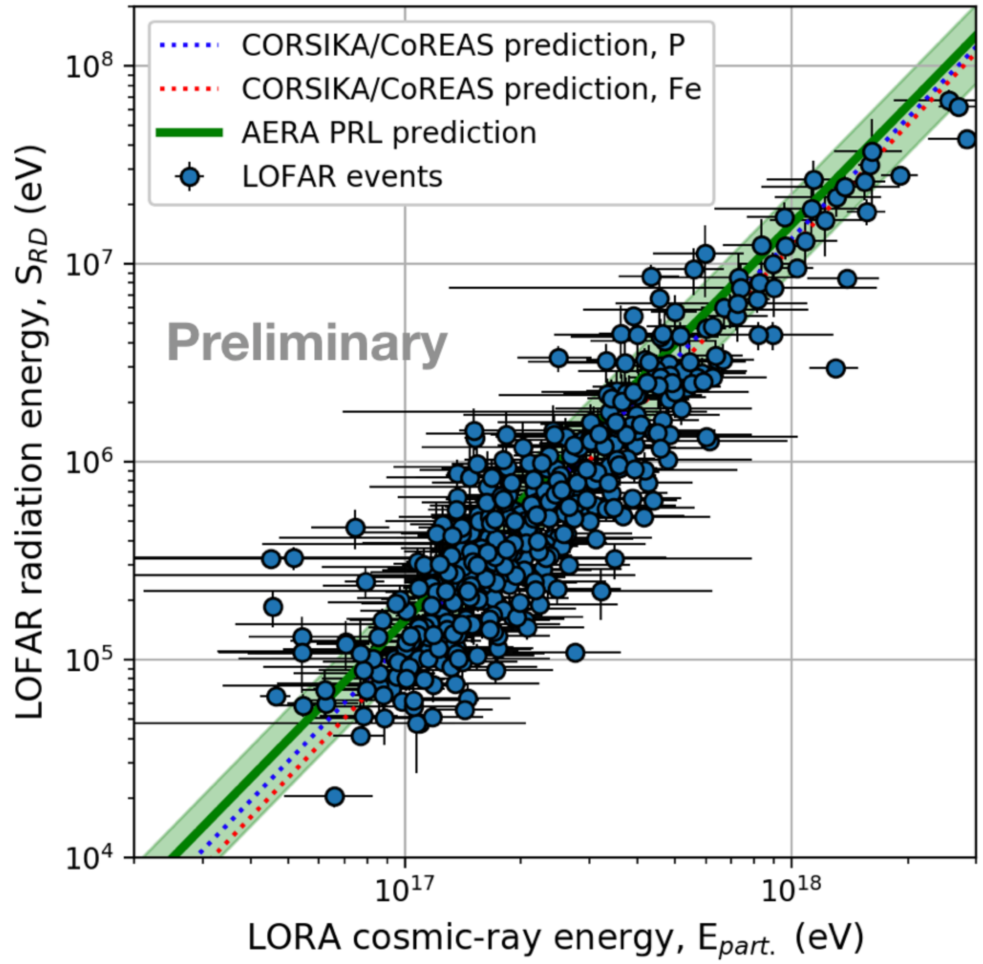
energy fluence → radiation energy → cosmic-ray energy

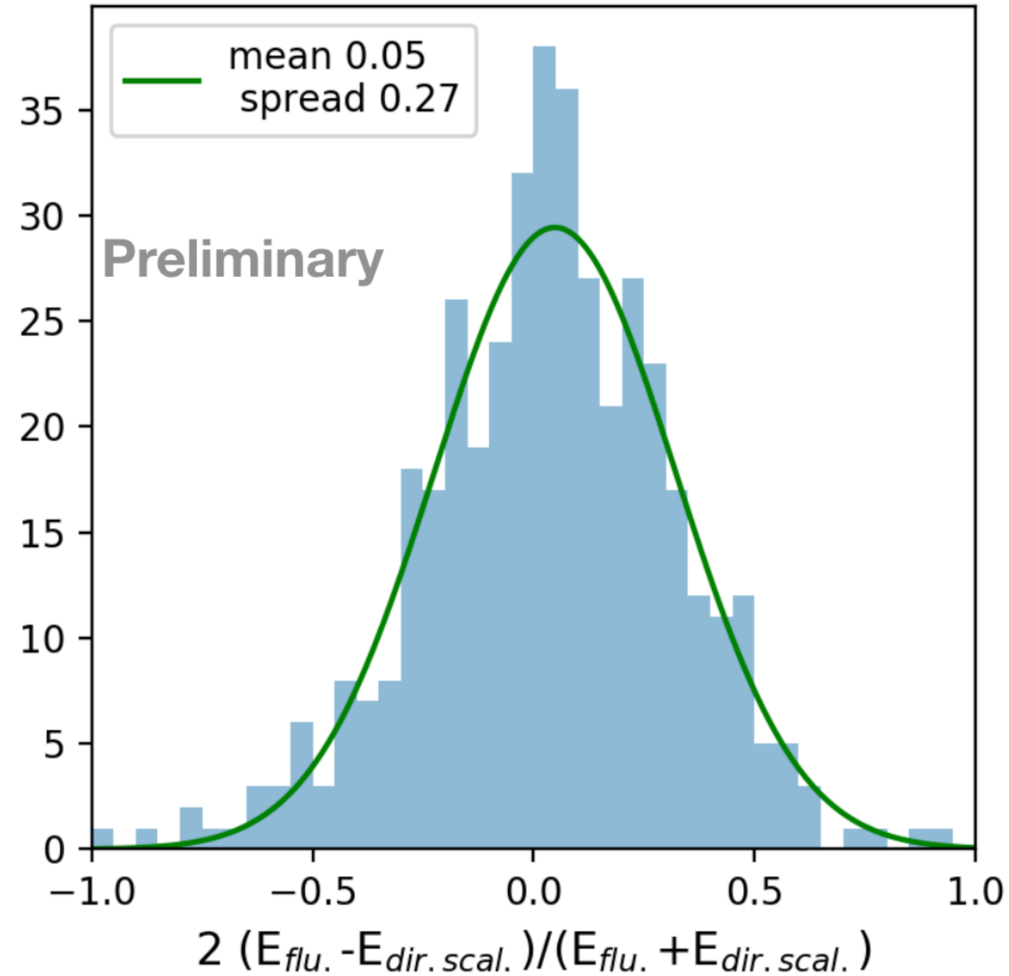




A. Aab et al. PRL 116 (2016

Energy Reconstruction





✔ **Calorimetric energy measure (no hadronic models)**

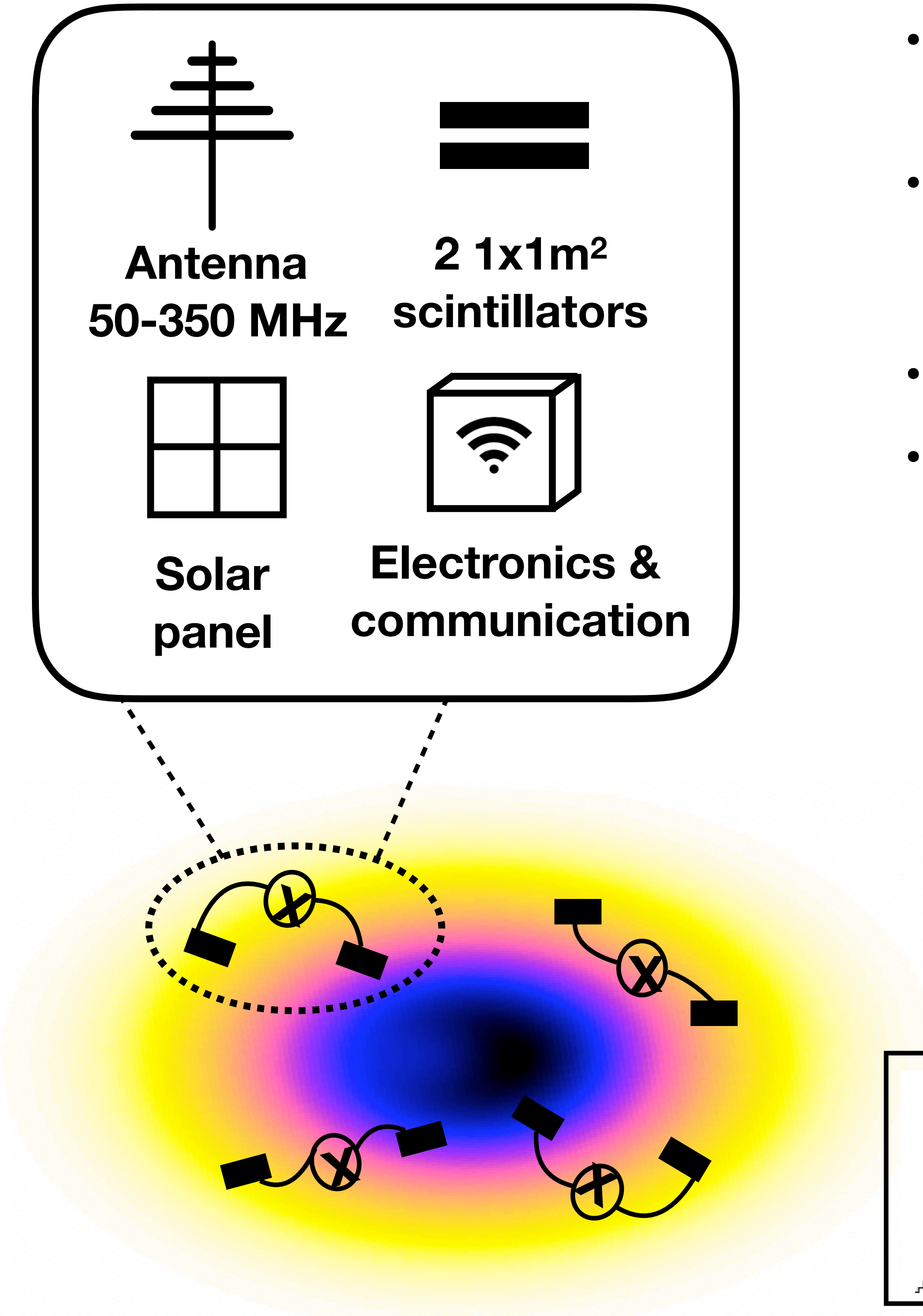
✔ **Low systematics- calibration well understood**

✔ **Total radiation energy only depends on local magnetic field**

Energy measurements from different experiments can be compared

A. Aab et al. PRL 116 (2016

Calibration to go!



