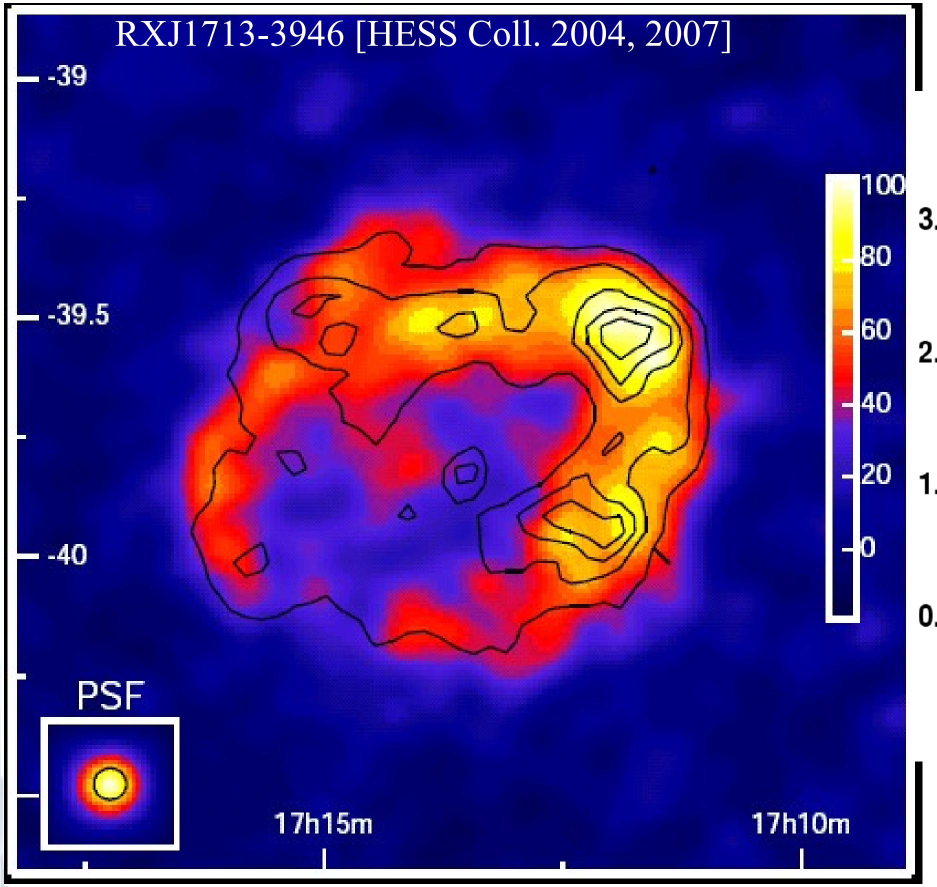
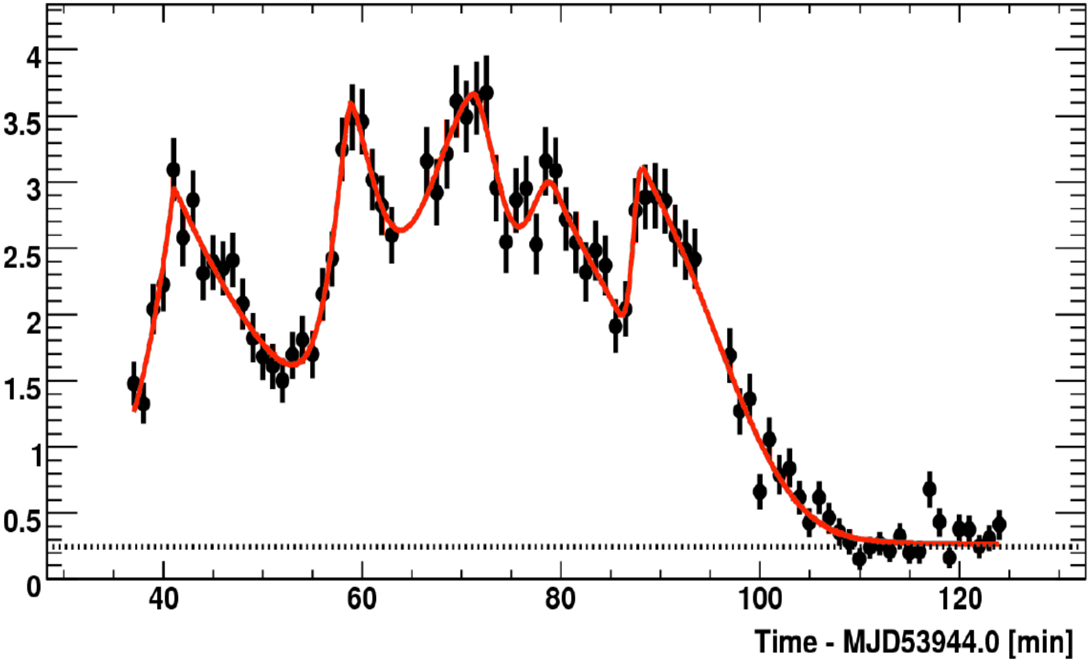
# Ground-based gamma-ray observations

Dieter Horns University of Hamburg




May 28/29 2012, APC-Paris

# Overview

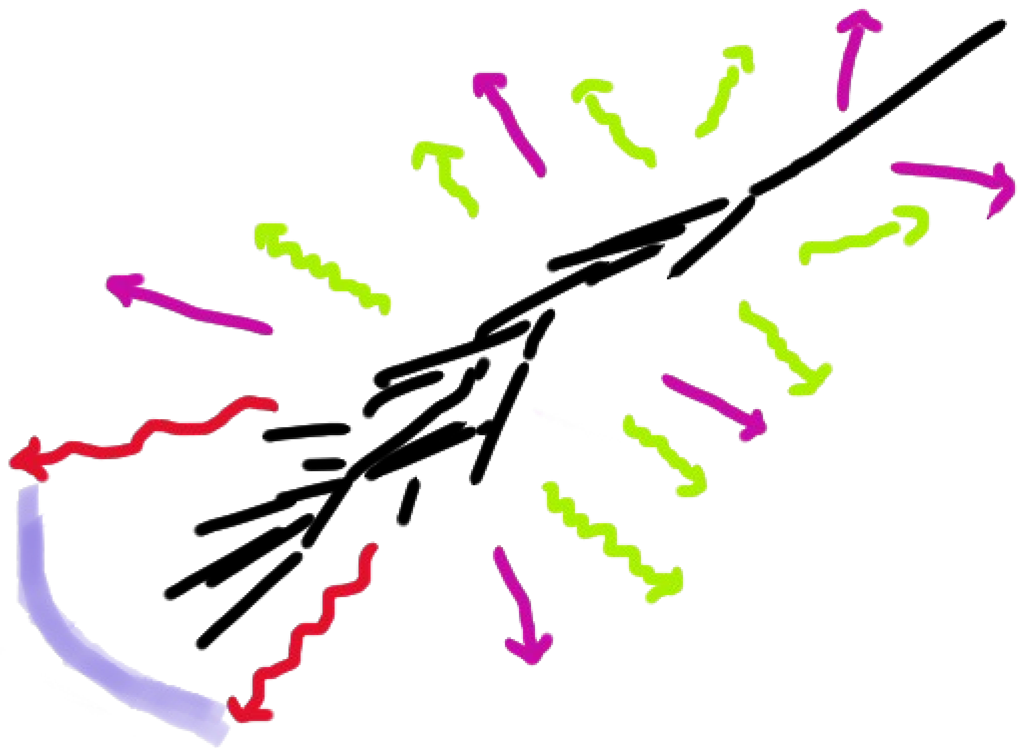
- Physics:
  - Gamma-ray production
  - Cosmic-ray origin
  - Cosmic-ray propagation
  - Indirect Dark Matter

# Overview

- Physics:
  - Gamma-ray production → Antoine
  - Cosmic-ray origin → Dmitri
  - Cosmic-ray propagation → Günter
  - Indirect Dark Matter → Joe

# Observing Light From Extended Air Showers

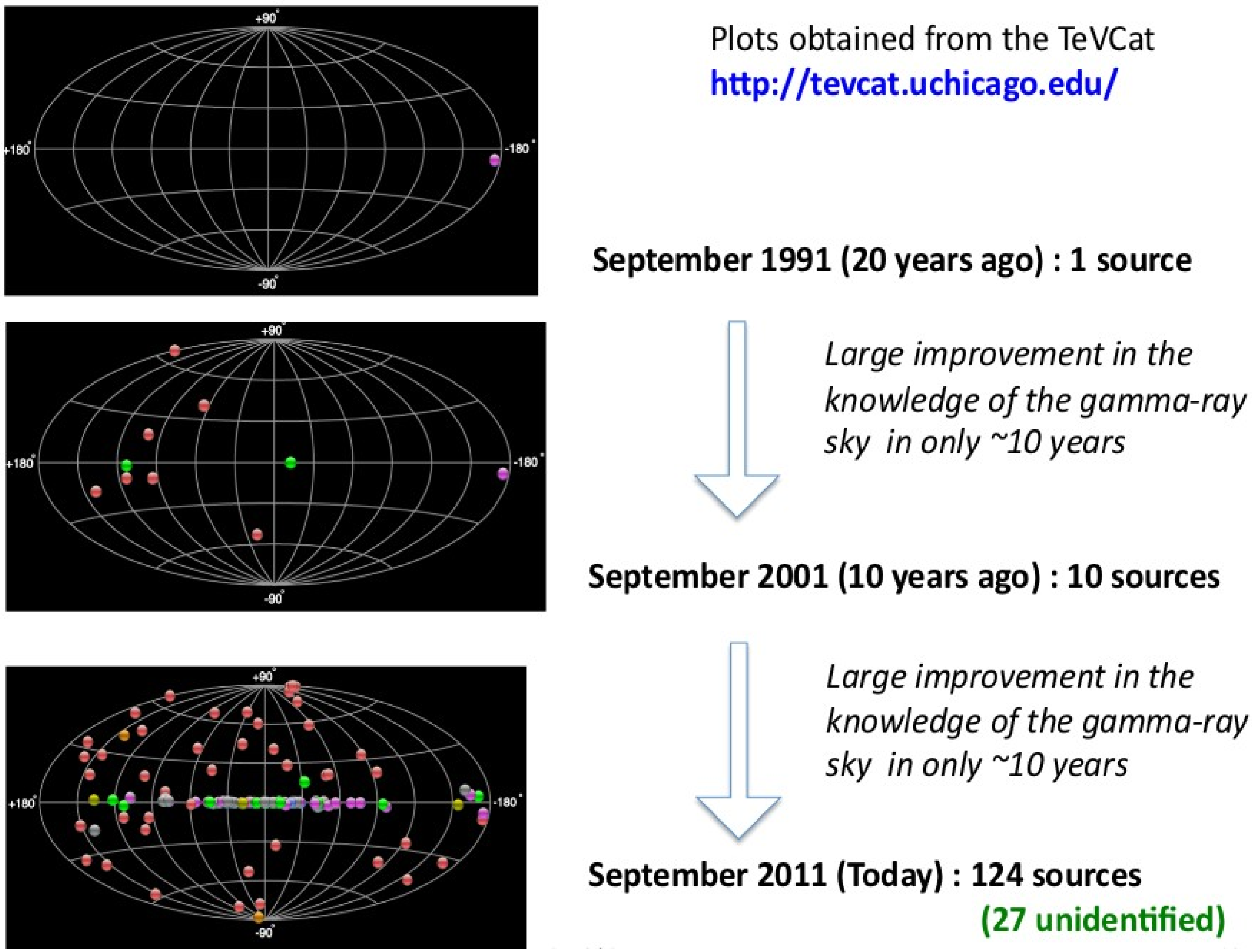
Dieter Horns University of Hamburg



**May 28/29 2012, APC-Paris**

# 1 Scope of this lecture

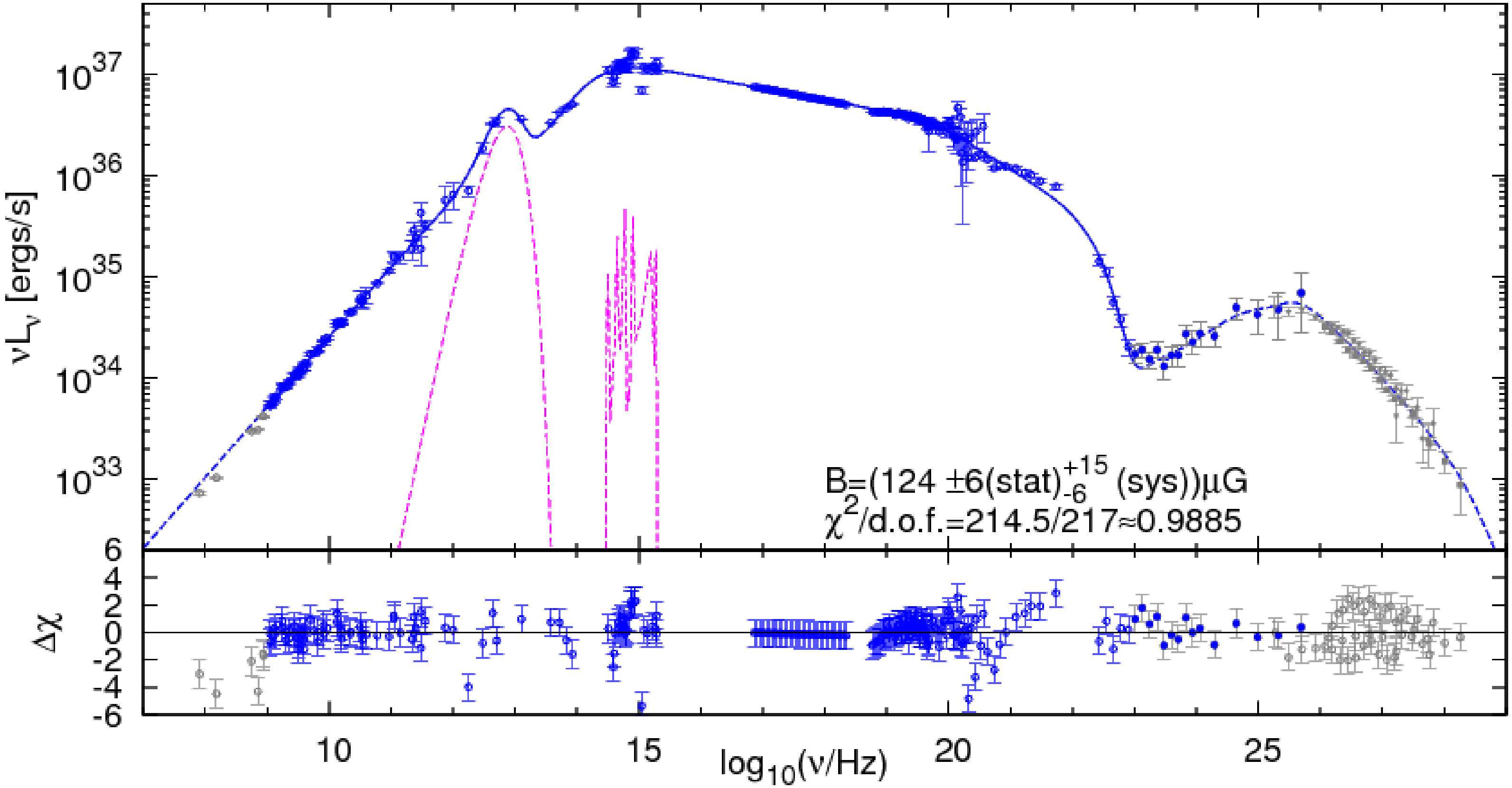
- This type of picture is often shown in scientific talks:



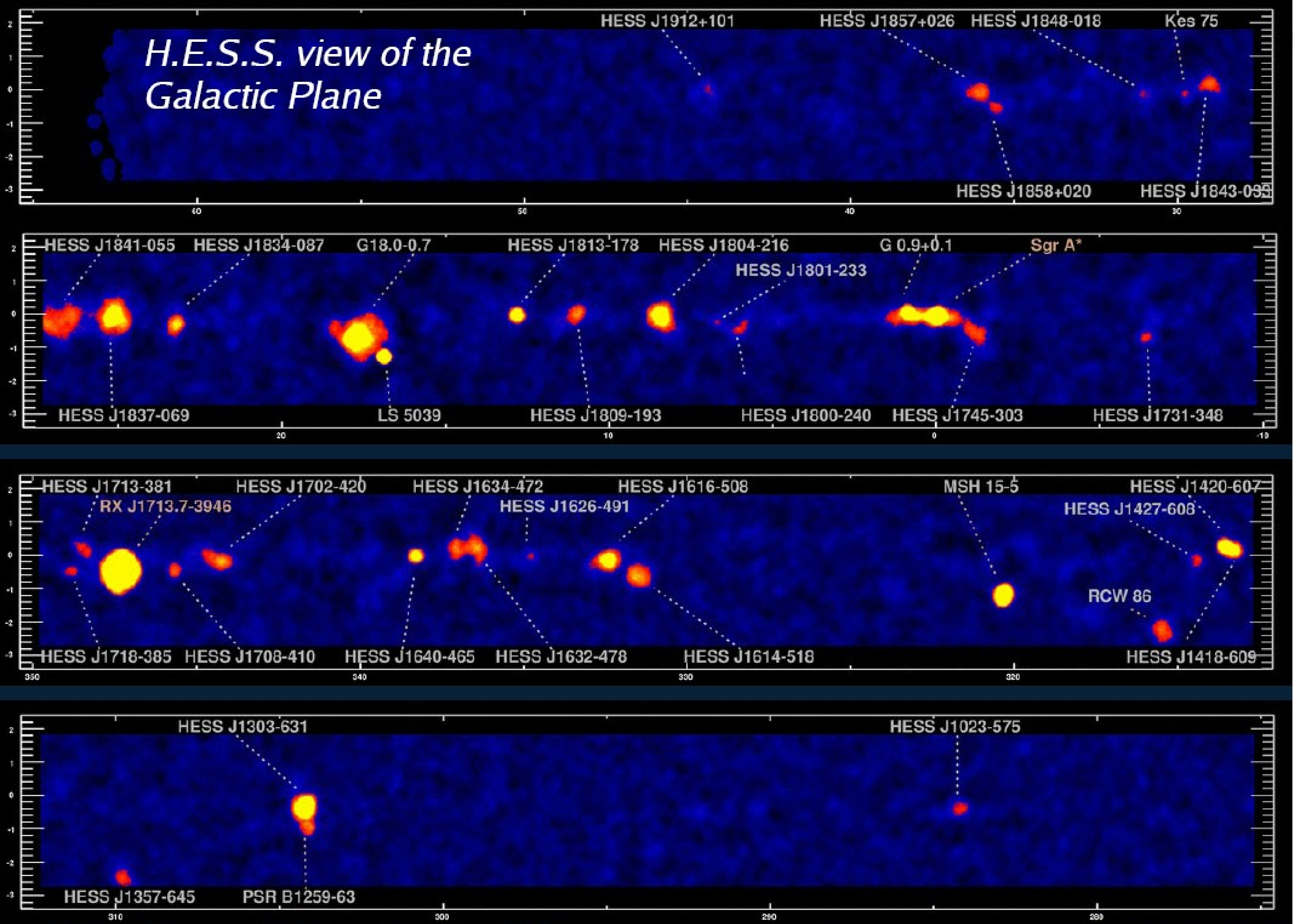

Paneque, TAUP 2011

# Scope of this lecture

- Spectral energy distribution (SED)



