BENASQUE III

GAMMA-ASTRONOMY

VHE γ ASTRONOMY

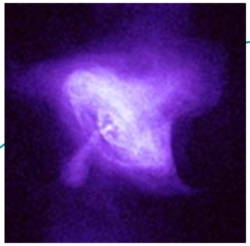
CONNECTED TO MANY HIGH ENERGY PROCESSES

- **point to the location of cosmic high energy processes (cosmic accelerators or tagets)**
- **carry time information (no mass)**
- **carry energy information ($E_{\gamma} \leq E_{intrinsic}$)**
- **VHE γs must have VHE/UHE parent particles**
- **reate electromagnetic showers in the atmosphere**

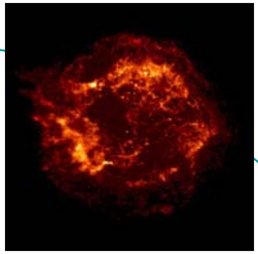
DIFFICULTIES

- **Universe not fully transparent for all energies (interaction with cosmic photon fields)**
- **The fluxes are very low**
- **One has to suppress the enormous hadronic cosmic ray background**
- **Best current detectors: Air Cherenkov telescopes that can record shower images**
- **can only run during night time. Background from night sky light background light >2* $10^{12}/m^{2}$,sec sterad ((300-600 nm)**
- **l ight losses due to Rayleigh, Mie scattering**

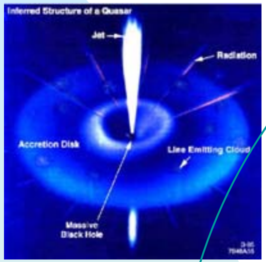
THE PHYSICS GOALS



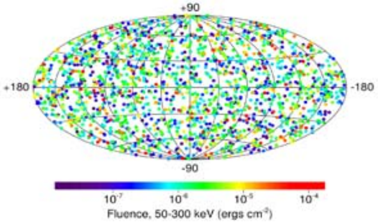
Pulsars



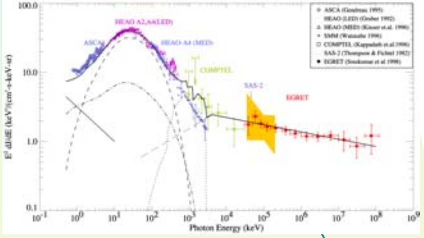
SNRs



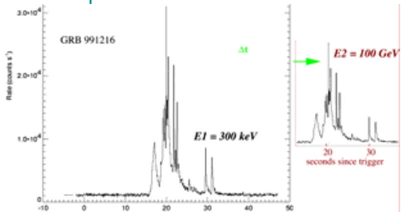
AGNs



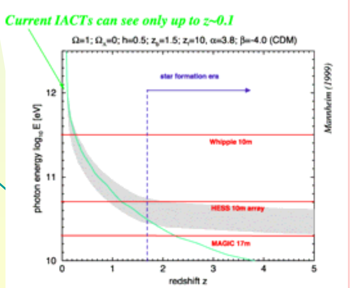
GRBs



Diffuse γ background



Quantum Gravity test



Cosmological γ horizon

Cold Dark matter

PROCESSES THAT CAN GENERATE GAMMA RAYS

- Thermal processes: energy too low

  Tail of the blackbody radiation can reach at high temperatures in the keV region
- Radioactive decays of nuclei-> γ lines, energy in keV, MeV region
- Annihilation e+ e- -> γ γ , rare: pbar+p -> γ γ
- Synchroton radiation of electrons in magnetic fields (p at highest energies)

Low energy synch. photons = radiowaves can be observed by radioastronomy

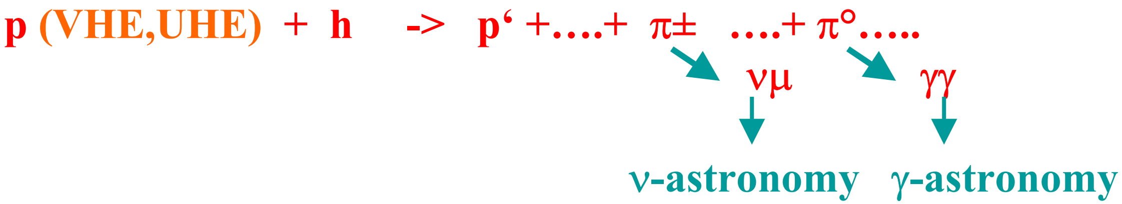
-> important tool to observe energetic electron accelerators

All these processes are generating low energy γ‘s (nevertheless can result in VHE γ‘s when the system, in which they are generated, is boosted in the lab towards the earth -> blueshifting (GRBs, AGNs ?)

HIGH ENERGY γ PRODUCTION

(γs cannot be accelerated like charged particles, they need higher energy (or massive) parent particles)
Bottom-up and top-down processes

* **Hadronic production:**



p (VHE,UHE) + h -> p‘ +….+ π± ….+ π°…..

νμ γγ

ν-astronomy γ-astronomy

* Inverse Compton Scattering (IC) e (VHE,UHE) + photon -> e (low) + γ (VHE)

special case: electrons generate synchrotron photons and upscatter them to high energies (the SSC model A. Harding, O.C. DeJager)

* Unlikely, but not excluded: Decay of supermassive particles left over from the Early Universe Topological Defects, Relic Particles (Mass 10**16 GeV??), a top-down process.

(*) VHE γs: boosted HE γs . Examples in Jets in AGNs (Γ≈ 10 in Mkn 501),-> blue shifted also in Gamma Ray Bursts (GRBs)

=======

Acceleration of charged particles: in shocks (for example in Super Novae explosions, Fermi acceleration Type I, II (slow process)
Also electron acceleration by variable B fields near pulsars (betatron acc.)
Not likely, but possible: by large electrostatic fields 10**14 V ???

The transport through the universe (from the production site to us)

THE UNIVERSE IS NOT TRANSPARENT FOR γs AT ALL ENERGIES

OUR UNIVERSE IS NOT TRANSPARENT TO PARTICLES OF THE HIGHEST ENERGIES DUE TO INTERACTION WITH VARIOUS (LOW ENERGY) PHOTON FIELDS :

COSMIC PHOTON FIELDS:

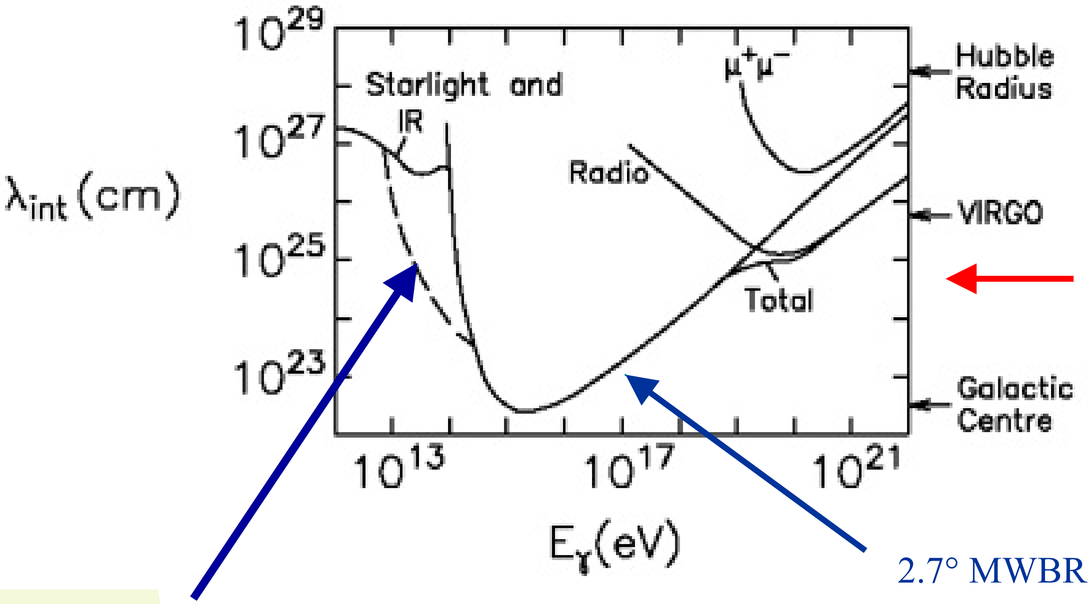
RADIOWAVES, 2.7° MICROWAVE BACKGROUND, IR- BACKGROUND (UNKNOWN), STARLIGHT….

γ (high energy) + photon(low energy) -> e^+e^-

cross section maximal close to threshold ≈ 1 MeV in the CM system (scales ≈ 1/s2)**

(2.7° K MWBG <--> 1015 eV γs : absorption length ≈ 10 kpc)**

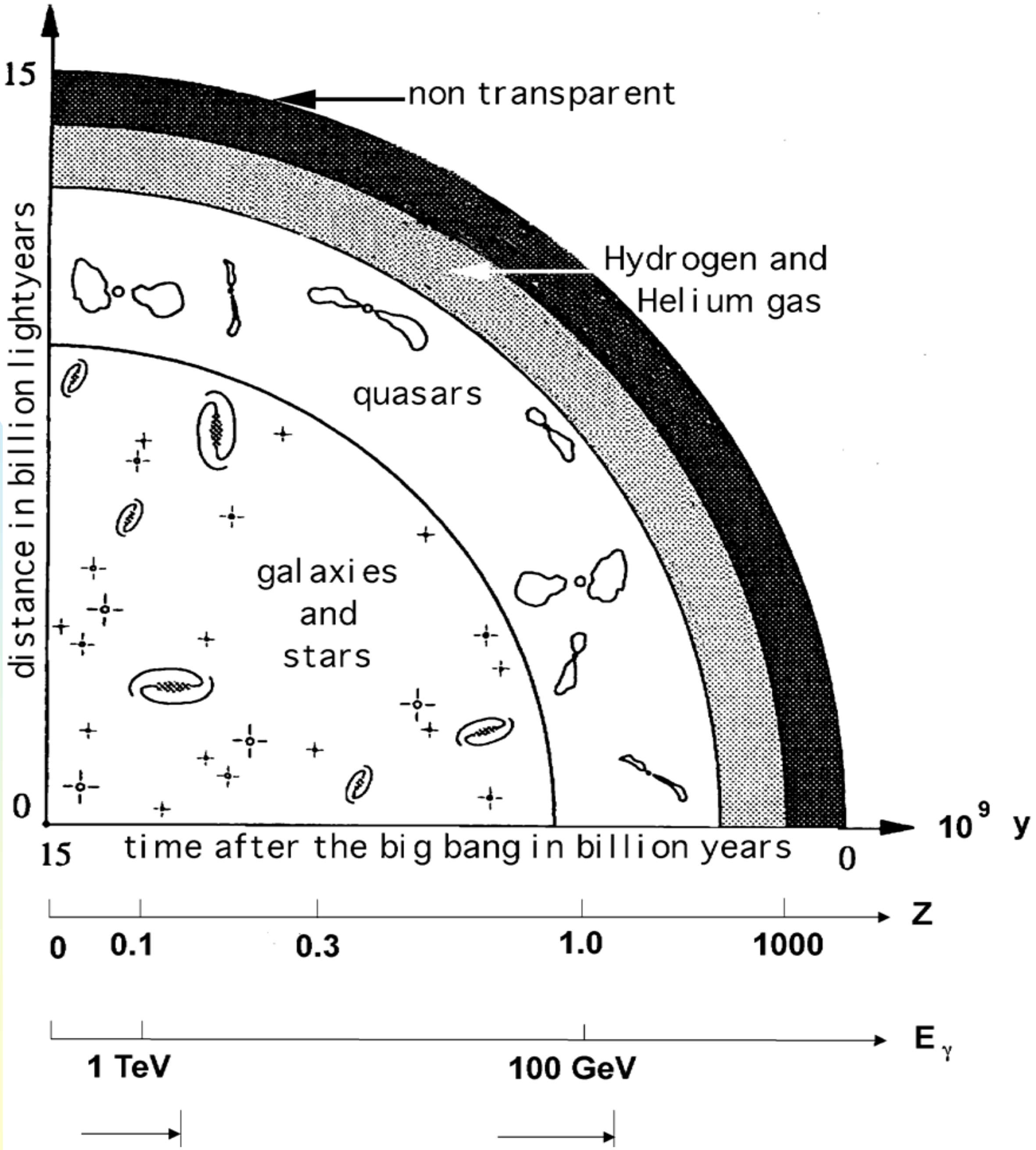
ABSORPTION LENGTH λ_{int}(cm) OF γs IN THE UNIVERSE AS FUNCTION OF ENERGY(Wdowczyk, Wolfendale, 1992)



Mkn 421, Mkn 501

2.7° MWBR

Uncertainty due to unknown IR background -> EBL can distort the γ spectra
But how to decide between source intrinsic processes and absorption processes
In the universe?



Current inst.

New instruments

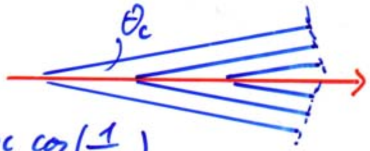
CHARGED PARTICLES PRODUCE ČERENKOV LIGHT WHEN PASSING MATTER IF

$\beta \cdot n > 1$ $\quad$ n = refractive index

air: $n(1\,\text{atm}, 0^\circ) = 1.000273$

$$n-1 = n'(h) = n'(0)\, e^{-\frac{h}{h_0}} \; ; \; h_0 \approx 7.3\ \text{km}$$

THRESHOLD : $\beta \cdot n = 1$ $\;;\; n \approx 1 \;\&\; \beta \approx 1 + \frac{m^2}{2p^2}$ for all practical cases



$\theta_c(\beta=1) = \arccos\left(\frac{1}{n}\right)$

$\theta_c = \arccos\left(\frac{1}{\beta \cdot n}\right)$

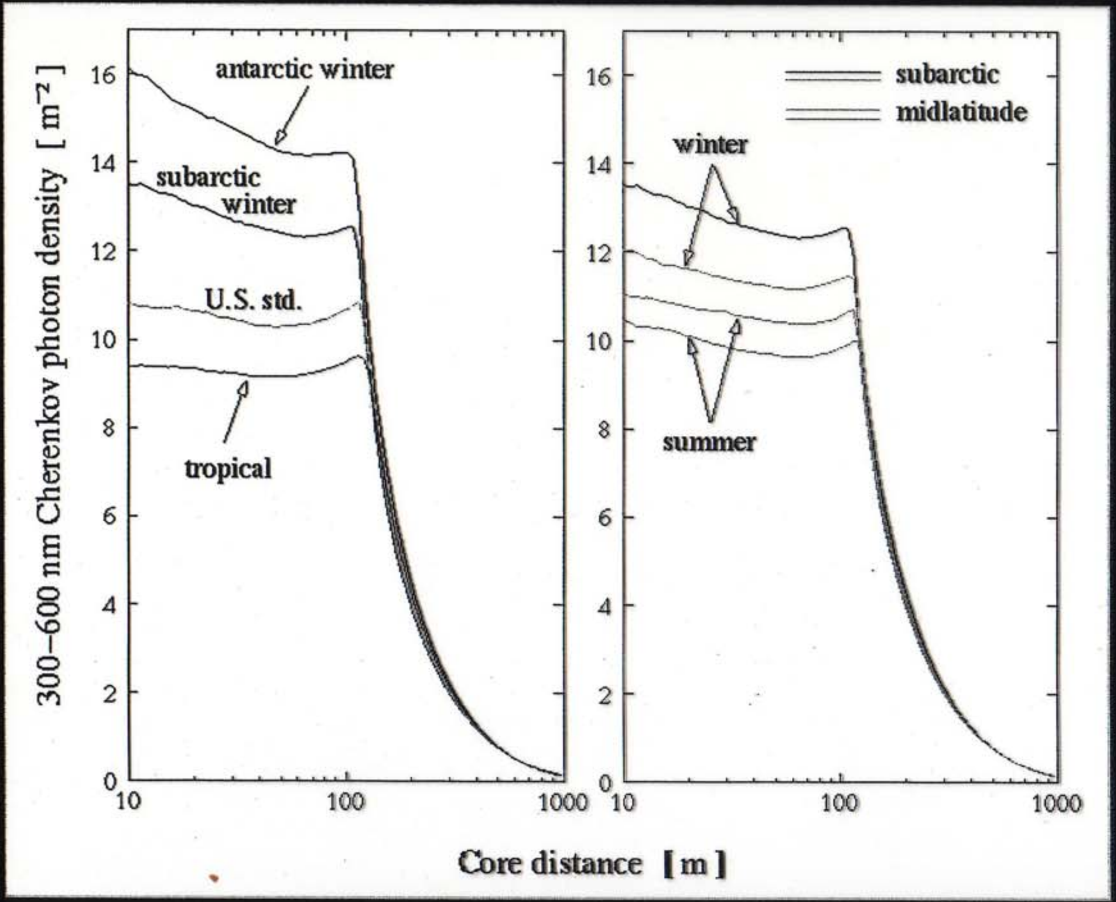
photon intensity: $$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\, Z^2}{137\,\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \equiv \frac{1}{\lambda^2} \sin^2\theta$$

for $n = 1.000273$, $N(400, 700\,\text{nm}, 1\,\text{m}) \approx 24$ photons/m

(energy loss of a MIP : ≈ 180 KeV/m at sea level)

