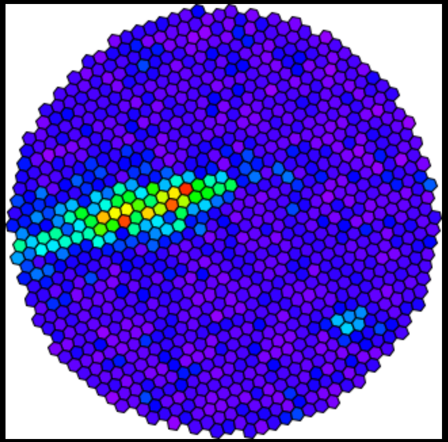
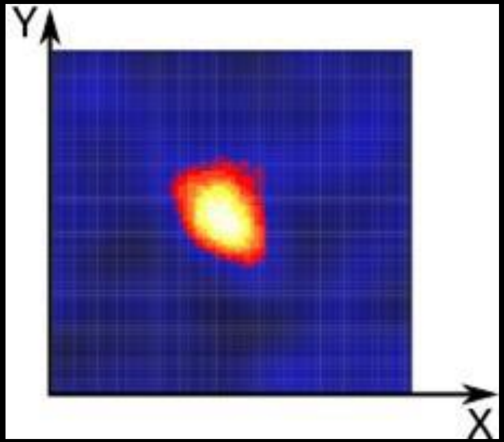
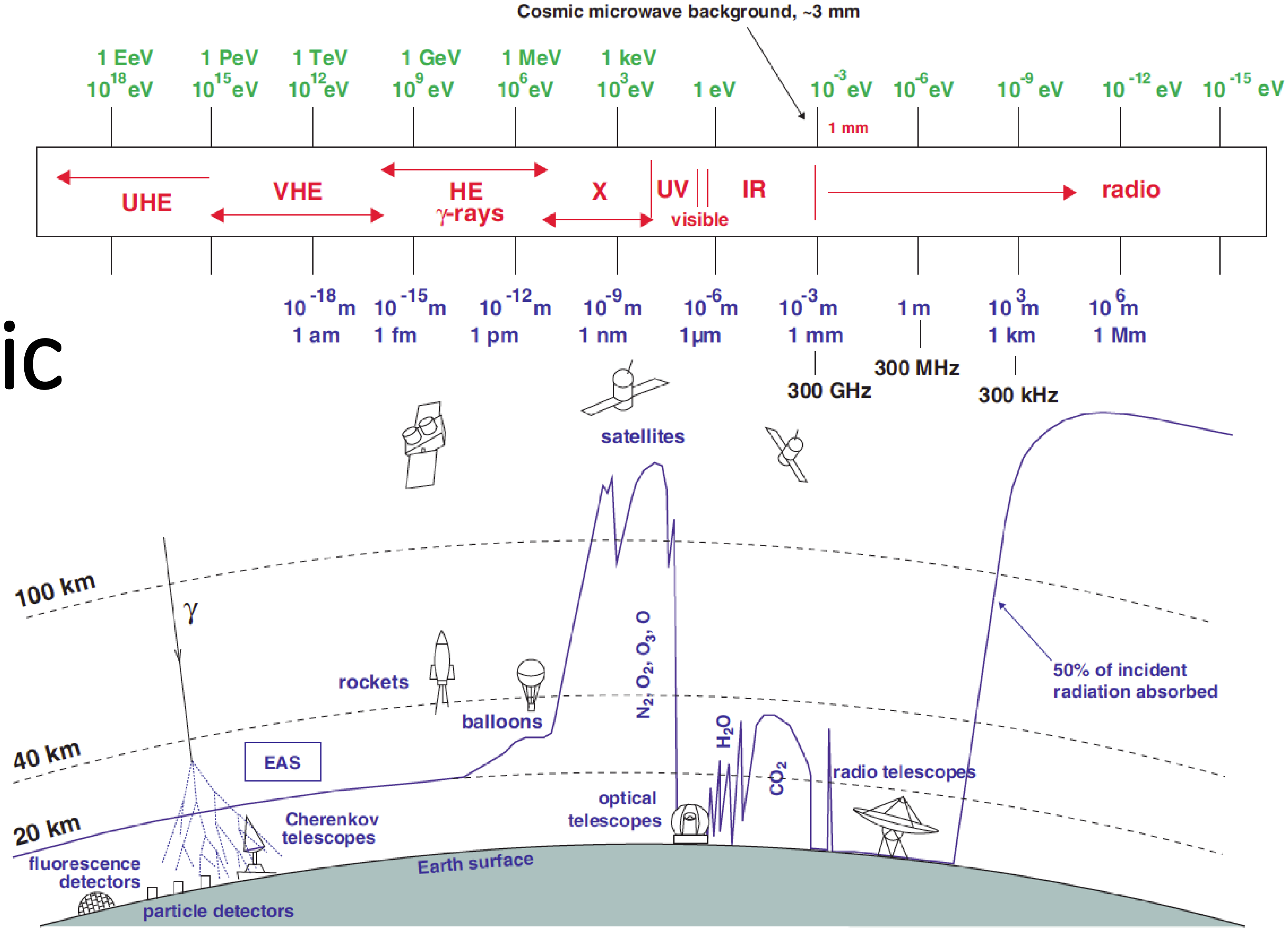
Analysis of VHE gamma-ray data from Imaging Atmospheric Cherenkov Telescopes (IACTs)

