Friedrich-Alexander-Universität
Erlangen-Nürnberg

Erlangen Centre for Astroparticle Physics

4D Air Shower Reconstruction and Radio Detection of PeV Gamma-rays with the SKA

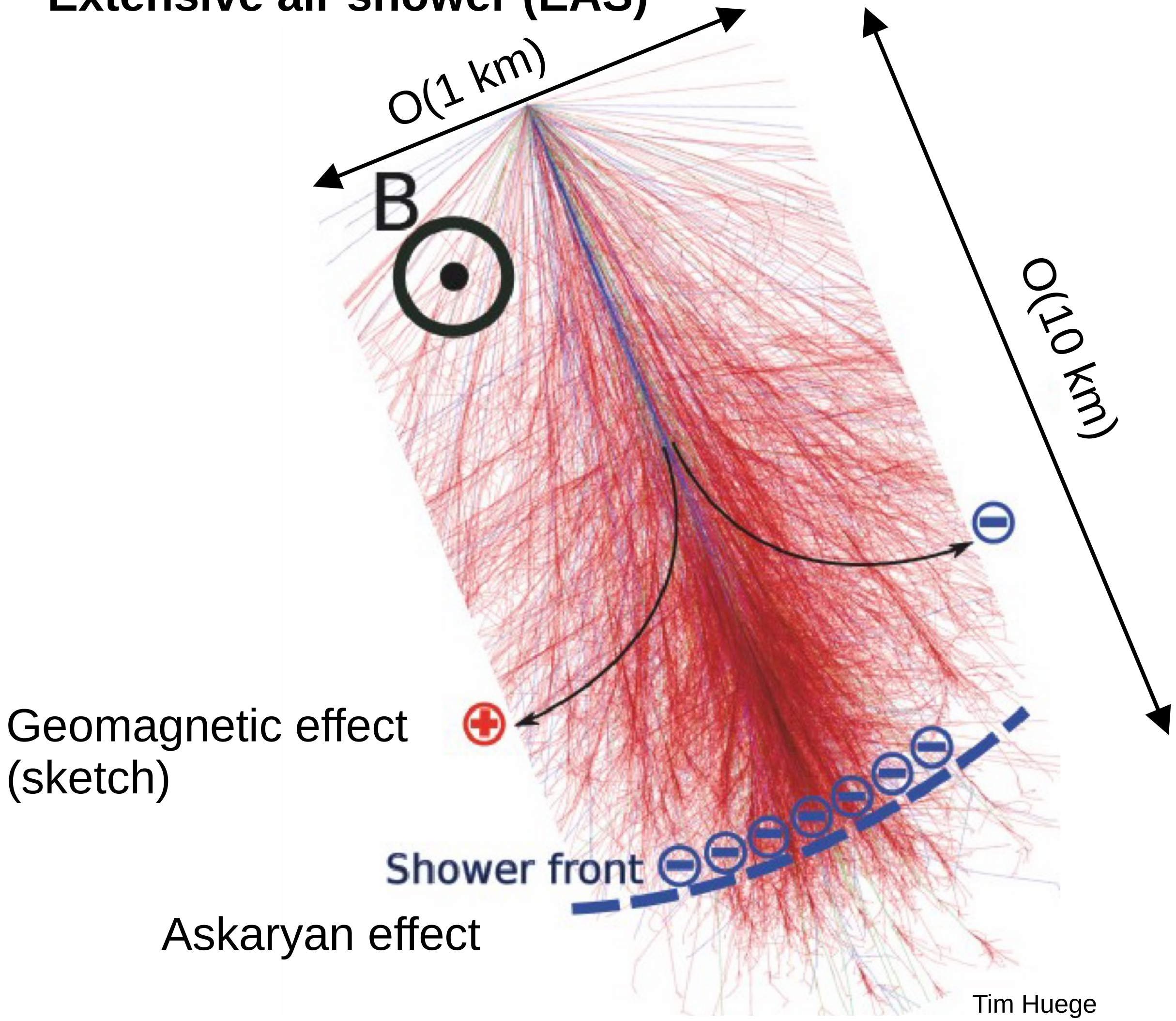
Astroparticle School 2024

Speaker: Philipp Laub*
Supervisor: Anna Nelles

*philipp.laub@fau.de

Radio detection of cosmic particles

Extensive air shower (EAS)



