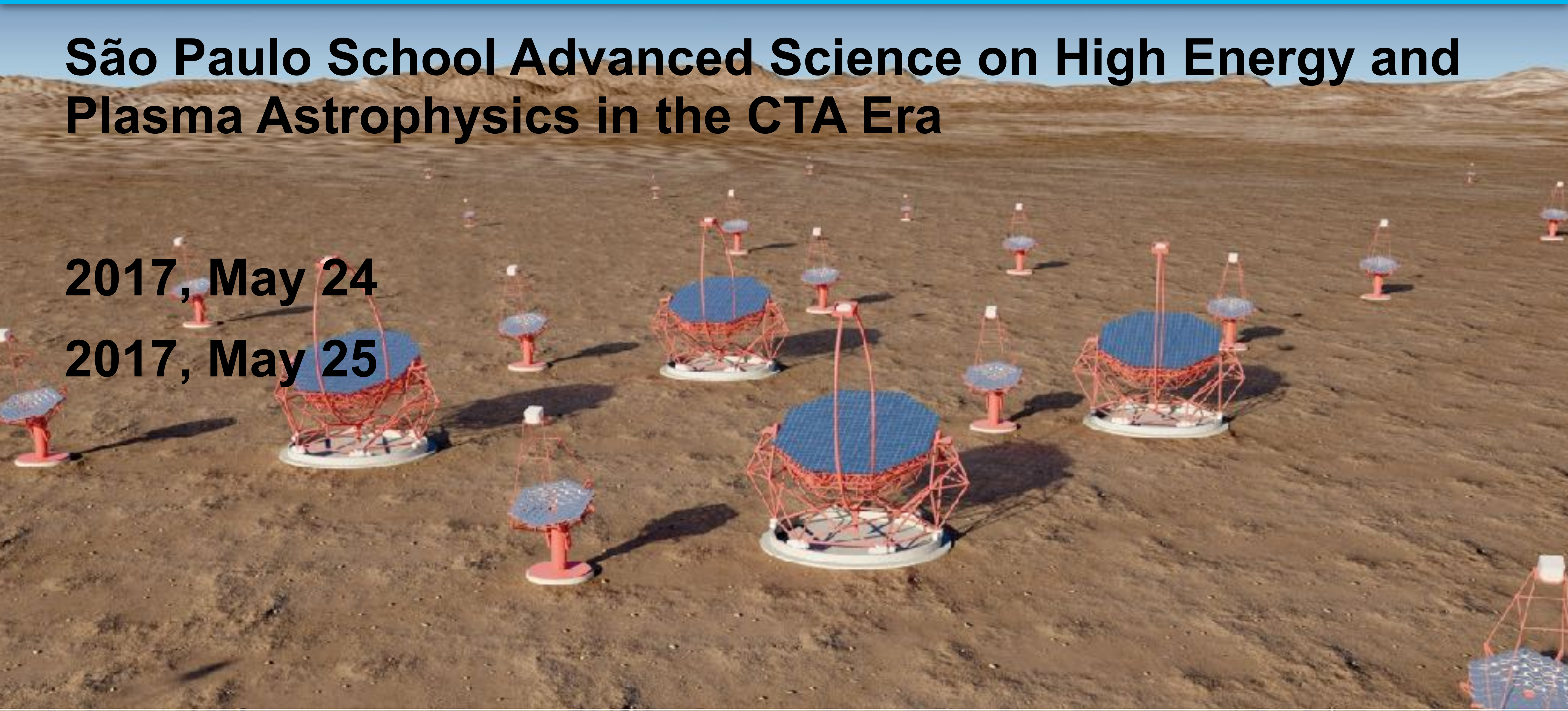
Gamma-Ray data analysis with Cherenkov Telescopes (Lecture IV)



São Paulo School Advanced Science on High Energy and Plasma Astrophysics in the CTA Era

2017, May 24

2017, May 25

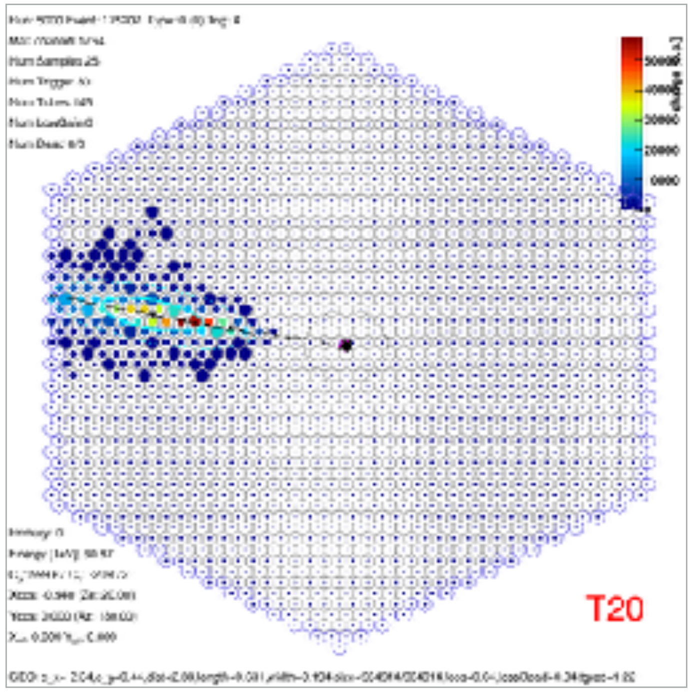
Gernot Maier

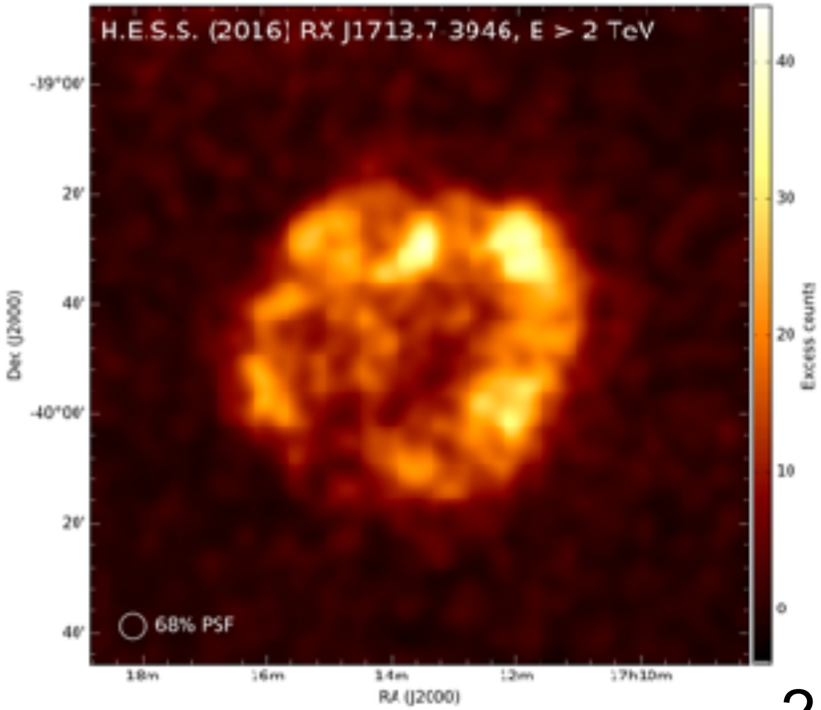
DESY

Overview

Analysis of data from imaging Cherenkov telescopes

- > **introduction**
- > **air showers and their detection**
- > **image analysis**
- > **direction, energy, gamma selection**
- > **spatial and spectral analysis**

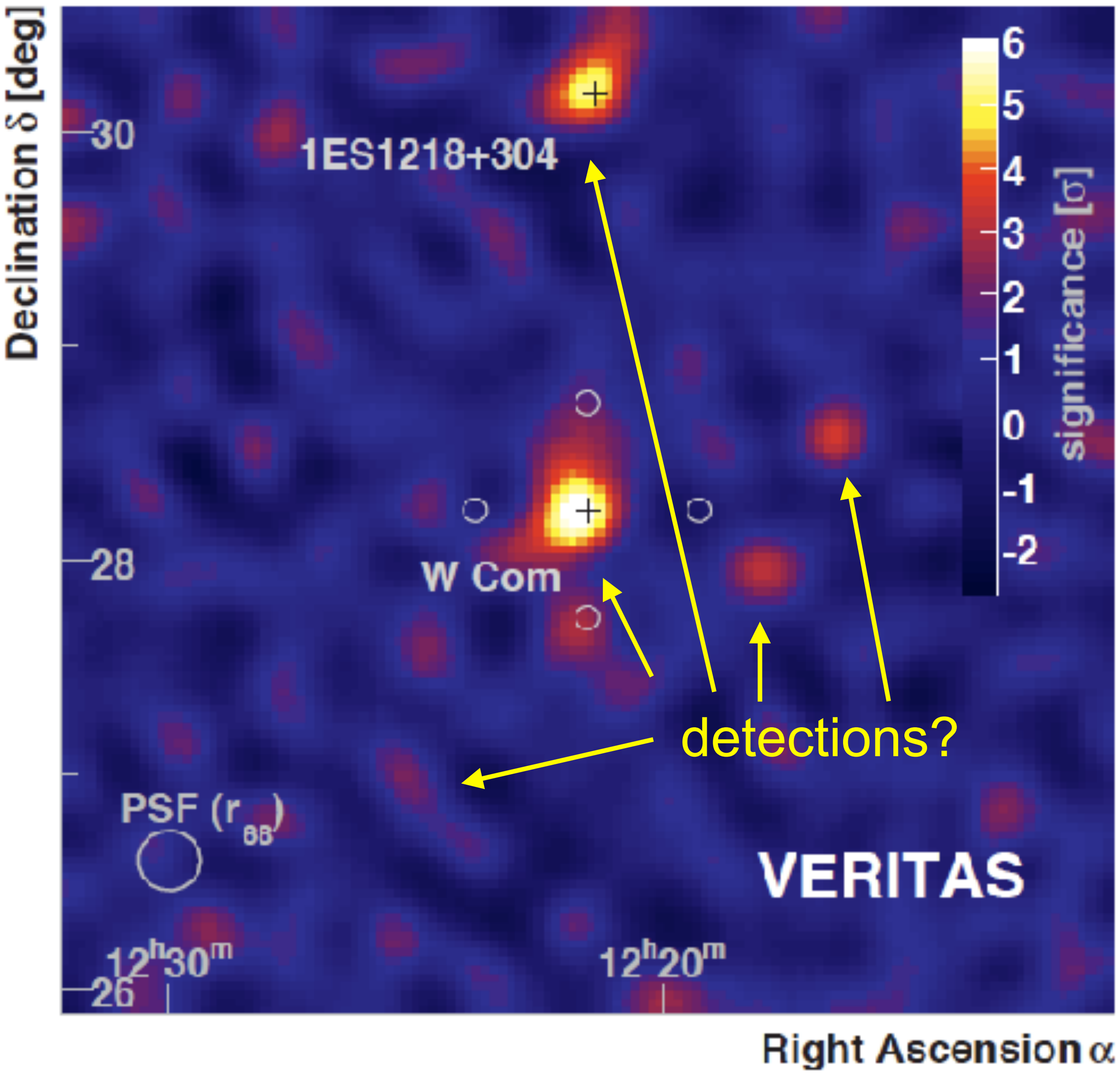




H.E.S.S. Collaboration (arXiv:1609.08671)

Analysis questions

> **Source detection probability?**
  - test statistics (TS), significance, …



Parameter estimation and hypothesis testing

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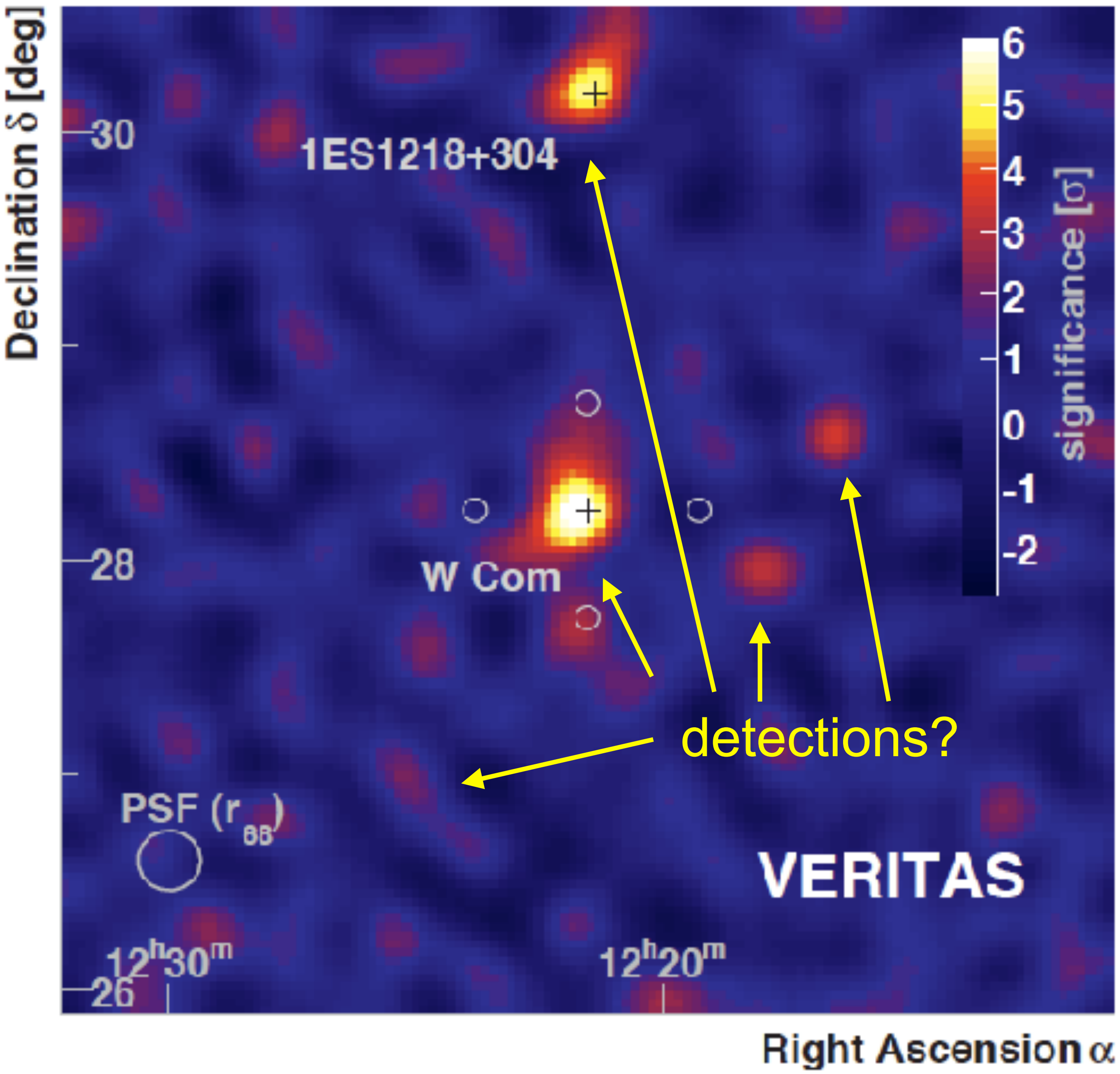
  - point-like source, extended, …



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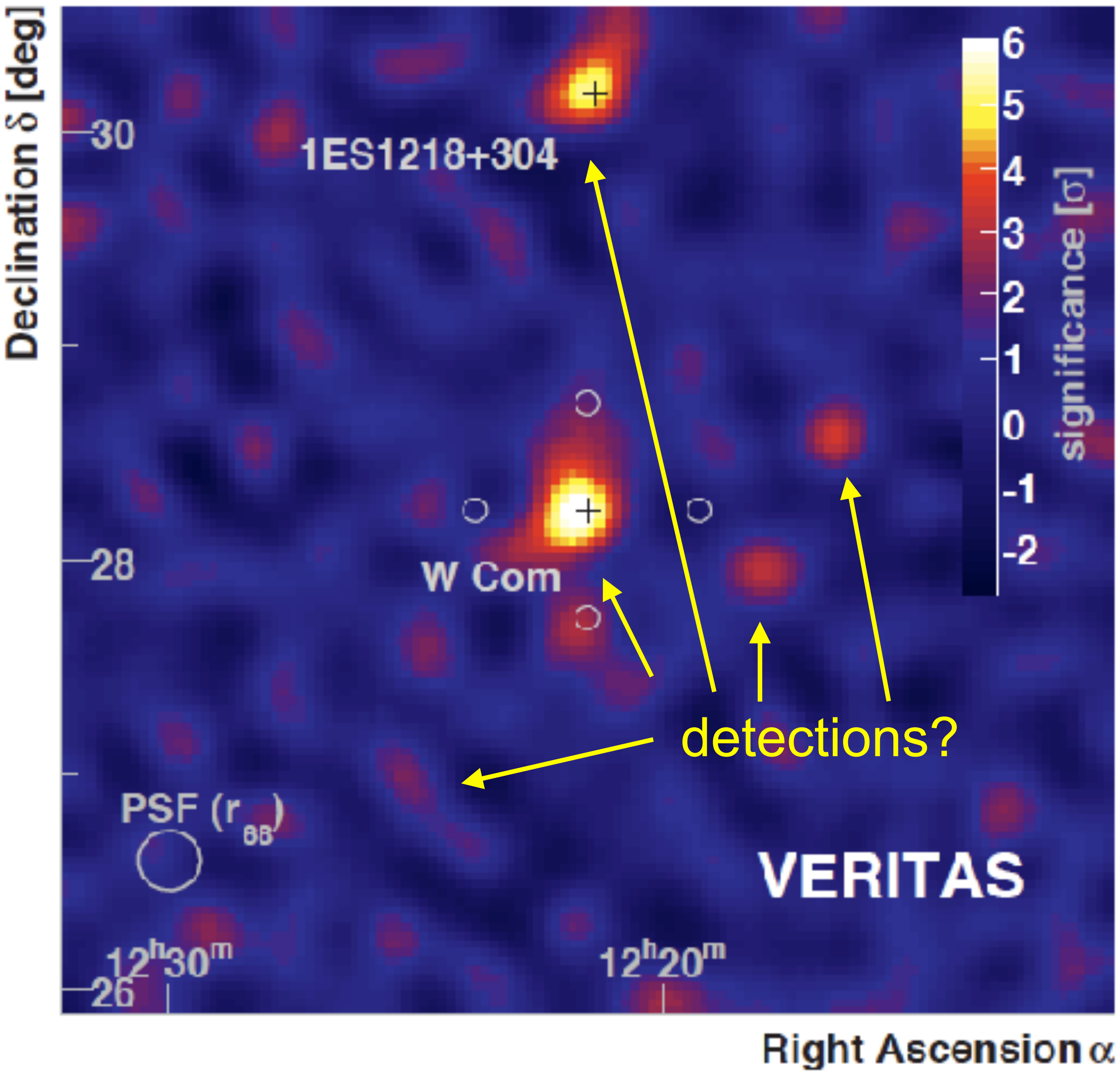

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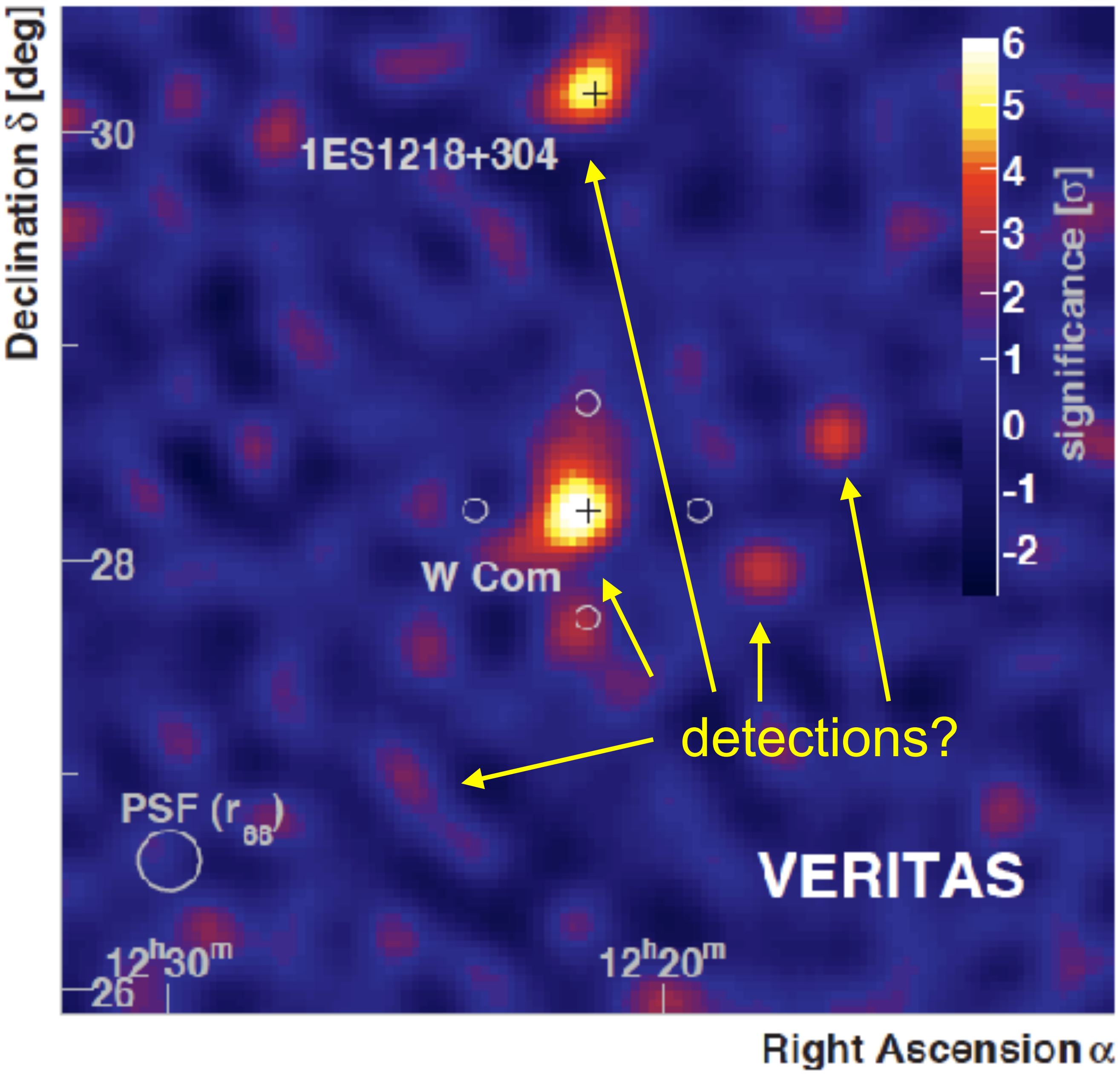

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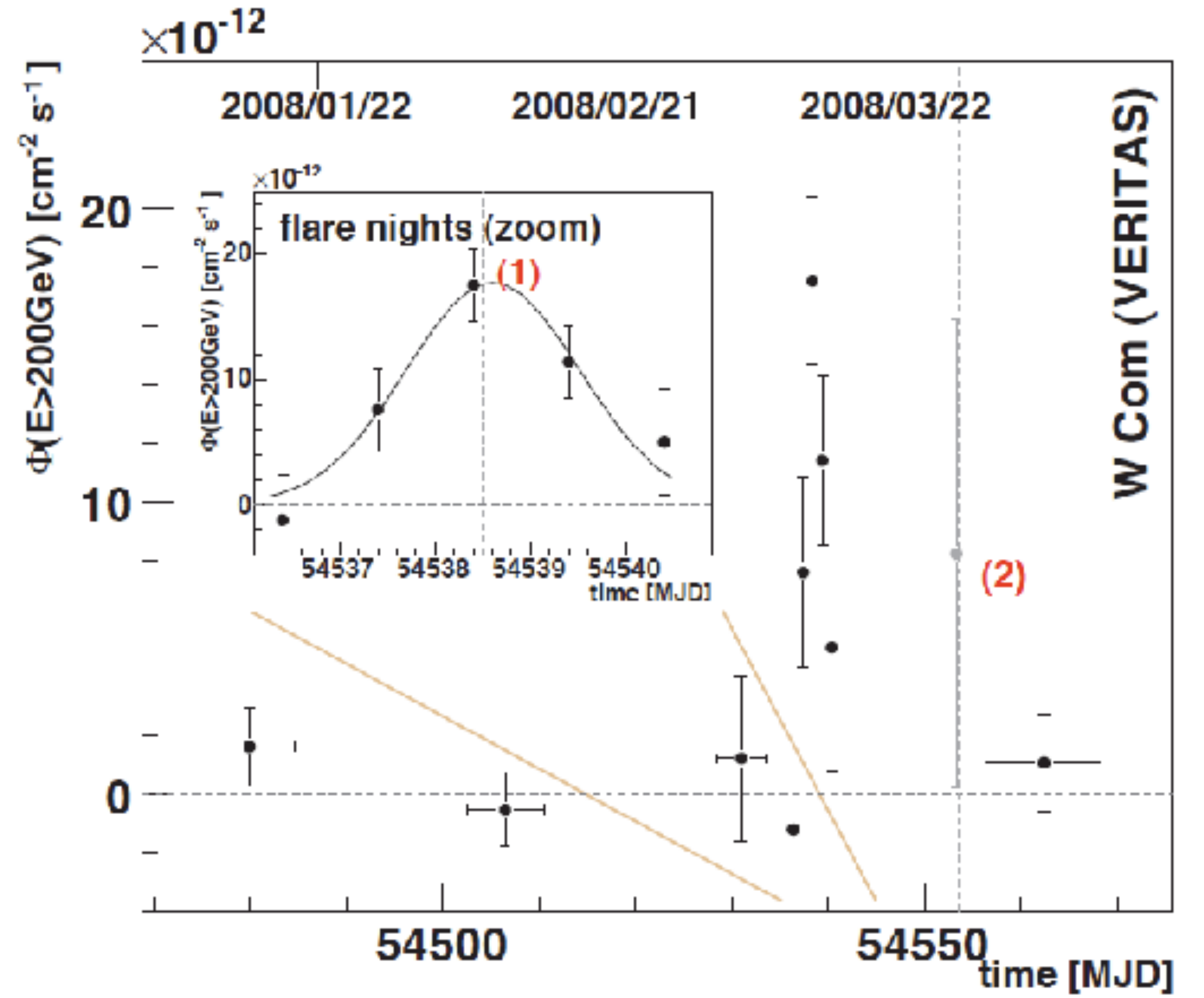

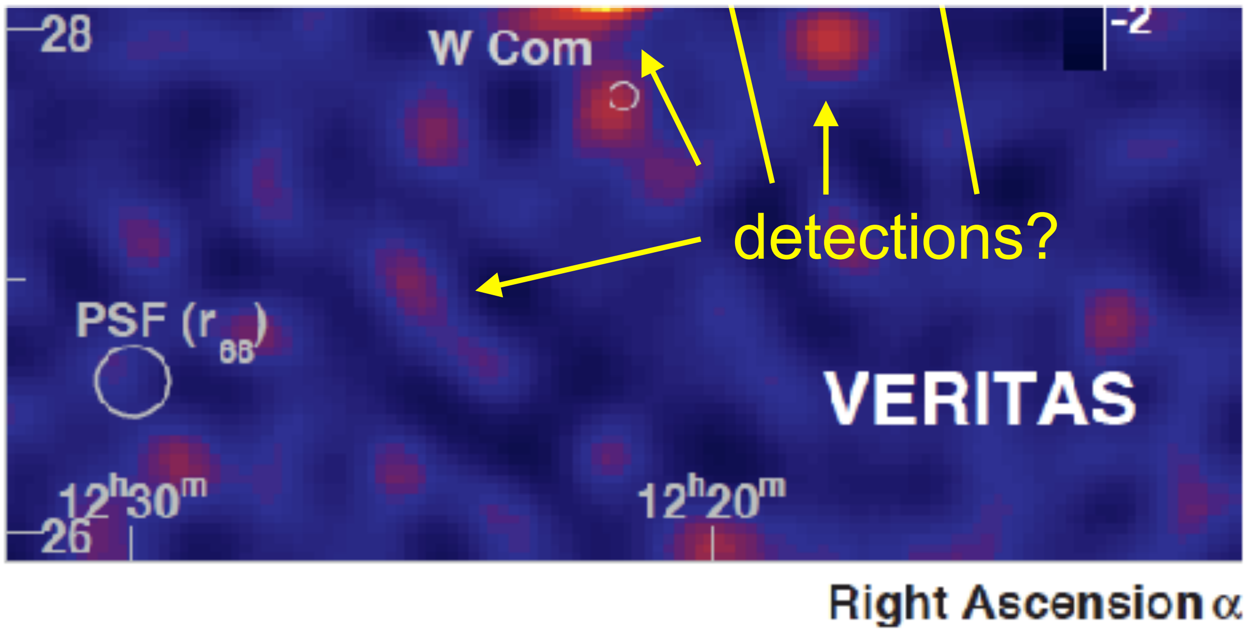

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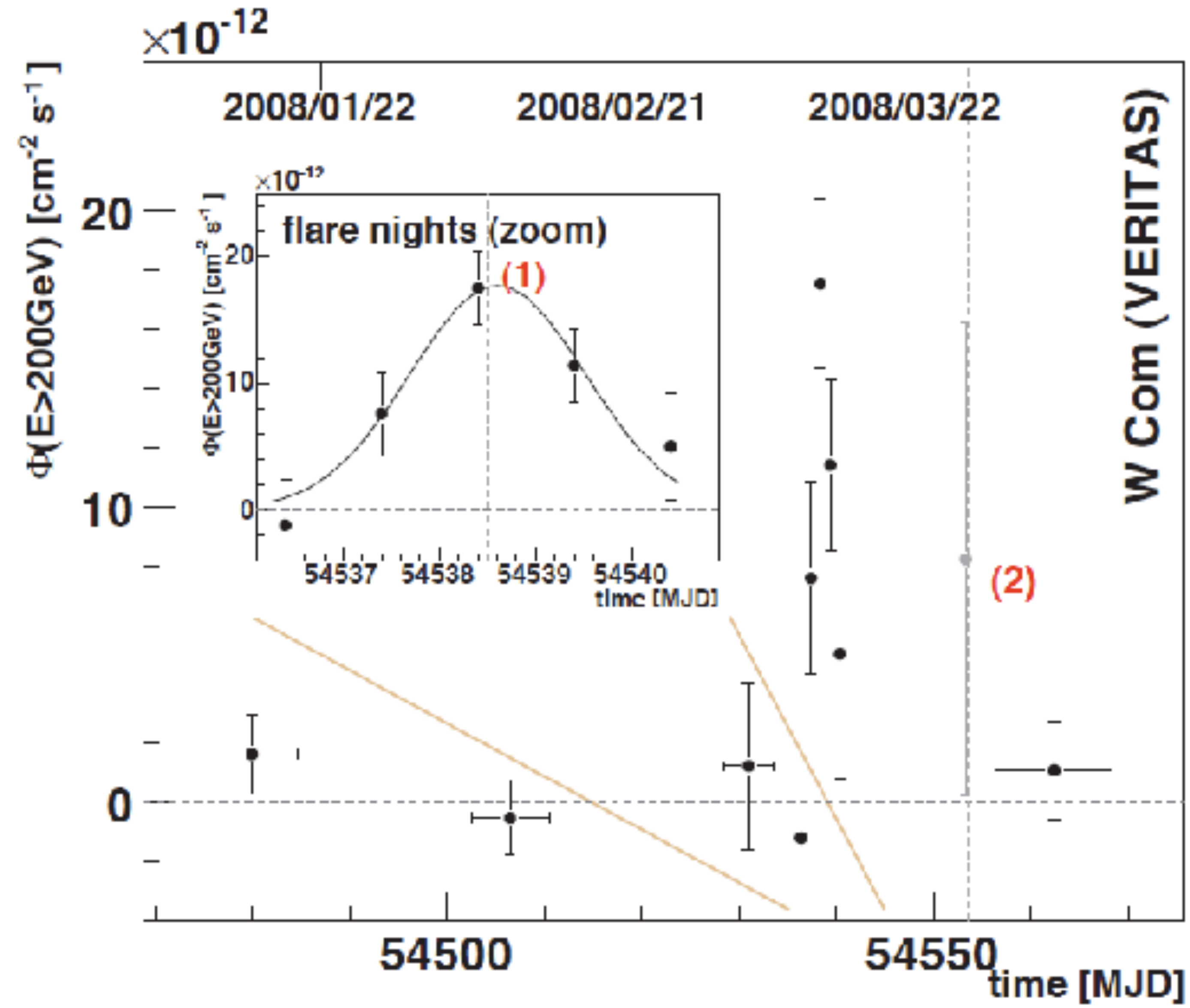

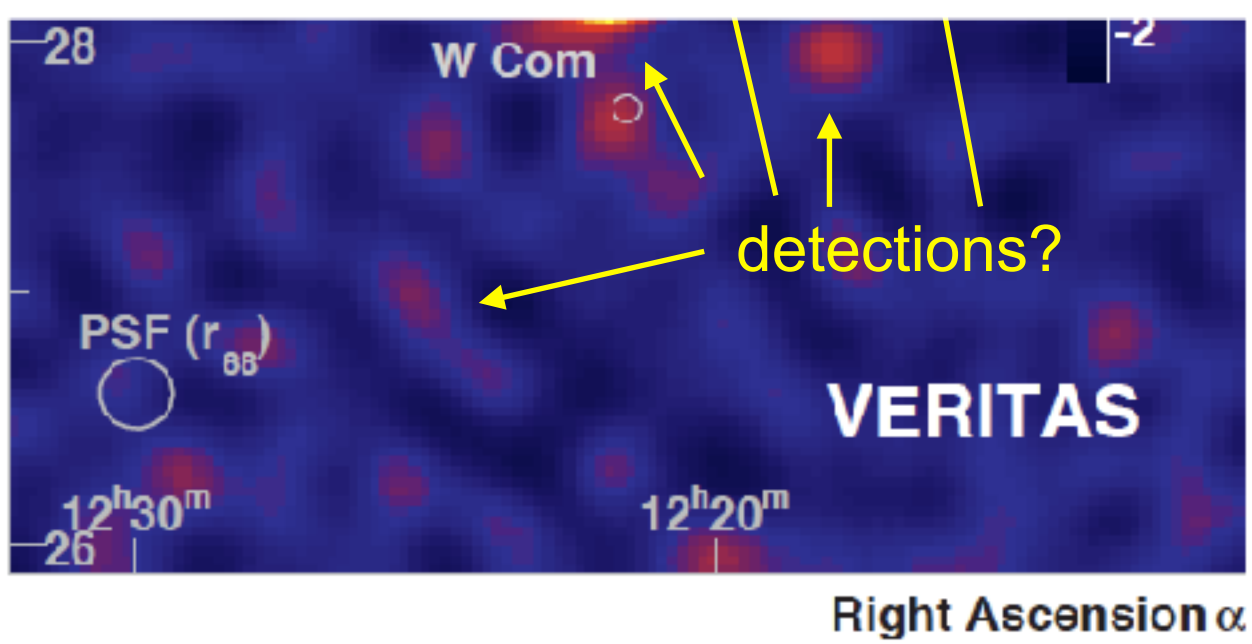

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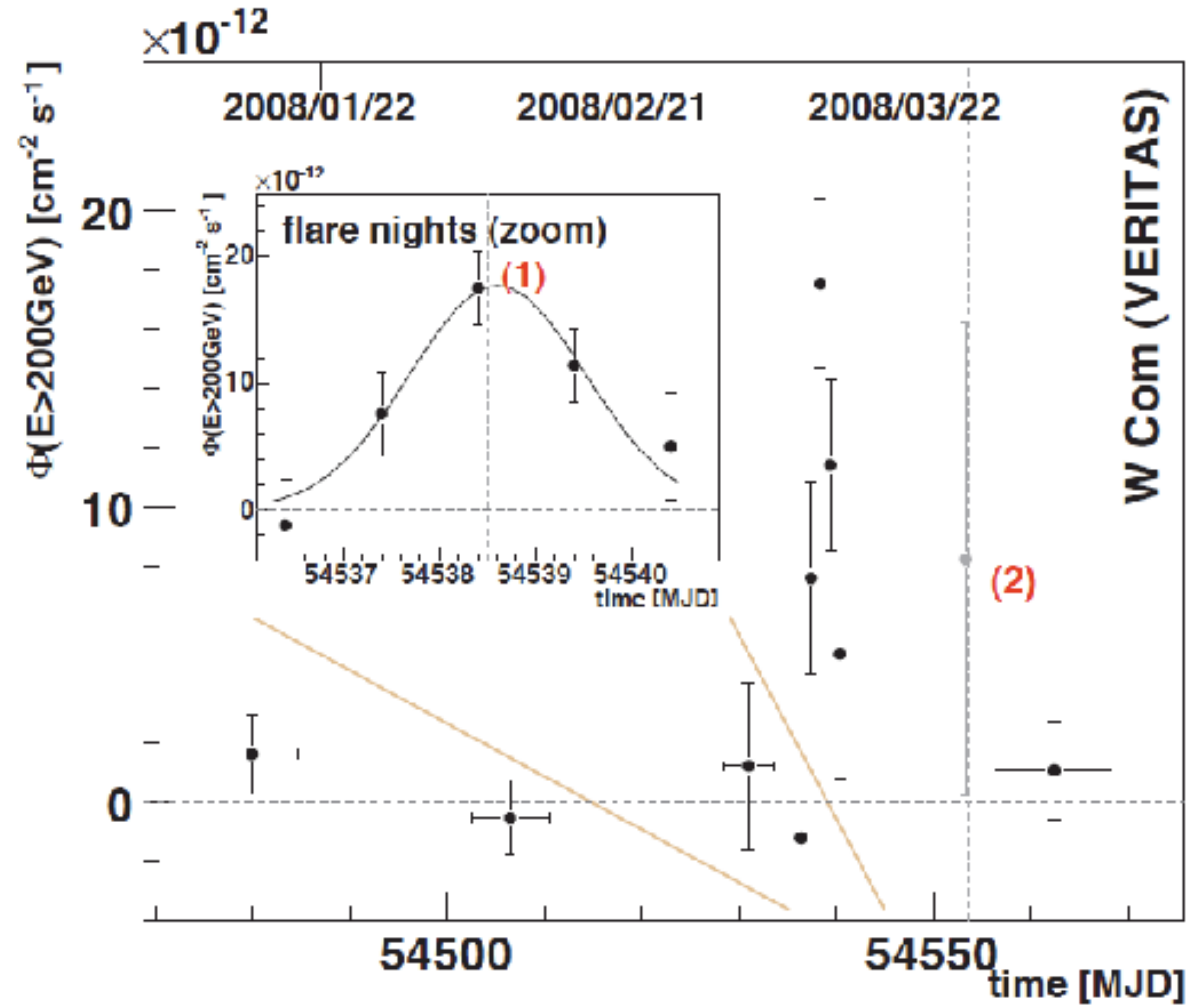
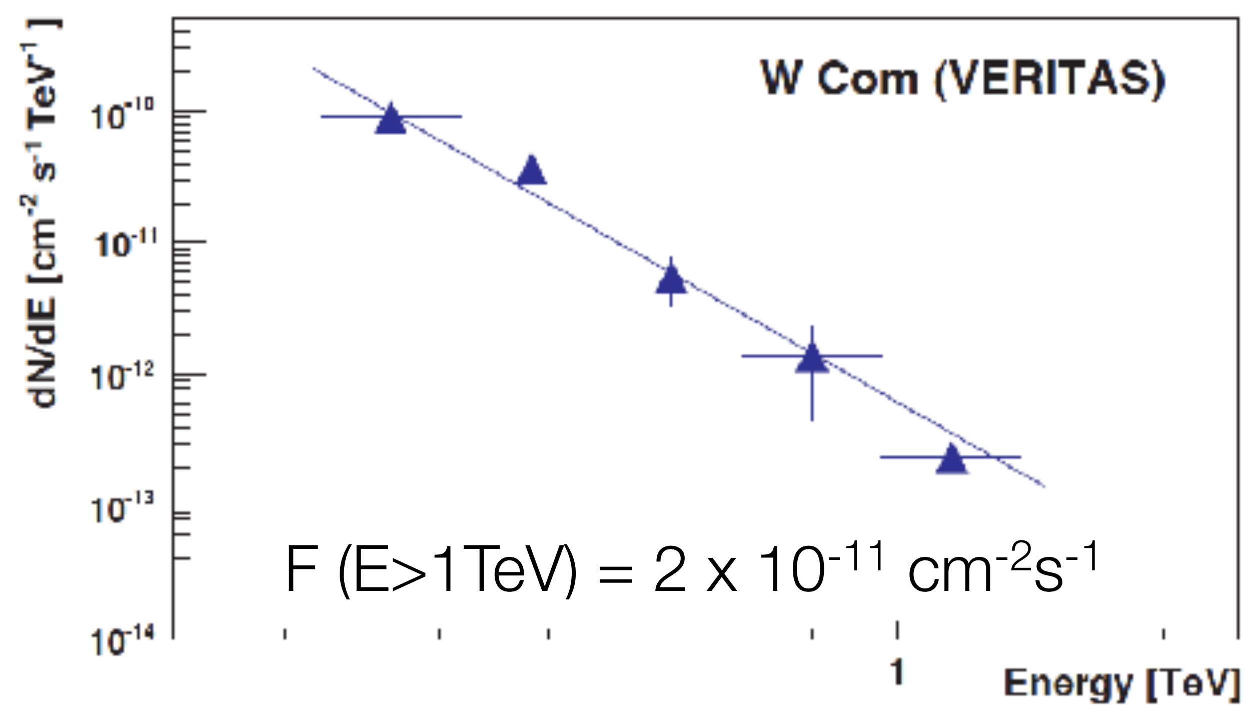
  - power laws + variations, …
  - line emission





$F\ (E>1\text{TeV}) = 2 \times 10^{-11}\ \text{cm}^{-2}\text{s}^{-1}$

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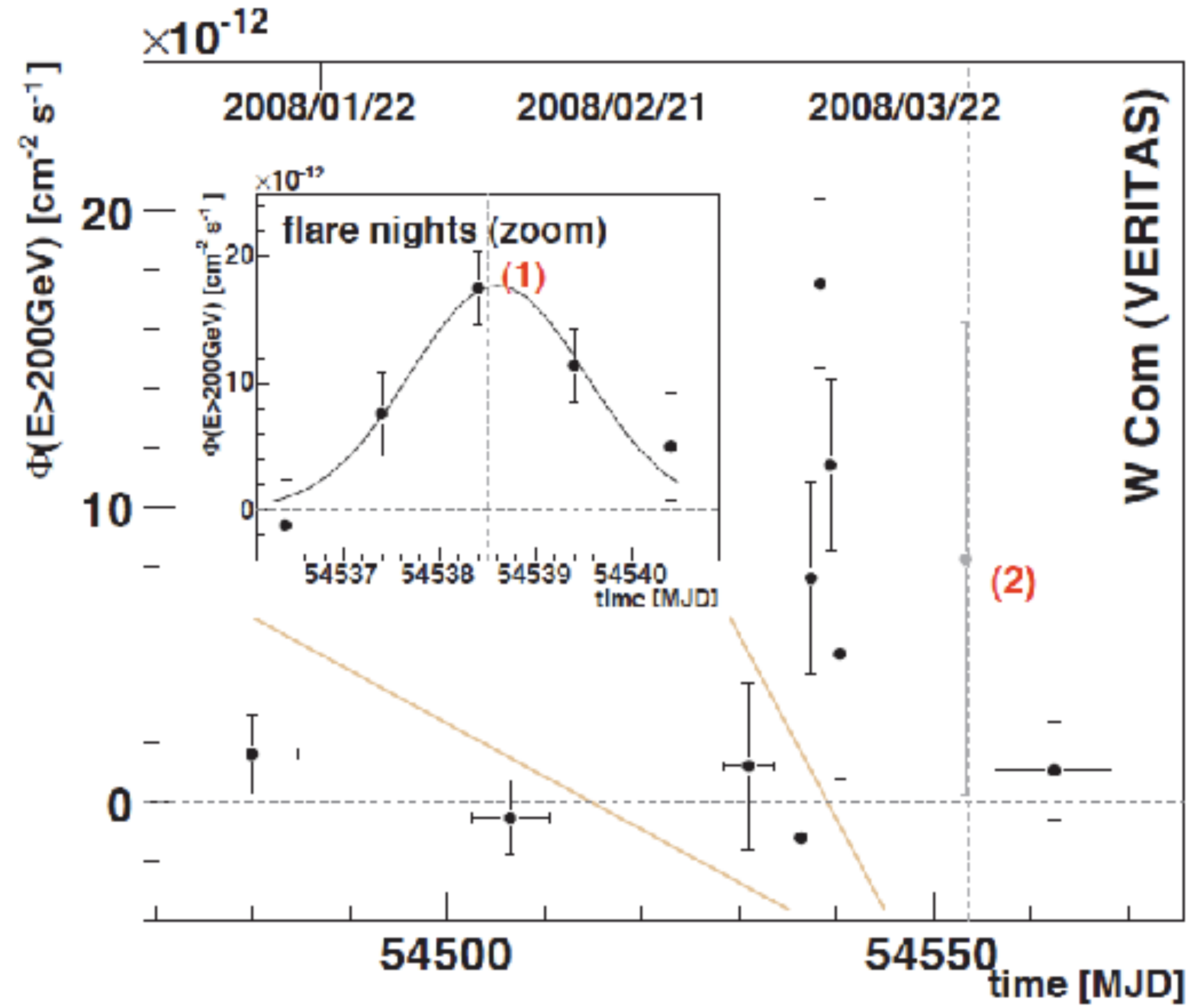
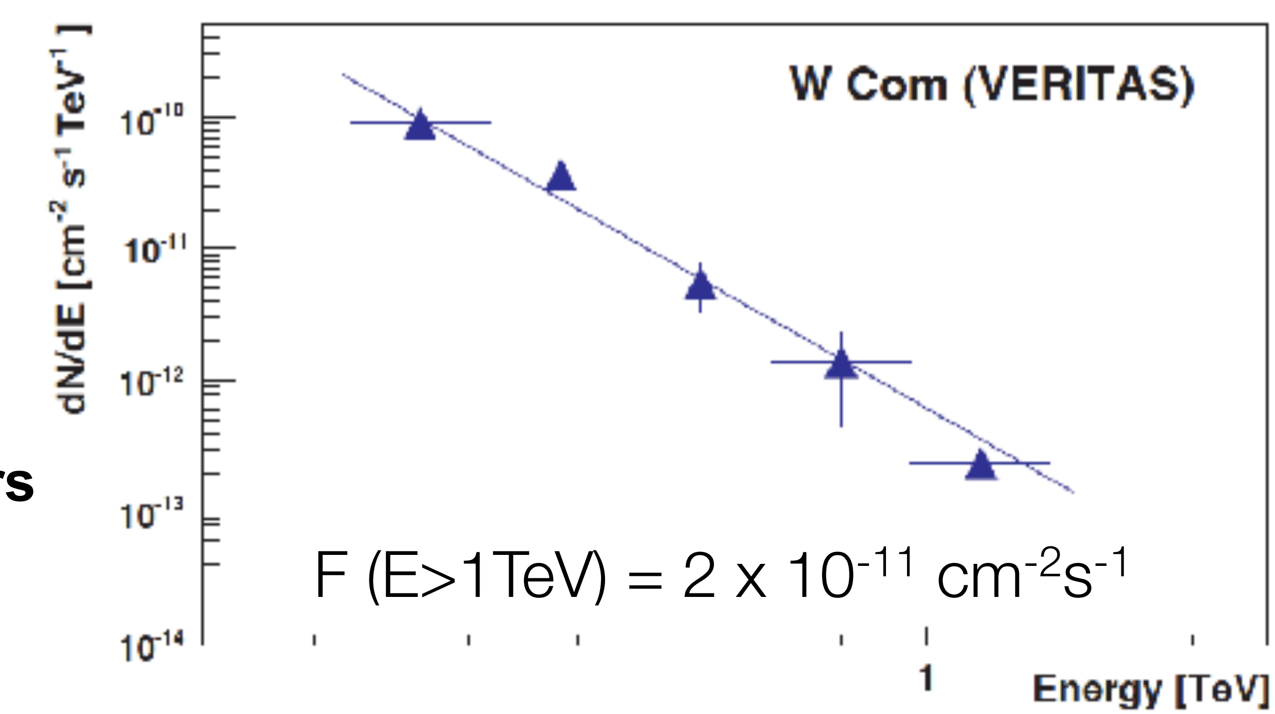
> **What are the statistical and systematic errors on all of that?**





Parameter estimation and hypothesis testing

Analysis - Input

- key observables for each gamma ray:
  energy, direction, arrival time

- detector response:
  - detection probability (effective areas)
  - angular point-spread function
  - energy dispersion matrix
  - instrument dead time

- background (lots of it)

- gamma-ray selection
  (or background suppression)

- systematic uncertainties
  - understanding of detector
  - fluctuations in the atmosphere
  - choices by you
  - ….

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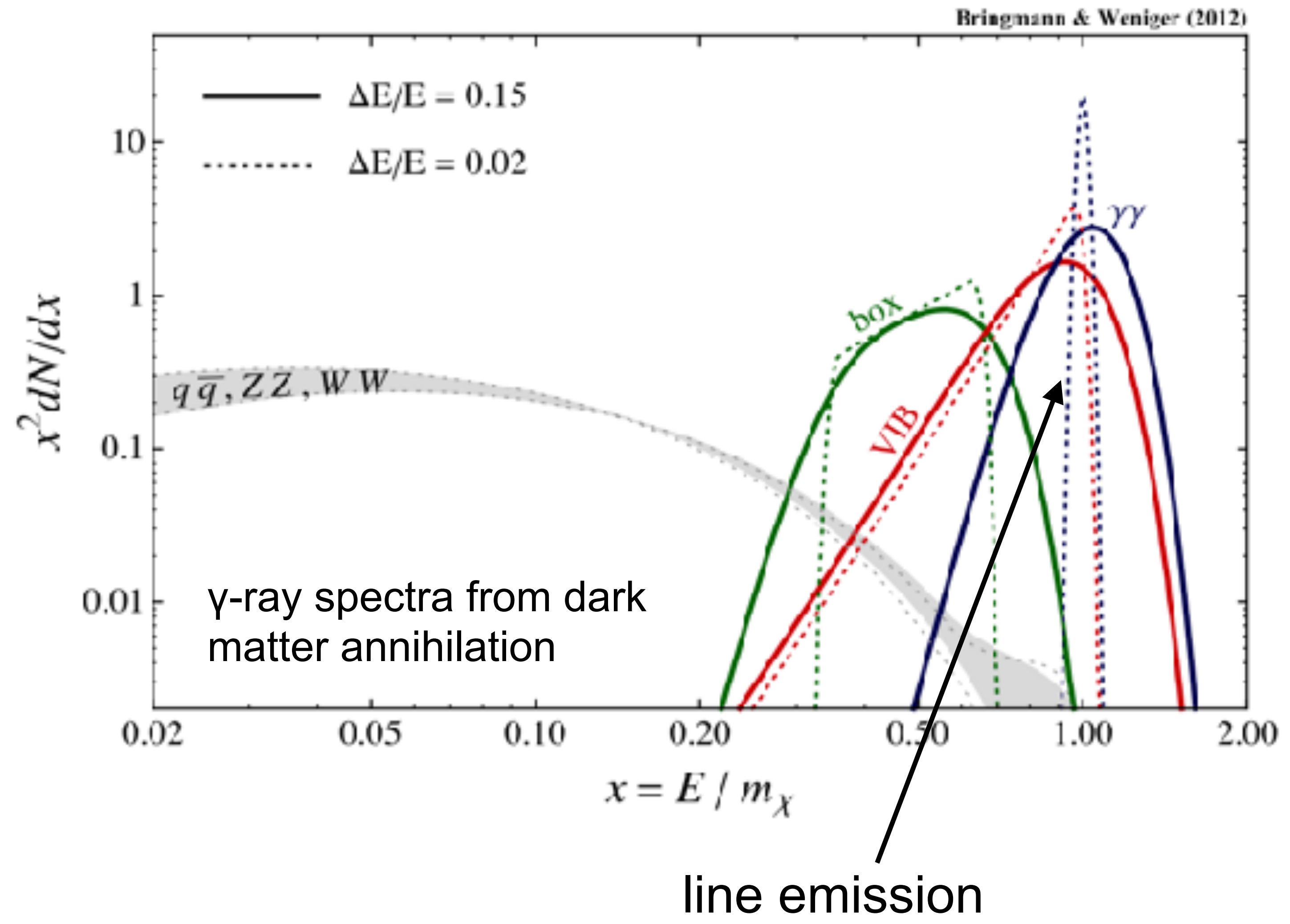

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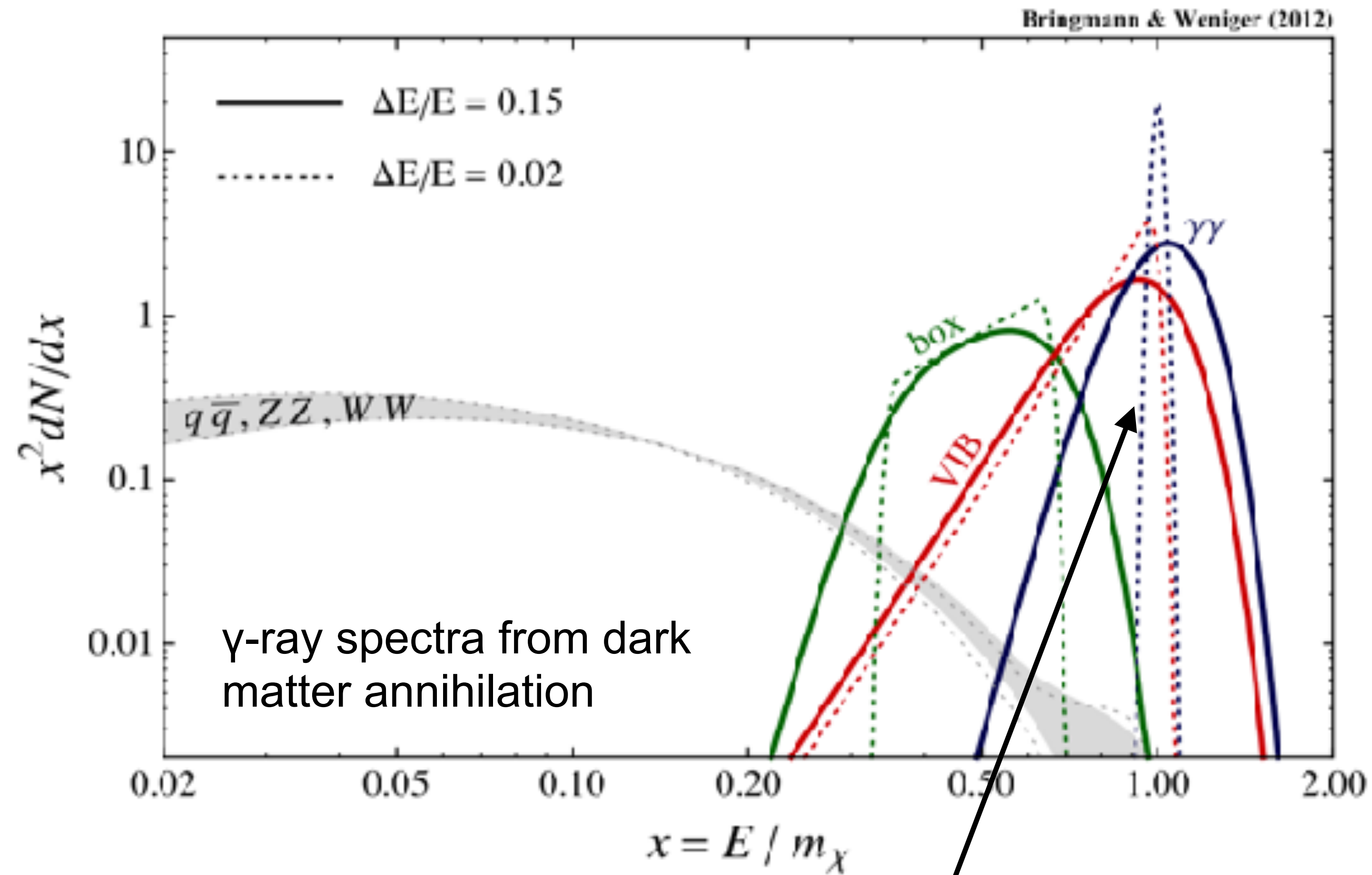
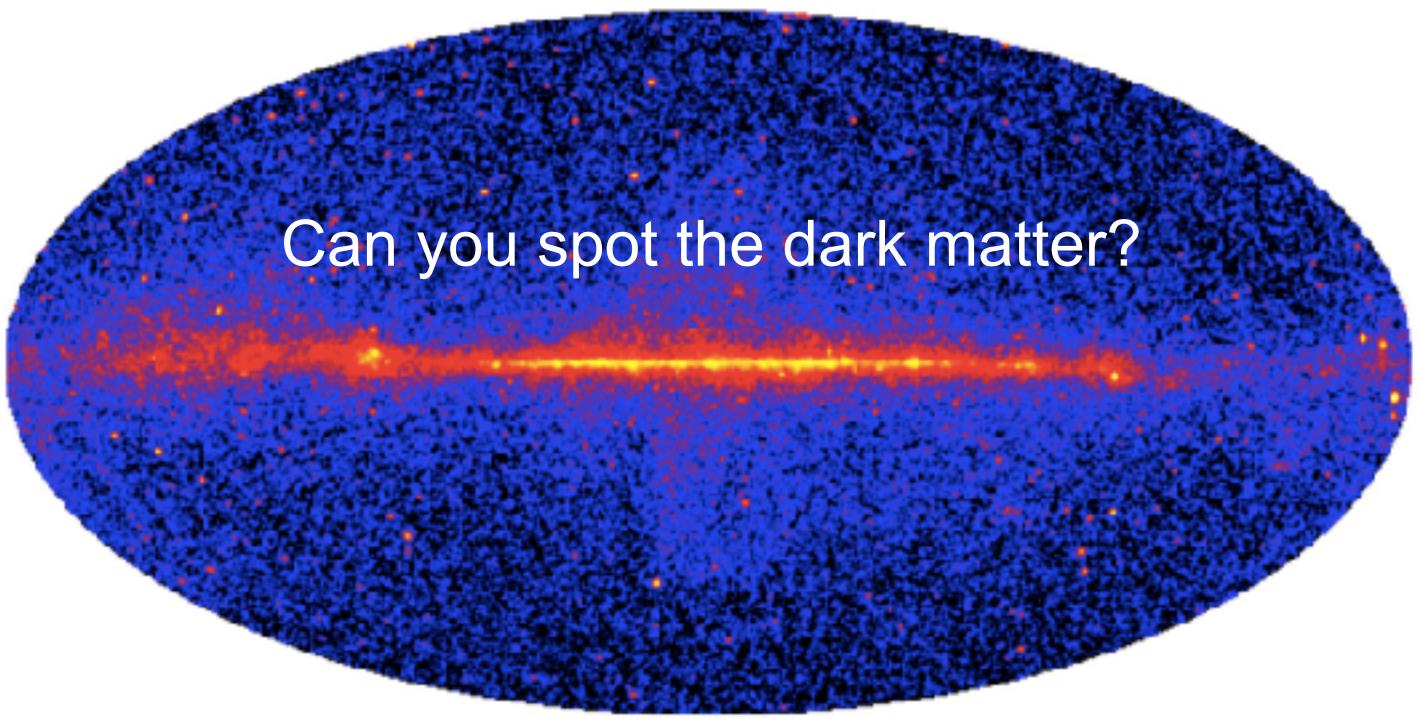




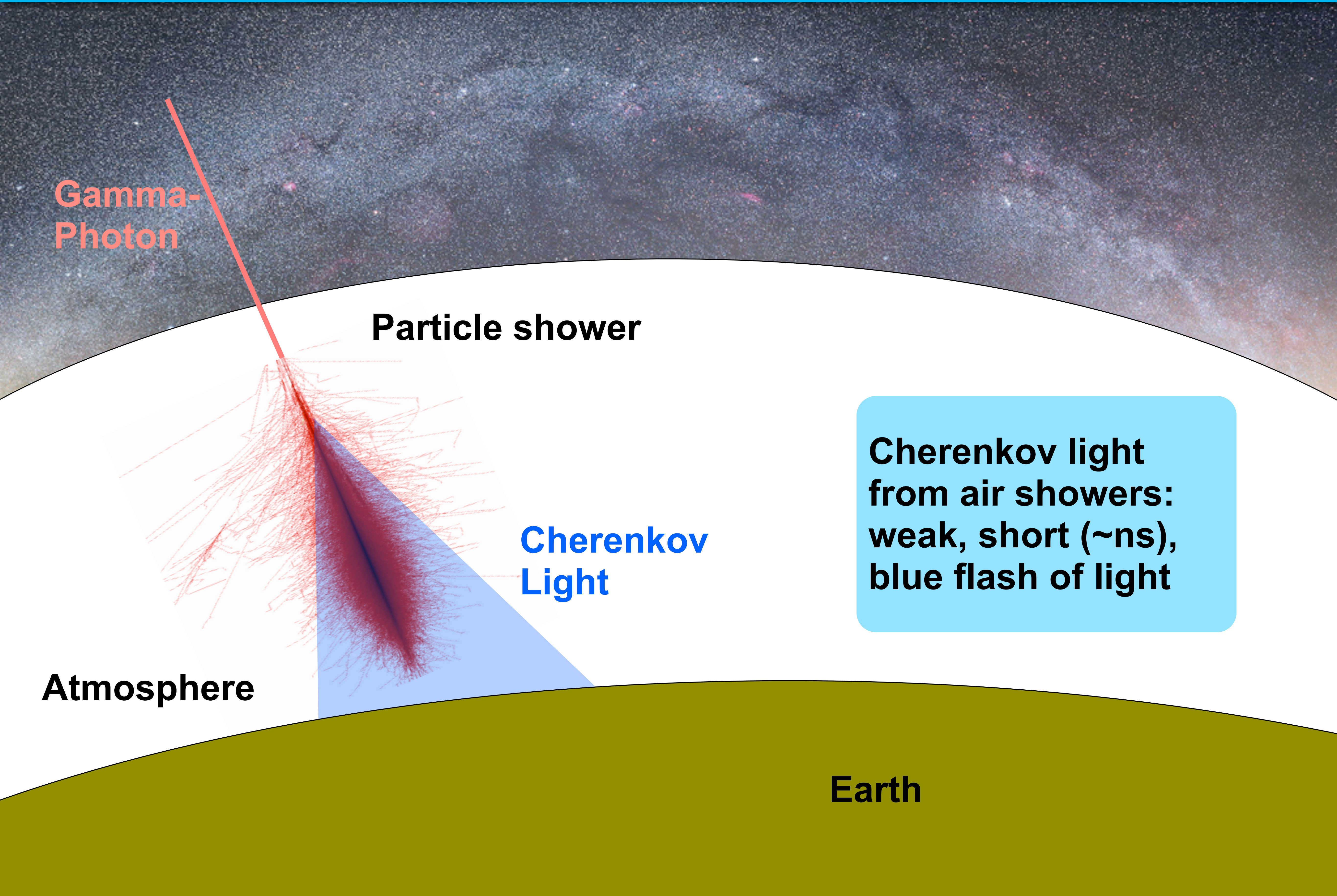
Fermi LAT 3-years sky map > 10 GeV (Ackermann et al (2013)

Analysis - Input

- key observables for each gamma ray: energy, direction, arrival time ← **event reconstruction**
- detector response: ← **instrument response functions (from Monte Carlo simulations)**
  - detection probability (effective areas)
  - direction resolution
  - energy dispersion matrix
  - instrument dead time
- background (lots of it) ← **measurements or Monte Carlo simulations**
- gamma-ray selection (or background suppression) ← **Monte Carlo simulations**
- systematic uncertainties ← **measurements or Monte Carlo simulations**
  - understanding of detector
  - fluctuations in the atmosphere
  - choices by you
  - ….

