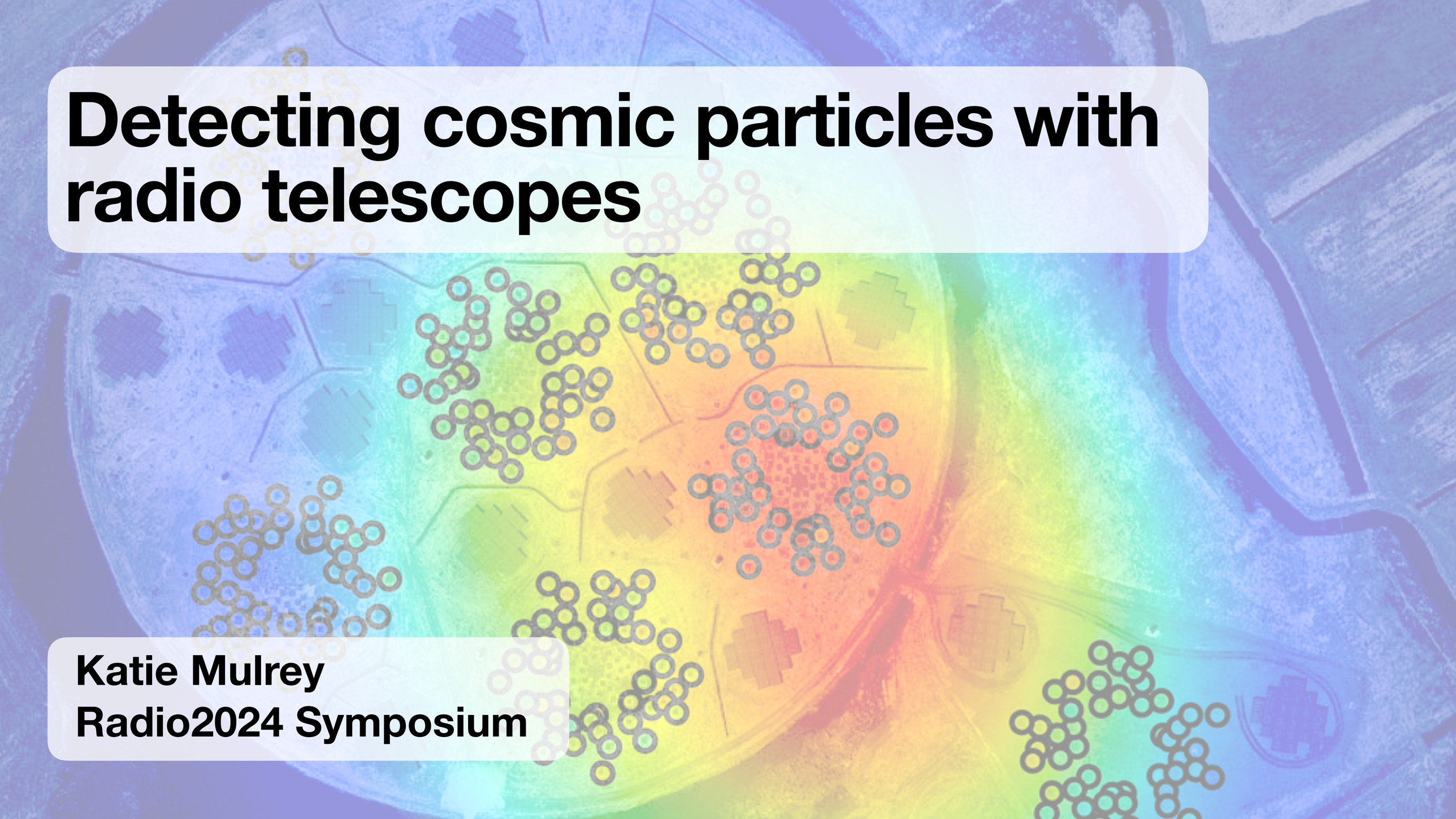
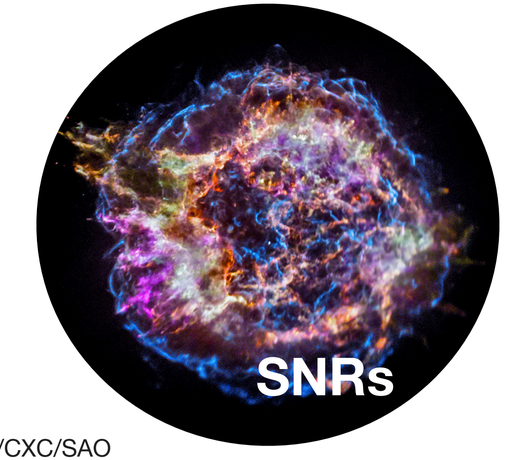
Detecting cosmic particles with radio telescopes



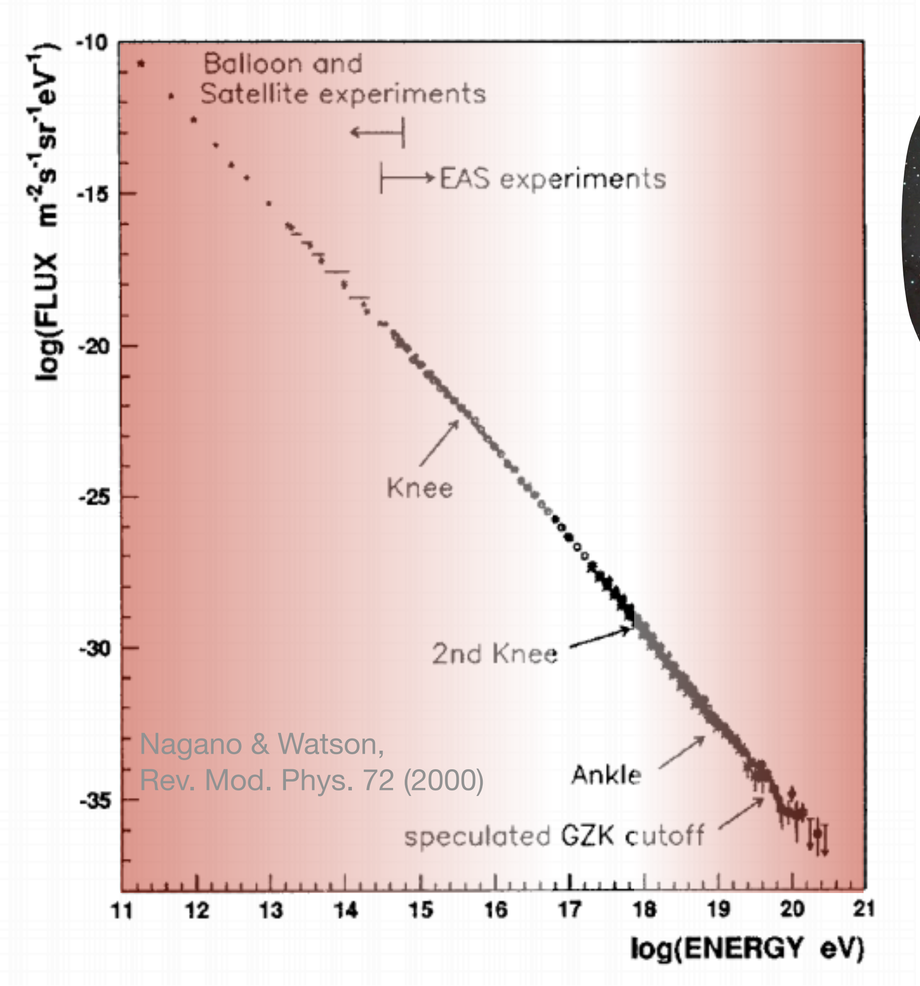
Katie Mulrey
Radio2024 Symposium

Cosmic-ray sources

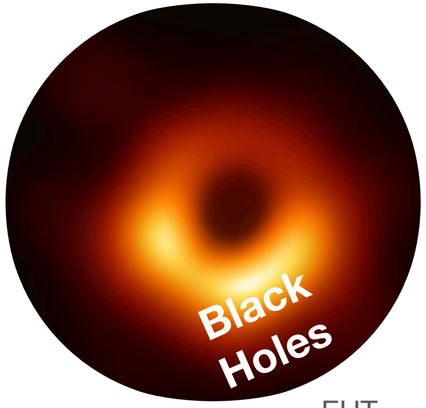
Galactic



NASA/CXC/SAO



NASA / ESO/MPIfR



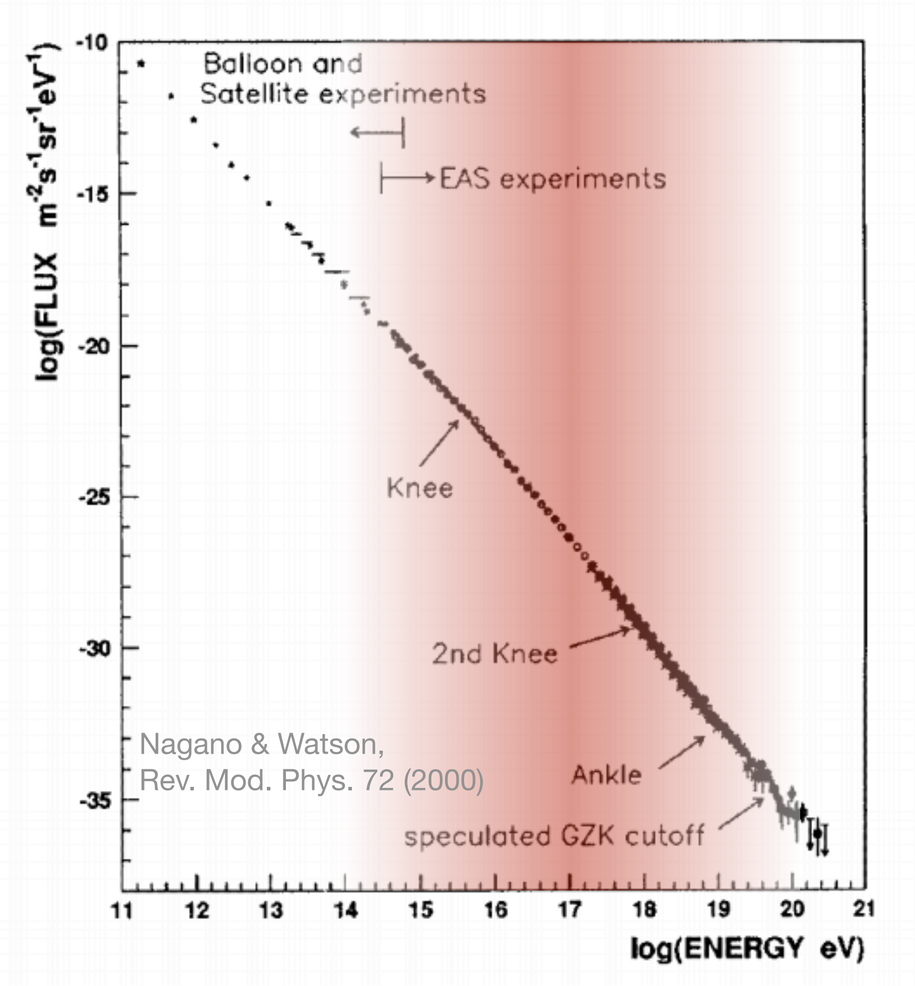
EHT

extragalactic

NASA / ESA

Cosmic-ray sources

transition region

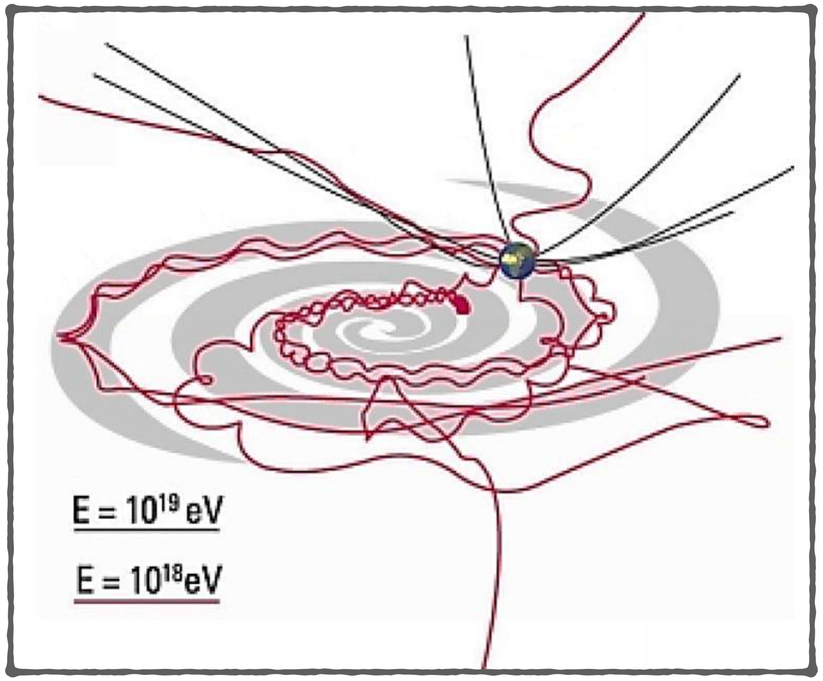


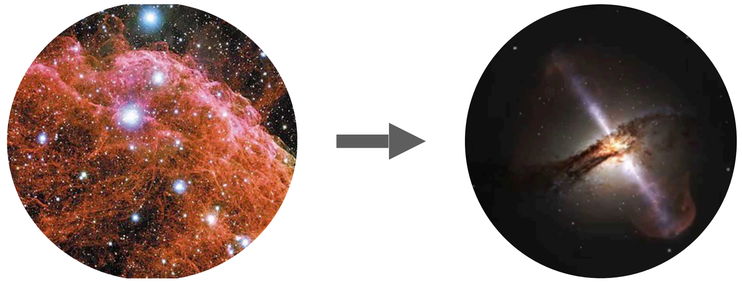
- Second Galactic CR component?
- Influence of Galactic and extragalactic magnetic fields?
- Hadronic physics at energies beyond the reach of the LHC?
- Connections to other cosmic messengers (PeVatrons)?

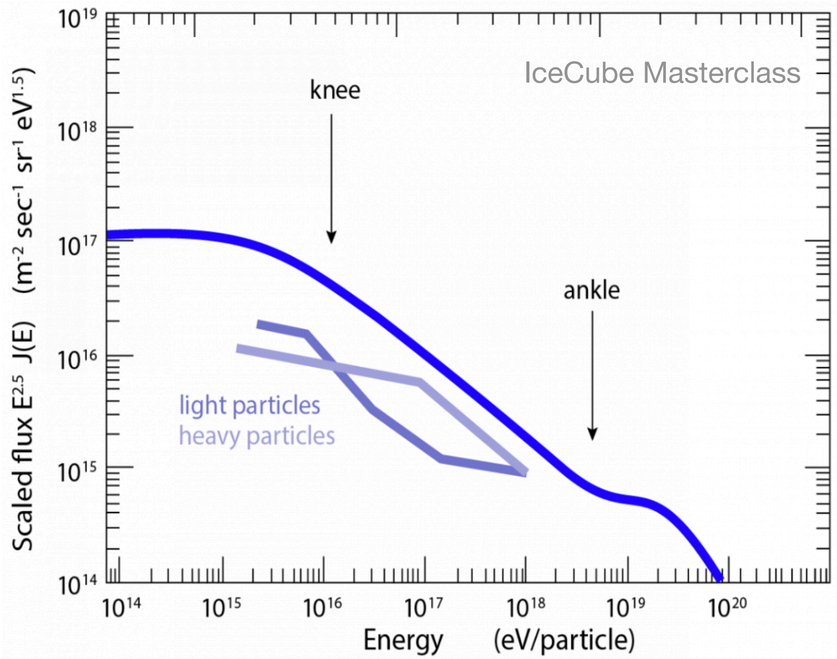
… the picture is not yet clear

Cosmic-ray sources

Challenge: CR trajectories are scrambled in magnetic fields







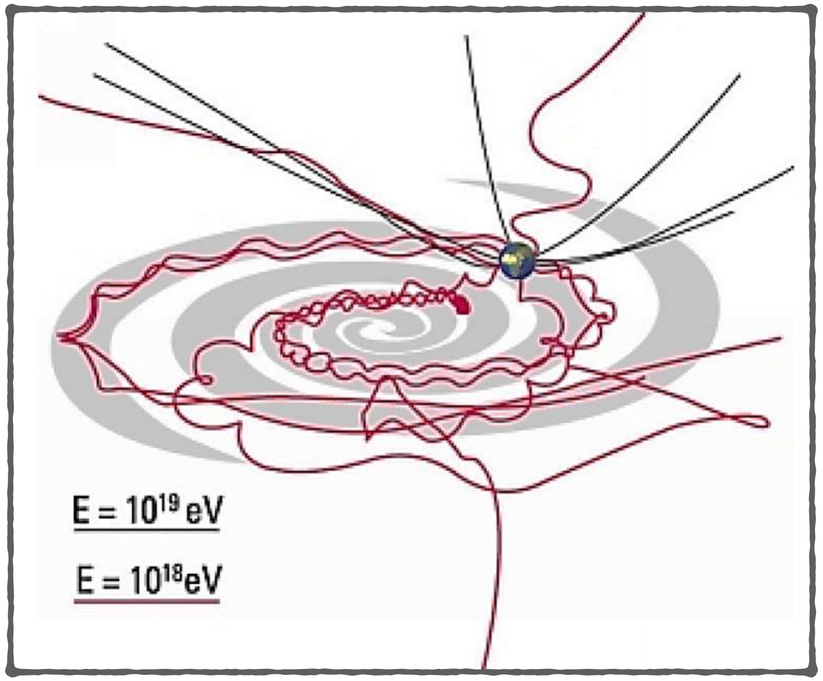
$$\mathrm{E_{max}} \propto Z\ e\ B\ r$$

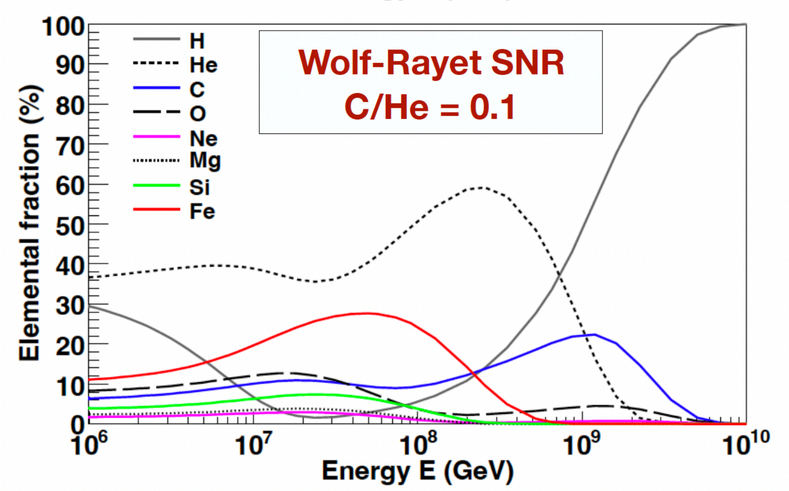
$$\mathrm{E_{Fe,\ max}} = 26 \times E_{\mathrm{p,\ max}}$$

