Friedrich-Alexander-Universität
Erlangen-Nürnberg

Deutsche Forschungsgemeinschaft

Erlangen Centre for Astroparticle Physics

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

Radio2024

Speaker: Philipp Laub*
Supervisor: Anna Nelles

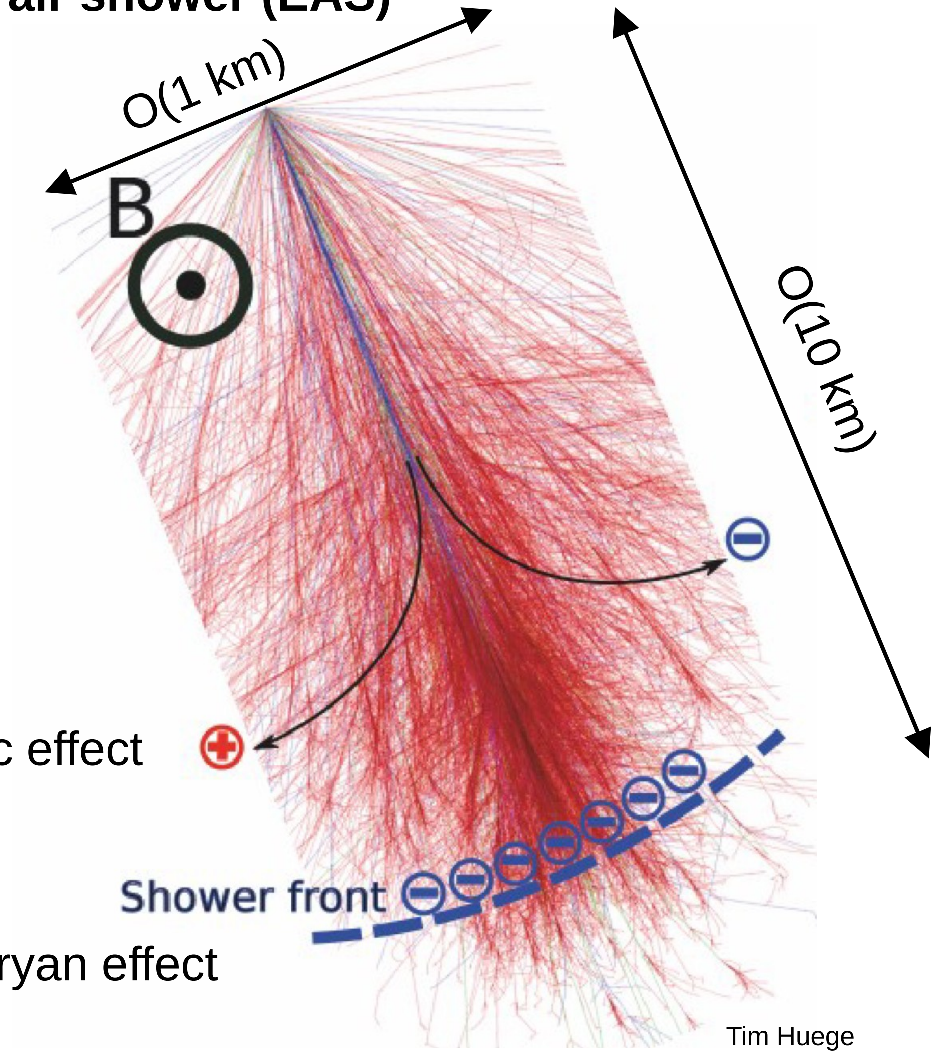
work carried out in the SKA High Energy Cosmic Particles SWG

*philipp.laub@fau.de

Radio detection of cosmic particles

→ more in talk by Katie Mulrey

Extensive air shower (EAS)



Geomagnetic effect (sketch)

Askaryan effect

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Buitink et al. PoS(ICRC2015)369

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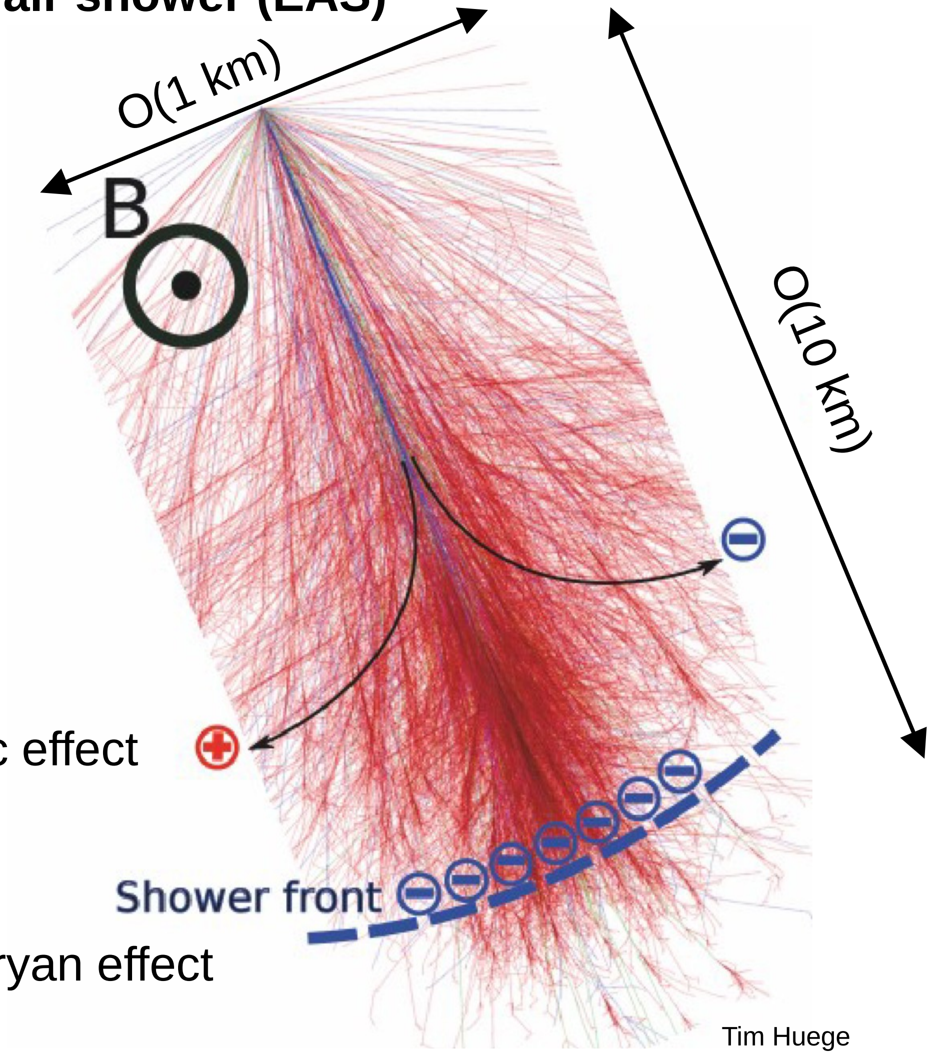

