Observatoires gamma au sol, l'existant et le futur (et le passé)

M. Punch

APC – CNRS/IN2P3

Les Motivations

Why do VHE γ-ray astronomy?

- "Free" access to high-energy accelerators in the Universe
  $\Rightarrow$ insights on the high-energy processes in our Universe and the evolution of the Cosmos
  - γ-rays signal the presence of high-energy particles (electrons or protons) which can be accelerated in pulsar/stellar winds, shocks from supernova remnants or wind termination shocks, or the pulsar "dynamos" ...
  - Measurement of VHE γ-rays (>100 GeV), provides e.g.
    - Spectra inform us on the accelerated particle populations
    - Morphology tells us about evolution
    - Variability gives us information on extension and clues on processes at work
  - But all must be combined with multi-wavelength (MWL) observations for good understanding!

Science Goals of Ground-Based Observatories

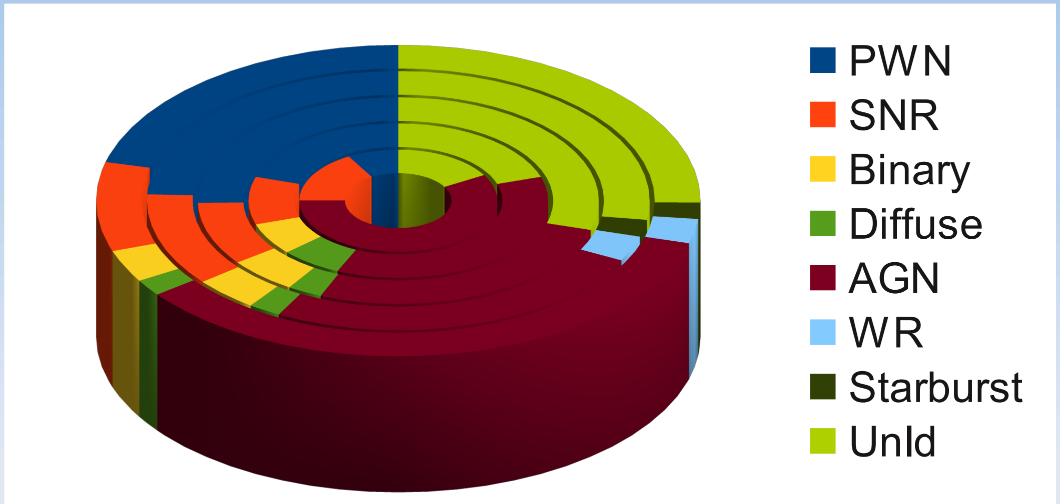
- Cosmic-ray origins
  - High-energy[W] and high resolution[A] spectra of Galactic sources
  - Galactic diffuse emission[W]
  - Discover Galactic cosmic-ray accelerators[A]
- Particle acceleration
  - Rôle of relativistic particles in AGNs, Starburst galaxies
  - Transient phenomena (AGN flares and GRBs)
    - prompt emission[W] & delayed[A]
    - orphan flares[W], TeV duty factors[W], fastest phenomena[A]
  - Physics of relativistic jets and shocks[A]
  - Multi-wavelength (Fermi, X-ray, optical, radio) [WA], multi-messenger[A]
  - Source morphology[A]
  - Pulsars[A]
- Fundamental Physics
  - Lorentz invariance (GRB[W], AGN[A])
  - Dark matter detector[A] (annihilation gammas from neutralinos)
- Discovery
  - Unbiased sky survey (2.6π sr) to few % of Crab Nebula level[W]
  - Deep Galactic survey to milliCrab level[A]

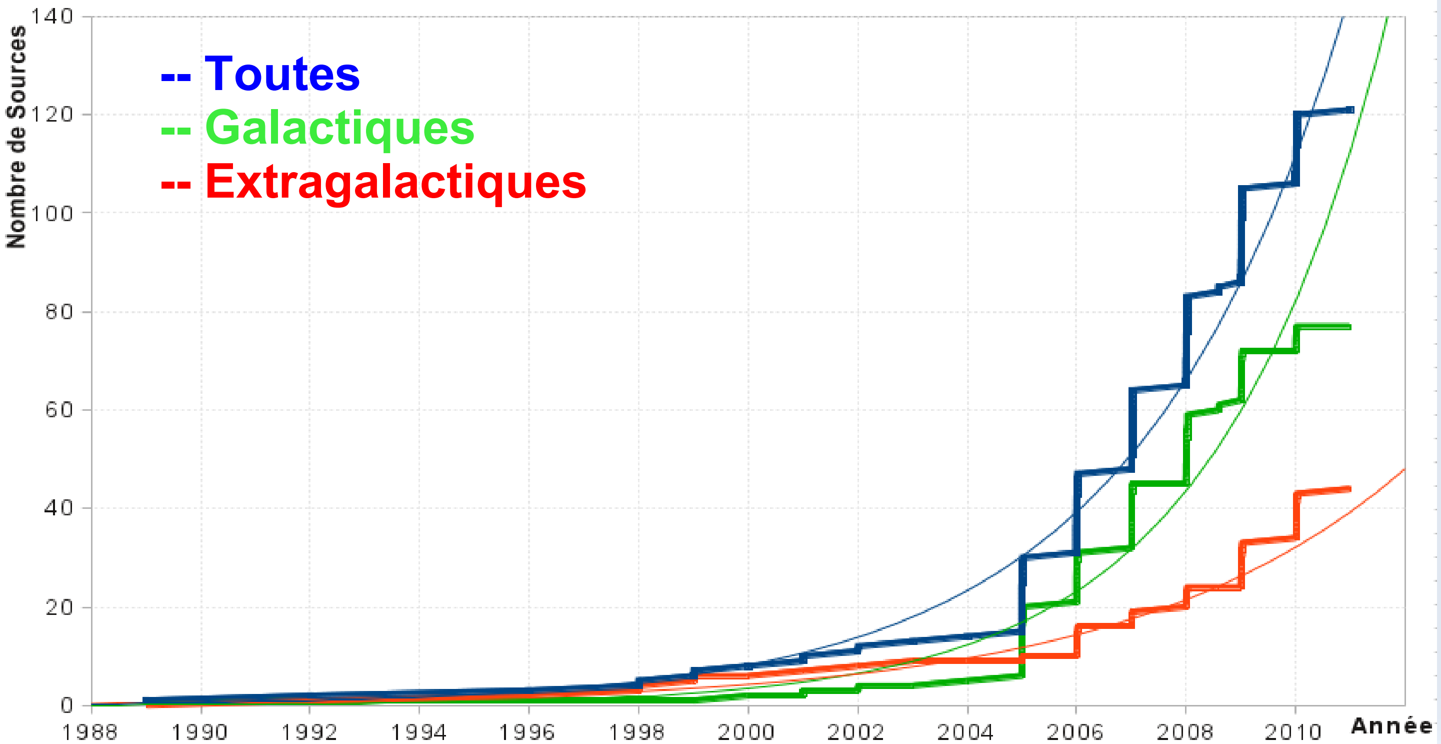
[W] Wide field instrument

[A] Air Cherenkov Array

Current VHE Source Numbers (2011)

Class	*2011*	*2009*	*2007*	*2005*	*2003*
PWN	25	23	18	6	1
SNR	11	11	7	3	2
Binary	4	4	4	2	
Diffuse	2	2	2	2	
WR	3	3			
AGN	42	24	19	11	7
Starburst	2	2			
UnId	30	26	21	6	2
Total	119	95	71	30	12

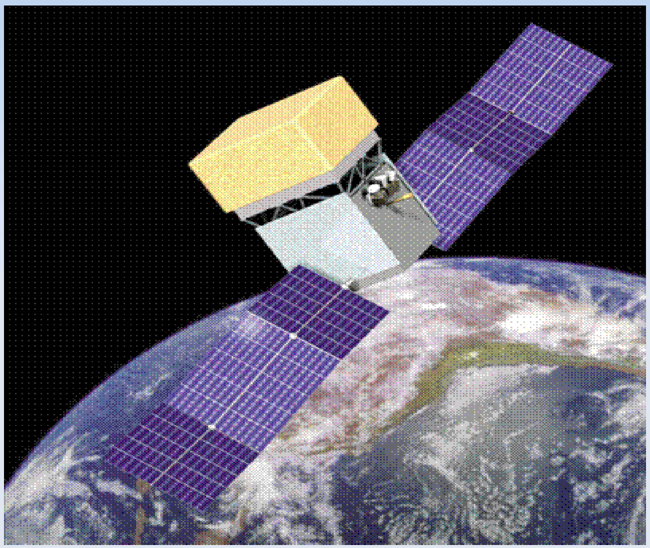




Les Techniques de Détection

Modern Gamma-Ray Telescopes

Low Energy Threshold
EGRET/FERMI



•Small collection area
•Large field of view: ~72° (20% sky)
•Live time ~100%
•Very good rejection of
the CR background

Sky Survey 100 MeV - 10 GeV
High Resolution Energy Spectra

High Sensitivity
HESS, MAGIC, VERITAS

•Large collection area
•Small field of view: ~5° (0.05% sky)
•Live time: ~10-15%
(clear nights, moonless/low-moon)
•No shield to reject the background
but efficient rejection exists

Surveys of limited regions of sky > ~ 100 GeV
High Resolution Energy Spectra
Source morphology
Fast timing

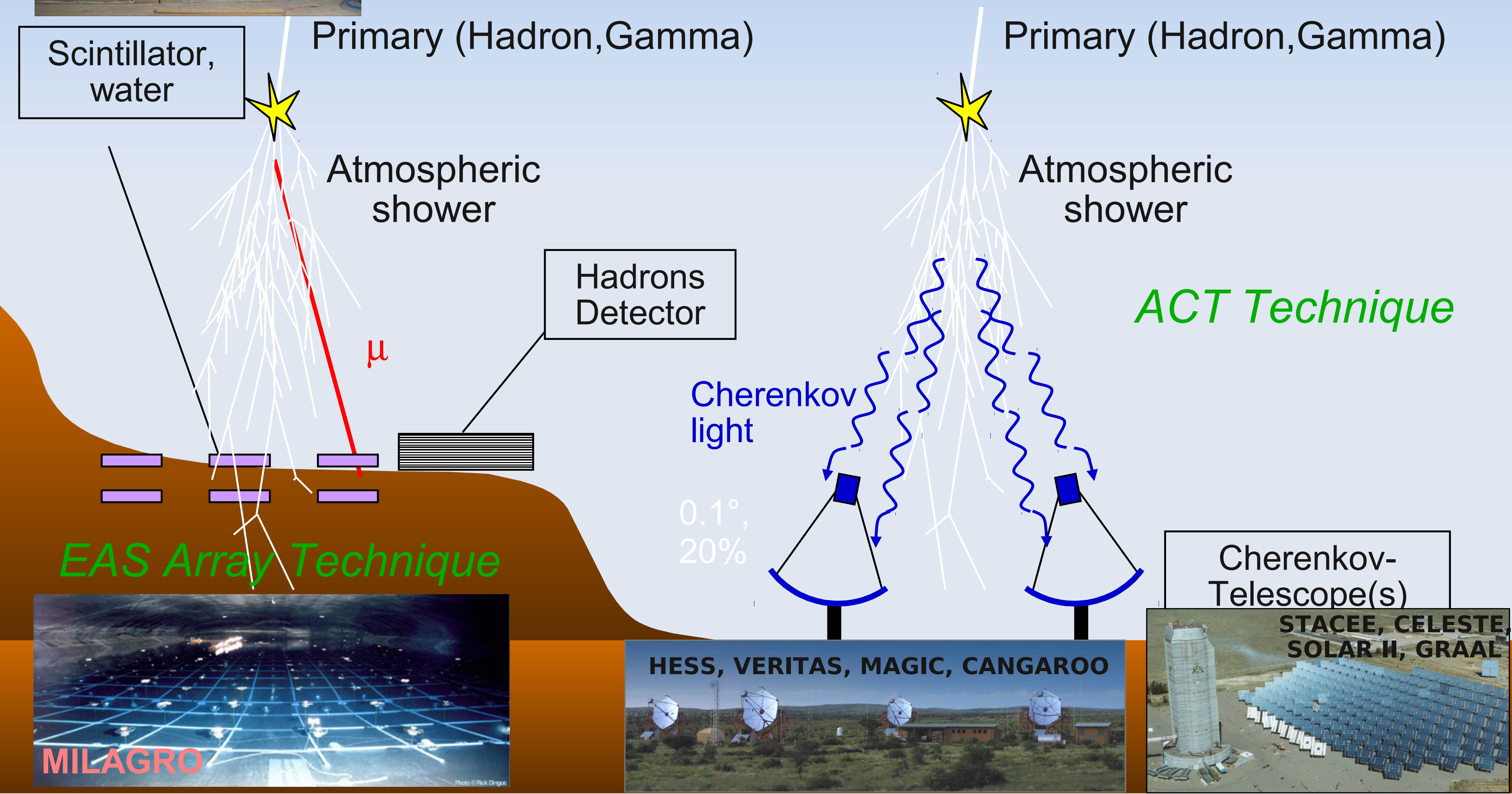
Large Aperture/High Duty Cycle
Milagro, Tibet, ARGO

•Medium collection area
•Large field of view: ~25° sky
•Live time ~100%
•Difficult rejection of
the CR background

Sky Survey > few TeV
Extended sources
Highest energies

Gamma-detection from ground

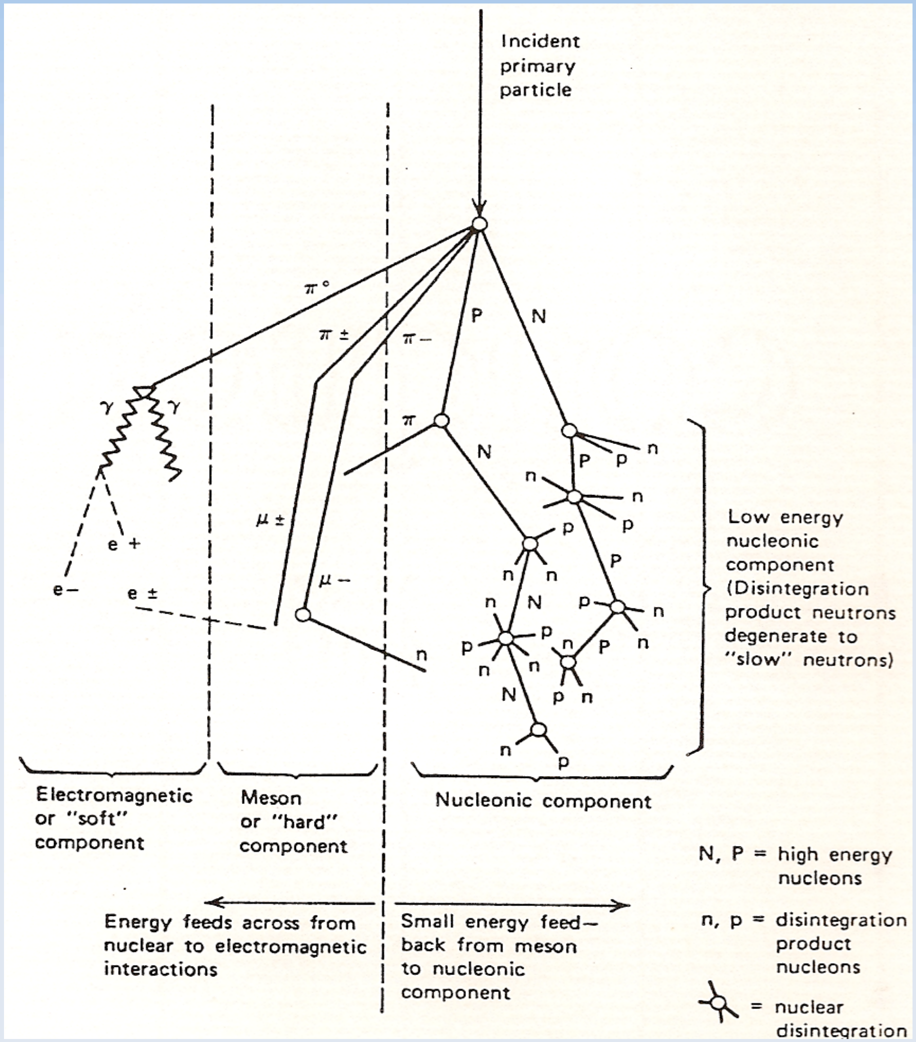
- No focusxing possible
- Flux ~ $E^{([-2,-3])}$ ⇒ Crab > 1 TeV : ~ 1 γ/century/m²
- Big Collection area needed
- Hadronic background high (1000 for 1γ)



Atmospheric Cherenkov Telescopes
… qu'est ce qu'on detecte ?

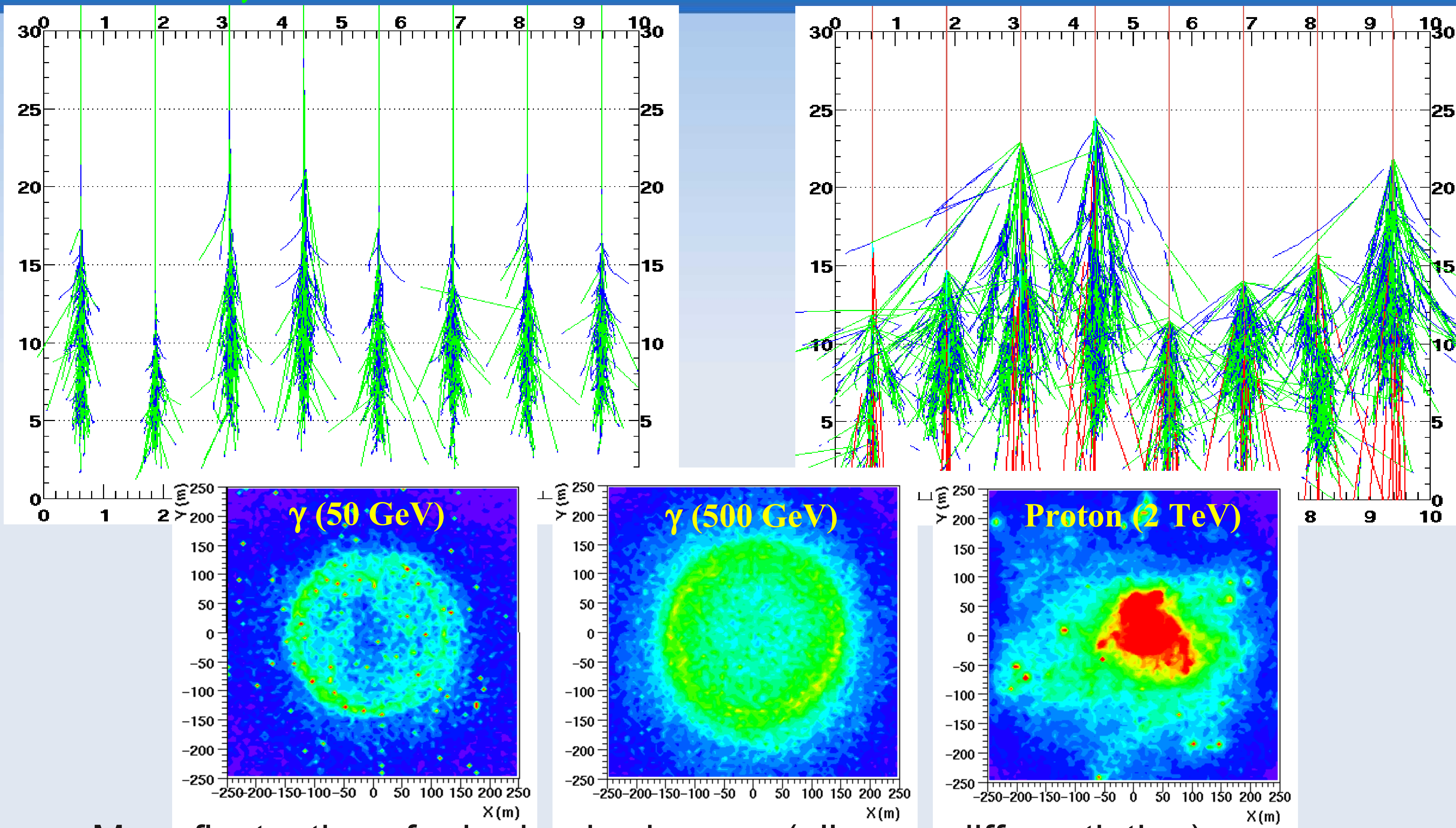
The development of EAS

- Extended air showers, caused by interaction of γ-ray or hadron in the atmosphere
- Cascade develops, then decays through bremmstrahlung and other losses
- Electromagnetic (γ-ray induced) cascade is simpler than hadronic
  - $e^{\pm}$ pair creation by γ-ray
  - γ-ray production by $e^{\pm}$ bremms.
- γ-ray showers more regular and smooth than hadronic showers, which have larger transverse momentum and electromagnetic sub-showers



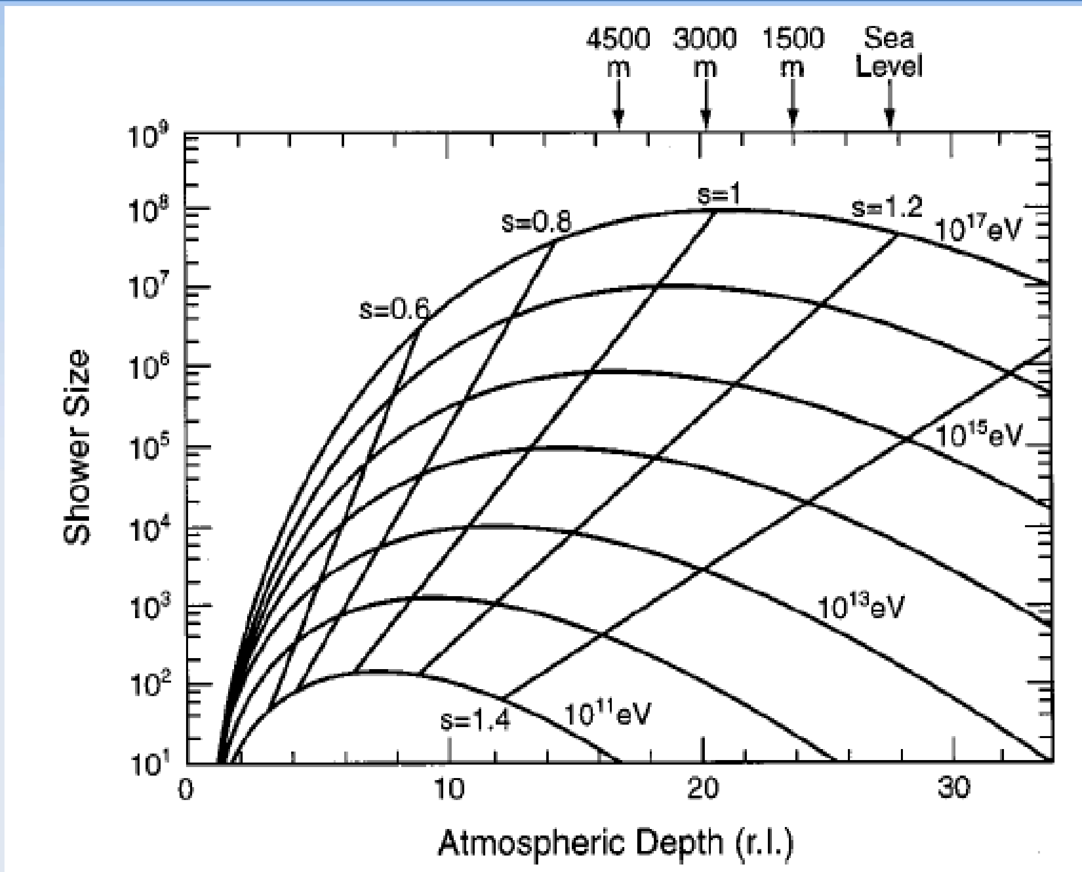
Some simulated showers

γ, 100 GeV | *Protons, 500 GeV*



- More fluctuations for hadronic showers (allows a differentiation)
- + muons (some red tracks) $N_\mu \approx 10 \cdot \left(E_o / m_\pi c^2\right)^{0.83}$ e.g. ~50 μ for a 1 TeV primary

Development of the E-M Shower



Shower characterized by shower age

$$\boldsymbol{s} \cong 3t / \left\{ t + 2\ln\left(E_o / \varepsilon_c\right) \right\}$$

where t is the depth
(units of *radiation length* $X_0 \approx 36.6\,\mathrm{g\,cm^{-2}}$)
and ε_c is the critical energy ε_c 84.2 MeV in air

… and parameterized approximately by

$$N(t, E_o) \cong \frac{0.31}{\sqrt{\ln(E_o / \varepsilon_c)}} e^{t\{1 - \frac{3}{2}\ln(s)\}}$$

So, the maximum of the shower occurs at

$$t_{\max} = \ln\left(E_o / \varepsilon_c\right)$$

and the *integral track length* is E_o / ε_c in radiation lengths

...and implying $N_{\max} = \frac{1}{10} \cdot \left(E_o / \varepsilon_c\right)$ … or ~1 $e^{\pm}$ per GeV of the initiating γ-ray

N_{max} and the integral track length scale linearly ⇒ **calorimetric measurement**

Cherenkov Emission in a medium

Emission of Cherenkov photons at fixed angle

$$\cos\theta = \frac{1}{n\beta}$$ where βc is the particle's velocity, v

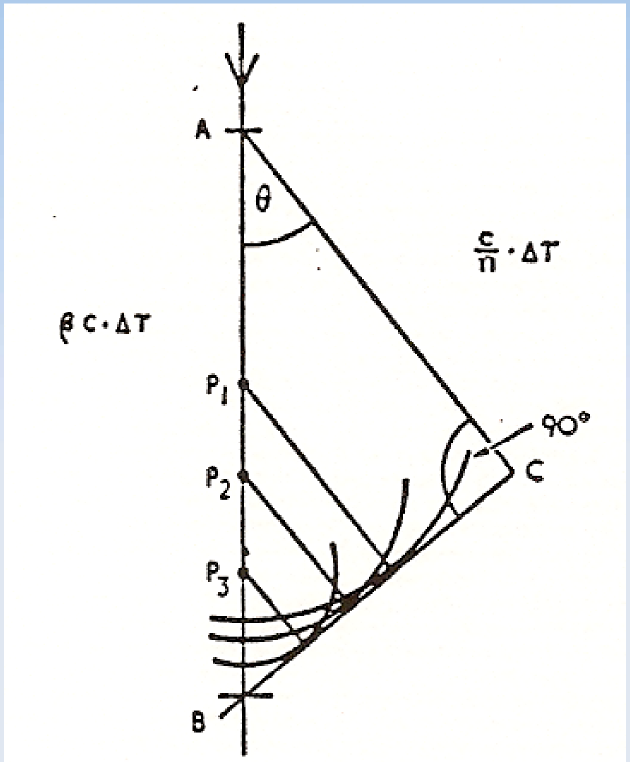
above the Cherenkov threshold

$$\beta_t = 1/n \qquad \text{where } \gamma_t = 1/\sqrt{1-\beta_t^2}$$

So threshold energy

$$E_{min} = \gamma_t m_0 c^2$$ for particle mass m_0

and maximum emission angle $\theta_{max} = \cos^{-1}(1/n)$



Huygens construction of the Cherenkov wavefront

Photon production rate over the particle track (between wavelengths [λ_1,λ_2], α = fine structure constant):

$$\frac{dN}{dl} = 2\pi\alpha \int \left\{1 - \left(\frac{1}{n\beta}\right)^2\right\} \frac{d\lambda}{\lambda} = 2\pi\alpha \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) \cdot \sin^2\theta \quad \text{photons m}^{-1}$$

Time dispersion depends only on dispersion of refractive index with wavelength and distance from track $\Rightarrow$ sub-ns

Cherenkov Emission in Atmosphere

Ideal isothermal atmosphere profile:

$$x_v = x_o e^{-h/h_o}$$

where

x_o , *atmospheric depth at sea level,* $\simeq 1033\ \mathrm{g\,cm^{-2}}$

and h_o , *scale height,* $= \dfrac{mg}{RT} = 7.1\ \mathrm{km}$

and with the density relation $\rho = -dx_v / dh$

Let η be the reduced refractive index $n = 1 + \eta$

then the reduced refractive index versus depth is

$$\eta = \eta_o e^{-h/h_o} \quad \text{where } \eta_o = 2.9 \times 10^{-4}$$

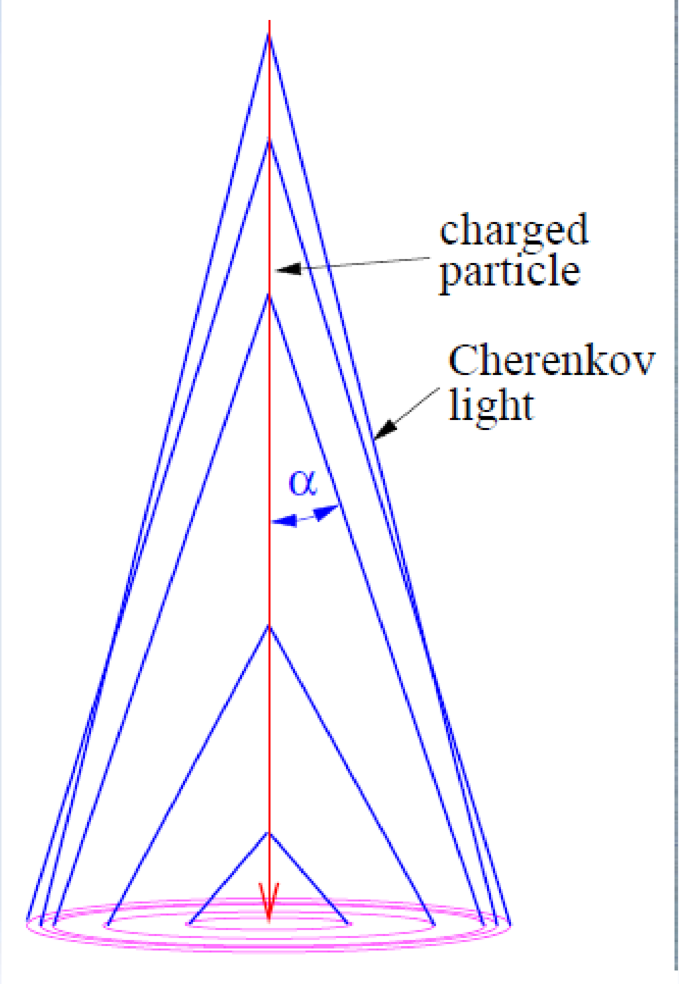
so in the atmosphere the following relations apply

$$E_{\min} \cong m_o c^2 / \sqrt{2\eta} \qquad \theta_{\max} \cong \sqrt{2\eta} \text{ radians}$$

(where $\eta \ll 1$)

e.g. Cherenkov angle is 1.3° a.s.l. decreasing with altitude
for $e^{\pm}$, threshold energy is 21 MeV at sea level,
or 35 MeV @ 7.5km a.s.l.
For μ, threshold is 4.4 GeV

Photon production rate over the particle track
(between wavelengths $[\lambda_1, \lambda_2]$, α = fine structure constant):



Cherenkov Emission in Atmosphere (II)

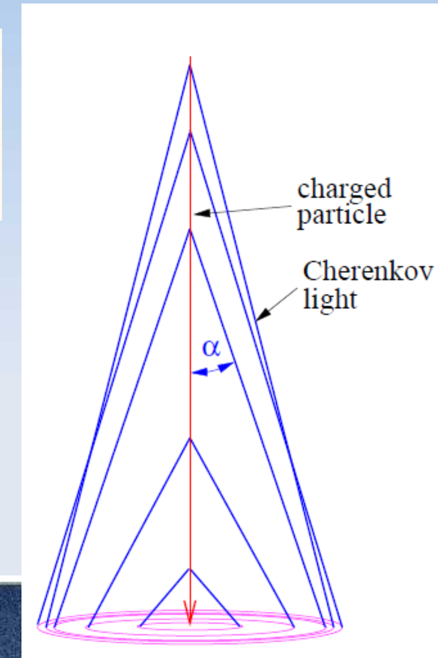
Photon production rate over the particle track in the atmosphere (between wavelengths $[\lambda_1,\lambda_2]$, α = fine structure constant):

$$\frac{dN}{dx_{v\,(max)}} = 4\pi\alpha\frac{h_o\eta_o}{x_o}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right) = 1.83\times10^{-4}\cdot\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\ \text{photons}/\text{g.cm}^{-2}$$

giving a rate of photons between 300-660 nm of

$$\sim 3\times10^5\cdot\eta\ \text{photons/m}\ \text{ or }\ 600\ \text{photons/g.cm}^{-2}$$

For a particle at height *h* km, emitting at the Cherenkov maximum angle a circle is produced at ground level with radius: $r = \sqrt{2\eta_o}\cdot h e^{-h/h_o}$

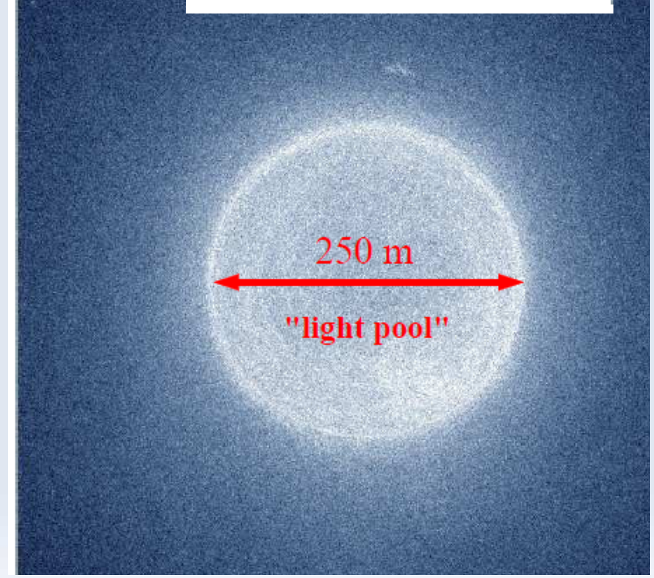


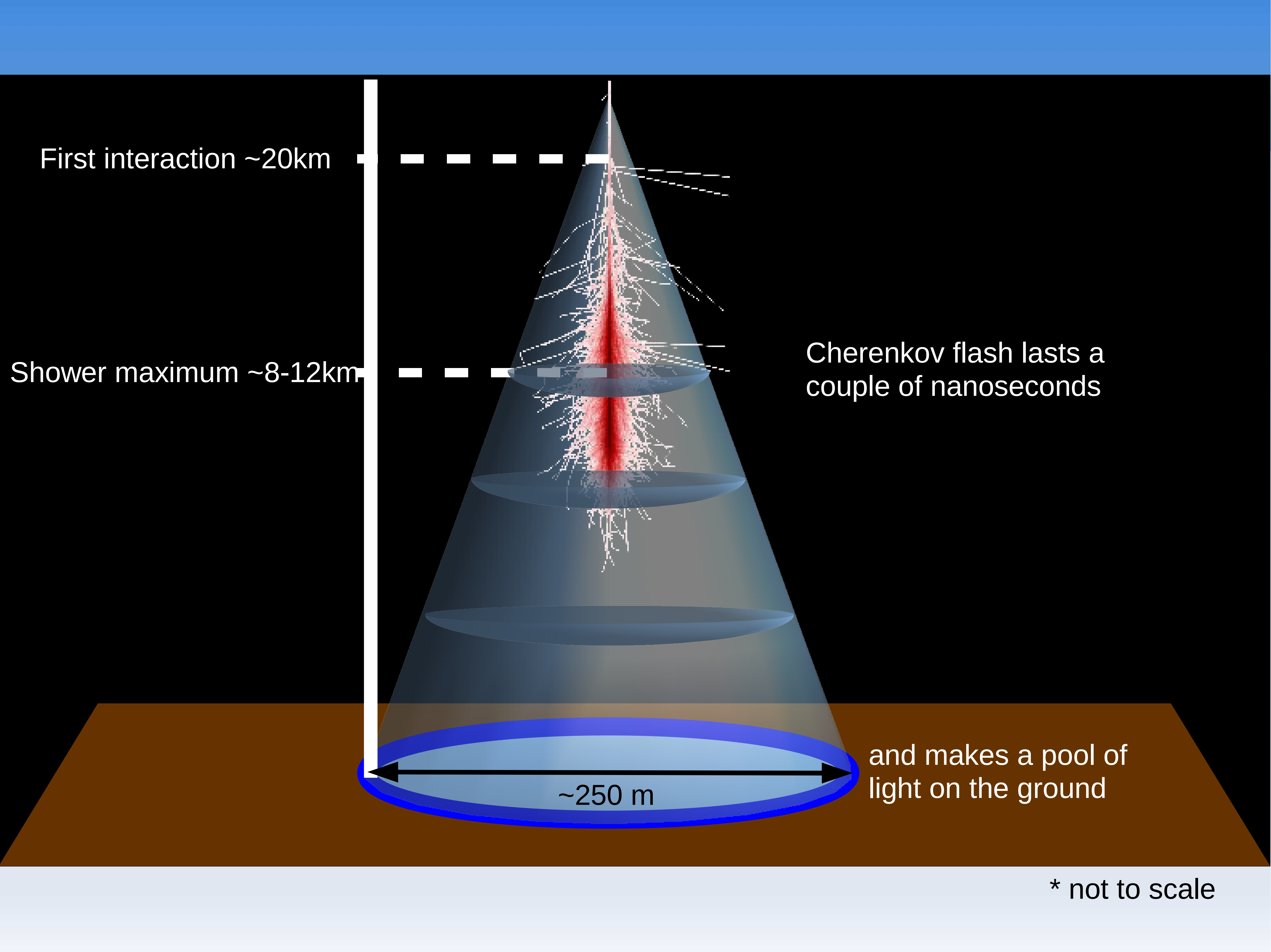
Note the focussing effect, due to competition between decreasing radius and increasing Cherenkov angle with decreasing height, so r_{max} = 126 m for $h_{max} = 2h_0$

⇒ creation of "**light-pool**" at ground level,

Effect persists for E-M shower with many particles,
⇒ **effective detection area >5 x 10^4 m^2**

