Cherenkov Telescopes for Gamma-Ray Astrophysics

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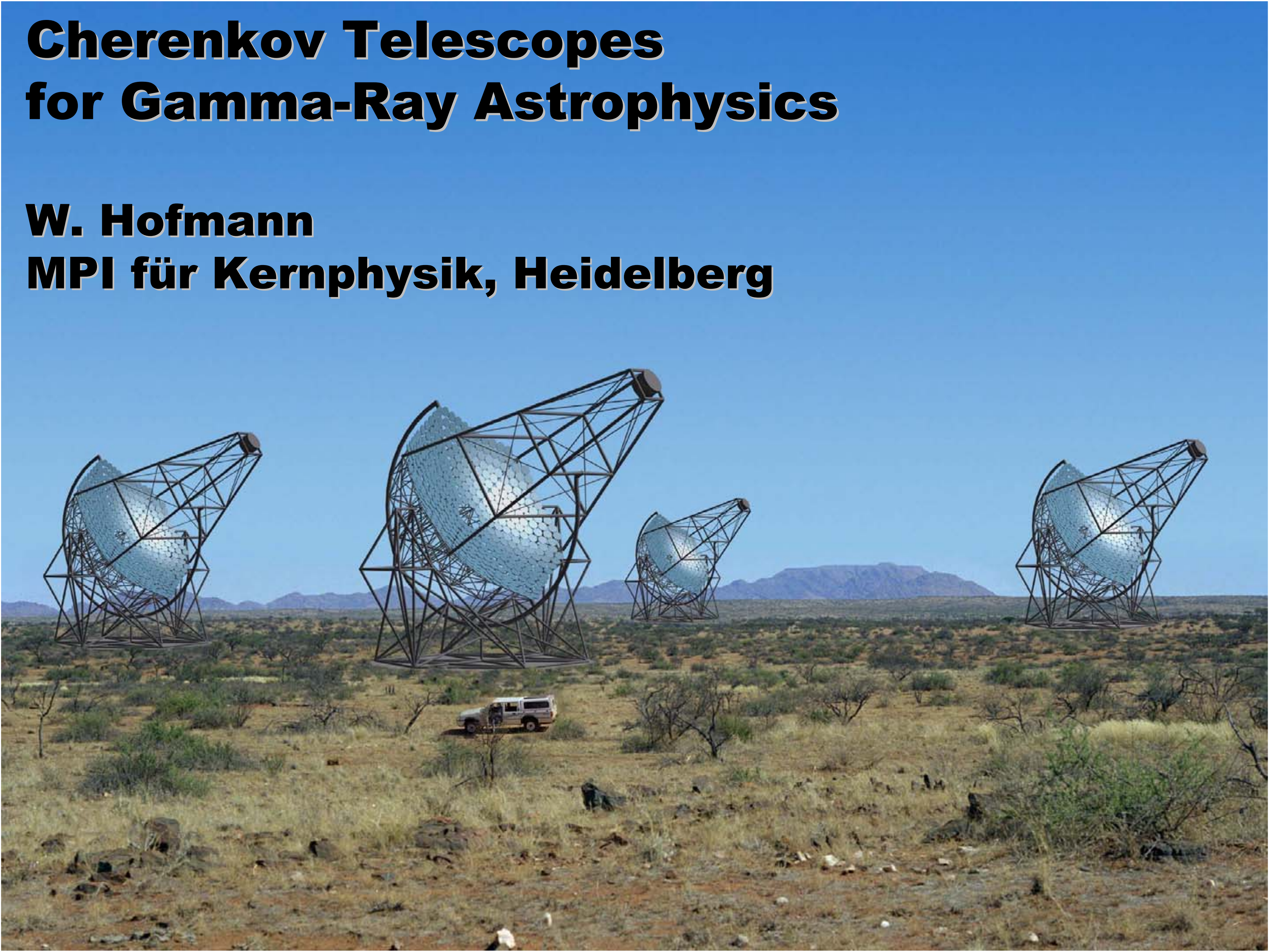
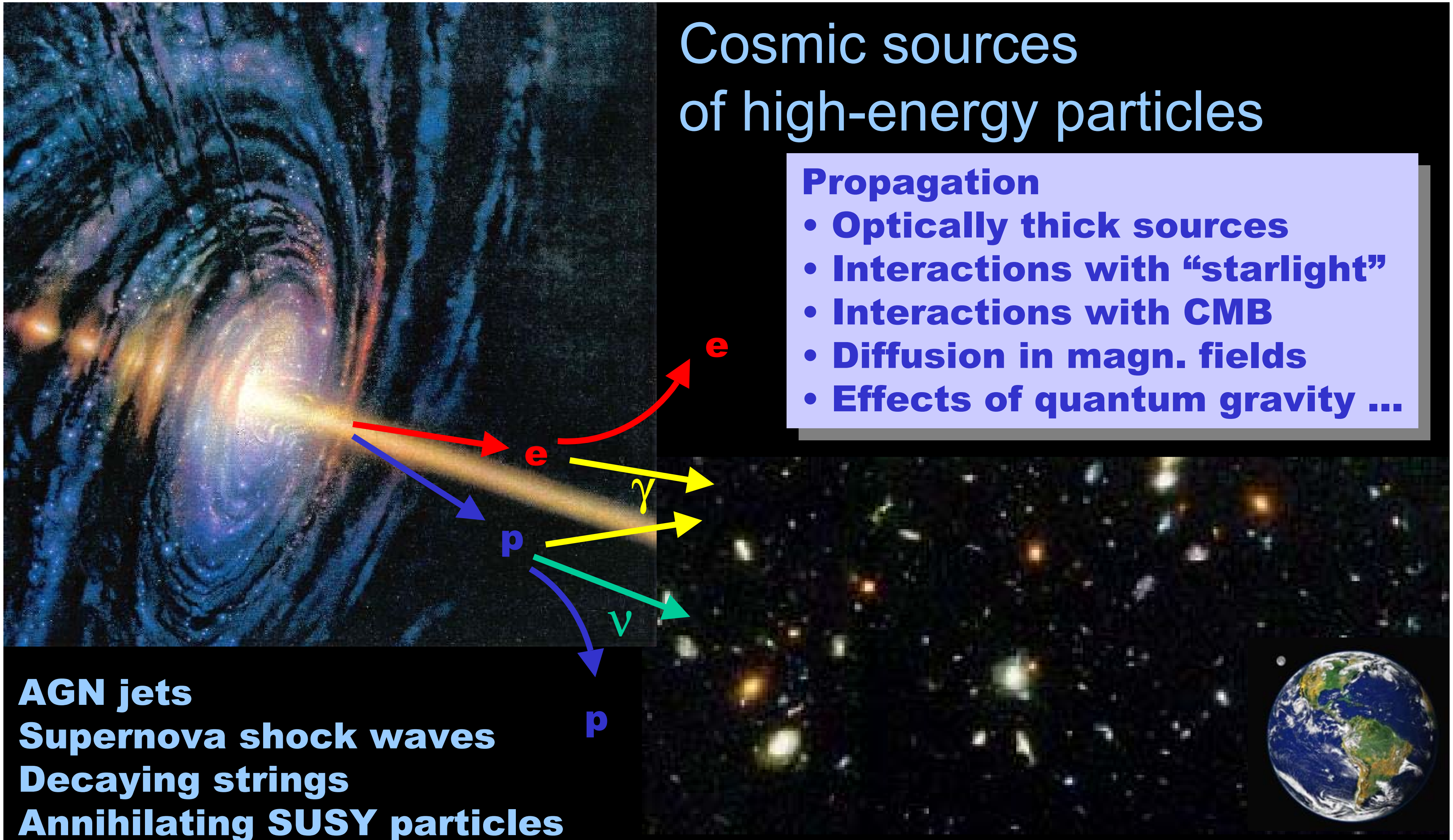


Cosmic sources of high-energy particles



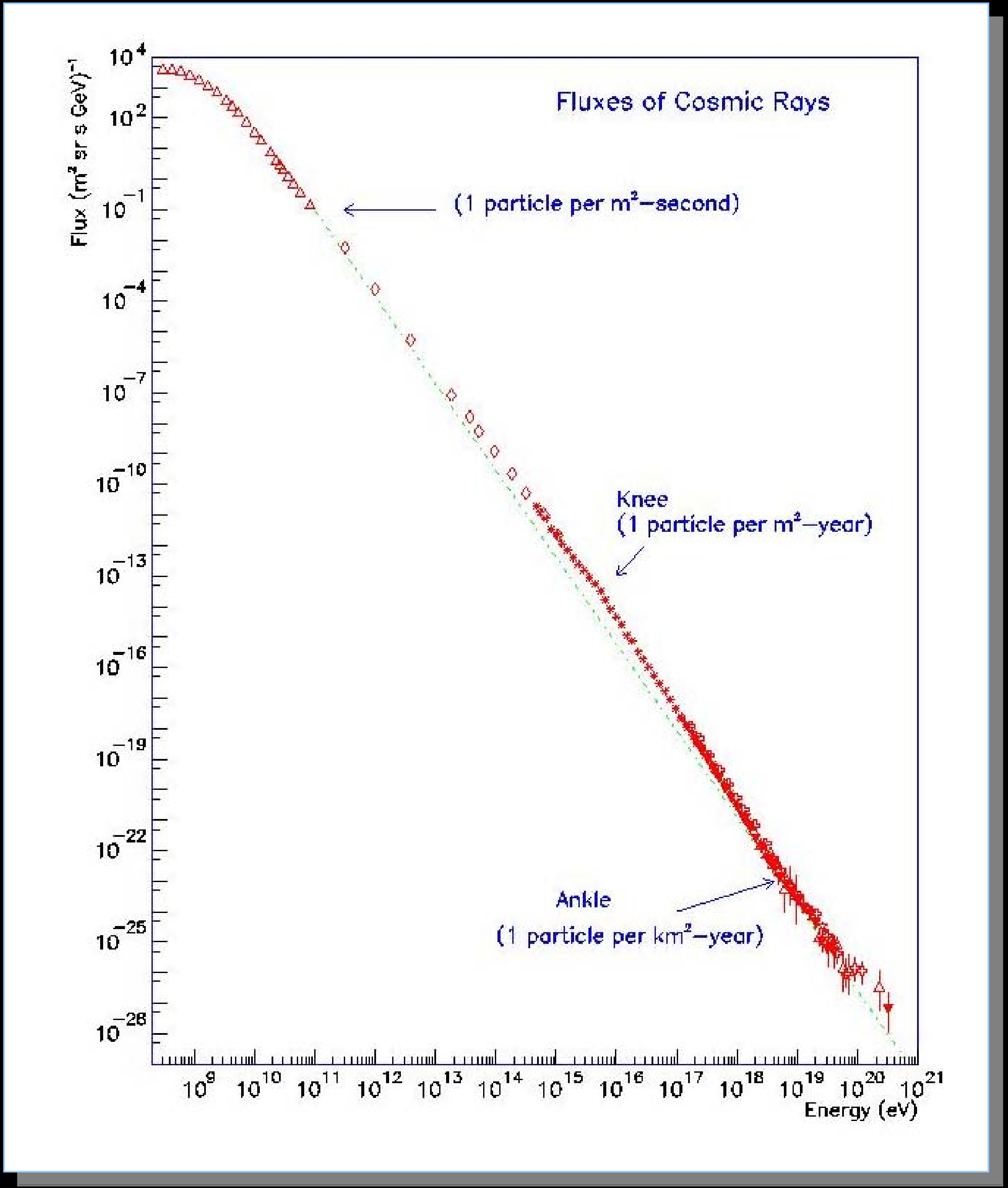
Propagation
- **Optically thick sources**
- **Interactions with "starlight"**
- **Interactions with CMB**
- **Diffusion in magn. fields**
- **Effects of quantum gravity ...**

AGN jets
Supernova shock waves
Decaying strings
Annihilating SUSY particles
...

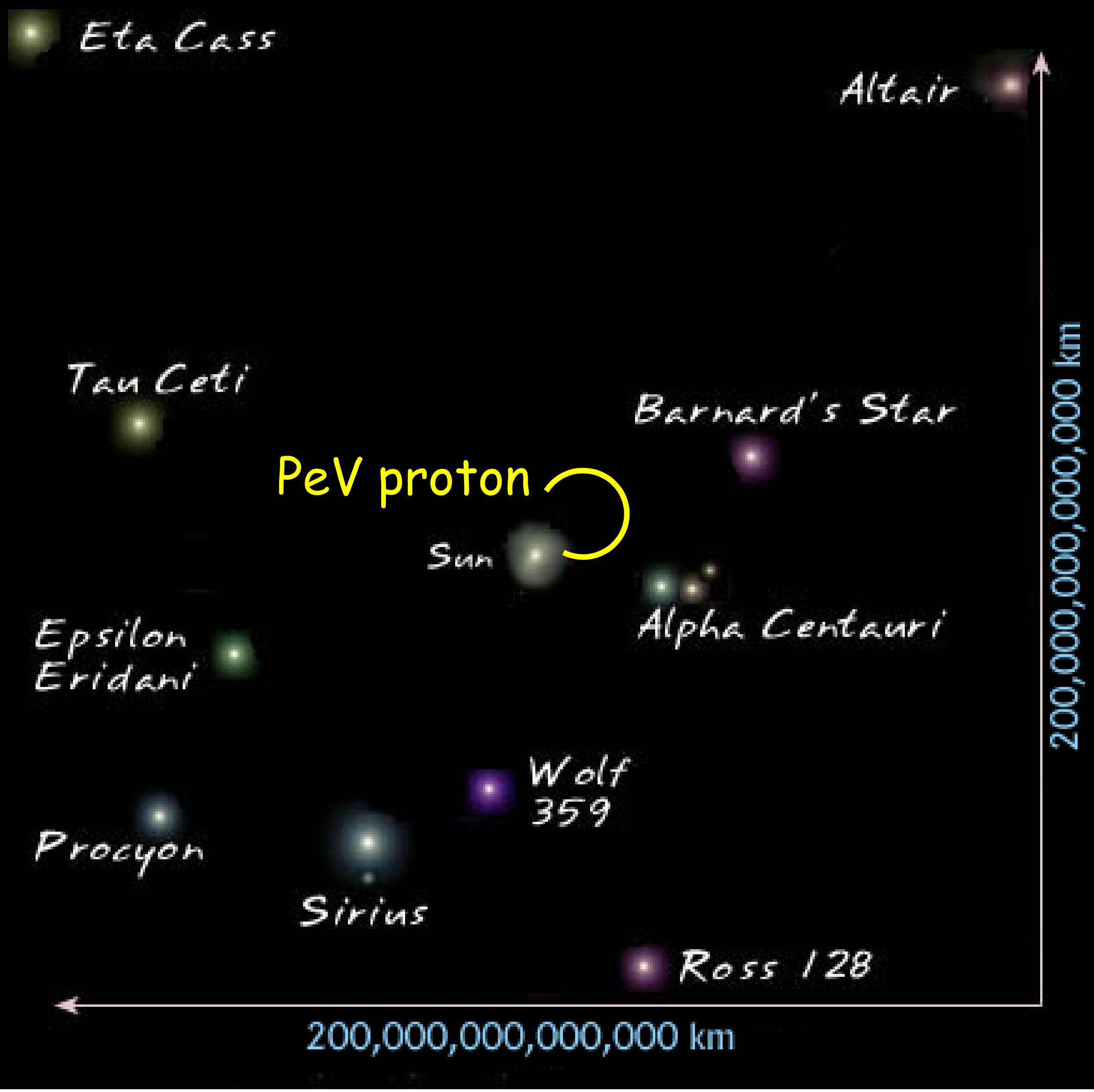
Identify mechanisms using
- **Particle composition**
- **Wide-band energy spectra**
- **Spatial and temporal characteristics**

Cosmic Rays:

messengers of the nonthermal Universe

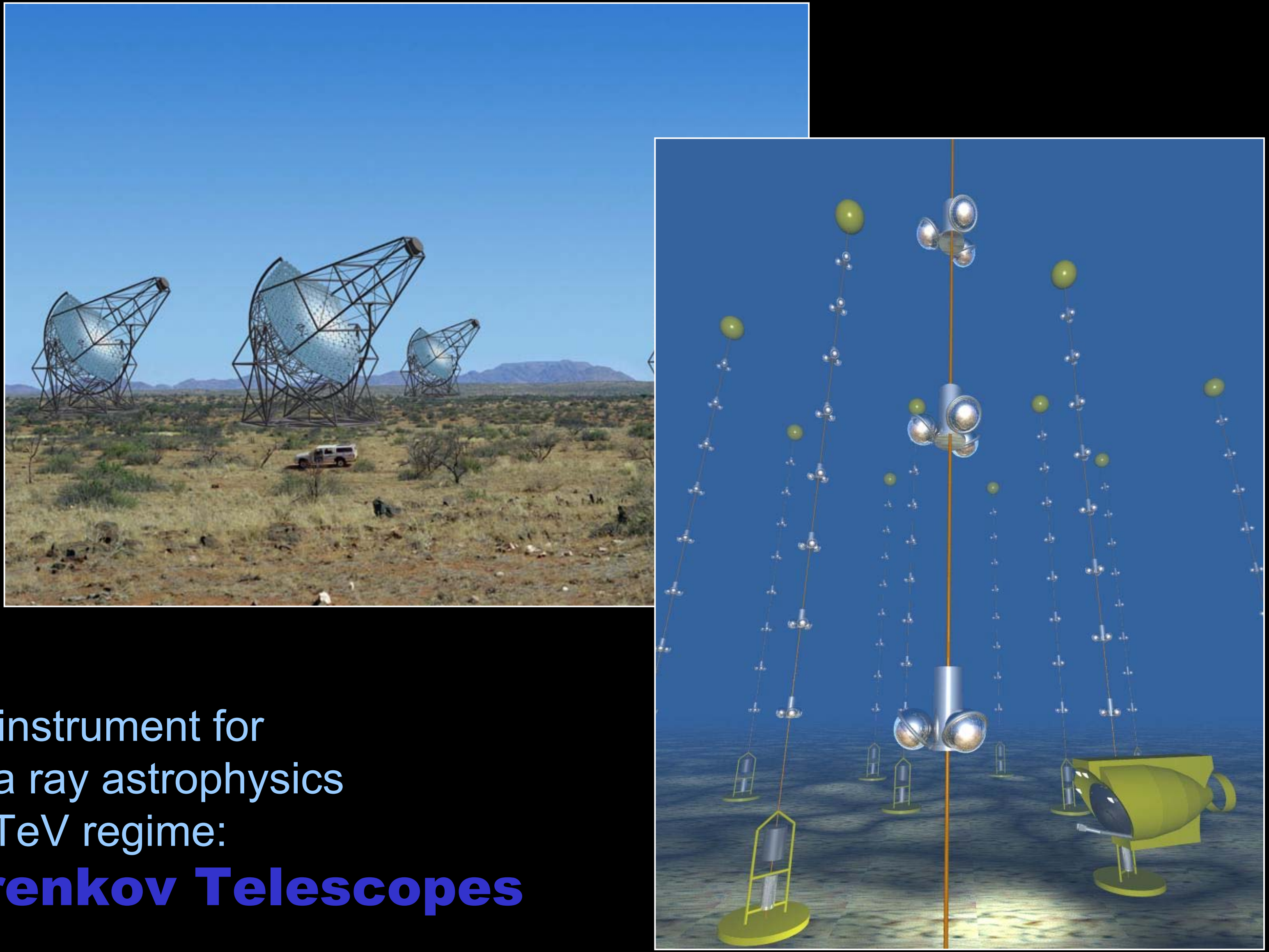


however, cosmic rays cannot be used to image the Universe...



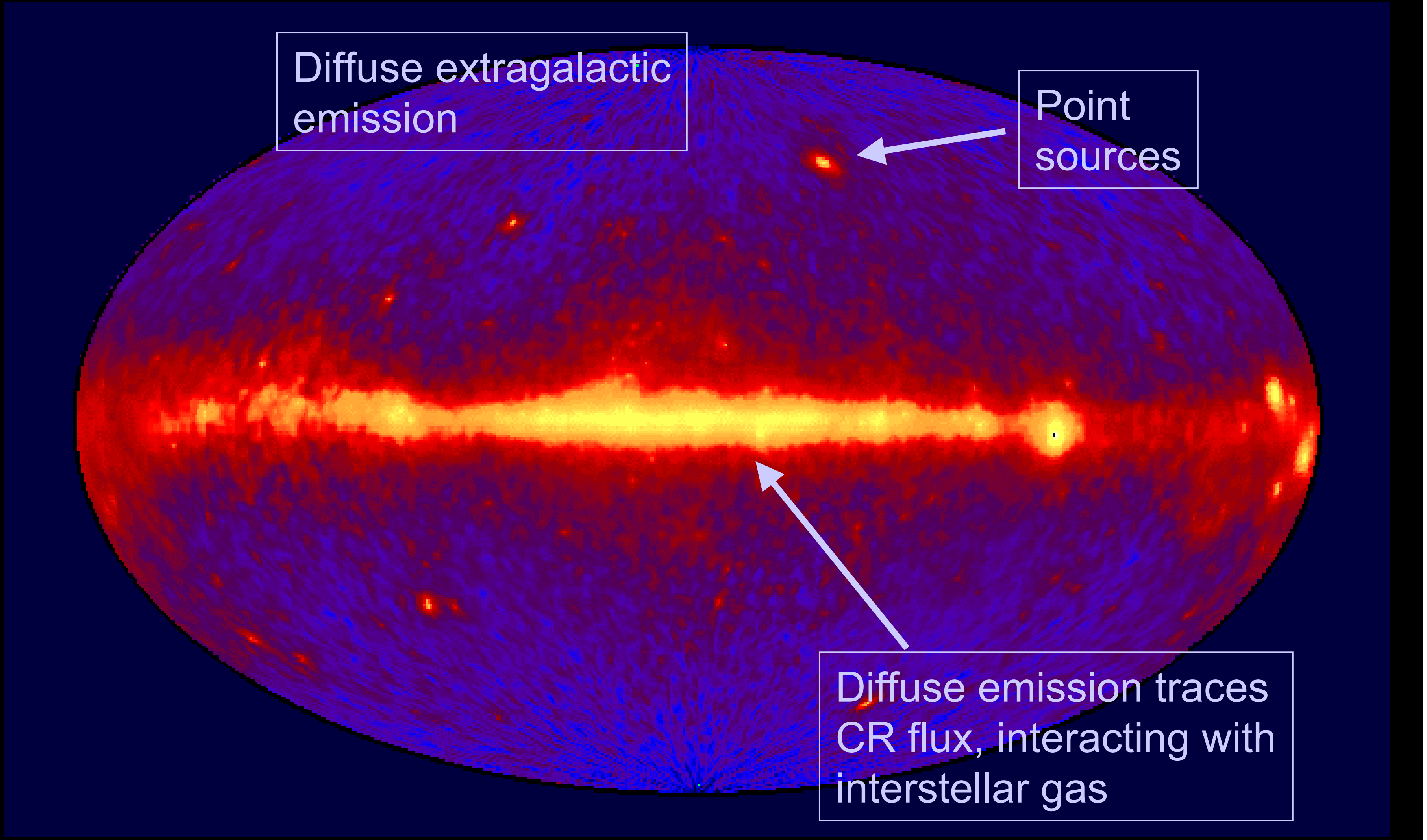
M. Masetti

➡ use gamma rays (or neutrinos)



Prime instrument for
gamma ray astrophysics
in the TeV regime:
Cherenkov Telescopes

Example: the 100 MeV Region of EGRET



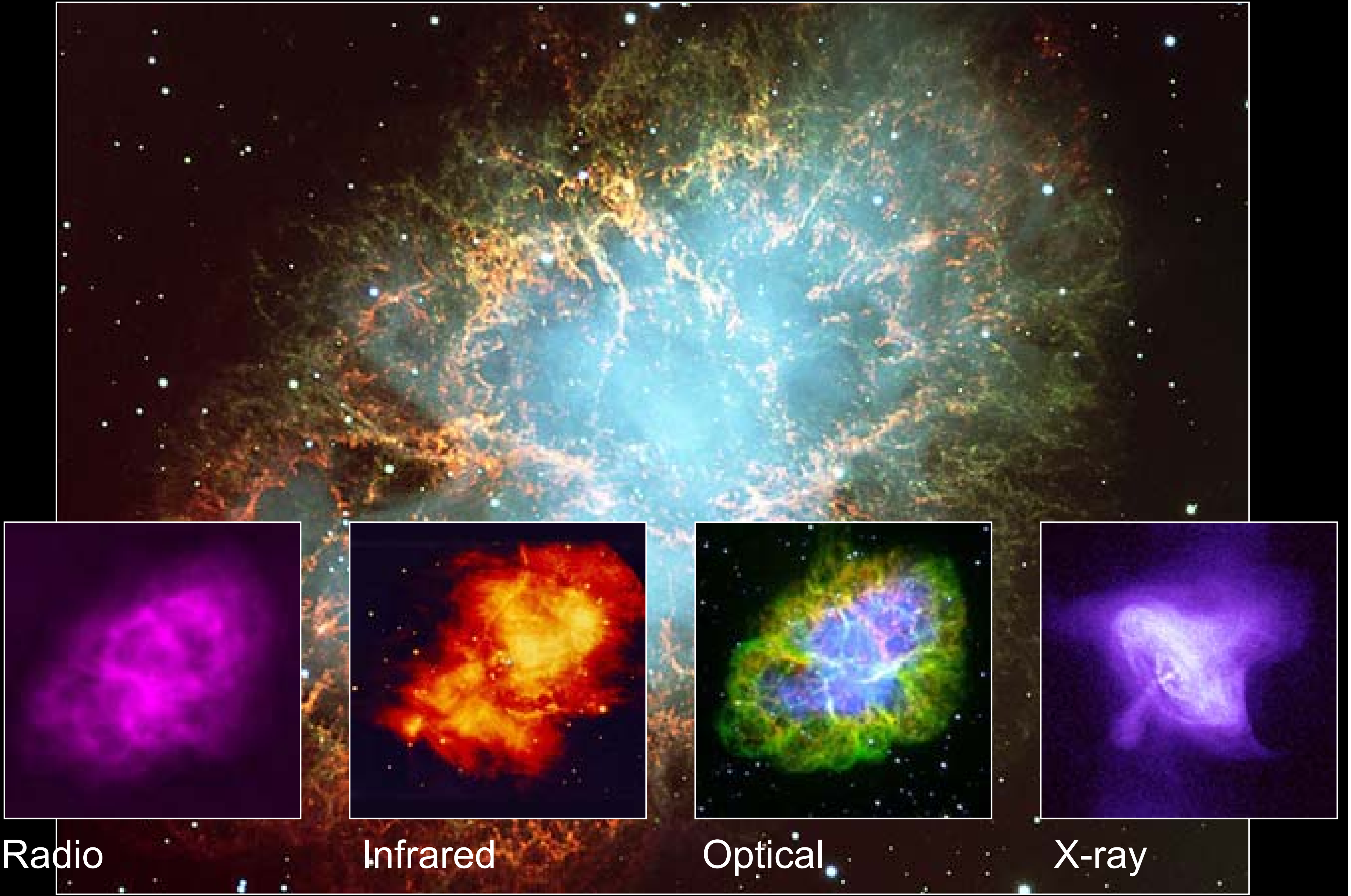
Diffuse extragalactic emission

Point sources

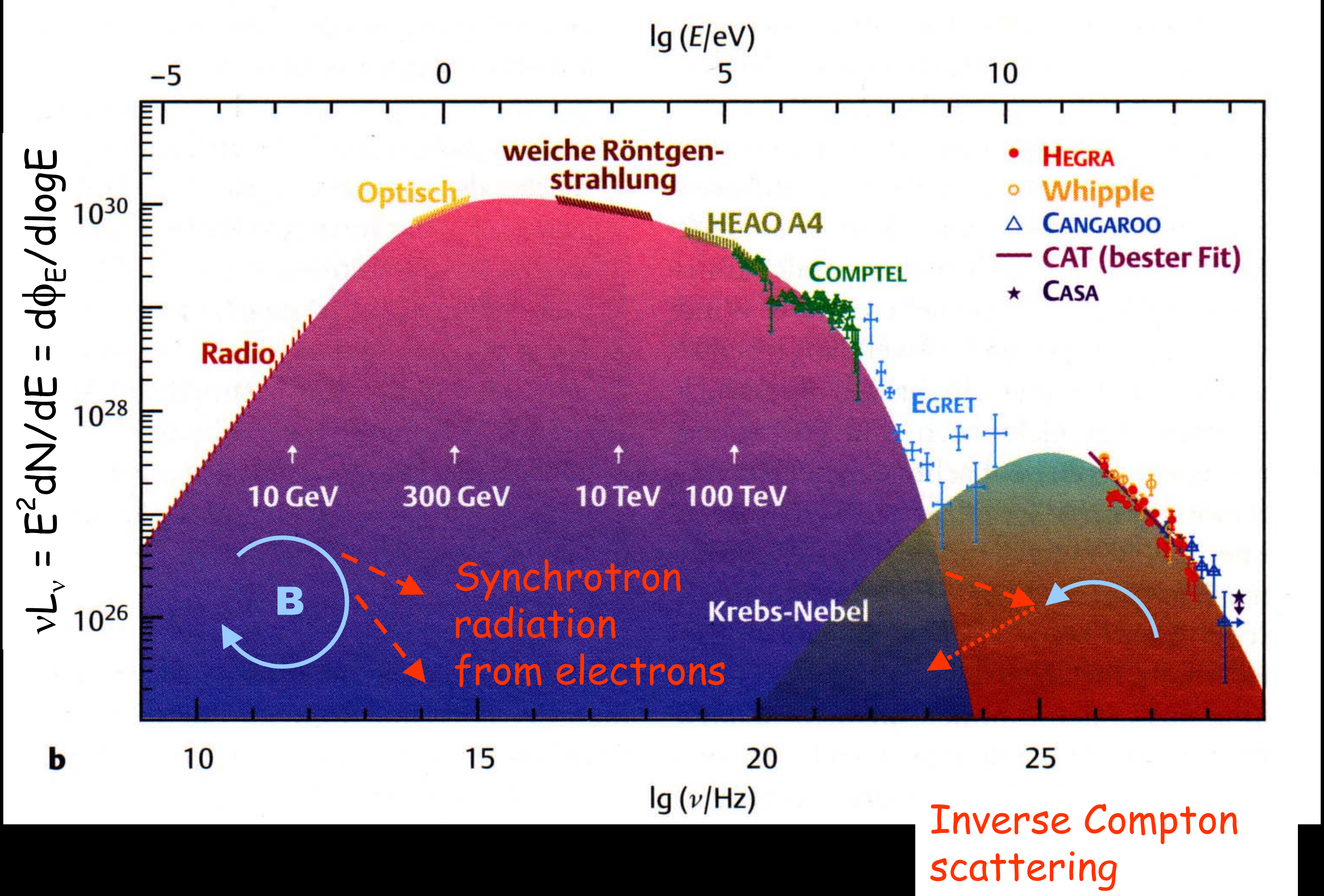
Diffuse emission traces CR flux, interacting with interstellar gas

… would like to see the same image for VHE gamma rays and neutrinos …

Emission mechanisms: the Crab tutorial



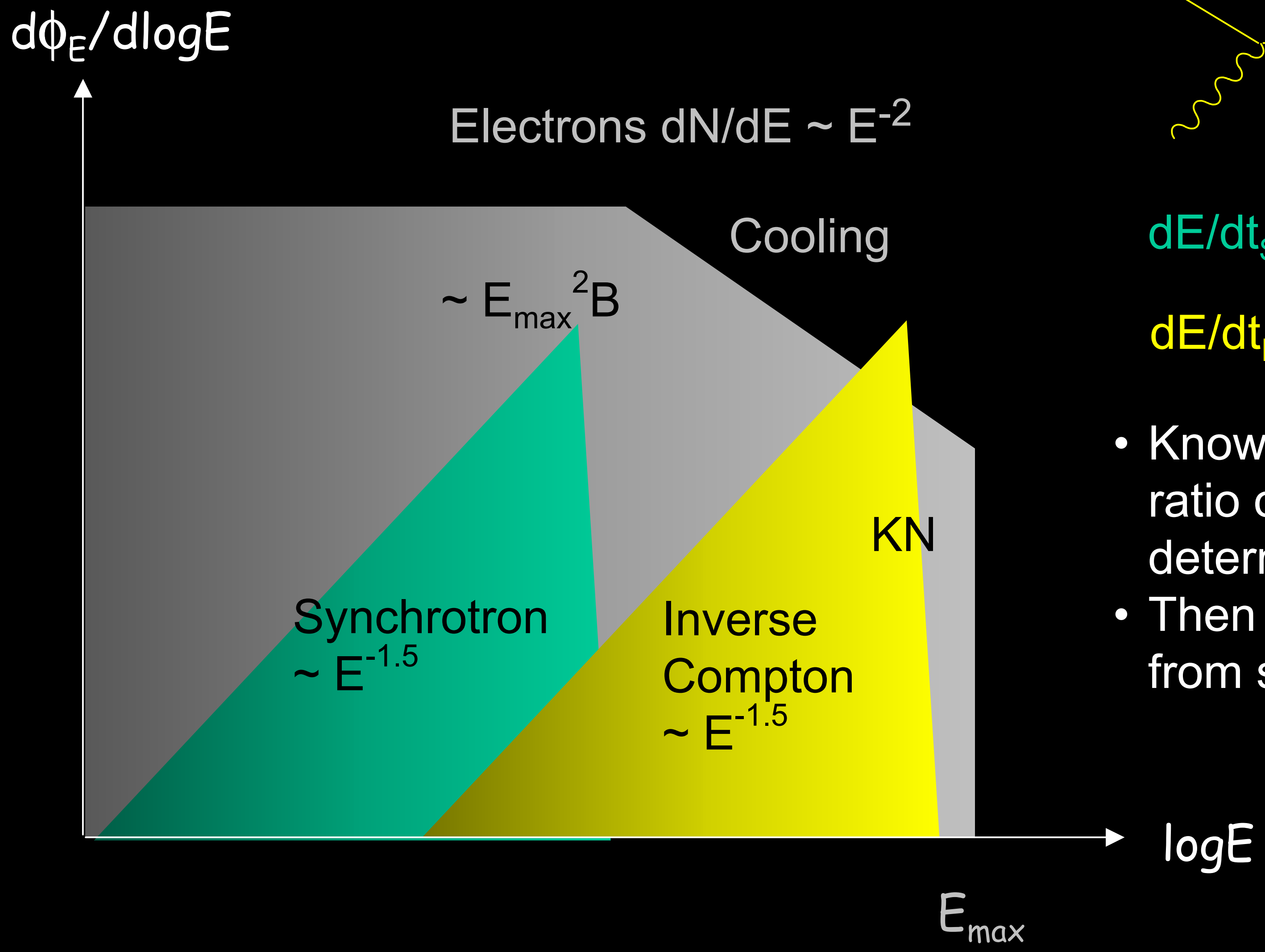
The Crab: gammas from electrons

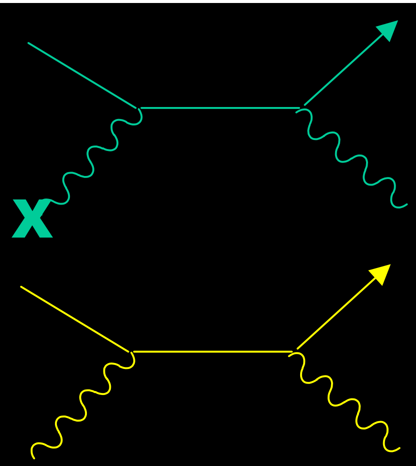


Synchrotron radiation from electrons

Inverse Compton scattering

Spectra



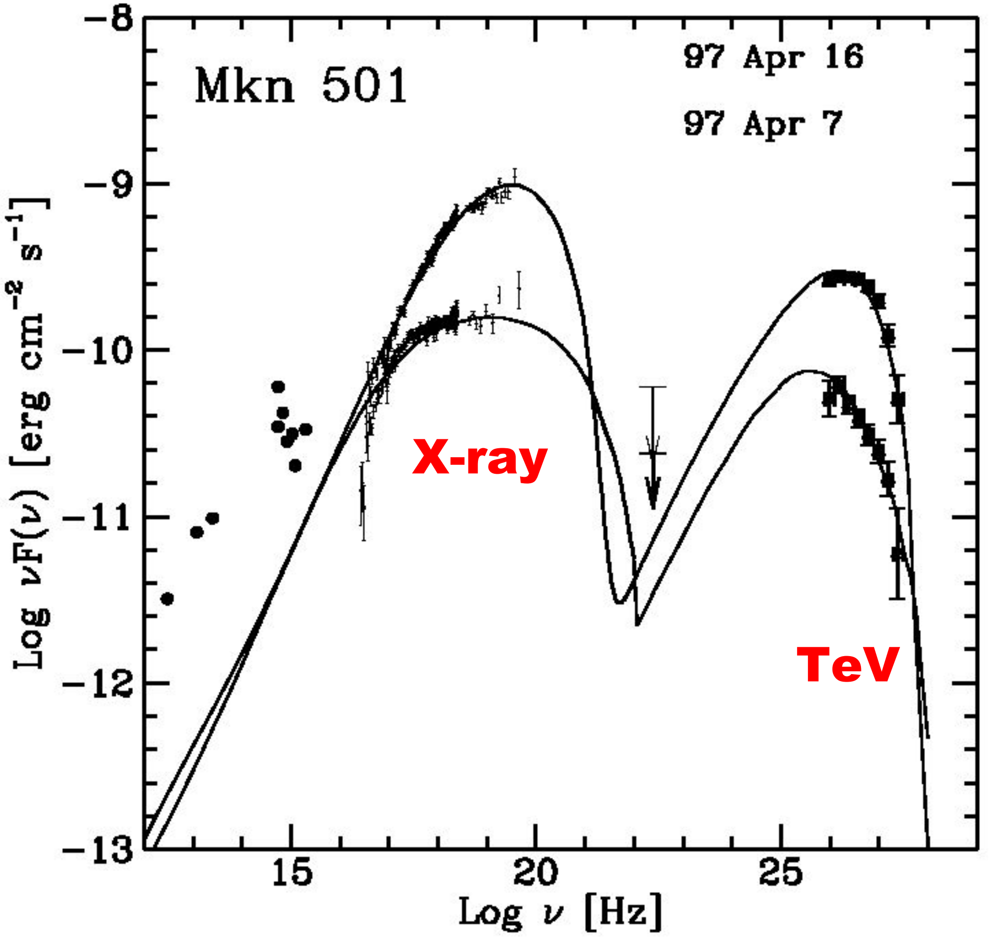


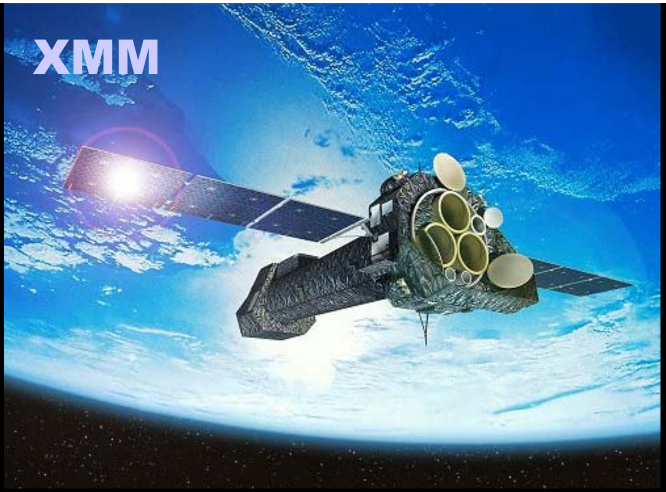
$dE/dt_{Sy} = k\gamma^2 U_{mag}$

$dE/dt_{IC} = k\gamma^2 U_{rad}$

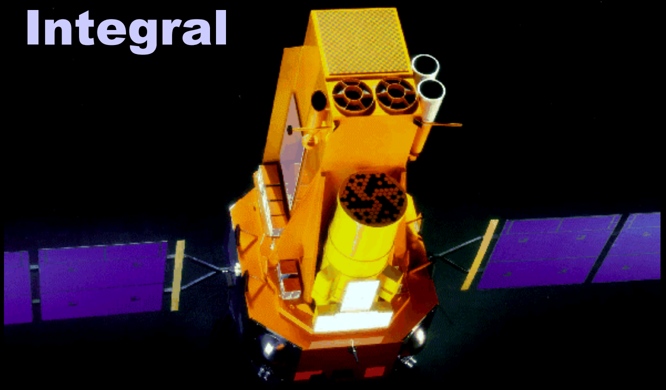
- Knowing U_{rad}, use ratio of peaks to determine $U_{mag} \sim B^2$
- Then determine E_{max} from synchr. peak