- ***Autonomous***: self triggering, independent energy measurement, no interference with main experiment
- ***Portable***: can be deployed at different sites, spacing can be adjusted to probe different energy regimes

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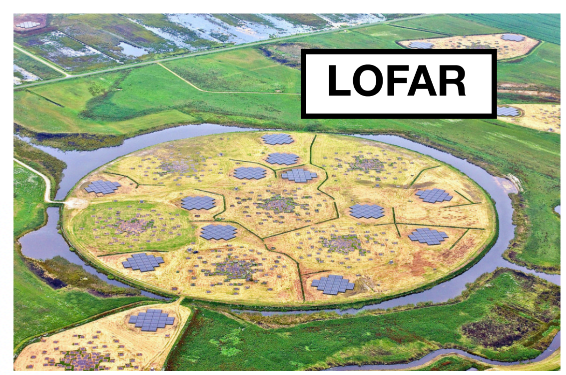
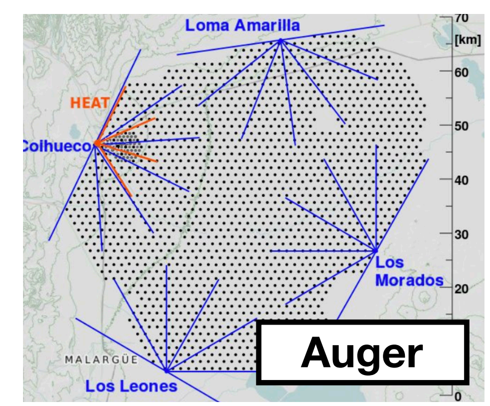
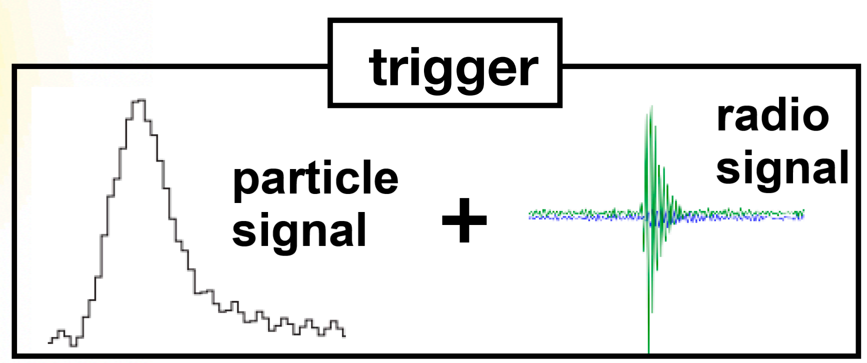
- ***Deployment***: 2020-2021 **LOFAR**, 2021-2022 **Auger**
- ***Result***: Quantify systematic differences between energy scales of the different experiments

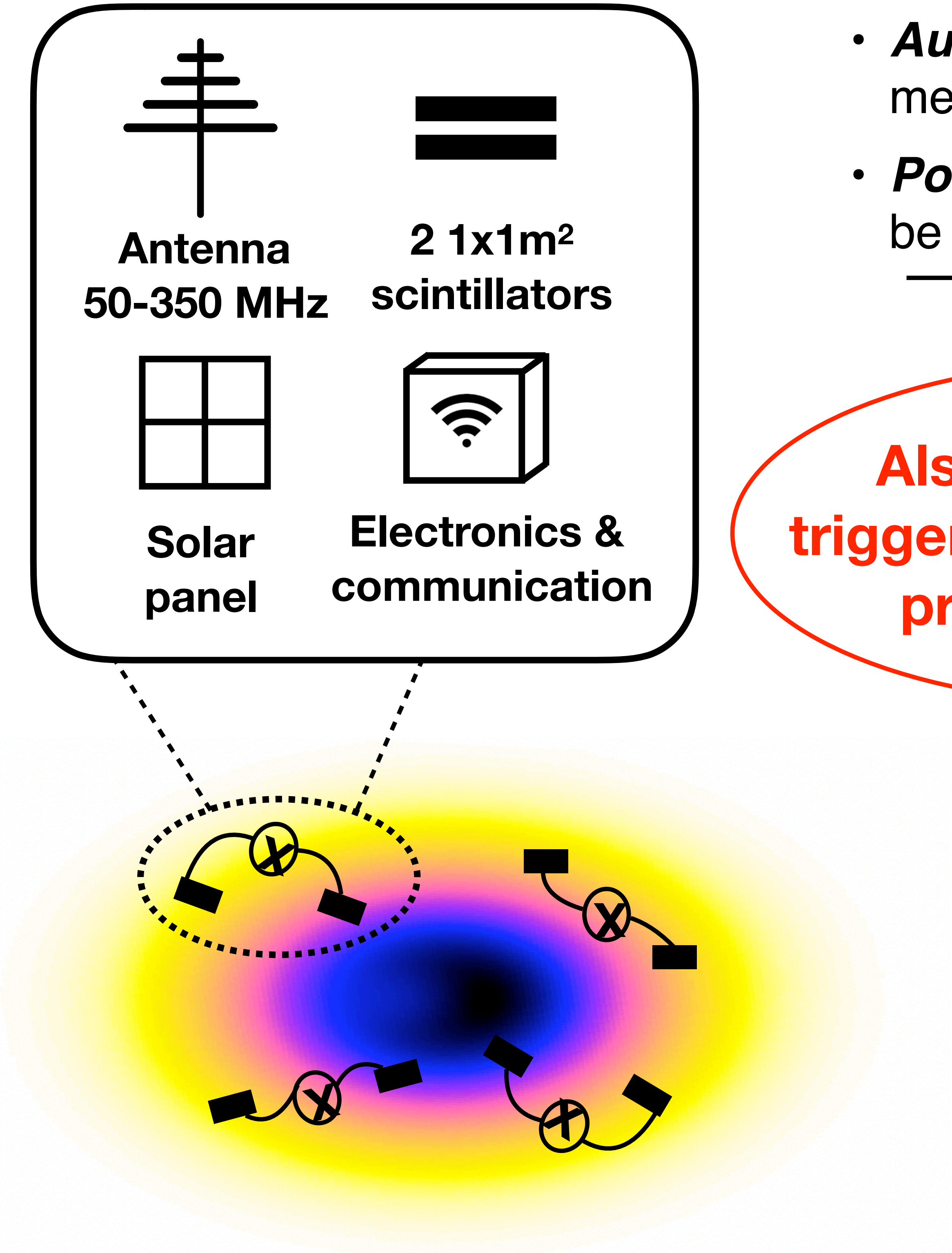






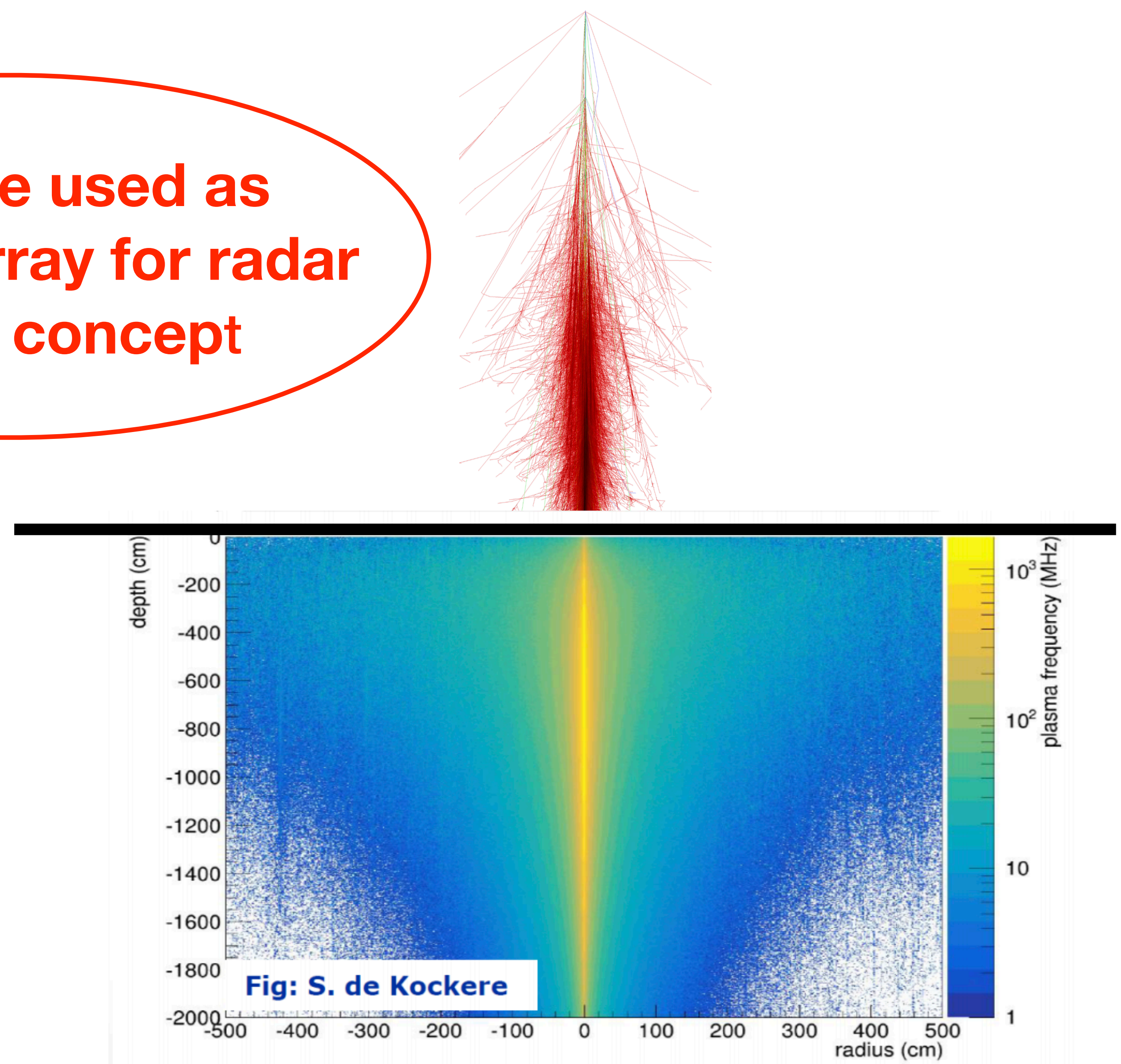
Ensures a cosmic ray ✓
Strong radio signal ✓

Calibration to go!

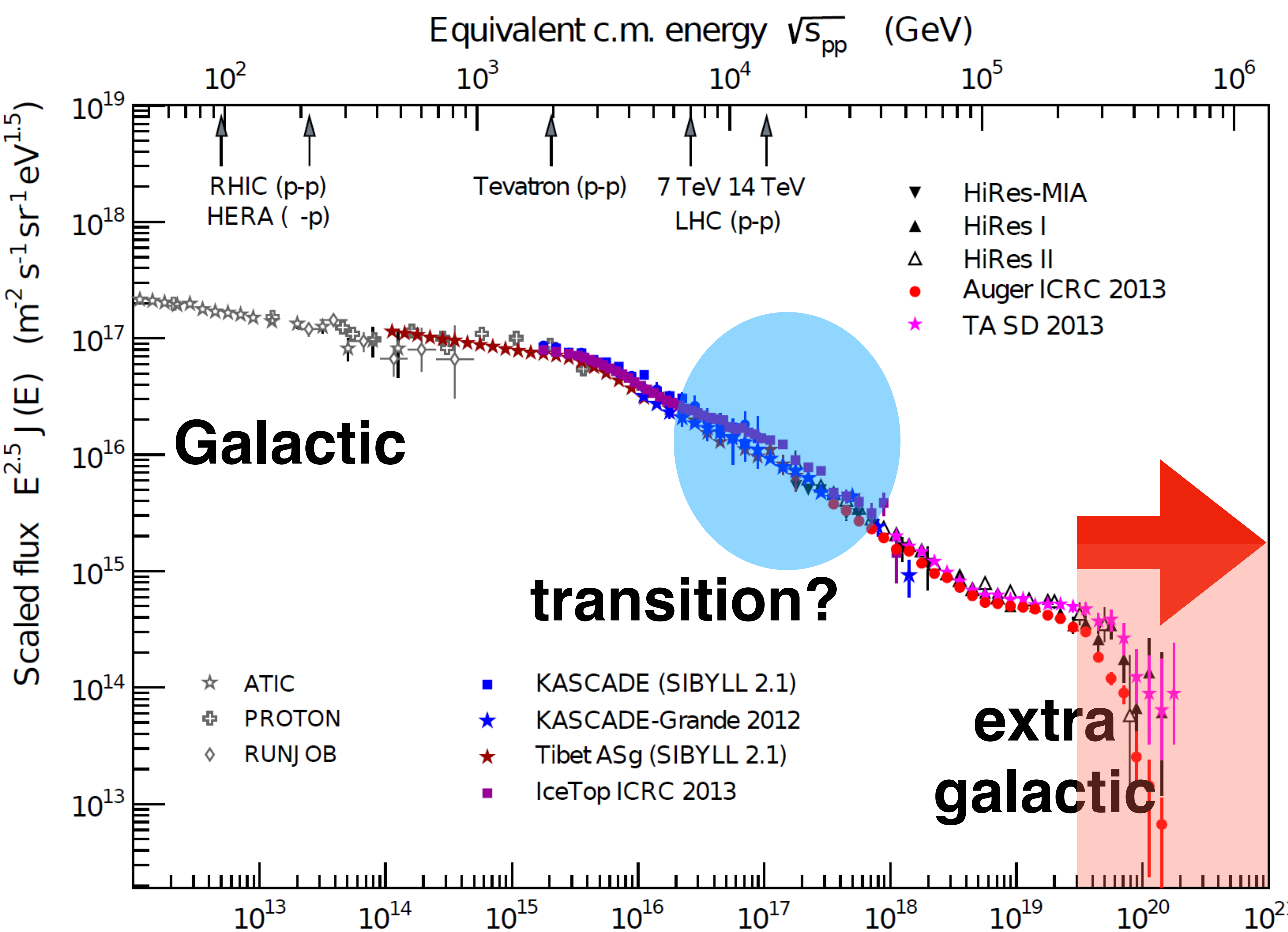


- ***Autonomous***: self triggering, independent energy measurement, no interference with main experiment
- ***Portable***: can be deployed at different sites, spacing can be adjusted to probe different energy regimes