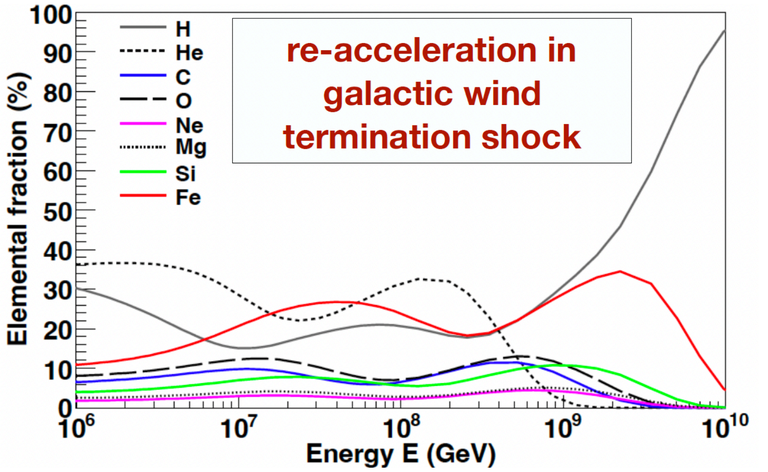
energy & composition

Cosmic-ray sources

Challenge: CR trajectories are scrambled in magnetic fields





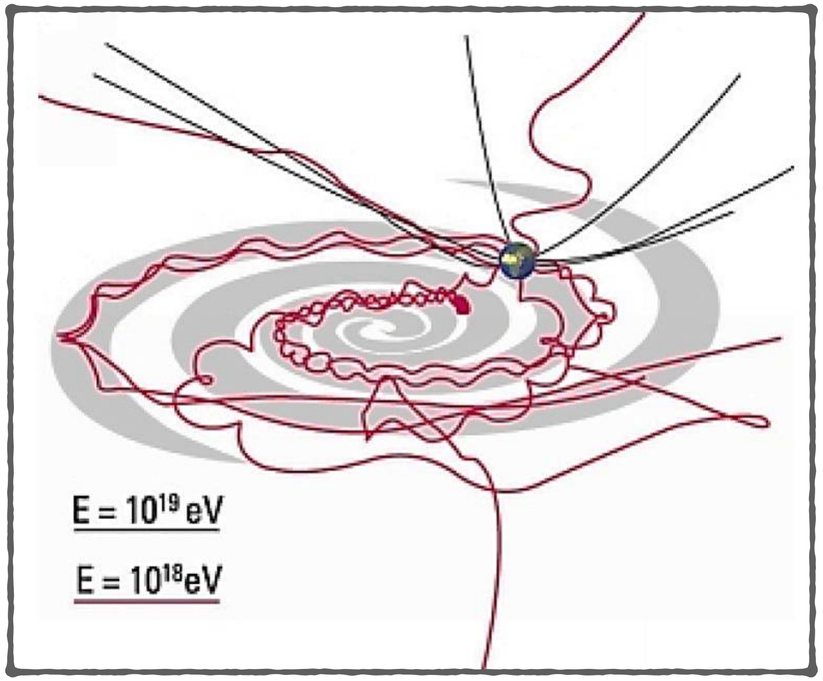


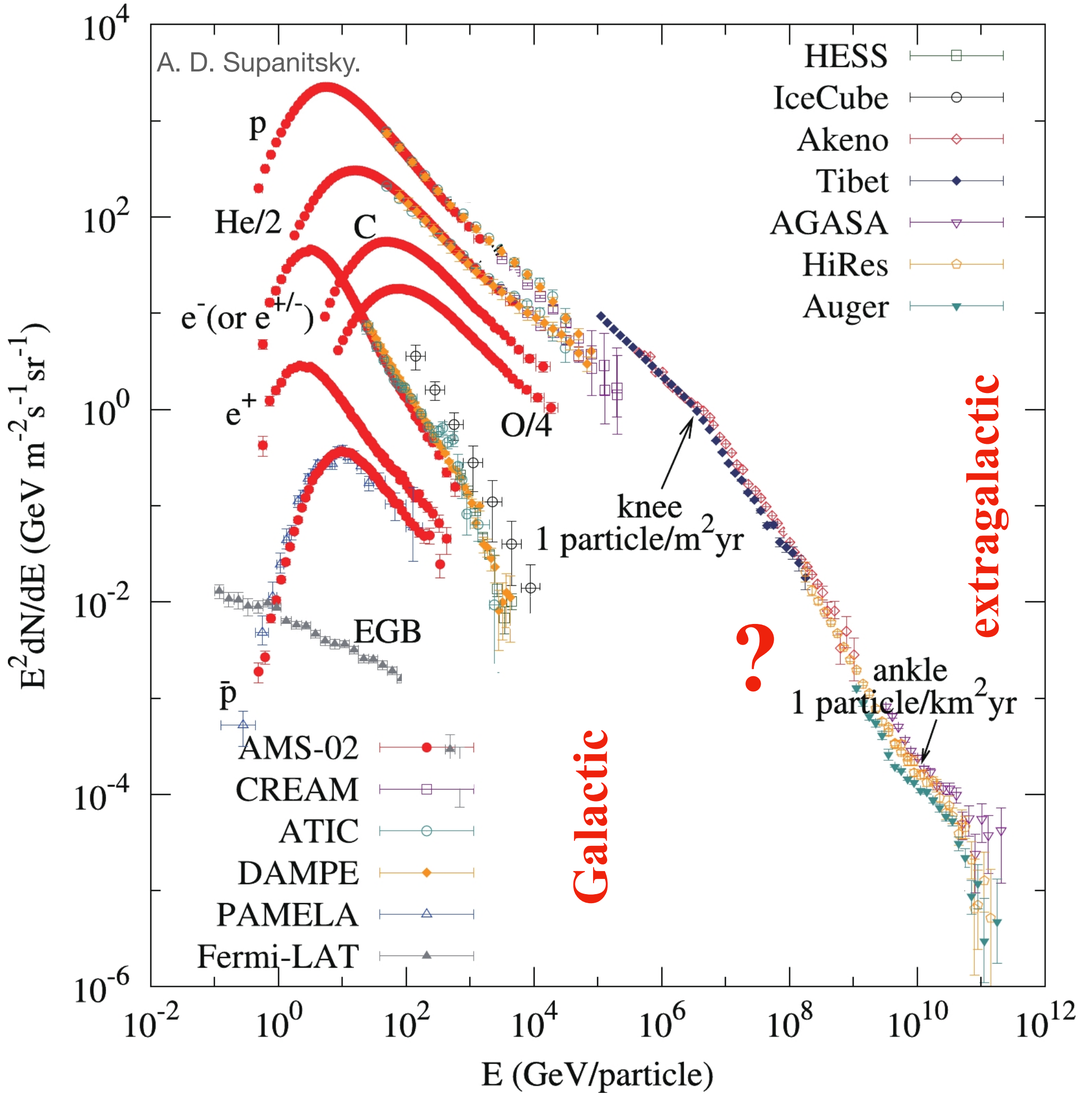
Source - specific composition signatures

S. Thoudam et al, A&A 2016.

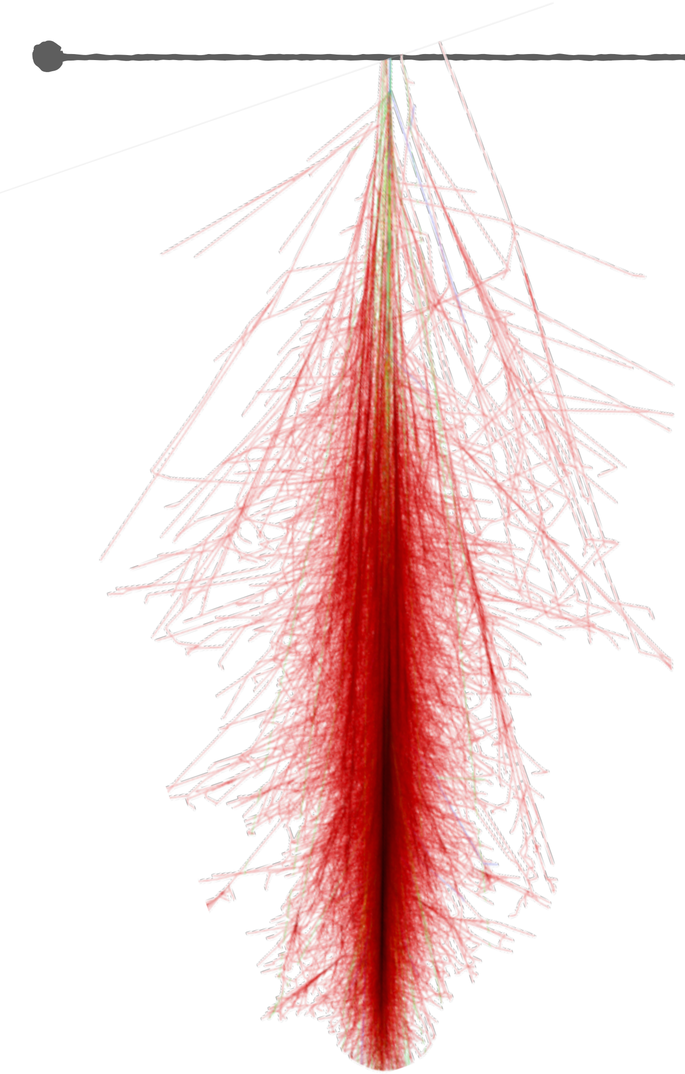
Cosmic-ray sources

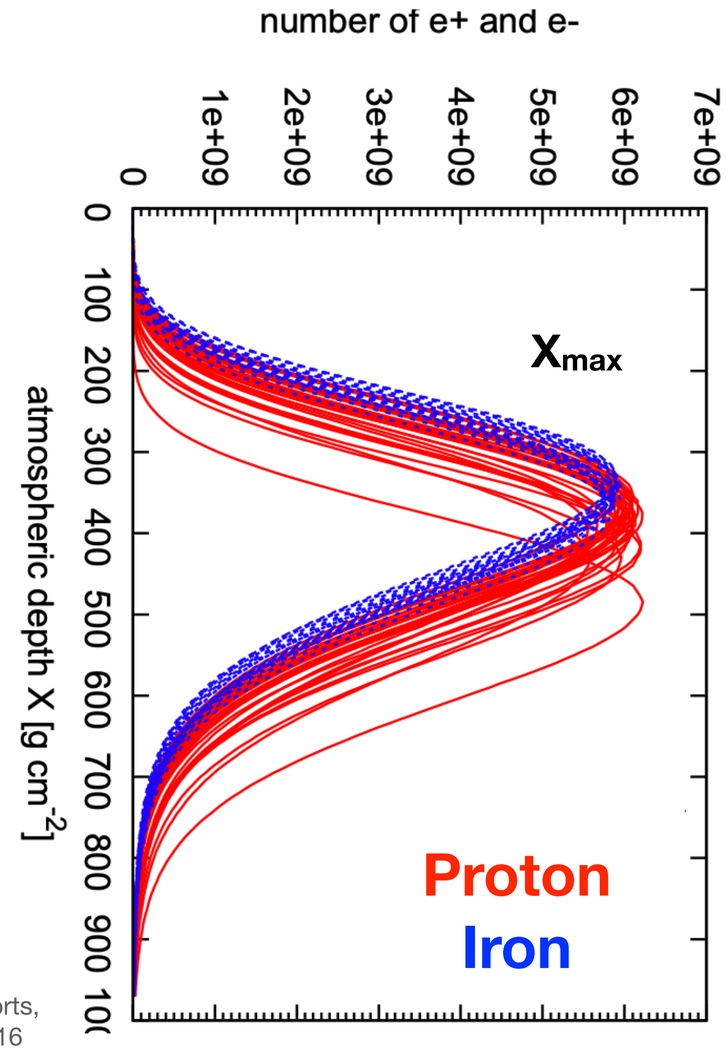
Challenge: CR trajectories are scrambled in magnetic fields