Important:
multiwavelength studies

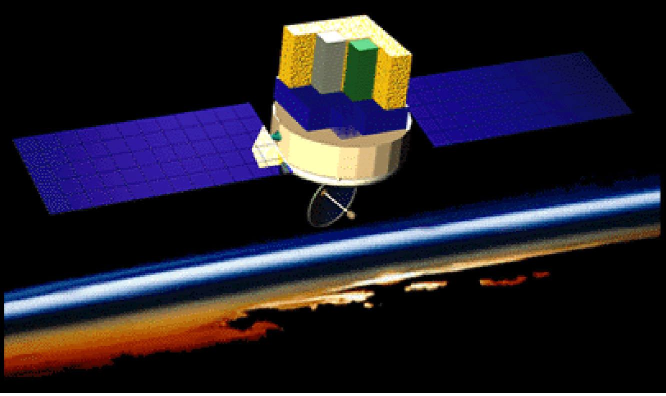




XMM



Integral



GLAST

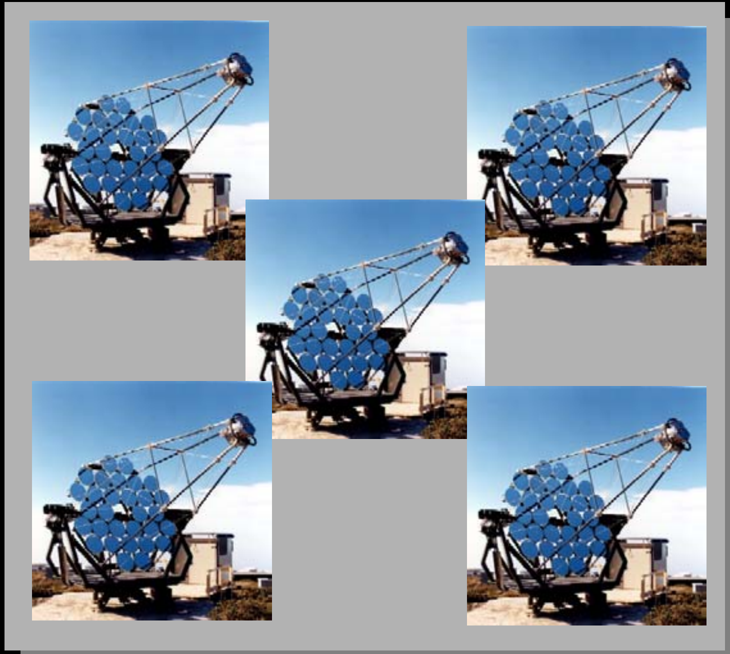
Cherenkov Telescopes
- Basics -

Imaging atmospheric Cherenkov telescopes

Pioneered by the
WHIPPLE group

Perfectioned in
CAT telescope

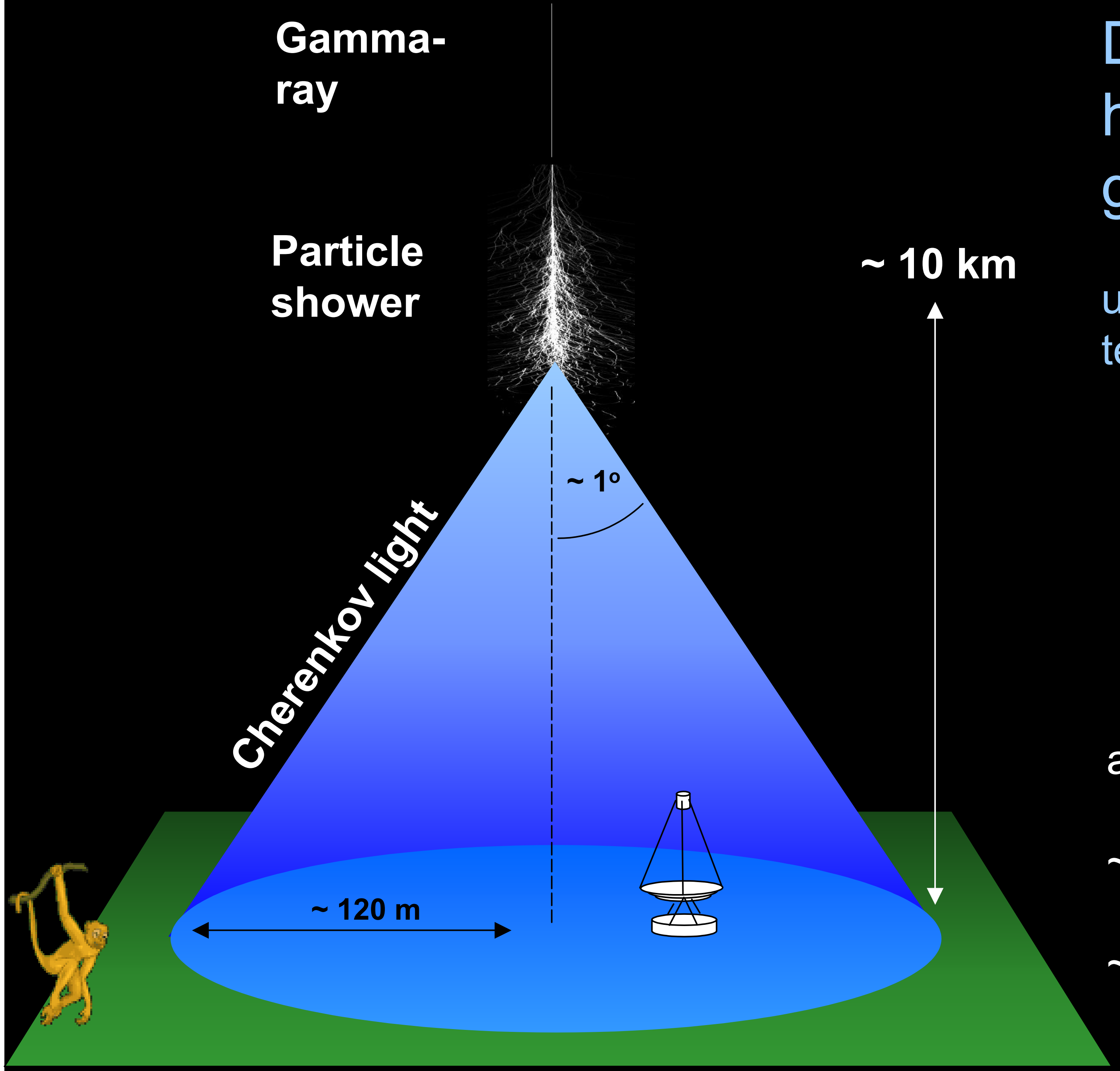
Stereoscopy
with HEGRA



WHIPPLE
490 PMT
camera

Detection of high-energy gamma rays

using Cherenkov telescopes



at 1 TeV

~ 100 photons/m^2
(300 – 600 nm)
~ 10 – 20 photoel./ m^2

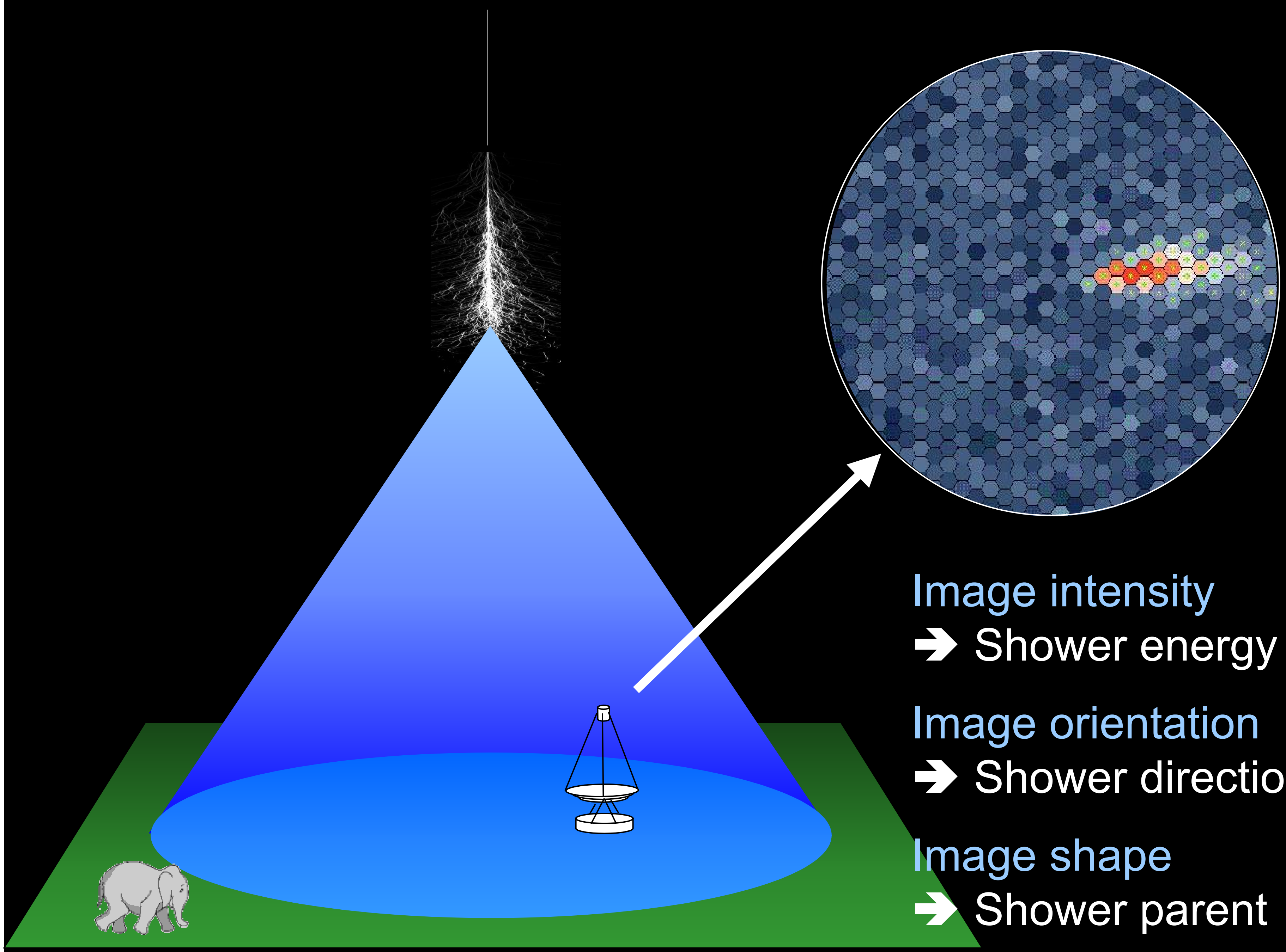
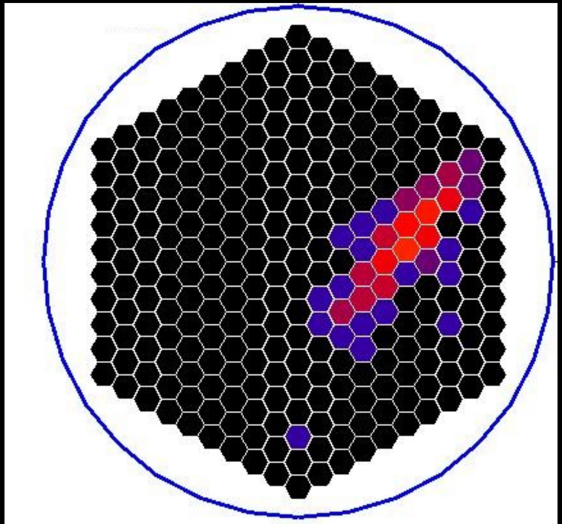


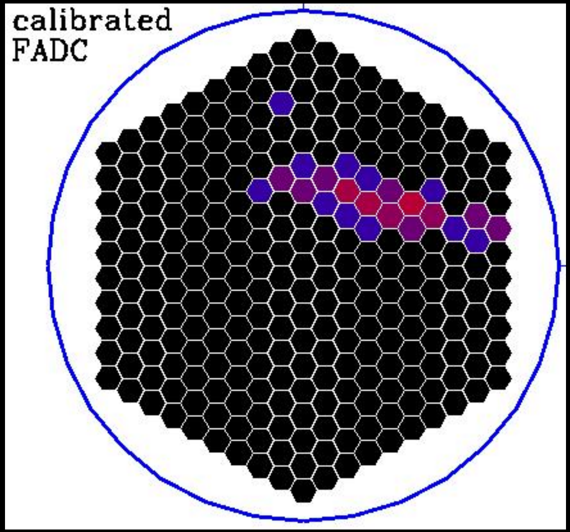
Image intensity
➔ Shower energy

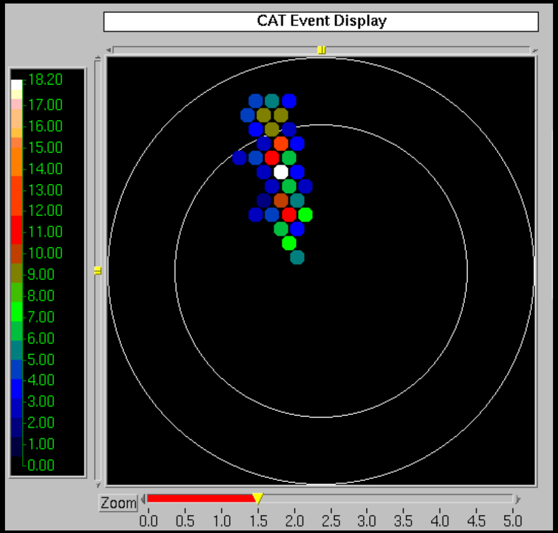
Image orientation
➔ Shower direction

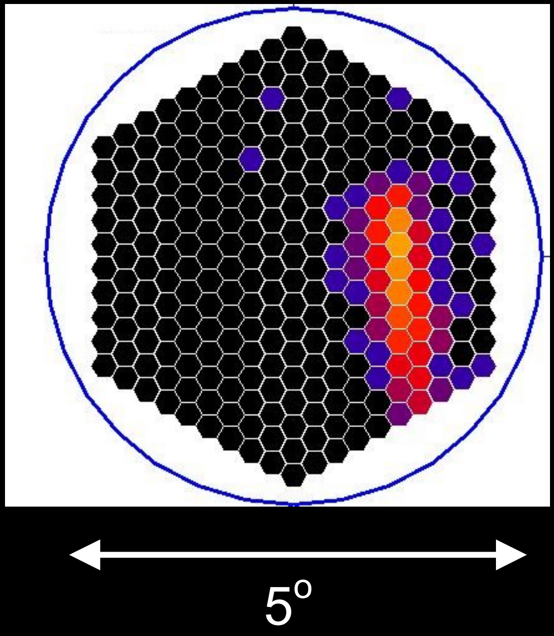
Image shape
➔ Shower parent

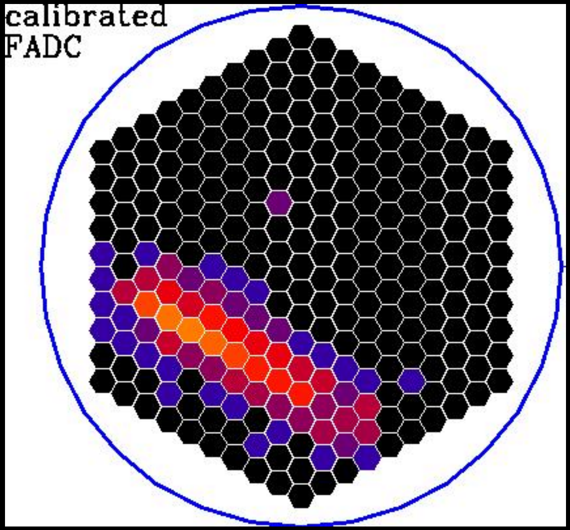
Image gallery

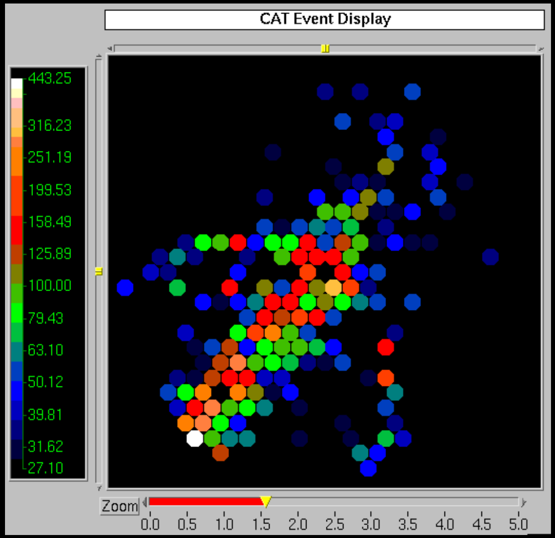












Air showers are
a bit like meteors

Systems of Cherenkov telescopes and stereoscopy

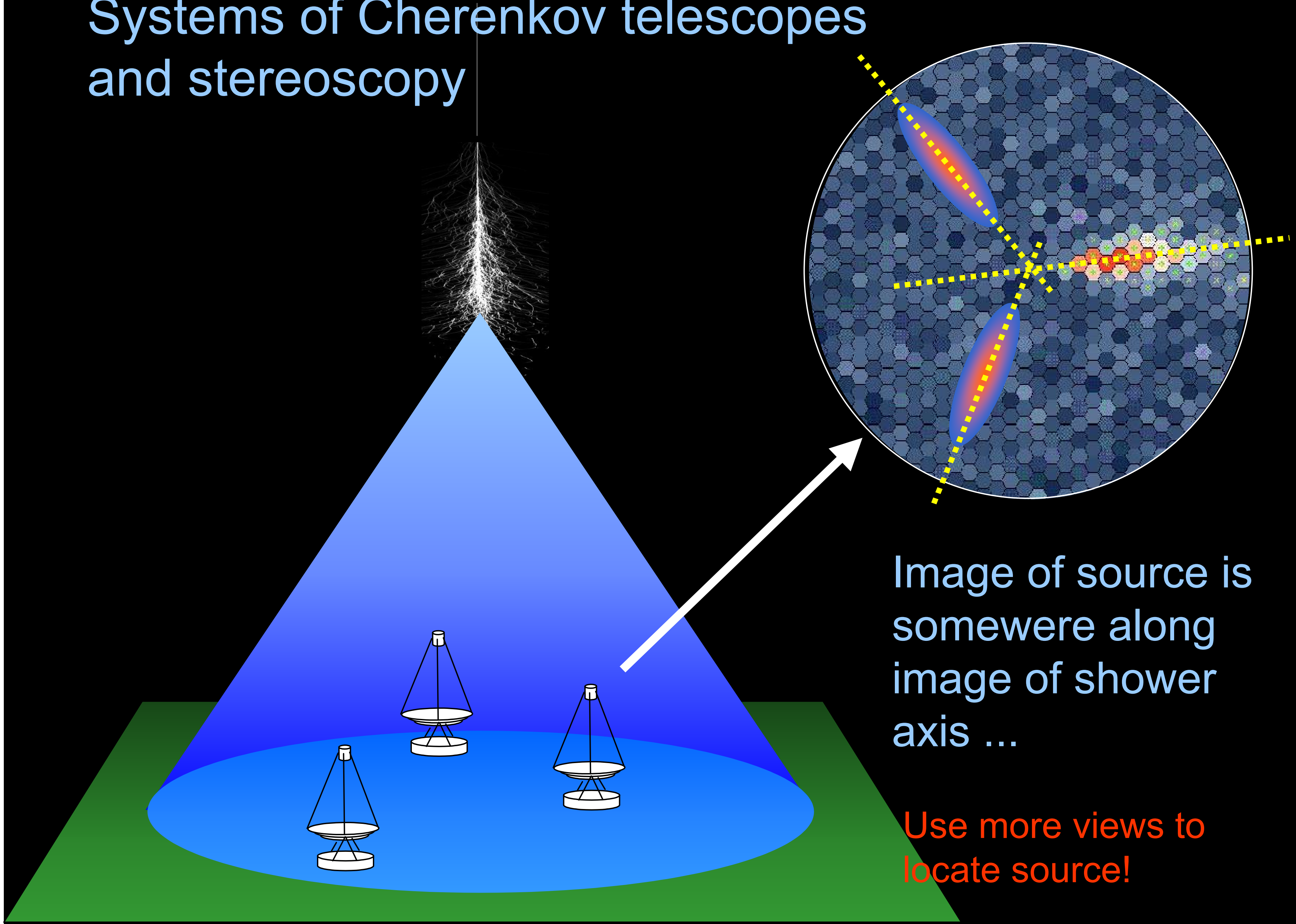
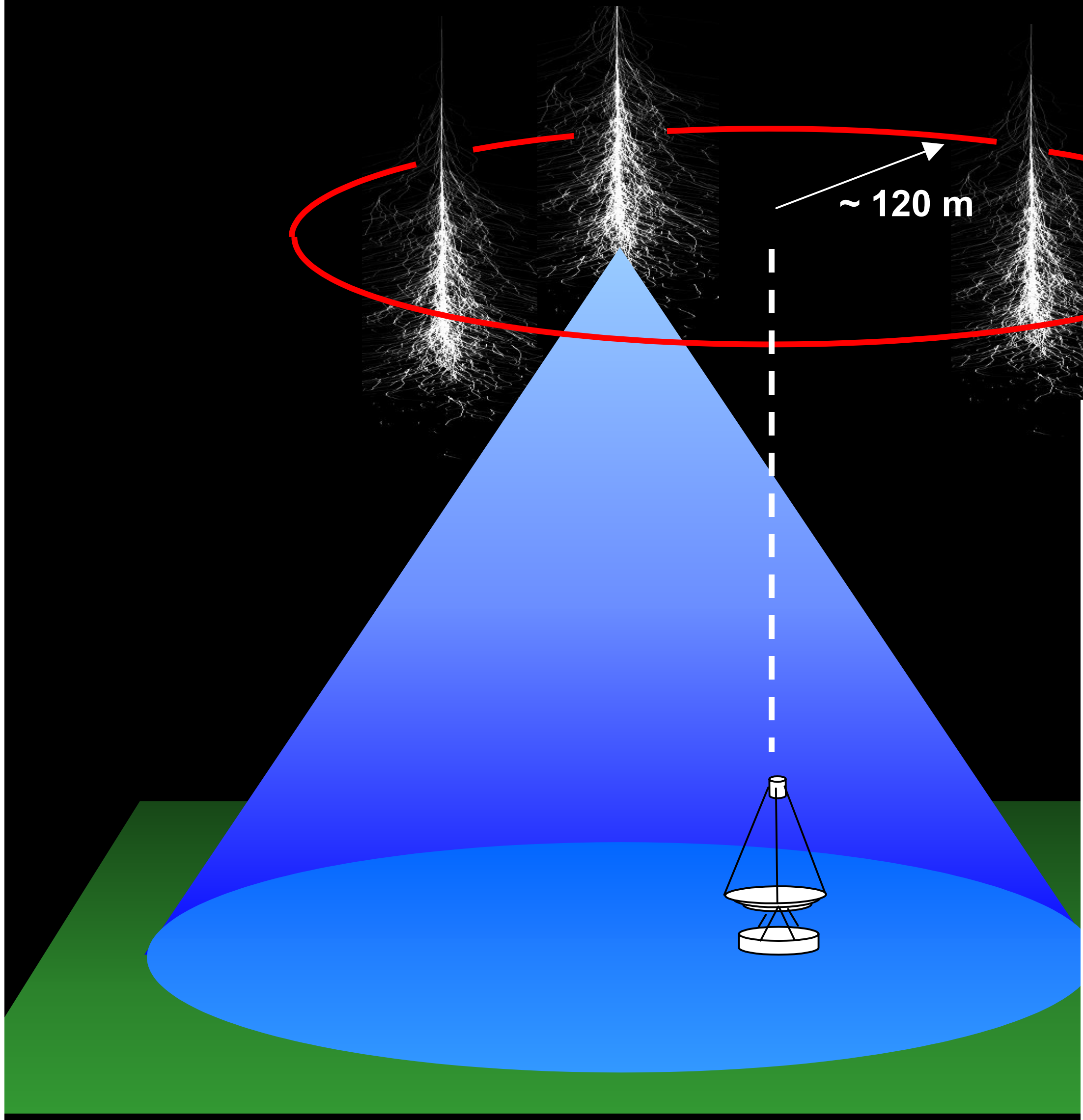


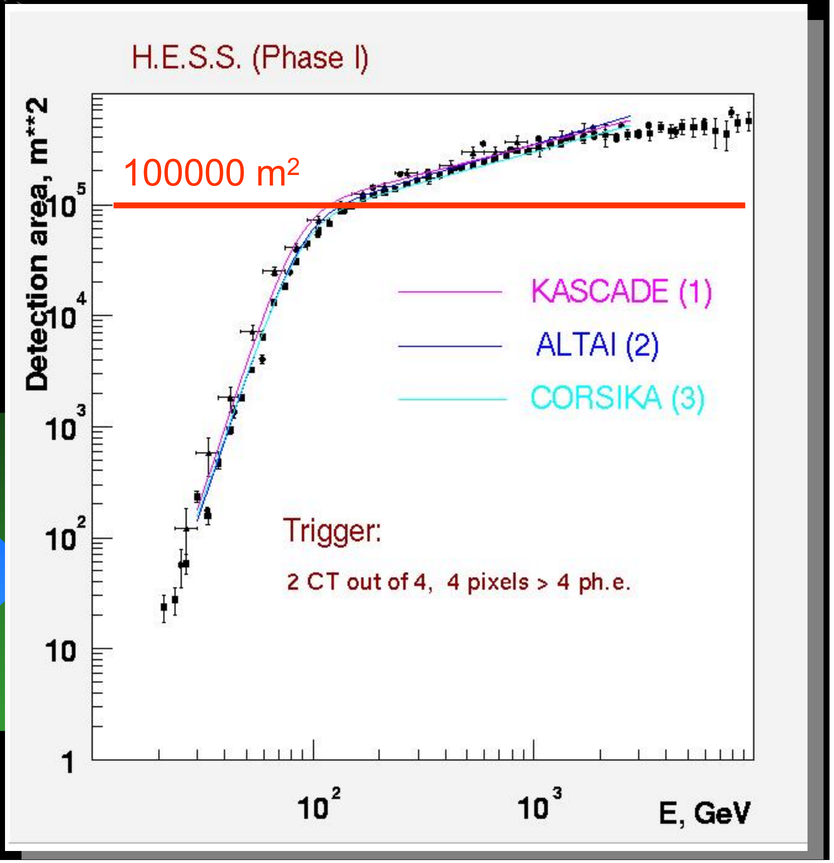
Image of source is somewere along image of shower axis ...

Use more views to locate source!

Effective detection area



about 50000 m^2



Telling γ-rays from hadronic cosmic rays

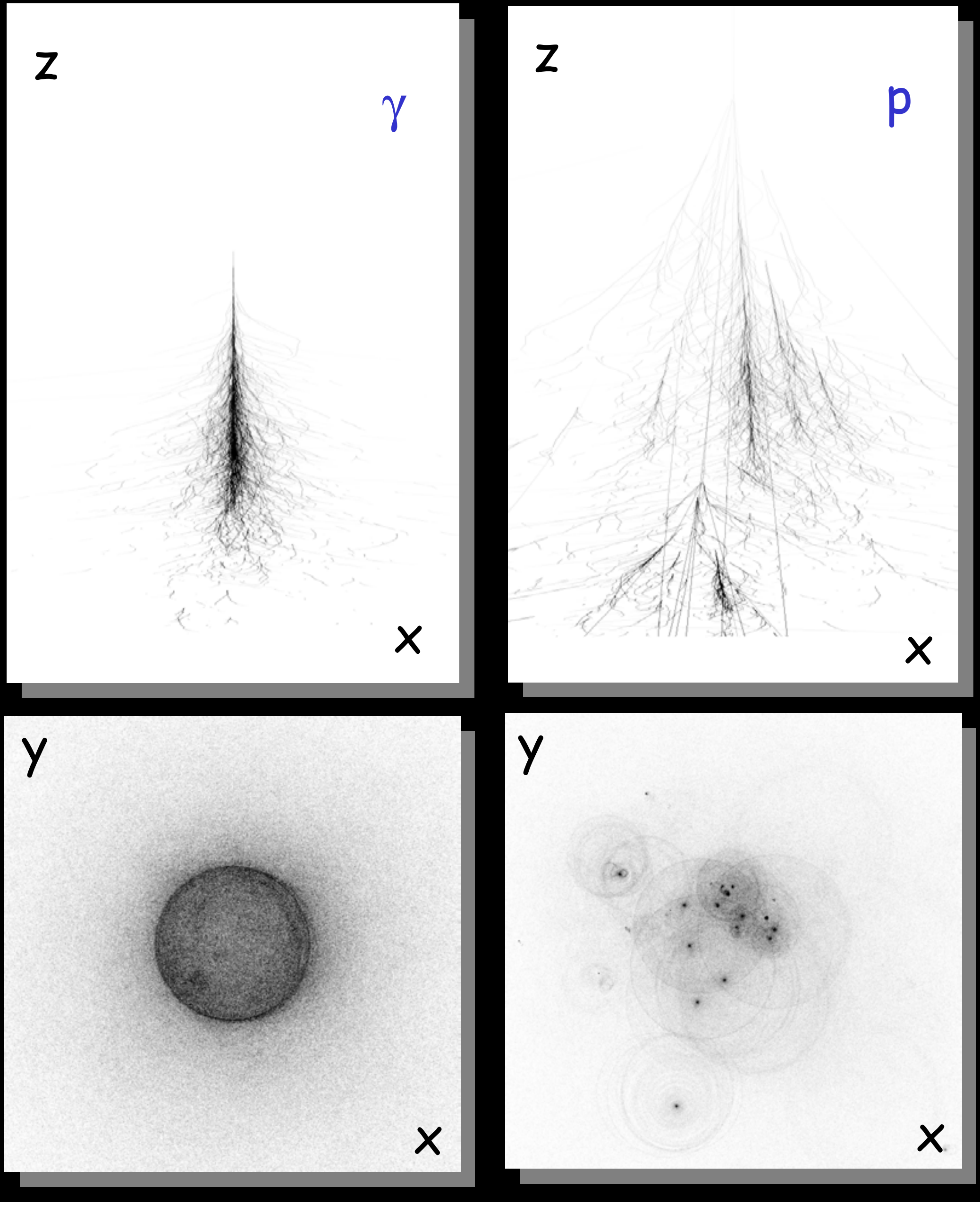
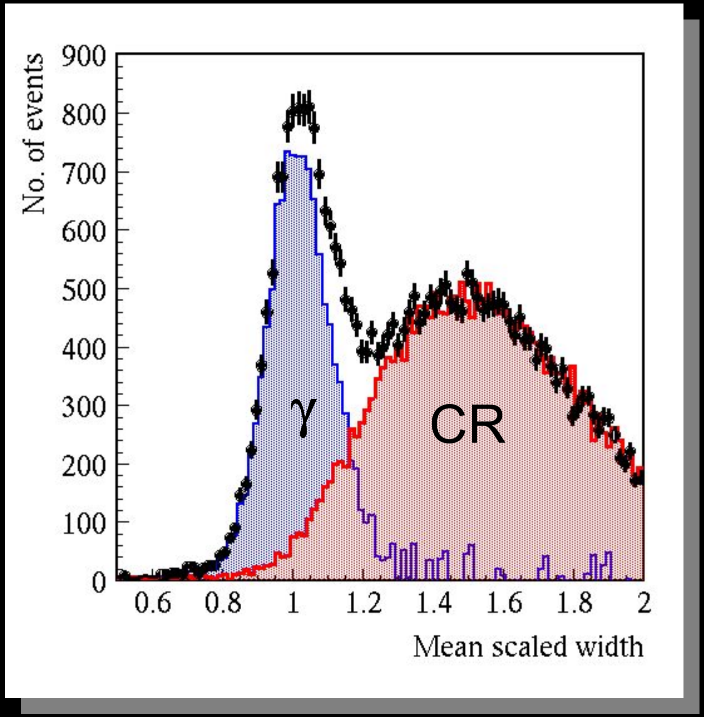
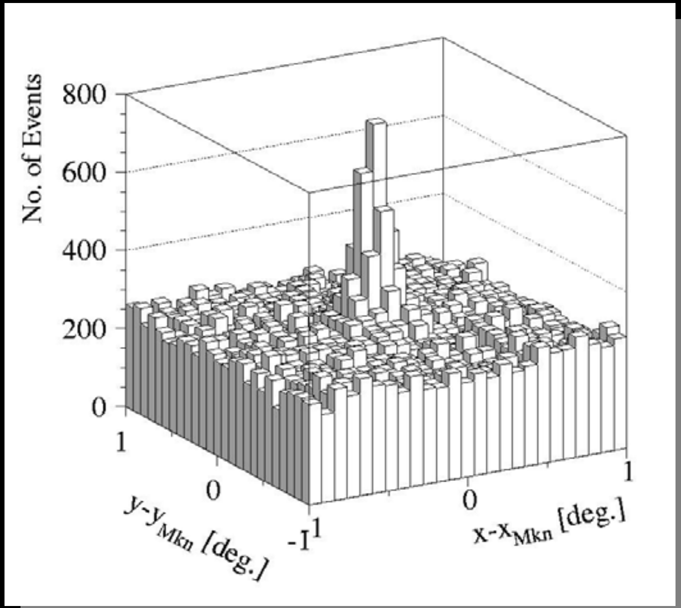


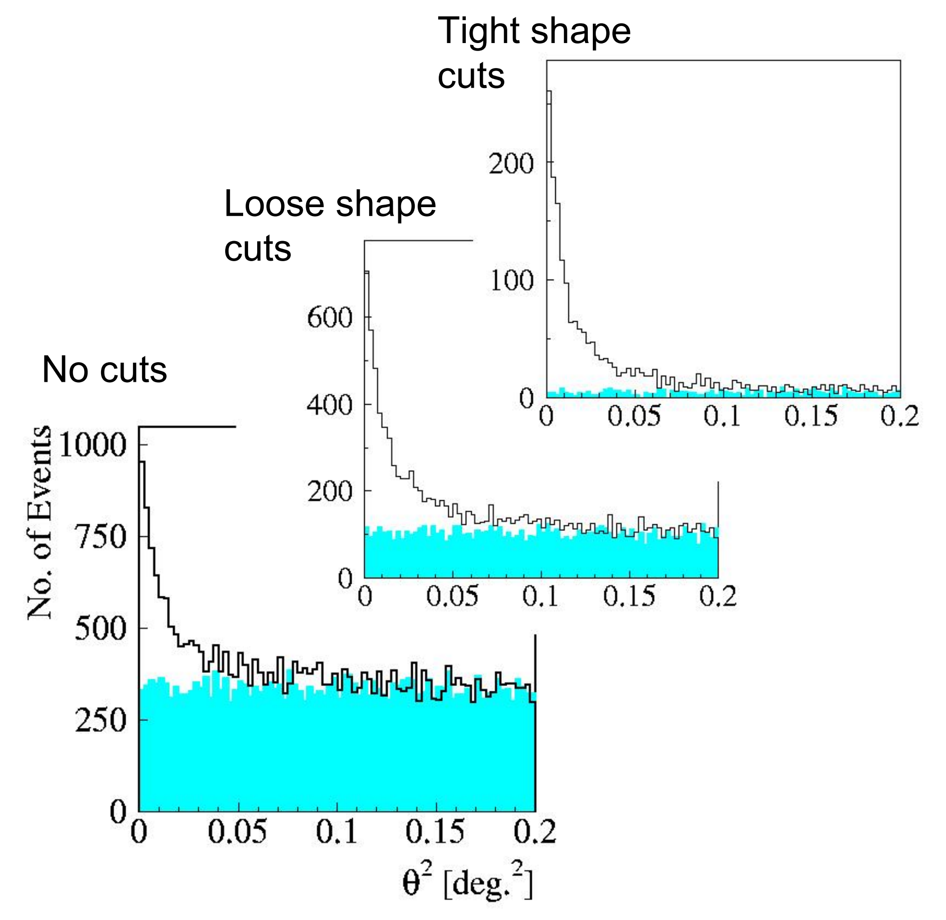
Image width normalized to expected width for γ



Signal and background



HEGRA, Mkn 501
(No cuts)



Significance (for faint source)
~ Signal / $\sqrt{\text{Background}}$

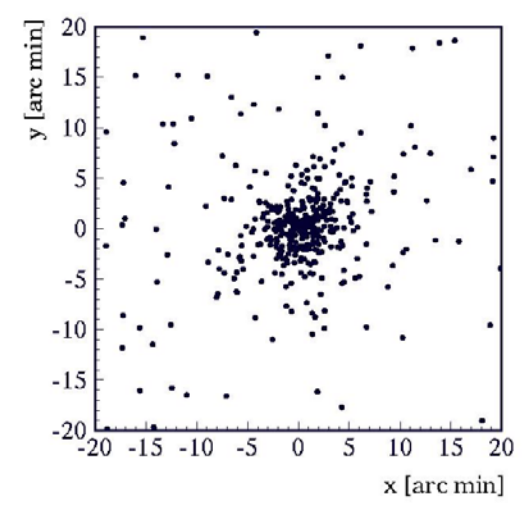
Background ~ $\Delta\theta^2\ \eta_{CR}$

Progress

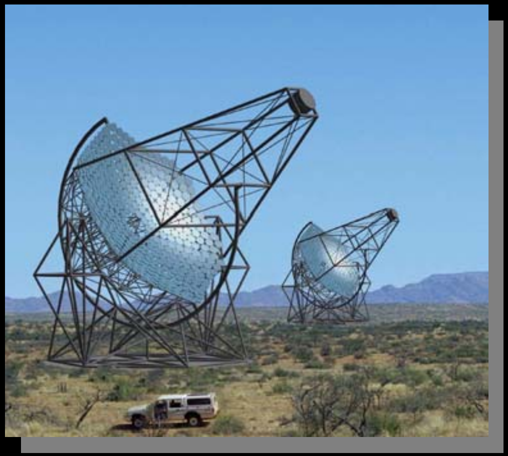
Time to detect the Crab Nebula:
first Whipple detection 1989: 50 h

HEGRA 1997:
10 min

HESS 2003:
15 sec



HEGRA Crab Sample:
3 arc-min resolution
very little background



also online: non-imaging Cherenkov instruments

CELESTE @ Themis

- Very large mirror area (2000+ m^2)
- Very low threshold (some 10 GeV)

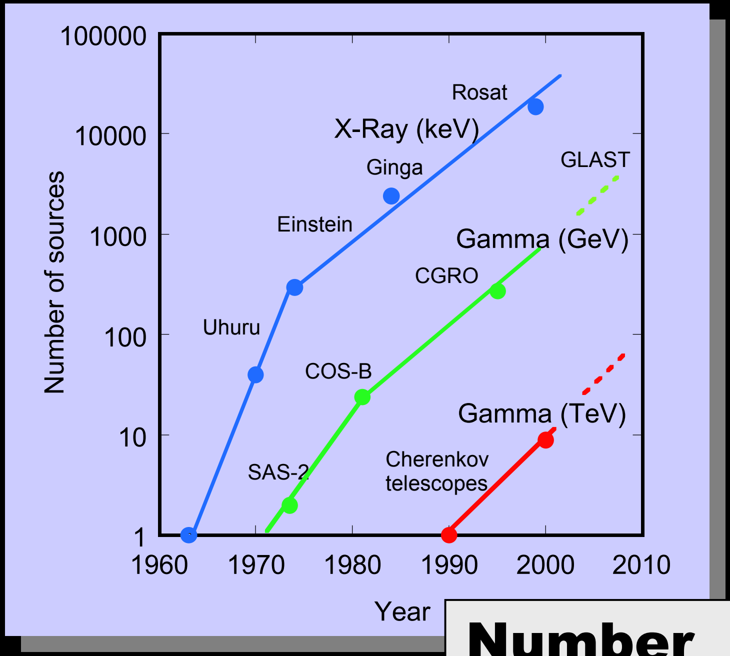
Obstacles: snow, ice ...

