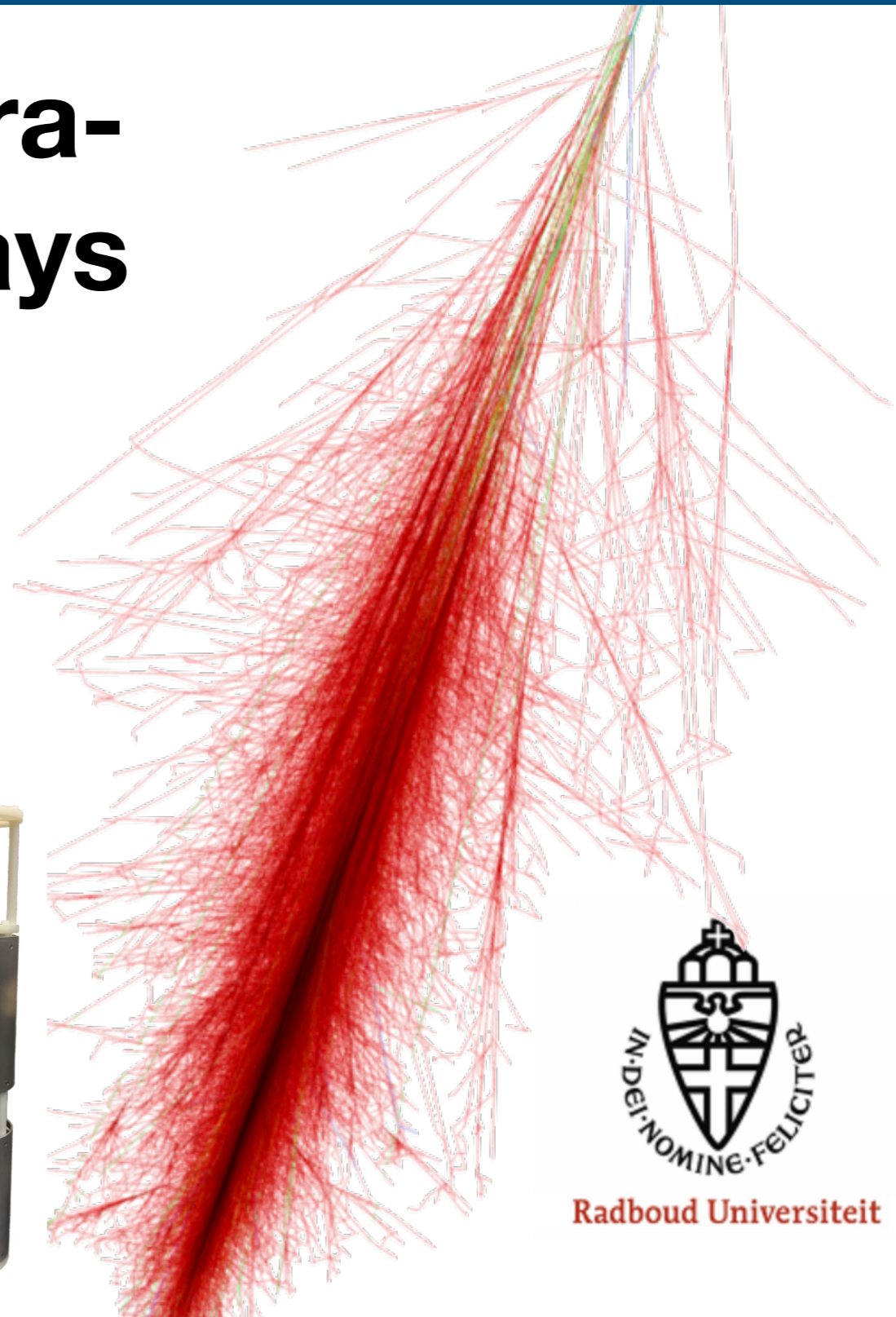
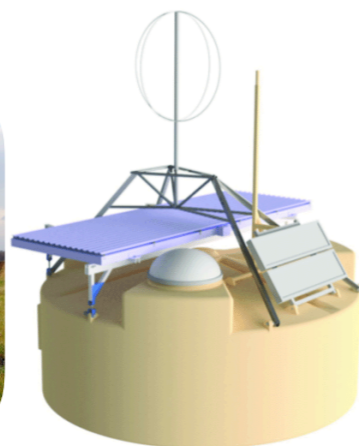


# Radio detection of ultra-high-energy cosmic rays and neutrinos

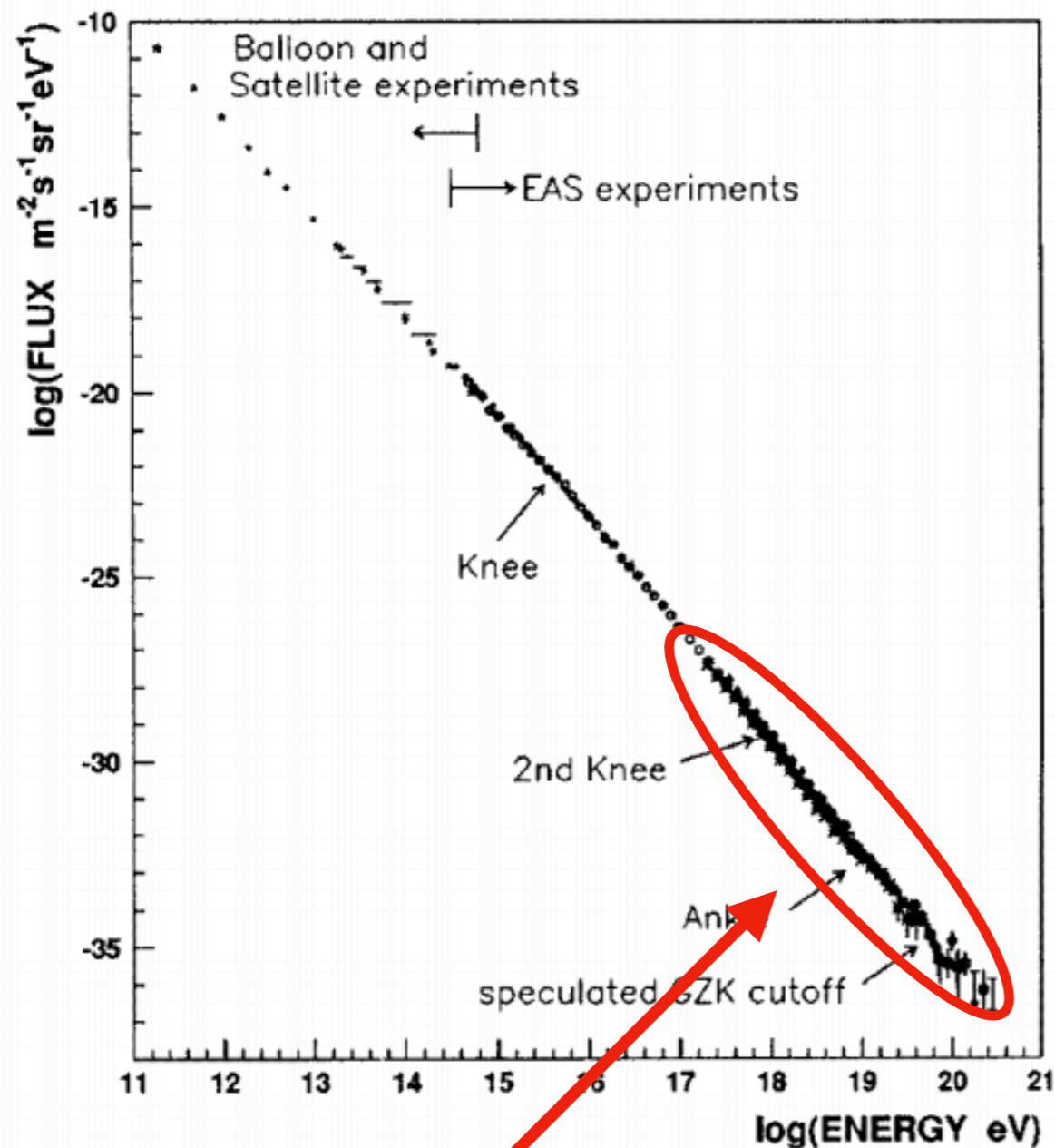
**Katharine Mulrey**  
13 September  
CRIS 2022



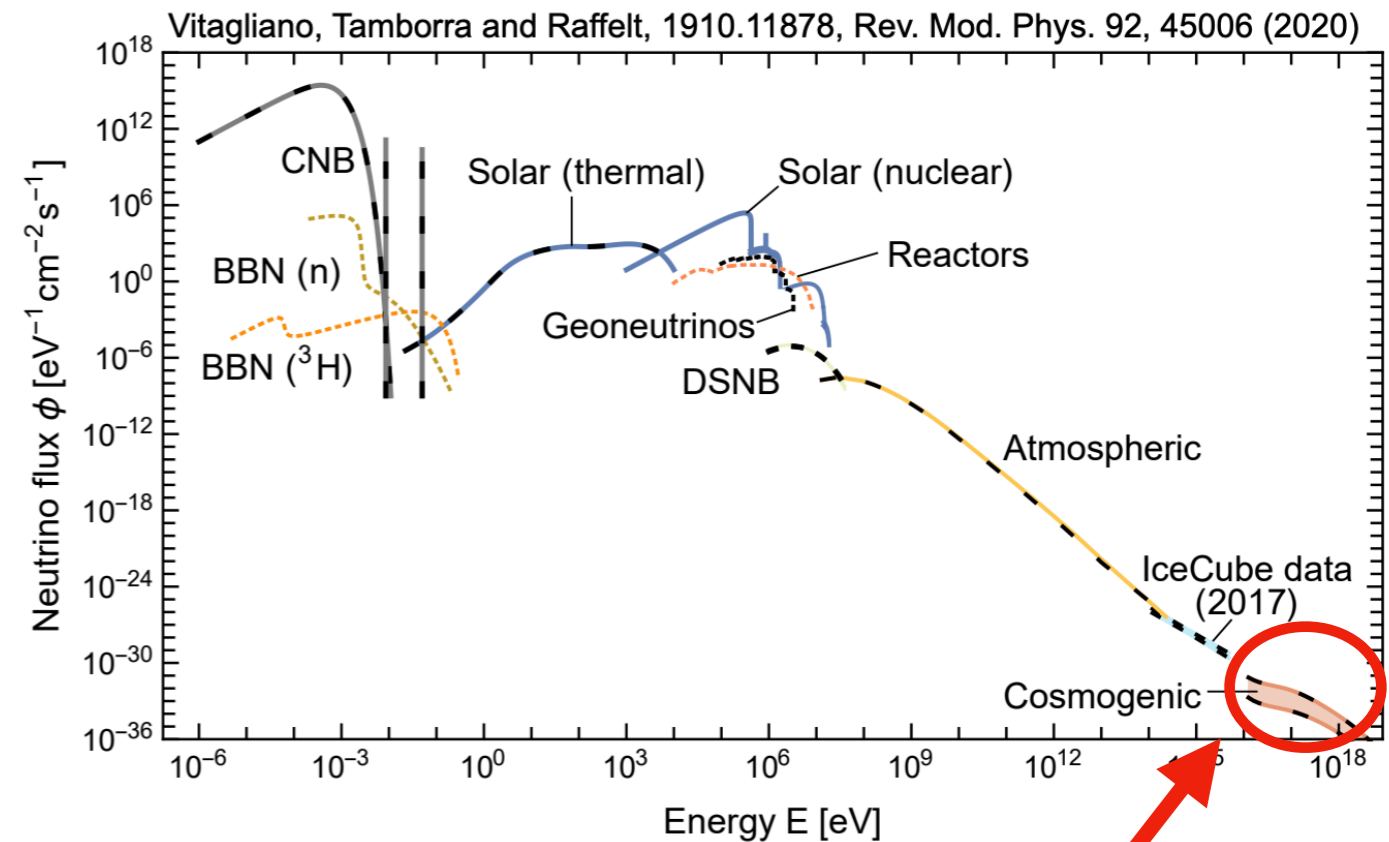
Radboud Universiteit

# Where do the most energetic particles come from?

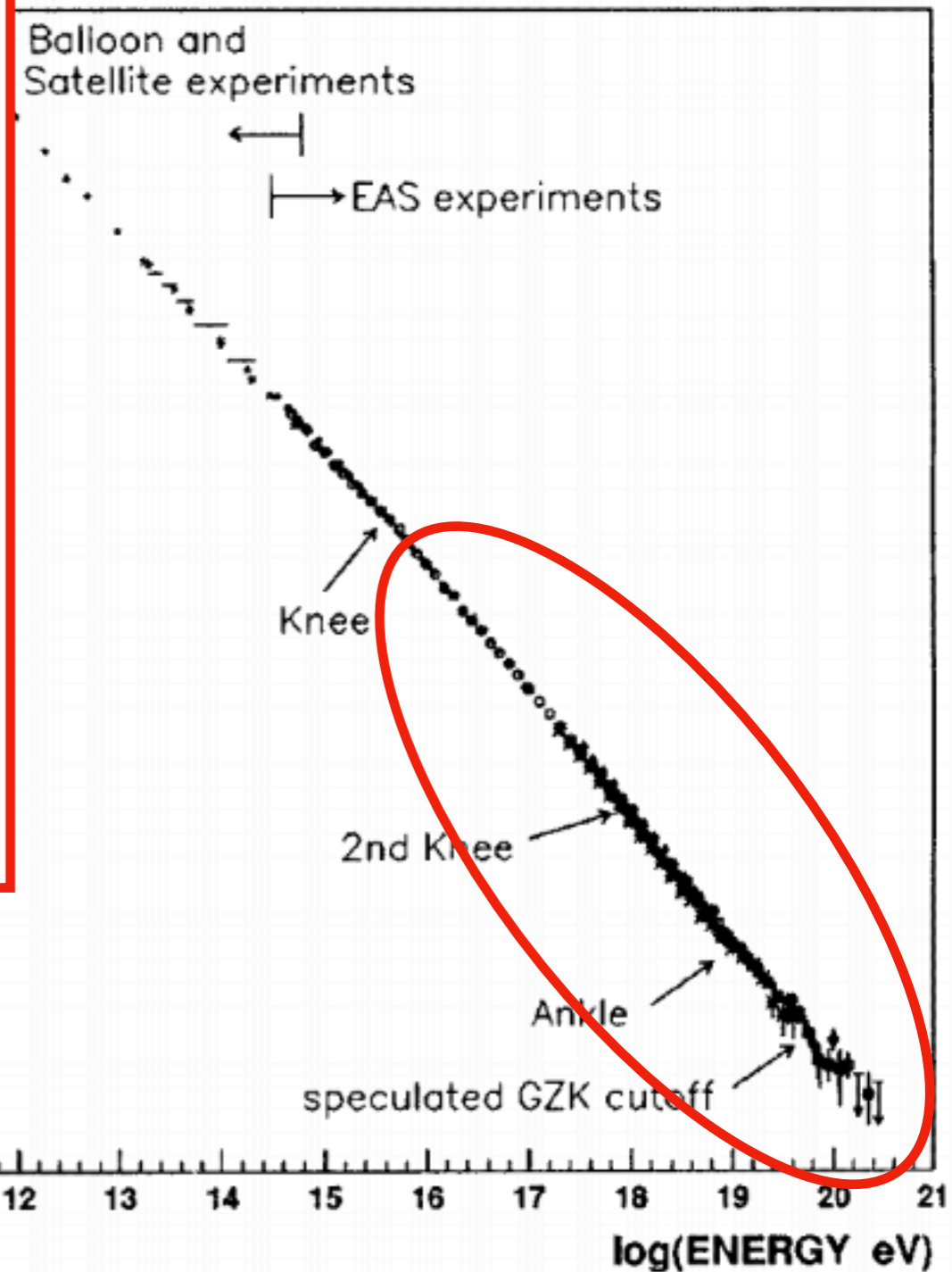
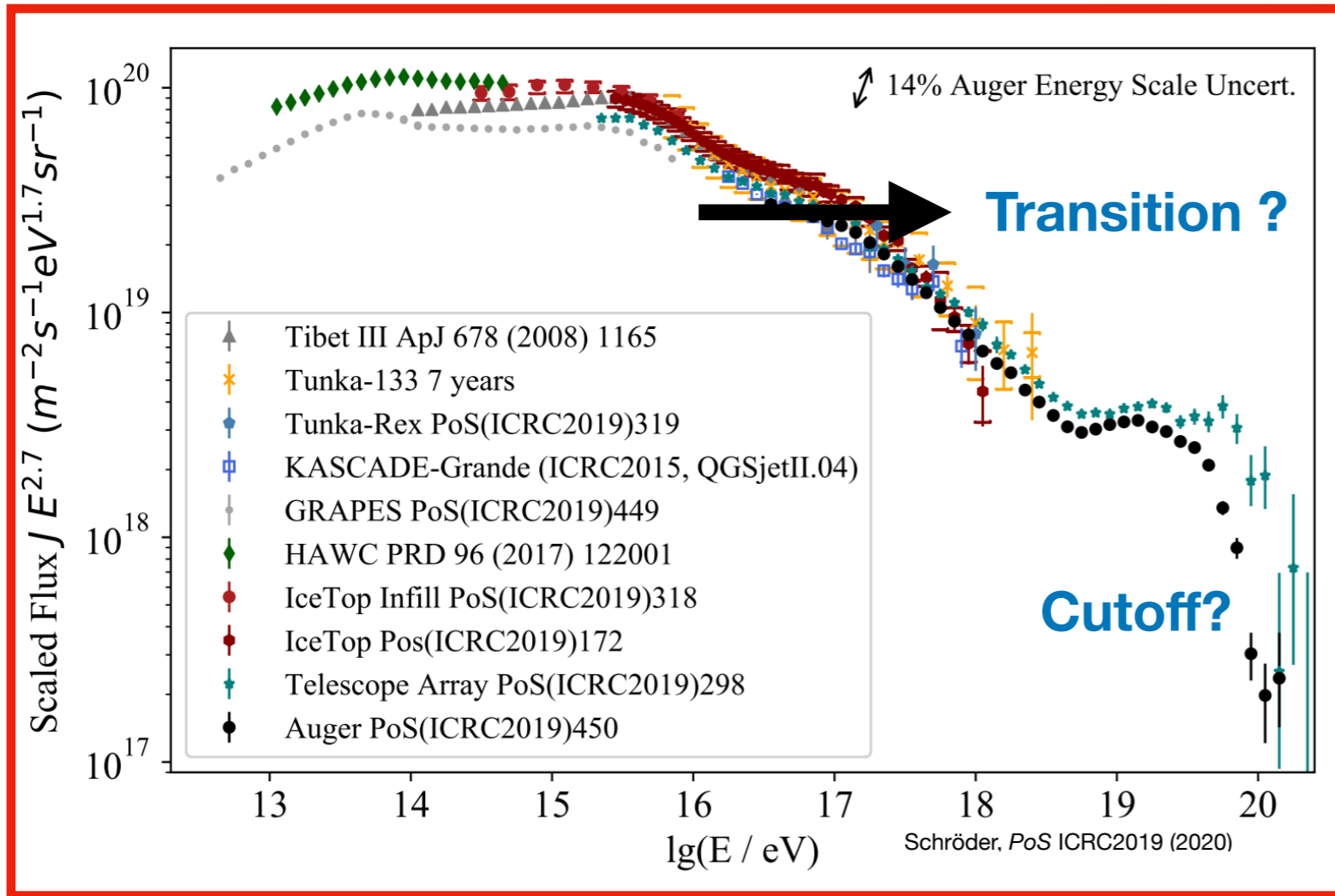
## Cosmic-ray Flux



## Neutrino Flux

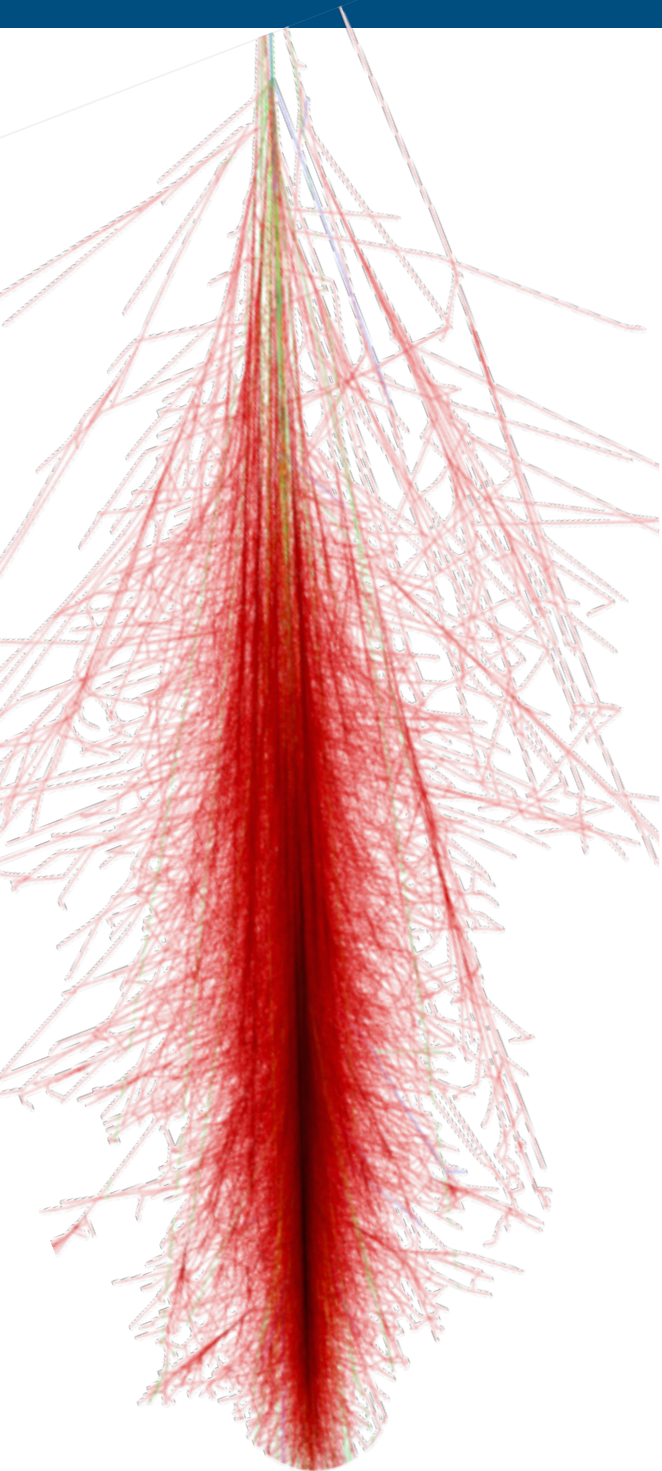


# Where do the most energetic particles come from?

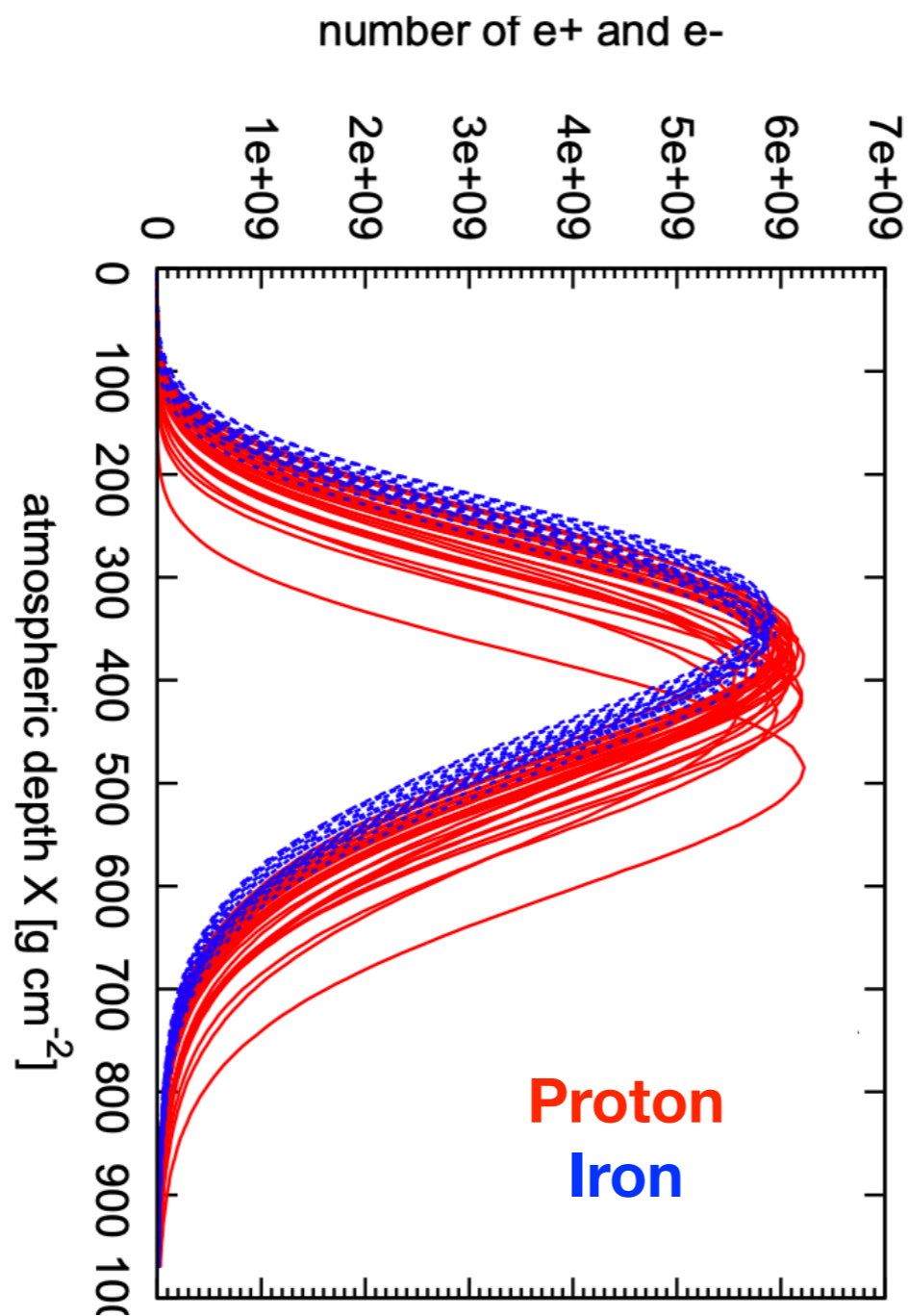


- Where is the transition from Galactic to extragalactic sources?
- Is the cut off due to sources or GZK / photo disintegration?
- Where are the UHE neutrinos?