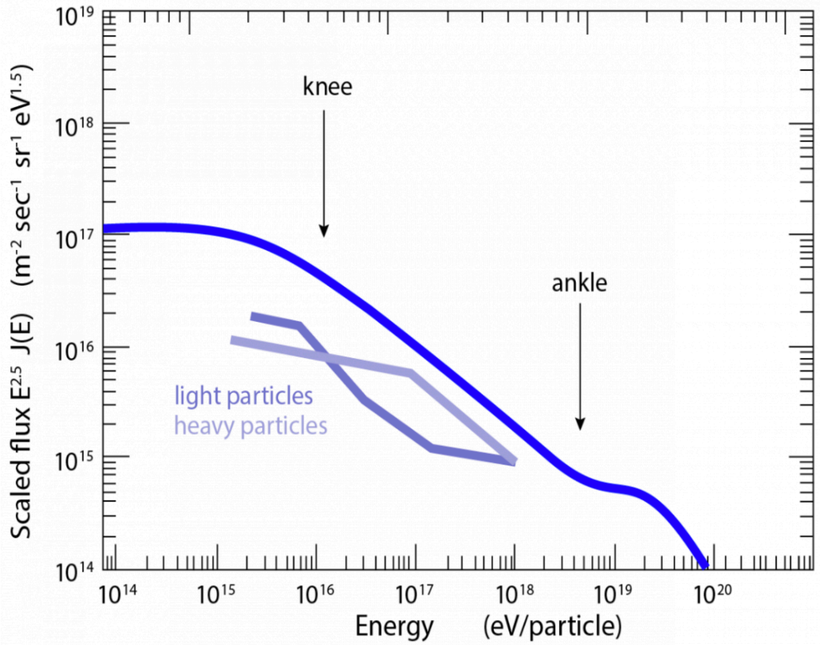


Cosmic-ray air showers





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



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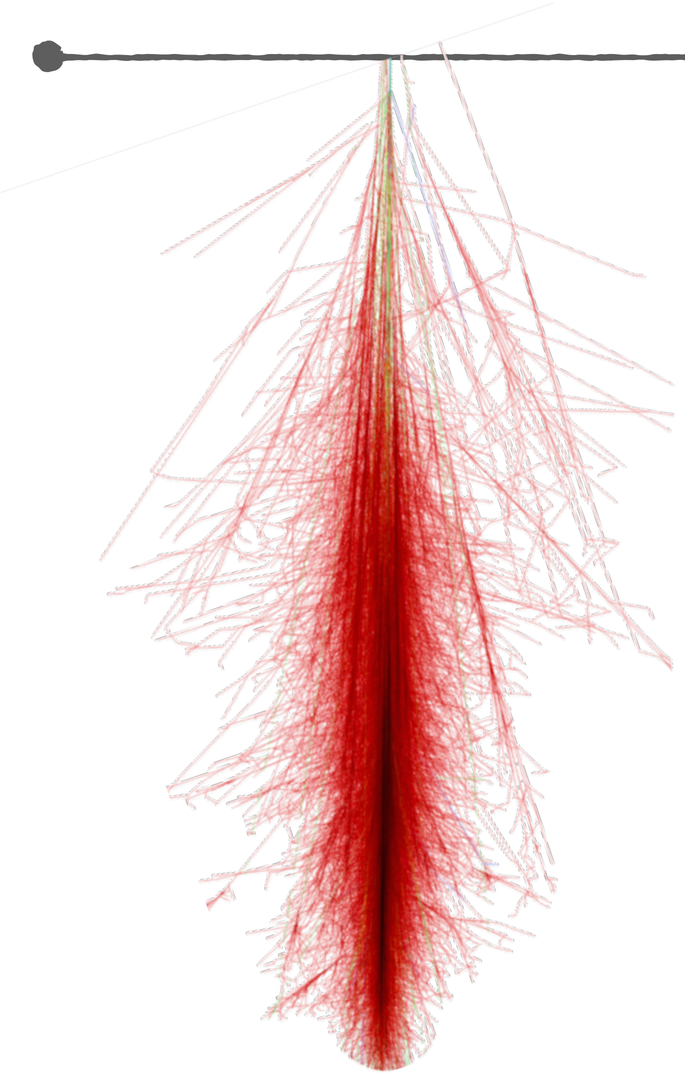
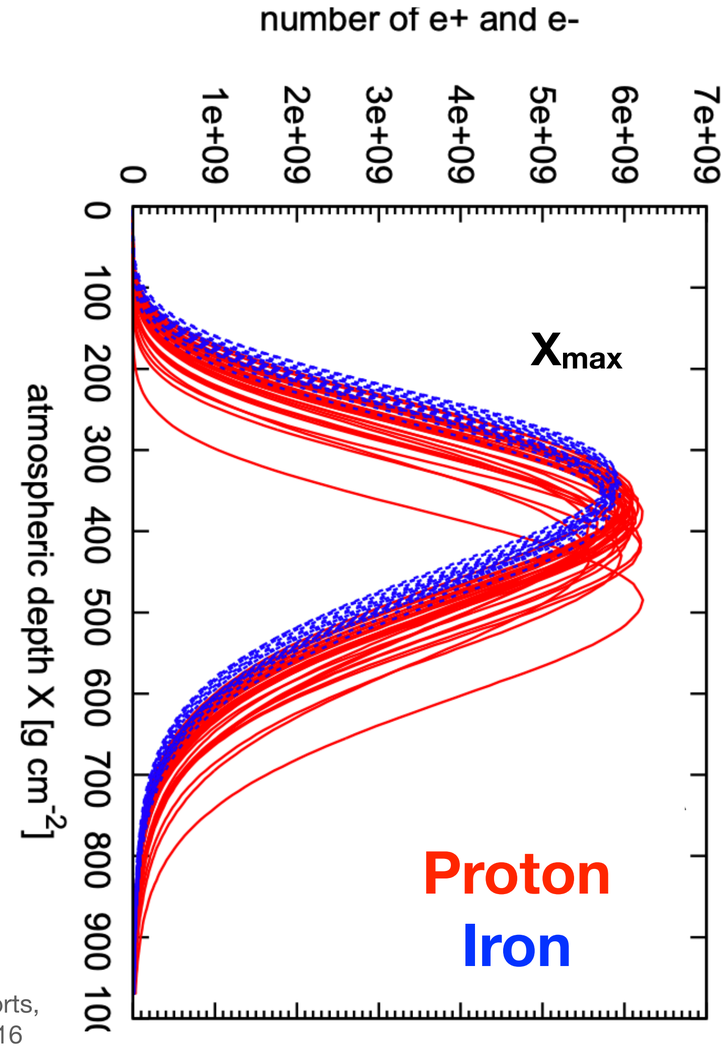
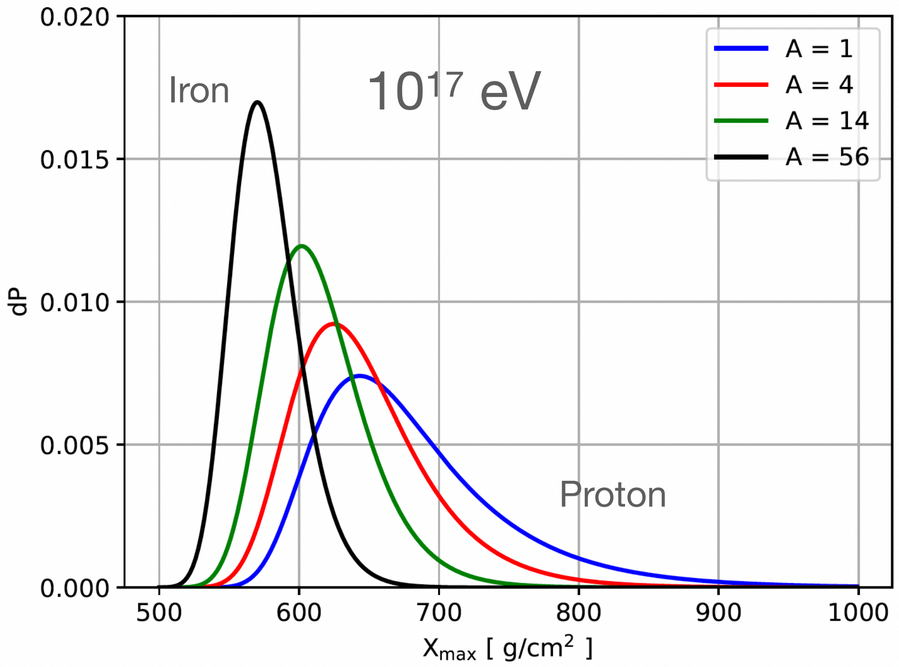




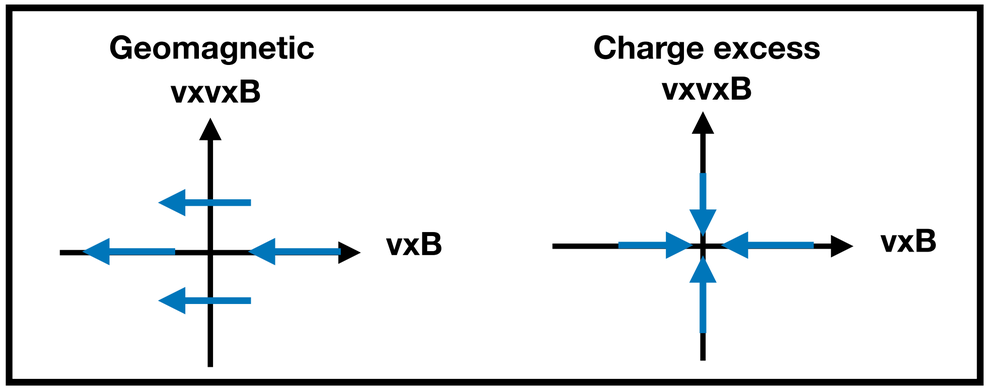
T. Huege.
Physics Reports,
620:1-52,2016

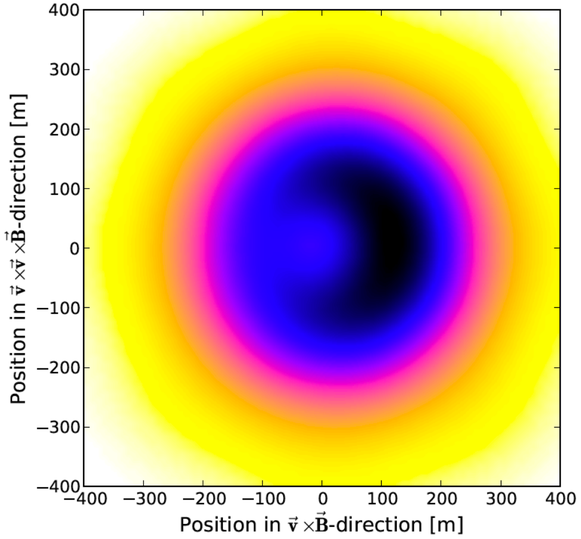
Challenge: distribution of Xmax values of different primaries naturally hard to distinguish

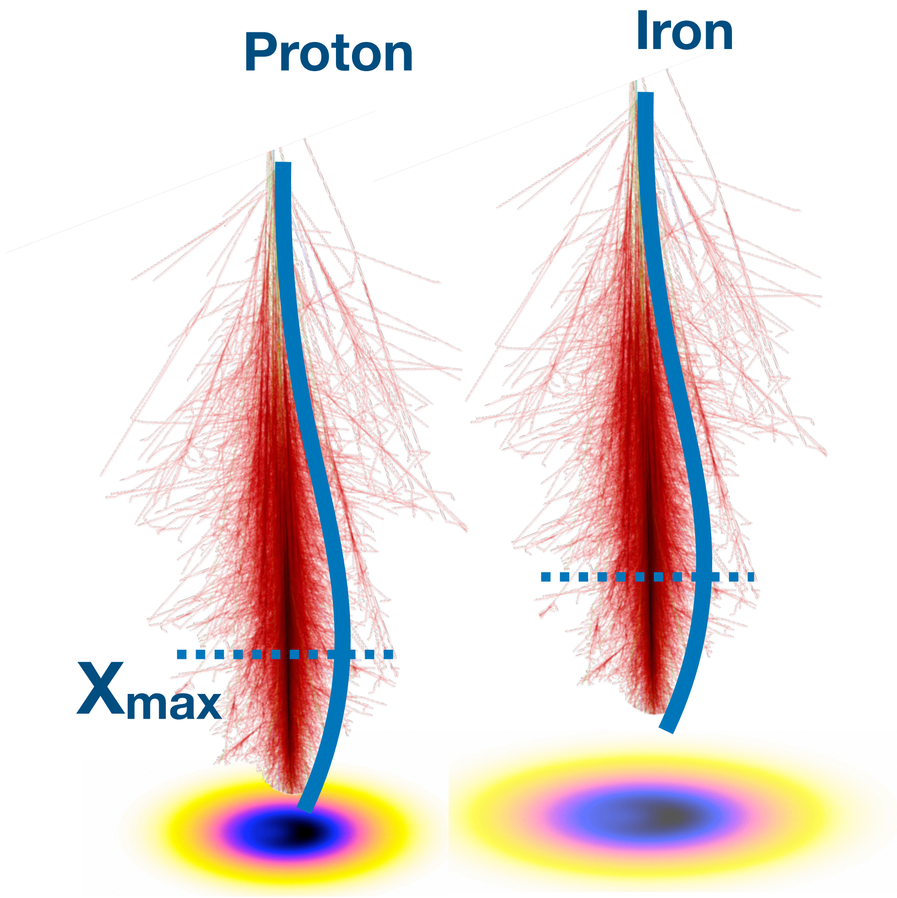


Corstanje et al. Phys. Rev. D. , 2021.

Radio emission from air showers



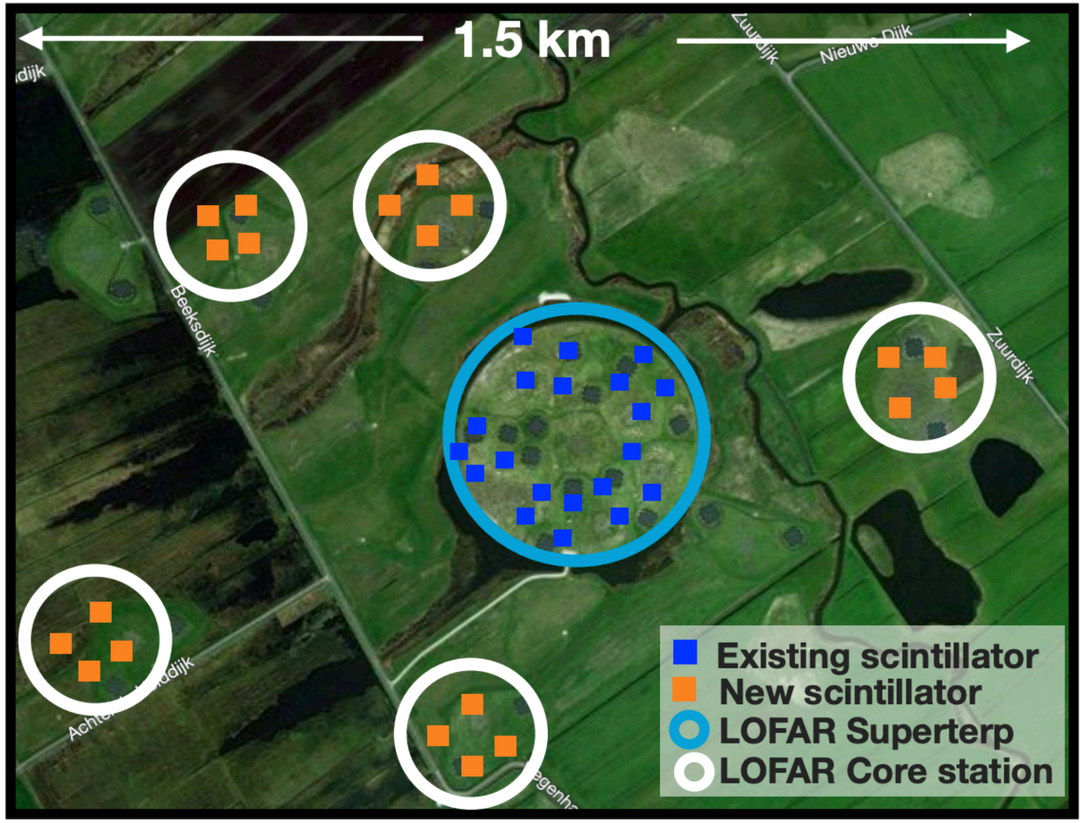




Cosmic rays at LOFAR

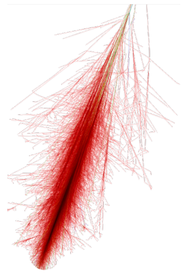
Low band (30-80 MHz)

~ 100s of antennas per event



Particle detector for triggering

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



CR event → **particle trigger** → **radio buffer readout** → **offline analysis**

Cosmic rays at LOFAR

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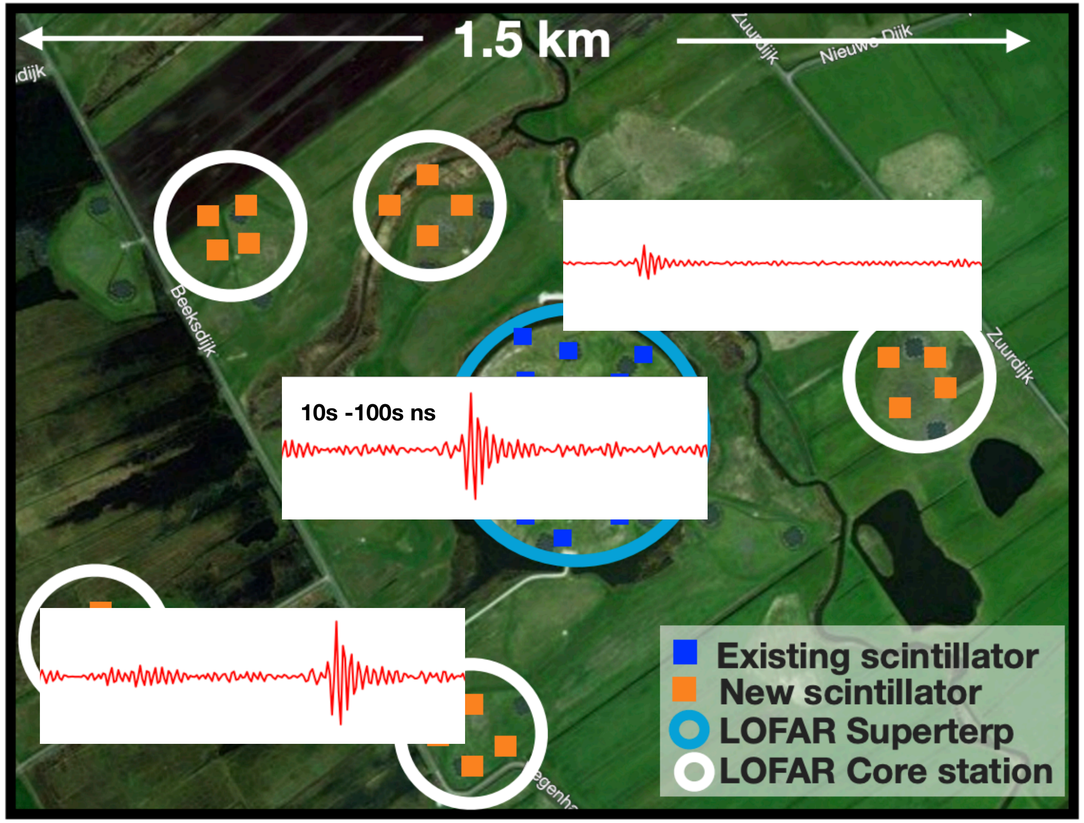

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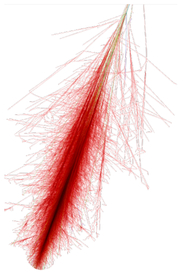