… and fire (HEGRA 1997)

La Palma Summer 2000

Namibia Fall 2001

State of the field evolving



Number of sources

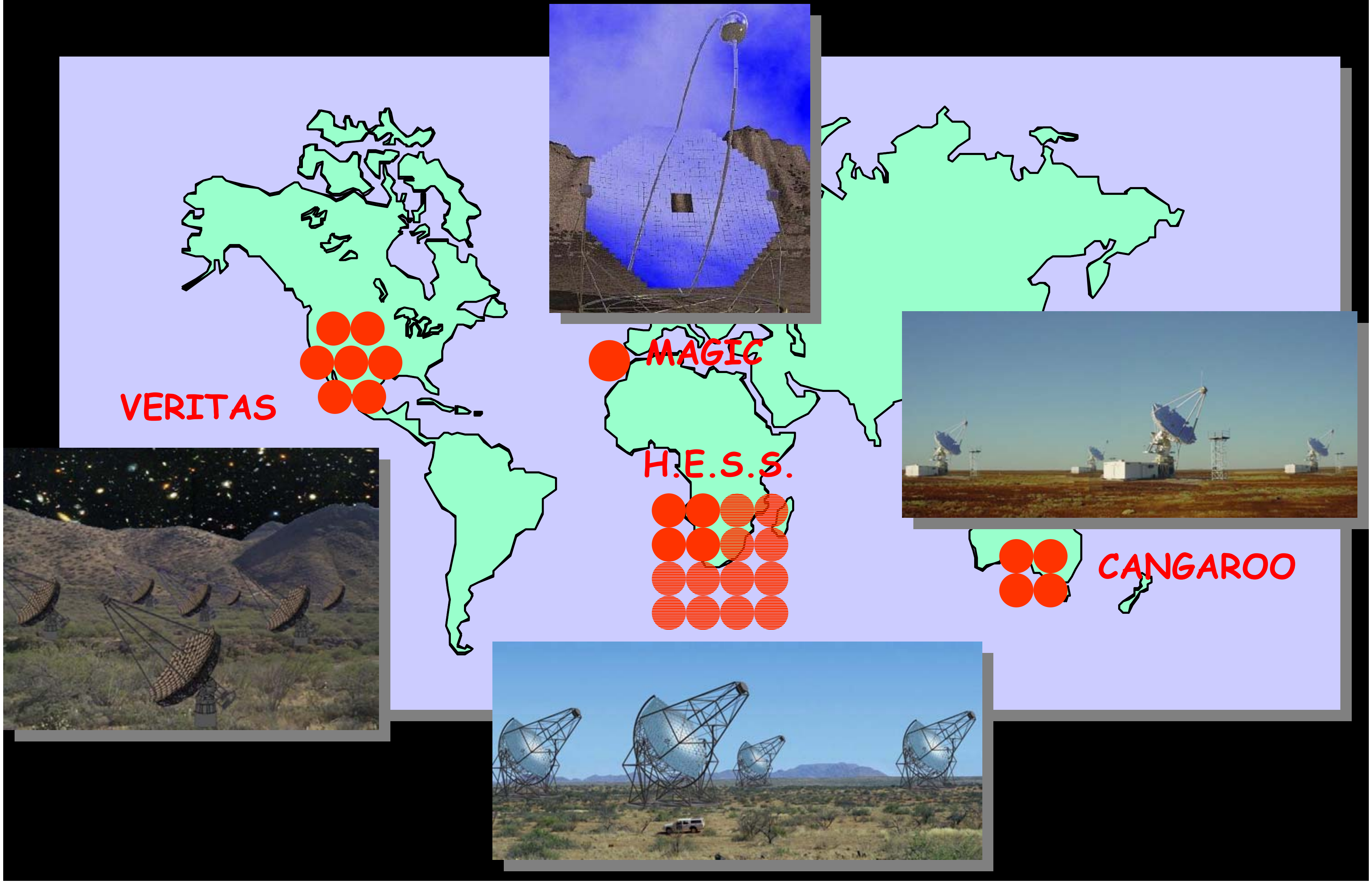
from

- source hunting
- order-of-magnitude flux estimates
- Crab-level sensitivity

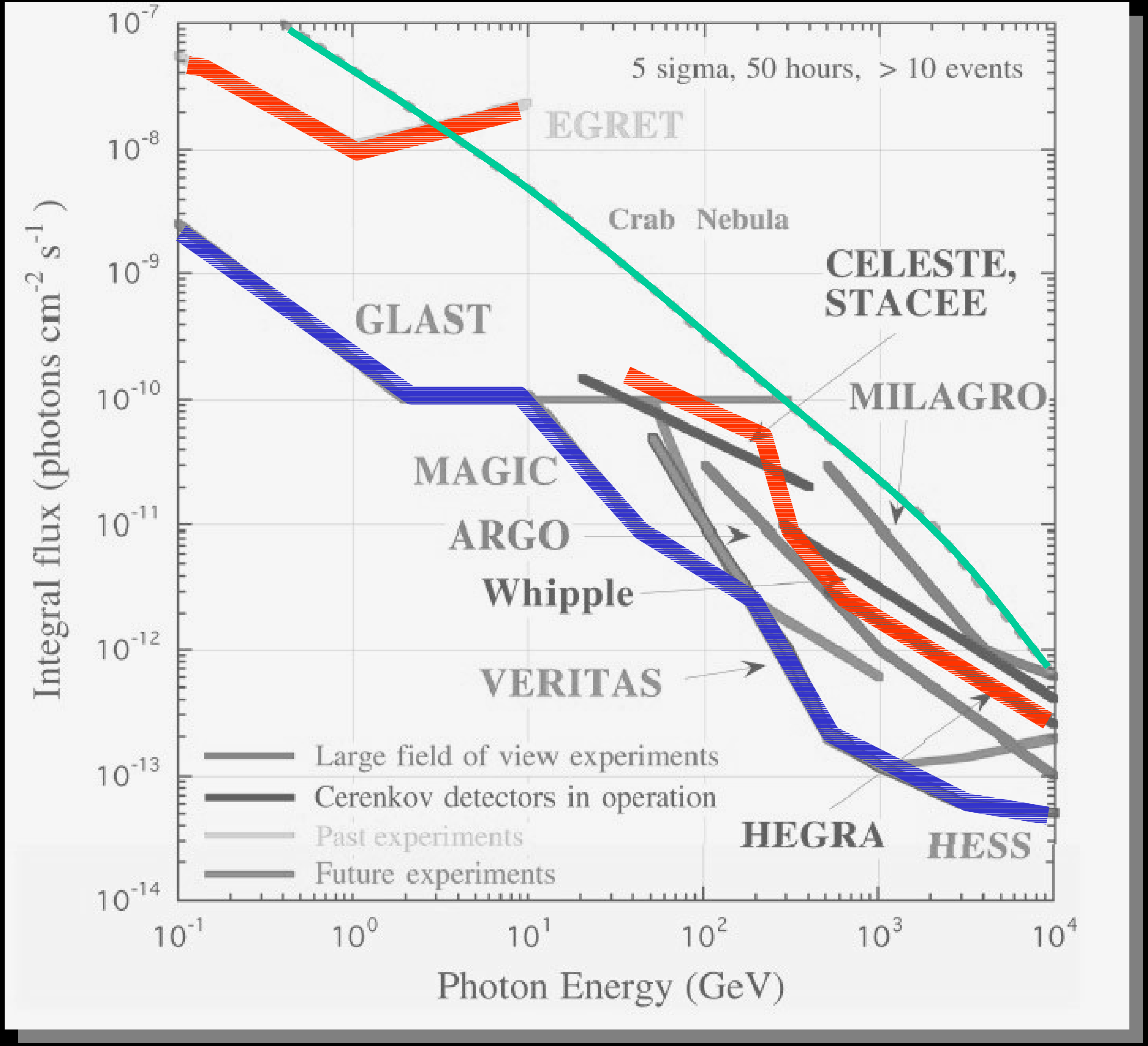
to provide

- “precision” spectroscopy with $\Delta E/E \sim 10\text{-}20\%$
- flux determinations at the 10-20% level
- spatial mapping of sources
- source locations to a few arc-seconds
- mCrab-level sensitivity
- taxonomy of sources

Large projects in high-energy gamma-ray astronomy



Sensitivity



from GLAST
science doc.

Outline – Part I

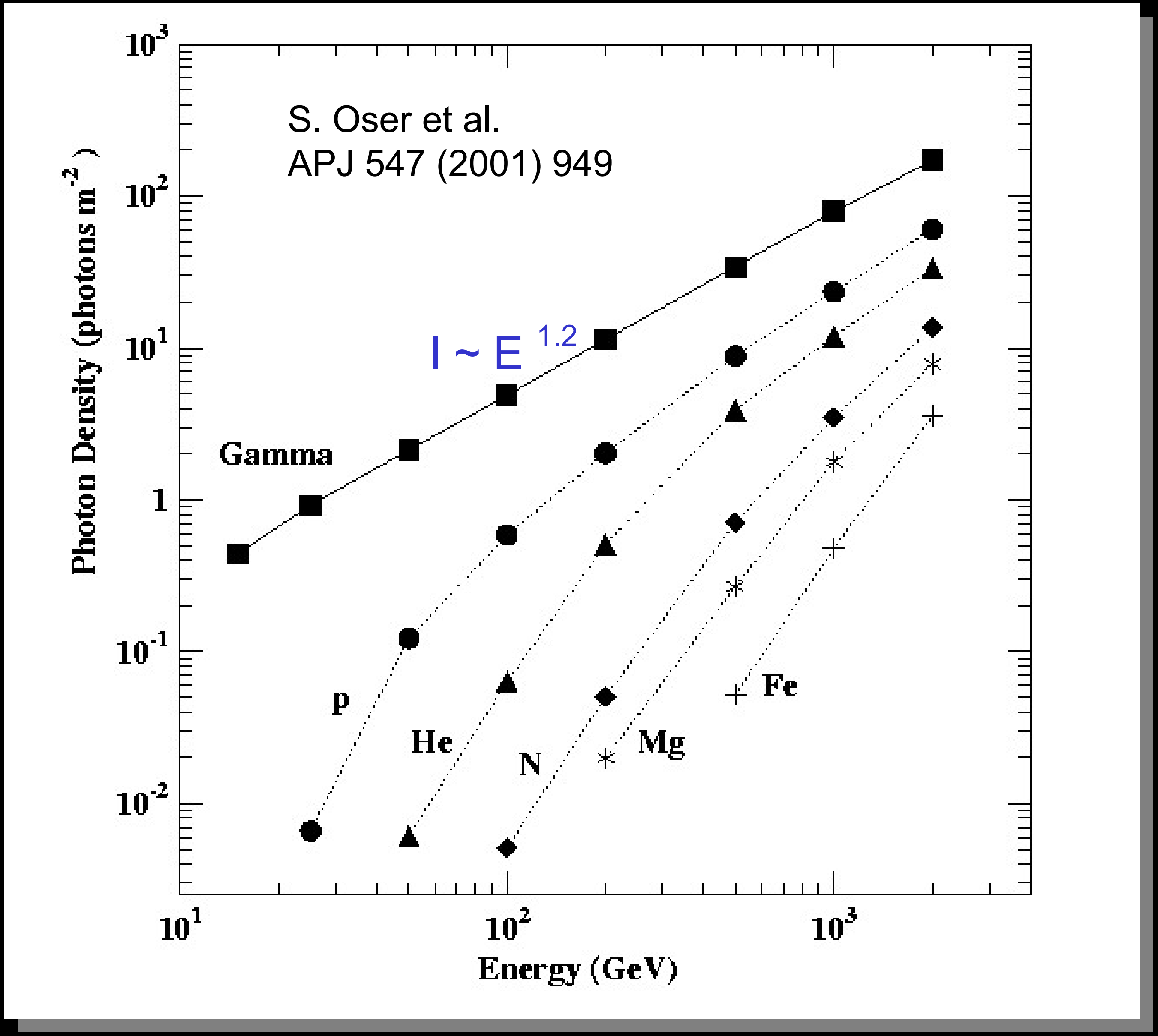
1. Cherenkov telescopes – basics
2. Characteristics of Cherenkov light
    - Distribution
    - Timing characteristics
    - Polarization
    - Influence of the atmosphere
    - Effects of the geomagnetic field
3. Imaging Cherenkov telescopes
    - Mount
    - Mirrors and optics
    - Camera and readout
    - Triggering
    - Image analysis
    - Calibration
    - Flux determination
4. Non-imaging Cherenkov instruments
5. The future

Emphasis:
- Future instruments
- Limitations of the technique

Examples often from HEGRA or H.E.S.S.

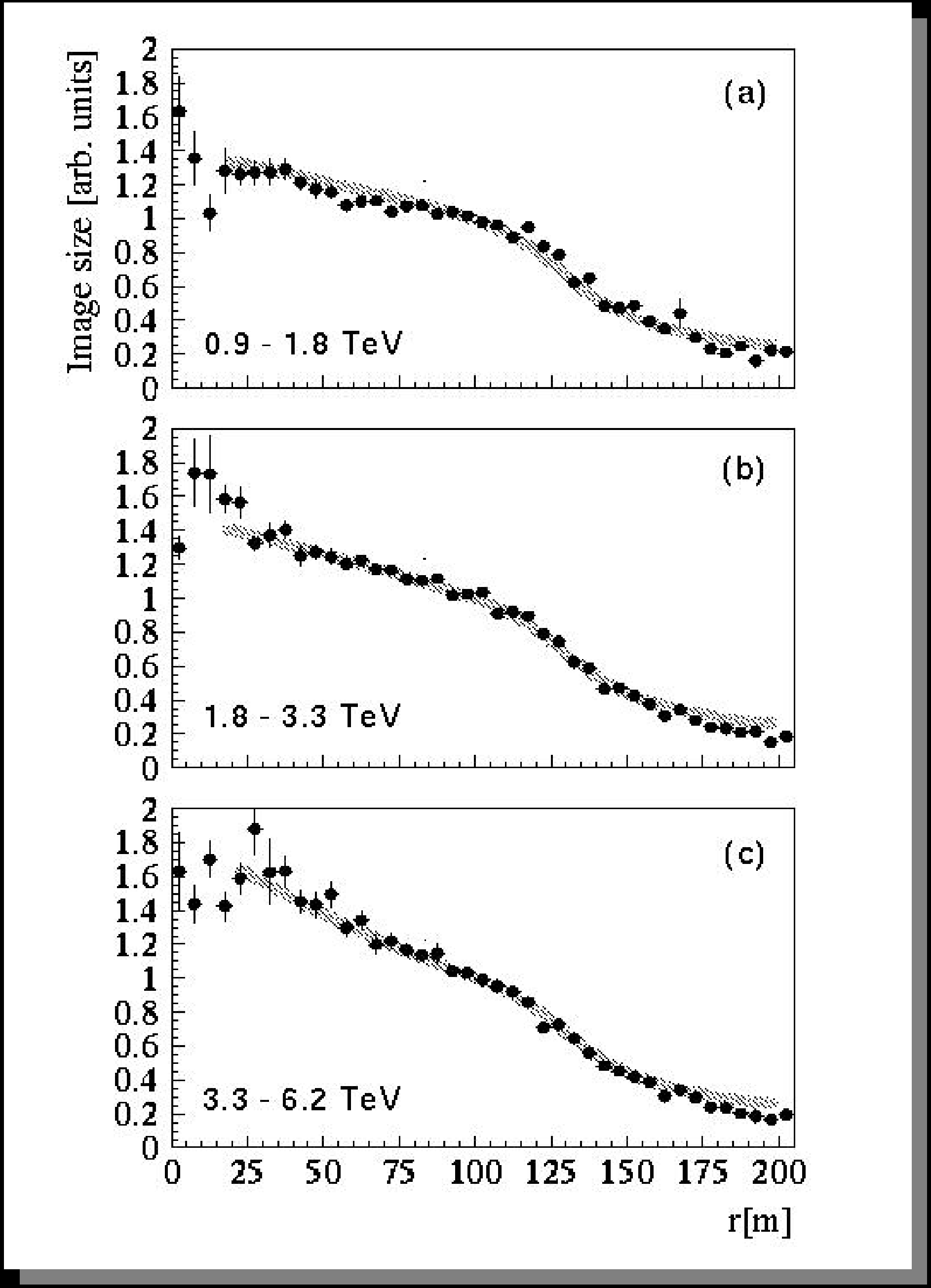
Characteristics of Cherenkov Light

Light yield


S. Oser et al.
APJ 547 (2001) 949

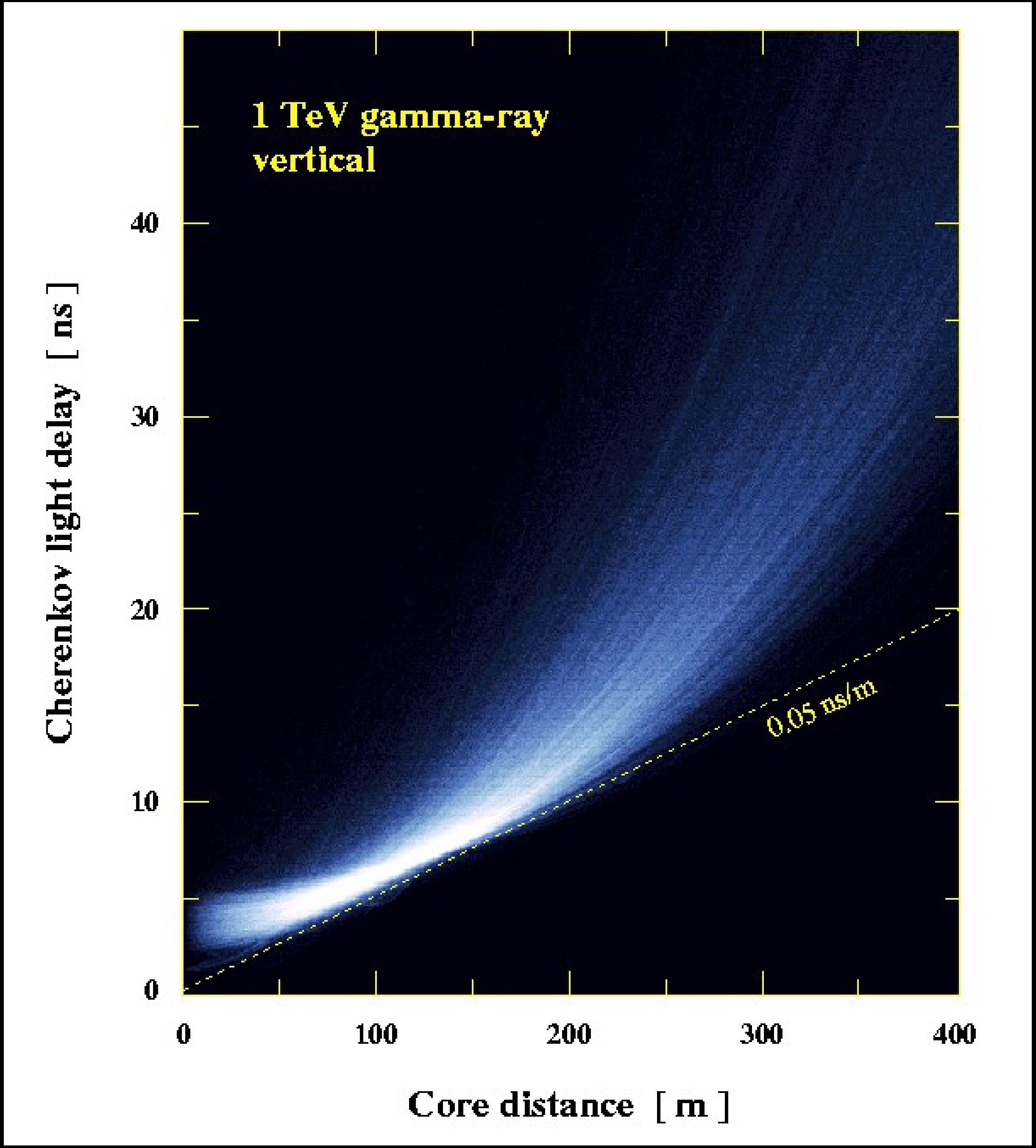
$I \sim E^{1.2}$

Radial distribution of Cherenkov light



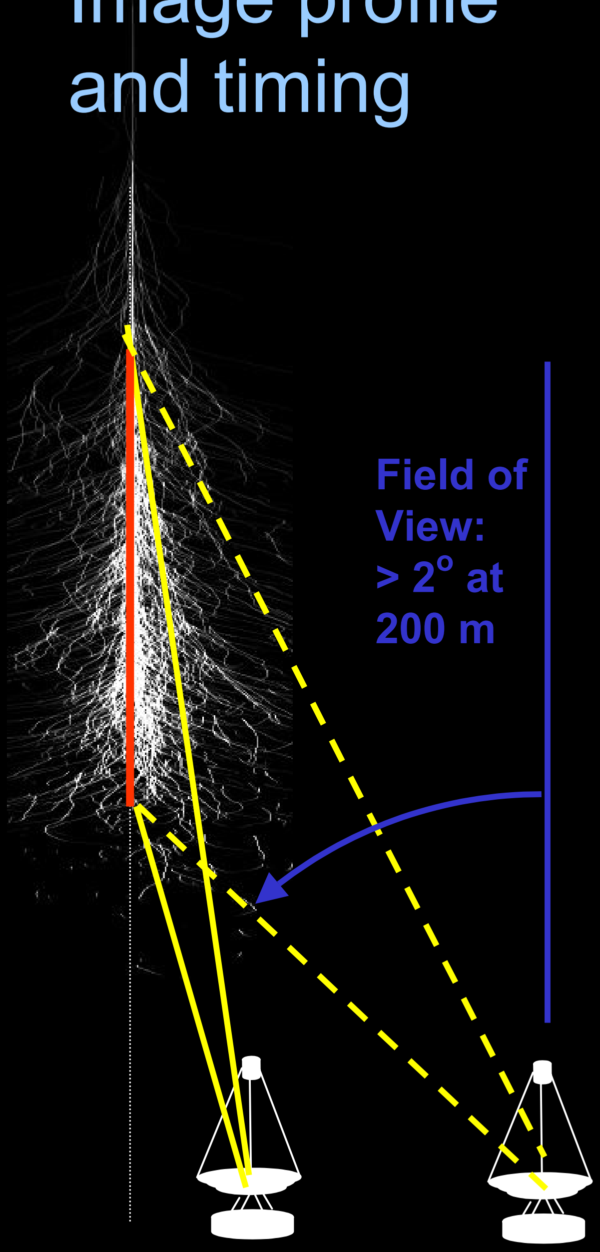
HEGRA Data, Aharonian et al.
Astroparticle Phys. 10 (1999) 21

