Analysing Ultra High Energy Cosmic Ray Air Showers with GRANDProto300

Pragati Mitra *(pmitra@fuw.edu.pl)*

High Energy Physics Seminar, UW

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Outline

- **Introduction**
- **Concept of GRAND**
- **Offline signal identification for GRANDProto300**
- **Prospects of reconstruction of air showers with radio**

Origin of UHE cosmic messengers?

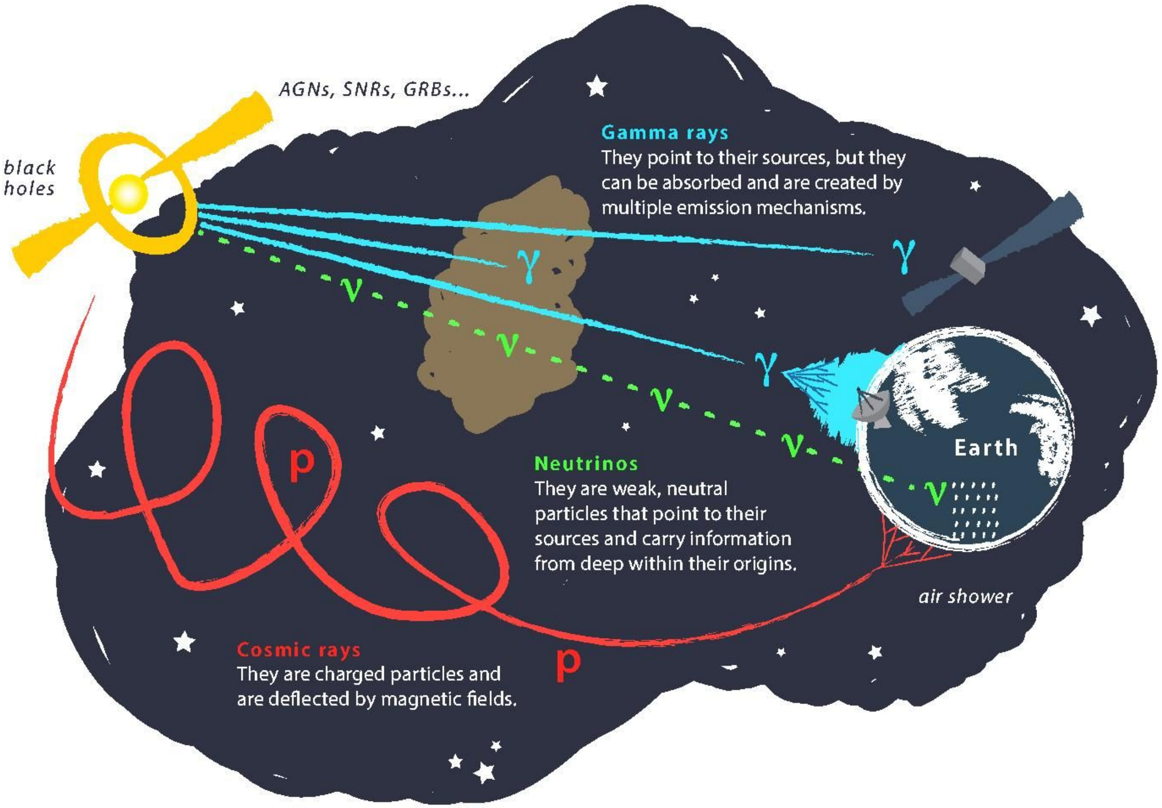
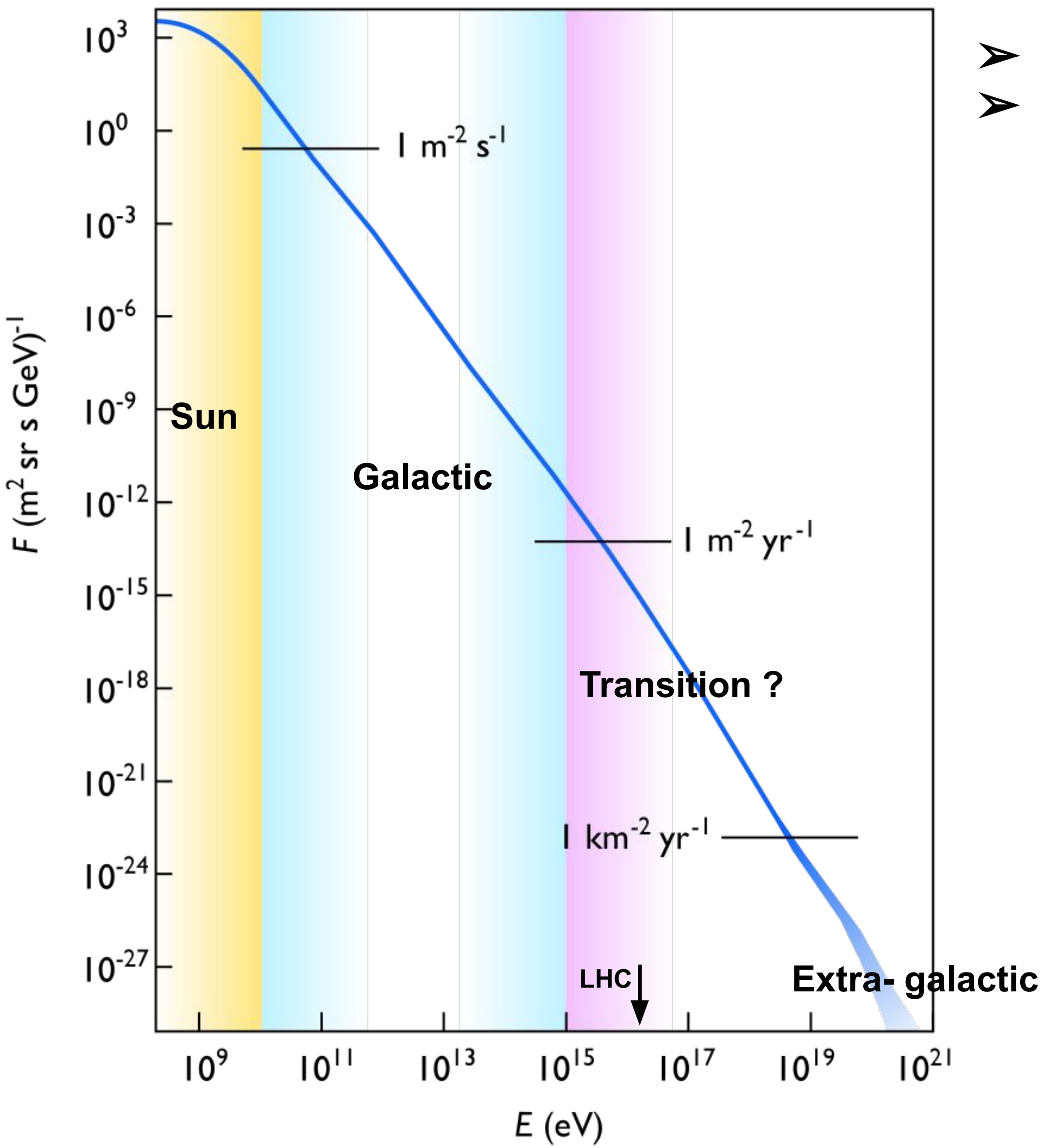


Image Source icecube.org

- Charged particles coming from outer space.
- Cosmic rays are deflected by magnetic fields, do not point back to source.
- Measure cosmic ray flux and their mass to know origin!

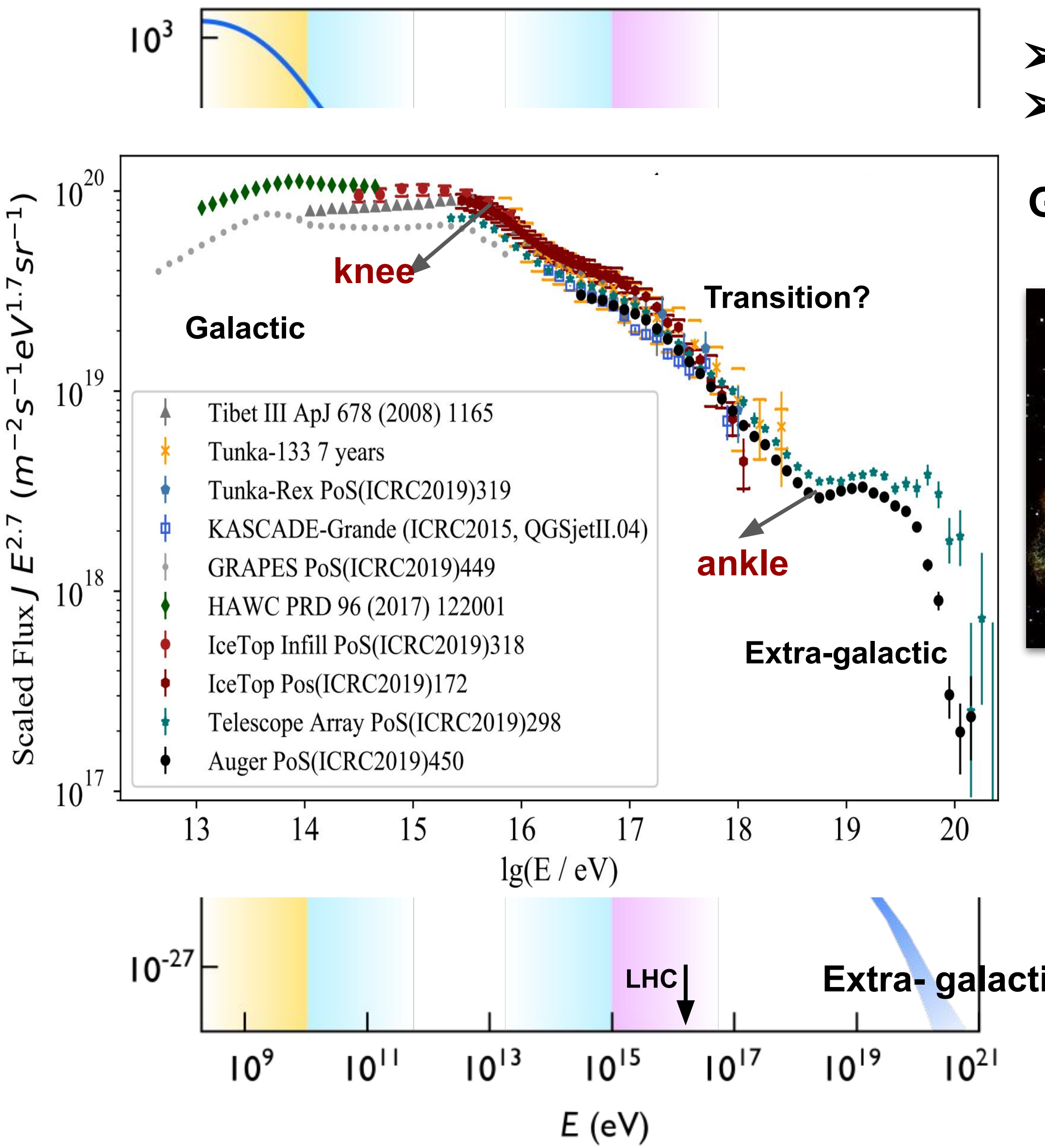
Cosmic ray spectrum



- Broken power law
- Spectrum features origin:

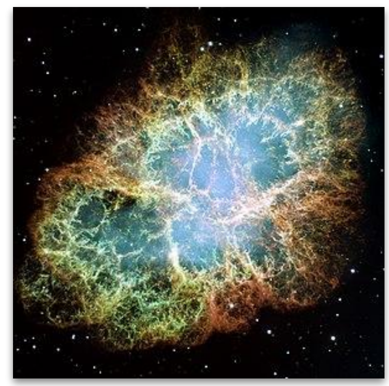
Images:http://bit.ly/17gvxC, F.G. Schröder, ICRC 2019

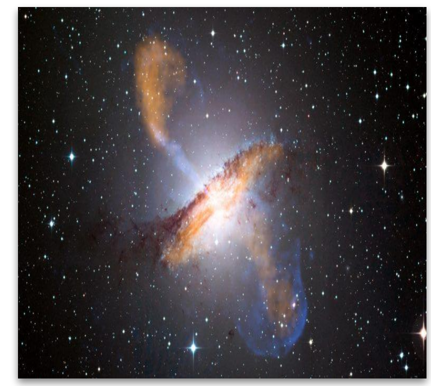
Cosmic ray spectrum



- ➢ **Broken power law**
- ➢ **Spectrum features origin:**

Galactic: SNR **Extra-galactic:AGN**

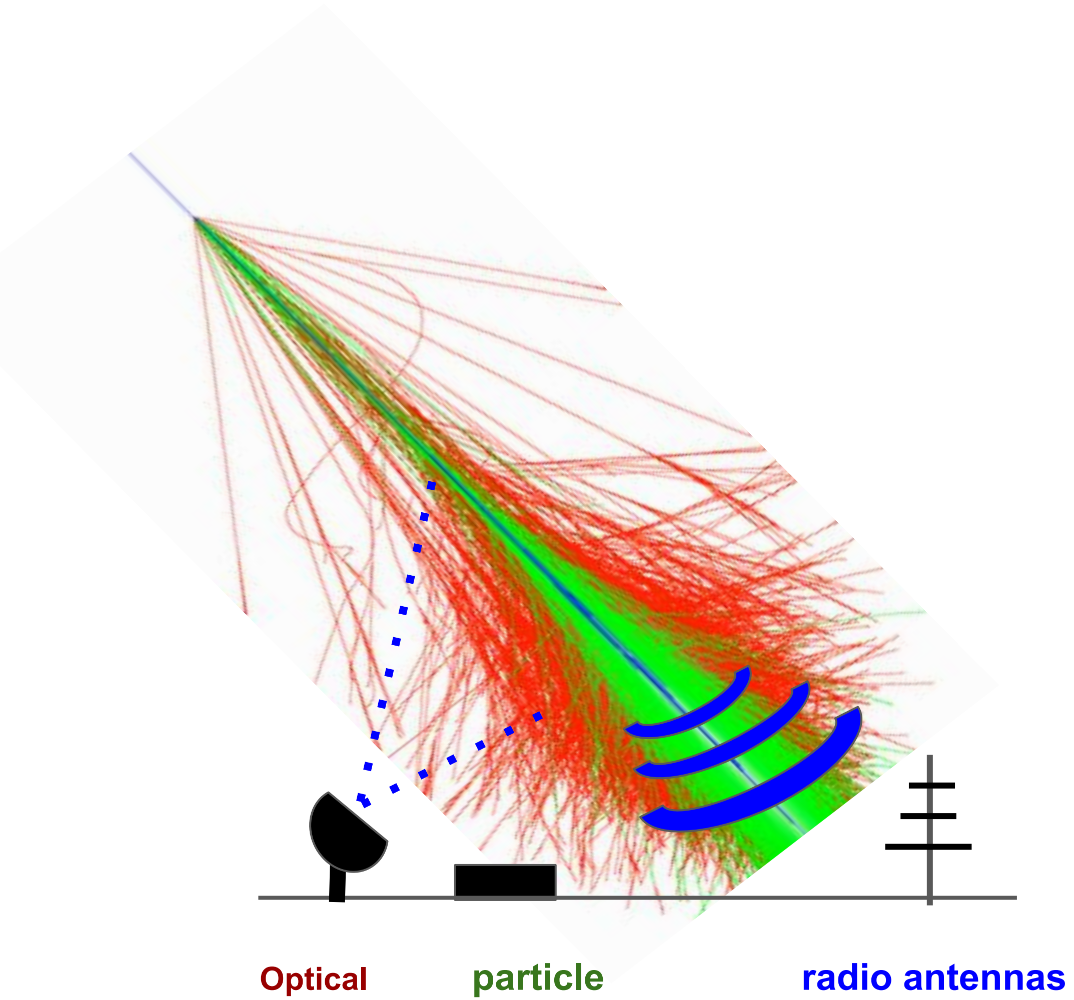




- ❑ **Below 10^{19} eV cosmic rays do not point to their sources.**
- ❑ **Mass composition to understand origin, specially at transition region!**

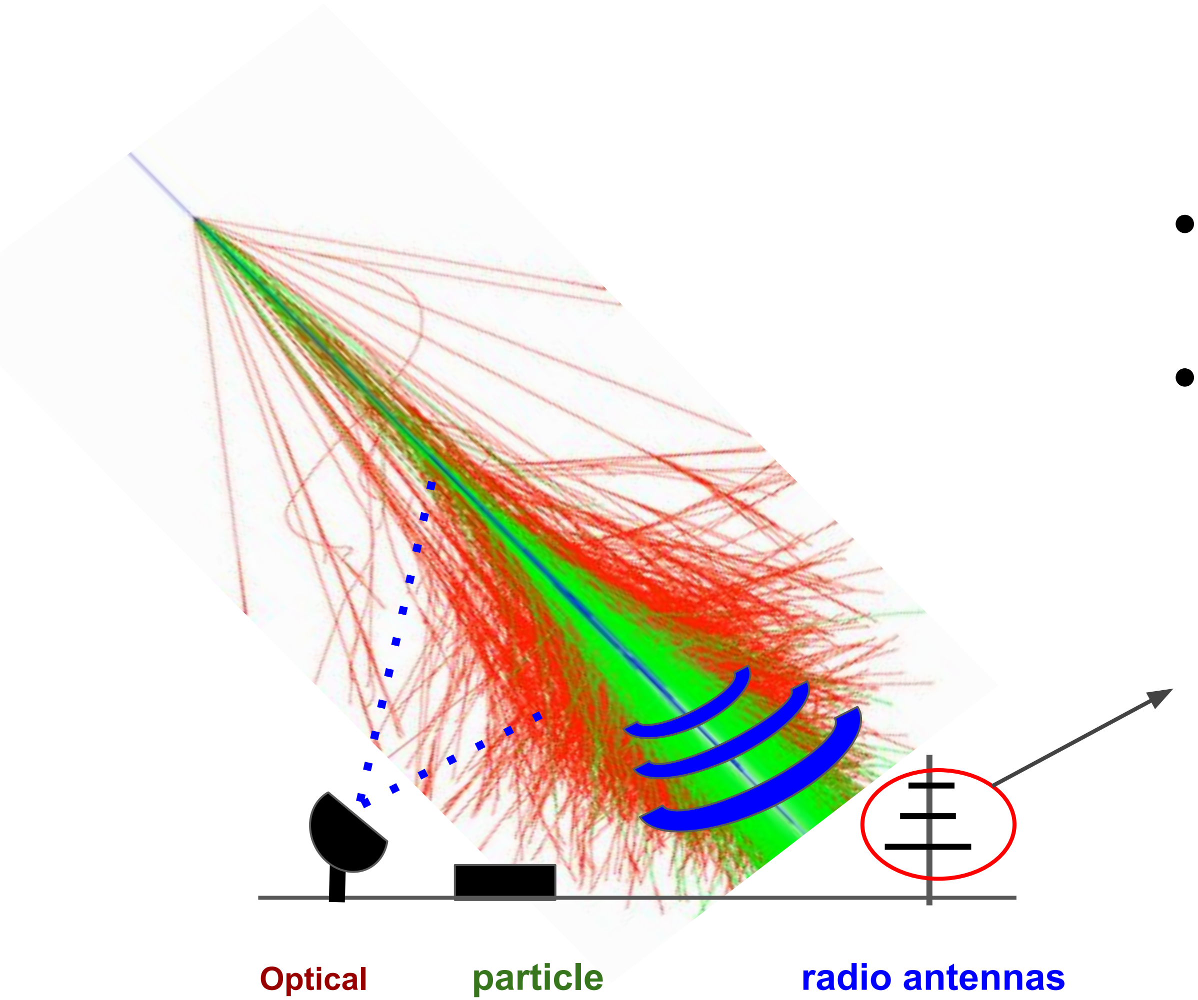
Images:http://bit.ly/17gvxC, F.G. Schröder, ICRC 2019

Ground based Detection



- Cosmic rays with $E > 10^{14}$ eV interact with atmosphere.
- Cascade of secondary particles upon the interaction of primary particles with the atmosphere: em + hadronic + muonic.