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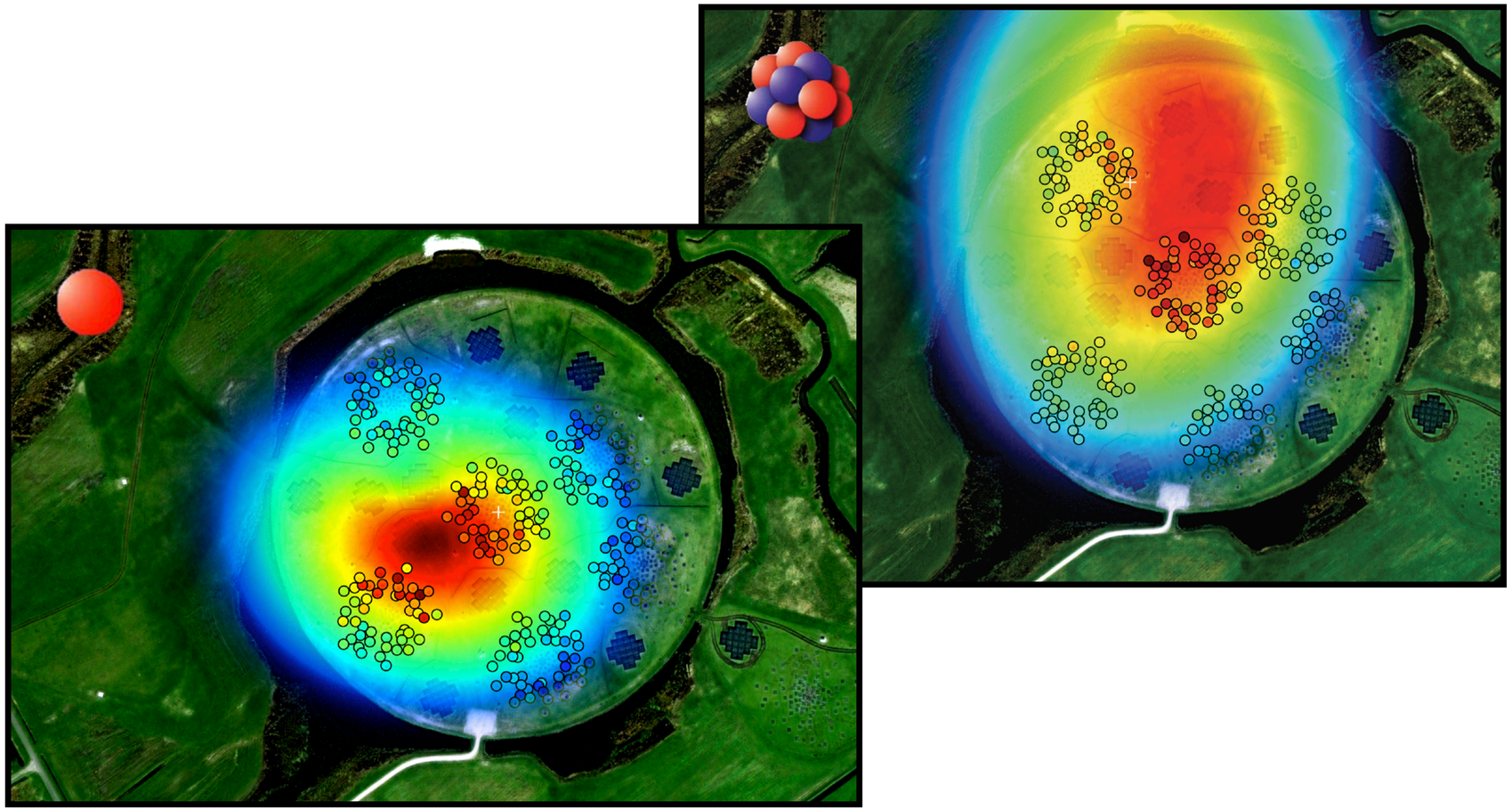
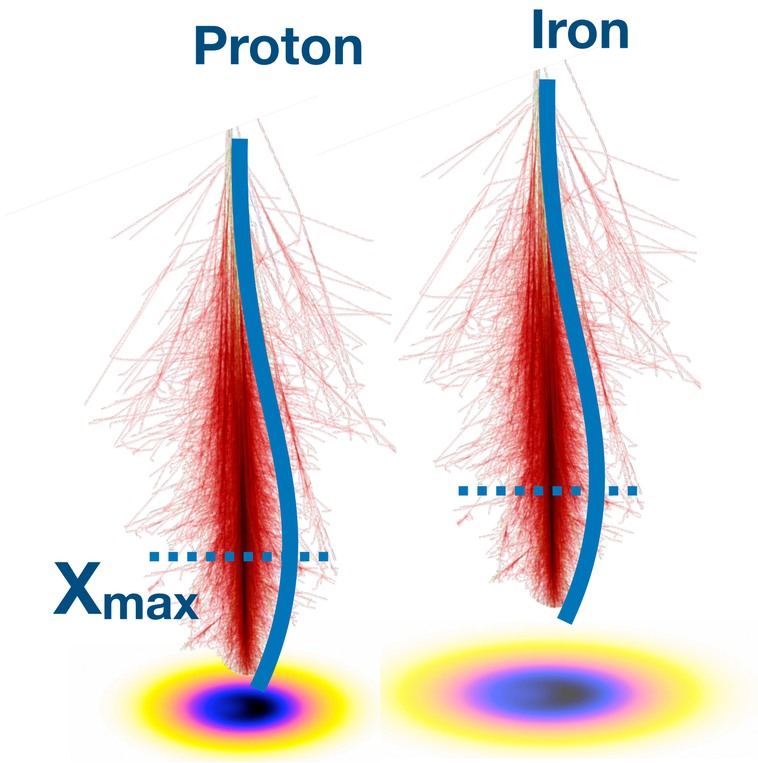
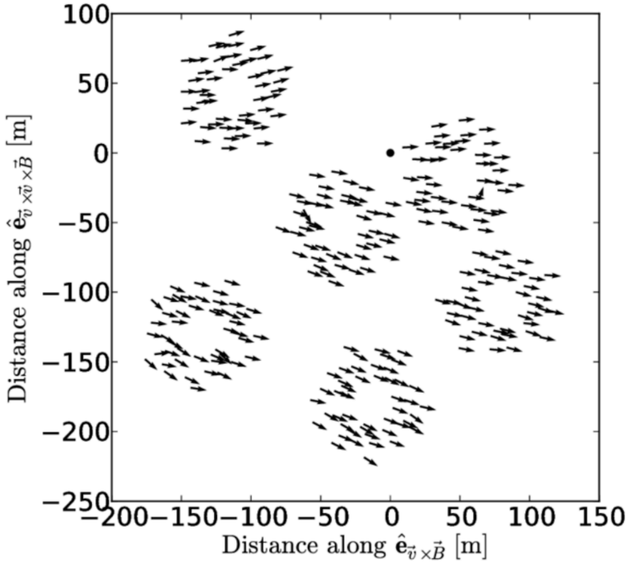
Cosmic rays at LOFAR





10 years of LOFAR analyses



Evidence of radio emission mechanisms

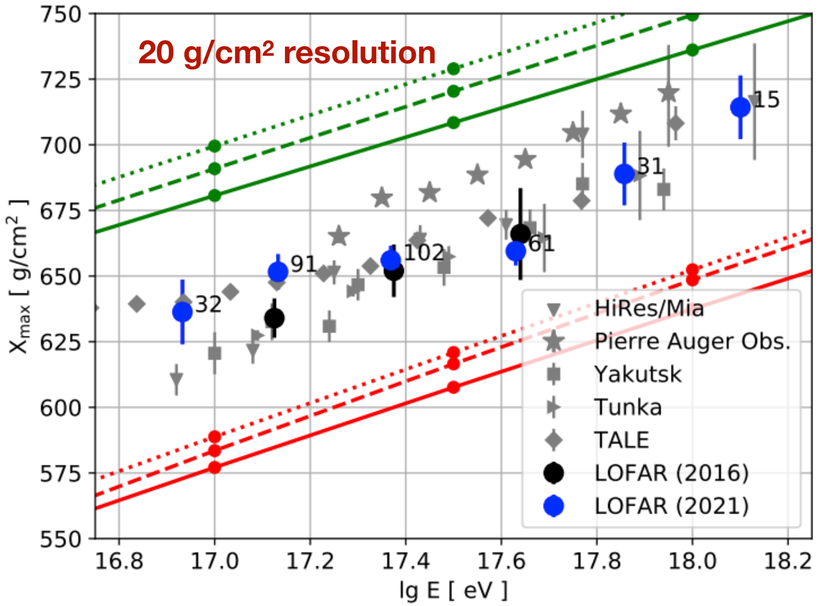
Schellart et al. JCAP, 2014.

Circular polarization

Scholten et al. Phys. Rev. D, 2016.

Wavefront shape

Corstanje et al. APP, 2014.



Radio-based X_{max} reconstruction

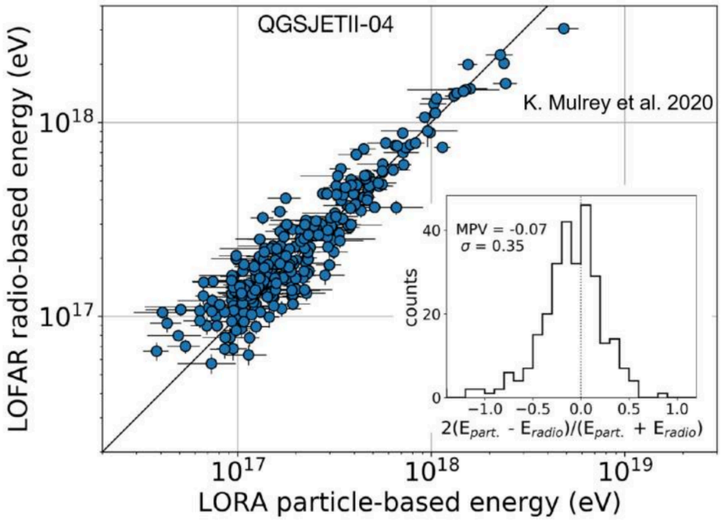
Buitink et al. Phys. Rev. D, 2014.

Buitink et al. Nature, 2016.

Corstanje et al. Phys. Rev. D. , 2021.

GDAS simulated atmosphere

Mitra et al. APP, 2020.



Absolute antenna calibration

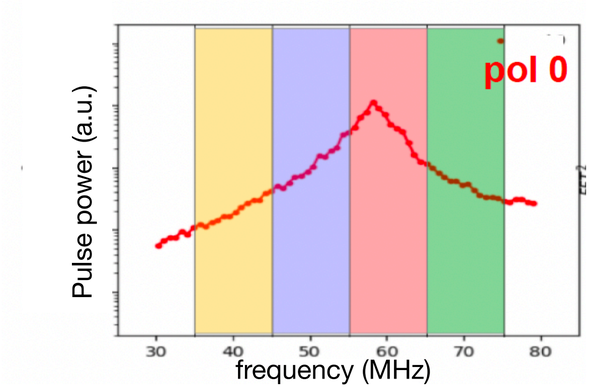
Mulrey et al. APP, 2019.

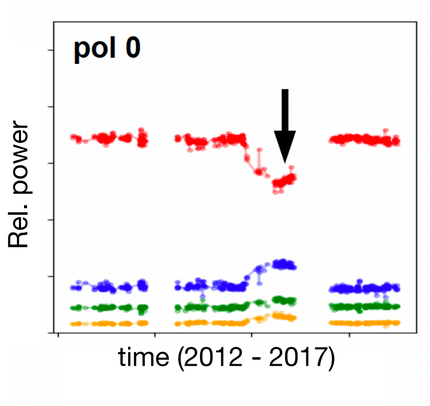
Radio-based energy scale

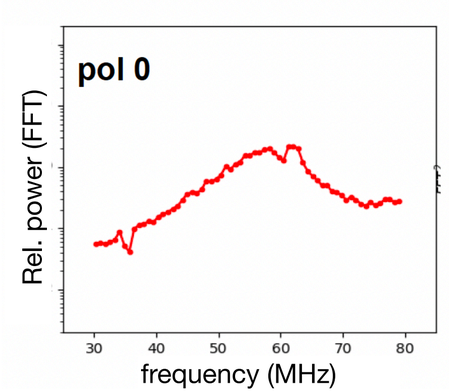
Mulrey et al. JCAP, 2020.

System diagnostics ✓

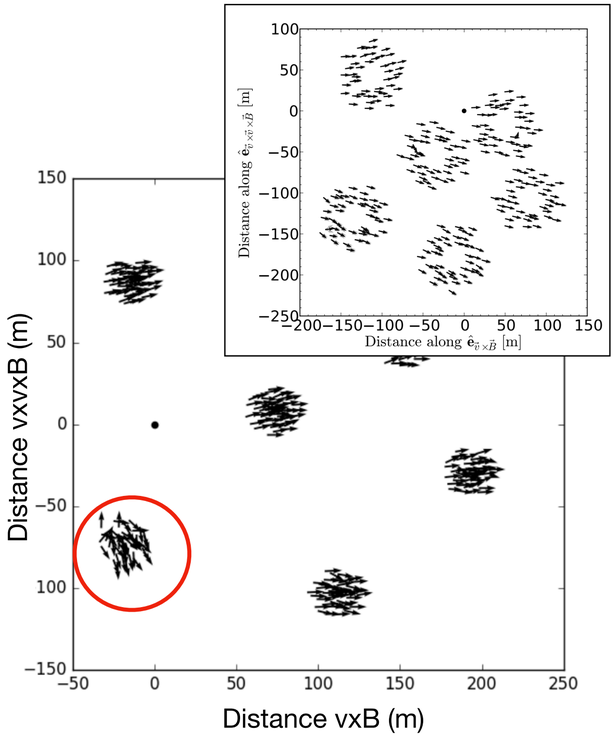
Antenna health



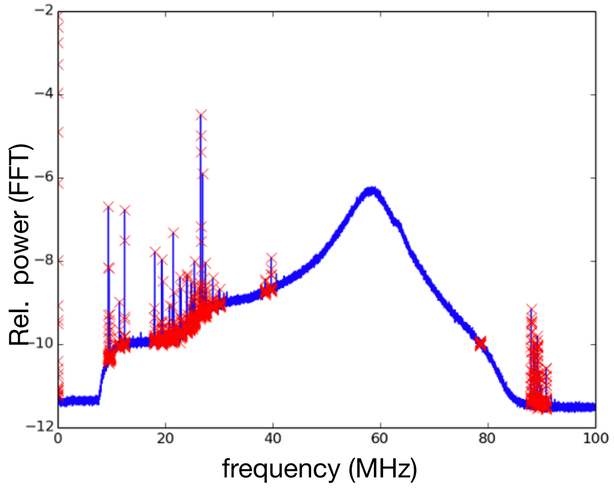


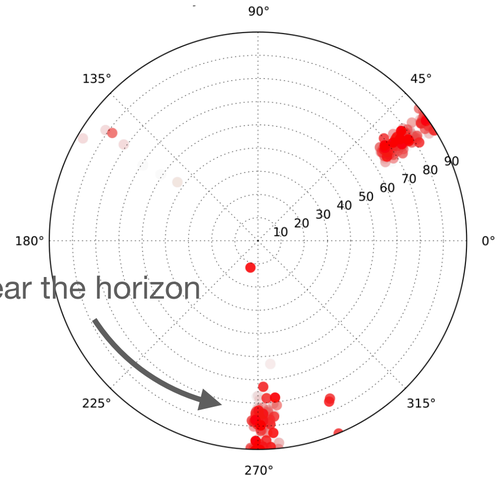


Polarization swaps



RFI localization





Local RFI near the horizon

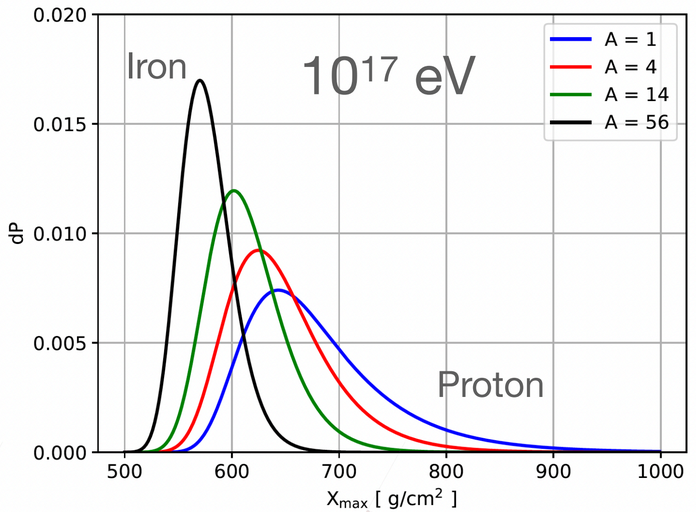
What's next?