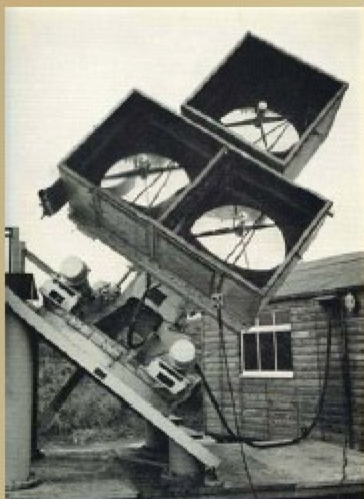

- Imaging (spectroscopy)


H.E.S.S. view of the Galactic Plane
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
G 0.9+0.1
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-5
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
HESS J1357-645
PSR B1259-63
310
300
290
280

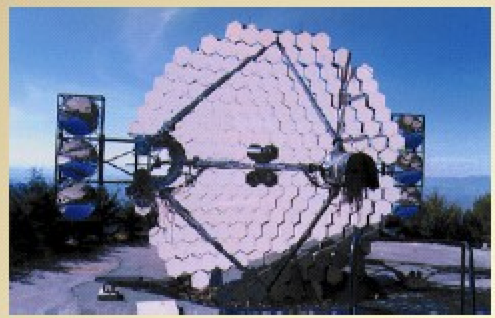
# Scope of this lecture: Questions

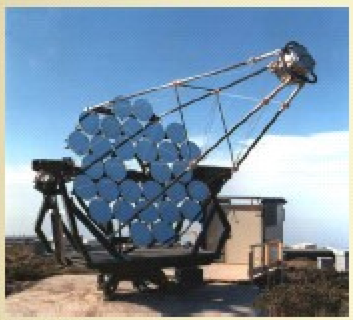
- How does air shower detection with light work (look behind the scenes)?
- What is driving the improvement in the field of air shower observations?
- Further references:
  - Astropart. Physics 22, 109 (2004)
  - Astropart. Physics 20, 267 (2003)

# Costs

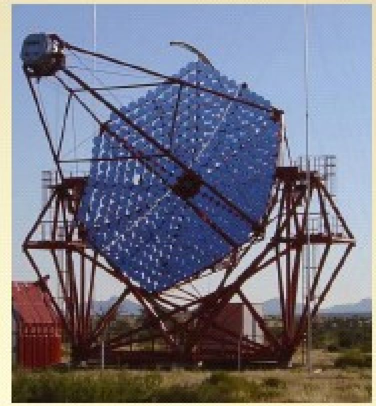


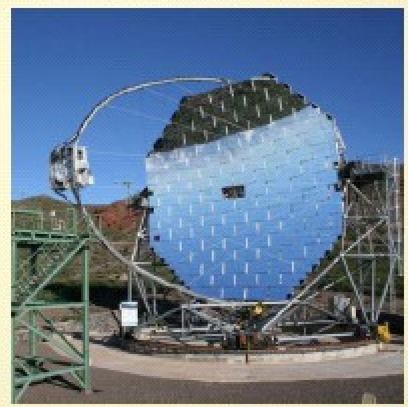
Early British-Irish, and Russian Observatories, 1960-1970
Recycled military hardware
~50K$



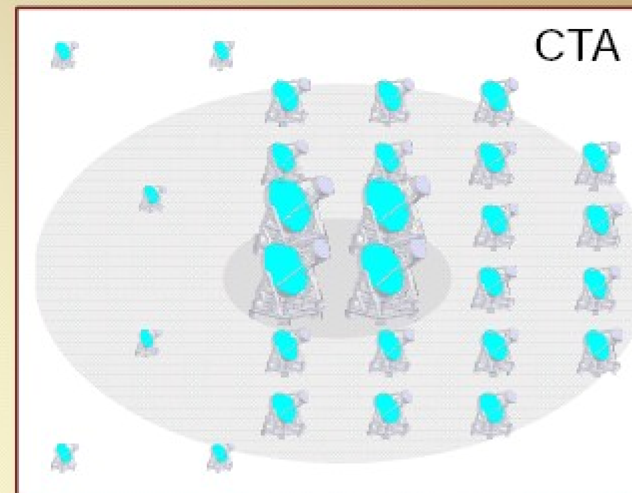


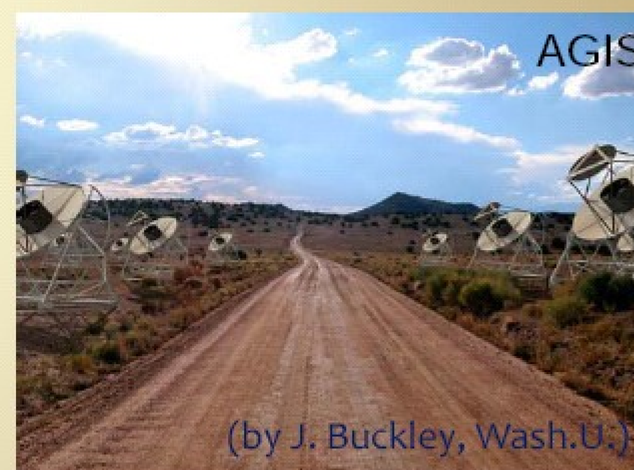
Whipple 10m, HEGRA
1980-2000
~1-3M$





HESS, MAGIC, VERITAS
2000 --, ~30M$



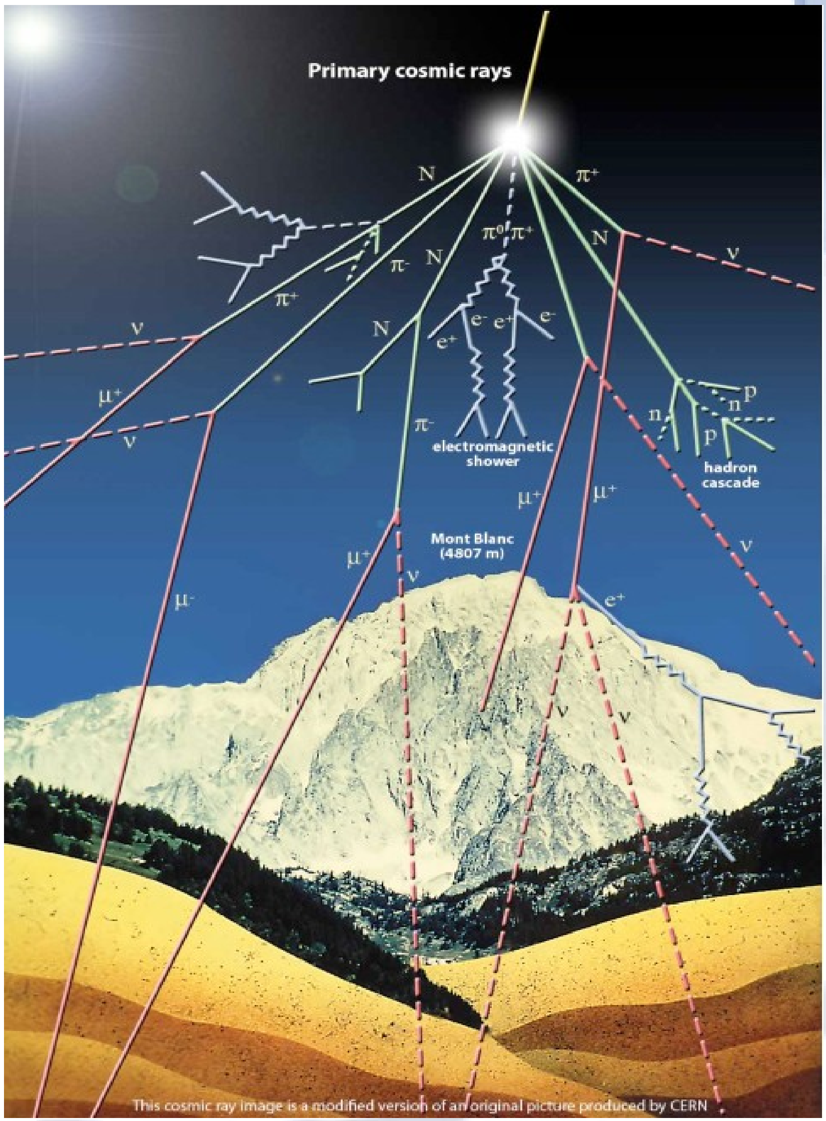




CTA, AGIS
2010 --,
~150 -200 M$

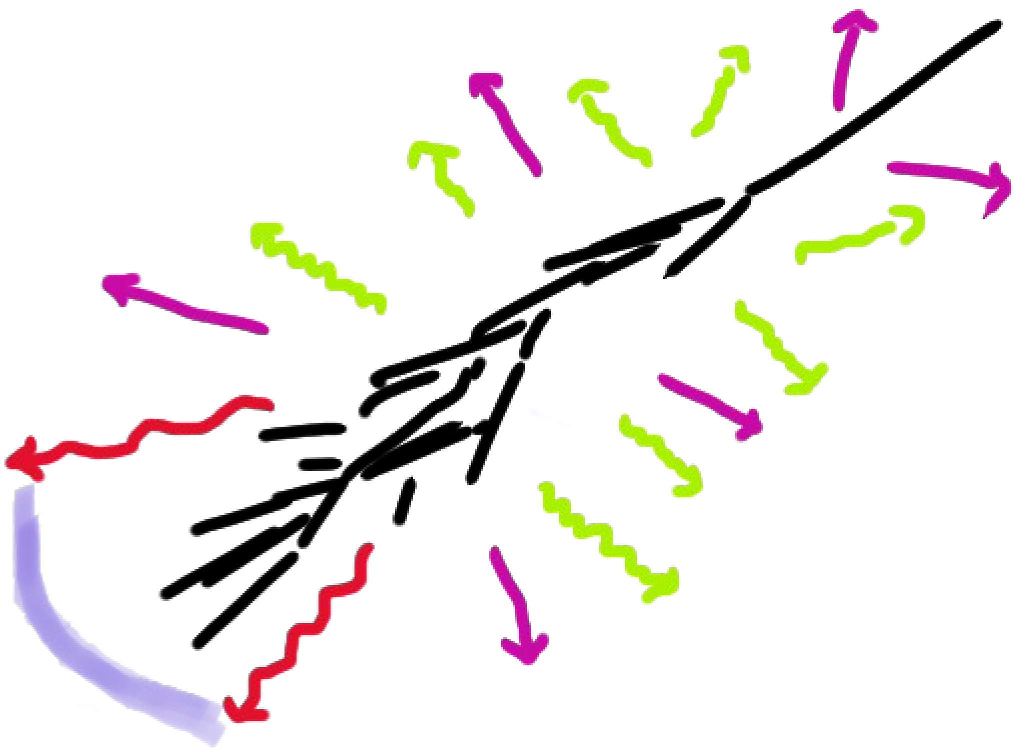
# Air Showers

- Hadronic cascade: driven by inelastic NN-scattering
- Electromagnetic cascade: driven by Pairproduction & Bremsstrahlung
- Electromagnetic cascade dominates
- Generic properties:
  - $N \propto E_0/E_c$
  - $X_{\max} \propto \log(E_0/A)$
  - $E_c \approx 80 \text{ MeV}$

$E_0$, A

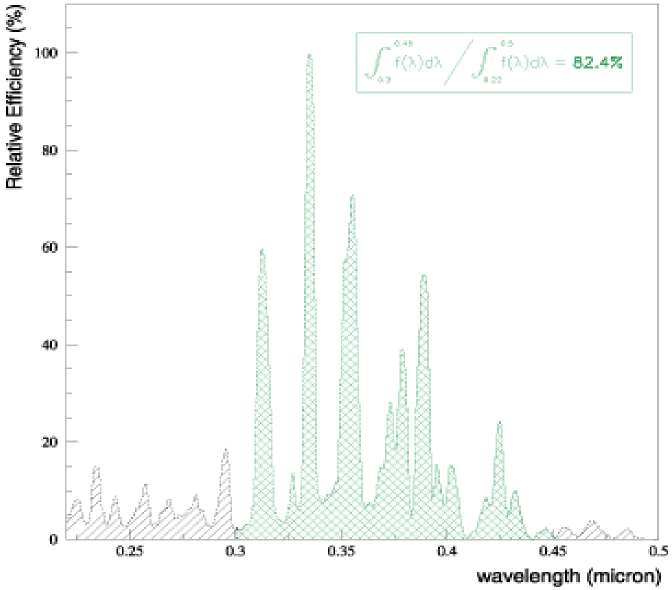


# Radiation from $e^+/e^-$-pairs



# Optical emission

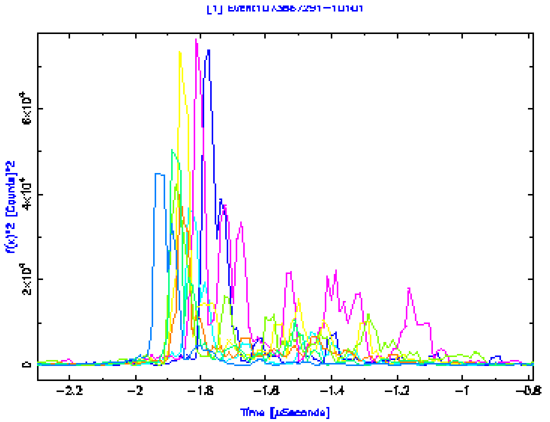
- Air Cherenkov light
  - $\cos\vartheta = \frac{1}{\beta n} \qquad \frac{d^2 N}{dx d\lambda} = 2\pi\alpha \sin^2\vartheta \frac{1}{\lambda^2}$
- Air fluorescence light
  - Isotropic emission
  - UV lines




**Very mature and well-calibrated detection channel**

# Radio emission

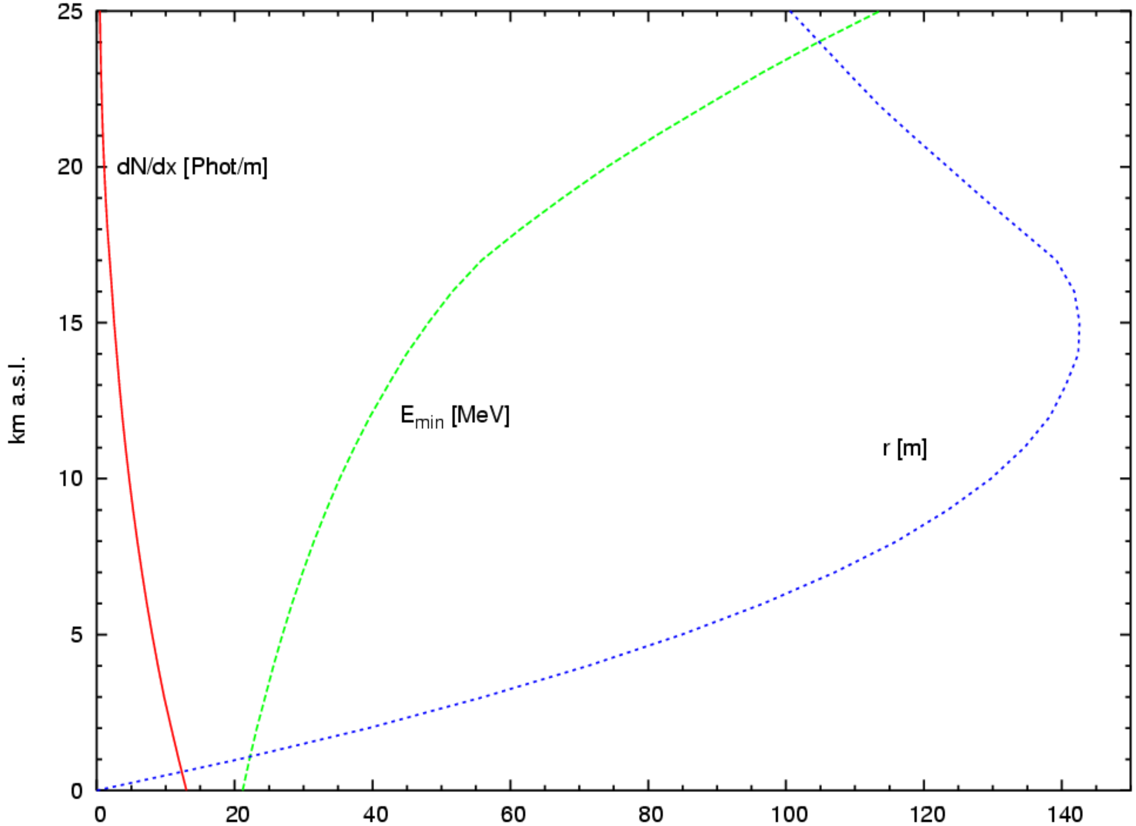
- Geo-Synchrotron and charge separation: beamed radio emission