Time profile of wave front

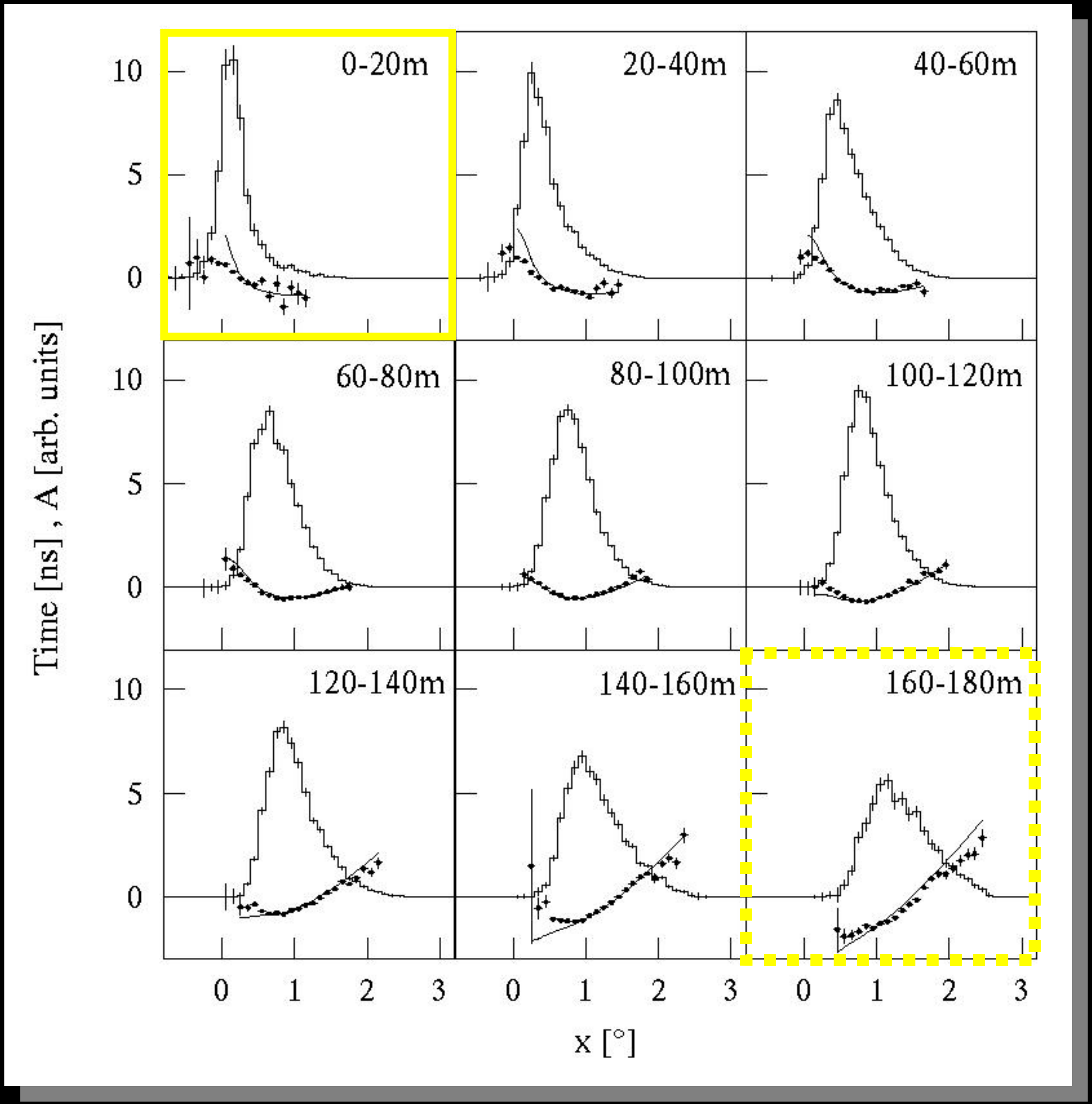


K. Bernlöhr

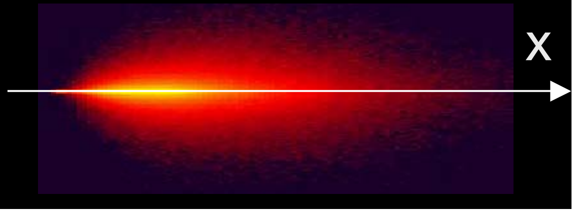
Image profile and timing



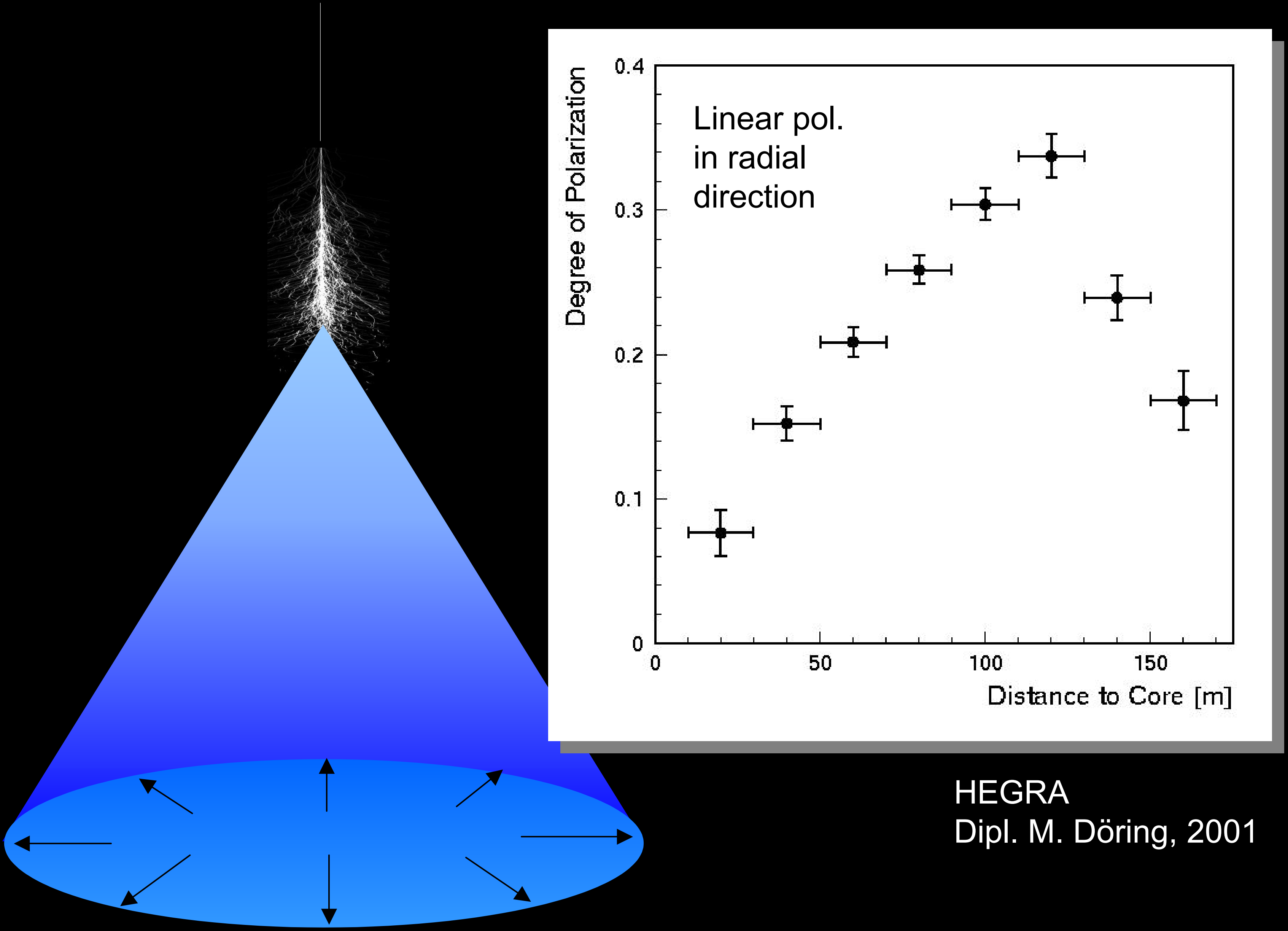
Field of View: > 2° at 200 m



HEGRA Data, Aharonian et al.
Astroparticle Phys. 11 (1999) 363



Polarization of Cherenkov light

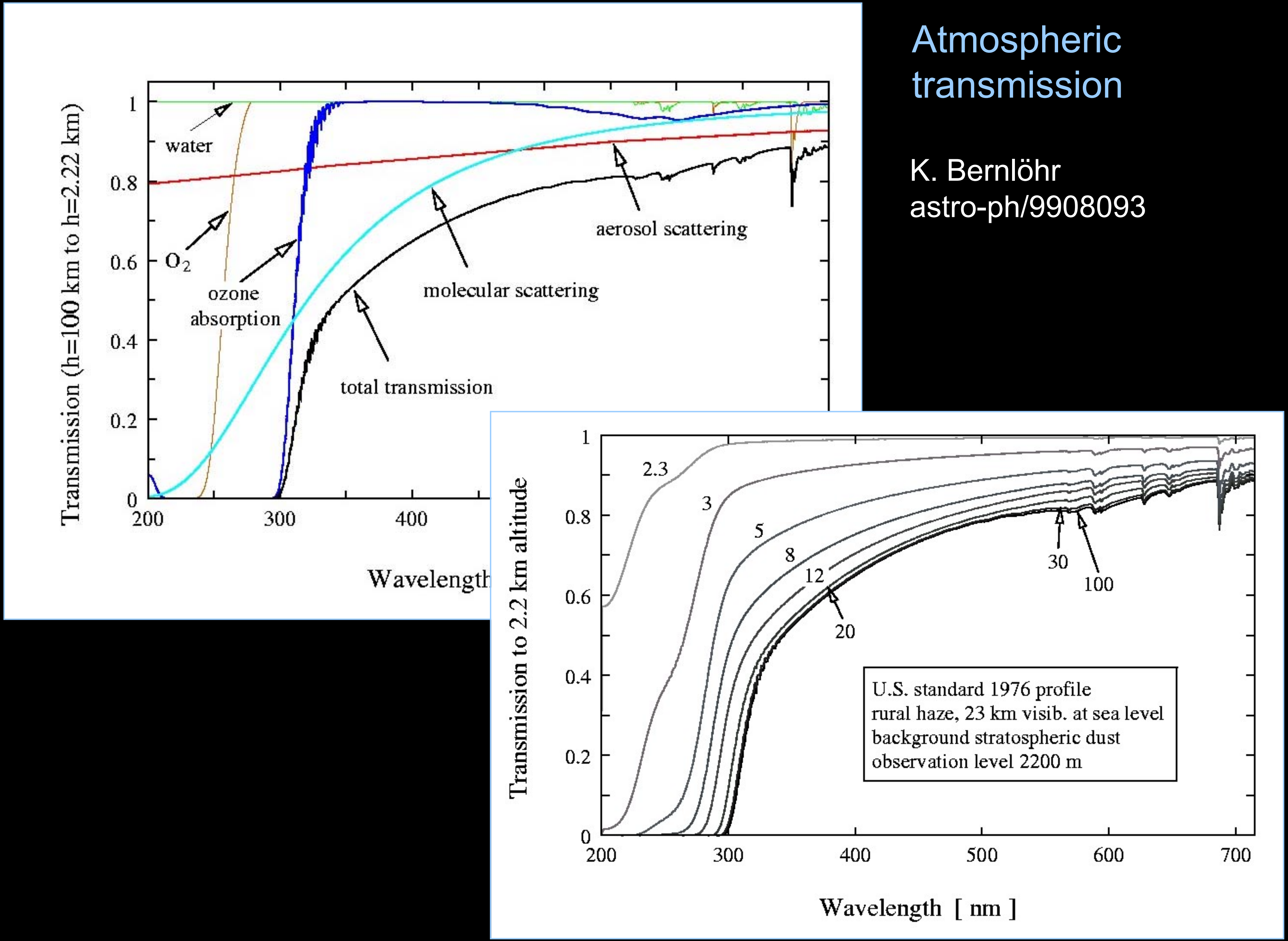


HEGRA
Dipl. M. Döring, 2001

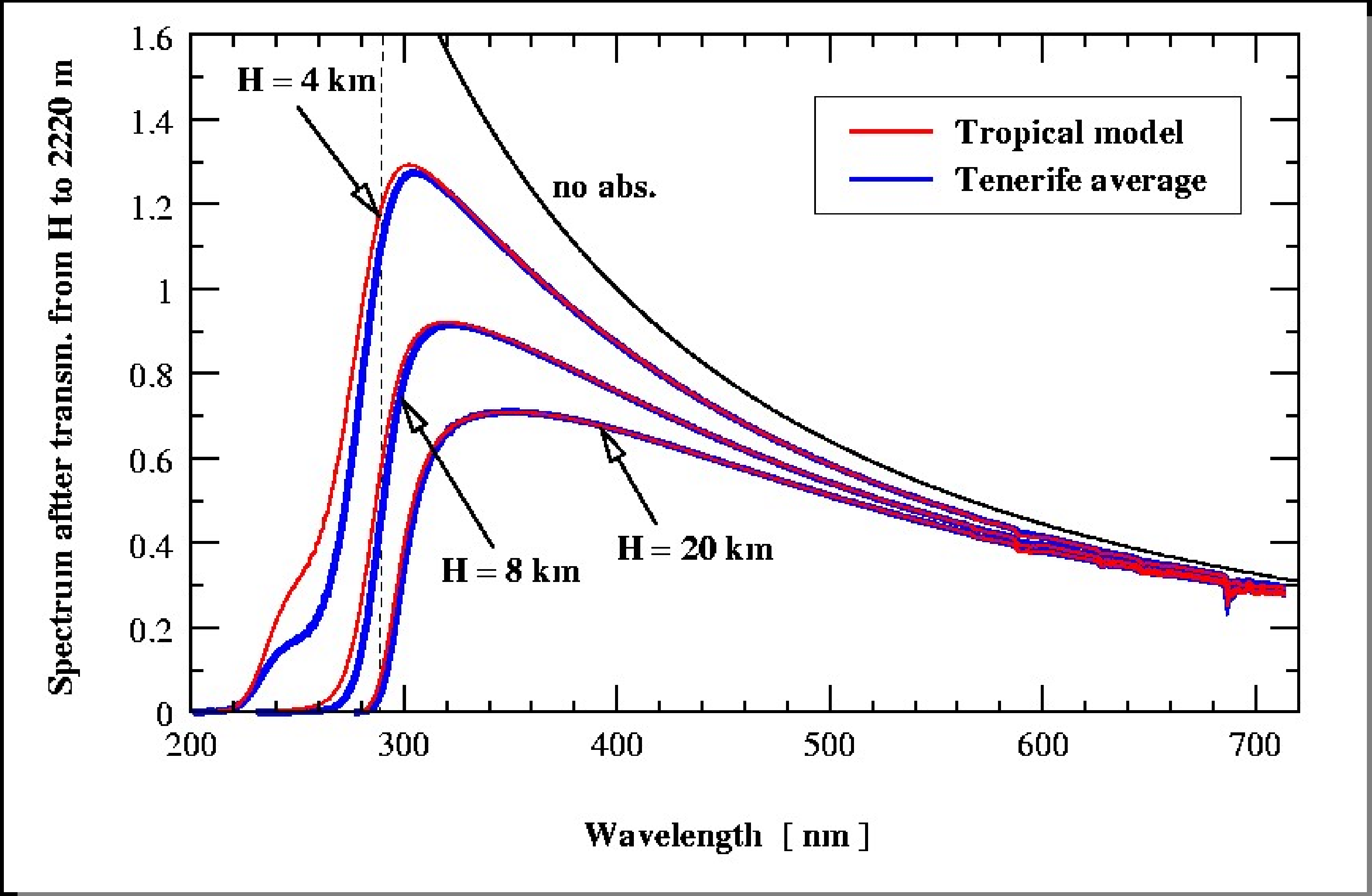
Influence of the Atmosphere

Atmospheric transmission

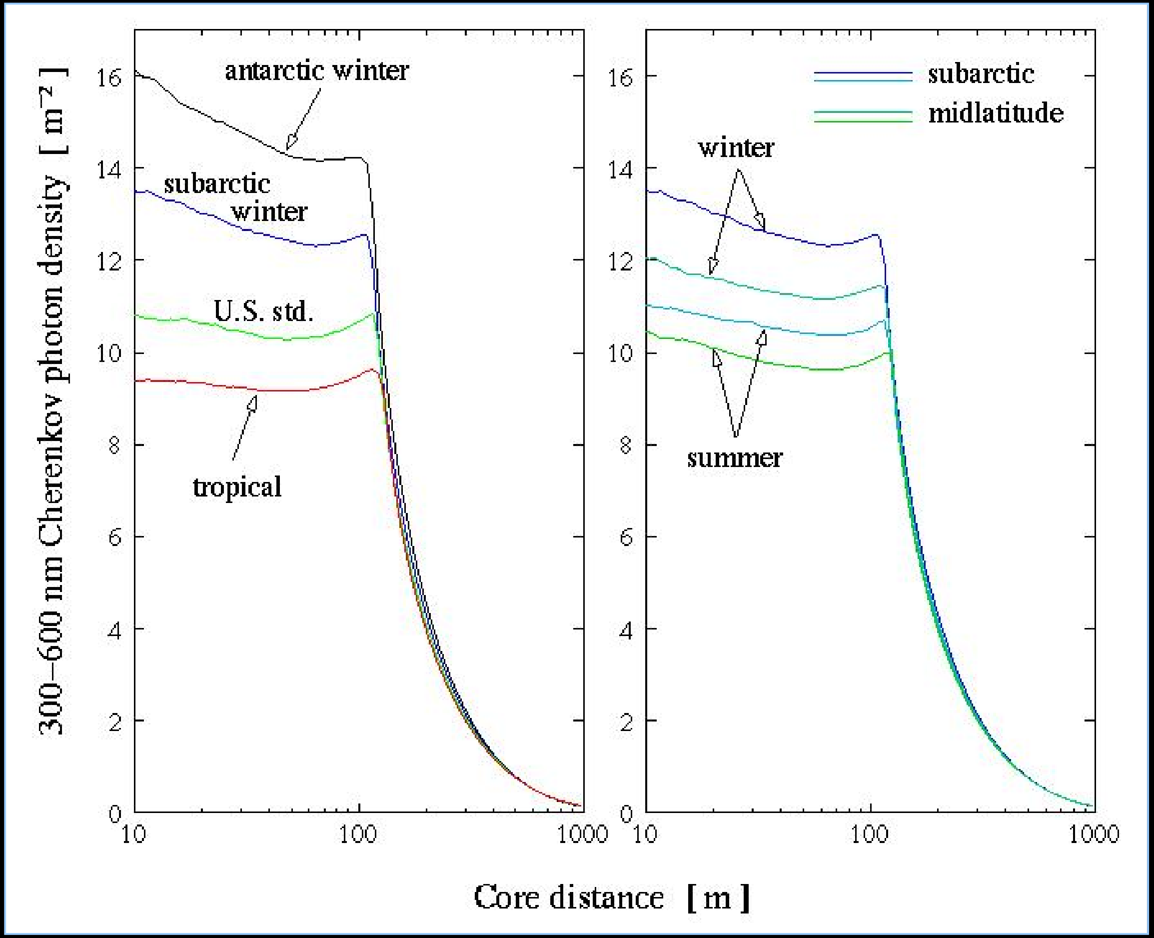
K. Bernlöhr
astro-ph/9908093



Spectrum of Cherenkov light



Atmospheric profile & light intensity

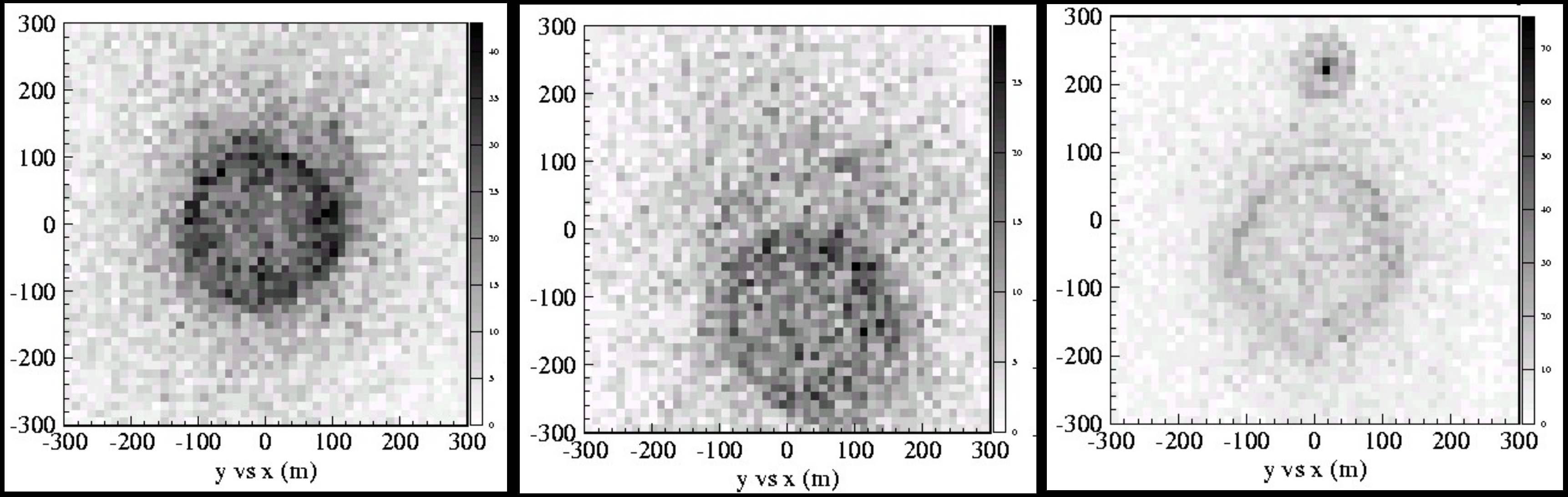


K. Bernlöhr
astro-ph/9908093

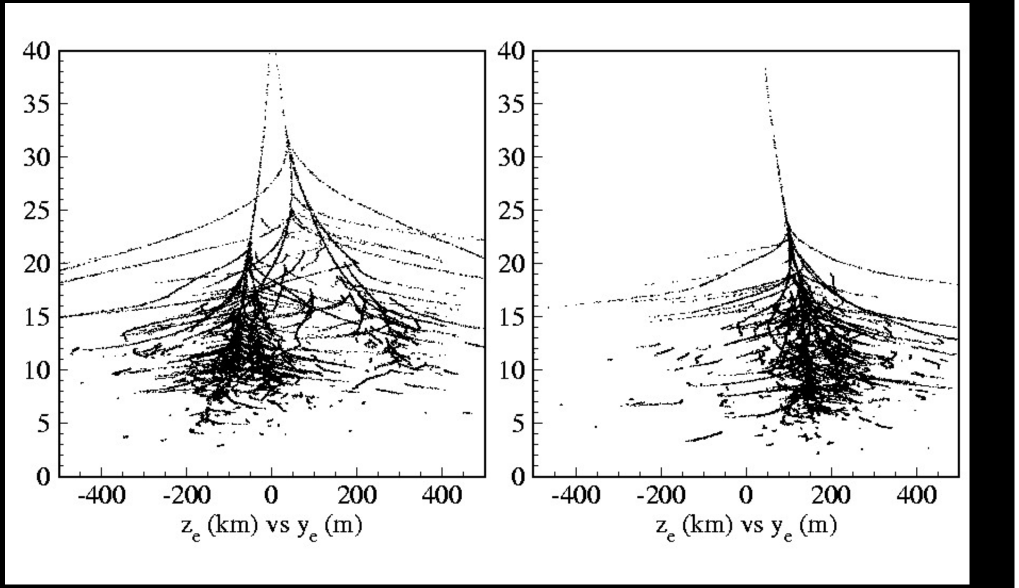
Atmospheric density profile influences both shower development and Cherenkov emission

Potentially large (> 10%) effects on energy calibration

Effects of the Geomagnetic Field



Geomagnetic deflection of primary pair limits angular resolution at low energies (starts to become relevant at a few 100 GeV)



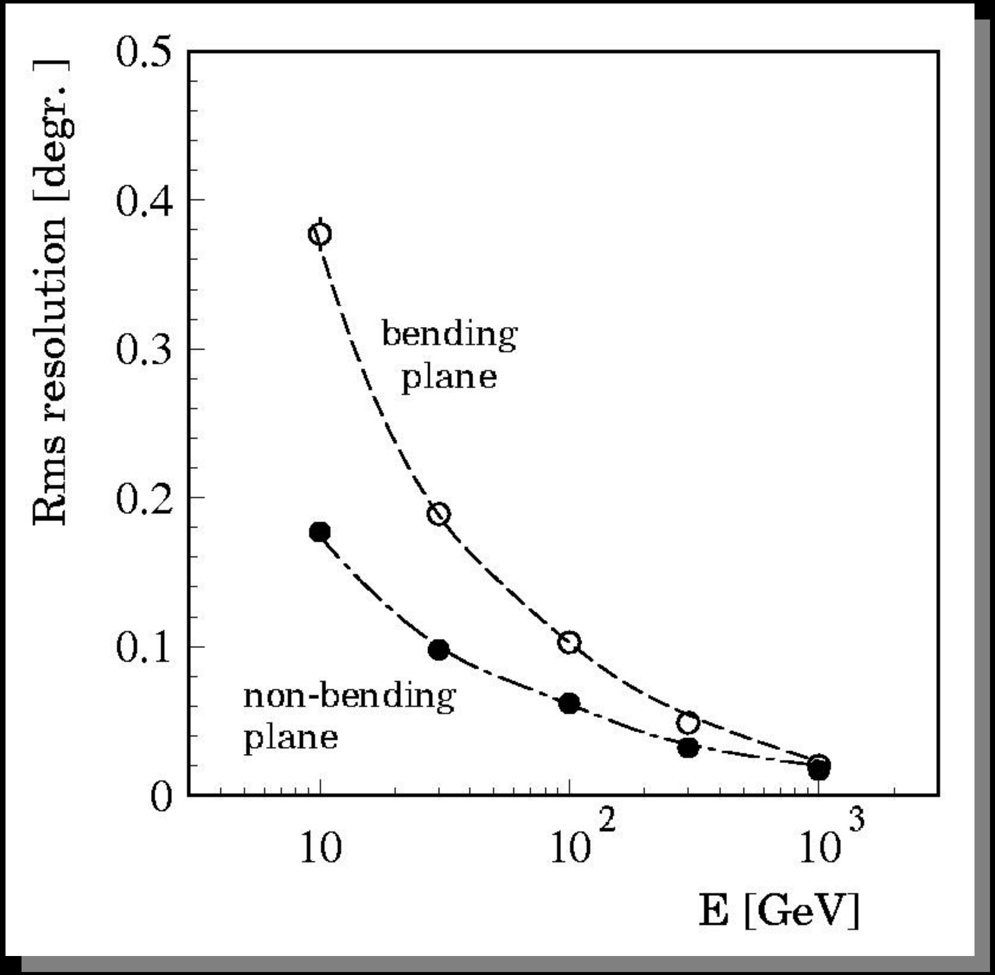
Effect I:

- Change of effective shower direction
- Depends on energy splitting in primary conversion
- Cannot be corrected

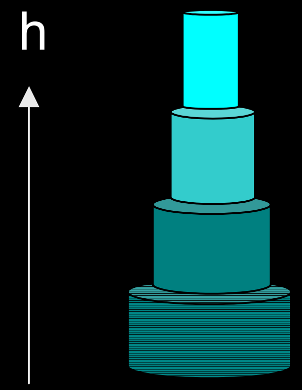
Angular resolution limits

for “ideal” detector,
limited by

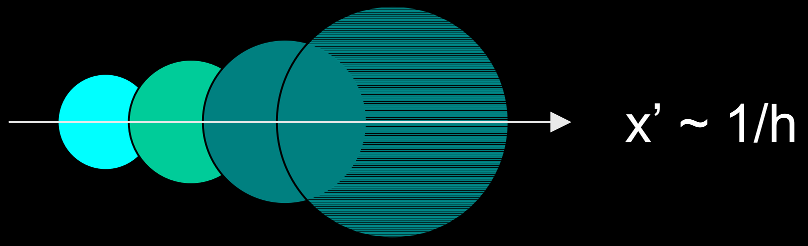
- Shower fluctuations
- Geomagnetic field



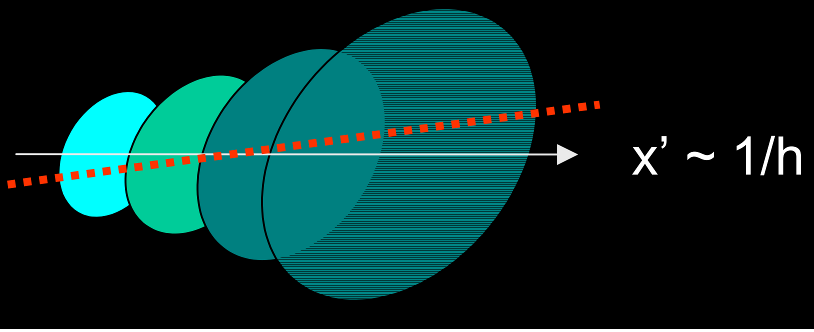
Shower model



Shower image w/o field



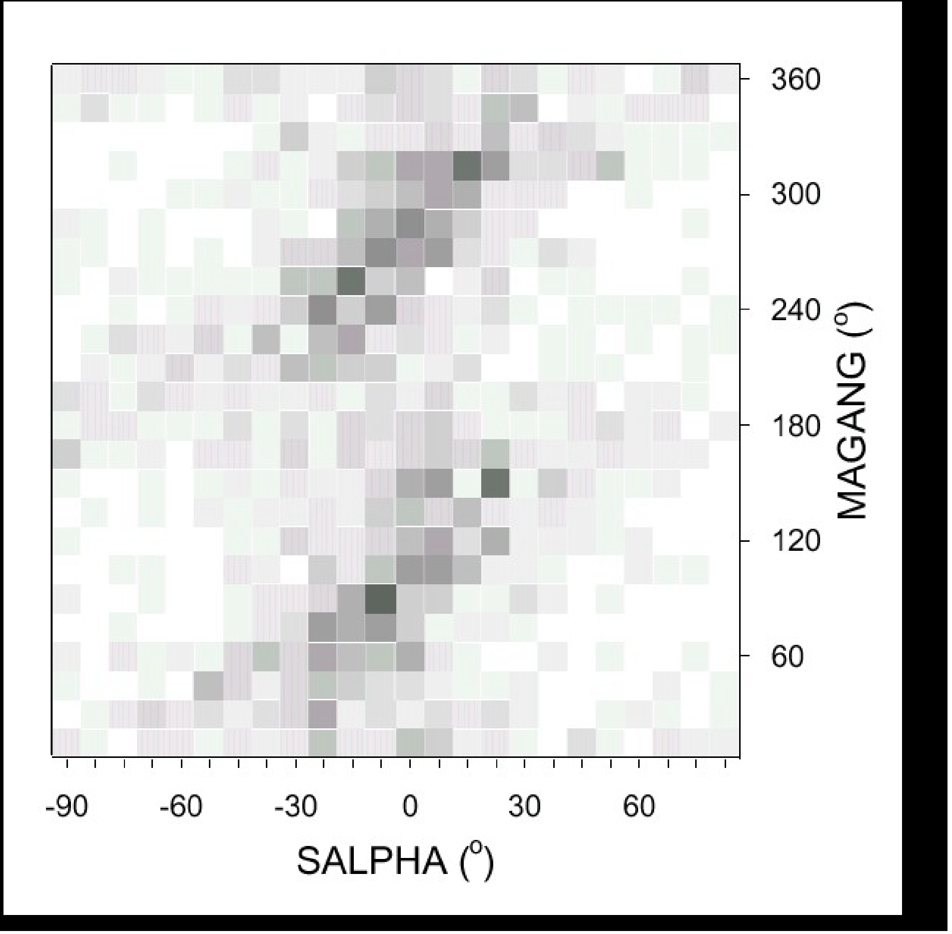
Shower image with field



Effect II:

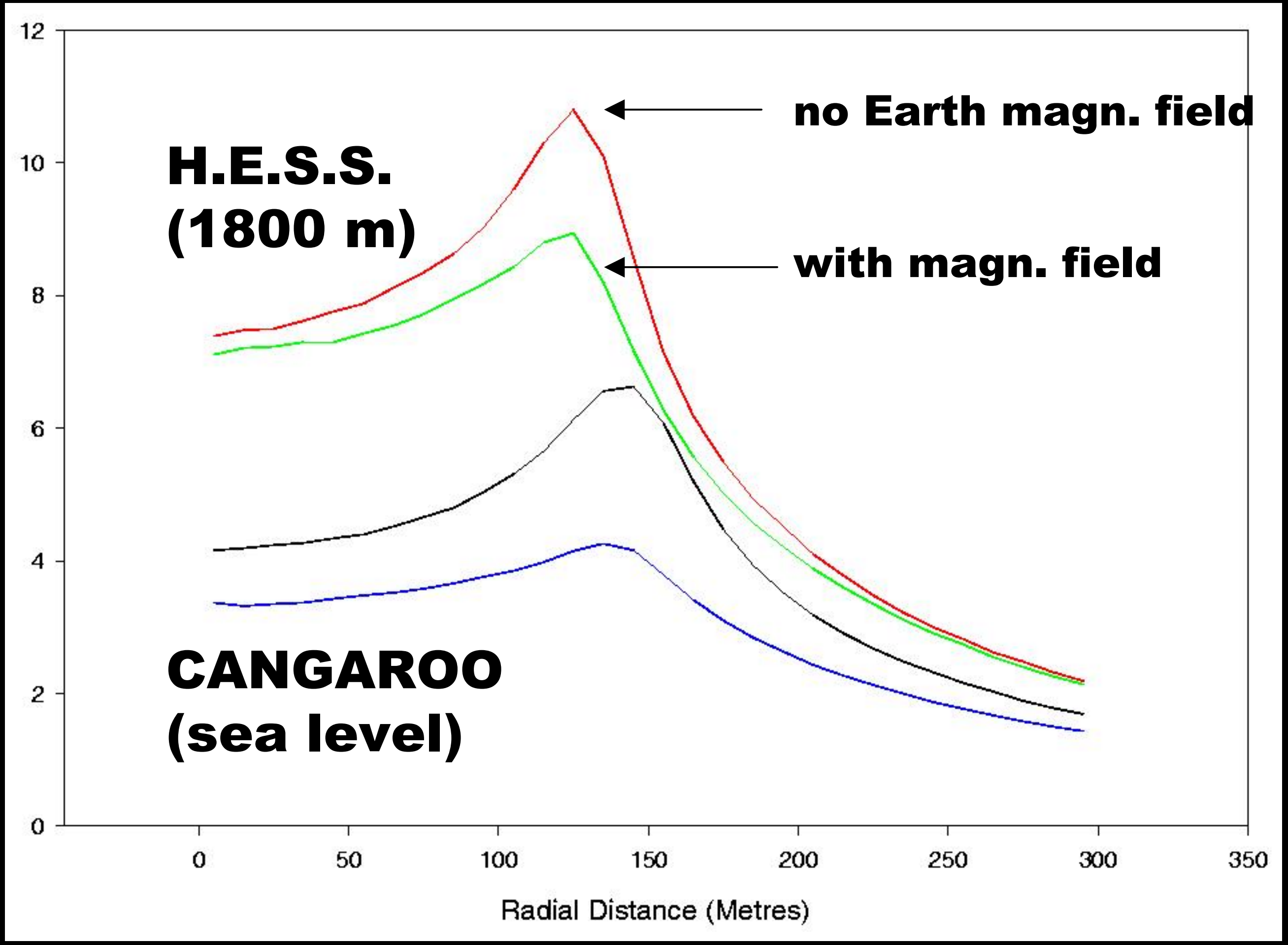
- Image rotation due to widening of cascade
- Can be corrected

P.M. Chadwick et al., J. Phys. G 26 (2000) L5; J. Phys. G 25 (1999) 1223



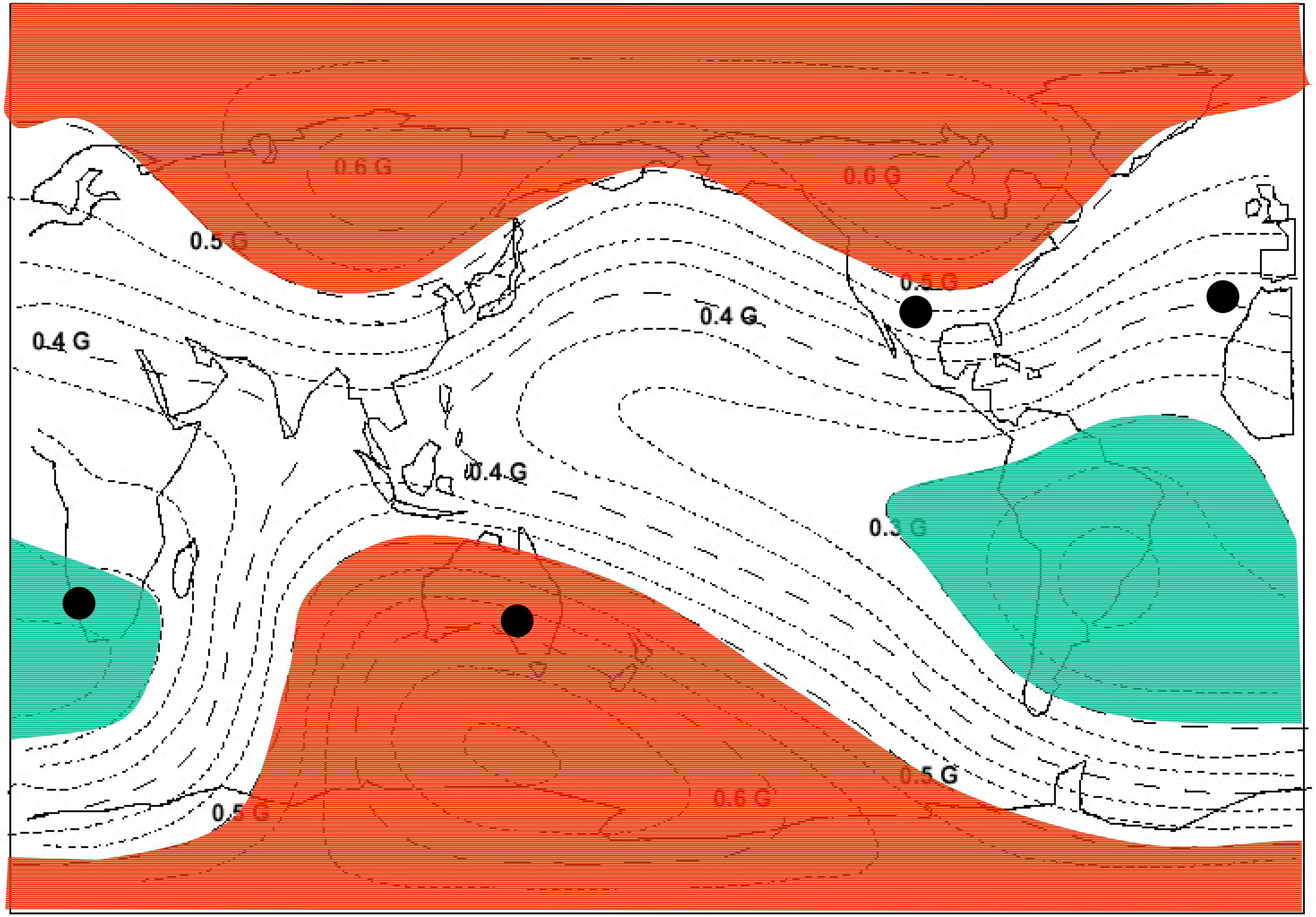
Effect III:

- Reduced image intensity for for core distances below a few 100 m
- Cannot be recovered



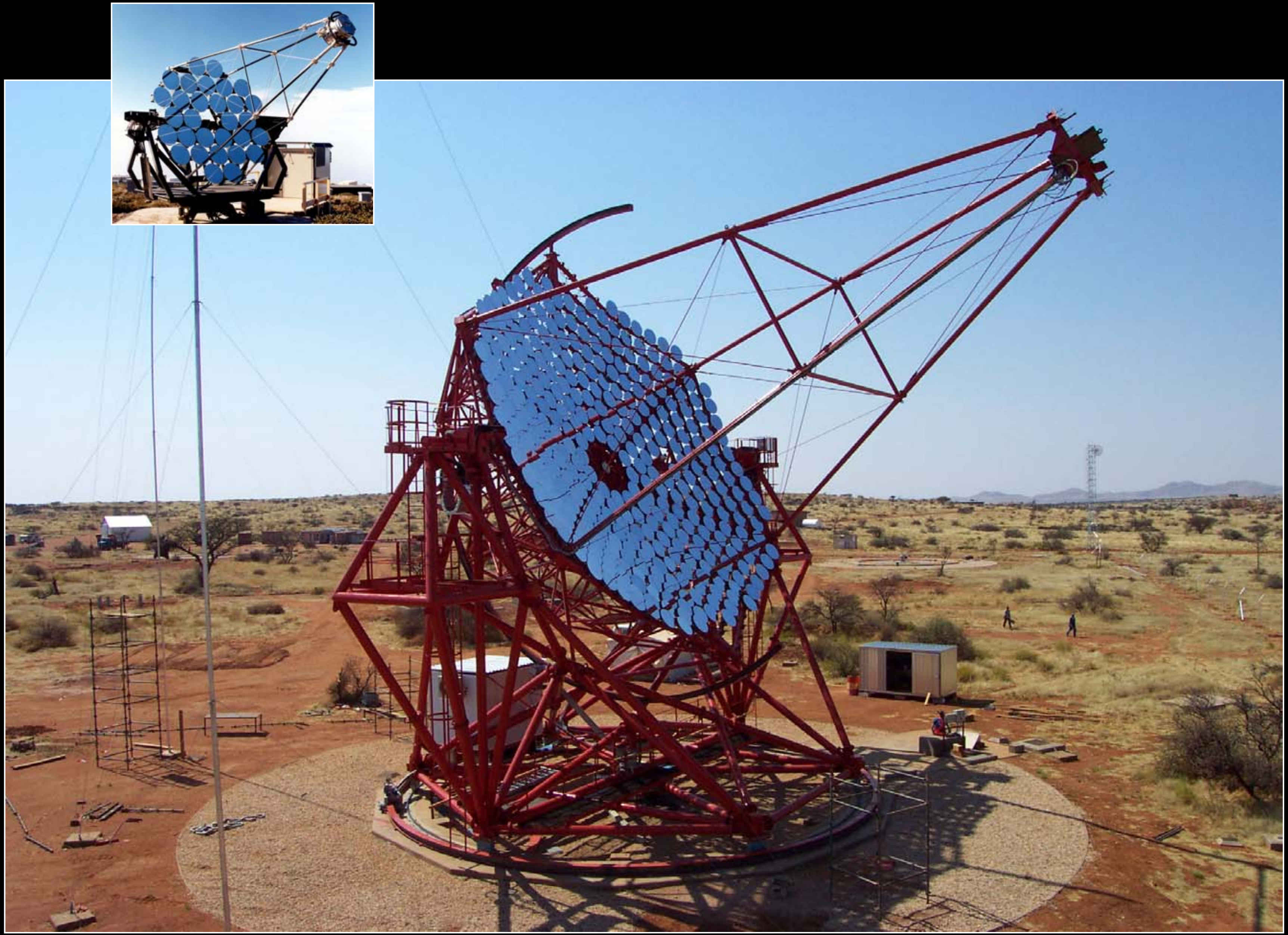
Where to be?

P.M. Chadwick et al., J. Phys. G 26 (2000) L5;
J. Phys. G 25 (1999) 1223

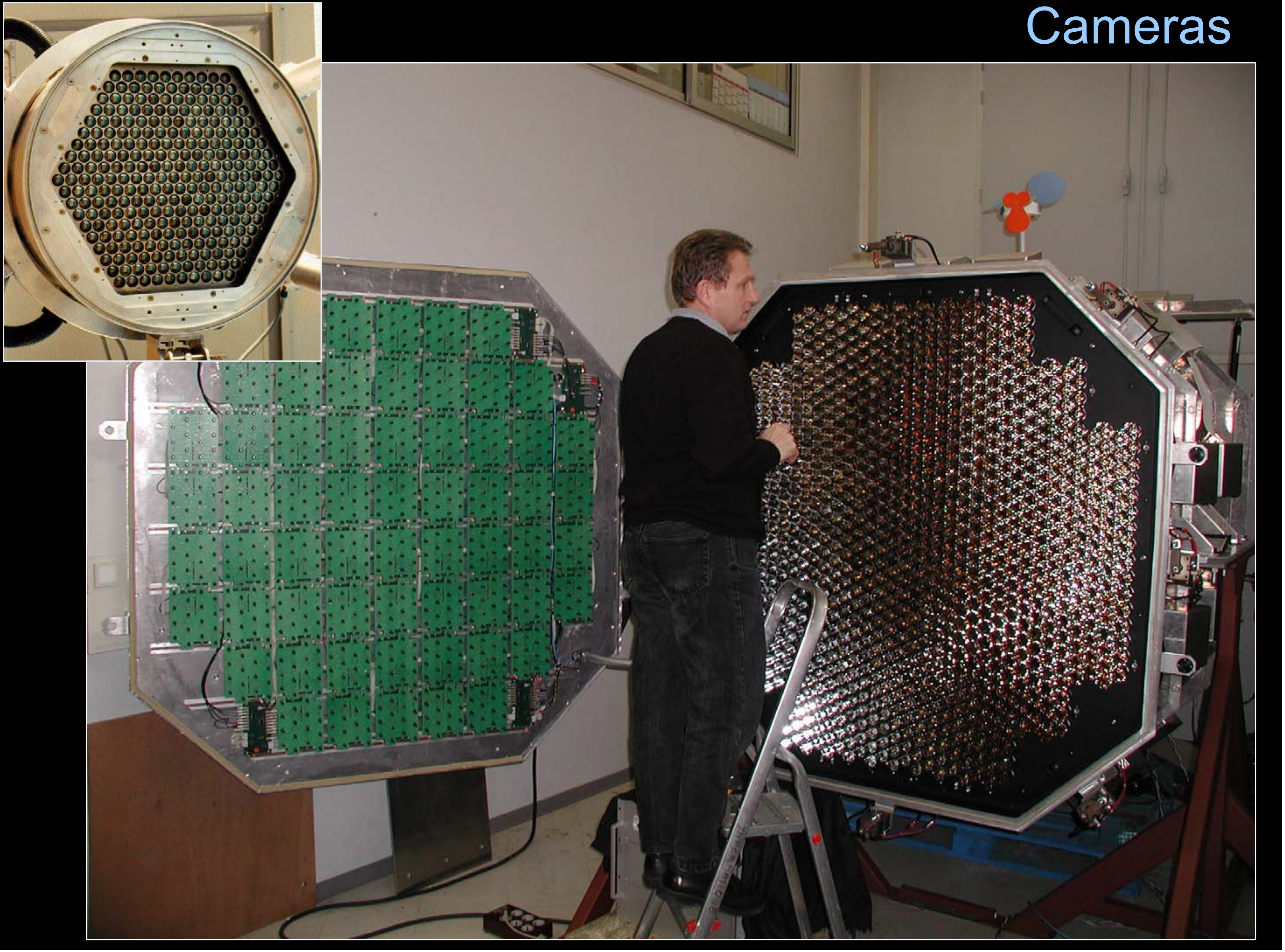


Imaging Cherenkov telescopes

HEGRA & H.E.S.S.