Tim Huege

Radio detection of cosmic particles

Buitink et al. PoS(ICRC2015)369

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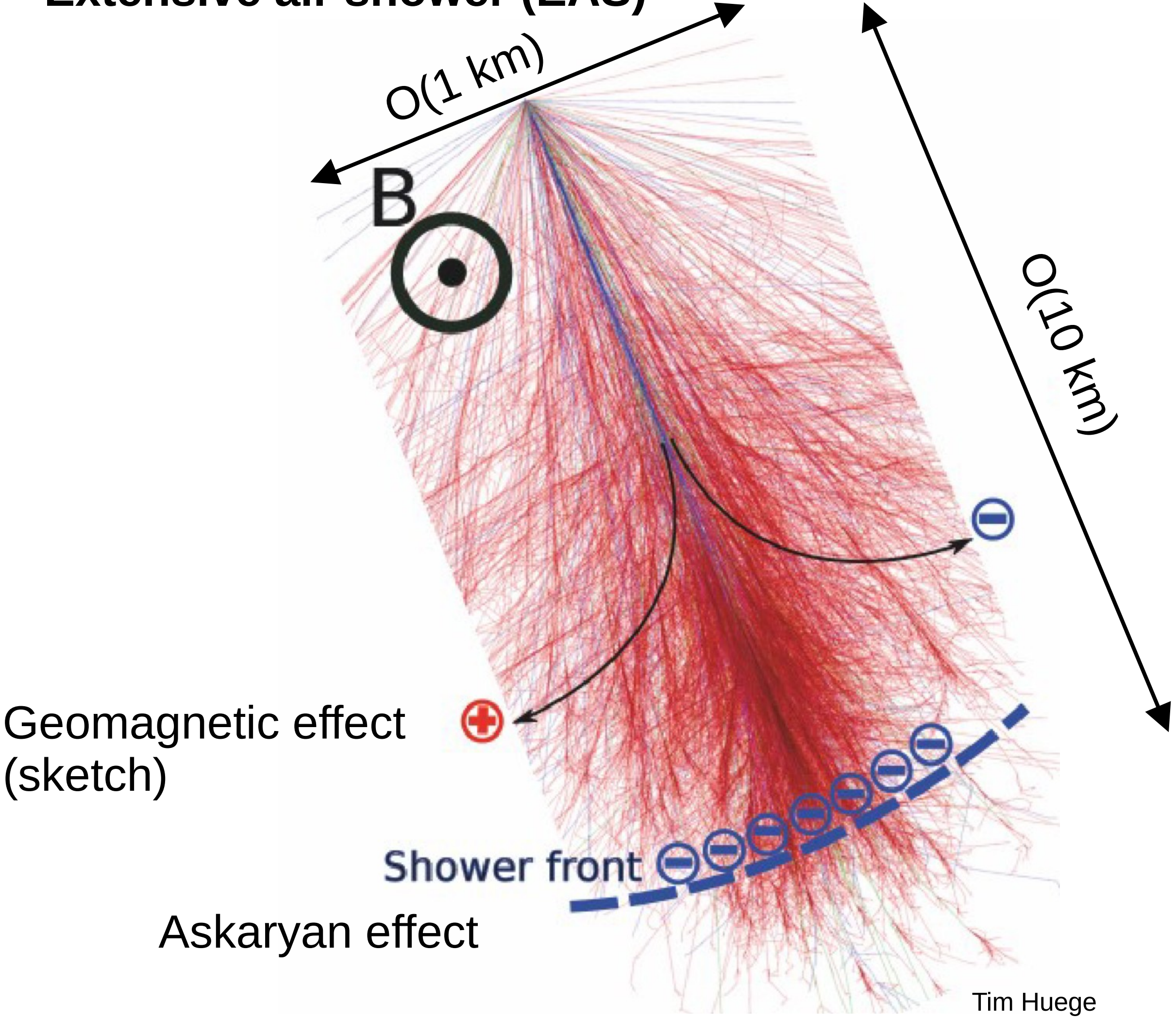

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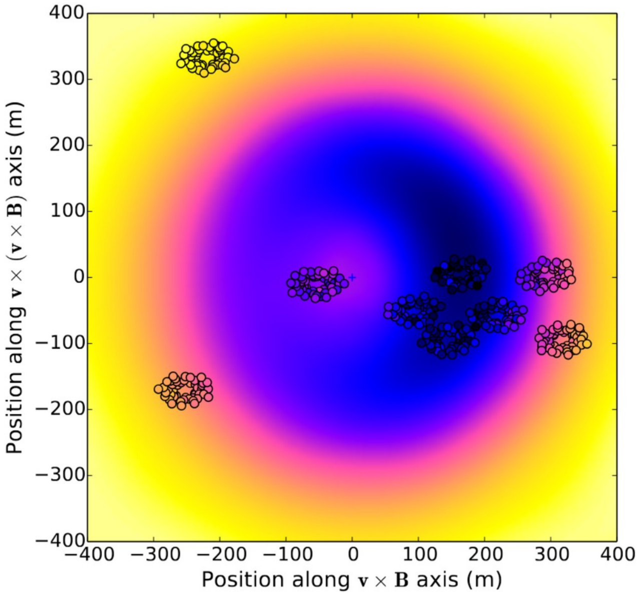
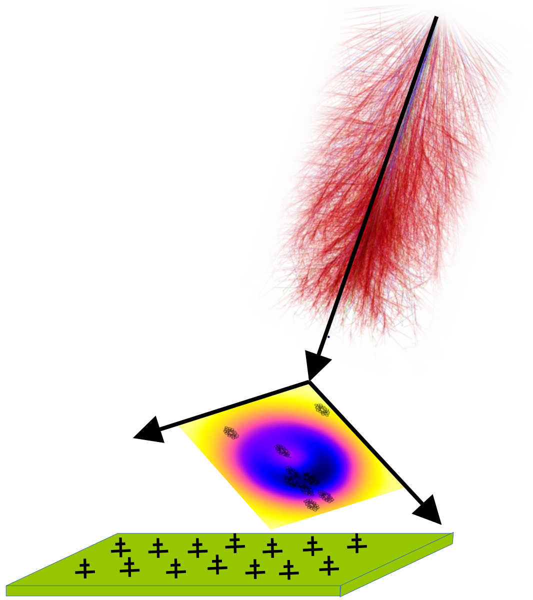




Why radio?

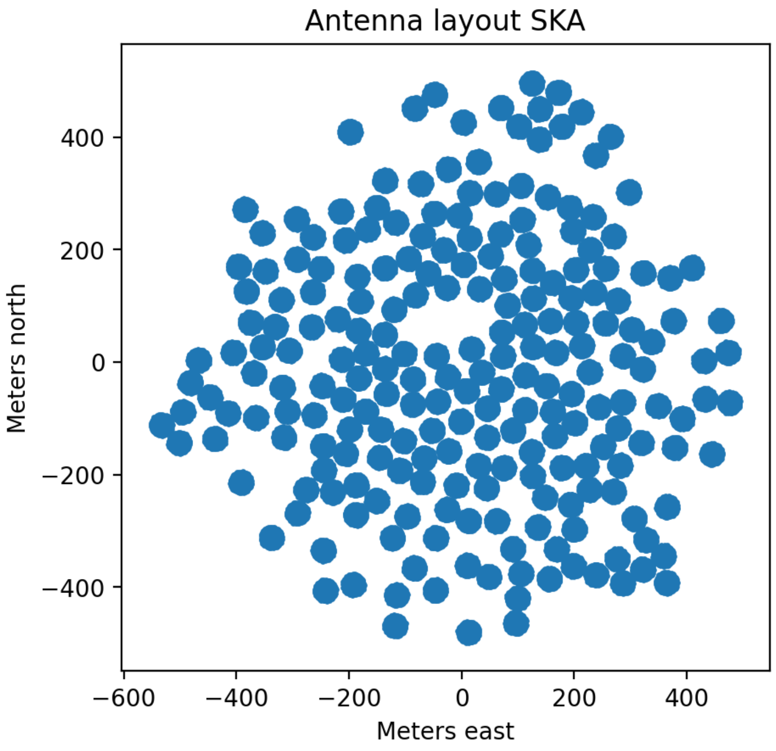
- Observable 24/7
- Almost no attenuation in air
- Inexpensive detectors
- Sensitive to em. shower component