Ground based Detection



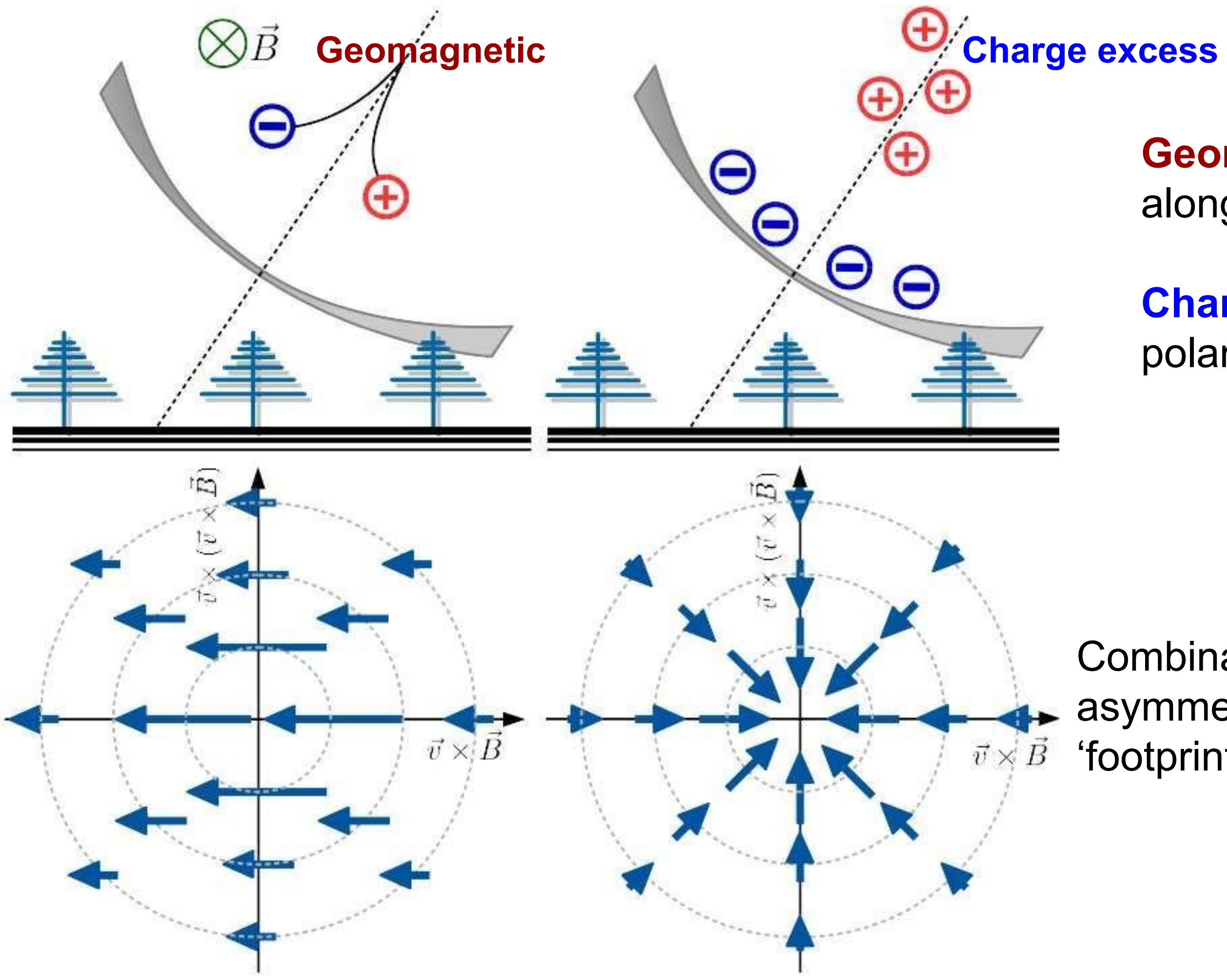
- Cosmic rays with E> 10^{14} eV interact with atmosphere.

- Cascade of secondary particles upon the interaction of primary particles with the atmosphere: em + hadronic + muonic.

Radio detection technique:

★ em component.
★ 100% duty cycle.
★ Cheap and easy to deploy
★ Operates in the transition region : 10^{16}- 10^{18} eV and beyond.

Radio emission mechanism



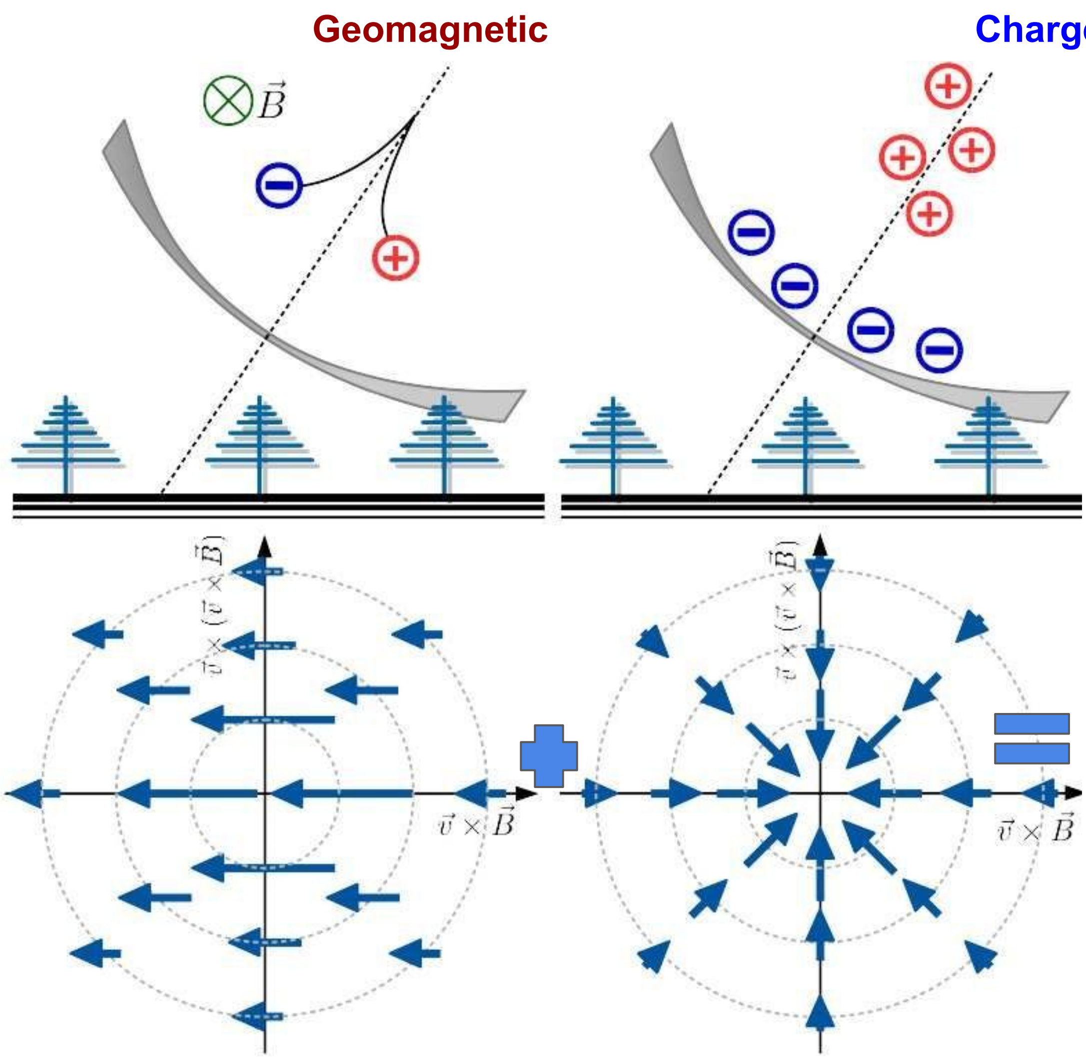
Geomagnetic: linearly polarized along vxB.

Charge excess: linearly polarized, radially to shower axis.

Combination of the two introduces asymmetry in the radio profile-'footprint'.

C.Glaser et al,arXiv:1706:01451[astro.ph.IM]

Radio emission mechanism



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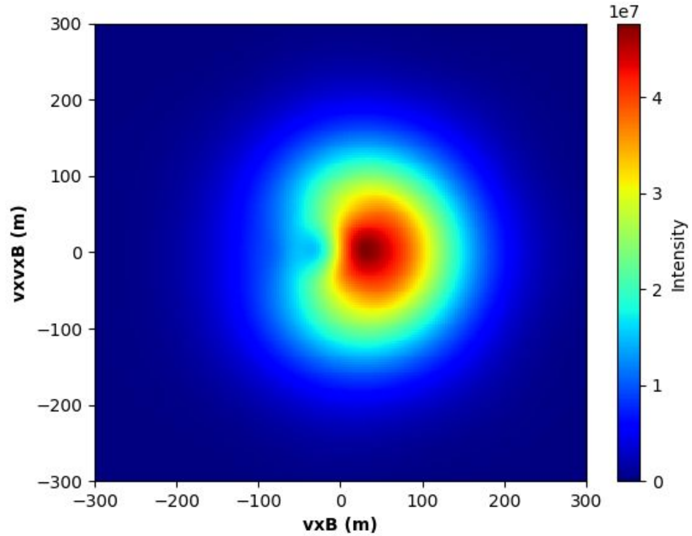
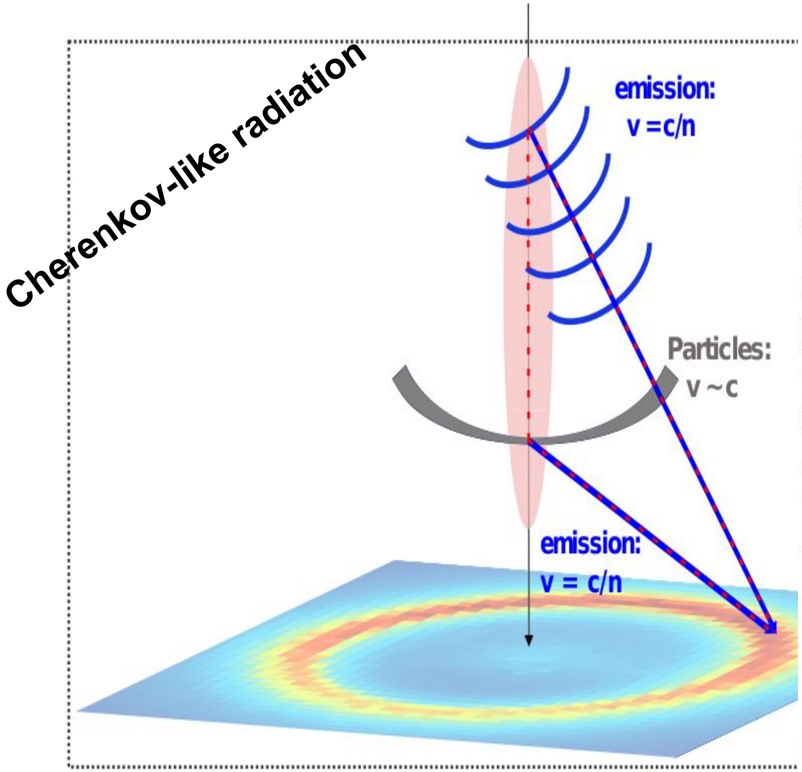
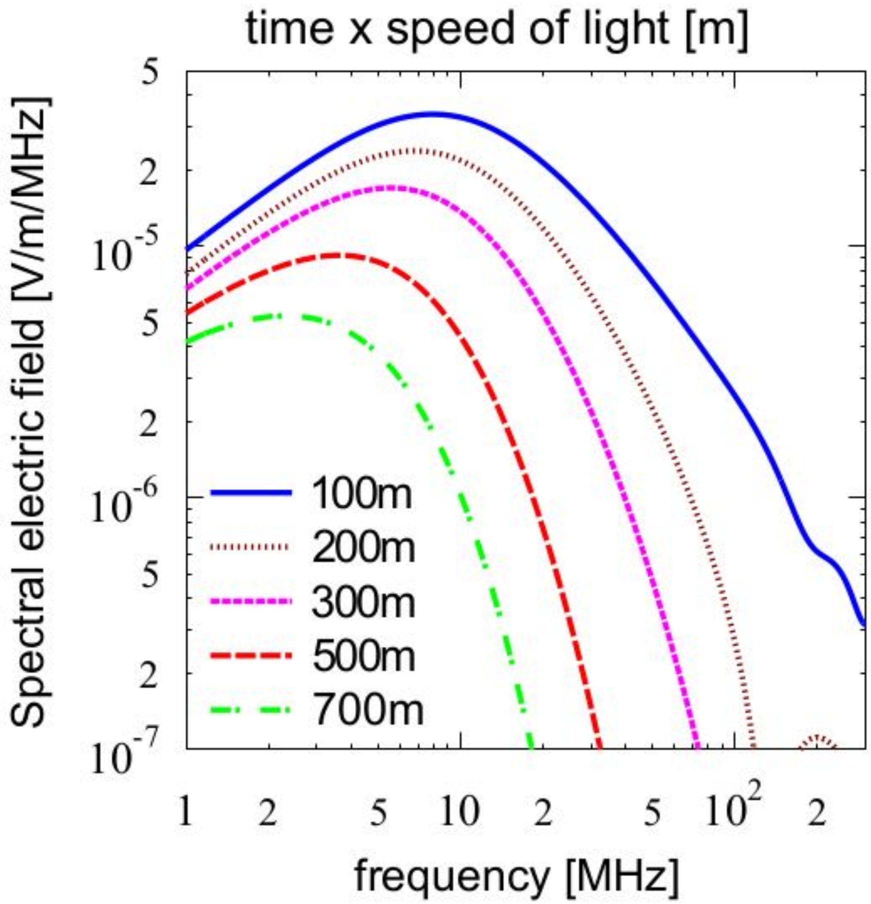


C.Glaser et al,arXiv:1706:01451[astro.ph.IM]

Properties of radio signal



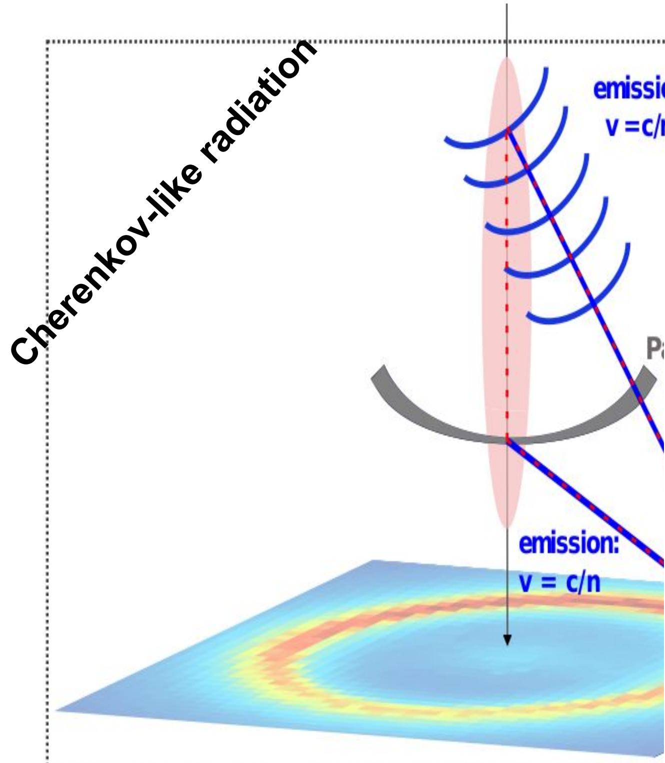


- Refractive index *n*>1, emission travels slower than particles.

- Highly compressed pulse ~ formation of ring like structure for observer at Cherenkov angle.