Also to be used as triggering array for radar proof of concept

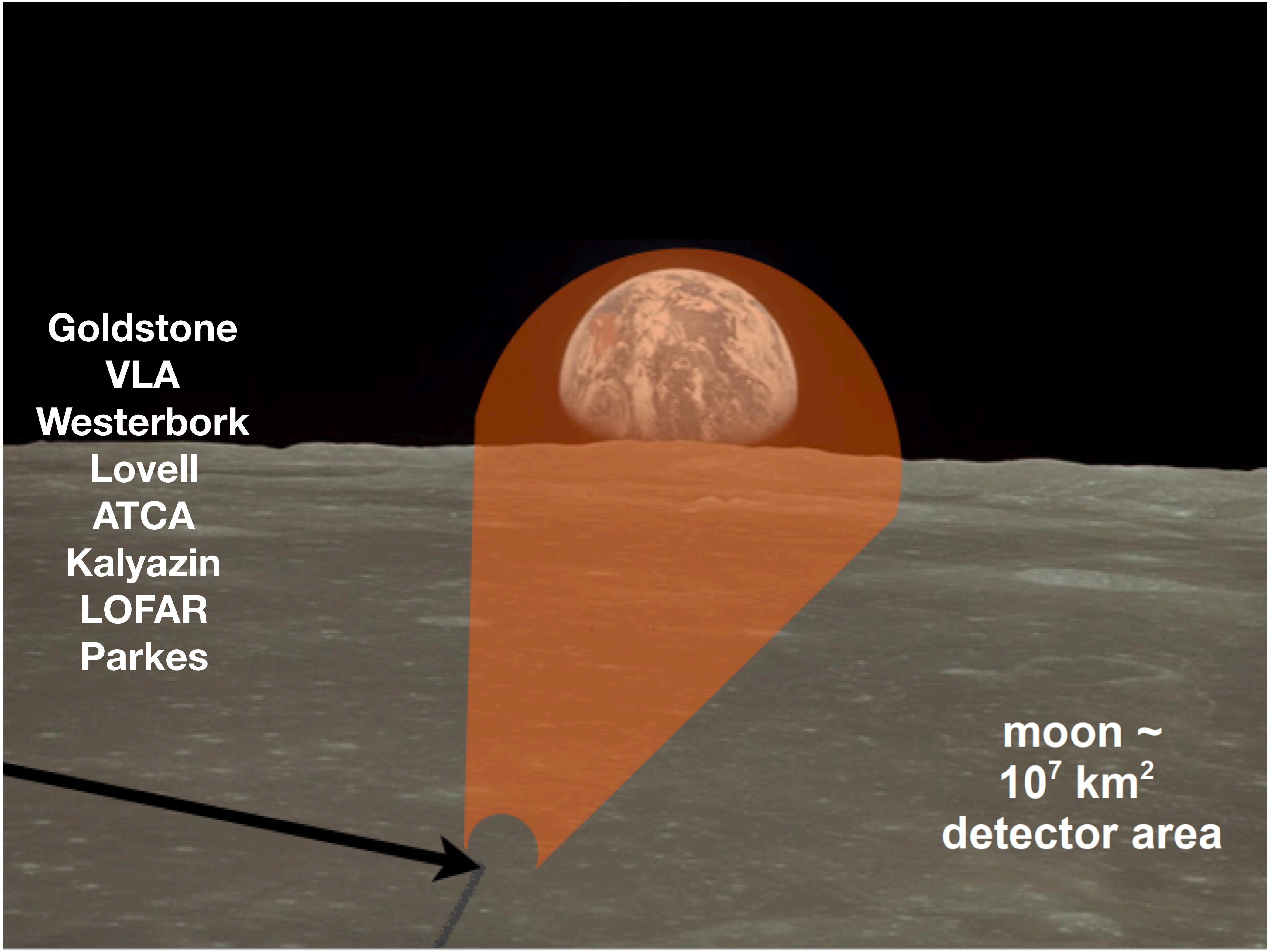


Cosmic Ray All-particle Spectrum



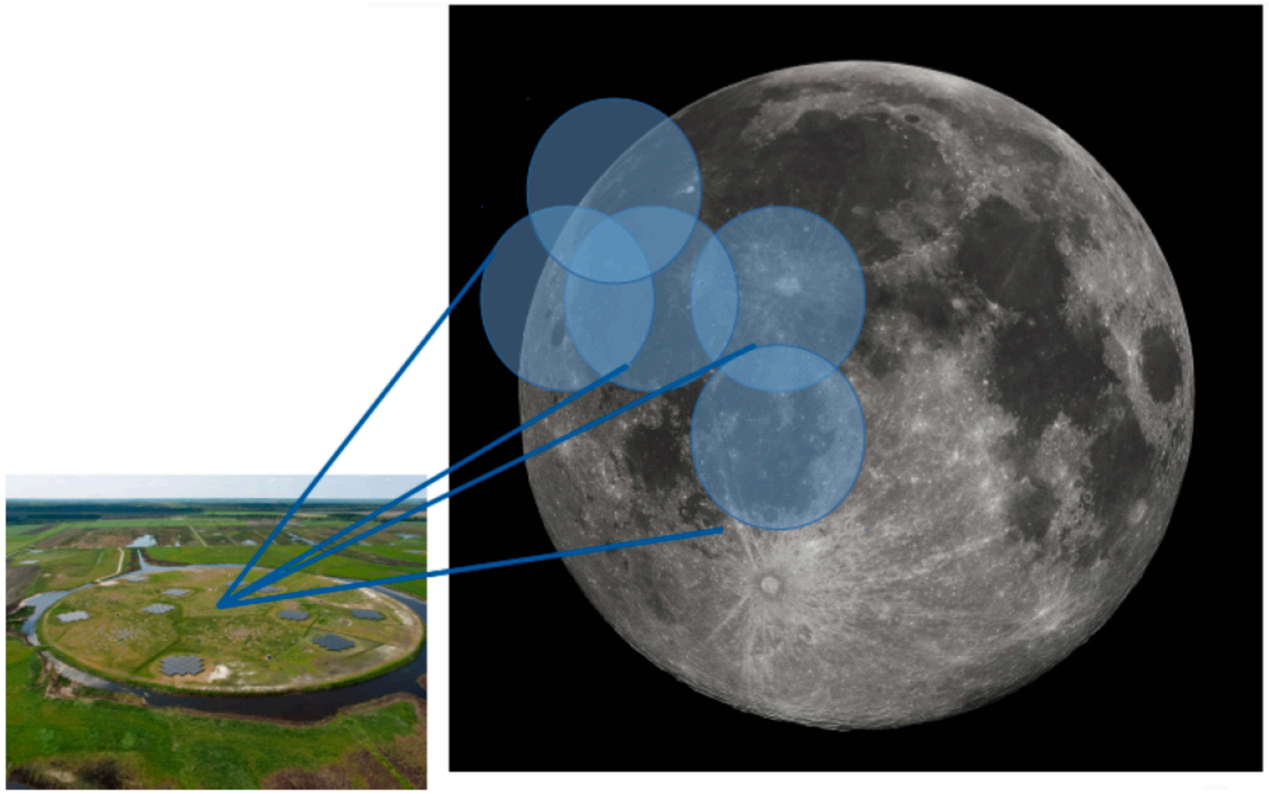
G. Matthiae et al. New J. Phys 12 (2010)

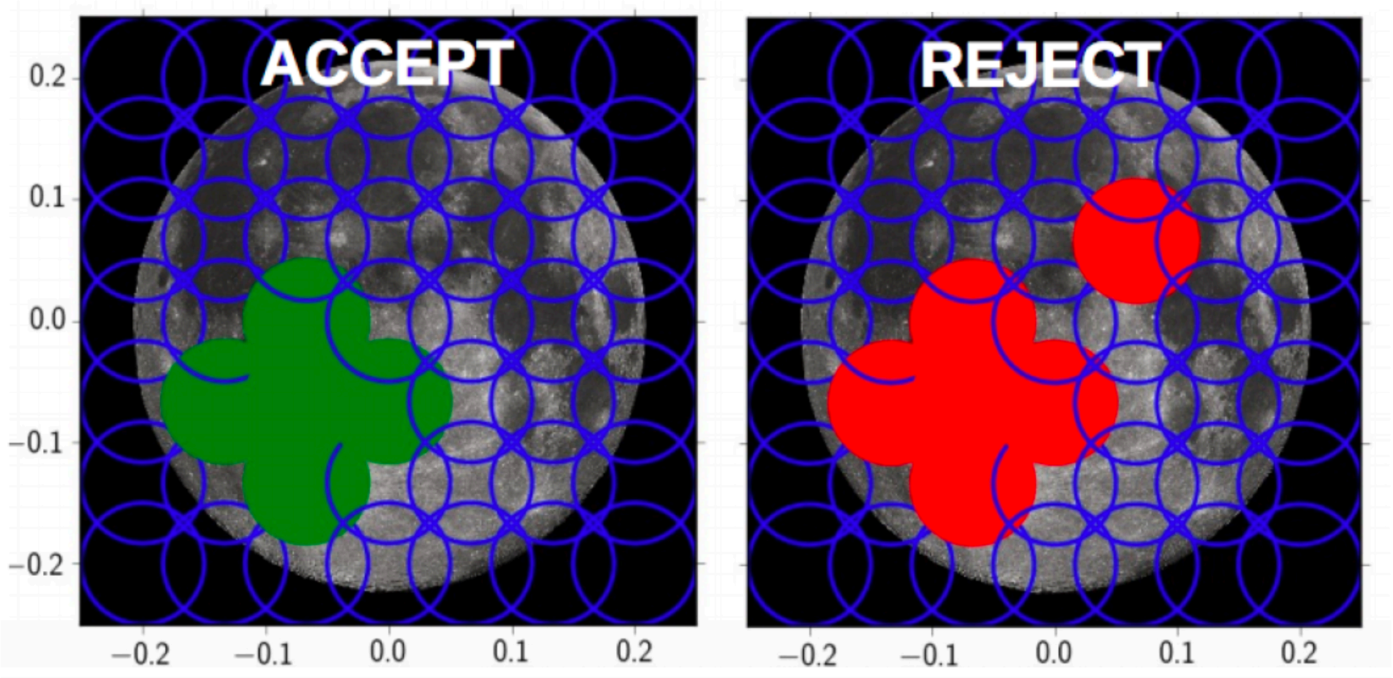
NuMoon: Lunar Detection Mode



NuMoon: Lunar Detection Mode

- The moon provides large target to detect rare, highest energy particles
- Use high band antennas (110-240 MHz) to form beams on the moon
- Search for nanosecond pulses while suppressing RFI