SKA

The Square Kilometre Array

- 2 parts (construction started):
  - Mid-frequency array SKA-mid in South-Africa
  - Low-frequency array **SKA-low** in Western Australia
- SKA-low:
  - 512 stations with 256 antennas each
  - Dense core with 3 spiral arms
  - Core: ~ 57,344 log-periodic antennas
  - Core area: ~ 1 km^2
  - Frequency band: 50 MHz – 350 Mhz
  - Energy range: 10^{16} eV – 10^{18} eV

Core



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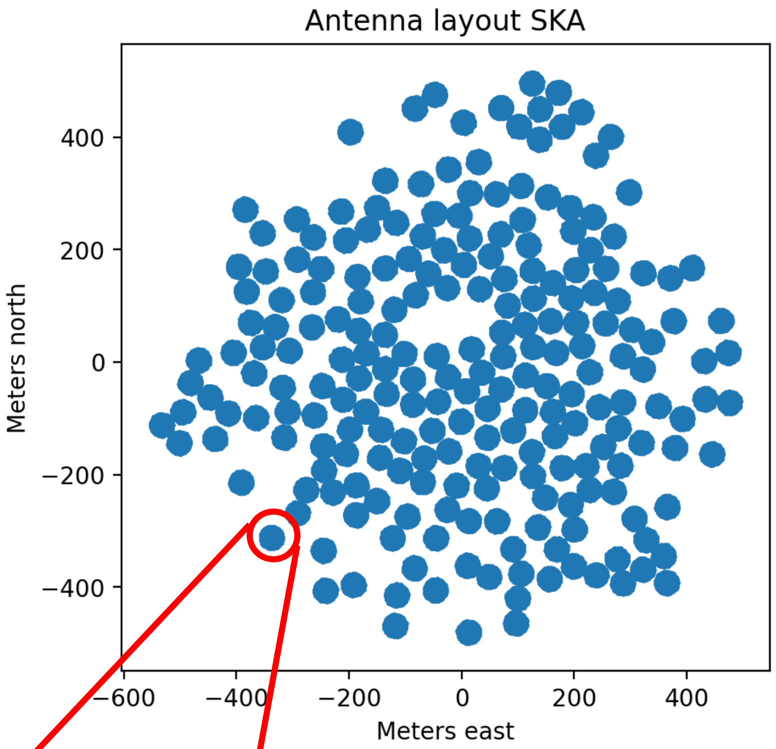
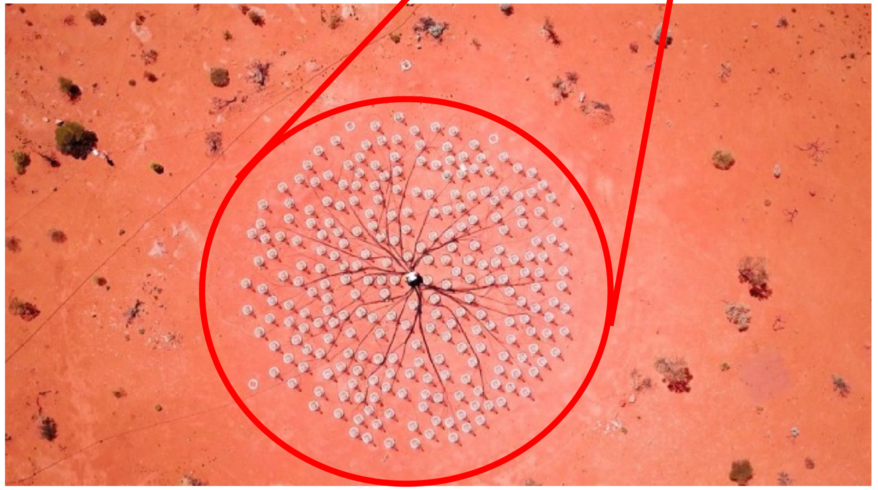


Prototype station



SKAO

SKA

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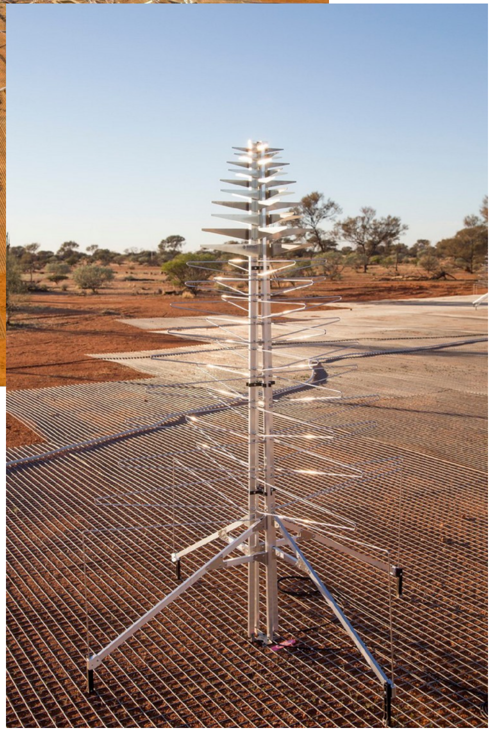

SKALA4.1 antenna

SKA

The Square Kilometre Array

SKA-low:

- 512 stations with 256 antennas each
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- Core: ~ 57,344 log-periodic antennas
- Core area: ~ 1 km²
- Frequency band: 50 MHz – 350 Mhz
- Energy range: 10^{16} eV – 10^{18} eV
- Particle detector (scintillator) array funded!

