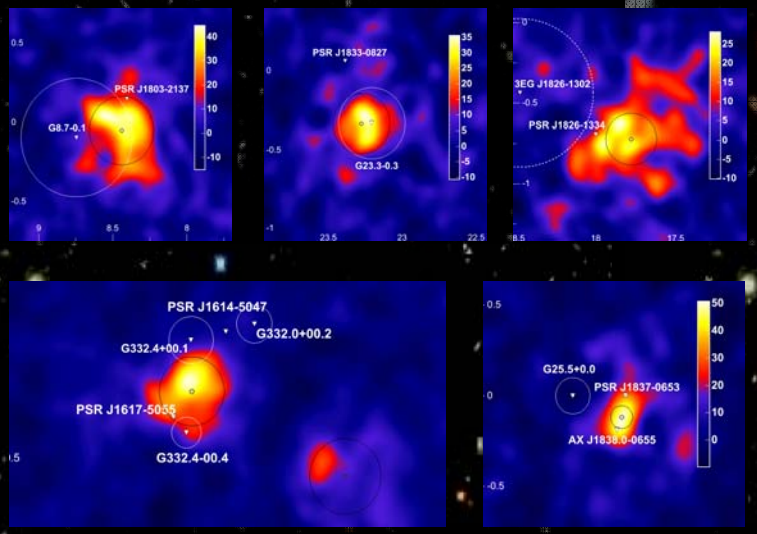
Ground-Based Gamma-Ray Instrumentation ...

PART 1

- Ground-Based Techniques
- Imaging Cherenkov Technique
- The H.E.S.S. Experiment
- Large FoV Experiments
- Future Instrumentation

G.Hermann
MPIK Heidelberg

... and Observational Results

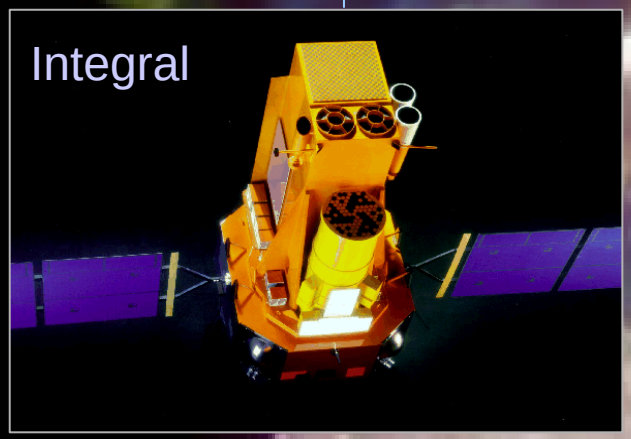


PART 2

- Counting TeV Sources
- Supernova Remnants
- The Galactic Plane
- Galactic Center Region
- The Extragalactic BG Light

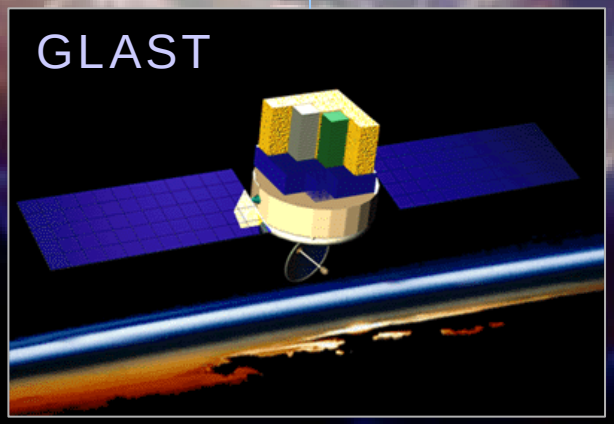
G.Hermann
MPIK Heidelberg

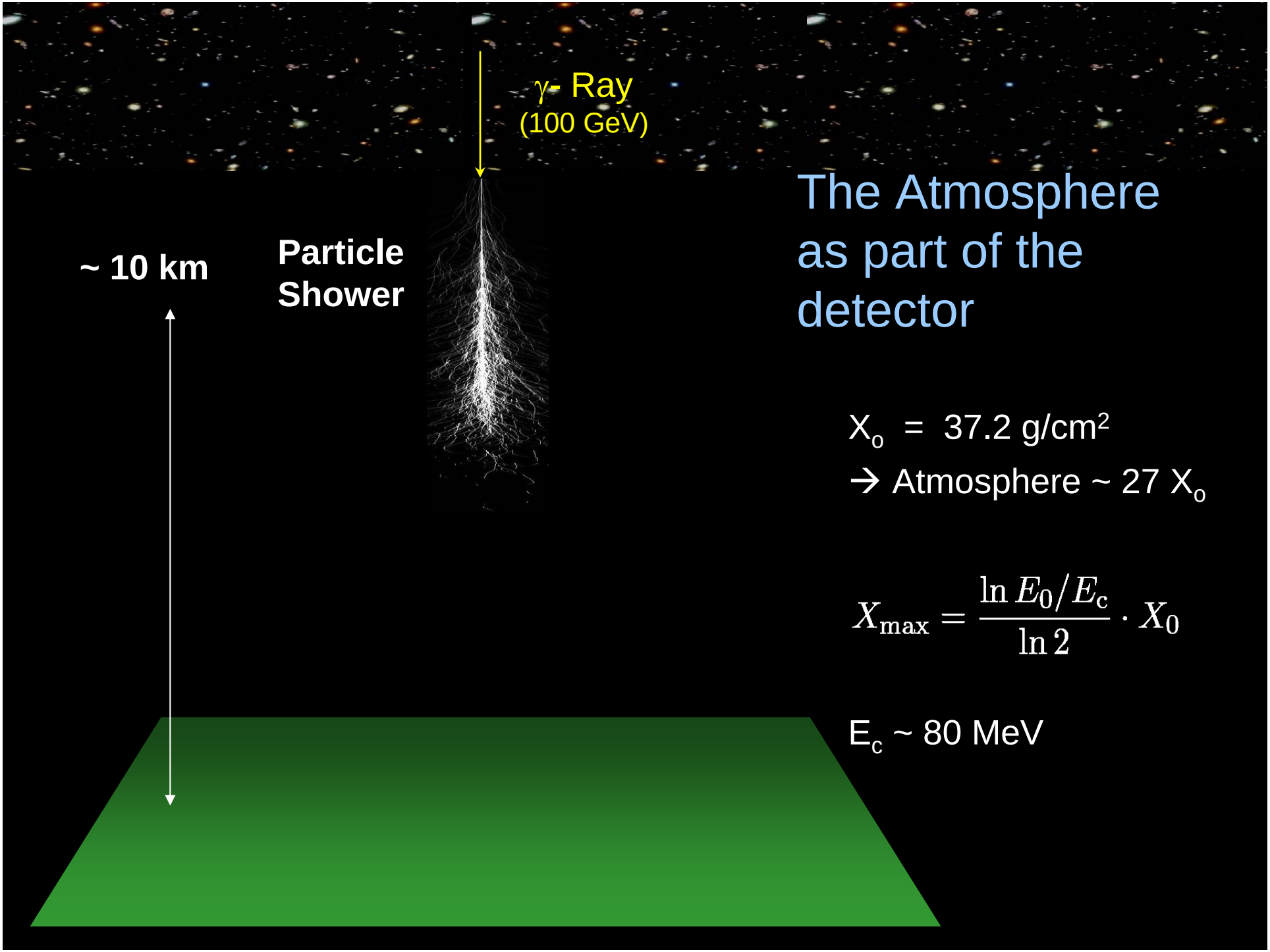
Visible light (eV) | X-rays (keV = 10^3 eV) | Gamma (MeV = 10^6 eV) | Gamma (GeV = 10^9 eV) | **Gamma (TeV = 10^{12} eV)**



Exploring the High Energy Universe:

Ground based experiments take over, where satellite based observations become impossible
- limited by detection area – 10-100 GeV





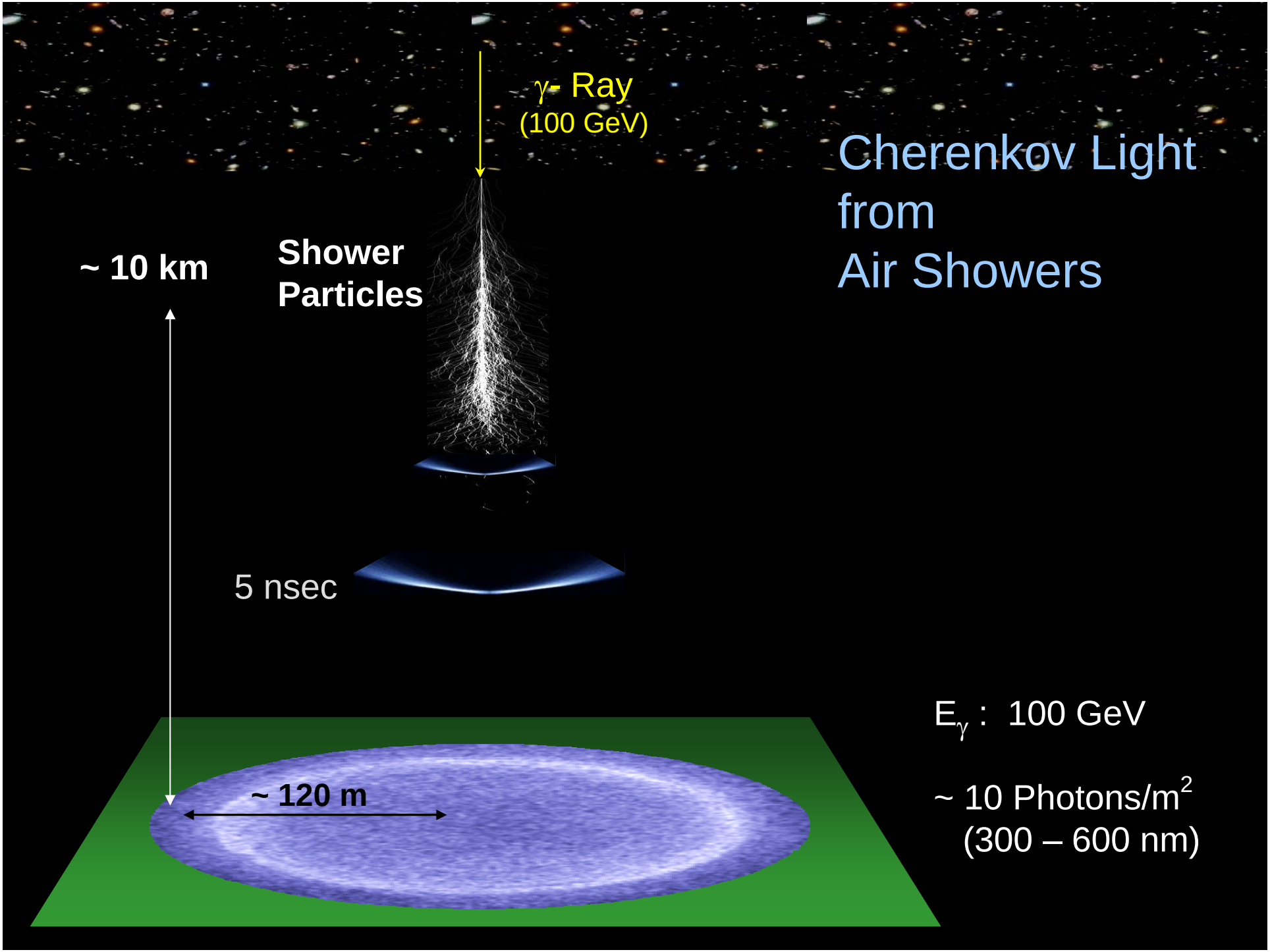
The Atmosphere as part of the detector

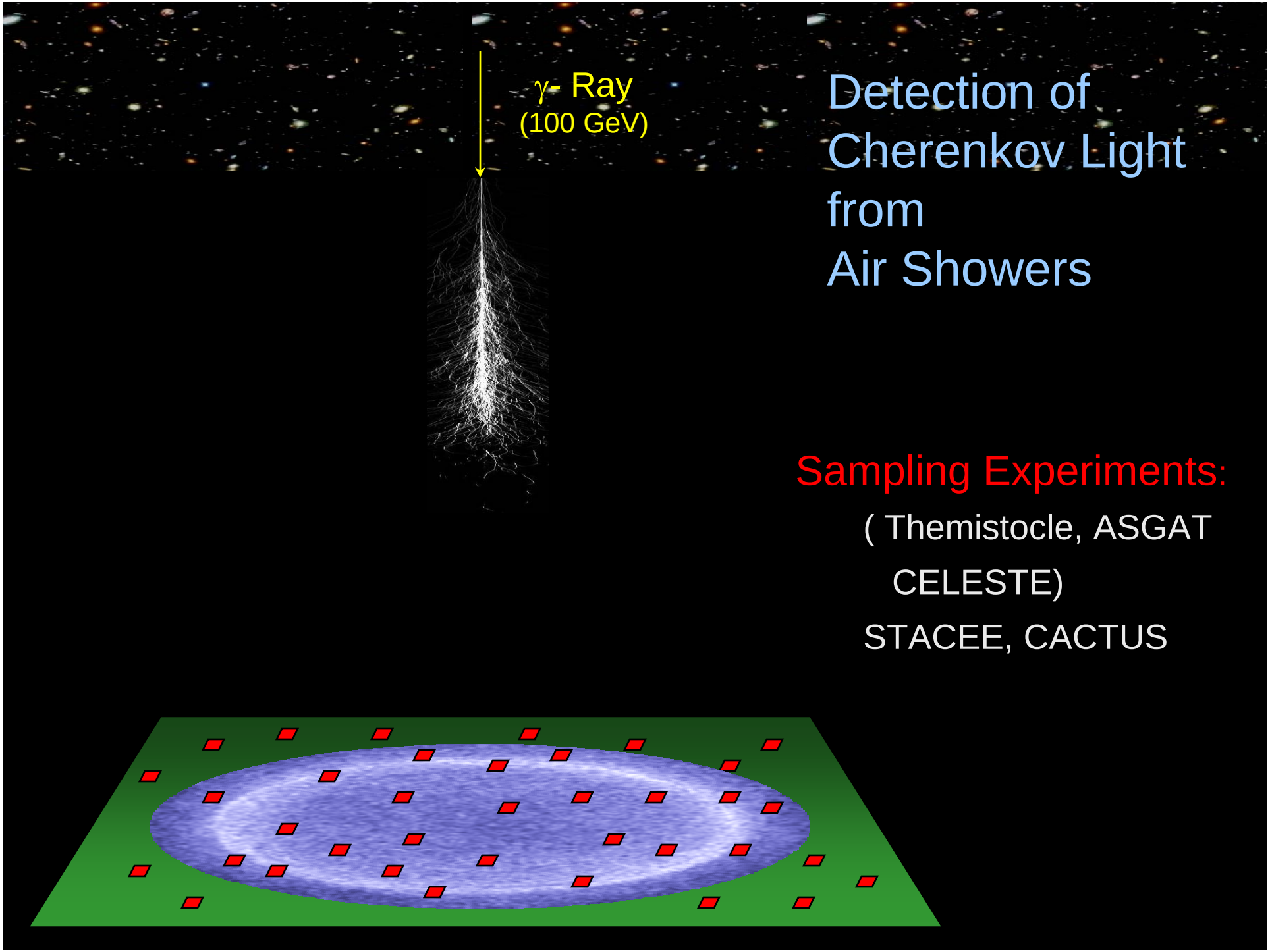
X_o = 37.2 g/cm^2

→ Atmosphere ~ 27 X_o

$$X_{\max} = \frac{\ln E_0/E_c}{\ln 2} \cdot X_0$$

E_c ~ 80 MeV


γ- Ray
(100 GeV)
Cherenkov Light
from
Air Showers
~ 10 km
Shower
Particles
5 nsec
~ 120 m
E_γ : 100 GeV
~ 10 Photons/m^2
(300 – 600 nm)



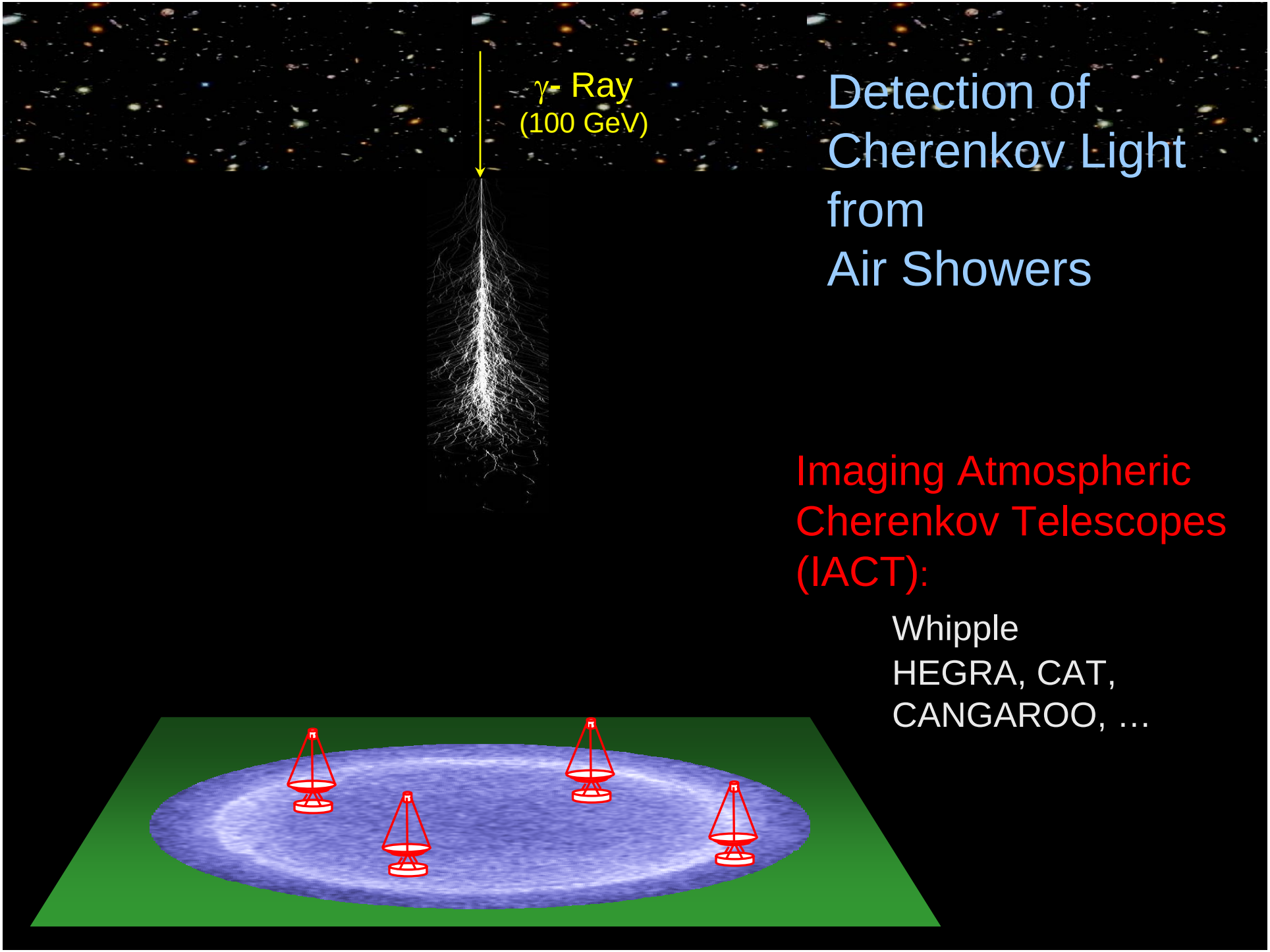
Detection of Cherenkov Light from Air Showers

Sampling Experiments:

(Themistocle, ASGAT

CELESTE)

STACEE, CACTUS



Detection of Cherenkov Light from Air Showers

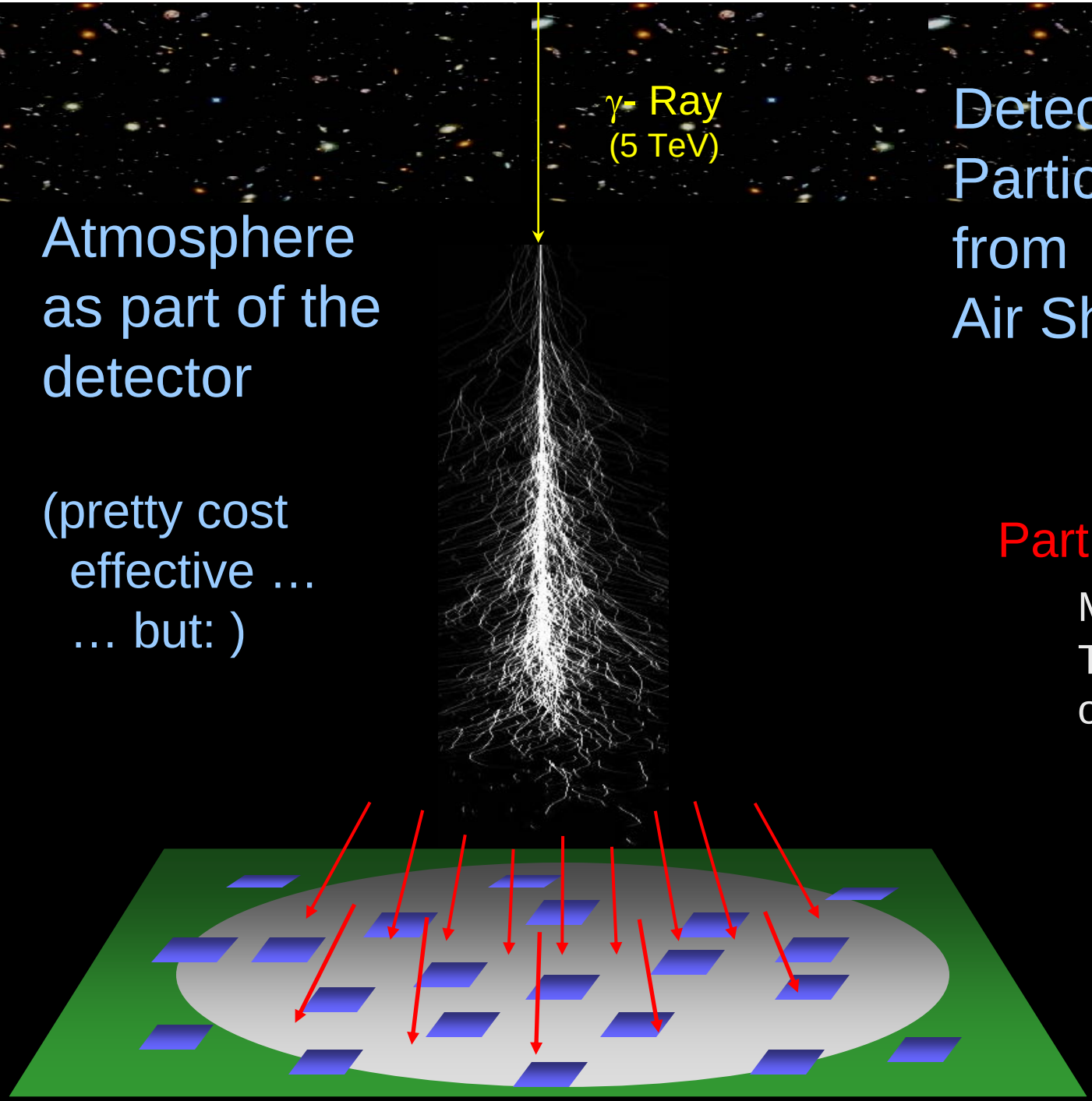
Imaging Atmospheric Cherenkov Telescopes (IACT):