Measuring air showers

Air shower measurement & Cherenkov emission

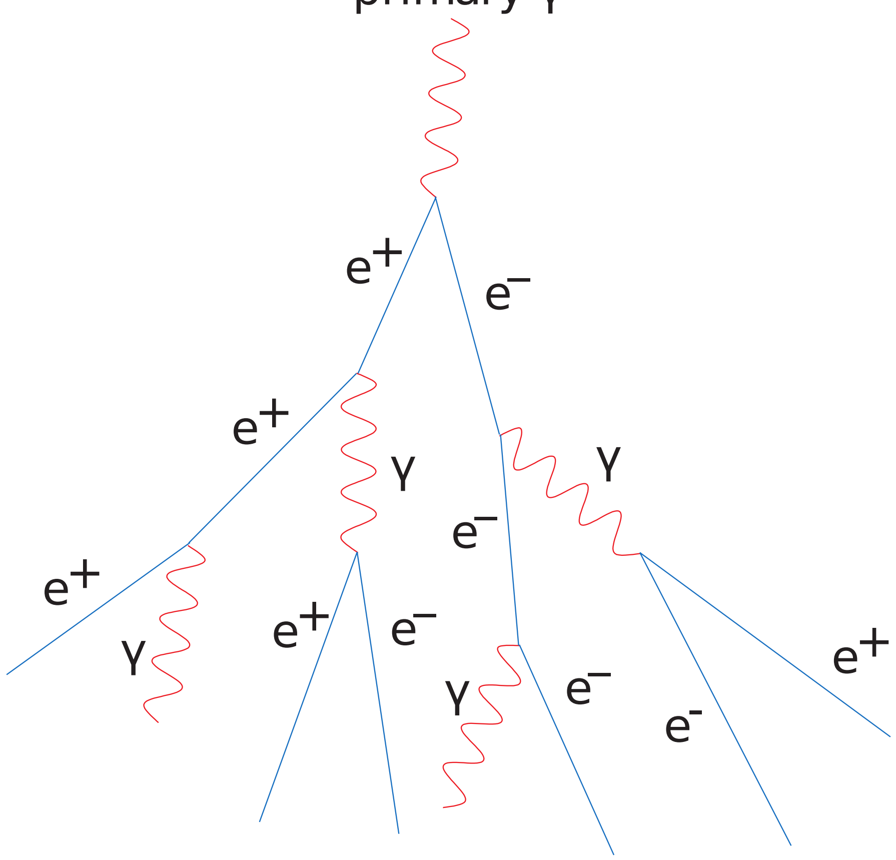


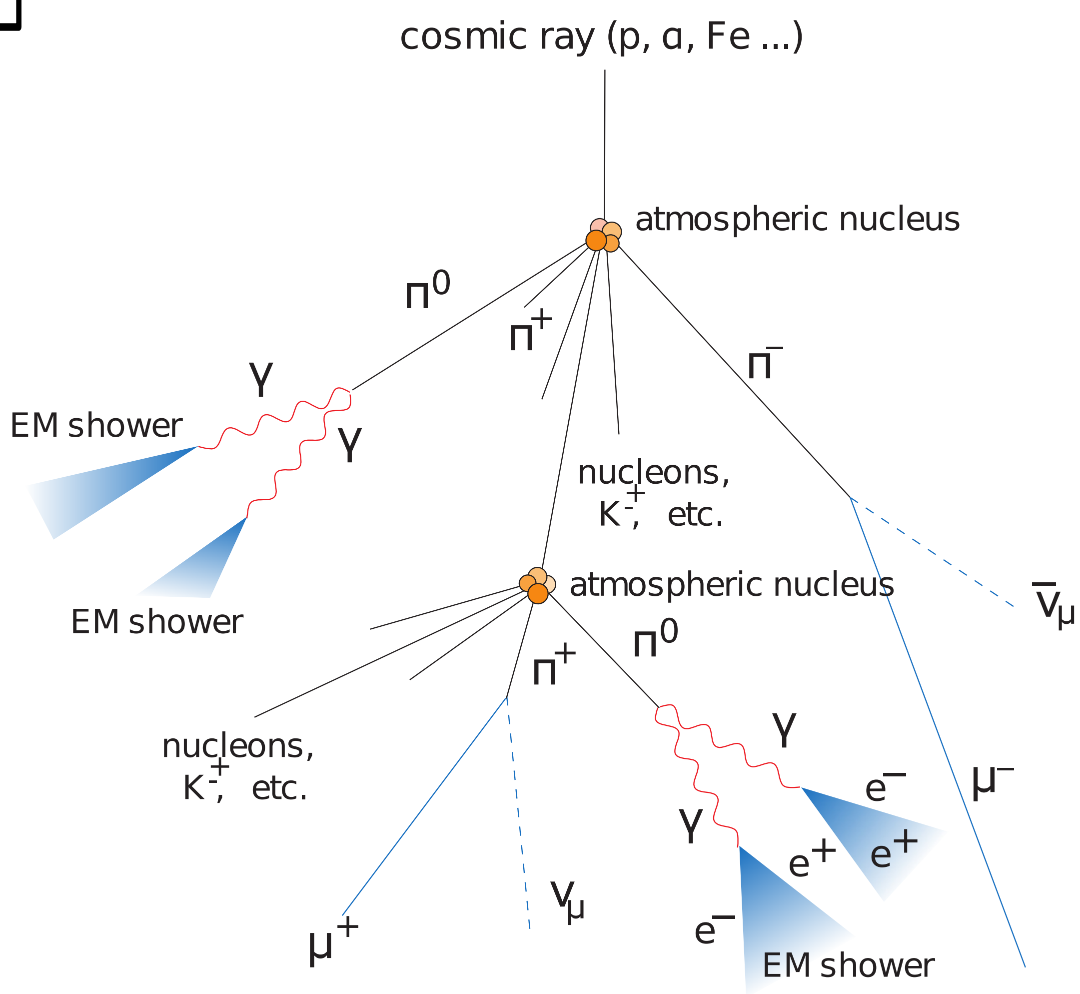
Cherenkov light from air showers: weak, short (~ns), blue flash of light

Air showers

a)

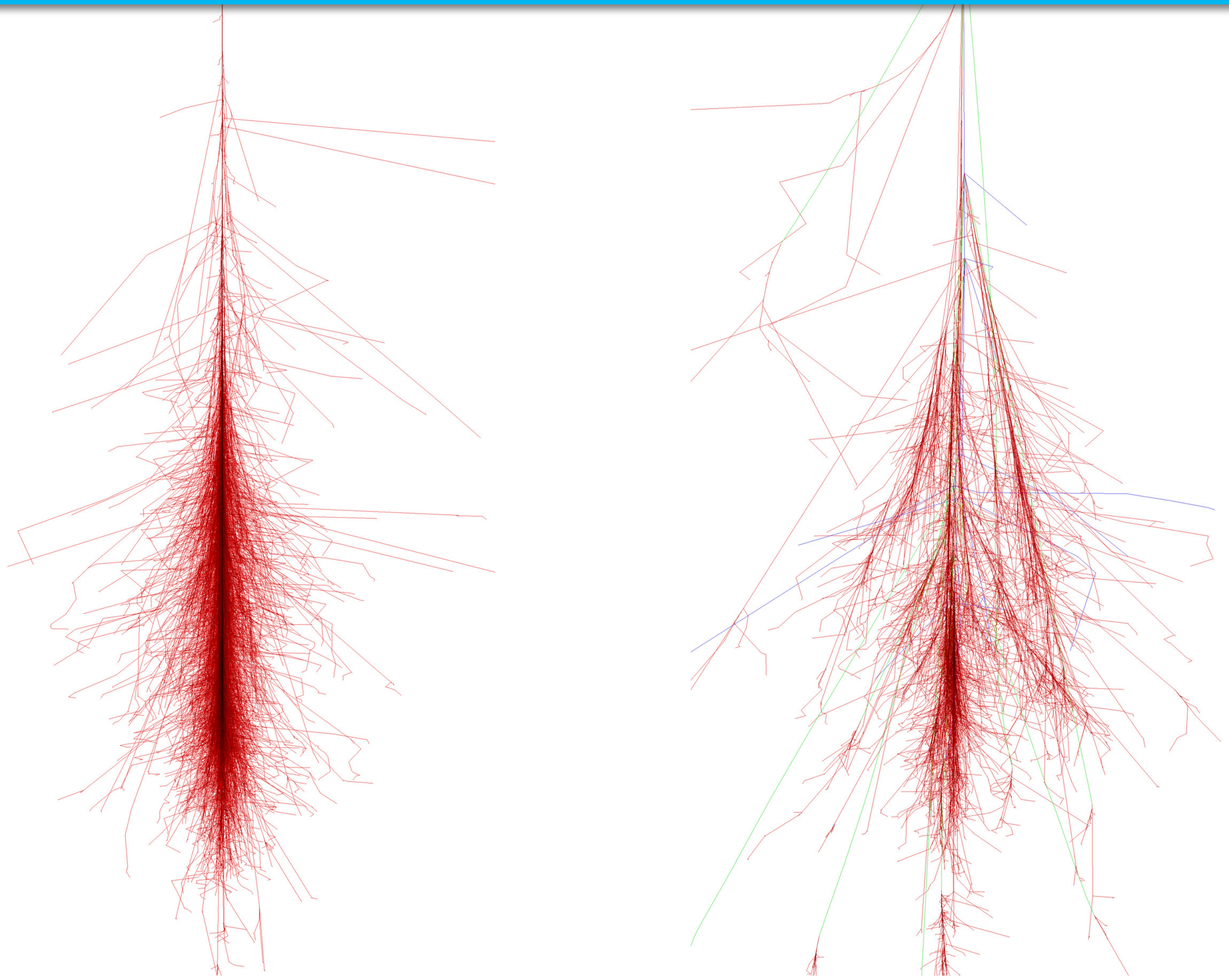
Model



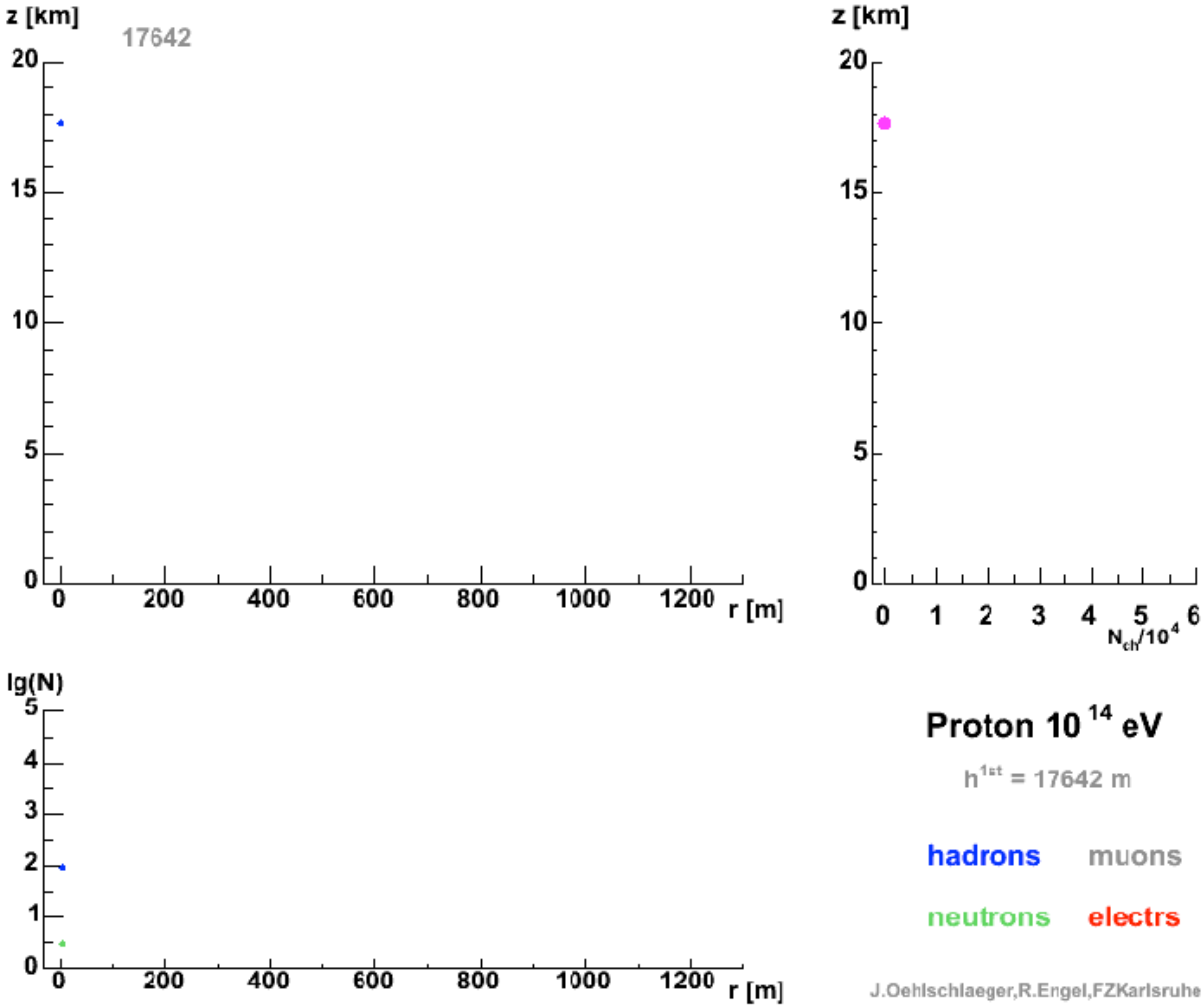


Otte (2007)

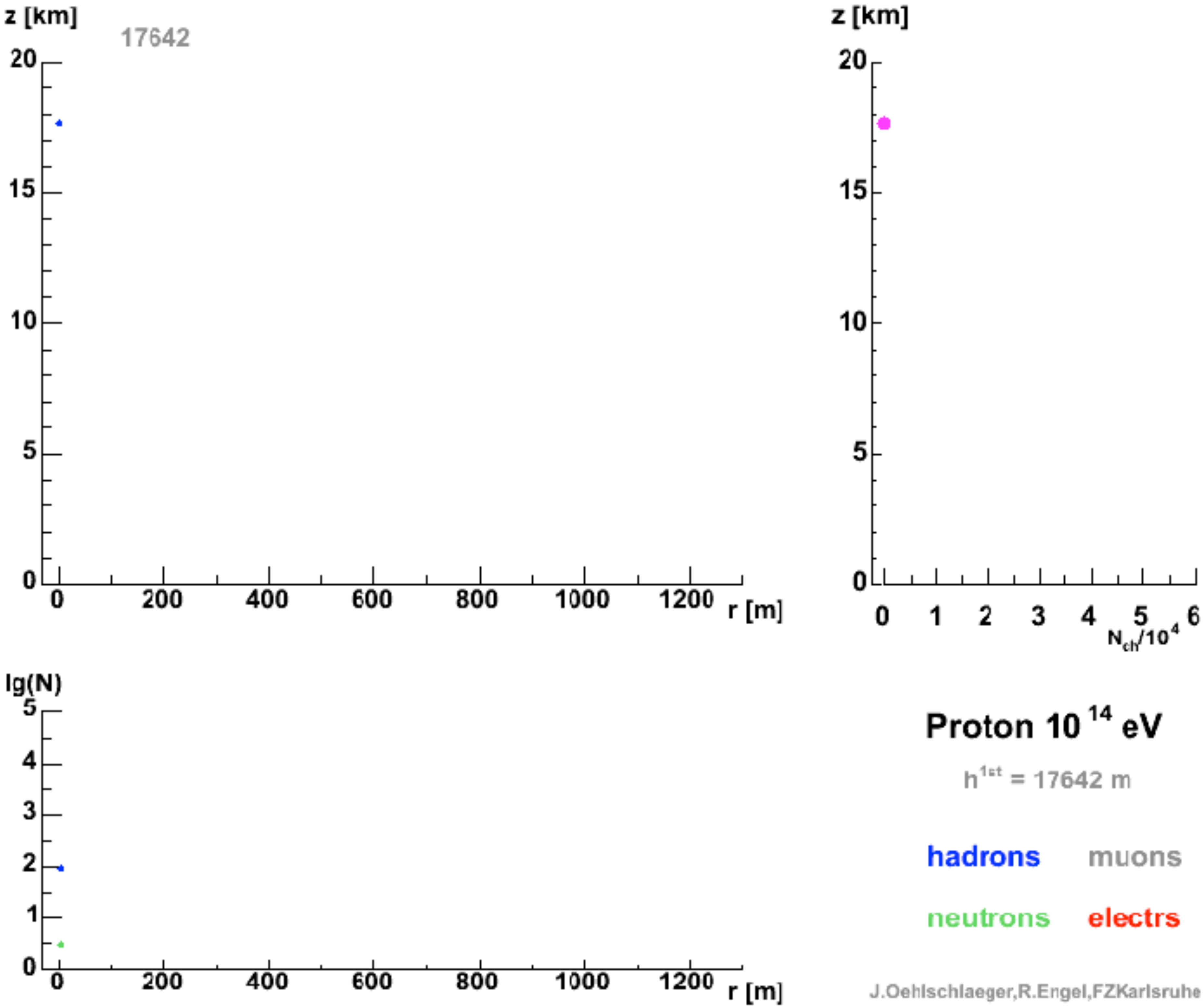
Air showers



Schmidt (2005)



z [km]
17642
20
15
10
5
0
0
200
400
600
800
1000
1200
r [m]
z [km]
20
15
10
5
0
0
1
2
3
4
5
6
N_ch/10^4
lg(N)
5
4
3
2
1
0
0
200
400
600
800
1000
1200
r [m]
Proton 10^14 eV
h^1st = 17642 m
hadrons
muons
neutrons
electrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe


z [km]
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5
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Extensive Air Showers and Cherenkov Emission

Pavel Alekseyevich
Cherenkov
(Nobel price1958)

emitted when velocity *v* of charged particle exceeds local speed of light:

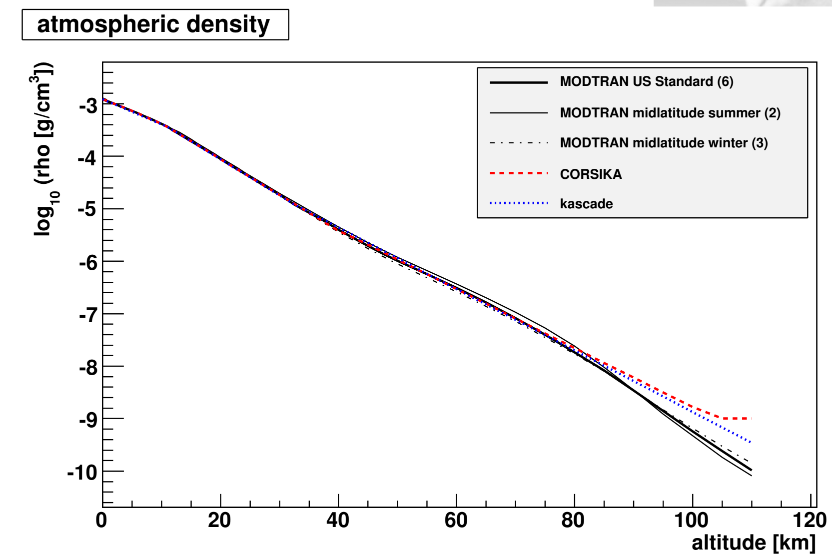
$$nv/c = n\beta > 1$$

light is emitted along a cone with half opening angle θ

$$\cos\Theta = 1/(\beta n)$$

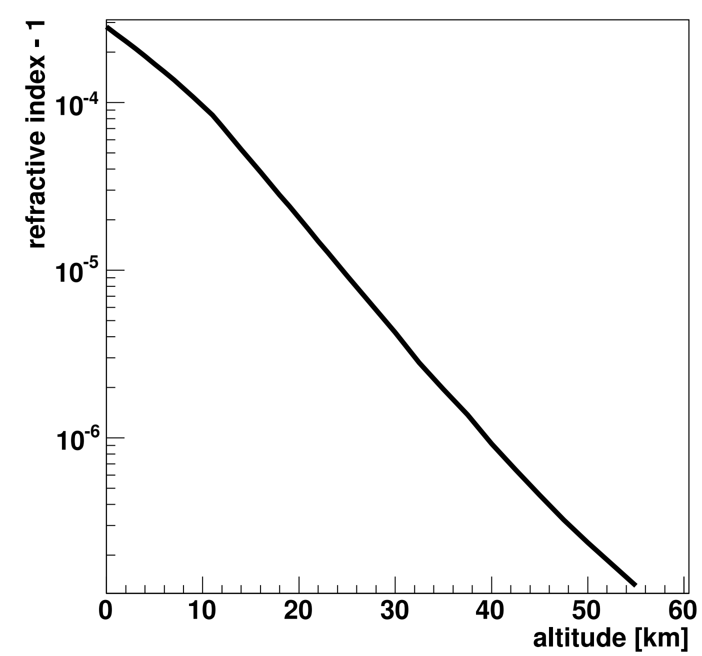
number of Cherenkov photons per path length x:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

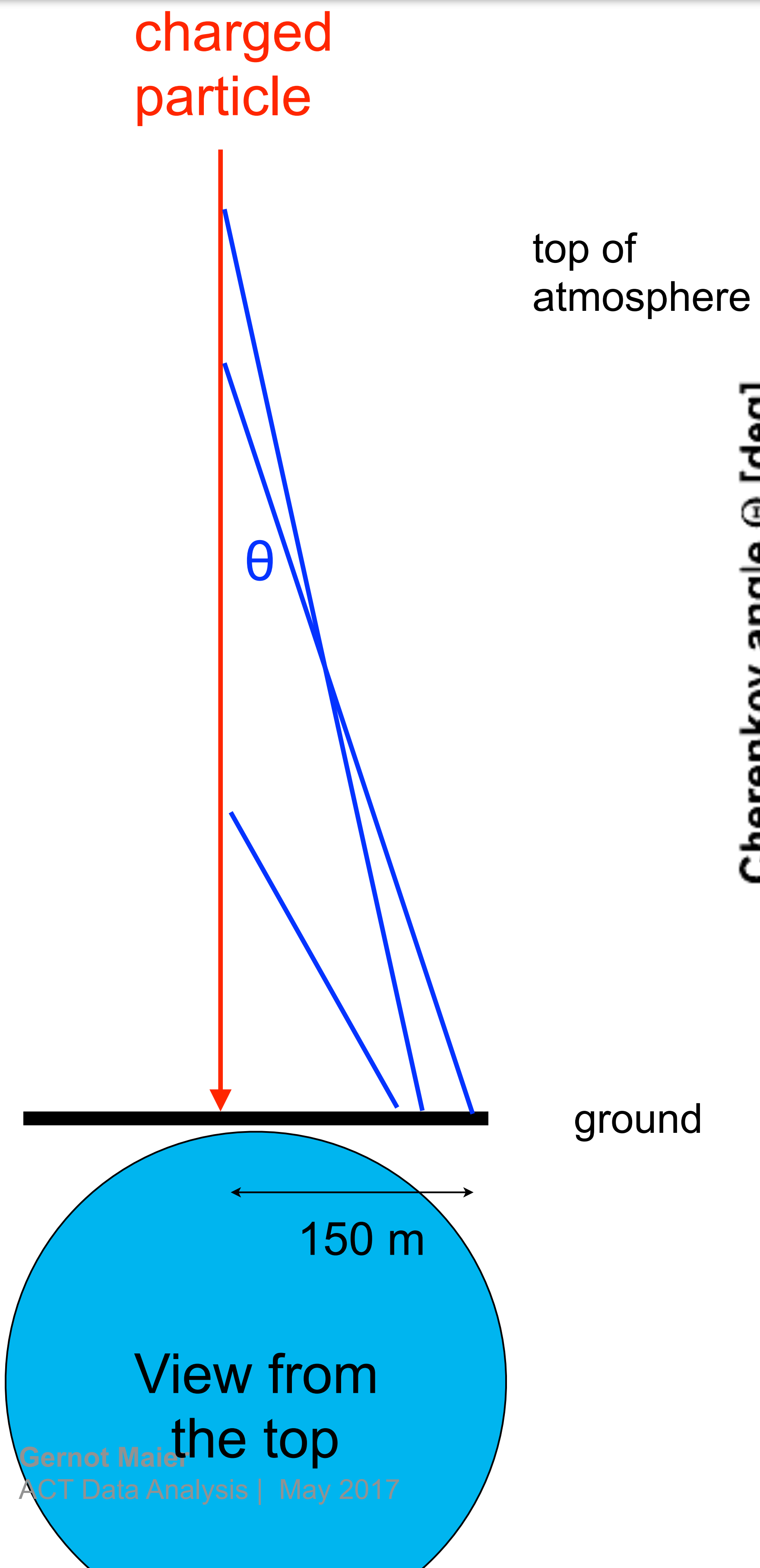


refractive index in air scales with density

$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$



Cherenkov radiation: emission angle



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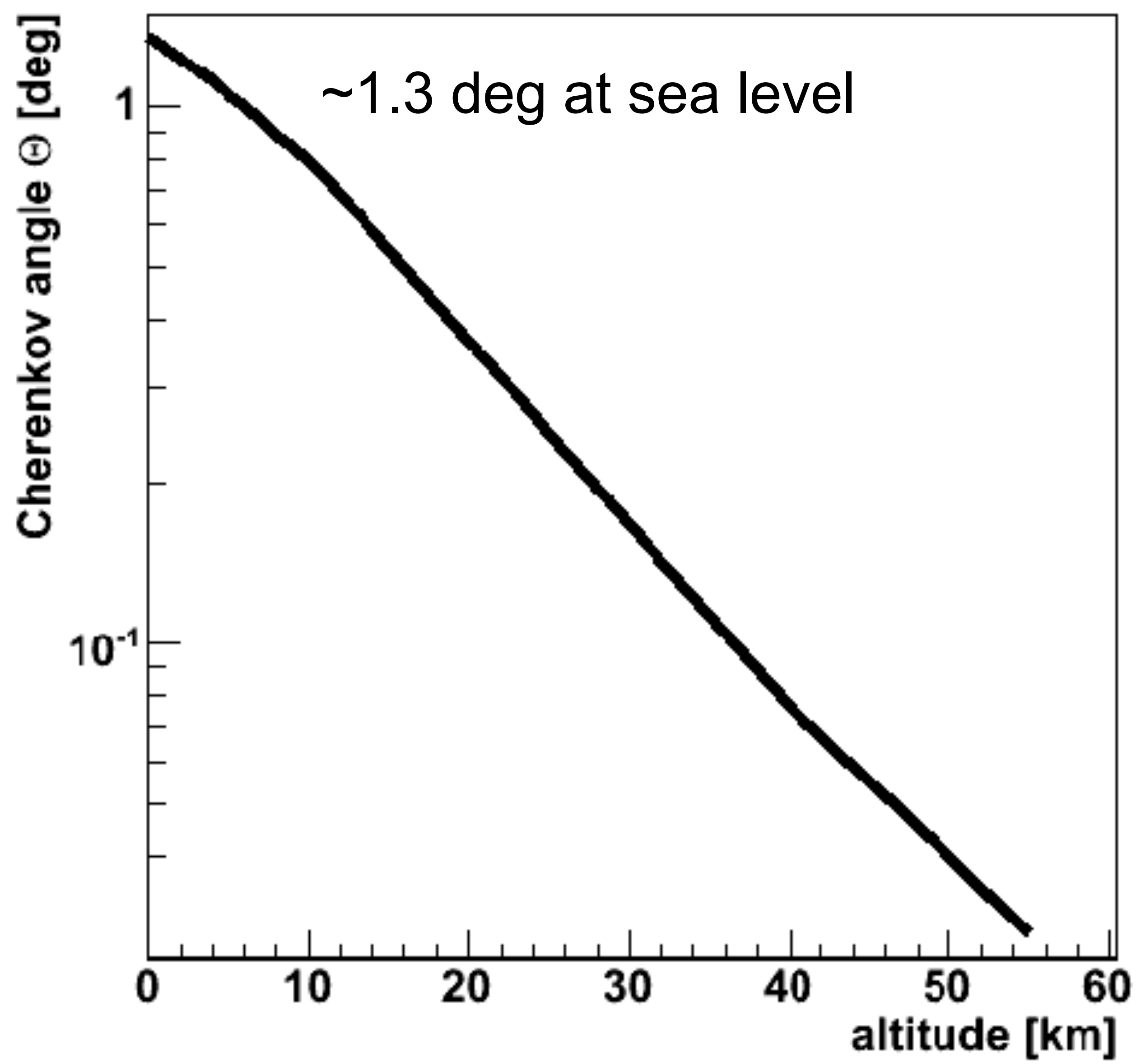

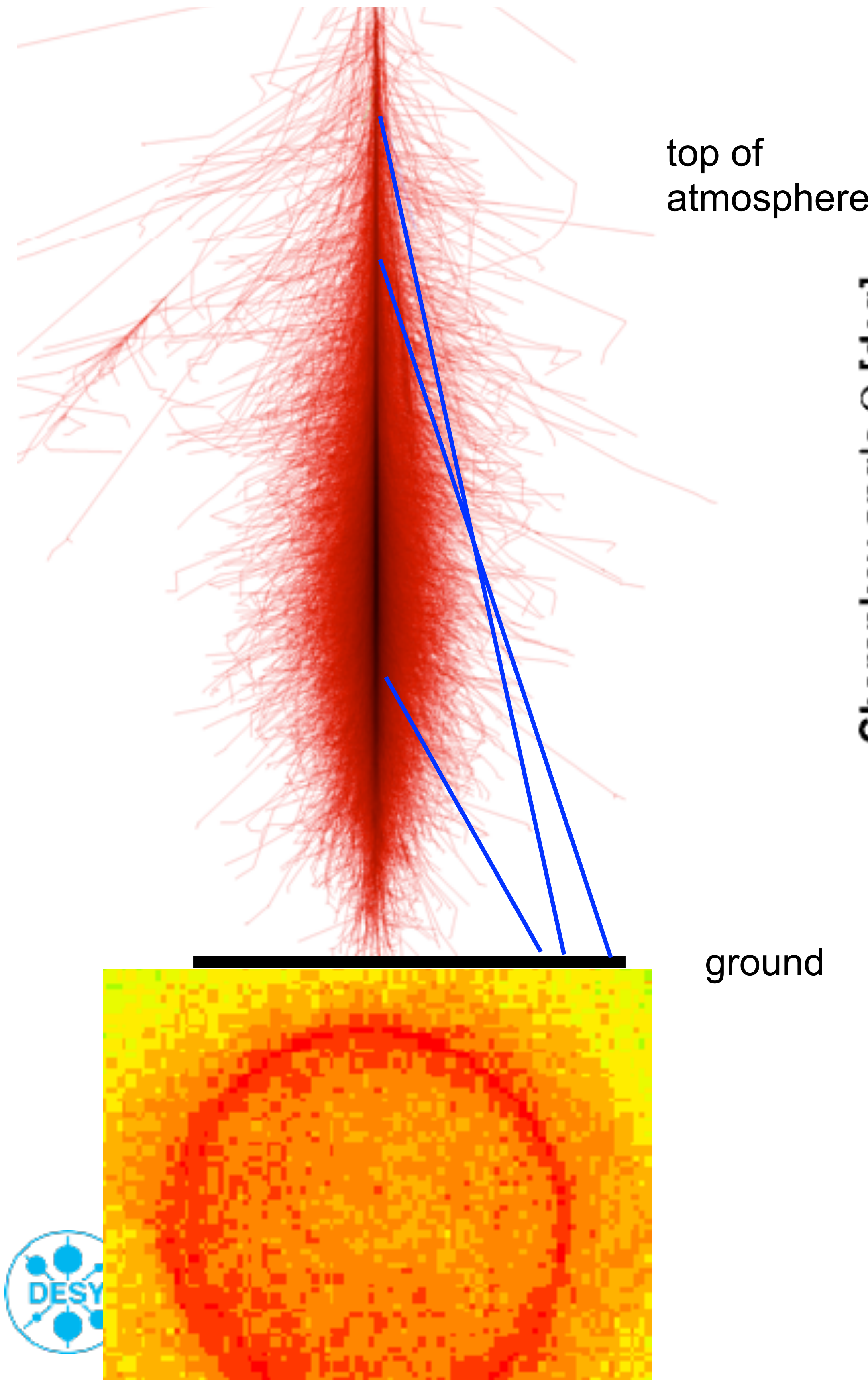

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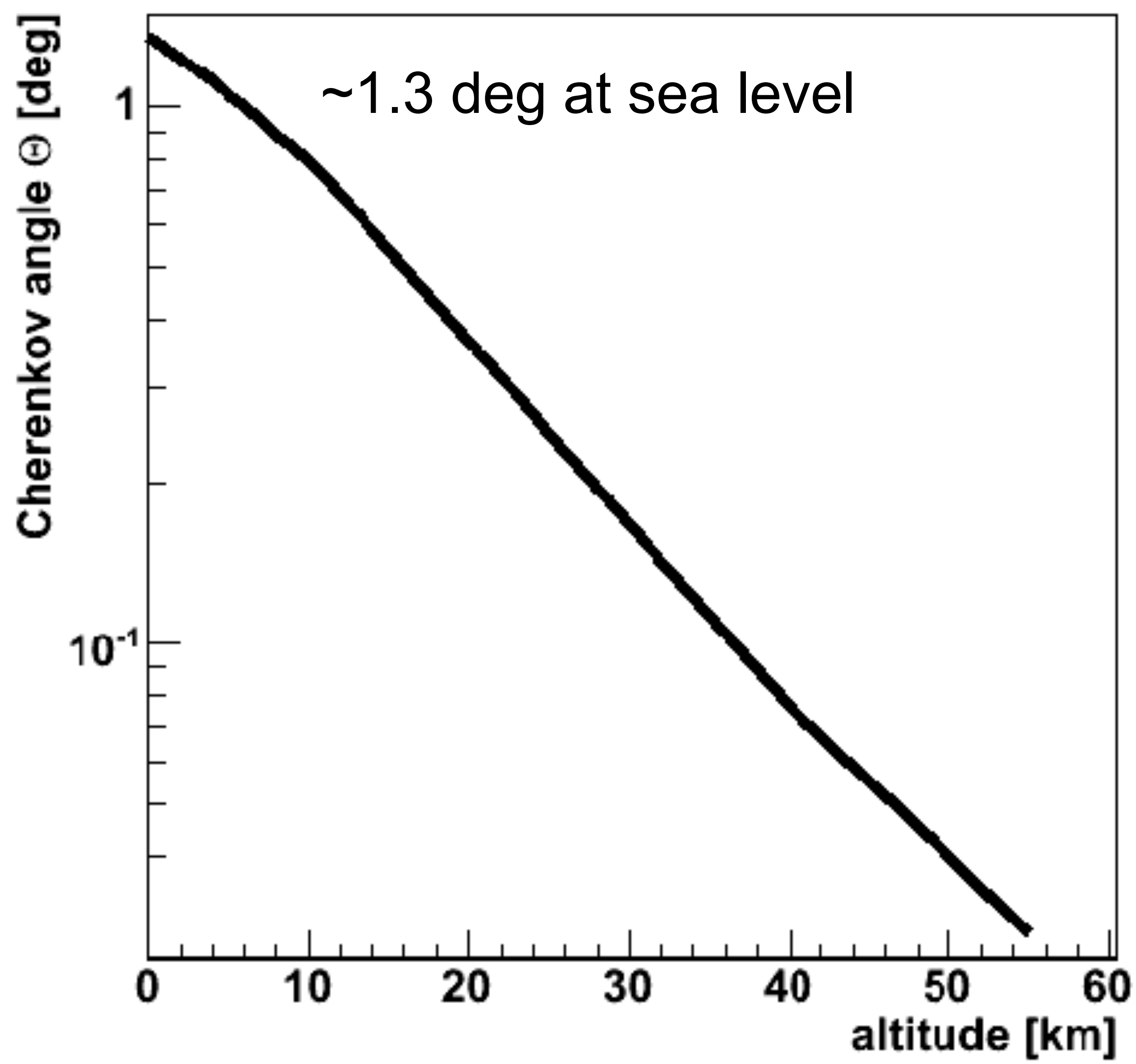

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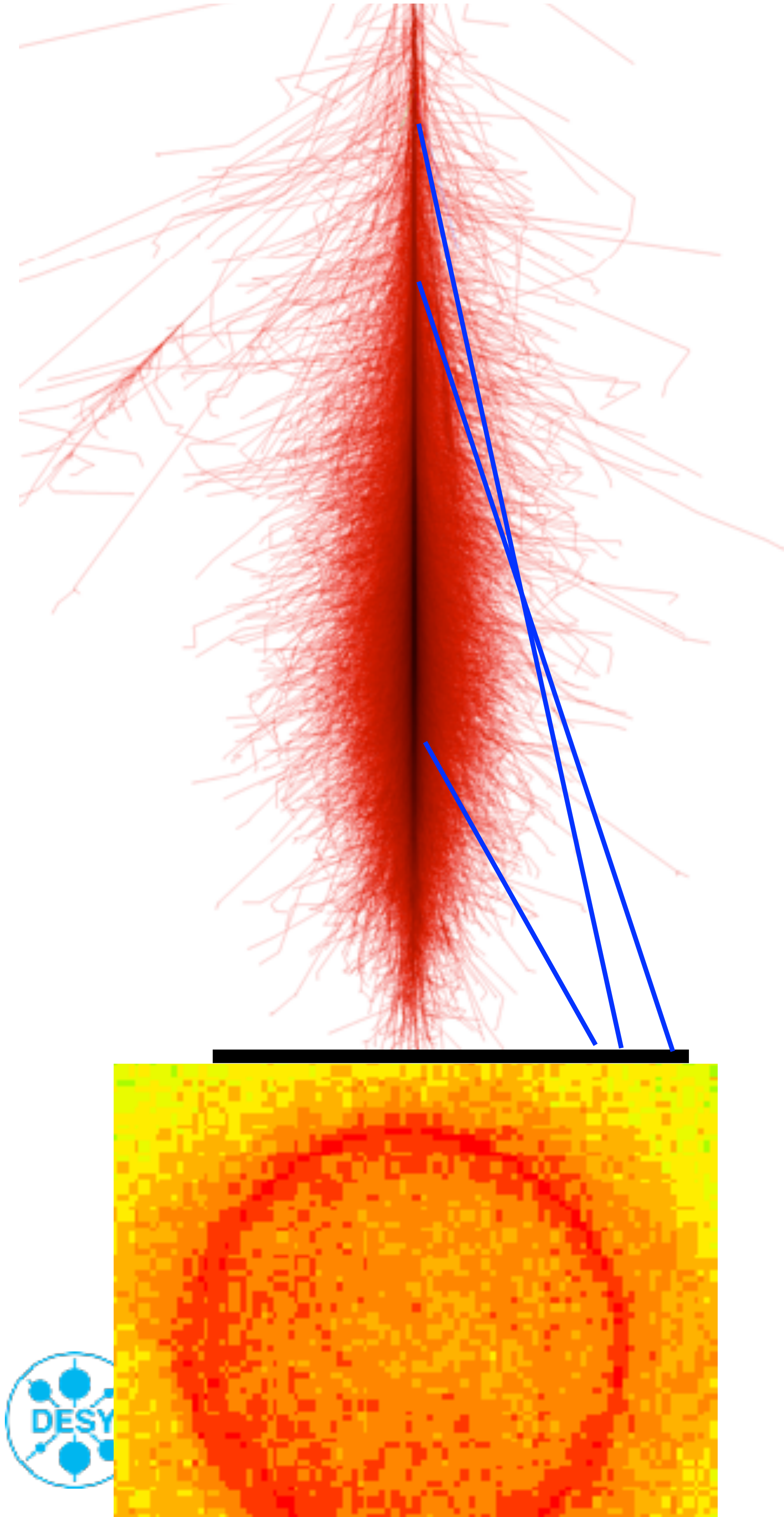

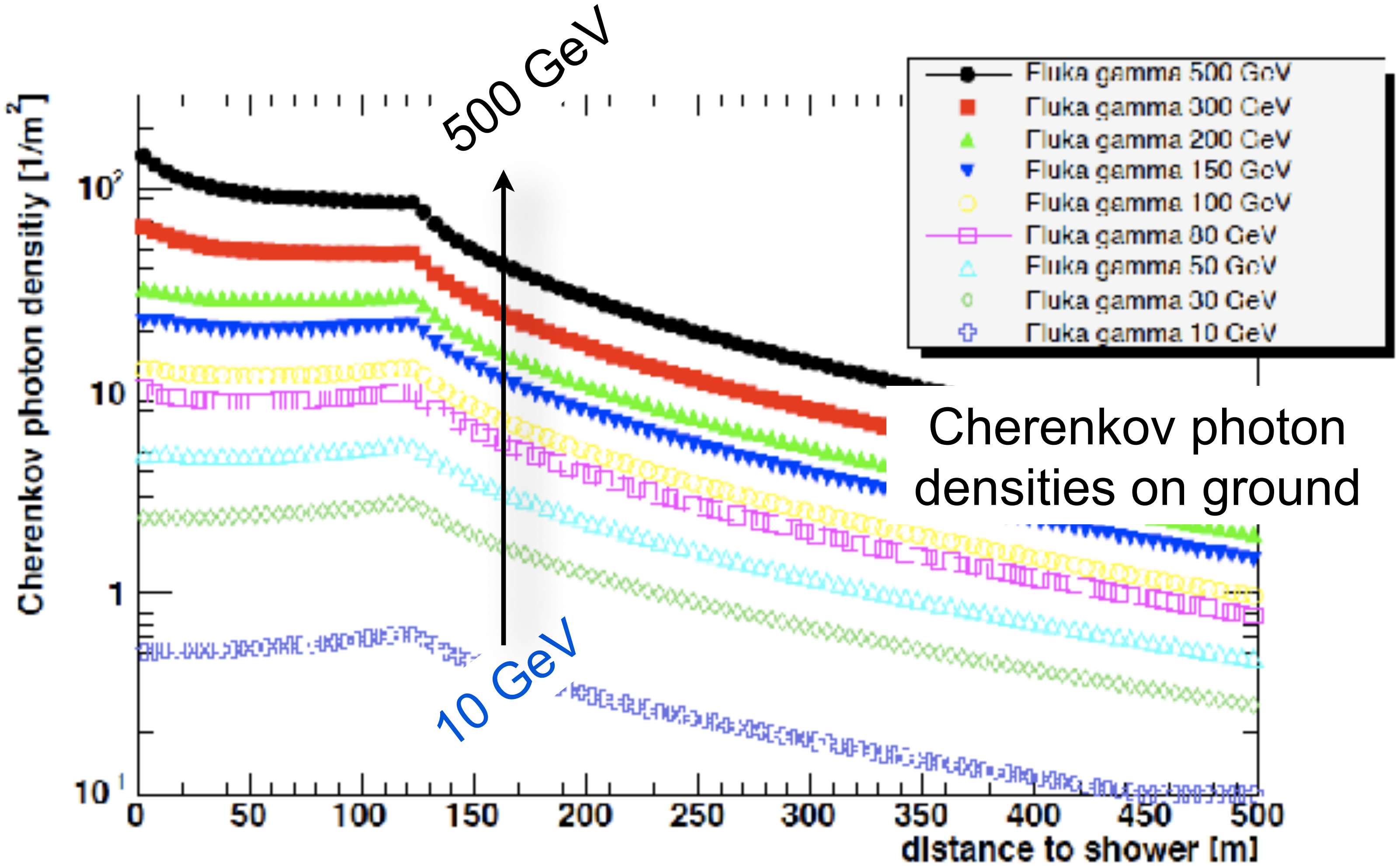

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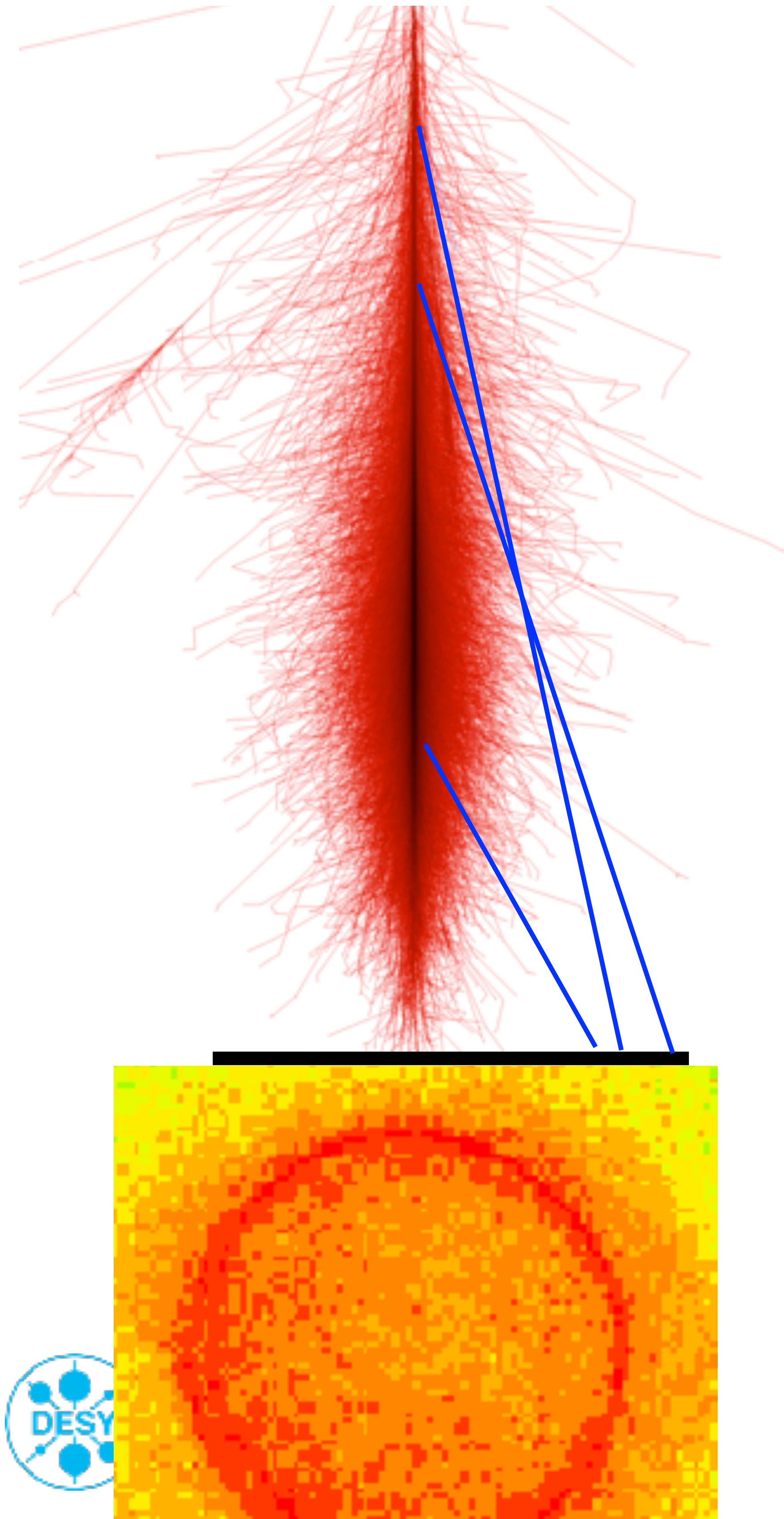

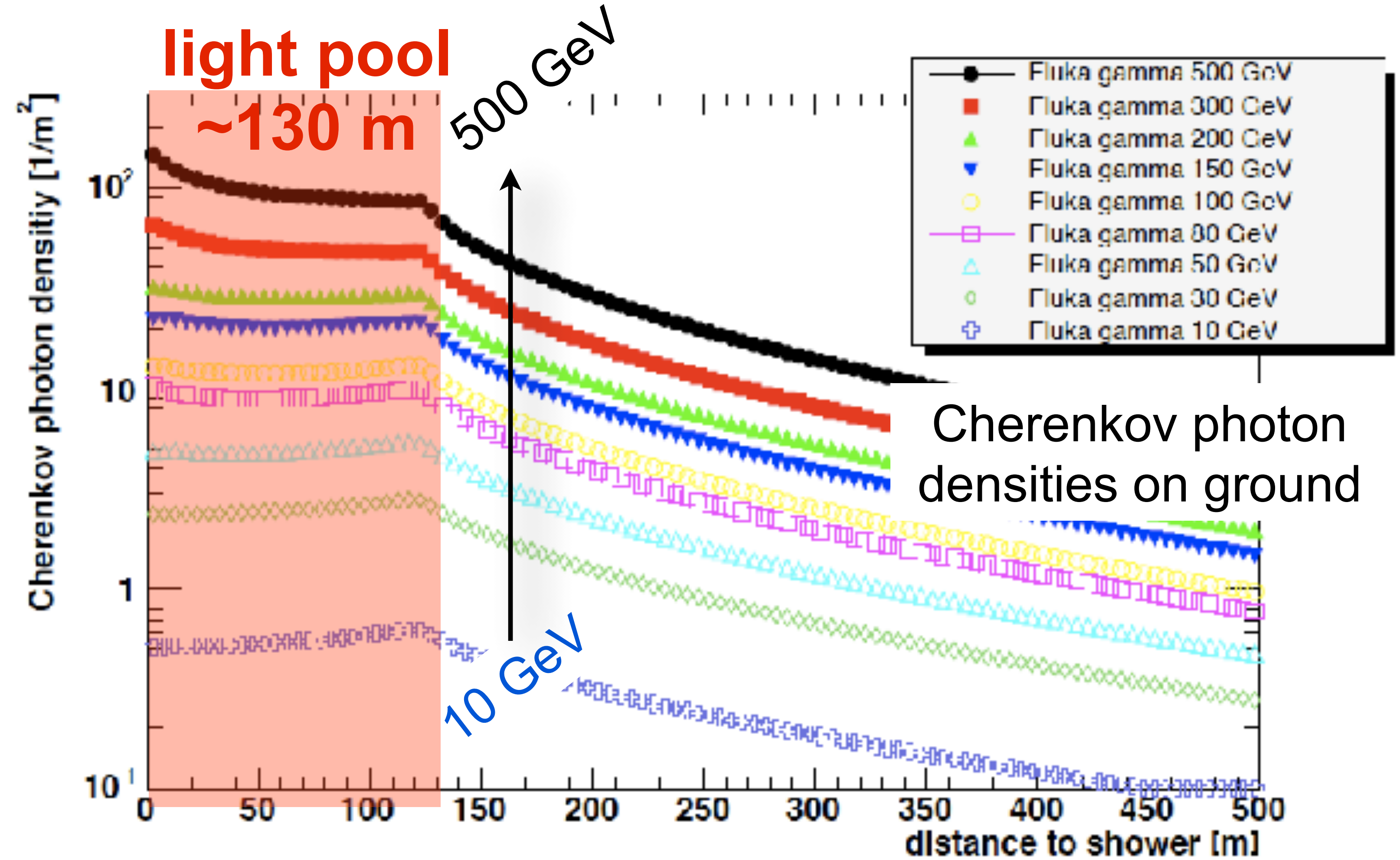

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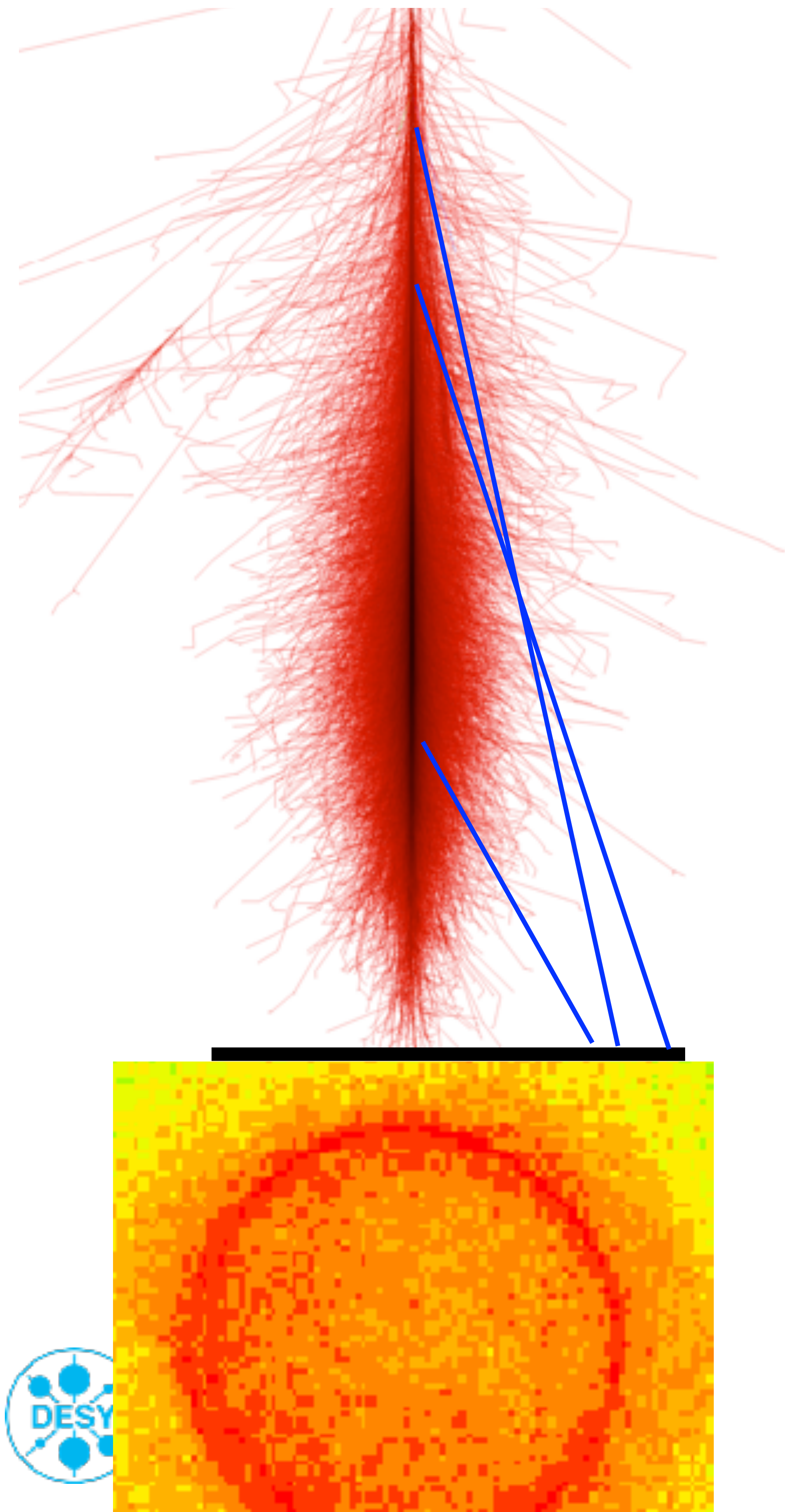
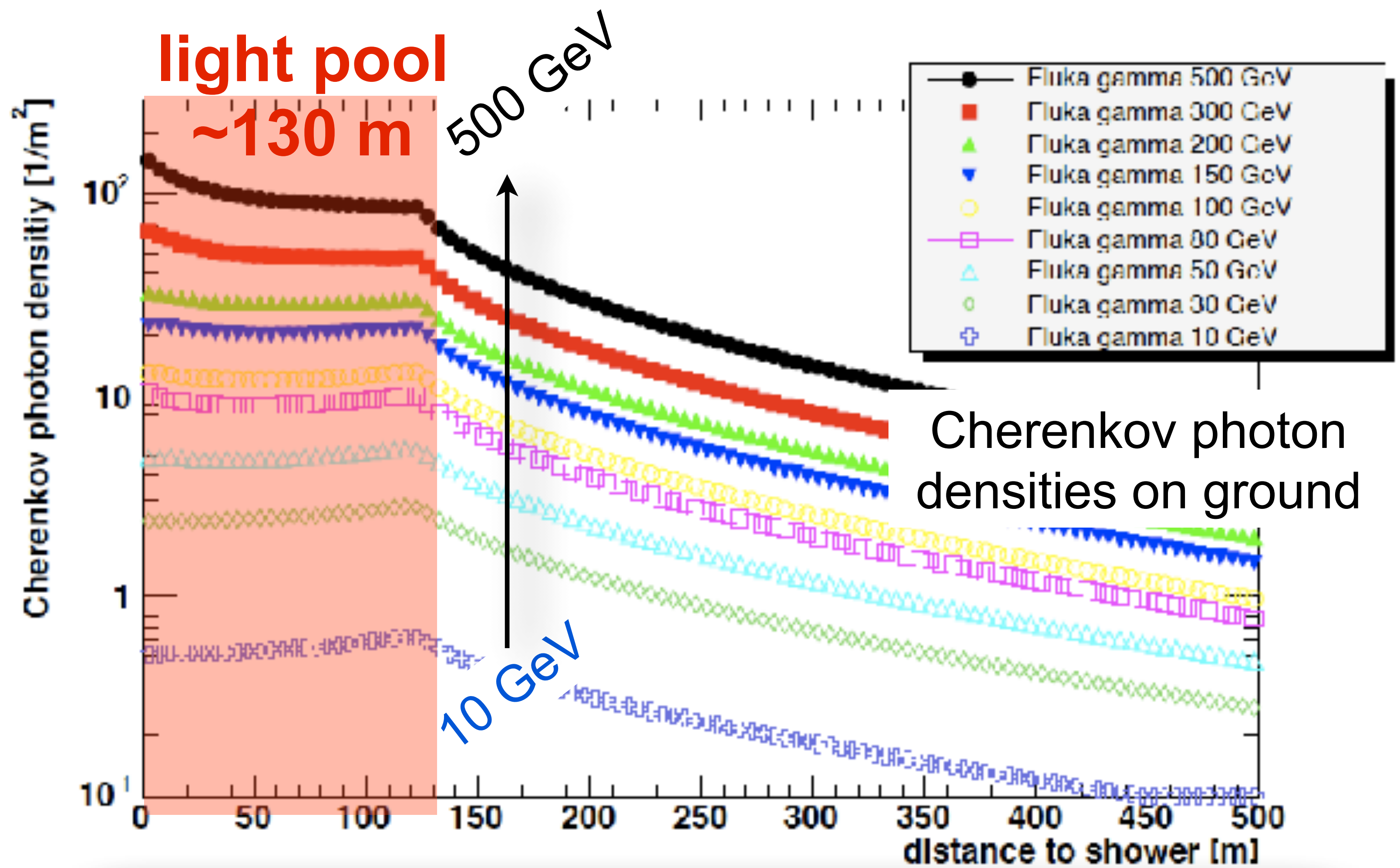
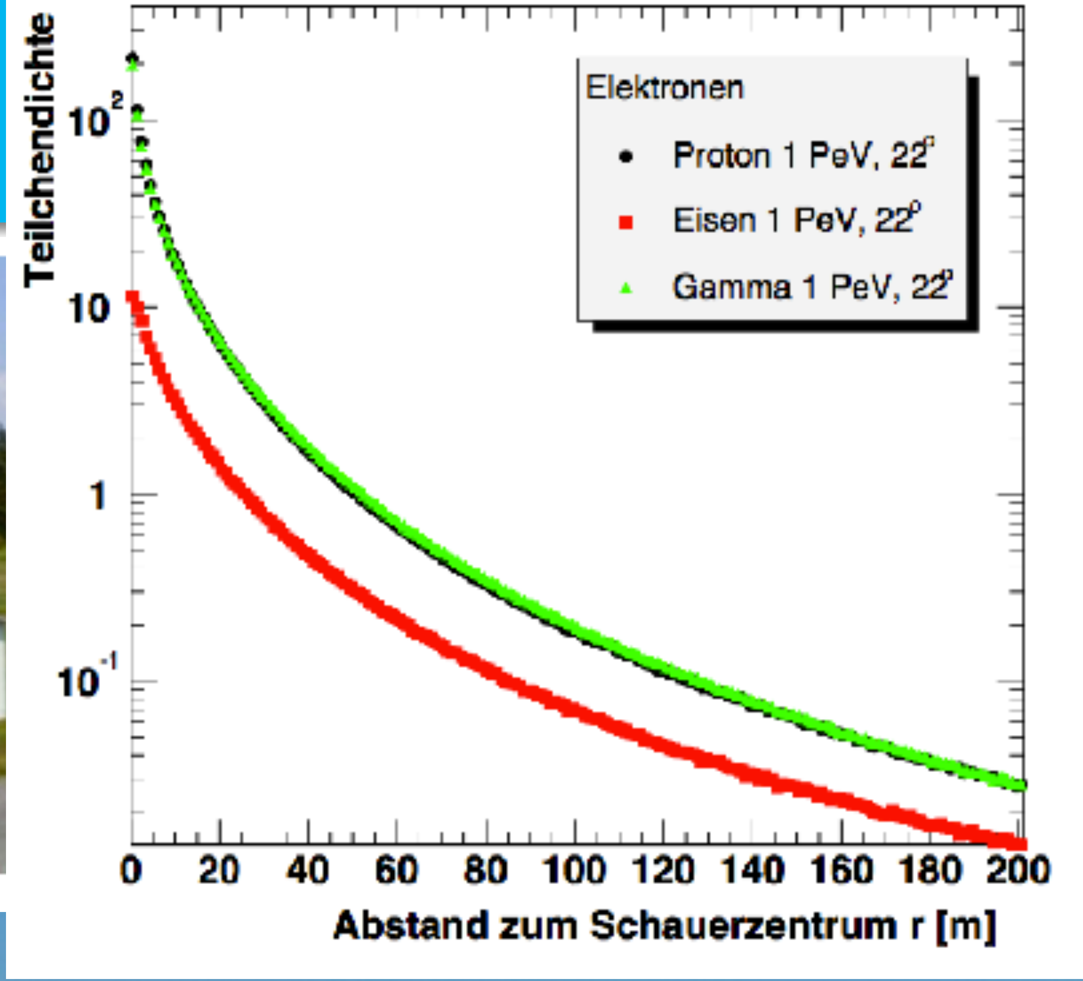