VHE hands-on session 2025



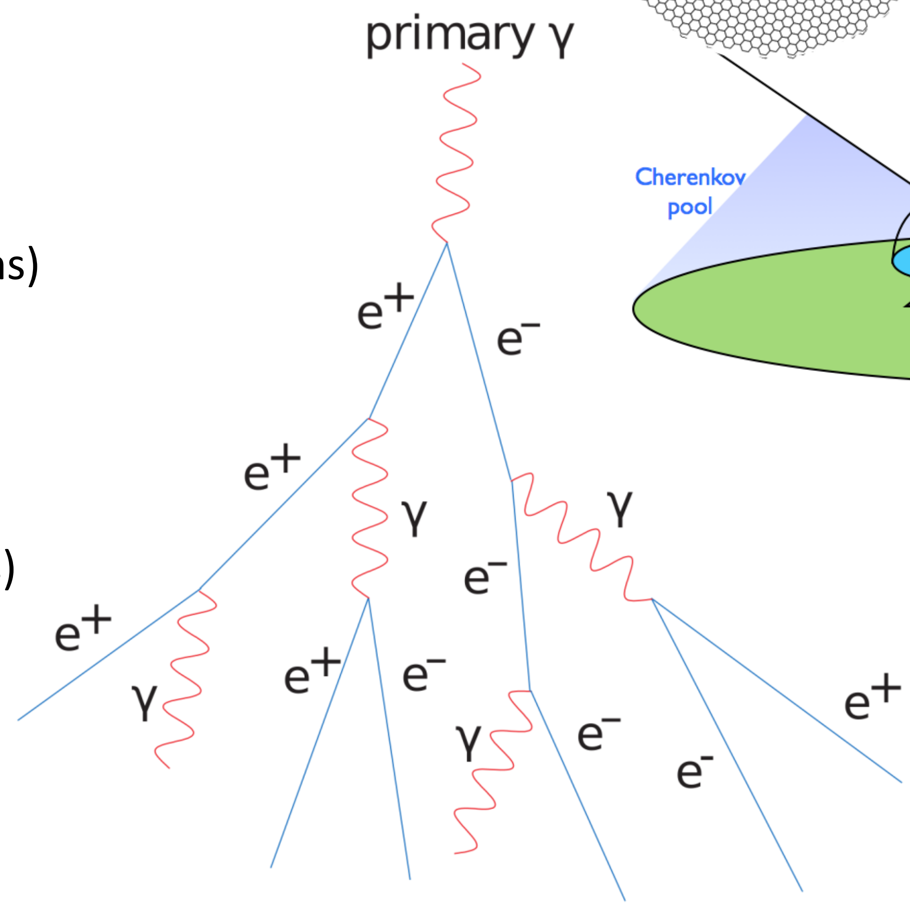


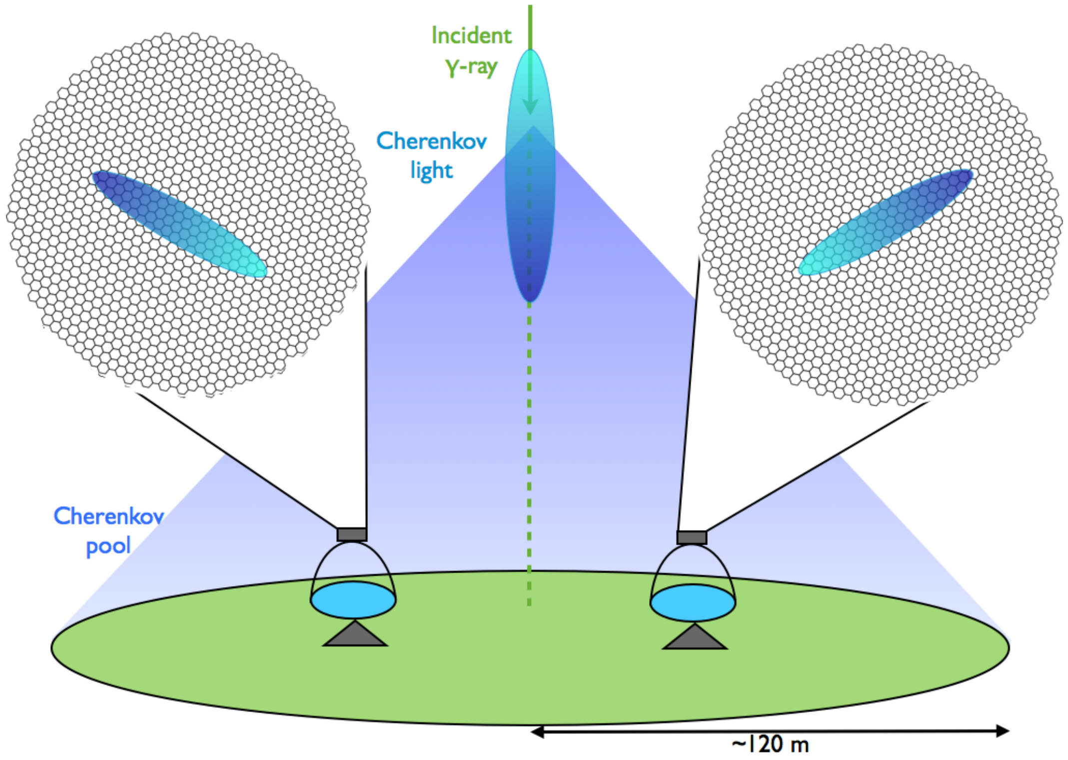
Atmospheric Shielding

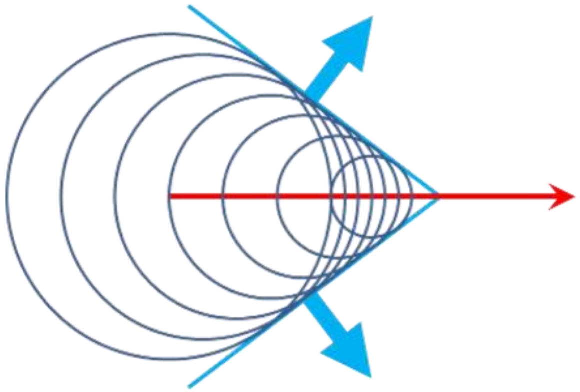


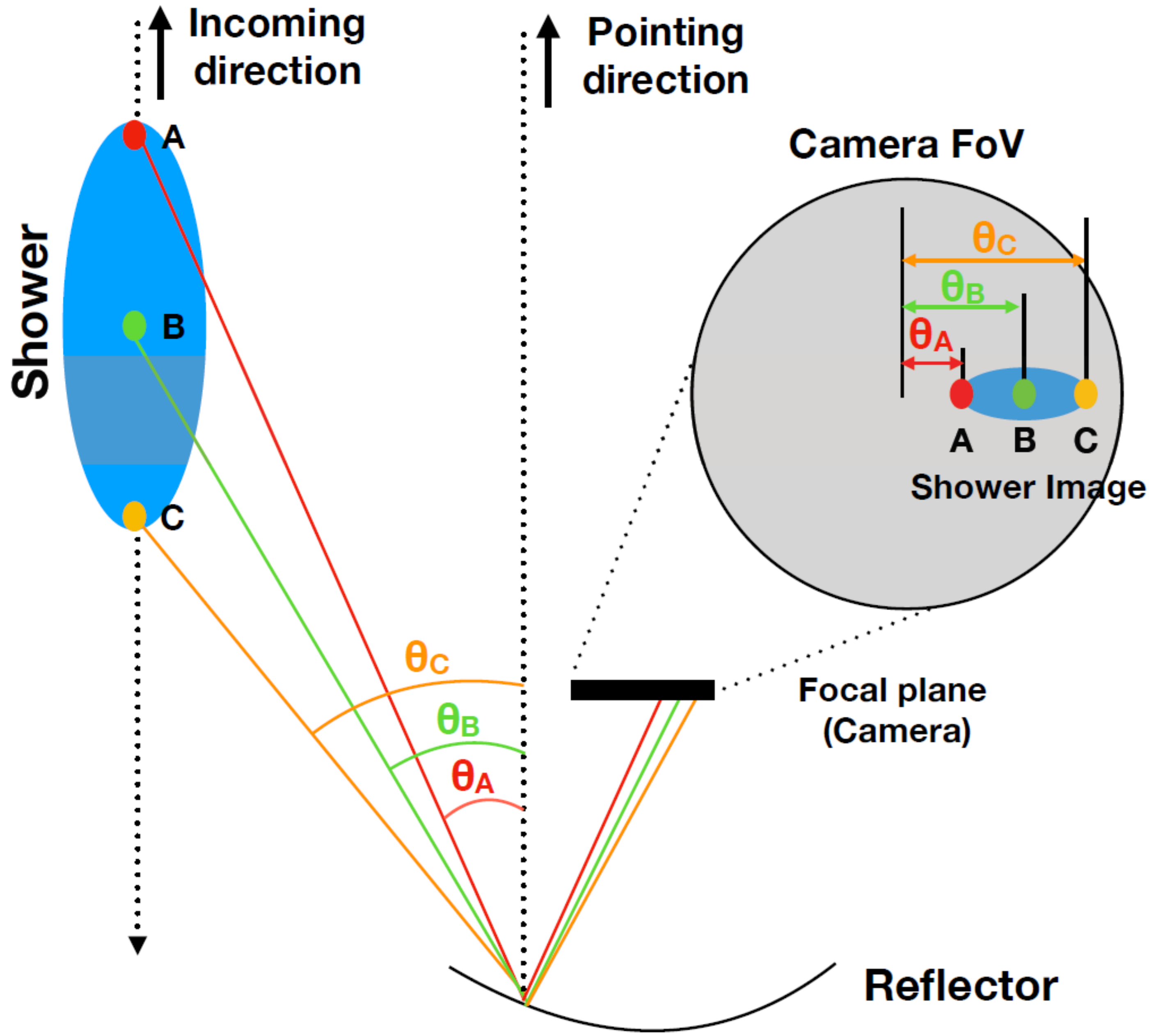
IACT technique

- Atmosphere as a **calorimeter**
- Gamma rays produce electromagnetic **particle showers** in the atmosphere
- Indirect measurement by **Cherenkov light** flashes (≈ 2ns) from particles
- Problem is protons and other cosmic rays also produce particle showers and Cherenkov light in the atmosphere (hadronic events)
- 1 gamma-ray event in 1000 hadronic events for the brightest sources → for faint sources even worse

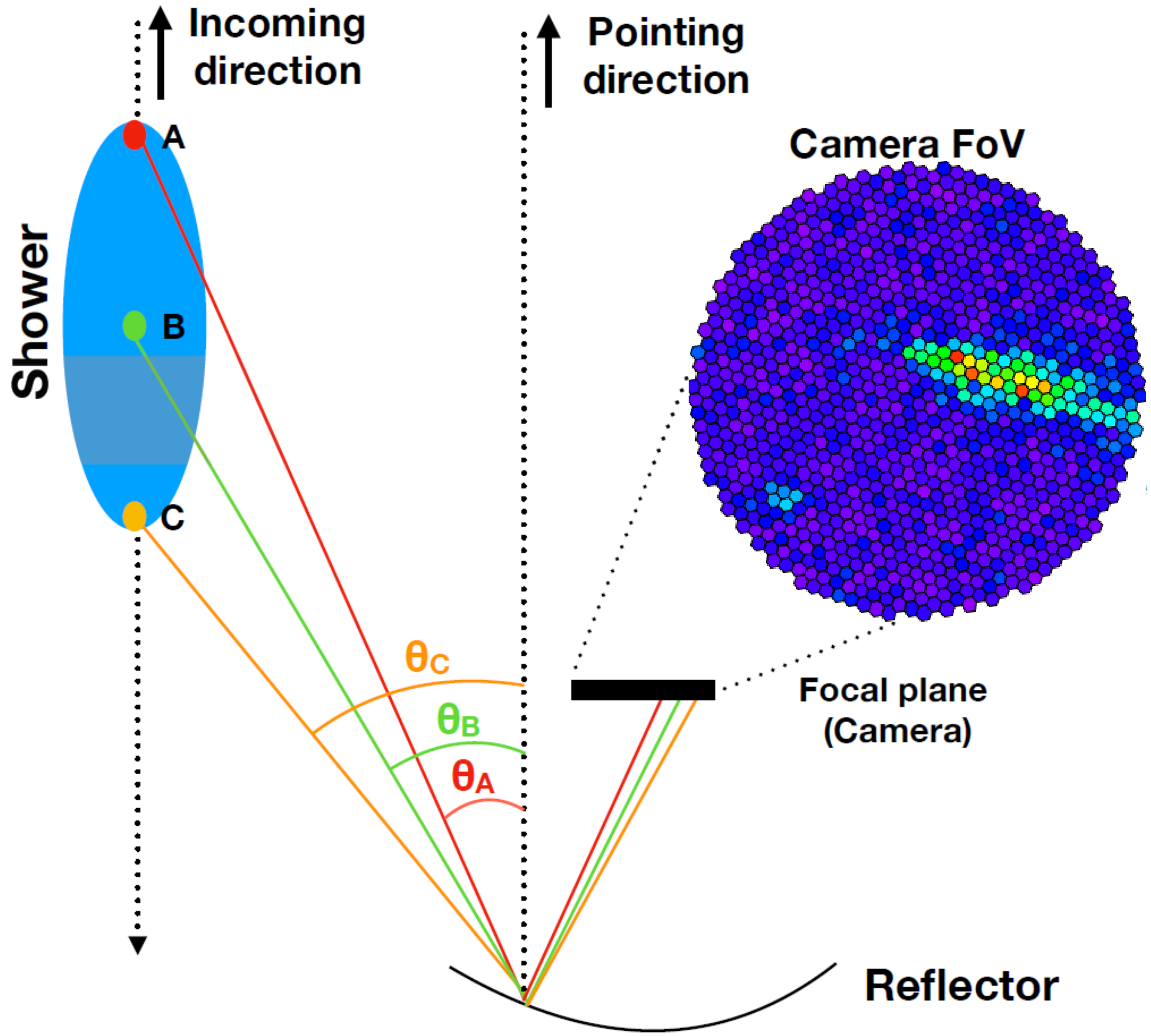








Incoming direction
Pointing direction
Camera FoV
Shower
A
B
C
θC
θB
θA
A B C
Shower Image
Focal plane (Camera)
Reflector


Incoming direction
Pointing direction
Camera FoV
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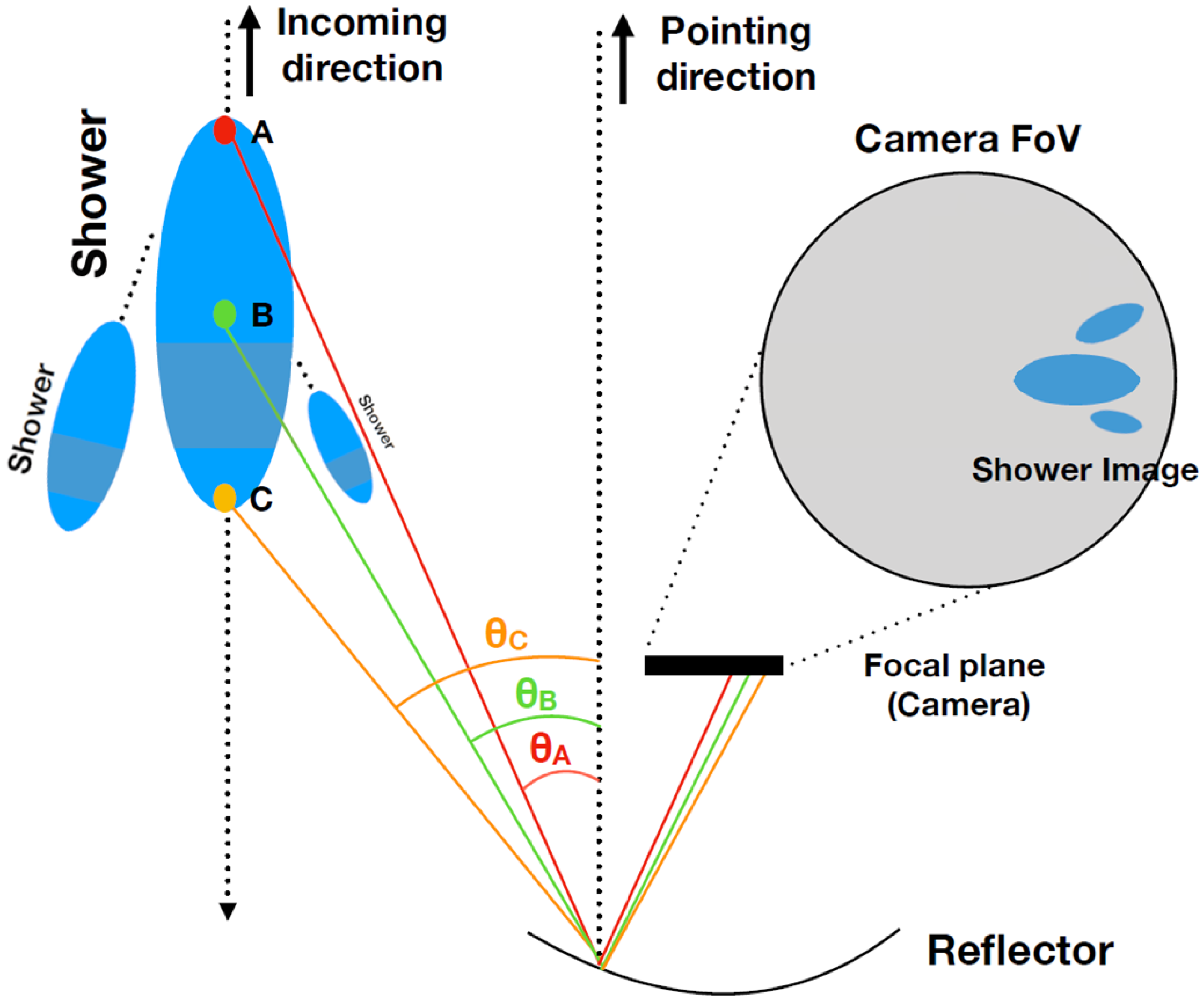
Focal plane (Camera)
Reflector