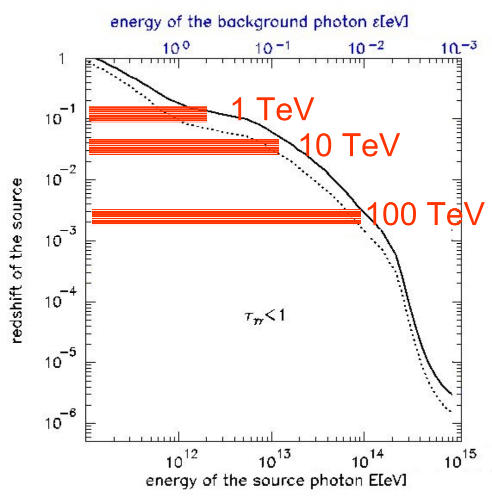
Cameras



Telescope parameters

Telescope	Mirror area (m^2)	Focal length (m)	f/d	Mirror type	PMTs per camera
Whipple	72	7.3	0.7	Glass	37 → 490
CANGAROO I	11	3.8	1.0	Alum.-Polished	256
Durham MK VI	3 x 42	7	1.0	Alum. HC	109 / 19
CAT	18	6	1.2	Ground-Glass	600
HEGRA System	4 x 8.5	5	1.4	Ground-Glass	271
MAGIC	**234**	**17**	**1.0**	**Alum.-Milled**	**577**
CANGAROO III	**4 x 57**	**8**	**0.8**	**Composite**	**427**
H.E.S.S.	**4 x 108**	**15**	**1.2**	**Ground-Glass**	**960**
VERITAS	**7 x 75**	**12**	**1.2**	**Glass**	**499**

Design criteria of next-generation instruments



Low energy threshold

(50-100 GeV for CANGAROO, H.E.S.S., MAGIC,
20-30 GeV for MAGIC)

- Reach to z ~ 1
- High photon rate

Increased photoelectron yield

Small images
High NSB rate per pixel

Large mirror area
(Improved photon detectors)

Small pixels

Cost drivers

At high (TeV) energy

- Large collection area
- Very good angular resolution
- Very good CR rejection

➔ High sensitivity

Highest angular and energy resolution, control of systematics

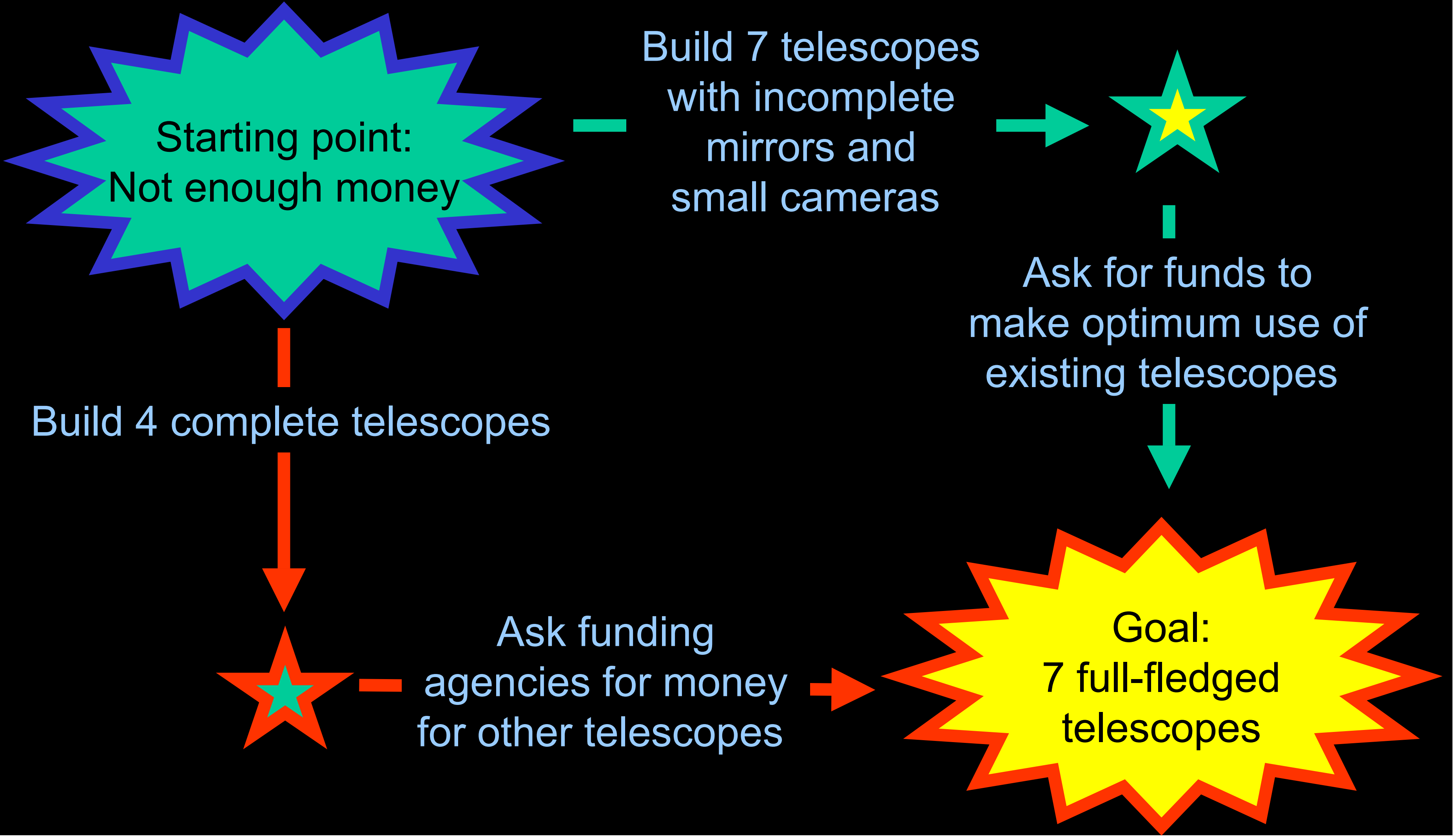
Extended sources & surveys

Stereoscopic CT systems

Cameras with large fov

Complex optimization strategies…

(My interpretation of) the VERITAS strategy:



Starting point:
Not enough money

Build 7 telescopes
with incomplete
mirrors and
small cameras

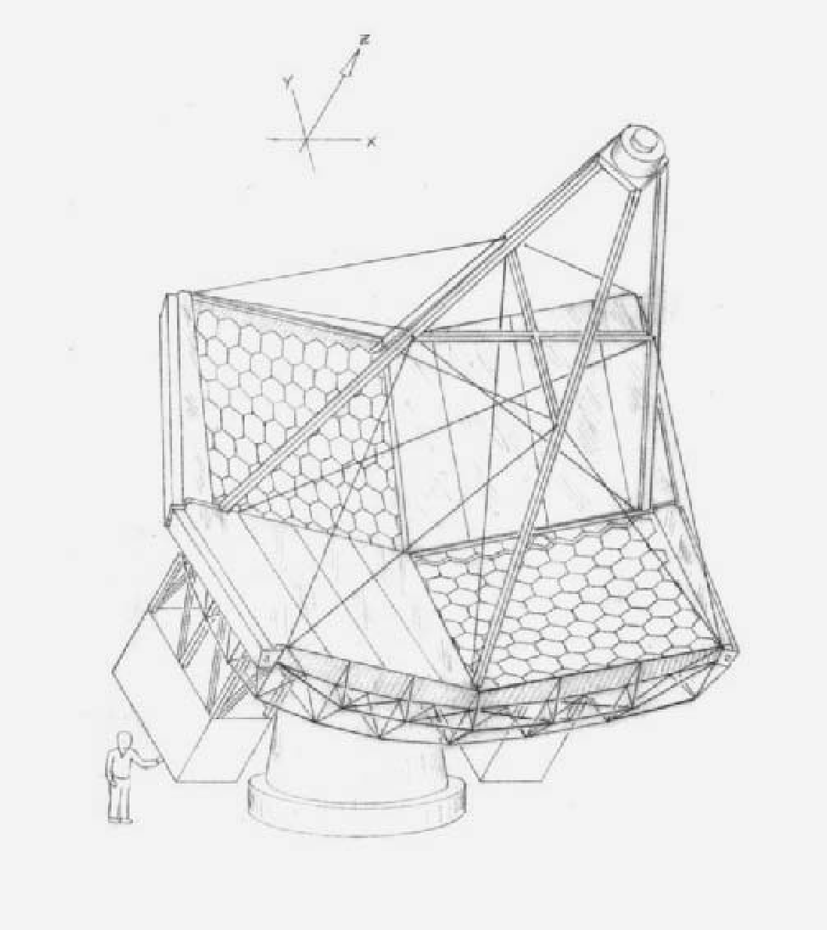
Ask for funds to
make optimum use of
existing telescopes

Build 4 complete telescopes

Ask funding
agencies for money
for other telescopes

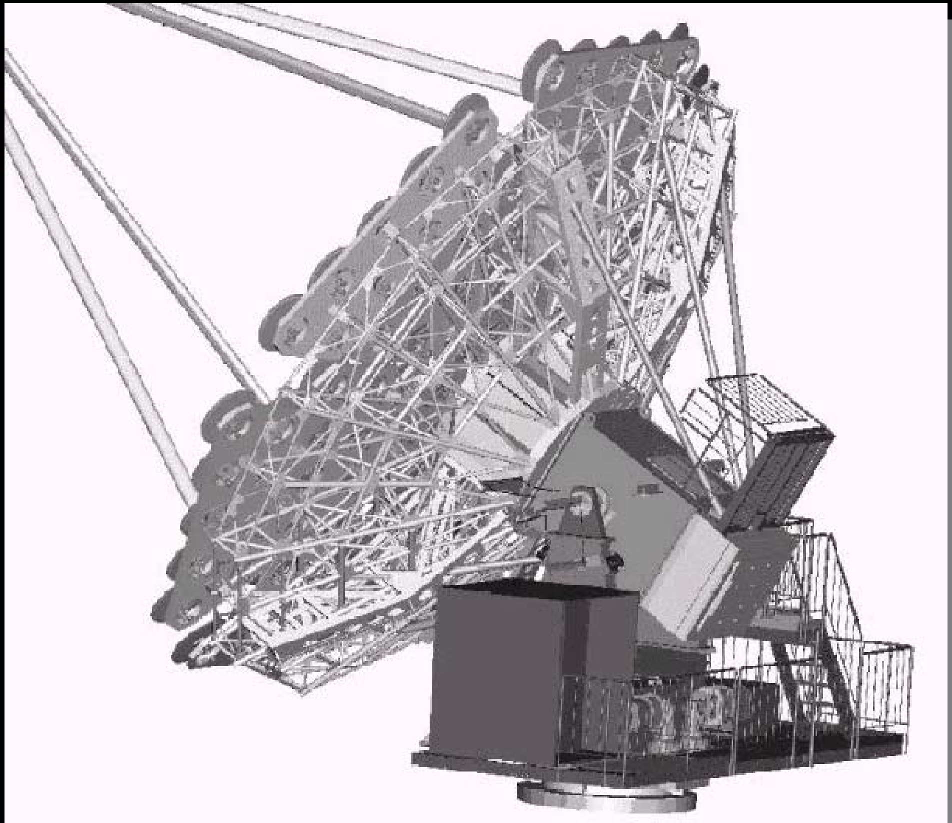
Goal:
7 full-fledged
telescopes

Mount and Dish



VERITAS

Welded-steel structure,
commercial positioner
Cost optimized

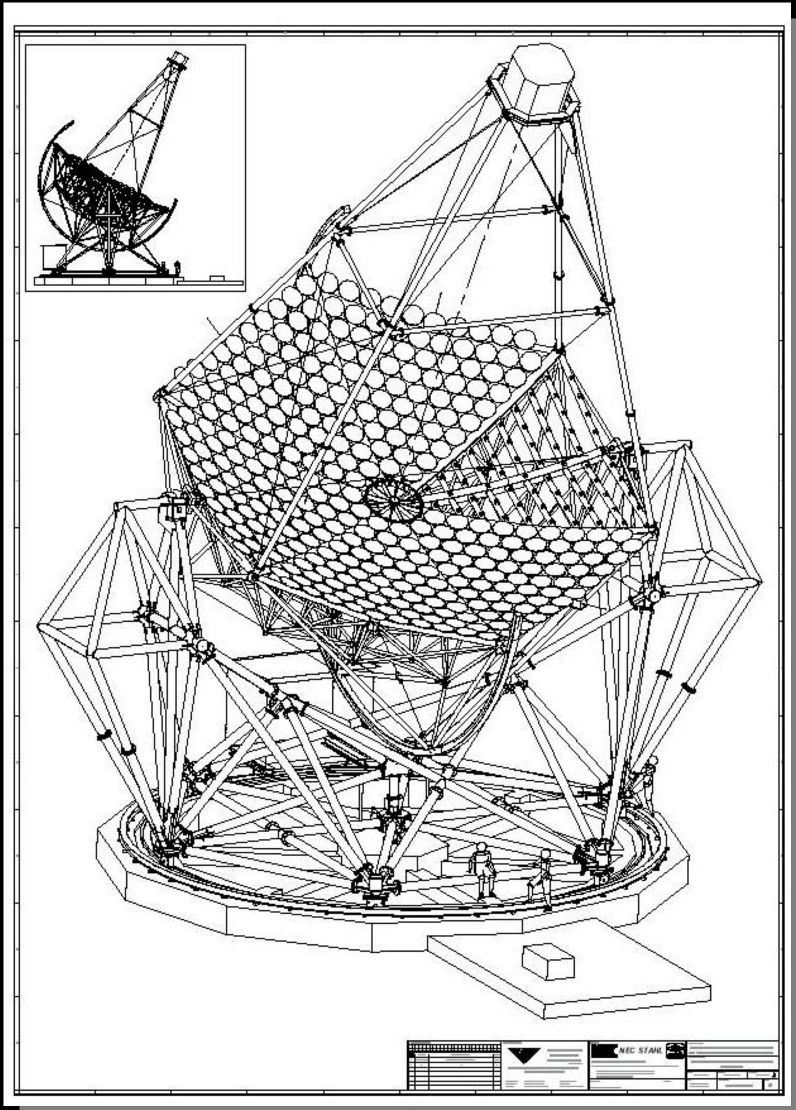


CANGAROO

H.E.S.S.

Steel spaceframe (welded)

Cost optimized

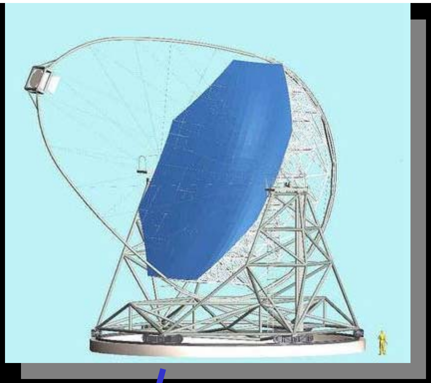


MAGIC

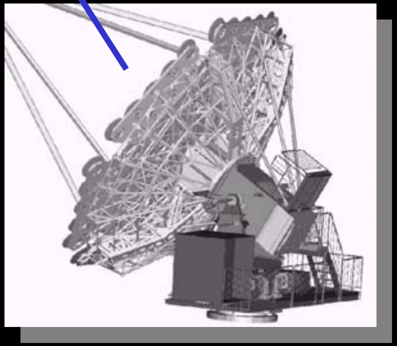
Carbon fibre spaceframe (MERO, screwed) , permanent active mirror control

Optimized for fast slewing (GRB hunting)

Mount and dish parameters



	Mirror area (m^2)	Weight (t)	Slew speed (degr./min)
MAGIC	234	40	**> 300**
H.E.S.S. (4 Tel.)	108	60	100
VERITAS (7 Tel.)	75	16	30/60
CANGAROO III (4 Tel.)	57	~8	?



Mirrors and optics

Parameters of optical systems

	Reflector	f/d	# of mirror tiles	Material	Shape	Align- ment
MAGIC	Parabolic	1.0	936	Milled aluminum comp. anodized	square	Motors
H.E.S.S.	Davies-Cotton	1.2	382	Ground glass, alumin., quartz coated	round	Motors
VERITAS	Davies-Cotton	1.2	~ 300	Glass, aluminized, anodized	hex	Manual
CANGAROO III	Parabolic	0.8	114	Composite, aluminum, fluoride coated	round	Motors

Davies-Cotton

- better off-axis imaging
- Same focal length for all mirror elements

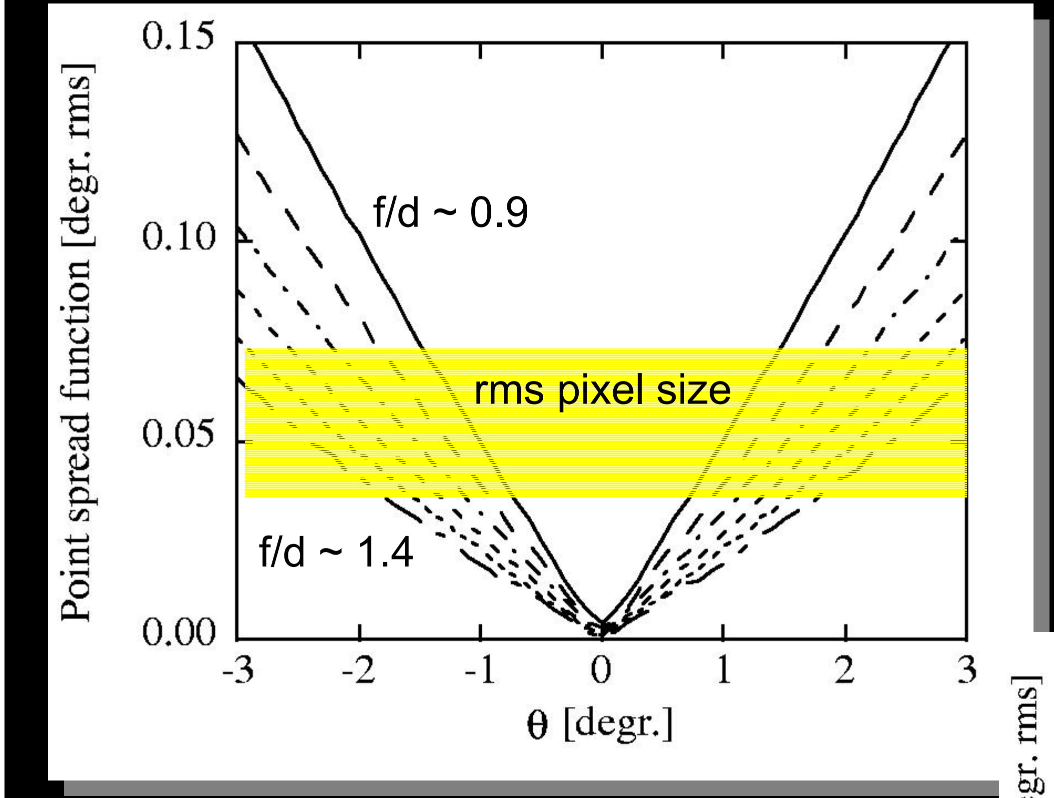
Parabolic

- Minimizes time dispersion of photons

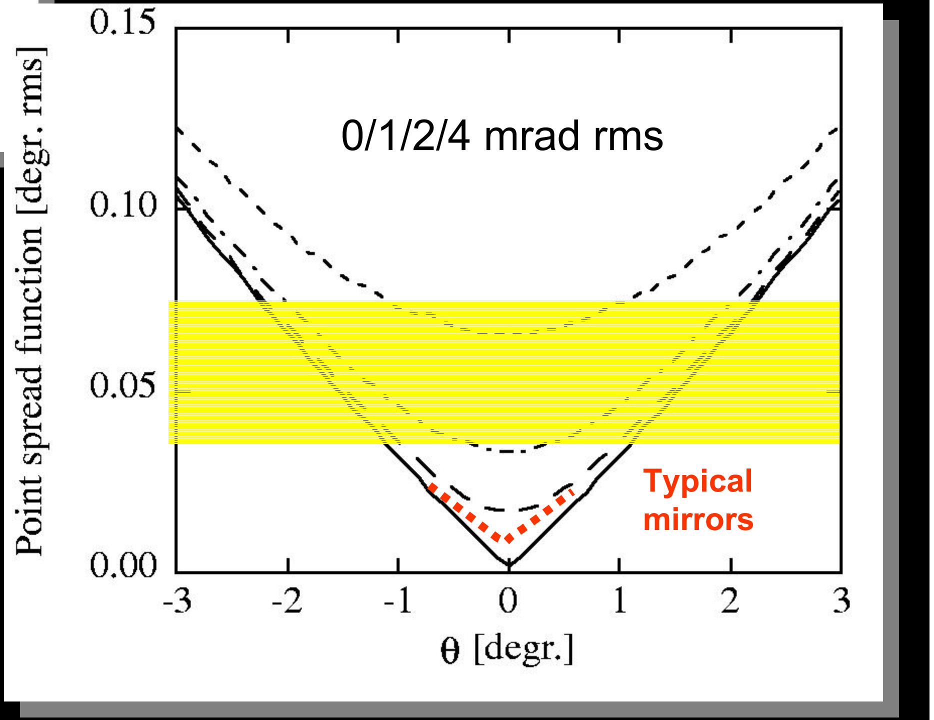
Composite / aluminum mirrors are lightweight

Square or hex mirrors Allow full area coverage

Mirror point spread function

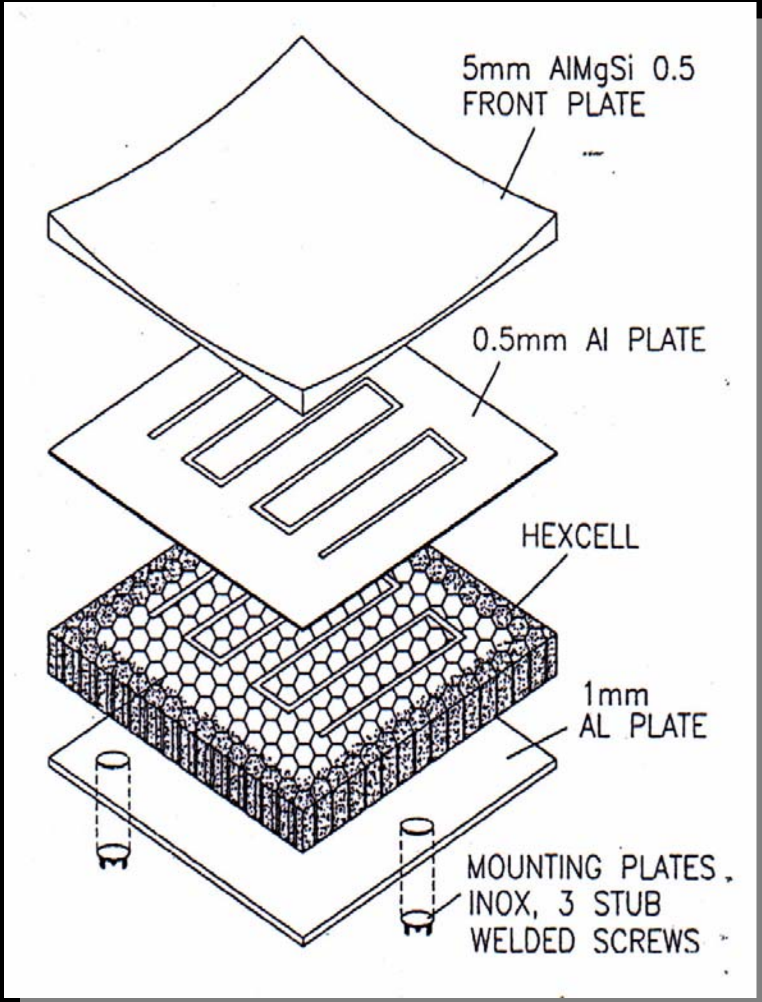


Effect of f/d

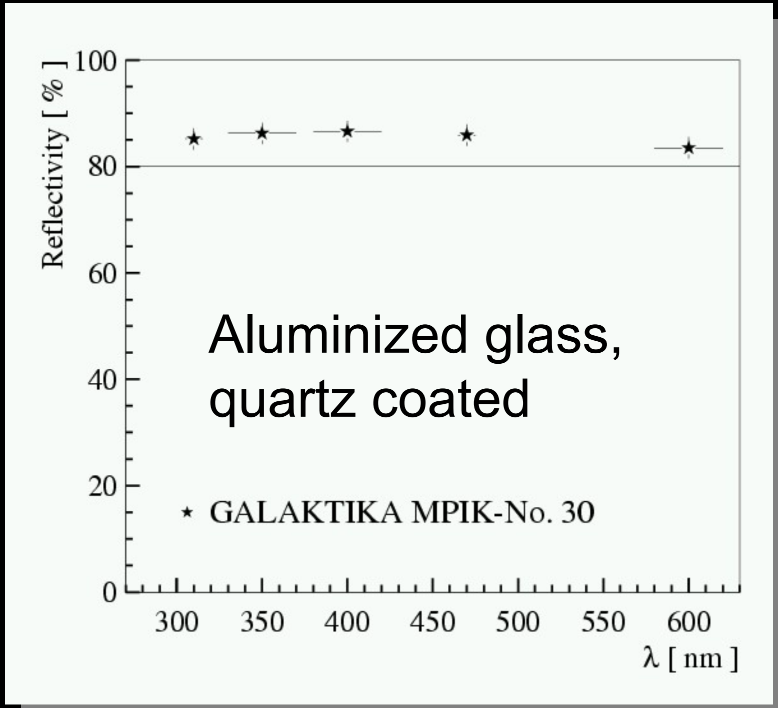


Effect of mirror quality

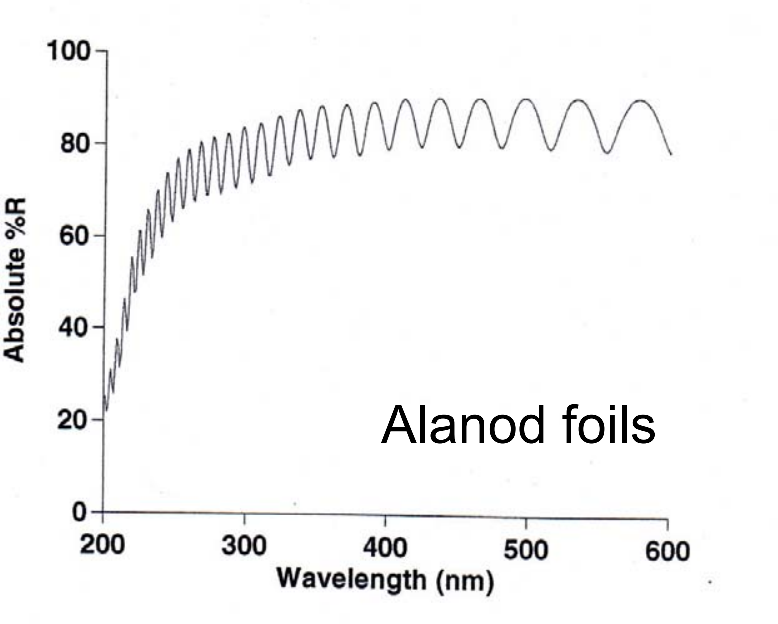
Reflector materials



MAGIC

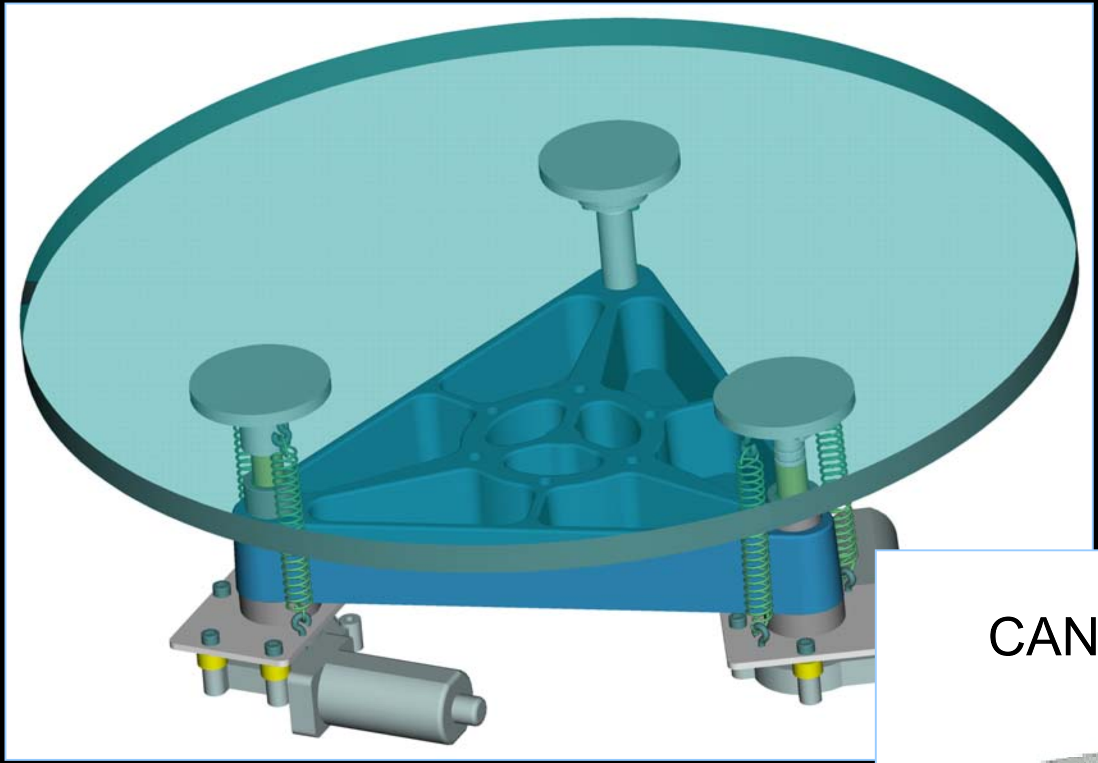


Aluminized glass, quartz coated



Alanod foils

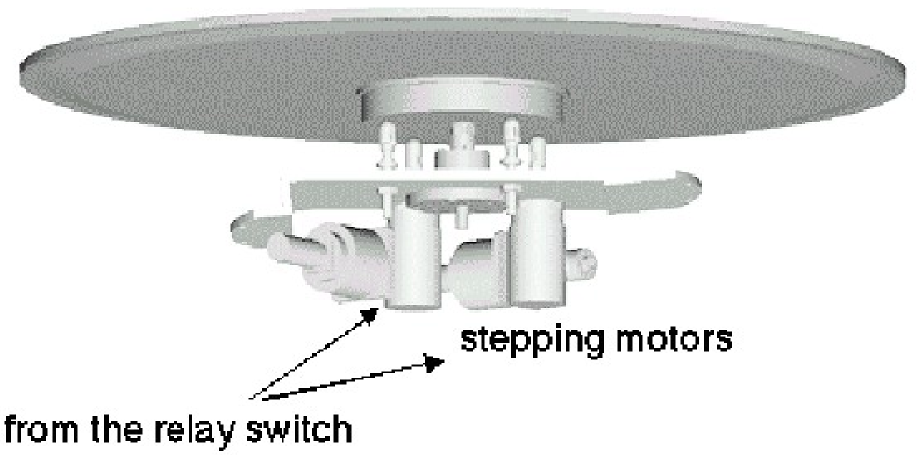
Mirror alignment

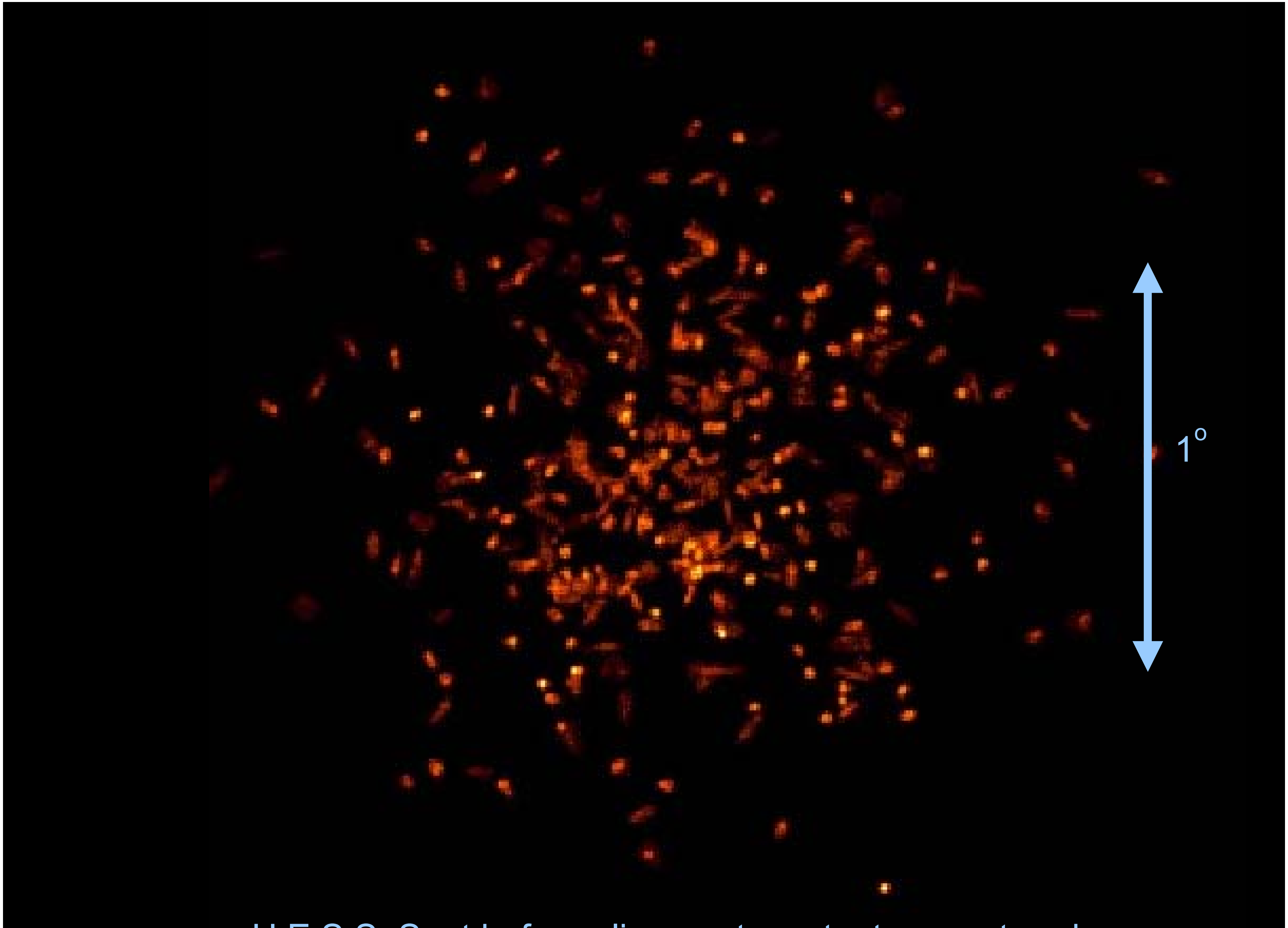


Mostly motor-driven actuators with encoders, remote-controlled by a CCD viewing the image

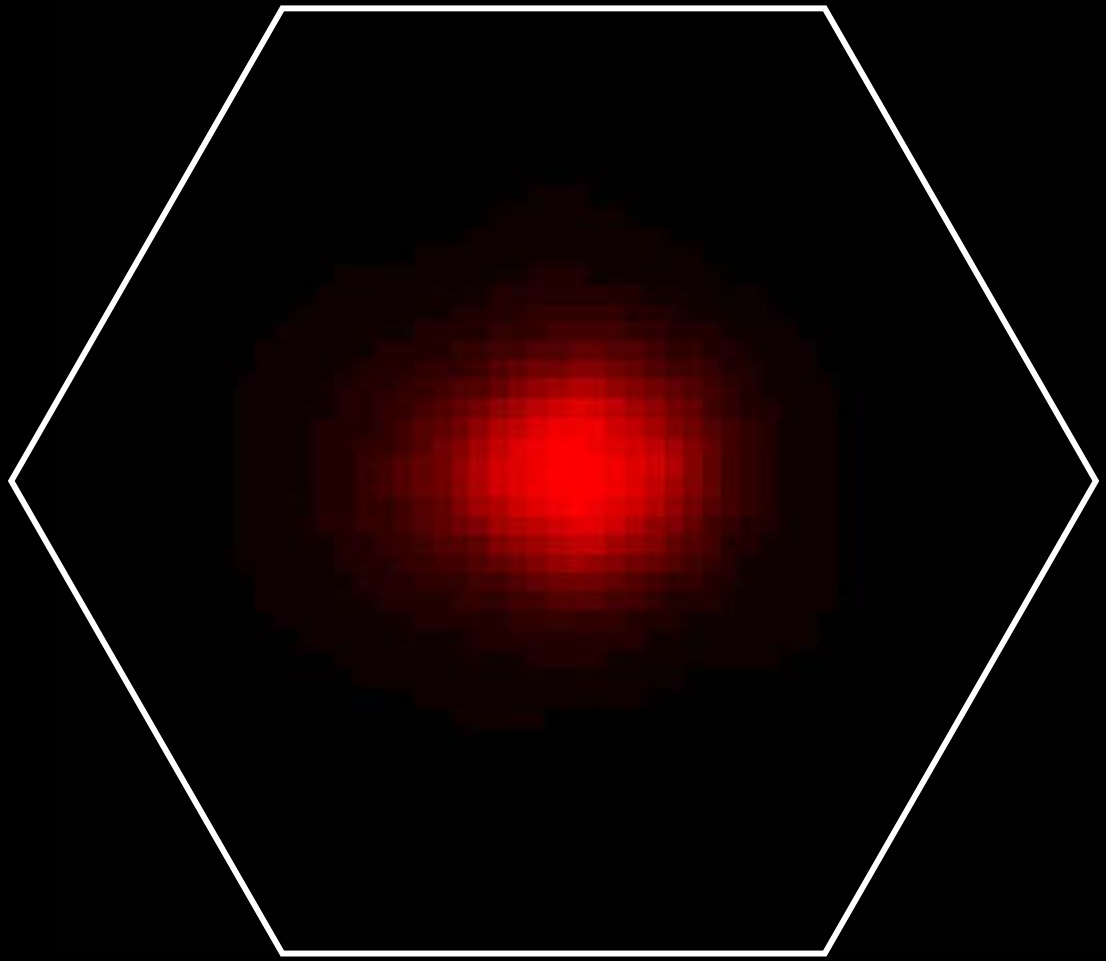
H.E.S.S.:
Typical accuracy 0.01 mrad rms, compared to single-mirror spot size of about 0.2 mrad rms