- Whipple
- HEGRA, CAT, CANGAROO, …

Detection of Particles from Air Showers

Atmosphere as part of the detector

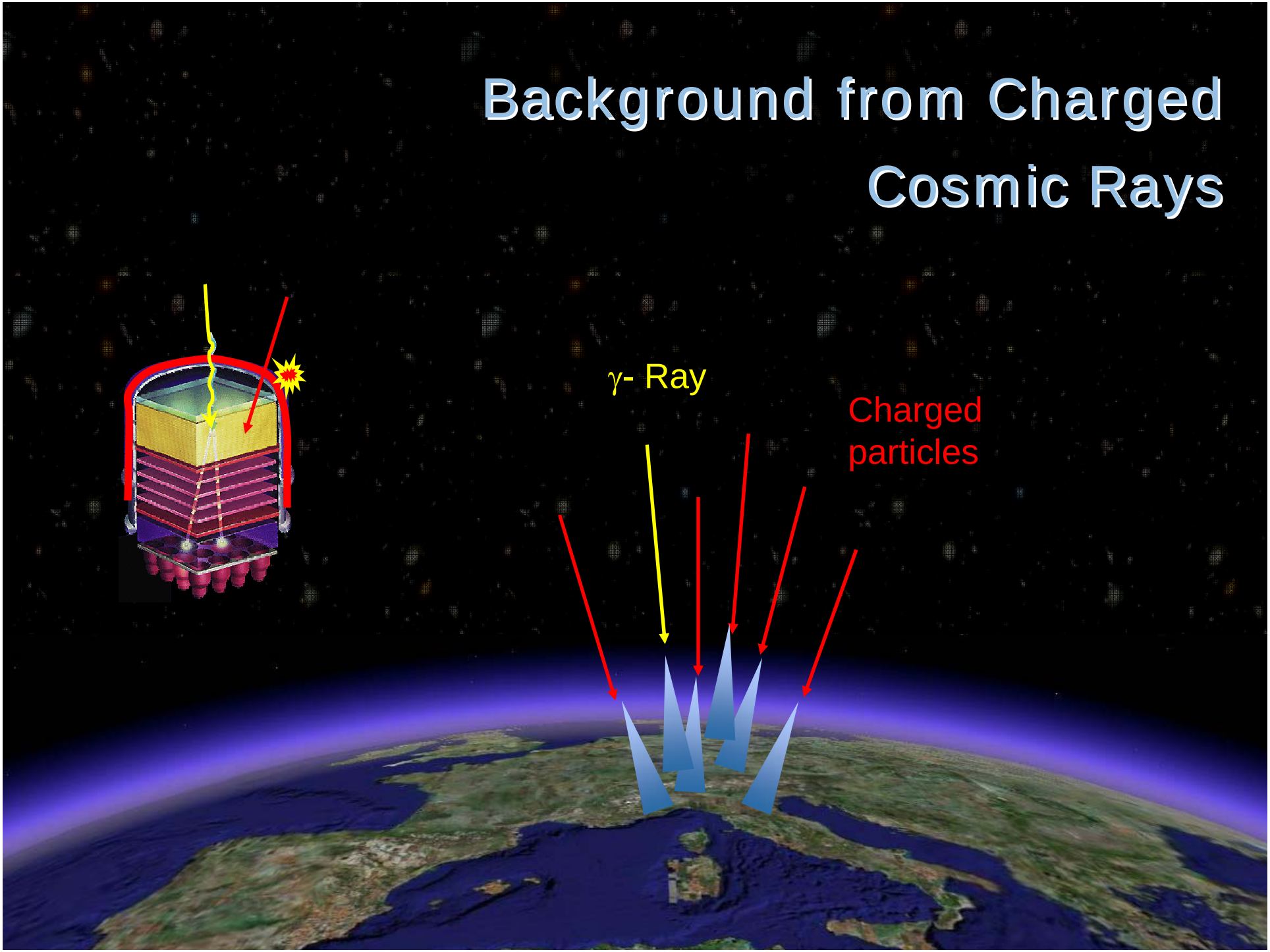
(pretty cost effective …
… but:)

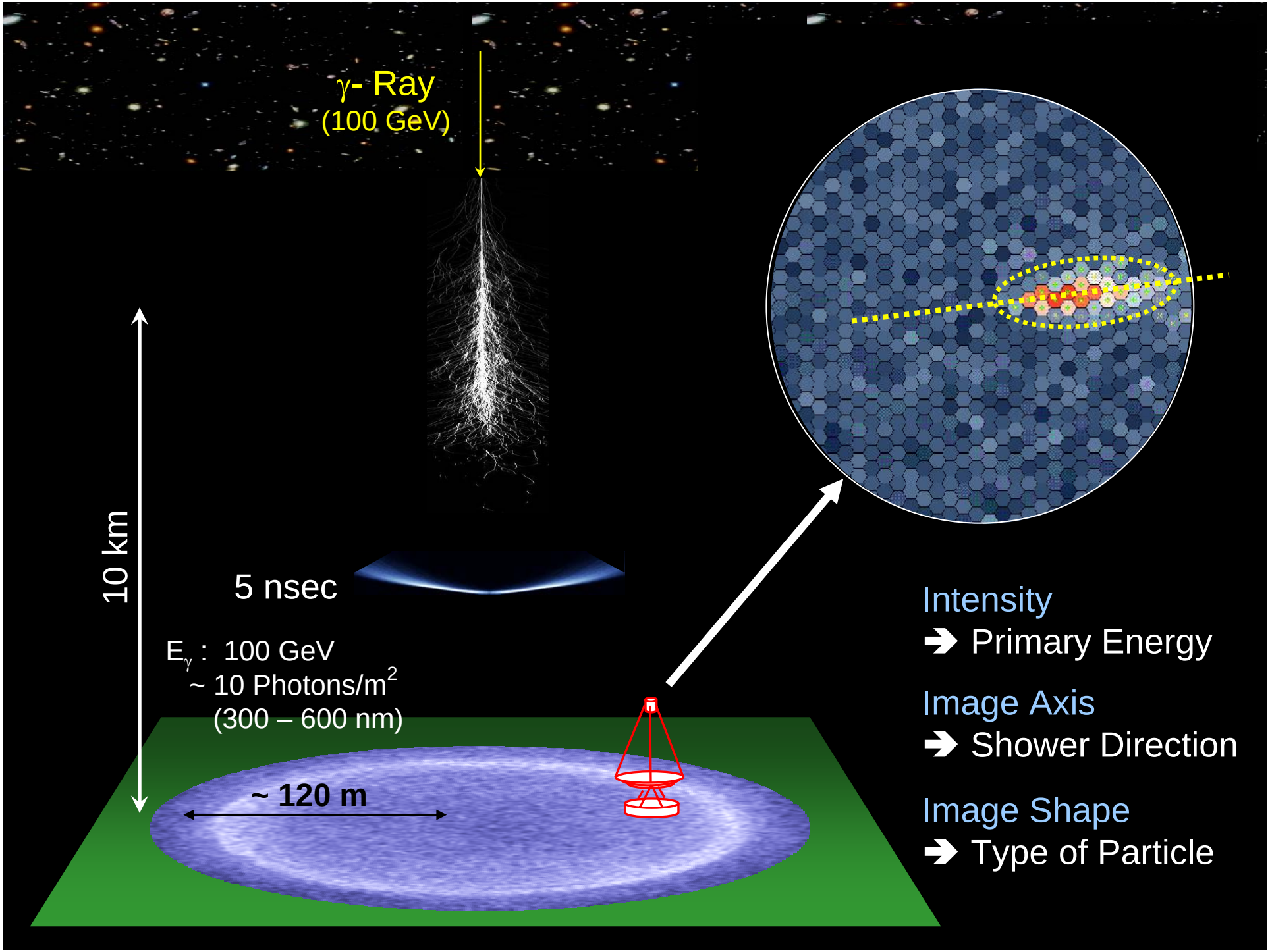


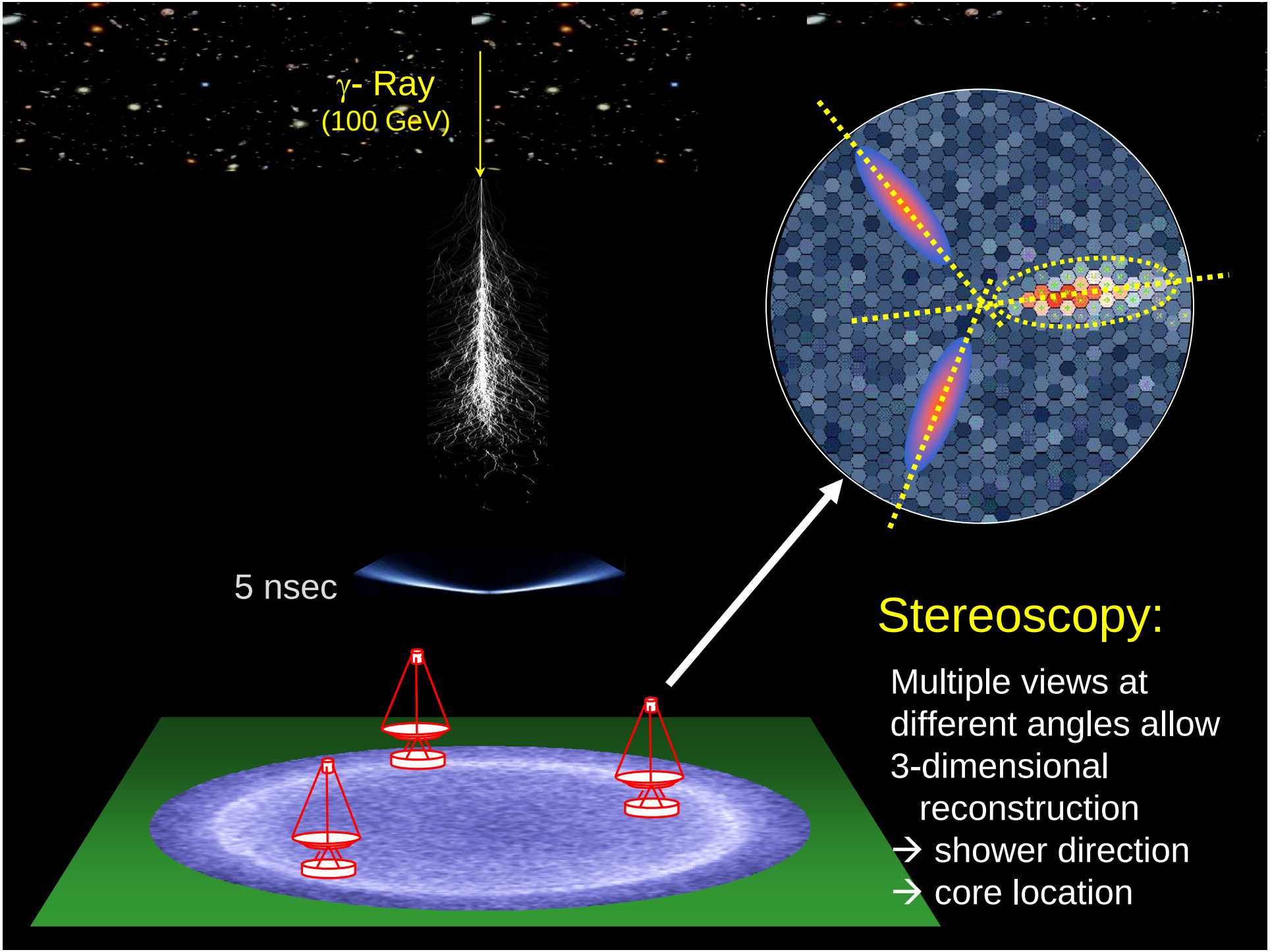
Particle Arrays:

Milagro
Tibet Array
others, …

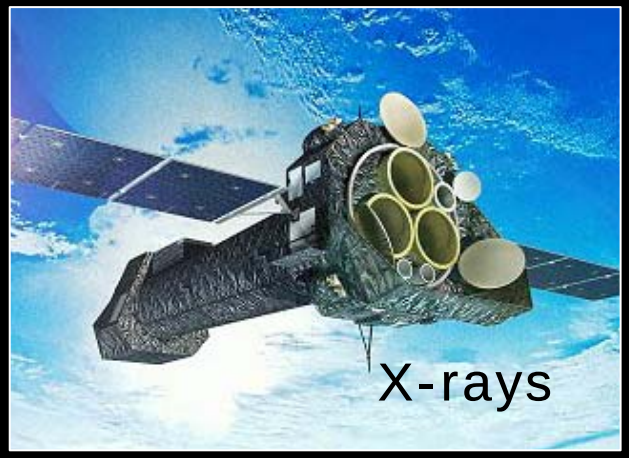
Background from Charged Cosmic Rays

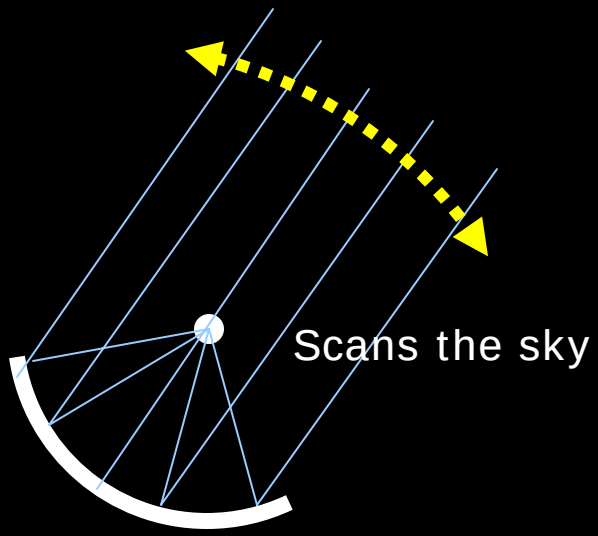


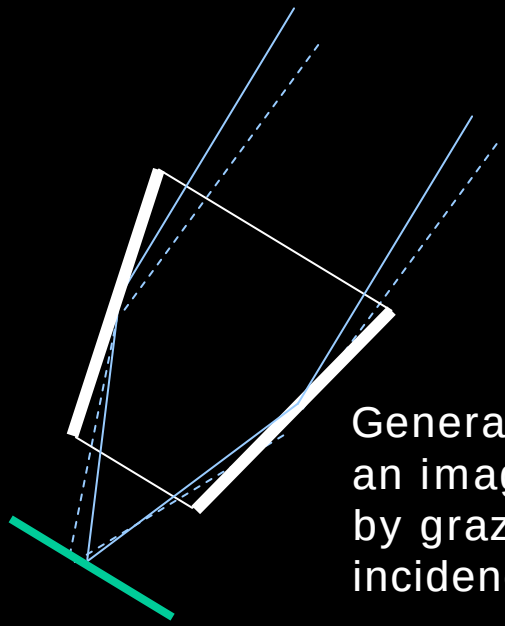

γ- Ray
(100 GeV)
10 km
5 nsec
E_γ : 100 GeV
~ 10 Photons/m^2
(300 – 600 nm)
~ 120 m
Intensity
➔ Primary Energy
Image Axis
➔ Shower Direction
Image Shape
➔ Type of Particle

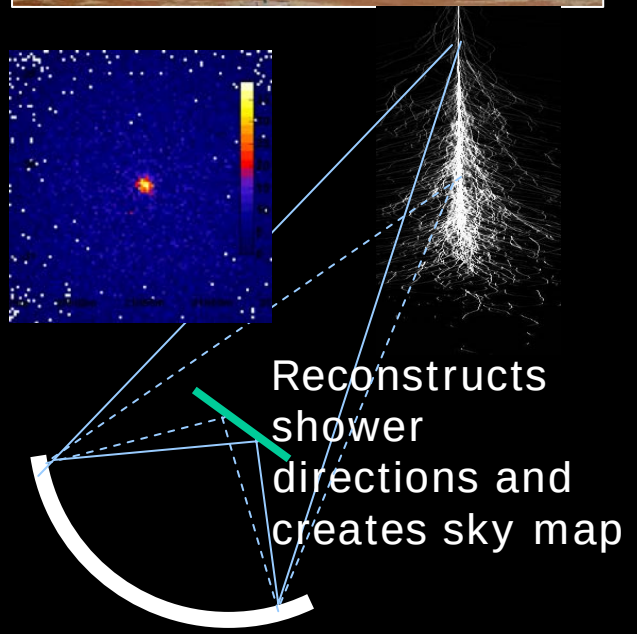

γ- Ray
(100 GeV)
5 nsec
Stereoscopy:
Multiple views at different angles allow 3-dimensional reconstruction
→ shower direction
→ core location

How do we get images of the sky ?

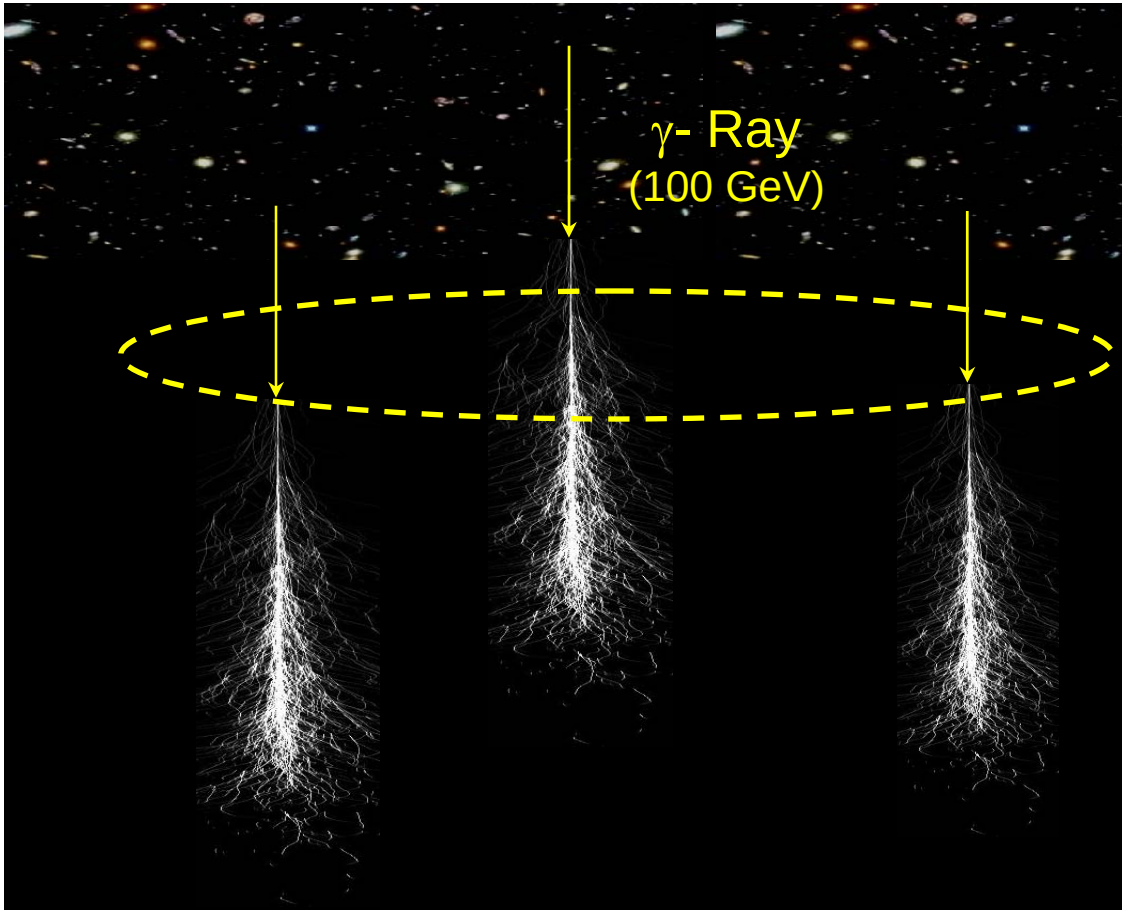


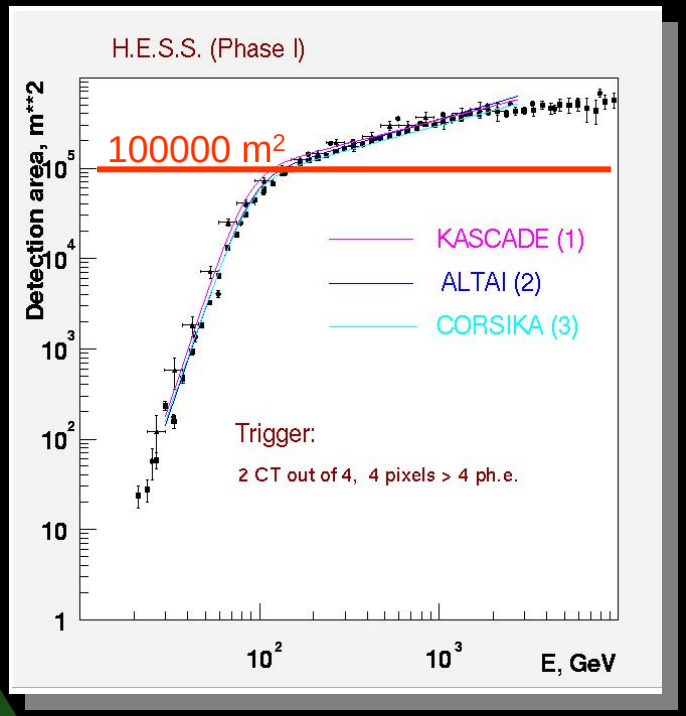


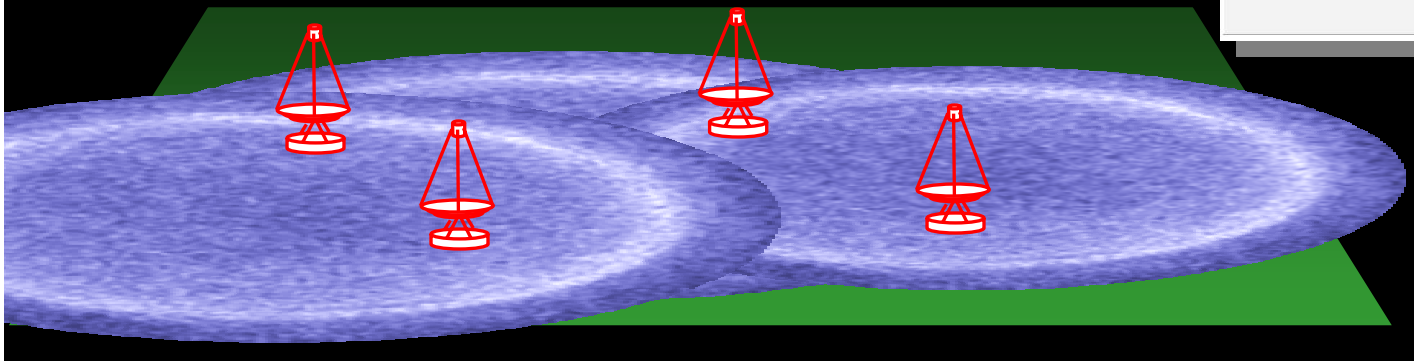




Effective Detection Area

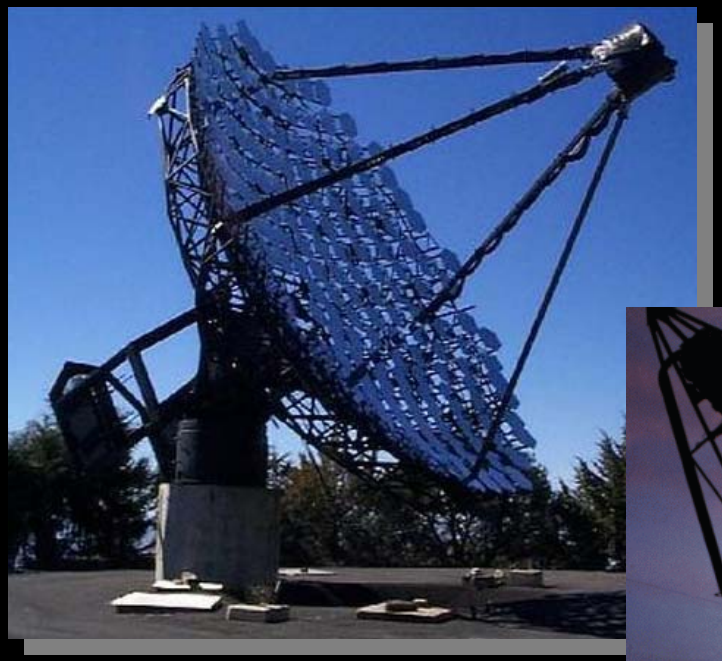






$S\,[\sigma] \sim \sqrt{A}$

The Pioneering Single Dish Instruments



The Pioneers:

WHIPPLE

10 m dish, 60s

Arizona, USA

first TeV source:

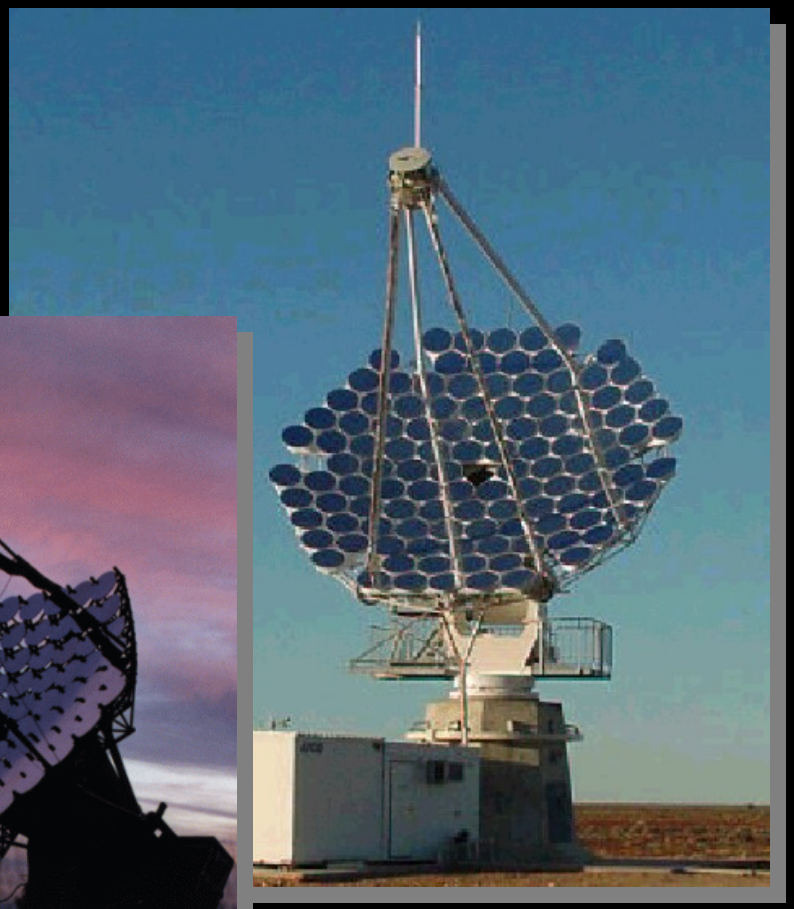
Crab Nebula (1989)

CAT

5 m dish

Themis, France

1996-2002



CANGAROO

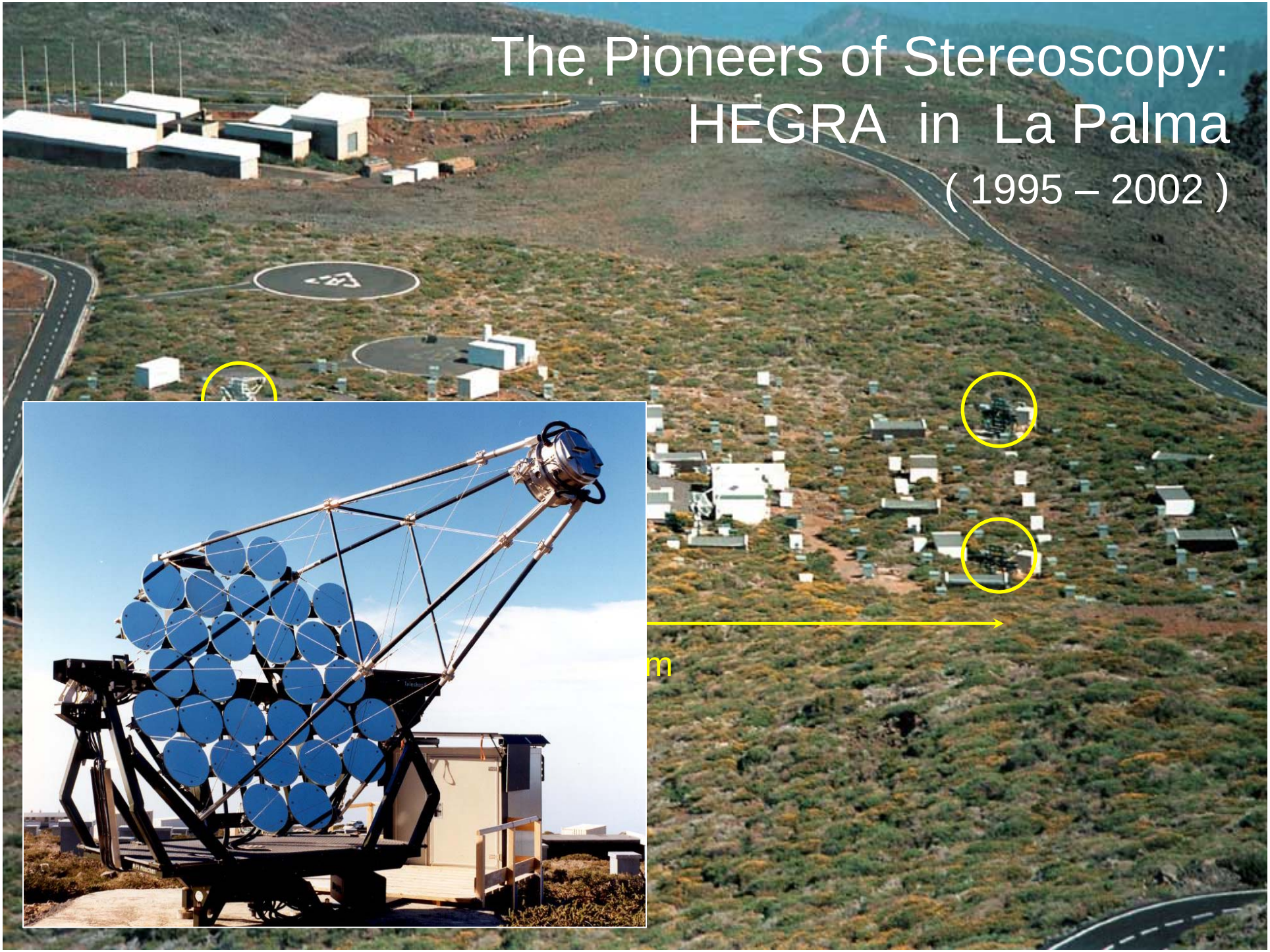
3.8, 7, 10 m dish

Australia

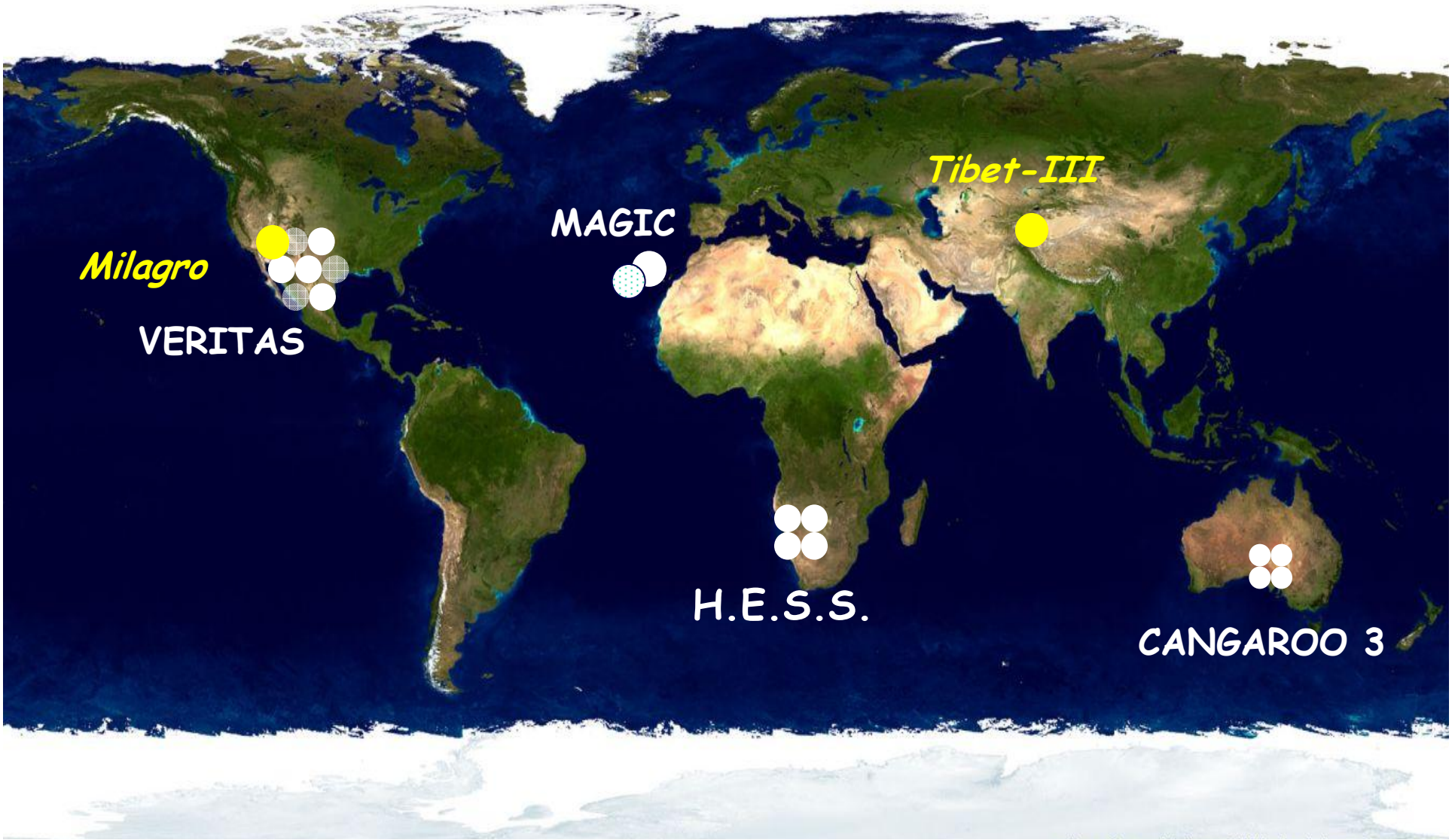
1992 - …

The Pioneers of Stereoscopy: HEGRA in La Palma

(1995 – 2002)

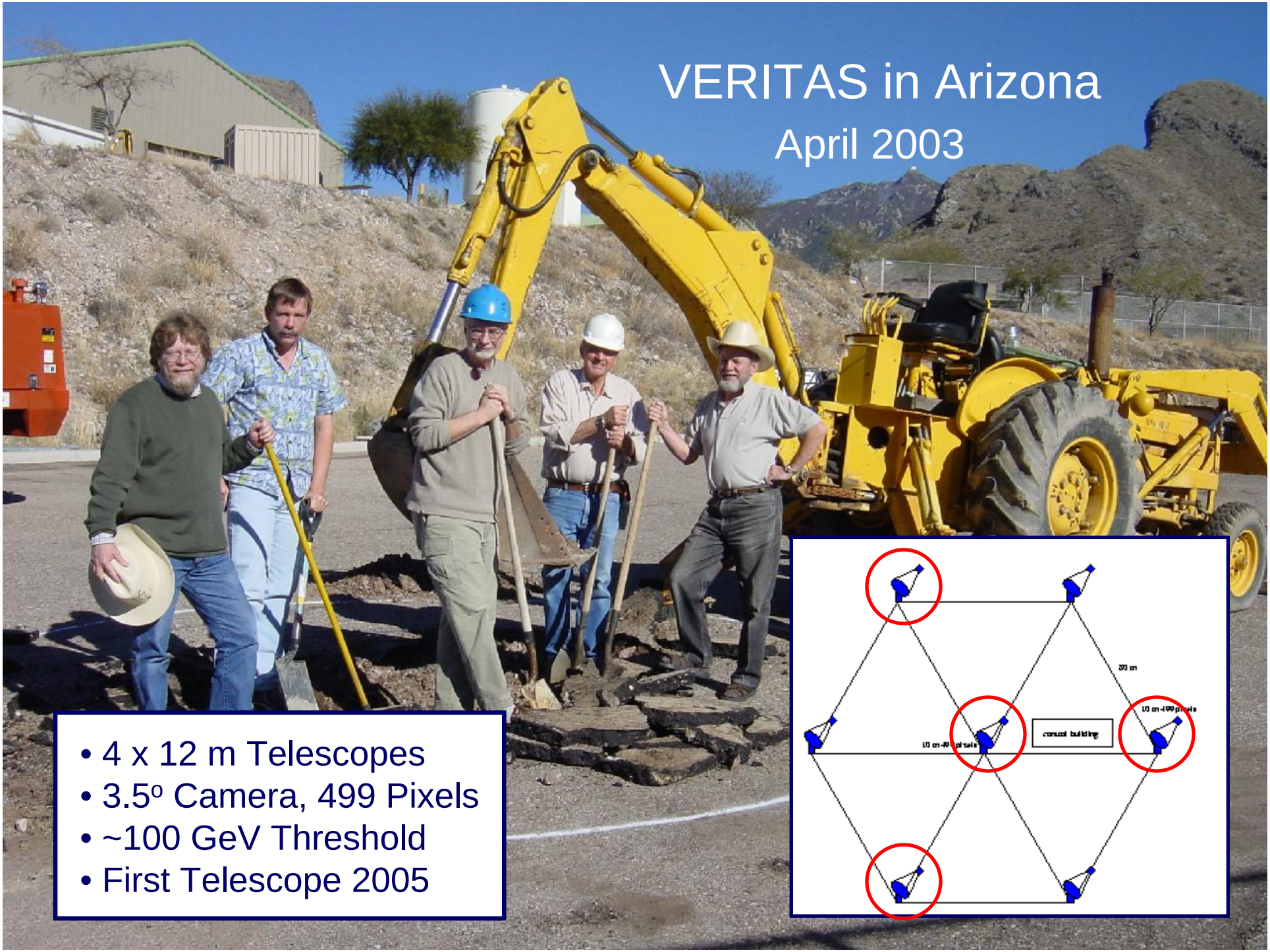


Major Ground-Based γ-Ray Installations



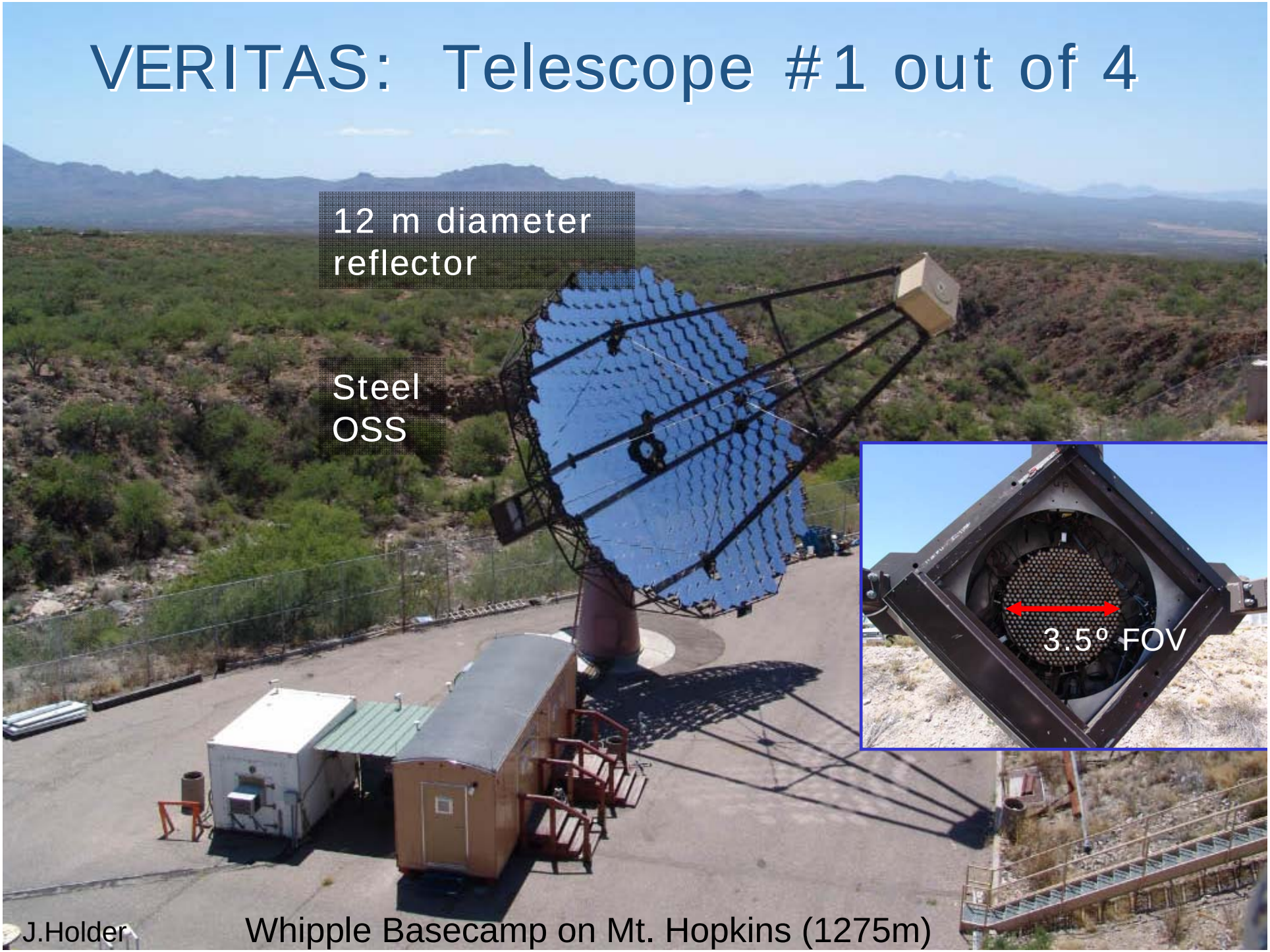
VERITAS in Arizona

April 2003



- 4 x 12 m Telescopes
- 3.5º Camera, 499 Pixels
- ~100 GeV Threshold
- First Telescope 2005

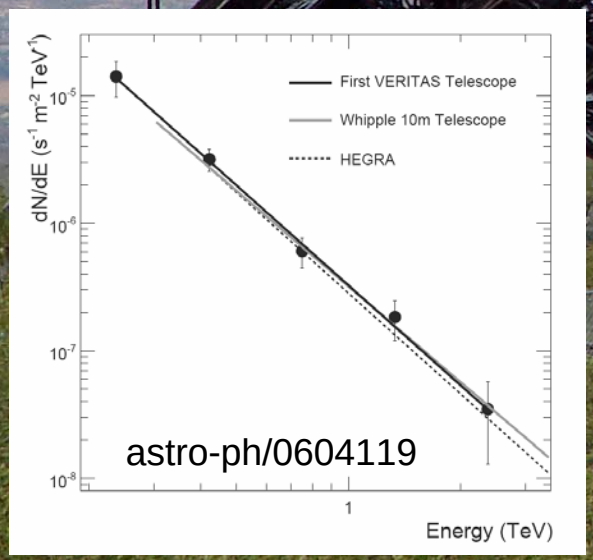
VERITAS: Telescope #1 out of 4



J.Holder

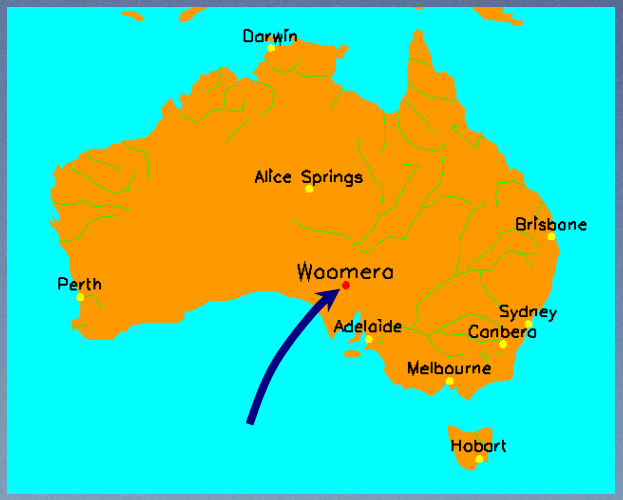
Whipple Basecamp on Mt. Hopkins (1275m)

VERITAS



Telescope #2: first light Dec. 2005
Hardware coincidence March 2006
4 telescopes by fall 2006

CANGAROO (Japan, Australia)



4 Telescope Stereo System

~ 57 m^2 mirror area each
Fiber reinforced mirrors (composite)

4 deg Camera
~ 500 Pixels

Energy Threshold : ~ 200 GeV

4 Telescopes since 3/2004

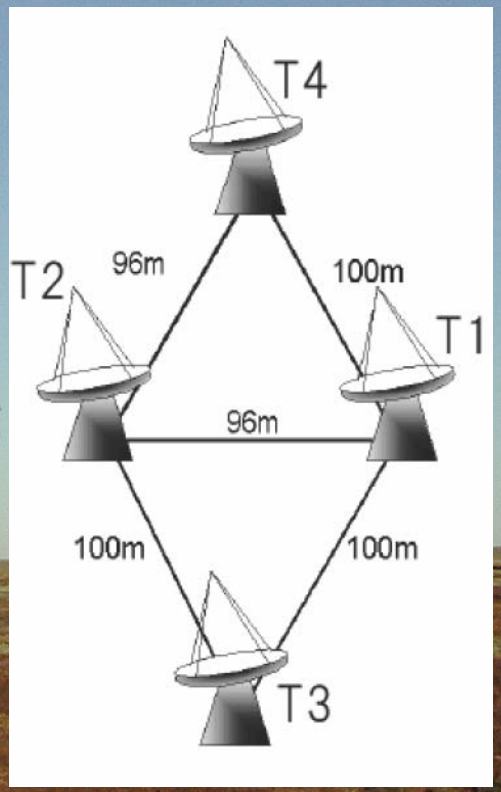
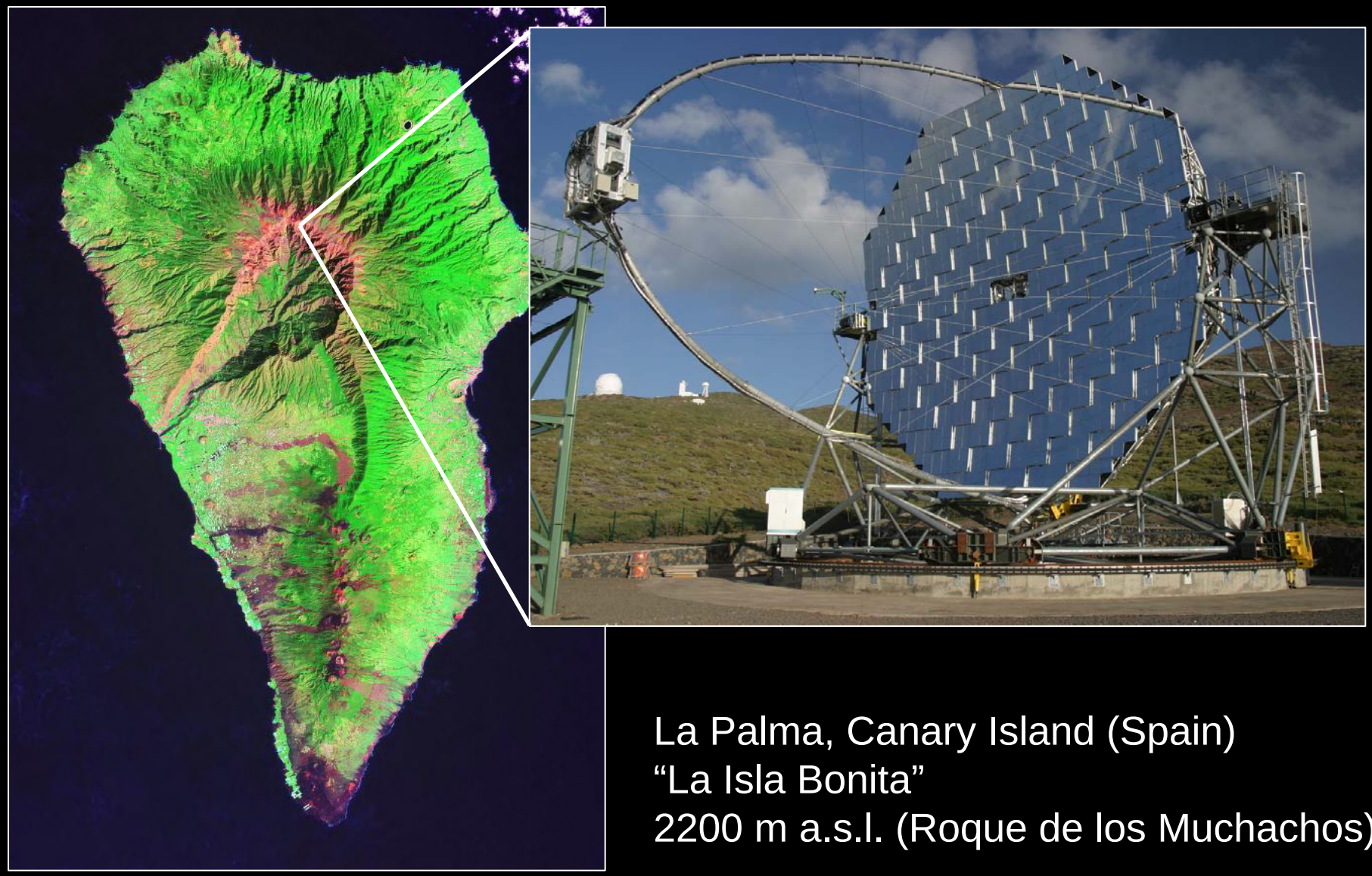