IMPORTANT : n CHANGES WITH ALTITUDE ⇒ LIGHT FOCUSSING

h	n	$\theta_c(\beta=1)$	$p_c(e)$	$p_c(\pi)$
30 Km	1.00000424	0.17°	175 MeV	48 GeV
20	1.0000173	0.34°	87 "	24 "
15	1.0000351	0.48°	61 "	17 "
10	1.000071	0.68°	43 "	12 "
8	1.000094	0.78°	37 "	10 "
6	1.00012	0.90°	32 "	9 "
4	1.00017	1.04°	28 "	8 "
2	1.00022	1.20°	21 "	7 "



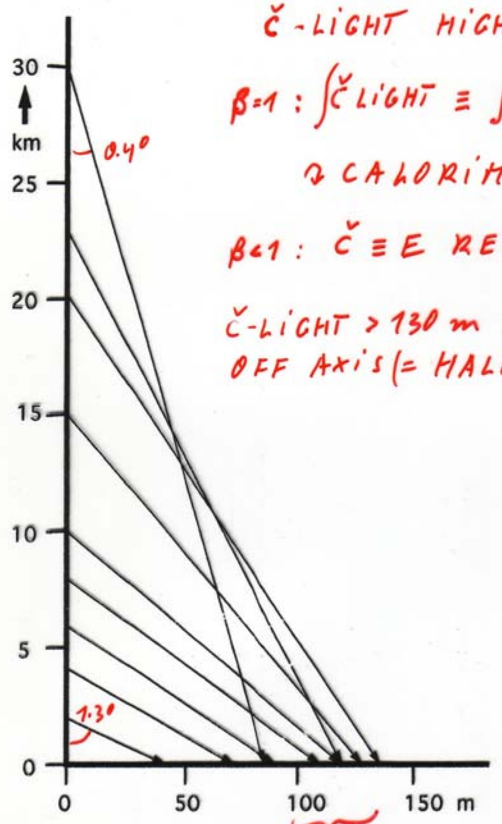
Atmospheric profile & light intensity

Atmospheric density profile influences both shower development and Cherenkov emission

Potentially large (> 10%) effects on energy calibration

K. Bernlöhr
astro-ph/9908093

FOOTPRINT OF A $\beta = 1$ MUON
(SHOWER CORE)



Č-LIGHT HIGHLY DIRECTIONAL

$\beta = 1 : \int \check{C}\text{ LIGHT} \equiv \int \frac{dE}{dx}\, dx$

→ CALORIMETER

$\beta < 1 : \check{C} \equiv E$ RELATION WRONG

Č-LIGHT > 130 m ONLY FROM OFF AXIS (= HALO) PARTICLES

- HIGHLY ENCRYPTED INFORMATION ABOUT SHOWER DETAILS
- TIME SPREAD AT GROUND $\Delta t \sim 1\text{-}2$ nsec (+ TAILS)

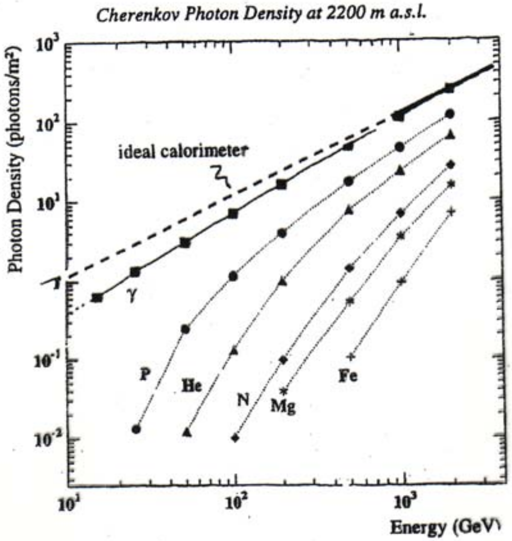


Figure 3.1: Photon density (300–600 nm) at 2000 m a.s.l. as a function of the incident energy and type of particle. The photon density is averaged over an area of 50 000 m². Taken from [22].

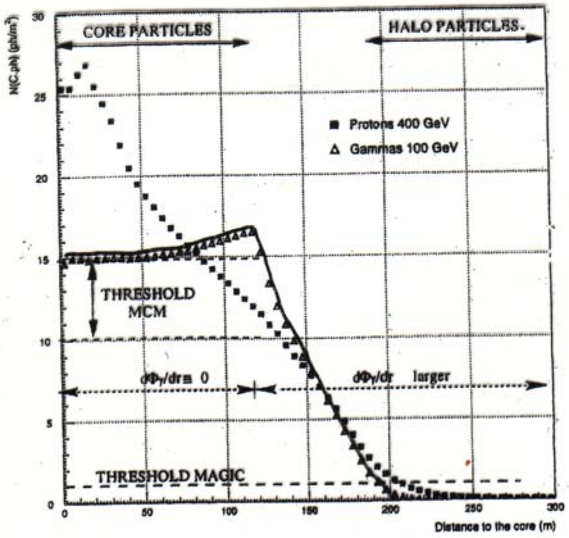
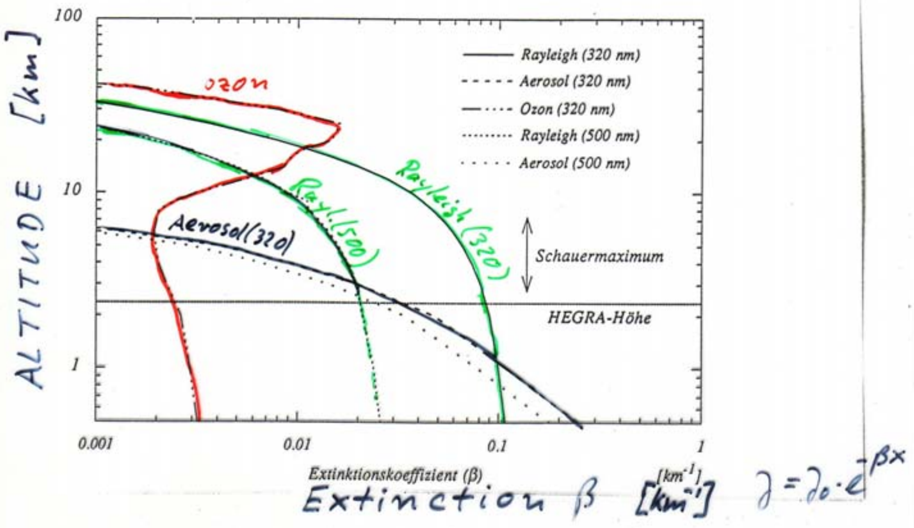
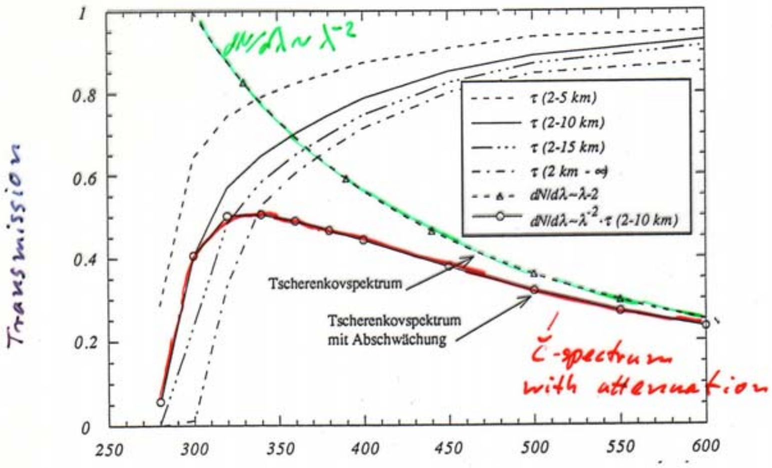


Figure 3.2: Lateral distributions of Čerenkov photon densities (N(C.ph)) for 100 GeV γ and 400 GeV proton showers at an altitude of 2220 m for vertical incidence. Threshold MCM stands for the range of threshold that could be achieved by 'Mini-

Light transmission in the atmosphere





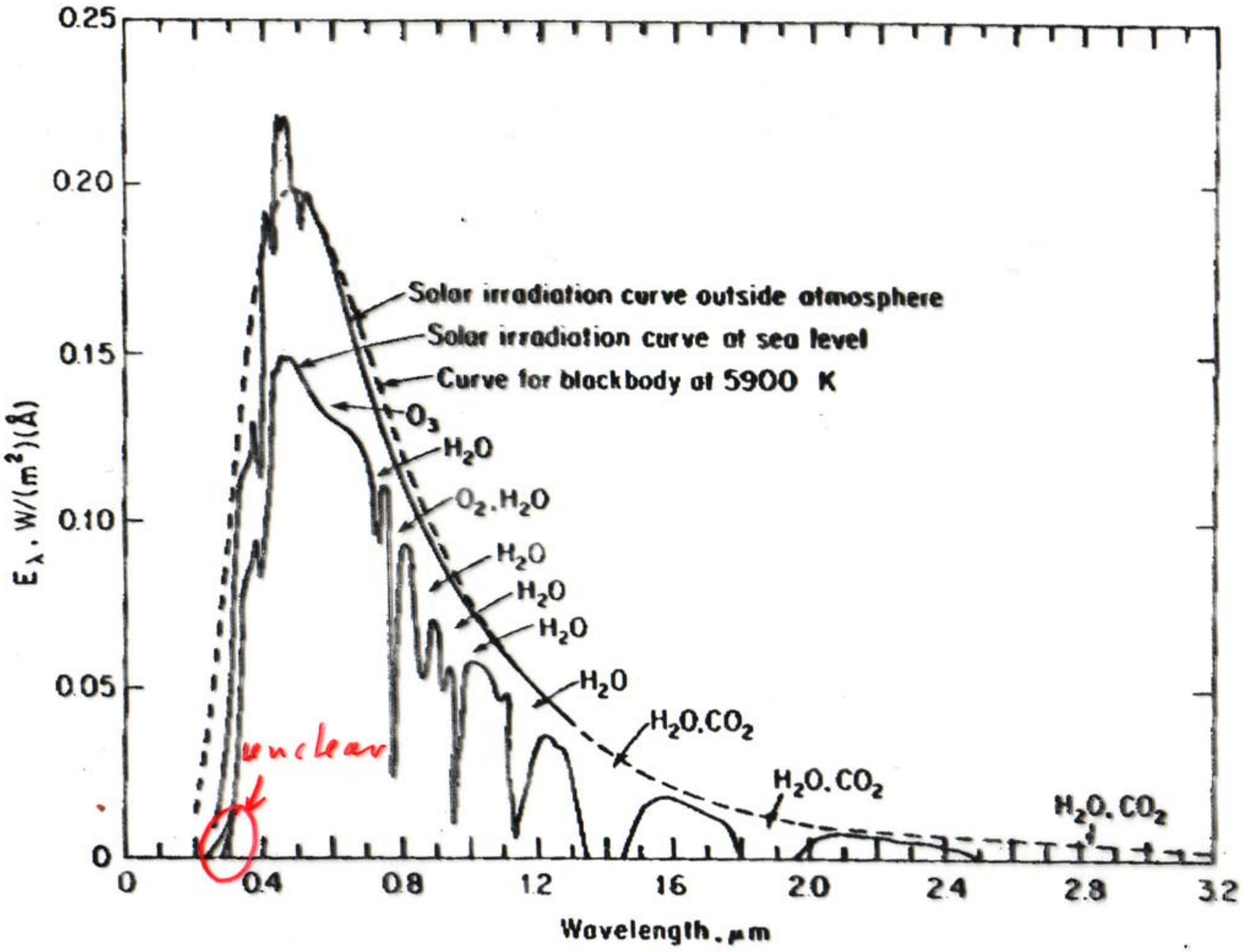
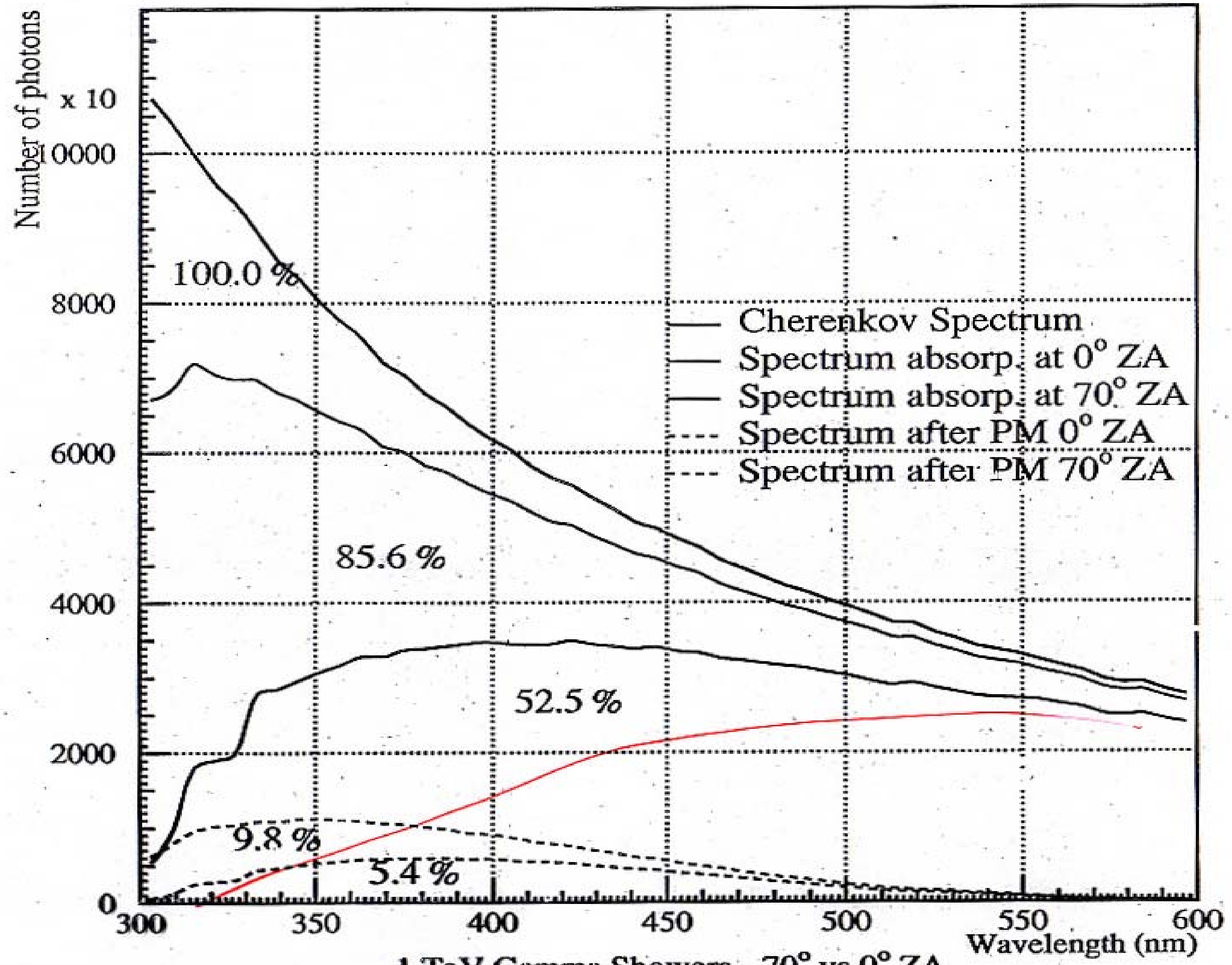


Fig. 51 Spectral distribution curves related to the sun; shaded areas indicate absorption at sea level due to the atmospheric constituents shown. [*Valley* (1965).]