CANGAROO II



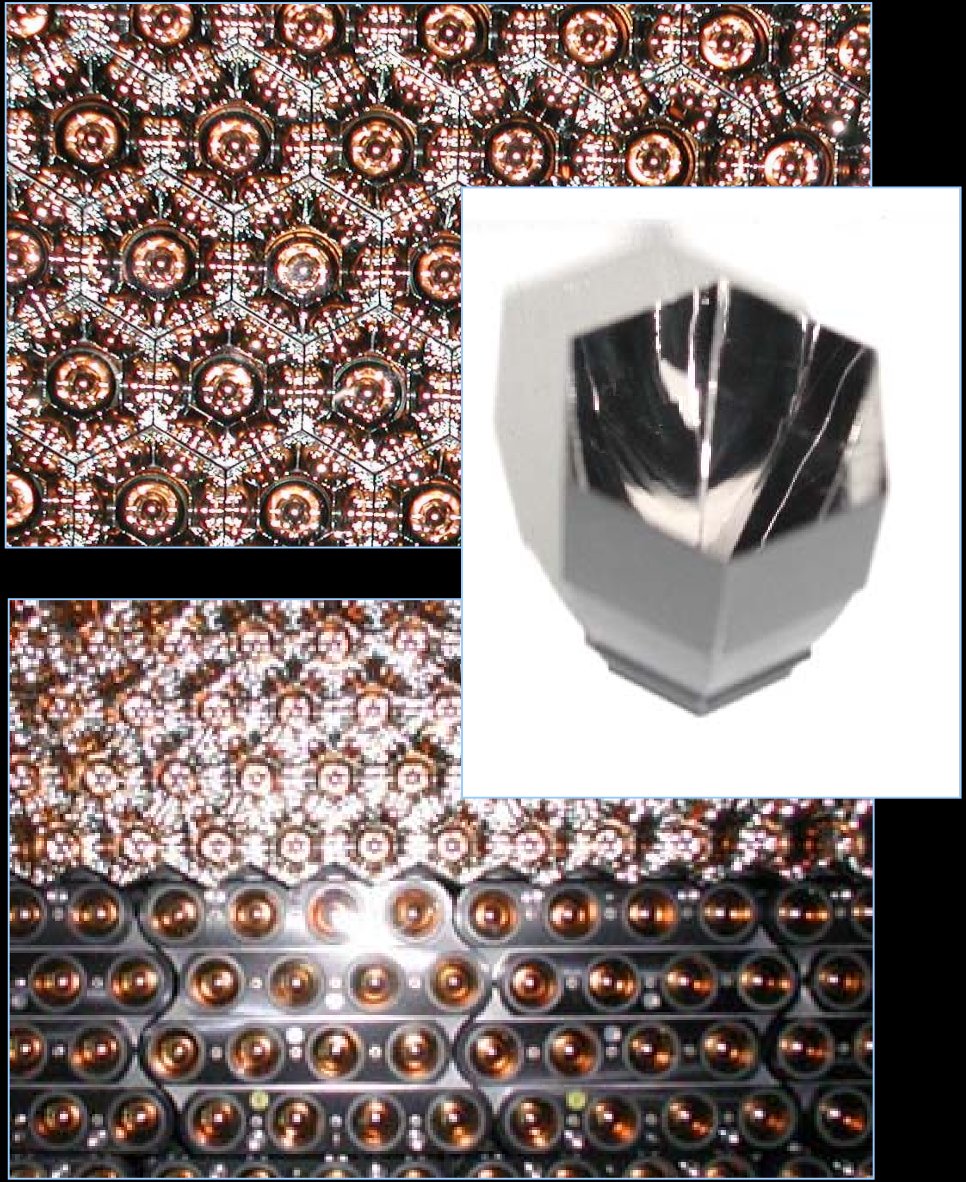


H.E.S.S. Spot before alignment – actuators centered



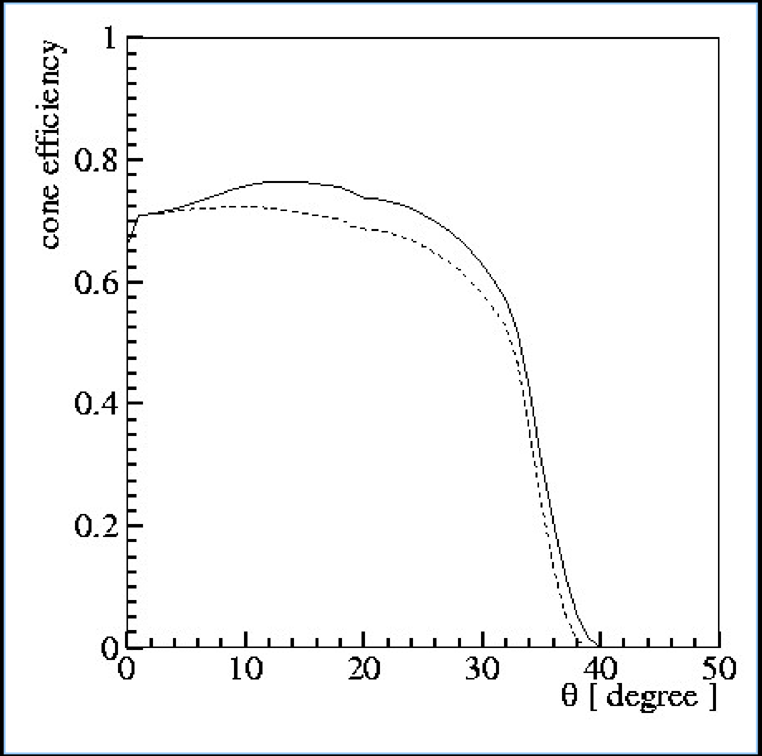
Pixel size

Winston cones for light collection

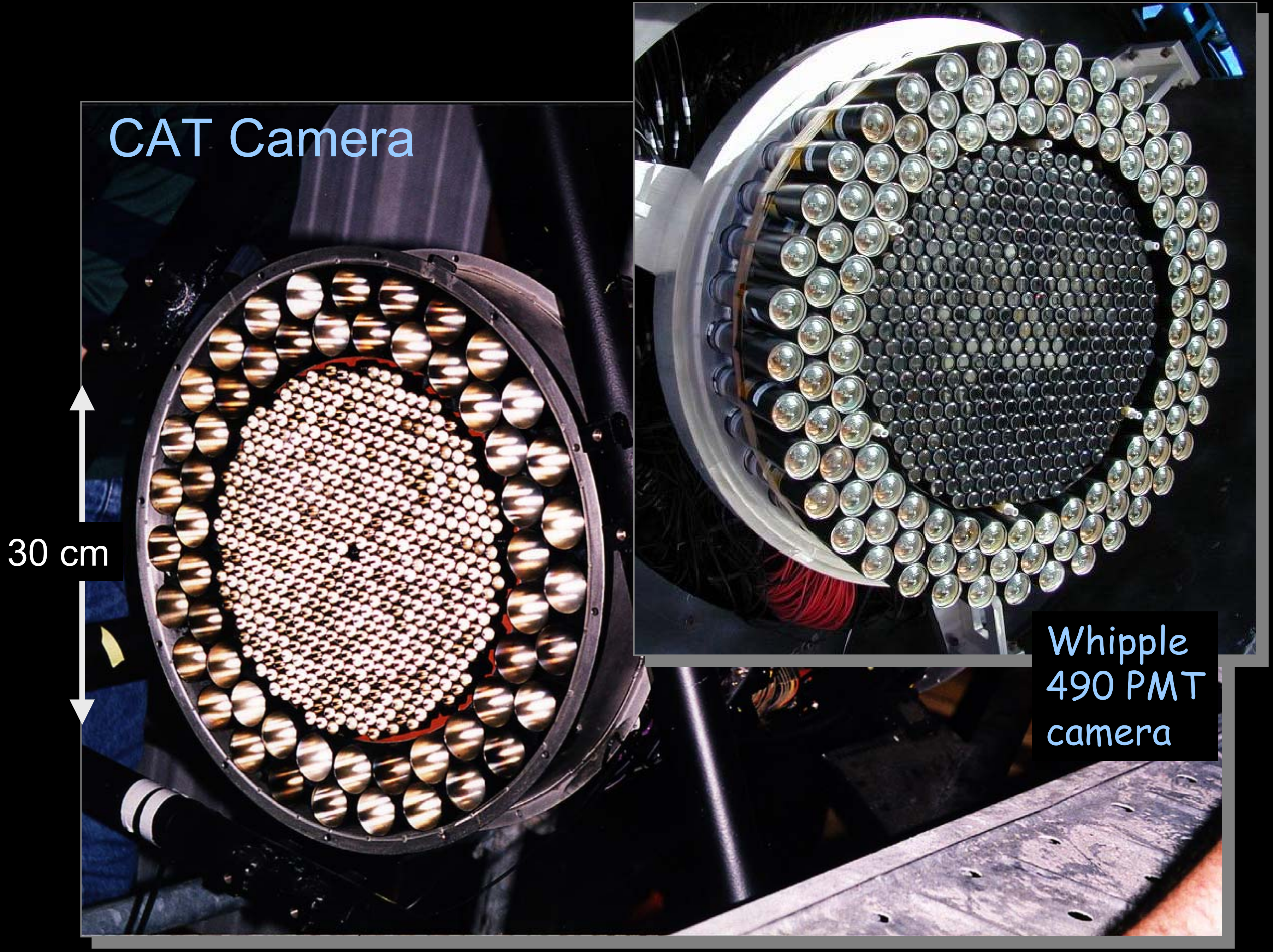


Winston cones serve to

- improve light collection
- limit the field of view of a pixel and reduce albedo



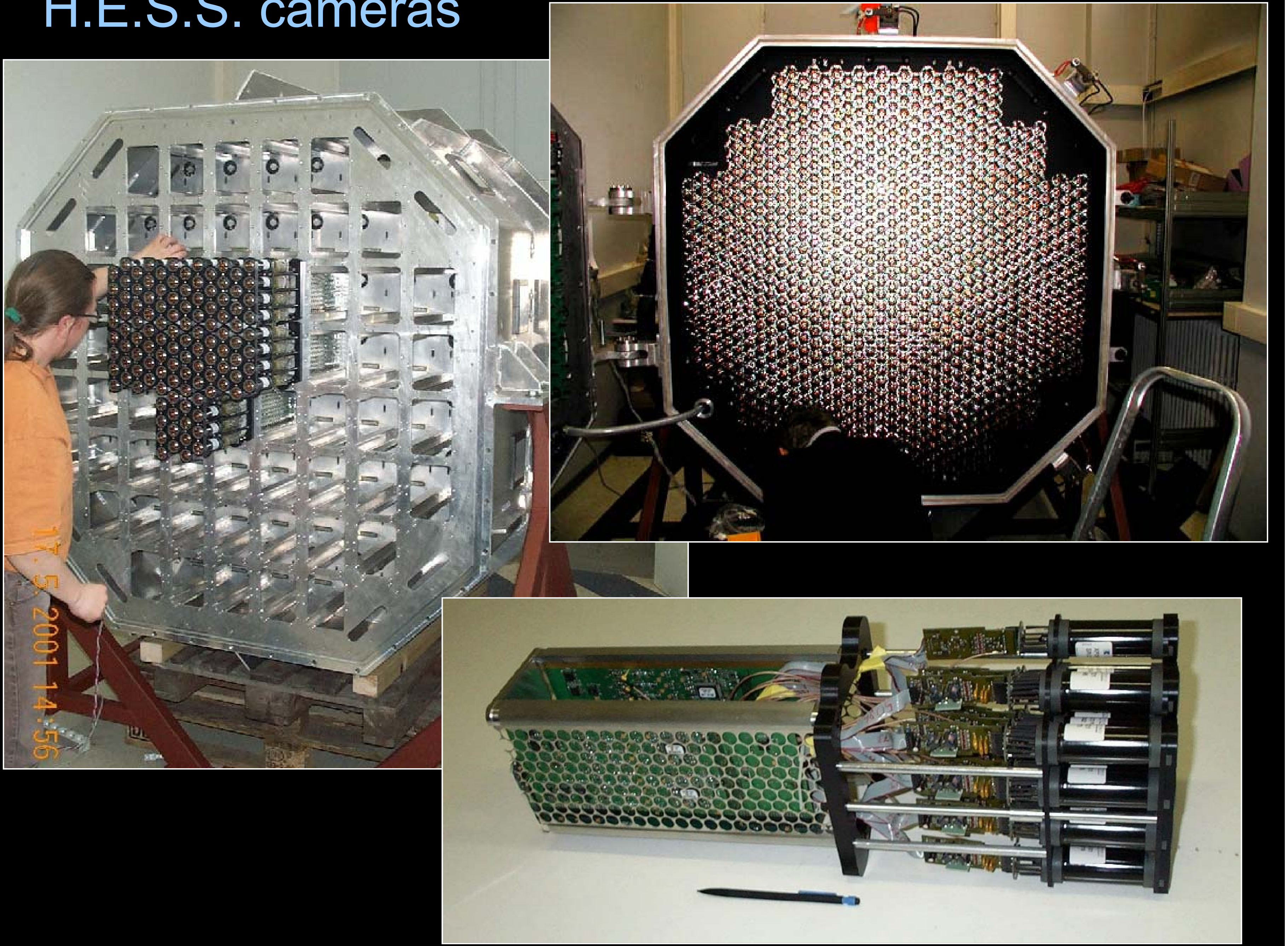
Cherenkov Cameras



CAT Camera

Whipple
490 PMT
camera

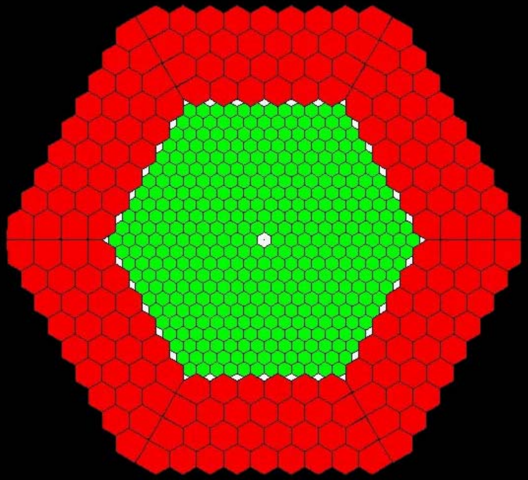
H.E.S.S. cameras



Camera characteristics

Telescope	**Year**	**PMTs per camera**	**Pixel size (degr.)**	**F.o.V. (degr.)**	**Signal transm.**	**Readout**
Whipple	1983	37	0.5	3.5	cable	ADC
CANGAROO I	1992	**220**	**0.18**	3.0	cable	ADC+TDC
Durham MK VI	1995	91 + 18	0.25 / 0.5	~ 2.8 / 3.8	cable	ADC
CAT	1996	**546** + 54	**0.12** / 0.4	3.1 / 4.8	cable	ADC
HEGRA	1996	271	0.25	**4.3**	cable	**120 MHz FADC**
Whipple	1997	331	0.25	**5.0**	cable	ADC
Whipple	1999	379 + 111	**0.12** / 0.24	2.6 / 4.0	cable / fiber	ADC
CANGAROO III	2000/ 2002	427	0.17	4.0	cable	ADC+TDC
MAGIC	2002	396 + 180	**0.1** / 0.2	2.2 / 3.9	**opt. fiber**	300 MHz FADC
H.E.S.S.	2002	**960**	0.16	**5.0**	electronics in camera	**1 GHz ARS** / ADC
VERITAS	2003	499	0.15	3.5	cable	**500 MHz FADC**

Camera characteristics



Pixel size , uniform field of view

CANGAROO, H.E.S.S., VERITAS ~0.16° uniform

MAGIC 0.1° in central part, 0.2° outside

Pro small pixels: Performance

Con: Cost

Electronics in camera (H.E.S.S.)

Pro: Speed, minimizes connections, components

Con: Access, flexibility, upgrade options

Optical links for transmission of PMT signals (MAGIC)

Pro: Performance, weight

Con: Cost, complexity

Recording of signal shape (MAGIC 300 MHz, VERITAS 500 MHz)

Pro: (Slight?) performance gain

Con: Cost, data rate & data storage

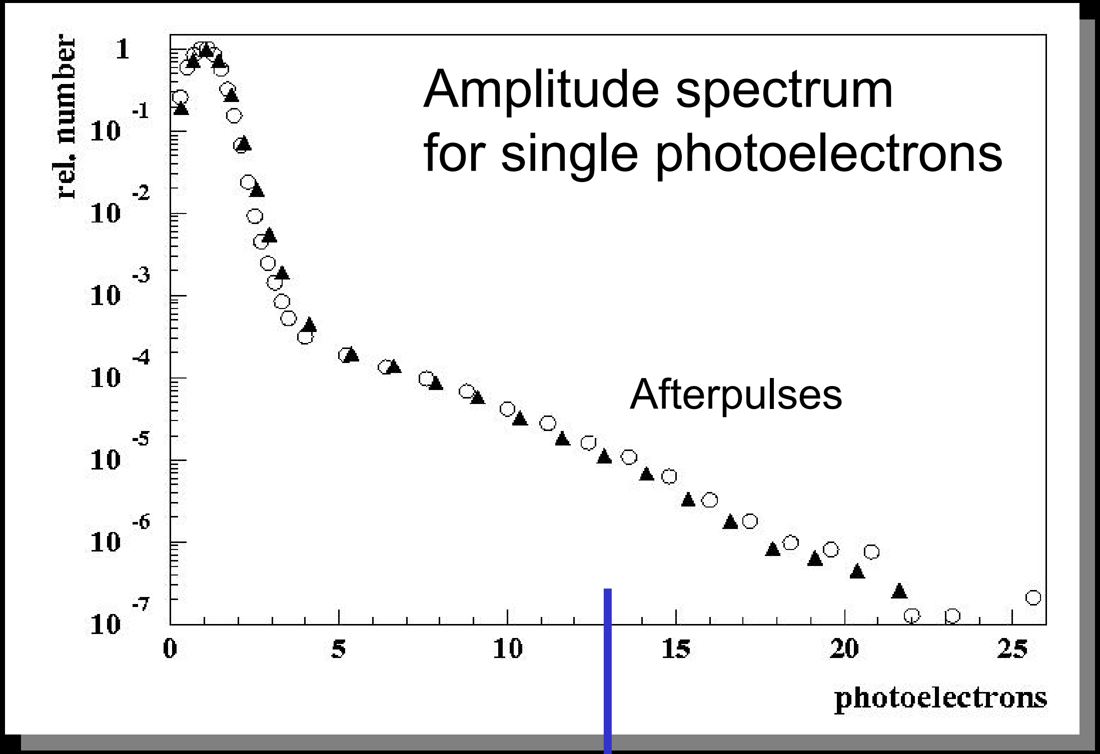
(H.E.S.S. ARS analog 1 GHz sampler, only sum read out)

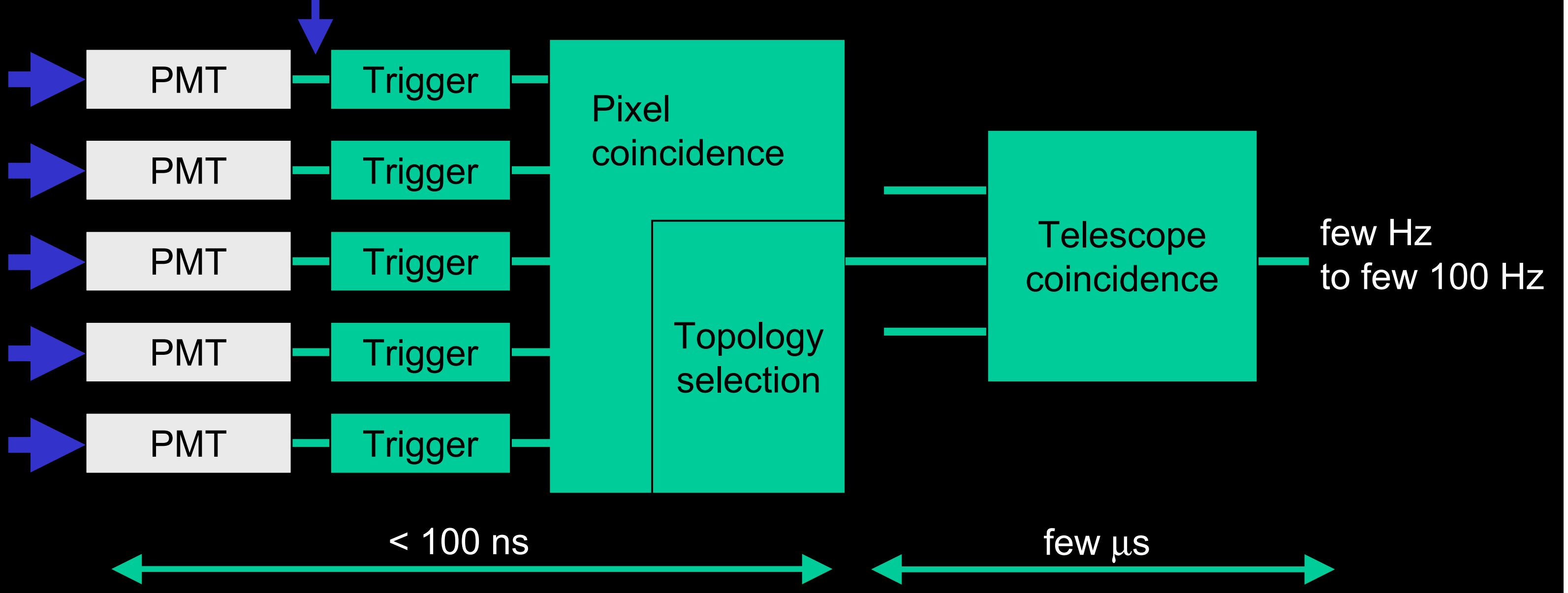
Triggering Imaging Cherenkov telescopes

Skip topic

Example: the HEGRA trigger

N. Bulian et al.,
Astropart. Phys. 8 (1998) 223





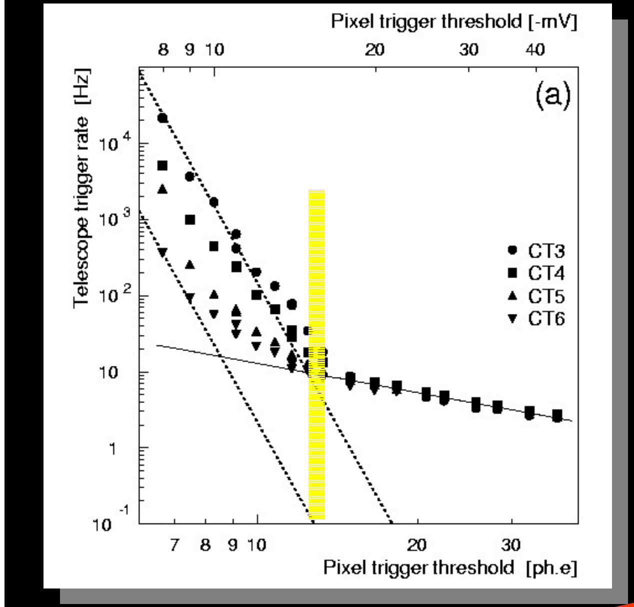
few 10 MHz
to few 100 MHz
photoelectron
rate

few Hz
to few 100 Hz

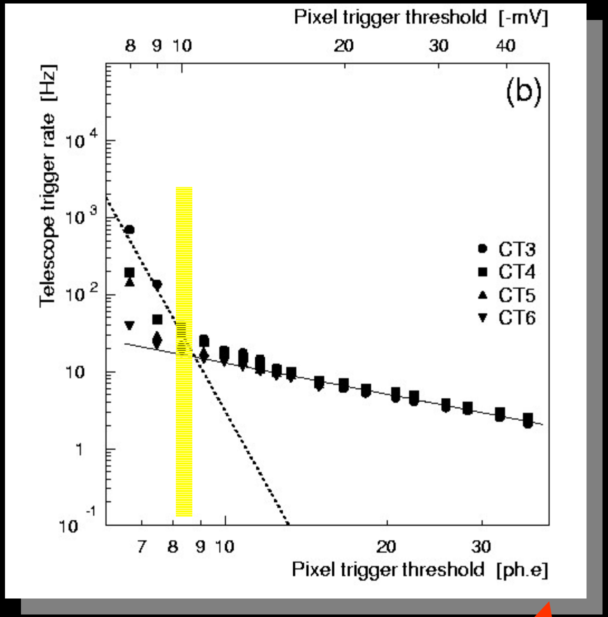
< 100 ns

few μs

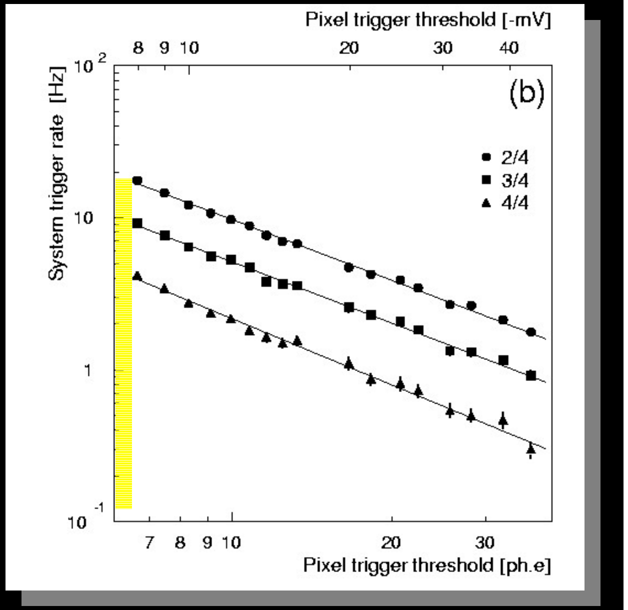
Coincidence of any 2 of 271 pixels

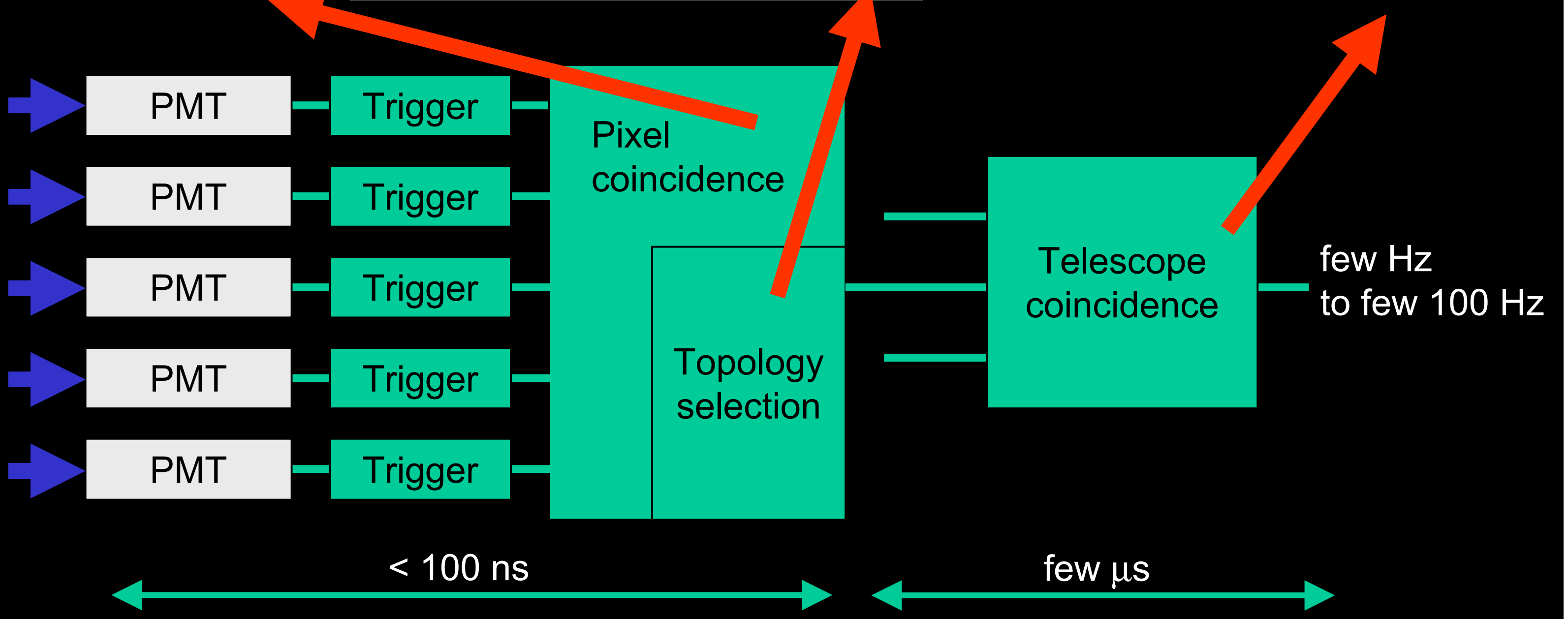


Coincidence of any 2 neighbor pixels



Coincidence of any 2 telescopes





few 10 MHz
to few 100 MHz
photoelectron
rate

PMT

Trigger

Pixel coincidence

Topology selection

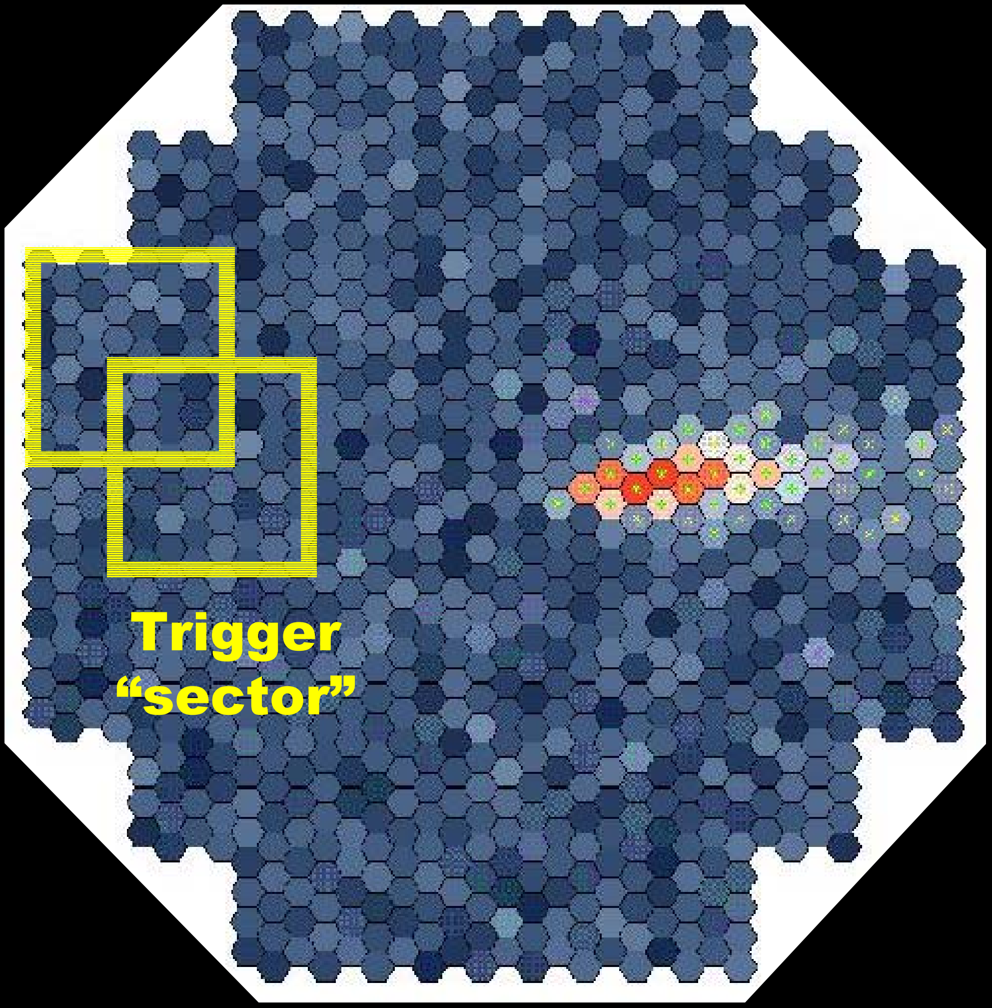
Telescope coincidence

few Hz
to few 100 Hz

< 100 ns

few µs

H.E.S.S. Trigger scheme



n = 3,4,5... pixels within an 8x8 pixel "sector" above a certain threshold (3...6 photoelectr.)

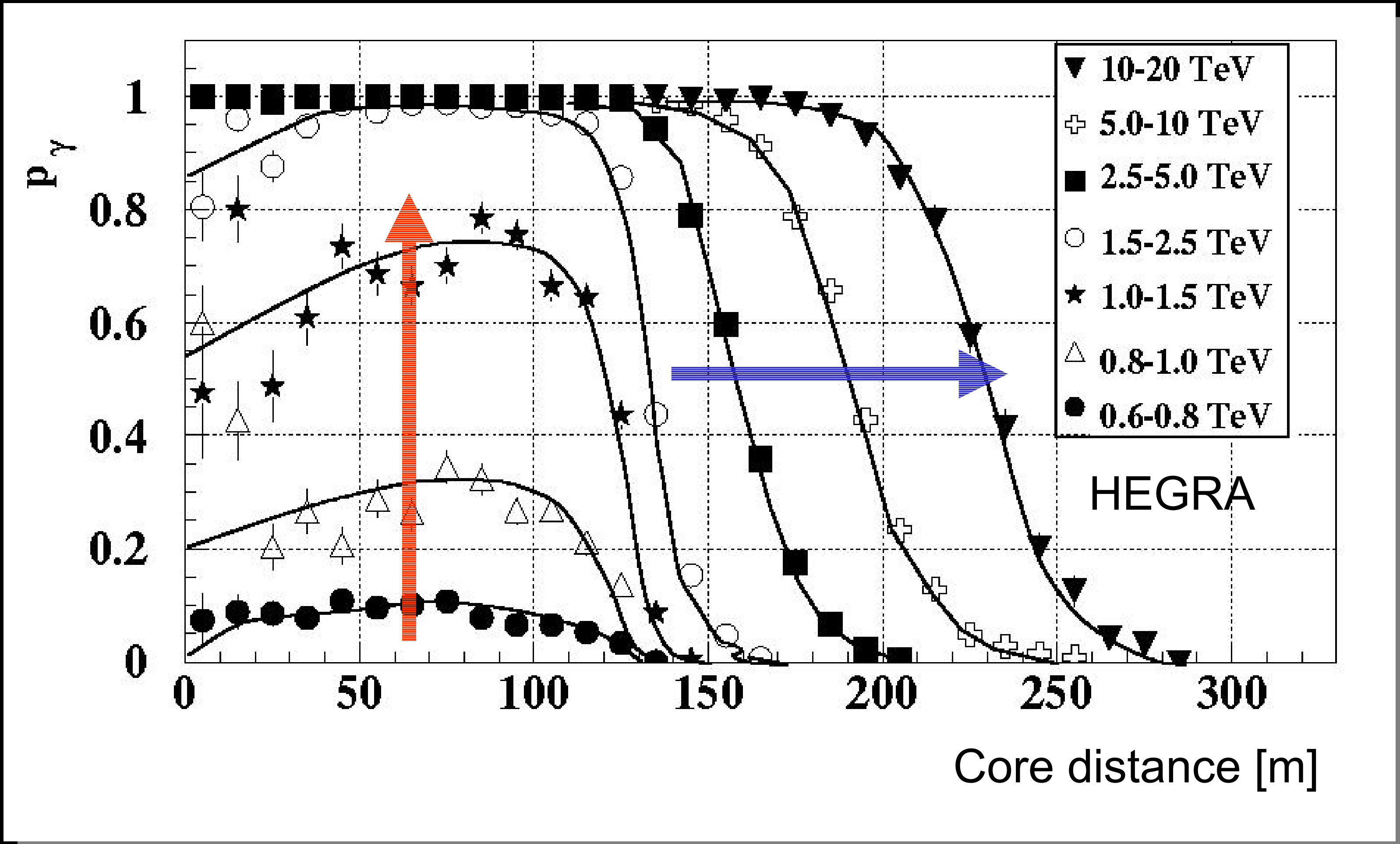
Coincidence window ~1.5 ns; low random rates

MAGIC, VERITAS: digital pattern logic

Single-telescope rates

Gamma (Crab)	~ 1 Hz
CR	~ 1000 Hz
Electrons	~ 2 Hz
Muons	~ 100 Hz
NSB	few Hz

Detection probability



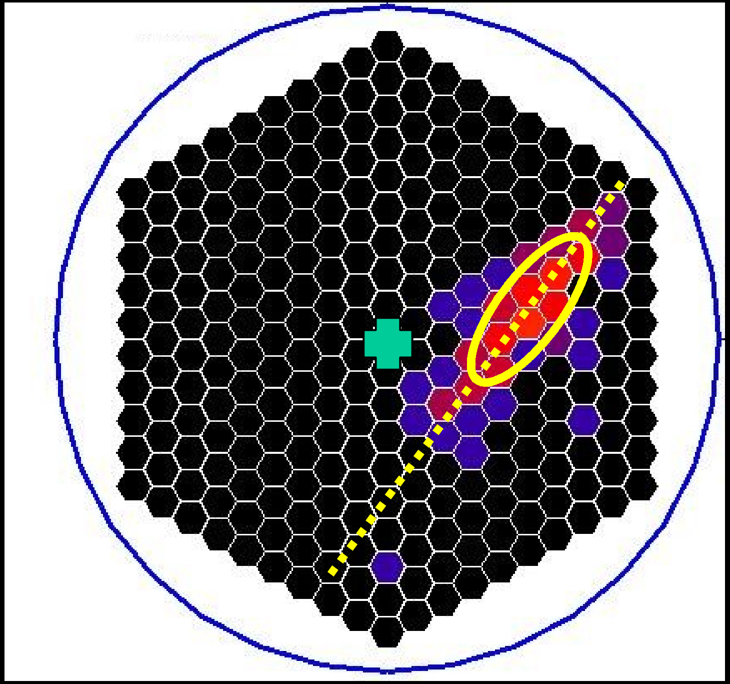
Threshold region

High-energy region

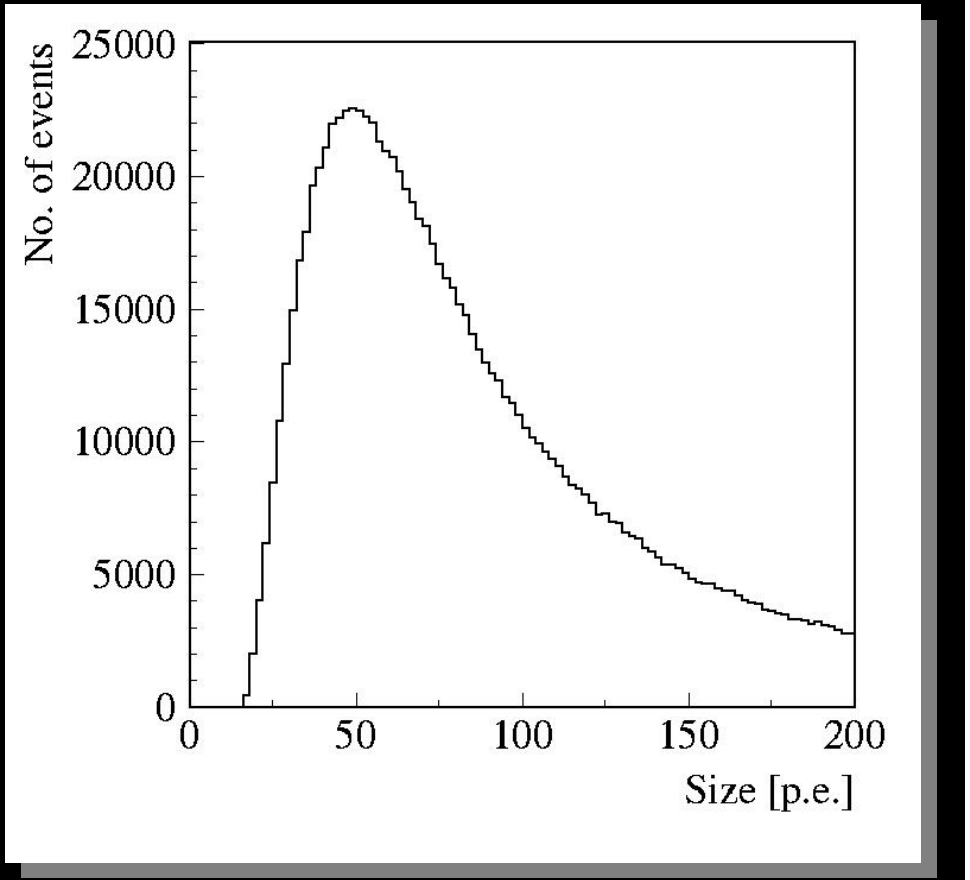
Data analysis techniques

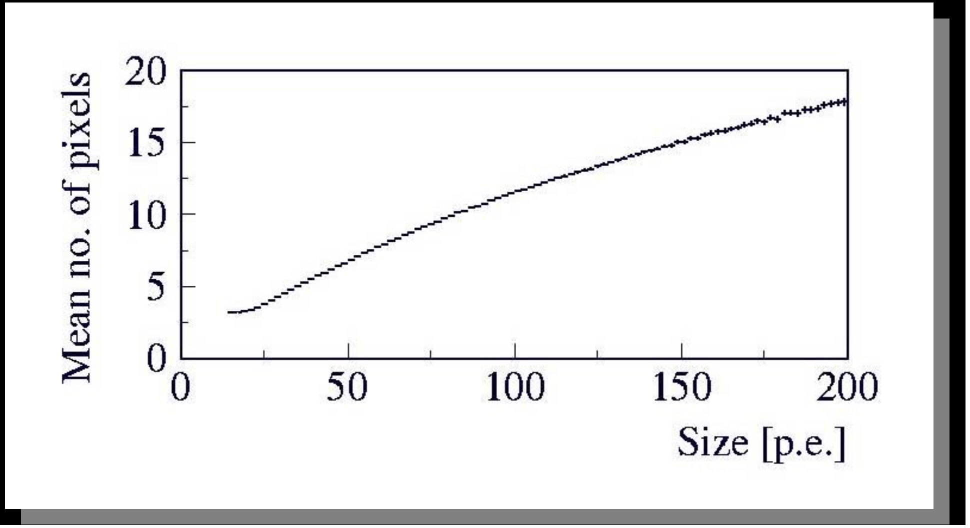
Image analysis

Hillas parameters:
width, length, ...