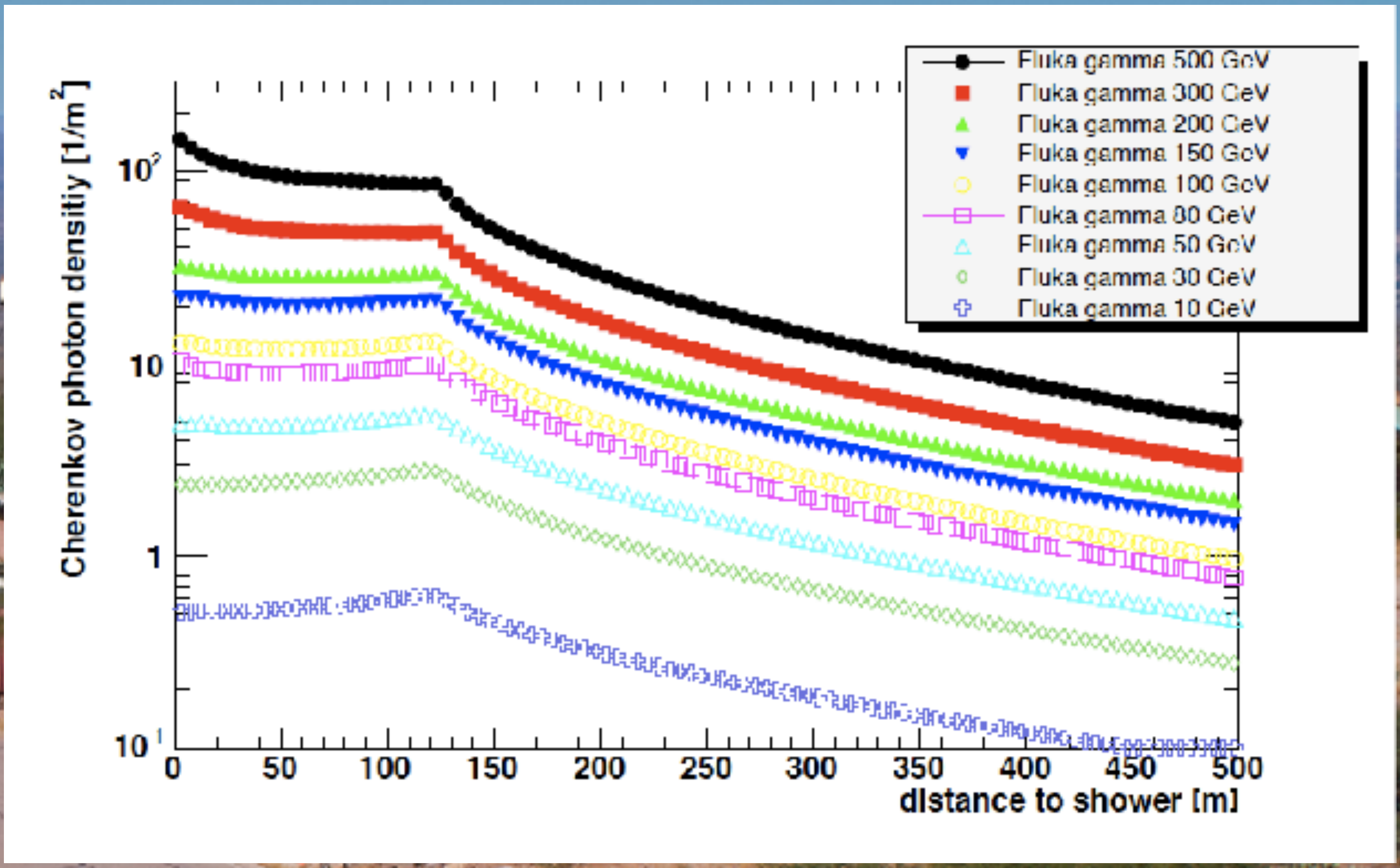


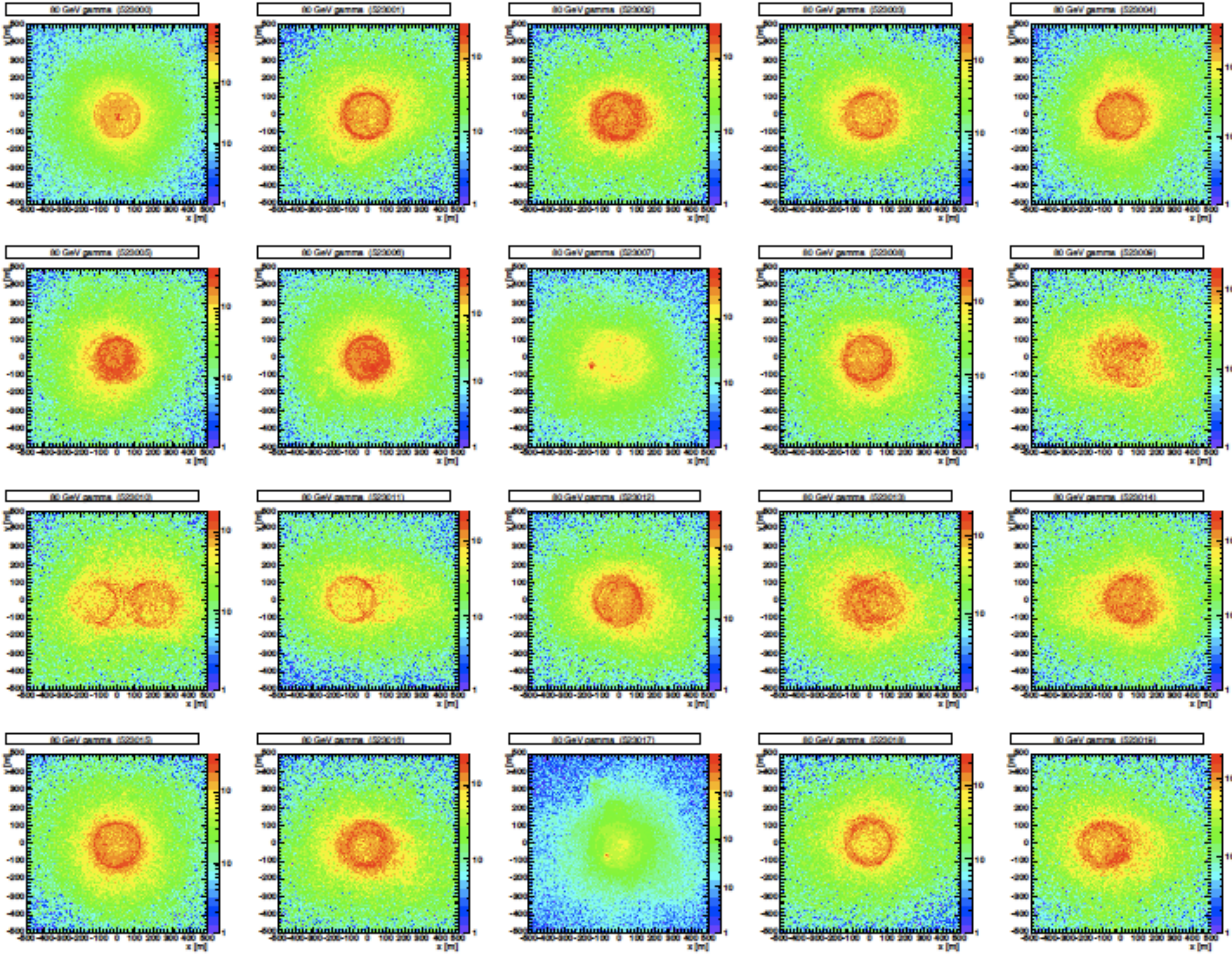
Nanoseconds long flash of mostly blue light; few photons / m^2

Lateral distribution comparison

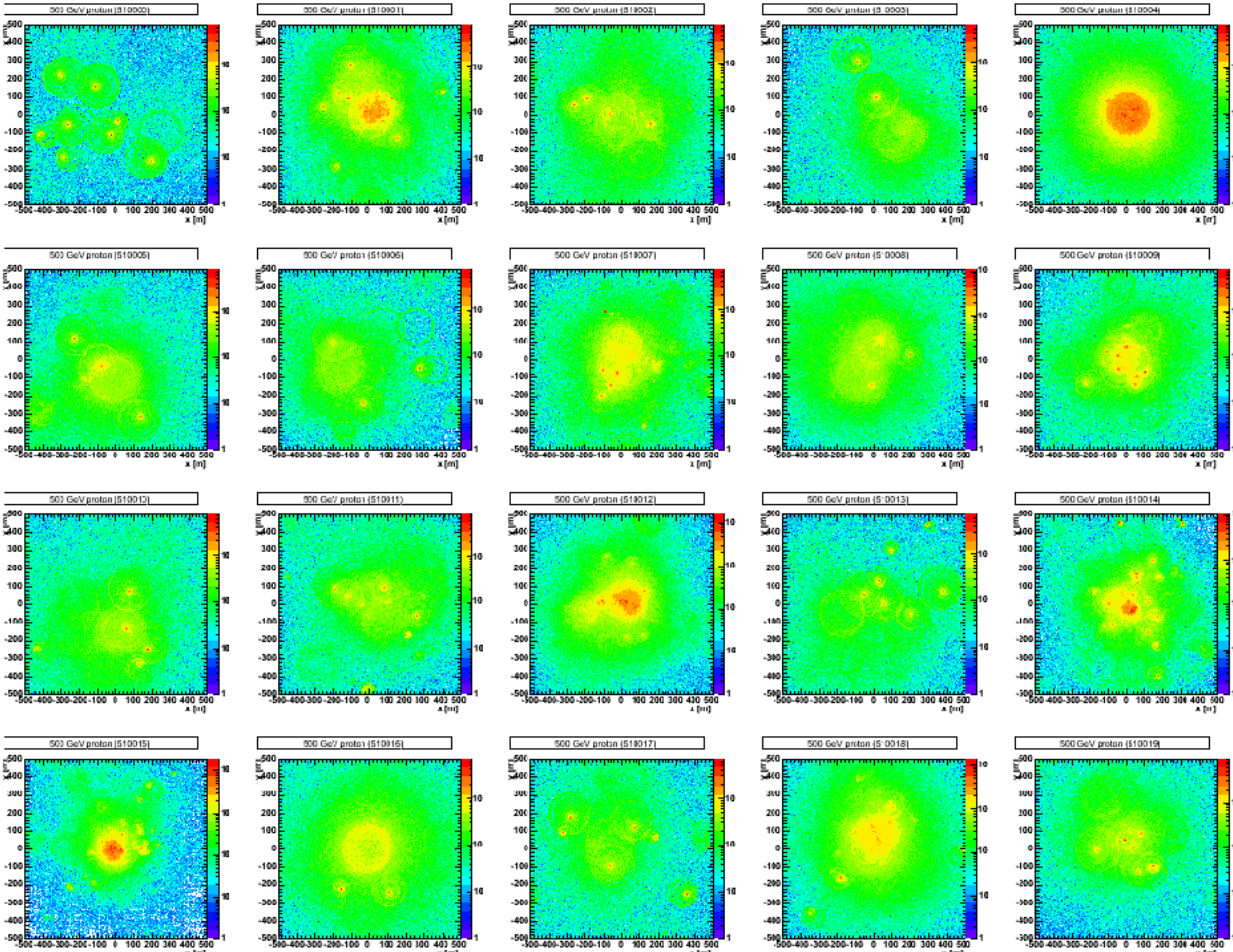
Lateral distribution comparison







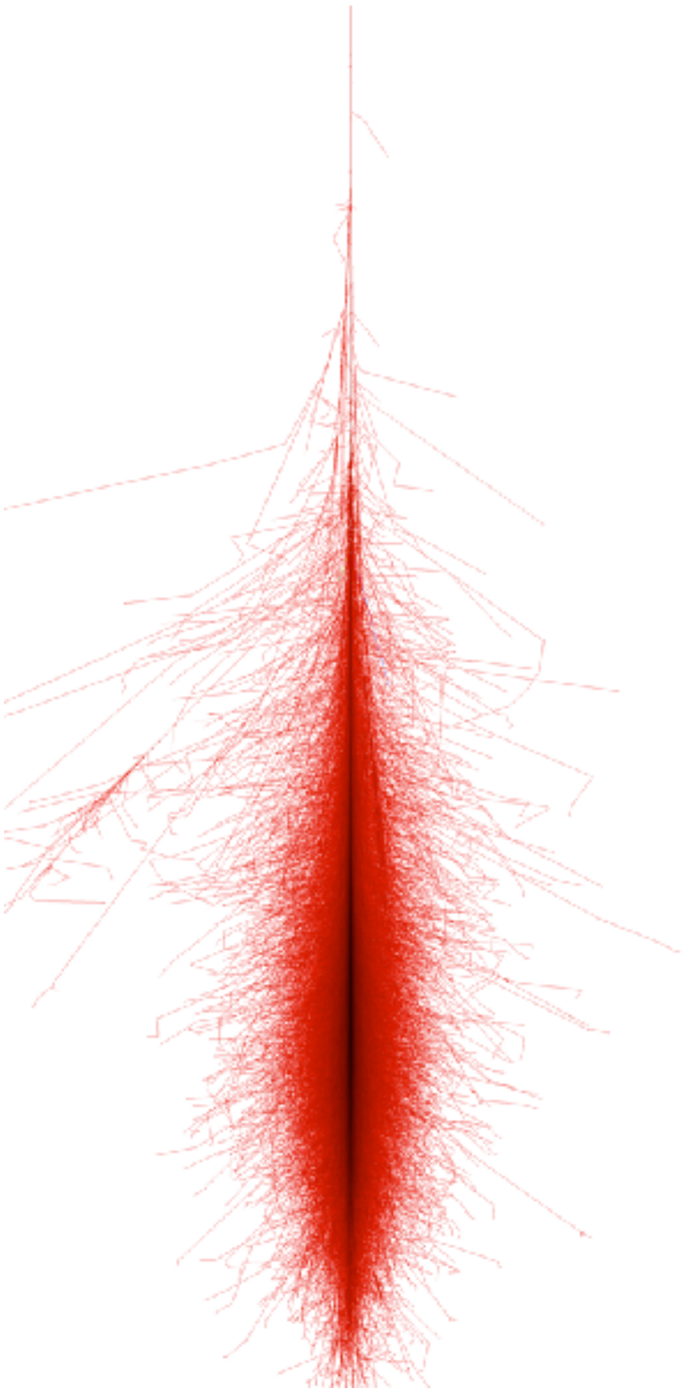
randomly selected showers with 80 GeV primary photon energy



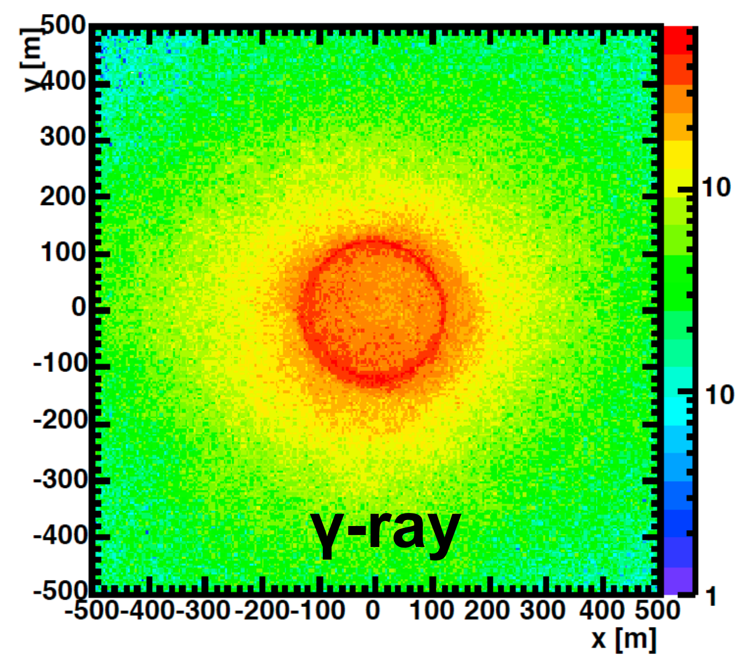
randomly selected showers with 500 GeV primary proton energy

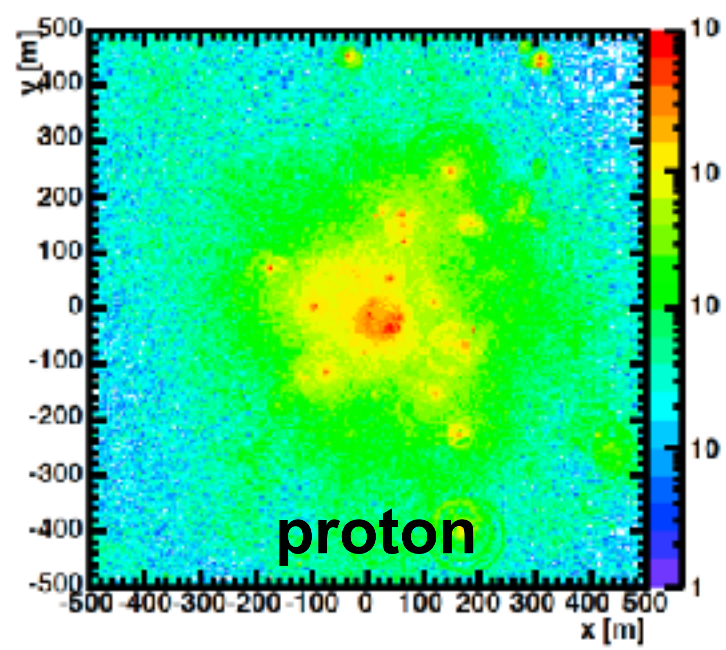
Proton vs Gamma-ray showers

γ-ray

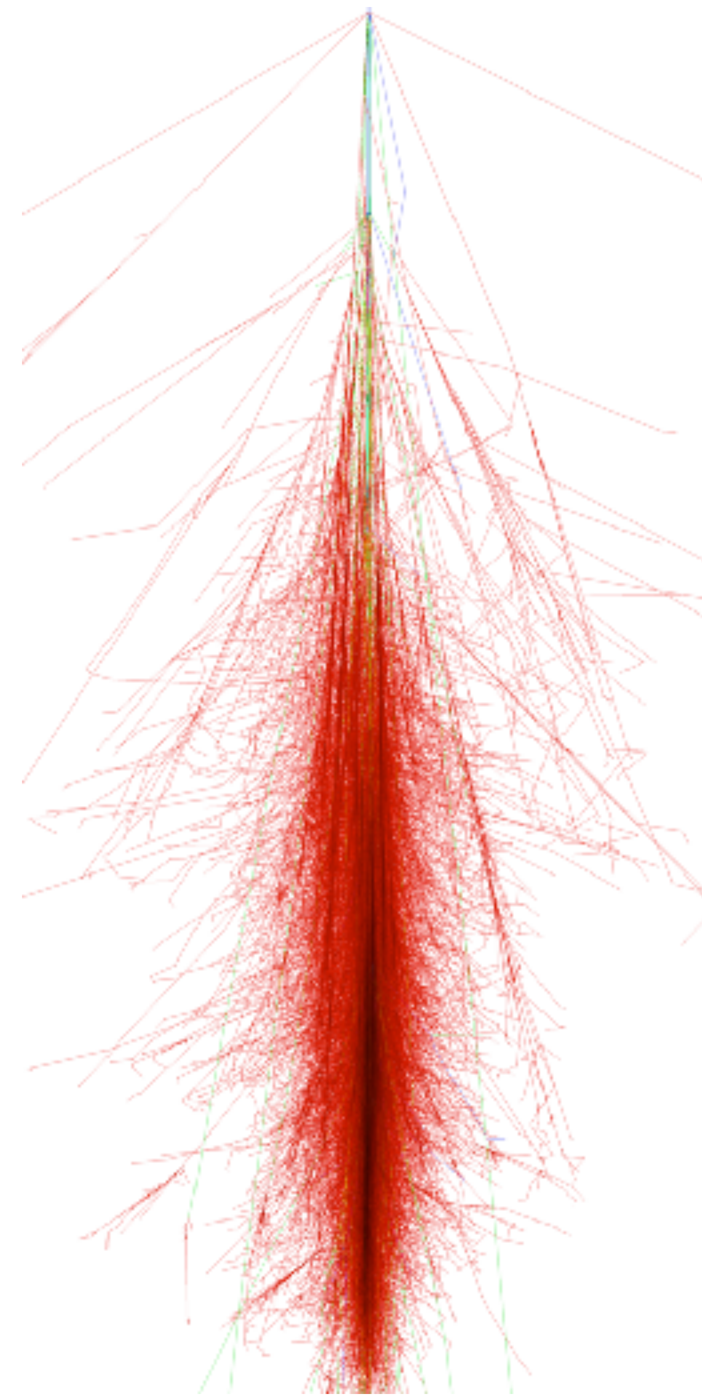


Cherenkov photons on ground

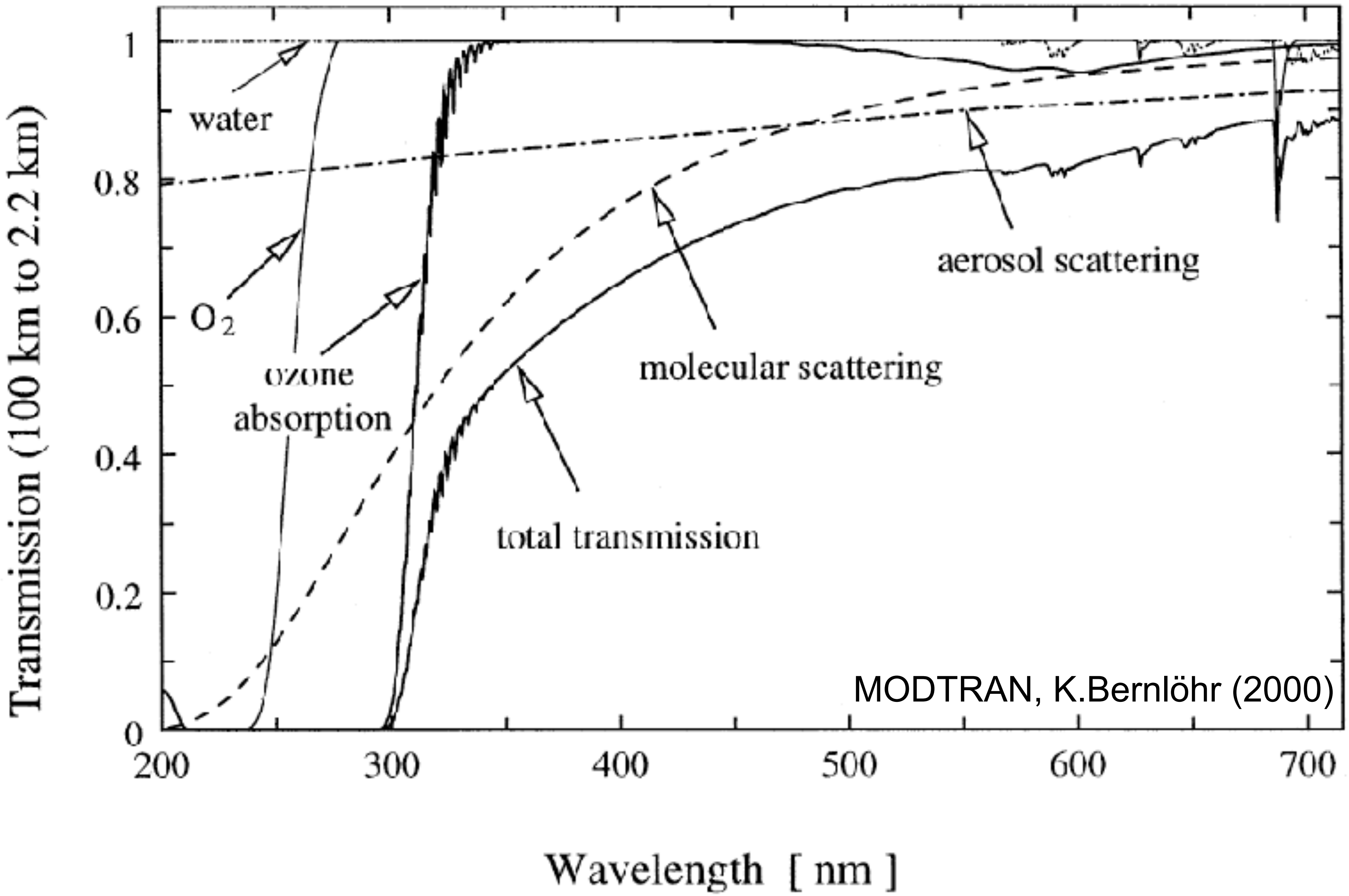




proton

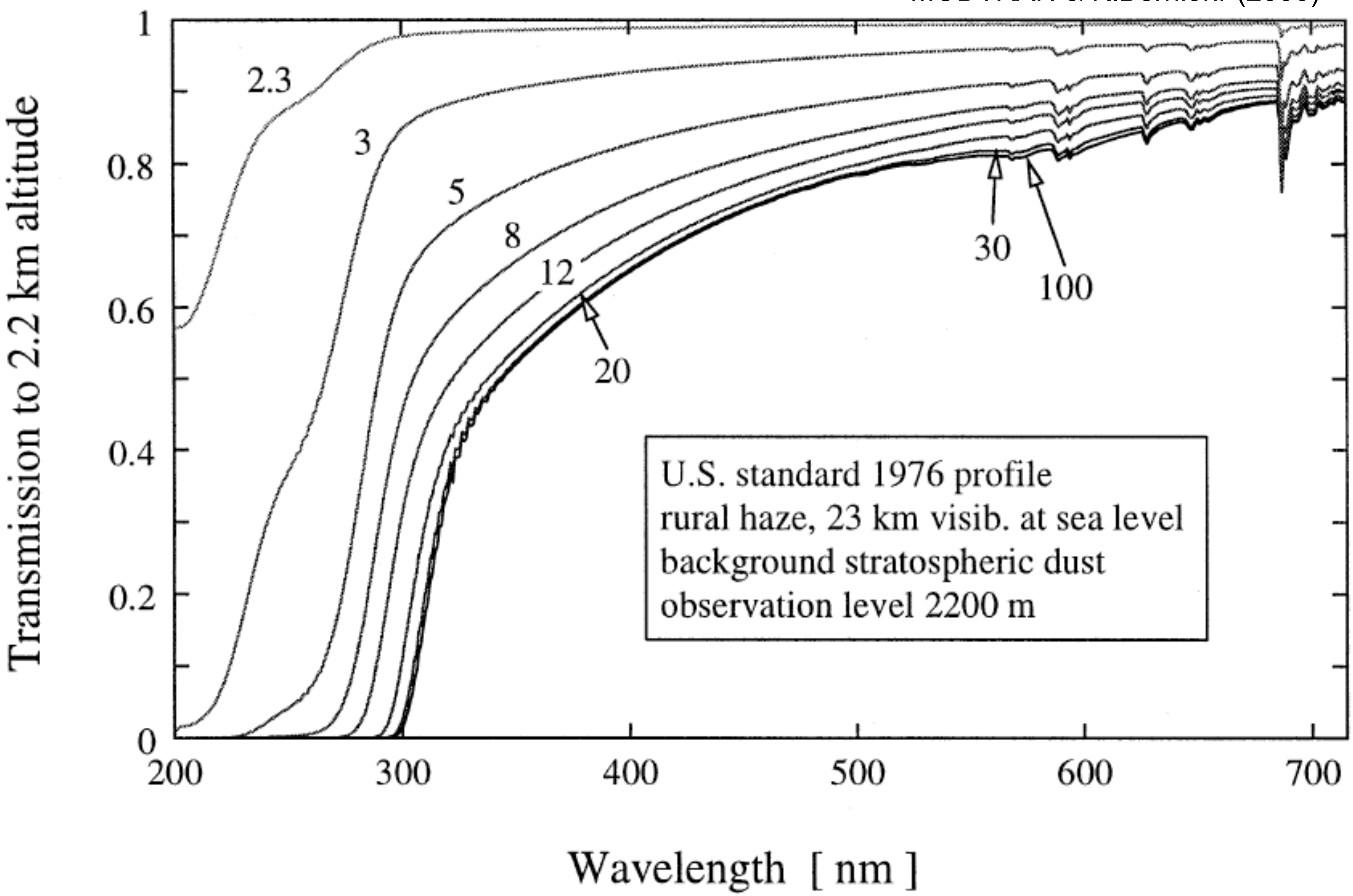


Propagation of Cherenkov Photons in the Atmosphere

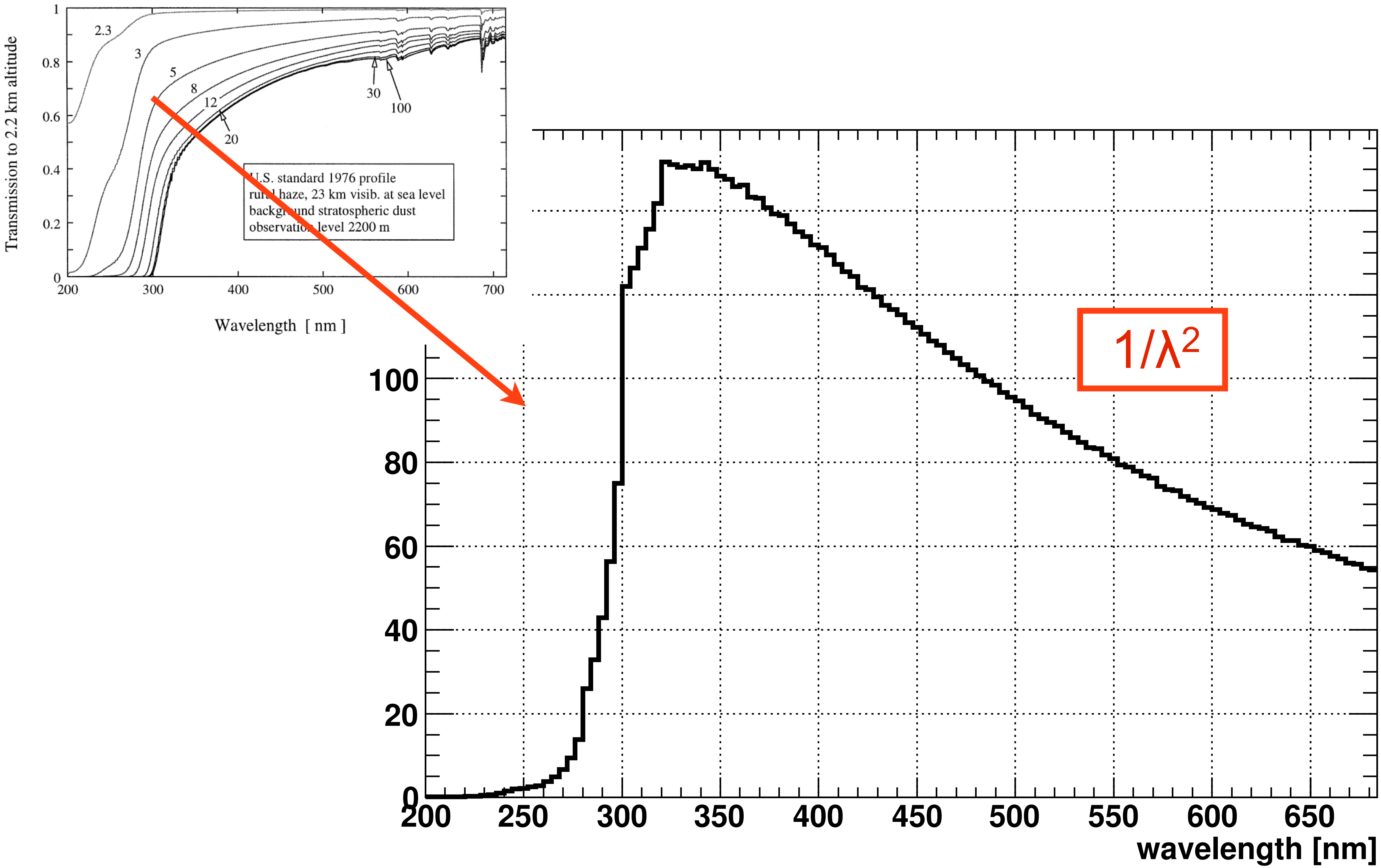


Propagation of Cherenkov Photons in the Atmosphere

MODTRAN & K.Bernlöhr (2000)



Cherenkov radiation: wavelength distribution



Measuring Air Showers

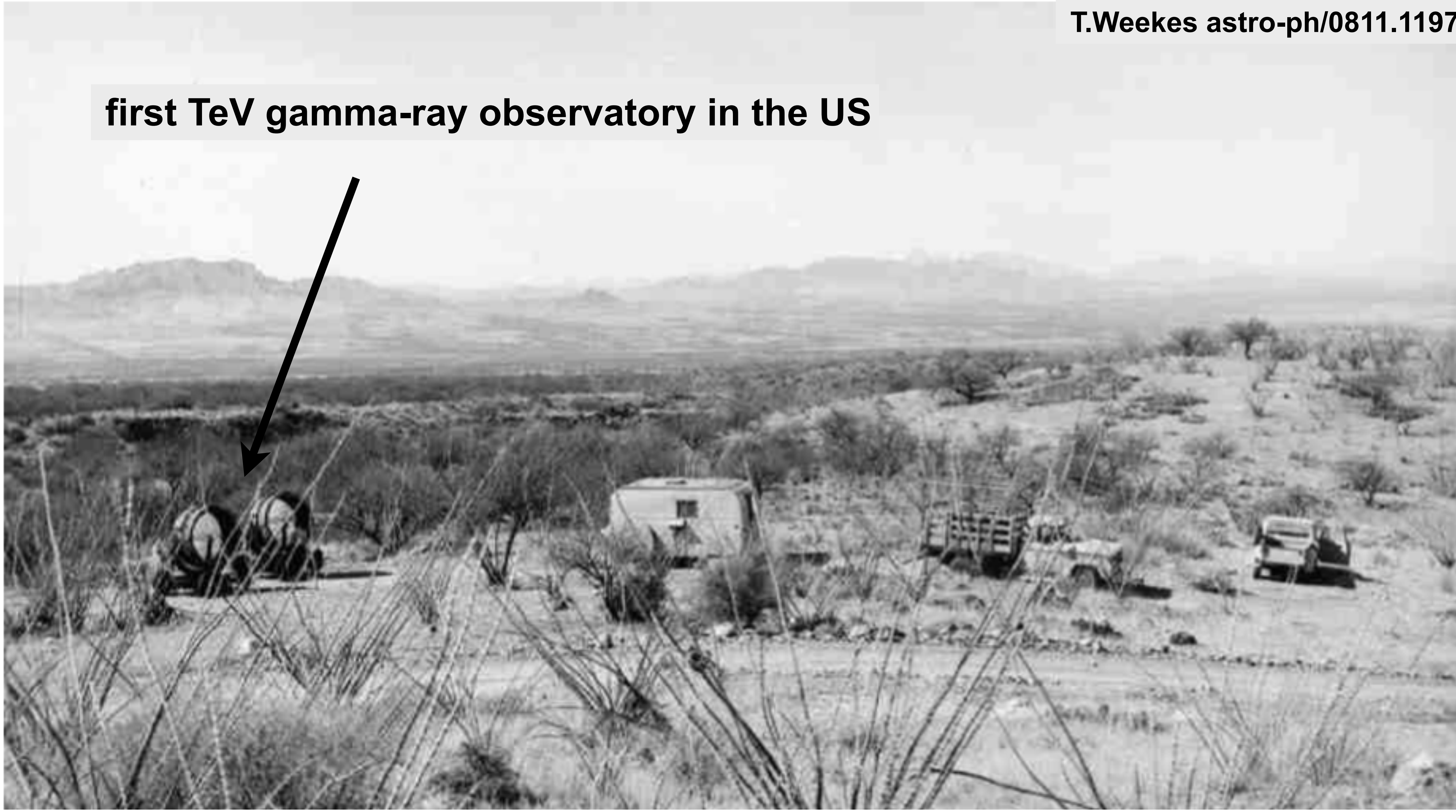


FIGURE 1. The first TeV gamma-ray observatory in the United States consisted of two 1.5m telescopes (made from World War II searchlight reflectors) above (left center); the telescopes were manually operated and were located at a dark site in southern Arizona during the winter of 1967-8 [10]. The telescopes were directed (by eye) at a point ahead of the position of the putative source so that the earth's rotation swept the source through the field of view. Power came from an electric generator on the back of the truck (center right) and the pulse counting electronics were housed in a small trailer (center). The system was mercifully free of computers and the analysis was done offline with a mechanical calculator. No sources were detected.

The Whipple Telescope

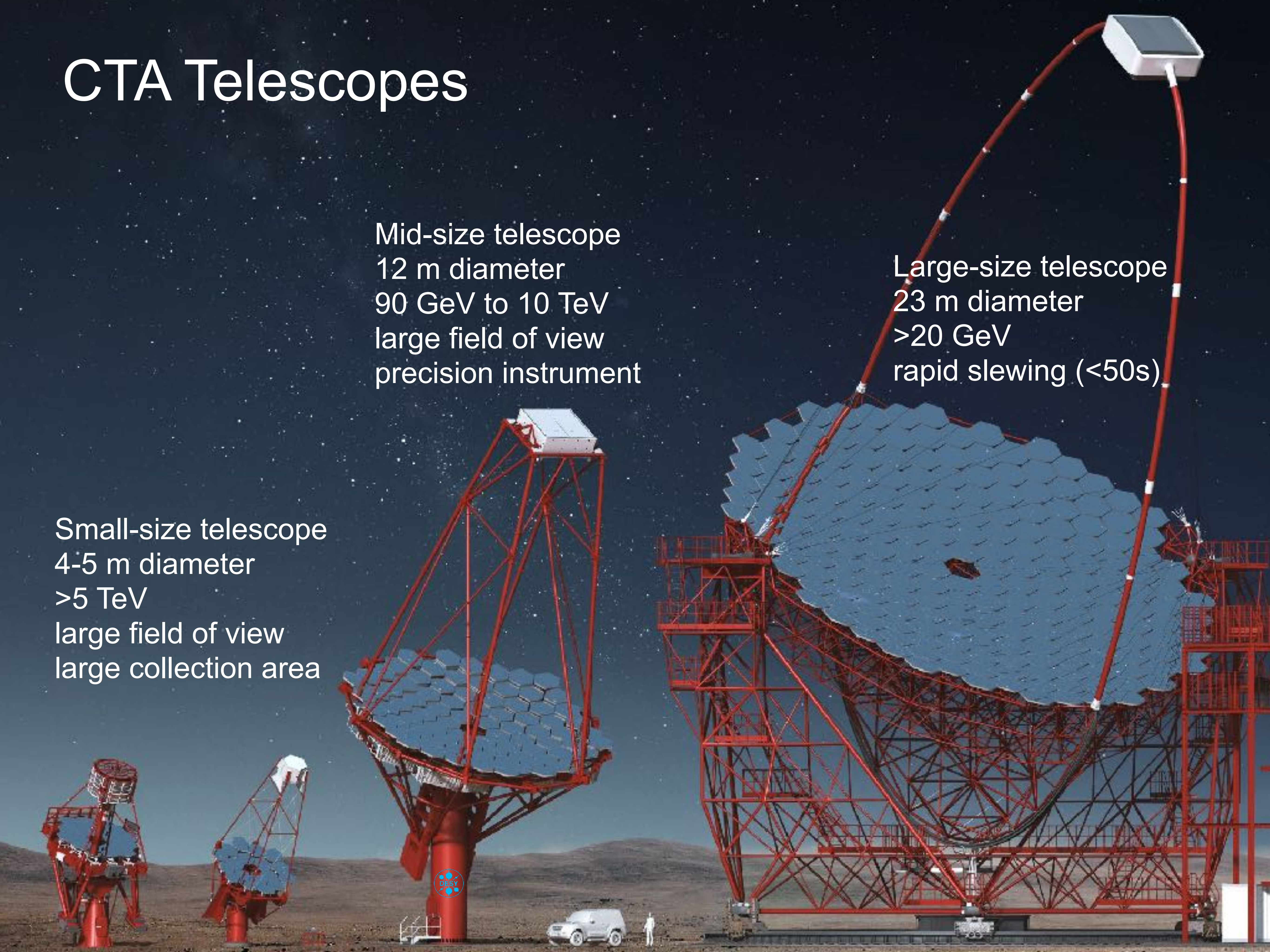
completed in 1968
upgrade with imaging camera proposed 1977
first detection (Crab Nebula) 1986


MAGIC

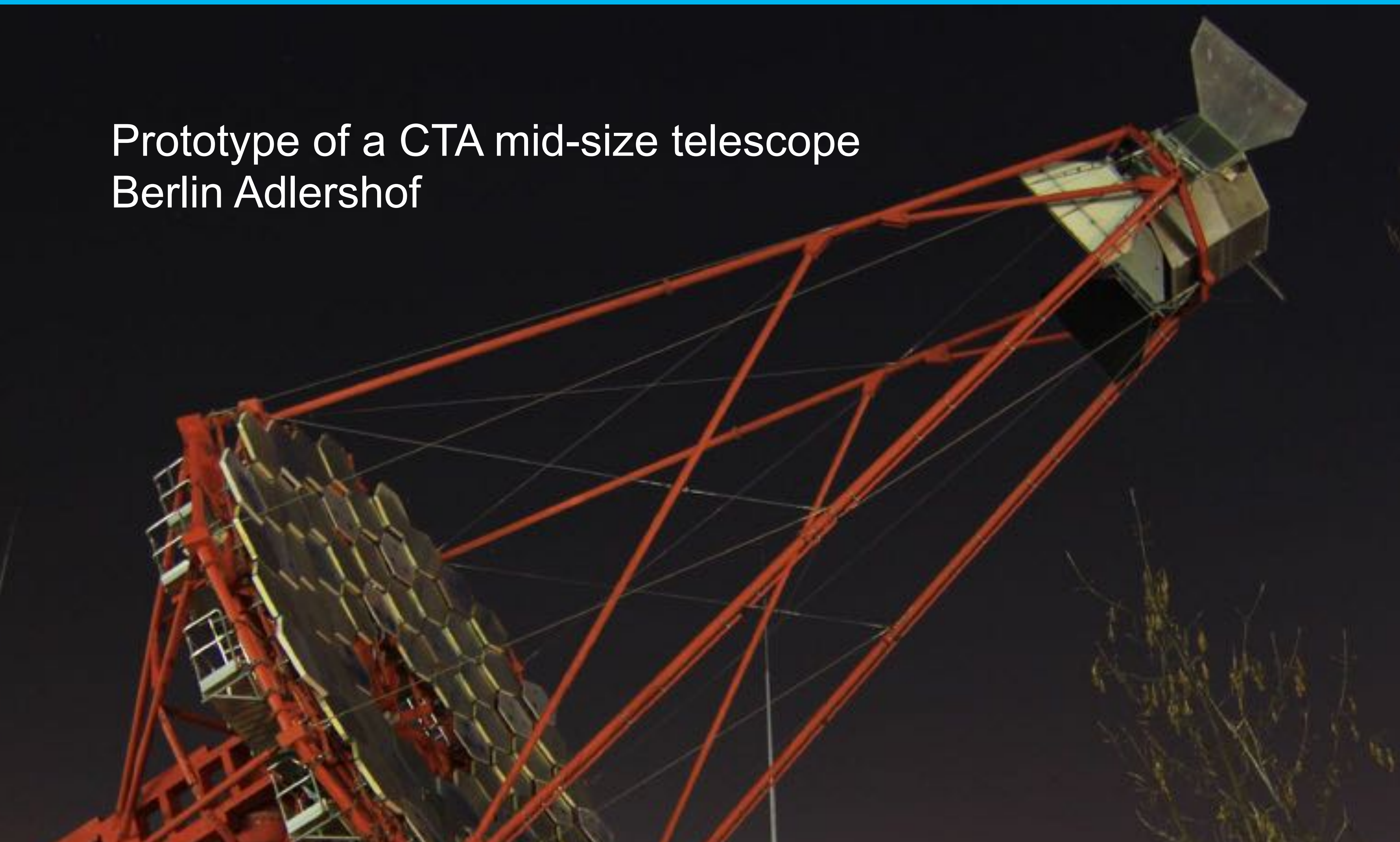

VERITAS


H.E.S.S.

CTA Telescopes



Prototypes


Prototype of a CTA mid-size telescope
Berlin Adlershof

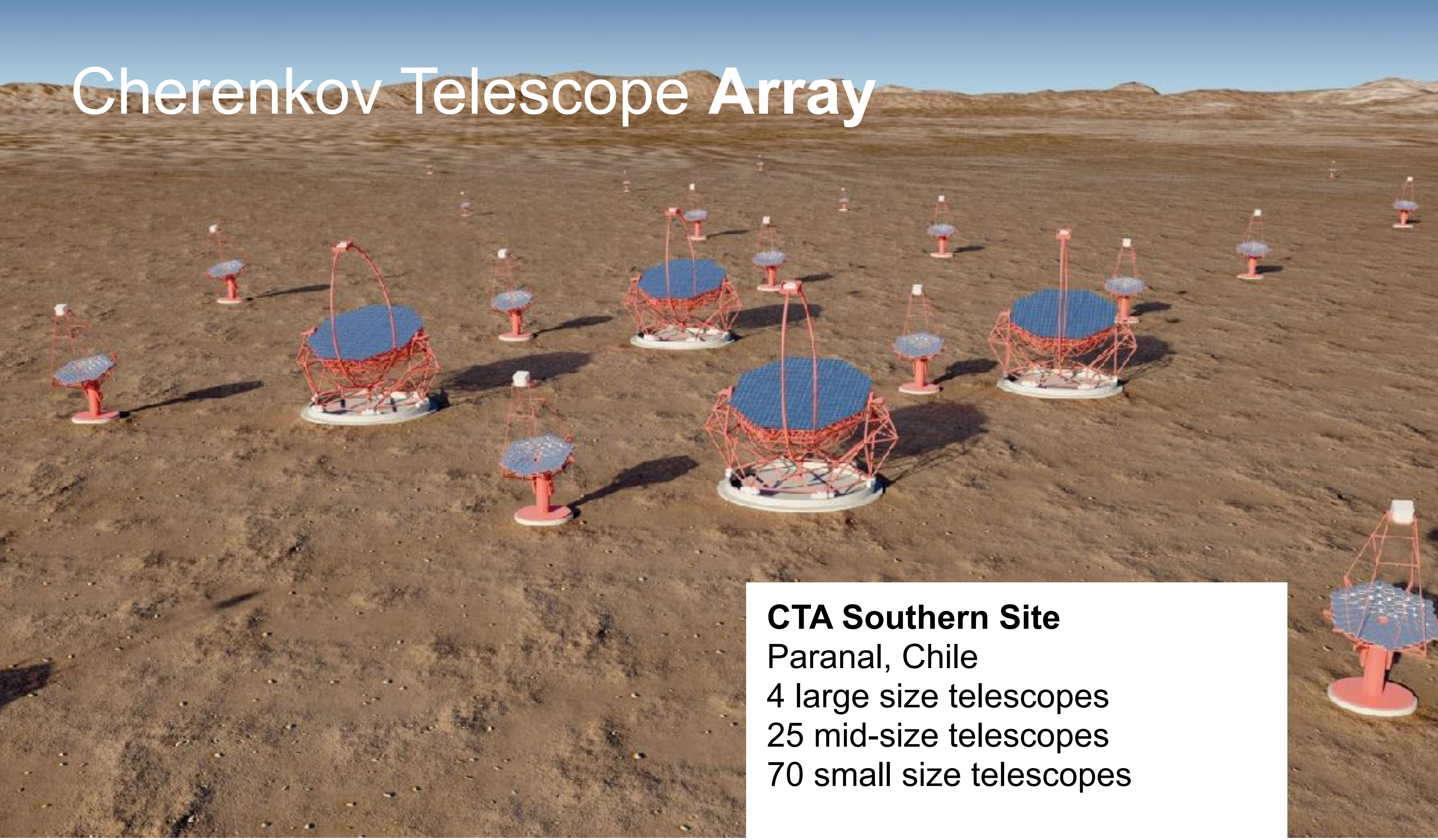

Dual-mirror mid-size telescope
(Arizona)


Small-size telescope
(Meudon)


Small-size telescope
(Krakow)


Small-size telescope
(Sicily)

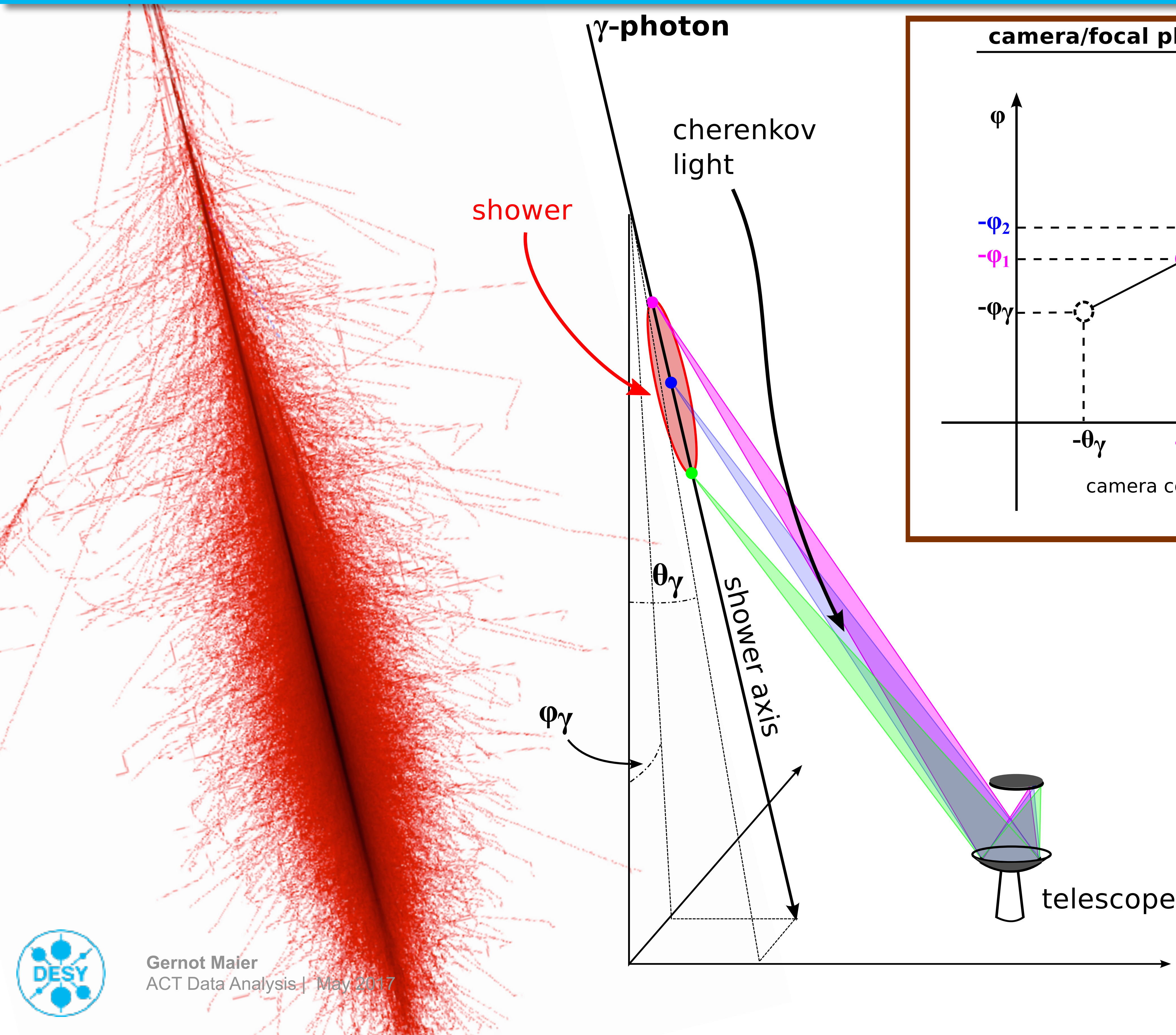
Cherenkov Telescope **Array**

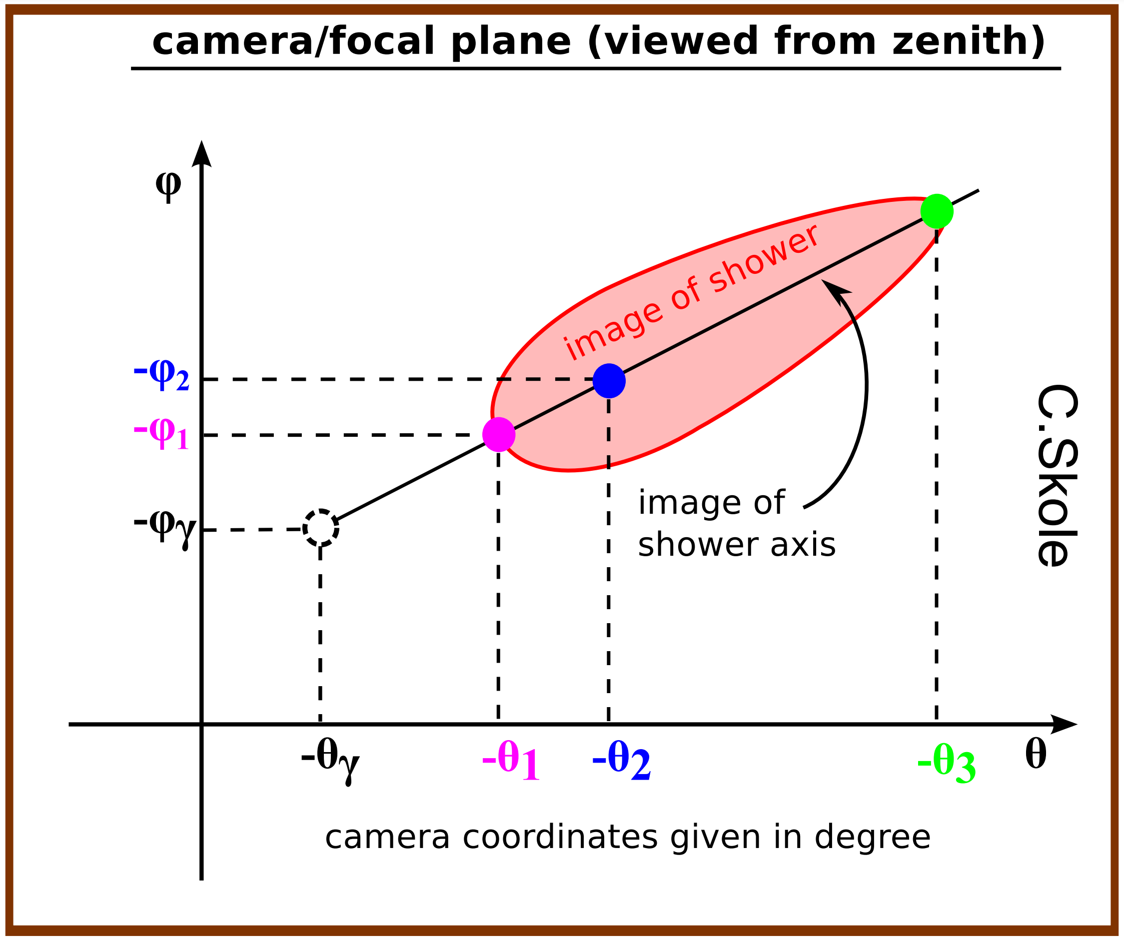


CTA Southern Site
Paranal, Chile
4 large size telescopes
25 mid-size telescopes
70 small size telescopes

CTA Northern Site
La Palma Island
4 large-size telescopes
15 mid-size telescopes

Measuring gamma-rays





Gamma-ray images

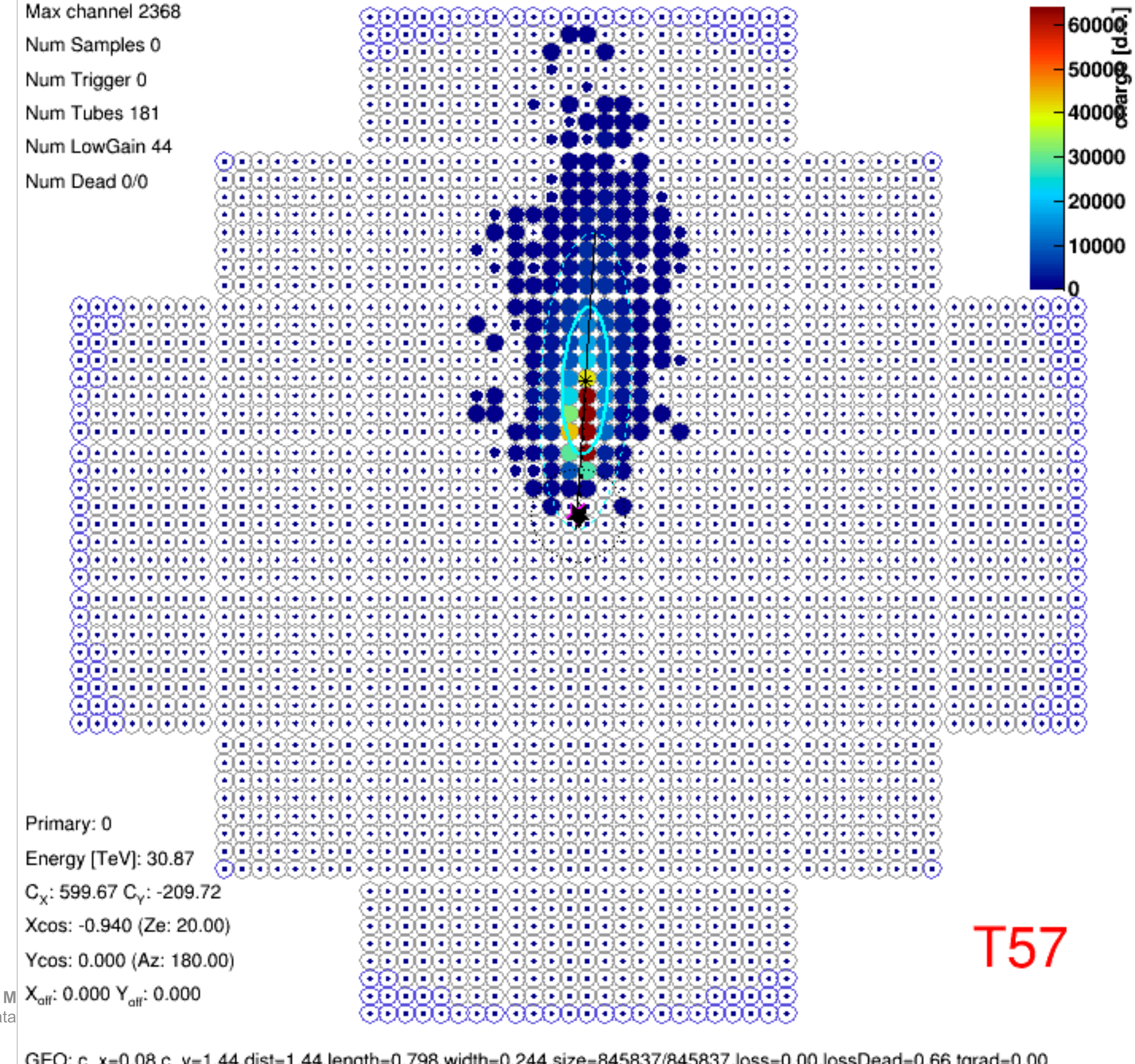
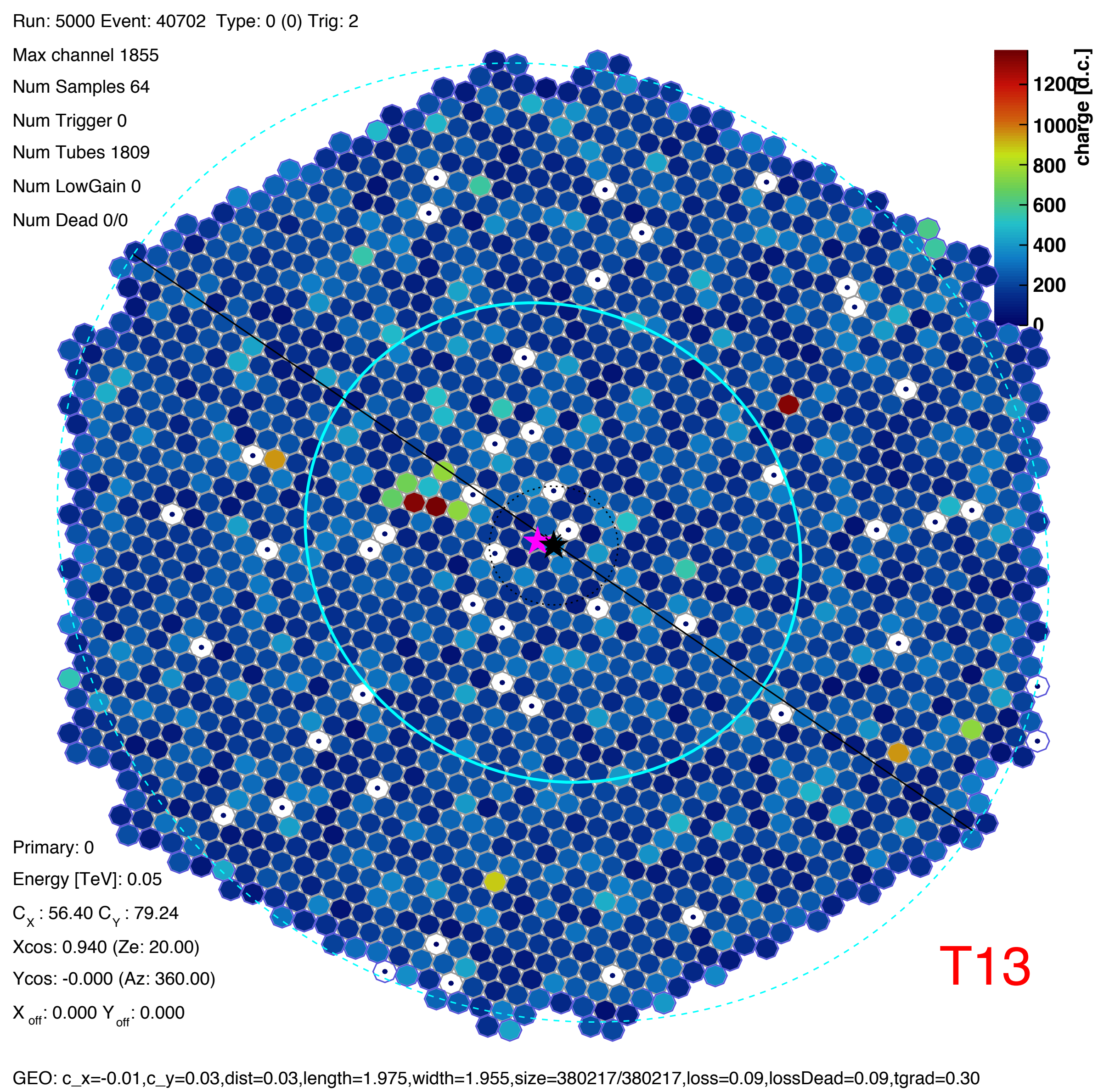