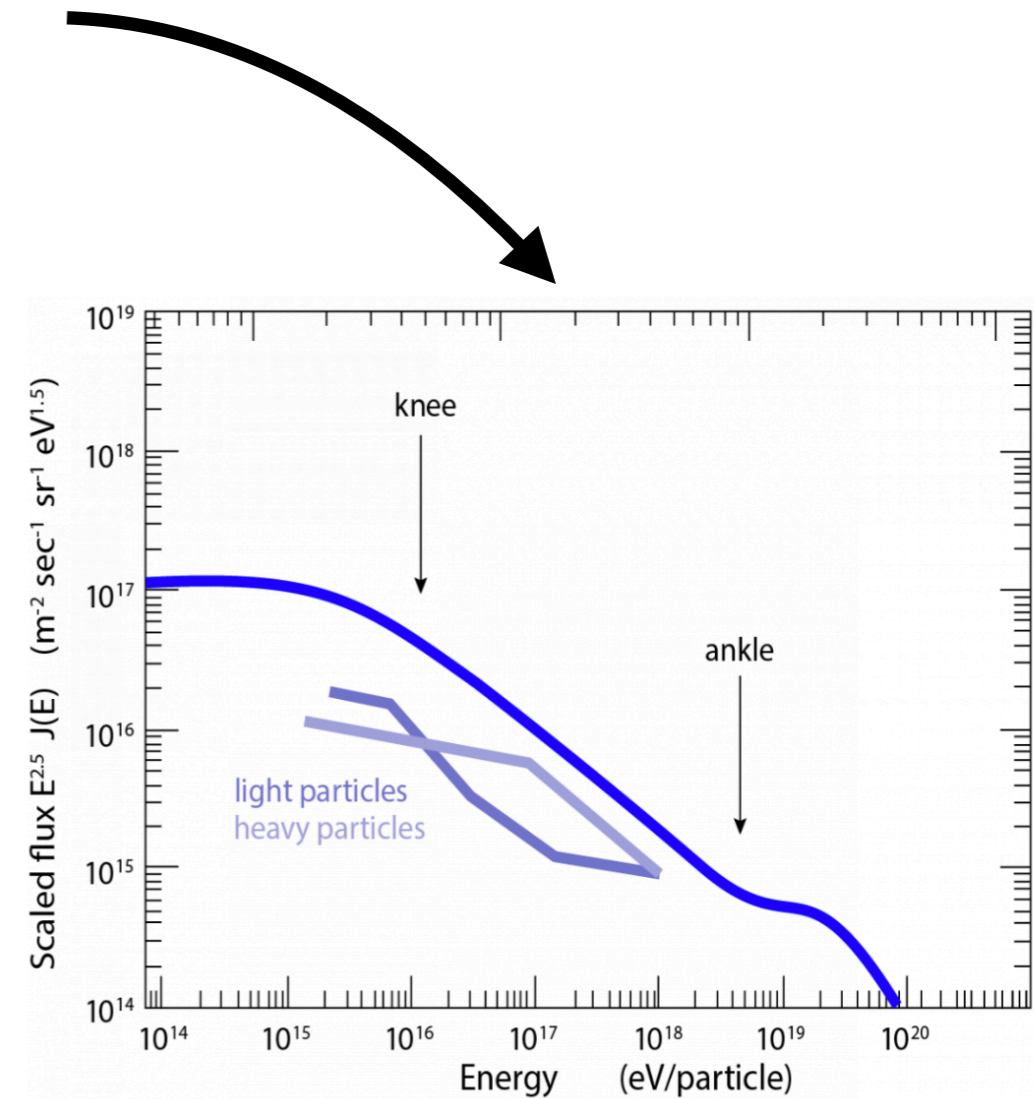
# Detecting cosmic-ray air showers



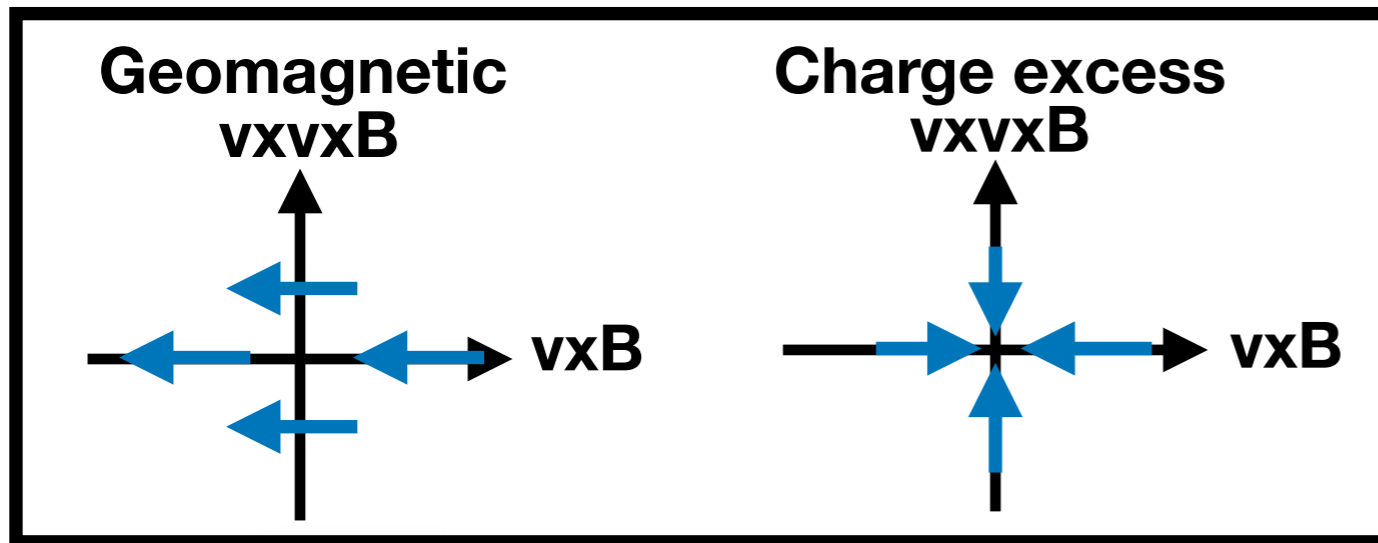
T. Huege.  
Physics Report  
620:1-52,2016



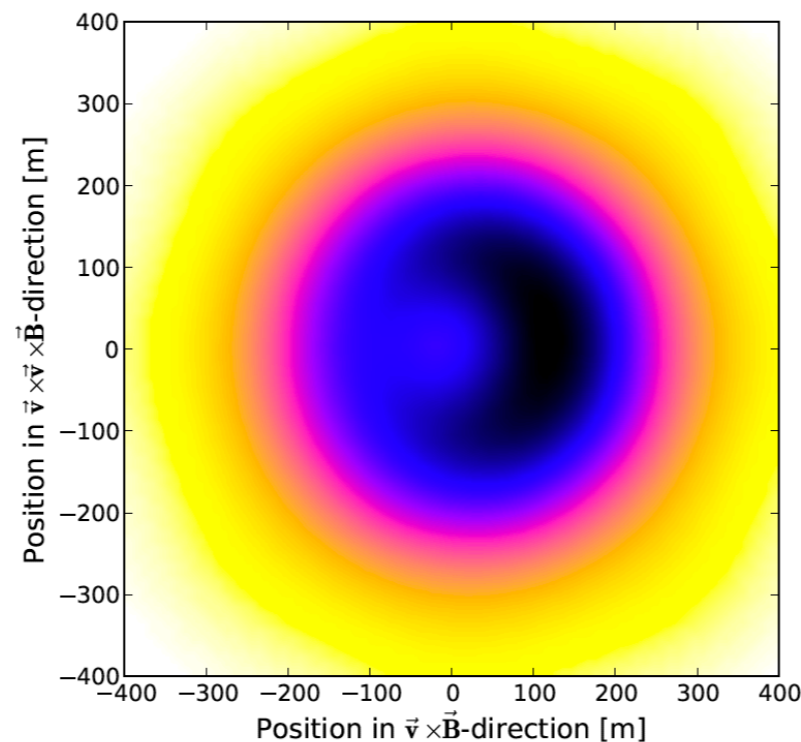
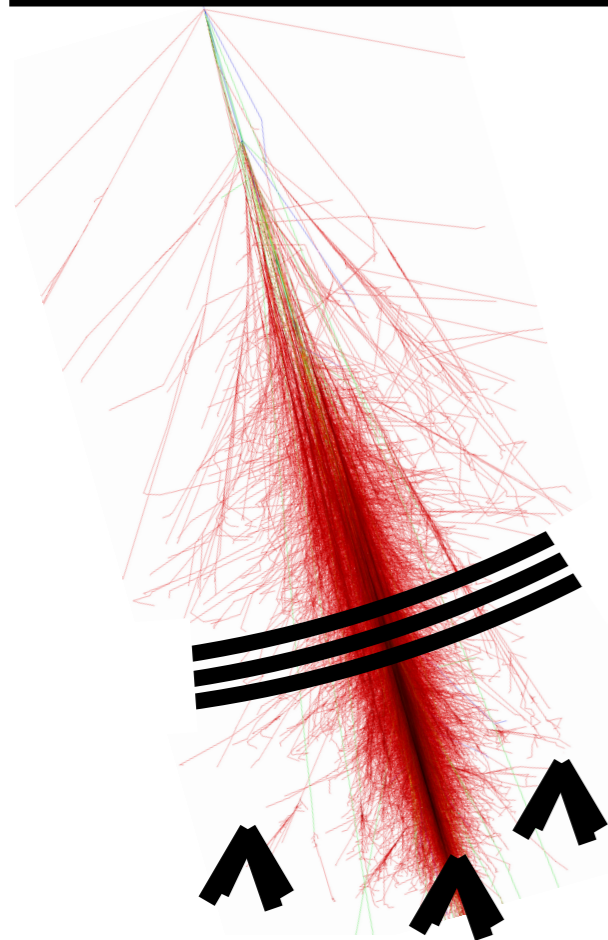
mass + energy + direction(?)  
( $X_{\max}$ )



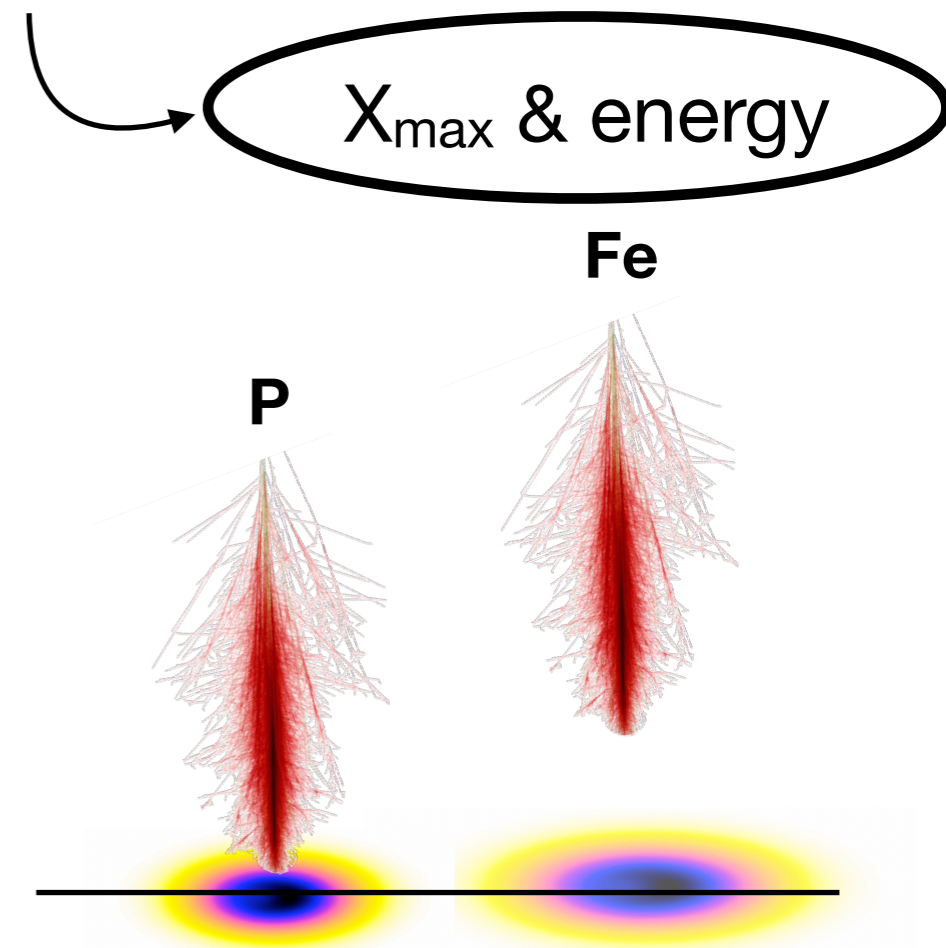
# Radio emission from air showers



- Generated in the electromagnetic components of the air shower
- Radiation pattern, signal strength, and pulse shapes contain information about shower development

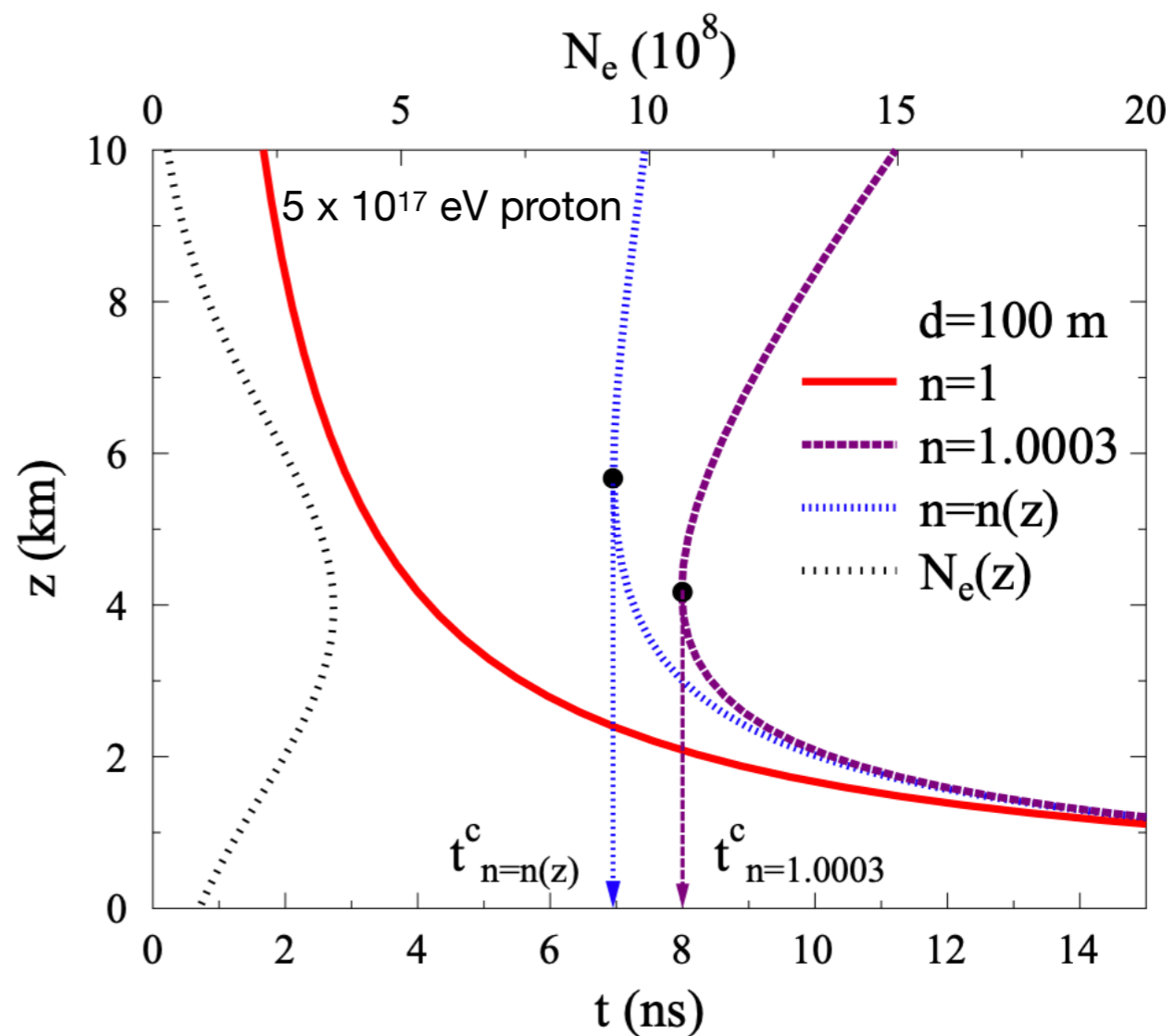
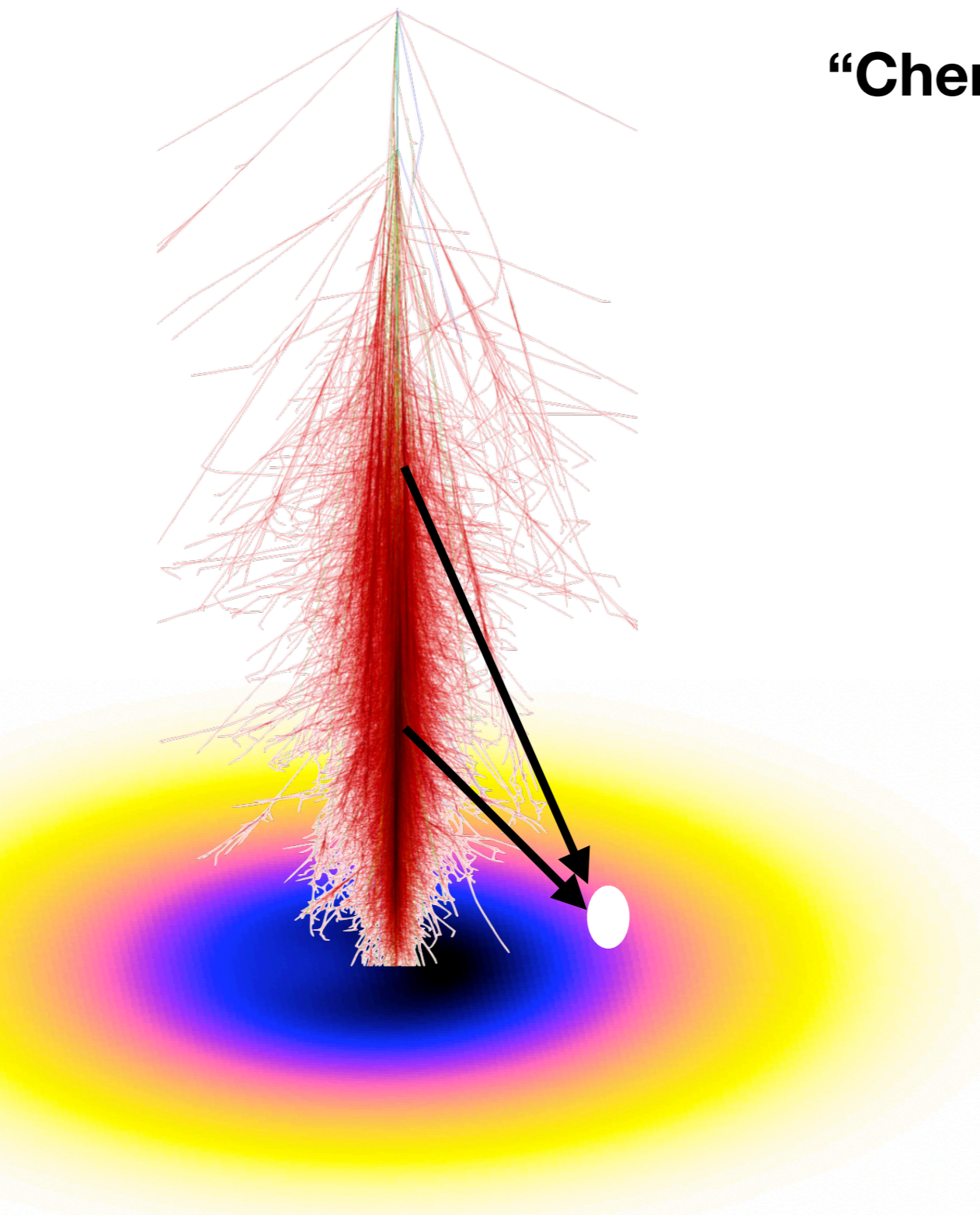


A. Nelles et al., Astropart. Phys. 60, 13 (2015)



# Radio emission from air showers

“Cherenkov-like” effects: signal coherence



de Vries et al. PRL 107:061101,2011

# Radio emission from “air showers” in the lab

Nature

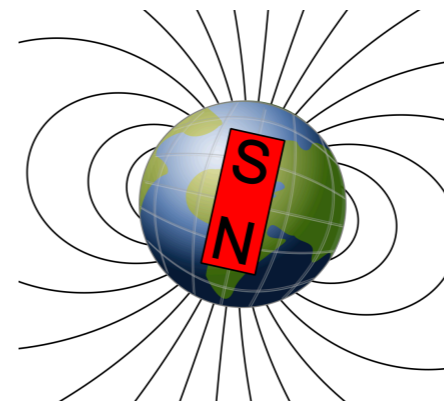
*Accelerator*



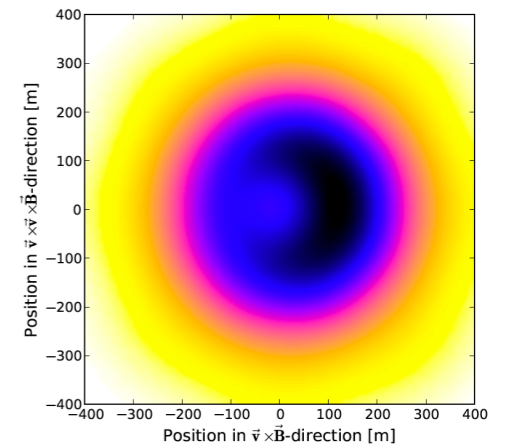
*Target*



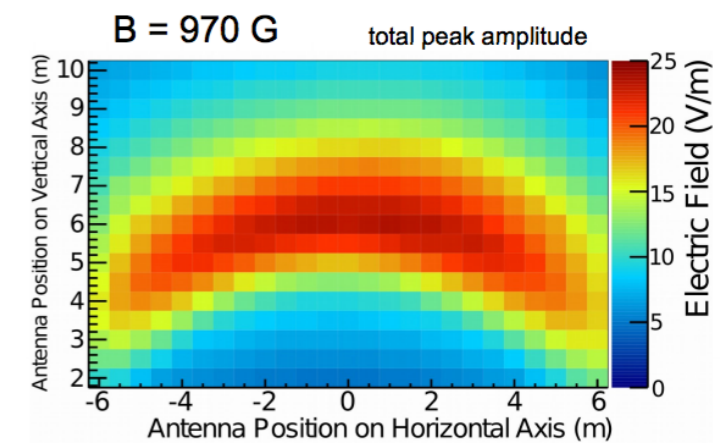
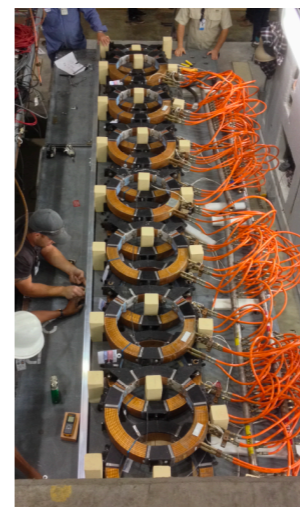
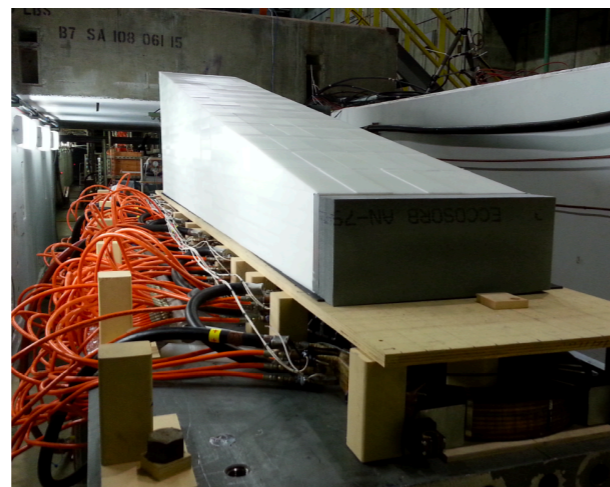
*Magnetic Field*



*Beam Pattern*



Lab

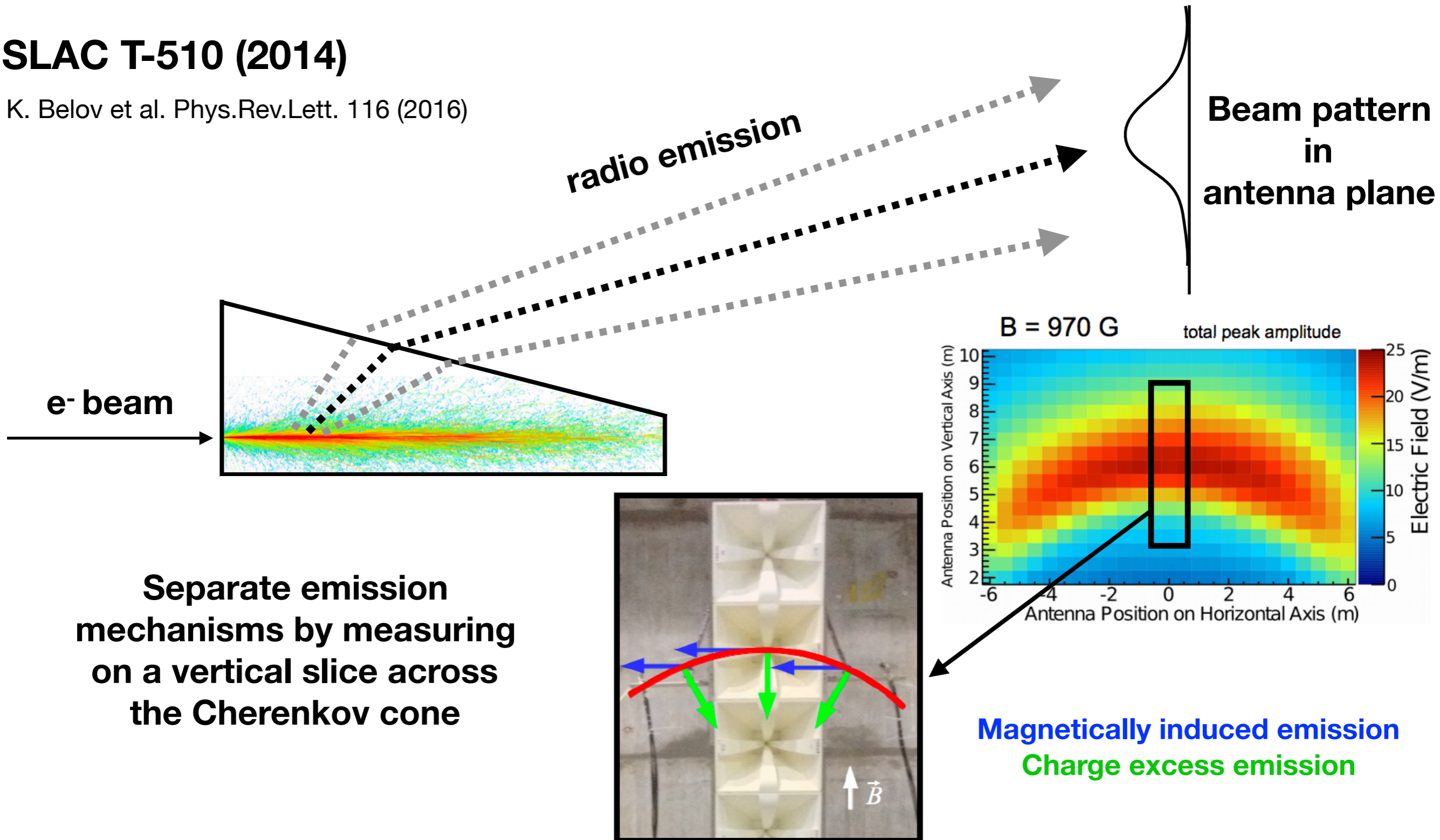


**SLAC T-510 (2014)**

# Radio emission from “air showers” in the lab

## SLAC T-510 (2014)

K. Belov et al. Phys.Rev.Lett. 116 (2016)



Separate emission mechanisms by measuring on a vertical slice across the Cherenkov cone