  → Particle trigger
  - Triggers on muons
  - Robust against radio noise

Prototype SKAPA particle detector

Bray et al. 2020 10.1016/j.nima.2020.164168

SKA

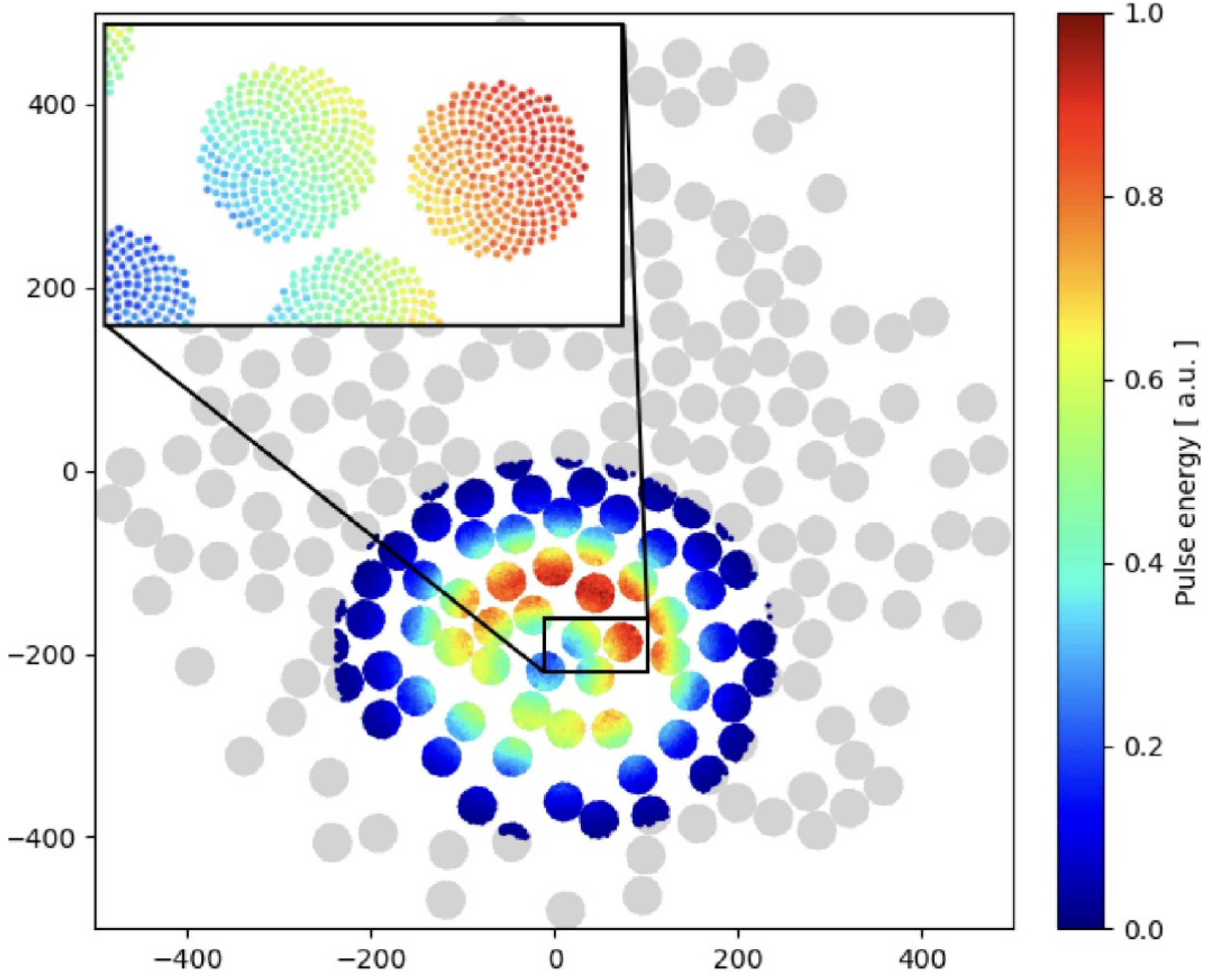
The Square Kilometre Array

- Extremely high antenna density in core

  → High-precision measurements of shower parameters

	SKA-low (simulations)	LOFAR
X_{max} resolution	6-8 g/cm^2	20 g/cm^2

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



S. Buitink et al. PoS(ICRC2023)503

Thesis project: science case

Status of current analyses/reconstruction efforts

- Radio detectors (LOFAR, future SKA-low,…)
  - Measurement of radio emission from EAS

  → Reconstruction of shower parameters (Xmax, direction, core position, …)

  → Reconstruction of the properties of the primary particles (energy, type, …)
- Current analyses:
  - Comparison between measured signals (footprint etc…) and many simulations
  - Time evolution of air showers not considered
- Simulations:
  - Dependent on choice of the hadronic interaction model
  - Very resource-hungry

Thesis project: science case

Science case / Project goal

→ New reconstruction method:

- Fast
- Model-agnostic/model-independent
- Time evolution of air showers (→ maximum level of detail)

  → **4D (space + time) air shower reconstruction algorithm**

→ Expectation:

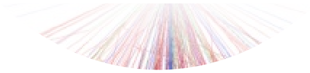
- High-precision reconstructions using SKA-lows vast data abundance
- Independent of hadronic interaction models
- Investigation of air shower physics to unseen depth

  → “new“ physics, e.g. sub-structures?

*together with **Keito Watanabe** and **Mrinal Jetti***

Project: 4D air shower reconstruction

https://www.zeuthen.desy.de/~jknapp/fs/iron-showers.html



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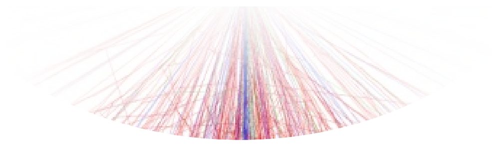

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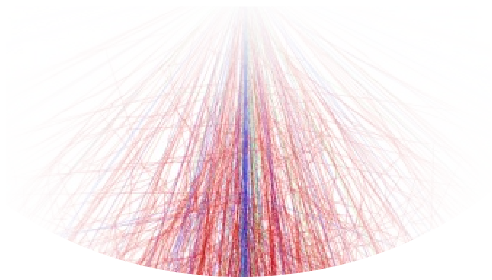

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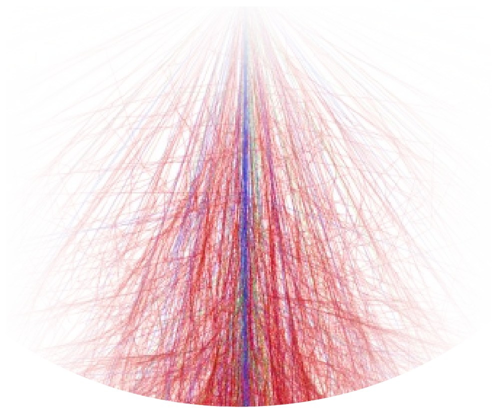