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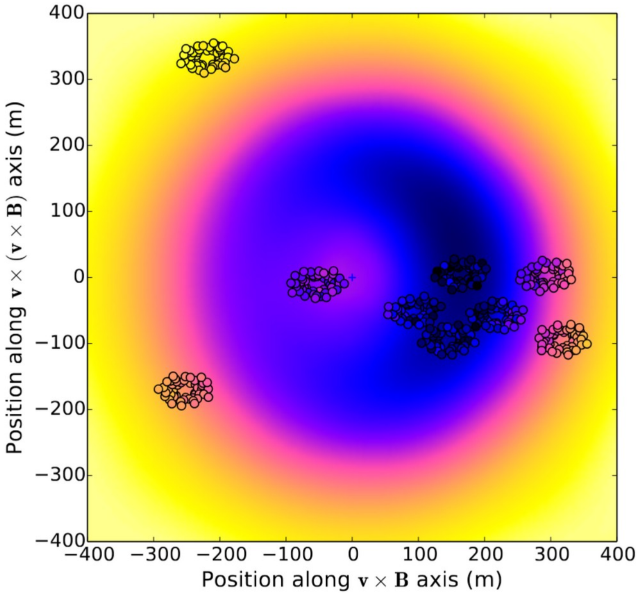
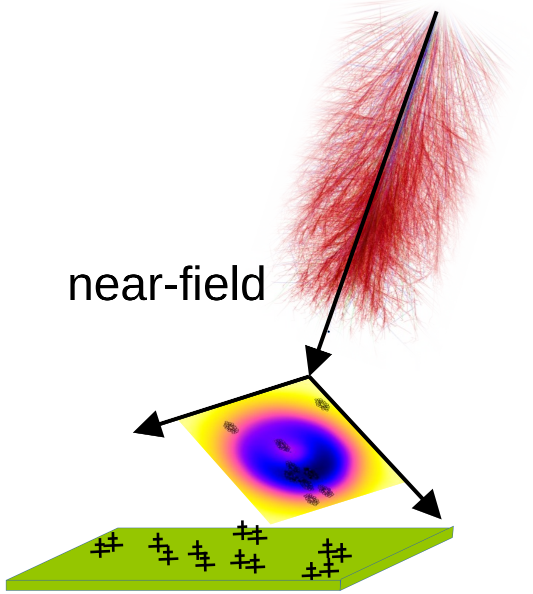




Why radio?

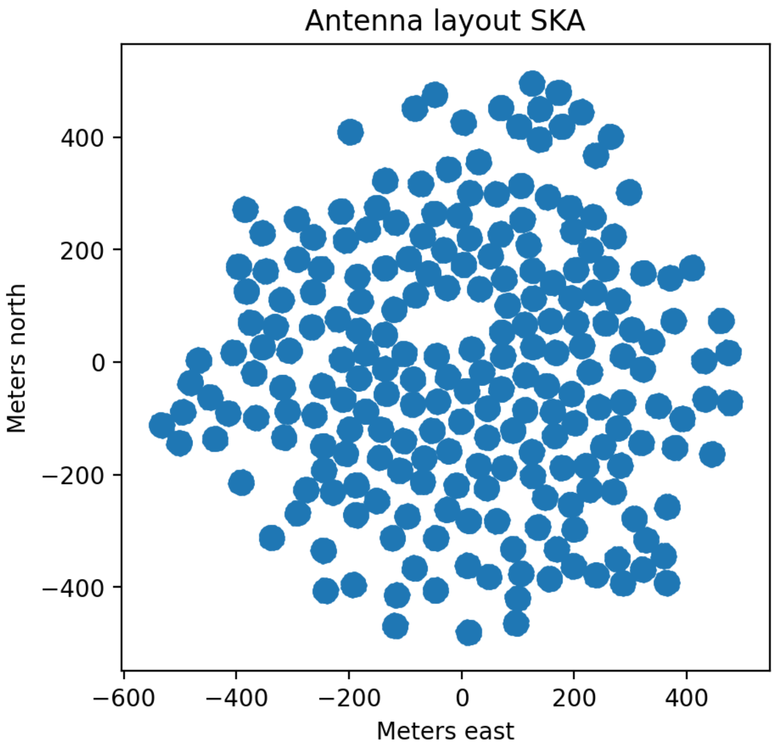
- Observable 24/7
- Almost no attenuation in air
- Inexpensive detectors
- Sensitive to em. shower component

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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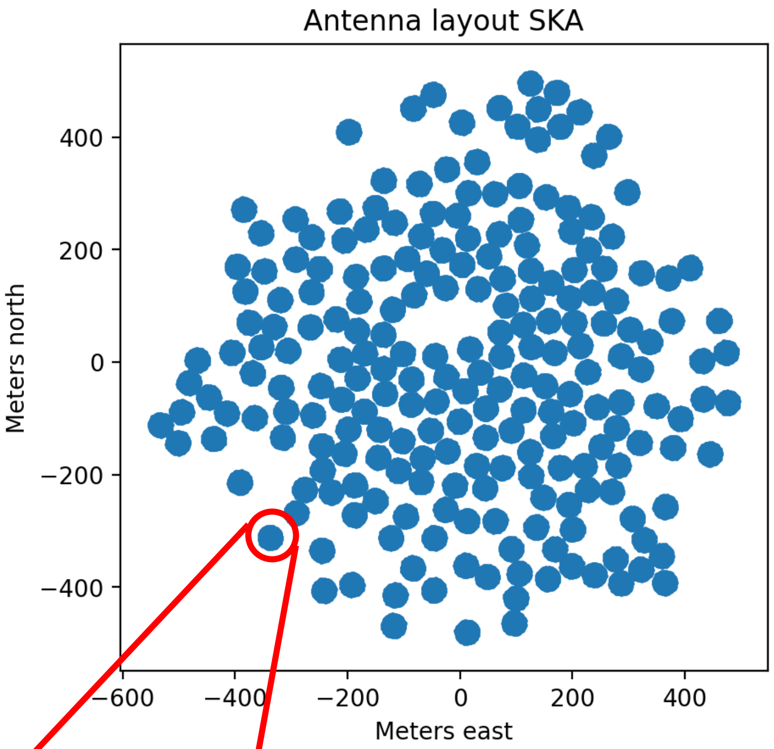
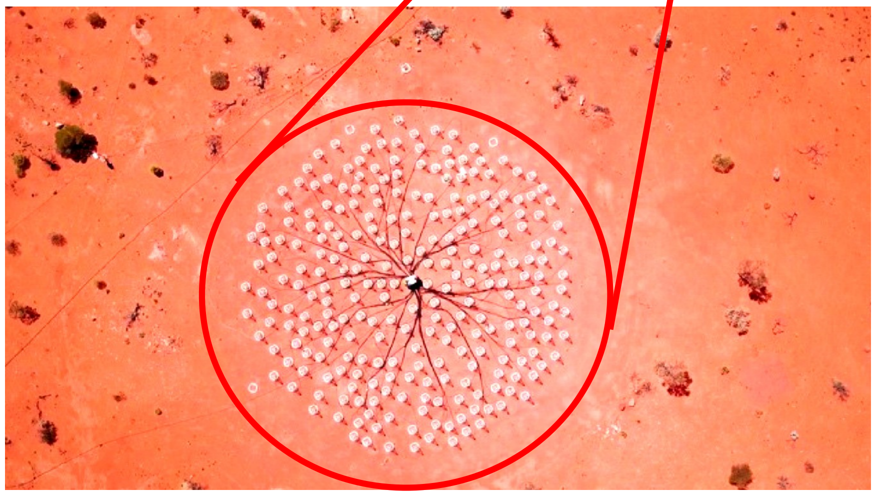