Spectral Distribution of Cherenkov Photons



1 TeV Gamma Showers - 70° vs 0° ZA

DETECTORS FOR γ ASTRONOMY:

SATELLITE BORNE DETECTORS (Small, high γ selectivity)
Could detect strongest sources up to 10 GeV

Ground-based array of open, large pmts, wave-front sampler
Thresholds above 10^{14} eV

GROUND BASED AIR CHERENKOV TELESCOPES (ACT)
(large detection areas > 10^4 m^2, modest γ/h separation)
Could detect γ sources above 300 (350) GeV only close to our Galaxy

-> going down in energy threshold with ACTs:
Universe becomes transparent
-> access to new objects, new physics

DETECTOR BASED ON SAMPLING OF THE CHERENKOV LIGHT FRONT

ARRAY OF OPEN PHOTOMULTIPLIERS

ALL SKY MONITORING

VERY GOOD ANGULAR RESOLUTION, VERY GOOD ENERGY RESOLUTION

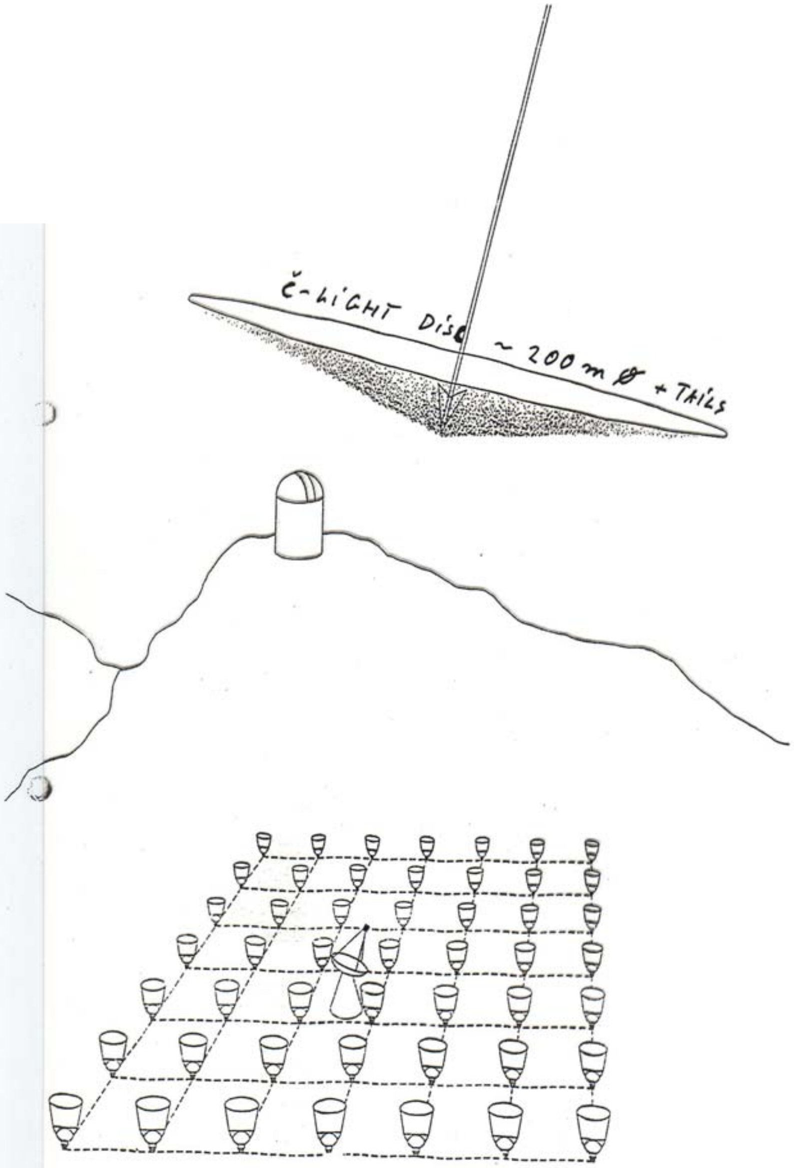
HIGH THRESHOLD: FEW TEV
MAIN LIMITATIONS: INTEGRATION OF NIGHT SKY LIGHT BACKGROUND OVER LARGE ANGULAR RANGE
LIMITED LIGHT COLLECTOR SIZE

MODEST γ/HADRON SEPARATION

RELATIVELY CHEAP

CAN ONLY WORK DURING CLEAR DARK NIGHTS

AIROBICC, VEGA, TUNKA ARRAY

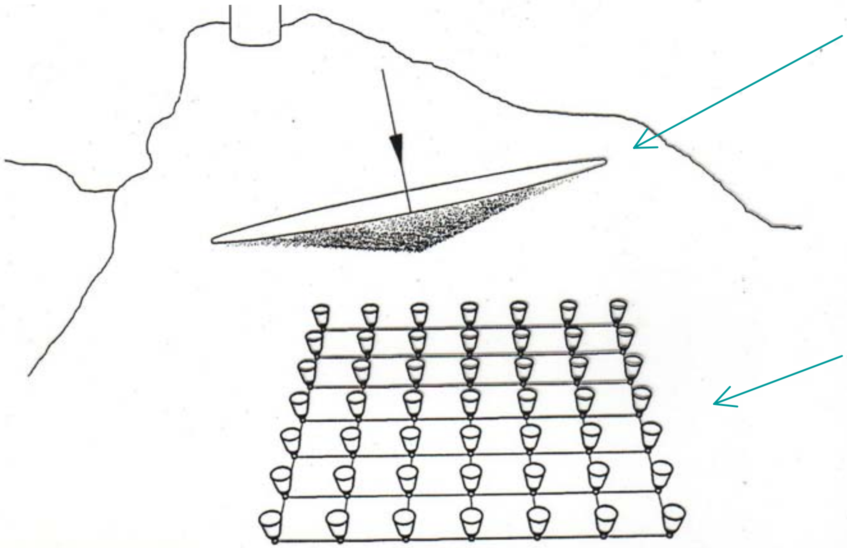


CONCEPT OF THE AIROBICC DETECTOR

ARRAY OF OPEN LARGE Ø PMTS LOOKING INTO NIGHT SKY

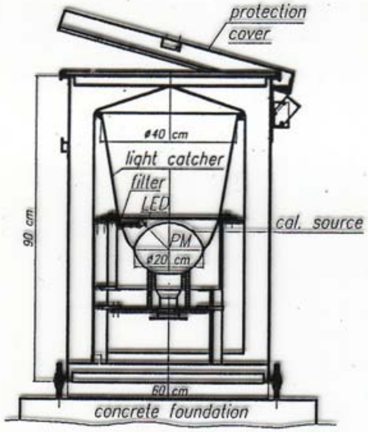
FULLY ACTIVE CALORIMETER (NOT COMPENSATING FOR HADRONIC SHOWERS)
γ(e) SHOWERS PRODUCE 2-3 TIMES MORE LIGHT THAN HADRON SHOWERS AT TEV ENERGIES
LIMITED g/h SEPARATION POWER
RADIAL SHOWER INTENSITY GIVES INFO ON SHOWER STRUCTURE
ABOUT 5 % ENERGY RESOLUTION FOR γ SHOWERS
LARGE ANGULAR ACCEPTANCE
THRESHOLD > 10 TEV

AIROBICC DATA
- 7X7 ARRAY
- 30 m GRID
- 8’ PMT, 6 DYNODES
- 40 cmØ CONE OPENING
- 1 STERAD ANGULAR ACC.
- ANGLE BY TIMING
- E,(XMAX) BY PULSE HEIGHT
- 12% UP-TIME



CHERENKOV LIGHT DISC FROM AIR SHOWER. TYP 250 mØ, VERY SHARP IN TIME , CONICAL

ARRAY OF OPEN PMTS LOOKING INTO NIGHT SKY



A DETECTOR HUT WITH A PM VIEWING DIRECTLY THE SKY.

ENHANCE COLLECTION AREA BY WINSTON CONE BUT LIMITS ANGULAR ACCEPTANCE (LIOUVILLE THEOREM)

HUGHE NIGHT SKY LIGHT INDUCED BG

CHERENKOV TELESCOPES FOR γ ASTRONOMY

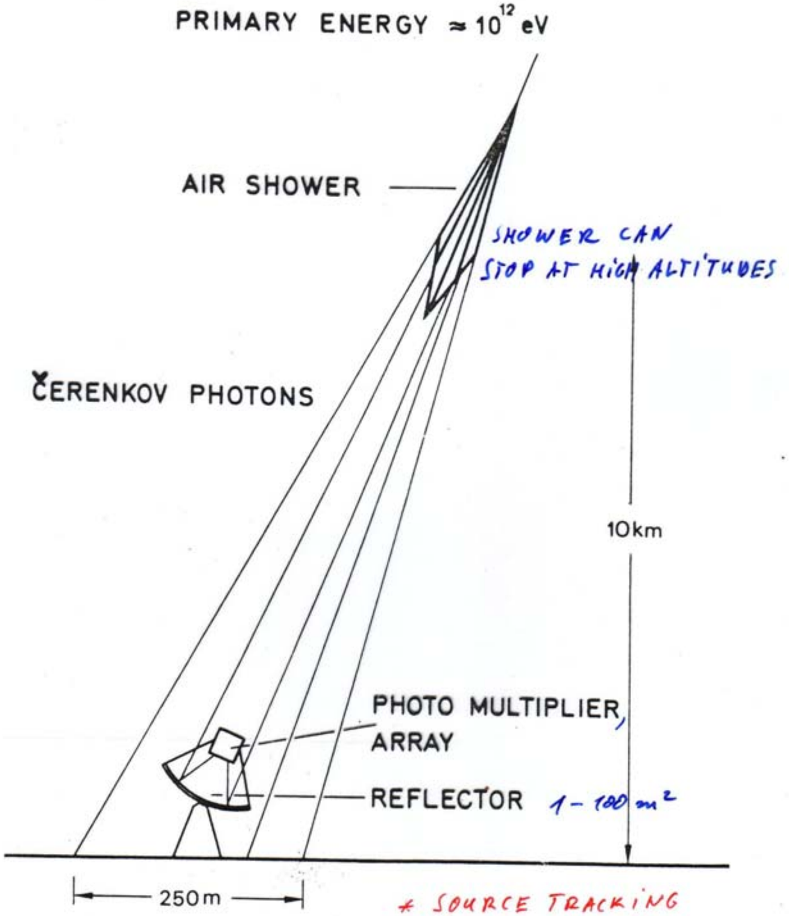
MOST SUCCESSFUL DETECTORS

ALL DISCOVERIES OF VHE SOURCES AND MANY PHYSICS RESULTS DONE BY

IMAGING AIR CHERENKOV TELESCOPES (IACTs)

γ-SOURCE

ATMOSPHERIC ČERENKOV LIGHT OF SMALL AIR SHOWERS



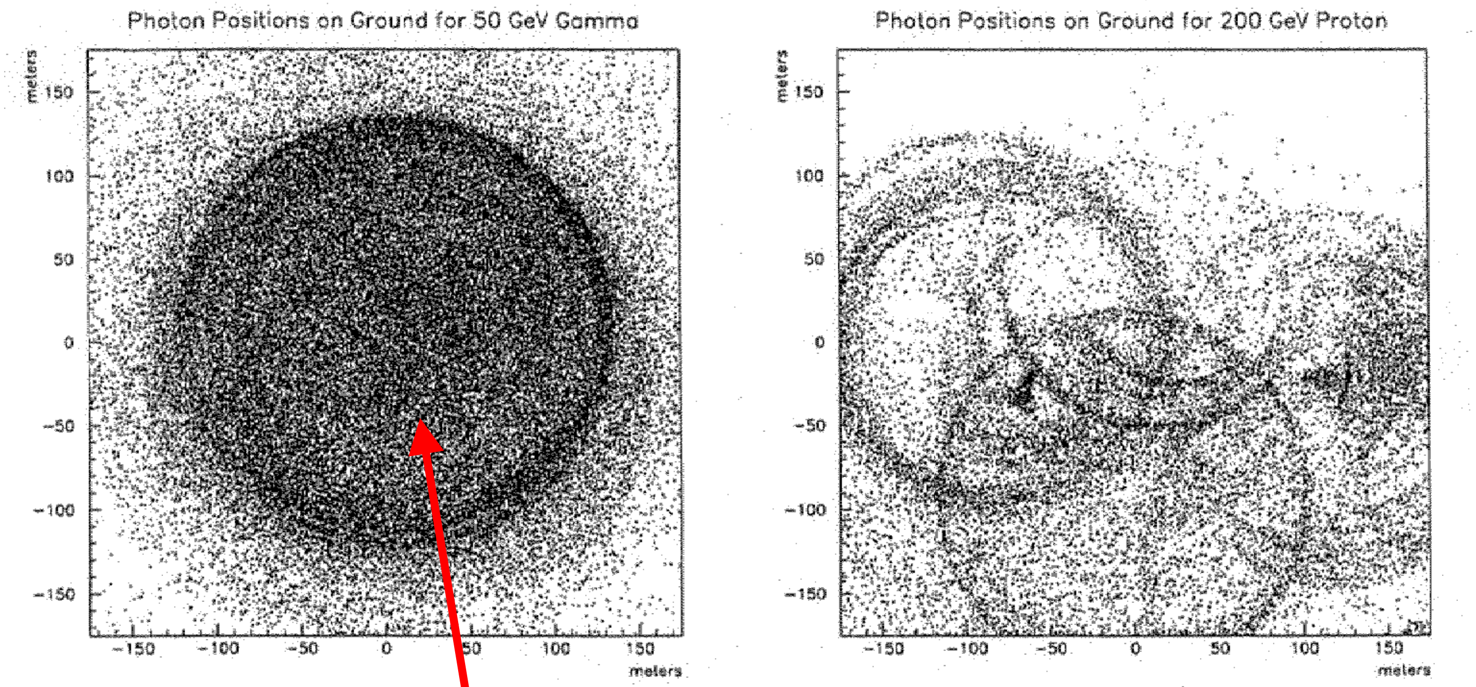
- * SOURCE TRACKING
  Č-ANGLE 1.3°
- * LIMITED OBSERVATION TIME
- * LOW E THRESHOLD

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

The γ/ hadron separation by image analysis

Zur Anzeige wird der QuickTime™
Dekompressor "Foto - JPEG"
benötigt.

MC SIMULATION OF CHERENKOV PHOTONS ON GROUND

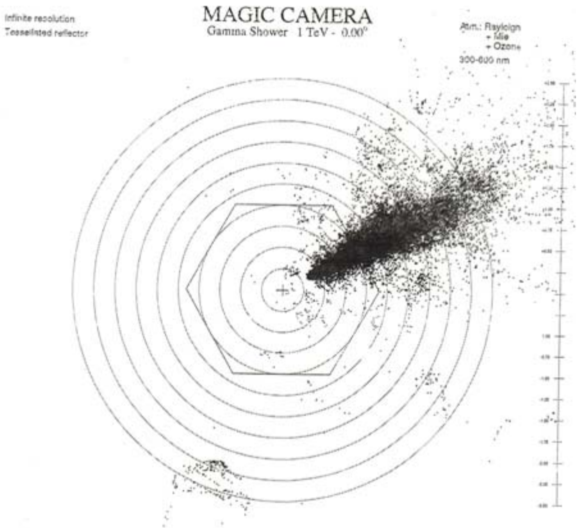

Photon Positions on Ground for 50 GeV Gamma

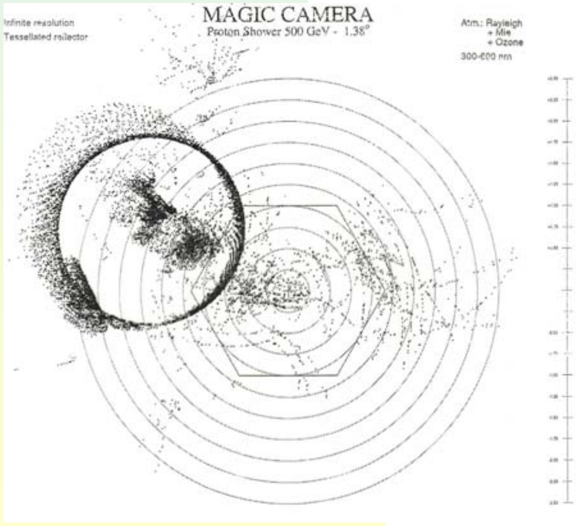
Photon Positions on Ground for 200 GeV Proton

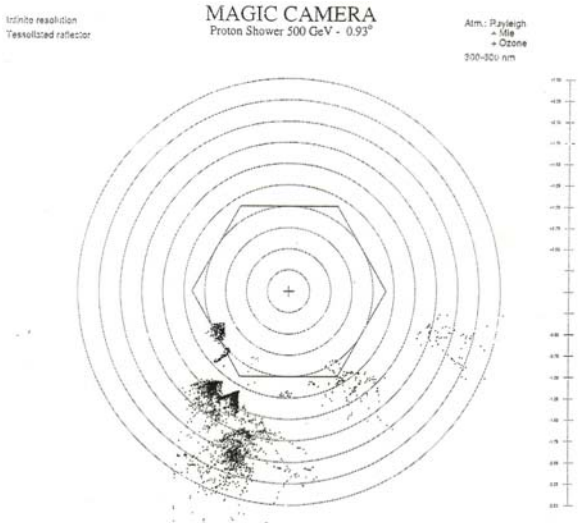
ANY CHERNKOV LIGHT DETRECTOR PLACED INSIDE LIGHT-POOL WOULD DETECT THE AIR SHOWER.