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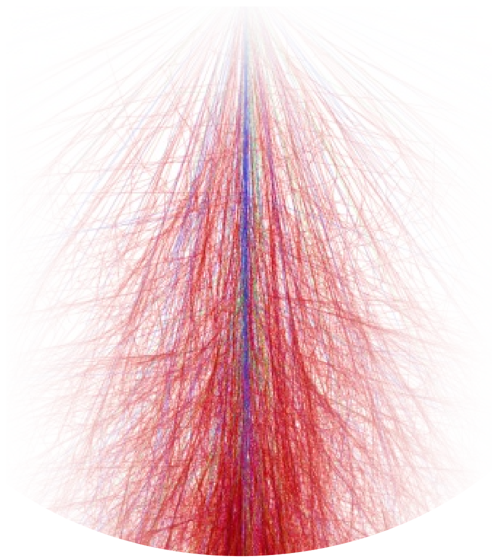

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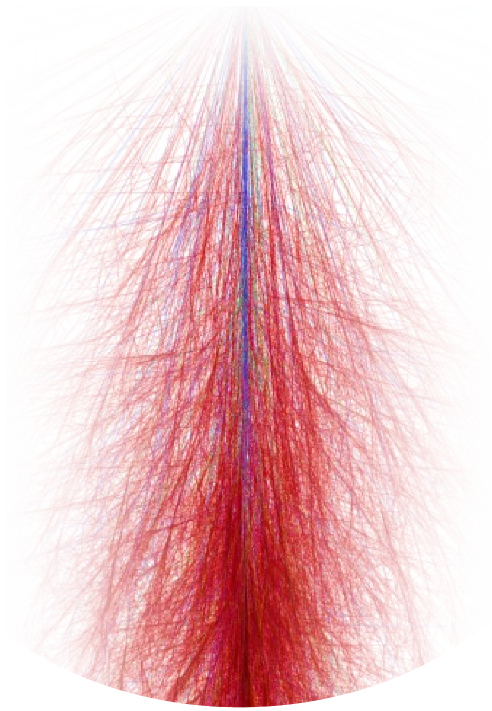

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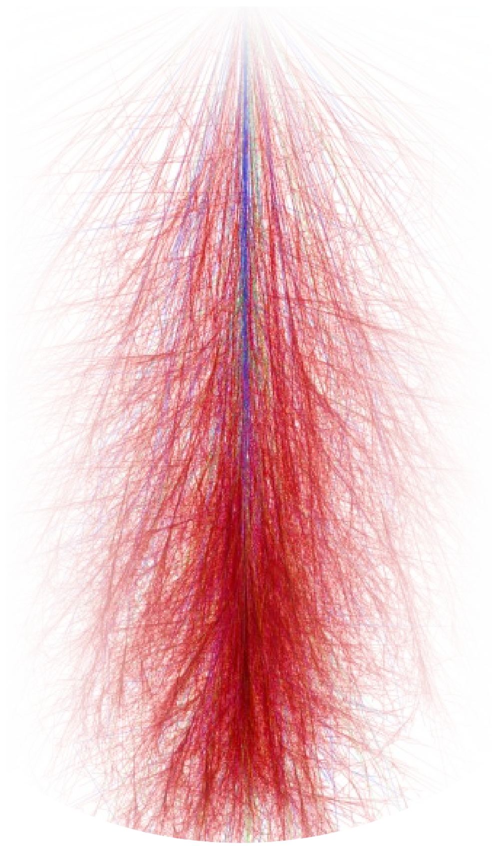

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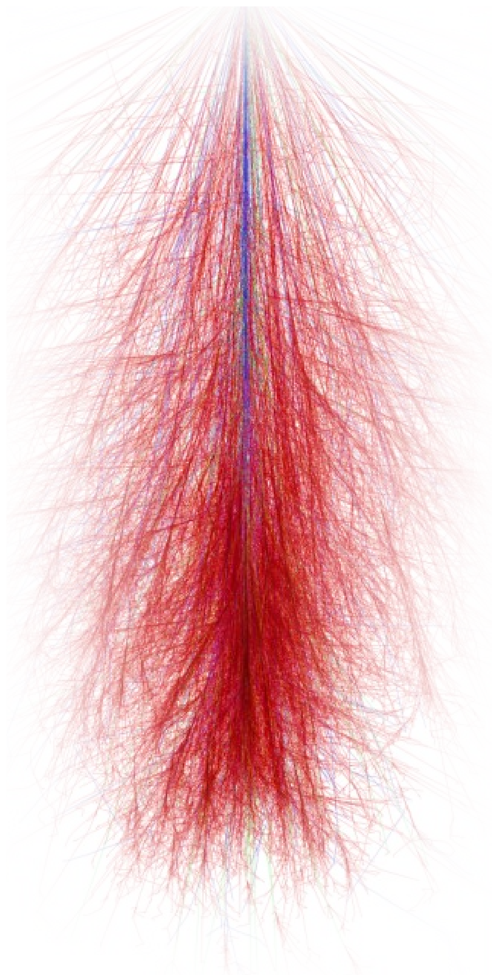