Photo Montage

The MAGIC Telescope

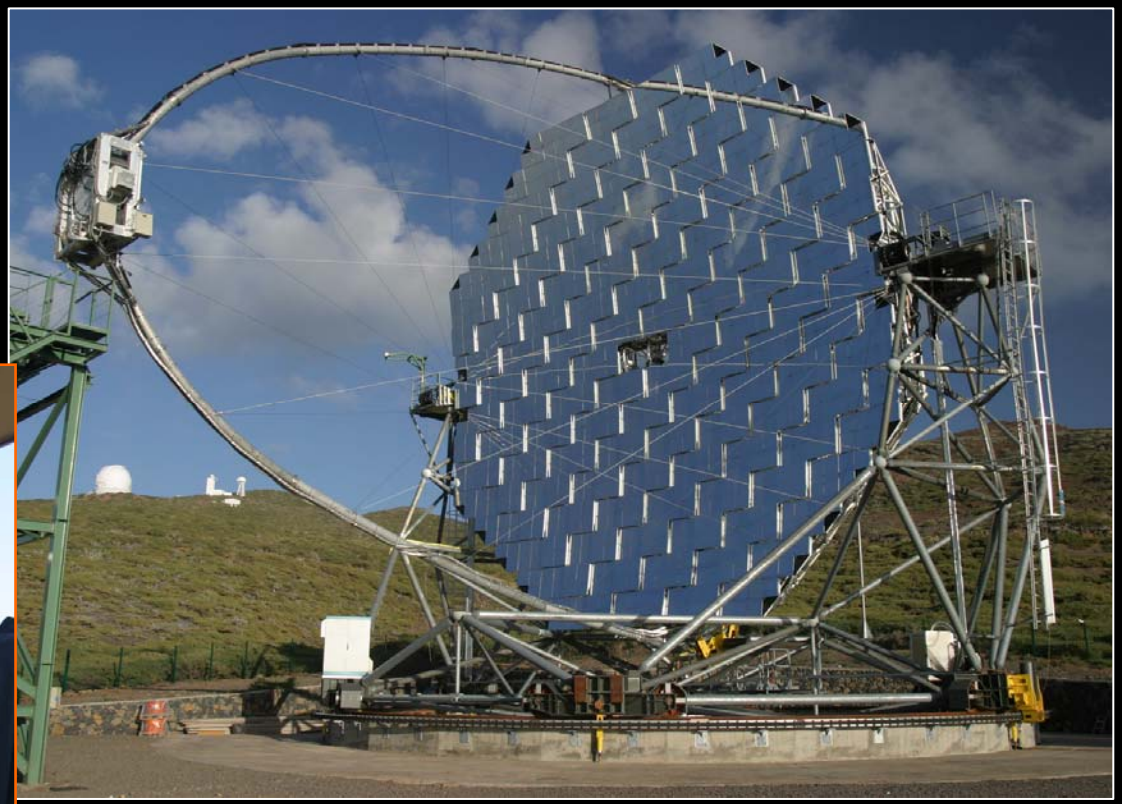


La Palma, Canary Island (Spain)
“La Isla Bonita”
2200 m a.s.l. (Roque de los Muchachos)

The MAGIC Telescope

17 meter diameter
236 m^2 mirror area

Camera:
3.5 deg FoV



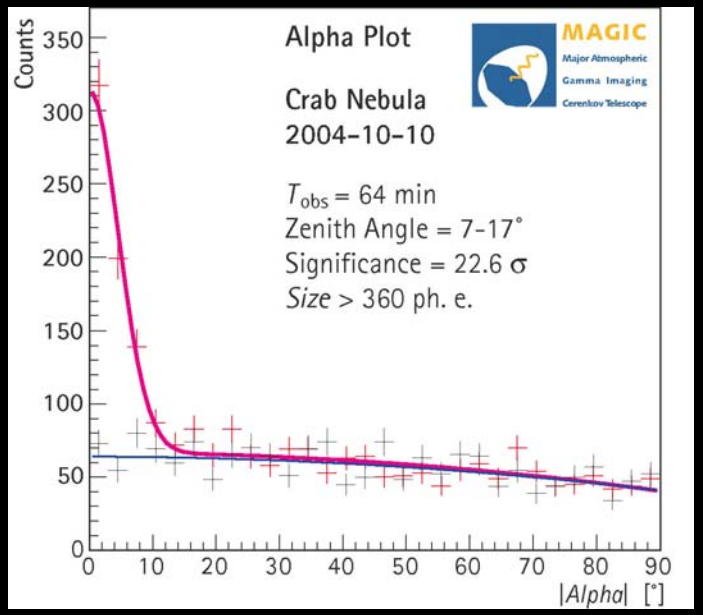
Energy threshold :
~50 GeV (<100 GeV analysis)

→ fast positioning
→ GRB follow-up within << 1 min

The MAGIC Telescope: Status

Inauguration October 2003

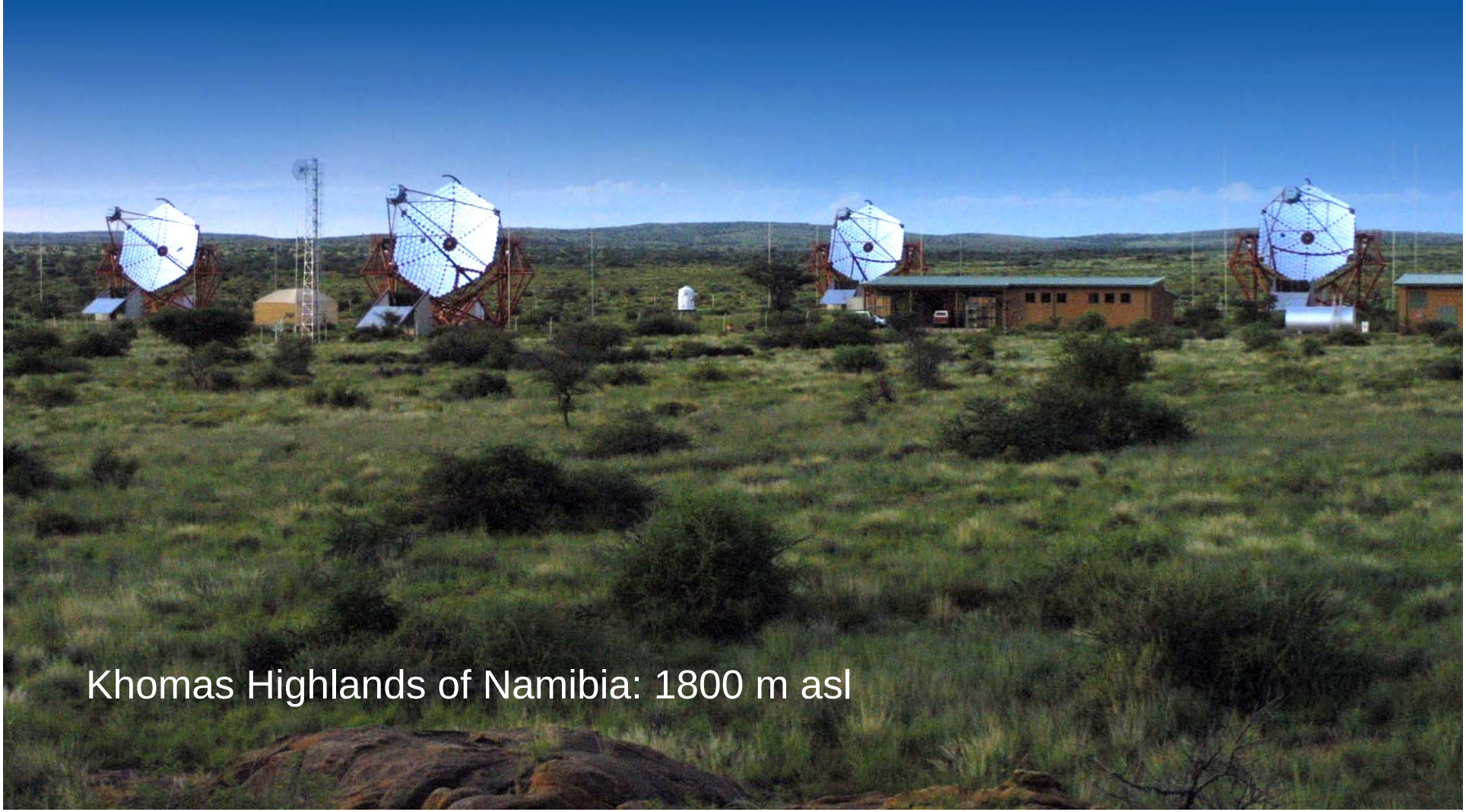
Physics data since Sept 2004



→ 5 σ detection in 3 min
@ E > 200 GeV

The High Energy Stereoscopic System

H.E.S.S.



Khomas Highlands of Namibia: 1800 m asl

Why Namibia ?

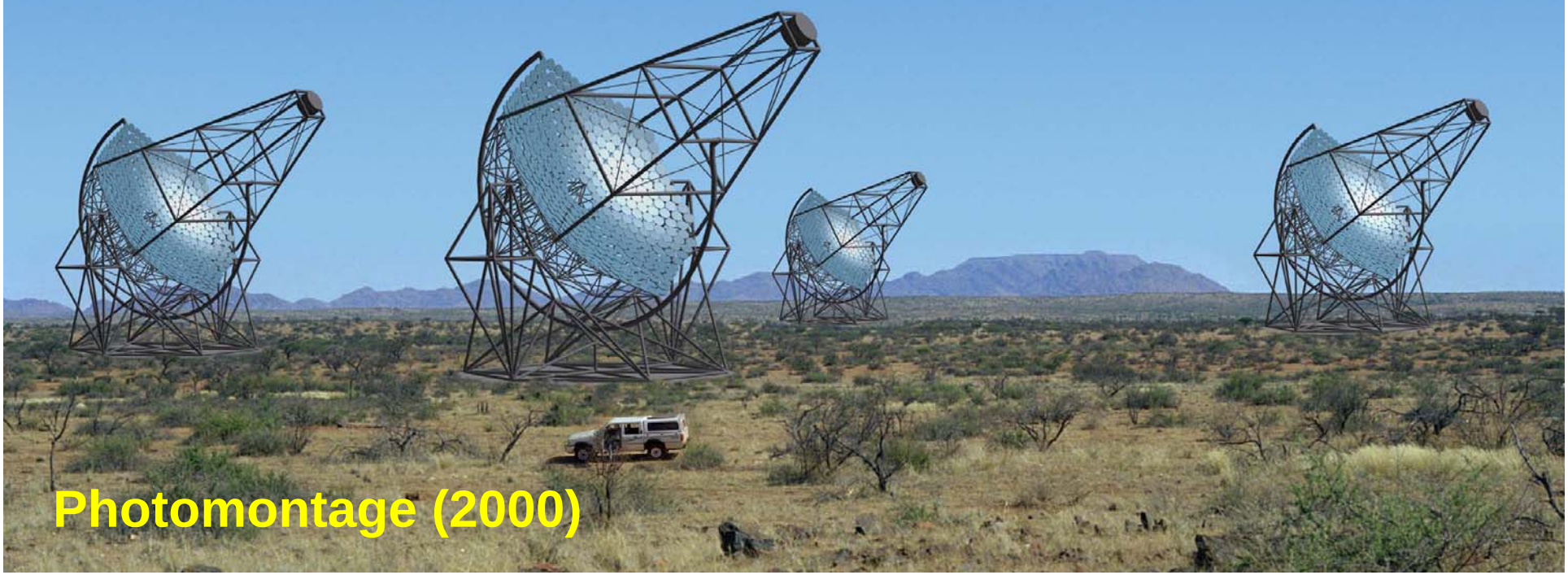
- Dark nights
- Clear sky
- Mild climate

- **Galactic plane**
- **Center of galaxy**

- Easy access
- Industrial partners
- Political support

Ambitious Goals …

Energy threshold	:	100 GeV
$\Delta E/E$	:	~ 15 %
Angular resolution	:	< 6 arcmin
Source location	:	< 10 arcsec
Sensitivity	:	x 10 (1/100 h)



Photomontage (2000)

Ambitious Goals …

Energy threshold	:	100 GeV
$\Delta E/E$	:	~ 15 %
Angular resolution	:	< 6 arcmin
Source location	:	< 10 arcsec
Sensitivity	:	x 10 (1/100 h)

H.E.S.S. in 2002

Ambitious Goals …

Energy threshold	:	100 GeV
$\Delta E/E$	:	~ 15 %
Angular resolution	:	< 6 arcmin
Source location	:	< 10 arcsec
Sensitivity	:	x 10 (1/100 h)

… reached !

December 2003

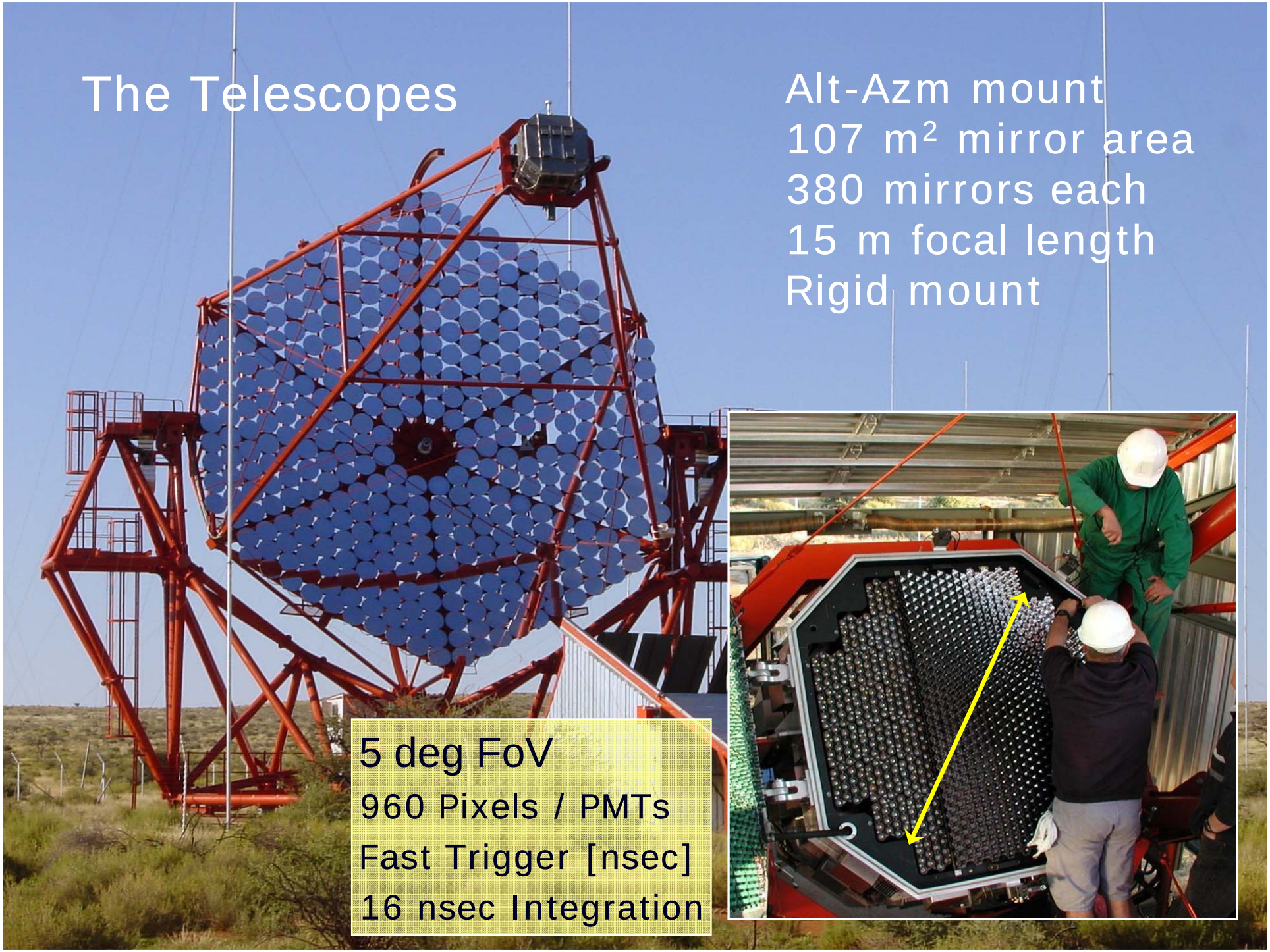
The Telescopes

Alt-Azm mount
107 m^2 mirror area
380 mirrors each
15 m focal length
Rigid mount

Optical PSF ~ 0.5 mrad (r_{80})
Identical for all CTs
Stable over 2 years

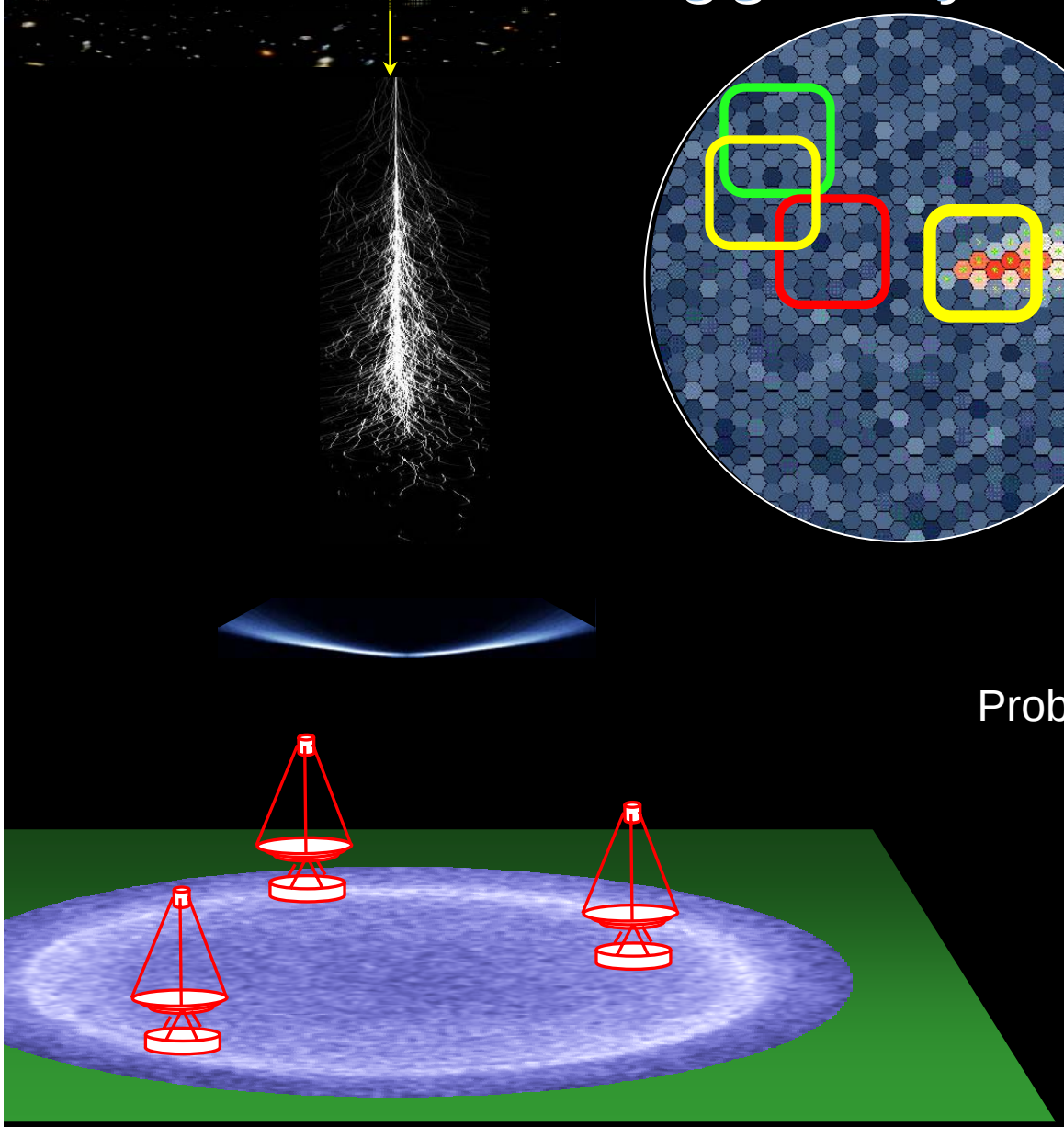
The Telescopes

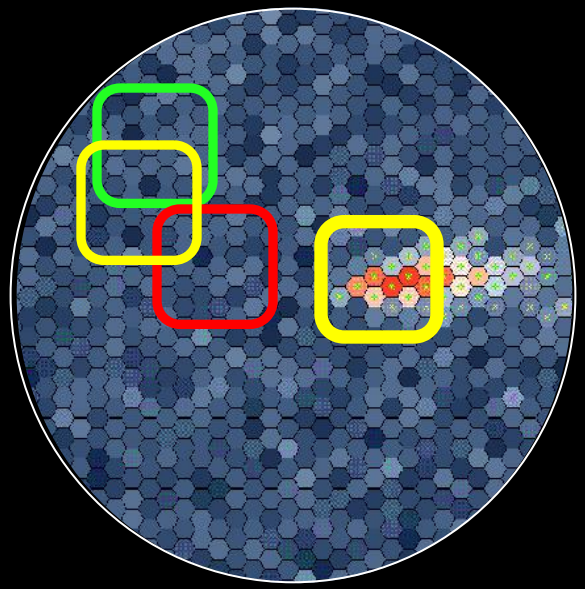
Alt-Azm mount
107 m^2 mirror area
380 mirrors each
15 m focal length
Rigid mount



5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
16 nsec Integration

The H.E.S.S. Trigger System





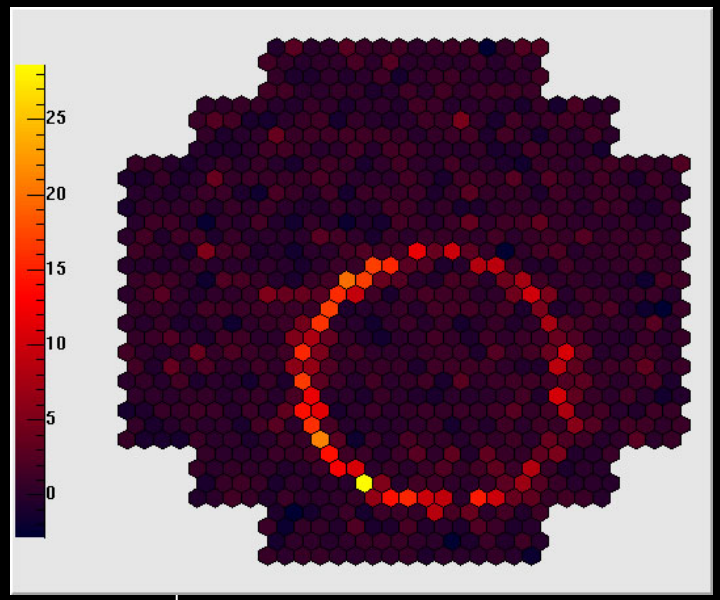
Each camera/telescope triggers individually