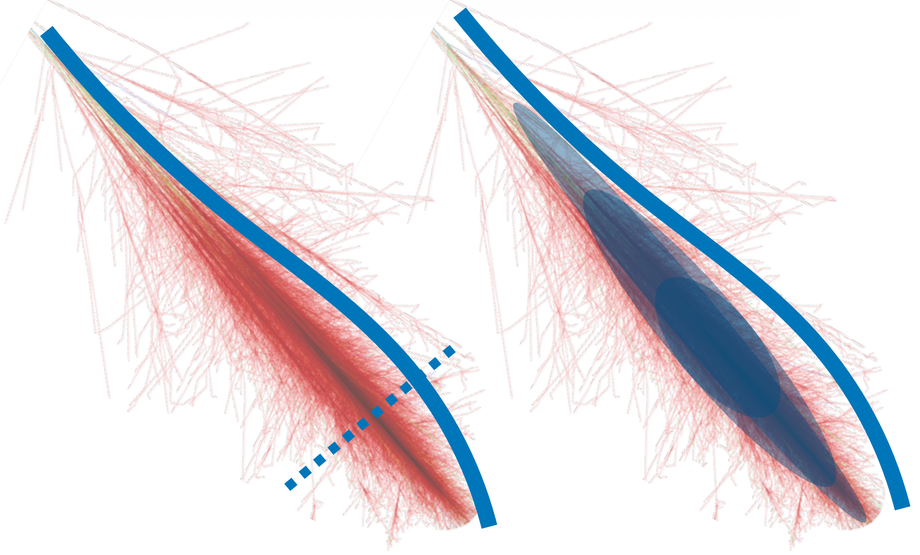
Remaining challenges

- Determining composition based on X_{max} alone is hard
- Composition studies require high statistics
- Measuring in a wide energy range (especially lower!) - weak radio signal

Ways to move forward

- Reconstruct entire air shower development, not just X_{max}
- Increase statistics
- Measure in a wider bandwidth (more info about shower)
- Increase antenna density / number





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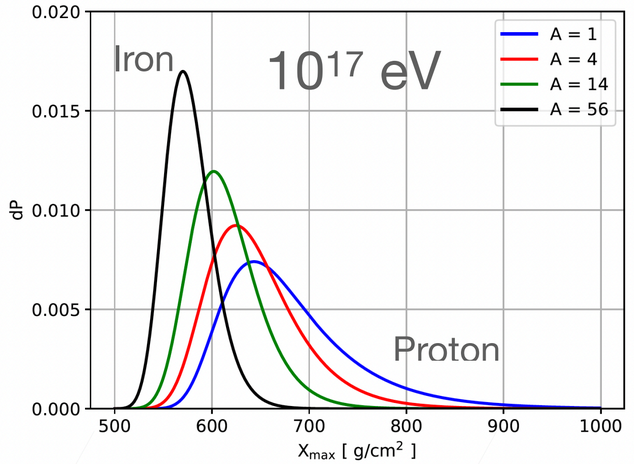

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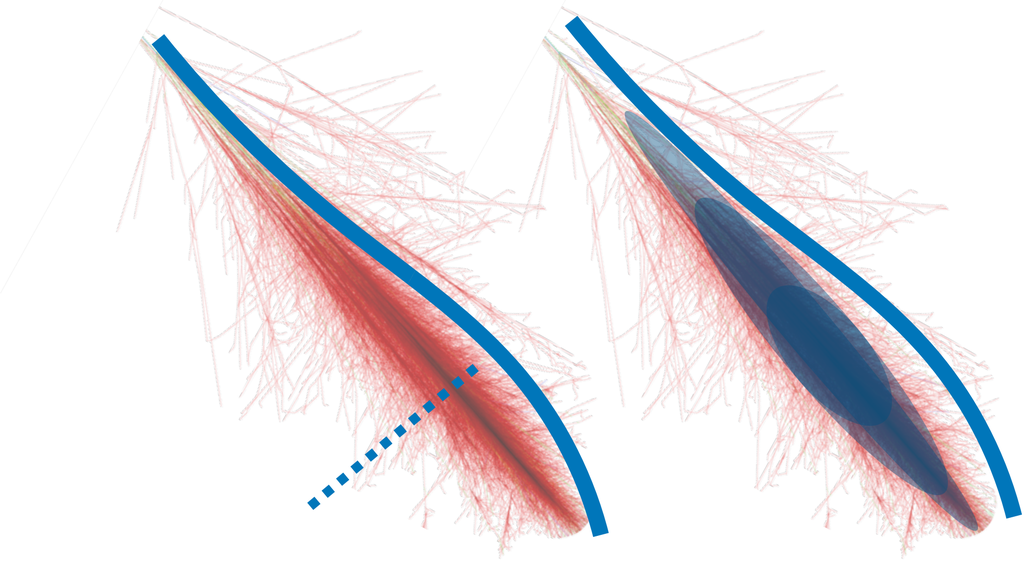
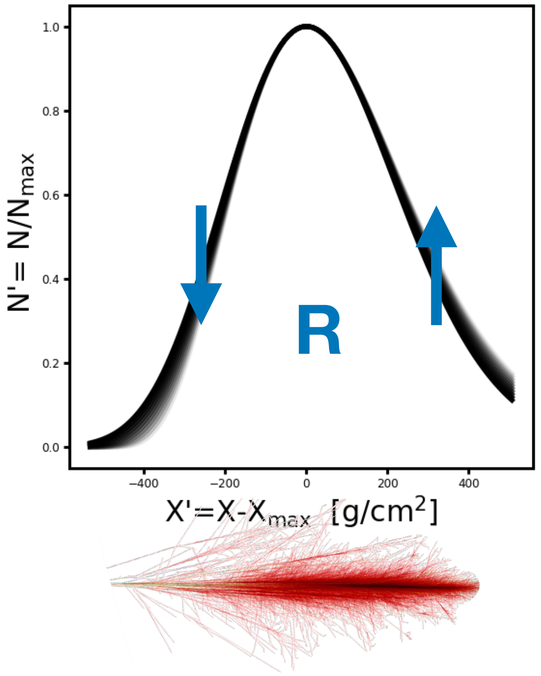
LOFAR 2.0 & SKA

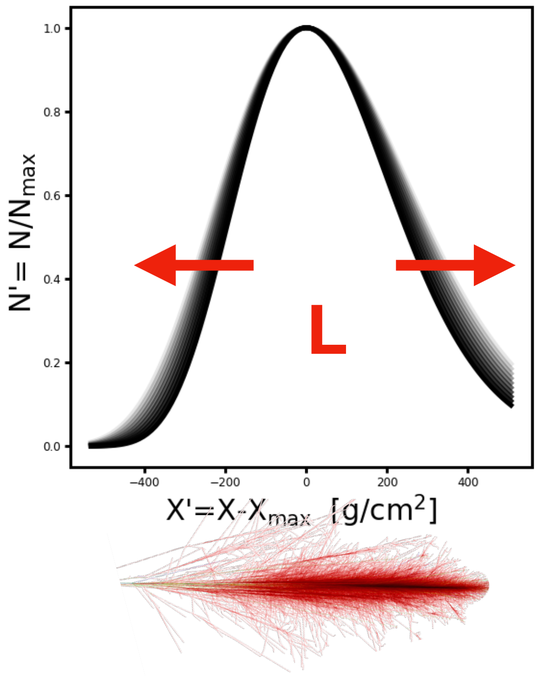


Beyond X_{max}

Changing R: asymmetry

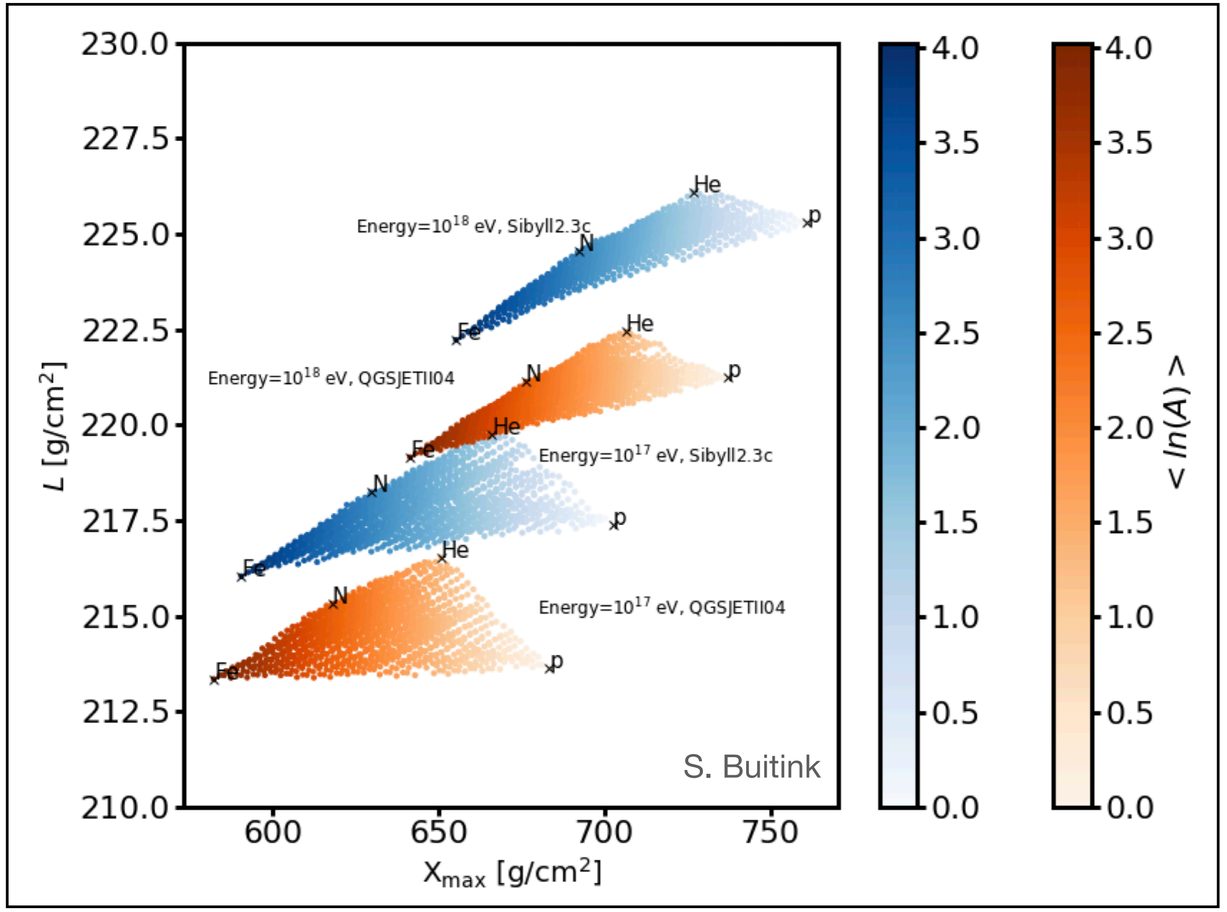


Changing L: width



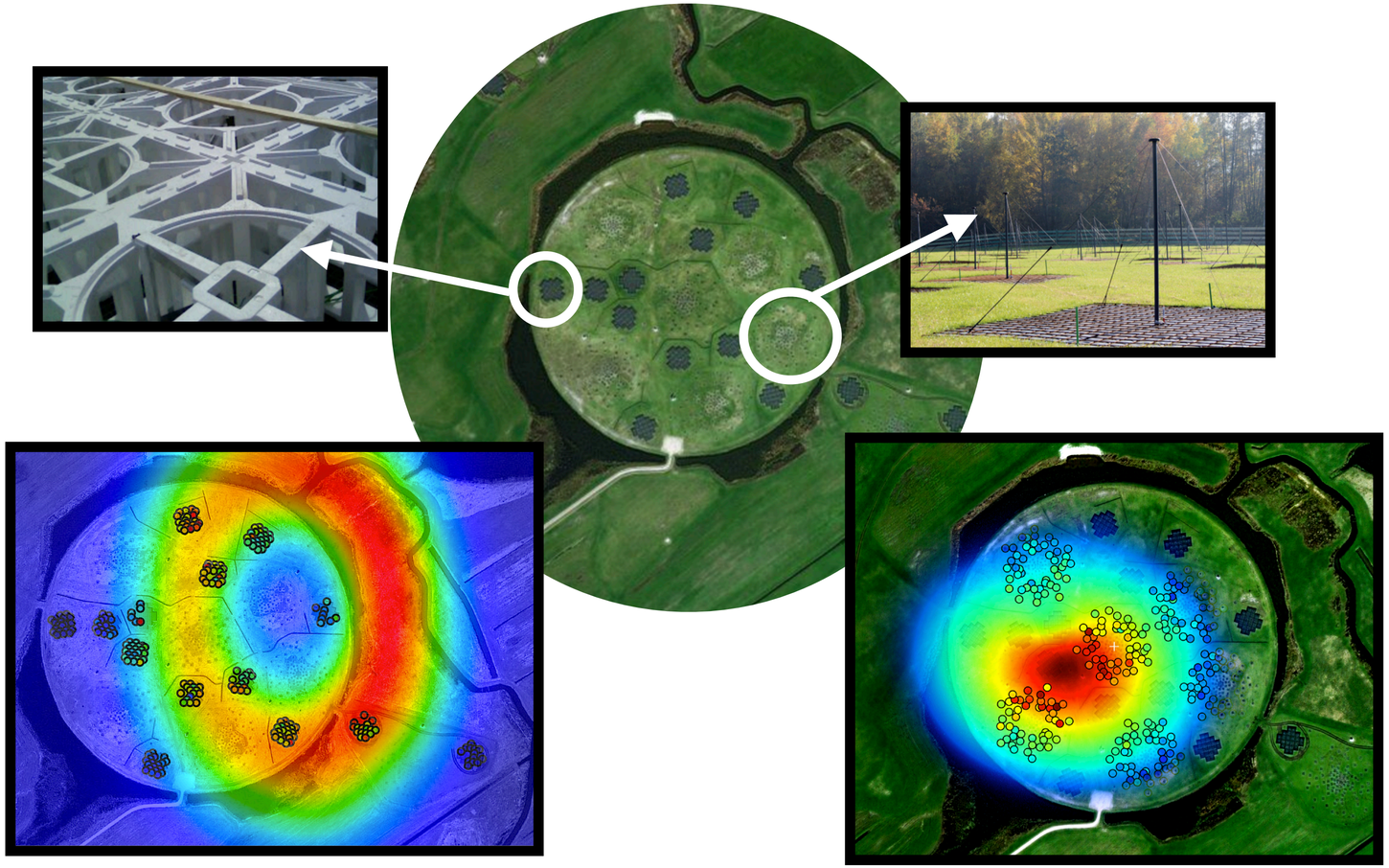
$$N(X) = \exp\left(-\frac{X - X_{\max}}{RL}\right)\left(1 + \frac{R}{L}(X - X_{\max})\right)^{\frac{1}{R^2}}$$

- More mass separation than X_{max} alone
- Sensitivity to hadronic interaction models



Cosmic rays at LOFAR 2.0

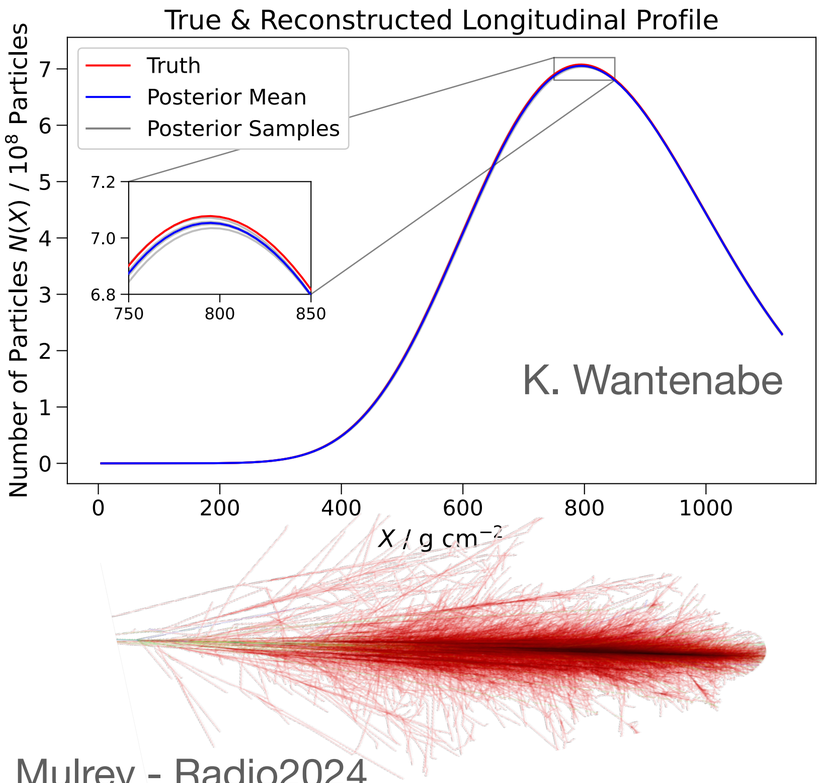
- Key improvements:
  - ***Statistics:***
    simultaneous observations for all antenna sets (10x increase)
  - ***Shower development:***
    un-beamformed HBA antennas
  - ***Low energy showers:***
    increased network speed