Image Cleaning

uncleaned image



cleaned image

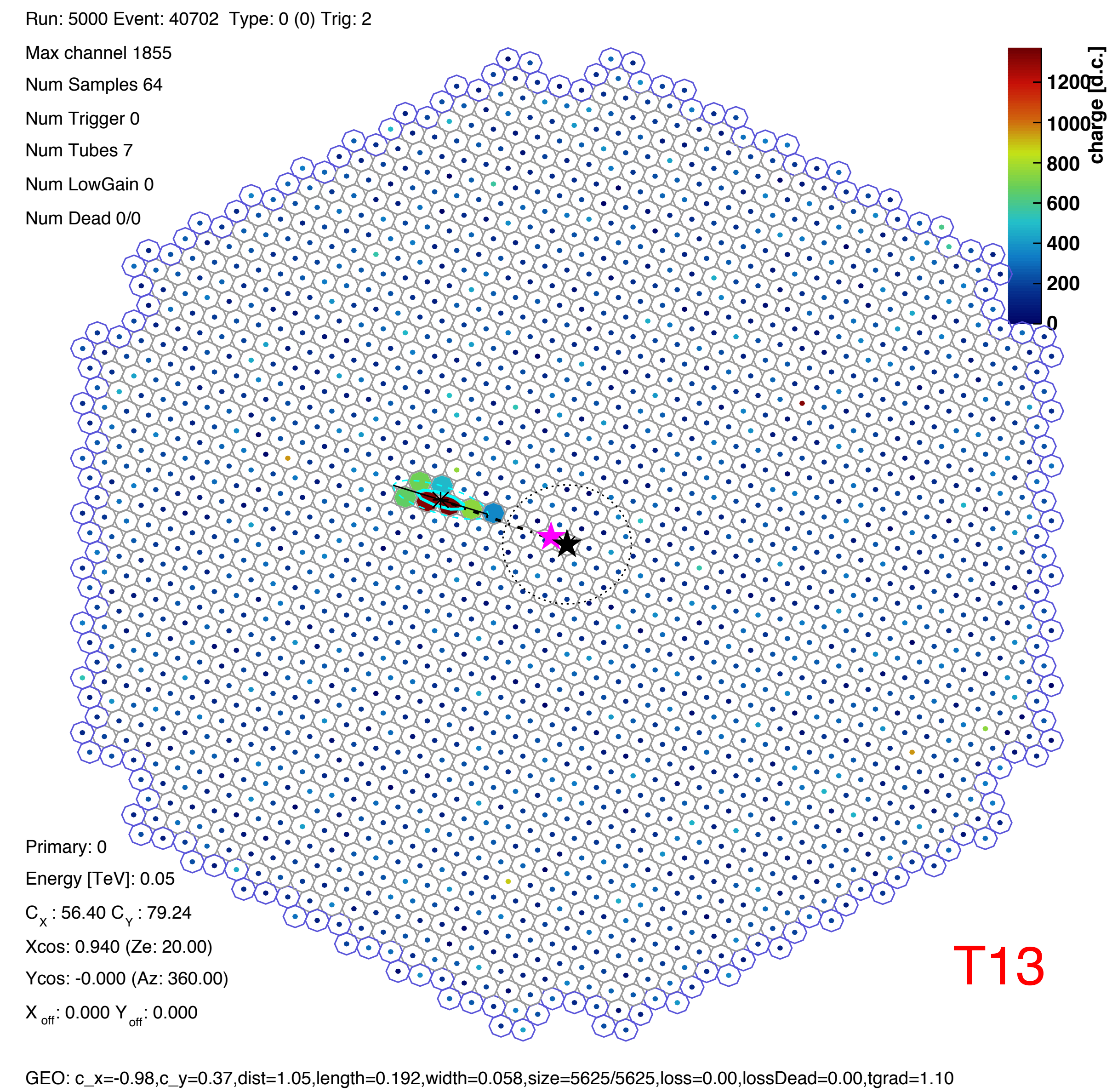
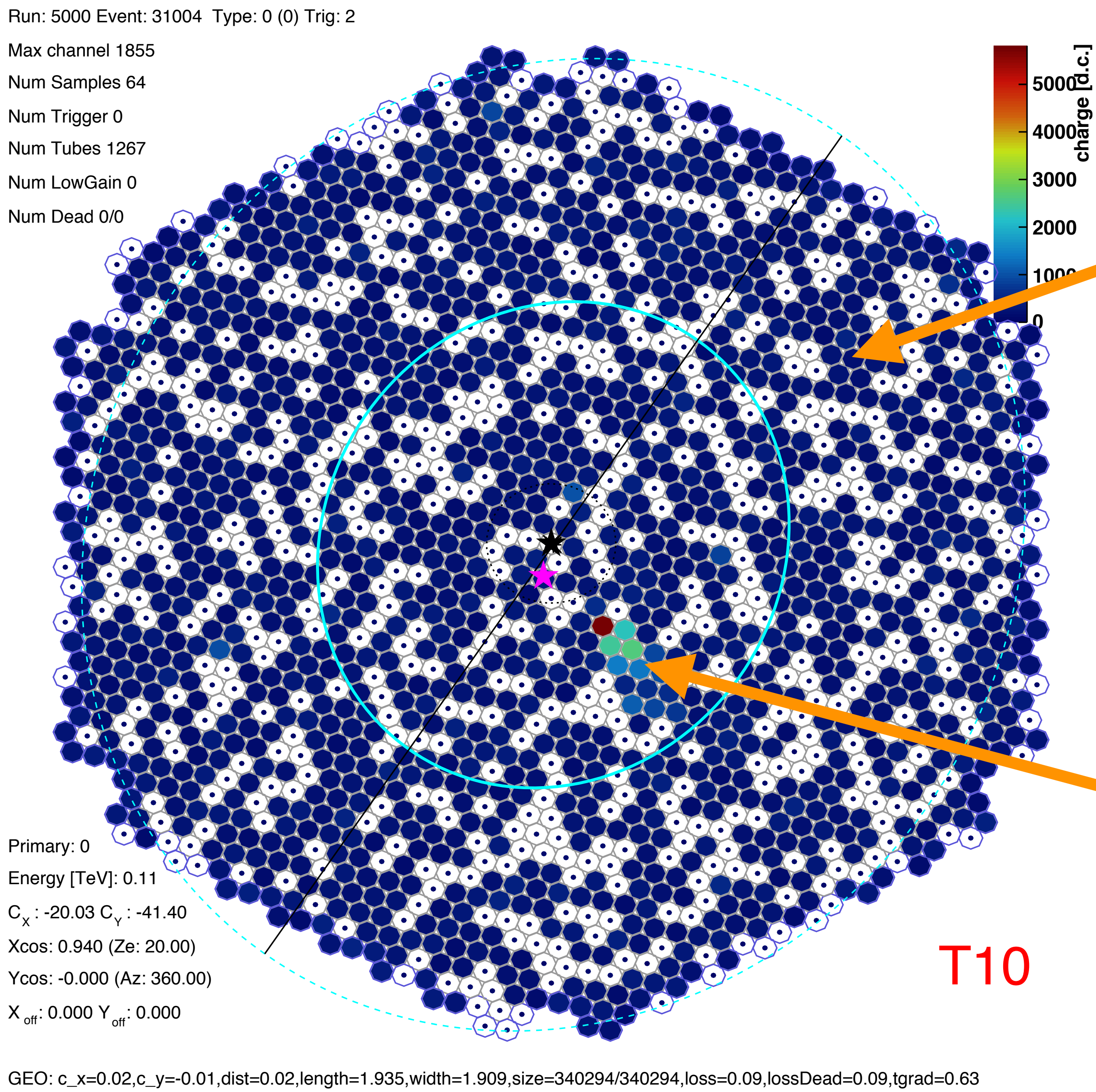
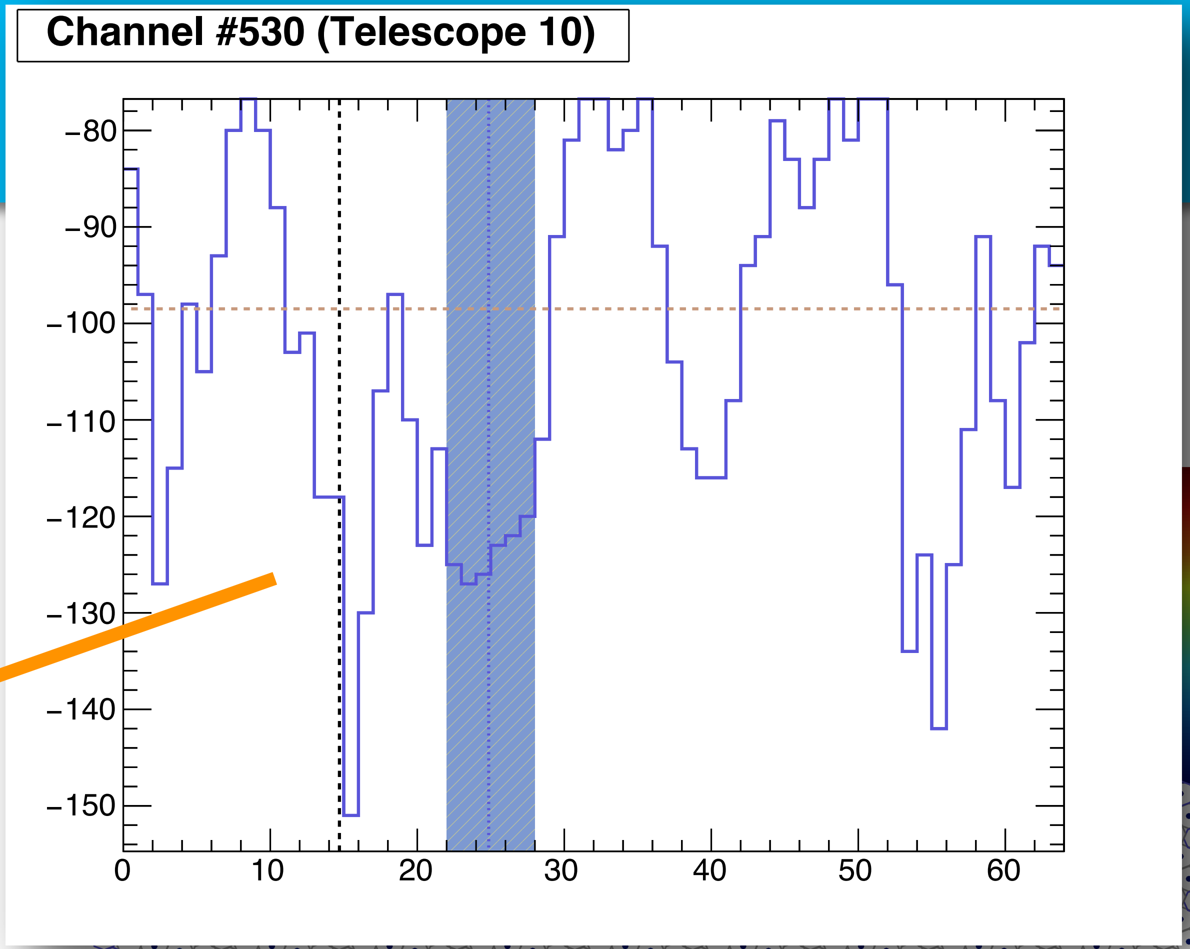


Image cleaning





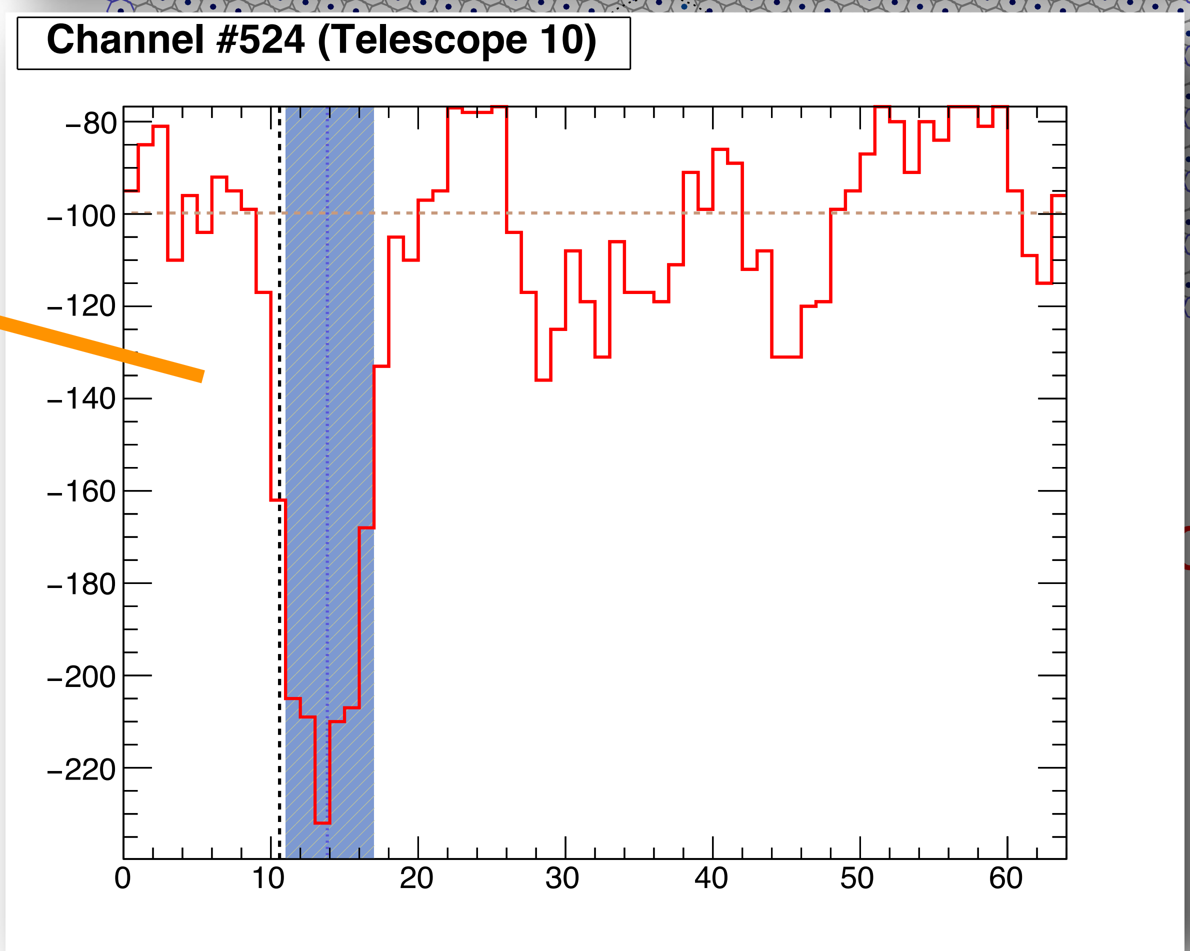
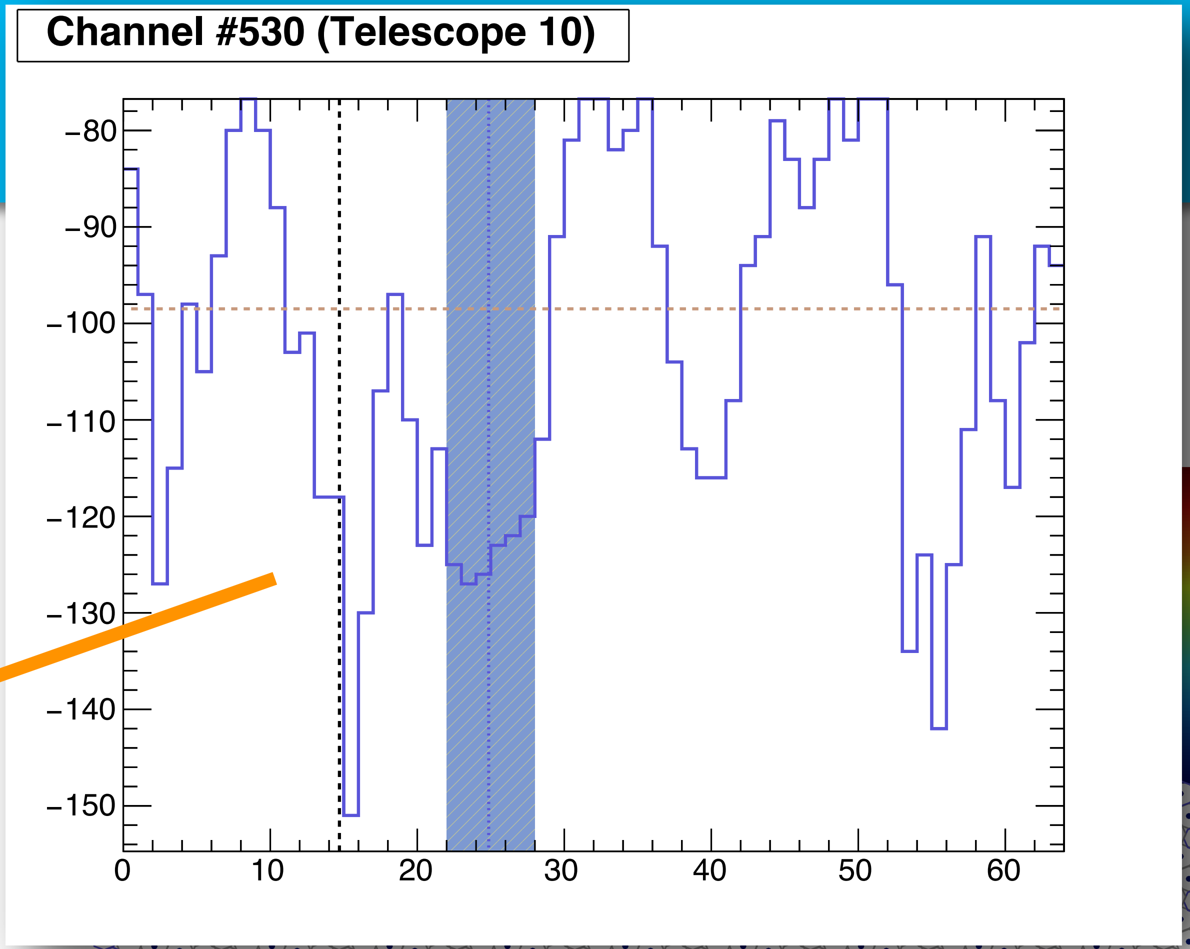
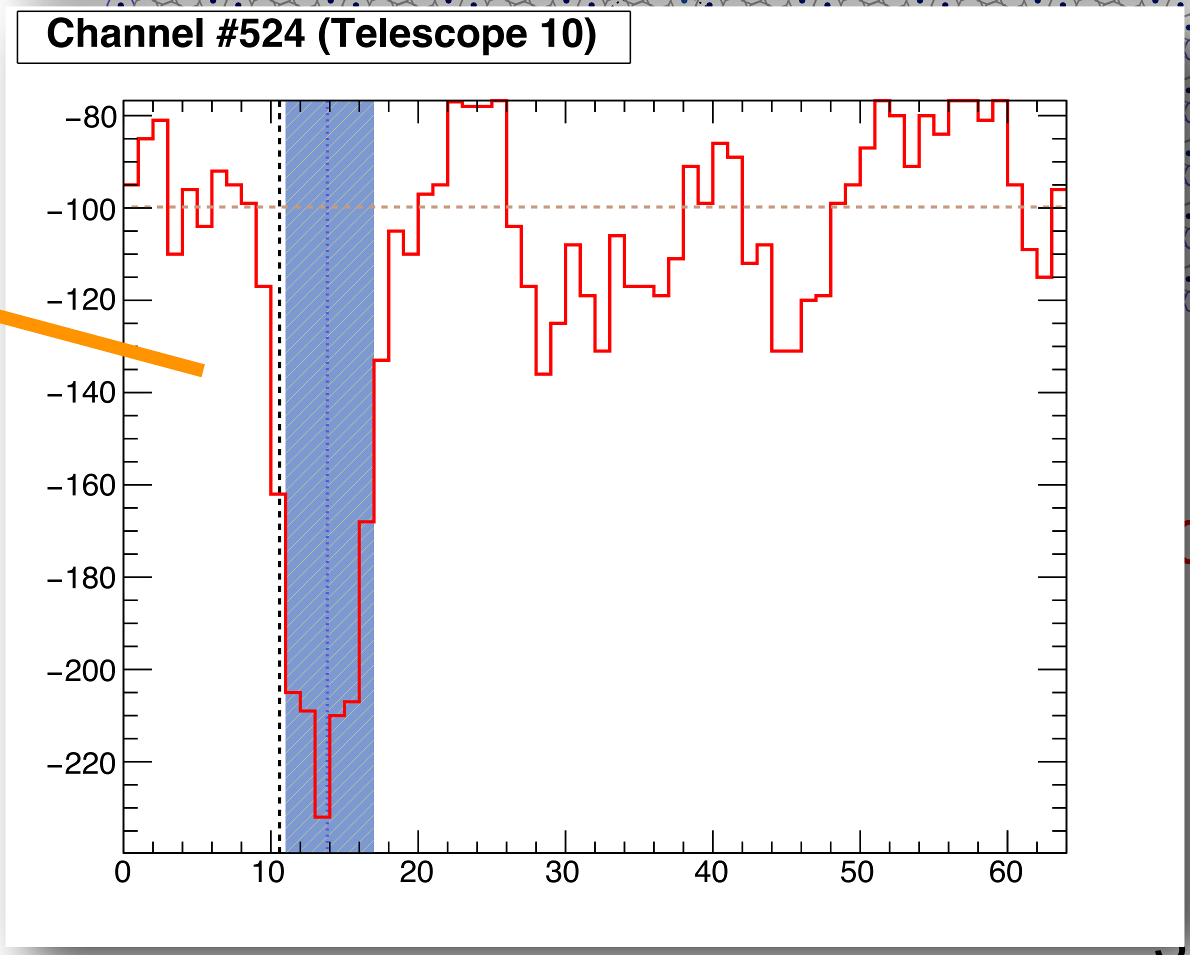


Image cleaning

- Classical image cleaning algorithms: two-level signal cleaning
  - signal pixels: charge > N_{signal}
  - border pixel (neighbour of signal pixel): charge > N_{border}
  - (plus requiring a minimum amount of signal pixels per image)
- Many variations of this classical algorithm:
  - island removal
  - time image cleaning
  - optimised next-neighbour cleaning





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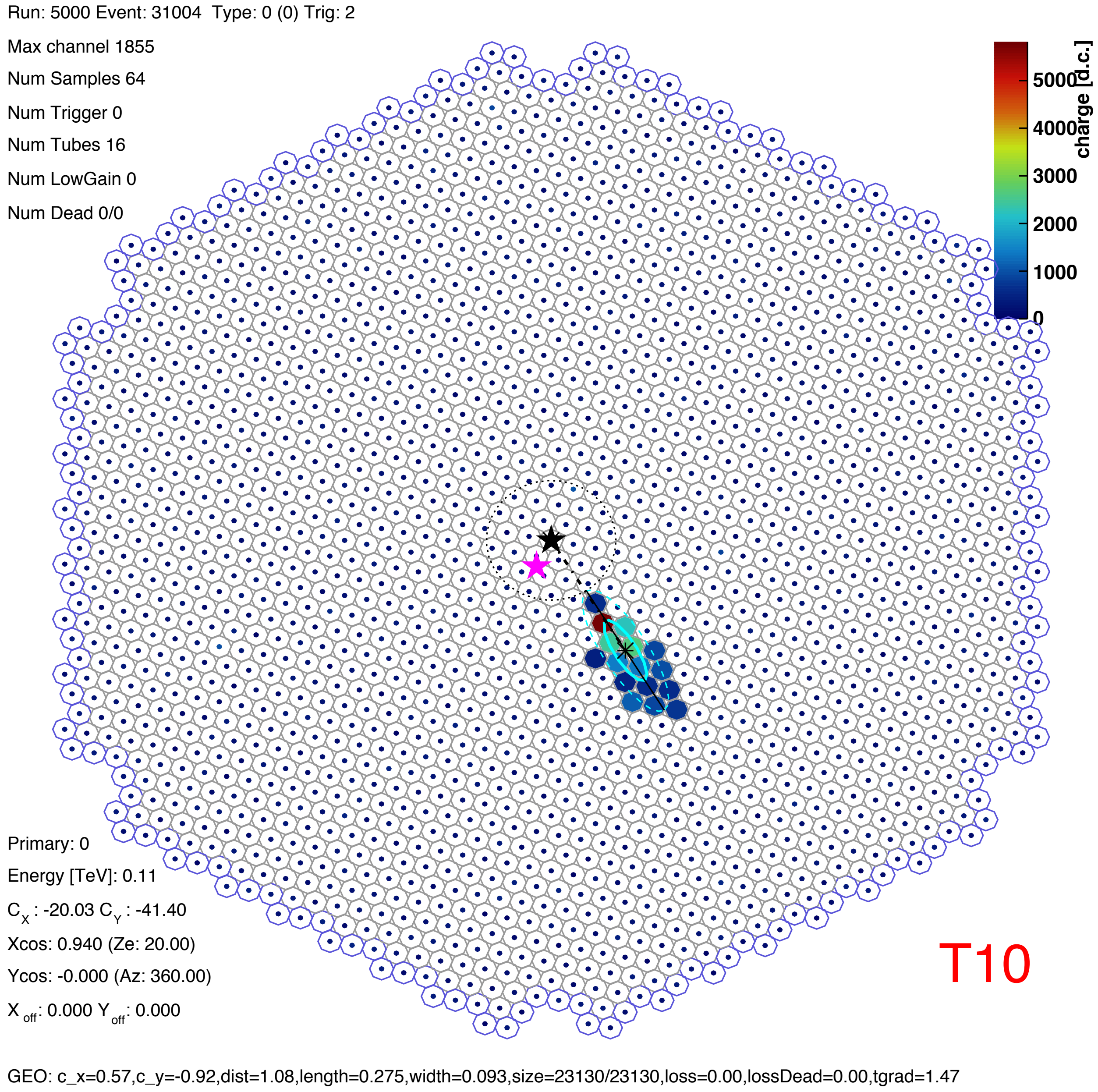
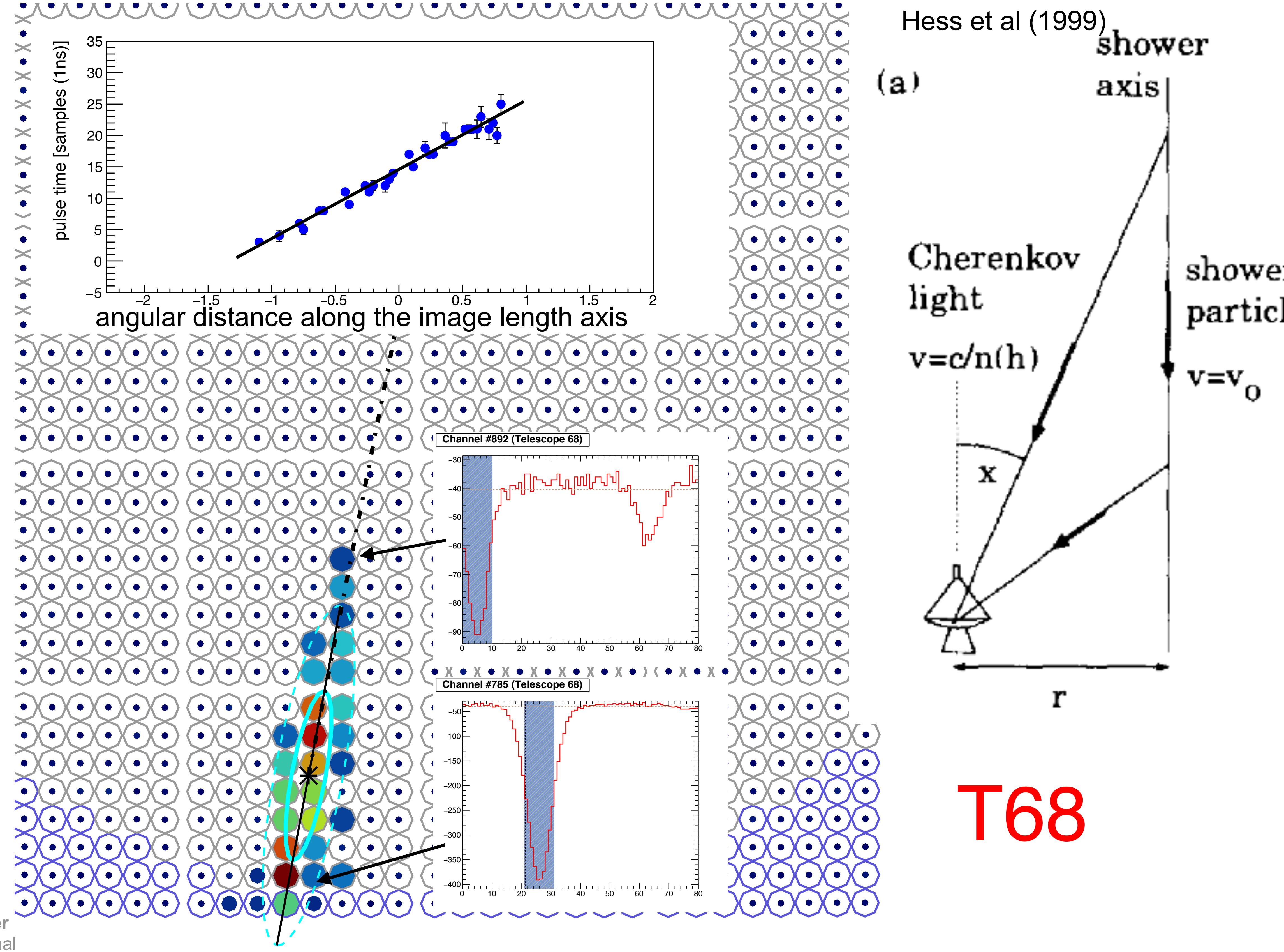


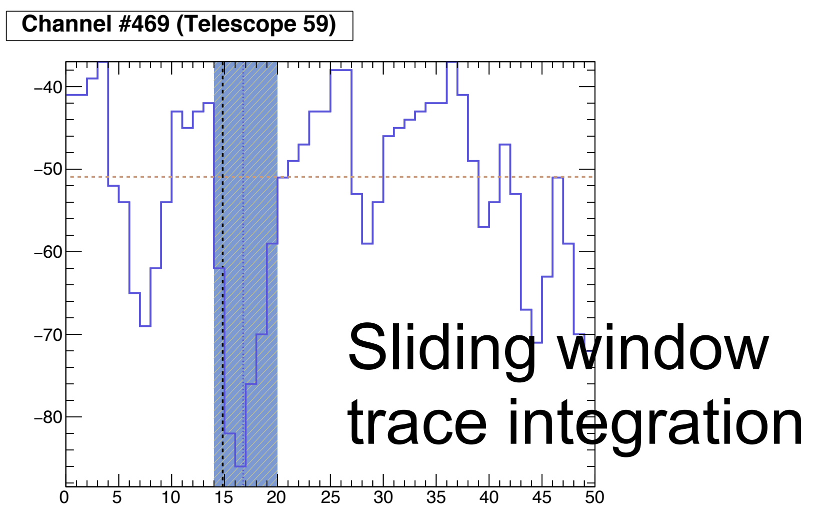
Timing and image cleaning

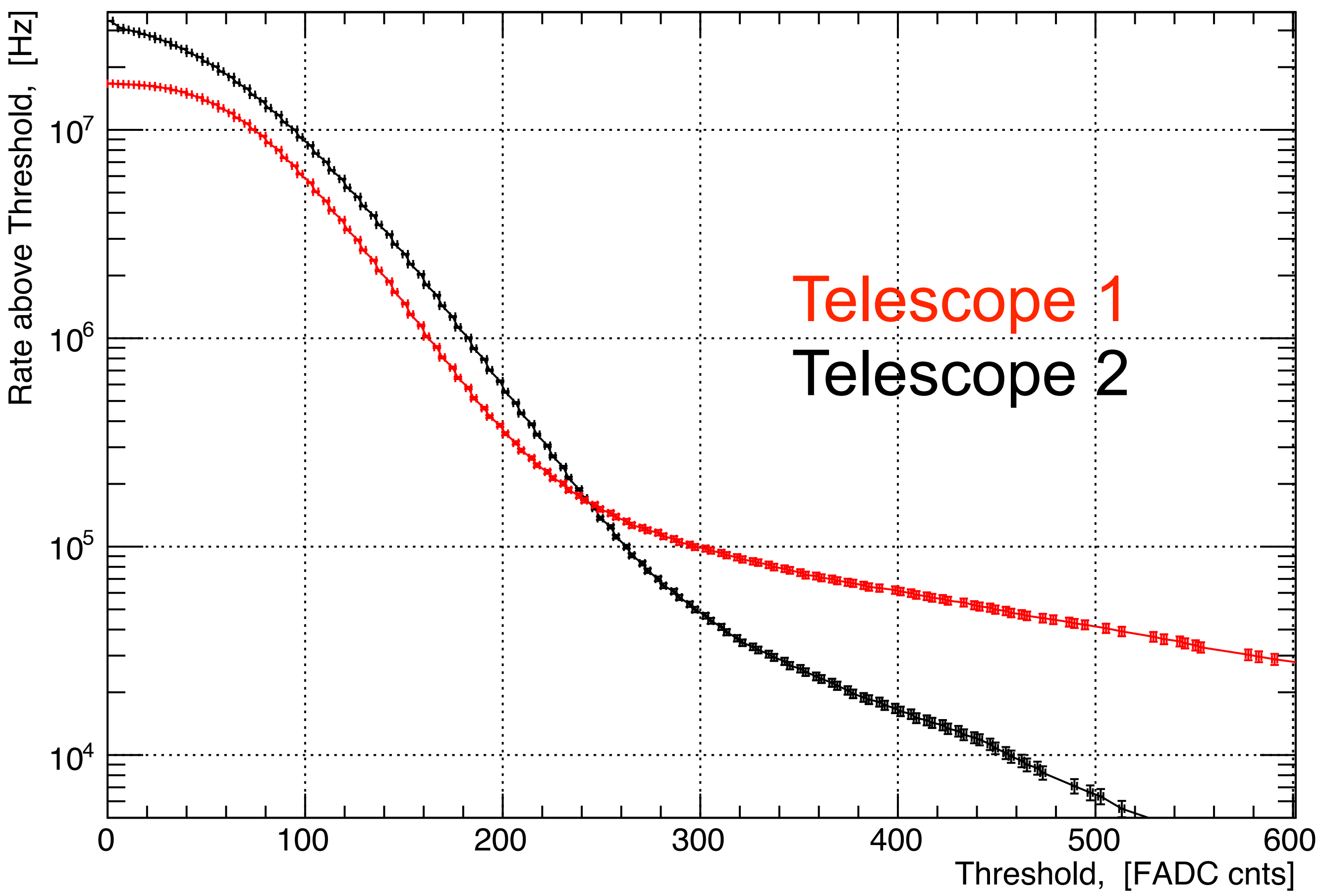


Optimised next-neighbour cleaning

Expert's slide

- requires simulations of night-sky background or measured pedestal events
- Maxim Shayduk, arXiv 1307.4939





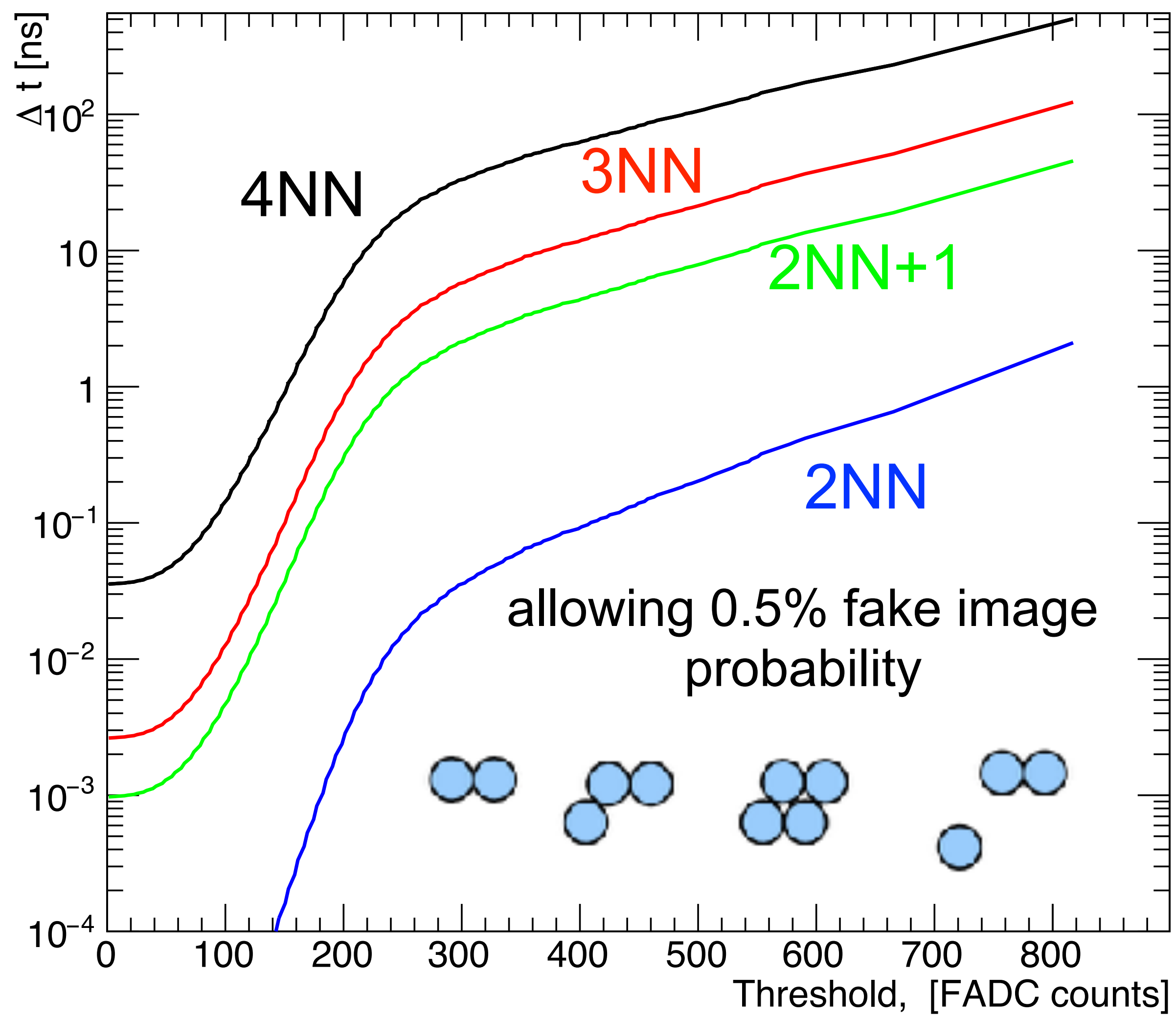
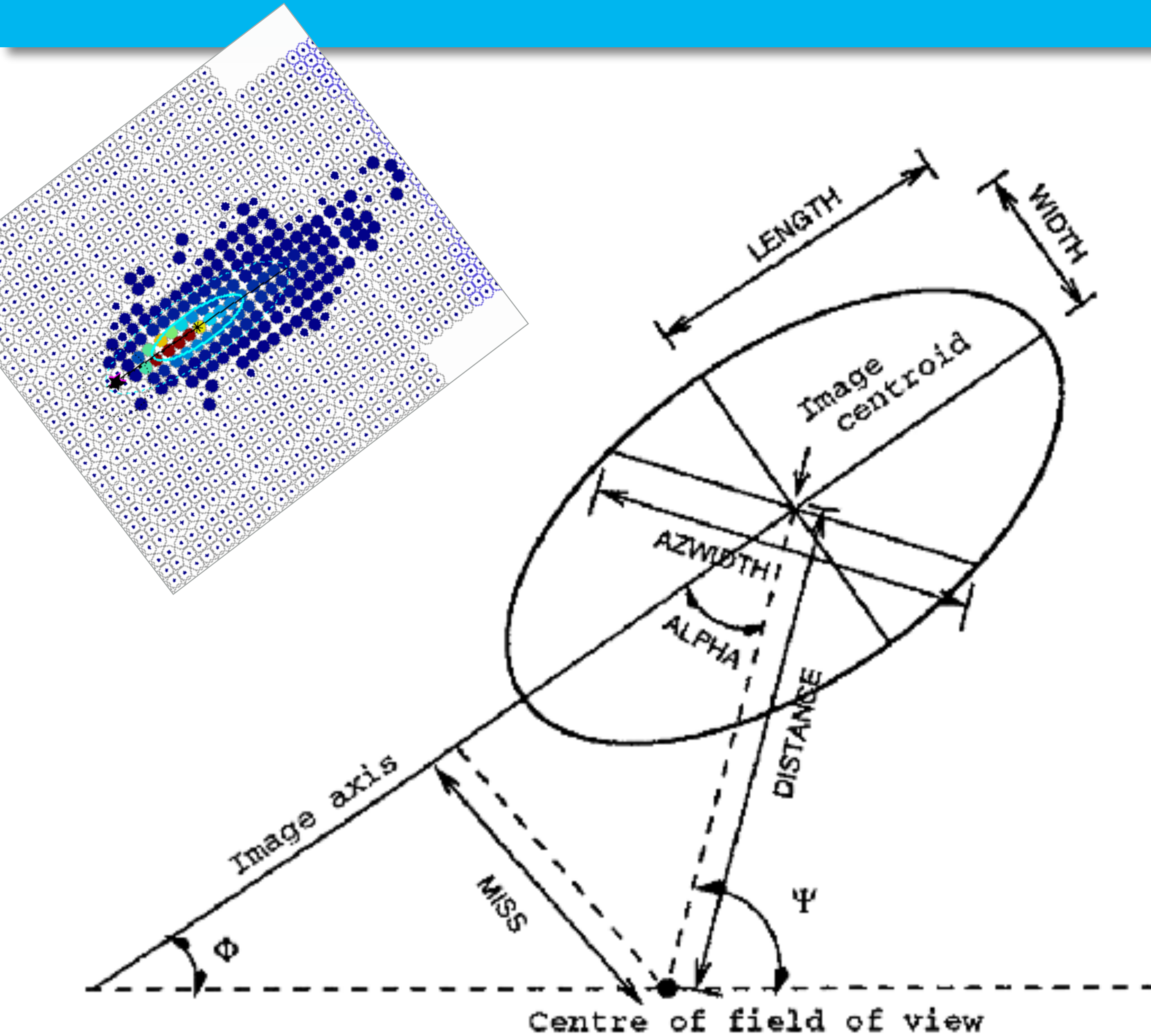
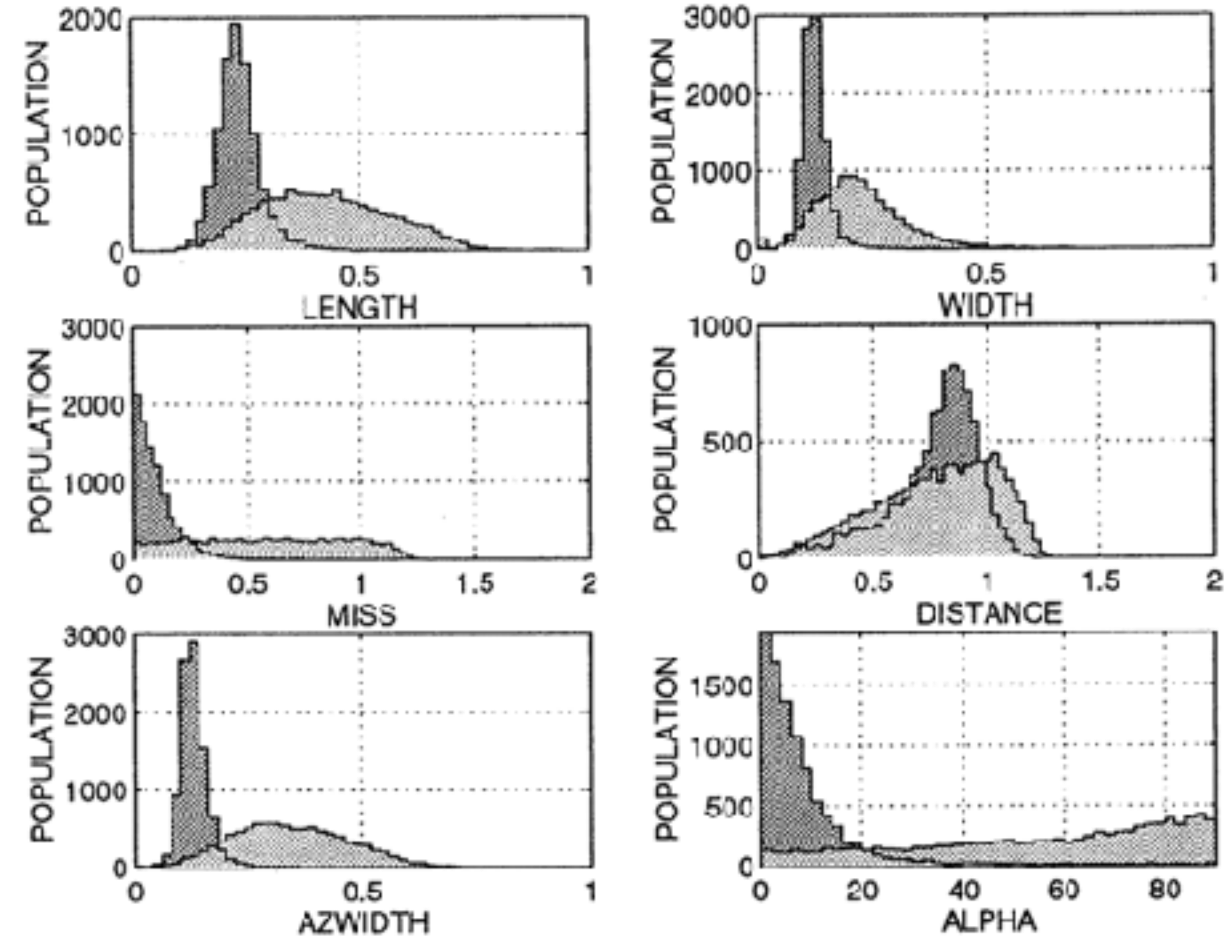


Image parameters (Hillas parameter)



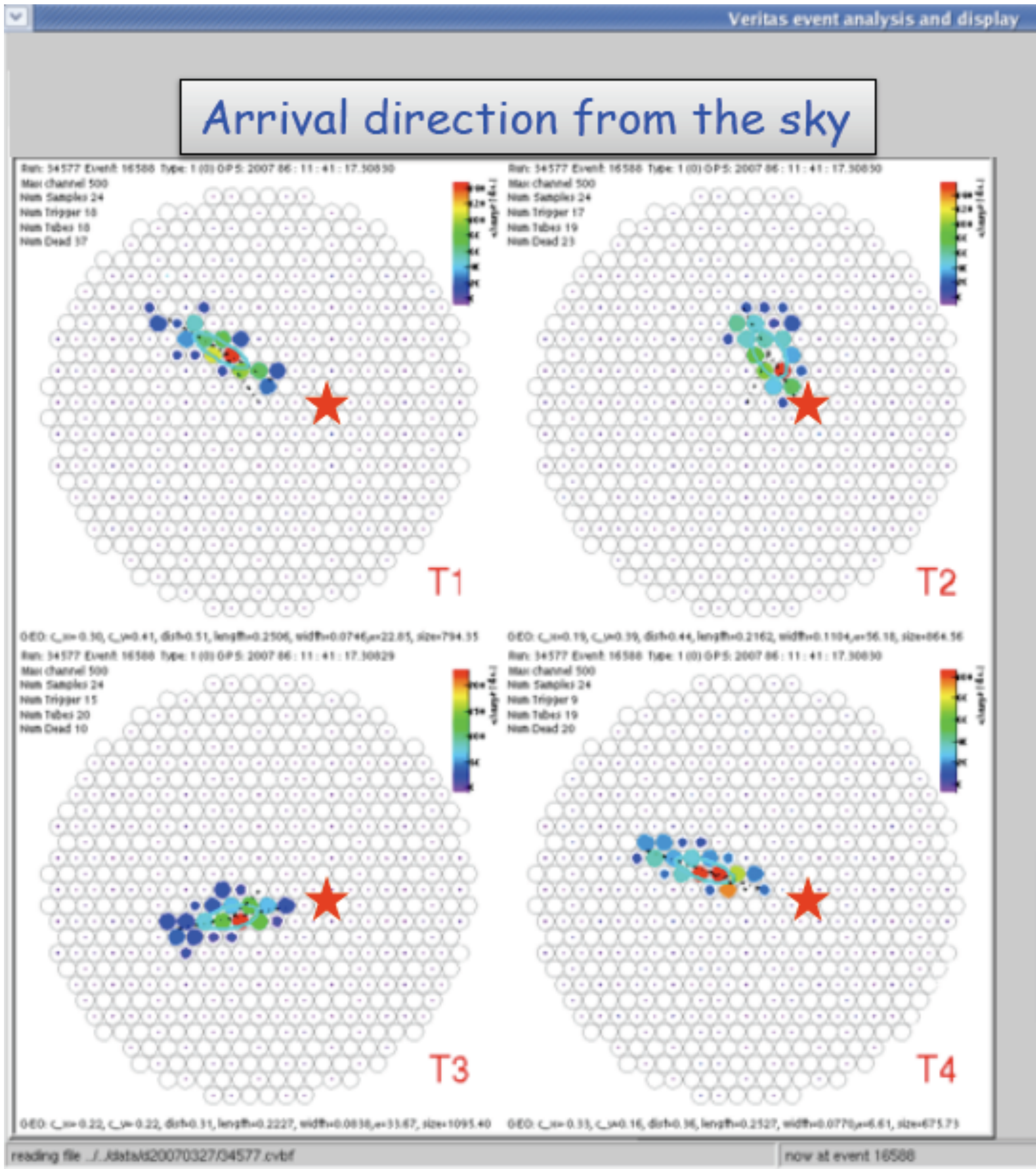


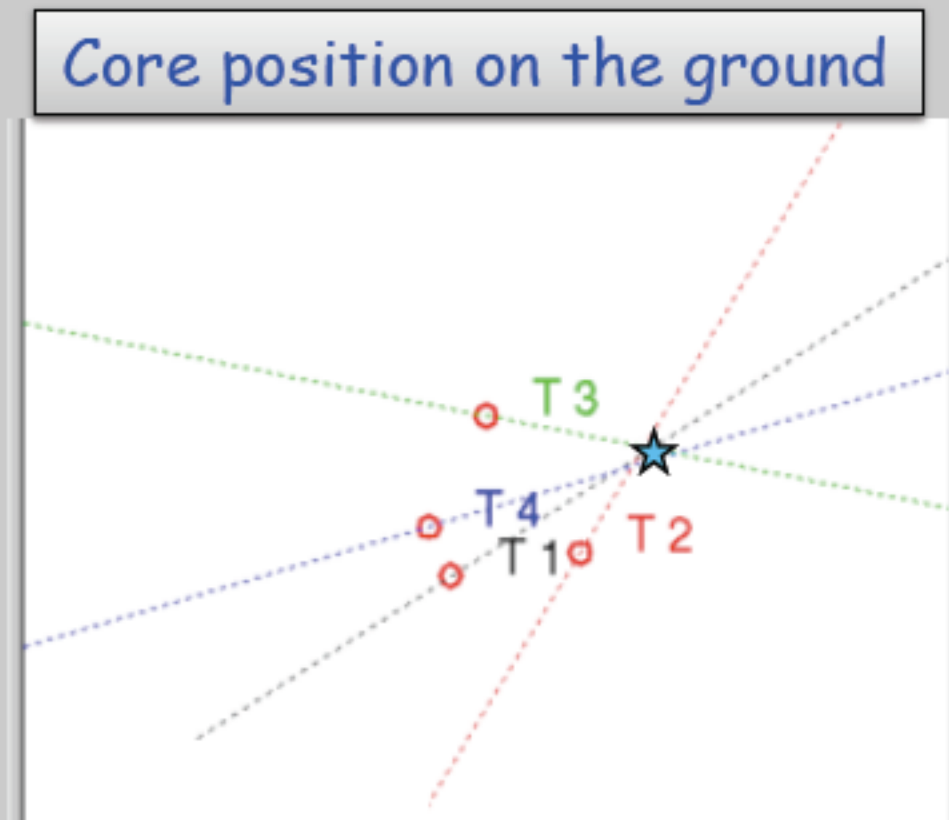
+many variations and additions

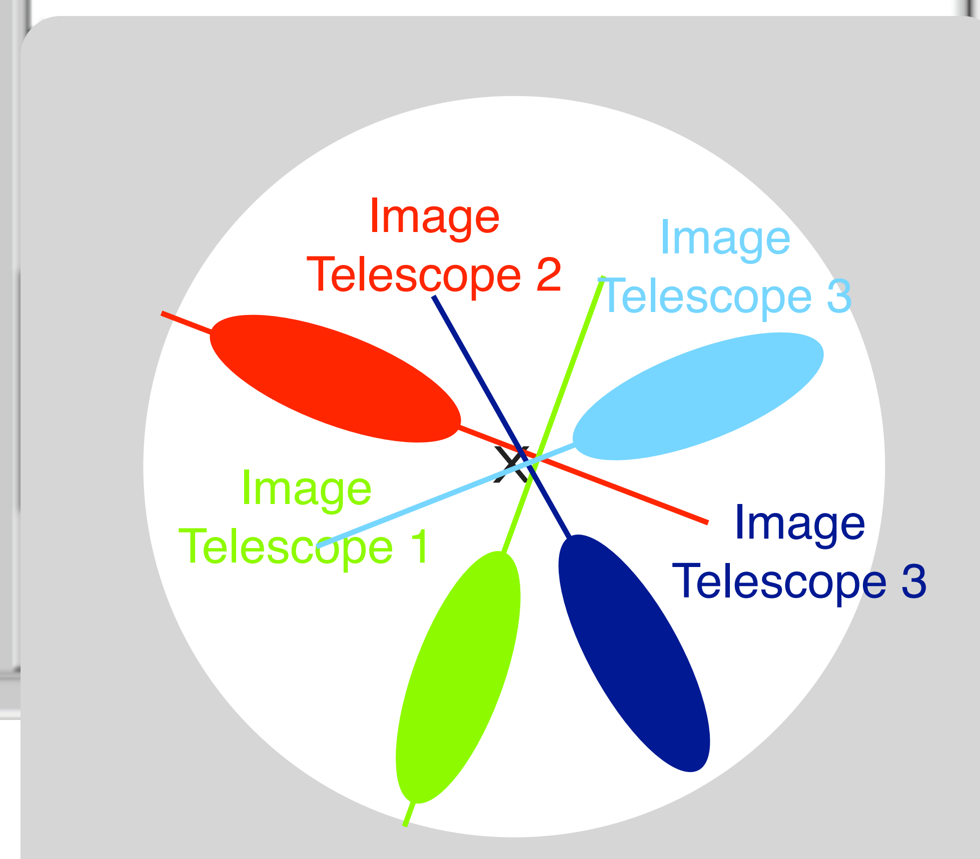
e.g. D.Fegan, J. Phys. G: Nucl. Part. Phys. 23 1013 (1997)

Direction reconstruction

W.Hofmann et al, Astroparticle Physics 12, 135 (1999)

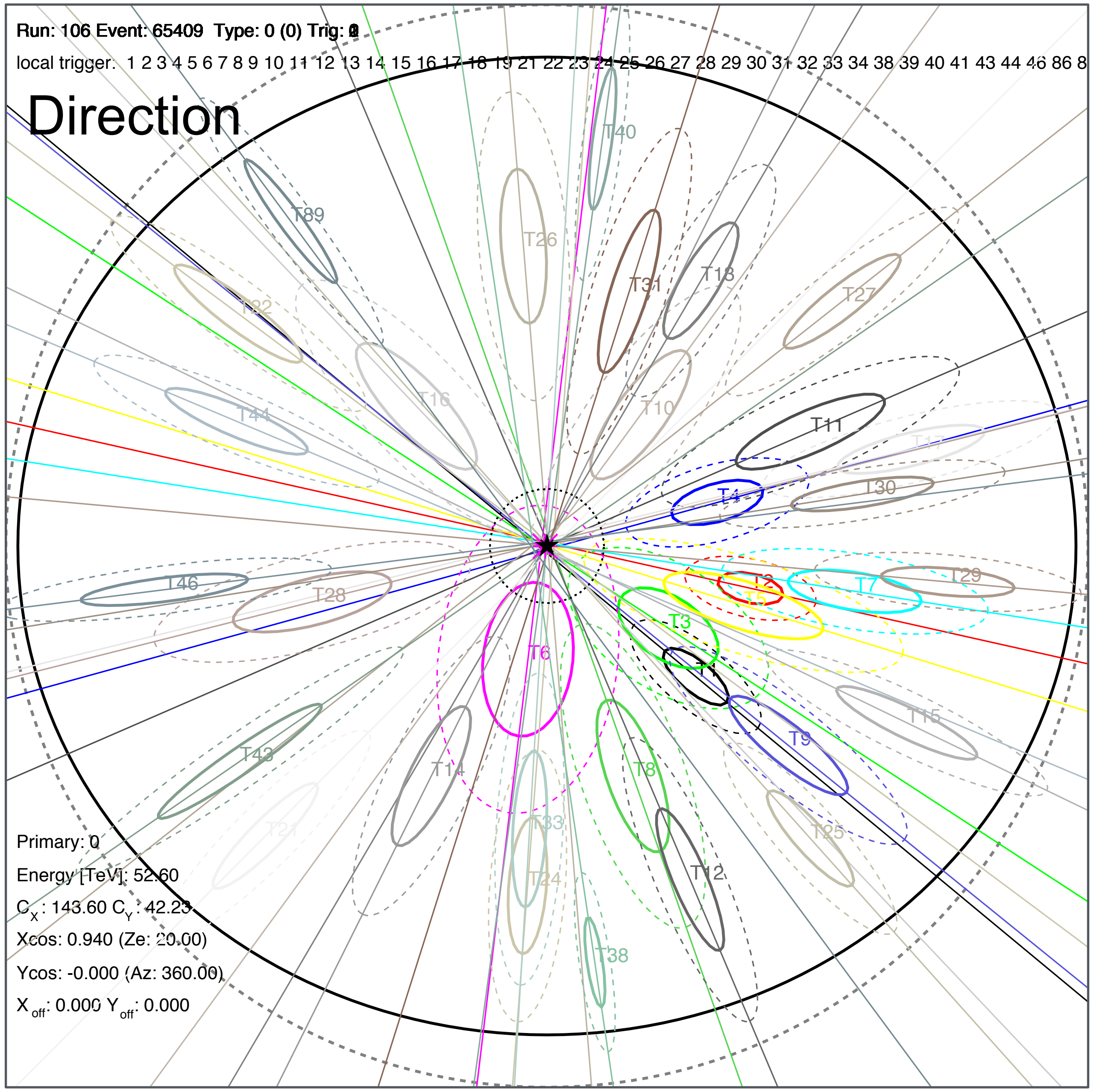


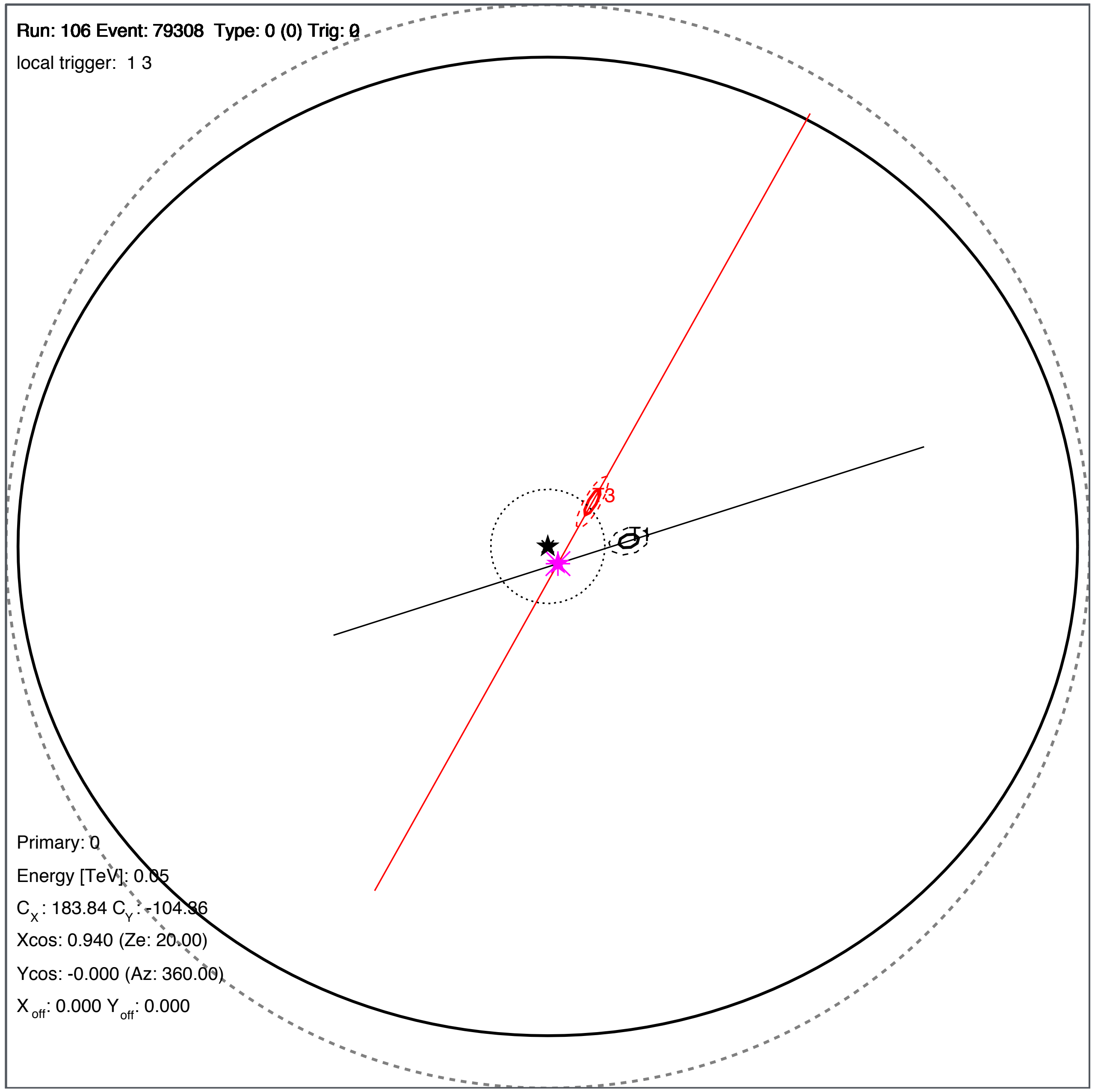




Direction and core reconstruction

Which one is a typical CTA shower?