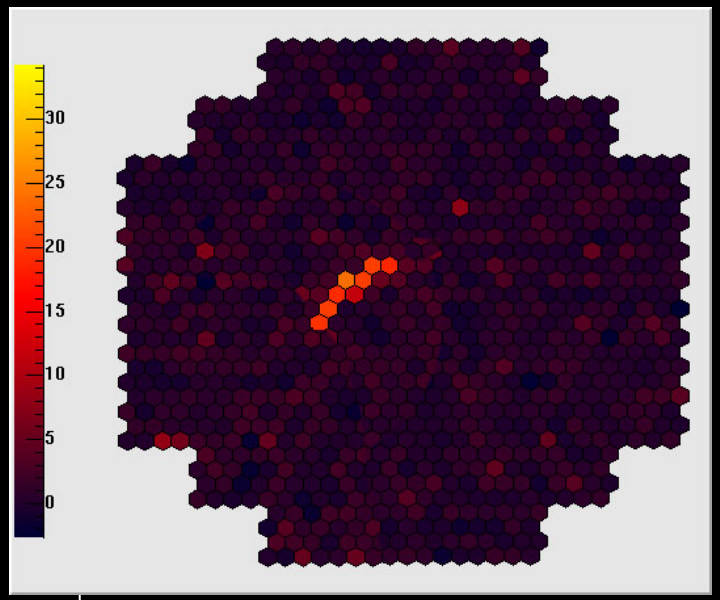
> 3 pixels above ~5 p.e. within 2 nsec in a 64 pixel sector

38 overlapping sectors

Problem: dead-time limitation due to 450 usec readout and high background rate

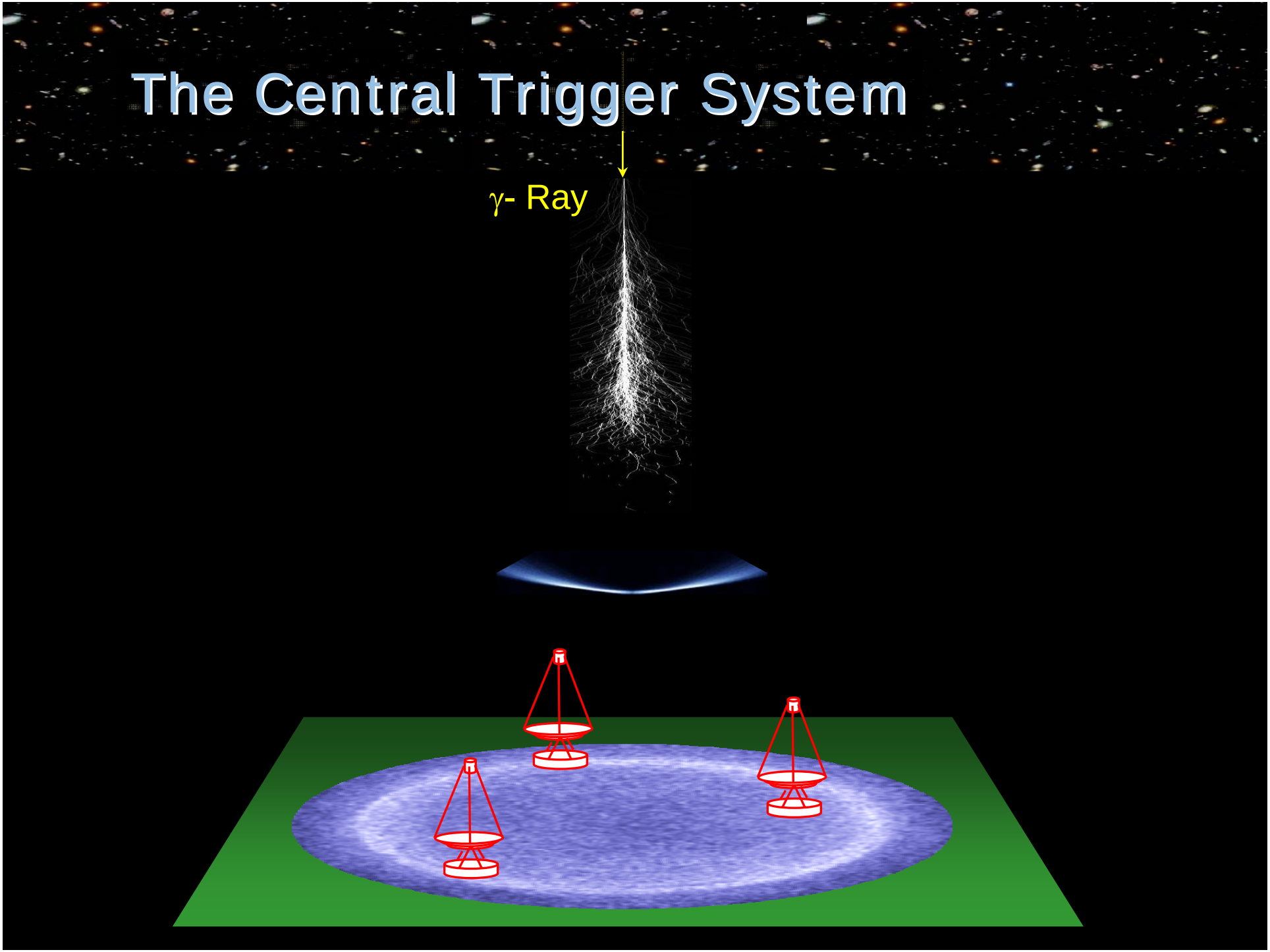
Muon Background





Muons: problem in single mode
→ Dead-time of readout
→ Increase energy threshold
at analysis level

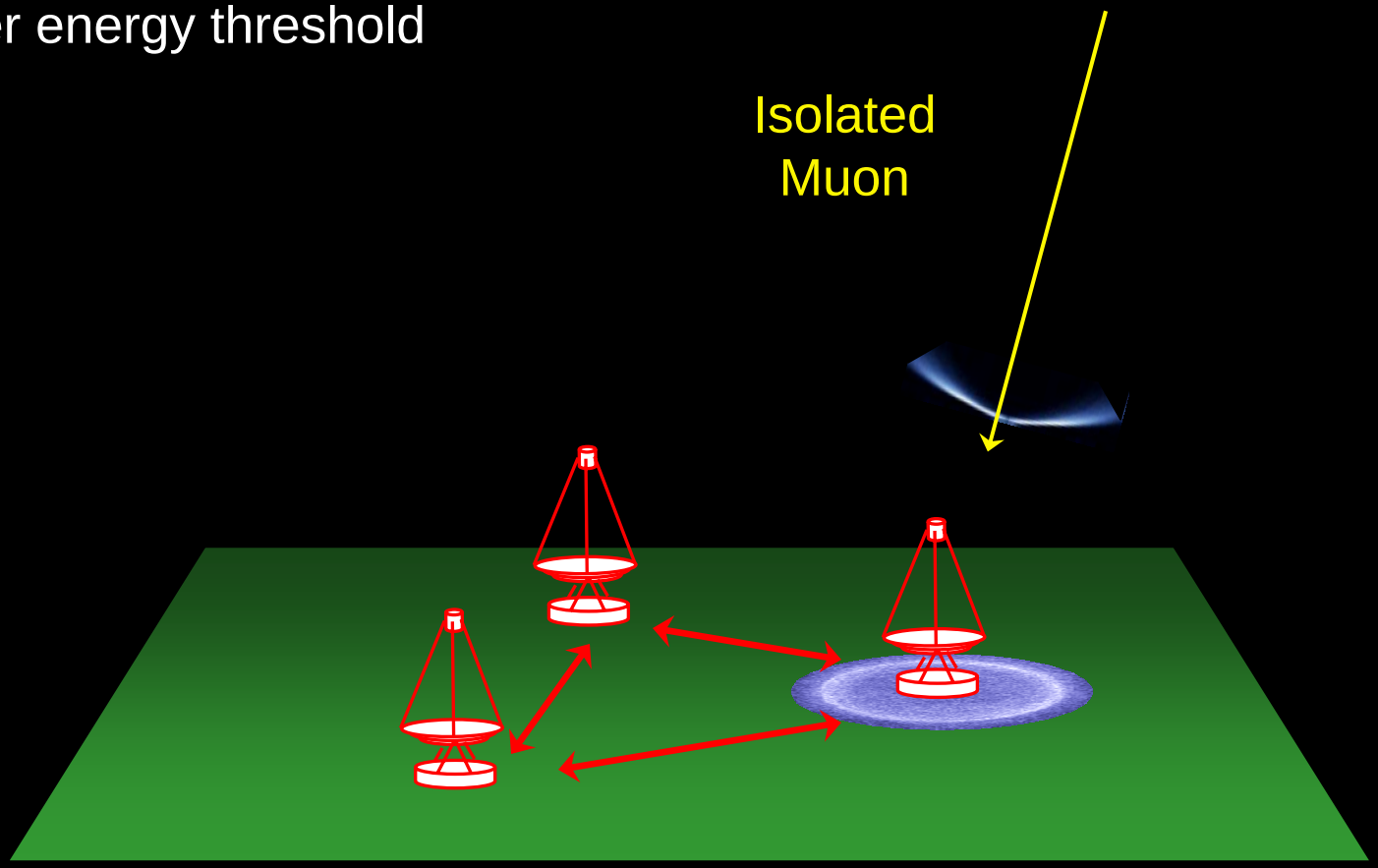
The Central Trigger System



The Central Trigger System

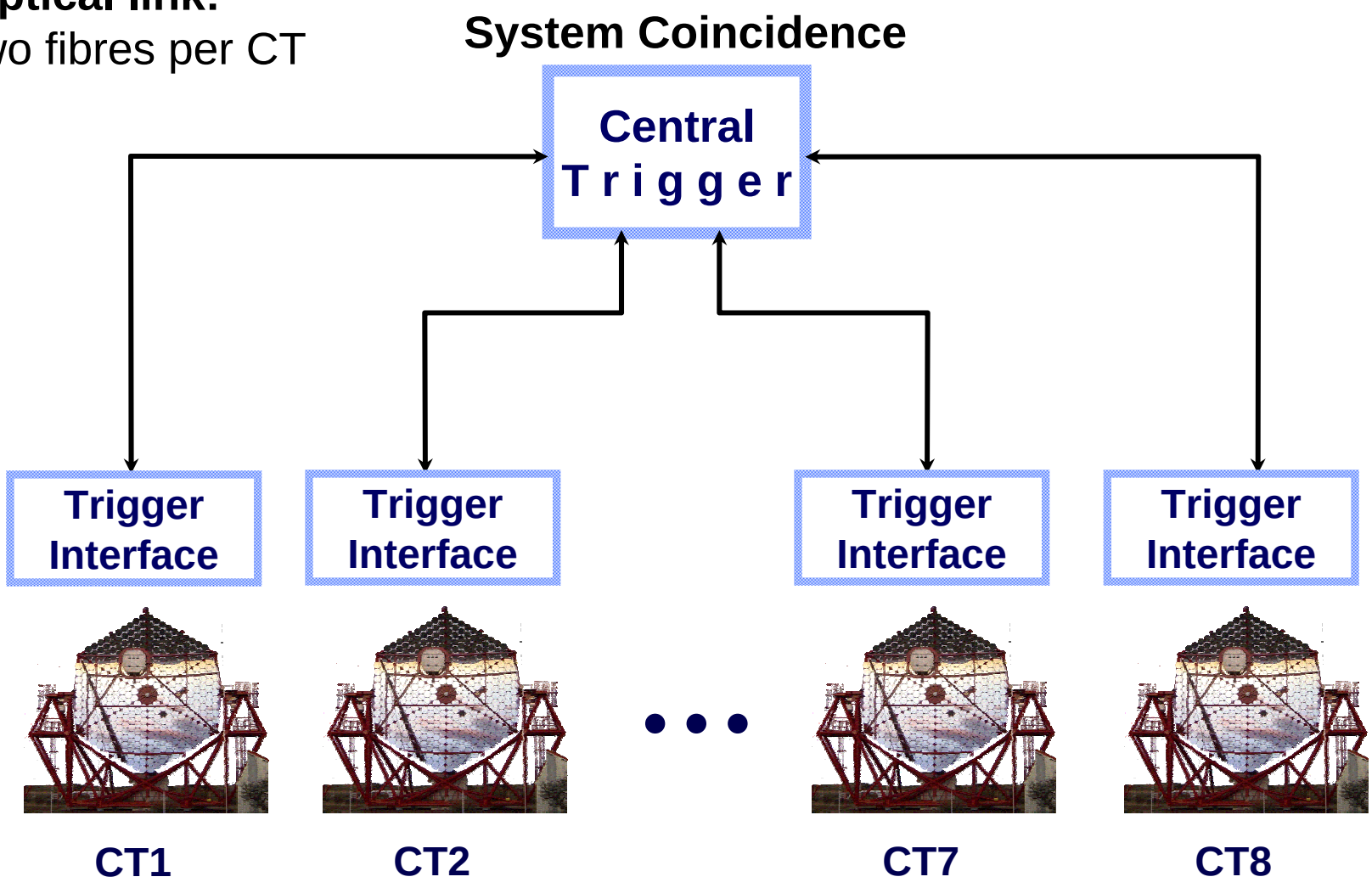
Stereoscopy on hardware level:

- Background suppression
- Dead time reduction
- Lower energy threshold



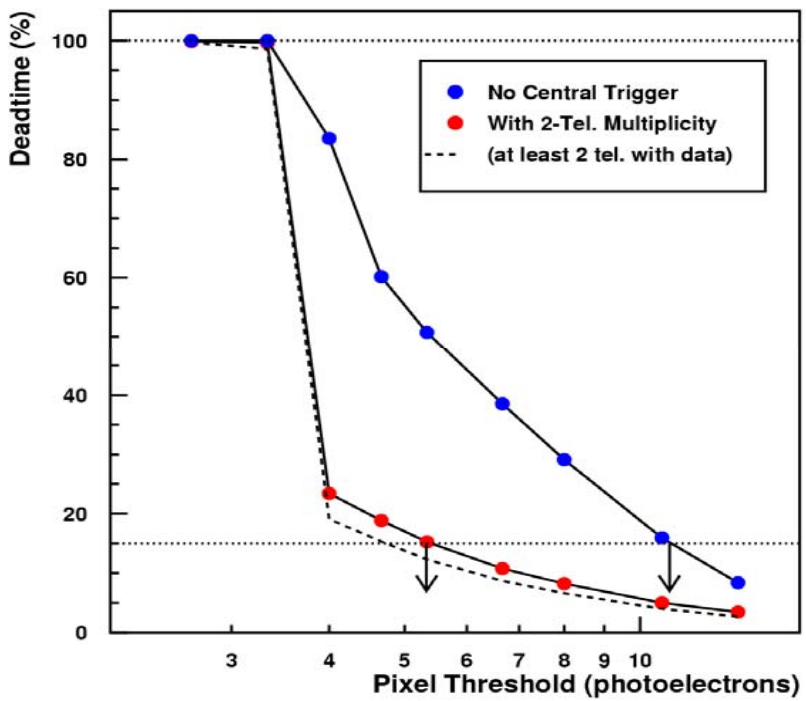
The Central Trigger System

Optical link:
two fibres per CT



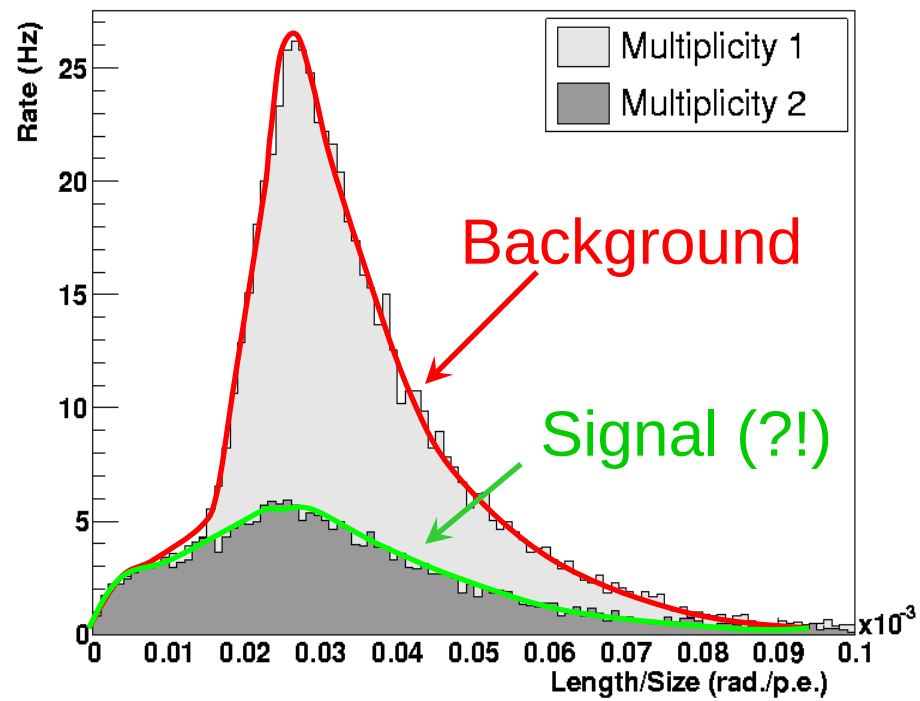
Central Trigger: System Performance

Deadtime vs Threshold



Lower threshold by factor ~ 2

Rate vs image parameter



BG suppression on HW level

Energy Threshold: 100 GeV

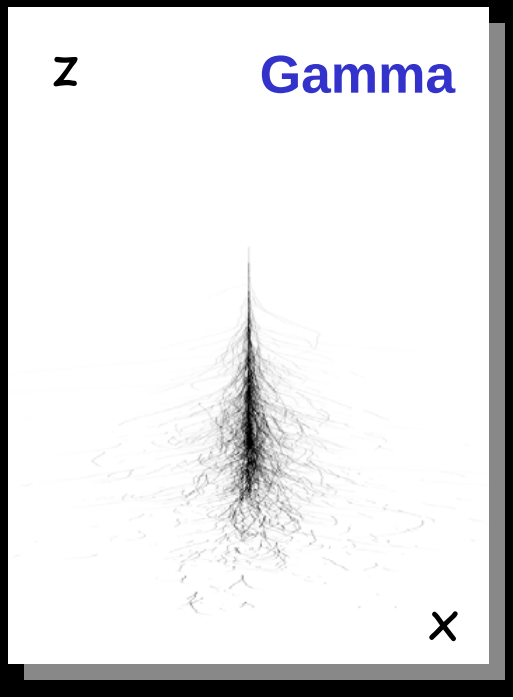
Performance of a Stereo System

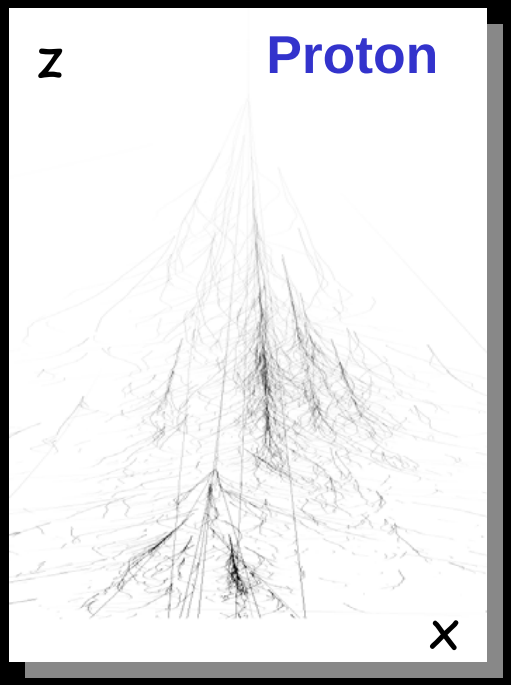
- Gamma-Hadron Separation
- Angular & Energy Resolution
- Sensitivity
- Energy Threshold
- (Pointing)

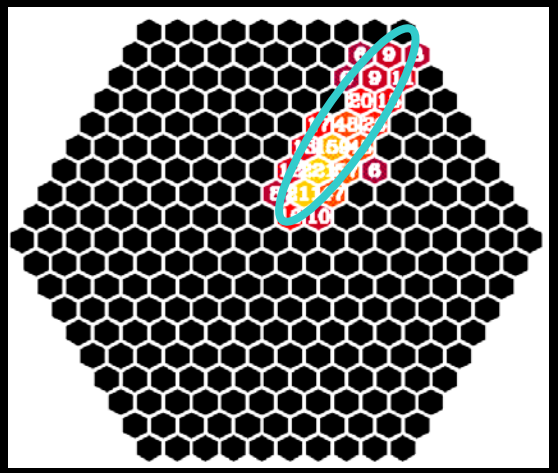
H.E.S.S. as example

VERITAS, MAGIC 2, CANGAROO similar

Who is who ? Gamma-Hadron Separation







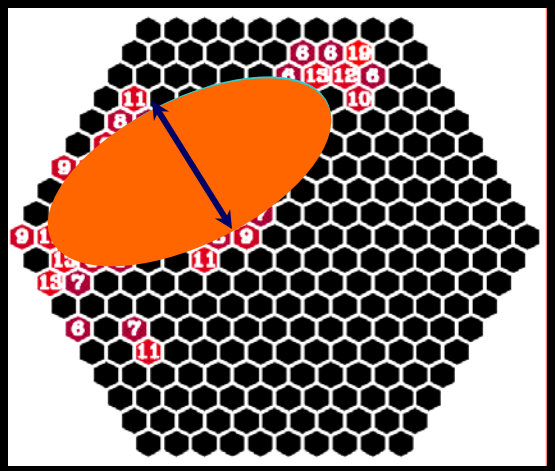
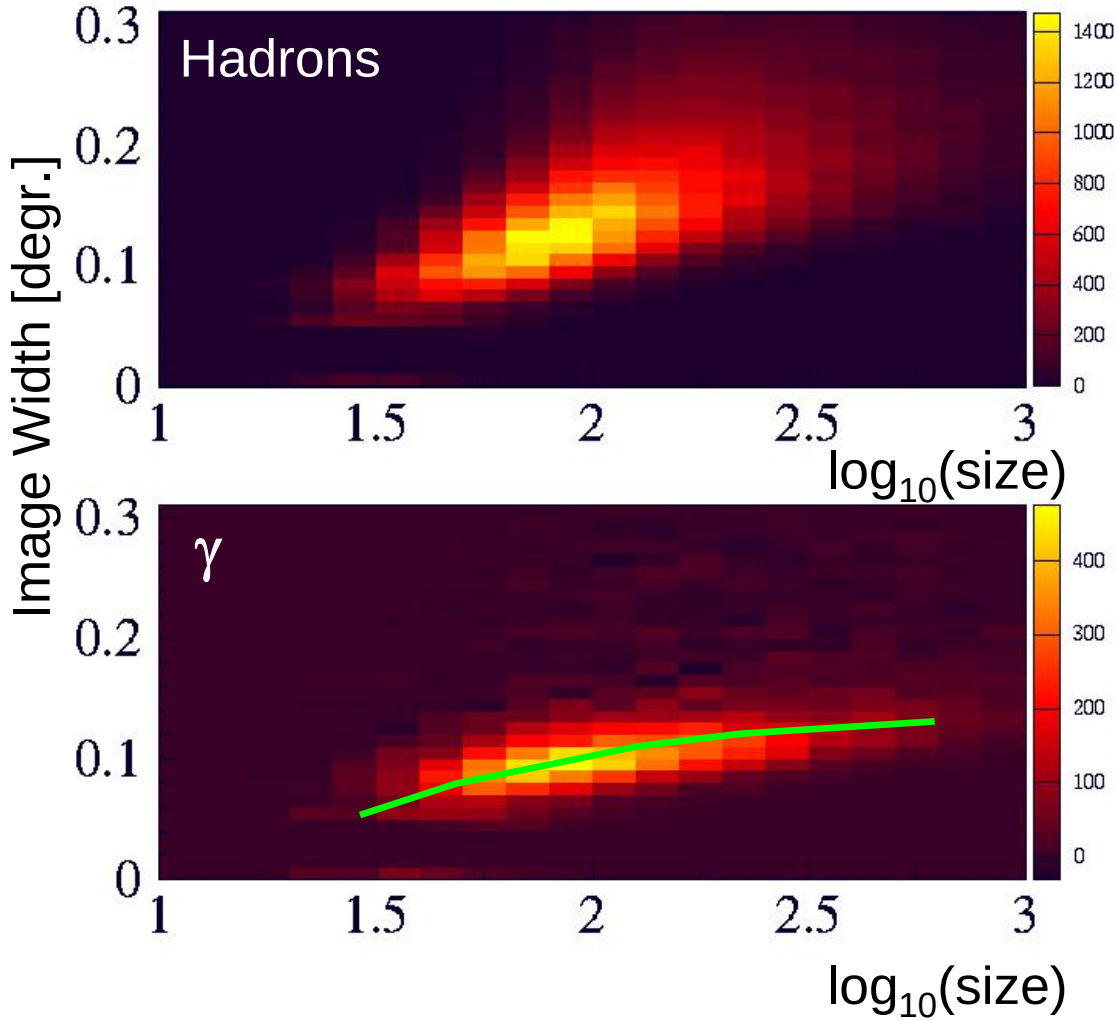