Project: 4D air shower reconstruction

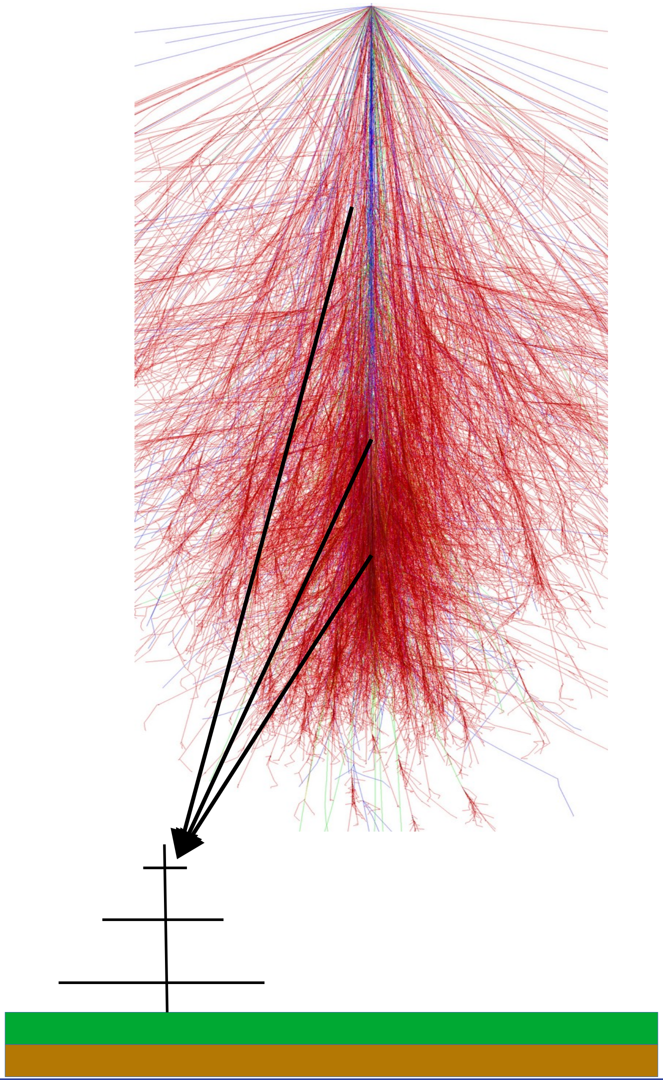
Challenge

https://www.zeuthen.desy.de/~jknapp/fs/iron-showers.html

Why is 4D hard?

→ **Time compression**:

- Refractive index in air > 1
- Shower propagation faster than light in air
- Signals from all stages of air shower development arrive at ~ same time
- Single short-timed pulse measured



4D air shower reconstruction

Plan

- Reconstruction using Information field theory (IFT)

Information field theory

- Framework for bayesian inference developed as a field theory
- Extremely large numbers of degrees of freedom
- Physics-informed, based on prior knowledge/assumptions
- Allows reconstructions using minimal information

→ see talk by Mrinal Jetti

Amplifier, antenna, atmosphere, ...

(Ideally physical) parameterization

Galaxy, electronics, ...

Data = System response x Signal + Noise

Distribution of parameters?
(prior assumptions)

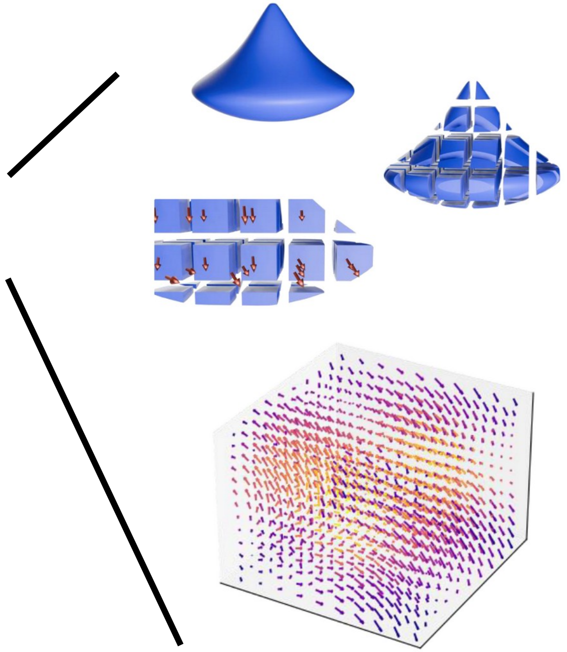
4D air shower reconstruction

Plan

- Reconstruction using Information field theory (IFT) → see talk by Mrinal Jetti

  → Multiple possible approaches:

  - Template synthesis (model-dependent) → see talk by Keito Watanabe
  - **Model-agnostic modelling of microscopic currents in a moving relativistic voxel**
  - Artificial Neural Network



Max Straub, ARENA 2024

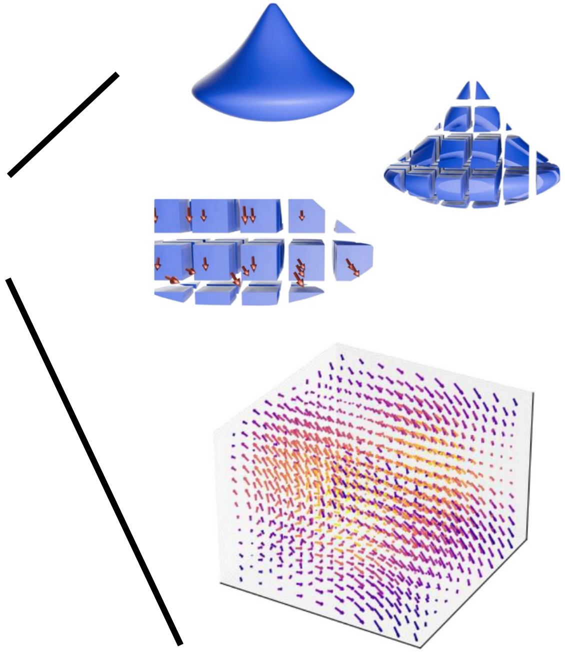
4D air shower reconstruction

Plan

- Reconstruction using Information field theory (IFT) → see talk by Mrinal Jetti

  → Multiple possible approaches:
  - Template synthesis (model-dependent) → see talk by Keito Watanabe
  - **Model-agnostic modelling of microscopic currents in a moving relativistic voxel**
  - Artificial Neural Network
- Simulation pipeline:
  - CORSIKA/CoREAS simulations
  - SKA-low detector description
  - SKALA4 antenna model
  - …

  → test algorithm on “realistic“ SKA-low events



Max Straub, ARENA 2024

Project 2: Gamma ray detection

- SKA-low designed for (hadronic) cosmic rays
- ***Can it be used for UHE gamma-ray detection?*** (for free!)