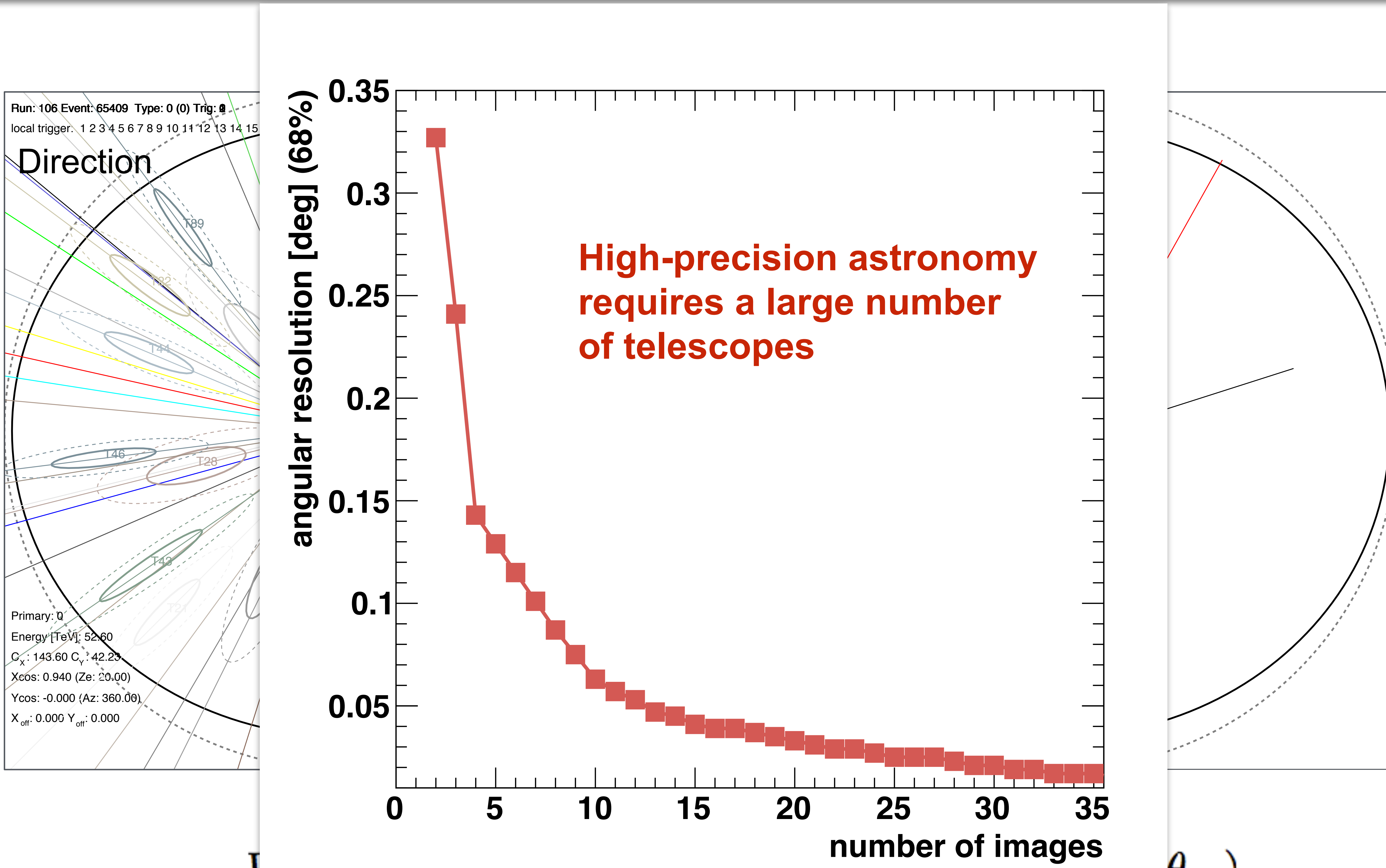


Weighting extremely important for direction reconstruction,

$$Weight = \left(\frac{1}{S_1} + \frac{1}{S_2}\right)^{-1} \times \left(\frac{w_1}{l_1} + \frac{w_2}{l_2}\right)^{-1} \times sin(\theta_{12})$$

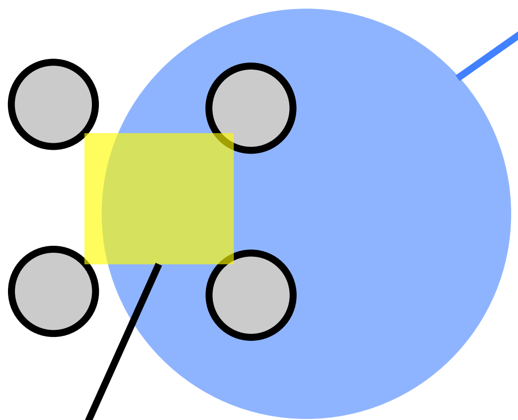
angle between two image axis

Direction and core reconstruction



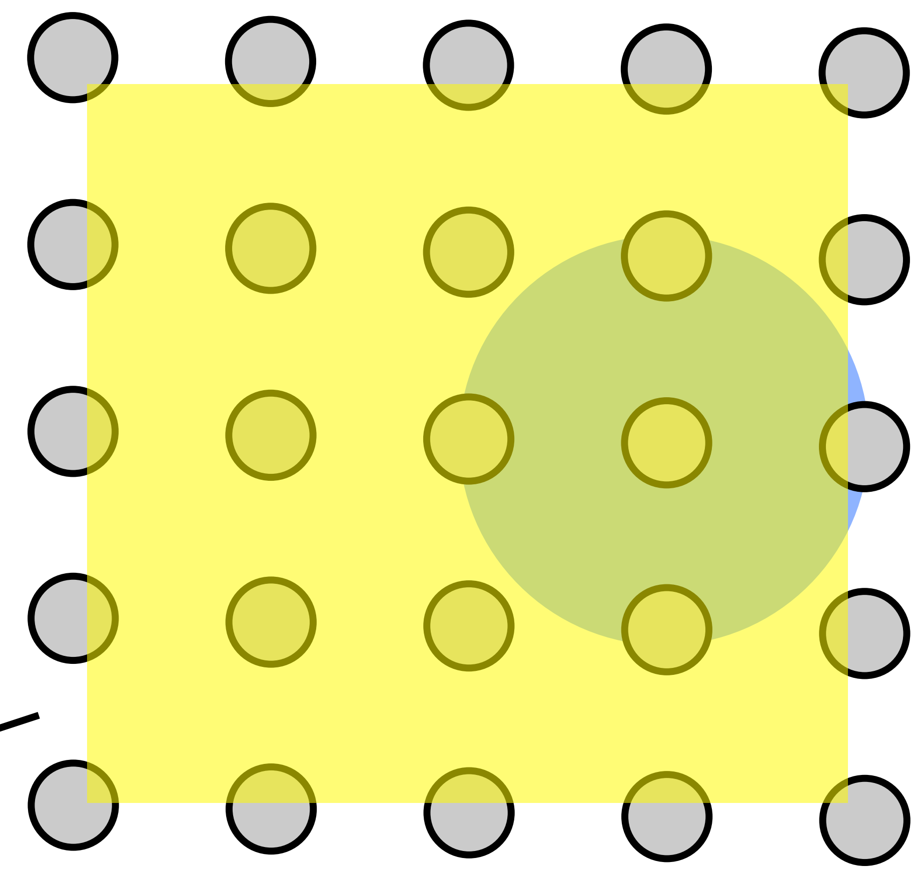
angle between two image axis

Large arrays of Cherenkov Telescopes



light pool radius
R ≈100-150 m
≈ typical telescope spacing

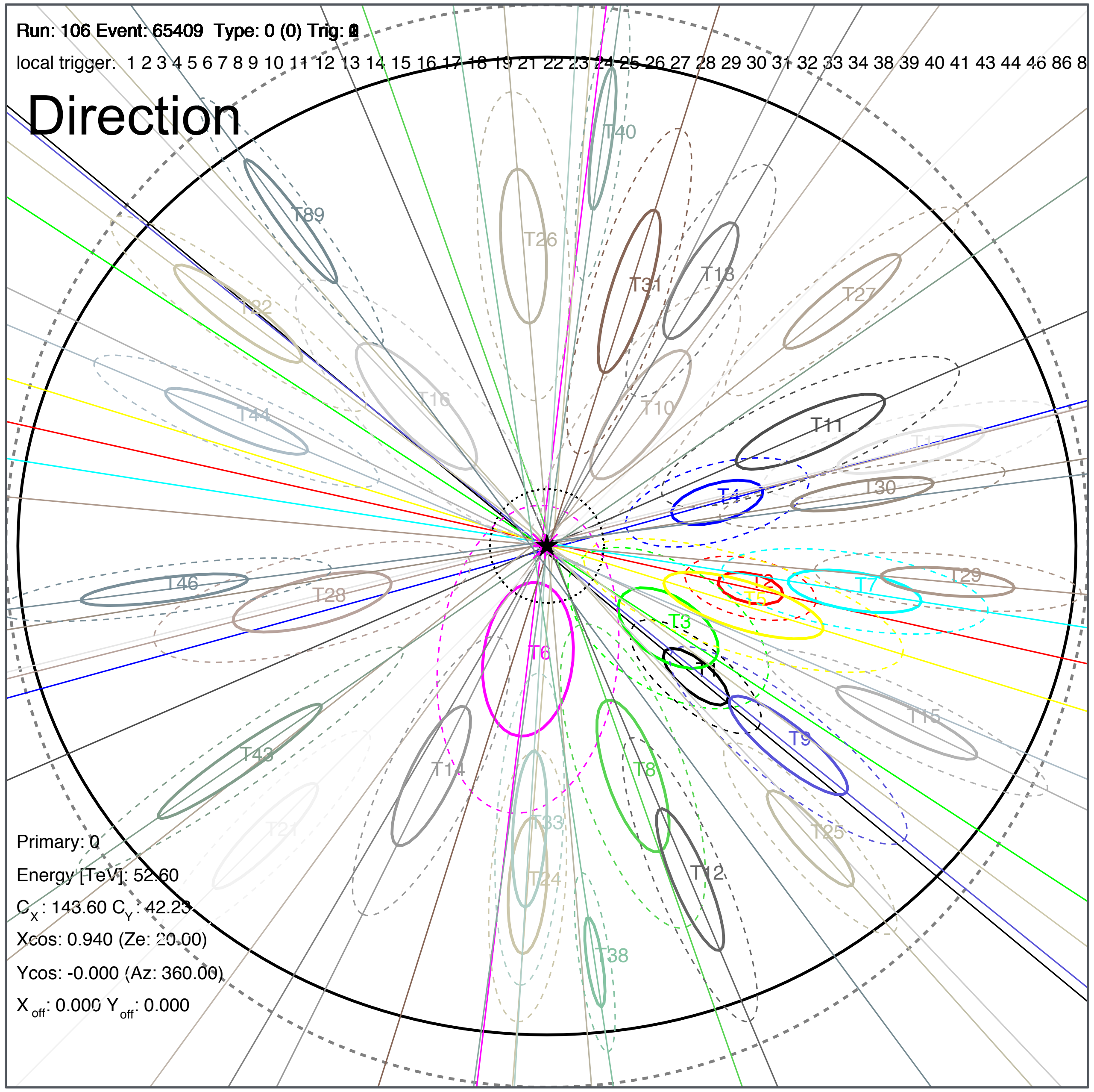
Sweet spot for
best triggering
and reconstruction:
most showers miss it!

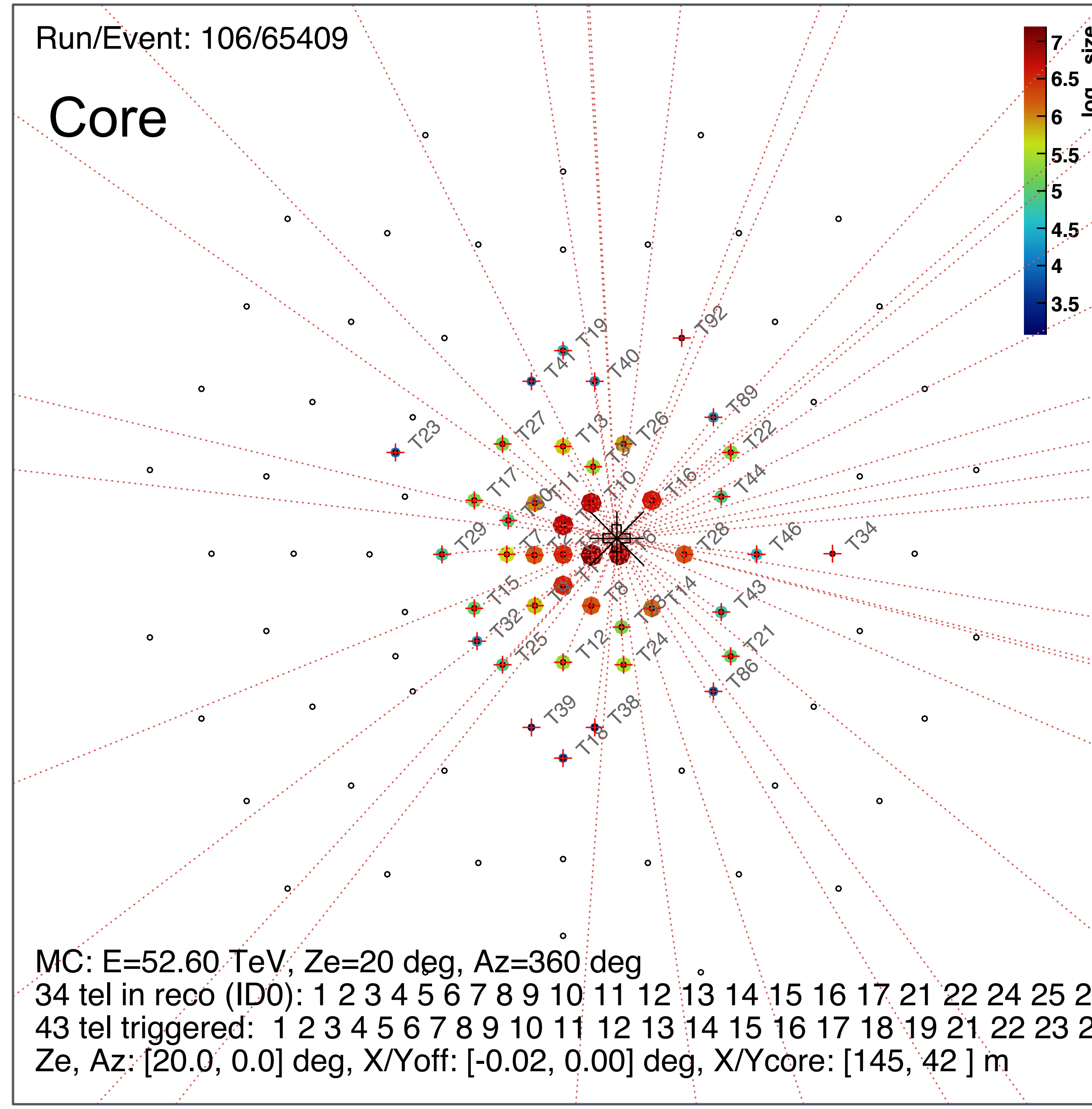


large detection area
more images per shower
lower trigger threshold

Direction and core reconstruction

A typical CTA shower!





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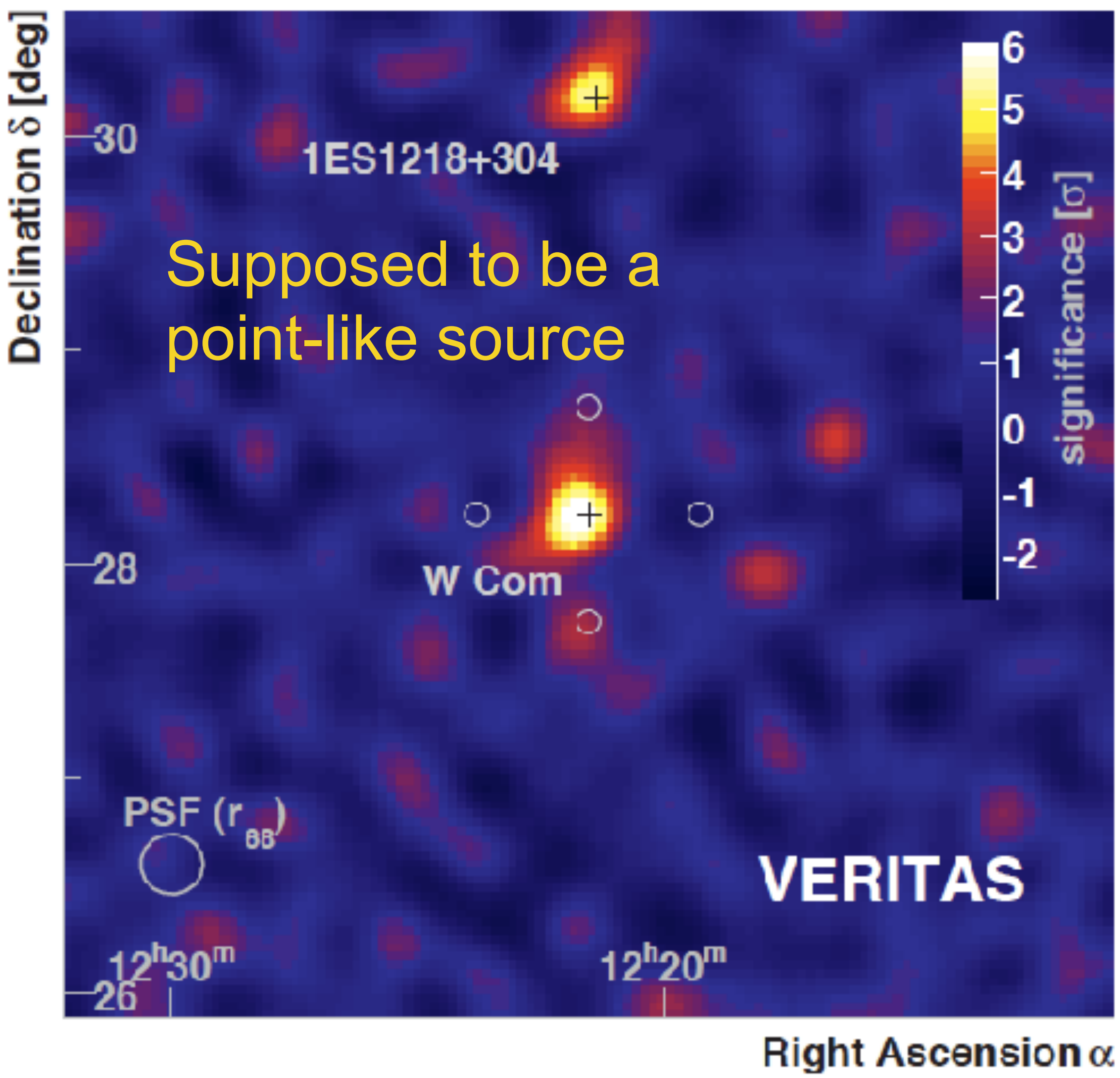
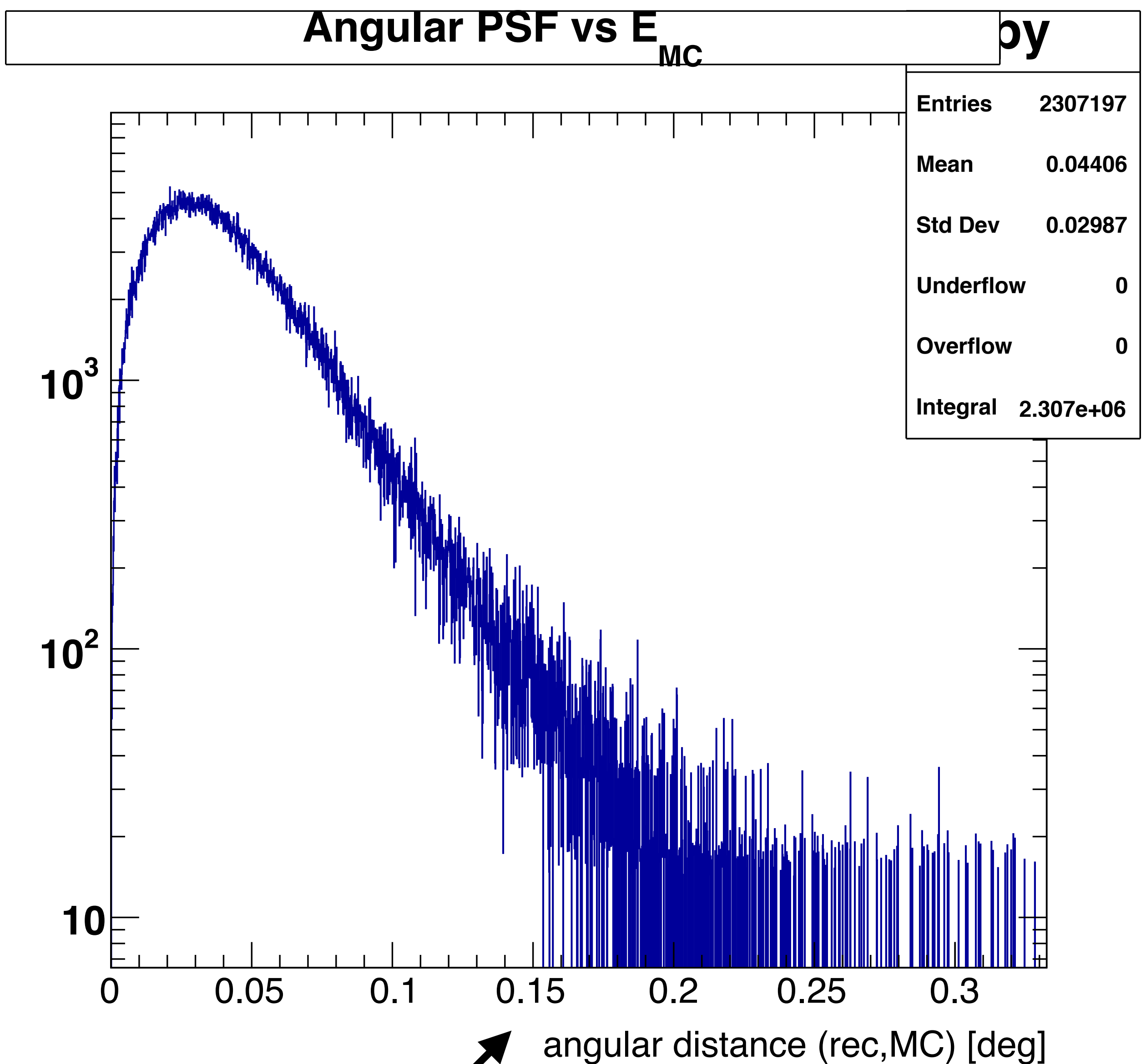
angle between two image axis

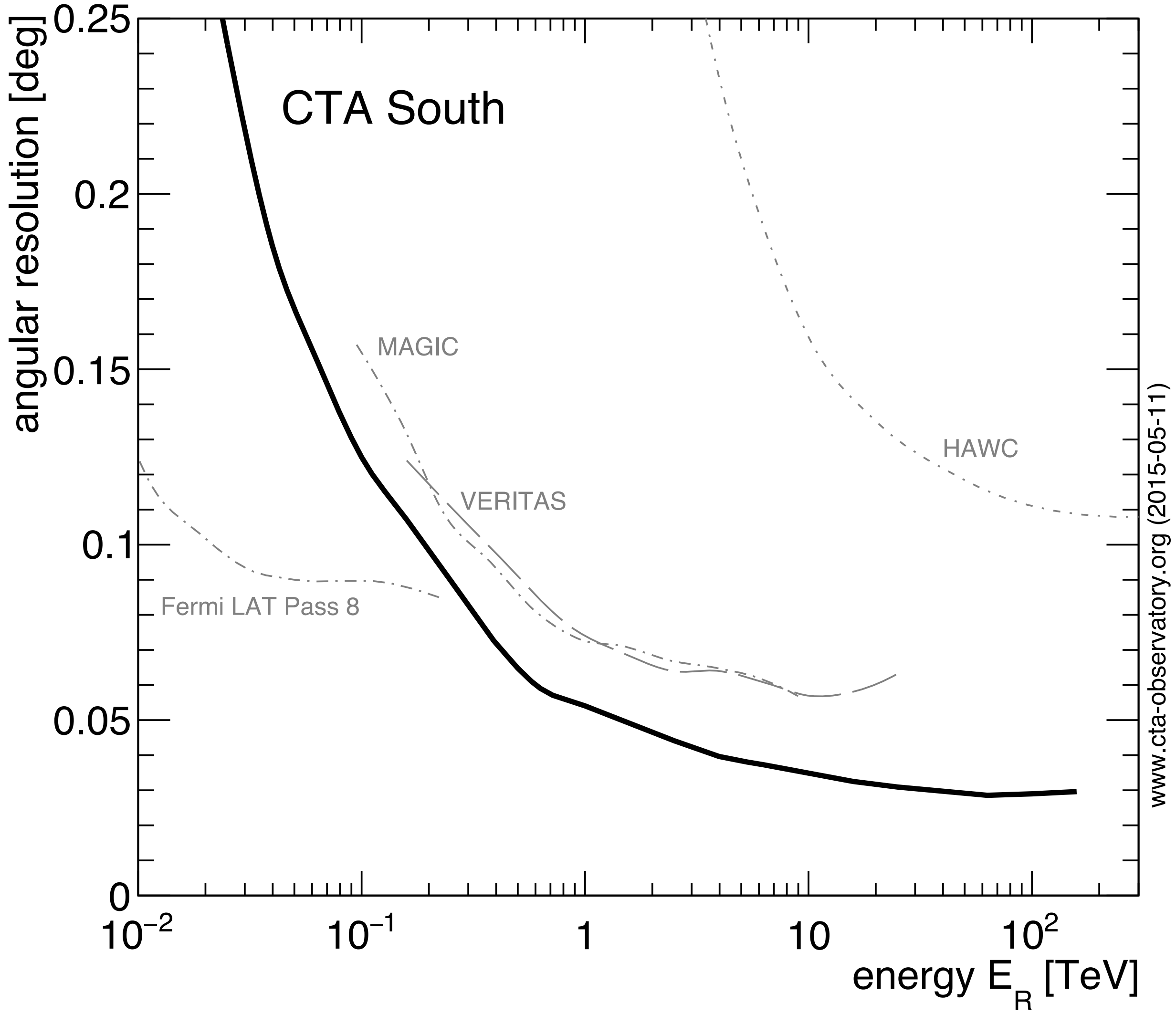
Angular resolution - angular point-spread function



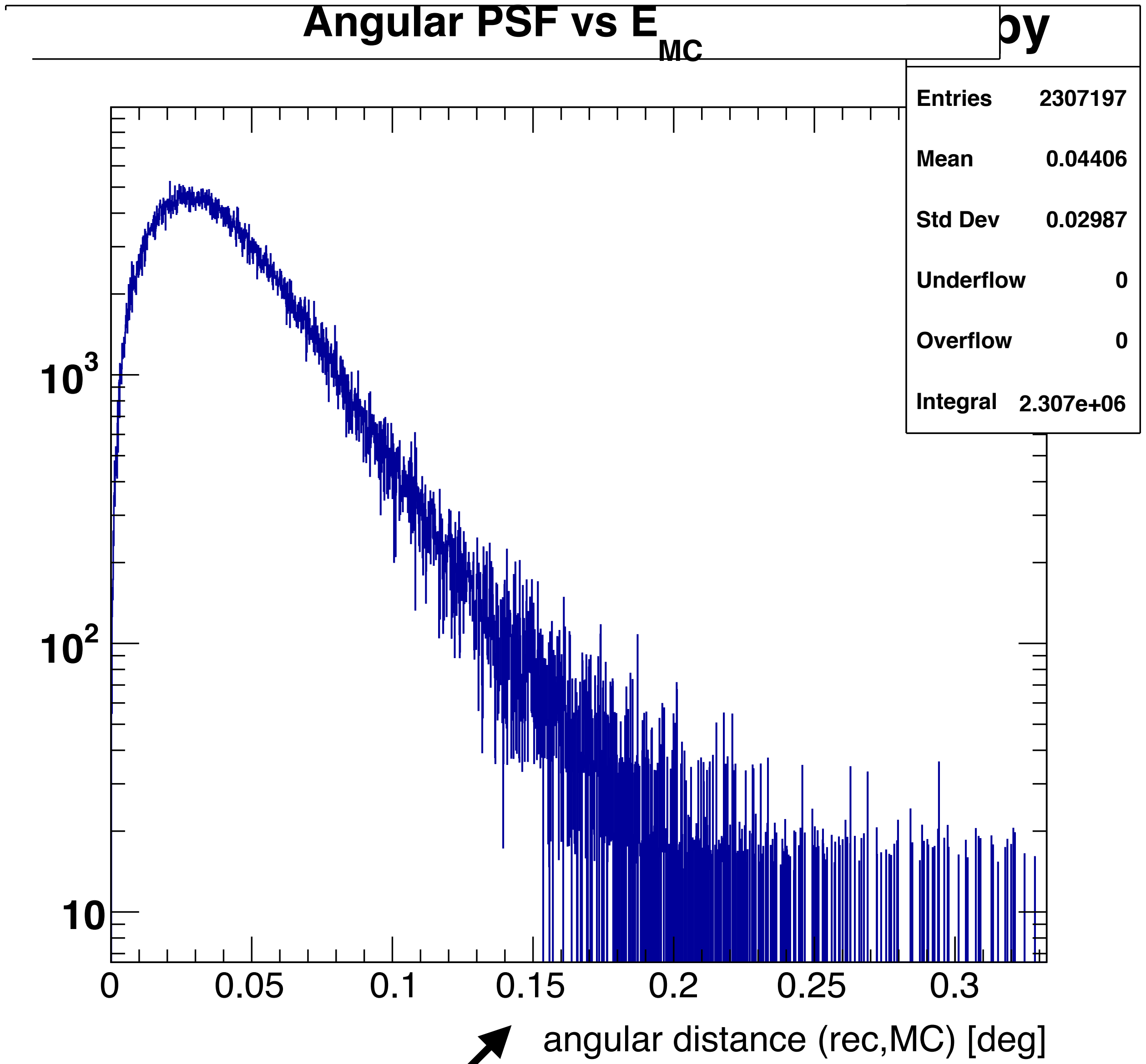


difference between true and reconstructed direction

Angular resolution - angular point-spread function



Angular resolution
= 68% containment radius



difference between true and reconstructed direction

Reconstruction & Analysis - ground-based analysis

- **key observables for each gamma ray: energy, direction, arrival time** ← **event reconstruction**

- **detector response:**
  - detection probability (effective areas)
  - direction resolution
  - energy dispersion matrix
  - instrument dead time

  ← **instrument response functions (from Monte Carlo simulations)**

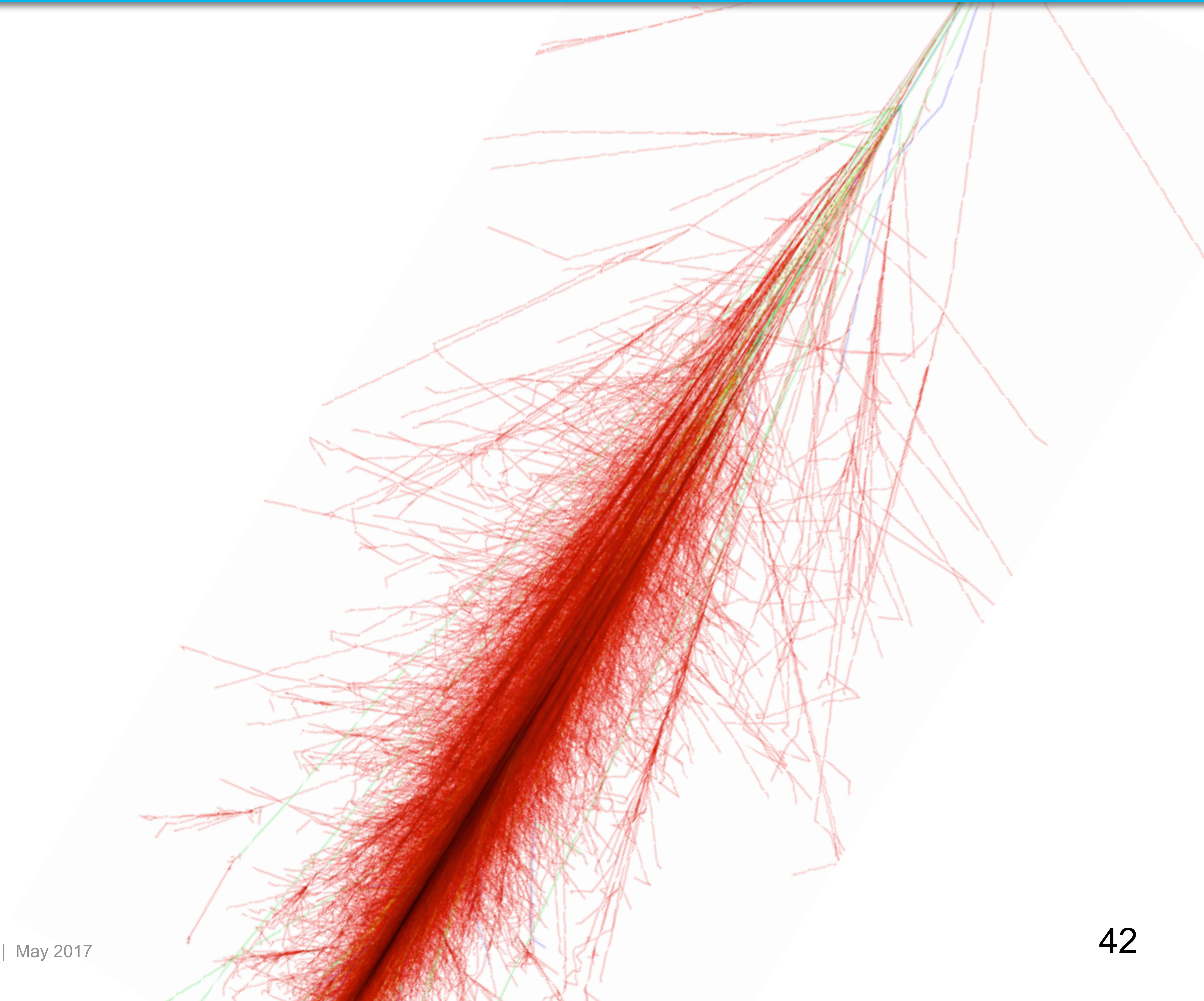
- **background** (lots of it) ← **measurements or Monte Carlo simulations**

- **gamma-ray selection** (or background suppression) ← **Monte Carlo simulations**

- **systematic uncertainties**
  - understanding of detector
  - fluctuations in the atmosphere
  - choices by you
  - ….

  ← **measurements or Monte Carlo simulations**

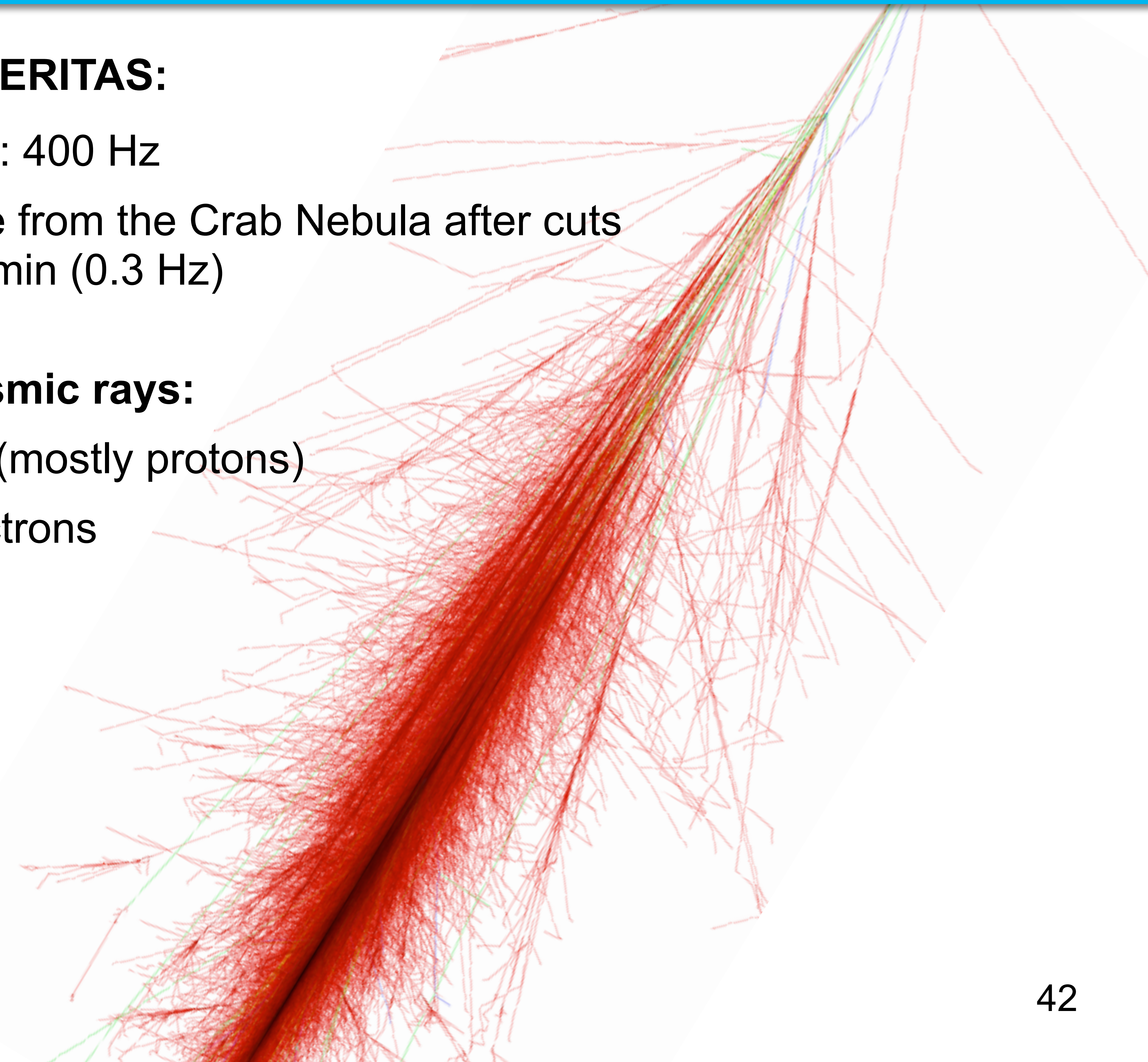
Background suppression



Background suppression

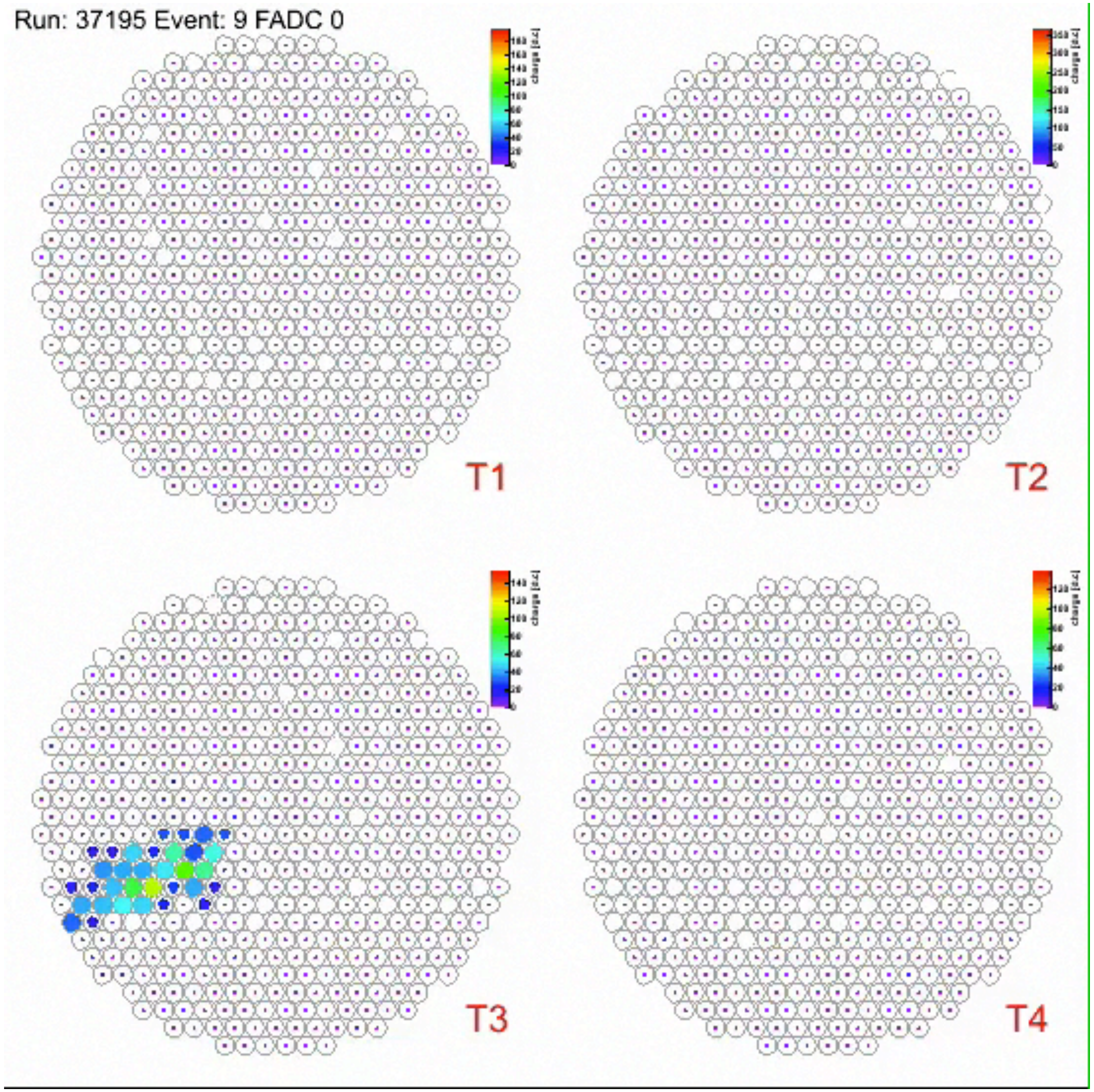
- **Example from VERITAS:**
  - data taking rate: 400 Hz
  - gamma-ray rate from the Crab Nebula after cuts
    <20 gammas / min (0.3 Hz)

- **background cosmic rays:**
  - charged nuclei (mostly protons)
  - cosmic-ray electrons



Observations - VERITAS

event display VERITAS

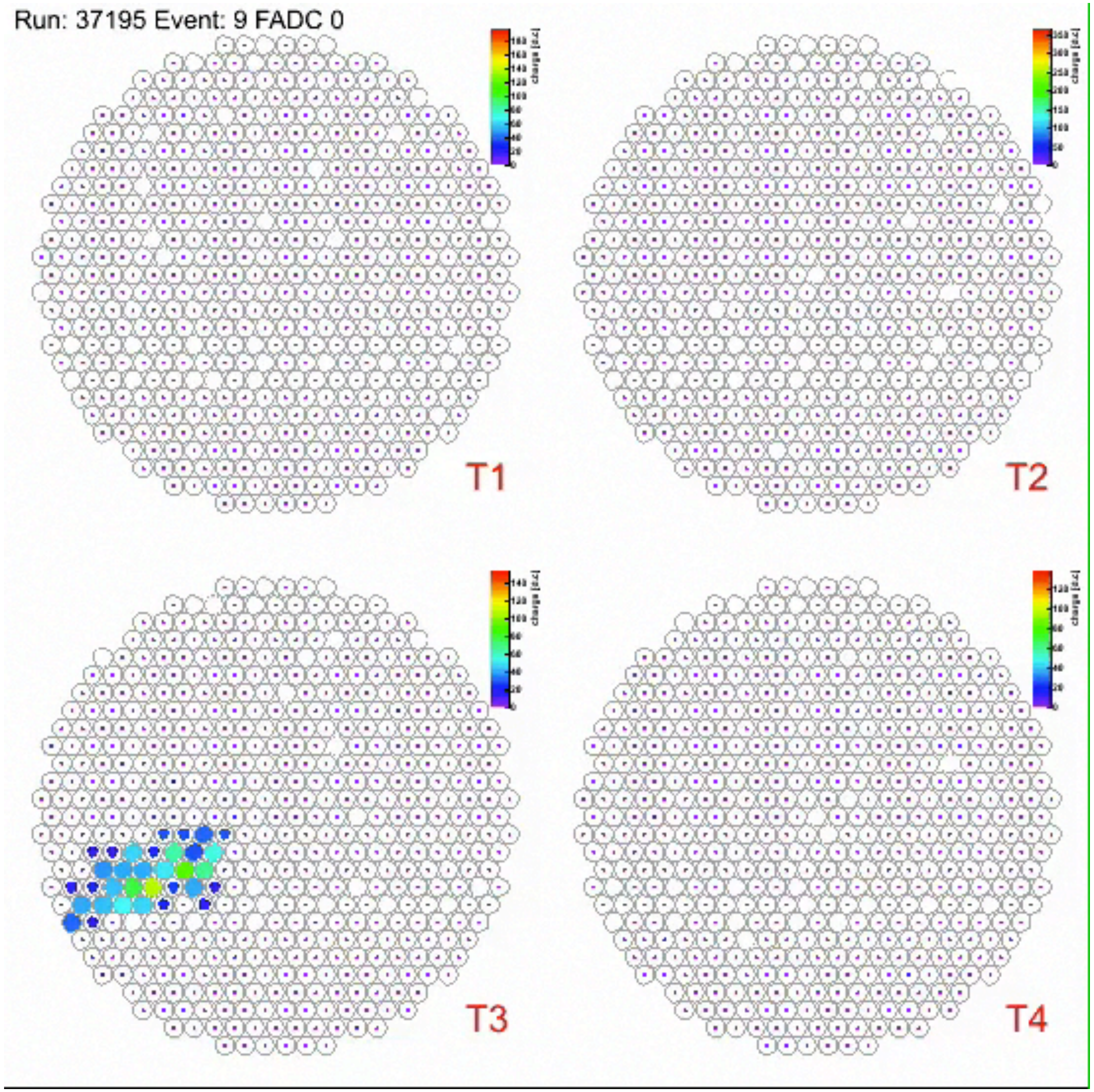


about every 1000th event is a γ-ray

(each frame 2 ns long)

Observations - VERITAS

event display VERITAS



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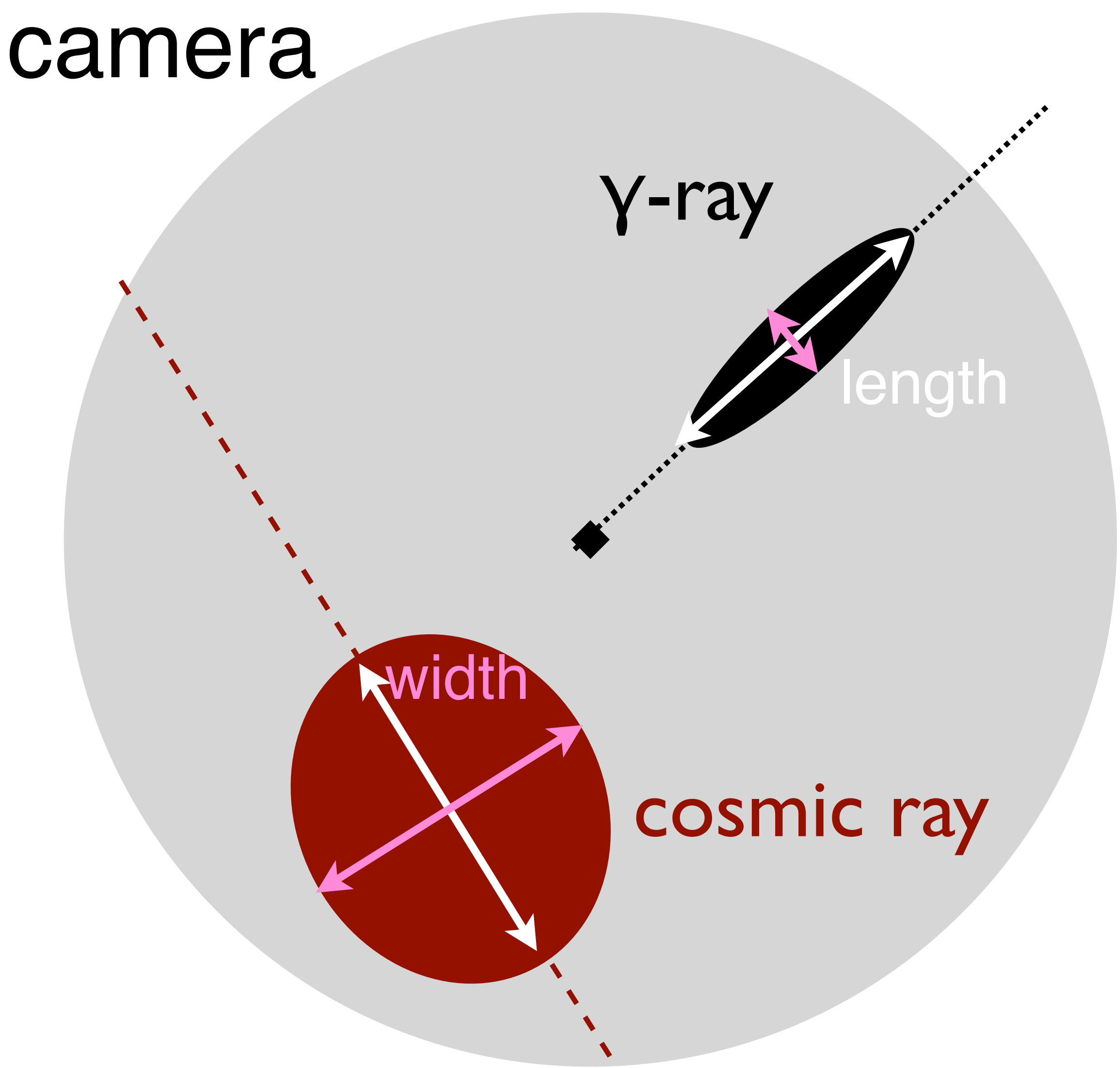
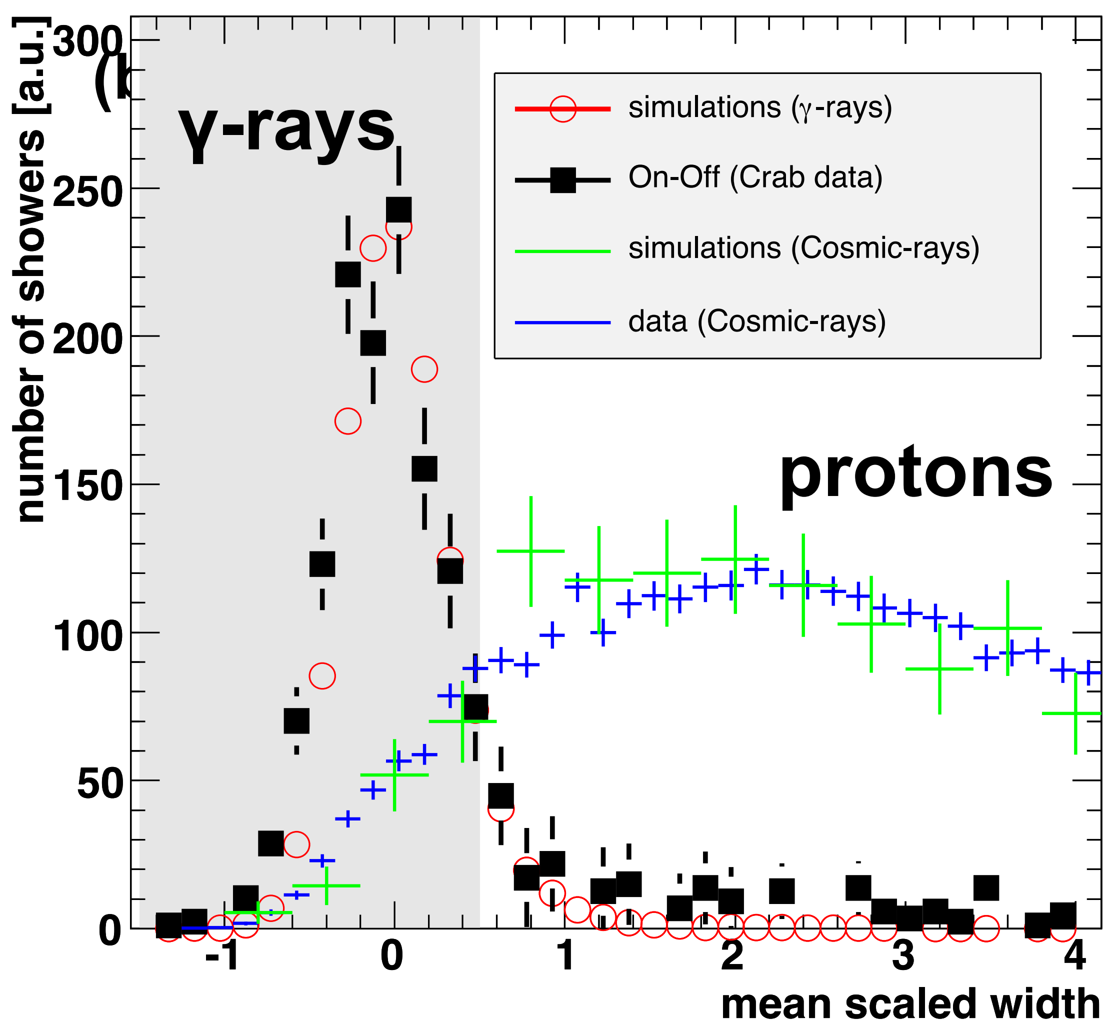
Gamma-hadron separation: mean scaled variables



mean reduced scaled width

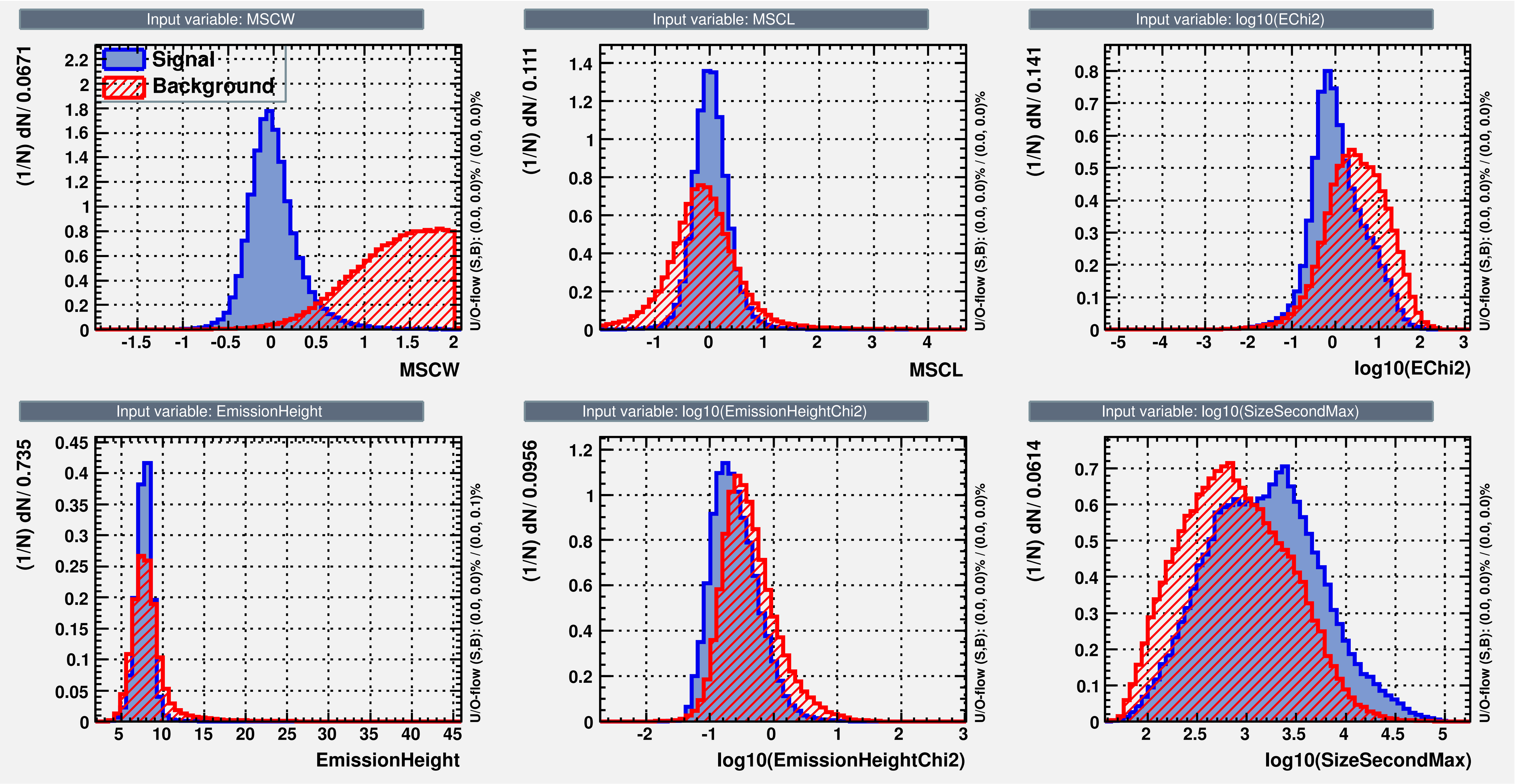
$$mscw = \frac{1}{N_{\text{images}}} \left[\sum_{i}^{N_{\text{images}}} \frac{\text{width}_i - w_{\text{MC}}(R, s, \Theta)}{\sigma_{\text{width, MC}}(R, s, \Theta)} \right]$$

(same for length)



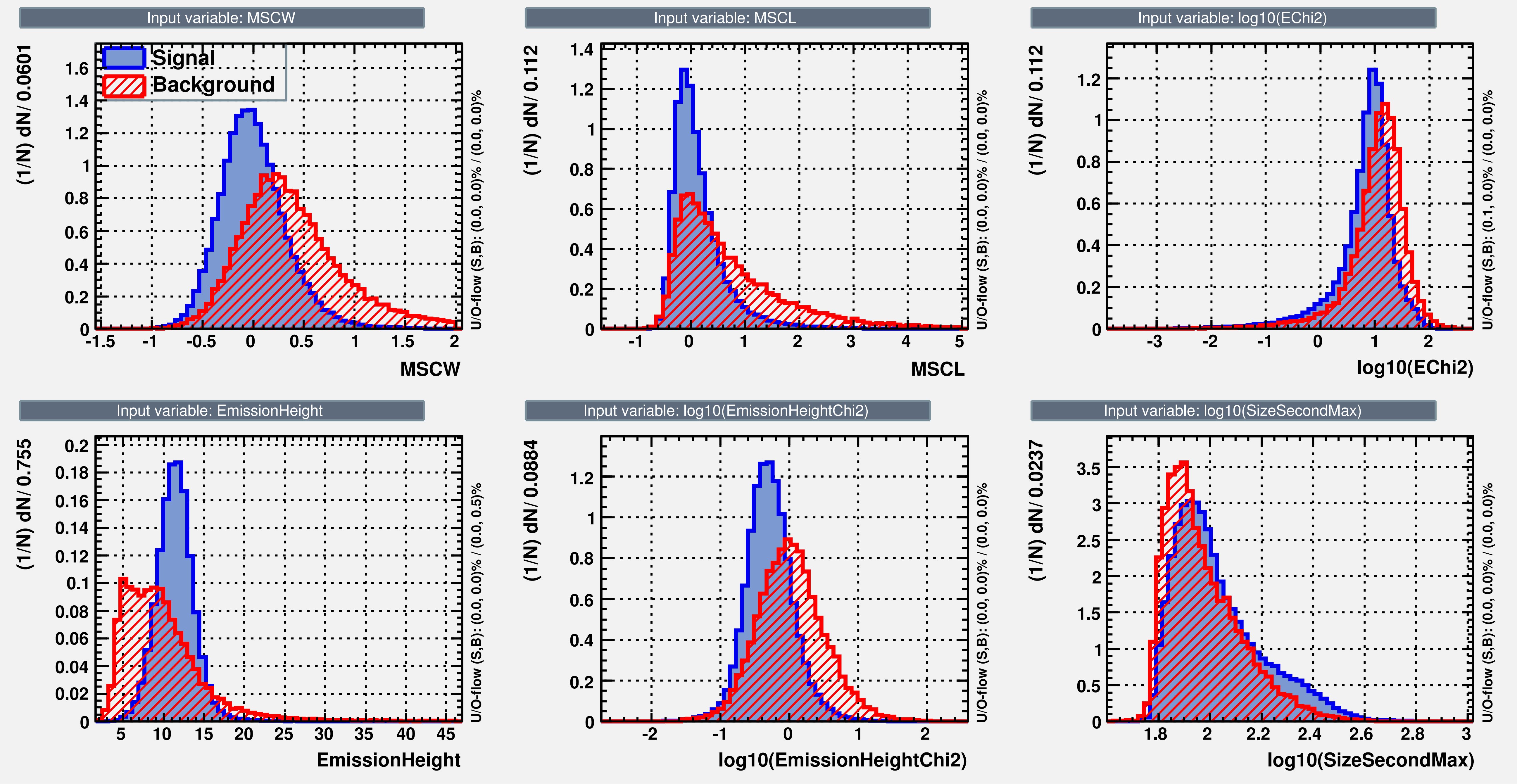
Gamma-hadron separation

reconstructed energies roughly 10 TeV



Gamma-hadron separation

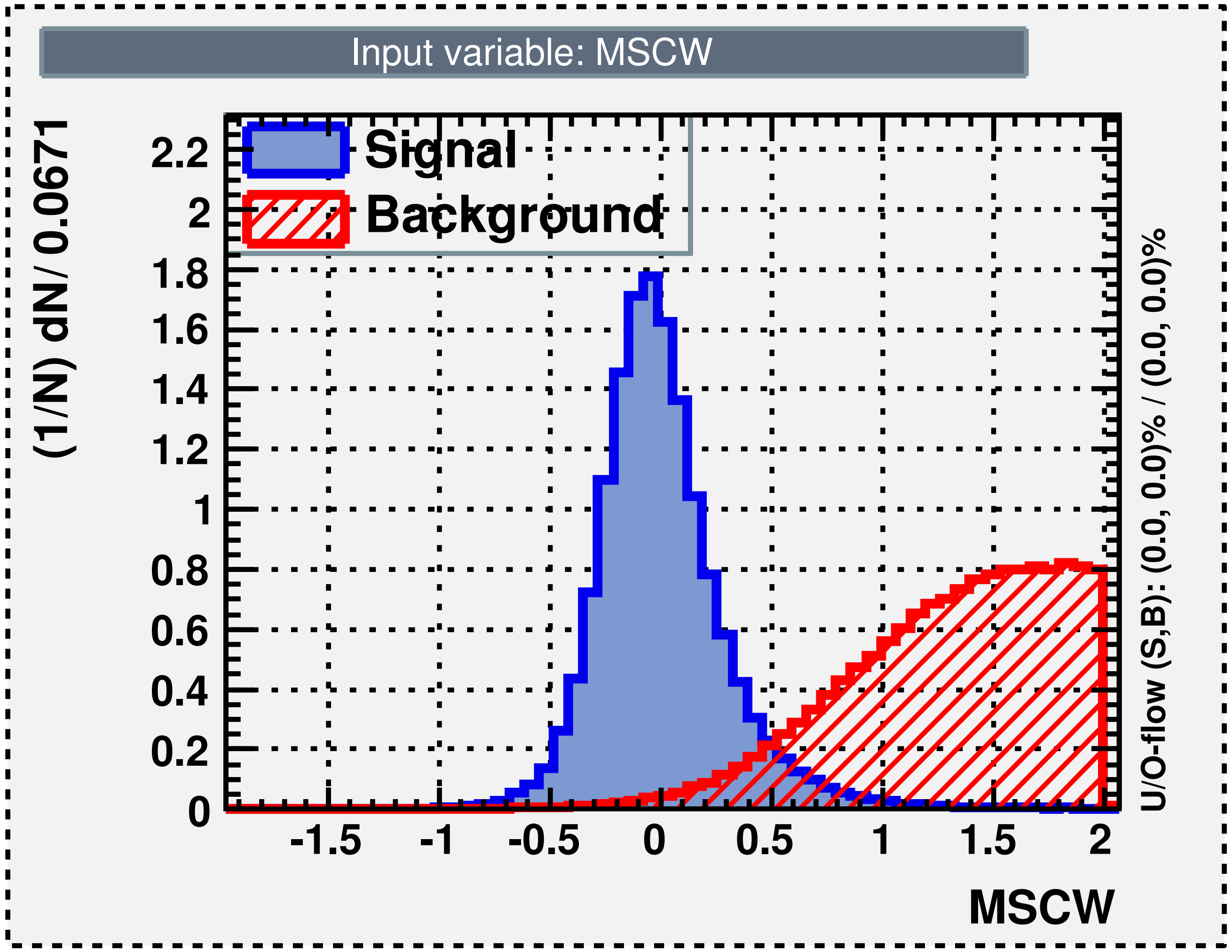
reconstructed energies roughly 60 GeV



Gamma/hadron separation methods

A.Hoecker et al (2007): TMVA 4 Users Guide

- box cuts
- multivariate analysis
  - neutral networks
  - k-Nearest neighbors
  - random forests
  - boosted decision trees
  - support vector machines
  - ....
- correlations between variables important