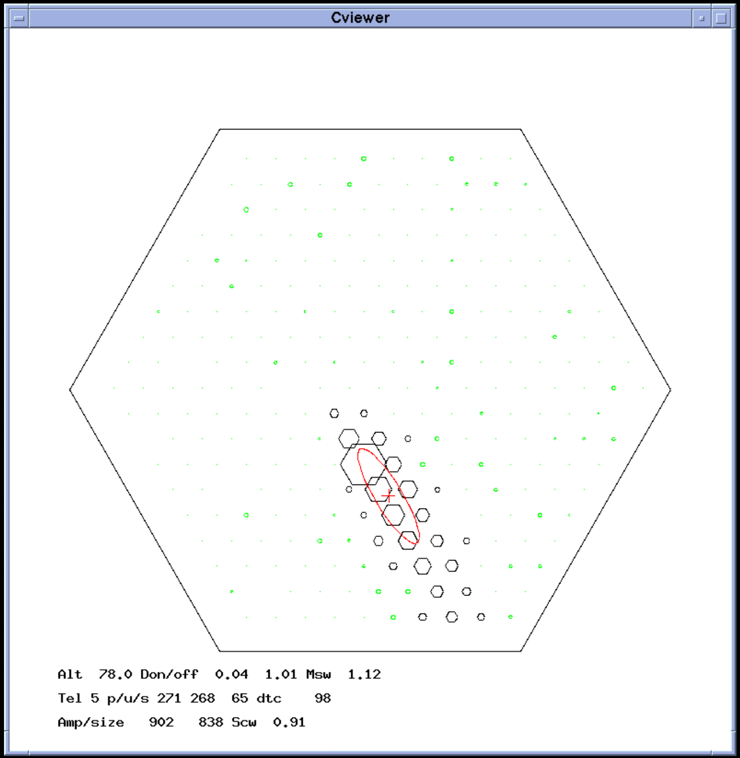


Note: typical images are small
50 - 100 p.e.
5 – 10 pixels



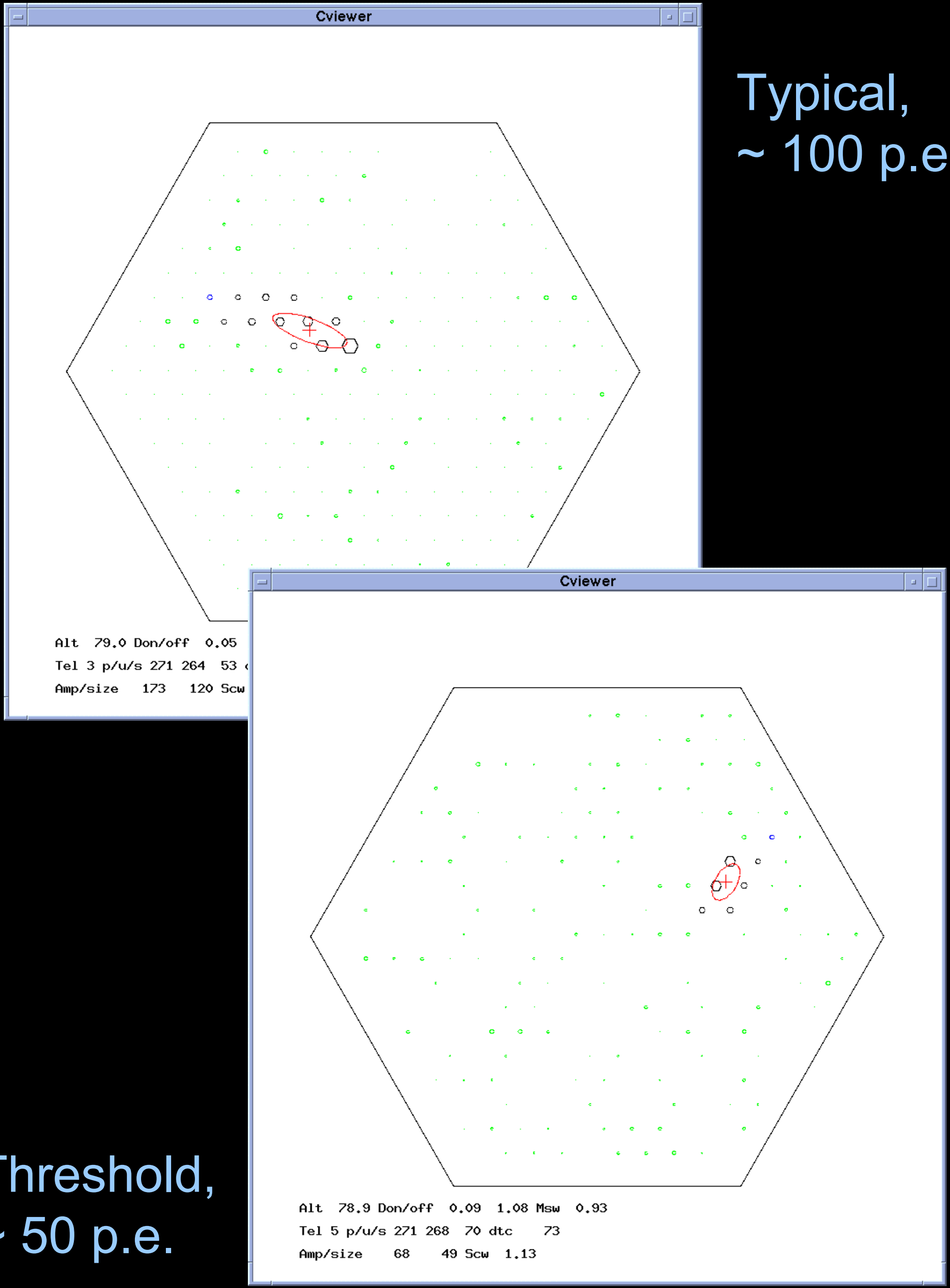


Images



```
Alt  78.0 Don/off  0.04  1.01 Msw  1.12
Tel 5 p/u/s 271 268  65 dtc    98
Amp/size   902   838 Scw  0.91
```

Usually shown



```
Alt  79.0 Don/off  0.05
Tel 3 p/u/s 271 264  53
Amp/size   173   120 Scw
```

```
Alt  78.9 Don/off  0.09  1.08 Msw  0.93
Tel 5 p/u/s 271 268  70 dtc    73
Amp/size    68    49 Scw  1.13
```

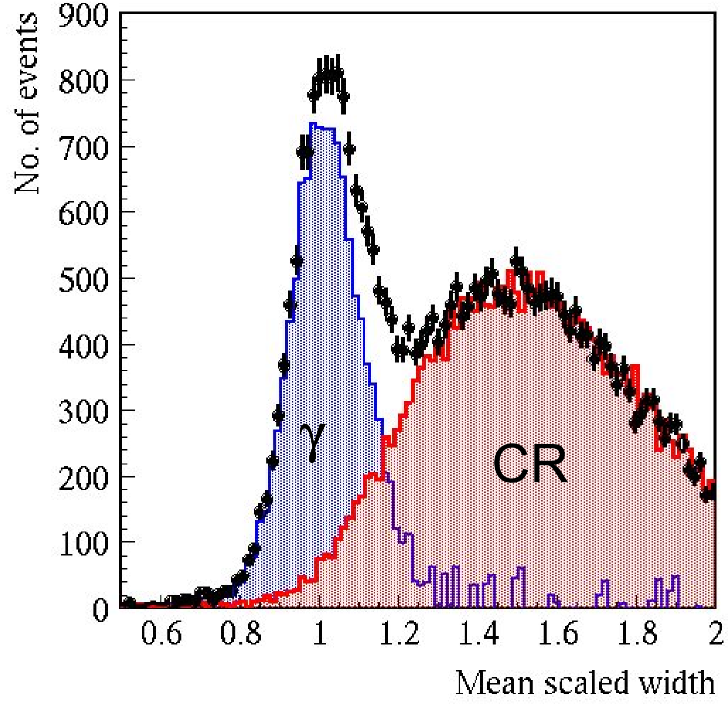
Typical,
~ 100 p.e.

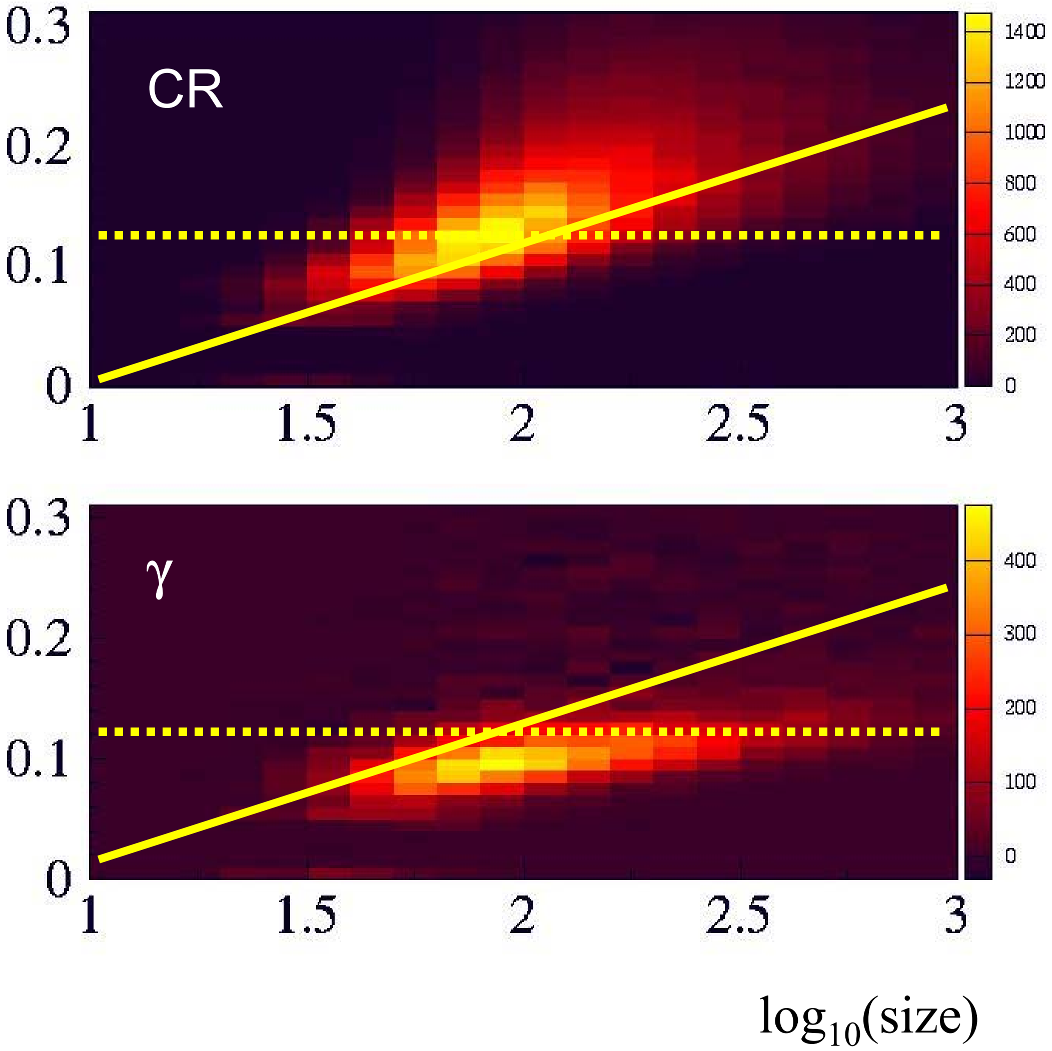
Threshold,
~ 50 p.e.

Cosmic-ray rejection using shape parameters

Simple cuts
and
“Supercuts”

Scaled width





Improved techniques for cosmic ray rejection

Using shape parameters

- Alternative shape parameters
- Multidimensional probability distribution for parameters
- Kernel analysis
- Neural networks fed with image parameters …

Using the full pixel information

- Image fits using shower templates
- Fits of transverse shape of image
- Neural networks fed with pixel data
- Fluctuation analysis
- Fractal parameters…

Using

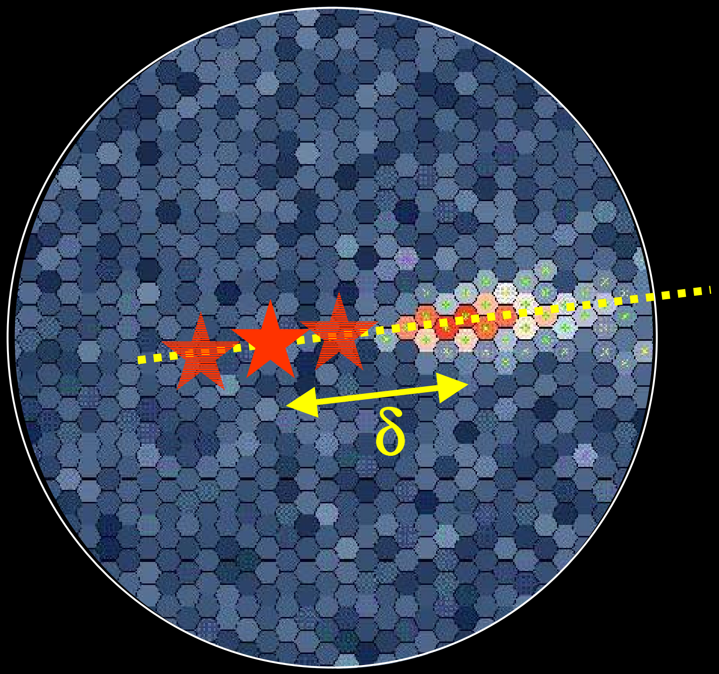
- Pixel timing
- Polarization
- UV content …

Note:

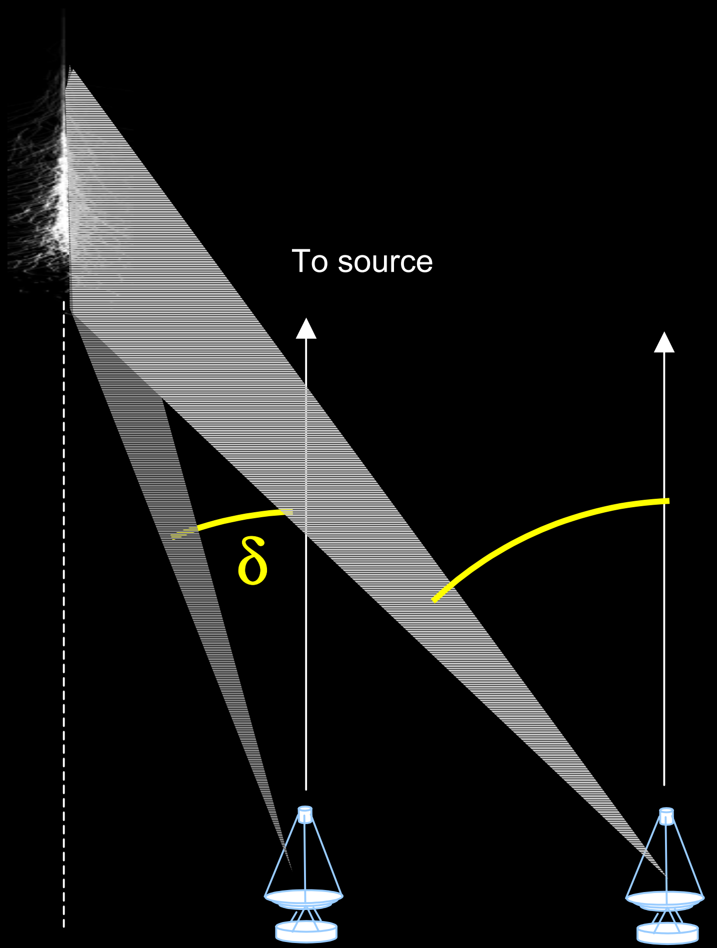
Significance of signal
~ # of events / √ background
~ $\varepsilon_\gamma / \sqrt{\varepsilon_{CR}}$

No “killer application” yet ...
most variants are at most 20-30% better than Hillas parameters
and much more complicated and sensitive to instrumental effects

Single-telescope analysis

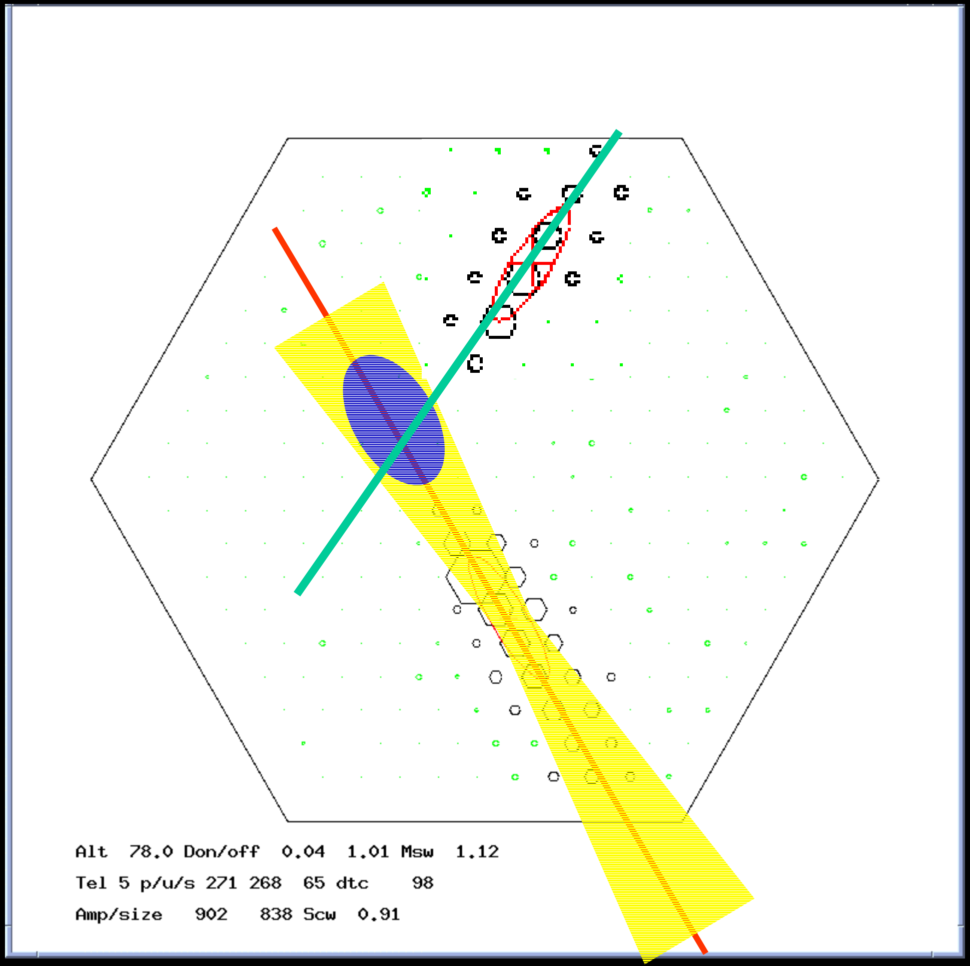


Use length of image, $L \sim \delta$
(and $\delta = d_{core}/h_{shower}$)



Key problem:
Would like to know angular distance between shower image and source image !
(~ equivalent to shower impact distance)

Reconstruction of shower direction



```
Alt  78.0 Don/off  0.04  1.01 Msw  1.12
Tel 5 p/u/s 271 268  65 dtc    98
Amp/size   902   838 Scw  0.91
```

Method 1 (1-D)

- Image axis
- including uncertainties ...

Method 2 (2-D)

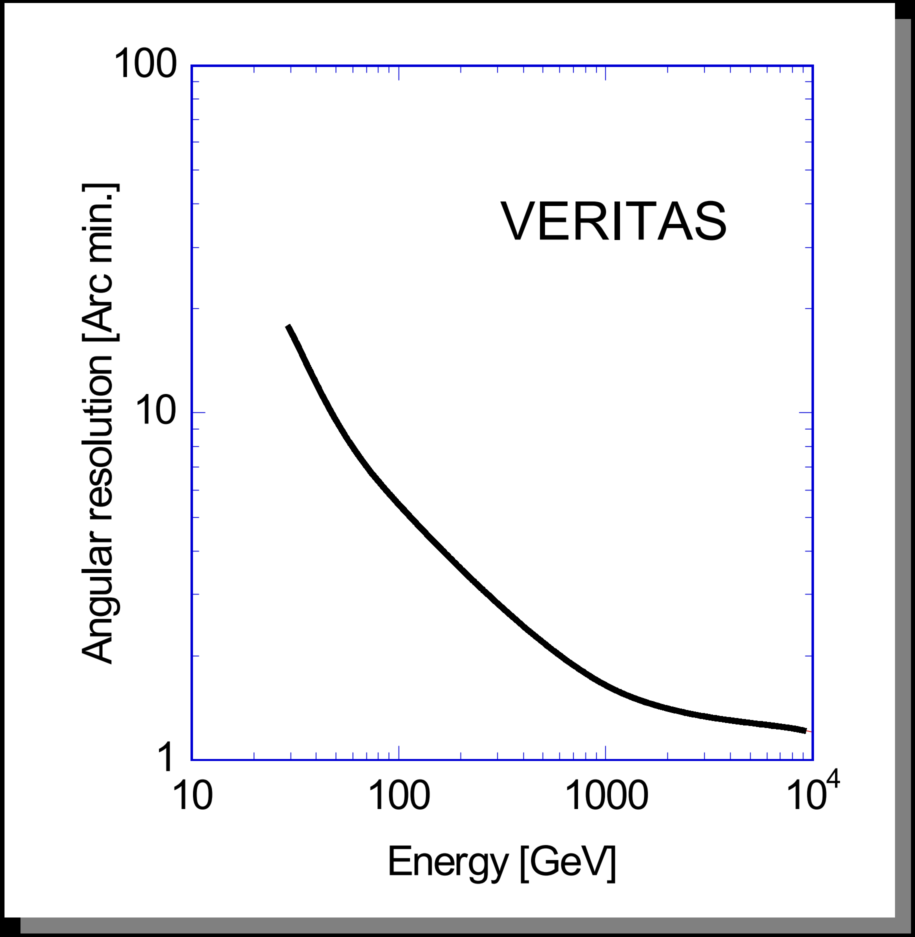
- Use image shape to estimate δ

Error along shower axis
~ 2 x error perp. to axis

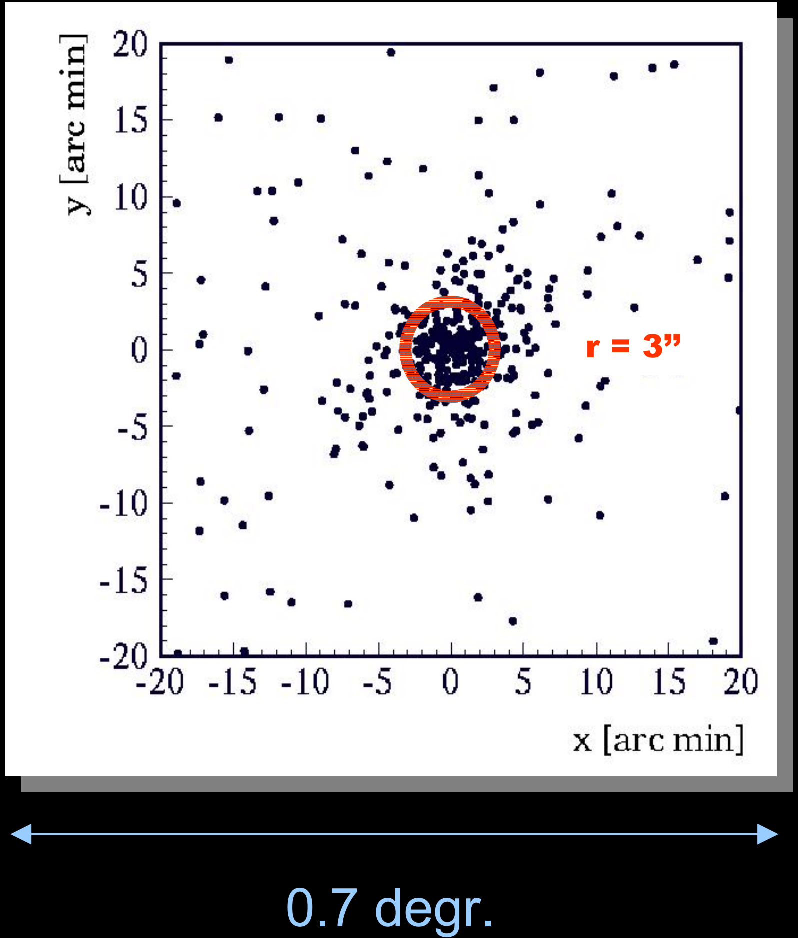
Method 3 (2-D)

- Stereoscopic reconstruction using multiple views

The Crab Nebula with EGRET and HEGRA



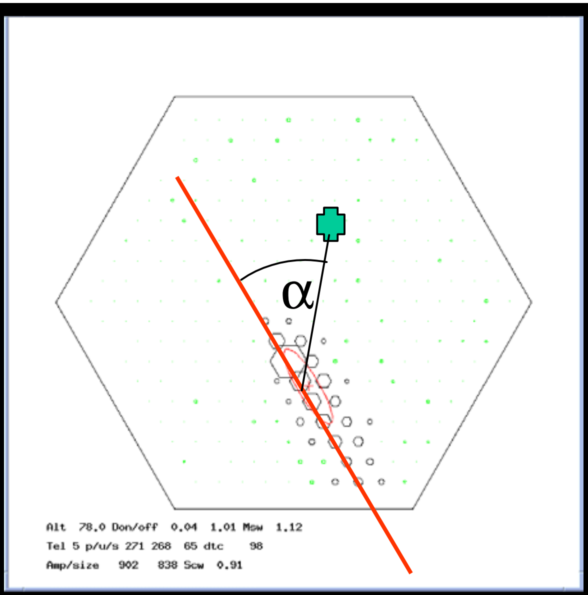
HEGRA CT System
at ~ 1 TeV

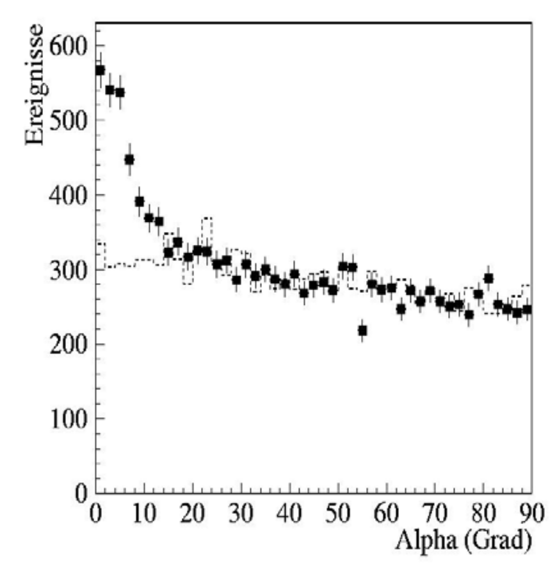


0.7 degr.

Single-telescope analysis

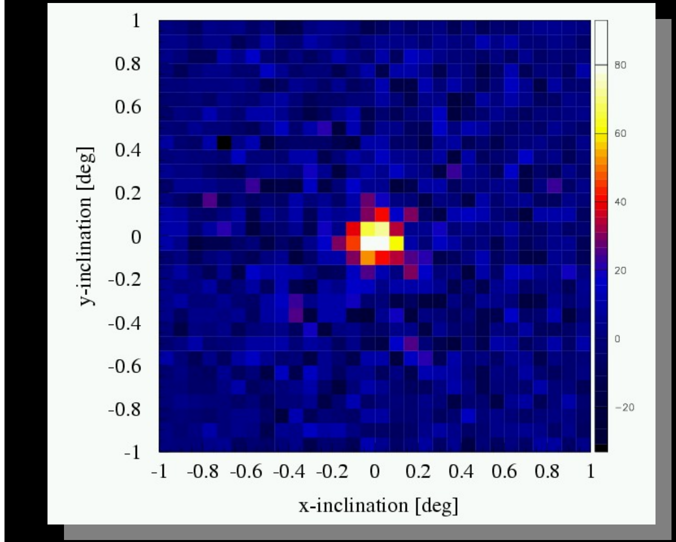
1-D analysis
using image orientation



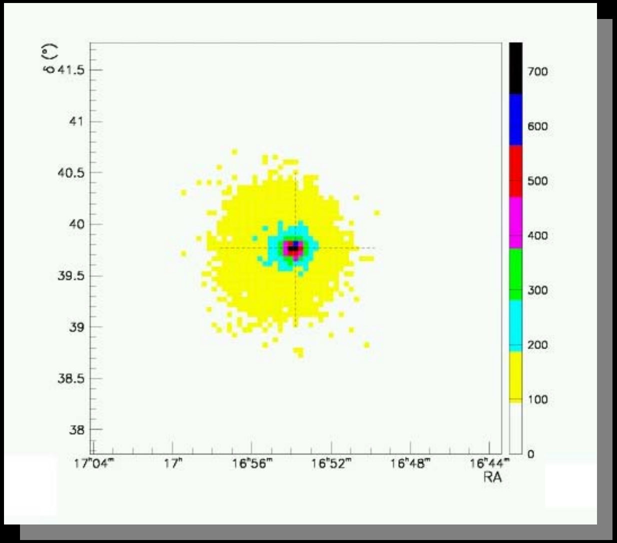


2-D reconstruction
using image shape

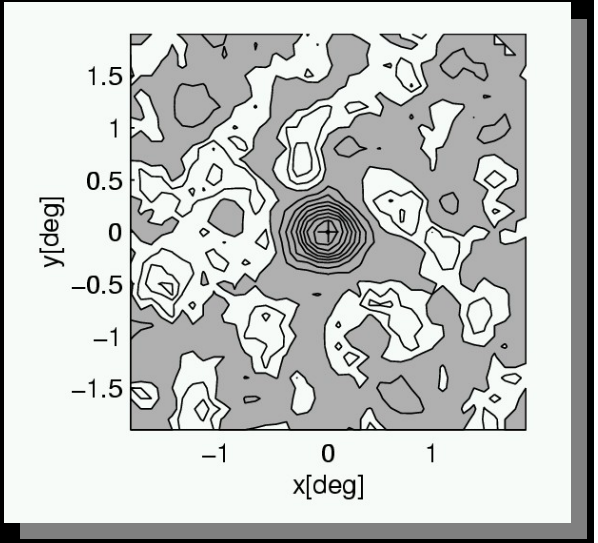
HEGRA CT3 Crab
M. Ulrich et al.
Astro-ph/9708003



CAT Mrk
S. LeBohec et al.
Astro-ph/9804133

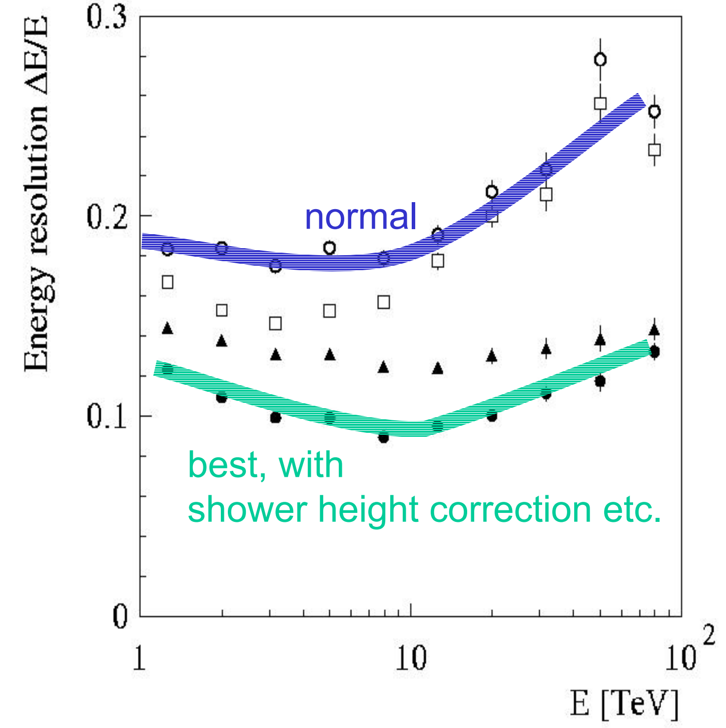


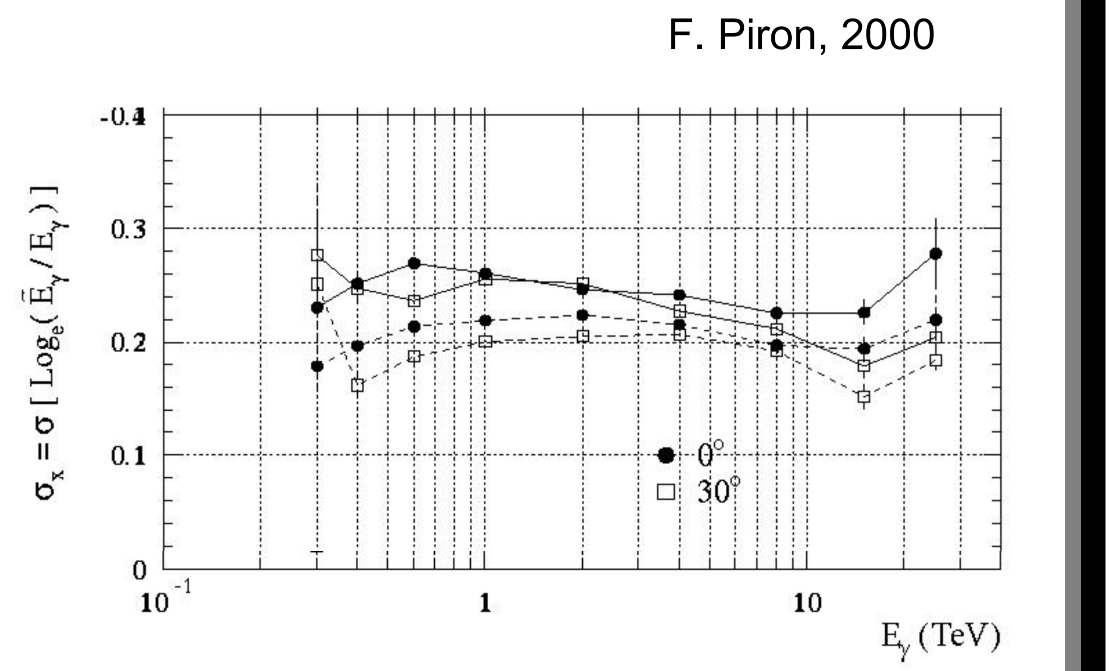
Whipple Crab
R. Lessard et al.
Astro-ph/0005468



Energy resolution

HEGRA CT System




F. Piron, 2000

CAT telescope

Calibration and Flux Determination

Skip topic

Calibration

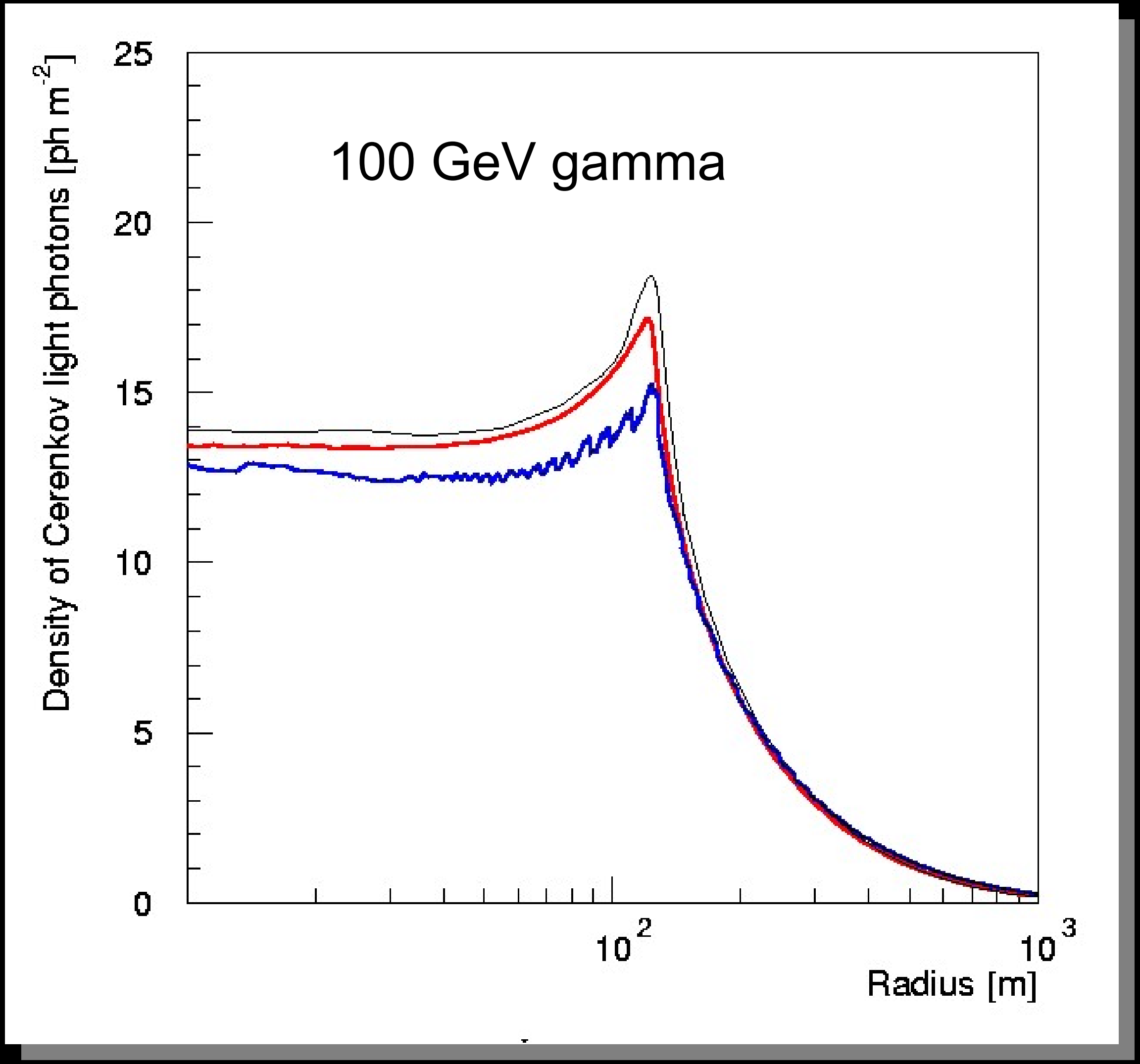
Issues

- Energy reconstruction / energy scale
- Effective area as a function of energy
- Cut efficiencies etc.