DETECTION AREA: A FEW 10^4 m^2

MONTE CARLO SIMULATION OF SHOWER PHOTONS IN THE CAMERA PLANE ASSUMING A CCD LIKE STRUCTURE (ALL PHOTON IMPACTS SHOWN





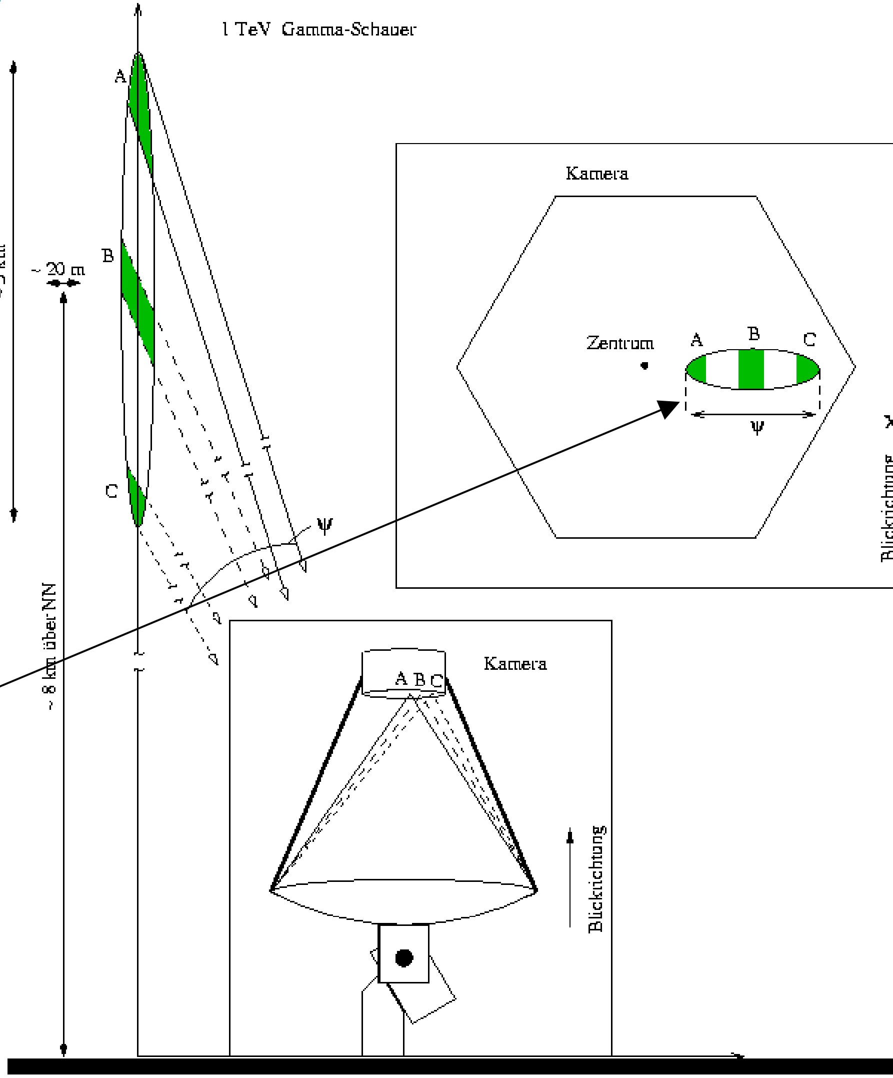


Imaging Cherenkov Telescopes

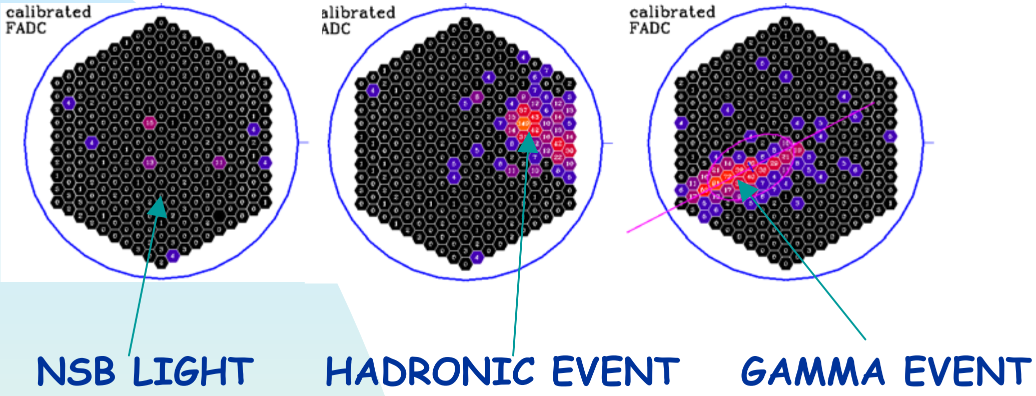
The Cherenkov technique:

- The Cherenkov light is produced by charged relativistic particles of a shower and propagate in the atmosphere down to the ground
- The Cherenkov flash (1-3 ns) is imaged in the telescope camera

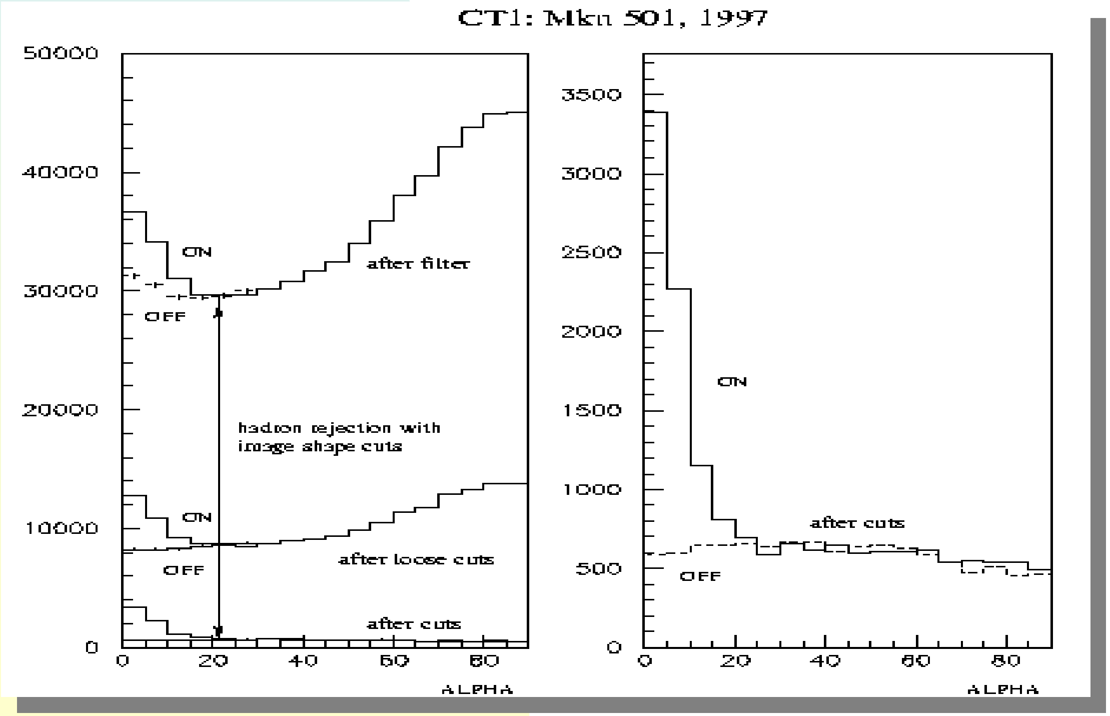
The image shape inherits the shower characteristics and information on the primary particle can be deduced from image shape (direction, energy, impact point)

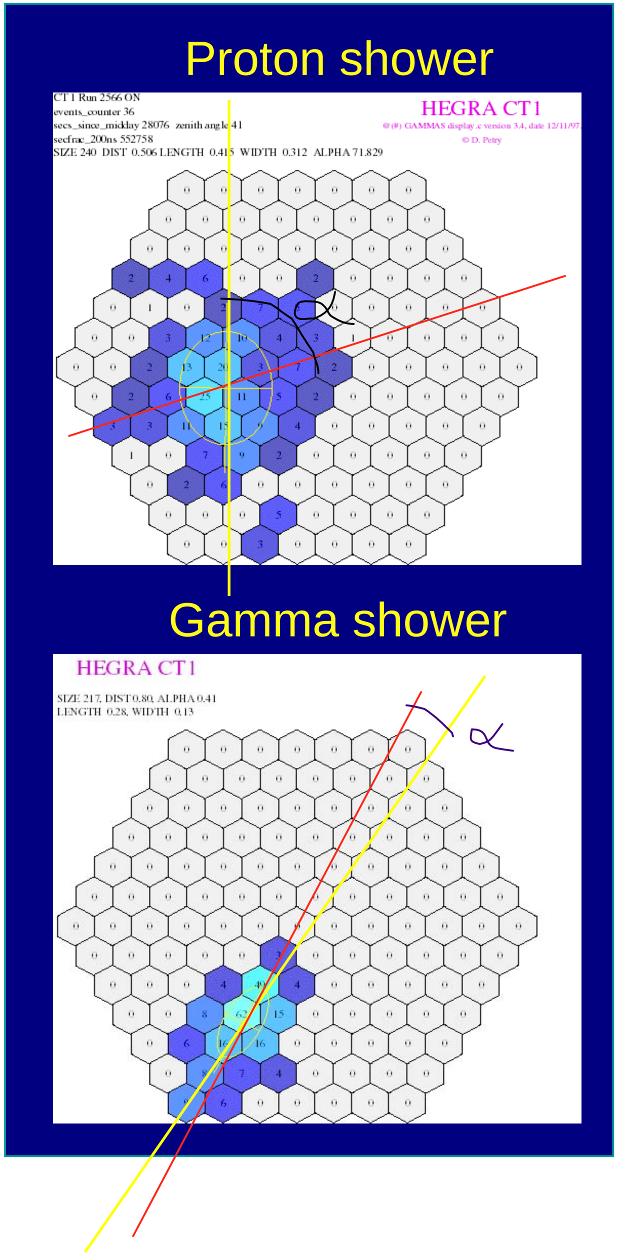


γ/HA Separation



NSB LIGHT **HADRONIC EVENT** **GAMMA EVENT**

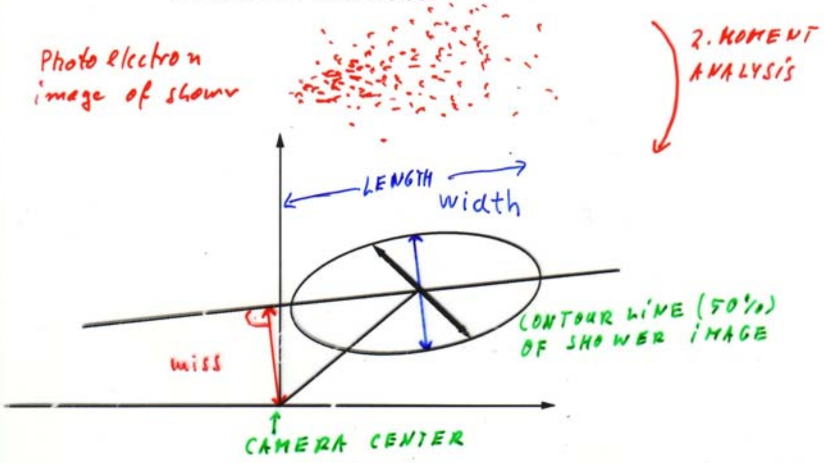

CT1: Mkn 501, 1997

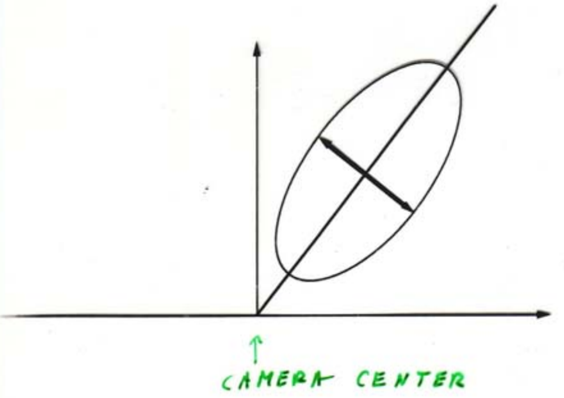

Proton shower

Gamma shower

IMAGE ANALYSIS PARAMETER FOR γ/h SEPARATION

Azwidth-Parameter





γ - IMAGES ARE:

- MORE CONCENTRATED
- POINT TO CAMERA CENTER
- ARE SHORTER
- HAVE A SMALL WIDTH 0.3° VS 0.45°

SOME PROBLEMS: CAMERA PIXEL SIZE (0.2 – 0.5°)
OPTICAL IMPERFECTIONS OF MIRROR
NIGHT SKY BACKGROUND $\sim 2\cdot10^{12}/\mathrm{m^2\cdot sec\cdot sr}$
EXCESS NOISE FACTOR OF PM'S
SINGLE STARS IN F.O.V.

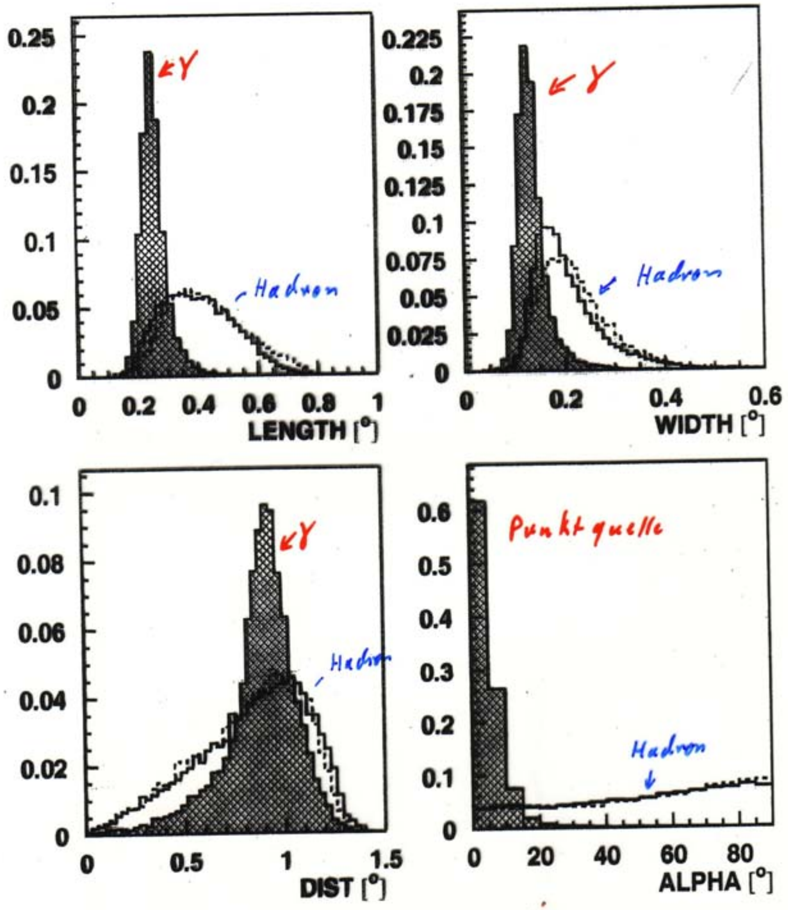
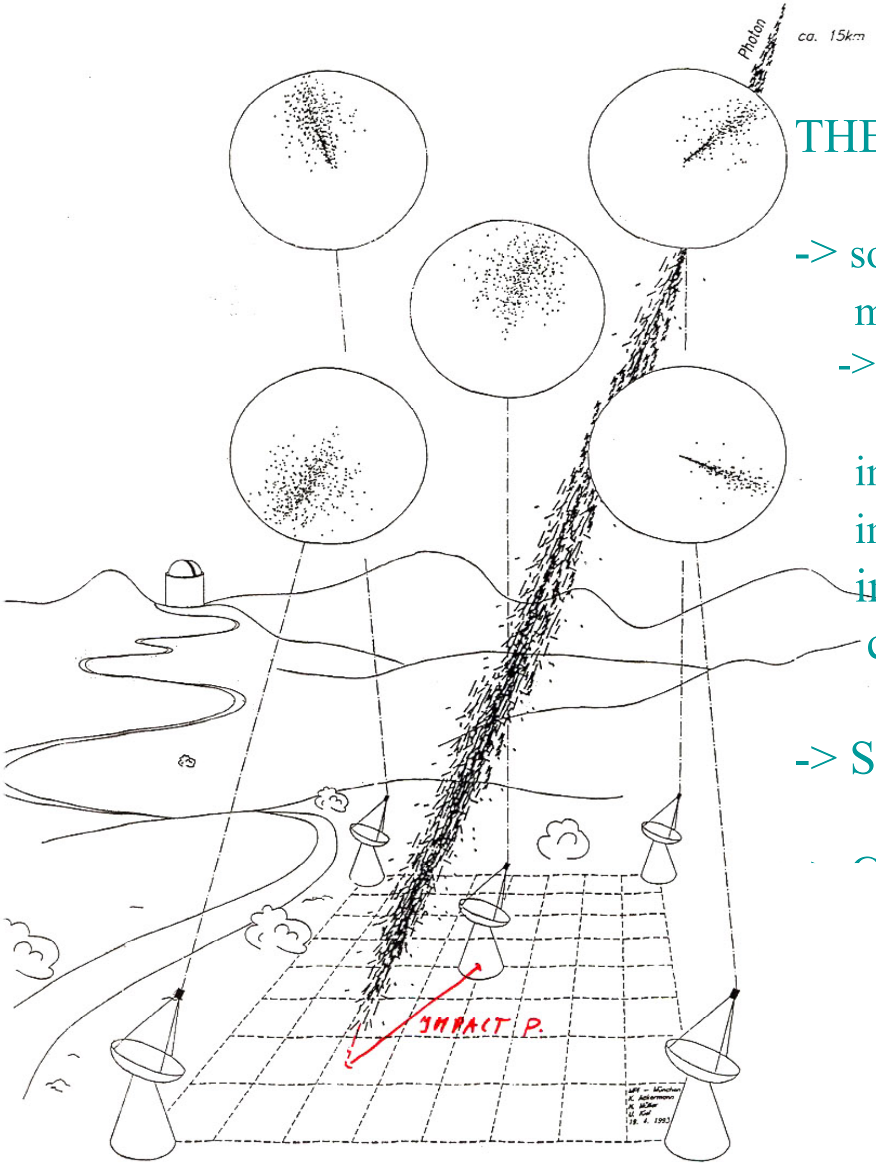


Fig. 4.2.6: Comparison between image parameters of simulated γ-ray showers (dashed region), simulated proton showers (solid line) and real hadronic showers (dashed line) from CT1. The MC showers were generated for 0°zenith angle and spectral index $\alpha = 2.7$, the hadronic showers were taken from observations below 5° zenith angle. All distributions are normalized to unit area.