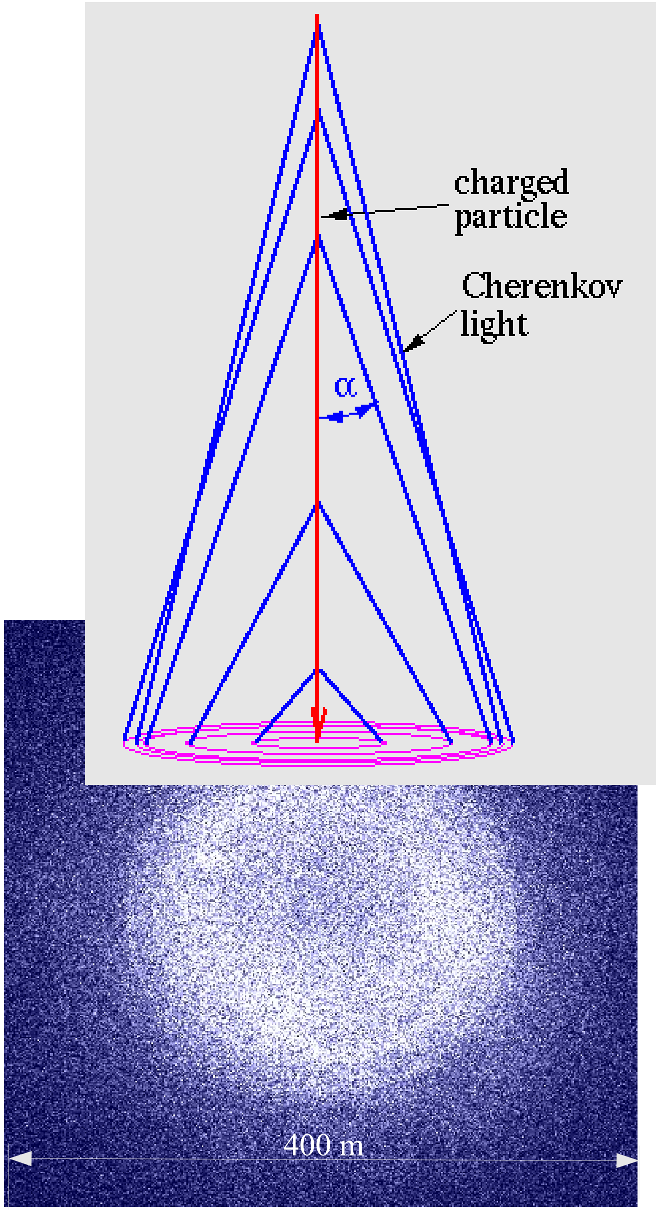

LOPES

- Molecular Bremsstrahlung: isotropic radio emission

**Radio techniques are currently tested – huge potential towards future air shower detection**




# Air Cherenkov light

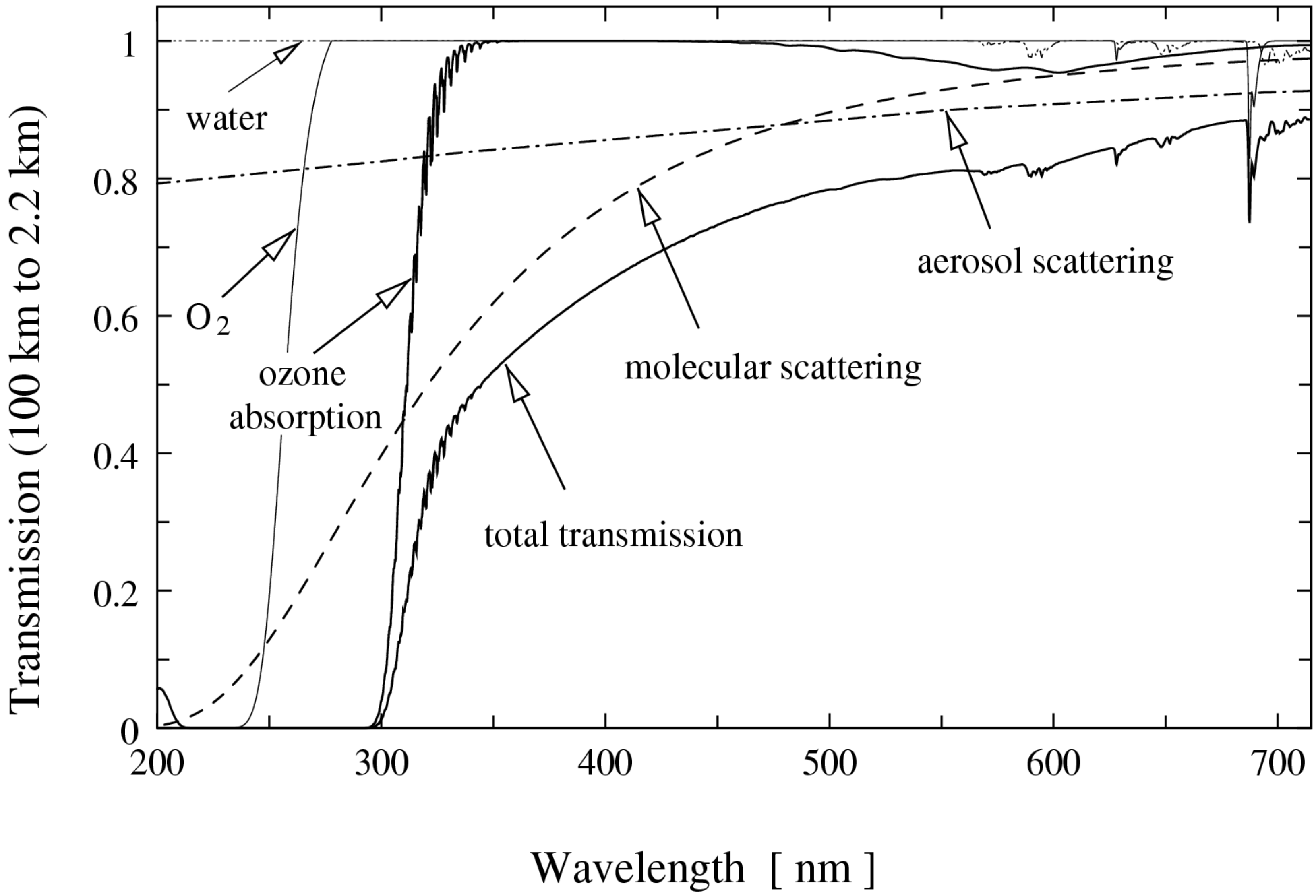



Atmosphere focusses light in time and space!

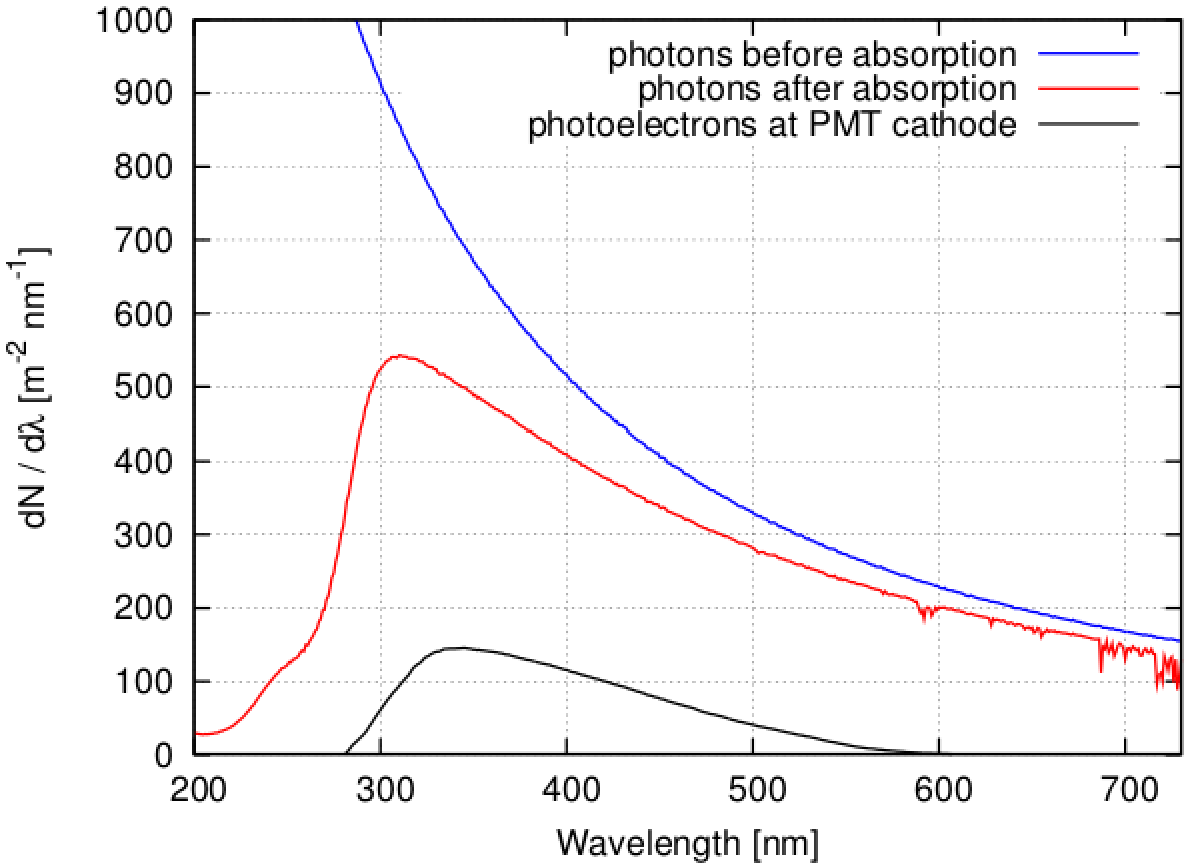
Light pool with
~10 ph/m$^2$ for $E_0$=100 GeV

Measure direction (timing or imaging) and Energy (amount of light)

# Absorption effects

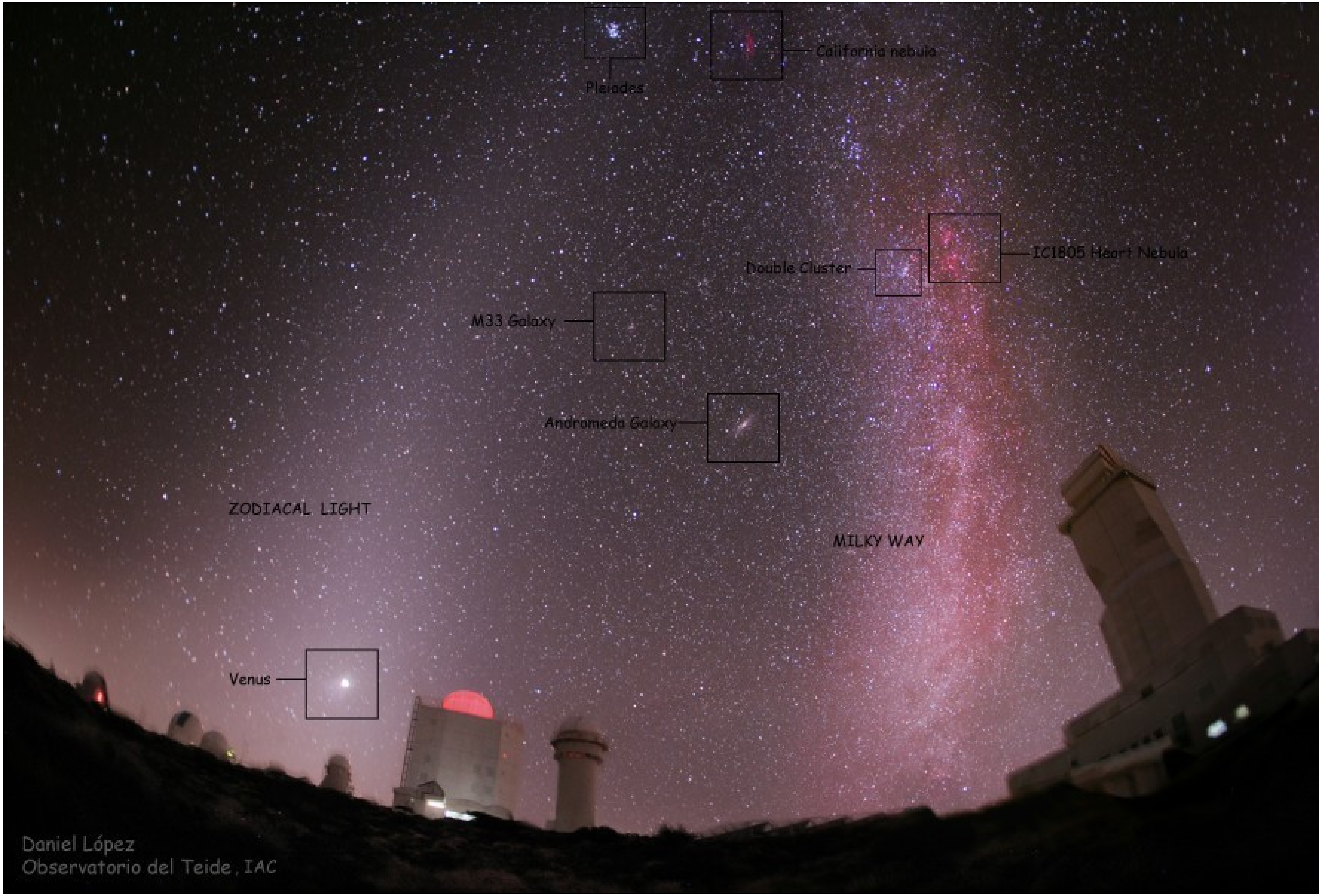


# Cherenkov spectrum on the ground



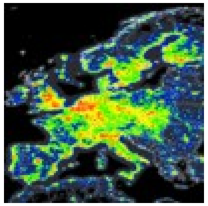

Hampf 2012

# Night sky background



# Night sky background

- Origin of NSB:
  - Stellar light (direct)
  - Scattered stellar light, moon light
  - Zodiacal light
  - Air glow (time dependent)
  - Human made light (direct and scattered)



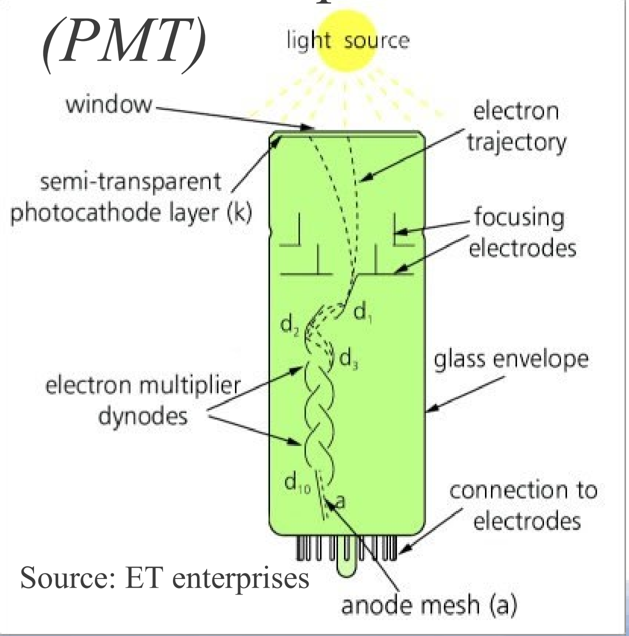
- NSB at a dark site (e.g. Hampf et al. 2011), integrated between 300 and 600 nm

$$2 \times 10^{12} \ \frac{\mathrm{ph}}{\mathrm{m^2 \ s \ sr}}$$

# 1. Detecting (air) Cherenkov light

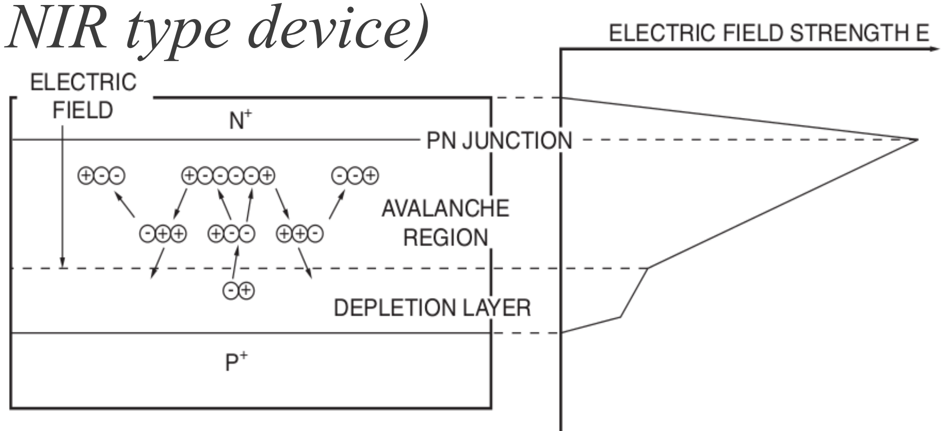
- Requirements:
  - Detect short pulses (~ns)
  - Detect and count single photons
  - Noise level < NSB (uncritical)

*Photomultiplier tube (PMT)*




Source: ET enterprises

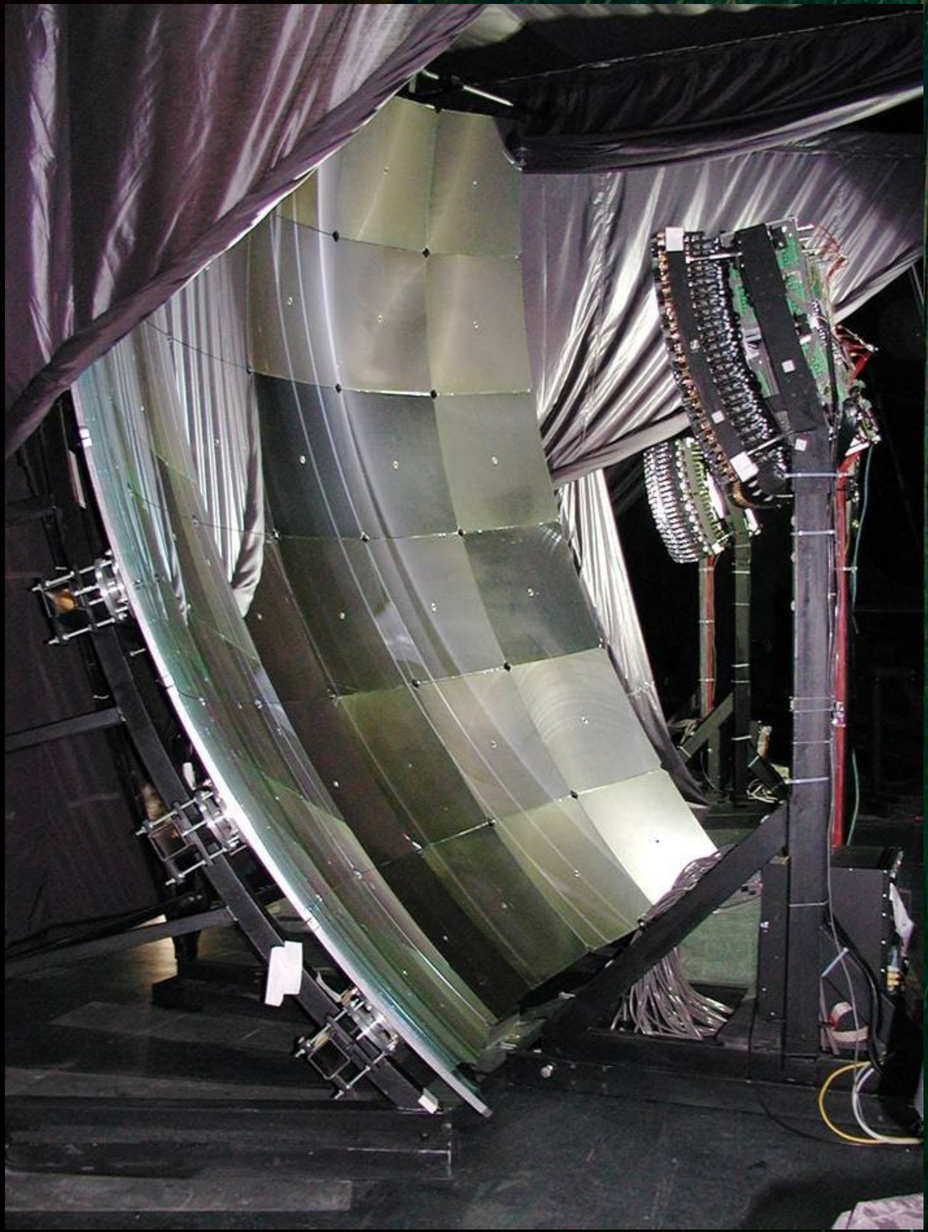
*Silicon avalanche photo diode (here a NIR type device)*