Incoming direction
Pointing direction
Camera FoV
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Shower Image
θ_C
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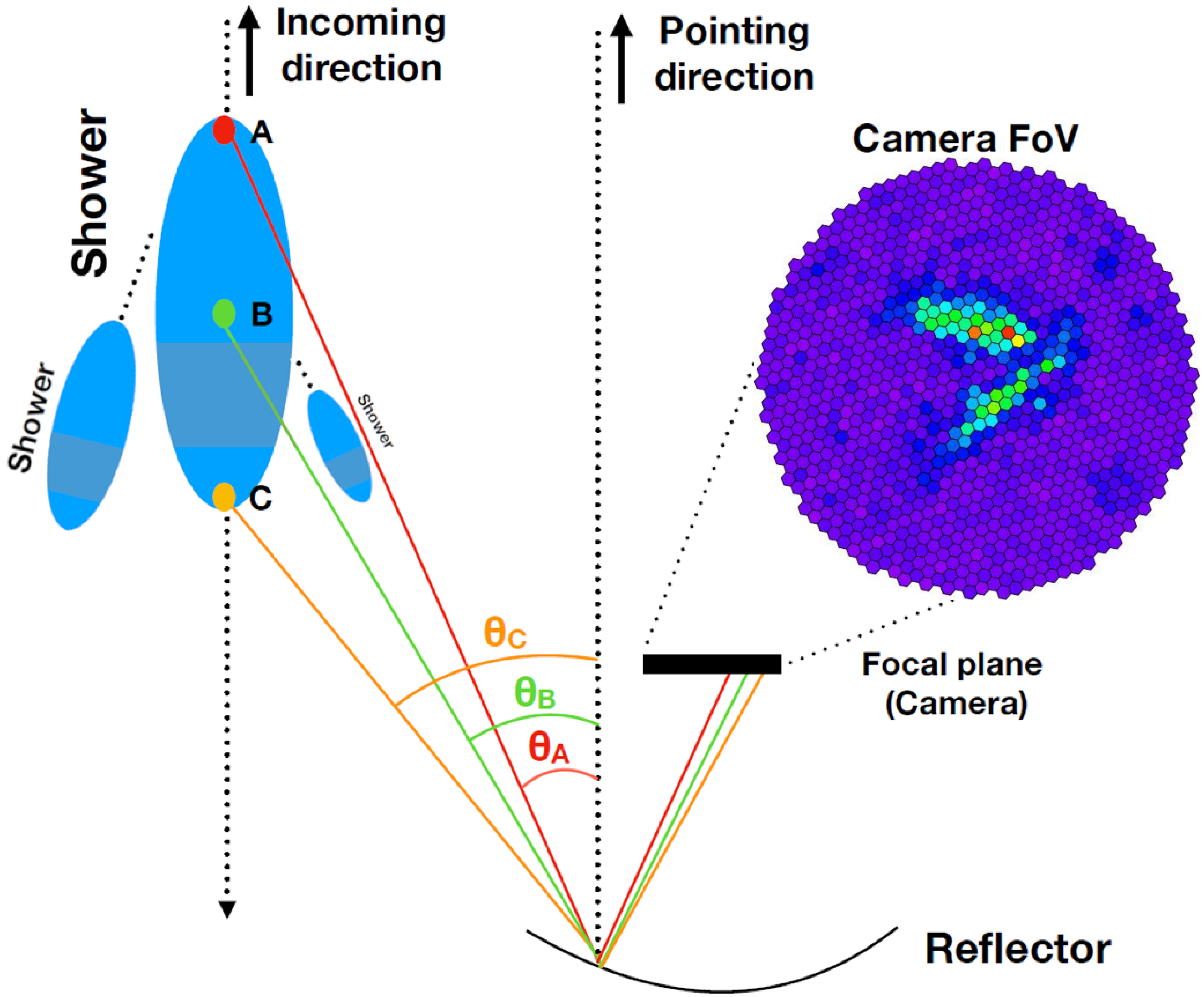
Focal plane (Camera)
Reflector


Incoming direction
Pointing direction
Camera FoV
Shower
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Focal plane (Camera)
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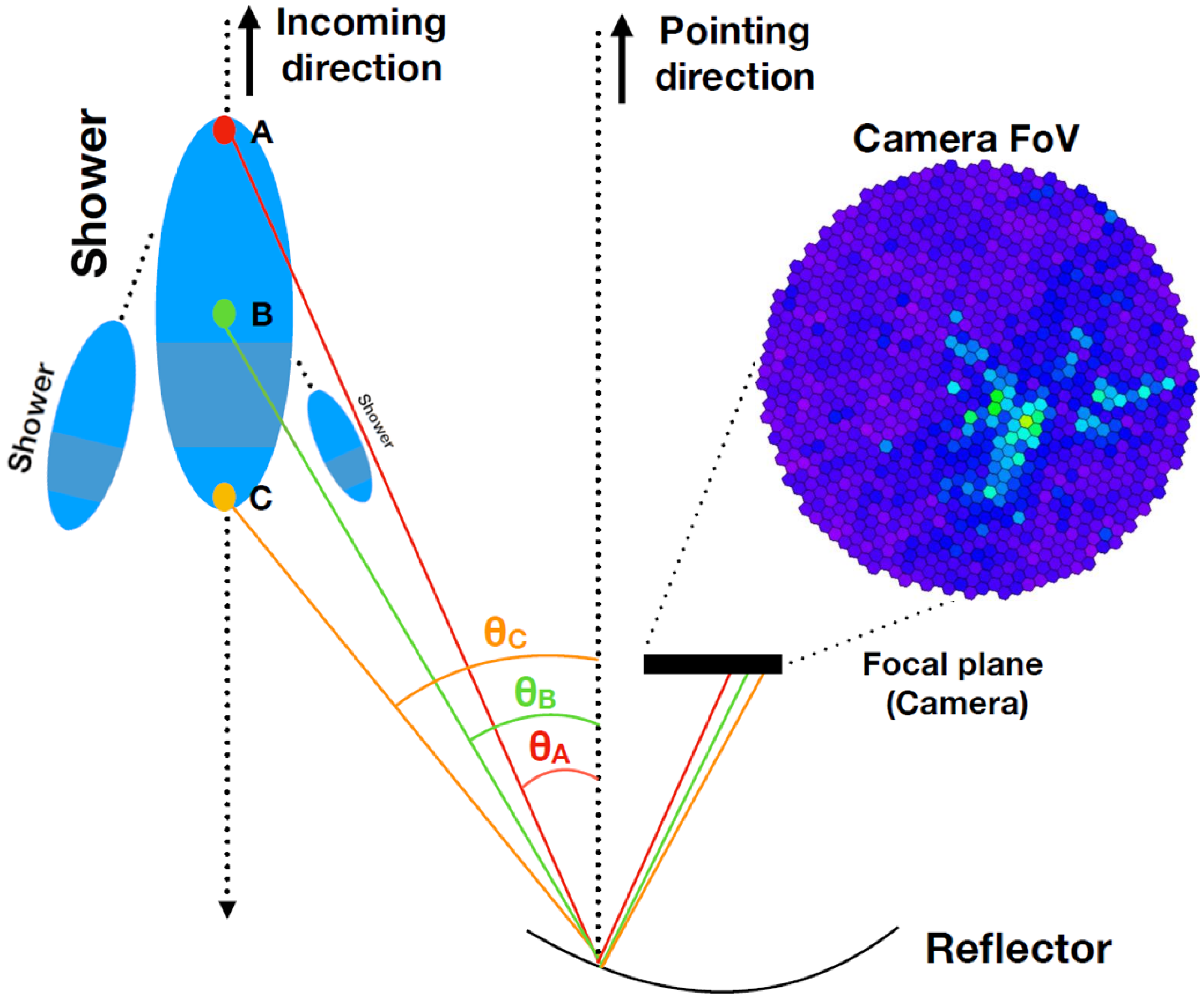