THE ‘STEREO CONCEPT

-> somewhat higher precision
    more precise impact parameter
  -> unambiguous correlation with sky position
    improved angular resolution
    improved energy resolution
    improved γ/h separation(limit cosmic electron background)

-> SENSITIVITY ≈ (1.2-1.4) x √ n

-> COSTS

THE NEW DETECTORS

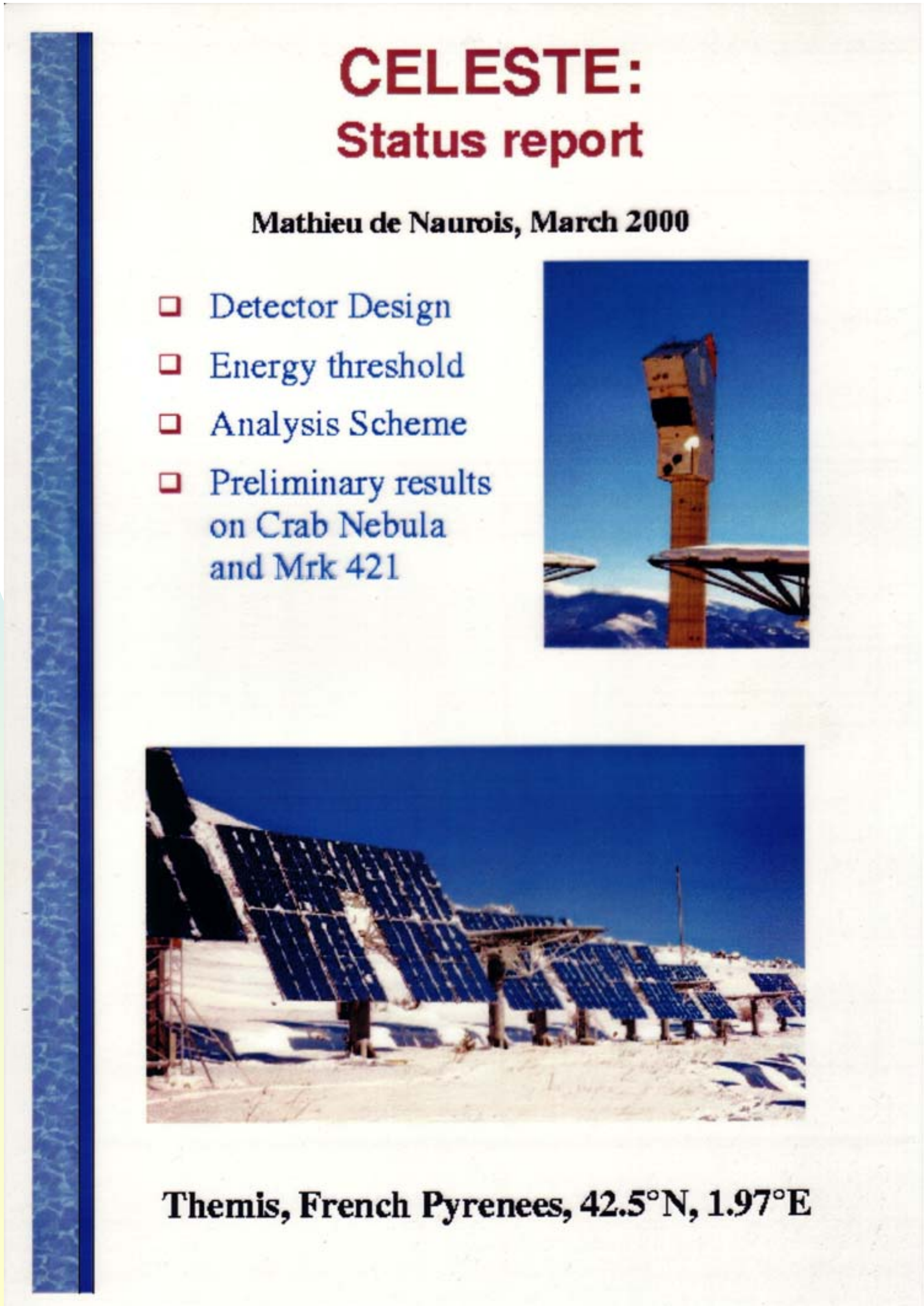
A) Detectors based on large solar power plants

B) Dedicated air Cherenkov telescopes with lower threshold and higher sensitivity

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

Zur Anzeige wird der QuickTime™
Dekompressor “TIFF (Unkomprimiert)”
benötigt.



CELESTE:

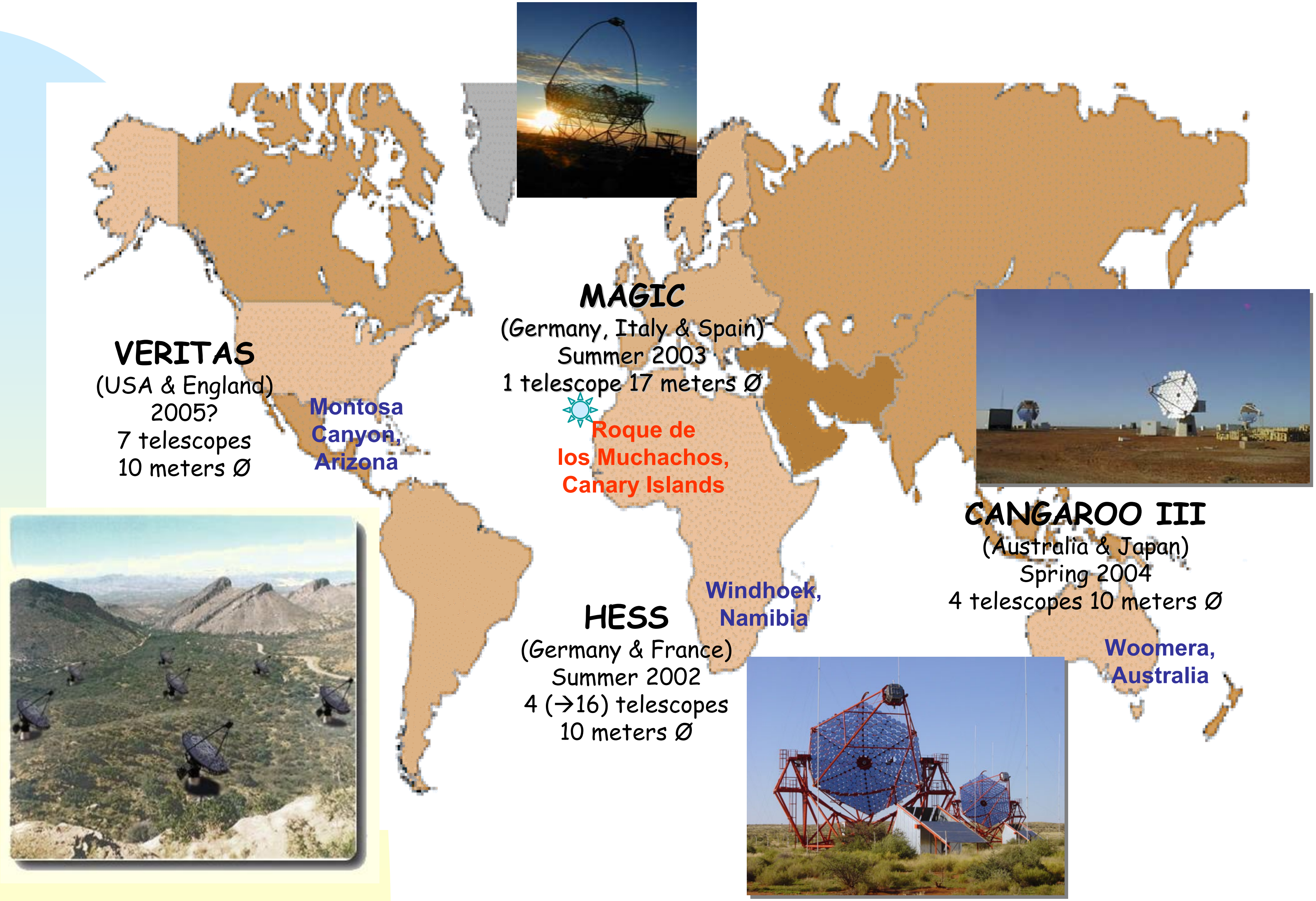
Status report

Mathieu de Naurois, March 2000

- Detector Design
- Energy threshold
- Analysis Scheme
- Preliminary results on Crab Nebula and Mrk 421

Themis, French Pyrenees, 42.5°N, 1.97°E

THE NEXT GENERATION OF HIGH SENSITIVITY CHERENKOV TELESCOPES



VERITAS
(USA & England)
2005?
7 telescopes
10 meters Ø

Montosa Canyon, Arizona

MAGIC
(Germany, Italy & Spain)
Summer 2003
1 telescope 17 meters Ø

Roque de los Muchachos, Canary Islands

CANGAROO III
(Australia & Japan)
Spring 2004
4 telescopes 10 meters Ø

Woomera, Australia

HESS
(Germany & France)
Summer 2002
4 (→16) telescopes
10 meters Ø

Windhoek, Namibia

THE NEXT GENERATION OF HIGH SENSITIVITY, LOW THRESHOLD TELESCOPES

EXPERIMENT, LOCATION	#, Ø OF MIRROR S	THRESHOLD
CANGAROO III, AUSTRALIA	4X 10 M Ø	- 100 GeV
HESS, NAMIBIA	4X 12 MØ	- 60 GeV
MAGIC, SPAIN	17 M Ø	30->15 GeV
VERITAS, USA	7 X 10 M Ø	80 GeV

THE CANGAROO III DETECTOR, 4 x 10 m IACTs

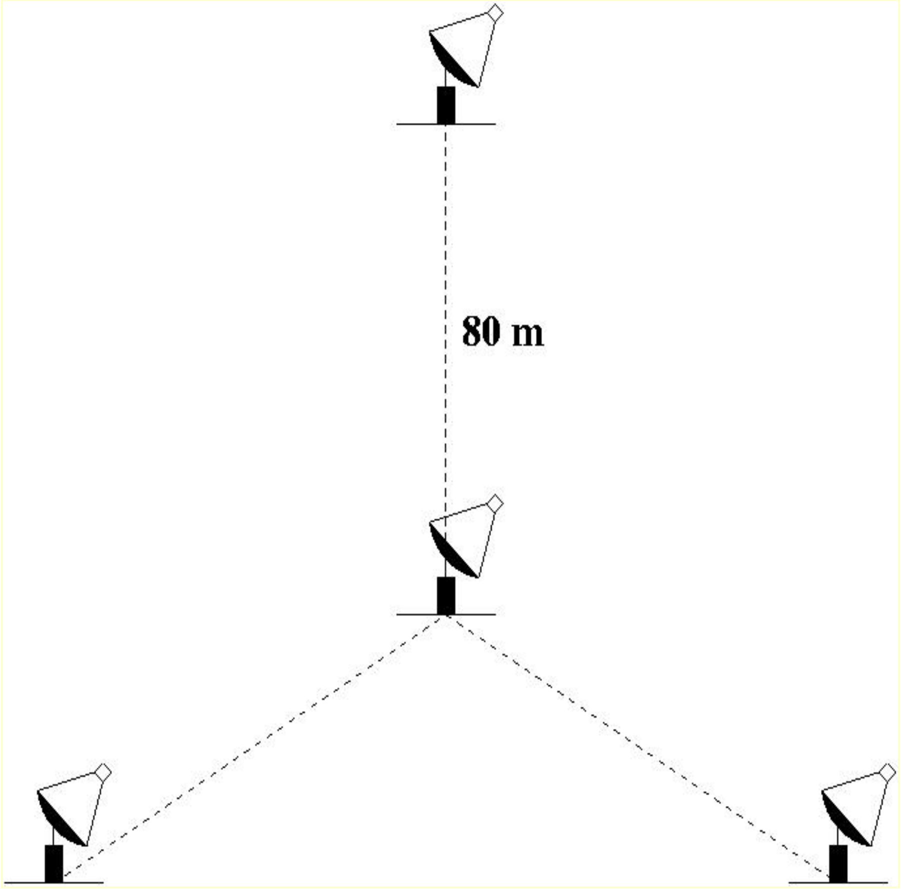
Zur Anzeige wird der QuickTime™
Dekompressor “GIF”
benötigt.

VERITAS TELESCOPE-1

VERITAS Telescope-1 completed and operating at temporary site.
First Light on February 1, 2005 (Crab detection)

VERITAS-4: Definition

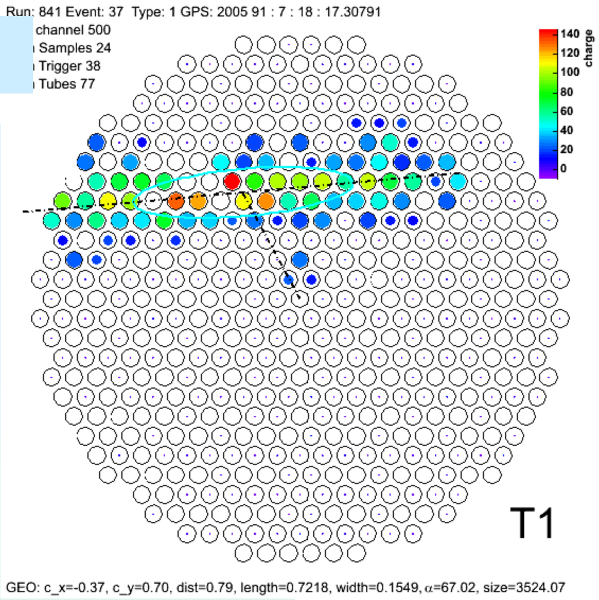
System of four telescopes
Aperture 12 m
Hexagonal Mirrors
Cameras with 499 pixels
Individual pulse shapes;
FADCs 500MHz sampling
High data rate; zero suppress.
Array Trigger
Southern Arizona location
Dark site: 1.8 km



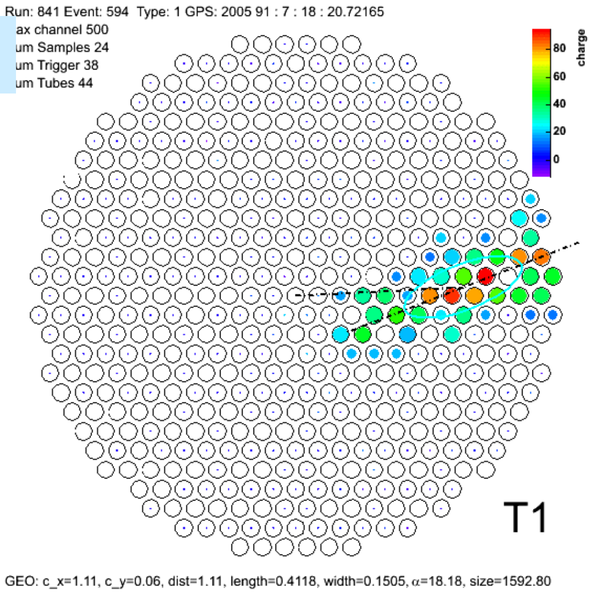
History: 1996 VERITAS proposed
2001 Prototype funded
2003 VERITAS approved
2006 VERITAS completed