Array of Si-APD in Geiger mode: Si-PMT

Gain: $\sim 10^6$

# Detection of faint light pulses



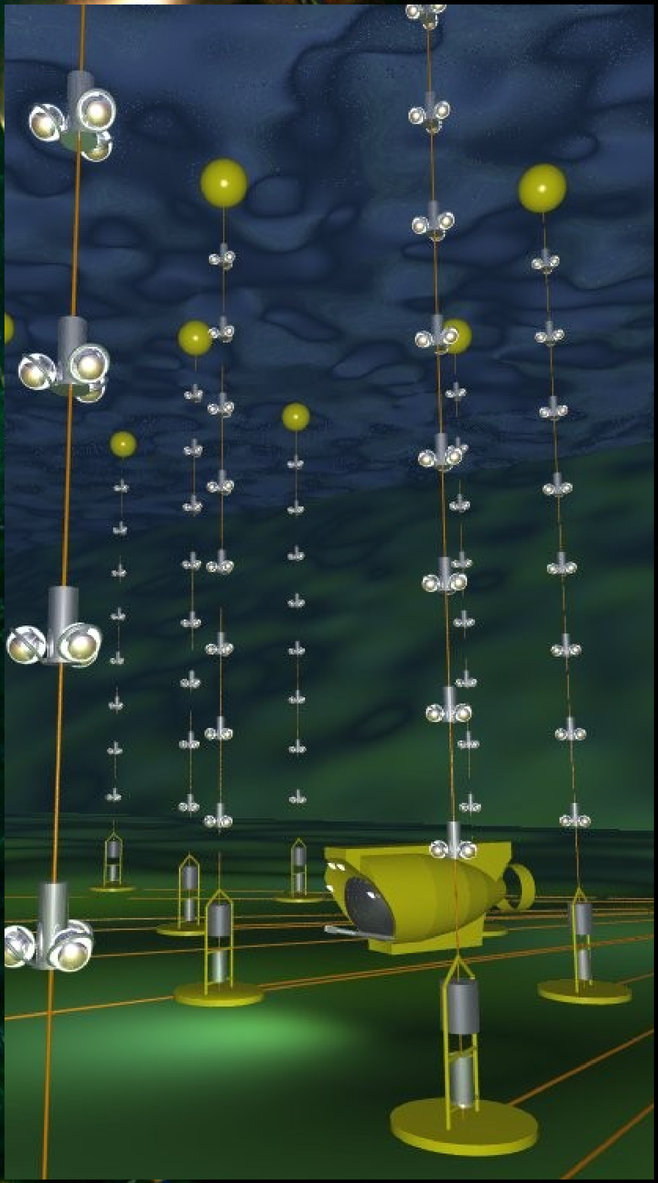
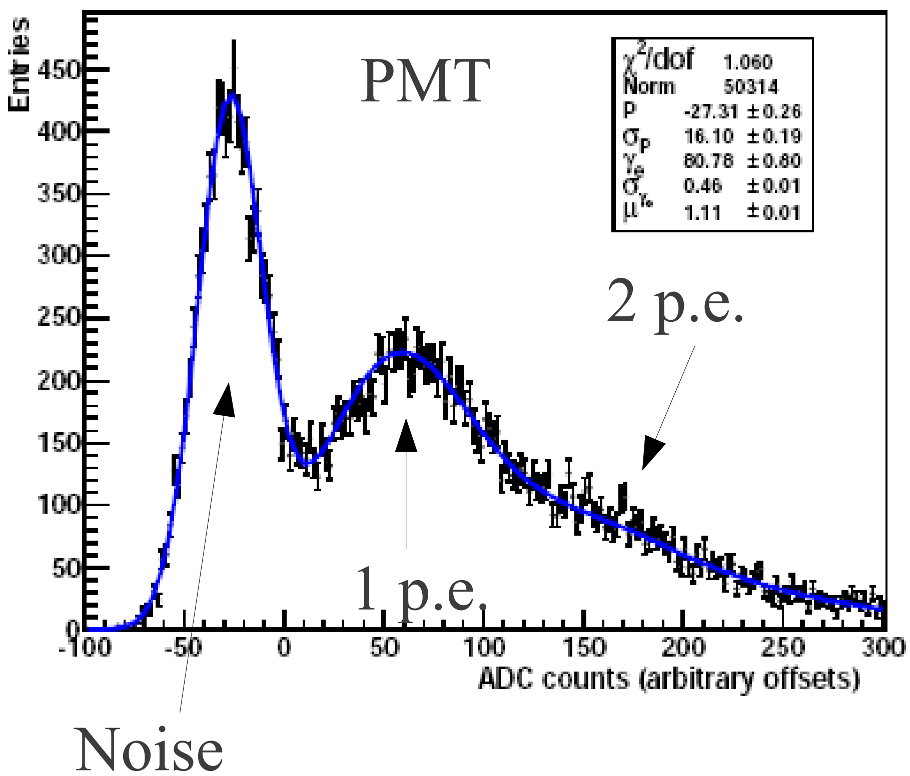


*photo: BOREXINO calibration*

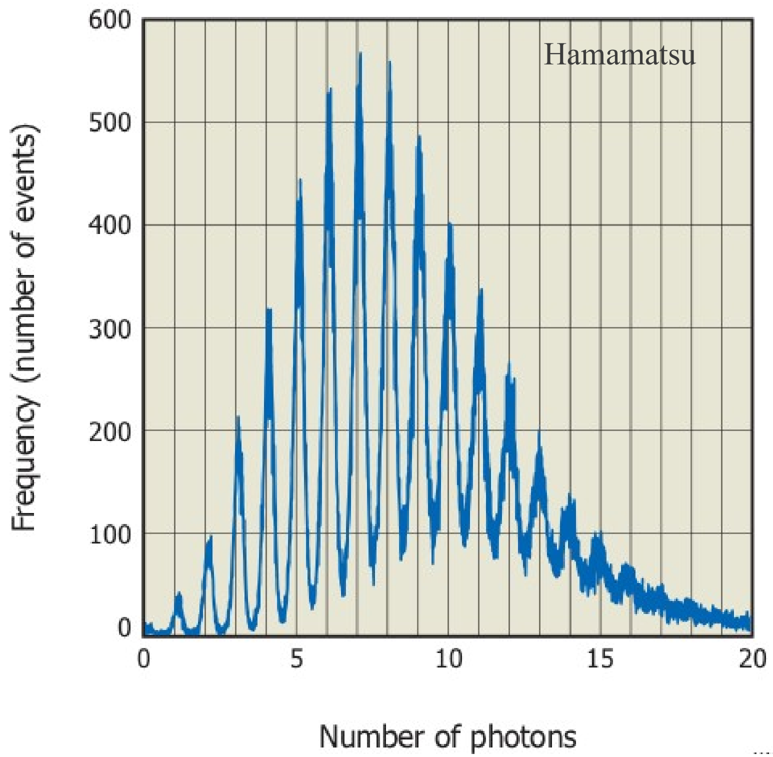
# Calibration of Photon counting devices

- Illuminate the device with a faint light source and determine the Single-PE-peak

Aharonian et al. 2004




SiPMT

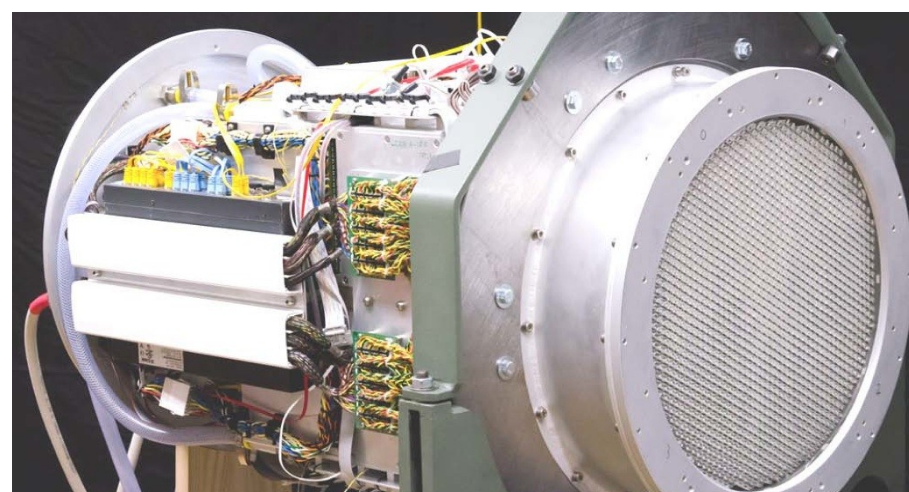


# Multi-Pixel “Camera”

MAGIC I

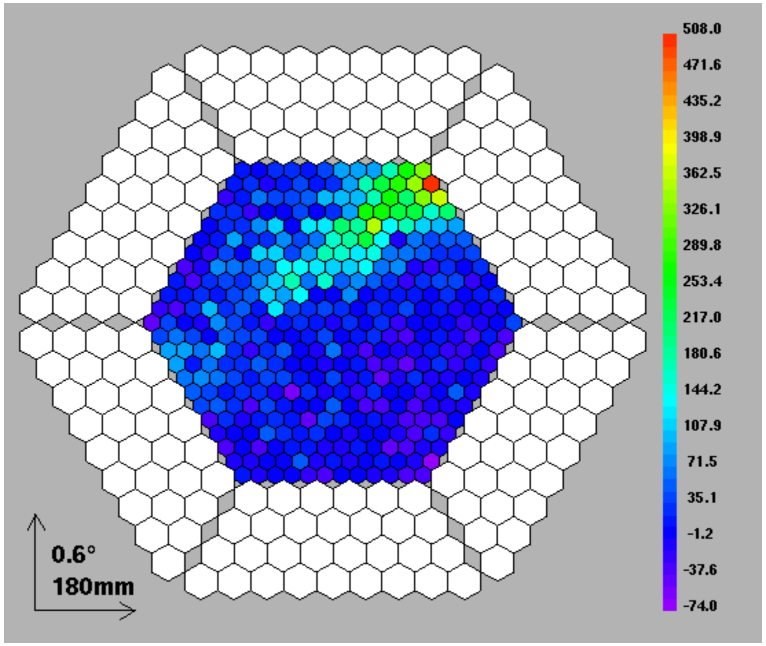
PMT camera (Fly's Eye)

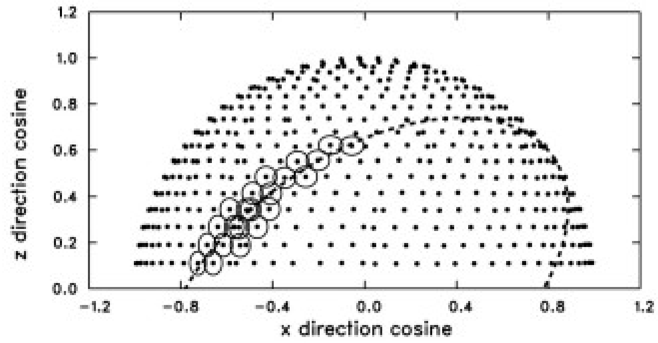
H.E.S.S. II

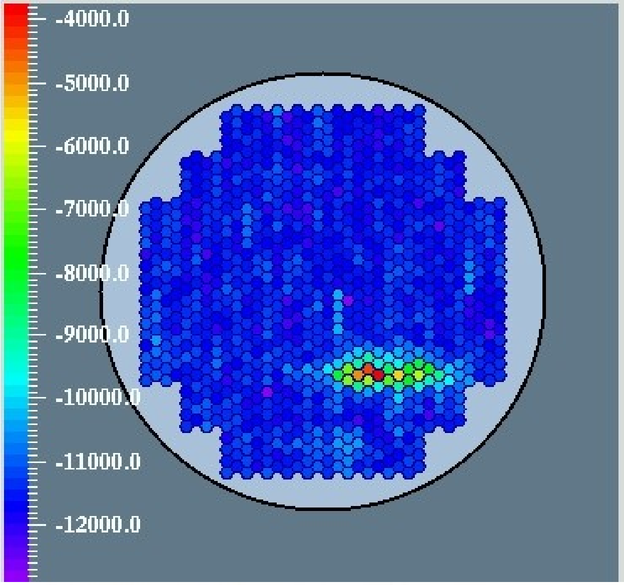


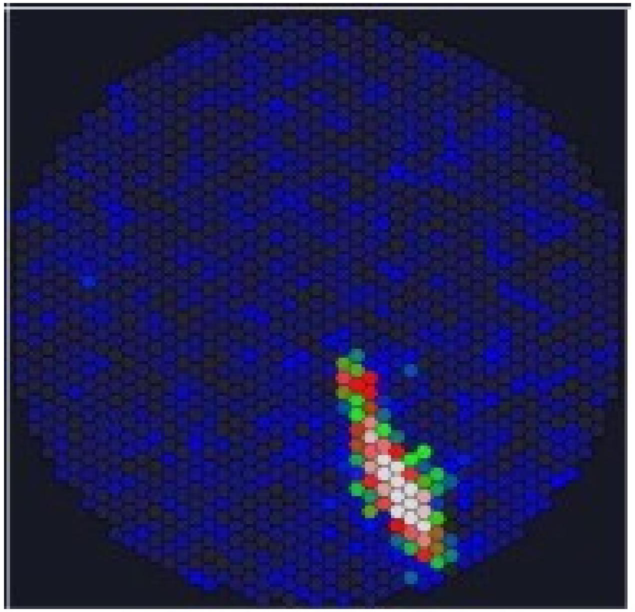
SiPMT-Camera (FACT)

# Raw air shower images



# Calibrating the images

- Starting point: Raw image (2d digitized intensity)
- Calibration step:

  (1)Subtract electronic pedestal

  (2)Correct for electronic gain (ADC → p.e.)

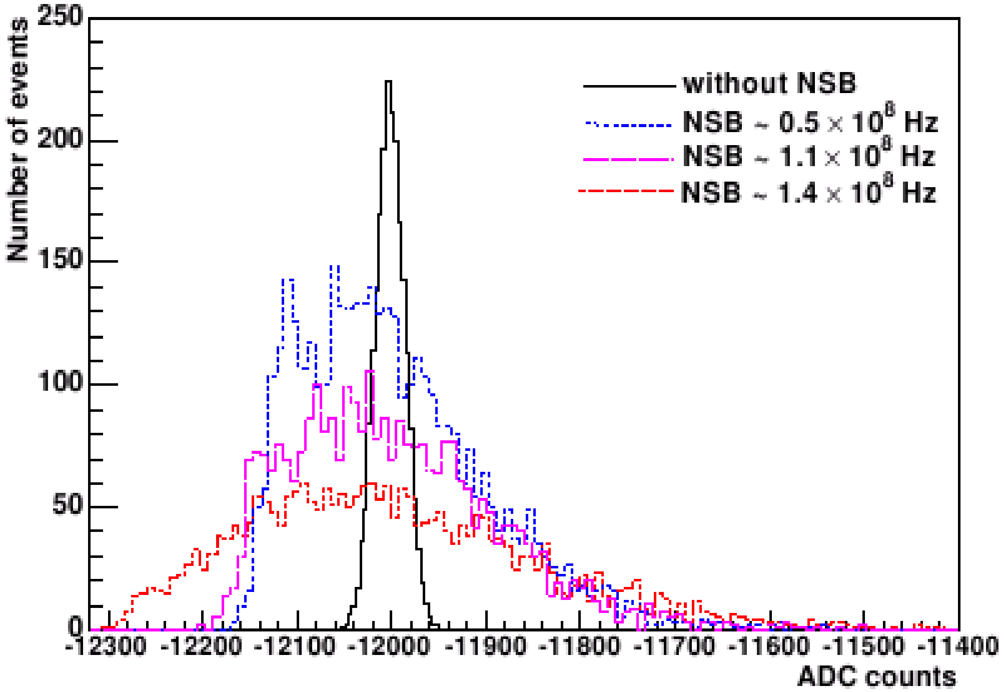
  (3)Correct for inhomogeneities ("flat fielding")

  (4)Correct for optics throughput (match simulations)

- Cleaning step:
  - remove noisy/broken pixels
  - Optionally: remove NSB ("tail cuts")

# Zero-line: Pedestal

- Pedestal (temperature/sky position dependent)
  - Closed lid data (no NSB*: electronic pedestal)
  - FADC+/ARS#: random slices (in parallel to normal data-taking)
  - ADC: Specific "Pedestal" runs




Width can be used to "measure" NSB*

*Night Sky Background
+Flash ADC
#Analogue Ring Sampler

# Amplification: Electronics gain

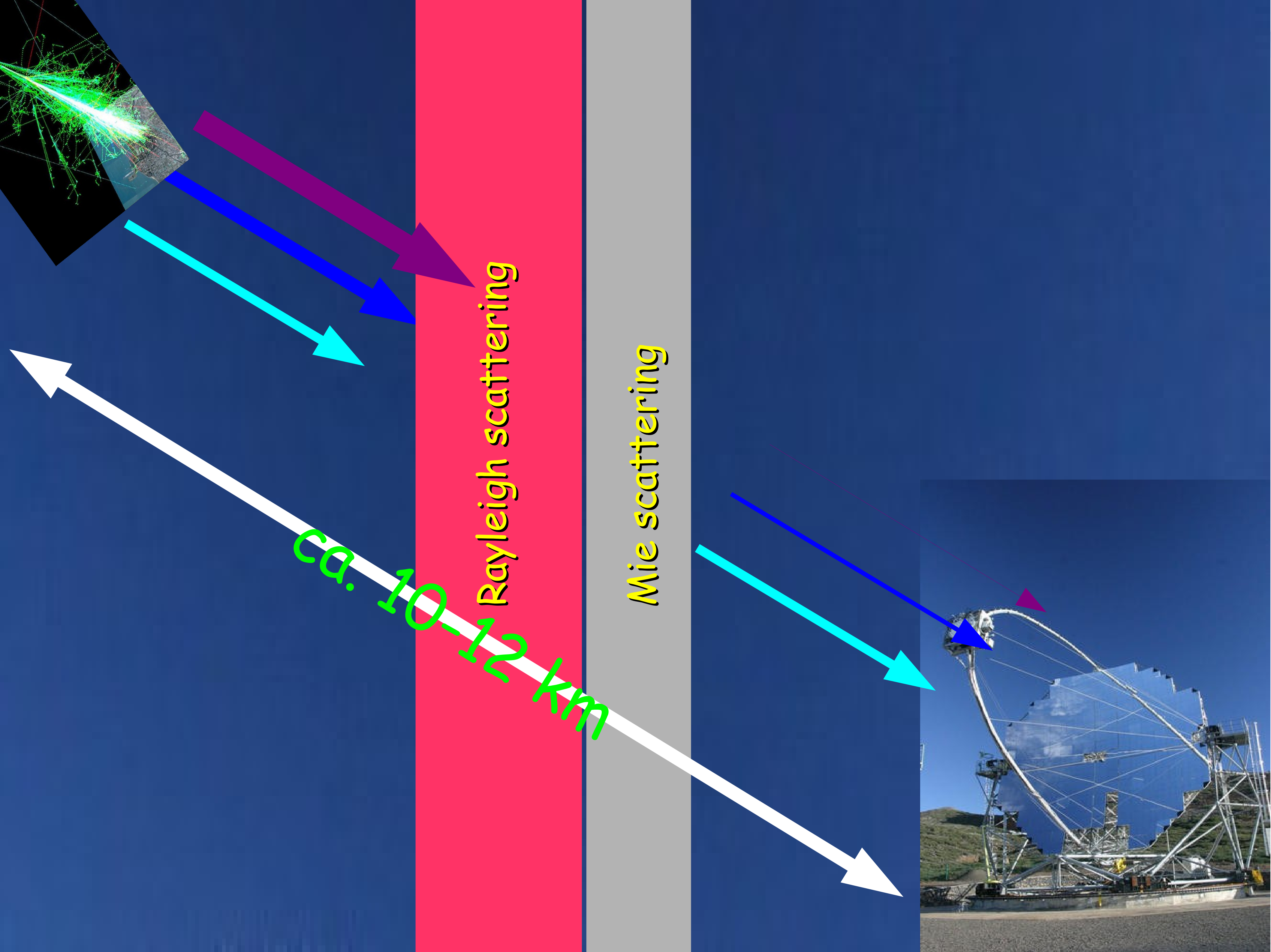
- Calibration runs:
  - Illuminate homogeneously the camera with a pulsed light source (Laser+diffusor ~ few Hz, pulsed LED+diffusor ~few 10 Hz)
  - Record the amplitude in each pixel (self-triggering)
- 2 methods:
  - Bright illumination (>>1 p.e.): use the width~$N_{p.e.}^{1/2}$, can be used for flat-fielding (e.g. HEGRA, MAGIC)
  - Faint illumination (~ 1 p.e.): Fit the single p.e. Peak, can not be used for flat-fielding (e.g. HESS)