Dispersion in time due to time-dispersion of particles in shower, **~3 ns** "Cherenkov pancake" width

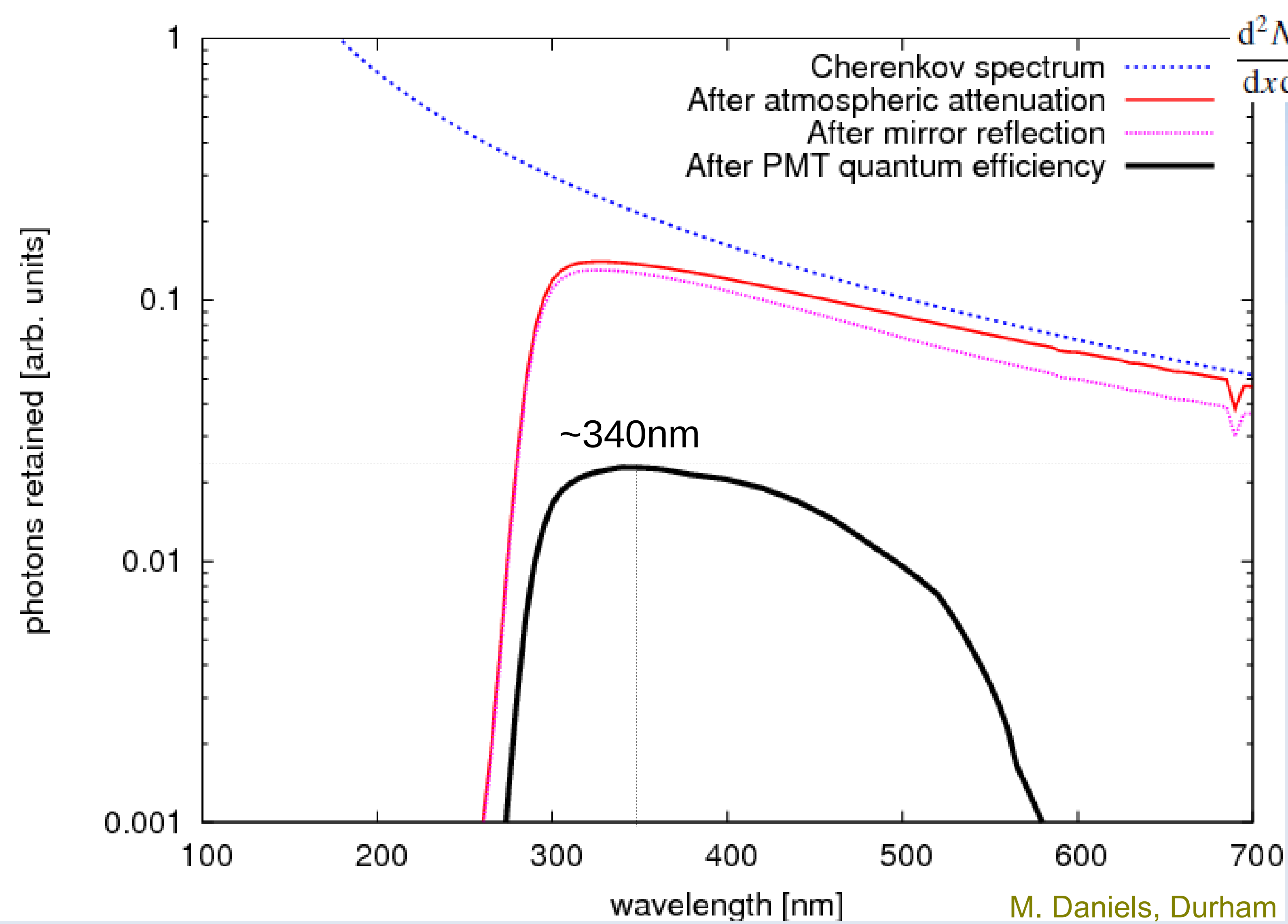



First interaction ~20km
Shower maximum ~8-12km
Cherenkov flash lasts a couple of nanoseconds
and makes a pool of light on the ground
~250 m
* not to scale

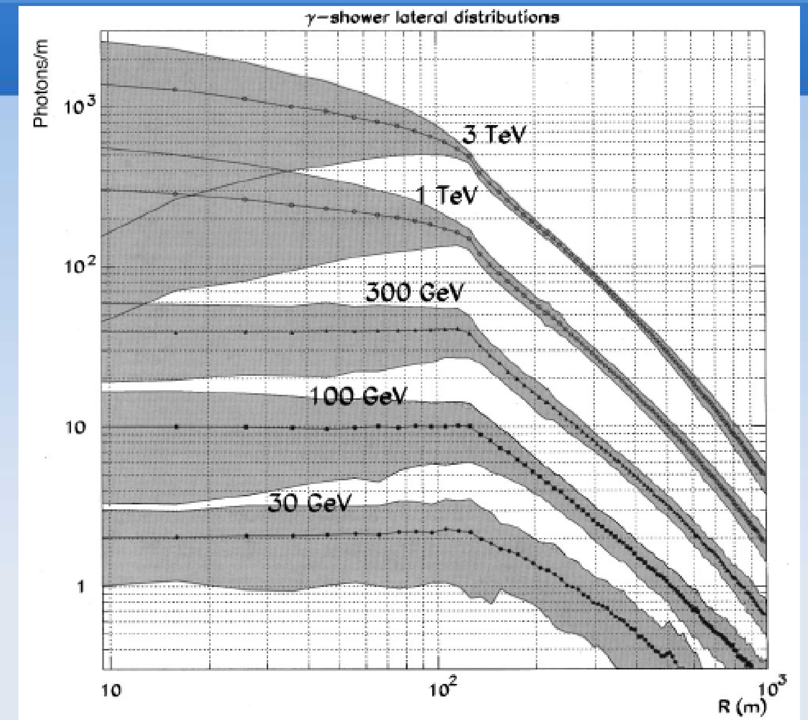
Modification of Cherenkov spectrum in Atmosphere

Spectrum of Cherenkov light

$$\frac{d^2 N_{ph}}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\sin^2(\theta_c)$$



Implications for Cherenkov detection



E-M shower gives light-pool, with
quasi-calorimetric photon density versus E_γ within pool

e.g. **S ~10 photons/m²** for a 100 GeV γ-ray

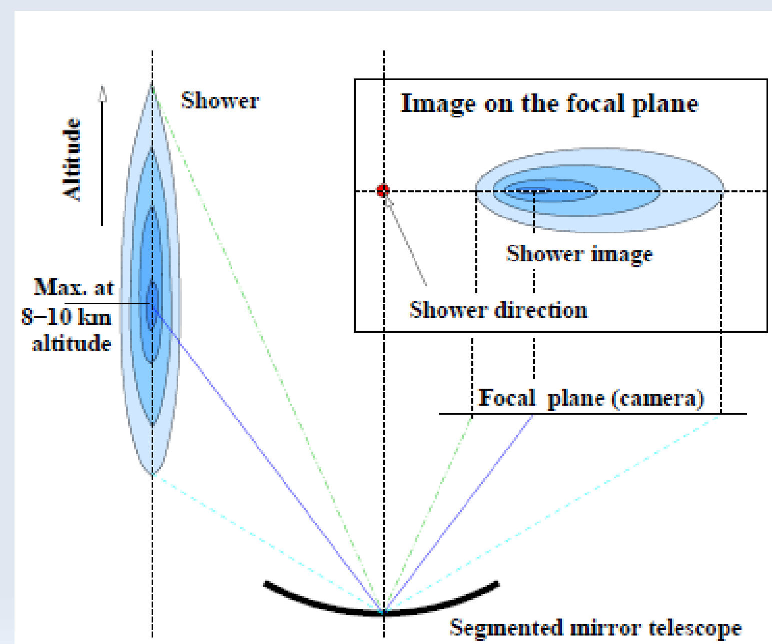
⇒ need large mirror collection area, **A**

Light pulse is short, ~ few ns, so can reduce noise
from night-sky background **B** by
limiting the integration time **τ**
(down to minimum of pulse width)

The EAS appears as an illuminated baton,
so can limit background
by reducing the angular area of integration **Ω**
(down to minimum of shower image size, 0.1-0.2°)

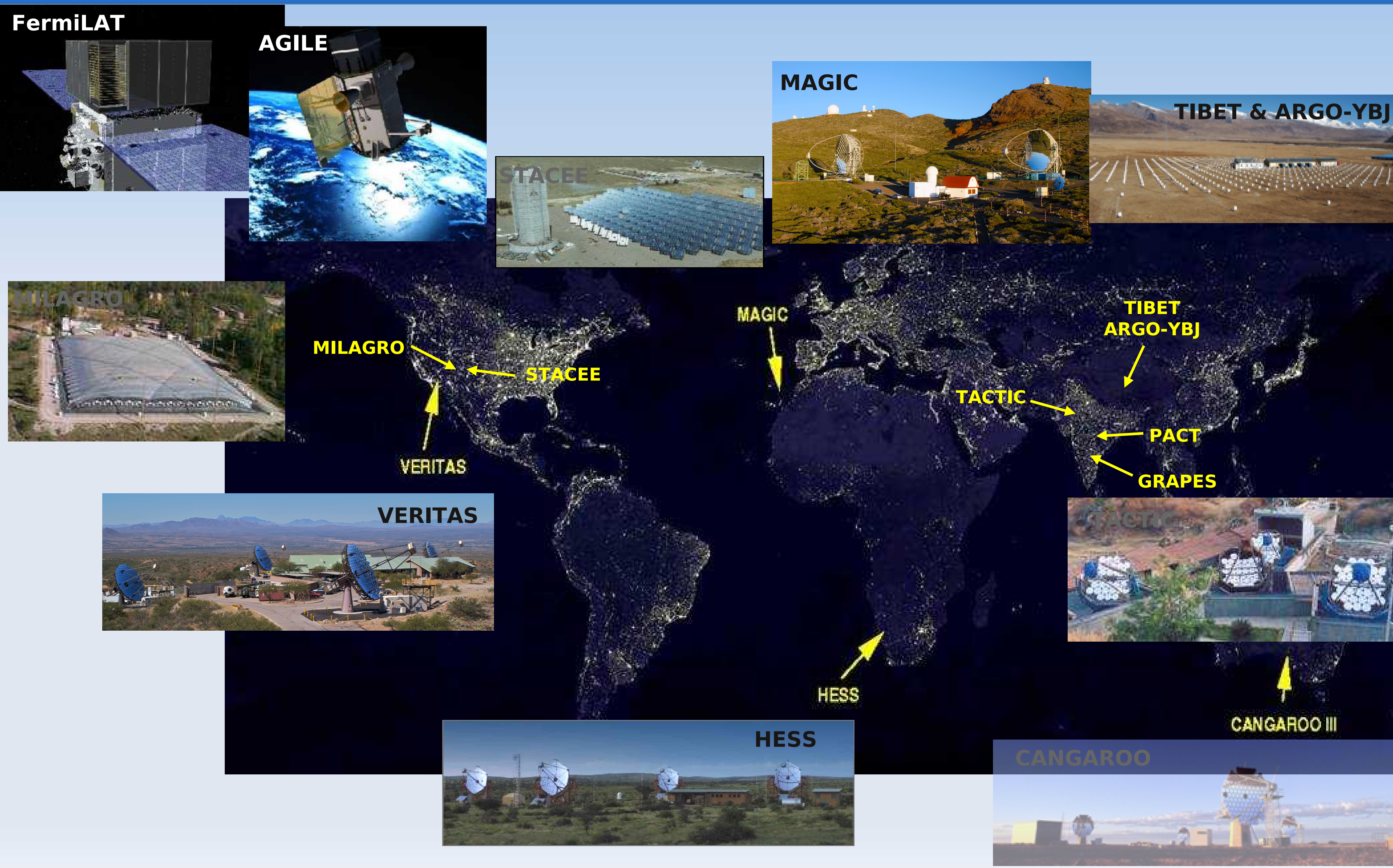
So, try to optimize the following relation:

$$\frac{S}{\sqrt{B}} \propto \sqrt{\frac{A}{\tau\Omega}}.$$



L'historique de la Technique Cherenkov

The Gamma-ray World



ACT Development over years

TeV Sources

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Lebedev, Glencullen, Whipple, Narrabri, Crimea

Zero

New Technology

- Second Generation Systems 1985 – 2004
  - Atmospheric Cherenkov Imaging Telescopes
  - Whipple, Crimea, CAT, HEGRA, Durham, CANGAROO

  ……

~ 12

Increase in Scale

- Third Generation Systems 2004 – 2010
  - Arrays of Large IACTs
  - MAGIC-2, HESS-5, VERITAS-4

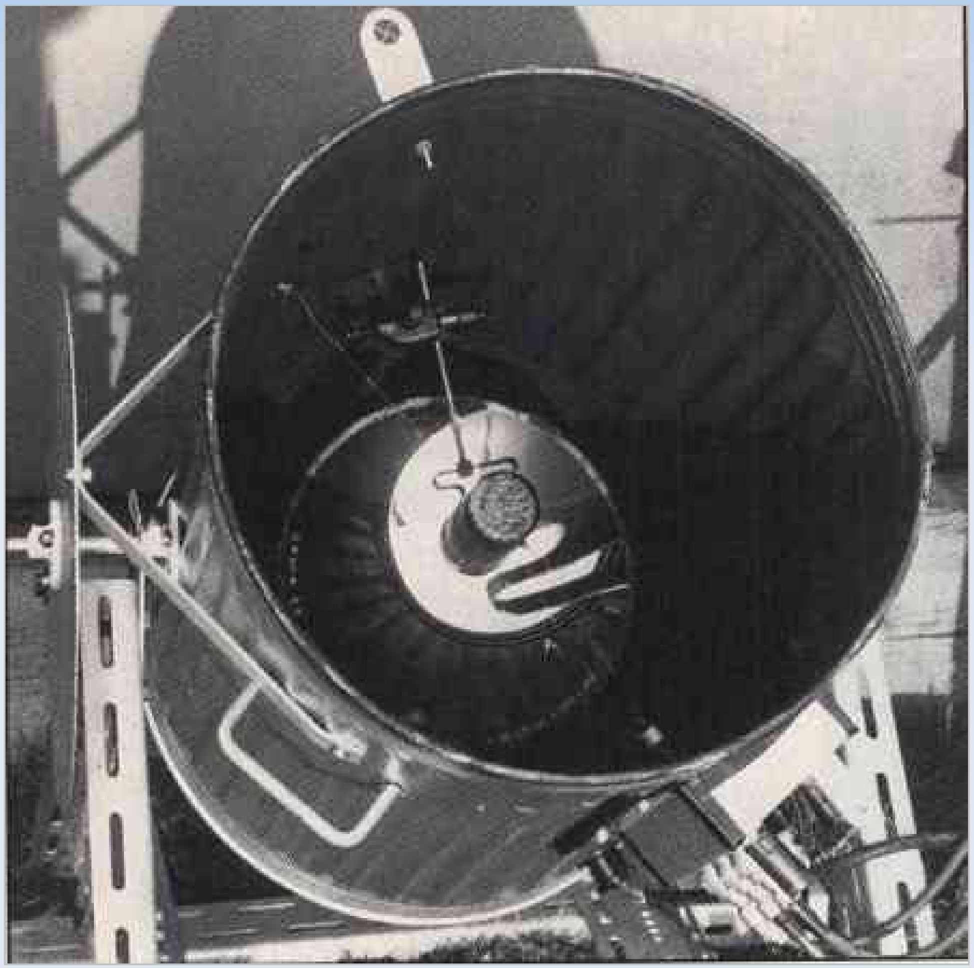
> 100

- Fourth Generation Systems 2010 -
  - TBD

1000?

The early days

Source:
T. Weekes



Galbraith and Jelley, 1953

February 21, 1953 NATURE

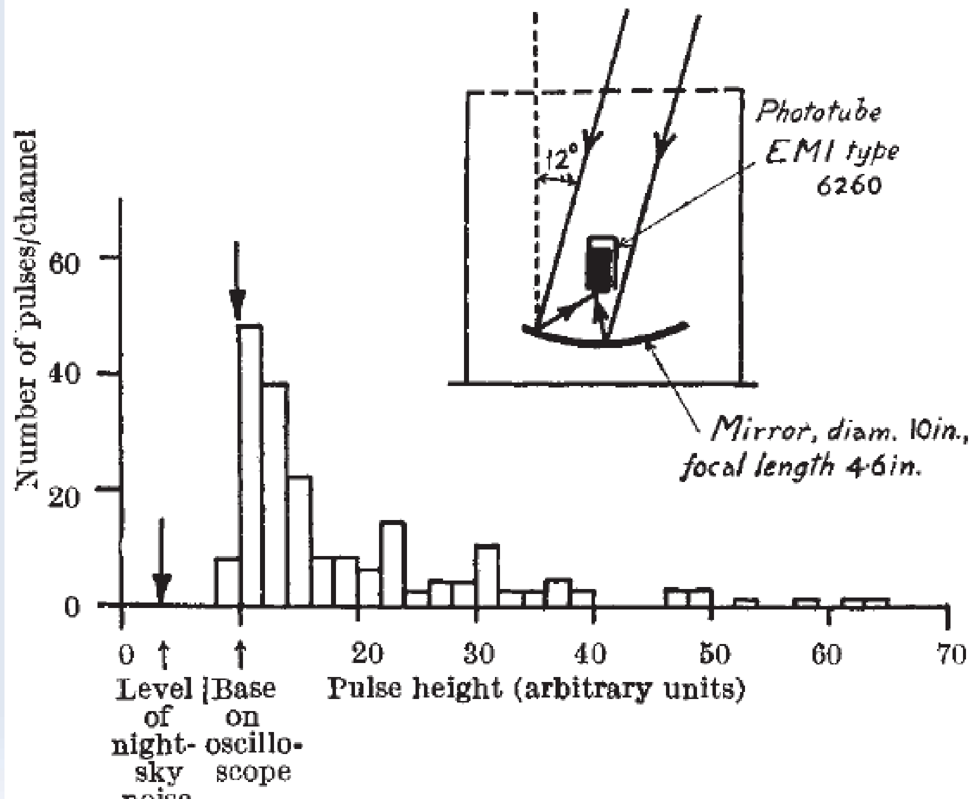
Light Pulses from the Night Sky associated with Cosmic Rays

In 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

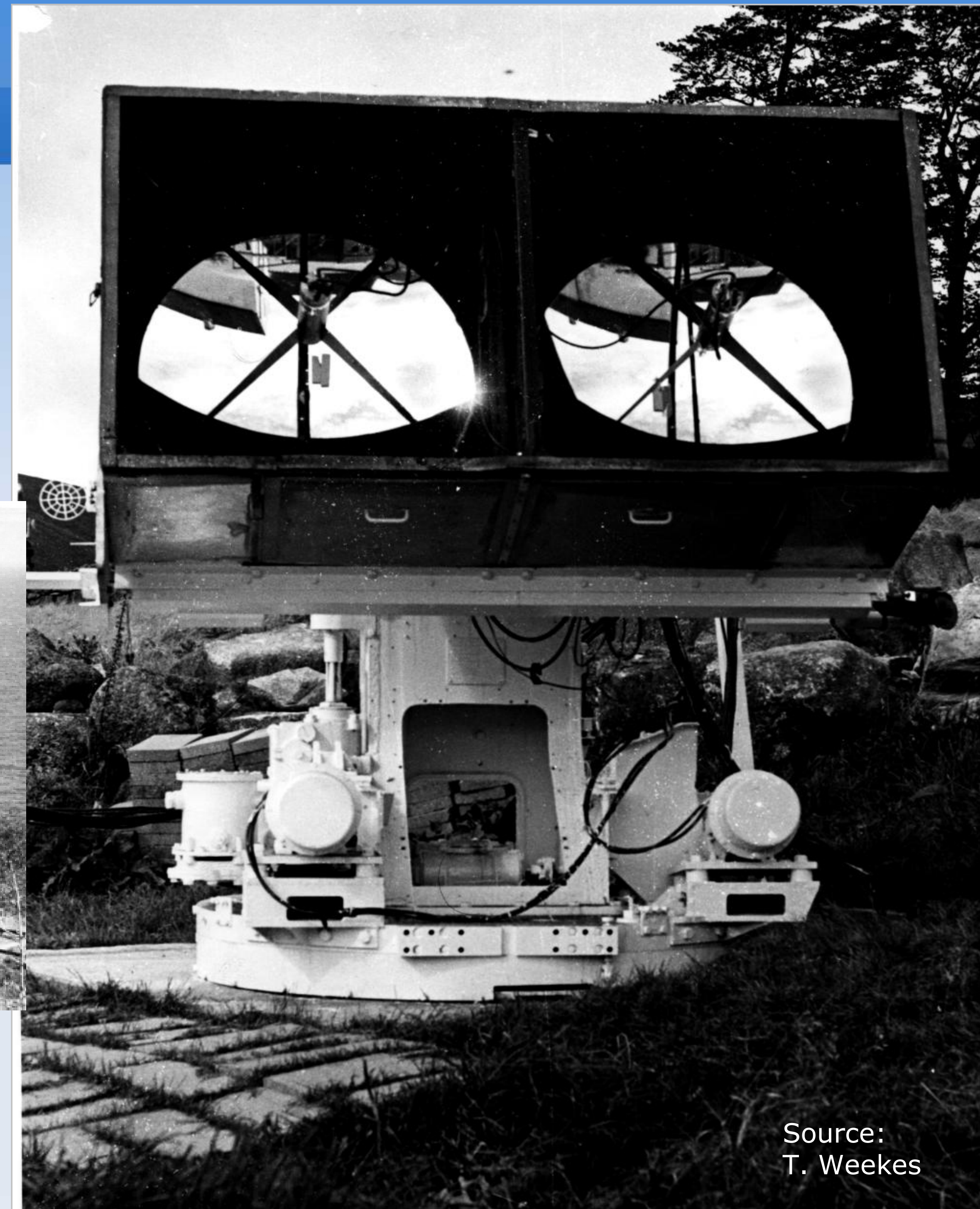
. . . .

thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. Galbraith
J. V. Jelley



Porter & Jelley
1962

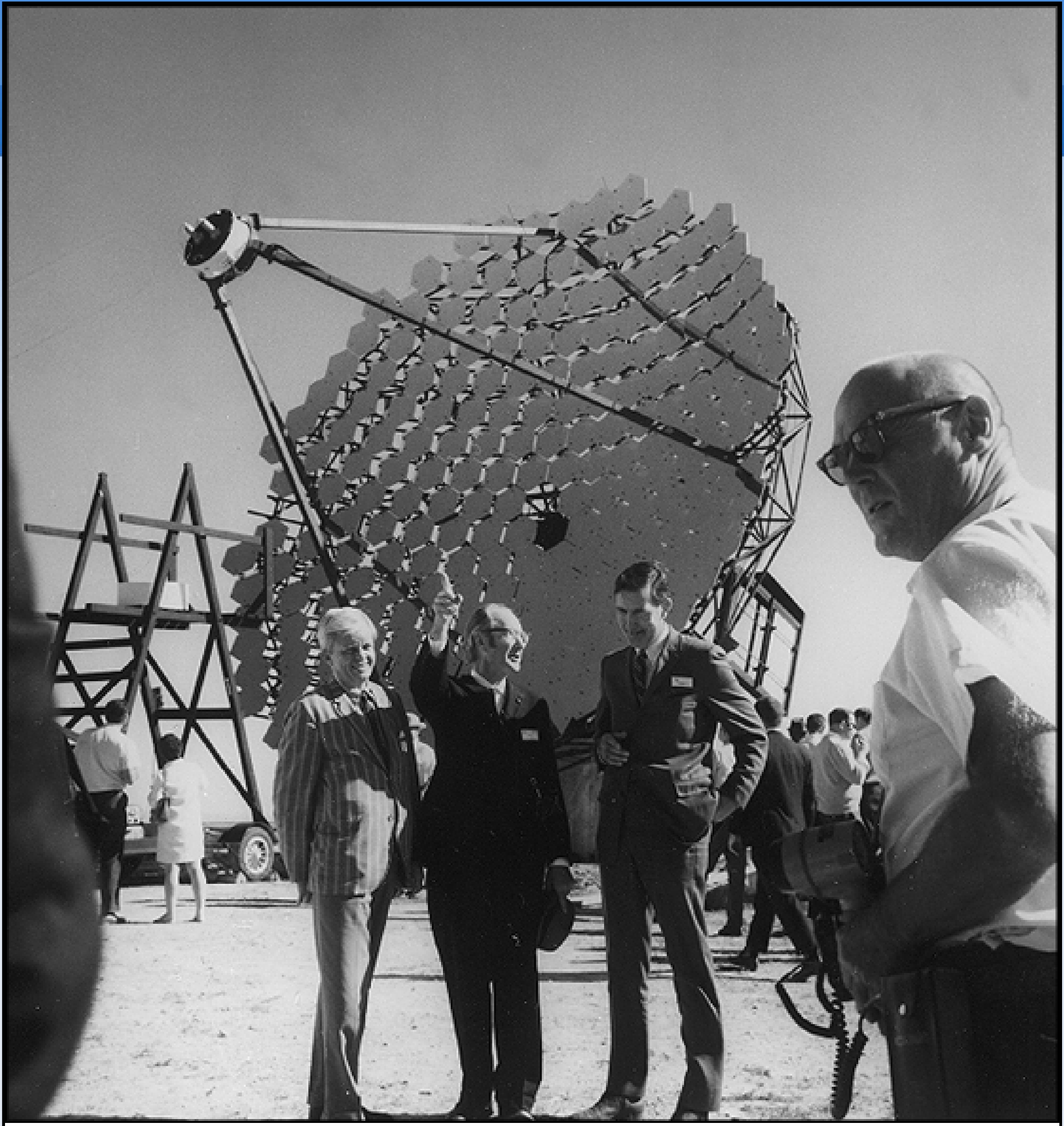


Chudakov,
early 1960's

Whipple 1968

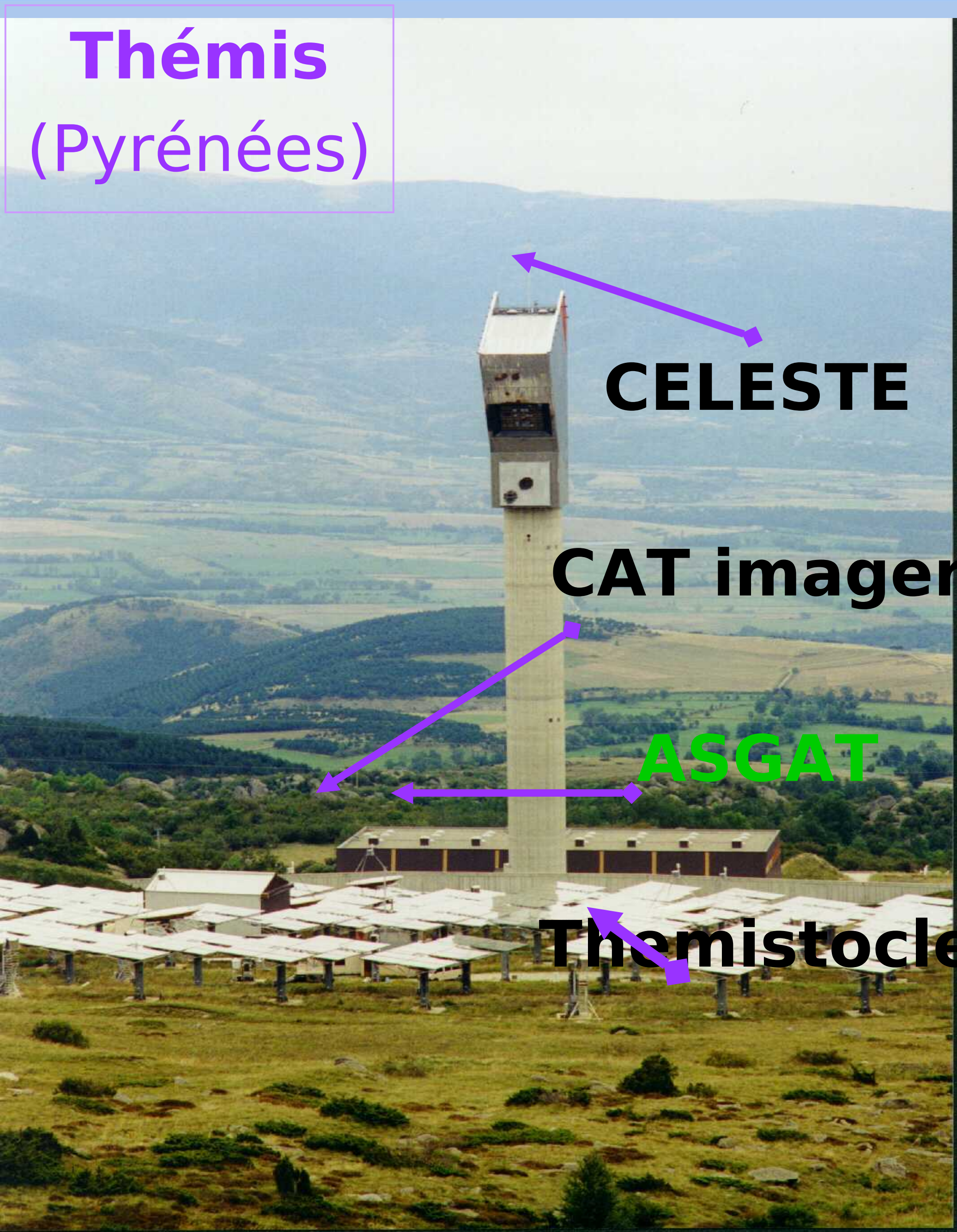
Detection of
the Crab Nebula
1989:

50 h observation
time for 5σ signal



L'historique de la Technique Cherenkov … les explorations infructueuses

CELESTE Wavefront Sampling

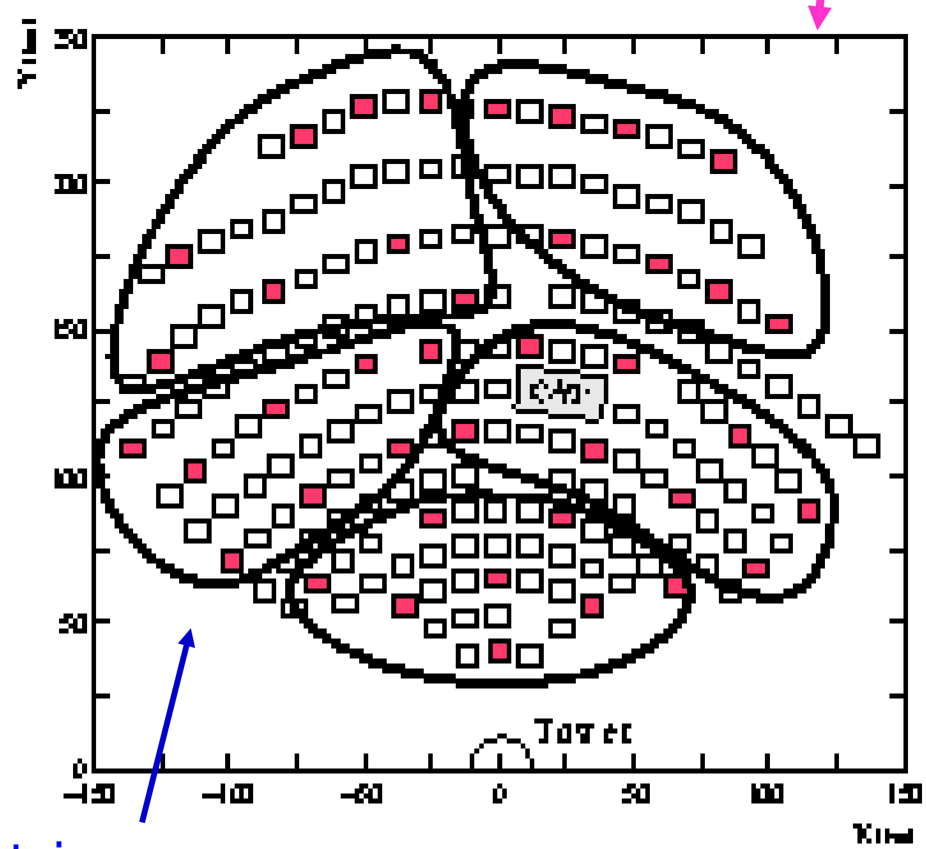


40 heliostats from 1999.

Trigger threshold: 30 GeV

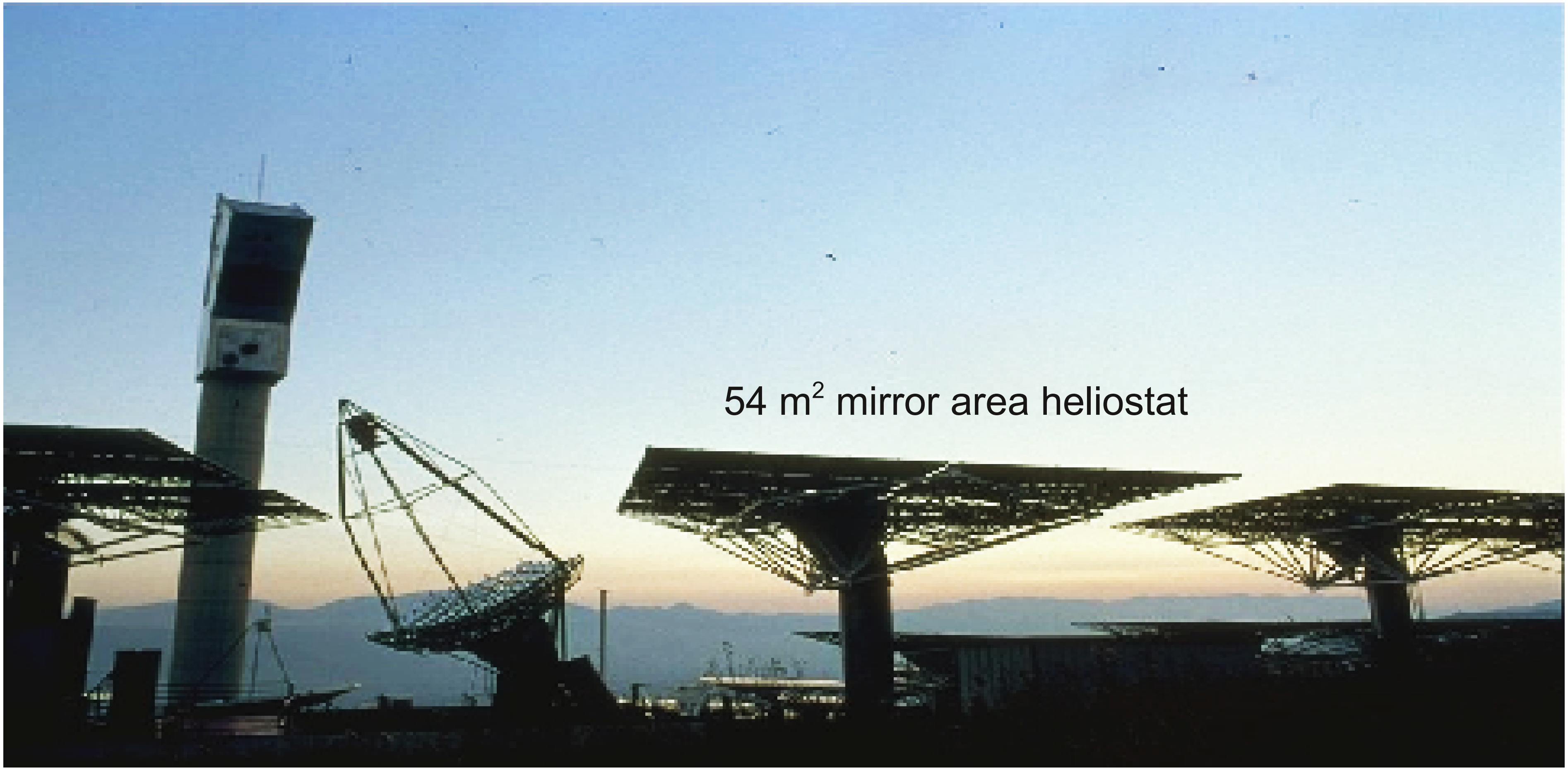
Analysis threshold: 50 GeV (at transit)

53 heliostats in final operation.