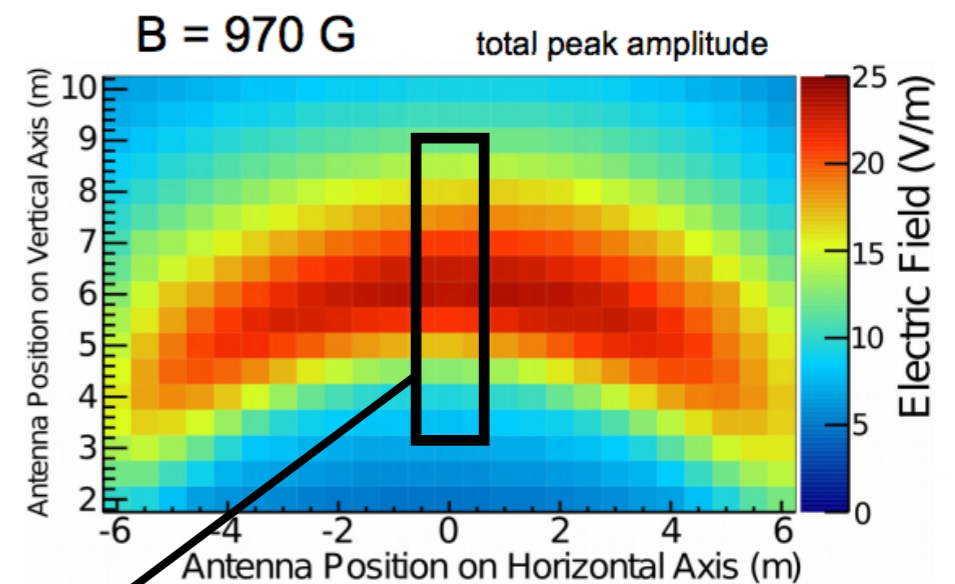
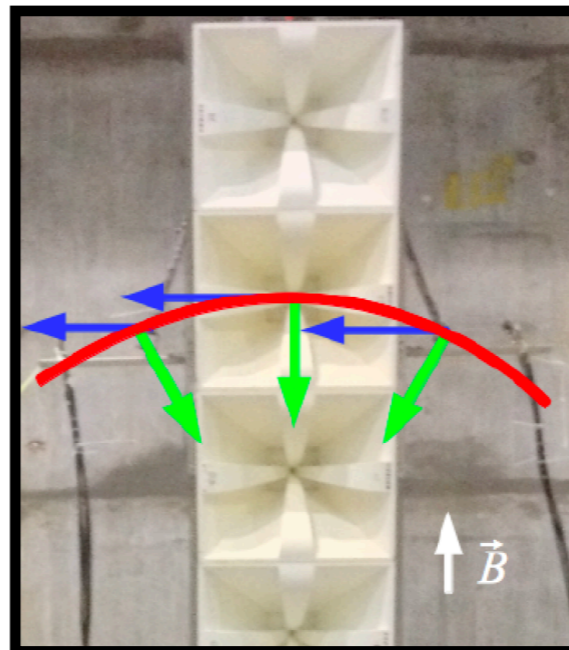
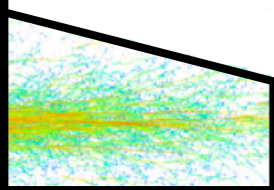
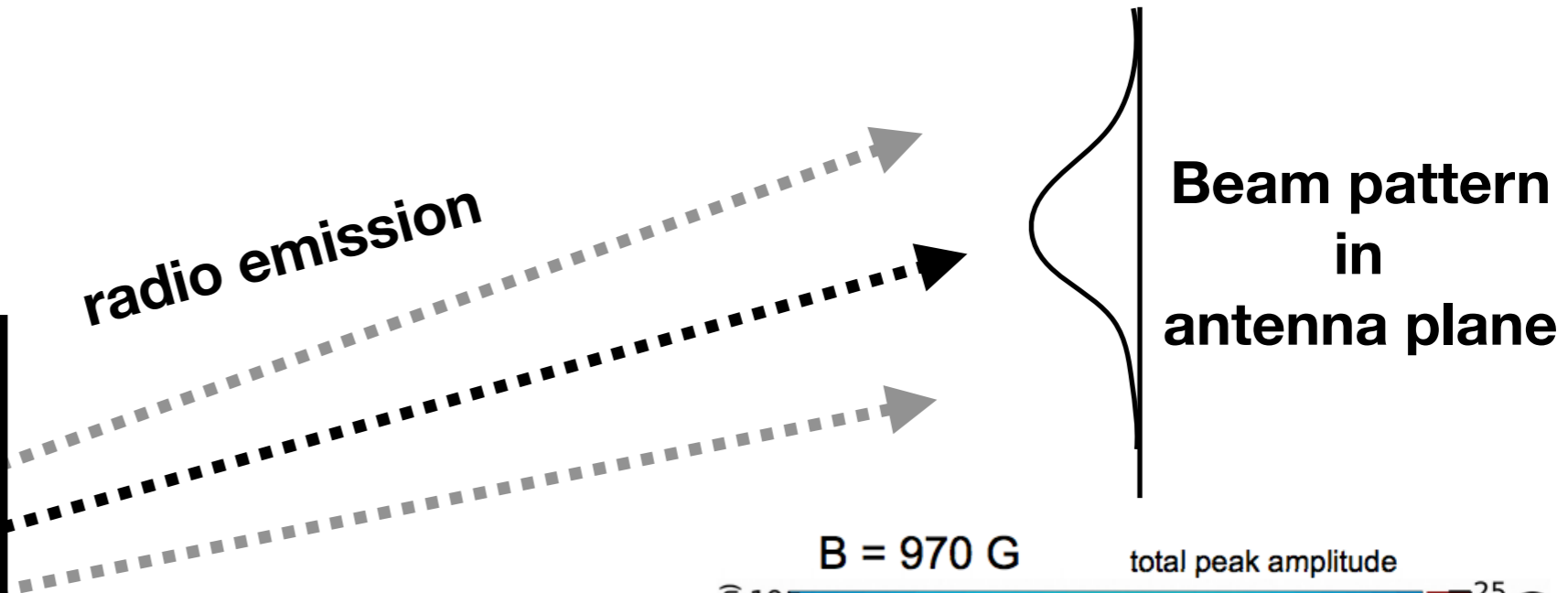
Magnetically induced emission  
Charge excess emission



# Radio emission from “air showers” in the lab

## SLAC T-510 (2014)

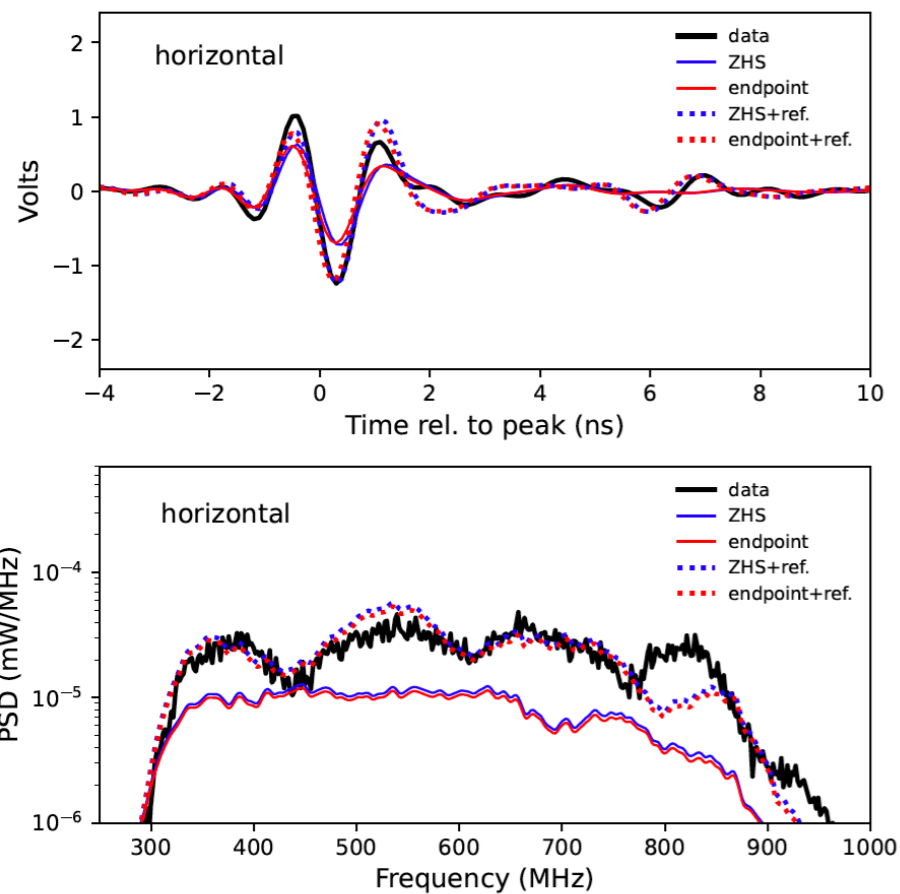
K. Belov et al. Phys.Rev.Lett. 116 (2016)



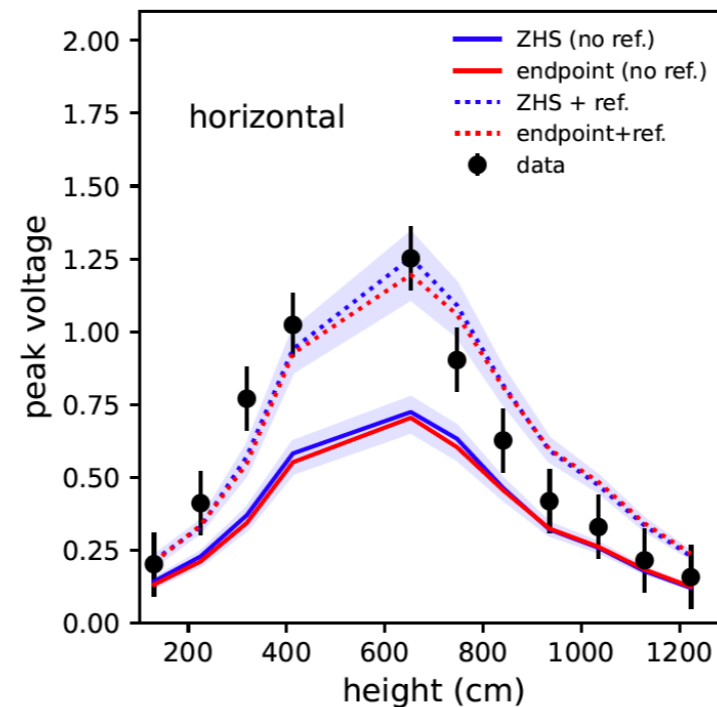
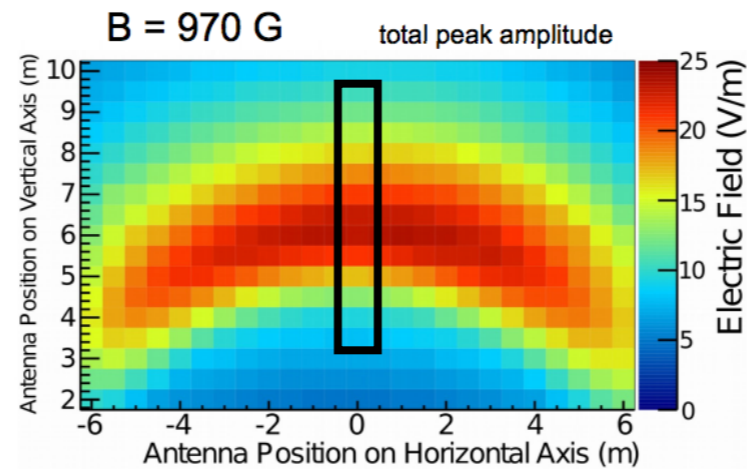
**Magnetically induced emission**  
**Charge excess emission**

# Radio emission from “air showers” in the lab

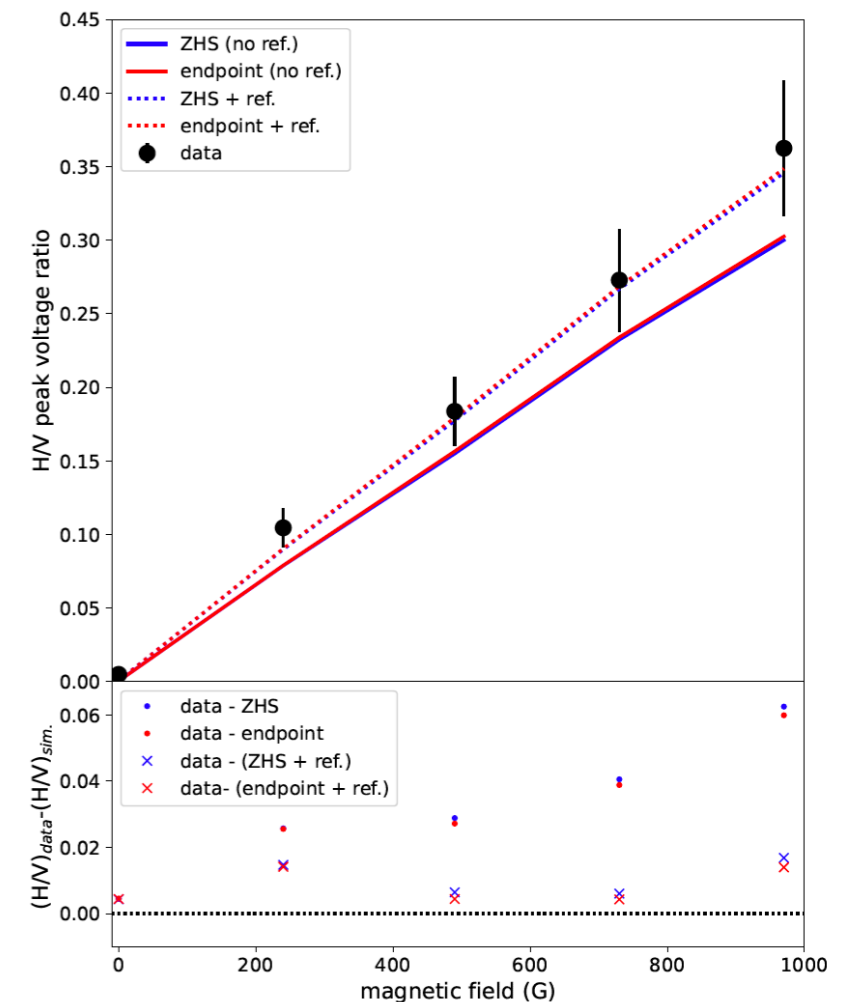
## Reproduce pulse shape and signal strength



## Scan across the Cherenkov cone



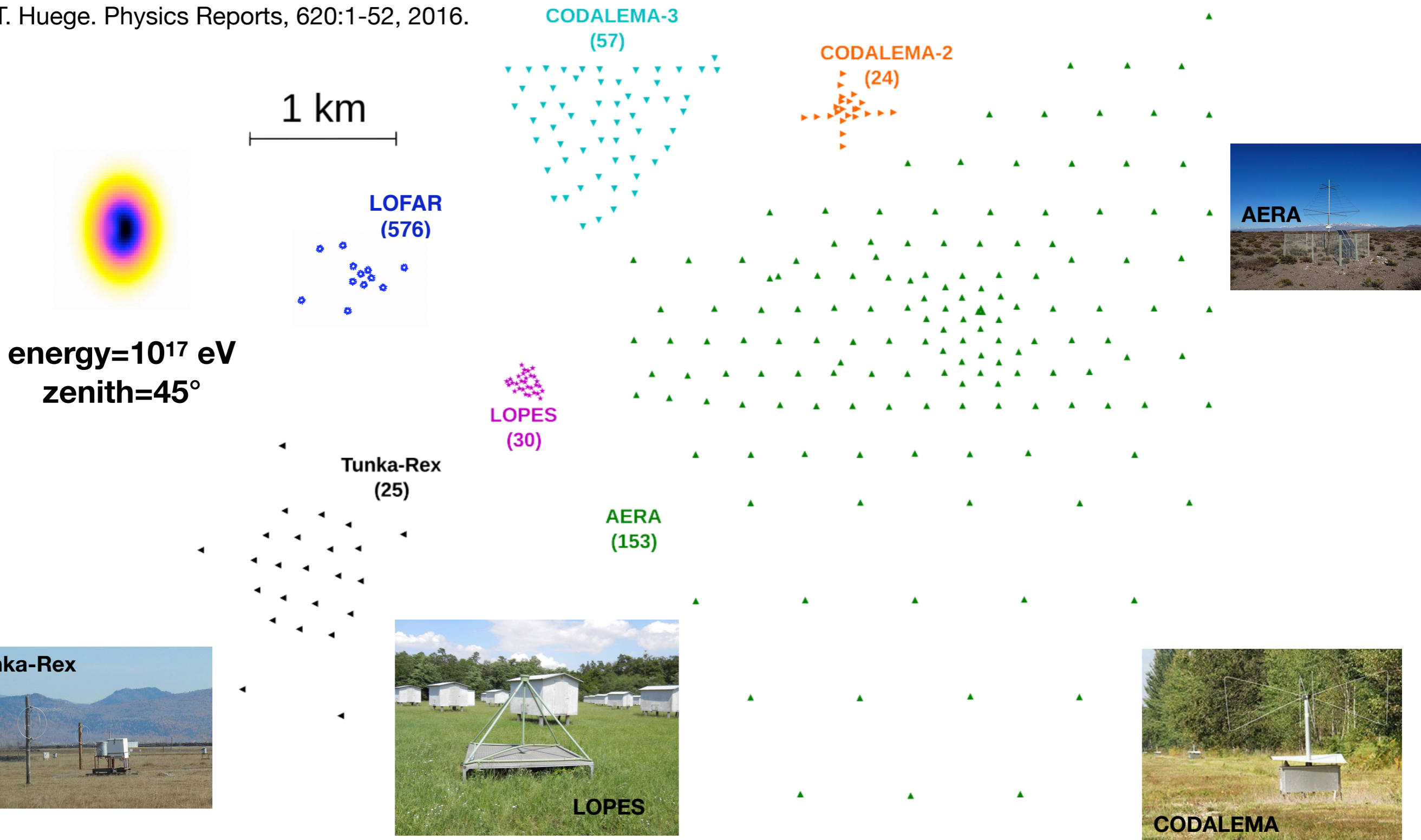
## Scaling of signal strength with magnetic field



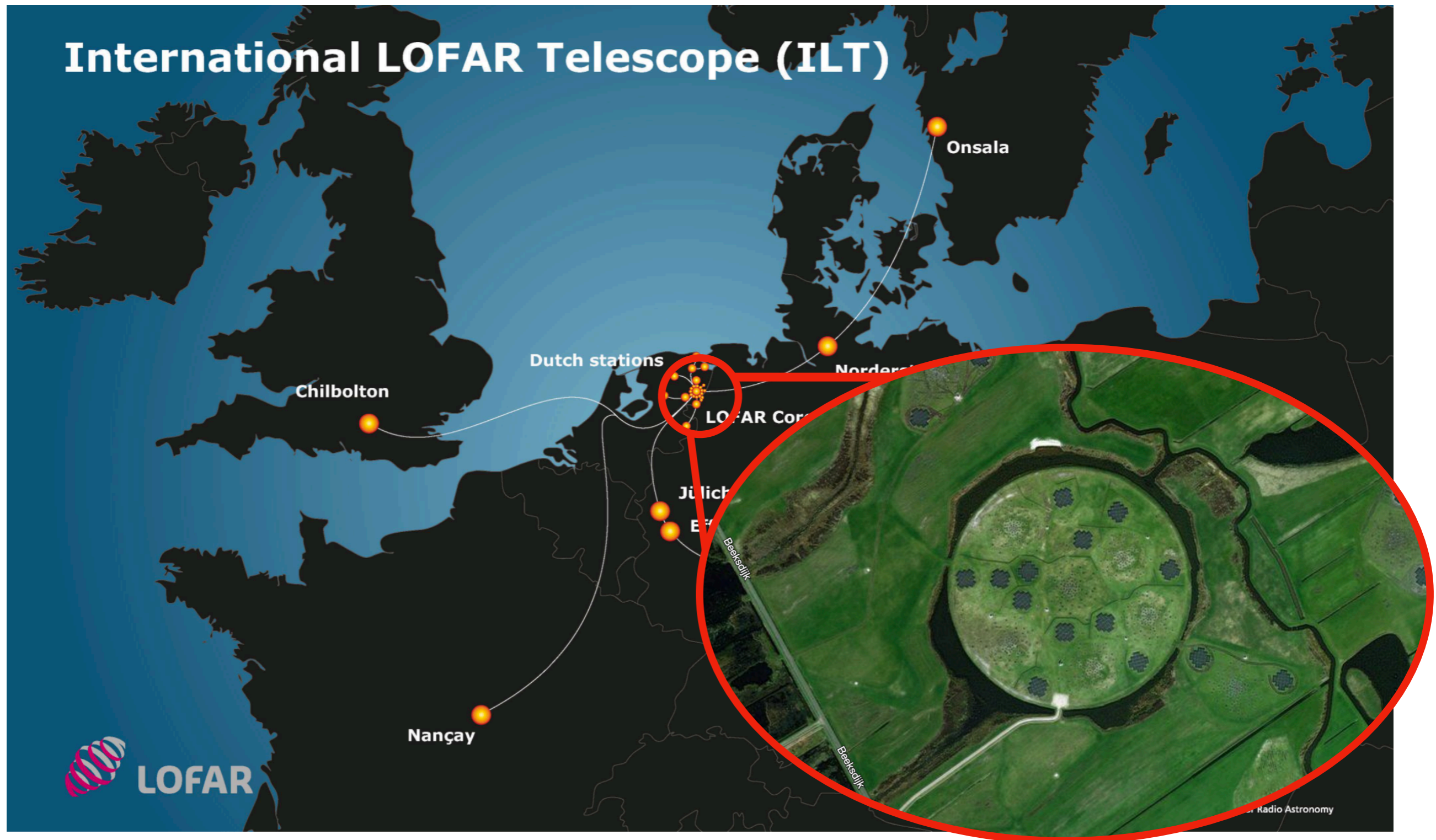
K. Bechtol, et al. PRD. (2022)

# Radio experiments: cosmic rays

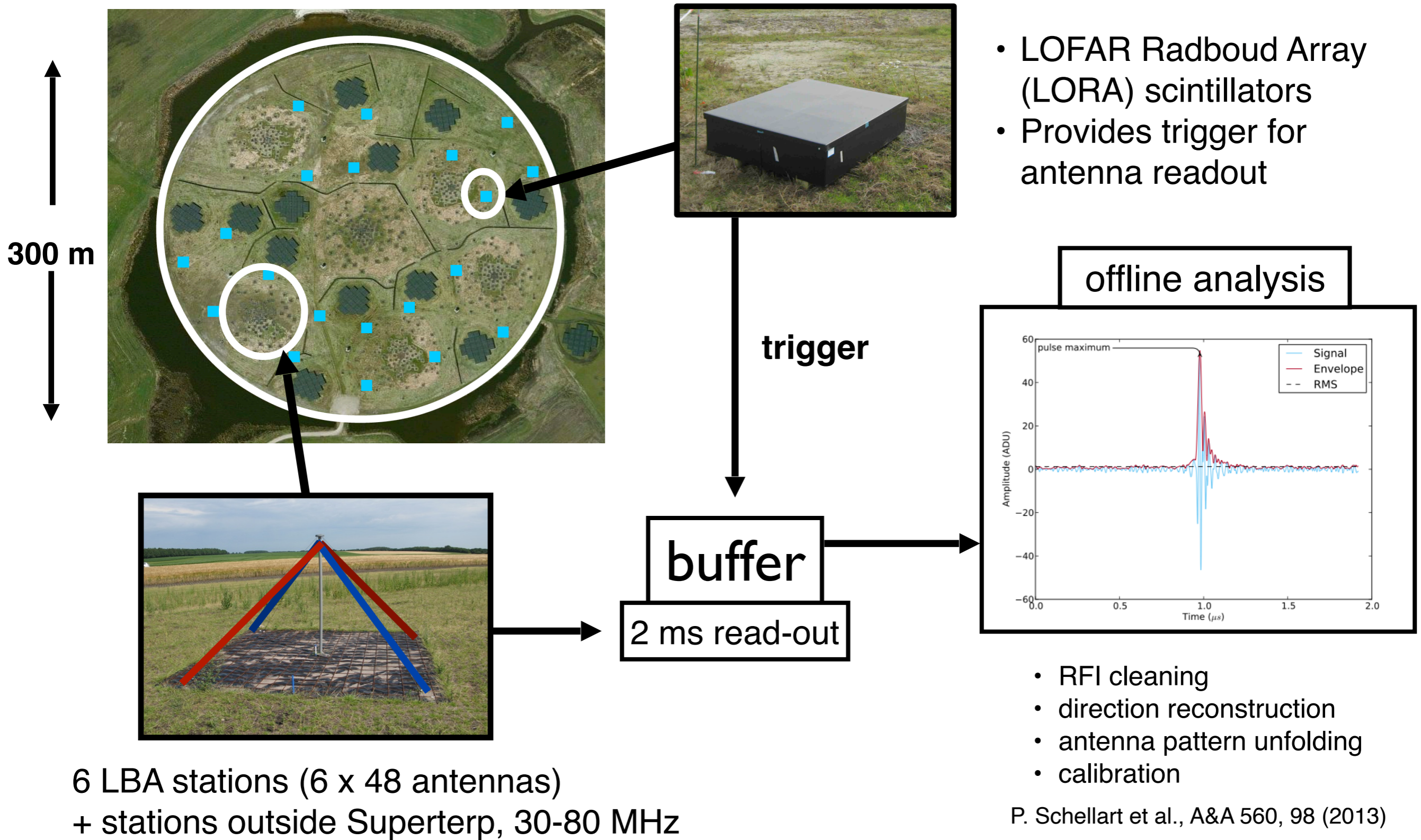
T. Huege. Physics Reports, 620:1-52, 2016.