Project 2: Gamma ray detection

Challenges

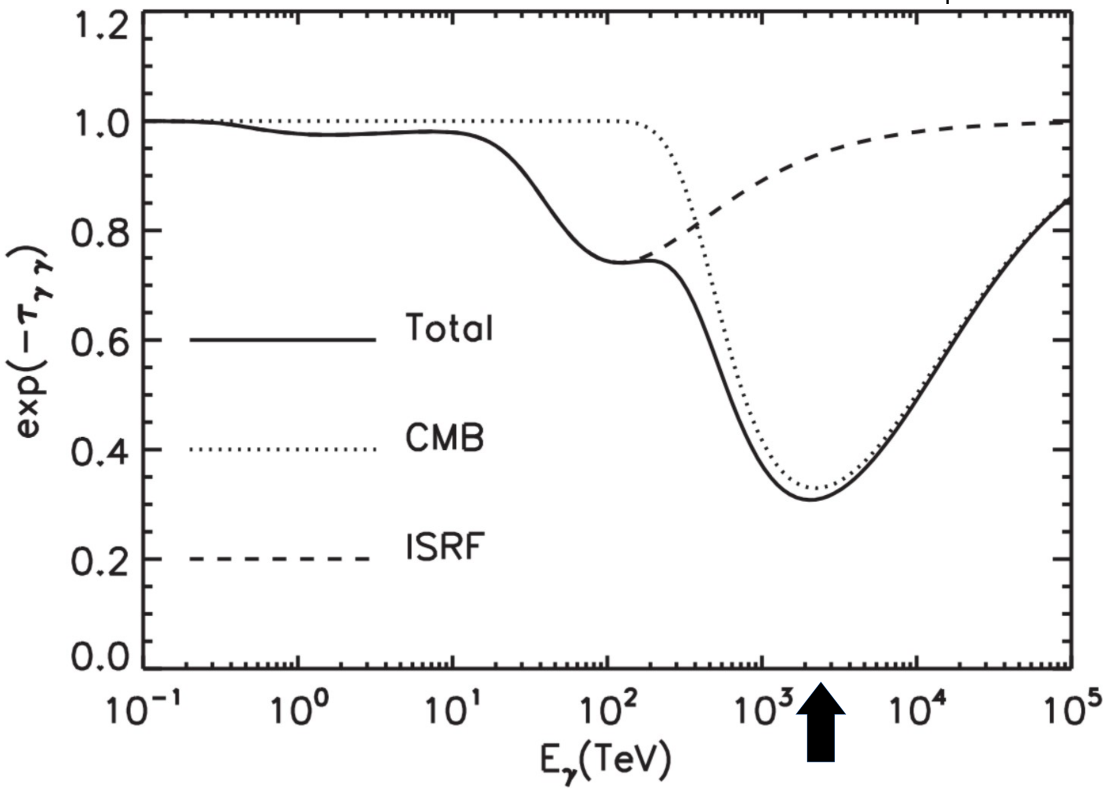
- SKA-low designed for (hadronic) cosmic rays
- *Can it be used for UHE gamma-ray detection?* (for free!)

  → Challenges:

  - Attenuation of gamma rays due to CMB (and Interstellar Radiation Field (ISRF)) strongest at ~ PeV

    → Low flux at ultra-high energies where SKA-low is sensitive

Popescu et al. 2017



Transmission vs. photon energy (source at Galactic Centre)

Project 2: Gamma ray detection

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    → Low flux at ultra-high energies where SKA-low is sensitive

  – Purely electromagnetic showers

    → Fewer muons expected from gamma ray air showers

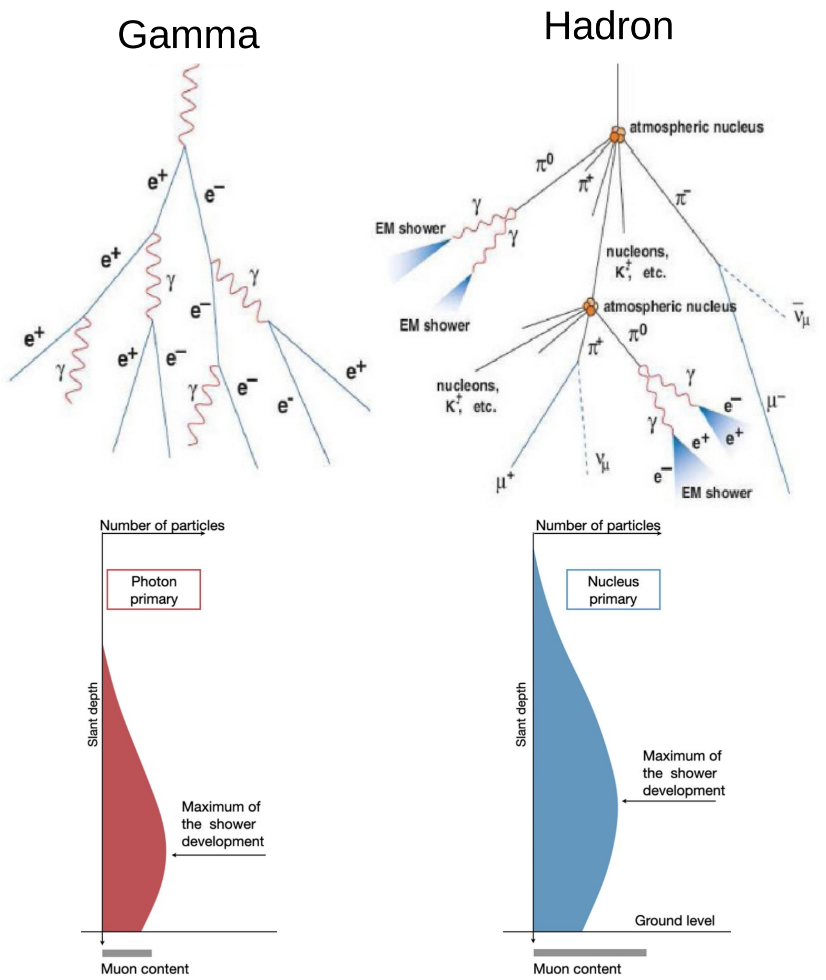
    → *Particle trigger not effective for gamma ray showers?*

    → *Signal trigger required?*

    → *Trigger threshold / Minimum energy?*

    → *Improvements through IFT / interferometry?*

Alicia López-Oramas 10.13140/RG.2.1.4140.4969



Abreu et. al. https://arxiv.org/abs/2209.05926

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  - Attenuation of gamma rays due to CMB (and Interstellar Radiation Field (ISRF)) strongest at ~ PeV

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    → No/few muons expected from gamma ray air showers