Prototype station



SKAO

SKA

The Square Kilometre Array

SKAO

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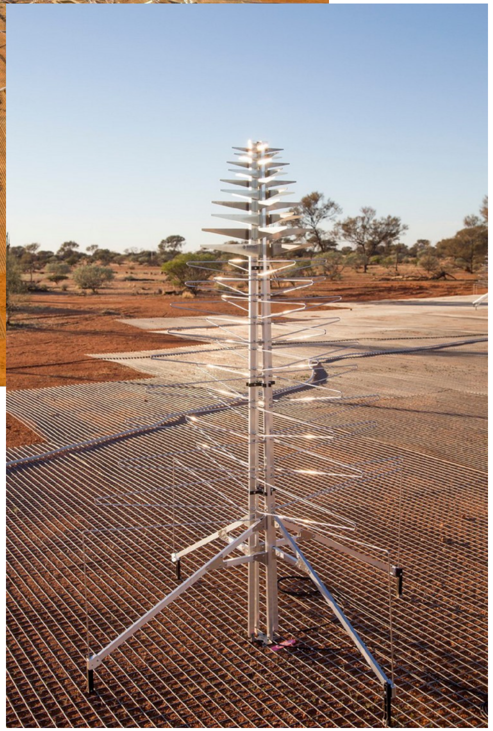

SKALA4.1 antenna

SKA

The Square Kilometre Array

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- Frequency band: 50 MHz – 350 Mhz
- Energy range: 10^{16} eV – 10^{18} eV
- Particle detector (scintillator) array funded!