# “Flat fielding”

- Using high p.e. homogenous illumination of camera:
  - Calculate intensity averaged over pixels
  - Calculate relative variations: FF
  - <1-FF>~0.01..0.05

# Non-linearity

- Reasons for non-linearity:
  (1)PMT
  (2)Pre-amplifier
  (3)Digitization (e.g. saturation)
  (4)Timing (FADC)
- Calibration:
  - Lab measurements: correction (1,2,3)
  - Pulse-shape correction (e.g. FADC: 3,4)



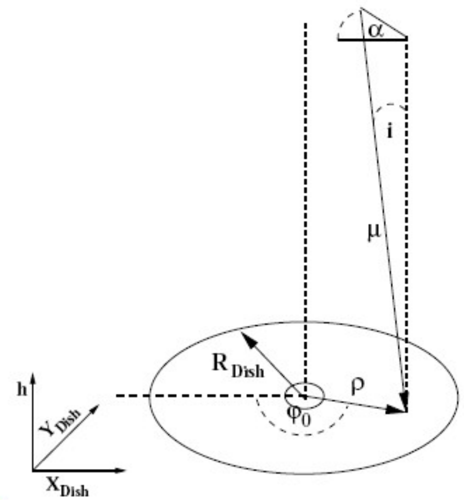
Rayleigh scattering
Mie scattering
ca. 10-12 km

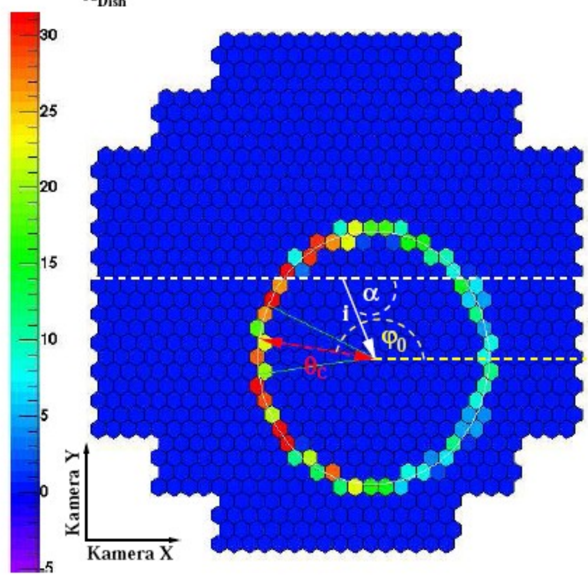
# Most challenging: “throughput” efficiency

- Definition of “throughput”:
  - Conversion of p.e. to Cherenkovphotons
- Throughput <-> energy calibration (MC simulation!)
- Contribution to the throughput:
  - Atmospheric absorption/scattering (transmissivity~0.7)
  - Light collection efficiency (Mirror: reflectivity~0.8-0.9, shadowing=0.89)
  - Light collection efficiency (Camera: transmissivity entrance window, Winston cones: 0.7-0.8, PMT q.efficiency: 0.15-0.20)
- Total throughput ~ 5-7% (1 p.e. ~ 10-20 Cherenkov-photons emitted)

# Probably best calibration: Muon-rings!

- Muons are produced mainly in hadronic air showers (background)
- Cherenkov light illuminates the dish for local muons ($l \sim R/\theta_C \sim 400$ m mit $R \sim 7$m, $\theta_C \sim 1^o$ )
- Imaging preserves the “angle”: focus on a ring
- Reconstruct the geometry
- Number of Cherenkov photons emitted per track length (~15 ph/m, total~15*400=6000 photons)

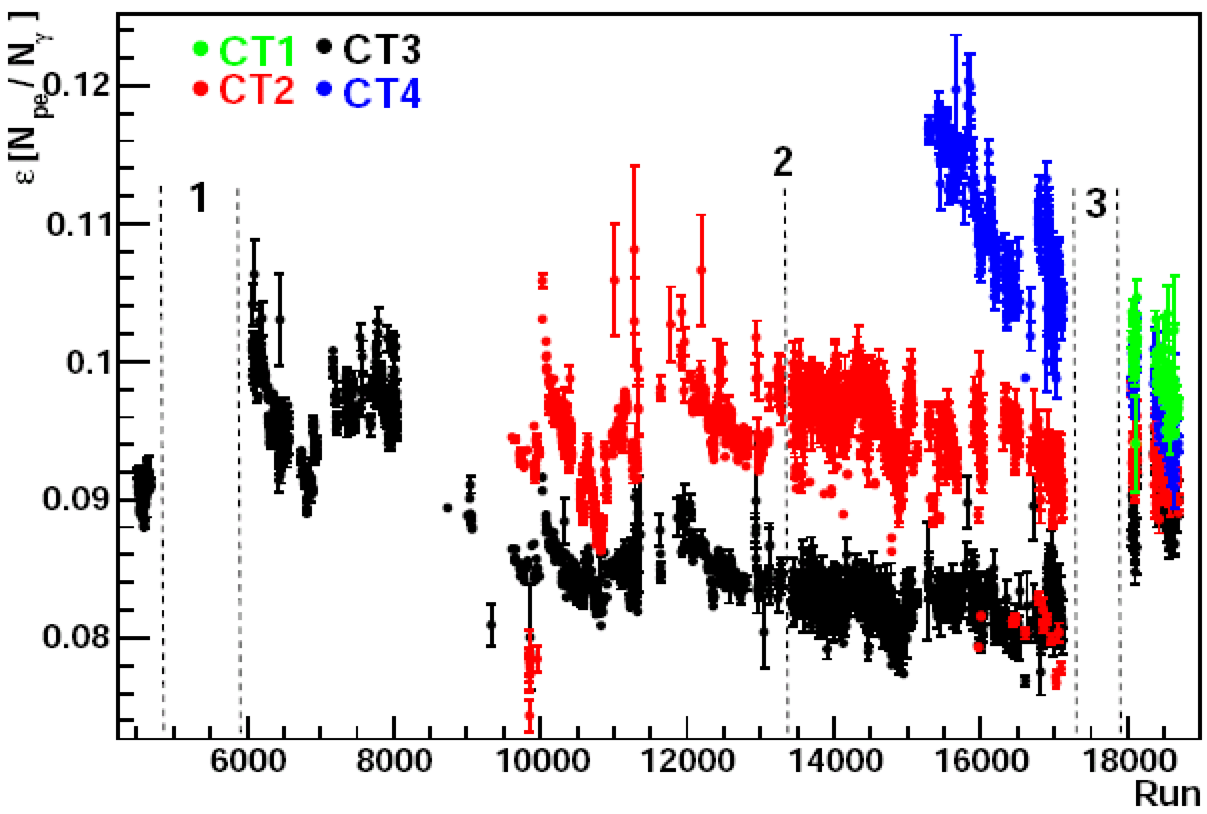



$$dN/d\lambda/dx = 2\pi\alpha^2 z^2/\lambda^2 \ (1-1/\beta^2 n^2) \sim 1/\lambda^2$$

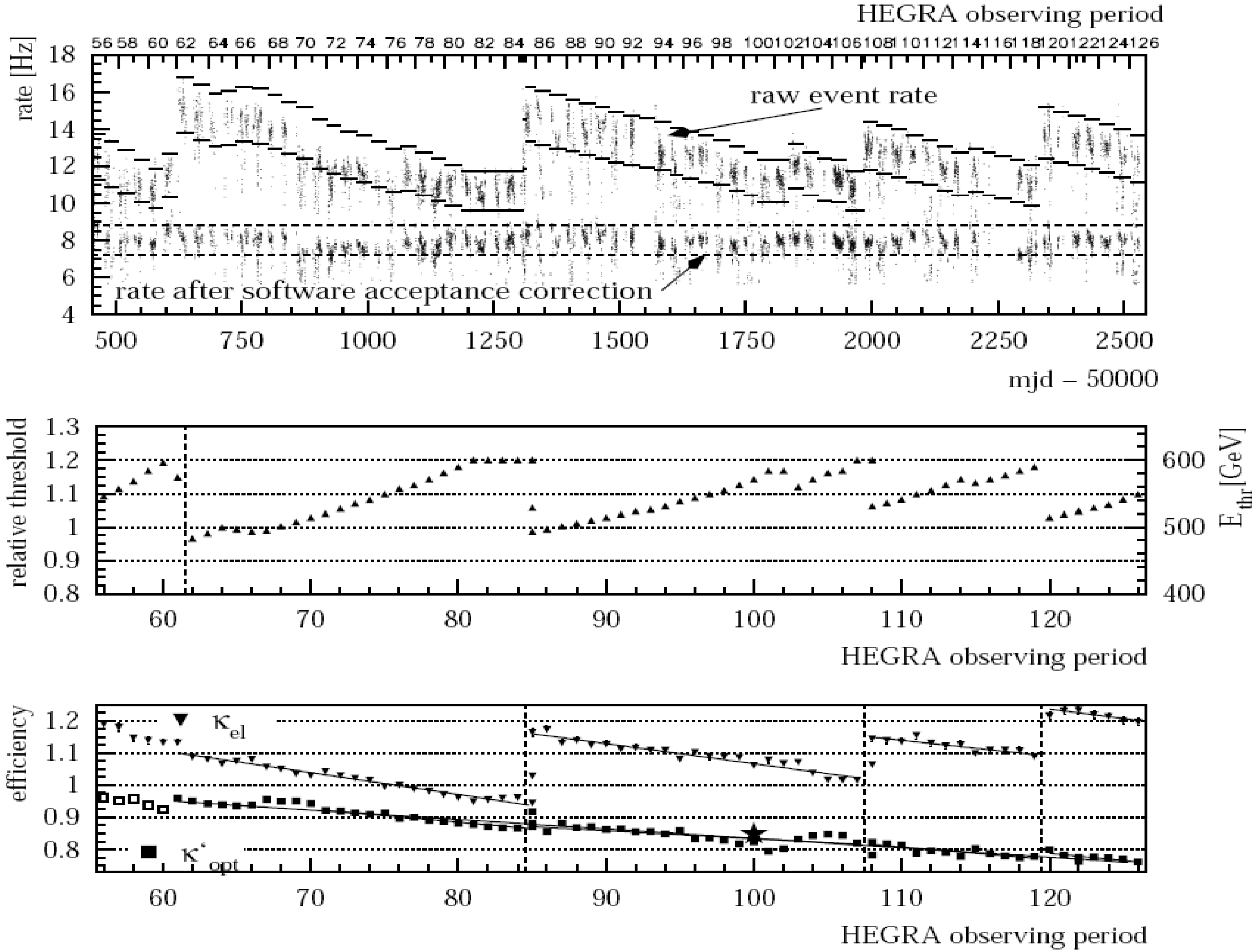
Optical throughput w/o atmospheric extinction!

# Result from muon ring calibration




O. Bolz, PhD thesis (2004)

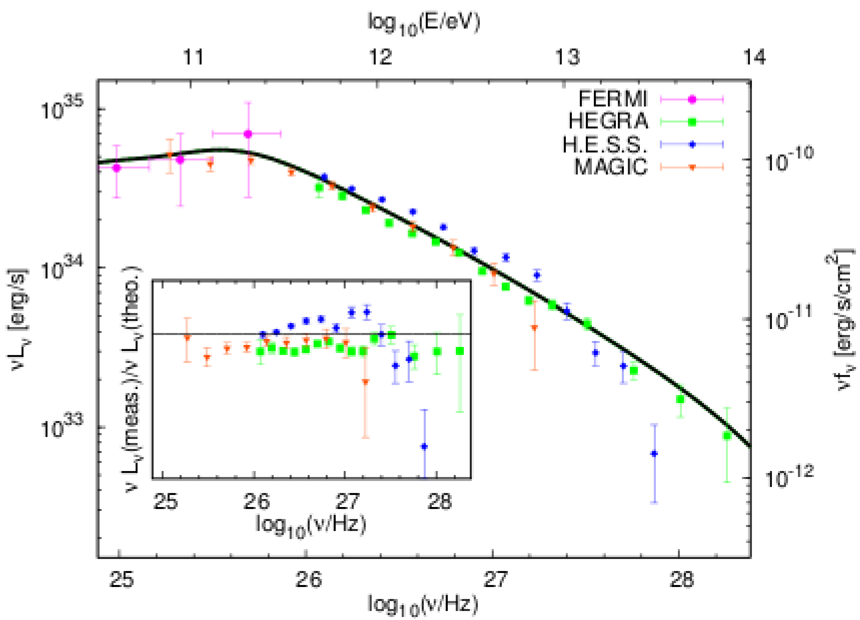
# Disentangling optics and electronics contribution: Cosmic ray rate is constant

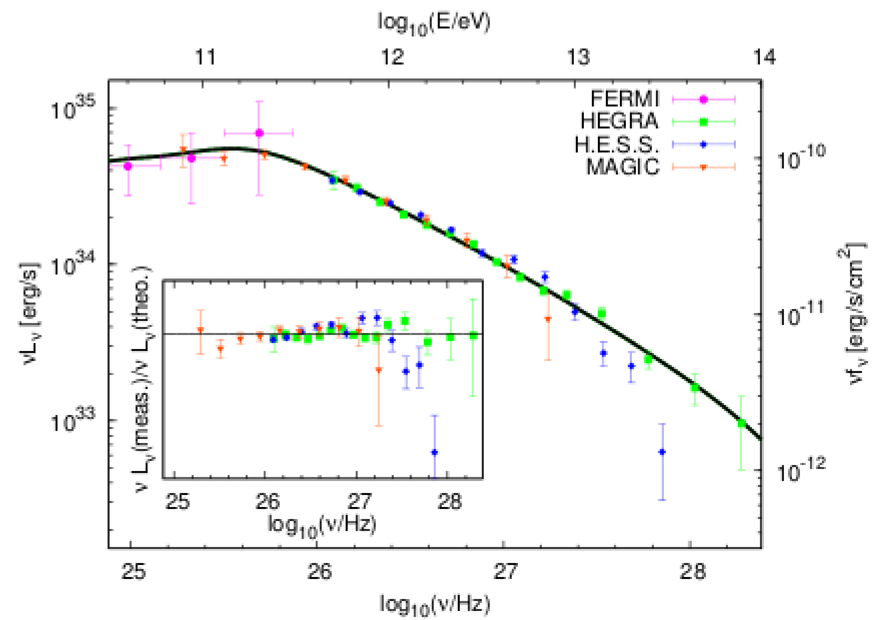



Puehlhofer et al. (2004) for HEGRA

# Approach to verify (instrumental and MC) calibration

- Energy calibration: Use of Fermi/LAT (beam calibrated energy scale) in overlapping energy range:



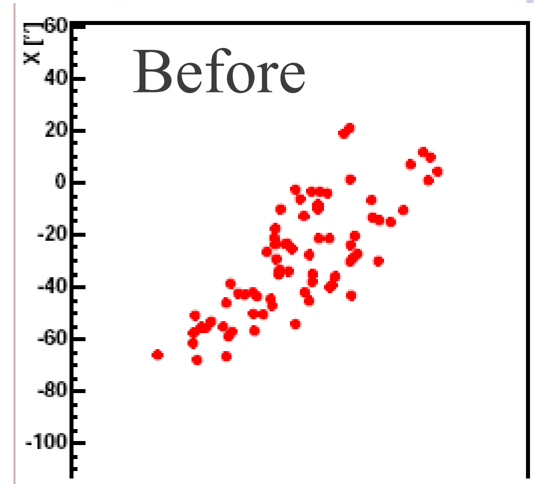

| Instrument | Scaling factor $s_{\rm IACT}$ | Stat. error $\Delta s$ | $\chi^2_{\rm before}$/d.o.f. | $\chi^2_{\rm after}$/d.o.f. |
|---|---|---|---|---|
| Fermi/LAT | 1 | +0.05 − 0.03 | – | 0.49 |
| HEGRA | 1.042 | ±0.005 | 7.652 | 1.046 |
| H.E.S.S. | 0.961 | ±0.004 | 11.84 | 6.476 |
| MAGIC | 1.03 | ±0.01 | 1.671 | 0.656 |

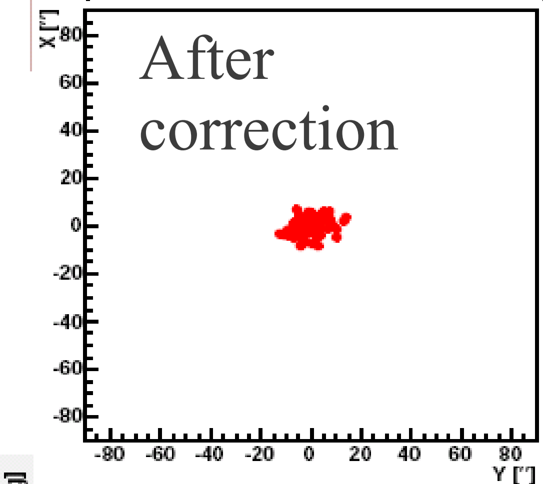
TABLE IV. Energy scaling factors of the IACTs for the cross calibration.