Application of MVA methods in VHE Astronomy:
F.Dubois et al, Astroparticle Physics 32, 73 (2009)
S.Ohm et al, Astroparticle Physics 31, 383 (2009)
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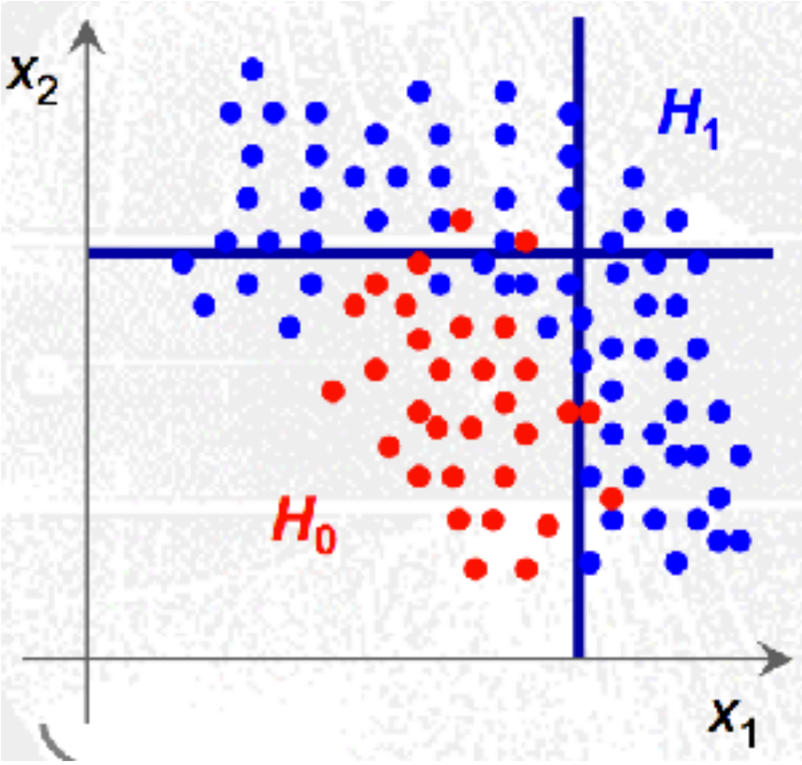

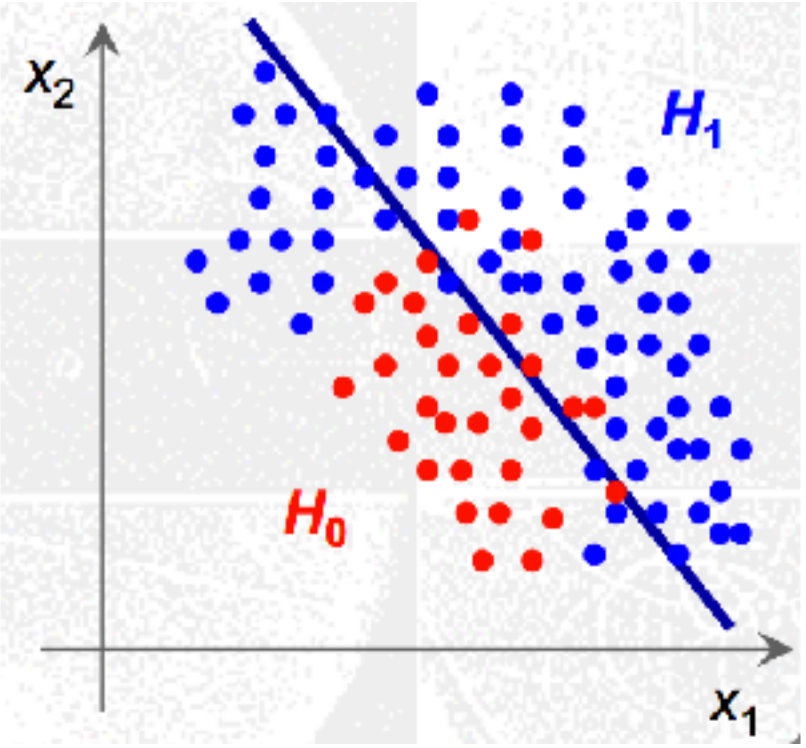

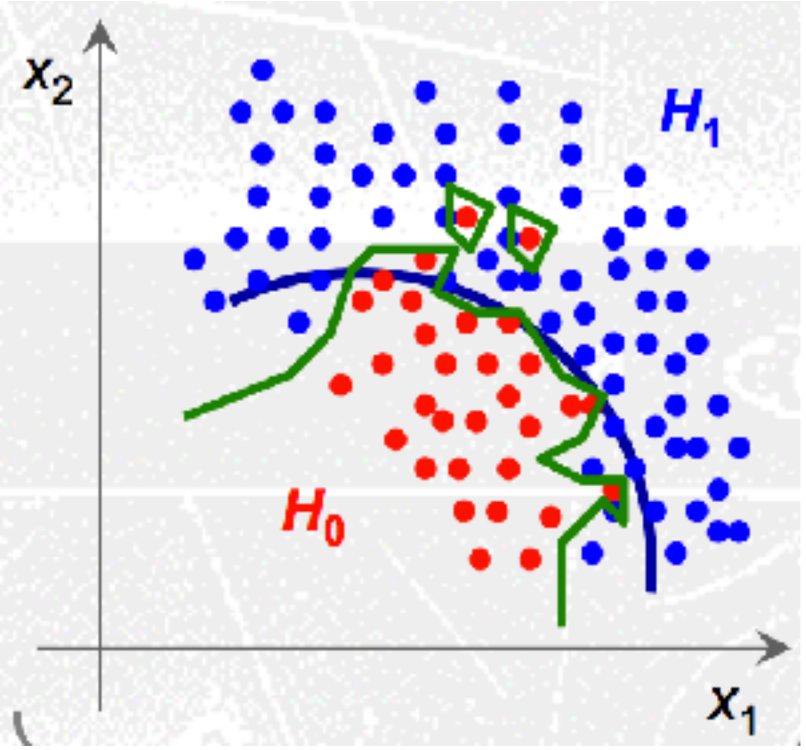

Hoecker 2009

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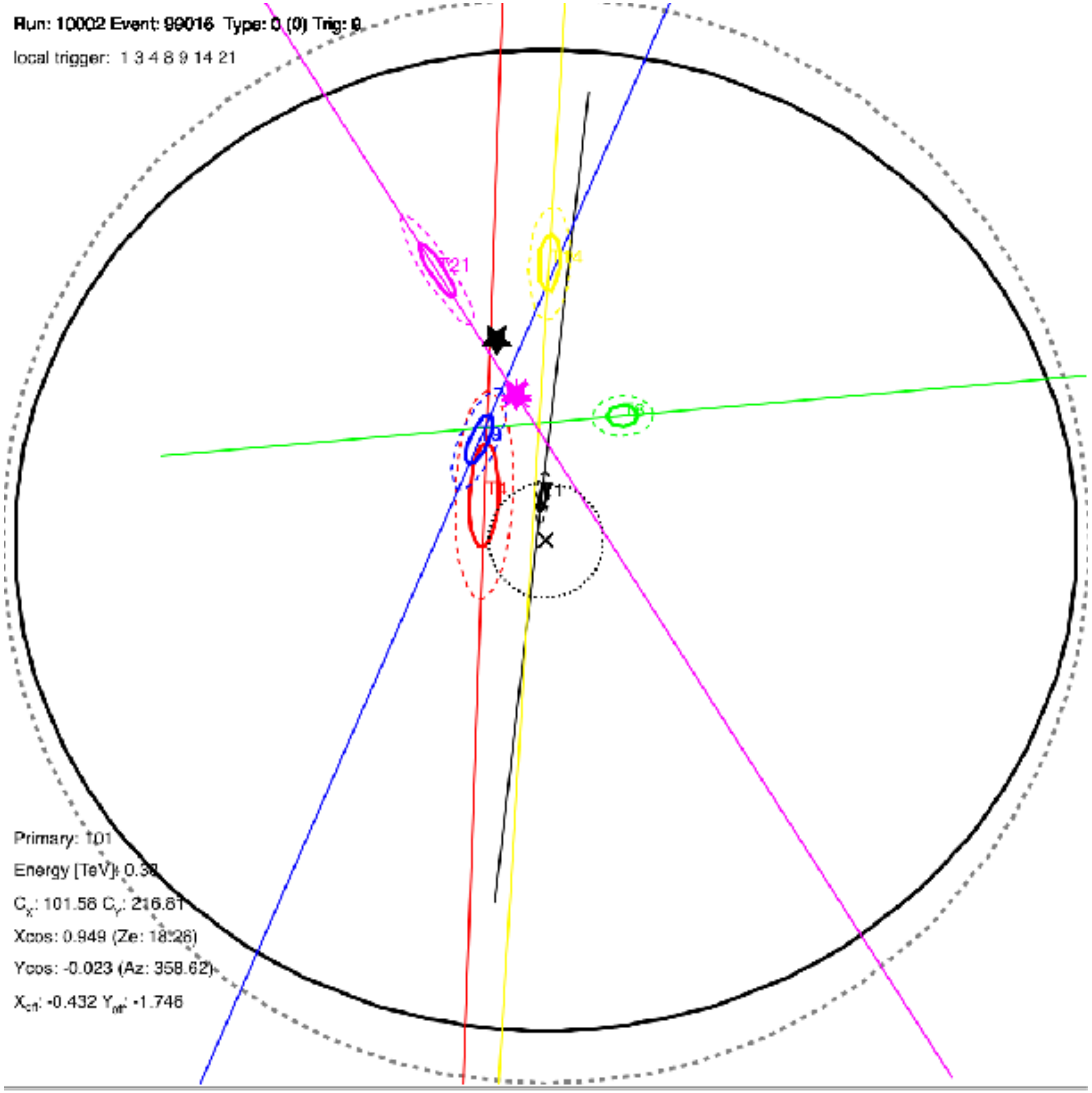
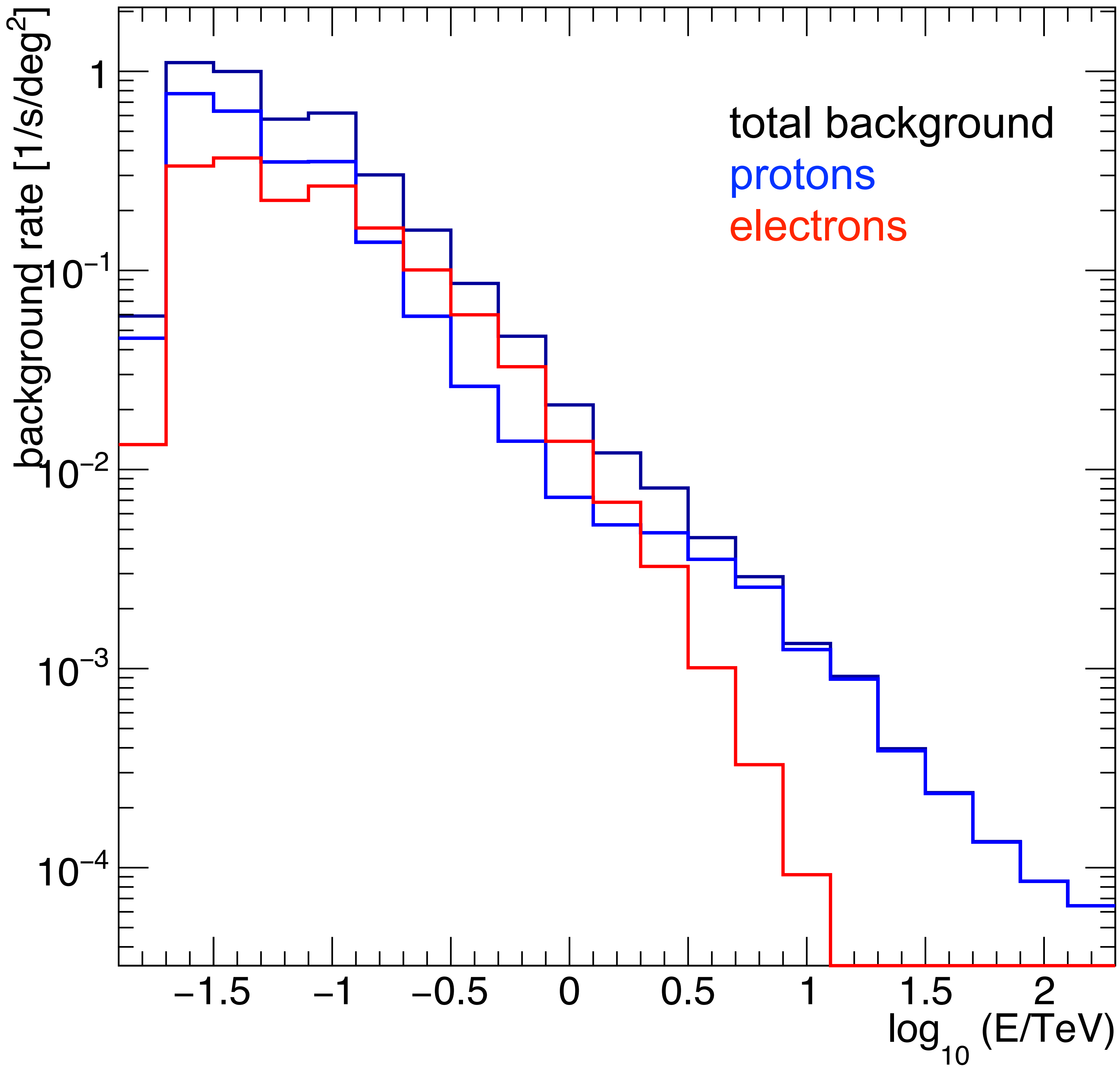
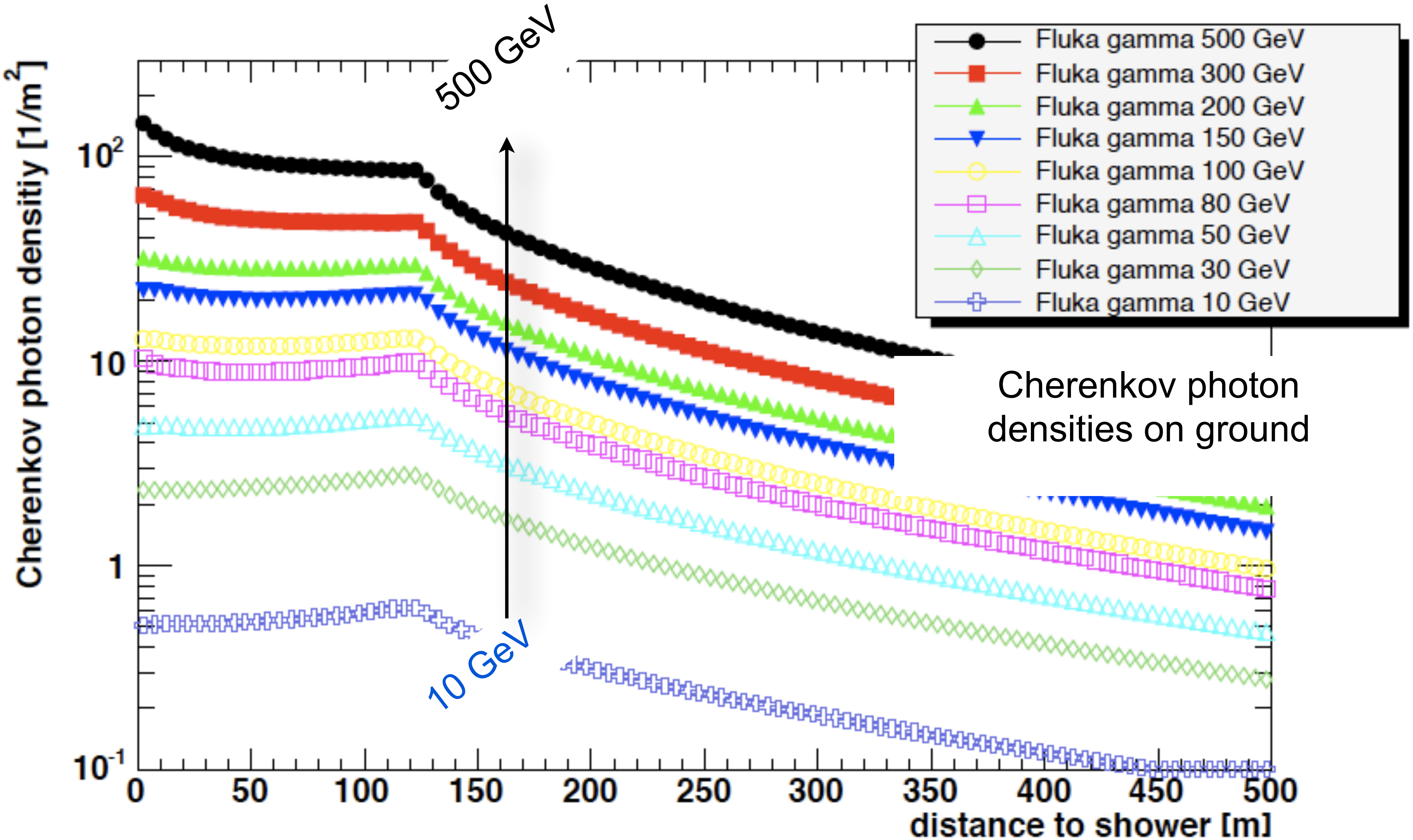
Background event seen with CTA



Background after gamma/hadron cuts for CTA



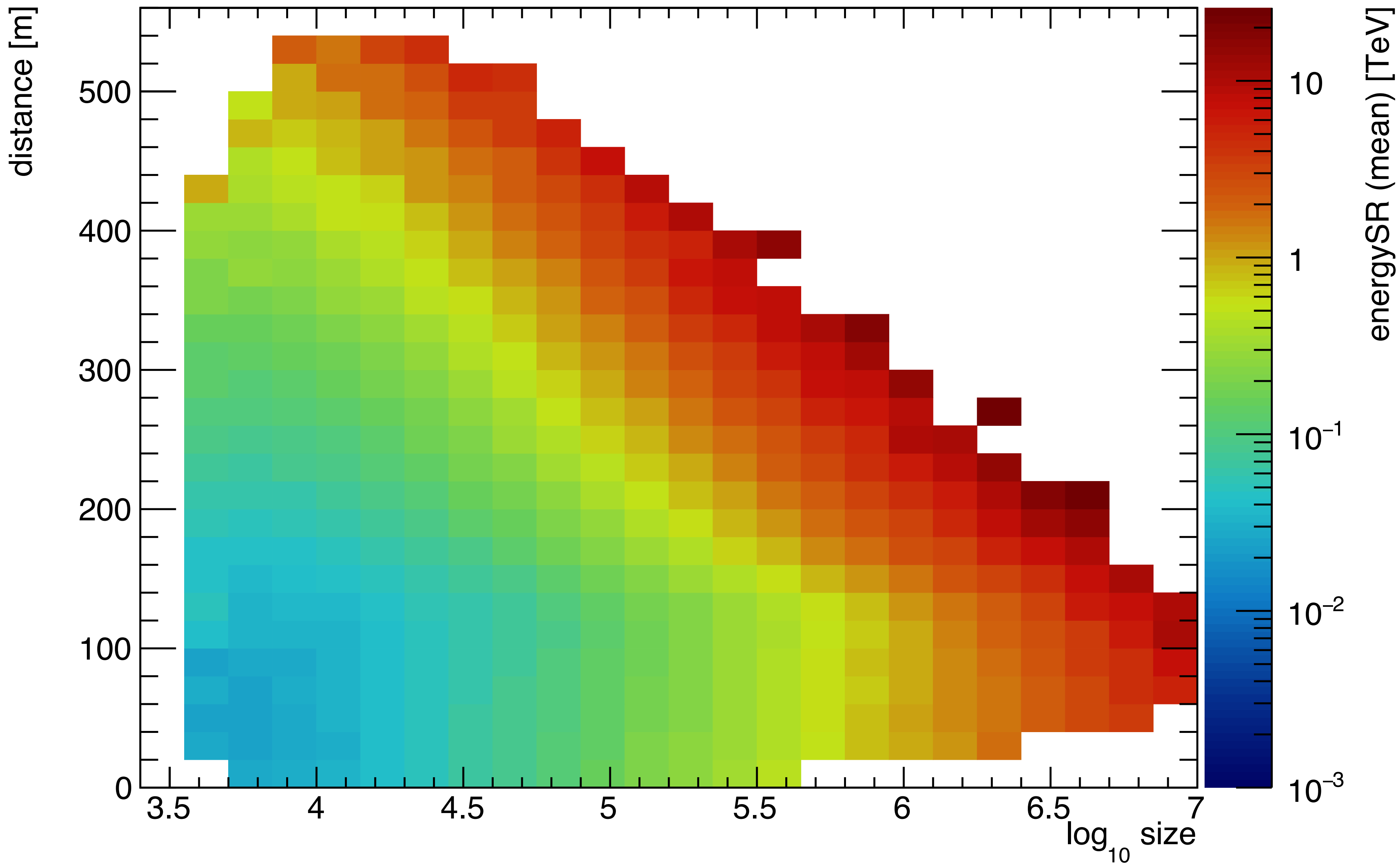
Energy estimation



Cherenkov photon densities on ground

Energy reconstruction: E = E(image size, core distance)

Energy estimation - simple lookup tables



one energy per telescopes -> event energy

$$E = \frac{1}{\sum w_i} \sum E_i w_i$$

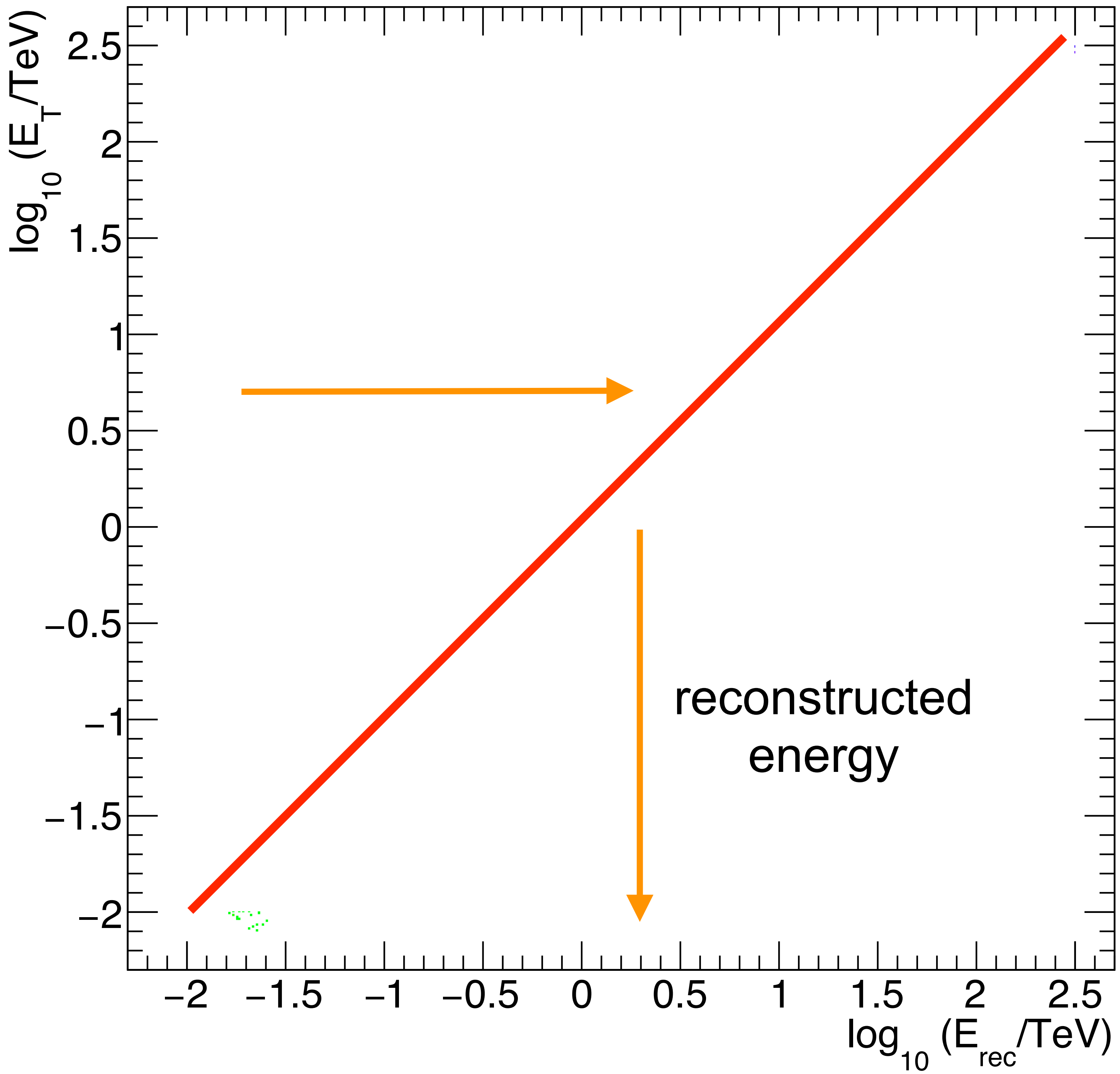
Alternatively:

> multivariate methods:
- take more dependencies into account
- take correlations between variables into account

> typically use random forests or boosted decision trees

Energy migration matrix - Energy Resolution

also called *energy dispersion matrix*



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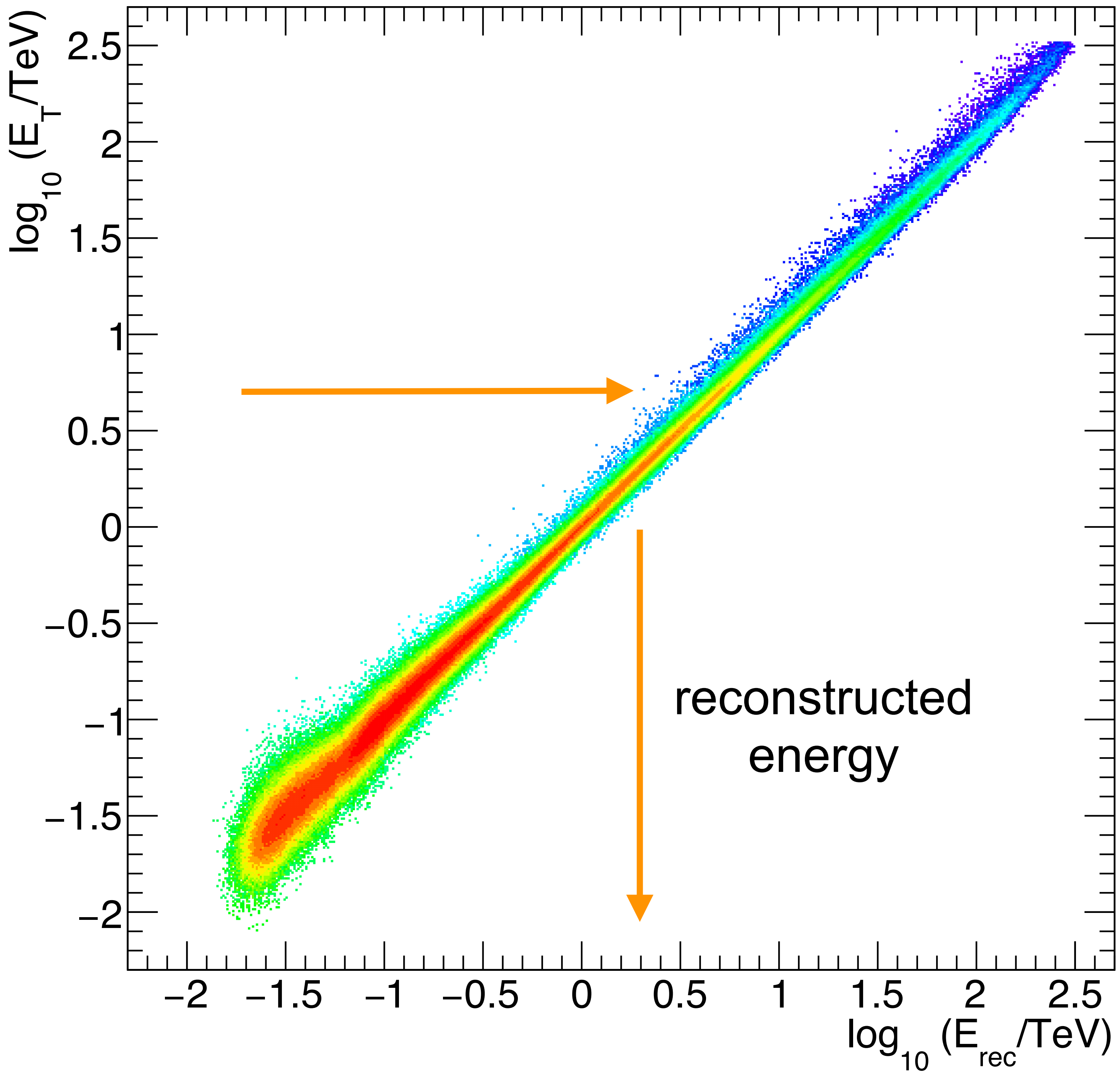

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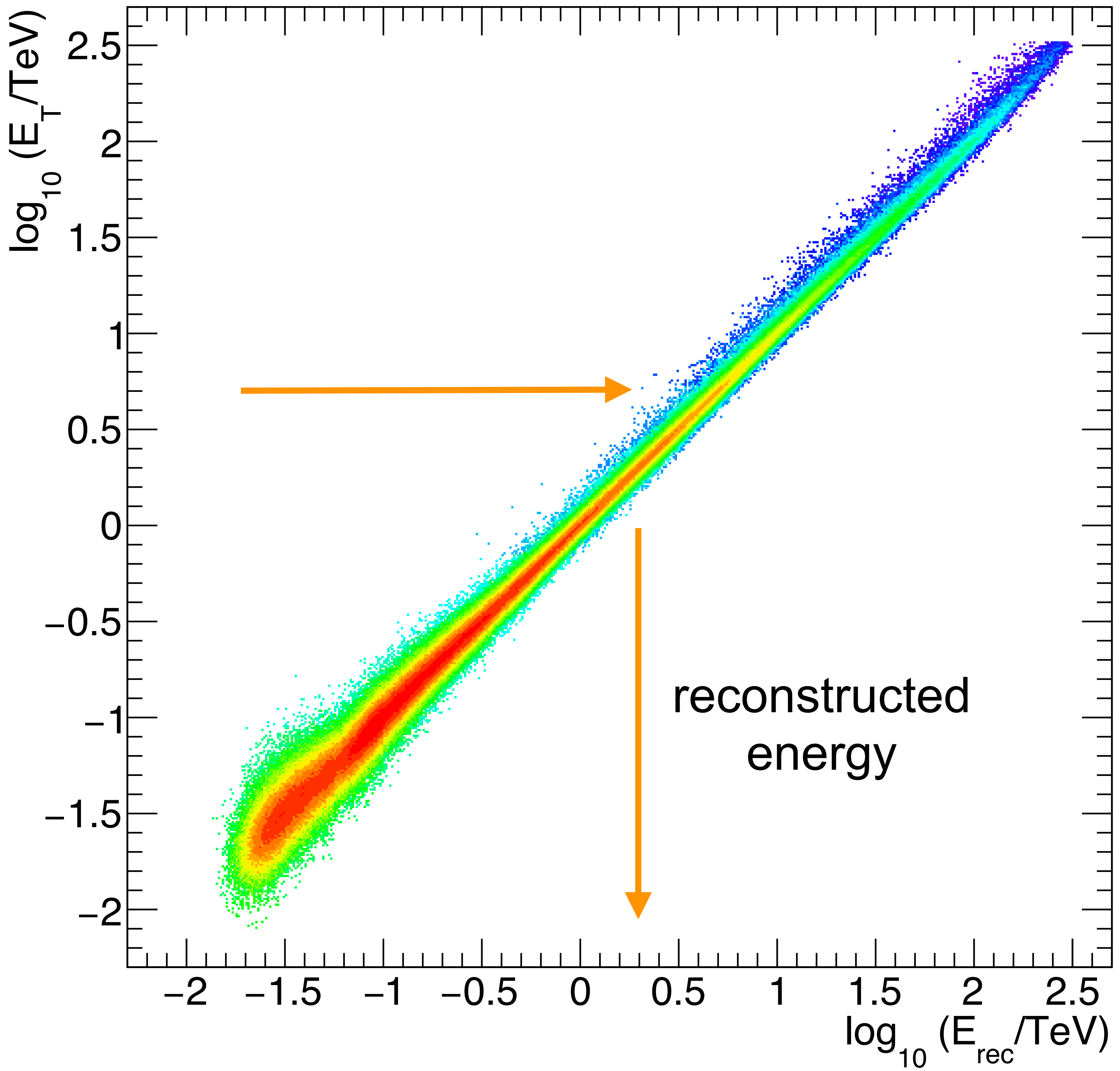

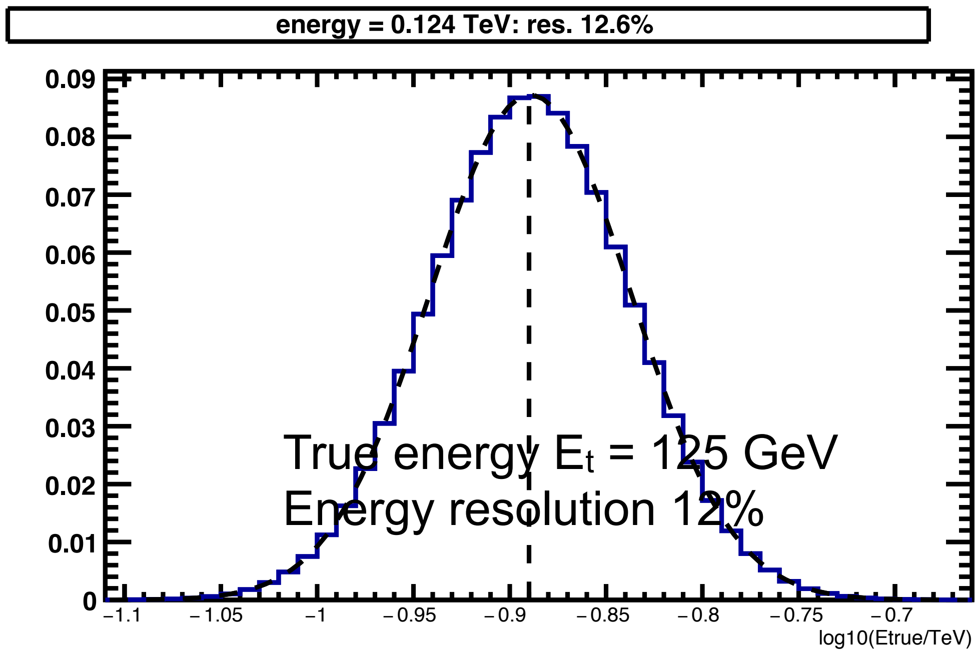

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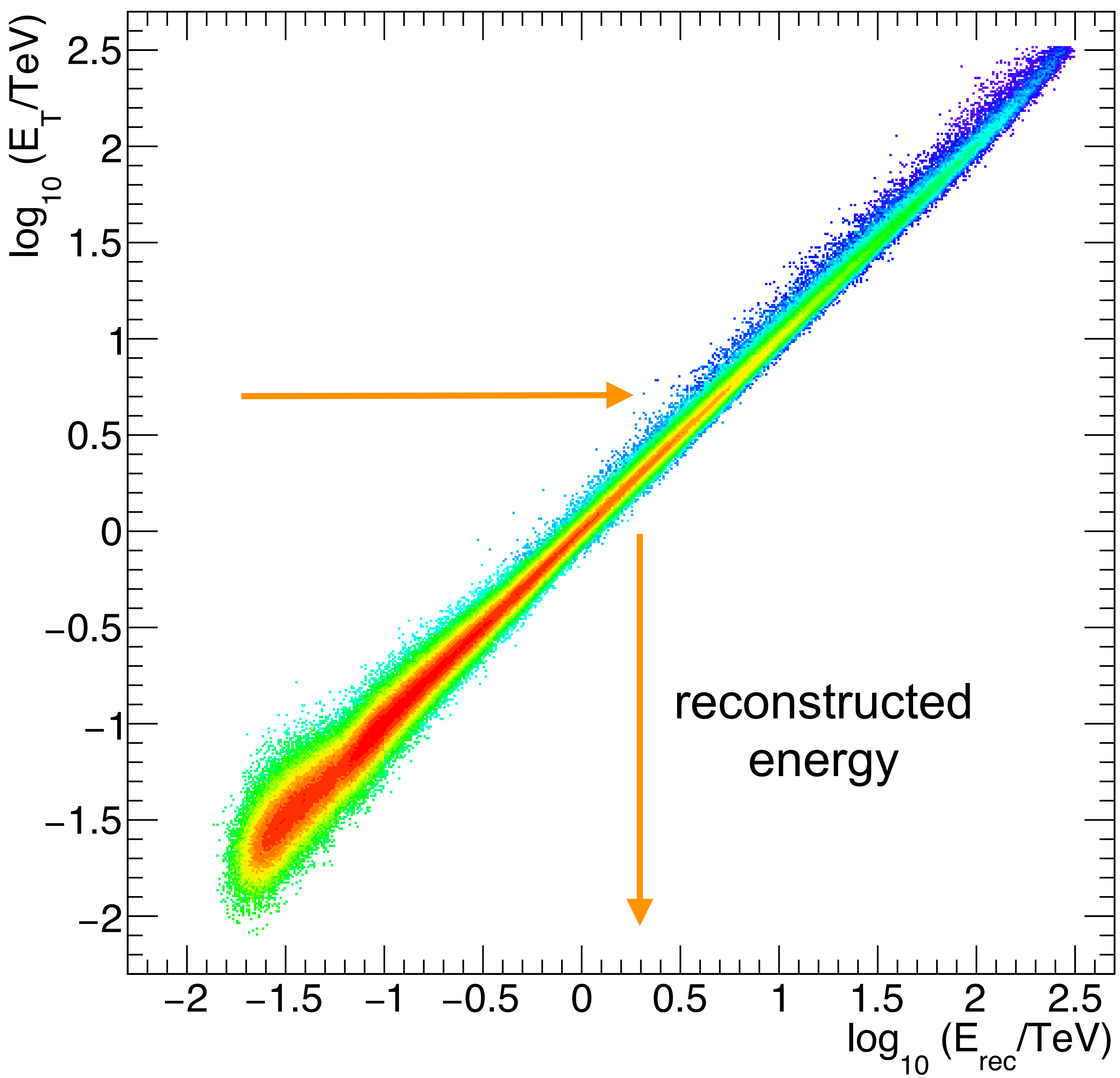
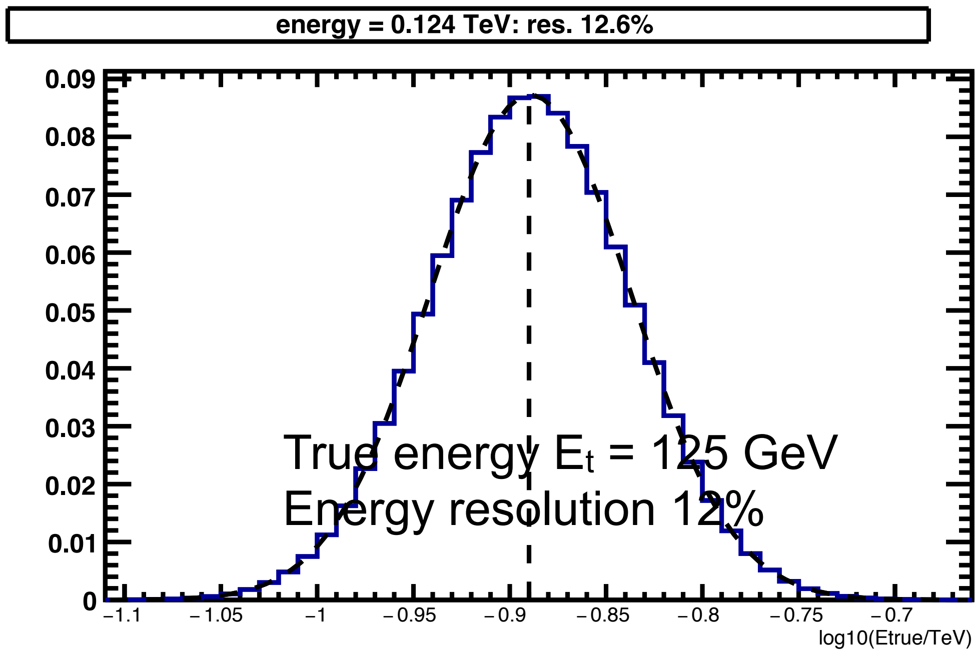
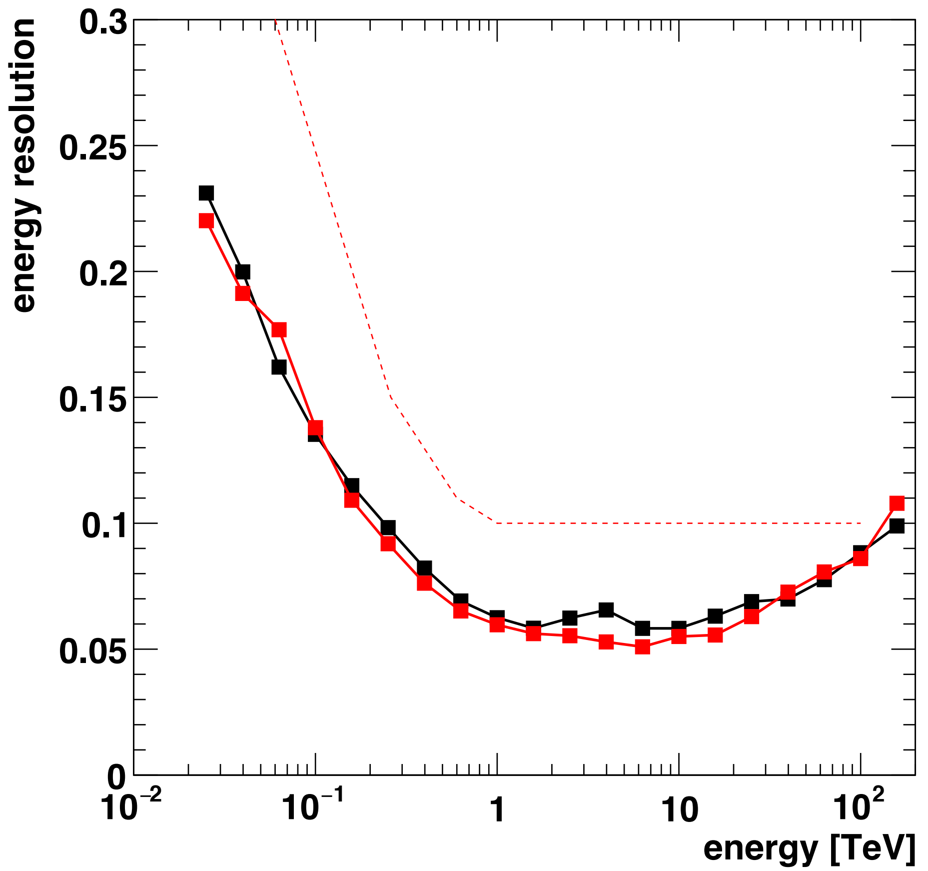






Spectral energy reconstruction

number of observed events in energy bin E_j

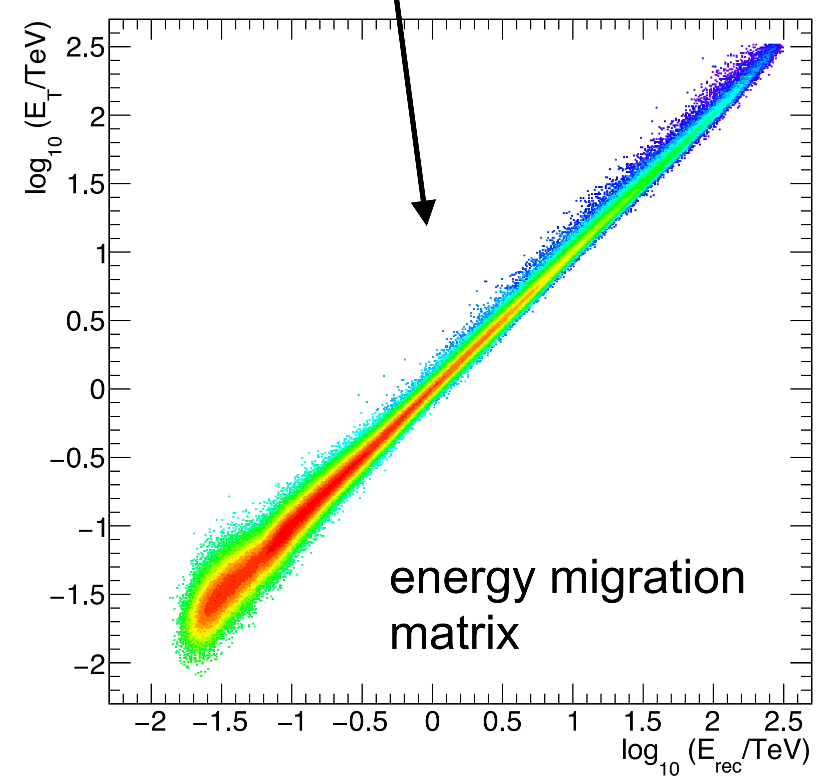
gamma-ray source spectrum

detector uptime

$$N_{obs}(E_j^{rec}) = \int_{t_0}^{t_1} dt \int_0^{\infty} dE \frac{dN_\gamma}{dE dA dt} A_0 \times p(E_j^{rec}|E) \times \epsilon(t)$$

observing interval

probability of measuring E^{rec}



Goal is to reconstructed the gamma-ray source spectrum: invert this integral

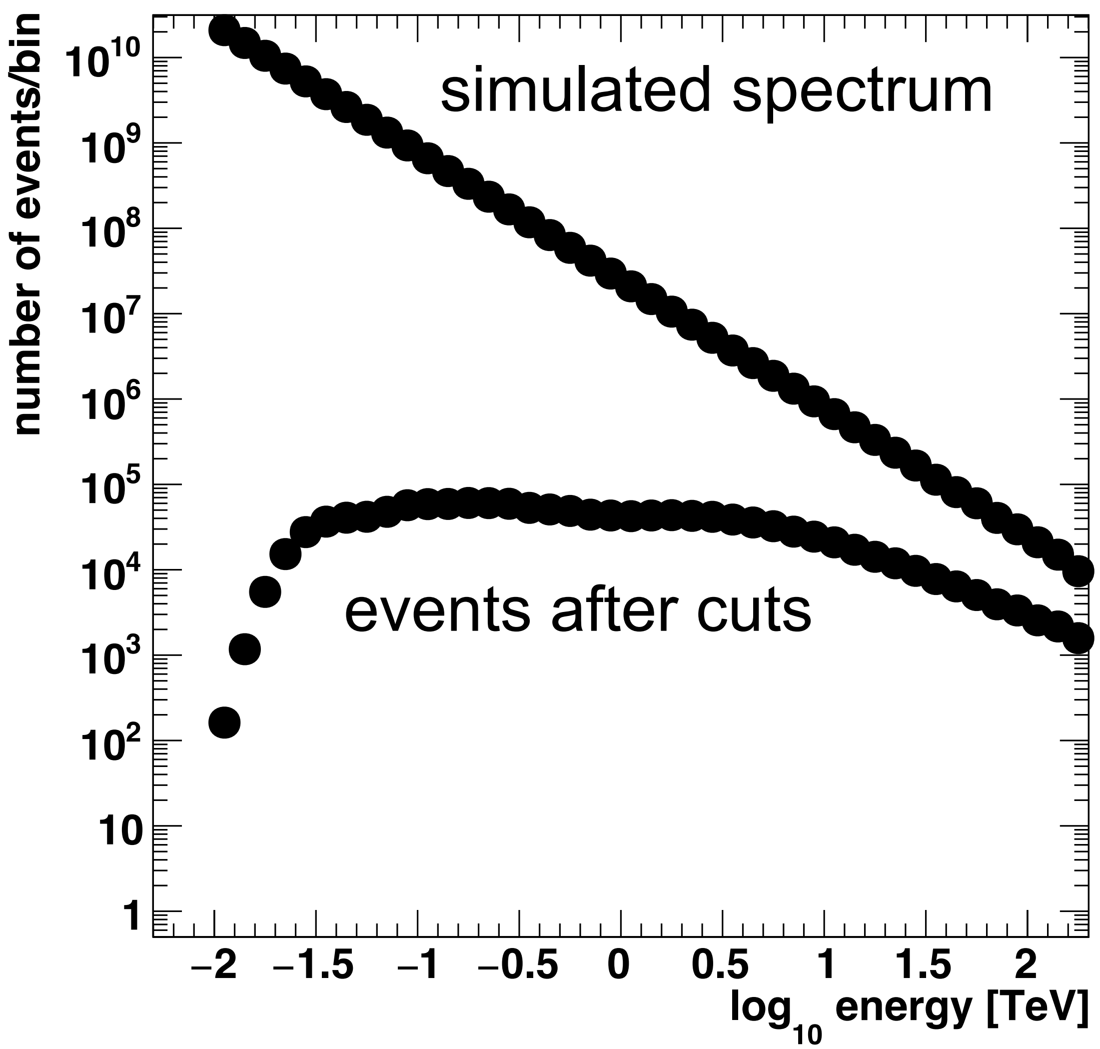
forward folding
unfolding
correction method

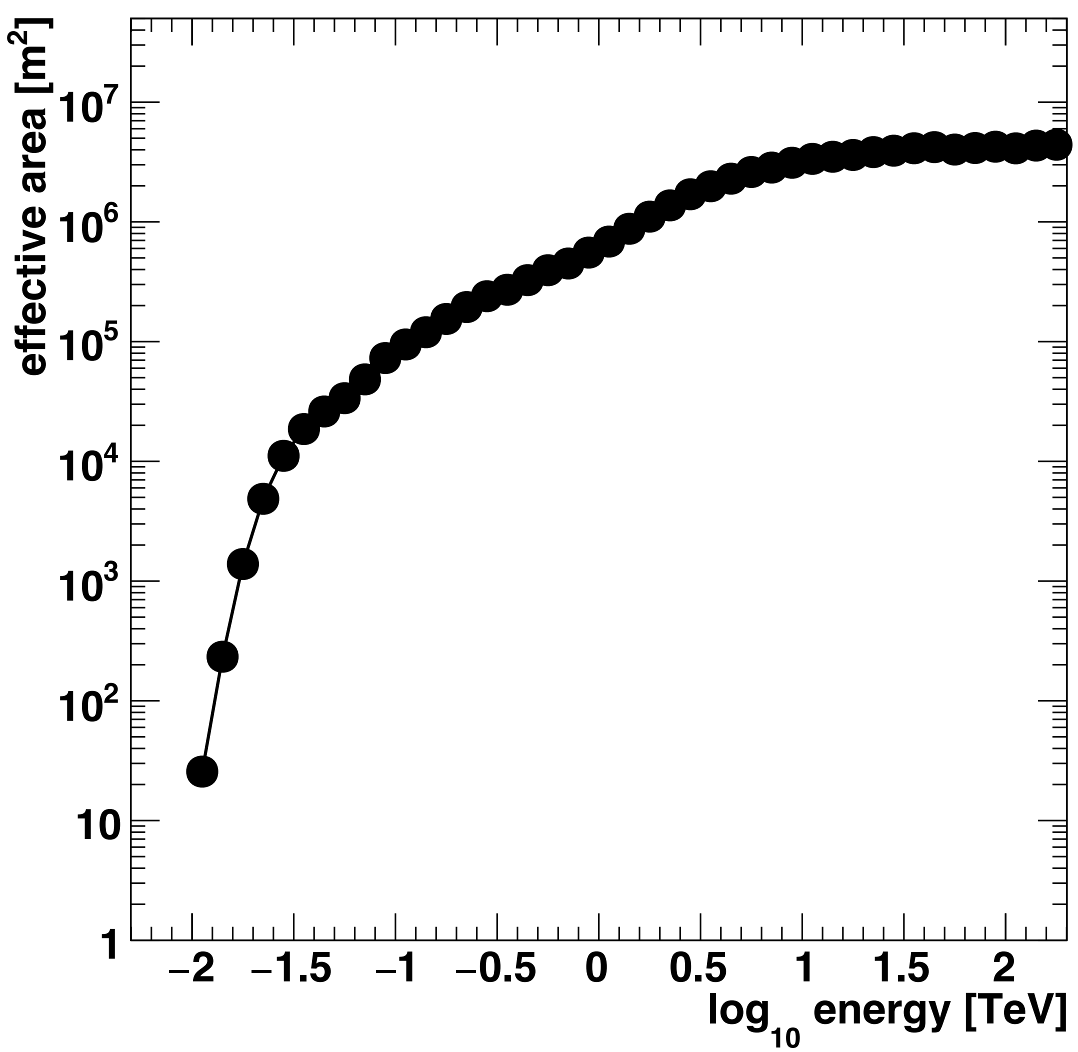
G.Mohanty et al, Astroparticle Physics 9, 15 (1998)
J.Albert et al, NIM A 583, 494 (2007)
Many textbooks, e.g. Cowan: Statistical Data Analysis, Oxford (1998)

Effective areas

$$A(E) = A_0 \left(\frac{\text{number passing selection at } E}{\text{number simulated at } E} \right)$$

A_0: sufficiently large throw area of MC events





Systematic Uncertainties

- **often ignored / forgotten / neglected**
- **Monte Carlo Simulations**
  - parameterisation of atmosphere and atmospheric transmission
  - mirror reflectivity changes
  - photon detection efficiency
  - bad / dead channels
- **Calibration**
  - flatfielding
  - pointing errors
  - non-linearities in the signal chain
- **Reconstruction**
  - signal extraction
  - cuts and methods used

Systematic Uncertainties

- **often ignored / forgotten / neglected**
- **Monte Carlo Simulations**
  - parameterisation of atmosphere and atmospheric transmission
  - mirror reflectivity changes
  - photon detection efficiency
  - bad / dead channels
- **Calibration**
  - flatfielding
  - pointing errors
  - non-linearities in the signal chain
- **Reconstruction**
  - signal extraction
  - cuts and methods used

CTA Requirements:

The systematic uncertainty of the energy of a photon candidate (at energies above 50 GeV) must be < 15%.

The uncertainty on the collection area of the system well above threshold (a factor of two above the lowest energy at which sensitivity is required) must be < 12%.

Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

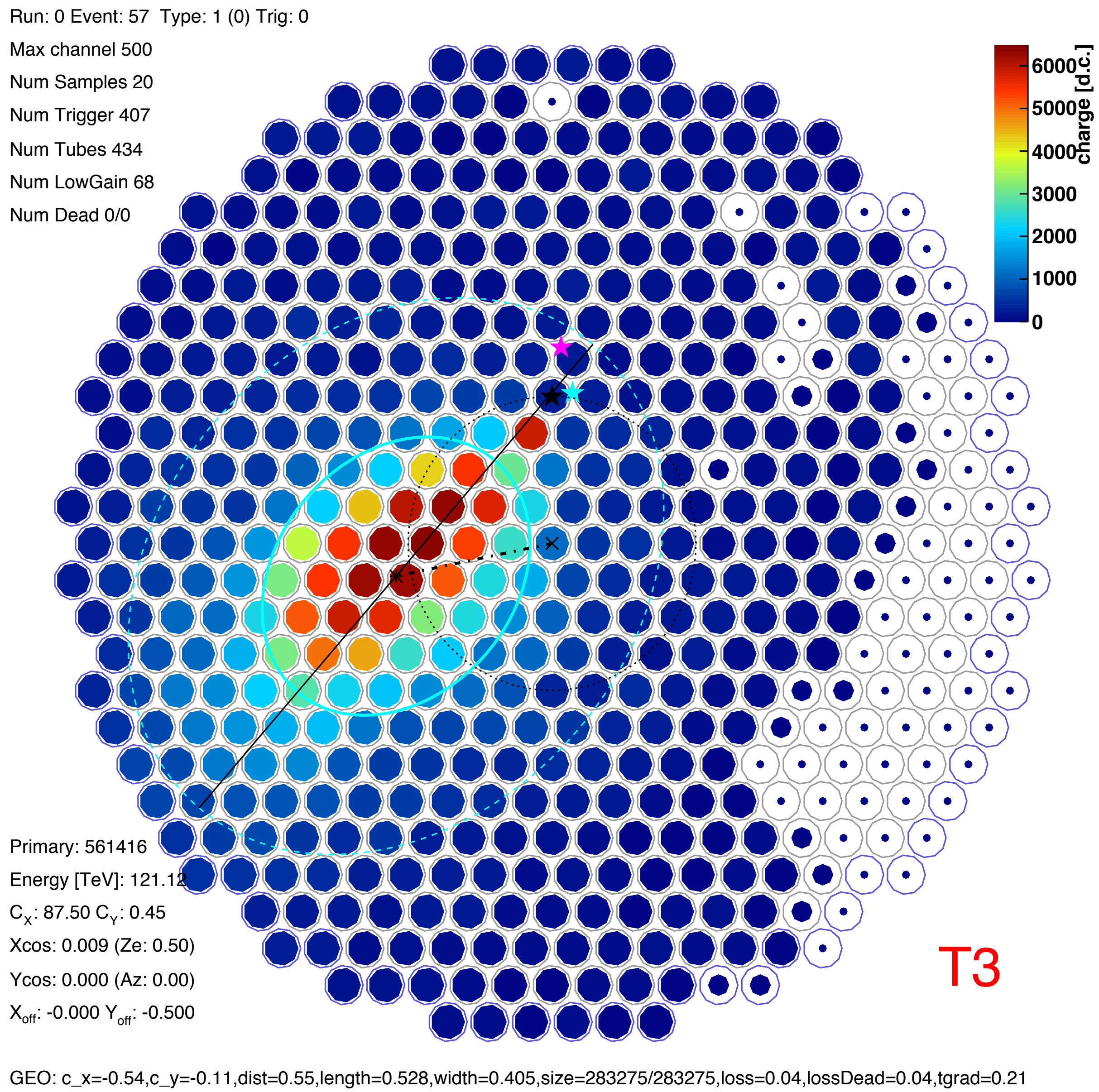
no image cleaning, no image parameterisation,
no lookup tables, no line intersection, etc…

Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

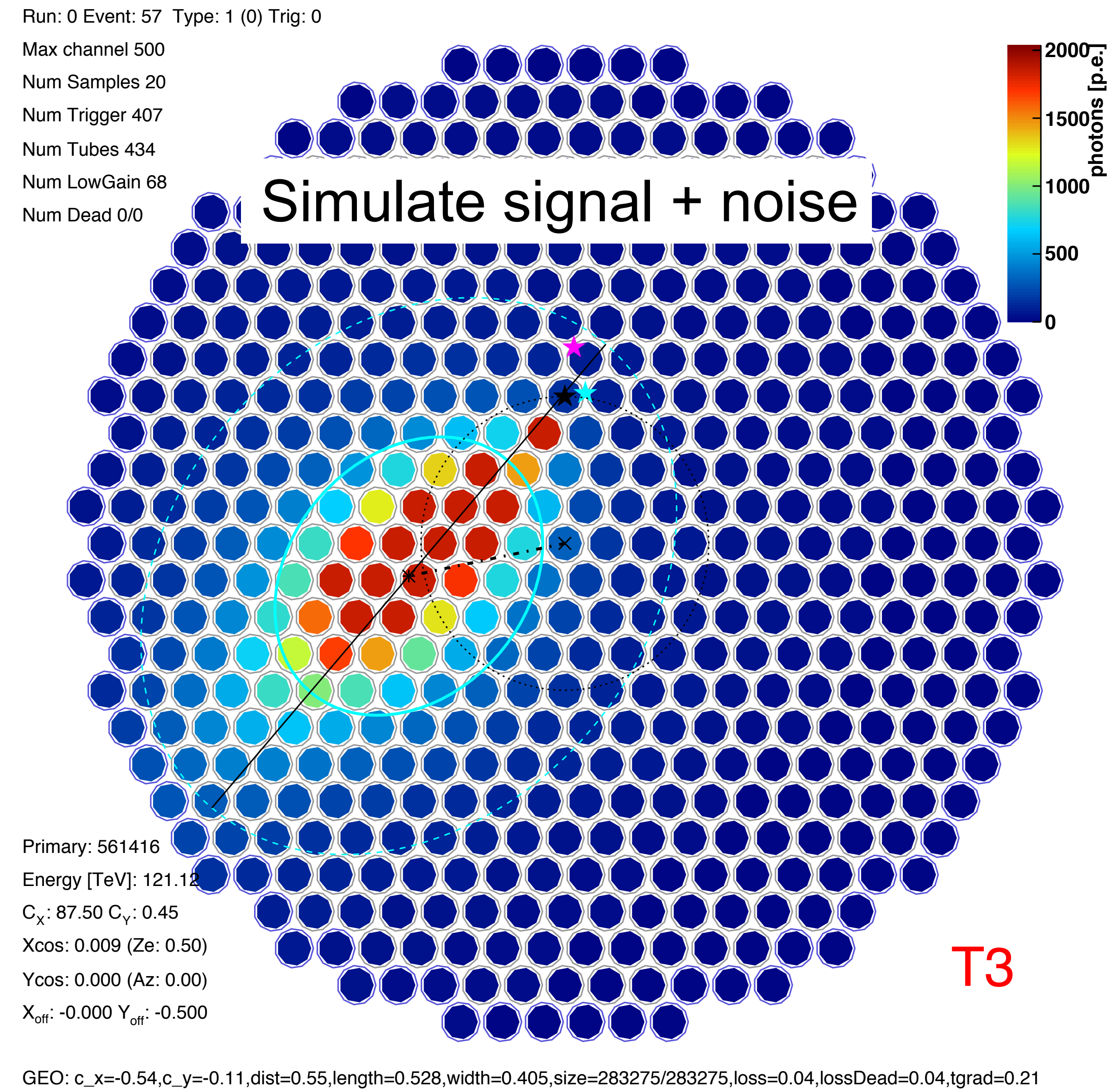
H.Fleischhack (2017)

Data



(a) Integrated charge per pixel.