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

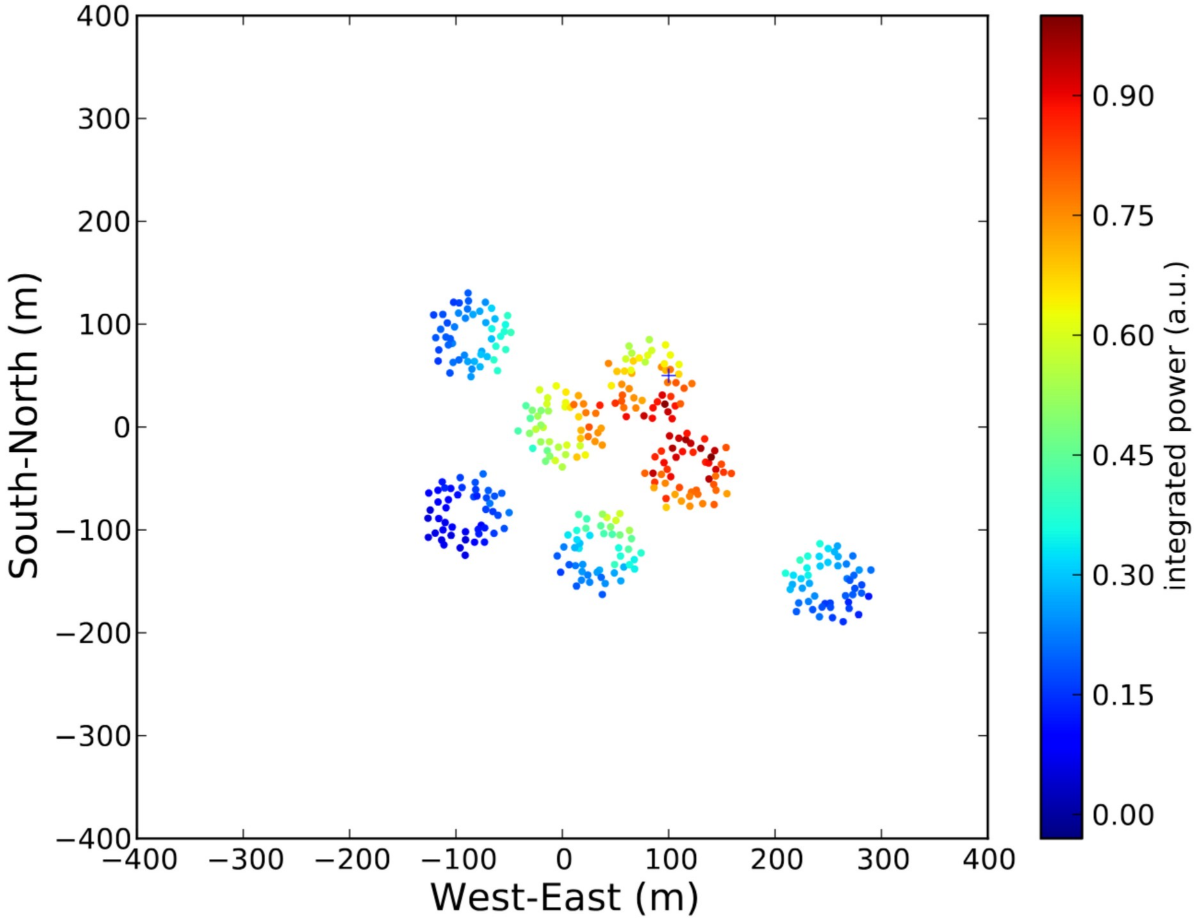
Prototype SKAPA particle detector

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

SKA

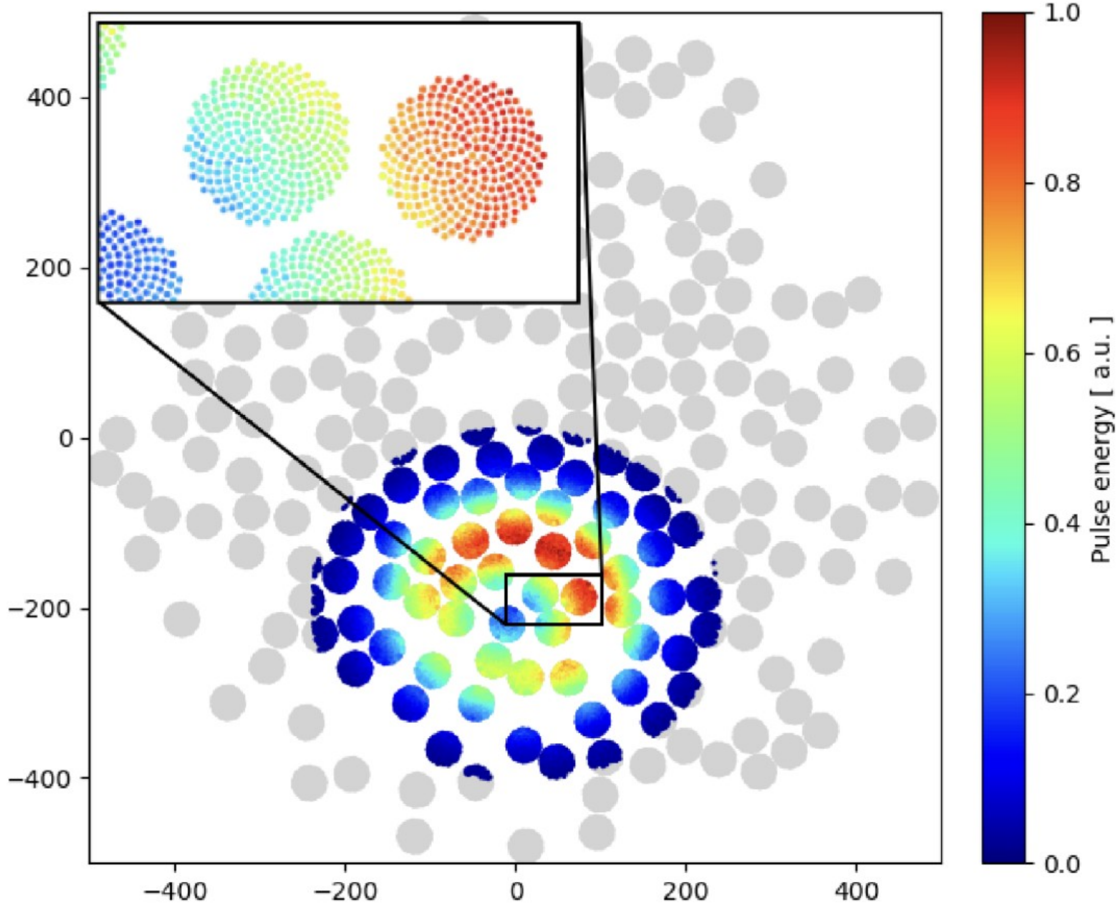
Maximum precision

LOFAR (core)



A. Zilles et al., EPJ Web Conf. Volume 135 (2017) 02004

SKA-low (core)



S. Buitink et al. PoS(ICRC2023)503

Maximum precision

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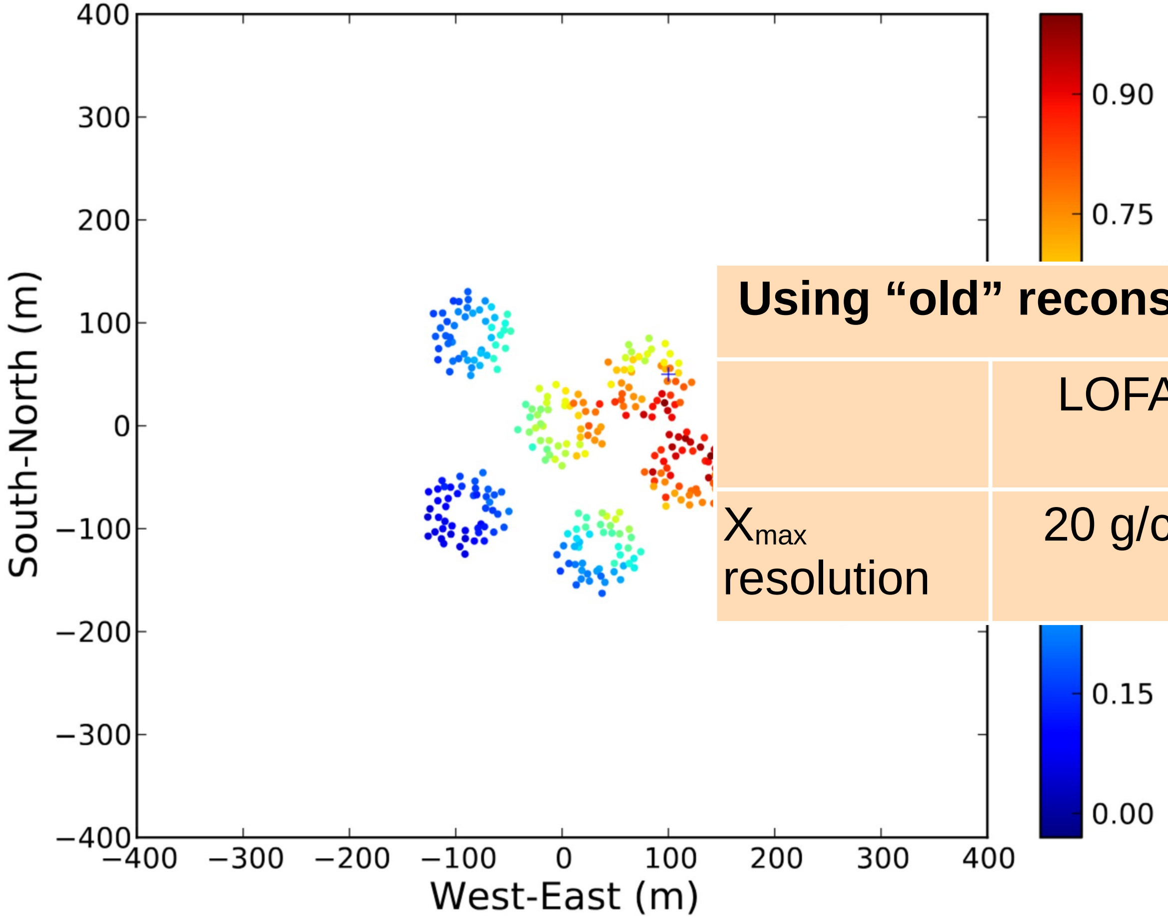