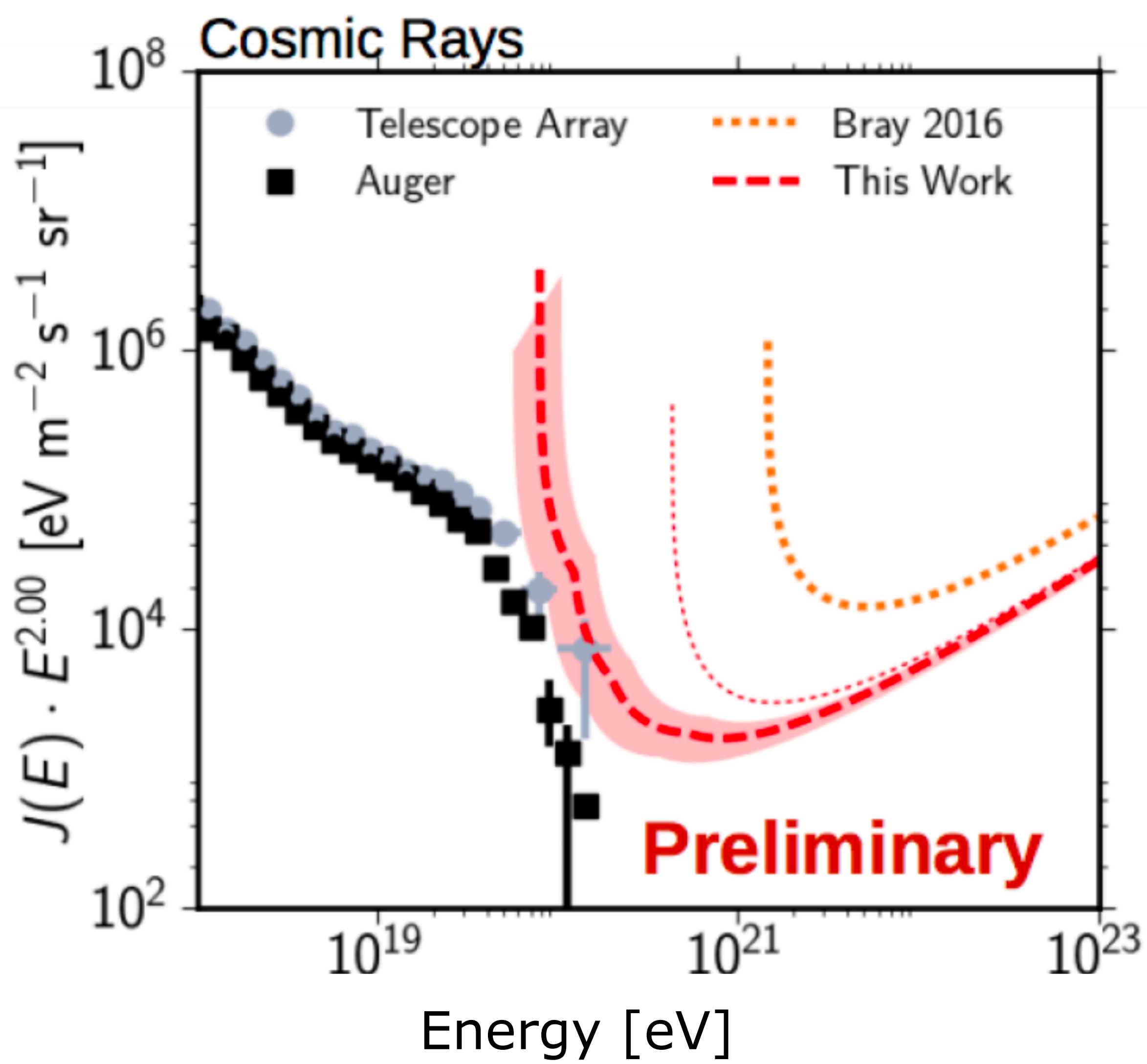


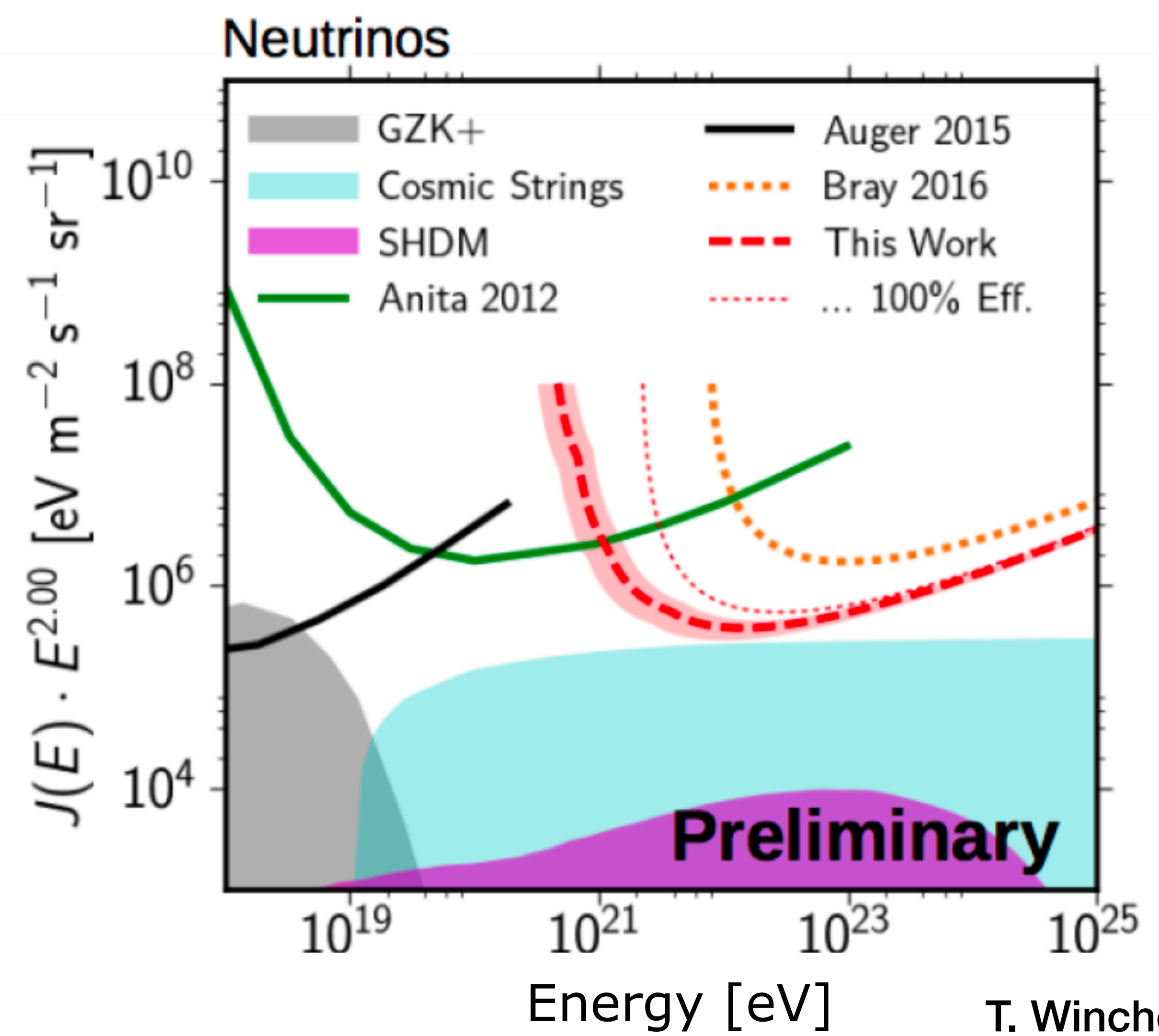


T. Winchen

- Must trigger in real time (5 s buffer)
- Signal is dispersed in ionosphere
- Only have access to processed signal

NuMoon: Expected Sensitivity





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New sensitivity values:

- 5 HBA stations used, increased bandwidth
- Reduced trigger threshold
- Full detector simulation

200 hours observation

Summary

LOFAR measures cosmic rays with high precision,
Active IIHE group- working towards improvements on many fronts!