Incoming direction
Pointing direction
Shower
A
B
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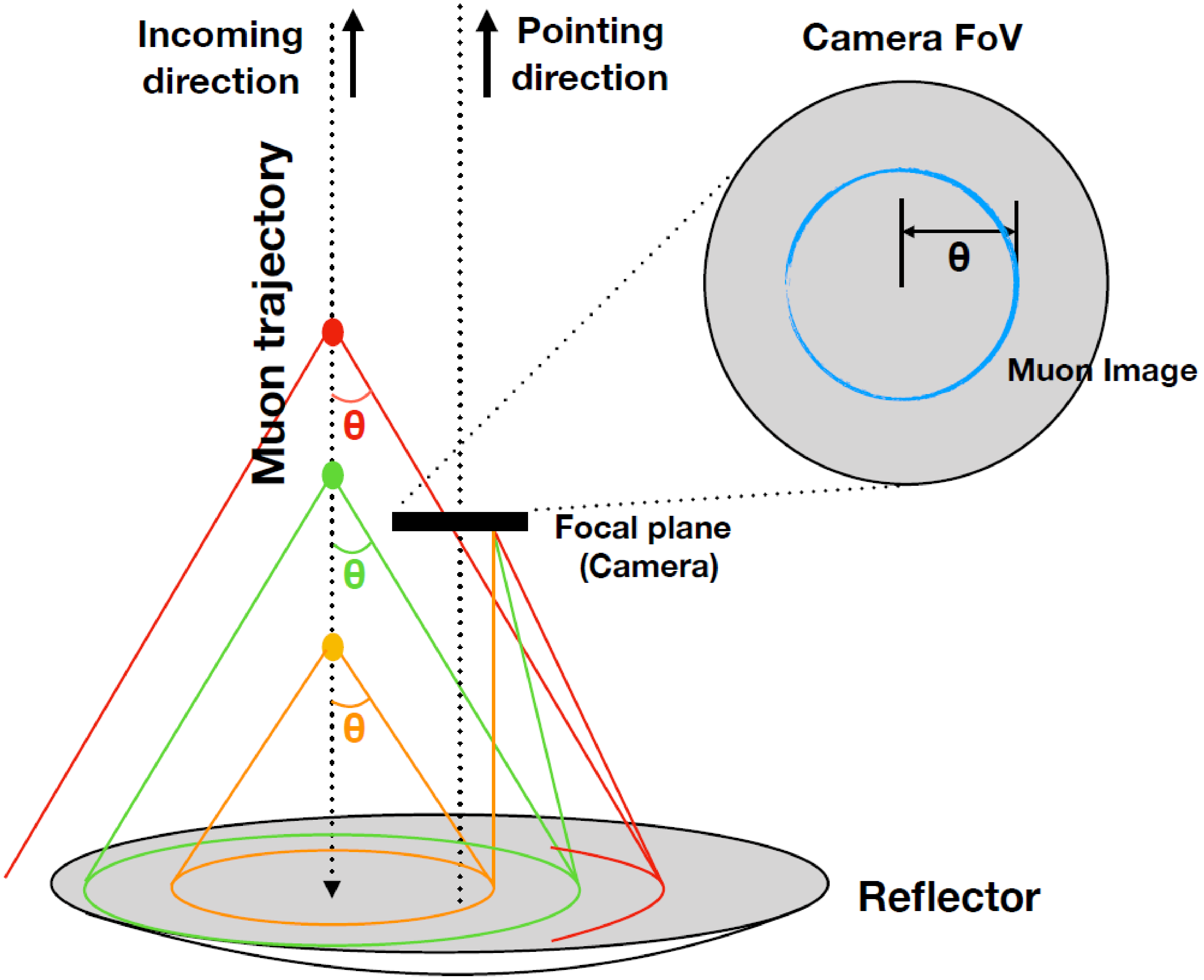
Shower
Shower
Camera FoV
θC
θB
θA
Focal plane (Camera)
Reflector


Incoming direction
Pointing direction
Camera FoV
Muon trajectory
θ
θ
θ
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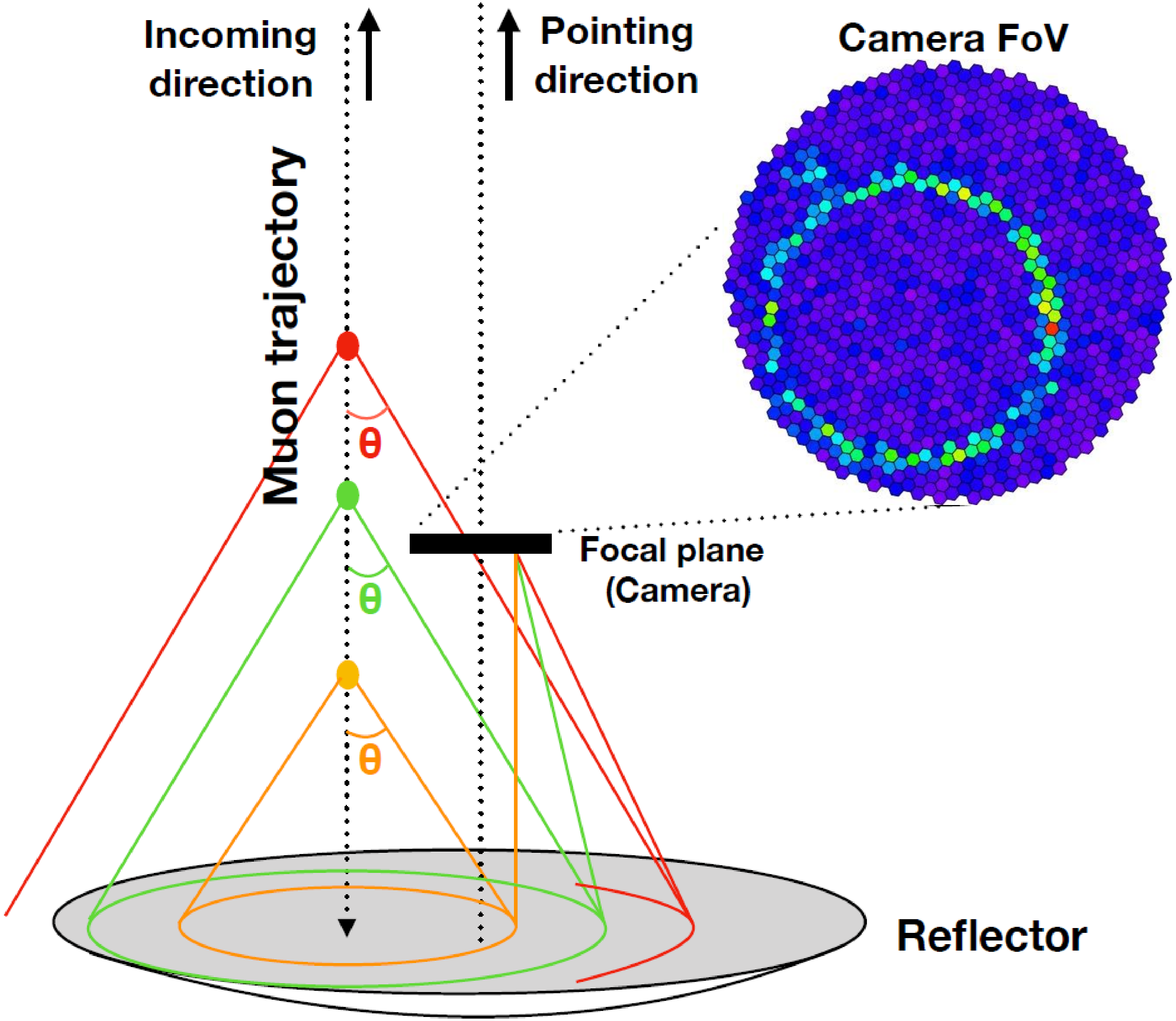
Muon Image
Focal plane (Camera)
Reflector


Incoming direction
Pointing direction
Camera FoV
Muon trajectory
θ
θ
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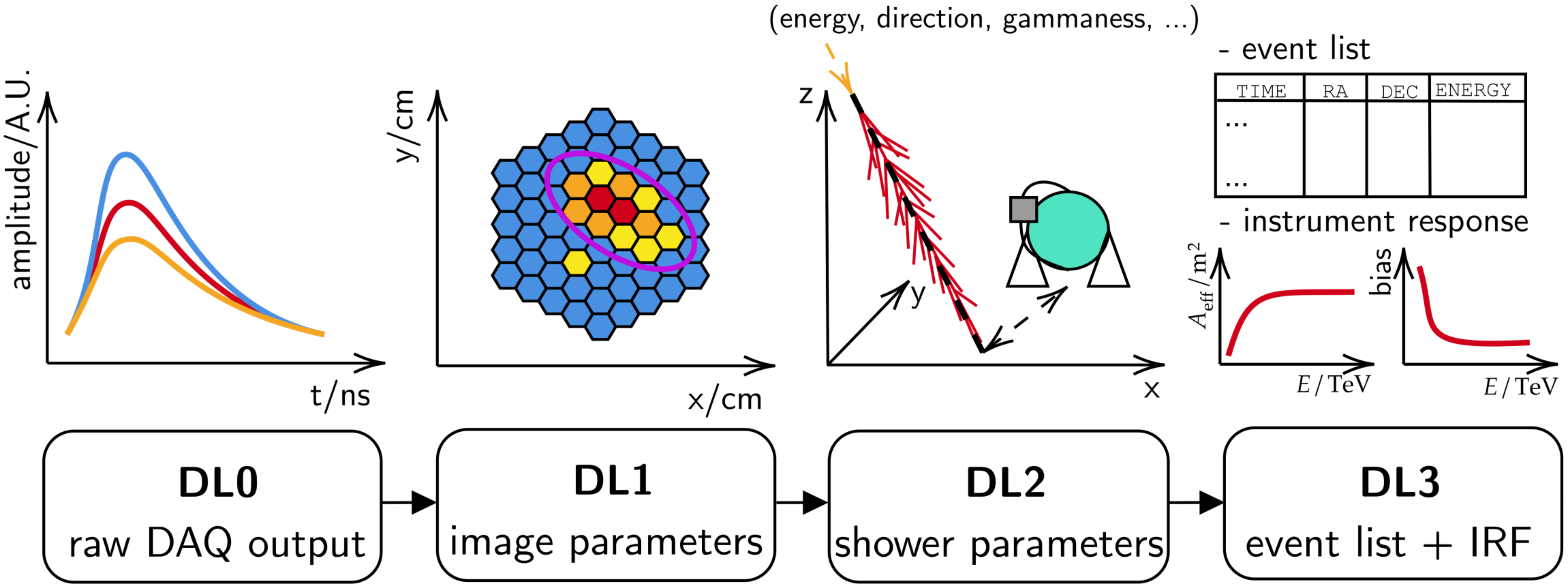
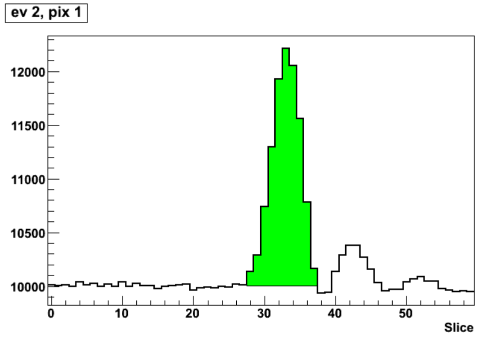
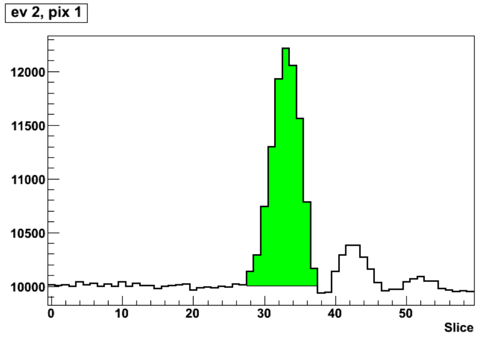
Focal plane (Camera)
Reflector