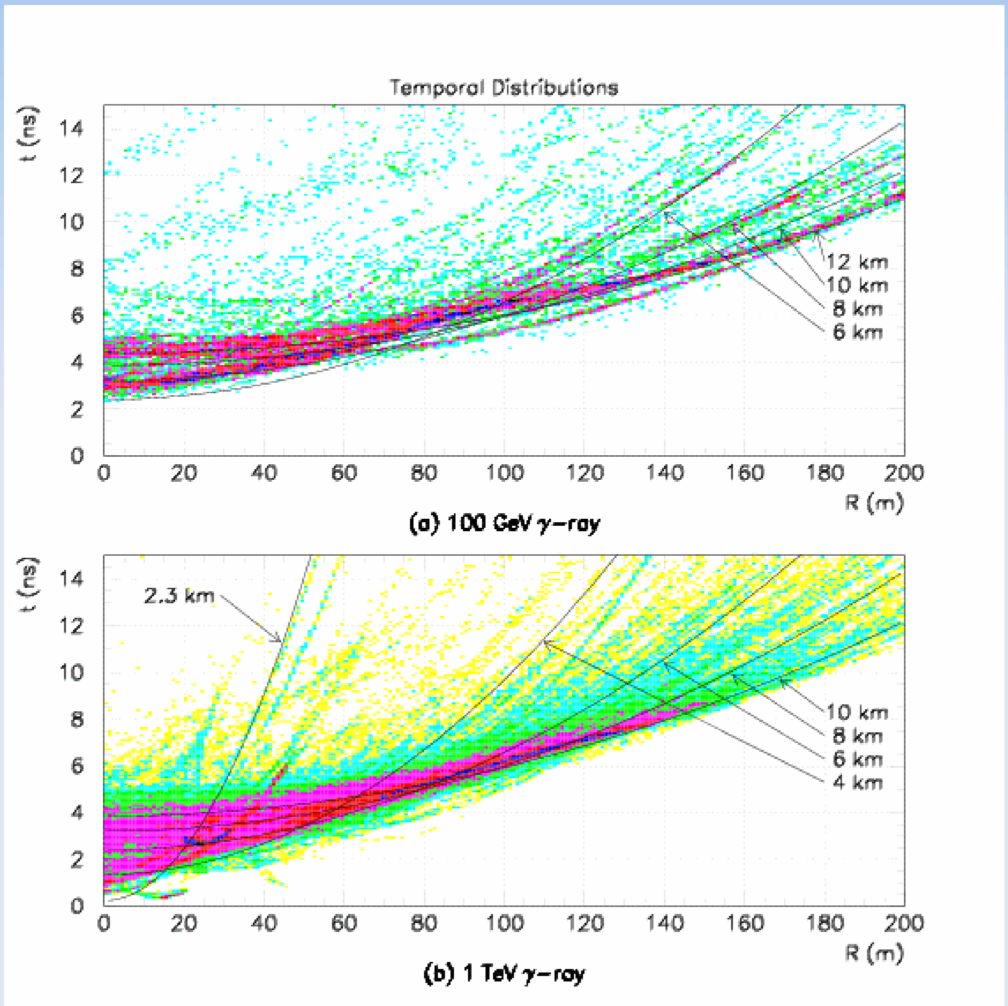


CELESTE at Thémis

Celeste wavefront sampler, detection from 50 GeV
(but difficult background rejection)
… with CAT imaging ACT in foreground



Wavefront sampling at Themis



CELESTE:

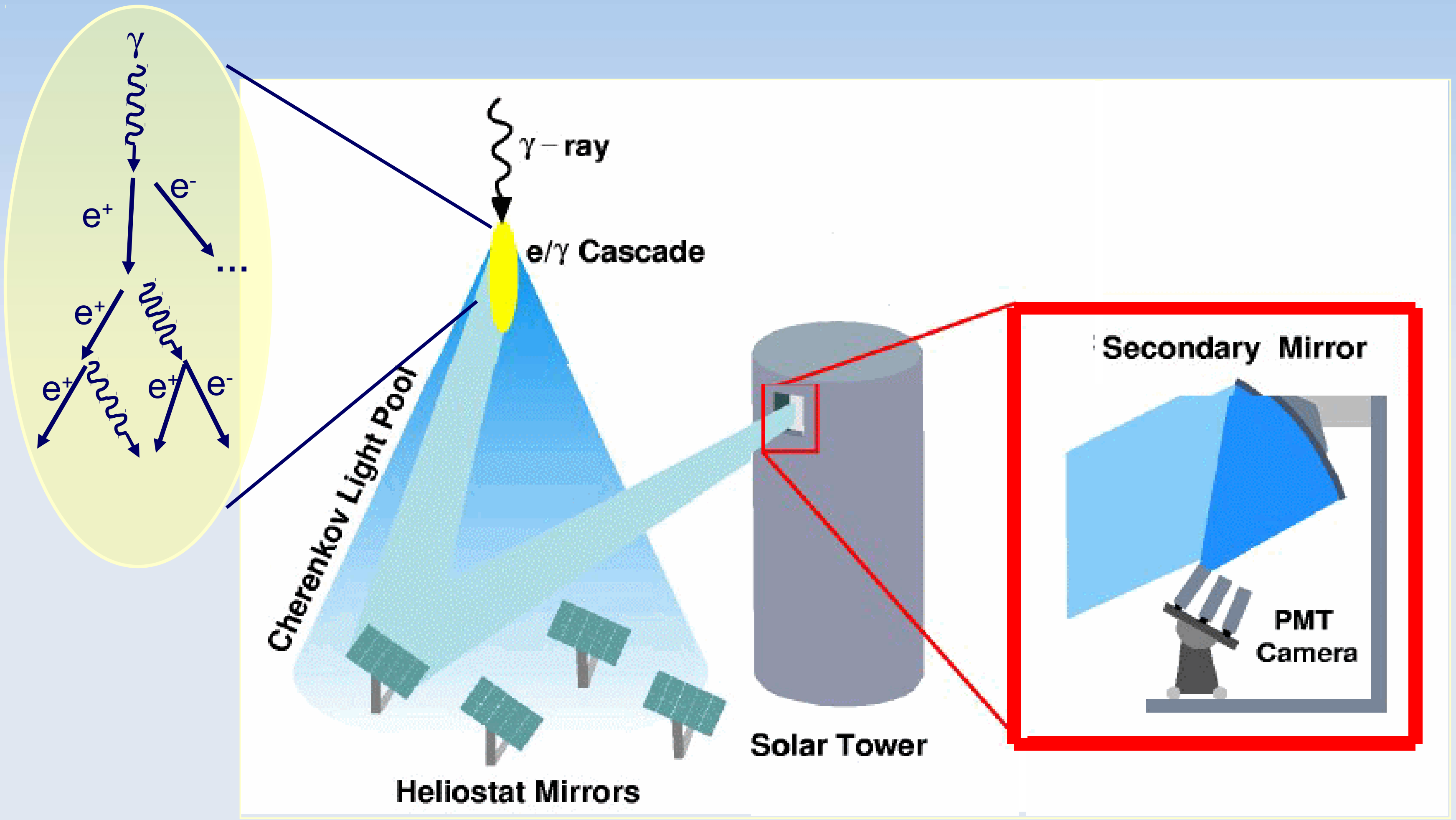
- 40-53 stations with ~30m separation
- 54 m^2 mirrors
- Threshold ~50 GeV
- Calibration by laser pulse from tower
- Spherical wave-front fit
- Timing resolution 0.25 ns

Thémistocle:

- 19 stations with ~80m separation
- 0.5m^2 mirrors
- Threshold 2 TeV
- Calibration by laser pulse from tower
- Conical wave-front fit
- Time Resolution 0.35ns

Wavefront Sampling Detectors

STACEE & CELESTE

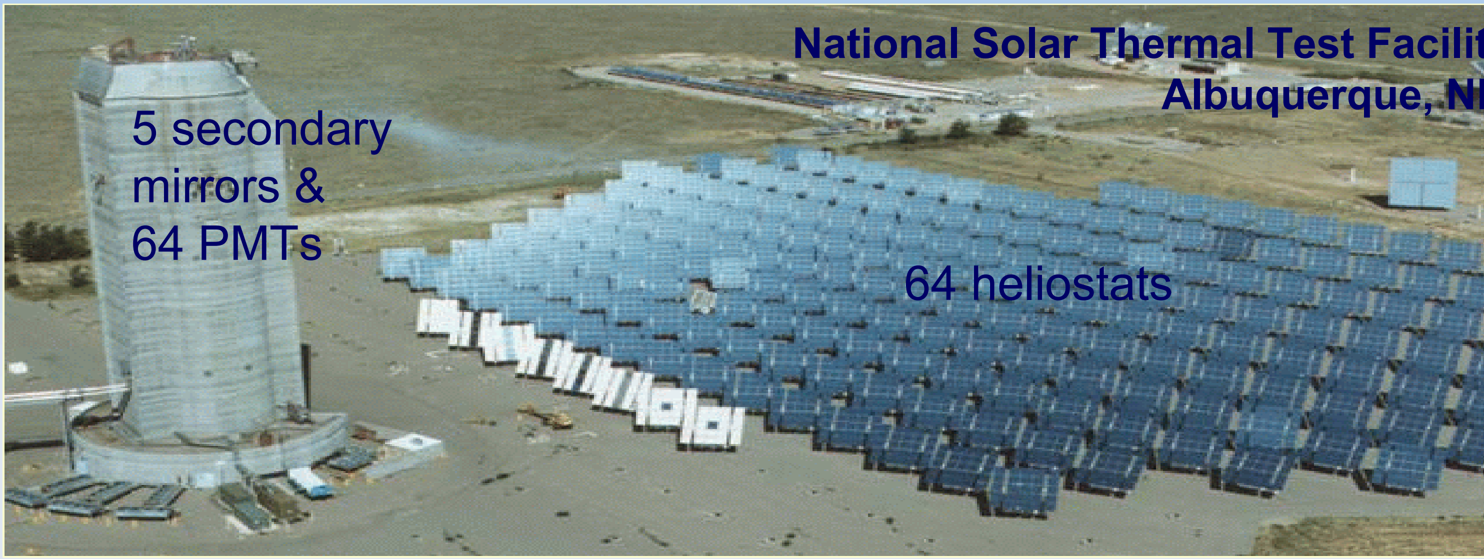


Cherenkov light intensity on ground → energy of gamma ray

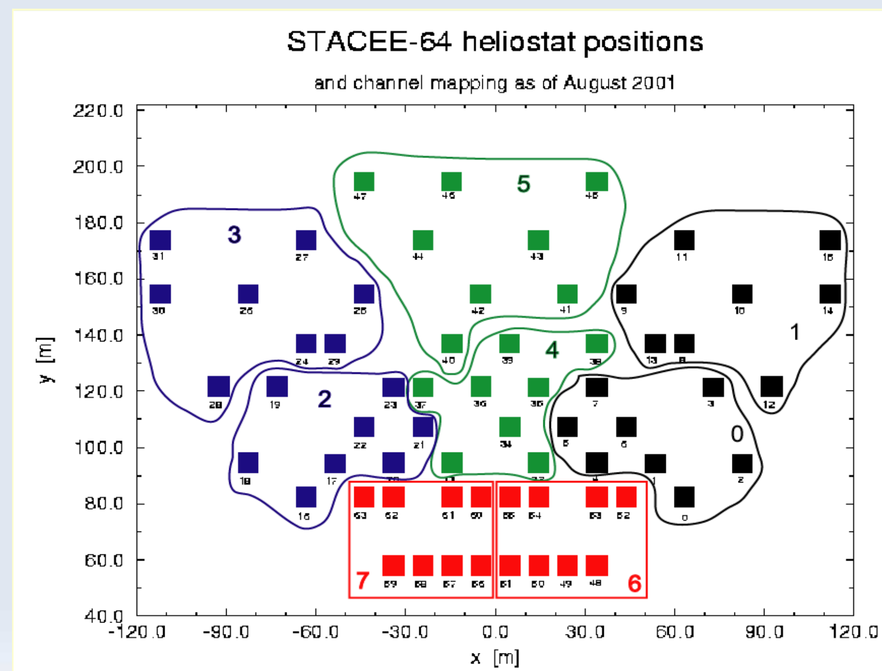
Cherenkov pulse arrival times at heliostats → direction of source

STACEE

Solar Tower Atmospheric Cherenkov Effect Experiment

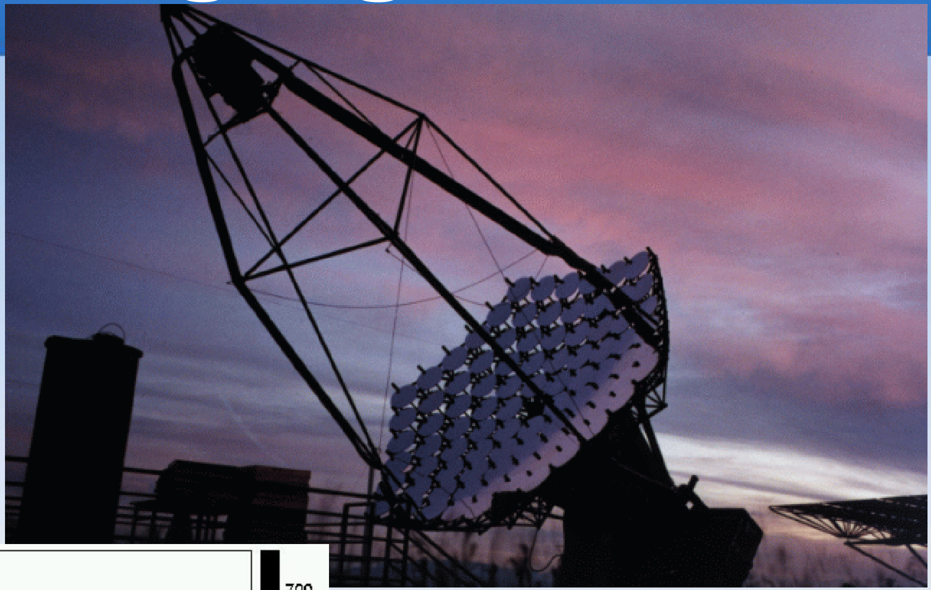


- PMT rate @ 4 PEs: ~10 MHz
- Two-level trigger system (24 ns window):
  - cluster: ~10 kHz
  - array: ~7 Hz
- 1-GHz FADCs digitize each Cherenkov pulse



L'historique de la Technique Cherenkov
… les bonnes pistes

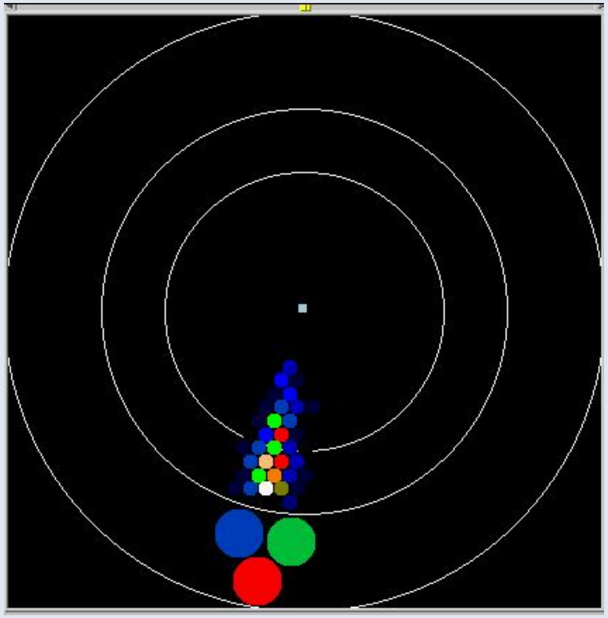
CAT fine-pixel imaging ACT



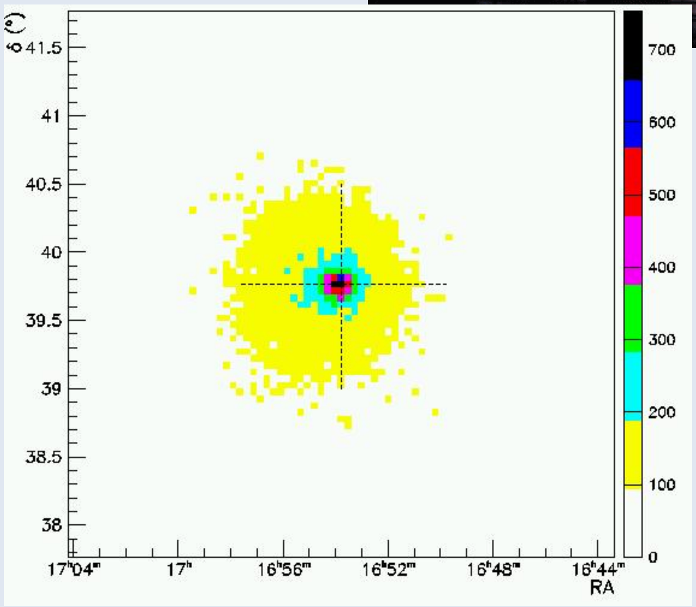
CAT

Thémis (French Pyrénées)

- first light summer 1996 – end operation ~2001
- Mirror area ~ $17.8 m^2$
- Fast electronics, 12 ns gate, ~3ns trigger
- fine-pixel camera : 600 pixels, 0.12° spacing min
- Threshold 250 GeV



One γ event (at rather high energy)



Mrk 501 one night flare (April 16 1997)

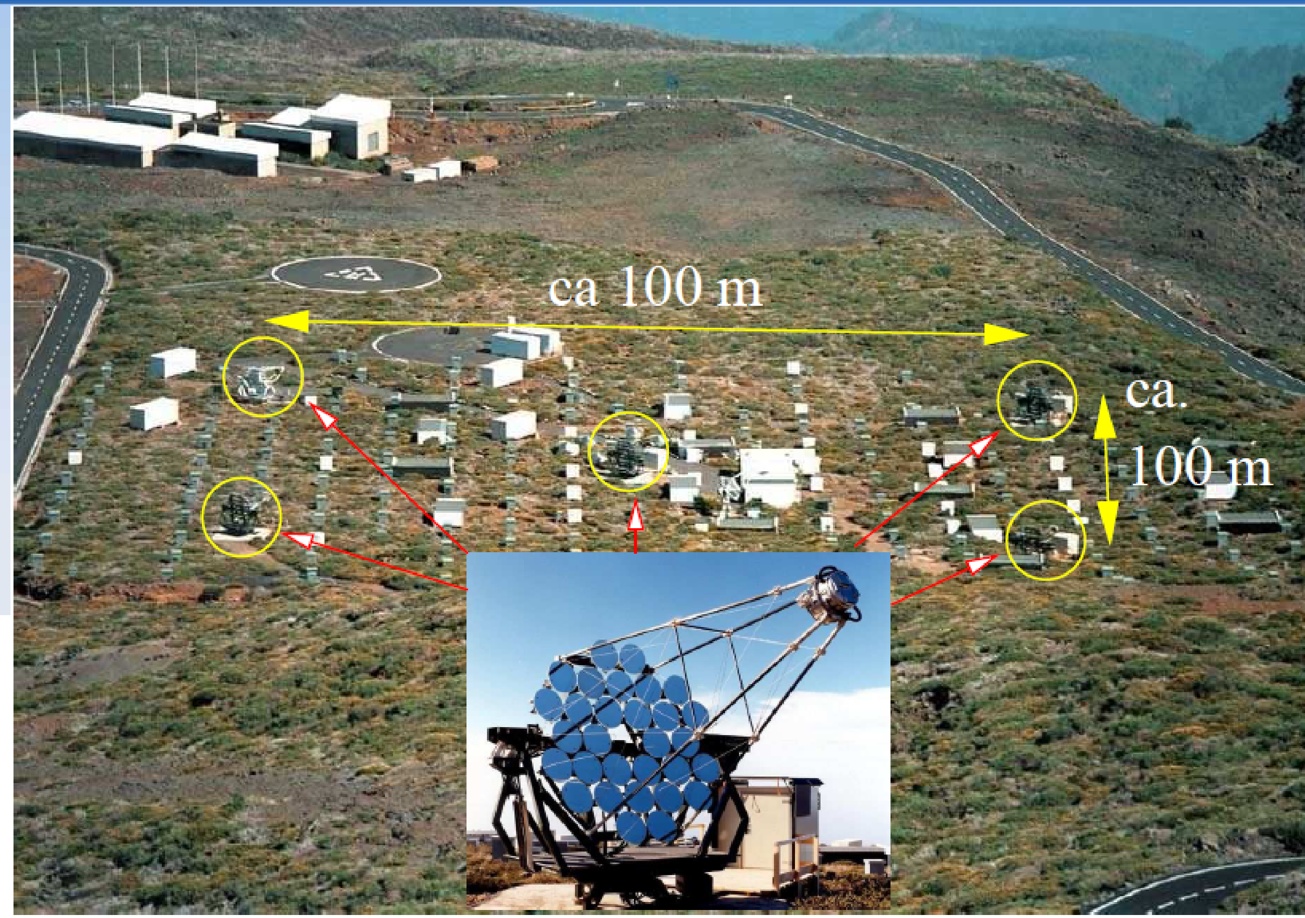
**With such a high resolution camera,
the angular origin of each individual event is computed from its image profile**

HEGRA stereoscopic system

HEGRA site at Canaries
co-located with HEGRA EAS array
and AEROBICC wavefront timing

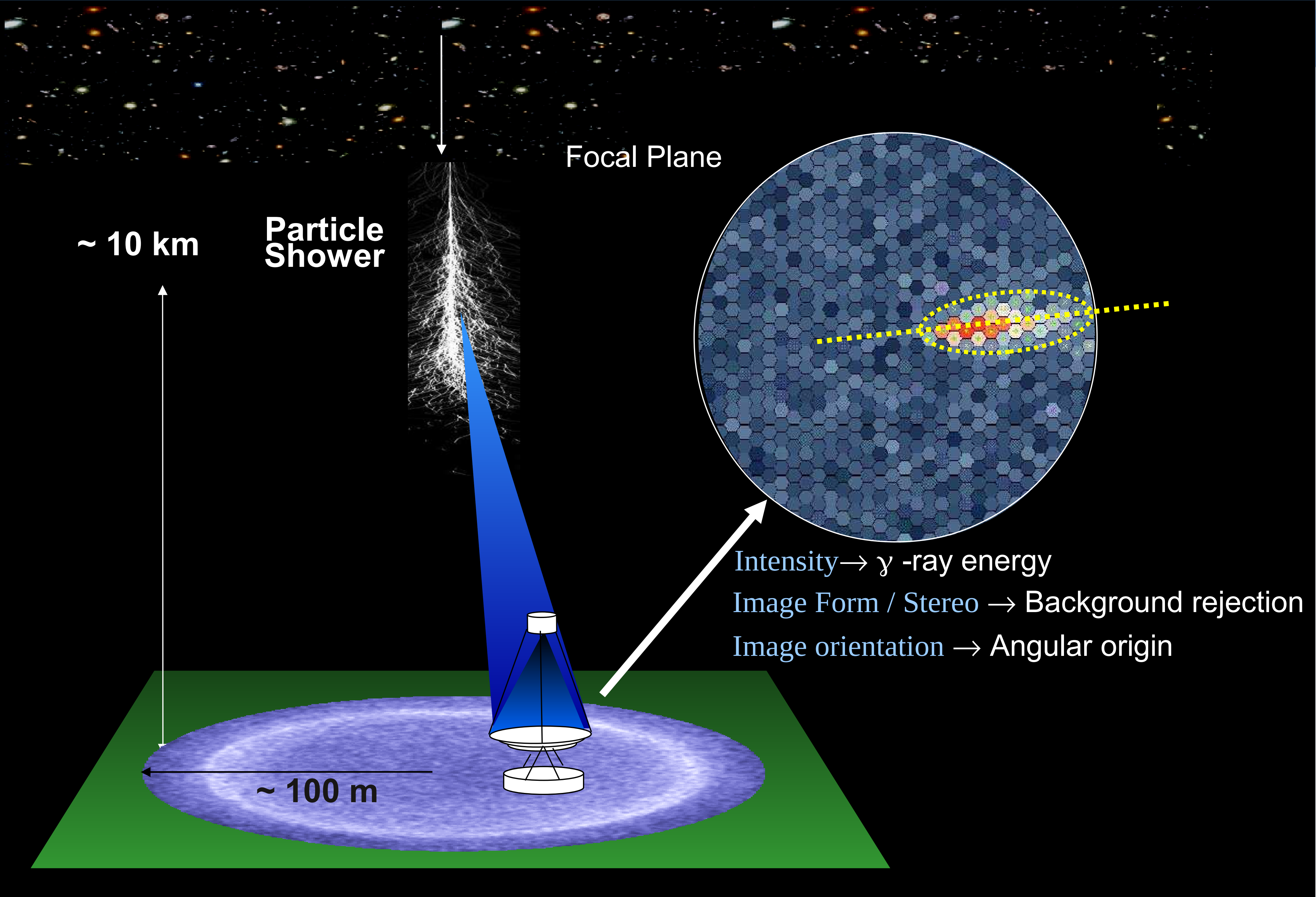
Stereoscopic System of 5 Telescopes:

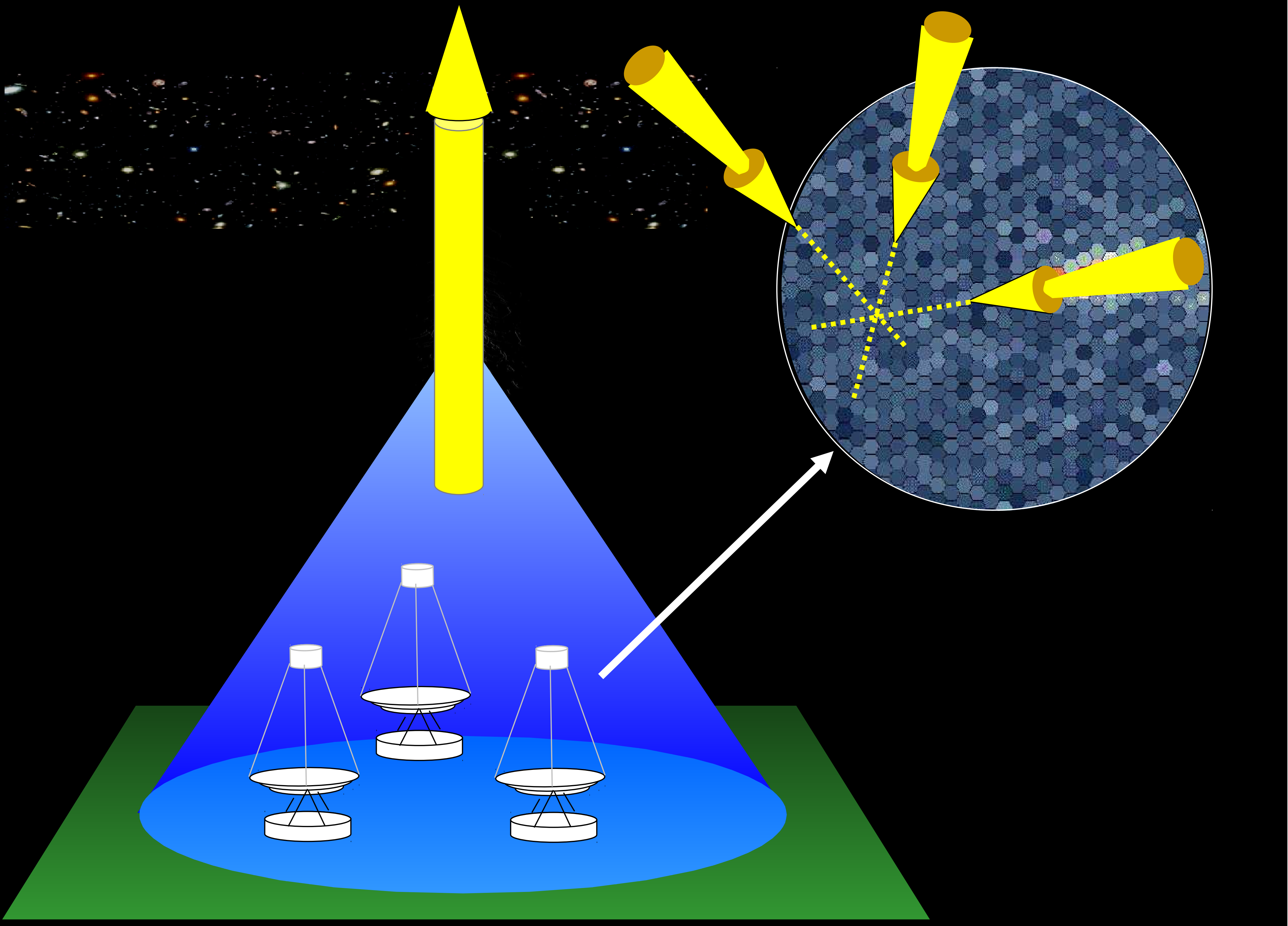
mirror area:	$8.5\,m^2$ each
field of view:	4.3° (271 pixels, 0.25° diam.)
energy threshold:	500 GeV
ang. resolution:	0.1°
energy resolution:	10 - 20 %
flux sensitivity:	Crab nebula $\longrightarrow$ $10\,\sigma$ within 1 h



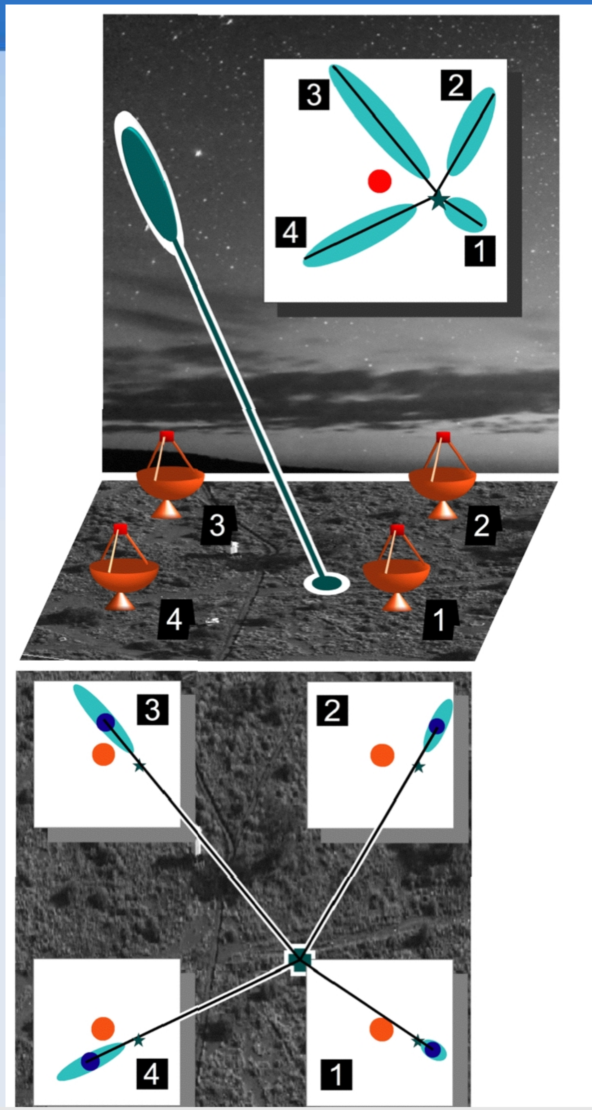
With stereoscopy,
the background rejection was greatly enhanced
and the events characterized better

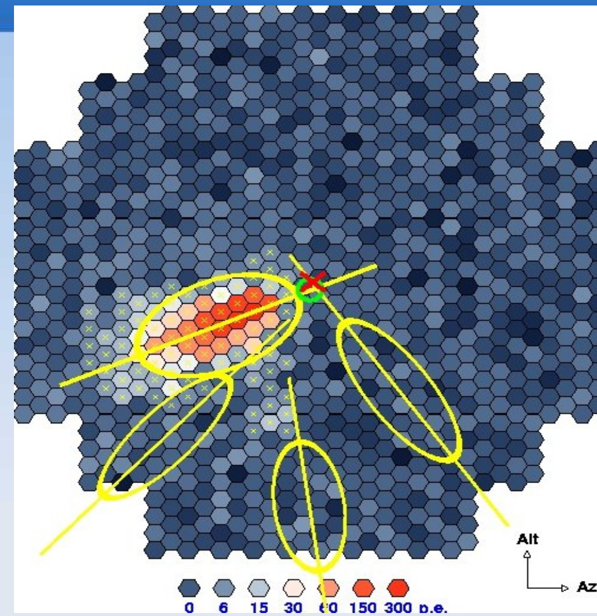
Cherenkov Imaging Technique

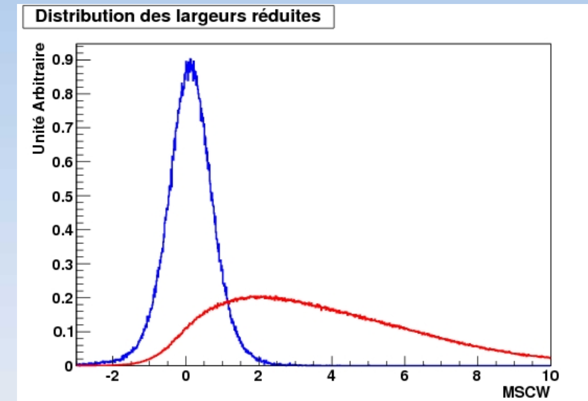


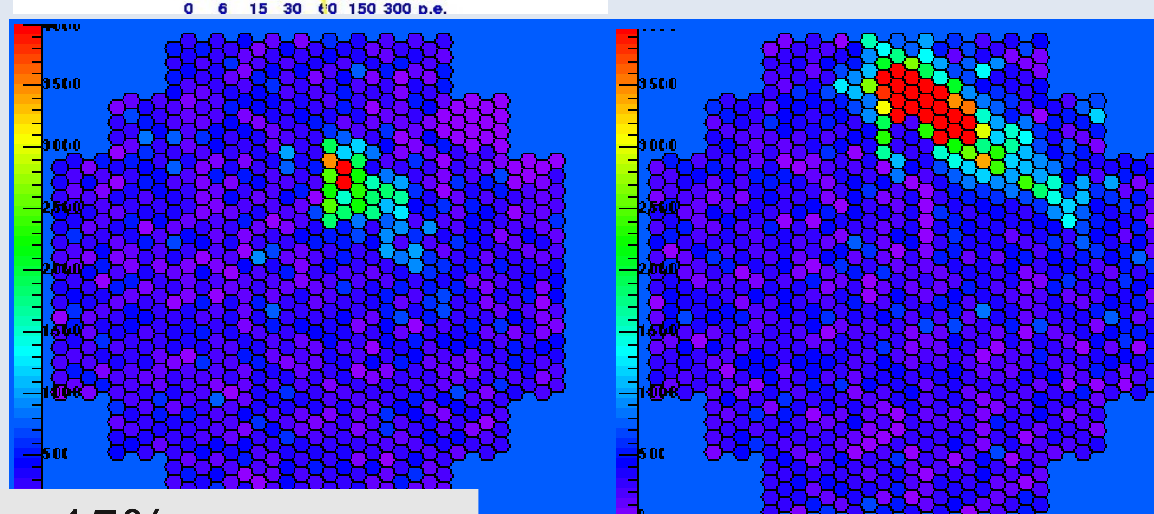


Stereoscopic Imaging (e.g. HESS)









Energy resolution	~ 15%
Angular resolution	~ 0.06° (5')
Background rejection	>99%
Sensitivity	~ 1% Crab in 25h

Les ACTs majeurs actuels

List of ACT & EAS installations (2008)

Experiment (site)	Location[a] altitude				Note
Imaging air Cherenkov telescope		N^b A^c	FoV[d] f^e	Imaging camera (No. × size) of pixel	Note
CANGAROO-III	31°S, 137°E	4	4°	427 × 0.17°	
(Woomera)	165 m	57 m^2	$f/0.8$		One telescope has smaller FoV of 2.7°
HESS	23°S, 17°E	4	5°	960 × 0.16°	
(Namibia)	1800 m	107 m^2	$f/1.25$		
MAGIC	28°N, 19°W	1	3–4°	397 × 0.1° + 180 × 0.2°	
(La Palma)	2230 m	226 m^2	$f/1$		Camera of two different pixel sizes
SHALON	43°N, 77°E	1	8°	144 × 0.6°	
(Tien Shan)	3338 m	11.2 m^2	$f/?$		
TACTIC	25°N, 73°E	1 + (3)	6°	349 × 0.3°	
(Mt Abu)	1300 m	9.5 m^2	$f/1.1$		3 more telescopes with 29 pixel camera
VERITAS	32°N, 111°W	4	3.5°	499 × 0.15°	Site may change
(Mt Hopkins)	1275 m	106 m^2	$f/1$		
Whipple	32°N, 111°W	1	2.9°	379 × 0.125°	
(Mt Hopkins)	2250 m	78 m^2	$f/0.75$		Pixel size has varied with time
Future Cherenkov instruments under construction					Camera/note
GAW	37°N, 3°W	3	24°		400 × 400 channel multi-anode PMT
(Calar Alto)	2150 m	2.13 $m\phi$			Refraction optics of Fresnel lens used
HESS-II	23°S, 17°E	(4)+1	3.2°	2048 × 0.7°	The new telescope
(Namibia)	1800 m	615 m^2	f/1.3		added to the existing HESS array
MAGIC-II	28°N, 19°W	2	$f/1$		Photo detector of quantum efficiency
(La Palma)	2250 m	226 m^2			~50% is to be used as camera
MACE	33°N, 79°E	2	4°	576 × 0.1° + 256 × 0.2°	
(Hanle)	4200 m	340 m^2	$f/1.2$		Concept similar to MAGIC is adopted
HAGAR	33°N, 79°E	7 × 4.4 m^2	$f/1.0$		Each telescope has seven mirrors of 90 $cm\phi$
(Hanle)	4200 m				Seven non-imaging telescopes with 50 m separation

From
Aharonian, Buckley, Kifune, Sinnis
Rep. Progr. Phys.71 (2008) 096901

Experiment (site)	Location[a] atm. depth	Array area (m^2)	N^b	μ^c (m^2)	Event rate (s^{-1})	Operation
CASA-MIA	40.2°N, 112.8°W	230 400	1089	2500	20	1991–1996
(Dugway, Utah)	870 g cm^{-2}					
CYGNUS	35.9°N, 106.3°W	86 000	204	120	5	1986–1996
(Los Alamos, NM)	800 g cm^{-2}					
Milagro	35.9°N, 106.7°W	40 000	898[d]	2400	1700	2000–present
(Jemez Mtns, NM)	750 g cm^{-2}					
ASγ	30.1°N, 90.5°E	53 000	497	NA	700	1990–present[e]
(YangBaJing, Tibet)	600 g cm^{-2}					
ARGO	30.1°N, 90.5°E	11 000	1848[f]	NA	2000	2007–present
(YangBaJing, Tibet)	600 g cm^{-2}					

Refined lists for ACTs (2008/2010)

Observatory	Elevation (km)	Telescopes #	Mirror Area (m^2)	FoV (degrees)	First Light	Threshold (GeV)	Sensitivity (%Crab)
H.E.S.S.	1.8	4	428	5	2003	100	0.7
VERITAS	1.3	4	424	3.5	2007	100	1
MAGIC	2.2	1	236	3.5	2005	50	1.6
HAGAR	4.3	7	31	3	2008	60	9
Whipple	2.3	1	75	2.2	1985	400	10
CANGAROO III	0.1	3(4)	172 (230)	4	2006	400	10
PACT	1.1	24	107	3	2001	750	11
TACTIC	1.3	1	10	2.8	2001	1500	70
SHALON	3.3	1	11.2	8	1996	1000?	?