Model from library of simulated showers or analytical calculation



(b) Best-fit image template.

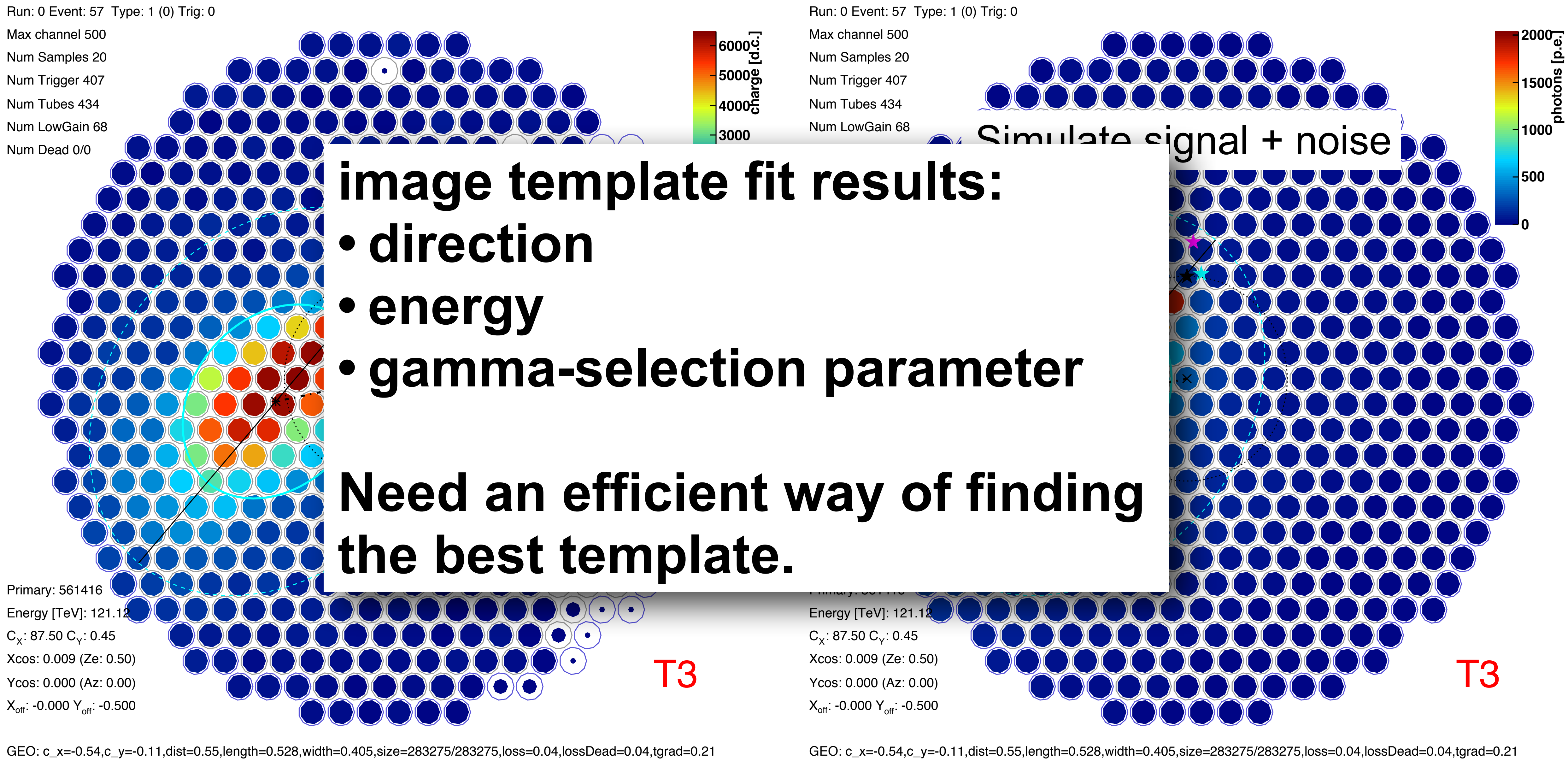
no image cleaning, no image parameterisation,
no lookup tables, no line intersection, etc…

Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

Data

Model from library of simulated showers or analytical calculation



Simulate signal + noise

image template fit results:

- **direction**
- **energy**
- **gamma-selection parameter**

Need an efficient way of finding the best template.

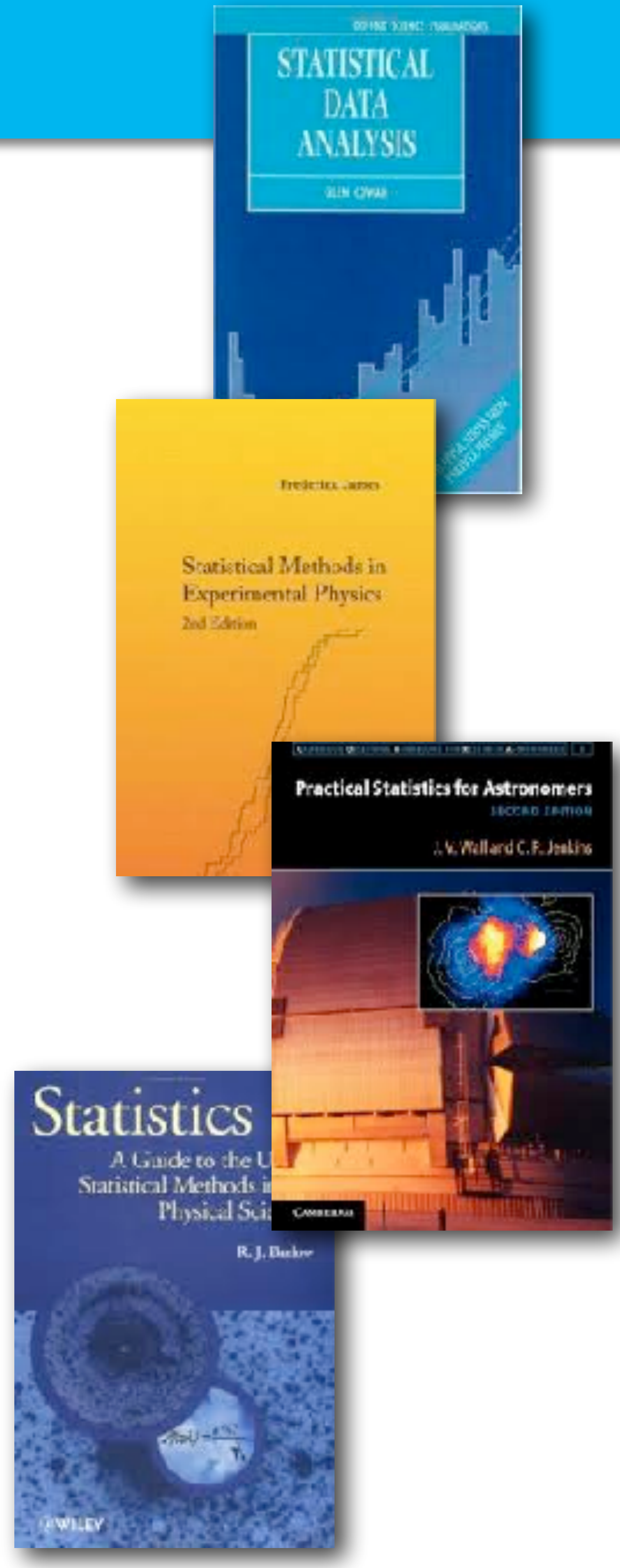
(a) Integrated charge per pixel. (b) Best-fit image template.

H.Fleischhack (2017)

no image cleaning, no image parameterisation, no lookup tables, no line intersection, etc…

Excursus: Maximum Likelihood Technique

- import method for parameter estimation
- provides unbiased and minimal variance estimation of parameters and parameter errors
- works with binned and unbinned data
- allows the combination of different measurements
- standard tool for estimation of spatial and spectral parameters of a gamma-ray source from measurements of e.g. in EGRET, Fermi LAT, CTA



Method of Maximum Likelihood

- *N independent* measurements

$$x = \{x_i\} = \{x_1, x_2, \ldots, x_N\}$$

- model with M parameters:

$$a = \{a_k\} = \{a_1, a_2, \ldots, a_M\}$$

- probability function of x is known: $f = f(x|a)$

$$\int_\Omega f(\boldsymbol{x}|a)\,\mathrm{d}\boldsymbol{x} = 1$$

for all a

- **Likelihood function**

$$L(a) = f(x_1|a) \cdot f(x_2|a) \cdots f(x_n|a) = \prod_{i=1}^{n} f(x_i|a)$$

Best estimator for a:

$$L(a) = \text{Maximum}$$

$$\frac{\partial L}{\partial a_k} = 0 \quad \text{for all k}$$

Method of Maximum Likelihood

in general: minimise negative log likelihood

$$F(a) = -l(a) = -\sum_{i=1}^{n} \ln f(x_i|a)$$

different methods to estimate variance of ML estimator

analytical method, Monte Carlo method, graphical method, RCF bound (Fisher information matrix)

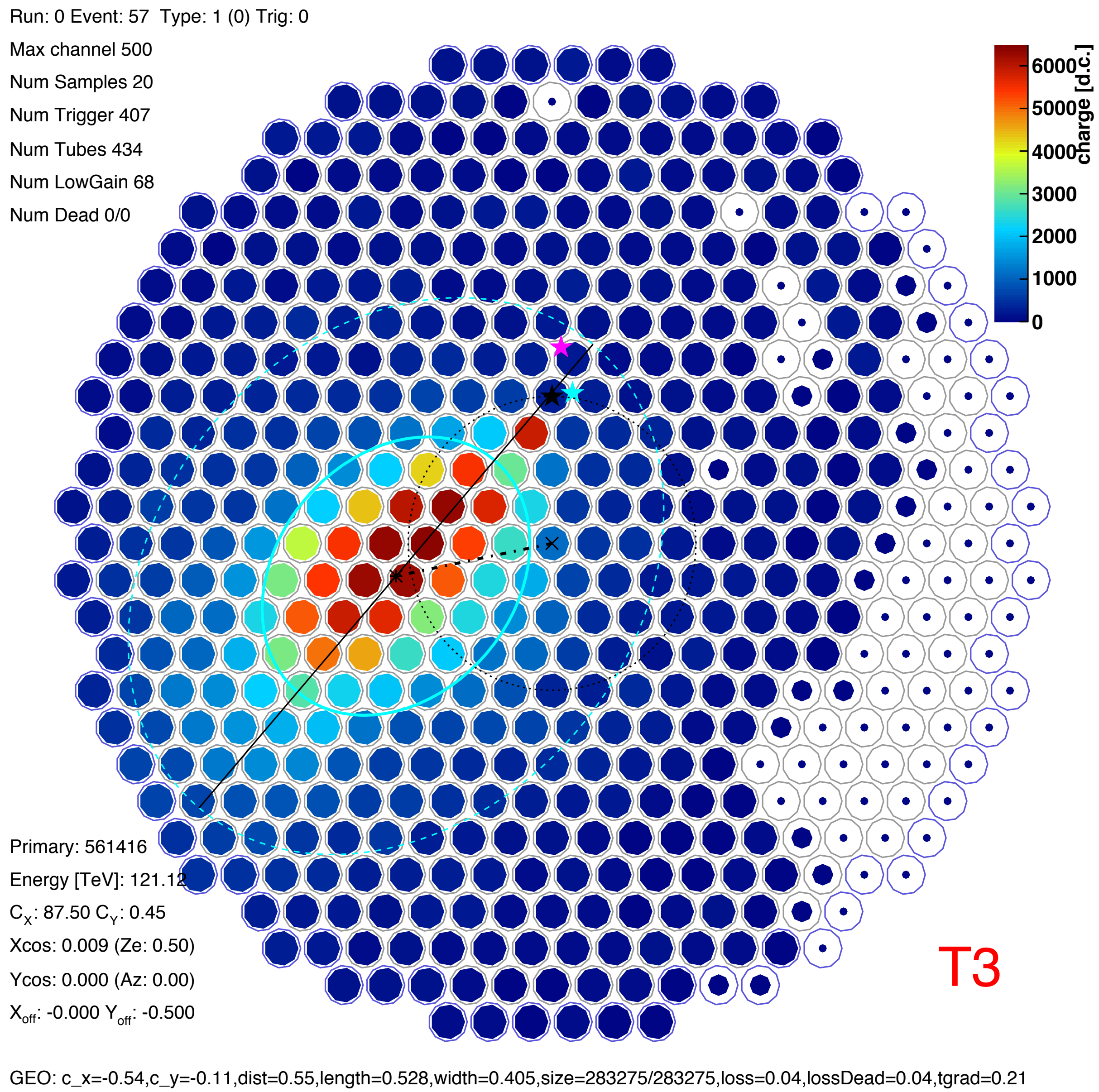
very often: solve numerically with e.g. MINUIT (MIGRAD and HESSE)

Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

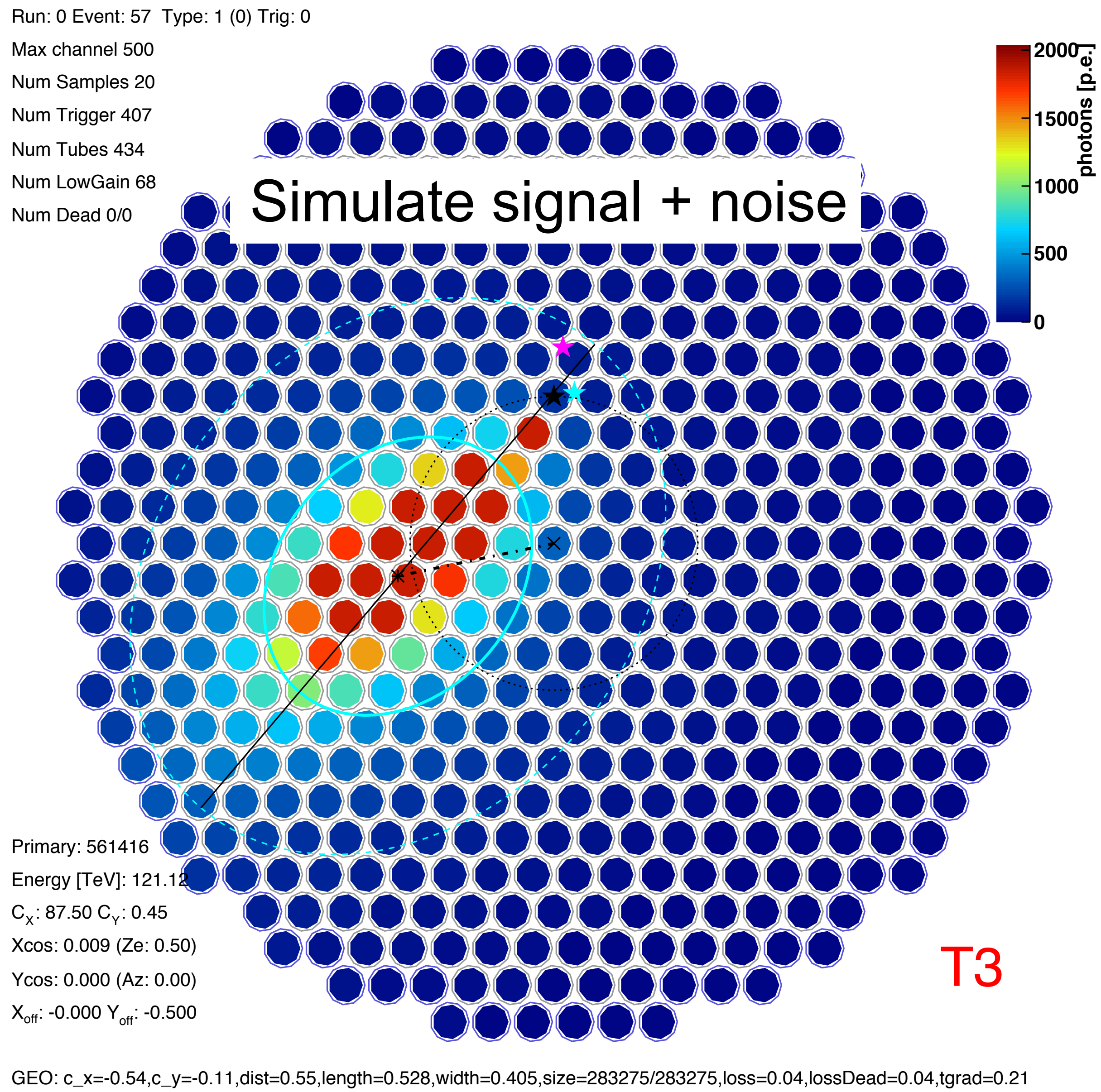
H.Fleischhack (2017)

Data



(a) Integrated charge per pixel.

Model from library of simulated showers or analytical calculation



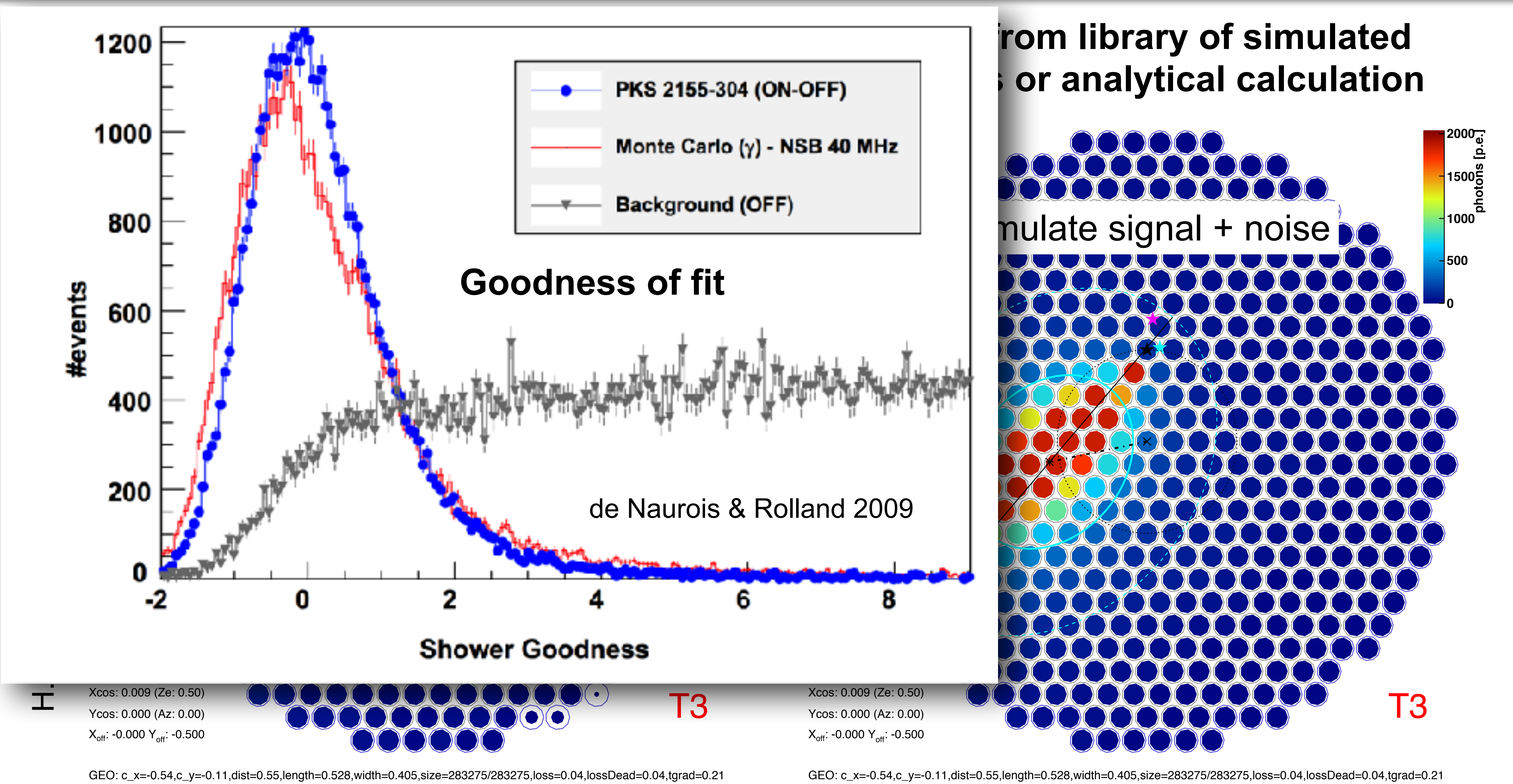
(b) Best-fit image template.

Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

rom library of simulated
s or analytical calculation

mulate signal + noise



(a) Integrated charge per pixel.

(b) Best-fit image template.

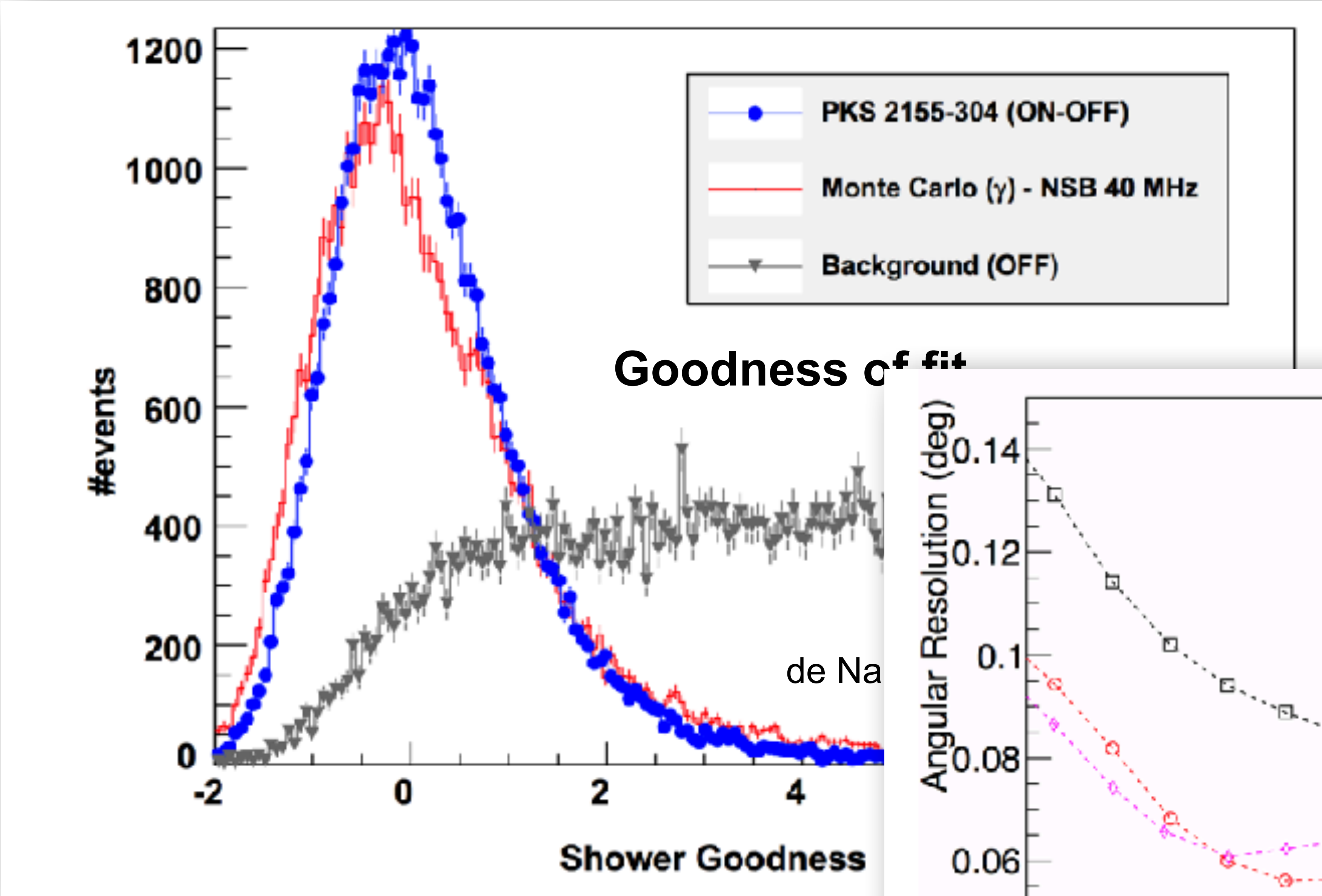
Image Template Analysis

Le Bohec et al 1998
de Naurois & Rolland 2009
Parson & Hinton 2014

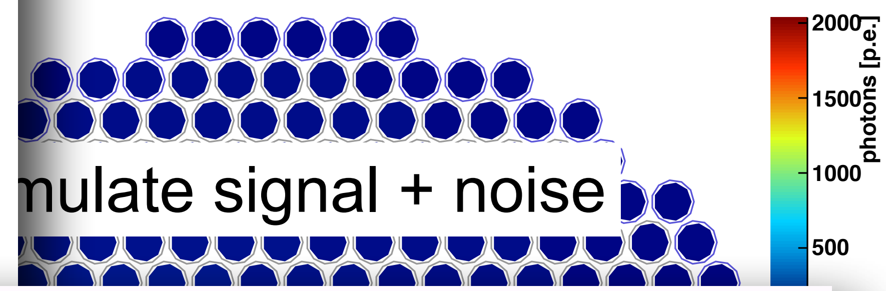
rom library of simulated
s or analytical calculation

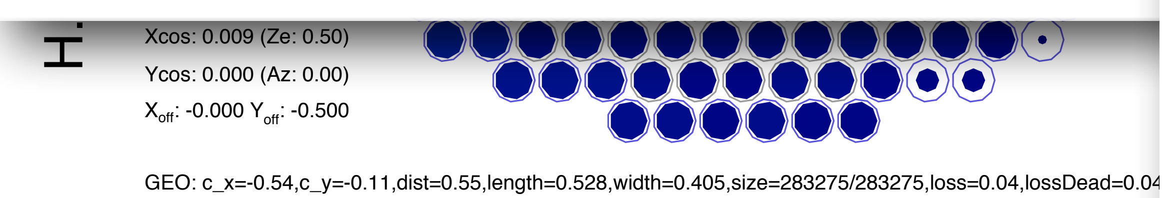
mulate signal + noise

Goodness of fit

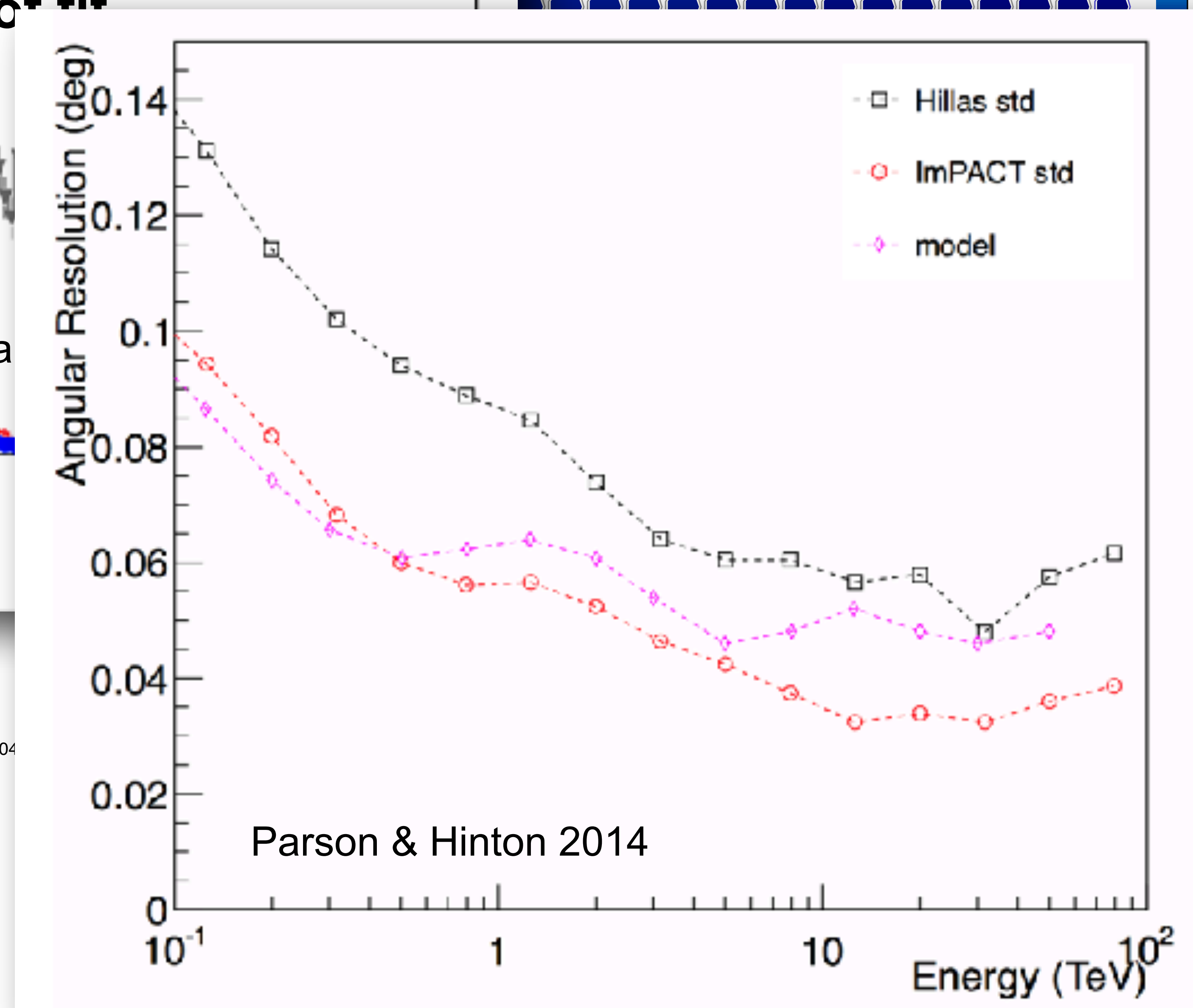


de Na





(a) Integrated charge per pixel.

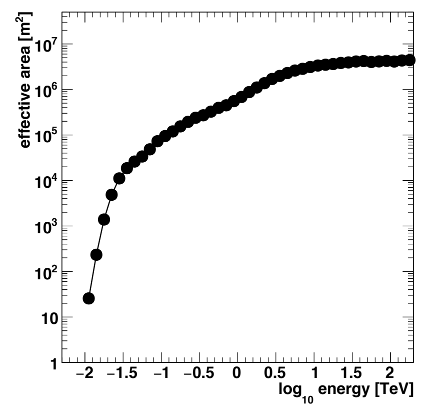


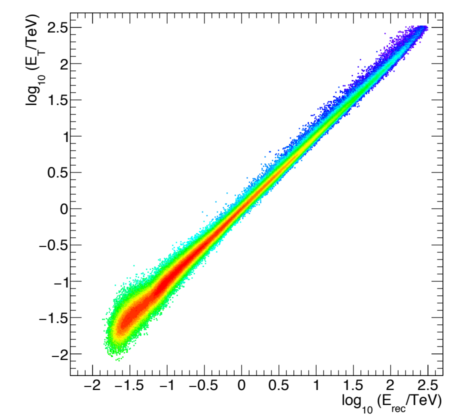
Analysis - Input

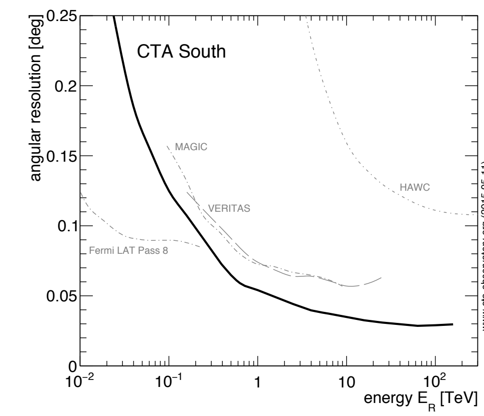
- **key observables for each gamma ray: energy, direction, arrival time**

event reconstruction (4 dimensions)

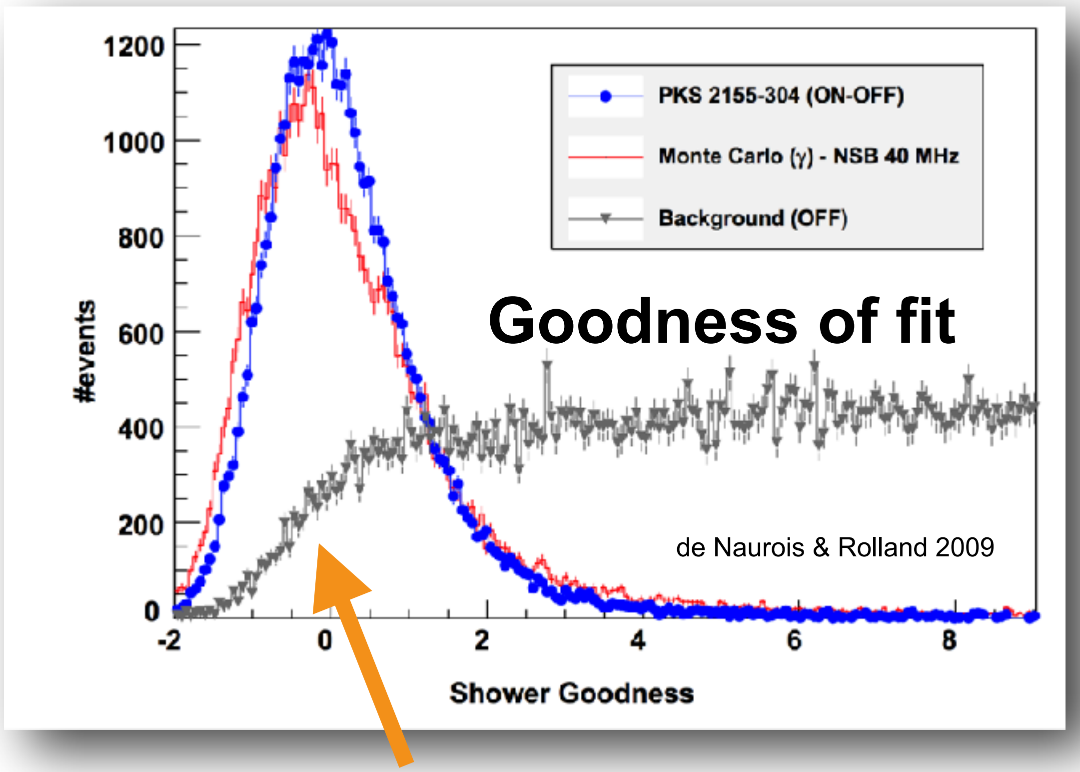
- **detector response:**
  - detection probability (effective areas)
  - direction resolution
  - energy dispersion matrix
  - instrument dead time





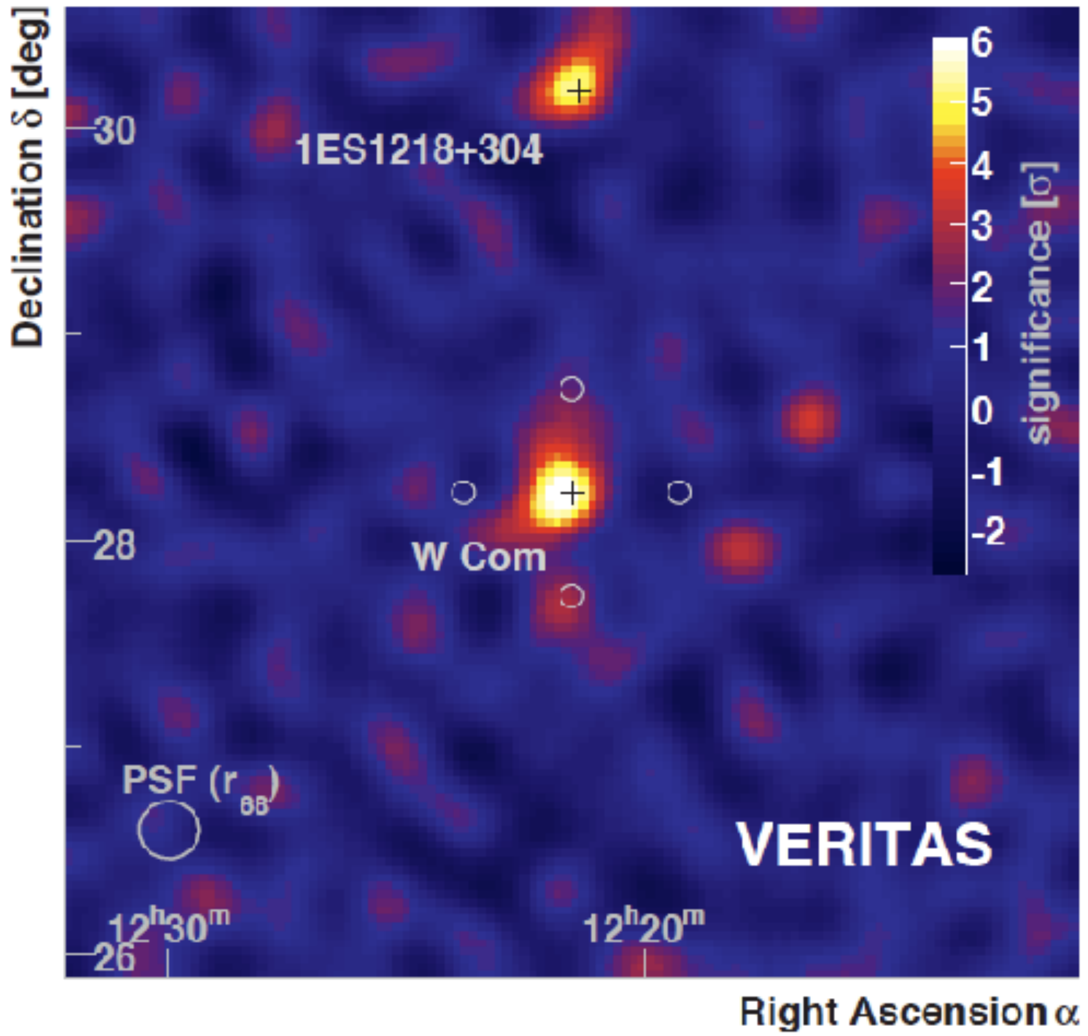


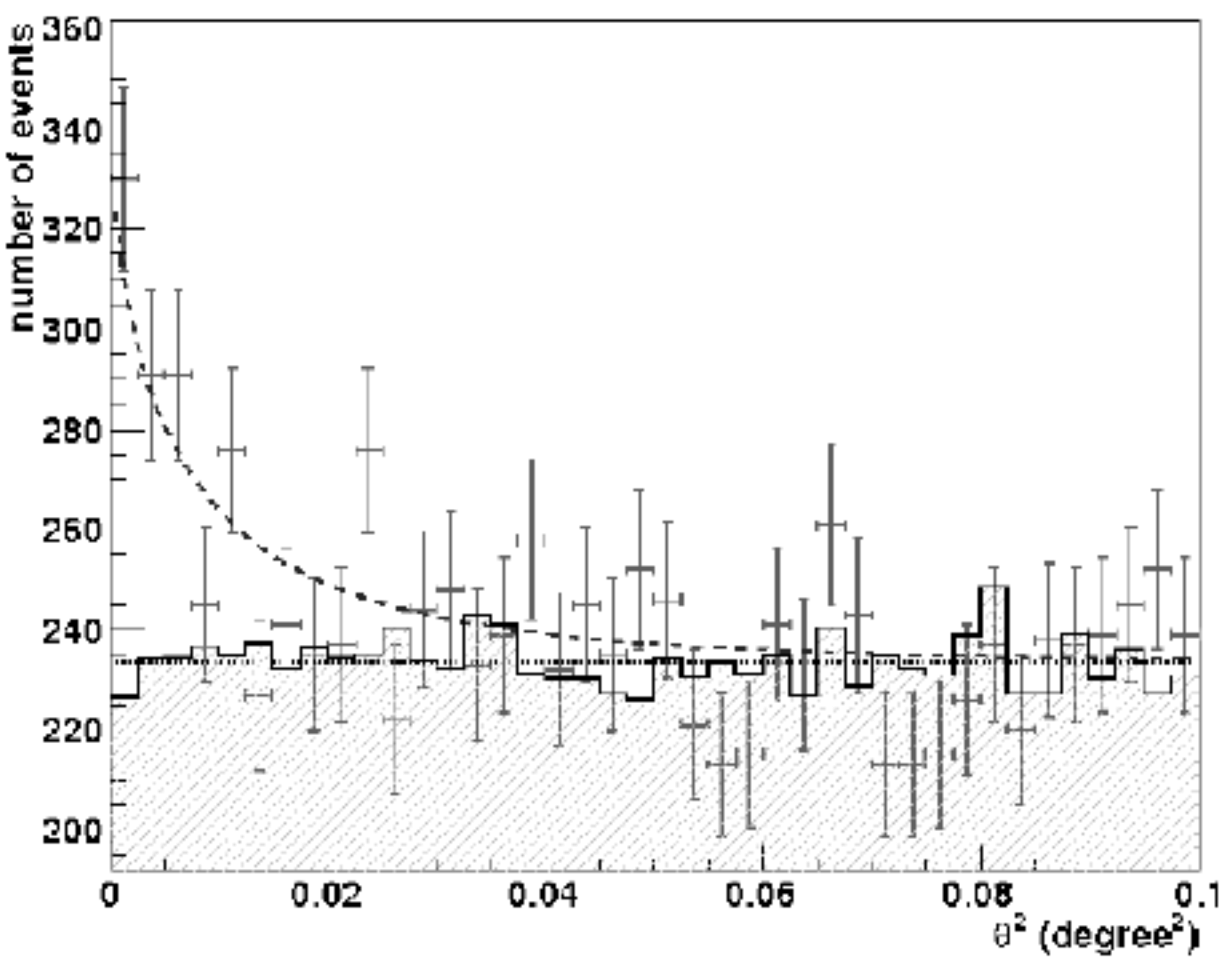
- **background** (lots of it)
- **gamma-ray selection** (or background suppression)
- **systematic uncertainties**
  - understanding of detector
  - fluctuations in the atmosphere
  - choices by you
  - ….



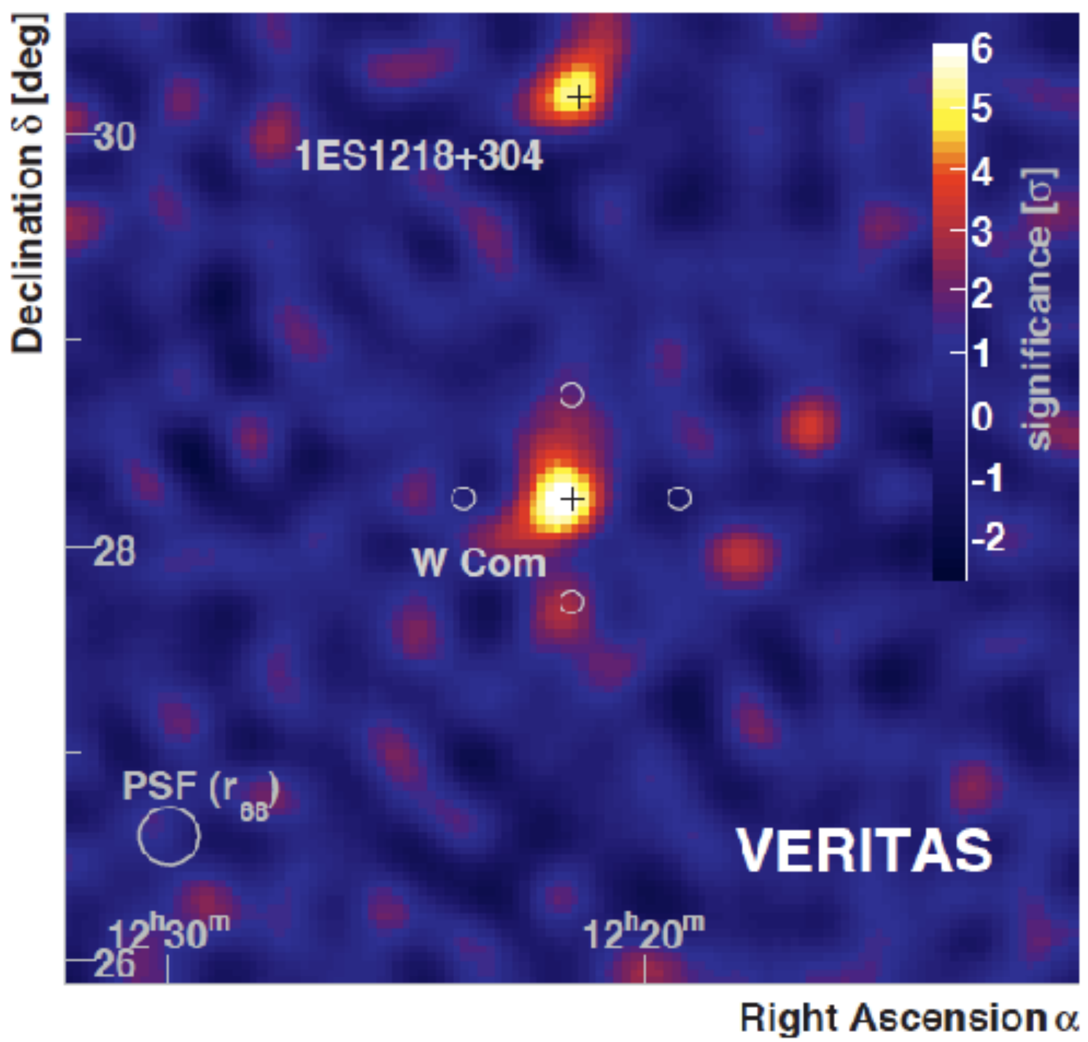
irreducible background

Background estimation

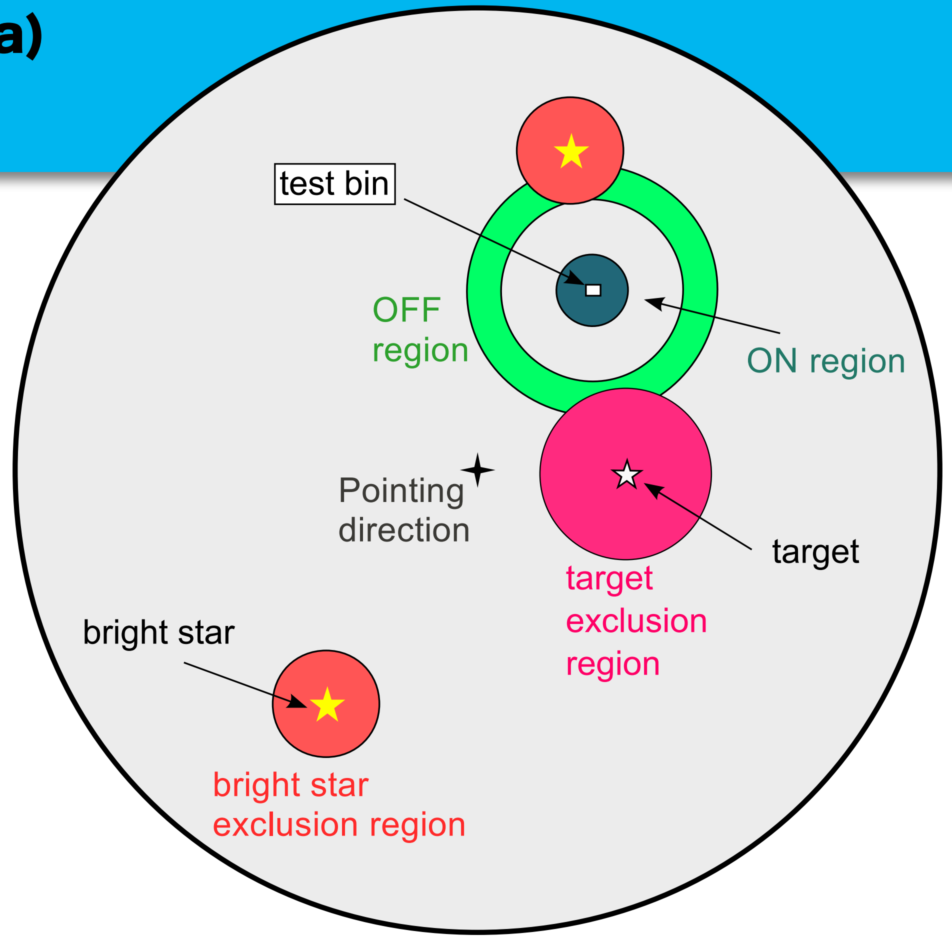




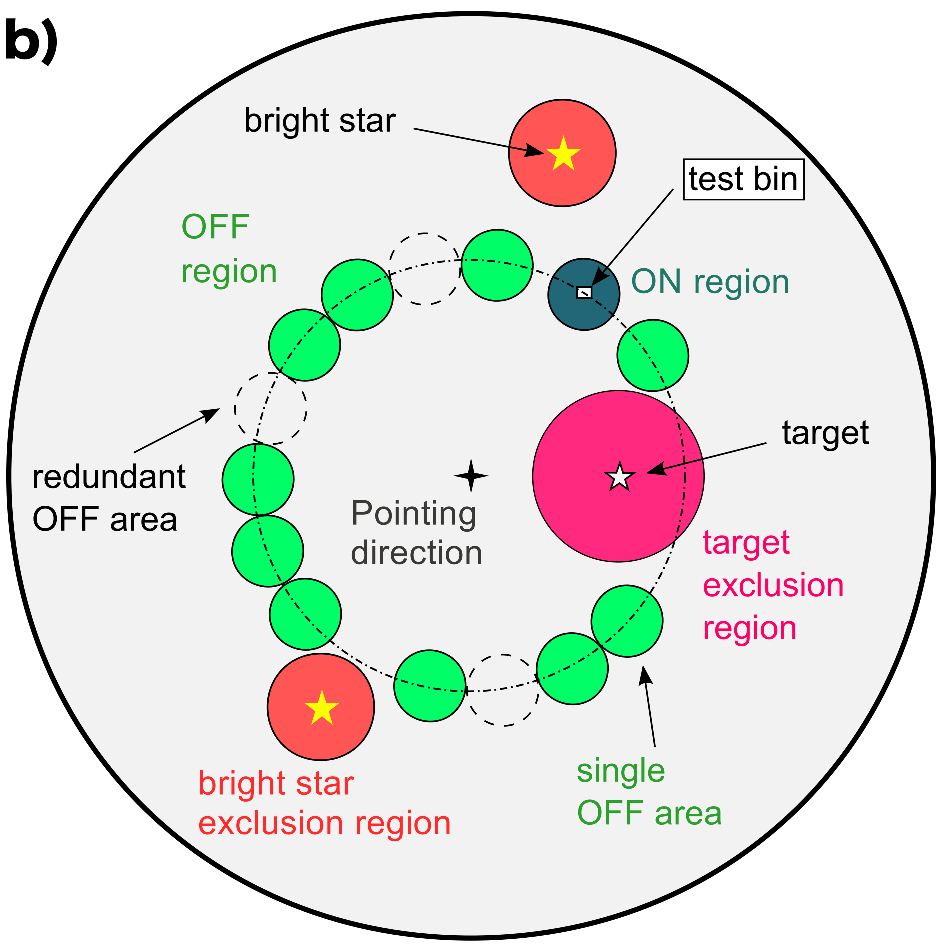
Background estimation



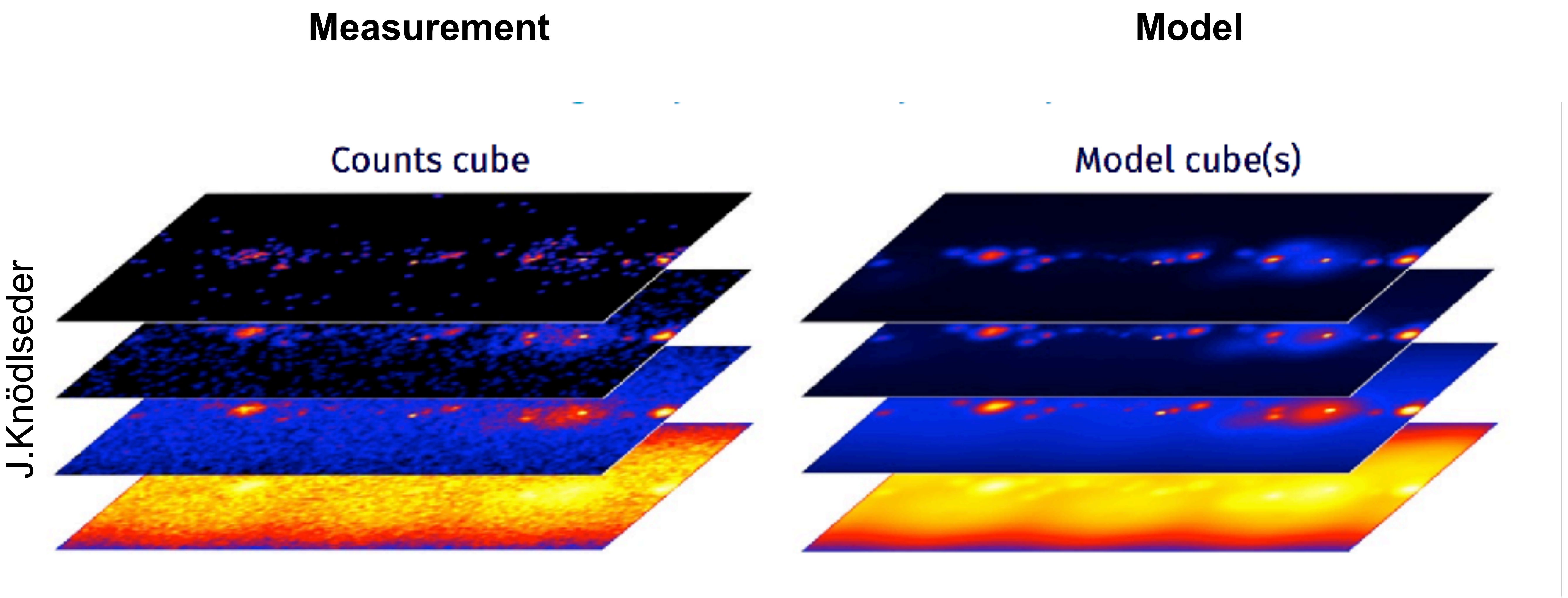
a)



b)



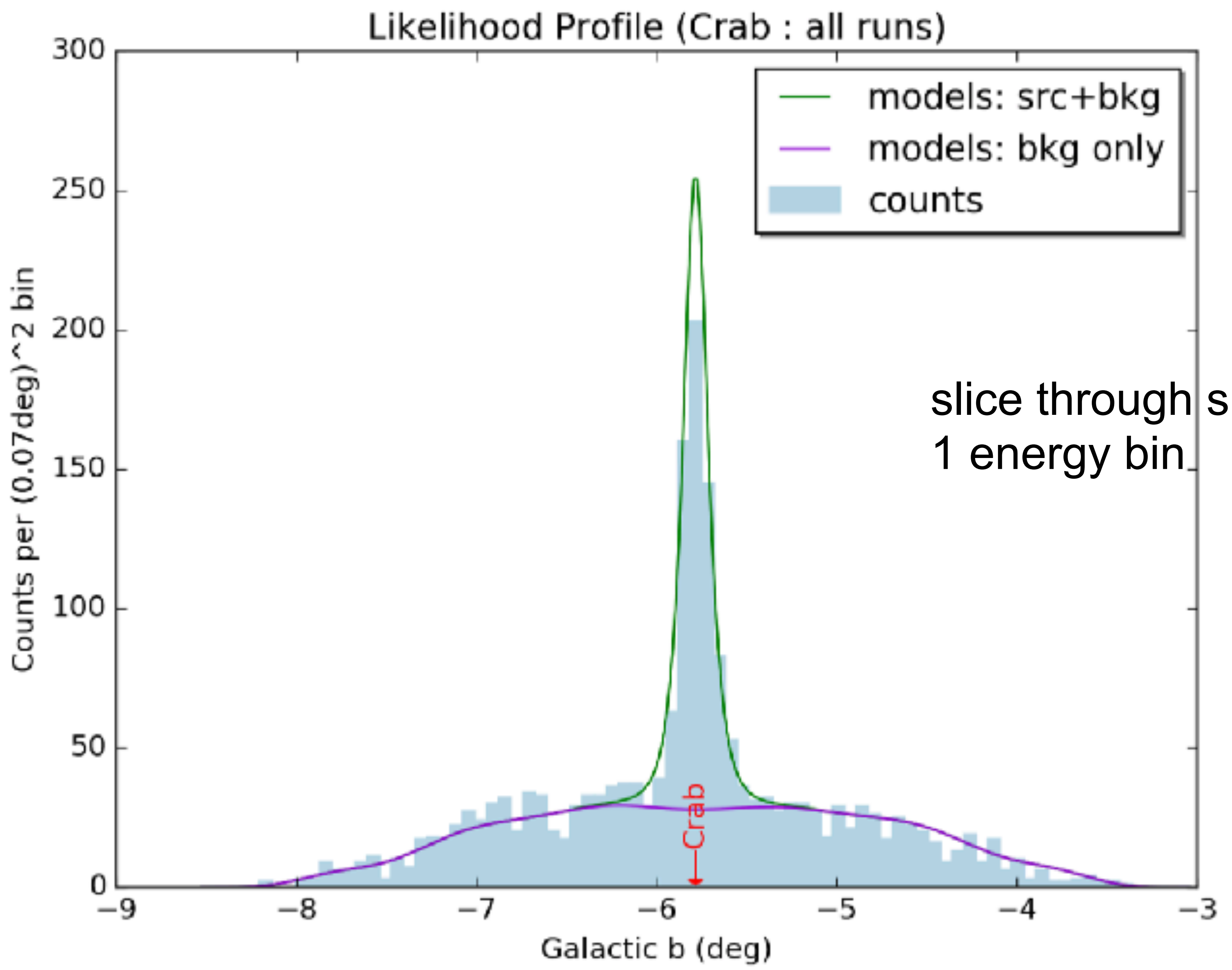
Spatial and spectral analysis - ML



maximum likelihood analysis in 4 dimensions: spatial coordinates, energy, time

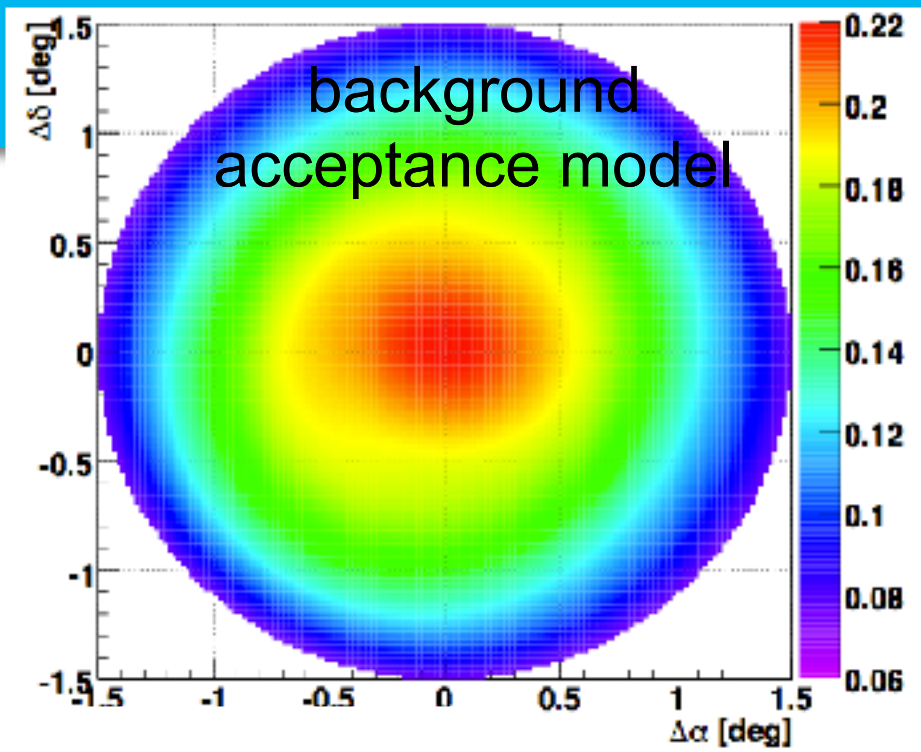
Maximum Likelihood analysis

N. Kelley-Hoskins



slice through sky map
1 energy bin

Maximum Likelihood analysis



- formulate likelihood function with background, source function, point-spread function
- can give at the same time information on source position, extension, spectral information

$$L = \prod_{ij} p_{ij}$$

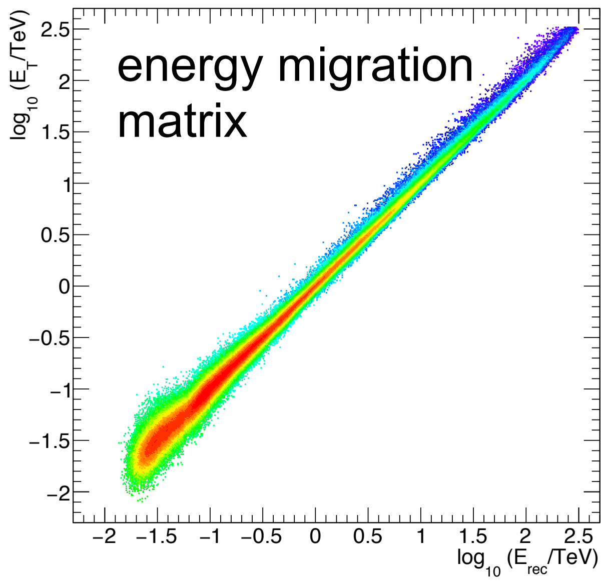
p_{ij} is probability of observing n_{ij} counts in a bin when the number of predicted counts is Θ_{ij}:

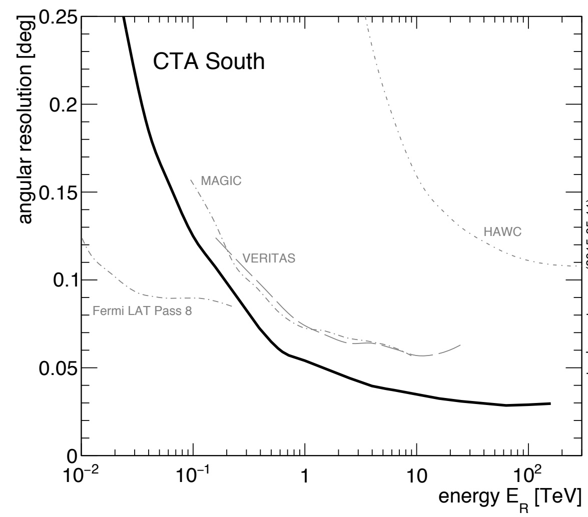
$$p_{ij} = \frac{\theta_{ij}^{n_{ij}} e^{-\theta_{ij}}}{n_{ij}!}$$

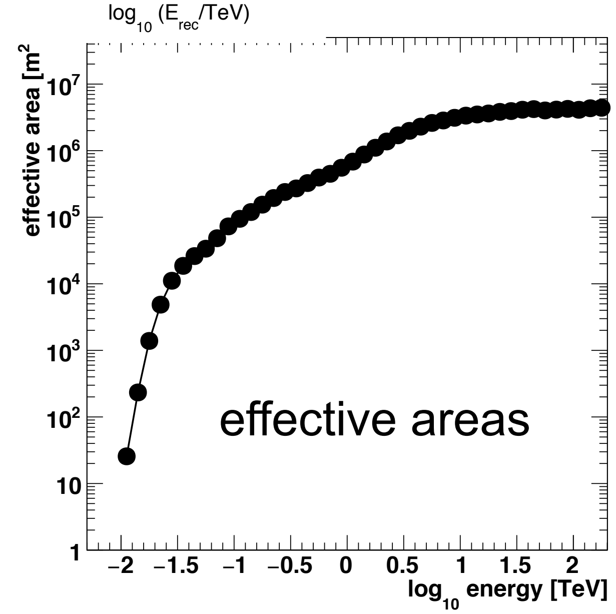
maximize log likelihood

$$\ln L = \sum_{ij} n_{ij} \ln(\theta_{ij}) - \sum_{ij} \theta_{ij}$$

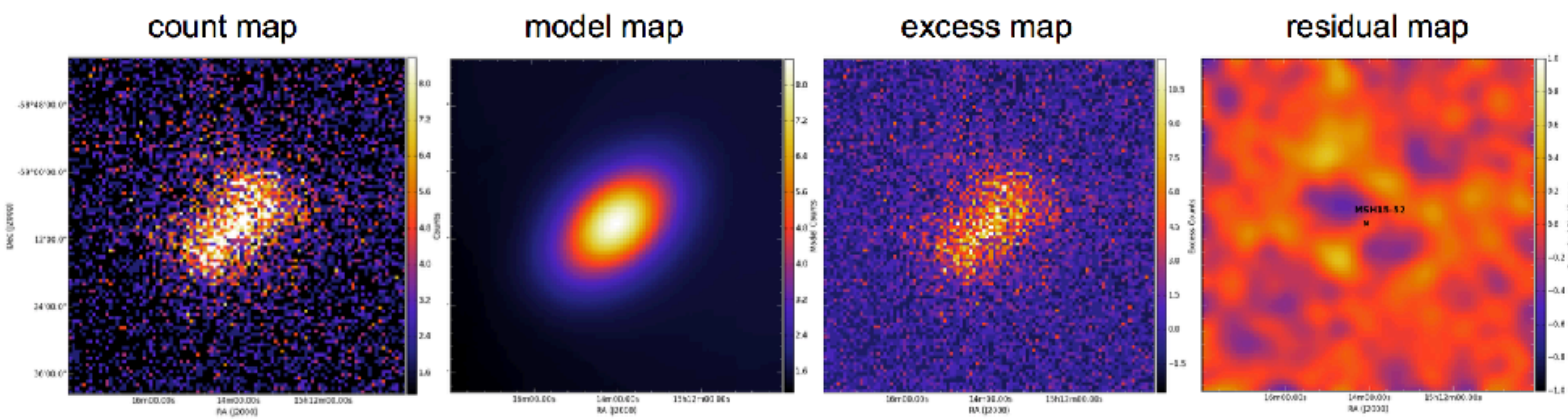
J.R.Mattox et al, ApJ 461, 396 (1996)







Maximum Likelihood analysis



M.Meyer

CTA science analysis tools

Two different prototypes for science analysis tools for CTA

cta cherenkov telescope array

ctools

Gammapy

A prototype for the CTA science tools

Similarity to FTOOLS

uses astropy, sherpa, …

Is a source significantly detected?