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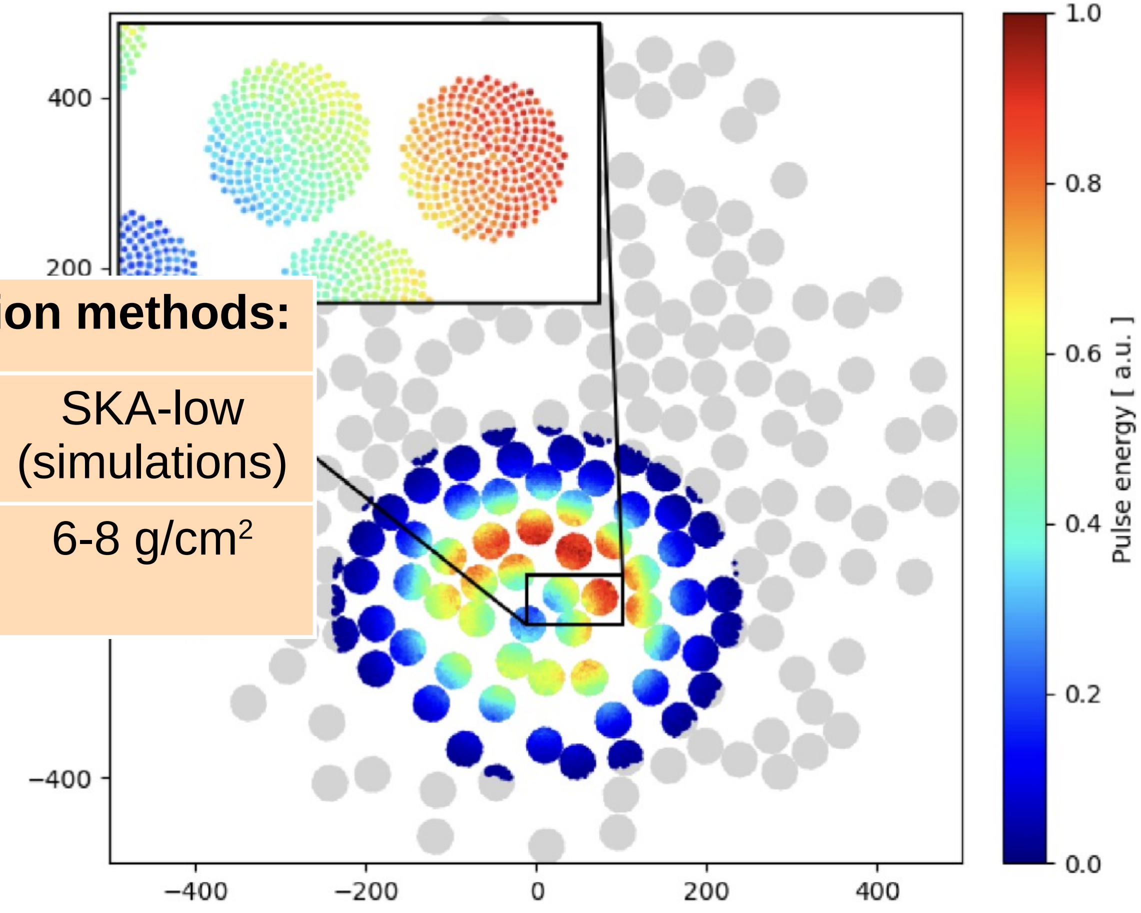


S. Buitink et al. PoS(ICRC2023)503

Using "old" reconstruction methods:

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

Project: science case

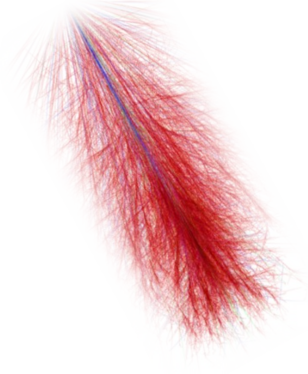
Status of current analyses/reconstruction efforts

- 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



Project: science case

Science case / Project goal

*together with **Keito Watanabe (KIT)** and **Mrinal Jetti (MPA)***

→ New reconstruction method:

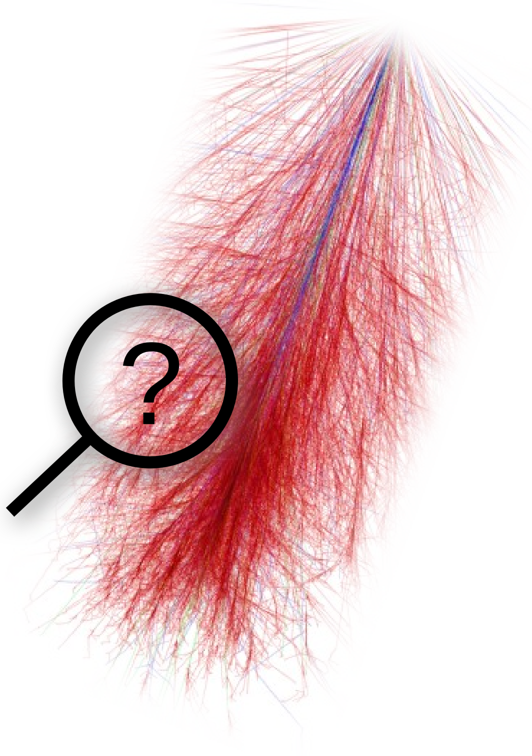
- Fast
- Model-agnostic/model-independent
- Time evolution of air showers (→ maximum level of detail)

  → **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?



Project: 4D air shower reconstruction

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

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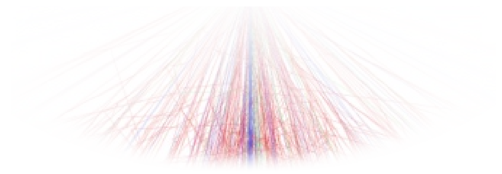

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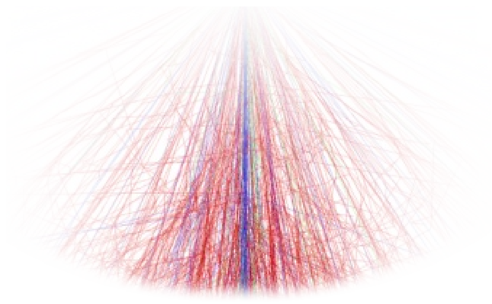

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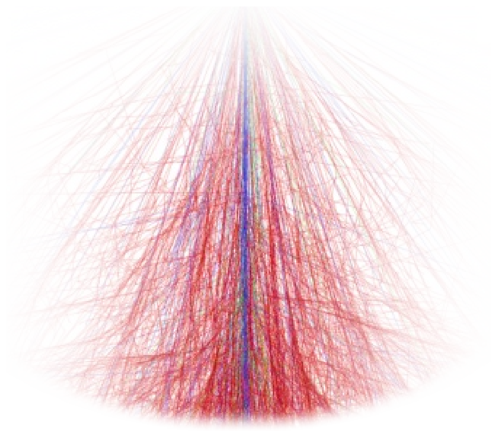

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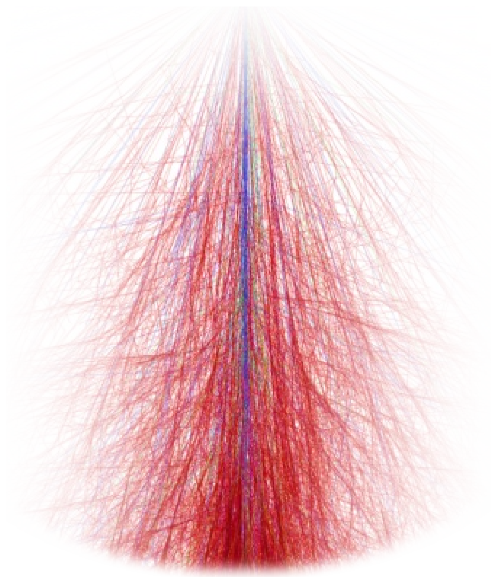

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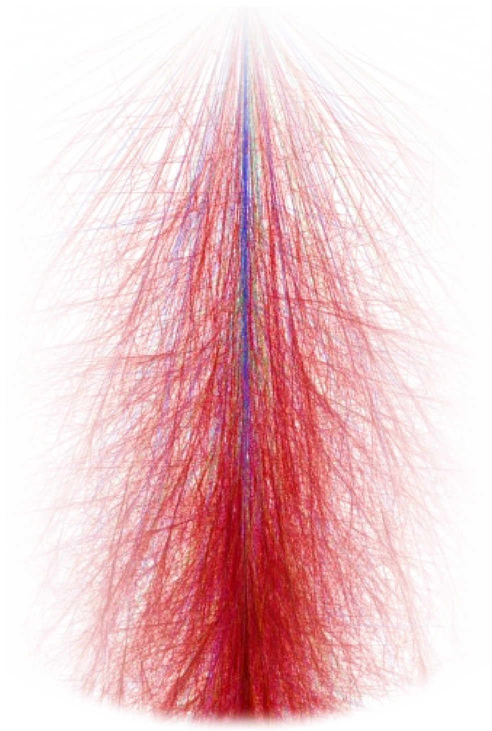