Data analysis – Low Level

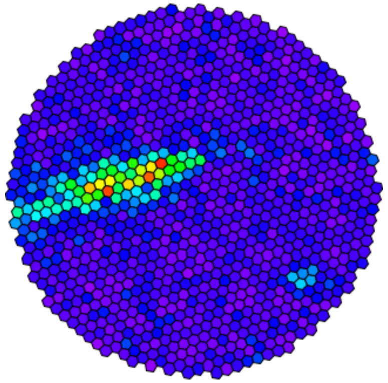


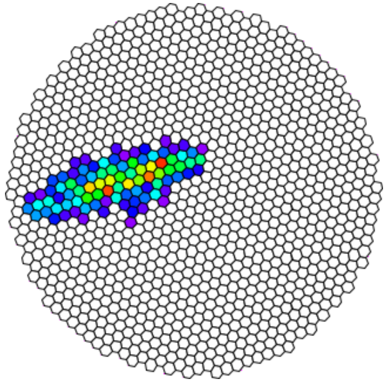
Calibration and Image Cleaning

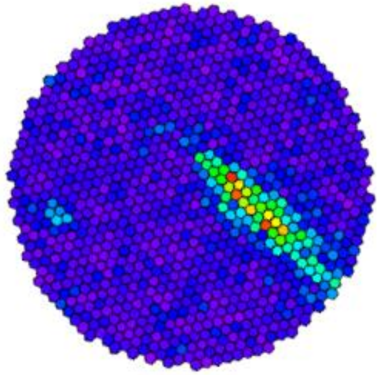


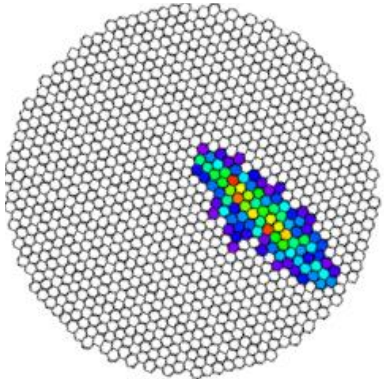


- Extraction of charge and arrival time from raw data (signal pulses) for each PMT of MAGIC 1 and 2
- Image cleaning (select only pixels triggered by the shower, not by noise)

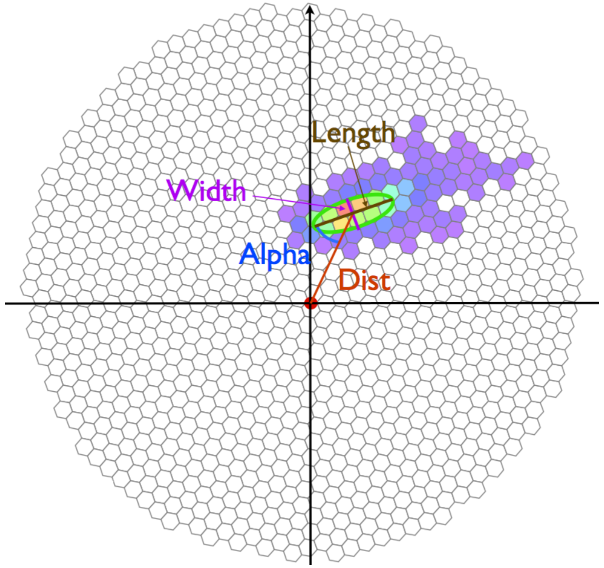




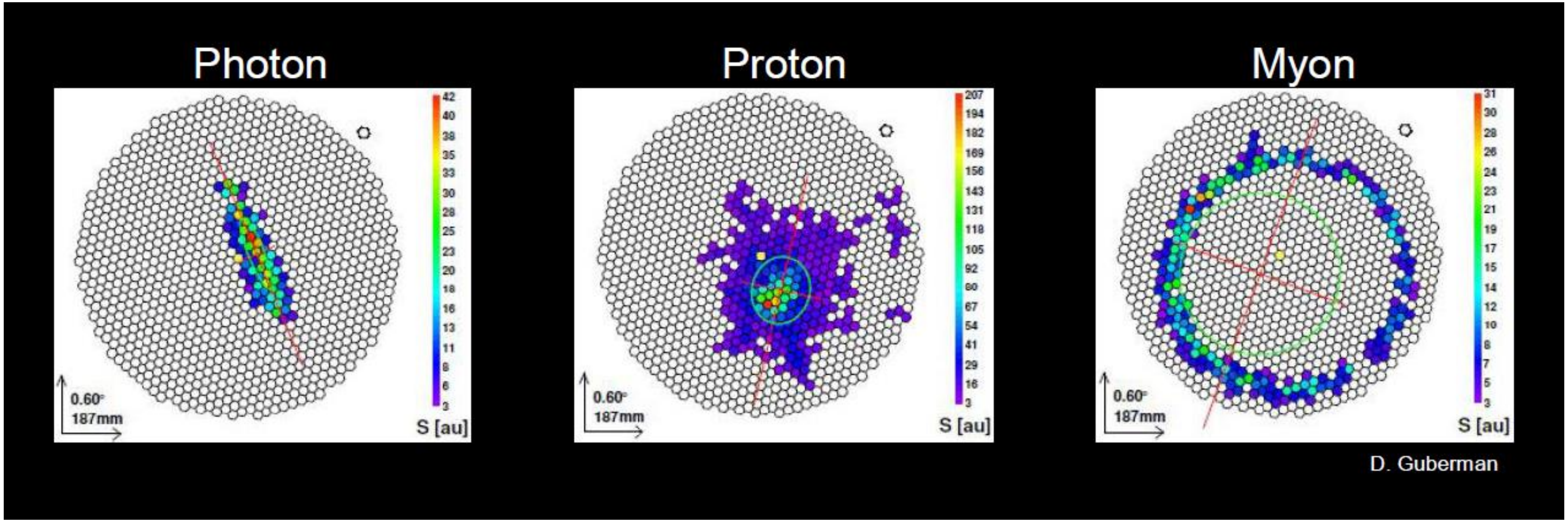




Stereo Reconstruction

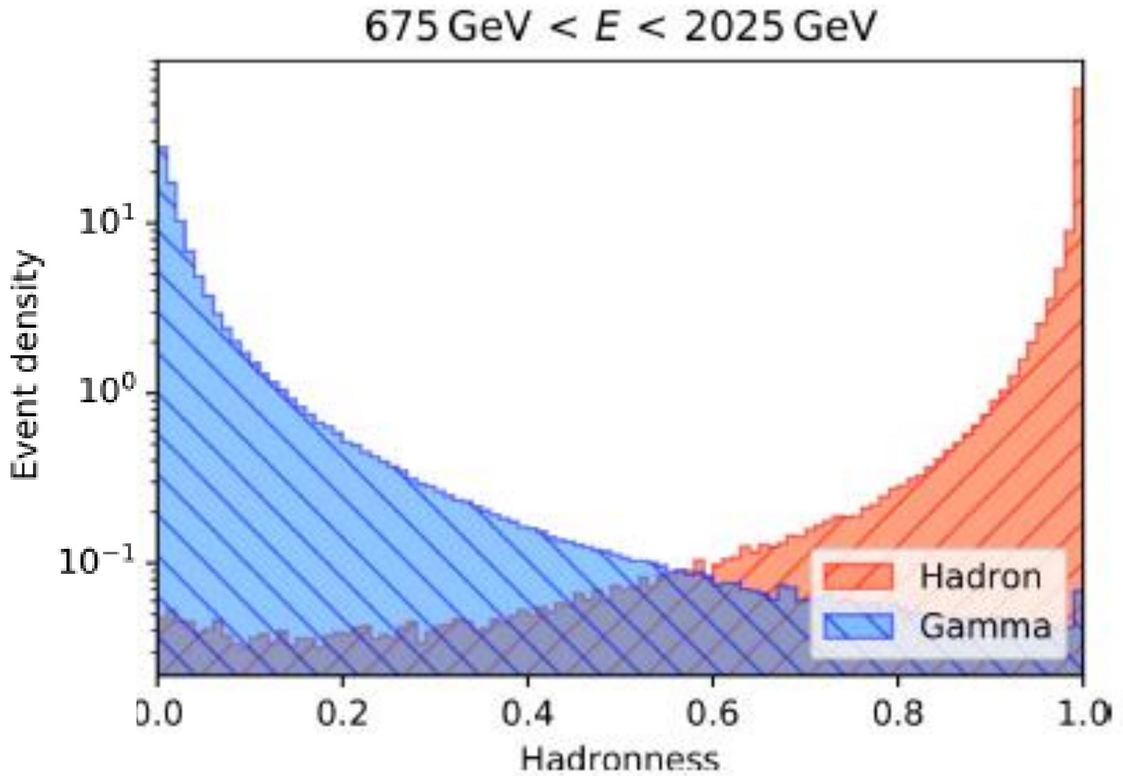


- Reconstruction of stereo parameters for each event (Hillas parameters) using the information from multiple telescopes if applicable



The Hadronic Background

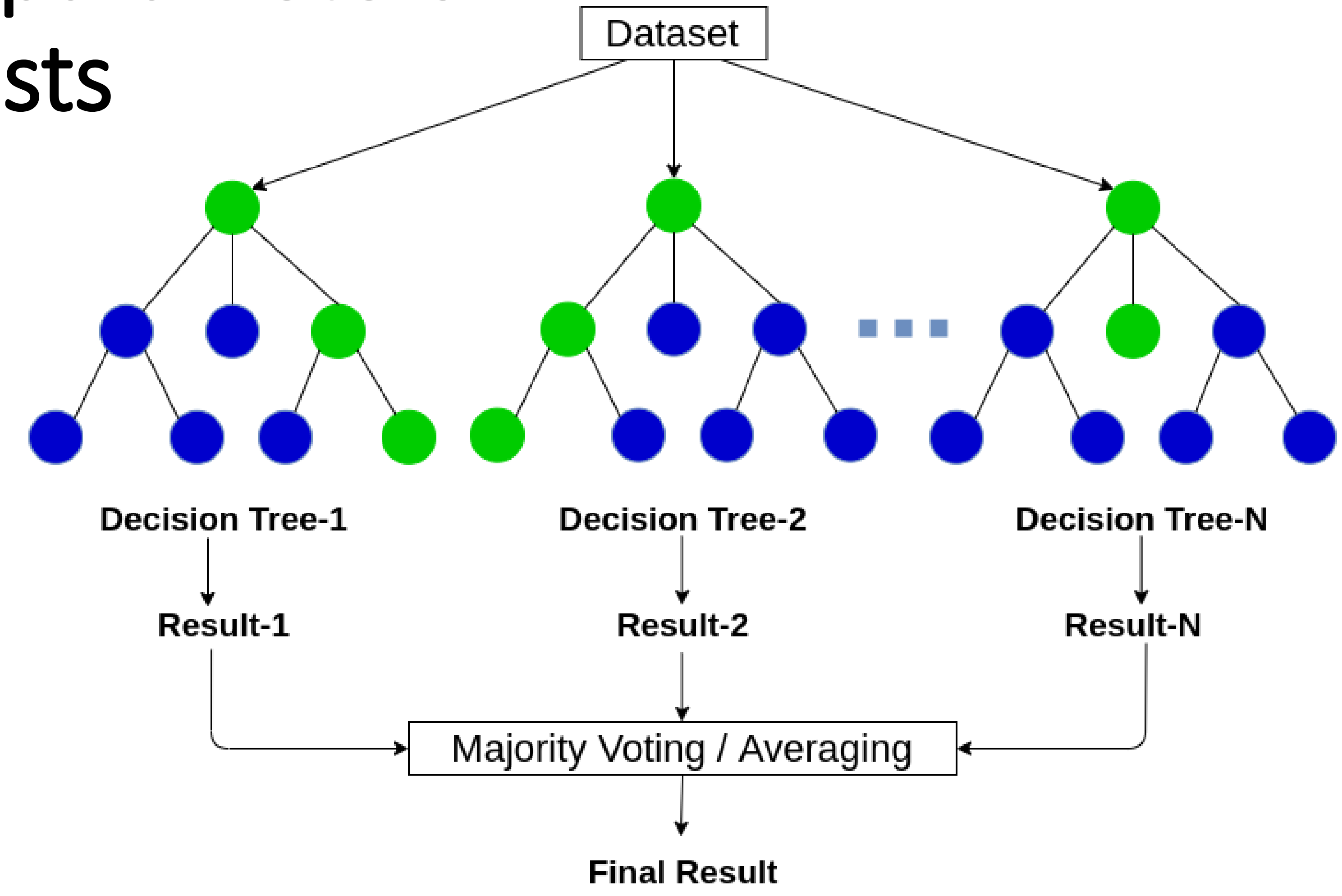
- Analysis removes most of hadronic showers estimating a parameter called hadronness and then introducing a cut in the events based on that parameter
- Hadronness parameter = probability for a shower to be produced by a hadronic particle
- Cut will never remove all hadronic events → Remaining background in final event selection has to be estimated to correctly measure the flux of a source



Ceribella, G.: *Insights into the 10-100 GeV gamma-ray emission of pulsars from extensive observations of MAGIC.* PhD thesis (2021). Technical University Munich.