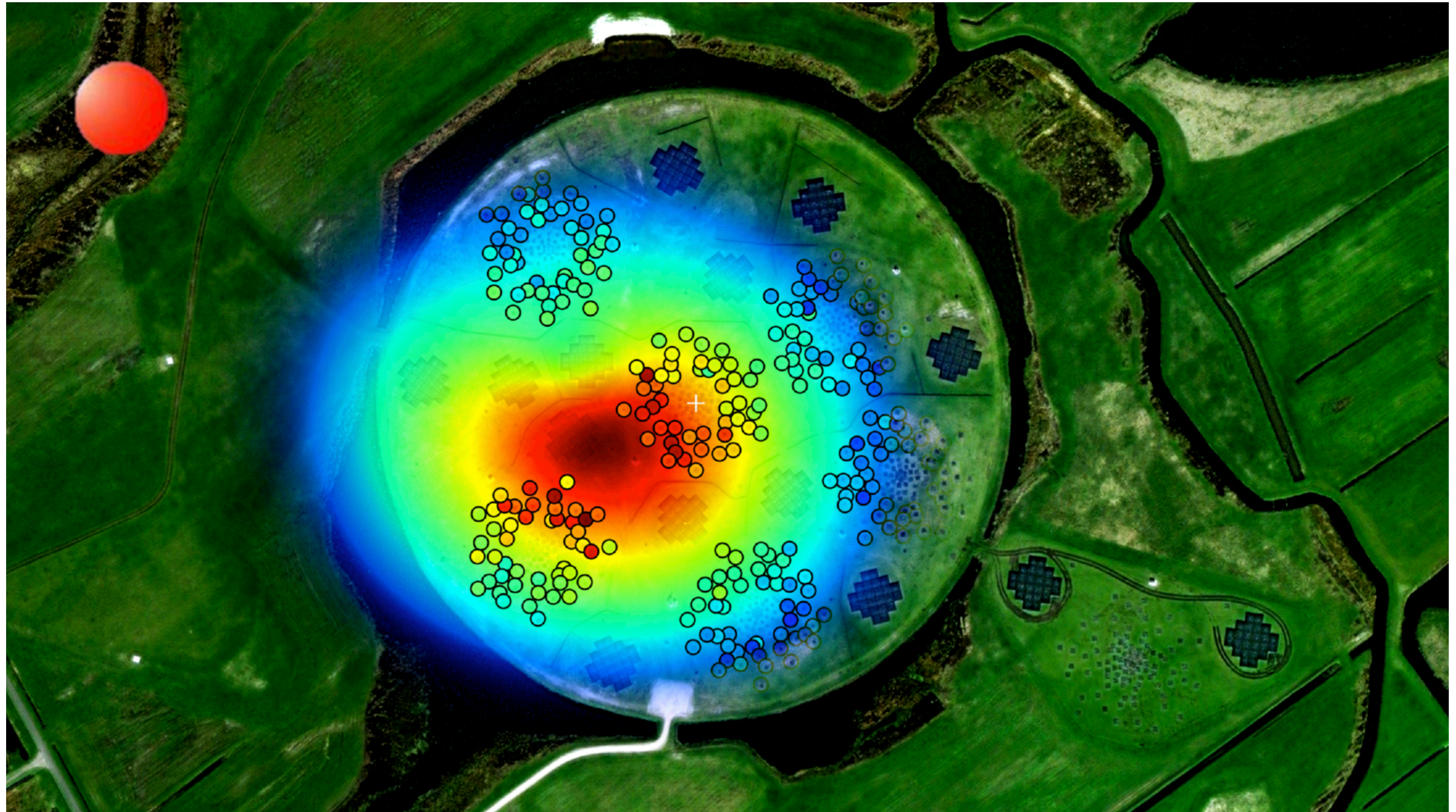
# Cosmic Ray Detection at LOFAR



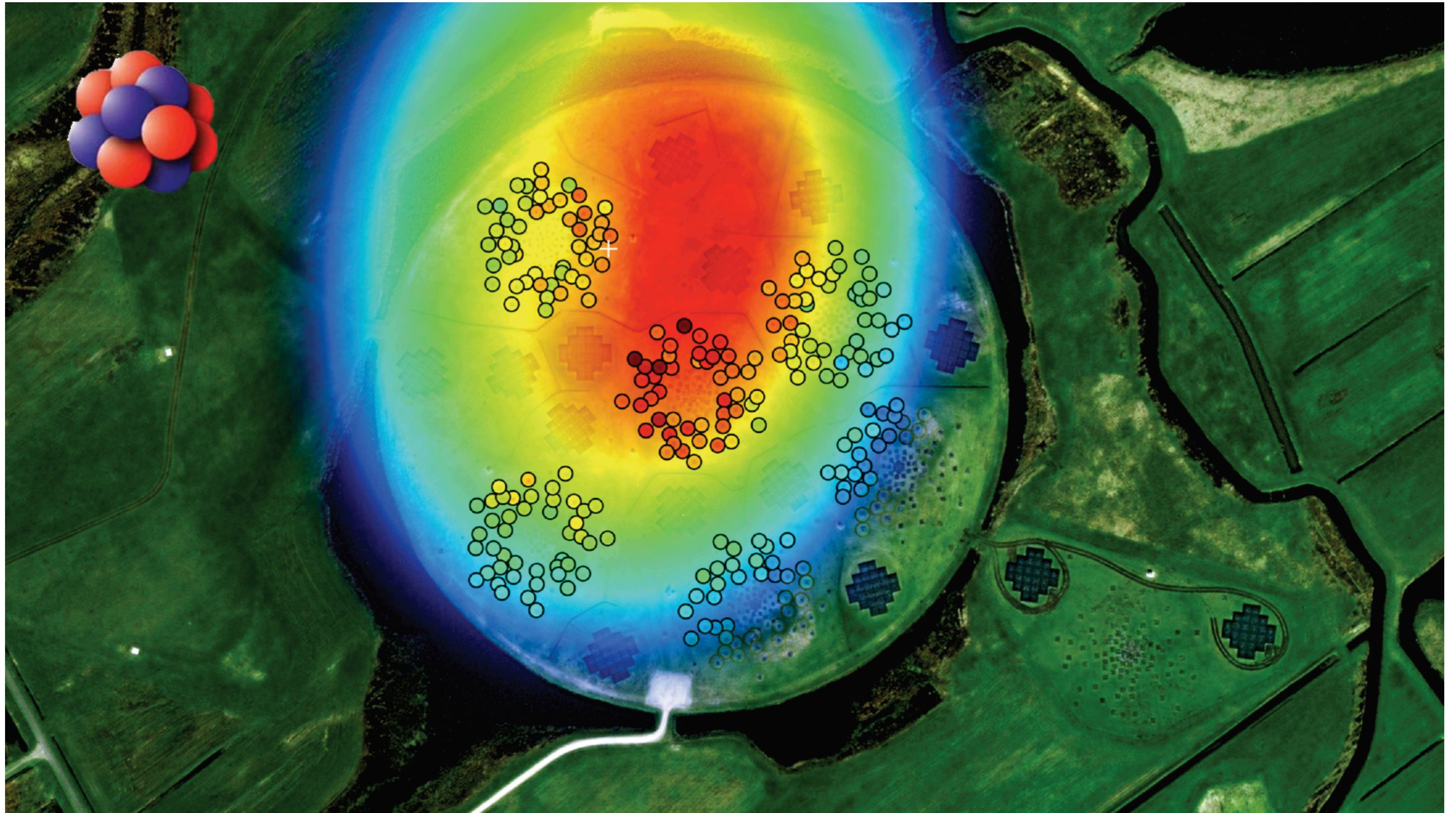
# Cosmic Rays at LOFAR



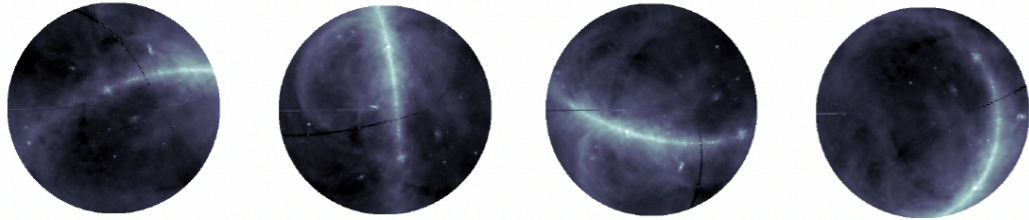
# Cosmic Rays at LOFAR



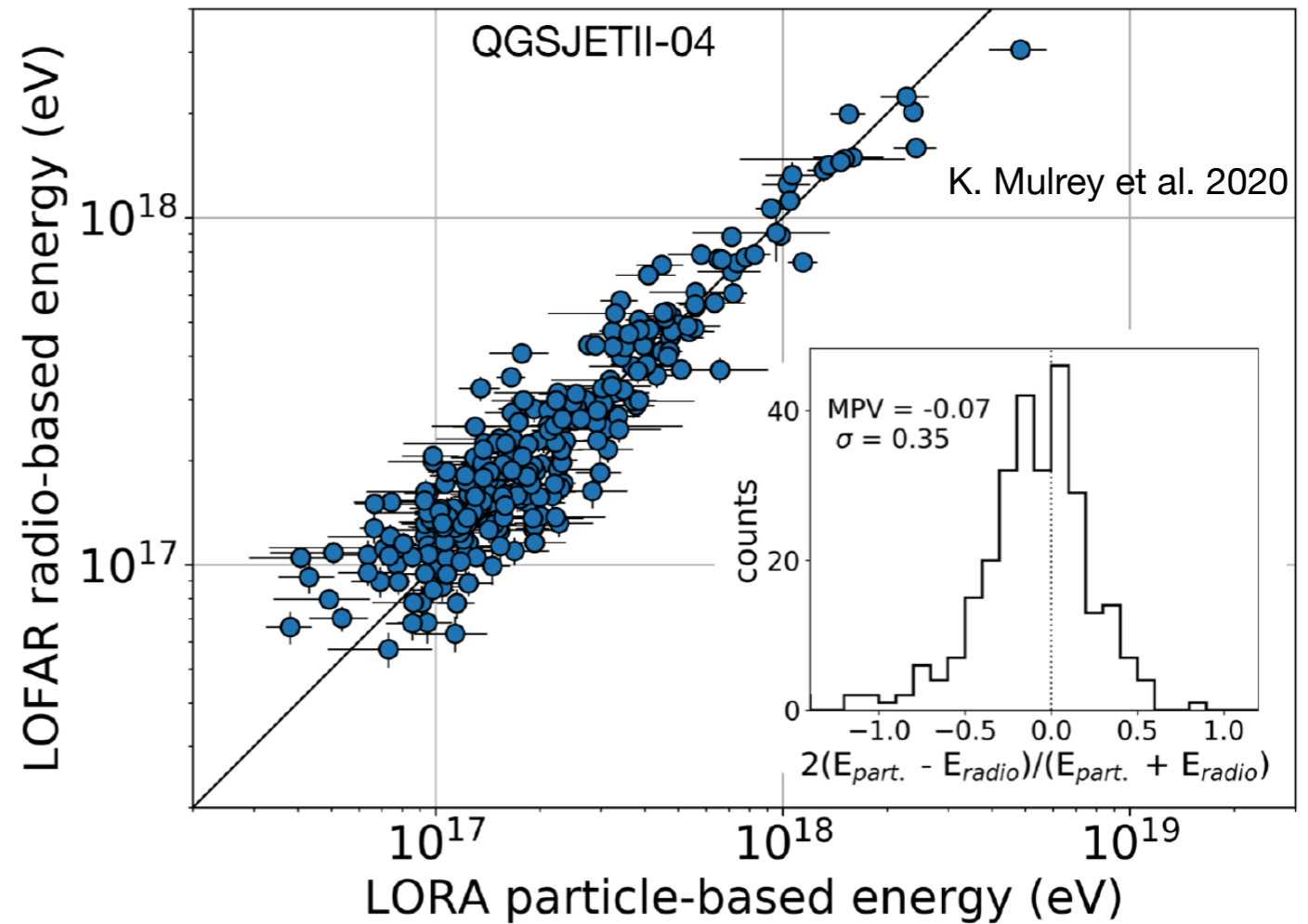
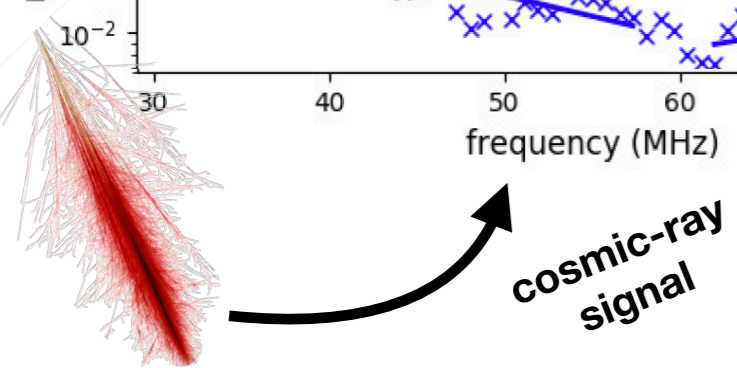
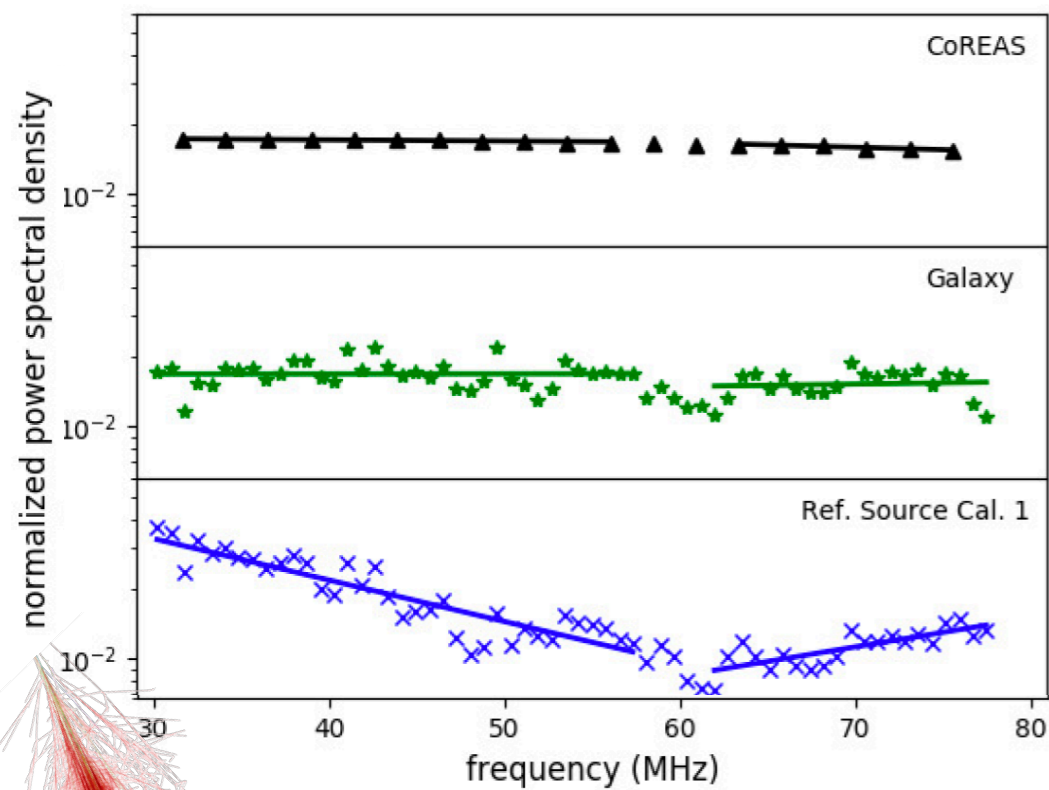
# Cosmic Rays at LOFAR



# Cosmic Rays at LOFAR



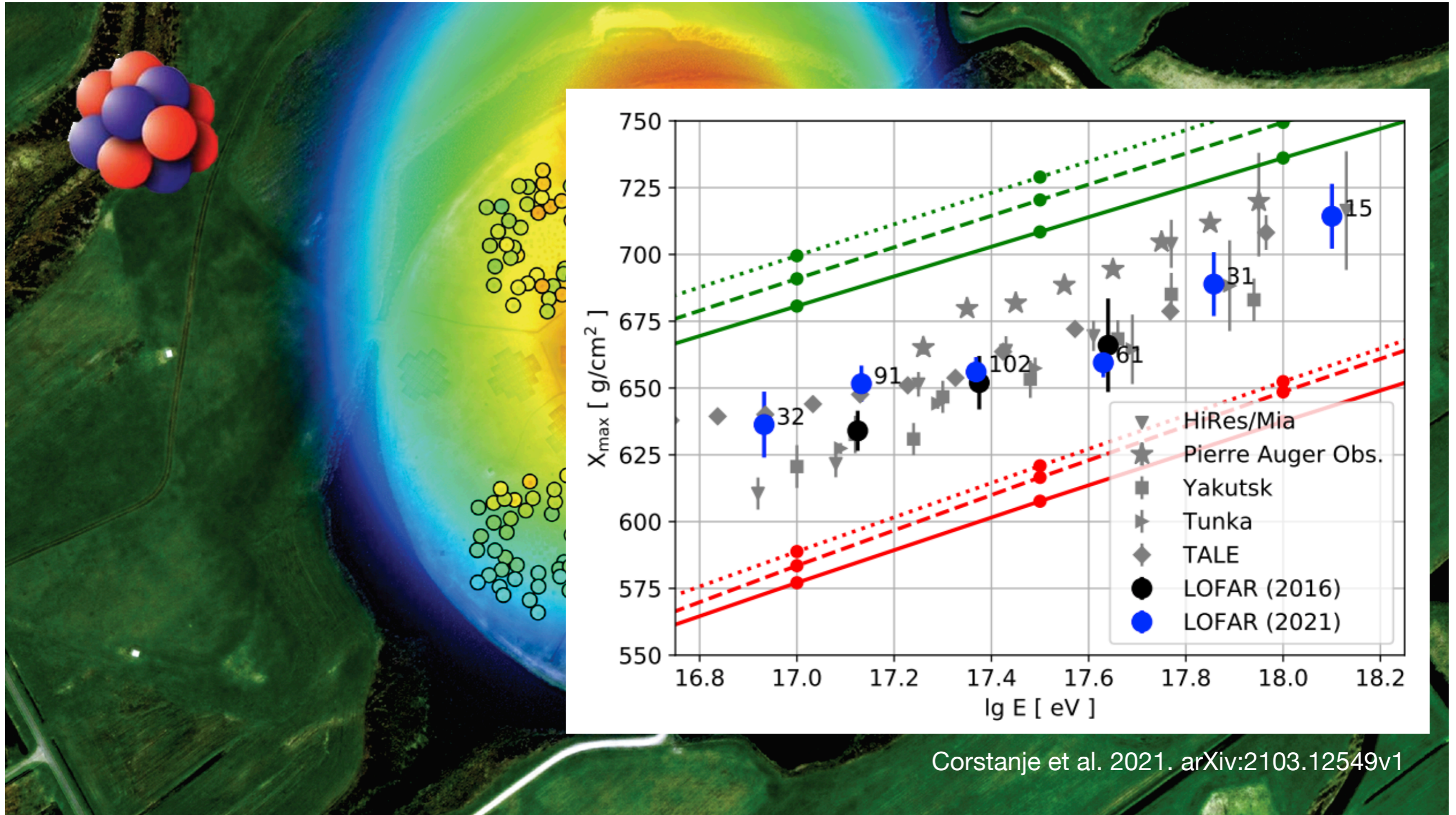
K. Mulrey et al. 2019



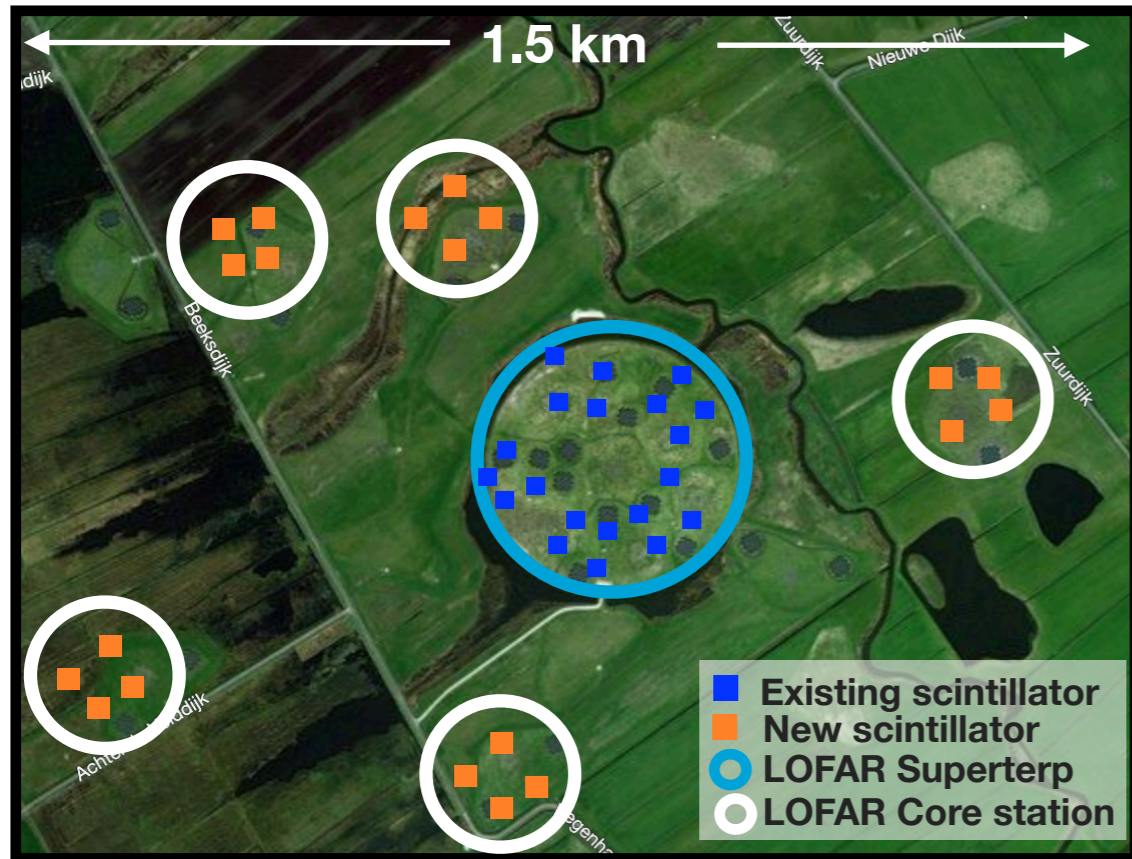
**Absolute calibration makes radio-based energy measurements possible**



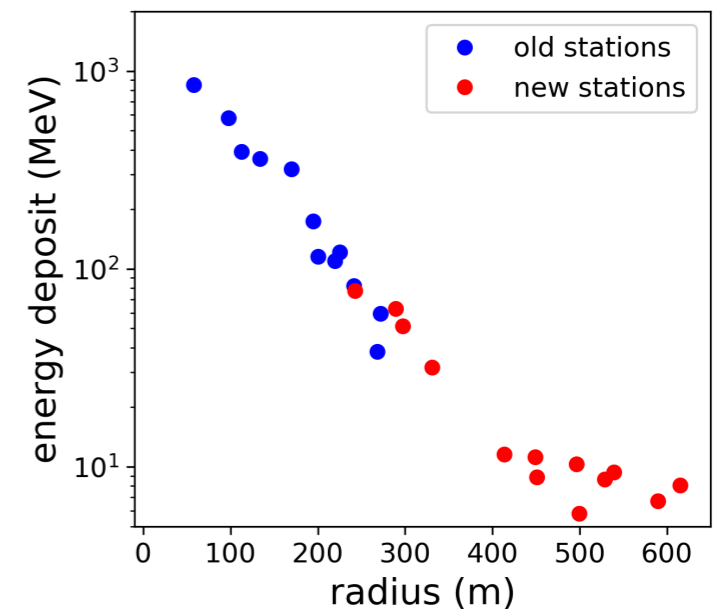
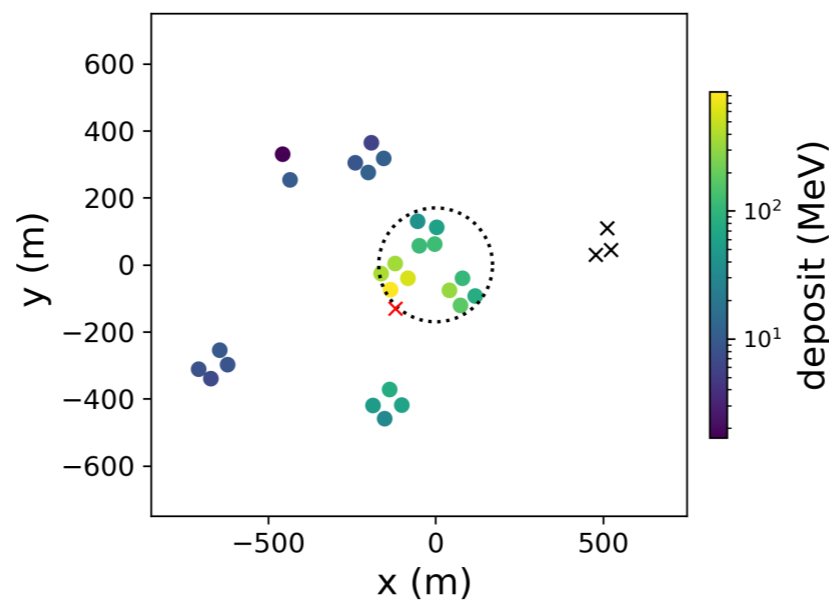
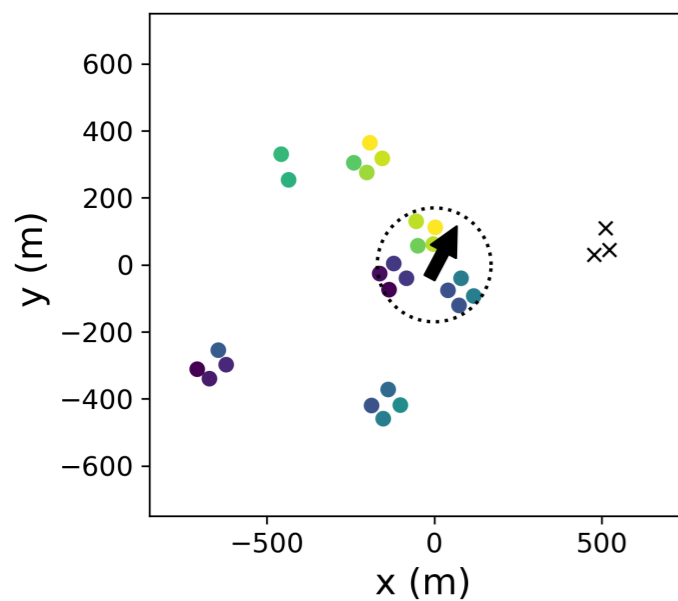
# Cosmic Rays at LOFAR



# Cosmic Rays at LOFAR



*Looking forward...*



# Cosmic Rays at LOFAR

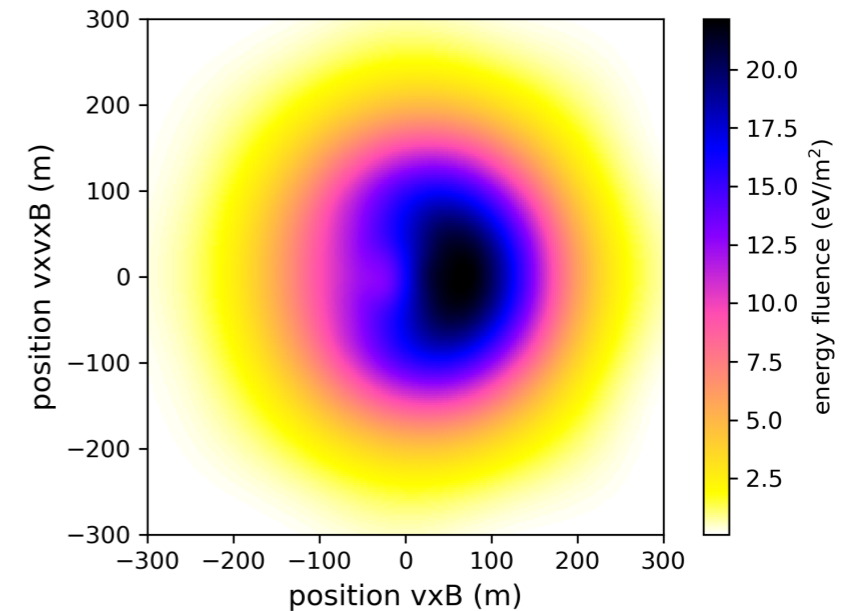
*Looking forward...*

## **LOFAR 2.0**

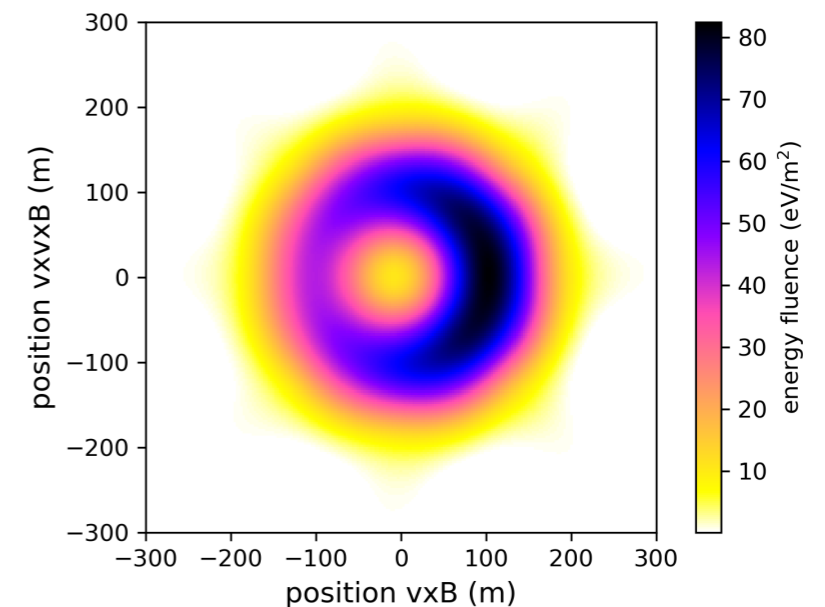
- **Continuous observation**
- **Simultaneous observation with low + high band antennas**