Stijn


Olaf


Tim


Jörg

Arthur


Hershal


Jörg

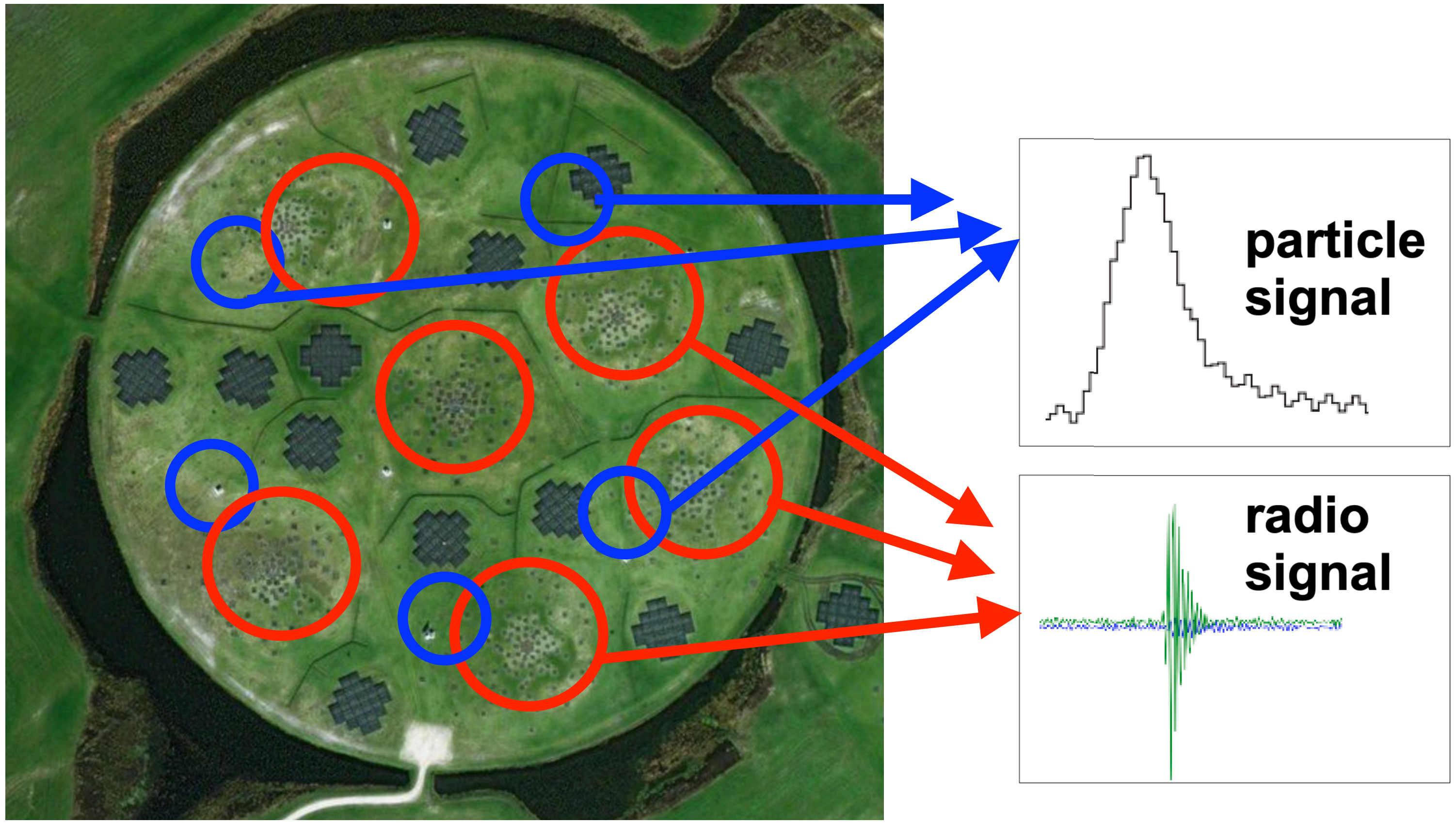

Katie

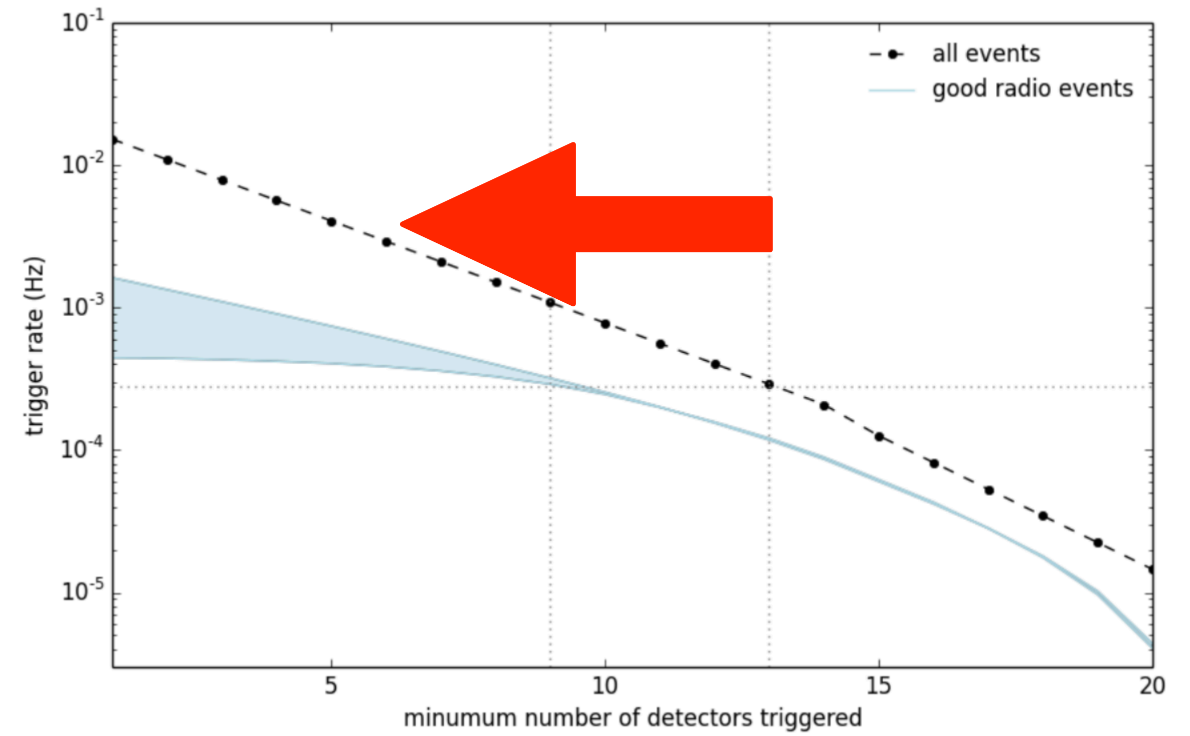

Godwin


Pragati

extra slides

Low Energy Extension: Hybrid Trigger





Particle

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

\+ Guaranteed cosmic ray

Radio

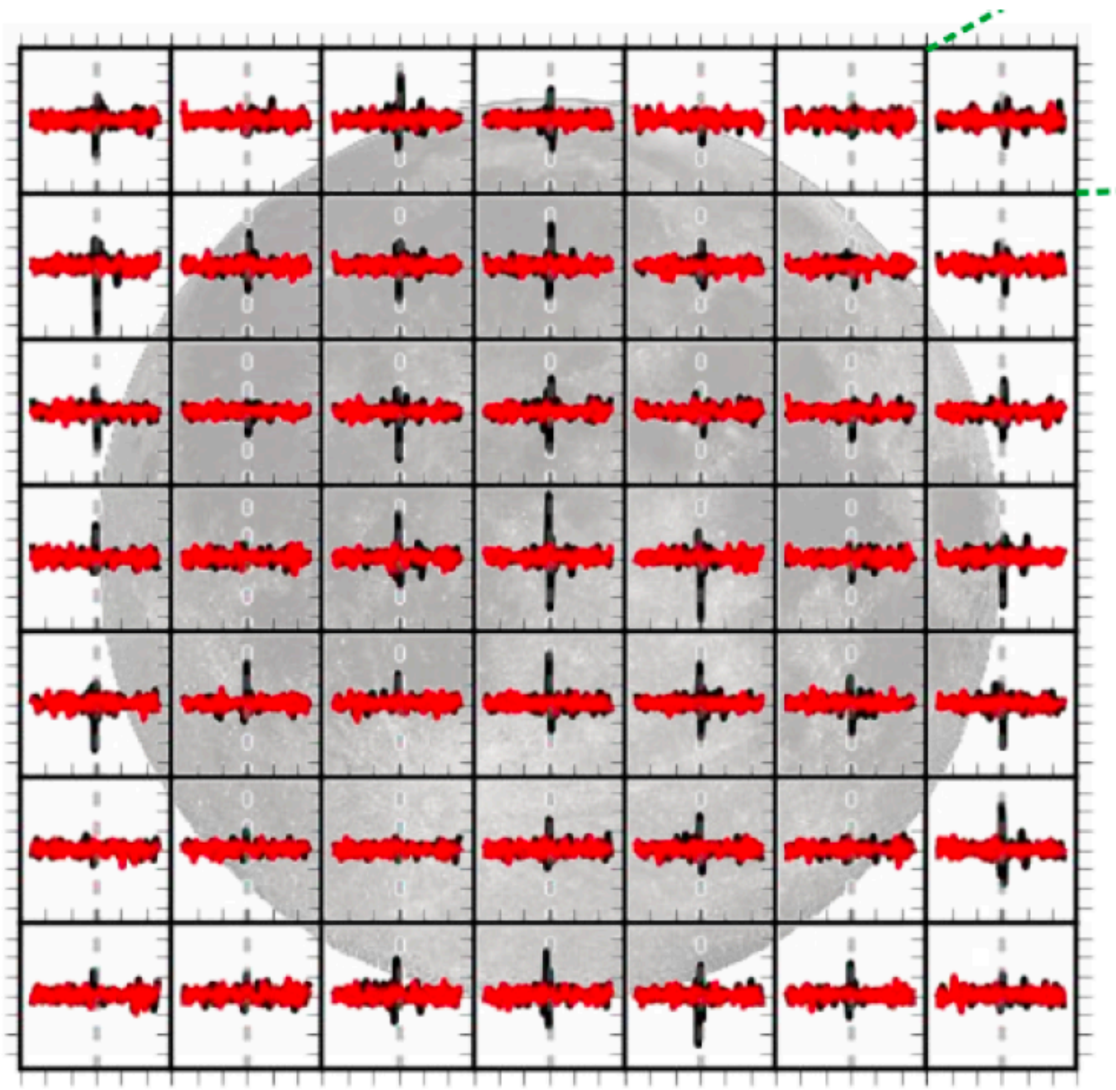
- Flooded with RFI

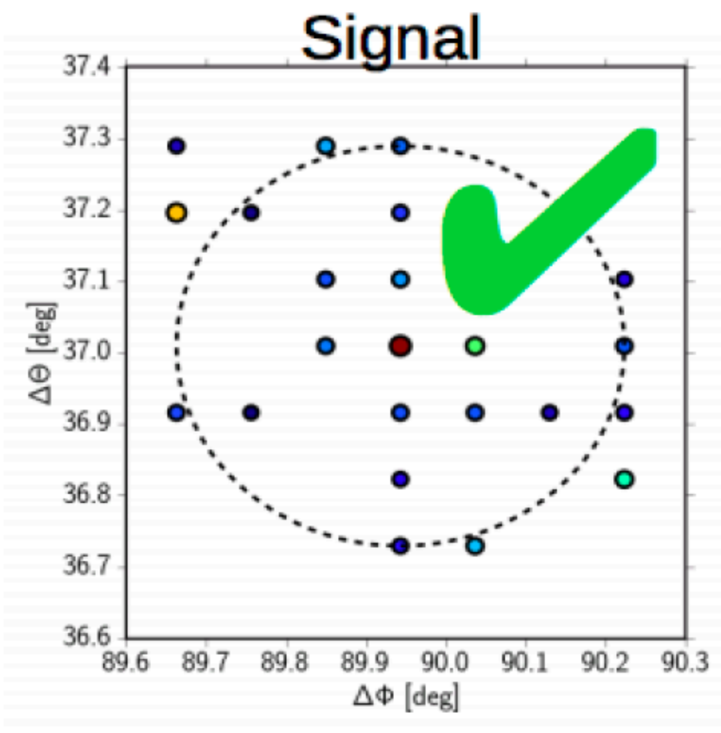
\+ Ensures a usable CR signal

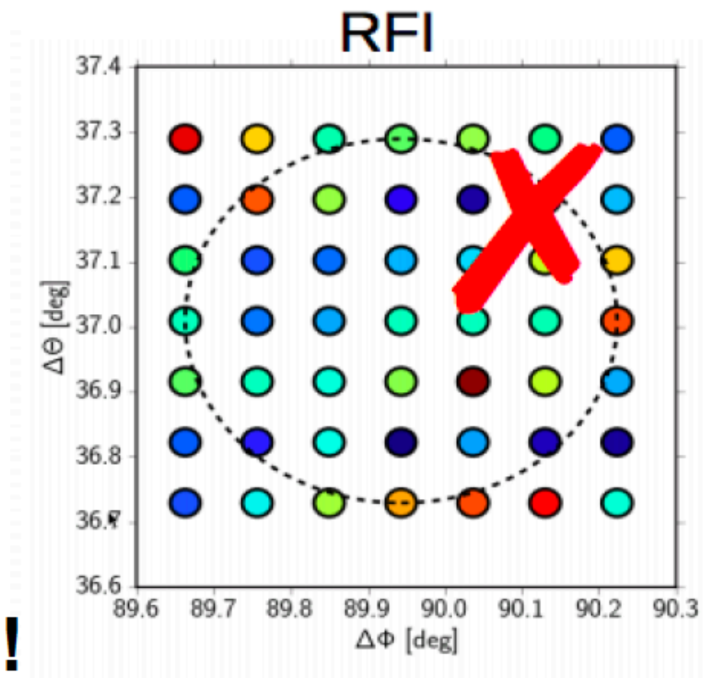
Cosmic ray
+
good radio signal
+
RFI rejection
+
Reduced trigger threshold

NuMoon: RFI rejection

Simulated pulse from moon







Real time RFI rejection is possible!