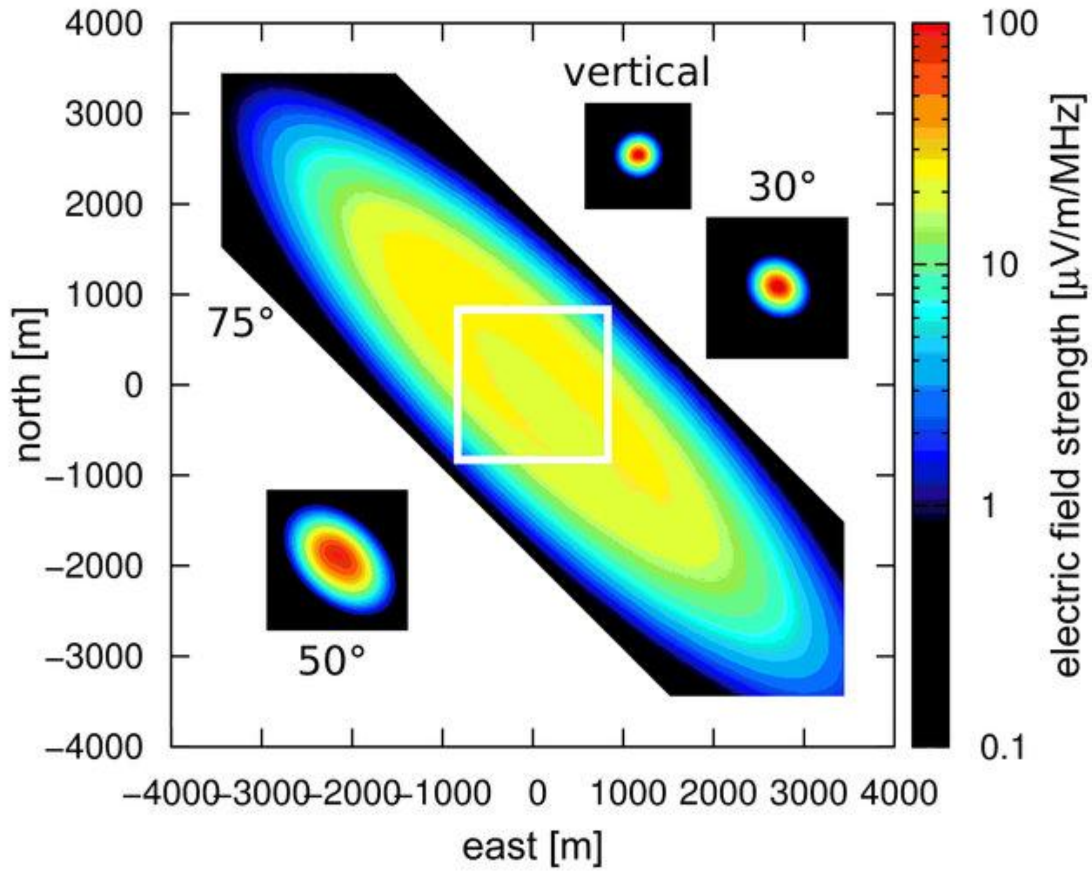
T.Huege, Phys. Report: 620,1-52,2016

Properties of radio signal



Inclined showers: large radio footprint on ground

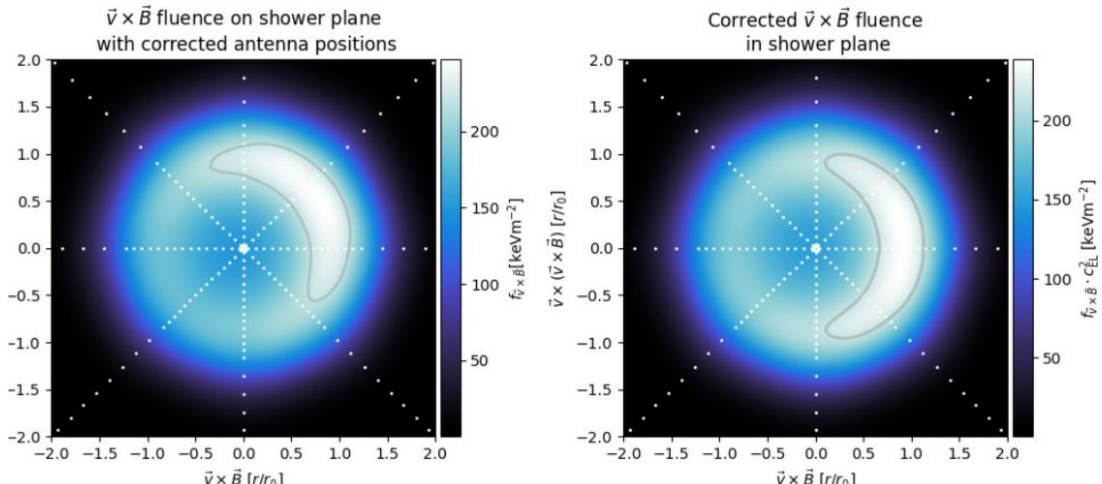
E= 5. 10^{18} eV



- Refractive index *n*>1, emission travels slower than particles.
- Highly compressed pulse ~ forı of ring like structure for observe

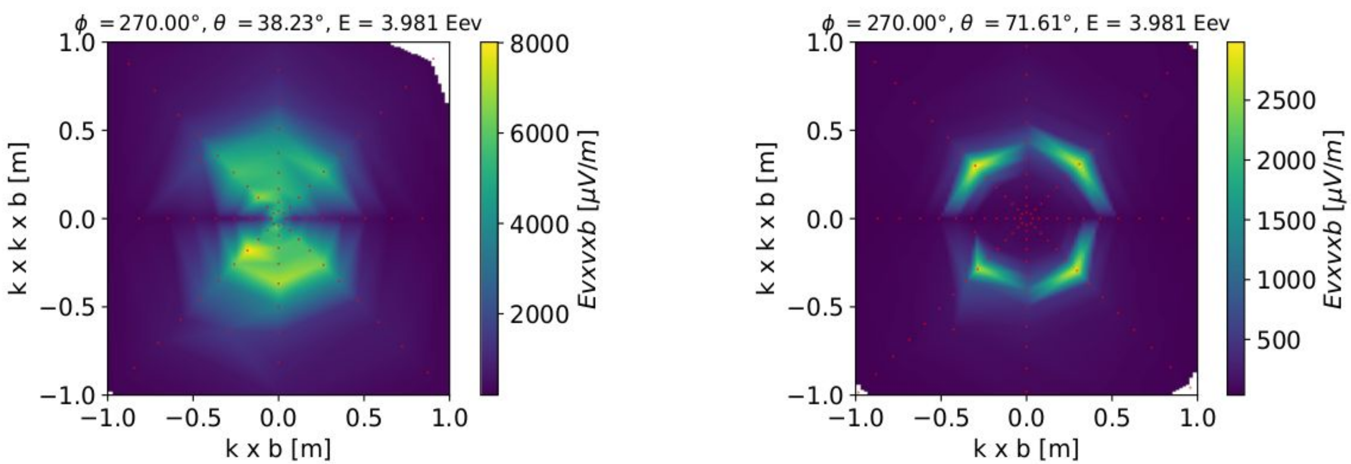
Highly Inclined Showers: New Territory

Asymmetry from Early-Late effect:



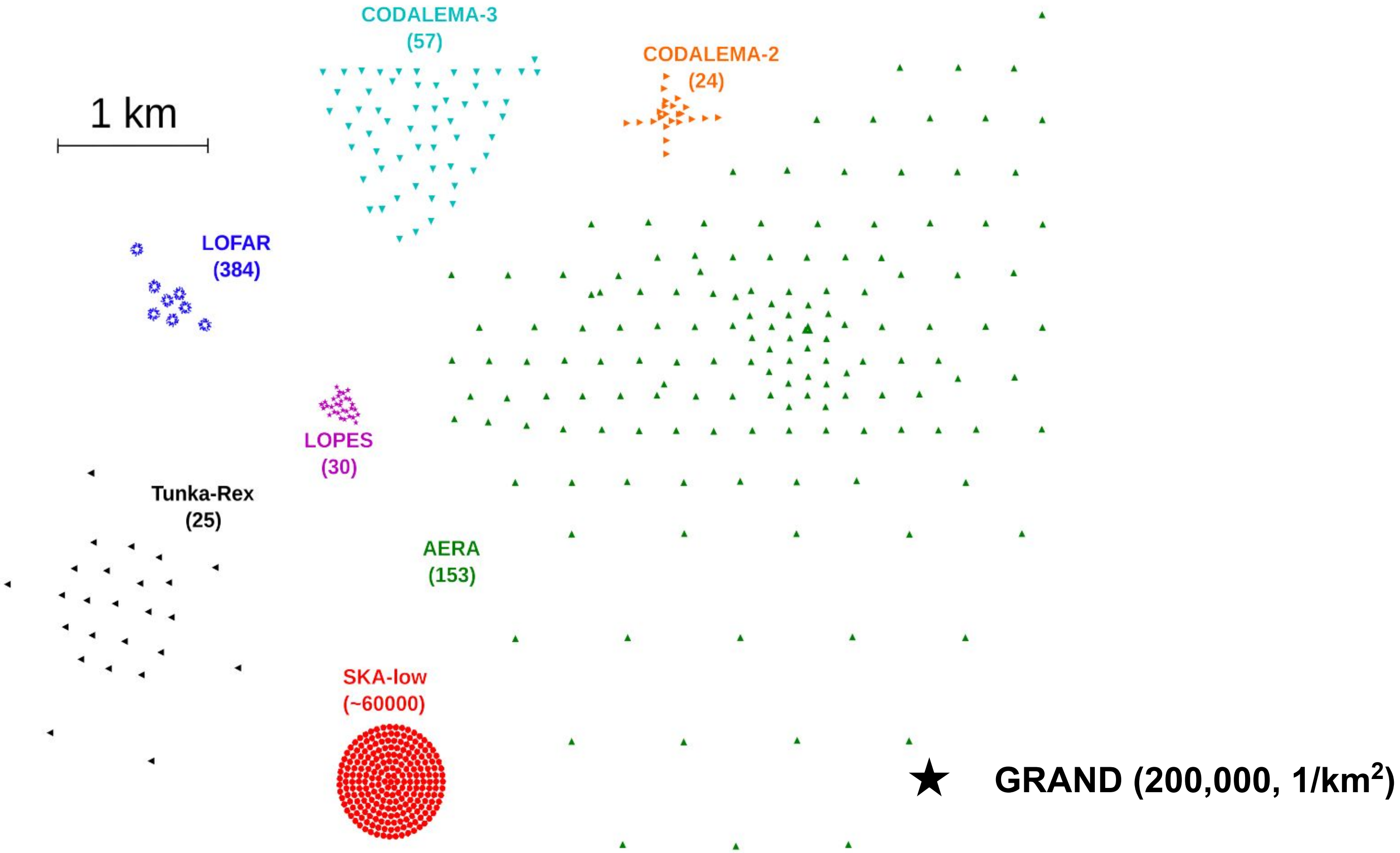
Plot by Lucas Guelzow

New feature of emission: Clover Leaf pattern



In preparation Simon Chiche, Chao Zhang et. al

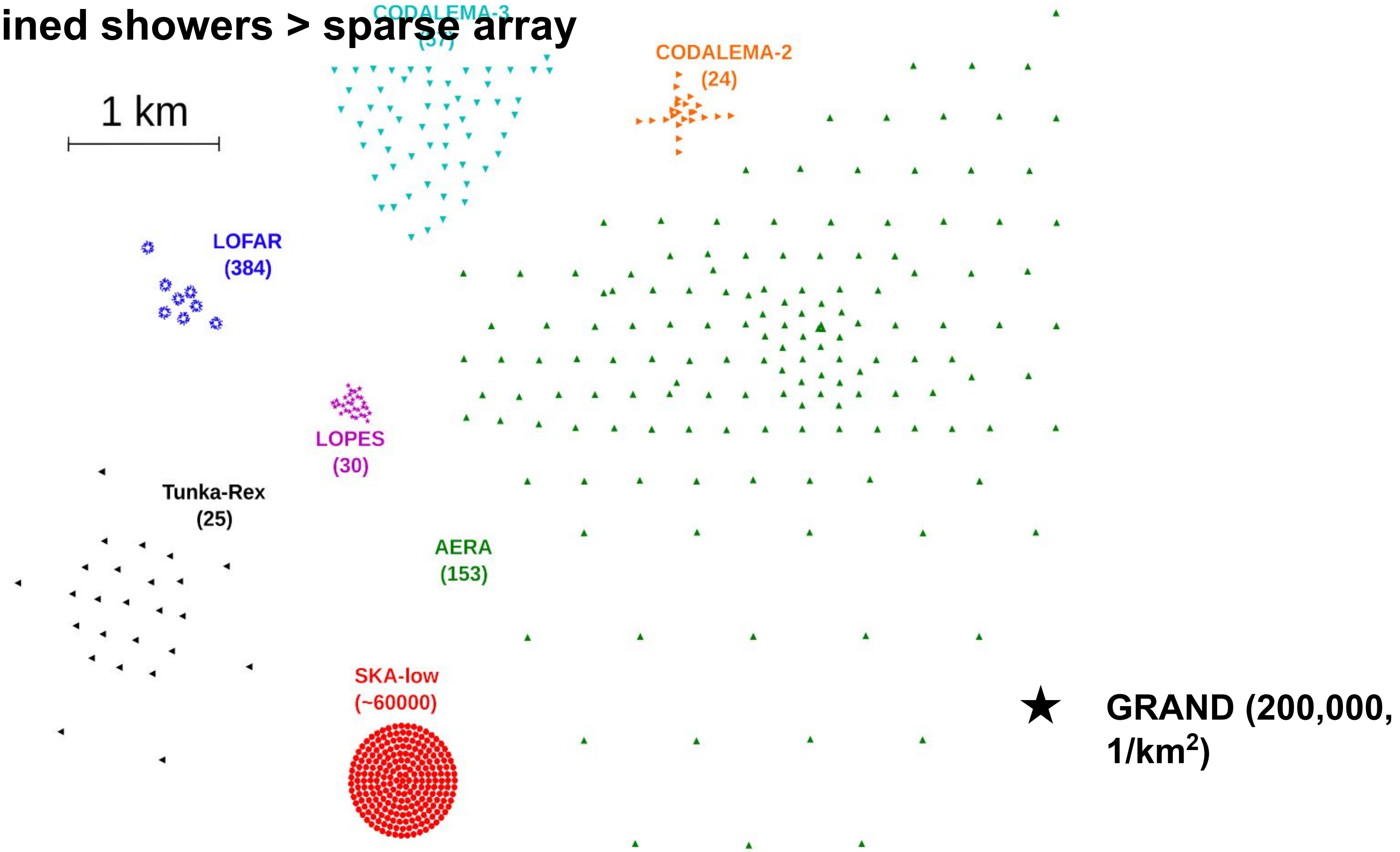
Radio detection of EAS experiments



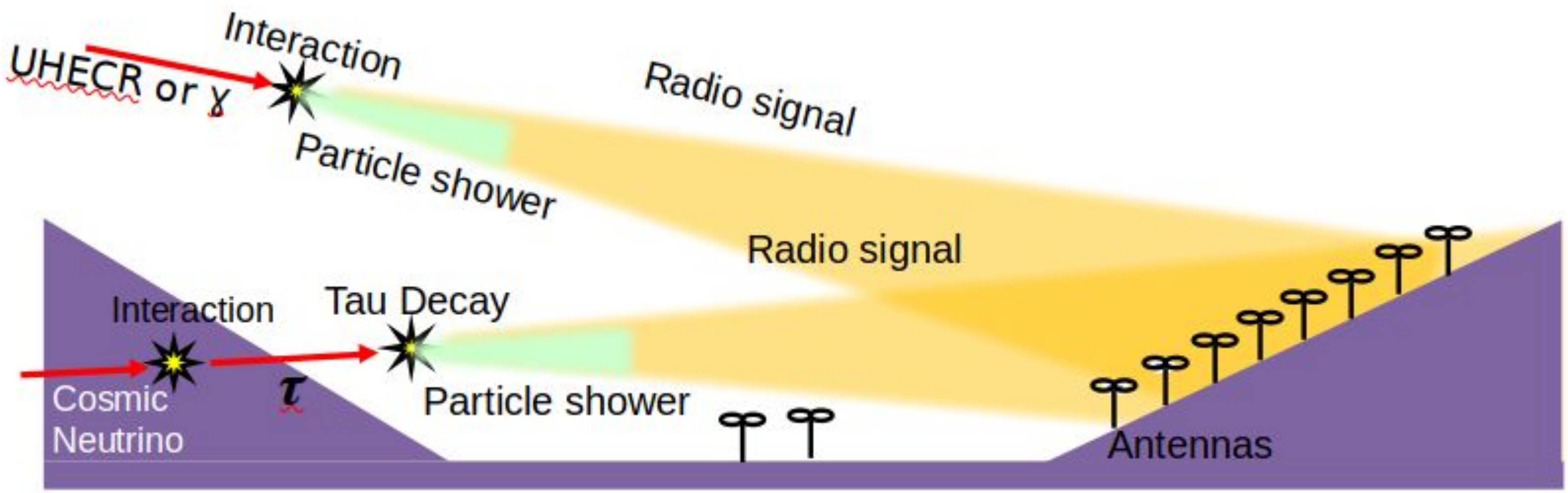
T.Huege, Phys. Report: 620,1-52,2016

Radio detection of EAS experiments

Non-inclined showers > dense array
Very inclined showers > sparse array



The Giant Radio Array for Neutrino Detection (GRAND)



P.C: Charles Timmerman

Upward-going "Earth-skimming neutrinos": $\nu_\tau \rightarrow \tau \rightarrow$ EAS

Detection of UHE Neutrino :
- Cosmogenic
- Astrophysical: diffuse, point sources, transients

Design Proposal
- 20 subarrays
- 10k antennas /array
- Radio quiet mountains: China + Worldwide

Detection of UHECR and gamma rays:
showers $>10^{10}$ GeV, highly inclined showers 65^o-85^o

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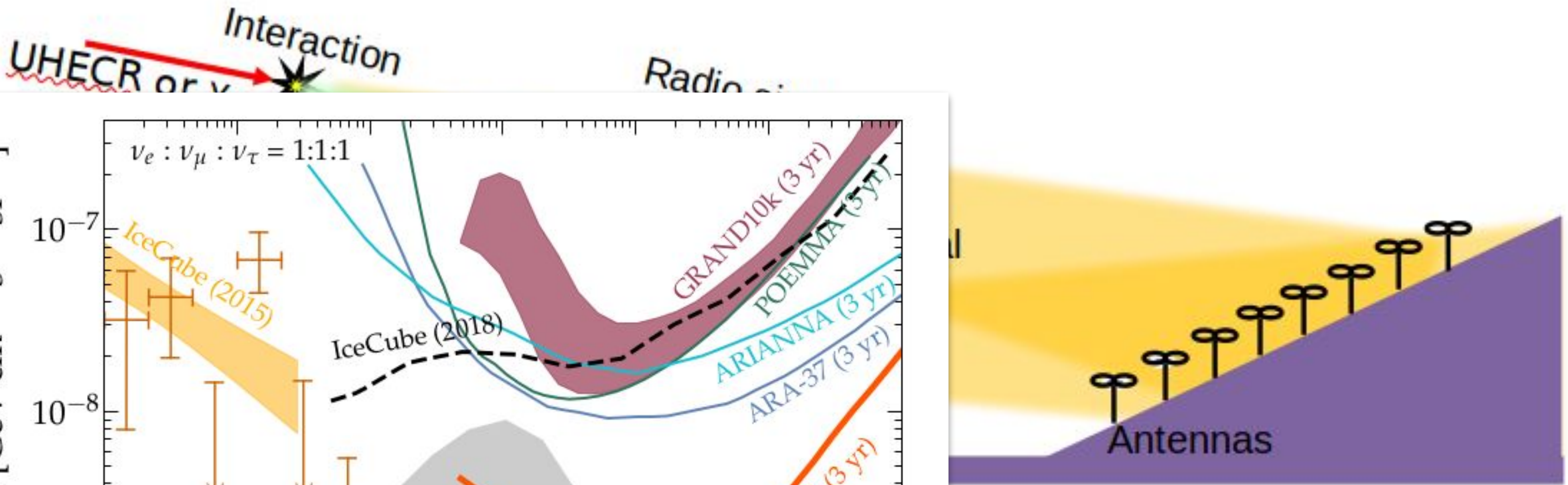
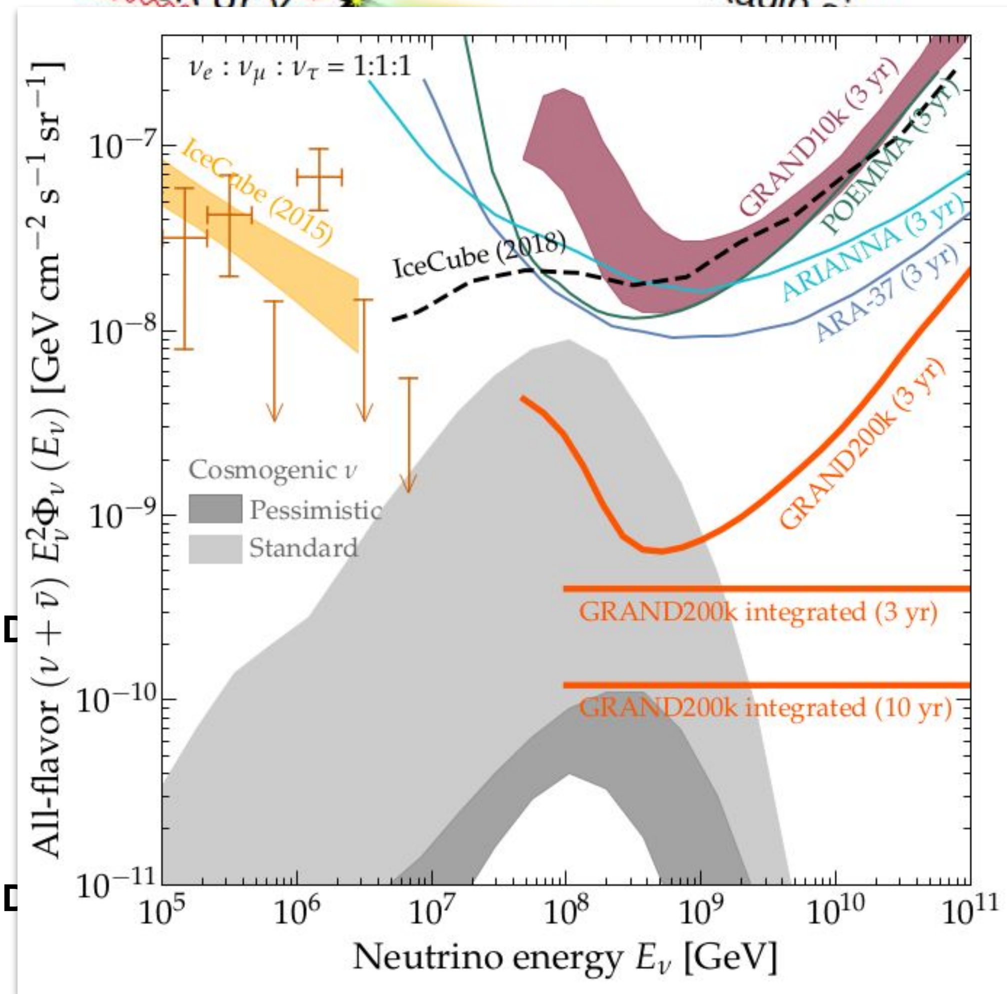