**30-80 MHz**



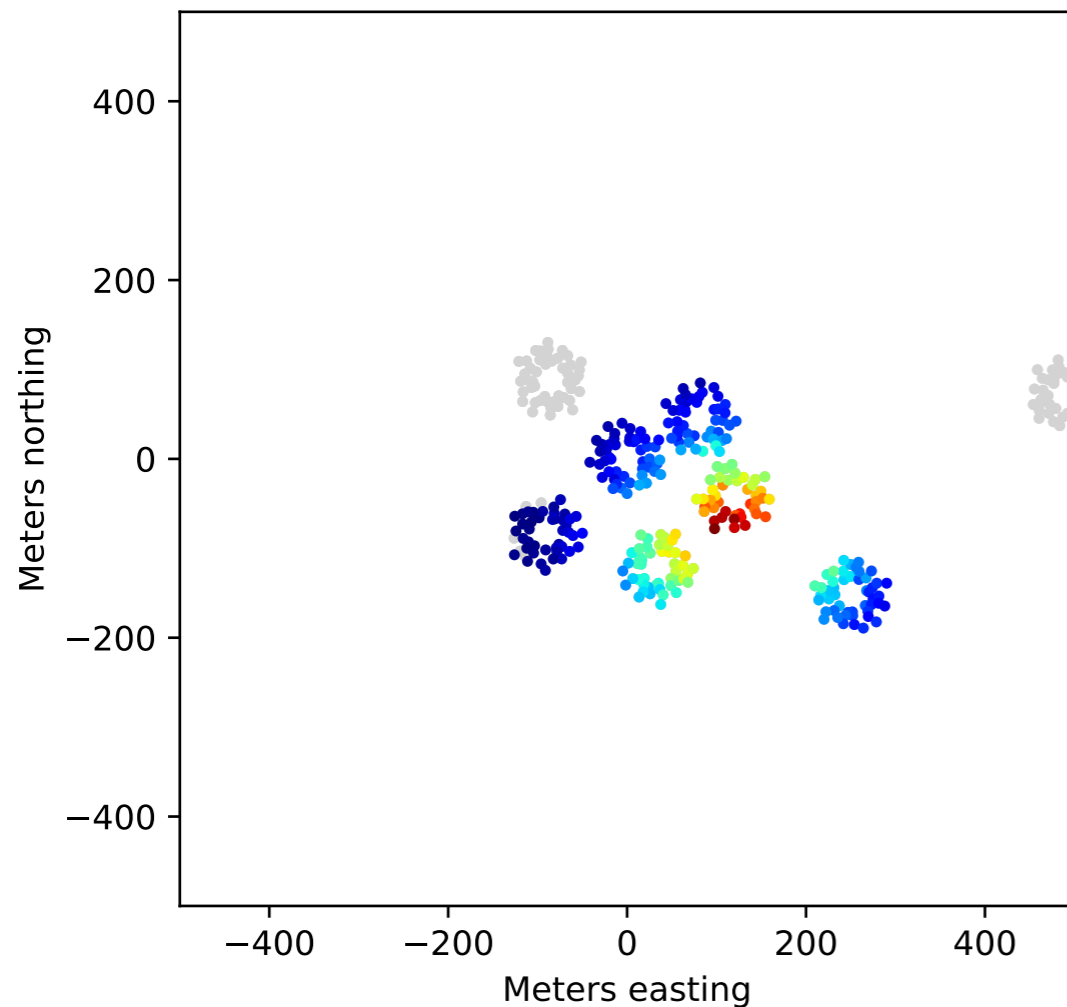
**50-350 MHz**



# Cosmic rays at SKA

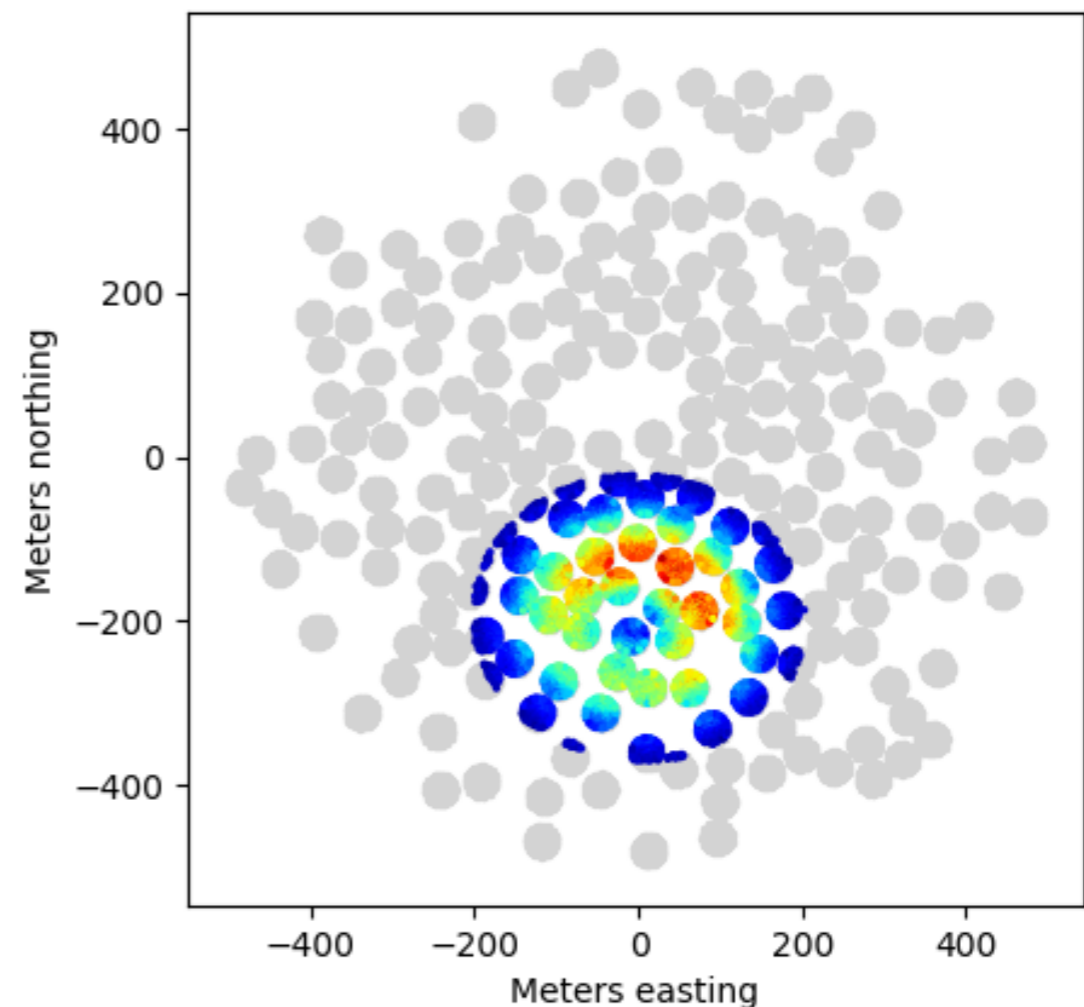
## LOFAR

- $X_{\max}$  resolution: 20 g/cm<sup>2</sup>
- Energy resolution: 9%
- Core resolution: 3-10 m
- Northern hemisphere

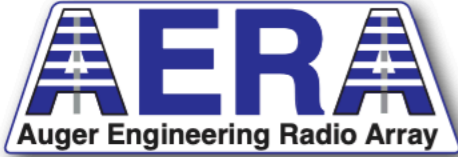


## SKA

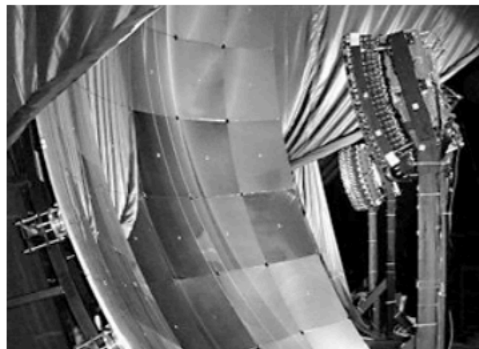
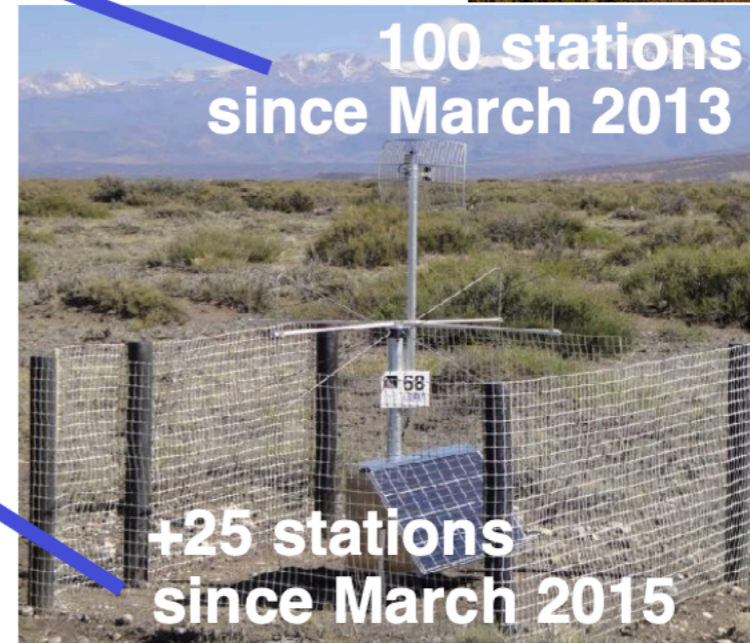
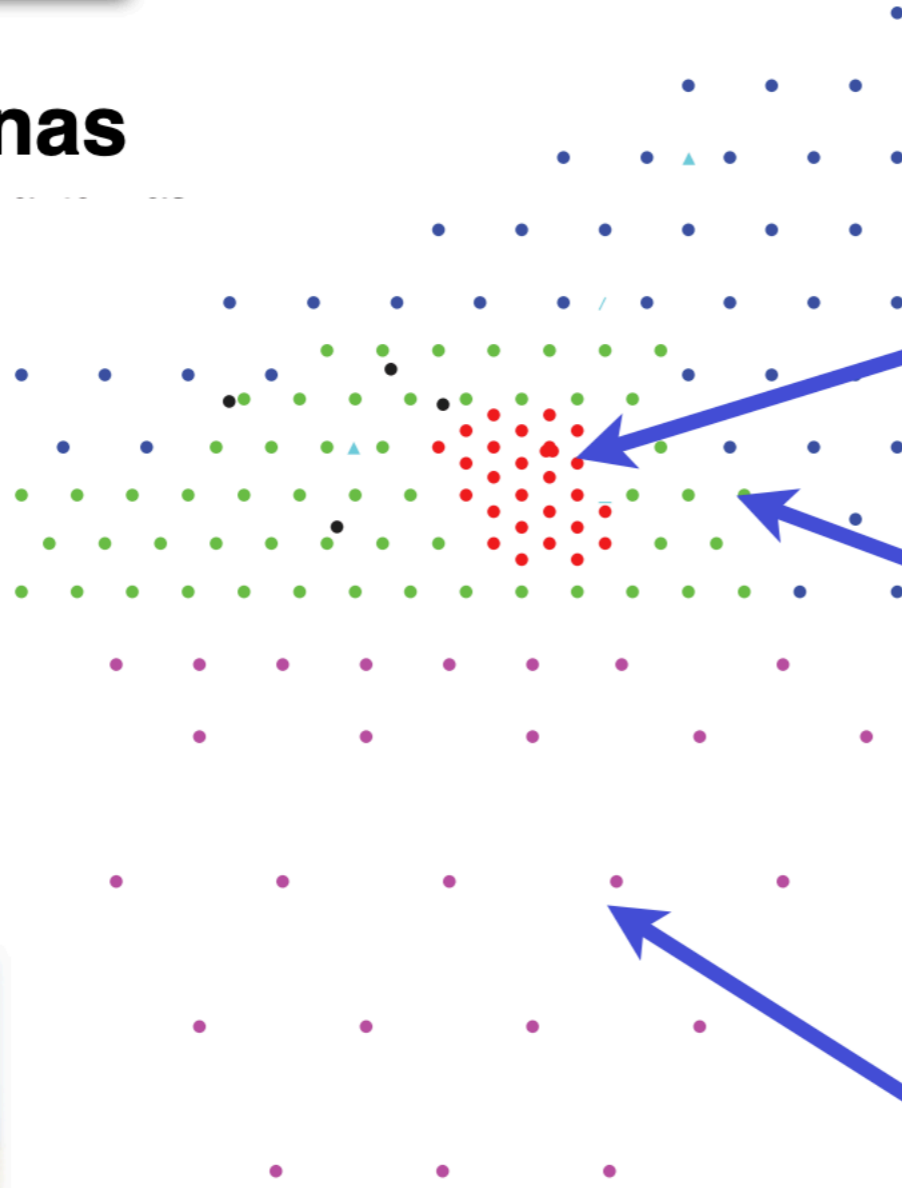
- $X_{\max}$  resolution: 6-8 g/cm<sup>2</sup>
- Energy resolution: 3%
- Core resolution: 50 cm
- Southern hemisphere



# Radio at Auger

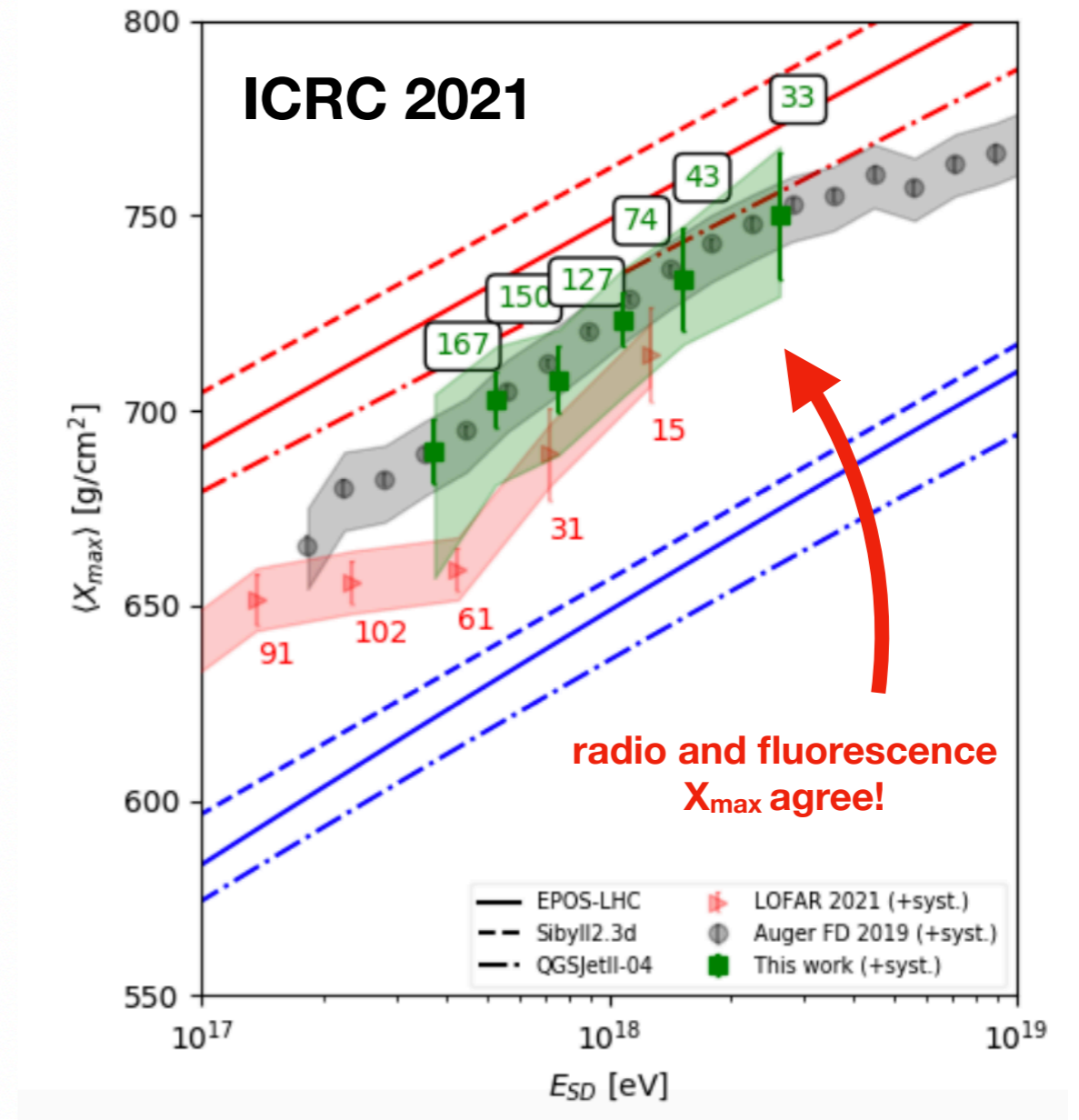
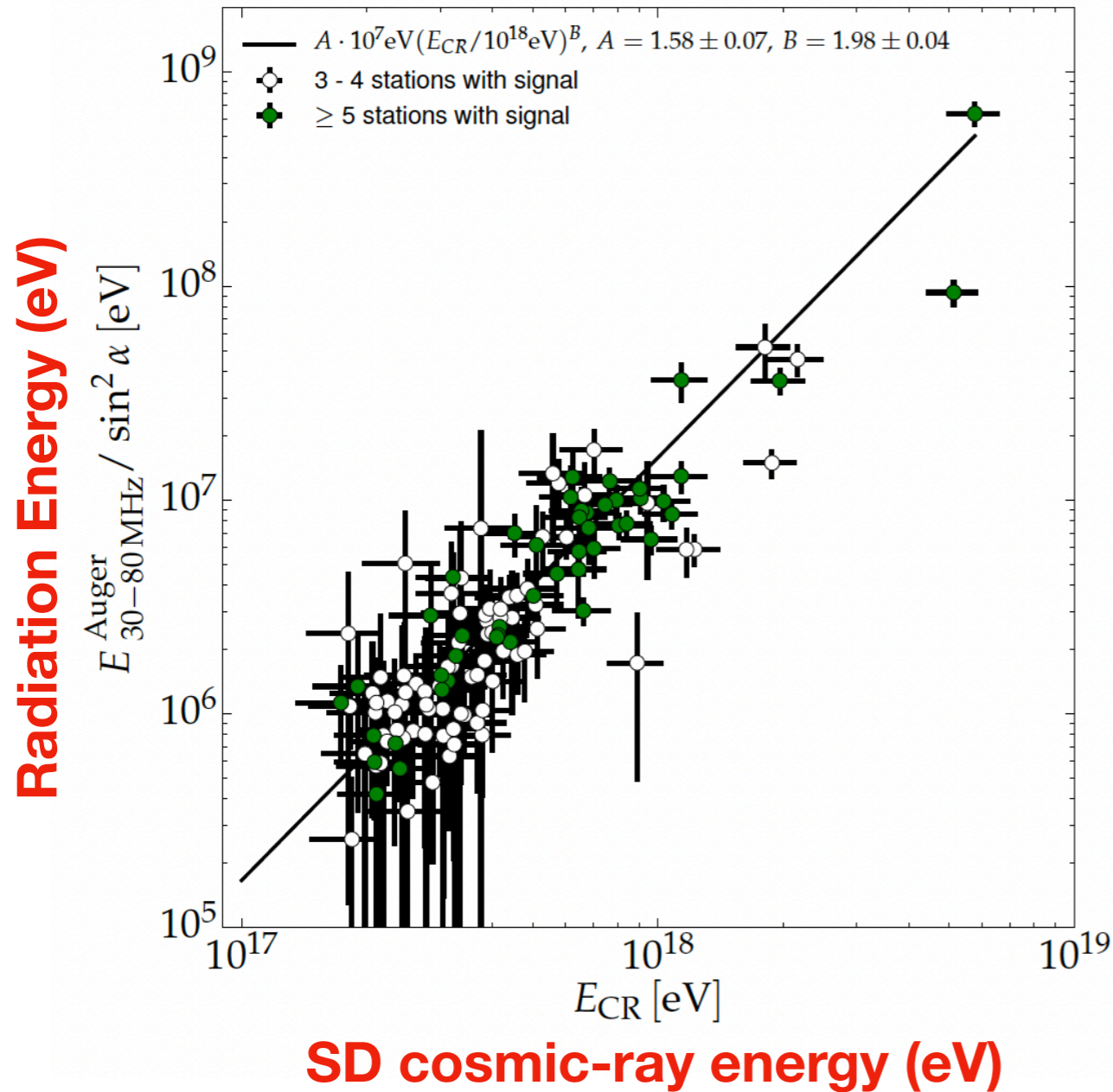


**~150 antennas**  
**~17 km<sup>2</sup>**  
**30-80 MHz**



Jörg R. Hörandel, CRIS 2018

# Radio at Auger



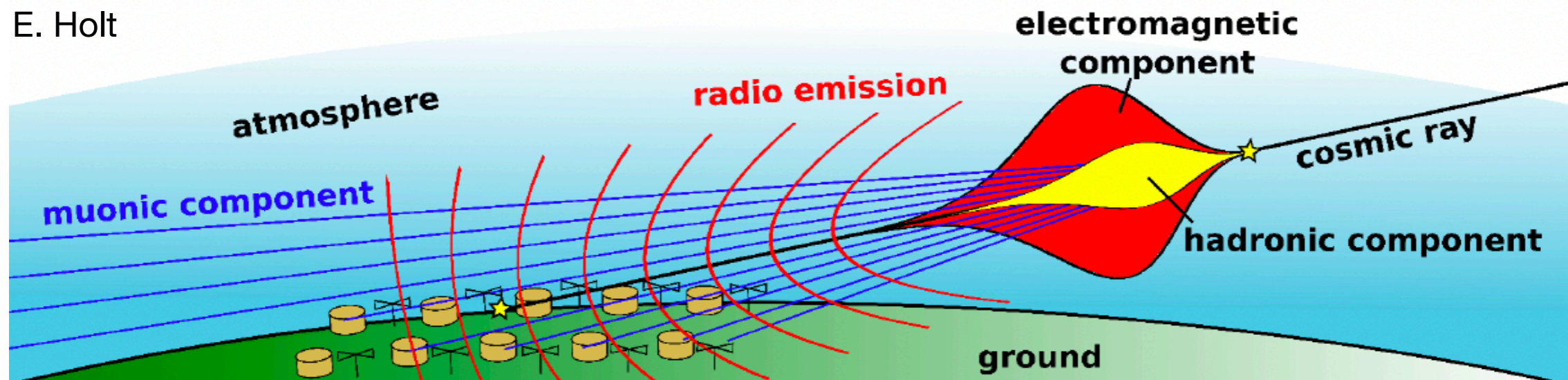
A. Aab et al., PRD 93 (2016)

A. Aab et al., PRL 116 (2016)

B. Pont PoS(ICRC2021)387

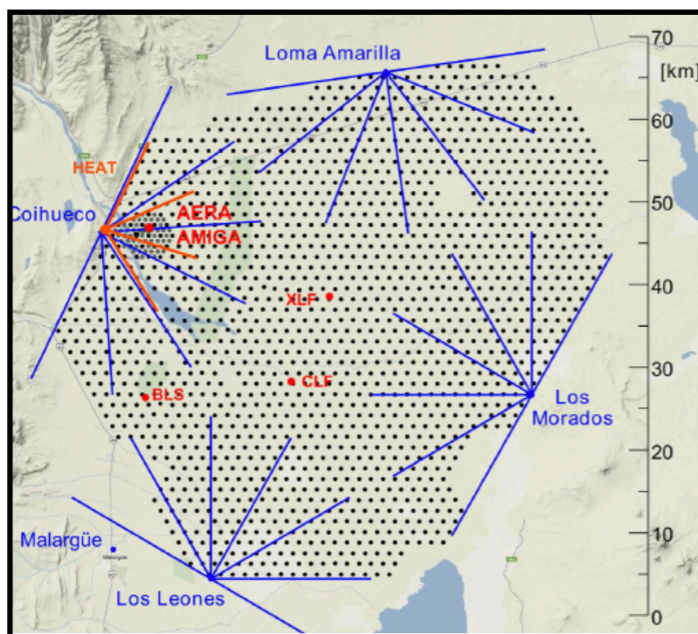
# Radio at Auger

E. Holt



Advanced Grant  
Hörandel 2018

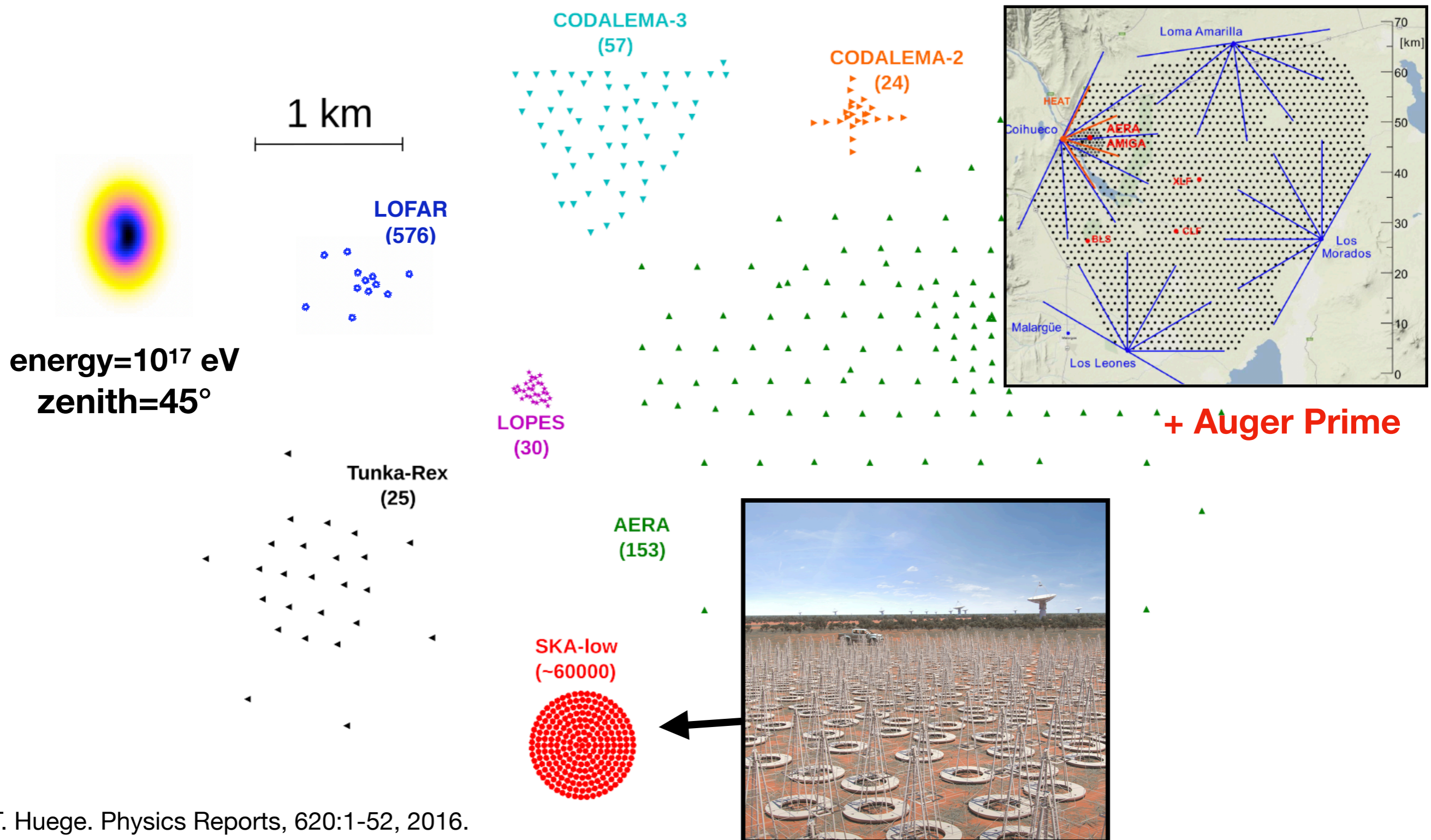
## Radio Upgrade



Electronics development @ Radboud

Deployment NOW!