From Weeks (2008) arXiv:0811.1197v1

Instrument	Lat. (°)	Long. (°)	Alt. (m)	Tels.	Area (m^2)	Pixels	FoV (°)	Thresh. (TeV)	Sens. (% Crab)
H.E.S.S.	-23	16	1800	4	428	960	5	0.1	0.7
VERITAS	32	-111	1275	4	424	499	3.5	0.1	1
MAGIC	29	18	2225	1	234	574	$3.5^\dagger$	0.06	2
CANGAROO	-31	137	160	3	172	427	4	0.4	15
Whipple	32	-111	2300	1	75	379	2.3	0.3	15
HEGRA	29	18	2200	5	43	271	4.3	0.5	5
CAT	42	2	1650	1	17.8	600	$4.8^\dagger$	0.25	15

Table 1: Properties of selected air-Cherenkov instruments, including two of historical interest (HEGRA and CAT). † These instruments have pixels of two different sizes. Adapted from Hinton (2008).

From Hinton & Hofmann (2010) arXiv:1006.5210v2

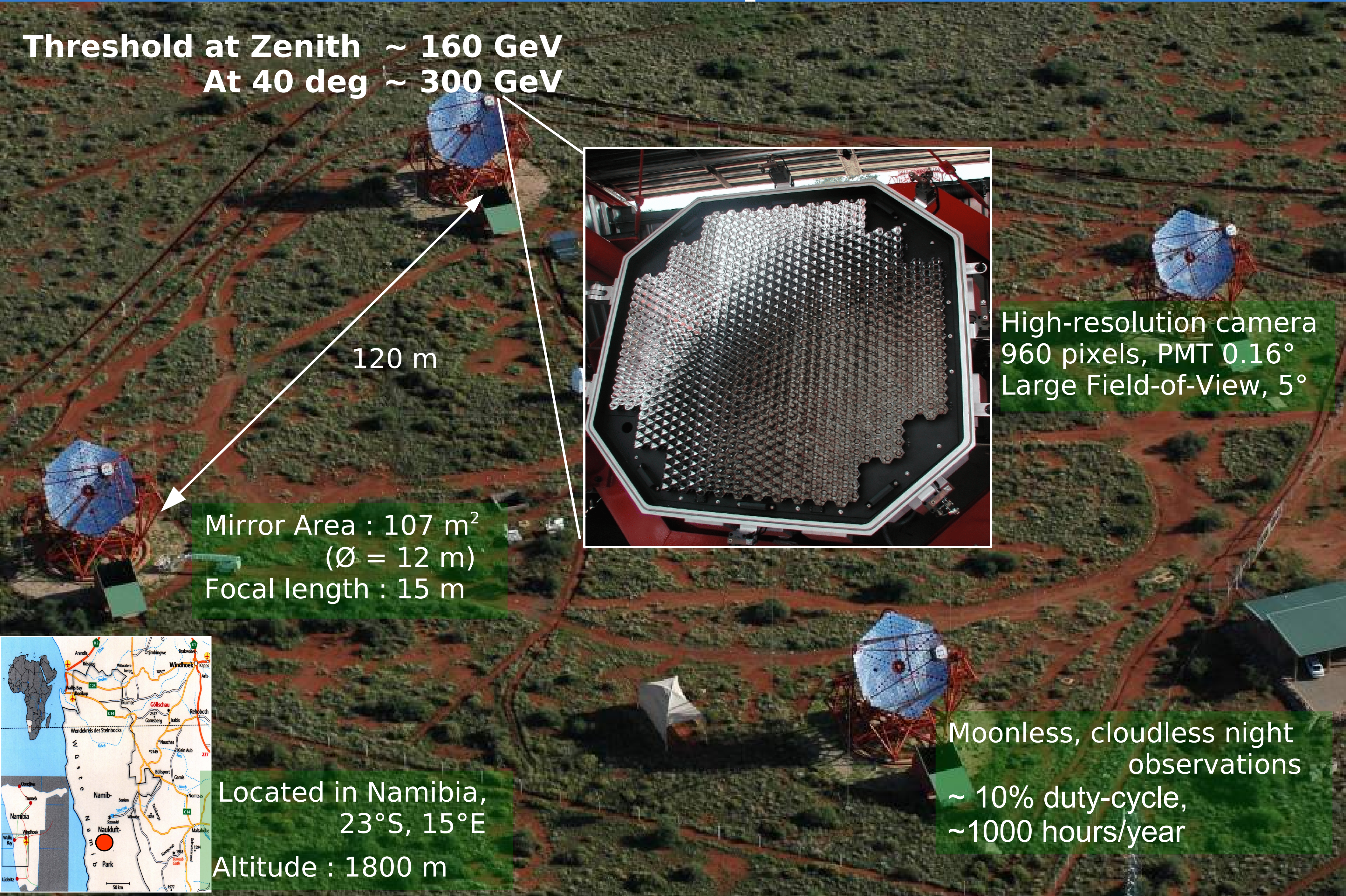
The main IACTs today

MAGIC - 236m^2 reflector
MAGIC II adds second telescope 85m distant

VERITAS
4x 110m^2 reflectors on irregular grid

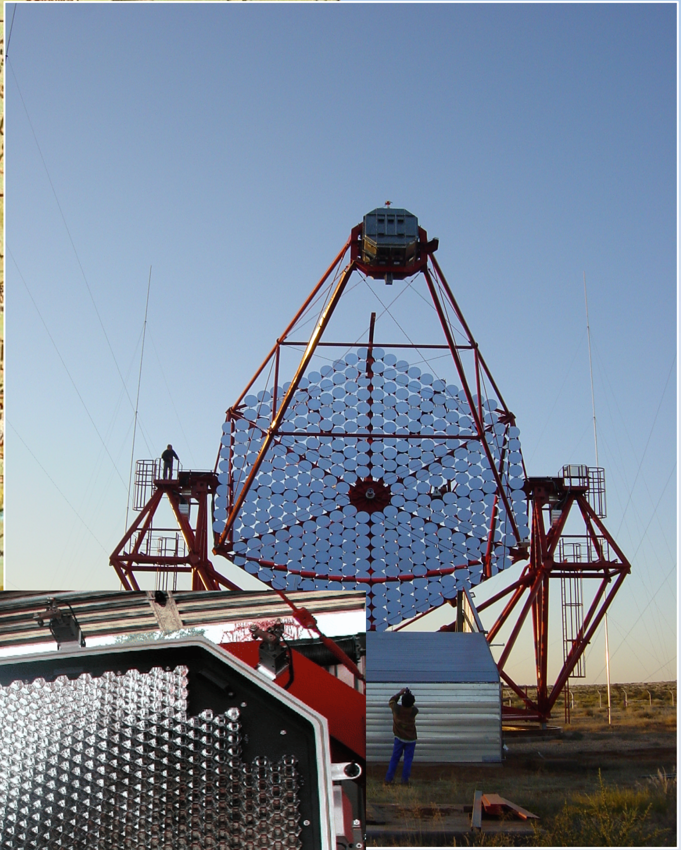
H.E.S.S.
4x 108m^2 reflectors on 120m square grid
H.E.S.S. II will add central ~600m^2 dish

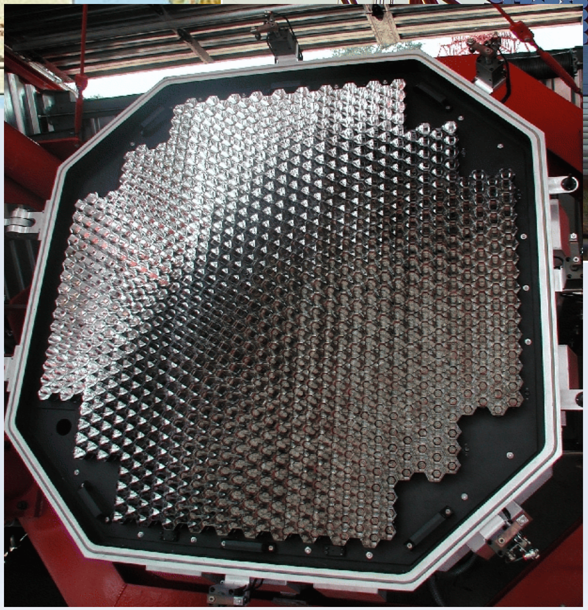
The HESS experiment



HESS Phase-I Essential Characteristics

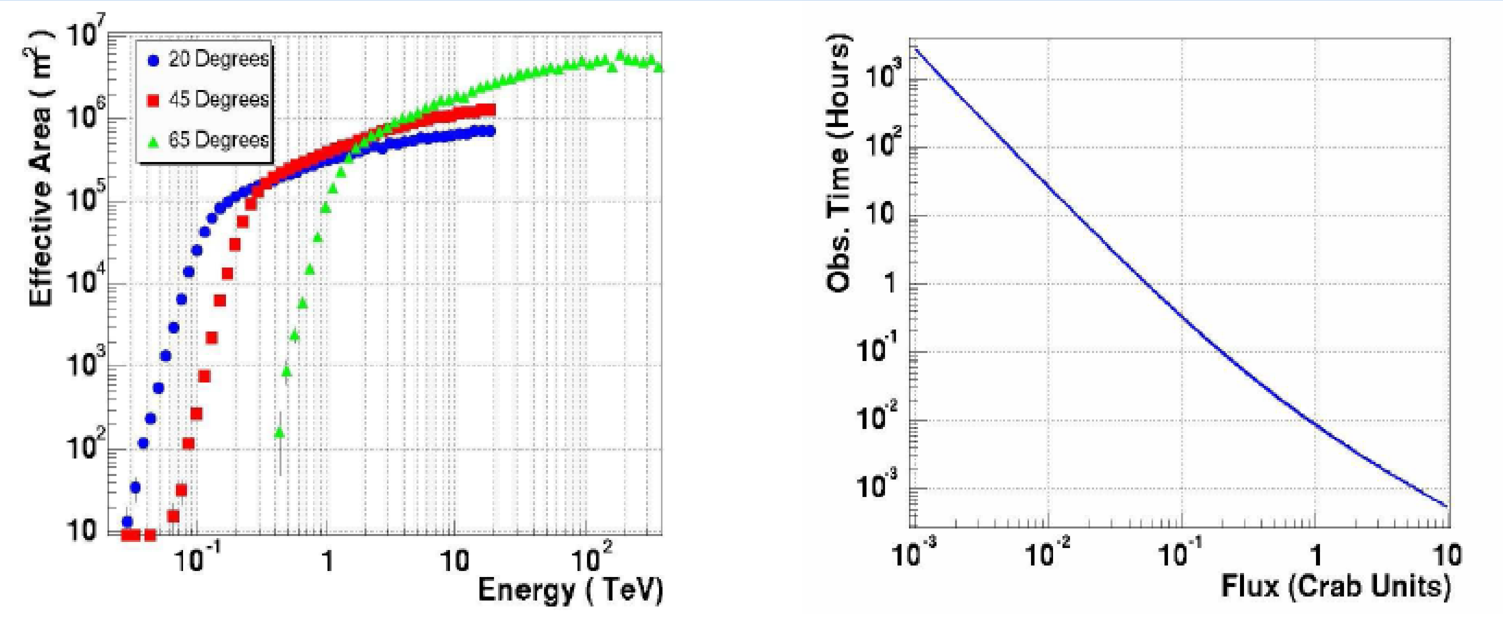
- Four-Telescope network
  - Sited in Namibia, 23°S, 15°E, 1800 m altitude
  - Telescope separation: 120 m
- Telescope Structures
  - Mirror dishes: 4 × 107 m^2
  - Diameter: 12 m, Focal length: 15 m
- Cameras
  - 960 photomultiplier pixels
  - Integrated electronics in camera (~2m cube, 900 kg)
  - Pixels of 0.16° / 2.8 mrad
  - Wide field of view, 5°
  - 16ns integration window, fast trigger coincidence
- Threshold ~100 GeV (trigger)



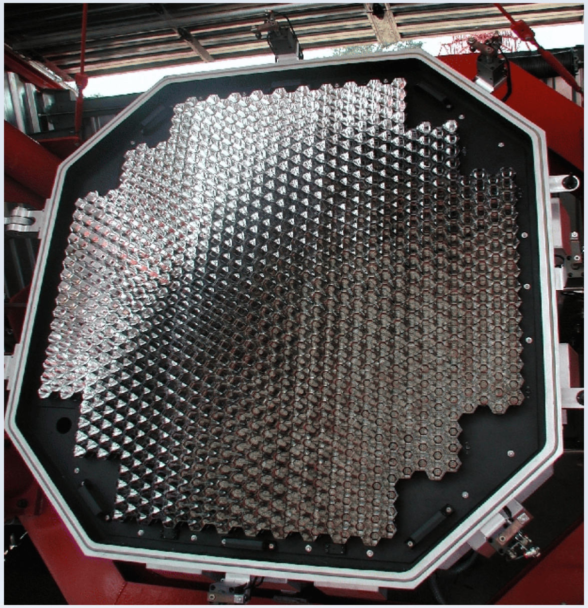


HESS Phase-I Essential Characteristics

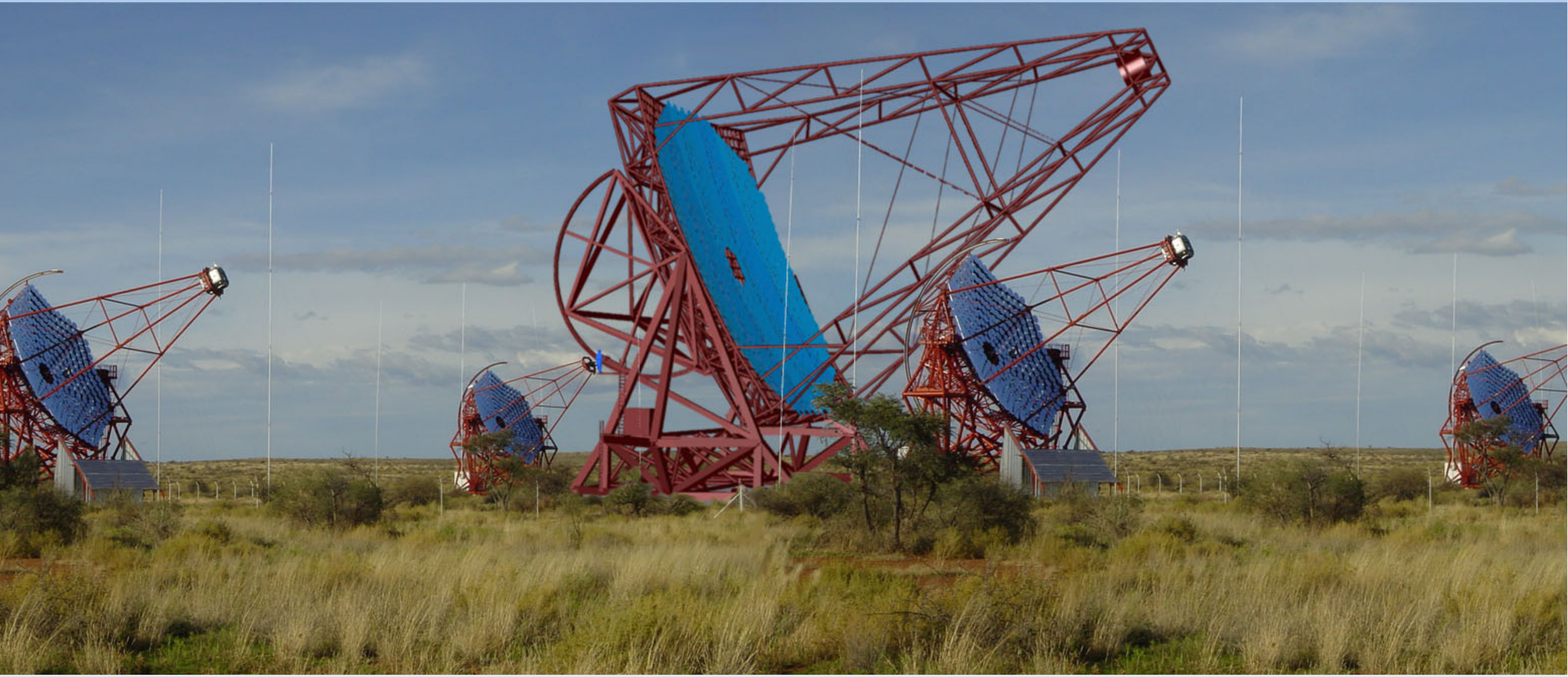
- Four-Telescope network
  - Sited in Namib
    1
  - Telescope sepa
- Telescope Structu
  - Mirror dishes: 4
  - Diameter: 12 m



- Cameras
  - 960 photomultiplier pixels
  - Integrated electronics in camera
    (~2m cube, 900 kg)
  - Pixels of 0.16° / 2.8 mrad
  - Wide field of view, 5°
  - 16ns integration window,
    fast trigger coincidence
- Threshold ~100 GeV (trigger)



H.E.S.S. Phase II

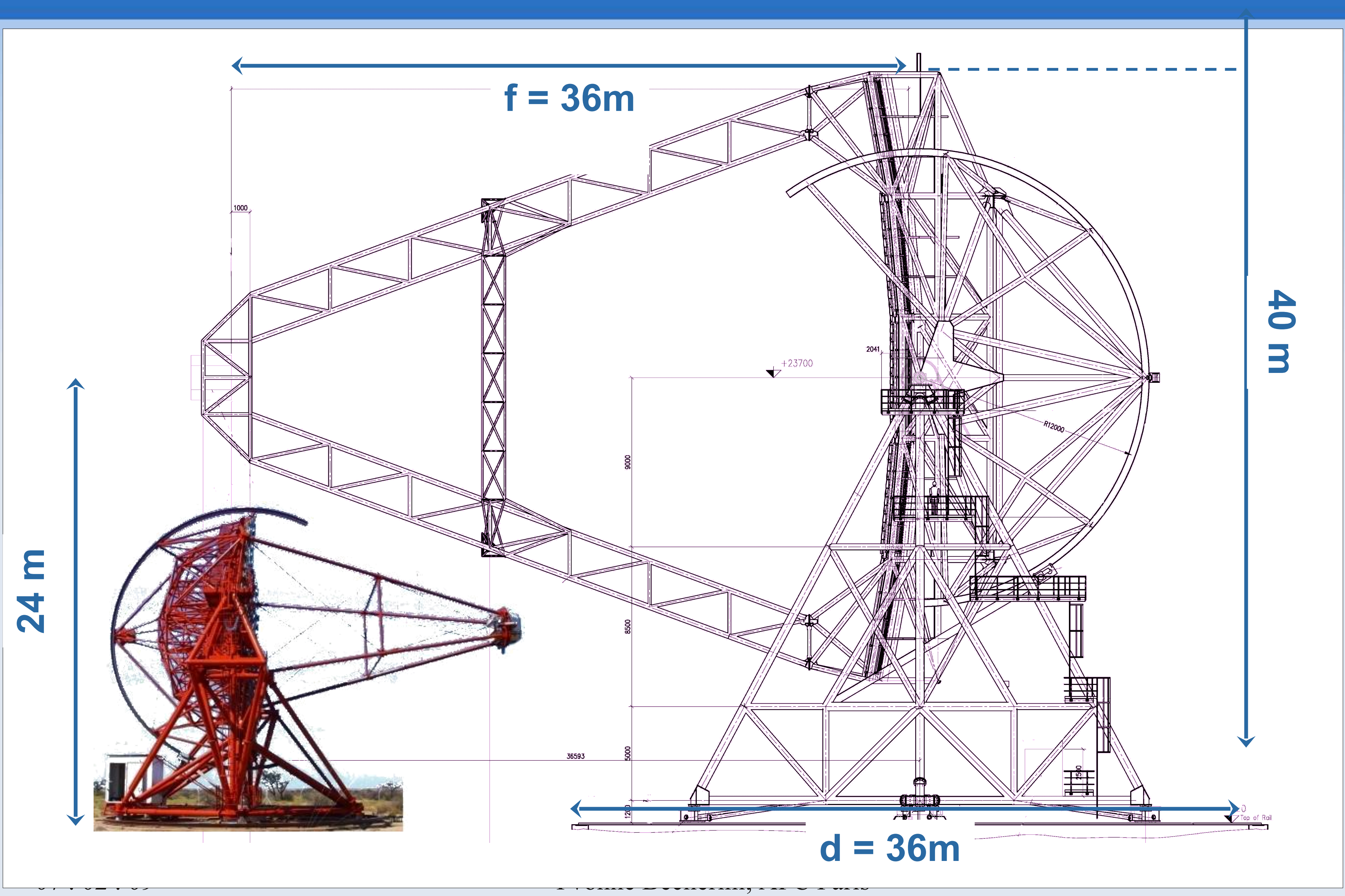


600 m² dish, 2000 x 0.07° pixel camera

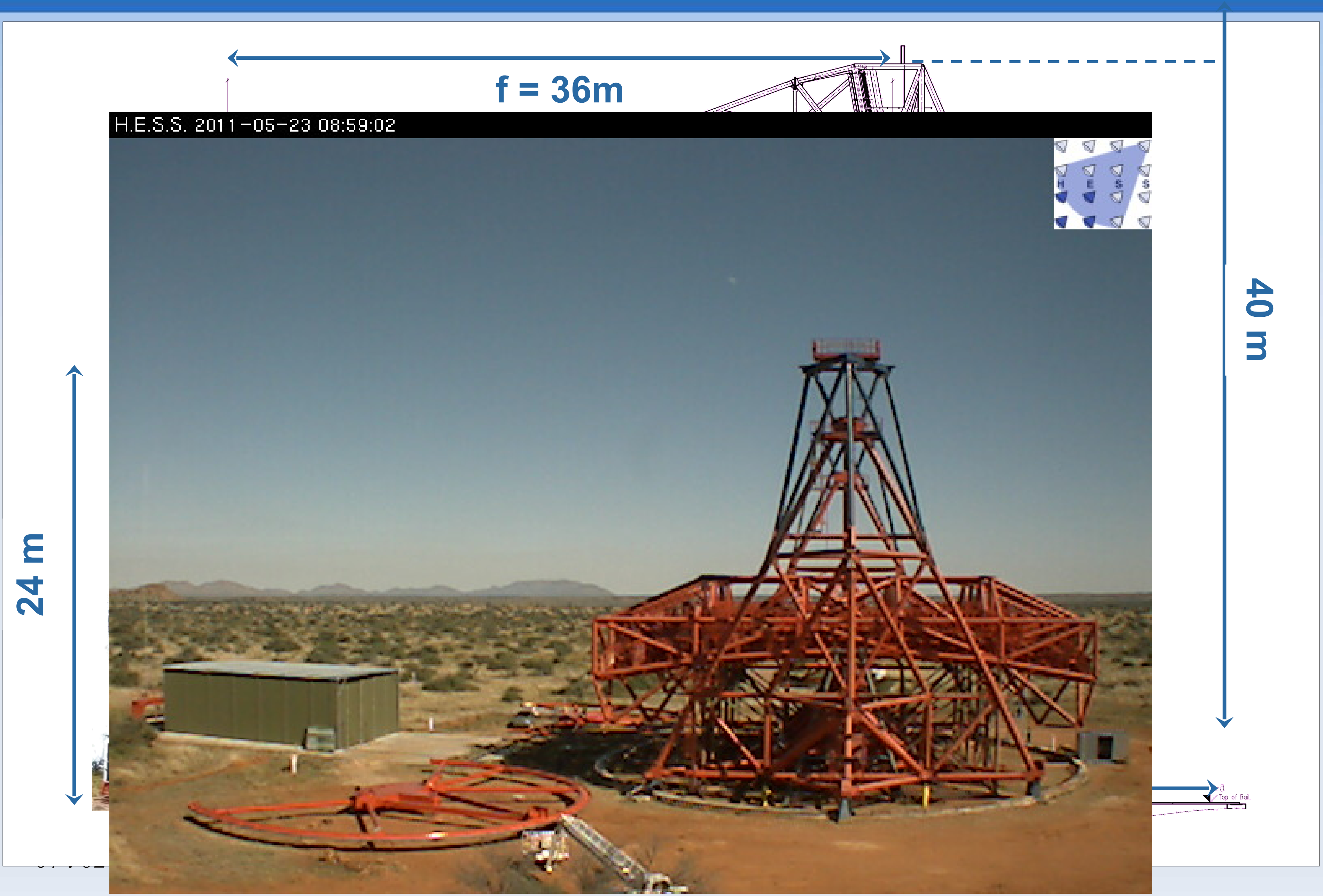
- Extends energy range down to ~30 GeV
- Improves sensitivity in 100 GeV – TeV range in stereo mode

Photomontage

HESS-II : the biggest telescope ever built



HESS-II : the biggest telescope ever built

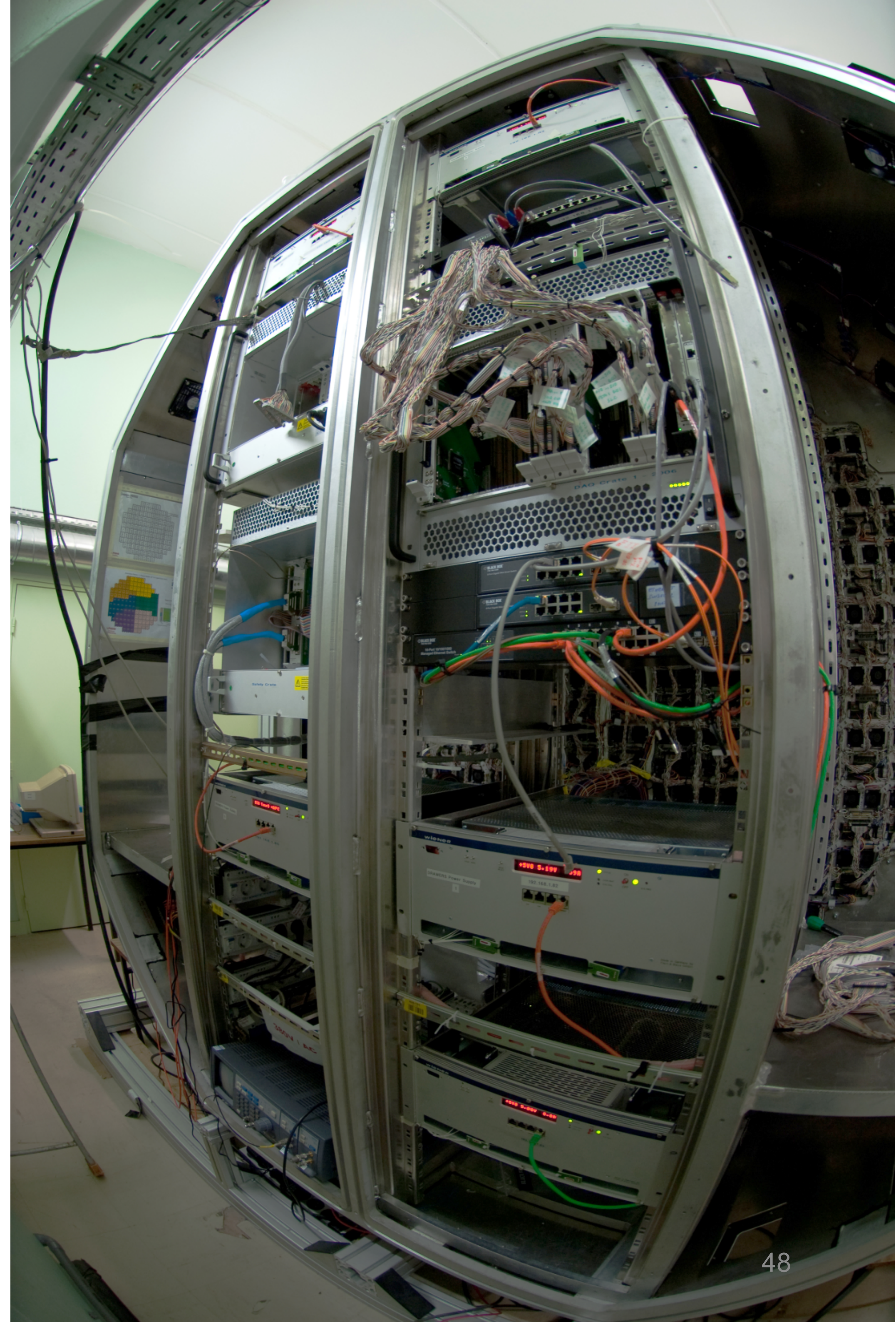


Le détecteur

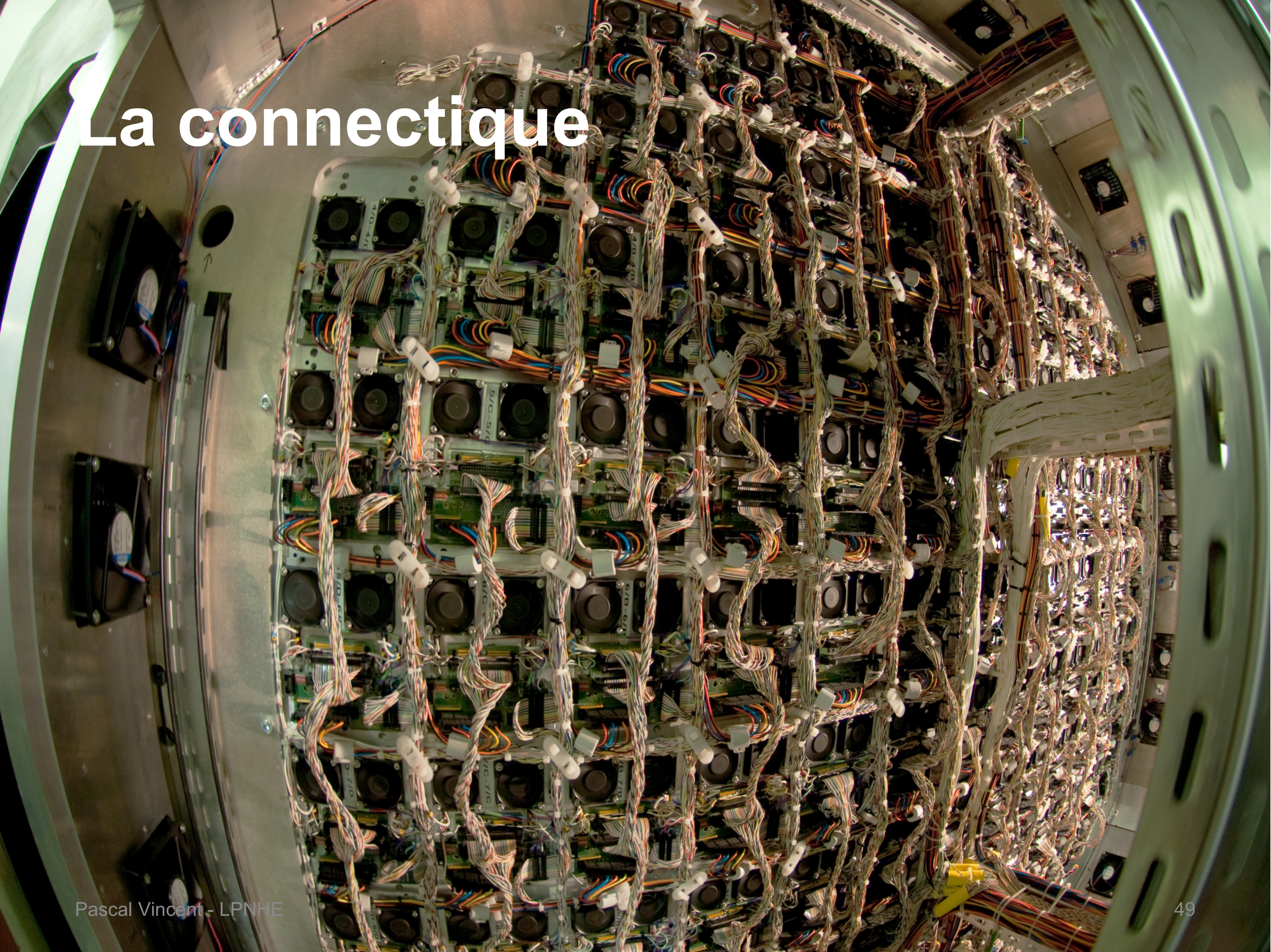
- 2 048 Photomultiplicateurs
- Nouvelle électronique (temps mort / 20), (LPNHE)
- Développement de mémoires analogiques (IRFU) : SAM
- Auto-focus + Débarquement de la caméra (LAPP, LUTH)
- Déclenchement de niveau 2 (IRFU)
- Mécanique (LLR)
- Calibrage (LUPM)

L'acquisition et le déclenchement

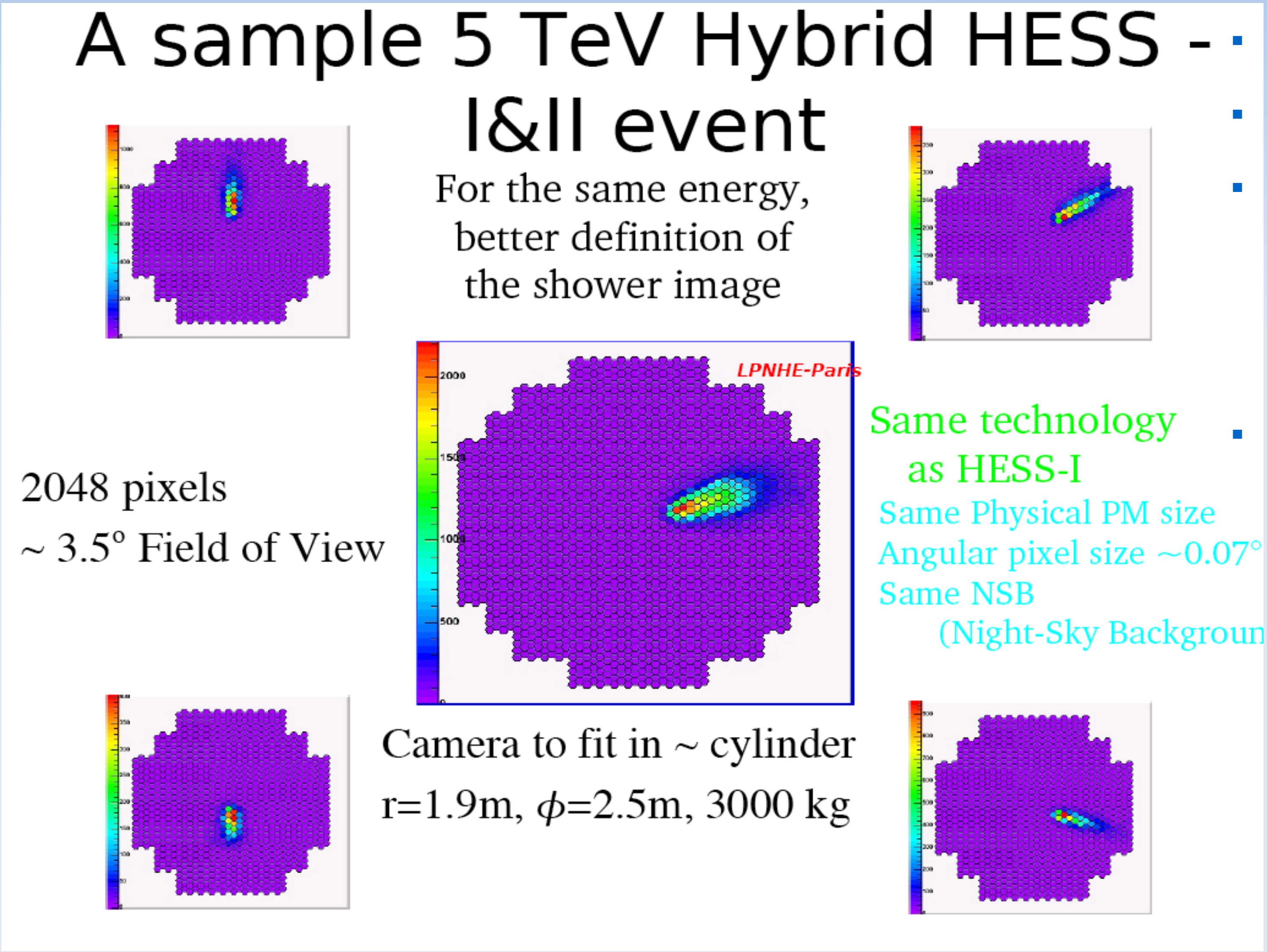
4 processeurs
650 cartes électroniques
4 096 voies de lecture
8 kWatt
~ 300 ventilateurs



La connectique



Sample HESS I/II event

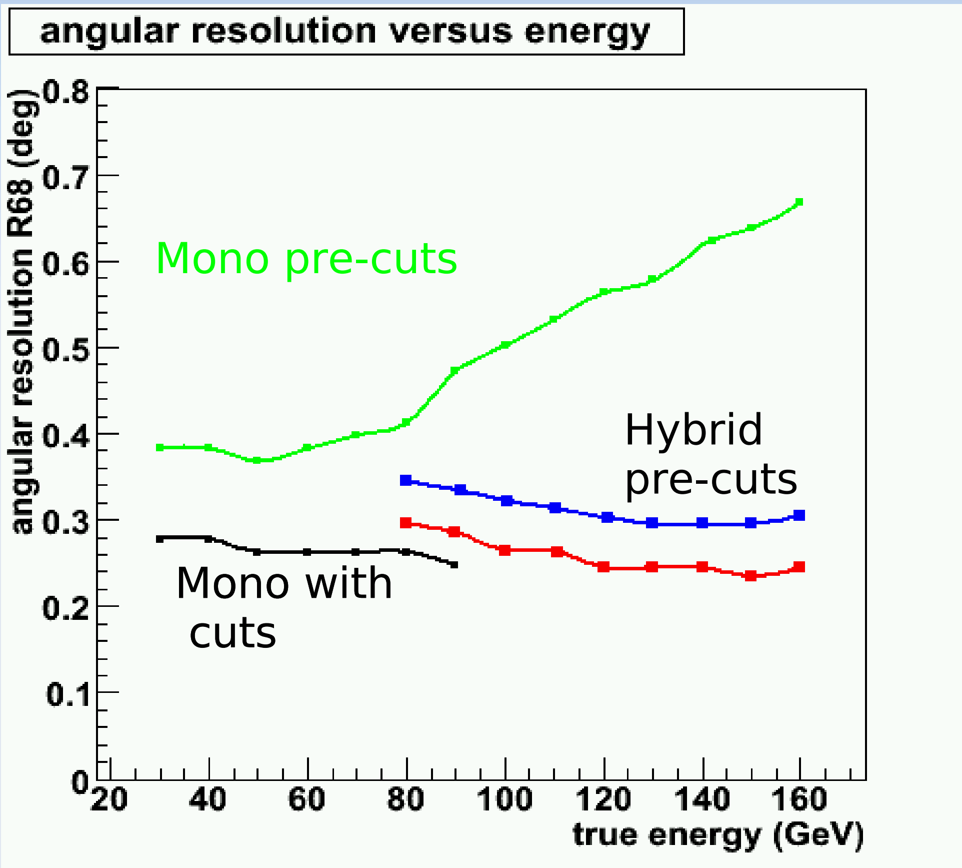


- 2048 pixels (0.07°)
- 16 PMTs = 1 Drawer
- New electronics (SAM Saclay)
  - Save charge and time
  - Expected timing resolution of the order of 1 ns
- Trigger based on superimposed sectors