[Meyer & DH 2010]

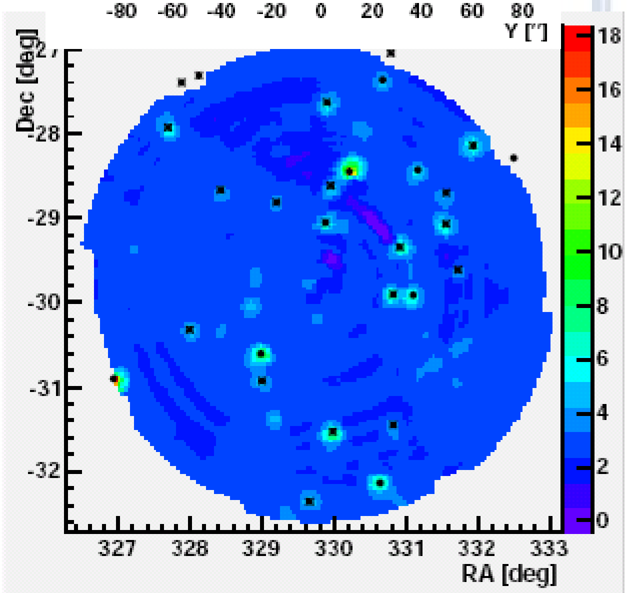
# Pointing calibration

- Systematic mispointing:
  - Sagging of the camera
  - Non-linearities/offsets in shaft encoders
  - Tilt of axes
- Calibration:
  - "Point runs"
  - "Guiding CCD"
- Events are pointing-corrected by arc min(systematic uncertainty~10")
- Cross-Check: Star positions during observations



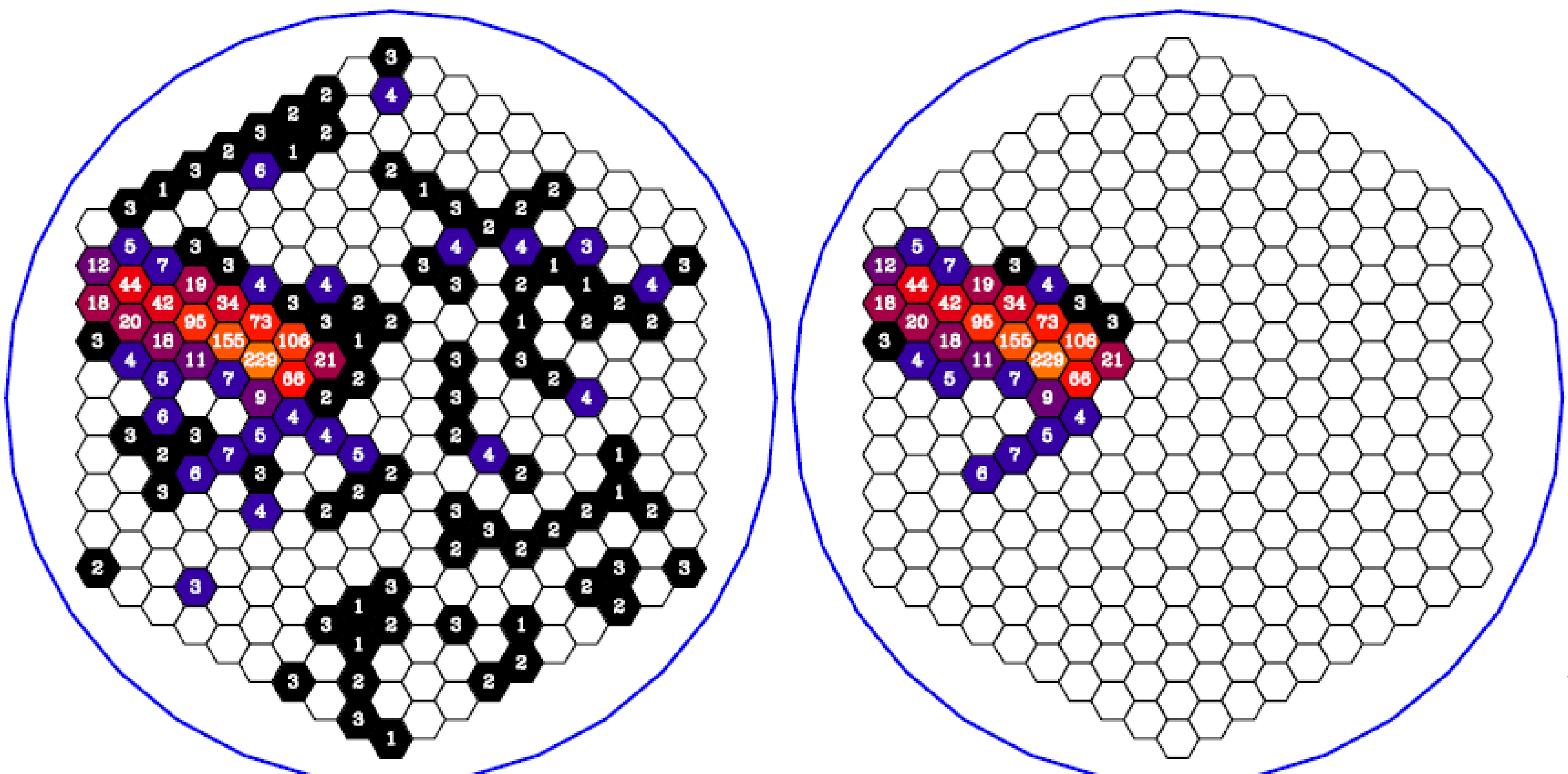




S. Gillessen (PhD 2004)



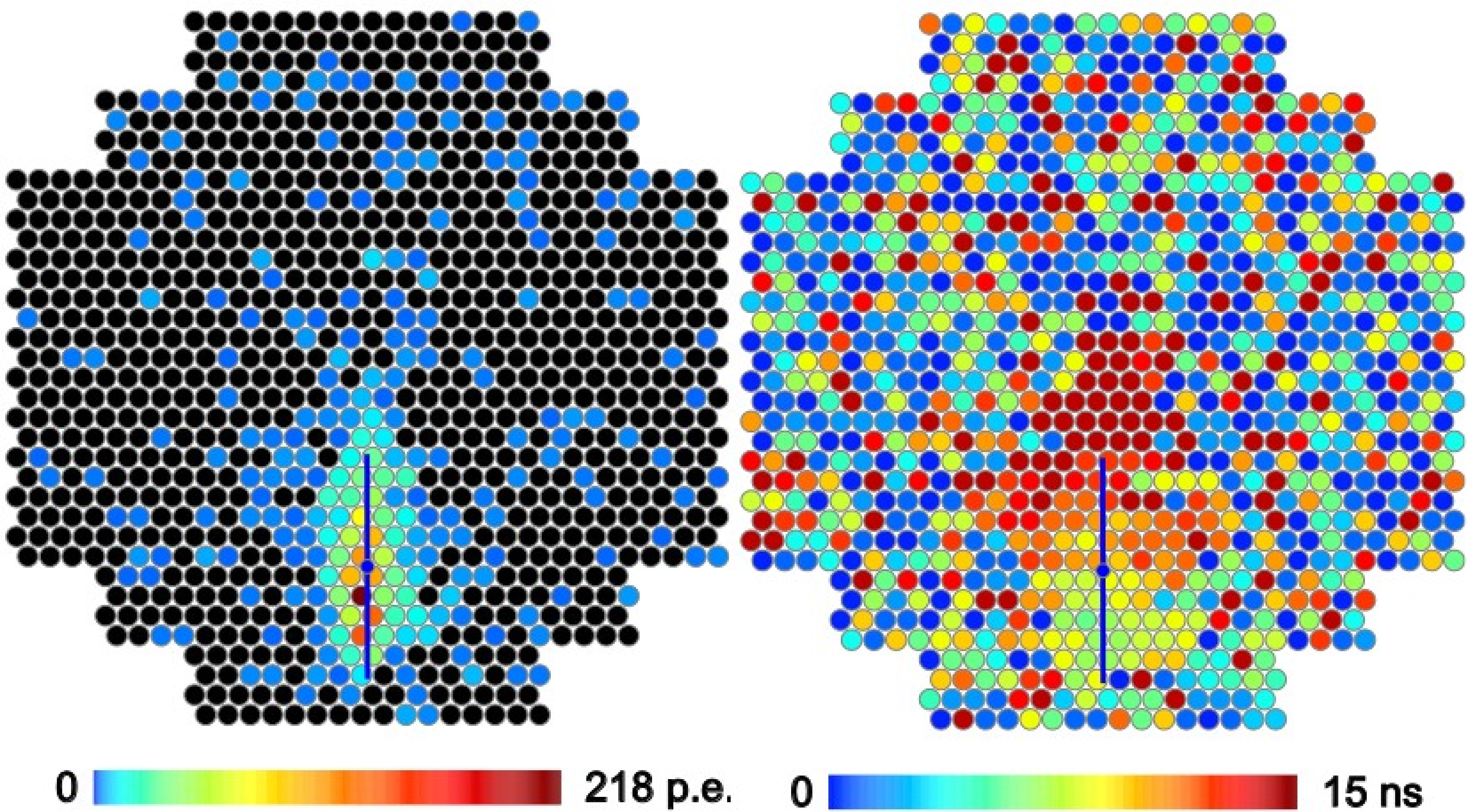
# Image cleaning

- Set bad/broken pixel to 0
- Apply “tail cut” to remove NSB affected pixel
  - Remove pixels with A<X p.e.
  - Remove pixels w/o adjacent pixel > Y > X p.e



X/Y= 3/6 p.e.

# Time information and image cleaning



# Data selection

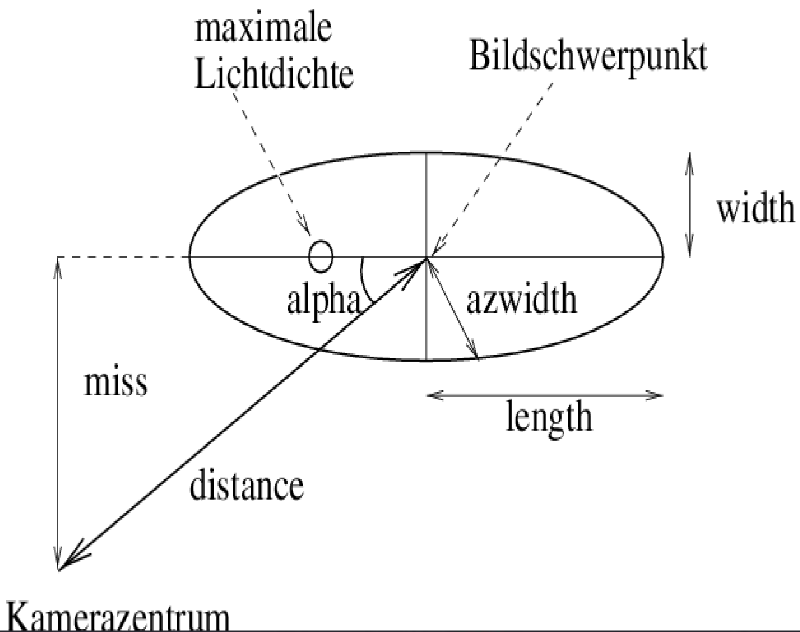
- Select for stable weather conditions e.g.
  - Atmospheric monitoring (e.g. lidar)
  - Variations of background rate (passing clouds)
  - Absolute (high) background rate
- Select for stable hardware performance e.g.
  - Number of broken pixels (stars, shooting stars..)
  - Homogeneity in camera
  - Fraction of dead time
  - Trigger behaviour of pixel

Data selection criteria vary:

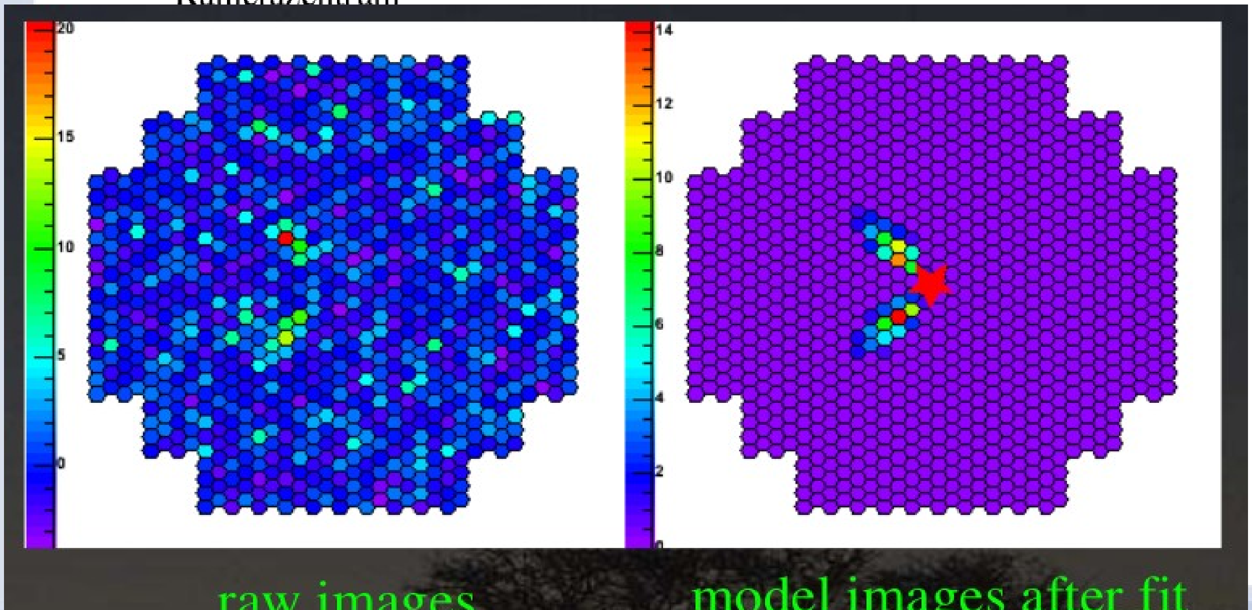
loose criteria: Search for sources, search for pulsation

strict criteria: Flux measurements, search for variability

# 2. Reconstruction: Imaging analysis and event selection



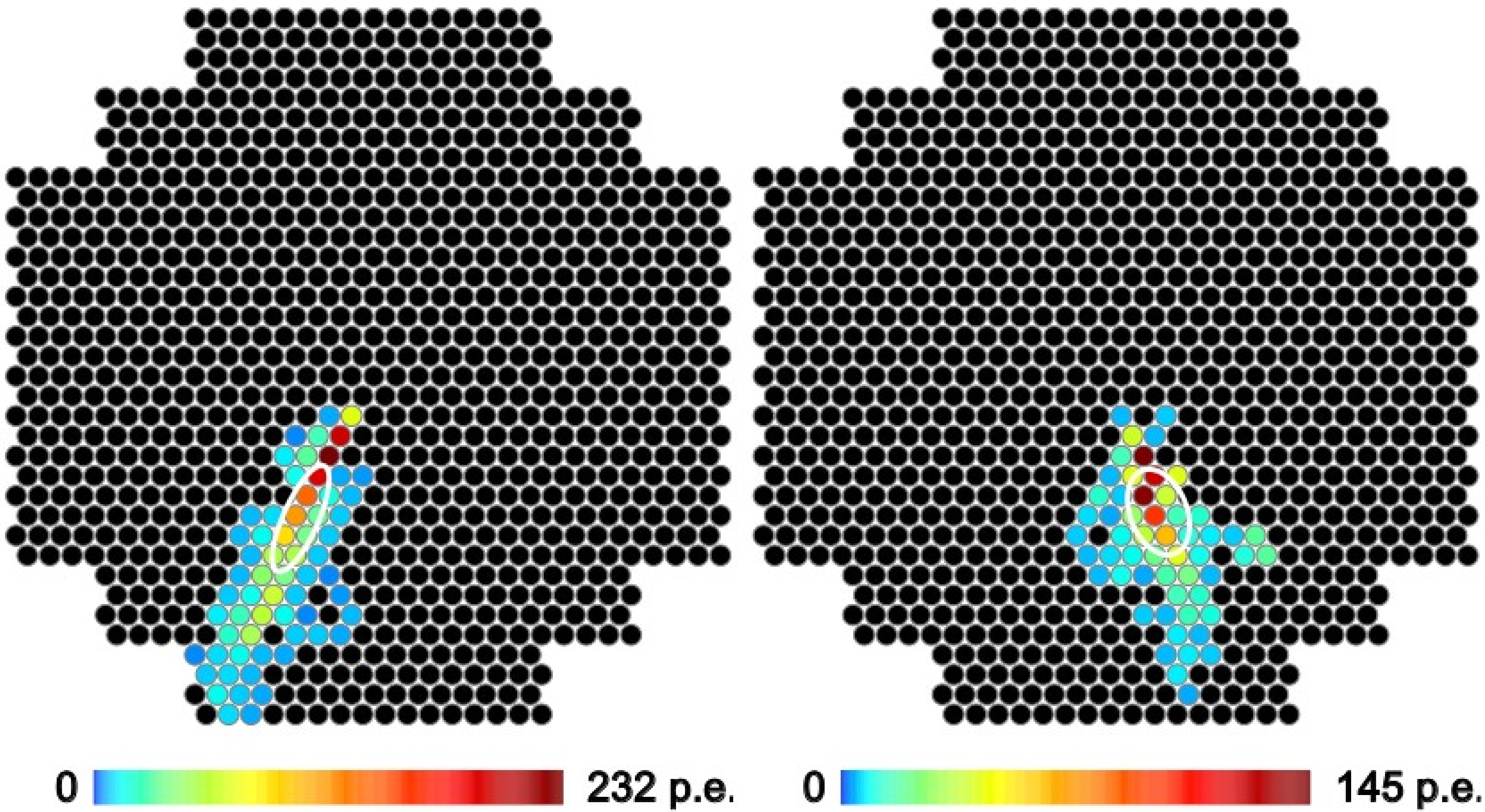

“Hillas” type analysis:
Use of image moments, orientation of major axis [Hillas 1984]




Model-type analysis:
Fit of image templates + NSB to the camera image [leBohec 1996, de Naurois & Rolland 2009]