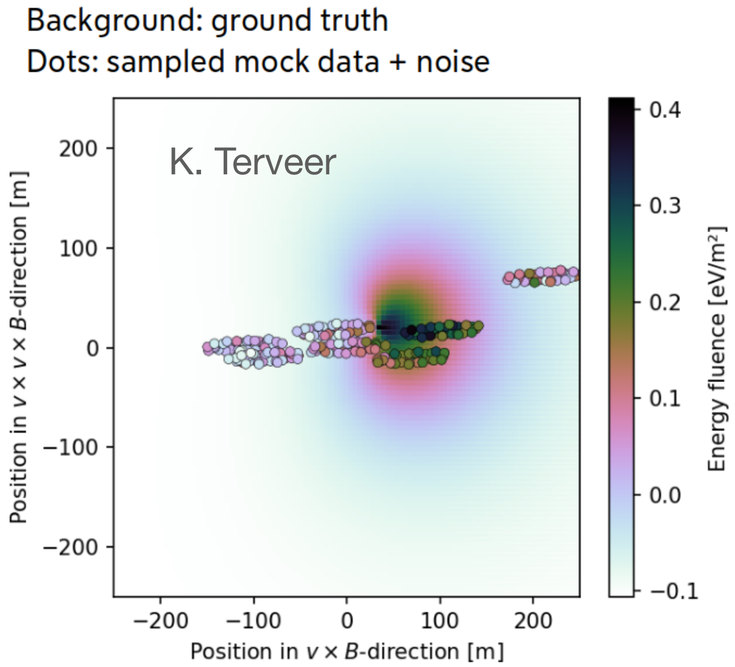
A. Nelles, 2015

Cosmic rays at LOFAR 2.0

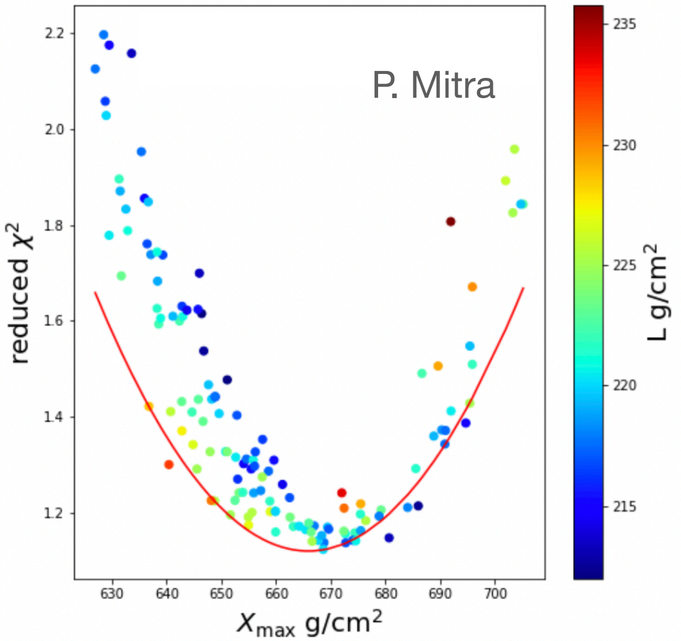
Reconstruction of the air shower profile using IFT



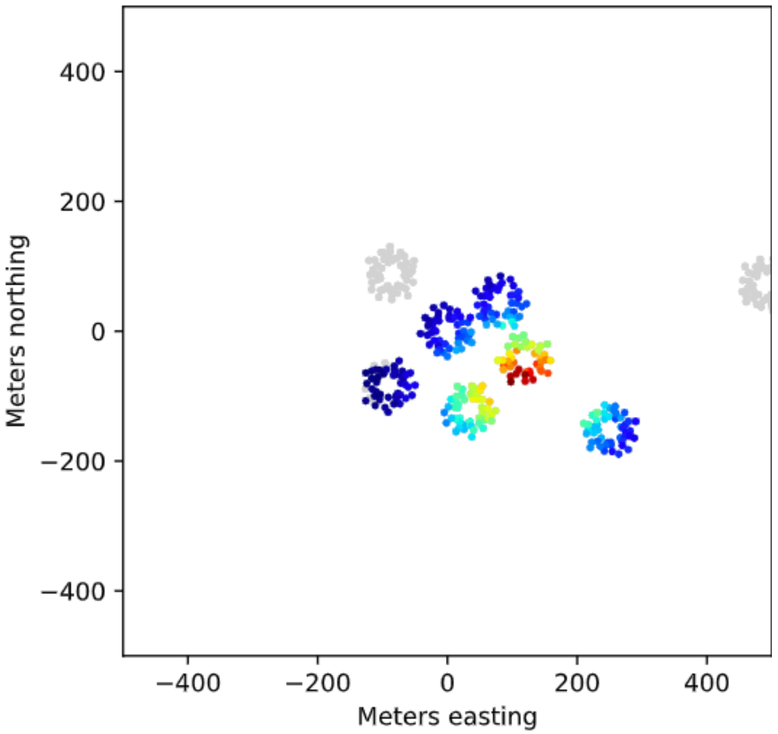
IFT reconstruction of the radio footprint

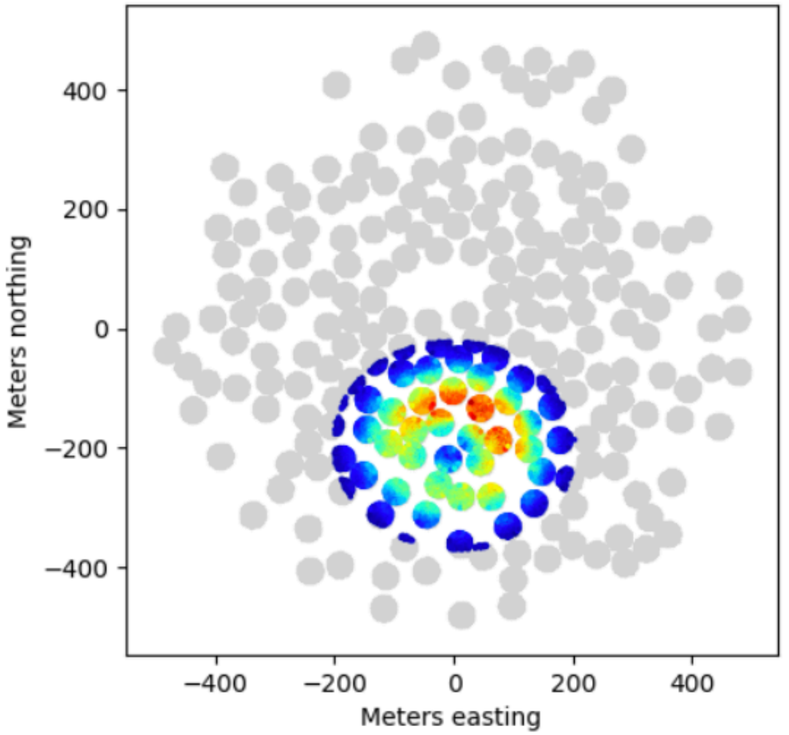


LOFAR sensitivity to the air shower profile

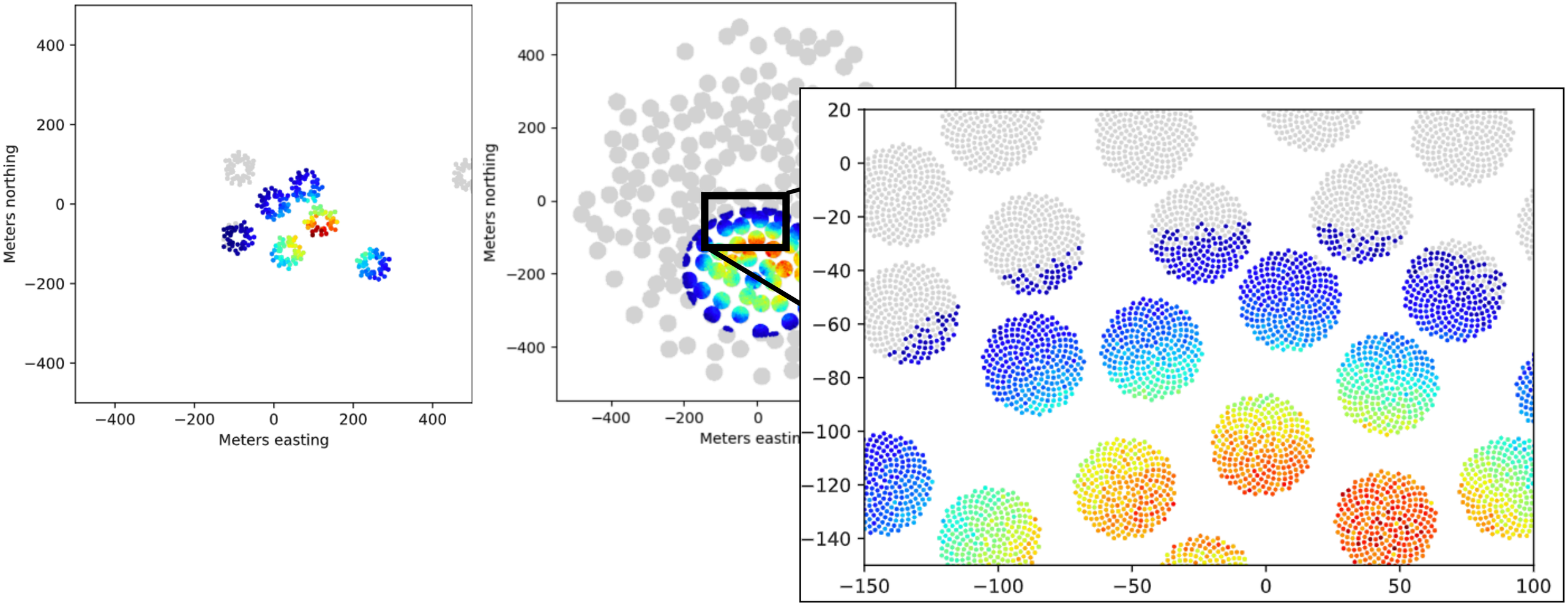


Cosmic rays at the SKA



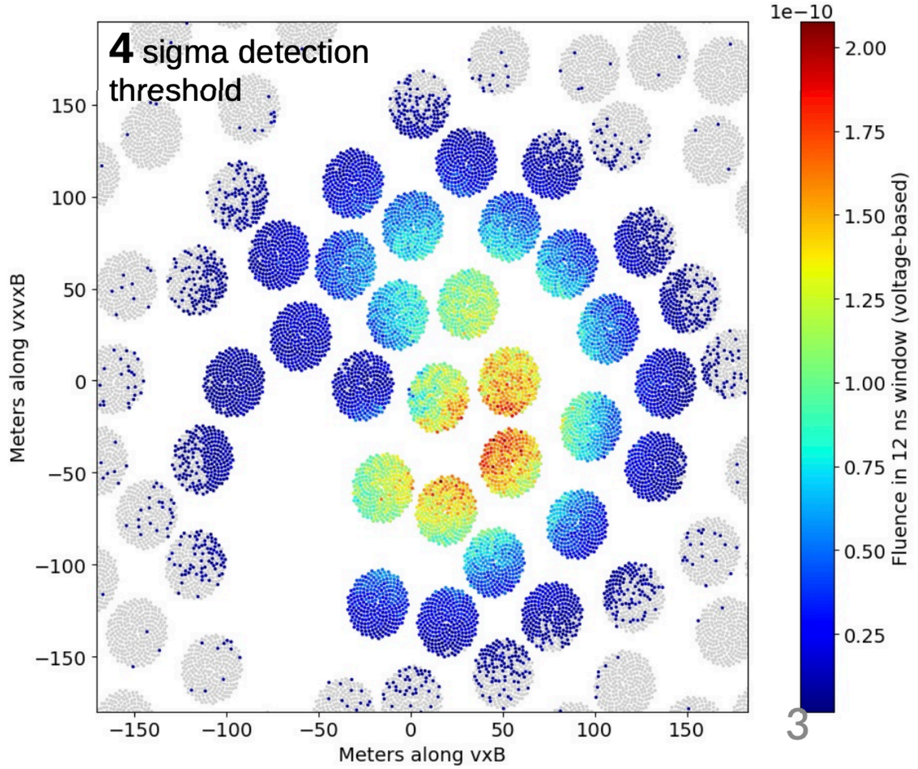


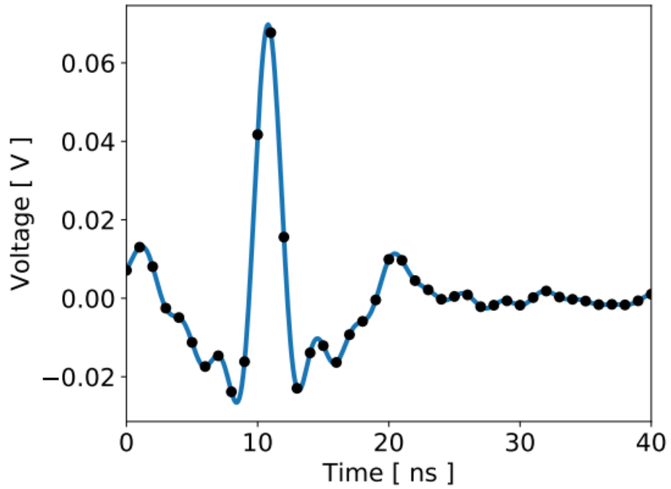
Cosmic rays at the SKA



Cosmic rays at the SKA

Standard X_{max} reconstruction



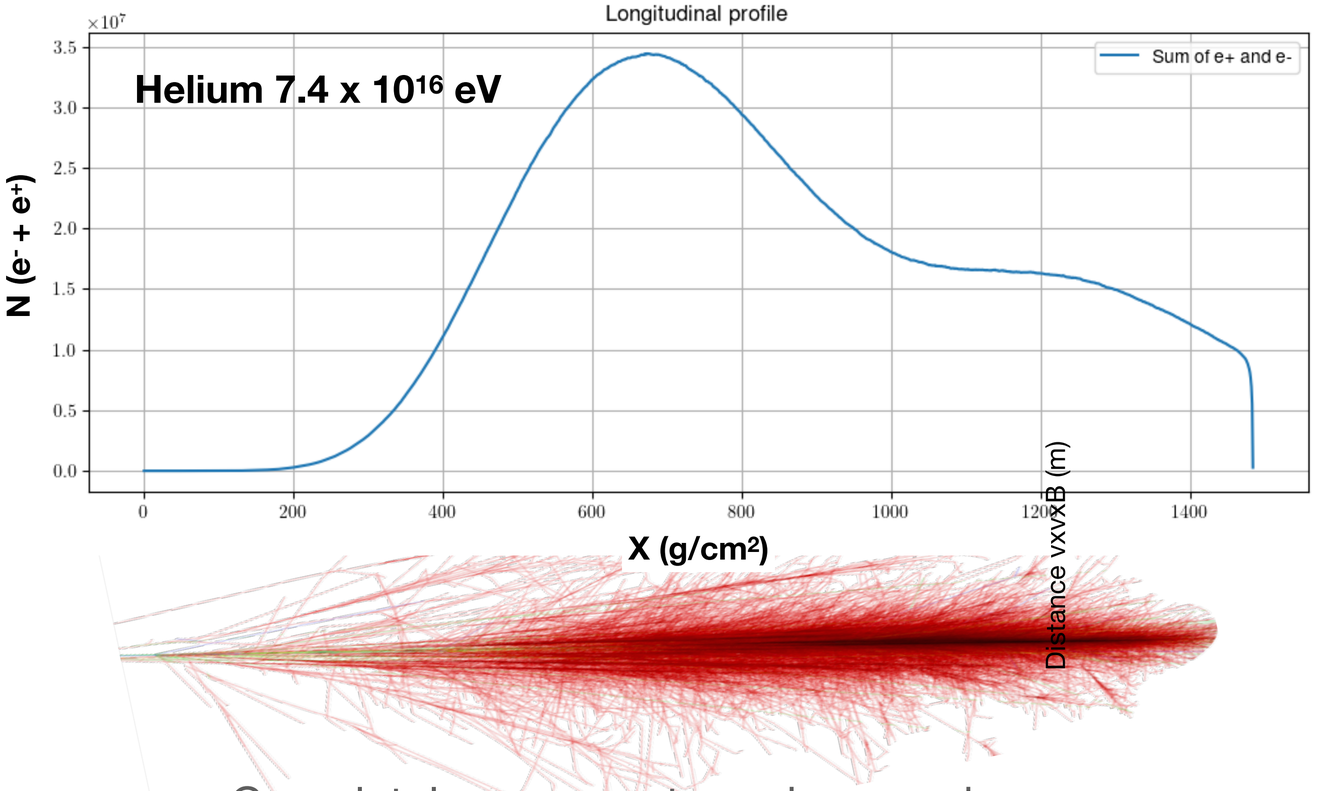


	SKA (simulated)	LOFAR
X_{max} resolution	: **6 - 8 g/cm²**	20 g/cm²
Energy resolution	: **3 %**	9 %
Core resolution	: **50 cm**	3 – 10 m

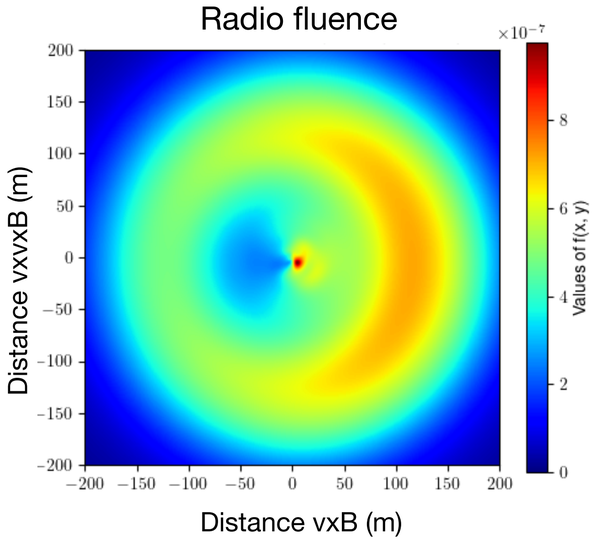
+ L parameter

A. Corstanje et al., PoS(ARENA2022)024

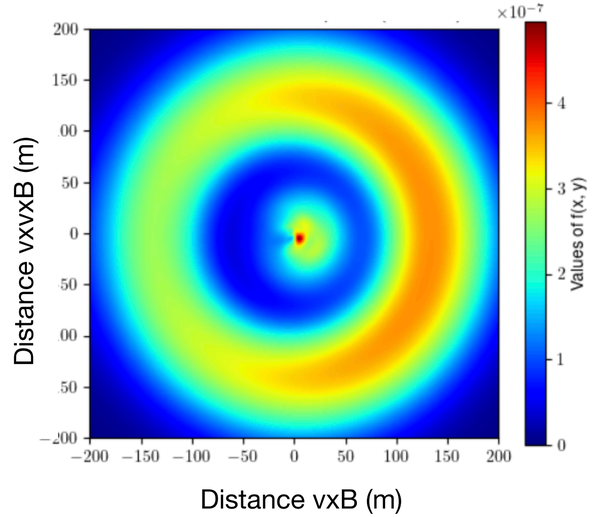
Cosmic rays at the SKA



- Completely new way to probe cosmic ray composition and high energy hadronic interactions.
- Can the SKA measure this?