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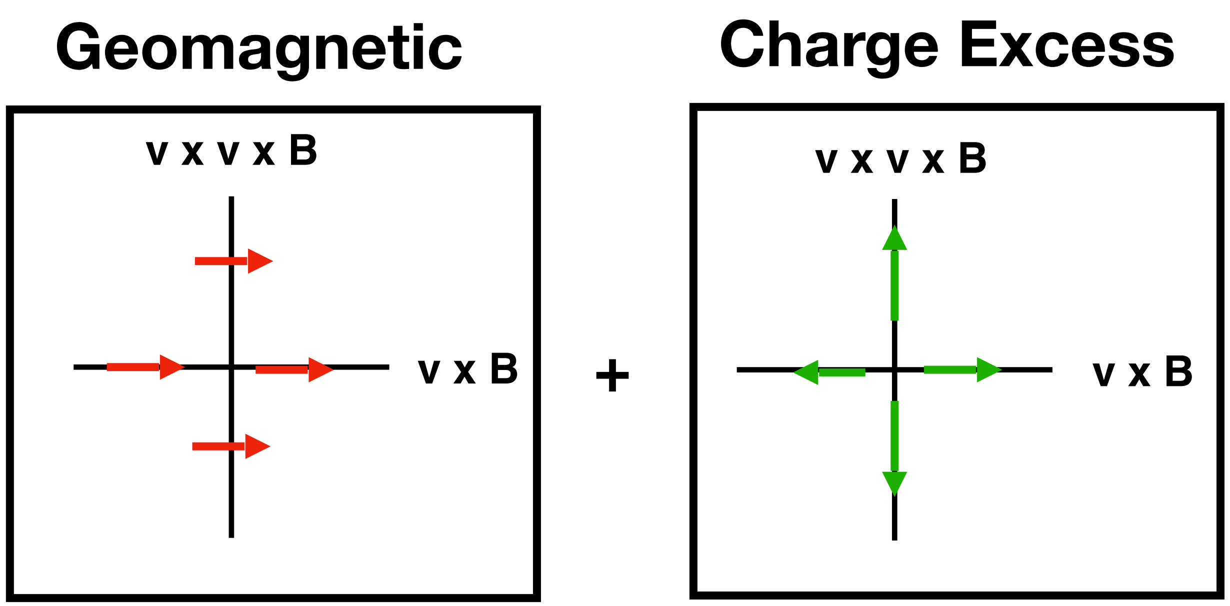
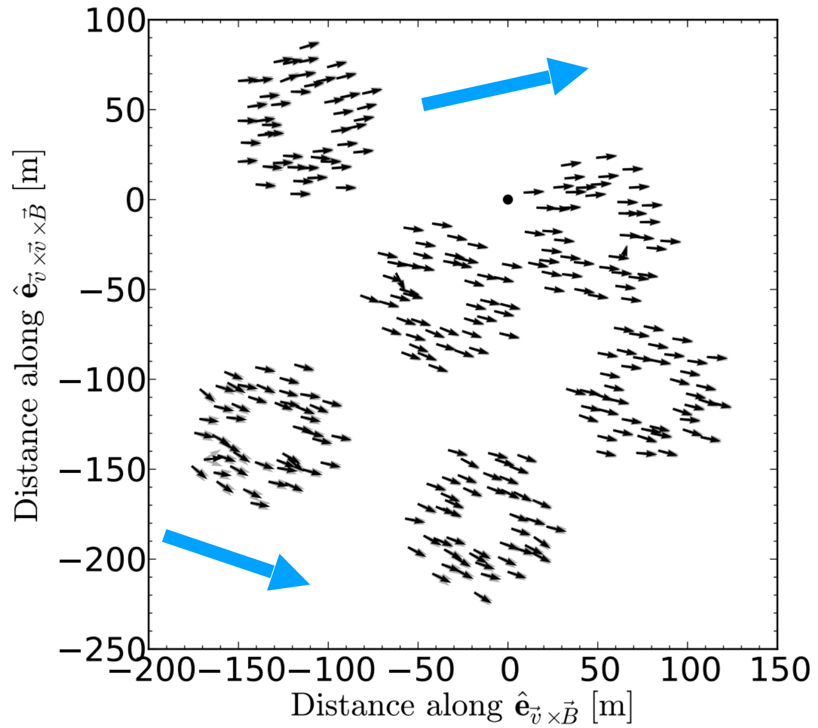
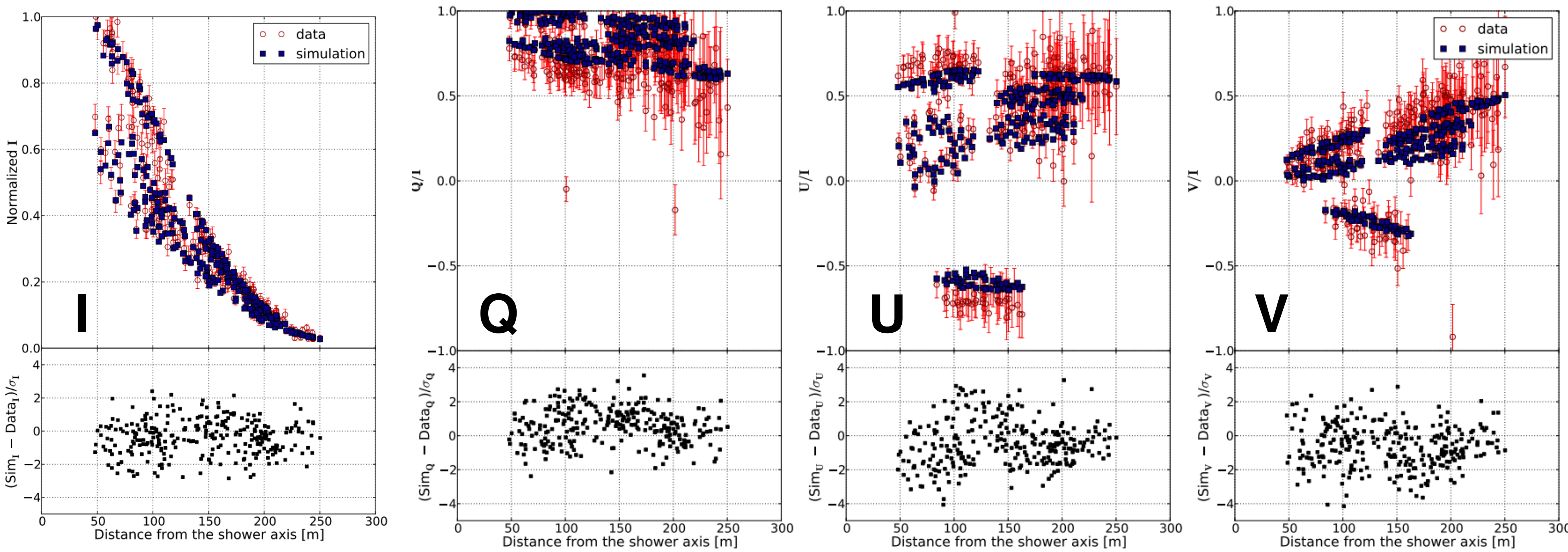
Stokes Parameters





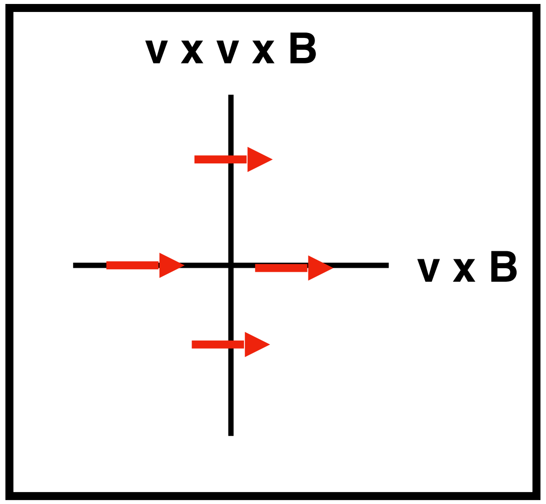
Pim Schellart et al., JCAP 10 14 (2014)



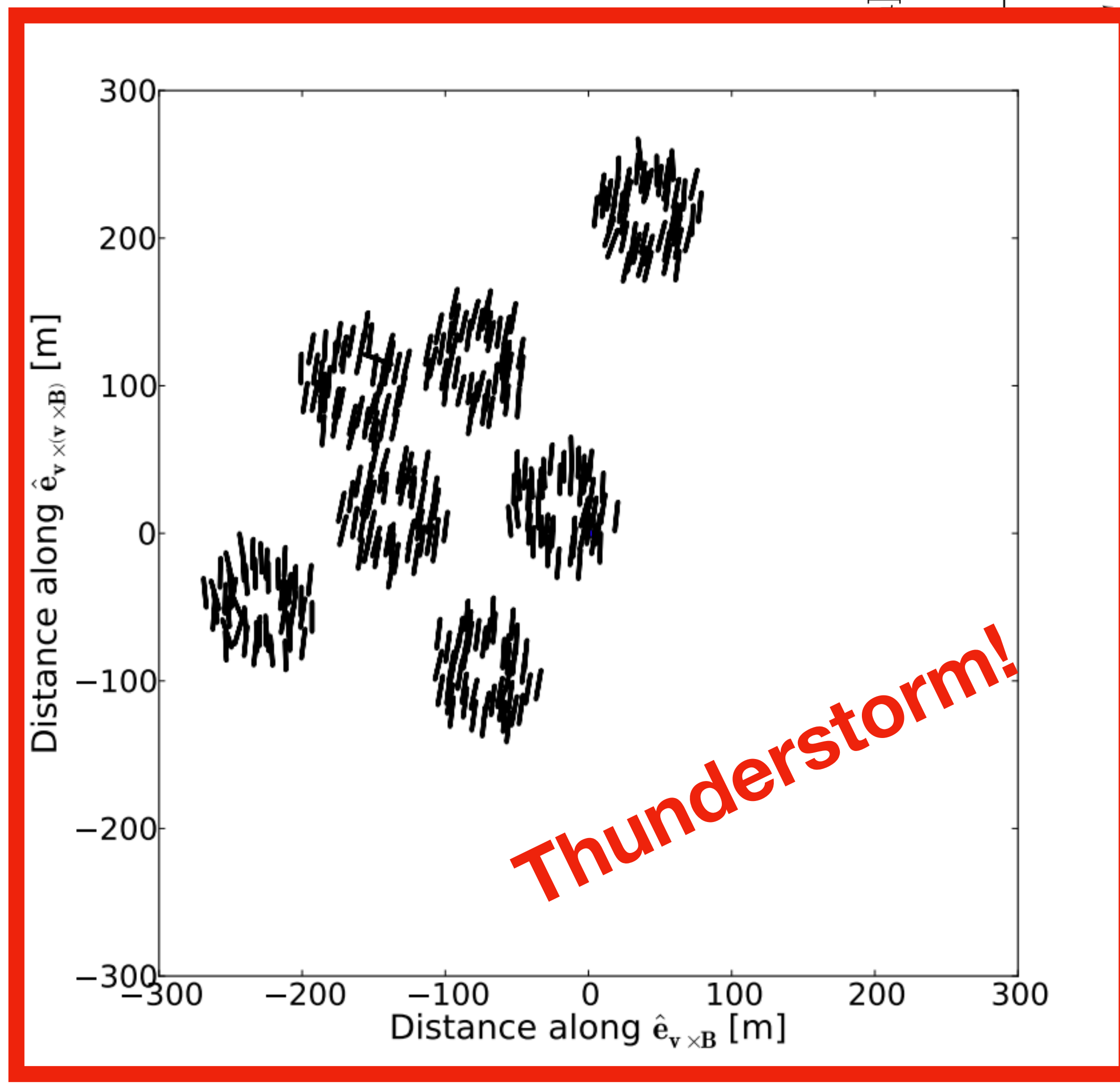
O. Scholten et al., PRD 94 1030101 (2016)