> **hypothesis testing**

> likelihood ratio test: compare likelihood of two hypotheses to see which one is supported by the data

> two unknown parameters:
- expected number of source photons $< N_S >$
- expected number of background events $< N_B >$

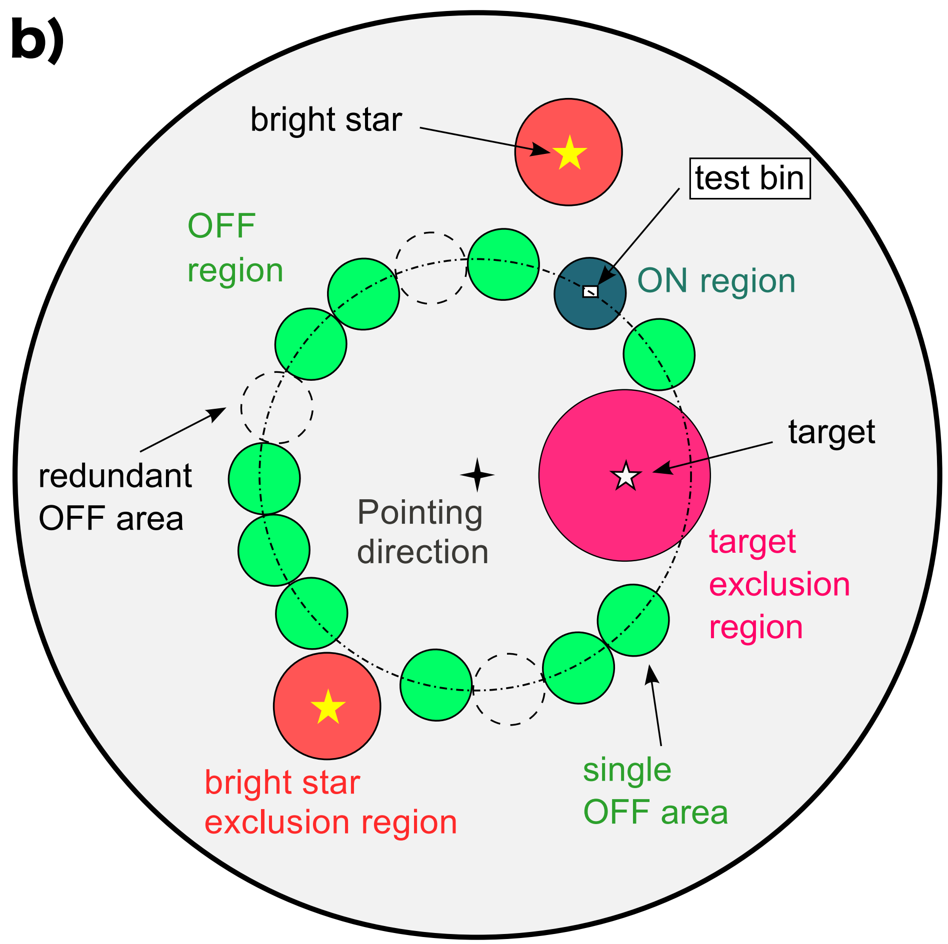
> null hypothesis: $< N_S >= 0 \quad \rightarrow L_0$

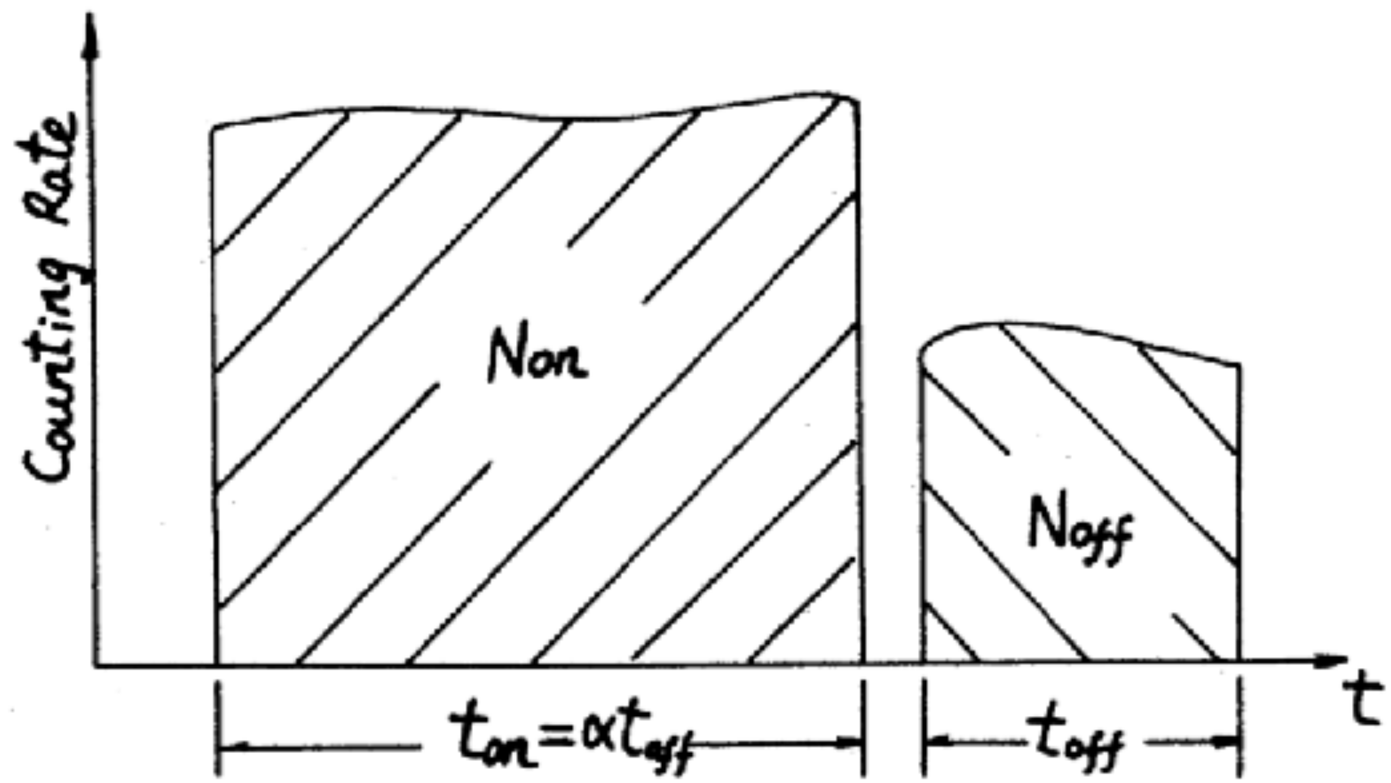
> alternative hypothesis: $< N_S > \neq 0 \quad \rightarrow L_1$

likelihood ratio test: $$2(\ln L_1 - \ln L_0) \sim \chi^2$$

Wilk's theorem

Source detected: Li & Ma method

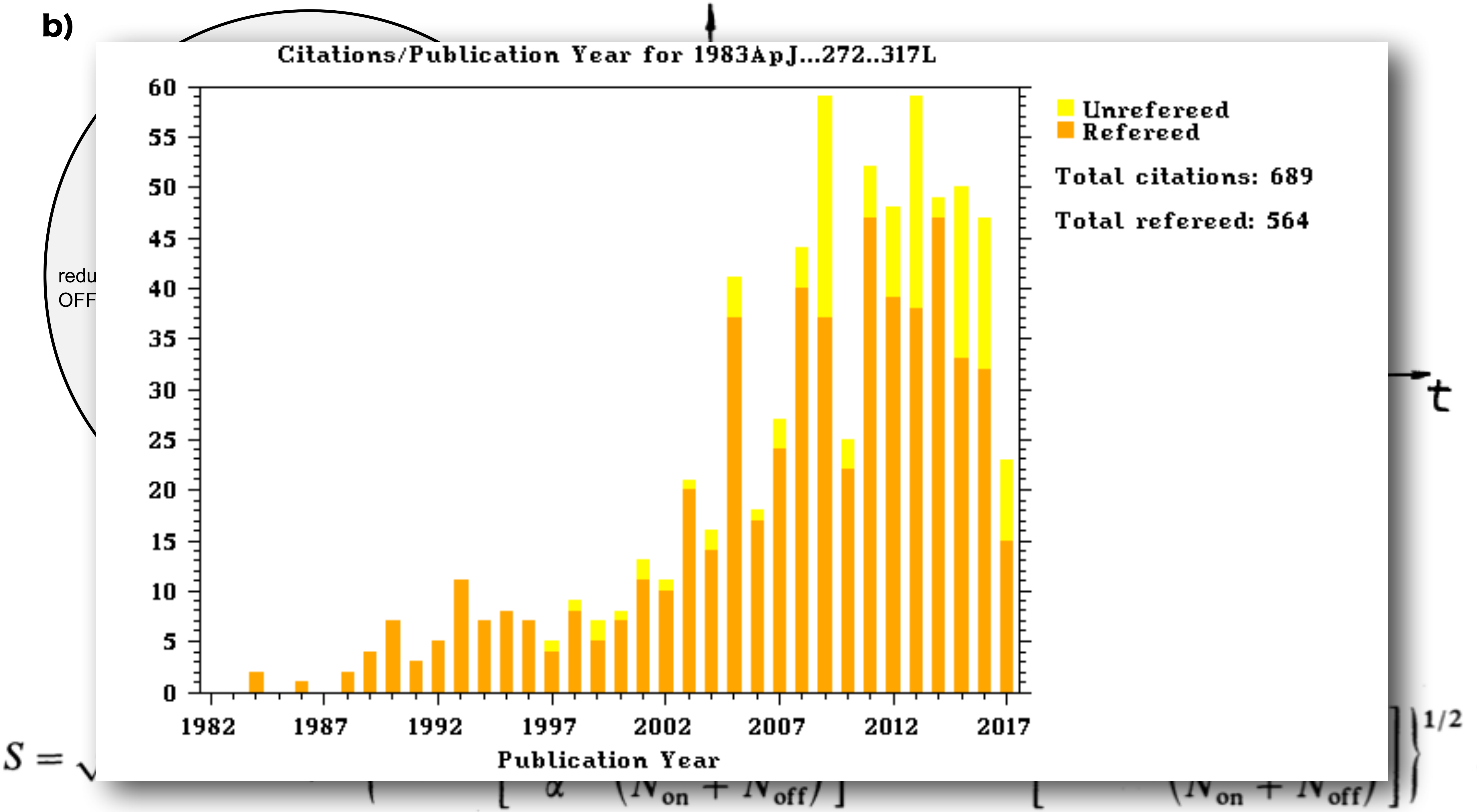




Likelihood ratio method after Li & Ma (1983):

$$S = \sqrt{-2\ln\lambda} = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}.$$

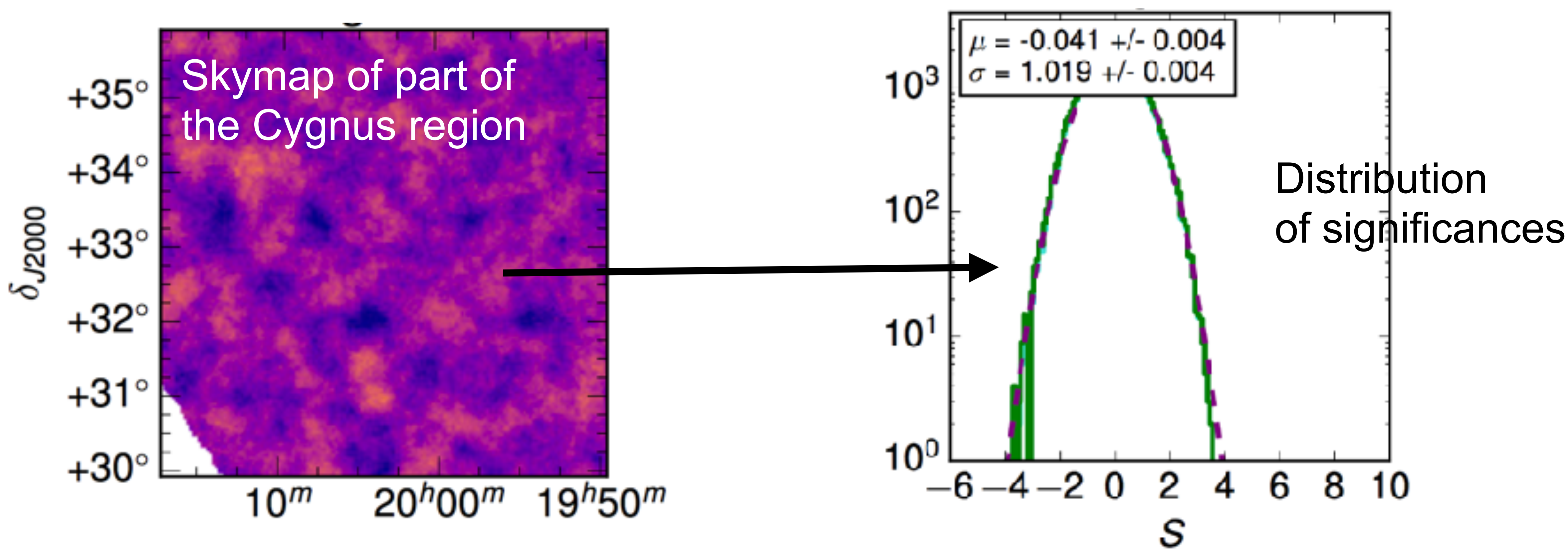
Source detected: Li & Ma method



Trials factors - look-elsewhere effect

- often not clear at the beginning of the analysis where to look for an effect
  - location of gamma-ray sources in the sky
  - energy (mass) of particle responsible for line emission

- search through data for a significant signal - but with statistical penalty



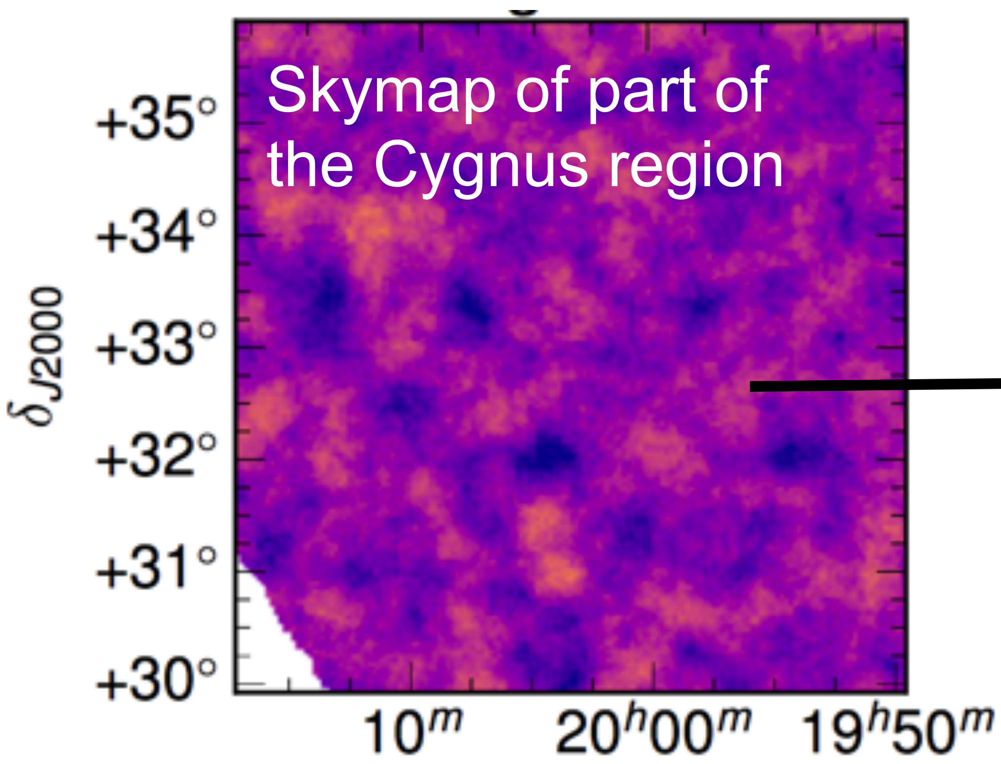
Krause (2017)

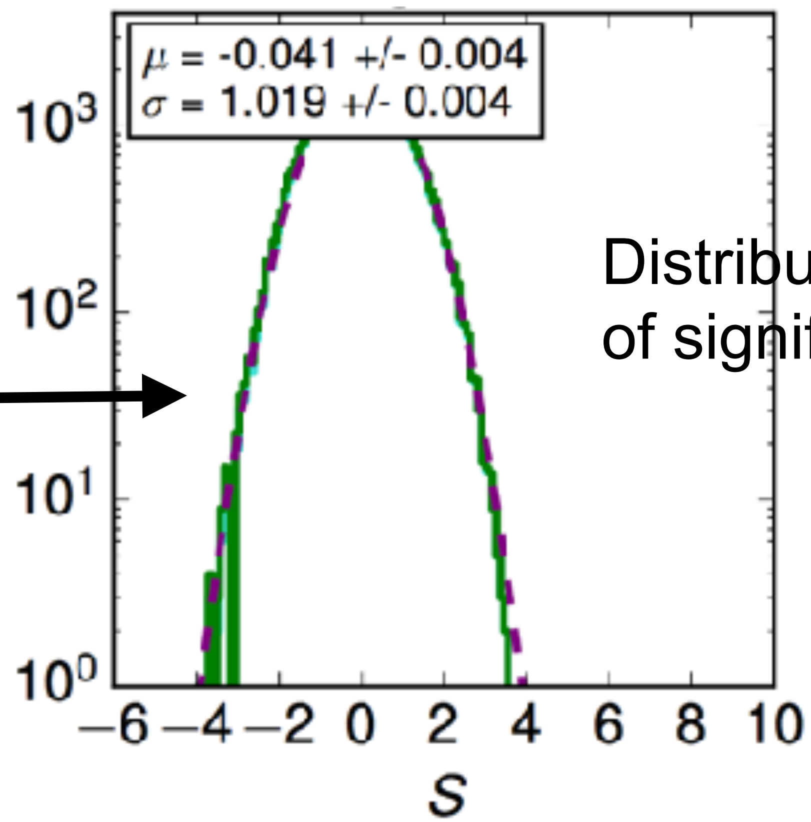
Trials factors - look-elsewhere effect - example

- 4σ event - P-value of 6.3 x 10^{-5}
- post-trial P-value: $$P_{post} = 1 - (1 - P_{pre})^N$$
- 1000 bins in sky map -> 1000 trials

$$P_{post} = 1 - (1 - 6.3 \times 10^{-5})^{1000} = 0.06 \simeq 1.9\sigma$$

Krause (2017)





Distribution of significances

Trials factors - avoid them, if possible!

- **fix always all possible parameter for your analysis before looking into the data**
  - each change of the parameters is trail
  - optimise parameters and cuts with a different data set or Monte Carlo simulations
- **never adjust the analysis parameters to enhance some small signal**
  - this is considered to be scientific misconduct
- clearly state assumptions and trials calculation in publications
- things to fix before the analysis
  - cuts
  - search regions
  - binning in energy or time

Can you make it 5 sigma?

Trials factors - avoid them, if possible!

- **fix always all possible parameter for your analysis before looking into the data**
  - each change of the parameters is trail
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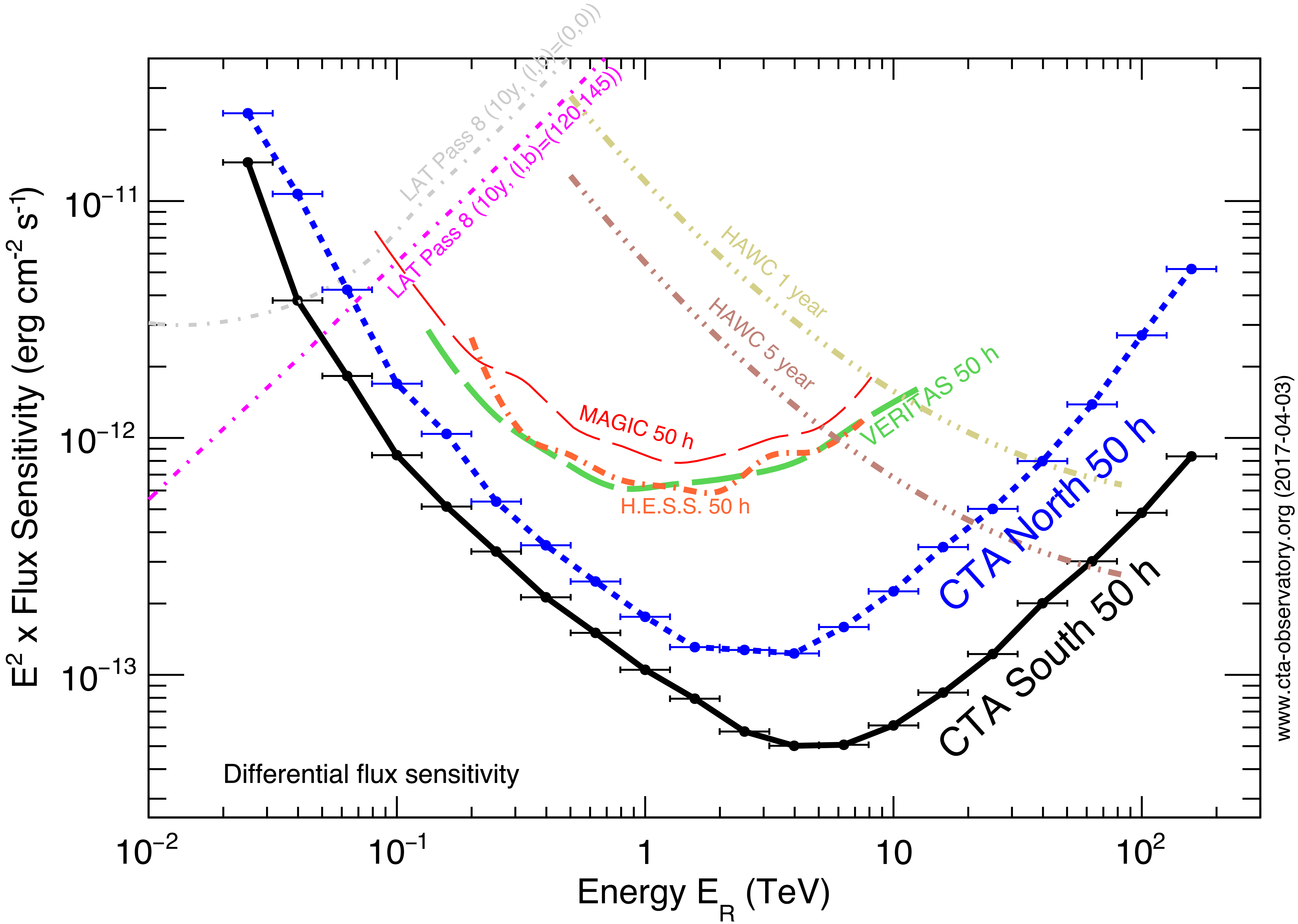
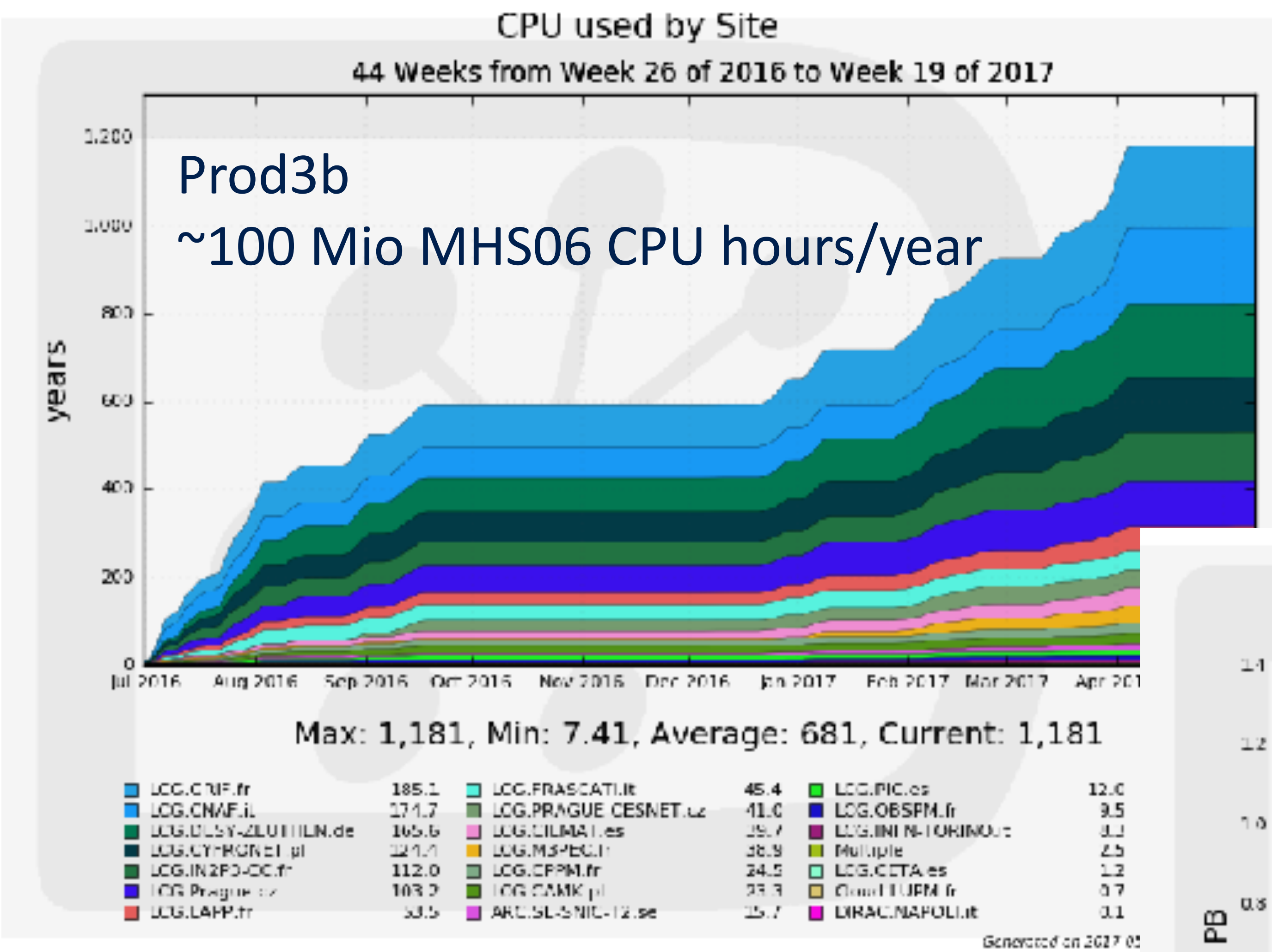
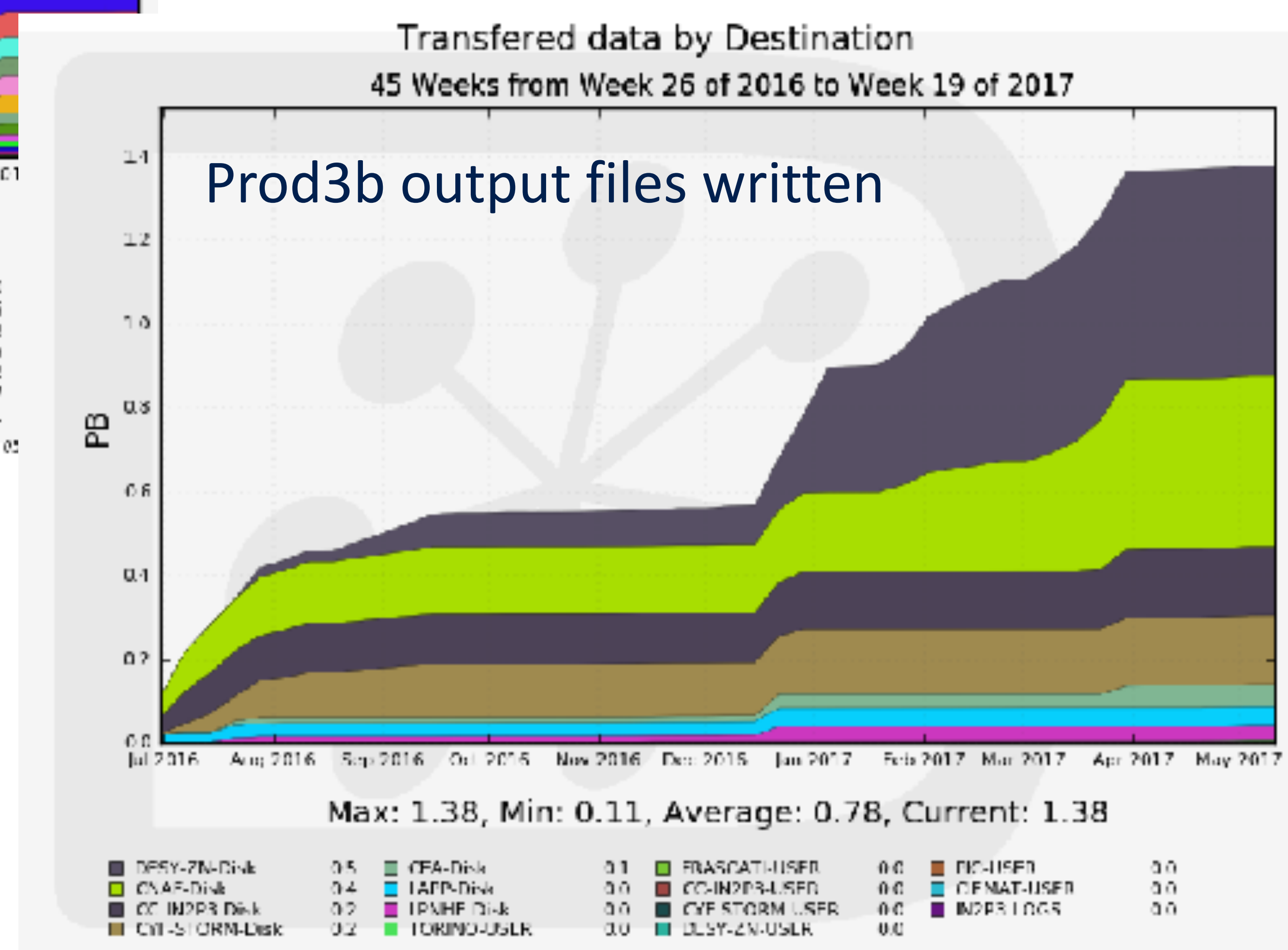
CTA Differential Flux Sensitivity



CTA Sensitivity Calculations

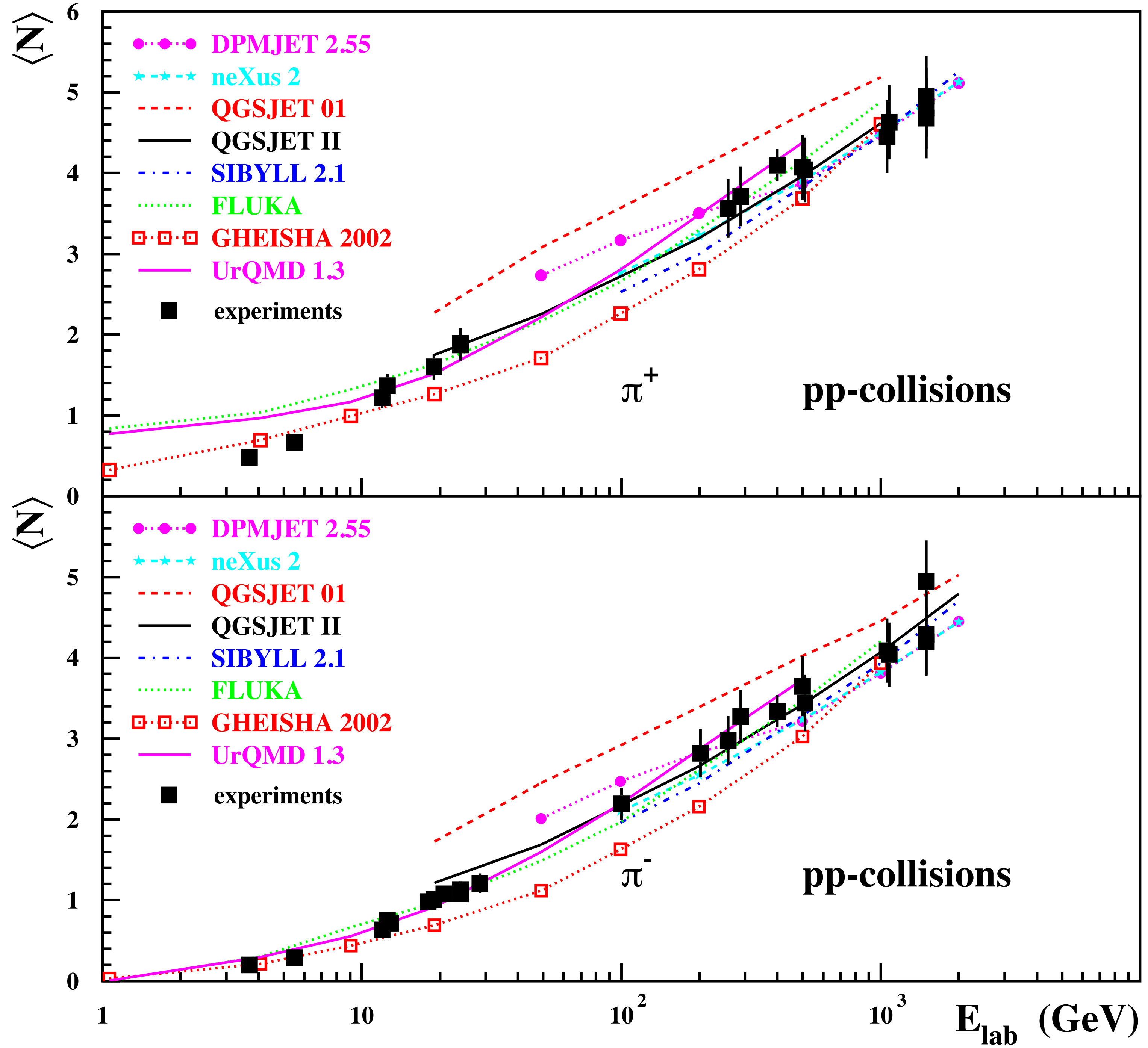


High-throughput computing using GRID resources



Luisa Arrabito - Johan Bregeon, LUPM

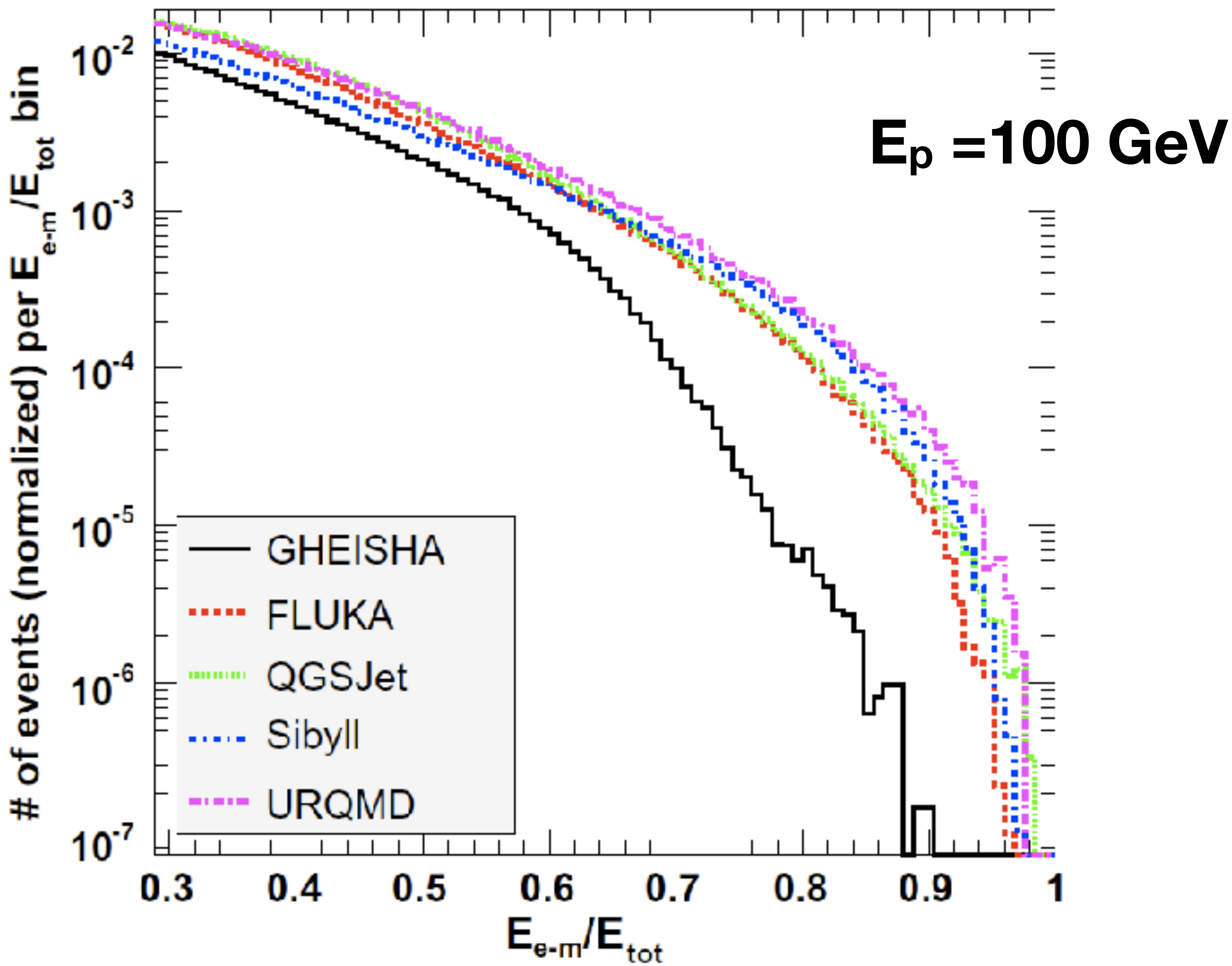
p-p Interactions: Multiplicity



$\pi^{\pm}$ **multiplicities in pp-collisions as function of energy.**

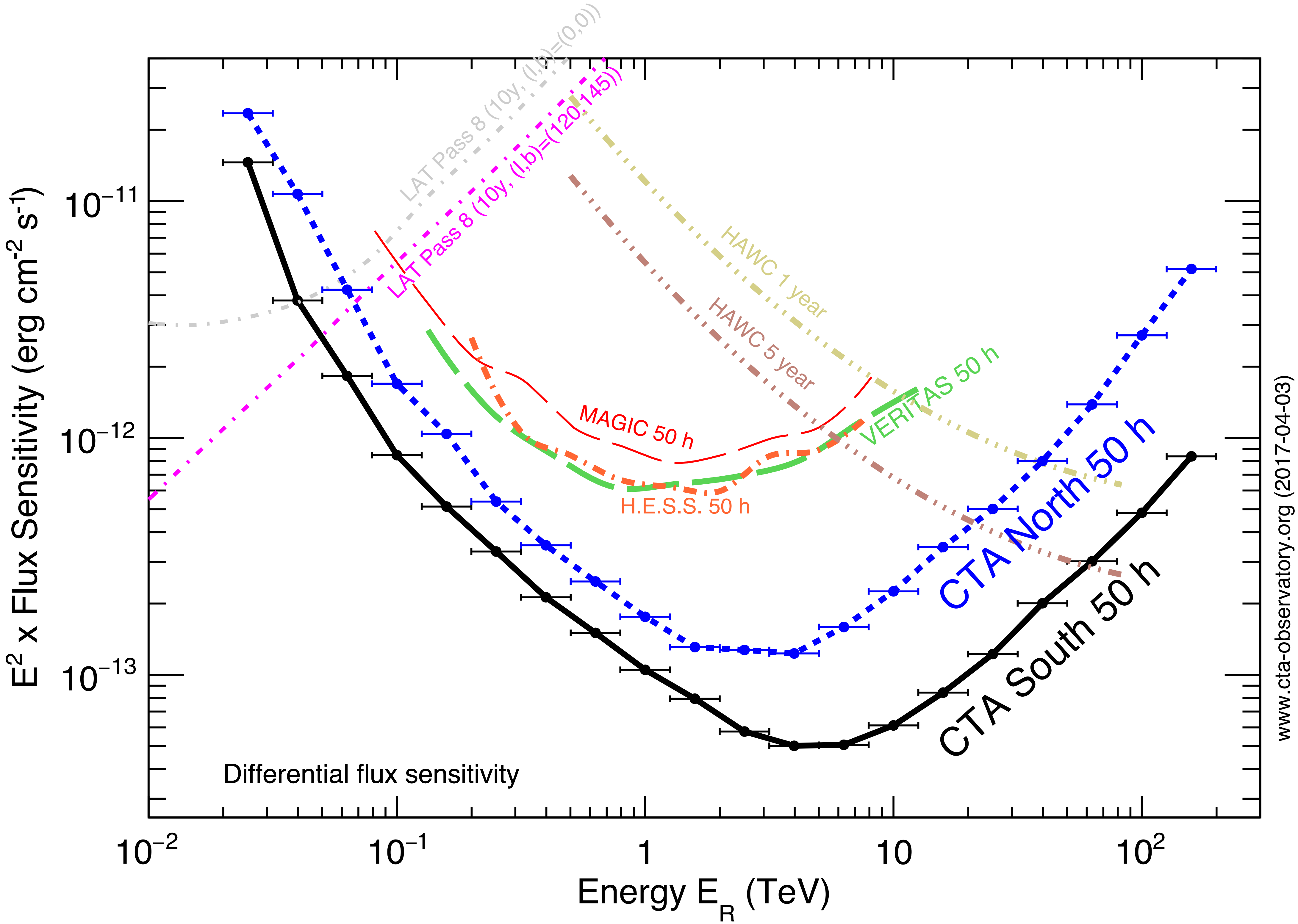
<dieter.heck@ik.fzk.de> VIHKOS CORSIKA School 31.5. - 5.6.2005

Background simulations - hadronic interaction models

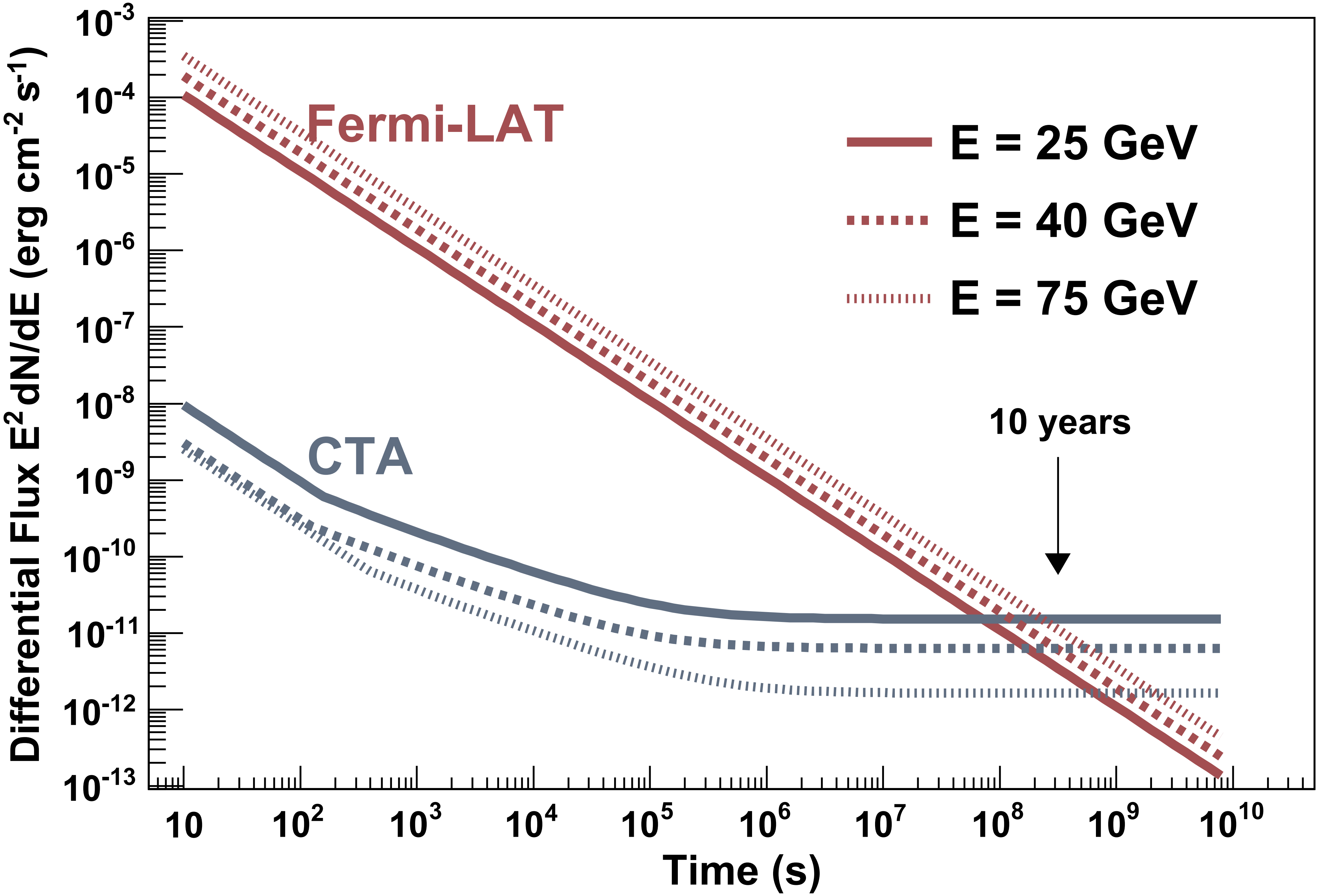


G.Maier & J.Knapp, Astroparticle Physics 28, 72 (2007)

CTA Differential Flux Sensitivity



CTA Short-term flux sensitivity



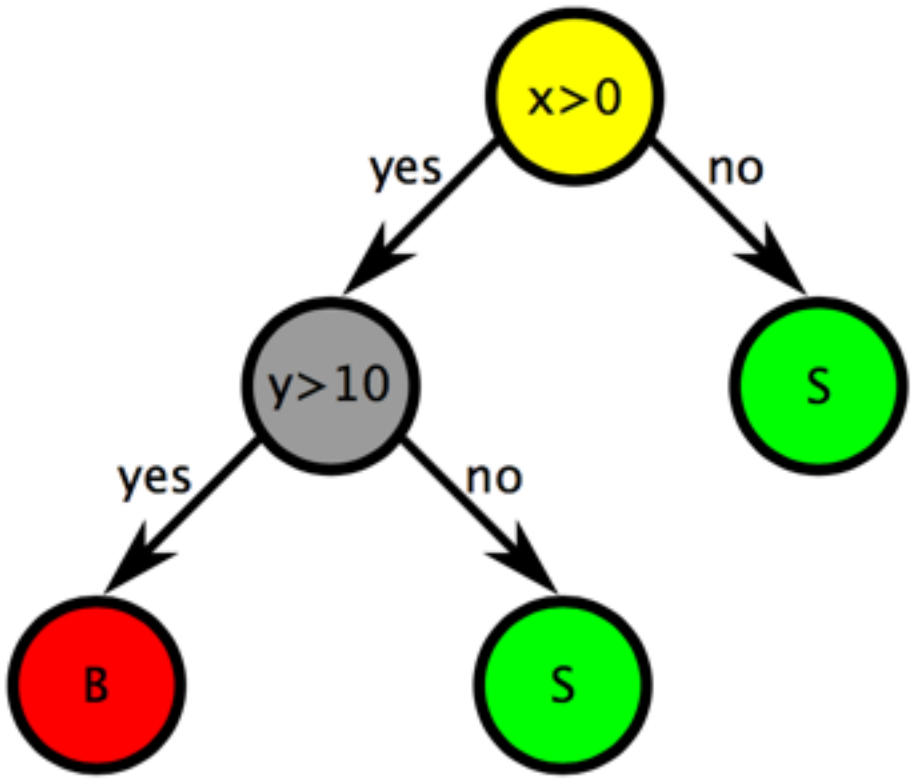
cta

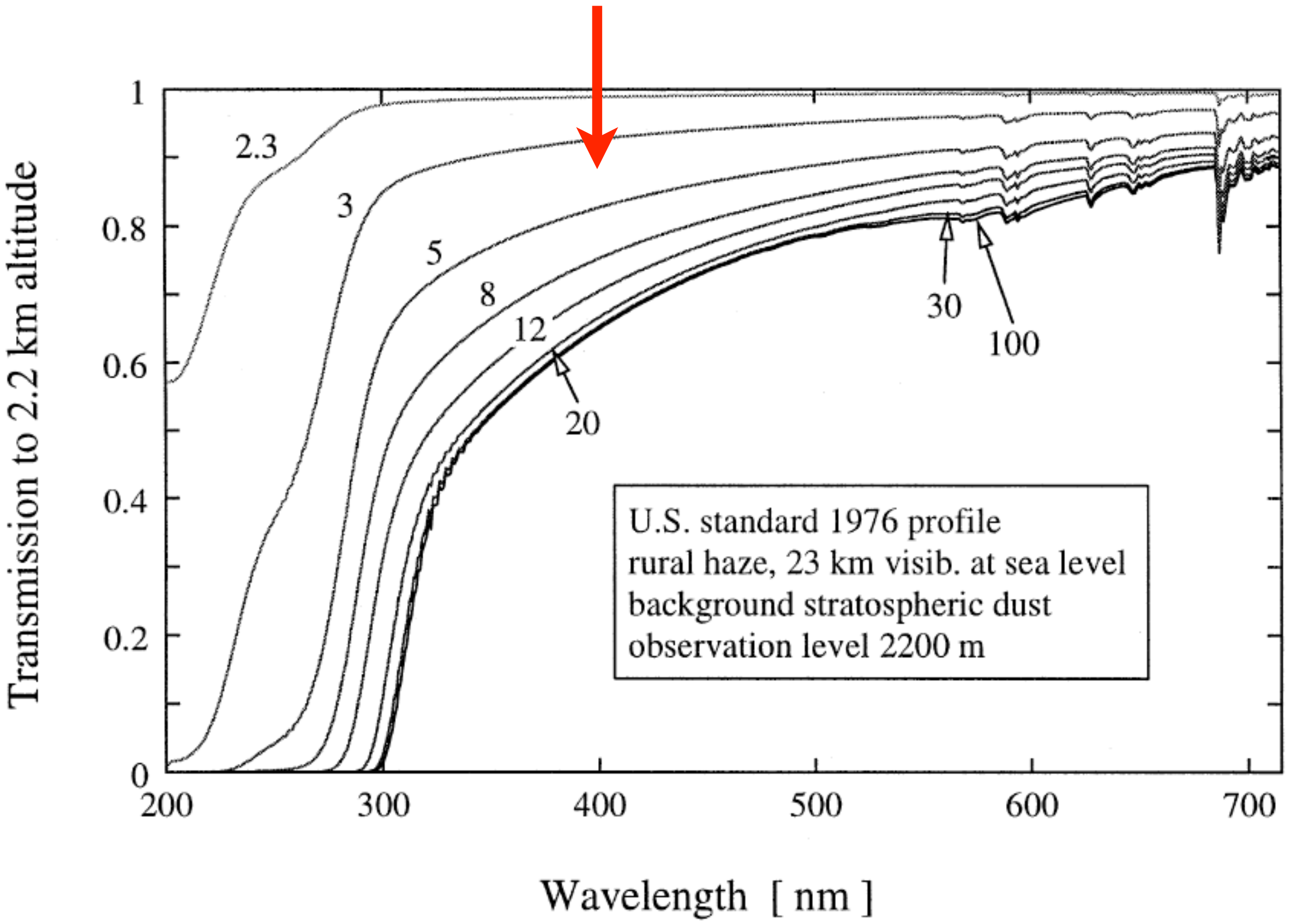
cherenkov telescope array

cta

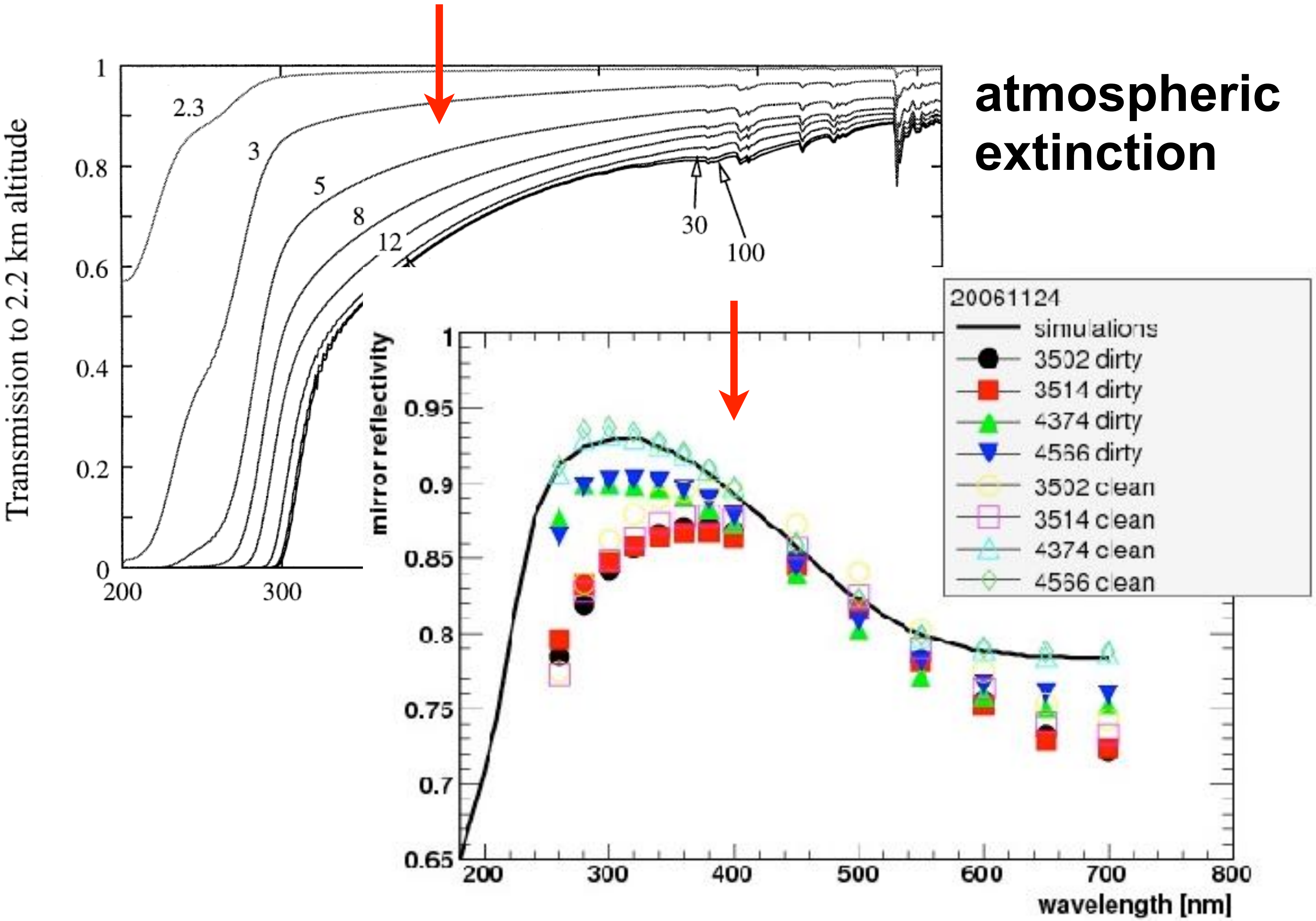
cherenkov telescope array

Boosted decision trees



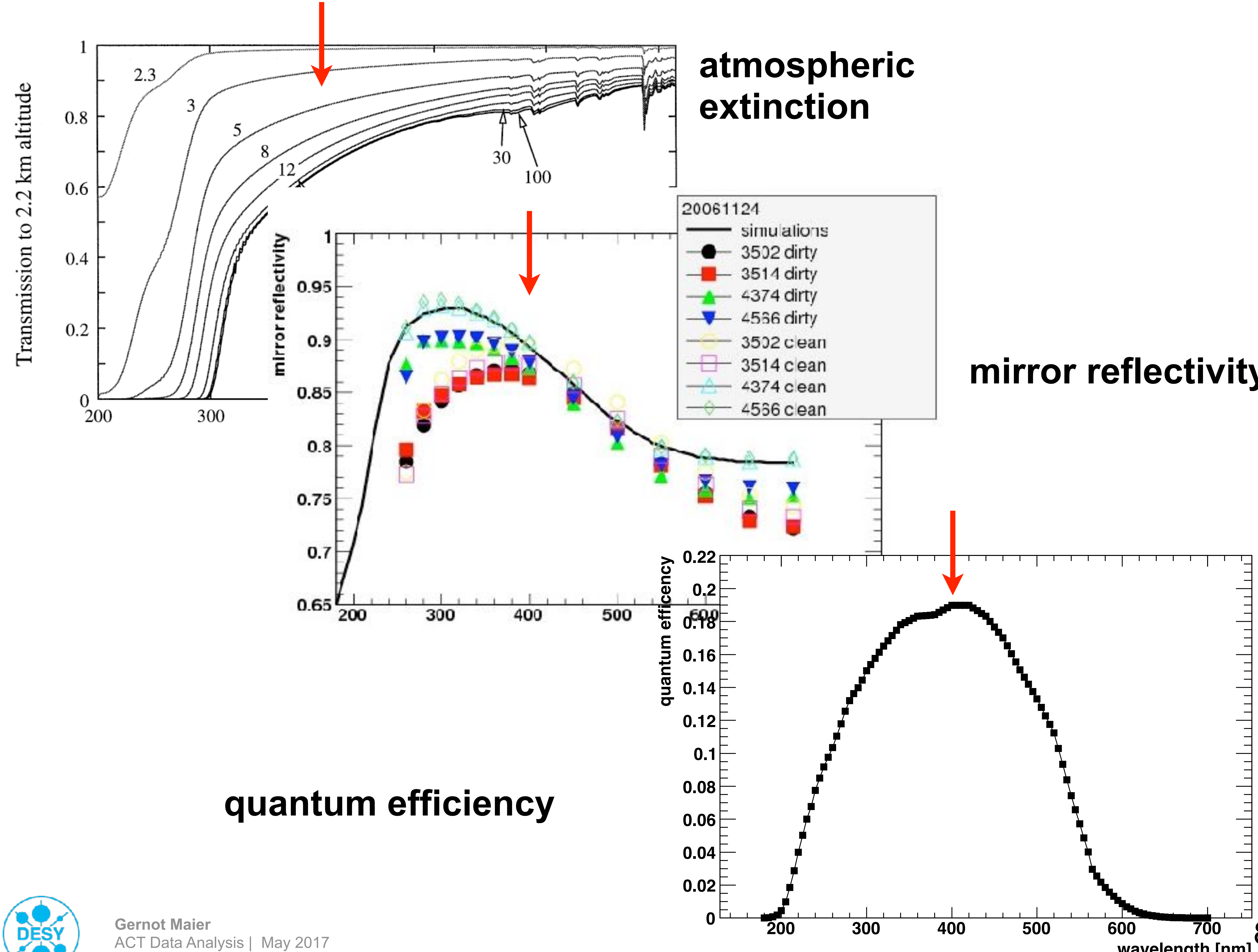


atmospheric extinction



atmospheric extinction

mirror reflectivity


atmospheric extinction
Transmission to 2.2 km altitude
2.3
3
5
8
12
30
100
mirror reflectivity
20061124
simulations
3502 dirty
3514 dirty
4374 dirty
4566 dirty
3502 clean
3514 clean
4374 clean
4566 clean
quantum efficiency
quantum efficency
wavelength [nm]

Geomagnetic Field