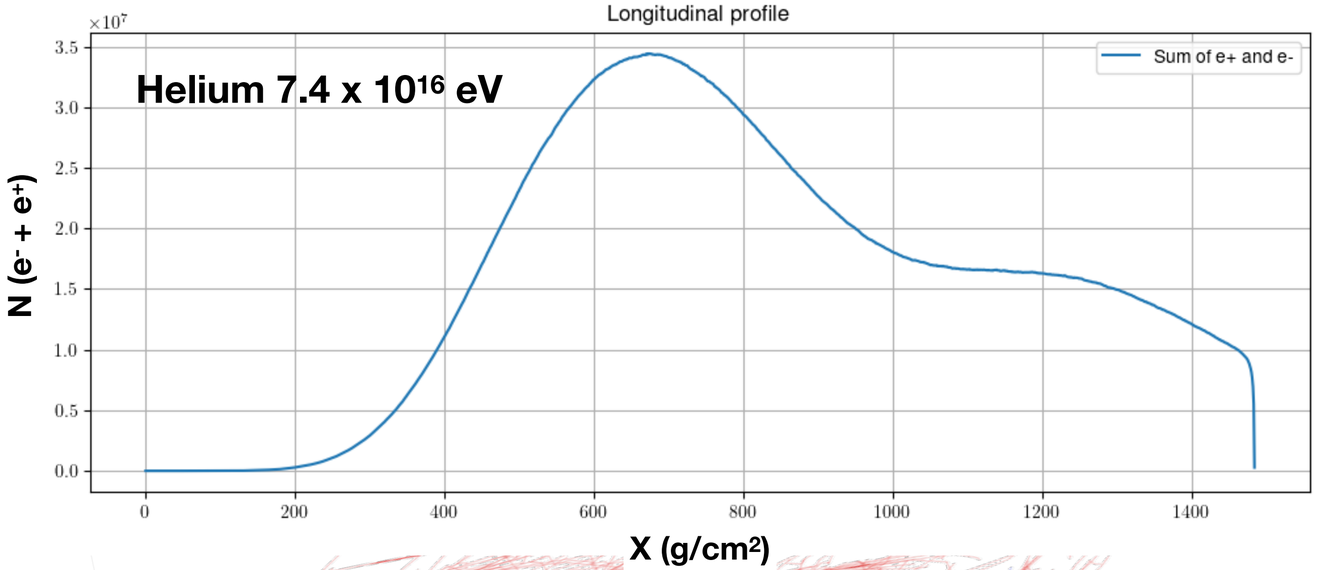


CORSIKA simulated E-field (full band: 50-350 MHZ)



High band: 150-350 MHz

Cosmic rays at the SKA



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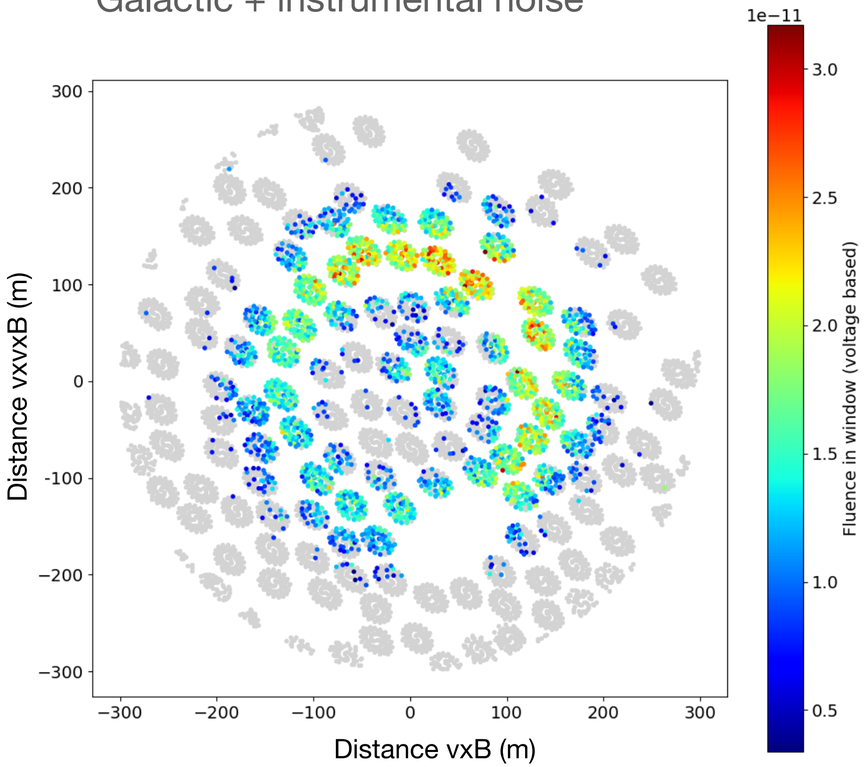
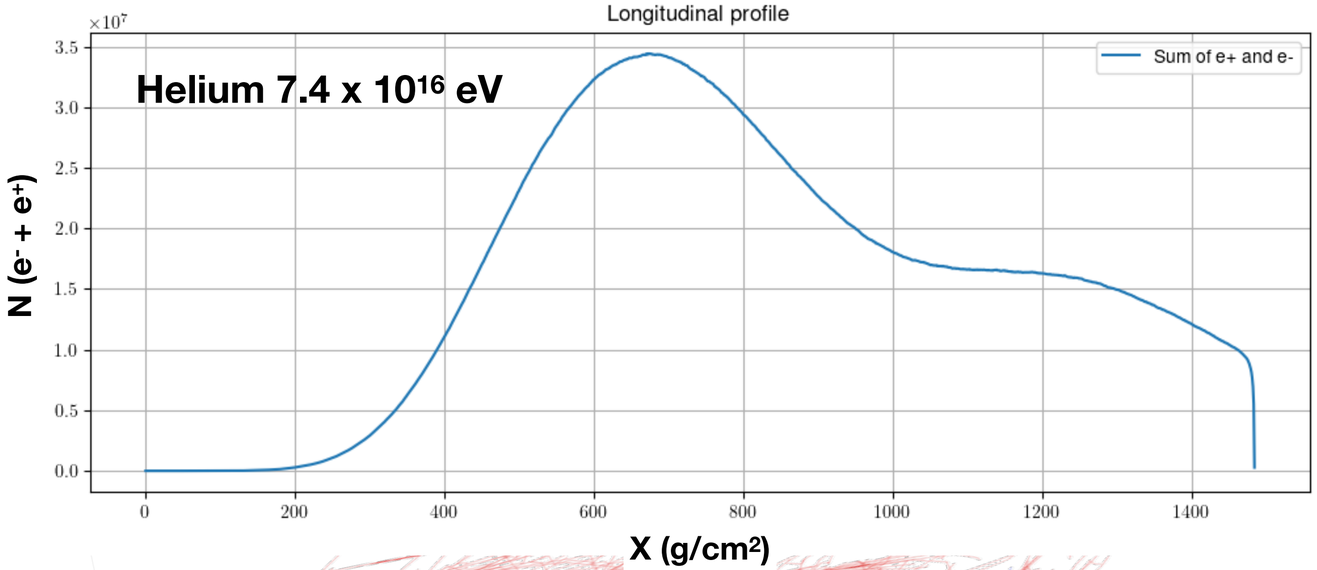
Full simulation including:
Antenna response
Galactic + instrumental noise



Antenna decimation factor 4
SNR increase 2

Cosmic rays at the SKA



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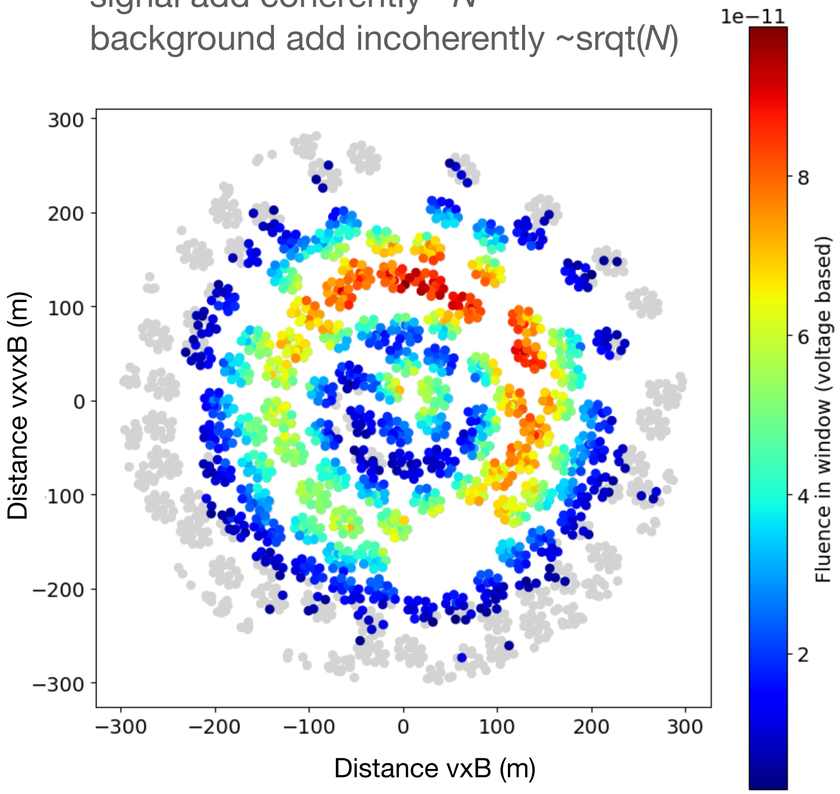
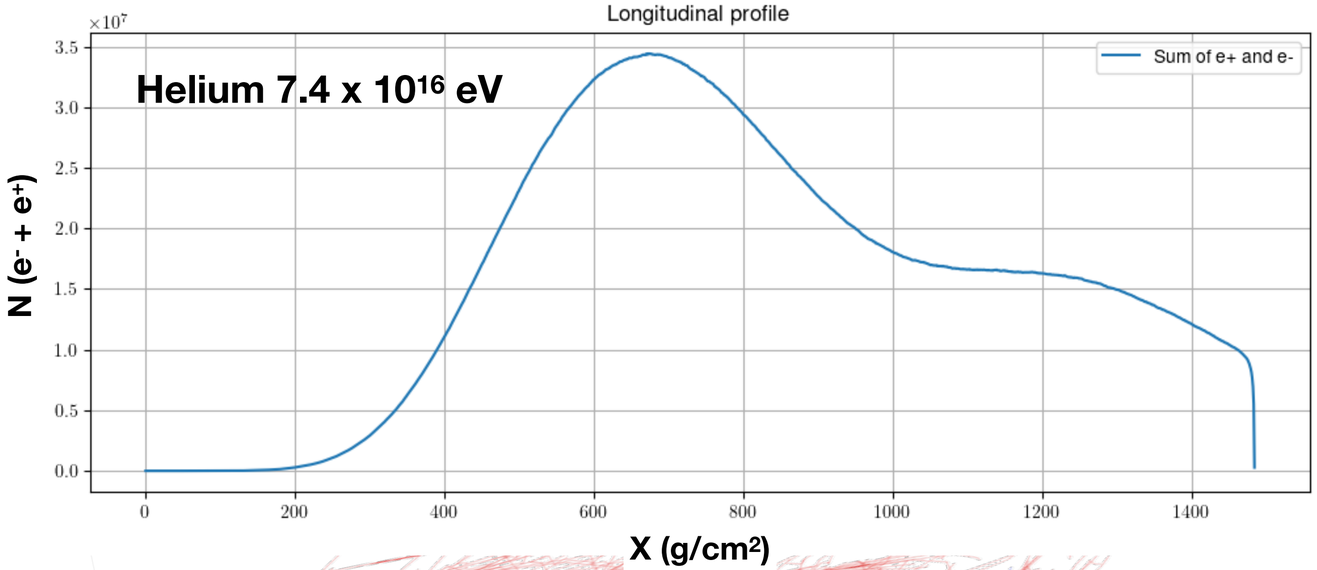
Beamforming:

add waveforms from *N* antennas
signal add coherently ~*N*
background add incoherently ~srqt(*N*)



Antenna decimation factor 16
SNR increase 4

Cosmic rays at the SKA



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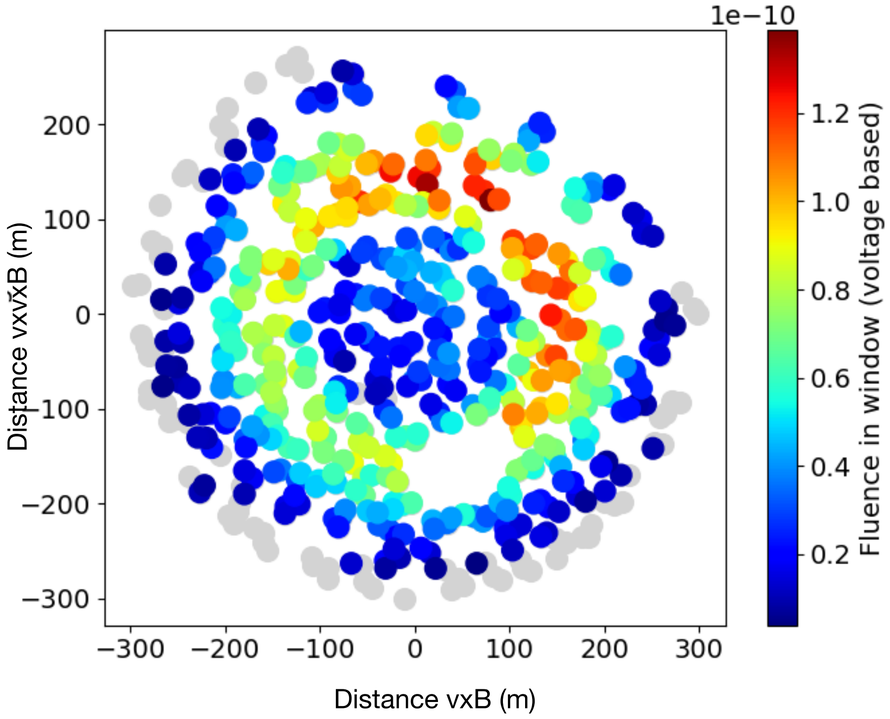
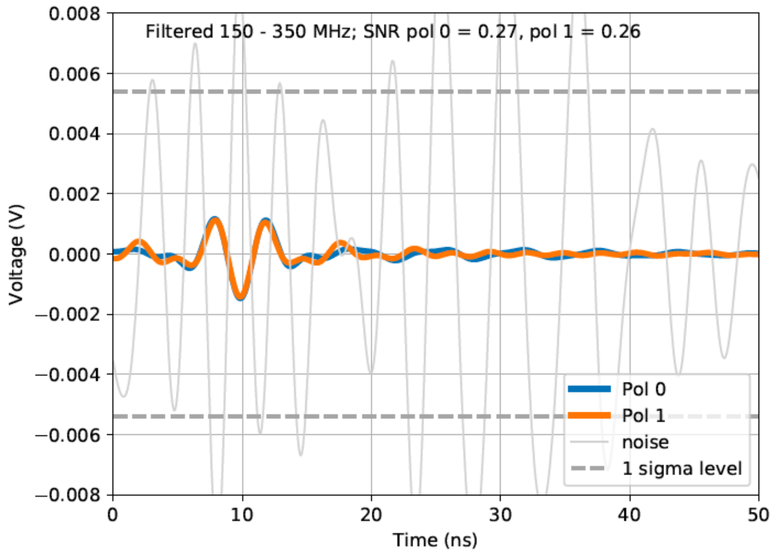