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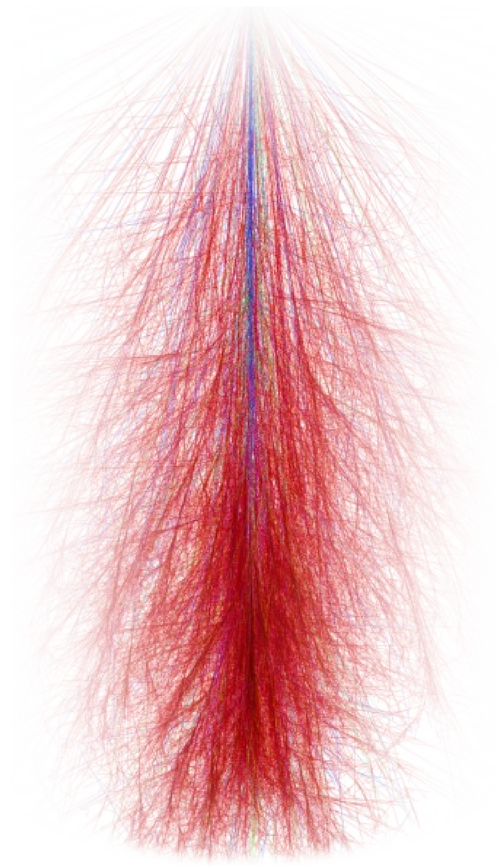

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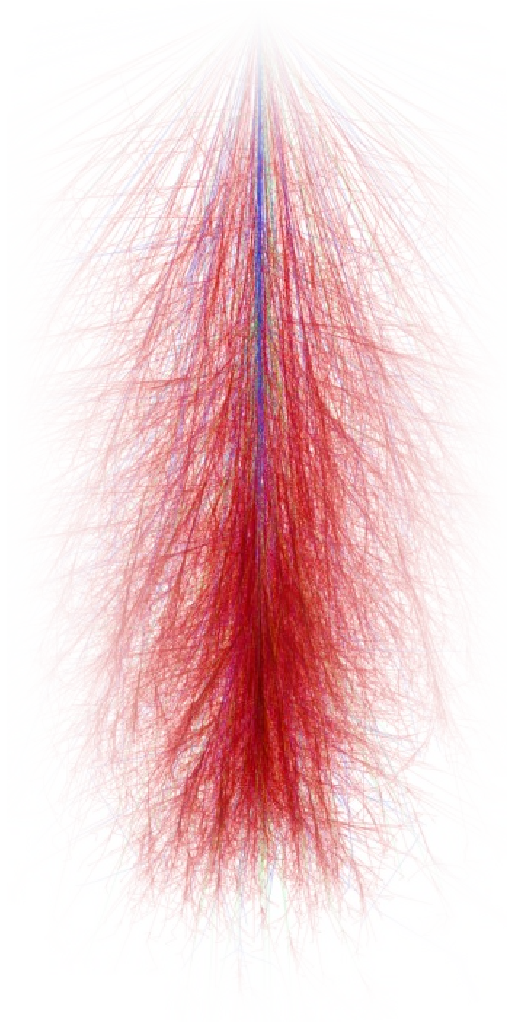


Project: 4D air shower reconstruction

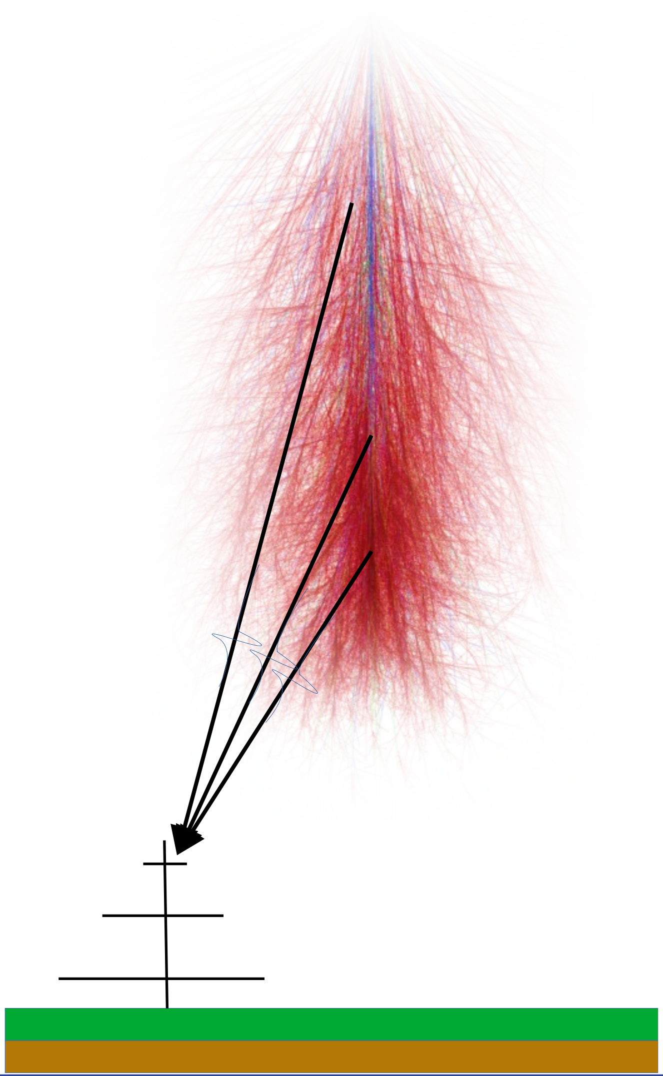
Challenge

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



- Near-field reconstruction problem

  → Not well-understood

4D air shower reconstruction

Plan

- Reconstruction using **Information field theory (IFT)** → see talk by Karen Terveer

4D air shower reconstruction

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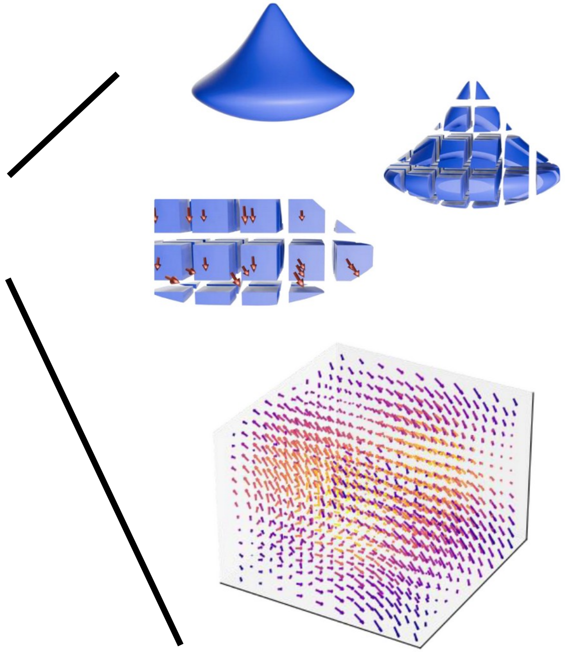
  → Multiple possible approaches:

  - 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

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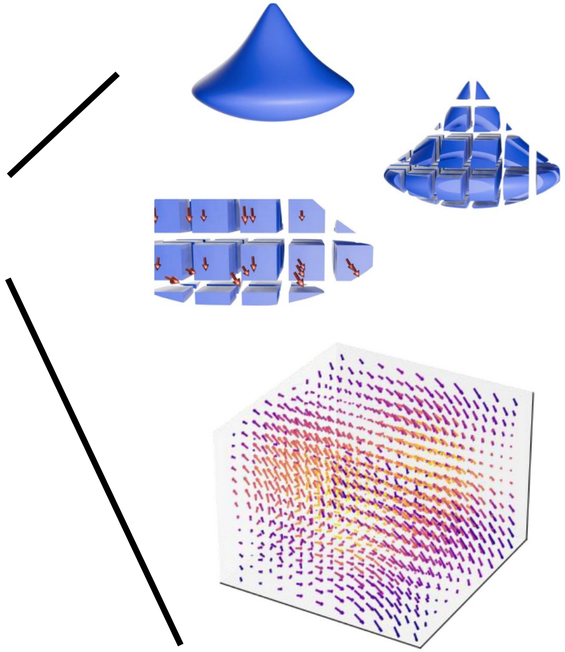
- Simulation pipeline:

  - CORSIKA/CoREAS simulations
  - SKA-low detector description
  - SKALA4 antenna model
  - …

  → test algorithm on “realistic“ SKA-low events



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Project 2: Gamma ray detection

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

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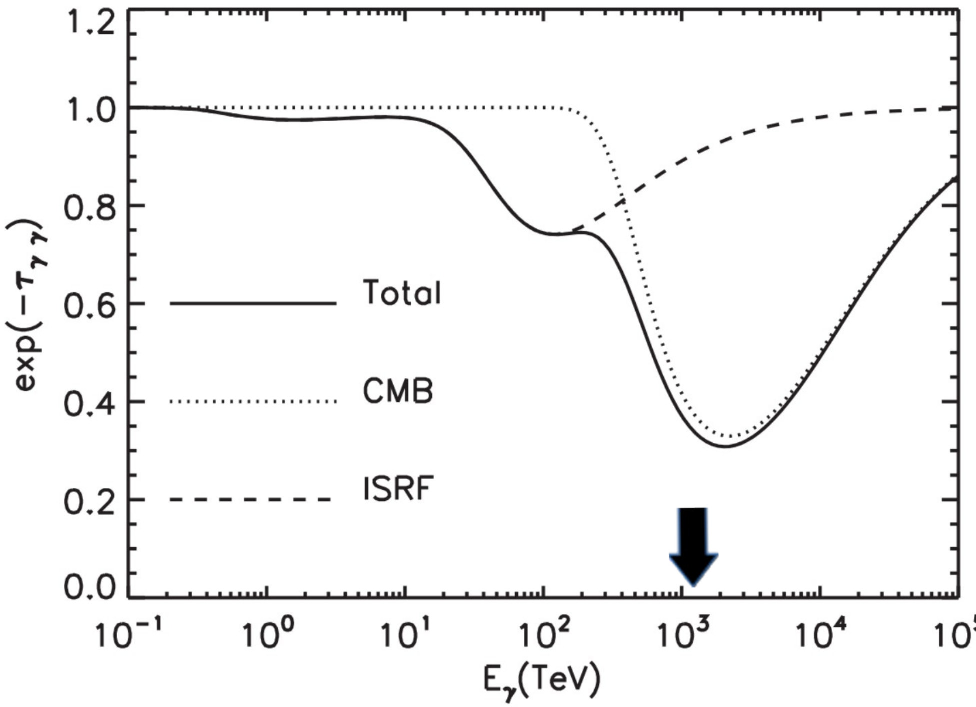
- SKA-low designed for (hadronic) cosmic rays
- *Can it be used for UHE gamma-ray detection?* (for free!)
- Highest energy gamma ray ever detected: **1.4 PeV (LHAASO)**
- 10 PeV (and above) crucial for understanding production mechanisms
- Several challenges
  - Attenuation due to CMB
  - Low flux at PeV energies

    → Lower trigger threshold required
  - Gamma – hadron separation

Popescu et al. 2017

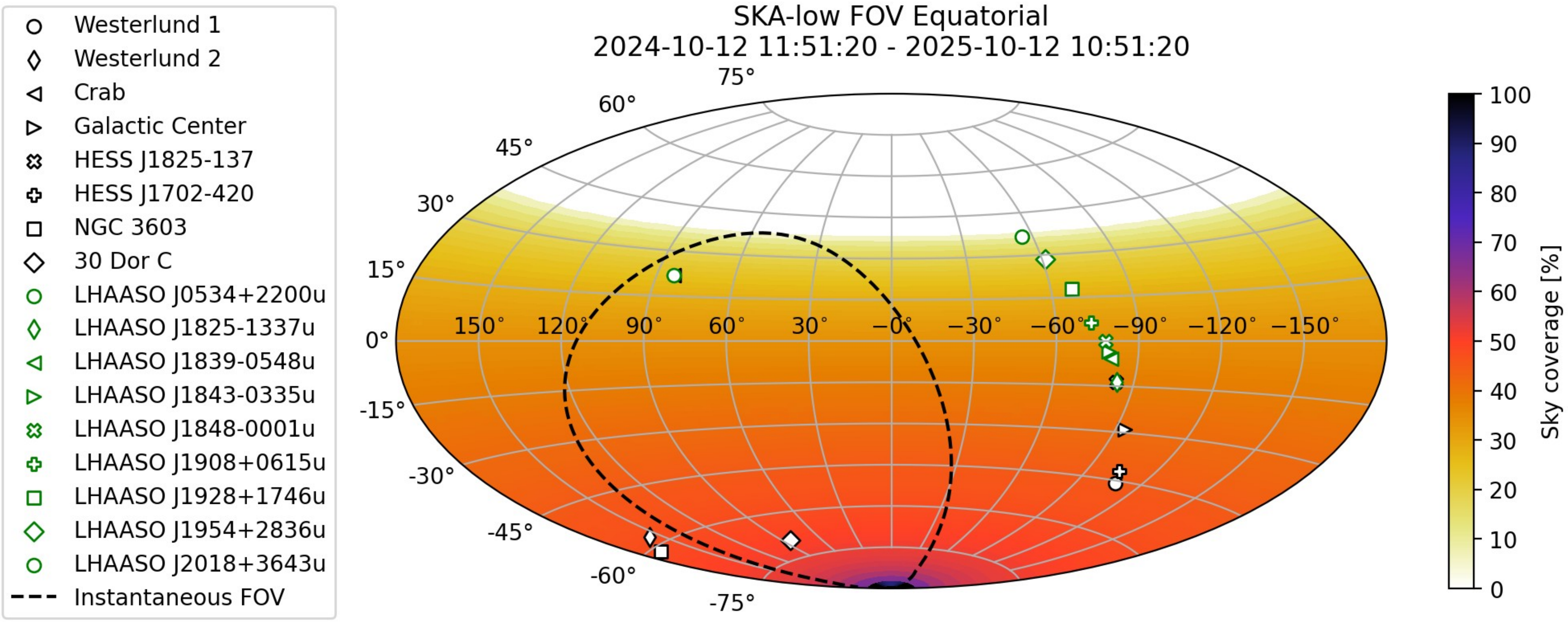


Transmission vs. photon energy (source at Galactic Centre)