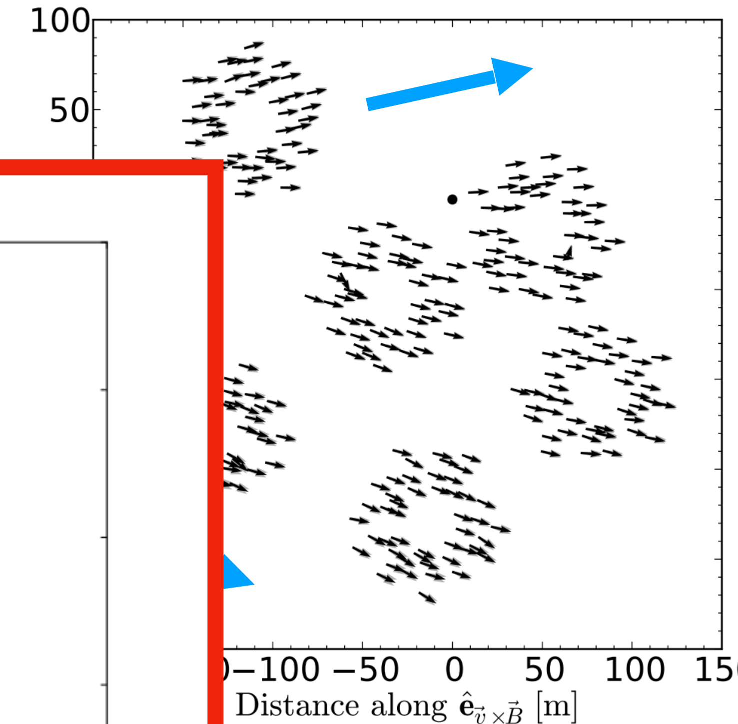
Stokes Parameters

Geomagnetic

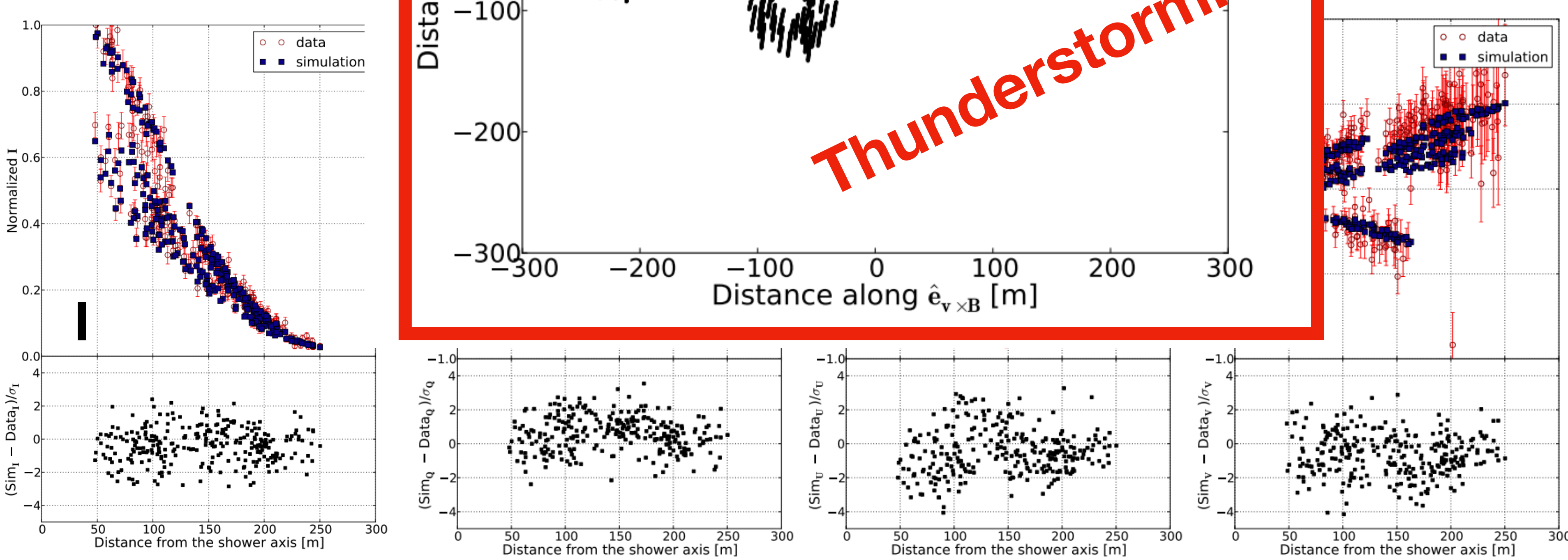


Charge Excess



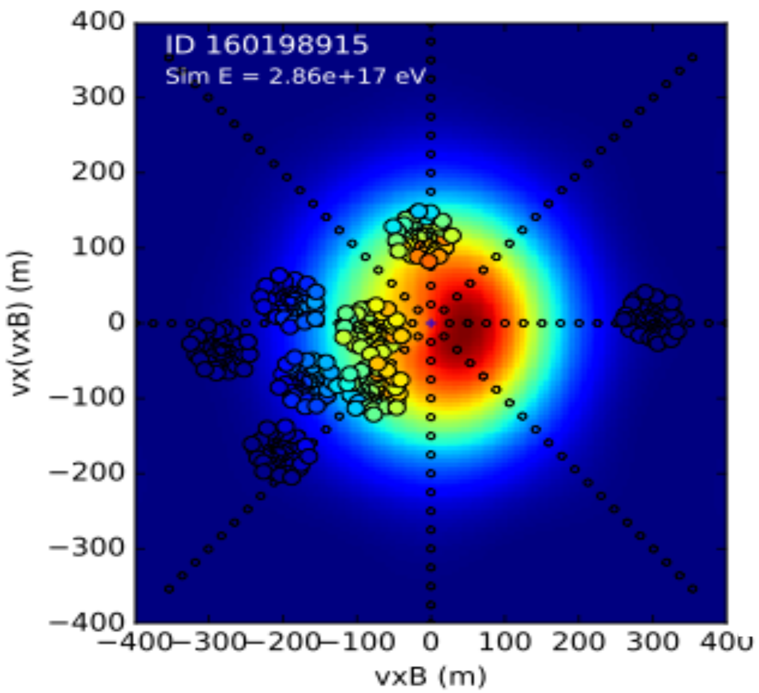


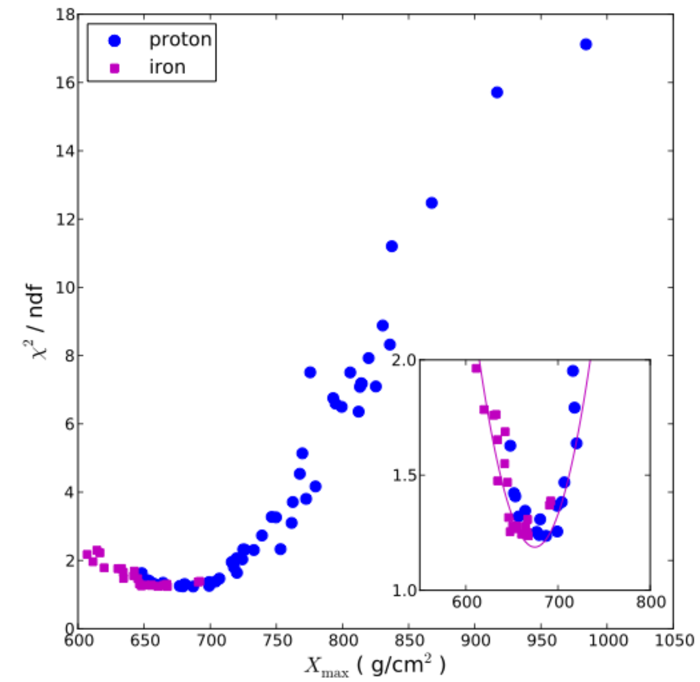
ellart et al., JCAP 10 14 (2014)