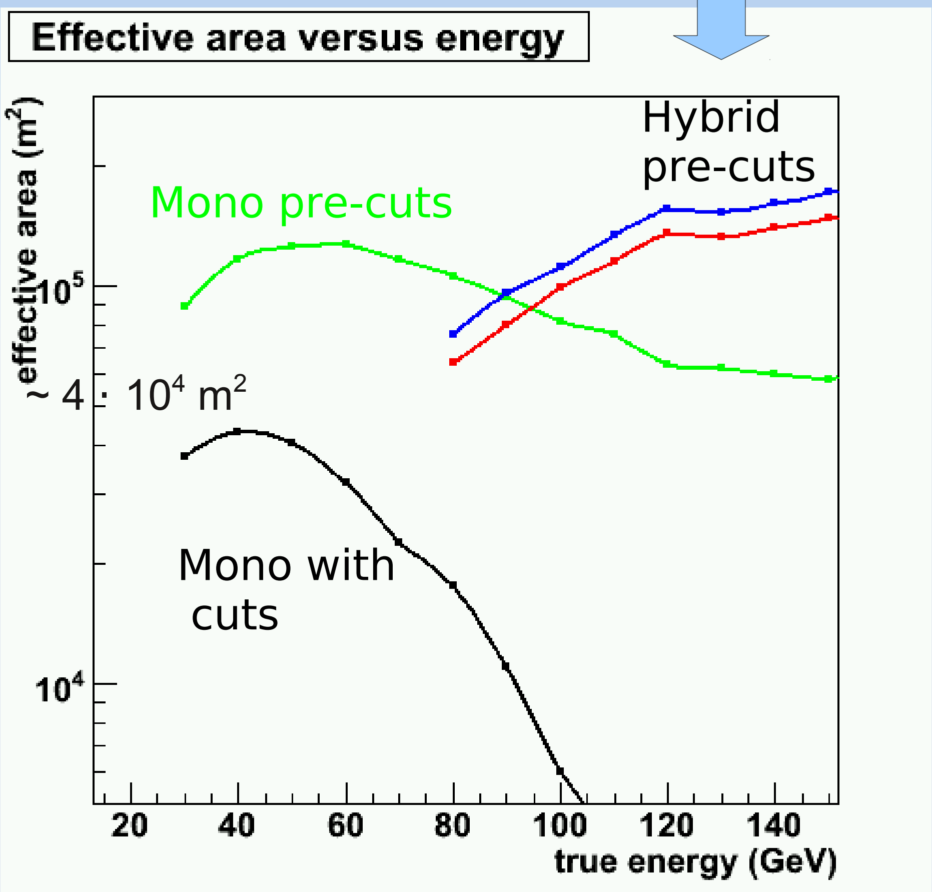
Installation now forseen in Summer 2012

Expected prelim. mono-telescope performance

- Angular resolution between 0.28° and 0.24° as a function of the energy



- Additional cut on the angular resolution
  - $\Theta^2 < 0.13\ deg^2$



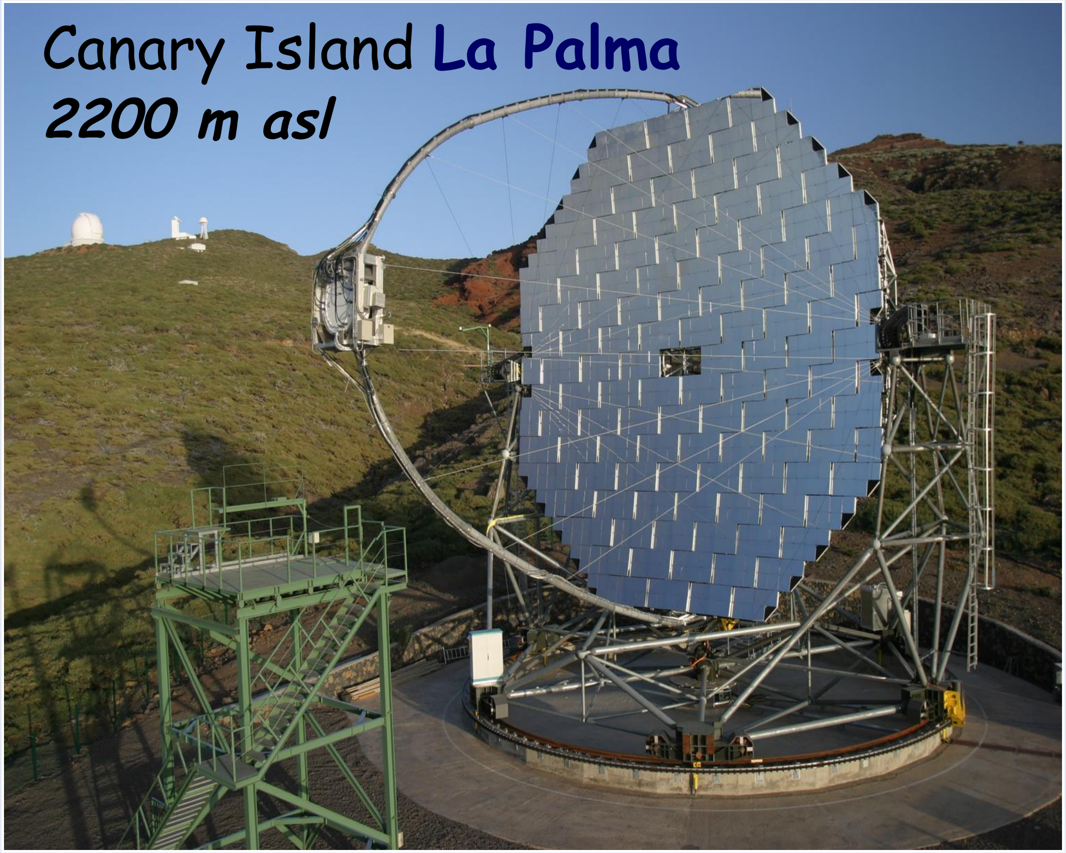
- Energy estimation through Neural Networks :
  the energy resolution varies from 40% to 10% as a function of the energy,
  the bias spans from +40% to −40% (further work needed!)

Y. Becherini, APC

The MAGIC telescope

First telescope in regular observation mode since autumn 2004
Extended observations during Moon

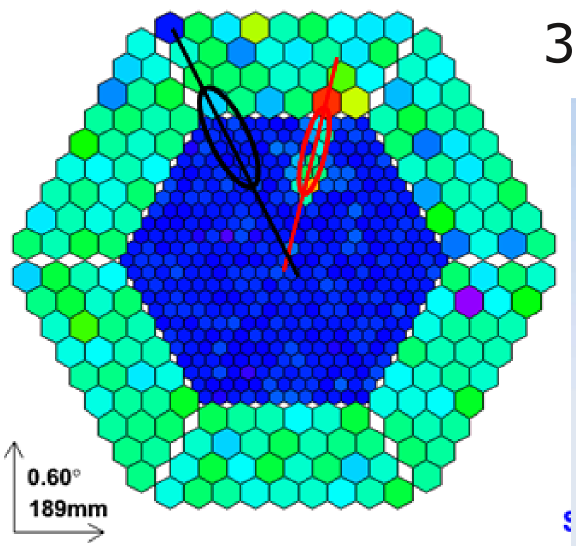
- Largest single dish Cherenkov Telescope:
  17 m ø mirror dish, **mirror surface (241 m^2)**
- 3.5° FoV Camera with 577 enhanced QE PMT's
- Fast repositioning for GRBs: average < 40 s, for MAGIC-II, 20s
- Low energy trigger threshold:
  50 - 60 GeV
- Sensitivity: 1.6% Crab / 50 h
  (improvement with 2 GHz sampling
  and timing parameters in g/h separation)
- γ-PSF: ~ 0.1° (E > 500 GeV)
- Energy resolution: 20 - 30%



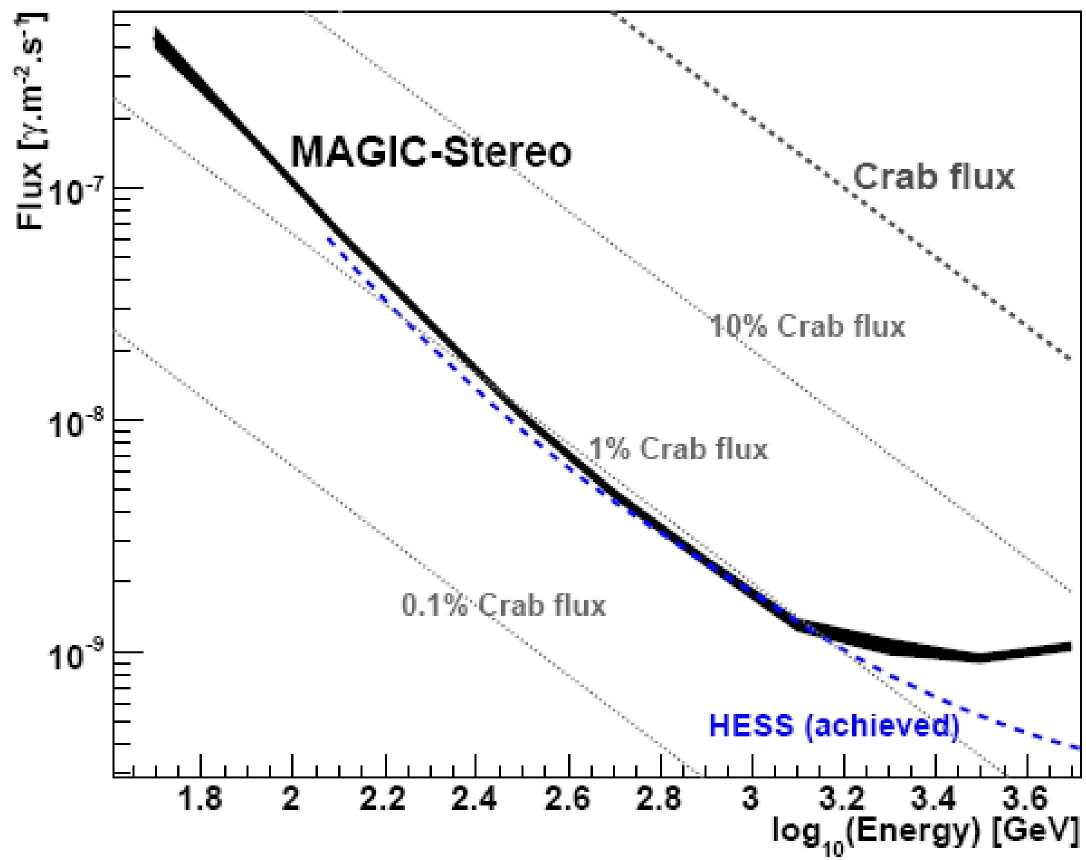
M. Mariotti

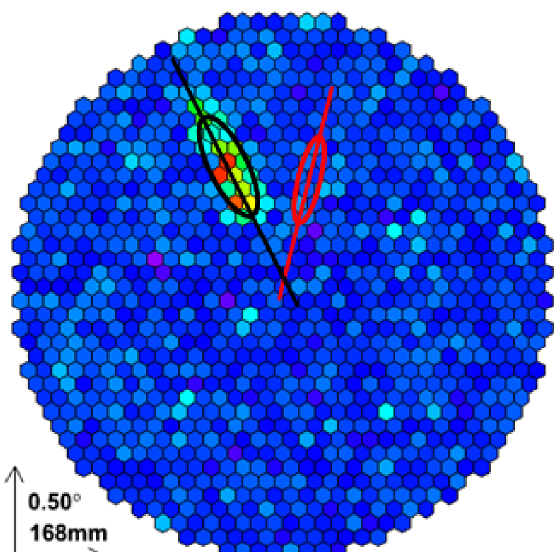
MAGIC II: Stereo, 2 x 236 m²

MAGIC II



MAGIC I
397 x 0.1° pixels (FoV 2°), 180 x 0.2°





MAGIC II
1039 x 0.1° pixels
FoV 3.2°

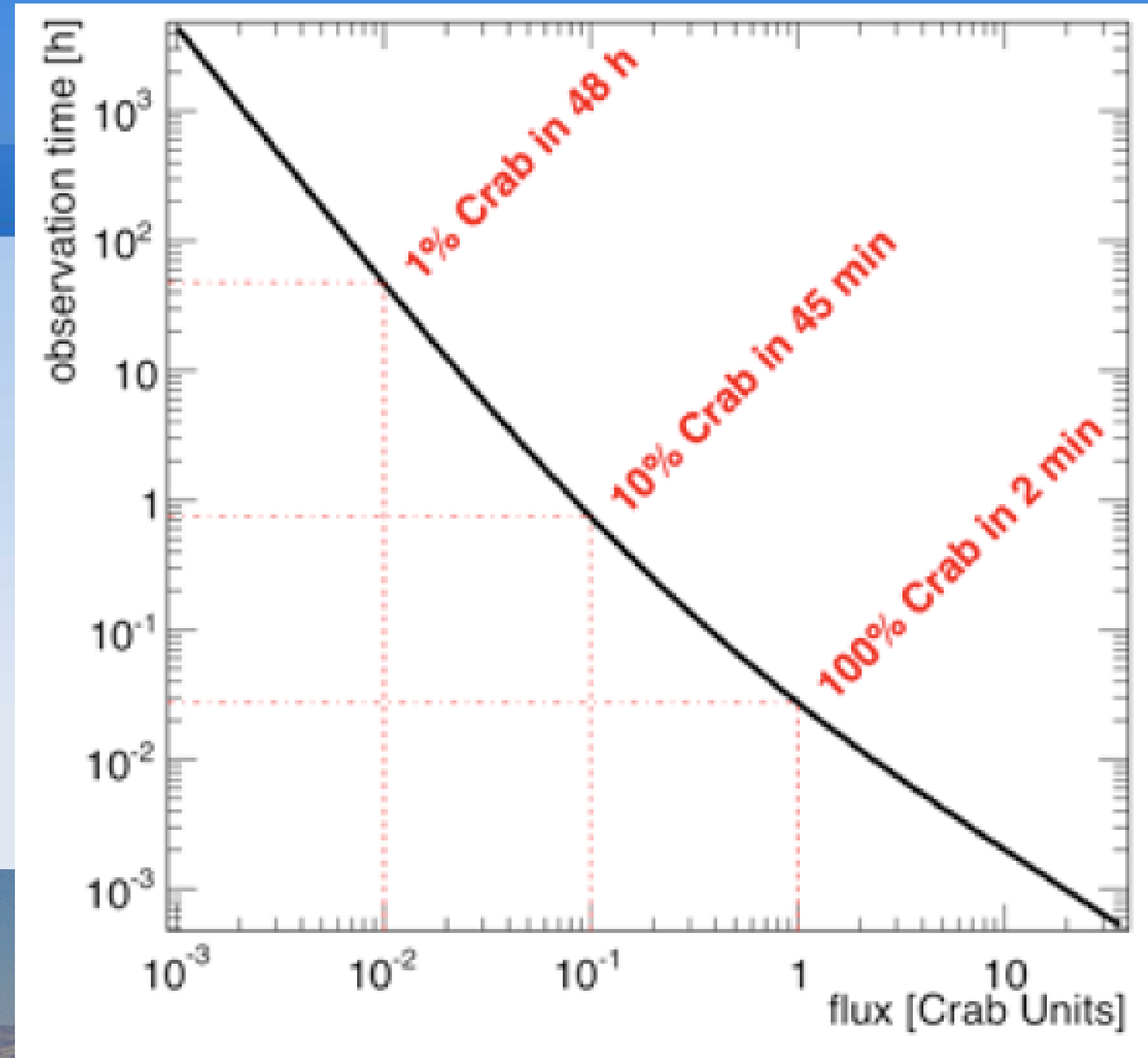
VERITAS

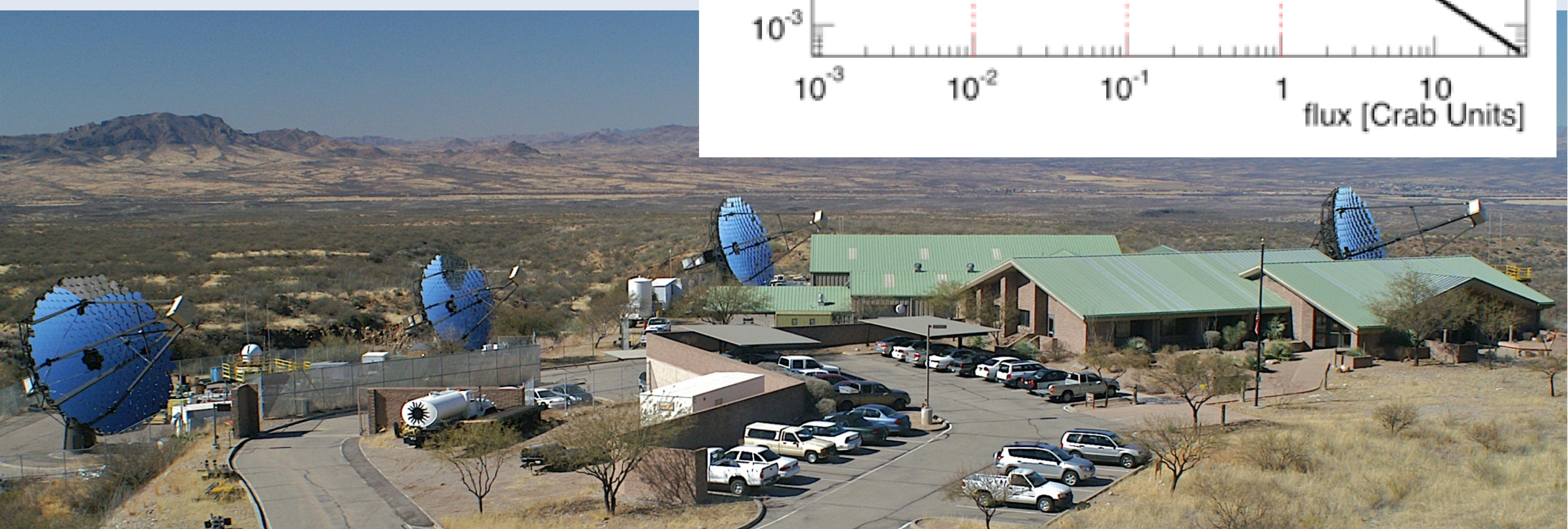
- Arizona: ~32° N, ~111° W, 1268 m a.s.l.
- Four identical telescopes:
  - Alt-Az mount; Steel; Davies-Cotton reflector
  - f/D ~ 1.0; D = 12 m; f = 12 m
- Mirror Area: ~106 m^2
  - 350 hexagonal mirrors (60 cm diagonal)
  - Optics: Focus star to 1 pixel (~0.15°)
- Camera: 499 pixels & 3.5° FoV
  - Readout: Dual-gain; 500 MHz FADC
- 3-level trigger: ~10% dead time; ~300 Hz
- Data: 800 h / year + 35% in moonlight
  - 4-tels operating >95% of time

VERITAS

T1: Jan 2005
T2: Spring 2006
T3: Autumn 2006
T4: Spring 2007

111 m², (1200 ft²) mirror area
499 x 0.15° pixels
FoV ~3.5°

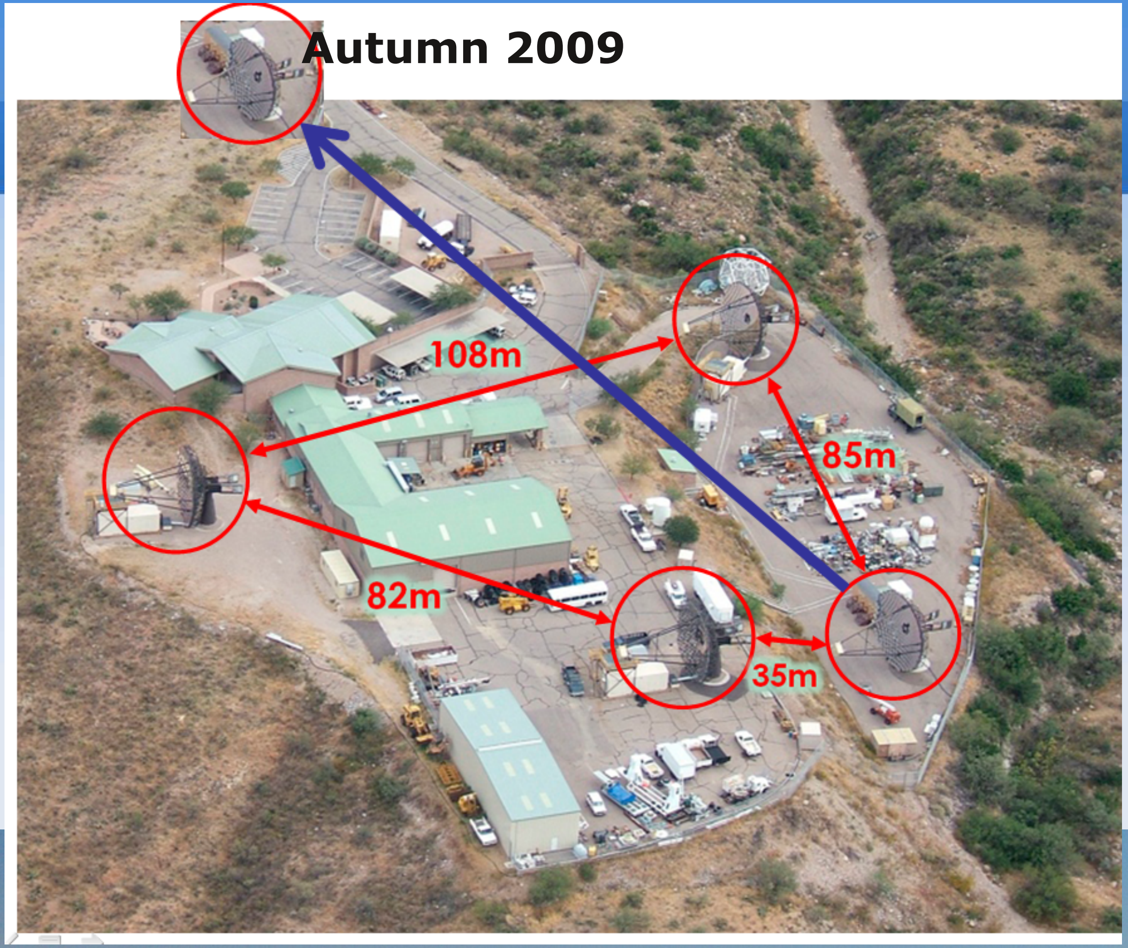




VERITAS

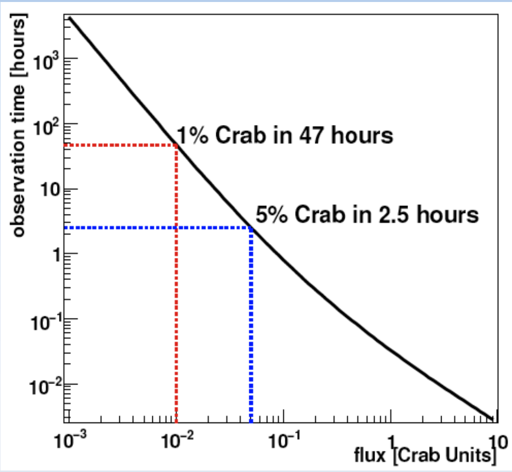
2009:
- improved optical psf
- move T1 for better sensitivity and angular resolution

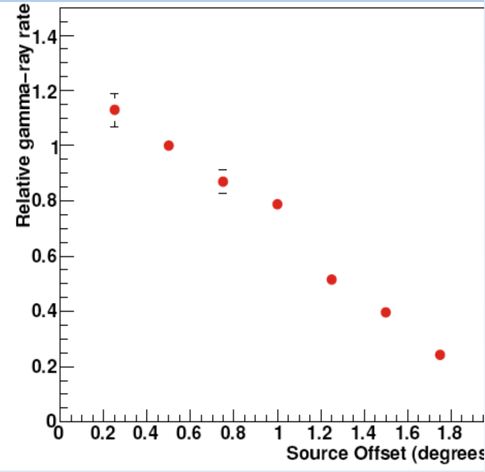
Proposed upgrades:
- High-QE PMTs (+35%)
- Trigger upgrade (topology)



VERITAS Figures of Merit

- Energy Range: ~100 GeV to ~30 TeV
- Crab-rate (triggered γ-rays @20°): 37 min^{-1}
- Pointing: ~90" (Conservatively)
- Angular resolution: $r_{68} < 0.14°$
- Energy resolution: ~15%
- Systematic Errors: Flux ~20%; Γ ~ 0.2
- Crab Nebula: Reasonable spectrum, flux, etc.
- Mirror re-coating: Each telescope / 2 yrs





~20% better since Autumn 2009

CANGAROO III

A most remarkable piece of archeology:

arXiv:0906.4924

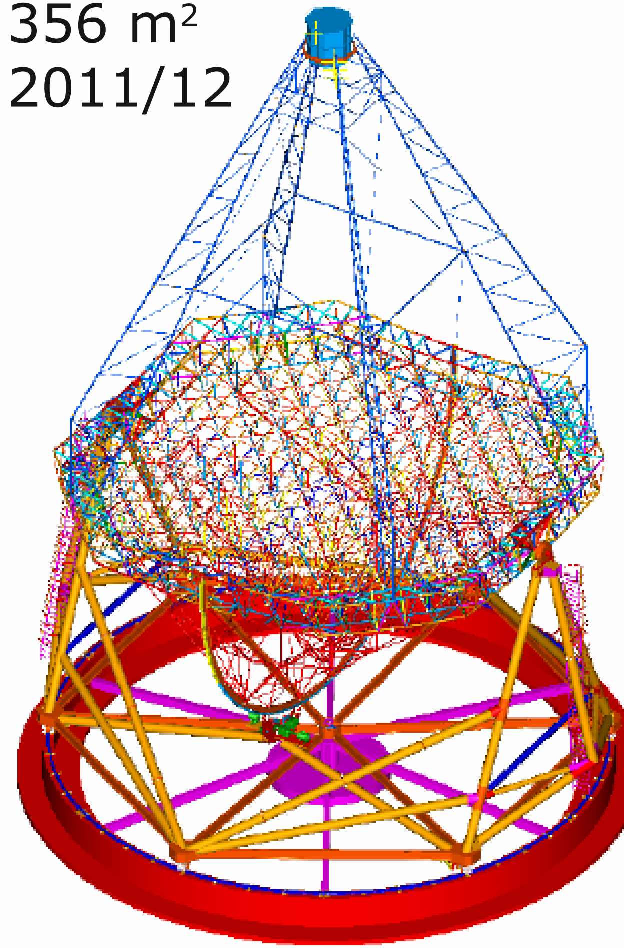
Early CANGAROO (3.8 m) claims for discovery of PSR B1706-44, SN1006 cannot be reproduced; problems in old (1993 – 1999!) calibration and analysis identified

Operational, but modest performance compared to other arrays

- Modest dish size (57 m^2)
- Sea-level altitude
- Serious mirror deterioration (10% / year)
- Partly outdated camera hardware

TeV astronomy in India

MACE
356 m^2
2011/12



TACTIC, Mt. Abu

PACT Array, Pachmari

First data: HAGAR Array, Hanle

EAS Arrays
Les réseau de détection de particules

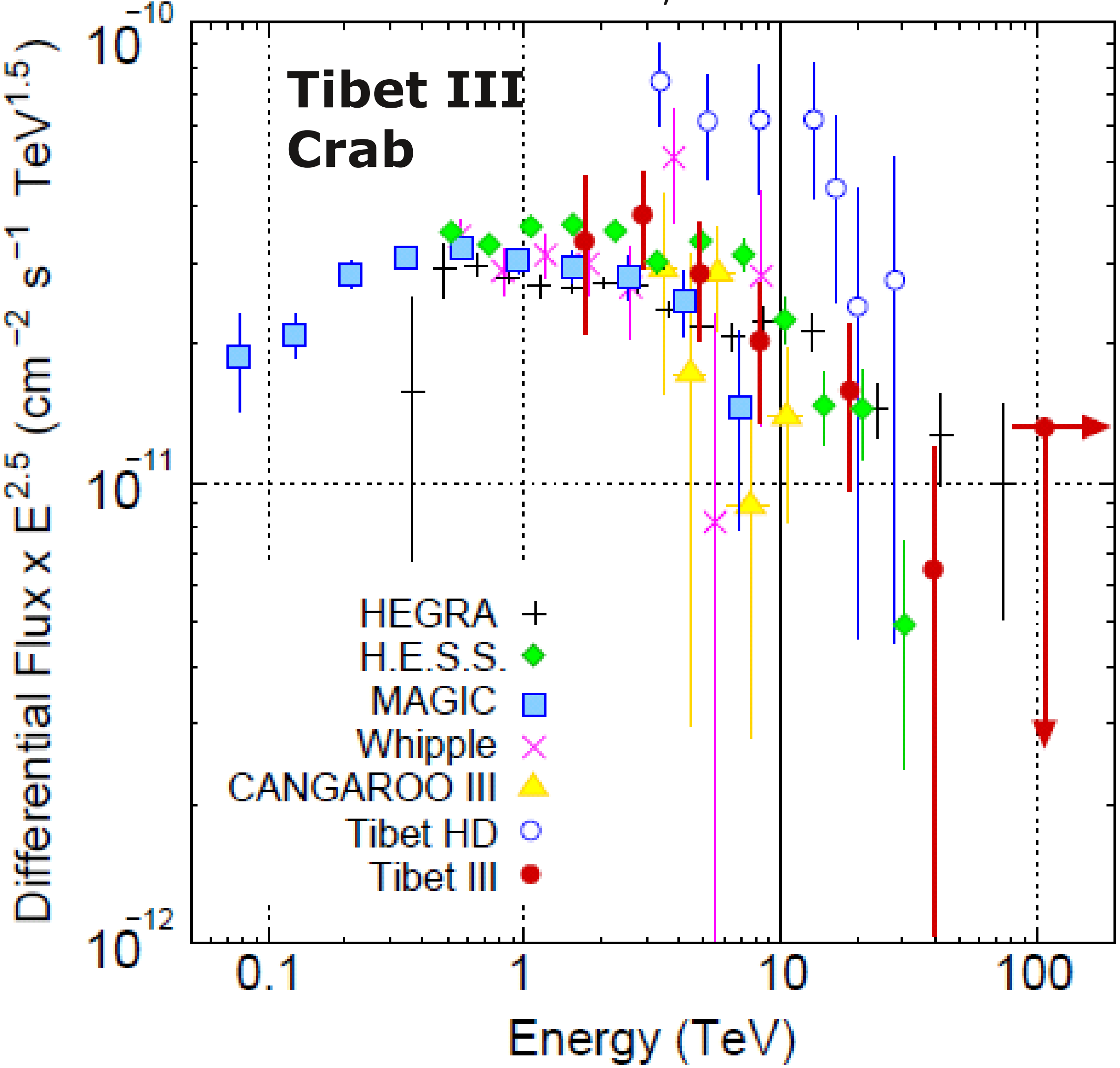
Air shower arrays

MILAGRO
Water Cherenkov,
ceased operation
in 2008, after 7 years

Tibet III
Scintillator array
arXiv:0810.3757, 0804.1862
CR spectra, moon shadow,
Crab & Mrk 421, 3 hotspots

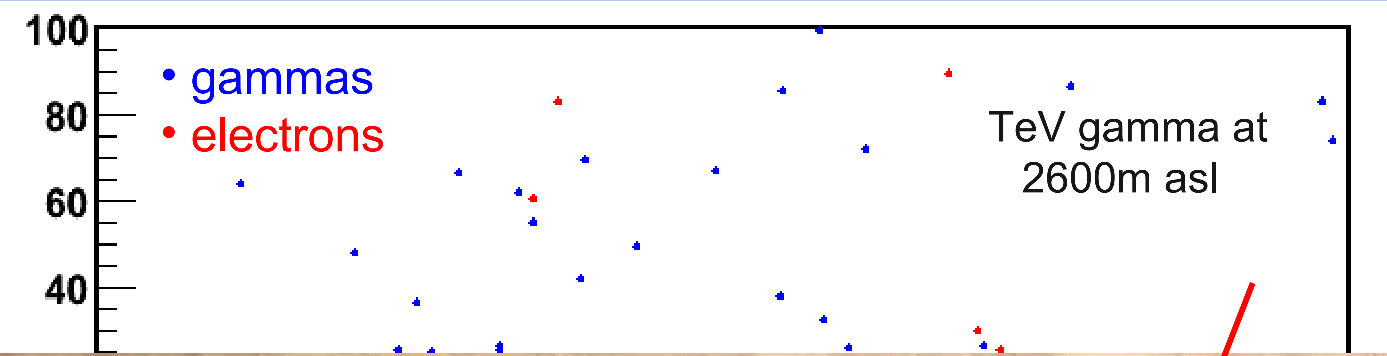
ARGO-YBJ
6700 m² RPC carpet
arXiv:0907.1164, 0905.1189,
0811.0997
Sun & moon shadow in CR;
Crab & Mrk421, GRB search;
P-Air Xsection, pbar-p ratio

M. Amenomori et al., arXiv:0810.3757




MILAGRO

Water Cherenkov Technology



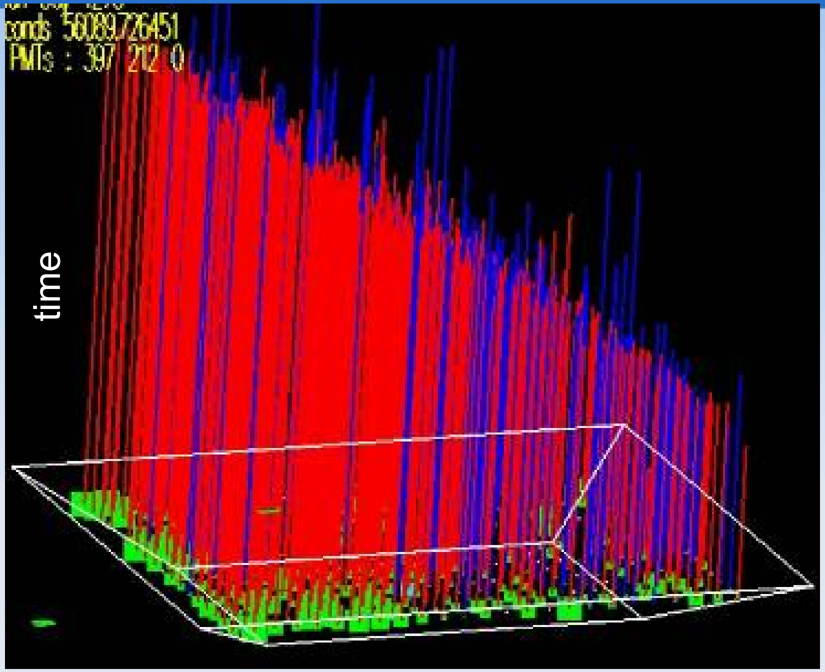
Provides fully active area
Converts γ's to electrons
γ : electron ~ 6:1

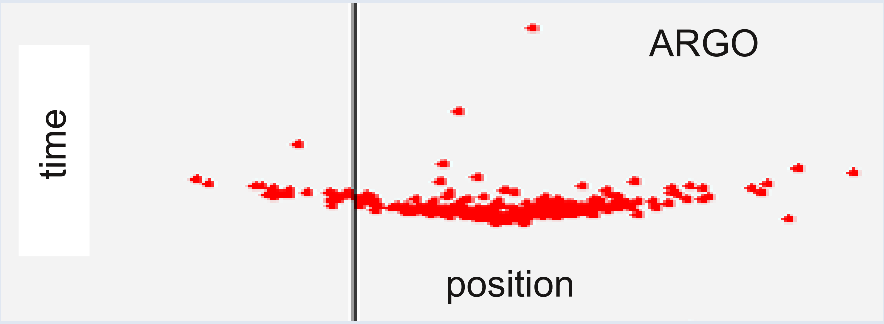
Milagro Gamma-Ray Observatory

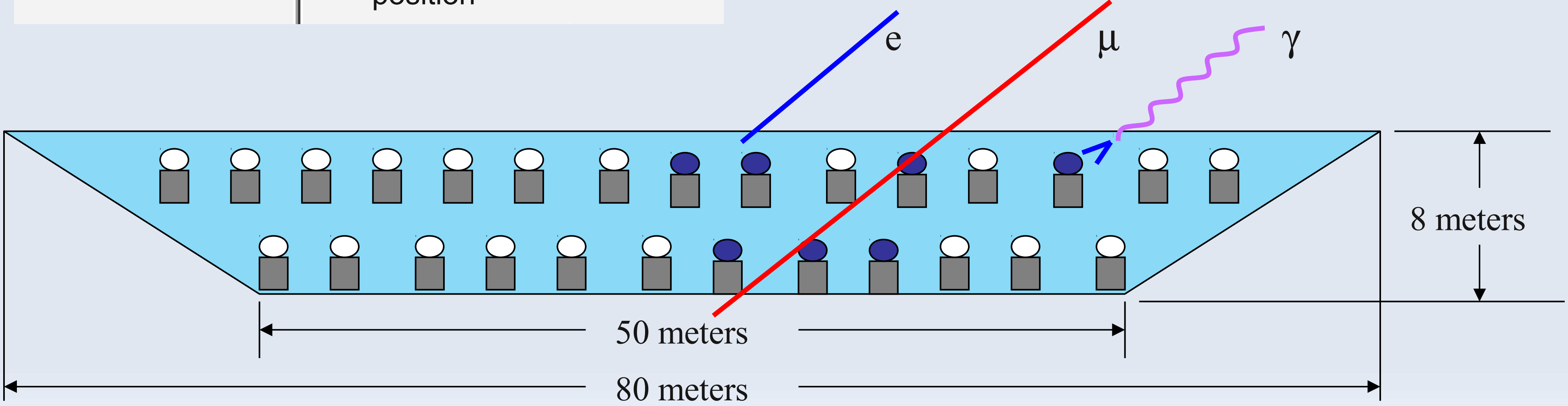
- 2600m above sea level
- 2 sr field-of-view
- 95% duty factor
- Angular resolution~0.5°
- 1700 Hz trigger rate