Shower Images from Telescope-1of Veritas

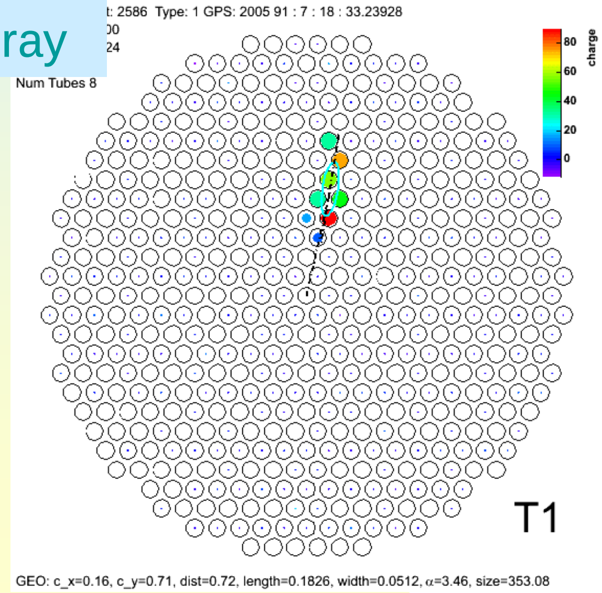
Hadron



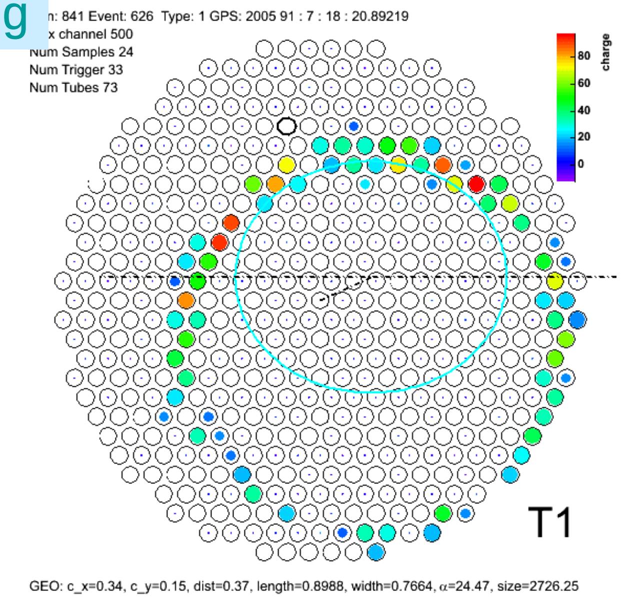
Hadron



Gamma ray



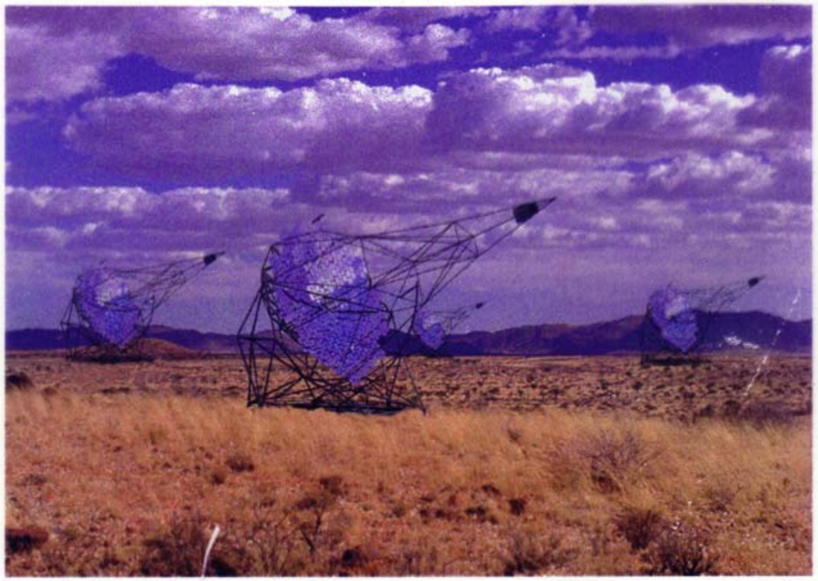
Muon Ring



HESS: High Energy Stereoscopic System

γ – Ray Astronomy above

40 GeV (detection)
100 GeV (spectroscopy and spatial resolution)



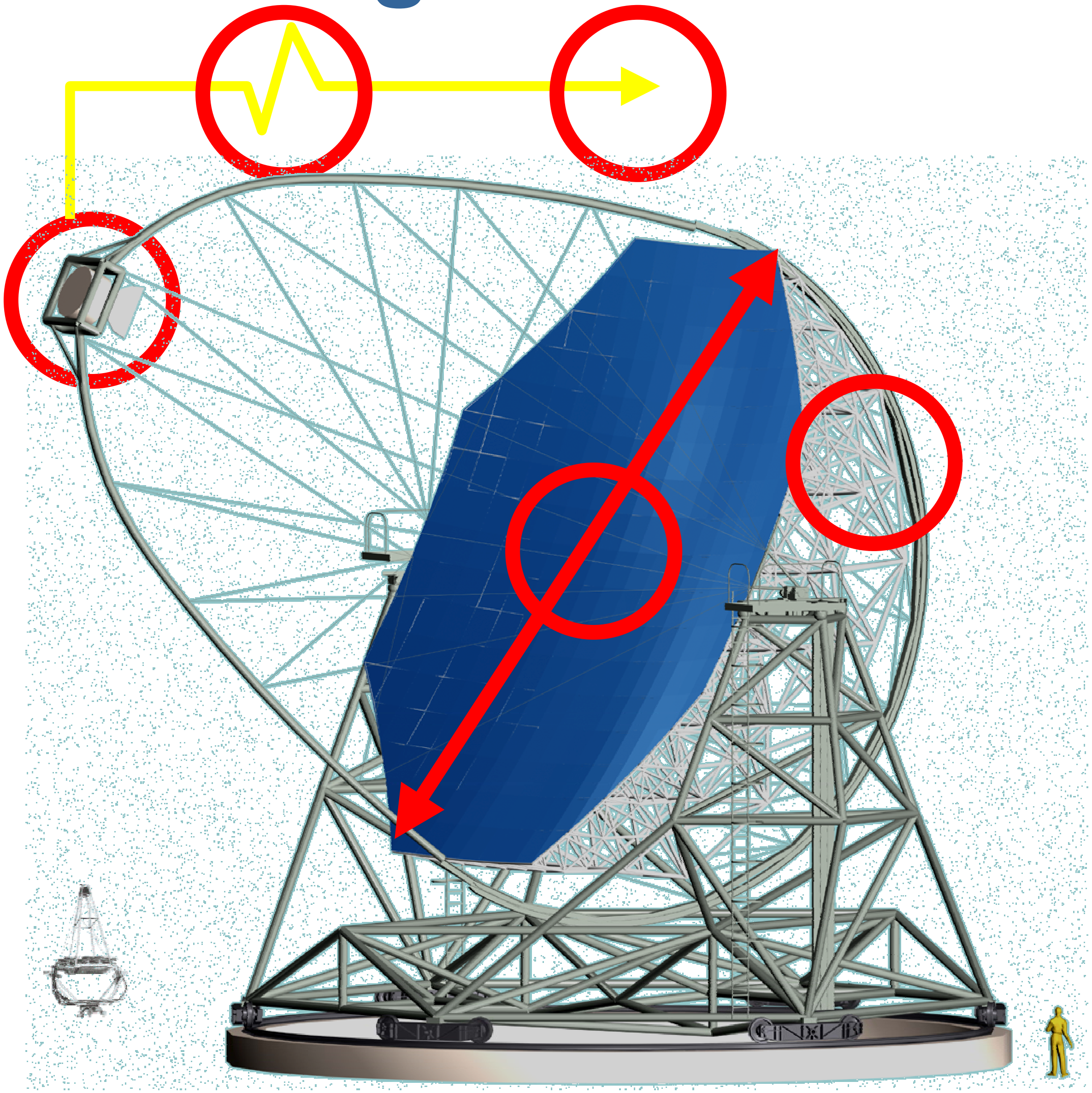
- First 4 (until 2001), then 16 telescopes
- Operate 16 together or in 4 cells
- Spatial seperation of cells?
- Segmented 80 m² mirror, 15 m focal length
- HiRes Camera, ~ 5 deg FoV, 800 pixels

THE MAGIC TELESCOPE ON LA PALMA

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

MAGIC Building blocks

- 17 m diameter dish
- Ultra light carbon fibre frame
- Active mirror control
- 577 pixels, 3.9 deg FOV camera
- Optical signal transport
- 2 level trigger system



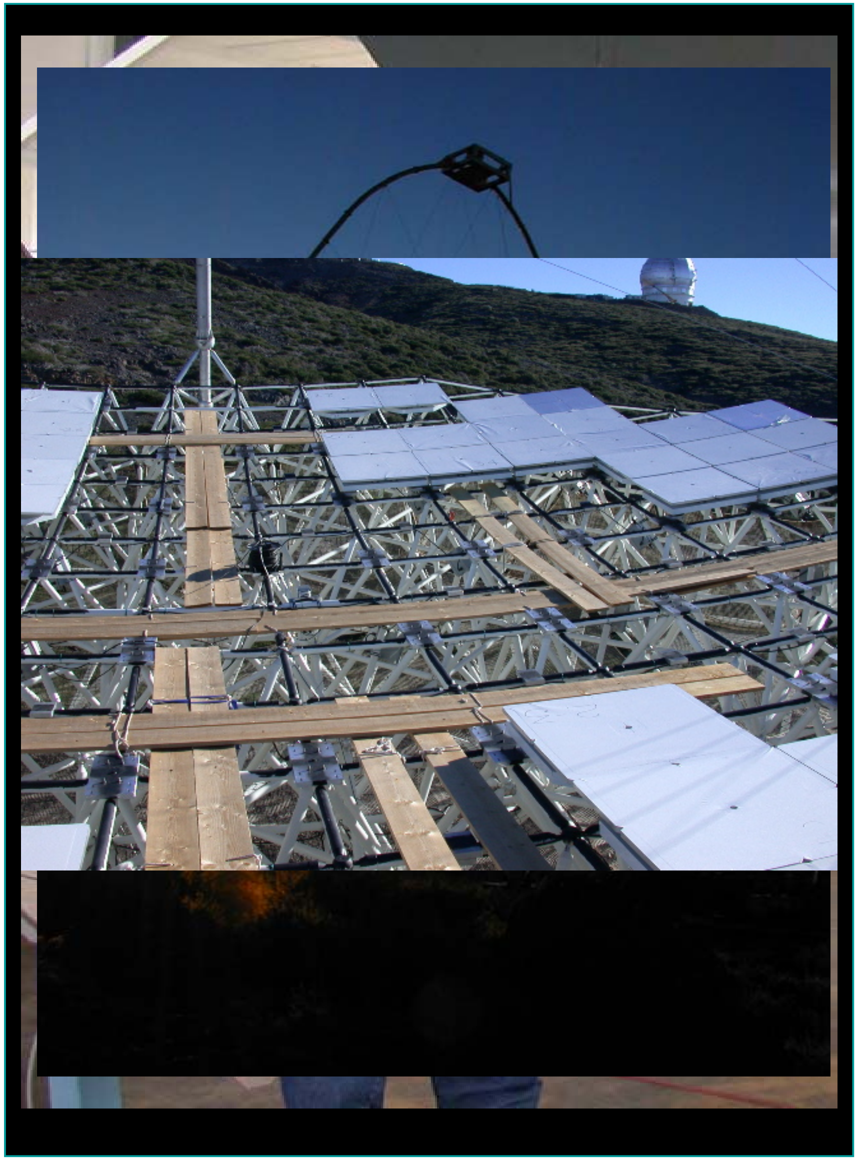
The reflector

- 17 m diameter!!

  3 x area of 10 m IACTs

- Parabolic: isochronous, allowing for bg reduction

- Tesselated reflector:
  - ~950 mirror elements
  - 49.5 x 49.5 cm^2
  - All-aluminum, quartz coated, diamond milled, internal heating
  - >85% reflectivity in 300-650nm



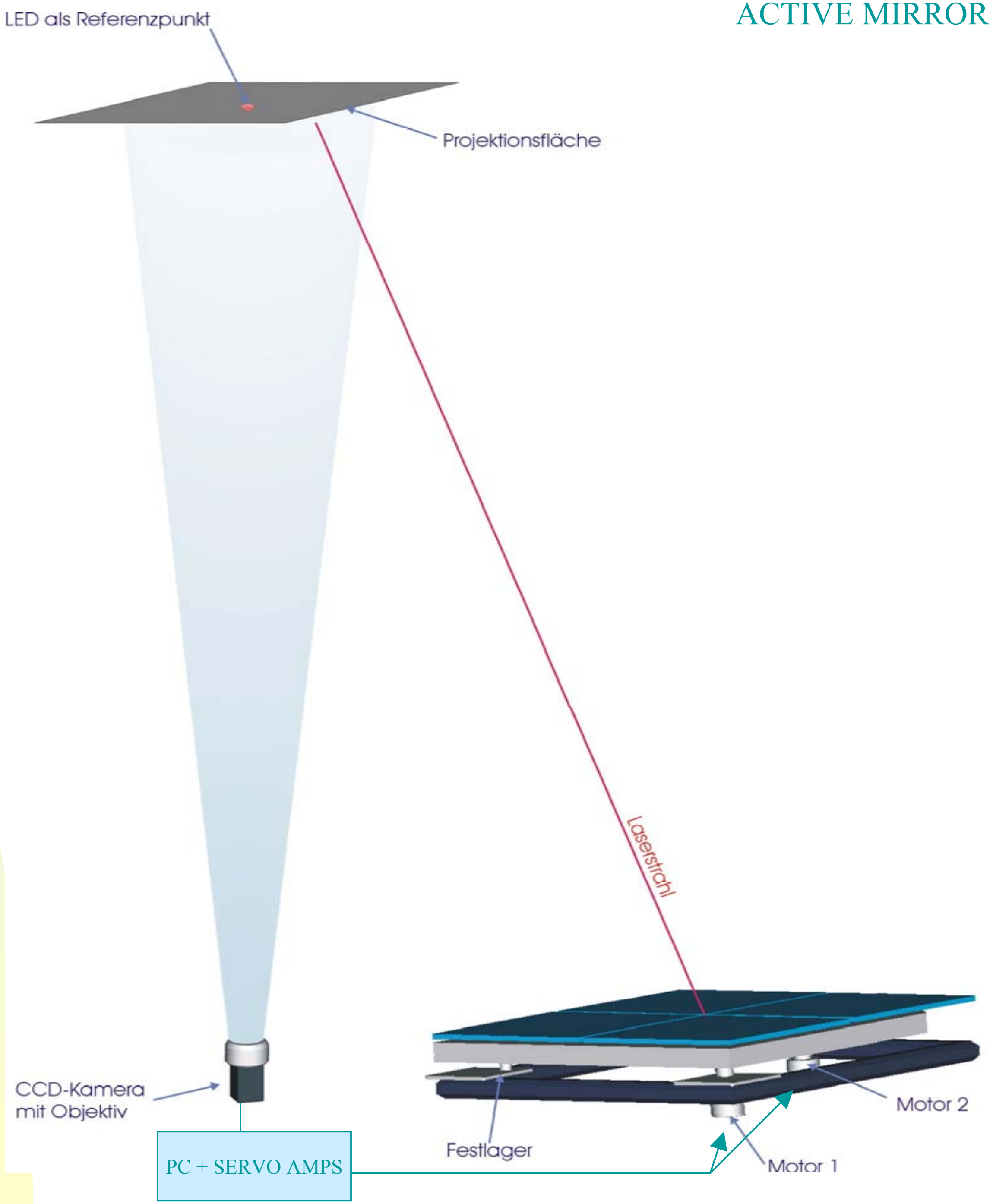
MIRROR

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

Mirrors quartz coated

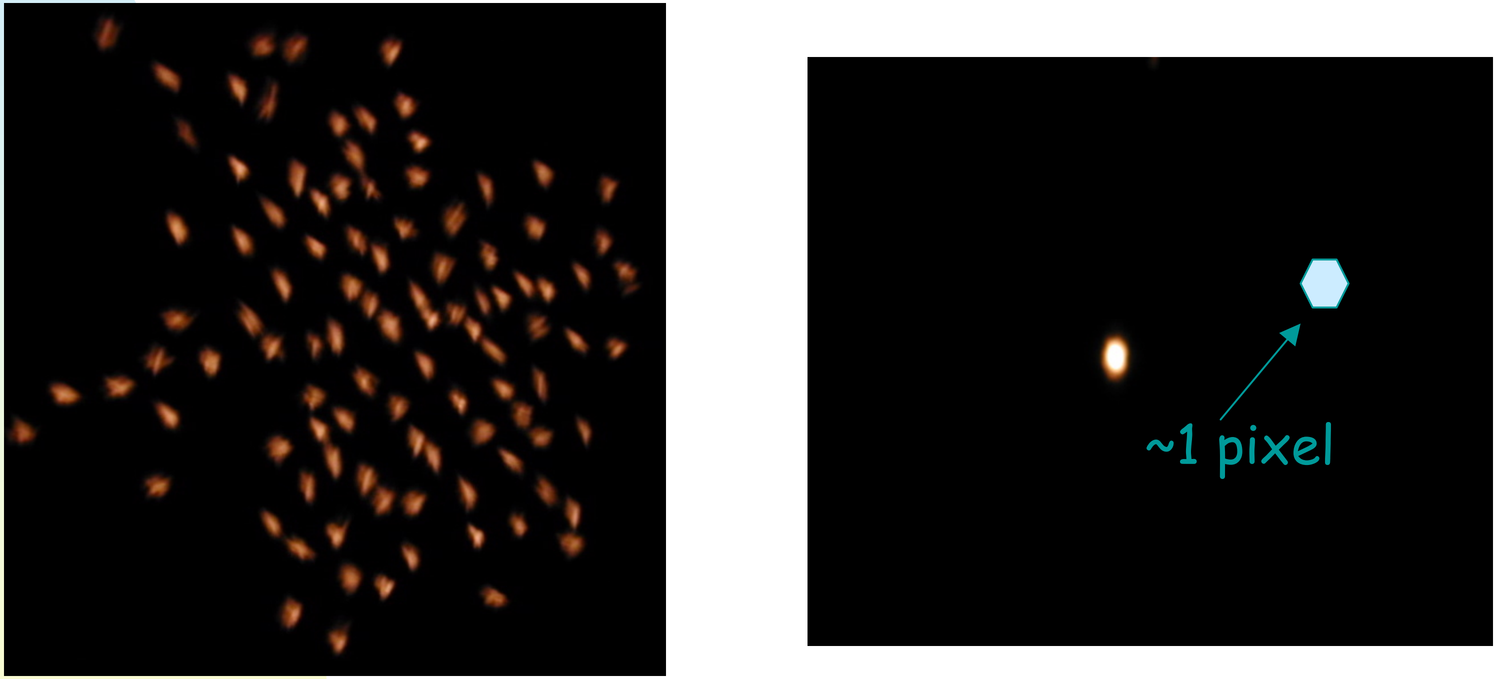
ACTIVE MIRROR CONTROL

Principle of active mirror Control (AMC)



The alignment of the mirrors

- The alignment of the first 103 mirrors in the telescope structure has been done by using an artificial light source at a distance of 920m
- The camera plane was moved 29 cm backward to focus the lamp light



103 spots before and after the alignment. It takes about 220 sec for the semiautomatic adjustment

The camera

- Matrix of 577 PMTs
- Two sections:
  - Inner part: 0.1^0 PMTs
  - Outer part: 0.2^0 PMTs

Plate of Winston cones ⇒
Active camera area ~100%

A METHOD TO INCREAS E THE QE:COAT WINDOW WITH A LAQUER LOADED WITH WLS AND USING A FAST EVAPORATING SOLVENT ->
FORMS FROSTED WINDOW SURFACE LAYER

Zur Anzeige wird der QuickTime™
Dekompressor "Foto - JPEG"
benötigt.