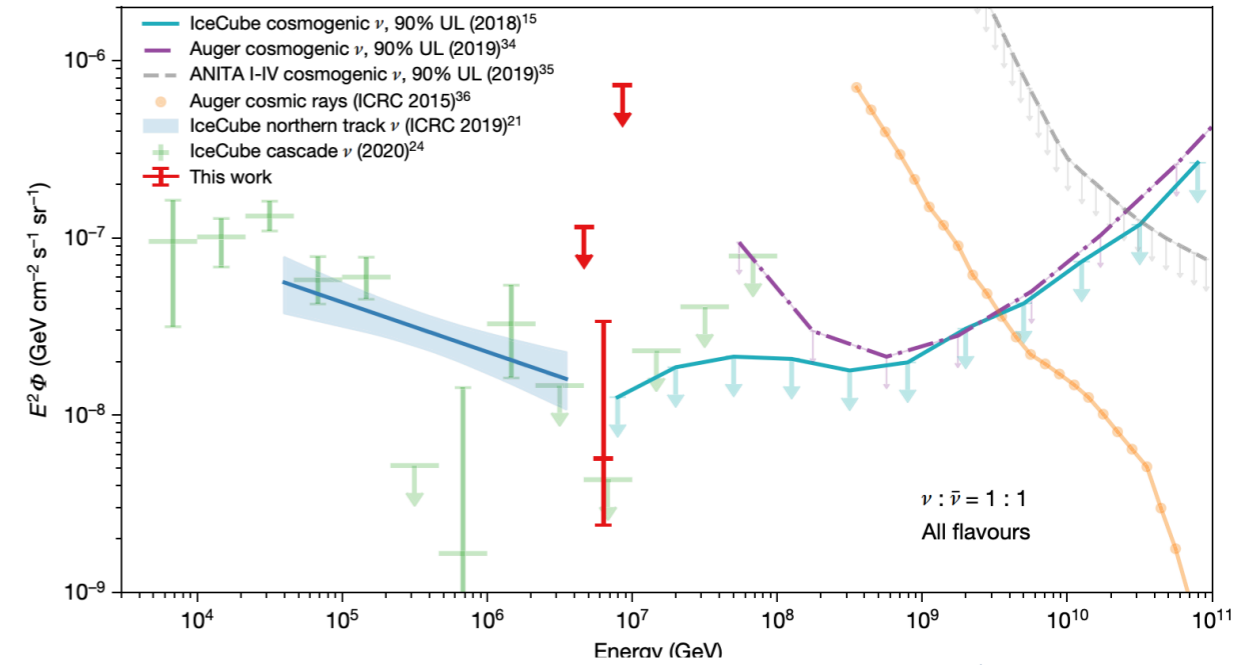
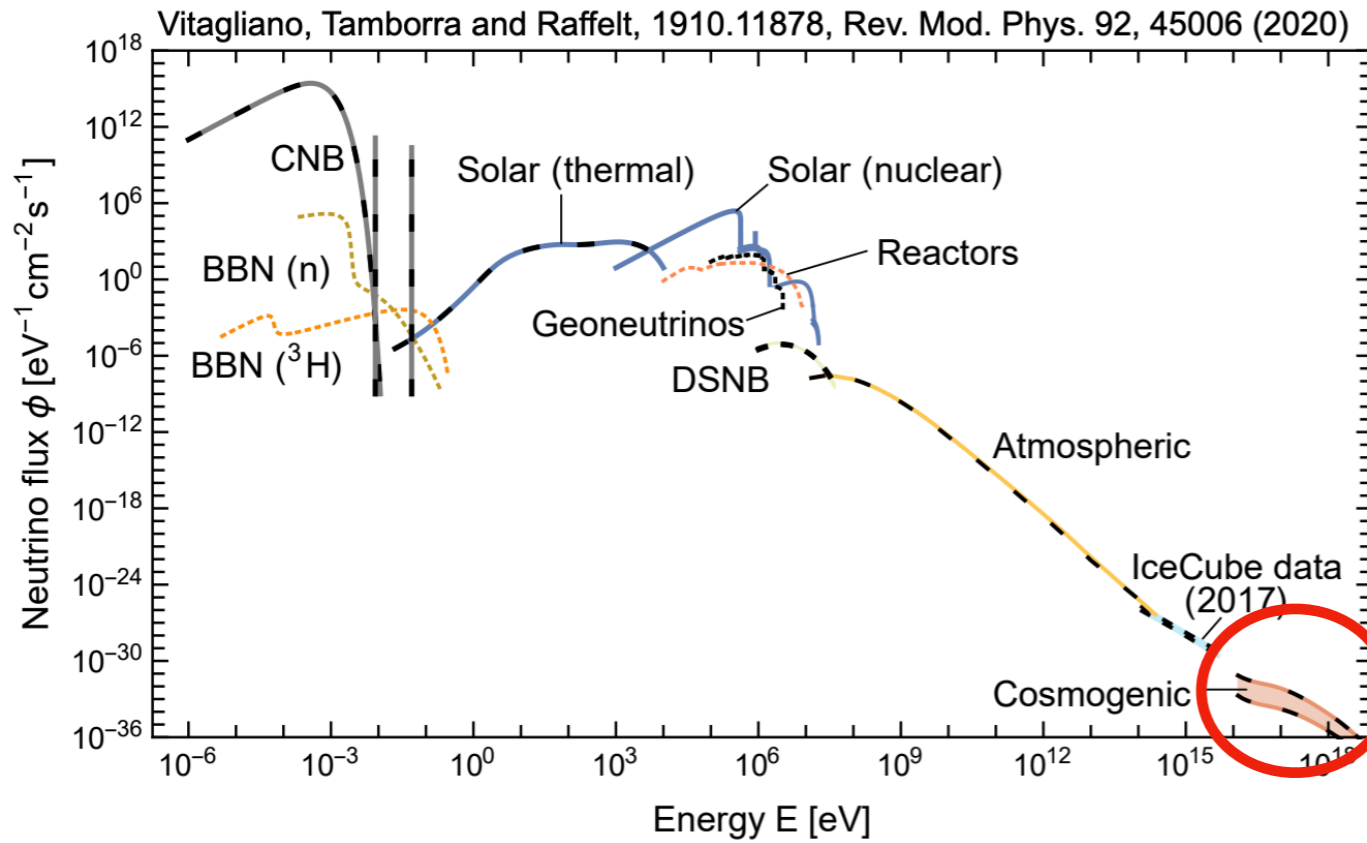
# Radio Detection Experiments



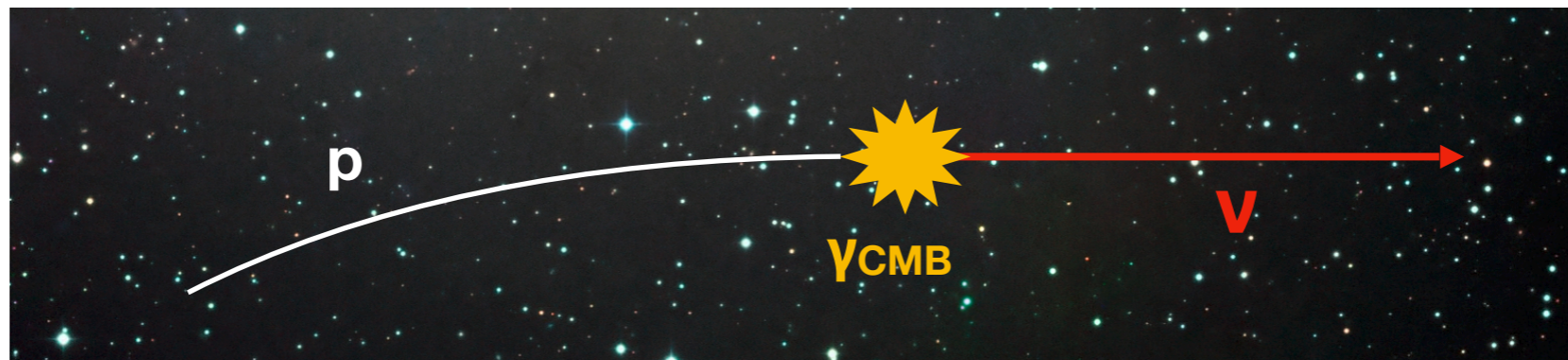
T. Huege. Physics Reports, 620:1-52, 2016.



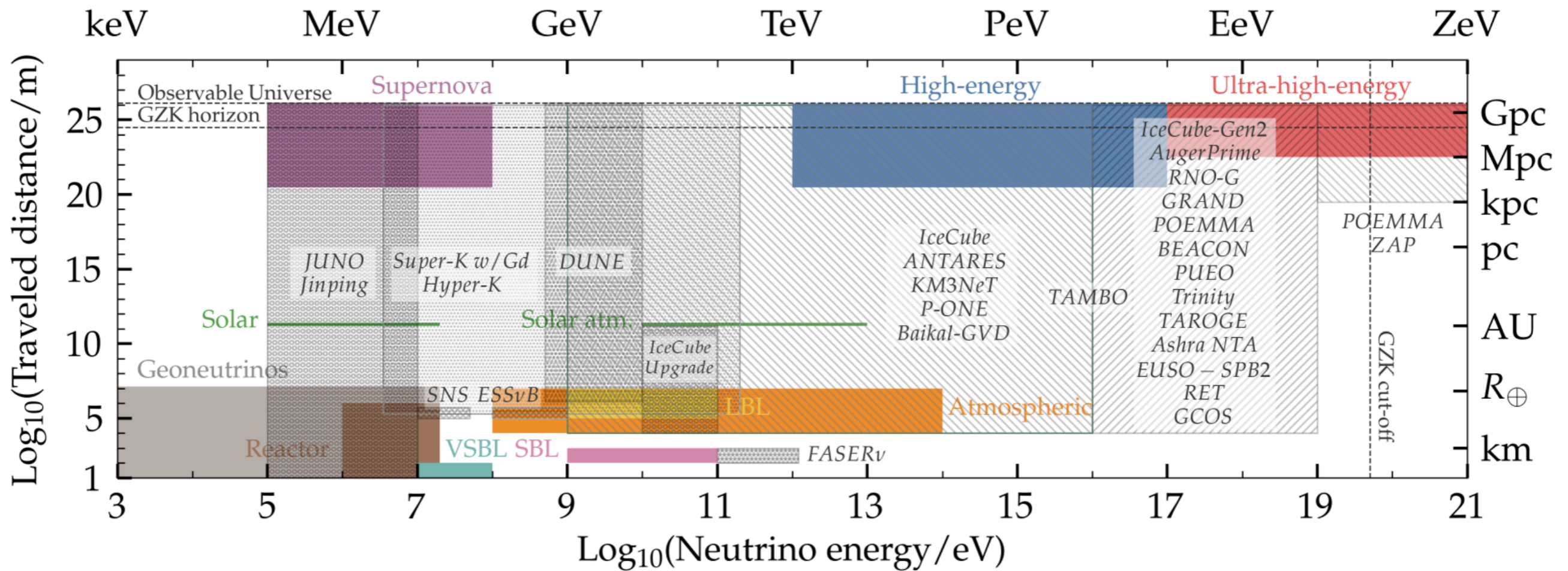
# UHE Neutrinos



IceCube in Nature, 2021

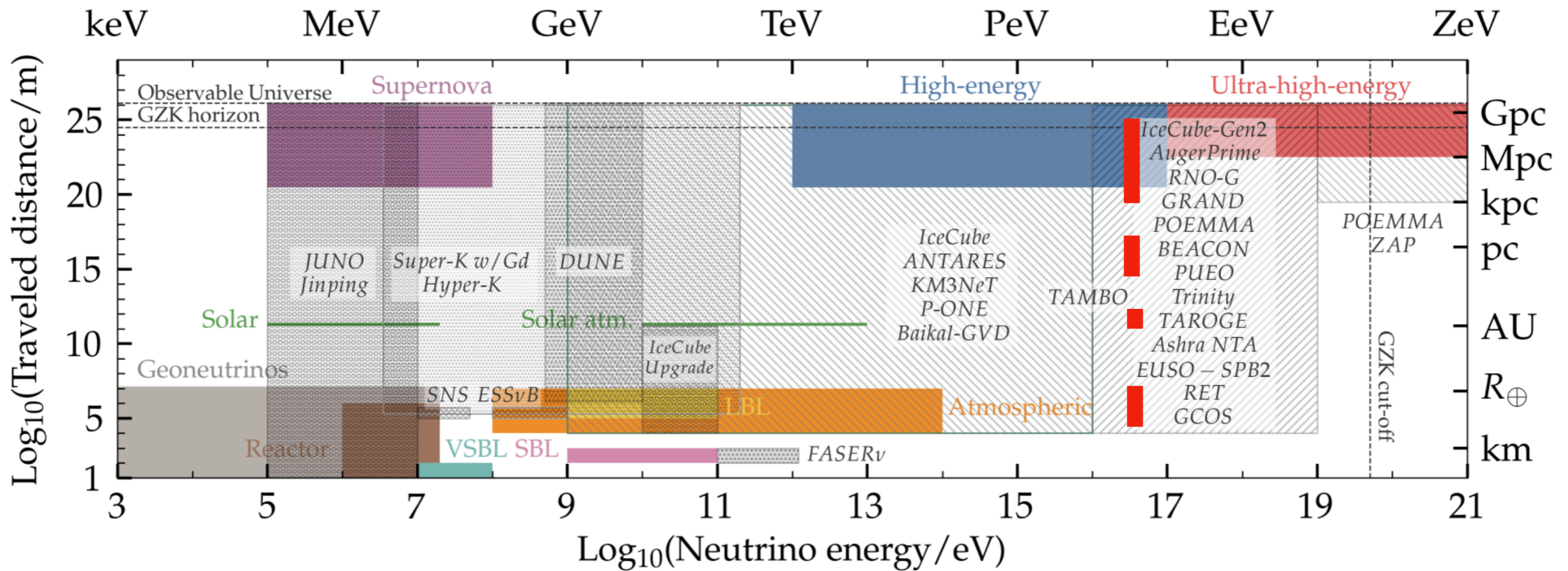


# UHE Neutrinos



UHE neutrino Snowmass: Ackermann et al, arXiv:2203.08096

# UHE Neutrinos

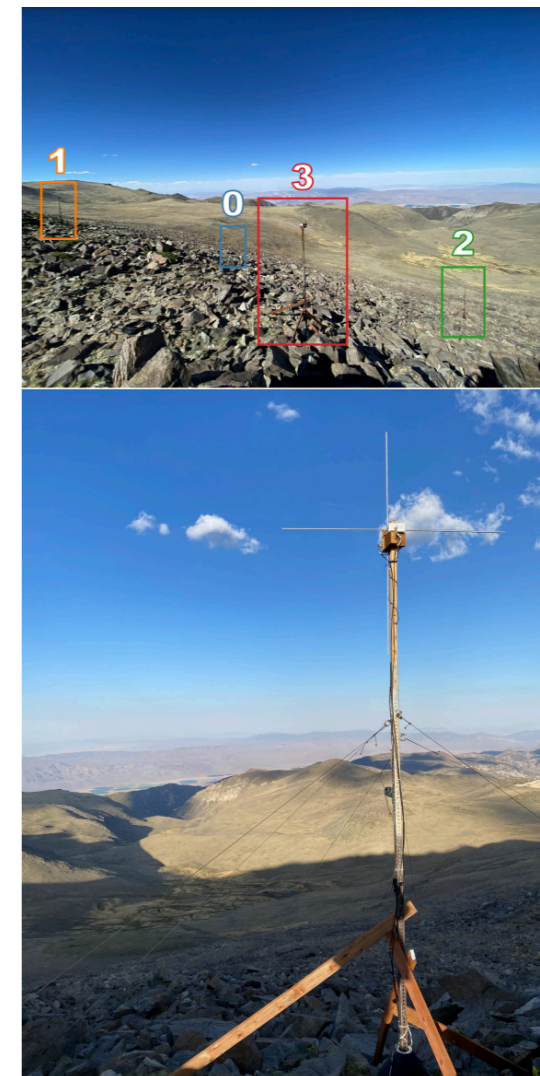
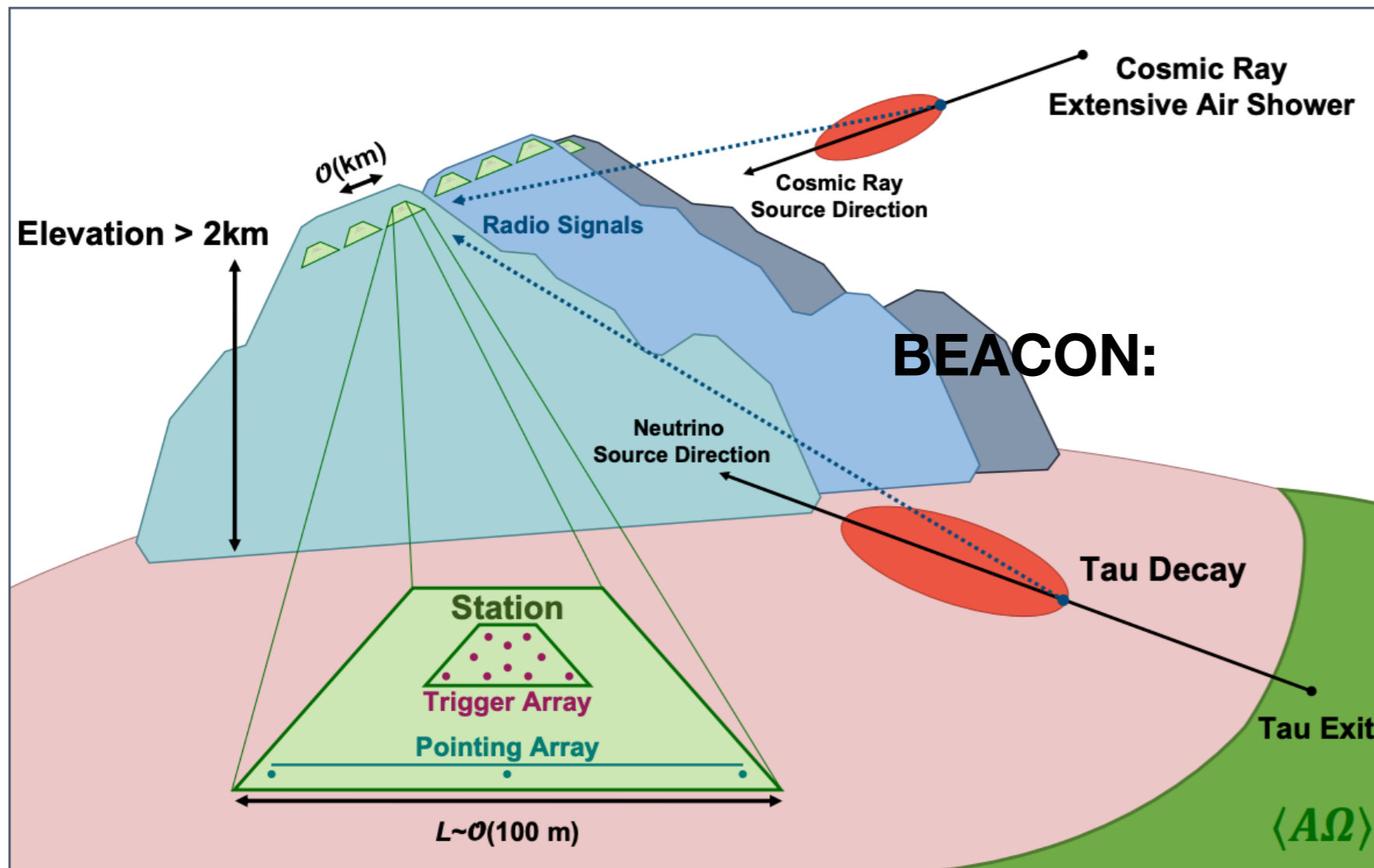


UHE neutrino Snowmass: Ackermann et al, arXiv:2203.08096

- **Modular**
- **Large detection area**

# BEACON

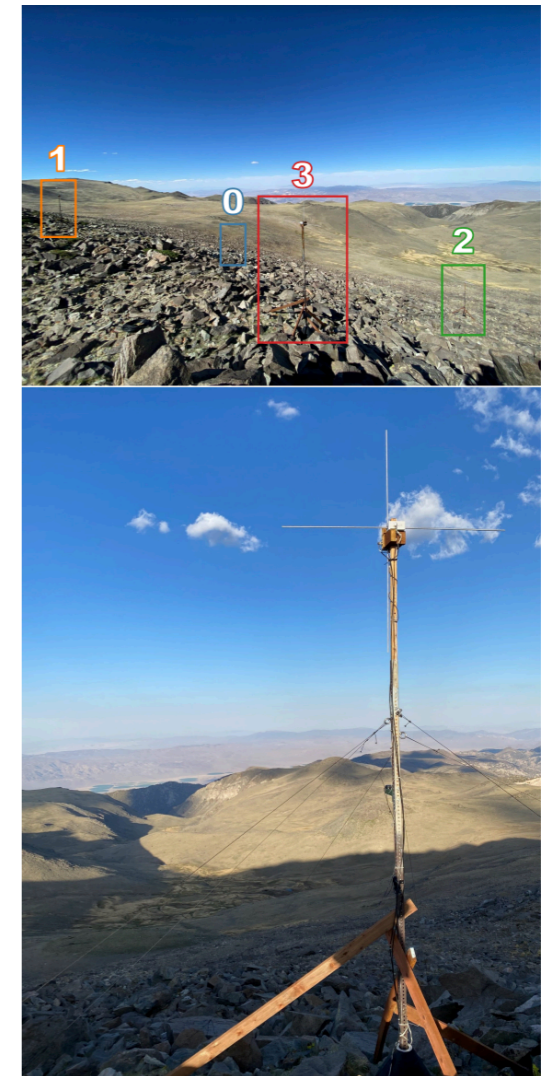
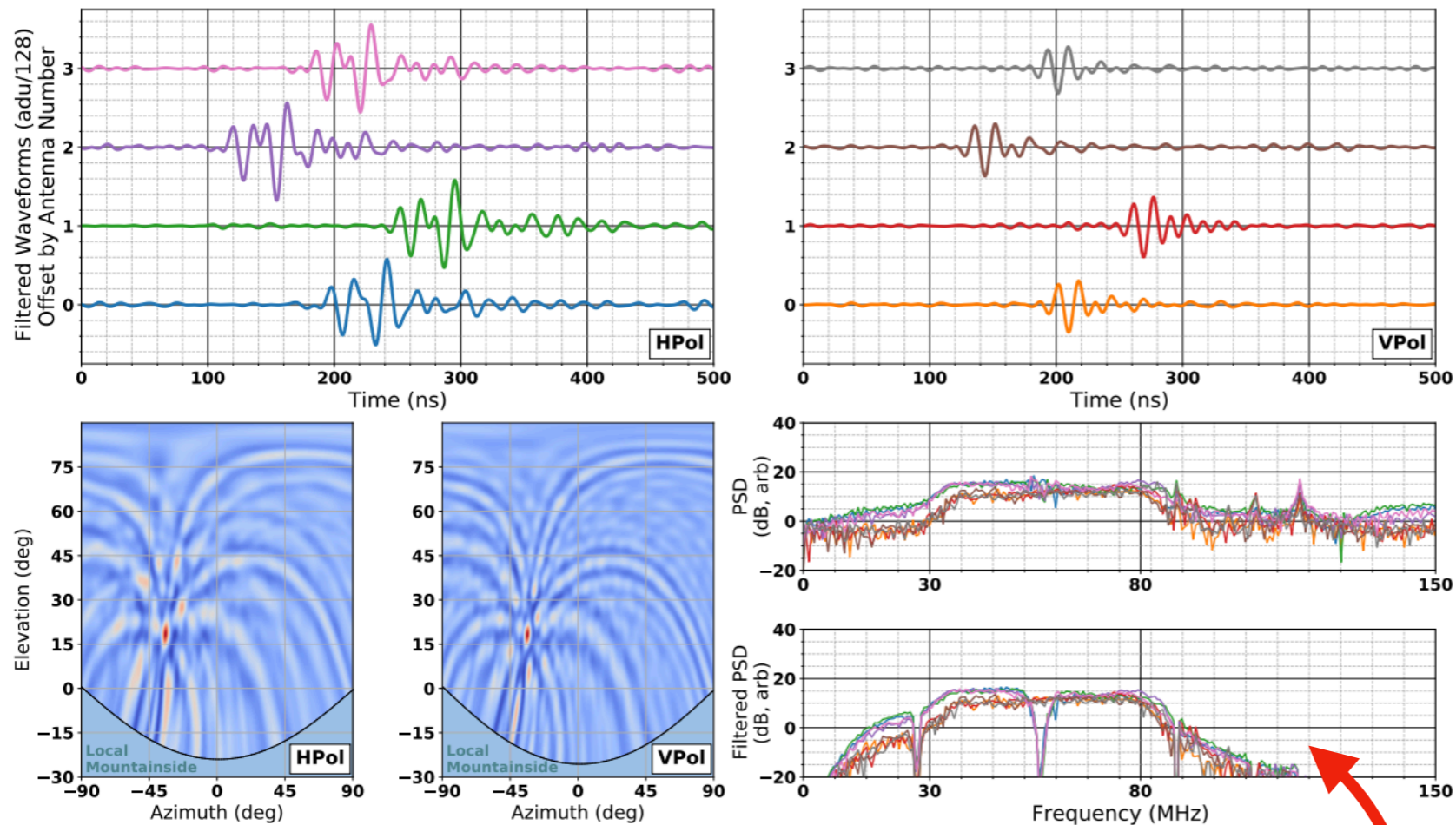
## Beamforming Elevated Array for COsmic Neutrinos



S. Wissel et al. JCAP 2020

# BEACON

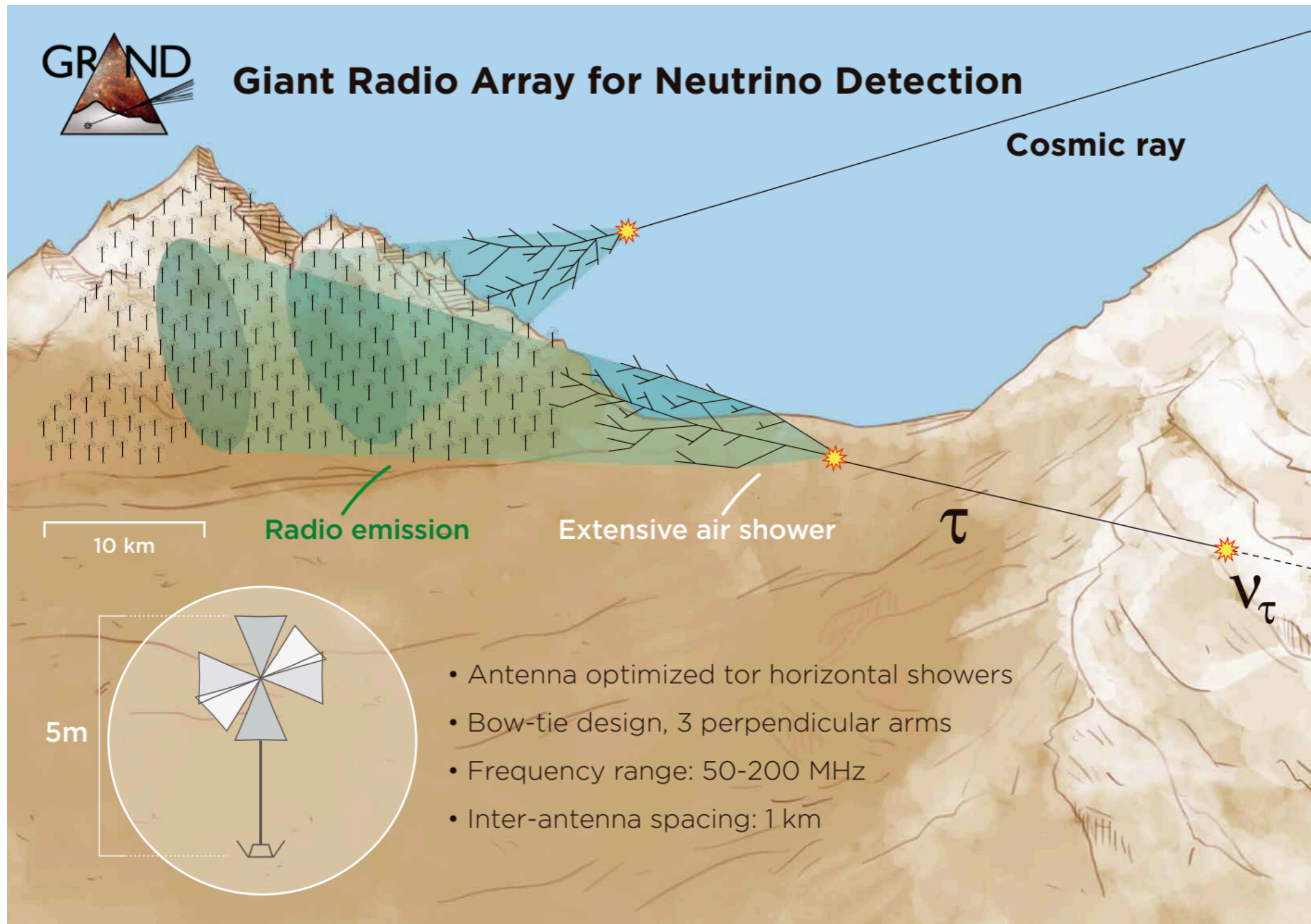
## Beamforming Elevated Array for COsmic Neutrinos