How Milagro Works

- Direction via timing (~1 ns)
- Background rejection via muons
- Energy via shower size

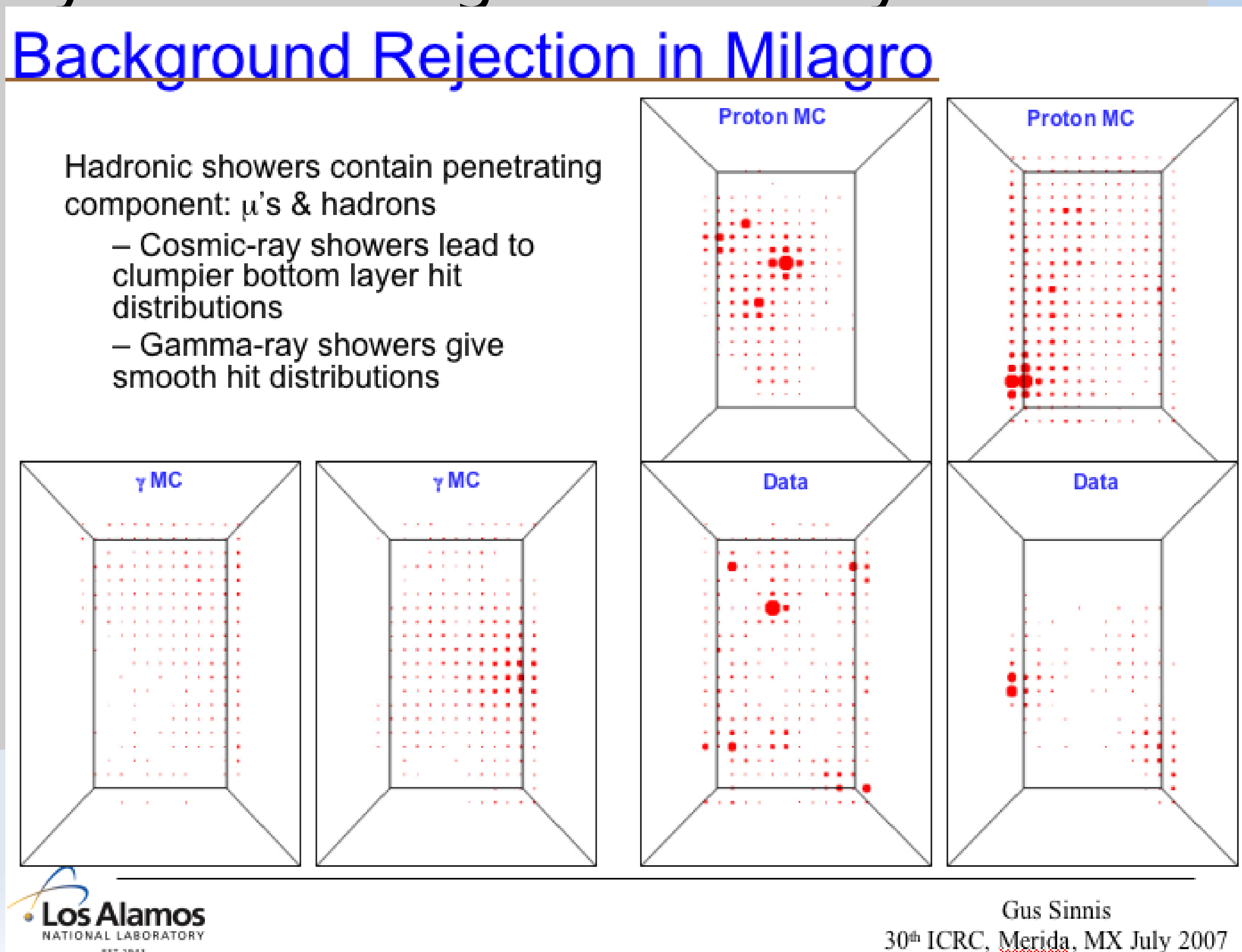




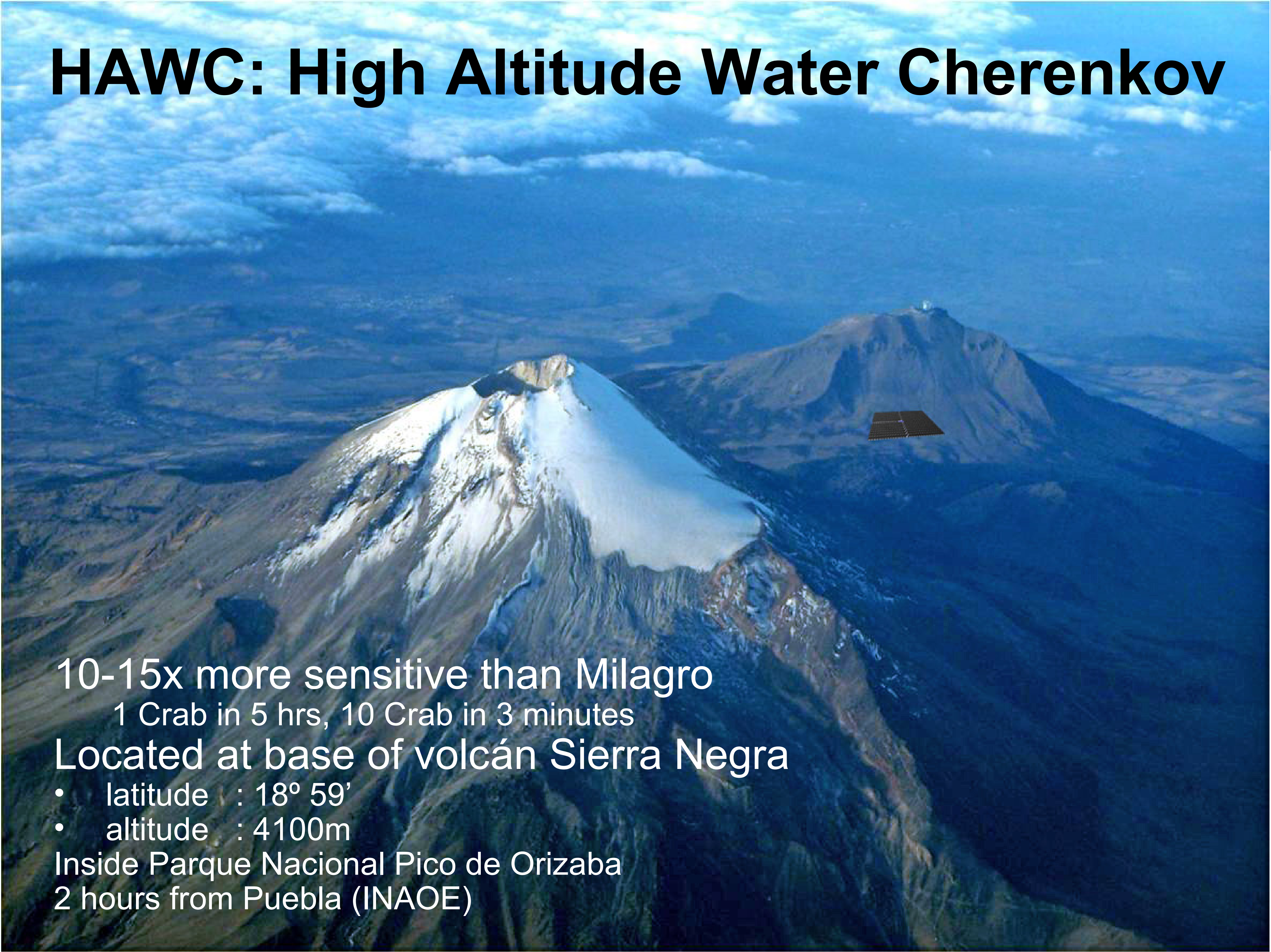


Milagro EAS detection

- Milagro technique now clearly works!
- Have all-sky monitoring and survey



HAWC: High Altitude Water Cherenkov



10-15x more sensitive than Milagro

1 Crab in 5 hrs, 10 Crab in 3 minutes

Located at base of volcán Sierra Negra

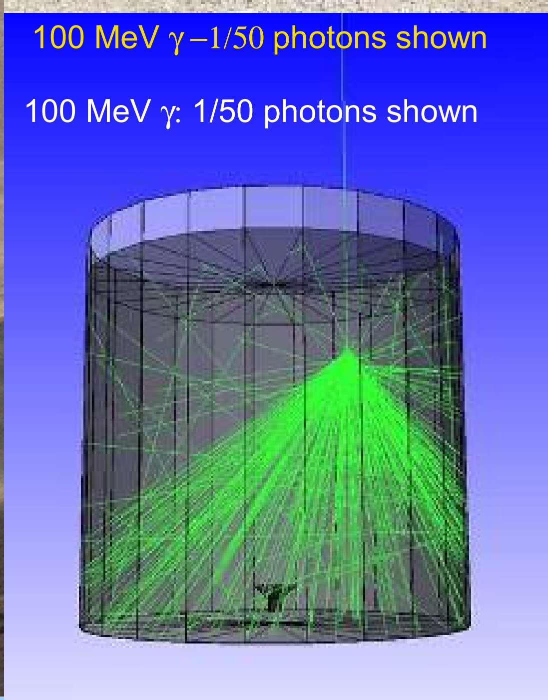
- latitude : 18º 59’
- altitude : 4100m

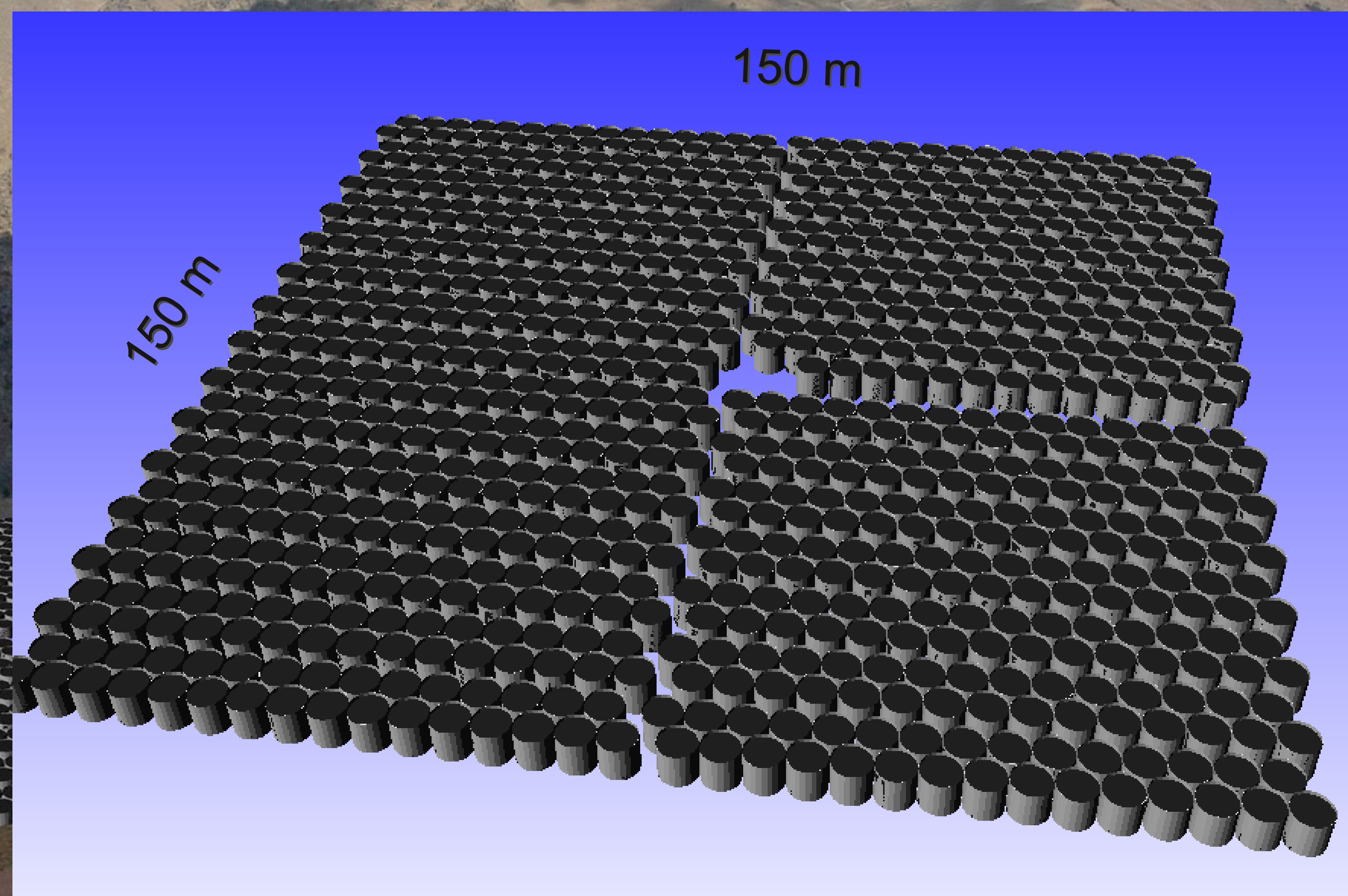
Inside Parque Nacional Pico de Orizaba

2 hours from Puebla (INAOE)

HAWC Design

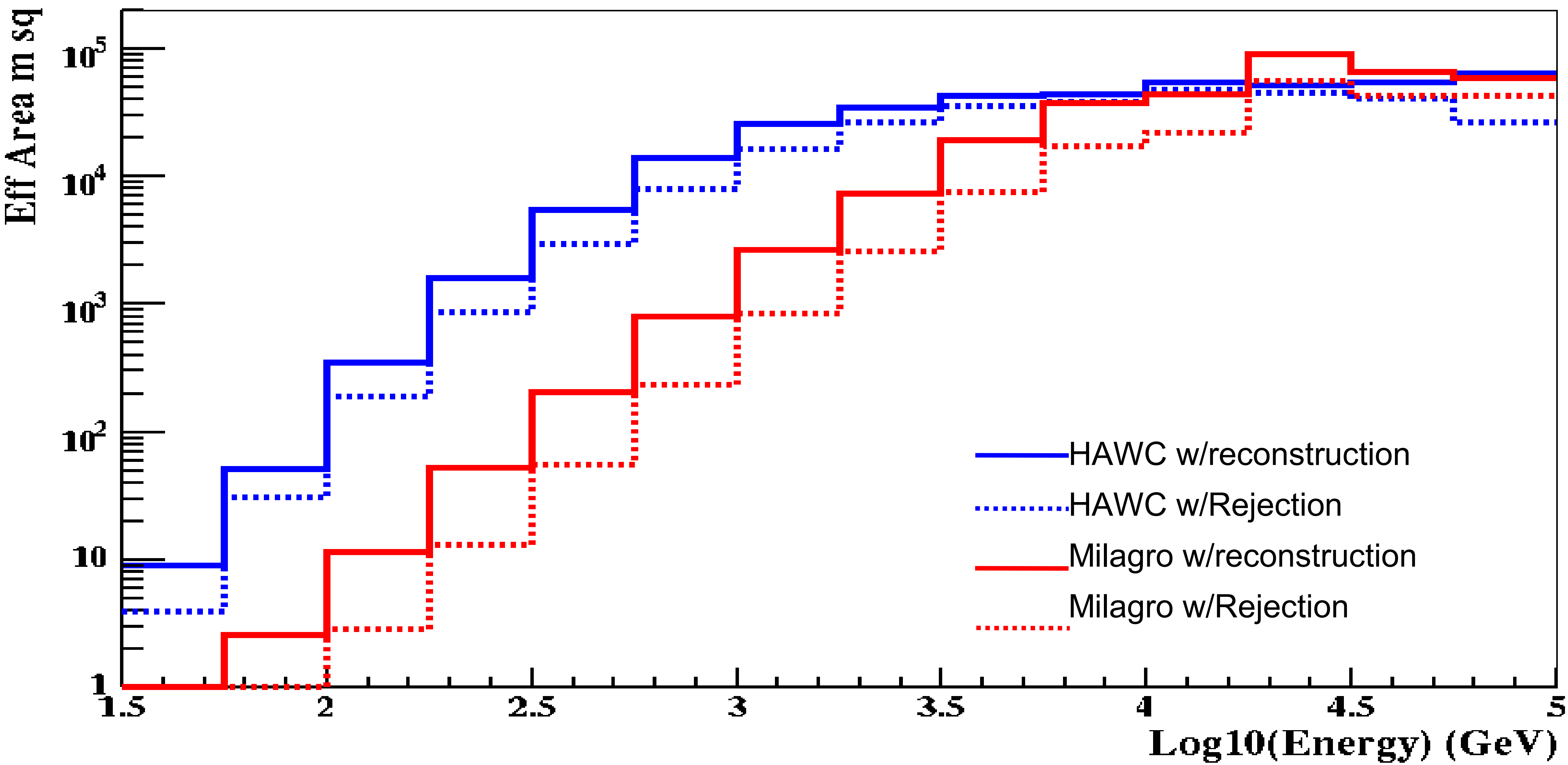
- ~1000 large tanks (~4m dia x ~4m height)
  - 1 PMT/tank (looking up)
  - Non-reflective interior
- 22,000 m² enclosed area
- 4100 m above sea level





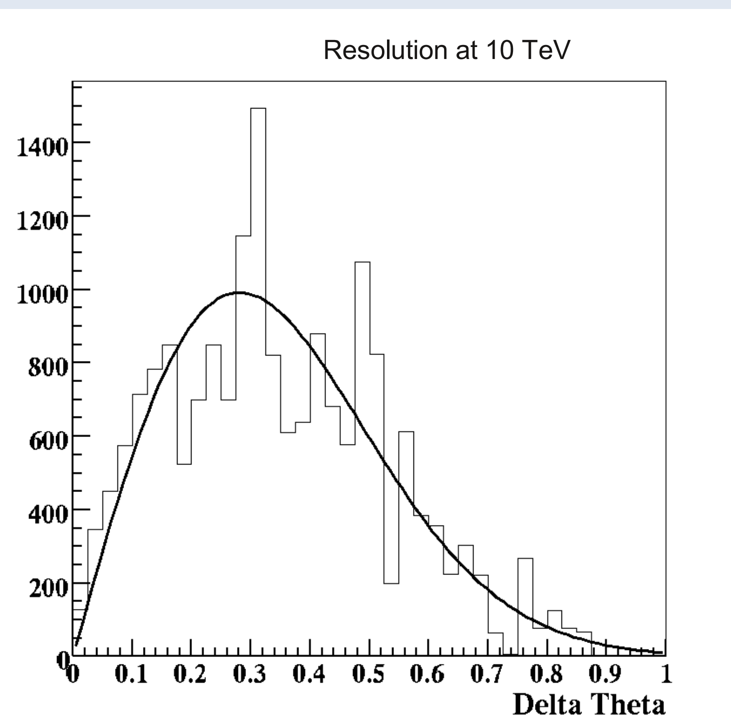
HAWC Performance: Effective Area

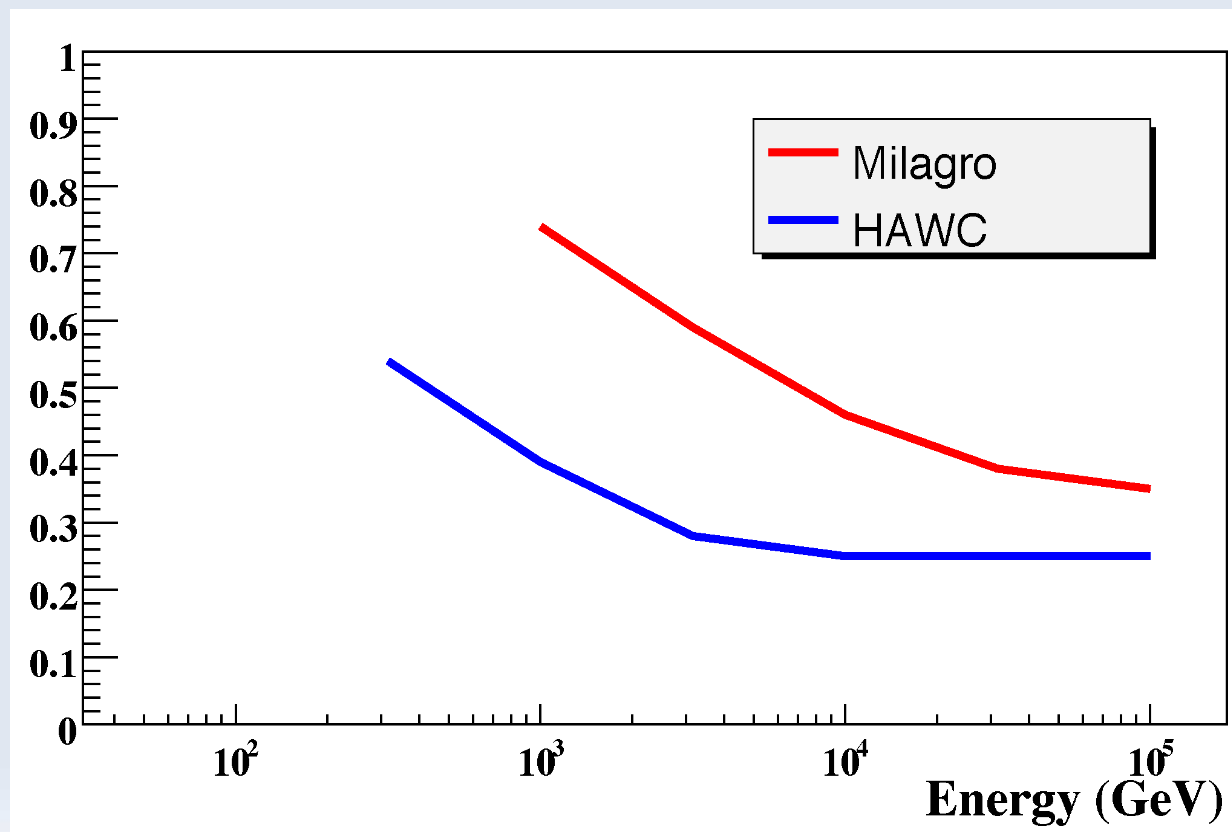
- At low energies (<1 TeV), HAWC has ~30x the effective area of Milagro
  - larger dense sampling area (5x)
  - higher altitude
  - Larger muon detection area (10x)



HAWC Performance: Angular Resolution

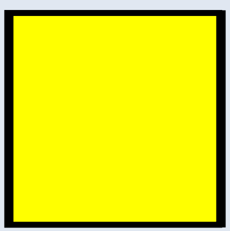
- At similar energies, HAWC's angular resolution is ~1.5x better than Milagro.
  - larger area
  - higher altitude
  - optical isolation
- Resolution defined as sigma of a 2-d Gaussian.



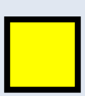


HAWC Background Rejection

- 10x better hadron rejection than Milagro above 10 TeV
  - larger muon detection area (10x)
  - optical isolation
- 2.5x higher gamma efficiency at lower energies (< 10 TeV)



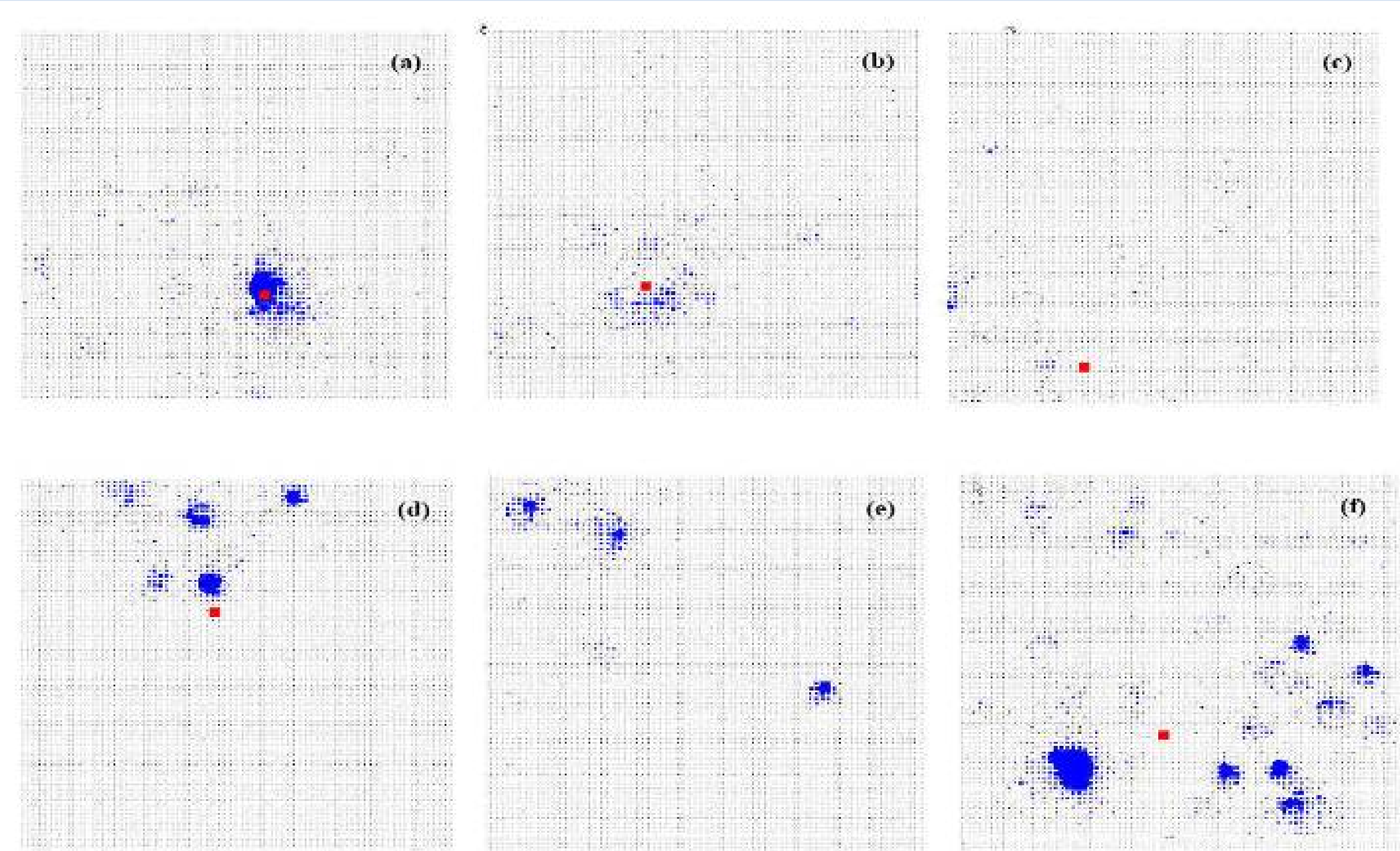
Size of HAWC



Size of Milagro deep layer

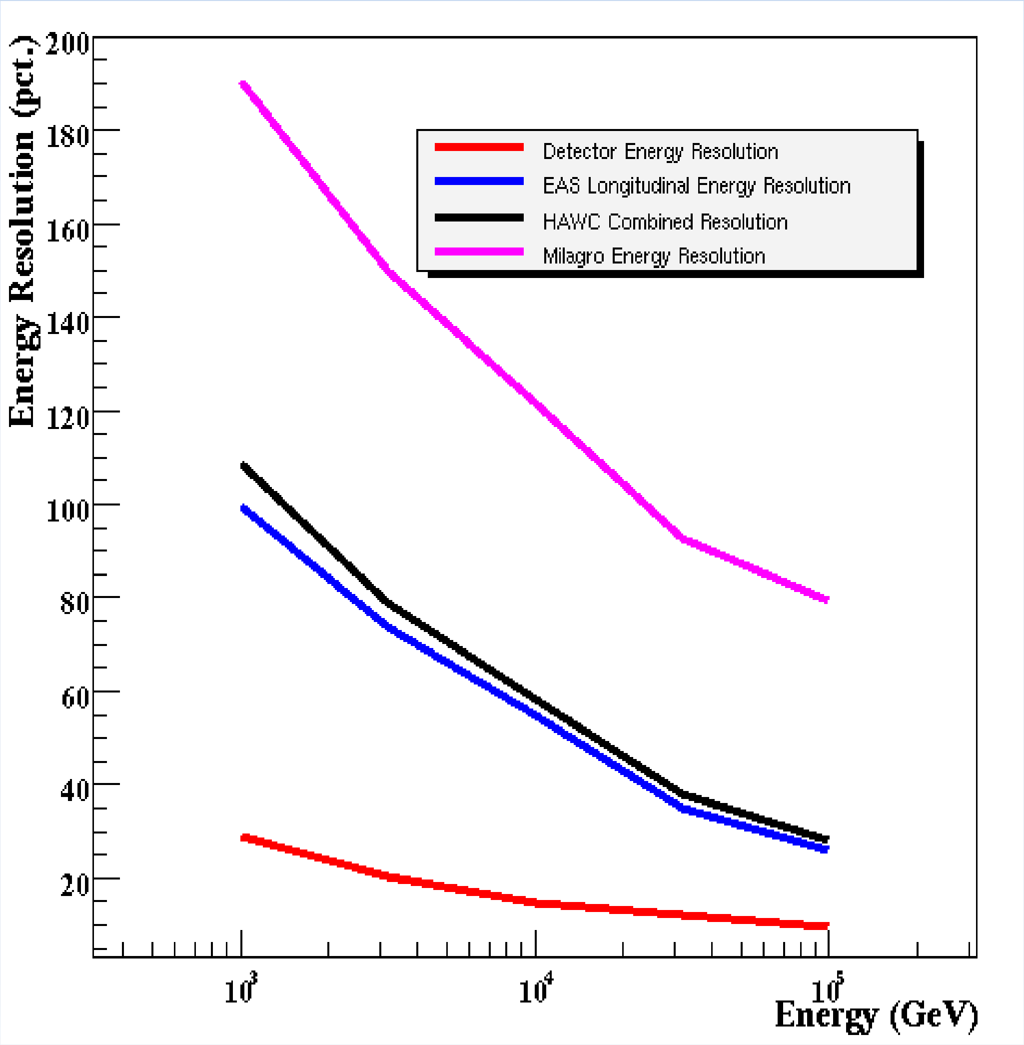
Gammas

Protons

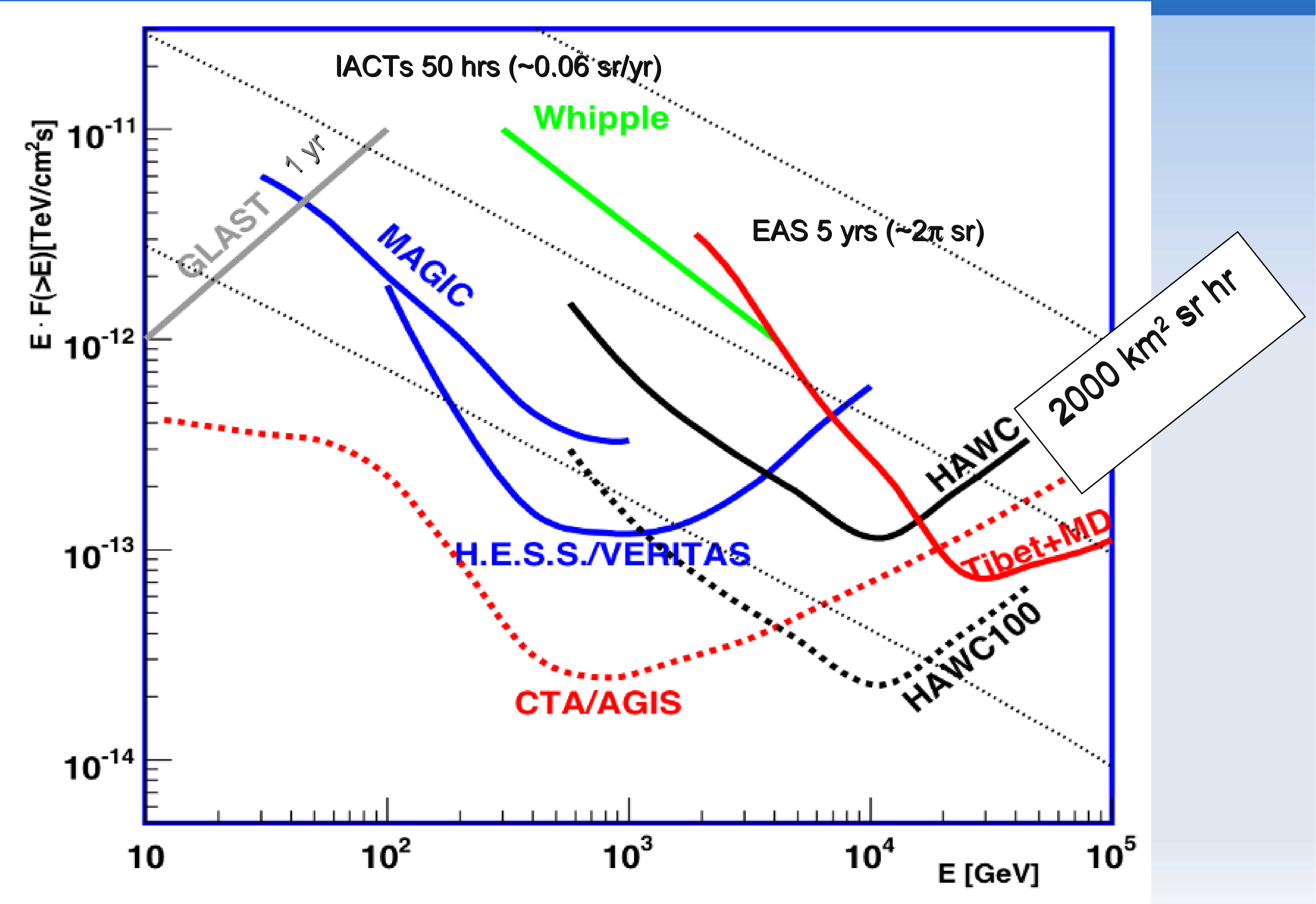


HAWC Performance: Energy Resolution

- EAS arrays can measure shower size very well (<20% resolution)
- Shower fluctuations (depth of 1st interaction) dominate energy resolution of array.
- Because of increased altitude HAWC will have much better energy resolution than Milagro