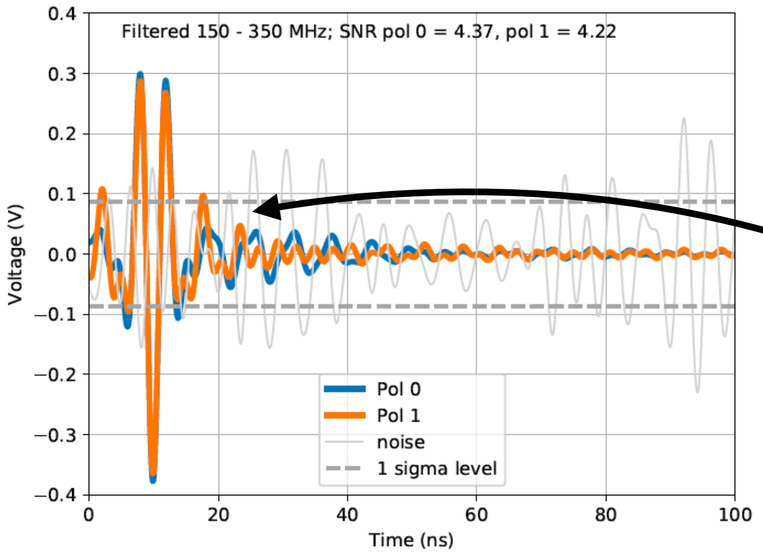
Antenna decimation factor 64
SNR increase

Cosmic rays at the SKA

High antenna number → very low energies (10^{15} eV)

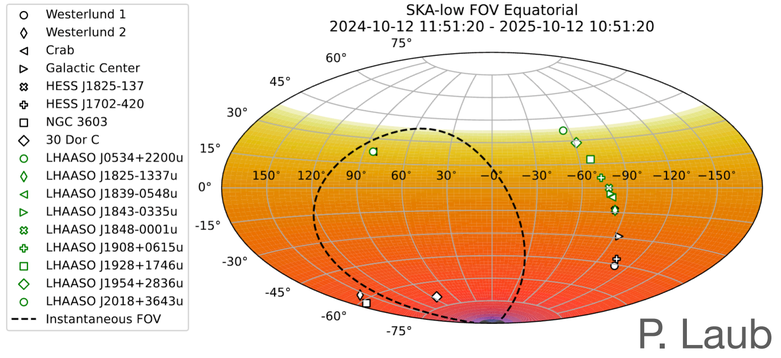


Radio pulse of PeV shower
filtered 150-350 MHz
SNR = 0.27

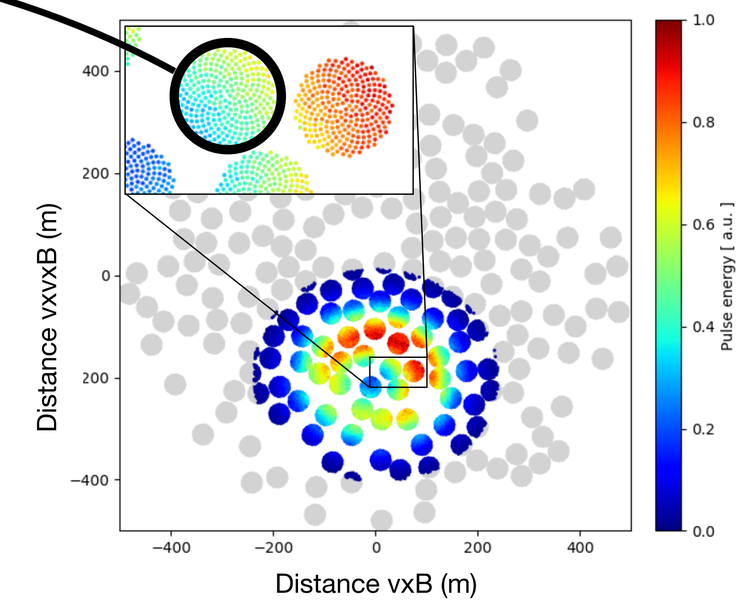


Beamformed with single field
filtered 150-350 MHz
SNR = 4.37

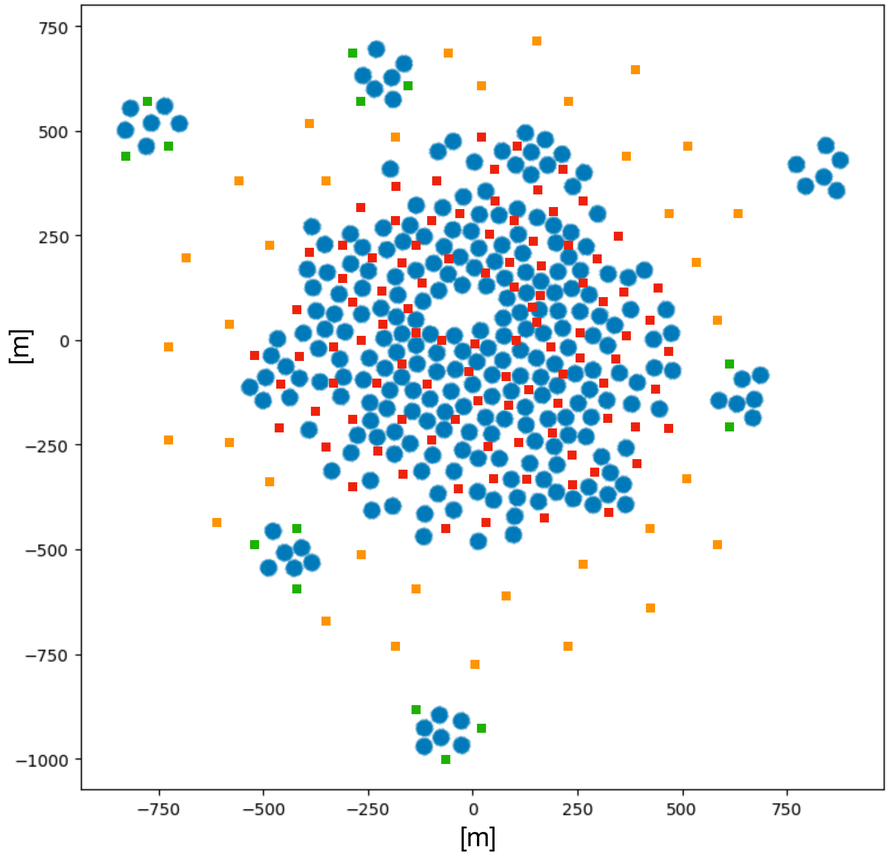
Gamma rays?



P. Laub



Cosmic rays at the SKA



Potential layout of particle detector array at SKA-low

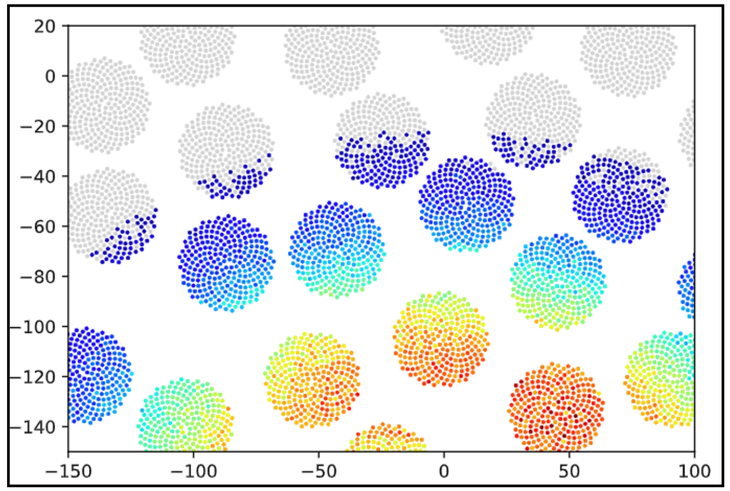
- Antenna field
- Particle detectors dense array (~100 units)
- Particle detectors ring (~50 units, optional)
- Particle detectors remote (~18 units, optional)

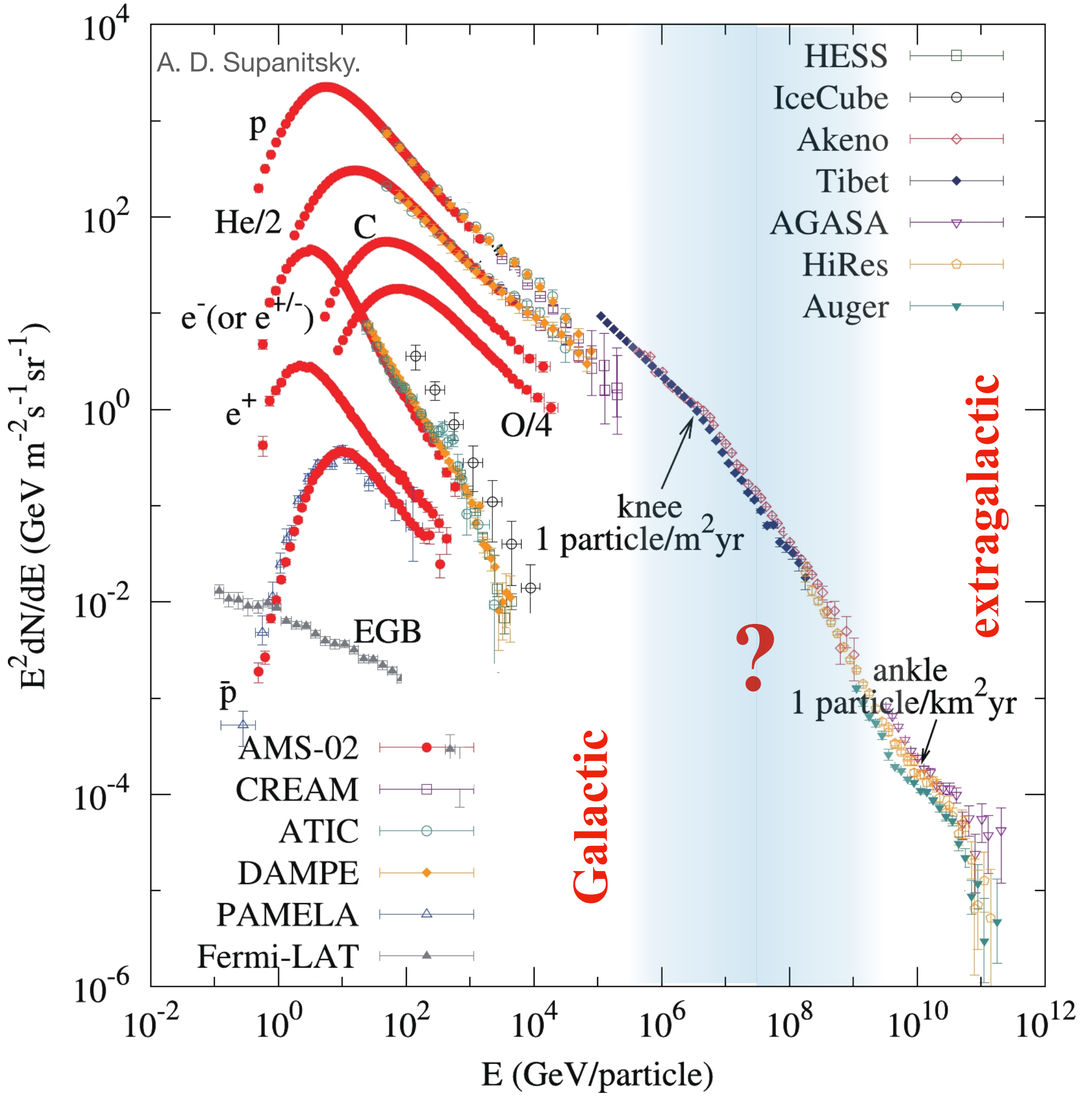
Prototype station @ Murchison Widefield Array (J. Bray et al., NIMPA 973, id. 164168 (2020))

2024: funding for CRs @ SKA!

Conclusions

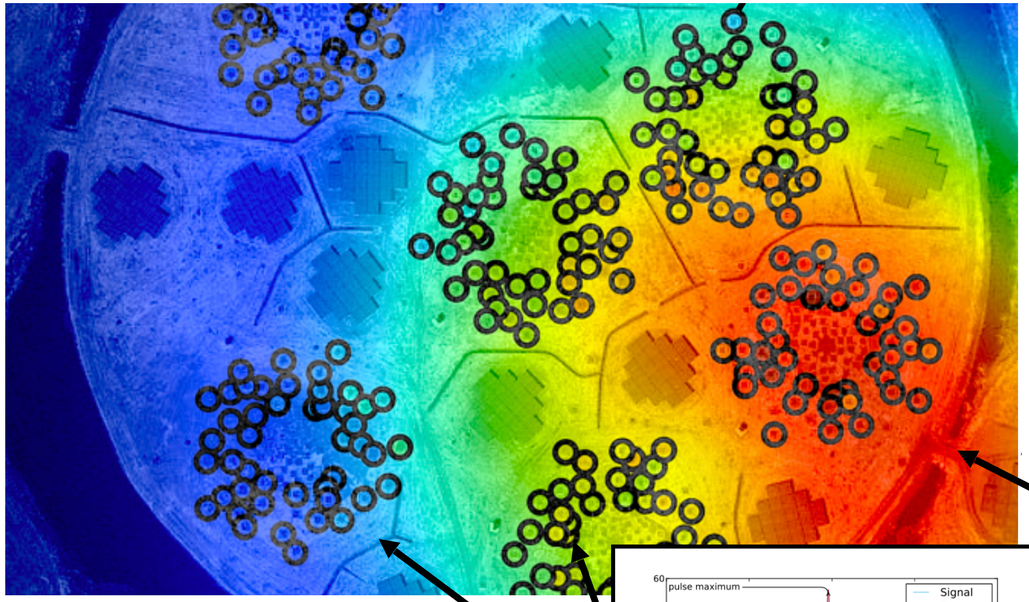
- After a decade of LOFAR observations, LOFAR2.0 & SKA will let us continue do precision air shower reconstructions throughout the transition region
- Key ***unique*** improvements: bandwidth, antenna density, statistics
- Vital input (composition, energy) in the energy range of the highest energy Galactic accelerators



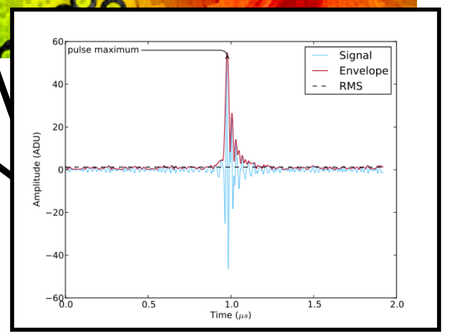


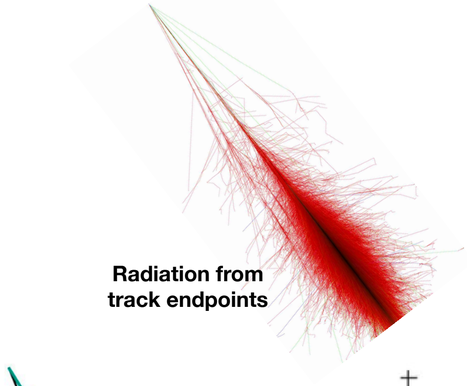
Thanks!

Event Reconstruction



SB et al. PRD 90 082003 (2014).





LOFAR data

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

CoREAS simulation

- no assumptions about emission
- independent of hadronic models

T. Huege et al. AIP Conf.Proc. 1535 (2013) no.1, 128

Event Reconstruction

- Simulate ~30 P and Fe showers with realistic atmosphere and known arrival direction (natural distribution of X_{max})
- Calculate reduced χ^2 for each simulation
- Parabola fit determines event X_{max}
- Resolution < 20 g/cm^2

$$\chi^2_{\text{radio}} = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}}\,(x_{\text{ant}} - x_0,\ y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2$$

$$E_{\text{radio}} = f_r \times E_{\text{sim}}$$

Free parameters: energy and core position