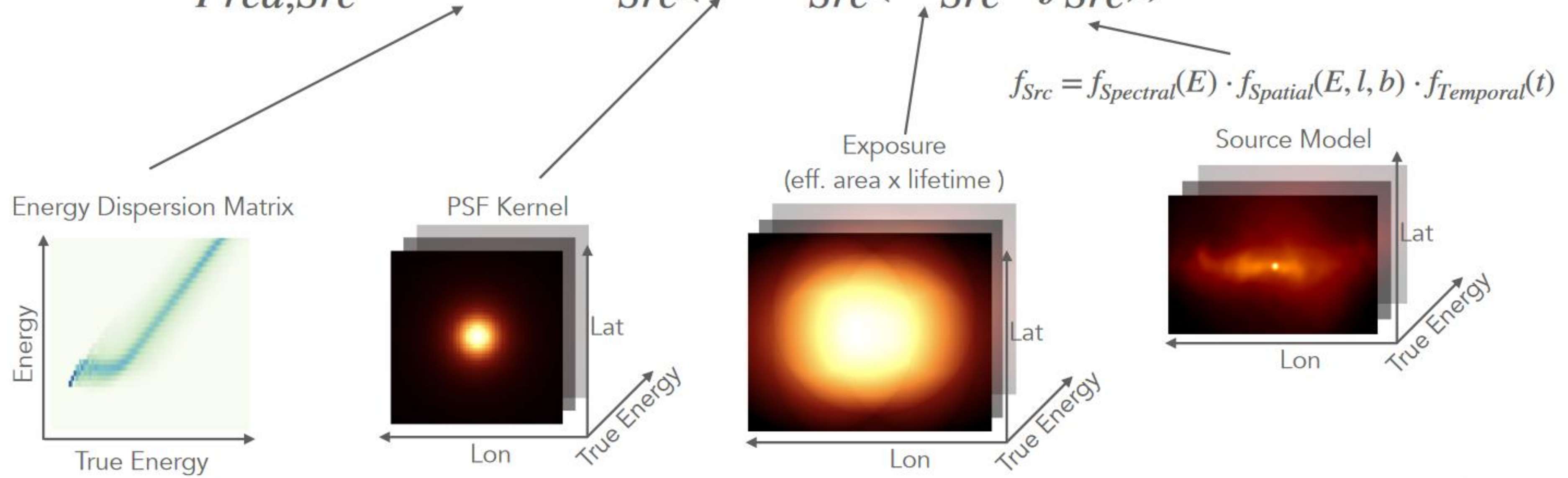
Reconstruction of parameters with Random Forests

- Produce Random Forest (RF) Decision trees using real OFF data and gamma-ray MC simulations for the training
- Certain reconstructed (Hillas) parameters such as the *size* are used to train the RF
- Estimate the properties of the progenitor
  - Particle type: Gamma ray or hadron?
  - Energy
  - Direction

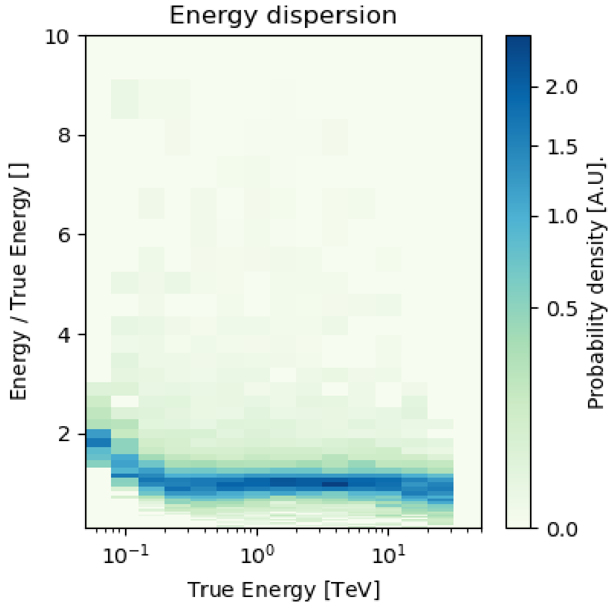


Instrument Response Functions (IRFs)

$$N_{Pred,Src} = \mathrm{EDISP}_{Src}(\mathrm{PSF}_{Src}(\mathscr{E}_{Src} \cdot f_{Src}))$$

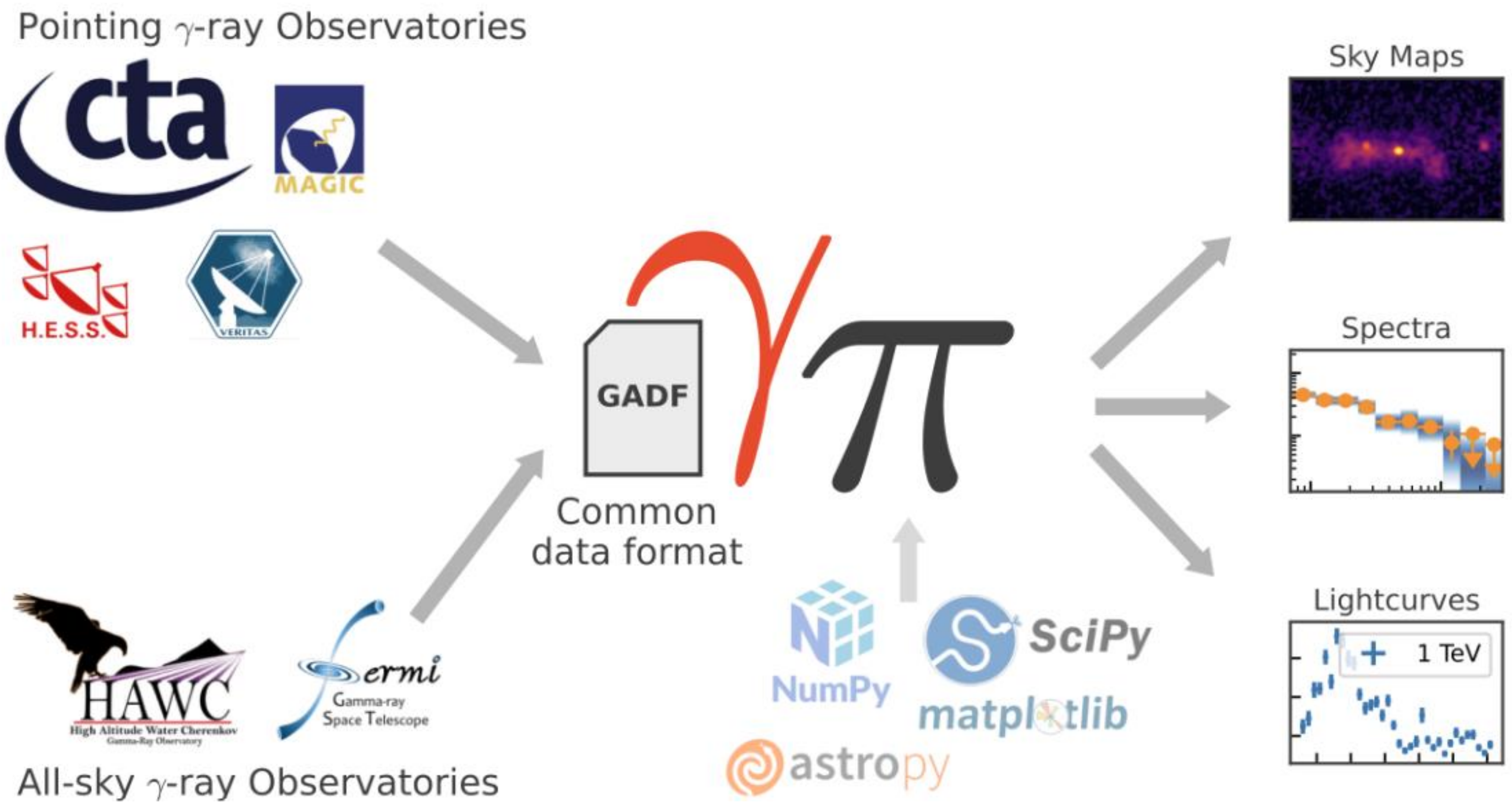


- IRF = probability functions describing the response of the observing system
- Tells us how estimated quantities relate to real ones (e.g. reconstructed vs true energy)
- Used to convert observables from “detector world” to “physical world” (e.g. counts into flux) or the other way around
- For an optical detector one IRF would be the Point-Spread-Function (PSF) of the system
- For IACTs there are three important IRFs: **Energy dispersion, effective area and PSF**