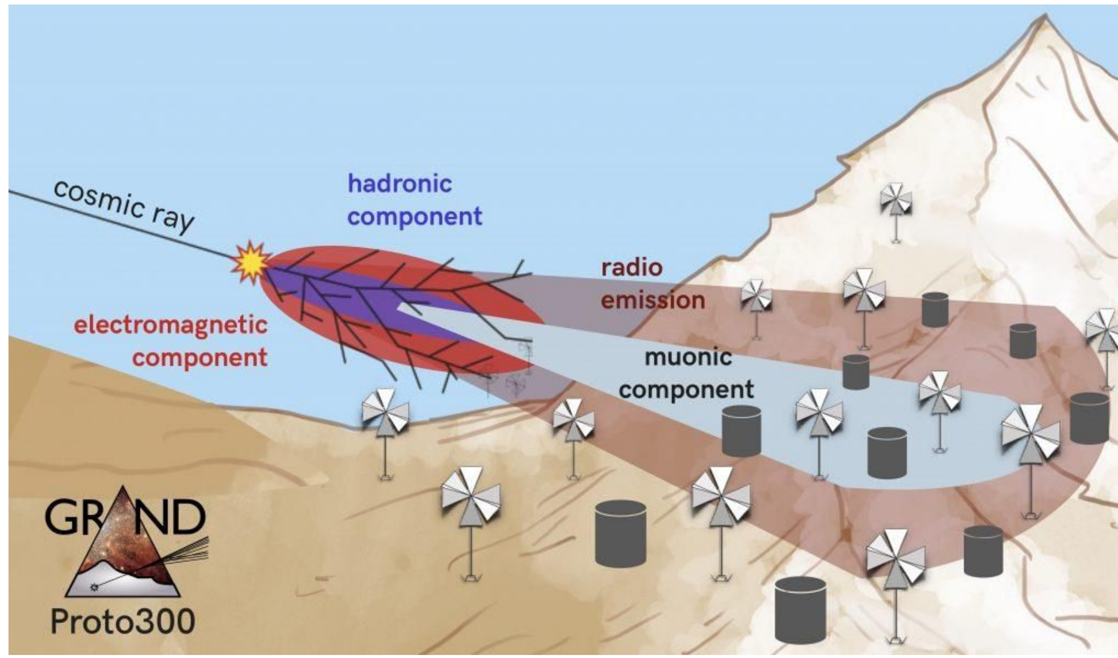
$\nu_\tau \rightarrow \tau \rightarrow$ **EAS**

P.C: Charles Timmerman

GRAND-Proto300

- **Pathfinder array for GRAND**
  - Detecting inclined CRs
  - 300 antennas in 200 km^2 area
  - Site ~ Subei county, Gansu province, China.
  - 100 antennas ready to be deployed.

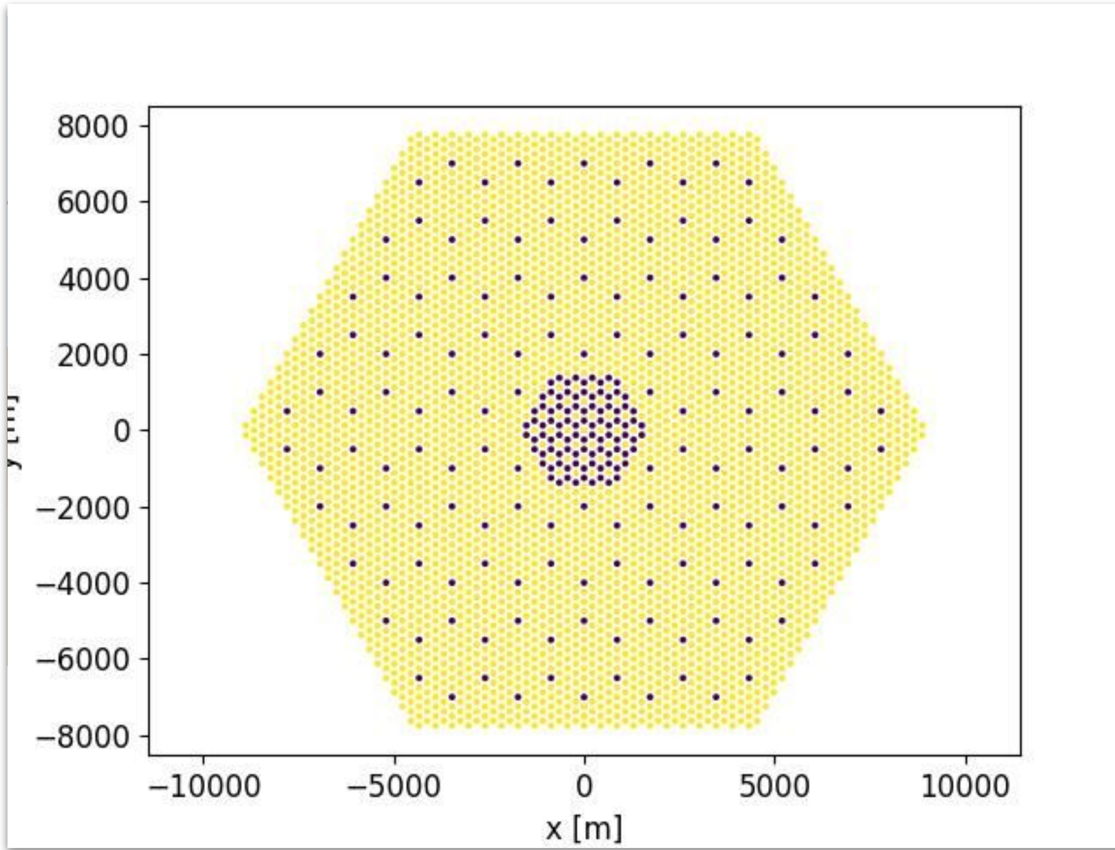
- **Testbench for GRAND**
  - Test self-triggering techniques.
  - Develop methods of calibration & monitoring.
  - Reconstruction of air shower parameters.



GRAND-Proto300

Planned layout:

❖ hexagonal pattern d~=850 m
❖ 200 antennas -> 200 km2, infill of 100 antennas



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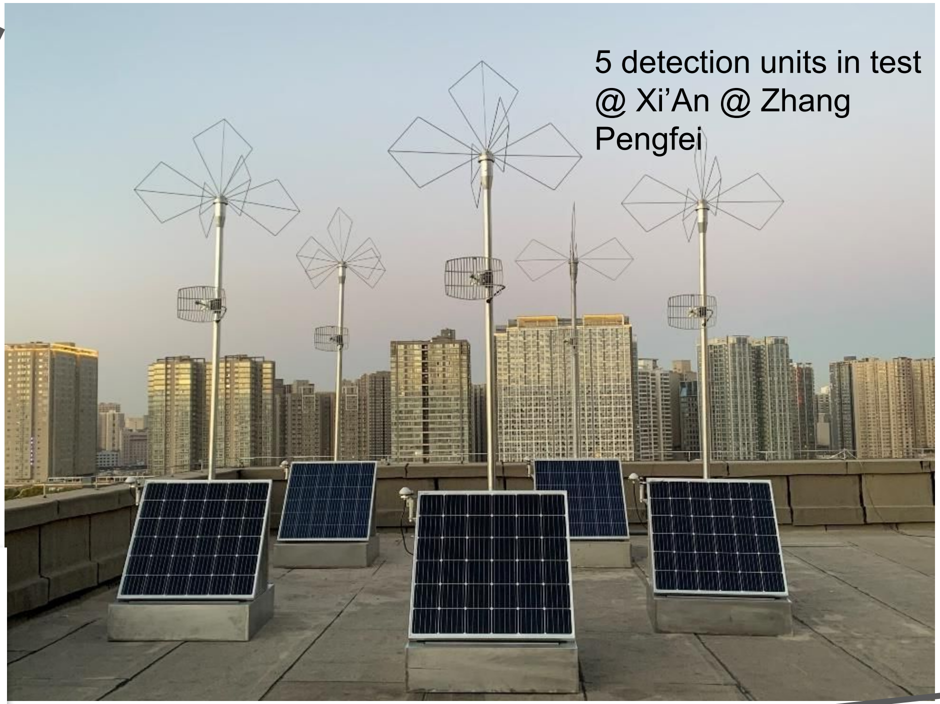
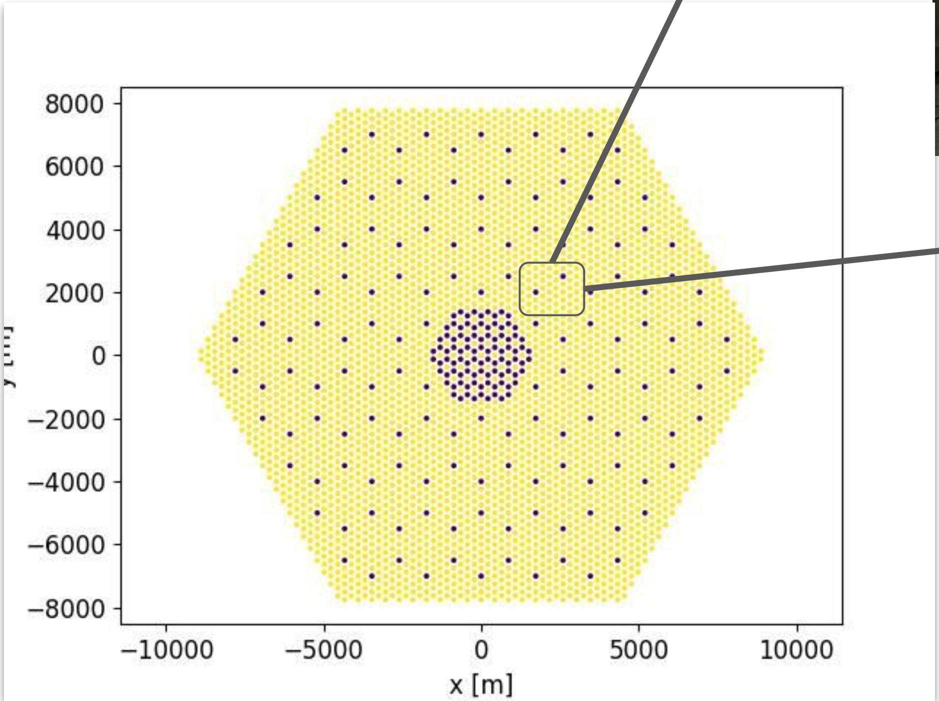
- **Testbench for GRAND**
  - Test self-triggering techniques.
  - Develop methods of calibration & monitoring.
- **Physics Goals**
  - Denser infill reaching energies down to $10^{16.5}$ eV.
  - Complemented by ground array for independent muon measurements.
  - Measurement of CR composition & energy in $10^{16.5}$ - 10^{18} eV (transition region).

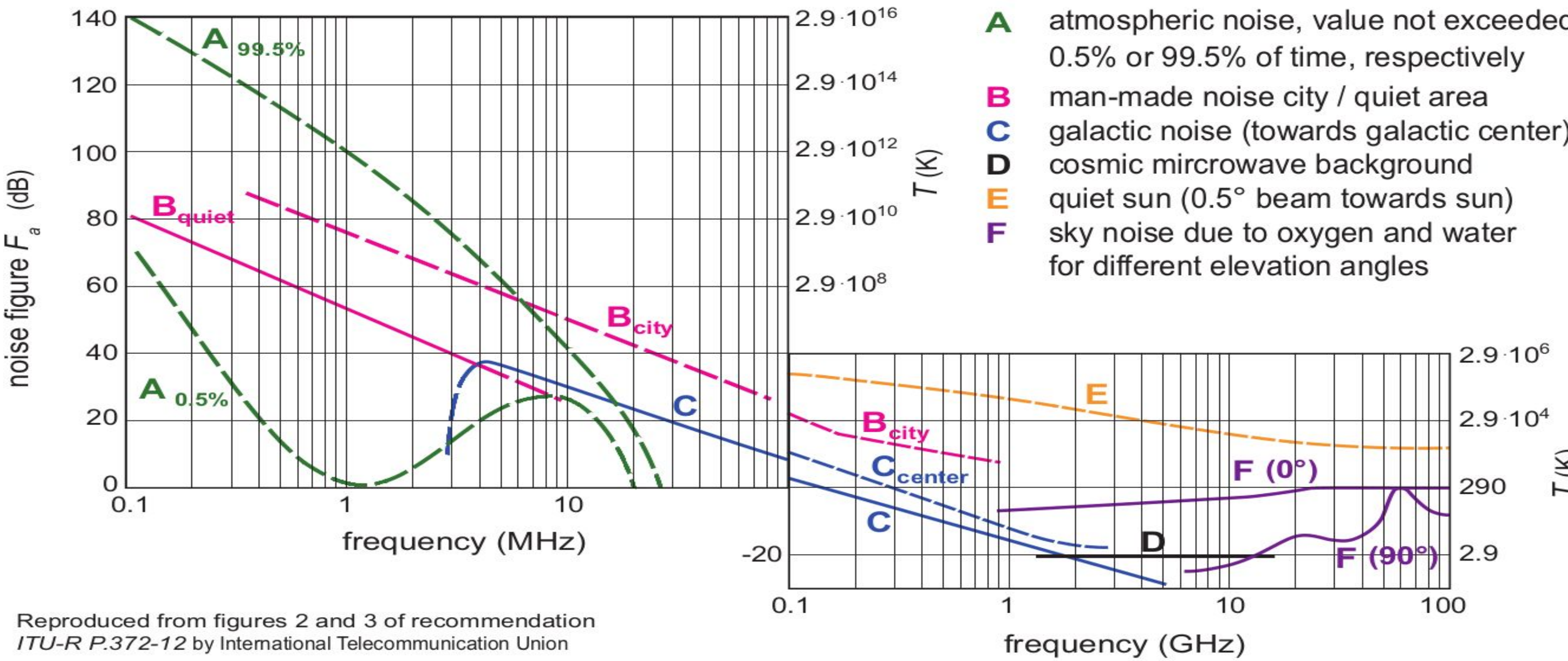
Antenna Design

- Butterfly antenna: 65 cm antenna arm.
- 3 arms(NS,EW,vertical) -> Voltage in 3 channels.
- Atop with 3.5 m pole.





Background of Radio detection



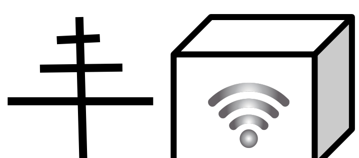
Frank G. Schröder, Prog. Part. Nucl. Phys., 93:1--68, 2017.

Main sources -

Galaxy

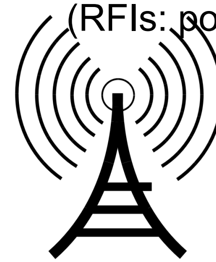
Electronics

(Antenna+hardware)



Anthropogenic

(RFIs: powerlines, FM etc.)