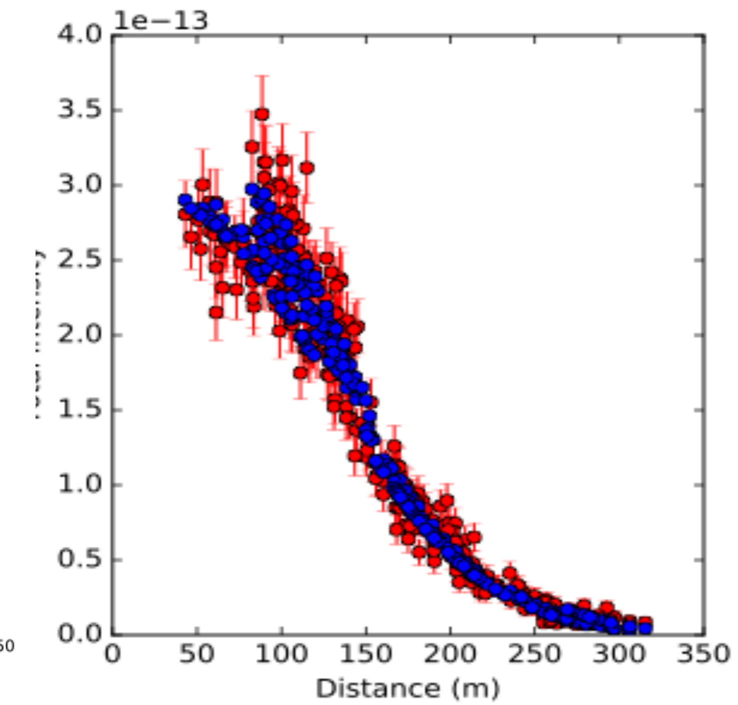


O. Scholten et al., PRD 94 1030101 (2016)

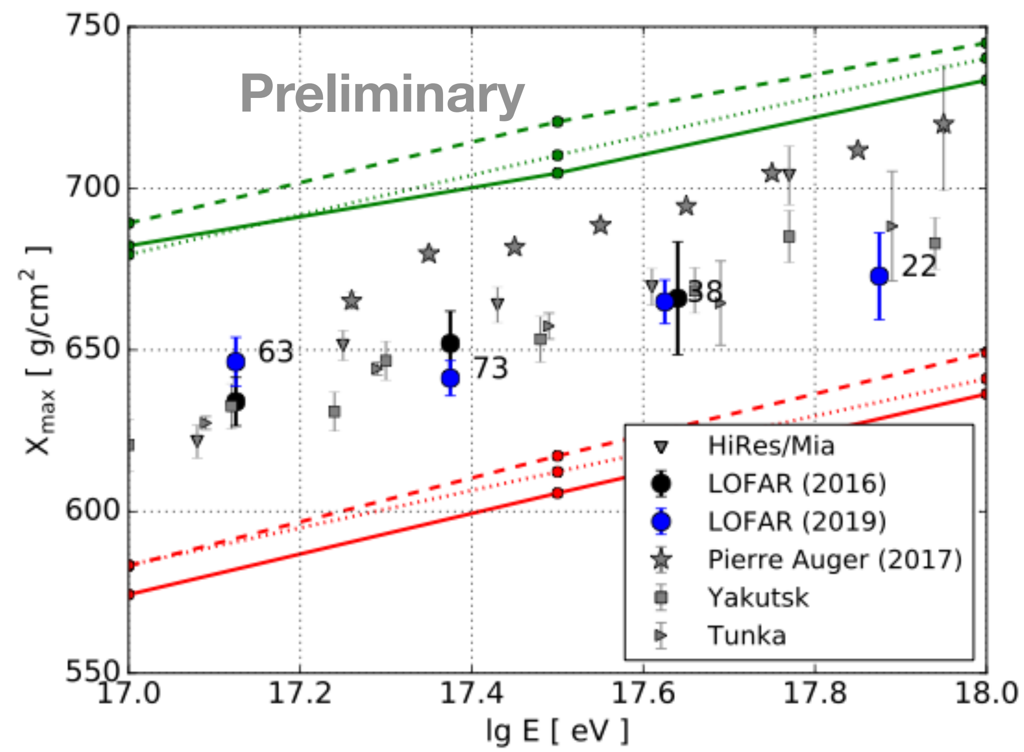
Event Analysis





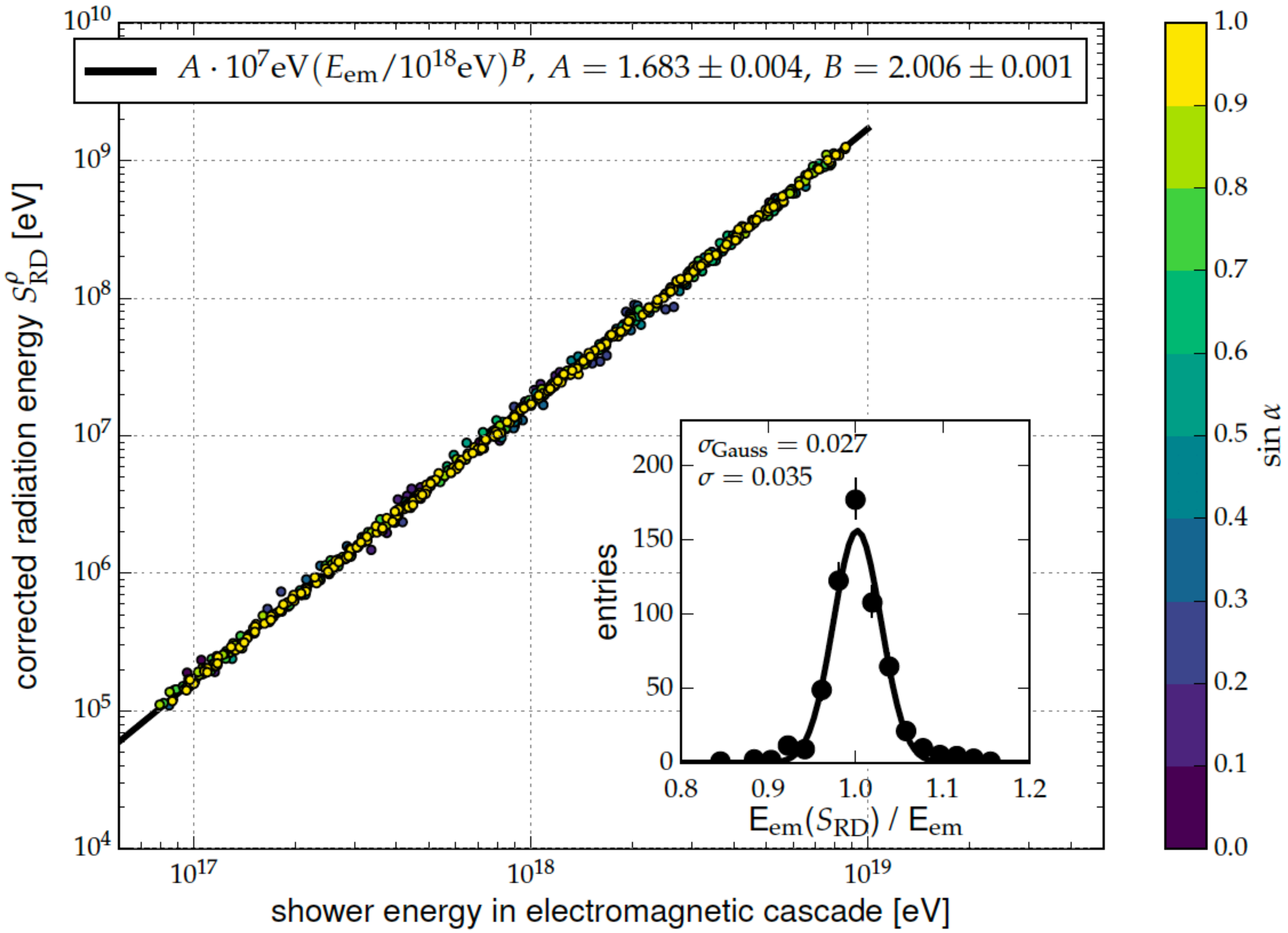


- **Simulate proton and iron sh**
- **Power scales with energy²**
- **Calculate reduced X^2 for each simulation**
- **Parabola fit determines event X_{max}**
- **Resolution < 20 g/cm²**
- **Best fit (2016): 80% light particles (p+He) at 10^{17} -$10^{17.5}$ eV**



Radiation Energy

Radiation Energy ∝ Electromagnetic Energy²



$$f(\vec{r}) = \varepsilon_0 c \Delta t \sum_i E^2(\vec{r}, t_i)$$

$$E_{\mathrm{rad}} = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\infty} \mathrm{d}r\, r f(r, \phi)$$

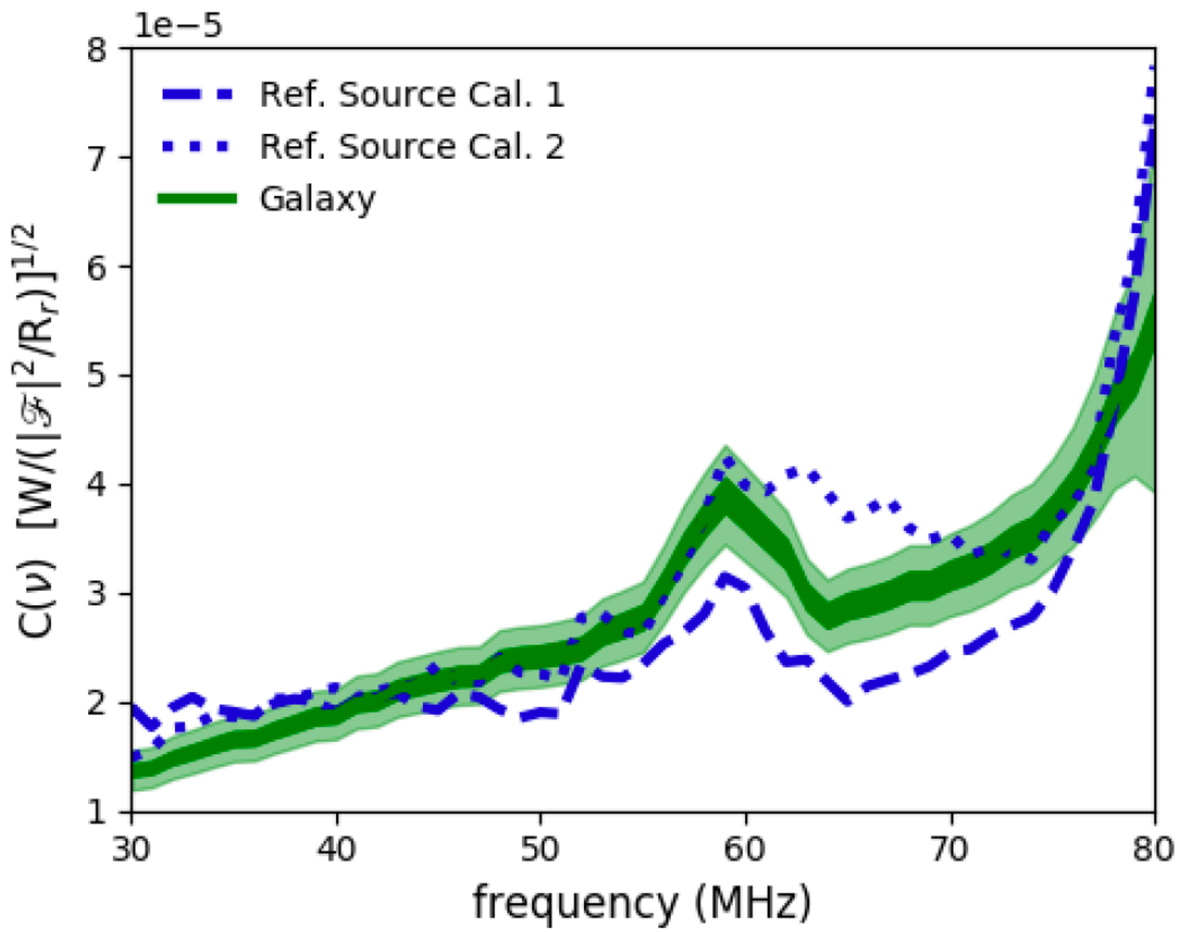
$$S_{RD} = \frac{E_{\mathrm{rad}}}{(a'^2 + (1 - a'^2))\sin^2\alpha \left(\frac{B_{\mathrm{Earth}}}{0.243\mathrm{G}}\right)^{1.8}}$$

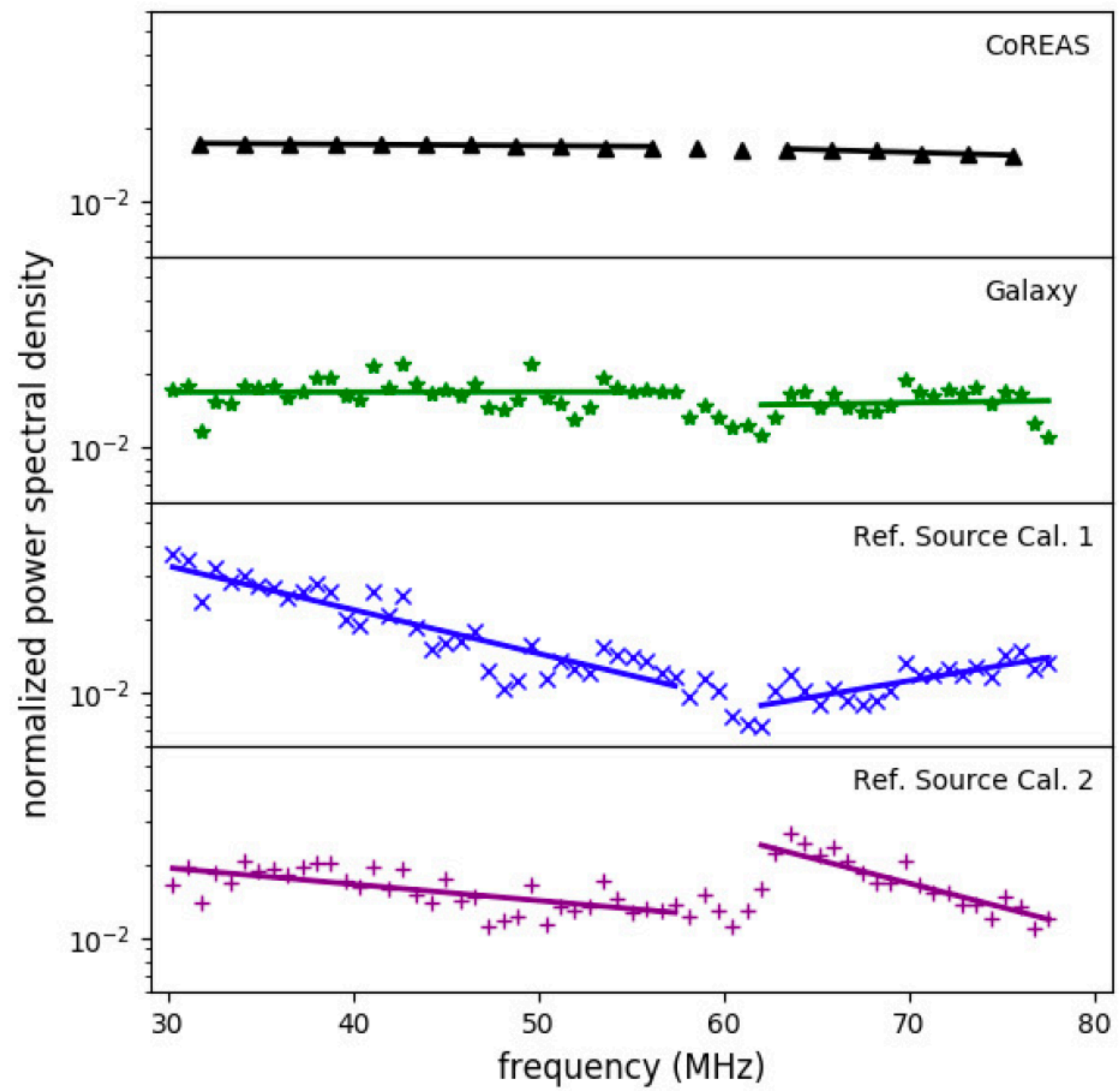
$$S_{RD} = A \times 10^7\mathrm{eV} \left(\frac{E}{10^{18}\mathrm{eV}}\right)^B$$

C. Glaser, et al. JCAP, 1609(09):024, 2016

Antenna Calibration

Systematic Uncertainty	Percentage
antenna model	2.5
sky model	11
electronic noise < 77 MHz	6.5
electronic noise > 77 MHz	20
total < 77 MHz	**13**





K. Mulrey et al. Astropart.Phys 111 (2019) 1-11.