Image Width

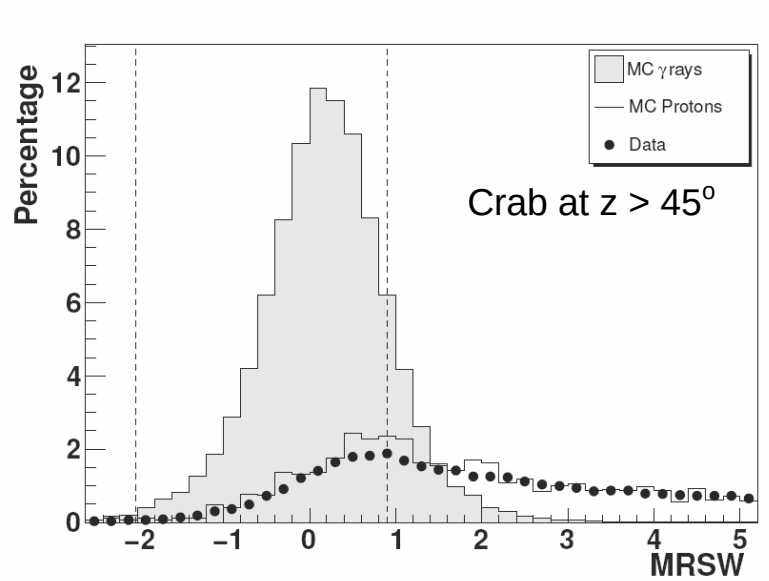
Gamma-Hadron Separation

Strong amplitude dependence of image width

Parameterize image width and Rms(width) vs. images size and core distance

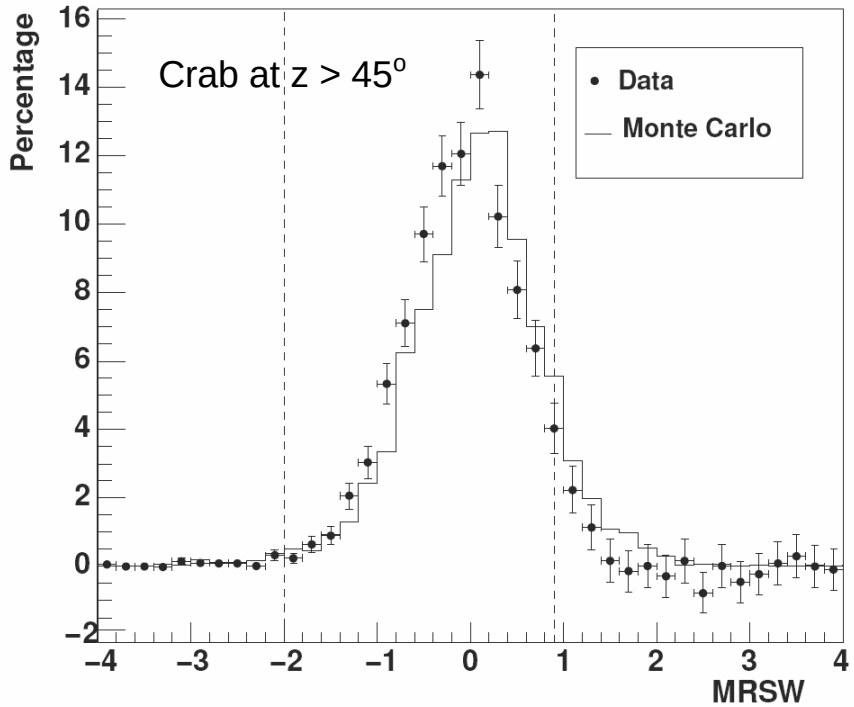


Gamma-Hadron Separation



Mean reduced scaled width

$$\text{MRSW} = \sum_{\text{tel}} \frac{\text{Width} - \text{expected W}}{\text{Rms (width)}}$$



ε_γ = 0.56 … 0.28

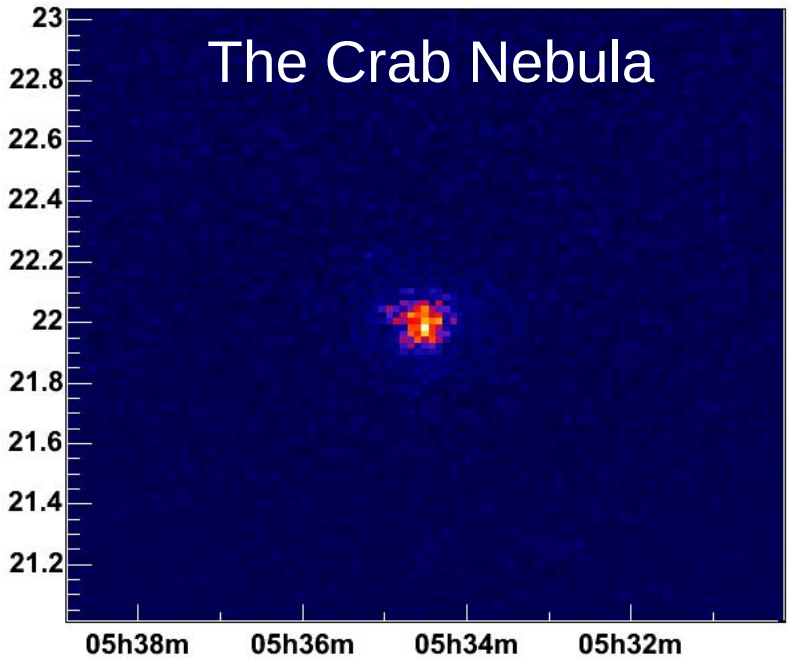
ε_b = 0.03 … 0.004

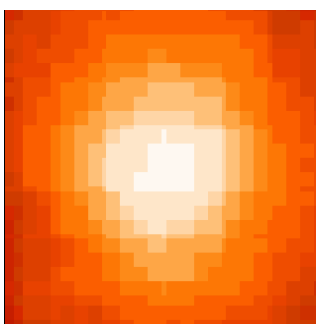
Typical γ – rate @ 20° :

~ 55 / min pre-Cut

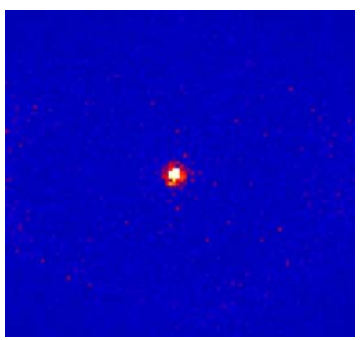
~ 15-25 / min post-Cut

Performance: Angular Resolution



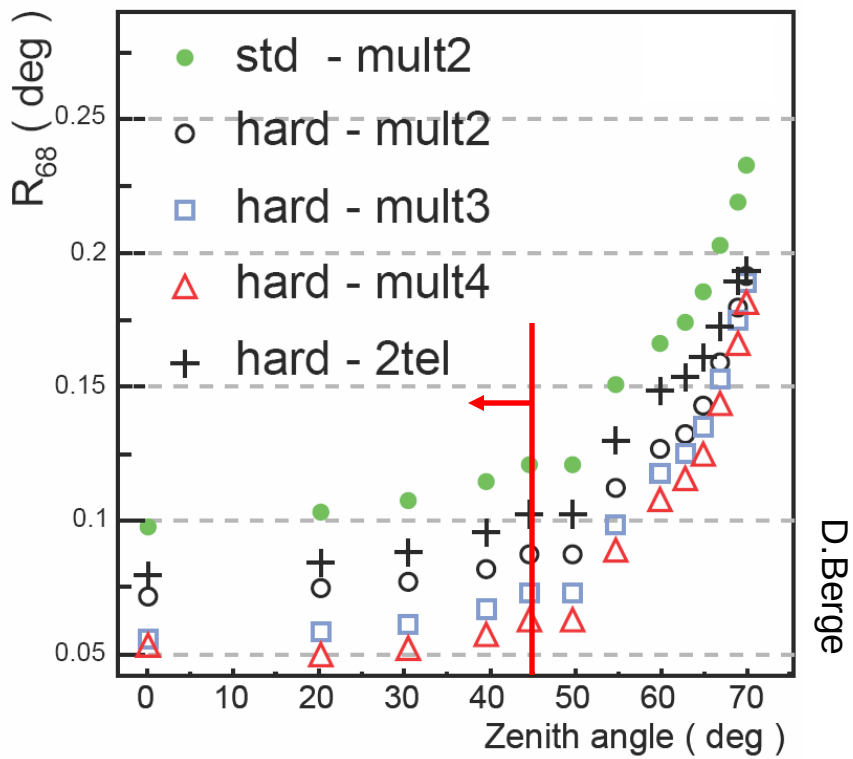


EGRET

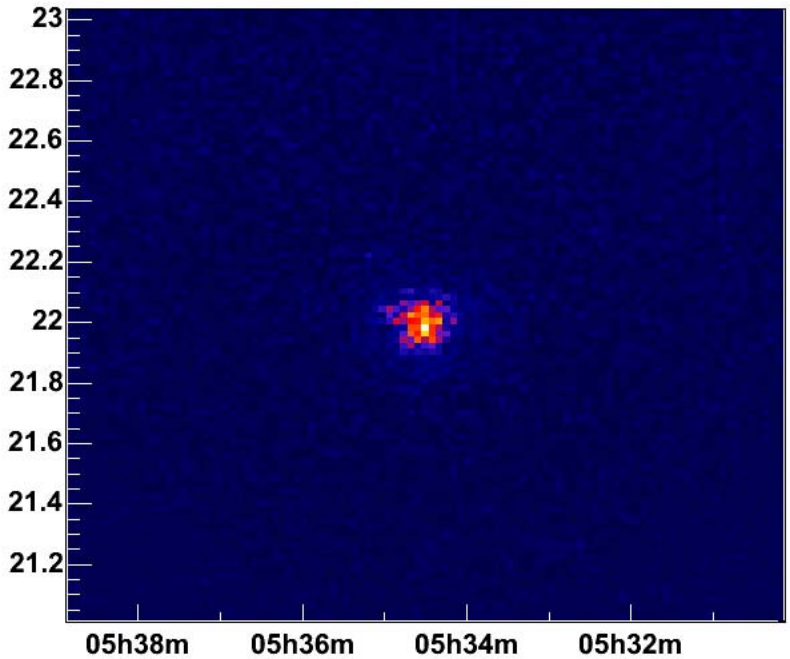


H.E.S.S

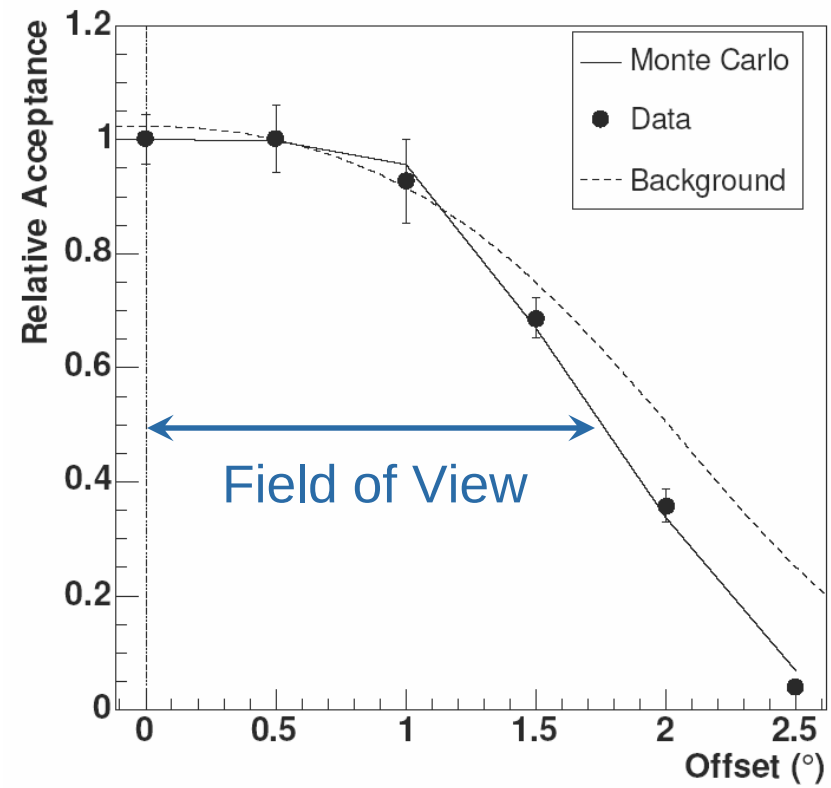
Angular resolution ~0.1°
(Point)source location O(arcsec)



Performance: Field of View



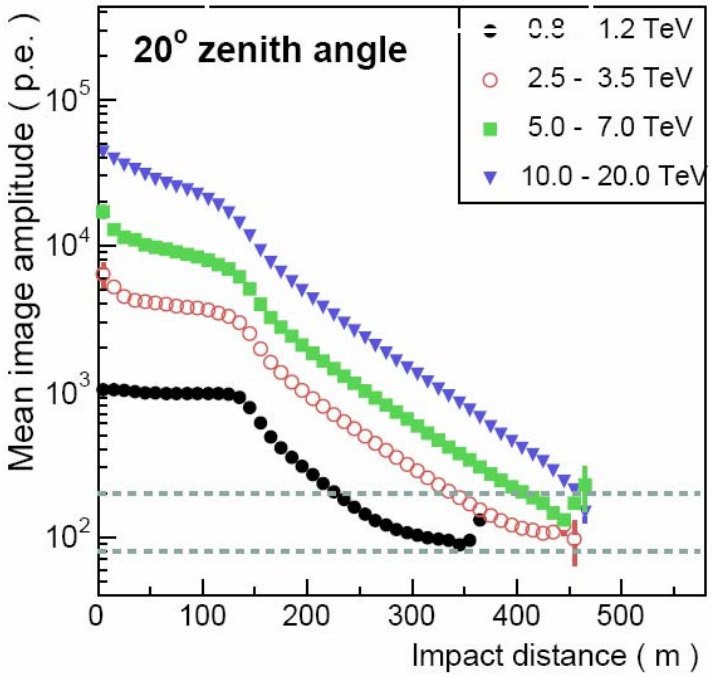
Angular resolution ~0.1°
(Point)source location O(arcsec)

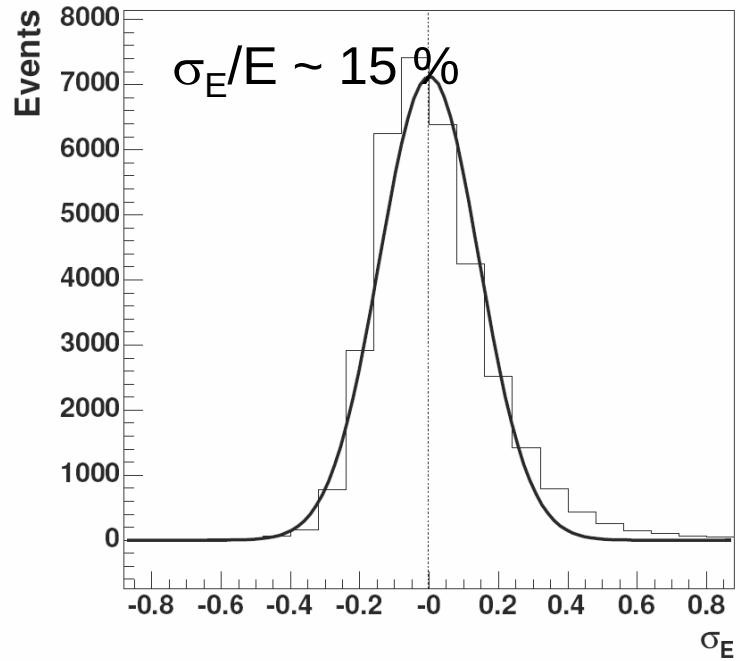


→ Point sources
→ Extended sources
→ Sky Surveys

Performance: Energy Reconstruction

Monte Carlo





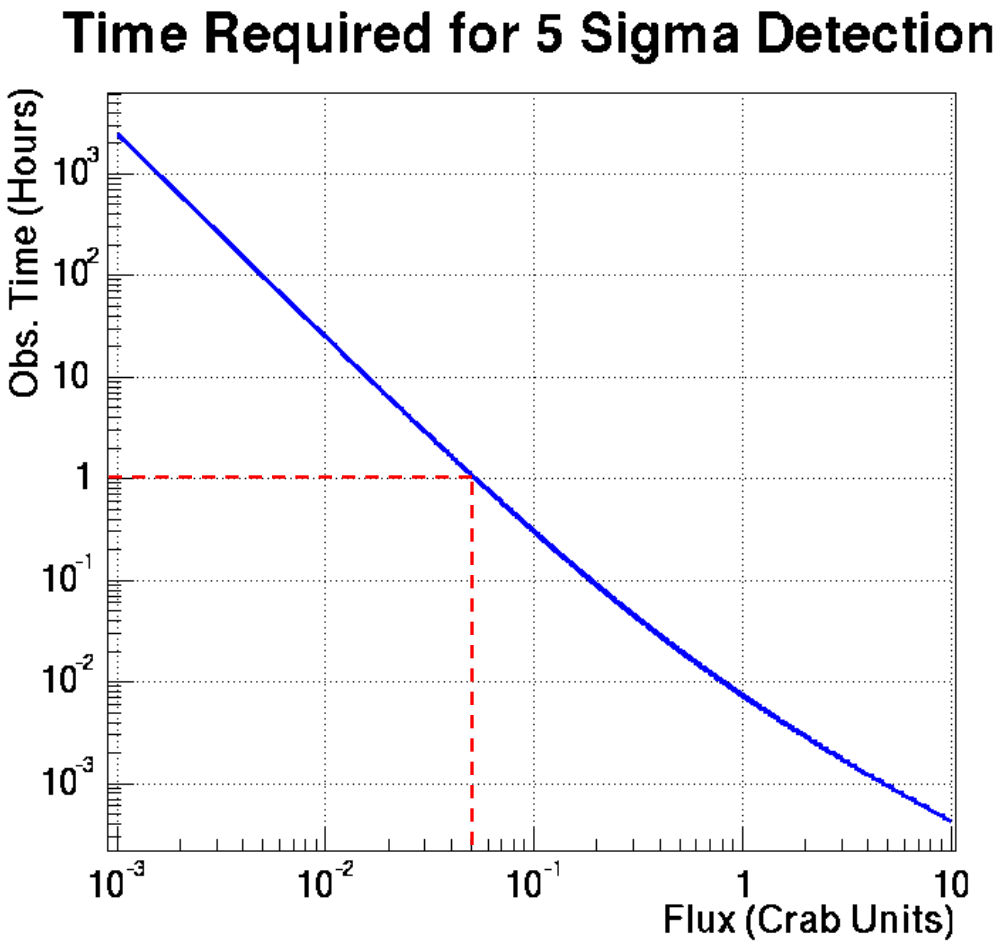
Energy from image amplitude and impact distance (Monte Carlo)