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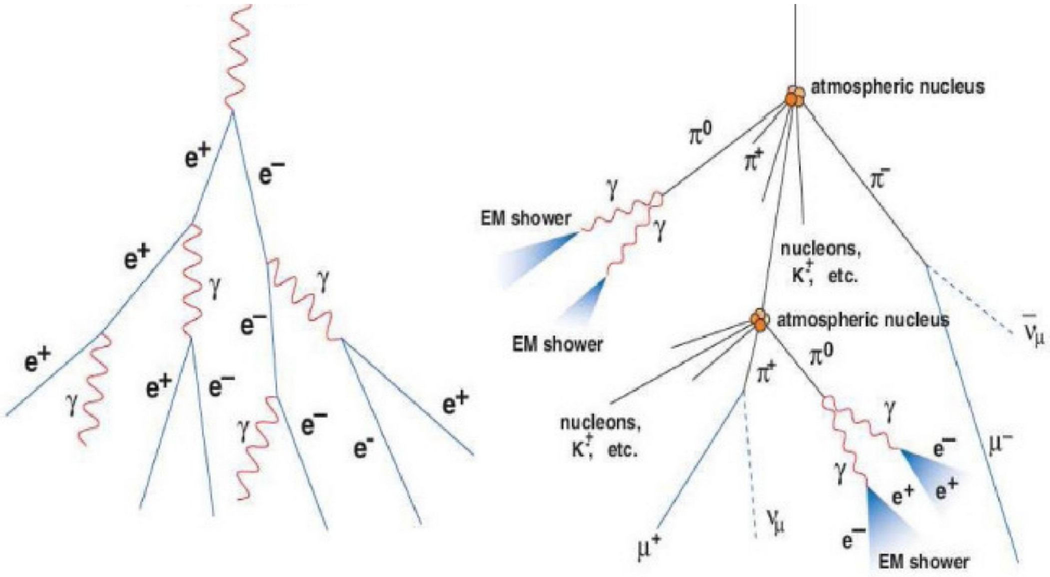
    → Improvements through IFT / interferometry?
  - Large (hadronic) cosmic ray background

    → Gamma – hadron separation

Alicia López-Oramas 10.13140/RG.2.1.4140.4969



Veto with particle (muon) detector?

Project 2: Gamma ray detection

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  - Large (hadronic) cosmic ray background

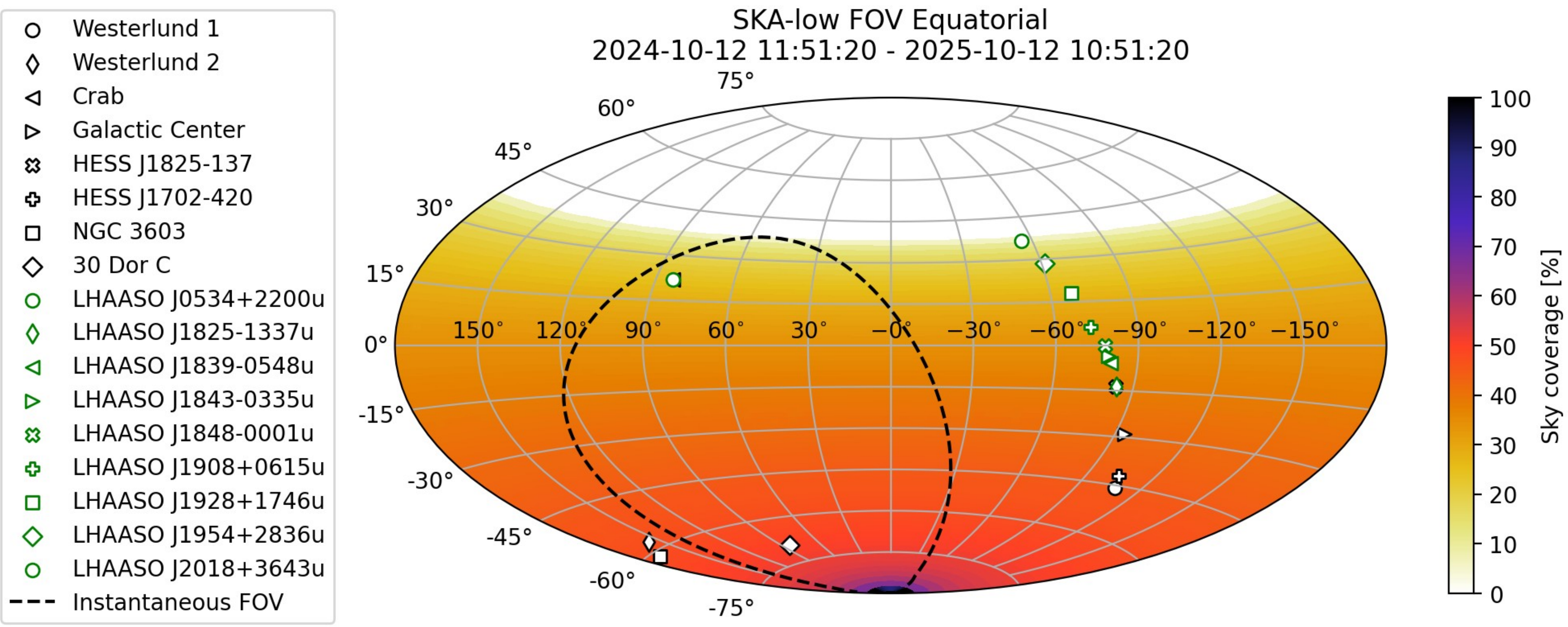
    → Gamma – hadron separation
  - Observable UHE gamma ray sources?

Project 2: Gamma ray detection

FOV

SKA-low field of view (FOV): (assume that SKA can see sources up to 65 degree zenith angle, 1 year)

→ Several LHAASO sources (some reported to emit up to few PeV gammas)



Summary

- SKA currently under construction
  - High antenna density
  - Extreme precision measurements
- Goal: 4D air shower reconstruction ***(WIP)***
  - Multiple possible approaches (model-agnostic, model-dependent, ANN)
  - IFT
  - More insights into air shower physics expected
- Radio detection of gamma rays with SKA ***(WIP)***
  - Several challenges: Trigger, CR background, low flux at ultra-high energies

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Thank you for your attention!