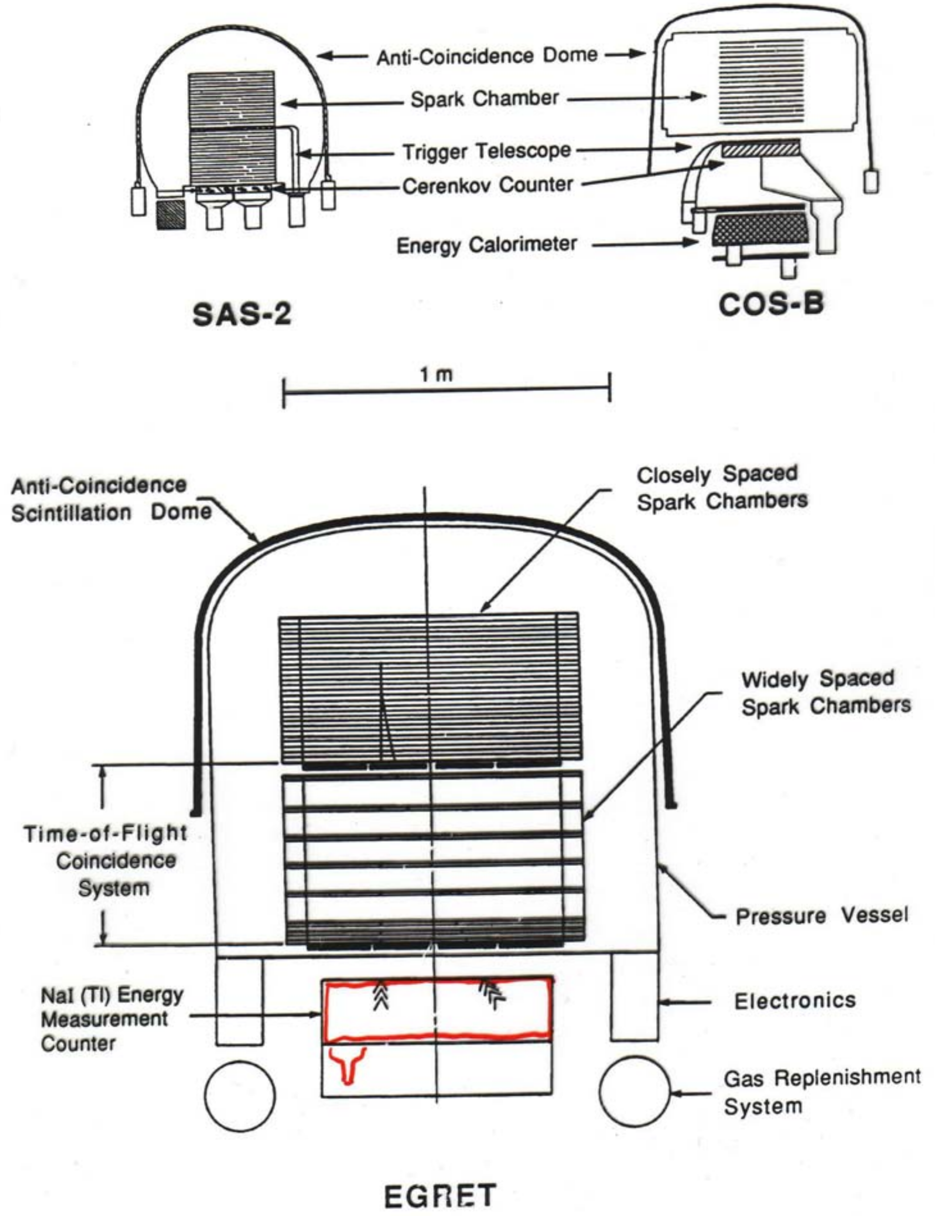
CAMERA

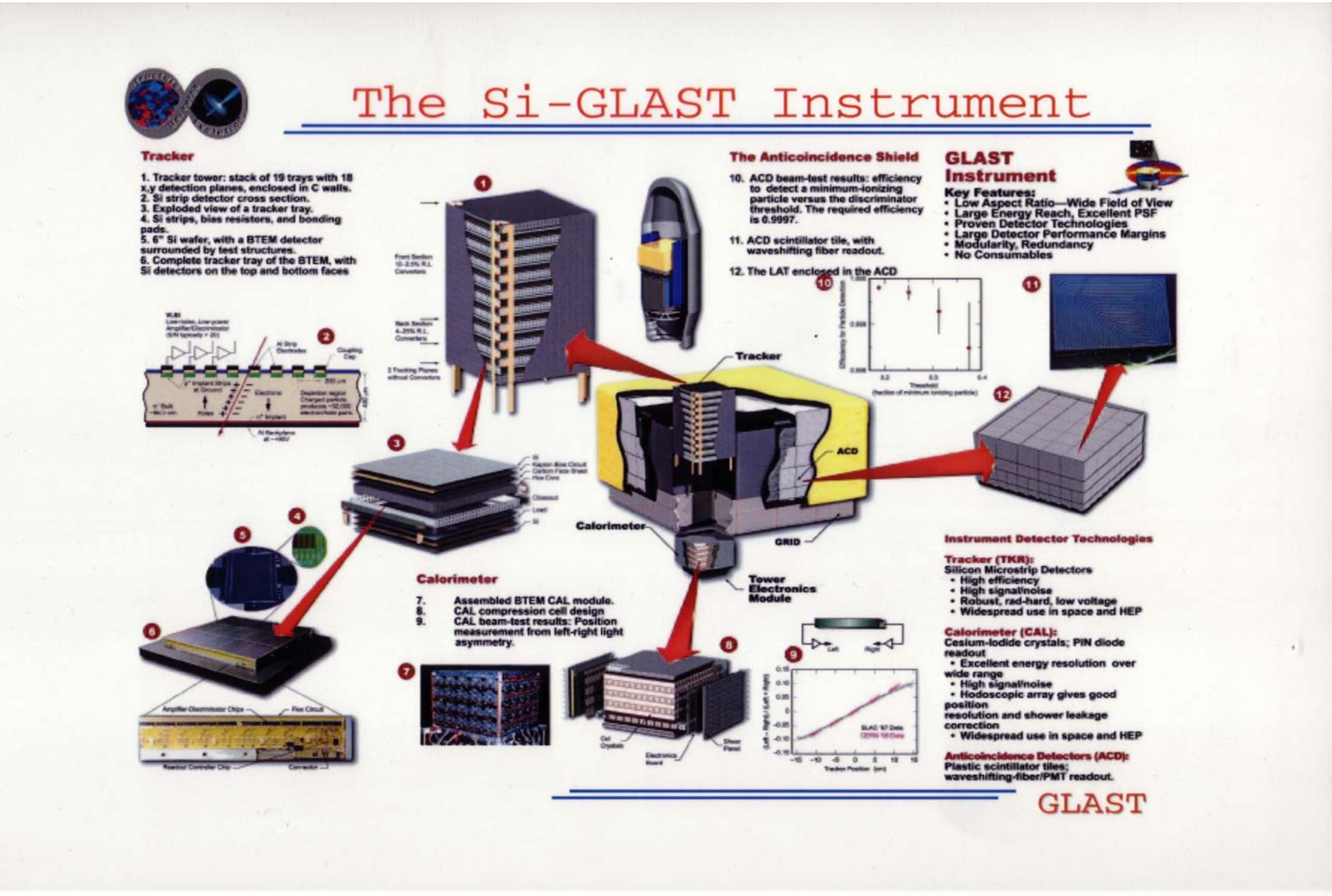
Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

Some Satellite γ detectors (1keV- few GeV)

- EGRET stopped working
- RXTE, operational
- CHANDRA (low keV), operational
- XMM operational
- INTEGRAL, operational
- HETE (GRB search), operational
- SWIFT (GRB search), launch fall 2003
- [AMS], launch 2004
- AGILE , launch 2005
- GLAST launch 2007

PREVIOUS γ SATELLITES





The Si-GLAST Instrument

Tracker

1. Tracker tower: stack of 19 trays with 18 x,y detection planes, enclosed in C walls.
2. Si strip detector cross section.
3. Exploded view of a tracker tray.
4. Si strips, bias resistors, and bonding pads.
5. 6" Si wafer, with a BTEM detector surrounded by test structures.
6. Complete tracker tray of the BTEM, with Si detectors on the top and bottom faces

The Anticoincidence Shield

10. ACD beam-test results: efficiency to detect a minimum-ionizing particle versus the discriminator threshold. The required efficiency is 0.9997.
11. ACD scintillator tile, with waveshifting fiber readout.
12. The LAT enclosed in the ACD

GLAST Instrument

Key Features:
- Low Aspect Ratio—Wide Field of View
- Large Energy Reach, Excellent PSF
- Proven Detector Technologies
- Large Detector Performance Margins
- Modularity, Redundancy
- No Consumables

Calorimeter

7. Assembled BTEM CAL module.
8. CAL compression cell design
9. CAL beam-test results: Position measurement from left-right light asymmetry.

Instrument Detector Technologies

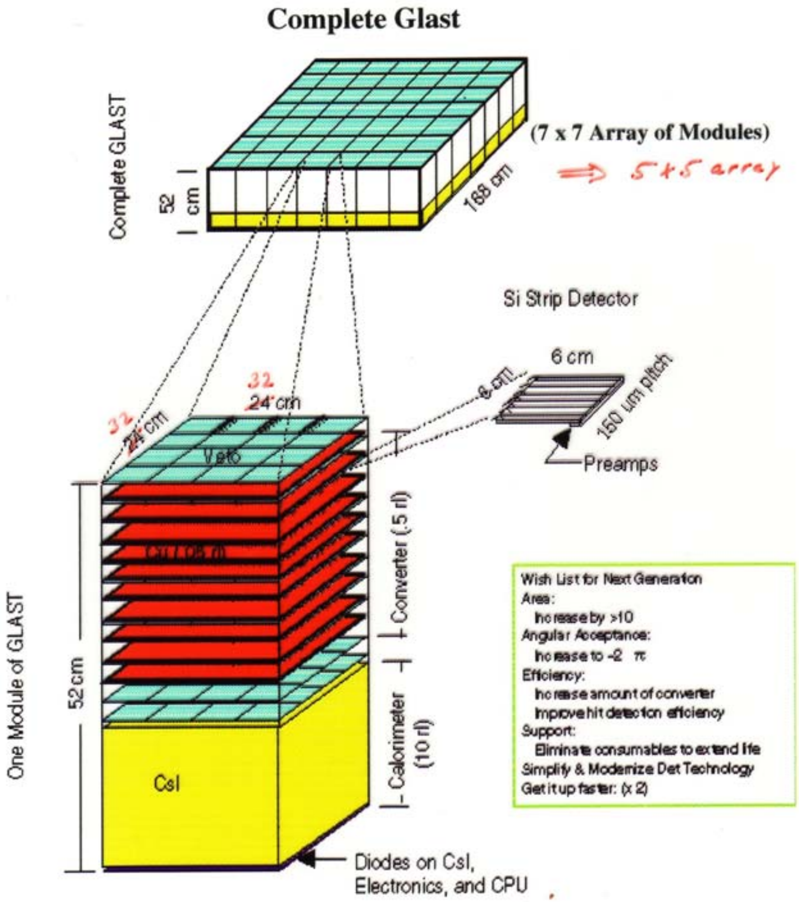
Tracker (TKR):
Silicon Microstrip Detectors
- High efficiency
- High signal/noise
- Robust, rad-hard, low voltage
- Widespread use in space and HEP

Calorimeter (CAL):
Cesium-Iodide crystals; PIN diode readout
- Excellent energy resolution over wide range
- High signal/noise
- Hodoscopic array gives good position resolution and shower leakage correction
- Widespread use in space and HEP

Anticoincidence Detectors (ACD):
Plastic scintillator tiles; waveshifting-fiber/PMT readout.

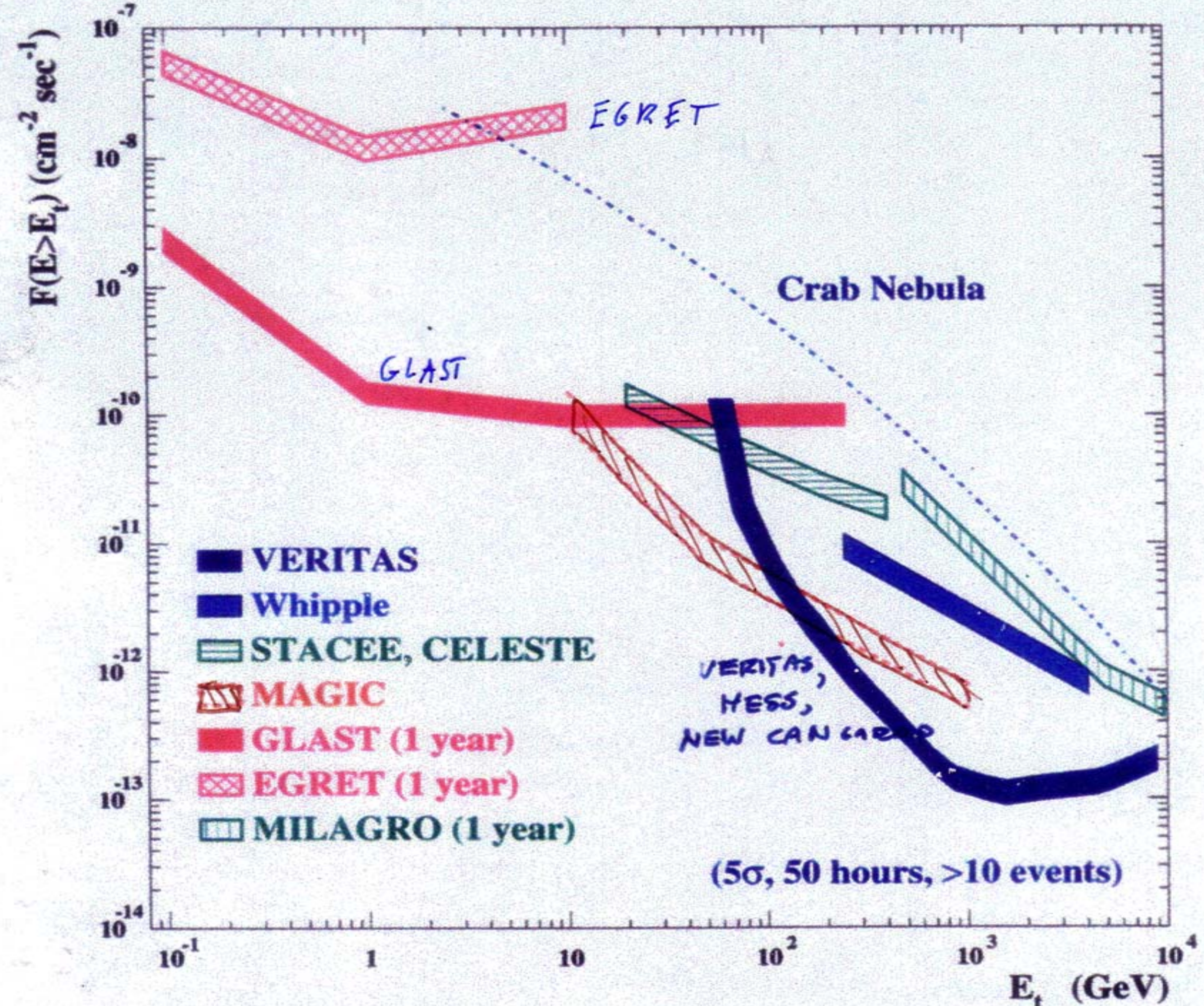
GLAST

GLAST Instrument Concept



Wish List for Next Generation
Area:
  Increase by >10
Angular Acceptance:
  Increase to ~2 π
Efficiency:
  Increase amount of converter
  Improve hit detection efficiency
Support:
  Eliminate consumables to extend life
Simplify & Modernize Det Technology
Get it up faster: (x 2)

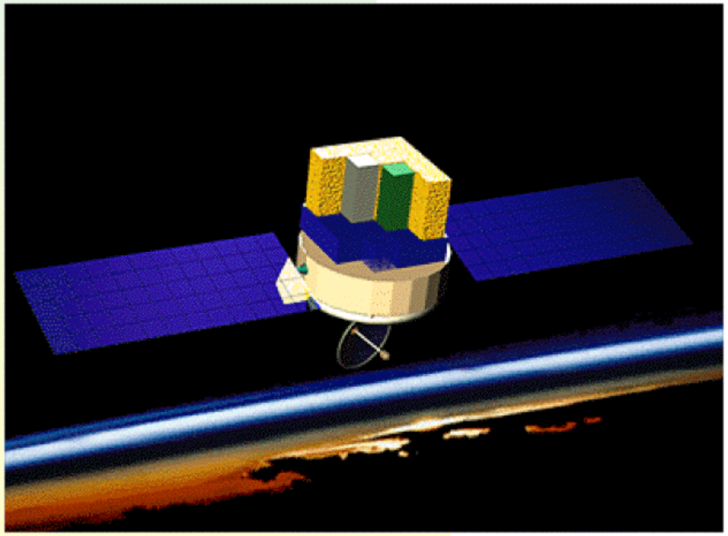
SENSITIVITY OF DIFFERENT γ RAY DETECTORS