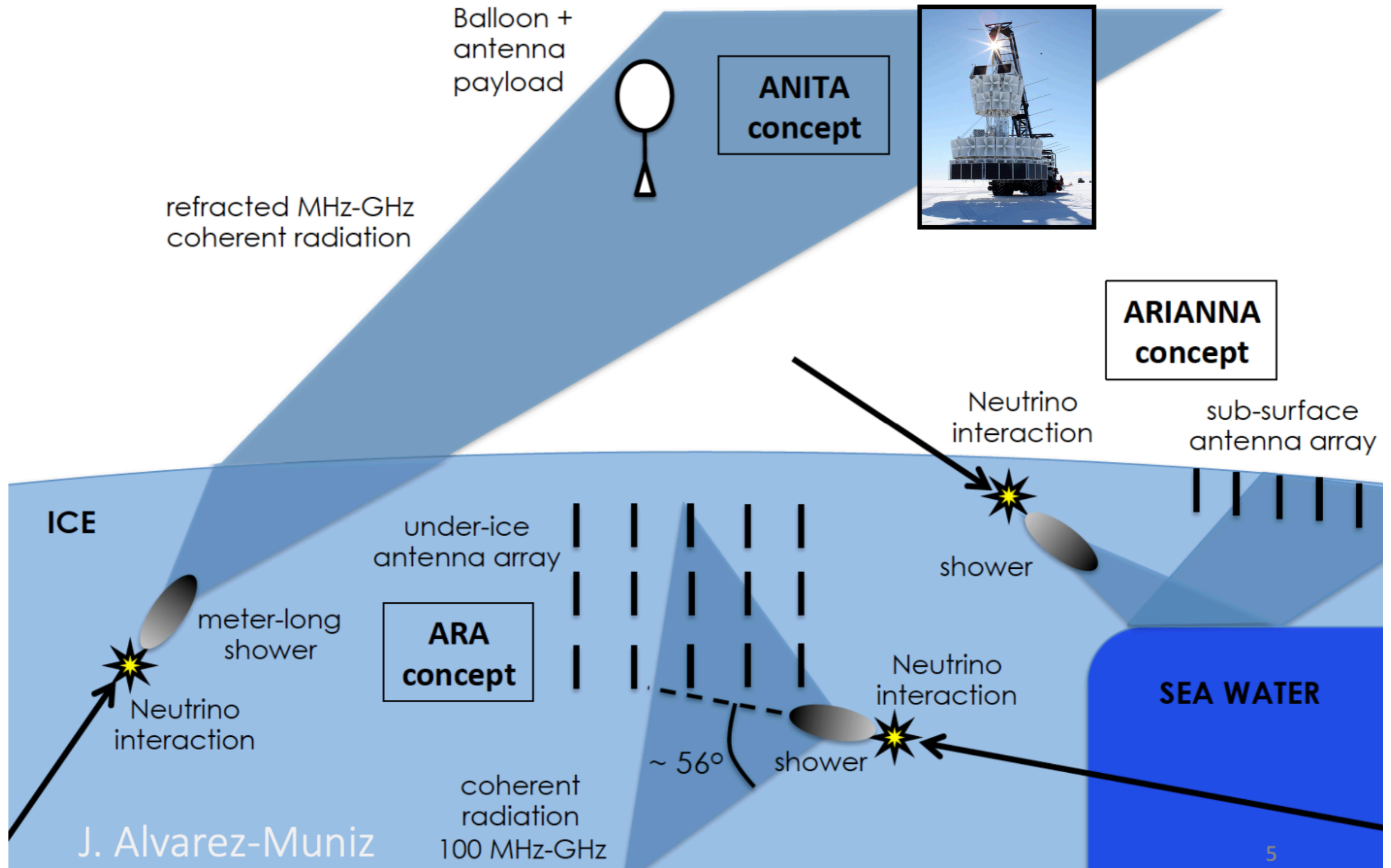
D. Southall et al arXiv:2206.09660v1 2022

**Candidate CR event**

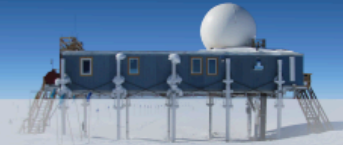
# GRAND



# In-ice radio experiments



# RNO-G



Surface

Deep

Askaryan  
Radiation

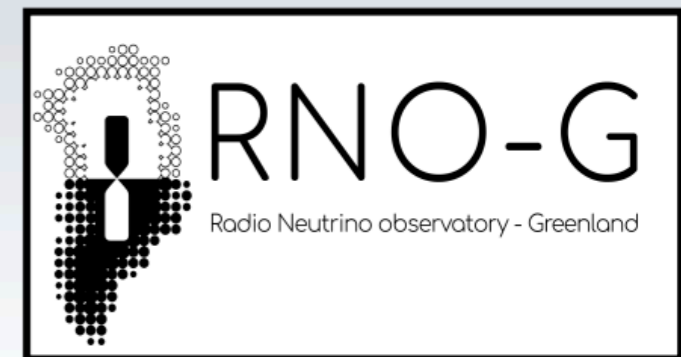
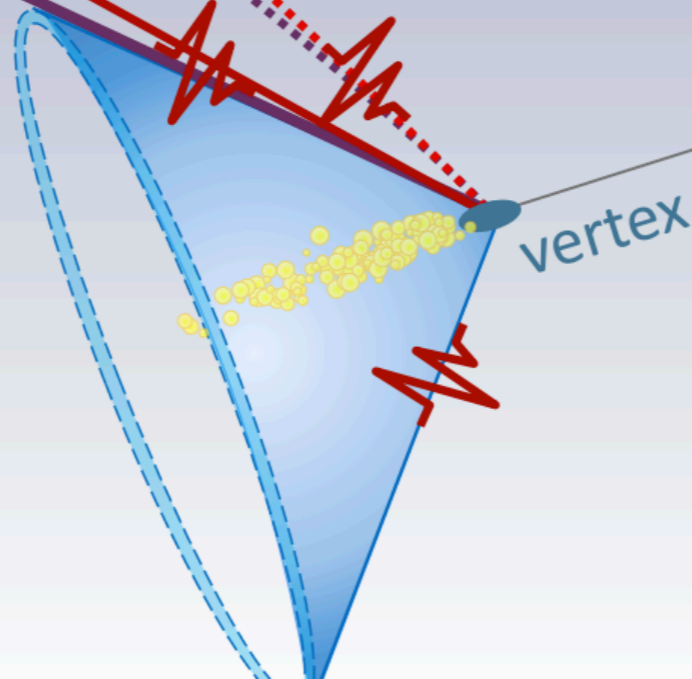
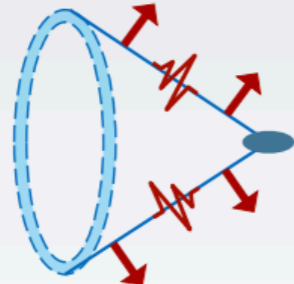
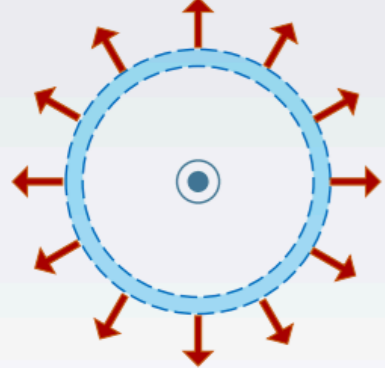
Neutrino  $\nu$

forward view

side view

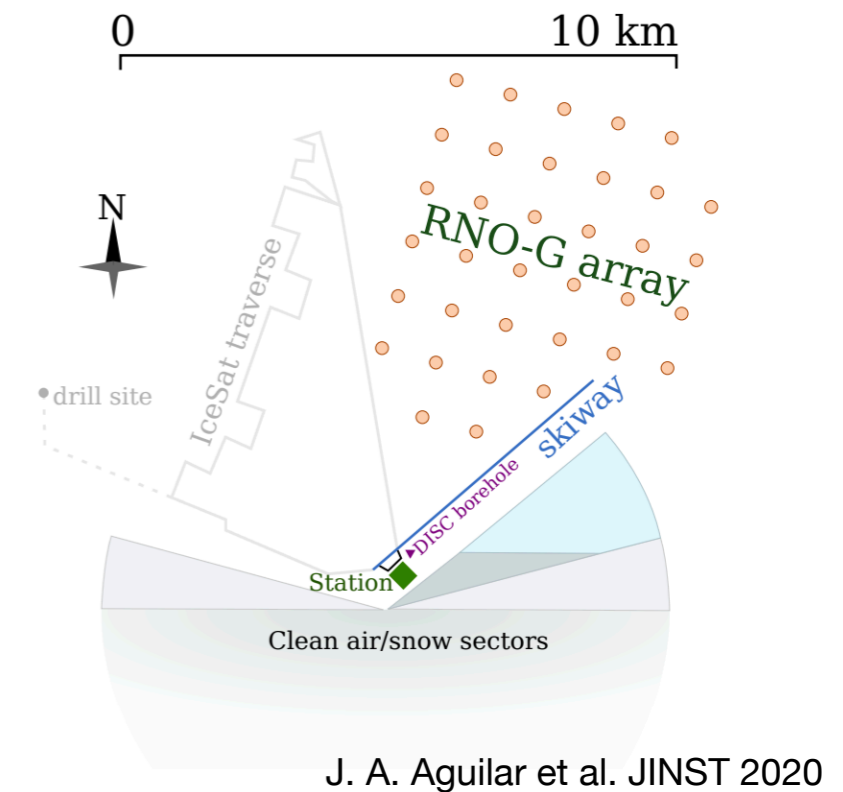
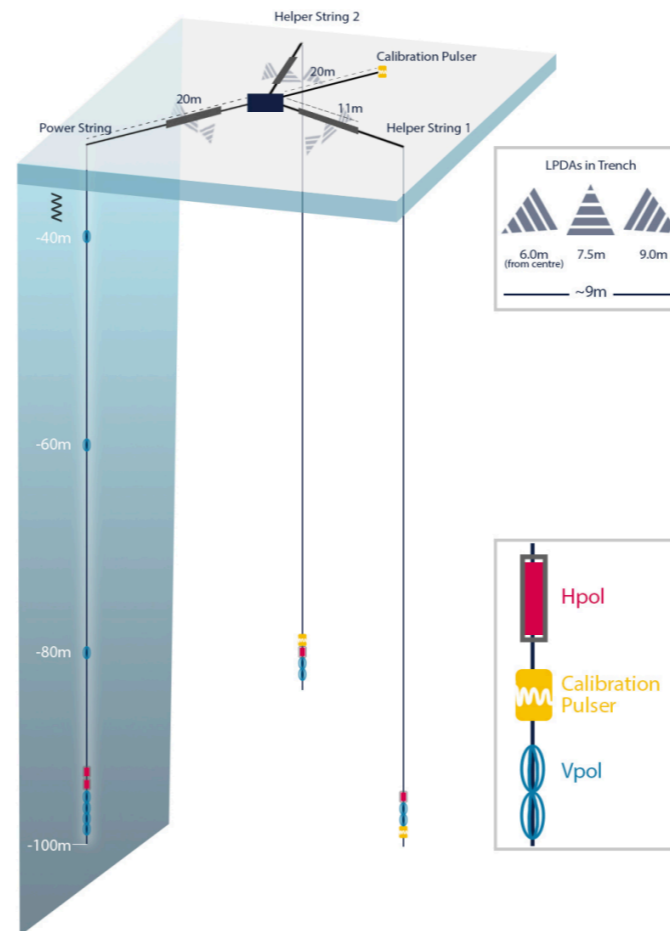
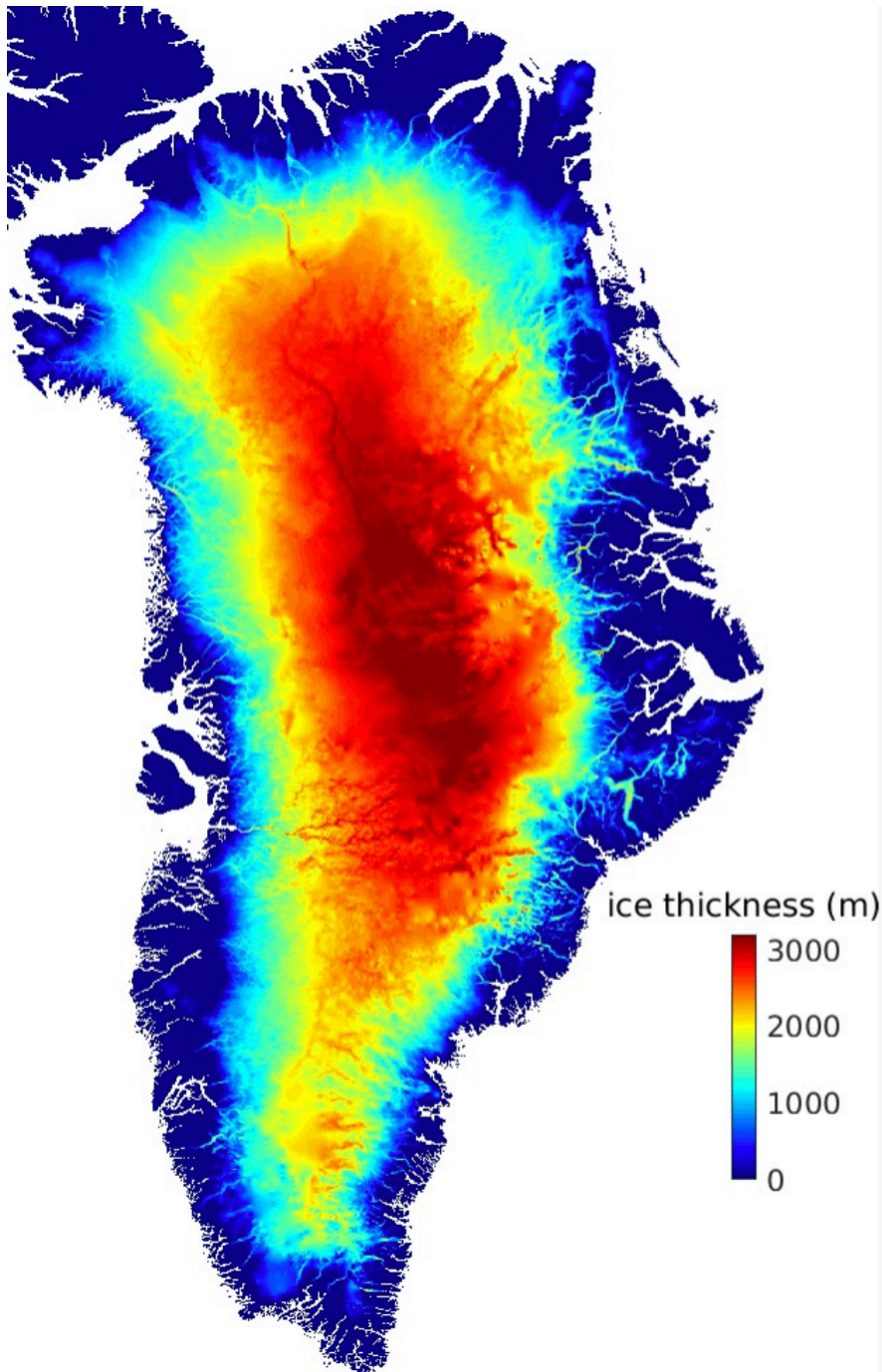
E-field polarization

E-field polarization





# RNO-G

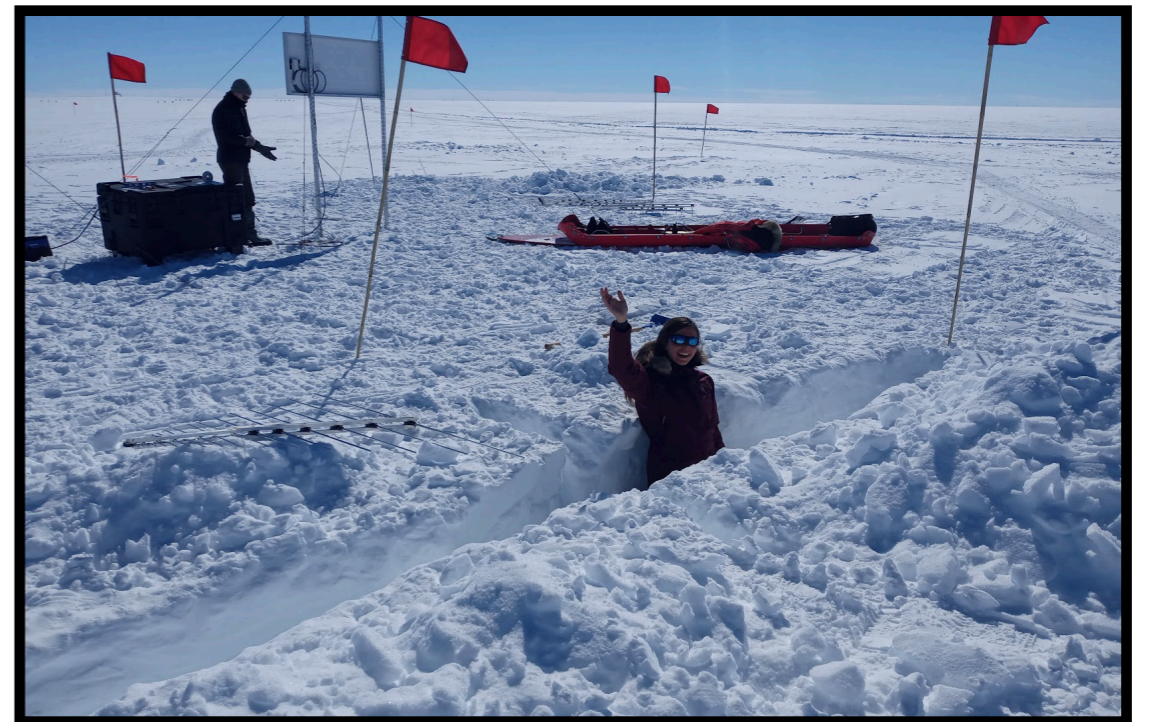


- Make use of the thick ice in Greenland
- Design based on ARA and ARIANNA experience
- 35 stations with ~1 km spacing
- Design study for IceCube Gen2

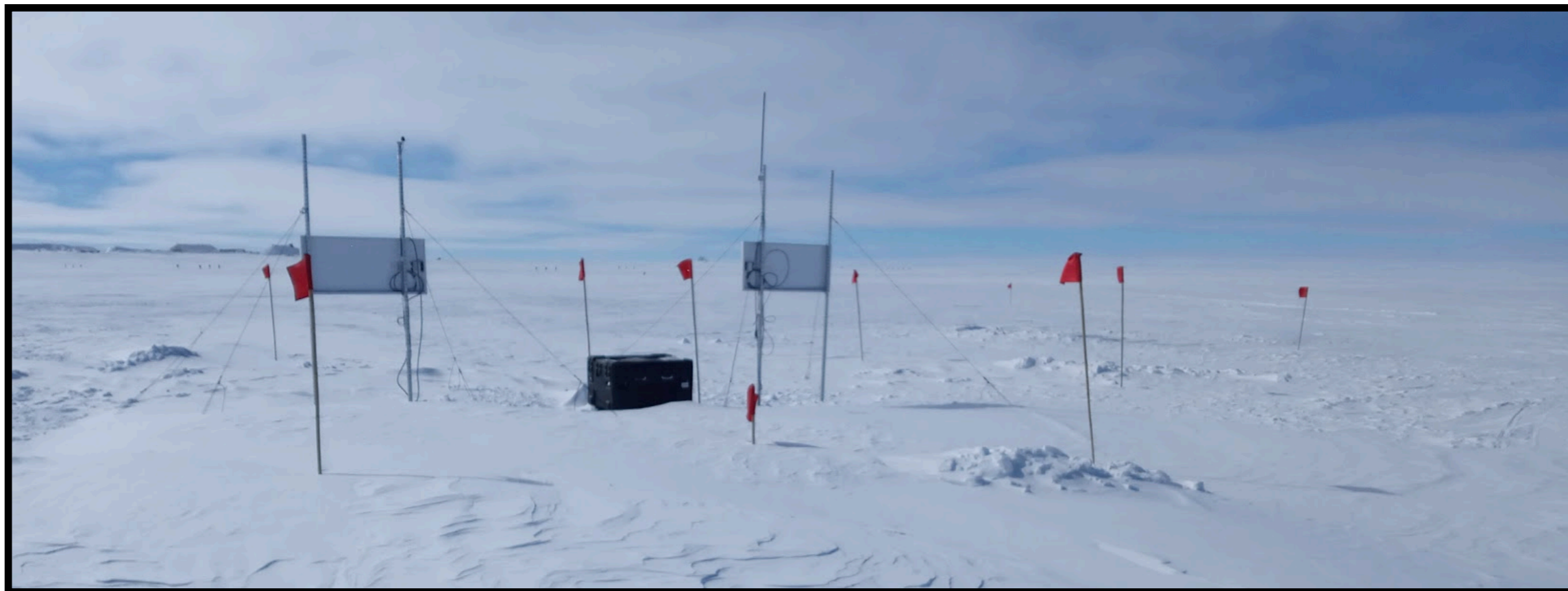
# RNO-G



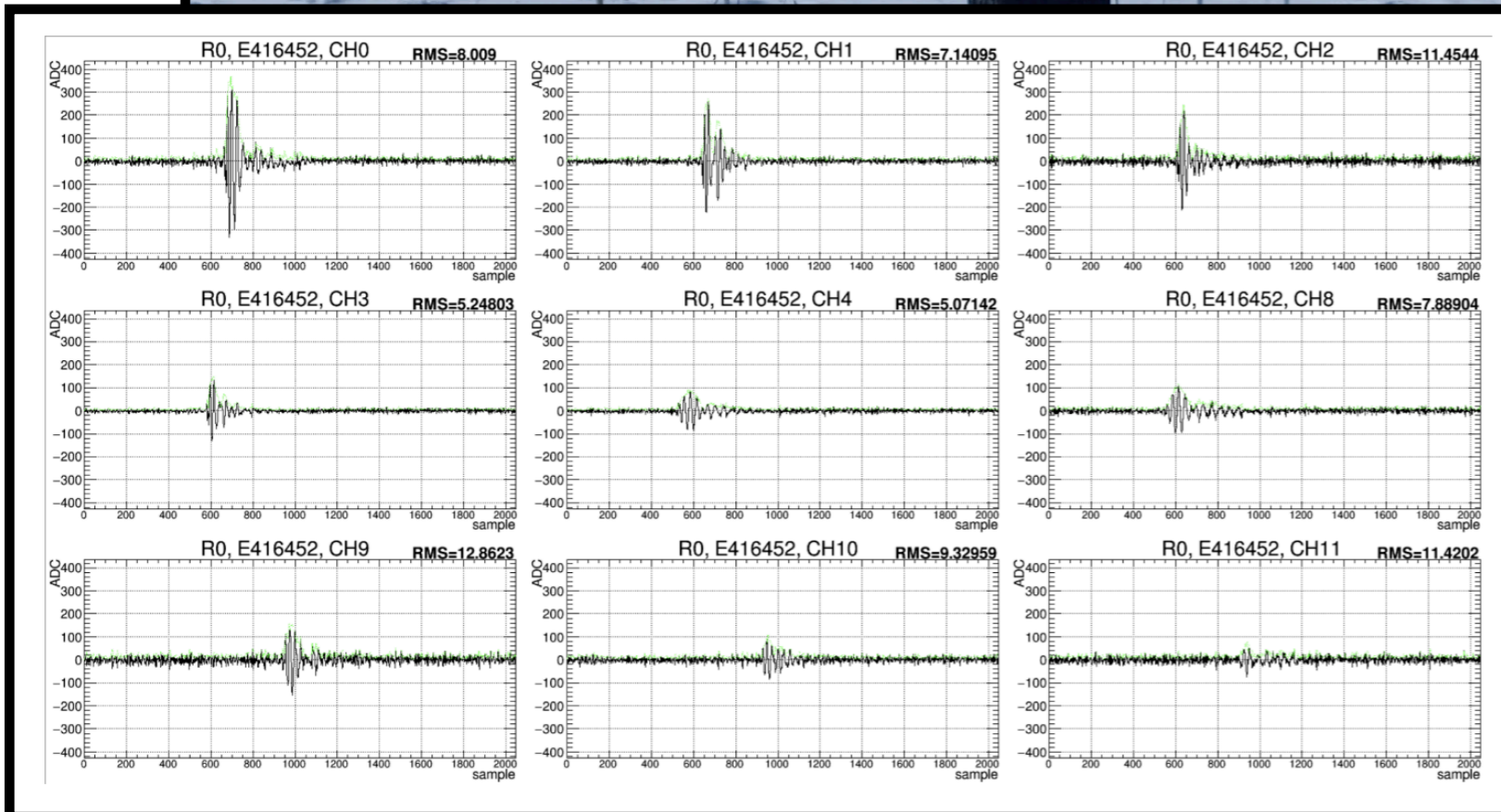
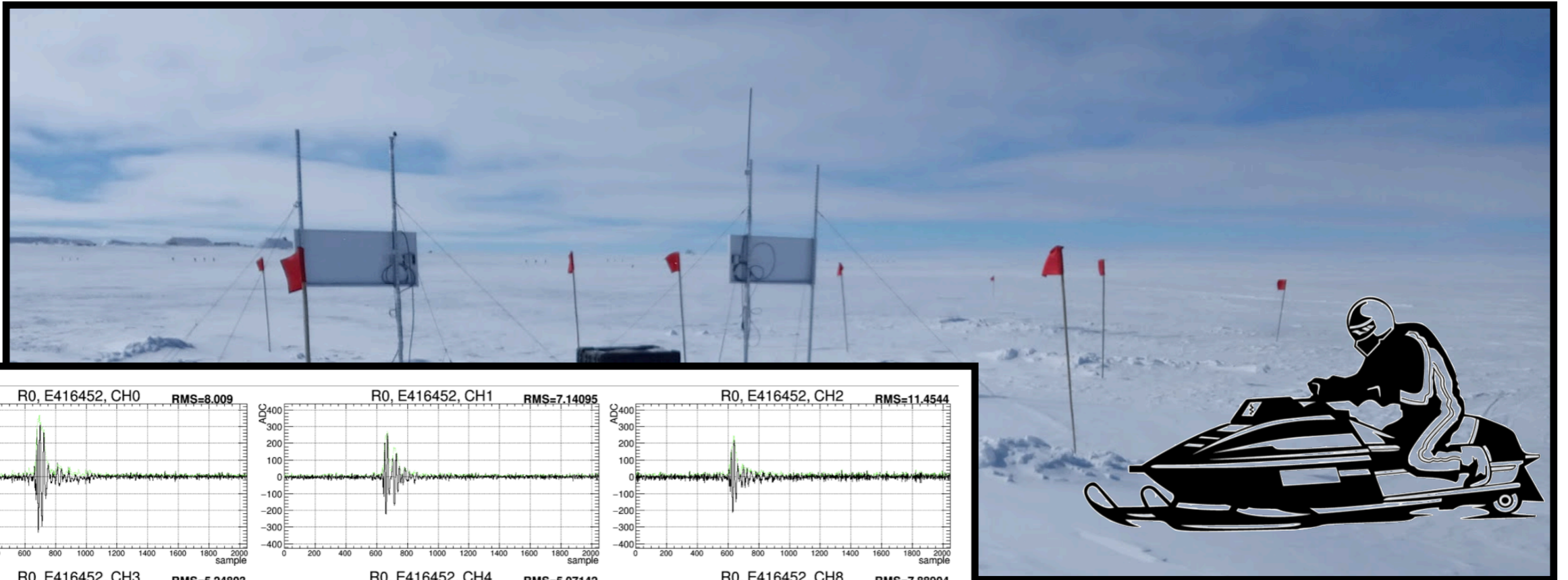
## Deployment 2021 -