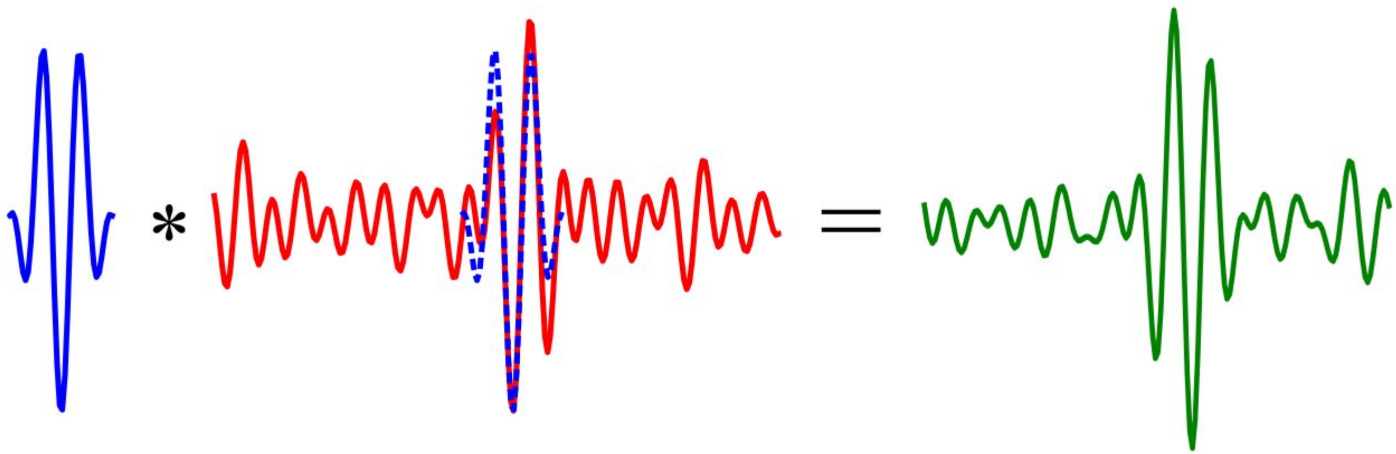
Signal ID: Matched Filter

Standard: Convolution of template with noisy signal (time domain)

$$s_{cc}[t] = \sum_{t_0} T[t_0 - t]u[t], \quad A_{cc} = \max(s_{cc}[t_0]),$$

Template **Signal**

√Acc ~ peak amplitude



Template **signal+noise** **output**

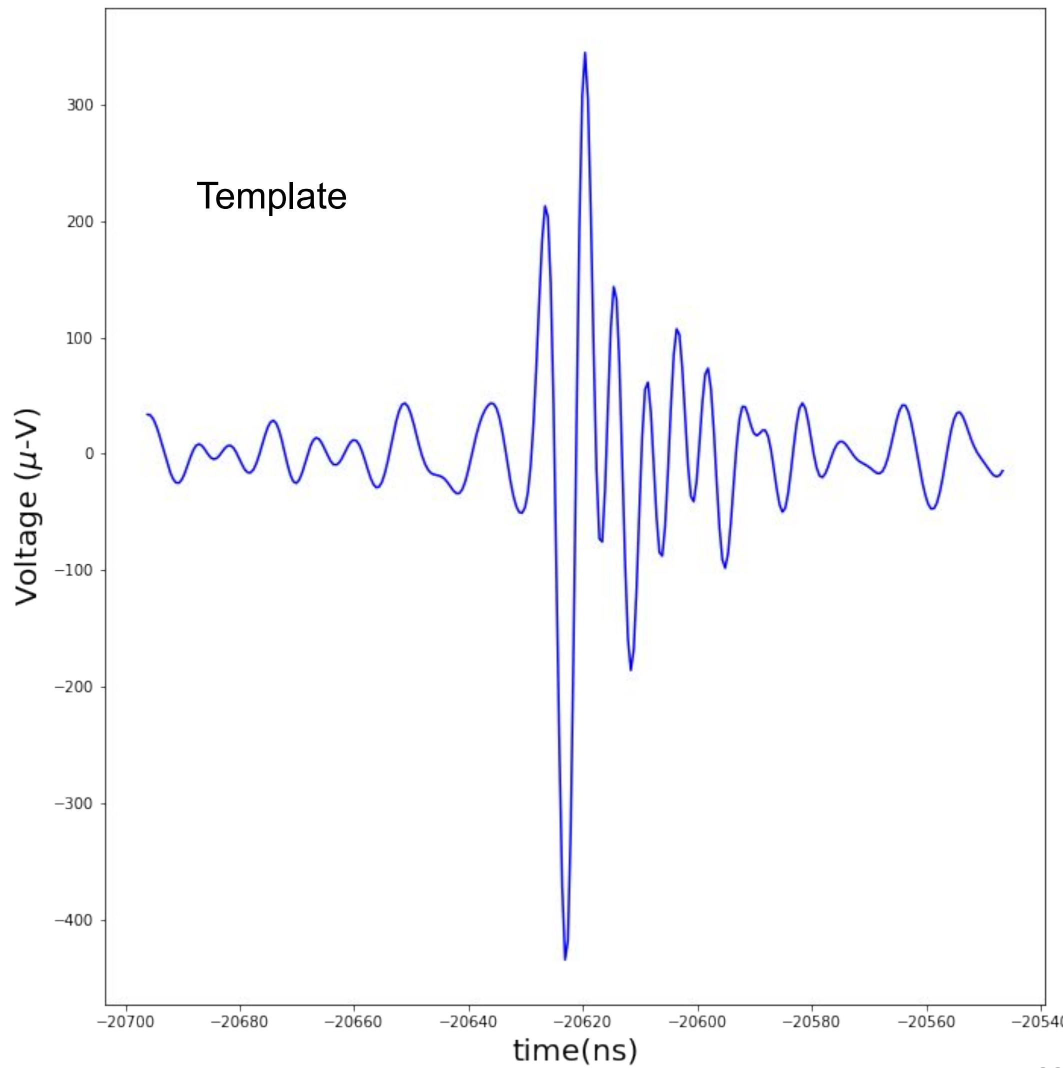
Ref: Tunka Rex: arxiv:1906:10947v2

Optimal Matched Filter - noise weighted ~ robust

S_{cc} (ω) = T(ω) u*(ω) / psd(noise(ω)) ✓

Signal ID: Matched Filter

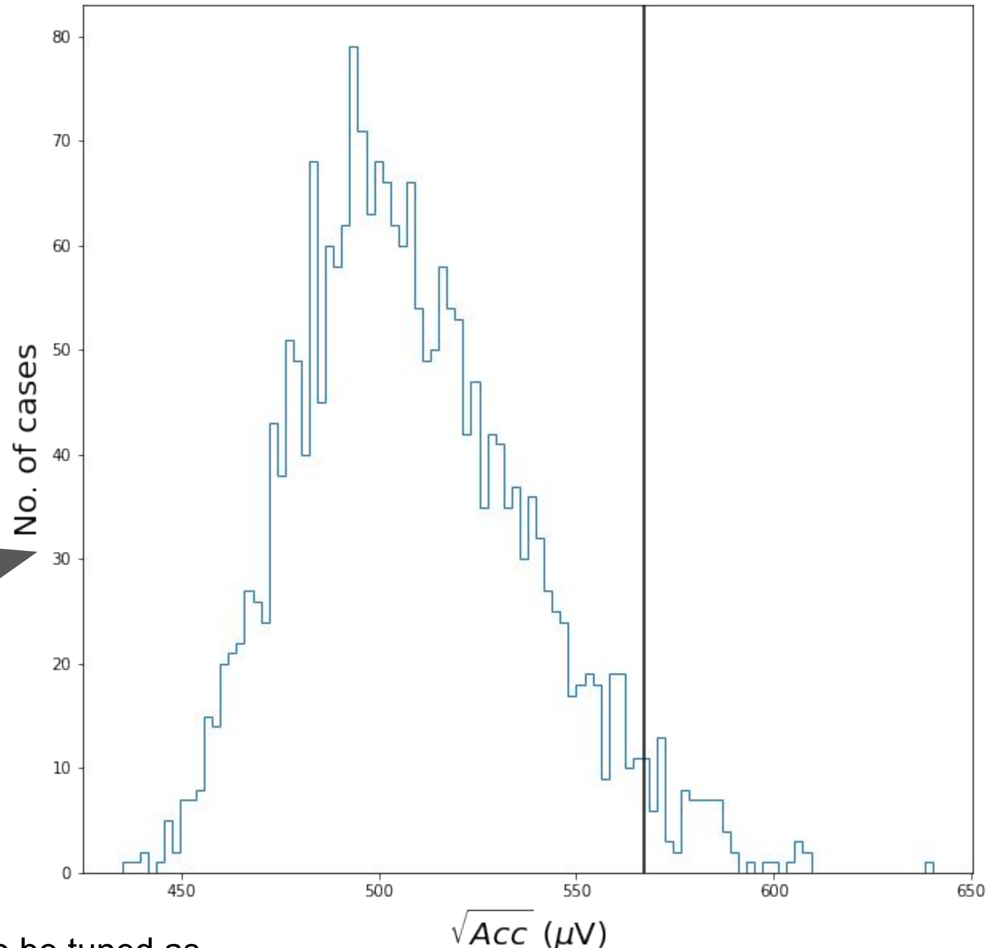
- Template: averaging from all simulations (taking 20 strong antennas/per shower) .
- Filtered between 50-200 MHz.
- 150 ns width.



Signal ID: Matched Filter

MF on Noise only traces

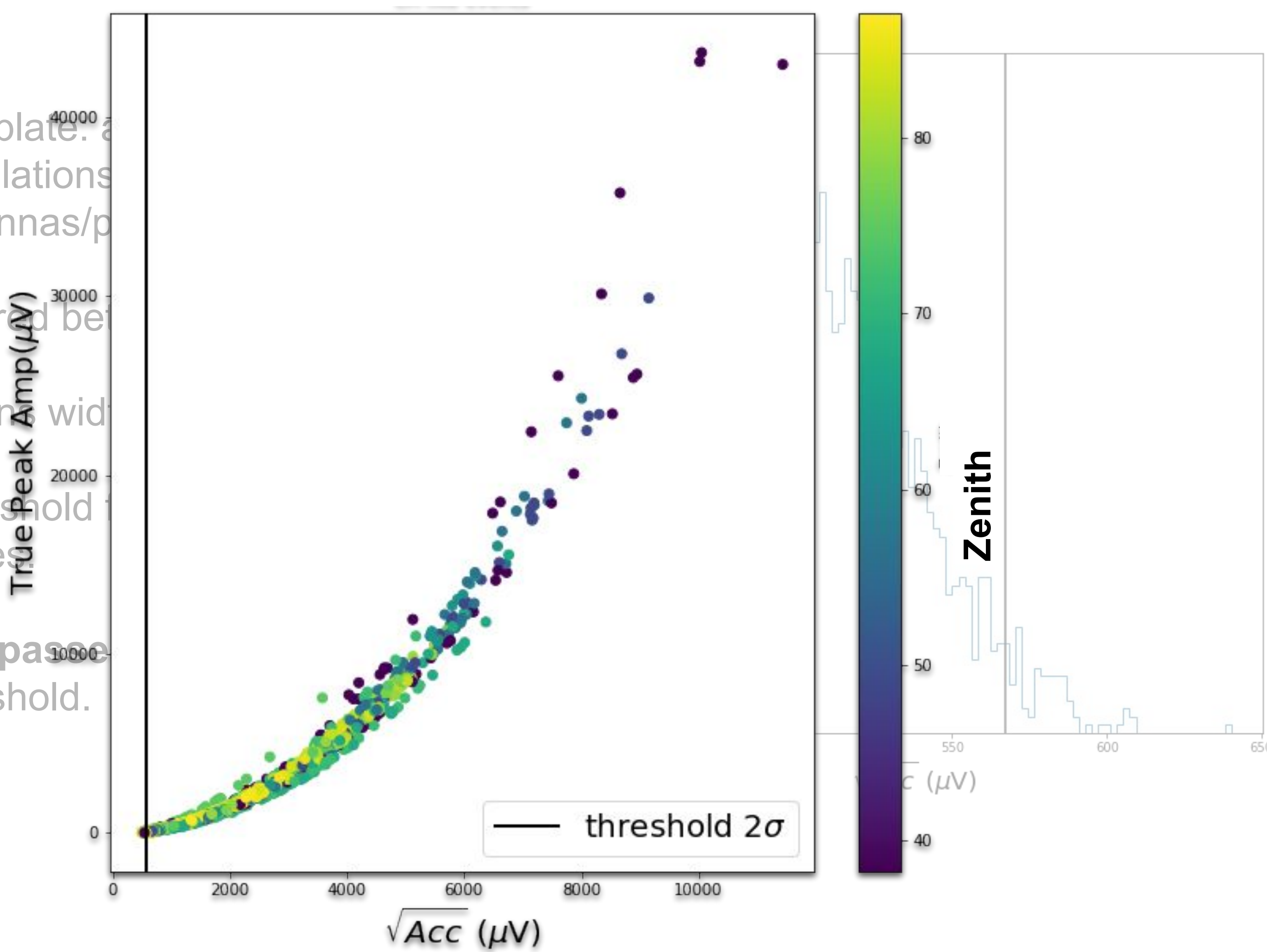
- Template: averaging from all simulations (taking 20 strong antennas/per shower) .
- Filtered between 50-200 MHz.
- 150 ns width.
- Threshold found from noise only traces.
- **'CR passed'**, if 3 antennas > threshold.



About 5% false positives, to be tuned as per hardware requirements

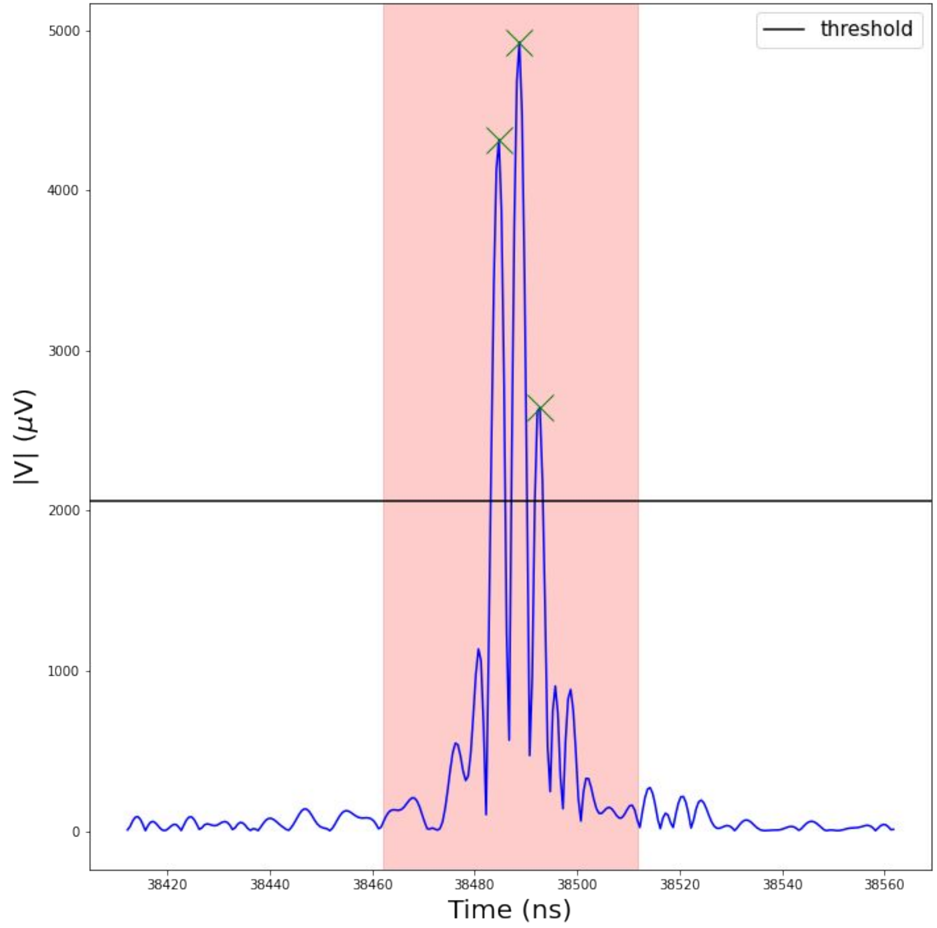
Signal ID: Matched Filter

- Template
  simulations
  antennas/p
- Filtered be
- 150 ns wid
- Threshold
  traces
- **'CR passe**
  threshold.



Signal ID: Pulse Shape Analysis

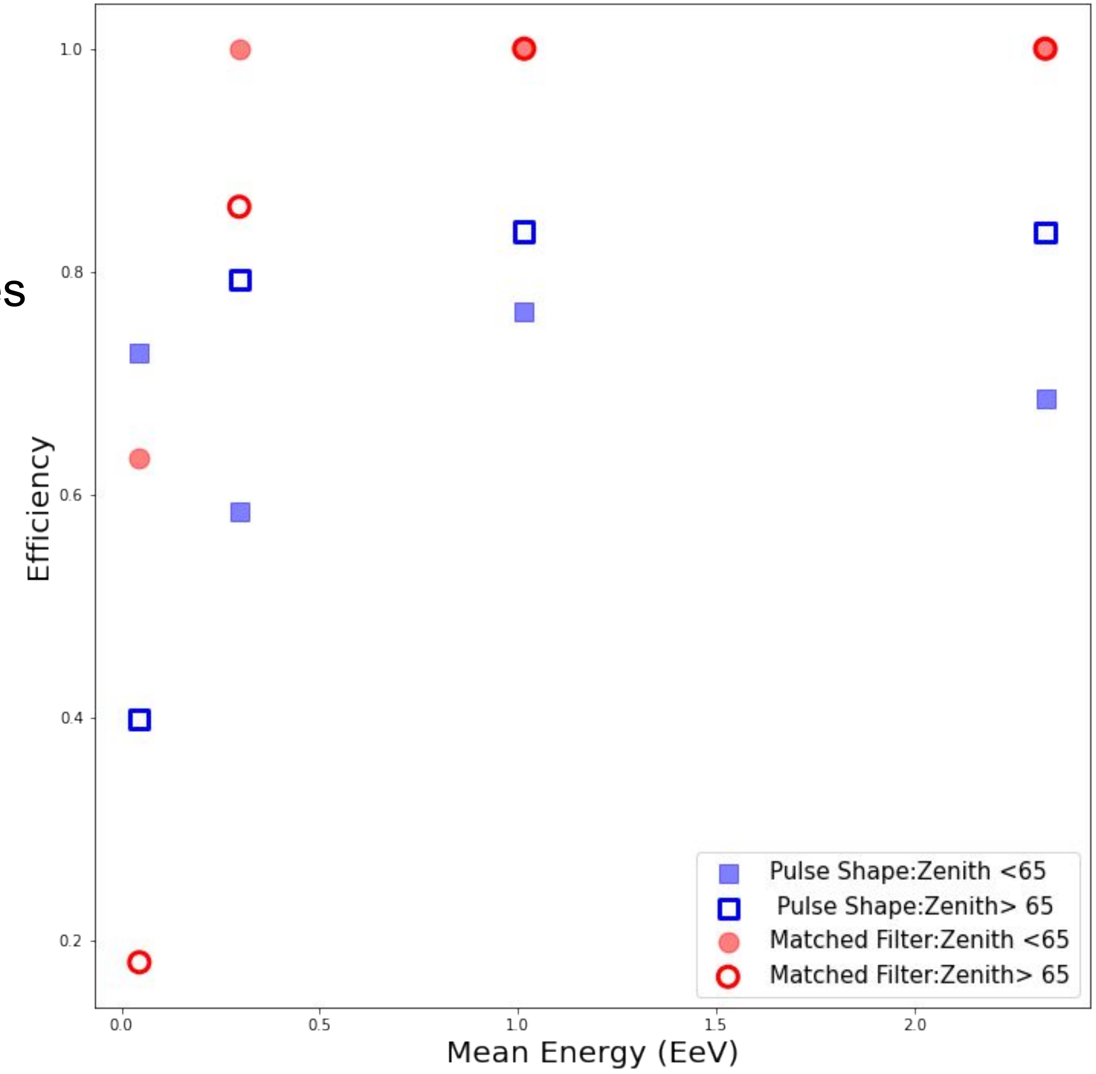
- CR pulses are shorter compared to BG
- Define threshold T
- Compute no of upward crossing N >T
  If ($N < N_{threshold}$) for 3 antennas: CR pass



Optimized: A1 =0.4, A2= 4, $N_{threshold}$= 4

Comparing Efficiency

- Efficiency = True Positives / Total cases.
- Binned in Energy and Zenith for two methods.
- At higher energies Matched Filter > pulse shape.