Point Source Sensitivity Comparison

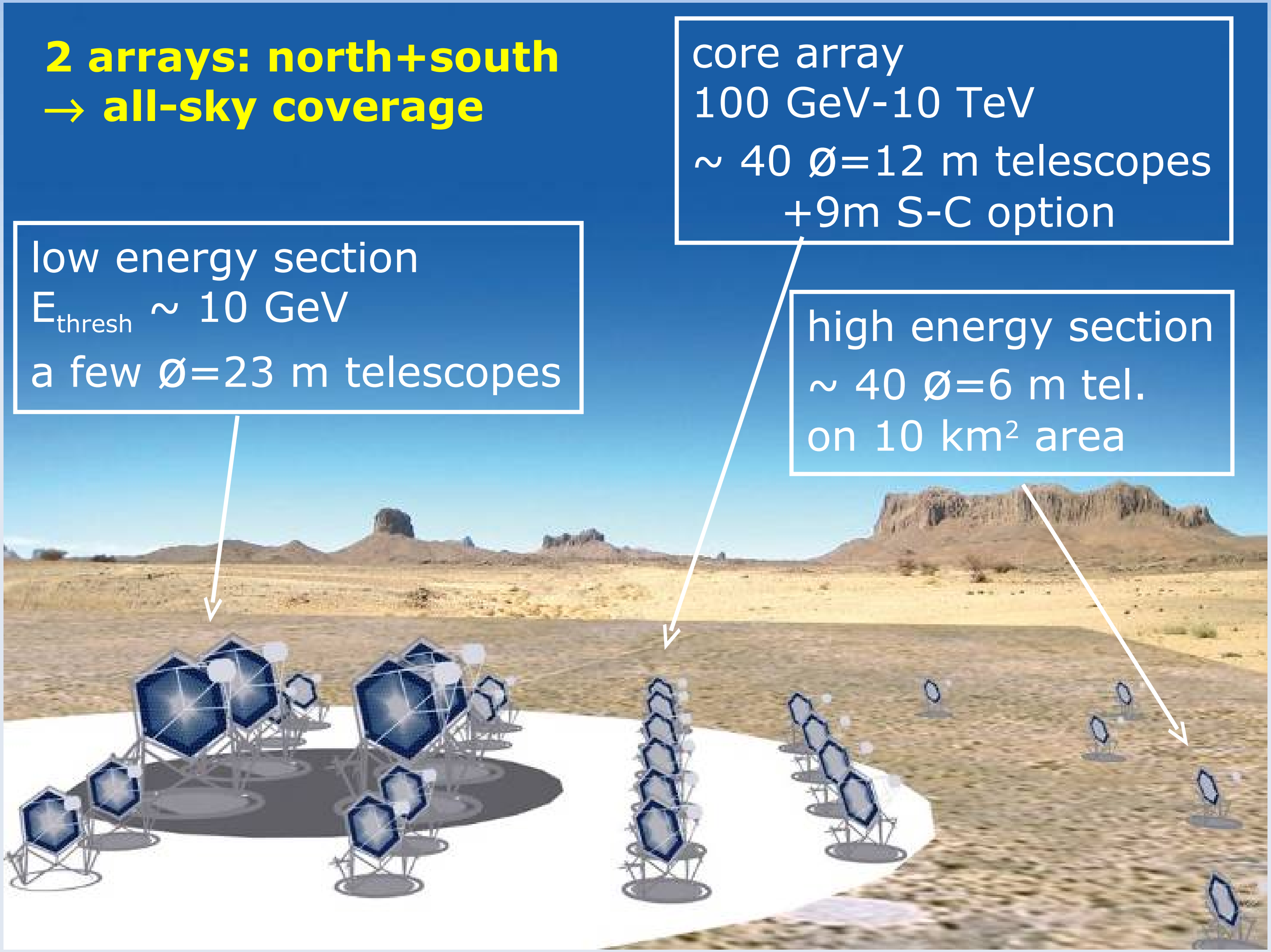


Le futur pour les ACTs

CTA

See “CTA Design Concepts”
arXiv:1008.3703v2

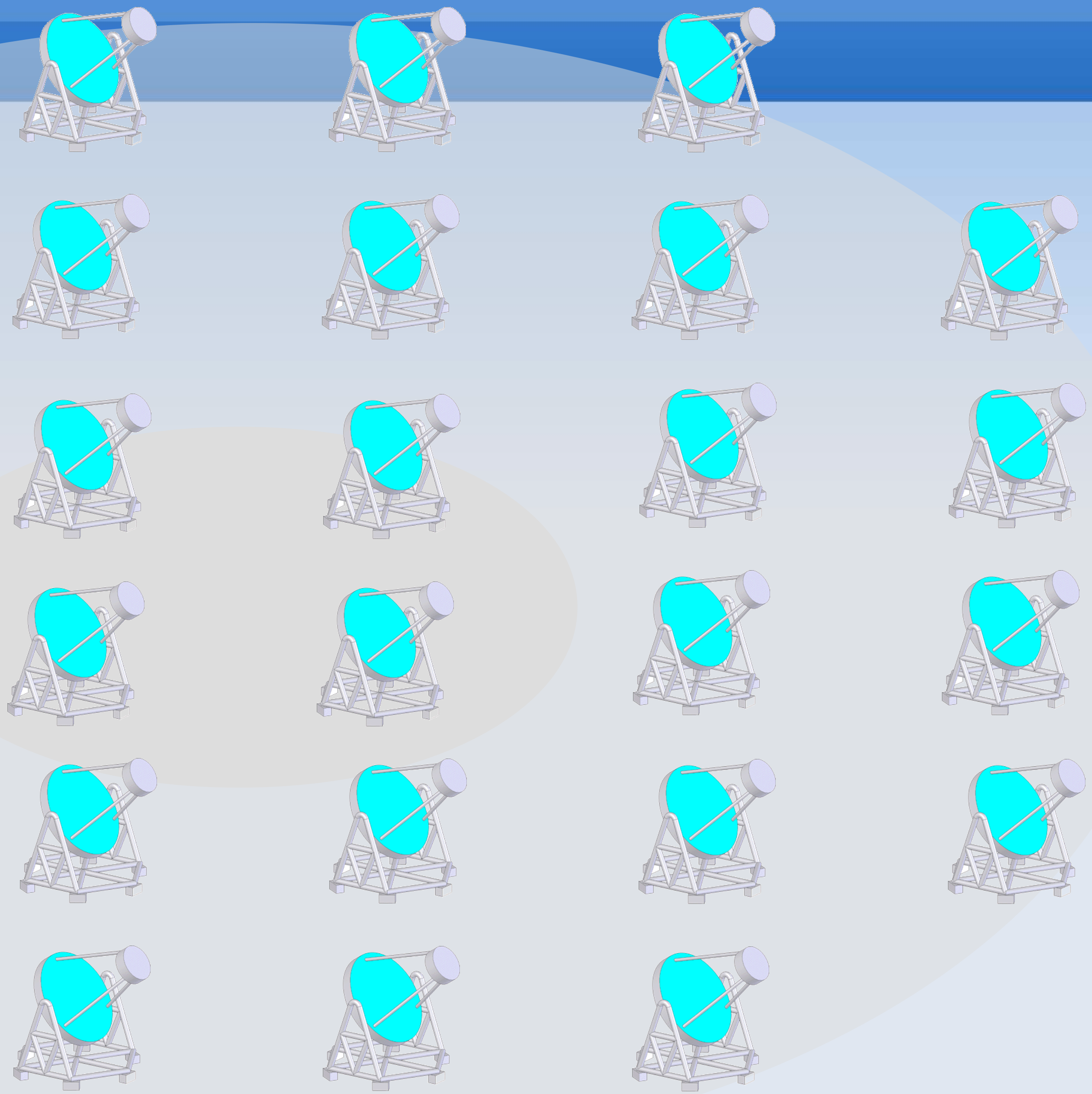
The CTA concept



CTA Ambitions and Performance goals

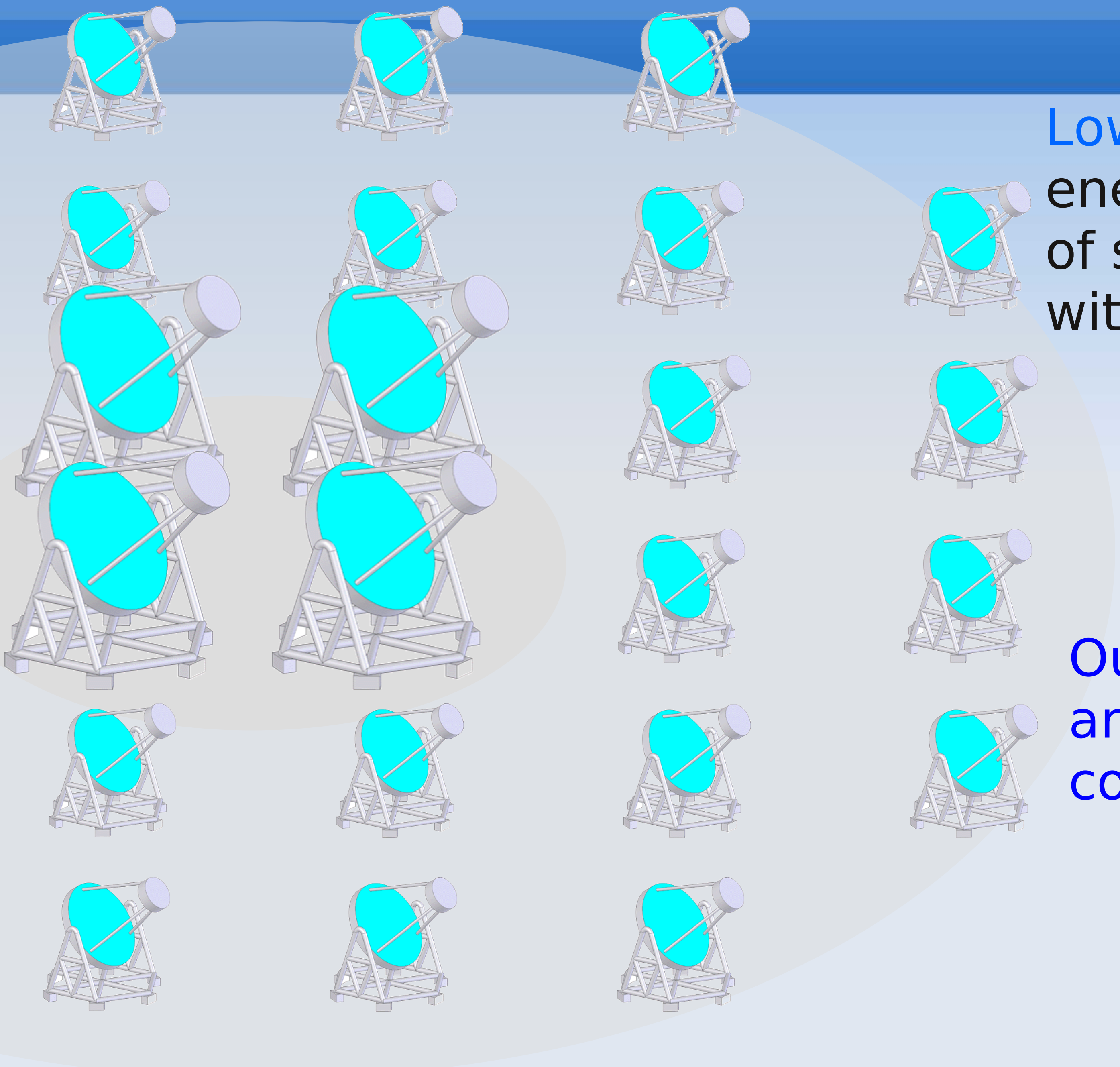
- Build on the extraordinary success of the current IACTs
  to create the future ground-based gamma-ray observatory
- Jump of factor 10 in sensitivity, down to mCrab: deeper VHE vision
- Very large spectral coverage: a few 10 GeV to above 100 TeV:
  New source classes, explore emission mechanisms
- Improved angular resolution down to arc-minute range: fine mapping
- Temporal resolution down to sub-minute time scale:
  a VHE timing explorer
- Flexibility of operations:
  deep field, monitoring, survey, alarms
- Full sky coverage using North & South installations

- Can achieve these goals with
  two extended, mixed arrays of Cherenkov telescopes



Core array:
mCrab sensitivity
in the 100 GeV–10 TeV
domain

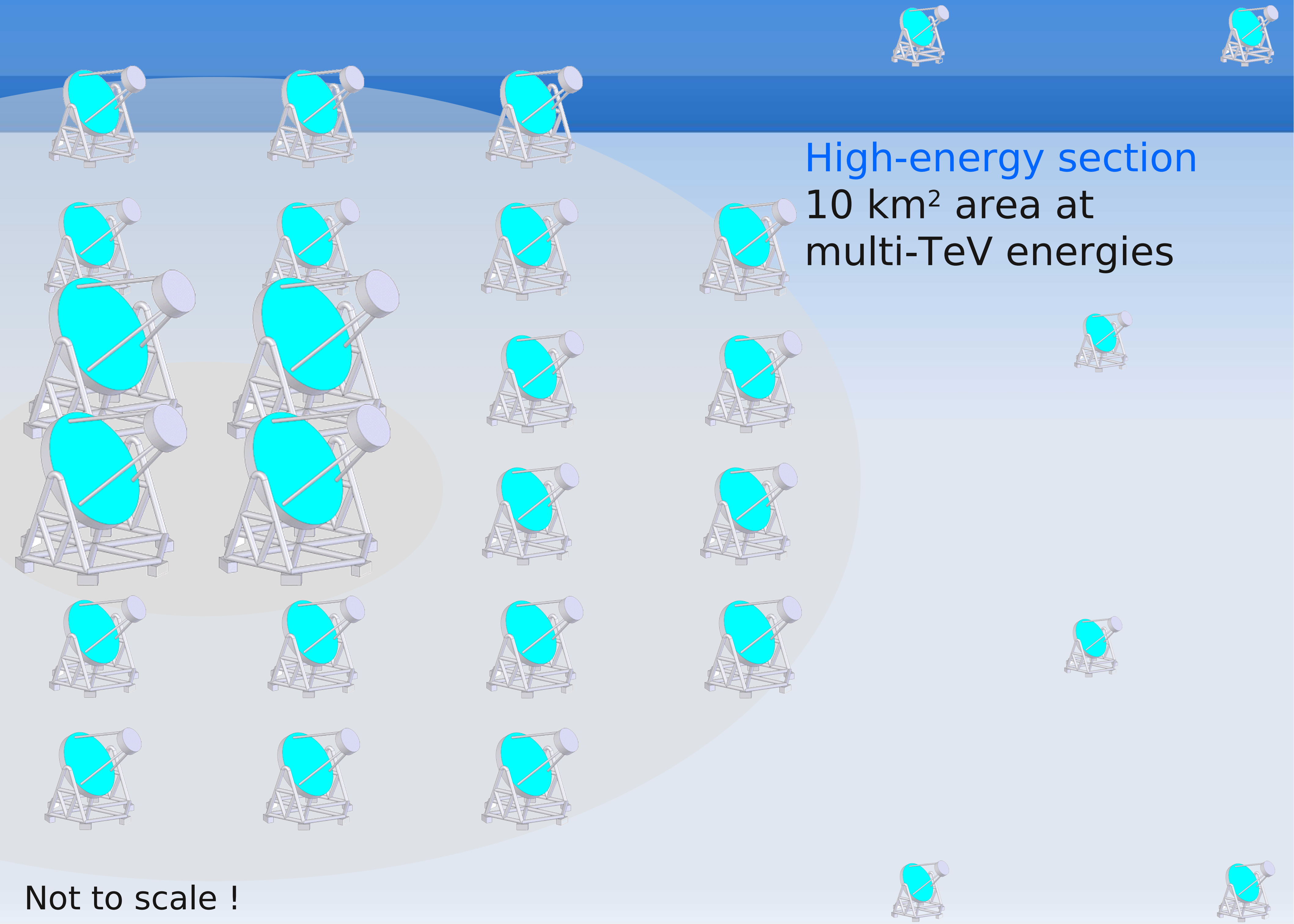
Not to scale !



Low-energy section
energy threshold
of some 10 GeV
with bigger dishes

Outer telescope
array serves as
cosmic-ray veto!

Not to scale !



High-energy section

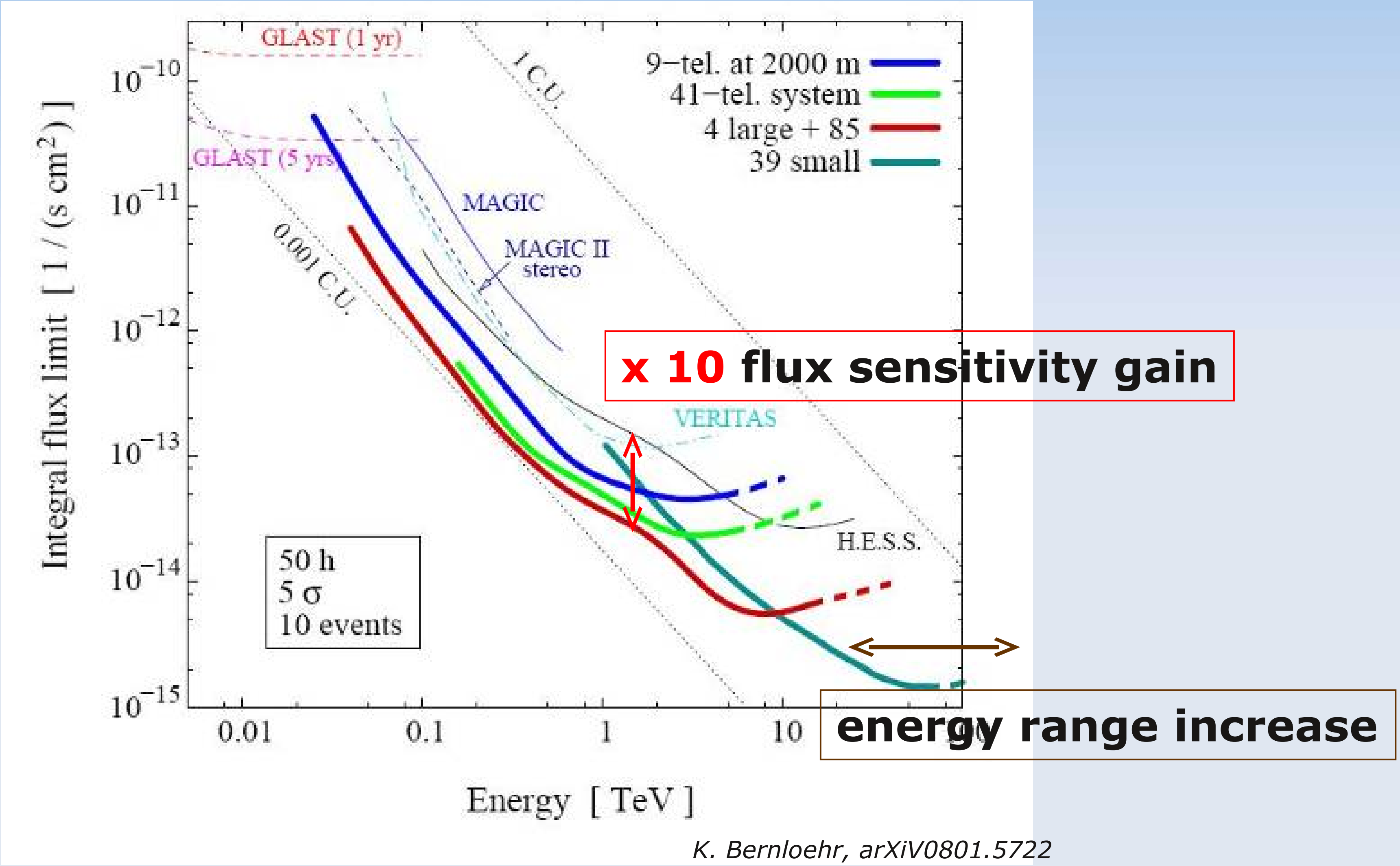
10 km² area at multi-TeV energies

Not to scale !

CTA technical realisation

- The technology to build CTA is available, base-line solutions:
  "Prototypes" exist with HESS-I/II, MAGIC-I/II, VERITAS ...
- Great challenges concern cost and reliability/durability
  - ~100 telescopes in remote locations ± 10k€ each ⇒ ± 1M€
  - O(100 000) electronics channels ± 10€ each ⇒ ± 1M€
  - O(10 000m^2) mirror area ± 100€/m^2 ⇒ ± 1M€
- Require x10 increase in sensitivity with x10 cost factor
- Developments are under-way to address these issues
  (e.g., fuller integration of electronics functions on ASICs)
- Some parallel speculative research taking place,
  planned design should allow integration if mature or
  in later upgrade cycles (e.g., SiPMs)
- Major studies proceeding on array optimization, mirror sizes, pixelization, field of view, etc... for best performance vs. cost

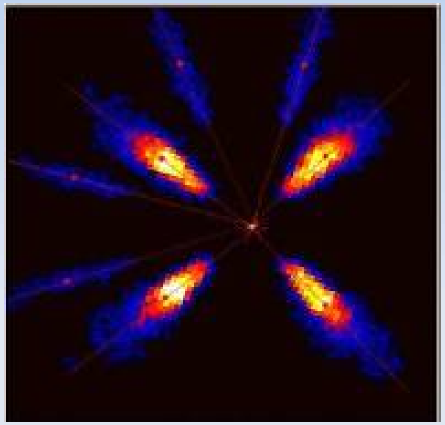
CTA Performances: array sensitivity

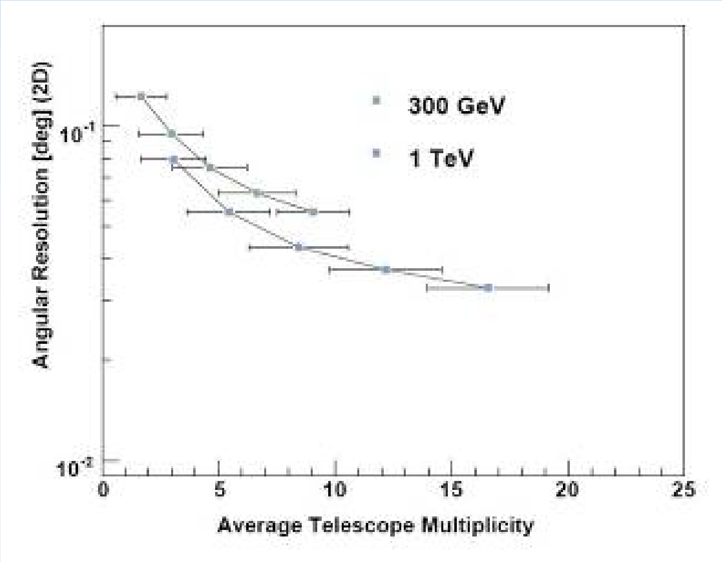


K. Bernloehr, arXiV0801.5722

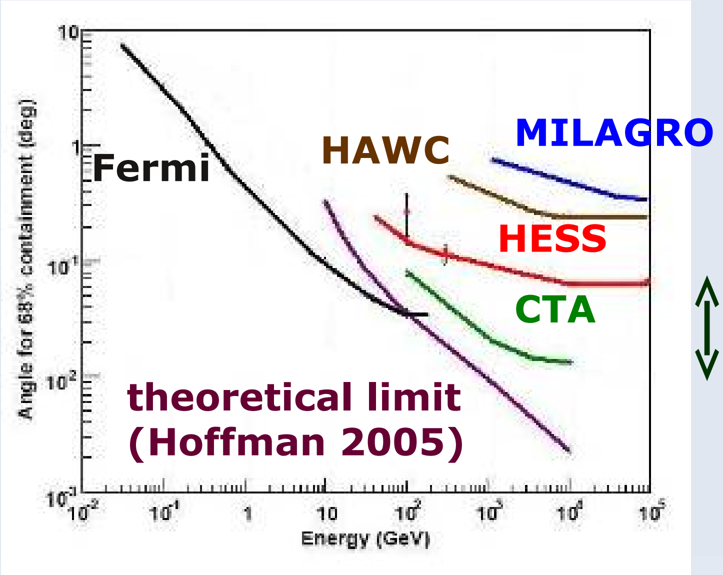
CTA Performances: angular resolution

- Angular resolution improves as more telescopes used in reconstrution





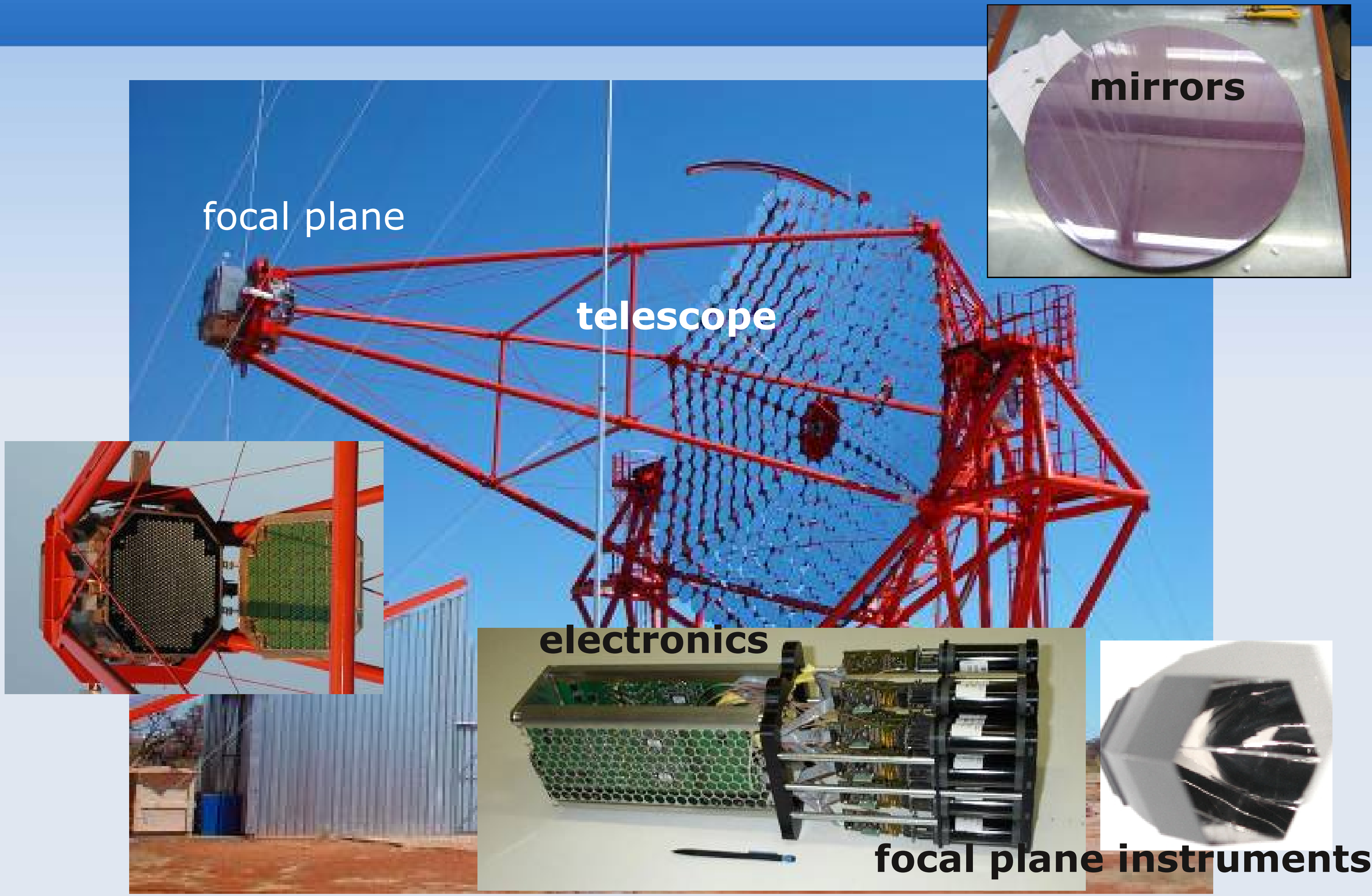
- Angular resolution
closer to theoretical limit



factor **3**
improvement

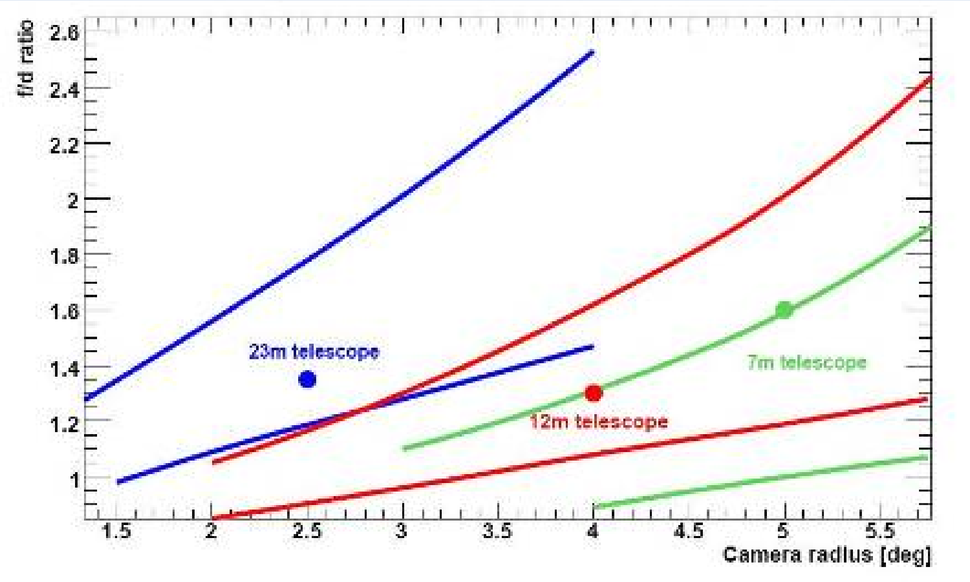
S.Funk, J.A. Hinton, arXiV0901.2153

CTA elements



CTA : Requirements for telescopes

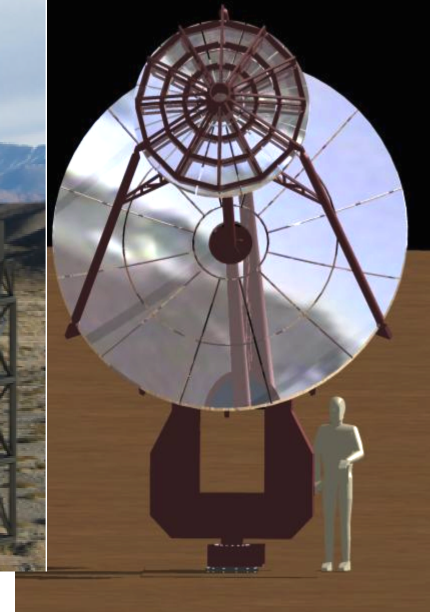
- dish ø=6 m (small) ø=12 m (medium) ø=23 m (large)
- dish shape spherical (Davies-Cotton): S+M, parabolic (L)
- f/d = 1.4 (M) and 1.2-1.4 (L)



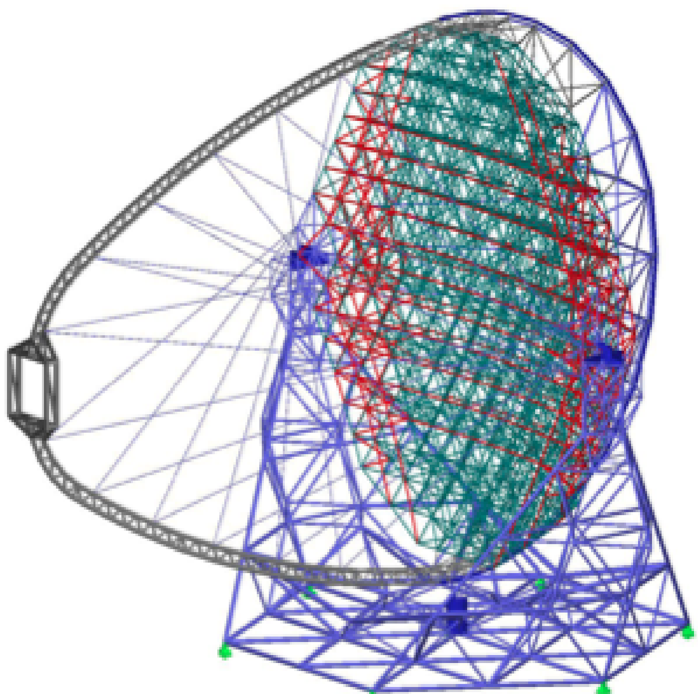
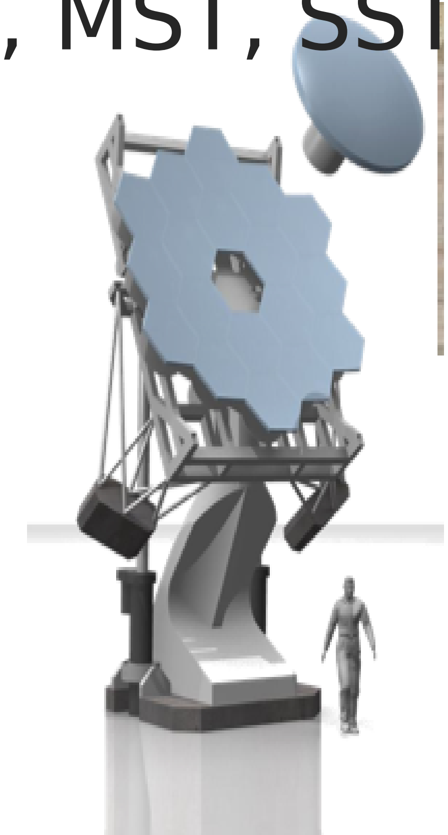
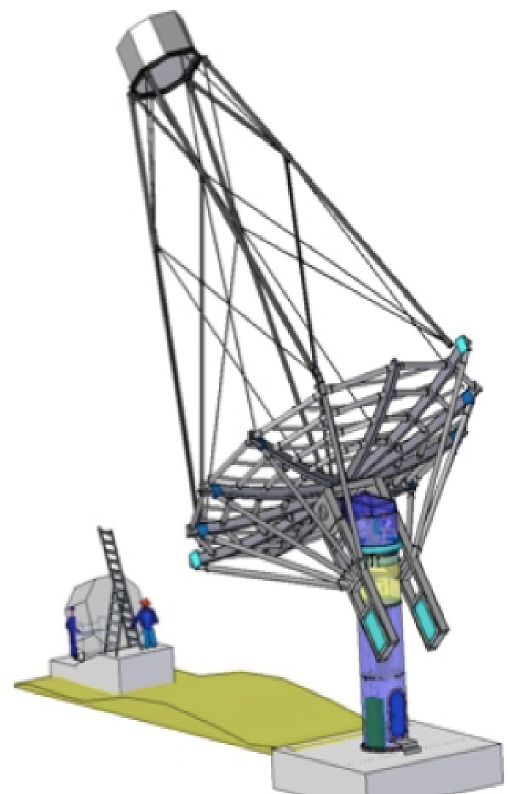
P.Colin

- Camera Field of View: 8° (M), 5° (L)
- Number of pixels in camera ~ 1500 (M), ~2500 (L)
- Camera weight: 2.5 tons (M), 2 tons (L)

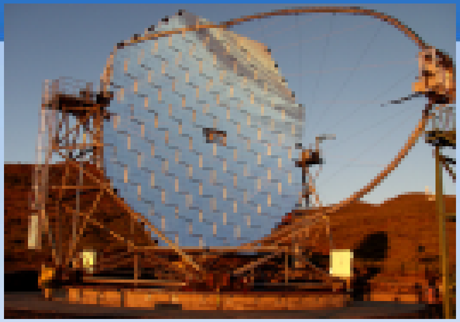





- Options for LST, MST, SST

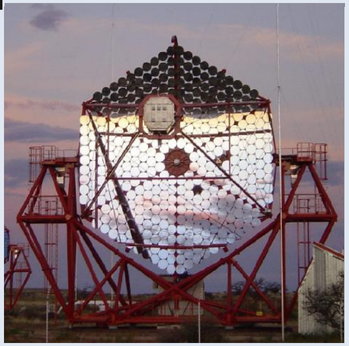




CTA – Telescope structure goals



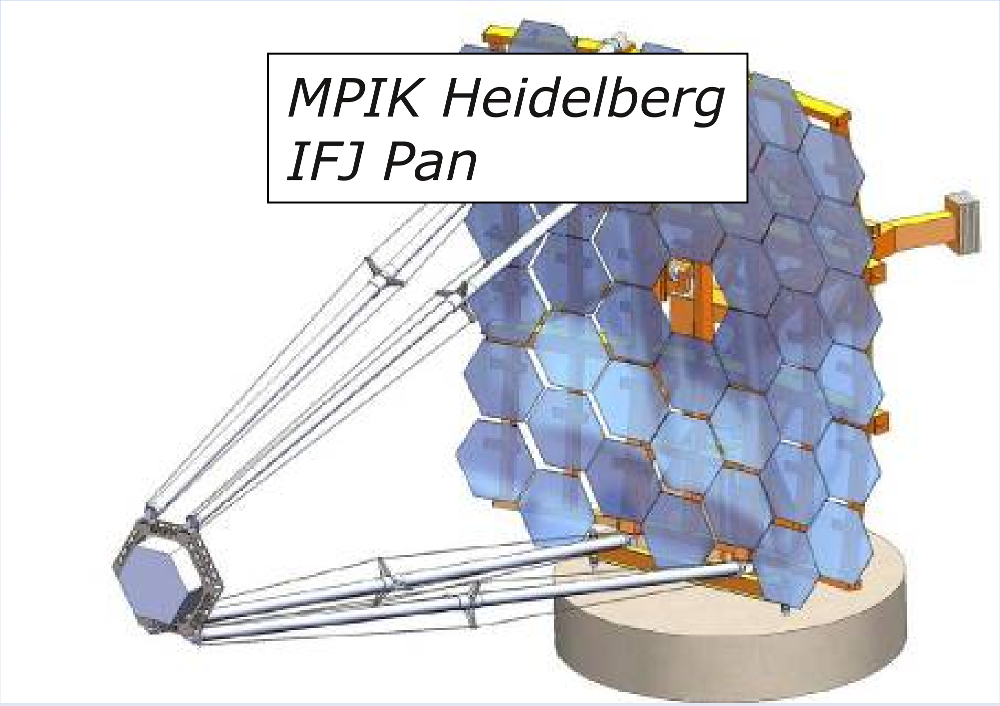
- Three telescope sizes being studied
  for full energy-range coverage,
  size S/M/L for diameters 6/12/23m
- “Standard” optics (no secondary) as base-line
- Field of view adapted to telescope size
  / physics goals / cost (6-8° for S/M, 5° for L)

- Dish type adapted to size (spherical for S, parabolic for L)
- f/D as large as affordable (1.4 – 2)
- Use of commercial positioners (S/M, L?)
- Stiffness adapted to active mirror control for PSF < 1mrad



- Elastic deformations of structure only
- 30 year lifetime (cf. Whipple > 40 years old)
- Failure rate an order of magnitude below current

CTA : Small size telescope

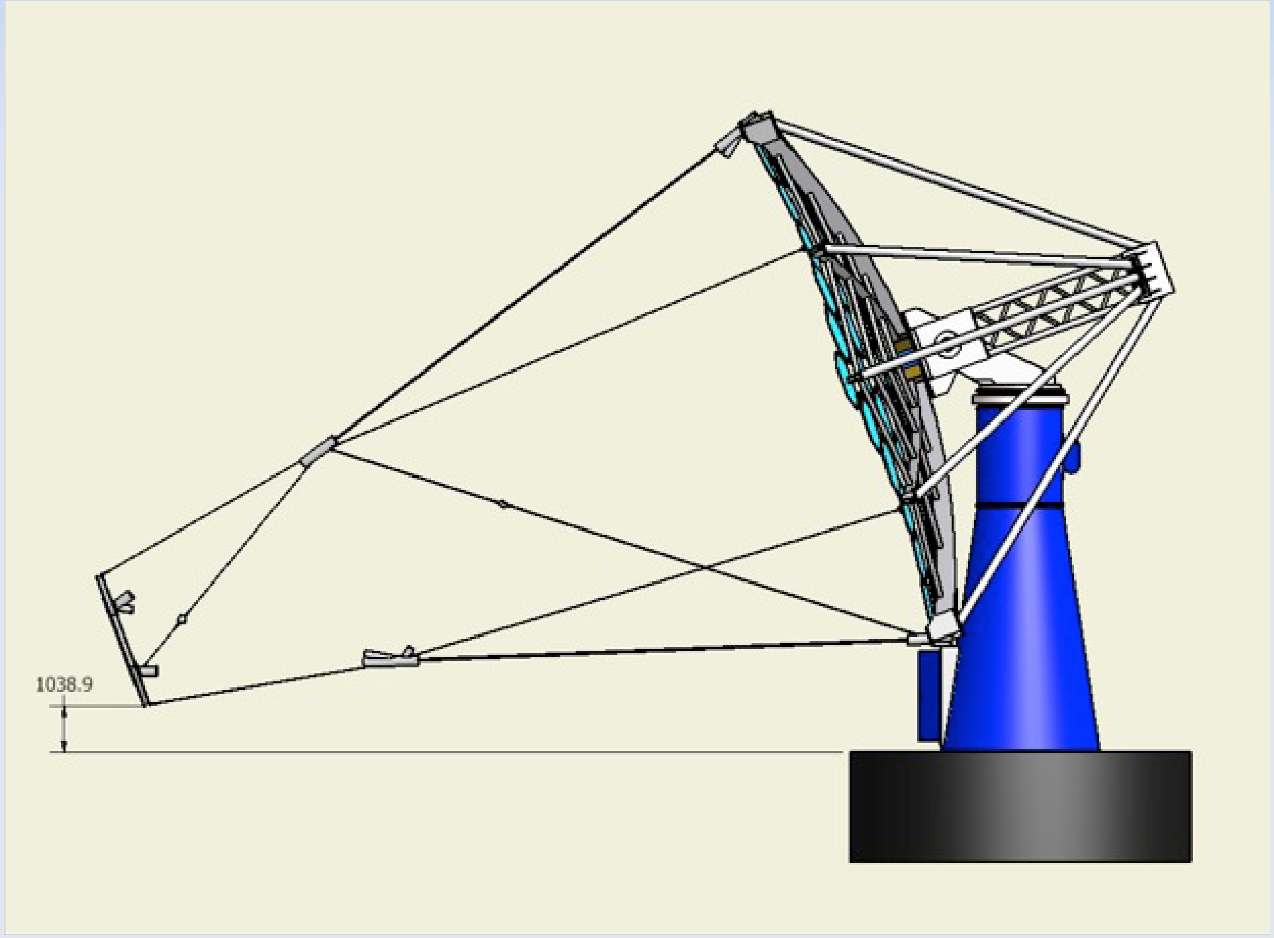


- 2 options:
  - (baseline) 6 meter dish, camera 9 deg FOV, 1300 PMT
  - 2 mirror design, primary mirror 3.5 m, camera 8 deg FOV, 1600 pixels MAPMT or SiPM