# Gamma/Hadron-Separation: Imaging

Hampf 2012

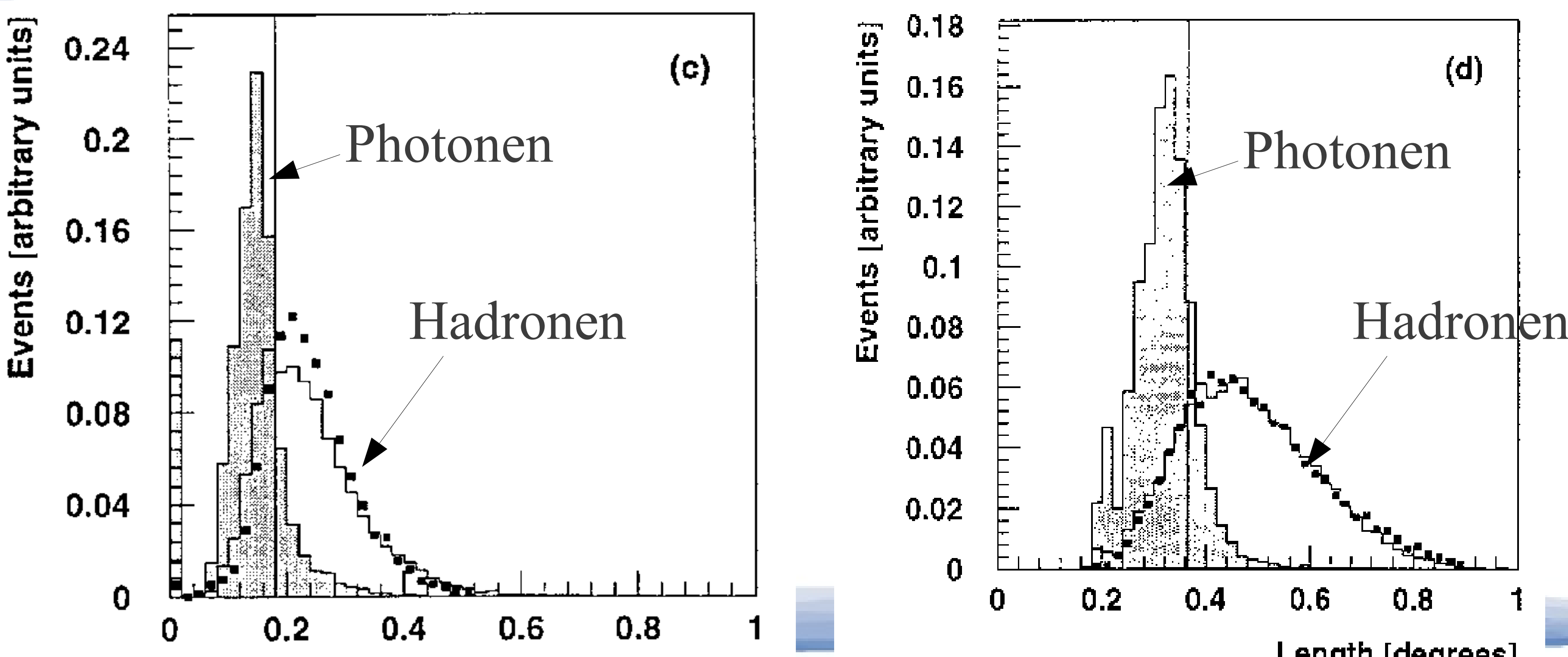



(a) Gamma-ray event

(b) Proton event

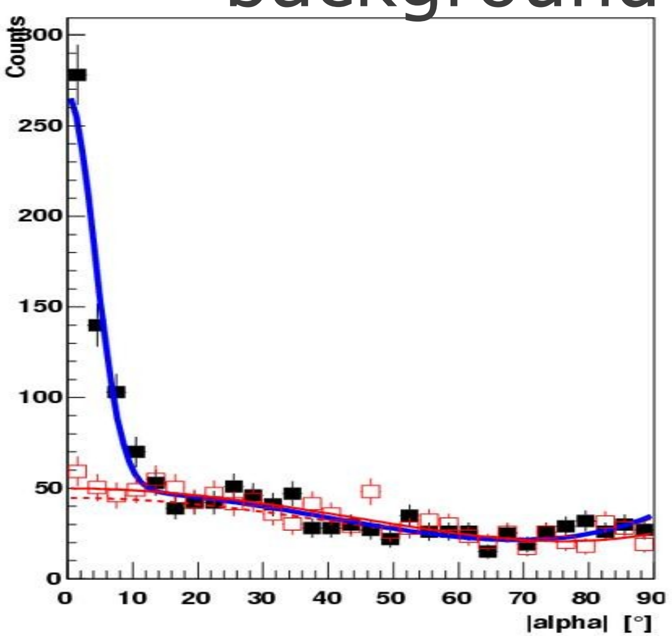
# Gamma/Hadron-Separation: Imaging

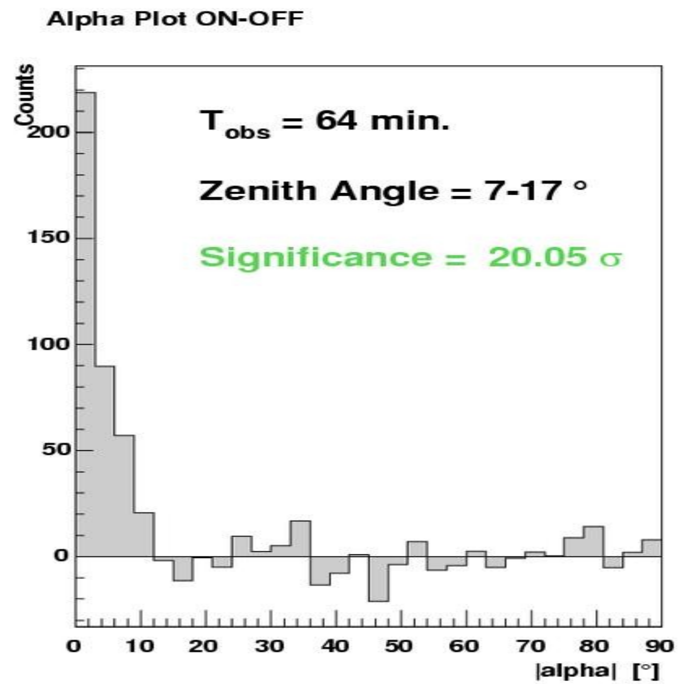
- Hadronic showers are broader ($p_t$)
- Hadronic showers are longer

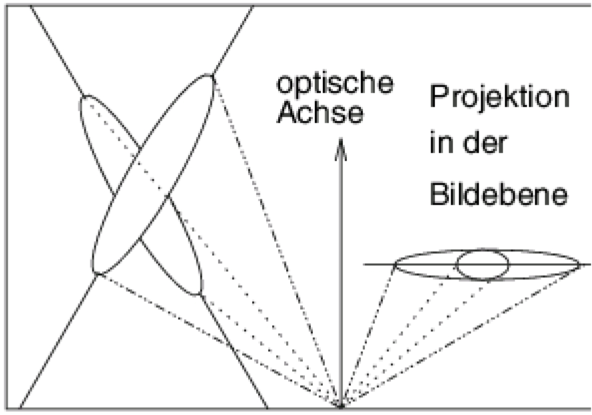


# Gamma/hadron separation: Image orientation

- Primary direction (shower axis) parallel to optical axis:
  - small “alpha” parameter against isotropic background



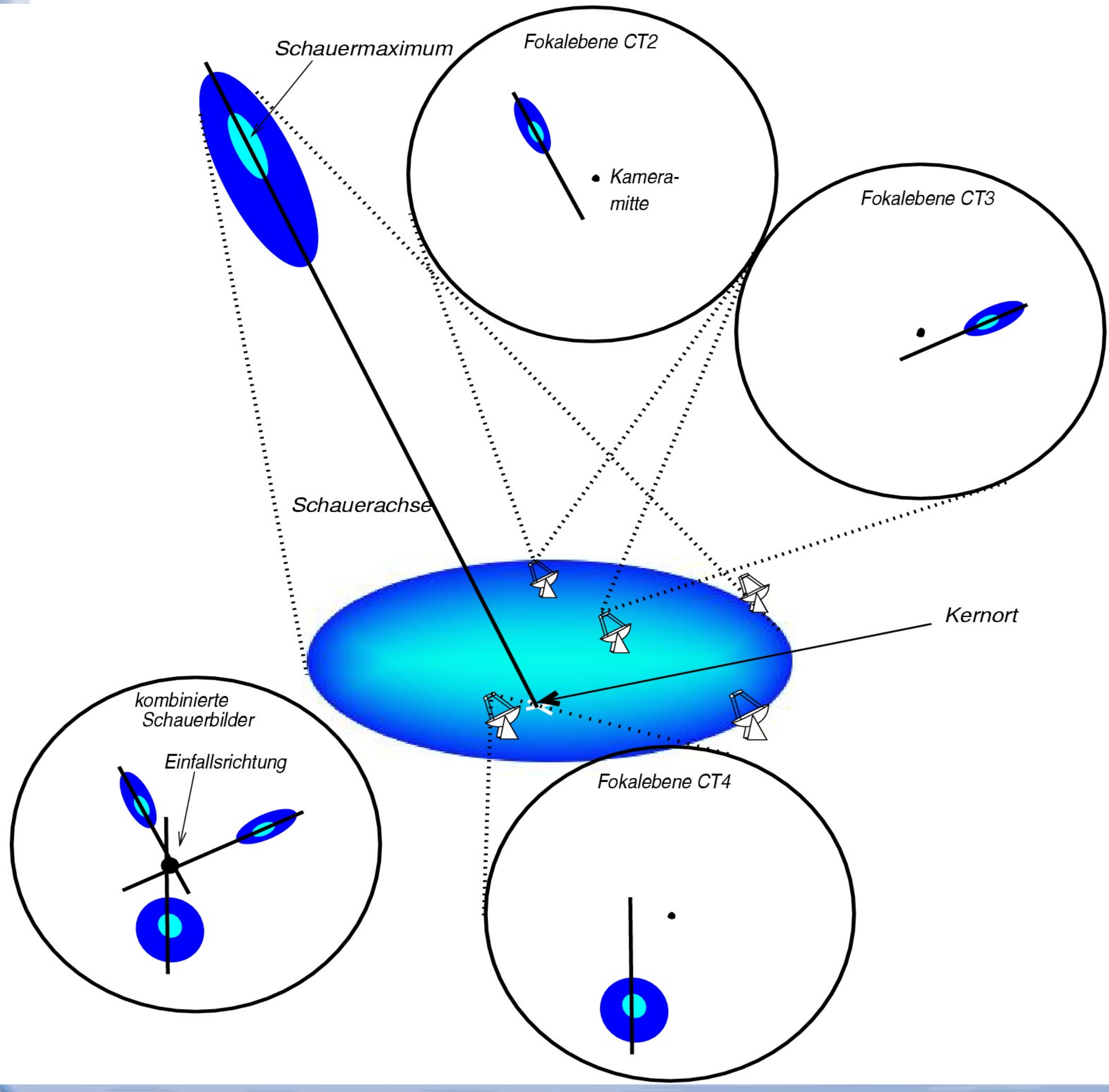



**2010 Perseid Meteor Shower and Sporadics**

AUG 13, 2010 • 09:20 - 10:40 UT • Naked Eye

Sketch by Jeremy Perez © 2010 • www.beltofvenus.net
Star field traced from Gnomonic Atlas Brno 2000.0 chart.

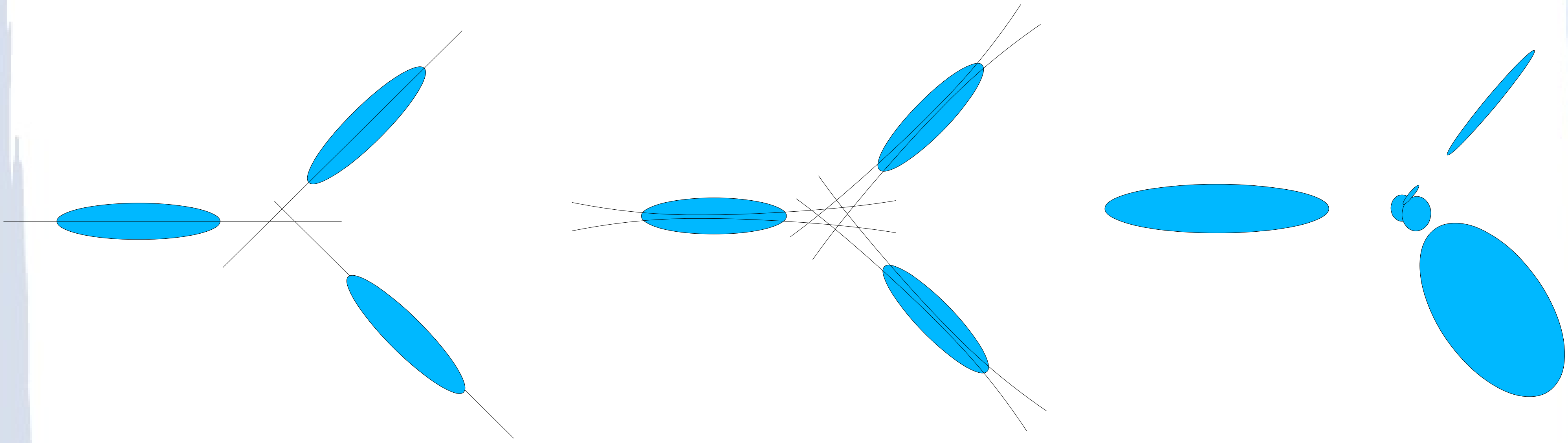
# Stereoscopic imaging: Multiple views of the same shower




Unique reconstruction of the shower geometry!

- Angular res. < 0.1°
- Core ~15 m
- Rel. Energy resol.: 15%
- $\kappa_\gamma$(Image)=0.5-0.9
- $\kappa_h$(Image)=0.01-0.05

# Directional reconstruction: 3 algorithms



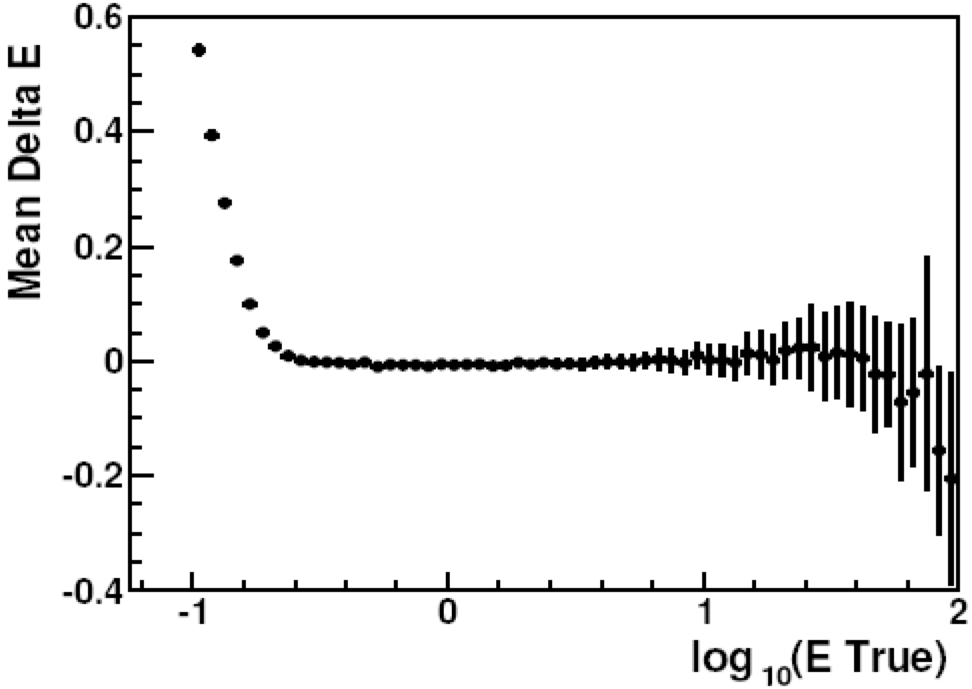
The same methods are used to reconstruct
the core position (just in different coordinates)

# Energy reconstruction: 2 approaches

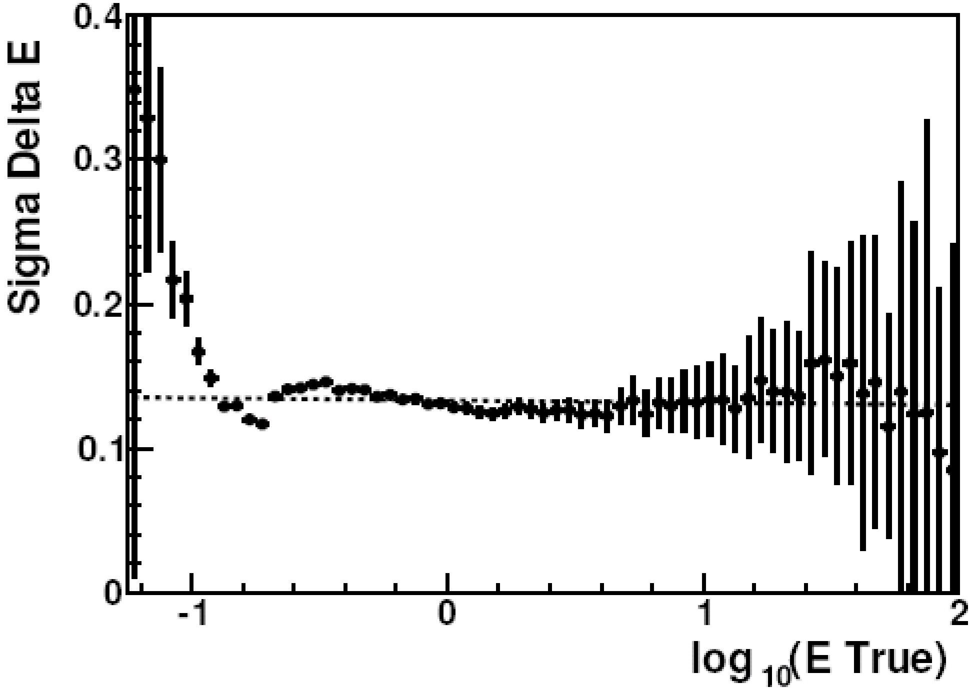
- Conventional approach (most often used):
  - Image amplitude = f(r,E)
  - For a measured amplitude and r->calculate E
- Improved approach
  - E=f(shower max, Image amplitude)
  - Best results: Keep position fixed (for known source), improves core position to ~3 m