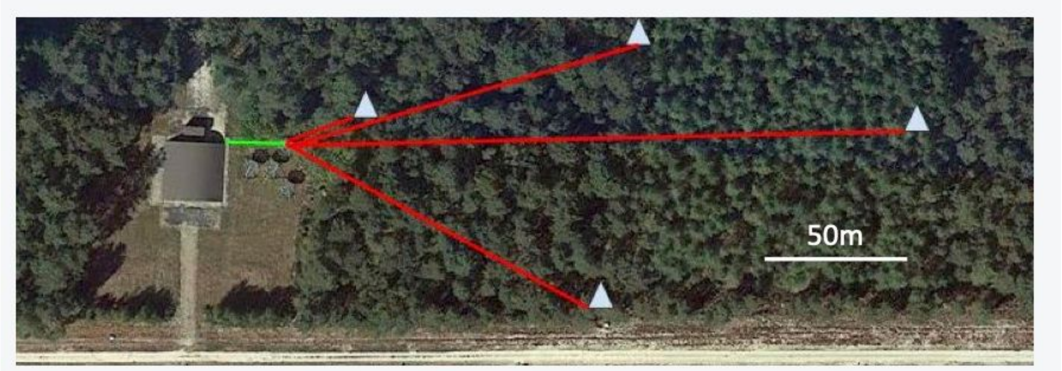


Current status : Antenna Deployment

GRAND@Auger:
8 units

GP 13 : 13 units @ XiaoDushan,
Dunhuang, China

GRAND@Nancy, 4
units

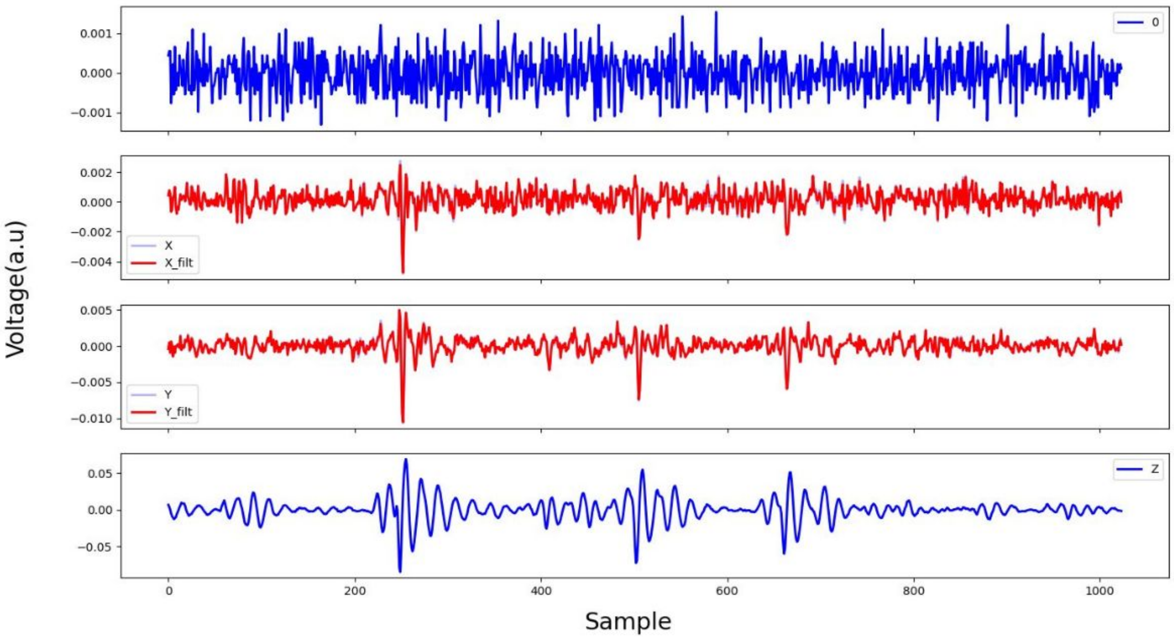


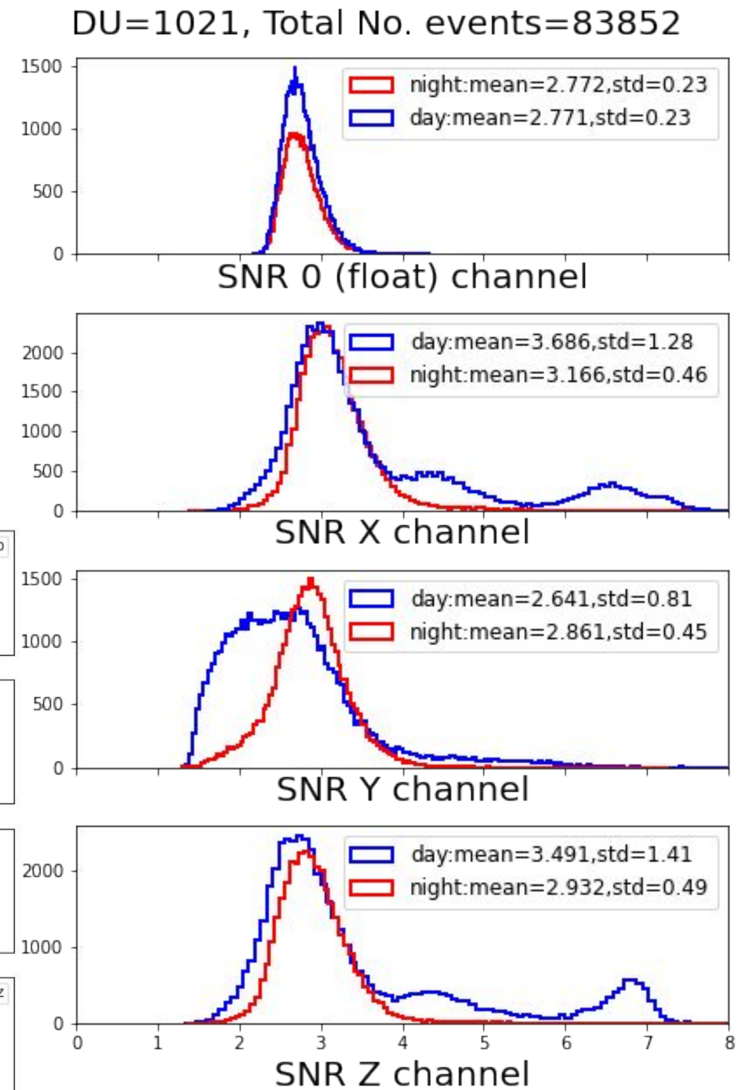
Looking at the first data

Playground to understand:

- Background
- Transient/RFI properties and rates
- Hardware responses

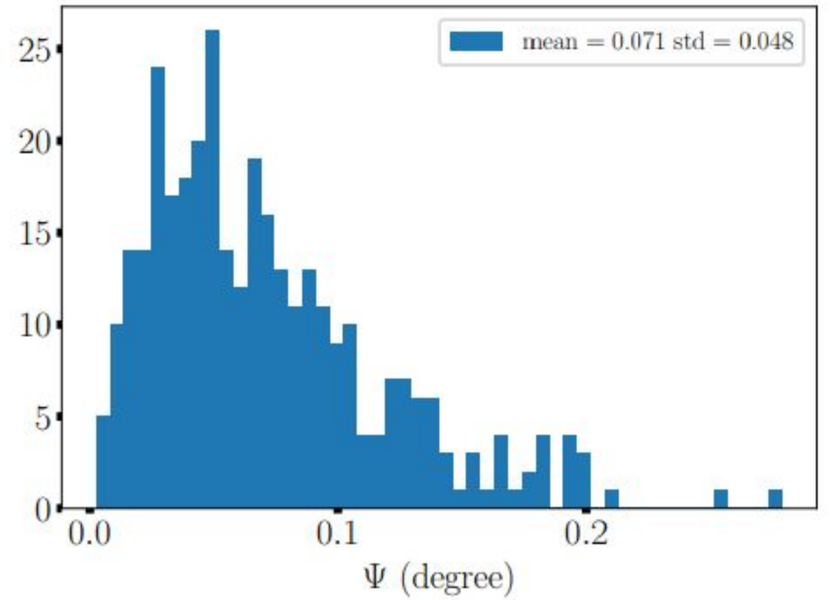
GP13 Data from May,2023



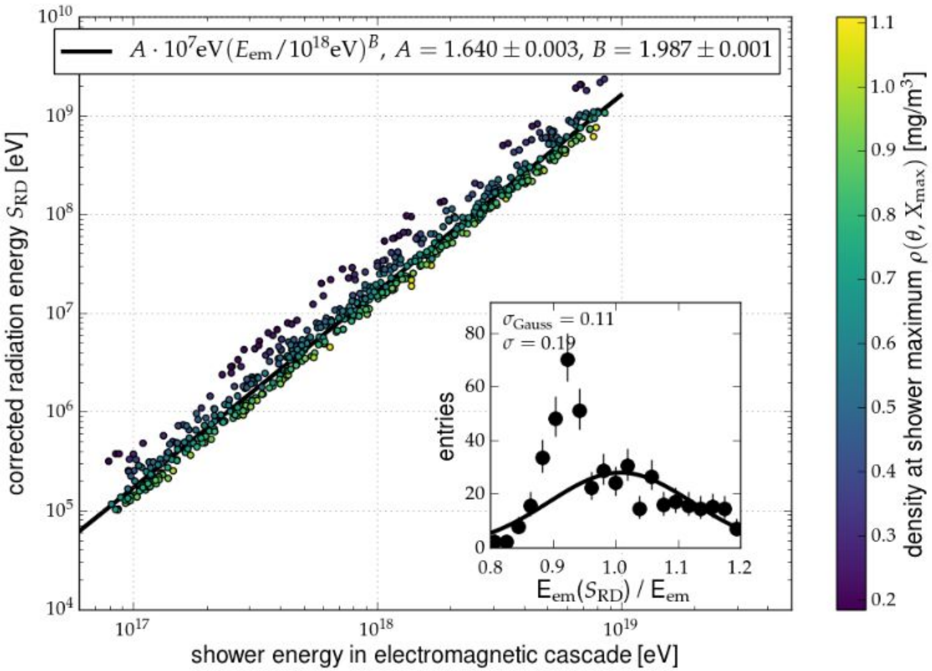


Reconstruction of shower parameters

- **Arrival direction**: angular resolution ~ 0.1°, combining spherical wavefront (arrival time) + angular distribution function.
- **Energy:** from the radiation energy of the shower, overall 10% resolution achievable.



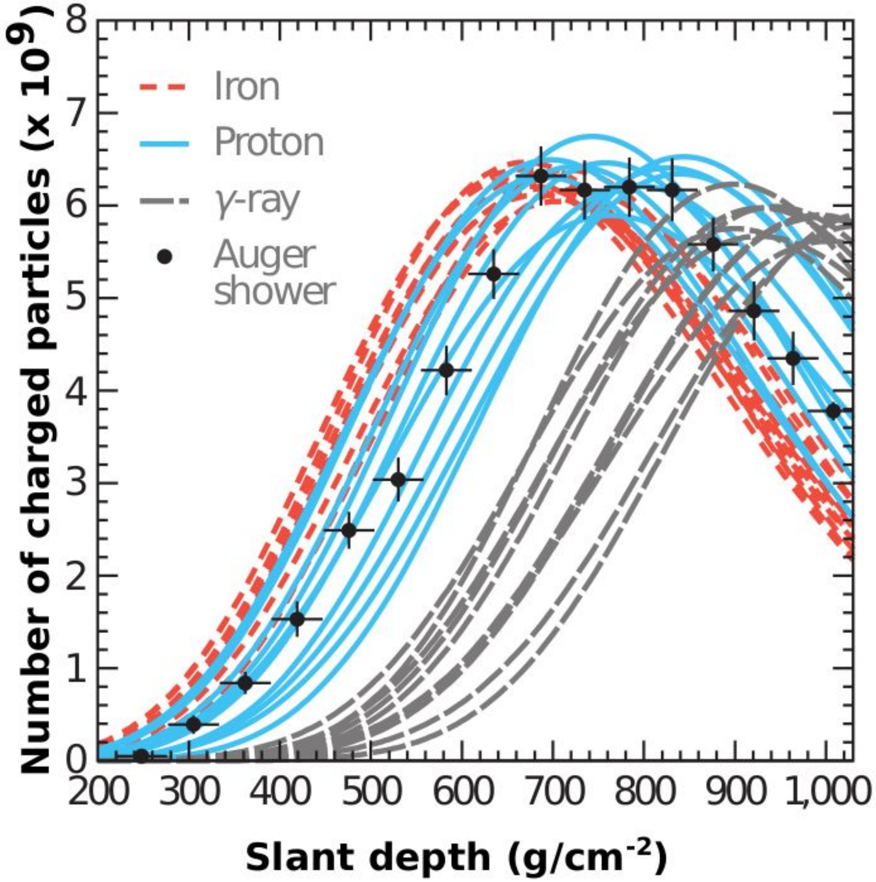
V.Decone, ICRC2021, arXiv:2107.03206



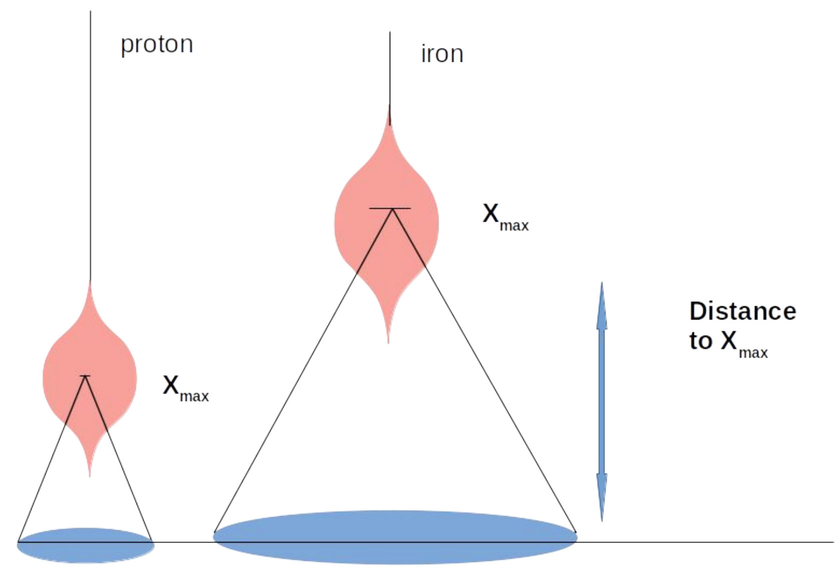
C.Glaser, Pierre Auger collab.

Estimator of cosmic-ray mass

X_{max}: Atmospheric depth where particles reach maximum.



Radio footprint:
Size ⟶ with mass



Pierre Auger Observatory, Ralph Engle etal.,Ann. Rev. Nucl. Part. Sci., 61:467--489, 2011.

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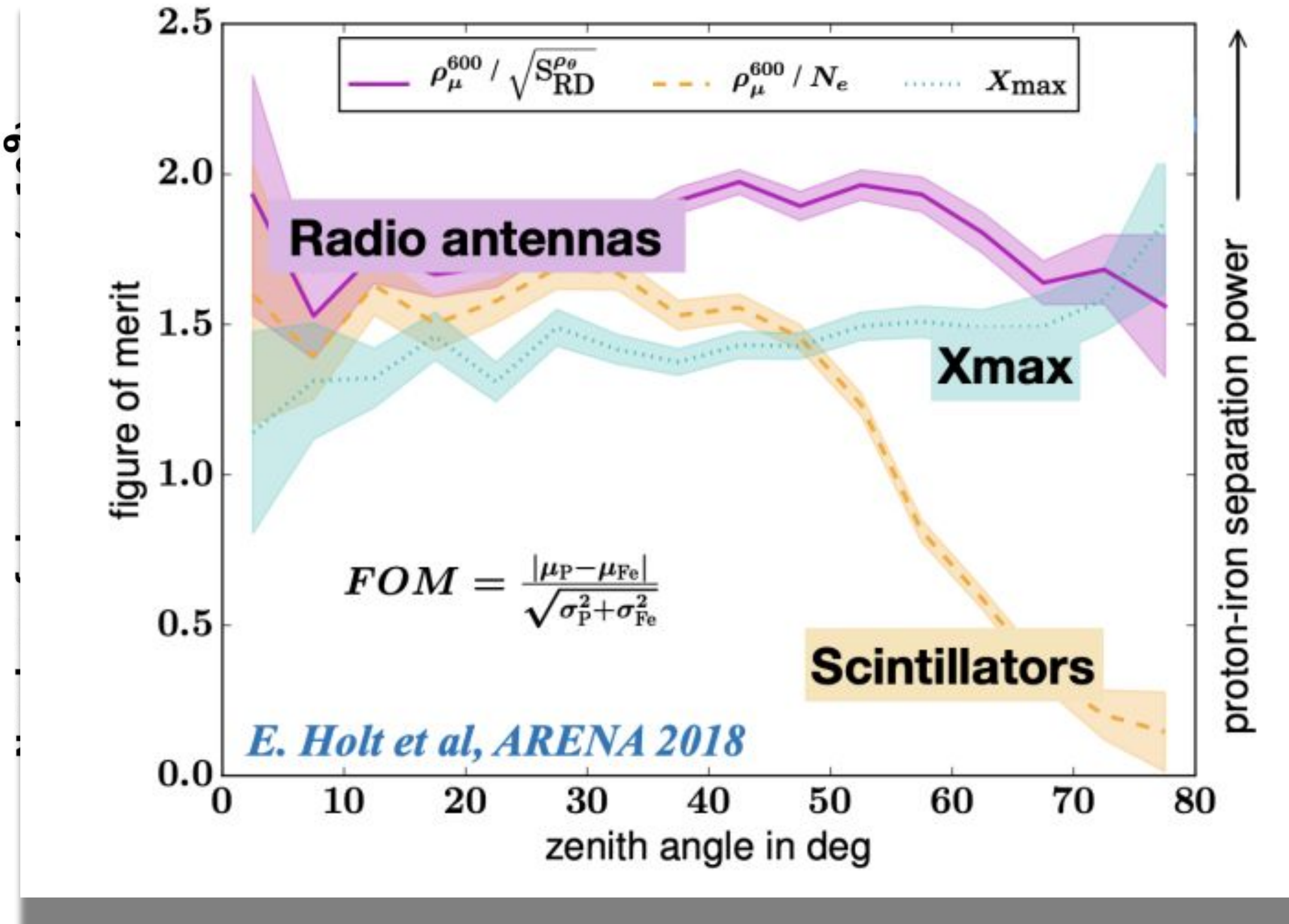


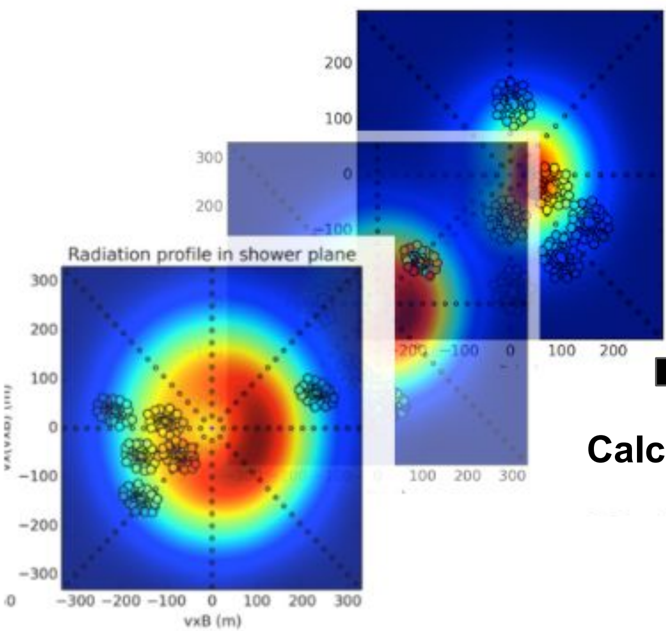
Distance to X_{max}

X_{max} reconstruction

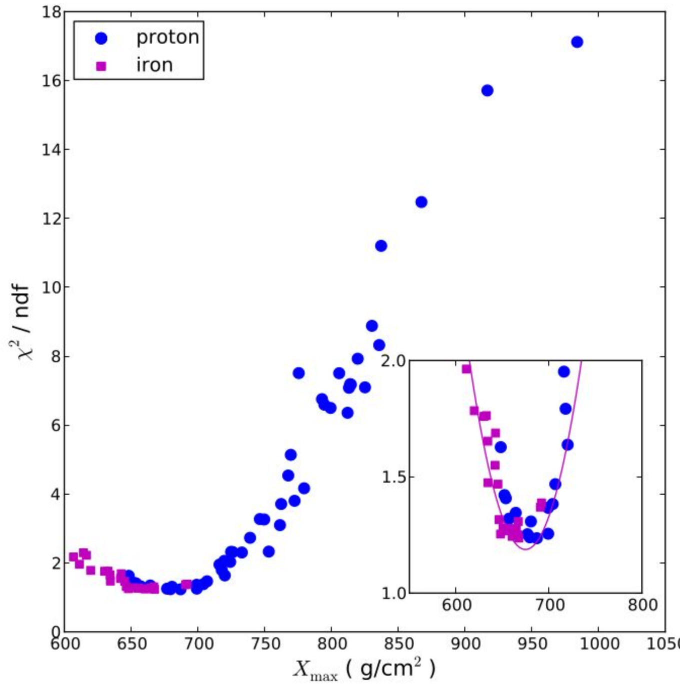
Monte Carlo Ensemble Method

- A set of simulated radio footprints per detected shower using MC (iron+ proton).
- Fit simulations to measured data.
- Simulations computationally extensive: each takes 1-2 days in a single CPU.