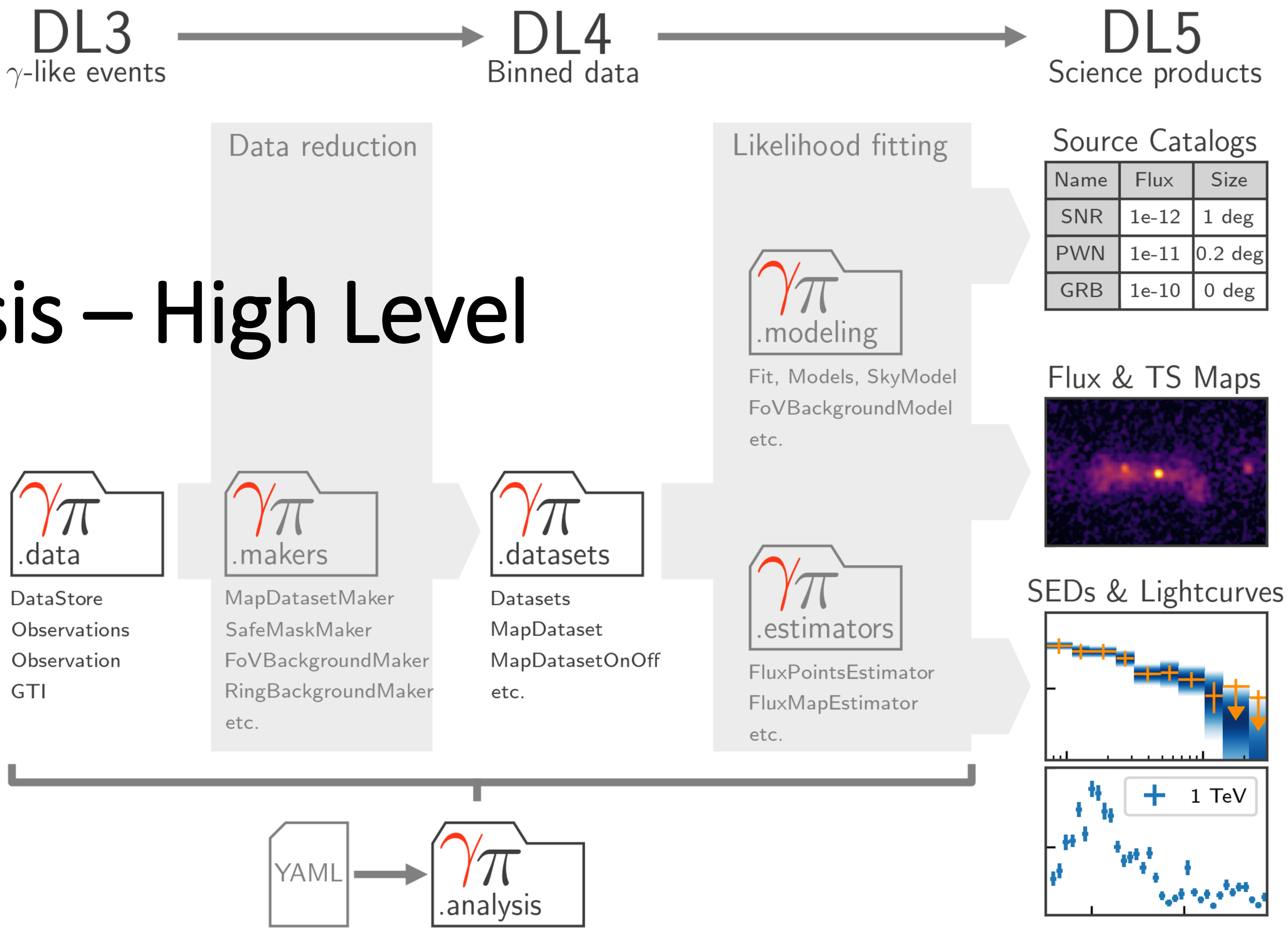


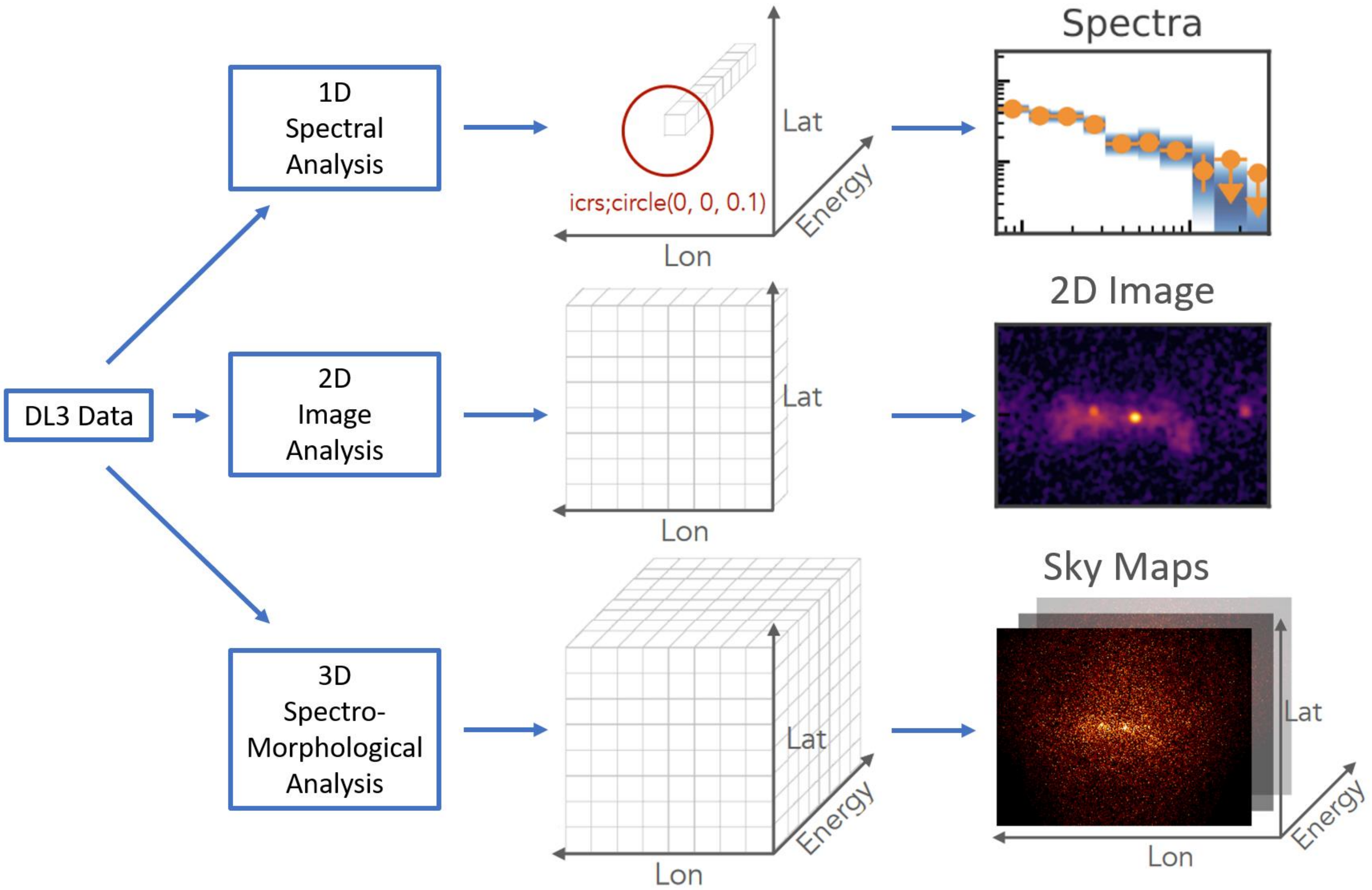
The open-source software *Gammapy*

- Open-source python package for high-level gamma-ray data analysis
- Based on common data formats (defined in the GADF: https://doi.org/10.3390/universe7100374) → supports data from different instruments (*Fermi*-LAT, IACTs, HAWC)
- Allows for combination of data from different facilities within the same pipeline
- Outputs high-level scientific results



Data analysis – High Level




DL3 Data
1D
Spectral
Analysis
2D
Image
Analysis
3D
Spectro-
Morphological
Analysis
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Lat
Energy
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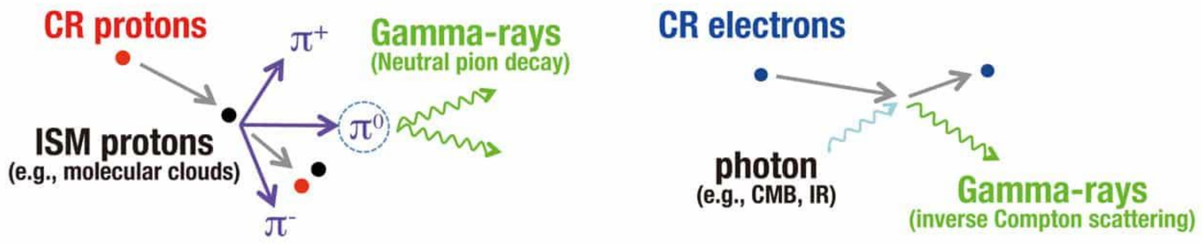
Lat
Lon
Lat
Energy
Lon
Spectra
2D Image
Sky Maps
Lat
Energy
Lon

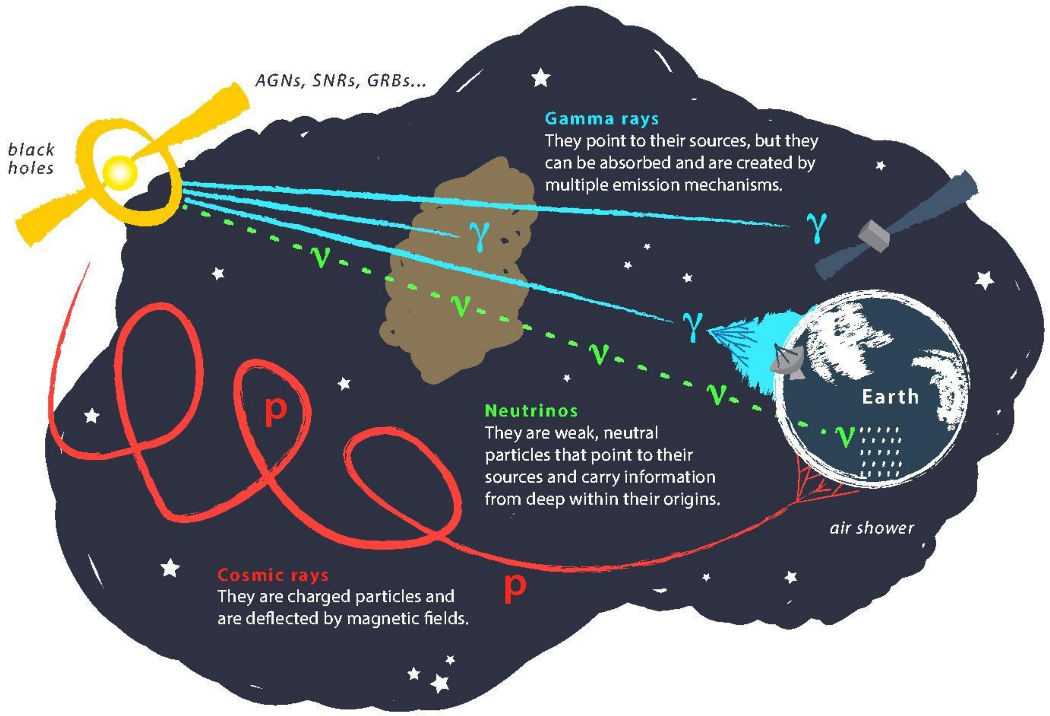
Any questions?

→ Hands-on

Let's set up the software for the analysis and start playing with the data!