12-meter class telescopes

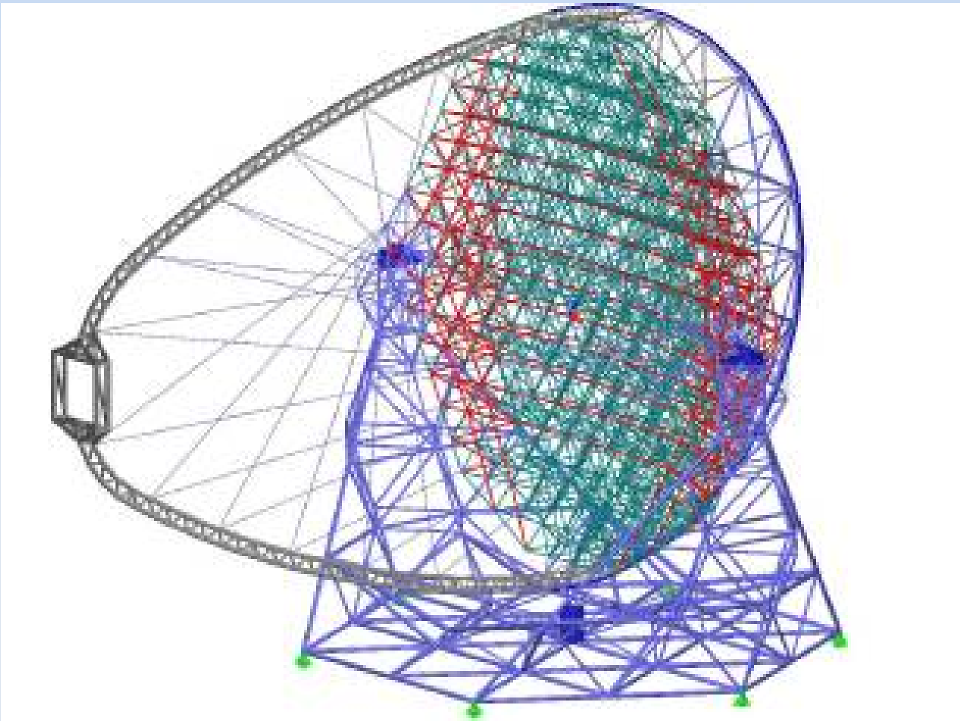
12-meter class telescopes (2)

- *DESY (Zeuthen, Hamburg), ANL, IRFU Saclay* design
- Prototype to be built in Berlin in 2010-2011



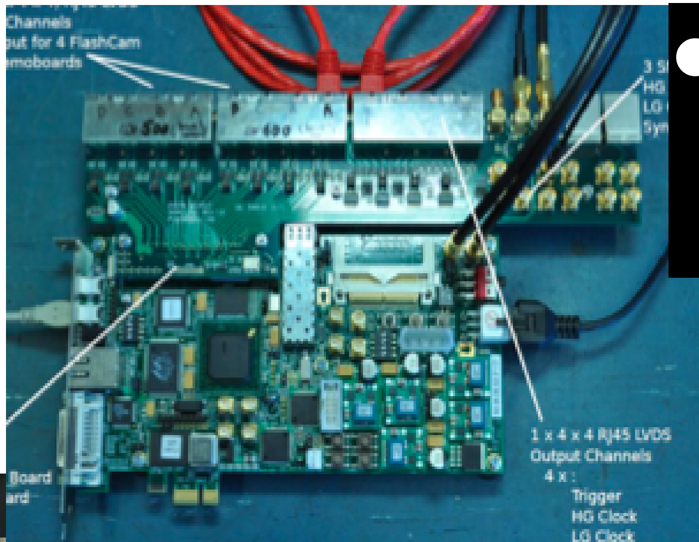
23-meter class telescopes

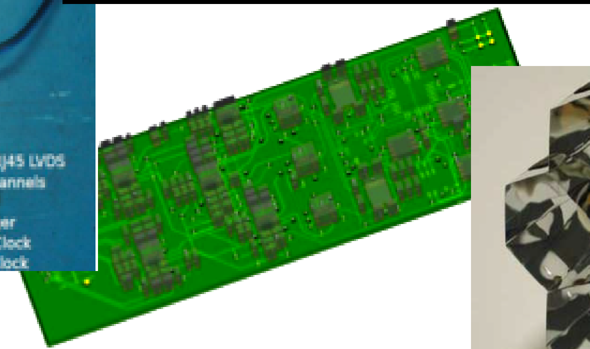
- possible design: extrapolate MAGIC 17 m telescopes

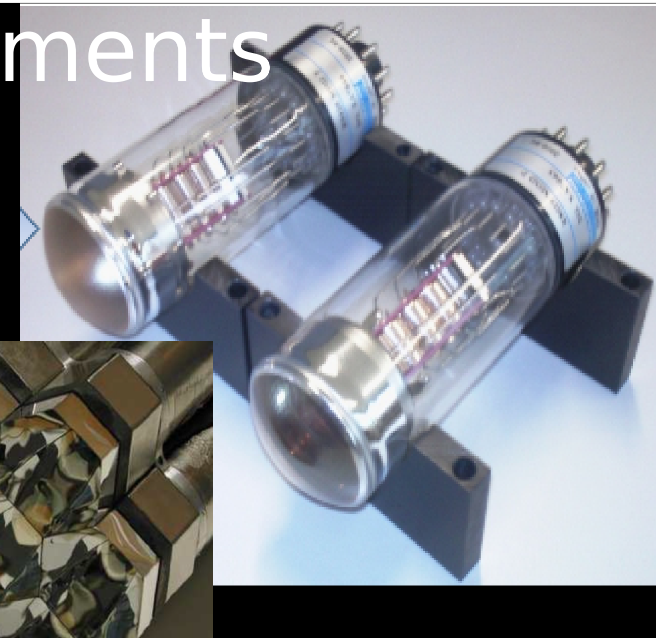


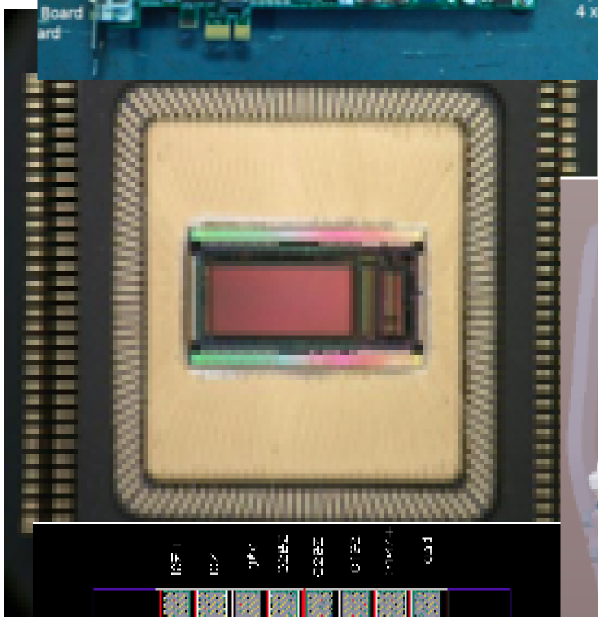
MERO (company) design
MPI-P Munich, LAPP Annecy

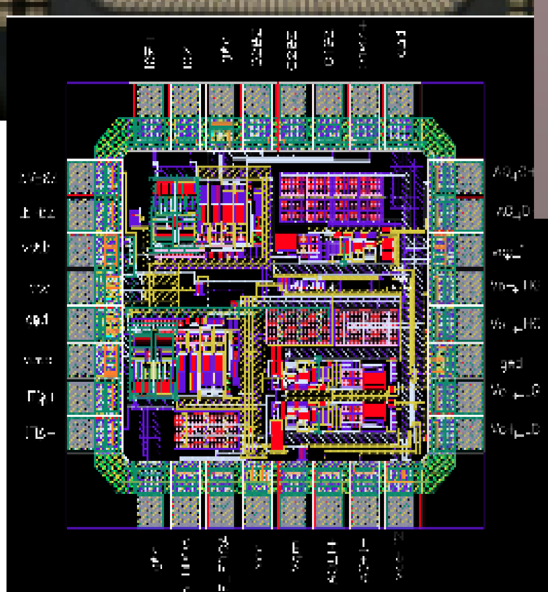
- Camera Elements

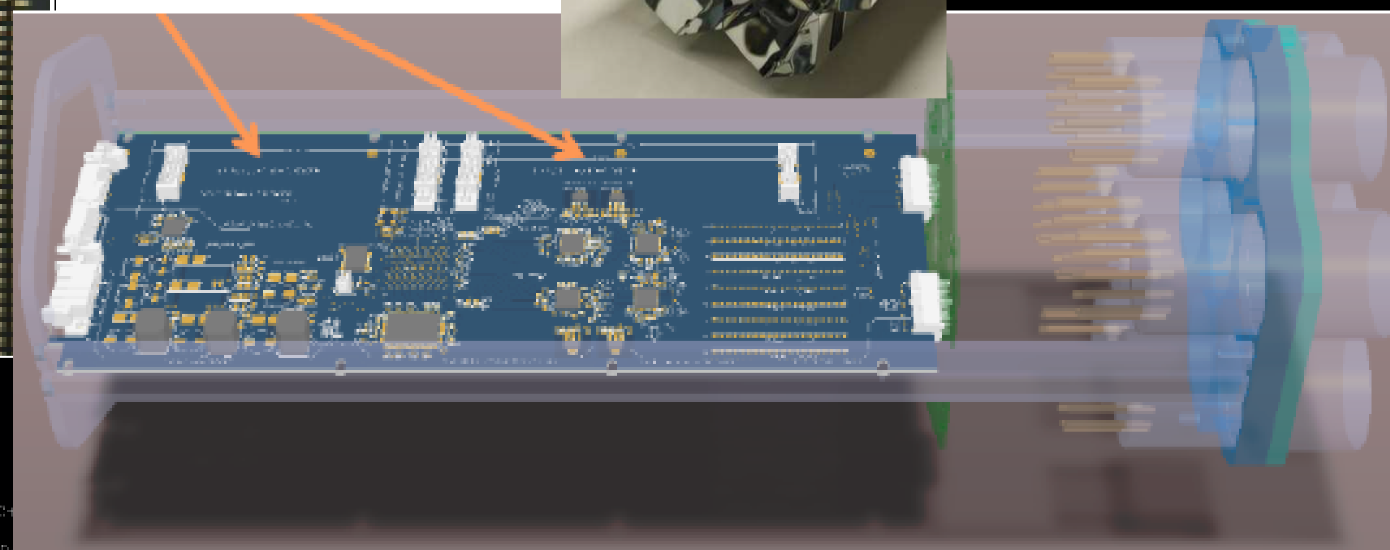


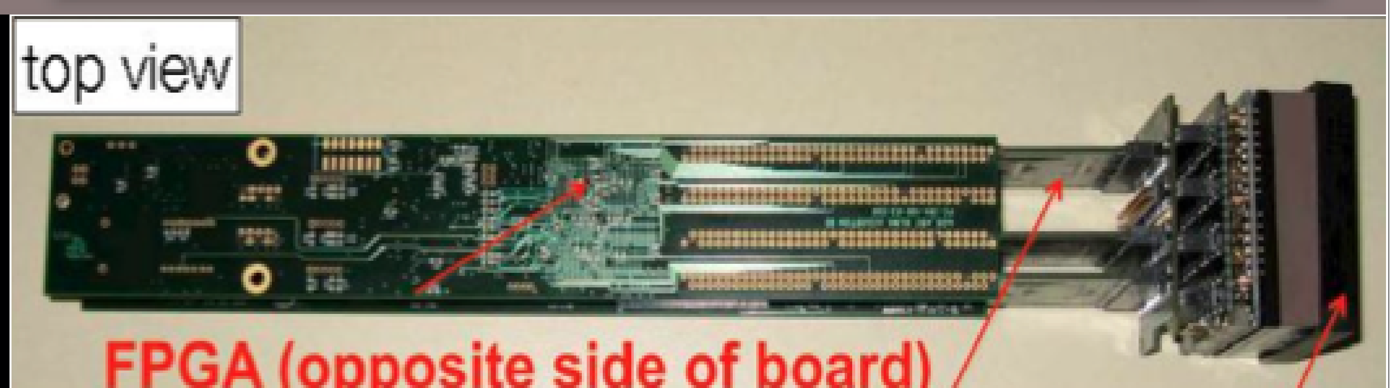










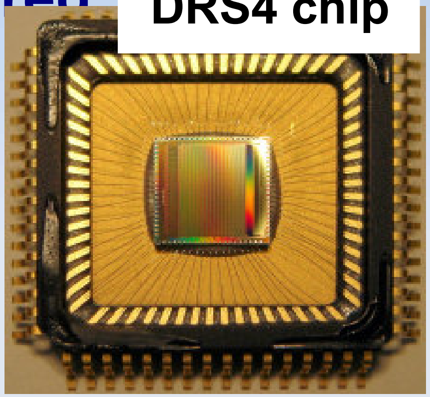


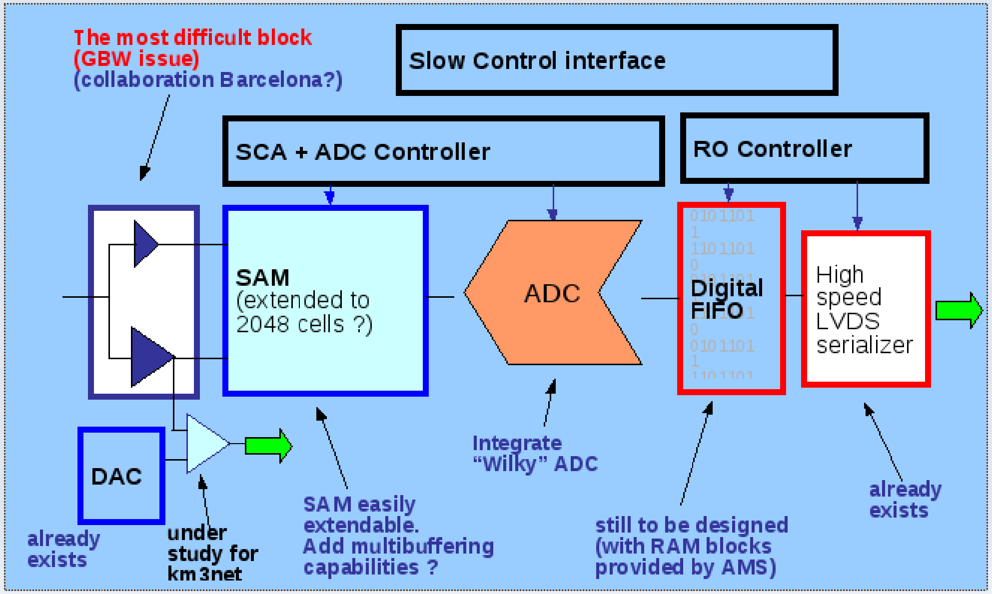
Electronics for CTA

- Analogue pipeline solution for the in-camera acquisition, several GHz-sampling most probable solution (existing SAM, DRS3, future DRS4, NeCTAr, from IRFU/IN2P3 and PSI/Pisa). Aim to integrate the maximum functionality in ASIC **(=cost+reliability)**
- **Alternative "Fully-digital camera (FlashCam) being explored**
- NeCTAr

  Amplification followed by long analogue pipeline (17-bit dynamic)
  Pixel-level trigger comparator controlled by DAC level
  On-board ADC for conversion
  Digital FIFO and serializer for data transmission
  Ethernet-output?
  Goal 300€/channel incl. PM

DRS4 chip





DRS4

1024 sampling cells per channel

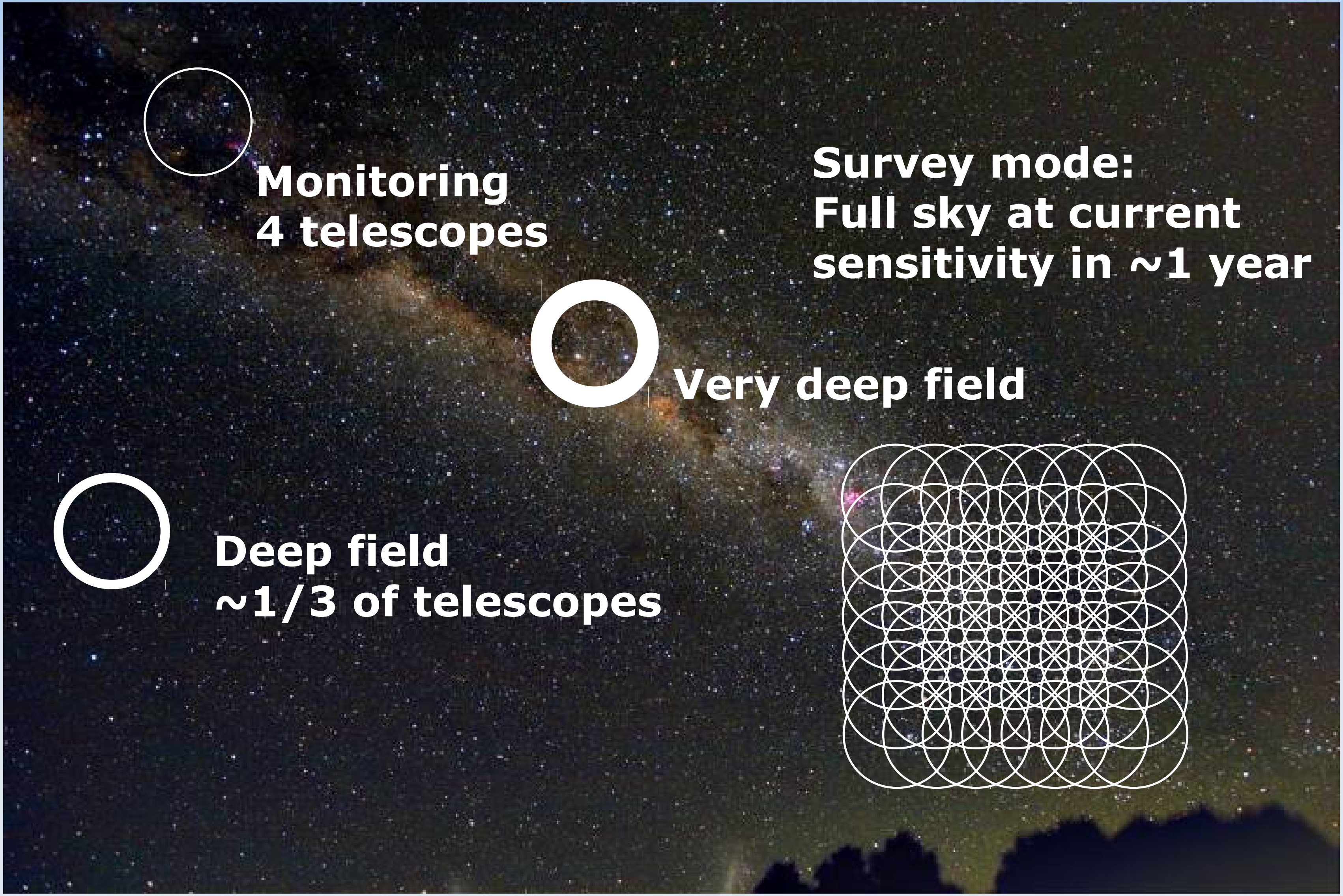
High speed	6 GHz,
High density	8+1 channels/chip
High resol.	11.5 bit
Timing resol.	3 ps
Readout speed	30MHz

Low power (10-40 mW / channel)

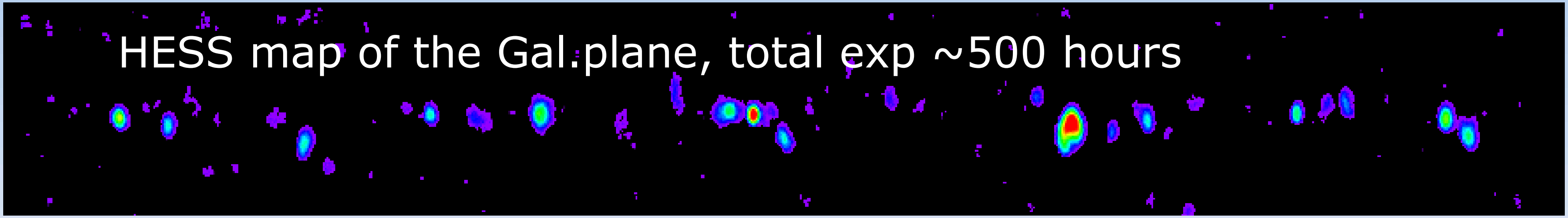
Low cost (~ 10$ / channel, excl external components)

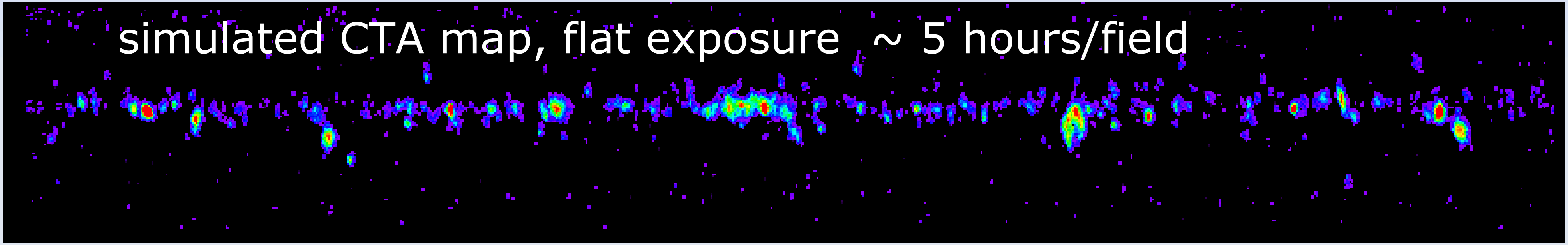
But, External ADC needed

CTA operation modes



CTA : Expectations for Galactic plane survey





Funk,Hinton,Hermann,Digel, arXiV0901.1885

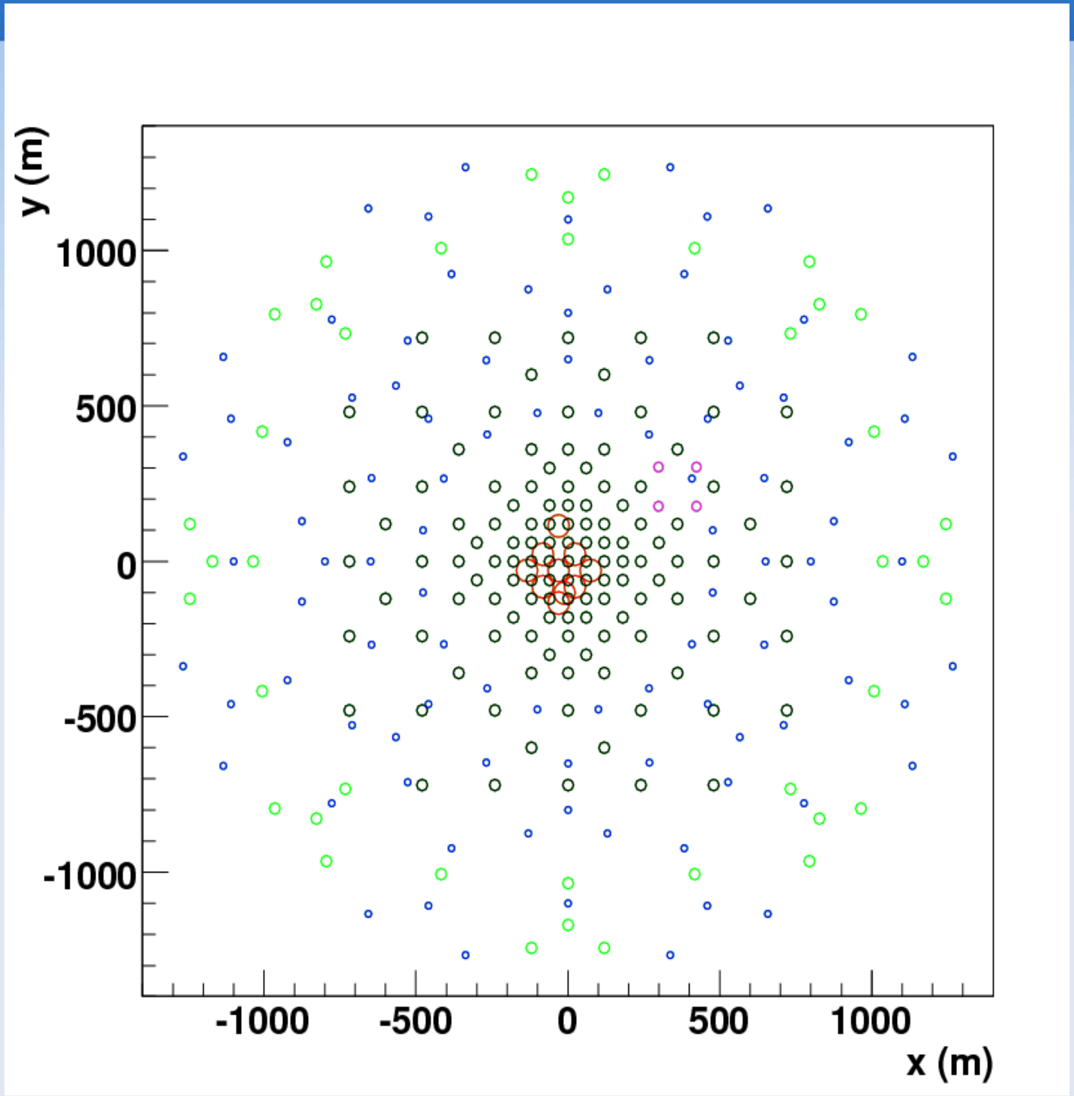
- x 2 improvement in hadron rejection
- x 2 gain in angular resolution
- x 10 gain in effective area

⇒ overall increase in sensitivity of ~ 9

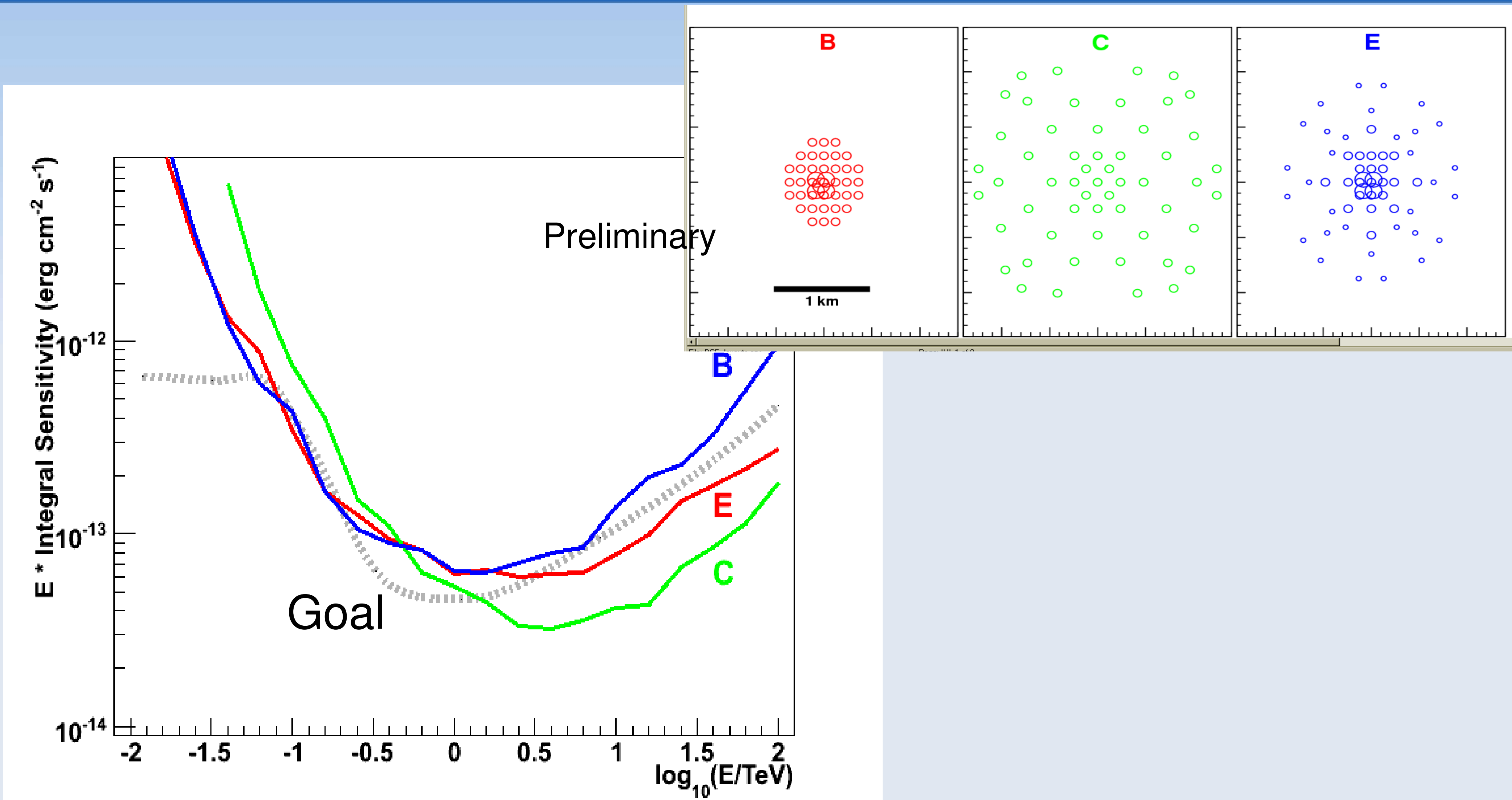
- expect ~ 300 sources in -30 deg≤ l ≤ 30 deg.

CTA full Monte-Carlo simulations

- Large scale simulation of "Hyper-array" with 275 telescopes of 5 different types, sizes, …
- Selection of candidate arrays under cost constraints (~40 candidate arrays)
- Huge library (~10^{11}showers) produced

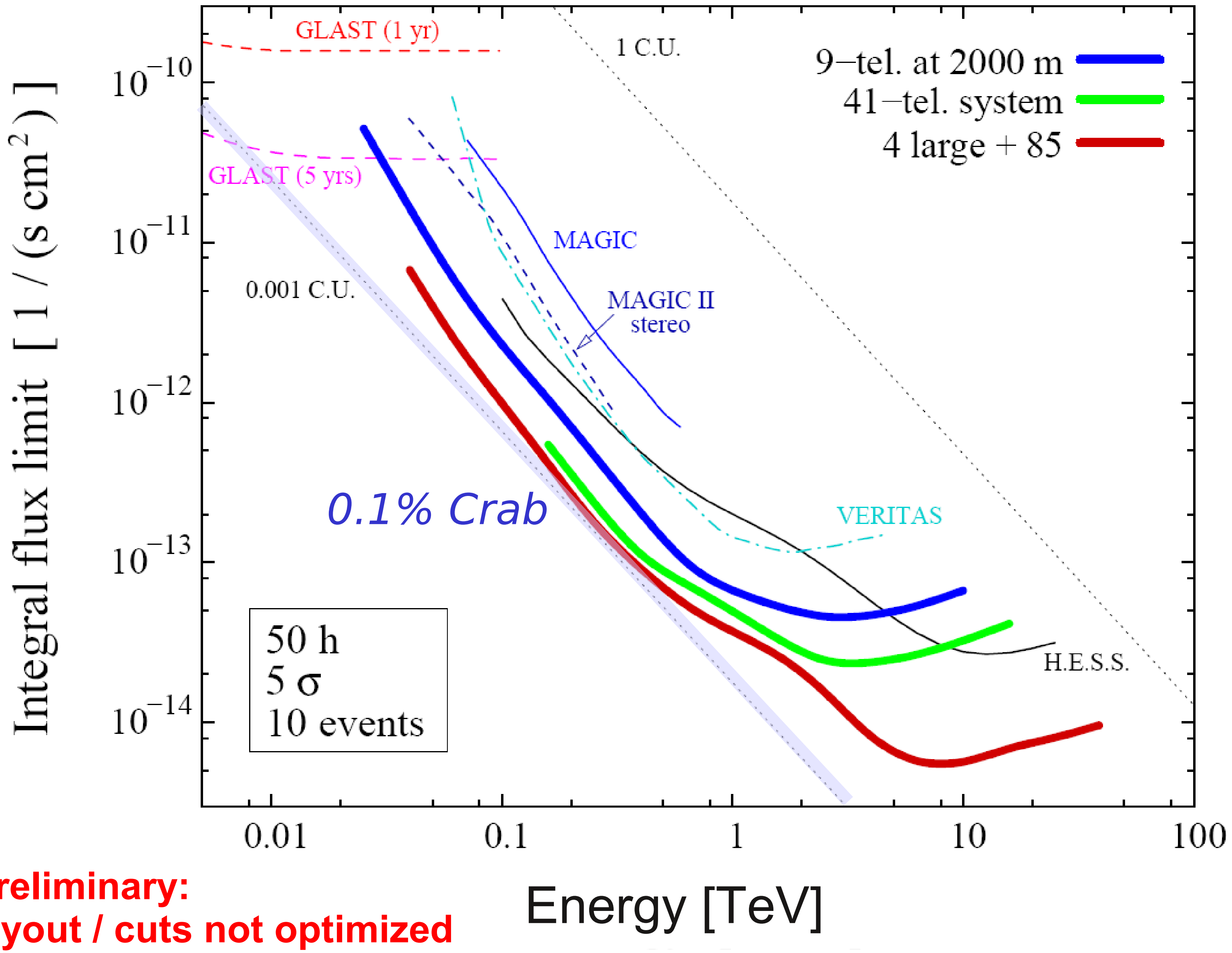


CTA Performance



- Preliminary – analysis and cuts not optimized
- Likely ~30% better with optimal analysis

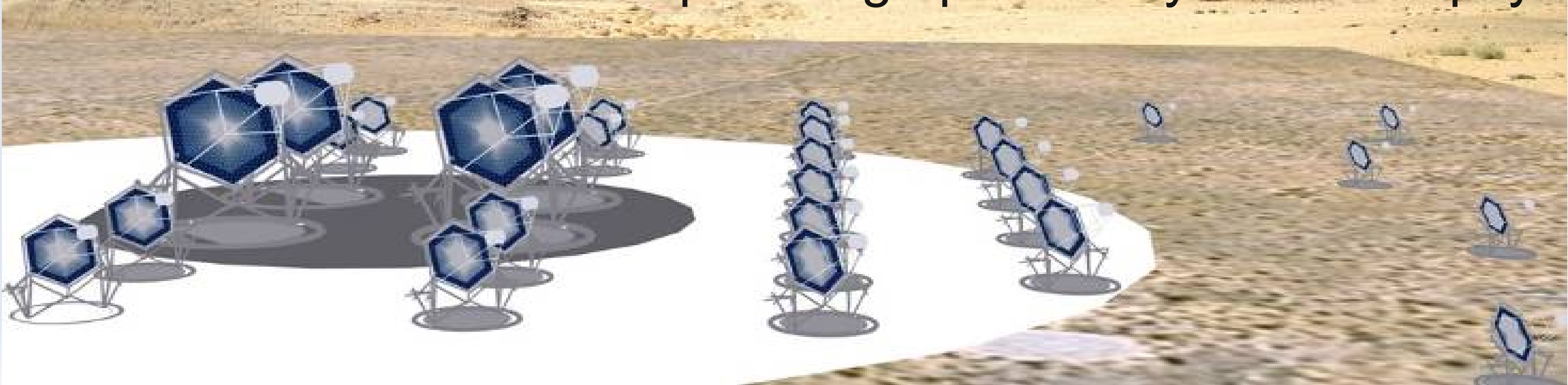
CTA comparison with current detectors



Preliminary:
layout / cuts not optimized

Conclusions

- VHE γ-ray astronomy, after a slow start, appears to have reached evolutionary equilibrium, with 2 ecological niches
  - Stereo-IACTs for deep and precise measurements
  - EAS arrays (esp. with water-technology) for wide-field monitoring
- For ACTs, convergence of all major groups/experiments worldwide for the design / construction of the future "Major Atmospheric Cherenkov Detector"
- Guaranteed scientific output + high probability of serendipity



That's all folks...

Example: Pixel size - How much is really needed?