10 % - 20 % on event by event basis

→ Energy Cut-off

→ Line features …

Sensitivity of HESS Phase I



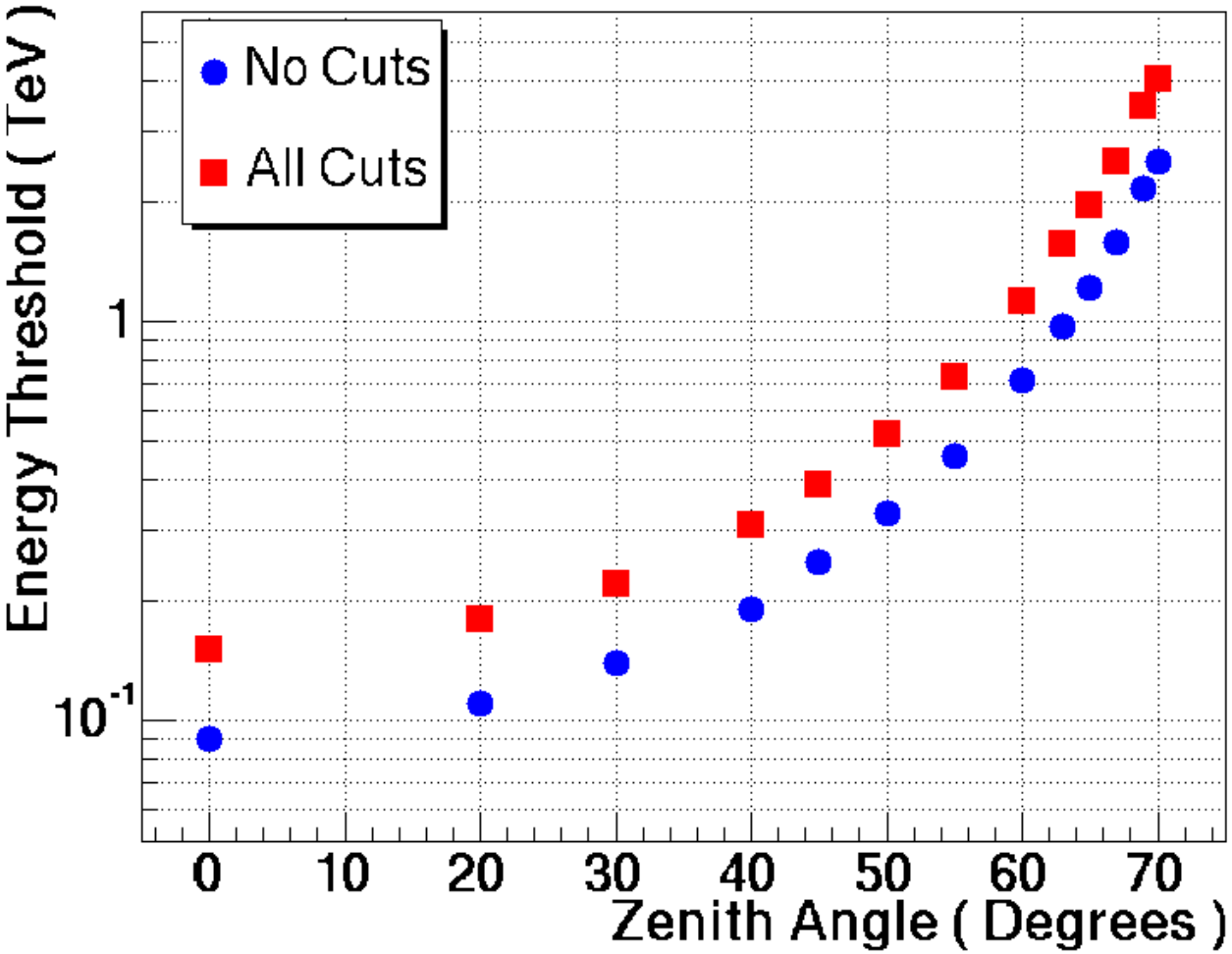
20 deg zenith angle, 0.5 deg offset

"Well educated" prediction from Monte Carlo Simulation confirmed by data

0.01 Crab in ~ 25 h
0.05 Crab in ~ 1 h
1.0 Crab in ~ 30 sec

HEGRA:
3 % of Crab in ~ 230 h

Performance: Energy Threshold

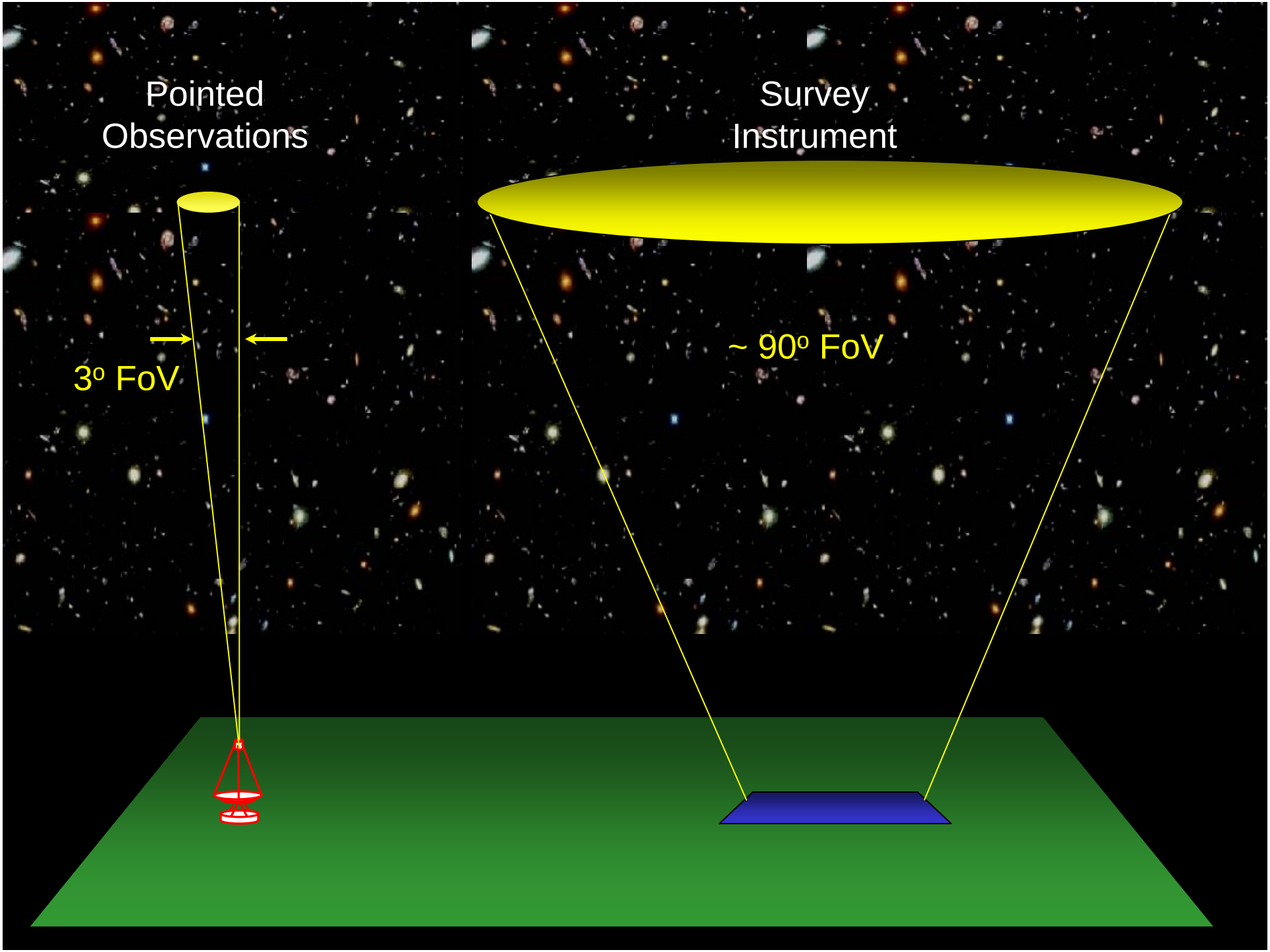


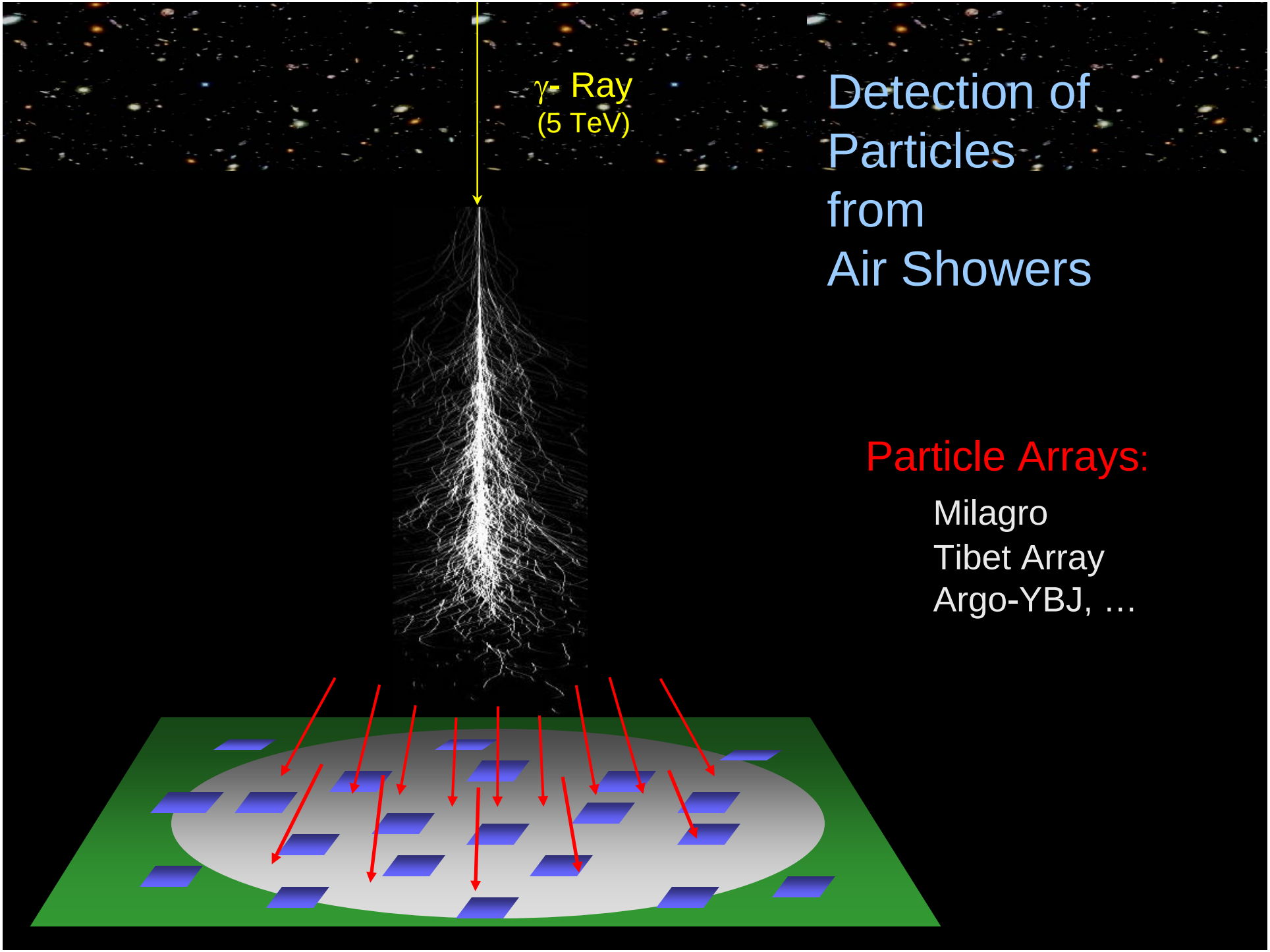
The H.E.S.S. Experiment

A precision experiment for ground-based gamma-ray astronomy

- Stereoscopic trigger
- μsec event timing
- Precision pointing

Skip


Pointed
Observations
3° FoV
Survey
Instrument
~ 90° FoV



Detection of Particles from Air Showers

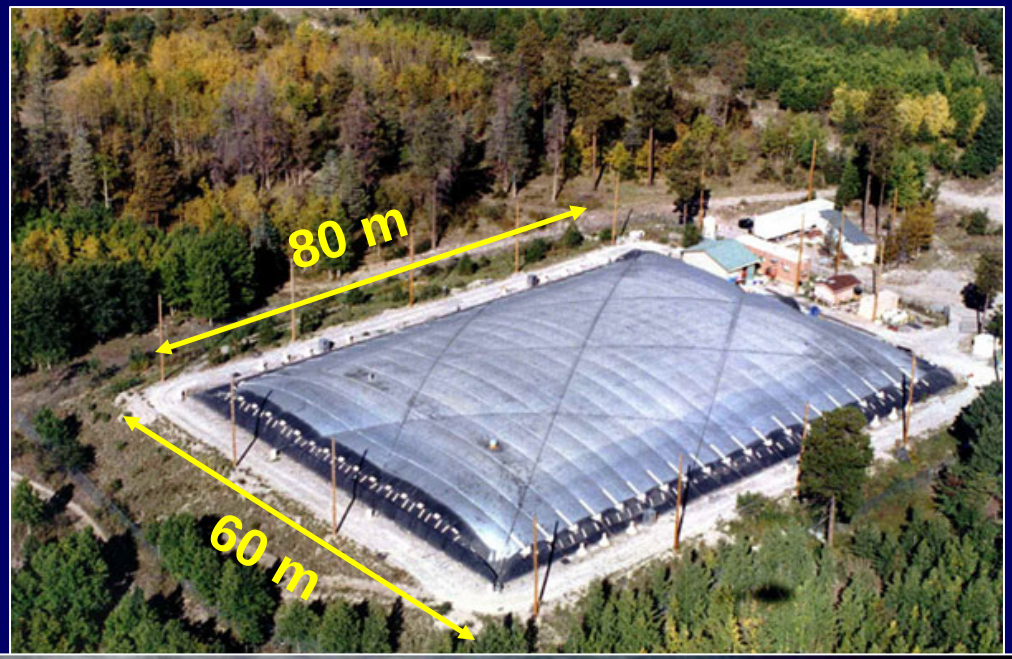
Particle Arrays:

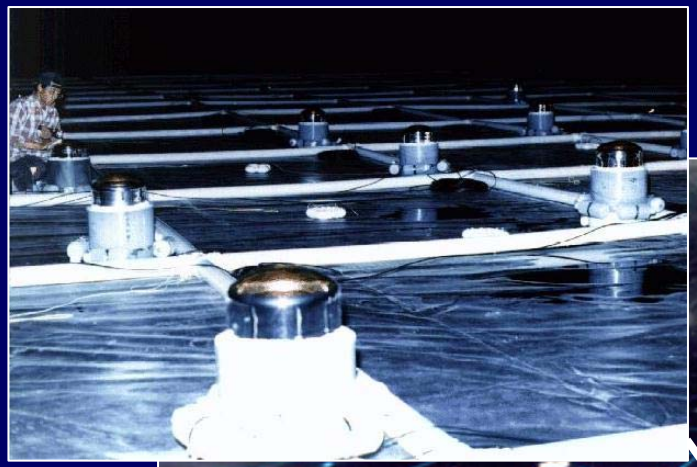
Milagro
Tibet Array
Argo-YBJ, …

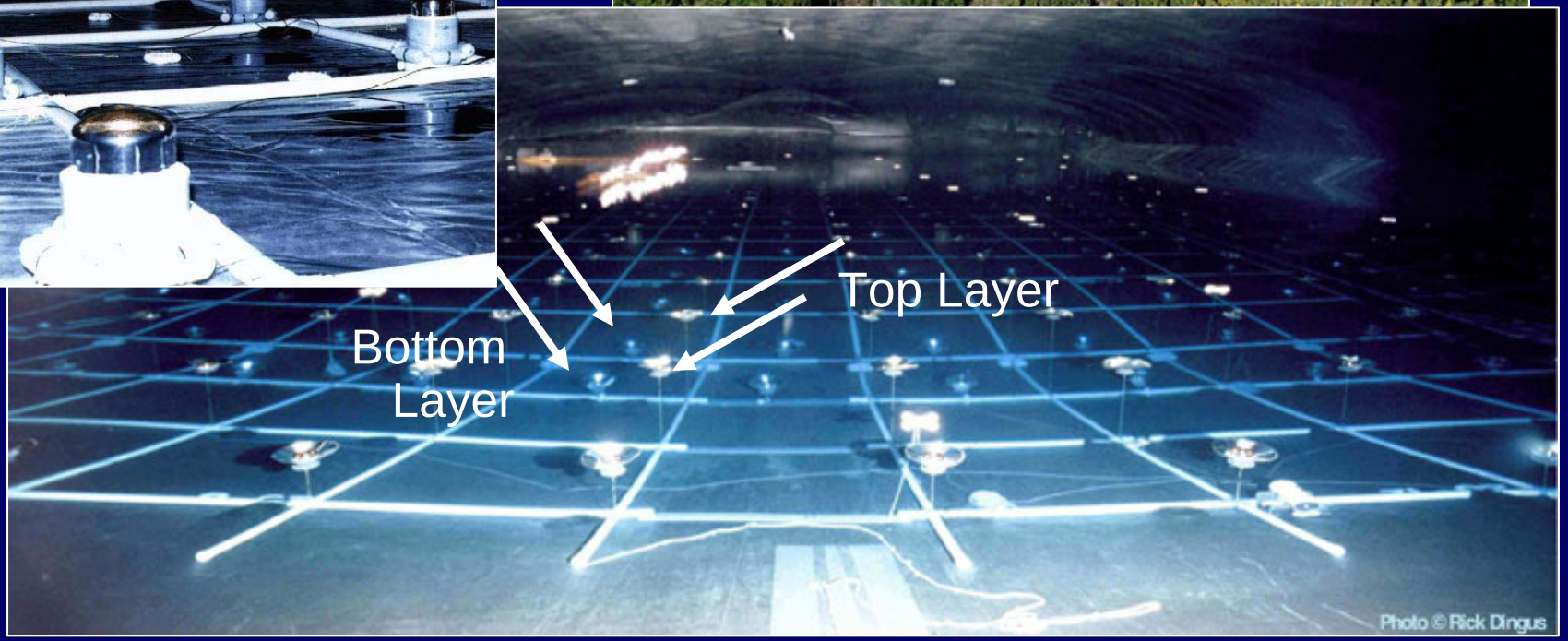
MILAGRO / Milagrito

Near Los Alamos
2630 m a.s.l.

1997/98 Milargrito
> 1999 Milagro







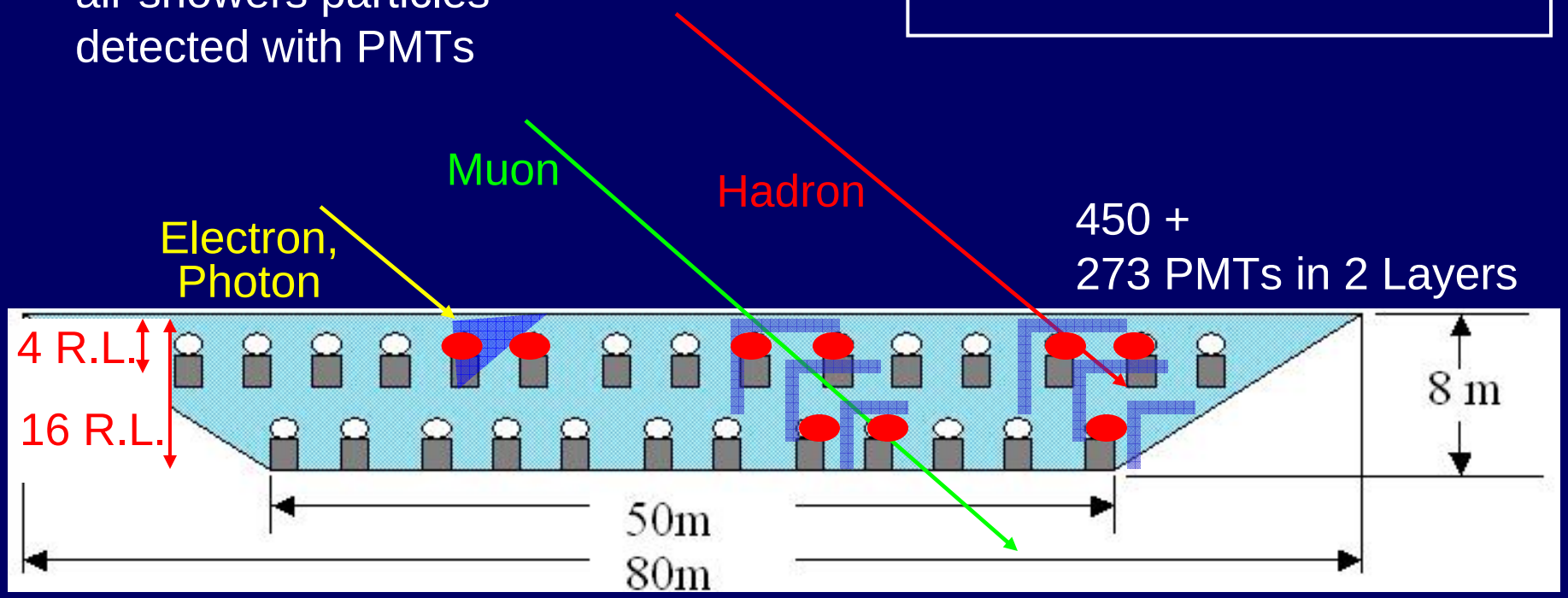
MILAGRO: The Principle

Water Cherenkov detector

- Use big water pond as particle detector
- Cherenkov light of from air showers particles detected with PMTs

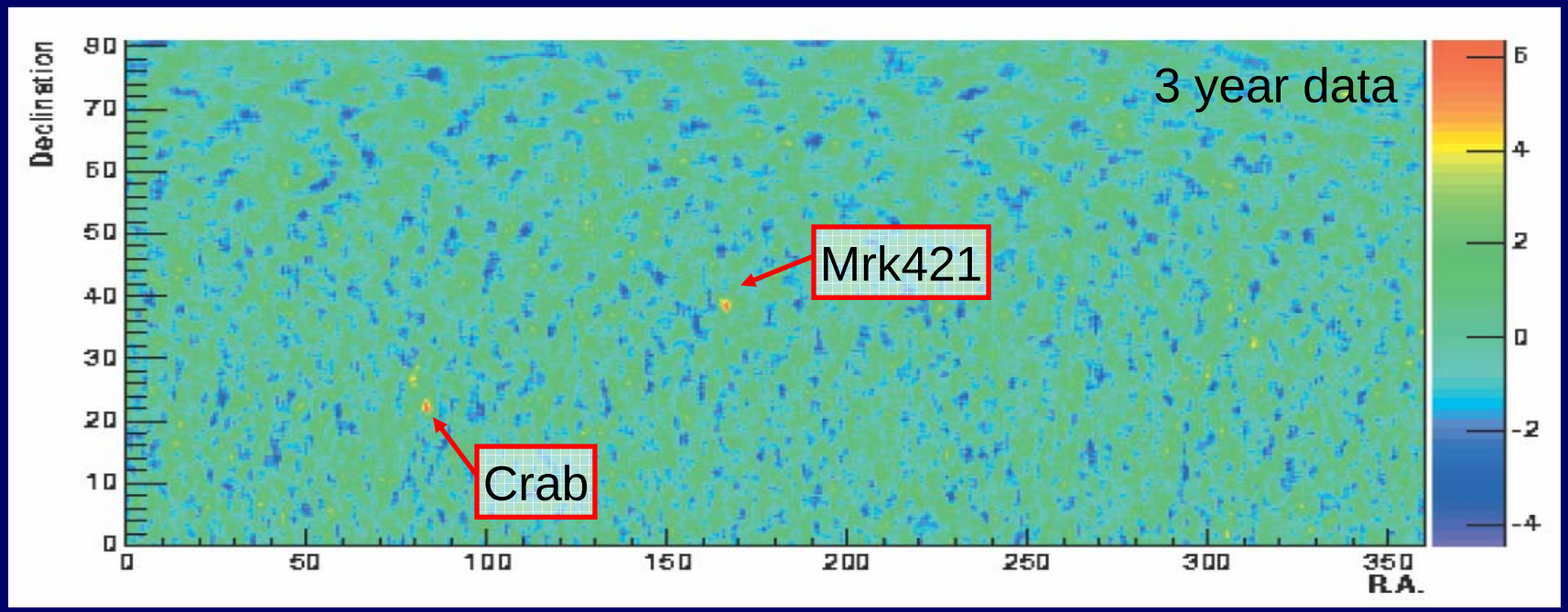
Observables:

→ Light intensity in 2 layers
Energy, γ/h separation
→ Arrival times
Shower direction



MILAGRO

Continuous Sky Coverage: 24 h/day, 365 days/year, large FoV ~ 2 π



Sensitivity: ~0.5 Crab in 1 yr (of patience)

Sensitive to transient sources (γ-ray bursts)

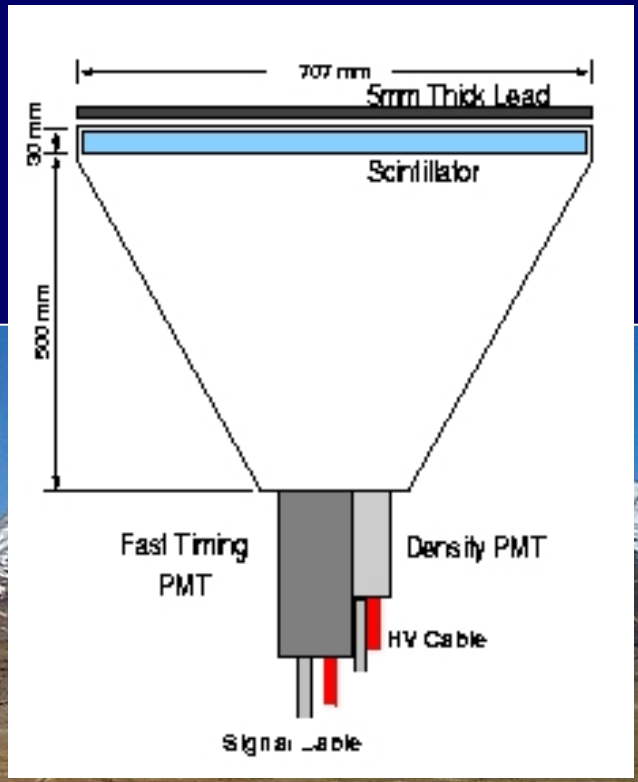
25 GRBs in FoV → no detection (yet)