Reconstructed X_{max} from the parabola fit

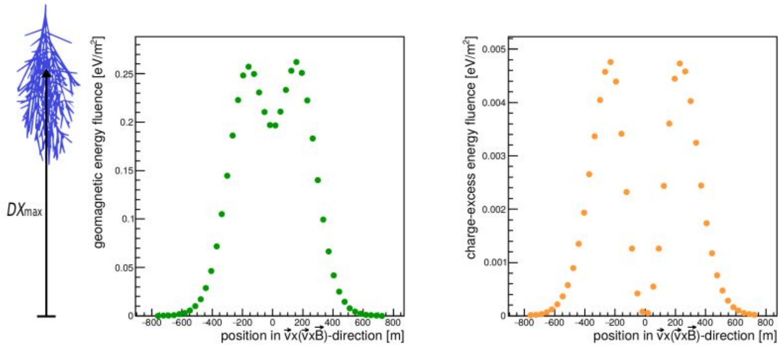


Calculate reduced χ^2

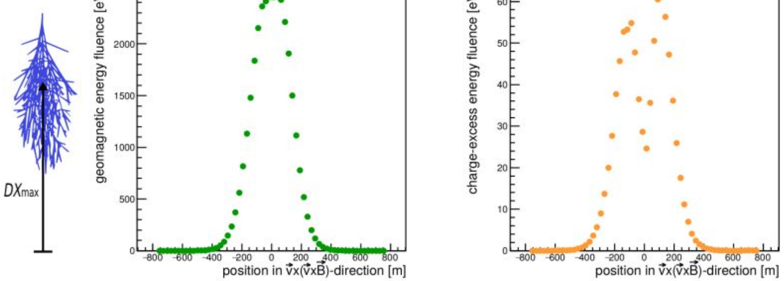


S.Buitink et al, PRD 2016

X_{max} reconstruction



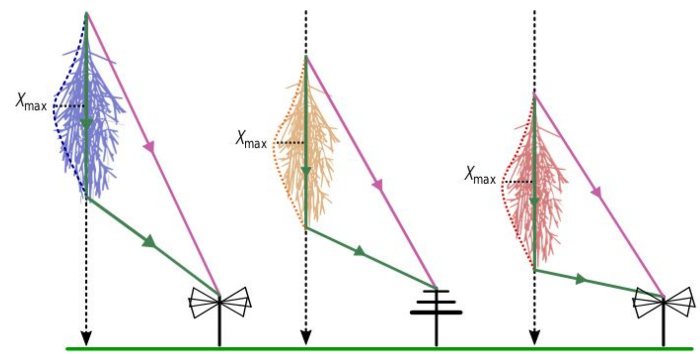
(a) $E = 0.1$ EeV, $(\theta, \varphi) = (58°, 150°)$, $D_{X_{max}} = 1060\ \mathrm{g/cm^2}$



(b) $E = 4.5$ EeV, $(\theta, \varphi) = (46°, 247°)$, $D_{X_{max}} = 590\ \mathrm{g/cm^2}$

1. Fluence LDF:

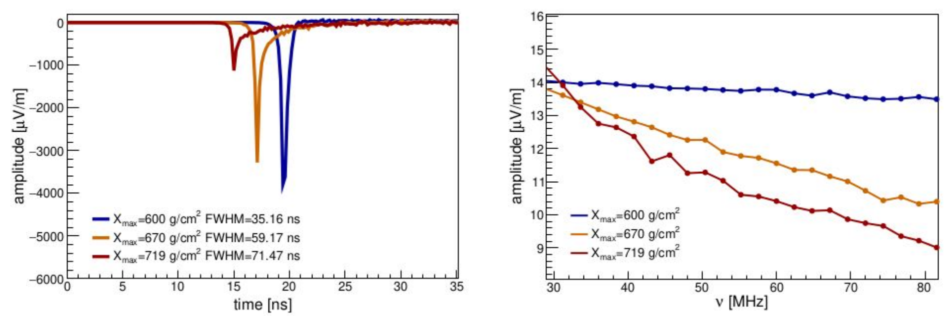
- Shape of the emission profile, Cherenkov radius.



(a)

2. Frequency spectrum:

- Slope correlates to the distance to Xmax

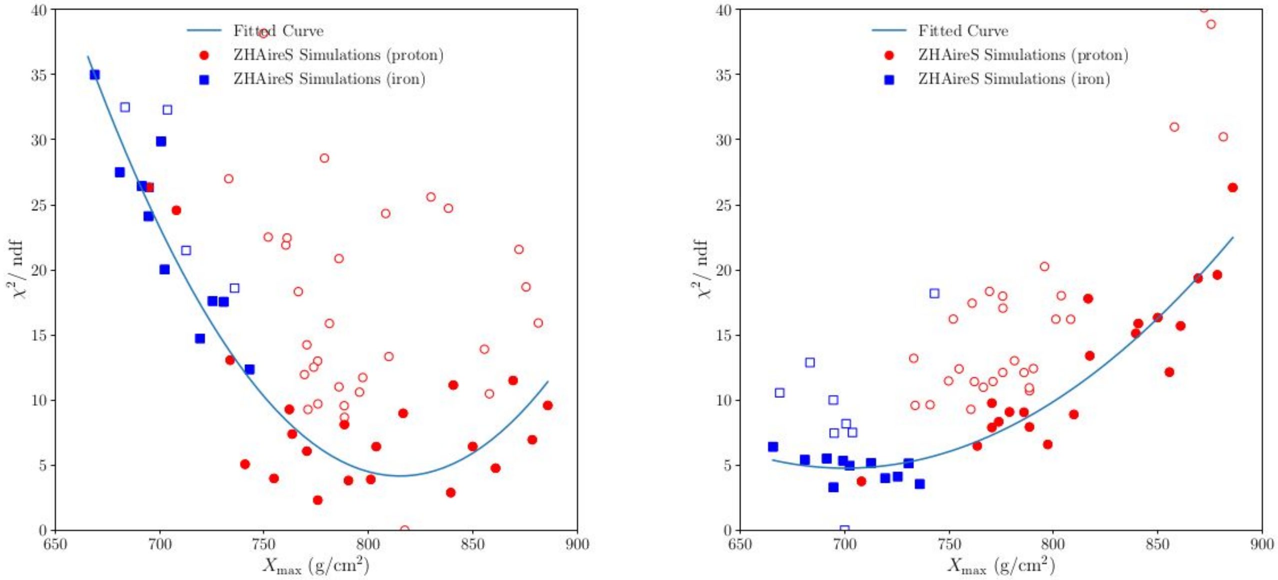


Thesis F.Canfora, Pierre Auger Collaboration

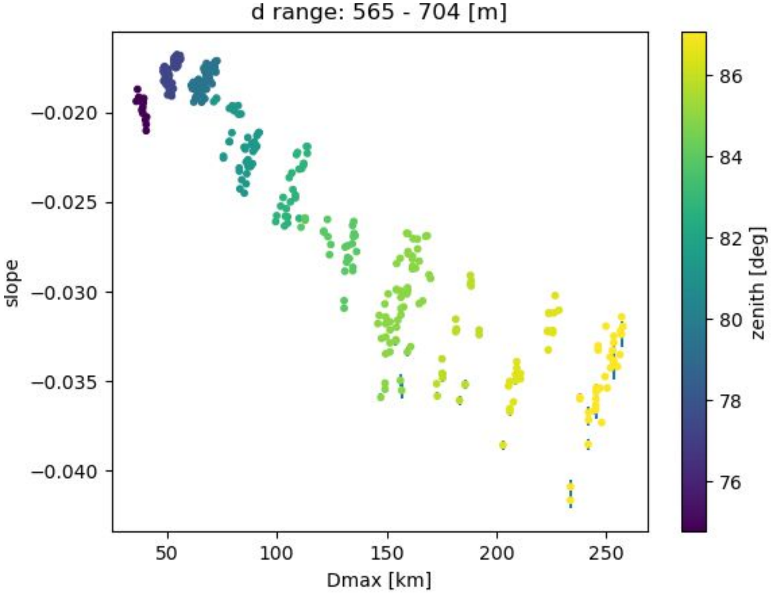
Efforts for GRAND

- Required Xmax resolution ~ 40 g/cm^2 for different messengers, 20 g/cm^2 for proton-iron.
- Depends on energy, antenna spacing, noise level etc.

Clare Guepin, PhD Thesis, Sorbonne University



Slope of frequency spectra vs Dmax



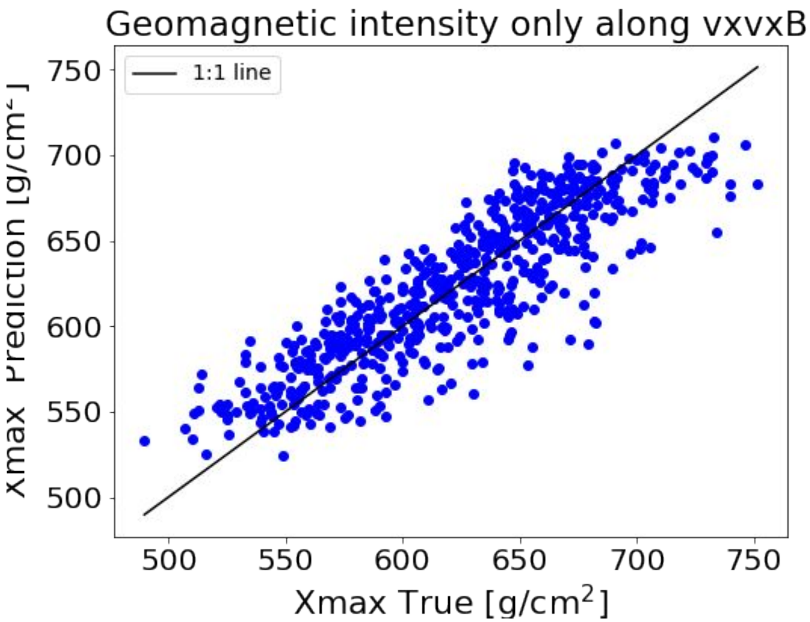
Plot by Szymon Sławiński, ongoing work*

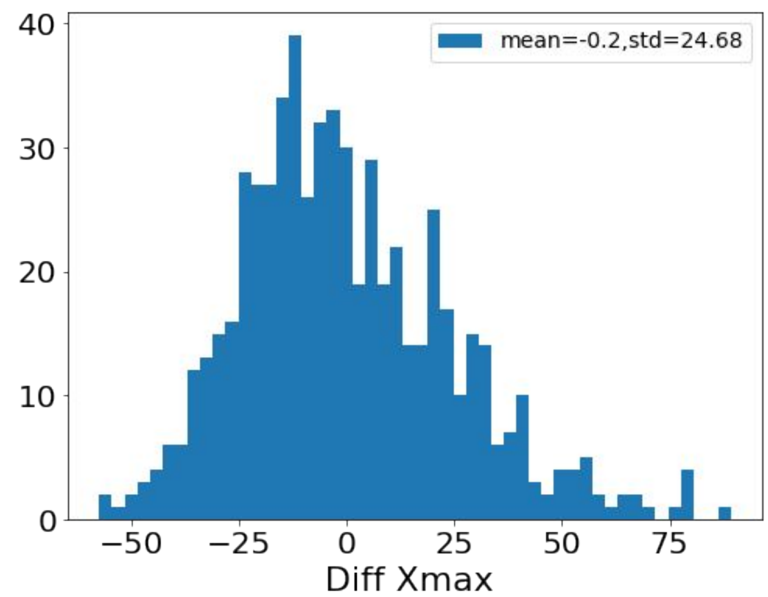
Efforts for GRAND

ML approach using high level features:

- Simulation sets- E-field traces.
- Features: radio intensity, slopes, target: Xmax
- Train on a Random Forest model

Preliminary results





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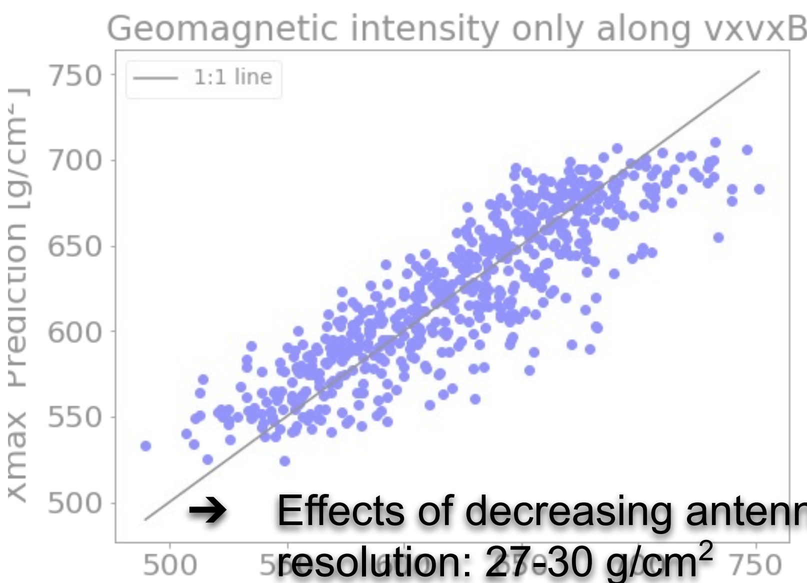
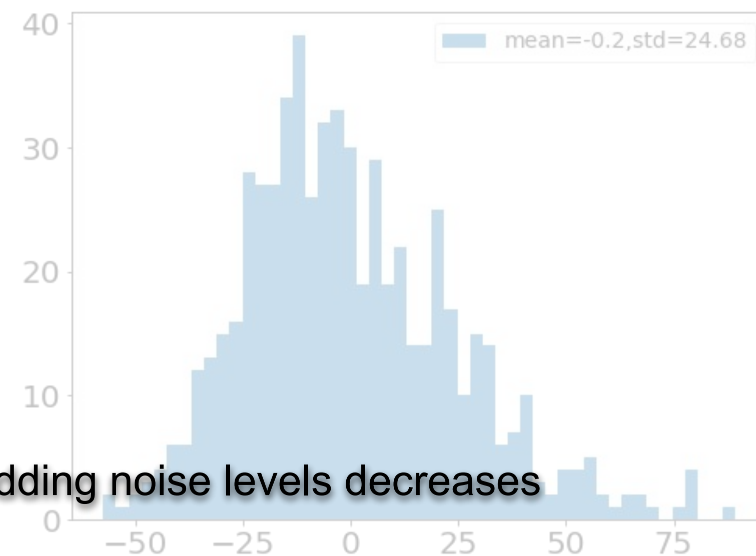
- Train on a Random Forest model





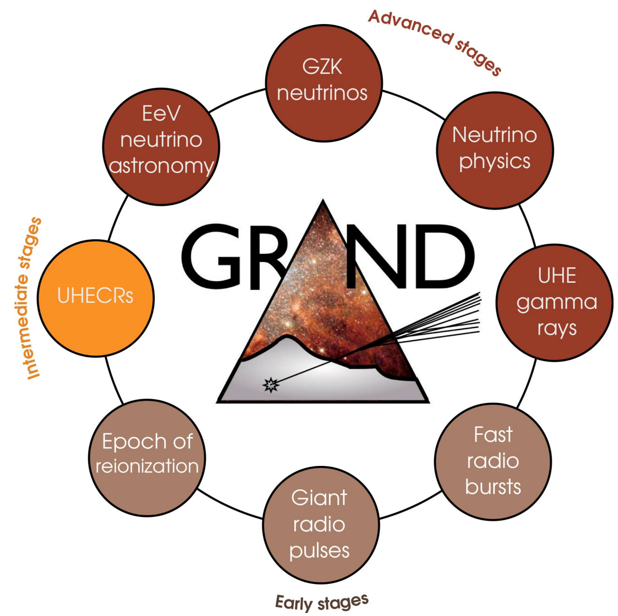
➔ Effects of decreasing antennas, adding noise levels decreases resolution: 27-30 g/cm^2

➔ More realistic antenna layout, detector response to be tested with different ML models and benchmark with classical methods.

Summary

GRAND-Proto300 a pathfinder for GRAND :

- Test self-triggering techniques.
- Develop methods of calibration & monitoring.
- Deployment started, more data to come in coming months/years.
- Measurement of CR composition & energy in $10^{16.5}$ - 10^{18} eV (transition region).