Problem: no test beam available

Energy calibration	Simulations	CR rate, spectrum	Muon rings	Calibration light source
Shower development	Model	(✓)	-	-
Generation of Ch. light	Model	✓	✓	-
Atmospheric transmission	Ext. input	✓	(✓)	-
Optical eff. and. QE	Measurement	✓	✓	✓
Electronics gain	Measurement	✓	✓	✓
Problems	Accumulated uncertainties	1) Sim. of hadronic showers; 2) incident CR flux	Incomplete	Incomplete

Comparison of shower simulations

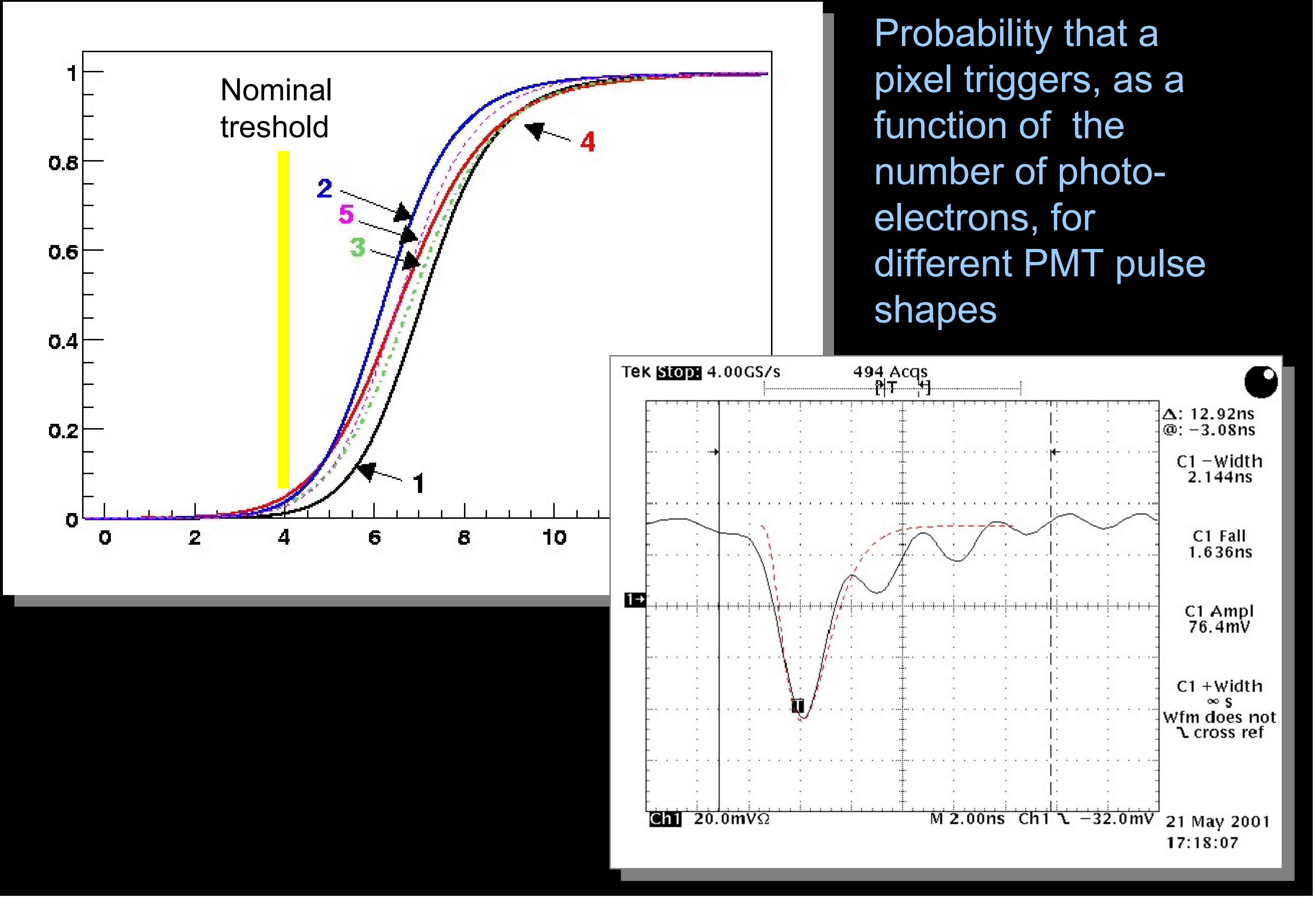


ALTAI,
CORSIKA,
KASKADE

Identical inputs (atmosphere etc.)

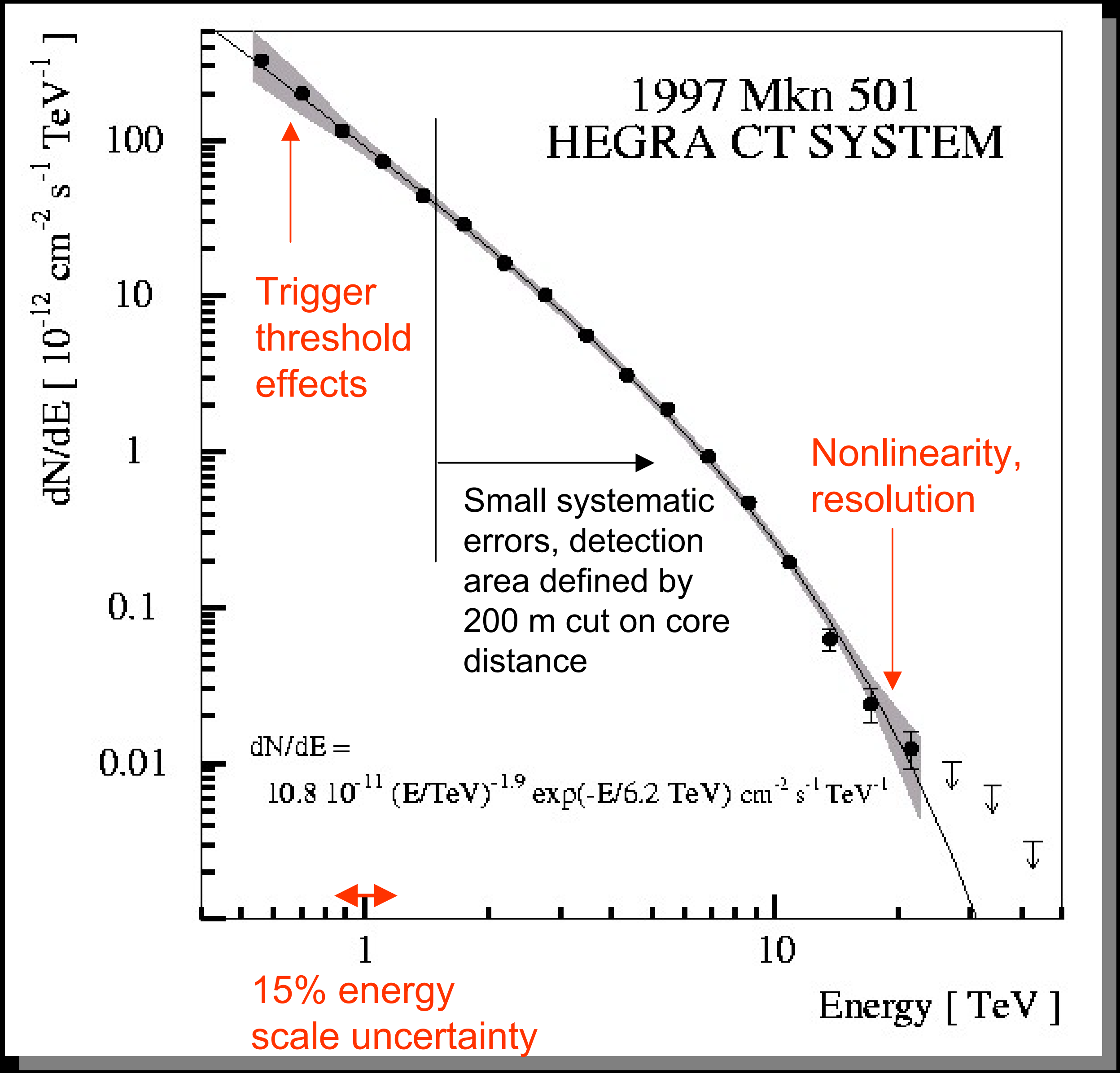
Worse disagreement for proton showers (20-30% or more)

Tricky: trigger simulation



Probability that a pixel triggers, as a function of the number of photo-electrons, for different PMT pulse shapes

Systematic errors



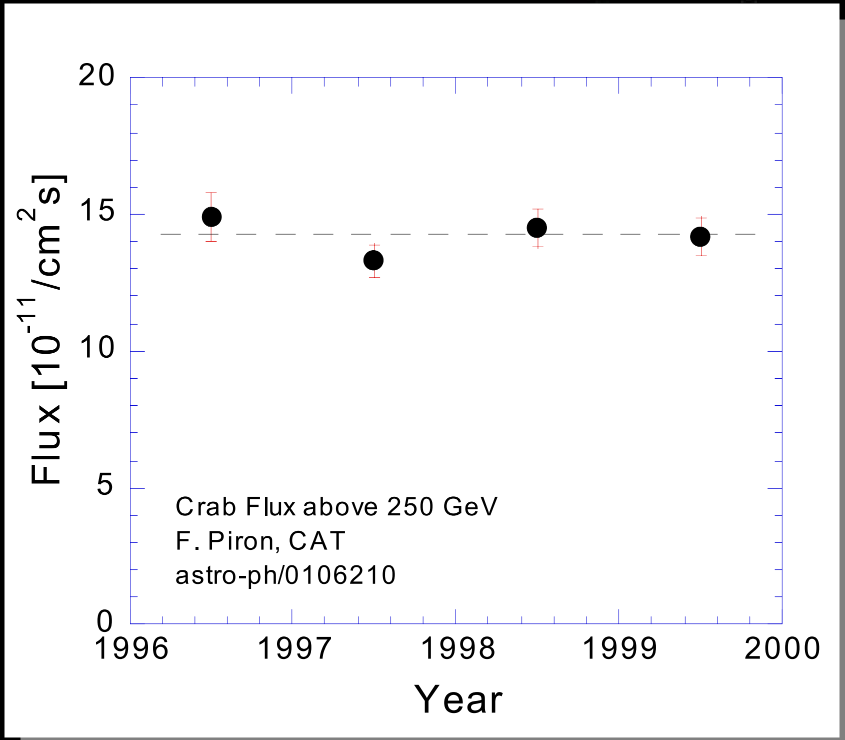
Trigger threshold effects

Small systematic errors, detection area defined by 200 m cut on core distance

Nonlinearity, resolution

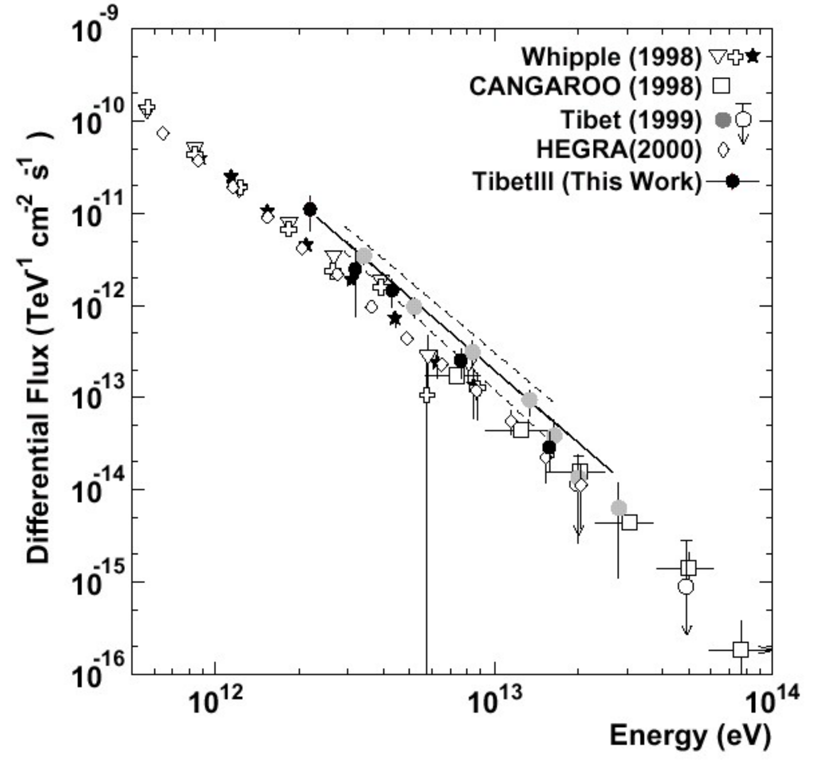
15% energy scale uncertainty

The Standard Candle: the Crab Nebula



Constant flux within errors on time scale between hours and years

	Flux @ 1 TeV	Spectral index
Whipple	3.2 ± 0.7	2.49 ± 0.07
HEGRA	2.8 ± 0.5	2.59 ± 0.06
CAT	2.2 ± 0.6	2.80 ± 0.06
CANGAROO	2.8 ± 0.5	2.53 ± 0.18
Tibet Array	8.2 ± 1.8	2.62 ± 0.17



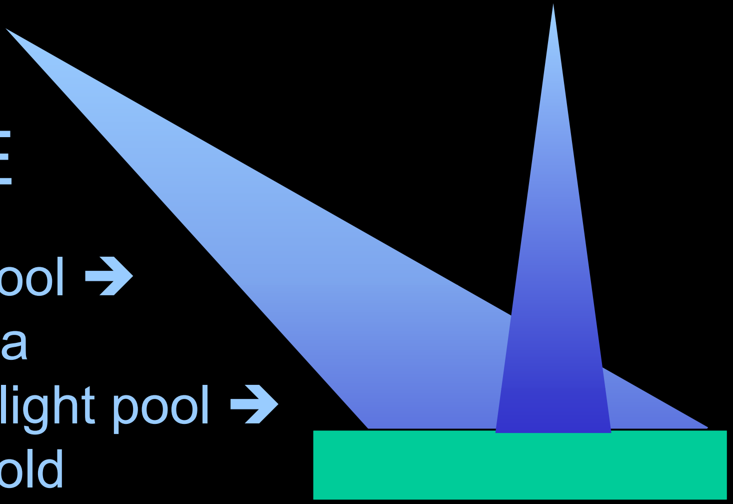
M. Amenomori et al.
ICRC 2001

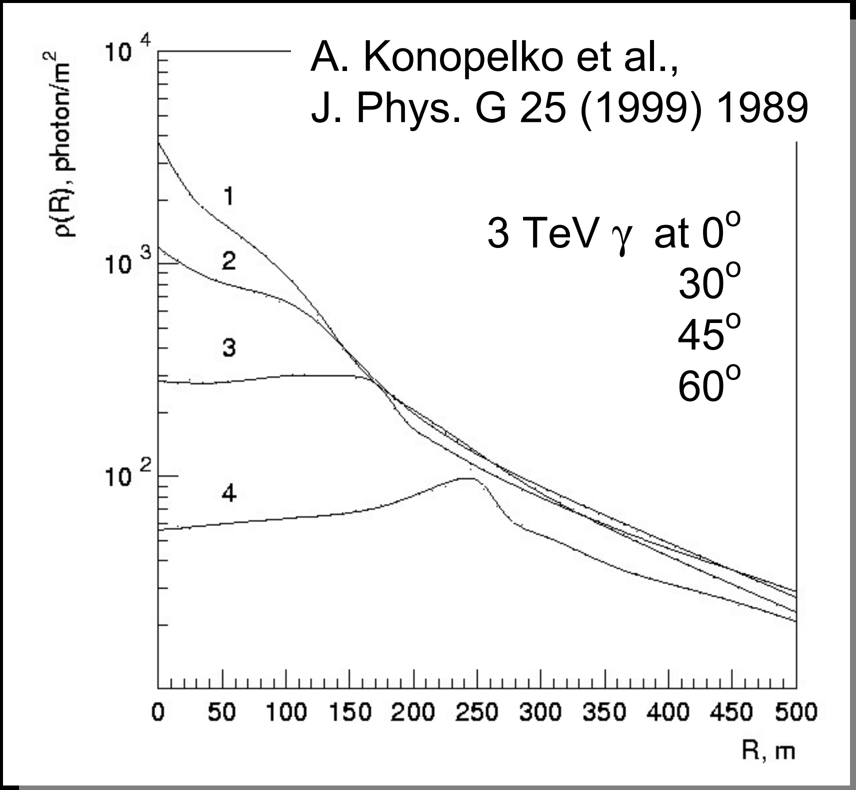
Observations at large zenith angles

Skip topic

Showers at large ZE

- Larger light pool ➔ larger eff. area
- Less intense light pool ➔ higher threshold

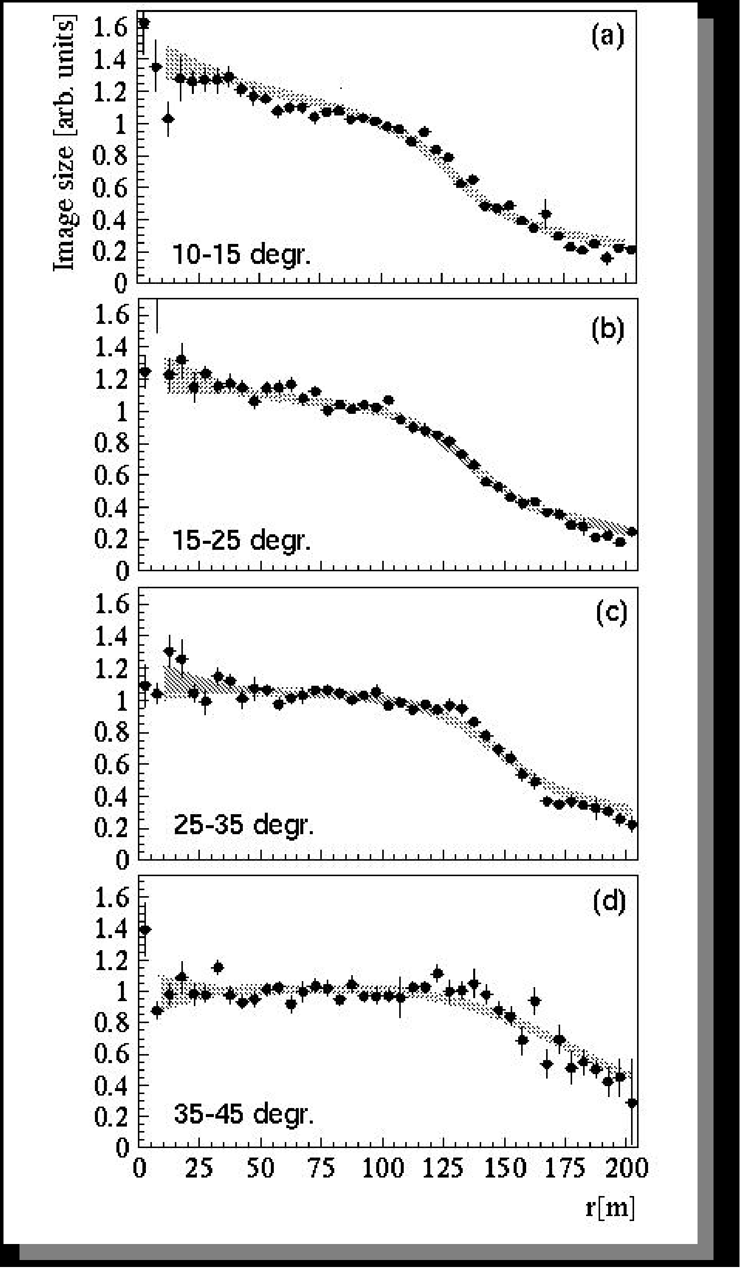




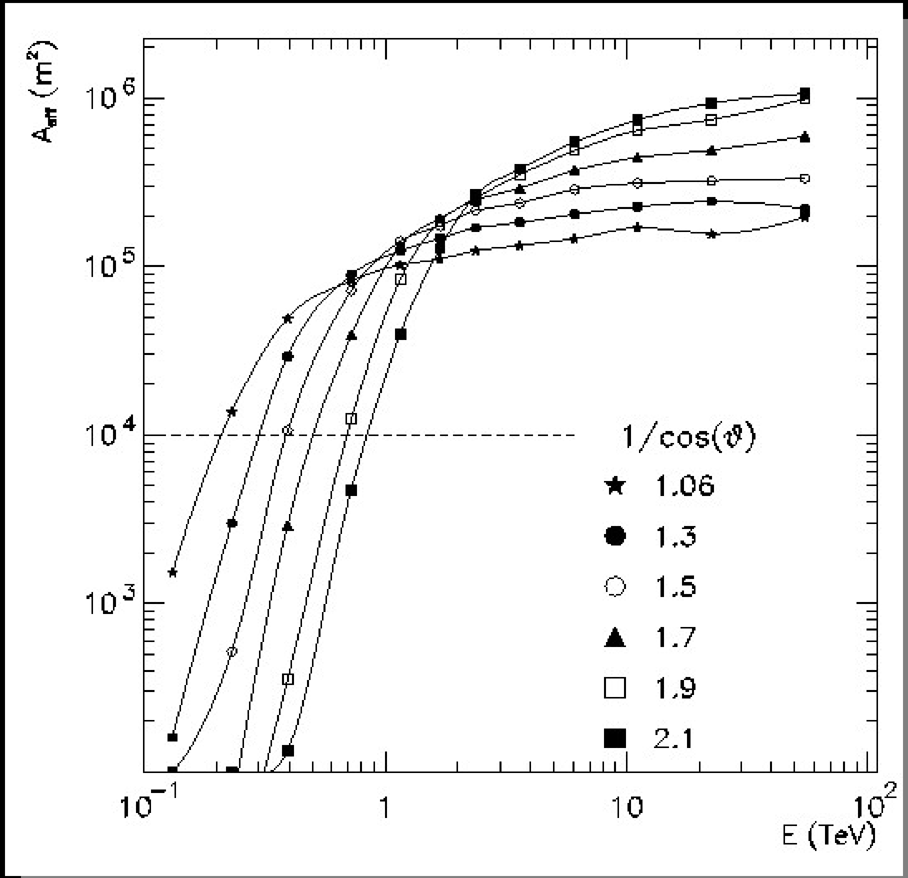
A. Konopelko et al., J. Phys. G 25 (1999) 1989

3 TeV γ at 0°, 30°, 45°, 60°

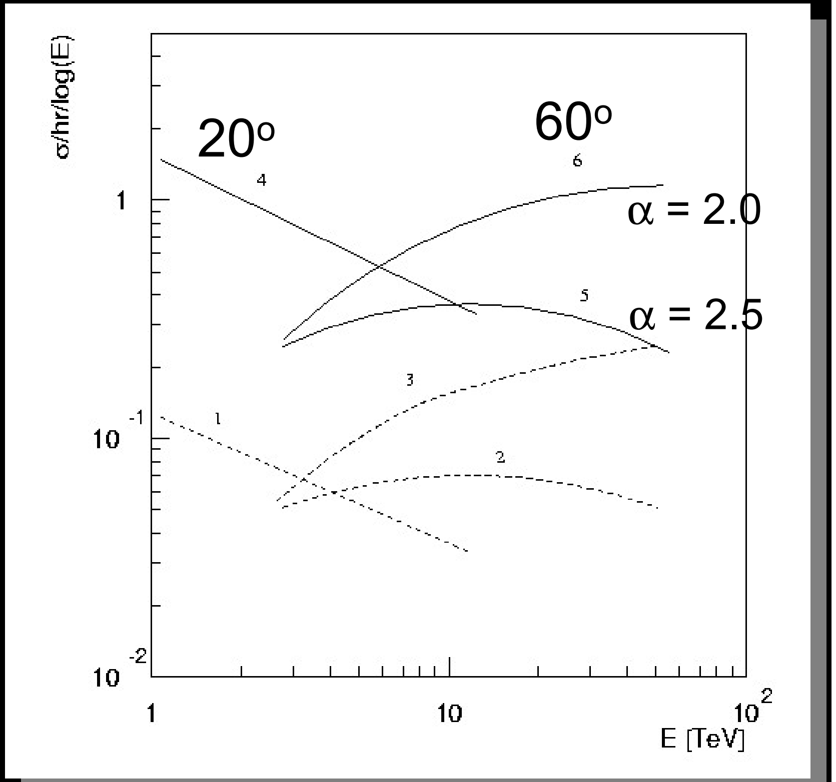
HEGRA Data, F. Aharonian et al. Astropart. Phys. 10 (1999) 21



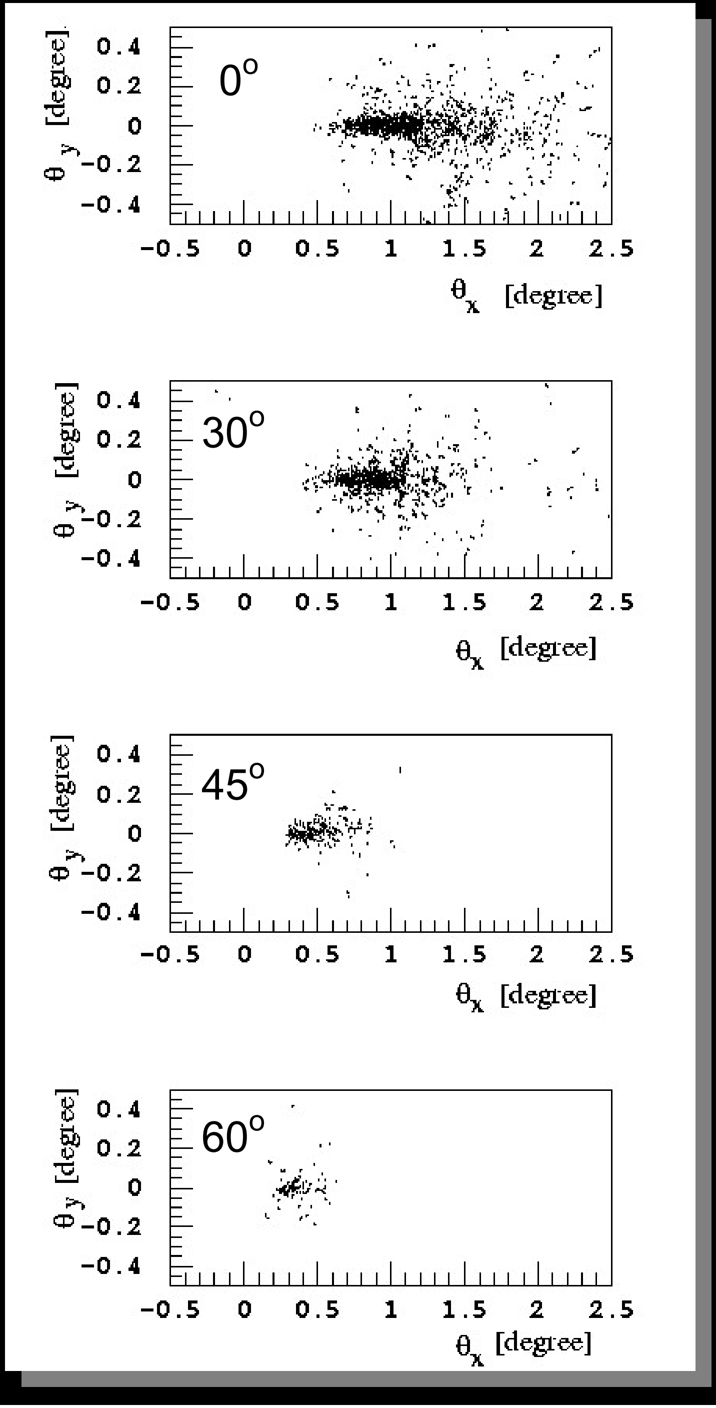
Effective area, threshold, sensitivity



D. Petry, VERITAS
astro-ph/0108085



A. Konopelko et al.,
J. Phys. G 25 (1999) 1989



Images at large ZE

- Larger distance to shower ➔ smaller images
- Need smaller pixels

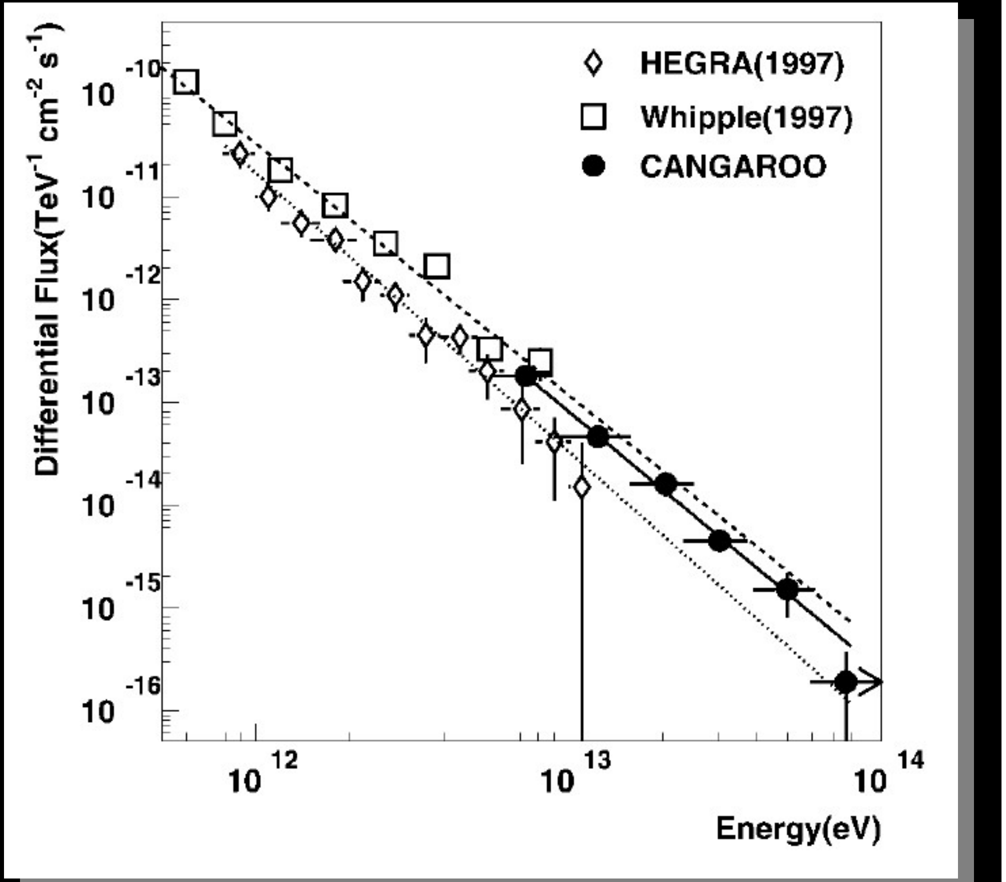
3 TeV γ at 100 m core distance

A. Konopelko et al.,
J. Phys. G 25 (1999) 1989

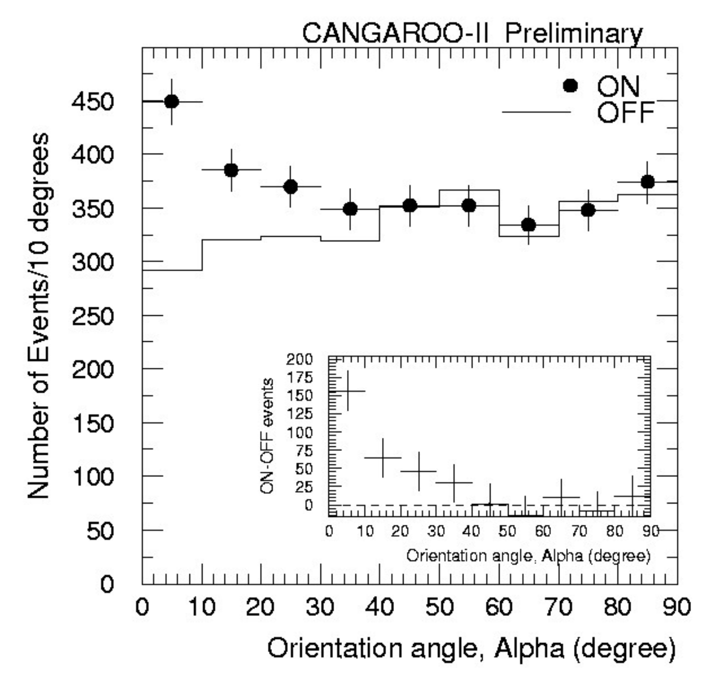
Physics from large-ZE observations

T. Tanimori et al.,
ApJ 492 (1998) L33

Crab



CANGAROO
- HE Crab spectrum
- HE AGN spectrum



Mrk 421, E > 10 TeV

K. Okumura et al.,
astro-ph/0106352