# Energy reconstruction: Bias and resolution

Bias




Resolution

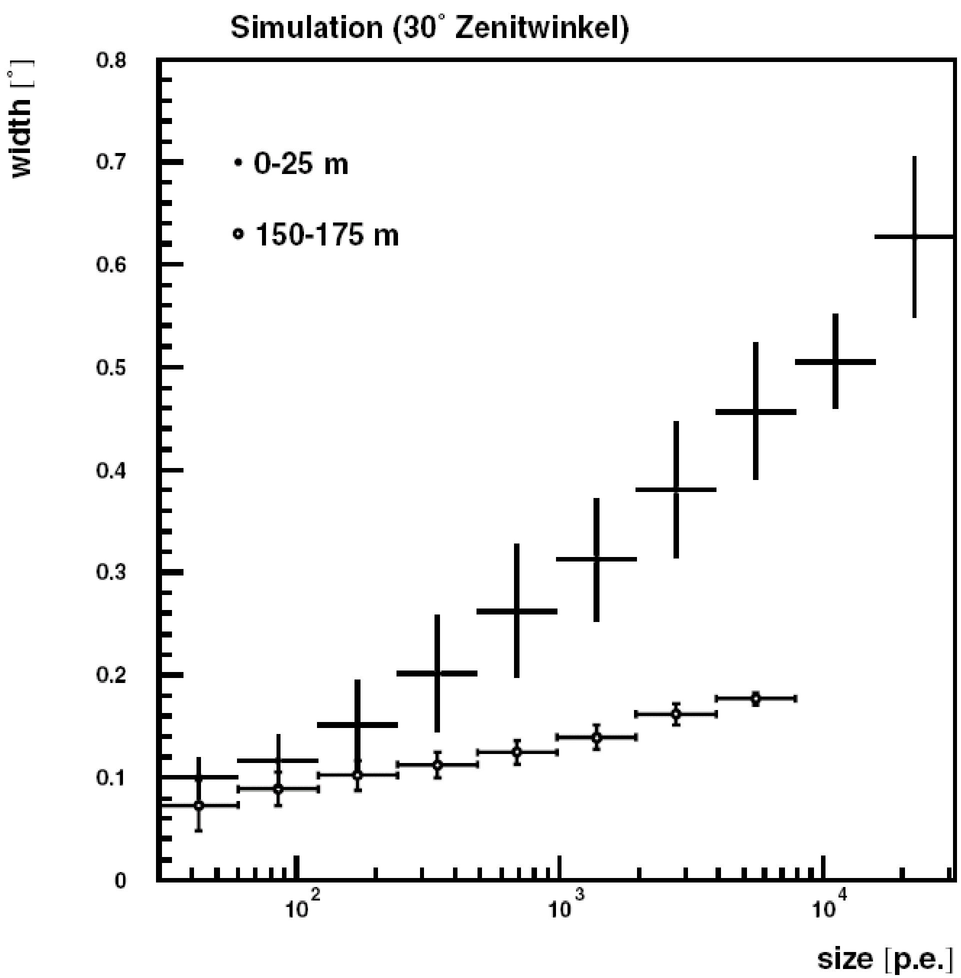


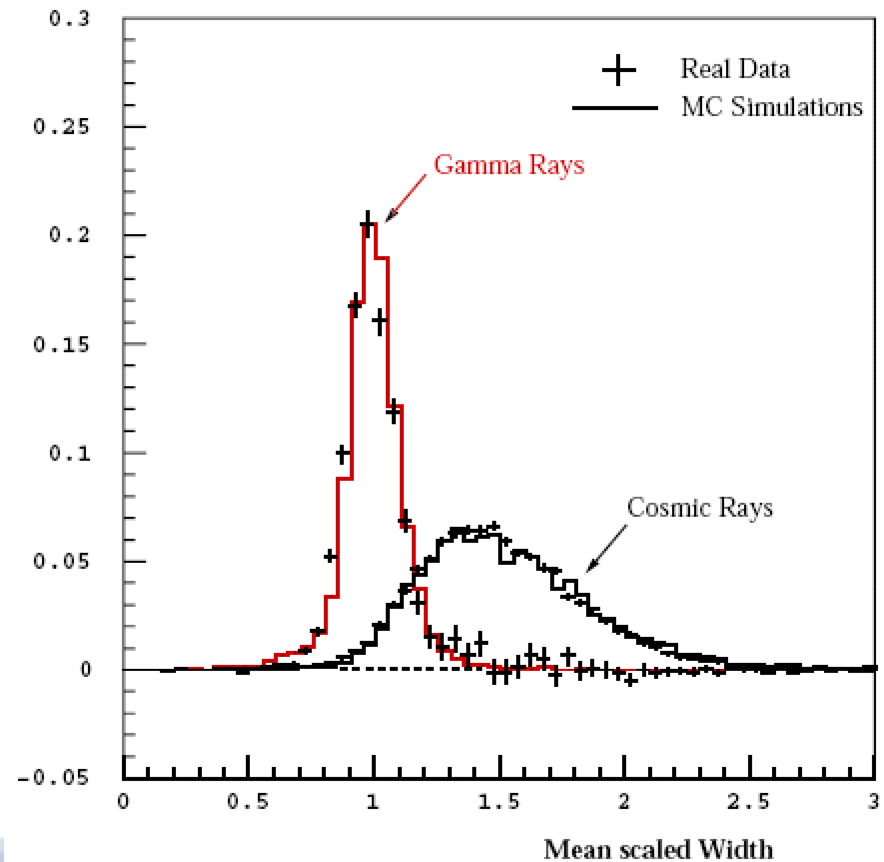

Benbow (2005)

# Example for scaling: Width

$$\langle width \rangle = f^{sim}(r, \theta, A)$$

$$mscw = \frac{1}{N} \sum_{i=1}^{N} \frac{width_i(r_i, \theta, A_i)}{\langle width \rangle_i}$$




DH, PhD thesis (2000)

# Event selection

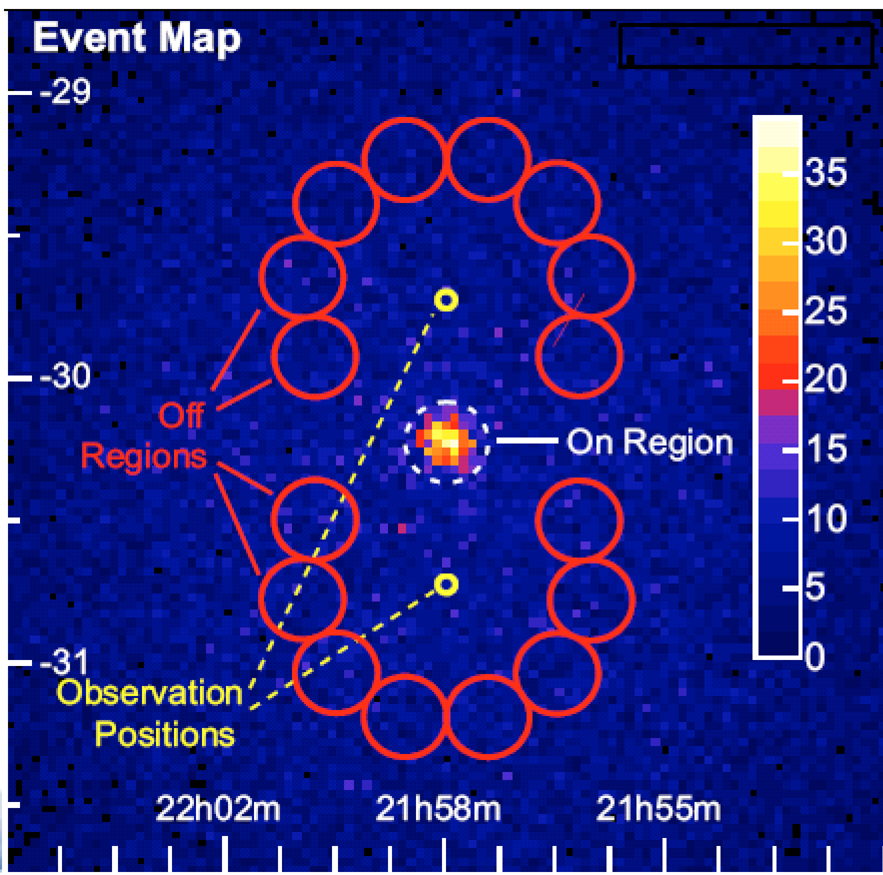
Event selection for Gamma-rays: small width & length, direction

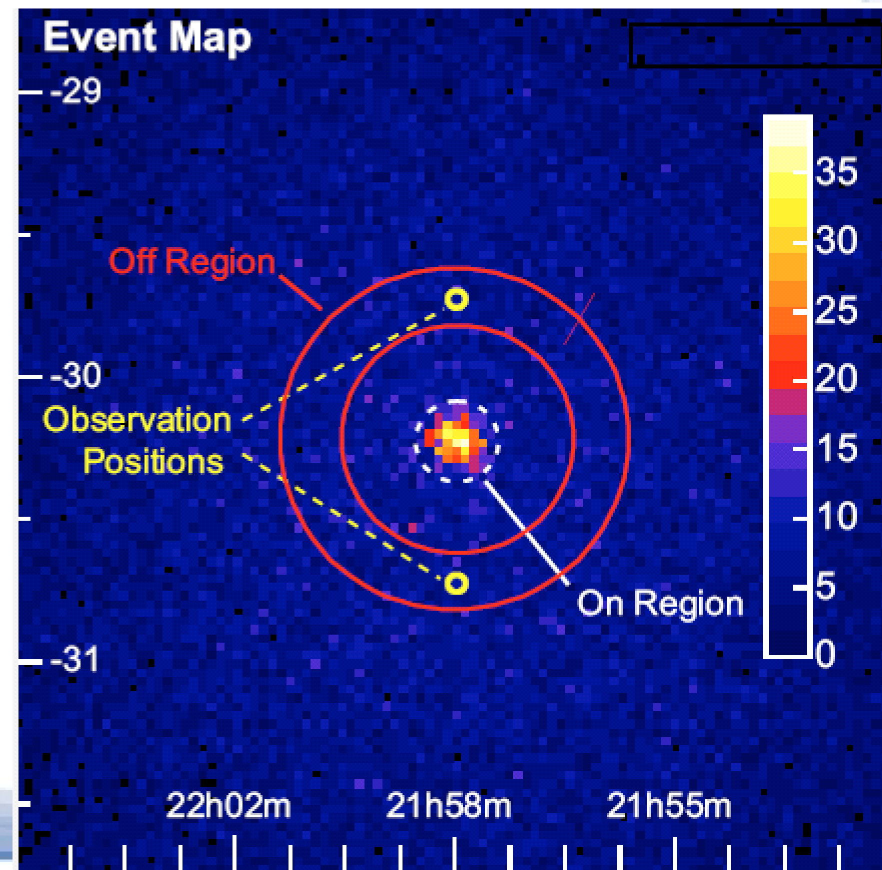
- Optimization of cuts for extended (Galactic) or point-like (extra-gal.) sources
- Optimization for sources with hard (e.g. Galactic) or soft (extra-gal.) spectra
- Optimization for spectral studies
- Optimization for (blind) source searches
- Optimization for timing studies (e.g. pulsars)
- ....

Optimization is a science on its own...
Faint (discovery) sources S/B~0.1-0.3

# Crucial: Background estimate

- Methods using separation in angle
  - Dedicated Off-data (same declination, shifted r.a.)
  - “Wobble” or “Nodding” background (Reflected background)
  - Ring background

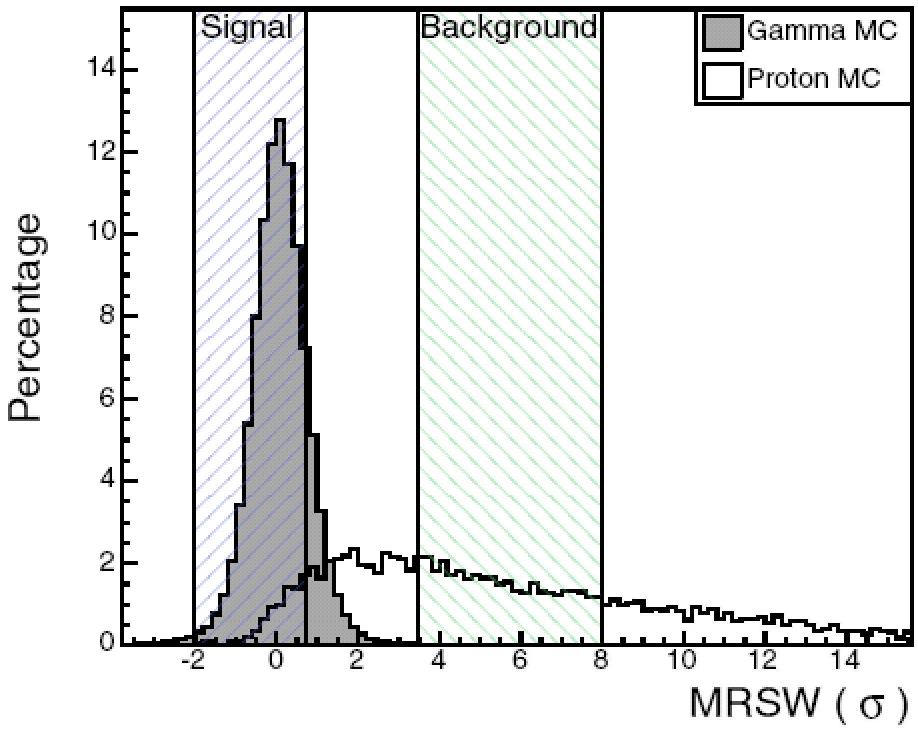


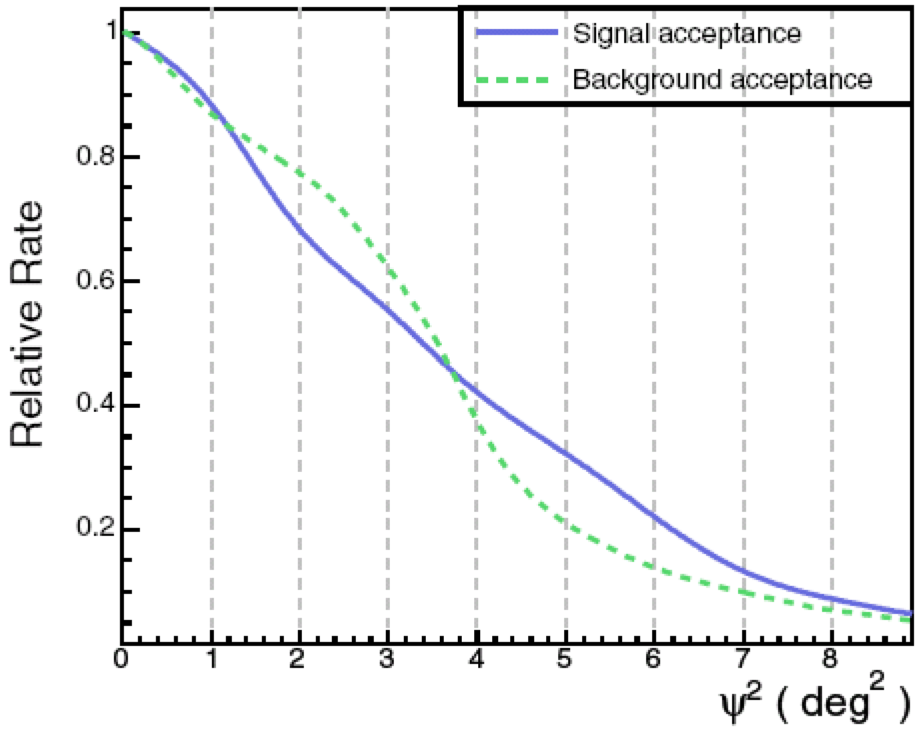




Berge et al. (2007)

# "Template" Background

Rowell (2003)




Define ON & OFF
Correct radial acceptance of OFF to match ON
Correct Zenith angle gradient
->OFF map with identical acceptance to ON map

# Comment on background estimate

- Future instruments: Lower threshold
- Signal ~ $E^{-a}$ mit a~2
- Background ~ $E^{-b}$ mit b=2.7
- $S/B \sim E^{b-a} = E^{-0.7}$
- Systematic uncertainties on Background will limit sensitivity (already with HESS II)

# Imaging analysis

- Sky excess maps (DC)
  - In coordinates of Ra, Dec or l,b
  - Fill an ON-map (sliding window)
  - Fill an OFF-map (sliding window)
  - ExcessMap=ON-OFF
  - SignificanceMap: S(ON,OFF,alpha)
- Sky variability maps
  - Calculate Kolmogorov prob. Between ON and OFF
  - Calculate exp-test prob. Between ON and OFF

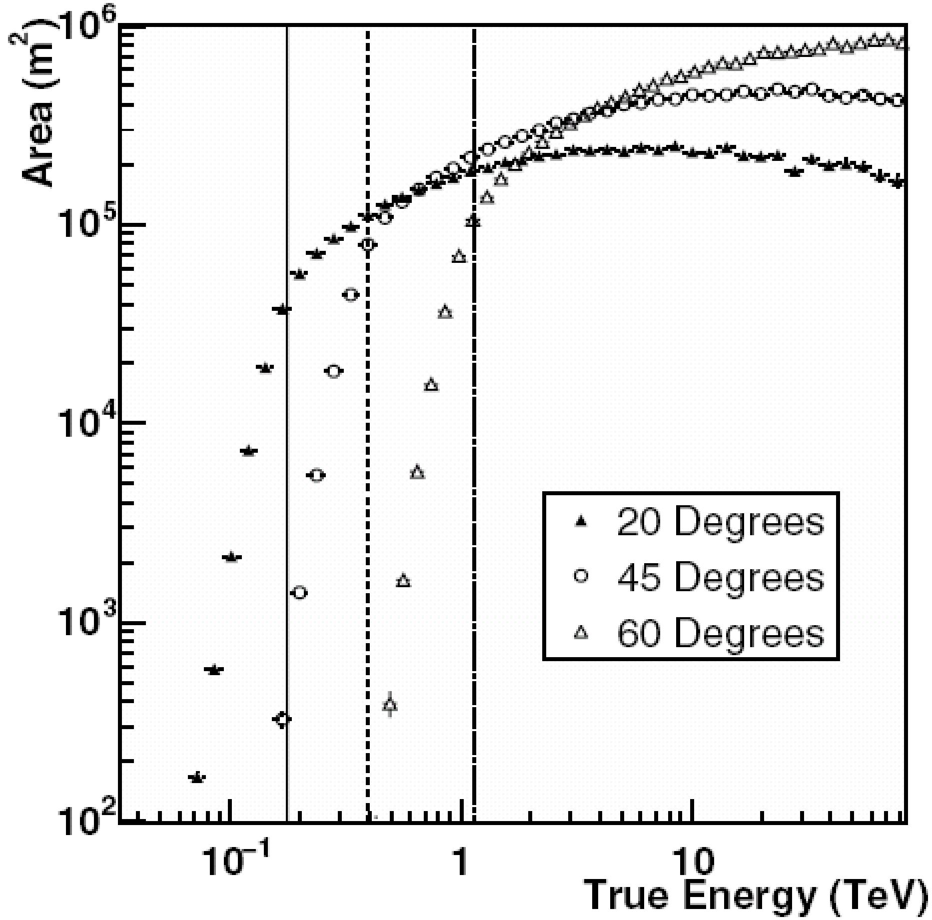
# Spectral analysis

- Observed differential rate:

$$R(E_{rec}) = \int A(E')\,N(E')\,G(E_{rec}, E')\,dE'$$

- Inverse problem: Reconstruct the initial spectrum N
  - Forward folding: Assuming N → compare with obs.
  - Unfolding method: Get rid of "oscillation" terms
- If $G(E_{rec},E)$ is "well-behaved" (little dependence on E, "narrow" response in comparison to spectral features
  - Direct reconstruction of N(E)

# Effective area



# 3. Limits of the imaging air shower technique

- Limit on the energy threshold: ~5 GeV (Pair-production and Cherenkov light production)
- Resolution on reconstructed parameters:
  - $\Delta E/E \sim 5\%$: sampling of the light pool
  - Direction: $\Delta\theta \sim$ arcmin (Geomagnetic deflection of pairs)
- Limit at the upper end of the energy: ~10 TeV (Photon statistics → remedy: collection area ~ 10-100 $km^2$)
- Sensitivity at E<100 GeV: Electrons and systematic uncertainty on the background
- Sensitivity at E>10 TeV: Photon starvation

# Overview on sensitivity