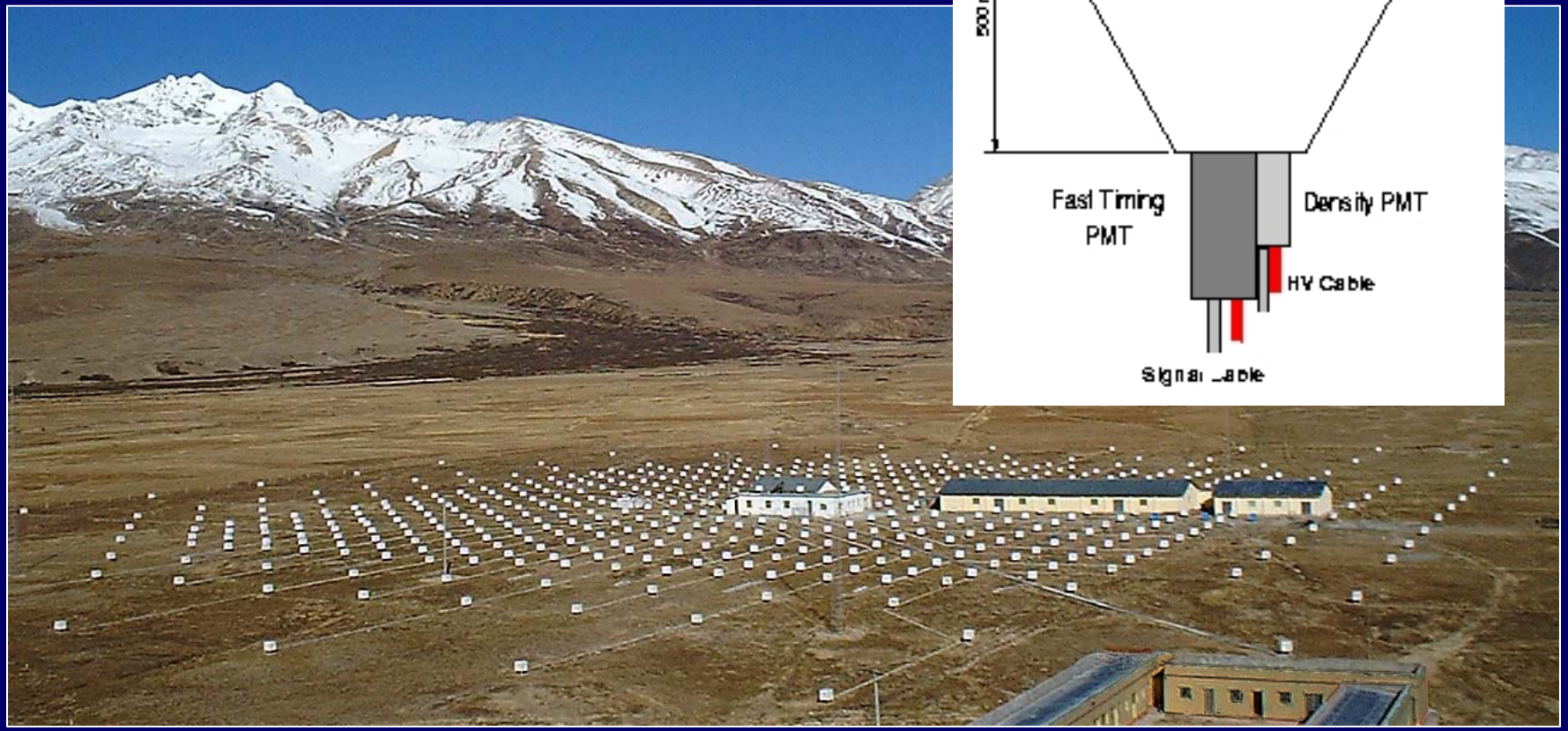
Atkins, ApJ 2005

The Tibet AS – γ Experiment

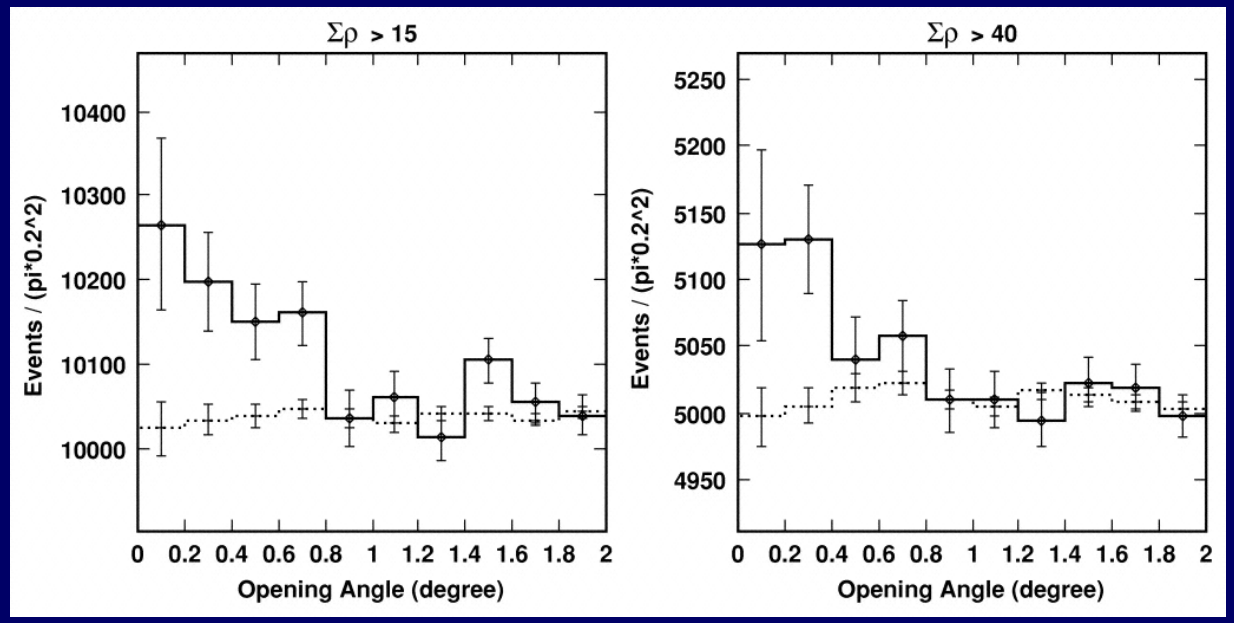
Yangbajing, 90° E, 30° N, 4300 m asl

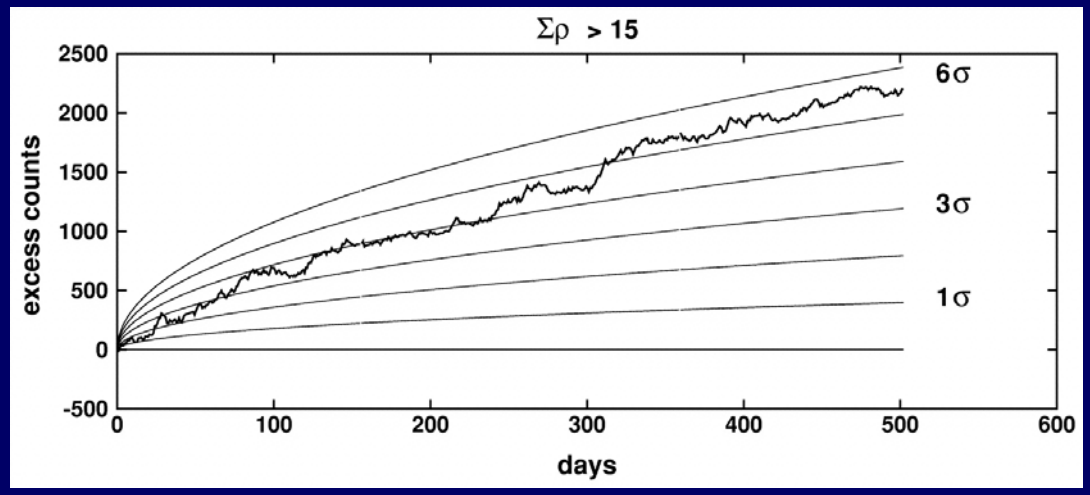
Air Shower Array out of
533 scintillator detectors
→ Particle density, arrival time





The Tibet AS – γ : The Crab Nebula





E_{thr} ~ 3 TeV

Angular res. : < 1° (γ-rays)

First detection of Crab with conventional air shower array !

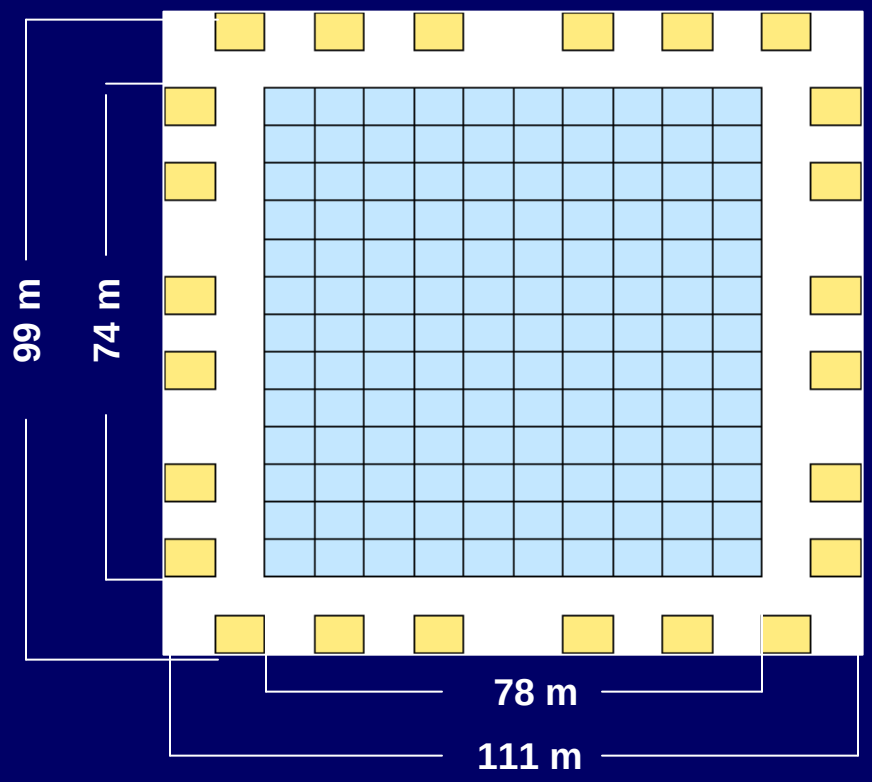
Amenomori ApJ 525 (1999)

Soon (2006): ARGO - YBJ

Tibet @ 4300 m a.s.l. : high density sampling of shower particles

Soon (2006): ARGO - YBJ

Detector layout



7000 m^2 active area
Resistive plate chambers (RPC)

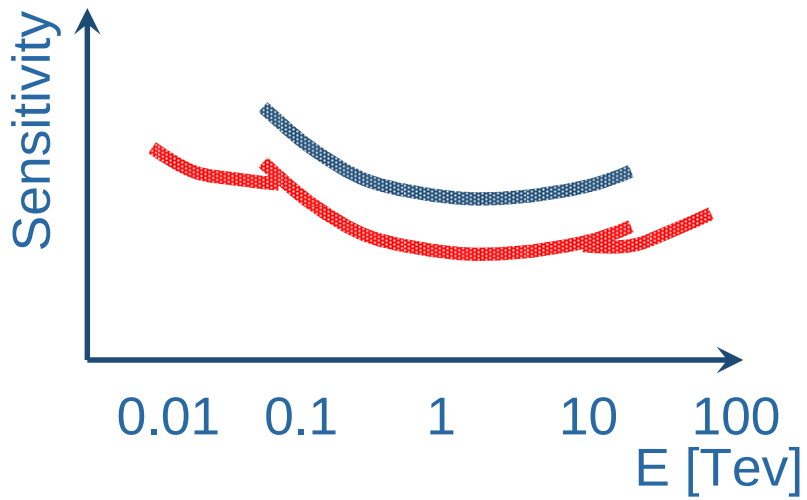
E_{thr} ~ 0.5… 1 TeV

Angular resolution: 0.5°…1°

Sensitivity: 0.5 Crab in 1 year

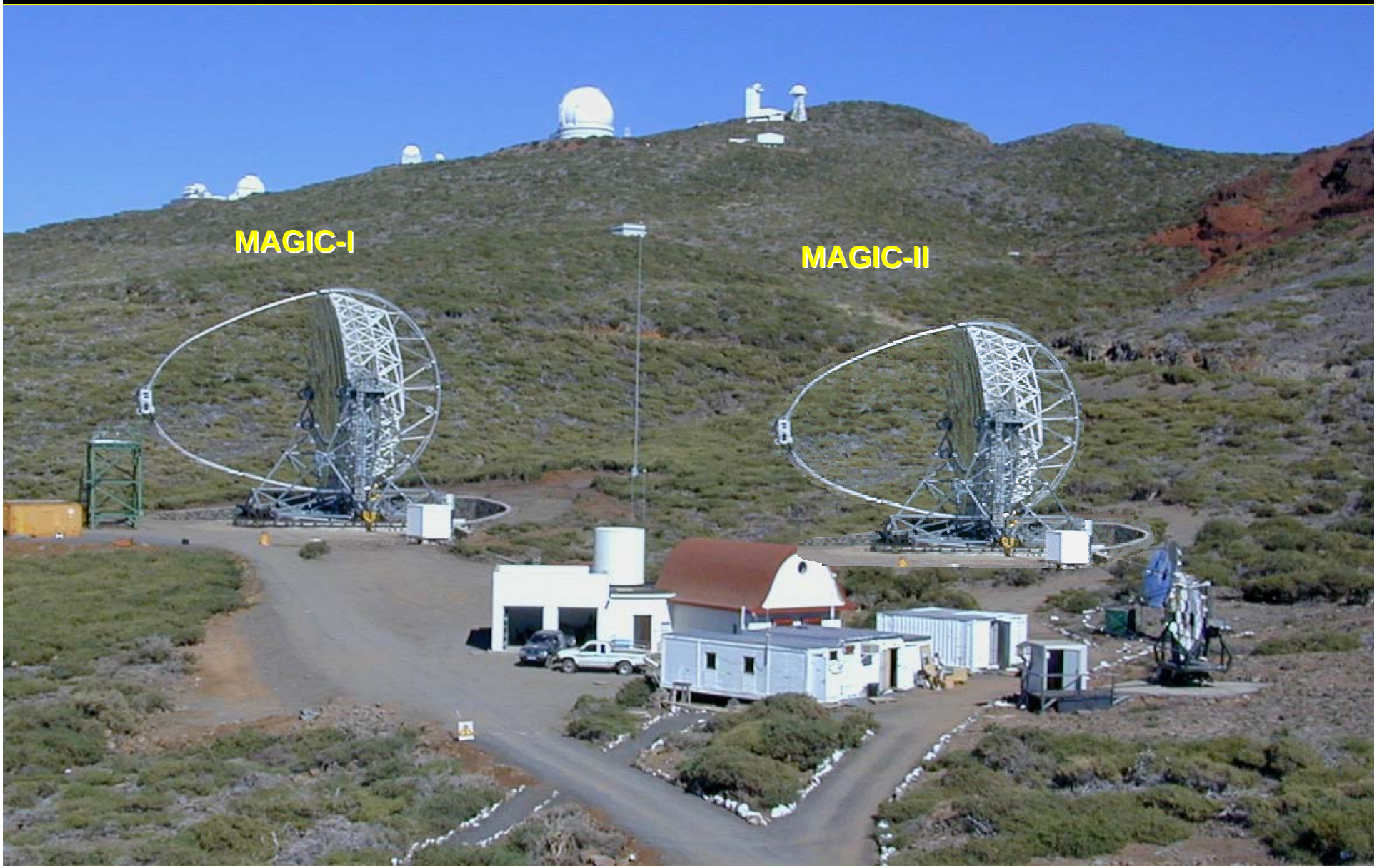
Goals for the next Generation

- *Improvement of sensitivity in current energy regime*
- *Large collection area at high energies*
- *Lower energy threshold down to about 5 GeV*
- *Large field of view*



- More telescopes O(100)
- Bigger telescopes 600 m^2
- Larger cameras 4000 pixel
- High Q.E. photon detectors

MAGIC Phase II : 2nd Telescope in 2007



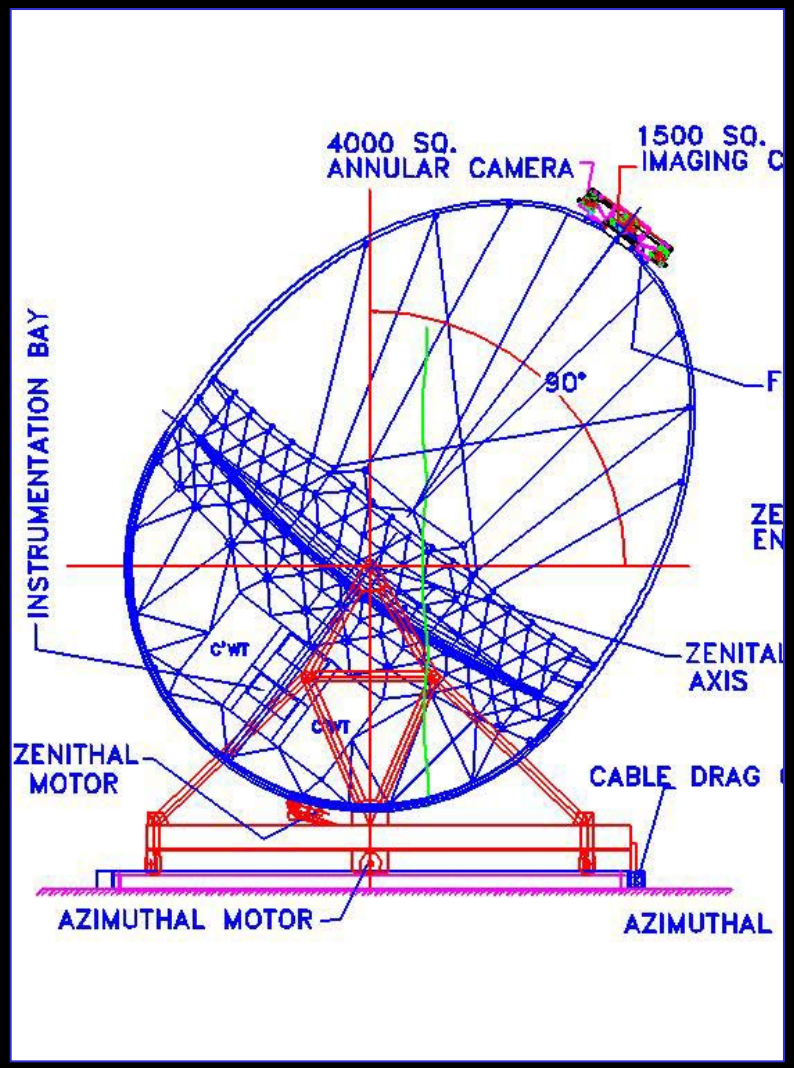
H.E.S.S. Phase II

- Improved sensitivity at higher energy in coincidence mode
- Lower threshold and increased energy range in stand-alone mode
- Test bed for future large telescopes and image analysis

MACE @ HiGRO
Himalaya Gamma-Ray Observatory

21 m mirror diameter

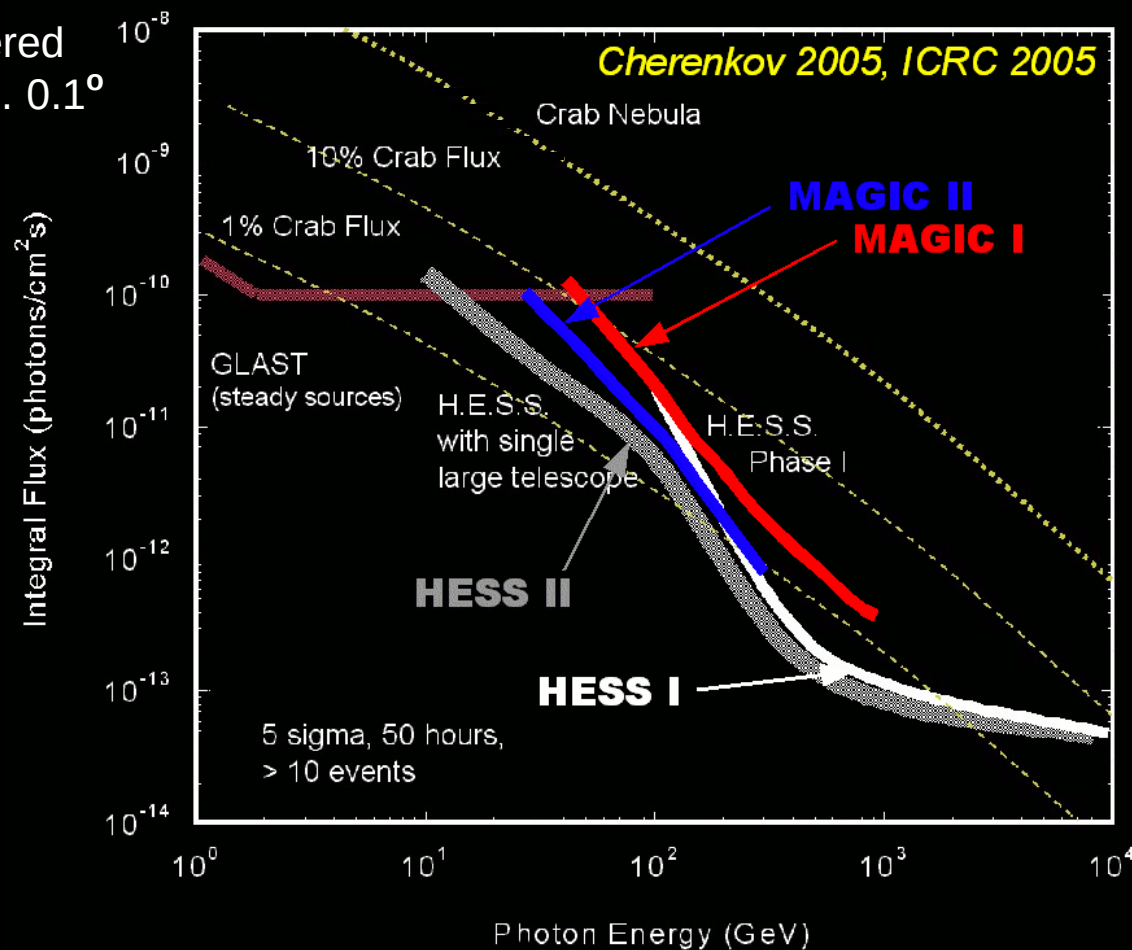
Energy Threshold: 20 GeV
@ 4200 m a.s.l.

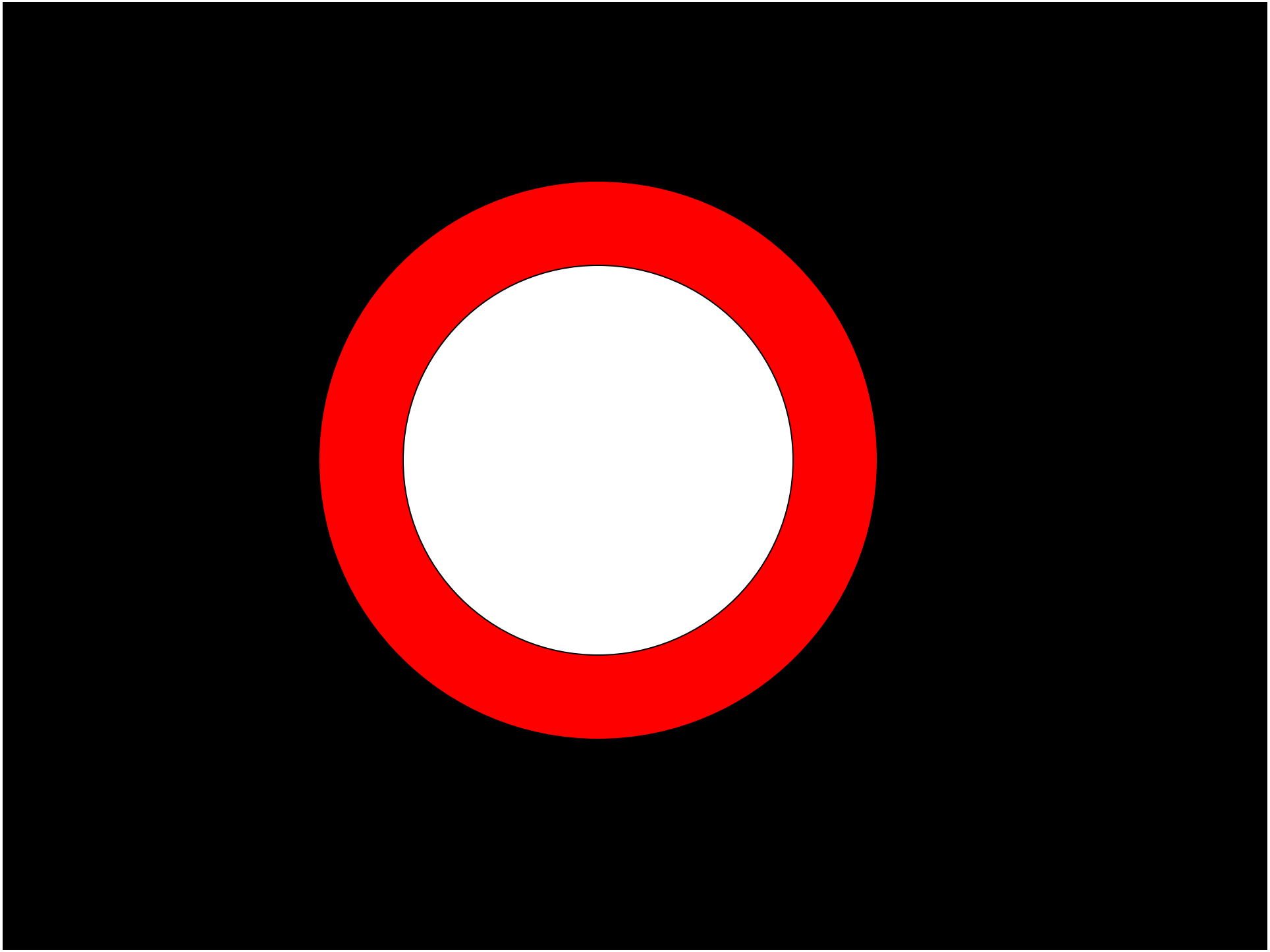


Conclusions …

IACT Instruments:

Unprecedented performance
- 100 GeV …. ~ 50 TeV well covered
- Typ. angular resolution ~ 0.05 … 0.1°
- Energy resolution O(15 %)
- FoV: 2-4° **f**
- ~ 10 % duty cycle
- Sensitivities: Crab in 30 sec



Particle Arrays:

- 2 steradian FoV
- ~ 100 % duty cycle
- Sensitivity:
  0.5 … 1 Crab in 1 year
  E > ~ 1 TeV