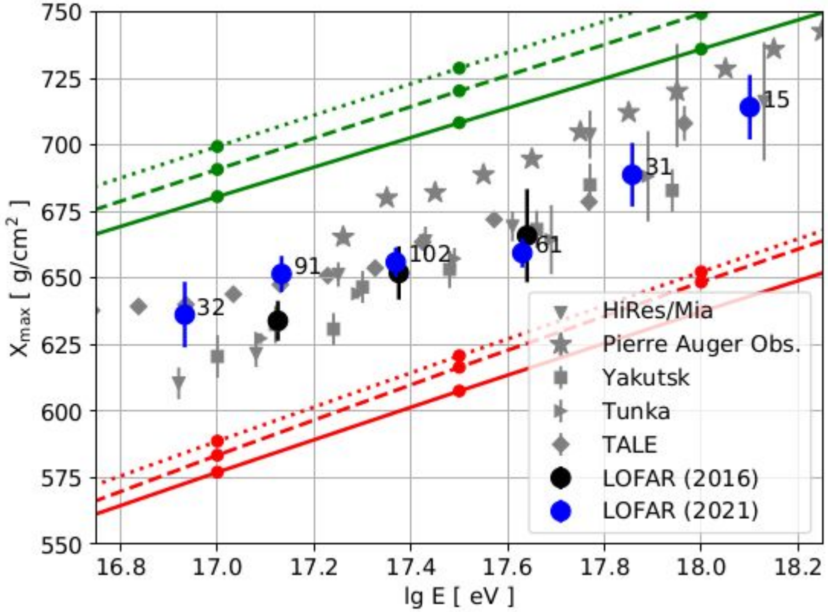
Ongoing tasks:

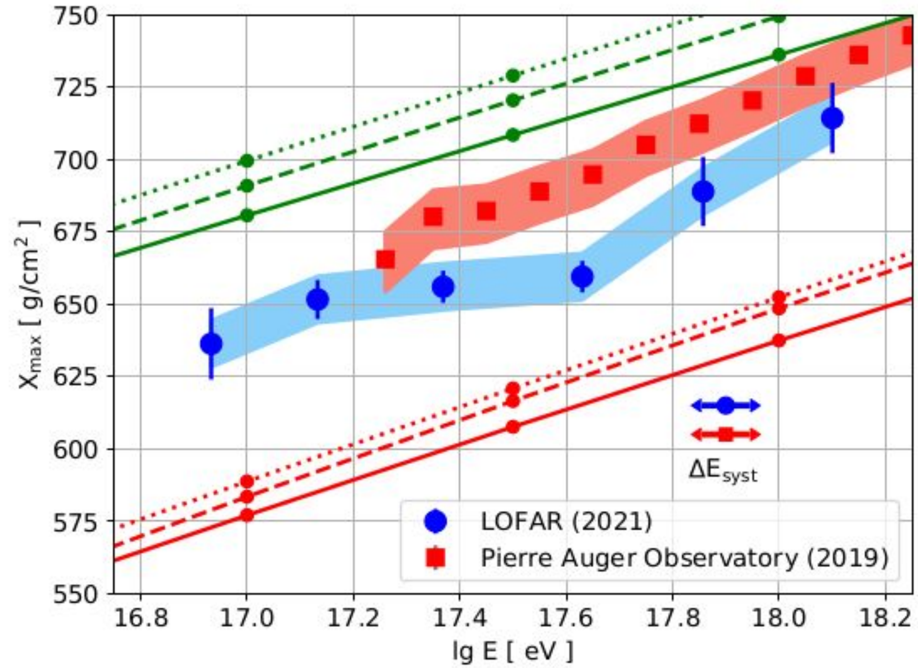
- Software development + data structure.
- Signal identification methods.
- Reconstruction techniques of shower maximum, CR mass.
- Developing new simulation libraries for analysis.

Thank you

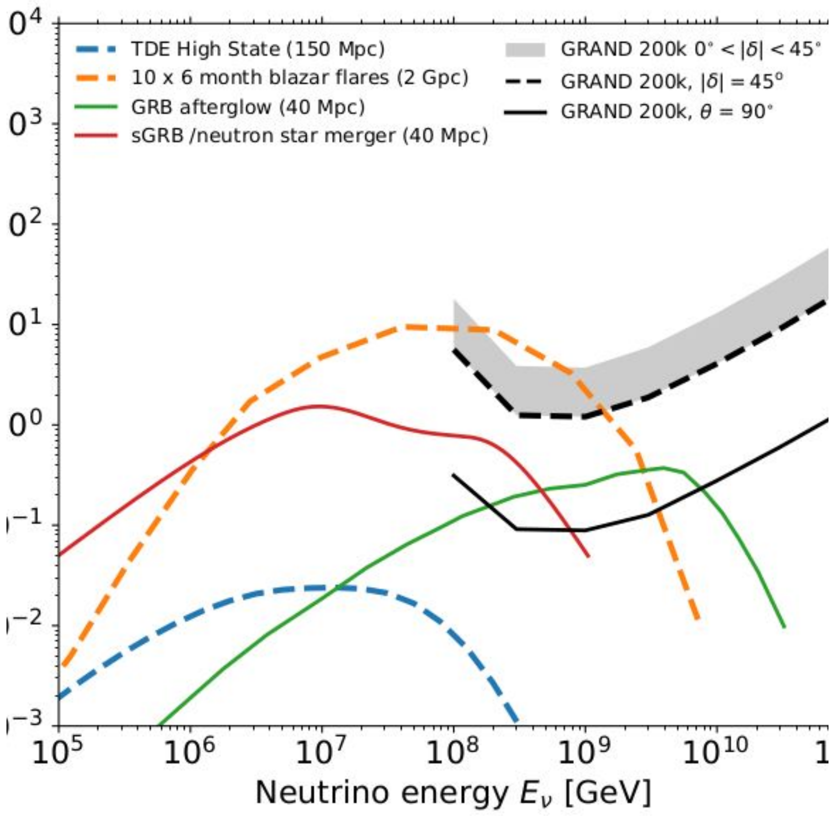
Appendices

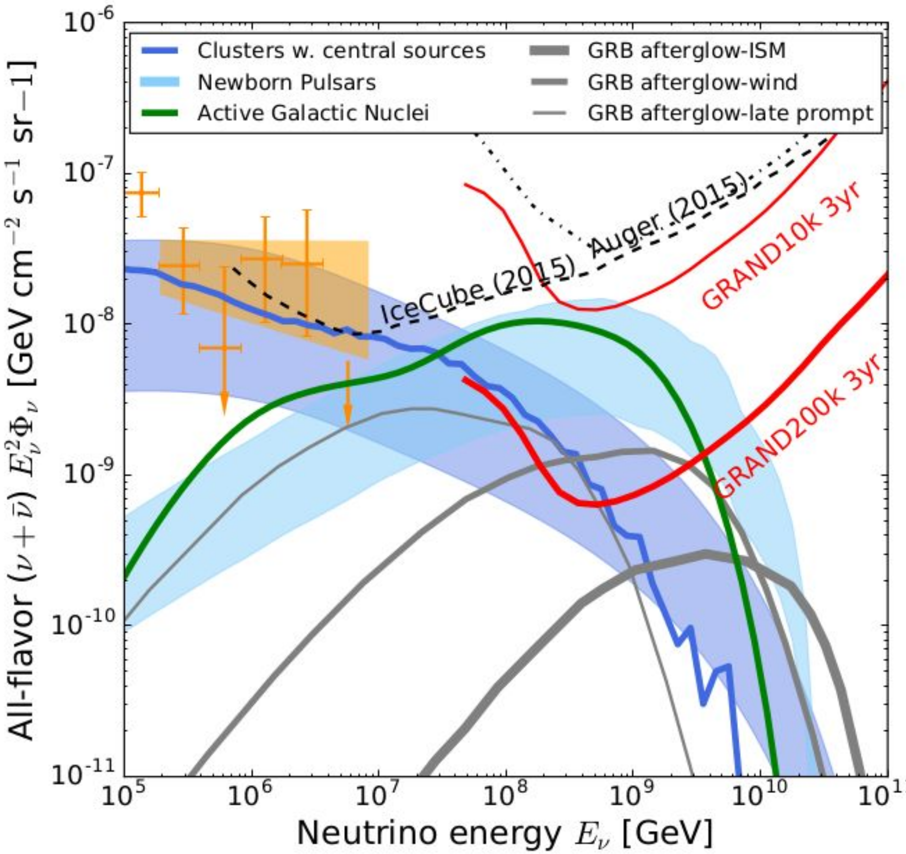
Mass composition



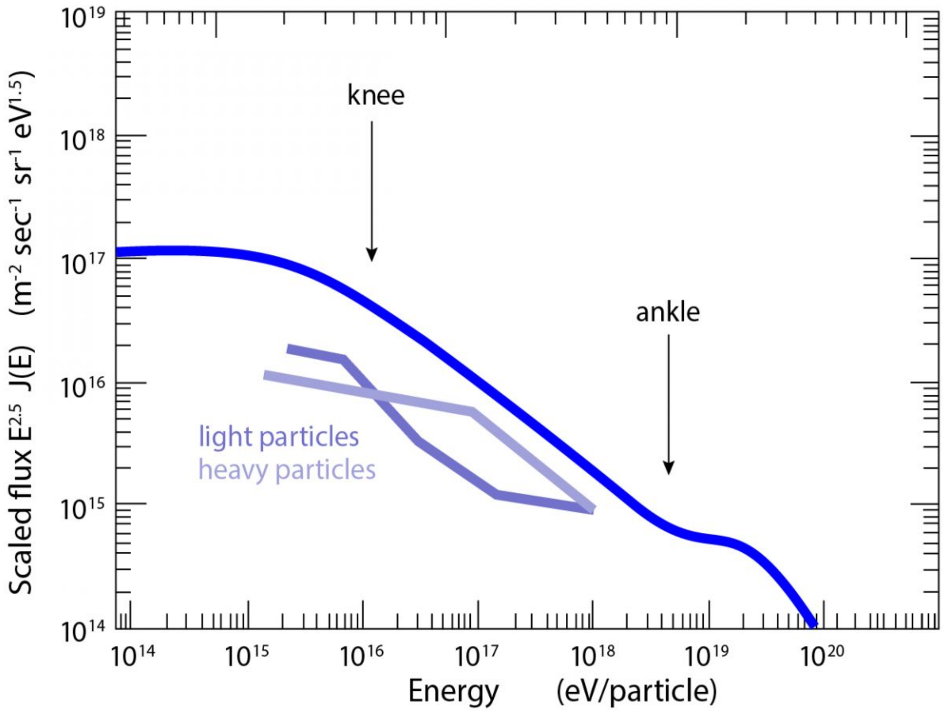


Neutrino flux





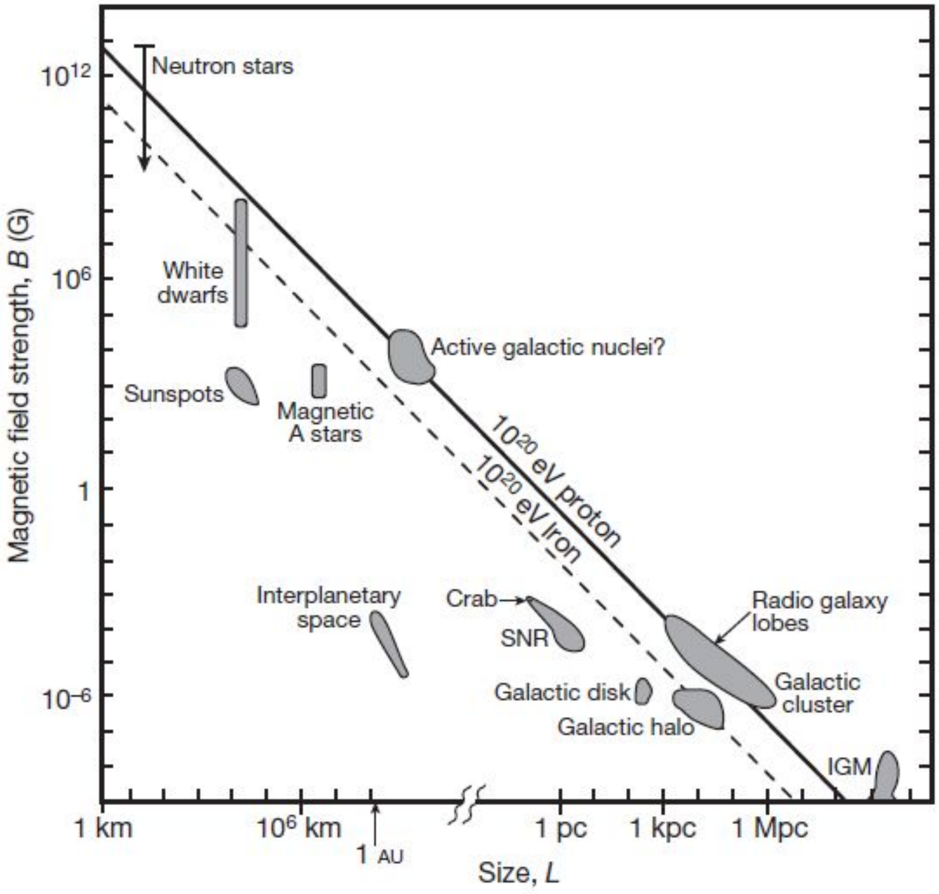
Mass of CR and flux



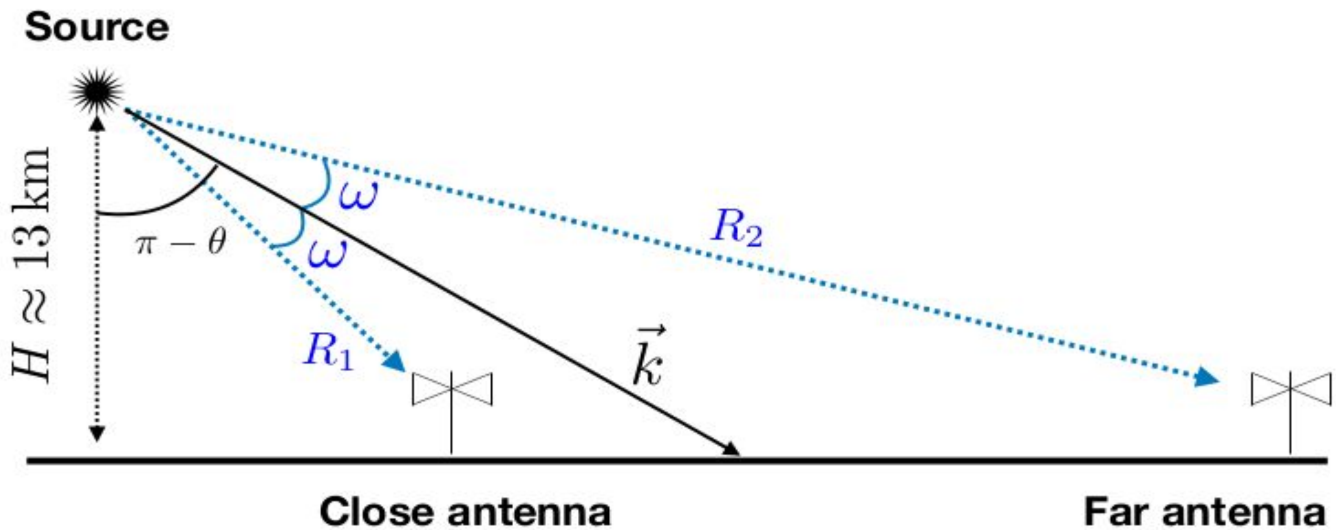
- **Hillas criteria E_{max} ~ Z B L β**
E^{i}_{max} ~ 26 E_{max}^{p}

knee< light particle
Transition to heavier composition indicates the maximum source energy is reached

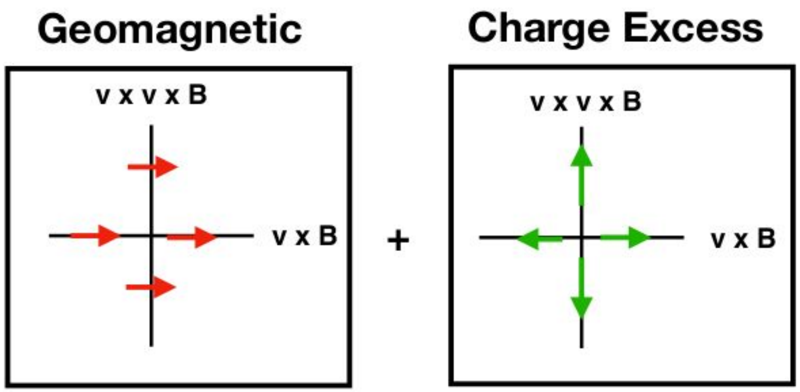
Hillas plot

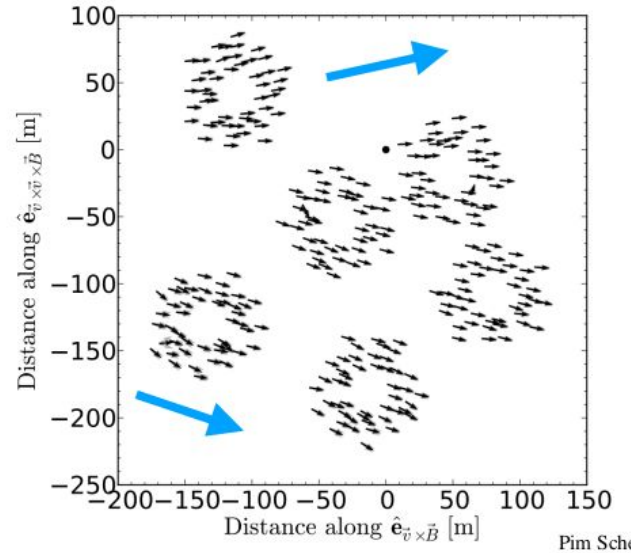


- **Hillas criteria E_{max} ~ Z B L β**

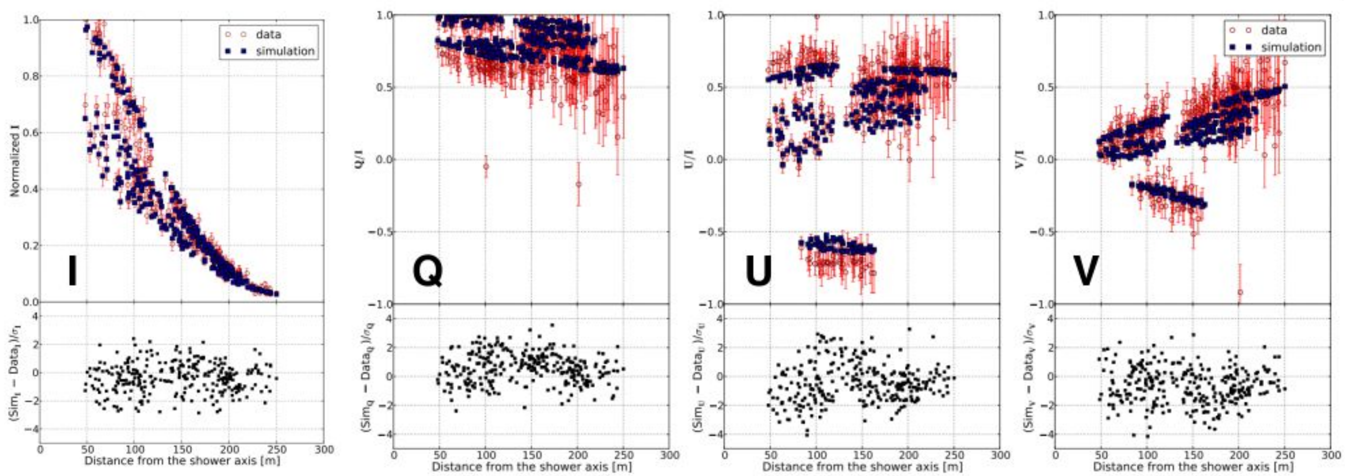

Source
$H \approx 13\,\mathrm{km}$
$\pi - \theta$
ω
ω
R_1
R_2
$\vec{k}$
Close antenna
Far antenna

Stokes Parameters





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



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