IACT vs Satellite

- Satellite :
  - primary detection
  - small effective area ~$1 m^2$
    - lower sensitivity
  - large angular opening
    - search
  - large duty-cycle
  - large cost
  - lower energy
  - low bkg

- IACT/ground based
  - secondary detection
  - huge effective area ~$10^4\ m^2$
    - Higher sensitivity
  - small angular opening
    - Serendipity search
  - small duty-cycle
  - low cost
  - high energy
  - high bkg



SOME FUNDAMENTAL DIFFERENCES BETWEEN TELESCOPES FOR OPTICAL AND γ ASTRONOMY

.	OPTICAL TELESCOPES	IACTS
WHAT IS OBSERVED	POINTLIKE SOURCE AT INFININITY	EXTENDED AIR SHOWERS (30- 5 KM)
RESOLUTION	ARC SEC	FEW ARC MIN
MIRROR GEOMETRY	DIFFRACTION LIMIT	TESSELATED MIRROR, CAN BE STAGGERED
	NEEDS MANY PHOTONS TO DETECT/ STUDY SOURCE	DETECTS SINGLE γ SHOWERS
MECHANICAL REQ.	VERY HIGH	MODEST
EXPOSURE	CAN BE LONG	FEW nsec/ SHOWER
CAMERA	VERY FINE PIXELS, CCD	COARSE PIXELS O 0.1°-0.2°
BACKGROUND	NIGHT SKY BG LIGHT	NSB, HADRONIC SHOWERS
OBSERVATION DURATION	SHORT	MANY HOURS
COSTS	HIGH	AT LEAST AN ORDER OF MAG. LOWER
MOST EXPENSIVE PART	MIRROR	CAMERA
DOME	YES	NO
TYP LIFETIME	MANY YEARS	5-10 YEARS (UPGRADE AFTER FEW YEARS)

THIRD EGRET CATALOGUE

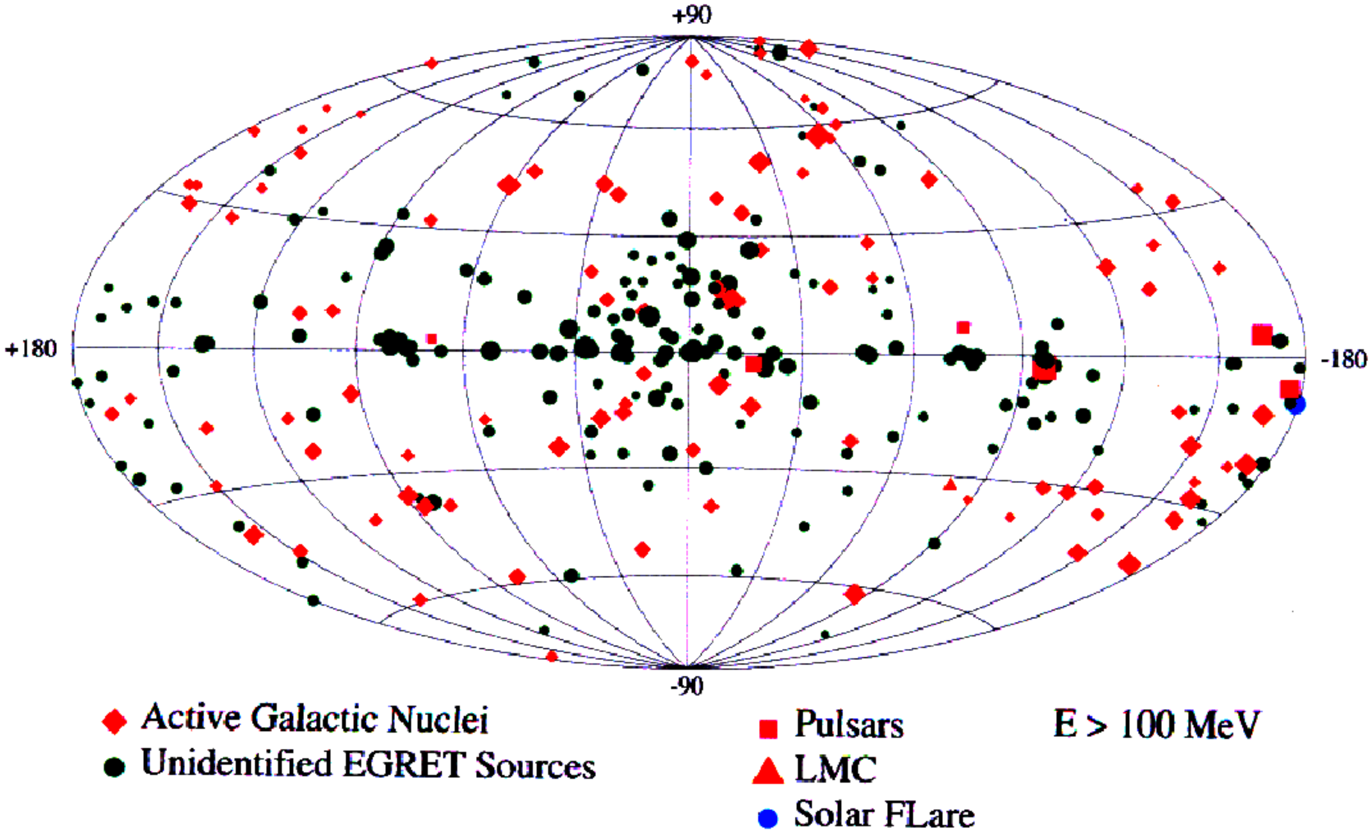
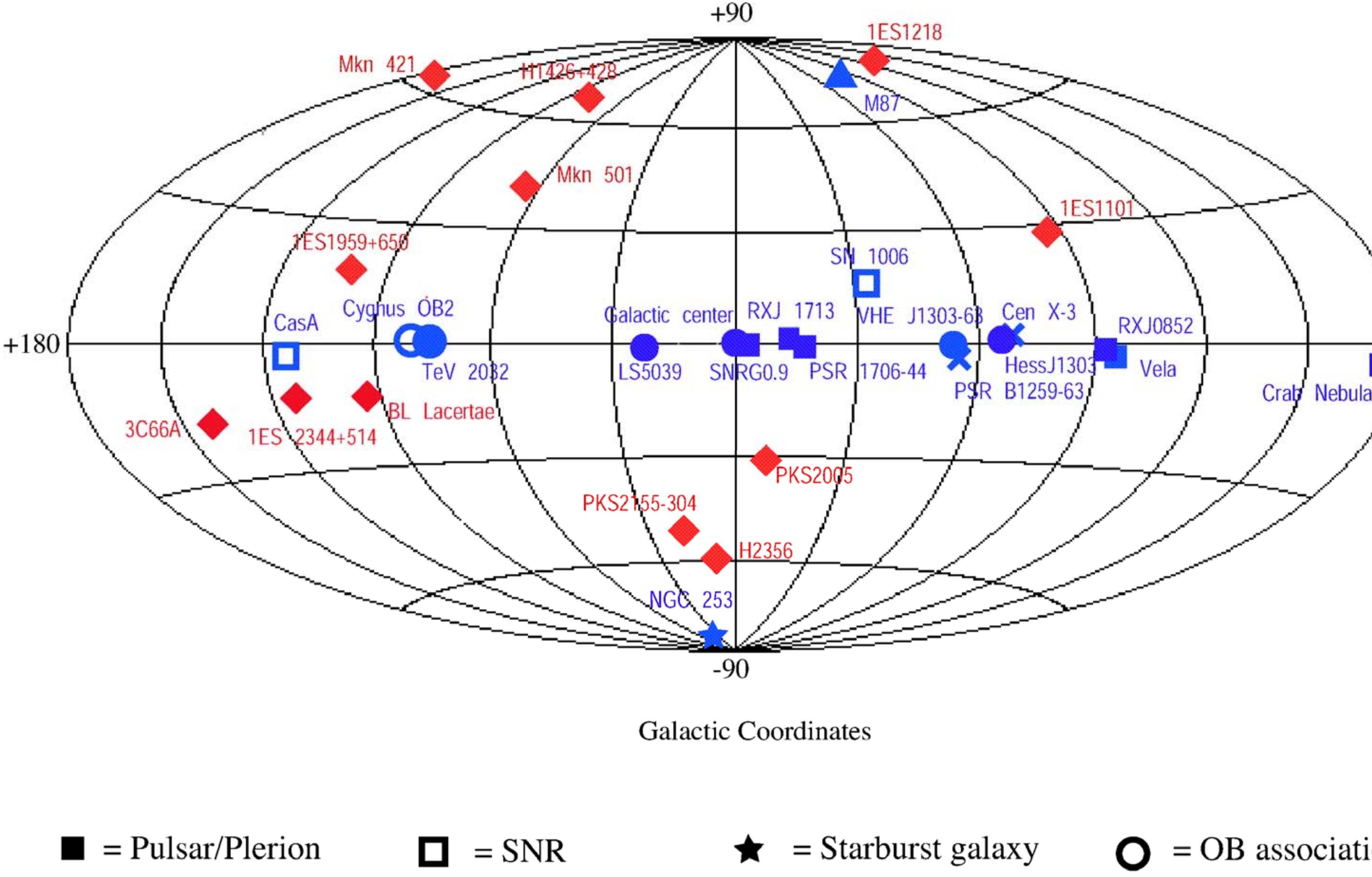
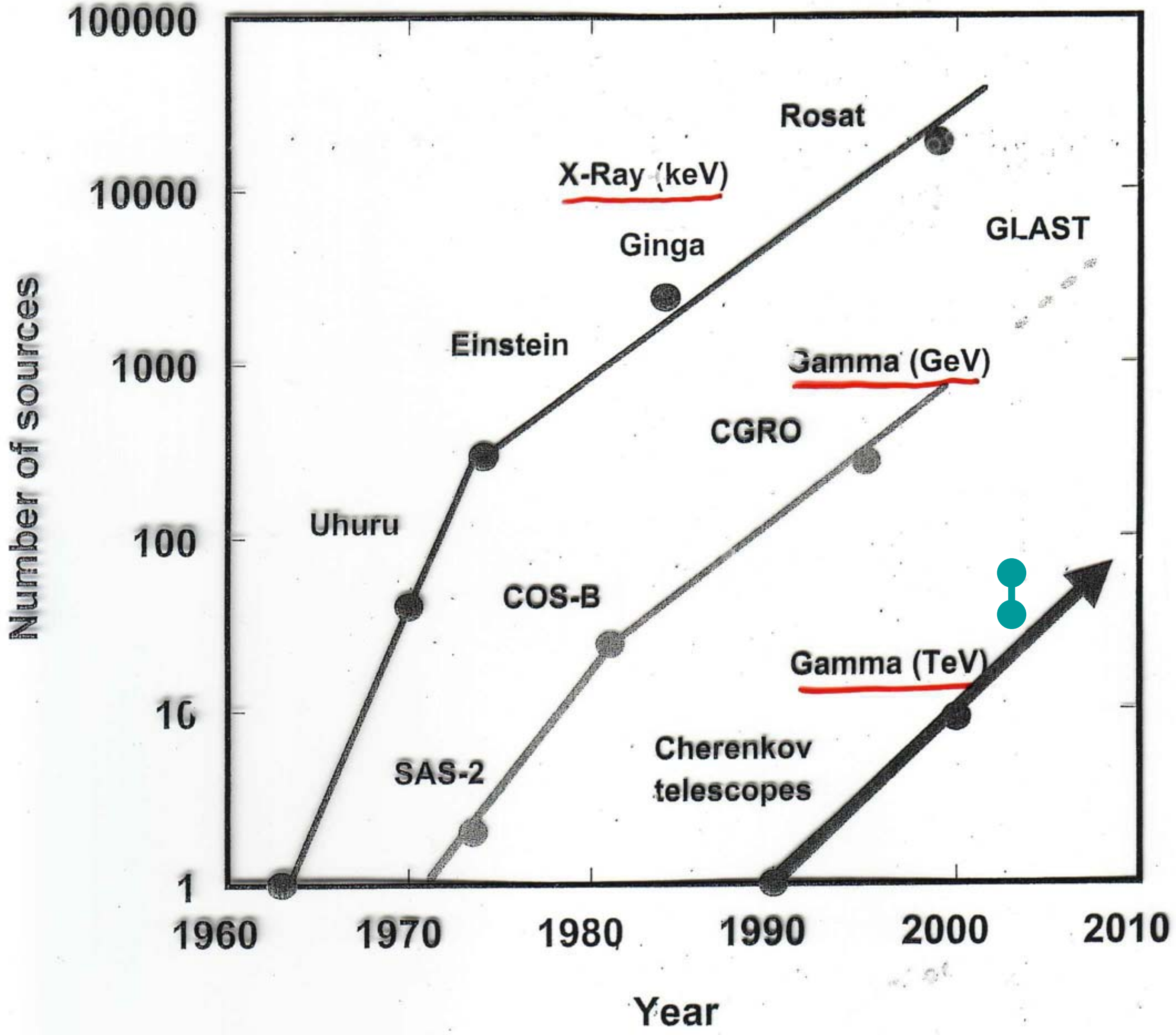


Figure 4-1 Third EGRET Catalog of high-energy gamma-ray sources (Hartman et al. 1999). The source locations are shown in Galactic coordinates.

VHE Gamma Sources (E > 100 GeV)

(Status August 2005)




100000
10000
1000
100
10
1
Number of sources
1960
1970
1980
1990
2000
2010
Year
Rosat
X-Ray (keV)
Ginga
GLAST
Einstein
Gamma (GeV)
CGRO
Uhuru
COS-B
Gamma (TeV)
SAS-2
Cherenkov telescopes

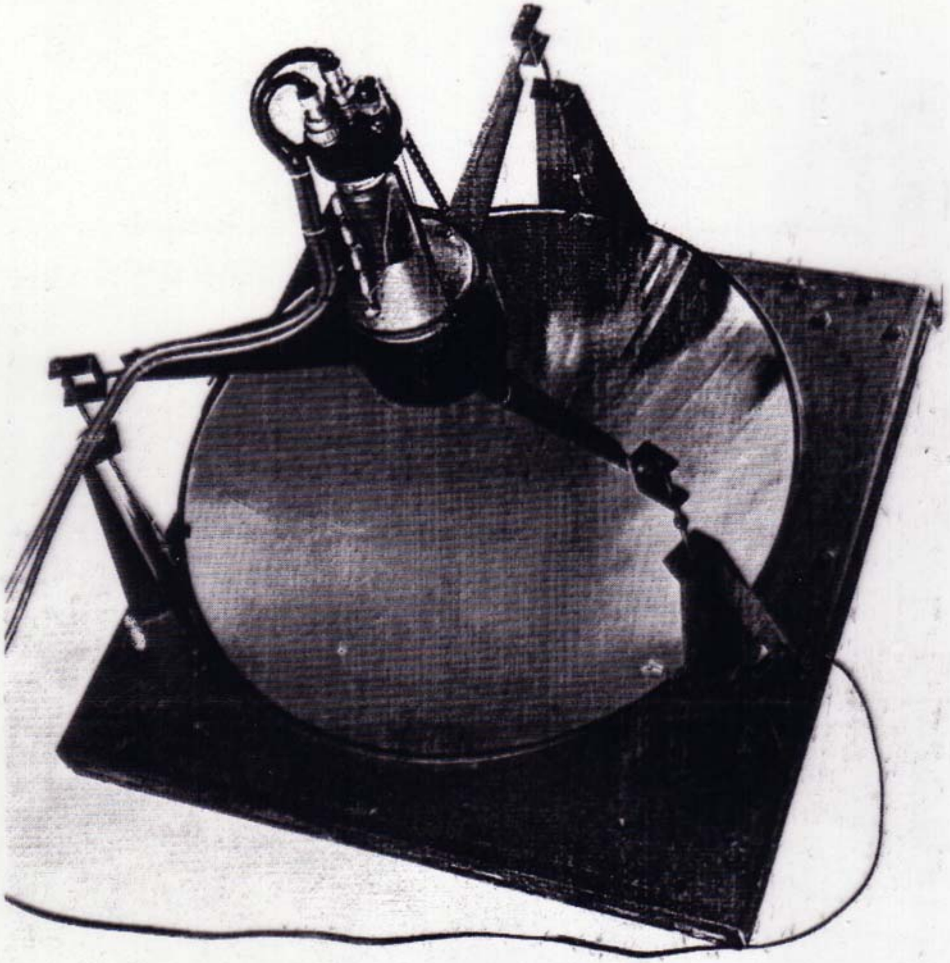


PLATE V (a).

(a) One of the light receivers used by Galbraith and the author (1955) for experiments on the Čerenkov light pulses from the night sky associated with cosmic-ray showers. In this instrument an EMI 12·5 cm dia. photomultiplier is mounted with its cathode in the focal plane of an f/0·5 61 cm dia. parabolic mirror, silvered on the under side. Also will be seen the cathode follower unit, the supporting "spider", and (close to the rim of the mirror by the nearest pillar), the small lamp used for maintaining a constant level of background light. The entire instrument is surrounded by a light screen, and warm air is arranged to blow across the mirror to prevent the formation of dew.