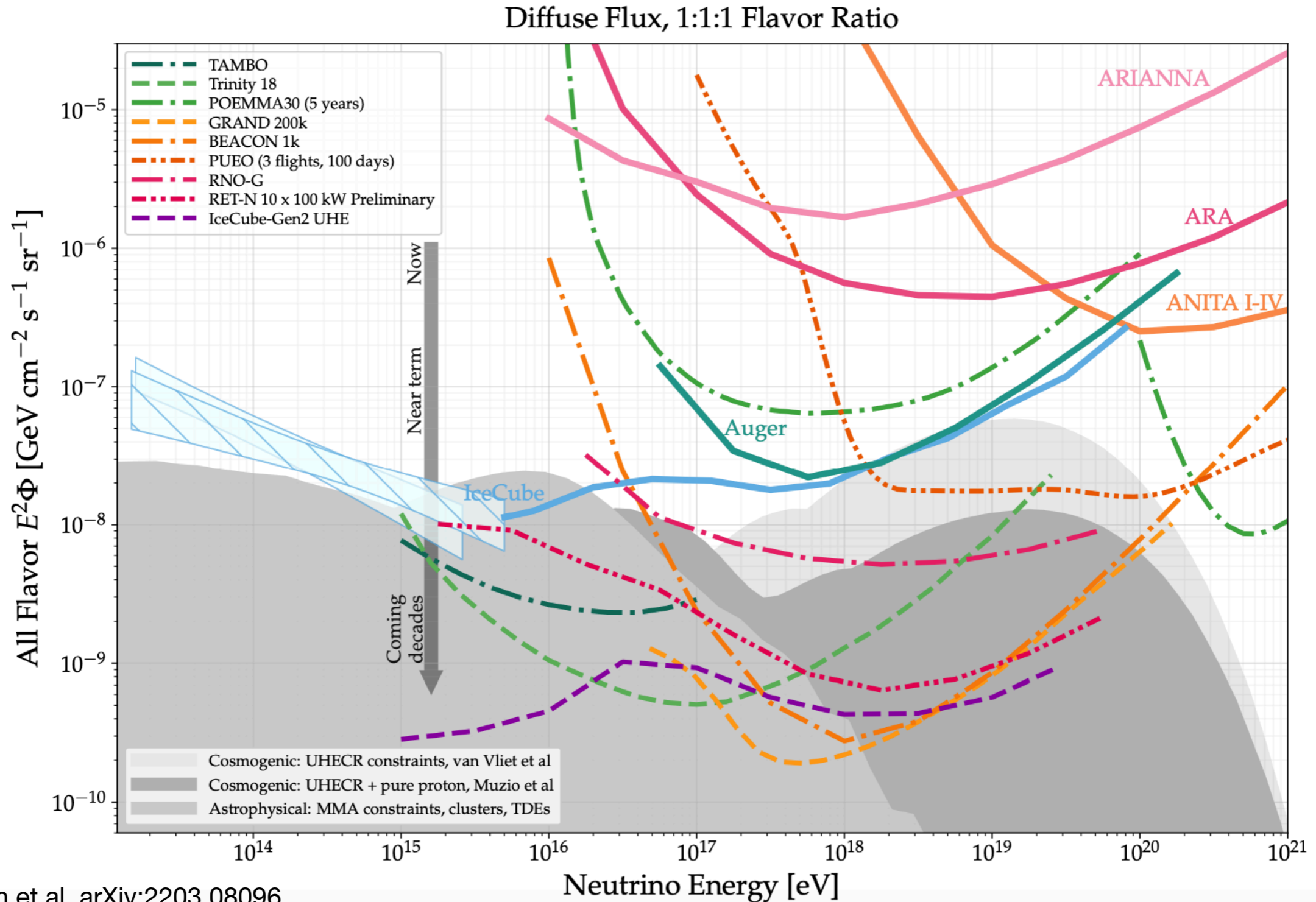
# RNO-G



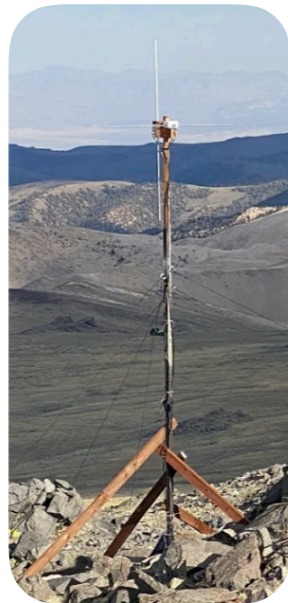
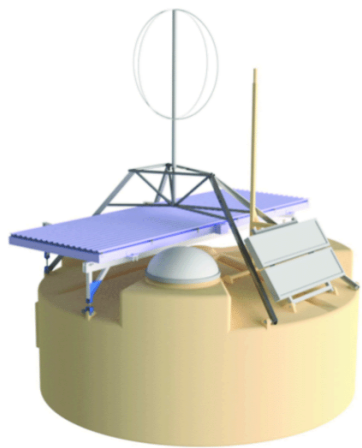
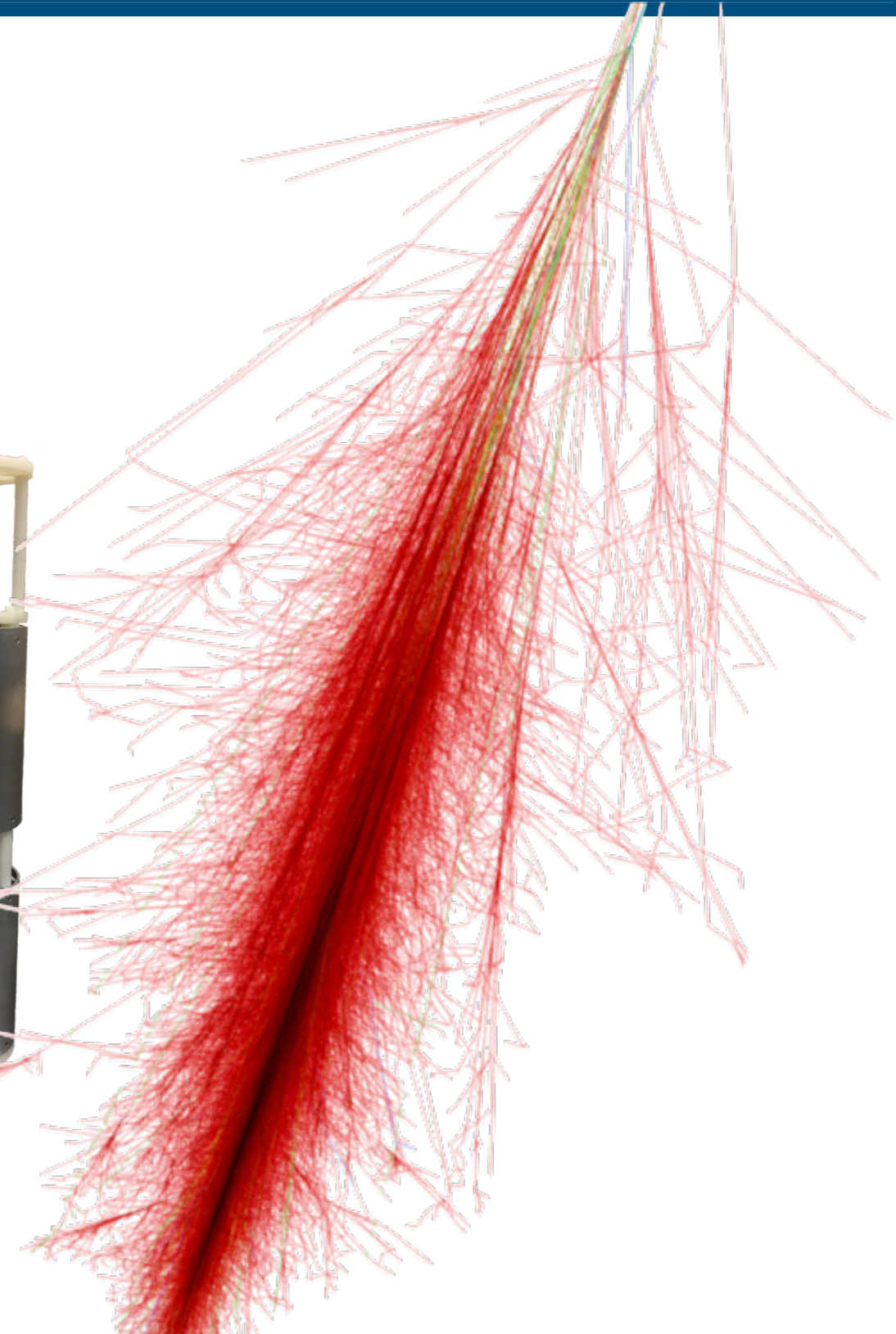
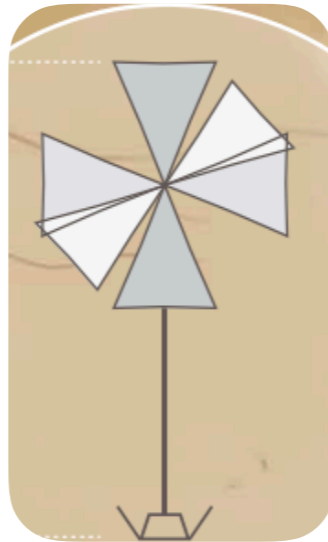
# RNO-G



# UHE Neutrinos



# Thanks!



# Where do the most energetic particles come from?

Galactic: SNR ?



Extragalactic: AGN ?



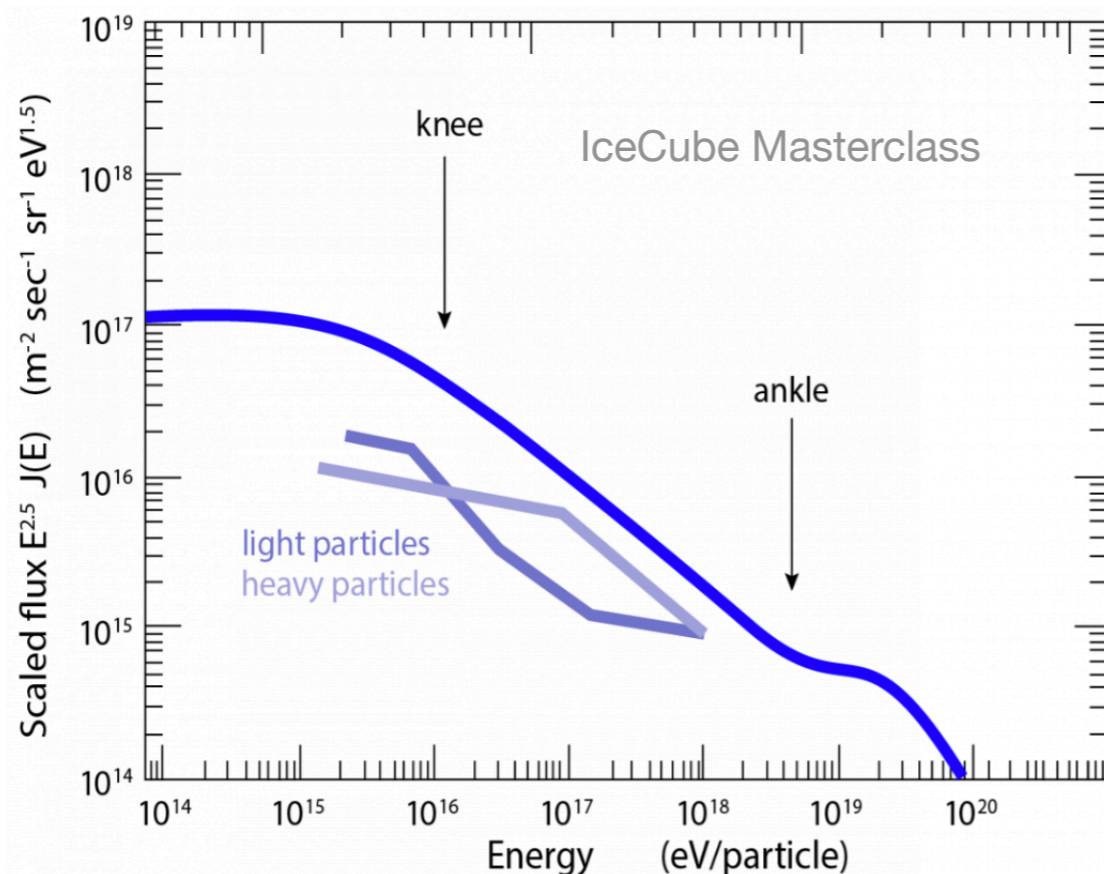
Hillas criterion:

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

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

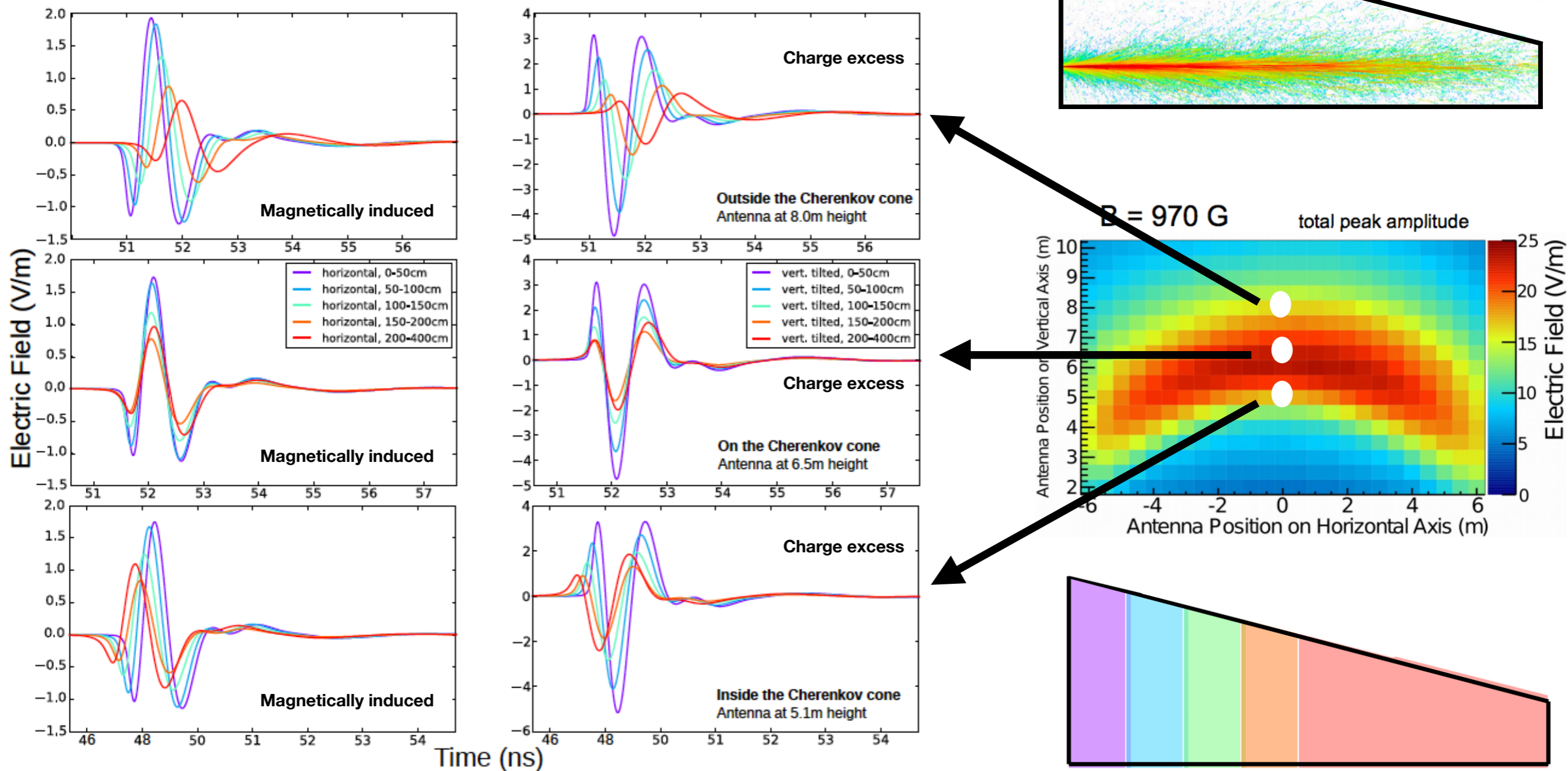
- Below  $10^{19}$  eV, can't point directly to sources
- Transition to heavier composition indicates the maximum source energy is reached

To answer this question, we need to determine the *energy* and *composition* of cosmic rays.



# Radio emission from “air showers” in the lab

## Cherenkov effects (simulation)





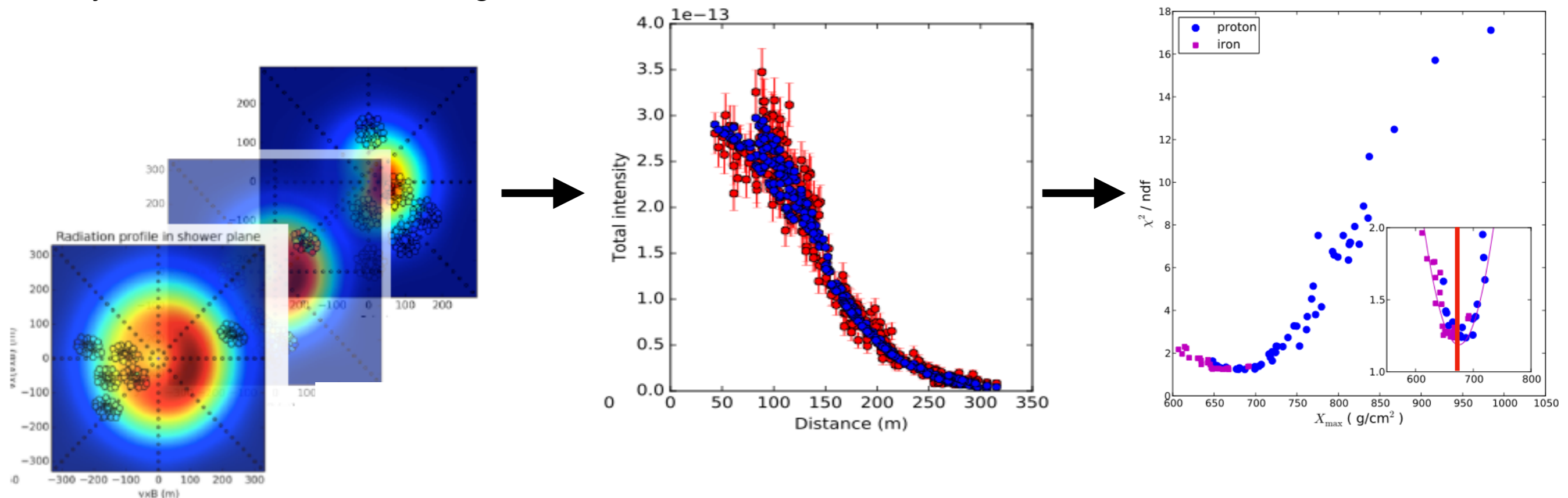
# Event Analysis

- Simulate ~30 P and Fe showers with realistic atmosphere and known arrival direction (natural distribution of  $X_{\max}$ )
- Calculate reduced  $\chi^2$  for each simulation
- Parabola fit determines event  $X_{\max}$
- Resolution  $< 20 \text{ g/cm}^2$
- Systematic uncertainties  $< 9 \text{ g/cm}^2$

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

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

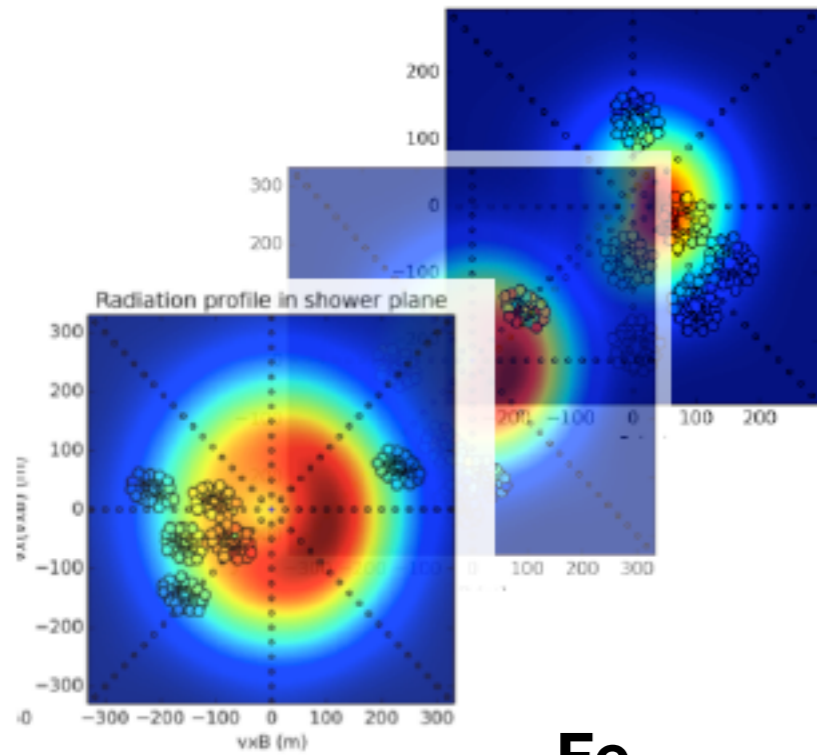
Free parameters: energy and core position



# Cosmic Rays at LOFAR

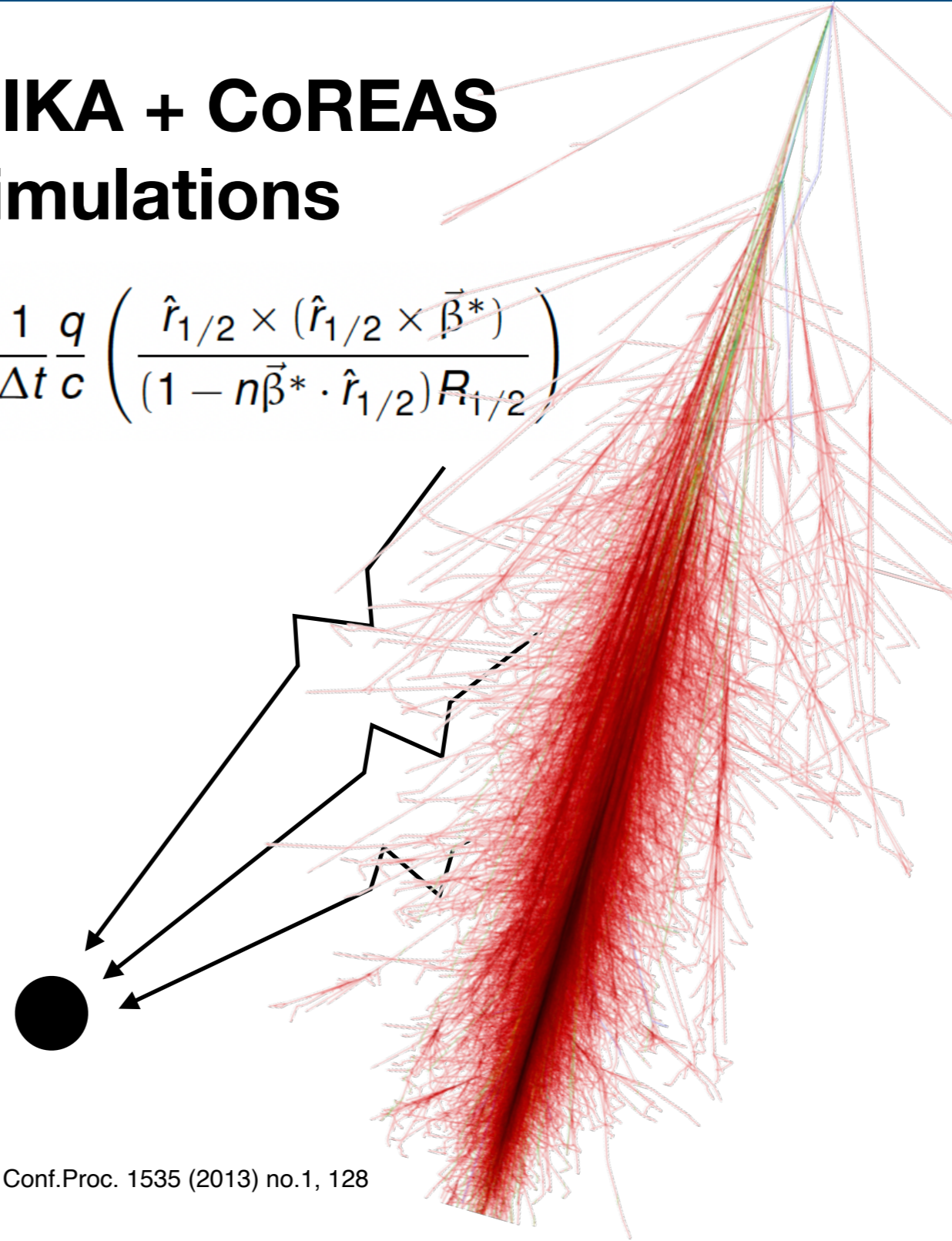
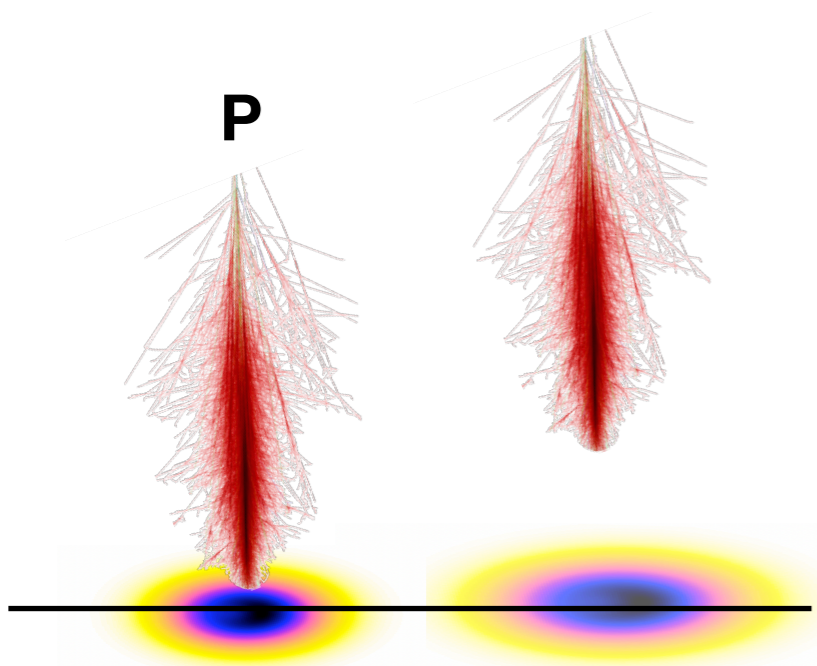
## CORSIKA + CoREAS simulations

$$\vec{E}_{\pm}(\vec{X}, t) = \pm \frac{1}{\Delta t} \frac{q}{c} \left( \frac{\hat{r}_{1/2} \times (\hat{r}_{1/2} \times \vec{\beta}^*)}{(1 - n\vec{\beta}^* \cdot \hat{r}_{1/2}) R_{1/2}} \right)$$



Fe

P



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