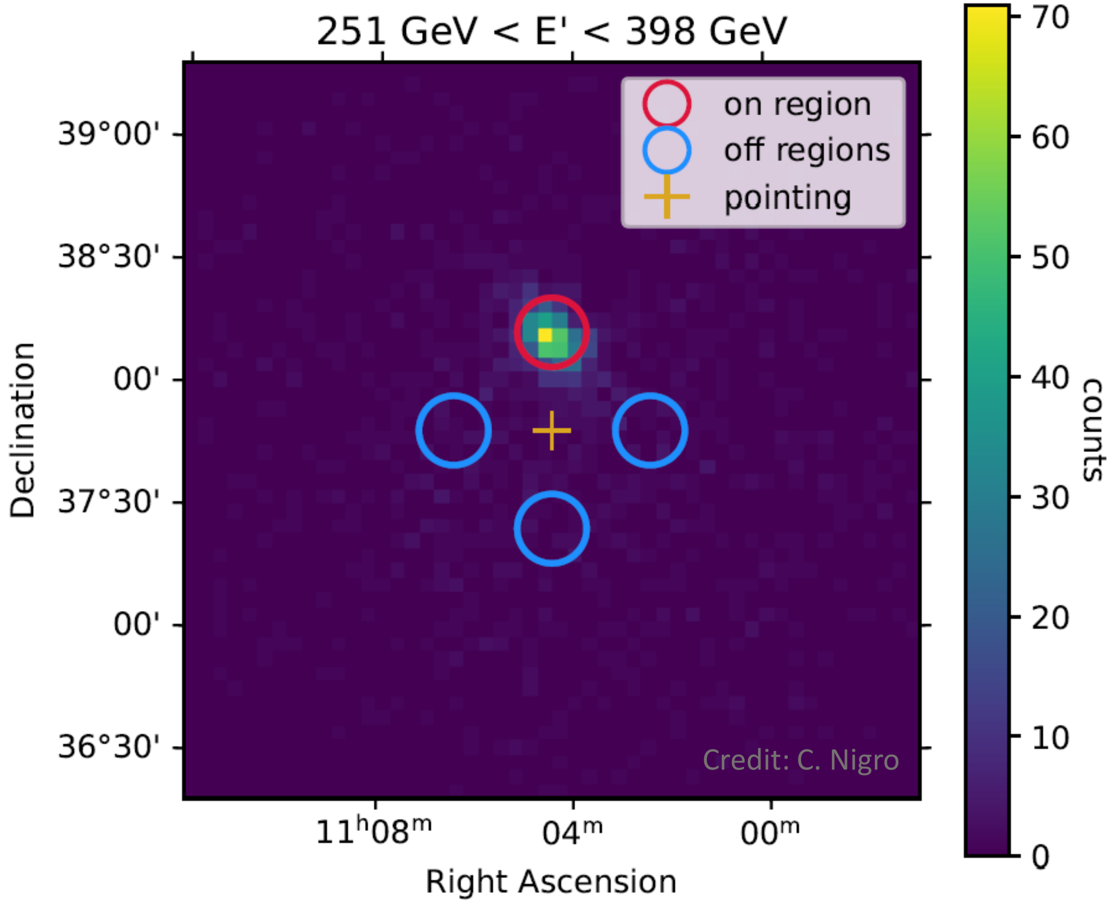
Cosmic Rays





- Dicovery of Cosmic Rays (CRs) with extraterrestial origin by Victor Hess in 1912
- **Production sites of high-energy CRs** are a major unsolved question since then
- Deviation of charged CRs on the way to earth => do not point back to source
- Other neutral messengers like gamma-rays can help to solve this mystery because accelerators of PeV CRs could also produce gamma-rays around hundreds of TeV in the process or by further interaction

Wobble observations



- Pointing position slightly shifted w.r.t. source position
- Change between several pointing positions while observing
- Use half of the camera without source for background estimation (no dedicated OFF data needed)

Instrument Response Functions

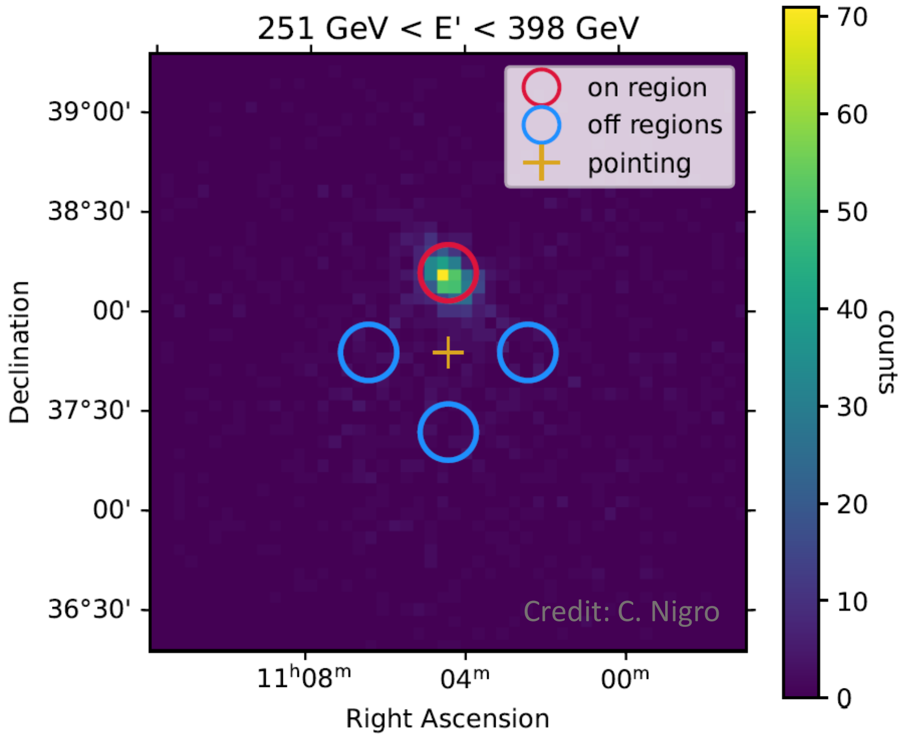
Energy dispersion: Mathematical relation between true and estimated (E_t and E) energy $E_{disp}\ (E \mid p_t, E_t)$, represented by the Probability Distribution Function (PDF) of the estimated energy. It also depends on the true direction of the primary γ-ray p_t.

PSF: Describes the spatial distribution function $\mathrm{PSF}\ (p \mid p_t, E_t)$ of the estimated event coordinates of photons from a point source, as seen through the telescope, where p is the reconstructed direction of the incoming γ-ray.

Effective area: Is embodied by the effective collection area of the telescopes $A_{MC,total}$, corrected with an energy-dependent efficiency originating from energy-dependent analysis cuts as

$$A_{eff}\ (p_t, E_t) = \frac{N_{MC,final}\ (p_t, E_t)}{N_{MC,total}\ (p_t, E_t)} A_{MC,total}$$

where $N_{MC,final}\ (p_t, E_t)$ and $N_{MC,total}\ (p_t, E_t)$ are the numbers of events, which survived the analysis cuts and which were simulated in total, respectively.



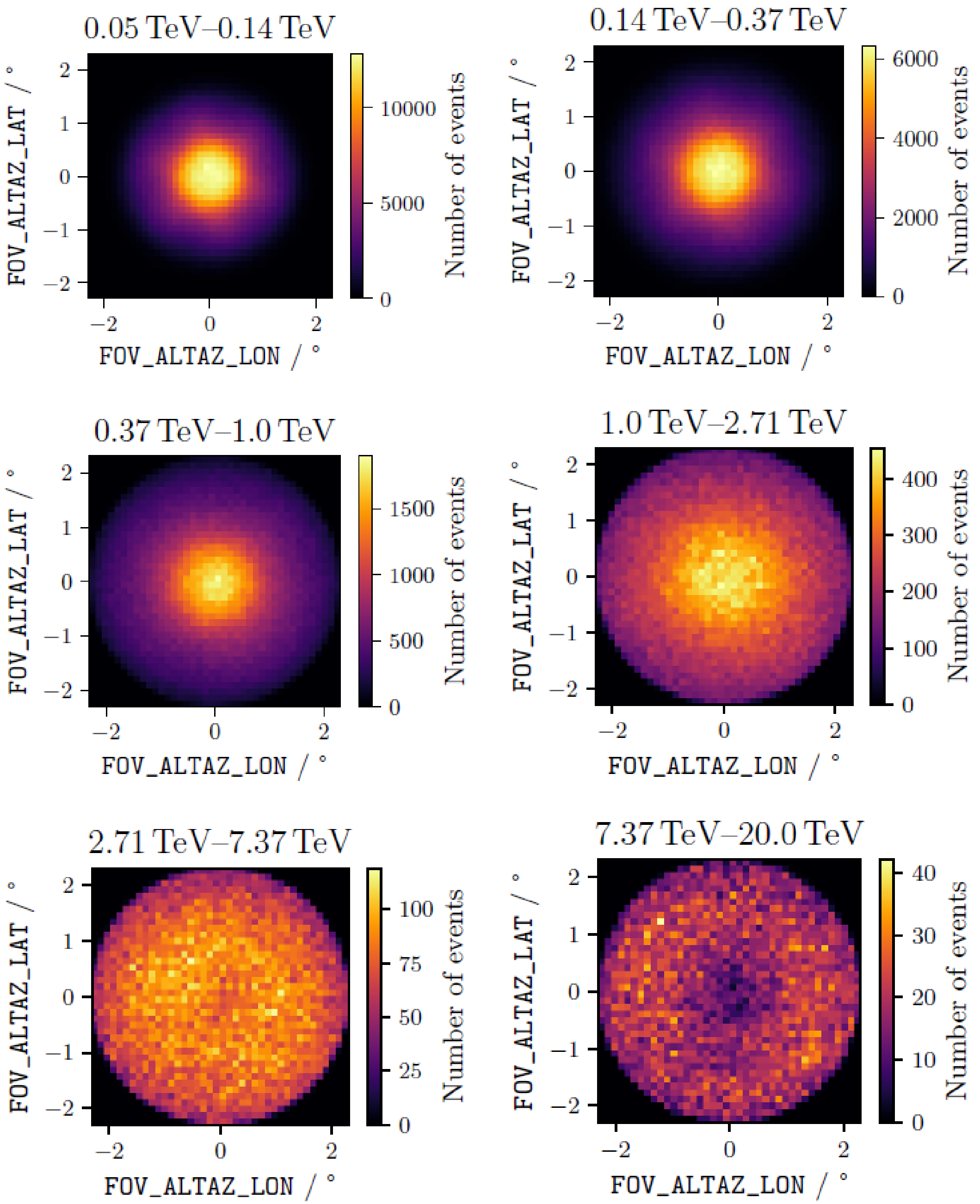
3-dimensional or spectro-morphological analyses

1D analysis

- Applicable on a single point-like source using ON and OFF regions (eliminates any spatial dependency)
- Data binned in **energy**
- Background estimated from OFF
- Try to reproduce counts vs. energy with model

3D analysis

- Accounts for the position and morphology of different sources in the FoV
- Data is binned in a data cube of 3 dimensions: **Two sky coordinates** and the **energy** of the events (Ra, Dec, Energy)
- Requires estimate of the gamma-ray **background over the whole FoV**
- Try to reproduce the counts from the whole data cube, taking into account the background model and also the PSF, because you want to know how your source looks like "looking through the telescopes"



Dependencies of shape and rate of the background

- Energy
- Zenith and azimuth coordinates of the observation
- Observational conditions (e.g. Night Sky Background)
- Instrumental performance → Different backgrounds for different periods
- Geomagnetic field (not stable over time, but effect small for hadronic showers)

Background 2D histograms of the DL3 events from off data in six logarithmic bins of the reconstructed energy from 0.05 TeV to 20 TeV.
From: Mender, S.: *Spectral and Spatial Analysis of MAGIC Telescope Data in a Standardized Format.* PhD thesis (2023). Technical University Dortmund.