Project 2: Gamma ray detection

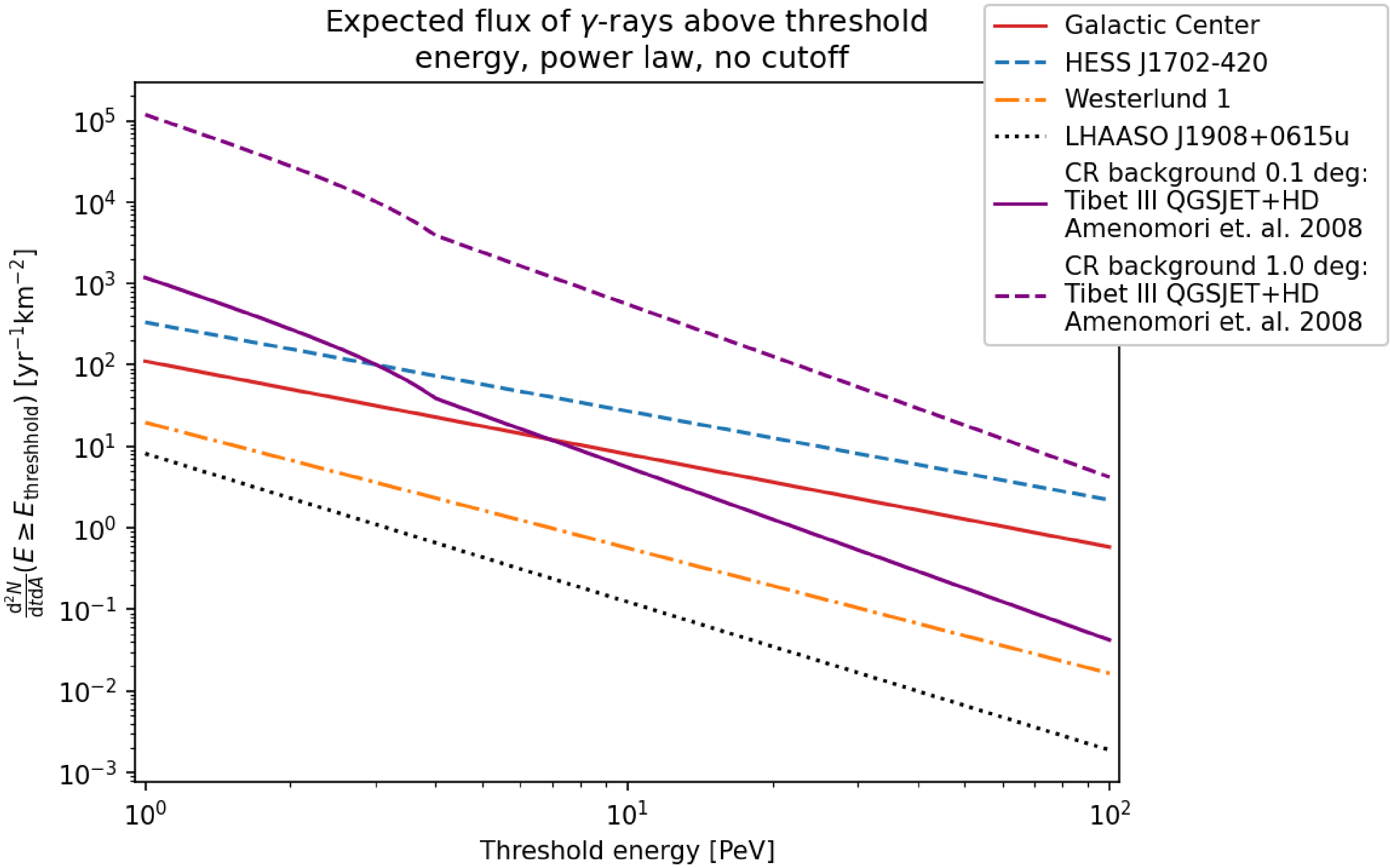
FOV and sources (selection)

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



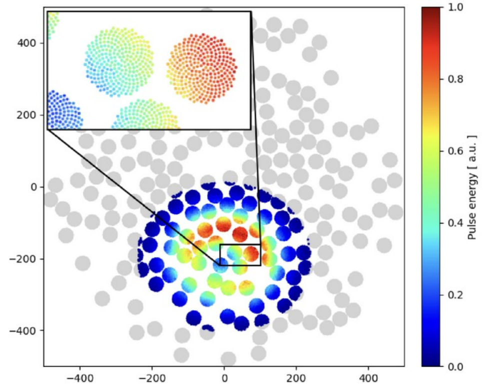
Project 2: Gamma ray detection

Flux estimation

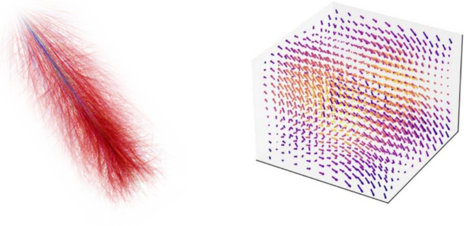


Summary

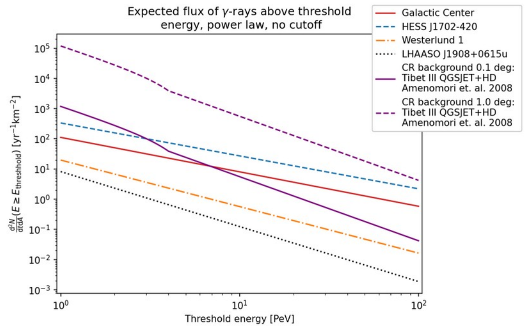
- **SKA** currently under construction!
  - High antenna density
  - Extreme precision measurements



- **4D** air shower reconstruction   ***(WIP)***
  - Multiple possible approaches (model-agnostic, model-dependent, ANN)
  - Time-resolved imaging using IFT
  - More insights into air shower physics expected



- Radio detection of **PeV gamma rays** with SKA   ***(WIP)***
  - Several challenges: Trigger, CR background, low flux at ultra-high energies
  - Flux estimations promising!



Backup

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

Amplifier, antenna, atmosphere, ... | (Ideally physical) parameterization | Galaxy, electronics, ...

Data = System response x Signal + Noise

Distribution of parameters?
(prior assumptions)